

**Bosonic Supersymmetry:
Getting Fooled at the LHC**

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hep-ph/0204342; hep-ph/0205314

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hep-ph/0207xxx

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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

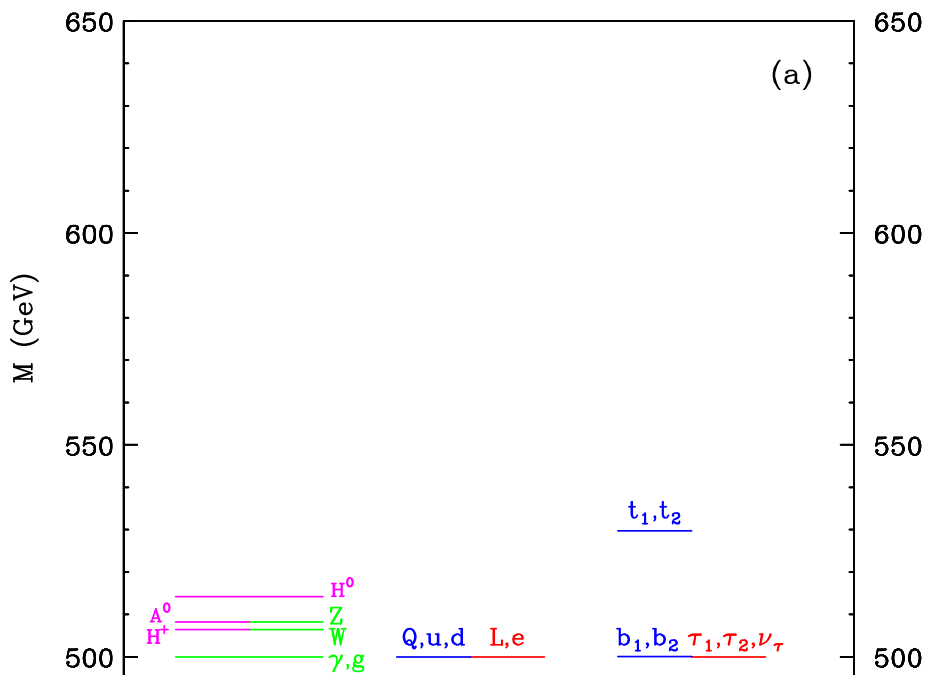
- UEDs: everybody in the bulk!
Appelquist, Cheng, Dobrescu hep-ph/0012100
- Motivation: EWSB, proton decay, N_{gen} , neutrinos...
Appelquist, Arkani-Hamed, Cheng, Dobrescu, Hall, Ponton, Poppitz, Yee
- The minimal model: $d = 4 + 1$, ED compactified on S^1/Z_2 .
- Symmetries
 - Z_2 – project out unwanted 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.

