Bosonic Supersymmetry

Konstantin Matchev

University of Florida

In collaboration with:

H.-C. Cheng and M. Schmaltz

Phys. Rev. D66, 036005 (2002), hep-ph/0204342;

Phys. Rev. D66, 056006 (2002), hep-ph/0205314

H.-C. Cheng and J. Feng

Phys. Rev. Lett. 89, 211301 (2002), hep-ph/0207125

Arlington Linear Collider Workshop,
University of Texas at Arlington,
January 10, 2003

Outline

- What is the model? (BS)
  - MUEDs (Minimal Universal Extra DimensionS)
- Collider phenomenology
  - What is the spectrum? Tree level? Radiative corrections?
  - What are the allowed decays?
  - How big are the cross-sections?
  - How do we discover it at the Tevatron and the LHC?
- Can we tell it from SUSY?
- Kaluza-Klein dark matter
  - Relic density
  - Direct detection
  - Indirect detection: neutrinos, positrons, photons.

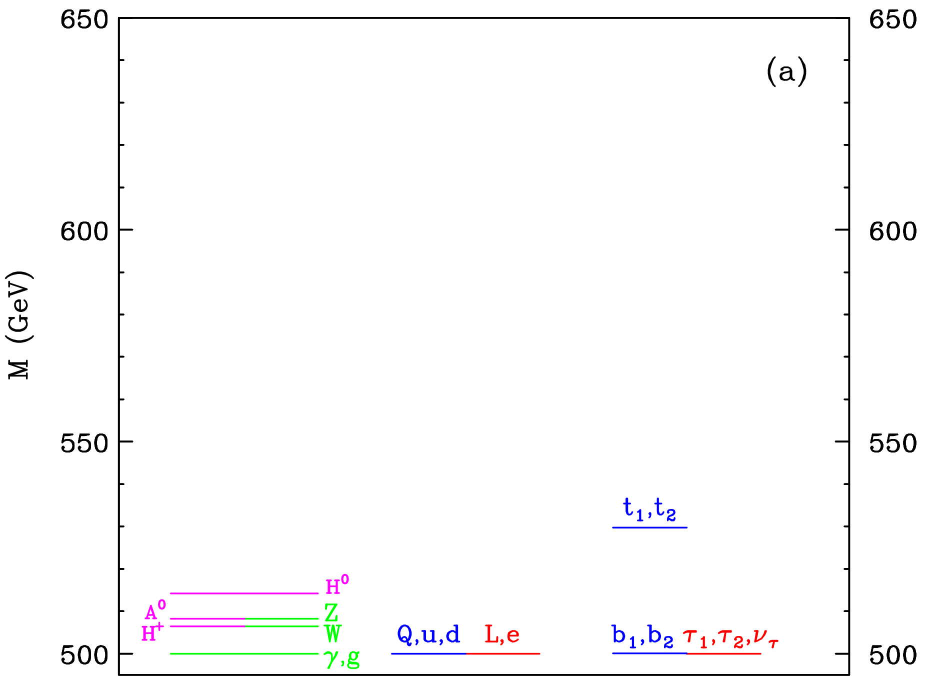
Universal Extra Dimensions

- 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 – identify opposite points on the circle. Can be used to project out unwanted zero modes – no branes!
  - KK number – due to 5d momentum conservation.
    New interactions localized on the fixed points break
    KK number down to KK parity: $(-1)^n$
    $\Rightarrow$ Lightest KK Particle is stable. (Dark Matter?)
- The minimal model is very predictive: $\{R, \Lambda, m_h\}$
- Current constraints exclude $R^{-1} \lesssim 300$ GeV, possibly less, depending on m_h.

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?

- If 5d Lorentz invariance were exact, the KK masses would be fixed by the dispersion relation

$$E^2 = \vec{p}^{\,2} + p_5^2 + m_0^2 = \vec{p}^{\,2} + \left(\frac{n}{R}\right)^2 + m_0^2$$

and the KK mass splittings would only depend on the m_0's.

- For example, consider a scalar field:

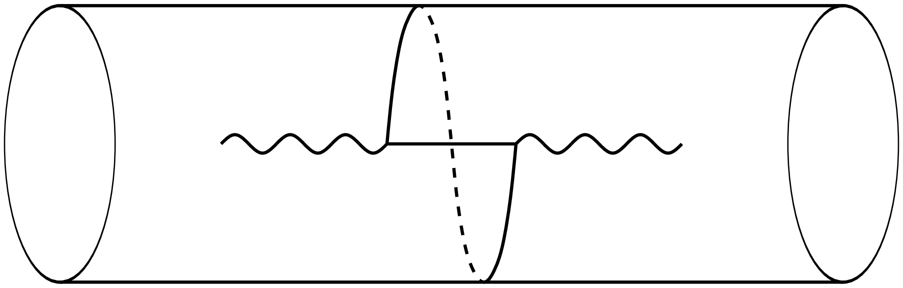
$$\mathcal{L} \supset Z\partial_\mu\phi\,\partial^\mu\phi - Z_5\partial_5\phi\,\partial_5\phi, \quad \mu = 0,1,2,3\ ,$$

and 5d Lorentz invariance requires $Z = Z_5$, hence the $\frac{n}{R}$ term stays uncorrected.

- 5d Lorentz breaking effects modify this conclusion.
- What are the possible 5d Lorentz violating effects?

“Bulk” radiative corrections

- 5d Lorentz invariance is broken at long distances by the compactification. ⇒ Loops with nonzero winding number wrapping around the
extra dimension would know about the compactification:



- The corrections are finite and scale with R^{-1}.

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

- No loss of predictive power! (yet...)

“Boundary” radiative corrections

- There can be local interactions on the boundaries which also break 5d Lorentz invariance. In fact, radiative corrections from bulk interactions do generate terms localized on the boundaries, e.g.

$$\frac{\delta(x_5)+\delta(x_5-\pi R)}{\Lambda}\ G_4(\mu)\ F_{\mu\nu}^2$$

Georgi, Grant, Hailu hep-ph/0012379

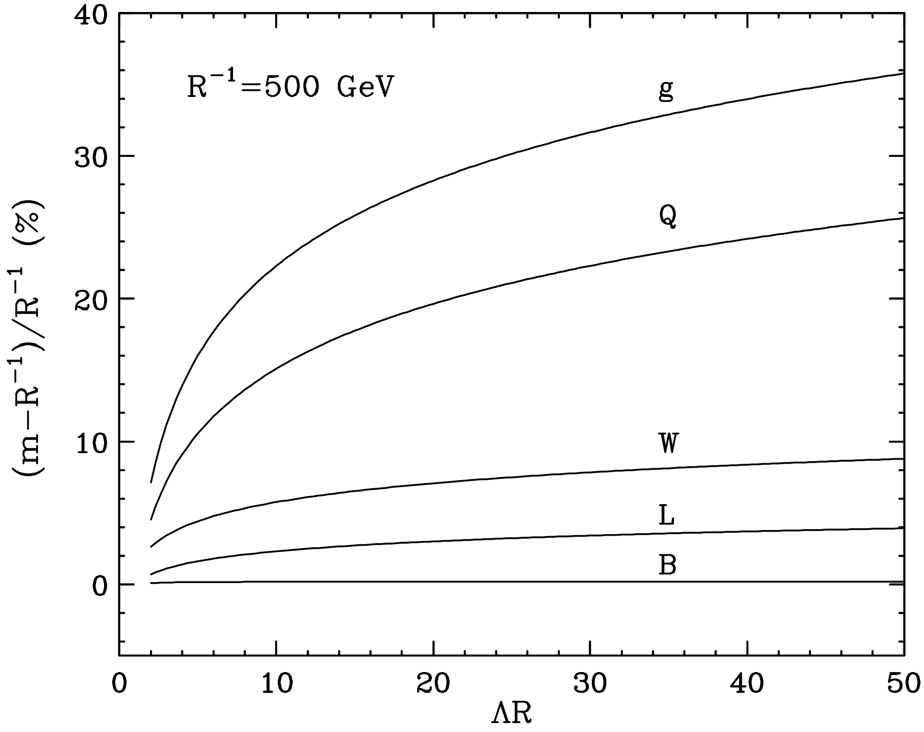
- The corresponding corrections to the KK masses are proportional to $\frac{n}{R}$ and log enhanced:

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

- The “boundary” corrections are larger than the “bulk” corrections and involve many new parameters...
What about predictivity???
- The usual approach: parameterize our ignorance.
- MUEDs (Minimal Universal Extra DimensionS):
the boundary terms vanish at the scale Λ.

