Standard Model
And Beyond

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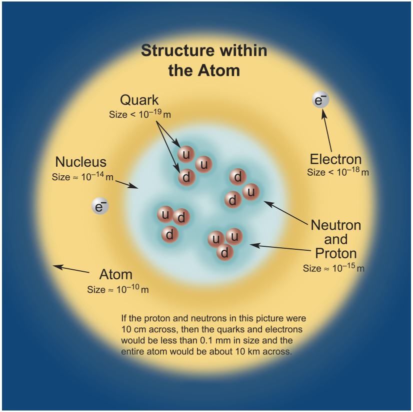
Outline

Particle Physics

Quest to understand fundamental aspects of Nature



Composites

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

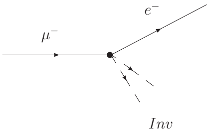
Particle Decays : Unstable Particles

Example: Muon μ (heavier cousin of e)

- μ interactions same as e ; $Q(\mu) = Q(e)$
- $m_\mu \approx 207\, m_e$;
  $m_e = 0.510998910(13) \times 10^{-3}\, GeV$; $m_\mu = 0.1056583668(38)\, GeV$

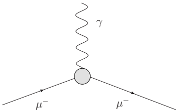
μ unstable, so **Decays** with **lifetime**

- $\tau_\mu = 2.197034(21)\, \mu s$



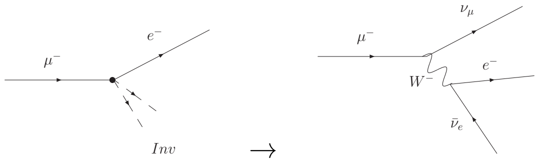
μ Anomolous Magnetic Moment

- $(g-2)/2 = 0.00116592080\,(63)$

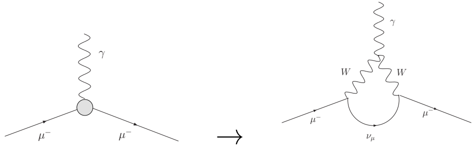


Virtual Particles

μ Decay



μ (g-2)



Theory and Experiment comparison - Precision Probe

- 1 part in 10^9 test of the Standard Model - Triumph!
- Small disagreement in the last 3 digits

New physics or non-perturbative effects?

Natural Units

- Velocity of light $c = 1$
- Plancks constant $\hbar = 1$

Recall $E = mc^2$

$\Rightarrow$ Measure Energy (E) & Mass (m) in Giga-electronVolt (GeV)

Eg: Proton mass $m_p \approx 1$ GeV

Eg: Electron mass $m_e \approx 5 \times 10^{-4}$ GeV

Accelerators as microscopes

Optical Microscope ($\lambda \approx 0.6\,\mu m$)

Electron Microsope ($\lambda \approx 0.2\,nm$)

Particle Accelerator ($\lambda \approx 1/E$) (E is Beam Energy)

- LEP (CERN, Europe), Tevatron (Fermilab, USA): $E \approx 100$ GeV , $\lambda \approx 10^{-17} m$
- Large Hadron Collider (LHC - CERN, Europe): $E = 14000$ GeV , $\lambda \approx 10^{-19} m$

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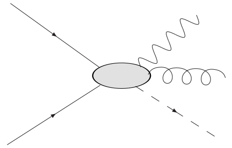
Standard Model (SM) of Particle Physics

Physics operating at $\lambda \approx 10^{-17} m$ distance scale

SM constructed and tested in

- Low energy precision experiments
- High energy particle accelerators
  - Create new particles ($E = mc^2$)



Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Symmetries (Groups)
  - Continuous
  - Discrete
  - Space-time
  - Internal

Example

Lorentz Invariance

- 4-dimensional Space-Time
- $E = mc^2$

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Example

Uncertainty Principle

$$\Delta p \, \Delta x \geq \hbar$$

$$\Delta E \, \Delta t \geq \hbar$$

Virtual Particles

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Example

Space-time, continuous symmetry

- Translation symmetry
  $\Rightarrow$ Momentum Conserved
- Rotation symmetry
  $\Rightarrow$ Angular Momentum Conserved

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Space-time, discrete symmetry

- Parity $\mathcal{P} : (t, \underline{x}) \to (t, -\underline{x})$

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Example

Internal, continuous local (gauge) symmetry $[\alpha(t, \underline{x})]$

- Electrodynamics : U(1) Invariance $\Longrightarrow$ Charge Conservation

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Example

Internal, continuous global symmetry ($\alpha = const.$)

- Chiral Symmetry $\Longrightarrow$ Light pion

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Internal, discrete global symmetry

- Charge Conjugation $\mathcal{C}$: $e^- \rightarrow e^+$

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Example

Dirac theory for e

Matter $\leftrightarrow$ Anti-matter

- electron $\leftrightarrow$ positron
- proton $\leftrightarrow$ antiproton

Eg: Quantum Electrodynamics (QED)

- QED is an $U(1)$ (Abelian) gauge theory
- The Lagrangian density is

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu) + \overline{\psi} i\gamma^\mu(\partial_\mu - ieA_\mu)\psi - m\overline{\psi}\psi$$

- The SM uses these notions : non-Abelian gauge theory
  - Gauge group : $SU(3)_c \times SU(2)_L \times U(1)_Y$

Particle Content and Interactions

Matter Particles

- Hadrons (Quarks) (p, n,...); Leptons (e,ν,...)

Interactions (Forces)

- Strong Interactions

  Responsible for bound Quarks, bound nucleons

- Electroweak Interactions

  Maxwell's Electromagnetism
  Weak interactions. Can change particle type: Radioactivity

- Gravity

  Trivial in the SM; Quantam gravity?

Mass generation (Spontaneous Symmetry Breaking)

- Higgs mechanism
- Chiral Symmetry Breaking and Confinement

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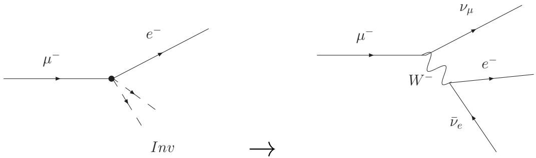
Strong Interactions

- Hadrons (Composites)
  - Baryons (p, n,...)
  - Mesons ($\pi^{\pm}, \pi^{0}$,...)
- Short range force : Effective theory by Yukawa (1935)
- Confinement (Open problem)
- Hadrons organized into multiplets (representations of $SU(3)$) [Gell-Mann, Ne'eman]
- Deep Inelastic Scattering (DIS) : Hadrons have structure $\Longrightarrow$ Quarks
- $\mathcal{CP}$ appears to be conserved - why? (open problem)

