Prospects of INO with Neutrino Beams

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!!! Thanks to all of you !!!

PLAN

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- Present Status & Missing Links
- Game Plan : ν Roadmap

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- "Golden Channel", $P_{e\mu}$
- "Eight-fold" degeneracy
- "Magic Baseline"

INO INO INO

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- India-Based Neutrino Observatory (INO)
- β-beam and ν-factory

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- Results
- Conclusions

Then and Now

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I have hit upon a desperate remedy to save the exchange theorem and the conservation of energy. Namely, the possibility that there could exist electrically neutral spin $\frac{1}{2}$ particles of small mass . . . .

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Now (2004): APS Neutrino Study Group

Much of what we know about neutrinos we have learned in the last six years. .... We have so many new questions, ... We are most certain of one thing : neutrinos will continue to surprise us ....

Past and Present

Neutrino physice, a bit player on the physics stage in yesteryears, has now donned a central role

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$\downarrow$

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Next generation experiments : planned/proposed world-wide to further pin down the values of the oscillation parameters

Present Status

Parameter	Best fit	3σ (1 d.o.f)
Δm^2_{21} $[10^{-5}\ eV^2]$	**7.6**	**7.1–8.3**
$\|\Delta m^2_{31}\|$ $[10^{-3}\ eV^2]$	**2.4**	**2.0–2.8**
$\sin^2\theta_{12}$	**0.32**	**0.26–0.40**
$\sin^2\theta_{23}$	**0.50**	**0.34–0.67**
$\sin^2\theta_{13}$	**0.007**	$\leq$ **0.050**

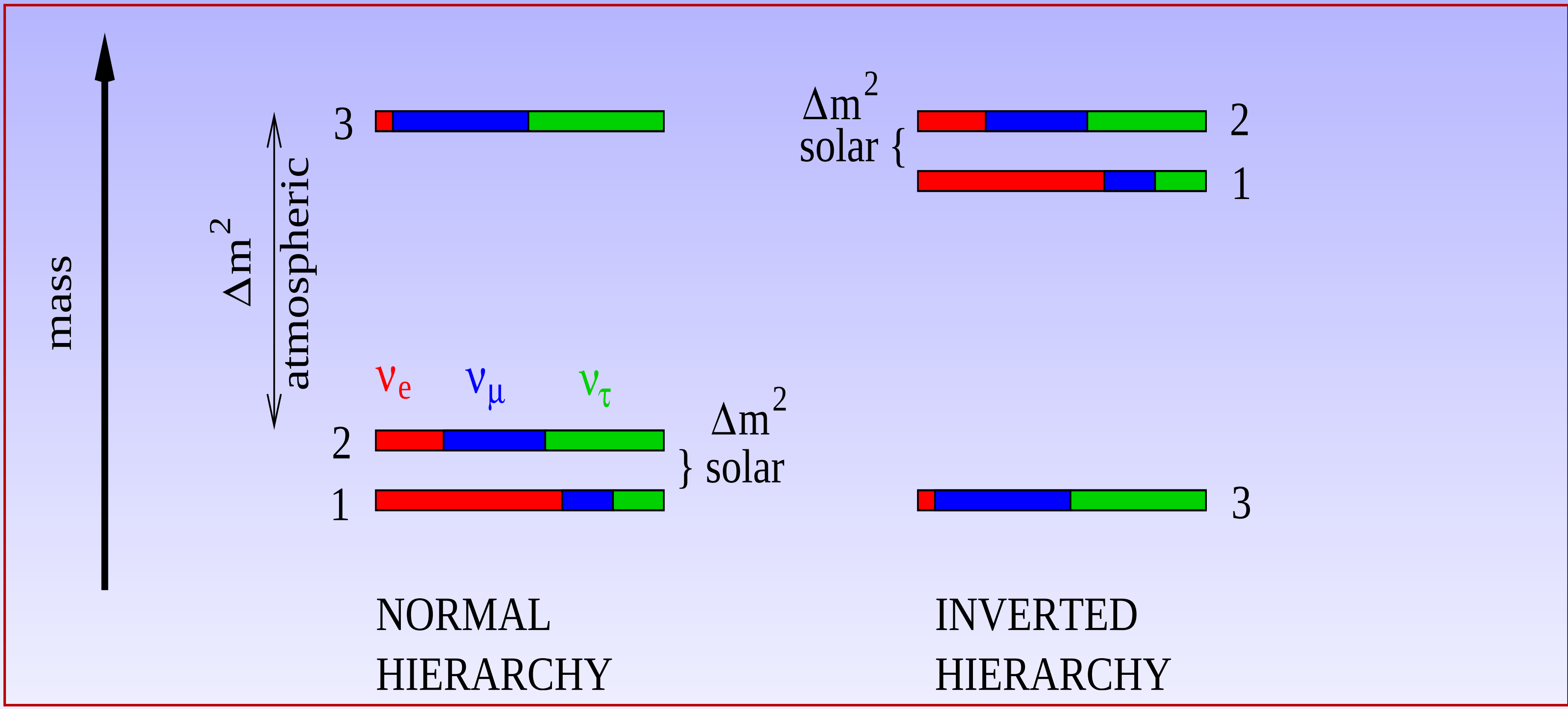
M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, hep-ph/0405172v6

Best-fit values under 3 flavour scheme

Data from Solar + Atmospheric + Reactor (KamLAND and CHOOZ) + Accelerator (K2K and MINOS) expts

Unsolved Issues

- **The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known.** **Neutrino mass spectrum can be normal or inverted hierarchical**



Unsolved Issues (Continued..)

Only an upper limit on

$\sin^2 2\theta_{13}$ (< 0.17 **at** 3σ) **exists**

Unsolved Issues (Continued..)

The Dirac CP phase (δ_{CP})

is unconstrained

We will focus on the first two issues. . .

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1st Step : Transition Era ⇒ Ongoing : 2005-2010 (phase-0)

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Aim

- **Improve the precision on the atmospheric parameters looking at ν_μ disappearance**
- **Study $\nu_\mu \to \nu_\tau$ to ascertain atm. osc and first see $\nu_\mu \to \nu_e$**

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Candidates (Conventional Beam Expts)

- K2K (terminated)
- MINOS, OPERA (running)
- ICARUS (starting soon)

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2nd Step : 1-3 mixing Era ⇒ Approved/Proposed : 2008-2015 (phase-1)

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- **Substantiate visibility of θ_{13} driven transitions :** $\nu_\mu \rightarrow \nu_e, \quad \bar{\nu}_e \rightarrow \bar{\nu}_e$
- **Penetrate $\sin^2 2\theta_{13}$ down to 0.01 (today < 0.17)**

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Candidates (Superbeam & Reactor Expts)

- **T2K [Superbeam] (Approved : Starting in 2009)**
- **Noνa [Superbeam] (Proposed : Expected in 2012)**
- **Double Chooz, Daya Bay, Reno, Angra, KASKA, ... [Reactor]**

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3rd Step : Precision Era ⇒ To be prepared : 2015-2025 (phase-2)

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$\sin^2 2\theta_{13} > 0.01$ $\longleftarrow$ **Known by 2012** $\longrightarrow$ $\sin^2 2\theta_{13} < 0.01$

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We can probe it by existing facilities

...Keep in mind...

Very small sensitivity to δ_{CP} and neutrino mass ordering

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...Keep in mind...

Very small sensitivity to δ_{CP} and neutrino mass ordering

$\sin^2 2\theta_{13} < 0.01$

Beyond the reach of on-going expts at that time

Pure and more intense beams with precisely known spectrum

Larger detectors with good energy resolution, granularity, ...

Game Plan : ν Roadmap

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Beta Beam

OR

Neutrino Factory

Do not forget SPL, T2HK, WBB, ...

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Excellent sensitivity to δ_{CP} and $Sgn(\Delta m^2_{31})$

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They can penetrate $\sin^2 2\theta_{13}$ down to 0.0001

Excellent sensitivity to δ_{CP} and $Sgn(\Delta m^2_{31})$

But journey from 0.01 to 0.0001

!!! Very Tough Ask !!!

Golden Channel ($P_{e\mu}$)

The appearance probability $(\nu_e \to \nu_\mu)$ **in matter, upto second order in the small parameters** $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin 2\theta_{13}$**,**

$$
\begin{aligned}
P_{e\mu} \quad \simeq \quad & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
+ \quad & \alpha \sin 2\theta_{13}\, \xi \, \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \quad & \alpha \sin 2\theta_{13}\, \xi \, \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \quad & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

Cervera *et al.*, hep-ph/0002108

Freund, Huber, Lindner, hep-ph/0105071

Eight-fold Degeneracy

- $(\theta_{13},\ \delta_{CP})$ intrinsic degeneracy

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}),\ \delta_{CP})$ degeneracy

  Minakata, Nunokawa, hep-ph/0108085

- $(\theta_{23}, \pi/2 - \theta_{23})$ degeneracy

  Fogli, Lisi, hep-ph/9604415

Severely deteriorates the sensitivity

Problem & Solution

Degeneracies create "Clone" Solutions

Barger, Marfatia, Whisnant, hep-ph/0112119

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$P_{\mu e} \quad \Rightarrow \quad$ **SuperBeam**

$P_{e\mu} \quad \Rightarrow \quad$ **Beta Beam**

$P_{e\mu} \quad \Rightarrow \quad$ **Neutrino Factory**

Need smart ideas to play with these channels

Solutions

- Combine data from appearance expts at different L and/or different E

Barger, Marfatia, Whisnant, hep-ph/0206038

Barger, Marfatia, Whisnant, hep-ph/0210428

Burguet-Castell et al, hep-ph/0103258

Huber, Lindner, Winter, hep-ph/0211300

Mena and Parke, hep-ph/0408070

and there are others also ...

Solutions

Add data from different channels

- **The Silver Channel, $P_{e\tau}$**

  Autiero et al, hep-ph/0305185

  Donini, Meloni, Migliozzi, hep-ph/0206034

- **The Disappearance Channel, $P_{\mu\mu}$**

  Donini, Fernandez-Martinez, Meloni, Rigolin, hep-ph/0512038

  Donini, Fernandez-Martinez, Rigolin, hep-ph/0411402

- **Adding reactor antineutrino data**

  Huber, Lindner, Schwetz, Winter, hep-ph/0303232

Solutions

- Adding atmospheric neutrino data

Huber, Maltoni, Schwetz, hep-ph/0501037

Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

@@@@ One of the most elegant ideas @@@@

Kill the “Clones” at the “Magic” Baseline

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

Magic Baseline

Magic Baseline

If one chooses : $\sin(\hat{A}\Delta) = 0$

- **The** δ_{CP} **dependence disappears from** $P_{e\mu}$
- **Golden channel enables a clean determination of** θ_{13} **and** $sgn(\Delta m^2_{31})$

Magic Baseline

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First non-trivial solution: $\sqrt{2}G_F n_e L = 2\pi$ **(indep of E)**

