What we expect to find at the Large Hadron Collider (LHC)

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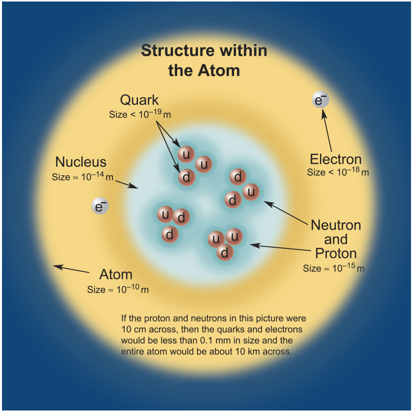
Outline

Particle Physics

Quest to understand fundamental aspects of Nature



Accelerators as microscopes

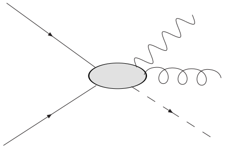
Optical Microscope ($\lambda \approx 0.6\,\mu m$)
Electron Microsope ($\lambda \approx 0.2\,nm$)
HEP Microscope (Particle Accelerator) $(\lambda \sim 1/E)$ (E is Beam Energy)

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

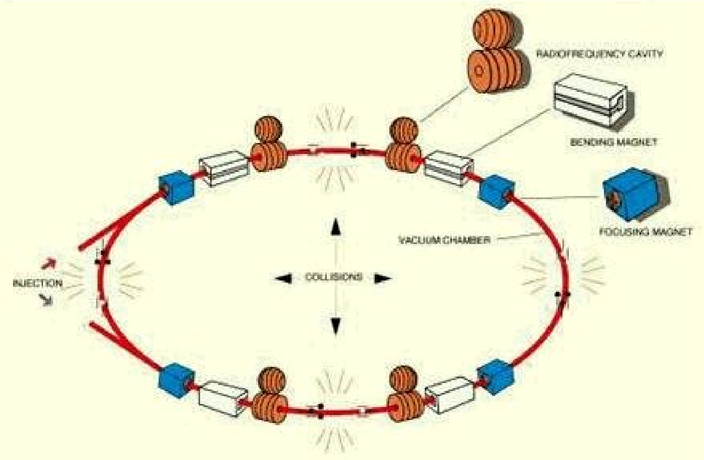
NB: $m_p \approx 1 GeV$

Physics operating at $\lambda \approx 10^{-17} m$ scale $\rightarrow$ Standard Model (SM)

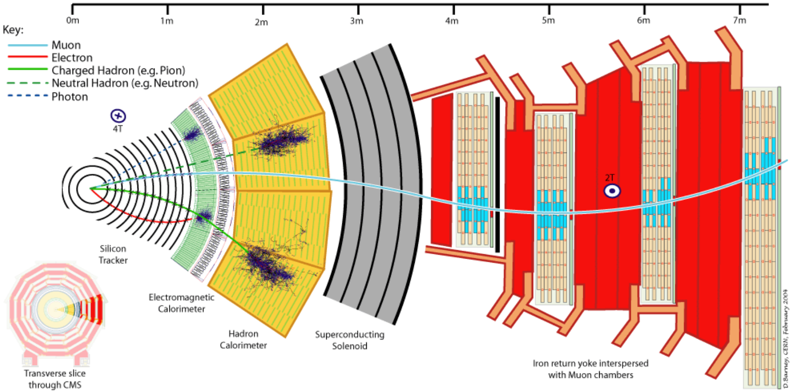
How do we probe this? $E = m\,c^2 \rightarrow$ new particles!



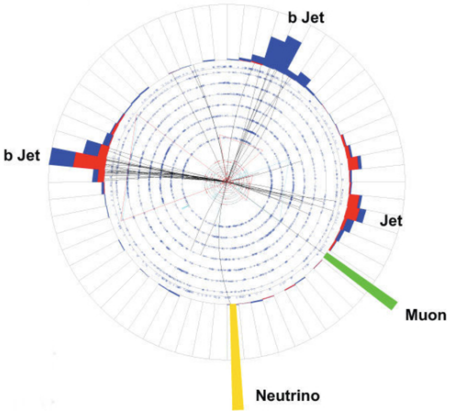
Accelerator schematic



Particle Detectors



Event reconstruction



D0 Single Top Event (Tevatron)

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*	$(0-0.13)\times10^{-9}$	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: proton $\rightarrow$ u u d ; neutron $\rightarrow$ u d d ; ...

