Phenomenology of Bosonic Supersymmetry

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hep-ph/0204342; hep-ph/0205314

SUSY 2002

DESY, Hamburg

Outline

- What is the model? (BS)
  - MUEDs (Minimal Universal Extra DimensionS)
- Why is it interesting?
- What is the spectrum?
- What are the decays?
- How big are the cross-sections?
- How do we discover it at the Tevatron and the LHC?
- Can we tell it from SUSY?
- Cosmology of BS
  - Relic density
  - Direct detection
  - Indirect detection: neutrinos, positrons, photons.

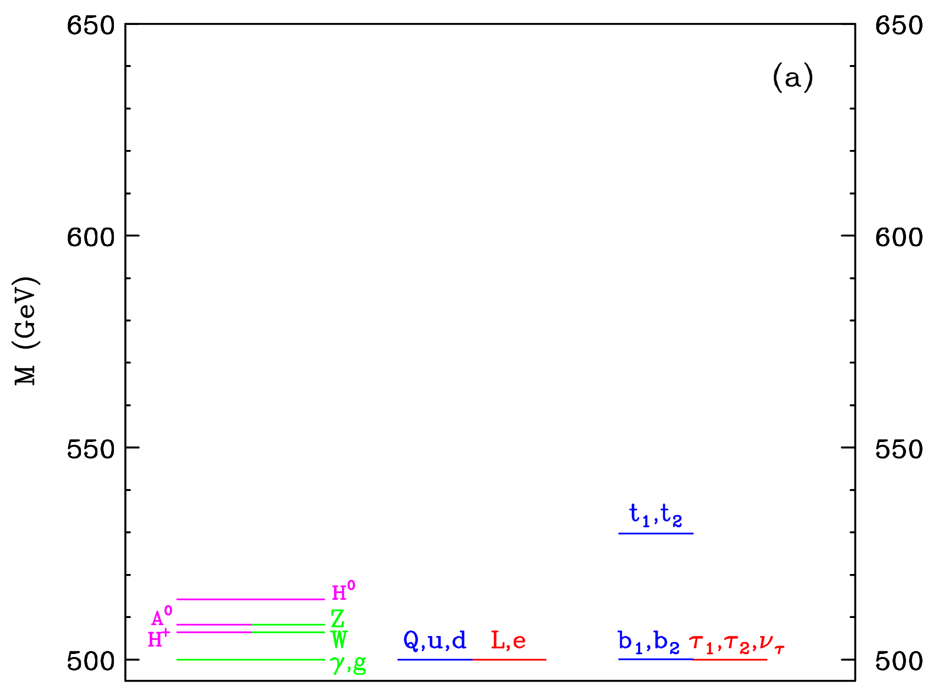
Minimal Universal Extra Dimensions

- UEDs: everybody in the bulk!
  Appelquist, Cheng, Dobrescu hep-ph/0012100
- Motivation: EWSB, proton decay, N_{gen}, neutrinos...
  Appelquist, Arkani-Hamed, Cheng, Dobrescu,
  Hall, Ponton, Poppitz, Yee
- The minimal model: $d = 4 + 1$, ED compactified on S^1/Z_2.
- Symmetries
  - Z_2 – project out unwanted zero modes
  - KK number – broken down to KK parity by boundary terms $(-1)^n$, for KK level $n \Rightarrow$ Lightest KK Particle is stable
- Minimal UEDs: boundary terms vanish at a scale $\Lambda > R^{-1}$
- The model is very predictive: $\{R, \Lambda, m_h\}$
- Current constraints exclude $R^{-1} \lesssim 300$ GeV.

