Potpourri:
DM and Physics BSM at HE Colliders

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Cast of characters

- Senior personnel
  - K. Matchev (UF, Cornell), (Anton, DOB August 2003)
- Postdocs
  - A. Birkedal (UF, Cornell), (Austin, DOB July 2003)
  - A. Datta (UF), (TBA, EDC April 2004)
- Graduate students
  - K.C. Kong (UF), (TBA, EDC June 2004)
  - C. Group (UF, 0.5 FTE, with R. Field).
- Undergraduate students
  - J. Blender (Cornell), REU student at UF, Summer 2003
  - T. Gleisberg (Dresden), diploma student at UF, Spring 2003.

Dark matter and new physics BSM

- Many motivations for new physics, but... dark matter is our best evidence for new physics BSM: $\Omega_{DM} = 0.23 \pm 0.04$.
- Questions to ask theorists:

  Who is the dark matter in your theory/model
  and can you calculate its relic abundance?

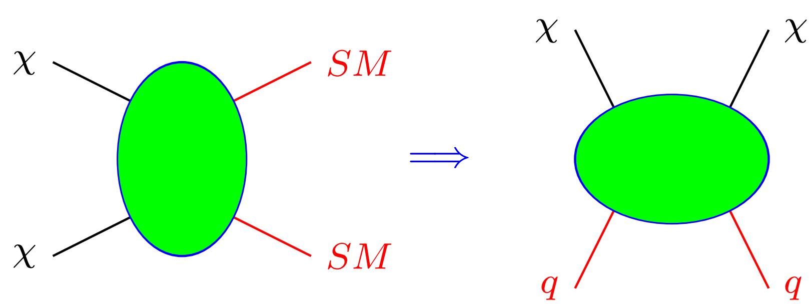
  How can we test this theory at the Tevatron/LHC/NLC?

- WIMPs: motivated by both particle and astrophysics.
  - Predicted in many particle physics scenarios BSM.
  - Give the right order of magnitude Ω_{DM}.

$$\Omega_{DM} h^2 \sim 0.1 \left(\frac{\sigma_{EW}}{\sigma_{ann}} \right)$$

    Is this simply a coincidence?

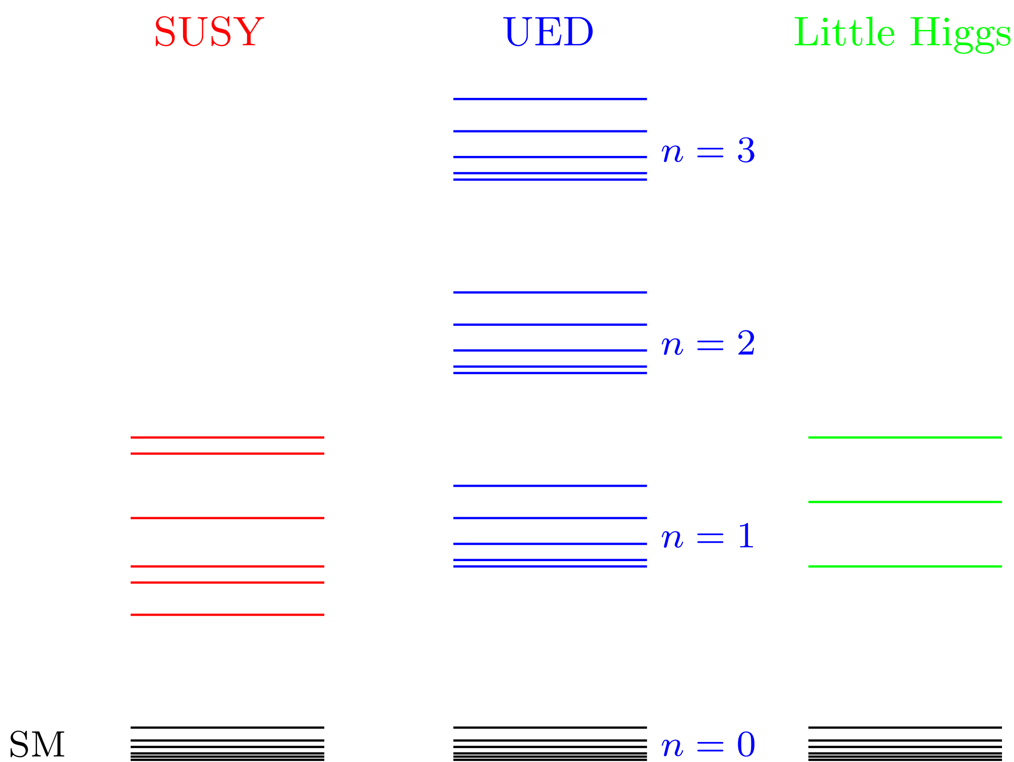
  - Potentially observable signals in DM detection expts.



New physics models with DM WIMPs

- Recipe for BSM dark matter
  - invent a model with new particles
  - invent a symmetry which guarantees a stable new particle
  - fudge parameters until the lightest new stable particle is neutral and has the correct relic density
- Three generic examples of new physics with a DM WIMP
  - supersymmetry: DM = lightest superpartner.
  - extra dimensions: DM = lightest Kaluza-Klein mode.
  - Little Higgs: DM = LPOP, LZOP? (billion, gatesino, ...)
- Intro, discovery prospects
- How can we distinguish the different scenarios?
  - in astroparticle physics experiments
  - at high energy colliders
- How well can we test cosmology at the LHC/NLC?
- What does WMAP say about collider signals?
- Outreach

Model summary



	SUSY	UED	Little Higgs
DM particle	LSP	LKP	LTP
Spin	1/2	1	0
Symmetry	R-parity	KK-parity	T-parity
Mass range	50-200 GeV	600-800 GeV	400-800 GeV

Supersymmetry

- Supersymmetry is an extra dimension theory with new anticommuting coordinates θ_α:

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

- SUSY relates SM particles and their superpartners ($\phi \leftrightarrow \psi$)
  - quarks, leptons $\Leftrightarrow$ squarks, sleptons
  - gauge bosons: g, $W^\pm$, W_3^0, B^0 $\Leftrightarrow$ gauginos: $\tilde{g}$, $\tilde{w}^\pm$, $\tilde{w}^0$, $\tilde{b}^0$
  - Higgs bosons: h^0, H^0, A^0, $H^\pm$ $\Leftrightarrow$ higgsinos: $\tilde{h}^\pm$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)
- Discovering new particles with those properties IS discovering supersymmetry
- The superpartners are charged under a conserved R-parity
  - SM particles: $R = +1$
  - superpartners: $R = -1 \Longrightarrow$ stable LSP (DM?).
- No tree-level contributions to precision EW observables

SUSY WIMPs

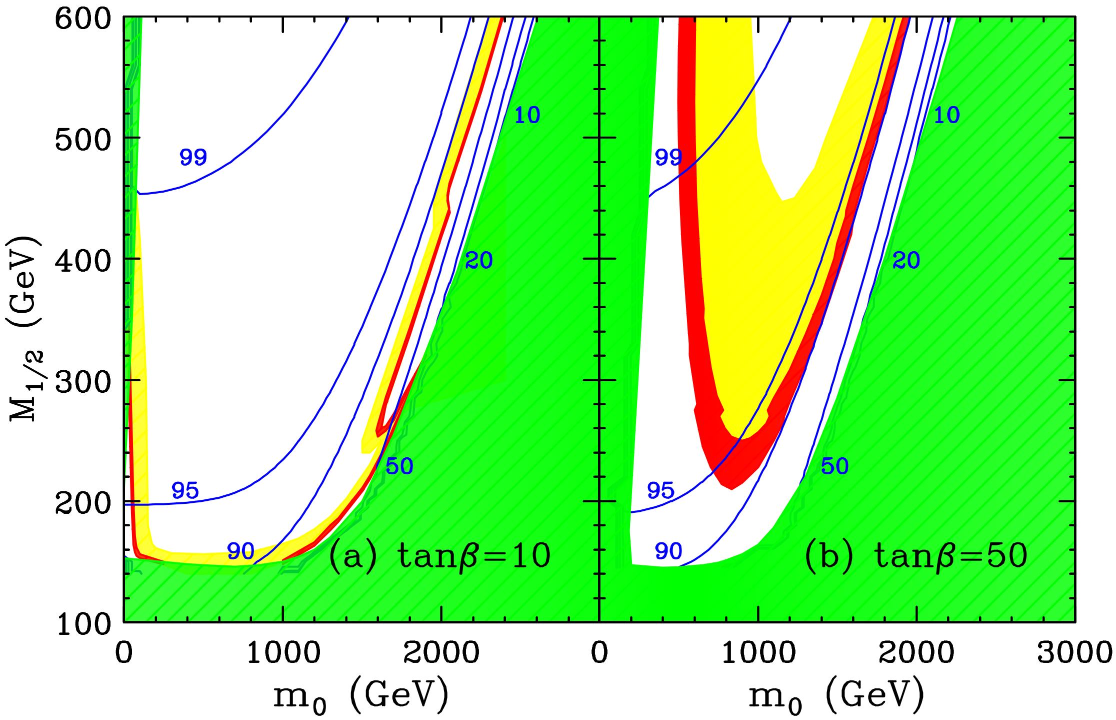
- The lightest neutralino $\tilde{\chi}_1^0$ is a mixture of $\tilde{b}^0$, $\tilde{w}^0$, $\tilde{h}_u^0$, $\tilde{h}_d^0$:

$$\tilde{\chi}_1^0 = a_1\,\tilde{b}^0 + a_2\,\tilde{w}^0 + a_3\,\tilde{h}_u^0 + a_4\,\tilde{h}_d^0$$

- Gaugino fraction R_χ of the LSP:

$$R_\chi \equiv |a_1|^2 + |a_2|^2 \approx |a_1|^2.$$

Feng,KM,Wilczek (2000)



- Focus point region: large m_0, mixed LSP.
- Coannihilation region: small m_0, $\tilde{\tau} - \tilde{\chi}_1^0$ degeneracy.

