Beyond the Standard Model of Particle Physics

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An Informal Talk

Oct. 2009

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*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04–0.14)\times10^{-9}$	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

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
$\bar{p}$	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

On the hunt for the Higgs boson

Standard Model (SM) theoretical structure

- Standard Model (SM)
  - Quantum Field Theory (QFT)
  - Gauge symmetry (Internal Symmetry)
  - $SU(3) \otimes SU(2) \otimes U(1)$ gauge group
    - Strong & EM & Weak forces

Eg: EM is invariance under local $U(1)$ transformations : QED : Massless γ

Spontaneously broken Gauge Symmetry $\Rightarrow$ Massive gauge boson

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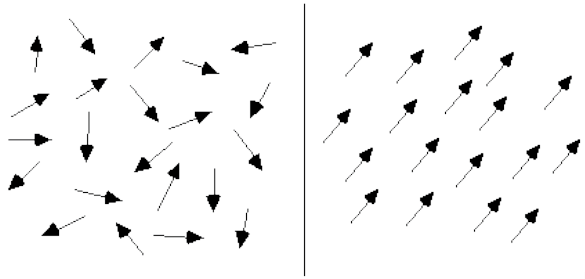
Spontaneously broken Gauge Symmetry $\Rightarrow$ Massive gauge boson

Spontaneous Symmetry Breaking (SSB)

SSB : Ground State NOT Symm , Microscopic laws Symm

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



[Fig by F. Heylighen]

- In Analogy to this, in QFT,
  - Vacuum Expectation Value (VEV) of a field breaks Internal Symm
  - SM Higgs VEV breaks EW Symm

The role of the Higgs boson in the SM

Spontaneous Electroweak Symmetry Breaking : (Give masses to $W^{\pm}$, Z)

Give fermions mass

Unitarize WW scattering [Lee, Quigg, Thacker, 1977]

But... a fundamental scalar comes with its own problems. More on this later.

The hunt for the Higgs is on!

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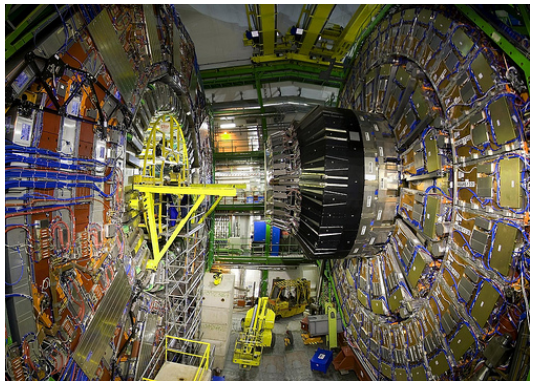
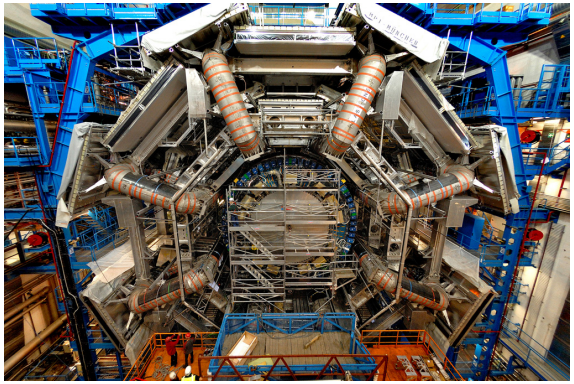
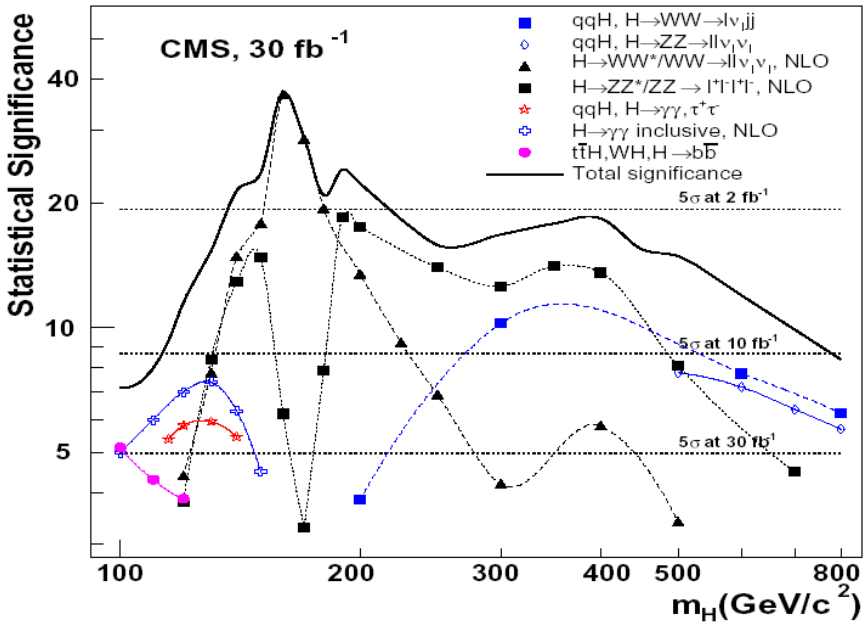
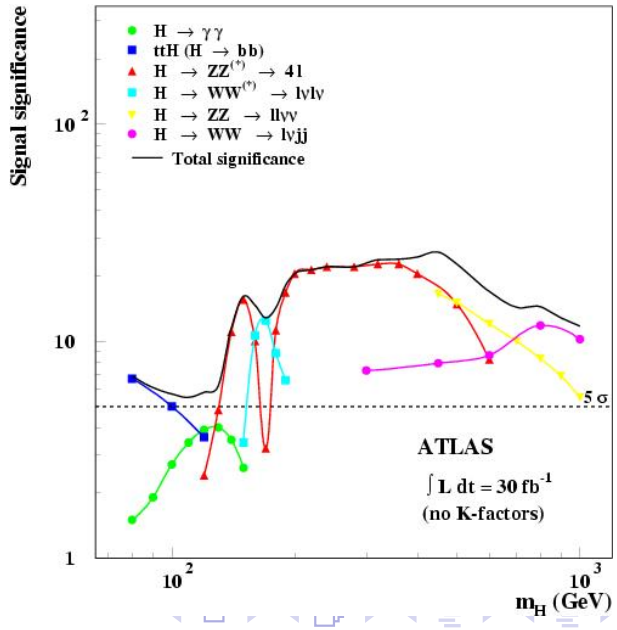
The Large Hadron Collider (LHC)

