Discovering and Testing Dark Matter in the Lab

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The Dark Matter Problem

- Two of the biggest mysteries in (astro)particle physics today

What, how and why breaks the electroweak gauge symmetry?

- SM answer: new particle, Higgs boson. Will be discovered and studied at the LHC and ILC. But... gauge hierarchy problem.

- Many models BSM were proposed to address this issue, collider experiments will tell us which one is right *in our lifetime*. Generic prediction: more new particles.

- With all due respect to the gauge hierarchy problem, dark matter is our best experimental evidence for new physics BSM.

What is the nature of the dark matter and the dark energy?

- Perhaps the two puzzles are related? $\Longrightarrow$ WIMPs?

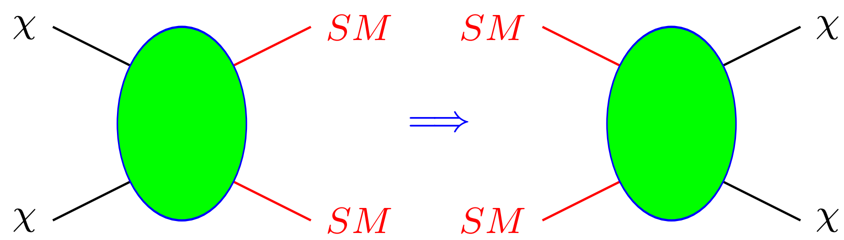
- The advantage of cosmological WIMPs
  - Predicted in many particle physics scenarios BSM.
  - Give the right order of magnitude Ω_{DM}.

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

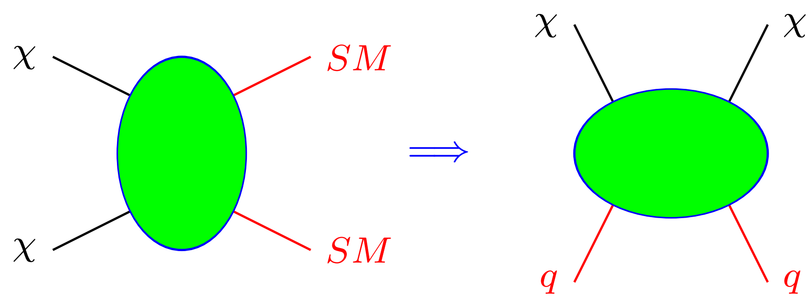
  - Can be detected!
  - Can be detected in different ways!

Avenues for WIMP detection

- Potentially observable signals at colliders



- Potentially observable signals of direct DM detection.



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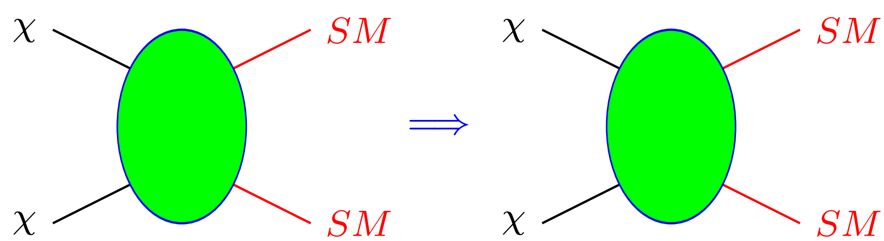
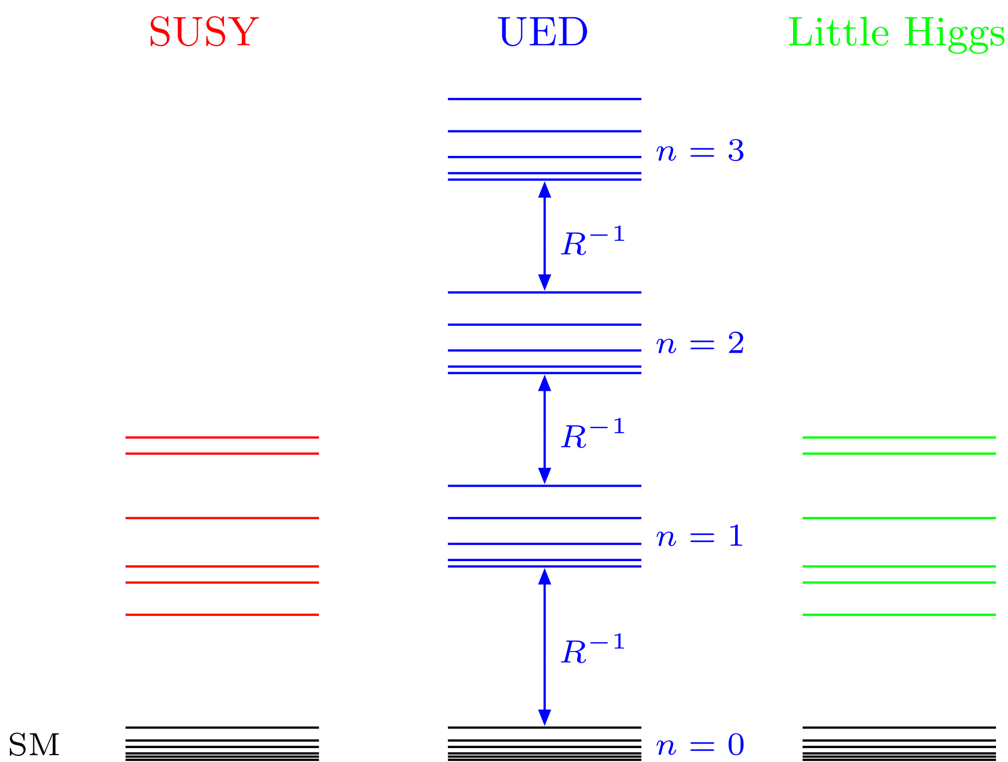


