Three examples for possible new physics at LHC: Supersymmetry, Tev Scale B-L, Extra dimensions

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Outline

- Why New Physics at TeV scale?
- Supersymmetry
- SUSY signatures in LHC
- TeV Scale B-L extended SM (MSSM)
- Signatures of TeV scale B-L in LHC
- Extra dimensions and Radion scalar field
- Radion signatures in LHC
- Conclusions

Introduction

- The SM, based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, is in excellent agreement with experimental results.

- Strong indications that it is just an effective of fundamental one:

1) Gauge hierarchy problem & Unification of forces.

2) Neutrinos are massless

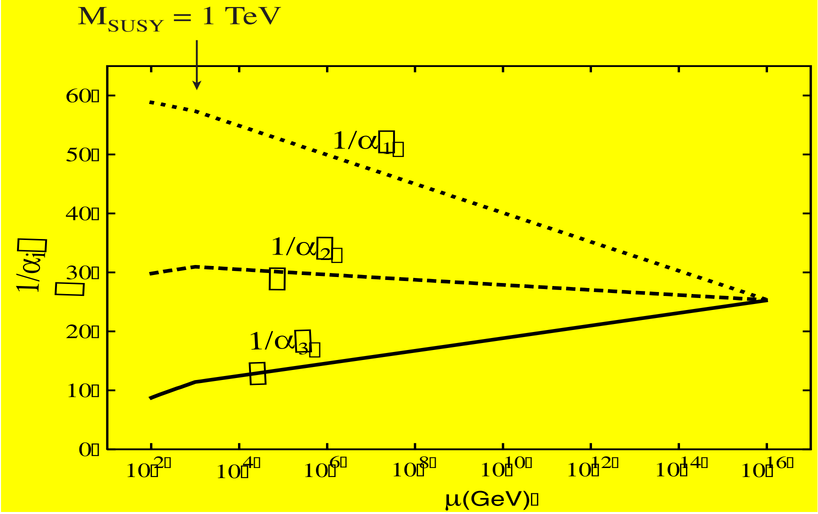
3) Flavor problem

3) Dark Matter & Dark Energy problem.

4) Why matter dominates antimatter.

Motivation For Supersymmetry

- SUSY ensures the stability of hierarchy between the week and the Planck scales.
- Supersymmetric theories are promising candidate for unified theory beyond the SM.
- In supersymmetric theories, the mechanism of the electroweak symmetry breaking is natural.
- Local supersymmetry leads to a partial unification of the SM with gravity 'supergravity'.
- Supersymmetry is a necessary ingredient in string theory.



- With supersymmetry, the SM gauge couplings are unified at GUT scale $M_G \approx$ 2 x10^{16} GeV.

Hierarchy problem and SUSY

- String and GUT unification -> A cutoff scale ~ Planck scale (10^{19} GeV).
- SUSY is a symmetry to avoid the fine tuning in the renormalization of the Higgs boson mass at the level of $O(10^{34})$.

$$
\begin{aligned}
M_h^2 &= M_{h,tree}^2 + c\frac{g^2}{4\pi^2}M_{pl}^2 && (w/o\ SUSY) \\
M_h^2 &= M_{h,tree}^2(1 + c'\frac{g^2}{4\pi^2}\ln(M_{pl}/M_W)) && (with\ SUSY)
\end{aligned}
$$

- In SUSY, the loop diagrams that are quadratically divergent cancel, term by term against the equivalent diagrams involving superpartners.
- If $m_H \sim O(100)$ GeV, the masses of superpartners should be ≤ O(1) TeV.
- Thus, some of the superpartners will be detected at the LHC.

What is Supersymmetry

- Supersymmetry (SUSY): a symmetry between bosons and fermions.
- Introduced in 1973 as a part of an extension of the special relativity.
- Super Poincare algebra.

$$\begin{array}{ll} P_\mu & (translation), \\ M_{\mu,\nu} & (rotation\ and\ Lorentz\ tranformation), \\ Q_\alpha & (SUSY transformation) \end{array}$$

$$\{Q_\alpha, Q_\beta\} = (\gamma^\mu)_{\alpha\beta} P_\mu$$

- SUSY = a translation in Superspace.

Space-time (x^μ) → Superspace (x^μ, θ)

SUSY transformation:

$$\begin{array}{lcl} x^\mu & \rightarrow & x'^\mu = x^\mu + \frac{i}{2}\bar{\epsilon}\gamma^\mu\theta \\ \theta & \rightarrow & \theta' = \theta + \epsilon \end{array}$$

Superfields &Supersymmetric Lagrangian

- ❑ We define superfied $\Phi(x,\theta,\bar{\theta})$ as function of the superspace coordinates.

1- Chiral Superfields $\bar{D}\Phi = 0$: $\Phi(x,\theta) = \phi(x) + \sqrt{2}\,\theta\psi(x) + \theta\theta F(x)$

2- Vector Superfields V=V⁺:

$$V(x,\theta,\bar{\theta}) = -\theta\sigma^{m}\bar{\theta}v_{m} + i\theta^{2}\bar{\theta}_{\dot{\alpha}}\bar{\lambda}^{\dot{\alpha}}(x) - i\bar{\theta}^{2}\theta_{\dot{\alpha}}\lambda^{\alpha}(x) + \frac{1}{2}\theta^{2}\bar{\theta}^{2}D(x)$$

- The most general supersymmetric lagrangian takes the form:

$$\begin{aligned} L = {} & \Sigma_i (|D \varphi_i|^2 + i\psi_i \sigma^m D_m \psi_i^* + |F_i|^2) \\ & - \Sigma_a \frac{1}{4 g_a^2}((v^a_{mn})^2 - i\lambda^a D\sigma\sigma^a - \frac{1}{2}(D^a)^2) \\ & + i\sqrt{2}\,\Sigma_{ia}\, g_a \psi_i T^a \lambda^a A^* + h.c. + \Sigma_{ij} \frac{1}{2} \frac{\partial^2 W}{\partial A_i \partial A_j}\psi_i \psi_j . \end{aligned}$$

- SUSY is broken if <0|F|0>≠0 or <0|D|0> ≠0

Supersymmetry Breaking

- SUSY must be broken symmetry or else SUSY particles should have been observed (with same mass as SM-partners)
- What happens to the cancellation of quadratic divergences?
  - SUSY partners must be not heavier than ~TeV.

The general structure for the SUSY breaking includes three sectors:

1) Observable sector: which comprises all the ordinary particle and their SUSY particles,

2) Hidden sector: where the breaking ofSUSY occurs,

3) The messengers of the SUSY breaking from hidden to observable sector.

- SUSY breaking is parameterized in observable sector by soft SUSY breaking terms.

Minimal Supersymmetric Standard Model

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q)	$\begin{pmatrix}u\\d\end{pmatrix}_L$, u_R, d_R	squarks ($\tilde{q}$)	$\begin{pmatrix}\tilde{u}\\\tilde{d}\end{pmatrix}_L$, $\tilde{u}_R$, $\tilde{d}_R$	
(spin-$\frac{1}{2}$)	$\begin{pmatrix}c\\s\end{pmatrix}_L$, c_R, s_R	(spin-0)	$\begin{pmatrix}\tilde{c}\\\tilde{s}\end{pmatrix}_L$, $\tilde{c}_R$, $\tilde{s}_R$	
	$\begin{pmatrix}t\\b\end{pmatrix}_L$, t_R, b_R		$\begin{pmatrix}\tilde{t}\\\tilde{b}\end{pmatrix}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l)	$\begin{pmatrix}e\\\nu_e\end{pmatrix}_L$, e_R	sleptons ($\tilde{l}$)	$\begin{pmatrix}\tilde{e}\\\tilde{\nu}_e\end{pmatrix}_L$, $\tilde{e}_R$	
(spin-$\frac{1}{2}$)	$\begin{pmatrix}\mu\\\nu_\mu\end{pmatrix}_L$, μ_R	(spin-0)	$\begin{pmatrix}\tilde{\mu}\\\tilde{\nu}_\mu\end{pmatrix}_L$, $\tilde{\mu}_R$	
	$\begin{pmatrix}\tau\\\nu_\tau\end{pmatrix}_L$, τ_R		$\begin{pmatrix}\tilde{\tau}\\\tilde{\nu}_\tau\end{pmatrix}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons	g, Z, γ, h, H, A	gauginos/Higgsinos	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}^0_1$ $\}$	$\tilde{\chi}^0_{1,2,3,4}$
(spin-1, spin-0)	$W^\pm$, $H^\pm$	(spin-$\frac{1}{2}$)	$\tilde{W}^\pm$, $\tilde{H}^\pm$ $\}$	$\tilde{\chi}^\pm_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