- **Isoscalar medium of constant density** ρ **:** $L_{\rm magic}[{\rm km}] \approx 32725/\rho[{\rm gm/cm}^3]$
- **According to PREM, the "Magic Baseline"**

$$L_{\rm magic} = \mathbf{7600\ km}$$

Resonance in matter effect

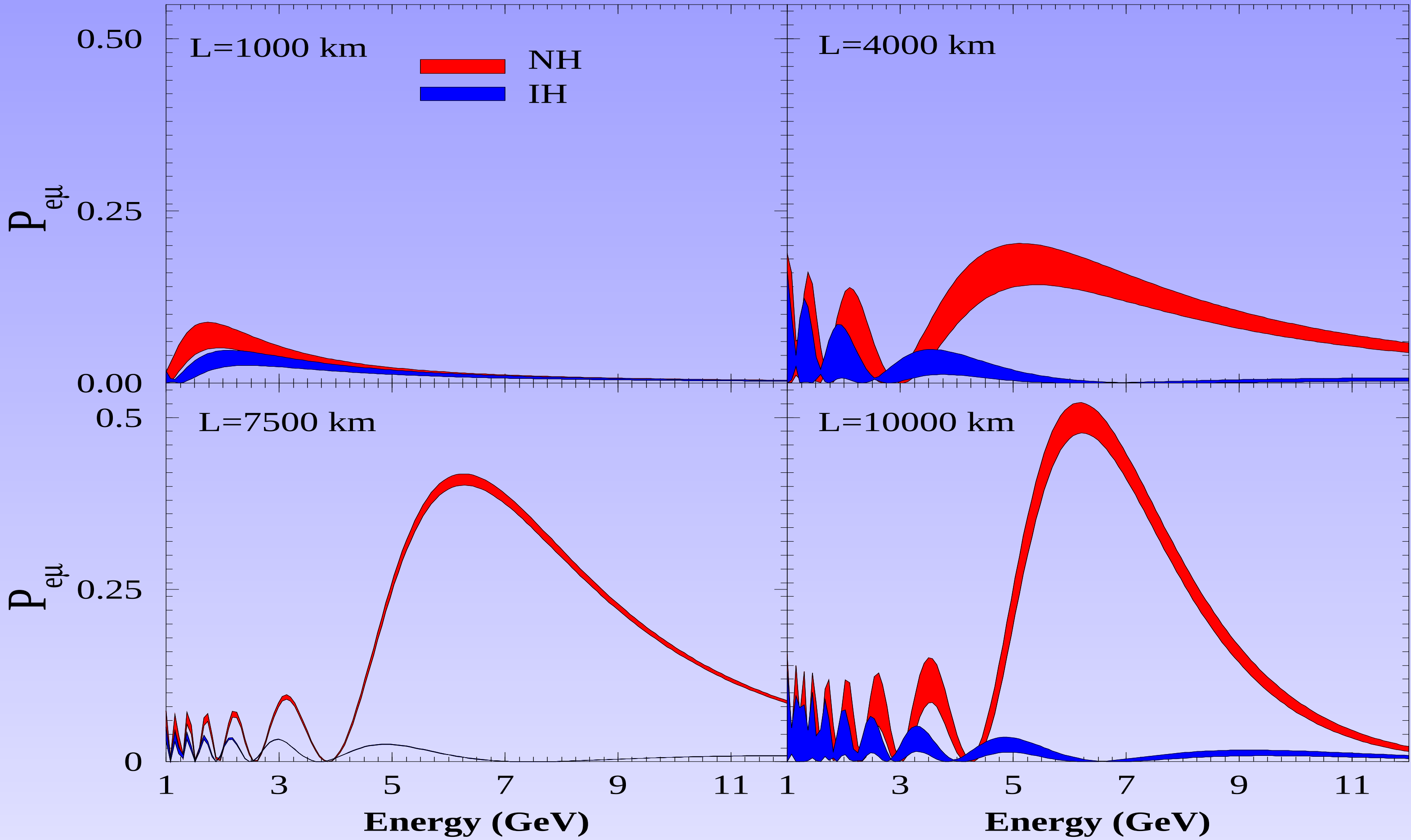
- **The very long CERN - INO baseline provides an excellent avenue to pin-down matter induced contributions**
- **In particular, a resonance occurs at**

$$E_{res} \equiv \frac{|\Delta m^2_{31}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

$$= \mathbf{7.45\ GeV}$$

with $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ **eV**^{2}, $\sin^2 2\theta_{13} = 0.1$ **and** $\rho_{av} = 4.17$ **gm/cc (PREM) for the baseline of 7152 km**

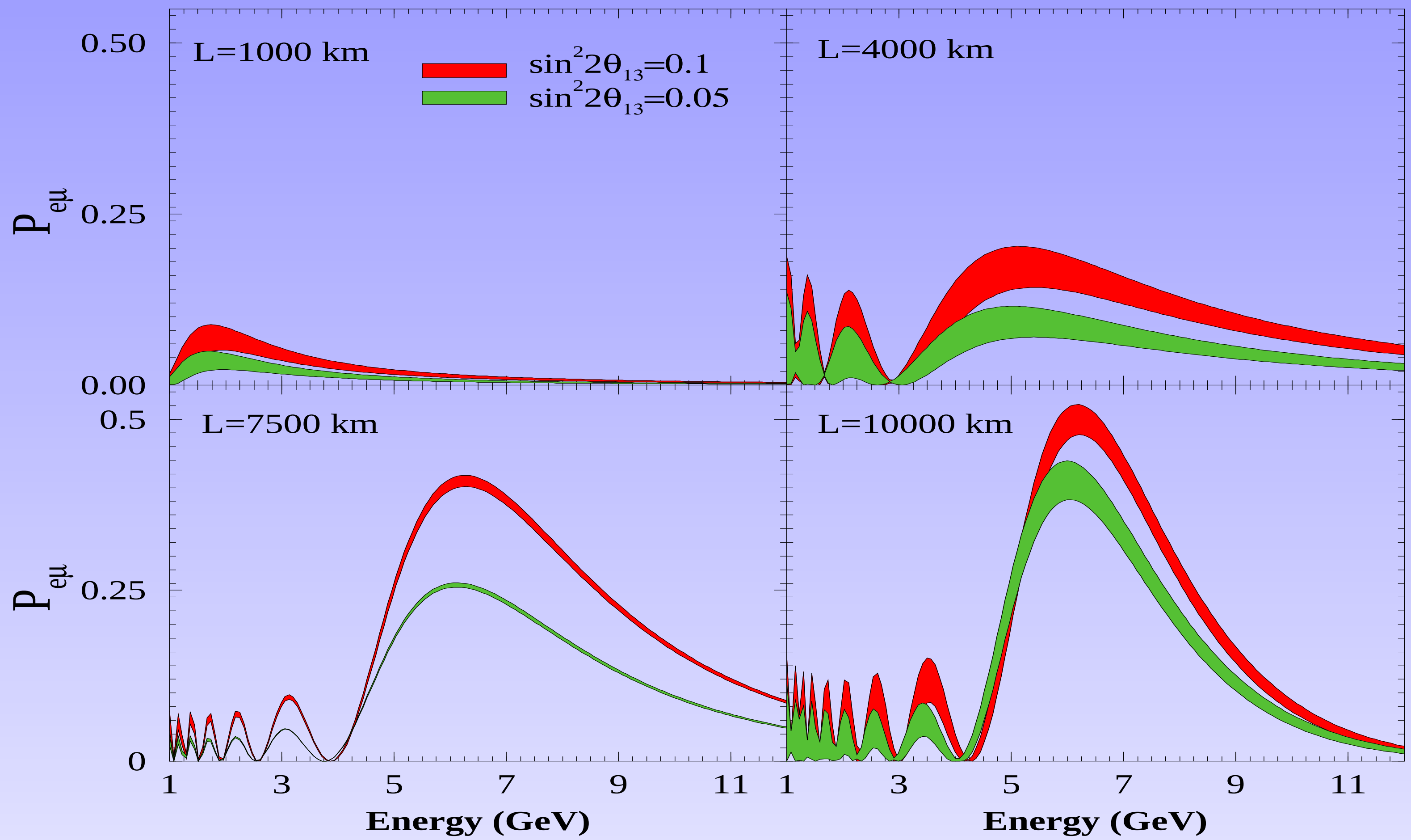
Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted hierarchy $\sin^2 2\theta_{13} = 0.1$

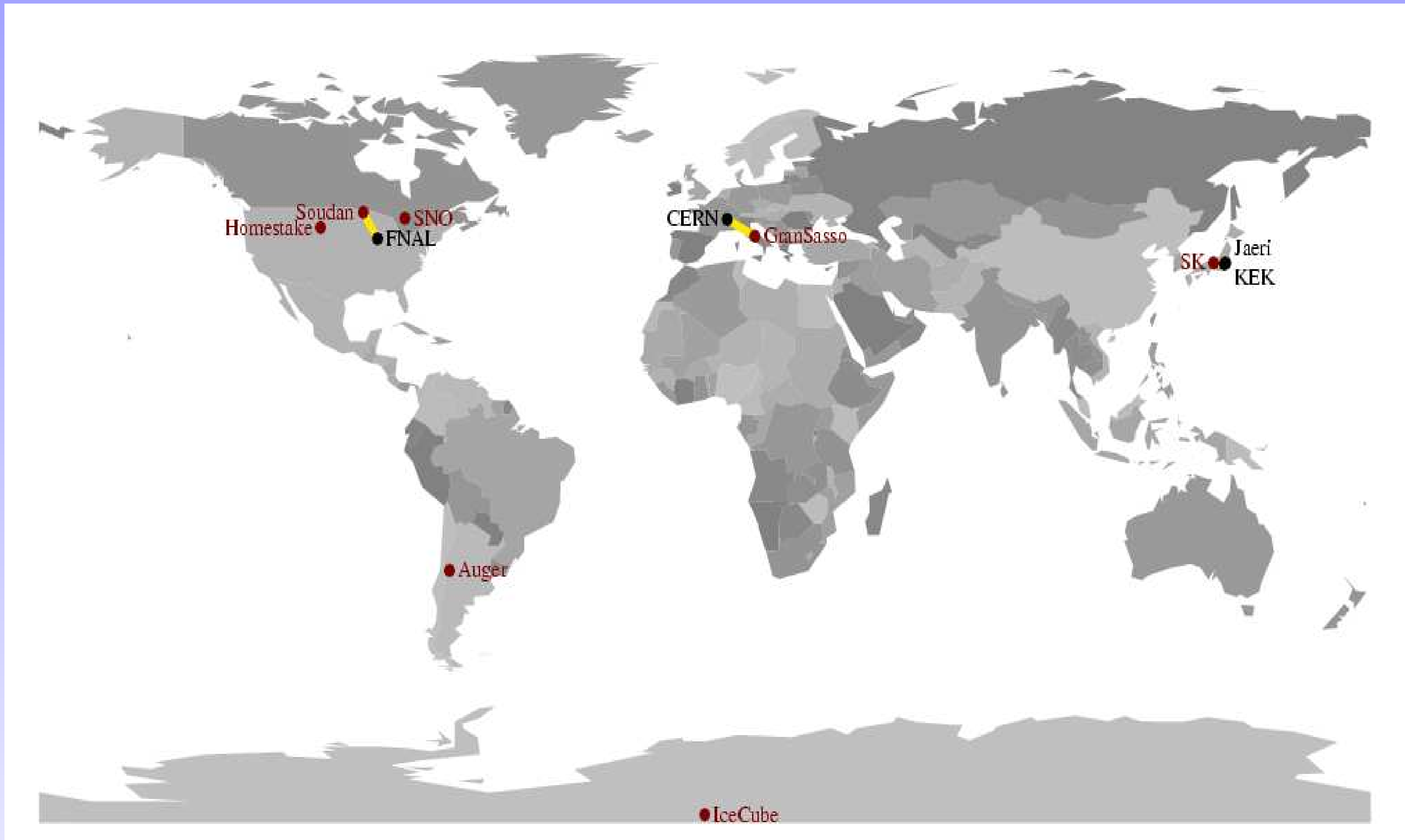
Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Two different values of $\sin^2 2\theta_{13}$ **Normal hierarchy**

Neutrino Observatories



Location of main neutrino-related observatories

The India-based Neutrino Observatory

The INO/ICAL will be the world's first magnetized large mass iron calorimeter with interleaved Glass RPC detectors

