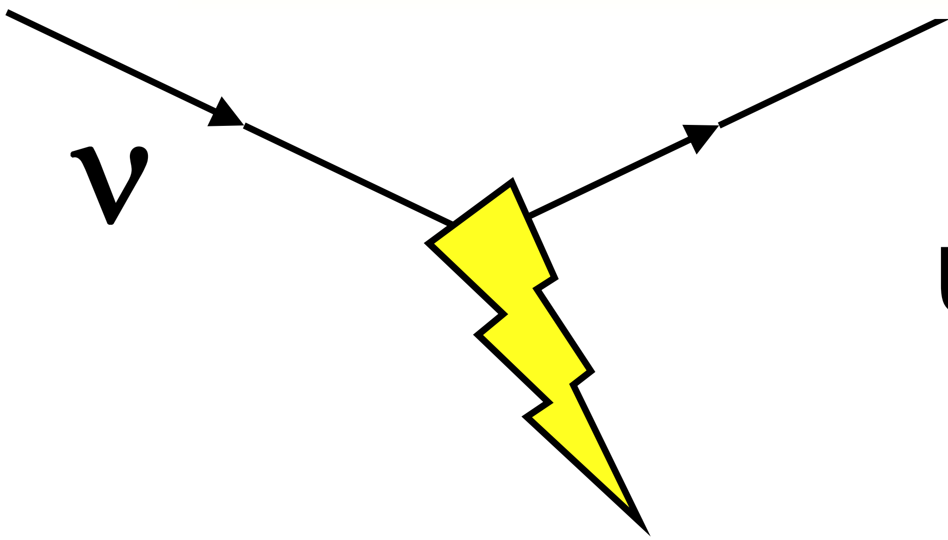
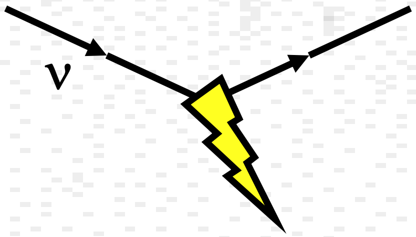
Interactions of Neutrinos at High and Low Energies



Kevin McFarland
University of Rochester
IMSc, Chennai
19-20 December 2011

Outline

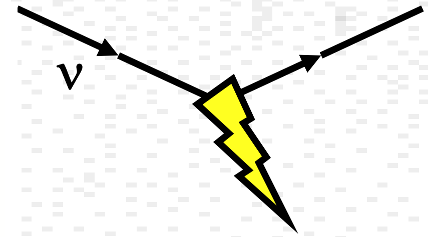


- Brief Motivation for and History of Measuring Neutrino Interactions
- Weak interactions and neutrinos
  - Elastic and quasi-elastic processes, e.g., νe scattering
  - Deep inelastic scattering, (νq scattering)
  - Other energies and difficulties of transition regions…
- Current & future cross-section knowledge
  - What we need to learn and how to learn it
  - How that knowledge is incorporated in generators

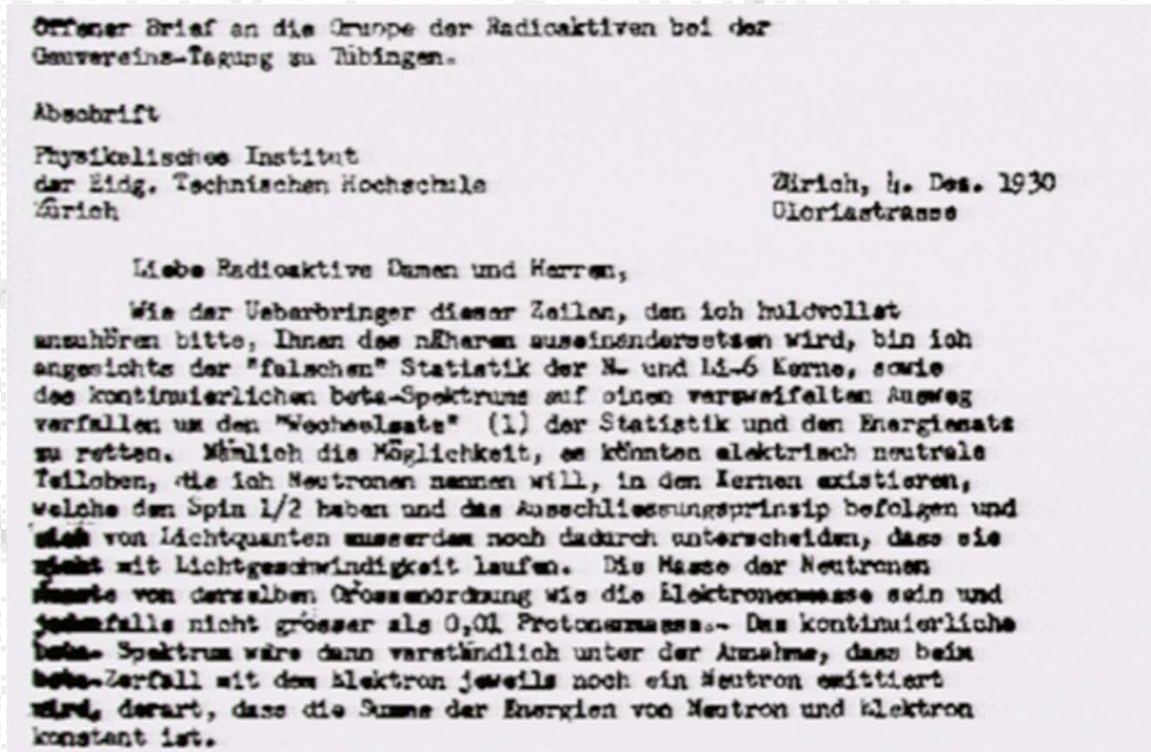
Focus of These Lectures

- This is not a comprehensive review of all the interesting physics associated with neutrino interactions
- Choice of topics will focus on:
  - Cross-sections useful for oscillation experiments
  - Estimating cross-sections
  - Understanding the most important effects qualitatively or semi-quantitatively
  - Understanding how cross-section knowledge is implemented in neutrino interaction generators

The Birth of the Neutrino



Wolfgang Pauli



Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

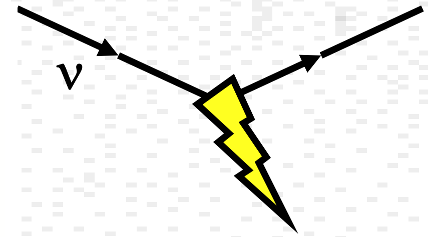
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

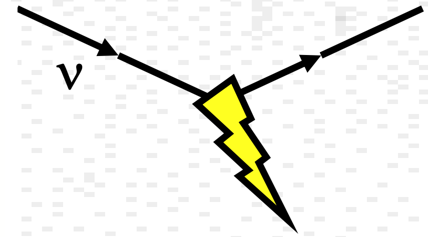
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Translation from the German, Please?

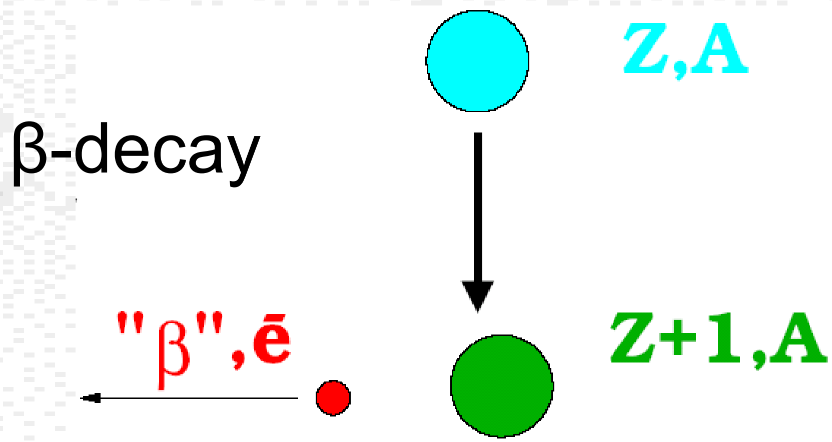


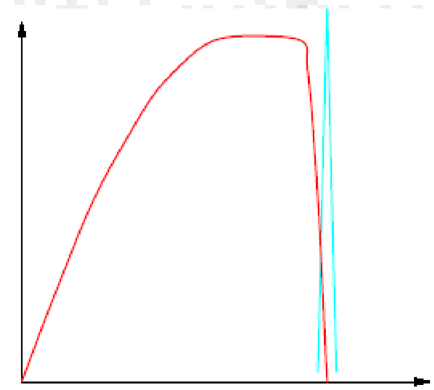
4th December 1930
Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7….
Your humble servant,
W. Pauli

Translation from the Archaic Physics Terms, Please?



- To save the law of conservation of energy?

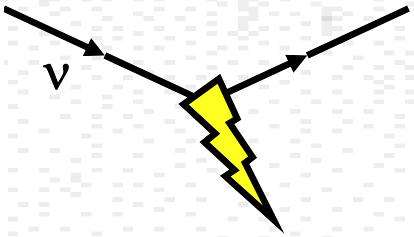




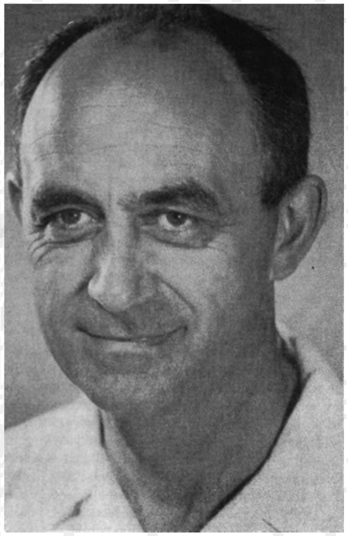
The Energy of the "β"

- If the above picture is complete, conservation of energy in this two body decay predicts monochromatic β
  - but a continuous spectrum had been observed (since 1914)
- Pauli suggests "neutron" takes away energy!
- *"The exchange theorem of statistics" refers to the fact that a spin½ neutron can't decay to an spin½ proton + spin½ electron*

Weak Interactions



- Current-current interaction Fermi, Z. Physik, 88, 161 (1934) $\mathcal{H}_w = \frac{G_F}{\sqrt{2}} \mathcal{J}^{\mu} \mathcal{J}_{\mu}$
  - Paper rejected by *Nature* because *"it contains speculations too remote from reality to be of interest to the reader"*

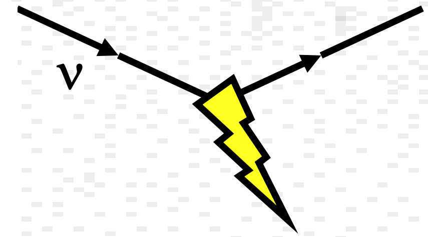


- Prediction for neutrino interactions
  - If $n \to pe^- \bar{\nu}$, then $\bar{\nu} p \to e^+ n$
  - Better yet, it is robustly predicted by Fermi theory
    - o Bethe and Peirels, Nature 133, 532 (1934)
  - For neutrinos of a few MeV from a reactor, a typical cross-section was found to be

$$\sigma_{\bar{\nu} p} \sim 5\times10^{-44}\,\mathrm{cm}^2$$

  - (Actually wrong by a factor of two (parity violation)

How Weak is This?

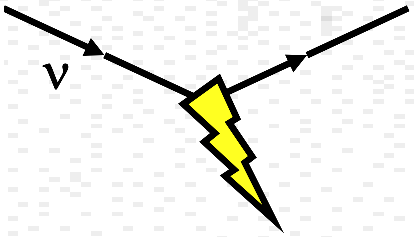


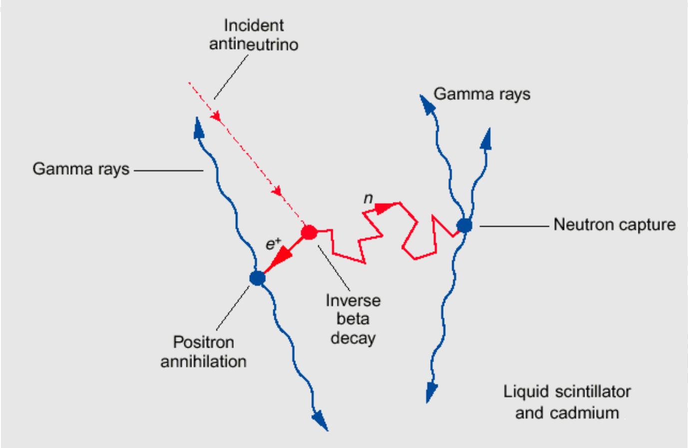
- $\sigma \sim 5 \times 10^{-44} cm^2$ compared with
  - $\sigma_{\gamma p} \sim 10^{-25}\ cm^2$ at similar energies, for example
- The cross-section of these few MeV neutrinos is such that the mean free path in steel would be 10 light-years

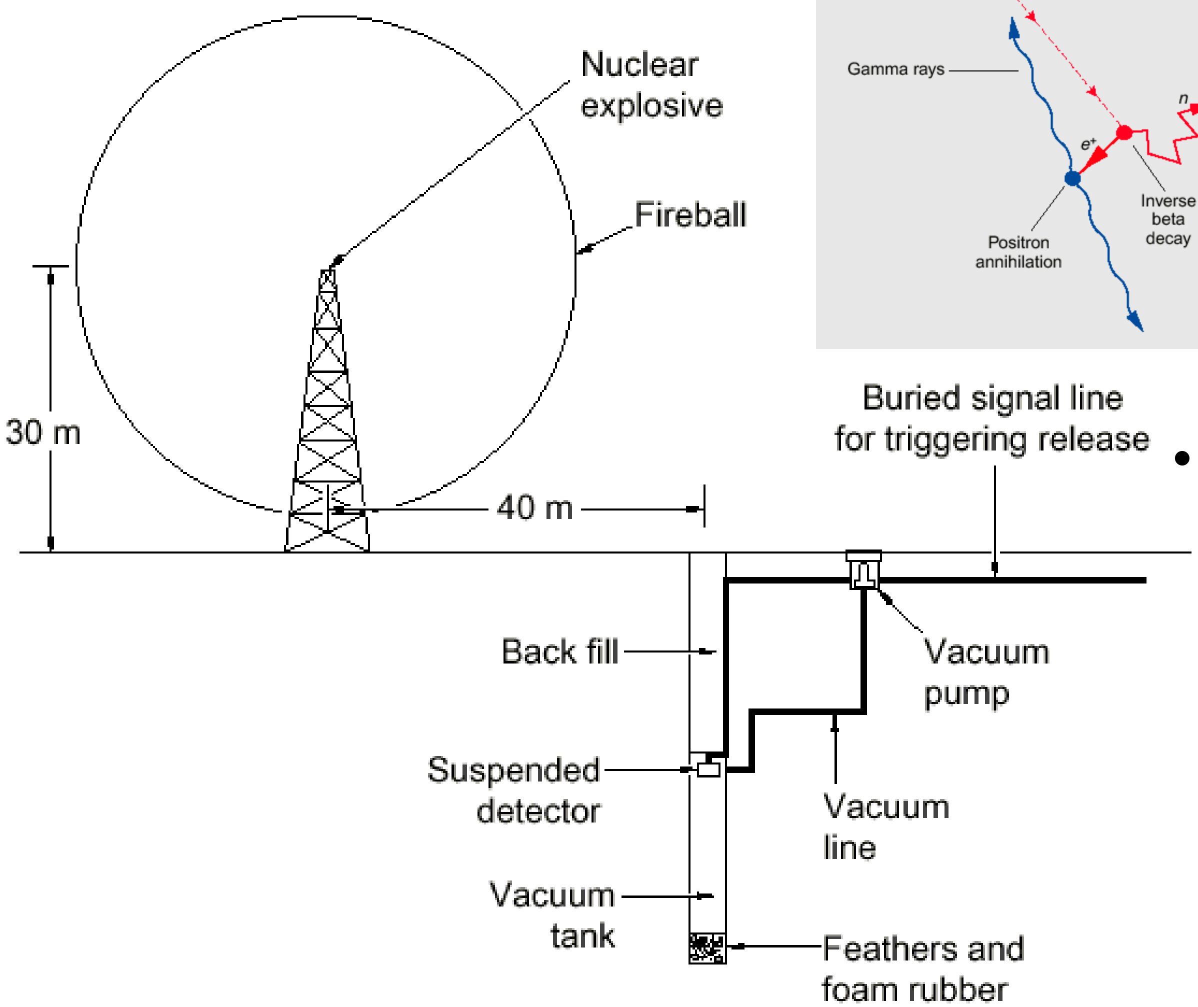
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

Wolfgang Pauli

Extreme Measures to Overcome Weakness (Reines and Cowan, 1946)



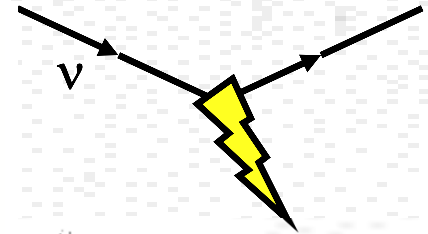




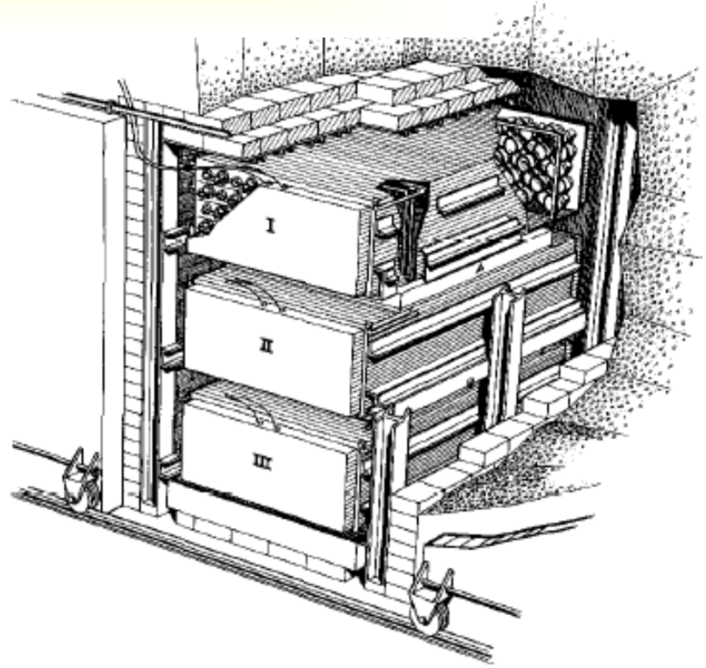
$$\bar{\nu}\, p \rightarrow e^{+} n$$

- Why inverse neutron beta decay?
  - clean prediction of Fermi weak theory
  - clean signature of prompt gammas from e^{+} plus delayed neutron signal.
    - Latter not as useful with bomb source.

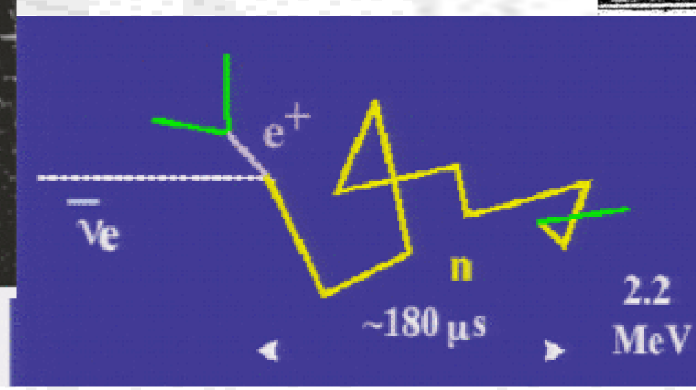
Discovery of the Neutrino

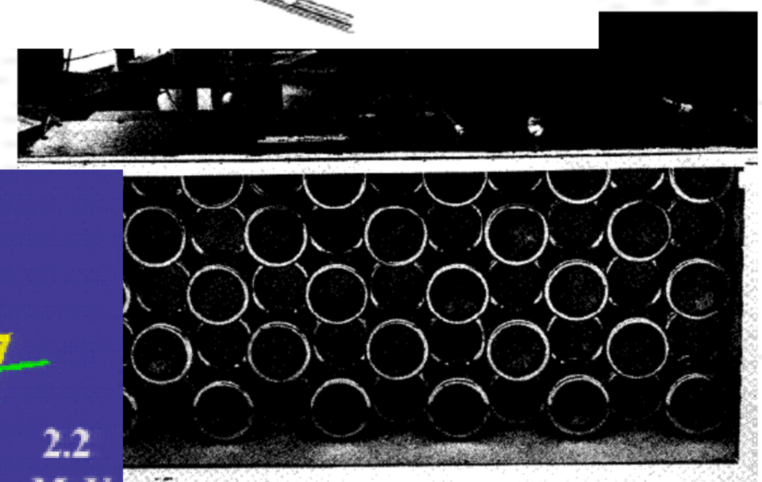


- Reines and Cowan (1955)
  - Chose a constant source, nuclear reactor (Savannah River)
  - 1956 message to Pauli: "We are happy to inform you [Pauli] that we have definitely detected neutrinos…"
  - 1995 Nobel Prize for Reines

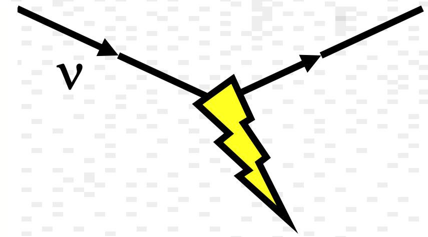


$$\bar{\nu}\, p \rightarrow e^{+} n$$





Better than the Nobel Prize?



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

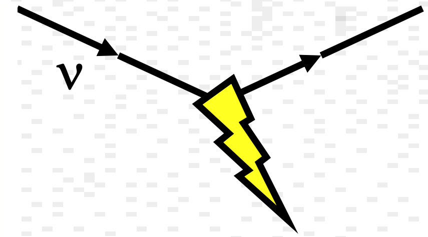
Thanks for message. Everything comes to him who knows how to wait.

Pauli

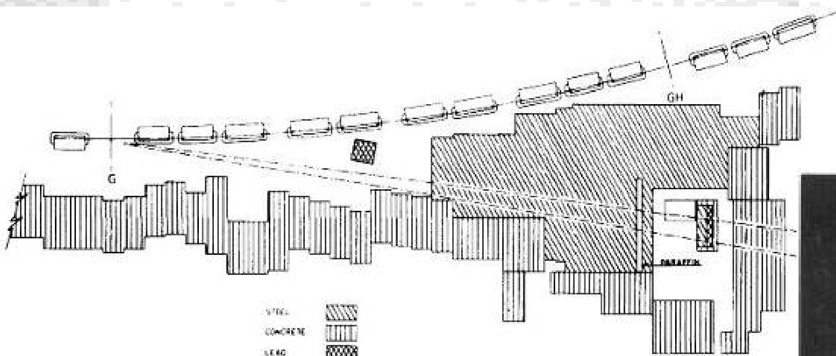
Thanks for the message. Everything comes to him who knows how to wait.

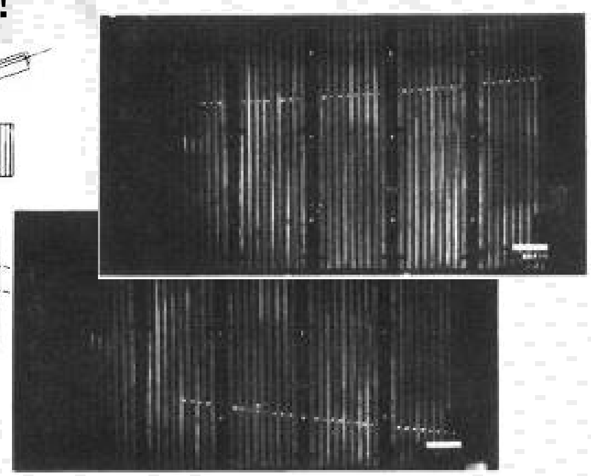
[illegible]

Interactions and Flavor



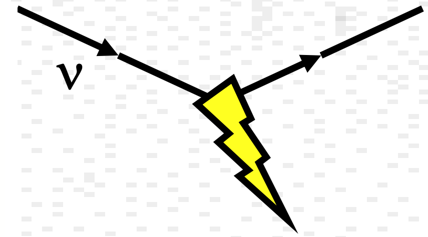
- 1962 Lederman, Schwartz, Steinberger at Brookhaven Nat'l Lab
- One neutrino was known (beta decay)
  - Question: if $\mu^+ \rightarrow e^+ \nu \bar{\nu}$, why not $\mu^+ \rightarrow e^+ \gamma$?
- First accelerator neutrino beam
  - 5 GeV protons on Be Target (3.5×10^{17} of them)
  - $\pi^+ \rightarrow \mu^+ \nu_\mu$ in a 21m decay region
  - Found 34 single-μ events, 5 background, but NO e-like events!





1988 Nobel citation: "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon-neutrino"

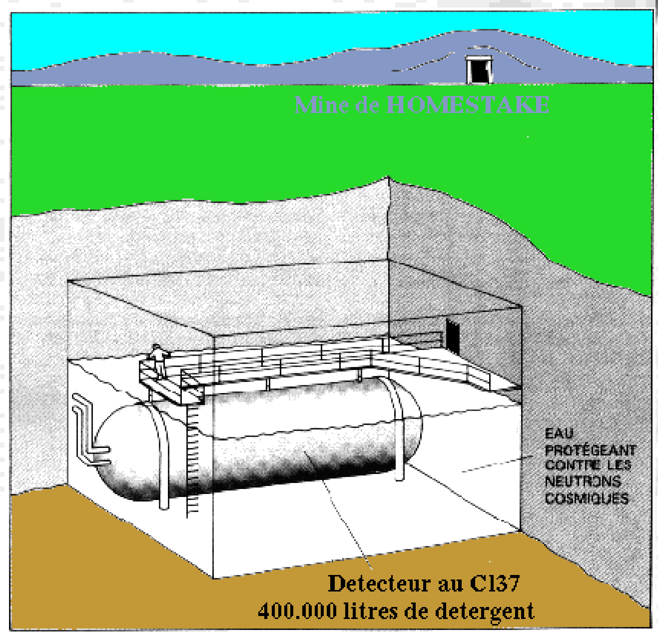
Another Flavor Example



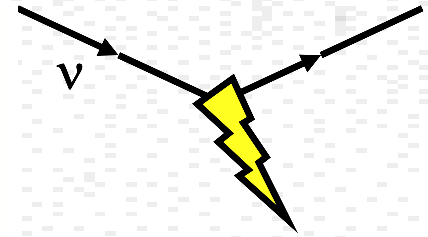
- Radiochemical Solar Neutrino Detector

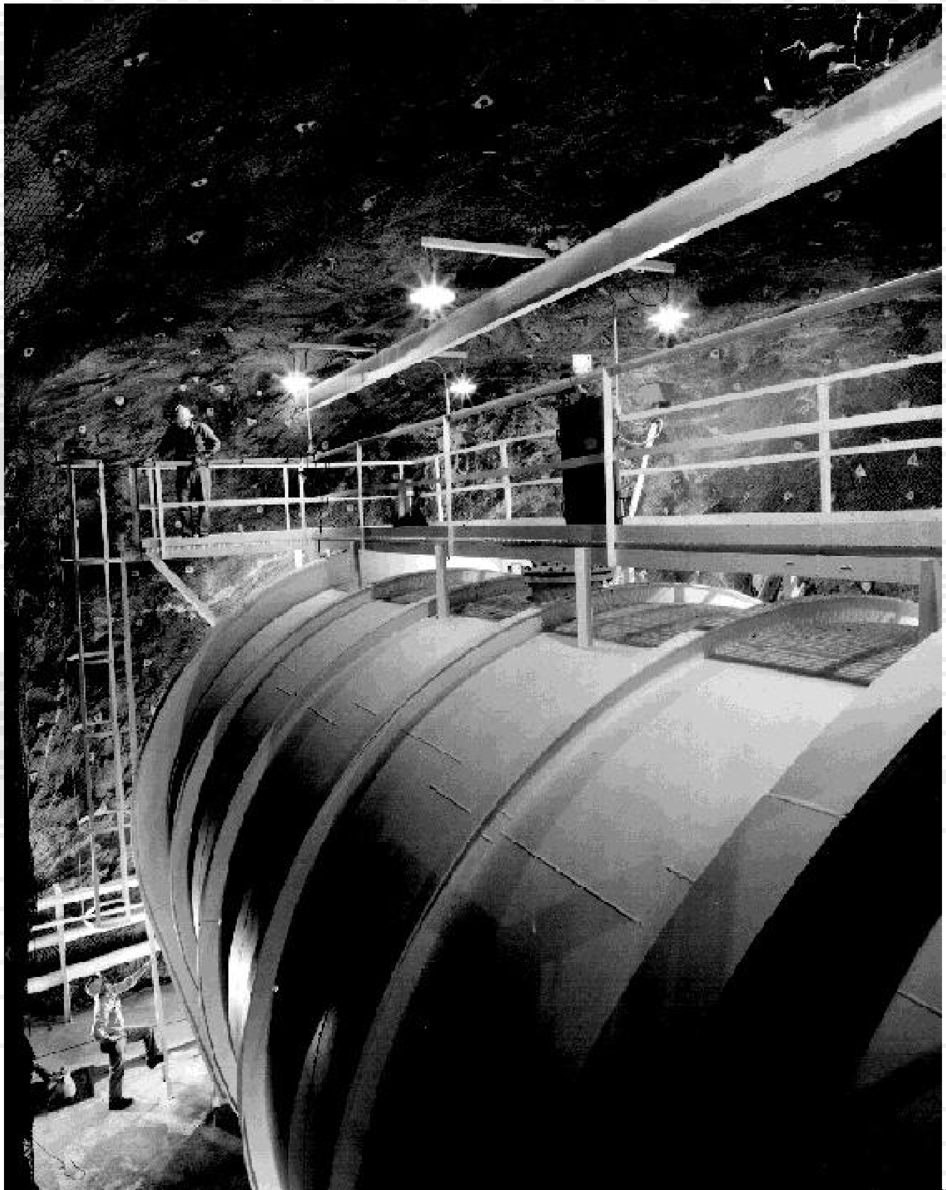
  Ray Davis (Nobel prize, 2002)

  - $\nu+n \rightarrow p+e^-$ (stimulated β-decay)
  - Use this to produce an unstable isotope, $\nu+{}^{37}Cl \rightarrow {}^{37}Ar+e^-$, which has 35 day half-life
  - Put 615 tons of Perchloroethylene in a gold mine
    - o expect one ^{37}Ar atom every 17 hours.

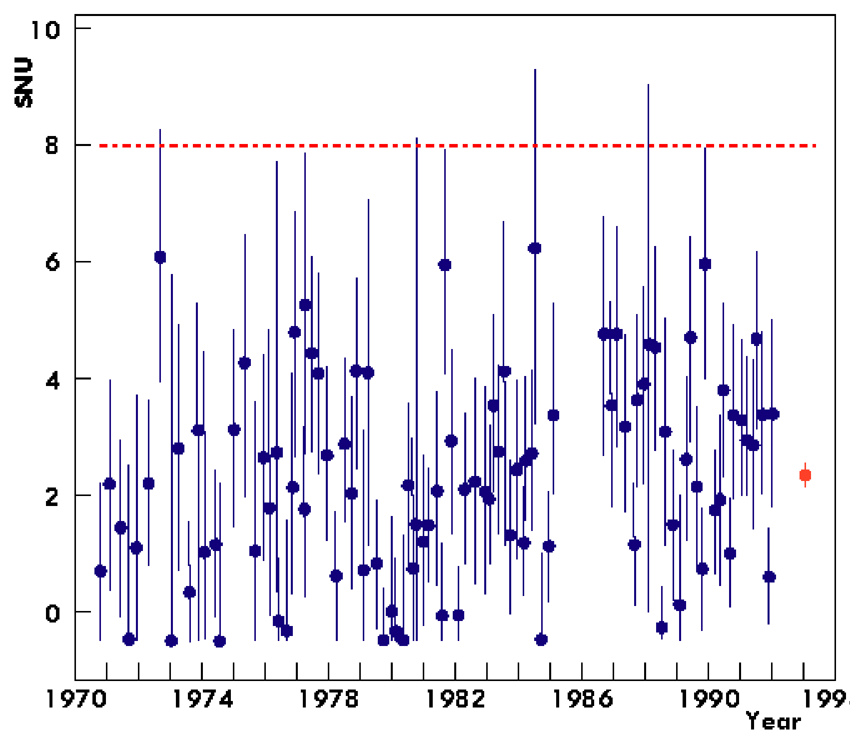


Another Flavor (cont'd)

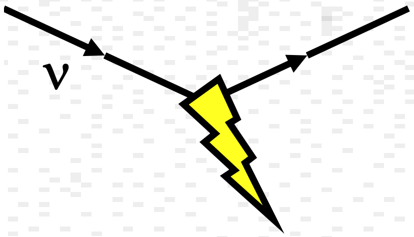




- Confirmed that sun shines from fusion, but 1/3 of ν !
- Of course this is oscillation and flavor selection of interaction $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

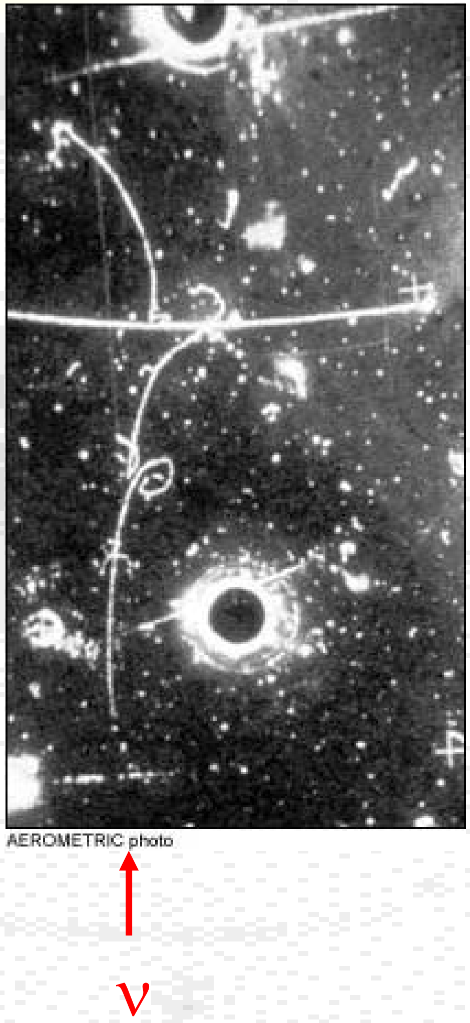


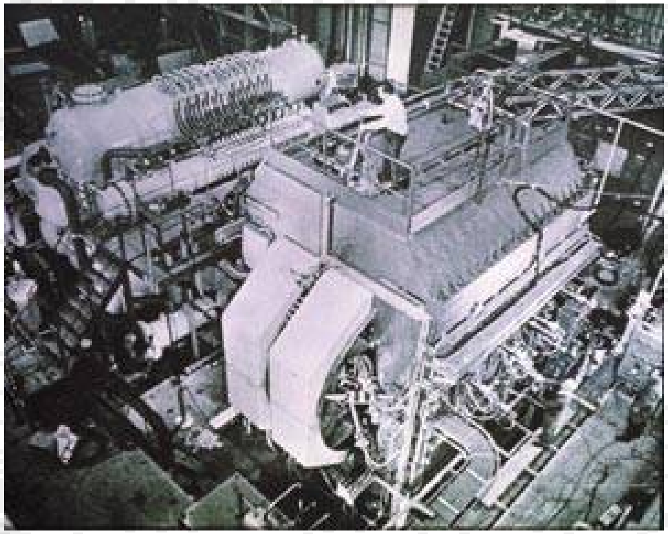
Another Neutrino Interaction Discovery



- Neutrinos only feel the weak force
  - a great way to study the weak force!
- Search for neutral current
  - arguably the most famous neutrino interaction ever observed is shown at right

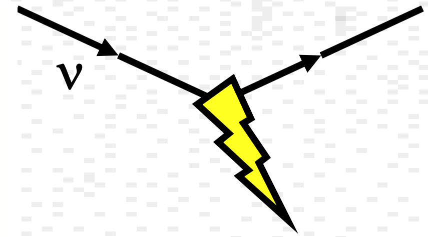
$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$





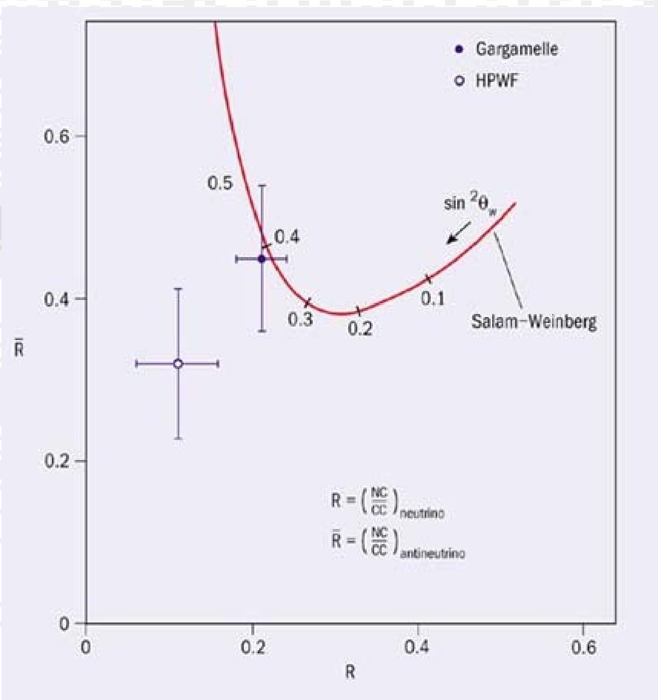
Gargamelle, event from neutral weak force

An Illuminating Aside



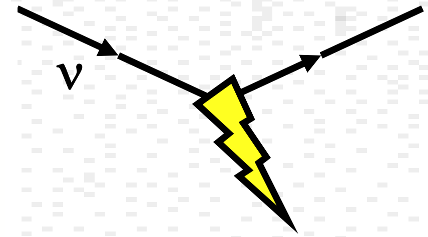
- The "discovery signal" for the neutral current was really neutrino scattering from nuclei
  - usually quoted as a ratio of muon-less interactions to events containing muons

$$R^{\nu} = \frac{\sigma(\nu_{\mu} N \rightarrow \nu_{\mu} X)}{\sigma(\nu_{\mu} N \rightarrow \mu^{-} X)}$$

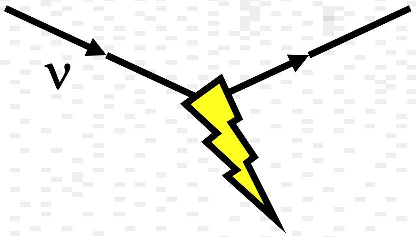


- But this discovery was complicated for 12-18 months by a lack of understanding of neutrino interactions
  - backgrounds from neutrons induced by neutrino interactions outside the detector
  - not understanding fragmentation to high energy hadrons which then "punched through" to fake muons

The Future: Interactions and Oscillation Experiments

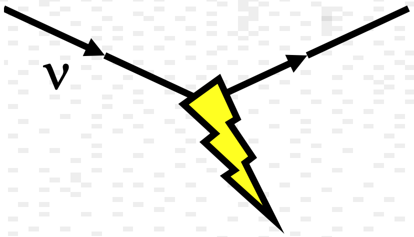


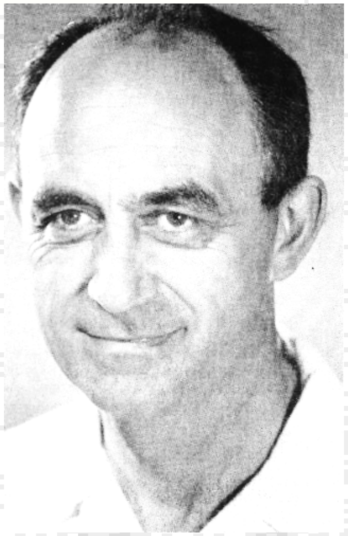
- Oscillation experiments point us to a rich physics potential at L/E~400 km/GeV *(and L/E~N·(400 km/GeV) as well)*
  - mass hierarchy, CP violation
- But there are difficulties
  - transition probabilities must be precisely measured for mass hierarchy and CP violation
  - the neutrinos must be at difficult energies of 1-few GeV for electron appearance experiments, few-many GeV for atmospheric neutrino and τ appearance experiments
- *We are not looking for neutrino flavor measurements in which distinguishing 1 from 0 or 1 from 1/3 buys a ticket to Stockholm*
  - Difficulties are akin to neutral current experiments
  - Is there a message for us here?



Present View of Weak Interactions

Weak Interactions Revisited





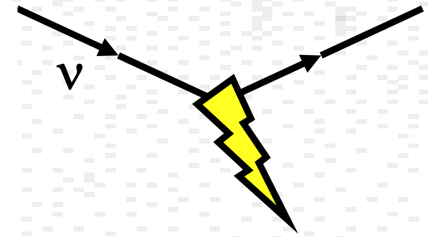
- Current-current interaction (Fermi 1934) $\mathcal{H}_w = \frac{G_F}{\sqrt{2}} \mathcal{J}^\mu \mathcal{J}_\mu$

- Modern version:

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} \left[\bar{l} \gamma_\mu (1-\gamma_5) \nu \right] \left[\bar{f} \gamma^\mu (V - A\gamma_5) f \right] + h.c.$$

- $P_L = 1/2(1-\gamma_5)$ is a projection operator onto left-handed states for fermions and right-handed states for anti-fermions

Helicity and Chirality



- ***Helicity*** is projection of spin along the particles direction
  - Frame dependent (if massive)

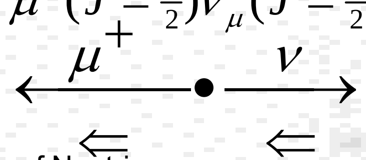
The operator: $\sigma \cdot \mathbf{p}$

- Neutrinos only interact weakly with a (V-A) interaction
  - All **neutrinos** are **left-handed**
  - All **antineutrinos** are **right-handed**
    - o **because of production!**
  - Weak interaction **maximally** violates parity

- However, ***chirality*** ("handedness") is Lorentz-invariant
  - Only same as helicity for massless particles.

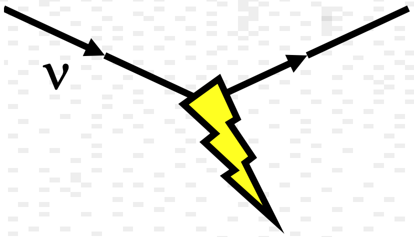
- If neutrinos have mass then left-handed neutrino is:
  - Mainly left-helicity
  - But also small right-helicity component $\propto$ *m/E*
- Only left-handed charged-leptons (e^-, μ^-, τ^-) interact weakly but mass brings in right-helicity:

$$\pi^+(J=0) \rightarrow \mu^+(J=\tfrac{1}{2})\nu_\mu(J=\tfrac{1}{2})$$



$$R_{theory} = \frac{\Gamma(\pi^\pm \rightarrow e^\pm \nu_e)}{\Gamma(\pi^\pm \rightarrow \mu^\pm \nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{{m_\pi}^2 - {m_e}^2}{{m_\pi}^2 - {m_\mu}^2}\right)^2 = 1.23 \times 10^{-4}$$

Two Weak Interactions



- W exchange gives Charged-Current (CC) events and Z exchange gives Neutral-Current (NC) events

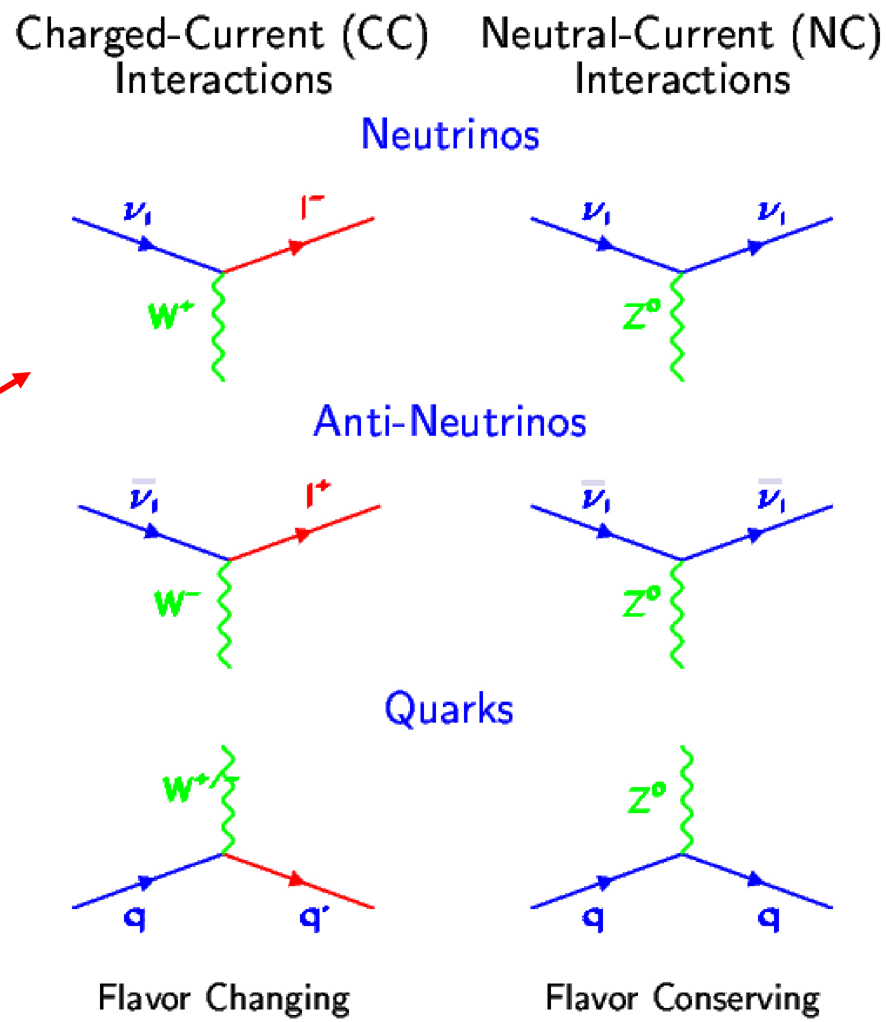
In charged-current events,

Flavor of outgoing lepton tags flavor of neutrino

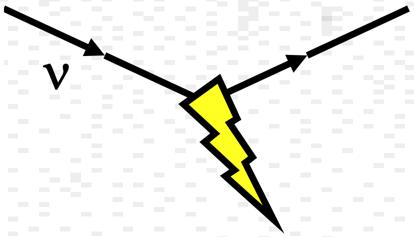
Charge of outgoing lepton determines if neutrino or antineutrino

$$l^- \Rightarrow \nu_l$$

$$l^+ \Rightarrow \bar{\nu}_l$$



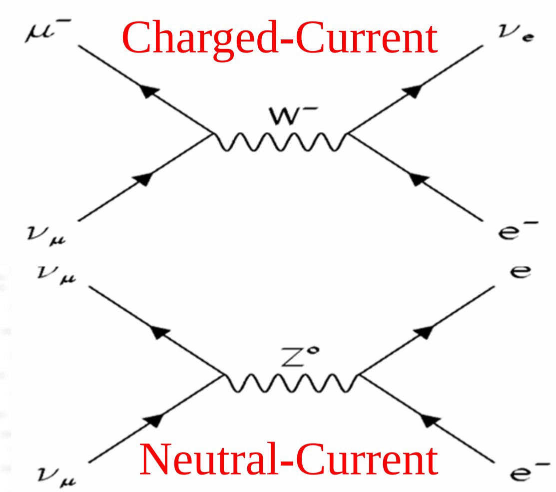
Electroweak Theory



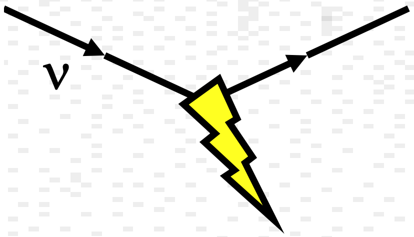
- Standard Model
  - SU(2) ⊗ U(1) gauge theory unifying weak/EM
    ⇒ weak NC follows from EM, Weak CC
  - Physical couplings related to mixing parameter for the interactions in the high energy theory

$$\mathcal{L}_{EW}^{int} = -Q_e A_\mu \bar{e}\gamma^\mu e + \frac{g}{\sqrt{2}} W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + \frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L \gamma^\mu \nu_L$$

$$+ \frac{g}{\cos\theta_W} Z_\mu^0 \left\{ \begin{array}{l} \frac{1}{2}\bar{\nu}_L \gamma^\mu \nu_L \\ +\left(\sin^2\theta_W - \frac{1}{2}\right)\bar{e}_L \gamma^\mu e_L \\ +\sin^2\theta_W \bar{e}_R \gamma^\mu e_R \end{array} \right\}$$



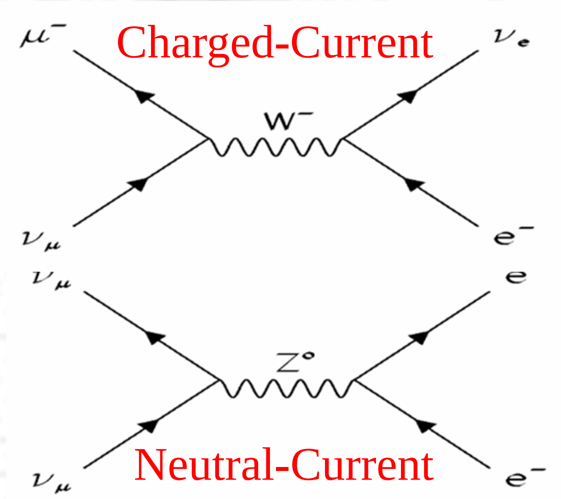
Electroweak Theory



- Standard Model
  - SU(2) ⊗ U(1) gauge theory unifying weak/EM
    ⇒ weak NC follows from EM, Weak CC
  - Measured physical parameters related to mixing parameter for the couplings.