Universal Extra Dimensions

Appelquist, Cheng, Dobrescu, hep-ph/0012100

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

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

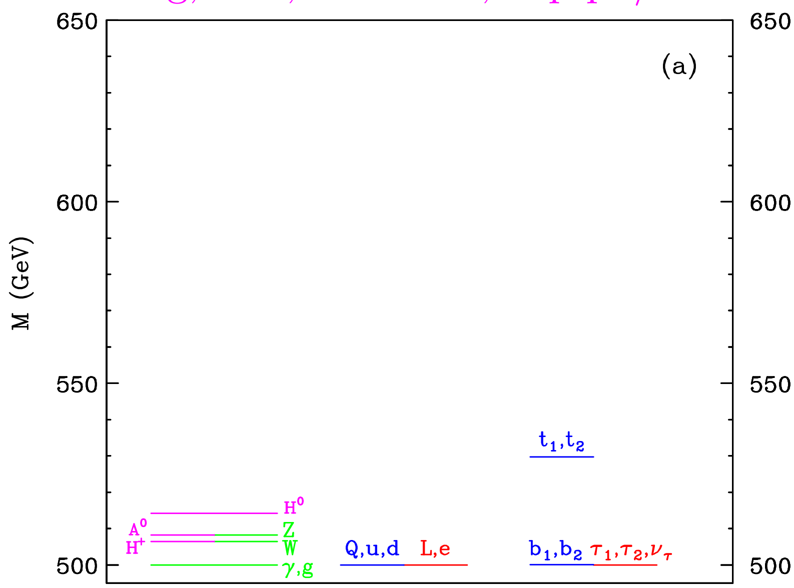
- Each SM field ϕ ($n = 0$) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with
  - identical spins
  - identical couplings
  - unknown masses of order n/R
- Remnant of p_5 conservation: KK-parity $(-1)^n$
  - $KK = +1$ for even n and $KK = -1$ for odd n.
  - lightest KK partner at level 1 (LKP) is stable.
    $P_3 \to P_3' P_0, P_2 P_1, P_1 P_0$;
    $P_2 \to P_2' P_0, P_1 P_1, P_0 P_0$;
    $P_1 \to P_1' P_0$.
- No tree-level contributions to precision EW observables

UED Spectrum - Tree level

- The KK modes at each KK level n are extremely degenerate:

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

Cheng, KM, Schmaltz, hep-ph/0204342



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

$$e_1 \longrightarrow \gamma_1 e_0?$$

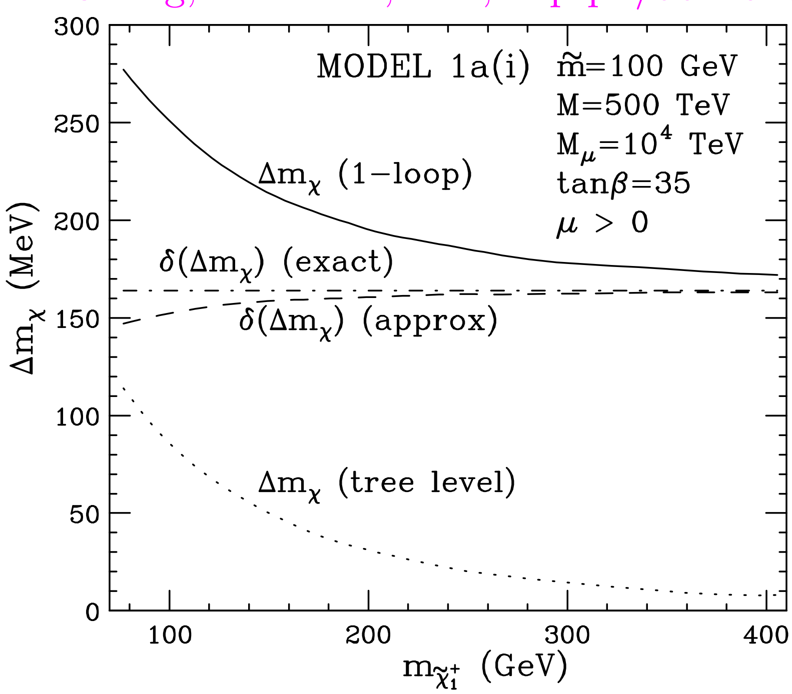
$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1}\left(\frac{m_e}{R^{-1}}\right) \sim -R^{-1}10^{-6}$$

- Lots of stable (charged, colored) heavy particles...

Impact of radiative corrections on discovery signatures

- Higgs searches
  - $gg \to h$, $h \to \gamma\gamma$ at LHC.
  - m_h, λ_b corrections in MSSM.
- Anomaly mediation (wino mass splitting determines charged wino lifetime)

Cheng, Dobrescu, KM, hep-ph/9811316

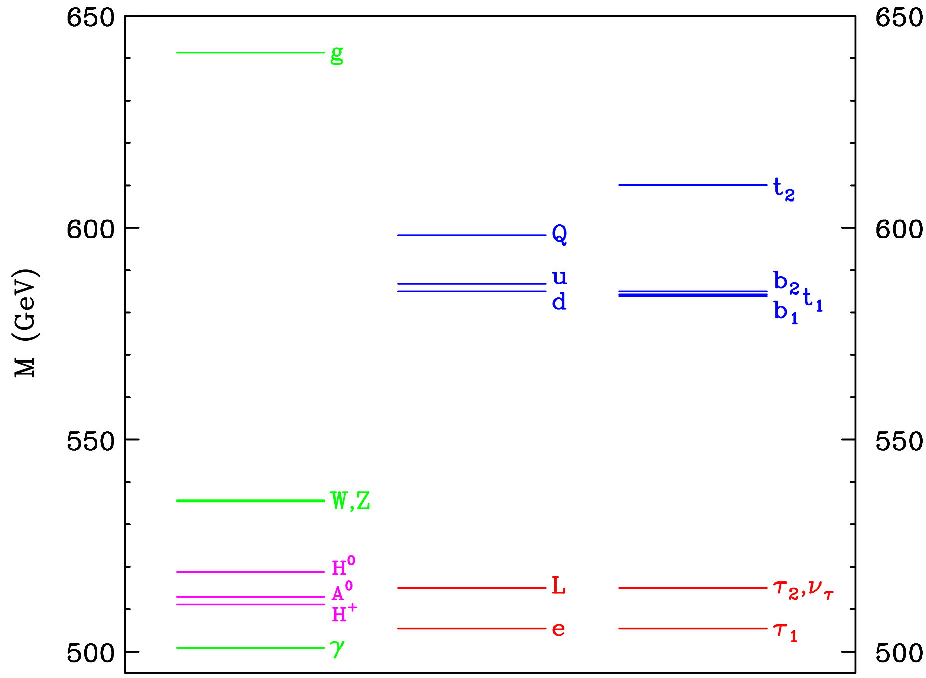


- Universal extra dimensions

UED spectrum at 1 loop

- Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this:

Cheng, KM, Schmaltz, hep-ph/0204342



- Mimics supersymmetry: prompt decays!
- Seems difficult to discover at the LHC, but...
- $W_1^\pm$, Z_1 have pure leptonic branchings!
- $\sin^2\theta_W^1 \approx 0 \Longrightarrow \gamma^1 \approx B^1$, similar to $\tilde{B}$ in SUSY.

The KK Weinberg angles

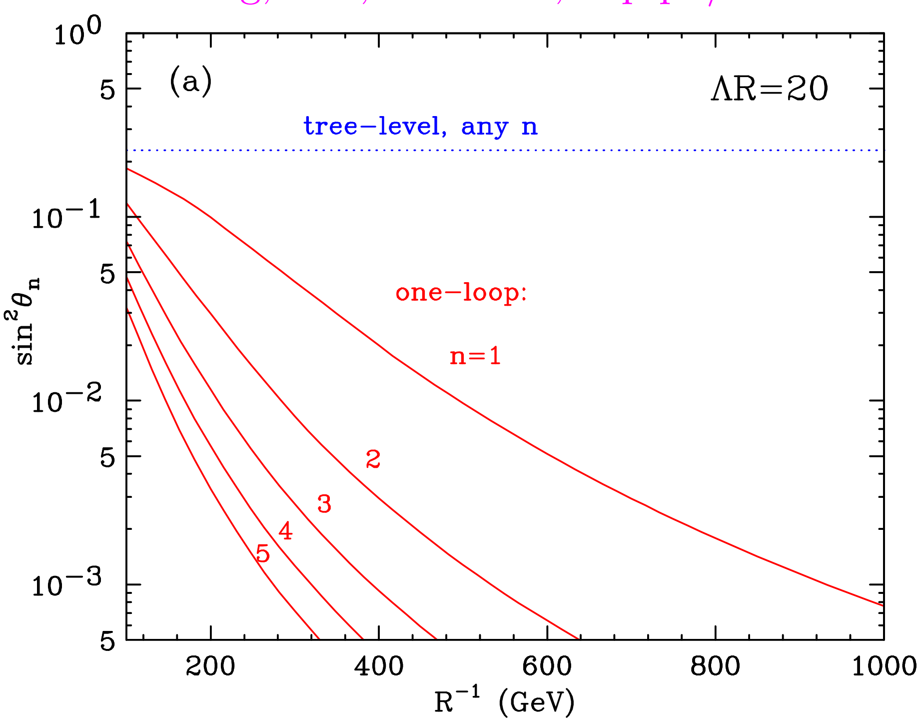
- Mass matrix for the neutral gauge bosons

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

- The Weinberg angle θ_n at KK level n

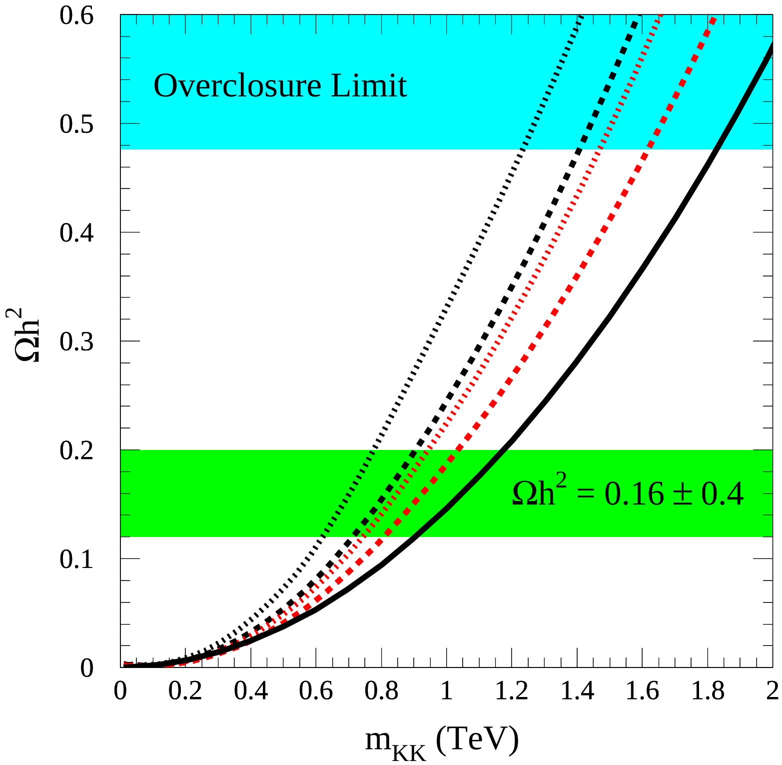
$$\gamma_n = \cos\theta_n B_n^0 + \sin\theta_n W_n^0 \approx B_n^0 .$$

Cheng, KM, Schmaltz, hep-ph/0204342



KK dark matter relic density

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



- Unlike supersymmetry: no helicity suppression

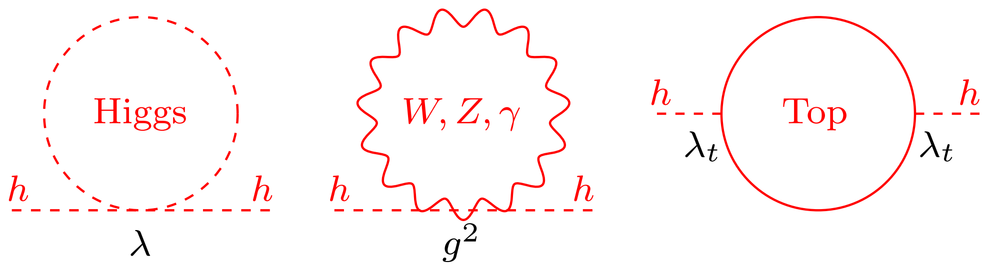
$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P\sqrt{g_*}}\frac{x_F}{a+3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