Radiative corrections

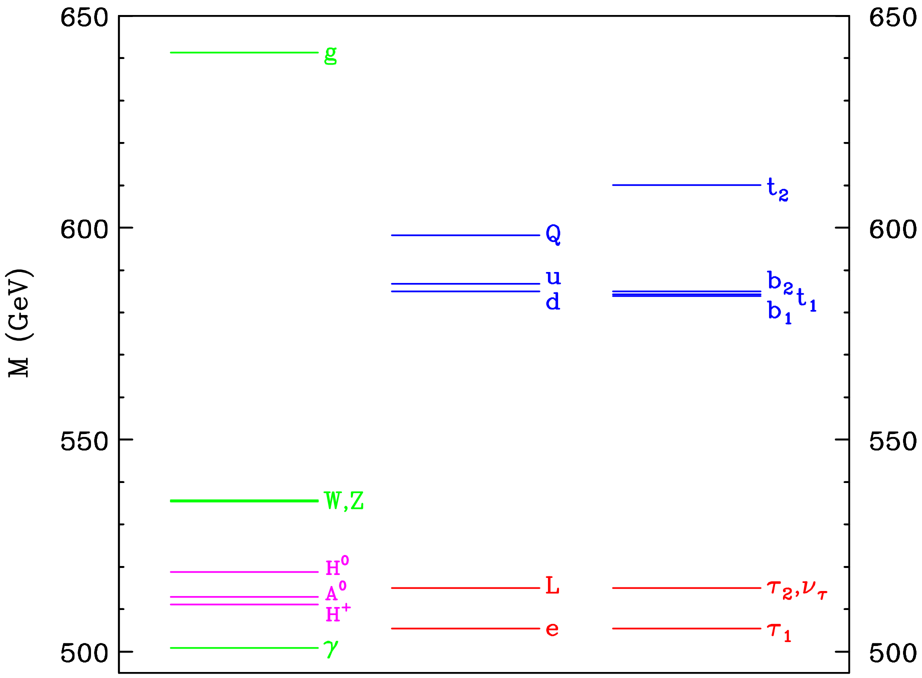
- Putting the two effects together:



- The colored KK particles are the heaviest, followed by $SU(2)$ multiplets etc.

Radiatively Corrected Mass Spectrum

- The radiative corrections split the spectrum ⇒ prompt decays!



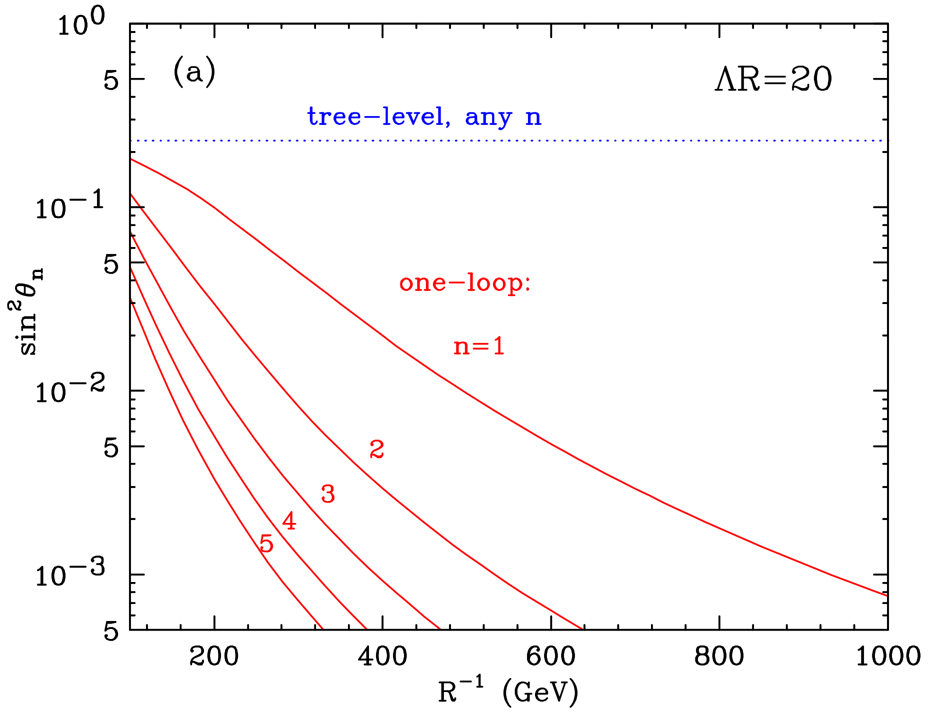
- LKP: KK “photon” ⇒ missing energy!
- Hadron collider searches appear problematic – soft decay products.

The KK Weinberg Angle

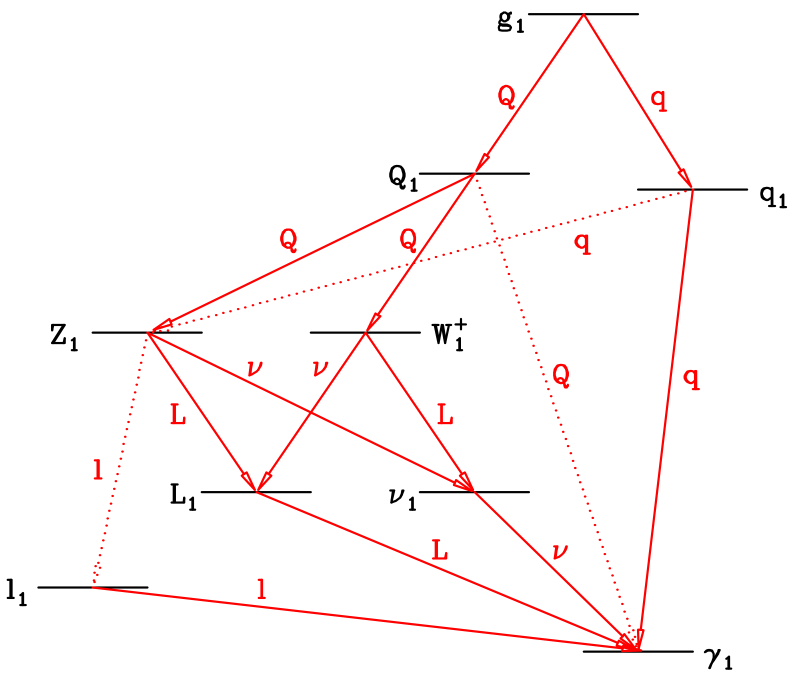
- Mass matrix for the neutral gauge bosons