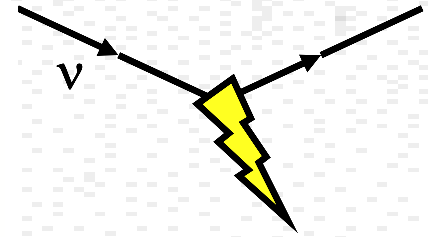
Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2 - 2/3\ \sin^2\theta_W$	$-2/3\ \sin^2\theta_W$
d , s , b	$-1/2 + 1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

$$e = g\sin\theta_W,\ G_F = \frac{g^2\sqrt{2}}{8M_W^2},\ \frac{M_W}{M_Z} = \cos\theta_W$$



- Neutrinos are special in SM
  - Right-handed neutrino has ***NO*** interactions!

Why "Weak"?

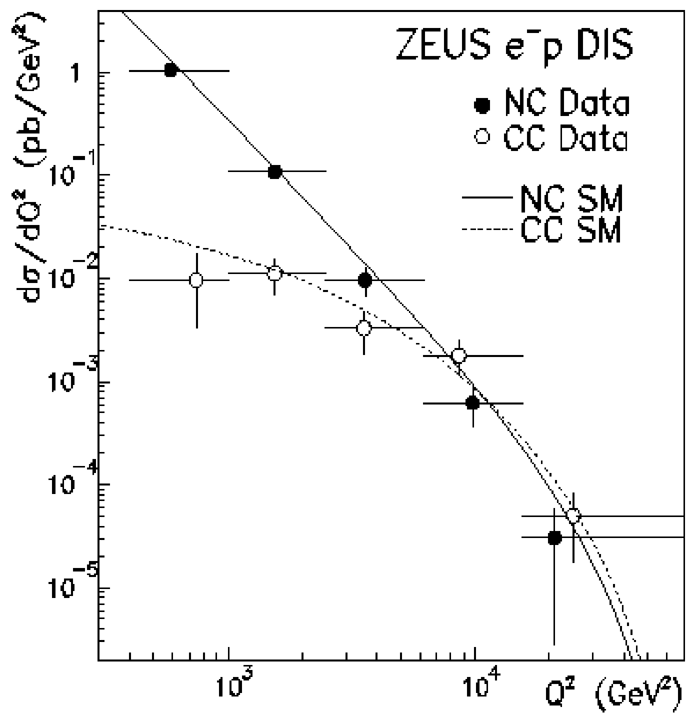


- Weak interactions are weak because of the massive W and Z bosons exchange

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

q is 4-momentum carried by exchange particle
M is mass of exchange particle

At HERA see W and Z propagator effects
- Also weak ~ EM strength



- Explains dimensions of Fermi "constant"

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2$$

$$= 1.166\times 10^{-5}\,/\,GeV^2 \quad (g_W \approx 0.7)$$

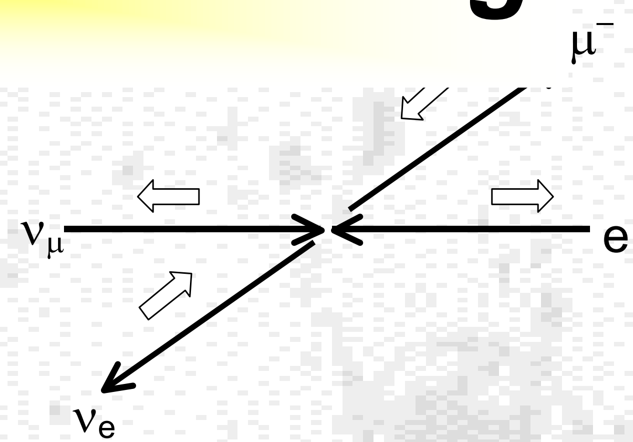
Neutrino-Electron Scattering

- Inverse μ–decay:

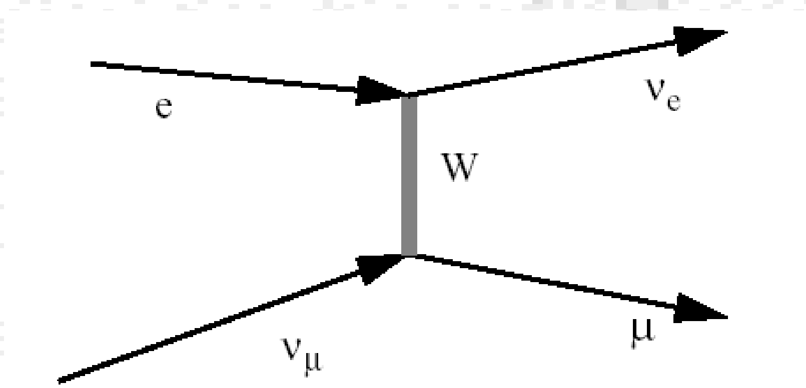
  $$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

  - Total spin J=0

    (*Assuming massless muon*, helicity=chirality)



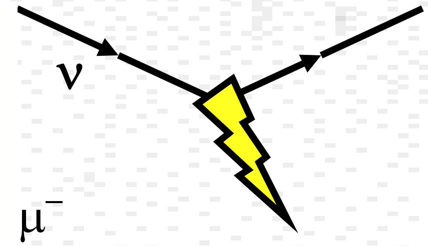
$$Q^2 \equiv -\left(\underline{e} - \underline{\nu}_e\right)^2$$



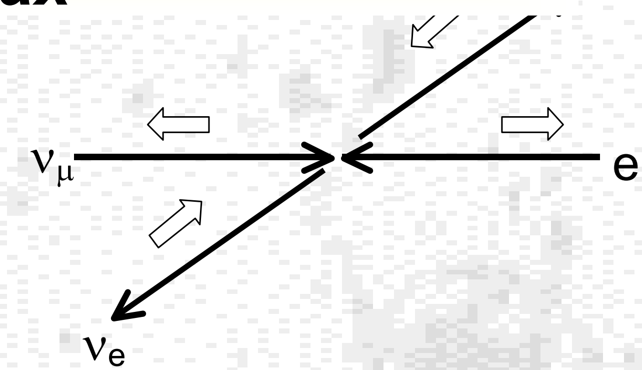
$$\sigma_{TOT} \propto \int_0^{Q^2_{\max}} dQ^2 \frac{1}{(Q^2 + M_W{}^2)^2}$$

$$\approx \frac{Q^2_{\max}}{M_W{}^4}$$

Touchstone Question #1
What is Q^2_{max}?



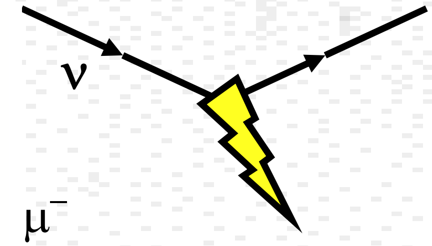
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$



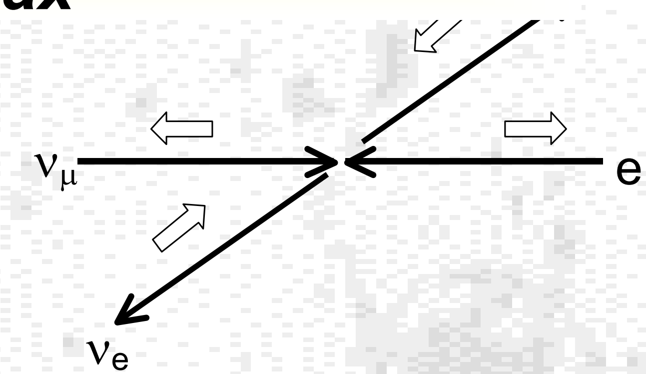
$$Q^2 \equiv -\left(\underline{e} - \underline{\nu}_e\right)^2$$

*Work in the center-of-mass frame and assume, **for now**, that we can neglect the masses.*

Touchstone Question #1
What is Q^2_{max}?



$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$



$$Q^2 \equiv -\left(\underline{e} - \underline{\nu}_e\right)^2$$

Work in the center-of-mass frame and assume, ***for now****, that we can neglect the masses.*

$$\underline{e} \approx (E_\nu^*, 0, 0, -E_\nu^*)$$

$$\underline{\nu}_e \approx (E_\nu^*, -E_\nu^* \sin\theta^*, 0, -E_\nu^* \cos\theta^*)$$

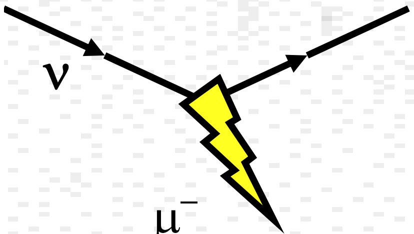
$$Q^2 = -\left(\underline{e}^2 + \underline{\nu}_e{}^2 - 2\underline{e}\bullet\underline{\nu}_e\right)^2$$

$$\approx -\left[-2E_\nu^{*2}\left(1-\cos\theta^*\right)\right]$$

$$0 < Q^2 < \left(2E_\nu^*\right)^2 \approx \left(\underline{e} + \underline{\nu}_\mu\right)^2$$

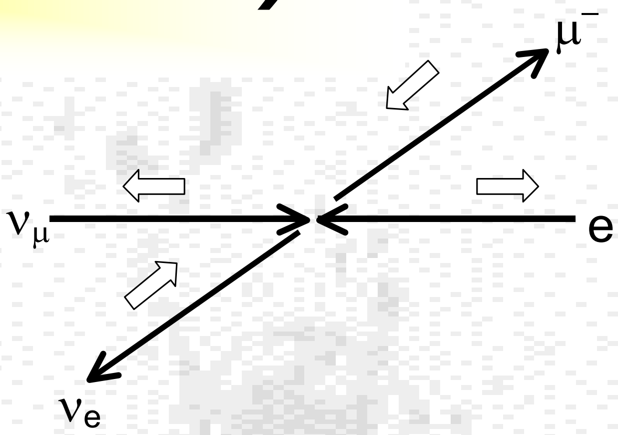
$$0 < Q^2 < s$$

Neutrino-Electron (cont'd)



$$\sigma_{TOT} \propto Q^2_{\max} = s$$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}$$
$$= 17.2 \times 10^{-42} cm^2 / GeV \cdot E_\nu (GeV)$$

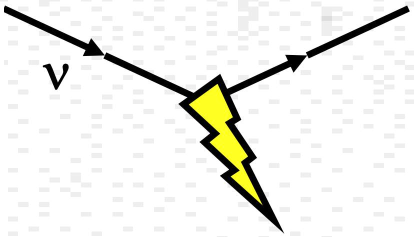


- Why is it proportional to beam energy?

$$s = (\underline{p}_{\nu_\mu} + \underline{p}_e)^2 = m_e^2 + 2 m_e E_\nu \text{ (e}^- \text{ rest frame)}$$

- Proportionality to energy is a generic feature of point-like scattering!
  - because $d\sigma/dQ^2$ is constant (at these energies)

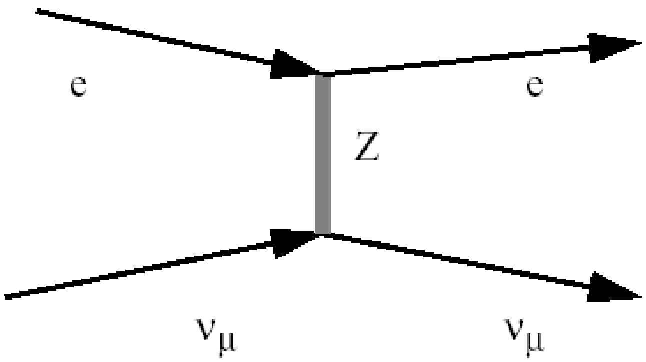
Neutrino-Electron (cont'd)



- Elastic scattering:

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

  - Recall, EW theory has coupling to left *or* right-handed electron
  - Total spin, J=0,1



Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	1/2	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2 - 2/3\ \sin^2\theta_W$	$-2/3\ \sin^2\theta_W$
d , s , b	$-1/2 + 1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

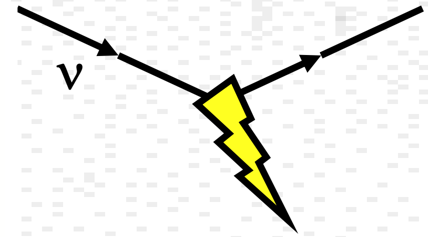
- Electron-Z^0 coupling
  - Left-handed: $-1/2 + \sin^2\theta_W$

$$\sigma \propto \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \sin^4\theta_W\right)$$

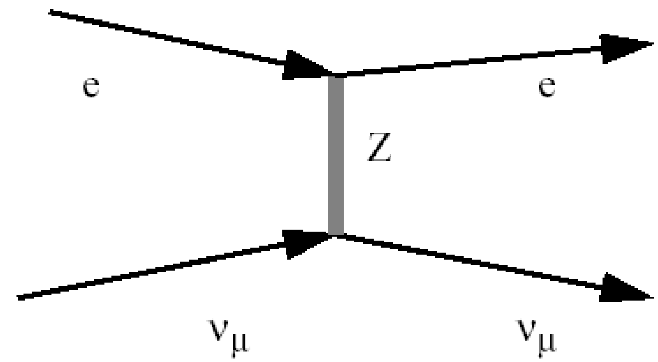
  - Right-handed: $\sin^2\theta_W$

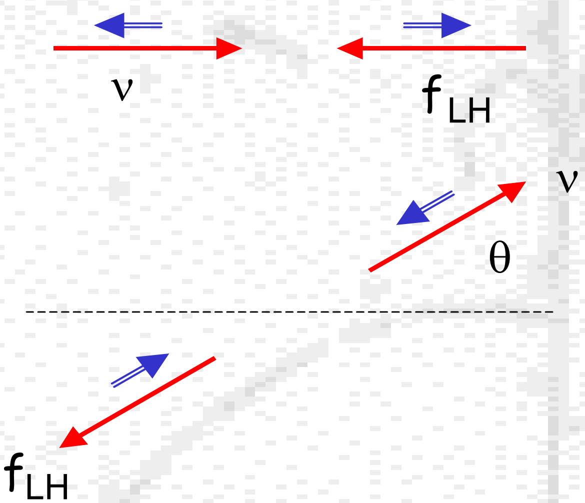
$$\sigma \propto \frac{G_F^2 s}{\pi}\left(\sin^4\theta_W\right)$$

Neutrino-Electron (cont'd)

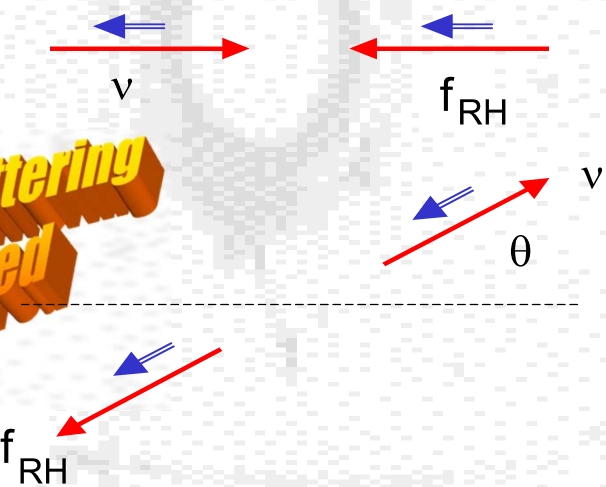


- What are relative contributions of scattering from left *and* right-handed electrons?





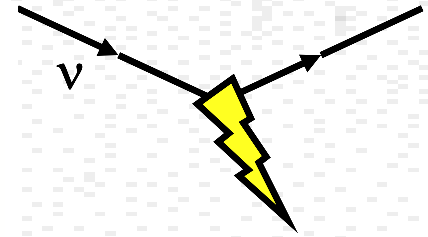
Backwards scattering is disfavored



$$\frac{d\sigma}{d\cos\theta} = \text{const}$$

$$\frac{d\sigma}{d\cos\theta} = \text{const} \times \left(\frac{1+\cos\theta}{2}\right)^2$$

Neutrino-Electron (cont'd)



- Electron-Z^0 coupling $\sigma \propto \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \sin^4\theta_W\right)$
  - (LH, V-A): $-1/2 + \sin^2\theta_W$
  - (RH, V+A): $\sin^2\theta_W$ $\qquad \sigma \propto \frac{G_F^2 s}{\pi}\left(\sin^4\theta_W\right)$

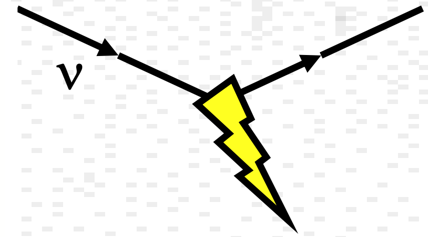
Let y denote inelasticity. Recoil energy is related to CM scattering angle by

$$y = \frac{E_e}{E_\nu} \approx 1 - \tfrac{1}{2}(1-\cos\theta)$$

$$\int dy \frac{d\sigma}{dy} = \begin{cases} \text{LH:} & \int dy = 1 \\ \text{RH:} & \int (1-y)^2\, dy = 1/3 \end{cases}$$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right) = 1.4\times10^{-42}\, cm^2/GeV \cdot E_\nu(GeV)$$

Touchstone Question #2: Flavors and νe Scattering



The reaction

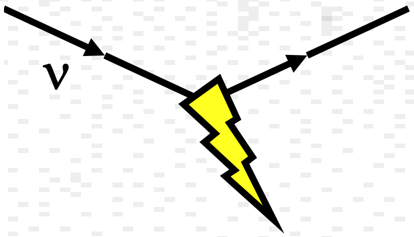
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

has a much smaller cross-section than

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Why?

Touchstone Question #2: Flavors and νe Scattering



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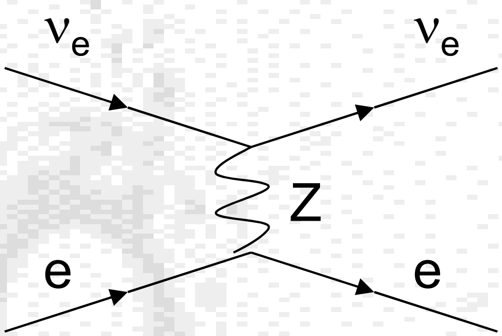
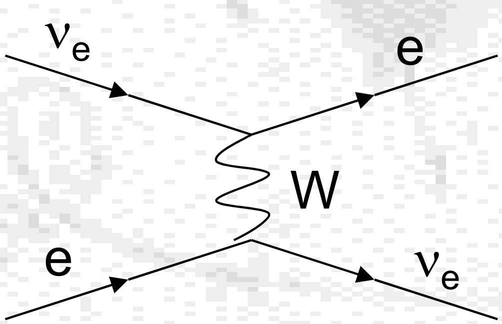


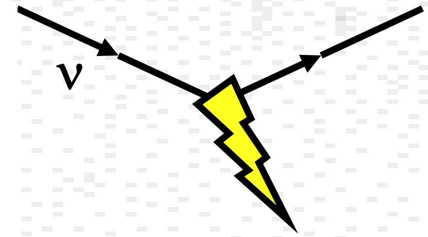
Why?

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

has a second contributing reaction, charged current



Touchstone Question #2: Flavors and νe Scattering



Let's show that this increases the rate

(Recall from the previous pages…

$$\sigma_{TOT} = \int dy \frac{d\sigma}{dy}$$

$$= \int dy \left[\frac{d\sigma^{LH}}{dy} + \frac{d\sigma^{RH}}{dy} \right]$$

$$= \sigma^{LH}_{TOT} + \tfrac{1}{3}\sigma^{RH}_{TOT}$$

$$\sigma^{LH}_{TOT} \propto \left| \text{total coupling}^{\text{LH}}_{\text{e}^-} \right|^2$$

For electron…	LH coupling	RH coupling
Weak NC	$-1/2+\sin^2\theta_W$	$\sin^2\theta_W$
Weak CC	-1/2	0

)

We have to show the interference between CC and NC is constructive.

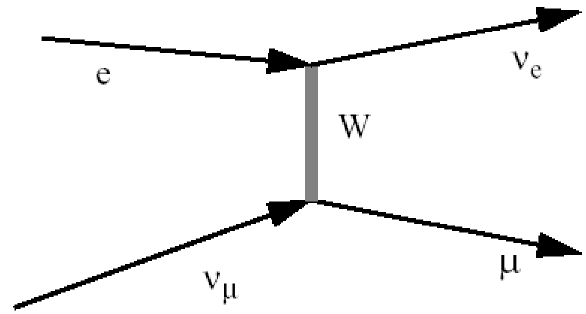
The total RH coupling is unchanged by addition of CC because there is no RH weak CC coupling

There are two LH couplings: NC coupling is $-1/2+\sin^2\theta_W \approx -1/4$ and the CC coupling is -1/2. We add the associated amplitudes… and get $-1+\sin^2\theta_W \approx -3/4$

Lepton Mass Effects

- Let's return to
  Inverse μ–decay:

$$\nu_\mu + e^- \to \mu^- + \nu_e$$



  - What changes in the presence of final state mass?
    - o pure CC so always left-handed
    - o BUT there must be finite Q^2 to create muon in final state!

$$Q^2_{\min} = m^2_\mu$$

$$\sigma_{TOT} \propto \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2 \frac{1}{(Q^2 + M_W{}^2)^2}$$

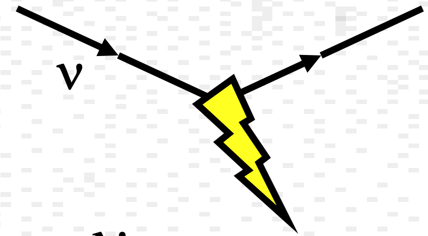
$$\approx \frac{Q^2_{\max} - Q^2_{\min}}{M_W{}^4}$$

$$\sigma_{TOT} = \frac{G_F^2 (s - m_\mu^2)}{\pi}$$

$$= \left[\sigma_{TOT}{}^{(\text{massless})}\right]\left(1 - \frac{m_\mu^2}{s}\right)$$

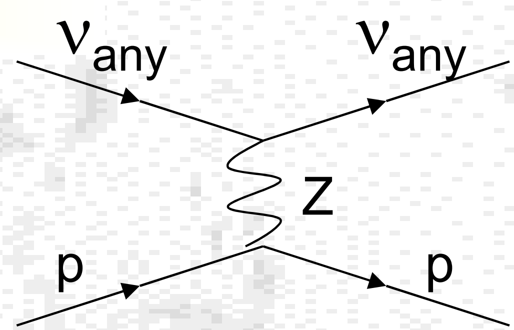
  - see a suppression scaling with **(mass/CM energy)^2**
    - o This can be generalized…

What about other targets?



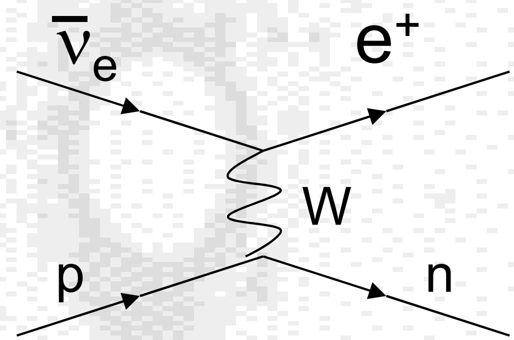
- Imagine now a proton target
  - Neutrino-proton elastic scattering:

$$\nu_e + p \rightarrow \nu_e + p$$



  - “Inverse beta-decay” (IBD):

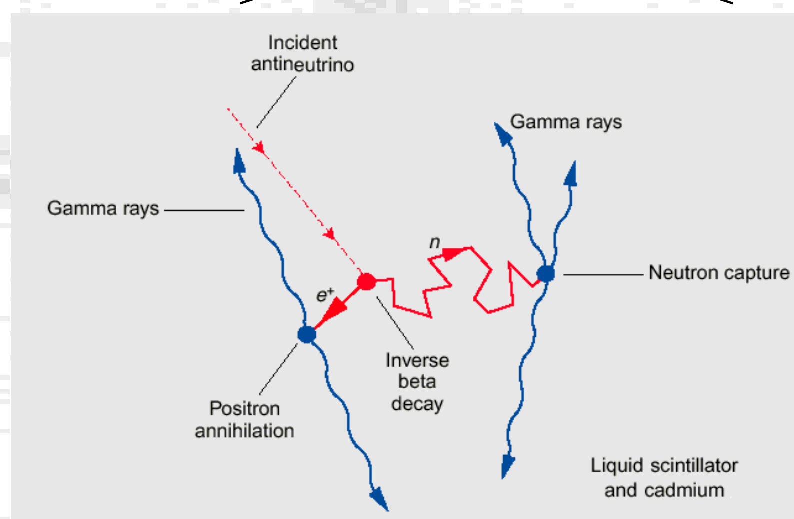
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



  - and its close cousin:

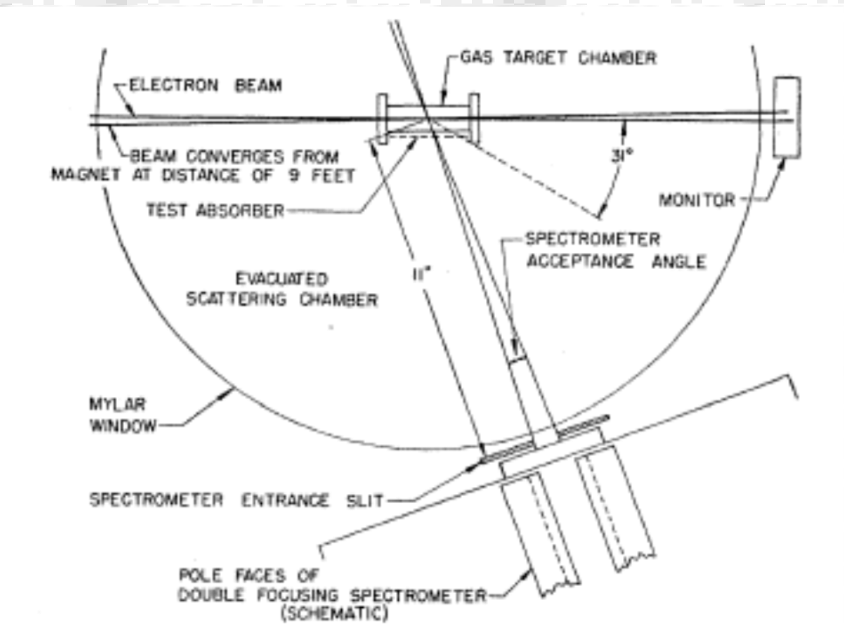
$$\nu_e + n \rightarrow e^- + p$$

  - Recall that IBD was the Reines and Cowan discovery signal

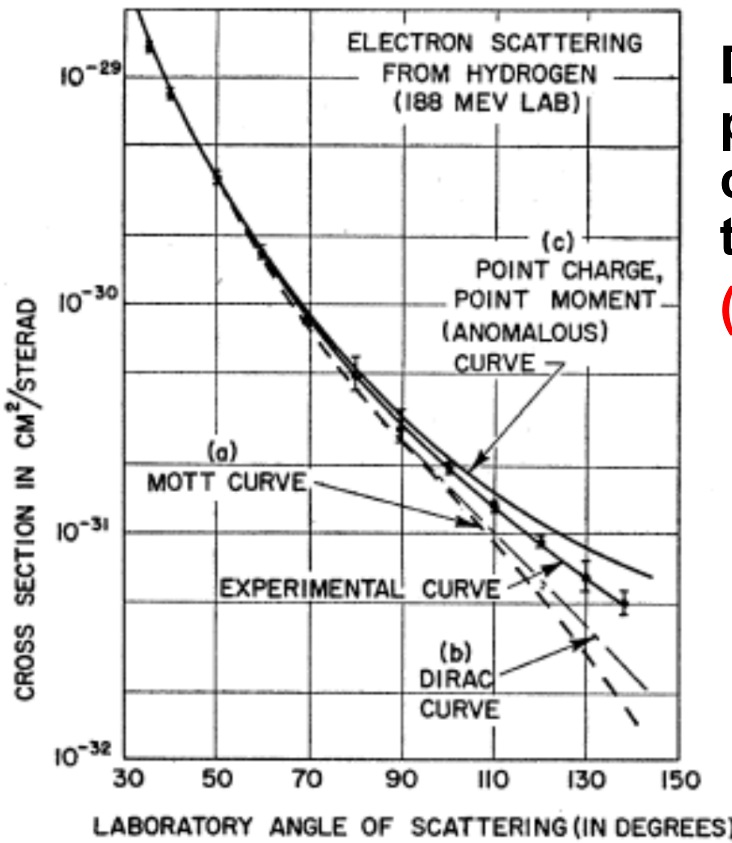


Proton Structure

- How is a proton different from an electron?
  - anomalous magnetic moment, $\kappa \equiv \frac{g-2}{2} \neq 1$
  - "form factors" related to finite size

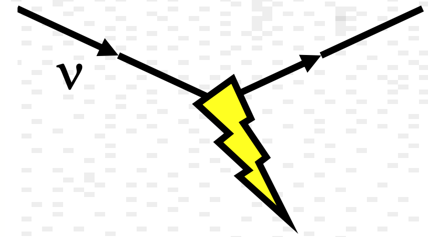


McAllister and Hofstadter 1956
188 MeV and 236 MeV electron beam from linear accelerator at Stanford

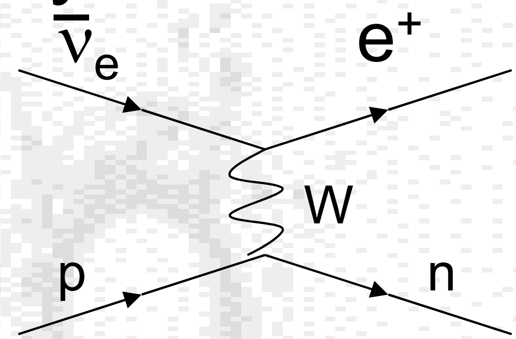


Determined proton RMS charge radius to be (0.7±0.2) x10^{-13} cm

Final State Mass Effects



- In IBD, $\bar{\nu}_e + p \rightarrow e^+ + n$, have to pay a mass penalty *twice*
  - *M_n-M_p≈1.3 MeV, M_e≈0.5 MeV*



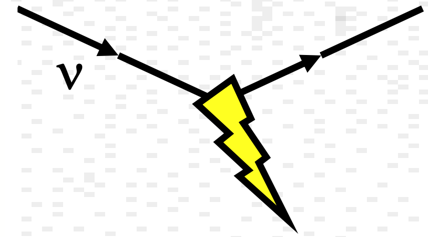
- What is the threshold?
  - kinematics are simple, at least to zeroth order in M_e/M_n → heavy nucleon kinetic energy is zero

$$s_{\text{initial}} = (\underline{p}_\nu + \underline{p}_p)^2 = M_p^2 + 2M_p E_\nu \quad \text{(proton rest frame)}$$

$$s_{\text{final}} = (\underline{p}_e + \underline{p}_n)^2 \approx M_n^2 + m_e^2 + 2M_n\left(E_\nu - \left(M_n - M_p\right)\right)$$

- Solving… $E_\nu^{\text{min}} \approx \dfrac{\left(M_n + m_e\right)^2 - M_p^{\,2}}{2M_p} \approx 1.806\text{ MeV}$

Final State Mass Effects (cont'd)



- Define δE as $E_\nu - E_\nu^{min}$, then

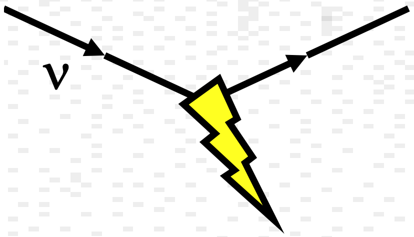
$$s_{\text{initial}} = M_p^2 + 2M_p\left(\delta E + E_\nu^{\text{min}}\right)$$
$$= M_p^2 + 2\delta E \times M_p + \left(M_n + m_e\right)^2 - M_p^2$$
$$= 2\delta E \times M_p + \left(M_n + m_e\right)^2$$

- Remember the suppression generally goes as

$$\xi_{\text{mass}} = 1 - \frac{m_{\text{final}}^2}{s} = 1 - \frac{\left(M_n + m_e\right)^2}{\left(M_n + m_e\right)^2 + 2M_p \times \delta E}$$

$$= \frac{2M_p \times \delta E}{\left(M_n + m_e\right)^2 + 2M_p \times \delta E} \approx \begin{cases} \delta E \times \dfrac{2M_p}{\left(M_n + m_e\right)^2} & \text{low energy} \\ 1 - \dfrac{\left(M_n + m_e\right)^2}{2M_p^2}\dfrac{M_p}{\delta E} & \text{high energy} \end{cases}$$

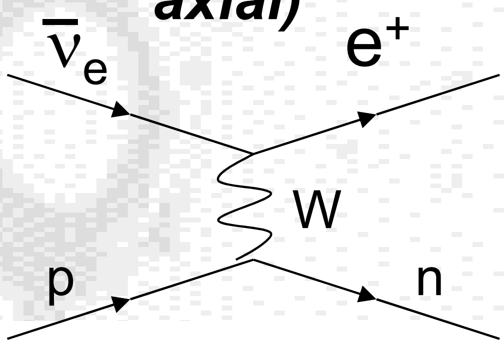
Putting it all together…

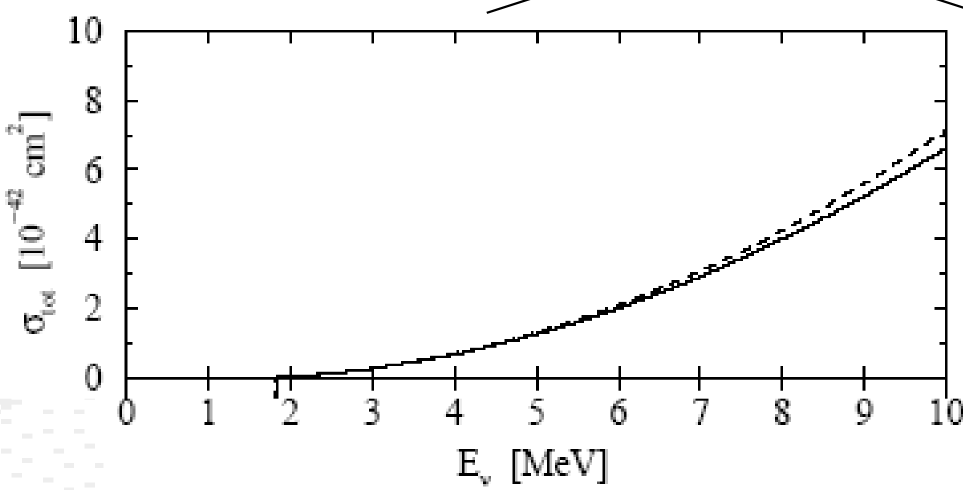


$$\sigma_{TOT} = \frac{G_F^2 s}{\pi} \times \cos^2 \vartheta_{\text{Cabibbo}} \times \left(\xi_{\text{mass}}\right) \times \left(g_V{}^2 + 3 g_A{}^2\right)$$

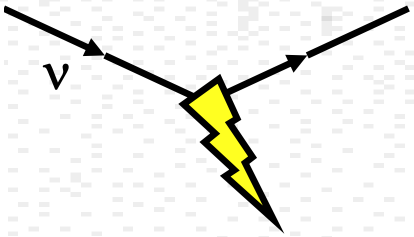
quark mixing! ***final state mass suppression*** ***proton form factors (vector, axial)***

- mass suppression is proportional to δE at low E_ν, so quadratic near threshold
- vector and axial-vector form factors (for IBD usually referred to as f and g, respectively) g_V, $g_A \approx 1$, 1.26.
  - FFs, $\theta_{Cabibbo}$, best known from τ_n



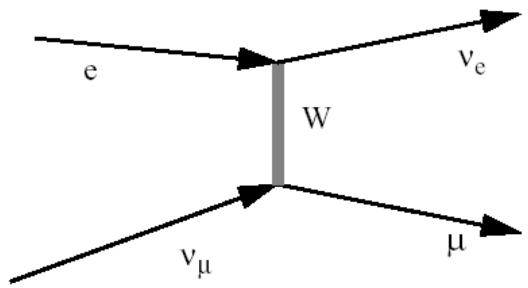


Touchstone Question #3: Quantitative Lepton Mass Effect



- **Which is closest to the minimum beam energy in which the reaction**

$$\nu_\mu + e^- \to \mu^- + \nu_e$$



can be observed?

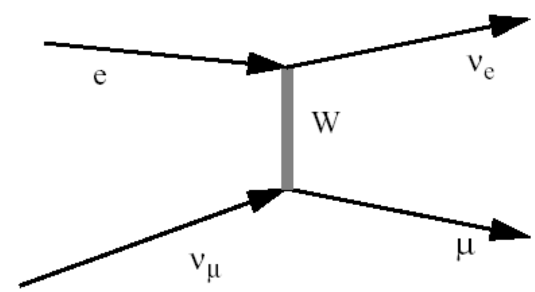
(a) 100 MeV **(b) 1 GeV** **(c) 10 GeV**

(It might help you to remember that $Q^2_{\min} = m^2_\mu$ or you might just want to think about the total CM energy required to produce the particles in the final state.)

Touchstone Question #3: Quantitative Lepton Mass Effect

- **Which is closest to the minimum beam energy in which the reaction**

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$



can be observed?

(a) 100 MeV (b) 1 GeV (c) 10 GeV

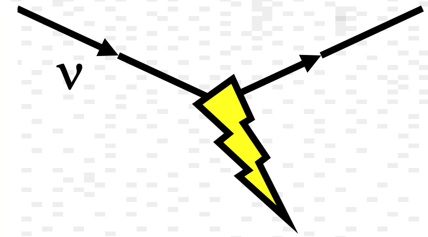
$$Q^2_{\min} = m_\mu^2$$

$$Q^2 < s = (\underline{p}_e + \underline{p}_\nu)^2$$

$$= (m_e + E_\nu, 0, 0, \sqrt{E_\nu{}^2 - m_\nu{}^2})^2 \approx m_e^2 + 2m_e E_\nu$$

$$\therefore E_\nu > \frac{m_\mu^2}{2m_e} \approx 10.9 \text{ GeV}$$

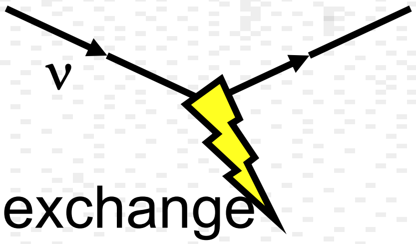
Summary… and Next Topic



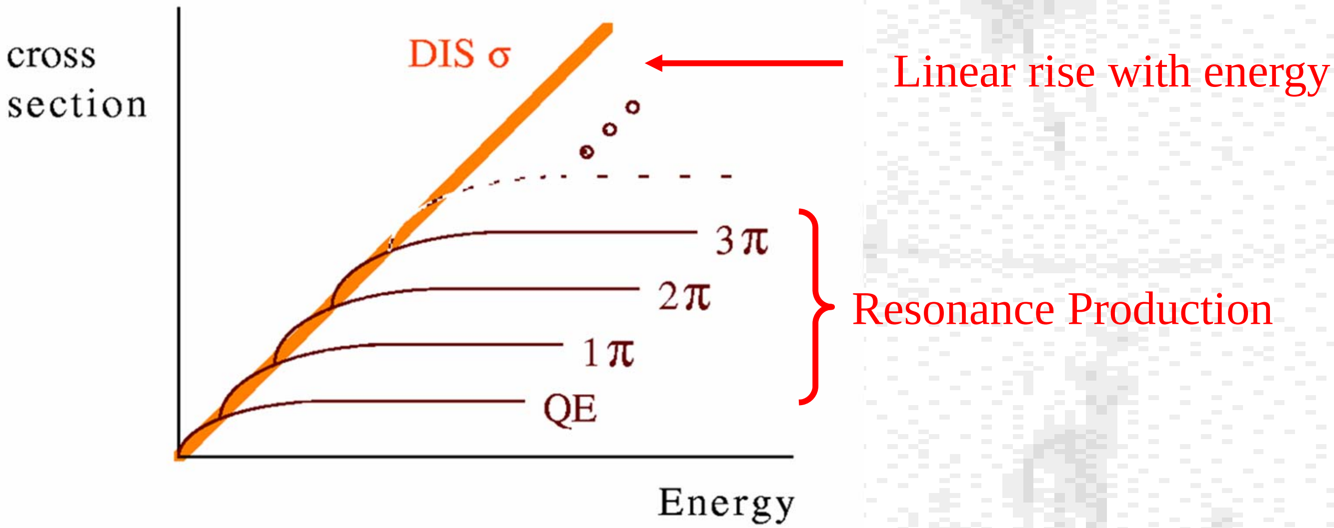
- We know νe^- scattering and IBD cross-sections!
- In point-like weak interactions, key features are:
  - $d\sigma/dQ^2$ is ≈ constant.
    - o Integrating gives $\sigma \propto E_\nu$
  - LH coupling enters w/ $d\sigma/dy \propto 1$, RH w/ $d\sigma/dy \propto (1-y)^2$
    - o Integrating these gives 1 and 1/3, respectively
  - Lepton mass effect gives minimum Q^2
    - o Integrating gives correction factor in σ of $(1-Q^2_{min}/s)$
  - Structure of target can add form factors
- Deep Inelastic Scattering is also a point-like limit where interaction is ν-quark scattering

Neutrino-Nucleon Deep Inelastic Scattering

Neutrino-Nucleon Scattering



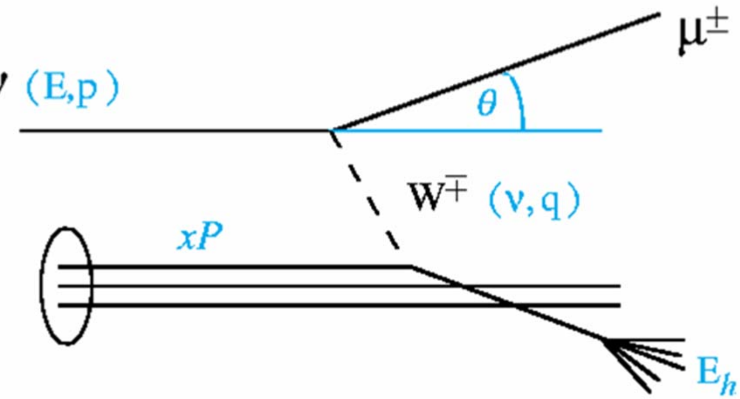
- Charged - Current: $W^{\pm}$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N^* or Δ)
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$
- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target unchanged)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N^* or Δ)
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}$



Scattering Variables

Scattering variables given in terms of invariants

- More general than just deep inelastic (neutrino-quark) scattering, although interpretation may change.



Measured quantities: E_h , E', θ

4-momentum Transfer^2: $Q^2 = -q^2 = -\left(p' - p\right)^2 \approx \left(4EE'\sin^2(\theta/2)\right)_{Lab}$

Energy Transfer: $\nu = \left(q\cdot P\right)/M_T = \left(E - E'\right)_{Lab} = \left(E_h - M_T\right)_{Lab}$

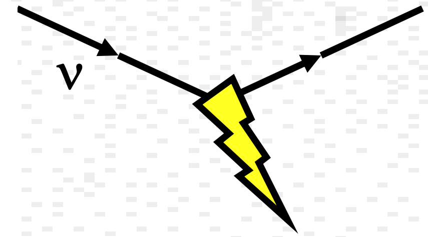
Inelasticity: $y = \left(q\cdot P\right)/\left(p\cdot P\right) = \left(E_h - M_T\right)/\left(E_h + E'\right)_{Lab}$

Fractional Momentum of Struck Quark: $x = -q^2/2\left(p\cdot q\right) = Q^2/2M_T\nu$

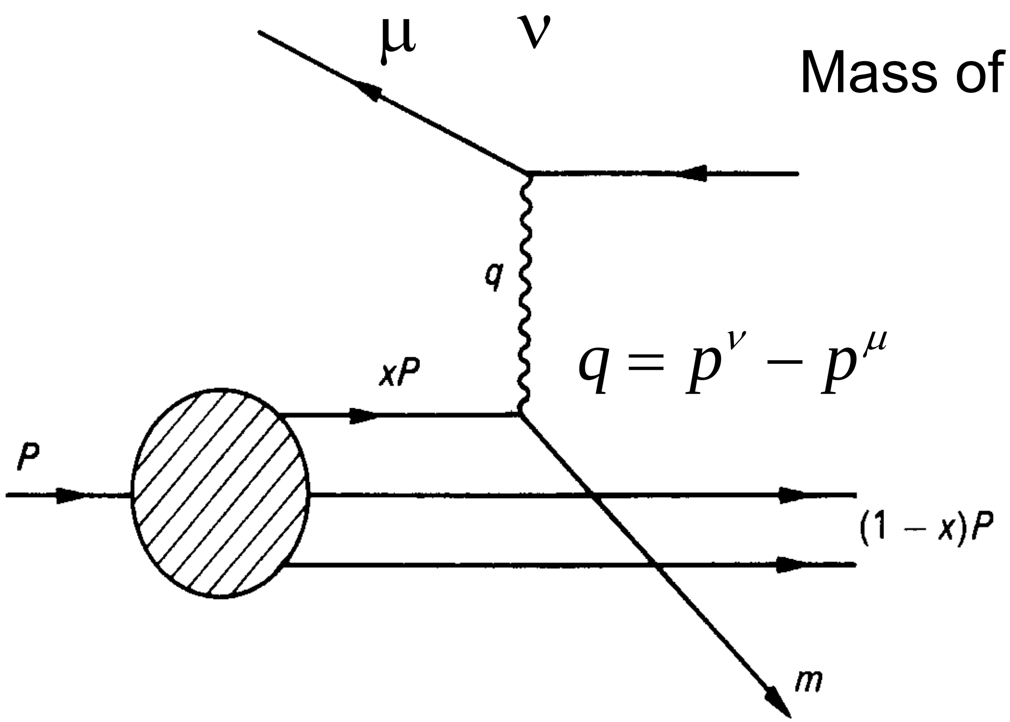
Recoil Mass^2: $W^2 = (q+P)^2 = M_T{}^2 + 2M_T\nu - Q^2$

CM Energy^2: $s = (p+P)^2 = M_T{}^2 + \dfrac{Q^2}{xy}$

Parton Interpretation of High Energy Limit



Mass of target quark $m_q^{\;2} = x^2 P^2 = x^2 M_T^2$



$q = p^{\nu} - p^{\mu}$

Mass of final state quark

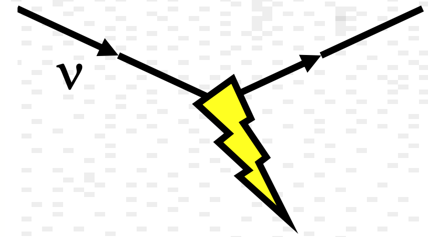
$$m_{q'}^{\;2} = (xP + q)^2$$

In "infinite momentum frame", xP is momentum of partons inside the nucleon

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M_T \nu}$$

Neutrino scatters off a parton inside the nucleon

So why is cross-section so large?



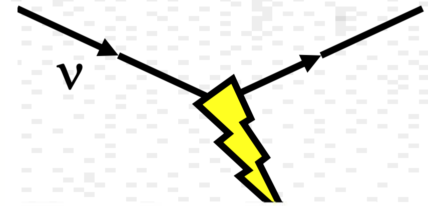
- (at least compared to νe^- scattering!)
- Recall that for neutrino beam and target at rest

$$\sigma_{TOT} \approx \frac{G_F^2}{\pi} \int_0^{Q^2_{\max} \equiv s} dQ^2 = \frac{G_F^2 s}{\pi}$$

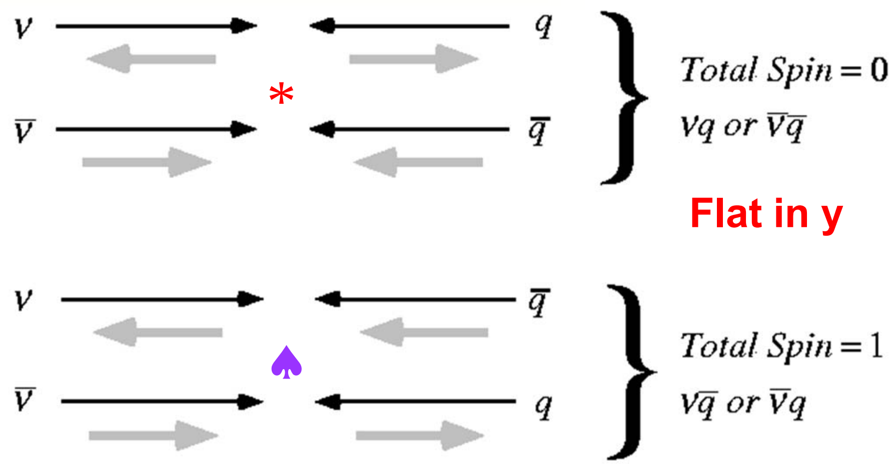
$$s = m_e^2 + 2 m_e E_\nu$$

- But we just learned for DIS that effective mass of each target quark is $m_q = x m_{\text{nucleon}}$
- So much larger target mass means larger σ_{TOT}

Chirality, Charge in CC ν-q Scattering



- Total spin determines inelasticity distribution
  - Familiar from neutrino-electron scattering



Flat in y

$\frac{1}{4}(1+\cos\theta^*)^2 = (1-y)^2$

$\int(1-y)^2 dy = 1/3$

point-like scattering implies linear with energy

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(x d(x) + x\bar{u}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(x\bar{d}(x) + x u(x)(1-y)^2\right)$$

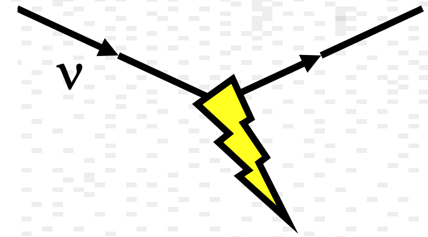
but what is this "q(x)"?

