

New Physics Expectations at the Large Hadron Collider

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The Standard Model

Building blocks:

[particleadventure.org]

FERMIONS			matter constituents		
			spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e lightest neutrino*	$(0-0.13)\times 10^{-9}$	0	u up	0.002	2/3
e electron	0.000511	-1	d down	0.005	-1/3
ν_μ middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0	t top	173	2/3
τ tau	1.777	-1	b bottom	4.2	-1/3

BOSONS			force carriers		
			spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W⁻	80.39	-1			
W⁺	80.39	+1			
W bosons					
Z⁰	91.188	0			
Z boson					

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

The role of the Higgs boson

Spontaneous Electroweak Symmetry Breaking : (Give masses to W^\pm, Z)
 $\mathcal{L} \supset D_\mu H^\dagger D^\mu H + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 \quad D_\mu = \partial_\mu - igW_\mu \quad \langle H \rangle \neq 0$

Give fermions mass : $L \supset \lambda H \bar{\psi} \psi$ CP violating Yukawa couplings !

Unitarize WW scattering :

[Lee, Quigg, Thacker, 1977]



$$\mathcal{M} = \sum (2l+1) a_l P_l(\cos\theta)$$

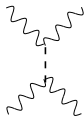
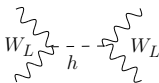
$$a_l = A (q/m_W)^4 + B (q/m_W)^2 + C$$

Perturbative Unitarity: $|a_l| \leq 1$

$A = 0$ by gauge invariance

B term bad high-energy behavior

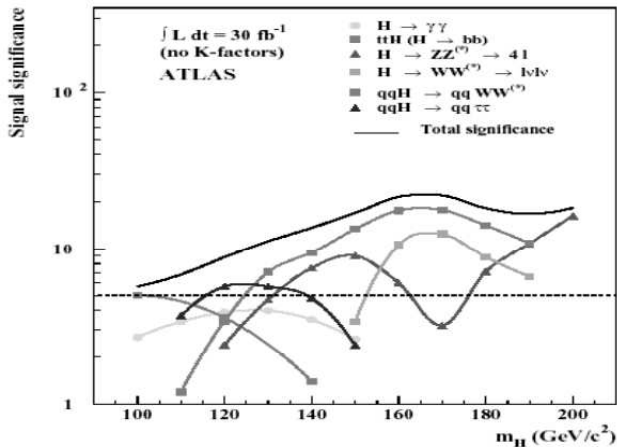
Deconstruction of Higgsless Theories : [Foadi, SG, Schmidt, 03, 04]



Cancels B , delays unitarity violation

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

Higgs at the LHC



Gauge hierarchy problem

- Higgs sector unstable (quadratic divergence)

Fermion mass hierarchy problem

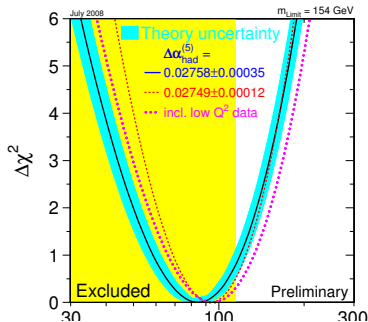
- Flavor symmetry?
- Challenge : Tiny neutrino masses
- Is neutrino Majorana or is it Dirac?

Cosmology connection

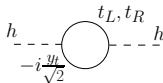
- What is the dark matter
- Inadequate source of CP violation for observed baryon asymmetry
- Cosmological constant problem

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 Expectation

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

- For $t_{L,R}$ loop $\Rightarrow \Lambda_{NP} \lesssim 2.5 \text{ TeV}$
- 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 vacua?

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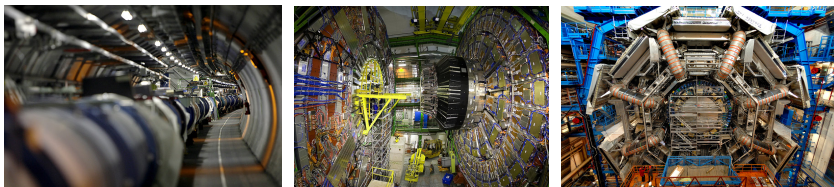


“LEP paradox” , “Little hierarchy problem”

Why not more convincing FCNC deviations?

