Open Questions

G.G.Ross, DIS07, Munich, April07

Open Questions Beyond the Standard Model

- The origin of mass?

  Due to a Higgs boson? Other physics?
  Solution at energy <1TeV

- Unification of fundamental forces?

  At a very high scale?

- Quantum theory of gravity?

  (Super)string theory, extra dimensions

- Origin of dark matter?

  WIMP SUSY KK …

LHC answers:

Electroweak spontaneous symmetry breaking $M_{W,Z}, m_{q_i}, m_{l_i}, V_{CKM}, V_{MNS}$

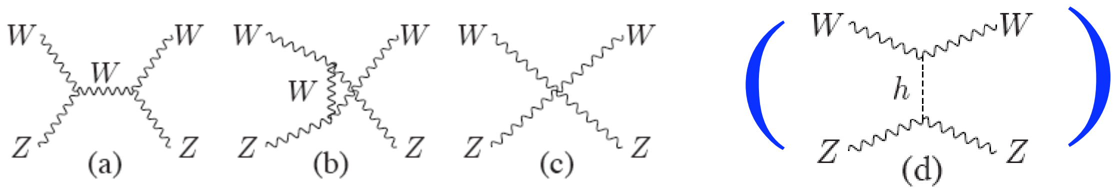
Higgs physics:

- Higgsless (or very heavy Higgs) KK, Technicolour…
- Light Higgs SUSY, eXtra Dimensions, little Higgs..

Higgsless (or very heavy Higgs)

A light Higgs scalar is needed for perturbative unification

- $W_L Z_L \to W_L Z_L$



Unitarity violation: $$\frac{g^2\Lambda^2}{16\pi^2 M_W^2} = 1 \quad \Rightarrow \quad \Lambda \sim 1.8 TeV$$

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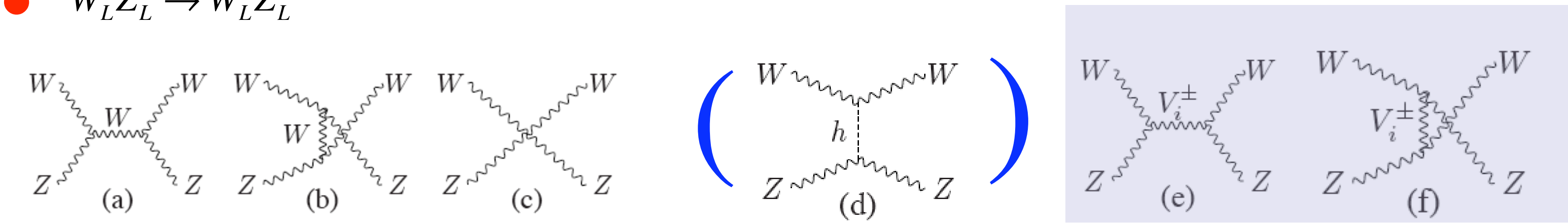

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$$\Lambda \sim \frac{3\pi^4}{g^2}\frac{M_W^2}{M} = (5-10) TeV$$

Higgsless

Chivukula, Discus, He

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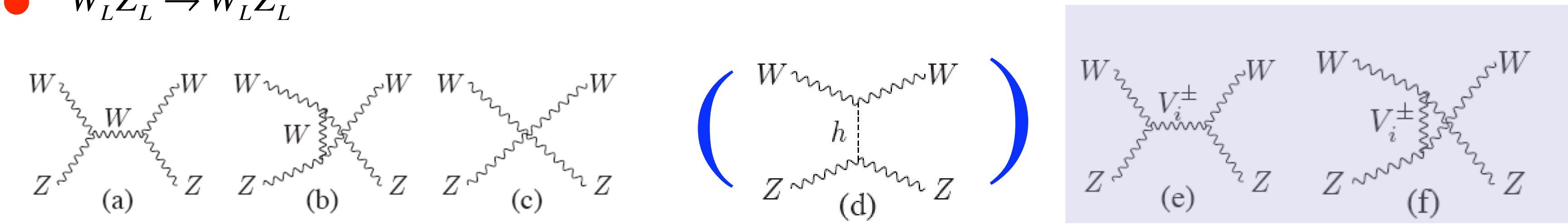

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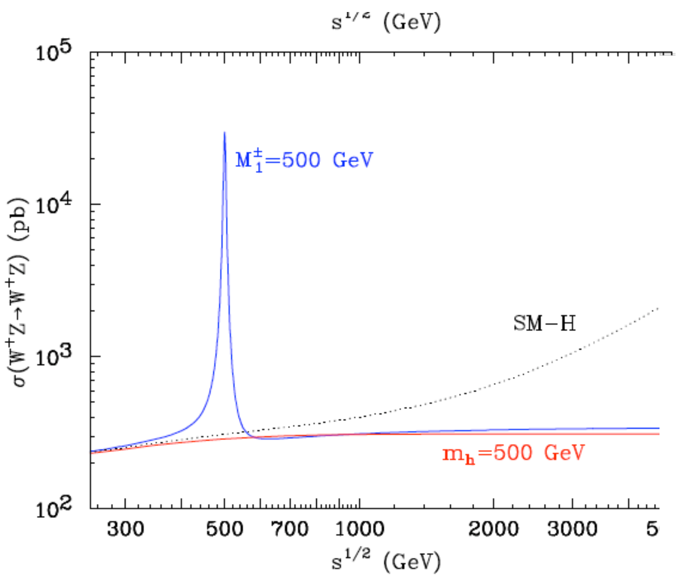
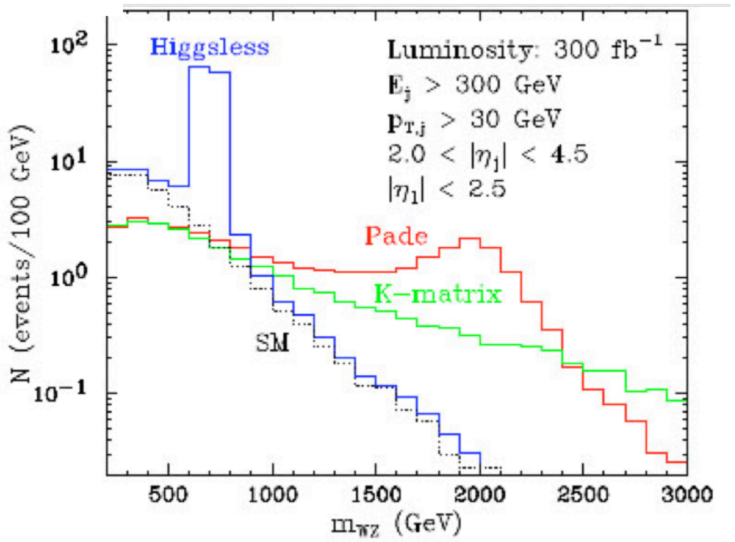
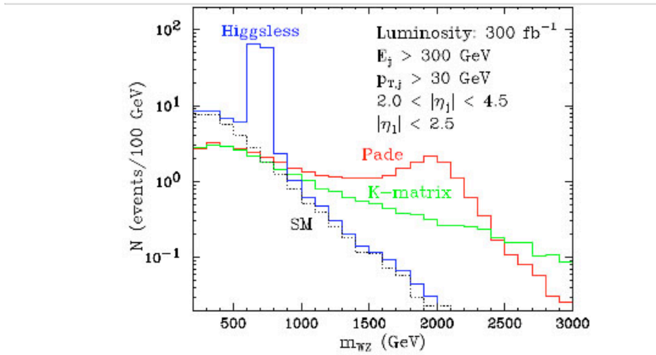
LHC: W/Z bremsstrahlung off quarks $\Rightarrow$ 2 forward jets + gauge boson pair $\Rightarrow$ 2j+3l+$\not{E}_T$





