The LHC/LC Complementarity: SUSY

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Theorists Rally for the Linear Collider,
Arlington Linear Collider Workshop,
University of Texas at Arlington,
January 9, 2003

Outline

- The big questions
  - How many dimensions are there?
  - Are the extra dimensions bosonic or fermionic?
  - Where are the new particles?
  - What is dark matter?
  - Do the forces unify?
- What shall we learn from the LHC?
  - Example: minimal SUGRA
- Bosonic vs fermionic supersymmetry
  - What is bosonic supersymmetry?
  - How do we tell them apart?
- What about dark matter?

Supersymmetry at the LHC

If SUSY exists, the LHC will find it.

- Is it really true? What if it's heavy?
  - More Minimal SSM
  - inverted hierarchy models
  - focus point models
  - naturalness (good)
  - flavor and CP problems (bad)

If SUSY exists at the TeV scale, the LHC will find it.

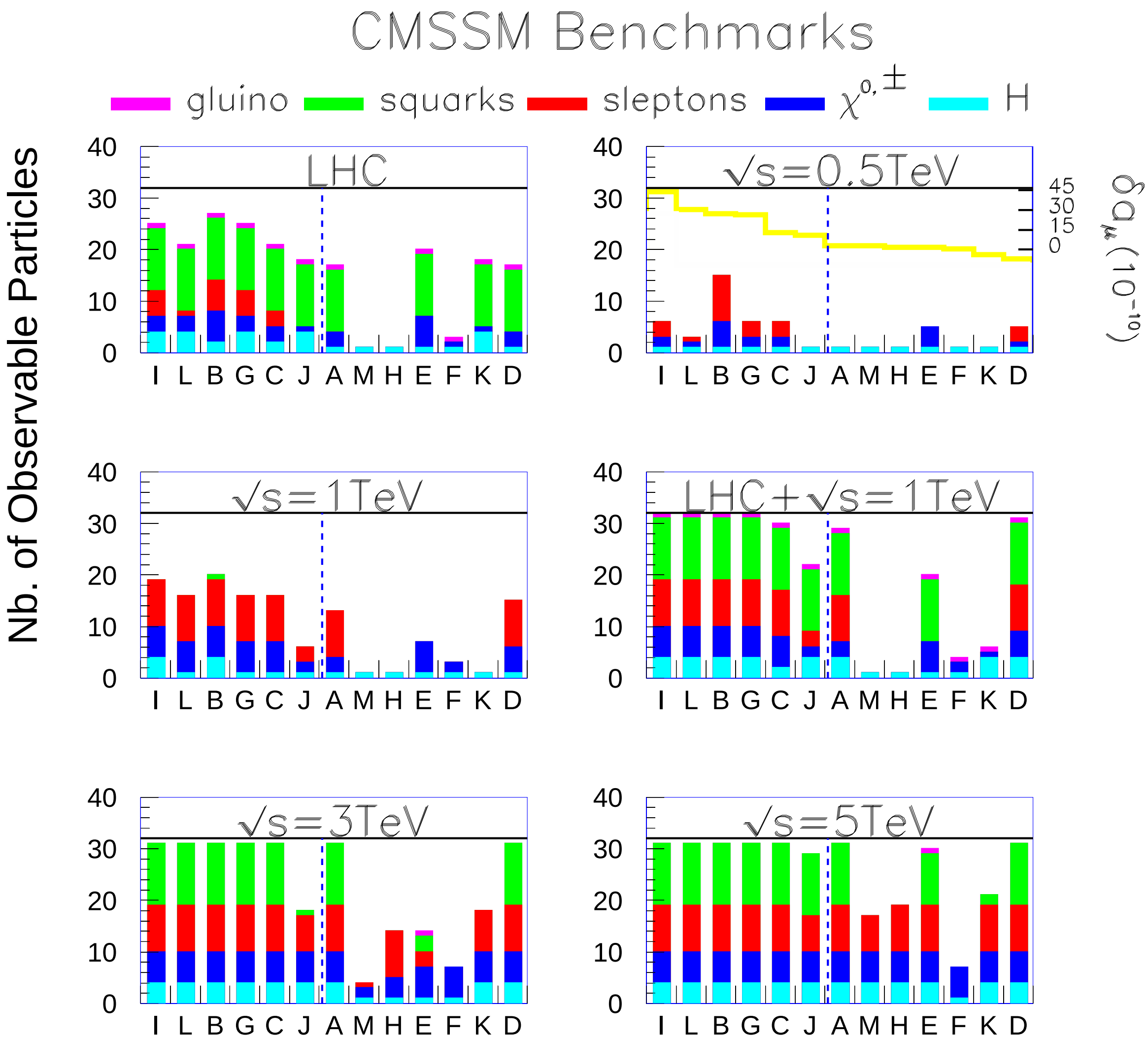
- Is it really true?
  - What if all superpartners are degenerate? ridiculous!
- So what is the true statement?

If SUSY exists at the TeV scale, the LHC will find an excess of events over SM backgrounds in several channels.

How do we know it is SUSY?

- There are superpartners, i.e. new particles
  - Long lived? $\Longrightarrow$ tracks.
  - Short lived? $\Longrightarrow$ bump hunting. (plot)
- Every SM particle has a superpartner
  - Can we count sparticle species? (plot)
- The superpartner couplings are the same
  - Can you measure the sparticle couplings?
    - lifetime? no.
    - width? no.
    - branching fractions? maybe...
    - pair-production cross-sections? maybe...
  - Additional complications: sparticle mixing, detector efficiencies, SM backgrounds...

Species counting at the LHC



How do we know it is SUSY?

- SUSY predicts superpartner masses
  - But SUSY is broken! $\Longrightarrow$ forget it.
- Imprint from SUSY: mass sum rules (good luck...)
  - $\tilde{u}_L - \tilde{d}_L$ mass difference
  - $\tilde{e}_L - \tilde{\nu}_e$ mass difference
  - $\tilde{\chi}_i^+, \tilde{\chi}_i^0$ mass sum rules (need to measure all...)
  - h, H, A, H^+ mass sum rule (radiative corrections)
- Spins of superpartners differ by 1/2
  - ?????
- Plausible conclusion:

LHC will do the best job in measuring SUSY breaking effects, i.e. mass differences and possibly masses, but strictly speaking, won't tell us it is SUSY

How confident can we be it is SUSY?