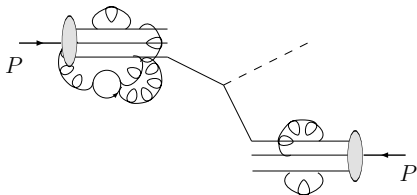
No dynamical explanation? Landscape of vacua?

The Large Hadron Collider (LHC)

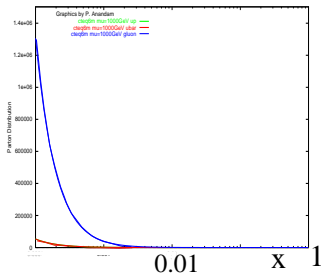


What new physics will the LHC find? How far can it go?

Keep in mind parton distribution function (pdf)



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



[Anandam,Soper,CTEQ]

Supersymmetry

Extra-dimensions : Warped or Flat

[Constraints and LHC Signatures in ADD: Cao, SG, Yuan, 2003]

Strong dynamics (Note AdS-CFT correspondence)

Neutrino mass connection and lepton number violation

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

Dark Matter signals (Missing Energy)

Supersymmetry (SUSY)

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

Superpotential $\mathcal{W} \supset y_t t_R^c Q H_u$

$$\mathcal{L} \supset -\frac{1}{2} \frac{\partial^2 \mathcal{W}}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + h.c. - \left| \frac{\partial \mathcal{W}}{\partial \phi_i} \right|^2$$

$$\text{Tree-level loop} + \text{One-loop diagram} = 0$$

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

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: $m_h < m_Z$.

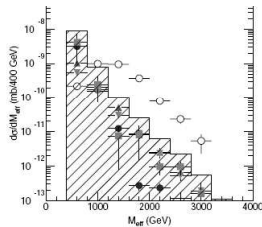
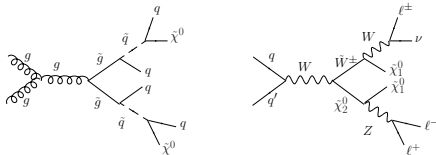
- But LEP bound $m_h \gtrsim 114 \text{ GeV}$
- Sizable one loop correction: $\delta m_h^2 \lesssim \frac{3}{4\pi^2} y_t^2 m_t^2 \log \frac{\tilde{m}_1 \tilde{m}_2}{m_t^2}$

LEP Higgs bound needs heavy stop \Rightarrow Increased fine tuning

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

[SG,Yuan,2004]

- Cascade decays
- Missing energy signals



[ATLAS Physics TDR]

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

Warped Extra-dimensions

5D Warped Space

[Randall, Sundrum, 99]

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

Z_2 Orbifold -

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

R : radius of Ex. Dim.

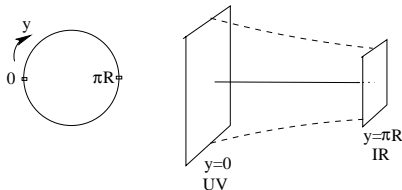
k : curvature

Hierarchy prob soln:

- TeV Brane Higgs : $M_{EW} \sim ke^{-k\pi R}$: Choose $k\pi R \sim 34$

Bulk fields \rightarrow AdS/CFT

- Bulk Fermions explain flavor (FCNC's safe)

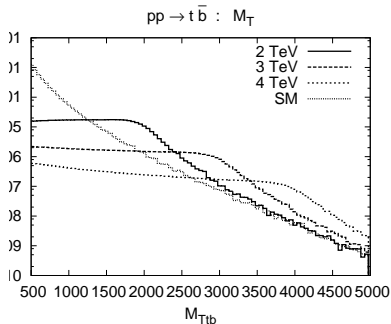
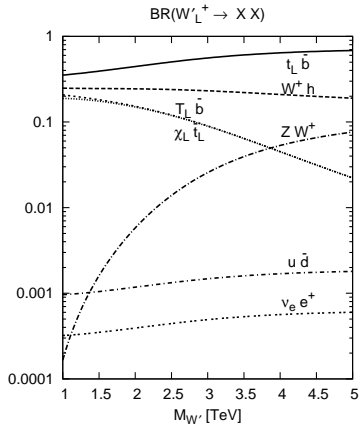