$$e_1 \rightarrow \gamma_1 e_0?$$

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



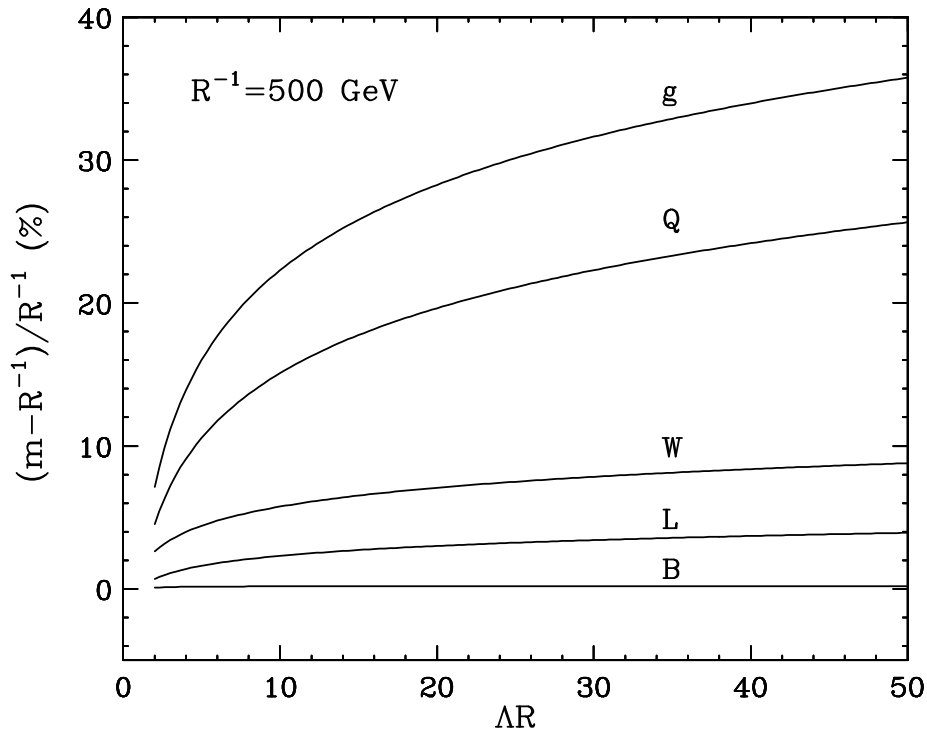
Radiative corrections

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

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

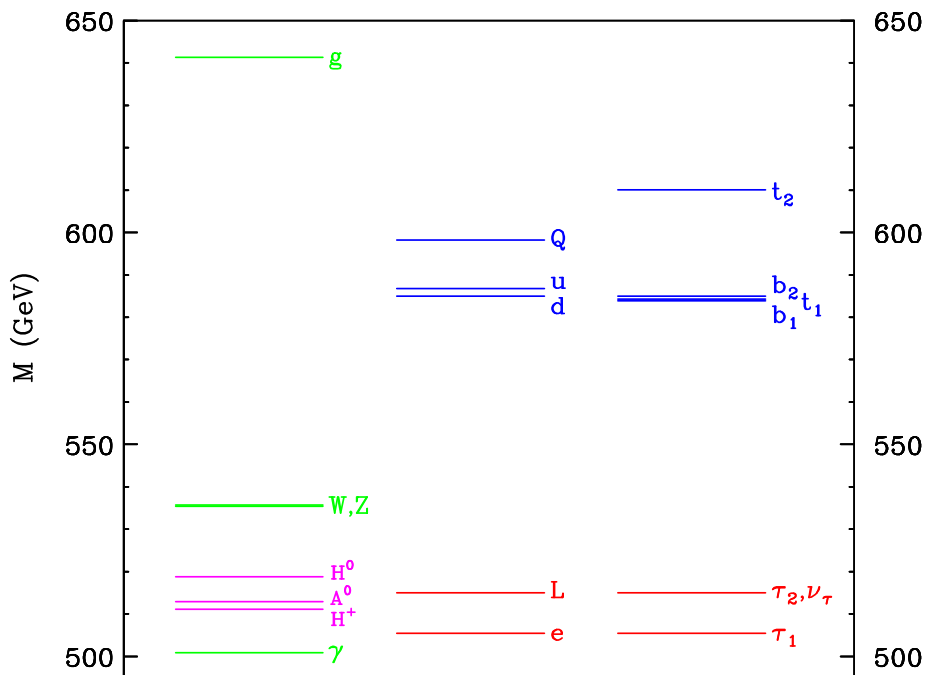
- “boundary” – from boundary counterterms

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



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.

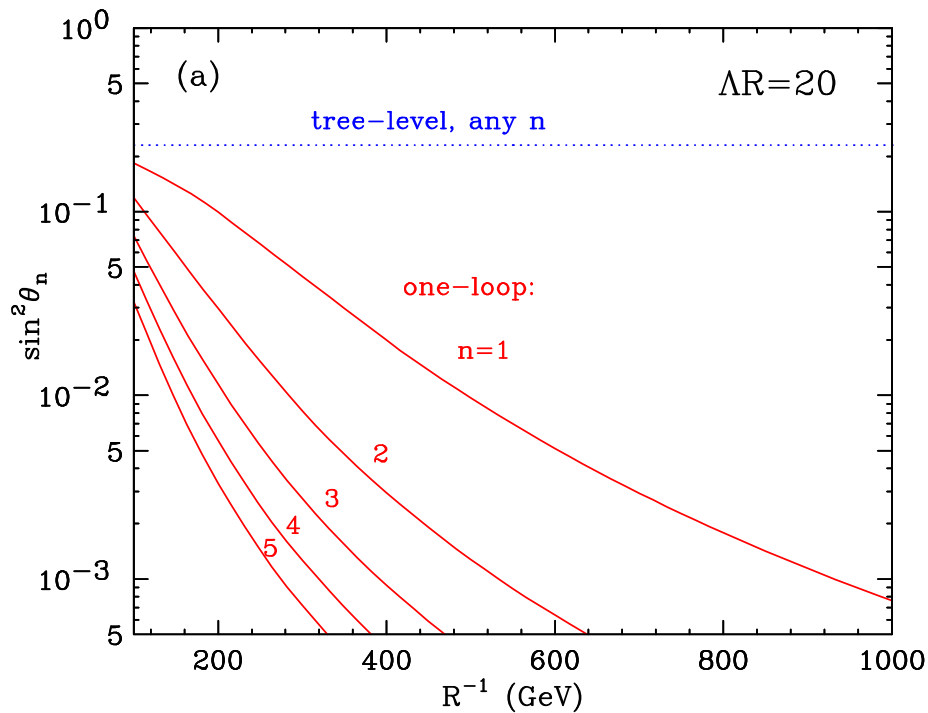


The KK Weinberg Angle

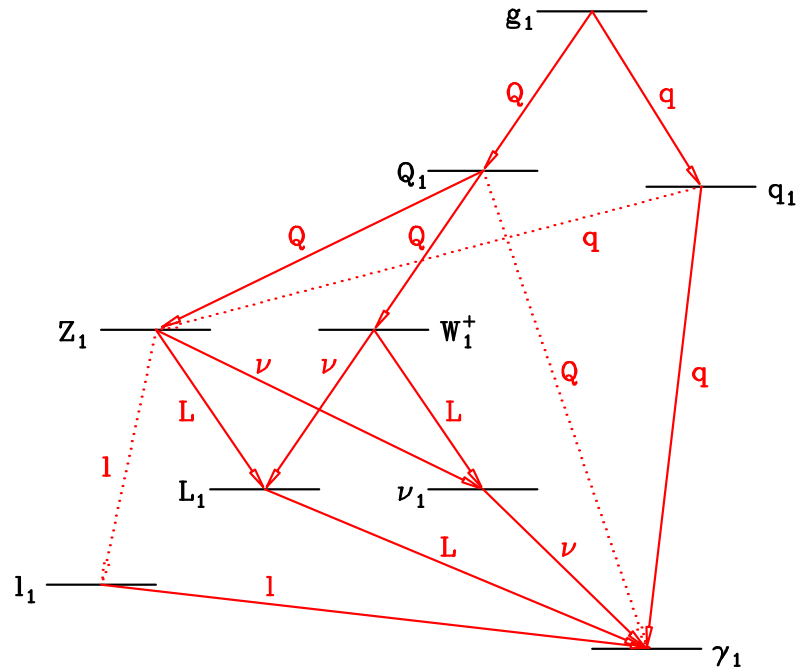
- Mass matrix for the neutral gauge bosons