F. Paige: If it quacks like SUSY, if it walks like SUSY, if it looks like SUSY, then it is probably SUSY!

J. Feng: If it quacks like X, if it walks like X, if it looks like X, then it is ... Y!

(X,Y) = (pion,muon), (charm,tau), ...

- But seriously, what else can it be?
  - It must be SUSY, doesn't it?
- Not any more: bosonic supersymmetry. (Cheng,KM,Schmaltz)

Fermionic supersymmetry

• Fermionic supersymmetry is an extra dimension theory with new anticommuting coordinates θ_α:

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

• If ψ^α are the SM fermions, ϕ are their superpartners (sfermions) with

- spins differing by 1/2
- identical couplings
- unknown masses

• Discovering new particles with those properties IS discovering supersymmetry

Bosonic supersymmetry

• Universal Extra Dimensions is an extra dimension theory with new bosonic coordinates y (spanning a circle of radius R):

$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \phi^n(x^\mu)\cos(ny/R) + \chi^n(x^\mu)\sin(ny/R)$$

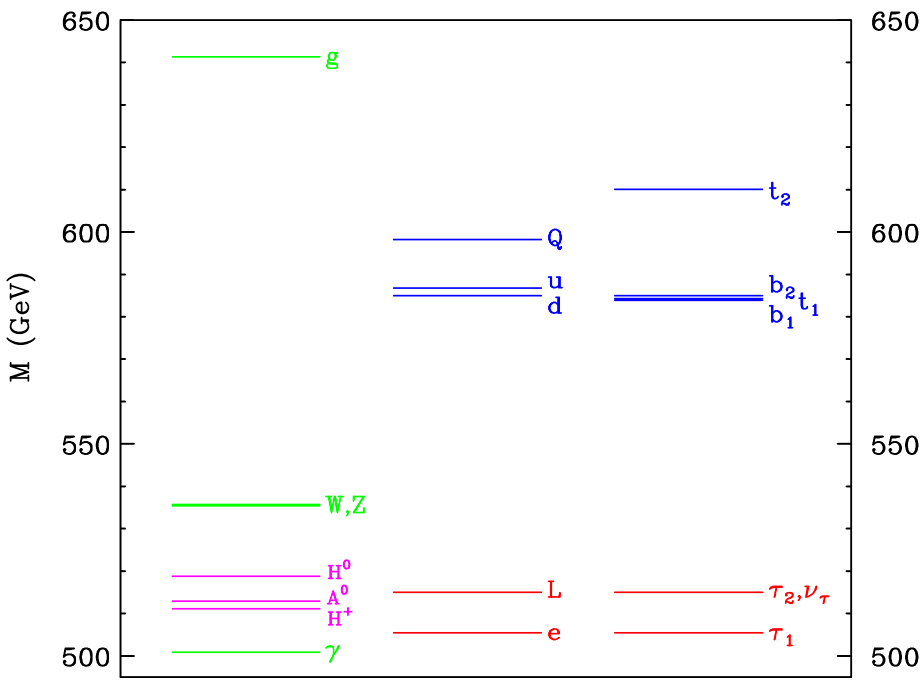
• If ϕ is a SM field, ϕ^n and χ^n are KK partners with

- identical spins
- identical couplings
- unknown masses of order n/R

• Discovering new particles with those properties IS discovering extra dimensions

Bosonic supersymmetry spectrum

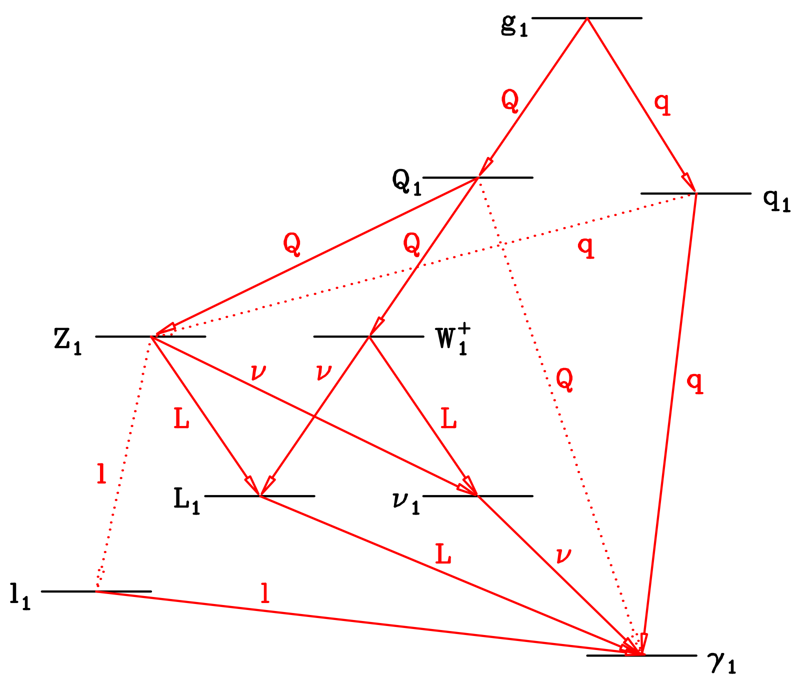
- Including radiative corrections, the mass spectrum of level 1 KK modes looks like this: (Cheng,KM,Schmaltz)



- Looks like SUSY!
- Seems difficult to discover at the LHC (remember the "ridiculous" scenario)