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

- 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):

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

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

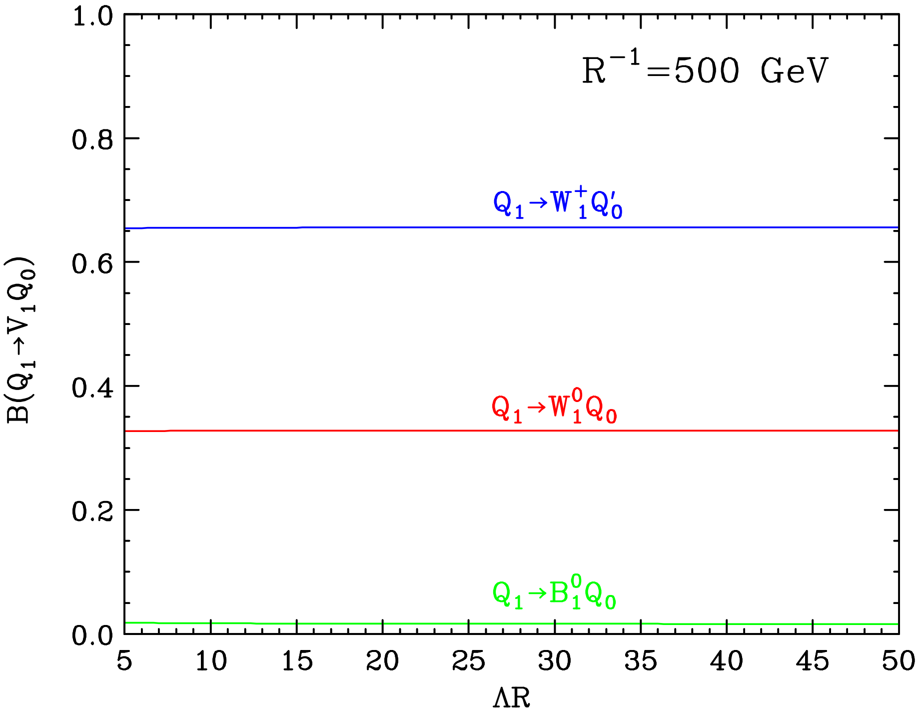
$$B(W_1^\pm \to \nu_1 L_0^\pm) = B(W_1^\pm \to L_1^\pm \nu_0) = 1/6$$
$$B(Z_1 \to \nu_1 \nu_0) \simeq B(Z_1 \to L_1^\pm L_0^\mp) \simeq 1/6$$

- KK leptons: 100% directly to the LKP.

Level 1 Branching Fractions

- Doublet KK quarks (Q).

$$\begin{aligned} B(Q_1 \to W_1^{\pm} Q_0') &\simeq 2B(Q_1 \to Z_1 Q_0) \\ \frac{B(Q_1 \to Z_1 Q_0)}{B(Q_1 \to \gamma_1 Q_0)} &\simeq \frac{g_2^2\, T_{3Q}^2\, (m_{Q_1}^2 - m_{Z_1}^2)}{g_1^2\, Y_Q^2\, (m_{Q_1}^2 - m_{\gamma_1}^2)} \end{aligned}$$



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

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

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

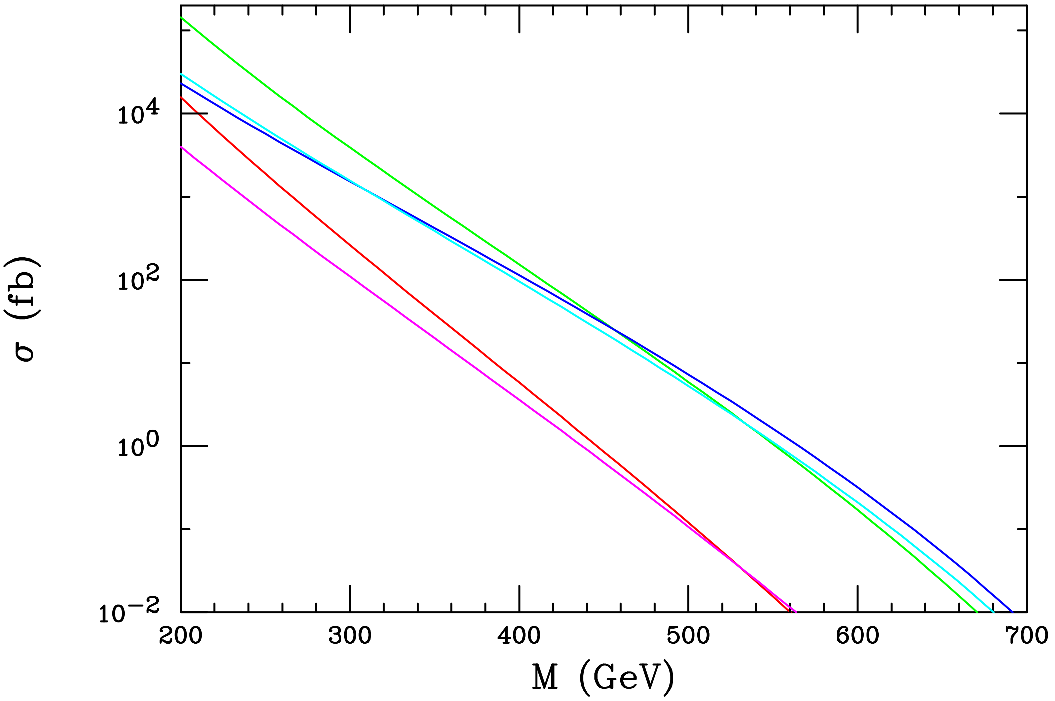
- We want: strong production, weak decays!

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

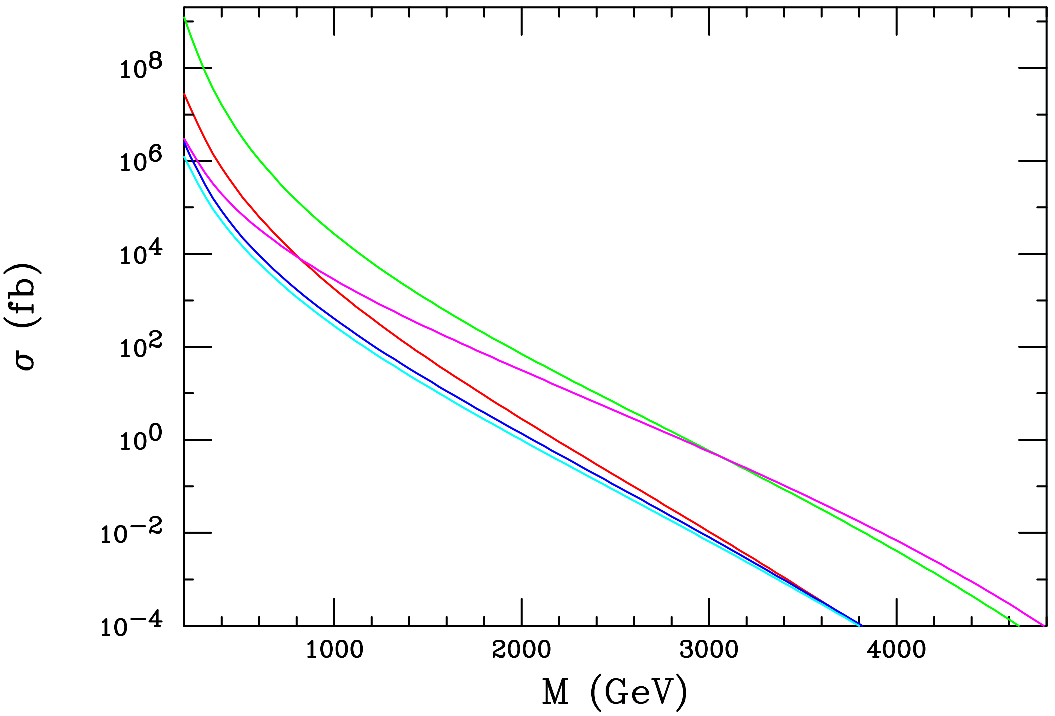
- Arises from inclusive $Q_1 Q_1$ production:

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

- 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}.