$$\begin{pmatrix} \frac{n^2}{R^2} + \frac{1}{4}g_1^2v^2 + \hat{\delta}m_{B_n}^2 & \frac{1}{4}g_1g_2v^2 \\ \frac{1}{4}g_1g_2v^2 & \frac{n^2}{R^2} + \frac{1}{4}g_2^2v^2 + \hat{\delta}m_{W_n}^2 \end{pmatrix}$$

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

$$B(q_1 \rightarrow Z_1 q_0) \simeq \sin^2 \theta_1 \sim 10^{-2} - 10^{-3}$$

$$B(q_1 \rightarrow \gamma_1 q_0) \simeq \cos^2 \theta_1 \sim 1$$

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

$$B(W_1^\pm \rightarrow \nu_1 L_0^\pm) = B(W_1^\pm \rightarrow L_1^\pm \nu_0) = 1/6$$

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

- KK leptons: 100% directly to the LKP.

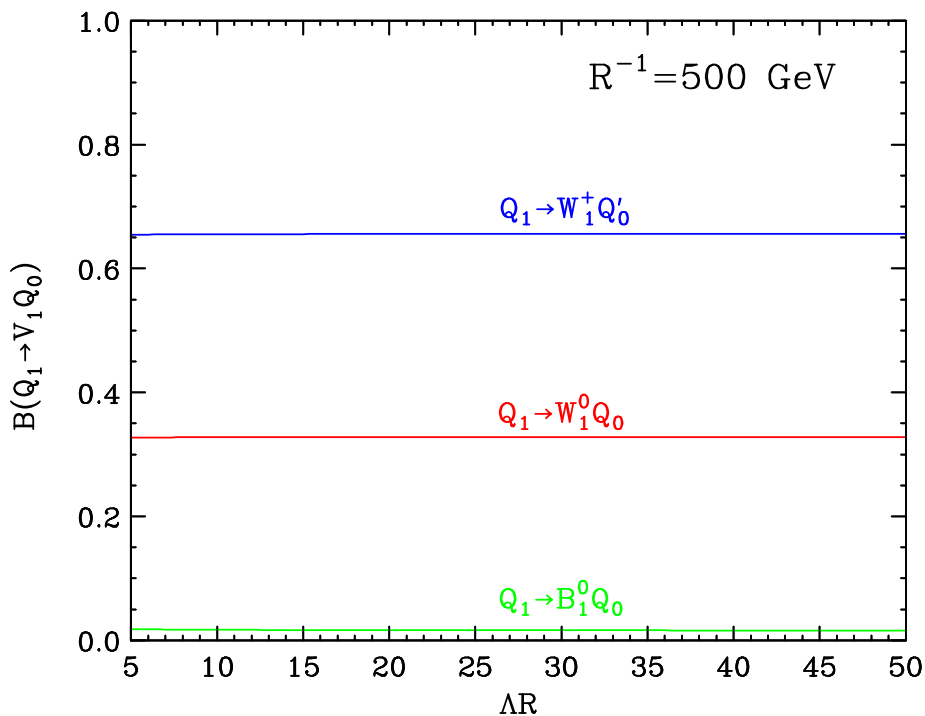


Level 1 Branching Fractions

- Doublet KK quarks (Q).

$$B(Q_1 \rightarrow W_1^\pm Q'_0) \simeq 2B(Q_1 \rightarrow Z_1 Q_0)$$

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



$$B(Q_1 \rightarrow W_1^\pm Q'_0) \sim 65\%$$

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

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

- We want: **strong** production, **weak** decays!