Higgs in MSSM

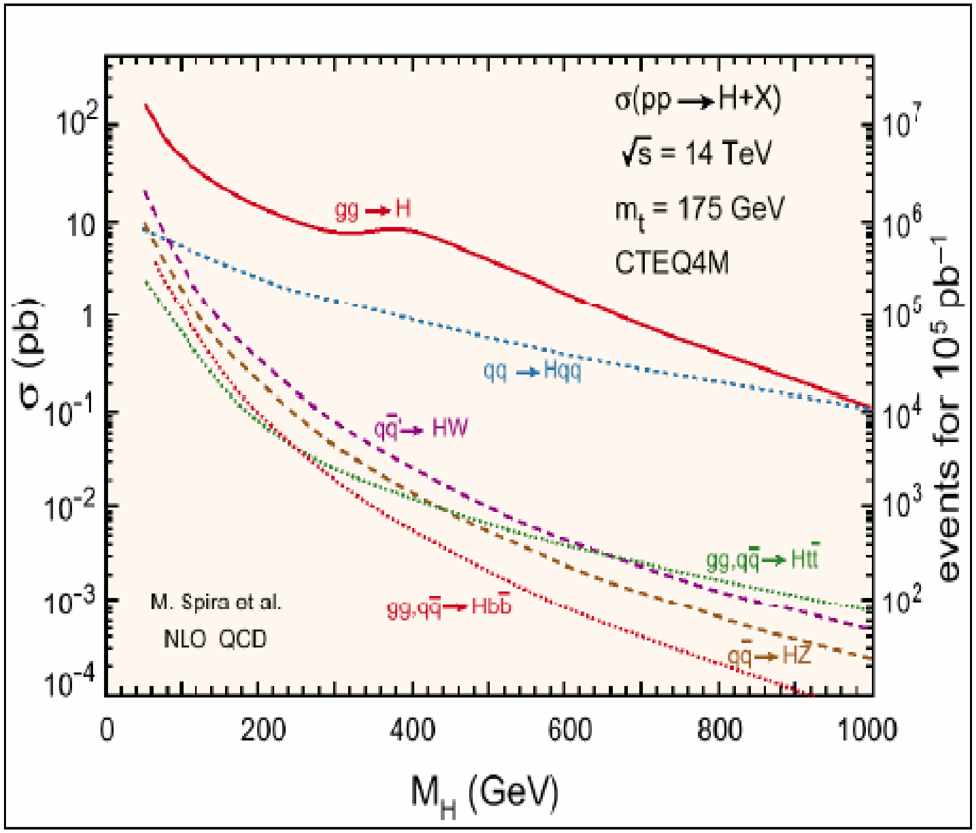
- In SUSY, two Higgs doublets are needed.
- This means: 8 degrees of freedom, 3 eaten up by the W± and Z $\Longrightarrow$ 5 Higgs fields: $h^0, A^0, H^0, H^\pm$
- Connection between Higgs masses and gauge boson masses:

$$M^2_{H^\pm} = M^2_A + M^2_W \Longrightarrow M_{H^\pm} > M_W$$

$$M_A^2 = m_1^2 + m_2^2$$

$$M^2_{H,h} = 1/2\,[M^2_A + M^2_Z \pm ((M^2_A+M^2_Z)^2 - 4\,M^2_A M^2_Z \cos 2\beta)^{0.5}]$$

$$\rightarrow\ M_h < M_Z$$



This is only true at tree level. When including higher order contributions:

$$M_h < \sim 130 \text{ GeV (or so…)}$$

R-parity and the LSP

- Unconstrained SUSY would lead to the proton decaying with lifetime of ~hours!!!
- Introduce R-parity

$$R = (-1)^{3(B-L)+2s}$$

- All SM particles have R=+1, all sparticles R=-1

- R-parity conservation implies that:
  1) SUSY particles are produced or destroyed only in pairs
  2) The LSP is absolutely stable and it is a candidate for Dark Matter.

Events with missing energy is the major signature for R-parity conserving models

- ☐ The neutralinos χ_i (i=1,2,3,4) are the physical (mass) superpositions of fermionic partners of bino, wino and Higgsinos.

$$\tilde{\chi} = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + U_{14}\tilde{H}_2^0$$

The lightest neutralino can LSP, Stable Weakly Interacting Massive Particle (WIMP). Interesting Candidate for DM.

Charginios & Sfermions

- The mixing of the charged gauginos and charged Higgsinos is described by:

$$M_C = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & -\mu \end{pmatrix}$$

$$\begin{aligned} M_{2,1}^2 &= 1/2(M_2^2 + \mu^2 + 2M_W^2 \\ &\pm \sqrt{(M_2^2 - \mu^2)^2 + 4M_W^4 \cos^2 2\beta + 4M_W^2 (M_2^2 + \mu^2 - 2M_2\mu \sin 2\beta))} \end{aligned}$$

- The up squark mass matrices

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_Q^2 + m_u^\dagger m_u + D_{LL}^u & m_u(A_U + \mu \cot\beta) \\ (A_U^\dagger - \mu^* \cot\beta) m_u^\dagger & M_U^2 + m_u m_u^\dagger + D_{RR}^u \end{pmatrix}$$

Experimental Constraints

- Today's negative SUSY search provide the following lower maas limits.
- The LHC at CERN is the machine that will take particle physics into a new phase of discovery.

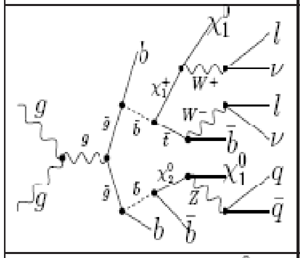
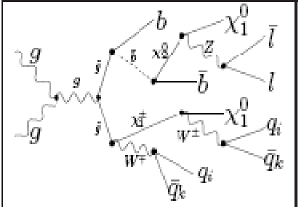
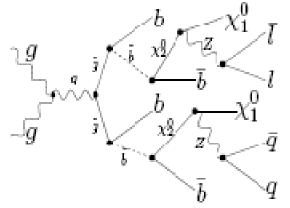
$$m_{\chi^{\pm}} > 100 \quad GeV$$

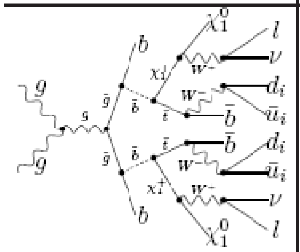
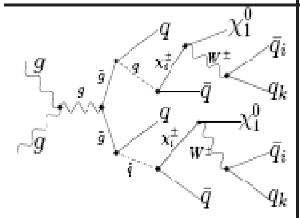
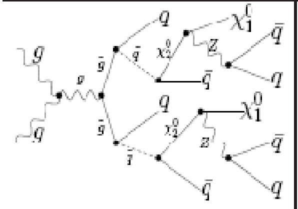
$$m_{\chi^{0}} > 36 \quad GeV$$

$$m_{\tilde{q}} > 300 \quad GeV$$

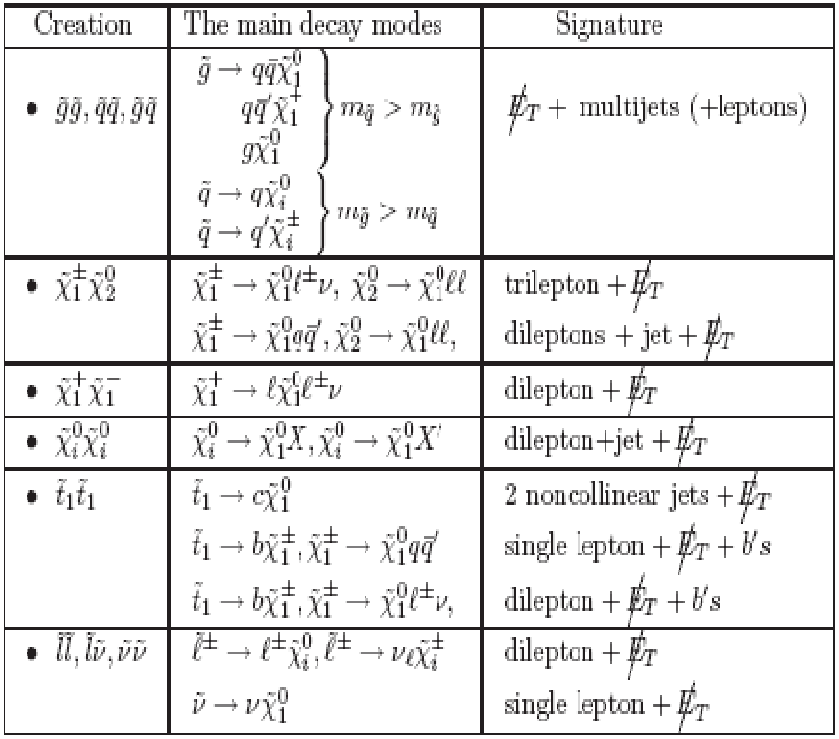
$$m_{\tilde{g}} > 195 \quad GeV$$

SUSY signatures at LHC

Process	final states
	2ℓ 2ν $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$