- Neutrino/Anti-neutrino CC each produce particular Δq in scattering

$$\nu d \rightarrow \mu^- u$$

$$\bar{\nu} u \rightarrow \mu^+ d$$

Brief Summary of Neutrino-Quark Scattering so Far

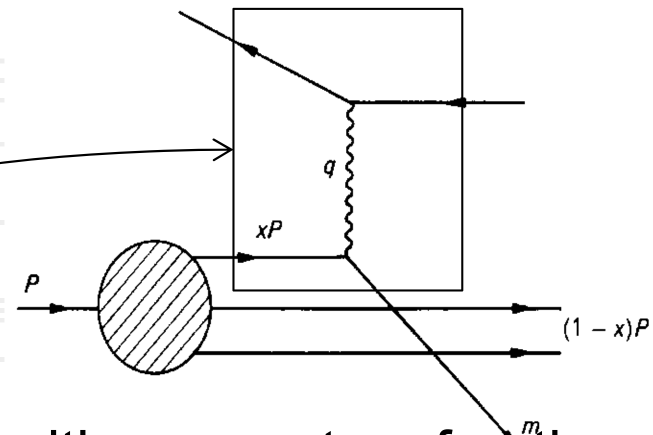


- $x \equiv Q^2/2M_T\nu$ is the fraction of the nucleon momentum ($\underline{P}$) carried by a given quark in the infinite momentum frame
  - Effective mass for struck quark, $M_q = \sqrt{(x\underline{P})^2} = xM_T$
- Quark and anti-quark scattering from neutrinos or anti-neutrinos defines total spin
  - νq and $\overline{\nu q}$ are spin 0, isotropic
  - $\nu\bar{q}$ and $\nu\bar{q}$ are spin 1, backscattering is suppressed
- Neutrinos and anti-neutrinos pick out definite quark and anti-quark flavors (charge conservation)

Factorization and Partons

- Factorization Theorem of QCD allows cross-sections for hadronic processes to be written as:

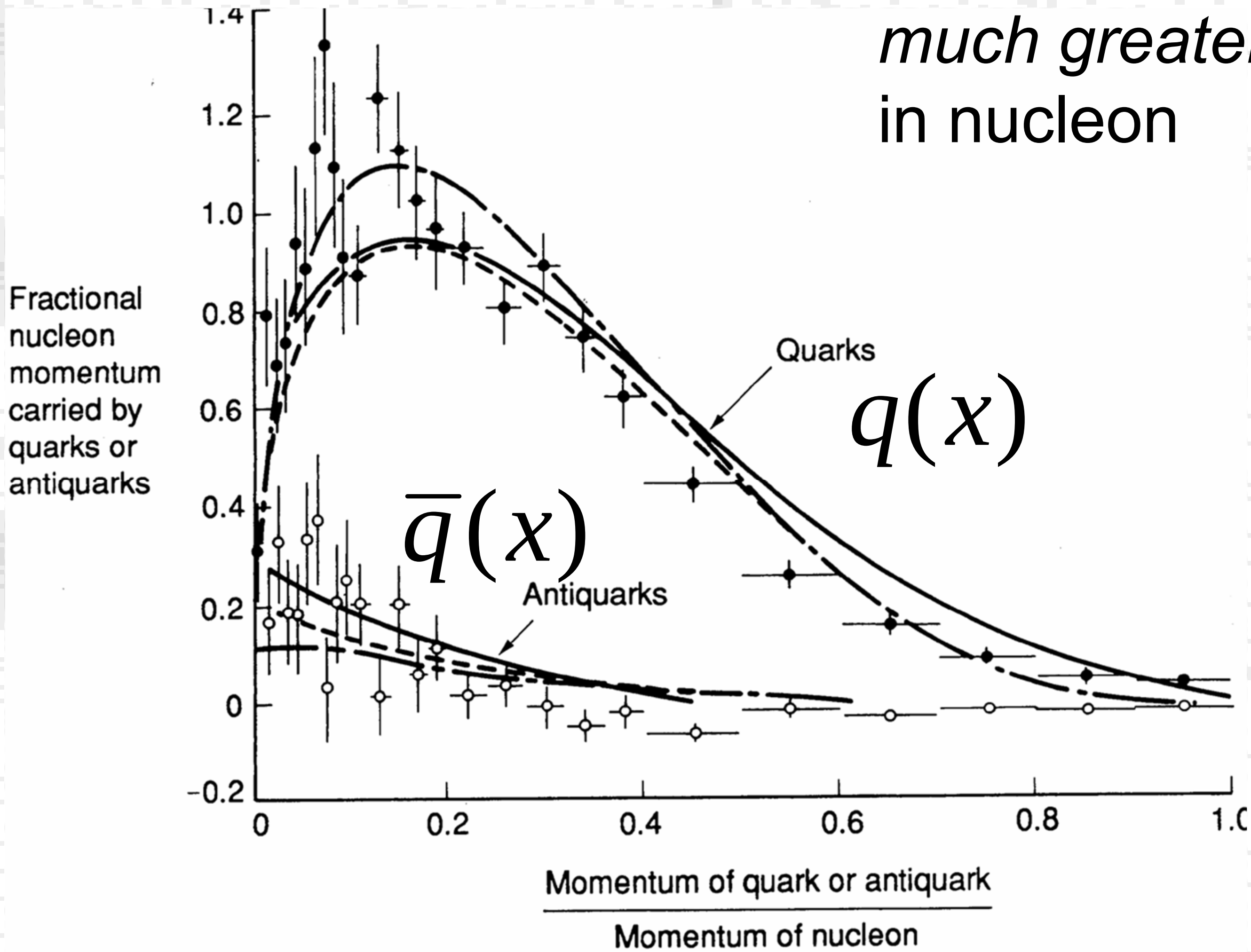
$$\sigma(l + h \rightarrow l + X) = \sum_q \int dx \sigma(l + q(x) \rightarrow l + X) q_h(x)$$



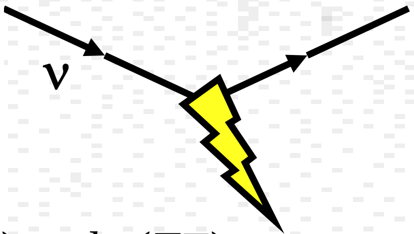
  - $q_h(x)$ is the probability of finding a parton, q, with momentum fraction x inside the hadron, h. It is called a parton distribution function (PDF).
  - PDFs are universal
  - PDFs are not (yet) calculable from first principles in QCD
- "Scaling": parton distributions are largely independent of Q^2 scale, and depend on fractional momentum, x.

Momentum of Quarks & Antiquarks

- Momentum carried by quarks *much greater* than anti-quarks in nucleon



y distribution in Neutrino CC DIS



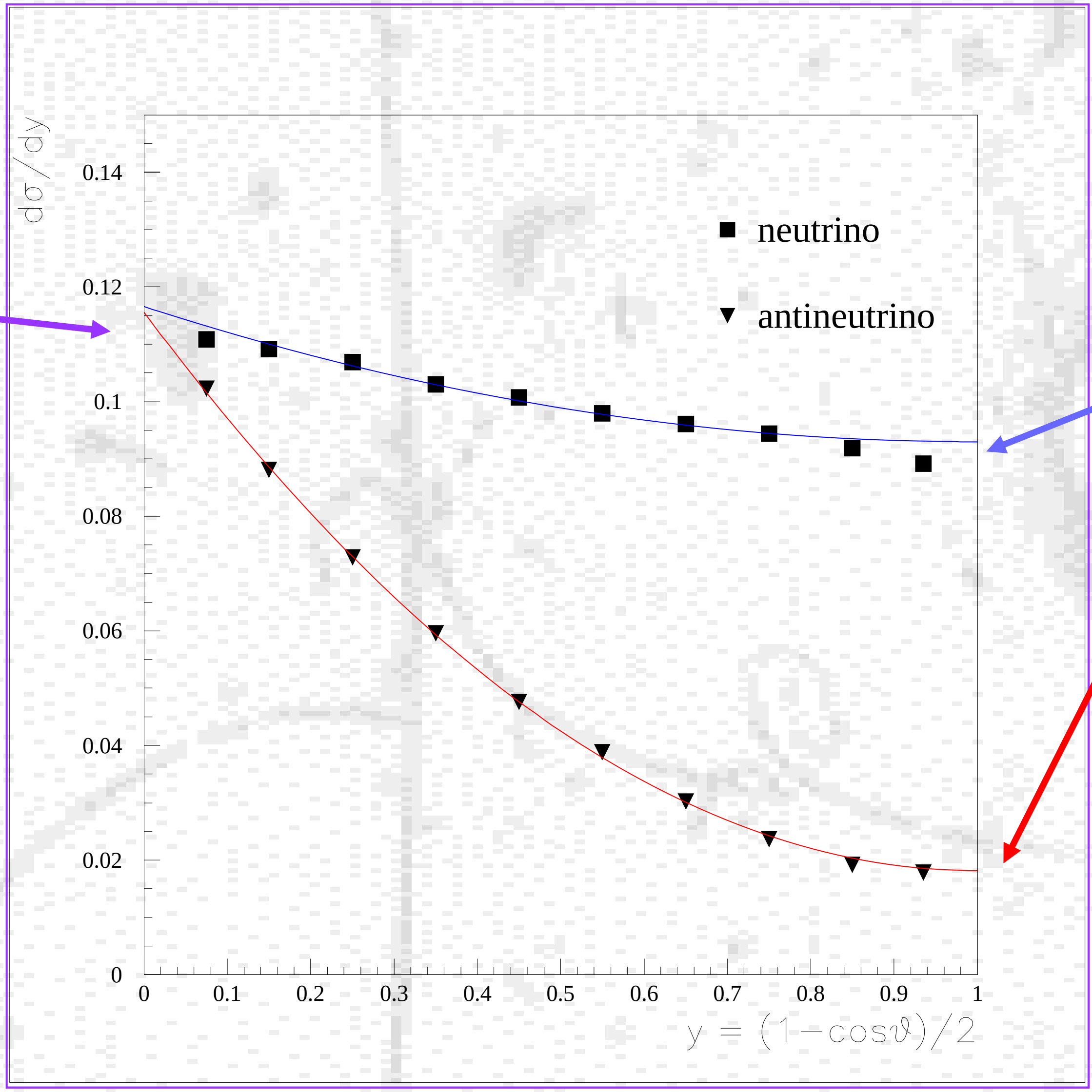
$$\frac{d\sigma(\nu q)}{dxdy} = \frac{d\sigma(\bar{\nu}\bar{q})}{dxdy} \propto 1$$

$$\frac{d\sigma(\nu \bar{q})}{dxdy} = \frac{d\sigma(\bar{\nu} q)}{dxdy} \propto (1-y)^2$$

At y=0:

Quarks & anti-quarks

Neutrino and anti-neutrino identical



At y=1:

Neutrinos see only quarks.

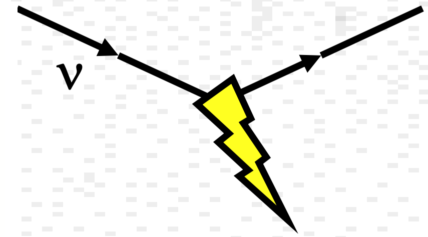
Anti-neutrinos see only anti-quarks

Averaged over protons and neutrons,

$$\sigma^{\bar{\nu}} \approx \frac{1}{2}\sigma^{\nu}$$

DIS: Relating SFs to Parton Distributions

Structure Functions (SFs)



- A model-independent picture of these interactions can also be formed in terms of nucleon "structure functions"
  - All Lorentz-invariant terms included
  - Approximate zero lepton mass (small correction)

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} \propto \left[y^2 2xF_1(x,Q^2) + \left(2 - 2y - \frac{M_T xy}{E} \right) F_2(x,Q^2) \pm y(2-y) xF_3(x,Q^2) \right]$$

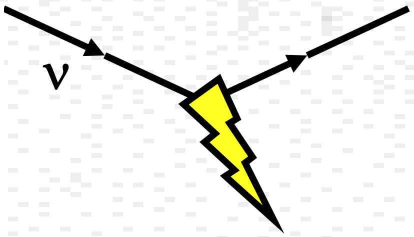
- For massless free spin-1/2 partons, one simplification…
  - Callan-Gross relationship, $2xF_1 = F_2$
  - Implies intermediate bosons are completely transverse

Can parameterize longitudinal cross-section by R_L.

Callan-Gross violations result from M_T, NLO pQCD, $g \to q\bar{q}$

$$R_L = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1}\left(1 + \frac{4M_T^2 x^2}{Q^2}\right)$$

SFs to PDFs



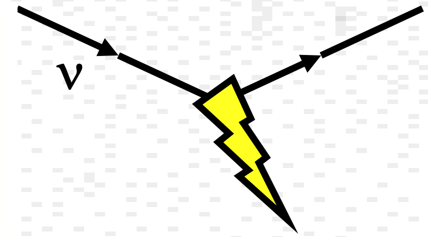
- Can relate SFs to PDFs in naïve quark-parton model by matching y dependence
  - Assuming Callan-Gross, massless targets and partons…
  - F_3: $2y-y^2=(1-y)^2-1$, $2xF_1=F_2$: $2-2y+y^2=(1-y)^2+1$

$$2xF_1^{\nu p,CC} = x\left[d_p(x)+\overline{u_p}(x)+s_p(x)+\overline{c_p}(x)\right]$$
$$xF_3^{\nu p,CC} = x\left[d_p(x)-\overline{u_p}(x)+s_p(x)-\overline{c_p}(x)\right]$$

- In analogy with neutrino-electron scattering, CC only involves left-handed quarks
- However, NC involves both chiralities (V-A and V+A)
  - Also couplings from EW Unification
  - And no selection by quark charge

$$2xF_1^{\nu p,NC} = x\left[(u_L^2+u_R^2)\left(u_p(x)+\overline{u_p}(x)+c_p(x)+\overline{c_p}(x)\right)+(d_L^2+d_R^2)\left(d_p(x)+\overline{d_p}(x)+s_p(x)+\overline{s_p}(x)\right)\right]$$
$$xF_3^{\nu p,NC} = x\left[(u_L^2-u_R^2)\left(u_p(x)-\overline{u_p}(x)+c_p(x)-\overline{c_p}(x)\right)+(d_L^2-d_R^2)\left(d_p(x)-\overline{d_p}(x)+s_p(x)-\overline{s_p}(x)\right)\right]$$

Isoscalar Targets



- Heavy nuclei are roughly neutron-proton isoscalar
- Isospin symmetry implies $u_p = d_n, d_p = u_n$
- Structure Functions have a particularly simple interpretation in quark-parton model for this case…

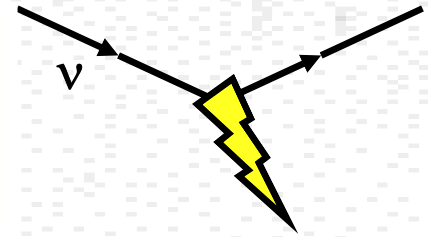
$$\frac{d^2\sigma^{\nu(\bar{\nu})N}}{dxdy} = \frac{G_F^2 s}{2\pi}\left\{\left(1+(1-y)^2\right)F_2(x) \pm \left(1-(1-y)^2\right)xF_3^{\nu(\bar{\nu})}(x)\right\}$$

$$2xF_1^{\nu(\bar{\nu})N,CC}(x) = x(u(x)+d(x)+\bar{u}(x)+\bar{d}(x)+s(x)+\bar{s}(x)+c(x)+\bar{c}(x)) = xq(x)+x\bar{q}(x)$$

$$xF_3^{\nu(\bar{\nu})N,CC}(x) = xu_{Val}(x)+xd_{Val}(x) \pm 2x(s(x)-c(x))$$

$$\text{where } u_{Val}(x) = u(x)-\bar{u}(x)$$

Touchstone Question #4: Neutrino and Anti-Neutrino $\sigma^{\nu N}$



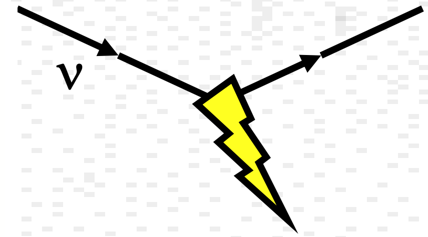
- **Given that** $\sigma_{CC}^{\bar{\nu}N} \approx \frac{1}{2}\sigma_{CC}^{\nu N}$ **in the DIS regime (CC)**

  and that $\frac{d\sigma(\nu q)}{dx} = \frac{d\sigma(\bar{\nu}\bar{q})}{dx} = 3\frac{d\sigma(\nu\bar{q})}{dx} = 3\frac{d\sigma(\bar{\nu}q)}{dx}$
  for CC scattering from quarks or anti-quarks of a given momentum,

  and that cross-section is proportional to parton momentum, what is the approximate ratio of anti-quark to quark momentum in the nucleon?

  (a) $\bar{q}/q \sim 1/3$ **(b)** $\bar{q}/q \sim 1/5$ **(c)** $\bar{q}/q \sim 1/8$

Touchstone Question #4: Neutrino and Anti-Neutrino $\sigma^{\nu N}$



- **Given that $\sigma_{CC}^{\bar{\nu}N} \approx \frac{1}{2}\sigma_{CC}^{\nu N}$ in the DIS regime (CC)**

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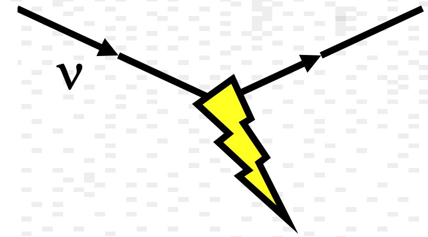
Touchstone Question #4: Neutrino and Anti-Neutrino $\sigma^{\nu N}$



- **Given:** $\sigma_{CC}^{\bar{\nu}N} \approx \frac{1}{2}\sigma_{CC}^{\nu N}$ **in the DIS regime (CC)**

and $$\frac{d\sigma(\nu q)}{dx} = \frac{d\sigma(\bar{\nu}\bar{q})}{dx} = 3\frac{d\sigma(\nu\bar{q})}{dx} = 3\frac{d\sigma(\bar{\nu}q)}{dx}$$

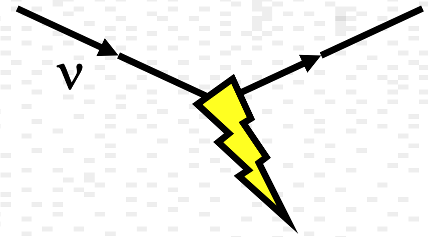
$$\sigma_\nu = \int_{q,\bar{q}} dx\left(\frac{d\sigma(\nu q)}{dx} + \frac{d\sigma(\nu\bar{q})}{dx}\right)$$

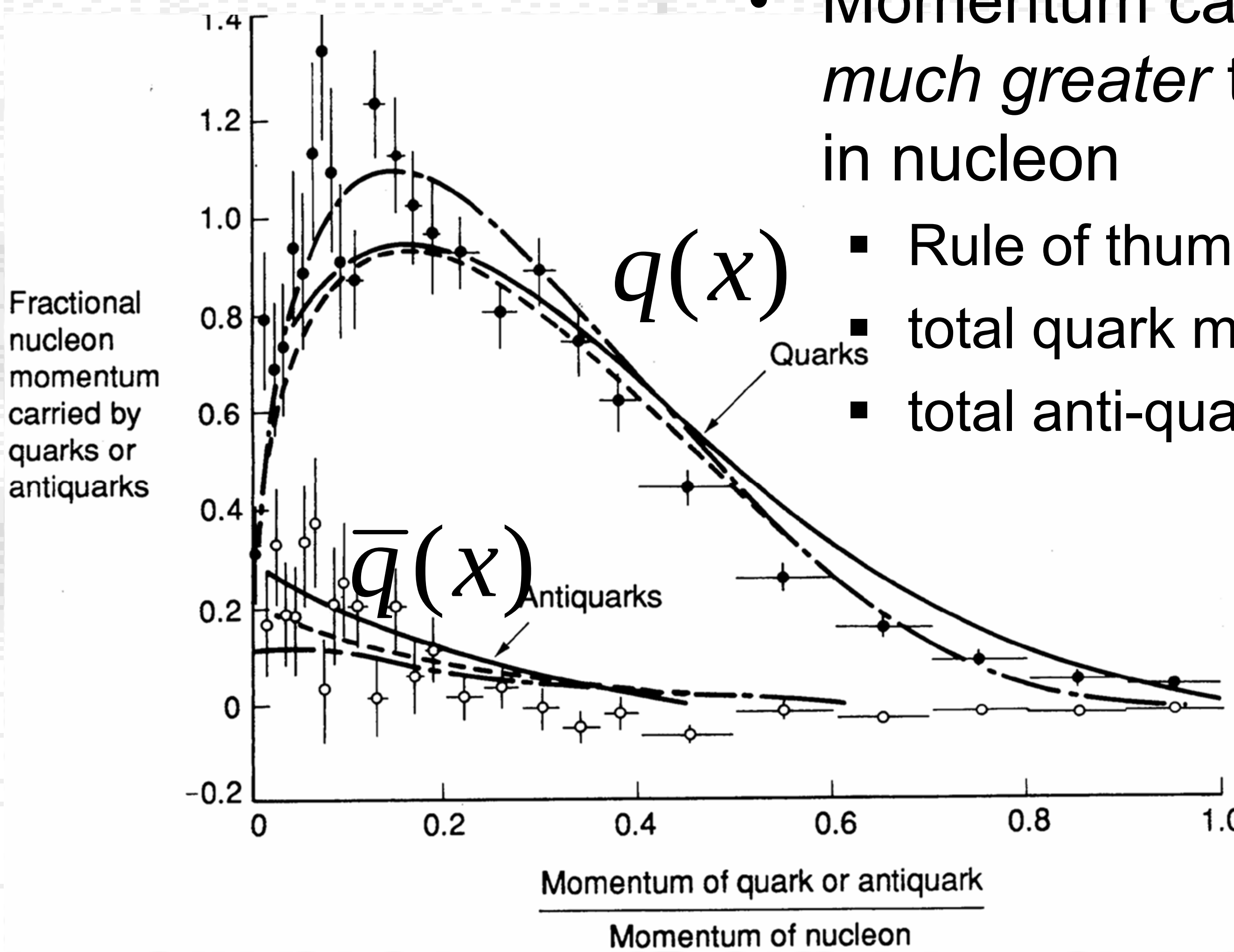
$$\sigma_{\bar{\nu}} = \int_{q,\bar{q}} dx\left(\frac{d\sigma(\bar{\nu}q)}{dx} + \frac{d\sigma(\bar{\nu}\bar{q})}{dx}\right) = \int_{q,\bar{q}} dx\left(\frac{d\sigma(\nu q)}{3dx} + \frac{3d\sigma(\nu\bar{q})}{dx}\right)$$

$$\therefore \int_{q,\bar{q}} dx\left(\frac{d\sigma(\nu q)}{dx} + \frac{d\sigma(\nu\bar{q})}{dx}\right) = 2\int_{q,\bar{q}} dx\left(\frac{d\sigma(\nu q)}{3dx} + \frac{3d\sigma(\nu\bar{q})}{dx}\right)$$

$$\frac{1}{3}\int_q dx\frac{d\sigma(\nu q)}{dx} = 5\int_{\bar{q}} dx\frac{d\sigma(\nu\bar{q})}{dx} = \frac{5}{3}\int_{\bar{q}} dx\frac{d\sigma(\bar{\nu}\bar{q})}{dx}$$

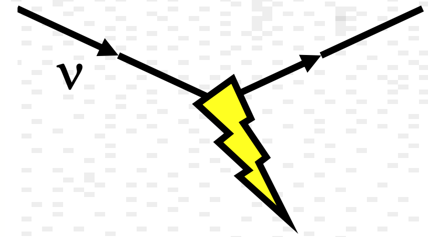
Momentum of Quarks & Antiquarks



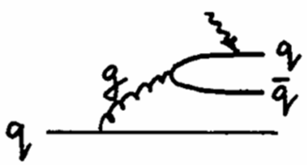


- Momentum carried by quarks *much greater* than anti-quarks in nucleon
  - Rule of thumb: at Q^2 of 10 GeV^2:
  - total quark momentum is 1/3,
  - total anti-quark is 1/15.

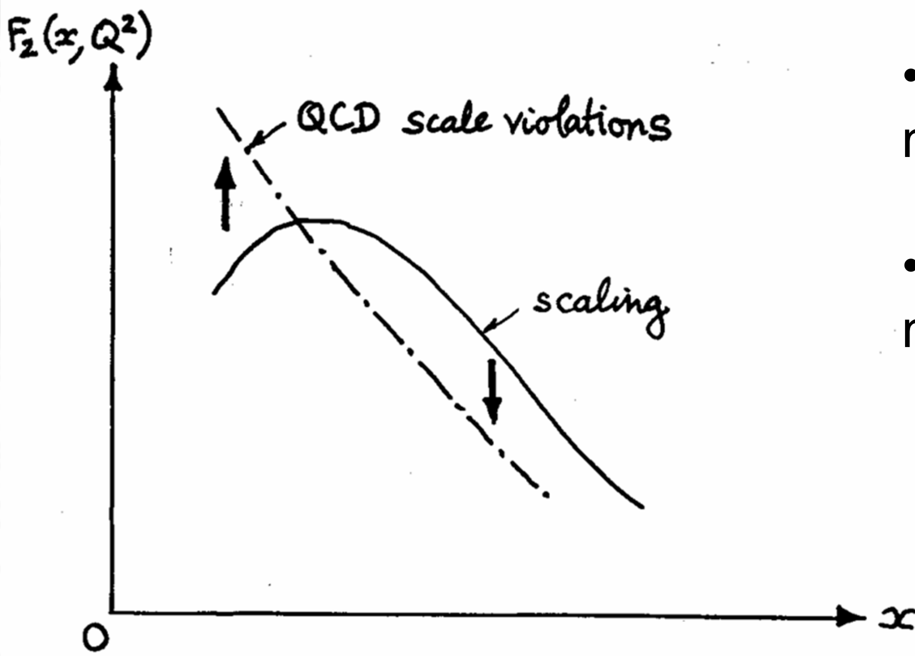
Strong Interactions among Partons



Q² Scaling fails due to these interactions



$$\frac{\partial q(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)q(y,Q^2) + P_{qg}\left(\frac{x}{y}\right)g(y,Q^2)\right]$$

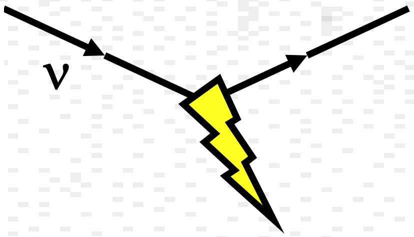


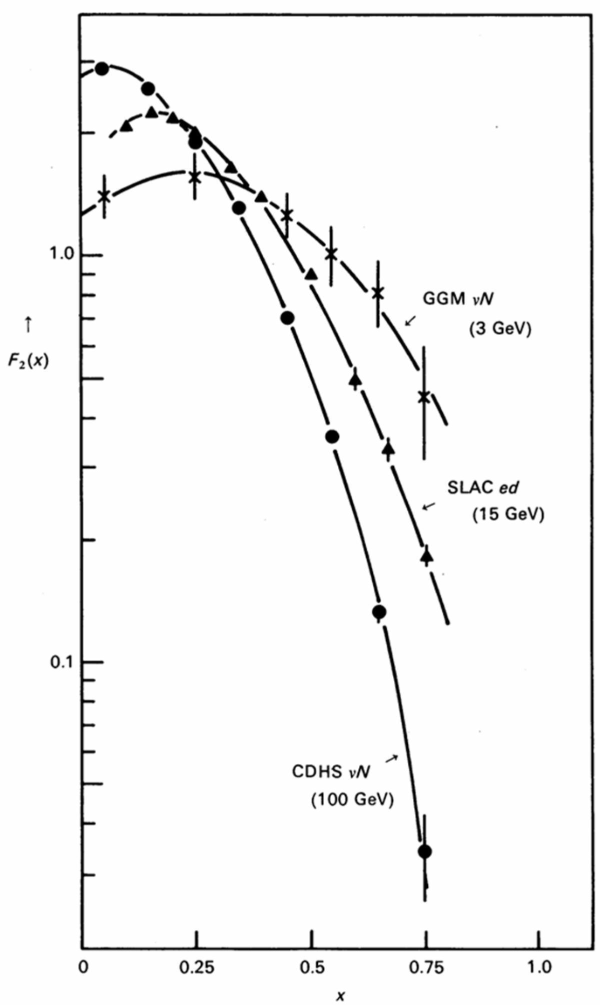
- Pqq(x/y) = probability of finding a quark with momentum x within a quark with momentum y
- Pqq(x/y) = probability of finding a q with momentum x within a gluon with momentum y

$$P_{qq}(z) = \frac{4}{3}\frac{1+z^2}{(1-z)} + 2\delta(1-z)$$

$$P_{gq}(z) = \frac{1}{2}\left[z^2 + (1-z)^2\right]$$

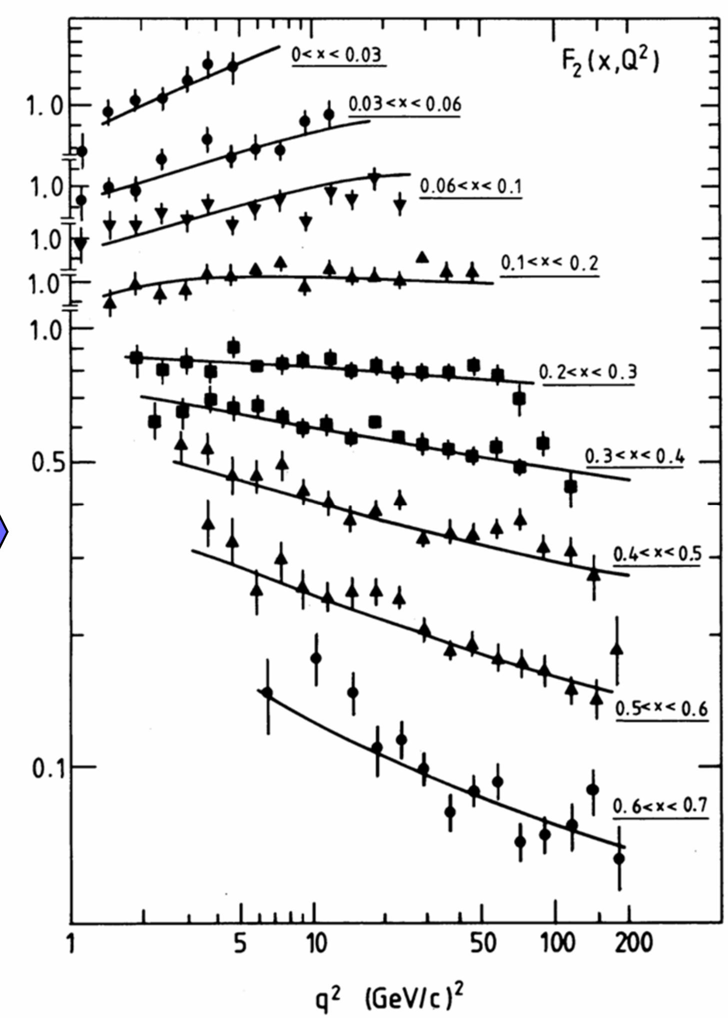
Scaling from QCD



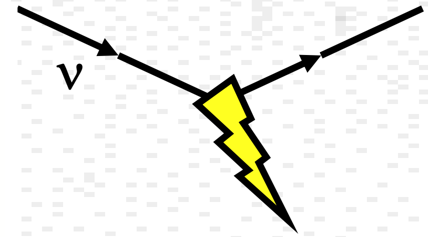


Observed quark distributions vary with Q^2

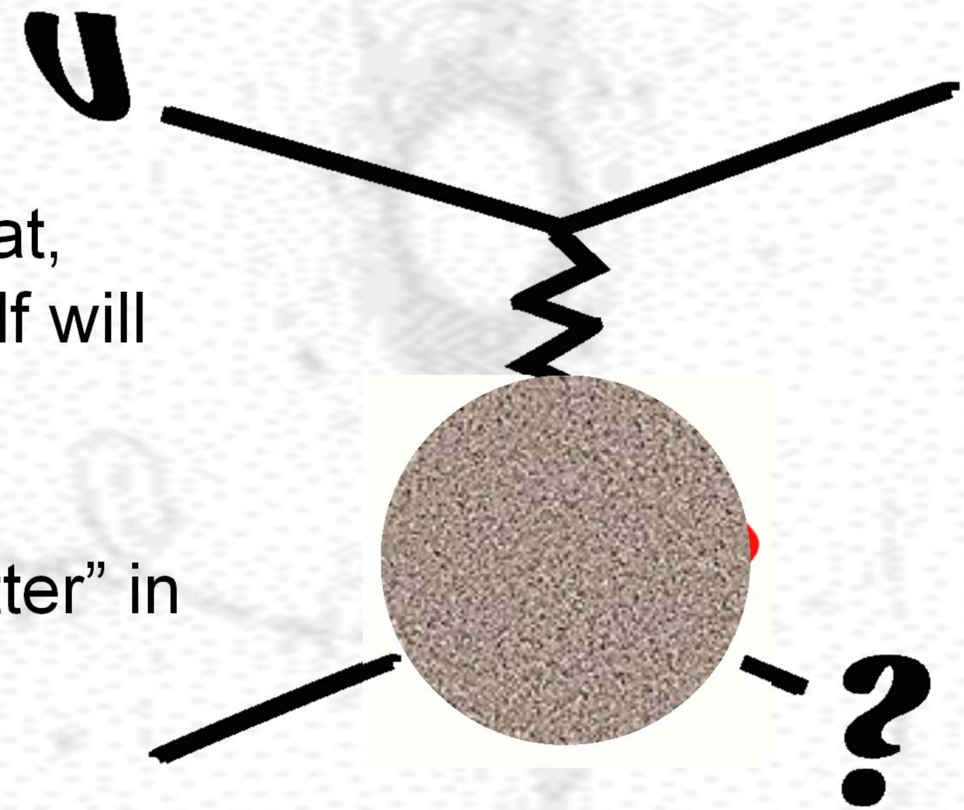
Scaling well modeled by perturbative QCD with a single free parameter (α_s)



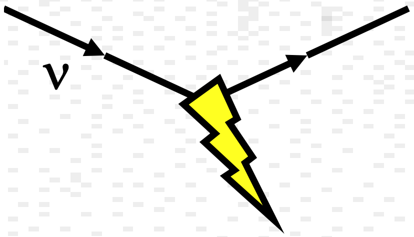
Is a nucleus more than a sum of nucleons?



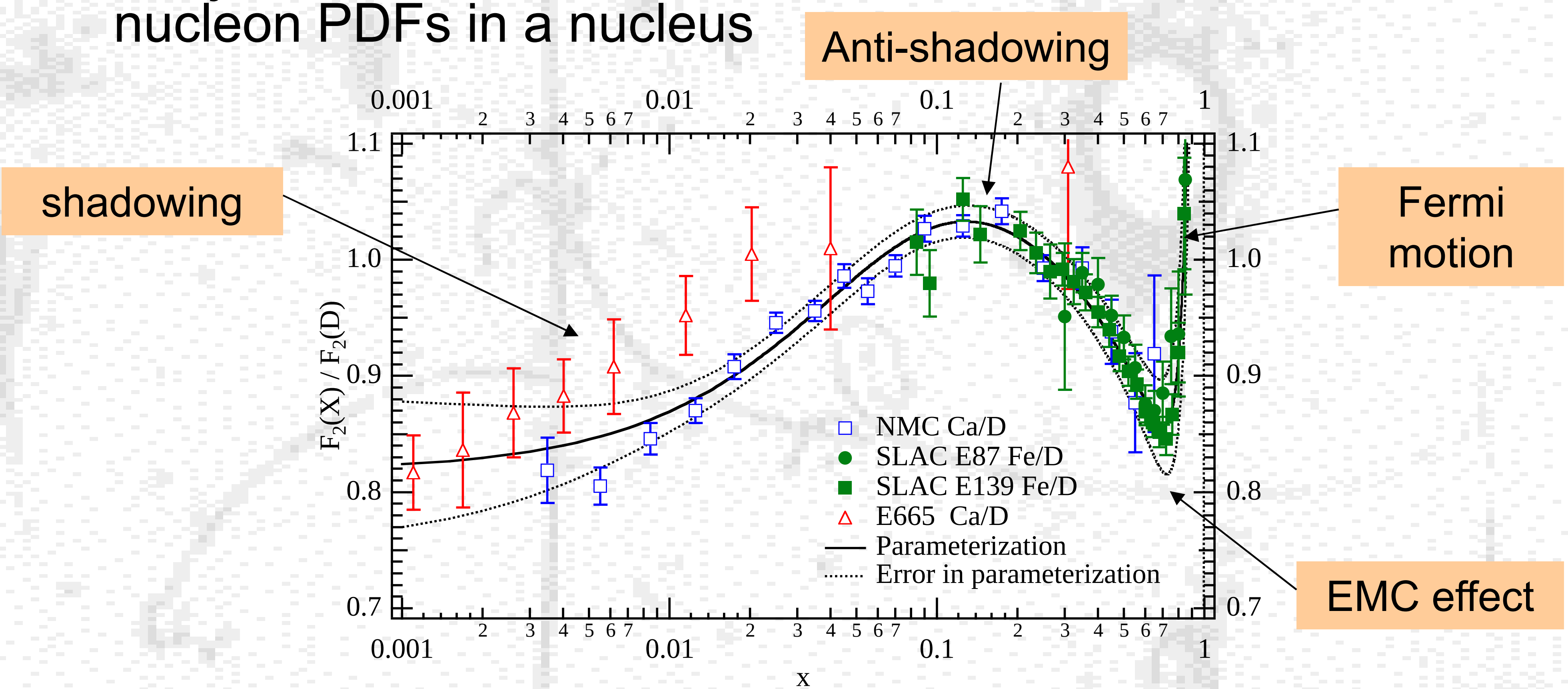
- Simply put, yes.
- Even if you know the structure of your free nucleon, it is not stationary in a nucleus
- And if you can understand that, then the nuclear medium itself will modify your target nucleons.
- And your final state hadronic particle may interact (“re-scatter” in the nucleus as it leaves.
- This can be messy…



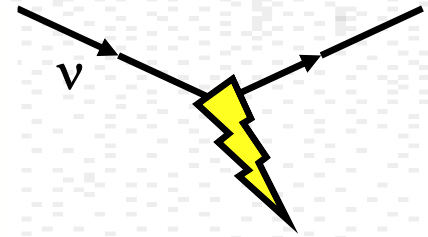
Is the DIS Limit Simple?

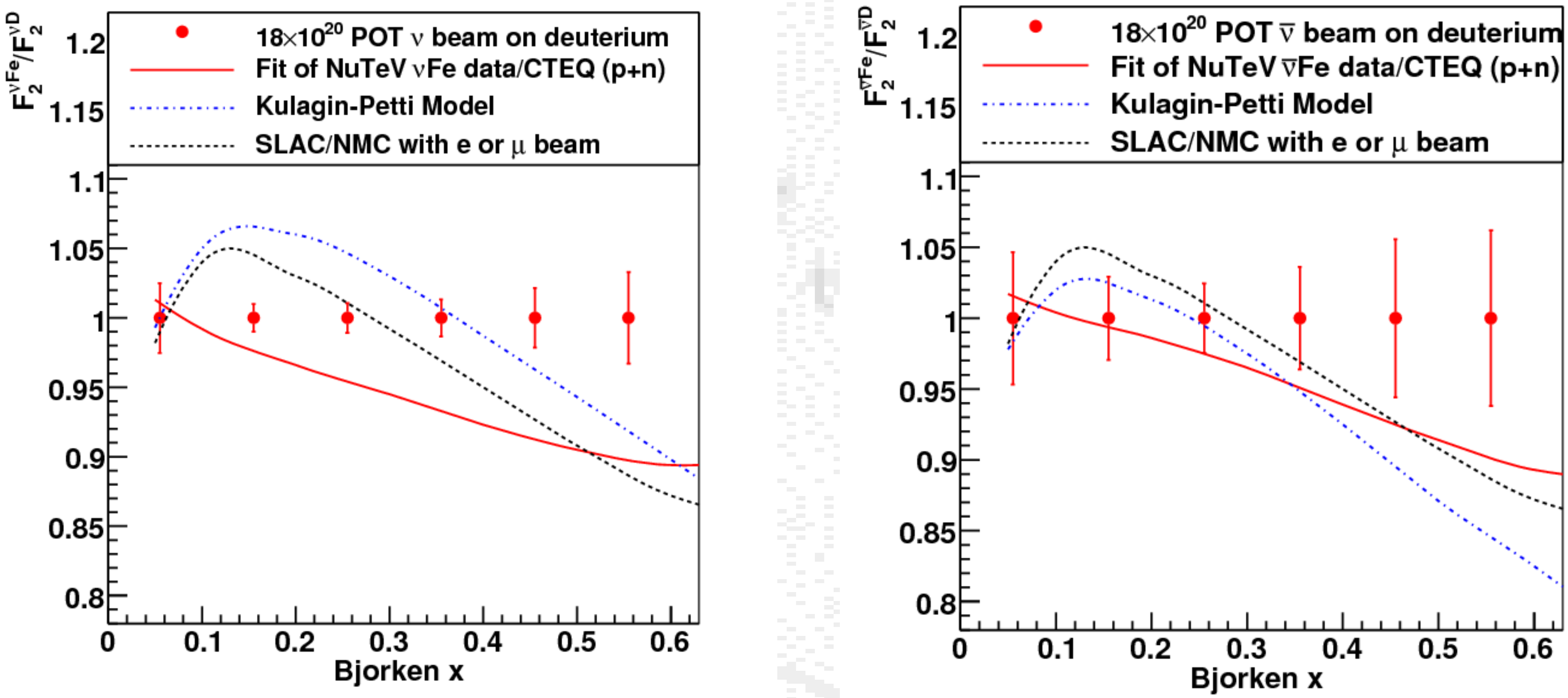


- Well measured effects in charged-lepton DIS
  - Maybe the same for neutrino DIS; maybe not… all precise neutrino data is on Ca or Fe targets!
  - Conjecture: these can be absorbed into effective nucleon PDFs in a nucleus



But that conjecture may be wrong…





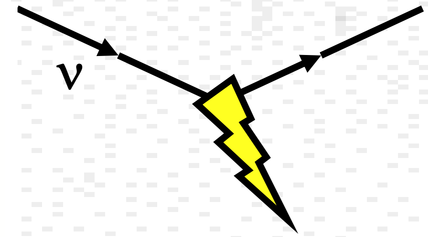
Curves from: Ingo Schienbein et al., Phys.Rev.D80(2009)094004; PRD77(2008)054013

- *(Problematic) fits to current data don't match theory or charged lepton data*
- *Only answer is to measure… red points are MINERvA experiment if it can add a deuterium target in the 2013-2018 run, parasitic with NOvA.*

From SFs to PDFs

- As you all know, there is a large industry in determining Parton Distributions for hadron collider simulations.
  - to the point where some of my colleagues on collider experiments might think of parton distributions as an annoying piece of FORTRAN code in their software package
- The purpose, of course, is to use factorization to predict cross-sections for various processes
  - combining deep inelastic scattering data from various sources together allows us to “measure” parton distributions
  - which then are applied to predict hadron-hadron processes at colliders, and can also be used in predictions for neutrino scattering, as we shall see.

From SFs to PDFs (cont'd)



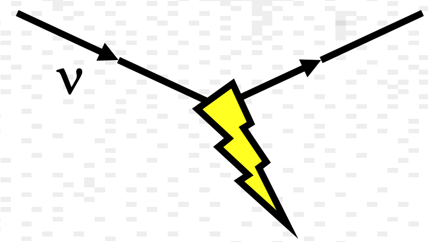
- We just learned that…

$$2xF_1^{\nu(\bar{\nu})N,CC}(x) = xq(x) + x\bar{q}(x)$$
$$xF_3^{\nu(\bar{\nu})N,CC}(x) = xu_{Val}(x) + xd_{Val}(x) \pm 2x(s(x) - c(x))$$
$$\text{where } u_{Val}(x) = u(x) - \bar{u}(x)$$

- In charged-lepton DIS

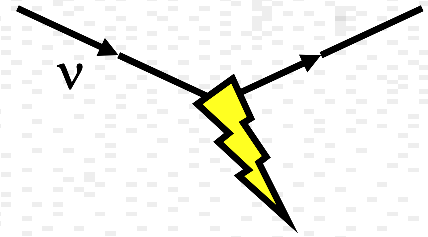
$$2xF_1^{\gamma p}(x) = \left(\tfrac{2}{3}\right)^2 \sum_{\text{up type quarks}} q(x) + \bar{q}(x)$$
$$+ \left(\tfrac{1}{3}\right)^2 \sum_{\text{down type quarks}} q(x) + \bar{q}(x)$$

- So you begin to see how one can combine neutrino and charged lepton DIS and separate
  - the quark sea from valence quarks
  - up quarks from down quarks



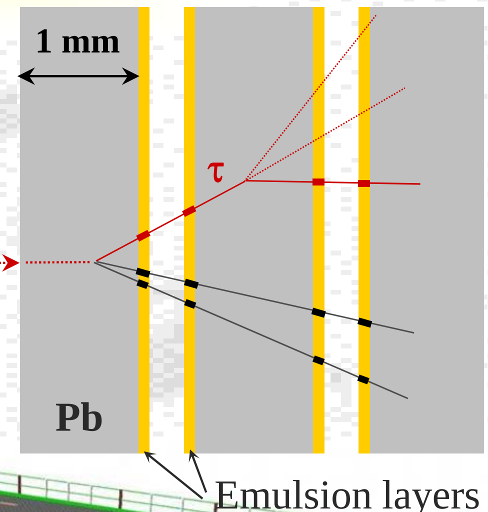
DIS: Massive Quarks and Leptons

Opera at CNGS

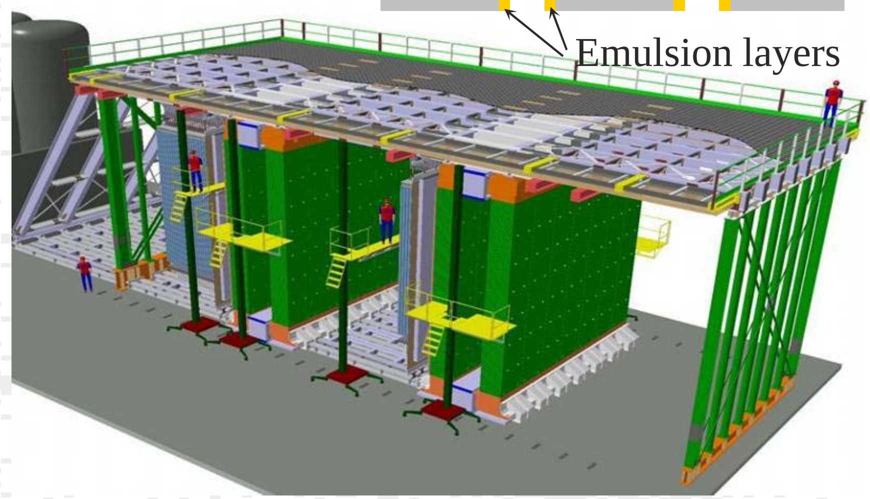


Goal: ν_τ appearance

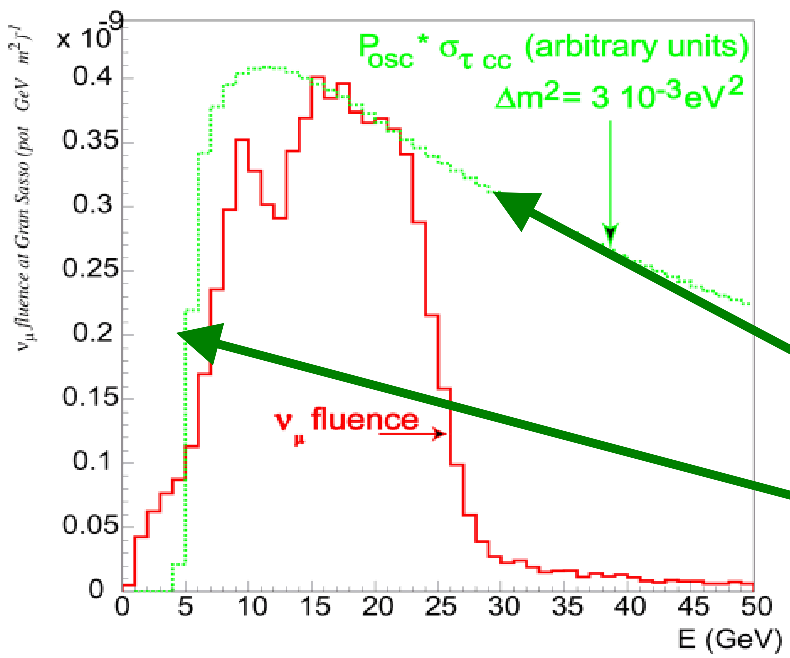
- 0.15 MWatt source
- high energy ν_μ beam
- 732 km baseline
- handfuls of events/yr



1.8kTon



figures courtesy D. Autiero



oscillation probability

but what is this effect?