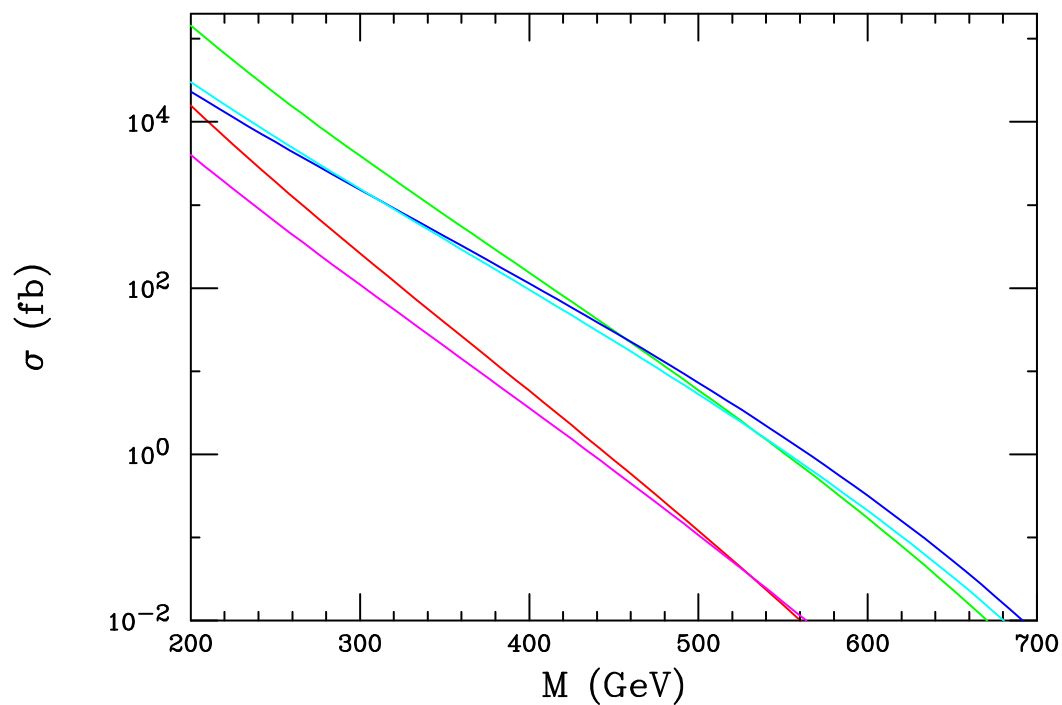


KK Production at the Tevatron

- The cross-section is quite significant

Rizzo hep-ph/0106336

Macesanu, McMullen, Nandi hep-ph/0201300



- q_1 production yields jets and \cancel{E}_T - doable.
- Q_1 production yields leptons and \cancel{E}_T - gold-plated.



Tevatron Search in $4\ell\cancel{E}_T$ Channel

- Arises from inclusive $Q_1 Q_1$ production:

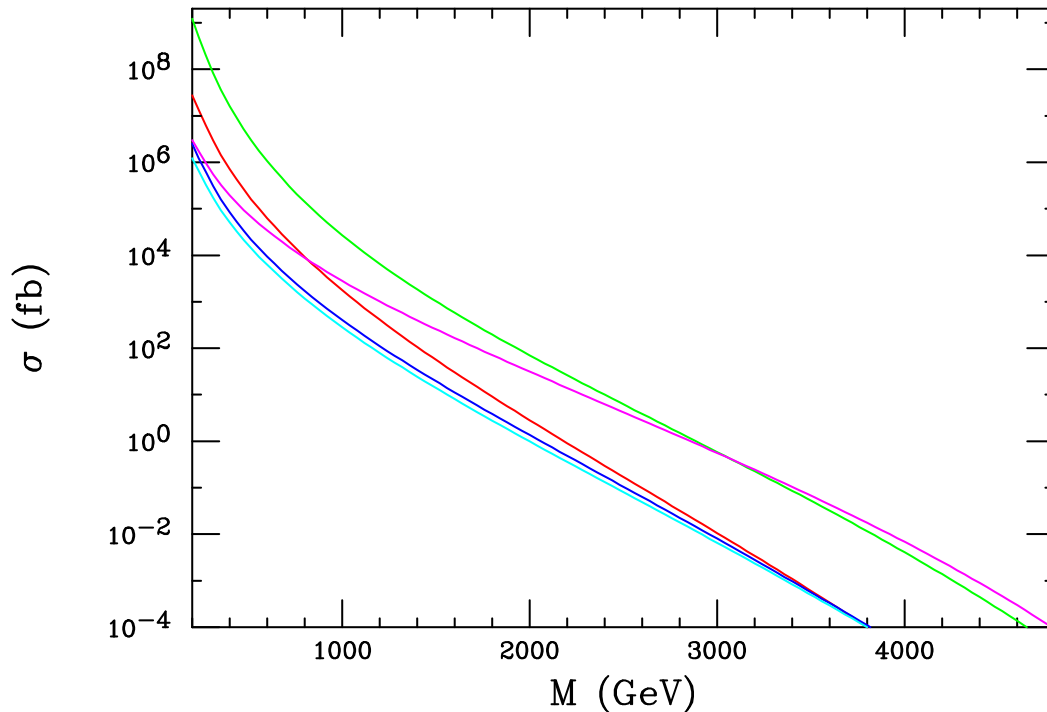
$$Q_1 \rightarrow Z_1 \rightarrow \ell^\pm \ell^\mp \gamma_1$$

- Triggers
 - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
 - Missing energy $\cancel{E}_T > 40$ GeV.
- Cuts
 - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
 - $\cancel{E}_T > 30$ GeV.
 - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Main background: $ZZ \rightarrow \ell^\pm \ell^\mp \tau^+ \tau^- \rightarrow 4\ell\cancel{E}_T$. Not a problem.
- $B(Q_1 \rightarrow 2\ell\cancel{E}_T + X) \sim \frac{1}{9}$. 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} .