Funding considerations in final stage

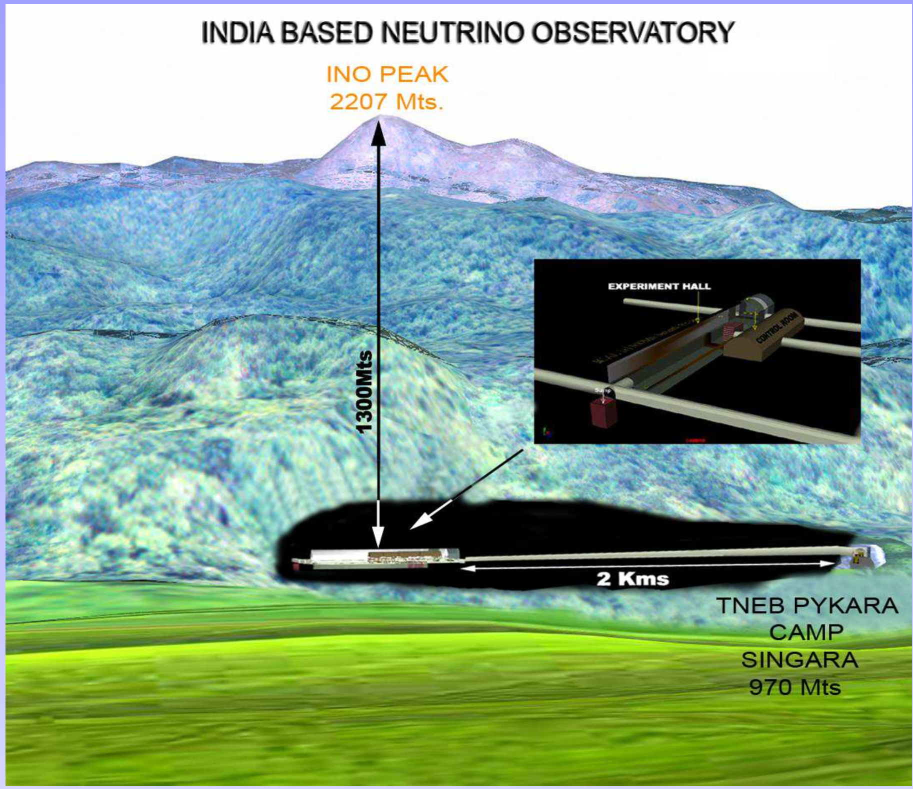
Location of INO

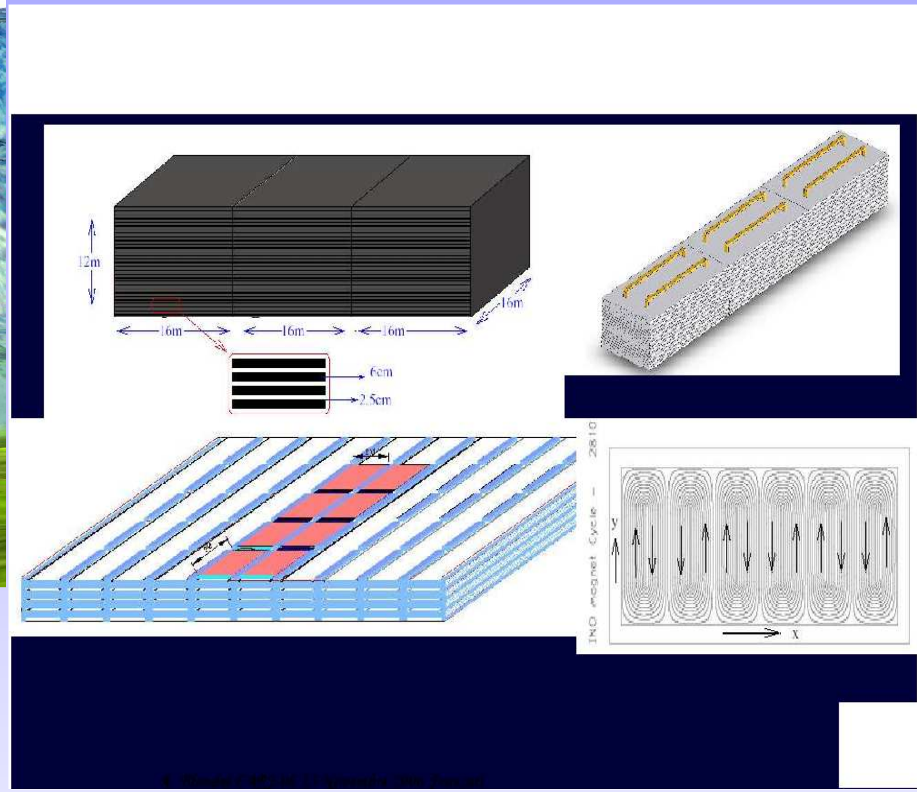
PUSHEP Site (Lat: N11.5°, Long: E76.6°)

PUSHEP-Bangalore: 250km

http://www.imsc.res.in/∼ino/

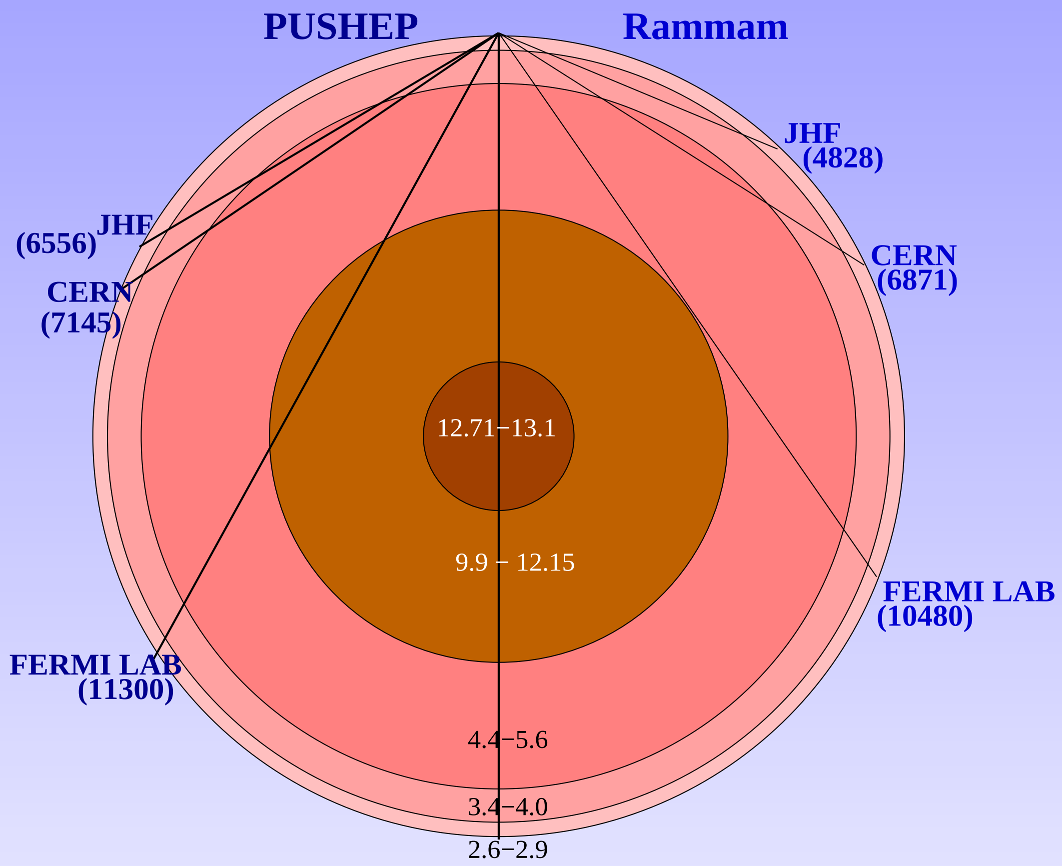
ICAL Design





Spokesperson: Prof. N.K. Mondal, TIFR

INO : 2nd Phase



Artificial Source

Beta Beam ?

Neutrino Factory ?

$L_{\rm magic}$ = **7600 km**

INO

- A magnetized Iron calorimeter (ICAL) detector with excellent efficiency of charge identification ($\sim$ 95%) and good energy determination
- Preferred location is Singara (PUSHEP) in the Nilgiris (near Bangalore), 7152 km from CERN
- A (50+50) Kton Iron detector
- Oscillation signal is the muon track ($\nu_e \rightarrow \nu_\mu$ channel)

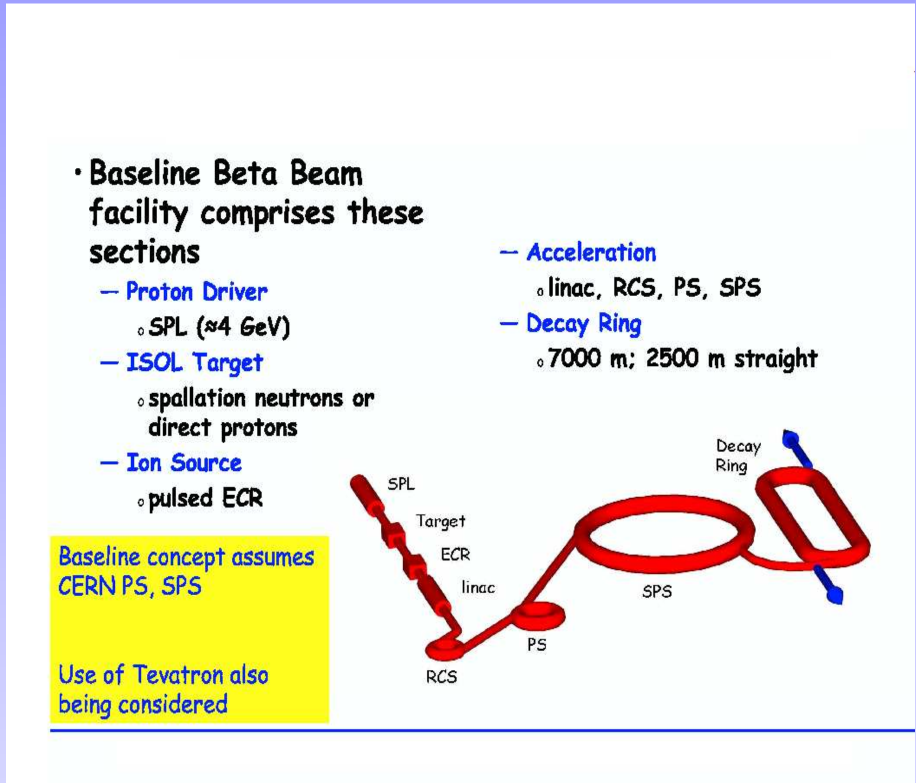
Detector assumptions

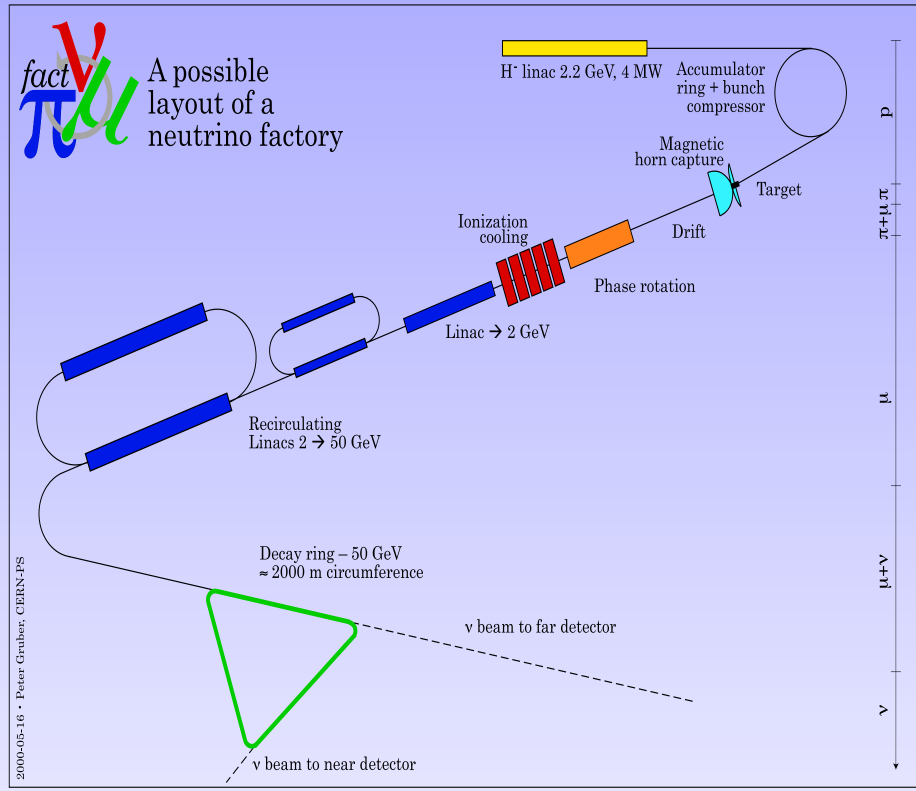
Total Mass	50 kton
Energy threshold	1 GeV
Detection Efficiency (ϵ)	80%
Charge Identification Efficiency (f_{ID})	95%

Detector characteristics used in the simulations

All studies assume a Gaussian energy resolution function with $\sigma = 0.15E$

β-beam vs. ν-factory





Schematic Lay-out

β-beam vs. ν-factory

ν-factory: proton $\xrightarrow{\text{target}}$ $\pi^+ + \ldots$

↳ $\mu^+ + \nu_\mu$ (super-beam)

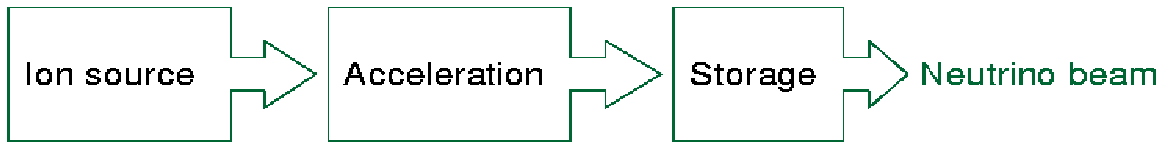
↳ $e^+ + \nu_\mu + \bar{\nu}_e$

and charge conjugated

beta-beam: proton $\xrightarrow{\text{target}}$ isotope

↳ isotope* + $e^+ + \nu_e$

ν-factory uses beam of 4th generation.
Beta-beam uses 3rd generation beam.
Beta-beam is technically closer to existing/used accelerator technology.