New physics models with DM WIMPs

- 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, ...)
- Brief review, discovery prospects
- How can we distinguish the different scenarios?
  - at high energy colliders
  - in astroparticle physics experiments
- How well can we test cosmology at the LHC/ILC?
- A model independent framework for discussing DM signals
  - at high energy colliders
  - in astroparticle physics experiments

Model Summary



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

Supersymmetry

- Supersymmetry is an extra dimension theory with new anticommuting coordinates $\theta_\alpha \Longrightarrow$ superspace $\{x^\mu, \theta\}$:

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

- 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: $\tilde{h}^\pm$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
  - graviton: G $\Leftrightarrow$ gravitino: $\tilde{G}$
- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)
- Prove discovery of SUSY $\Longleftrightarrow$ prove the above
- 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 electroweak data

SUSY WIMPs

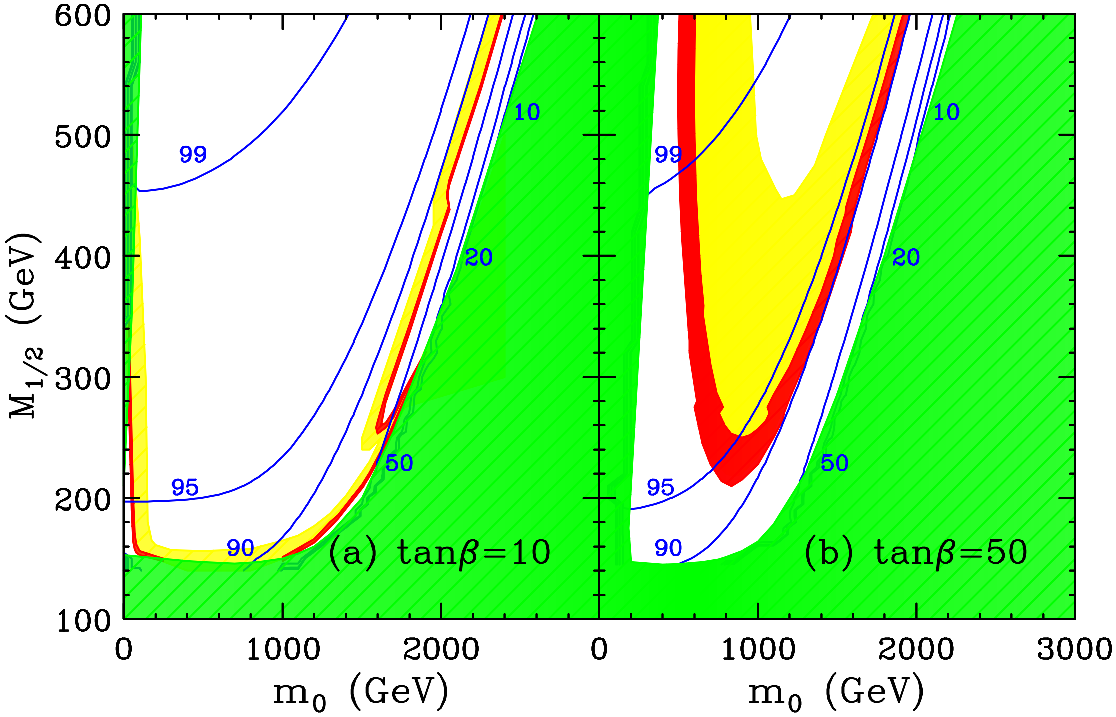
- The lightest neutralino $\tilde{\chi}_1^0$ is a mixture of $\tilde{b}^0$, $\tilde{w}^0$, $\tilde{h}_u^0$, $\tilde{h}_d^0$:

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

- 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):