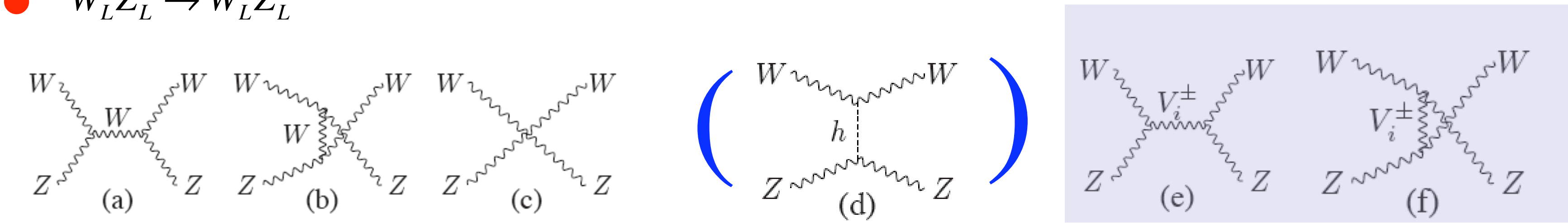
Birkedal, Matchev, Perelstein

$V^{\pm}$ Resonance structure



Narrow resonance
c.f. strongly bound state

- $W_L Z_L \to W_L Z_L$



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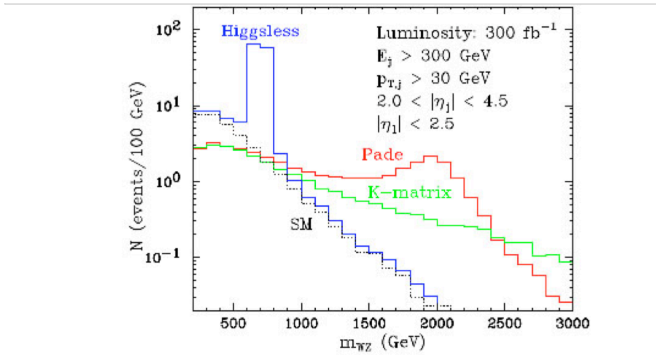

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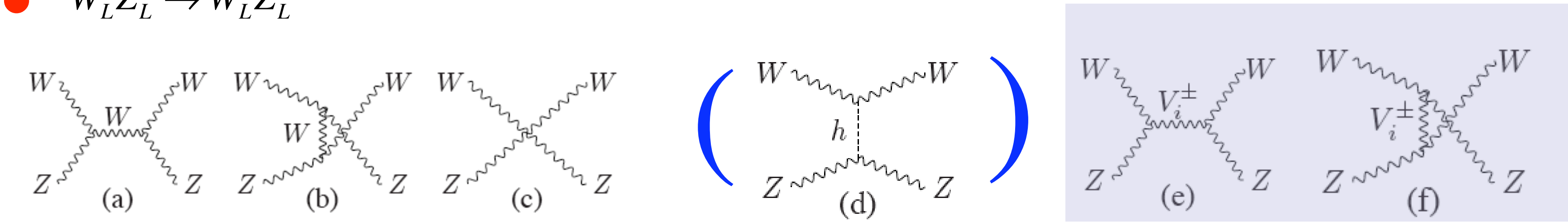

Model	$WW \to WW$	$WZ \to WZ$	$WW \to ZZ$
SM	Yes	No	Yes
Higgsless	Yes	Yes	No

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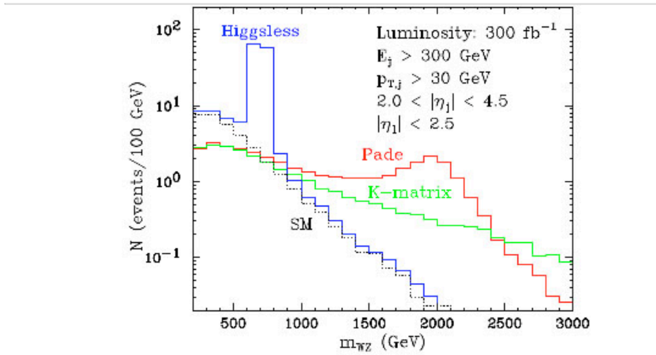

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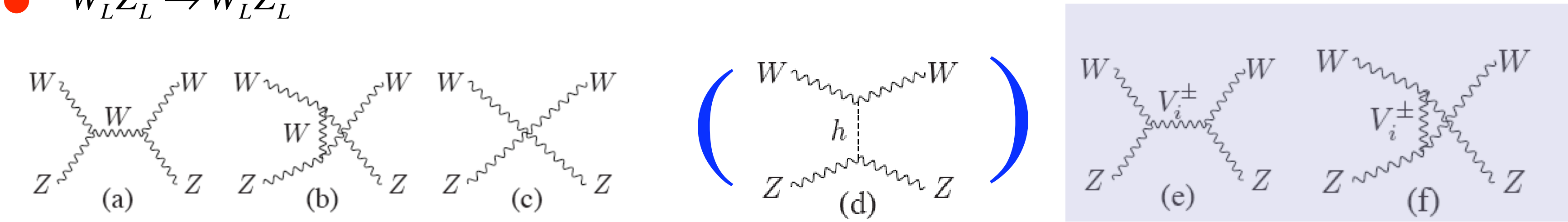

Difficult as large QCD backgrounds in multijet channel

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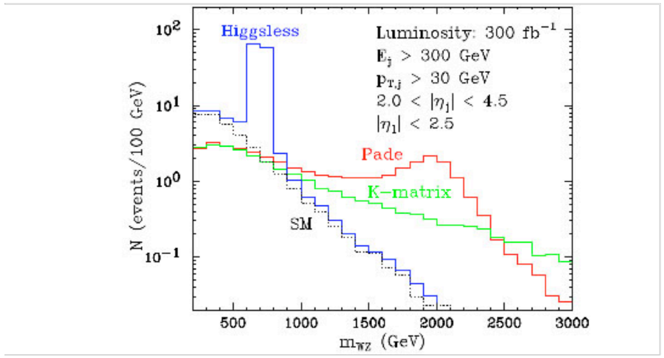

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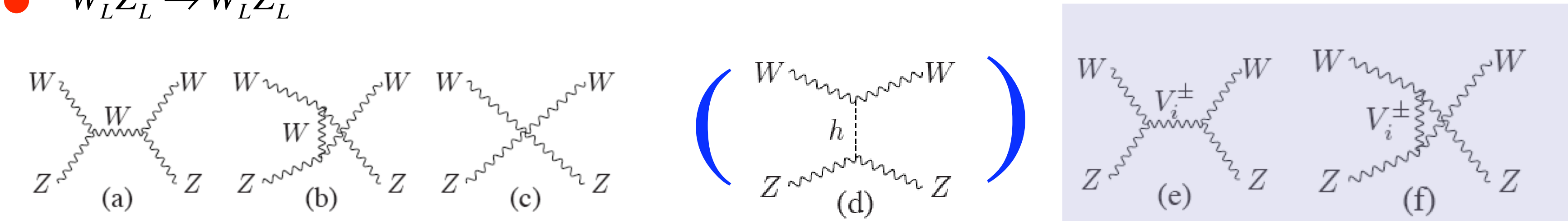

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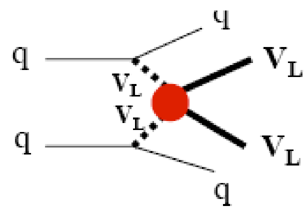
Mass measurement can establish Higgsless models

$$g_{\mathrm{WWZZ}} = g_{\mathrm{WWZ}}^2 + \sum_i (g_{\mathrm{WZV}}^{(i)})^2,$$

Csaki et al

$$2(g_{\mathrm{WWZZ}} - g_{\mathrm{WWZ}}^2)(M_{\mathrm{W}}^2 + M_{\mathrm{Z}}^2) + g_{\mathrm{WWZ}}^2 \frac{M_{\mathrm{Z}}^4}{M_{\mathrm{W}}^2} = \sum_i (g_{\mathrm{WZV}}^{(i)})^2 \left[3(M_i^{\pm})^2 - \frac{(M_{\mathrm{Z}}^2 - M_{\mathrm{W}}^2)^2}{(M_i^{\pm})^2}\right]$$

Strongly coupled vector boson sector



Unitarity saturation signals strong interaction,-
observation of no excess means weakly coupled quanta below 1TeV

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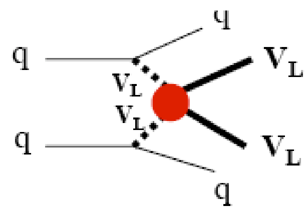