What new physics will the LHC find? How far can it go?

Higgs Significance at the LHC





But... the SM is not without problems

Gauge hierarchy problem

- Higgs sector unstable (quadratic divergence)

Fermion mass hierarchy problem

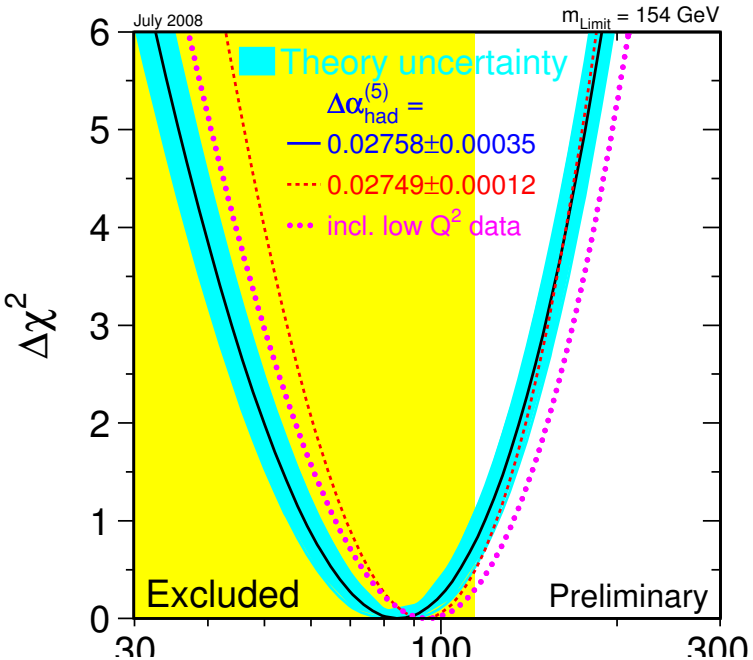
- Flavor symmetry?
- Challenge : Tiny neutrino masses
- Is neutrino Majorana or is it Dirac?

