Theoretical Developments Beyond the Standard Model

by

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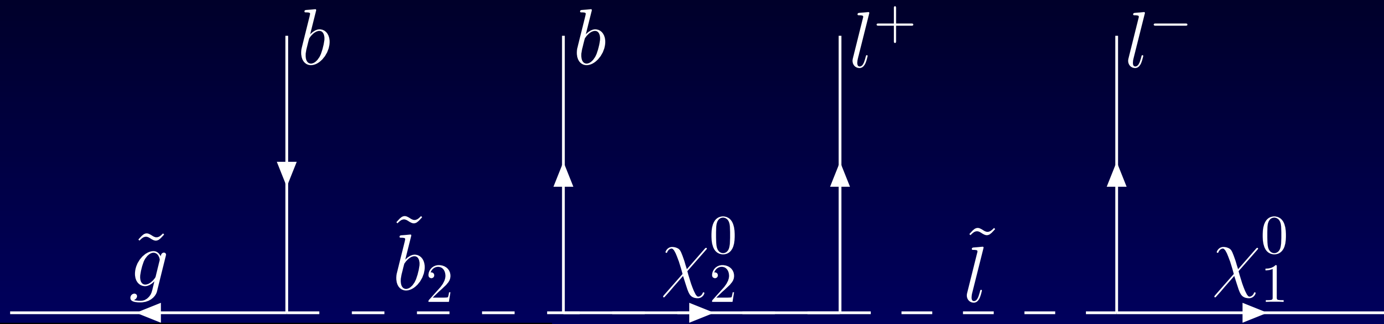
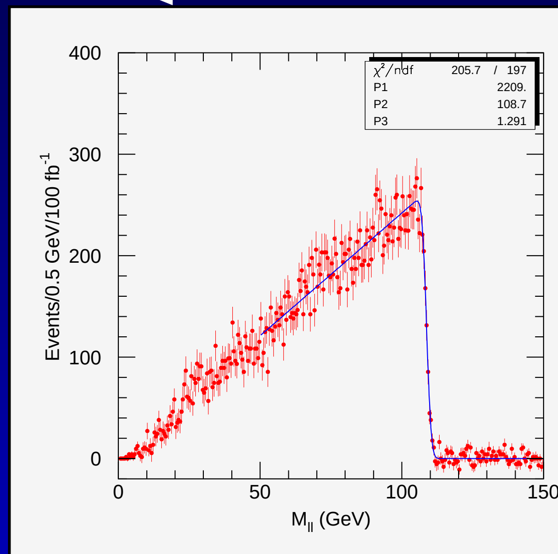
Talk outline

- Bestiary of some relevant models
- SUSY dark matter
- Spins and alternatives

Hadronic SUSY Measurements





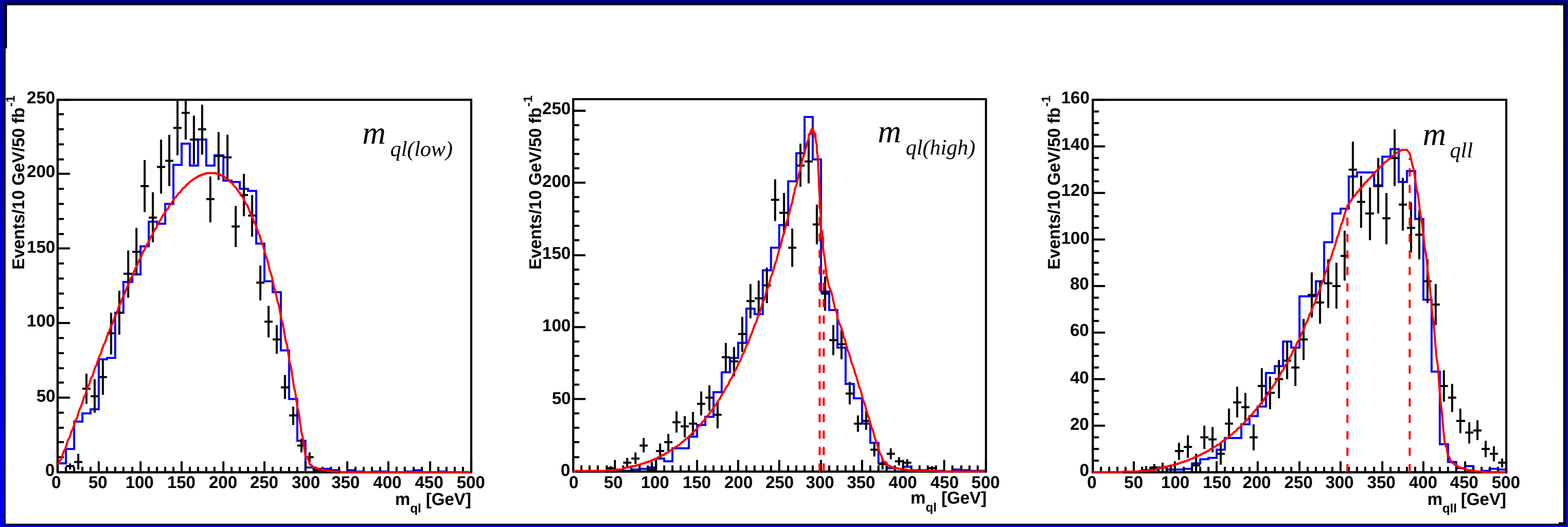
$$m_{ll}^2 = \frac{(m_{\chi_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\chi_1^0}^2)}{m_{\tilde{l}}^2}$$