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

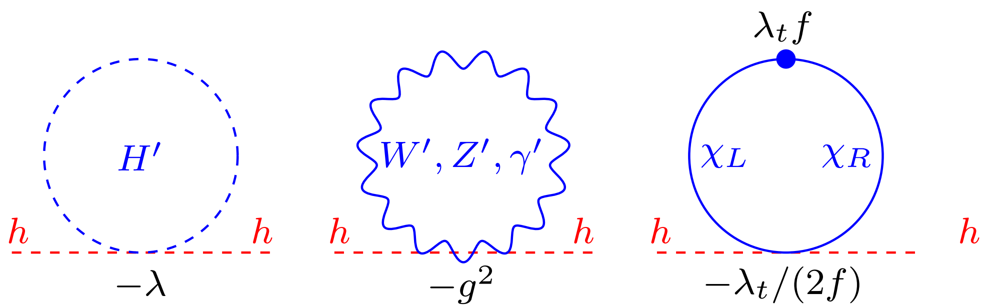
- Unlike supersymmetry: coannihilation lowers the bound

Little Higgs models

- The hierarchy problem in the SM



- Introduce new particles at TeV scale to cancel the one-loop quadratic divergences



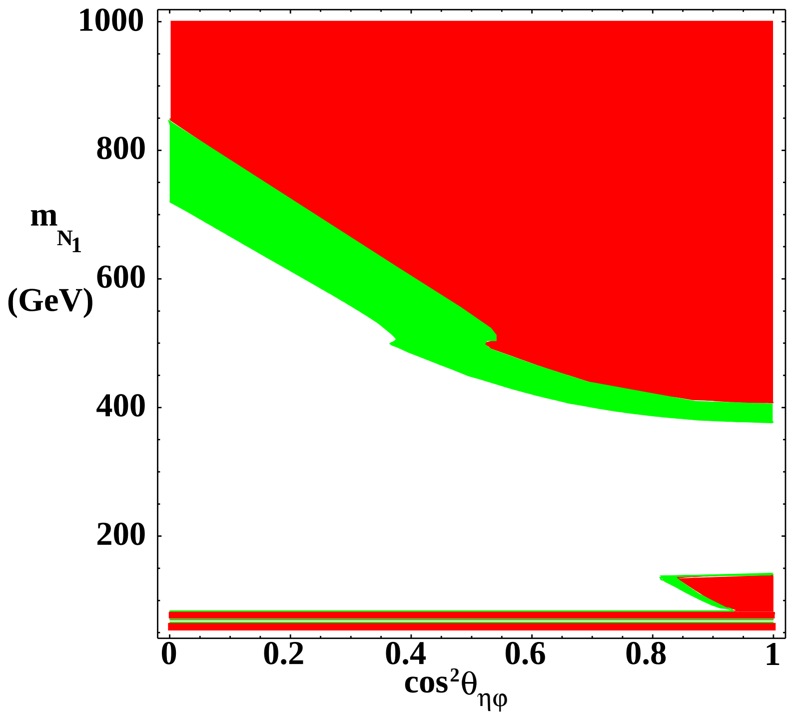
- Conserved T-parity (Cheng, Low hep-ph/0308199)
  - $T = +1$ for SM particles, $T = -1$ for new particles.
  - the lightest T-odd particle is stable.
- No tree-level contributions to precision EW observables

Relic density in LH models

- If the lightest T-odd particle is a scalar, it can be a mixture of an SU(2)-triplet $\phi^0_{\mathbf{3}}$ and an SU(2)-singlet $\eta^0_{\mathbf{1}}$:

$$N_1 = \cos\theta_{\eta\phi}\,\eta^0_{\mathbf{1}} + \sin\theta_{\eta\phi}\,\phi^0_{\mathbf{3}}$$

Birkedal-Hansen, Wacker hep-ph/0306161

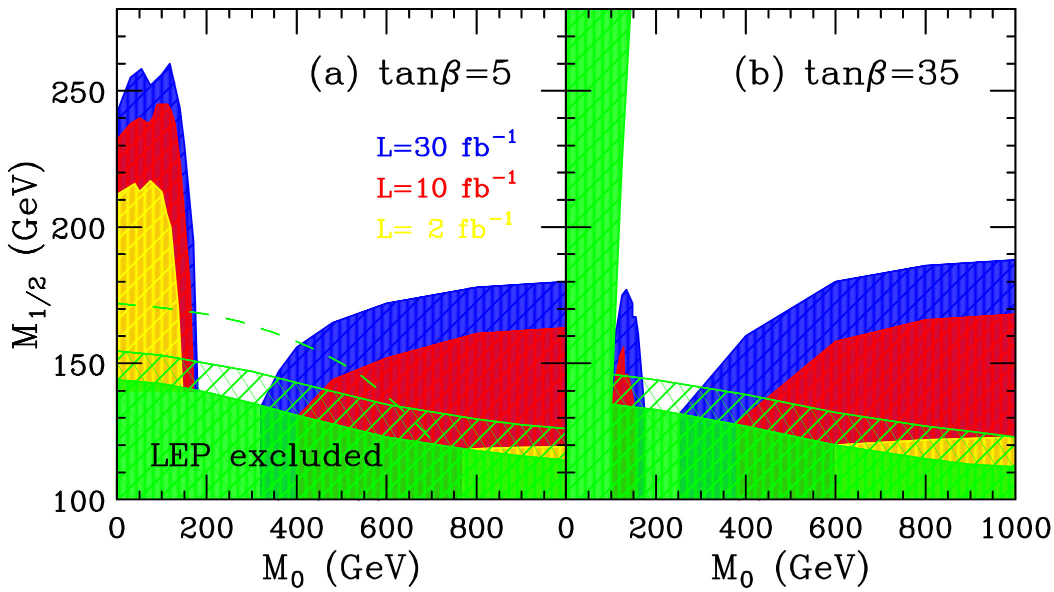


- The absence of helicity suppression requires large masses for the WIMP case.
- For 150 GeV $< m_{N_1} <$ 350 GeV, annihilation into $t\bar{t}$ and hh is very efficient.

SUSY discovery reach at colliders

- The estimated Tevatron trilepton leach in Run II

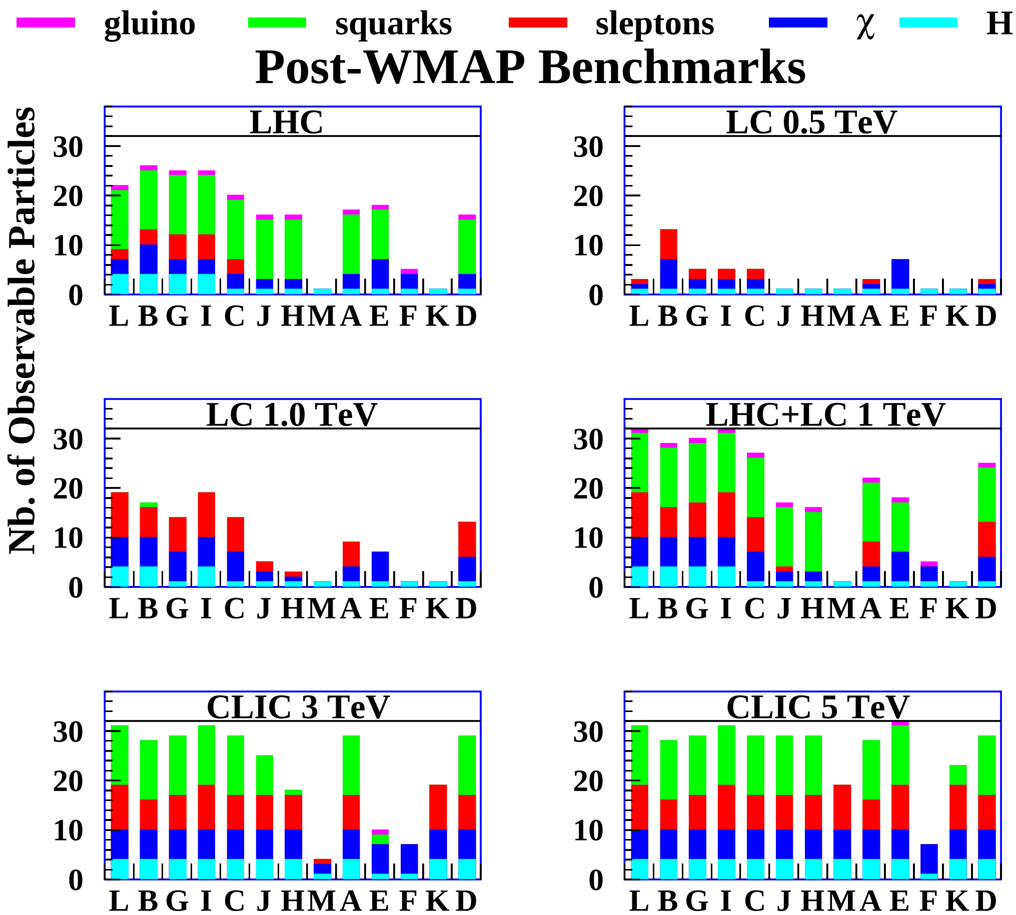
KM, D.Pierce (1999)



- When do we know we have seen supersymmetry?
  - Many superpartners: can we count squark, slepton species?
  - Spins?
  - Couplings? $\sigma \times BR$, confusion, PDF uncertainty...

Sparticle count

Battaglia et al., hep-ph/0306219



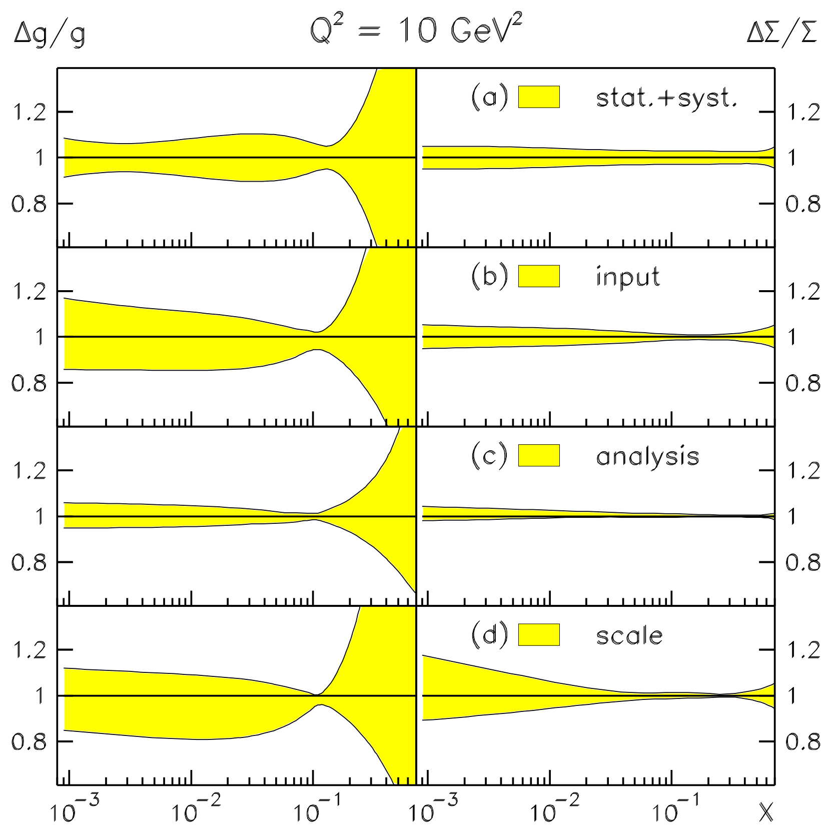
- Squarks are difficult to count:
  - can be mistaken for gluinos
  - $\tilde{q}_R$ decays mostly give jets
  - Many more 1st gen. $\tilde{q}$'s than 2nd gen. $\tilde{q}$'s.