Lepton Mass Effects in DIS

- Recall that final state mass effects enter as corrections:

$$1-\frac{m^2_{\text{lepton}}}{s_{\text{point-like}}} \rightarrow 1-\frac{m^2_{\text{lepton}}}{xs_{\text{nucleon}}}$$

  - *relevant center-of-mass energy is that of the "point-like" neutrino-parton system*
  - *this is high energy approximation*
- For ν_τ charged-current, there is a threshold of

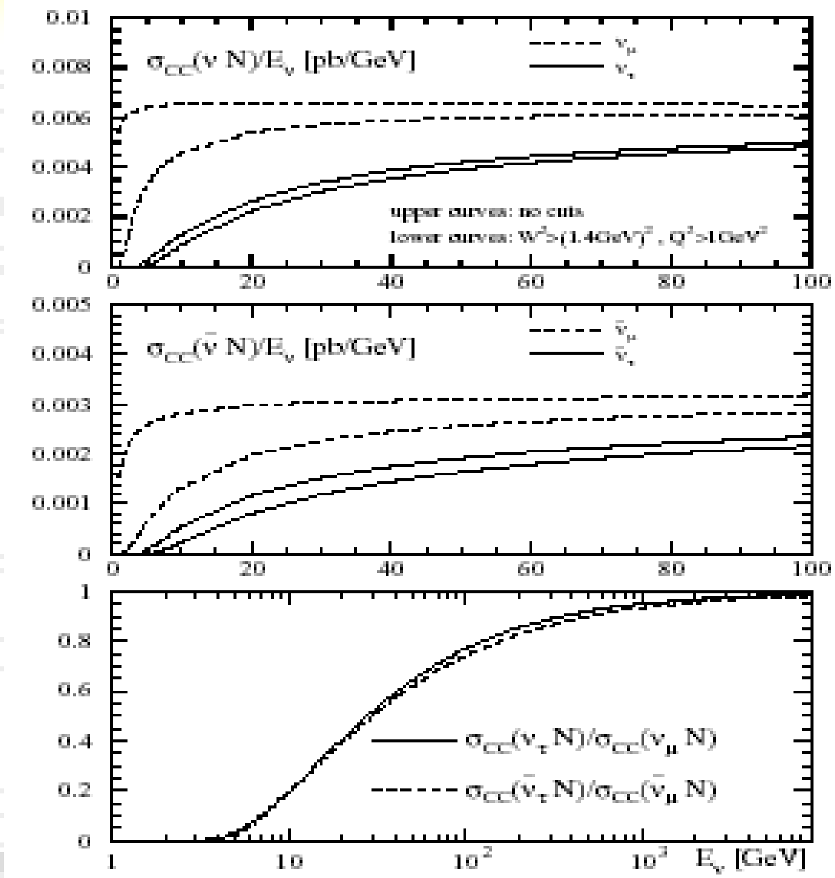
$$s_{\min} = (m_{\text{nucleon}} + m_\tau)^2$$

where

$$s_{initial} = m^2_{\text{nucleon}} + 2E_\nu m_{\text{nucleon}}$$

$$\therefore E_\nu > \frac{m_\tau{}^2 + 2m_\tau m_{\text{nucleon}}}{2m_{\text{nucleon}}} \approx 3.5\text{ GeV}$$

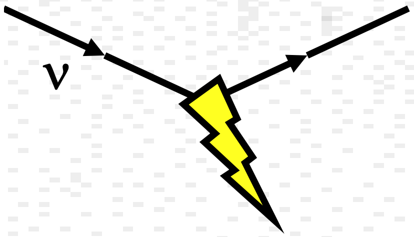
"m_{nucleon}" is M_T elsewhere, but don't want to confuse with m_τ...



(Kretzer and Reno)

- This is threshold for partons with *entire* nucleon momentum
  - effects big at higher E_ν also

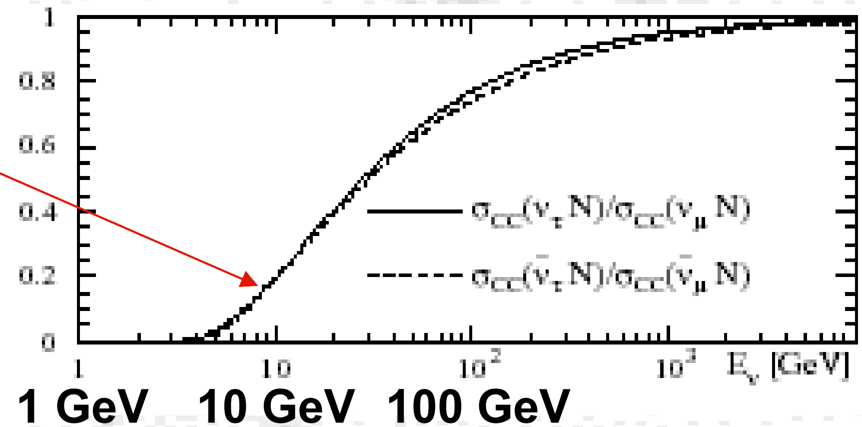
Touchstone Question #5: What if Taus were Lighter?



- Imagine we lived in a universe where the tau mass was not 1.777 GeV, but was 0.888 GeV
- By how much would the tau appearance cross-section for an 8 GeV tau neutrino increase at OPERA?

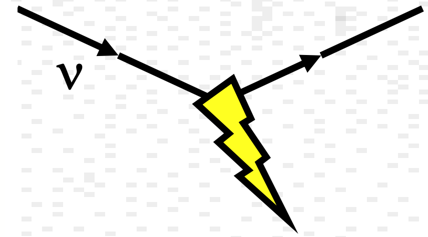
mass suppression: $$1-\frac{m_{\text{lepton}}^2}{x s_{\text{nucleon}}}$$

$$s_{\text{nucleon}} = m_{\text{nucleon}}^2 + 2E_\nu m_{\text{nucleon}}$$



(a) $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 1.4$$ **(b)** $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 2$$ **(c)** $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 3$$

Touchstone Question #5: What if Taus were Lighter?



- Imagine we lived in a universe where the tau mass was not 1.777 GeV, but was 0.888 GeV
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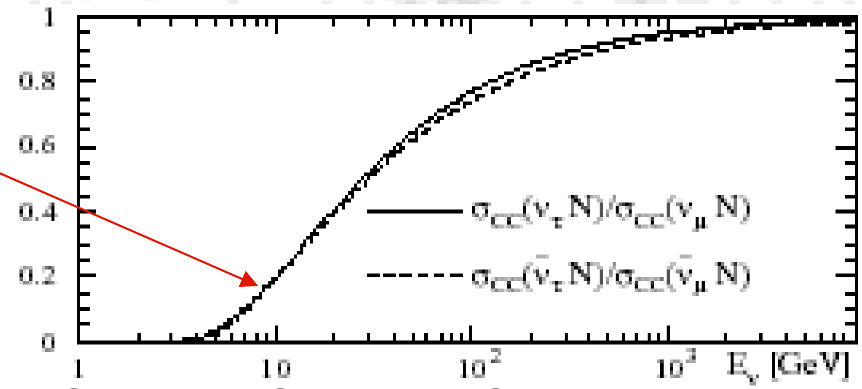

1 GeV 10 GeV 100 GeV

(a) $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 1.4$$

(b) $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 2$$

(c) $$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 3$$

Touchstone Question #5: What if Taus were Lighter?

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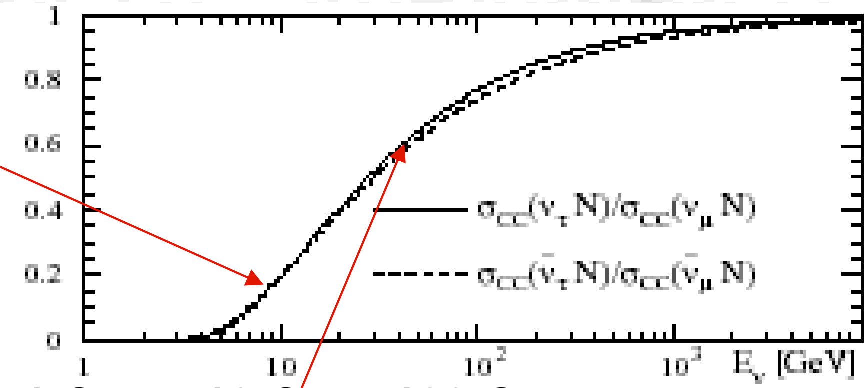
mass suppression: $1-\frac{m^2_{\text{lepton}}}{xs_{\text{nucleon}}}$



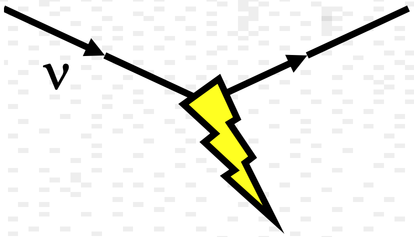
Numerator goes down by factor of four. Equivalent to denominator increasing by factor of four and tau mass unchanged…

$$s_{\text{nucleon}} = m^2_{\text{nucleon}} + 2E_\nu m_{\text{nucleon}}$$

energy term dominates…
so set energy a factor of four higher

$$\frac{\sigma_{\text{Light Tau}}}{\sigma_{\text{Reality}}} \sim 3$$

Opera at CNGS



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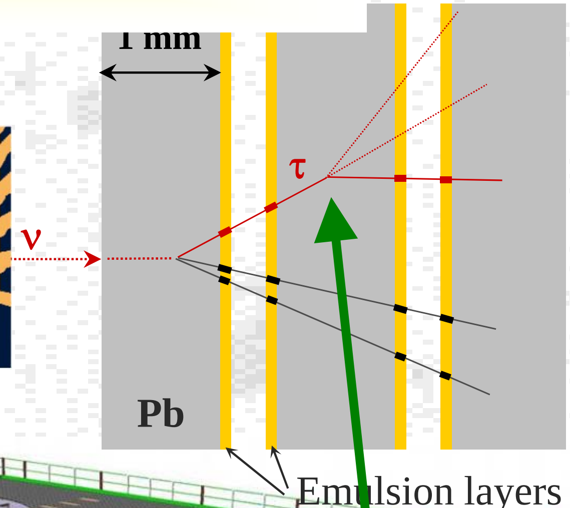
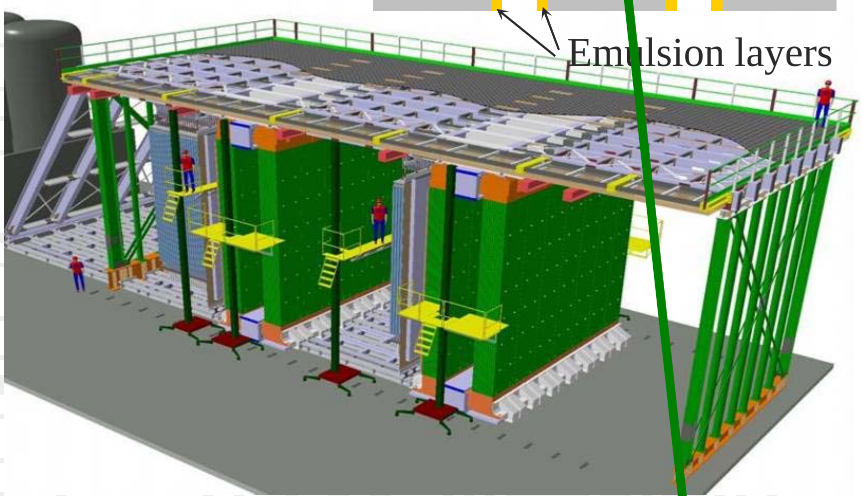
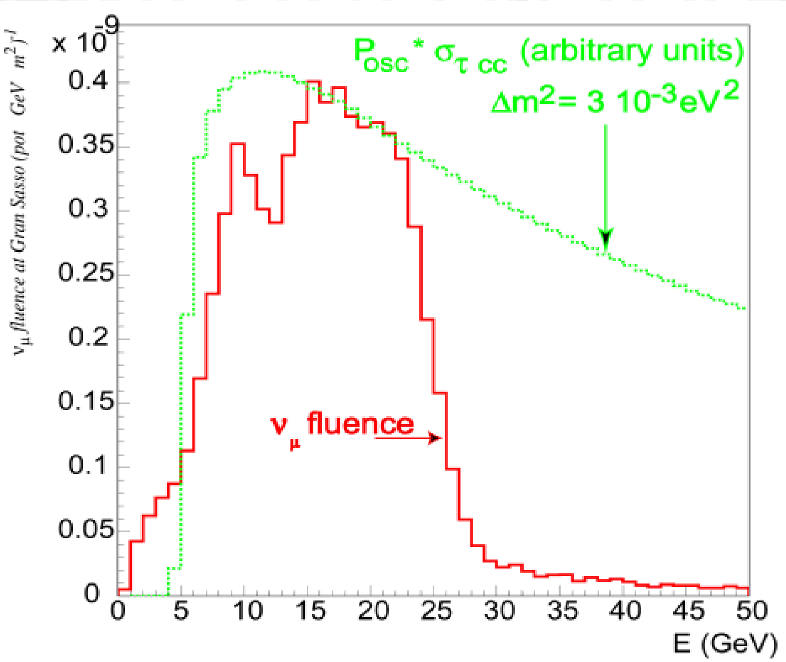


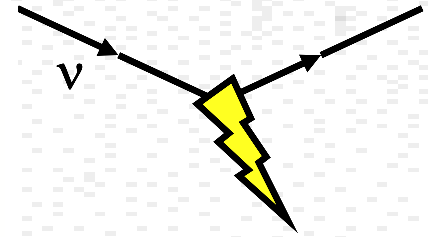




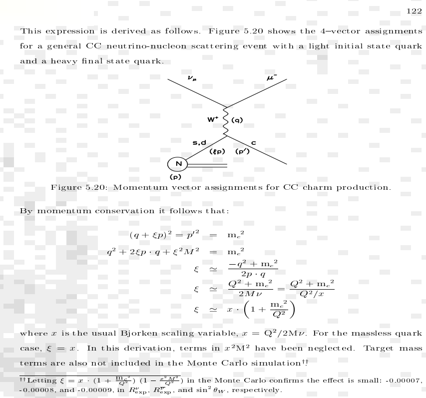
figures courtesy D. Autiero

what else is copiously produced in neutrino interactions with $c\tau \sim 100\mu m$ and decays to hadrons?

Heavy Quark Production



- Production of heavy quarks modifies kinematics of our earlier definition of x.
  - Charm is heavier than proton; hints that its mass is not a negligible effect…



This expression is derived as follows. Figure 5.20 shows the 4–vector assignments for a general CC neutrino-nucleon scattering event with a light initial state quark and a heavy final state quark.

Figure 5.20: Momentum vector assignments for CC charm production.

By momentum conservation it follows that:

$$(q+\xi p)^2 = p'^2 = m_c^2$$

$$q^2 + 2\xi p\cdot q + \xi^2 M^2 = m_c^2$$

$$\xi \simeq \frac{-q^2 + m_c^2}{2p\cdot q}$$

$$\xi \simeq \frac{Q^2 + m_c^2}{2M\nu} = \frac{Q^2 + m_c^2}{Q^2/x}$$

$$\xi \simeq x\cdot\left(1+\frac{m_c^2}{Q^2}\right)$$

where x is the usual Bjorken scaling variable, $x = Q^2/2M\nu$. For the massless quark case, $\xi = x$. In this derivation, terms in x^2M^2 have been neglected. Target mass terms are also not included in the Monte Carlo simulation††.

†† Letting $\xi = x\cdot(1+\frac{m_c^2}{Q^2})\,(1-\frac{x^2M^2}{Q^2})$ in the Monte Carlo confirms the effect is small: -0.00007, -0.00008, and -0.00009, in R^{ν}_{exp}, $R^{\bar\nu}_{exp}$, and $\sin^2\theta_W$, respectively.

$$(q+\zeta p)^2 = p'^2 = m_c^2$$

$$q^2 + 2\zeta p\bullet q + \zeta^2 M^2 = m_c^2$$

$$\text{Therefore } \zeta \cong \frac{-q^2 + m_c^2}{2p\bullet q}$$

$$\zeta \cong \frac{Q^2 + m_c^2}{2M\upsilon} = \frac{Q^2 + m_c^2}{Q^2/x}$$

$$\zeta \cong x\left(1+\frac{m_c^2}{Q^2}\right)$$

Note different definition of fractional momentum

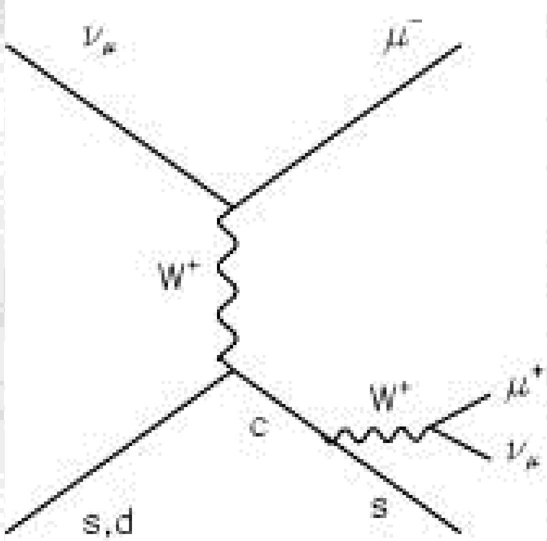
"slow rescaling" leads to kinematic suppression of charm production

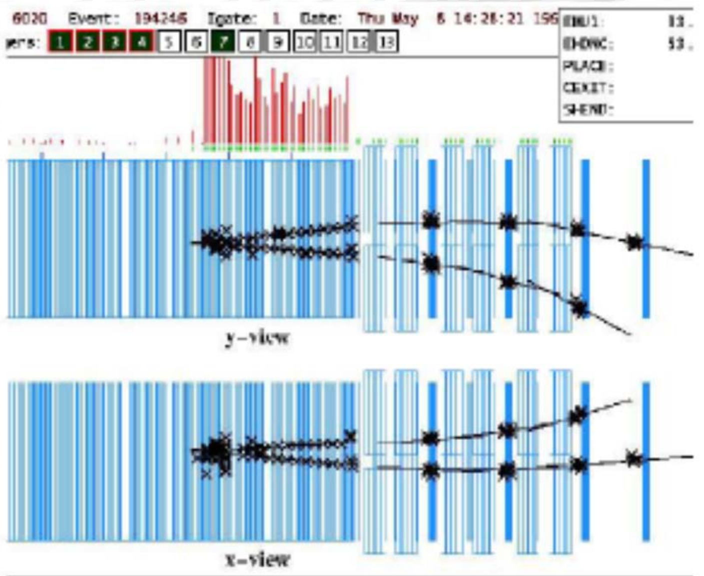
Neutrino Dilepton Events

- Neutrino induced charm production has been extensively studied
  - Emulsion/Bubble Chambers (low statistics, 10s of events). Reconstruct the charm final state, but limited by target mass.
  - "Dimuon events" (high statistics, 1000s of events)

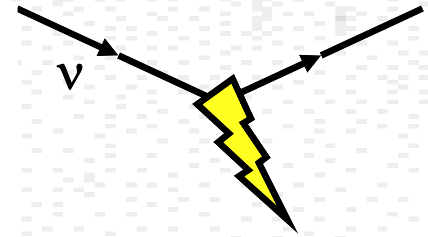
$$\nu_\mu + \begin{pmatrix} d \\ s \end{pmatrix} \to \mu^- + c + X, \qquad c \to \mu^+ + \nu_\mu + X'$$

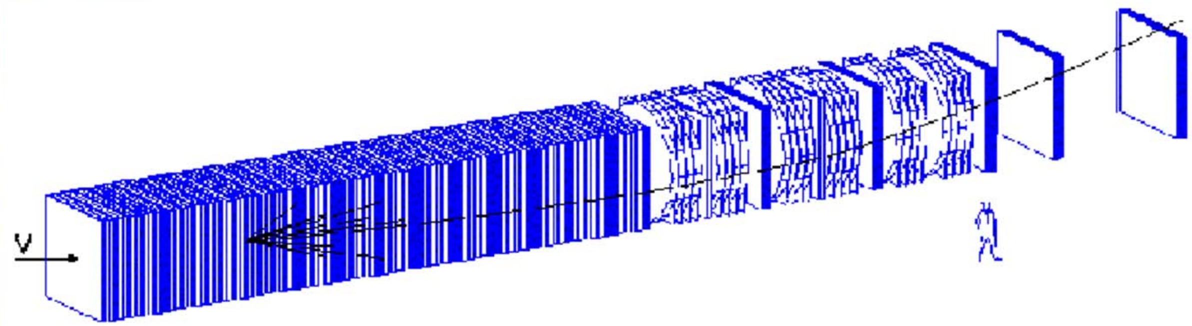
$$\bar{\nu}_\mu + \begin{pmatrix} \bar{d} \\ \bar{s} \end{pmatrix} \to \mu^+ + \bar{c} + X, \qquad \bar{c} \to \mu^- + \bar{\nu}_\mu + X'$$

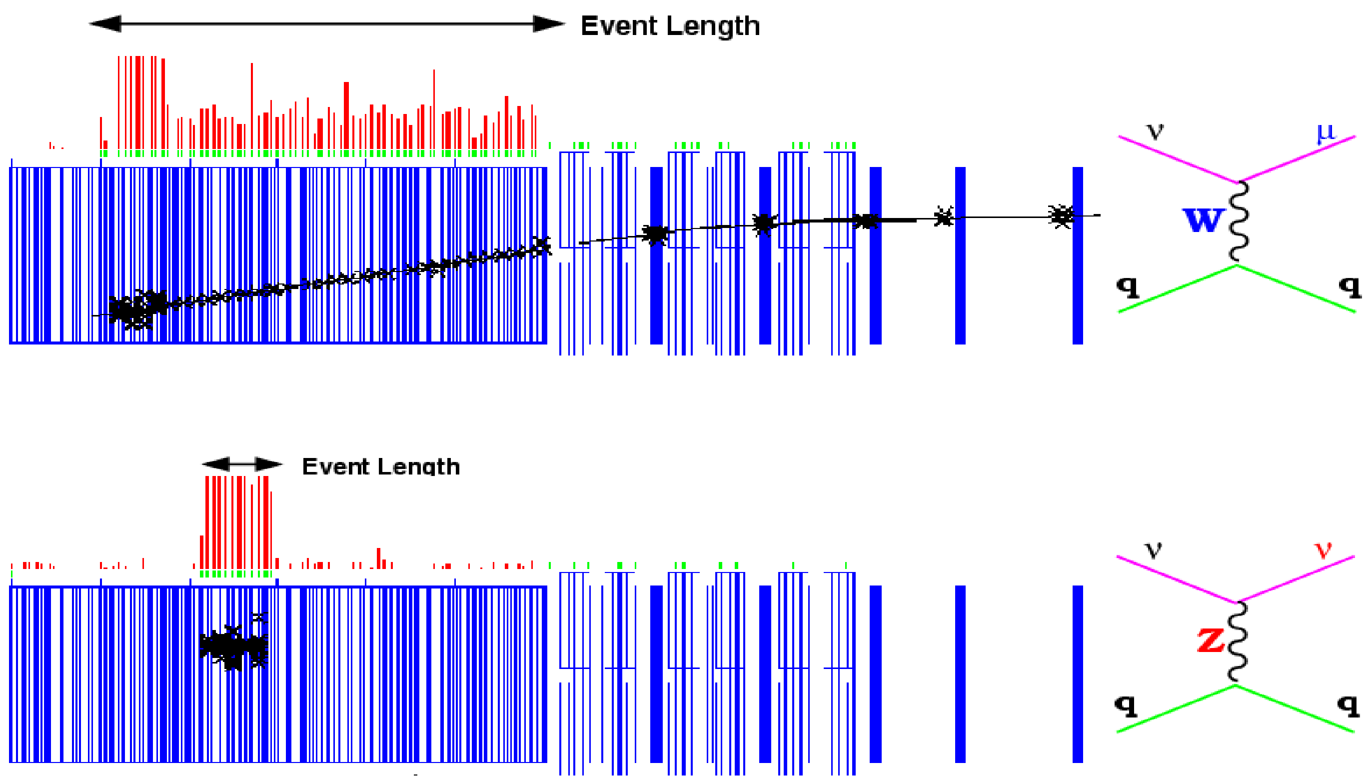




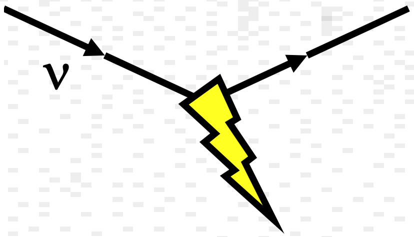
NuTeV at Work…







Neutrino Dilepton Events



- Rate depends on:
  - d, s quark distributions, $|V_{cd}|$
  - Semi-leptonic branching ratios of charm
  - Kinematic suppression and fragmentation

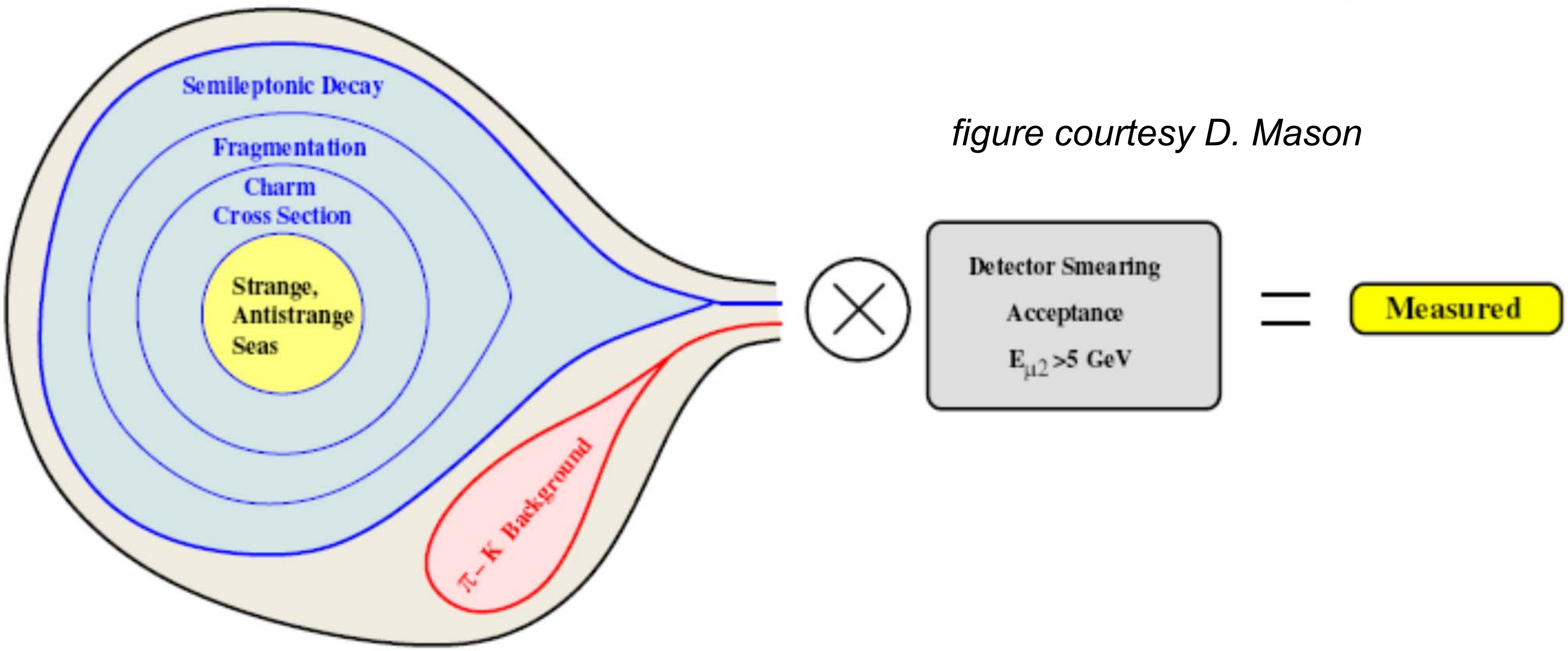
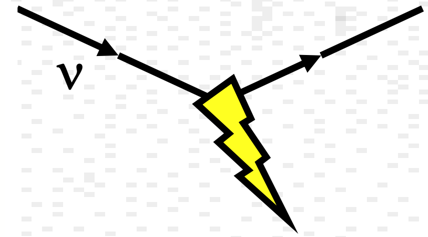
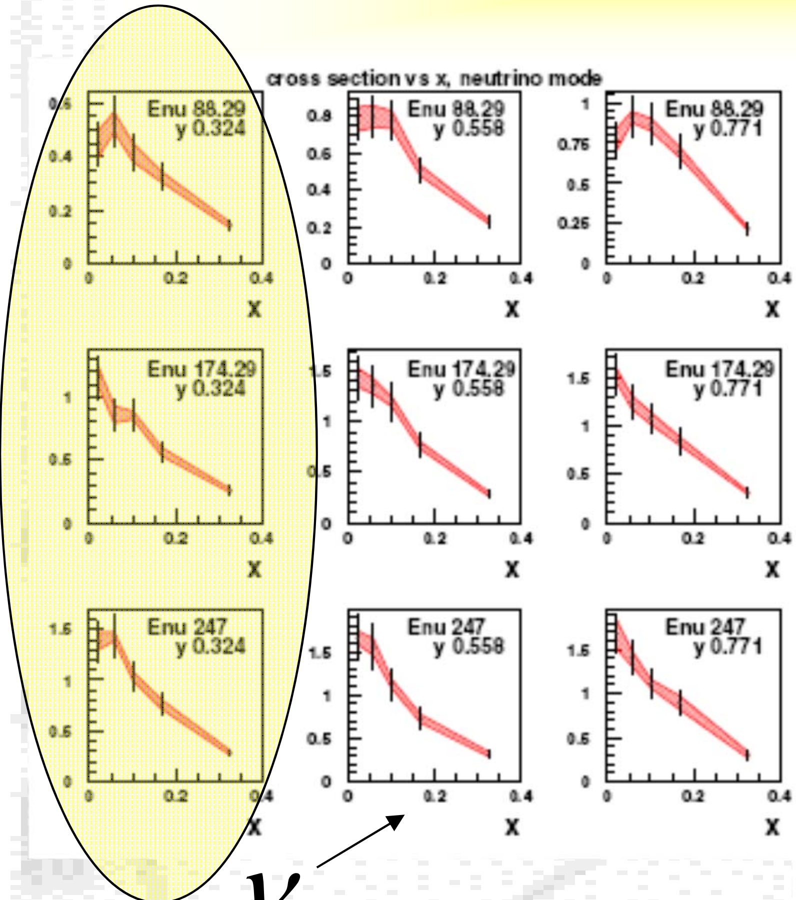


figure courtesy D. Mason

NuTeV Dimuon Sample

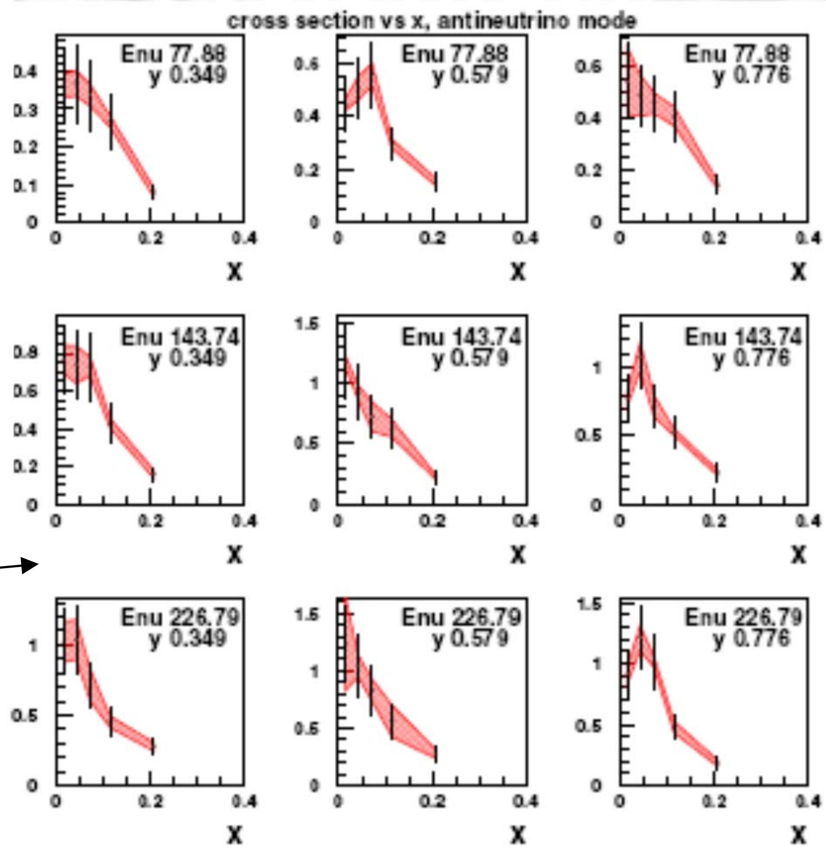


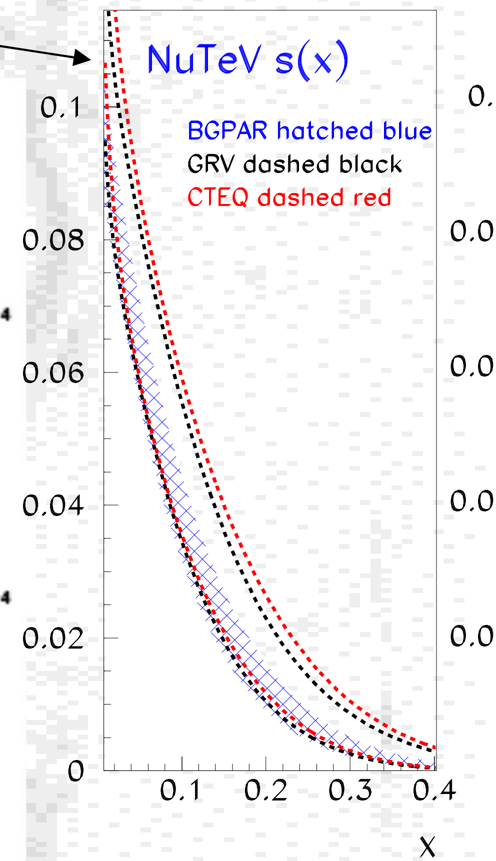
- Lots of data!
- Separate data in energy, x and y (inelasticity)
  - Energy important for charm threshold, m_c
  - x important for s(x)



ν

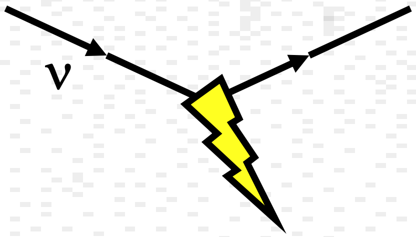
$\overline{\nu}$



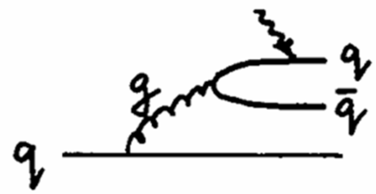


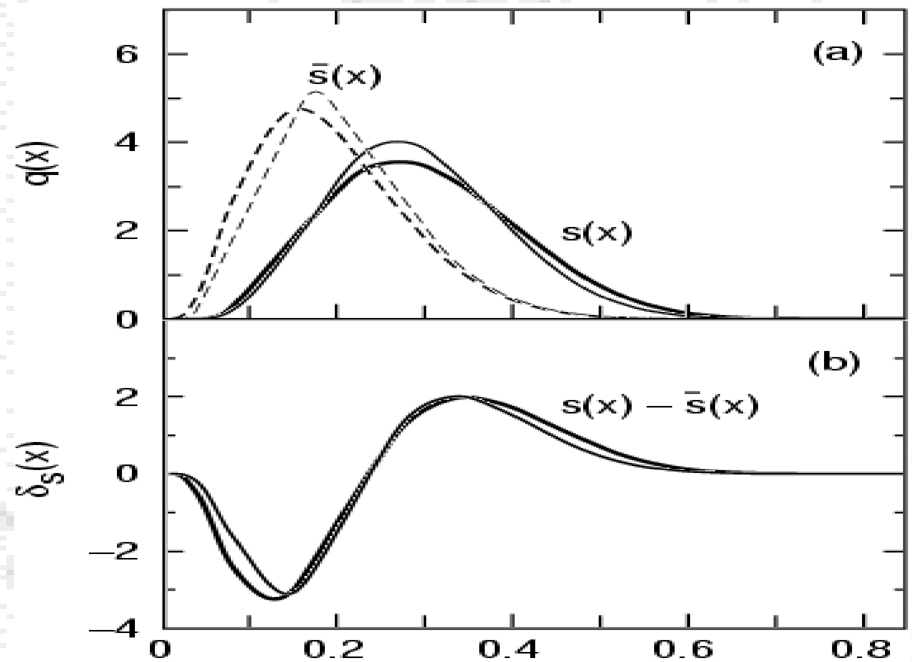
$$\frac{\pi \times \dfrac{d^2\sigma(\nu N \rightarrow \mu\mu X)}{dxdy}}{G_F^2 M_N E_\nu}$$

QCD at Work: Strange Asymmetry?



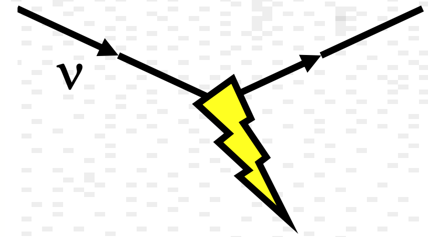
- An interesting aside…
  - The strange sea can be generated perturbatively from g→s+sbar.
  - BUT, in perturbative generation the momenta of strange and anti-strange quarks is equal
    - o well, in the leading order splitting at least. At higher order get a vanishingly small difference.
  - SO s & sbar difference probe non-perturbative ("intrinsic") strangeness
    - o Models: Signal&Thomas, Brodsky&Ma, etc.





(Brodsky & Ma, s-sbar)

NuTeV's Strange Sea



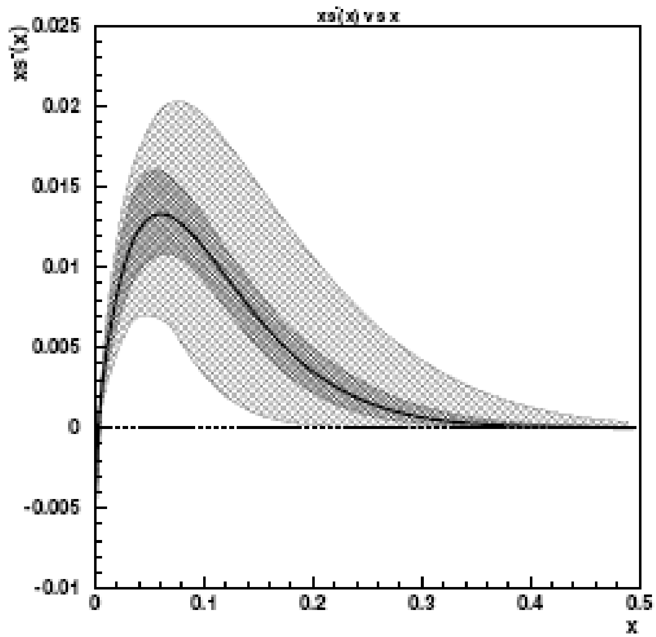
- NuTeV has tested this
  - NB: very dependent on what is assumed about non-strange sea
  - Why? Recall CKM mixing…

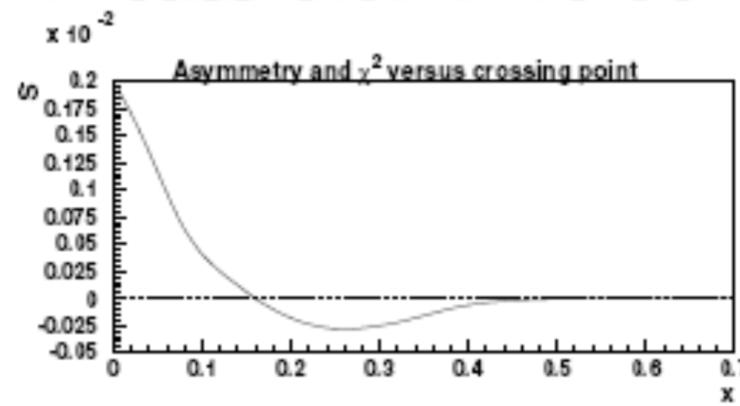
$$V_{cd}\, d(x) + V_{cs}\, s(x) \rightarrow s'(x)$$
$$V_{cd}\, \bar{d}(x) + V_{cs}\, \bar{s}(x) \rightarrow \bar{s}'(x)$$

small *big*

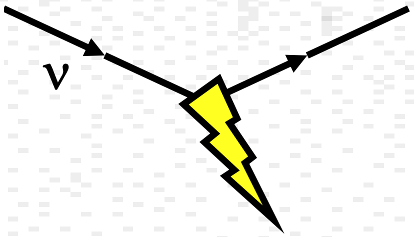
  - Using CTEQ6 PDFs…

$$\int dx\left[x\left(s-\bar{s}\right)\right] = 0.0019 \pm 0.0005 \pm 0.0014$$
$$\text{c.f.,}\ \int dx\left[x\left(s+\bar{s}\right)\right] \approx 0.02$$

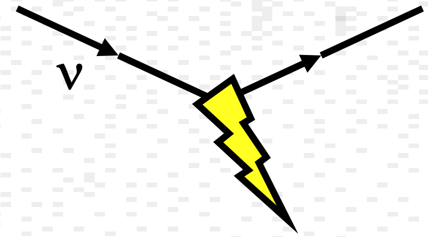




Deep Inelastic Scattering: Conclusions and Summary



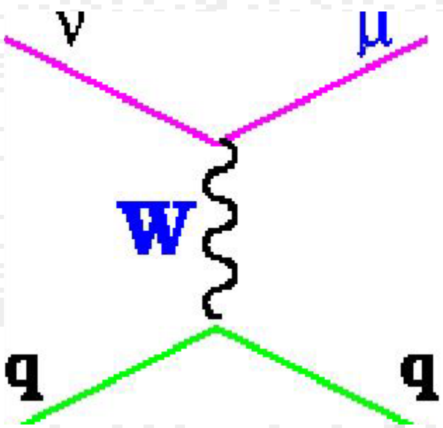
- Neutrino-quark scattering is elastic scattering!
  - complicated by fact that quarks live in nucleons
- Important lepton and quark mass effects for tau neutrino appearance experiments
- Neutrino DIS important for determining parton distributions
  - particularly valence and strange quarks



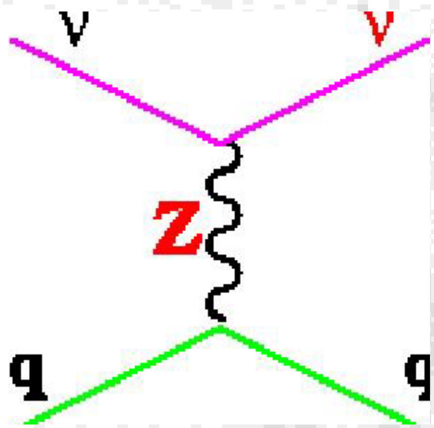
Neutrino-Nucleon Deep Inelastic Scattering Applied…

DIS NC/CC Ratio

- Experimentally, it's "simple" to measure ratios of neutral to charged current cross-sections on an isoscalar target to extract NC couplings



W-q coupling is I_3



Z-q coupling is $I_3\text{-}Q\sin^2\theta_W$

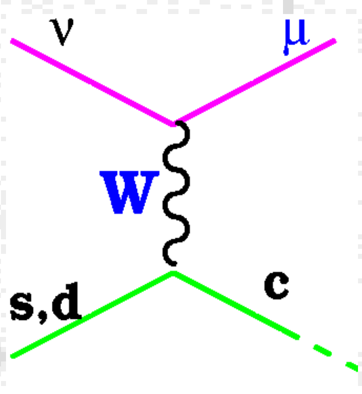
Llewellyn Smith Formulae

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \left(\left(u_L^2 + d_L^2\right) + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}} \left(u_R^2 + d_R^2\right) \right)$$

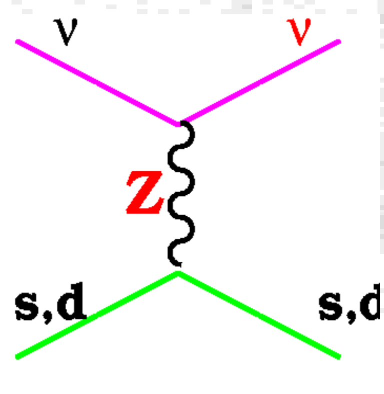
- Holds for isoscalar targets of u and d quarks only
  - Heavy quarks, differences between u and d distributions are corrections
- Isospin symmetry causes PDFs to drop out, even outside of naïve quark-parton model

Touchstone Question #6: Paschos-Wolfenstein Relation

Charged-Current

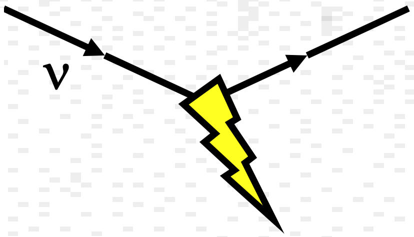


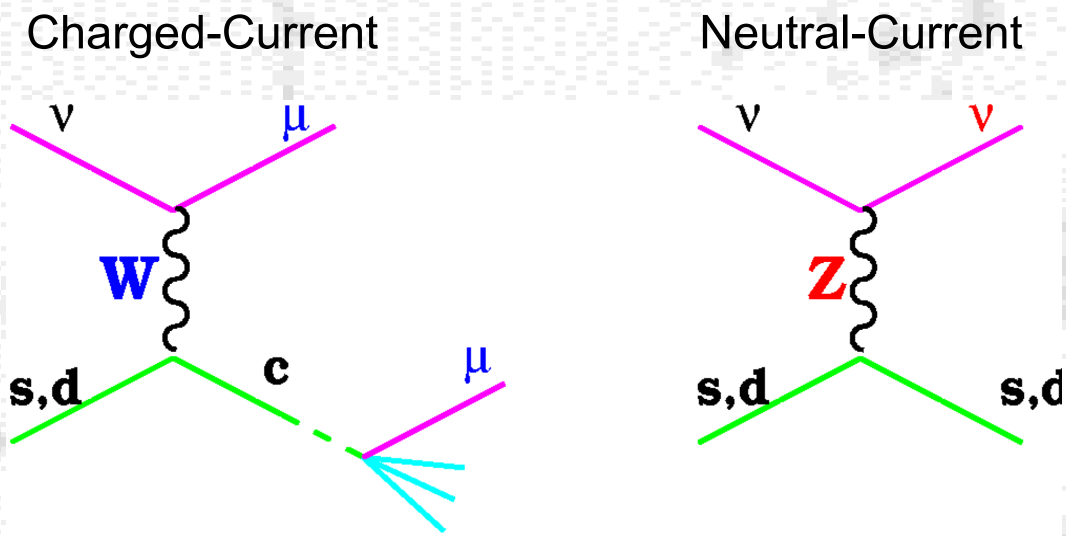
Neutral-Current



- If we want to measure electroweak parameters from the ratio of charged to neutral current cross-sections, what problem will we encounter from these processes?

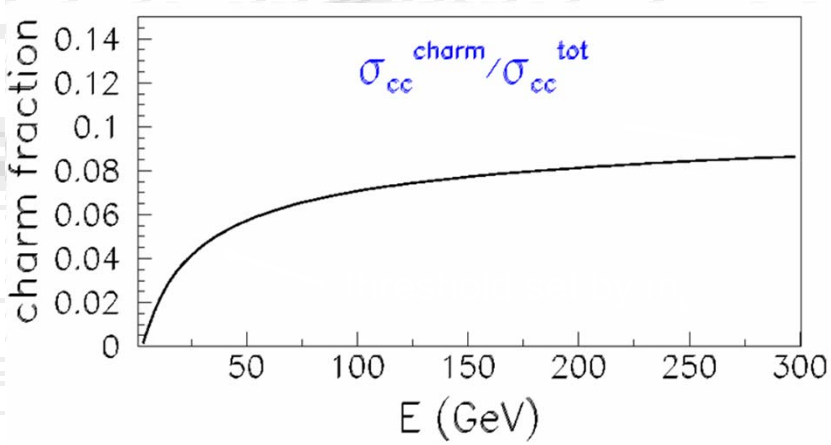
Touchstone Question #6: Paschos-Wolfenstein Relation



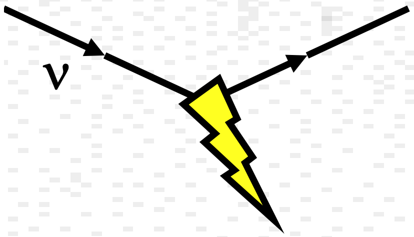


- CC is suppressed due to final state charm quark
  - $\Rightarrow$ Need strange sea and m_c
  - Remember heavy quark mass effect:

$$x \rightarrow \xi = x\left(1 + \frac{m_c^2}{Q^2}\right)$$



Touchstone Question #6: Paschos-Wolfenstein Relation



- The NuTeV experiment employed a complicated design to measure

Paschos - Wolfenstein Relation

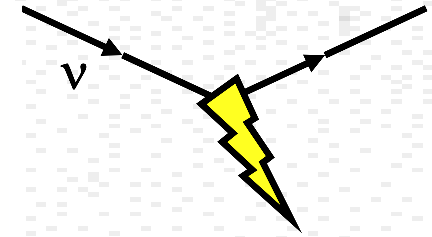
$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\tfrac{1}{2} - \sin^2 \theta_W \right)$$

- How did this help with the heavy quark problem of the previous question?

Hint: what to you know about the relationship of:

$$\sigma(\nu q) \text{ and } \sigma(\bar{\nu}\bar{q})$$

Touchstone Question #6: Paschos-Wolfenstein Relation



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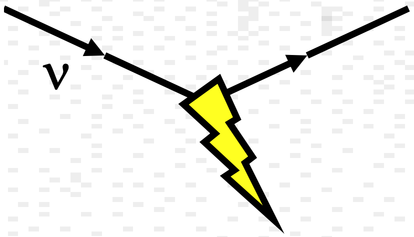
- How did this help with the heavy quark problem of the previous question?

$$\sigma(\nu q) = \sigma(\bar{\nu}\bar{q})$$
$$\sigma(\nu \bar{q}) = \sigma(\bar{\nu} q)$$

$$\therefore \sigma(\nu q) - \sigma(\bar{\nu}\bar{q}) = 0$$

So any quark-antiquark symmetric part is not in difference, e.g., strange sea.

