Research in High Energy Physics - Phenomenology

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Institute of Mathematical Sciences (IMSc), Chennai

Graduate Student Talk
IMSc
Feb 2014

High Energy Physics - Phenomenology

Study of the Fundamental Particles, Physical Laws and Organizing Principles in Nature & their Experimental Tests

HEP - Phenomenology @ IMSc

Faculty Members

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- M.V.N Murthy
- Nita Sinha
- Rahul Sinha
- Ravindran
- Rajasekaran
- Shrihari Gopalakrishna

Post-doctoral Fellows

- Hijam Zeen Devi
- Rahul Srivastava
- Saurabh Gupta
- Sunanda Patra
- Tapasi Ghosh

Graduate Students

- Arithra Biswas
- Dibyakrupa Sahoo
- Dhargyal
- Rusa Mandal
- Soumya Sadhukhan
- Tanmoy Modak
- Tuhin Subhra Mukherjee

INO Graduate Students

- Lakshmi S. Mohan
- Meghana K.K.
- Kanishka Rawat

HRI Graduate Students

- Maguni Mahakhud
- Narayan Rana
- Taushif Ahmed

Recent Alumni

- Diganta Das (Dortmund)
- Saveetha (IMSc)
- Subhadip Mitra (Orsay/Paris)
- Sumantha Pal (Edinburgh)
- Tanumoy Mandal (HRI)

Pheno Club Email List : *Pheno@imsc.res.in*

Please sign-up for announcements

The 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

Added Higgs in 2012

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

Standard Model (SM) theoretical structure

- Gauge Theory, Relativistic Quantum Field Theory (QFT)
  - $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge group (Internal Symmetry)
    - Strong, Weak, Electromagnetic Interactions

Eg: EM (QED) is $U(1)$ gauge symmetry

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Eg: EM (QED) is $U(1)$ gauge symmetry

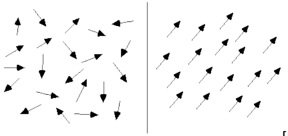
Some Gauge Symmetries Spontaneously broken $\Rightarrow$ Massive Weak gauge bosons

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

Spontaneous Symmetry Breaking (SSB)

SSB : Microscopic laws symmetric, but ground state is NOT

- Analogy: Spontaneous Magnetization in Condensed Matter Systems



[Fig by F. Heylighen]

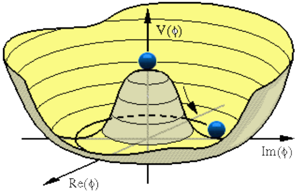
- Higgs Mechanism in QFT
  - $\mathcal{L}$ is invariant under Gauge Symmetry, but nonzero Vacuum Expectation Value (VEV) of Higgs field breaks EW symmetry

The Higgs Mechanism in the SM

$$\mathcal{L} \supset (D_\mu H)^\dagger D^\mu H + \mu^2 H^\dagger H - \frac{\lambda}{4!} (H^\dagger H)^2$$

Spontaneous Breaking of Electroweak Symmetry

$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$ (The E-B-Higgs-G-H-K Mechanism)



- Give masses to $W^\pm$, Z (γ massless)
- Generates fermion masses

$$\mathcal{L}_{Yuk} \supset -\lambda_u \overline{Q} \tilde{H} u_R - \lambda_d \overline{Q} H d_R - \lambda_e \overline{L} H e_R + h.c.$$

Under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

$H = (1,2)_{1/2}$

$Q \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}$; $u_R = (3,1)_{2/3}$

$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}$; $e_R = (1,1)_{-1}$

- Complex Yukawa couplings $\lambda \implies$ CP violation
- Unitarize WW scattering

[Lee, Quigg, Thacker, 1977]

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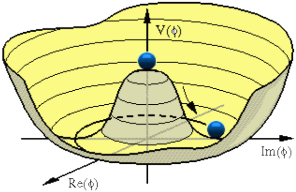

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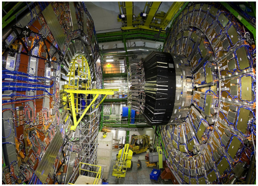
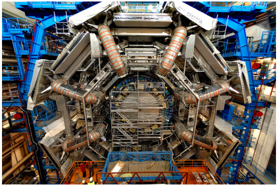
- Complex Yukawa couplings $\lambda \implies$ CP violation
- Unitarize WW scattering [Lee, Quigg, Thacker, 1977]

But, mass of a fundamental scalar is not protected against getting large quantum correction. We'll come back to this ...

The Large Hadron Collider (LHC)

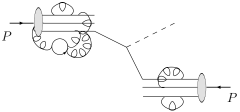




Seen the Higgs. Continue searching for more ...