Cosmology connection

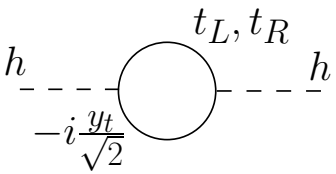
- What is the dark matter
- Inadequate source of CP vioation for observed baryon asymmetry
- Cosmological constant problem

Hierarchy problem in detail

LEP indicates that the Higgs boson is light



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



$$\delta m_h^2 = -\frac{3y_t^2}{16\pi^2}\Lambda^2$$

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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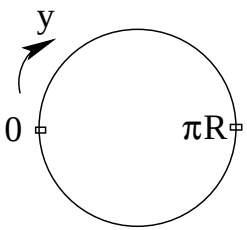
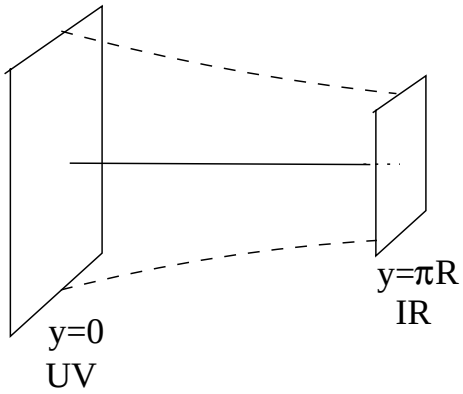
Eg: 5-D Warped Extra-dimensions

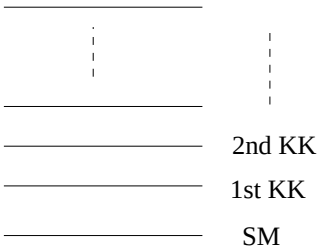
[Randall, Sundrum, 99]

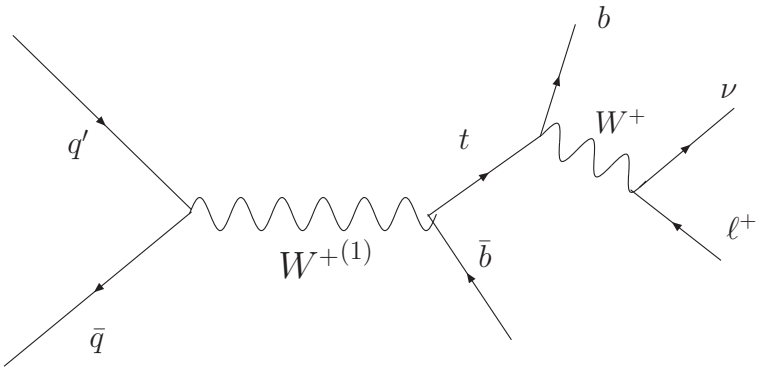
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$