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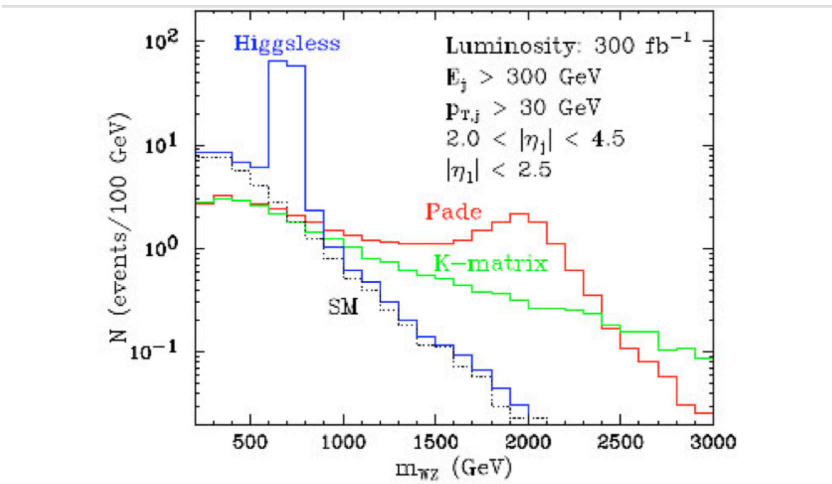
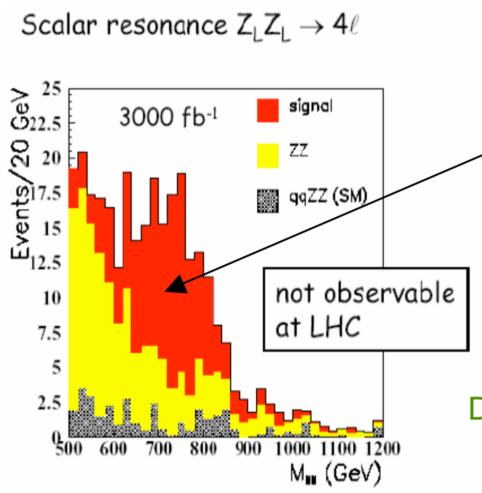
Chanowitz “No-lose” theorem

- Unfortunately

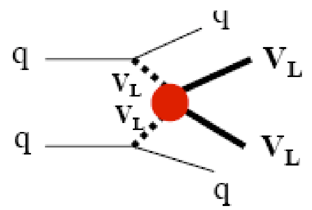




Need v accurate q dist fns..

De Rocek

Strongly coupled vector boson sector



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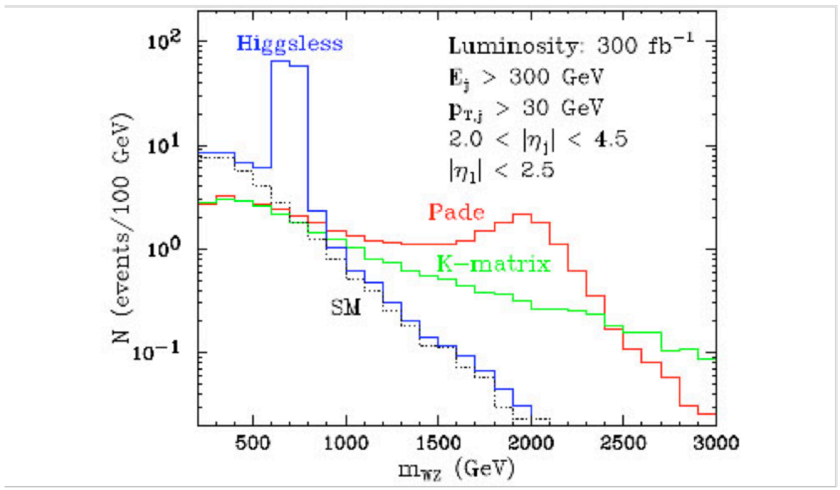
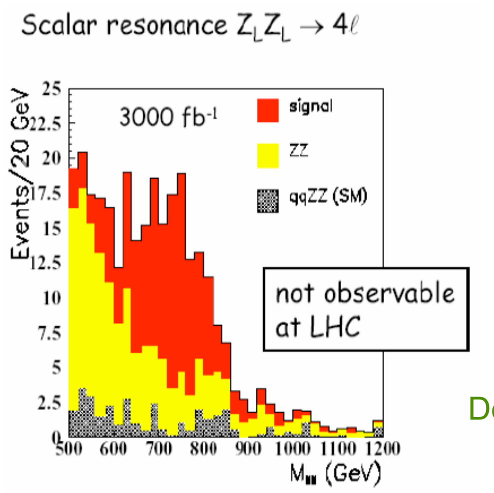
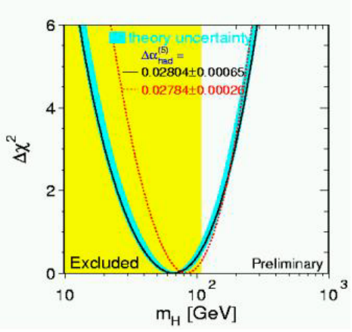