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

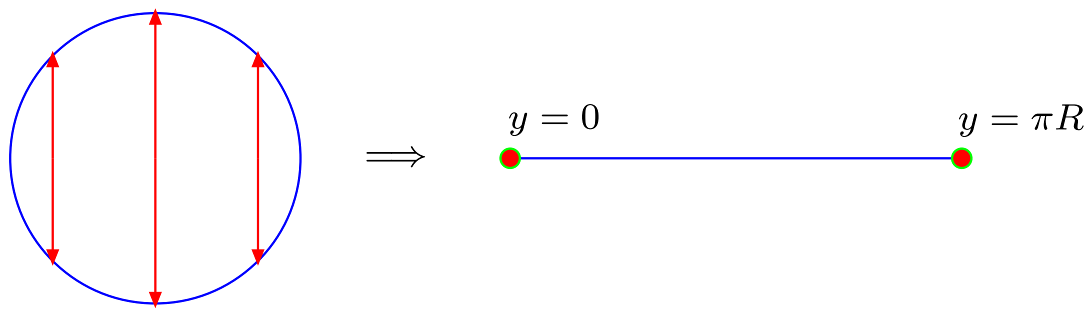
- Each SM field ϕ ($n = 0$) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with
  - identical spins
  - identical couplings
  - unknown masses of order n/R
- Prove discovery of UED $\Longleftrightarrow$ prove the above
- KK number $n \Longleftarrow$ units of p_y.
- Bulk interactions: conserve KK number $\Longleftarrow p_y$ conservation.

$$S = \int d^4x dy \mathcal{L}_{SM}$$

- Problem: chiral fermions.

KK number versus KK parity

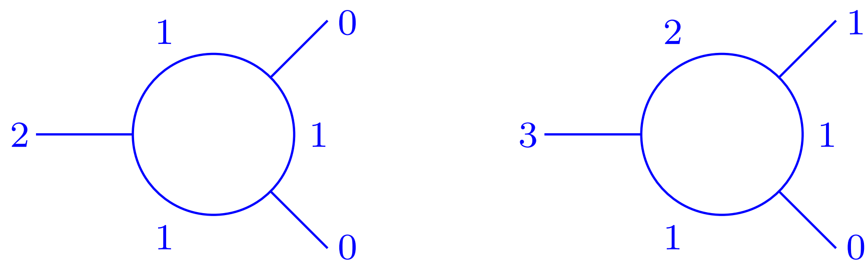
- The ED is not really a circle, but orbifold S_1/Z_2:



- Loop corrections generate boundary terms

$$S = \int d^4x dy \Big[\delta(y) + \delta(y - \pi R)\Big] \Big\{ F_4(\mu)\overline{\Psi} i \not{D} \Psi + ... \Big\}$$

which break KK number n down to KK parity $(-1)^n$

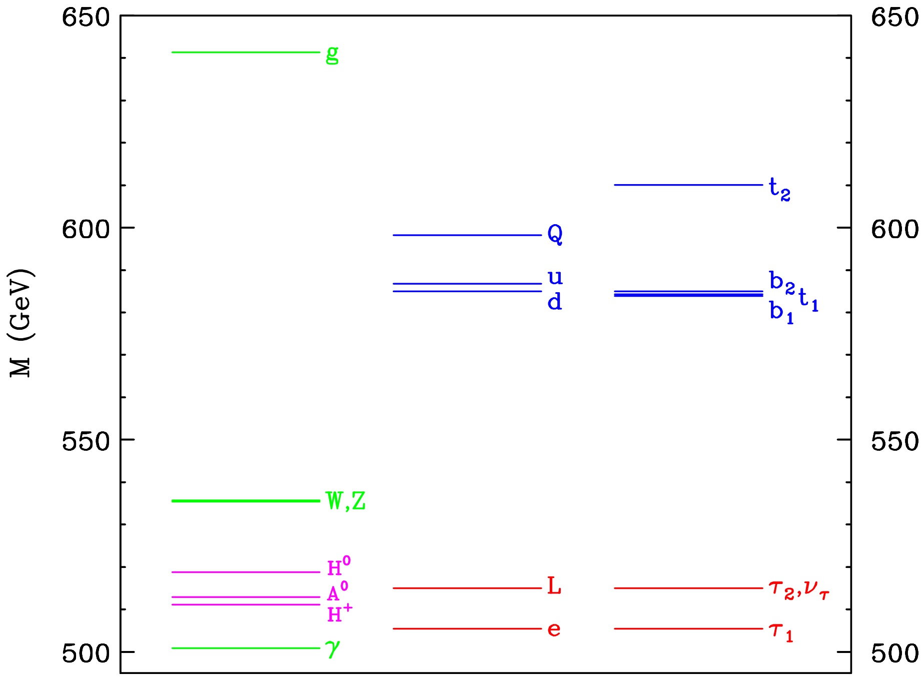


- Additional allowed decays: $2 \to 00$, $3 \to 10$, ...
- The lightest KK partner at level 1 (LKP) is stable. (DM?)
- No tree-level contributions to precision EW observables