Ultimate choice depends on future R&D

β-beam vs. ν-factory

β-beam

Origin

$^8_5B \rightarrow ^8_4Be + e^+ + \nu_e$

$^8_3Li \rightarrow ^8_4Be + e^- + \bar{\nu}_e$

CID (Mag Field)

Not Mandatory

Lumi (useful decays)

1.1×10^{18}/yr (ν)

2.9×10^{18}/yr ($\bar{\nu}$)

Parameters

Boost, γ (50 to 650)

Baseline, L

ν-factory

Origin

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

CID (Mag Field)

Mandatory (ICAL)

Lumi (useful decays)

1.2×10^{20}/yr (1 MW)

4.8×10^{20}/yr (4 MW)

Parameters

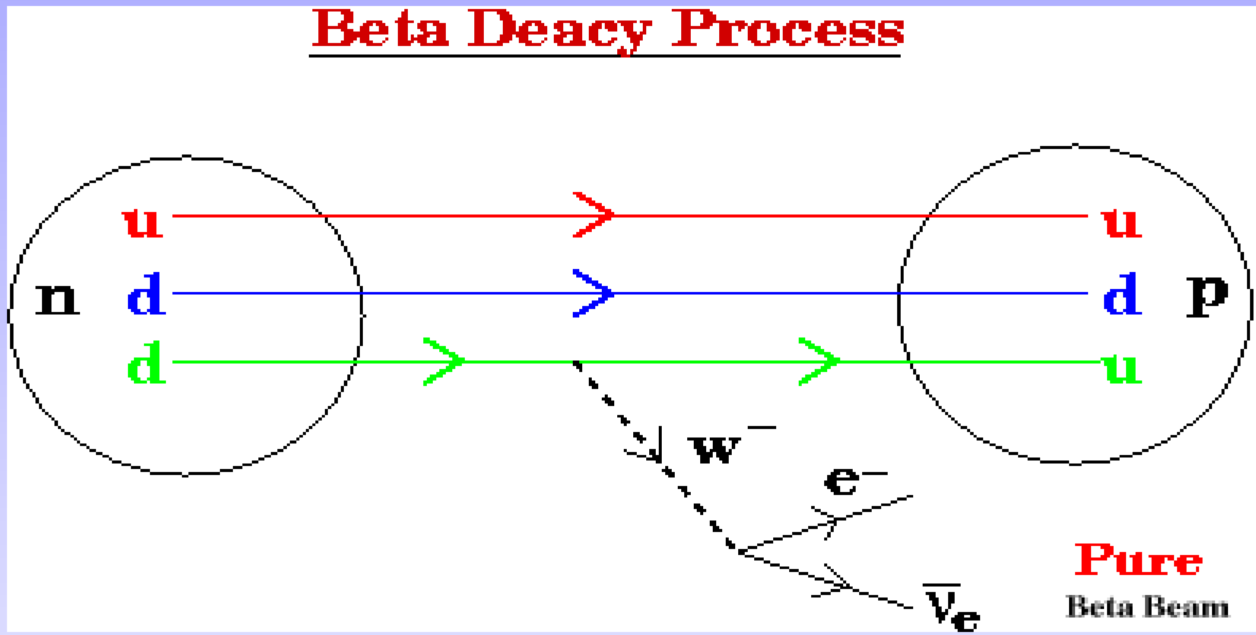
E_μ (20 to 50 GeV)

Baseline, L

! They will draw the punch line in this business !

What is Beta Beam?

A pure, intense, collimated beam of ν_e or $\bar{\nu}_e$, essentially background free



P. Zucchelli, Phys. Lett. B 532 (2002) 166

Beta decay of completely ionized, radioactive ions circulating in a storage ring. No contamination of other types of neutrinos

Beta Beam : Ion sources

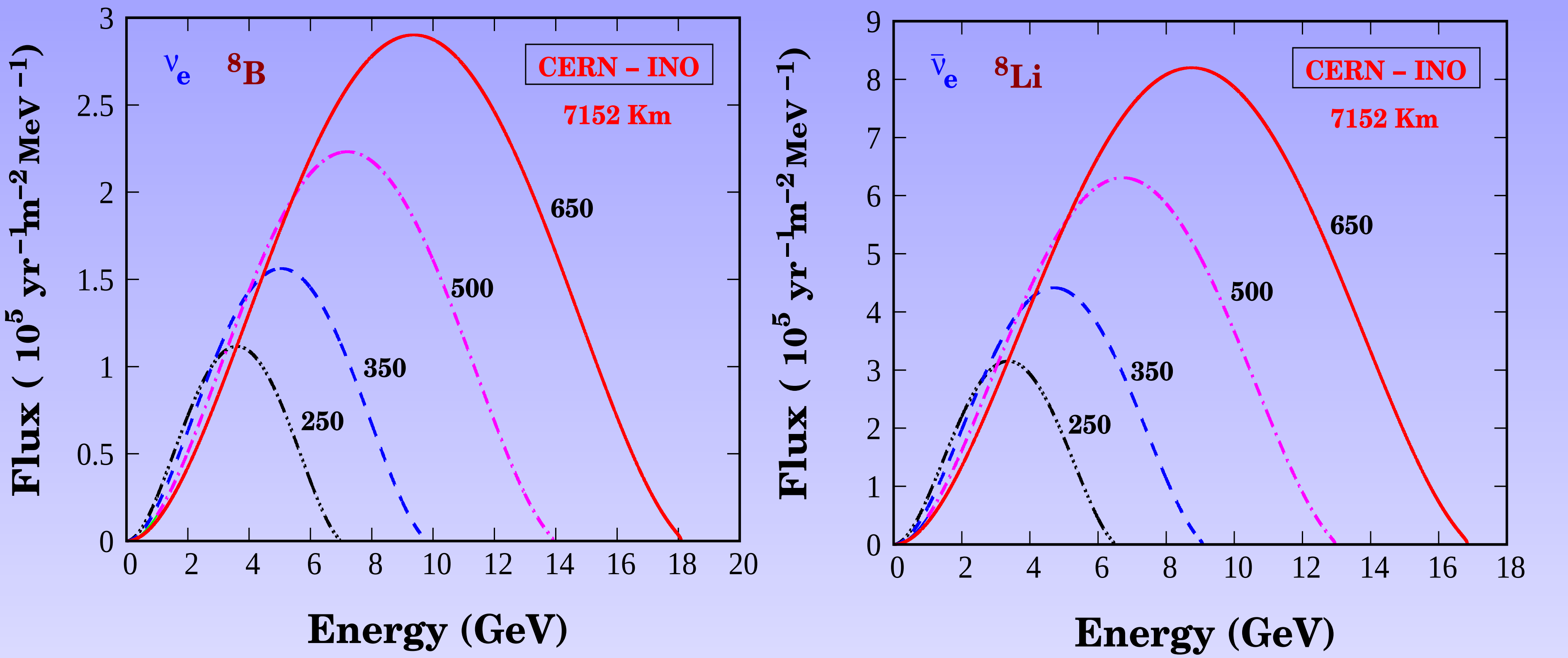
Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
$^{18}_{10}$Ne	2.41	3.92	820.37	92.1%	ν_e
$^{6}_{2}$He	1.17	4.02	934.53	100%	$\bar{\nu}_e$
$^{8}_{5}$B	1.11	14.43	600684.26	100%	ν_e
$^{8}_{3}$Li	1.20	13.47	425355.16	100%	$\bar{\nu}_e$

Comparison of different source ions

Low-γ design, useful decays in case of anti-neutrinos can be 2.9×10^{18}/year and for neutrinos 1.1×10^{18}/year

Larger total end-point energy, E_0 is preferred

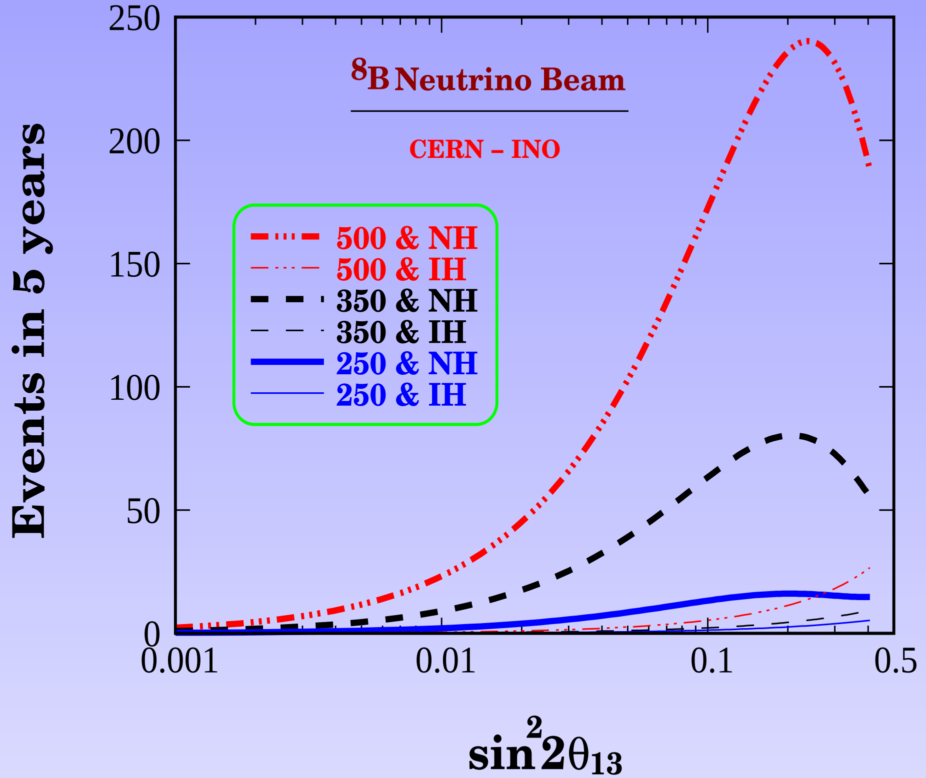
β-beam flux at INO-ICAL

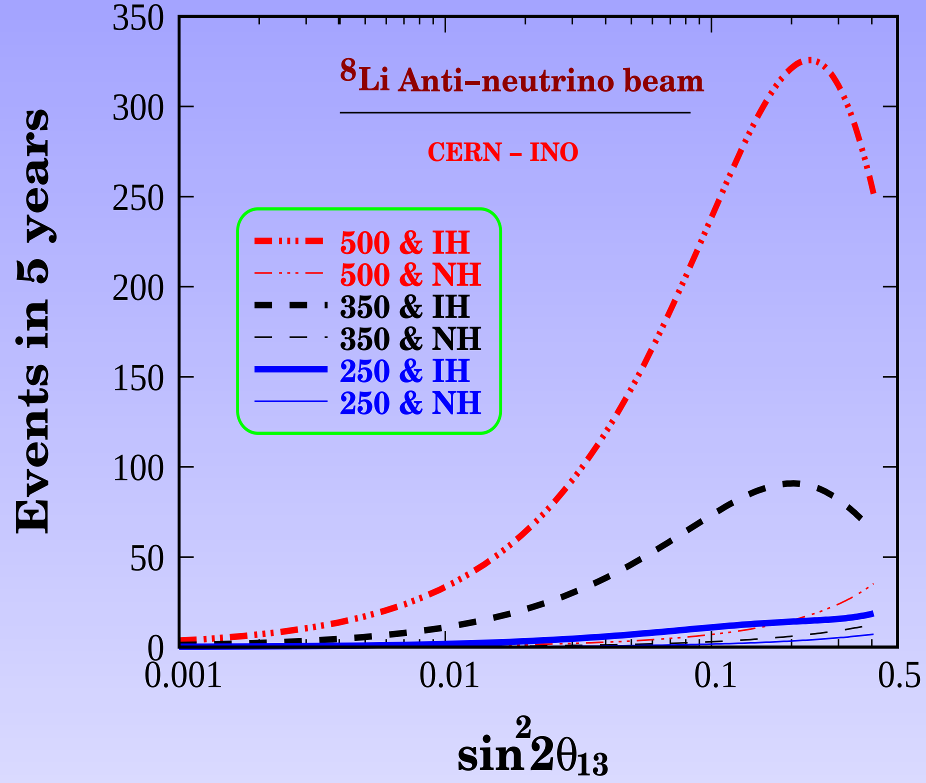


Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Boosted on-axis spectrum of ν_e and $\bar{\nu}_e$ at the INO-ICAL assuming no oscillation