Process	final states
	2ℓ 2ν $8j$ $\not{E}_T$
	$8j$ $\not{E}_T$
	$8j$ $\not{E}_T$

Creation of the pair of gluino with further cascade decay



Creation	The main decay modes	Signature
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ \quad q\bar{q}'\tilde{\chi}_1^+ \\ \quad g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T +$ multijets (+leptons)
• $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$ $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell,$	trilepton $+\not{E}_T$ dileptons + jet $+\not{E}_T$
• $\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to \ell\tilde{\chi}_1^0\ell^\pm\nu$	dilepton $+\not{E}_T$
• $\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	dilepton+jet $+\not{E}_T$
• $\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu,$	2 noncollinear jets $+\not{E}_T$ single lepton $+\not{E}_T + b's$ dilepton $+\not{E}_T + b's$
• $\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{\ell}^\pm \to \ell^\pm\tilde{\chi}_i^0, \tilde{\ell}^\pm \to \nu_\ell\tilde{\chi}_i^\pm$ $\tilde{\nu} \to \nu\tilde{\chi}_1^0$	dilepton $+\not{E}_T$ single lepton $+\not{E}_T$

Creation of superpartners and the main decay modes

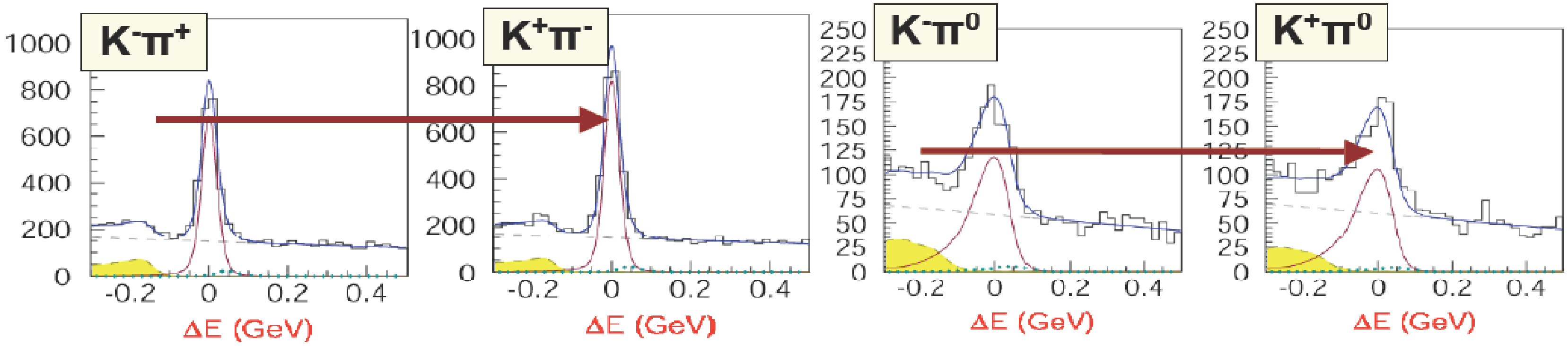
❑ Squarks/gluinos decay to leptons+jets+missing energy (LSPs). By studying decay kinematics, lightest neutralino mass to be measured to ~10% precision

Indirect SUSY Search: LHCb

Nature 452, 332-335(2008)

The Kπ "Puzzle"

A_{CP} results from the B factories:



A_{cp}=-0.094±0.018±0.008

A_{cp}=-0.107±0.018±0.006

A_{cp}=-0.086±0.023±0.009

A_{cp}=+0.07±0.03±0.001

A_{cp}=+0.03±0.04±0.01

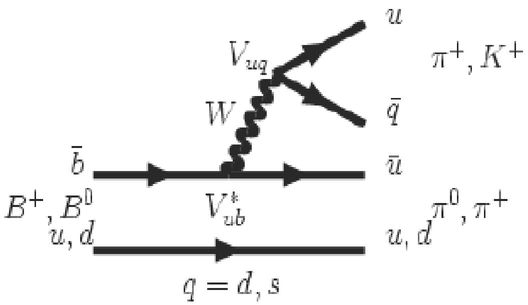
Deviation ≈ 5.2σ !

A_{cp}=-0.086±0.023±0.009 ≠ **A_{cp}=+0.03±0.04±0.01**

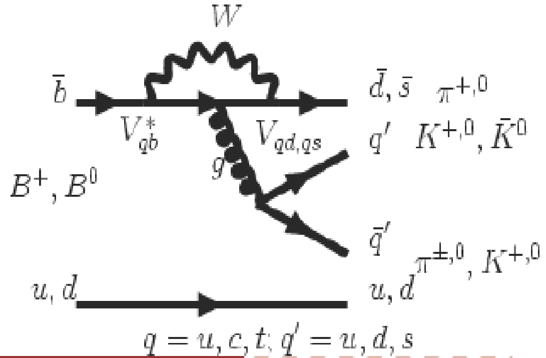
The Kπ "Puzzle"

Two more amplitudes for $K^+\pi^0$

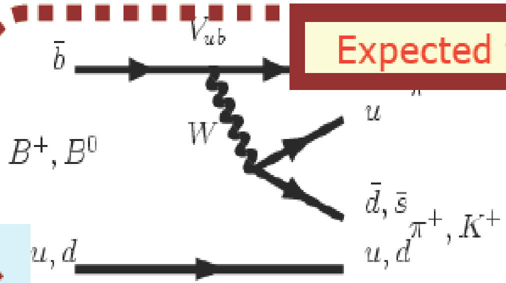
T



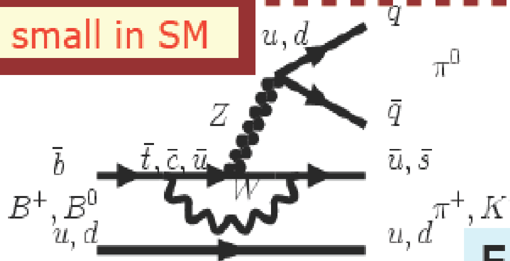
P



C



Expected to be small in SM



P_{EW}

Color suppressed Tree

Electro Weak Penguin

$\Delta A_{CP} \sim 0$ if C and P_{EW} are neglected

Enhancement of C ?

- ➢ C>T is needed (C/T = 0.3–0.6 in SM)
- ➢ breakdown of theoretical understanding

Enhancement of P_{EW} ?

- ➢ Would indicate new physics

"Puzzle" due to **poor understanding of strong int.?**

TeV Scale B-L

- The minimal extension of SM to account for Neutrino oscillations and observed baryon asymmetry is based on the gauge group

$$G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- TeV scale $B-L$ symmetry breaking and see-saw mechanism have been considered recently:
  - account for the experimental results of the light neutrino masses and their large mixing

- New particles are predicted:
  - Three SM singlet fermions (ν_R) (cancellation of gauge anomalies)
  - Extra gauge boson corresponding to $B-L$ gauge symmetry
  - Extra SM singlet scalar (heavy Higgs)

- These new particles have significant impact on the SM phenomenology
  - Interesting signatures at the LHC

$U(1)_{B\text{-}L}$ Model

- **Under *U(1)*$_{B-L}$ we demand:** $\psi_L \to e^{iY_{B-L}\theta(x)}\psi_L, \qquad \psi_R \to e^{iY_{B-L}\theta(x)}\psi_R,$
- **Derivatives are covariant if a new gauge field C_μ is introduced:**

$$D_\mu \psi_L \equiv (\partial_\mu - \frac{ig}{2}W^r_\mu \tau_r - \frac{ig'}{2}YB_\mu - \frac{ig''}{2}Y_{B-L}C_\mu)\psi_L$$

$$D_\mu \psi_R \equiv (\partial_\mu - \frac{ig'}{2}YB_\mu - \frac{ig''}{2}Y_{B-L}C_\mu)\psi_R$$