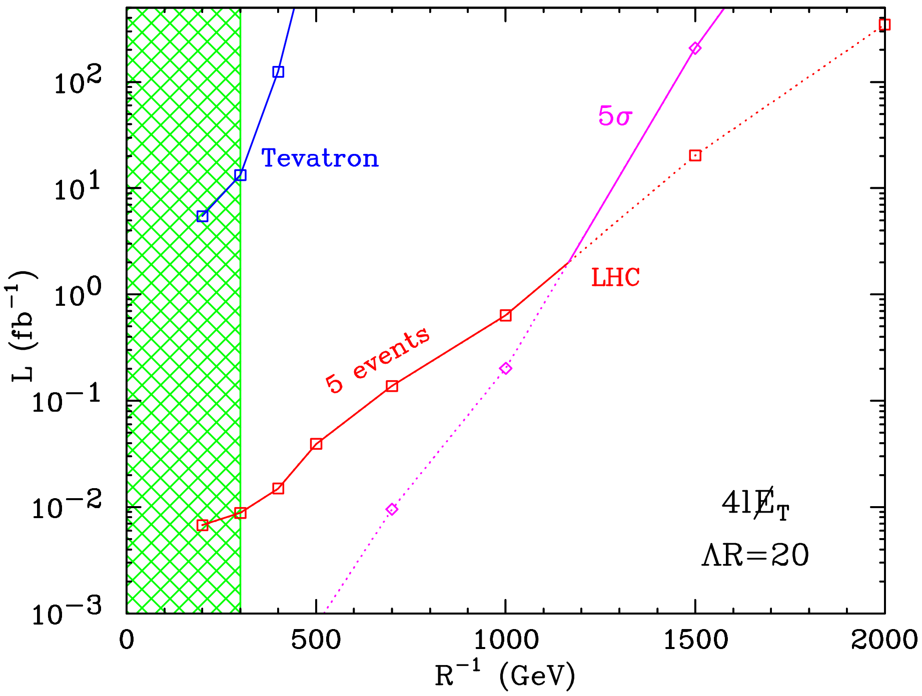


- Cuts (pass the single lepton trigger)
  - $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 50$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
- Backgrounds: multi-boson, ttZ, fakes, etc.

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

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?

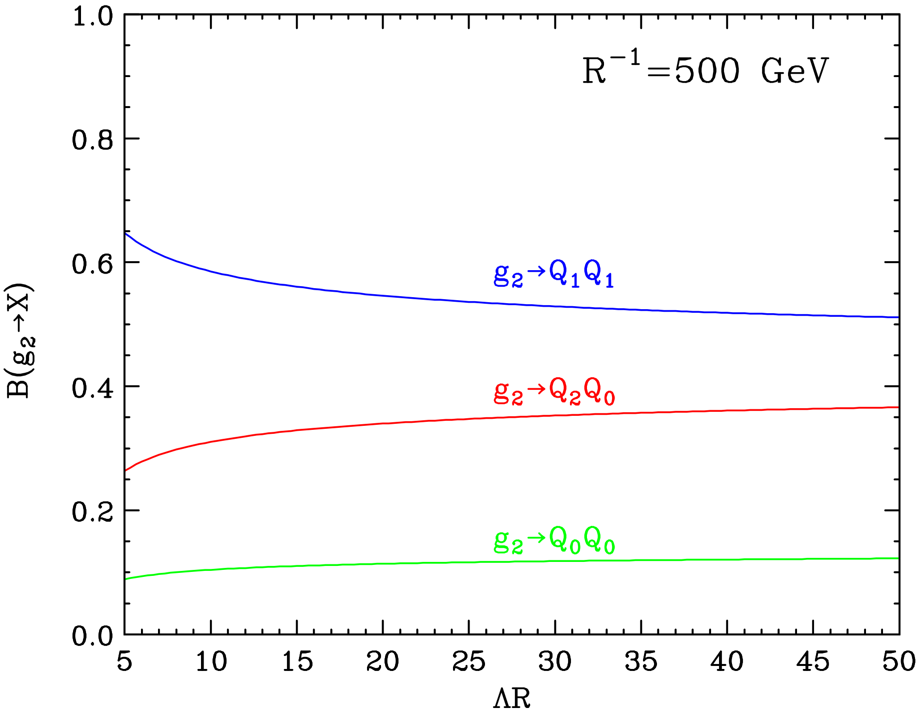
Can you prove SUSY at the LHC?

- Yes. Tenth Conference on String Phenomenology in 2011.

J.Ellis hep-ph/0208109

Second KK level

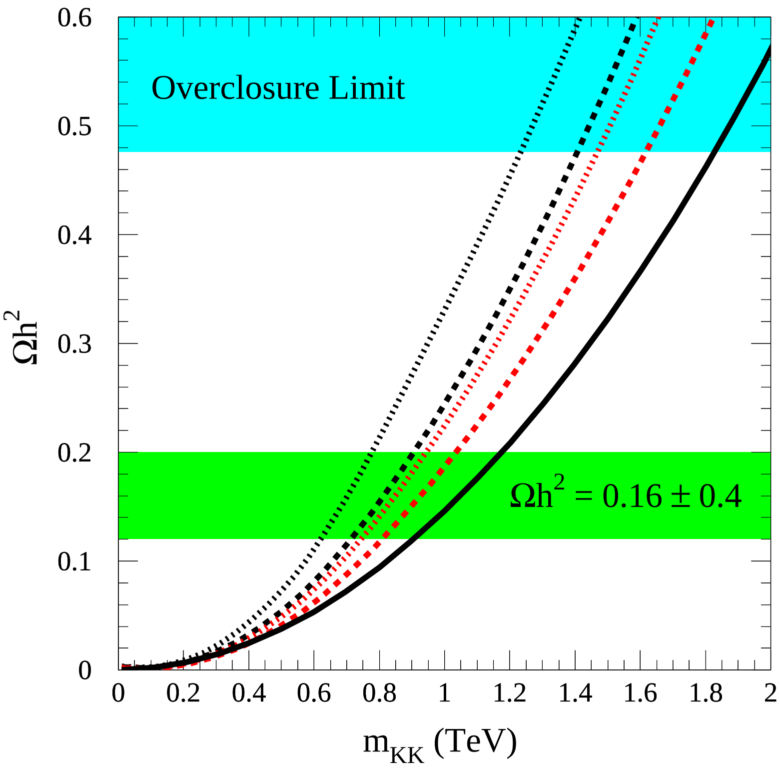
- KK fermions: $f_2 \to V_1 f_1$ or $f_2 \to V_2 f_0$ (also $f_2 \to f_2' W^{\pm}$). Same for scalars. See level 1 KK searches.
- KK gauge bosons: $V_2 \to f_1 \bar{f}_1$, $V_2 \to f_2 \bar{f}_0$, but also $V_2 \to f_0 \bar{f}_0$.