Higgs Production @ LHC

LHC is a $p - p$ collider



p contains partons: $g, u, d, \bar{u}, \bar{d}, \ldots$

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

Parton momentum is fraction of $\sqrt{S}$:
parton distribution function (pdf)

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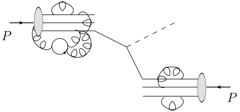

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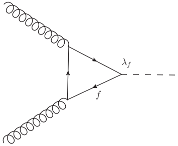
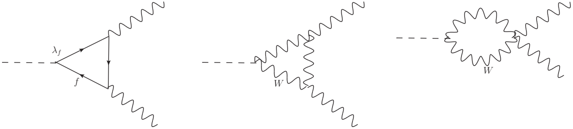
parton distribution function (pdf)

$pp \to h \to \gamma\gamma$ @ LHC

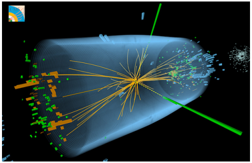
$\sigma(gg \to h)$

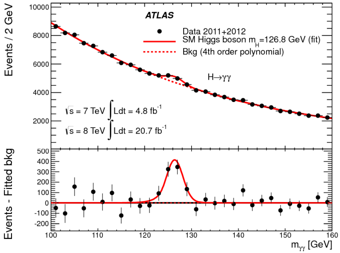


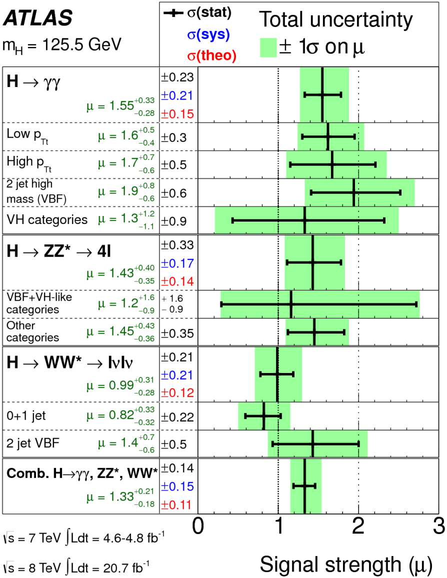
$\Gamma(h \to \gamma\gamma)$



LHC Higgs Measurements







The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013


Photo: A. Mahmoud
François Englert


Photo: A. Mahmoud
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

Are we done?

Are we done?

I don't think so ...

Motivation for Physics Beyond the Standard Model (BSM)

Observational

- What is the observed Dark Matter?
- What generates the Baryon Asymmetry of the Universe (BAU)?
- What generates the neutrino masses?

Theoretical

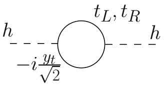
- SM hierarchy problem (Higgs sector): $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
  - Extra dimensions (Warped (AdS), Flat)
  - Supersymmetry
  - Strong dynamics
  - Little Higgs

Hierarchy problem in detail

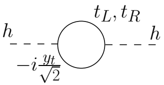
LHC (and LEP) tell us that the Higgs boson is light $m_h = 126$ GeV

$$\mathcal{L} \supset \frac{1}{2}\mu^2 H^\dagger H - \frac{\lambda}{4!}\left(H^\dagger H\right)^2$$

No symmetry protecting the Higgs mass!



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



(Λ is momentum cut-off, say M_{pl})

Quadratic divergence in the Higgs sector

New physics possibilities

- Belief that some new physics cures these problems
- Look for these at the LHC

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Supersymmetry

[SG,Yuan,2004]

Extra-dimensions : (Warped or Flat)
[Mandal, Mitra, Moreau, SG, Tibrewala 2011, 13][Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni,, 2007, 08, 10] [Cao, SG, Yuan, 2003]

Strong dynamics (Note AdS-CFT correspondence)

Little Higgs

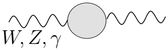
Neutrino mass connection and lepton number violation
[EDM with Triplet Higgs: de Gouvea, SG, 2005]

Dark Matter candidates

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

Precision Probes of BSM

In addition to Collider probes, New Physics can also be probed in:



- Precision Electroweak Probes (S, T, $Zb\bar{b}$)
- Flavor Changing Neutral Currents (FCNC)
  - $K^0\bar{K}^0$ mixing, $b \to s\gamma$, $b \to s\,\ell^+\ell^-$, $b \to s\,s\,\bar{s}$, $K \to \pi\nu\bar{\nu}$, $b \to \tau\nu X$, ...
  - Relaxed with flavor alignment : MFV, flavor symmetries
- $(g-2)_\mu$, EDM, ...

Generally result in bound : $M_{BSM} \gtrsim few - 100$ TeV

SUPERSYMMETRY

Supersymmetry (SUSY)

Reviews: [Wess & Bagger]

Symmetry: Fermions ⇔ Bosons

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

Q_α is a spinorial charge

SUSY algebra:

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

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

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

Under a SUSY transformation

$$\delta_\xi\phi = \sqrt{2}\xi\psi$$
$$\delta_\xi\psi = i\sqrt{2}\sigma^m\bar\xi\partial_m\phi + \sqrt{2}\xi F$$
$$\delta_\xi F = i\sqrt{2}\bar\xi\bar\sigma^m\partial_m\psi$$

$$\delta_\xi A_{mn} = i\left[\left(\xi\sigma^n\partial_m\bar\lambda + \bar\xi\bar\sigma^n\partial_m\lambda\right) - (n\leftrightarrow m)\right]$$
$$\delta_\xi\lambda = i\xi D + \sigma^{mn}\xi A_{mn}$$
$$\delta_\xi D = \bar\xi\bar\sigma^m\partial_m\lambda - \xi\sigma^m\partial_m\bar\lambda$$