Weak Interactions

- Changes particle type

Eg:μ Decay



- Lee and Yang (1956) : Does Weak Interactions respect Parity $\mathcal{P}$?
- Wu (1956) : $\mathcal{P}$ violation in $Co^{60} \to Ni^{60} + e + \bar{\nu}_e + 2\gamma$
  (Co^{60} oriented in a B field)
    - e preferentially emitted in the lower hemisphere $\Longrightarrow$ $\mathcal{P}$ violation (maximal)
    - ν is left-chiral : "Nature is left-handed"
- $V - A$ structure of weak interactions $\quad \mathcal{L} \supset -\frac{g}{2\sqrt{2}} \bar{u}(\gamma^\mu - \gamma^\mu \gamma^5) d \, W^+_\mu + h.c.$
  [Sudarshan, Marshak; Feynman, Gell-Mann]

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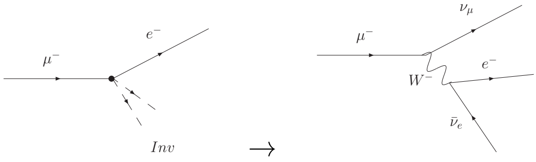

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Outline

The Standard Model (SM)

Building blocks:

[particleadventure.org]

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	(0–0.13)×10^{-9}	0
e electron	0.000511	–1
ν_M middle neutrino*	(0.009–0.13)×10^{-9}	0
μ muon	0.106	–1
ν_H heaviest neutrino*	(0.04–0.14)×10^{-9}	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

2012: Added the Higgs Boson (h), mass 125 GeV, spin 0, charge 0

Standard Model Interactions

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Standard Model (SM) structure

Theory of Quarks, Leptons and their Interactions (Gauge bosons)

- Quantum Field Theory (QFT)
  - *Quantum Mechanics*
  - *Particle/Antiparticle creation/annihilation*
- Symmetry
  - *Lorentz Invariance (Space-time symmetry)*
  - *Gauge symmetry (Internal symmetry)*
    - $SU(3) \otimes SU(2) \otimes U(1)$ gauge group
    - Strong, Electromagnetic, Weak forces

Electroweak Symmetry spontaneously broken $\Rightarrow$ Massive gauge bosons $W^{\pm}$, Z

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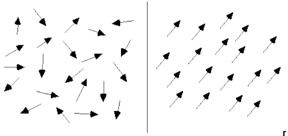
Spontaneous Symmetry Breaking (SSB)

Microscopic laws symmetric , but ground state NOT symmetric

Aside: Eg: In Condensed Matter Systems : Spont. Magnetization



[Fig by F. Heylighen]

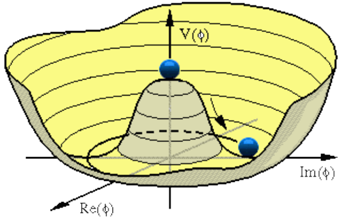
- In analogy to this, in SM QFT,
  - Vacuum Expectation Value (VEV) of Higgs field breaks Electroweak symmetry

The role of the Higgs boson in the SM

Spontaneous Breaking of Electroweak Symmetry

$\mathcal{L} \supset D_\mu H^\dagger D^\mu H - \mathcal{V}(H)$

$\mathcal{V}(H) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$



- $\frac{\partial V}{\partial H} = 0$: $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
- $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$
- Gives particles MASS !!!

Gives mass to Gauge Bosons ($W^\pm$, Z)
Gives mass to fermions

- $L \supset -\lambda_d \bar{Q}_L H d_R - \lambda_u \bar{Q}_L \cdot H^\dagger u_R + \text{h.c.}$ (λ are complex CP violating Yukawa couplings)

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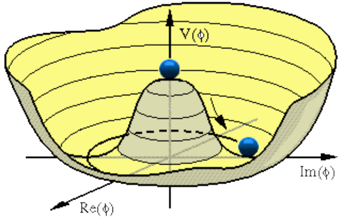

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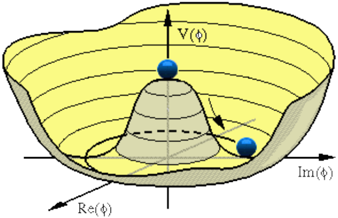

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$\mathcal{CP}$ Violation

- Weak Interaction violates $\mathcal{P}$, but how about $\mathcal{CP}$?

  Eg: Kaon $(K^0, \bar{K}^0)$ system $\quad \mathcal{CP}(K^0) = -\bar{K}^0$; $\mathcal{CP}(\bar{K}^0) = -K^0$

  Experiment by Cronin, Fitch (1963) in the Kaon system :

  Weak interaction violates $\mathcal{CP}$ (by a tiny amount)

- Kobayashi, Maskawa (1973) : $\mathcal{CP}$ Violation if 3 generations (or more)

  SM $\mathcal{CP}$ violation in the $W^{\pm}$ (charged current) interactions (CKM matrix)

- $B^0_{d,s} - \bar{B}^0_{d,s}$ mixing, $\mathcal{CP}$ violation studied in B-factories (BaBar and Belle)

  Largely agrees with SM

  A few tantalizing hints of new physics? Await more from LHCb, Belle-II

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Unanswered in the SM

Gauge hierarchy problem

- Higgs sector unstable (quadratic divergence)

Flavor problem

- Fermion mass hierarchy - Flavor symmetry?
- Tiny neutrino masses : $m_\nu \sim 10^{-2}$ eV
  - India-based Neutrino Observatory (INO)
  - Is neutrino Majorana or is it Dirac? $0\nu\beta\beta$ experiment

Cosmology connection

- What is the dark matter
- Inadequate source of CP vioation for observed baryon asymmetry
- Cosmological constant problem

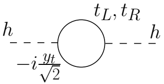
Quantum theory of gravity?

- String Theory, Loop Quantum Gravity, ...

Gauge hierarchy problem in detail

$\mathcal{L} \supset -\frac{1}{2} m_h^2 h^2$ No symmetry protecting the Higgs mass!

$$\mathcal{L} \supset -\frac{y_t}{\sqrt{2}} h \bar{t}_R t_L + h.c.$$



$$\frac{\delta m_h^2}{2} = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$ (Λ is momentum cut-off)

Quadratic divergence! $\Longrightarrow$ unnatural (fine-tuning)

New physics (BSM) restores naturalness?

Below what scale (Λ) should it appear?

Fine-tuning measure: $f_T \equiv \frac{m_h^2}{\delta m_h^2}$

$f_T > 0.1 \Longrightarrow \Lambda < 2\text{TeV}$ (for $m_h = 120$ GeV)

So expect new physics below 2 TeV scale

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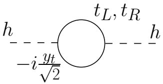

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Some new physics possibilities

Belief that something may cure the Hierarchy problem. But what?

- Supersymmetry
- Extra-dimensions : Warped or Flat
- Strong dynamics (Note AdS-CFT correspondence)
- Little Higgs

Neutrino mass connection and lepton number violation

Baryon Number (B) appears to be conserved - Really?

- Grand-unified Theories (GUT) predict Proton Decay (B violation)
  But $\tau_p \gtrsim 10^{32}$ years

Dark Matter signals

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Neutrino mass connection and lepton number violation

Baryon Number (B) appears to be conserved - Really?

- Grand-unified Theories (GUT) predict Proton Decay (B violation)
  But $\tau_p \gtrsim 10^{32}$ years

Dark Matter signals

Some new physics possibilities

Belief that something may cure the Hierarchy problem. But what?