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



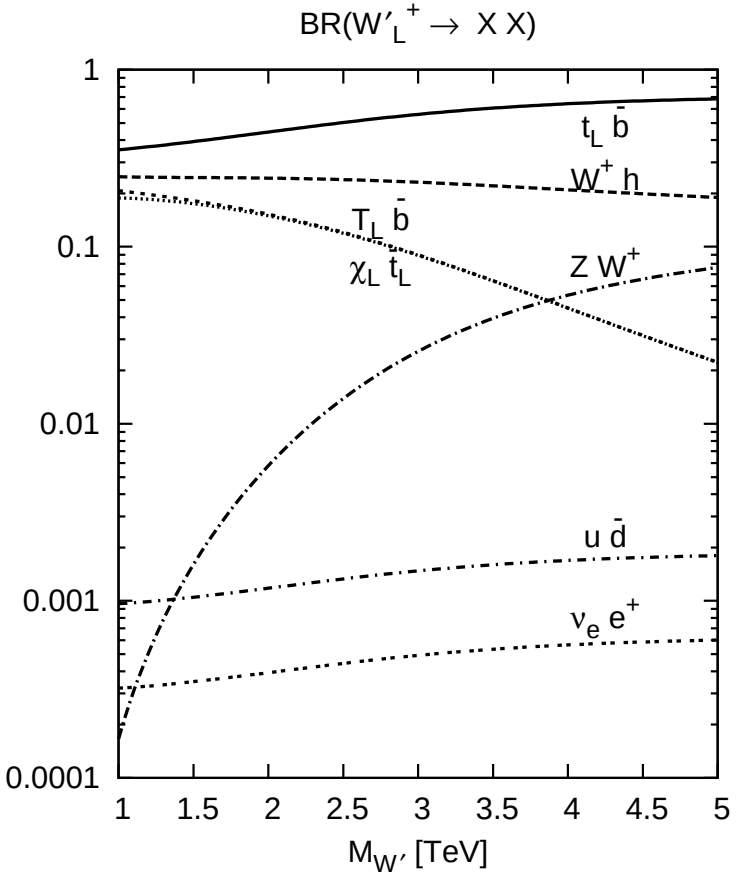


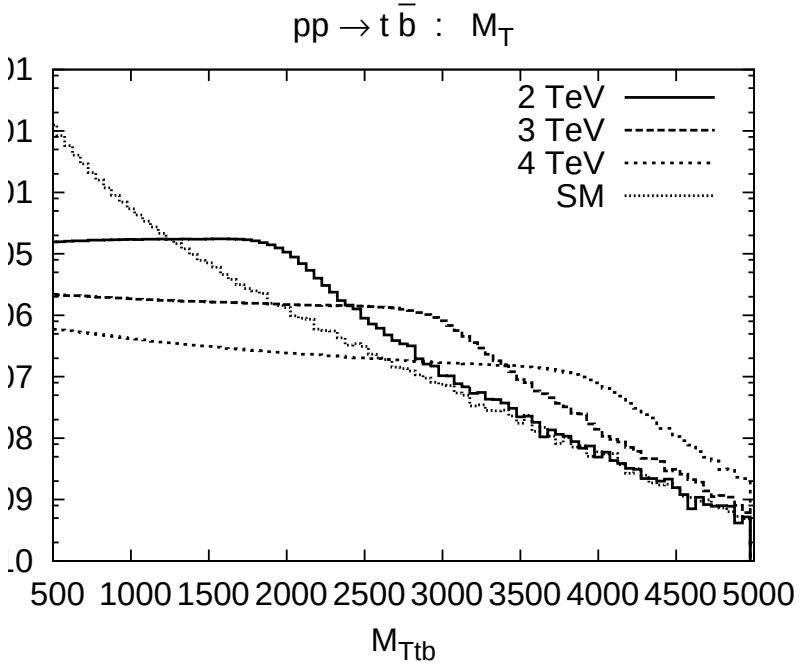
Warped Ex-Dim at LHC

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

Example: $W' \to XX$

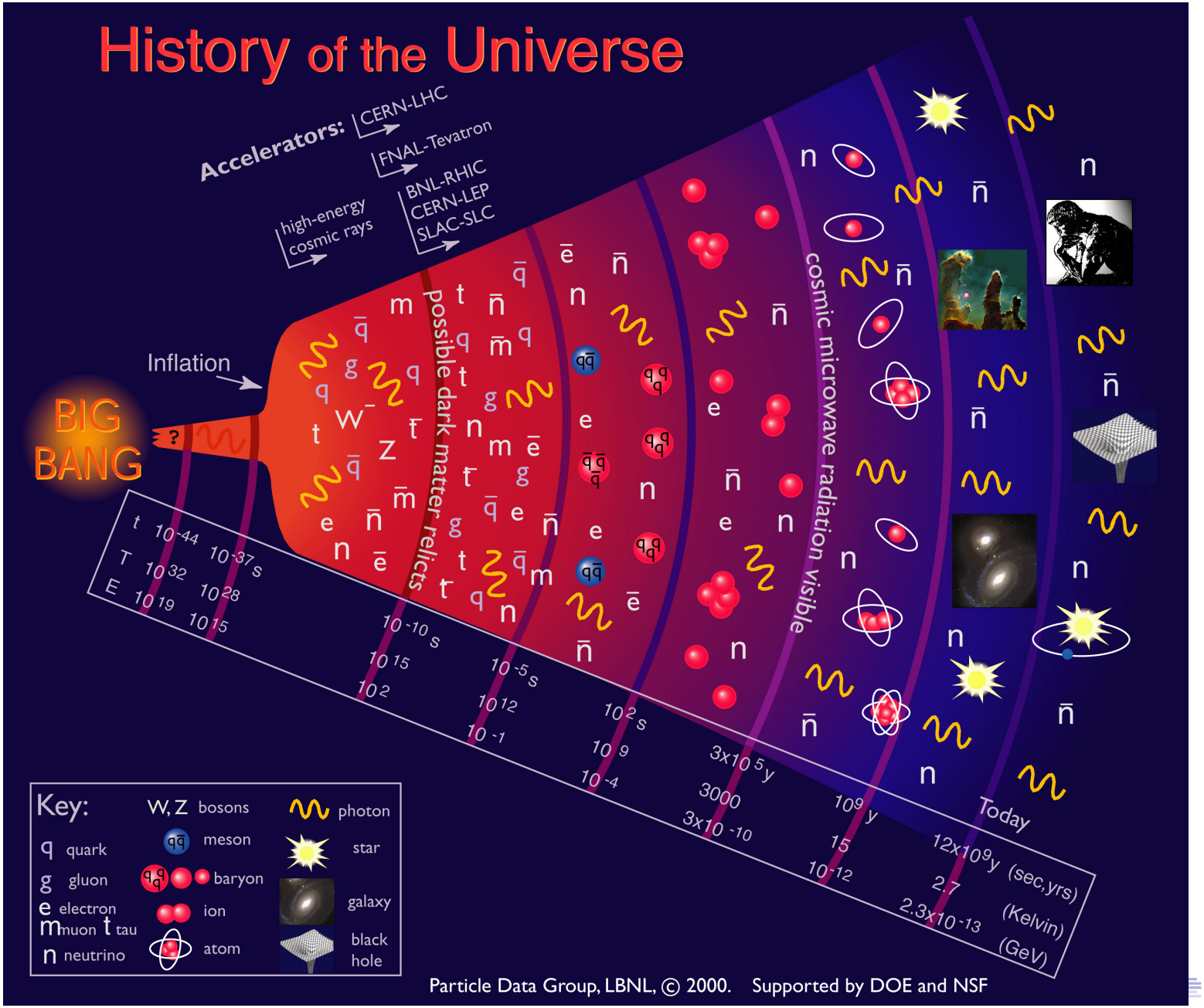
$pp \to W' \to t\bar{b} \to Wb\bar{b} \to \ell\nu b\bar{b}$