Spectroscopy of bosonic supersymmetry

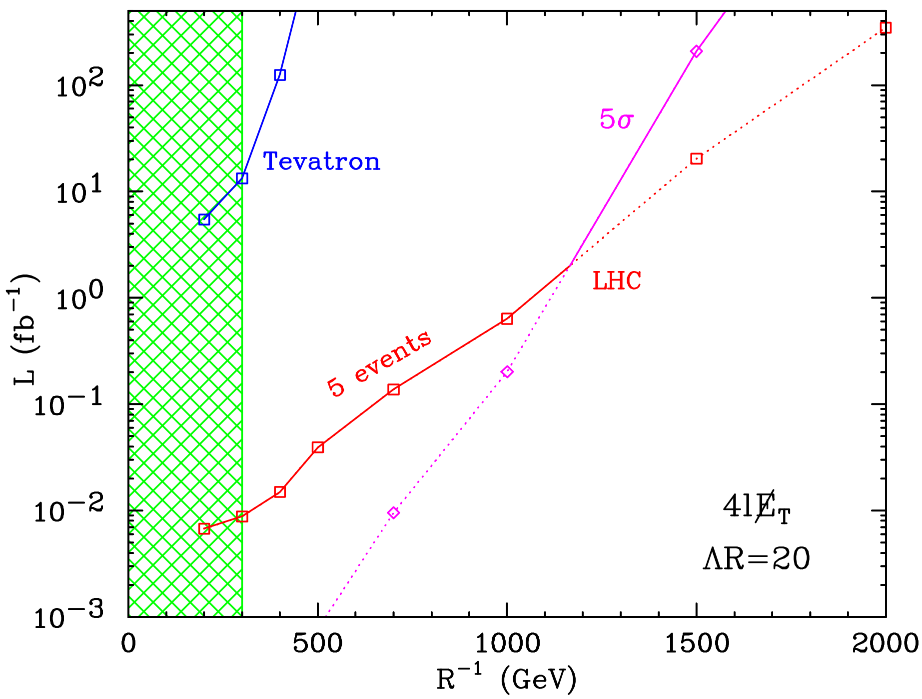
- Transitions among level 1 KK states: (Cheng,KM,Schmaltz)



- Signatures:
  - soft leptons
  - soft jets
  - not a lot of $\not{E}_T$
  - a lot of missing mass (LHC can't measure it)
- Notice the large leptonic branching fractions.

Bosonic supersymmetry discovery reach at the Tevatron and LHC

- The reach in the $Q_1 Q_1 \to 4\ell \not{E}_T$ channel. Require 5σ or 5 ev.

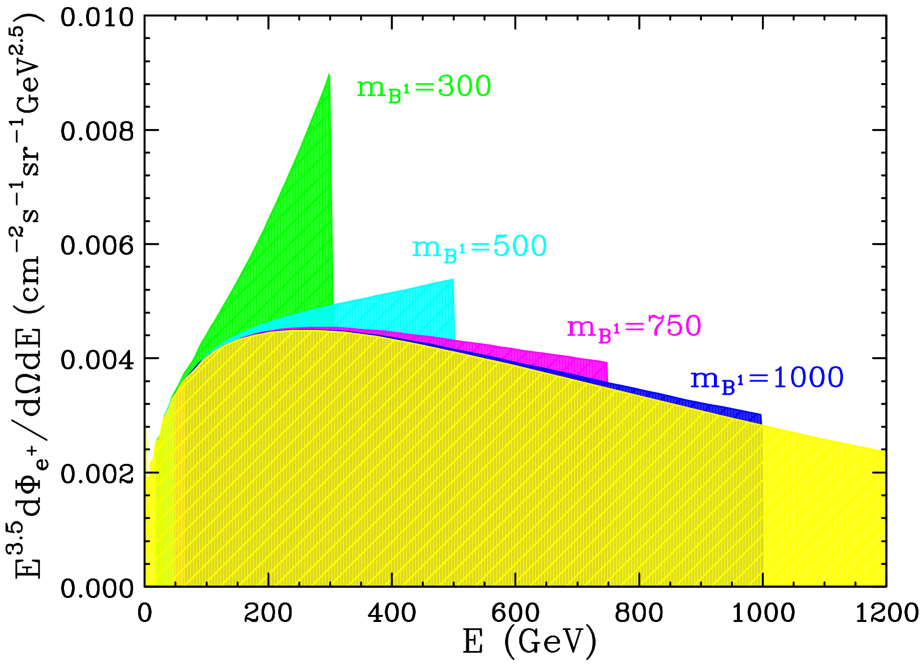


- Other channels with larger statistics may give better reach (especially at the Tevatron).
- We did not optimize cuts.
- More studies are needed. The software is available.

How do we tell the difference?

- Build a collider capable of measuring spins and missing mass.
  - A linear collider at CM energy $> R^{-1}$.
- Look for dark matter signals in a variety of experiments.
  - Smoking gun: bumps in the cosmic ray positron spectrum

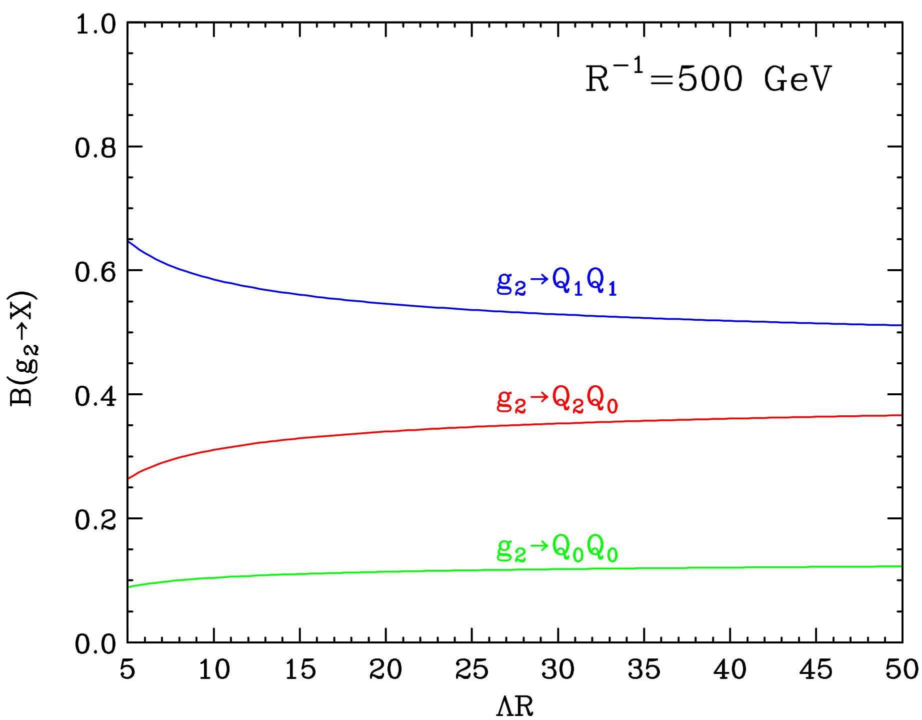
Cheng, Feng, KM



  - More dark matter signals: direct detection, neutrinos from the Sun, cosmic ray photons...