- Supersymmetry
- Extra-dimensions : Warped or Flat
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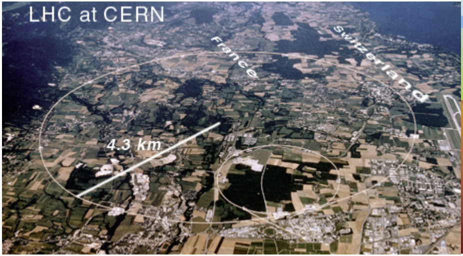
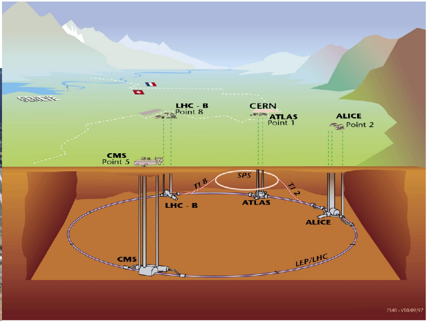
Dark Matter signals

Outline

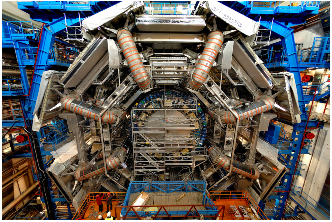
The Large Hadron Collider (LHC)

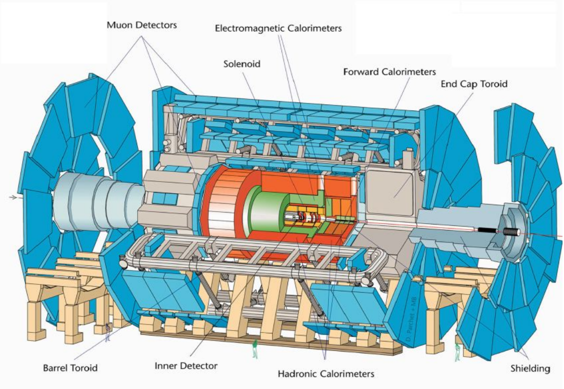




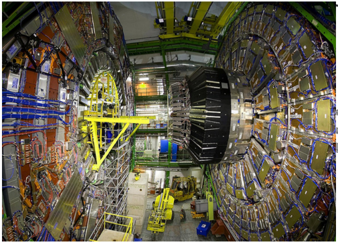
14,000 GeV Collision Energy
Price tag : About US $ 9 Billion

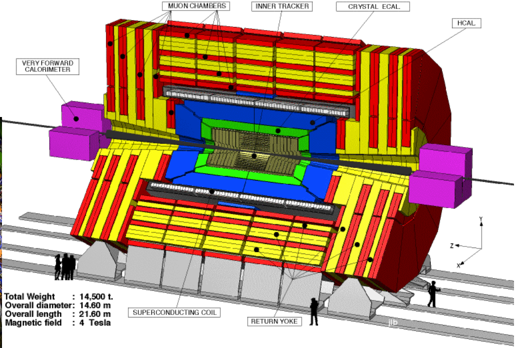
LHC ATLAS Detector



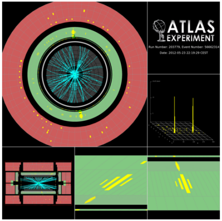


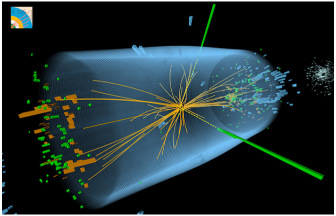
LHC CMS Detector

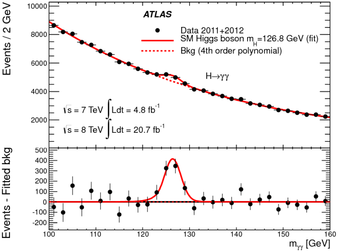


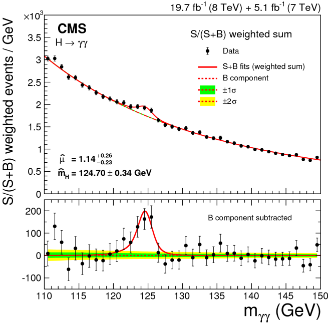


Higgs discovery @ LHC



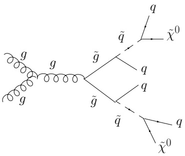


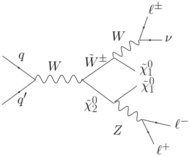


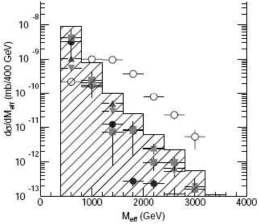


Supersymmetry (SUSY) at LHC

- Cascade decays
- Missing energy signals







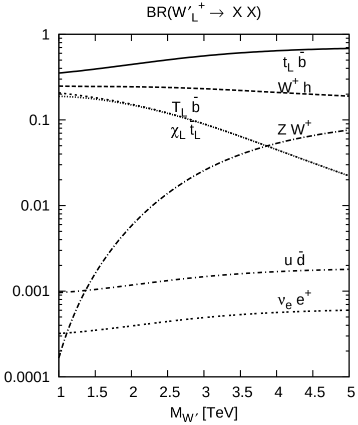
[ATLAS Physics TDR]

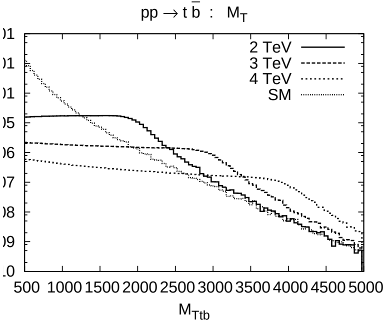
- Can we determine the spin and couplings to show SUSY?
  - Angular distributions

Composite Higgs/Warped Ex-Dim at LHC

Look for heavy Resonances/Kaluza-Klein states (Heavy Gluon, Graviton, W, Z)
LEP precision electroweak constraints $\Rightarrow V' \gtrsim 2\ TeV$

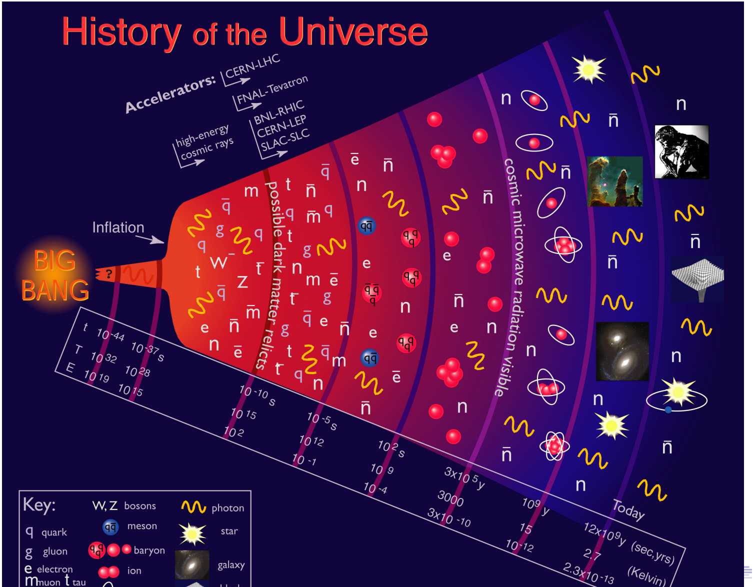
Example: $W' \to XX$ $\qquad pp \to W' \to t\bar{b} \to Wb\bar{b} \to \ell\nu b\bar{b}$