Q: Can we measure enough of these to pin SUSY down

Shapes

Shape of invariant mass distribution obviously difficult due to detector effects. There are now analytical expressions: Miller, Osland, Raklev, hep-ph/0510356

- Some anti-SM cuts distort analytical shape
- Shape largely *survives* modelled detector effects
- Feet are dangerous



R-Parity Violation

There are now some R-parity violating mSUGRA *benchmarks* [a]

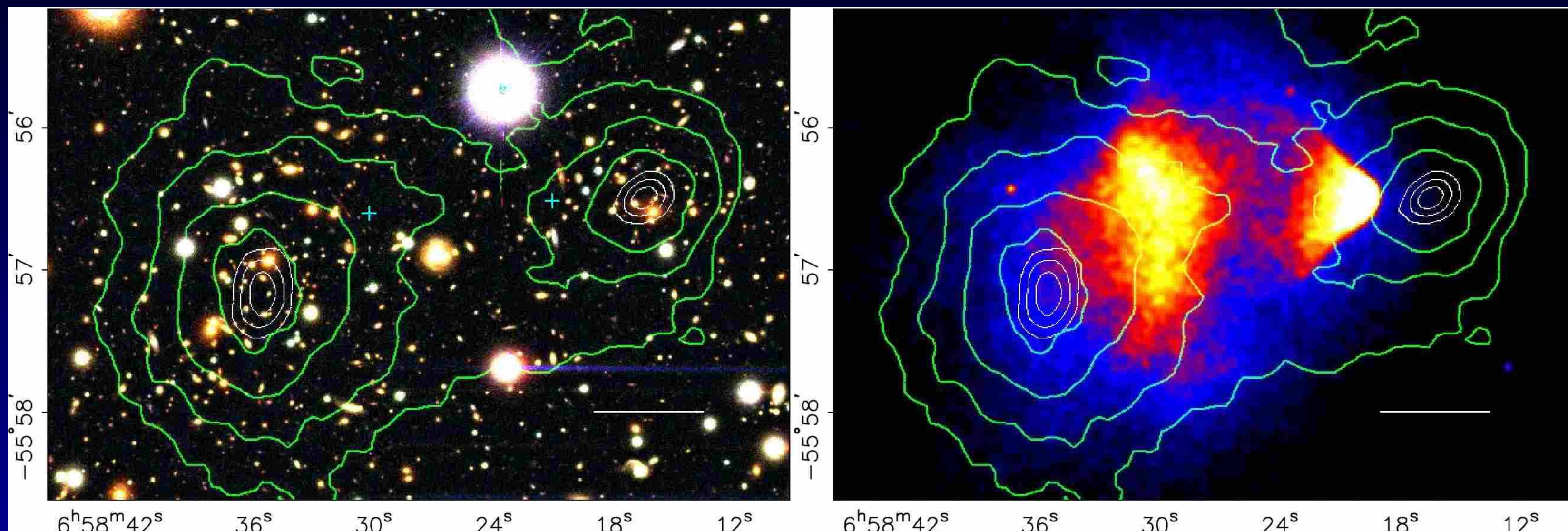
- $\tilde{\tau}/\tilde{\nu}$ LSP
- 2 or 4-body decays. Lots of τs
- One benchmark with cm decay length
- One benchmark with jets

`http://hepforge.cedar.ac.uk/~allanach/rpv/`

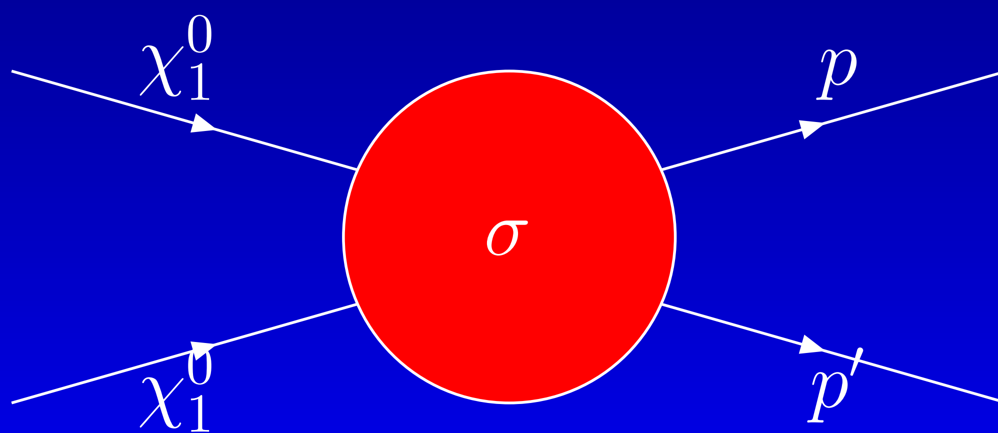
All benchmarks pass current experimental constraints.