NuTeV Fit to R^ν and $R^{\bar{\nu}}$



- NuTeV result:

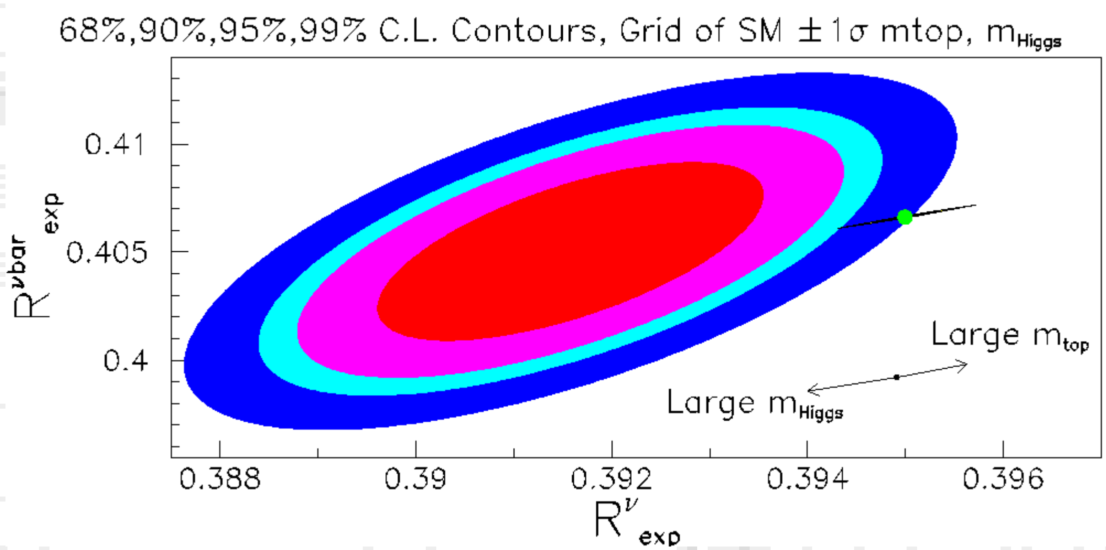
$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

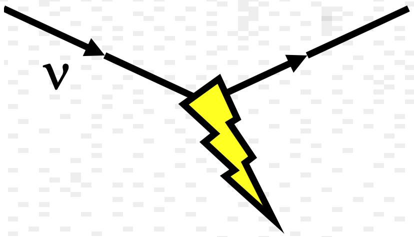
- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

A 3σ discrepancy…

$$R^\nu_{exp} = 0.3916 \pm 0.0013$$
$$(SM: 0.3950) \quad \Leftarrow 3\sigma \ difference$$
$$R^{\bar{\nu}}_{exp} = 0.4050 \pm 0.0027$$
$$(SM: 0.4066) \quad \Leftarrow Good \ agreement$$



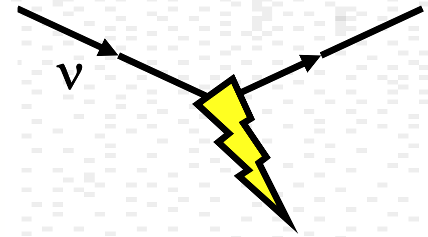
NuTeV Electroweak: What does it Mean?



- If I knew, I'd tell you.
- It could be BSM physics. Certainly there is no exclusive of a Z' that could cause this. But why?
- It could be the asymmetry of the strange sea…
  - it would contribute because the strange sea would not cancel in
  - but it's been measured; not anywhere near big enough
- It could be very large isospin violation
  - if $d_p(x) \neq u_n(x)$ at the 5% level… it would shift charge current (normalizing) cross-sections enough.
  - no data to forbid it. any reason to expect it?

Connections to Low Energy and Ultra-High Energy Cross-Sections

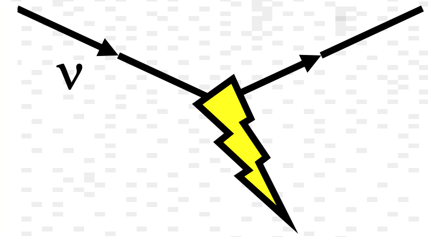
Ultra-High Energies



- At energies relevant for UHE Cosmic Ray studies (e.g., IceCube, ANITA)
  - ν-parton cross-section is dominated by high Q^2, since $d\sigma/dQ^2$ is constant
    - o at high Q^2, scaling violations have made most of nucleon momentum carried by sea quarks
    - o see a rise in σ/E_ν from growth of sea at low x
    - o neutrino & anti-neutrino cross-sections nearly equal
  - *Until* $Q^2 \gg M_W^2$, then propagator term starts decreasing and cross-section becomes approximately constant with energy

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

Touchstone Question #7: Where does σ Level Off?



- *Until* $Q^2 \gg M_W^2$, then propagator term starts decreasing and cross-section becomes constant

$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

- To within a few orders of magnitude, at what beam energy for a target at rest will this happen?

(a) $E_\nu \sim 10\text{TeV}$ **(b)** $E_\nu \sim 10{,}000\text{TeV}$ **(c)** $E_\nu \sim 10{,}000{,}000\text{TeV}$

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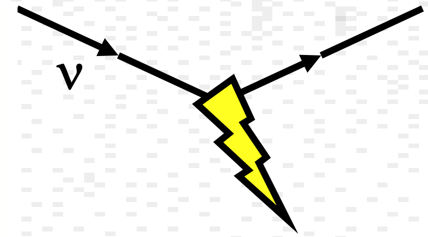

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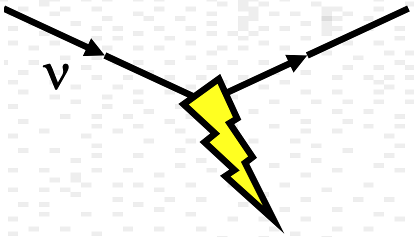

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$$\frac{d\sigma}{dq^2} \propto \frac{1}{(q^2 - M^2)^2}$$

- At what beam energy for a target at rest will this happen?

$$Q^2 < s_{\text{nucleon}} = m_{\text{nucleon}}^2 + 2E_\nu m_{\text{nucleon}}$$

$$Q^2 < s_{\text{nucleon}} \approx 2E_\nu m_{\text{nucleon}}$$

$$\frac{M_W^2}{2m_{\text{nucleon}}} < E_\nu$$

$$\therefore E_\nu \gtrsim \frac{(80.4)^2 \text{ GeV}^2}{2(.938)\text{GeV}} \sim 3000\text{GeV}$$

Q^2 limit is s. So won't start to plateau until $s>M_W^2$

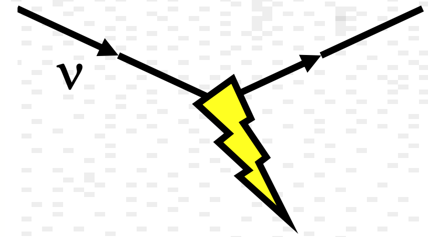
Bonus point realization…

In reality, that is only correct for a parton at x=1. Typical quark x is much less, say ~0.03

$$\frac{M_W^2}{2m_{\text{nucleon}}x} < E_\nu$$

$$\therefore E_\nu \gtrsim \frac{3000\text{GeV}}{0.03} \sim 100\text{TeV}$$

Ultra-High Energies



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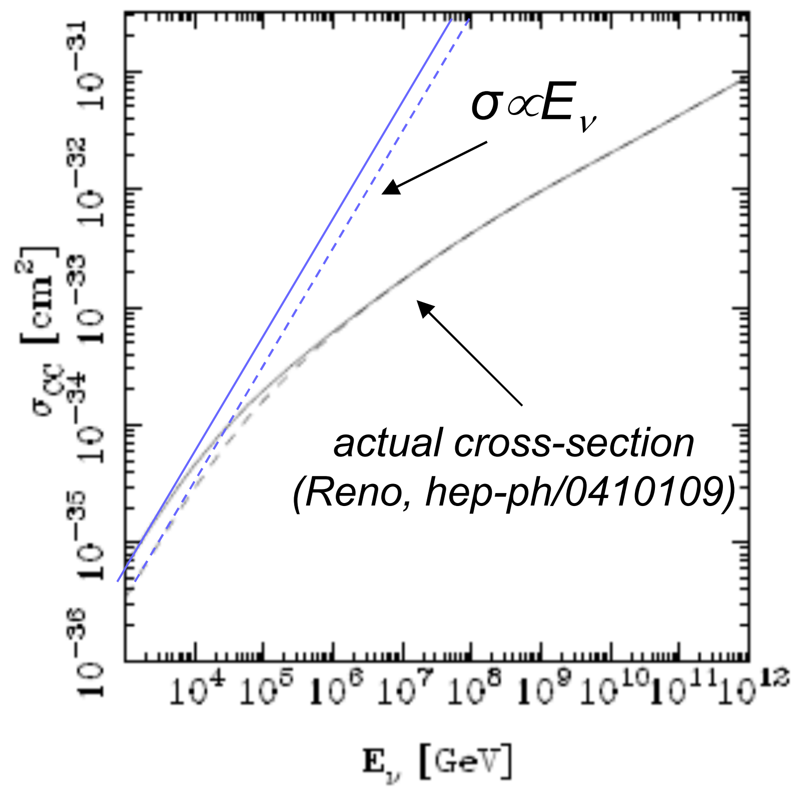
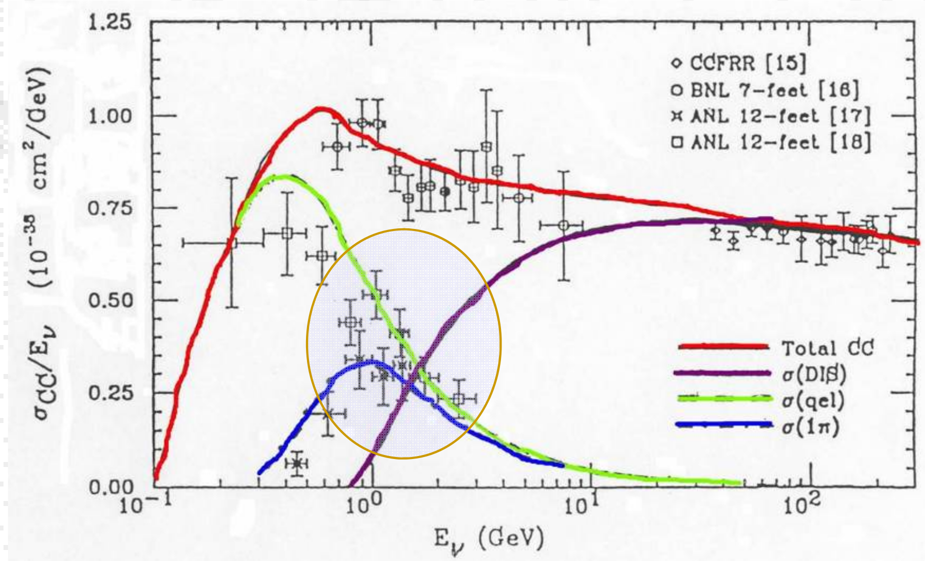


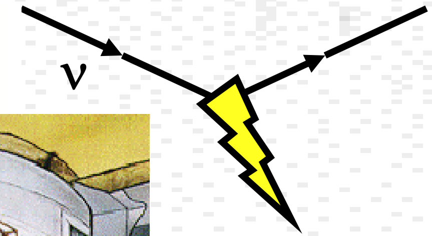
Thresholds

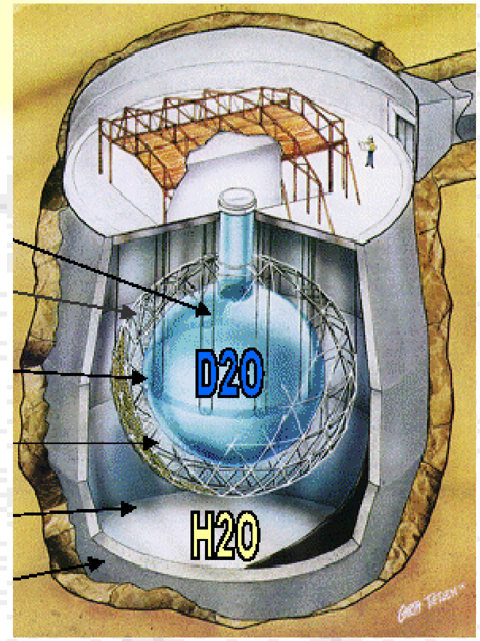
- At 1-few GeV, cross-section makes a transition between DIS-like and resonant/elastic
  - Why? "Binding energy" of target (nucleon) is ~1 GeV, comparable to mean Q^2



- What are other thresholds?
  - Binding energy of nucleus is of order $(M_n\text{-}M_p)$>>1 MeV, typically 10s – 100s of MeV
  - Binding energies of atoms are <~$Z^2 m_e c^2 \alpha_{EM}/2$~$10\text{-}10^5$ eV
  - Binding energies of ν, ℓ±, quarks (*into hypothetical constituents that we haven't found yet*) are > 10 TeV

Example: SNO





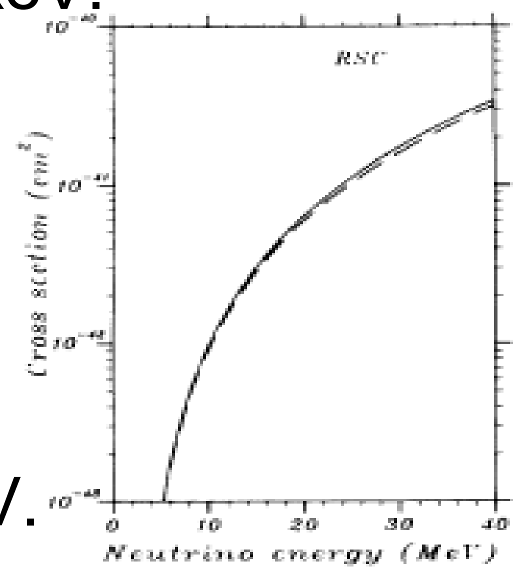
- Three reactions for observing ν from sun (E_ν ~ few MeV

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

  - ^2H, ^{16}O binding energies are 13.6eV, ~1 keV.
  - Therefore, e^- are "free". $\sigma \propto E_\nu$

CC $\nu_e + d \Rightarrow p + p + e^-$

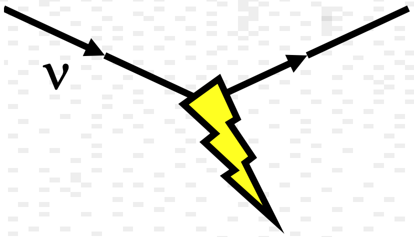
NC $\nu_x + d \Rightarrow p + n + \nu_x$



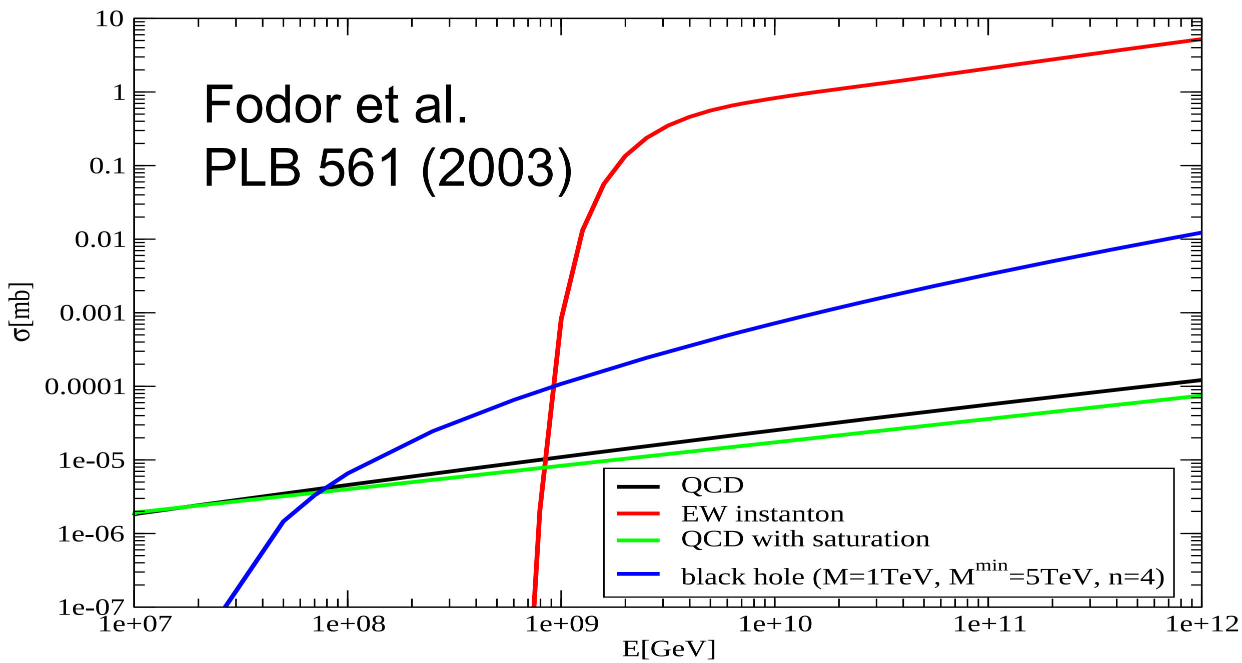
  - But binding energy of deuteron is 2.2 MeV. Energy threshold for NC of a few MeV.

(Bahcall, Kuboeara, Nozawa, PRD38 1030)

Example: Ultra-High Energies

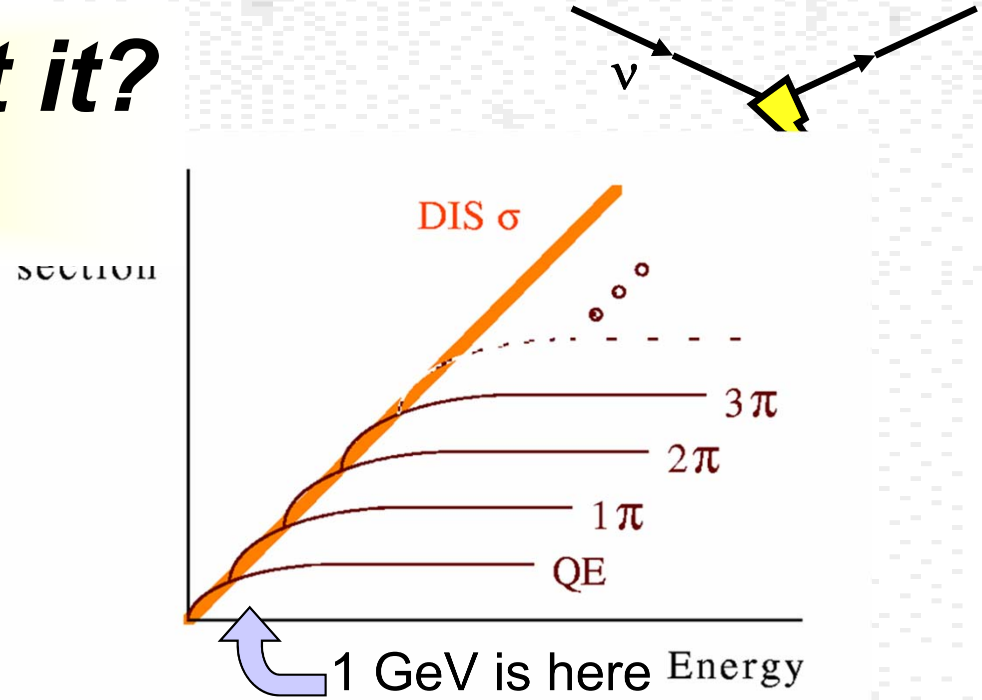


- At UHE, can we reach thresholds of non-SM processes?
  - E.g., structure of quark or leptons, black holes from extra dimensions, etc.
  - Th

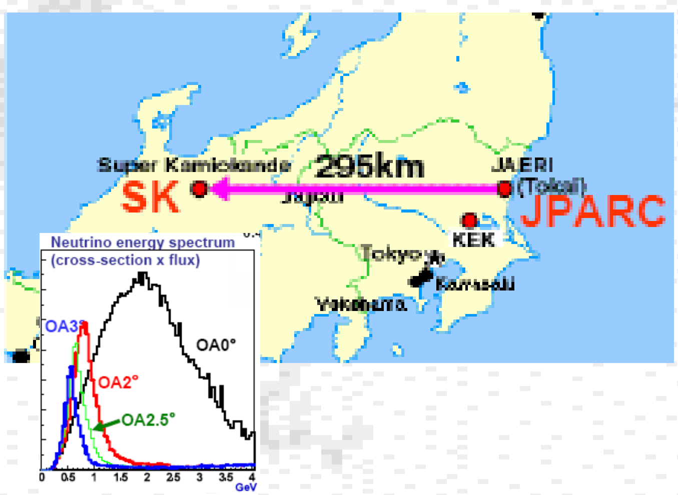


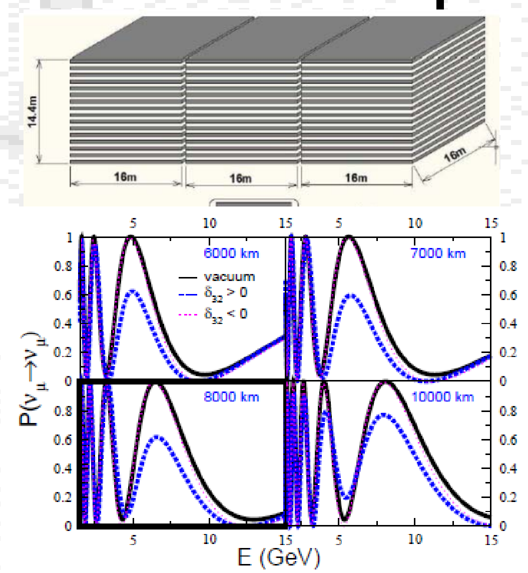
Motivation for Understanding GeV Cross-Sections

What's special about it? Why do we care?



- Remember this picture?
  - 1-few GeV is exactly where these additional processes are turning on
  - It's not DIS yet! Final states & threshold effects matter
- Why is it important? Examples from T2K, ICAL



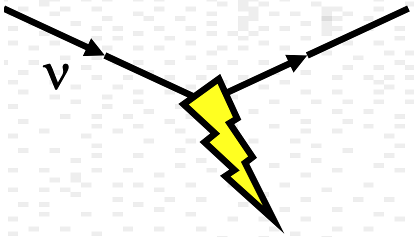


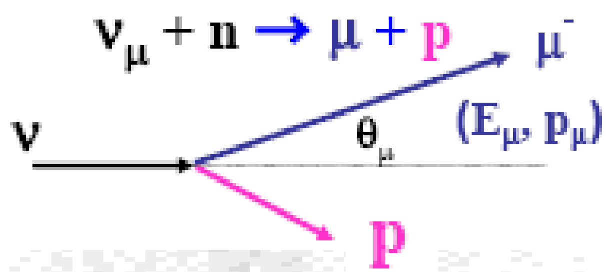
Goals:

1. $\nu_\mu \to \nu_e$
2. ν_μ disappearance

E_ν is 0.4-2.0 GeV (T2K) or 3-10 GeV (INO ICAL)

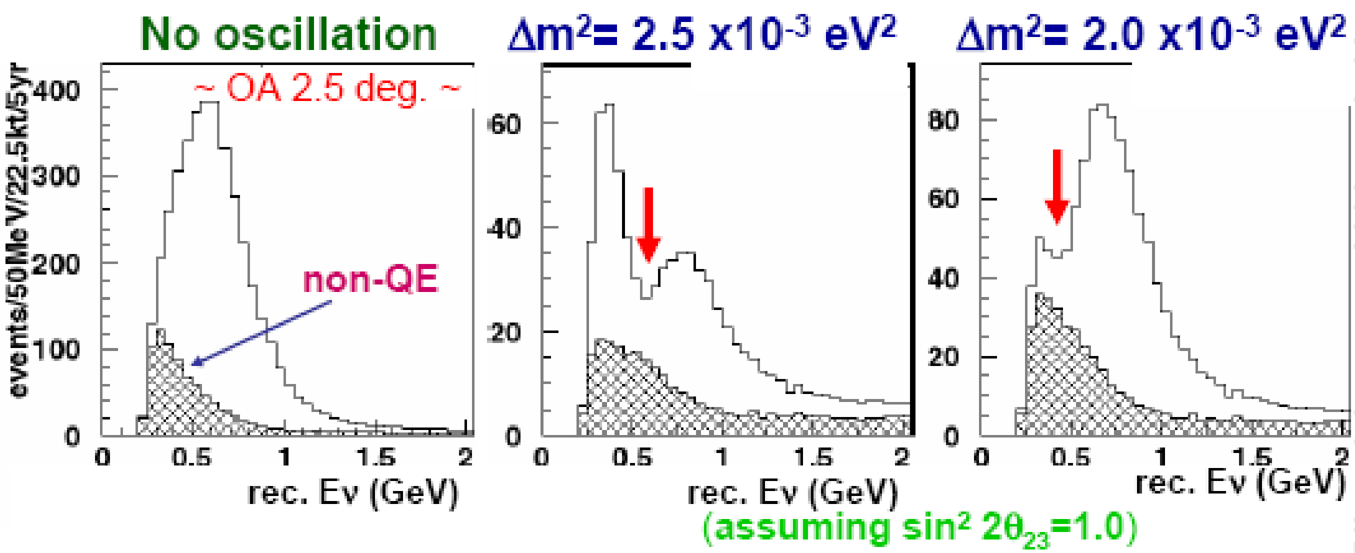
How do cross-sections effect oscillation analysis?



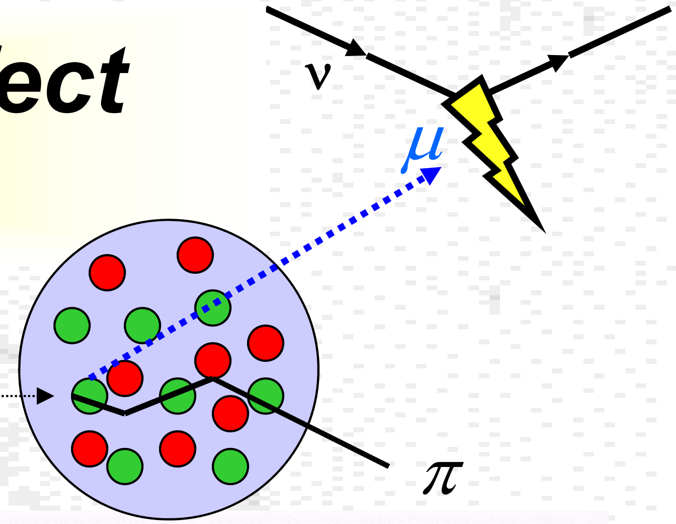


- ν_μ disappearance (low energy)
  - at Super-K reconstruct these events by muon angle and momentum (proton below Cerenkov threshold in H_2O)
  - other final states with more particles below threshold ("non-QE") will disrupt this reconstruction
- T2K must know these events at few % level to do disappearance analysis to measure Δm^2_{23}, θ_{23}

(fig. courtesy Y. Hayato)

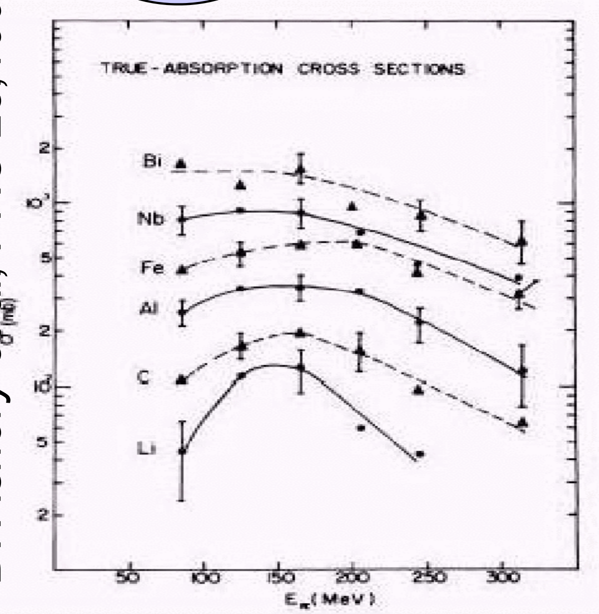


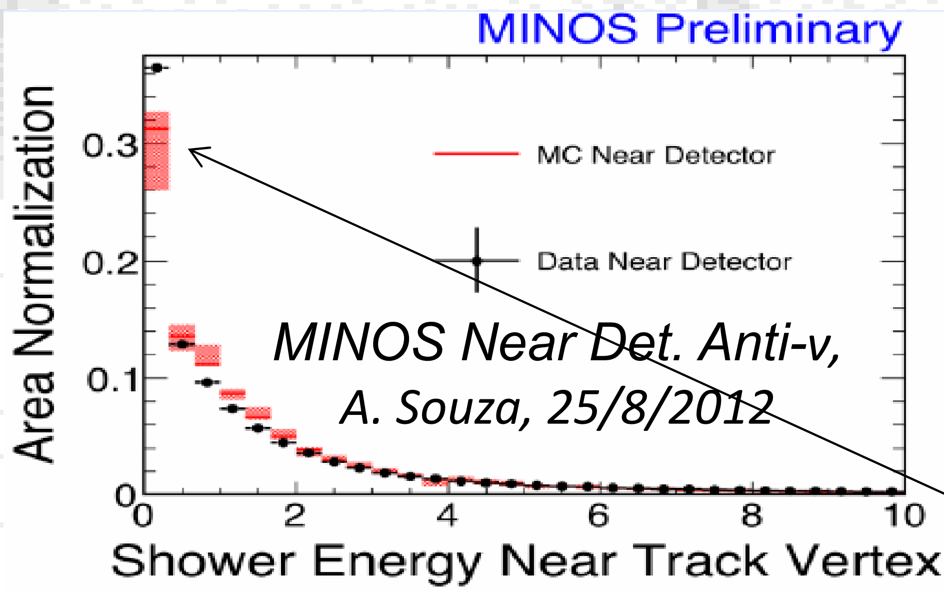
How do cross-sections effect oscillation analysis?



- ν_μ disappearance (high energy)
- Visible Energy in a calorimeter is NOT the ν energy transferred to the hadronic system
    - π absorption, π re-scattering, final state rest mass effect the calorimetric response
        - Can use external data to constrain

D. Ashery et al, PRC **23**, *1993*

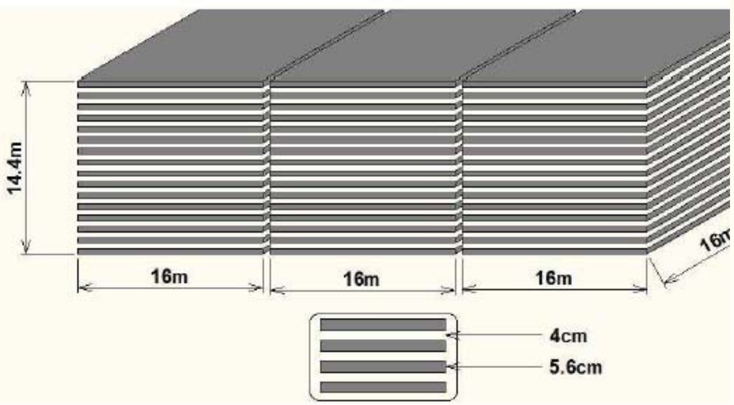




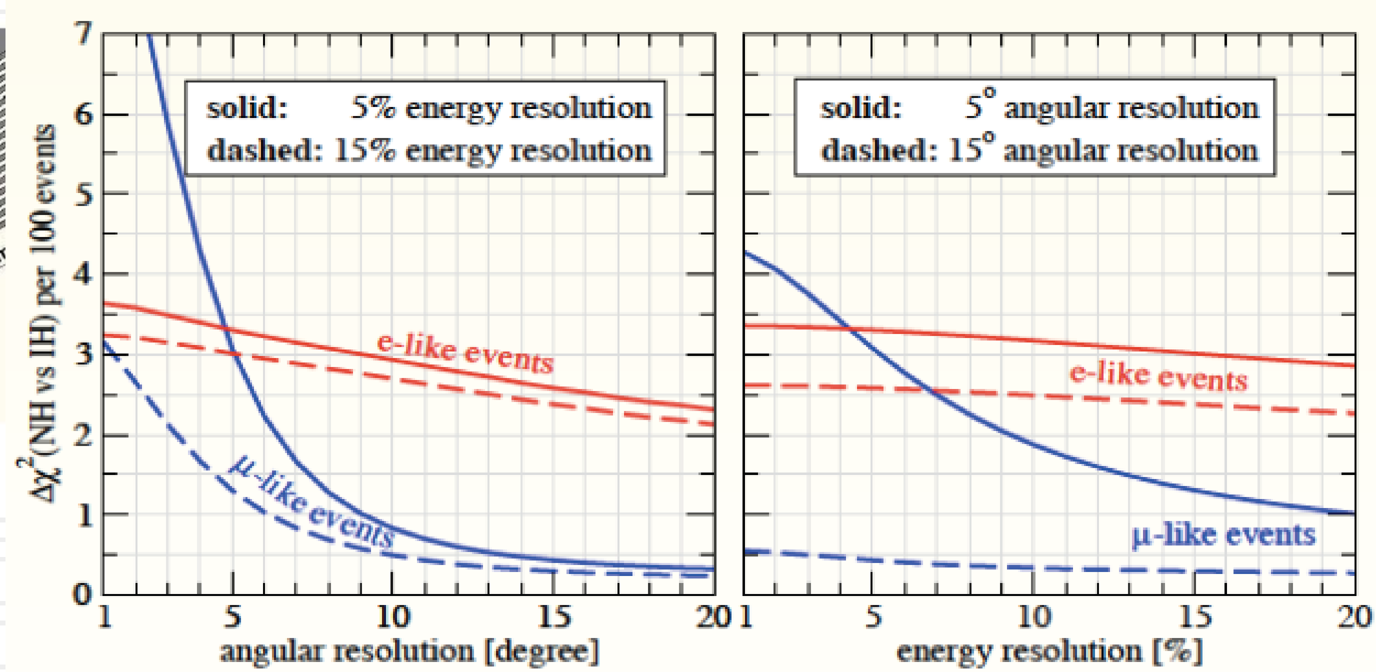
- *At very high energies, particle multiplicities are high and these effects will average out*
- *Low energy is more difficult*

How do cross-sections effect oscillation analysis?

- In the case of INO ICAL, need good energy and angle resolution to separate normal and inverted hierarchy
  - Best sensitivity requires survival probability in both E_ν and L

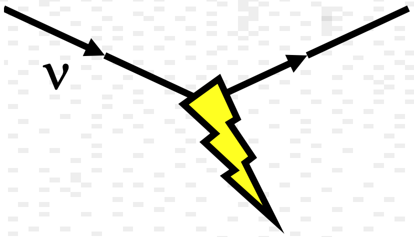


- Interaction models are understanding of detector response both needed to optimize resolution

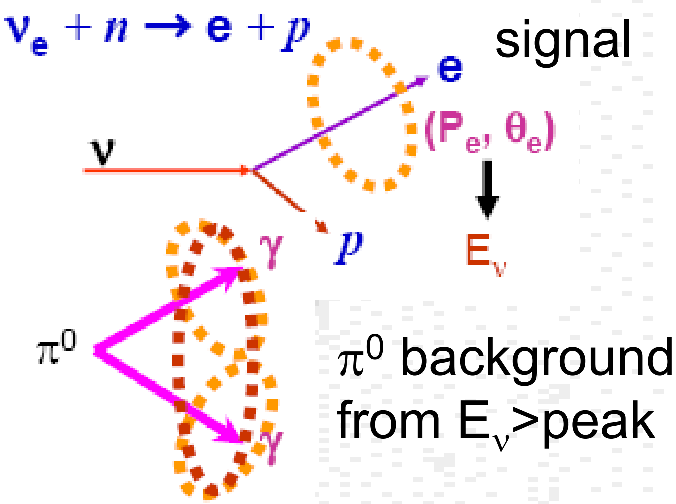


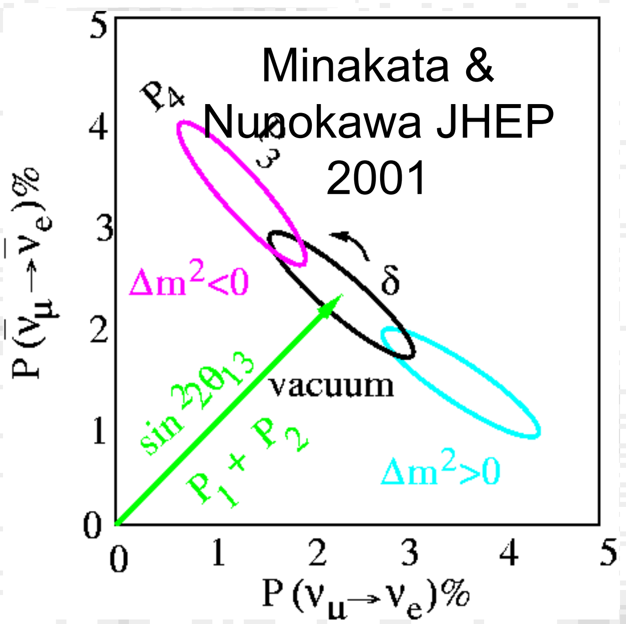
Petcov, Schwetz, hep-ph/0511277

How do cross-sections effect oscillation analysis?



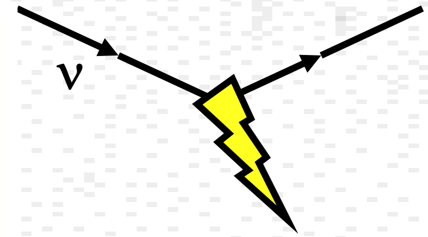
- ν_e appearance
  - different problem: signal rate is very low so even rare backgrounds contribute!
- Remember the end goal of electron neutrino appearance experiments
- Want to compare two signals with two different sets of backgrounds and signal reactions
  - with sub-percent precision
  - Requires precise knowledge of background and signal reactions





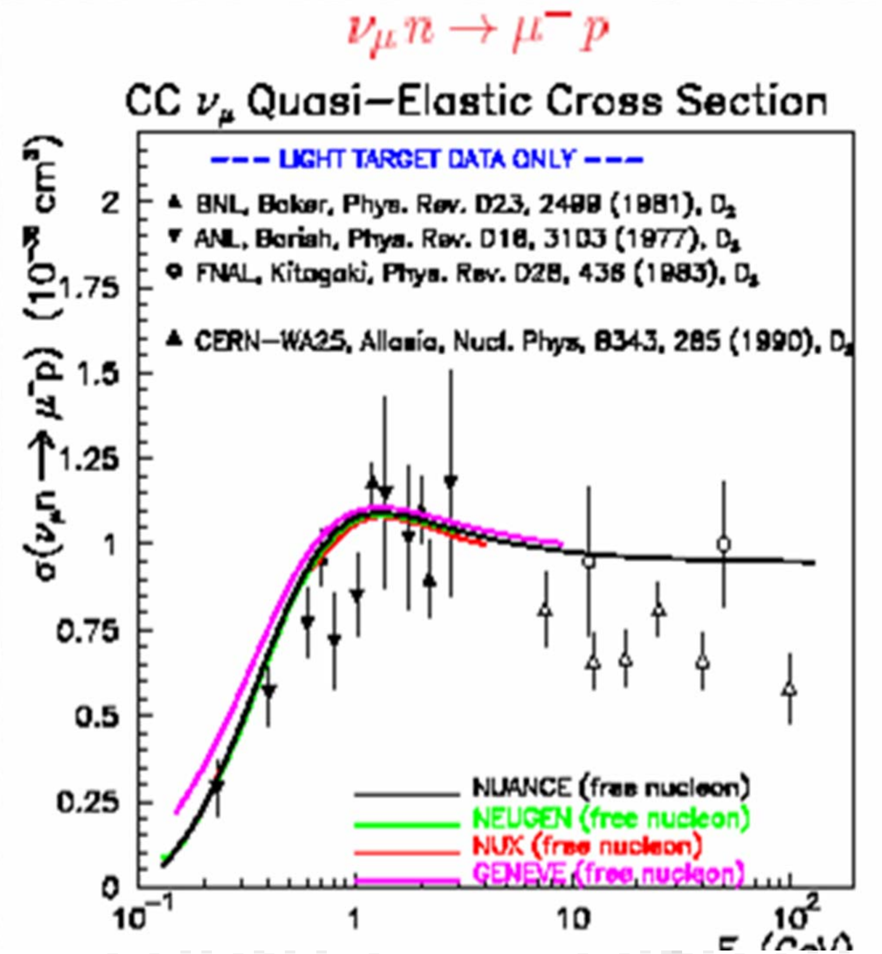
Models for GeV Cross-Sections

(Quasi-)Elastic Scattering



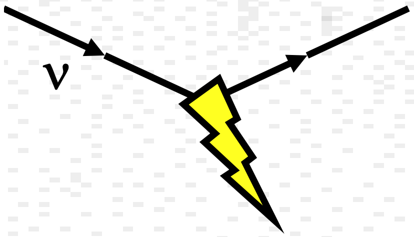
- Elastic scattering leaves a single nucleon in the final state
  - CC "quasi-elastic" easier to observe

$$\nu n \to l^- p$$
$$\bar{\nu} p \to l^+ n$$
$$\overset{(-)}{\nu} N \to \overset{(-)}{\nu} N$$



- State of data is marginal
  - No free neutrons implies nuclear corrections
  - Low energy statistics poor
- Cross-section is calculable
  - But depends on incalculable form-factors of the nucleon
- Theoretically and experimentally constant at high energy
  - 1 GeV^2 is ~ a limit in Q^2

What was that last cryptic remark?



- Theoretically and experimentally constant at high energy
  - 1 GeV^2 is ~ a limit in Q^2

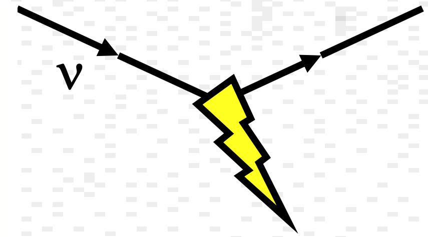
- Inverse μ–decay:

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

$$\sigma_{TOT} \propto \int_0^{Q^2_{\max}} dQ^2 \frac{1}{(Q^2 + M_W{}^2)^2} \approx \frac{Q^2_{\max}}{M_W{}^4}$$

a maximum Q^2 independent of beam energy ⇒ constant σ_{TOT}

Elastic Scattering (cont'd)



- How does nucleon structure impact elastic scattering?

$$\nu n \to l^- p$$
$$\bar{\nu} p \to l^+ n$$
$$\overset{(-)}{\nu} N \to \overset{(-)}{\nu} N$$

C.H. Llewellyn Smith, Phys. Rep. **3C**, 261 (1972)

$$< N'|J_\mu|N > \; = \; \overline{u}(N')\left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right] u(N)$$

$$F_V(q^2) \sim \frac{1}{(1-q^2/M_V^2)^2} \qquad F_A(q^2) = \frac{F_A(0)}{(1-q^2/M_A^2)^2}$$

← "dipole approximation"

- $\hookrightarrow \mathbf{M_A = 1.032}$ **GeV**
- $\hookrightarrow \mathbf{M_V = 0.84}$ **GeV**
- $\hookrightarrow \mathbf{F_A(q^2) = \frac{F_A(0)}{(1-q^2/M_A^2)^2};\ F_A(0) = -1.25}$

} parameters determined from data

n.b.: we've seen $F_V(0)$ and $F_A(0)$ before in IBD discussion (g_V and g_A)

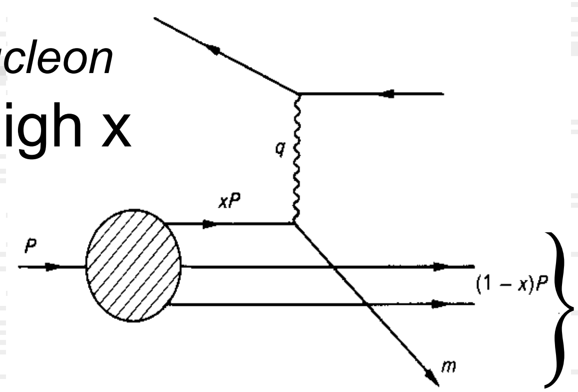
- "Form factors" modify vanilla V-A prediction of point-like scattering in Fermi theory
  - vector part can be measured in electron elastic scattering, e.g., Bradford-Bodek-Budd-Arrington ("BBBA"), Nucl.Phys.Proc.Suppl.159:127-132,2006

Low W, the Resonance Region

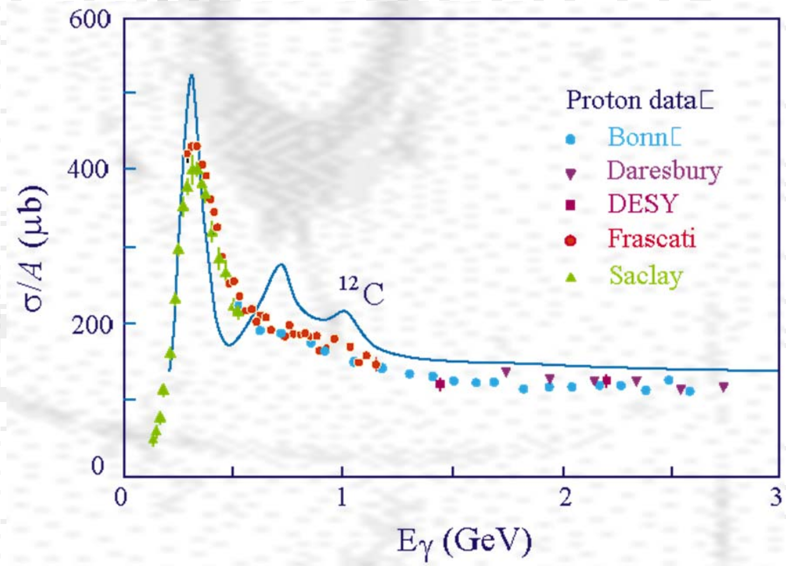
- Intermediate to elastic and DIS regions is a region of resonance production
  - Recall mass[2] of hadronic final state is given by

$$W^2 = M_T^2 + 2M_T\nu - Q^2 = M_T^2 + 2M_T\nu(1-x)$$

  - At low energy, nucleon-pion states dominated by N* and Δ resonances
- Leads to cross-section with significant structure in *W* just above $M_{nucleon}$
  - Low ν, high x

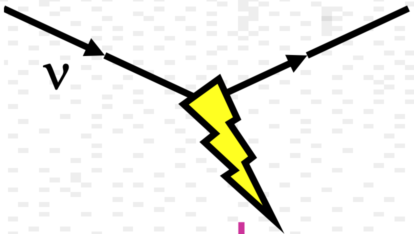


W^2



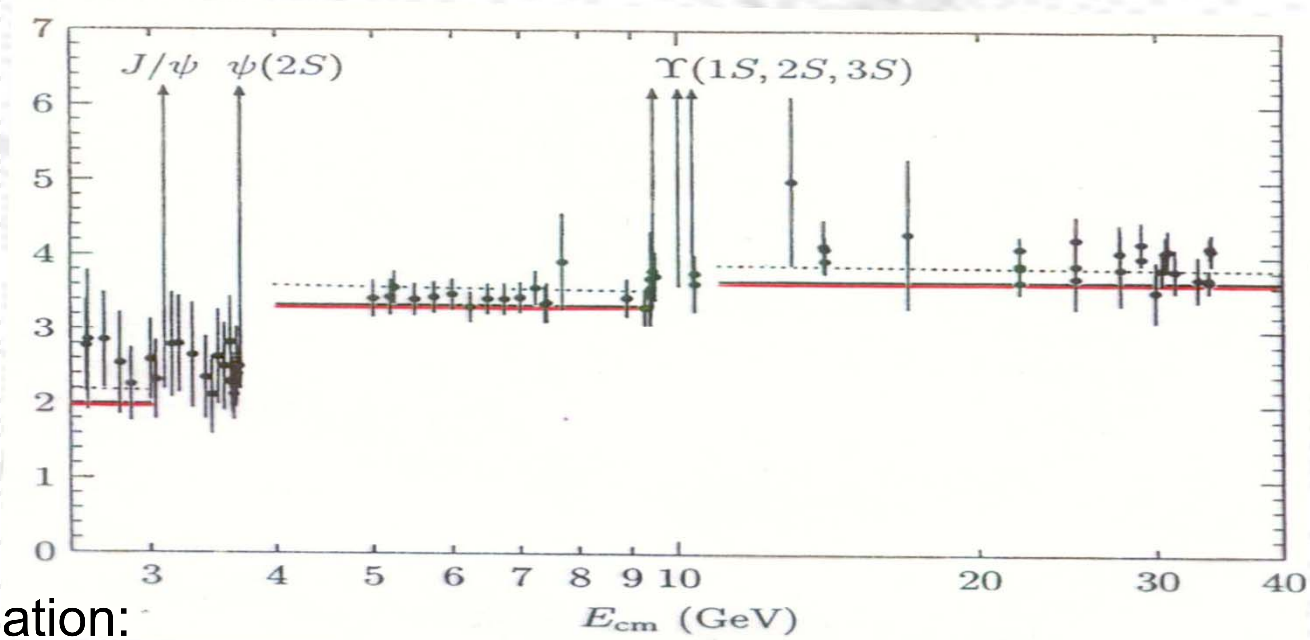
photoabsorption vs E_γ. Line shows protons. More later…

Quark-Hadron Duality



- Bloom-Gilman Duality is the relationship between quark and hadron descriptions of reactions. It reflects:
  - link between *confinement* and *asymptotic freedom*
  - transition from *non-perturbative* to *perturbative* QCD

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

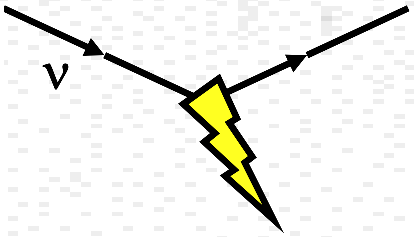


quark-parton model calculation:

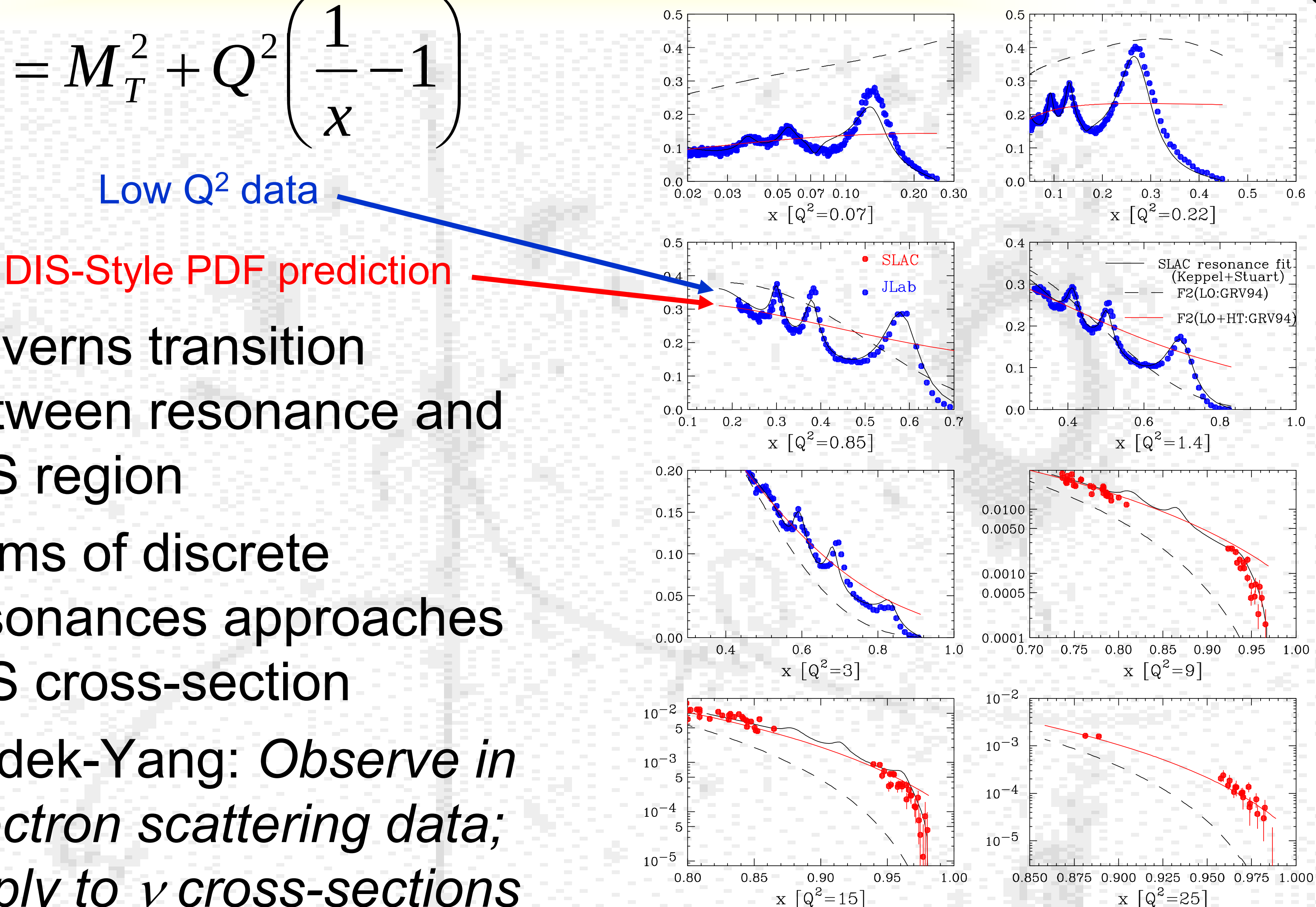
$$R = N_C \sum_{q \ni' s > m_q^2} \left(Q_q^{EM}\right)^2 + O(\alpha_{EM} + \alpha_S)$$

but of course, final state is really sums over discrete hadronic systems

Duality and ν

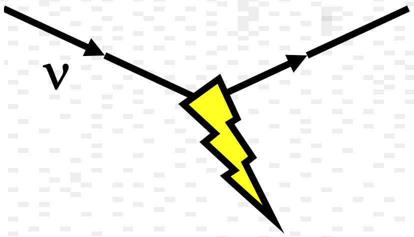


$$W^2 = M_T^2 + Q^2\left(\frac{1}{x} - 1\right)$$



- Governs transition between resonance and DIS region
- Sums of discrete resonances approaches DIS cross-section
- Bodek-Yang: *Observe in electron scattering data; apply to ν cross-sections*

Duality's Promise



- In principle, a duality based approach can be applied over the entire kinematic region
- The problem is that duality gives "averaged" differential cross-sections, and not details of a final state

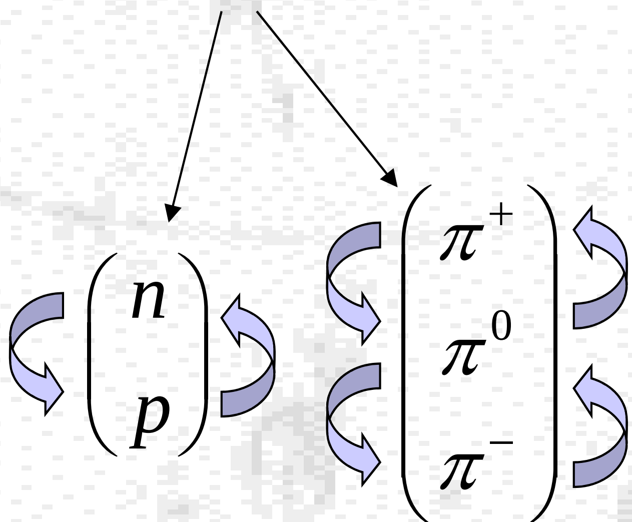
Microphysical models of exclusive processes

Duality models based on data of inclusive rates

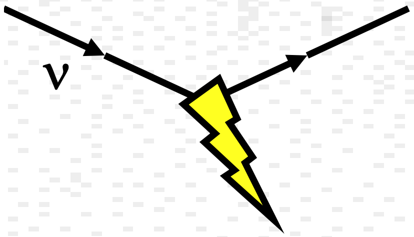
- Microphysical models may lack important physics, but duality models may not predict all we need to know
  - How to scale the mountain between the two?