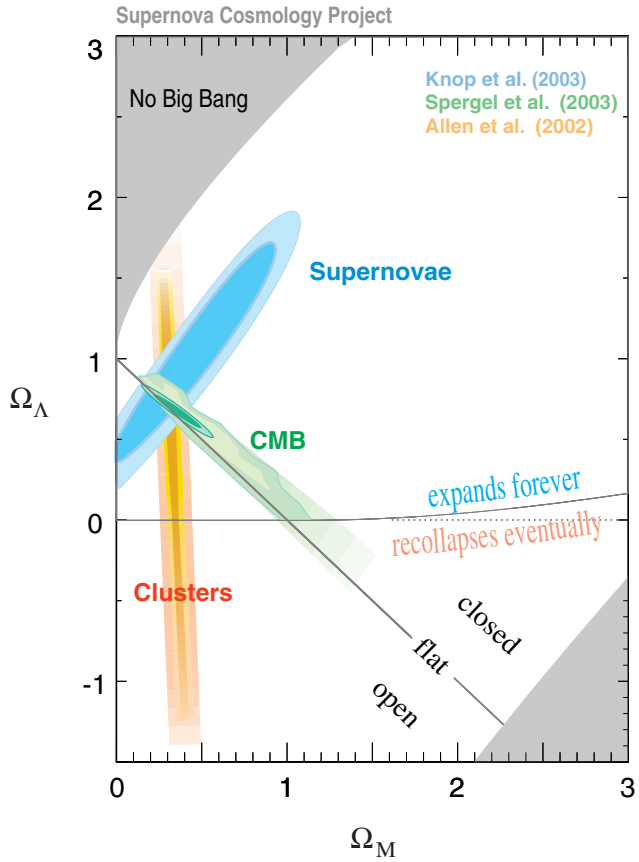


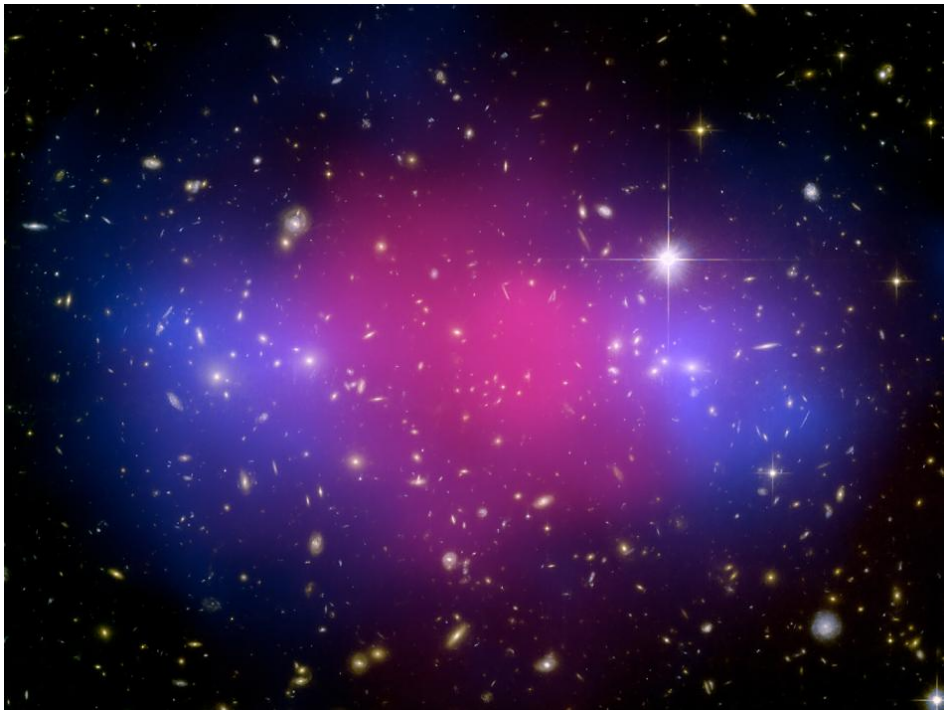
[Agashe, SG, Han, Huang, Soni, 2008]