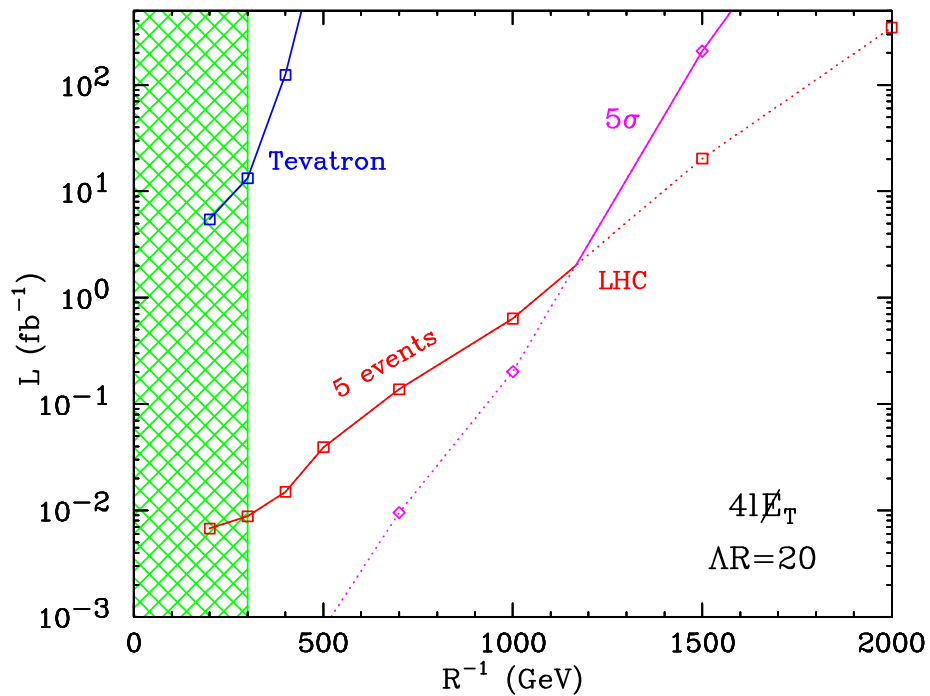


- Cuts (pass the single lepton trigger)
 - $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
 - $\cancel{E}_T > 50$ GeV.
 - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Backgrounds: multi-boson, ttZ , fakes, etc.
Assumption: 50 events/year (100 fb^{-1}).



Tevatron and LHC Reach

- The reach in the $4\ell\cancel{E}_T$ channel. Require 5σ or 5 events.



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



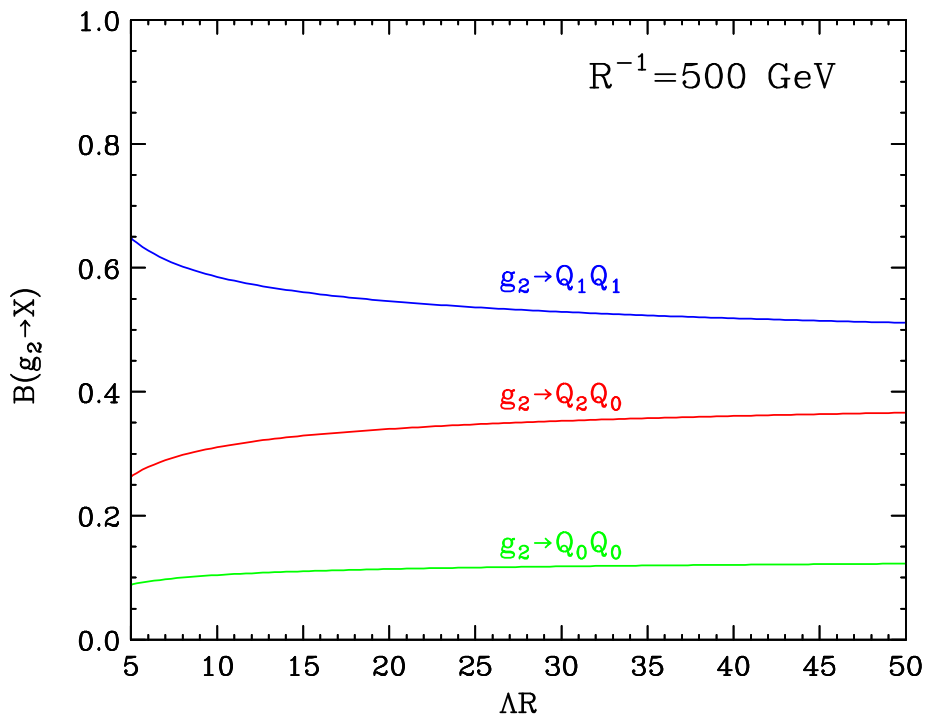
UED or SUSY?

- 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: $f_2 \rightarrow V_1 f_1$ or $f_2 \rightarrow V_2 f_0$ (also $f_2 \rightarrow f'_2 W^\pm$). Same for scalars. See level 1 KK searches.
- KK gauge bosons: $V_2 \rightarrow f_1 \bar{f}_1$, $V_2 \rightarrow f_2 \bar{f}_0$, but also $V_2 \rightarrow f_0 \bar{f}_0$.