Touchstone Question #8: Duality meets Reality

- A difficulty in relating cross-sections of electron scattering (photon exchange) to charged-current neutrino scattering ($W^{\pm}$ exchange) is that some e-scatting reactions have imperfect ν-scattering analogues.
- Write all possible ν_μ CC reactions involving the same target particle and isospin rotations of the final state for each of the following…
  - (a) $e^- n \rightarrow e^- n$
  - (b) $e^- p \rightarrow e^- p$
  - (c) $e^- p \rightarrow e^- n \pi^+$
  - (d) $e^- n \rightarrow e^- p \pi^-$



Touchstone Question #8: Duality meets Reality



Write all possible ν reactions involving the same target particle and isospin rotations of the final state for each of the following…

(a) $e^- n \to e^- n$

$$\nu_\mu n \to \mu^- p$$

(b) $e^- p \to e^- p$

there are none!

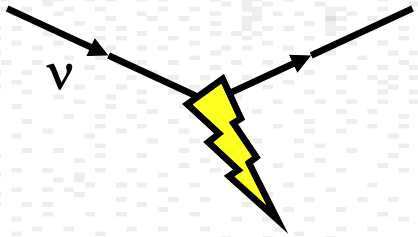
(c) $e^- p \to e^- n \pi^+$

$$\nu_\mu p \to \mu^- p \pi^+$$

(d) $e^- n \to e^- p \pi^-$

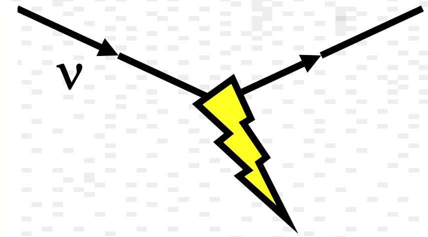
$$\nu_\mu n \to \mu^- n \pi^+$$

$$\nu_\mu n \to \mu^- p \pi^0$$



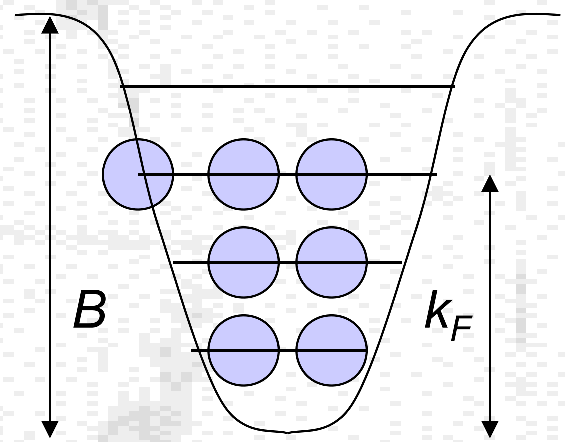
Cross-Sections on Nucleons in a Nucleus

Nuclear Effects in Elastic Scattering

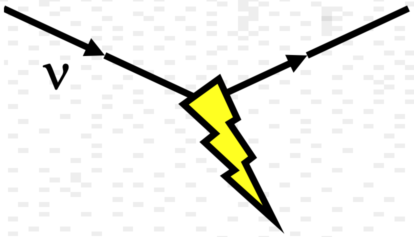


- Several effects:
  - In a nucleus, target nucleon has some initial momentum which modifies the observed scattering
    - o Simple model is a "Fermi Gas" model of nucleons filling available states up to some initial state Fermi momentum, k_F

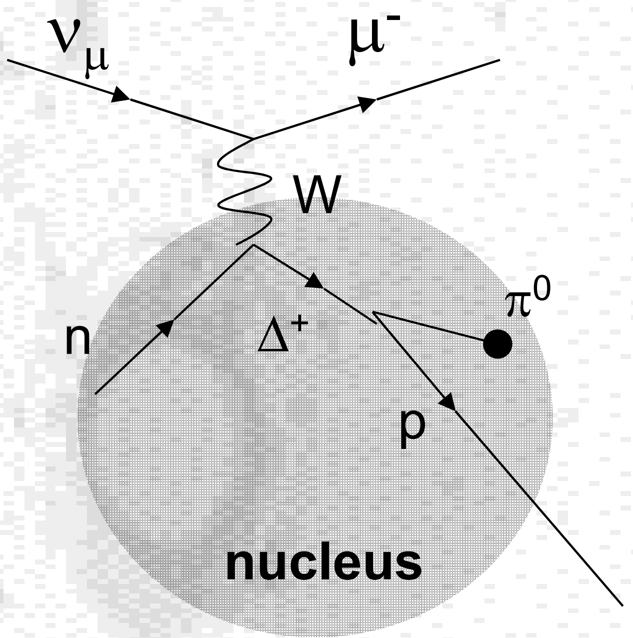
  - The nucleon is bound in the nucleus, so it take energy to remove it
  - Pauli blocking for nucleons not escaping nucleus… states are already filled with identical nucleon
  - Outgoing nucleon can interact with the target



Nuclear Effects in Elastic Scattering (cont'd)



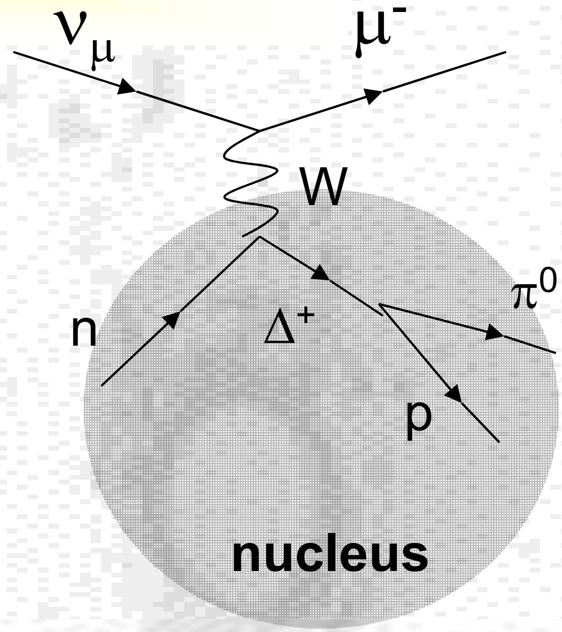
- Also other final states can contribute to apparent "quasi-elastic" scattering through absorption in the nucleus…
  - kinematics may or may not distinguish the reaction from elastic

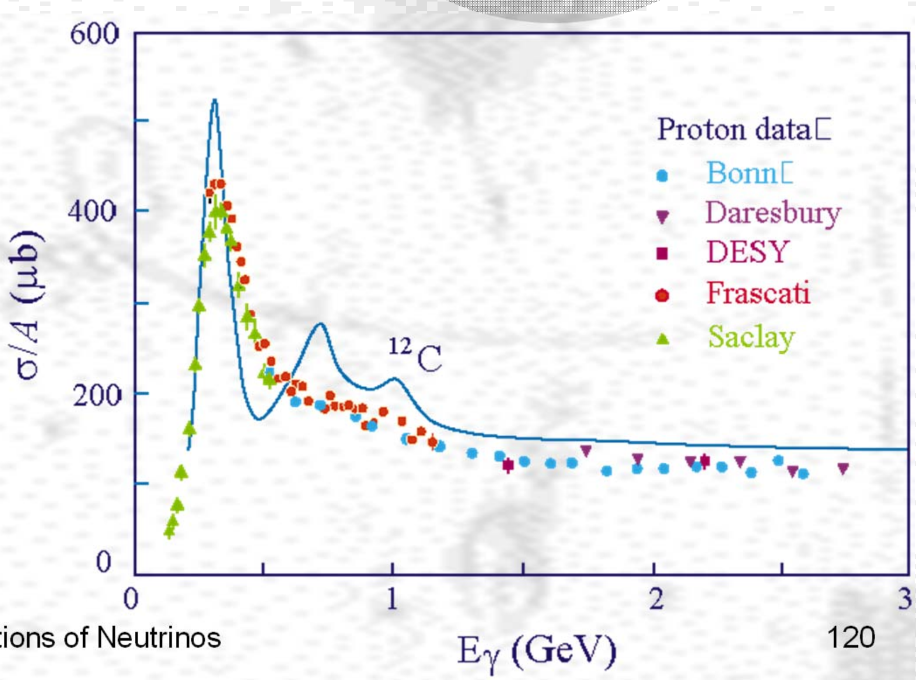


- Theoretical uncertainties are large
  - At least at the 10% level
  - If precise knowledge is needed for target (e.g., water, liquid argon, hydrocarbons), dedicated measurements will be needed
    - Most relevant for low energy experiments, i.e., T2K

Nuclear Effects in Resonance Region

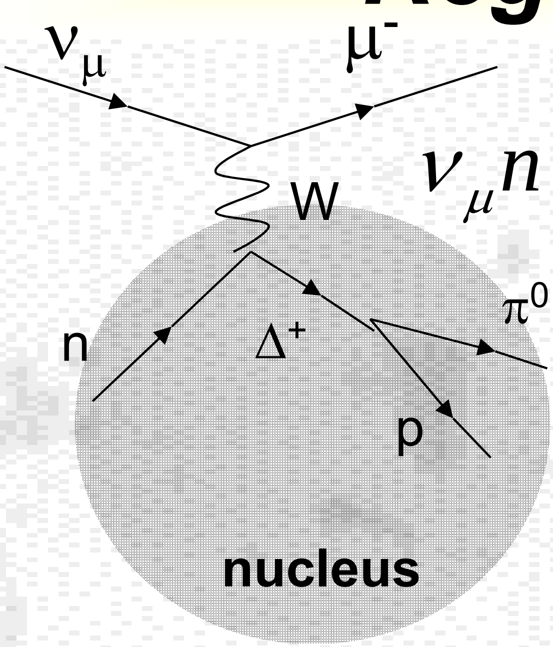
- An important reaction like
$$\nu_\mu n \rightarrow \mu^- p \pi^0$$
(ν_e background) can be modified in a nucleus
- Production kinematics are modified by nuclear medium
  - at right have photoabsorption showing resonance structure
  - line is proton; data is ^{12}C
  - except for first Δ peak, the structure is washed out
  - interactions of resonance inside nucleus



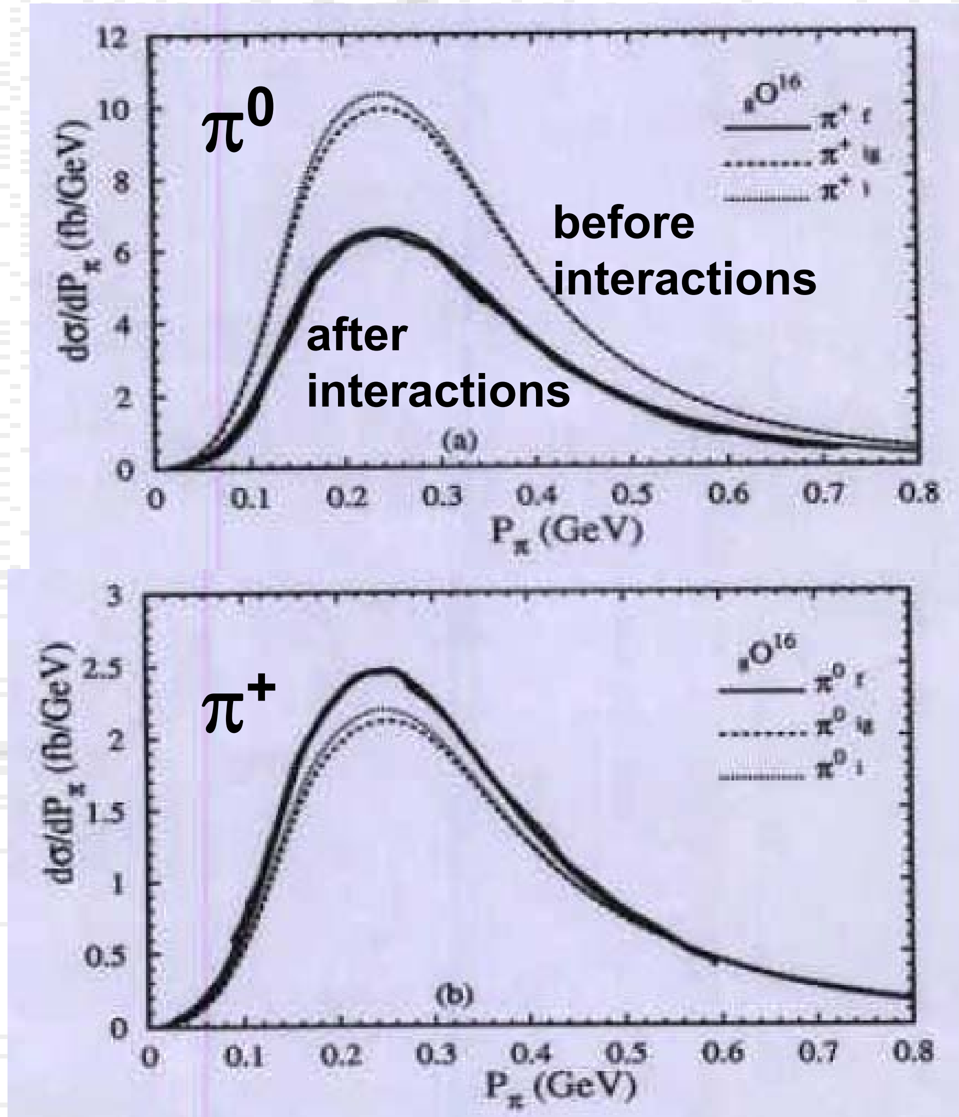


Nuclear Effects in Resonance Region (cont'd)

model of E. Paschos, NUINT04



$$\nu_\mu n \to \mu^- p \pi^0$$

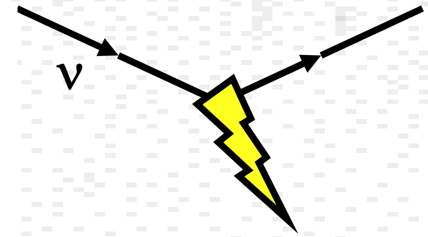


- How does nucleus affect π^0 after production?
- "Final State Interactions": rescattering and absorption.
- Must measure to predict ν_e backgrounds!

Approaches to Final State Interactions

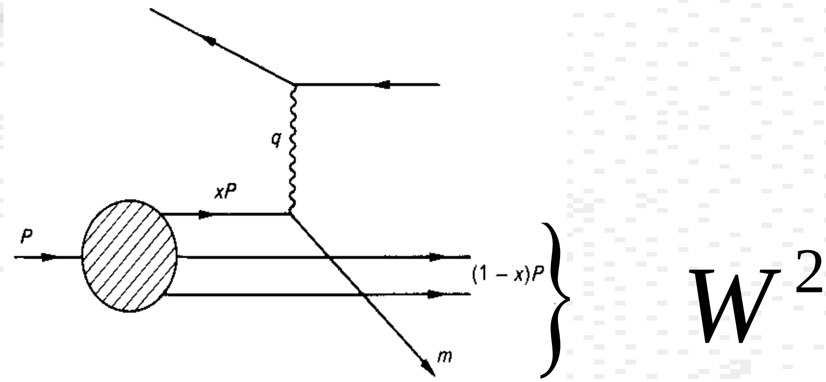
- Propagate final state particles through the nuclear medium with varying degrees of sophistication where they interact according the measured cross-sections or models
- Issues:
  - Are the hadrons modified by the nuclear medium?
  - Are hadrons treated as only on-shell or is off-shell transport allowed?
  - How to cleanly separate the initial state particles from their final state interactions?

Touchstone Question #9



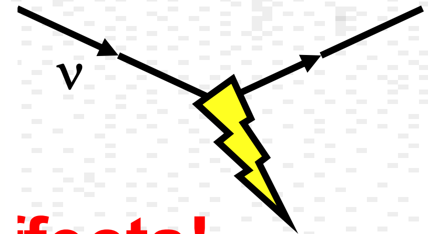
- **Two questions with (*hint*) related answers…**
  1. **Remember that W^2 is…**

$$W^2 = M_P^2 + 2M_P\nu - Q^2$$
$$= M_P^2 + 2M_P\nu(1-x)$$

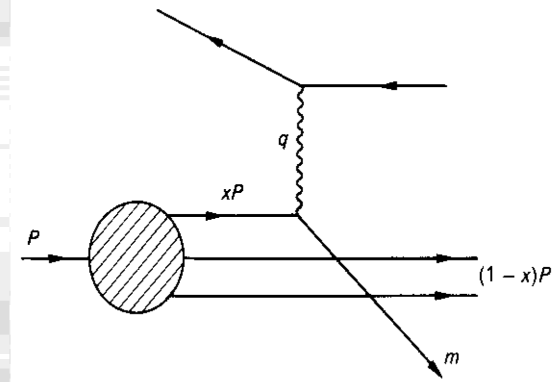


     the square of the invariant mass of the hadronic system. ($\nu = E_\nu - E_\mu$; x is the parton fractional momentum)
     It can be measured, as you see above with only leptonic quantities (neutrino and muon 4-momentum).
     In neutrino scattering on a scintillator target, you observe an event with a recoiling proton and with W reconstructed (perfectly) from leptonic variables $<M_p$. Explain this event.
  2. **In the same scintillator target, you observe the reaction…** $\nu_\mu\, {}^{12}\mathrm{C} \rightarrow \mu^- p \pi^- + \text{remnant nucleus}$
     Why might this be puzzling? Explain the process.

Touchstone Question #9



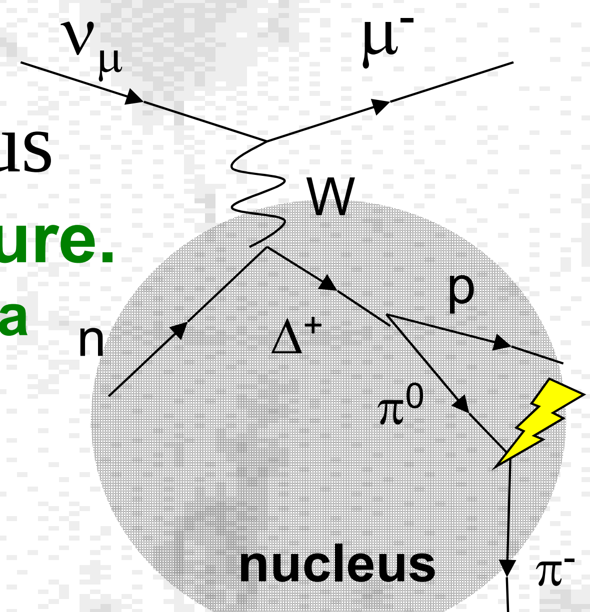
fects!



1. $M_P > W^2 = M_P^2 + 2M_P\nu(1-x)$

can only be true if x>1.

That means the fractional momentum by the struck target parton is >1! This can only happen for in a nucleon boosted towards the collision in the CM frame by interactions within the nucleus ("Fermi momentum")



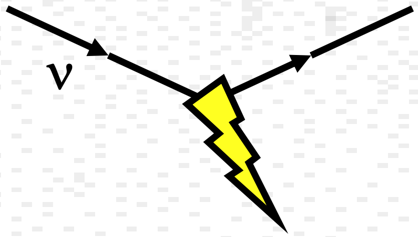
3. $\nu_\mu\,{}^{12}\mathrm{C} \to \mu^- p \pi^-$ + remnant nucleus

is nonsense in a free nucleon picture.

It is forbidden to occur off of a proton or a neutron target by charge conservation!

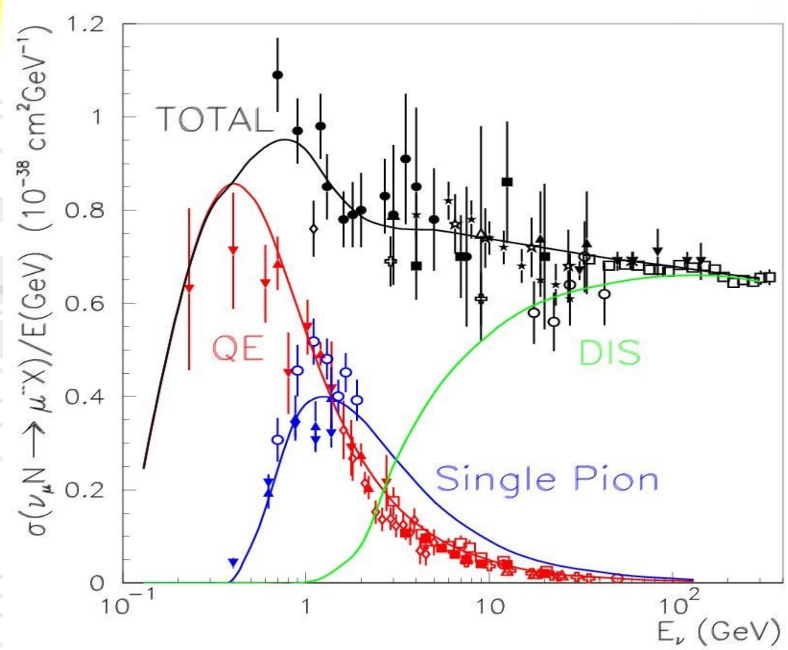
But remember…

reinteraction of pions!

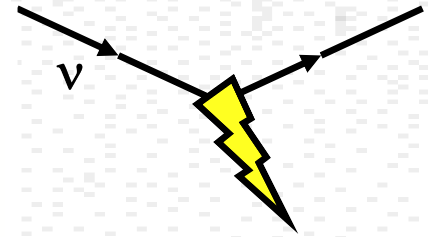


Highlights of Current Data

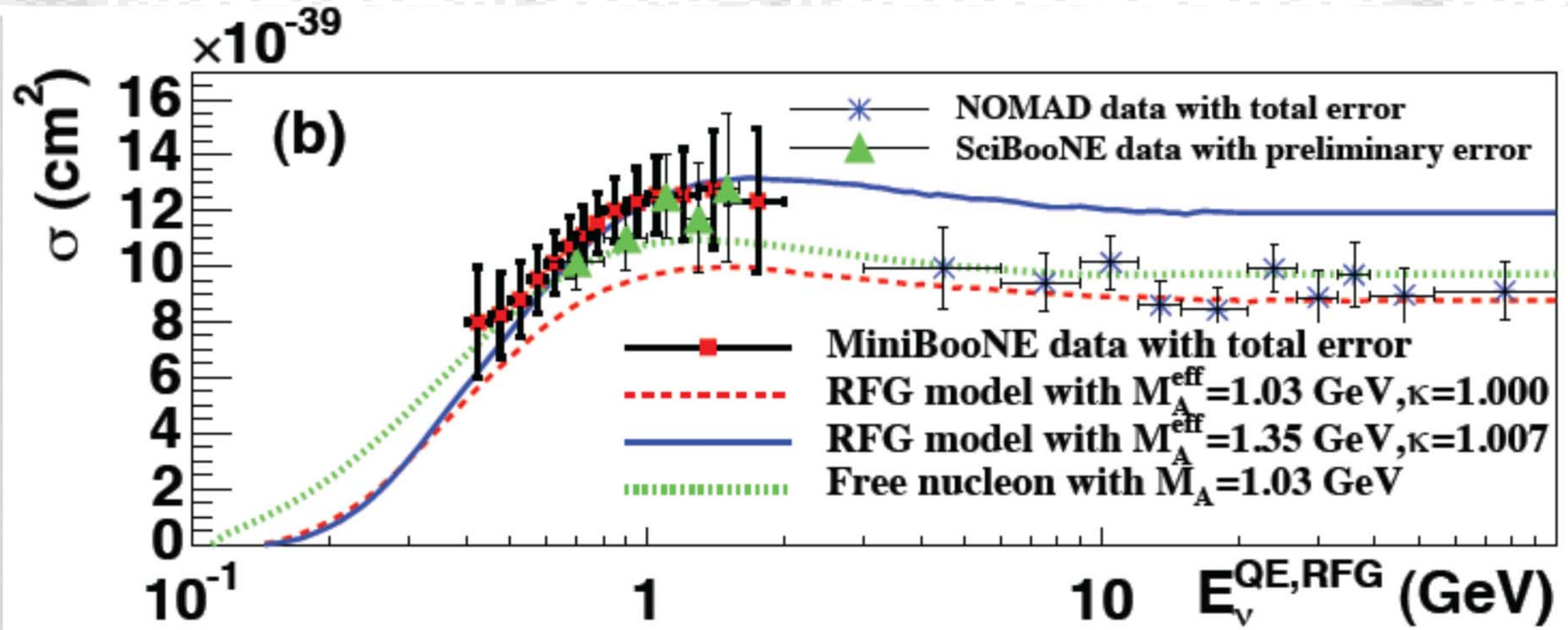
1. Quasi-elastic scattering
2. Single pion production
3. Inclusive Cross-Sections



Overview of Recent CCQE Data

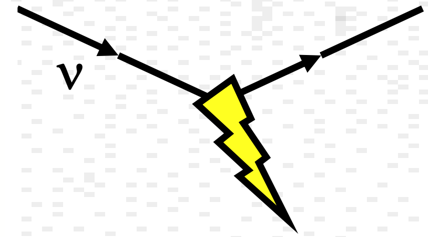


- Current data cannot be fit by a single prediction for low energy data (BooNEs) and high energy data (NOMAD)
  - In dipole form-factor picture, different "M_A"
  - Free nucleon "correct" M_A is probably ~1 GeV from other data

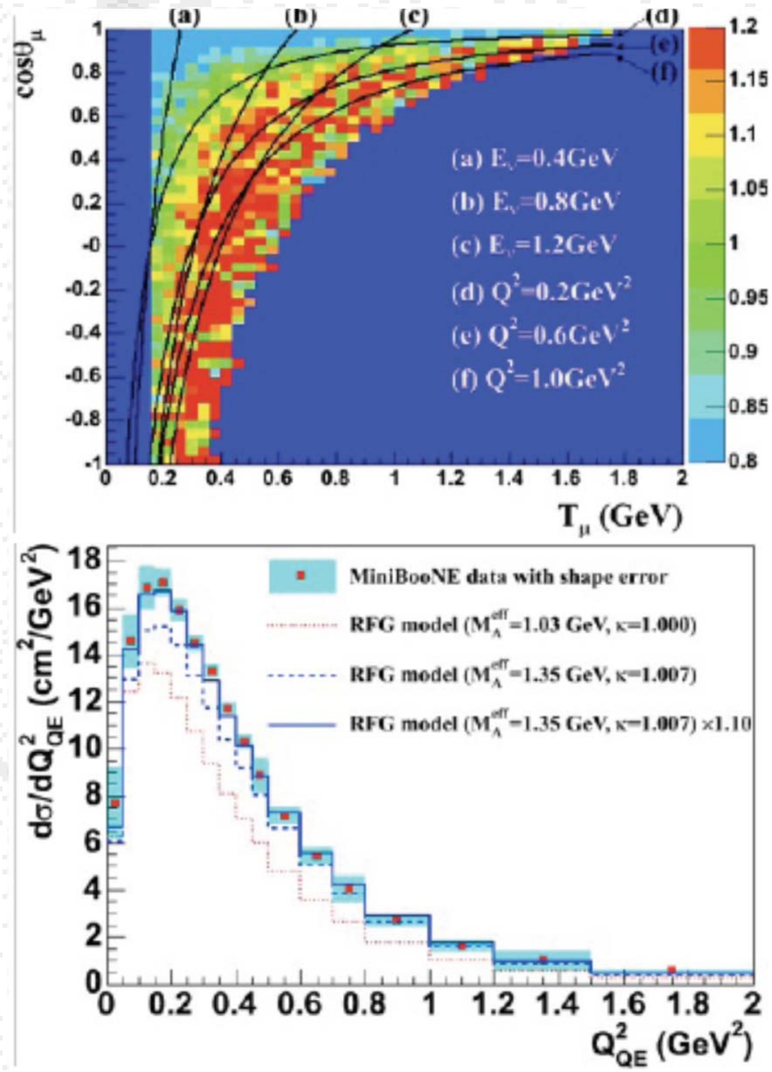


Plot courtesy of T. Katori

MiniBooNE *(Phys. Rev. D81 092005, 2010)*



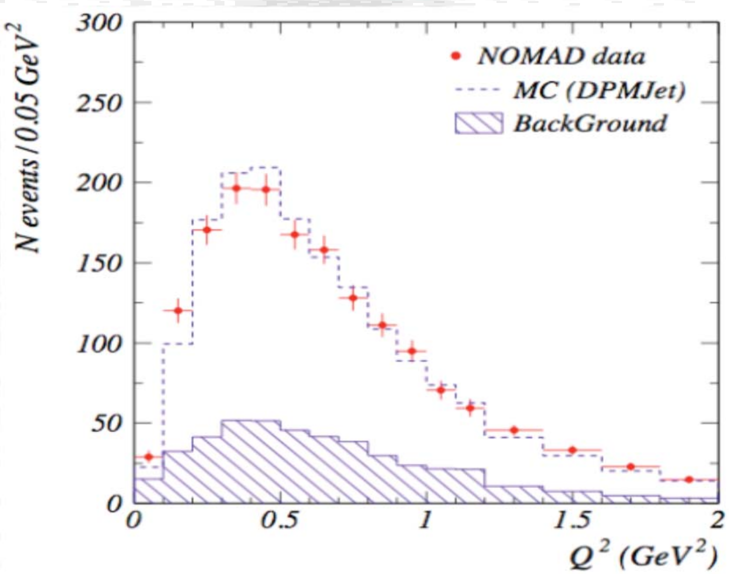
- Oil Cerenkov detector, views only muon
- Fit to observables, muon energy & angle, confirm discrepancy with low "M_A" is a Q^2 distortion
- Good consistency between total cross-section and this Q^2 shape



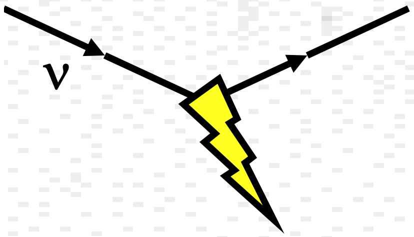
NOMAD (Eur.Phys.J.C63:355-381,2009)

- Like MiniBooNE, target is mostly carbon (drift chamber walls)
- Reconstruct both recoiling proton and muon
- Total cross-section is used to infer M_A, but Q^2 shape is also consistent
- *Two experiments, same target, but different energies and reconstruction…*

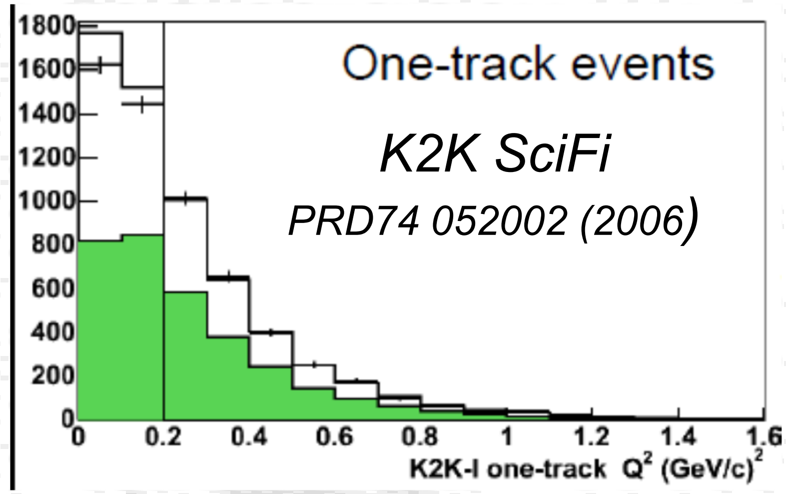
  … incompatible results?

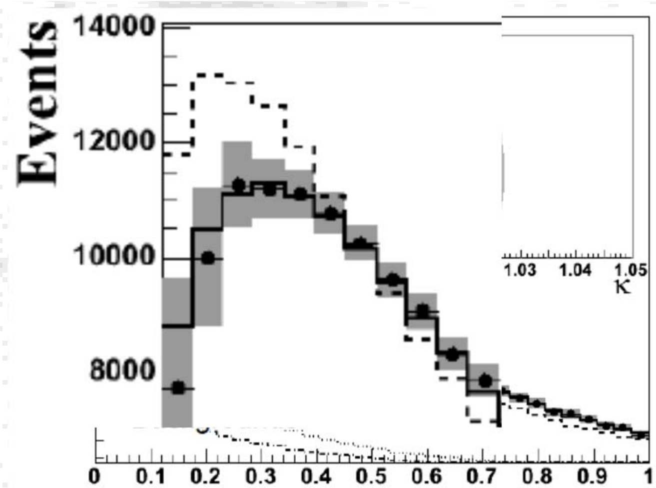


Role of Backgrounds to CCQE



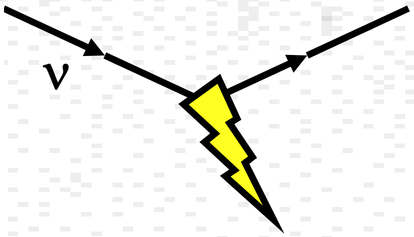
- K2K famously observed a "low Q^2 deficit" in its analysis
- MiniBooNE originally had a significant discrepancy at low Q^2 as well
  - Original approach was to put in a large enhancement to Pauli suppression to "fix" low Q2
  - Was resolved by using single pion background seen in data





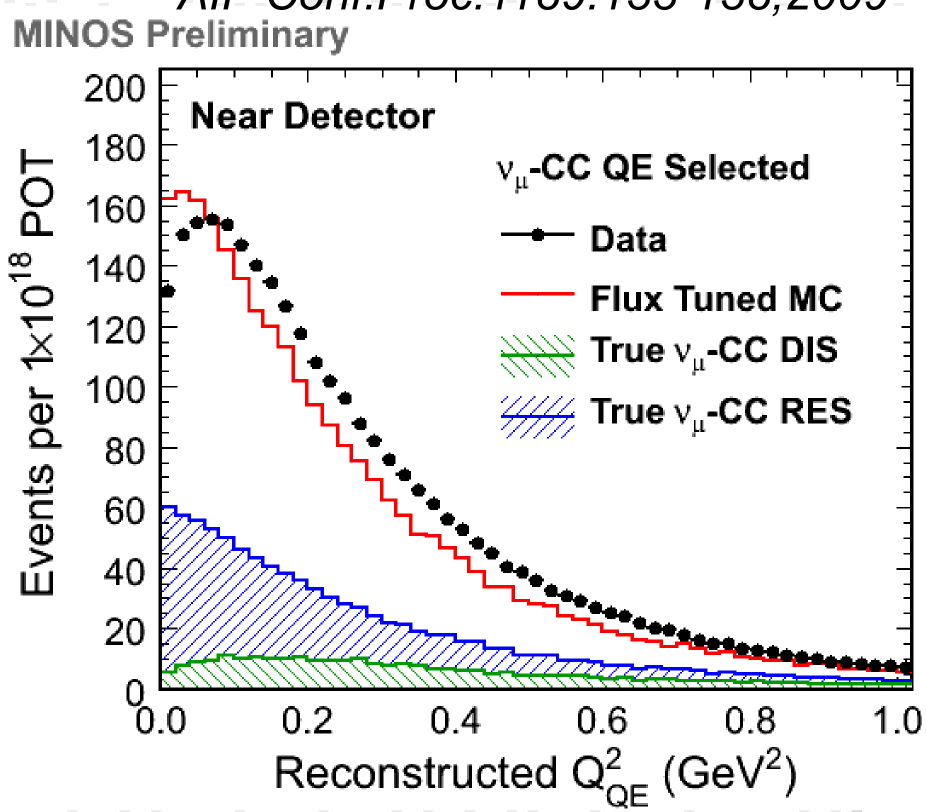
PRL100 032301 (2008)

MINOS CCQE



- Different target, iron, and different reconstruction technique
  - Select events with little visible hadronic energy in MINOS target calorimeter
- See significant discrepancy at low Q^2 and a excess at high Q^2 relative to M_A~1 GeV
- MINOS did a Mini-BooNE style analysis with extra Pauli suppression and floating M_A
  - Background to blame here also?

AIP Conf.Proc.1189:133-138,2009

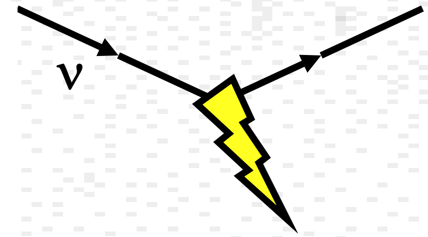


MINOS Preliminary

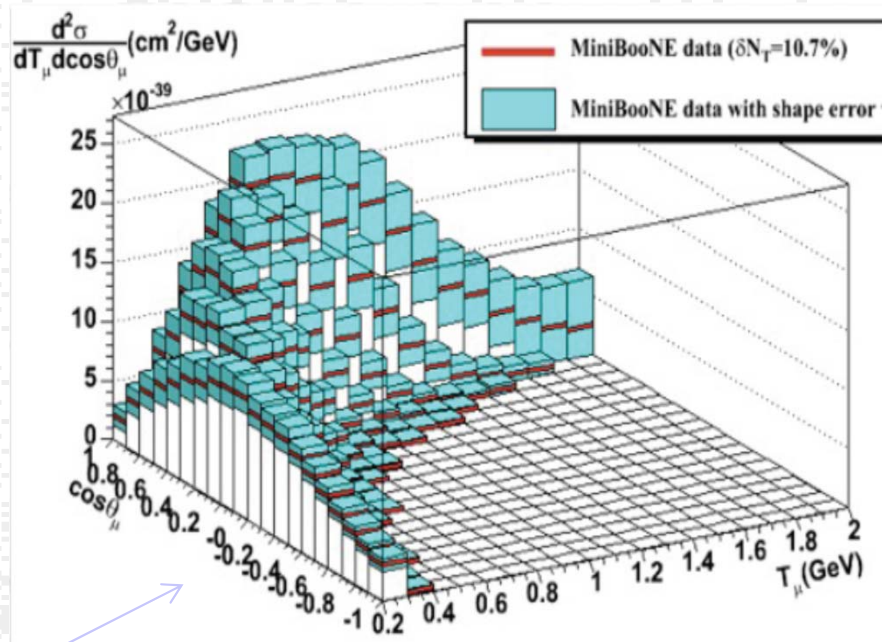
$M_A^{QE} = 1.19\ ^{+0.09}_{-0.10}\ (fit)\ ^{+0.12}_{-0.14}\ (syst)\ GeV$

$k^{Fermi} \rightarrow 1.28 \times k^{Fermi}$

Next Steps Forward

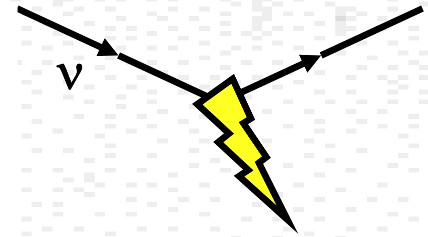


- With more sophisticated analyses and models, we need a new paradigm
- Experimental measurements and calculations are moving to final states, rather than process-specific measurements and extracted parameters
  - MiniBooNE CCQE a good example
- These results can support development new to understand underlying physics and support oscillation experiments



(Phys. Rev. ***D81*** *092005, 2010)*

Resonant Pion Production

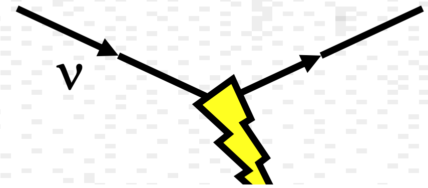


- Recall that these are major backgrounds to ν_μ disappearance and ν_e appearance exp'ts

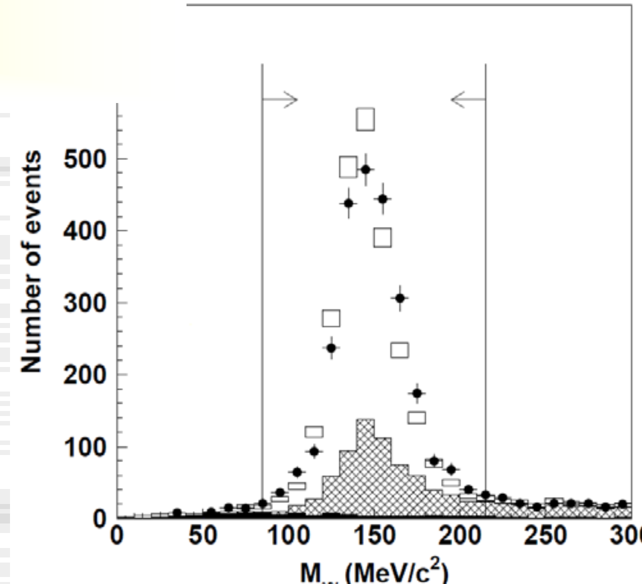
Experiments	$\langle E_\nu \rangle$ GeV	Main goal	Detector	ν target	ν MC	Cross section results
K2K	1.3	θ_{23}, Δm_{23}	Fine Grained, Water Cher	CH, H_2O	NEUT	Pub: $NC\pi^0$, $CC\pi^+$ Prelim: $CC\pi^0$
MiniBooNE	0.7	$\nu_\mu \rightarrow \nu_e$	Oil Cher	CH_2	NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^+$, $CC\pi^0$
SciBooNE	0.7	σ_ν	Fine Grained	CH	NEUT, NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^0$

Compilation by Martin Tzanov

ν_μ NC π^0 Cross Section



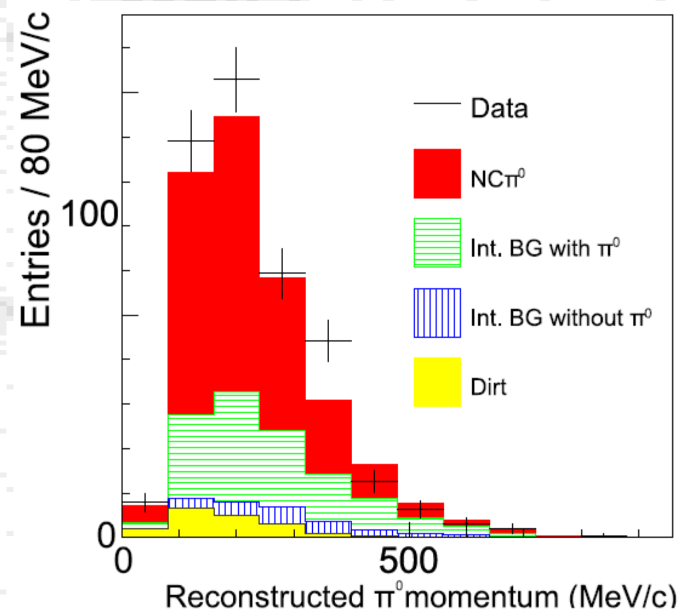
- K2K made first measurement of this with a goal of verifying their background prediction
  - Require two rings in 1kTon near det.
  - $\sigma^{NC\pi^0}/\sigma^{CC}$= 0.064±0.001(stat.)±0.007(sys.)
  - MC prediction is 0.065.