[a] BCA, Bernhardt, Dreiner, Kom, Richardson, coming very soon

SUSY Dark Matter

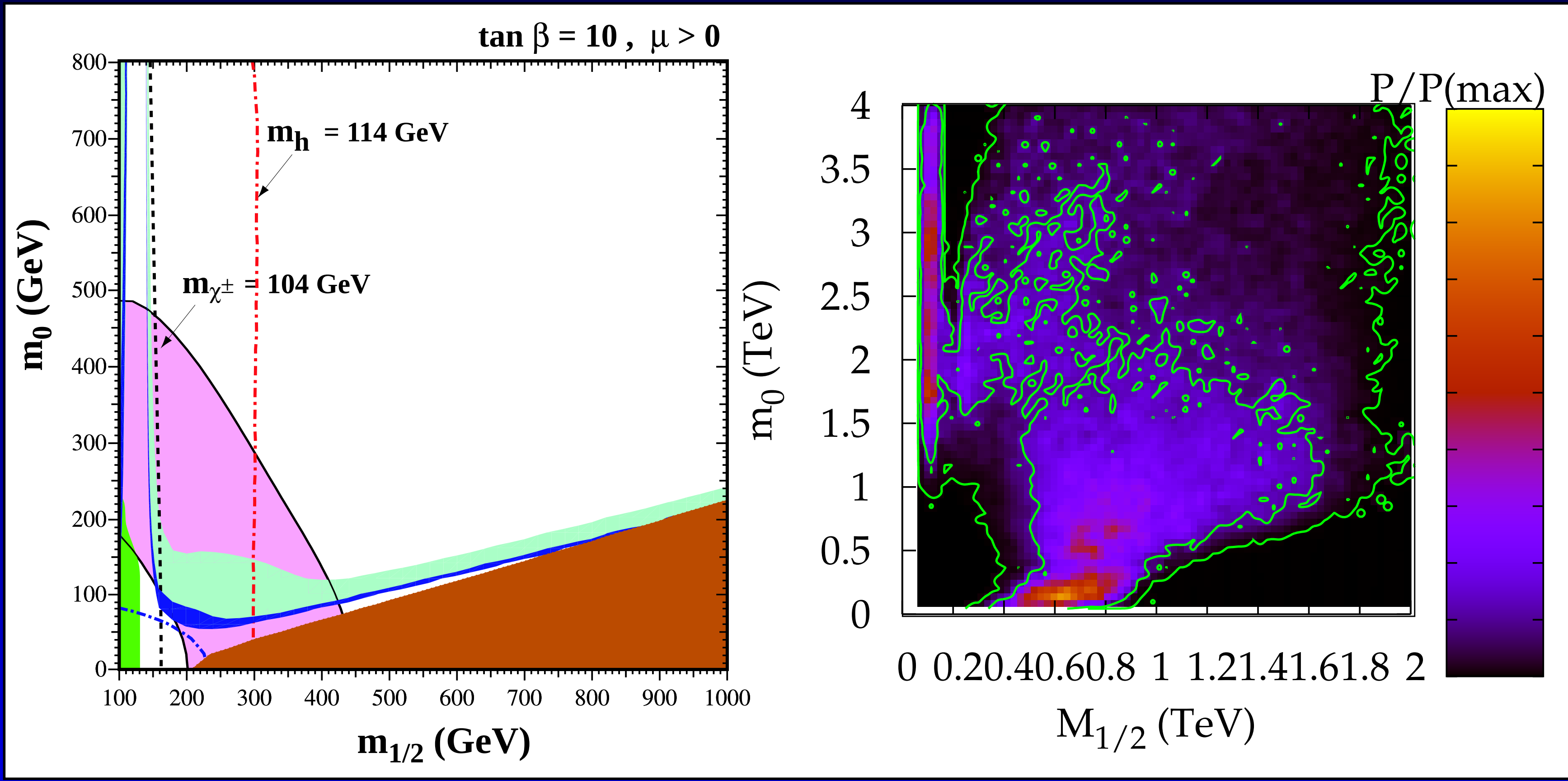


astro-ph/0608407



Constraints on SUSY Models

mSUGRA well-studied in literature [a]: eg Ellis, Olive *et al* PLB565 (2003) 176; Baltz, Gondolo, JHEP 0410 (2004) 052