Outreach I: PDF uncertainties

Bourilkov,Group,KM 2004

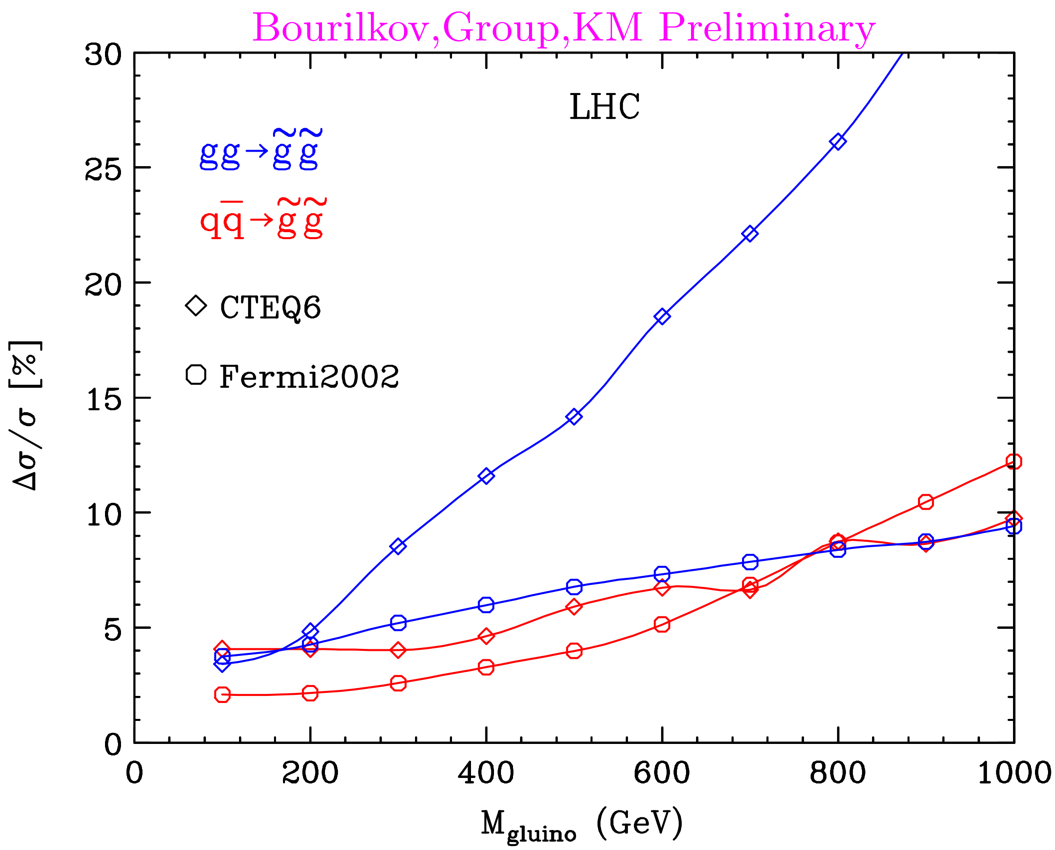
- The LHAPDF interface is designed to work with pdf sets
  - Fermi2002 (100) (Giele,Keller,Kosower)
  - CTEQ6 (40) (Pumplin et al, hep-ph/0201195)
- LHAPDF has been interfaced with PYTHIA 6.2 and HERWIG
- 100k events per pdf member on the UF CMS PC farm.

Botje, hep-ph/9912439



PDF uncertainties: gluino production

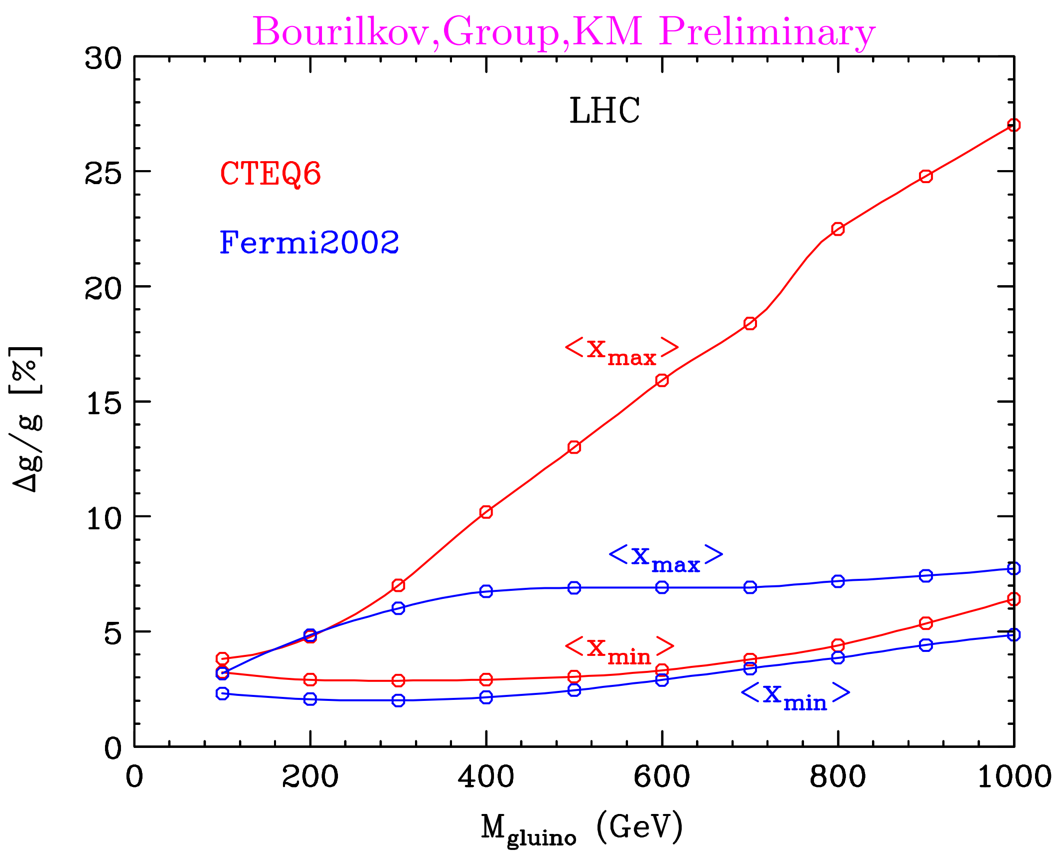
- Example: gluino production at the LHC



- $q\bar{q} \rightarrow \tilde{g}\tilde{g}$ agree (sort of)
- Large discrepancy in $gg \rightarrow \tilde{g}\tilde{g}$ (?)

PDF uncertainties: CTEQ6 vs Fermi

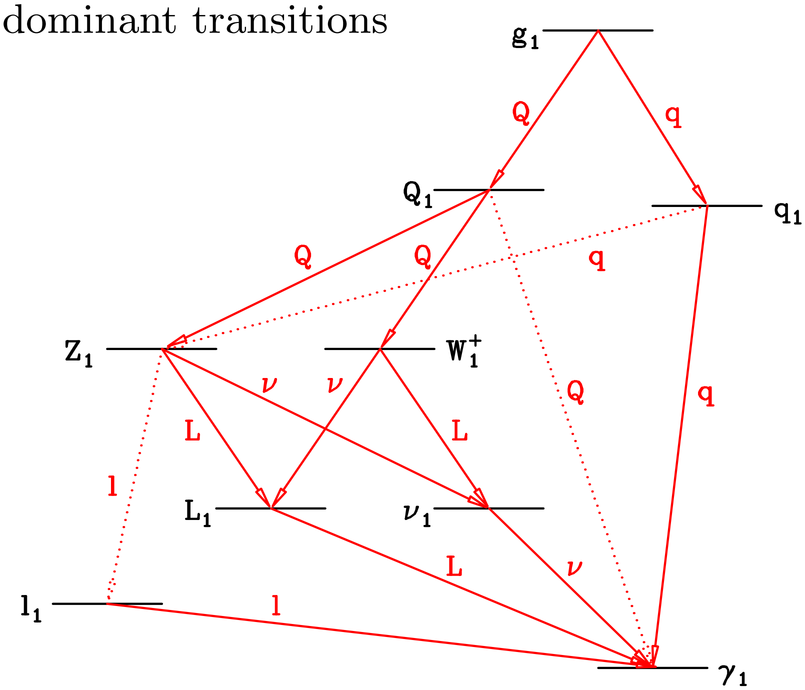
- Compare the PDF uncertainties at typical values of $x_{max} = max\{x_1, x_2\}$ and $x_{min} = min\{x_1, x_2\}$.
- Averages: $0.01 < \langle x_{min} \rangle < 0.1$ and $0.1 < \langle x_{max} \rangle < 0.3$



- Goal: estimate PDF uncertainties in Higgs and sparticle production at the Tevatron and the LHC.

Collider phenomenology of UED

- Allowed dominant transitions



- 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: preferentially $q_1 \to \gamma_1 q_0$
- Doublet KK quarks:

$$B(Q_1 \to W_1^{\pm} Q_0') \sim 65\% \qquad B(Q_1 \to Z_1 Q_0) \sim 33\%$$

- KK W- and Z-bosons: only leptonic decays!
- KK leptons: 100% directly to the LKP.

- At hadron colliders we want: strong production, weak decays!