Event Rates in INO-ICAL

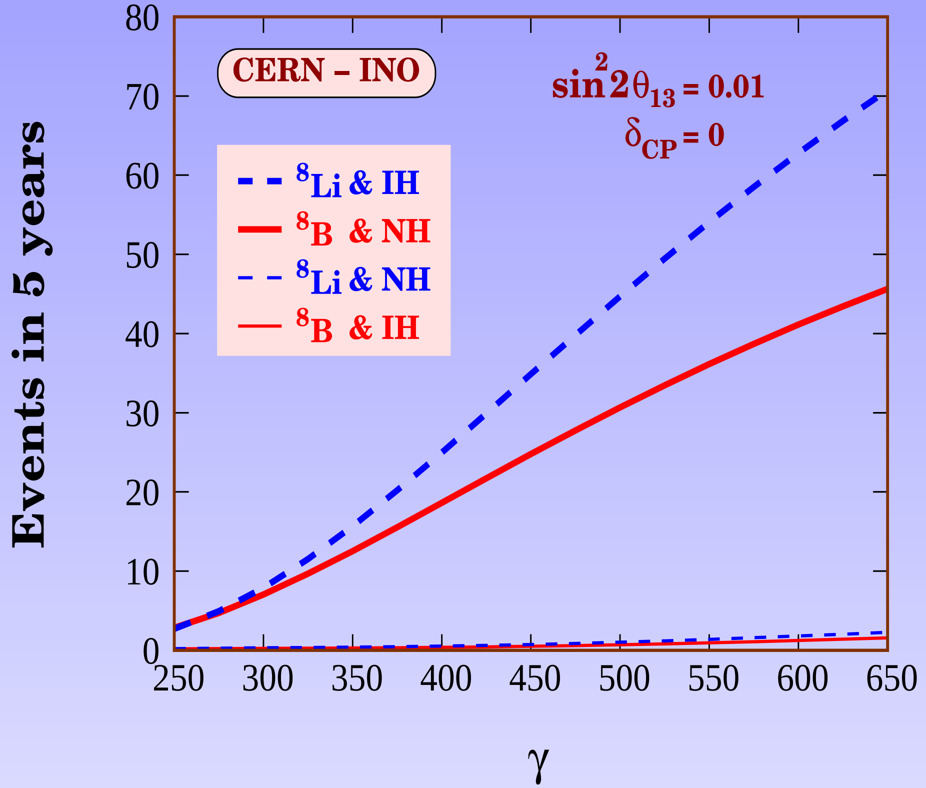


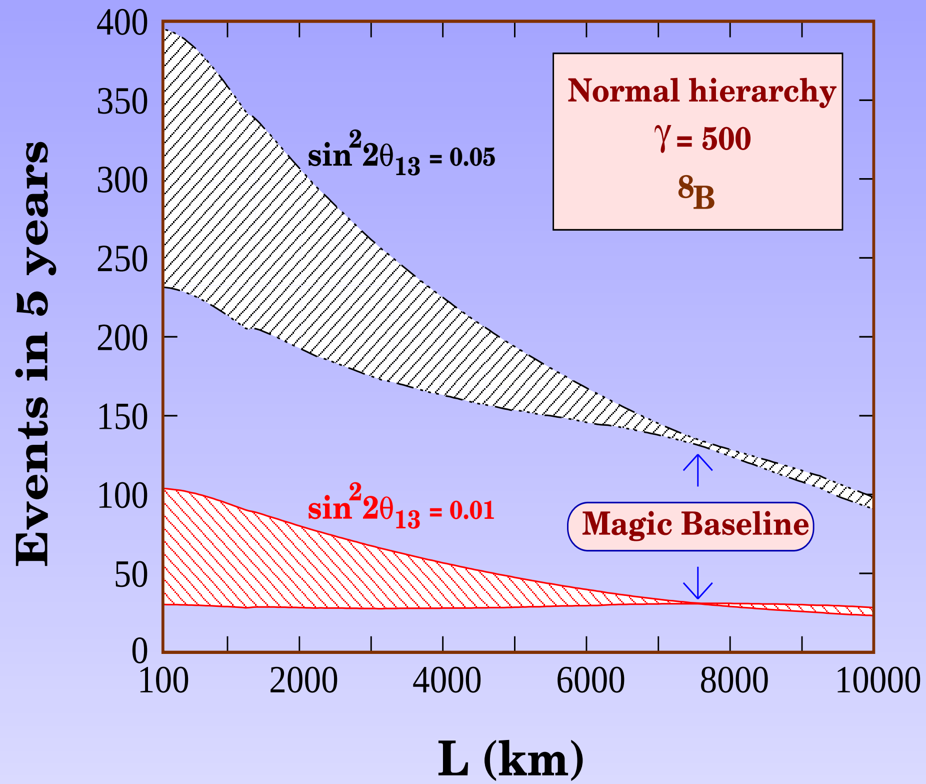


Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Event rates sharply depend on mass ordering and θ_{13}

See the "Magic"



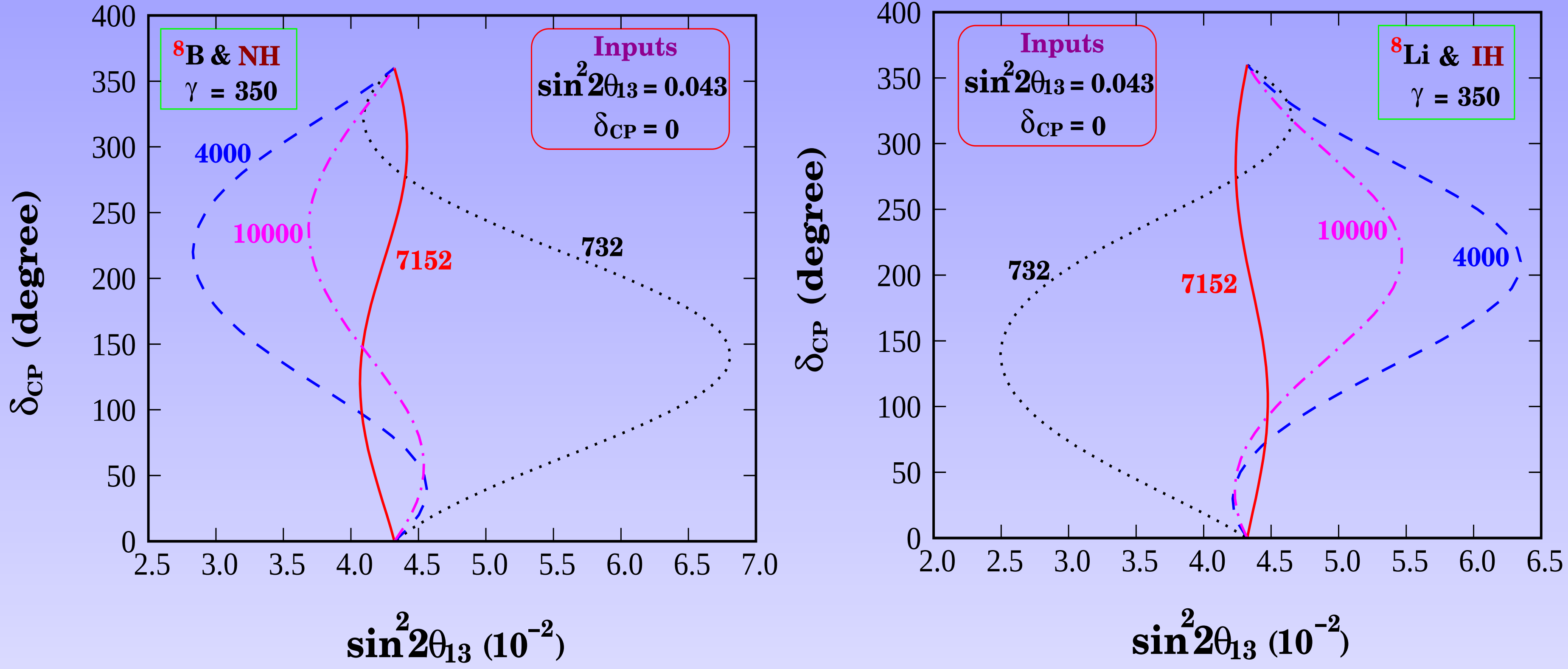


Agarwalla, Choubey, Raychaudhuri, 0711.1459

Event rates sharply depend on mass ordering and θ_{13}

Effect of δ_{CP} is negligible at magic baseline

Iso-event curves



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

At CERN-INO distance, the effect of δ_{CP} on the measurement of θ_{13} is less

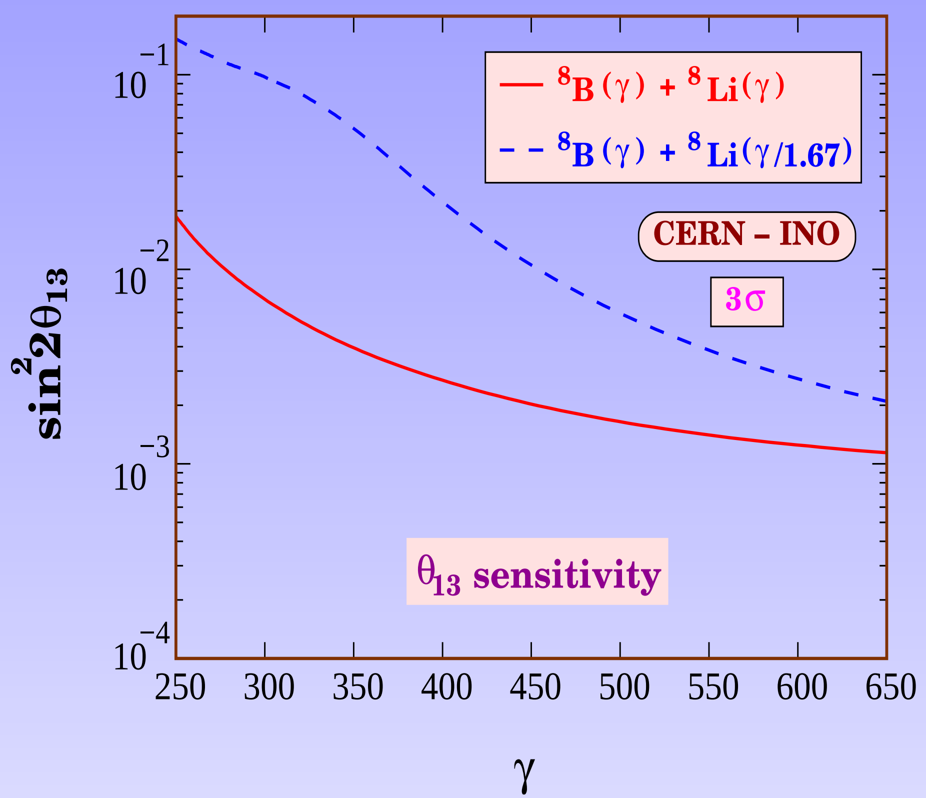
Results

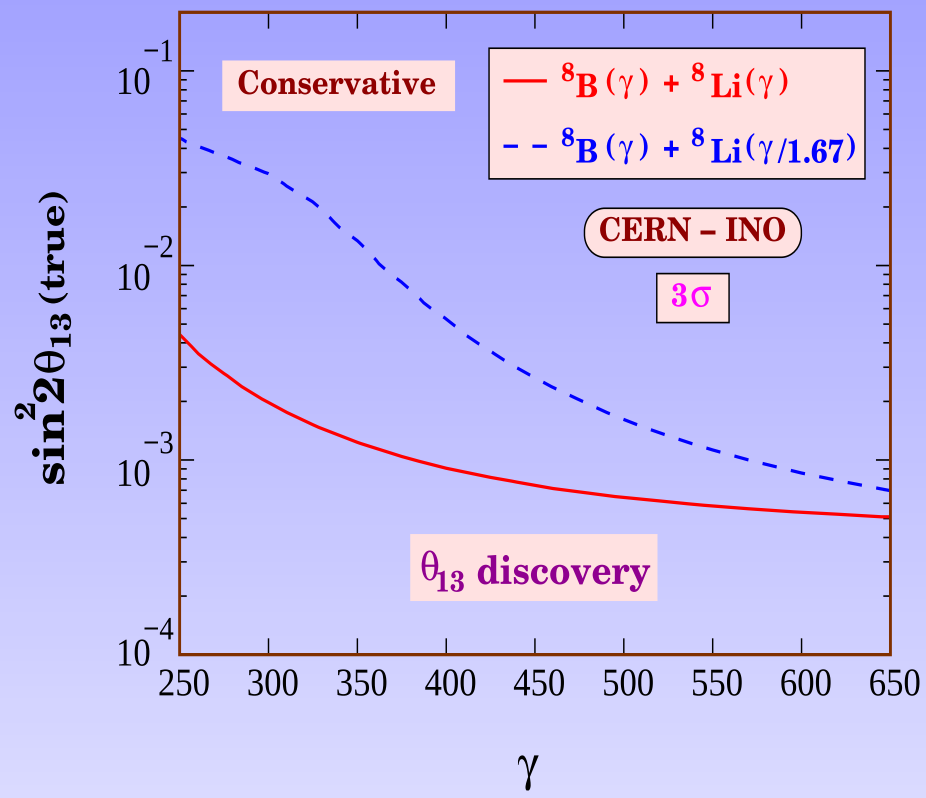
Measurement of $\sin^2 2\theta_{13}$

Full marginalization over

- hierarchy
- all oscillation parameters
- the normalization factor of the Earth matter density distribution