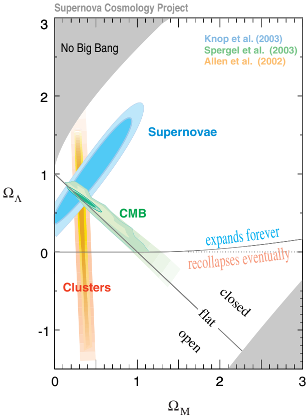


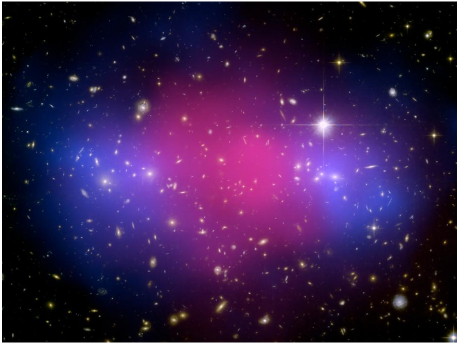
Outline

Particle Physics and the Universe



Evidence for Dark Matter (DM)



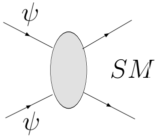


Bullet Cluster [Hubble+Chandra, NASA, ESA, CXC, M. Bradac (UCSB), and S. Allen (Stanford)]

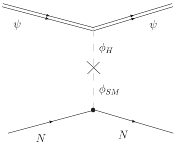
$\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

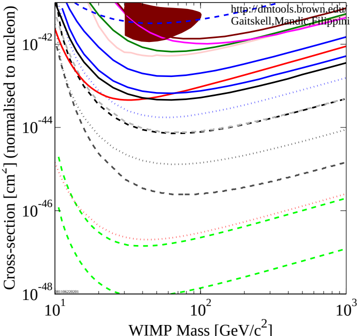
PARTICLE DARK MATTER (DM)

Self-Annihilation cross-section gives present DM Relic density



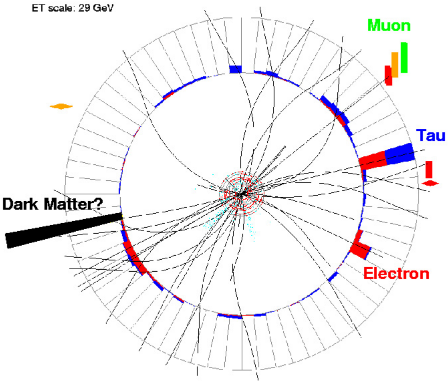
Direct Detection





Dark Matter at the LHC?

Missing momentum!



Outline

Conclusions

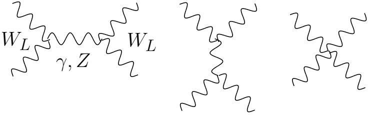
- Standard Model is now firmly established
  - Tested in a multitude of experiments to great precision
- Clues that there is physics beyond SM
  - LHC is looking for BSM
    - Physics responsible for stability of EW scale?
    - 14 TeV run to start soon - Exciting time!
- Cosmology connection
  - Dark Matter, Baryon Asymmetry

BACKUP SLIDES

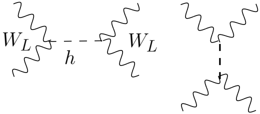
ROLE OF THE HIGGS (CONTD...)

Unitarizes WW scattering

[Lee, Quigg, Thacker, 1977]



$\mathcal{M} = \sum(2l+1)\, a_l\, P_l(cos\theta)$
$a_l\ =\ A\ (q/m_W)^4\ +\ B\ (q/m_W)^2\ +\ C$
Perturbative Unitarity: $|a_l| \leq 1$
$A\ = 0$ by gauge invariance
B term bad high-energy behavior



Cancels B, delays unitarity violation

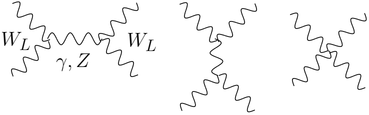
"No-loose theorem" from C term: $\Rightarrow\ \ m_h^2 \leq \frac{8\pi\sqrt{2}}{3G_F} \approx (1\ TeV)^2$

But... a fundamental scalar has (quadratic) divergence instability problem
More on this later

Role of the Higgs (contd...)

Unitarizes WW scattering

[Lee, Quigg, Thacker, 1977]



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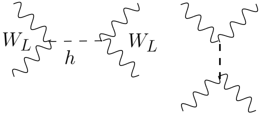

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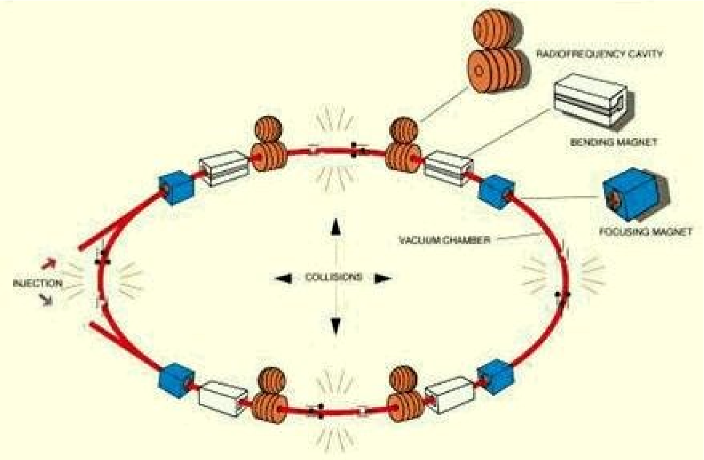
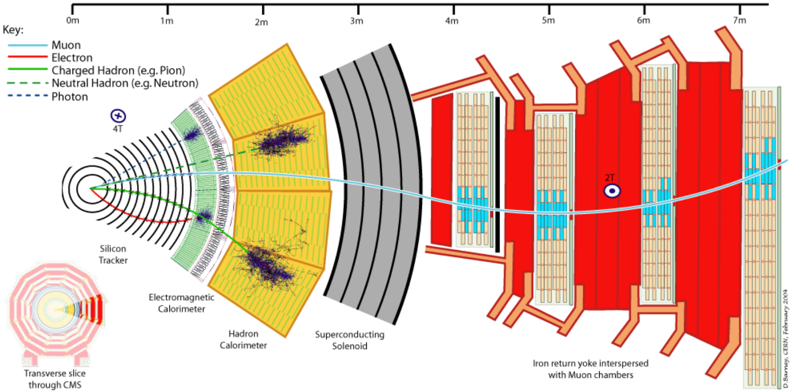
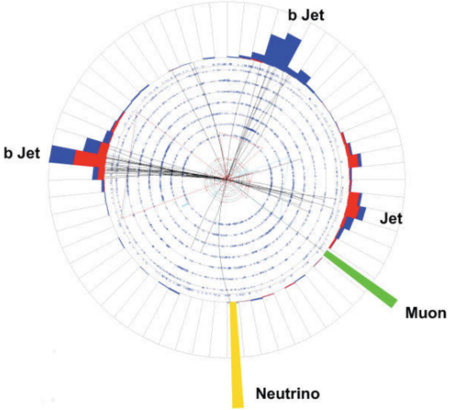
Accelerator schematic