Tree Level Mass Spectrum

- The tree-level spectrum is extremely degenerate:

$$m_n^2 = \left(\frac{n}{R}\right)^2 + m_0^2$$



- The radiative corrections are crucial for phenomenology, e.g.

$$e_1 \to \gamma_1 e_0?$$

$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1}\left(\frac{m_e}{R^{-1}}\right) \sim -R^{-1}10^{-6}$$

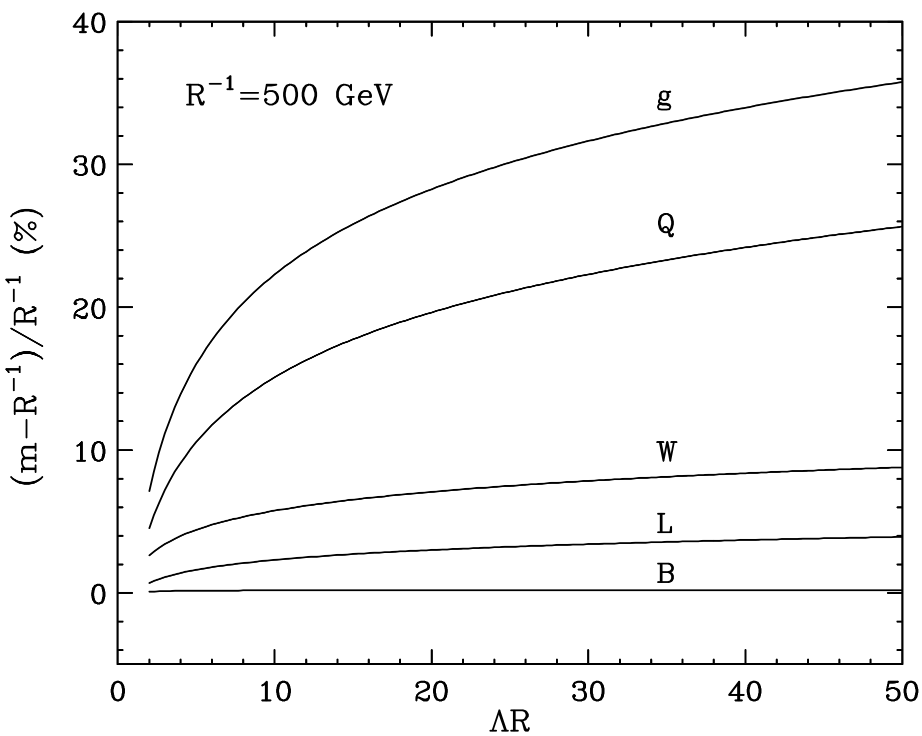
Radiative corrections

- Two types of corrections:
  - "bulk" – from loops with nonzero winding number

$$\delta m_n \sim R^{-1}$$

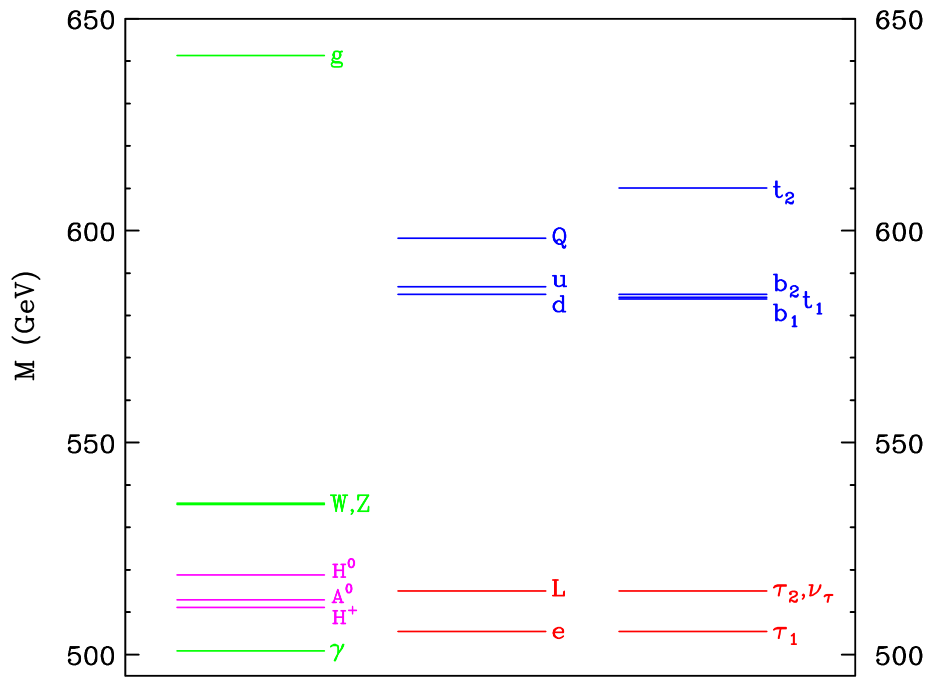
  - "boundary" – from boundary counterterms