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

Cosmology

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



- Unlike supersymmetry: no helicity suppression

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

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

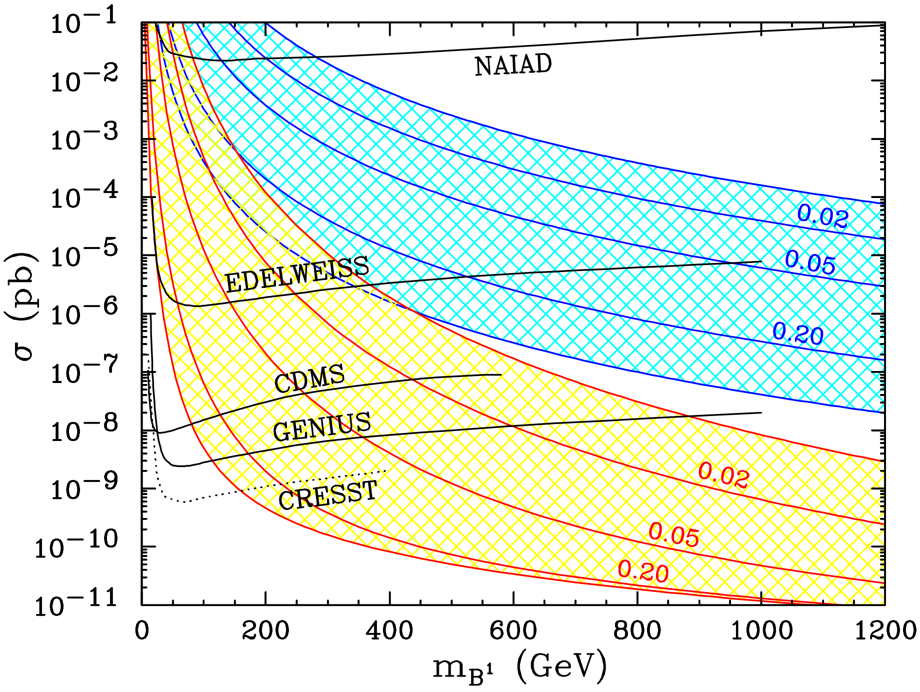
- Unlike supersymmetry: coannihilation lowers the bound

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: promising. Hard γ spectrum.
- 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:

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

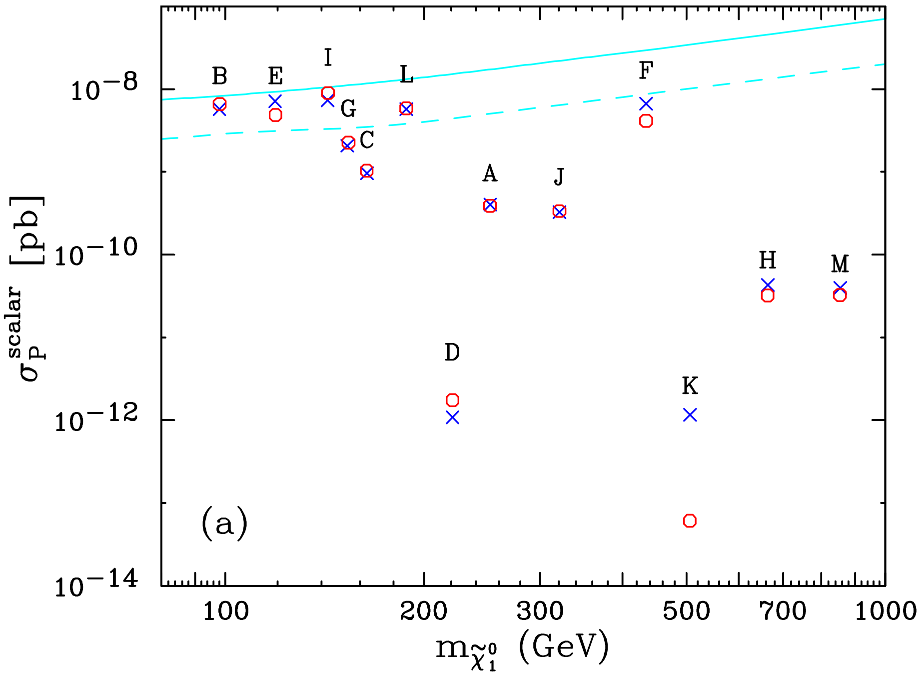
Unnatural in SUSY - guaranteed here.

- Constructive interference: lower bound!
- Conservative calculation: ignoring heavy quarks.

MSSM Direct Detection

- Compare to the rates predicted in supersymmetry
- Spin-independent cross-sections for the 13 benchmark points of Battaglia et al. hep-ph/0106204.

Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225

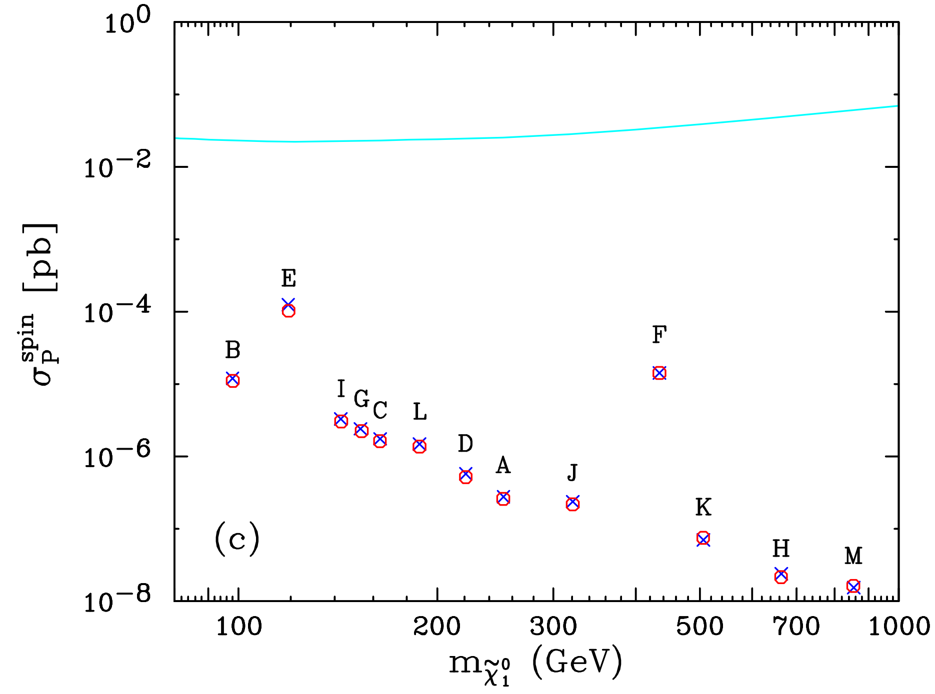


- No lower limit: cancellations are possible.

MSSM Direct Detection

- Spin-dependent cross-sections for the 13 benchmark points of Battaglia et al. hep-ph/0106204.

Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- Far below sensitivity of near-term future experiments.