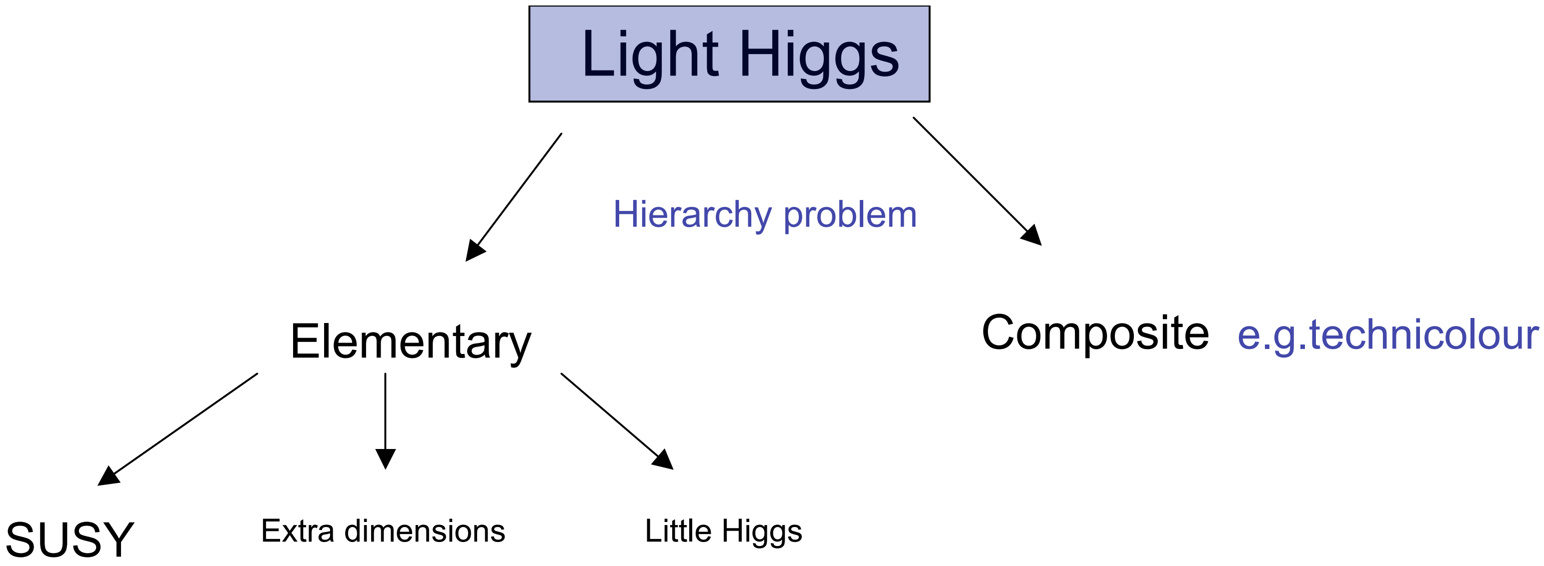


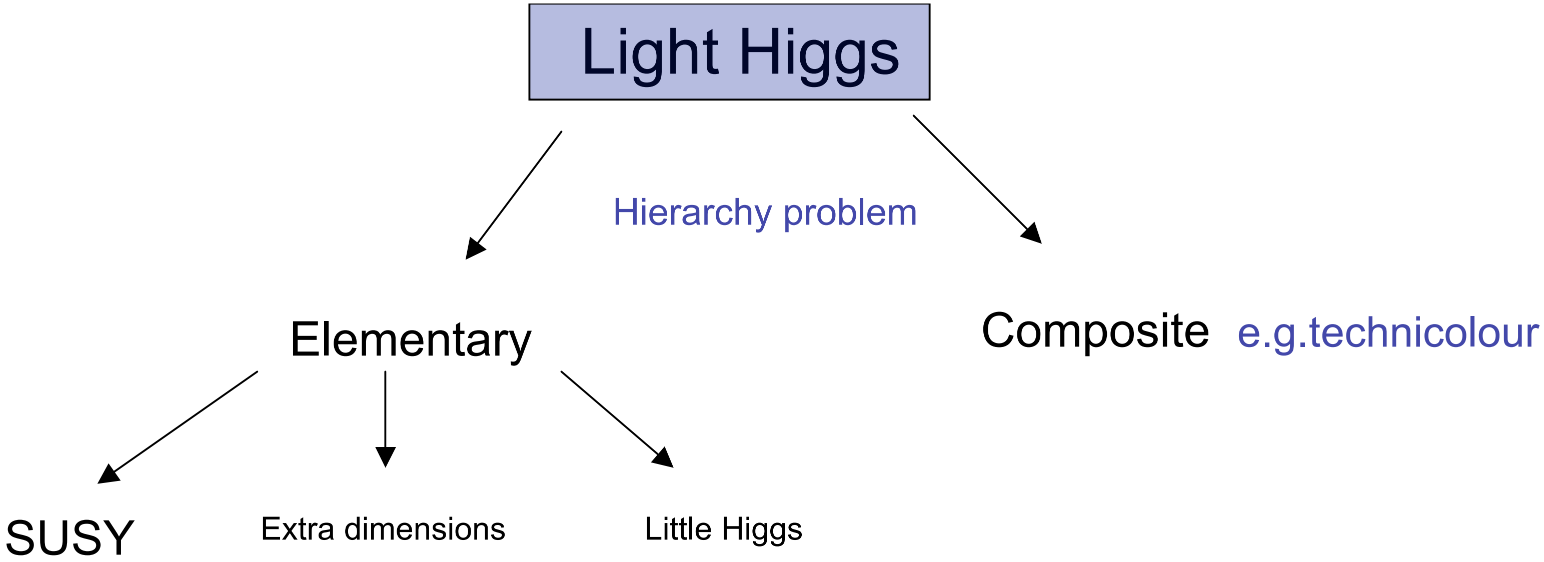
De Rocek

- But precision tests suggest strong interaction cannot be all



Light Higgs


Light Higgs
Hierarchy problem
Elementary
Composite
e.g.technicolour
SUSY
Extra dimensions
Little Higgs



How will we distinguish these possibilities?

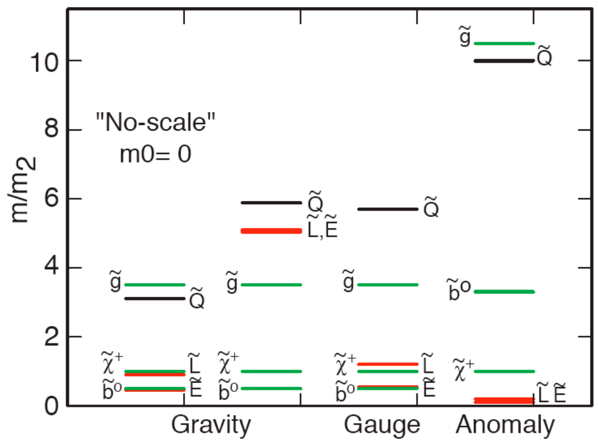
Light Higgs

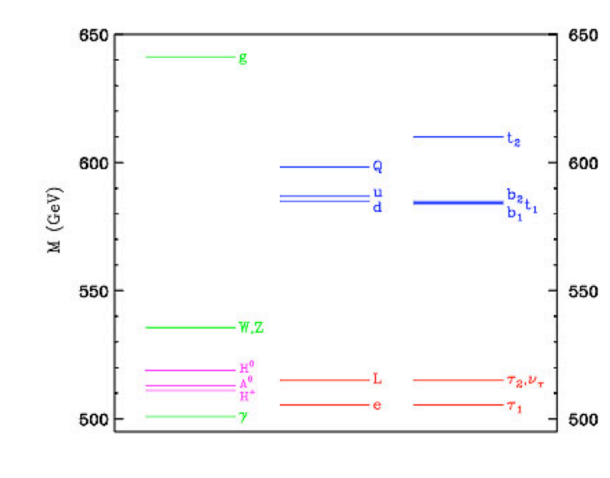
Hierarchy problem

- **Elementary**
  - SUSY
  - Extra dimensions
  - Little Higgs
- **Composite** e.g.technicolour

How will we distinguish them?

e.g. SUSY and UED have similar level structure



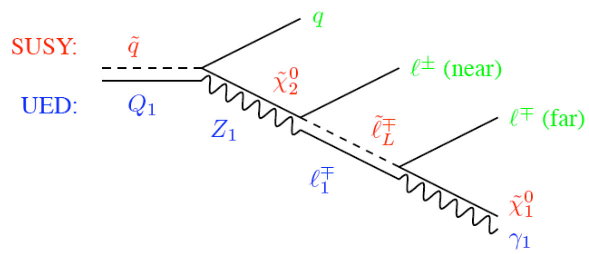


Similar radiative corrections

Cheng et al

Also the couplings of both the SUSY and KK states are the same as their SM partners

Spin discriminant



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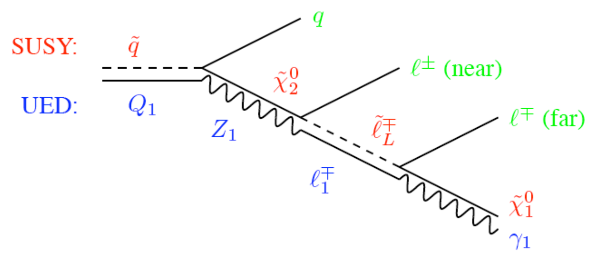
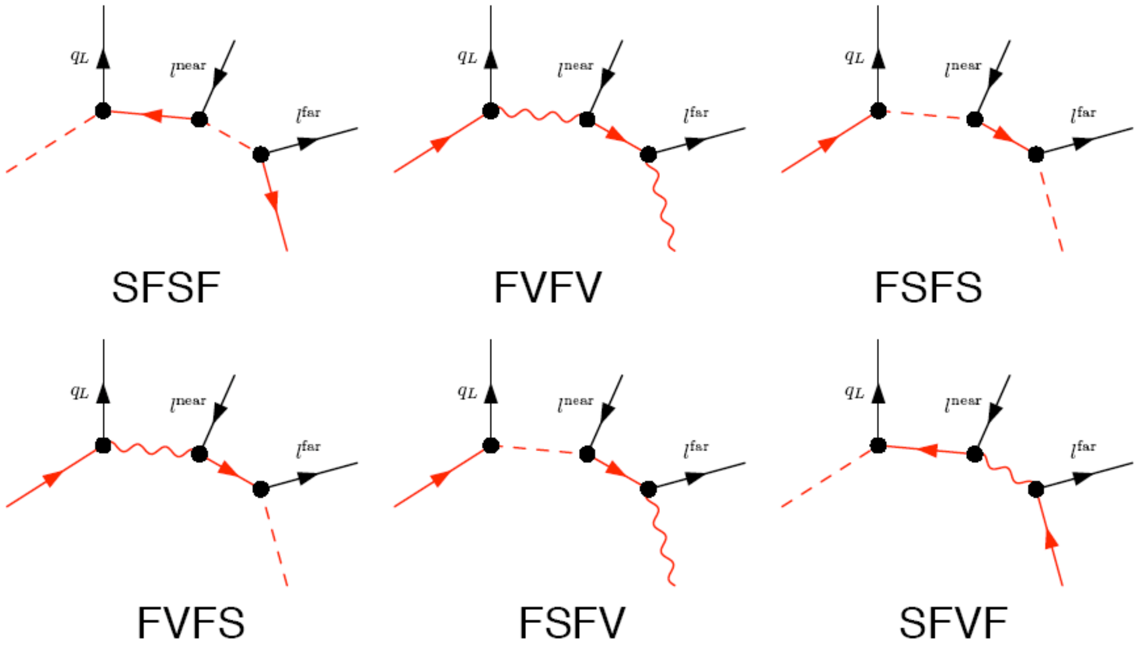


Cascade Decay Chains

There are 6 possible spin assignments:



S = scalar F = fermion V = Vector

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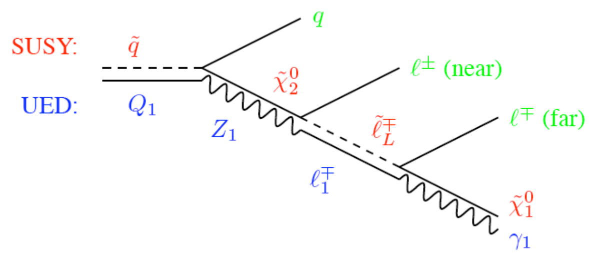