Supersymmetry (SUSY)

Reviews: [Wess & Bagger]

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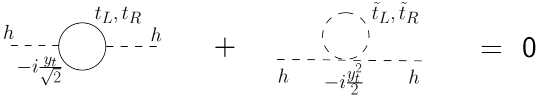
$$\delta_\xi\lambda = i\xi D + \sigma^{mn}\xi A_{mn}$$

$$\delta_\xi D = \bar{\xi}\bar{\sigma}^m\partial_m\lambda - \xi\sigma^m\partial_m\bar{\lambda}$$

Consequences

Solution to gauge hierarchy problem



Λ^2 divergence cancelled [Romesh Kaul, '81, '82] [Witten]

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

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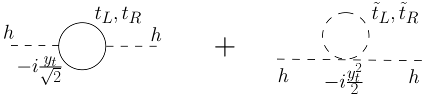


$= 0$

Λ^2 divergence cancelled [Romesh Kaul, '81, '82] [Witten]

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

- Lightest SUSY Particle (LSP) stable dark matter (if R_p conserved)
- Gauge Coupling Unification - SUSY $SO(10)$ GUT
  Includes $\nu_R \Rightarrow$ Neutrino mass via seesaw

SUSY breaking

- Exact SUSY $\Longrightarrow$ $M_\psi = M_\phi \quad ; \quad M_A = M_{\tilde{\lambda}}$
  - So experiment $\Longrightarrow$ SUSY must be broken
- Supersymmetrize the SM + SUSY breaking $\rightarrow$ Minimal Supersymmtric Standard Model (MSSM)

125 GeV Higgs in the MSSM

At 1-loop [Haber, Hempfling, Hoang, 1997]

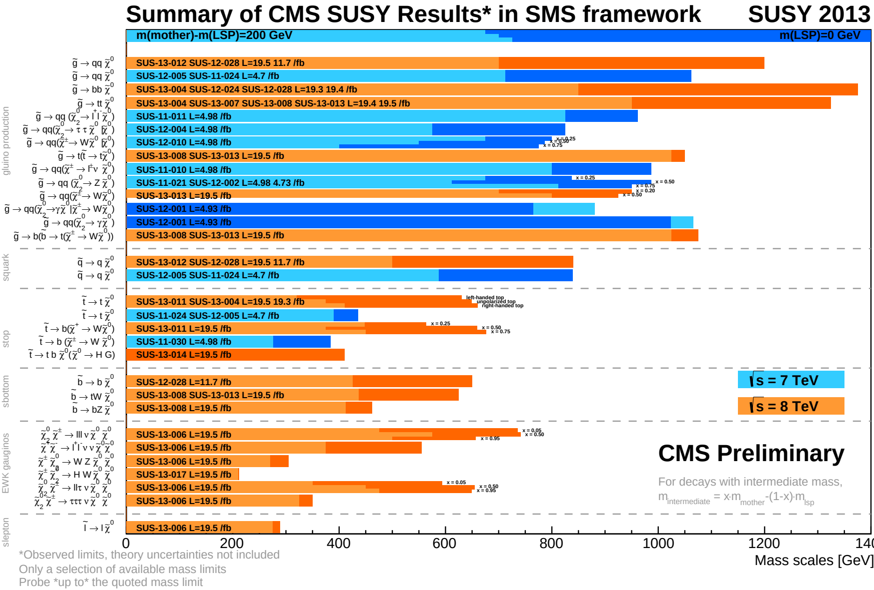
$$m_h^2 \approx m_Z^2 \cos^2(2\beta) + \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$$

where $X_t = A_t - \mu \cot\beta$

- $m_h = 125$ GeV needs sizable loop contribution
  - Hard! Needs large $m_{\tilde{t}_1} m_{\tilde{t}_2}$ or large X_t^2
  - But $\delta m_{H_u}^2 \approx \frac{3g_2^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{2 m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{6 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$

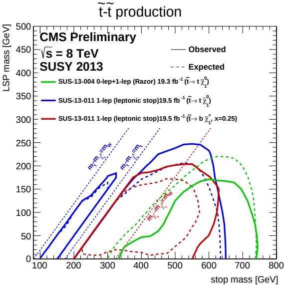
    So fine-tuning necessary to keep m_Z^2 correct

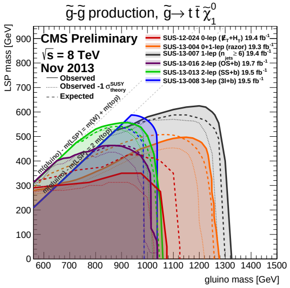
    "Little hierarchy problem"