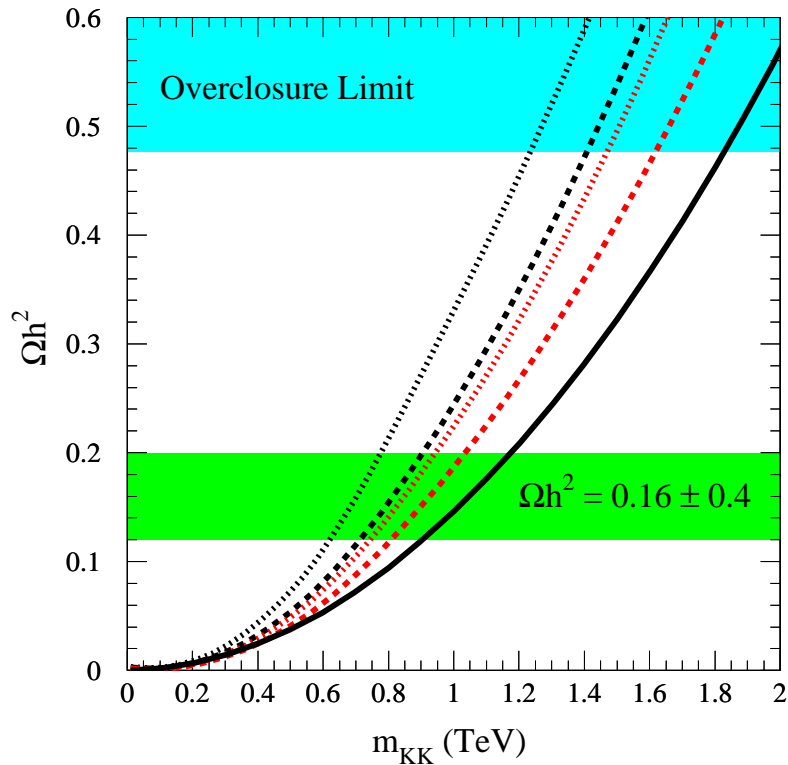


- KK2 pair production + **KK number violating** decays \Rightarrow dilepton/dijet bumps at high inv. mass + large \cancel{E}_T + soft stuff.
- KK2 single production + **KK number violating** decays \Rightarrow similar to Z' , W' searches.



Cosmology

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



- Unlike supersymmetry: no helicity suppression

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

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

- Unlike supersymmetry: coannihilation lowers the bound



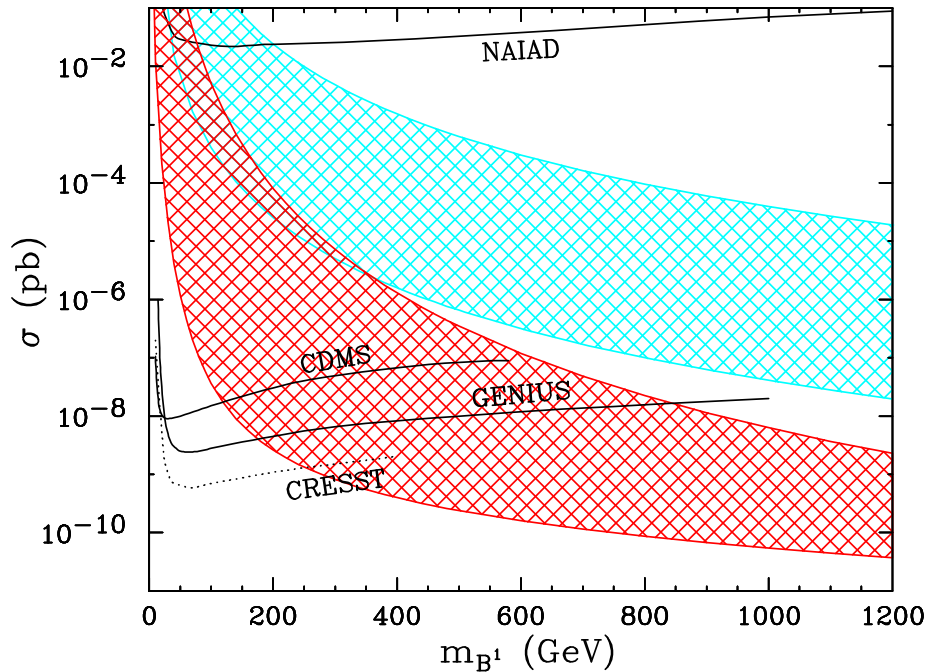
KK dark matter detection

- 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?



KKDM: Direct Detection

- As usual, spin-dependent and spin-independent cross-sections.



- The signals are enhanced by the proximity to the s -channel resonance:

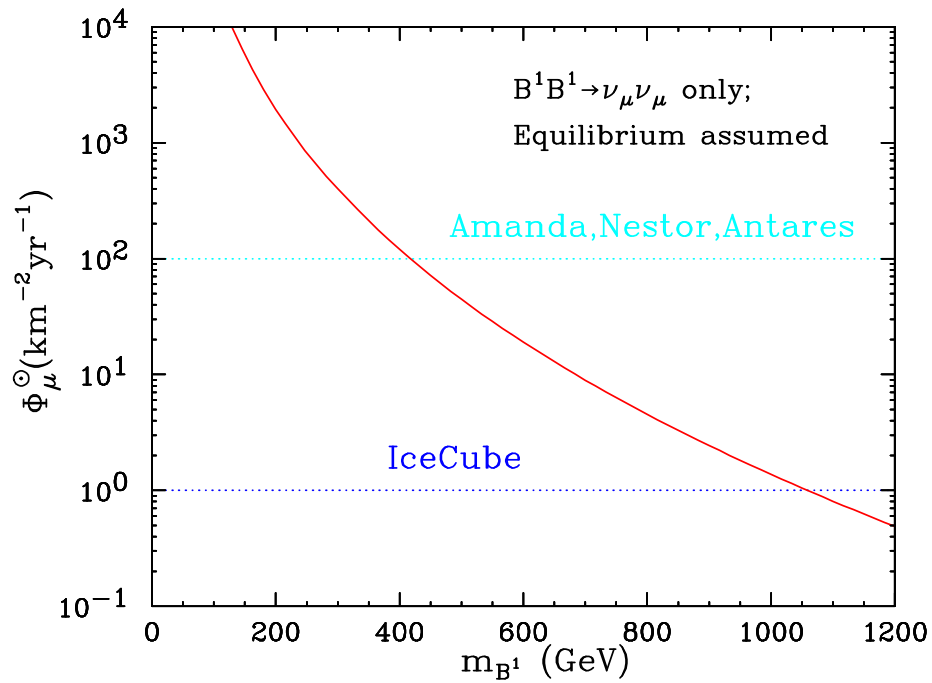
$$\sigma \sim \left(\frac{1}{m_{q^1} - m_{B^1}} \right)^2$$