Second KK level

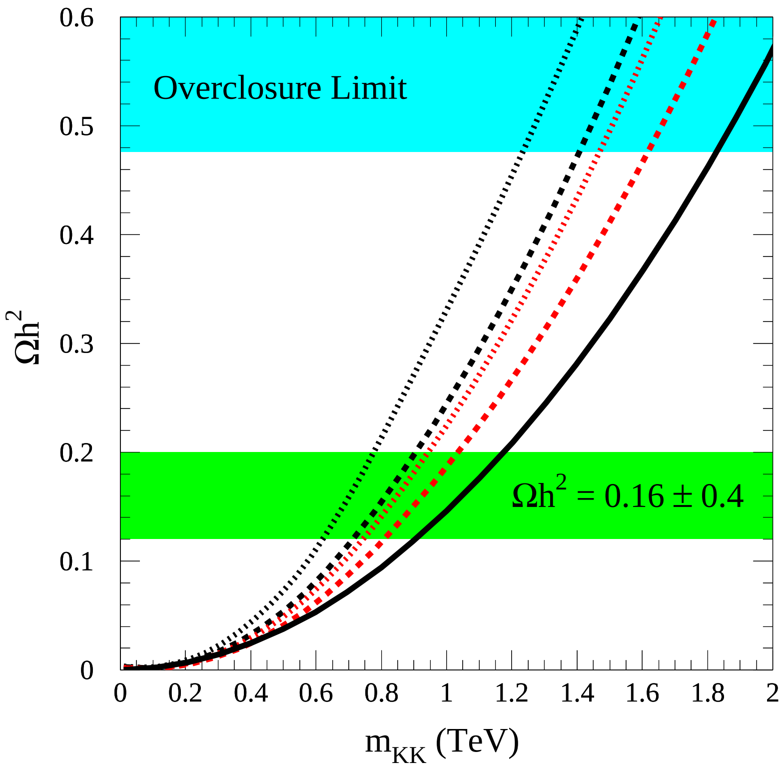
- KK fermions: $f_2 \to V_1 f_1$ or $f_2 \to V_2 f_0$ (also $f_2 \to f_2' W^\pm$). Same for scalars. See level 1 KK searches.
- KK gauge bosons: $V_2 \to f_1 \bar{f}_1$, $V_2 \to f_2 \bar{f}_0$, but also $V_2 \to f_0 \bar{f}_0$.



- 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

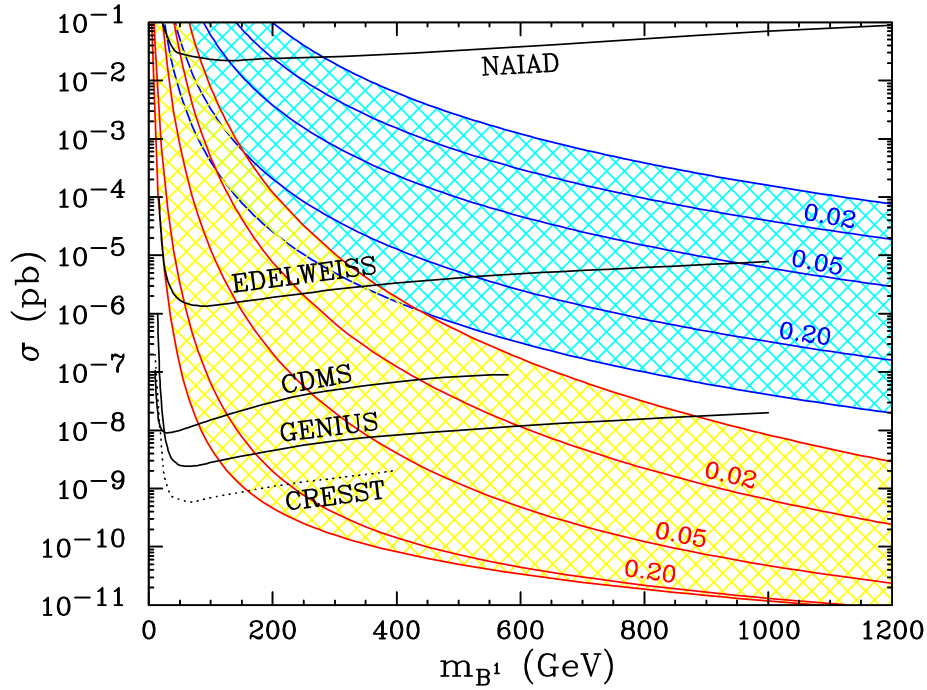
$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P\sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