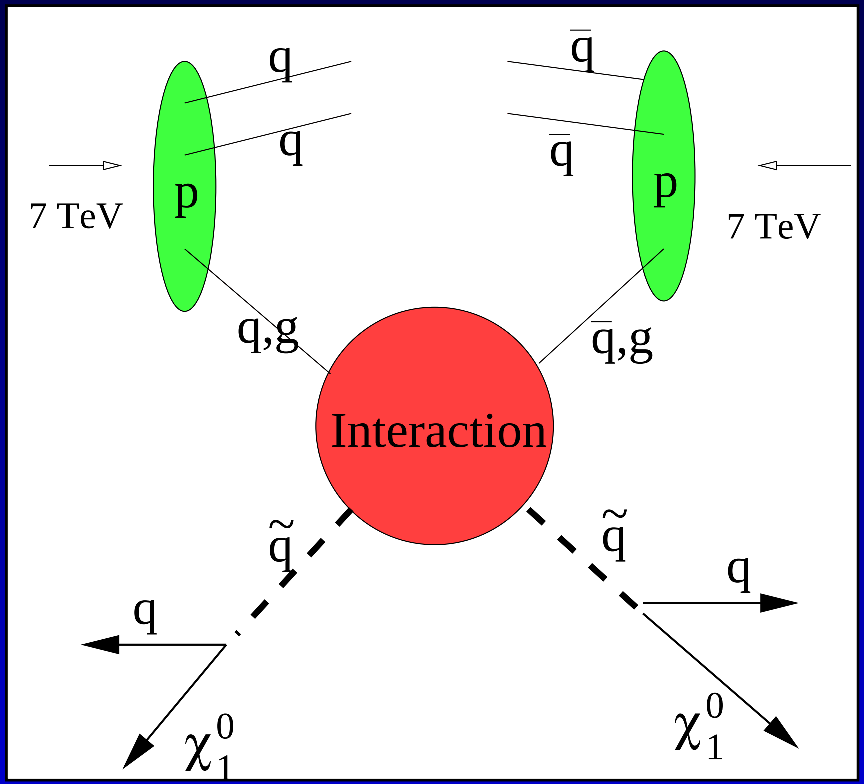
[a] BCA, Lester hep-ph/0507283, hep-ph/0601089

Dark Matter Caveats

- Implicitly assumed that LSP constitutes *all* of dark matter
- Assumed radiation domination in post-inflation era. No clear evidence between freeze-out+BBN that this is the case (t_{eq} changes).
- Examples of non-standard cosmology that would change the prediction:
  - Extra degrees of freedom
  - Low reheating temperature
  - Extra dimensional models
  - Anisotropic cosmologies
  - Non-thermal production of neutralinos (late decays?)

Collider SUSY Dark Matter Production

Strong sparticle production and decay to dark matter particles.



$\mathcal{Q}$: Can we measure enough to predict σ?

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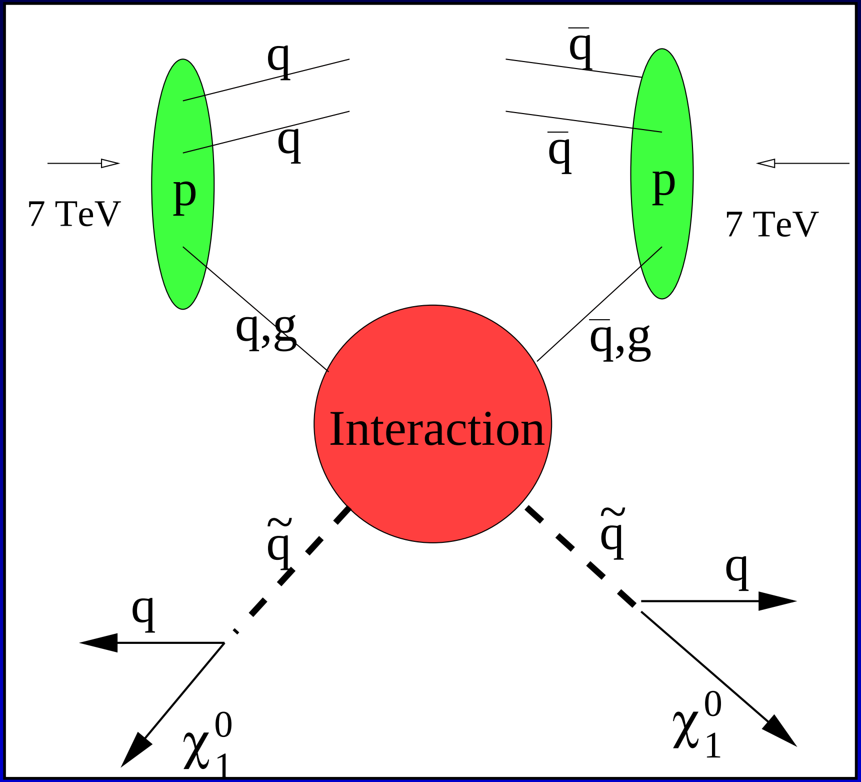