Unnatural in SUSY - guaranteed here.



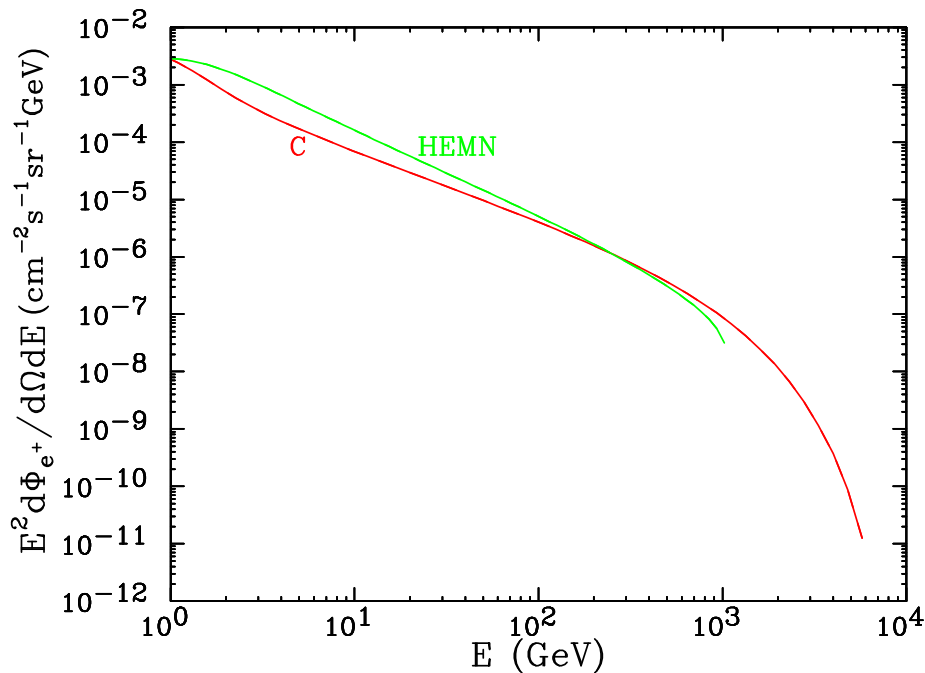
Indirect Detection: Neutrinos

- The Sun or the Earth? The Sun.
- Several channels: $\nu_\mu \bar{\nu}_\mu$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $t\bar{t}$, $b\bar{b}$, $c\bar{c}$, hh ...



Indirect Detection: Positrons

- Both the shape and the normalization of the background are uncertain:



- Unless you see a bump, it is difficult to tell...
- Generic SUSY does **not** predict large signals. Exception: focus point region.
- AMS-II will be able to measure high- p_T positrons!

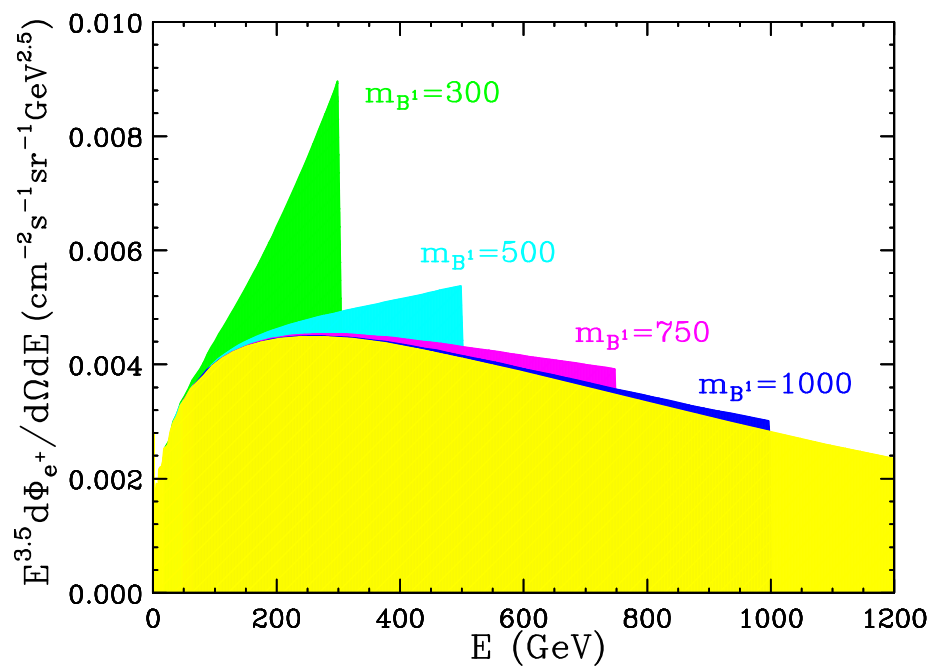


Indirect Detection: Positrons

- Annihilation into fermion pairs is **not** helicity suppressed.