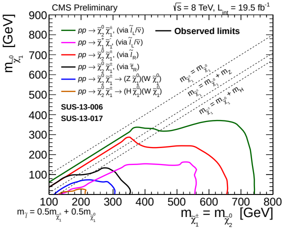


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother-(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

MSSM


t̃-t̃ production
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Expected
SUS-13-004 0-lep+1-lep (Razor) 19.3 fb⁻¹
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ x=0.25)
LSP mass [GeV]
stop mass [GeV]


g̃-g̃ production, g̃→ t t̄ χ̃⁰₁
CMS Preliminary
√s = 8 TeV
Nov 2013
Observed
Observed -1 σ theory SUSY
Expected
SUS-12-024 0-lep 19.4 fb⁻¹
SUS-13-004 0+1-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep 19.4 fb⁻¹
SUS-13-016 2-lep (OS+b) 19.7 fb⁻¹
SUS-13-013 2-lep (SS+b) 19.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
m(gluino) - m(LSP) = m(W) + m(top)
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]


CMS Preliminary
Observed limits
SUS-13-006
SUS-13-017
[GeV]

EXTRA DIMENSION(S)

Warped Extra Dimensions (WED, RS)

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

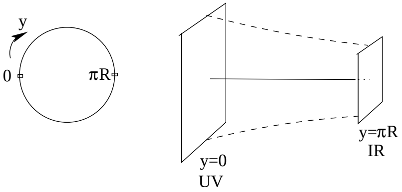
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$

Z_2 orbifold fixed points:

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

R : radius of Ex. Dim.

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

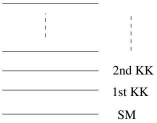


Hierarchy prob soln:

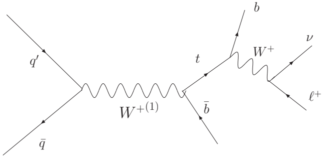
- IR localized Higgs : $M_{EW} \sim k e^{-k\pi R}$: Choose $k\pi R \sim 34$
  - Gauge Theory Dual may be a composite Higgs model

Equivalent 4D theory

- 5D (compact) field $\leftrightarrow$ "Infinite" tower of 4D fields
- Look for this tower at the LHC



Example:

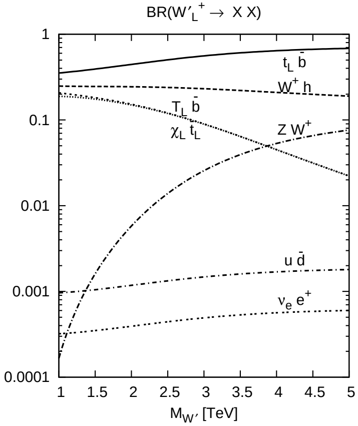


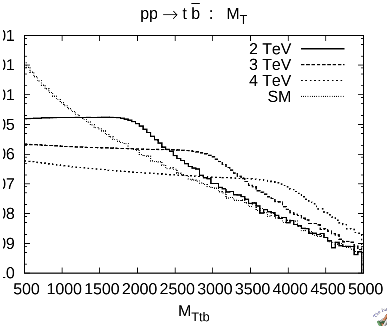
Warped Ex-Dim at LHC

Look for heavy Kaluza-Klein (KK) states : KK Gluon, Graviton, W, Z

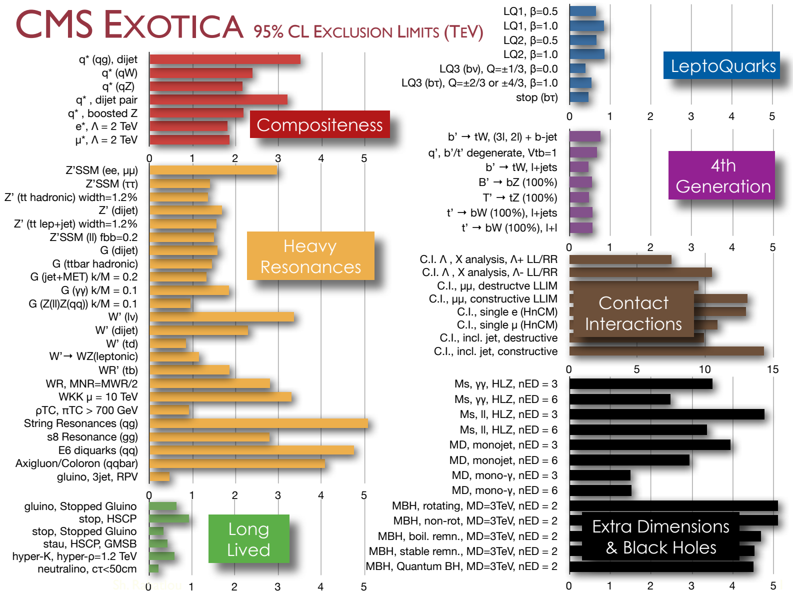
LEP precision electroweak constraints $\Rightarrow V' \gtrsim 2\ TeV$