- **Lagrangian: fermionic and kinetic sectors**

$$L_{B-L} = i\bar{l}D_\mu \gamma^\mu l + i\bar{e}_R D_\mu e_R + i\bar{\nu}_R D_\mu \gamma^\mu \nu_R - \frac{1}{4}W^r_{\mu\nu}W^{r\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu}$$

Lagrangian: Higgs and Yukawa sectors

$$L_{\text{Higgs+Yukawa}} = (D_\mu \phi)(D^\mu \phi) + (D_\mu \chi)(D^\mu \chi) - V(\phi,\chi) - (\lambda_e \bar{l}\phi e_R + \lambda_\nu \bar{l}\tilde{\phi}\nu_R + \frac{1}{2}\lambda_{\nu_R}\bar{\nu}^c_R \chi \nu_R + h.c.)$$

$U(1)_{B\text{-}L}$ Symmetry Breaking

The $U(1)_{B-L}$ gauge symmetry can be spontaneously broken by a SM singlet complex scalar field χ:

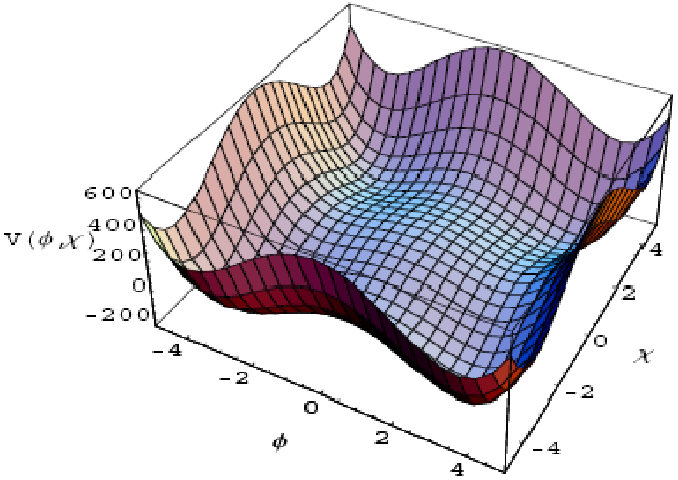
$$|\langle\chi\rangle| = v'/\sqrt{2}$$

- **The $SU(2)_L \times U(1)_Y$ gauge symmetry is broken by a complex $SU(2)$ doublet of scalar field φ:**

$$|\langle\phi\rangle| = v/\sqrt{2}$$

- **Most general Higgs potential:**

$$V(\phi,\chi) = m_1^2\phi^+\phi + m_2^2\chi^+\chi + \lambda_1(\phi^+\phi)^2 + \lambda_2(\chi^+\chi)^2 + \lambda_3(\phi^+\phi)(\chi^+\chi)$$



- **After the $B-L$ gauge symmetry breaking, the gauge field C_μ acquires mass:**

$$M_{z'}^2 = 4g''^2 v'^2$$

- **Strongest Limit comes from LEP II:**

$$\frac{M_{z'}}{g''} \approx O(TeV),\ g'' \approx O(1) \ \Rightarrow v' > O(TeV)$$

SUSY and B-L radiative symmetry breaking.

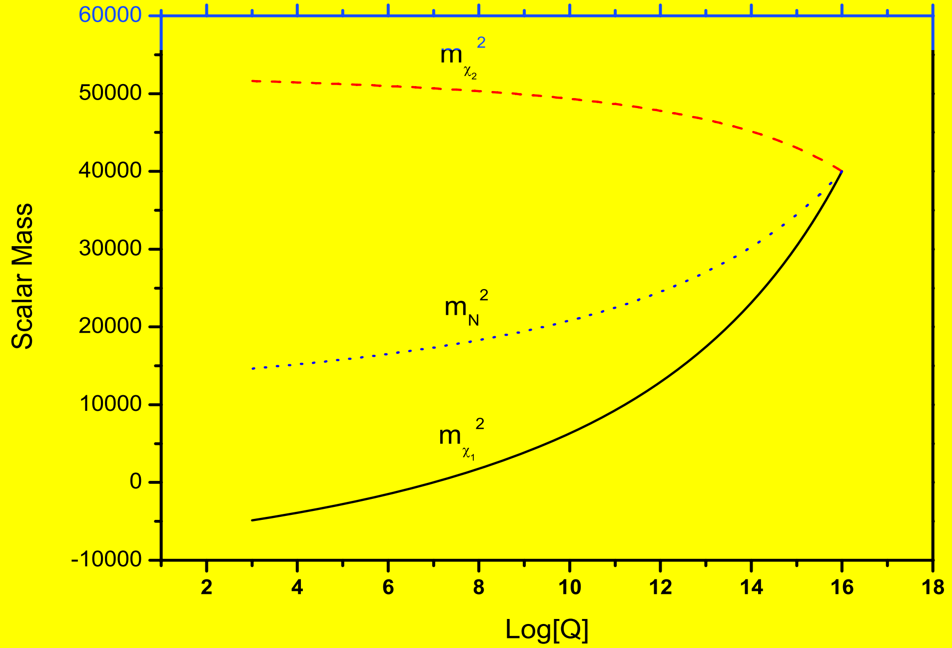
S.K., A. Masiero, 2007

$$\begin{aligned} W &= (h_U)_{ij} Q_i H_2 U_j^c + (h_D)_{ij} Q_i H_1 D_j^c + (h_L)_{ij} L_i H_1 E_j^c + (h_\nu)_{ij} L_i H_2 N_j^c \\ &+ (h_N)_{ij} N_i^c N_j^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2. \end{aligned}$$

$$\begin{aligned} \frac{dm^2_{\chi 1}}{dt} &= 6\tilde{\alpha}_{B-L} M^2_{B-L} - 2\tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right), \\ \frac{dm^2_{N_3}}{dt} &= \frac{3}{2}\tilde{\alpha}_{B-L} M^2_{B-L} - \tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right). \end{aligned}$$

$$\mu'^2 = \frac{m^2_{\chi_2} - m^2_{\chi_1}\tan^2\theta}{\tan^2\theta - 1} - \frac{1}{4} M^2_{Z_{B-L}}.$$

$$\sin 2\theta = \frac{2\mu_3^2}{\mu_1^2 + \mu_2^2}.$$



TeV scale B-L from GUT

- $G_{B\text{-}L}$ can be obtained from SO(10) in the following branching rule:

$$SO(10)$$

$$\Downarrow$$

AT scale ~ GUT though (1,1,1) in 54_H or 210_H.

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$\Downarrow$$

Below GUT scale (15,1,3) Higgs

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B\text{-}L}$$

$$\Downarrow$$

At TeV scale via (1,1,0,2) Higgs

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Neutrino masses and mixing

- Left and right-handed neutrino form 2x2 mass matrix:

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

  - ❑ M_R Majorana mass ($U(1)_{B-L}$ symmetry breaking)

$$M_R = \lambda_{\nu_R} v'$$

$$v' \sim O(TeV),\ \lambda_{\nu_R} \sim O(1) \Rightarrow M_R \approx O(TeV)$$

  - ❑ m_D Dirac mass (Electroweak symmetry breaking)

$$m_D = h_\nu v$$

$$h_\nu \sim O(1) \Rightarrow m_D \approx O(100) GeV, h_\nu \sim h_e \Rightarrow m_D \approx O(10^{-4}) GeV$$

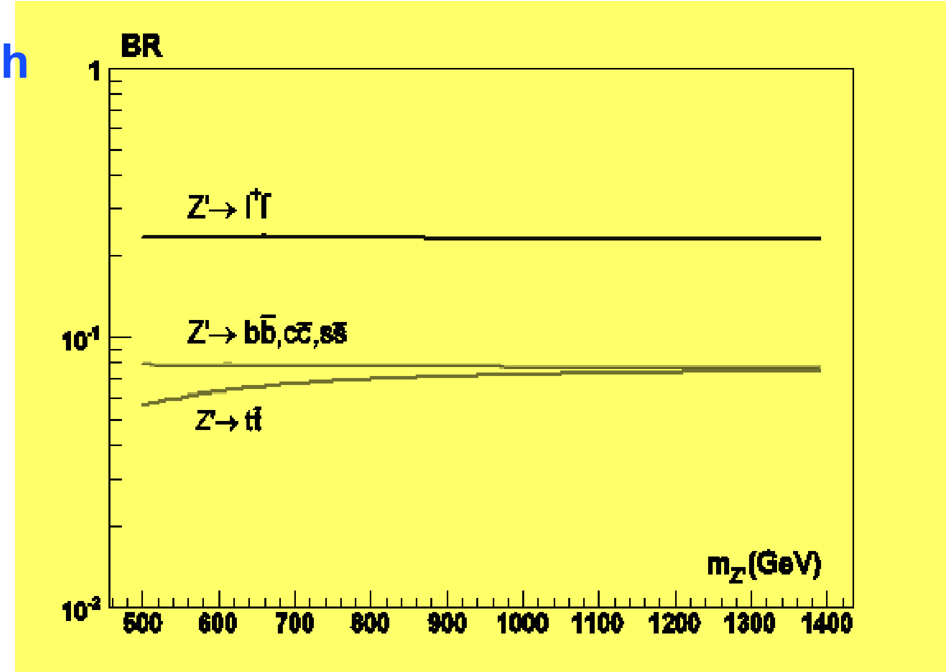
$$\begin{array}{rcl} \Delta m_{12}^2 & = & (7.9 \pm 0.4) \times 10^{-5} \mathrm{eV}^2, \\ |\Delta m_{32}^2| & = & (2.4 + 0.3) \times 10^{-3} \mathrm{eV}^2, \\ \theta_{12} & = & 33.9^\circ \pm 1.6^\circ, \\ \theta_{23} & = & 45^\circ, \\ \sin^2\theta_{13} & \leq & 0.048. \end{array}$$

❑ In order to fix the angles of R, one needs a favor symmetry.