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

- Unlike supersymmetry: coannihilation lowers the bound

KKDM Direct Detection

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



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

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

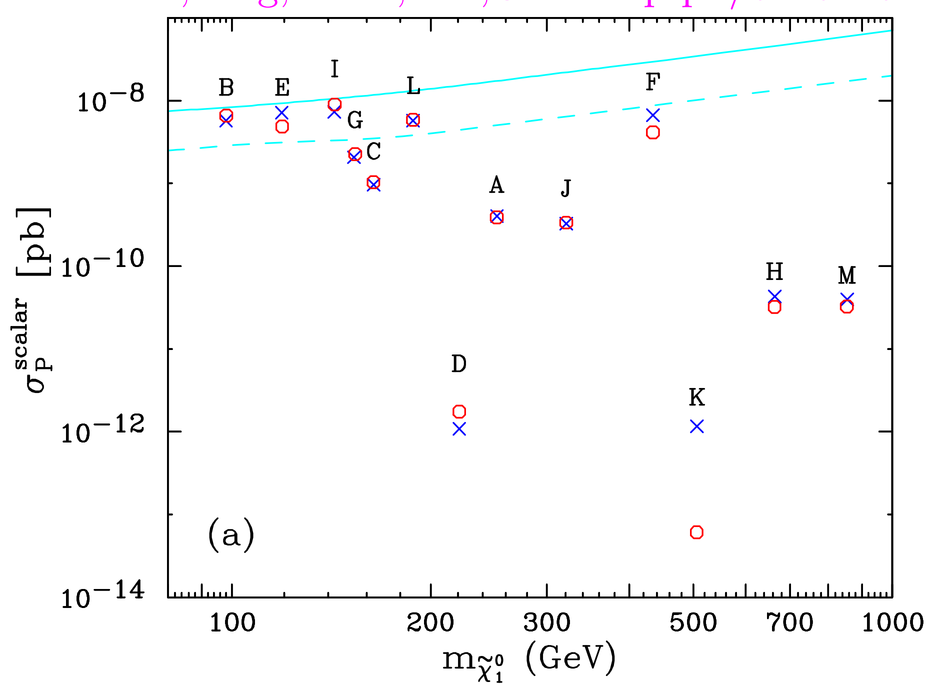
Unnatural in SUSY - guaranteed here.

- 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

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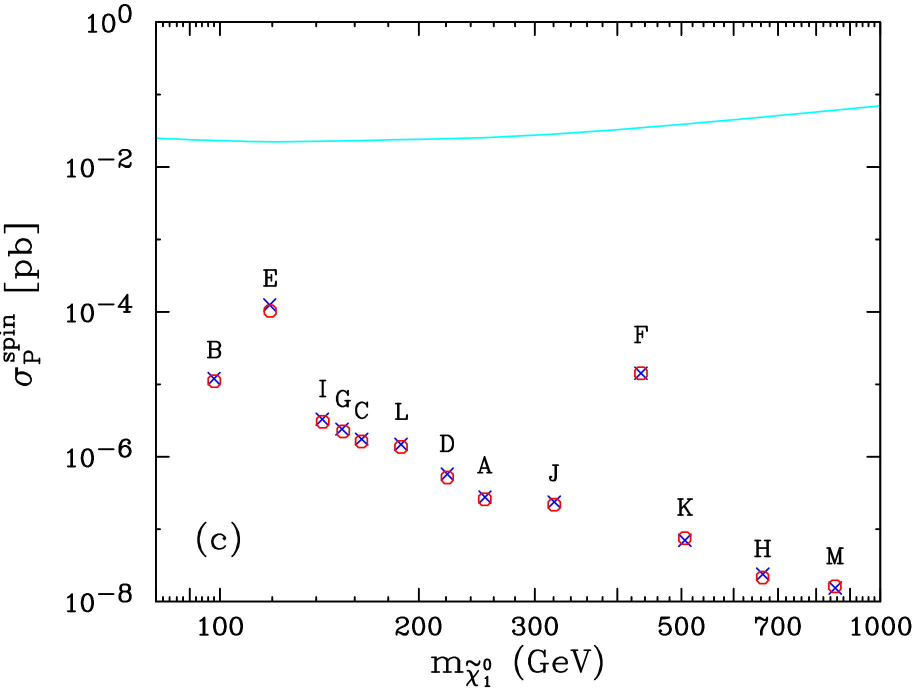


- Far below sensitivity of near-term future experiments.

KKDM Indirect Detection: Neutrinos

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

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

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

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

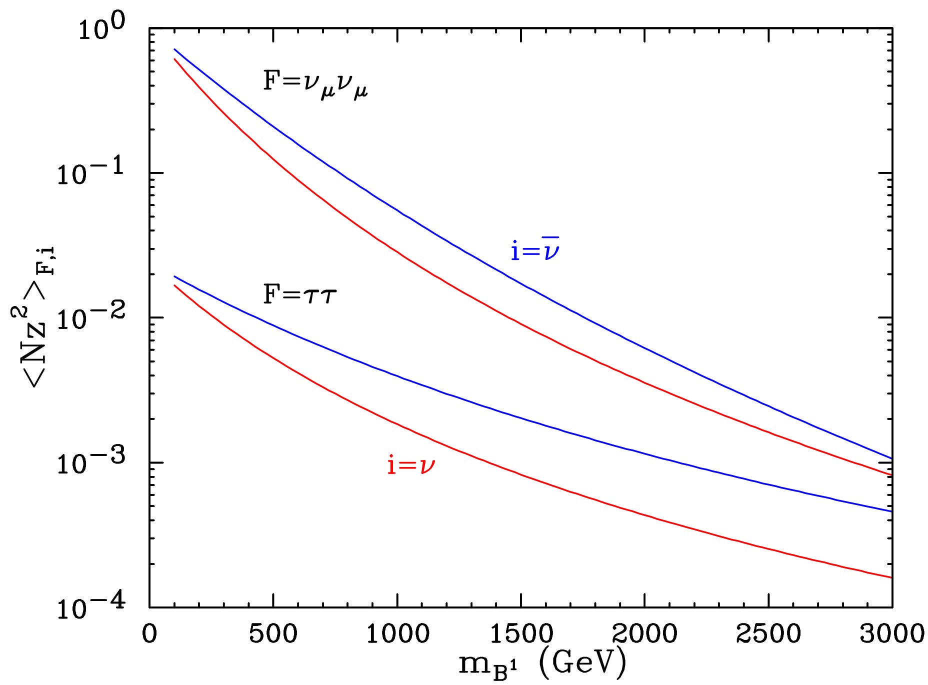
• The flux is proportional to the second moment of the neutrino energy spectrum:

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

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...