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

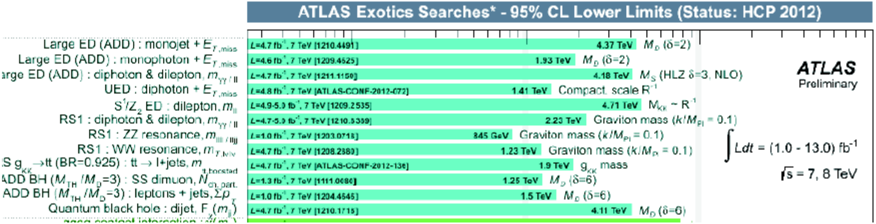




CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



ATLAS Extra Dimensions Limits (Moriond 2013)



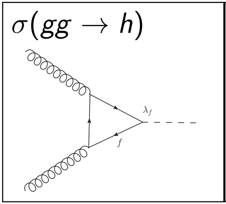
Fourth (Chiral) Generation

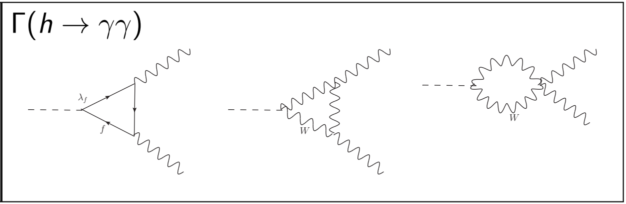
SM has 3 generations. Why not a fourth generation?

LHC strongly disfavors 4^{th} **Generation**!

Reason: In a Chiral theory M_f and $\bar{f}\, f\, h$ both given by λ_f

$gg \to h \to \gamma\gamma$ altered too much due to heavy Q_4 with large λ_{Q_4}





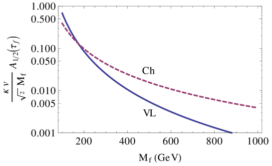
Vectorlike Fermions

Vector Like (VL) fermions: ψ_L , ψ_R : conjugate reps of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Can write $\mathcal{L} \supset -M_{VL}\bar{\psi}\psi$ consistent with SM Gauge Symmetry

so don't need large λ for large M_f

Vectorlike fermions		Chiral (4-gen) fermions
M ok with Gauge Symmetry		M only after EWSB i.e. $\langle H \rangle$
can be arbitrarily heavy		Landau pole in Yukawa coupling
CC + NC tree-level decays		only CC tree-level decays
loops decoupling		some loops nondecoupling



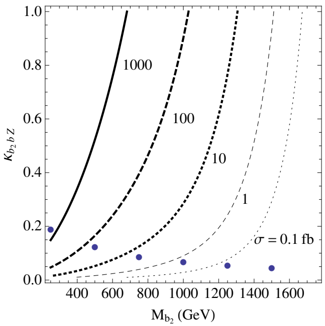
Vectorlike fermion Probes

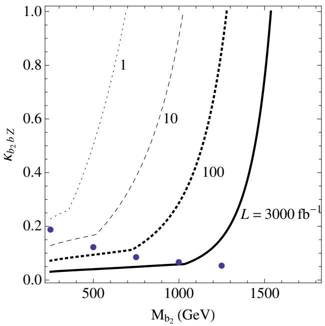
- How do we look for ψ_{VL} directly @ LHC?
  - t', b', χ Signatures [SG, Mandal, Mitra, Moreau, Tibrewala, 2011, '13]
- How do the ψ_{VL} modify 1-loop Higgs production and decay @ LHC? [S.Ellis, Godbole, SG, Wells, Ongoing]
- How do the ψ_{VL} modify precision EW observables (LEP)? [S.Ellis, Godbole, SG, Wells, Ongoing]

b' Single Production - II

[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306]

Single Production : $bg \to b'Z \to bZZ \to bjj\ell\ell$



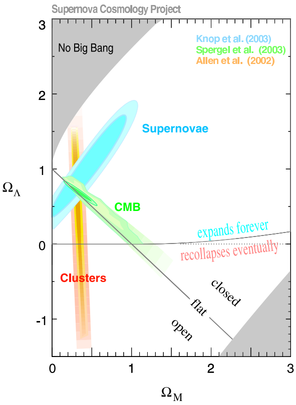


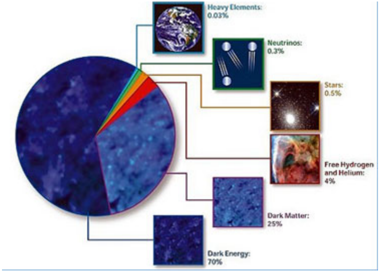
Cuts:

Rapidity: $-2.5 < y_{b,j,Z} < 2.5$,
Transverse momentum: $p_{T\,b,j,Z} > 0.1 M_{b_2}$,
Invariant mass cuts:
$M_Z - 10\ \text{GeV} < M_{jj} < M_Z + 10\ \text{GeV}$,
$0.95 M_{b_2} < M_{(bZ)\ OR\ (bjj)} < 1.05 M_{b_2}$.