Z’ Decay

- **The interactions of the *Z′* boson with the SM fermions are described by**

$$\sum_f Y_{B-L} g'' C_\mu \bar{f} \gamma^\mu f$$



➢ **Branching ratios**

$$\Gamma(Z' \to l^+l^-) \approx \frac{Y_l^2 g''^2}{24\pi} M_{Z'}$$

$$\Gamma(Z' \to b\bar{b}, c\bar{c}, s\bar{s}) \approx \frac{Y_q^2 g''^2}{8\pi} M_{Z'} (1 + \frac{\alpha_s}{\pi})$$

$$\Gamma(Z' \to t\bar{t}) \approx \frac{Y_q^2 g''^2}{8\pi} M_{Z'} (1 - \frac{m_t^2}{M_{Z'}^2})(1 - \frac{4m_t^2}{M_{Z'}^2})^{1/2} [1 + \frac{\alpha_s}{\pi} + O(\frac{\alpha_s m_t^2}{M_{Z'}^2})]$$

- **Branching ratios of *Z’* → *l⁺l⁻* are relatively high compared to *Z’* → *qq*:**
- **Search for Z’ at LHC via dilepton channels are accessible at LHC.**

$$Z' \to l^+l^- \quad \mathrm{BR} = 30\%$$

$$Z' \to q\bar{q} \quad \mathrm{BR} = 10\%$$

Higgs Sector

- One complex *SU(2)$_L$* doublet and one complex scalar singlet
  - Six scalar degrees of freedom
  - Four are eaten by *C,Z^0,W$^\pm$* after symmetry breaking
  - Two physical degrees of freedom: *φ, χ*
- Mass matrix:

$$\frac{1}{2}M^2(\phi,\chi) = \begin{pmatrix} \lambda_1 v^2 & \lambda_2 v v'/2 \\ \lambda_2 v v'/2 & \lambda_2 v'^2 \end{pmatrix}$$

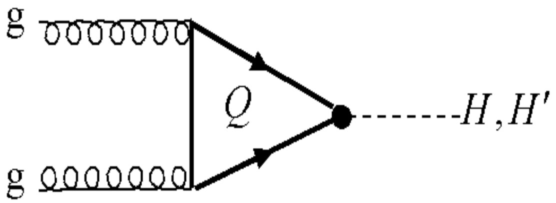
- Mass eigenstates:

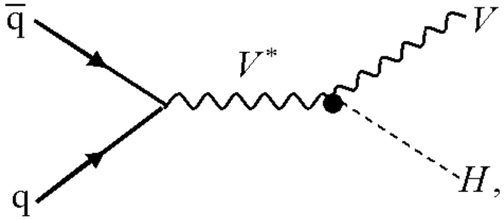
$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix}, \qquad \tan 2\theta = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}$$

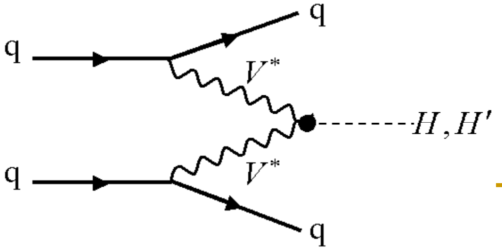
- Masses: $m_{1,2}^2 = \lambda_1 v^2 + \lambda_2 v'^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v^2 v'^2}$
- Mixing is controlled by λ_3: $\lambda_3 = 0 \rightarrow m_\phi = \sqrt{\lambda_1}\, v, \quad m_\psi = \sqrt{\lambda_2}\, v'$

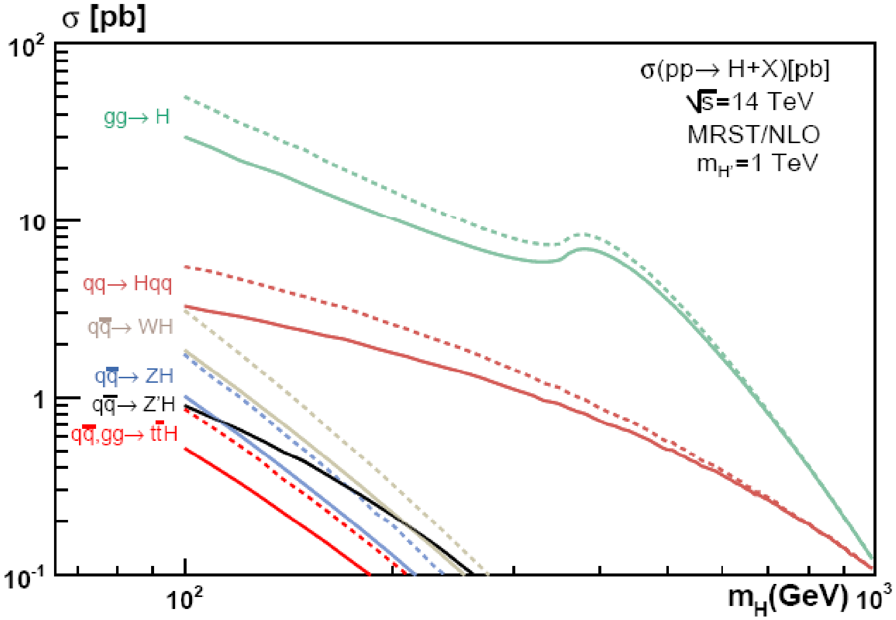
Higgs Production

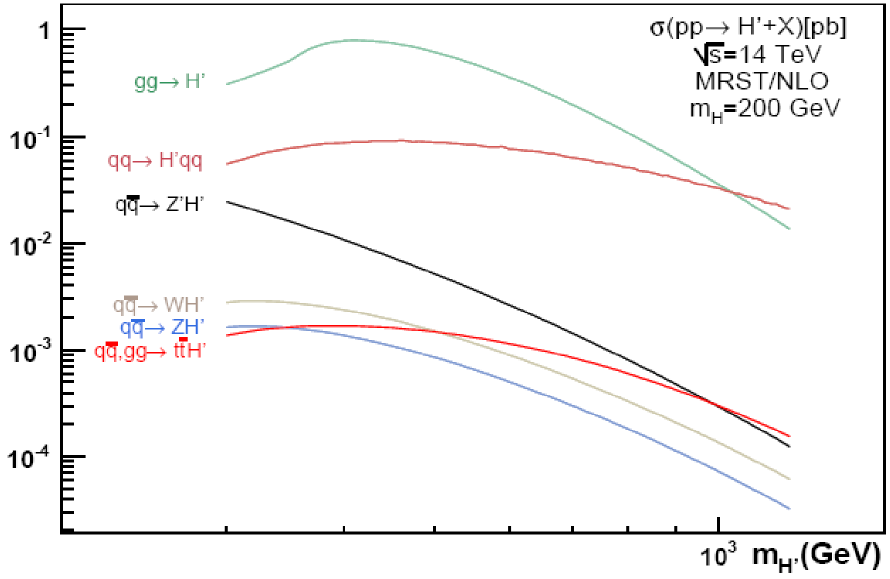
- **Heavy and light Higgses are produced through same processes:**
  - **gluon-gluon fusion**
  - **vector boson fusion**
  - **associated production with *W/Z/Z'***
  - **associated production with heavy quarks**