Phys.Lett. B619 (2005) 255

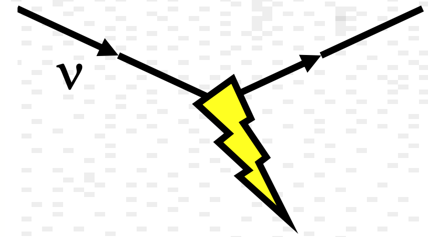
- SciBooNE made a similar measurement in spirit, but completely different reconstruction
  - 2 γ tracked in SciBar and contained in external EM calorimeter

- $\sigma^{NC\pi^0}/\sigma^{CC}$= (7.7 ± 0.5(stat.) ± 0.5(sys.)) × 10^{-2}
  - MC prediction 6.8×10^{-2}

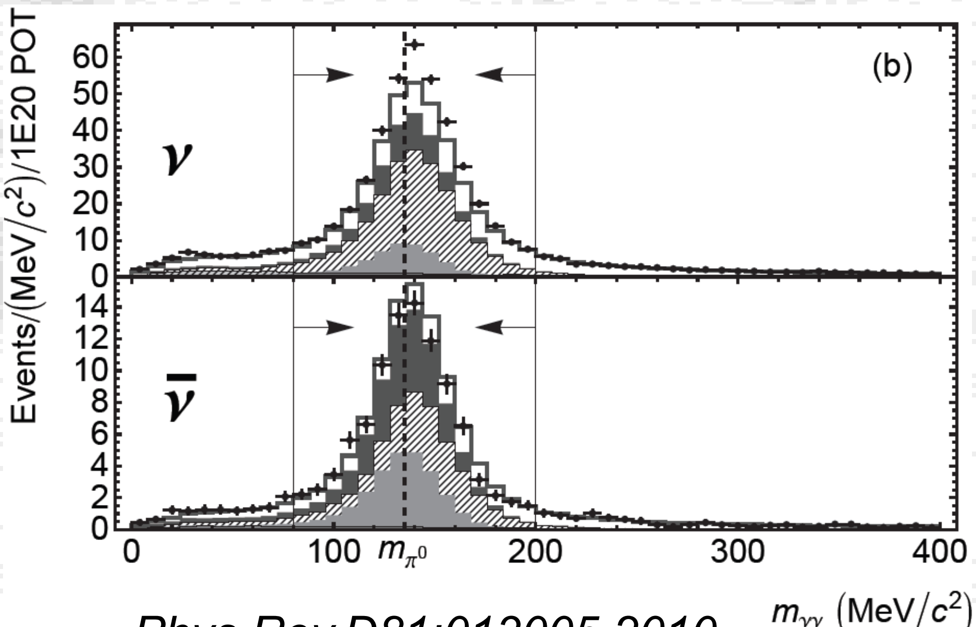


Phys. Rev. D 81, 033004 (2009)

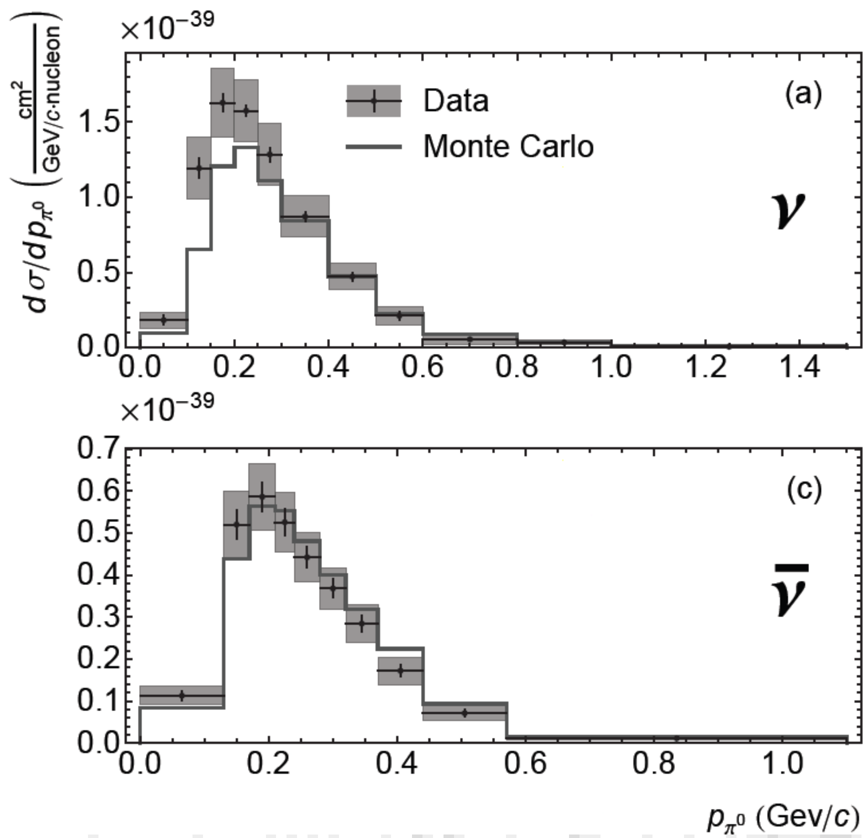
ν_μ NC π^0 Cross Section



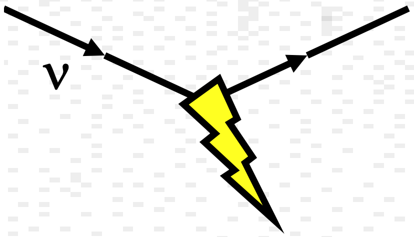
- MiniBooNE differential cross-section analysis
  - Reconstruction by two Cerenkov rings, excellent mass resolution as with K2K 1kTon analysis
  - 21K events! K2K, SciBoone and MiniBooNE represent a vast improvement in knowledge.
- $d\sigma/dp_\pi$ for ν and anti-ν



Phys.Rev.D81:013005,2010

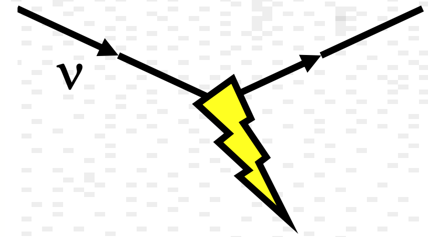


Inclusive Interactions



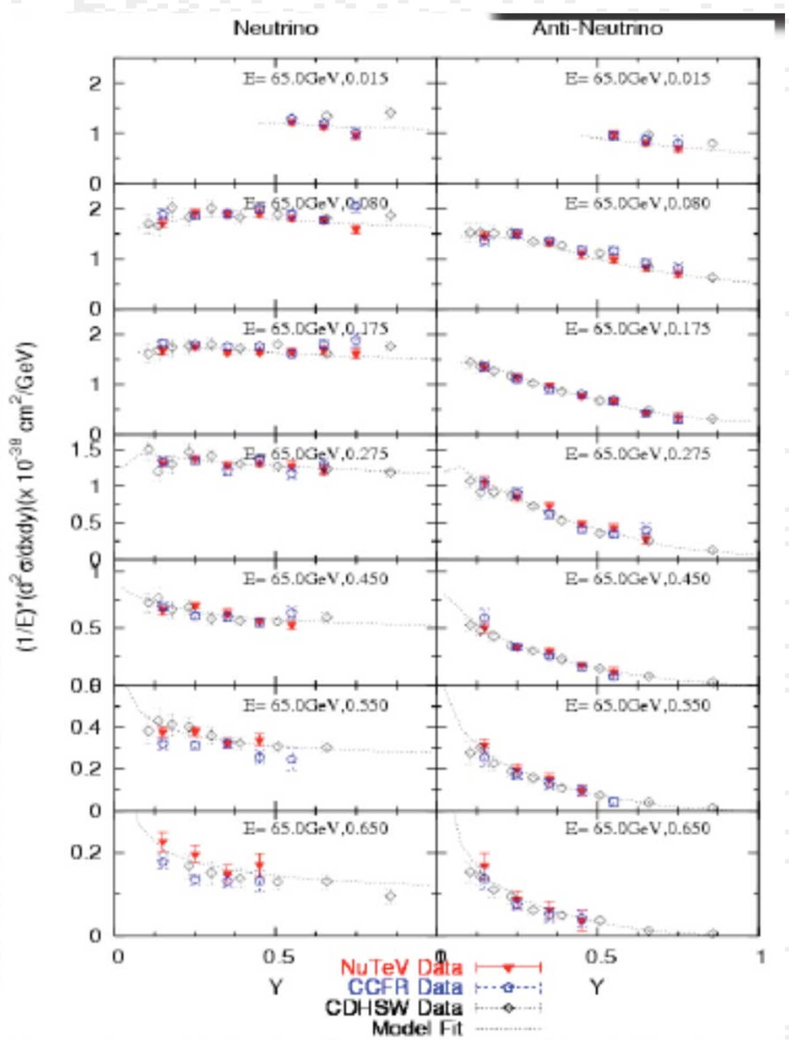
- Much of the data we have is at high energies
  - Common wideband technique is "low recoil" method which uses the observation that $\lim_{\nu \to 0} \frac{d\sigma}{d\nu}$ is independent of E_ν
  - Cross-section normalized from narrow band expt's which counted secondary particles to measure flux
- Typical goal is to extract structure functions from dependence in x, Q^2 and E_ν.
- Most recently, NuTeV, CHORUS, NOMAD, MINOS

NuTeV CC Differential Cross-Sections

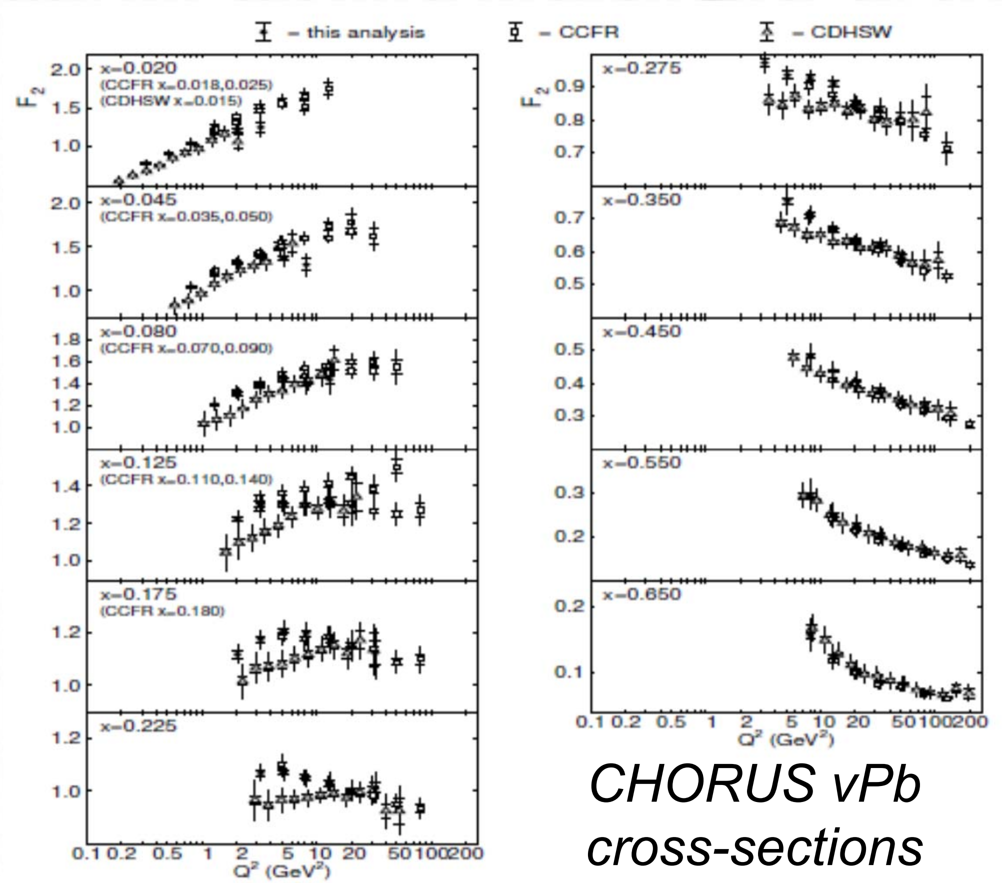


- NuTeV has a very large data sample on iron
  - High energies, precision calibration from testbeam
- Uses:
  - pQCD fits for Λ_{QCD}
  - Extract structure functions for comparisons with other experiments

Phys.Rev.D74:012008,2006

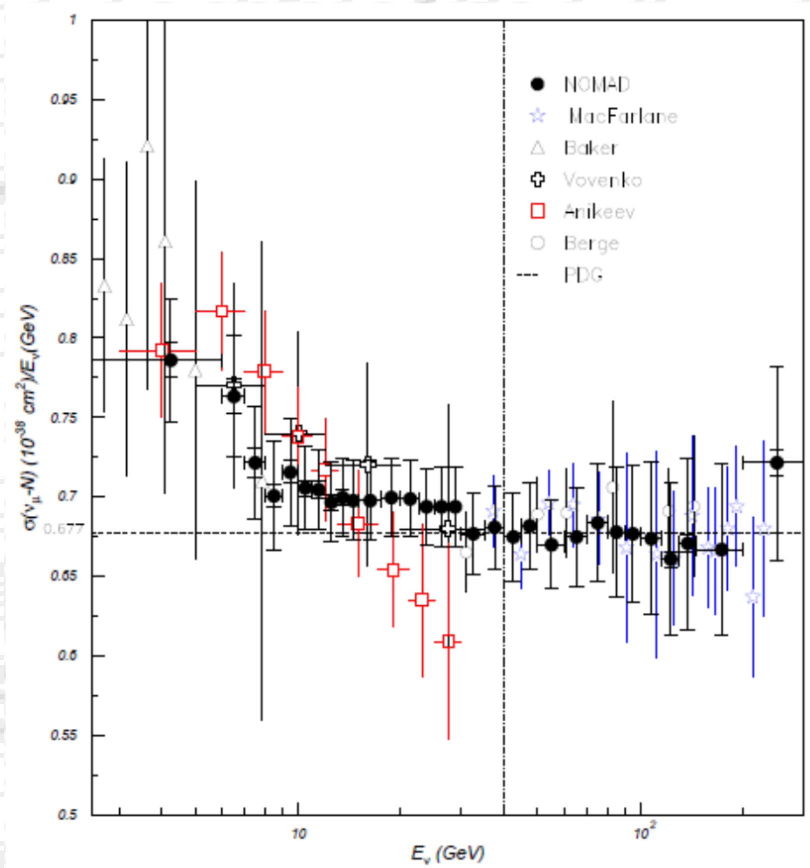


CHORUS and NOMAD



CHORUS νPb cross-sections

Phys.Lett..632(2006) 65



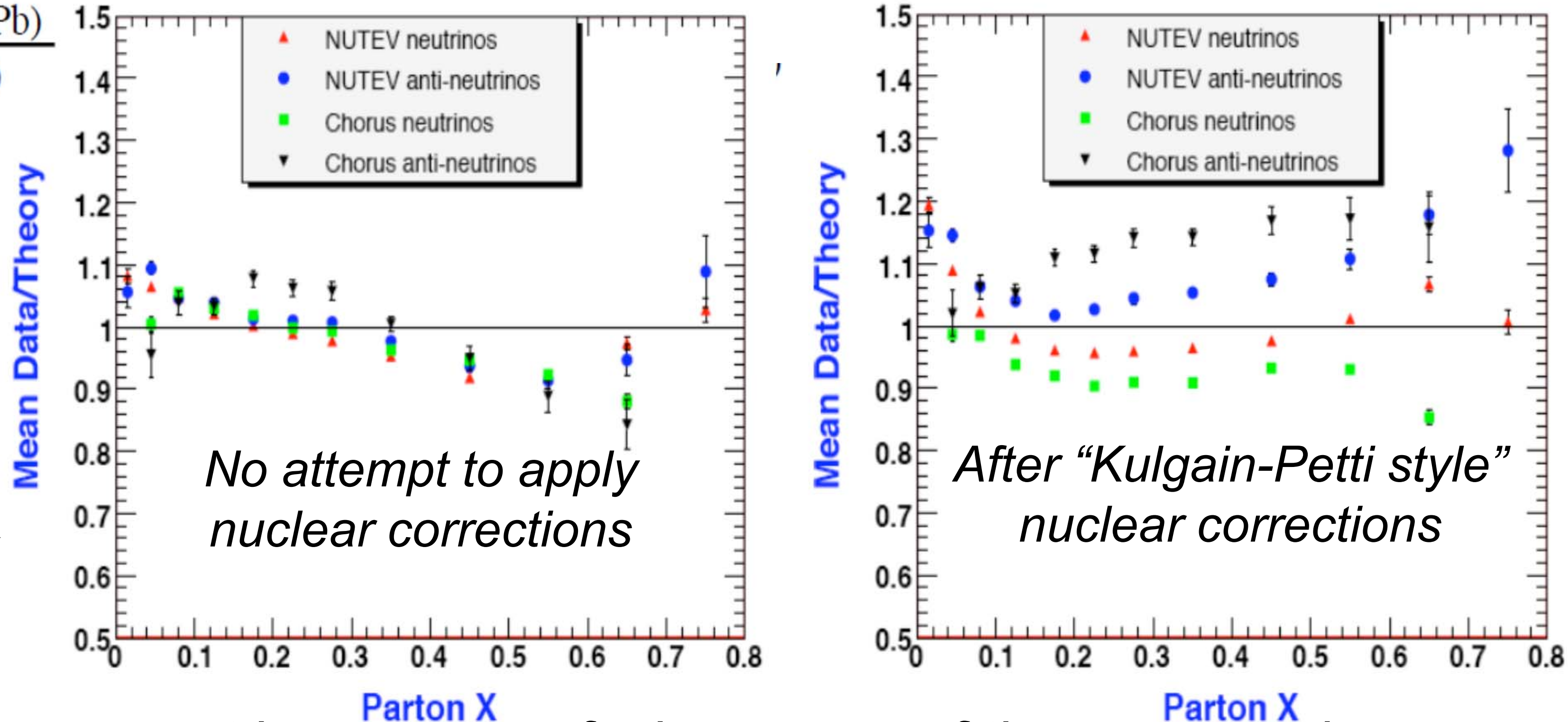
NOMAD νC CC total cross-sections

Phys.Lett.B660:19-25,2008

Nuclear Corrections and High-x PDFs

CTEQ global fit compared to neutrinos

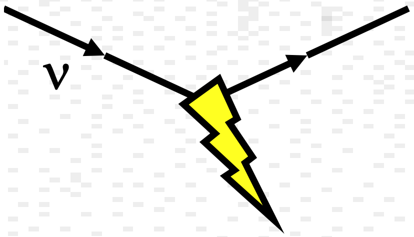
$\frac{\sigma(\nu Fe \text{ or } \nu Pb)}{\sigma(\nu "D_2")}$



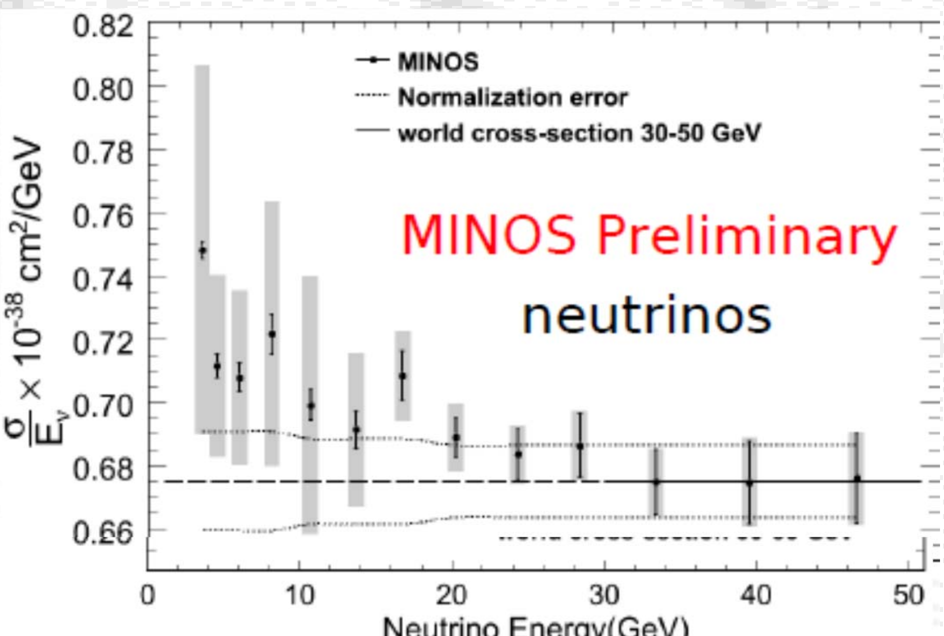
Figures courtesy J. Morfín

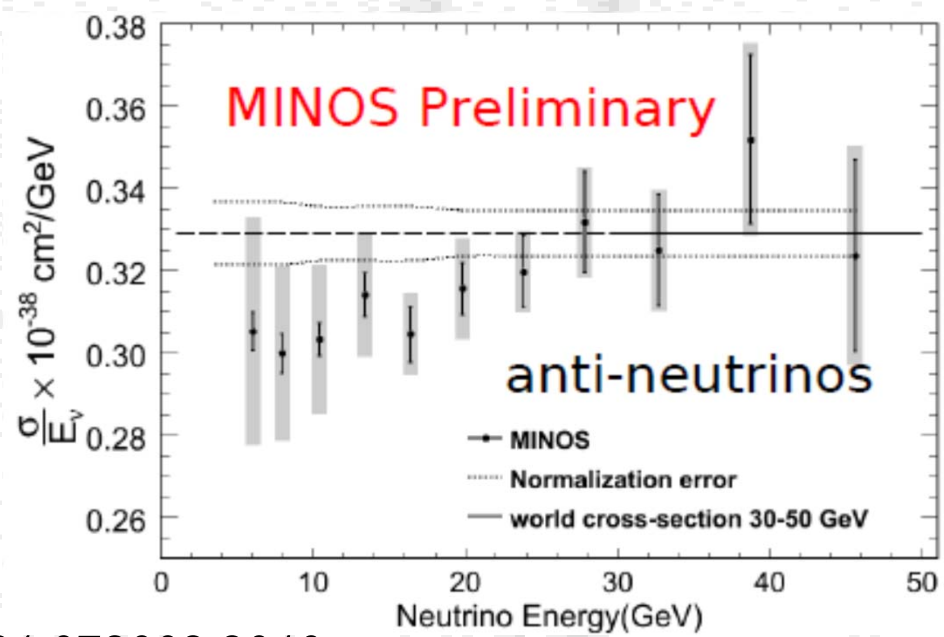
- *There are at least two confusing aspect of these comparisons*
  - *We observed problems before in nuclear corrections from models*
  - *Also, some strange behavior at high x… difficult to incorporate both data sets in one model*

MINOS Total Cross-Section

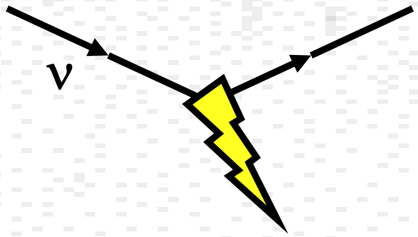


- Attempt to bravely extend low recoil technique to very low energies
  - "Low recoil" sample is visible hadronic energy below 1 GeV, so a fair fraction of the cross-section at the lowest energy (3 GeV)



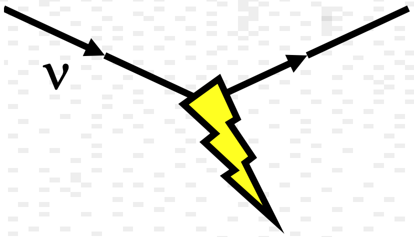


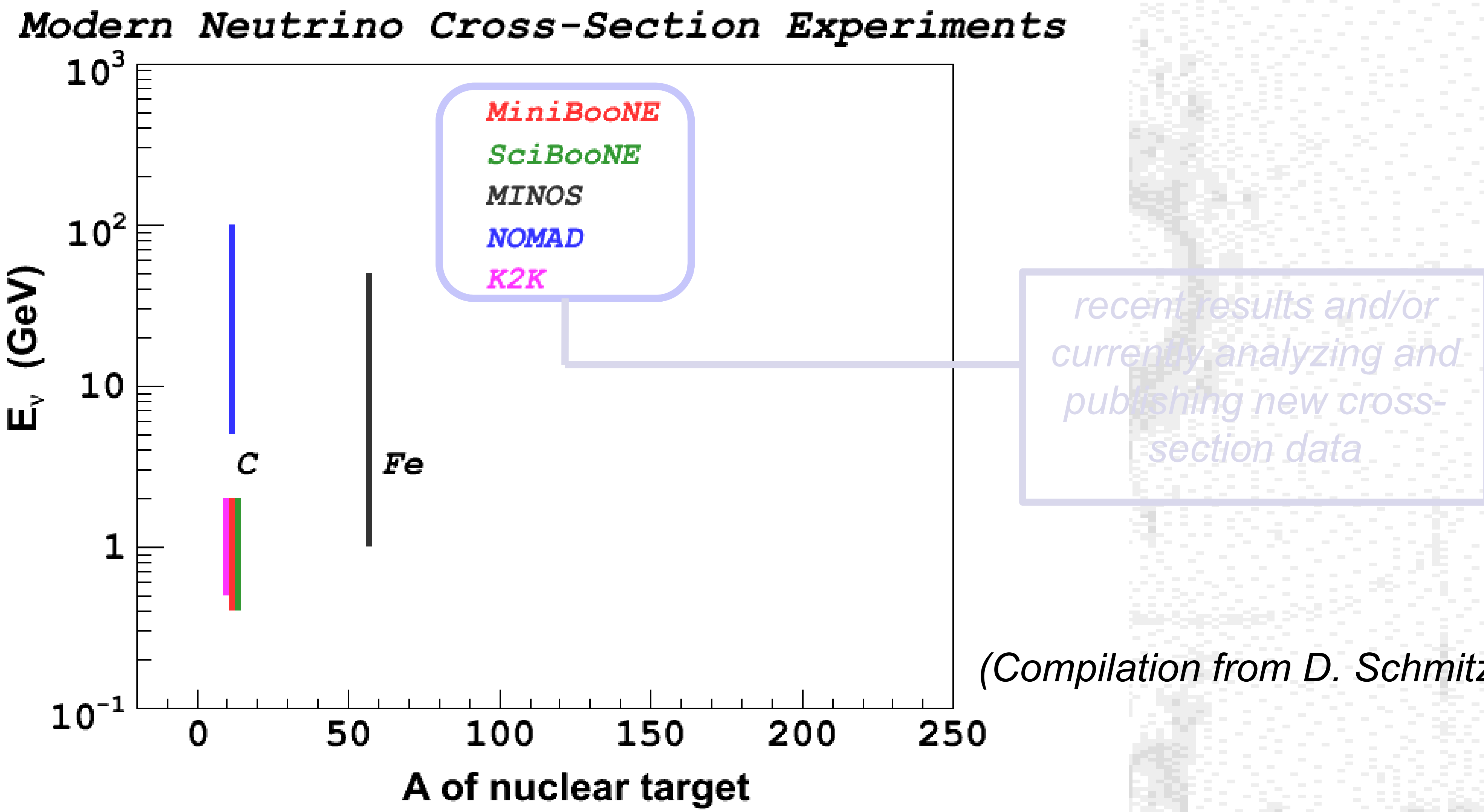
Phys.Rev.D81:072002,2010



Measuring GeV Cross-Sections

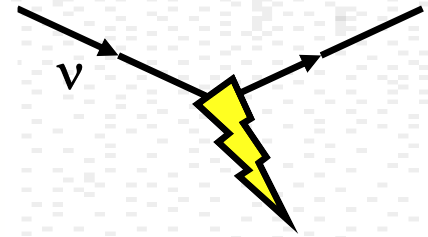
Energies and Targets of Cross-Section Measurements





(Compilation from D. Schmitz)

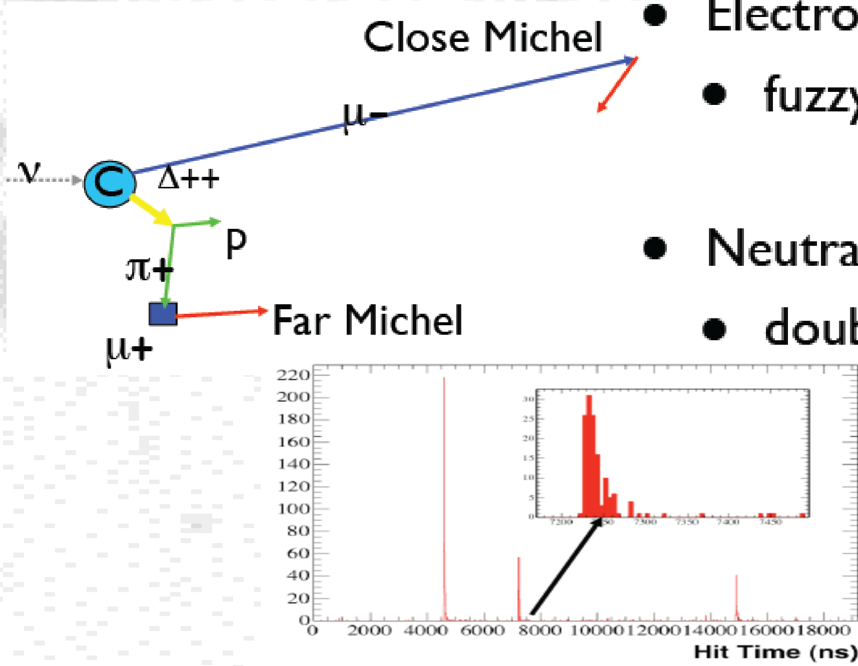
Technologies of Recent Experiments

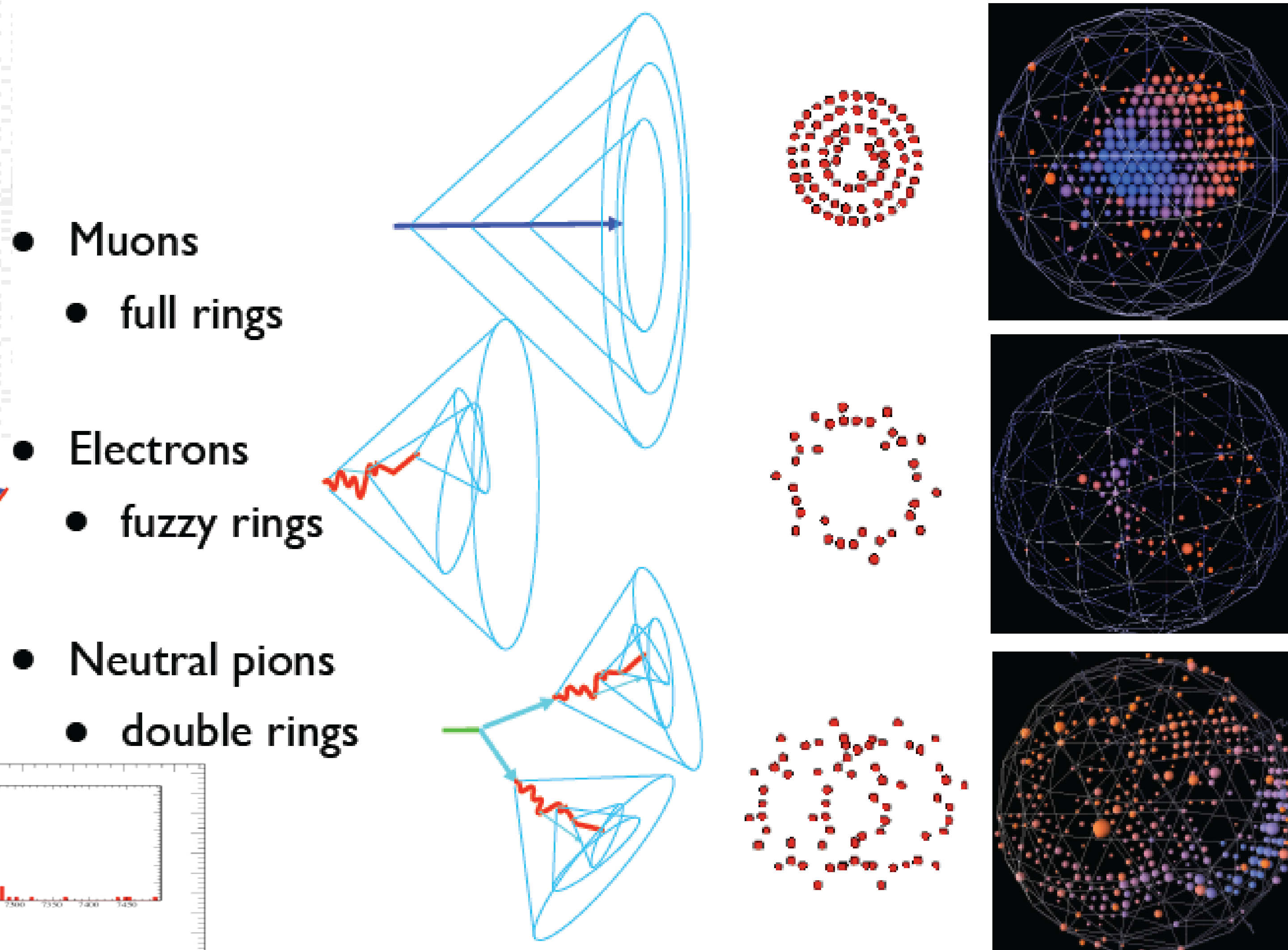


- BooNE and K2K: both have Cerenkov and Scintillator Bar detectors for measuring neutrino interactions
  - Cerenkov detectors have uniform acceptance, but high thresholds for massive particles
  - Scintillator bar detectors usually have a directional bias, typically smaller and may not contain interaction, but thresholds are lower than Cerenkov and particles can be identified by dE/dx
- NOMAD: drift chambers in an analyzing magnet
  - Good momentum measurement and possibly better particle identification by dE/dx, but diffuse material makes photon reconstruction difficult
- MINOS: coarse sampling iron detector
  - Difficult to distinguish particles other than muons, but very high rate

Technologies: Cerenkov Detectors

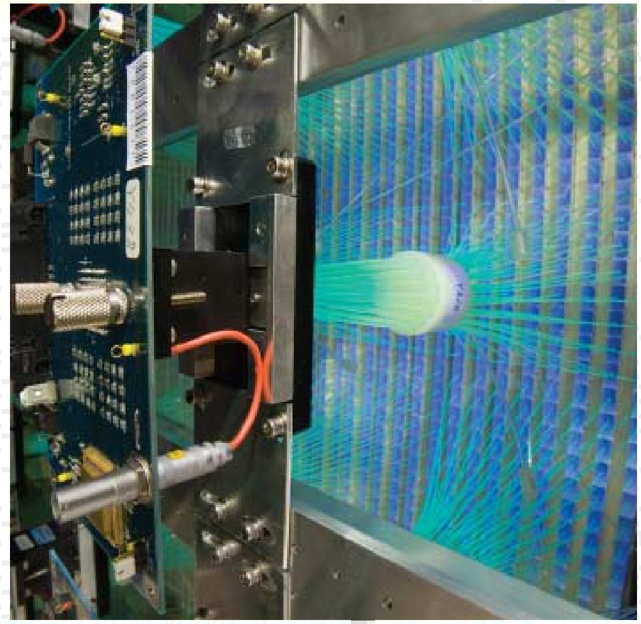
- Cerenkov gives efficient muon or e/γ identification
- Also, tag soft pions by decay



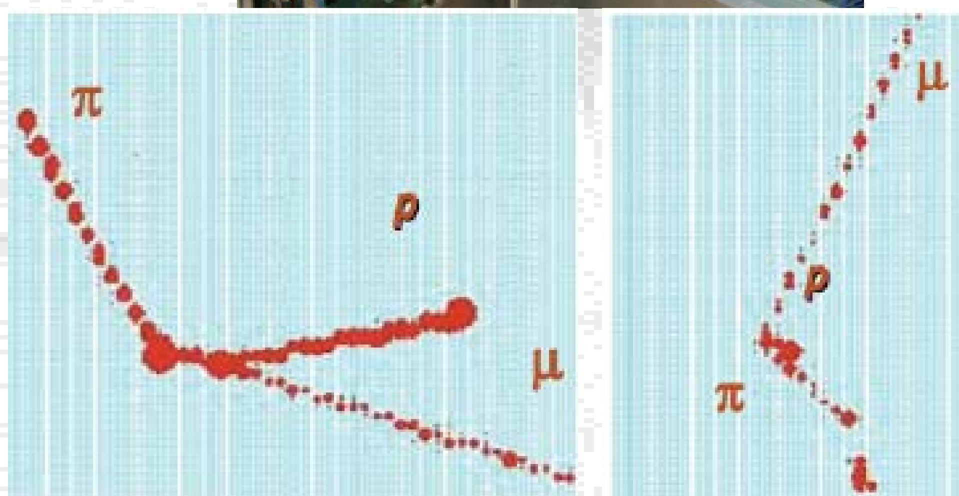


Figures from M. Wascko

Technologies: Segmented Scintillator

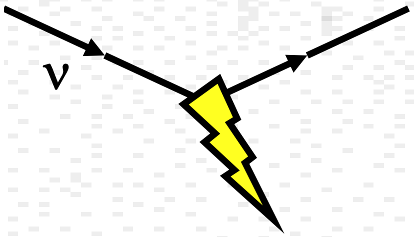


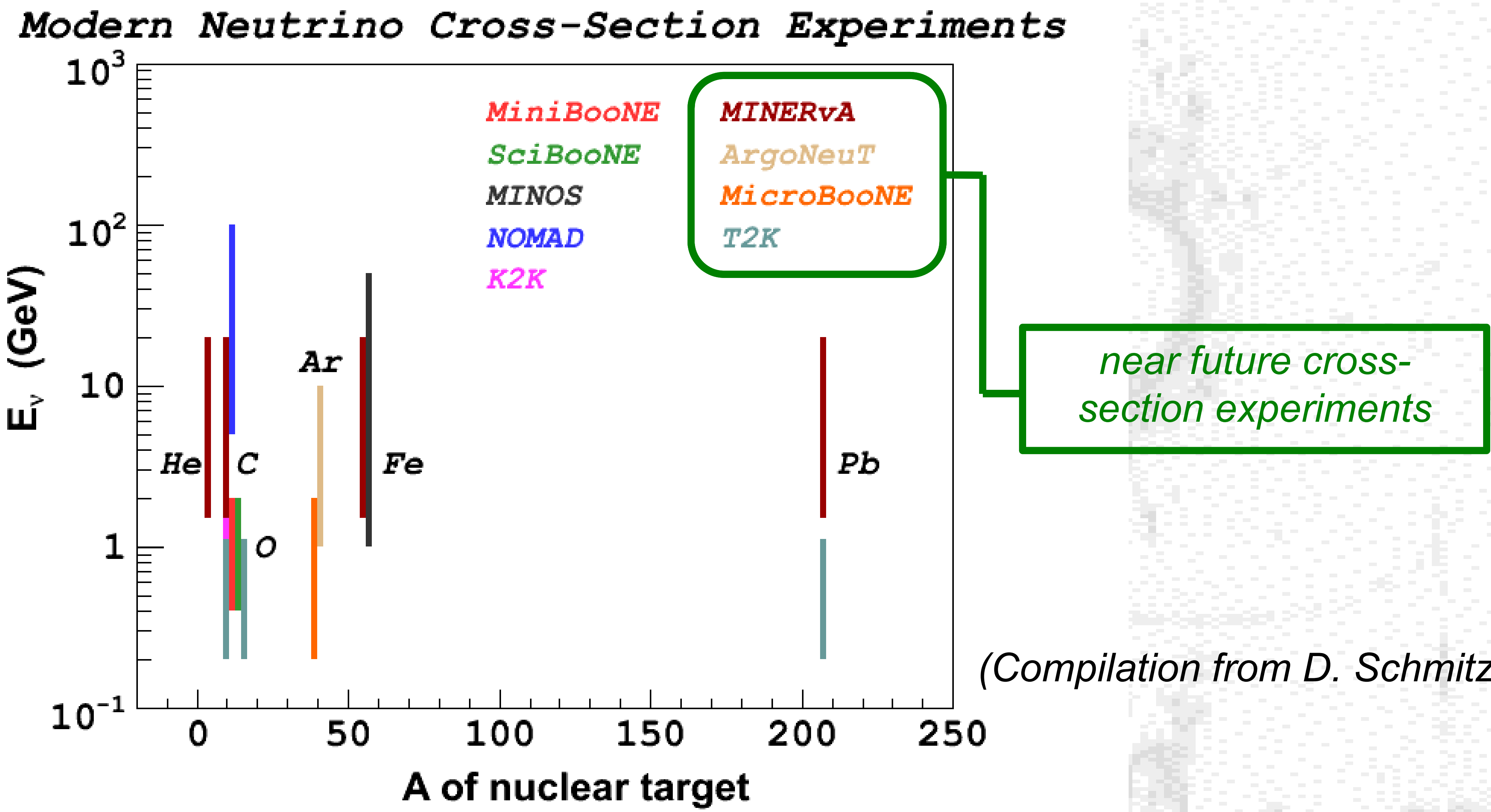
- Lower thresholds, particle ID by dE/dx, calorimetric energy reconstruction
  - i.e., vertex activity
- But detectors must be smaller (cost), so escaping particles
- Reconstruction not uniform in angle



Figures from M. Wascko

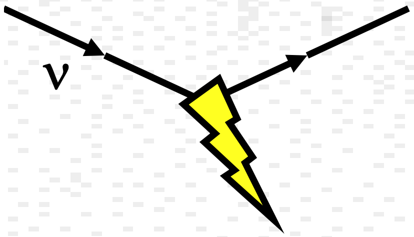
Energies and Targets of Cross-Section Measurements



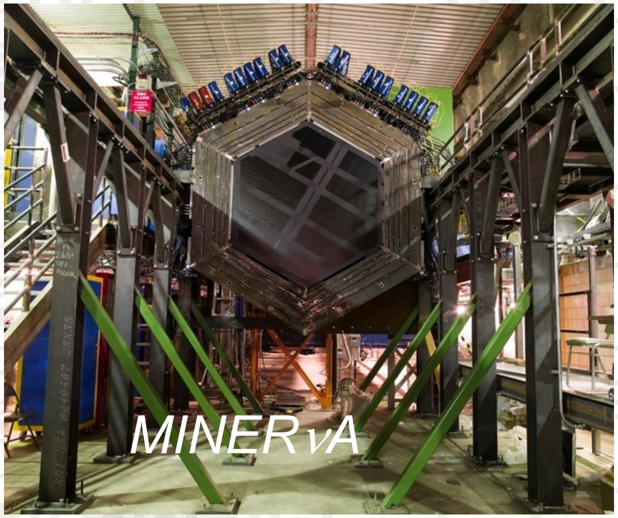


(Compilation from D. Schmitz)

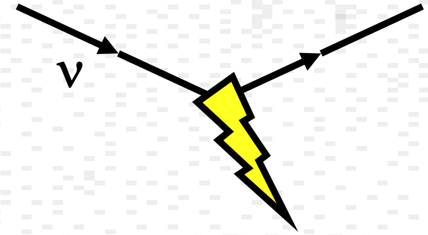
What are these new experiments?



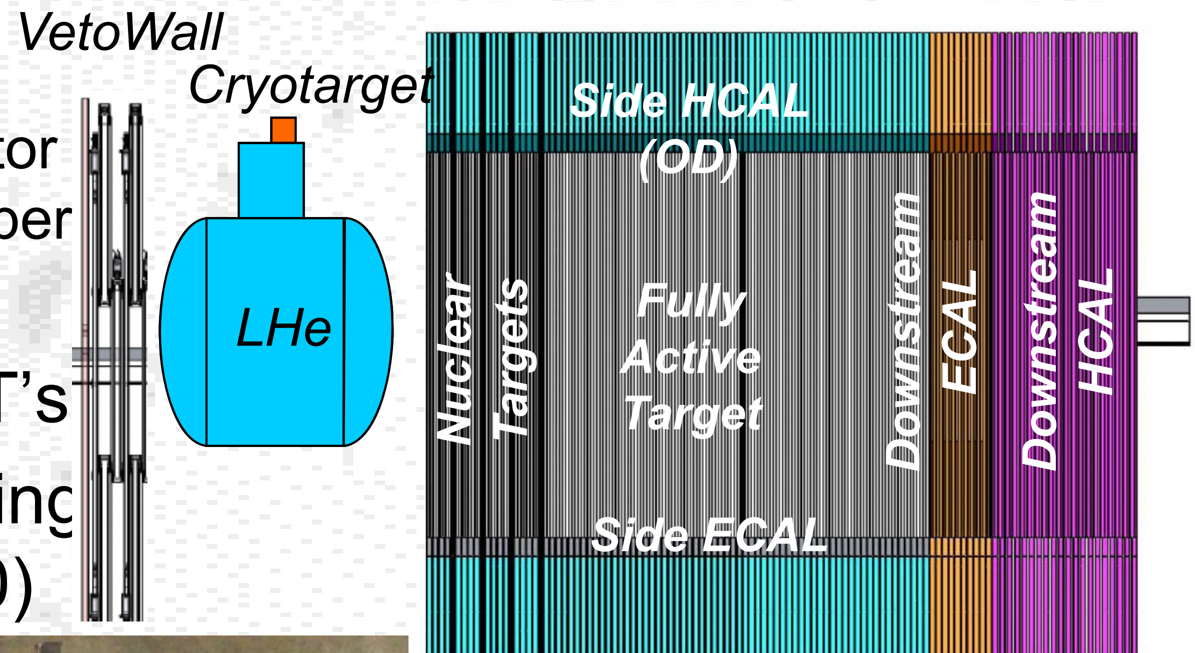
- MINERνA: in NuMI at Fermilab
  - Fine-grained scintillator detector
  - Nuclear targets of He, C, H_2O, Fe, Pb
- T2K 280m Near Detector at J-PARC
  - Fine-grained scintillator, water, and TPC's in a magnetic field
- NOνA near detector: to run in 2013
  - Liquid scintillator in off-axis beam, running above ground before 2013
- MicroBooNE: to run in/after 2013
  - Liquid Argon TPC in FNAL Booster Beam
  - Some data from ArgoNeuT test in NuMI

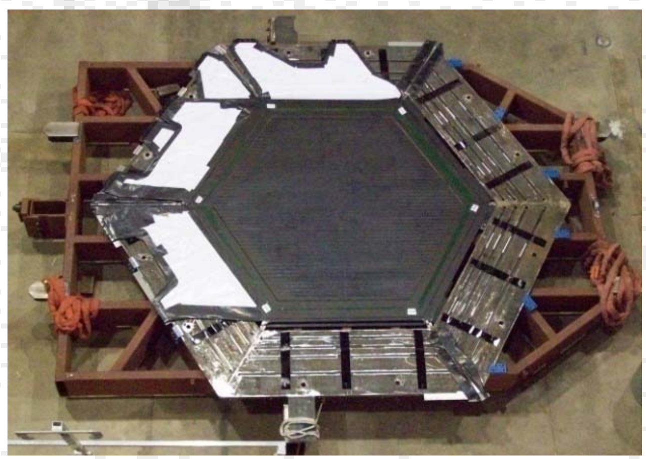


MINERνA Detector



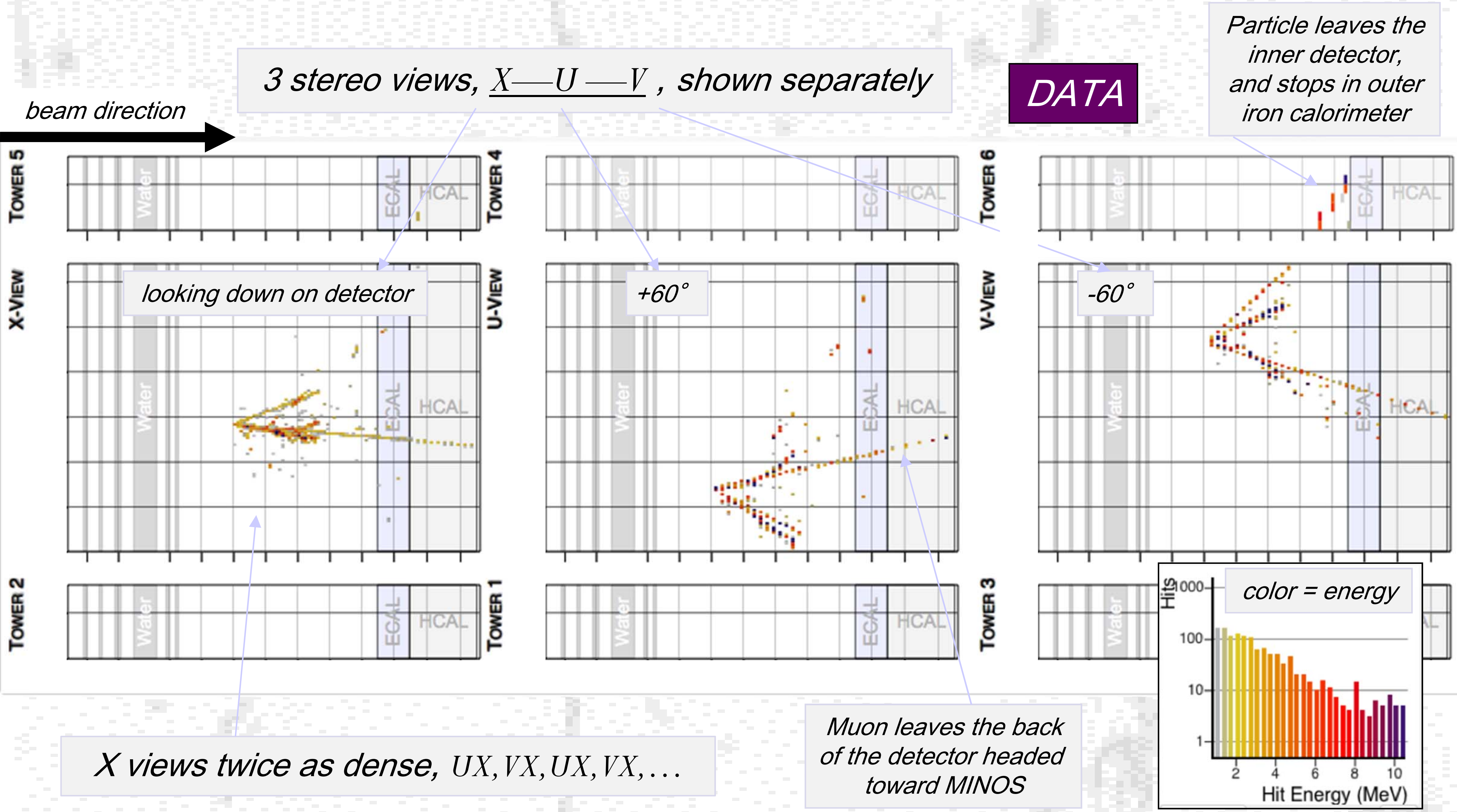
- 120 modules
  - Finely segmented scintillator planes read out by WLS fiber
  - Side calorimetry
- Signals to 64-anode PMT's
- Front End Electronics using Trip-t chips (thanks to D0)
- Side and downstream EM and hadron calorimetry
- MINOS Detector gives muon momentum and charge