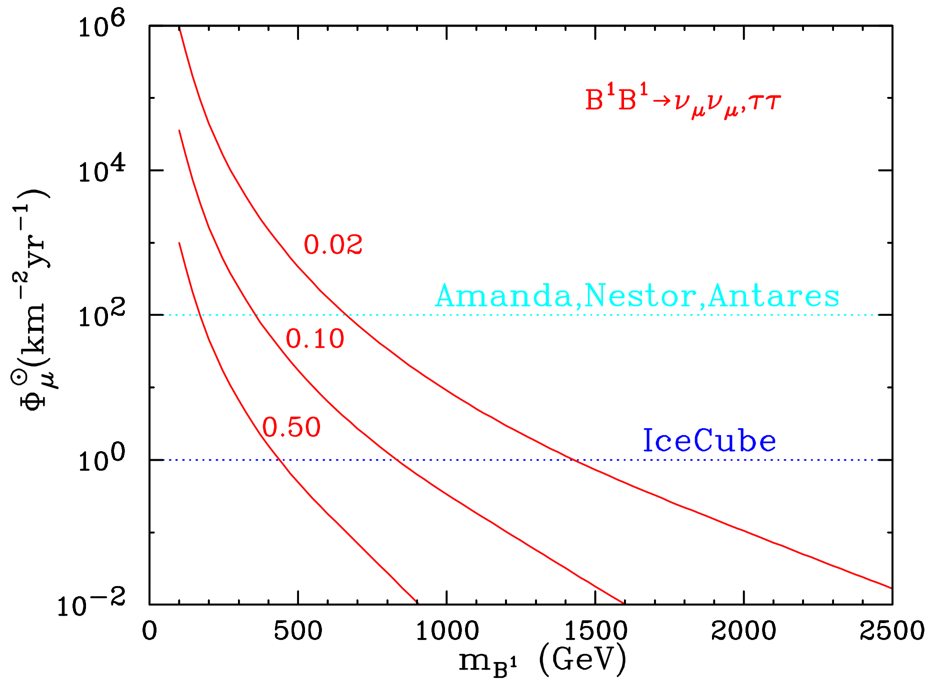
$$B(B^1 B^1 \to \nu_\mu \bar{\nu}_\mu) = 1.2\%$$
$$B(B^1 B^1 \to \ell^+ \ell^-) = 20\% \text{ per generation!}$$



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

KKDM Indirect Detection: Neutrinos

- Discovery reach of neutrino telescopes



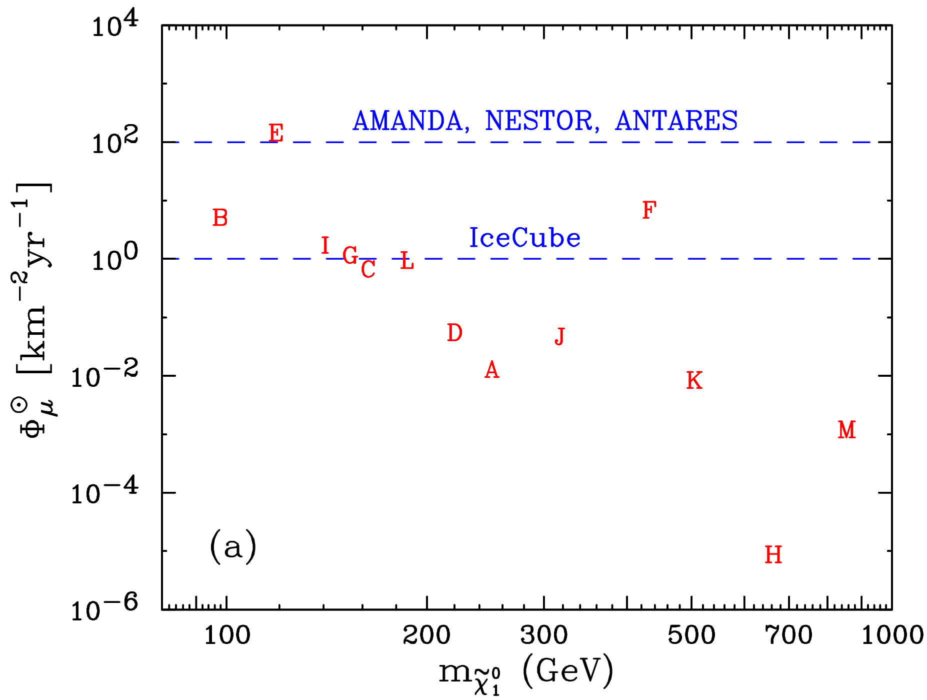
- Conservative estimate:
  - neglecting neutrinos from hadronic final states
  - neglecting $\tau - \mu$ neutrino oscillations

Hooper,Kribs hep-ph/0208261

MSSM: Neutrino signal

- Expectations in supersymmetry:

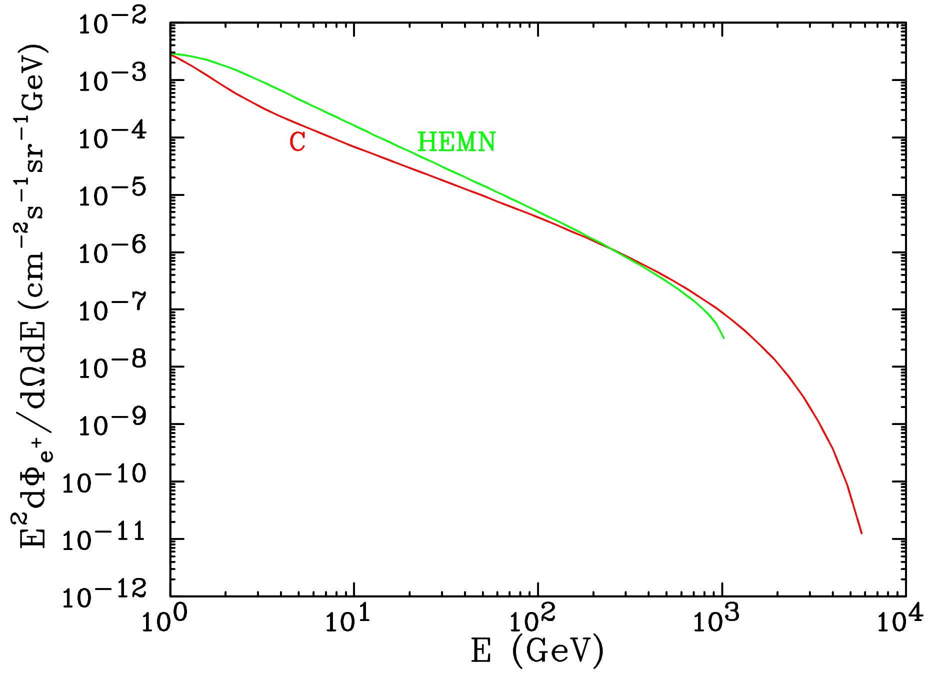
Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- 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:



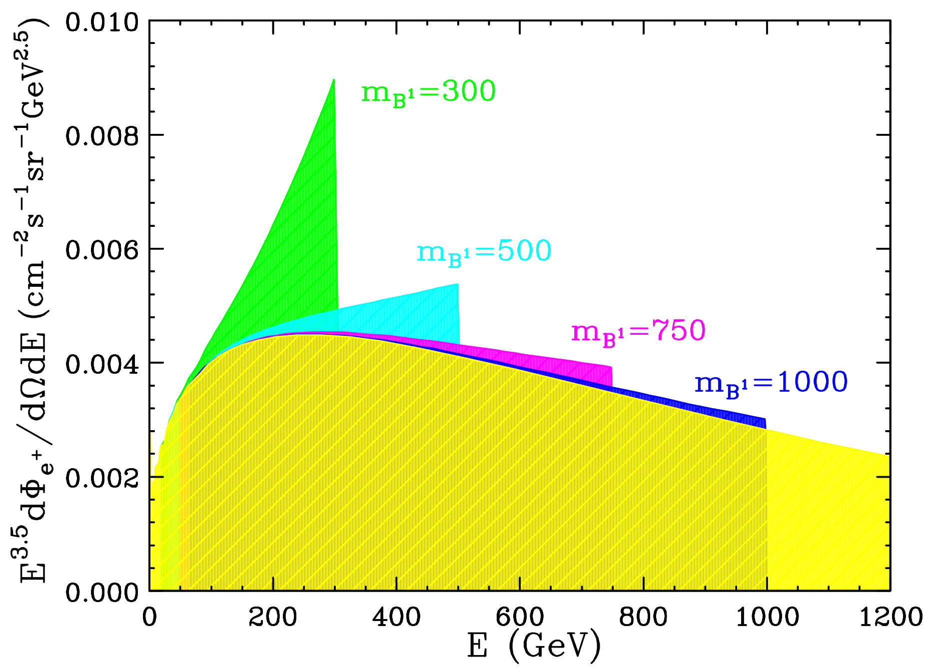
- Unless you see a bump, it is difficult to tell...
- It is easier to see a bump at high E_{e^+}.
- AMS-II will be able to measure high-p_T positrons!

KKDM Indirect Detection: Positrons

- Annihilation into fermion pairs is not helicity suppressed.

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

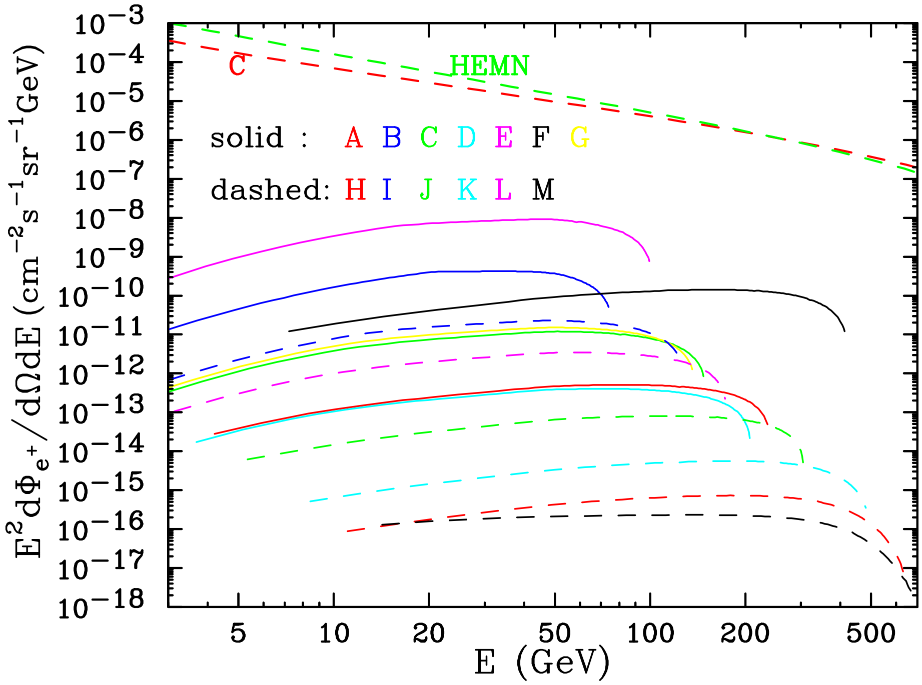
- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.