Higgs Decay

- **Branching Ratios of Light Higgs are very close to those of SM**
  - **Couplings are cancelled in the ratio**
  - **Decay width of *H→Z'Z' is very tiny***
  - **Low mass range M_H < 130 GeV:**

$$H \to b\bar{b} \quad \text{BR} = 60\text{-}90\%$$

$$H \to \tau^+\tau^-, c\bar{c}, gg \quad \text{BR} = \text{a few }\%$$

$$H \to \gamma\gamma, \gamma Z \quad \text{BR} = \text{a few }\%$$

  - **High mass range M_H > 130 GeV:**

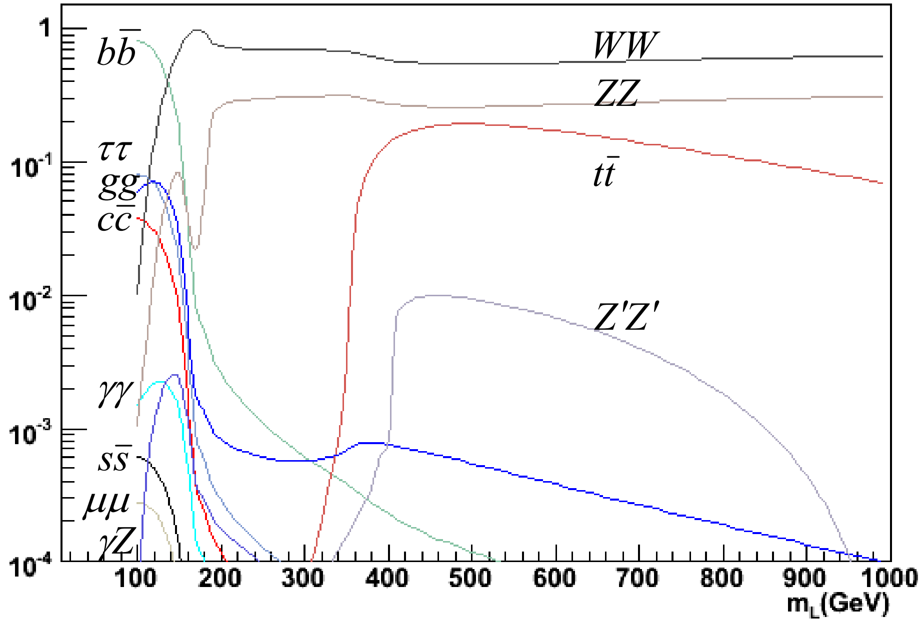
$$H \to WW, ZZ\,(\text{BR}=\frac{2}{3},\frac{1}{3})$$

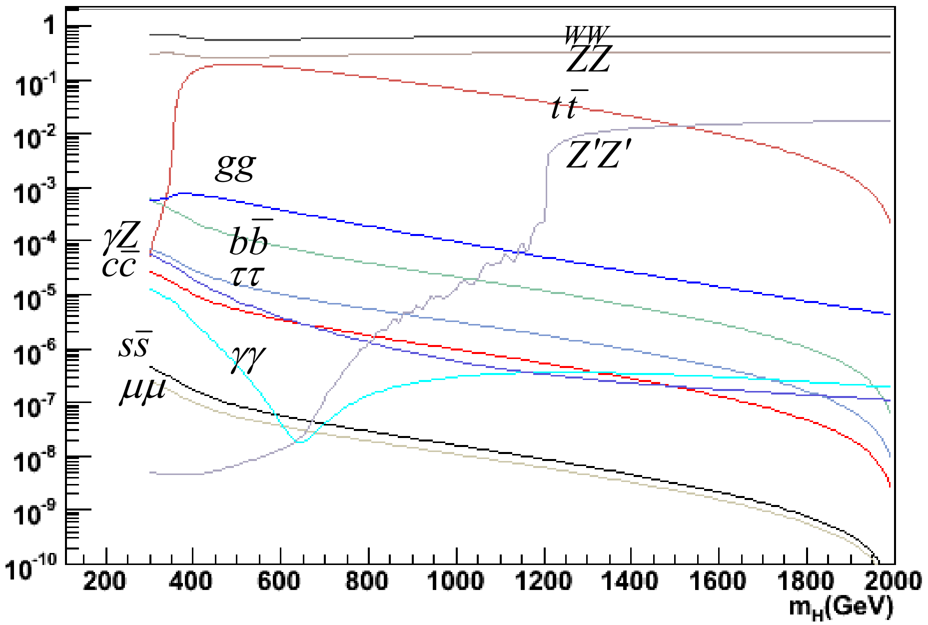
$$H \to t\bar{t} \quad \text{BR} \le 20\%$$

Interesting mass range of Heavy Higgs (200<$m_{H'}$):