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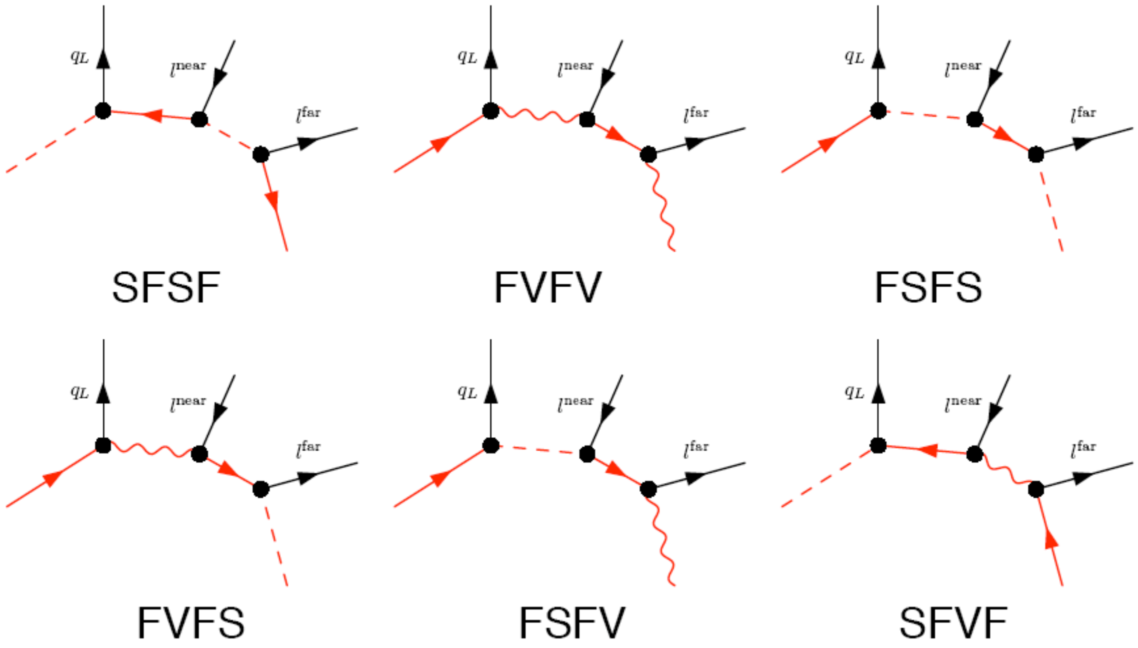

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Discriminant:

$$\frac{dP}{dm} = \frac{1}{\Gamma}\frac{d\Gamma}{dm}$$

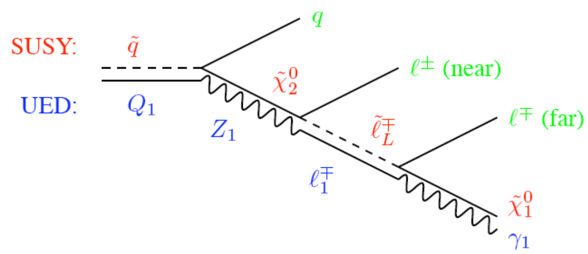
Γ total decay rate of chain

$$m_{ab}^2 = (p_a + p_b)^2$$

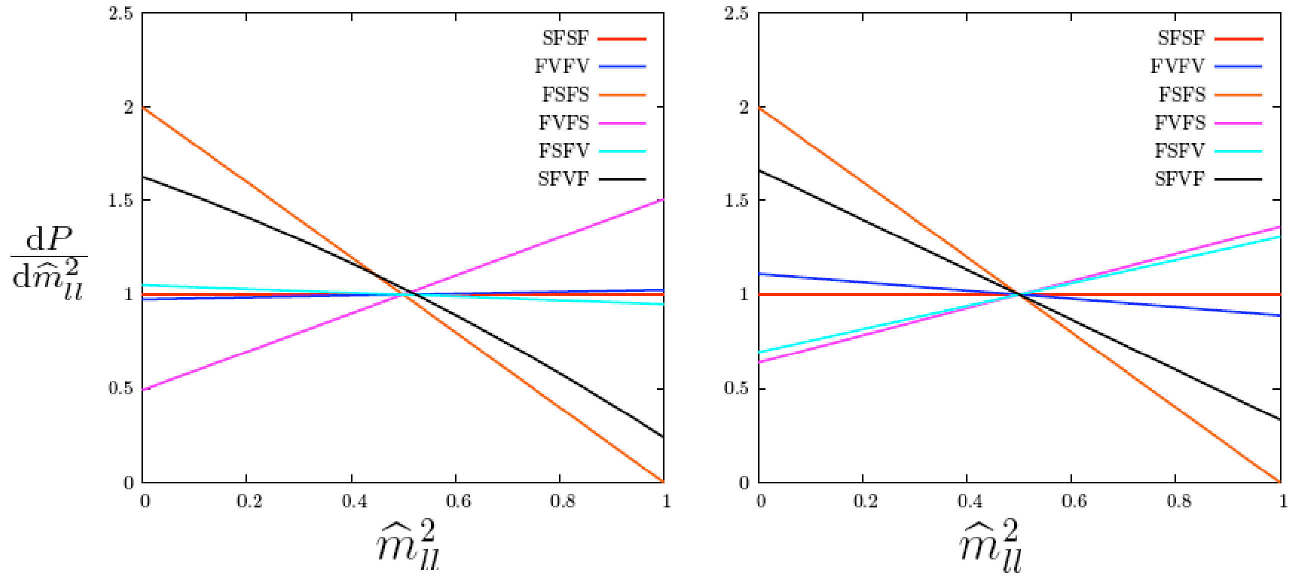
Barr

Athanasiou, Lester, Smillie, Webber

For Example, l^+l^-



The m_{ll}^2 distributions for SPS 1a masses and UE
$(R^{-1} = 800\mathrm{GeV}, \Lambda R = 20)$ are:



$$\frac{dP}{dm} = \frac{1}{\Gamma}\frac{d\Gamma}{dm}$$

Γ total decay rate of chain

Discrimination

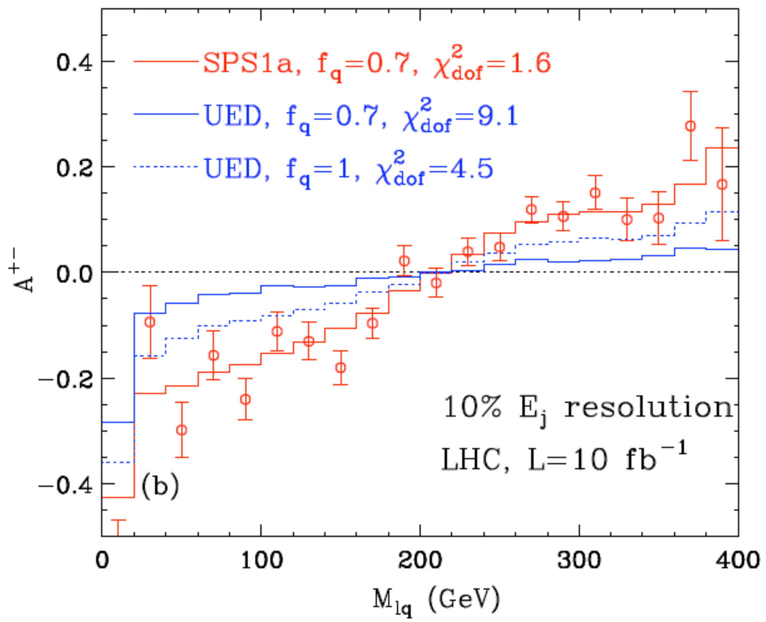
T↓ S→	SFSF	FVFV	FSFS	FVFS	FSFV	SFVF
SFSF	∞	60486	23	148	15608	66
FVFV	60622	∞	22	164	6866	62
FSFS	36	34	∞	16	39	266
FVFS	156	173	11	∞	130	24
FSFV	15600	6864	25	122	∞	76
SFVF	78	73	187	27	90	∞

Number of events, assuming FSFS is true, such that FSFS is 1000 times more likely than other model.