UED spectrum at 1 loop

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

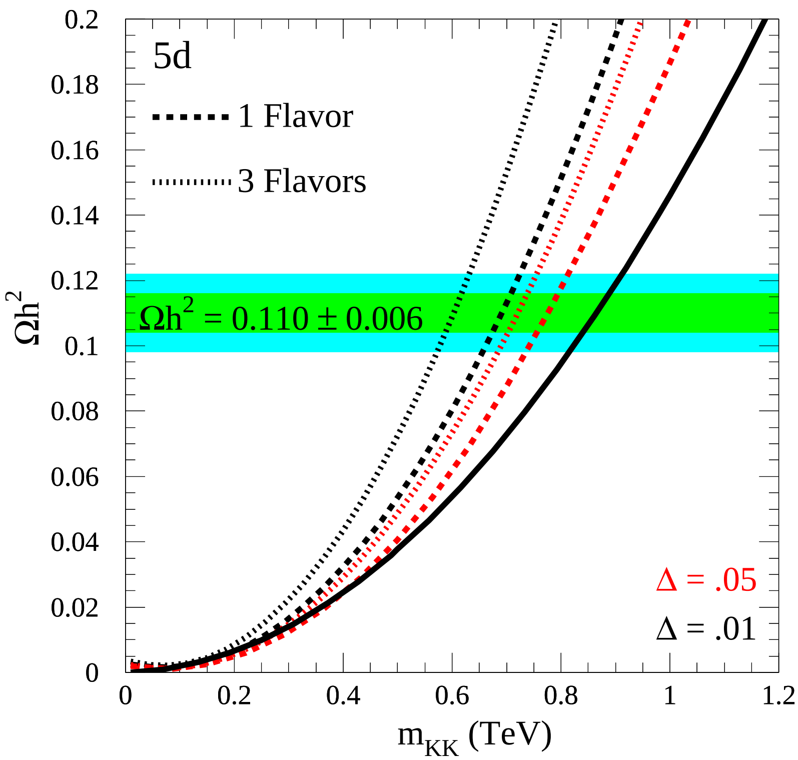
Cheng, KM, Schmaltz, hep-ph/0204342



- 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.

KK dark matter relic density

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



- Unlike supersymmetry: no helicity suppression

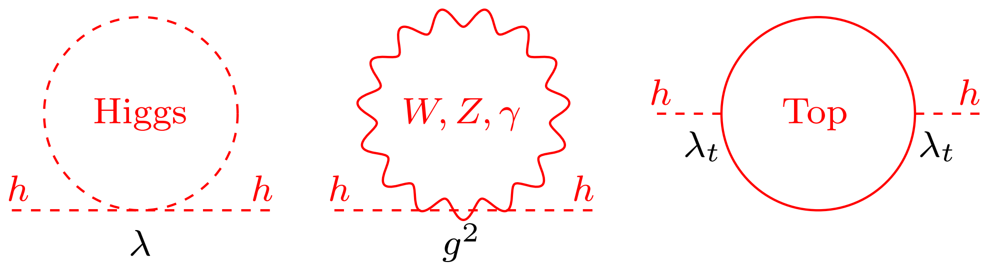
$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P \sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

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

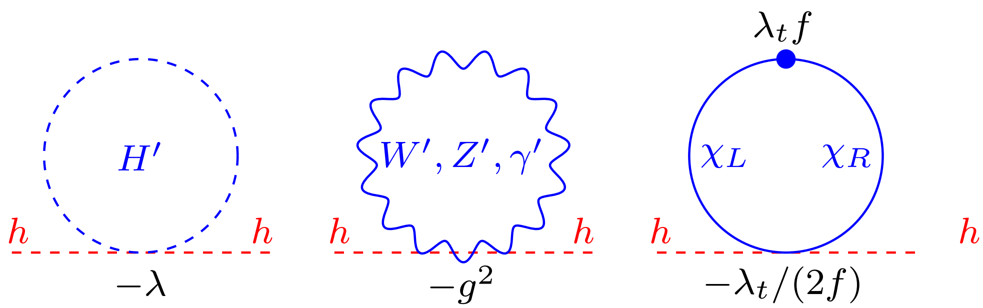
- Unlike supersymmetry: coannihilation lowers the bound

Little Higgs models

- The hierarchy problem in the SM



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



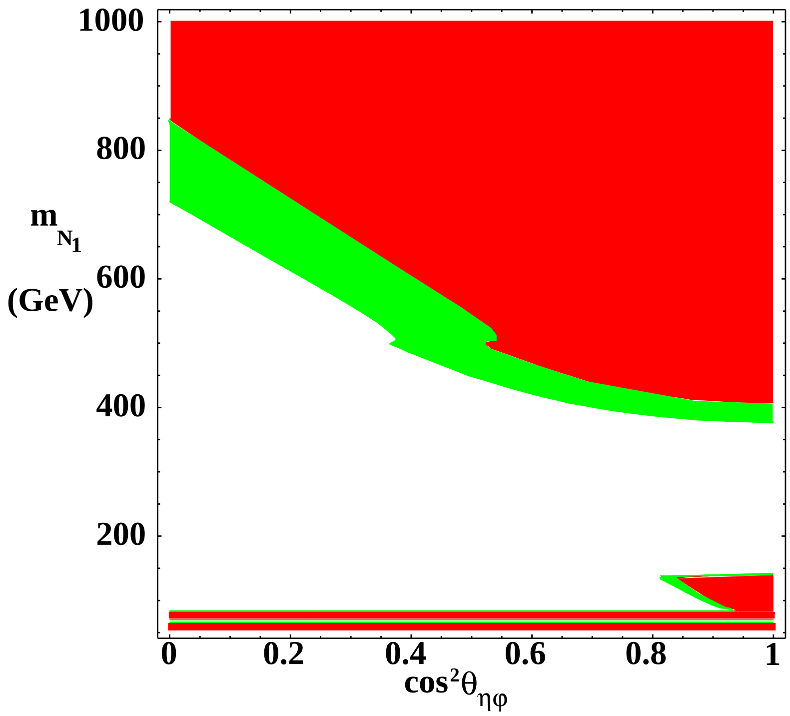
- Conserved T-parity (Cheng, Low hep-ph/0308199)
  - $T = +1$ for SM particles, $T = -1$ for new particles.
  - the lightest T-odd particle is stable.
- No tree-level contributions to precision EW observables