Particle Detectors



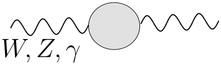
Event reconstruction



D0 Single Top Event (Tevatron)

Electroweak precision observables

Lagrangian parameters in the electroweak sector: $g,\ g',\ v$



$$\equiv i\,\Pi^{\mu\nu} = i\left[\Pi(q^2)g^{\mu\nu} - \Delta(q^2)q^\mu q^\nu\right]$$

SM and BSM can contribute to "blob"

(SM includes Higgs!)

Observables are given by

$$M_Z^2 = (g'^2 + g^2)\frac{v^2}{4} + \Pi_{ZZ}(M_Z^2)$$

$$4\pi\alpha = e^2\left[1 + \Pi'_{\gamma\gamma}(0)\right]$$

$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}\left(1 - \frac{\Pi_{WW}(0)}{M_W^2}\right)$$

$$M_W^2 = g^2\frac{v^2}{4} + \Pi_{WW}(M_W^2)$$

$$A_{LR}^f :\ \sqrt{g'^2 + g^2}\left(T^3 - s_*^2 Q\right)$$

$$s_*^2 \equiv \frac{g'^2}{\sqrt{g'^2+g^2}} - \frac{e}{\sqrt{g'^2+g^2}}\frac{\Pi_{\gamma Z}(M_Z^2)}{M_Z^2}$$

"Oblique parameters" : [Peskin, Takeuchi: 1990,92]

$$\alpha S = 4 s_W^2 c_W^2\left[\Pi'_{ZZ} - \frac{(c_W^2 - s_W^2)}{s_W c_W}\Pi'_{\gamma Z} - \Pi'_{\gamma\gamma}\right]_{q^2=0} = -4e^2\Pi'_{3Y}(0)$$

$$\alpha T = \frac{1}{M_W^2}\left[\Pi_{WW} - c_W^2\Pi_{ZZ}\right]_{q^2=0}$$

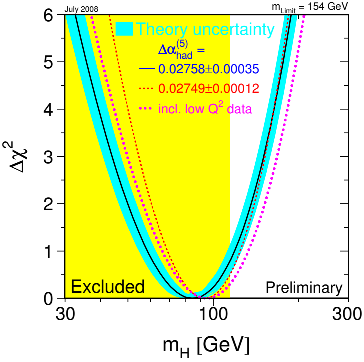
$$\alpha U = 4 s_W^2\left[\Pi'_{WW} - c_W^2\Pi'_{ZZ} - s_W^2\Pi'_{\gamma\gamma} - 2 s_W c_W \Pi'_{\gamma Z}\right]_{q^2=0}$$

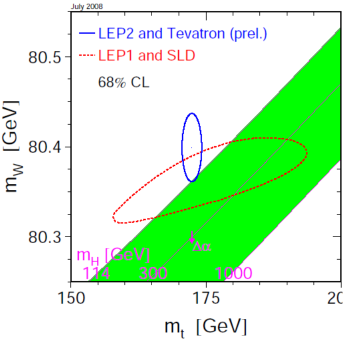
Vertex corrections ($Z\bar{b}b$) separate constraint

LEP (and Tevatron) constraints

CERN LEP I & II (e^+e^- collider)

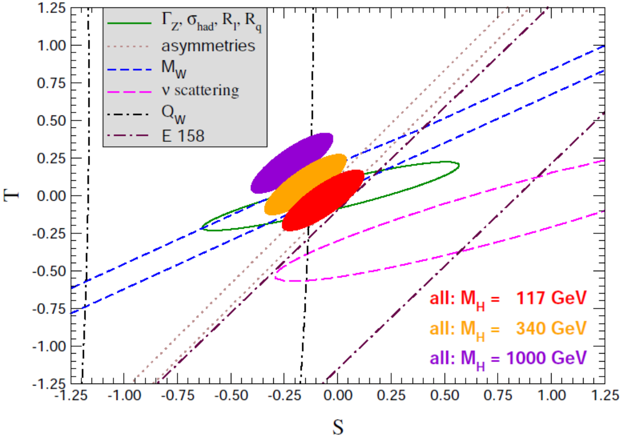
- Tested EW precision observables
- Direct LEP-II bound $m_h \gtrsim 114\,\text{GeV}$; Best fit : $m_H \approx 90\,GeV$
  - 4 events consistent with Higgs!





LEP Constraint on BSM

[PDG 2005]

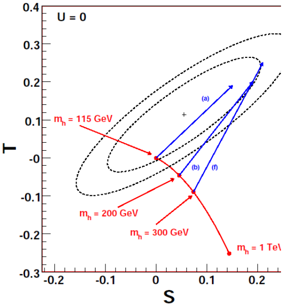


LEP Paradox

If New Physics is there, LEP should have seen hints of this (but didn't):
"LEP paradox" , "Little hierarchy problem"

Eg: Chiral Doublet: $S = \frac{1}{6\pi}\left[1 - Y \log\left(\frac{m_u^2}{m_d^2}\right)\right]$

Eg: Vector-like Doublet: $S = \frac{1}{6\pi}\left[-8Y \log\left(\frac{m_u^2}{m_d^2}\right)\right]$



[Kribs et al, 2008]

Why not more convincing FCNC deviations?
Kaon, B-meson, g-2, EDM, ...

No dynamical explanation? *Landscape* of vacuua?
Depressing! So we will be hopeful that there's new physics

Searching for (new) Physics at the LHC

Quantum Mechanics is probabilistic

- In given theory, predict probability of new particle production and decay into given SM particles
- Compare to LHC event rate observed and see if devation from SM
  - LHC is a counting experiment - Statistical Evidence!

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Analogy: Coin Toss to ascertain fairness

Toss coin many times : plot probability distribution
Smaller deviation from fairness ⇒ larger number of tosses required

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    - LHC is a counting experiment - Statistical Evidence!

LHC Outcomes

- Agree with new theory

New particle in Nature

New theory established

Searching for (new) Physics at the LHC

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- Compare to LHC event rate observed and see if devation from SM
    - LHC is a counting experiment - Statistical Evidence!