  - ***H'→WW/ZZ* channel is dominant**

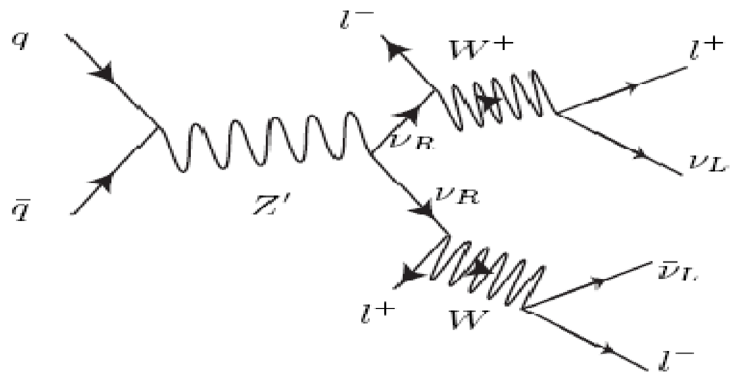
BR

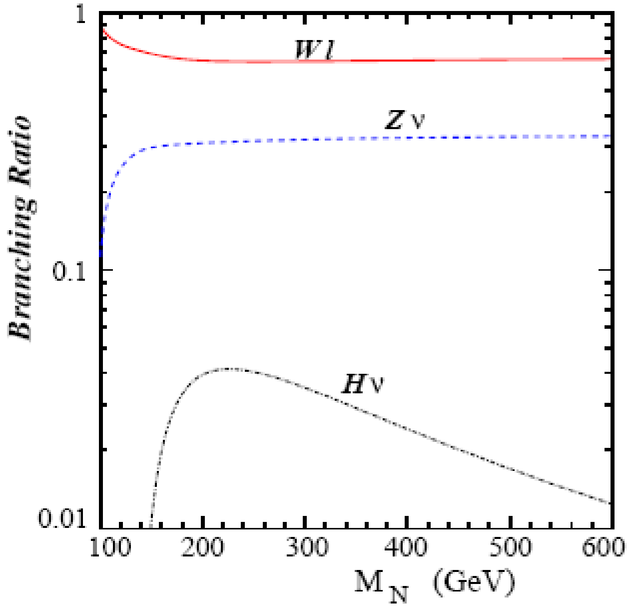




Signatures for ν_R at the LHC

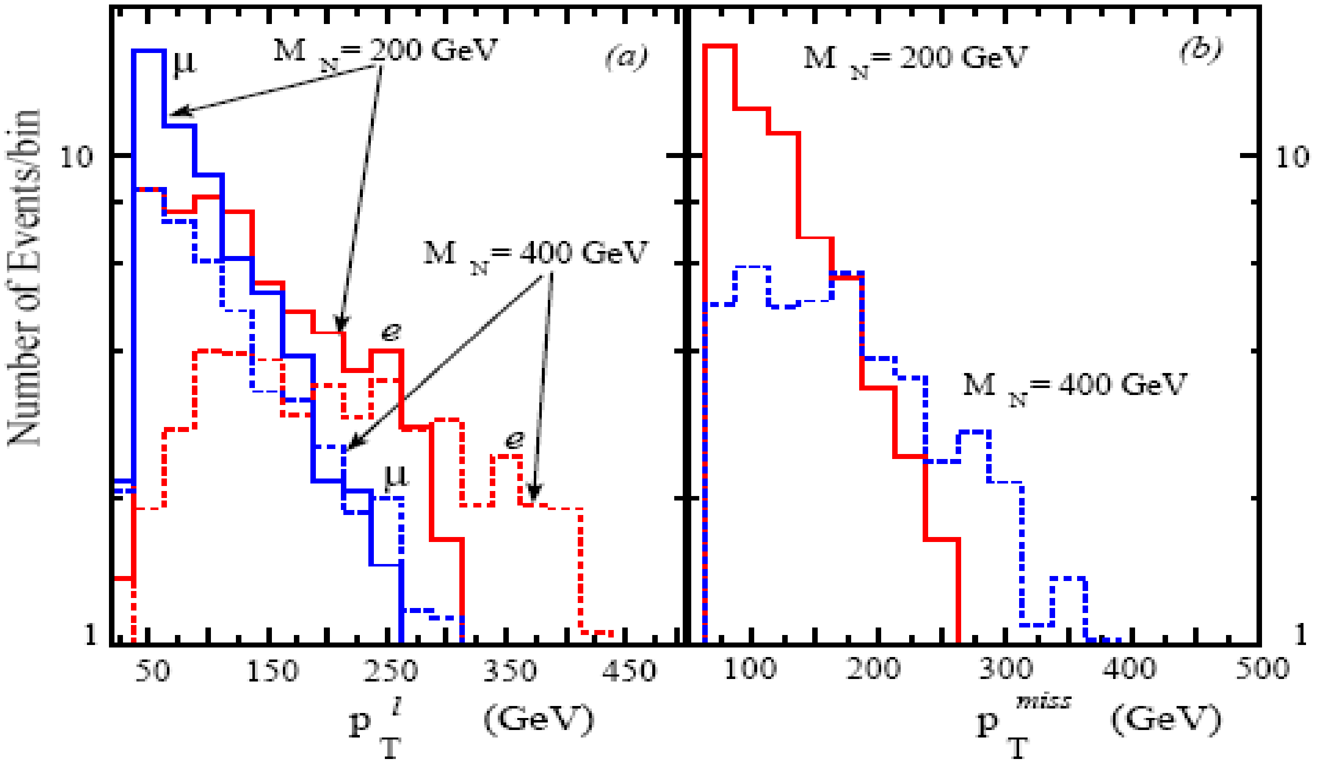
$$\mathcal{L}_{int.} \sim -g'' C_\mu [(\overline{\nu_R})_i \gamma^\mu (\nu_R)_i + b_{ij} \overline{(\nu_L)^c}_i \gamma^\mu (\nu_R)_j + h.c.] + \frac{g_2}{\sqrt{2}} [W_\mu^- l_i^+ \gamma^\mu U_{ij} (\nu_L)_j + b_{ij} W_\mu^- l_i^+ \gamma^\mu (\nu_R)_j^c + h.c.],$$





The decay modes, which go through the Higgs H or H' and Z boson, can be neglected compared to the main mode $\nu_R \to W\,l$.

These decays are very clean with four hard leptons in the final states and large missing energy due to the associated neutrinos.



The transverse momentum distribution for the charged leptons and the missing transverse momentum, for the $4l + \not{E}_T$ signal at the LHC for M_N = 200 GeV and M_N = 400 GeV.

Integrated luminosity ~ 300 fb^{-1} gives 71 events for the right handed neutrino mass of 200 GeV while it gives 46 events for the right handed neutrino mass of 400 GeV.

Warped Extra Dimension

Why Extra dimensions

- String theory: at least six unseen dims.
- General Relativity: why 4?
- New ways of approaching old problems: Hierarchy problem:
-
- What do extra dimensions look like?
- How many? What shape? How big are they?
- Are they all the same?

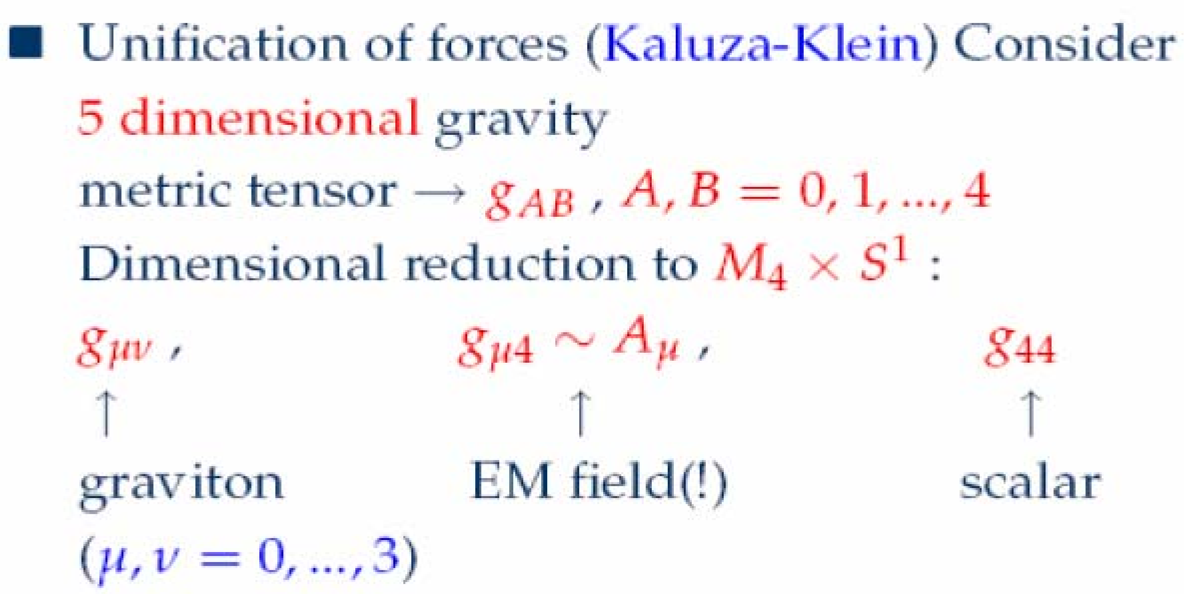
- We don''t know how many. Up to six (seven?) in string theory .

- Extra dimension can be curled up : Can be simple (circle, torus) or complicated (Calabi – Yau)

- They can be bounded between branes
- They can be flat or they can be warped.

Kaluza-Klein theory

- **5-Dimensional spacetime**
  - **In 1919, Kaluza united Einstein’s and Maxwell’s equation using a fourth spatial dimension**
  - **extra dimension ‘wrapped up’ in a tight circle**



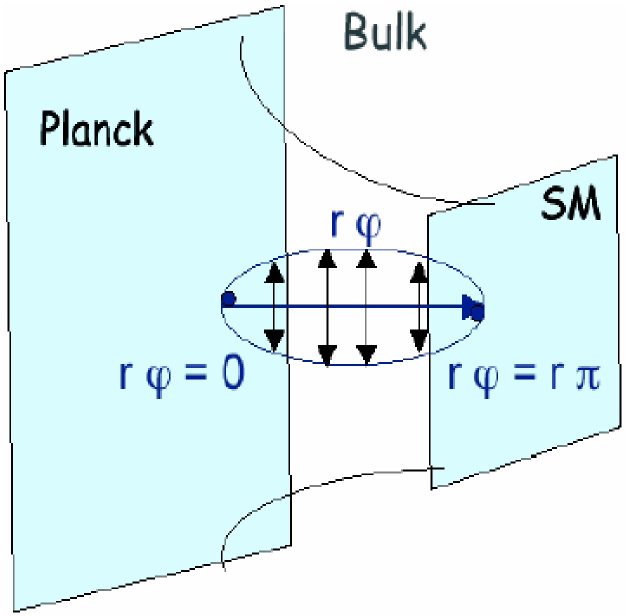
- Unification of forces (Kaluza-Klein) Consider 5 dimensional gravity

metric tensor → $g_{AB}\,,\ A, B = 0, 1, \ldots, 4$

Dimensional reduction to $M_4 \times S^1$:

$$\begin{array}{lll} g_{\mu\nu}\,, & g_{\mu 4} \sim A_\mu\,, & g_{44} \\ \uparrow & \quad\uparrow & \uparrow \\ \text{graviton} & \text{EM field(!)} & \text{scalar} \\ (\mu, \nu = 0, \ldots, 3) & & \end{array}$$

Warped Extra Dimensions: RS I model



- The Randall-Sundrum model:
  - 5D space-time with 2 branes of 4D:
    - Metric: $e^{-2kr|\varphi|}\,\eta_{\upsilon\mu}\,dx^{\upsilon}\,dx^{\mu} + r_c^2 d\varphi^2$
    - $k\ (\sim M_{pl})$ curvature of the space
    - r_c compactification radius of extra dimension, $r_c \approx 10^{-32}$ m
    - New coordinate: $\varphi\ (-\pi \le \varphi \le \pi)$
    - Traditional 4D coordinates: x^{v}
  - Gravity scale :
    - Gravity is localized on the brane at $\varphi = 0$ and $\Lambda_\pi = M_{Pl}\,e^{-kr\pi}$
    - $Kr_c \approx 11\text{-}12 \rightarrow \Lambda_\pi \sim 1$ TeV (i.e. no hierarchy)

Search for Extra Dimensions

- Only the graviton can propagate in 5D:
  - On the 4D branes, Kaluza-Klein excitations of the graviton can be observed :