On the hunt for the **Higgs boson**

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 (Electroweak)	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

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries

Example

Implications

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

  Natural Units: $c = 1$
  Measure E, m in GeV

Dirac : QM + Sp. Rel. $\Longrightarrow$ Anti-matter

electron (e^-) $\leftrightarrow$ positron (e^+)

proton ($\bar{p}$) $\leftrightarrow$ antiproton (p)

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Example

Implications

- Uncertainty Principle

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

Virtual Particles

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- Momentum Conserved

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Example

Implications

- Charge Conserved
- Some Internal Symm broken

Dirac : QM + Sp. Rel. $\Longrightarrow$ Anti-matter

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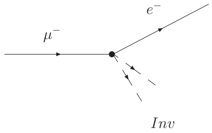
proton ($\bar{p}$) $\leftrightarrow$ antiproton (p)

Unstable Particles (Eg: Muon μ^- & Antimuon μ^+)

Heavier cousins of e^- & e^+

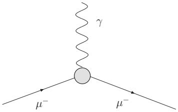
- $Q(\mu) = Q(e)$ So μ interacts same as e
- $m_\mu \approx 207\ m_e$
  $m_e = 0.510998910(13) \times 10^{-3}\ GeV$; $m_\mu = 0.1056583668(38)\ GeV$

Unstable, so **Decays** with **lifetime**



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

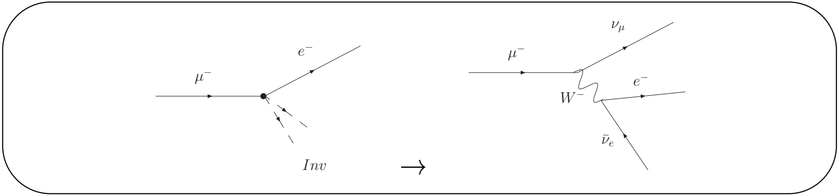
Anomolous Magnetic Moment



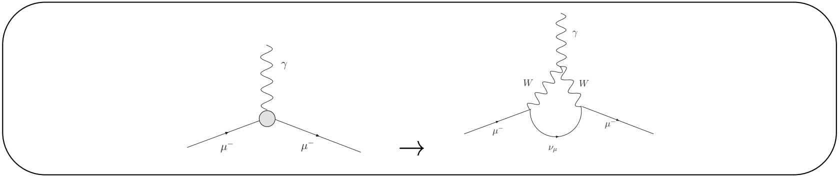
- $(g-2)/2 = 0.00116592080\,(63)$

Virtual Particles

- μ^- Decay



- μ (g-2)



Theory and Measurement agree!

- 1 part in 10^9 test of the Standard Model theory
- Seeing small disagreement in the last 3 digits - New Physics?

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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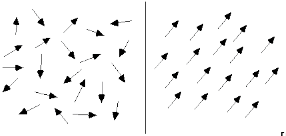
Spontaneous Symmetry Breaking (SSB)

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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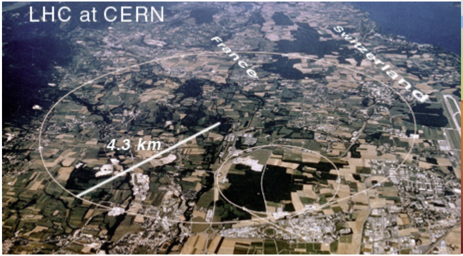
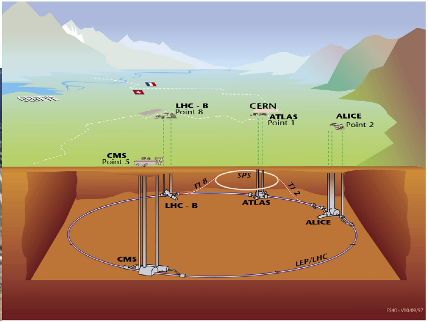
The Large Hadron Collider (LHC)

Will we find the Higgs? ... and more?