$$\bar{\delta} m_n \sim m_n \ln\left(\frac{\Lambda^2}{\mu^2}\right)$$



Radiatively Corrected Mass Spectrum

- The radiative corrections split the spectrum $\Rightarrow$ prompt decays!



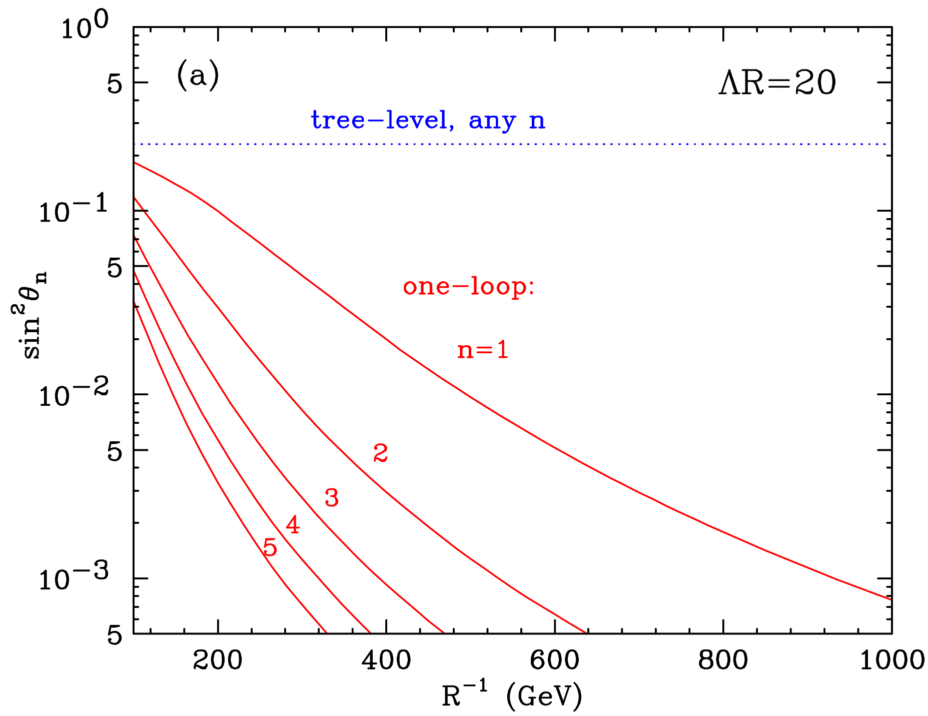
- LKP: KK "photon" $\Rightarrow$ missing energy!
- Hadron collider searches appear problematic – soft decay products.

The KK Weinberg Angle

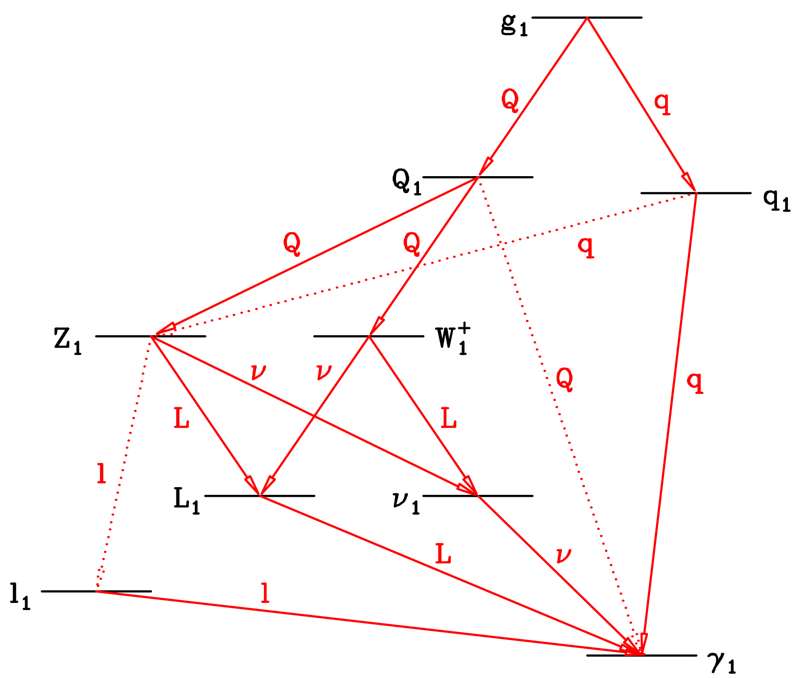
- Mass matrix for the neutral gauge bosons