- $M_n^2 = K x_n e^{-kr\pi}$
- x_n is the nth root of the Bessel function J_1

  - Excited gravitons are coupled to matter

$$L = -\frac{1}{\Lambda_\pi} T^{\mu\nu} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}$$

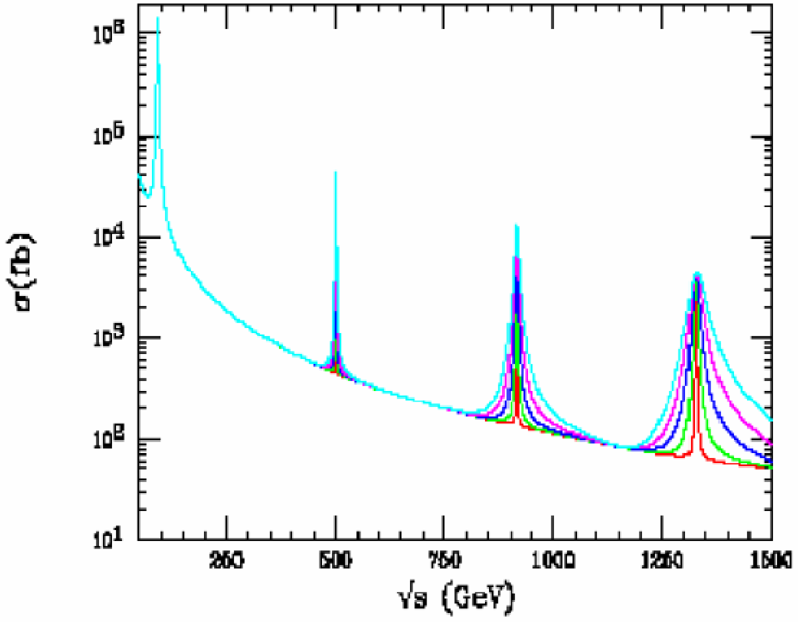


Figure 4: The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\overline{M}_{Pl}$ = in the range 0.01 – 0.05.

Stabilization RS and Radion Field

- **GW proposed a mechanism for stabilizing the size of the extra dimension in RS model.**

$$ds^2 = e^{-2k|\phi|T(x)} g_{\mu\nu}(x) dx^\mu dx^\nu - T^2(x) d\phi^2,$$

- **The corresponding action is given by:** Defining $\varphi = f \exp(-k\pi T)$ with $f = \sqrt{24M^3/k}$,

$$S = \frac{2M^3}{k} \int d^4x \sqrt{-g} \left(1 - (\varphi/f)^2\right) R + \frac{1}{2} \int d^4x \sqrt{-g} \partial_\mu \varphi \partial^\mu \varphi,$$

- **The potential for the modulus field that sets the size of the fifth dimension is generated by a bulk scalar with quartic interactions localized on the two 3-branes.**

$$S_b = \frac{1}{2} \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{G} \left(G^{AB} \partial_A \Phi \partial_B \Phi - m^2 \Phi^2\right),$$

$$S_h = -\int d^4x \sqrt{-g_h} \lambda_h \left(\Phi^2 - v_h^2\right)^2, \qquad S_v = -\int d^4x \sqrt{-g_v} \lambda_v \left(\Phi^2 - v_v^2\right)^2$$

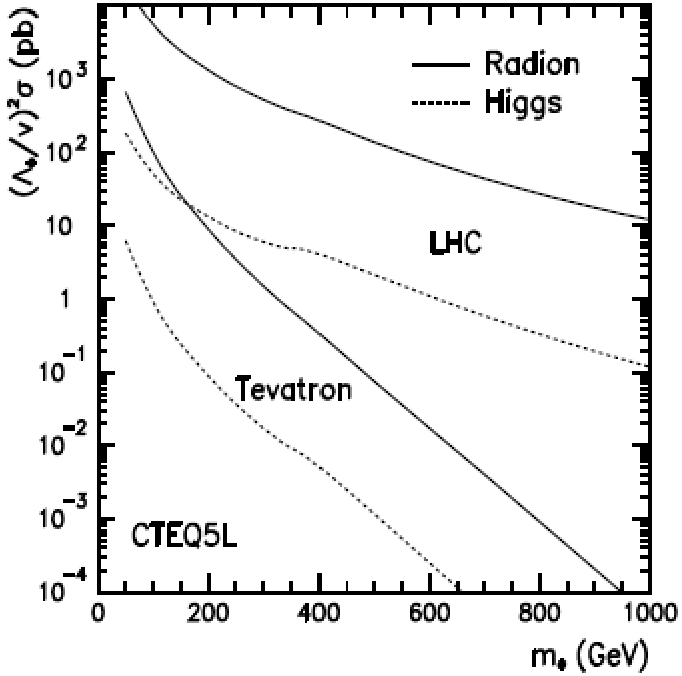
- **The mass of the radion is** $$m_\varphi^2 = \frac{\partial^2 V}{\partial \varphi^2}(\langle\varphi\rangle) = \frac{k^2 v_v^2}{3M^3}\epsilon^2 e^{-2kr_c\pi}.$$

- **Radion can be lighter than the lightest graviton KK mode.**

- **The radion couple to standard model fields via the trace of the energy-momentum tensor with a coupling given by 1/Λ_ϕ**

$$\Lambda_\phi = (\sqrt{24M_5^3/k})e^{-kr_c\pi}.$$

The cross-section of the radion production via the gluon fusion process at the evatron $(\sqrt{s}=2\ \mathrm{TeV})$ and at the LHC $(\sqrt{s}=14\ \mathrm{TeV})$ compared to the cross- sections of the SM Higgs boson production.

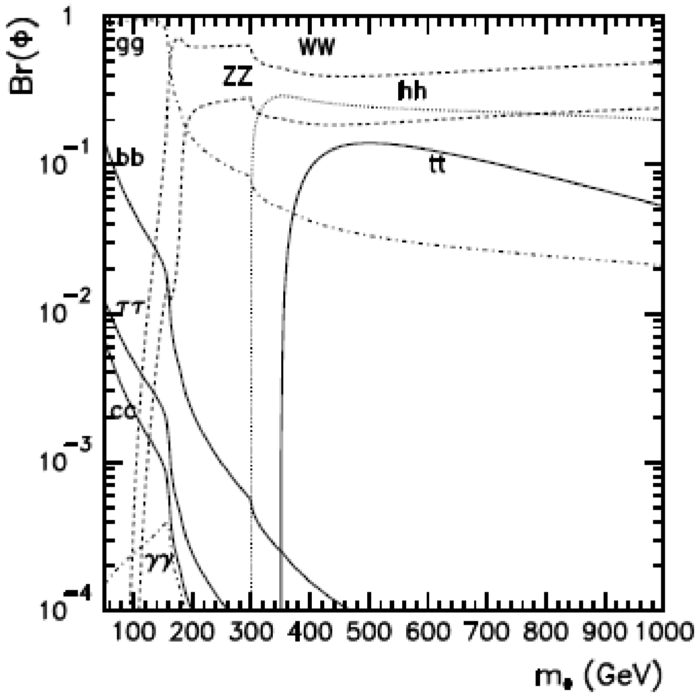


- **the radion predominantly decays into a gluon pair at low mass or W pair above the WW mass threshold.**
- **The phenomenology of the radion resembles the phenomenology of the SM Higgs boson except for the coupling to gluons which is enhanced in the case of the radion because of the trace anomaly.**

branching ratios of a radion of 300 GeV mass

Possible radion and SM Higgs mixing allows new physical mass eigenstates.

The decay branching ratios of these eigenstates are different from those of the SM Higgs boson.



Summary

- **The importance of the LHC for the future of high energy physics cannot be overemphasized. Some of the most interesting/ well motivated topics include:**
  - Electroweak Symmetry Breaking (Higgs, Technicolor, ...)
  - Supersymmetry
  - Dark Matter (LSP)
  - Extra Dimension (Kaluza Klein excitation)
  - Neutral gauge boson (Z')
  - Exotic States (Magnetic Monopoles, Fractionally charged color singlets, Z flux tubes, Leptoquarks, ...).
- Discovery of any New Physics beyond the SM would be a revolution of physics in 21st century.

Summary

- **Three Possible Scenarios for the future of Particle Physics, based on LHC results:**

- 1- Higgs and other particles, confirm physics beyond the SM, are found.
  Very optimistic scenario

- 2- Higgs only is found. Very bad for particle physics future.

- 3- Higgs is not found but other (expected) particles are detected.
  Interesting scenario