KKDM Indirect Detection: Neutrinos

- Neutrinos from B^1B^1 annihilations in the core of the Sun/Earth may convert near the detector (neutrino telescope) into muons:

$$\Phi_\mu^\odot = 2.54\times 10^{-17}\ \mathrm{km}^{-2}\mathrm{yr}^{-1}\left[\frac{\Gamma_A}{\mathrm{s}^{-1}}\right]\left[\frac{m_{B^1}}{1\ \mathrm{TeV}}\right]^2 \times \sum_{i=\nu,\bar\nu} a_i b_i \sum_F B_F \langle Nz^2\rangle_{F,i}\ ,$$

- The annihilation rate Γ_A is determined by the balance between capture and annihilation. In equilibrium $\Gamma_A = \frac{1}{2}C^\odot$

$$\frac{C^\odot}{1.3\times 10^{22}\ \mathrm{s}^{-1}} = \left[\frac{\rho}{0.3\ \mathrm{GeV/cm^3}}\right]\left[\frac{1\ \mathrm{TeV}}{m_{B^1}}\right] \times \left[\frac{\sigma_{spin}}{10^{-4}\ \mathrm{pb}}\right]\left[\frac{270\ \mathrm{km/s}}{\bar v}\right] S\left(\frac{m_{B^1}}{m_p}\right)\ ,$$

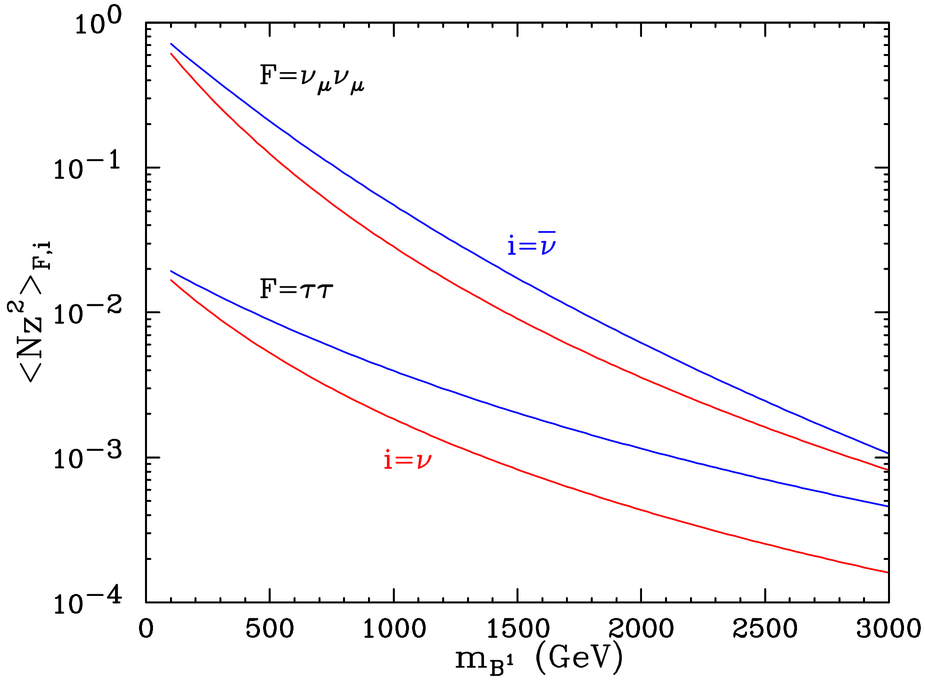
- The flux is proportional to the second moment of the neutrino energy spectrum:

$$\langle Nz^2\rangle_{F,i} \equiv \frac{1}{E_{in}^2}\int_{E_{th}^\nu}^\infty \left(\frac{dN}{dE}\right)_{F,i}(E,E_{in})\ E^2\ dE$$

KKDM 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...

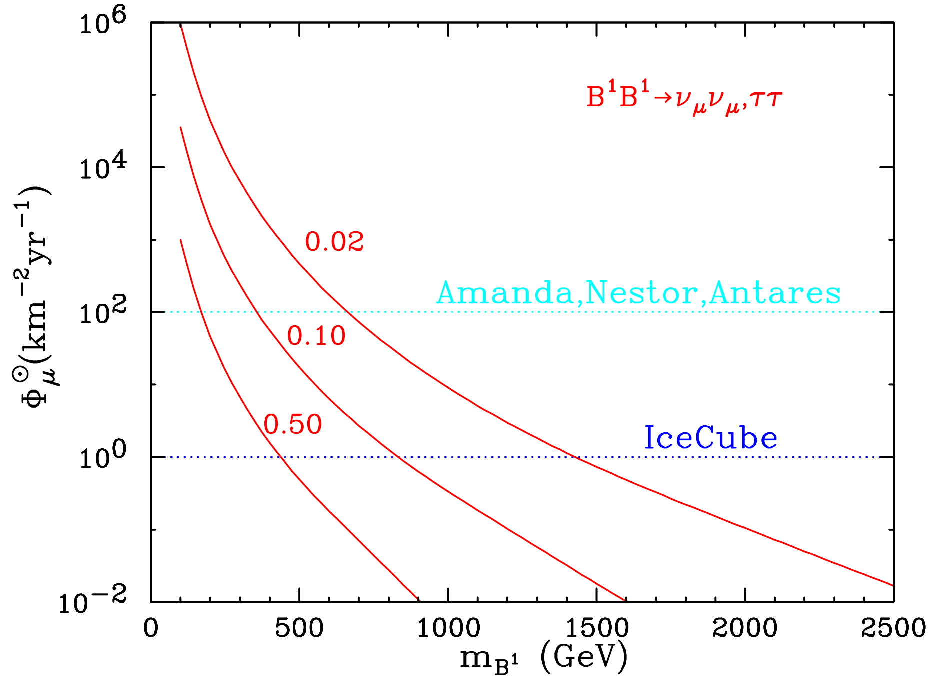
$$\begin{aligned} B(B^1B^1 \to \nu_\mu\bar{\nu}_\mu) &= 1.2\% \\ B(B^1B^1 \to \ell^+\ell^-) &= 20\% \text{ per generation!} \end{aligned}$$



- Muons in the Sun get stopped before they can decay.
- Polarized annihilation products!

KKDM Indirect Detection: Neutrinos

- Discovery reach of neutrino telescopes



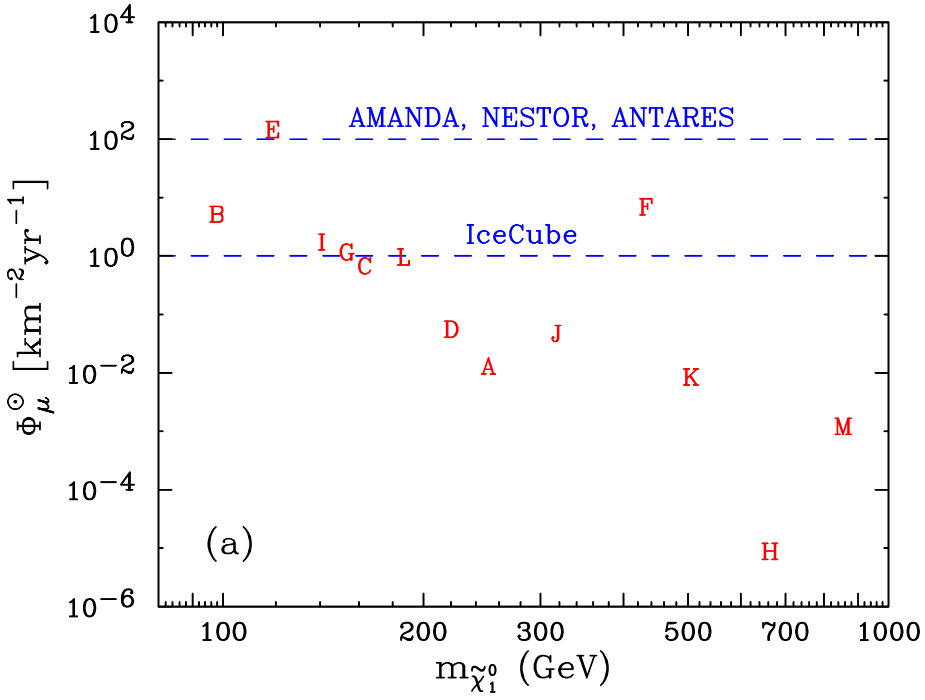
- Conservative estimate:
  - neglecting neutrinos from hadronic final states
  - neglecting $\tau - \mu$ neutrino oscillations