Particle Physics and the Universe



Evidence for Dark Matter (DM)



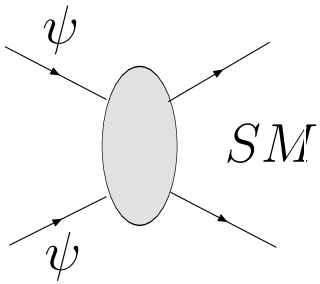


Bullet Cluster [Hubble+Chandra, NASA, ESA, CXC, M. Bradac (UCSB), and S. Allen (Stanford)]

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

Particle Dark Matter (DM)

Self-Annihilation cross-section gives present DM Relic density



$$\Omega_0 h^2 = 10^{-29} x_f \left(\frac{eV^{-2}}{\langle \sigma v \rangle} \right)$$

Doesn't apply to Non-thermal DM [Rt Sneutrino DM & LHC Signatures: de Gouvea, SG, Porod, 06]

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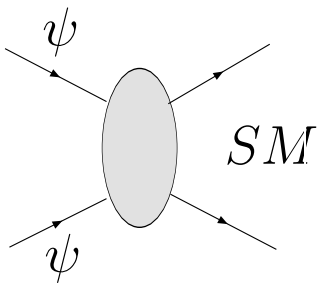

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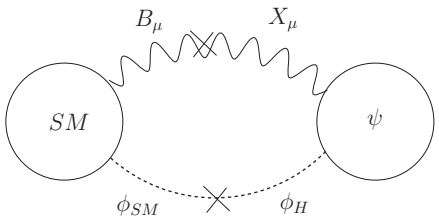
$U(1)_X$ Hidden sector

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

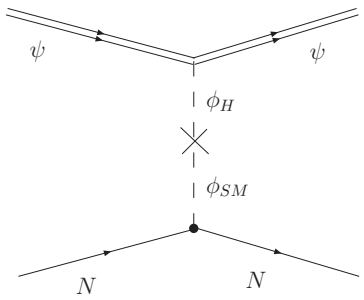
Accidental Z_2 symmetry : $\psi \to -\psi$, $SM \to SM$

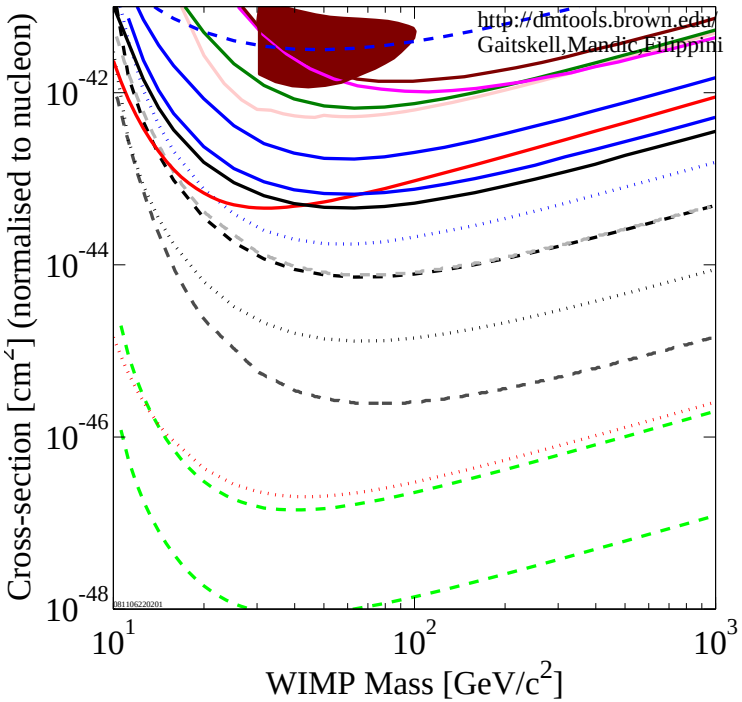
- So ψ cosmologically stable $\Longrightarrow$ Dark Matter



Direct Detection? Hidden sector signature at the LHC?