Dark Matter Candidates from BSM

Observations tell us





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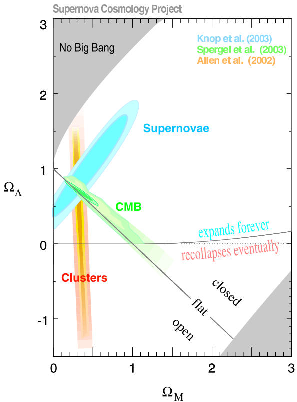
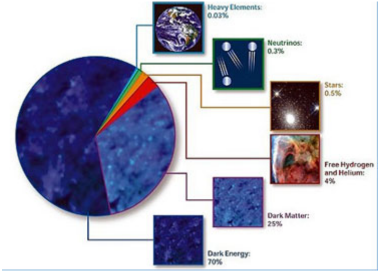
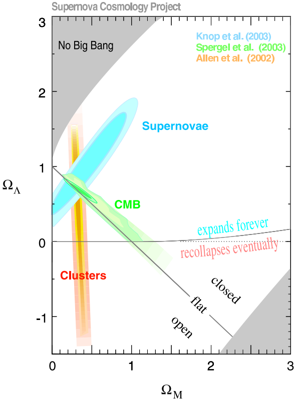
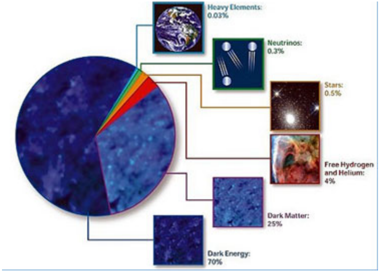




- **Flat** on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter** + **dark energy**
  - **What is it**??

Observations tell us





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The DARK SIDE rules!

What is the dark sector?

- Dark Matter
  - Astrophysical objects? (Disfavoured)
    - MAssive Compact Halo Objects (MACHO) or Black Holes or ...
  - Particle dark matter? More on this...
    - Hot or Warm or Cold Dark Matter (CDM)

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Particle DM Possibilities

- LSP - Lightest Supersymmetric Particle
- SuperWIMP - Gravitino (SUSY partner of graviton)
- E-WIMP - Right-handed sneutrino (partner of neutrino)
- WIMPzilla - Extremely massive particle
- LKP - Lightest Kaluza-Klein Particle - Extra space dimensions
- LTP - Lightest T-odd Particle - Little-higgs theory with Z_2
- Hidden sector DM

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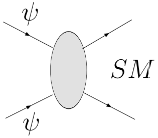
- Your candidate here

Particle Dark Matter (DM)

Self-Annihilation cross-section gives present DM Relic density



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

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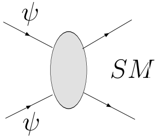


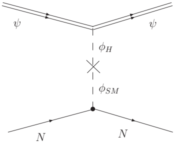
$$\Omega_0 h^2 = 10^{-29} x_f \left(\frac{eV^{-2}}{\langle \sigma v \rangle} \right)$$

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

Dark Matter Detection

- Direct Detection
  - DM directly intereacts with a detector
- Indirect Detection
  - Look for products of DM-DM annihilation
- Collider Detection
  - DM carries away invisible momentum

Direct Detection



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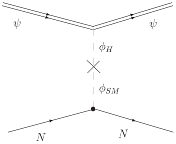
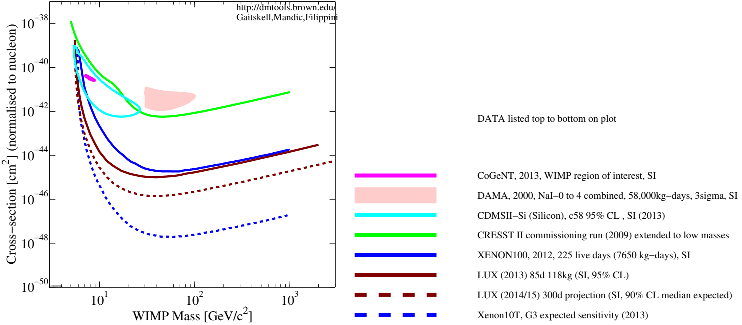
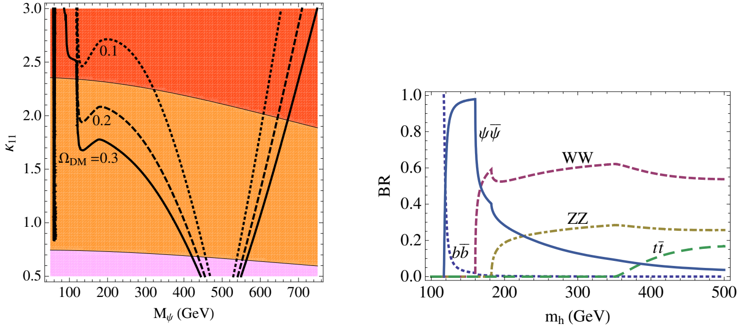




Hidden Sector Dark Matter at LHC

[SG, Lee, Wells:2009]



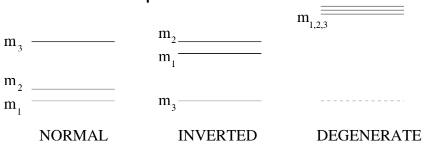
Look for LHC signal in $pp \to jj + \not{E}_T$

Neutrino Mass Generation

Neutrino Mass Generation

Questions

- What is the scale of m_ν
- Is the ν a DIRAC or MAJORANA particle? (Is $L_\#$ good?)
- Which mass spectrum?