$$\begin{pmatrix} \frac{n^2}{R^2} + \frac{1}{4}g_1^2 v^2 + \hat{\delta} m_{B_n}^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{n^2}{R^2} + \frac{1}{4} g_2^2 v^2 + \hat{\delta} m_{W_n}^2 \end{pmatrix}$$

- The Weinberg angle θ_n at KK level n
  - At tree level: the same for all n
  - At one loop: decreasing with n, much smaller than θ_0.



Level 1 Spectroscopy



- KK gluon: $B(g_1 \to Q_1 Q_0) \simeq B(g_1 \to q_1 q_0) \simeq 0.5$.
- Singlet KK quarks (q):

$$B(q_1 \to Z_1 q_0) \simeq \sin^2\theta_1 \sim 10^{-2} - 10^{-3}$$
$$B(q_1 \to \gamma_1 q_0) \simeq \cos^2\theta_1 \sim 1$$

- KK W- and Z-bosons: only leptonic decays!

$$B(W_1^\pm \to \nu_1 L_0^\pm) = B(W_1^\pm \to L_1^\pm \nu_0) = 1/6$$
$$B(Z_1 \to \nu_1 \nu_0) \simeq B(Z_1 \to L_1^\pm L_0^\mp) \simeq 1/6$$

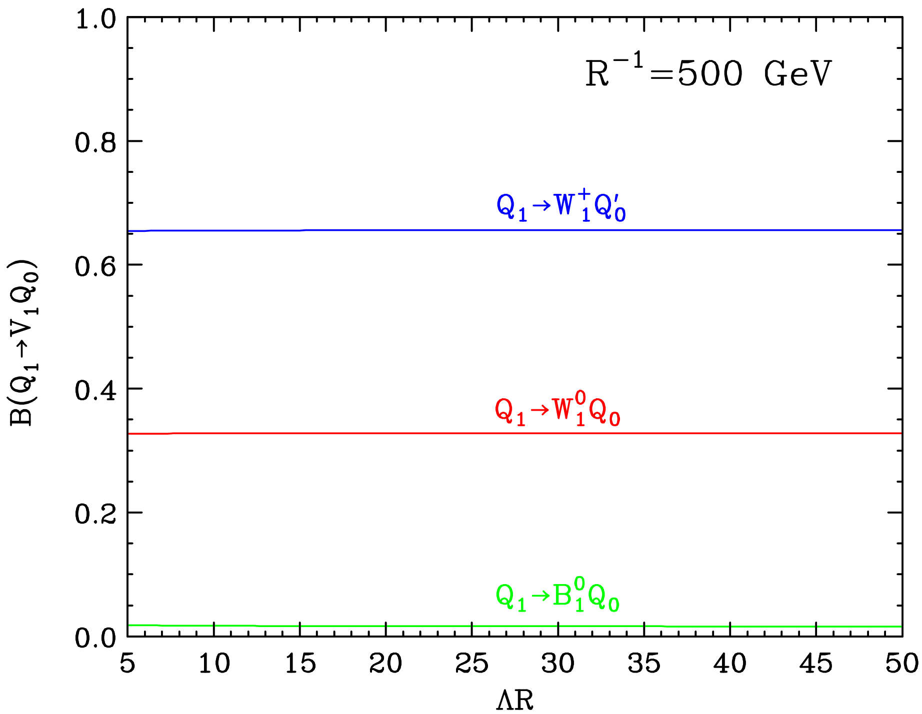
- KK leptons: 100% directly to the LKP.