Relic density in LH models

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

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

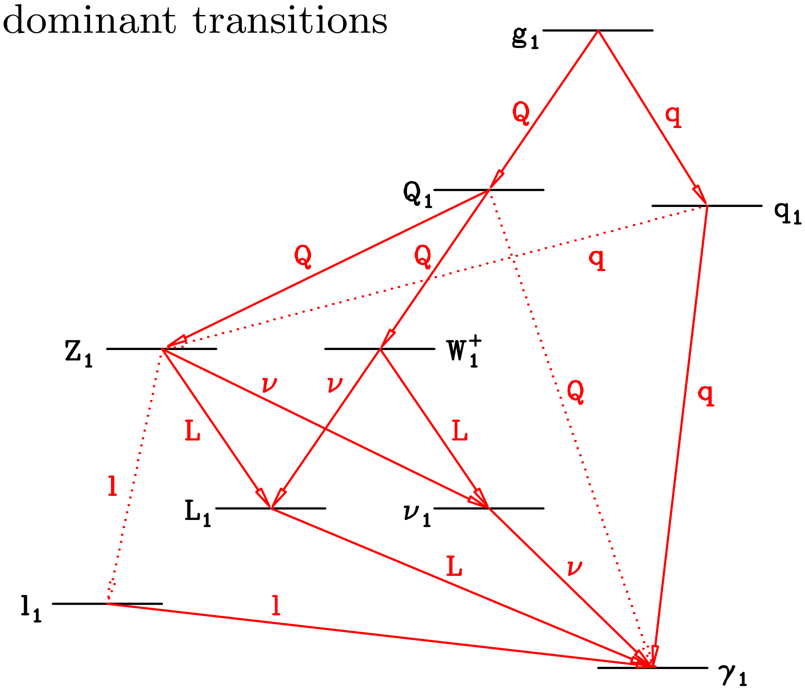
Birkedal, Wacker hep-ph/0306161



- 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.

Collider phenomenology of UED

- Allowed dominant transitions

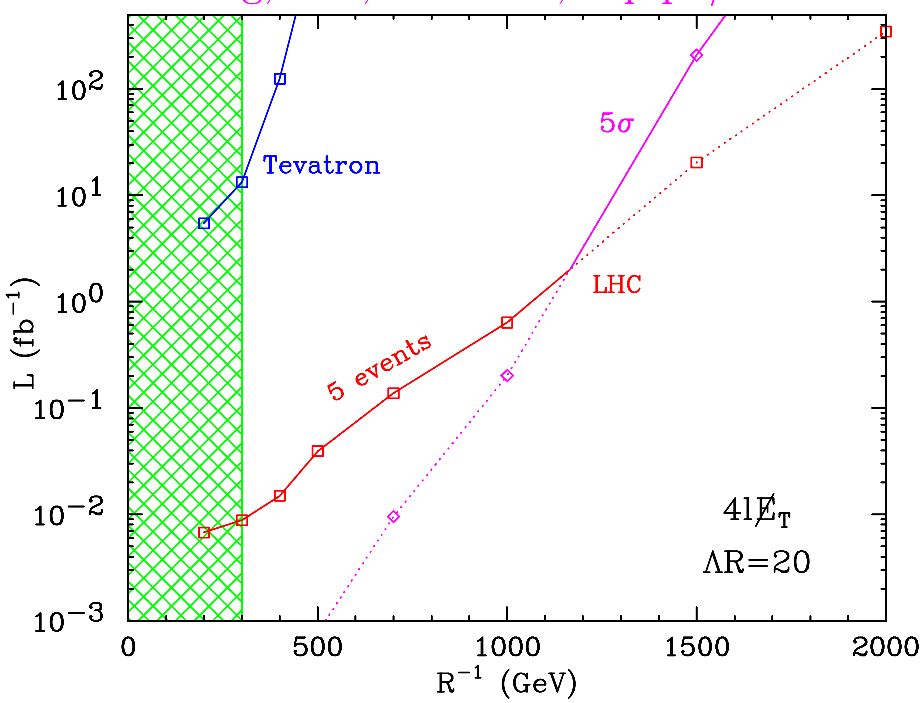


- KK gluon: $B(g_1 \to Q_1 Q_0) \simeq B(g_1 \to q_1 q_0) \simeq 50\%$.
- SU(2)-singlet KK quarks: preferentially $q_1 \to \gamma_1 q_0$
- SU(2)-doublet KK quarks: preferentially to W_1 and Z_1
- KK W- and Z-bosons: only leptonic decays!
- KK leptons: 100% directly to the LKP.
- At hadron colliders we want: strong production, weak decays!
- Cleanest signature at LHC: $4\ell + \not{E}_T$.