Athanasiou, Lester, Smillie, Webber

Caveats: jet identification, mass measurements uncertain, charge asymmetry only comes from quark production…

$$e.g. \quad \frac{dP}{dm_{ll}^2} \text{ - Difference between SUSY and UED } \propto \beta(\mathrm{m_i}), \text{ small in favoured parameter space}$$



Kong, Matchev

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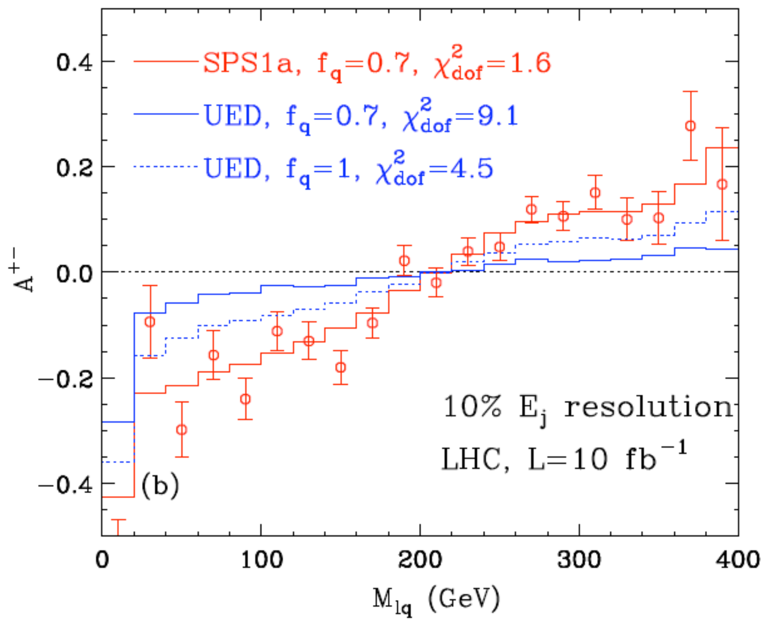


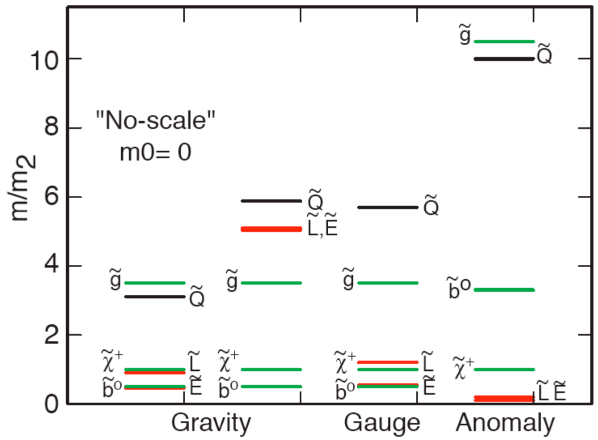
Alternative methods being developed may offer complementary information

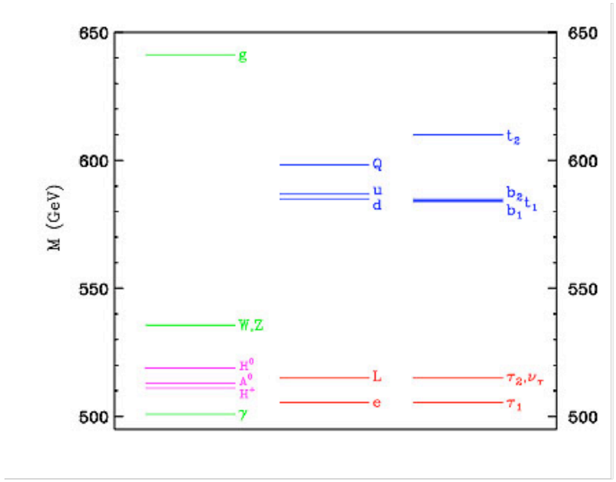
e.g. $\left(\frac{d\sigma}{d\cos\theta^*}\right)$; θ^* angle between incoming quark and lepton

$$q\bar{q} \to Z^0/\gamma \to \tilde{\ell}^+\tilde{\ell}^- \to \tilde{\chi}_1^0\ell^+ \, \tilde{\chi}_1^0\ell^- ,$$
$$q\bar{q} \to Z^0/\gamma \to \ell_1^+\ell_1^- \to \gamma_1 \, \ell^+\gamma_1 \, \ell^- .$$

Barr

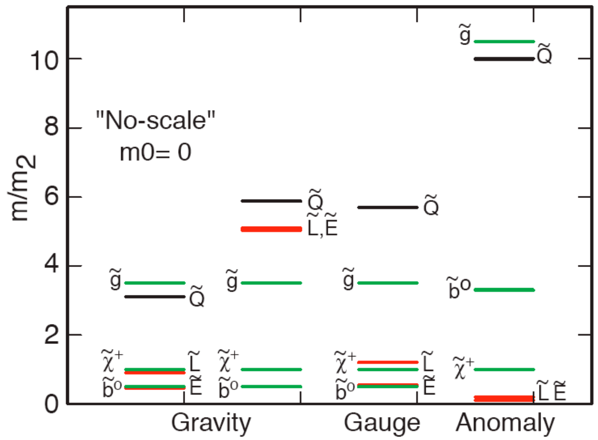
Spectrum

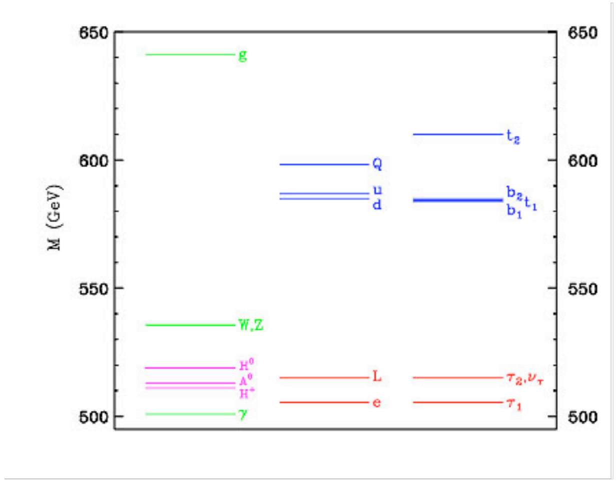




What do we learn from measuring the spectrum?

Spectrum





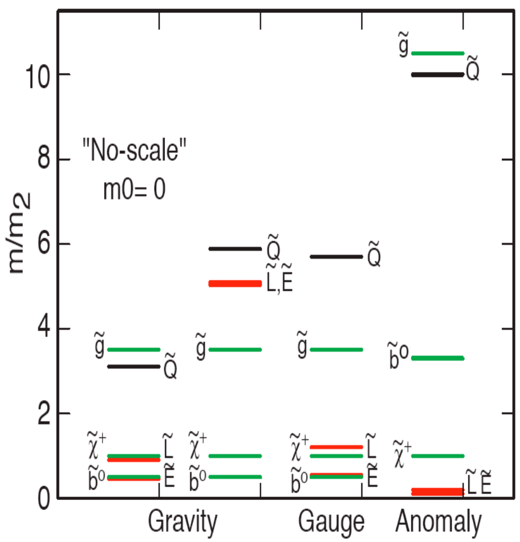
What do we learn from measuring the spectrum?

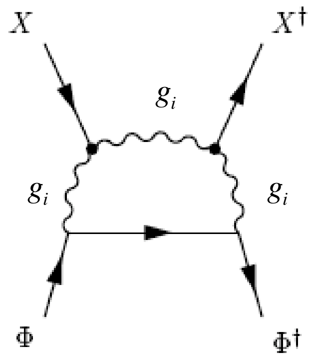
SUSY: SUSY breaking mechanism, hidden sector, unification

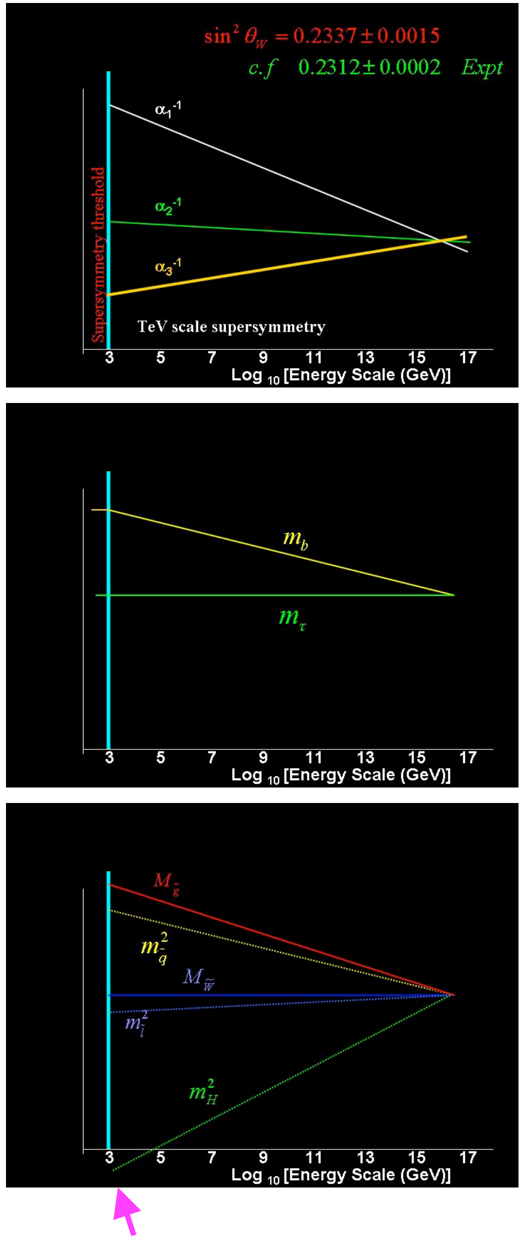
XD: Compactification (need higher levels)