Level 1 Branching Fractions

- Doublet KK quarks (Q).

$$B(Q_1 \to W_1^{\pm} Q_0') \simeq 2B(Q_1 \to Z_1 Q_0)$$

$$\frac{B(Q_1 \to Z_1 Q_0)}{B(Q_1 \to \gamma_1 Q_0)} \simeq \frac{g_2^2\, T_{3Q}^2\, (m_{Q_1}^2 - m_{Z_1}^2)}{g_1^2\, Y_Q^2\, (m_{Q_1}^2 - m_{\gamma_1}^2)}$$



$$B(Q_1 \to W_1^{\pm} Q_0') \sim 65\%$$

$$B(Q_1 \to Z_1 Q_0) \sim 33\%$$

$$B(Q_1 \to \gamma_1 Q_0) \sim 2\%$$

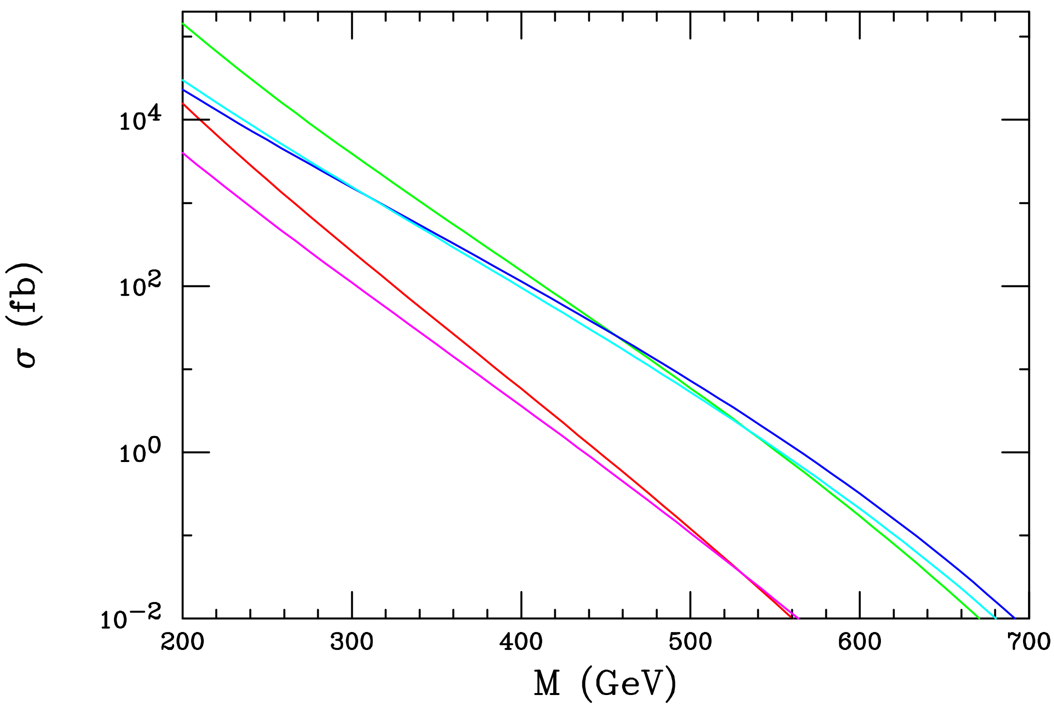
- We want: strong production, weak decays!

KK Production at the Tevatron

- The cross-section is quite significant

  Rizzo hep-ph/0106336

  Macesanu, McMullen, Nandi hep-ph/0201300



- q_1 production yields jets and $\not{E}_T$ - doable.
- Q_1 production yields leptons and $\not{E}_T$ - gold-plated.