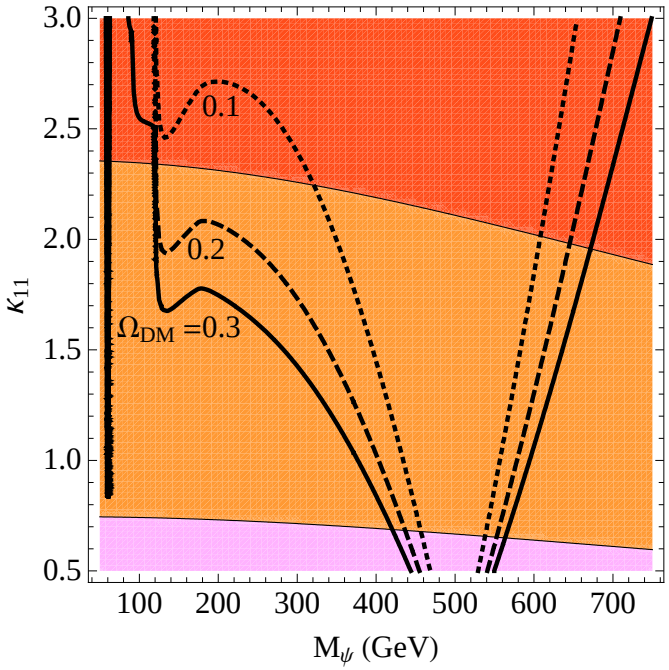
Direct Detection

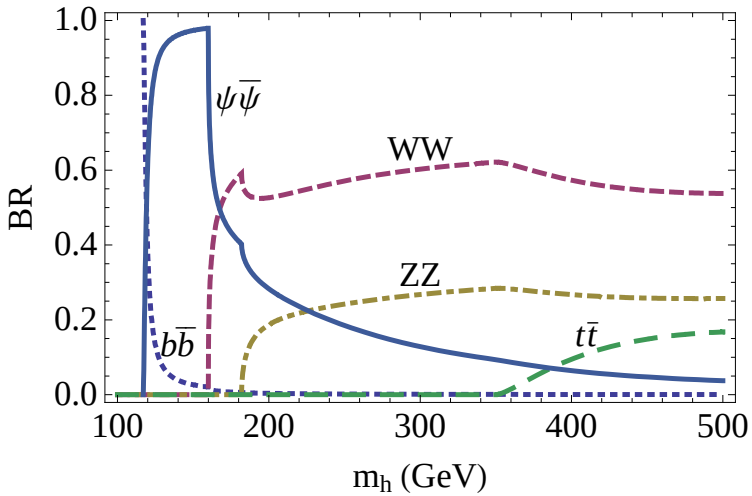




Hidden Sector Dark Matter at LHC

[SG, Lee, Wells:2009]





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

Conclusions

Compelling arguments for new physics at the LHC

- Higgs discovery expected
- Physics responsible for stability of EW scale

Exciting Times !

Cosmology connection

Unexpected physics shows up?

LHC inverse problem to get underlying physics

BACKUP SLIDES

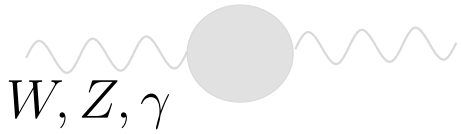
New Physics Expectation

Resonable to demand $\frac{m_h^2}{\delta m_h^2} \gtrsim 0.1$

- For $t_{L,R}$ loop $\Rightarrow$ $\Lambda_{NP} \lesssim 2.5\ TeV$
- So new physics should show up before this

Why didn't LEP collider see hints of this :

S, T parameters, $Z\, b\, \bar{b}$, ...



"LEP paradox" , "Little hierarchy problem"

Why not more convincing FCNC deviations?

No dynamical explanation? Landscape of vacuua?