UED discovery reach at the Tevatron and LHC

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

Cheng, KM, Schmaltz, hep-ph/0204342

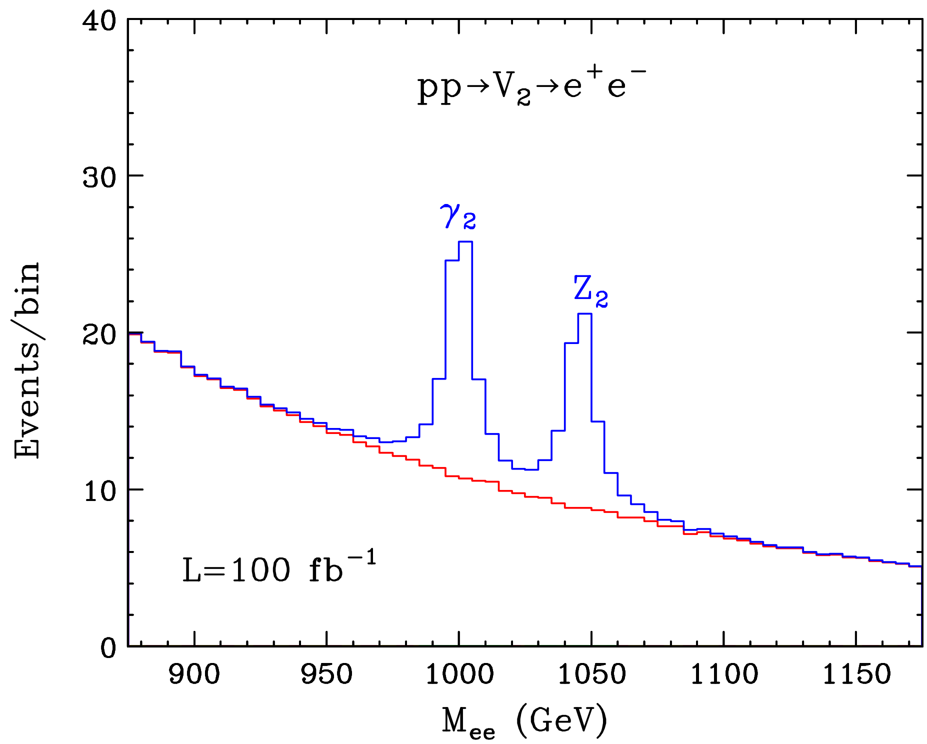


- Other typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (unobservable at hadron colliders)
- The "good" dark matter region is covered

Bosonic or fermionic supersymmetry?

- How does one tell SUSY from UED?
- Look for the higher states of the KK tower: e.g. Z_2, γ_2 resonances.

Datta,Kong,KM (preliminary)



- Still... could be SUSY with extra (degenerate) Z's.
- Measure the spins of the superpartners (KK-partners)!

SUSY versus UED at a LC

- The spin information is encoded in the angular distributions!

SUSY

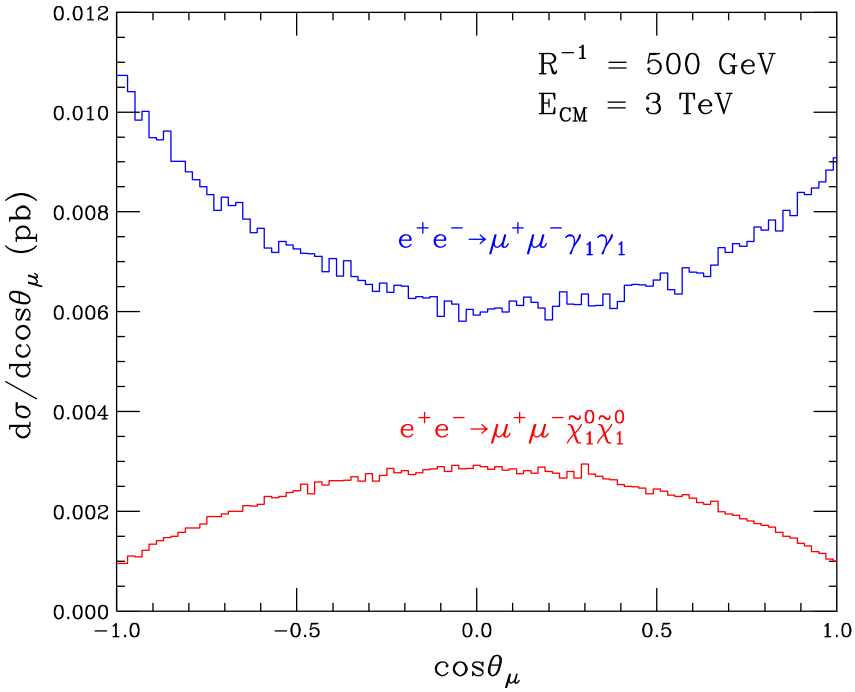
$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