- Is there CP violation in the lepton sector?

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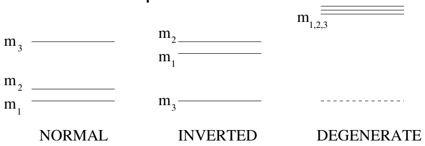


- Is there CP violation in the lepton sector?

Possible Answers

- Dirac ν : Add ν_R with TINY (10^{-12}) Yukawa coupling
- Type I seesaw: Add ν_R and a BIG (10^{11} GeV) mass
- Type II seesaw: Add SU(2) triplet scalar ξ with TINY (0.1 eV) VEV
- Type III seesaw: Add SU(2) triplet fermion Ξ
- Extra dimensions: Add BULK ν_R with BRANE coupling to ν_L

Conclusions

- Standard Model has shortcomings
  - Observational: DM, BAU, ν mass
  - Theoretical: Gauge (& flavor) hierarchy problem
- Beyond the Standard Model physics to resolve these
  - Supersymmetry, Extra dimension(s), Strong dynamics, Little Higgs, ...
- Which (if any) of these realized in Nature?
  - *Desperately seeking experimental guidance*
  - Experiments poised for discovery?
    - LHC7,8 constraints already nontrivial.
      LHC14 high luminosity run crucial
    - DM Direct, Indirect, Collider detection
    - Flavor and precision probes (Belle)

BACKUP SLIDES

BACKUP SLIDES

MSSM fields

To every SM particle, add a ***superpartner*** *(spin differs by* $1/2$*)*

Matter fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
Q	$(3,2)_{1/6}$	$(\tilde{q}_L, q_L, F_Q)$; $\tilde{q}_L = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$; $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
U^c	$(\bar{3},1)_{-2/3}$	$(\tilde{u}_R^*, u_R^c, F_U)$
D^c	$(\bar{3},1)_{1/3}$	$(\tilde{d}_R^*, d_R^c, F_D)$
L	$(1,2)_{-1/2}$	$(\tilde{\ell}_L, \ell_L, F_L)$; $\tilde{\ell}_L = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$; $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
E^c	$(1,1)_1$	$(\tilde{e}_R^*, e_R^c, F_E)$
(N^c)	$(1,1)_0$	$(\tilde{\nu}_R^*, \nu_R^c, F_N)$

Gauge fields
(Vector Superfields)

	Components
$SU(3)$	$(g_\mu, \tilde{g}, D_3)$
$SU(2)$	$(W_\mu, \tilde{W}, D_2)$
$U(1)$	$(B_\mu, \tilde{B}, D_1)$

Higgs fields (Chiral Superfields)

	$(SU(3), SU(2))_{U(1)}$	Components
H_u	$(1,2)_{1/2}$	$(h_u, \tilde{h}_u, F_{H_u})$; $h_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}$; $\tilde{h}_u = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix}$
H_d	$(1,2)_{-1/2}$	$(h_d, \tilde{h}_d, F_{H_d})$; $h_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$; $\tilde{h}_d = \begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$

AdS/CFT Correspondence

[Maldacena, 1997]

- A classical supergravity theory in $AdS_5 \times S_5$ at weak coupling is **dual** to a 4D large-N CFT at strong coupling
- The CFT is at the boundary of AdS [Witten 1998; Gubser, Klebanov, Polyakov 1998]

$$Z_{CFT}[\phi_0] = e^{-\Gamma_{AdS}[\phi_0]}$$

$\mathcal{S} \supset \int d^4x\, \mathcal{O}_{CFT}(x)\, \phi_0(x)$	$\Gamma_{AdS}[\phi]$ supergravity eff. action
Eg: $\langle \mathcal{O}(x_1)\, \mathcal{O}(x_2) \rangle = \frac{\delta^2 Z_{CFT}[\phi_0]}{\delta\phi_0(x_1)\delta(x_2)}$	$\phi(y,x)$ is a solution of the EOM ($\delta\Gamma = 0$)
with Z_{CFT} given by the RHS	for given bndry value $\phi_0(x) = \phi(y = y_0, x)$

4D Duals of Warped Models

[Arkani-Hamed, Porrati, Randall, 2000; Rattazzi, Zaffaroni, 2001]