Measurement of $\sin^2 2\theta_{13}$



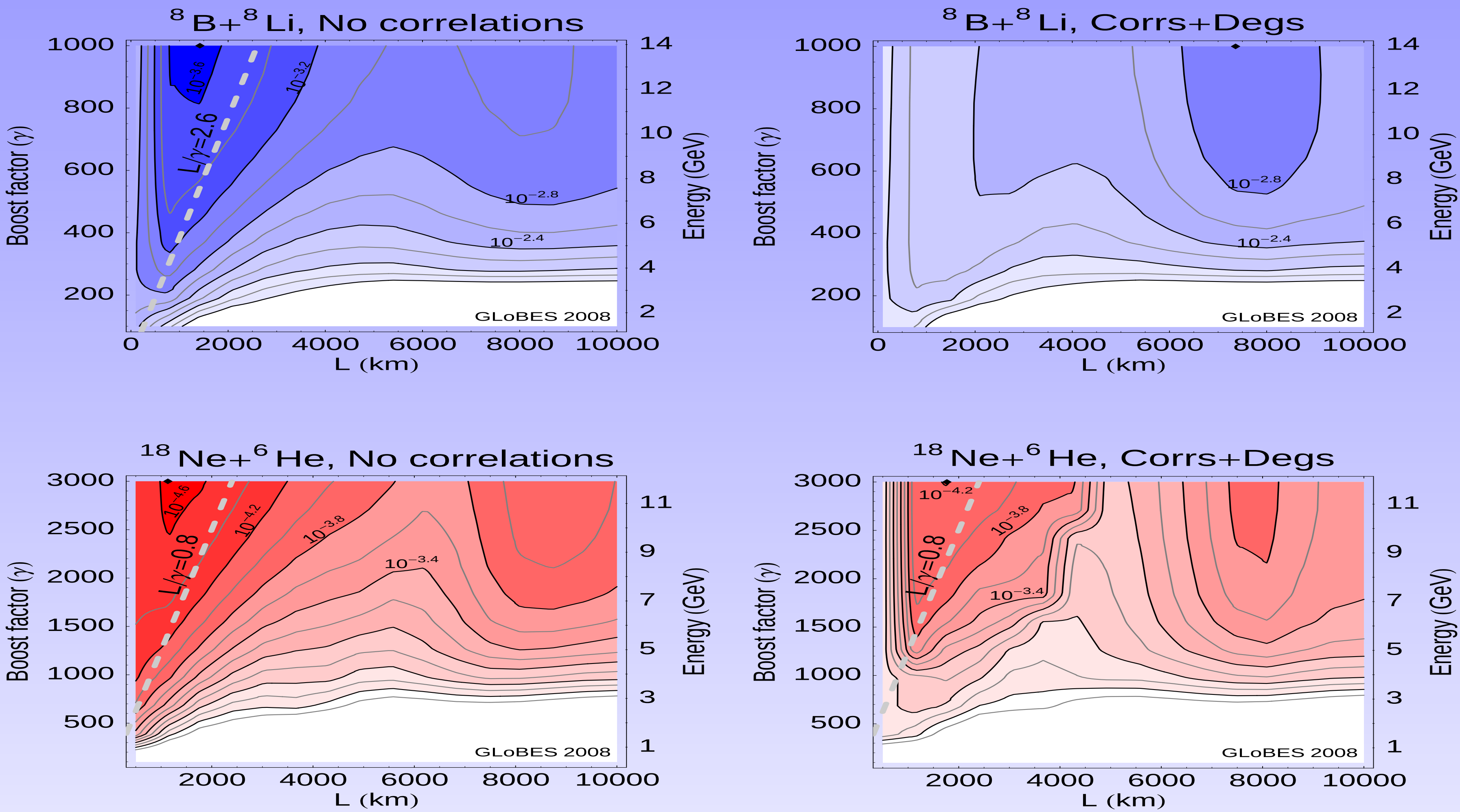


Agarwalla, Choubey, Raychaudhuri, 0711.1459

Left panel shows the 3σ sensitivity limit for $\sin^2 2\theta_{13}$

Right panel shows the 3σ discovery reach for $\sin^2 2\theta_{13}$

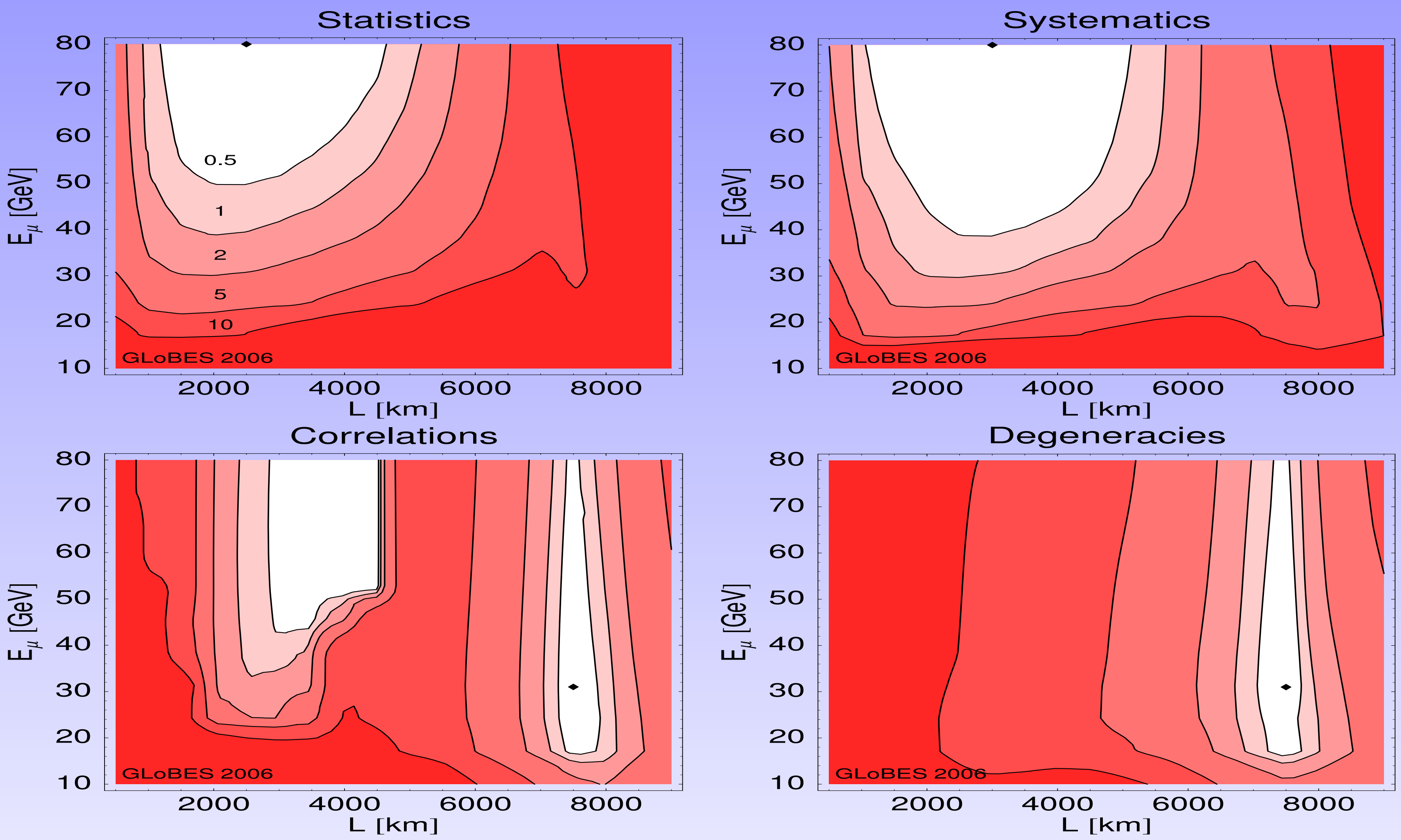
β-beam Optimization



Agarwalla, Choubey, Raychaudhuri, Winter, 0802.3621

$\sin^2 2\theta_{13}$ sensitivity at 3σ as a function of L and Boost factor γ

ν-factory Optimization



Huber, Lindner, Rolinec, Winter, hep-ph/0606119

$\sin^2 2\theta_{13}$ **sensitivity at** 5σ**,** $E_\mu = 30\ GeV$**, L = 7500 km (Optimal choice)**

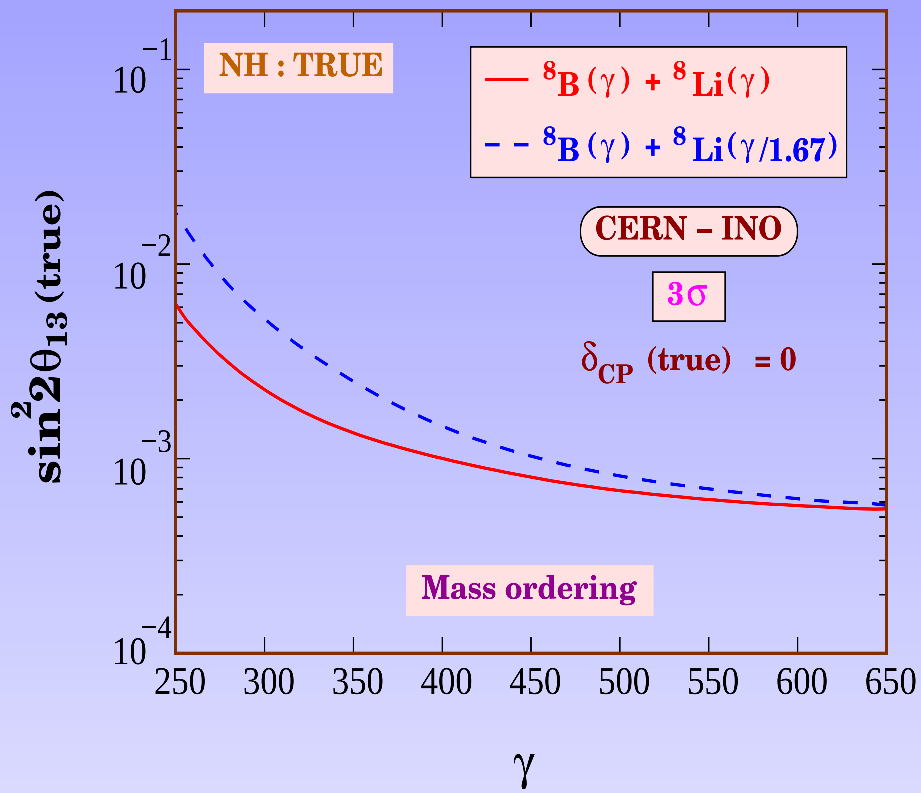
Results

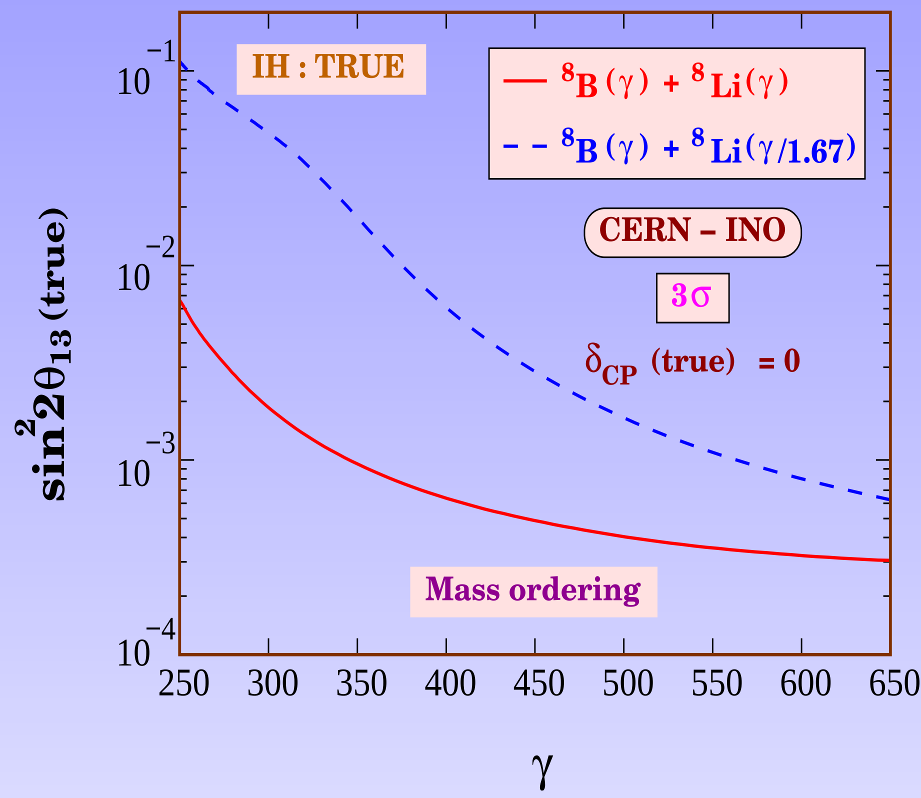
Sensitivity to $Sgn(\Delta m^2_{31})$

Full marginalization over

- all oscillation parameters
- the normalization factor of the Earth matter density distribution