UED

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

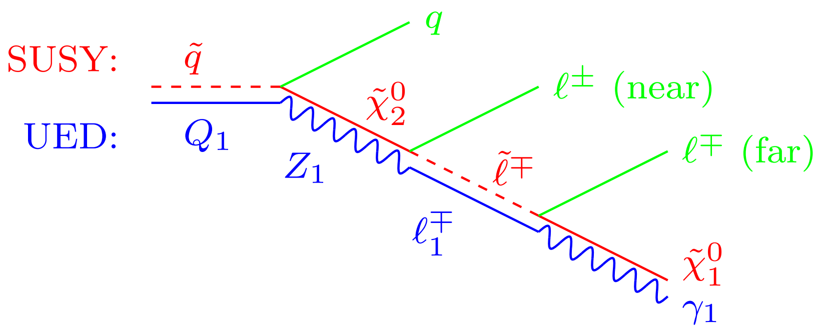
$$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta \qquad \frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta$$

Battaglia,Datta,De Roeck,Kong,KM hep-ph/0502041



- 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.

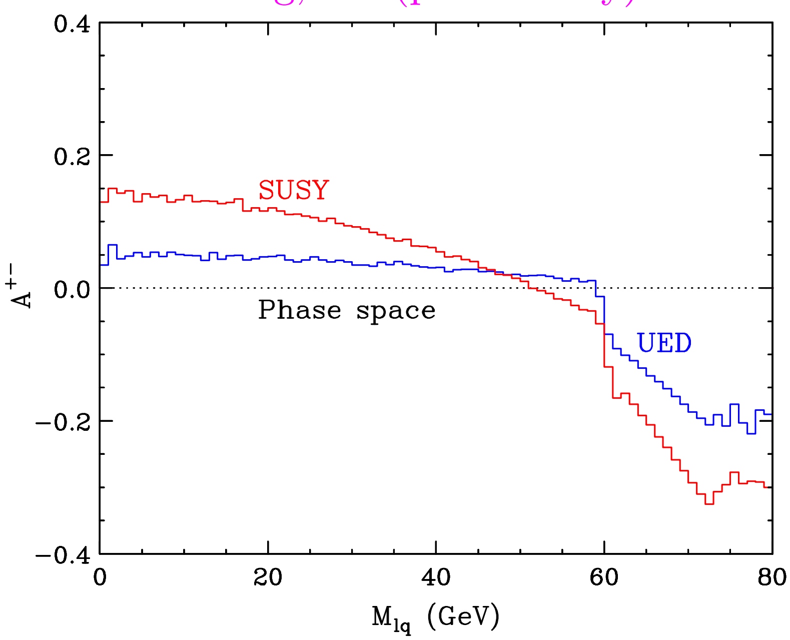
Spin measurements at LHC: SUSY vs UED



- Charge asymmetry in the differential cross-section Barr (2004)

$$A^{+-} = \frac{\sigma(\ell^+) - \sigma(\ell^-)}{\sigma(\ell^+) + \sigma(\ell^-)}$$

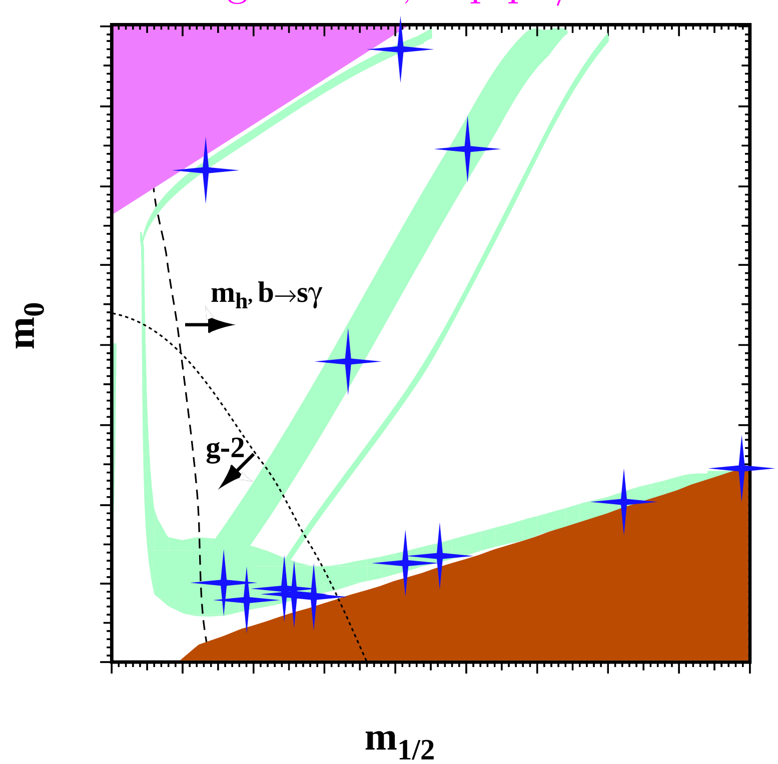
Kong,KM (preliminary)