Dark matter abundance

SUSY: Soft mass unification

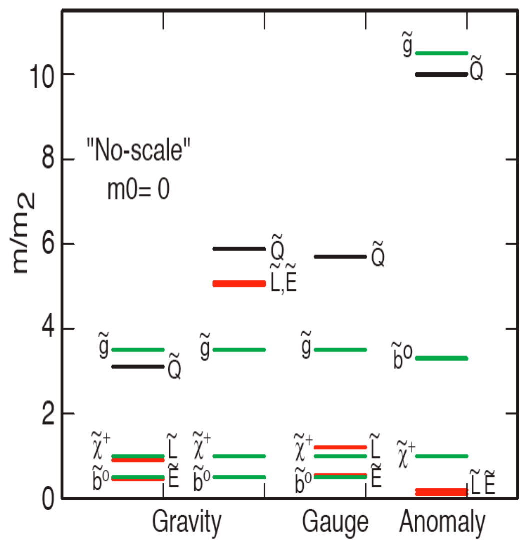


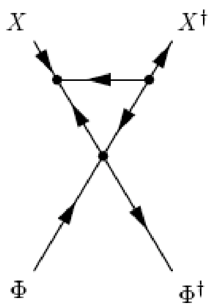


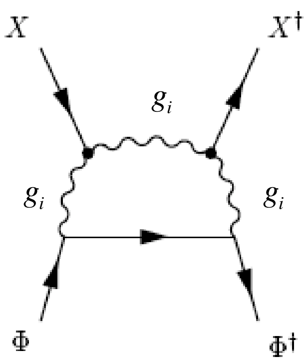


$$SU(3) \otimes SU(2) \otimes U(1) \rightarrow SU(3) \otimes U(1)_{EM}$$

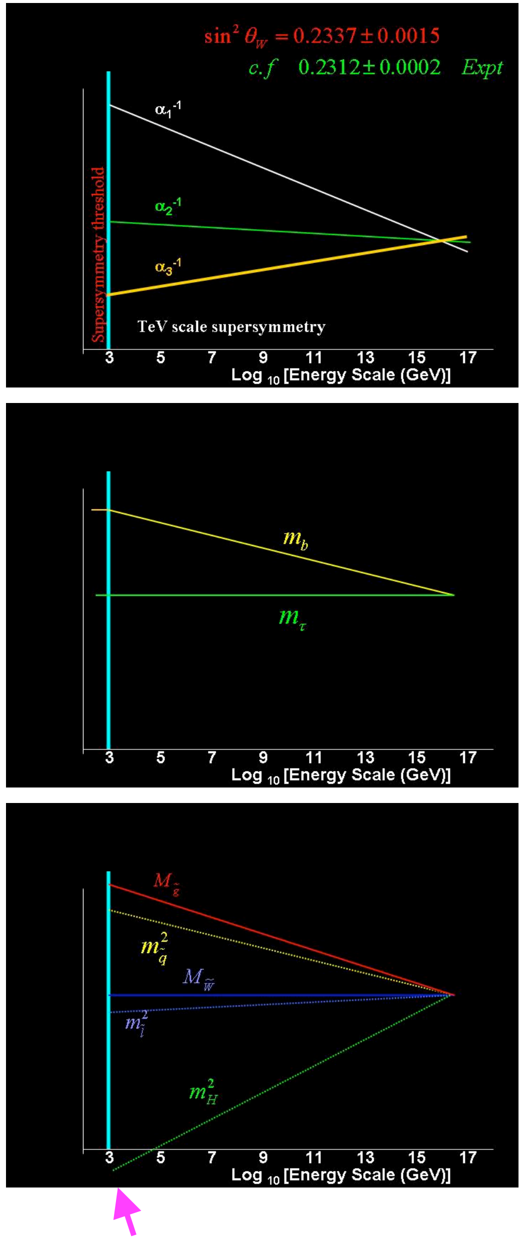
SUSY: Soft mass unification







Cohen, Roy, Schmaltz



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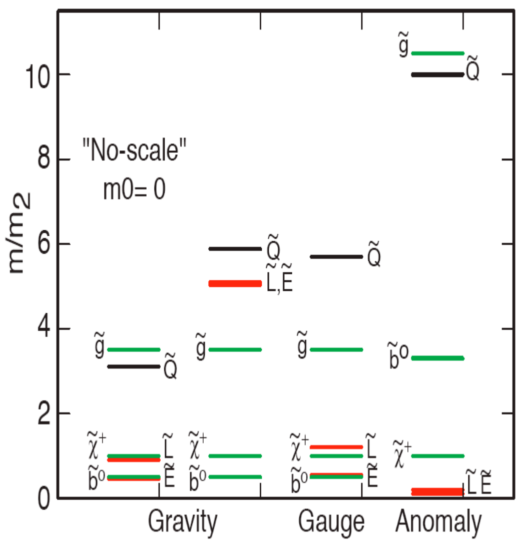
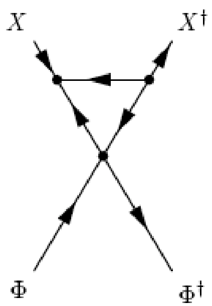
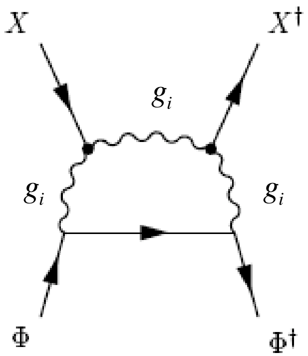
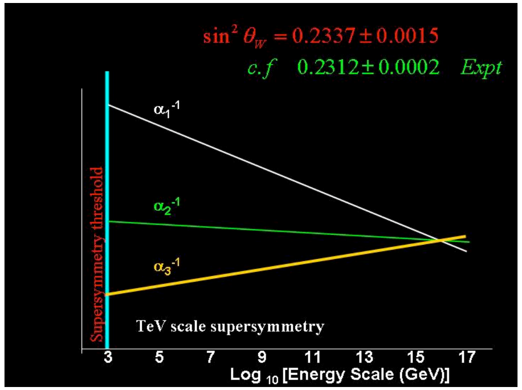
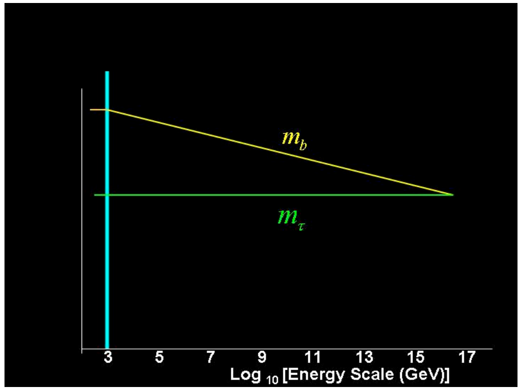
SUSY: Soft mass unification

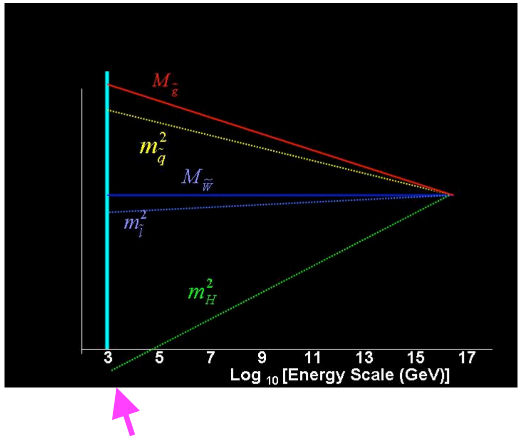












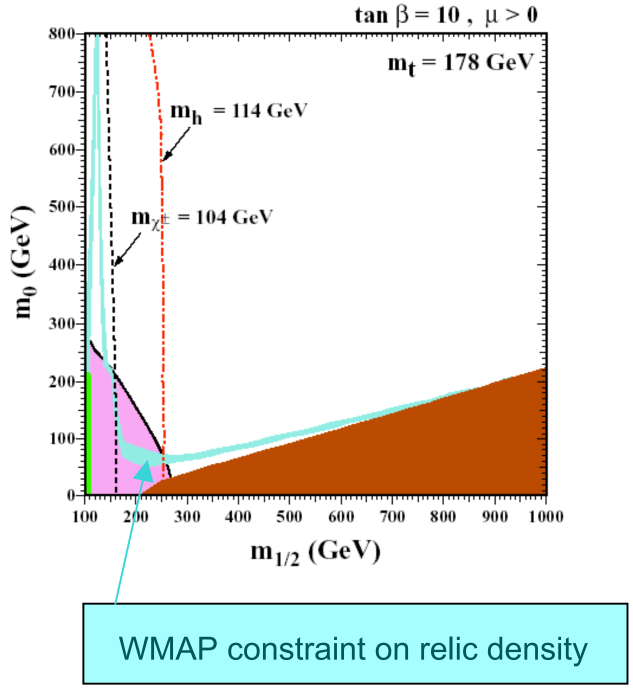
$$SU(3)\otimes SU(2)\otimes U(1)\rightarrow SU(3)\otimes U(1)_{EM}$$