MSSM: Positron signal

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

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

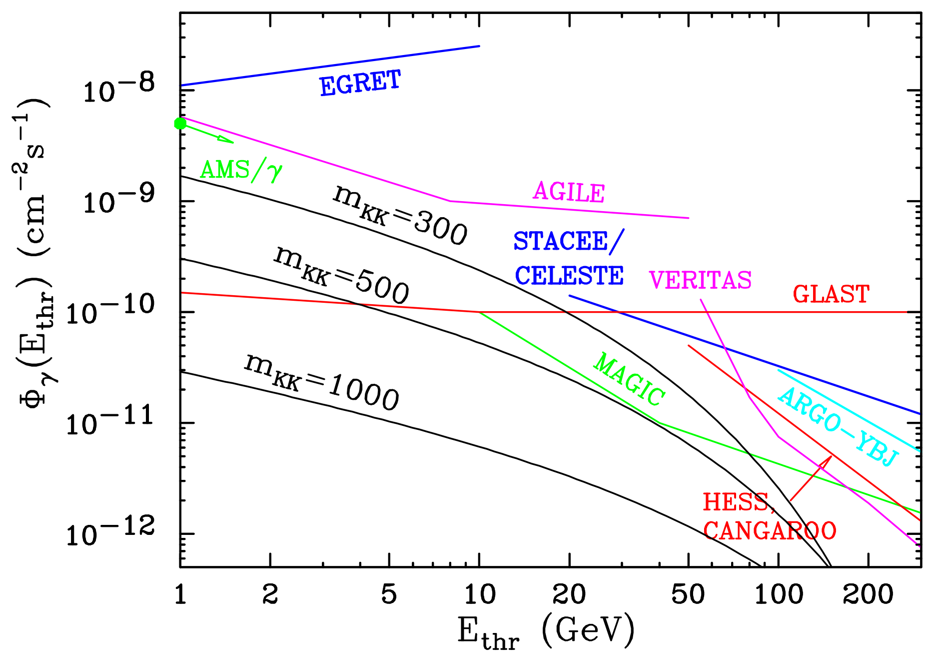


- The signal is typically a small fraction of the background, and the shape is not very characteristic.

KKDM Indirect Detection: Photons - I

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

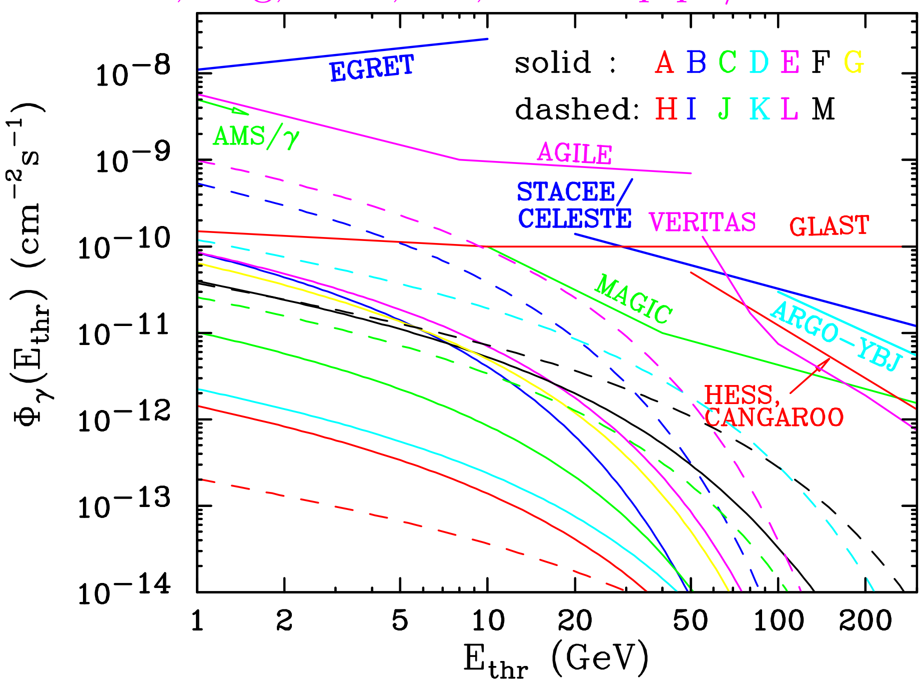
$$\Phi_\gamma(E_{th}) = 5.6 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\, \bar{J}(\Delta\Omega)\, \Delta\Omega$$
$$\times \left[\frac{1\ \mathrm{TeV}}{m_{B^1}}\right]^2 \sum_q \frac{\langle \sigma_{qq} v\rangle}{\mathrm{pb}} \int_{E_{th}}^{m_{B^1}} dE \frac{dN_\gamma^q}{dE}\ .$$



MSSM: Photon signal

- Expectations in supersymmetry

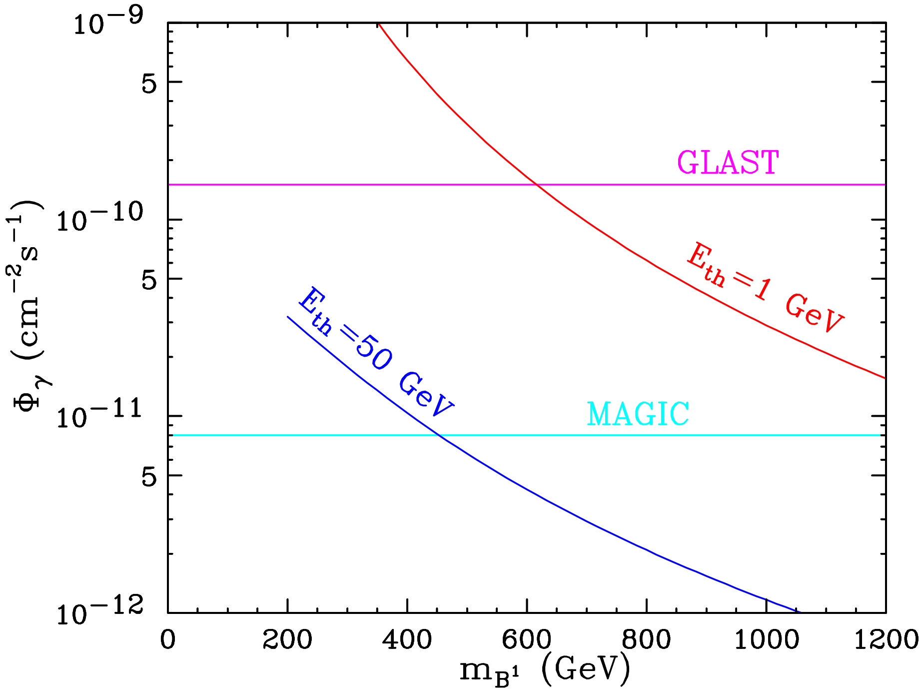
Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- 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 $\Rightarrow$ 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.