UED signature: $4\ell \not{E}_T$

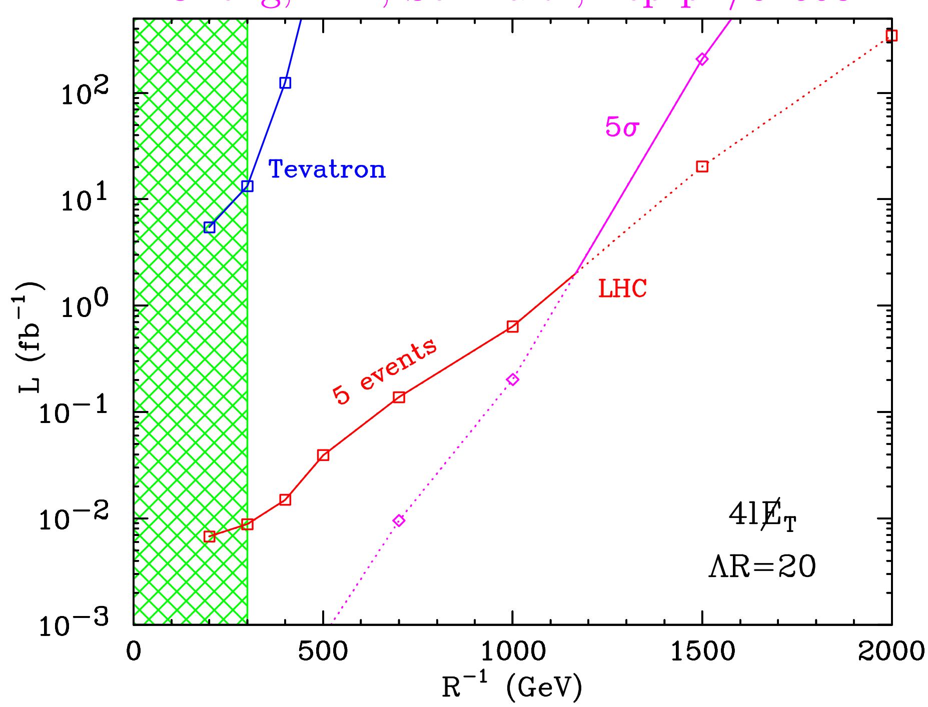
- Arises from inclusive $Q_1 Q_1$ production: $Q_1 \to Z_1 \to \ell^\pm \ell^\mp \gamma_1$
- Tevatron triggers
  - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
  - Missing energy $\not{E}_T > 40$ GeV.
- Tevatron cuts
  - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 30$ 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.
- LHC 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.
- LHC backgrounds: multi-boson, ttZ, fakes, etc.

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

UED discovery reach at the Tevatron and LHC

- Discovery reach in the $Q_1 Q_1 \to 4\ell \not{E}_T$ channel.

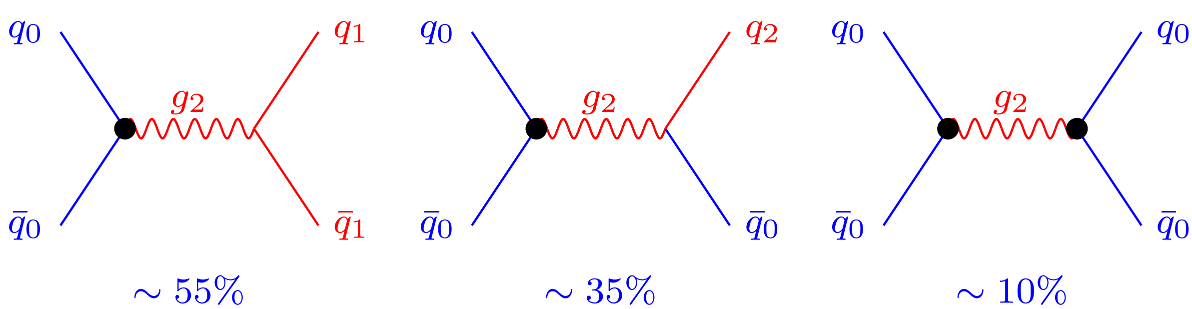
Cheng, KM, Schmaltz, hep-ph/0205314



- Typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (LHC can't measure it)
- $B(Q_1 \to 2\ell \not{E}_T + X) \sim \frac{1}{9}$. In principle, channels with W_1's can also be used – less leptons, but more often.

Bosonic or fermionic supersymmetry?

- Can you tell SUSY from UED?
- Yes. Tenth Conference on String Phenomenology in 2011.
  J.Ellis hep-ph/0208109
- Look for the higher KK levels: e.g. g_2 resonance.
- Single production of KK level 2 is suppressed (involves KK-number violating couplings).

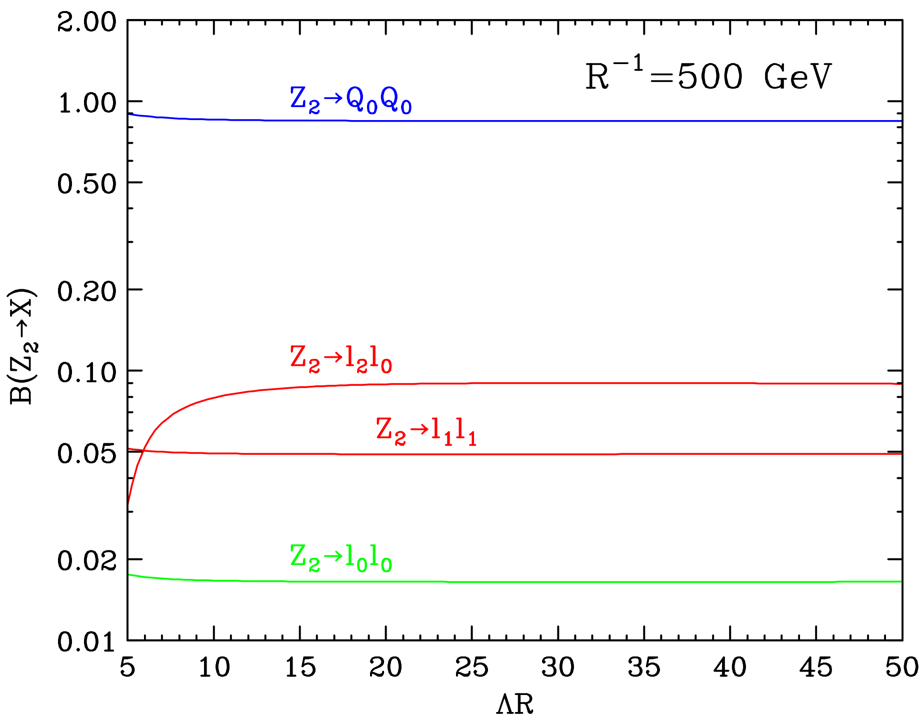


- g_2 appears a high mass dijet resonance. Z'?
- Pair production? Typically the rate is too small.

Looking for KK level 2: Z_2 resonance

- Z_2 appears promising: $Z_2 \to Q_1 Q_1$ and $Z_2 \to Q_2 Q_0$ are closed. Lots of hard leptons? No! $Z_2 \to Q_0 Q_0$ wins over $Z_2 \to \ell_0 \ell_0$.
- Z_2 branching fractions:

Datta,Kong,KM preliminary



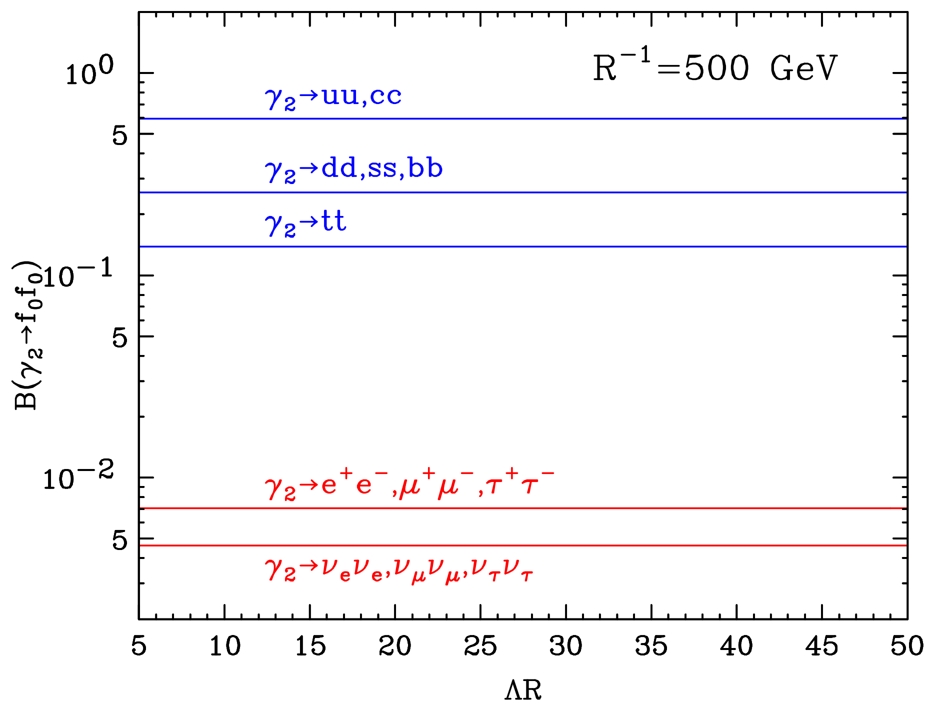
- Z_2 also a high mass dijet resonance. Z'? g_2?
- Z_2 may also appear as a dilepton resonance, but $B(Z_2 \to \ell^+ \ell^-) \sim 1\%$.

Looking for KK level 2: γ_2 resonance

- γ_2 appears most promising. All $\gamma_2 \to f_2 f_0$ and $\gamma_2 \to f_1 f_1$ decays are closed. Every γ_2 decay dumps a lot of energy.

- γ_2 branching fractions:

Datta,Kong,KM (preliminary)



- γ_2 also a high mass dijet resonance. Z'? g_2? Z_2?

- In all cases the natural width is negligible compared to the detector dijet mass resolution.

LHC reach for level 2 KK modes

- Inclusive search for high-mass dijet/dilepton resonances
- Recycle existing LHC analyses for Z' searches
- Rescale the background to account for the narrow width
- Reach for R^{-1} in GeV, assuming 100 fb^{-1}

KK mode	jj	$\mu^+\mu^-$	e^+e^-
g_2	350	NA	NA
Z_2	worse	350	400
γ_2	worse	350	400

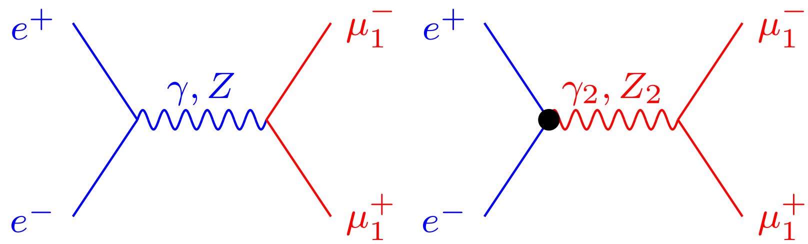
- Can we discriminate the Z_2 and γ_2 resonances?
- Confusion: Supersymmetry plus one or more Z'?

UED implementation in COMPHEP

- Why COMPHEP?
  - Spin correlations accounted for.
  - Automated: ideal for new models which are straightforward generalizations of the Standard Model (UED, little Higgs).
  - Once the Feynman rules are defined, any final state signature can be studied.
  - It already has SUSY.
  - It is interfaced to PYTHIA.
  - The experimentalists know how to deal with it.
- What we have done so far:
  - Level 1 is fully implemented with correct 1-loop masses. Approximation: $Z_1 \approx W_1^3$, $\gamma_1 \approx B_1$. Widths: reasonable guess, but can be recalculated with COMPHEP.
  - Level 2 fully implemented ($Z_2 \approx W_2^3$, $\gamma_2 \approx B_2$, ℓ_2) with the correct widths.