LHC Outcomes

- Disagree

Consider alternate theory

Searching for (new) Physics at the LHC

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Eg: Higgs in $\gamma\gamma$ channel

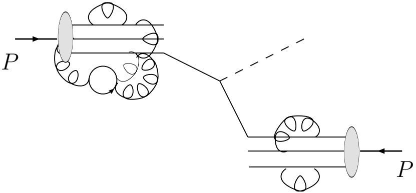
Theoretically compute the cross-section (probability) σ

- "signal" cross-section $\sigma(pp \to h \to \gamma\gamma)$
- "background" cross-section $\sigma(pp \to \gamma\gamma)$

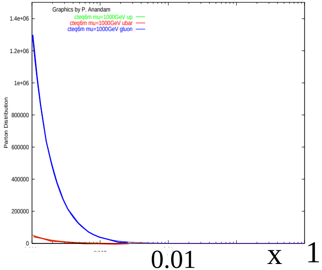
At LHC establish signal over background to discover Higgs

LHC PDF

Keep in mind parton distribution function (pdf)

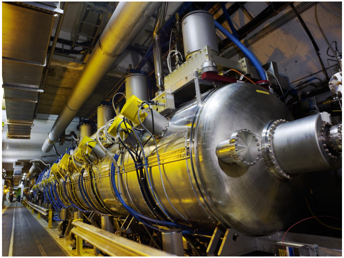


$$x \equiv \frac{\sqrt{\hat{s}}}{\sqrt{S}{=}14\ TeV}$$



[Anandam,Soper,CTEQ]

LHC RF Cavities



Accelerating system:

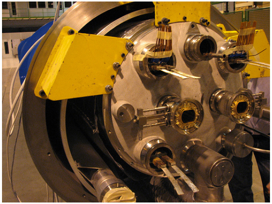
- Superconducting cavities
- 8 single-cell cavities per ring
- 2 MV/cavity at 400 MHz.
- 1 klystron per cavity

LHC Magnets

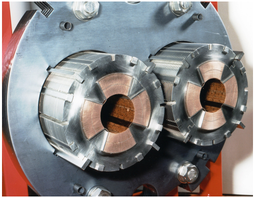
Dipole Magnets

5000 Dipole magnets (14.2m)
Superconducting (1.9K) Liquid Helium
8.33 Tesla field
Nominal Current 11796A
Stored Energy 7.1 MJ/magnet (1.1 GJ total)

Dipole section



Quadrupole section



LHC Computing

Raw Data 300 GB/s

Trigger - multiple levels - 300 MB/s

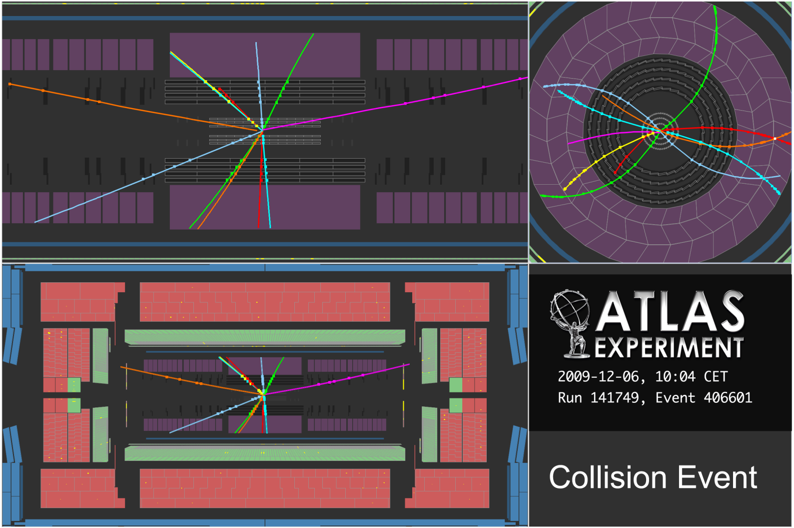
Interesting events sent to tape

Data processing on World-Wide LHC Computing Grid (WLCG)

- CERN is Tier-0
- 11 Tier-1 Centers
- 150 Tier-2 Centers

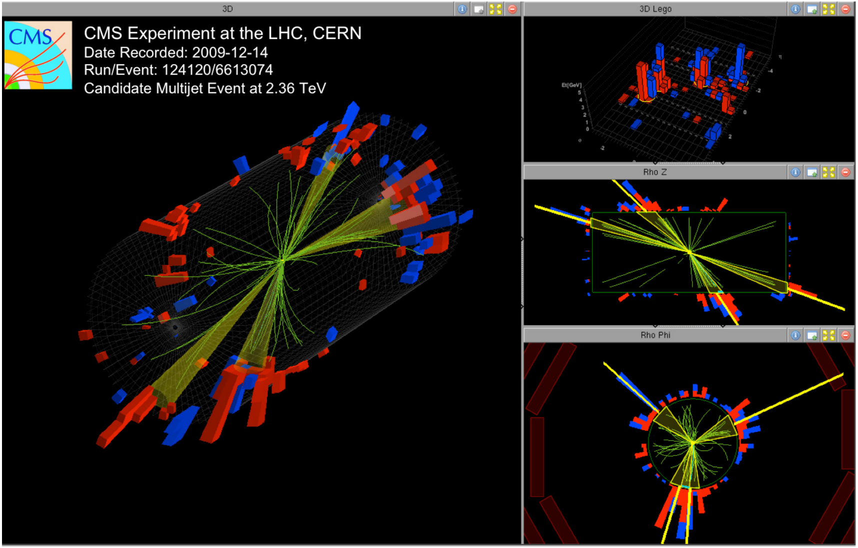
Data estimate: $10 - 15 \times 10^6$ GB/yr !!!

Early LHC (ATLAS) Events



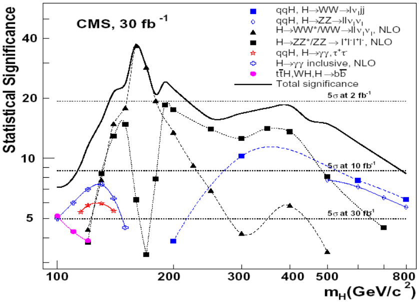
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

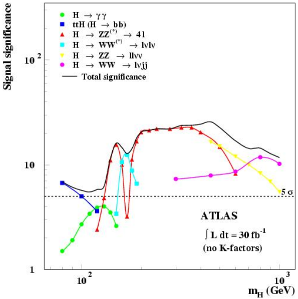
Early LHC (CMS) Events



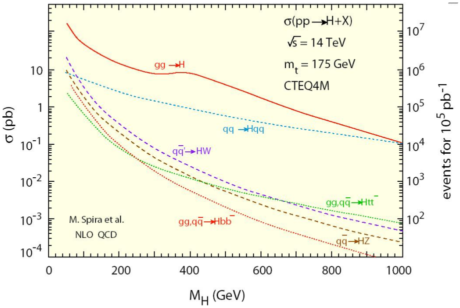
LHC Higgs significance

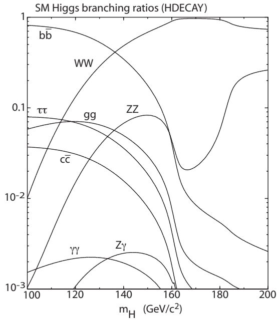
Higgs Significance at the LHC





LHC Higgs Production and Decay





New physics possibilities

Belief that something should cure these problems. But what?