Any dark matter candidate that couples to hadrons can be produced at the LHC

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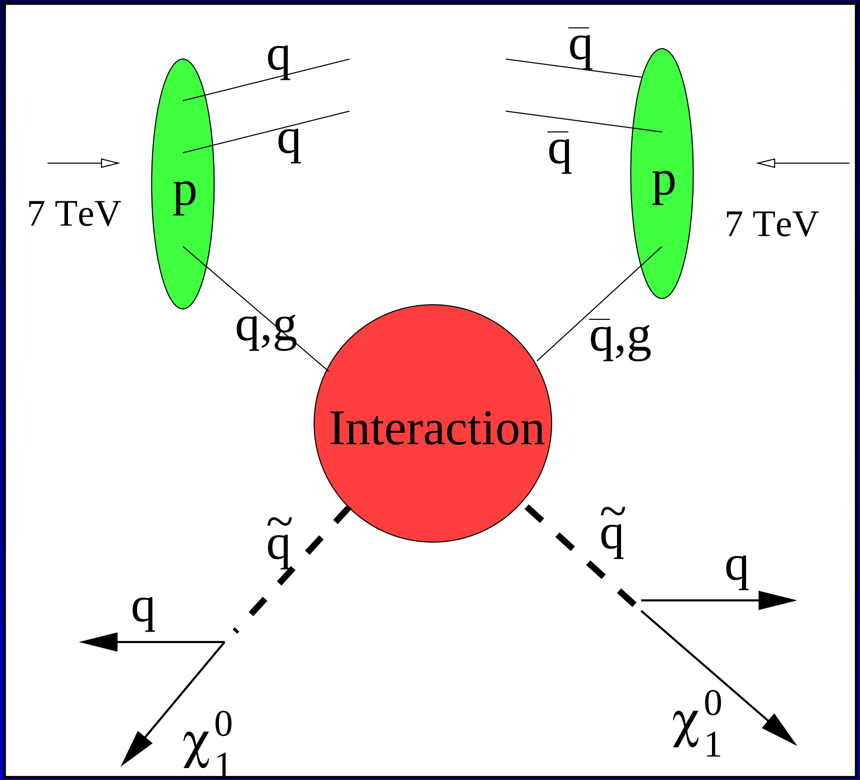


Don't know lifetime - need confirmation from direct detection

Cosmological Constant

Cosmological constant $\Lambda \sim (10^{-3}eV)^4$ provides a much *worse* hierarchy than Higgs fine tuning. Perhaps same thing that solves cosmological constant fine-tuning solves Higgs fine-tuning - *a logical possibility* eg string landscape. Some of Suggestion is to have all scalars except Higgs at say $M_{GUT} \sim 10^{16}$ GeV but light gauginos to:

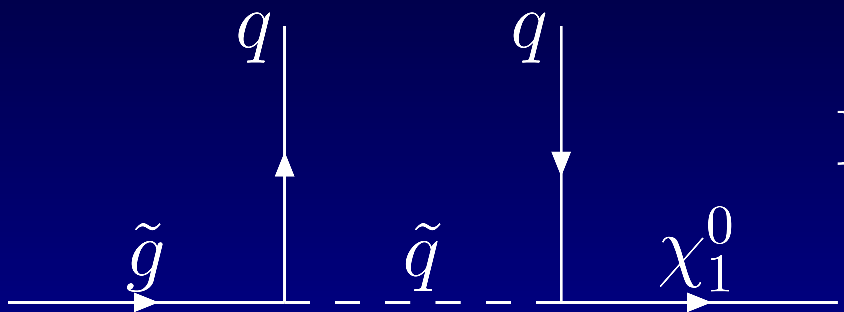
- Preserve gauge unification
- Have WIMP candidate
- Solve SUSY flavour problem, proton decay etc

Q: Throw away SUSY altogether?

Arkani-Hamed, Dimopoulos, hep-ph/0405159

Split SUSY

Gluinos are *quasi-stable* and form $R-$hadrons: neutral or charged .



$$\Gamma \propto \frac{1}{m_{\tilde{q}}^4}$$

Look like a slow heavy muon that loses some of its energy in interactions with the detector. Charginos/neutralinos decay through *mixing effects*.

Kilian *et al*, hep-ph/0408088, Kraan `hep-ex/0404001`

UED

- 5D model compactified on 1 TeV S_1/Z_2: everything in bulk
- Get KK copies of SM separated by TeV: KK parity $(-1)^n$. $m_n^2 = \sqrt{(n/R)^2 + m_{SM}^2}$
- Probably only the first level will be measurable at LHC, and they cascade decay down to the LKP copy of the photon (a dark matter candidate!)
- Earned UED the title "bosonic supersymmetry", worried that it could be confused with SUSY model through cascade decays through the various KK modes.