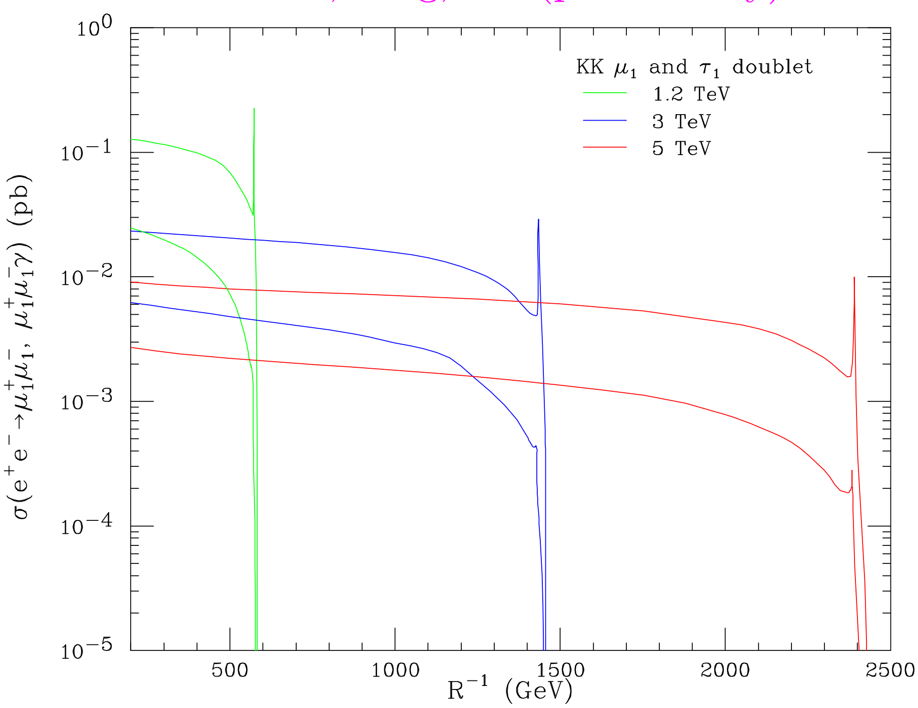
UED phenomenology: Lepton colliders

- The importance of the level 2 widths.



- Comparative study of SUSY and UED at LCs under way.

Datta,Kong,KM (preliminary)



SUSY versus UED at a LC

- The spin information is encoded in the angular distributions!

SUSY

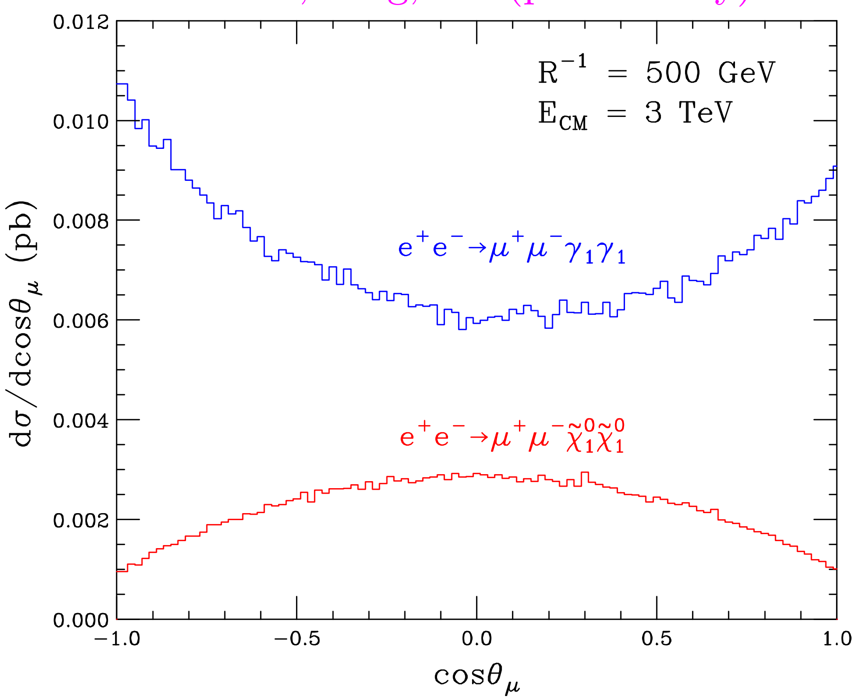
$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

UED

$$e^+e^- \to \mu_1^+\mu_1^- \to \mu^+\mu^-\gamma_1\gamma_1$$

$$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos\theta^2 \qquad \frac{d\sigma}{d\cos\theta} \sim 1 + \cos\theta^2$$

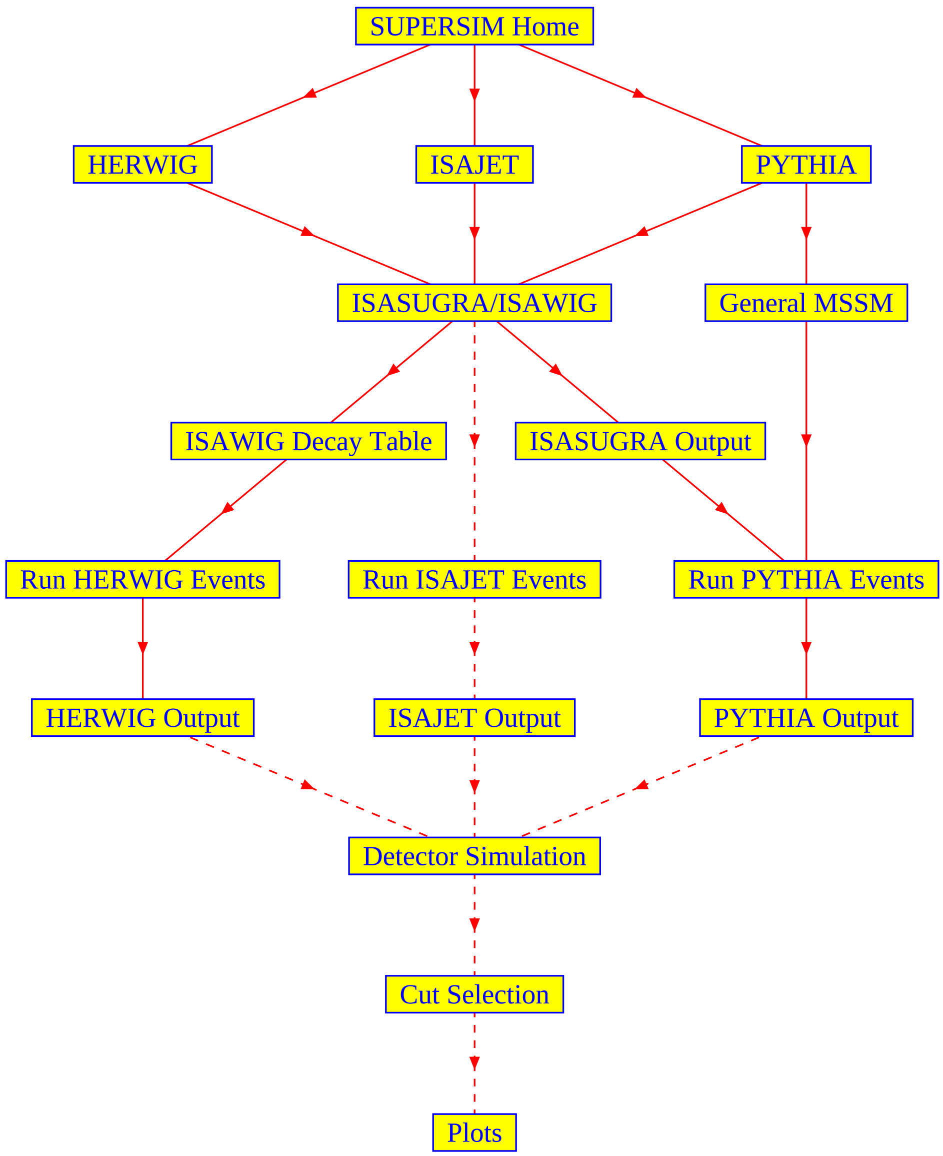
Datta,Kong,KM (preliminary)



- Significant difference in the total cross-section as well!
- The masses can be extracted from the E_μ distribution.
- Threshold scan would confirm the spins.

Outreach II: event generators online

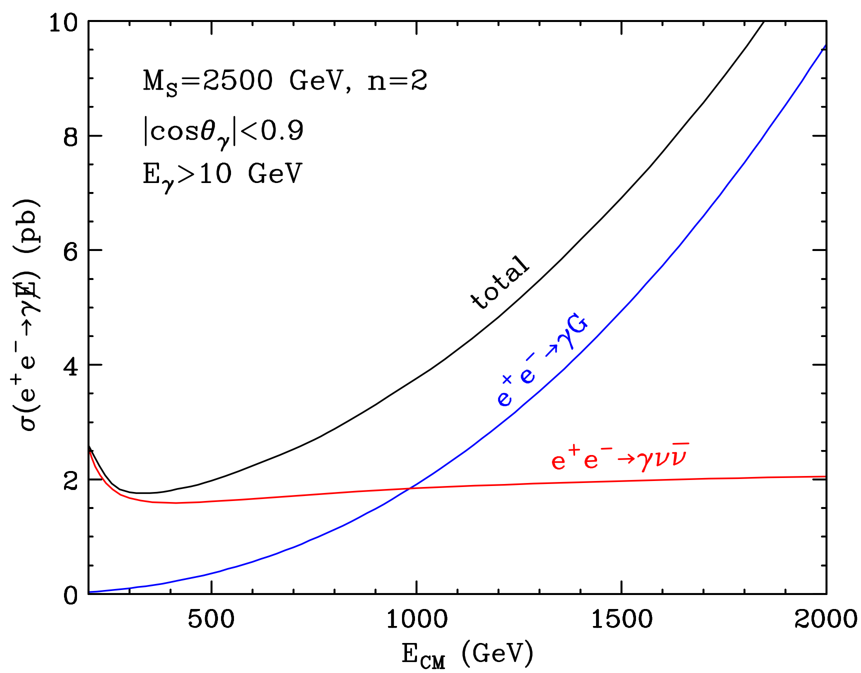
- SUPERSIM flow chart (Blender,Group,KM)



Outreach III: ADD in AMEGIC++

- Run I: bootleg version of PYTHIA with real graviton production added as an external process (Lykken,KM, 1999)
- The full ADD model recently implemented in AMEGIC++.
  - Real graviton production
  - Virtual exchange (3 conventions)
  - New Feynman rules included