14,000 GeV Energy

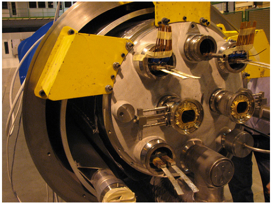
First collisions in Nov 2009

LHC Magnets

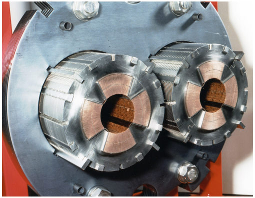
Dipole Magnets (14.3m)

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)

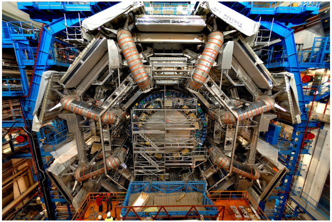
Dipole section

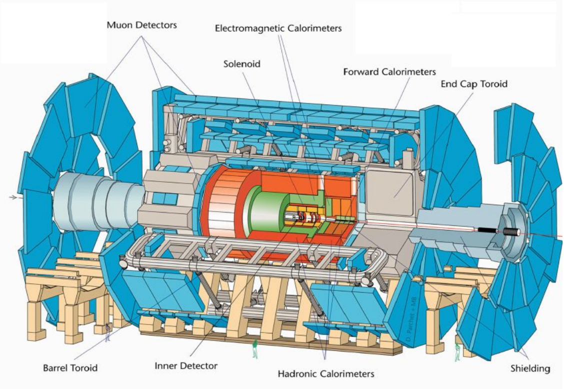


Quadrupole section

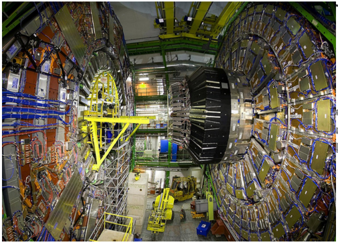


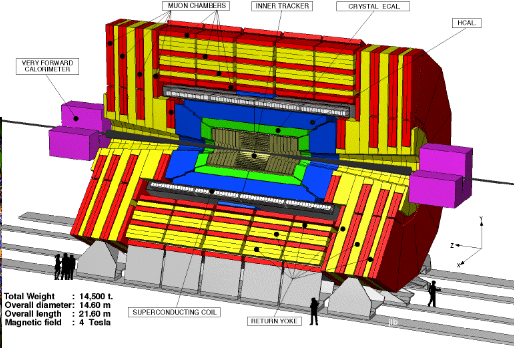
ATLAS Detector





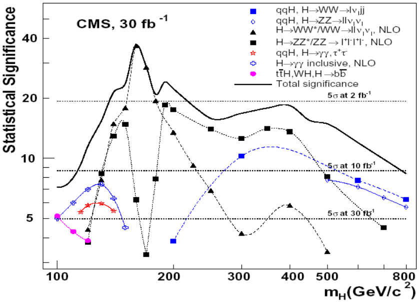
CMS Detector

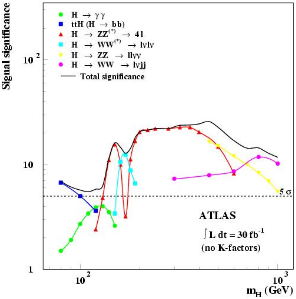




LHC Higgs significance

Higgs Significance at the LHC





Outline

But... the SM is not without problems

Gauge hierarchy problem

- Higgs sector unstable (quadratic divergence)

Fermion mass hierarchy problem

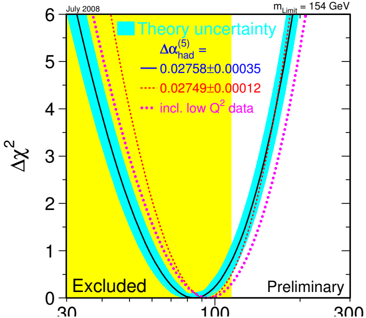
- Flavor symmetry?
- Challenge : Tiny neutrino masses
- Is neutrino Majorana or is it Dirac?