Measurement of $Sgn(\Delta m^2_{31})$

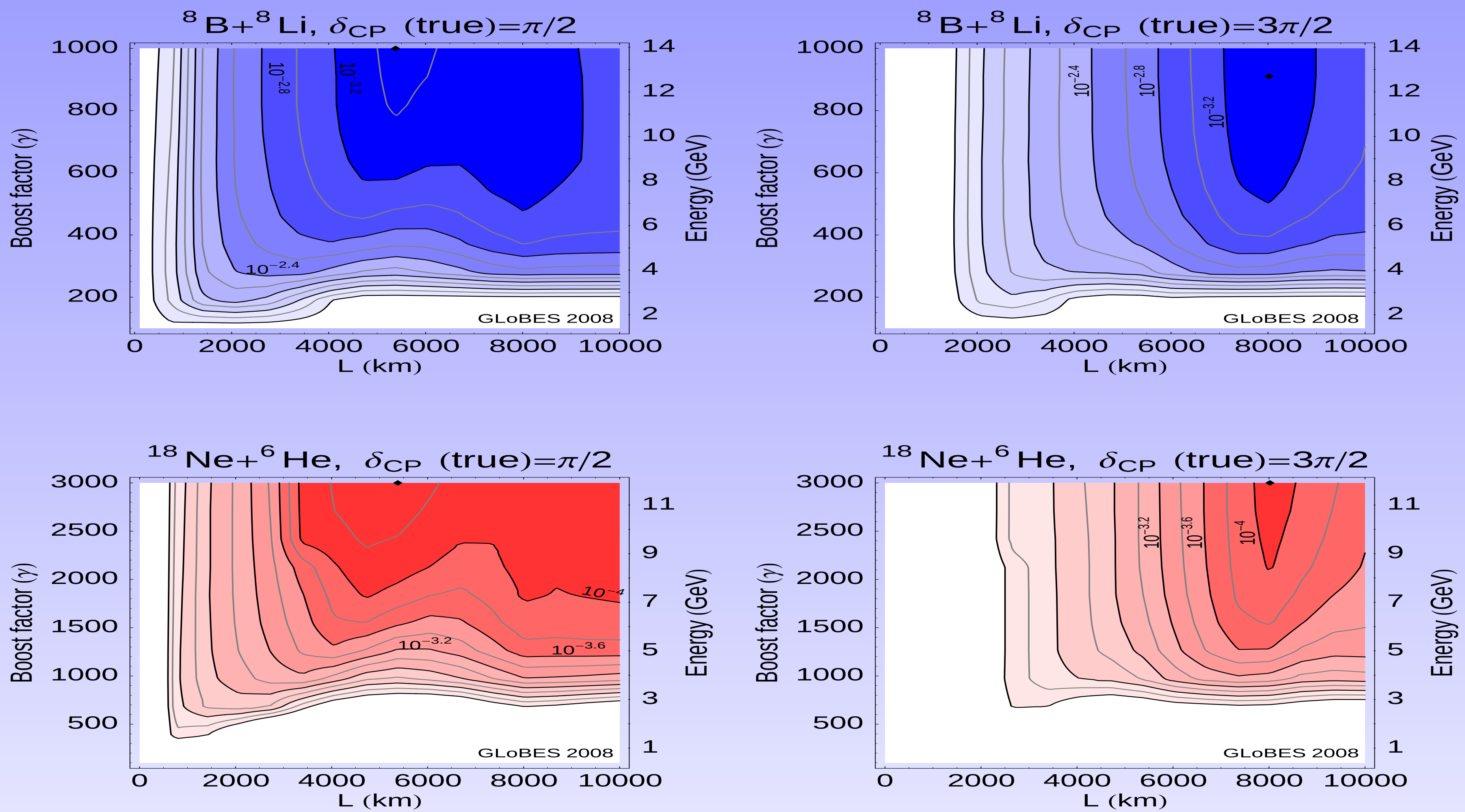




Agarwalla, Choubey, Raychaudhuri, 0711.1459

Minimum value of $\sin^2 2\theta_{13}$(true) for which the the wrong hierarchy can be ruled out at the 3σ C.L.

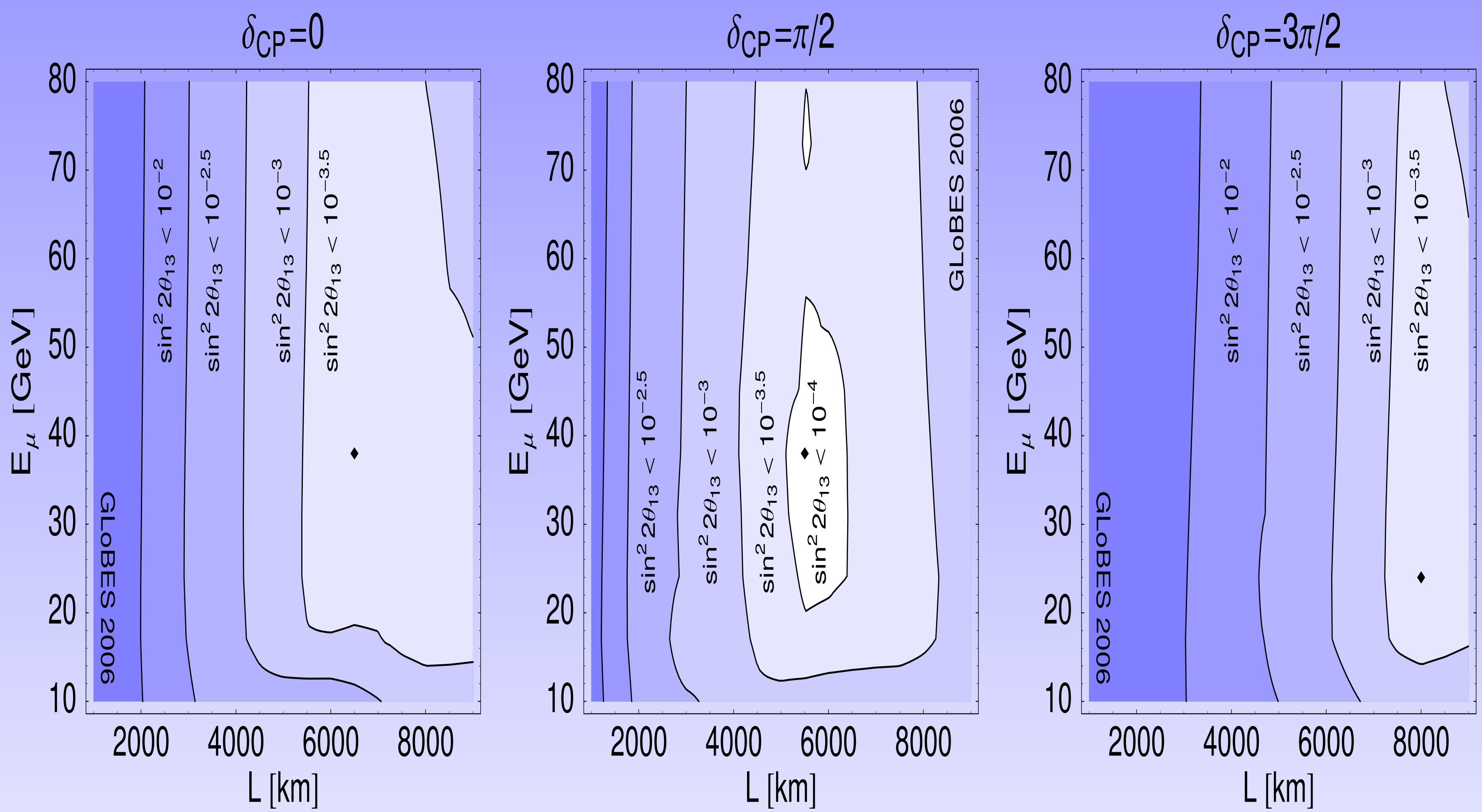
β-beam Optimization



Agarwalla, Choubey, Raychaudhuri, Winter, 0802.3621

Sensitivity to normal mass ordering at 3σ as a function of L and γ

ν-factory Optimization



Huber, Lindner, Rolinec, Winter, hep-ph/0606119

Sensitivity to NH (true) at 3σ, E_μ = 20 to 40 GeV, L = 7500 km (Best)

An ask : New Physics

- Can upcoming neutrino experiments probe non-standard interactions (NSI) like $\not{R}$ supersymmetry?
- Can they become fatal in attempts to further sharpen the neutrino properties?

A possible experiment

CERN based β-beam neutrino source

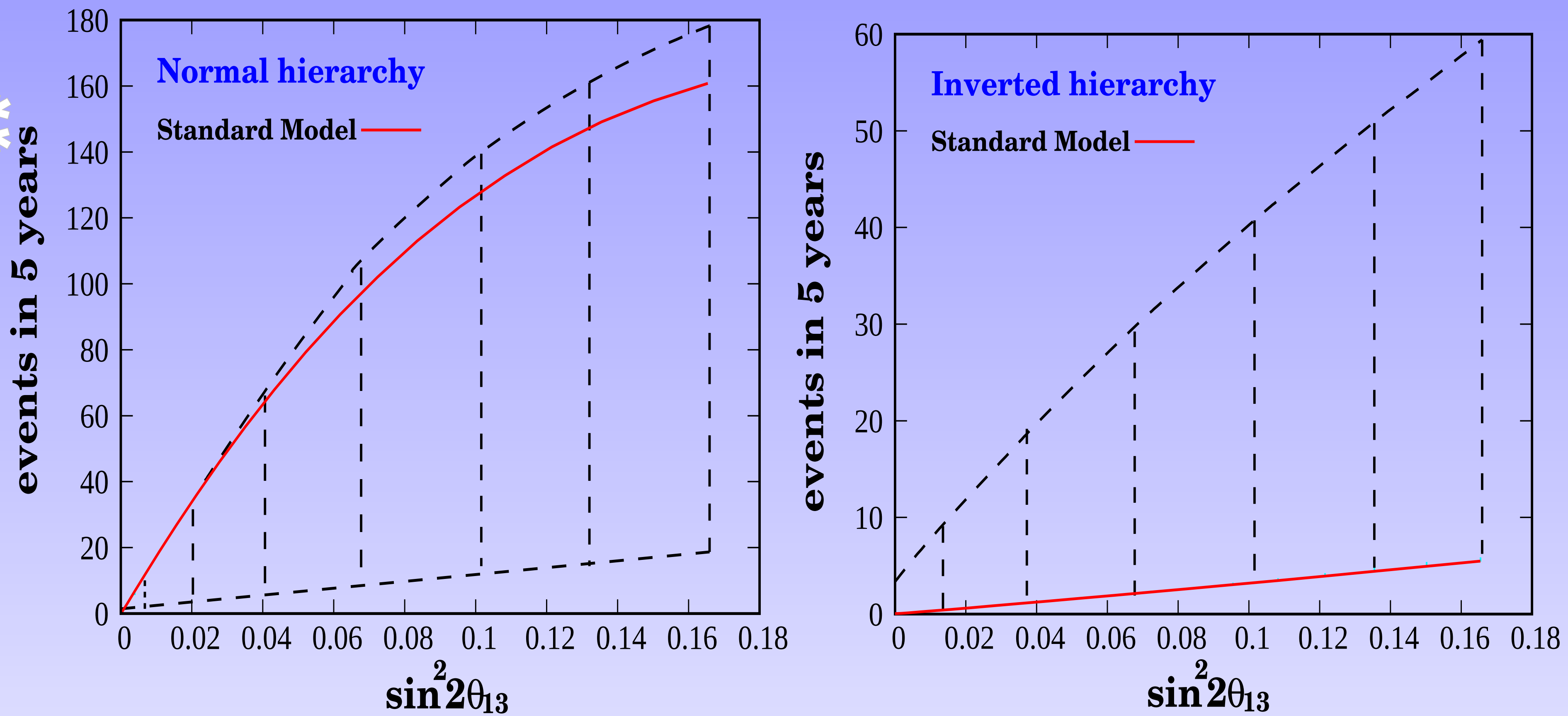
$+$

The proposed India-based Neutrino Observatory (INO)