Hooper,Kribs hep-ph/0208261

MSSM: Neutrino signal

- Expectations in supersymmetry:

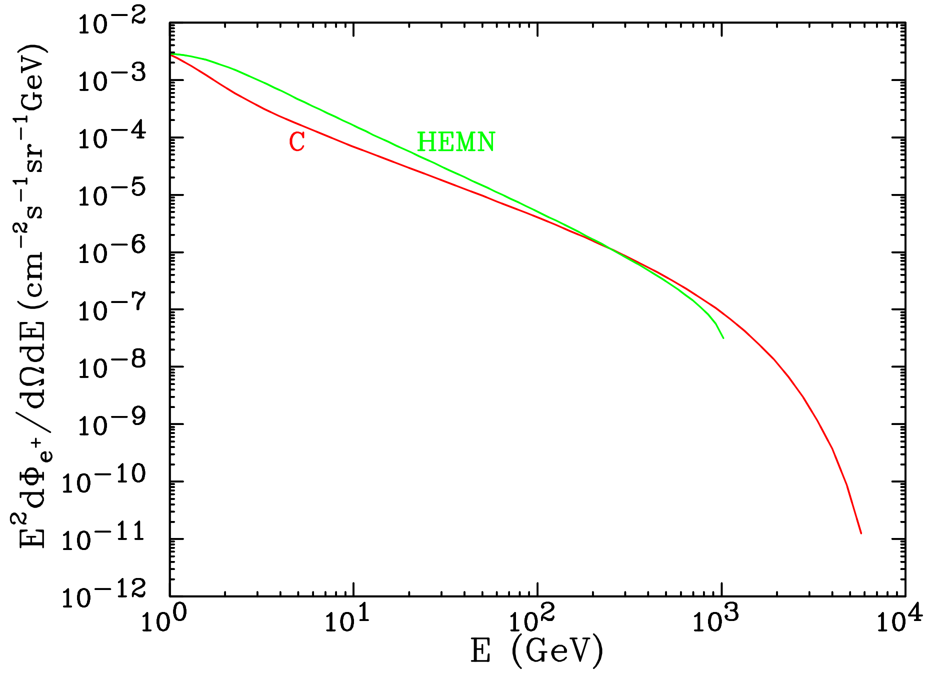
Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- Enhanced signals in the focus point region (E,F) due to $\chi\chi \to WW, ZZ$.

KKDM Indirect Detection: Positrons

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



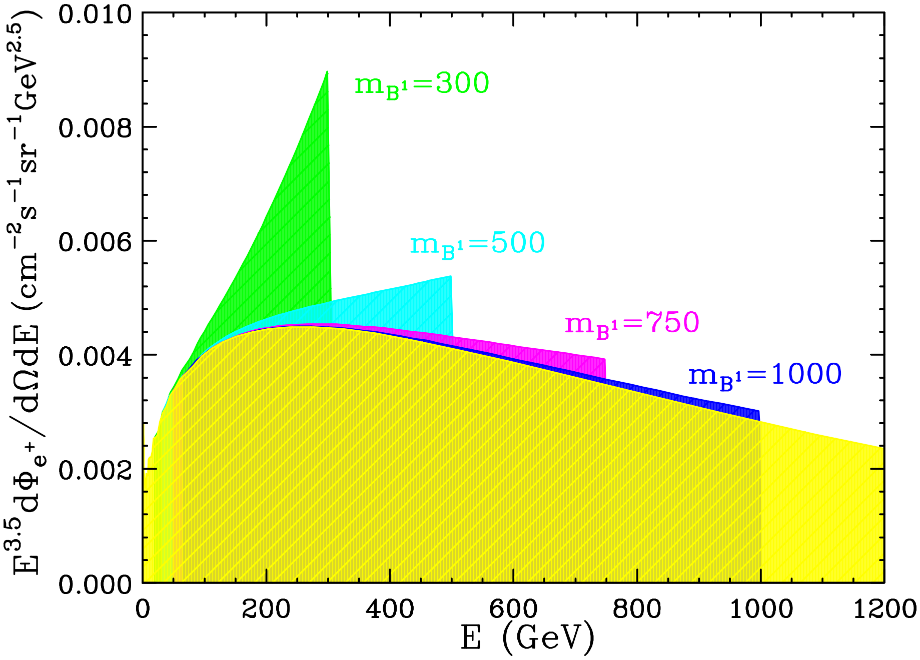
- Unless you see a bump, it is difficult to tell...
- It is easier to see a bump at high E_{e^+}.
- AMS-II will be able to measure high-p_T positrons!

KKDM Indirect Detection: Positrons

- Annihilation into fermion pairs is not helicity suppressed.

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

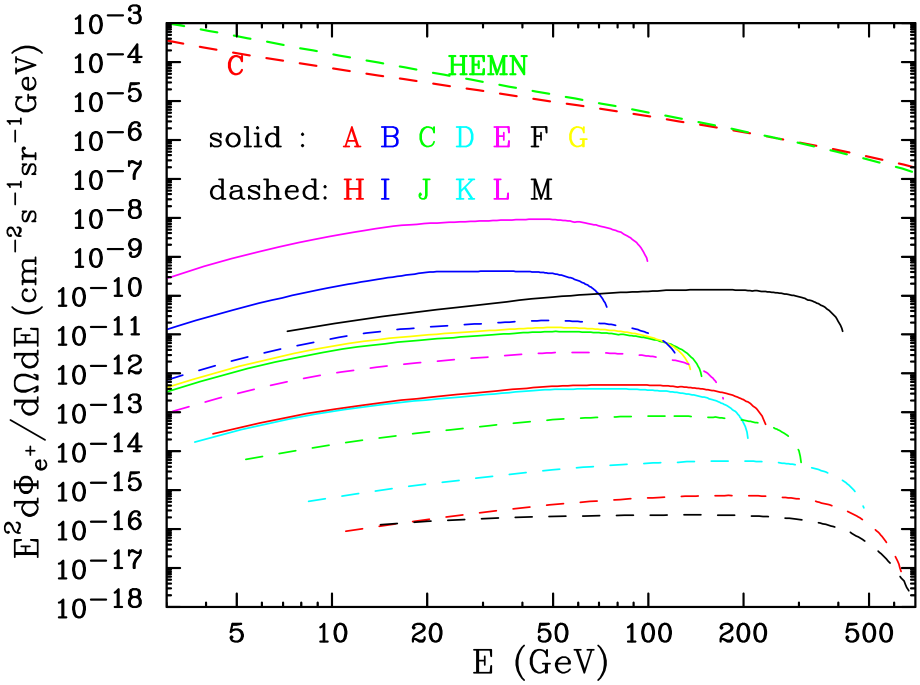
- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.



MSSM: Positron signal

- Hard positrons come from $\chi\chi \to WW$ and $\chi\chi \to ZZ$.

Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225

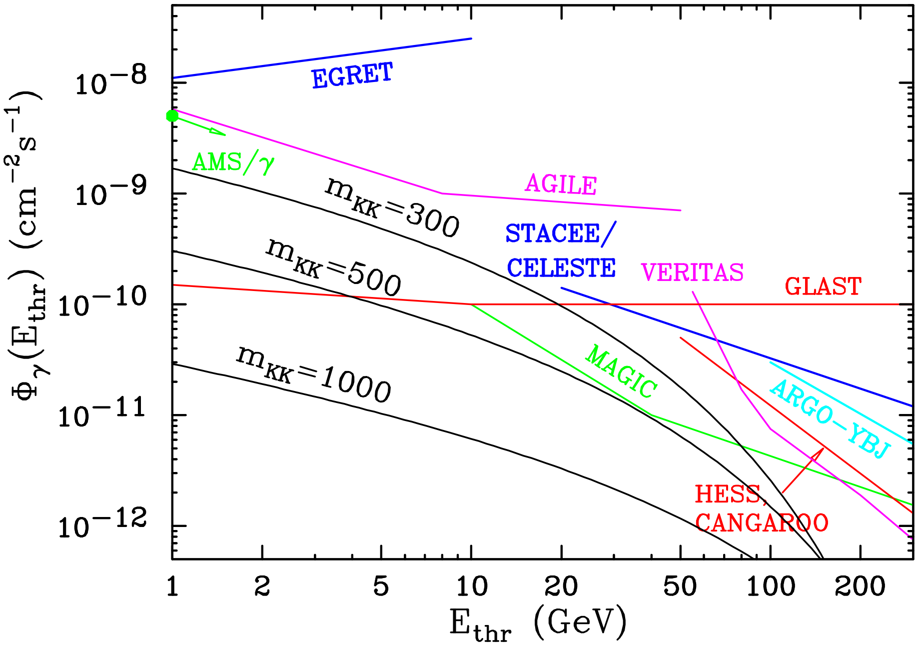


- The signal is typically a small fraction of the background, and the shape is not very characteristic.

KKDM Indirect Detection: Photons - I

- Hard photons from dark matter annihilation in the galactic centre.

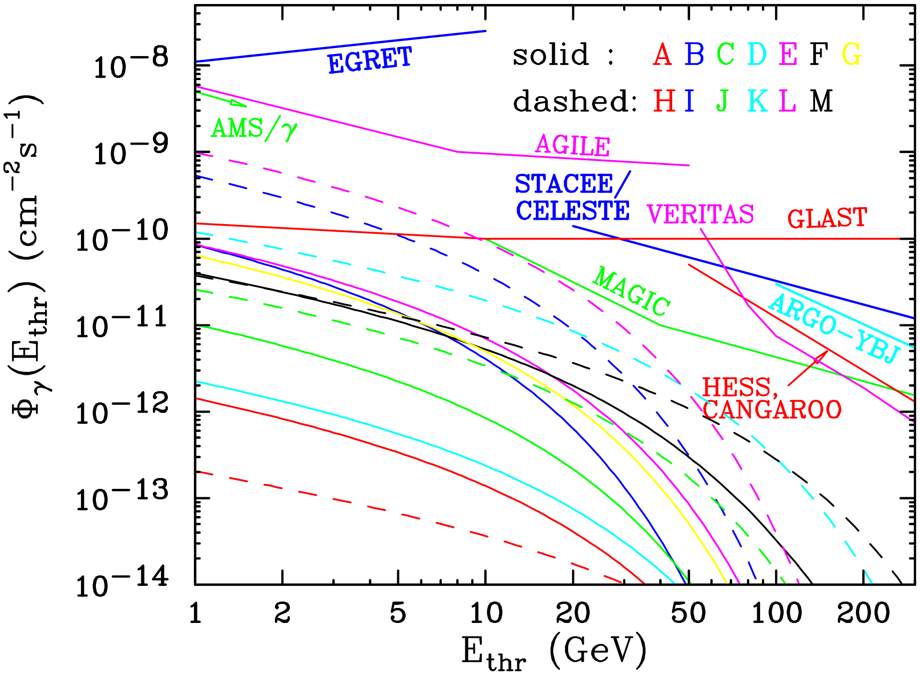
$$\Phi_\gamma(E_{th}) = 5.6 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \bar{J}(\Delta\Omega)\,\Delta\Omega$$
$$\times \left[\frac{1\ \mathrm{TeV}}{m_{B^1}}\right]^2 \sum_q \frac{\langle\sigma_{qq}v\rangle}{\mathrm{pb}} \int_{E_{th}}^{m_{B^1}} dE \frac{dN_\gamma^q}{dE}\ .$$



MSSM: Photon signal

- Expectations in supersymmetry

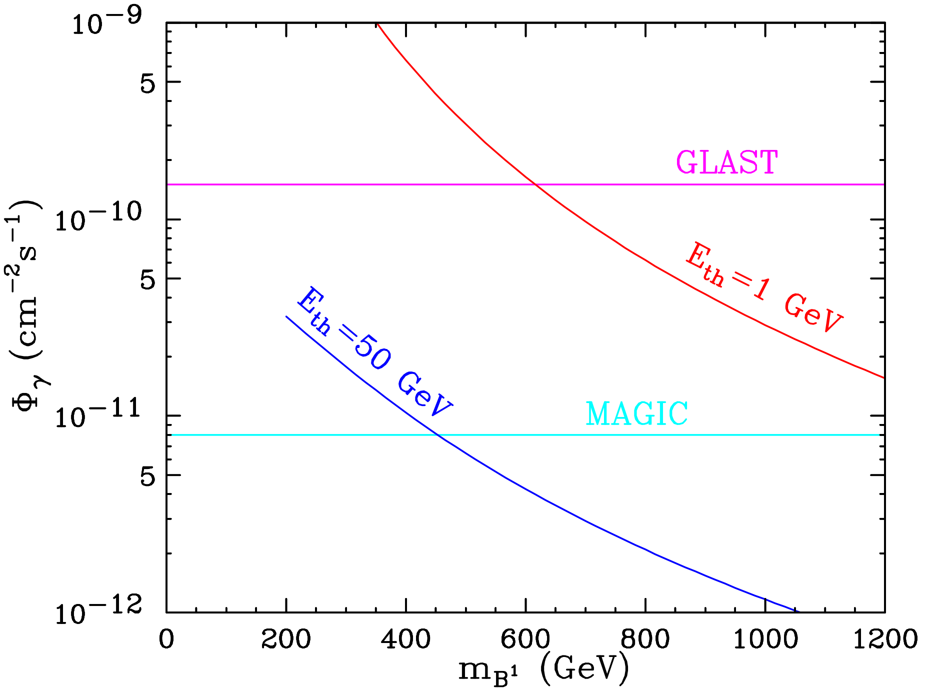
Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- Advantages over supersymmetry:
  - The preferred m_{KK} is larger ⇒ harder spectrum.
  - The hardest fragmentation functions are for light quarks. Absent in supersymmetry, dominant here.

KKDM 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

- UEDs have a rich phenomenology which for a long time went unnoticed.
- KK particles cascade-decay promptly to the LKP, which is neutral and stable ⇒ the generic collider signature is $\not{E}_T$.
- The LHC can probe R^{-1} up to ~ 1.5 TeV in multilepton channels. Other channels? Beyond MUEDs? Broken KK parity?

  Macesanu,McMullen,Nandi hep-ph/0207269
- KK level 1 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.
- DM experiments may provide valuable clues in discriminating b/n bosonic and fermionic extra dimensions.