Supersymmetry

[SG,Yuan,2004]

Extra-dimensions : Warped or Flat

[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni,, 2007, 08] [Cao, SG, Yuan, 2003]

Strong dynamics (Note AdS-CFT correspondence)

Little Higgs

Neutrino mass connection and lepton number violation

[EDM with Triplet Higgs: de Gouvea, SG, 2005]

Dark Matter signals (Missing Energy)

[SG, Jung, Lee, Wells, 2008, 09]

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Supersymmetry (SUSY)

Reviews: [Martin] [Dress]

SUSY: Fermions ⇔ Bosons :
(Doubles particle spectrum)

$Q\ |\Phi\rangle = |\Psi\rangle \quad ; \quad Q\ |\Psi\rangle = |\Phi\rangle$

SUSY algebra:

$$\left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$$

$$\left\{Q_\alpha, Q_\beta\right\} = \left\{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\right\} = 0$$

$$\left[P^\mu, Q_\alpha\right] = \left[P^\mu, \bar{Q}_{\dot\alpha}\right] = 0$$

Introduce fermionic (Grasmann) coordinate θ : $\{\theta,\theta\} = \{\theta,\bar\theta\} = \{\bar\theta,\bar\theta\} = 0$

Superfield : $\Phi\left(x_\mu, \theta, \bar\theta\right)$

Finite SUSY transformation

$$\Phi \to e^{i(\theta Q + \bar\theta\bar Q - x_\mu P^\mu)}\Phi$$

$$Q_\alpha = \frac{\partial}{\partial\theta^\alpha} - i\sigma^\mu_{\alpha\dot\beta}\bar\theta^{\dot\beta}\partial_\mu$$

$$\bar Q_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta^{\dot\alpha}} + i\theta^\beta\sigma^\mu_{\beta\dot\alpha}\partial_\mu$$

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} + i\sigma^\mu_{\alpha\dot\beta}\bar\theta^{\dot\beta}\partial_\mu$$

$$\bar D_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta^{\dot\alpha}} - i\theta^\beta\sigma^\mu_{\beta\dot\alpha}\partial_\mu$$

Chiral Superfield: $\bar D\Phi_L = 0 \ ; \ D\Phi_R = 0$

$$\Phi_L = \phi(x) + \sqrt{2}\theta\psi(x) + \theta\theta F(x)$$

Vector Superfield: $V = V^\dagger$

$$V(x,\theta,\bar\theta) = -\theta\sigma_\mu\bar\theta A^\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - \bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta D(x)$$

SUSY $\mathcal{L}$

$$\mathcal{L} = \mathcal{L}^{Kin} + \mathcal{L}^{Pot} + \mathcal{L}^{G-Kin}$$

$$\mathcal{L}^{Kin} = \int d^2\theta d^2\bar{\theta}\, \Phi^\dagger e^{2gV} \Phi$$

$$\mathcal{L}^{Pot} = \int d^2\theta\, W(\Phi_i) + h.c. \qquad W \text{ is ``Superpotential''}$$

$$\mathcal{L}^{G-Kin} = \frac{1}{32g^2}\mathcal{W}_\alpha \mathcal{W}^\alpha \qquad \mathcal{W}_\alpha = \bar{D}De^{-gV}D_\alpha e^{gV}$$

$$\begin{aligned}\mathcal{L} = {} & |D_\mu\phi_i|^2 - i\bar{\psi}\sigma_\mu D^\mu\psi + ig\sqrt{2}(\phi^*\lambda\psi - \lambda\bar{\psi}\phi) \\ & - \left|\frac{\partial W}{\partial\phi_i}\right|^2 + \left(\frac{\partial^2 W}{\partial\phi_j\partial_k\phi}\psi_j\psi_k + h.c.\right) \\ & - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\sum_a \left|\sum_{i,j} g\phi_i^* T^a_{ij}\phi_j\right|^2 - \frac{i}{2}\lambda^a\sigma_\mu\partial^\mu\bar{\lambda}_a + \frac{1}{2}gf^{abc}\lambda_a\sigma_\mu A^\mu_b\bar{\lambda}_c\end{aligned}$$

Minimal Supersymmetric Standard Model (MSSM)

MSSM Superpotential : $\mathcal{W} = y_u U^c Q H_u - y_d D^c Q H_d - y_e E^c L H_d + \mu H_u H_d$

SUSY $\Longrightarrow$ $M_\psi = M_\phi$ Experiment $\Longrightarrow$ SUSY broken

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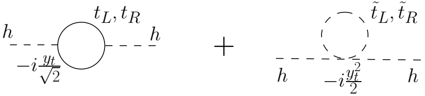
SUSY solves gauge hierarchy problem



$= 0$

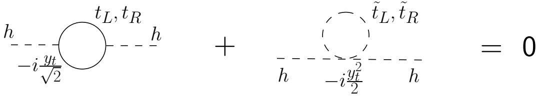
Λ^2 divergence cancelled

Similarly $h, W^\pm, Z$ divergences cancelled by $\tilde{\lambda}$

Gauge Coupling Unification - GUT SUSY $SO(10)$

Includes $\nu_R \Rightarrow$ Neutrino seesaw mass

SUSY solves gauge hierarchy problem



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SUSY BREAKING

SUSY has to be broken

- Spectrum depends on SUSY Breaking/Mediation + RGE
- Minimal Supersymmetric SM (MSSM) general parametrization

$$\mathcal{L}^{soft}_{SUSY\ Br} \supset -\frac{1}{2} M_{\tilde{\lambda}} \tilde{\lambda}\tilde{\lambda} - \tilde{u}^c a_u \tilde{Q} H_u - \tilde{Q}^\dagger \tilde{m}^2_Q \tilde{Q} - m^2_H H^* H - b\mu H_u H_d + \cdots$$

MSSM predicts a LIGHT Higgs. At tree level: $m_h < m_Z$.