Tevatron Search in $4\ell \not{E}_T$ Channel

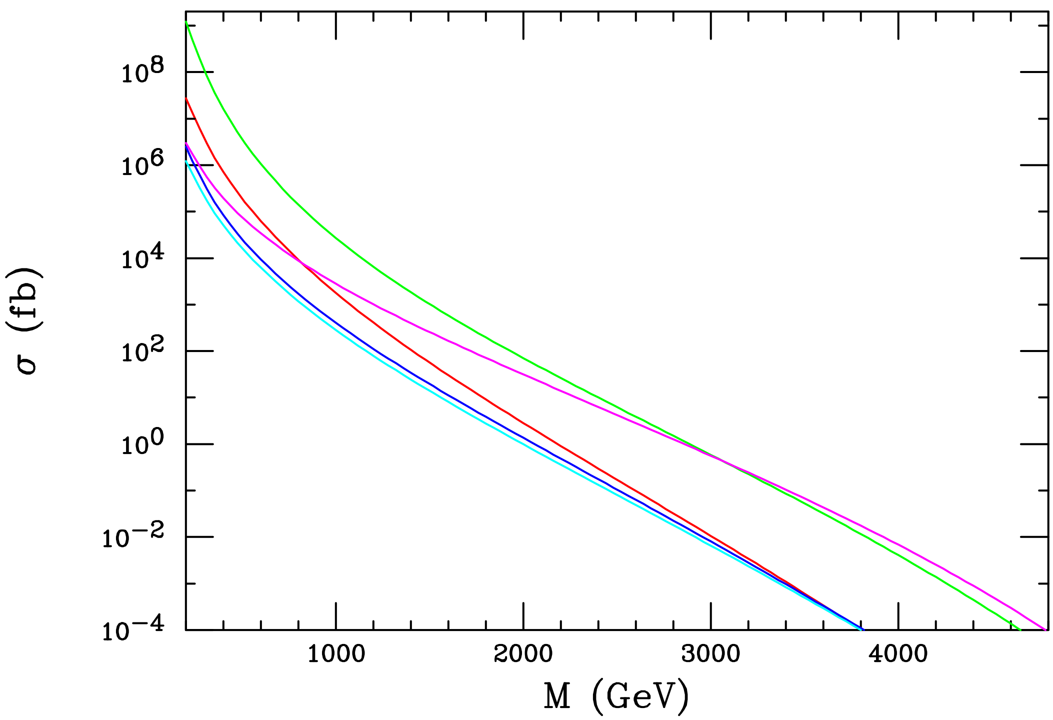
- Arises from inclusive $Q_1 Q_1$ production:

$$Q_1 \to Z_1 \to \ell^{\pm}\ell^{\mp}\gamma_1$$

- Triggers
  - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
  - Missing energy $\not{E}_T > 40$ GeV.
- Cuts
  - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 30$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Main background: $ZZ \to \ell^{\pm}\ell^{\mp}\tau^{+}\tau^{-} \to 4\ell\not{E}_T$. Not a problem.
- $B(Q_1 \to 2\ell\not{E}_T + X) \sim \frac{1}{9}$. In principle, channels with W_1's can also be used – less leptons, but more often.

LHC Search

- Humongous cross-sections at small R^{-1}.