Cheng et al, hep-ph/0205314

Spins at LHC

Crucial check of SUSY is spin (cf UED). Consider $\tilde{q}_L \to q l \tilde{l}$: $m \equiv m_{ql}/m_{ql}(max) = \sin\theta/2$

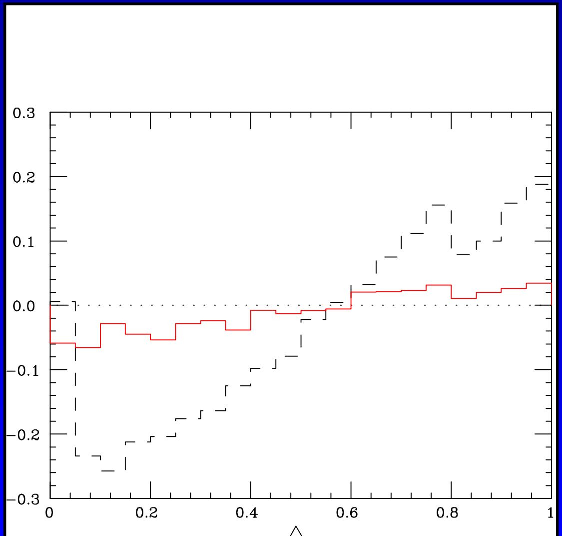
$$\frac{dP(l^+ q / l^- \bar{q})}{dm} = 4m^3, \qquad \frac{dP(l^- q / l^+ \bar{q})}{dm} = 4m(1-m^2$$

whereas pure PS is always $2m$. Seems hopeless, since we cannot tag quarks vs anti-quarks (average is PS). pp collider leads to spin-generated lepton charge asymmetry

$$A^{+-} = \frac{m_{jl^+} - m_{jl^-}}{m_{jl^+} + m_{jl^-}}$$

Barr, hep-ph/0405052

Smillie, Webber, hep-ph/0507170



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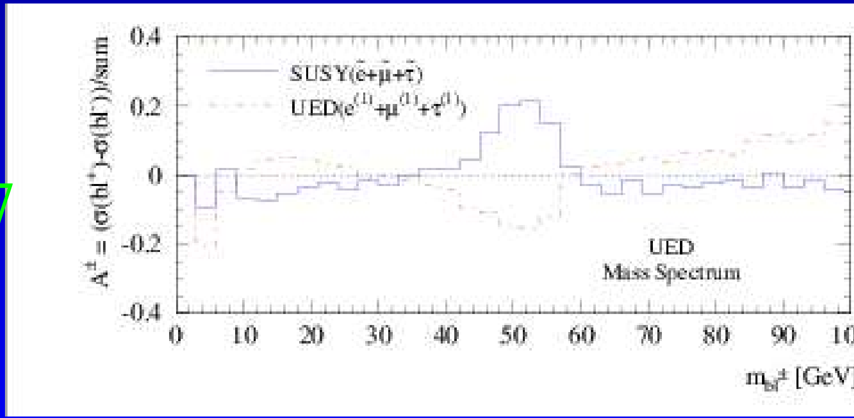
Gluino spin+di-leptons