- But LEP bound $m_h \gtrsim 114\,\text{GeV}$
- Sizable one loop correction: $\delta m^2_h \lesssim \frac{3}{4\pi^2}\, y^2_t\, m^2_t\, log \frac{\tilde{m}_1 \tilde{m}_2}{m^2_t}$
  - LEP Higgs bound needs heavy stop ⇒ "Little hierarchy problem"

R-PARITY

SM gauge symmetry allows

$$W_{\Delta L} = LH_u + LE^c L + QD^c L \; ; \qquad W_{\Delta B} = U^c D^c D^c$$

These induce proton decay : $\tau_p \sim 10^{-10} s$ for $\tilde{m} \sim 1$ TeV

Impose Matter Parity $R_M = (-1)^{3(B-L)}$ to forbid ΔL *and* ΔB terms

For components this implies : R-parity $R_p = (-1)^{3(B-L)+2s}$

Consequence : The Lightest SUSY Particle (LSP) is stable

- Cosmologically stable Dark Matter
- Missing Energy at Colliders

Warped Extra dimension

SM in background 5D warped AdS space [Randall, Sundrum 99]

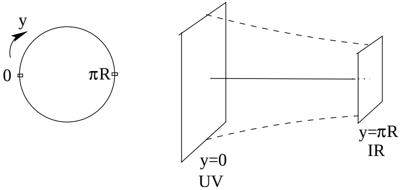
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

Z_2 orbifold fixed points:

- Planck (UV) Brane
- TeV (IR) Brane

R : radius of Ex. Dim.

k : AdS curvature scale ($k \lesssim M_{pl}$)



Hierarchy prob soln:

- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - CFT dual is a composite Higgs model

Bulk Gauge Group

[Agashe, Delgado, May, Sundrum 03]

Bulk gauge group : $SU(3)_{QCD} \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

- 8 gluons
- 3 neutral EW (W_L^3, W_R^3, X)
- 2 charged EW $(W_L^\pm, W_R^\pm)$

Gauge Symmetry breaking:

- By Boundary Condition (BC): $A_{-+}(x,y)$ BC: $A|_{y=0} = 0\,;\ \partial_y A\,|_{y=\pi R} = 0$
  - $SU(2)_R \times U(1)_X \to U(1)_Y$
- By VEV of TeV brane Higgs Higgs $\Sigma = (2,2)$
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

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Kaluza-Klein (KK) expansion

[See for example: Gherghetta, Pomarol, 2000]

$$S_5 = -\int d^4x \int dy \sqrt{-g} \left[\frac{1}{4g_5^2} F_{MN}^2 + |\partial_M \phi|^2 + i\bar{\Psi}\gamma^M D_M \Psi + m_\phi^2 |\phi|^2 + i m_\Psi \bar{\Psi}\Psi \right]$$

EOM:

$$\left[e^{2\sigma} \eta^{\mu\nu} \partial_\mu \partial_\nu + e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) - M_\Phi^2 \right] \Phi(x^\mu, y) = 0$$

Kaluza-Klein expansion

$$\Phi(x^\mu, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0}^{\infty} \Phi^{(n)}(x^\mu) f_n(y)$$

Orthonormality relation:

$$\frac{1}{2\pi R} \int_{-\pi R}^{\pi R} dy\, e^{(2-s)\sigma} f_n(y) f_m(y) = \delta_{nm}$$

EOM implies

$$\left[-e^{s\sigma} \partial_5 (e^{-s\sigma} \partial_5) + \widehat{M}_\Phi^2 \right] f_n = e^{2\sigma} m_n^2 f_n$$

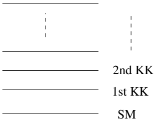
Solution is

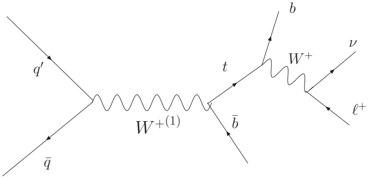
$$f_n(y) = \frac{e^{s\sigma/2}}{N_n} \left[J_\alpha\left(\frac{m_n}{k} e^\sigma\right) + b_\alpha(m_n)\, Y_\alpha\left(\frac{m_n}{k} e^\sigma\right) \right]$$

$\Phi^{(n)}$ →KK tower with mass m_n. Equivalent 4D theory

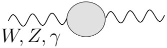
Find the KK tower

Prediction: A Kaluza-Klein tower of states .... Look for it at the LHC





Constraints on Warped Extra dimension



Precision Electroweak Constraints (S, T, $Zb\bar{b}$)

- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
  - T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced
- AdS bulk gauge symm $SU(2)_R \quad \Leftrightarrow \quad$ CFT Custodial Symm
  [Agashe, Delgado, May, Sundrum 03]
  - T parameter - Protected
  - S parameter - $\frac{1}{k\pi R}$ for light bulk fermions
  - Problem: $Zb\bar{b}$ shifted
- 3rd gen quarks (2,2) [Agashe, Contino, DaRold, Pomarol 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{KK} \gtrsim 2 - 3$ TeV

[Carena, Ponton, Santiago, Wagner 06,07] [Bouchart, Moreau-08] [Djouadi, Moreau, Richard 06]

KK STATES AT THE LHC

- $h^{(1)}_{\mu\nu}$ (KK Graviton) $gg \to h^{(1)} \to t\bar{t}$

  $L = 300\, fb^{-1}$ LHC reach is about 2 TeV

  [Agashe, Davoudiasl, Perez, Soni 07]
  [Fitzpatrick, Kaplan, Randall, Wang 07]

- $g^{(1)}_{\mu}$ (KK Gluon) $q\bar{q} \to g^{(1)} \to t\bar{t}$

  $L = 100\, fb^{-1}$ LHC reach is 4 TeV

  [Agashe, Belyaev, Krupovnickas,Perez,Virzi 06]
  [Lillie, Randall, Wang, 07] [Lillie, Shu, Tait 07]

- $Z^{(1)}_{\mu}$, $W^{(1)\pm}_{\mu}$ ($Z_{KK} \equiv Z'$, $W^{\pm}_{KK} \equiv W'$) $q\bar{q} \to Z', W' \to XX$

  [*Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni* 0709.0007 & 0810.1497]

- $\psi^{(1)}$ (KK Fermion)

  [Agashe, Servant 04][Dennis et al 07][Contino, Servant 08][SG et al ongoing]

- Radion

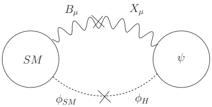
Review: [Davoudiasl, SG, Ponton, Santiago, New J.Phys.12:075011,2010. arXiv:0908.1968 [hep-ph]]

$U(1)_X$ Hidden sector

Coupled to SM (us) via the Higgs [SG, Jung, Lee, Wells:2008, 2009]

Accidental Z_2 symmetry : $\psi \to -\psi$, $SM \to SM$

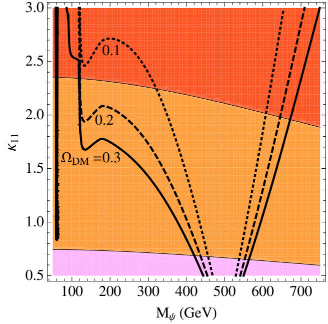
- So ψ cosmologically stable $\Longrightarrow$ Dark Matter

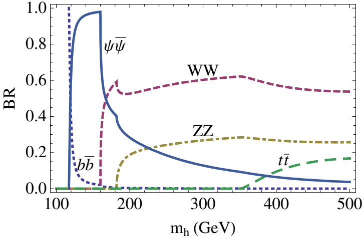


Direct Detection? Hidden sector signature at the LHC?

Hidden Sector Dark Matter at LHC

[SG, Lee, Wells:2009]





Look for LHC signal in $pp \to jj + \not{E}_T$