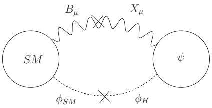
- Dual of Randall-Sundrum model **RS1 (SM on IR Brane)**
  - Planck brane $\Longrightarrow$ UV Cutoff; Dynamical gravity in the 4D CFT
  - TeV (IR) brane $\Longrightarrow$ IR Cutoff; Conformal invariance broken below a TeV
    - All SM fields are composites of the CFT
- Dual of Warped Models with **Bulk SM**
  - UV localized fields are elementary
  - IR localized fields (Higgs) are composite
    - 4D dual is Composite Higgs model [Georgi, Kaplan 1984]
    - Shares many features with Walking Extended Technicolor
  - Partial Compositeness
    - AdS dual is weakly coupled and hence calculable!
  - KK states are dual to composite resonances

$U(1)_X$ Hidden sector

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

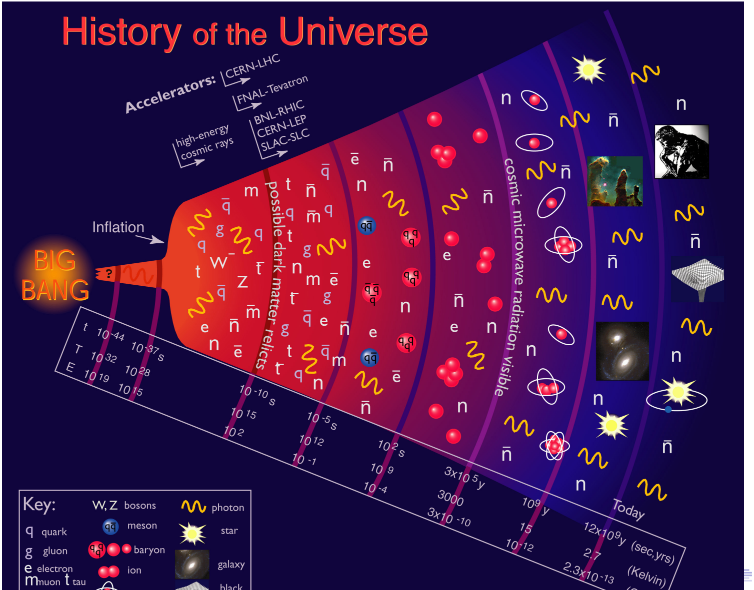
Accidental Z_2 symmetry : $\psi \to -\psi$, $SM \to SM$

- So ψ cosmologically stable $\Longrightarrow$ Dark Matter

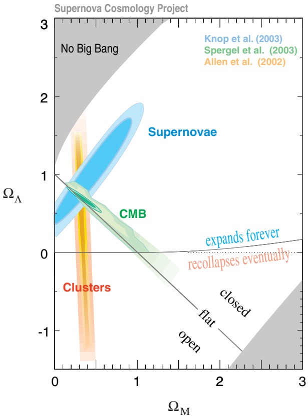


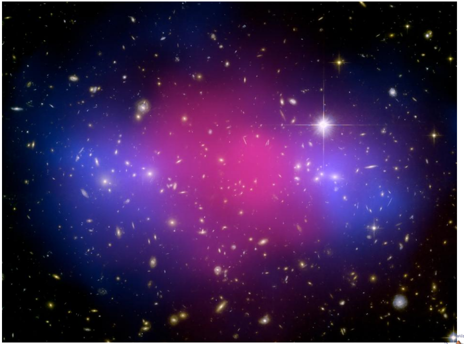
Direct Detection? Hidden sector signature at the LHC?

Particle Physics and the Universe



Evidence for Dark Matter (DM)

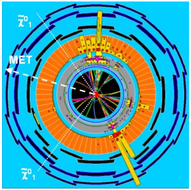




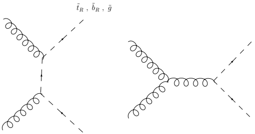
Bullet Cluster [Hubble+Chandra, NASA, ESA, CXC, M. Bradac (UCSB), and S. Allen (Stanford)]

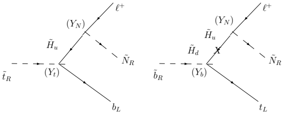
$\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

DM at Colliders II



- Example: Supersymmetry





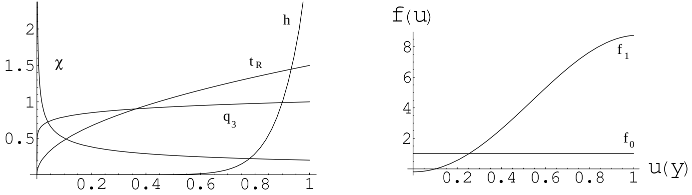
- LSP leads to "missing momentum"

Explaining SM (gauge & mass) hierarchies (WED)

Bulk Fermions explain SM mass hierarchy [Gherghetta, Pomarol 00][Grossman, Neubert 00]

$$\mathcal{S}^{(5)} \supset \int d^4x\, dy \,\left\{ c_\psi\, k\, \overline{\Psi}(x,y)\, \Psi(x,y) \right\}$$

Fermion bulk mass (c_ψ parameter) controls $f^\psi(y)$ localization



RS-GIM keeps FCNC under control

For details, see our review: [Davoudiasl, SG, Ponton, Santiago, New J.Phys.12:075011,2010. arXiv:0908.1968 [hep-ph]]

CMS Resonances Limits (Moriond 2013)