Alves, Éboli, Plehn, hep-ph/0605067

$\tilde{g} \to \tilde{b}_1 \to \chi_2^0 \to \tilde{l} \to \chi_1^0$

tag charge of b's



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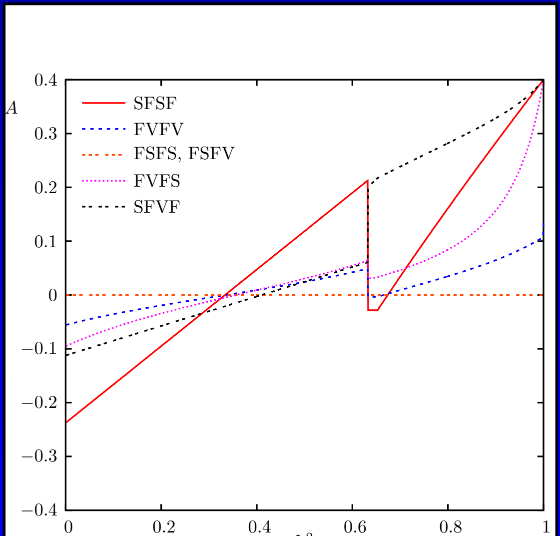
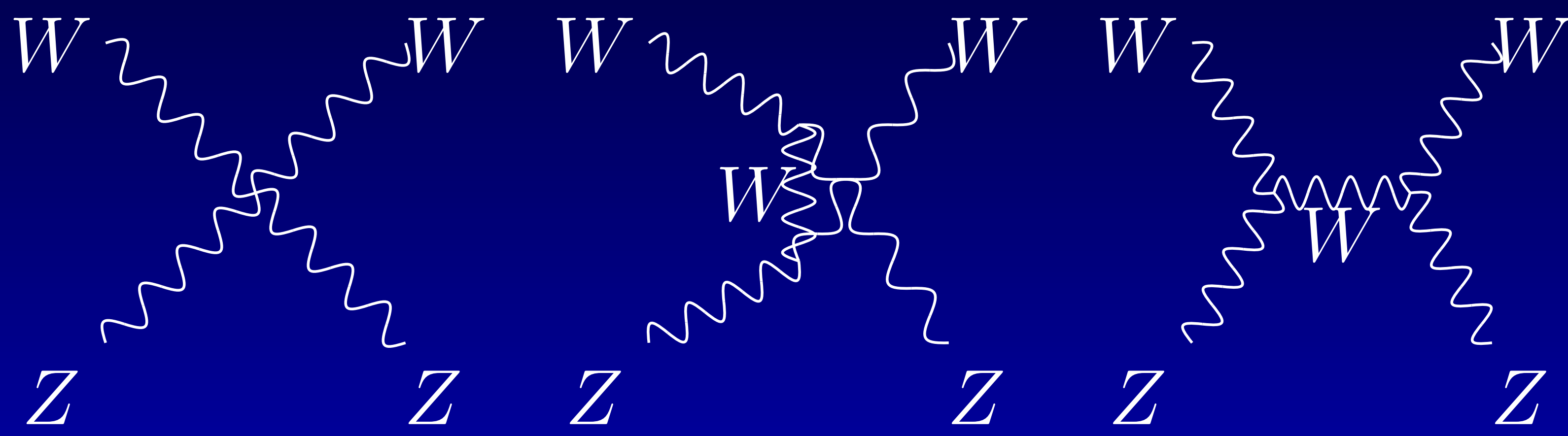
More general spins

Athanasiou, Lester, Smillie, Webber, hep-ph/0605286; ibid hep-ph/0606212



Higgsless Models

Unitarity violation through longitudinal weak boson scattering:

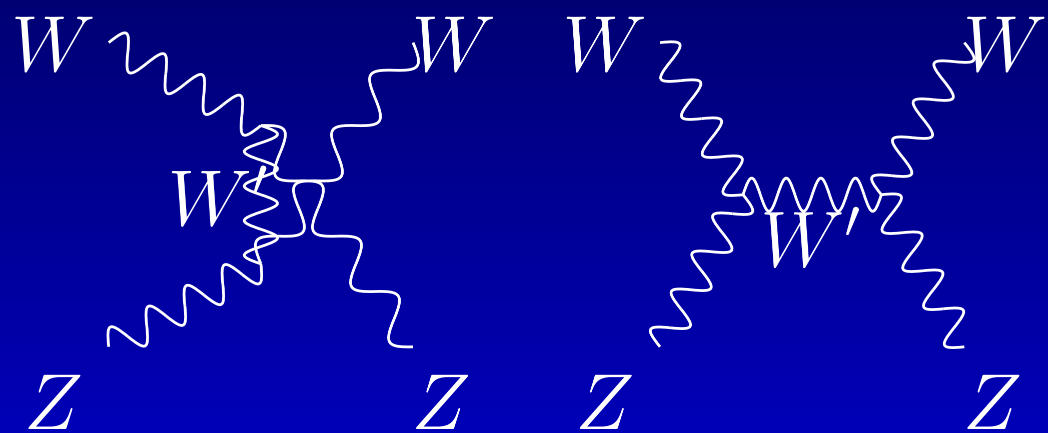


$$
\begin{aligned}
M &= (g_4 - g_3^2)[(c^2 - 6c - 3)E^4 + (c^2 - 3c - 2)M_Z^2 \\
&\quad -(c^2 - 9c - 4)M_W^s E^2] + g_3^2 \frac{M_Z^4(1-c)}{2M_W^2} E^2 +
\end{aligned}
$$

Higgs normally gets rid of $E^{2,4}$ terms.