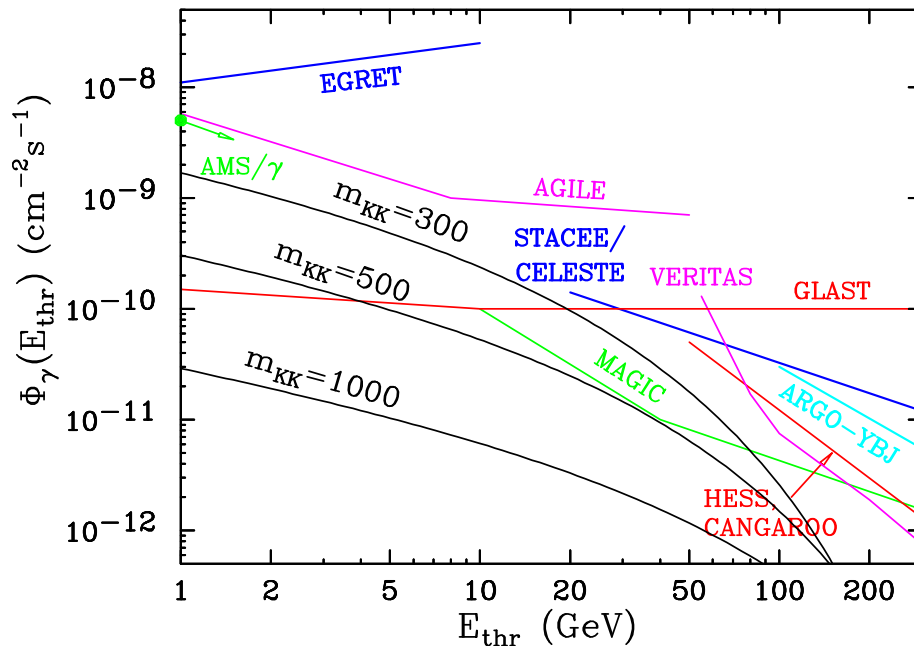
$$B(B^1 B^1 \rightarrow e^+ e^-) = 20\%$$

- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.



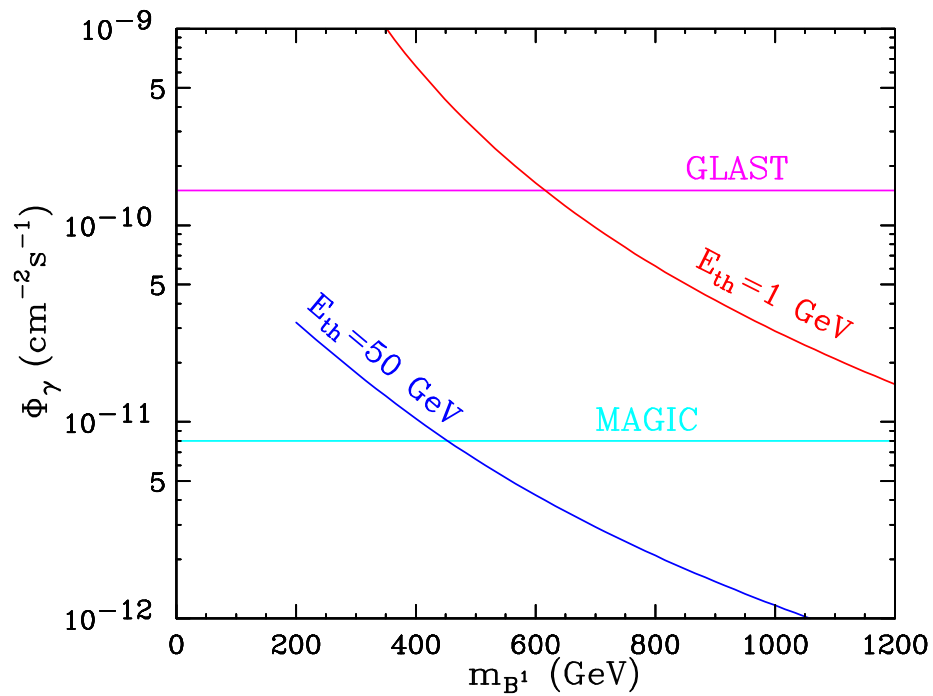
Indirect Detection: Photons - I

- Hard photons from dark matter annihilation in the galactic centre.
- Advantages over supersymmetry:
 - The preferred m_{KK} is larger \Rightarrow harder spectrum.
 - The hardest fragmentation functions are for light quarks. Absent in supersymmetry, dominant here.



Indirect Detection: Photons - II

- Reach of two representative experiments: low and high threshold.



- The signals may be further enhanced by halo clumpiness.



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 \cancel{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 excellent opportunities for detection.