Cosmology connection

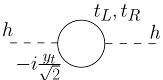
- What is the dark matter
- Inadequate source of CP vioation for observed baryon asymmetry
- Cosmological constant problem

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

Extra-dimensions : Warped or Flat

Strong dynamics (Note AdS-CFT correspondence)

Little Higgs

Neutrino mass connection and lepton number violation

Dark Matter signals (Missing Energy)

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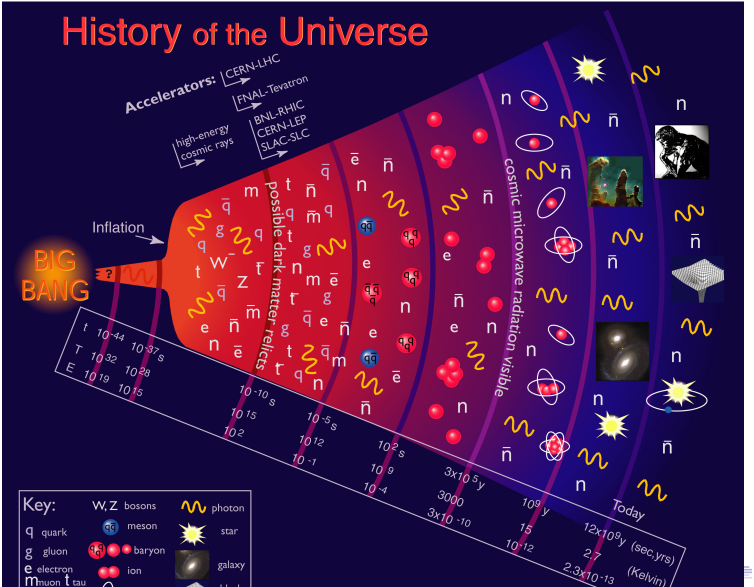
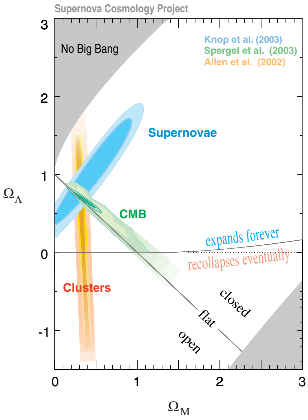
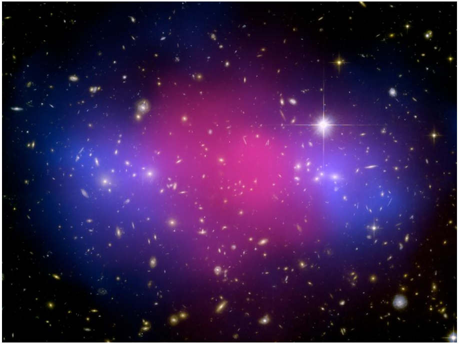
Particle Physics and the Universe



Evidence for Dark Matter (DM)



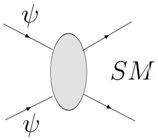


Bullet Cluster [Hubble+Chandra, NASA, ESA, CXC, M. Bradac (UCSB), and S. Allen (Stanford)]

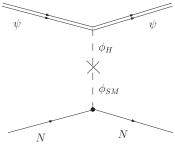
$\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

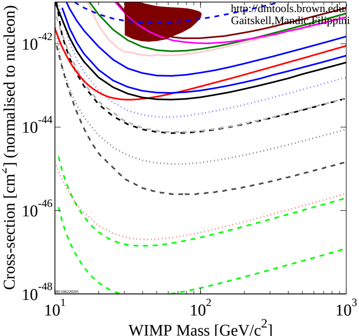
Particle Dark Matter (DM)

Self-Annihilation cross-section gives present DM Relic density



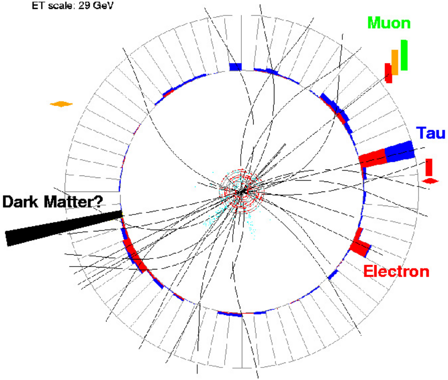
Direct Detection





Dark Matter at the LHC?

Missing momentum!



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?