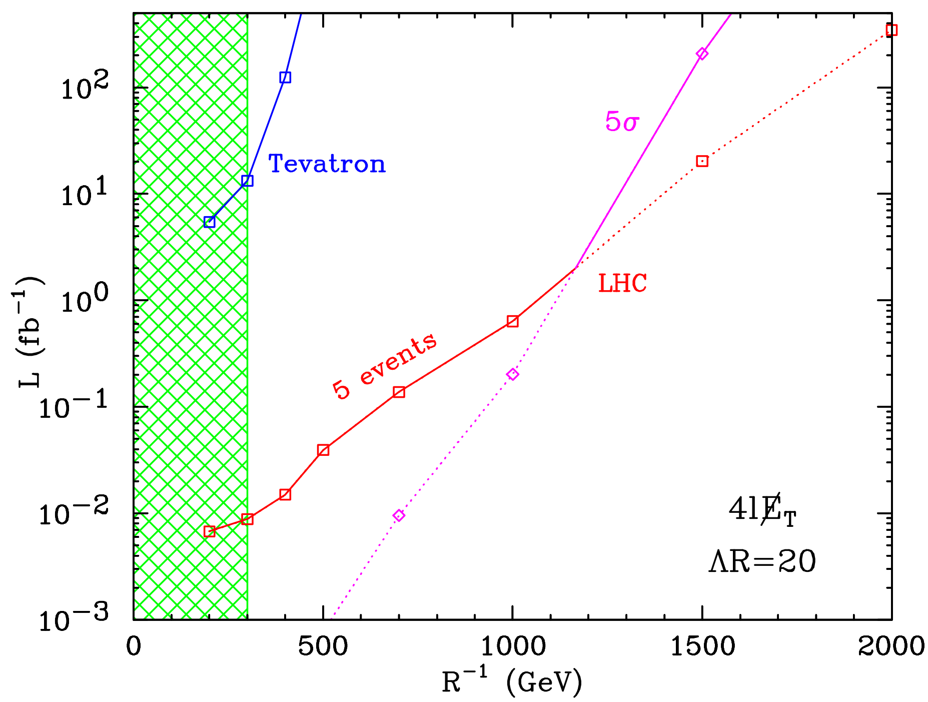


- Cuts (pass the single lepton trigger)
  - $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not\!\!E_T > 50$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Backgrounds: multi-boson, ttZ, fakes, etc.

Assumption: 50 events/year (100 fb^{-1}).

Tevatron and LHC Reach

- The reach in the $4\ell \not{E}_T$ channel. Require 5σ or 5 events.



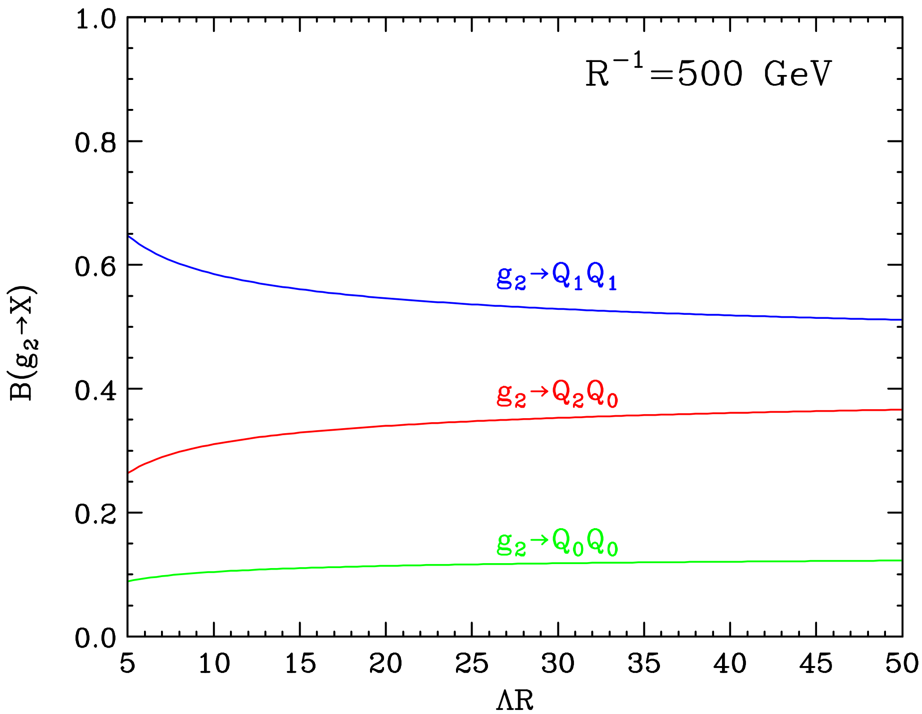
- Other channels with larger statistics may give better reach (especially at the Tevatron).
- We did not optimize cuts.

UED or SUSY?

- Similarities between SUSY and the first KK level:
  - Superpartners versus KK modes
  - Couplings to SM particles
- Differences
  - Spins ("bosonic supersymmetry")
  - Absence of "Heavy Higgses" in MUEDs
  - No D-term splittings
  - Higher KK levels! Is this distinctive enough?
- How does a linear collider help?