A baseline of $\sim$ 7152 Km

ν interacts with earth matter $\Rightarrow$ a possible ground for NSI

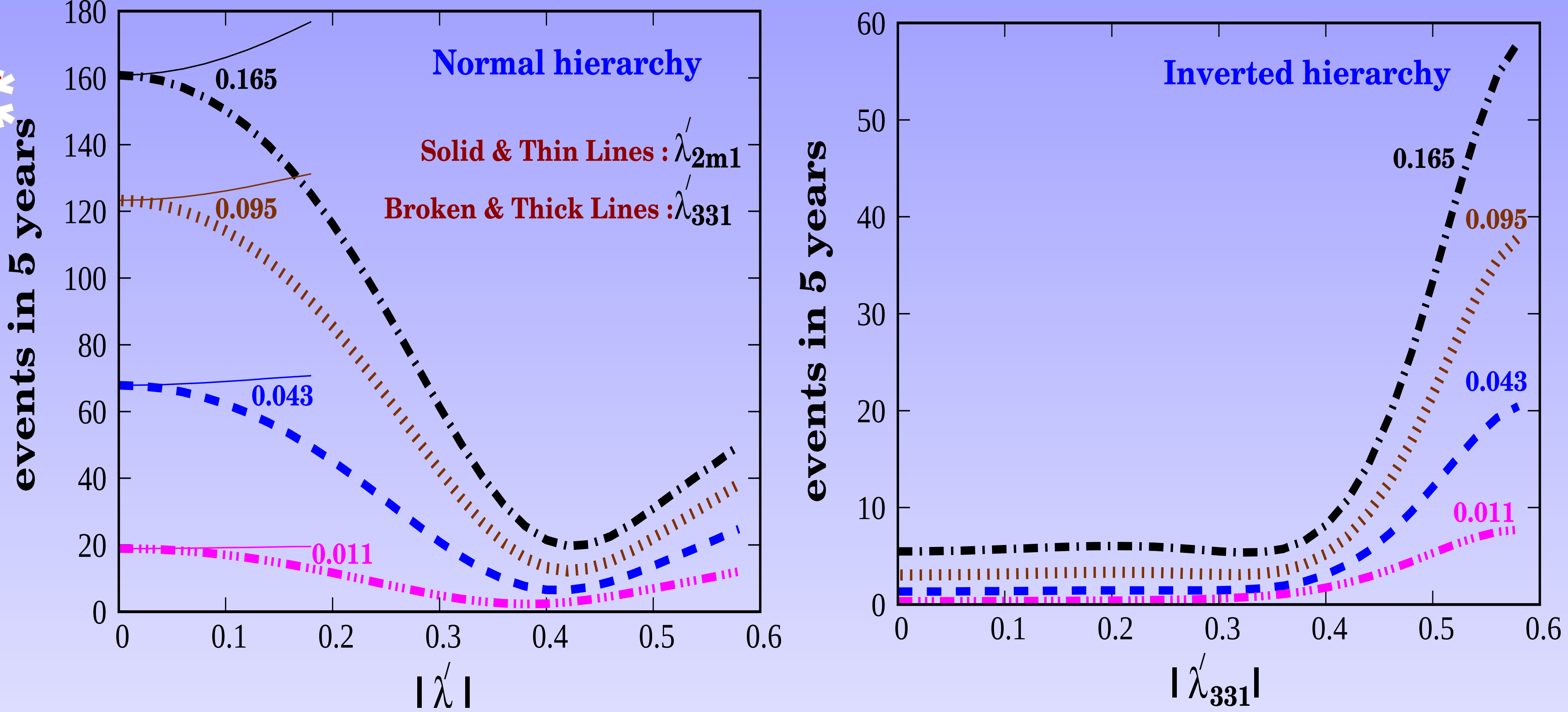
Extracting θ_{13} & $sgn(\Delta m^2_{31})$



Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

Muon events .vs. $\sin^2 2\theta_{13}$ for NH and IH. The solid lines correspond to the SM. The shaded area is covered if the λ' couplings are varied over their entire allowed range

Constraining λ'



Adhikari, Agarwalla, Raychaudhuri, hep-ph/0608034

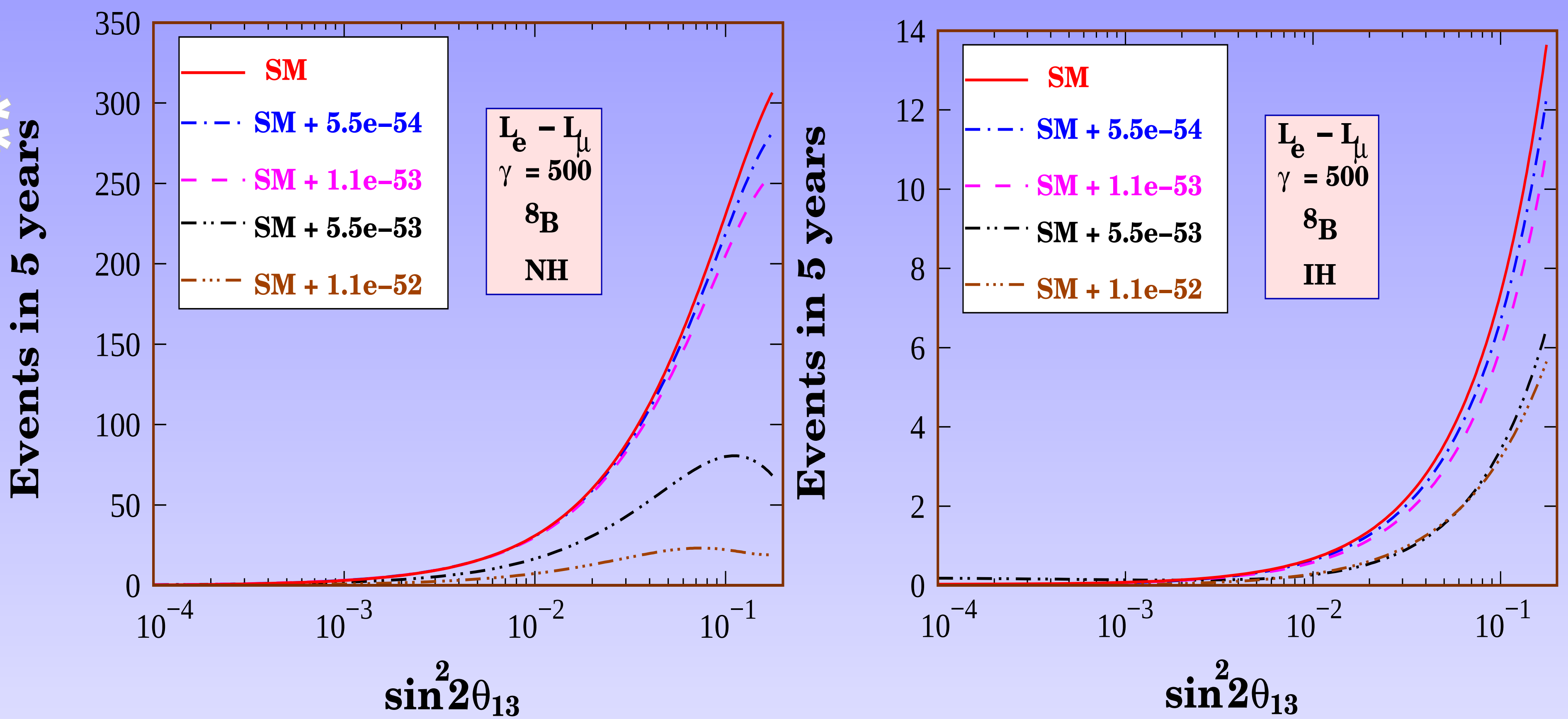
Event rates .vs. $|\lambda'|$, present singly, for NH and IH. The thick (thin) lines are for $|\lambda'_{331}|$ ($|\lambda'_{2m1}|$, m =2,3). The chosen $\sin^2 2\theta_{13}$ are indicated next to the curves

Long Range Forces at ICAL

Can upcoming long baseline neutrino experiments probe flavor dependent long range (LR) leptonic forces, mediated by the $L_e - L_\mu$ or $L_e - L_\tau$ gauge bosons?

Can ICAL play an important role along this direction?

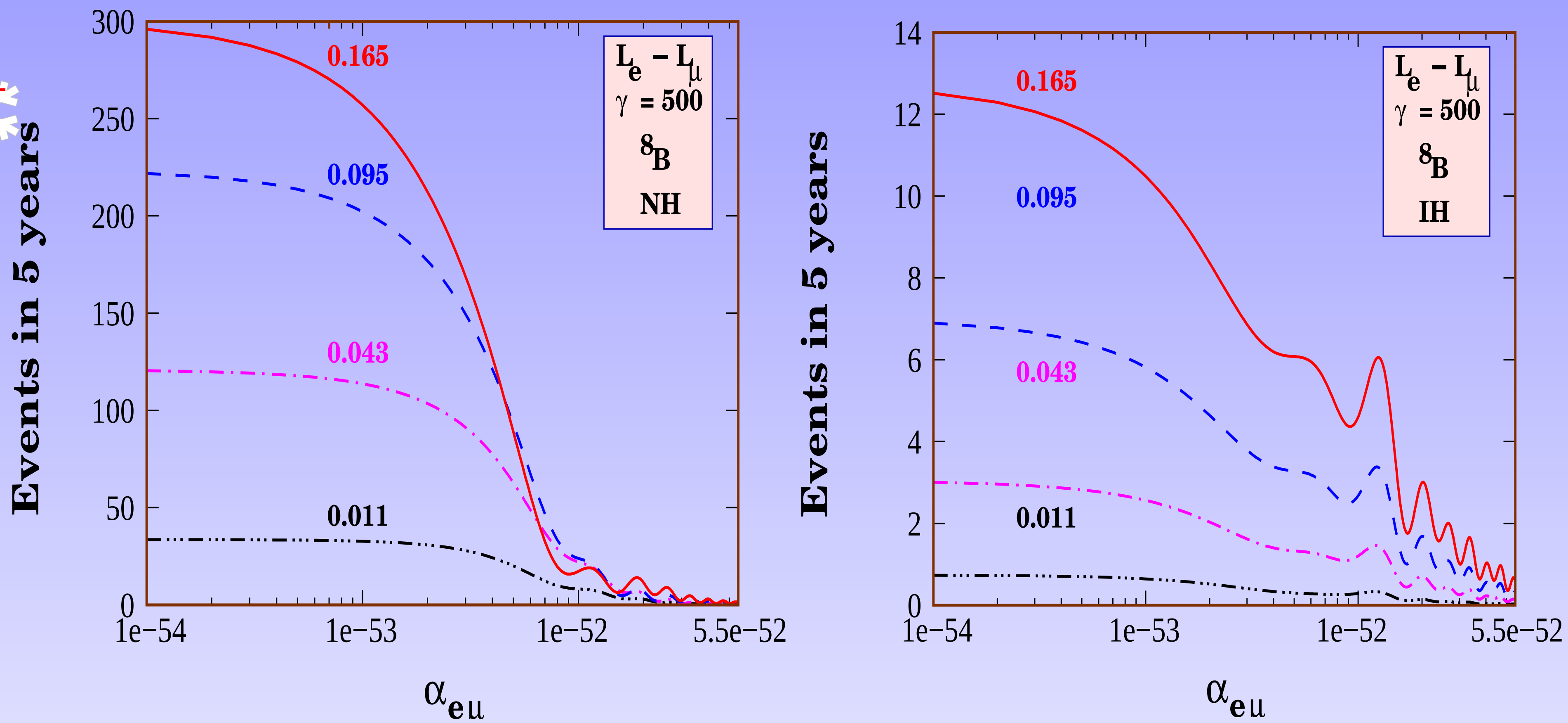
Extracting θ_{13} & $sgn(\Delta m^2_{31})$



Coming soon → Agarwalla, Joshipura, Mohanty

Event rates for the normal and inverted mass hierarchies in the presence of $L_e - L_\mu$ symmetry with $\gamma = 500$ and neutrino run

Constraining Long Range Forces



Coming soon → Agarwalla, Joshipura, Mohanty

Events vs. $\alpha_{e\mu}$ for the NH (left panel) and IH (right panel) with $L_e - L_\mu$ symmetry with $\gamma = 500$ and ν run. Chosen $\sin^2 2\theta_{13}$ are indicated next to the curve

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S. K. Agarwalla, Anjan S. Joshipura, S. Mohanty In preparation

Conclusions

- **Long baseline neutrino oscillation experiments using neutrino factories and β-beams hold promise of refining our knowledge of θ_{13}, δ, and the sign of Δm^2_{31}**

! They will draw the punch line in this business !

- **ICAL at INO will be an admirable choice as a far detector for a very long baseline experiment, with a source either in CERN, or in JHF, or even in Fermilab**

- **A magnetized iron calorimeter detector like INO is essential for Neutrino Factory and its performance with Beta Beam is quite impressive**