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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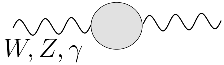

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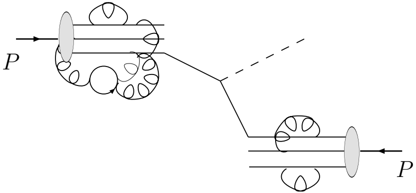
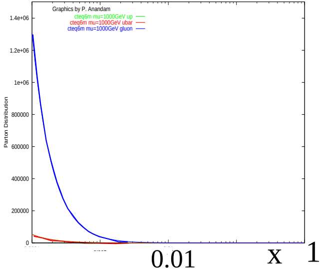
LHC PDF

Keep in mind parton distribution function (pdf)



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



[Anandam,Soper,CTEQ]

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]

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Dark Matter signals (Missing Energy)

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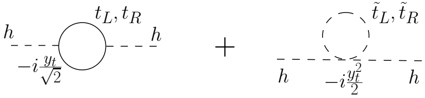
Supersymmetry (SUSY)

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



$= 0$

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

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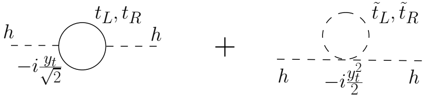

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SUSY BREAKING

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

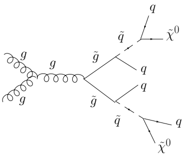
LEP Higgs bound needs heavy stop $\Rightarrow$ Increased fine tuning

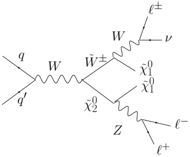
FCNC effects in $b \to s\bar{s}s$?

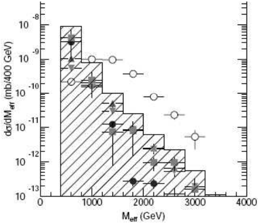
[SG,Yuan,2004]

SUSY AT LHC

- Cascade decays
- Missing energy signals







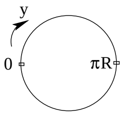
[ATLAS Physics TDR]

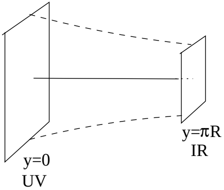
- Can we determine the spin and couplings to show SUSY?
  - Angular distributions

Eg: 5-D Warped Extra-dimensions

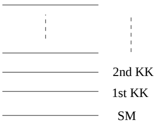
[Randall, Sundrum, 99]

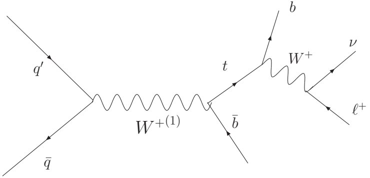
$$ds^2 = e^{-2k|y|}(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2$$





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



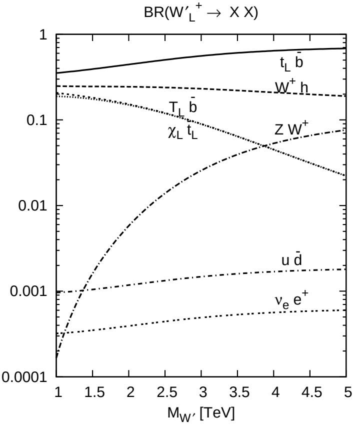


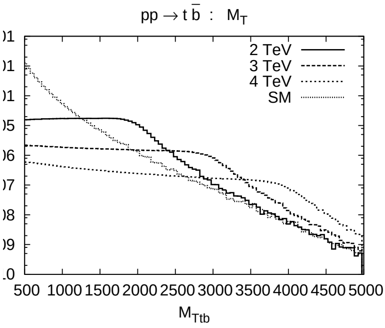
Warped Ex-Dim at LHC

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

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

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

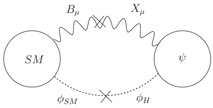




$U(1)_X$ Hidden sector

Coupled to SM (us) via the Higgs [SG, Jung, Lee, Wells:2008, 2009]
Accidental Z_2 symmetry : $\psi \to -\psi$, $SM \to SM$

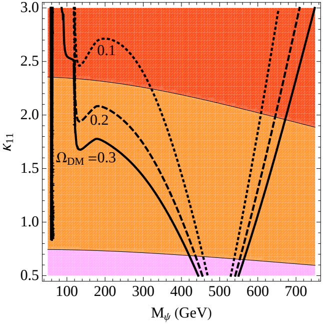
- So ψ cosmologically stable $\Longrightarrow$ Dark Matter

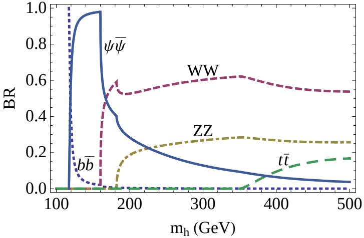


Direct Detection? Hidden sector signature at the LHC?

Hidden Sector Dark Matter at LHC

[SG, Lee, Wells:2009]





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