Second KK level

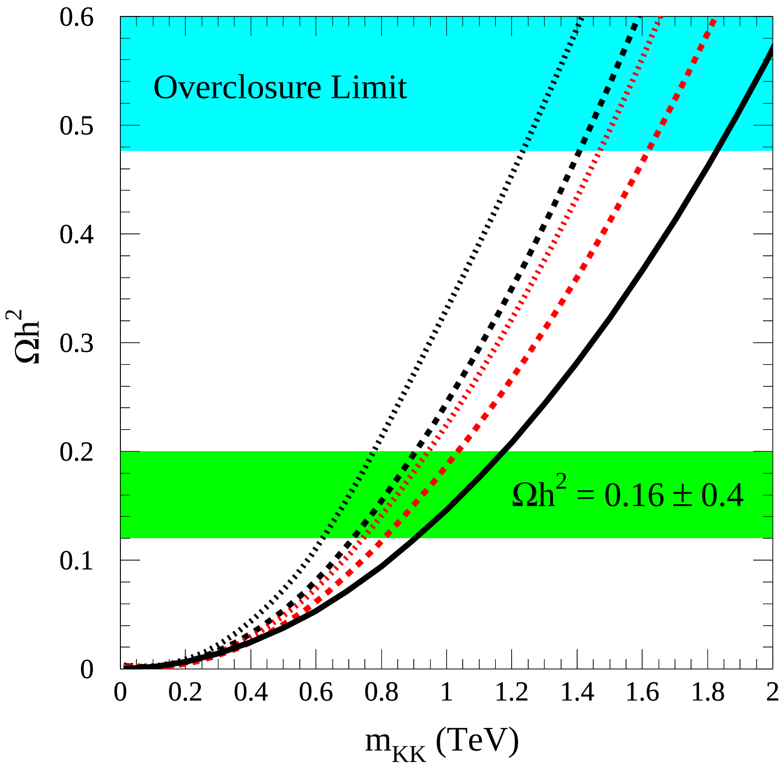
- KK fermions: $f_2 \to V_1 f_1$ or $f_2 \to V_2 f_0$ (also $f_2 \to f_2' W^\pm$). Same for scalars. See level 1 KK searches.
- KK gauge bosons: $V_2 \to f_1 \bar{f}_1$, $V_2 \to f_2 \bar{f}_0$, but also $V_2 \to f_0 \bar{f}_0$.



- KK2 pair production + KK number violating decays $\Rightarrow$ dilepton/dijet bumps at high inv. mass + large $\not{E}_T$ + soft stuff.
- KK2 single production + KK number violating decays $\Rightarrow$ similar to Z', W' searches.

Cosmology

- Relic density: G.Servant, T.Tait hep-ph/0206071



- Unlike supersymmetry: no helicity suppression

$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P\sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

$$a = \frac{\alpha_1^2}{M_{KK}^2}\frac{380\pi}{81}; \qquad b = -\frac{\alpha_1^2}{M_{KK}^2}\frac{95\pi}{162}.$$

- Unlike supersymmetry: coannihilation lowers the bound

KK dark matter detection

- Direct detection: promising. (Similar to SUSY models with small sfermion–LSP mass splitting.)
- Indirect detection
  - Neutrinos: promising. Hard E_ν spectrum.
  - Positrons: promising. Narrow peak at large E_{e^+}.
  - Photons: similar to SUSY.
- Can DM experiments help in determining the LKP spin?

Conclusions and Outlook

- MUEDs are a complete and calculable model of ED.
- The LKP is neutral and stable $\Rightarrow$ the generic collider signature of MUEDs is $\not\!\!E_T$.
- The LHC can probe R^{-1} up to ~ 1.5 TeV in multilepton channels. Other channels? Beyond MUEDs?
- KK level 1 of MUEDs looks just like supersymmetry!
  - How do we tell the difference? (challenge for Tevatron and LHC experimentalists...)
  - Can we make sense of KK level 2 if we see it?
- The role of a linear collider in all of this?
- A 1 TeV LKP is a good dark matter candidate and offers very good opportunities for detection.