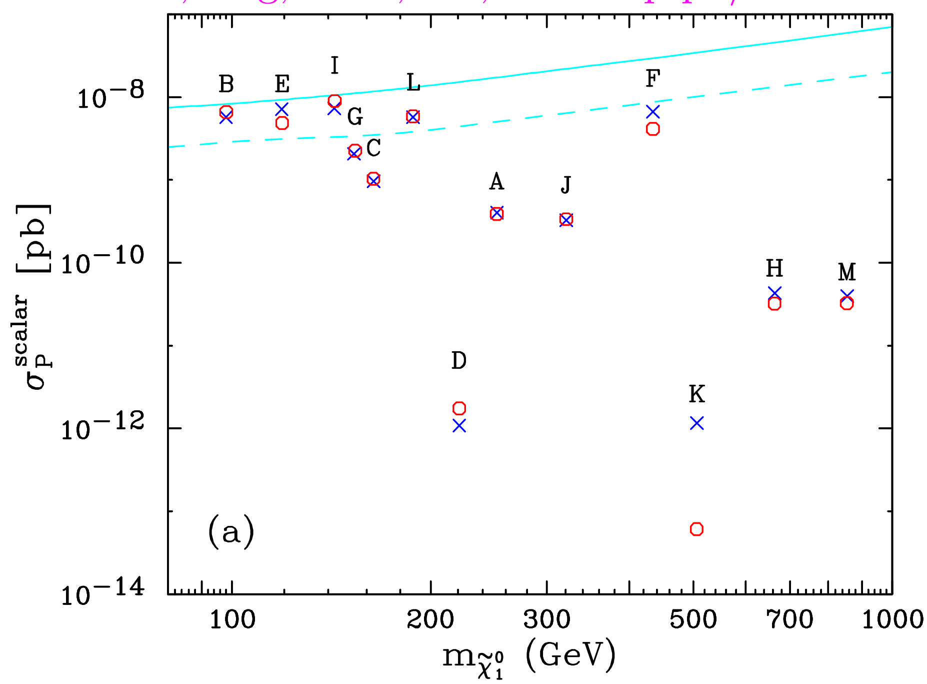
Gleisberg,Krauss,KM,... hep-ph/0306182



SUSY DM: direct detection

- 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.

SUSY DM: direct detection

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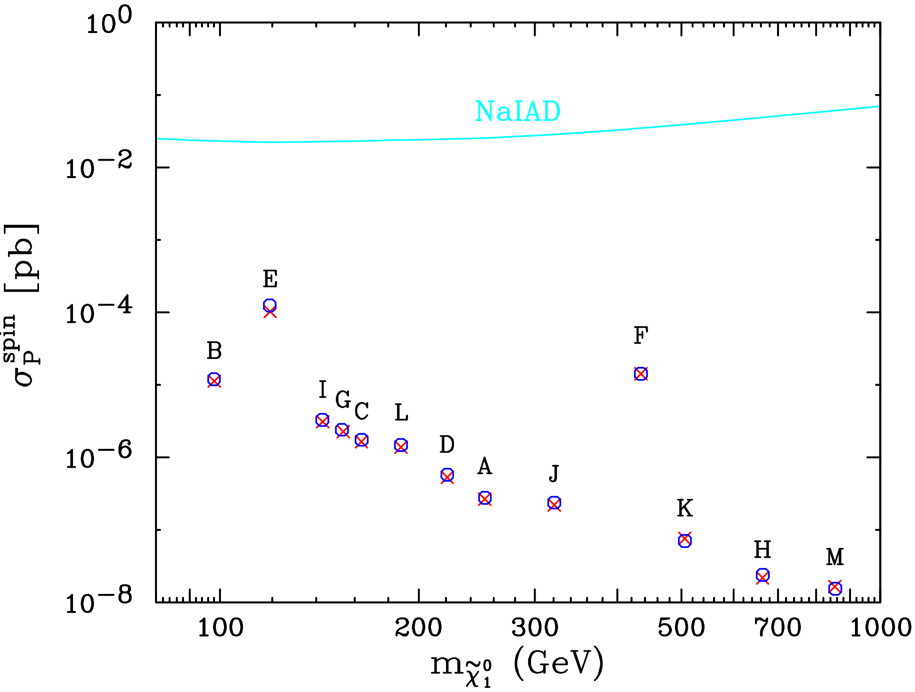
Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225

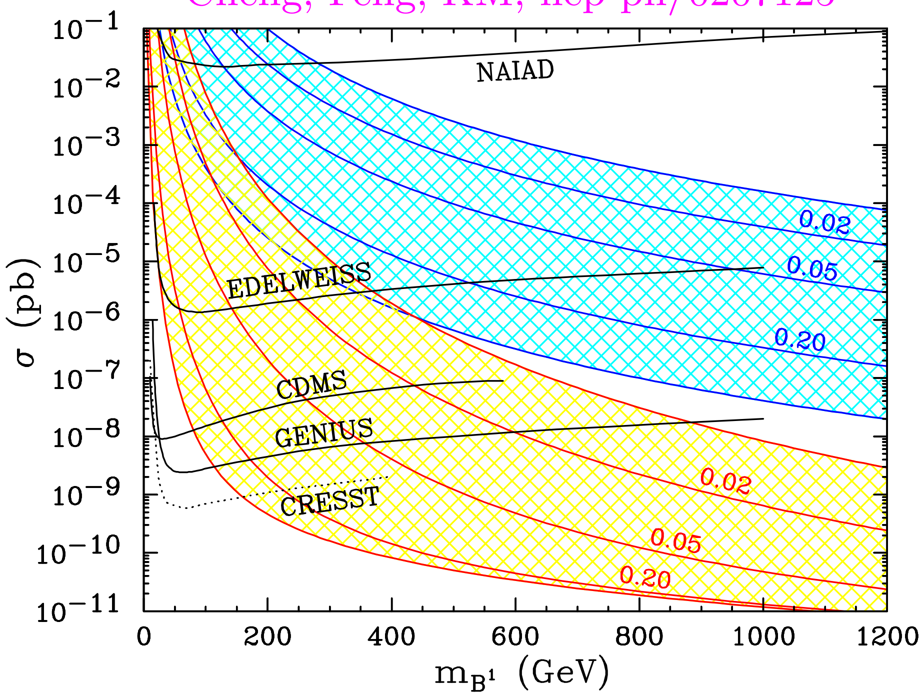


- Far below sensitivity of near-term future experiments.

KK DM: direct detection

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

Cheng, Feng, KM, hep-ph/0207125



- The signals are enhanced near the s-channel resonance:

$\sigma \sim (m_{q^1} - m_{B^1})^{-2}$. Unnatural in SUSY, guaranteed here.

Cheng, Feng, KM, hep-ph/0207125

Servant, Tait, hep-ph/0209262

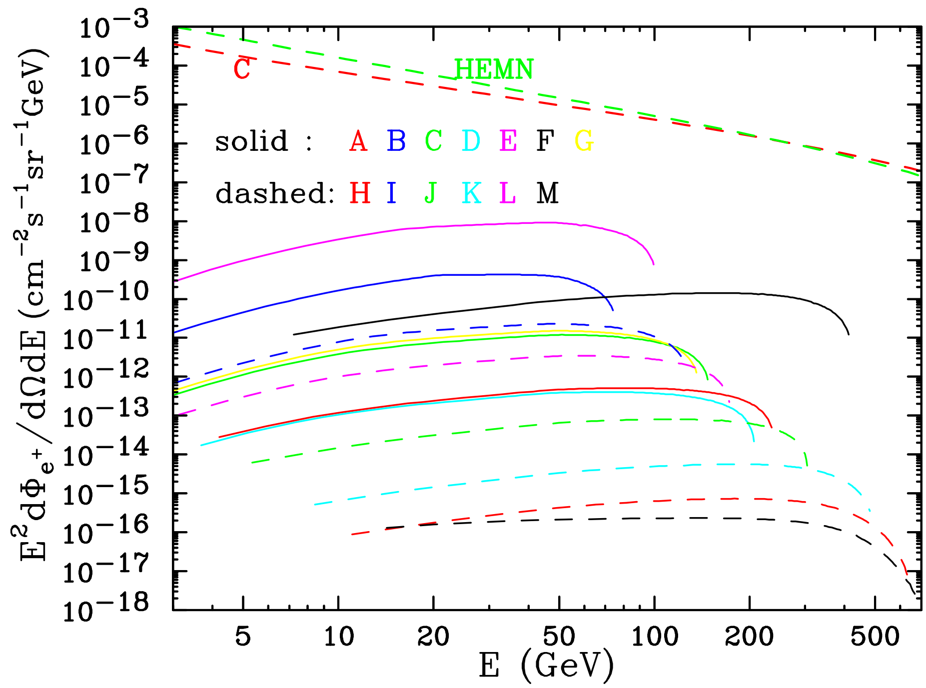
Majumdar, hep-ph/0209277

- Constructive interference: lower bound!

MSSM: Positron signal

- Both the shape and the normalization of the background are uncertain:
- Hard positrons come from $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to WW$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to ZZ$.

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



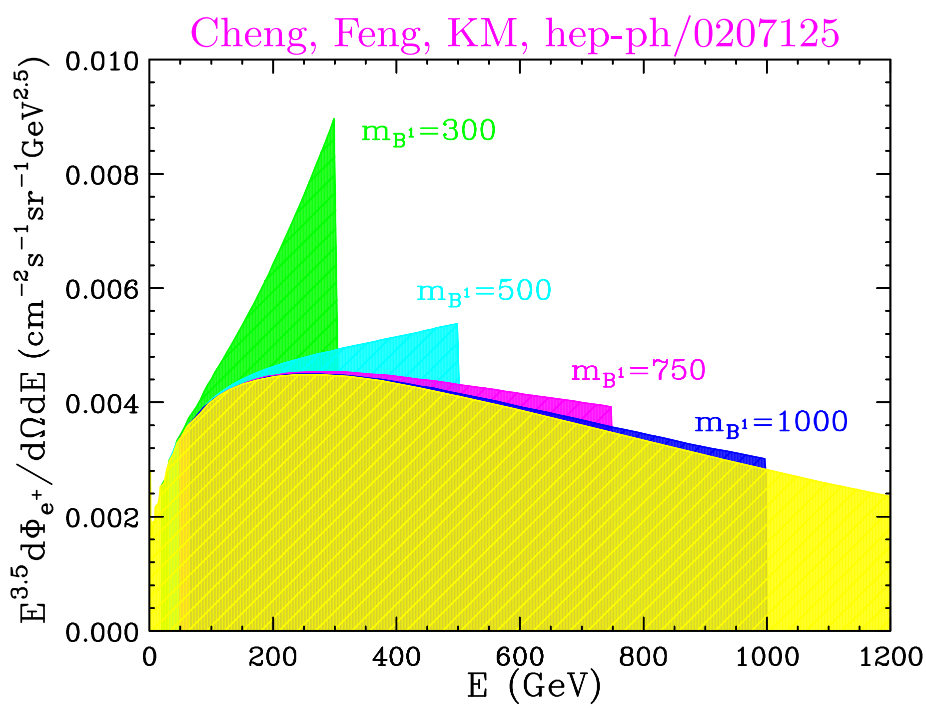
- The signal is typically a small fraction of the background, and the shape is not very characteristic.

KKDM Indirect Detection: Positrons

- Annihilation into fermion pairs is not helicity suppressed.