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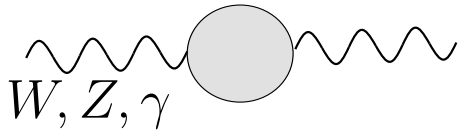

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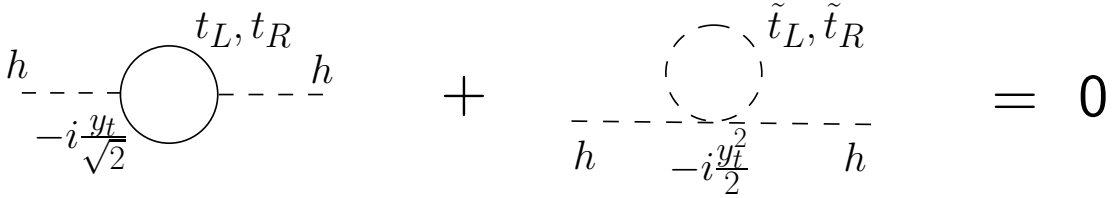
Supersymmetry (SUSY)

SUSY: Fermions $\Leftrightarrow$ Bosons : (Doubles particle spectrum)



Λ^2 divergence cancelled

Proton stability needs R_p symmetry $\Rightarrow$Dark Matter!

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

Includes $\nu_R \Rightarrow$ Neutrino seesaw mass

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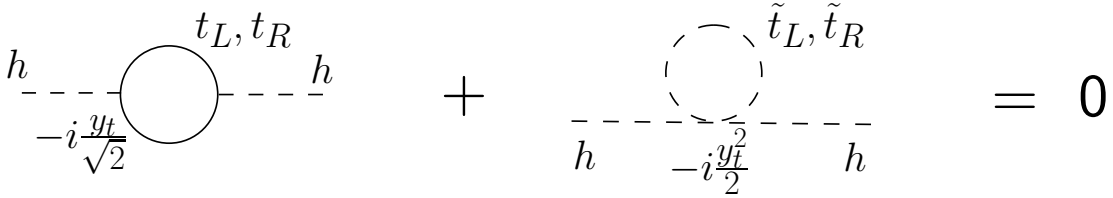

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SUSY breaking

SUSY has to be broken

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

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: $\delta m_h^2 \lesssim \frac{3}{4\pi^2}\, y_t^2\, m_t^2\, log\, \frac{\tilde{m}_1 \tilde{m}_2}{m_t^2}$

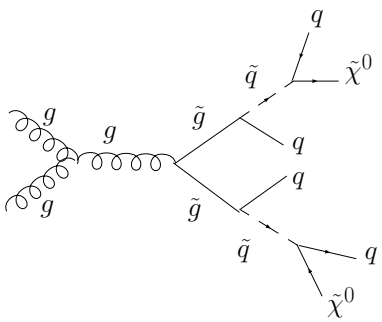
LEP Higgs bound needs heavy stop $\Rightarrow$ Increased fine tuning

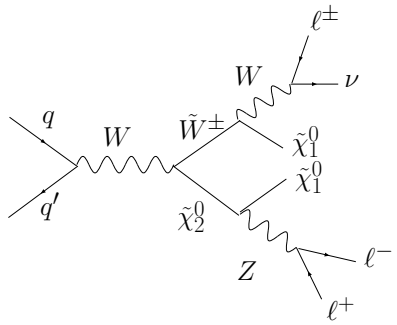
FCNC effects in $b \longrightarrow s\bar{s}s$?

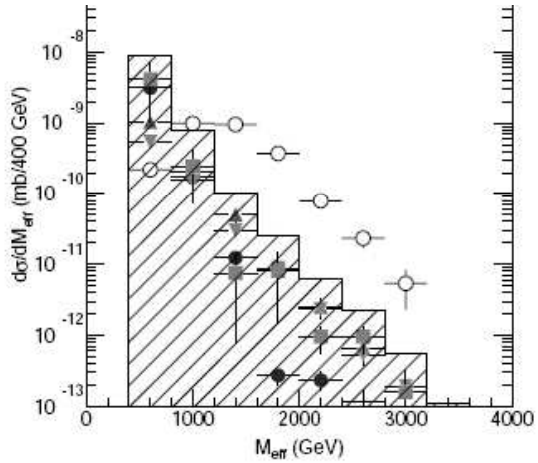
[SG,Yuan,2004]

SUSY at LHC

- Cascade decays
- Missing energy signals







[ATLAS Physics TDR]

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