Unitarity

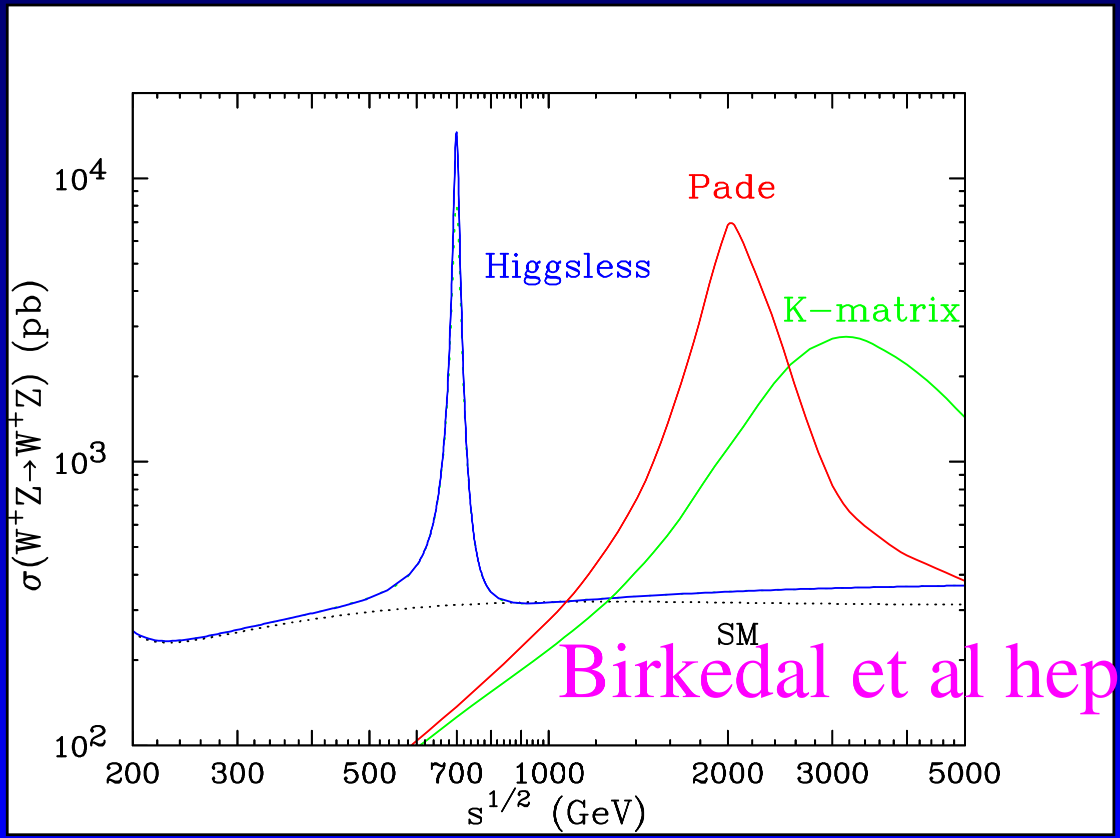
is lost at $\Lambda \sim 4\pi M_W/g \sim 1.8$ TeV. Precision EW constraints usually rule out strongly interacting physics at this scale. However, can *increase* this scale by adding extra W' bosons if $g_4 = g_3^2 + \sum_i g'^2_{i3}$



$$2(g_4 - g_3^2)(M_W^2 + M_Z^2) + g_3^2 M_Z^4/M_W^2 = \sum_i g'^2_{i3}[3M'^2_i - (M_Z^2 - M_W^2)^2/M'^2_i]$$

Unitarity Cancellation

In KK theories summing up infinite number of modes yields the relations *exactly* because of 5D gauge symmetry. However, strong coupling scale provides another cut off but can be increase Λ a factor of 10 and pass the EW constraints.



Birkedal et al hep-ph/04122

Little Higgs

Global $SU(5) \rightarrow SO(5)$ non linear sigma model broken by $\underline{24}$. Gauged subgroup $(SU(2) \otimes U(1))^2 \rightarrow SU(2)_L \otimes U(1)_Y$. The "pions" are:

$$1_0 \oplus 3_0 \oplus H \sim 2_{1/2} \oplus 3_{\pm 1}$$

1_0, 3_0 eaten when gauge group broken. Gauge generators embedded such that if we "globalise" an initial $SU(2) \otimes U(1)$ by $g \rightarrow 0$, H would be an exact Goldstone boson, i.e. massless. Mass terms generated at one-loop are only *log* divergent: hierarchy only a problem if $\Lambda > 10$'s of TeV.

Q: SUSY?

T-Parity

Original model had problems with T parameter. $T-$Parity swaps the two $SU(2) \otimes U(1)$ groups and protects W', Z' ($T = -1$) from tree-level interactions with W, Z ($T = +1$). Also, protects the triplet ($T = -1$) from getting a VEV, since H is $T = +1$. Add additional vector-like representations of singlet$\oplus$double fermions for each EW doublet to cancel quartic and one-loop quadratic divergences. $T-$parity relieves the tuning associated with original little Higgs models in order to be compatible with T-parameter.

Lightest T-odd particle can be hypercharge boson prime: forms dark matter candidate.

Cheng and Low, hep-ph/0405243; Hubisz et al, hep-ph/0506042

Final Slide

- An additional parity (R, T or KK) in order to keep lightest parity-odd partner *stable*
- Associated dark matter candidate
- As long as it's lighter than a few TeV and couples to hadrons, we'll be producing it at the LHC: this would be a fantastic collider window into cosmology!