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

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



- AMS-II will be able to measure high-p_T positrons!

Can we test cosmology at the LHC/NLC?

- LCWG: Connections to Astrophysics and Cosmology (2003)
- The charge:
  - Assume the LHC has already "discovered" SUSY and performed the expected measurements of SUSY masses etc.
  - How well can we predict the neutralino relic density based on the LHC results?
  - How much do we benefit from the NLC?
- Our approach: (Birkedal,KM 2004)
  - What are the relevant model parameters?
  - How well can the LHC and NLC determine those?
  - What is the expected uncertainty in $\Omega_{DM} h^2$?
- We necessarily have to choose a model (benchmark point)

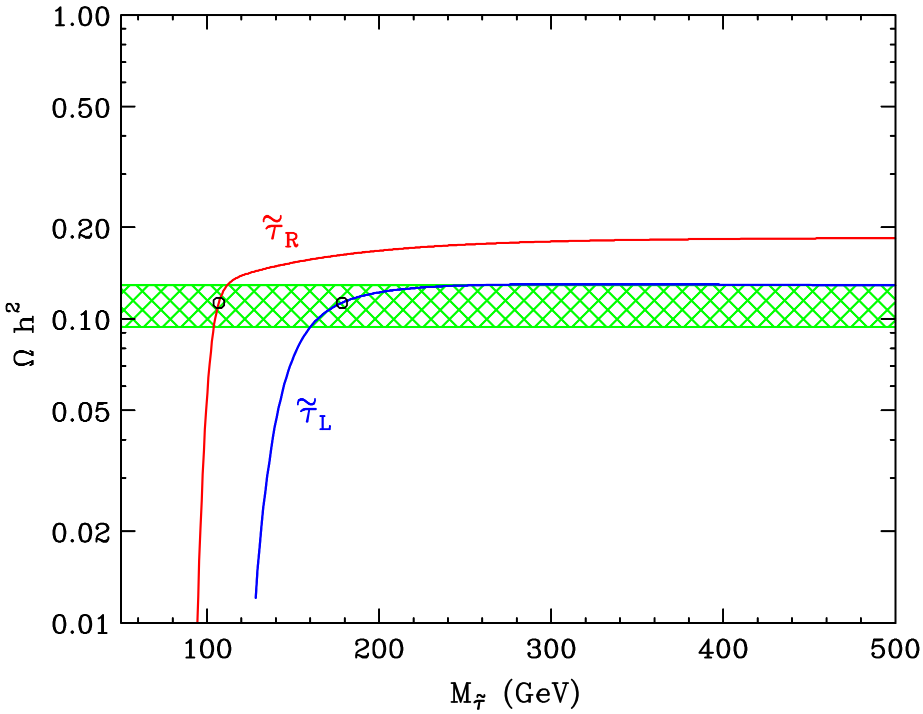
point B: $m_0 = 57$, $M_{1/2} = 250$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

  - Typical for any benchmark set
  - Similar points discussed in the LHC literature

What are the relevant parameters?

- Point B: neutralinos annihilate through t-channel sfermion exchange. Need to measure squark, slepton masses.
- Squarks are heavy $\Longrightarrow$ small effect on Ωh^2
- Right-handed sleptons are most important:

Birkedal,KM Preliminary

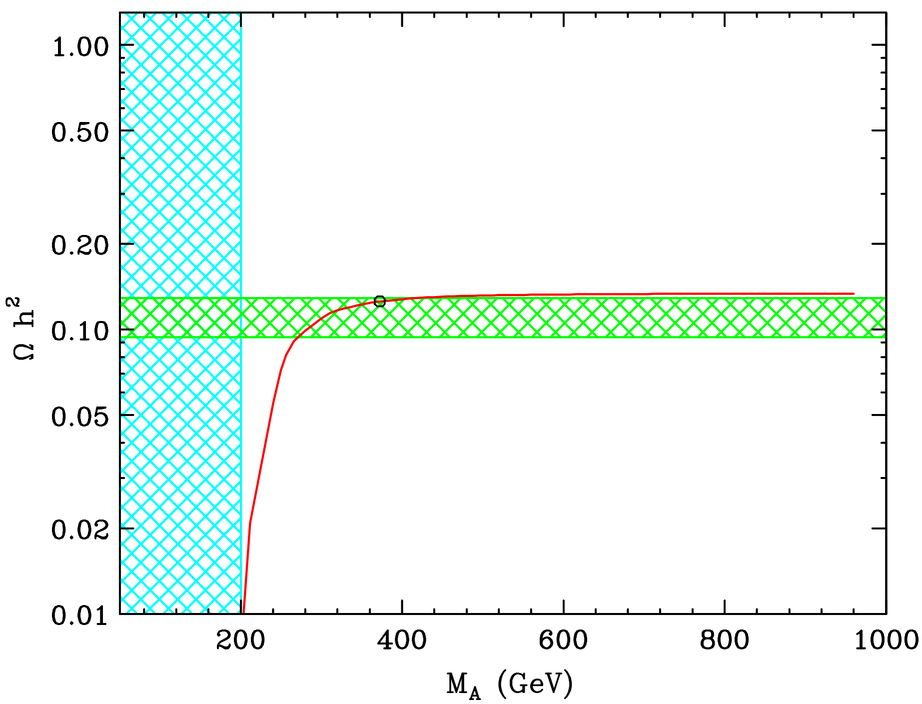


- $M_{\tilde{\ell}_R} - M_{\tilde{\chi}_1^0} = 15$ GeV < 30 GeV. Unobservable at LHC?
- $M_{\tilde{\ell}_L} > M_{\tilde{\chi}_2^0} \Longrightarrow \tilde{\ell}_L$ will not be produced in cascades.

What about irrelevant parameters?

- Constraining the irrelevant parameters is also important!
- The Higgs pole $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow H^0, A^0$ appears at small m_A.

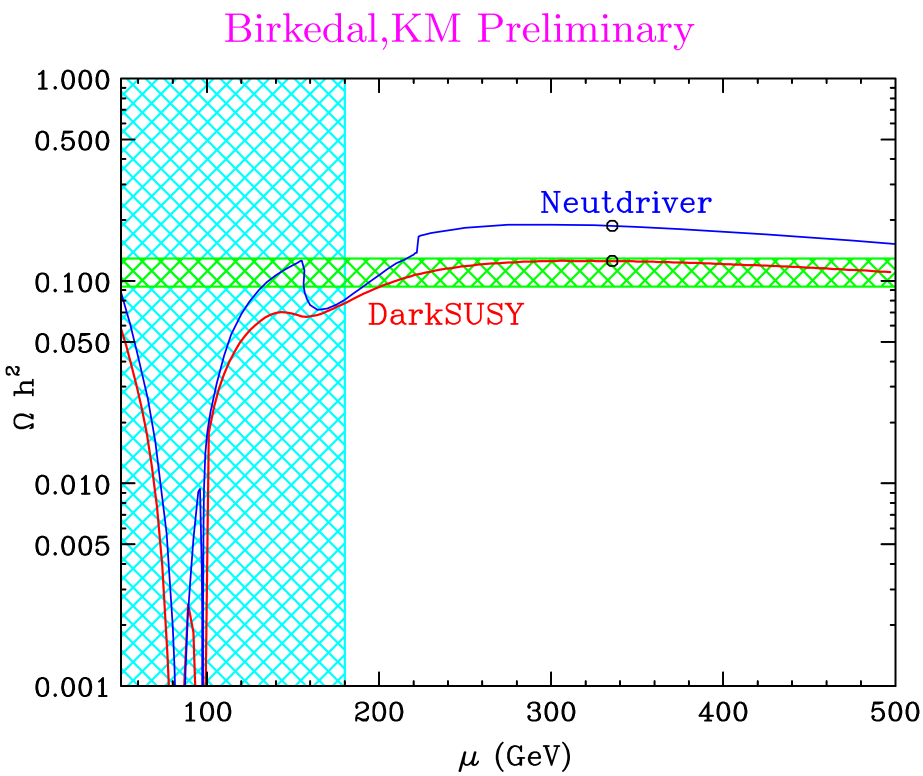
Birkedal,KM Preliminary



- However, $m_A < 200$ GeV would have been discovered...

More irrelevant parameters

- The size of μ determines the gaugino-higgsino mixing.

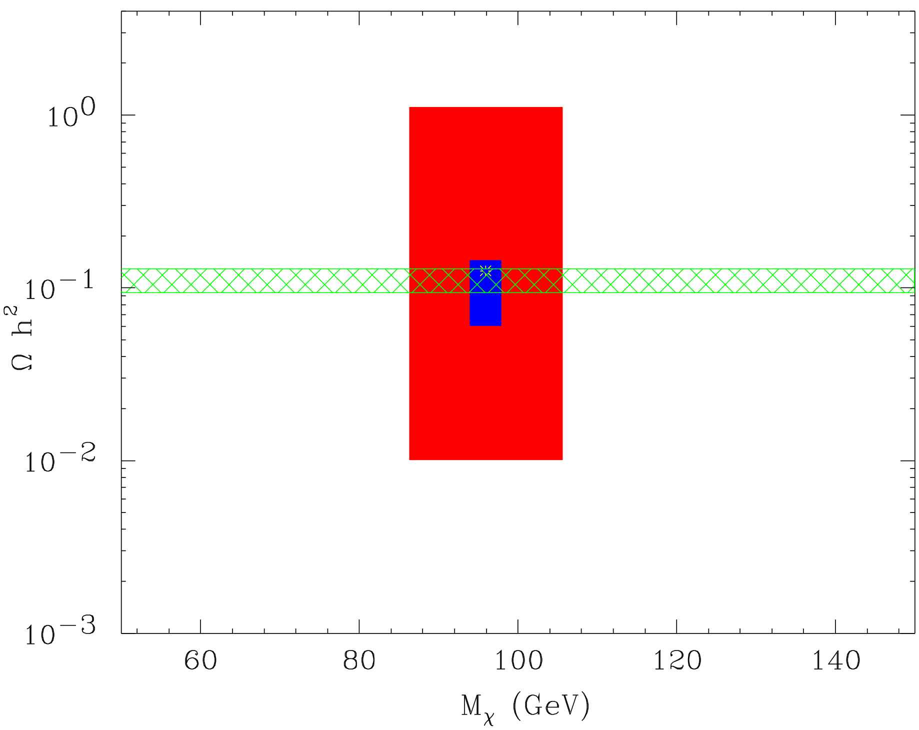


- How well can we trust the relic density codes?

LHC vs. NLC vs. WMAP

- LHC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{q}_L$ to within 10%.

Birkedal,KM Preliminary



- NLC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\ell}_L, \tilde{\ell}_R$ to within 2%. Everything else above 250 GeV.

The Message

- Recent new ideas in particle physics lead to novel alternatives for dark matter candidates. SUSY DM? Not so fast...
- Extra dimensions also yield natural dark matter candidates, with calculable rates for detection.
- Little Higgs theories, with certain assumptions, also have a dark matter candidate.
- The usual question: how do we discover these models?
- How do we tell the difference?
- How do we uncover the identity of the dark matter?
- How will we know we have found the dark matter at the LHC?