Warped Ex-Dim at LHC

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

Example: $W' \rightarrow XX$

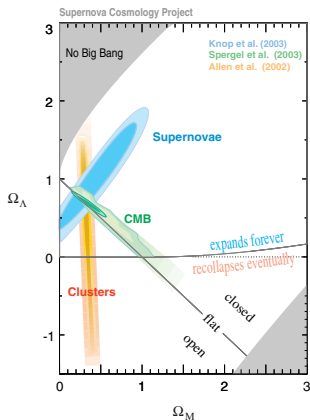
$pp \rightarrow W' \rightarrow t\bar{b} \rightarrow Wb\bar{b} \rightarrow \ell\nu b\bar{b}$



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

The Cosmology Connection

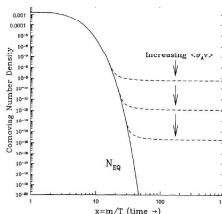
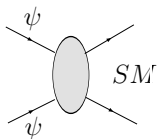
Evidence for dark matter



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

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

Self-Annihilation and Freeze-out



[Kolb & Turner]

$$\sigma v_{rel} = a + b v_{rel}^2 + O(v_{rel}^4)$$

$$\langle\sigma v\rangle = a + b/x_f \quad x_f \equiv M_\psi/T_f \approx 21$$

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

Doesn't apply to Non-thermal DM

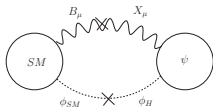
[Rt Sneutrino DM & LHC Signatures: de Gouvea, SG, Porod, 06]

[SG, Lee, Wells: ongoing]

$$\mathcal{L} \supset \bar{\psi} i \gamma^\mu D_\mu \psi + \kappa \phi_H \bar{\psi} \psi$$

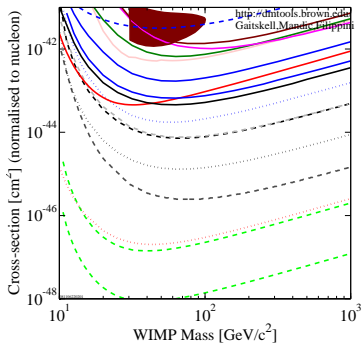
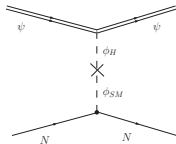
Accidental Z_2 symmetry : $\psi \rightarrow -\psi$, $SM \rightarrow SM$

- So ψ cosmologically stable \implies **Dark Matter**



Hidden sector signature at the LHC?

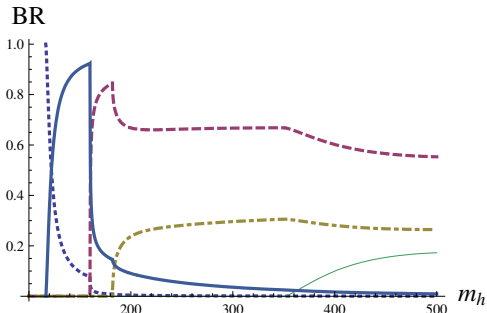
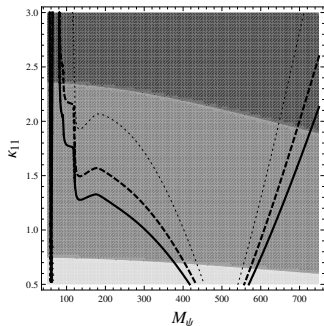
Direct Detection



- DATA listed top to bottom on plot
- CDMS (Soudan) 2005 Si (7 keV threshold)
- Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003 limit
- DAMA 2000 58kg kg-days Natl Ann. Mod. Sigma w/DAMA 1996
- WARP 2.3L, 96.5 kg-days 55 keV threshold
- ZEPLIN II (Jan 2007) result
- CRESST 2007 60 kg-day CaWO4
- CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
- CDMS 2008 Ge
- CDMS: 2004+2005 (reanalysis) + 2008 Ge
- XENON10 2007 (Net 136 kg-d)
- CDMS Soudan 2007 projected
- DEAP-CLEAN 25kg FV (proj)
- SuperCDMS (Projected) 2-ST @ Soudan
- SuperCDMS (Projected) 2-Skg (7-ST@Snolab)
- DEAP-CLEAN 100kg FV (proj)
- XENON1T (projected, 1 ton-year exposure)
- LUX/ZEP 1 tonne LXe Proj (3 tonne-year)
- LUX/ZEP 20 tonne LXe Proj (48 tonne-year)

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Hidden Sector Dark Matter at LHC



Look for signal in $pp \rightarrow jj + \cancel{E}_T$

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