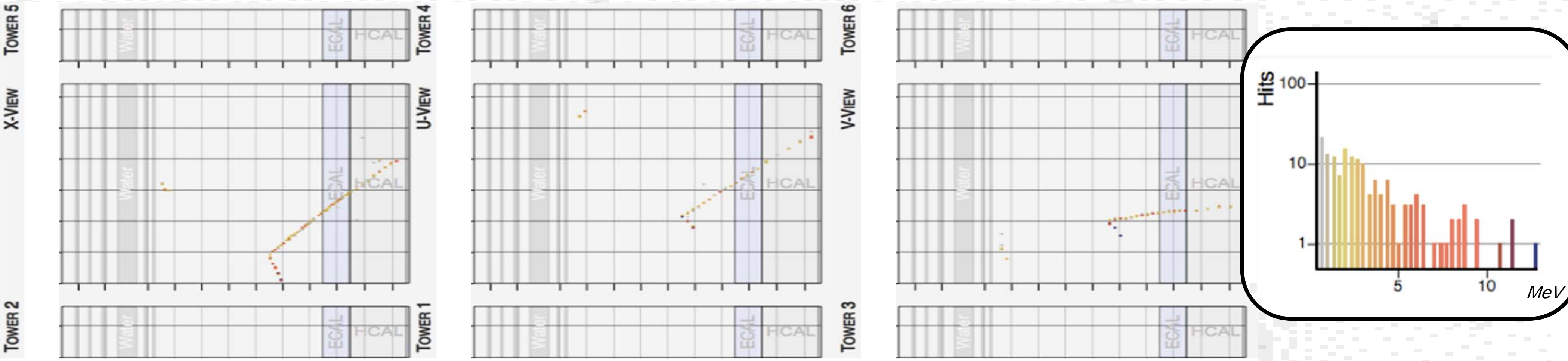
ν Events in MINERνA

- So what does an event look like in MINERνA…



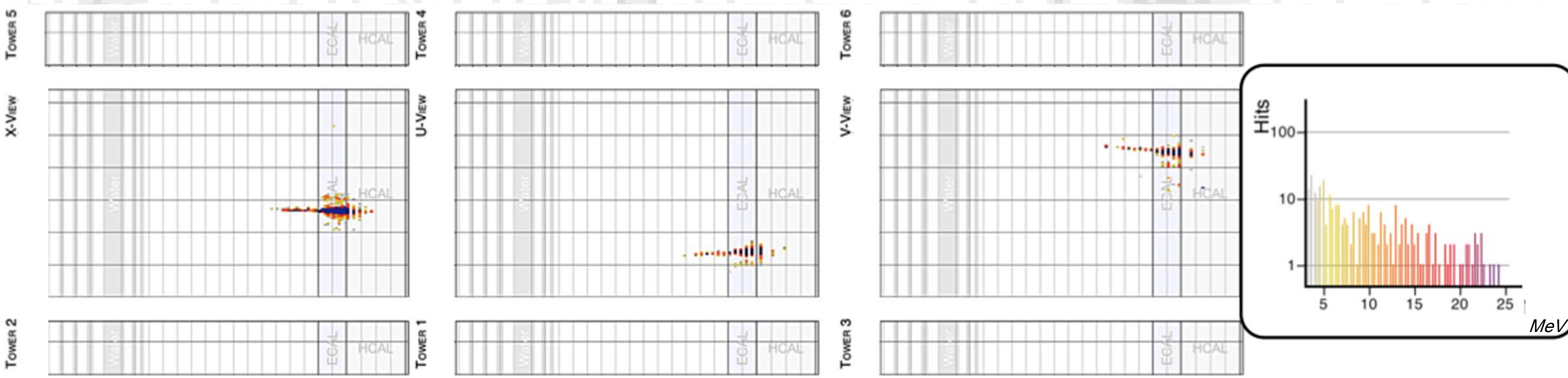
ν Events in MINERνA

- Charged-current Quasi-elastic candidate



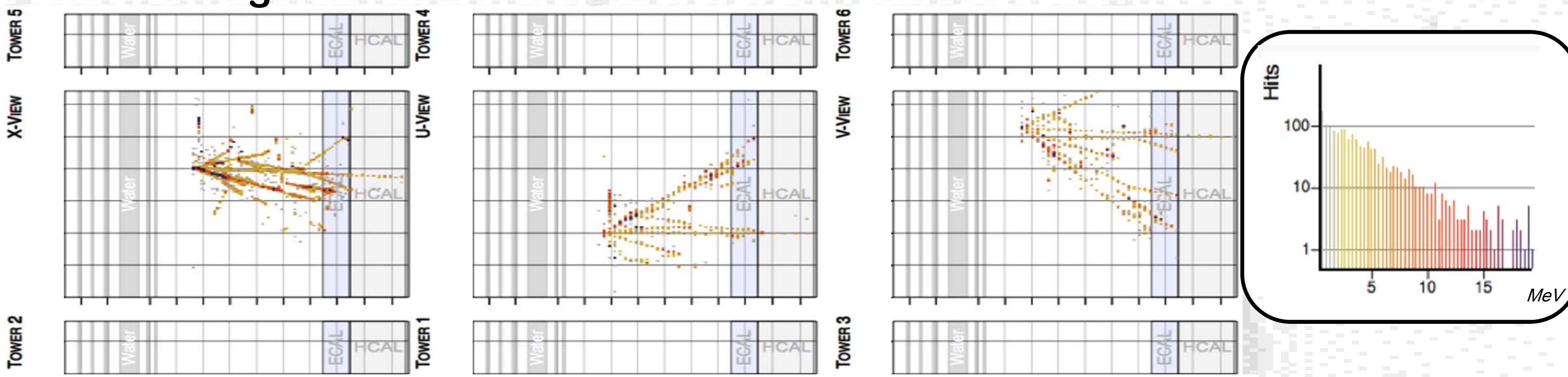
DATA

- Single Electron Candidate



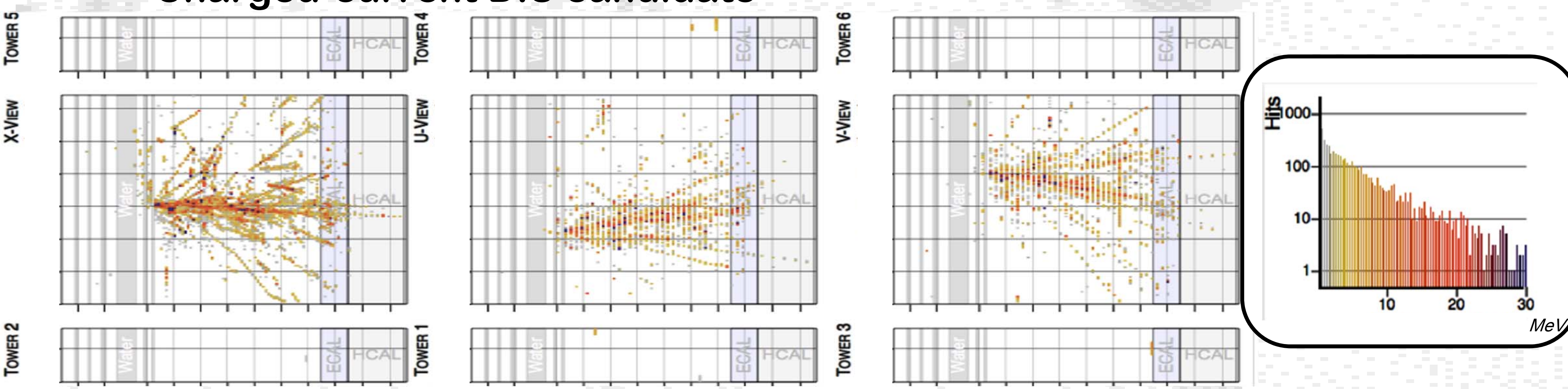
ν Events in MINERνA

- **Charged-current DIS candidate**

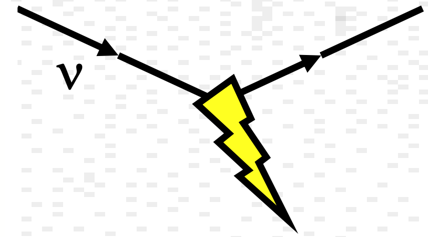


DATA

- **Charged-current DIS candidate**

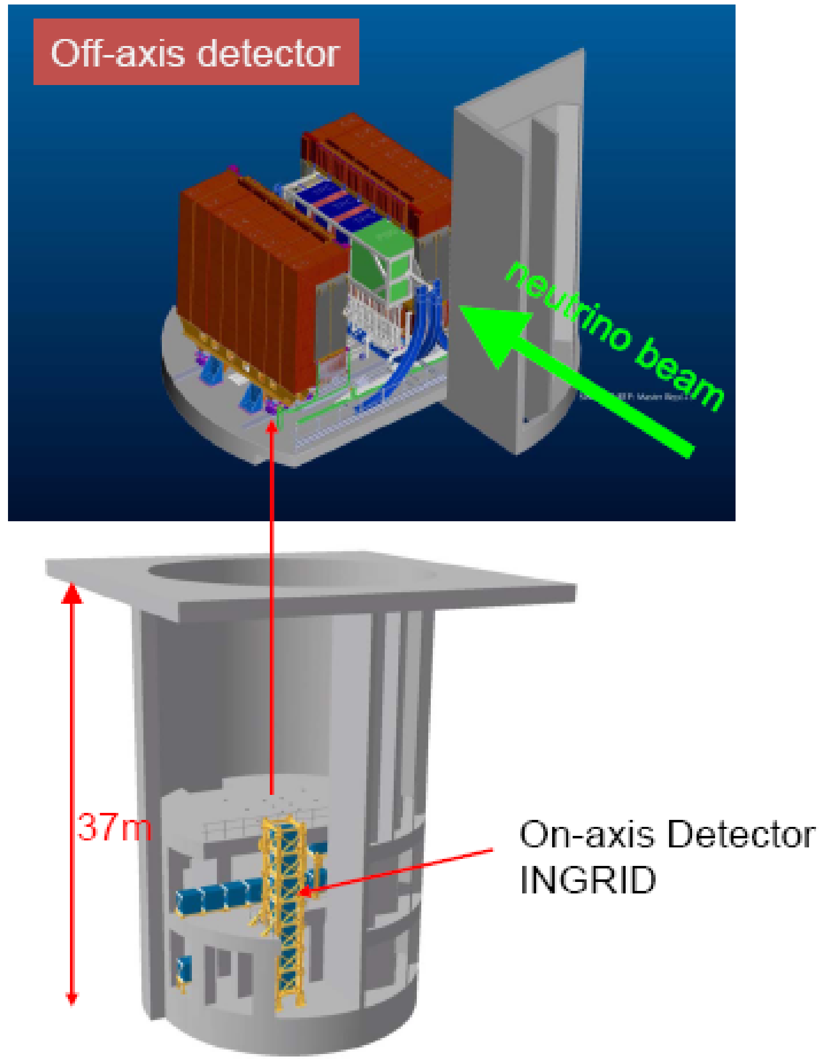


T2K Near Detectors



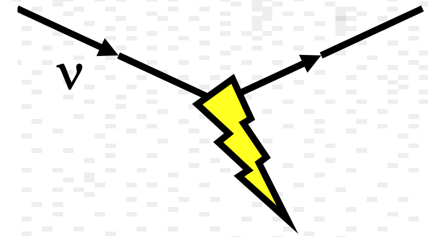
T2K Near Detector Suite

- Understand the neutrino beam before oscillations occur
- On – Axis Detector
  - Monitor beam direction
  - Monitor beam intensity
- Off – Axis Detector
  - Beam flux
  - Beam ν_e contamination
  - Cross sections

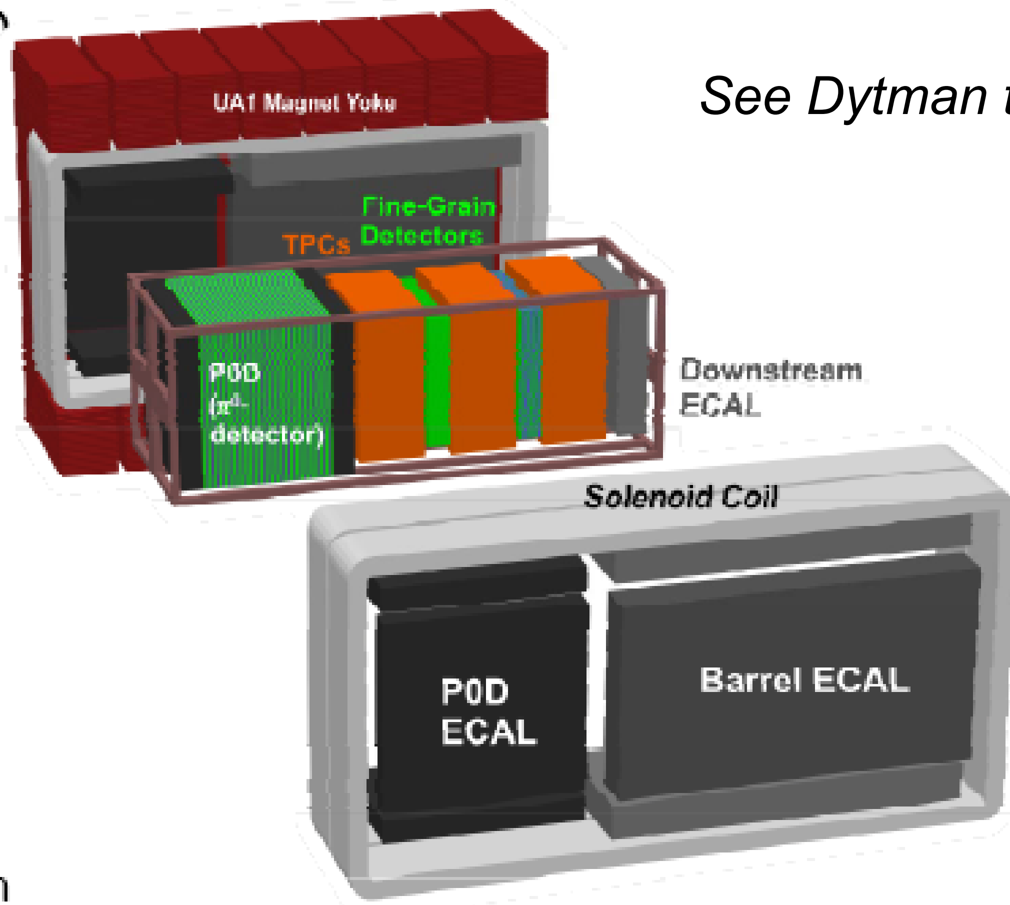


slide courtesy of R. Terri

Off-Axis Detector



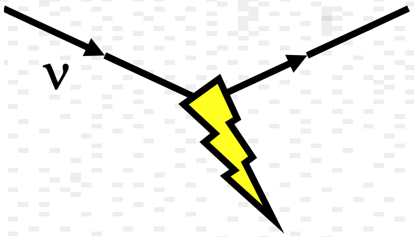
- UA1 Magnet 0.2T field
- Includes a water target in P0D and Tracker
  - Understand interactions at SK
- Tracker Region
  - Fine Grained Detectors (FGDs) & TPCs
  - Particle Tracking
- P0D
  - Measure NC π^0 rate
- ECAL
  - Surrounds tracker and P0D
  - Capture EM energy
- SMRD
  - Muon ranging instrumentation in the magnet yoke



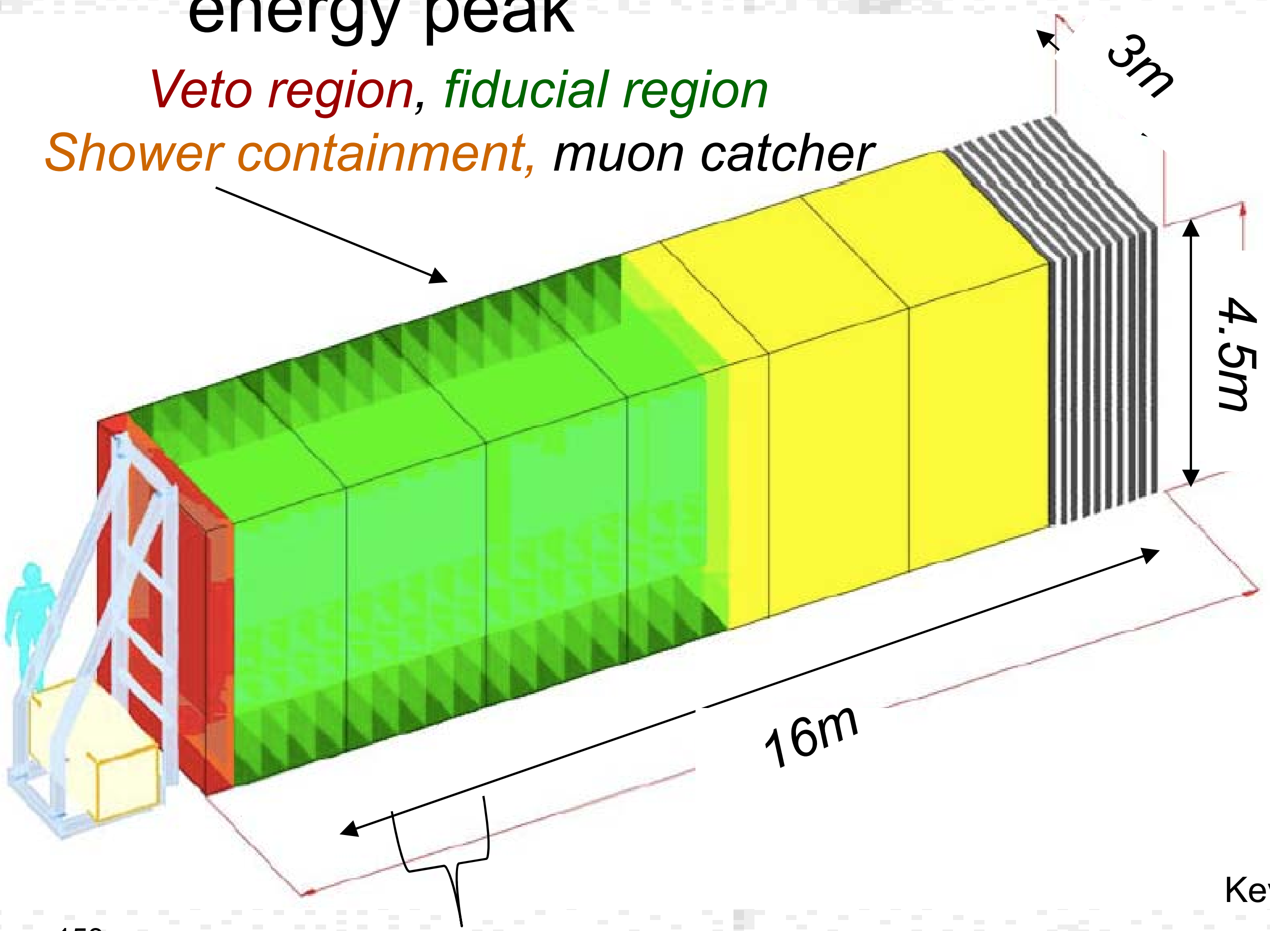
See Dytman talk

slide courtesy of R. Terri

NOvA Near Detector

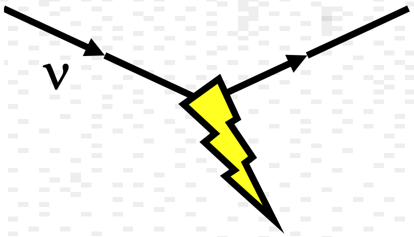


- Scintillator extrusion cross section of 3.87cm x 6cm , but with added muon range stack to see 2 GeV energy peak



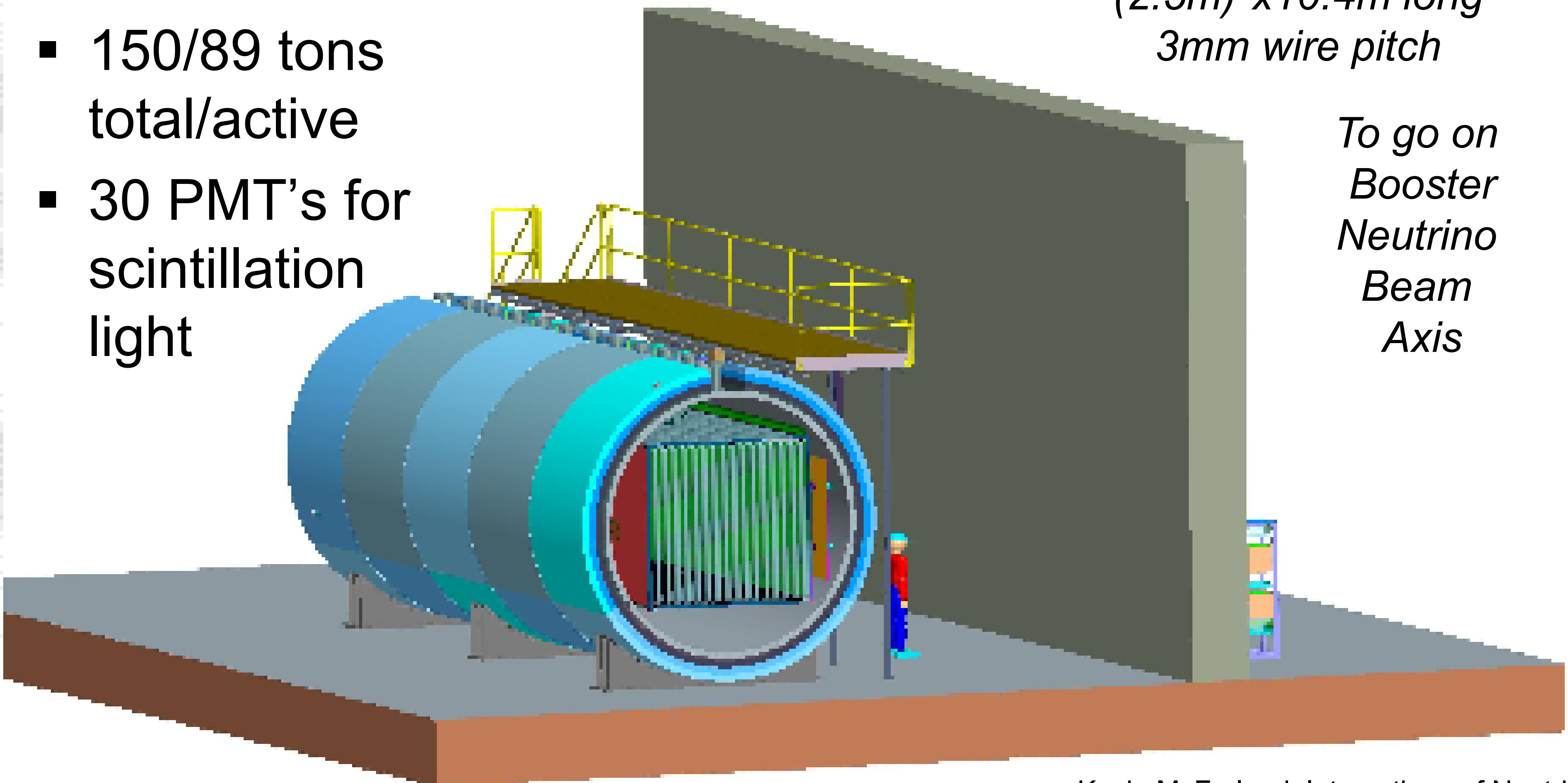
•Range stack: 1.7 meters long, steel interspersed with 10 active planes of liquid scintillator
•First located on the surface, then moved to final underground location

MicroBooNE



- Liquid Argon TPC
  - 150/89 tons total/active
  - 30 PMT's for scintillation light

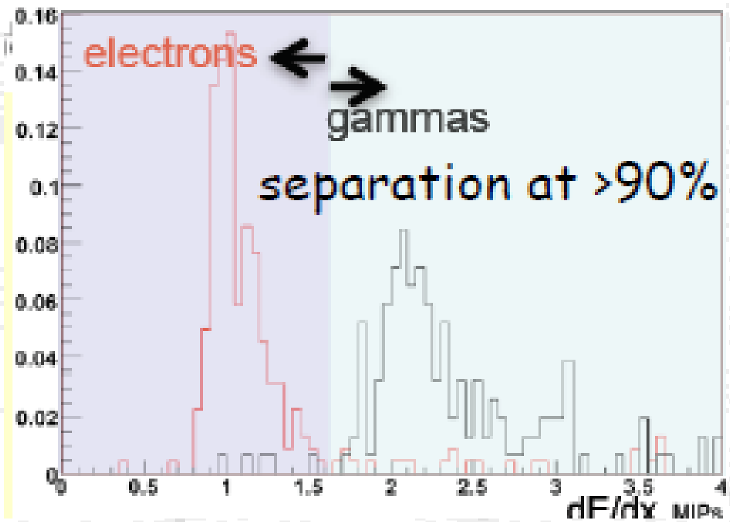
TPC:
$(2.5m)^2$x10.4m long
3mm wire pitch



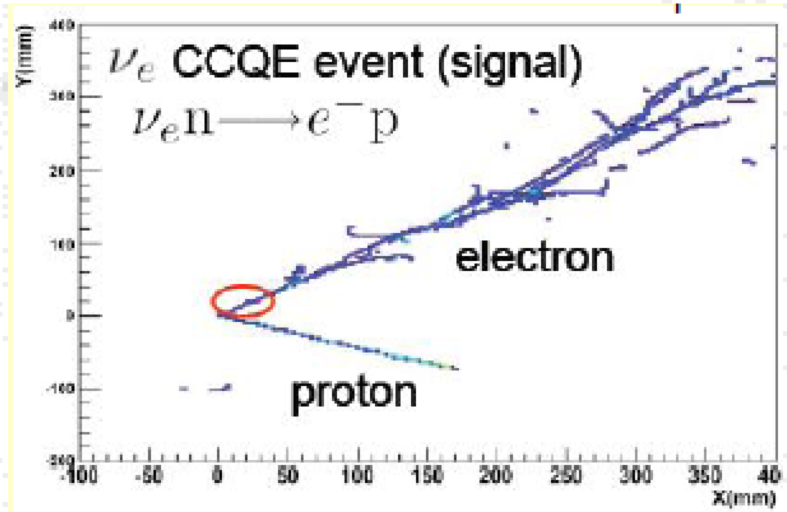
To go on Booster Neutrino Beam Axis

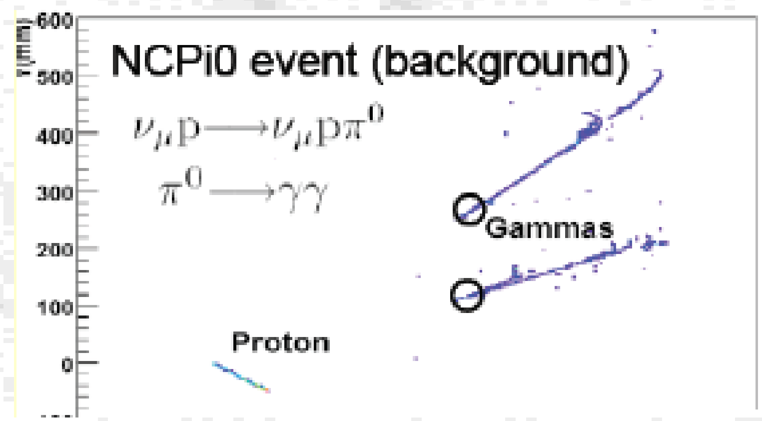
Technologies: Liquid Argon

- Very low threshold, excellent particle ID
  - Even electron/photon separation!



- Reconstruction is not always so straightforward with this level of detail available





Figures from G. Barker

Future Experiments at a Neutrino Factory

- Early on in the consideration of neutrino factories, this possibility was pointed out by a number of groups
  - Concepts for experiments tried to leverage flux in high energy beams
  - Precision weak interaction physics through $\nu e \rightarrow \nu e$
  - Separated flavor structure functions through neutrino and anti-neutrino scattering on H_2 and D_2 targets
- Expect proposals for these experiments, or sensible versions thereof, to match parameters of whatever we eventually build

D. Harris, KSM, AIP Conf.Proc.435:376-383,1998;
AIP Conf.Proc.435:505-510,1998,
R. Ball, D. Harris, KSM, hep-ph/0009223
M. Mangano et al. CERN-TH-2001-131, 2001
I.I. Bigi et al, Phys.Rept.371:151-230,2002.

What's in a Generator?

(some examples)

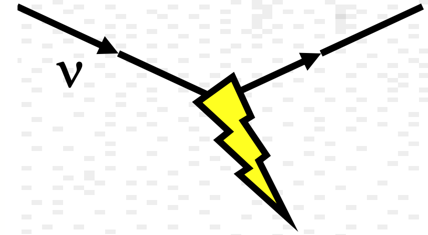
The Essential Tension

- Ulrich Mösel’s brilliant observation at NuINT11:
  - Theorist’s paradigm: “A good generator does not have to fit the data, provided [its model] is right”
  - Experimentalist’s paradigm: “A good generator does not have to be right, provided it fits the data”
- Most of the generators currently used by oscillation experiments (NUANCE, GENIE, NEUT) are written and tuned by experimentalists
- We don’t have models which fit (all) the available data, although many models provide valuable insight into features of this data

Impulse Approximation and Spectral Functions

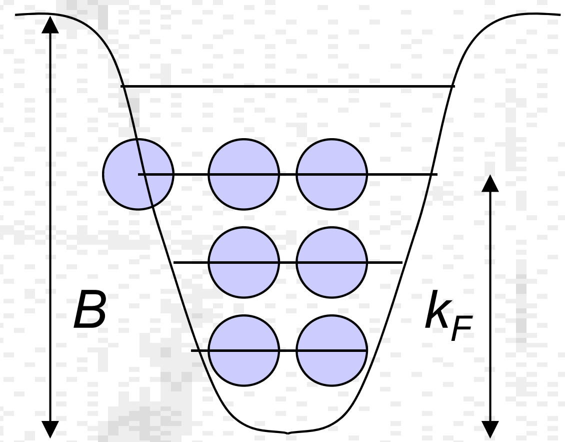
- An interesting illustration of the sort of compromise that exists in generators
- As implied earlier, there are many complications in quasi-elastic scattering from bound nucleons

Nuclear Effects in Elastic Scattering

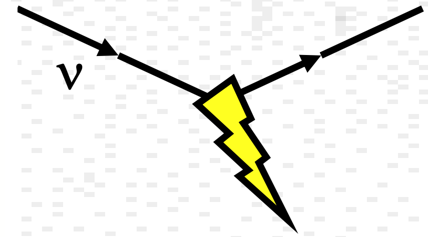


- Several effects:
  - In a nucleus, target nucleon has some initial momentum which modifies the observed scattering
    - o Simple model is a "Fermi Gas" model of nucleons filling available states up to some initial state Fermi momentum, k_F

  - Also, the nucleon is bound in the nucleus, so it take energy to remove it
  - Outgoing nucleon can interact with the target
    - o Usually treated as a simple binding energy
    - o Also, Pauli blocking for nucleons not escaping nucleus… states are already filled with identical nucleon



Impulse Approximation and Spectral Functions



- An illustration of compromises in generators
- As implied earlier, there are many complications in quasi-elastic scattering from bound nucleons
- Most generators use the idea of the previous cartoon literally, the "impulse approximation"
  - Target nucleon is in motion (distribution from a "fermi gas"), and pay a fixed binding energy price to remove it
- A better approach is use of spectral functions

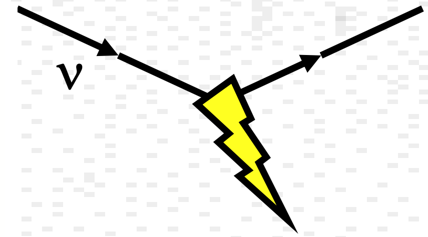
Probability of finding a nucleon with momentum p and removal energy ω →

$$P_h(p,\omega) = \langle A | a^\dagger_{\mathbf{p}} \delta(\hat{H} - E_A - \omega) a_{\mathbf{p}} | A \rangle$$

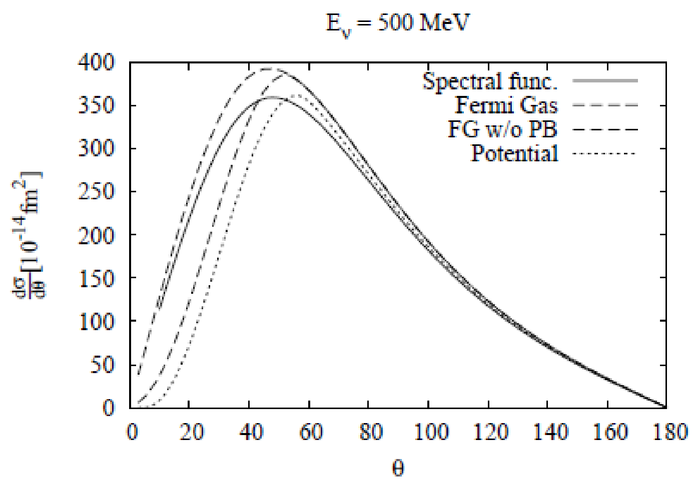
Energy-momentum spectrum of final-state nucleons →

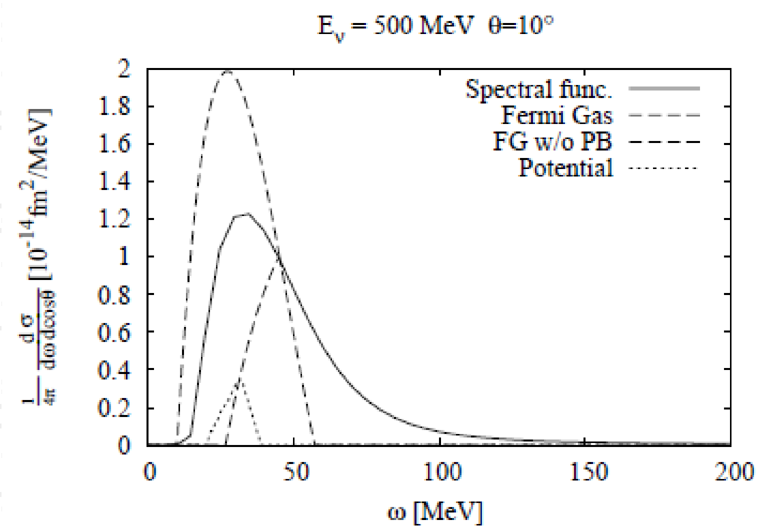
$$P_p(p,\omega) = \langle A | a_{\mathbf{p}} \delta(\hat{H} - E_A - \omega) a^\dagger_{\mathbf{p}} | A \rangle$$

Impulse Approximation and Spectral Functions (cont'd)



- This model difference does produce measurable effects

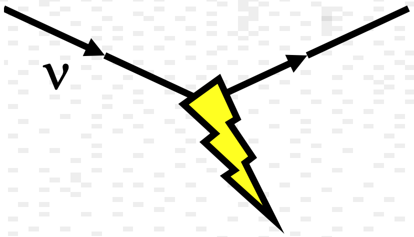




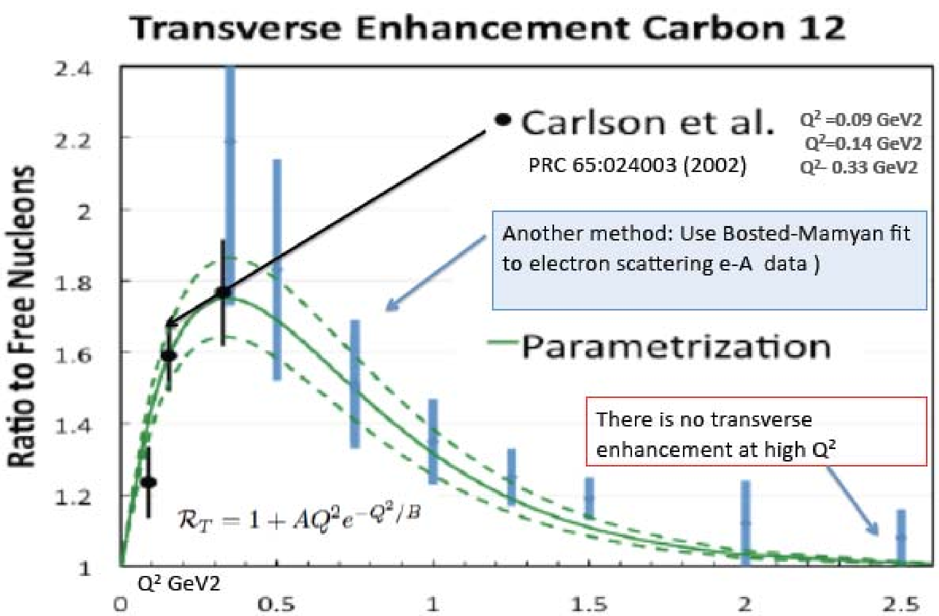
Hiroki Nakamura and Ryoichi Seki, NuINT02

- So why use the impulse approximation, effectively approximating the spectral function with thresholds and delta functions, in generators at all?
- There are not good calculations of spectral functions for all relevant nuclei in detectors!

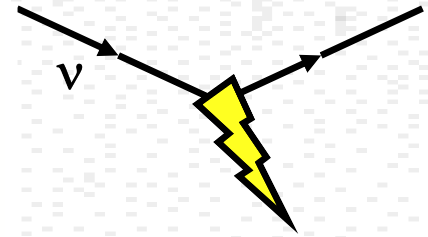
Multi-Nucleon Correlations

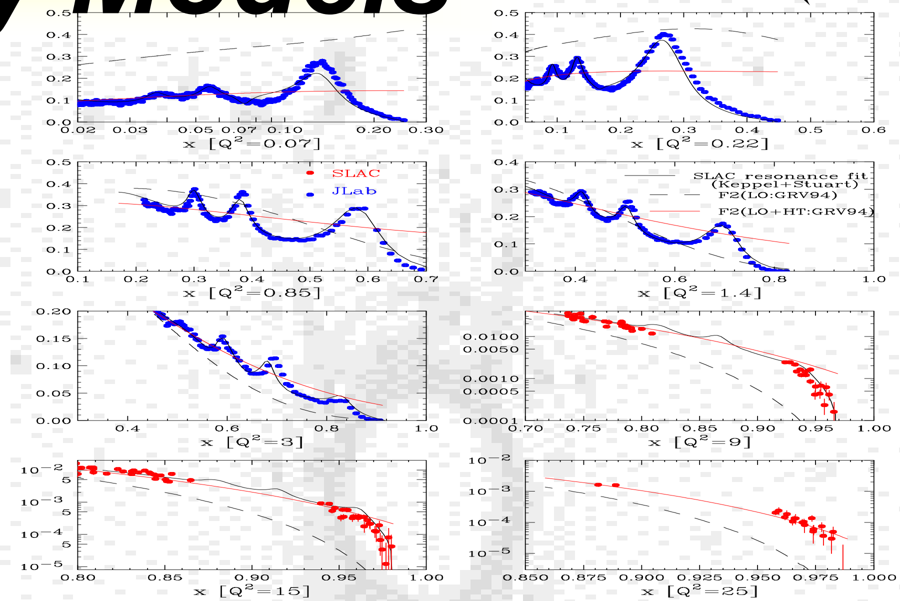


- One "solution" to the high MiniBooNE CCQE cross-section is enhancement of scattering due to correlations among nucleons in nucleus
  - Could alter kinematics and rate in a way that would make a better fit to the data
- How to implement?
  - Microphysical models don't give complete final state description
  - "Ad hoc" enhancement scaled from electron scattering? (Bodek, Budd, Christy)



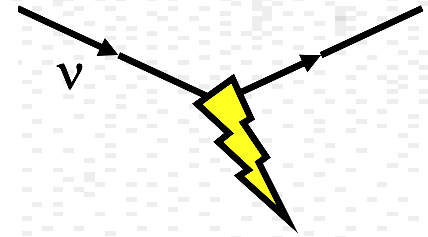
Exclusive Resonance Models and Duality Models



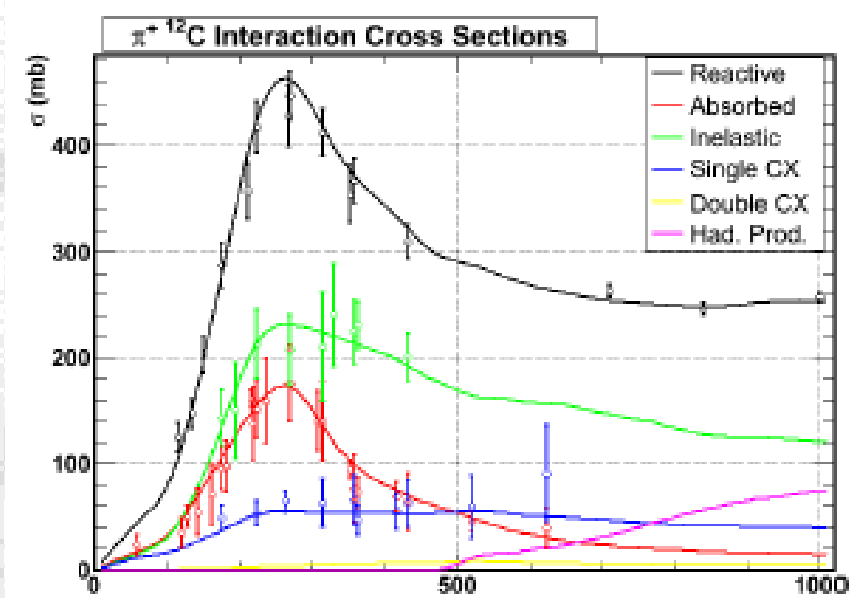


- Duality models, as argued before, fit data by construction
  - However, in a generator context, have to add details of final state
- Typical approach (GENIE, NEUT and NUANCE) is to use a resonance model (Rein & Seghal) below W<2 GeV, and duality + string fragmentation model for W>2 GeV
  - Almost the worst possible solution!
  - Discrete resonance model (probably) disagrees with total cross-section data below W<2 GeV and is difficult to tune
  - Average cross-section at high W does agree with data, but final state simulation is of unknown quality and difficult to tune also.

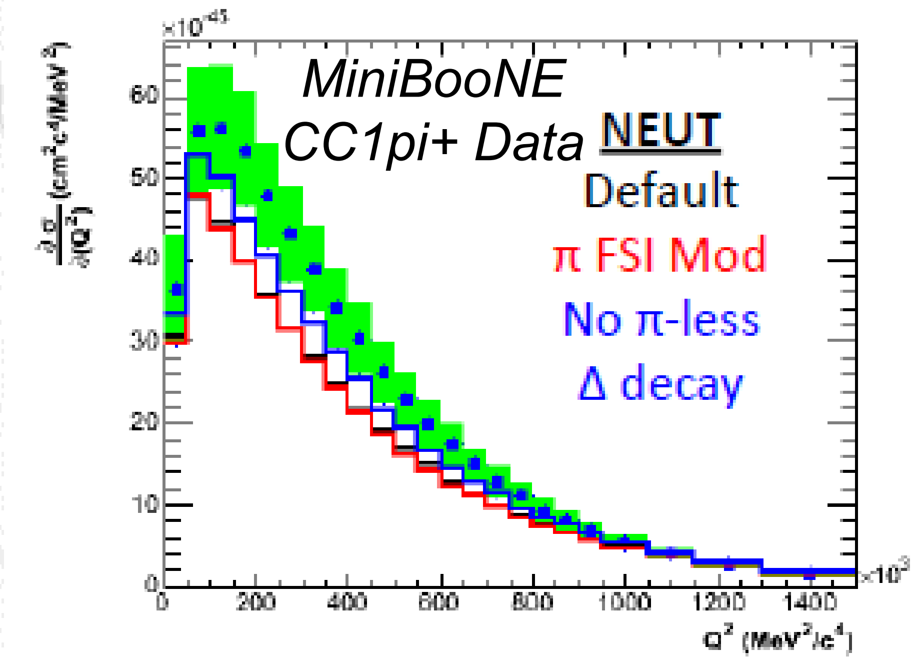
Final State Interactions



- Most generators implement a semi-classical cascade model of transport for FSI. E.g., NEUT:



Pion-C scattering data compared to NEUT's tuned model

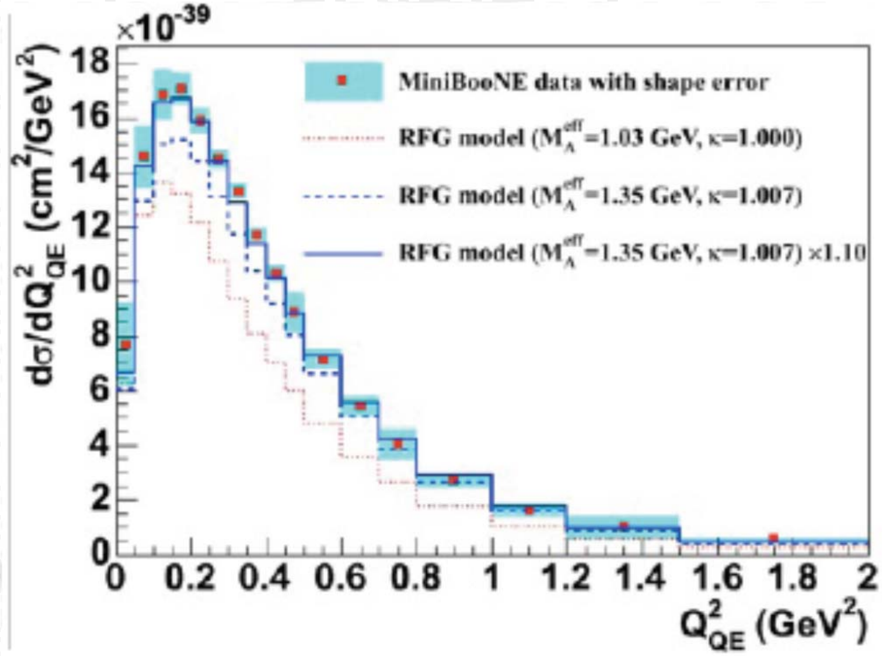


Figures and analysis from P. dePerio, NuINT11

- But attempts to retune still don't reproduce precise data. Is it nucleon-level model? Simplicity of FSI model?

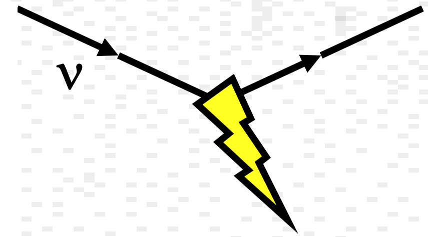
What to do when models and data don't agree?

- Most of these models give absolute predictions. So how to make them agree with data?
- MiniBooNE oscillation analysis approach:
  - Modify the dipole axial mass and Pauli blocking until model fits data.

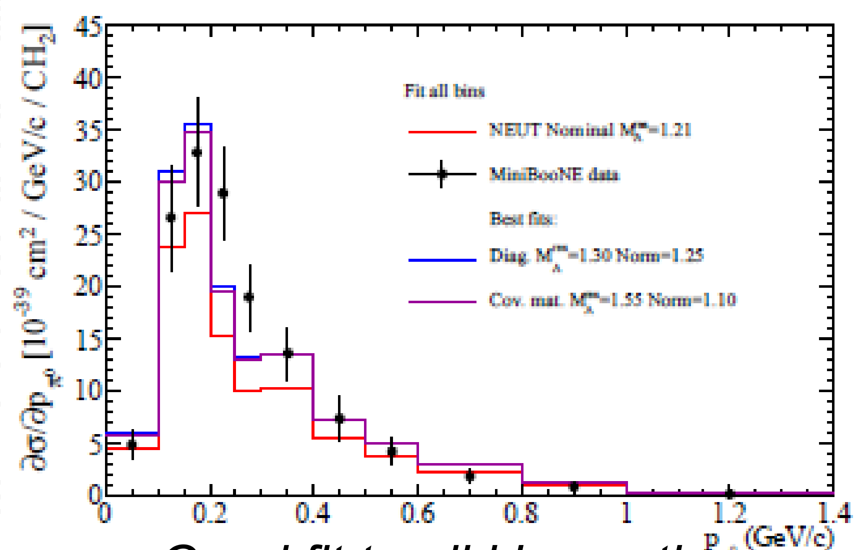


  - But there is nothing fundamental behind this approach. It's a mechanical convenience. Dipole form factor is unlikely to be right, and changes in Pauli blocking are masking deficiencies in models!

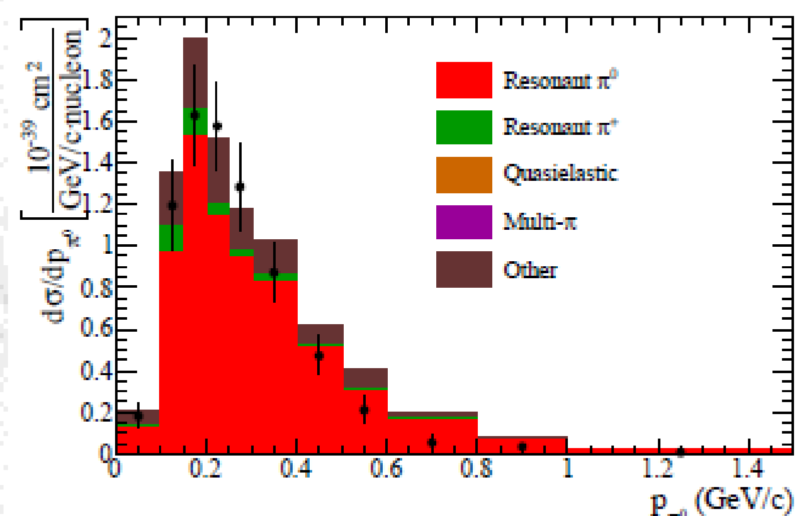
What to do when models and data don't agree? (cont'd)



- Here's another example… (current work by Phil Rodrigues, a Rochester postdoctoral researcher on T2K; definitely still "in progress")
- Want to tune multiple data sets that should have similar physics, e.g., $CC1\pi^0$ and $NC1\pi^0$, using similar methods
  - E.g., should be able to modify parameter X or Y and fit both



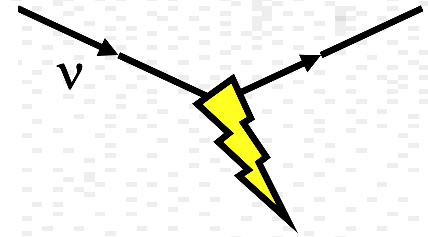
Good fit to all kinematic distributions for CC by increasing dipole mass and normalization



But the same tune in the NC makes a large enhancement, not seen in data, at high pion momentum!

Conclusions

What Should I Remember from These Lectures?



- Understanding neutrino interactions is necessary for precision measurements of neutrino oscillations
- Point like scattering: weak interactions couple differently to each chirality of fermions, neutrino scattering rate proportional to energy (until real boson exchange)
- Target (proton, nucleus) structure is a significant complication to theoretical prediction of cross-section
  - Particularly problematic near inelastic thresholds
- Our best models are incomplete, and even those best models often aren't the ones in generators
- Resolving differences between data and models is a major conceptual challenge