- Gaugino mass unification unaffected
- Soft mass unification (usually) unchanged

Dark matter abundance

Dark matter abundance in SUSY LSP very sensitive to slepton mass(es)

Neutralino LSP



Ellis, Olive, Santoso, Spanos

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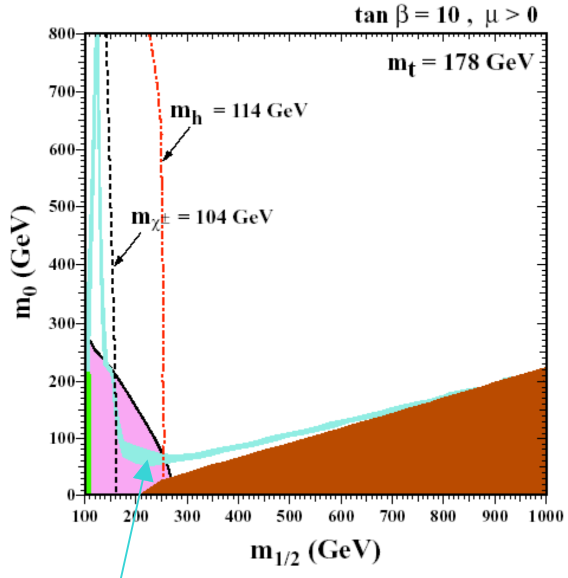


WMAP constraint on relic density

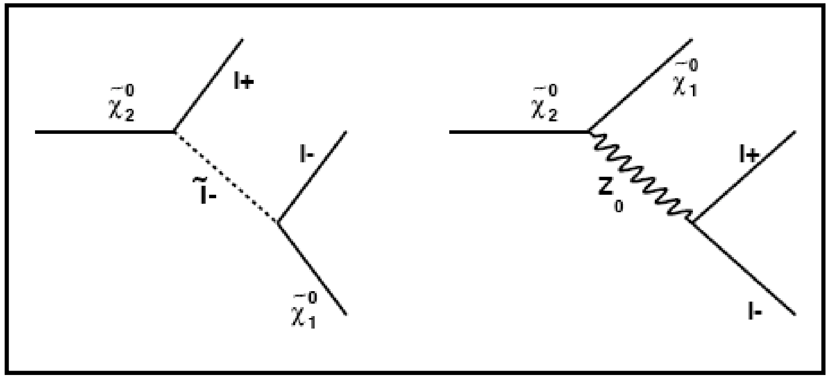
Ellis, Olive, Santoso, Spanos

Slepton mass measurement at the LHC

- Direct production channel has large WW, tt backgrounds
- Cascade decays promising - dilepton invariant mass distribution

e.g. $\tilde{\chi}_2^0 \to l^\pm l^\mp \tilde{\chi}_1^0$

Endpoint for virtual intermediate states: $m_{ll,\max} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

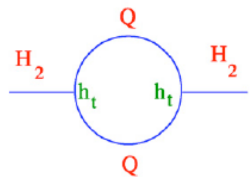


Event rate for mSUGRA study points:

Point	M_0	$M_{\frac{1}{2}}$	$M_{\tilde{l}}$	σ	N(10fb^{-1})
A	40GeV	189 GeV	92 GeV	170 pb	$1.7 * 10^6$
B	150GeV	187 GeV	96 GeV	150 pb	$1.5 * 10^6$
C	3280GeV	300 GeV	3277 GeV	4.4 pb	44,000
$t\bar{t}$ (SM background)	NA	NA	NA	425 pb	$4.25 * 10^6$

Birkedal, Group, Matchev

Heavy SUSY - Little Higgs



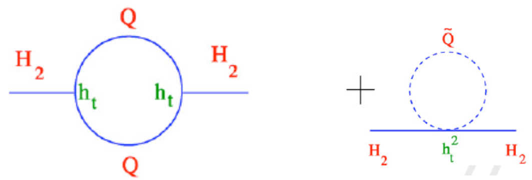
Little hierarchy problem:

Fine tuned

Standard Model

$$\delta m_H^2 \propto y_t^2 \Lambda_{UV}^2$$

Heavy SUSY - Little Higgs



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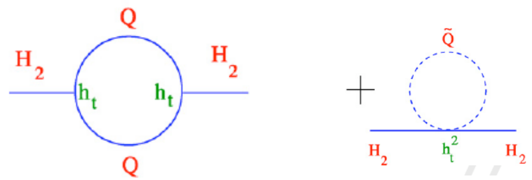

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(Pseudo Goldstone boson)

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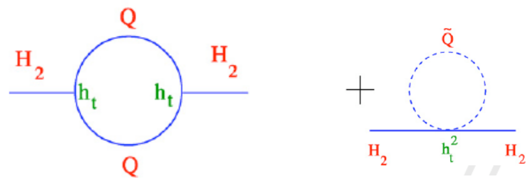

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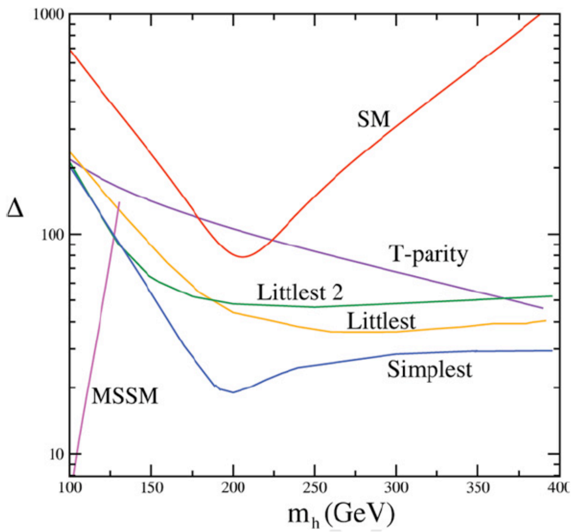
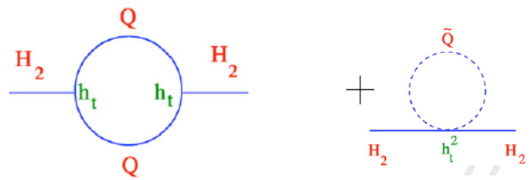


Heavy SUSY - Little Higgs



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Little Higgs $$\delta m_H^2 \propto \frac{y_t^2}{16\pi^2} f^2$$

(Pseudo Goldstone boson)

..but precision tests $\Rightarrow f = O(TeV)$ Fine tuned

Double protection $$\delta m_H^2 \approx -\frac{3y_t^2}{8\pi^2}\left[(m_{\tilde{t}}^2 + m_T^2)\log(m_{\tilde{t}}^2 + m_T^2) - m_{\tilde{t}}^2 \log(m_{\tilde{t}}^2) - m_T^2 \log(m_T^2)\right]$$

(SUSY+PG boson)

Vectorlike top quark

(Needed to cancel top quark contribution)

Falkowskiet al;Csaki et al…

$$M_{SUSY} \rightarrow 10TeV, \quad m_T \leq 1TeV$$

New heavy quarks, new heavy gauge bosons $\sim TeV$

SUMMARY

LHC will probe new energy regime relevant to EW breaking.

Many possibilities identified - it will require extensive correlated information to distinguish between them. This will need:

- Control over SM backgrounds in a wide variety of (multiparticle) processes
- Higher order radiative corrections $(\sigma(gg \to H) \simeq \sigma_{LO}(1 + 0.7 + 0.3 + ..))$
- Develop techniques to measure spin and mass of new states

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Much has been done but much still to do!