SUSY vs UED: astroparticle probes

- How do we find the dark matter experimentally?
  - We can make it at high energy colliders
  - Direct detection: underground.
  - Indirect detection:
    - underground/underwater/underice: ν_μ
    - in space: e^+, $\bar{p}$, γ ...
- SUSY benchmark points as examples

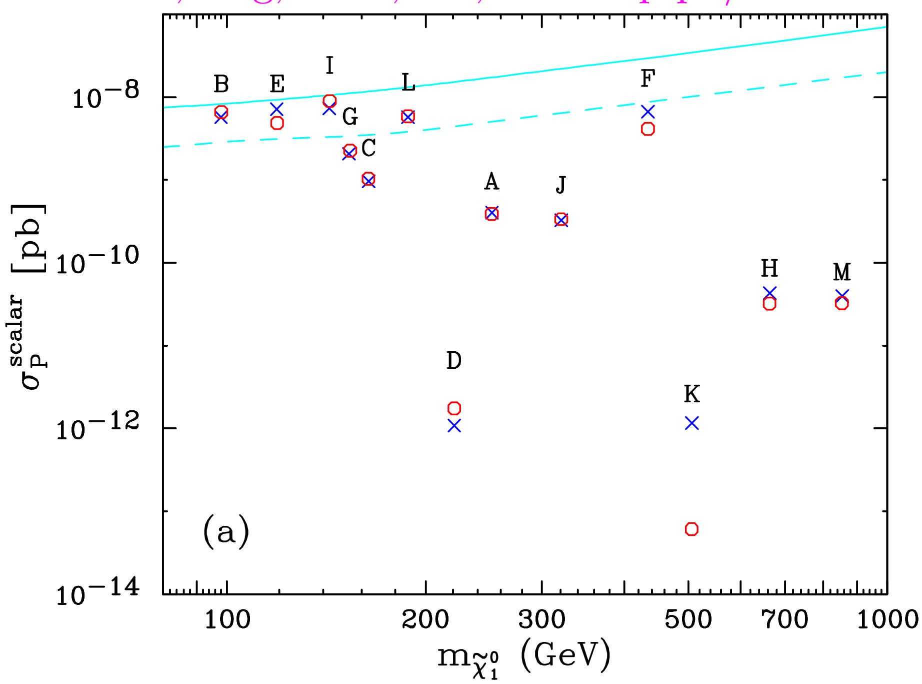
Battaglia et al., hep-ph/0106204



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

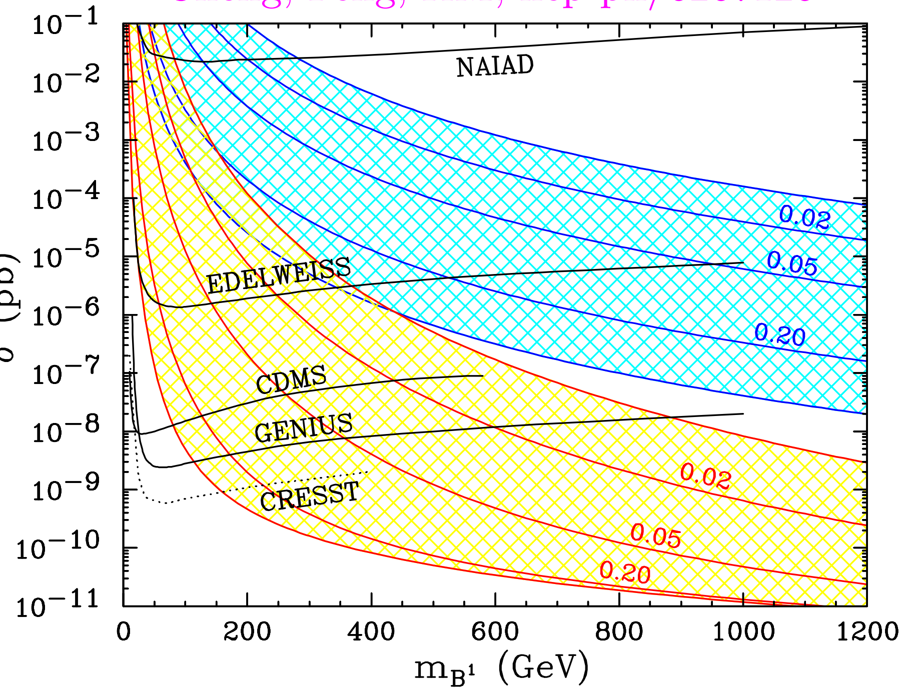


- No lower limit: cancellations are possible.

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

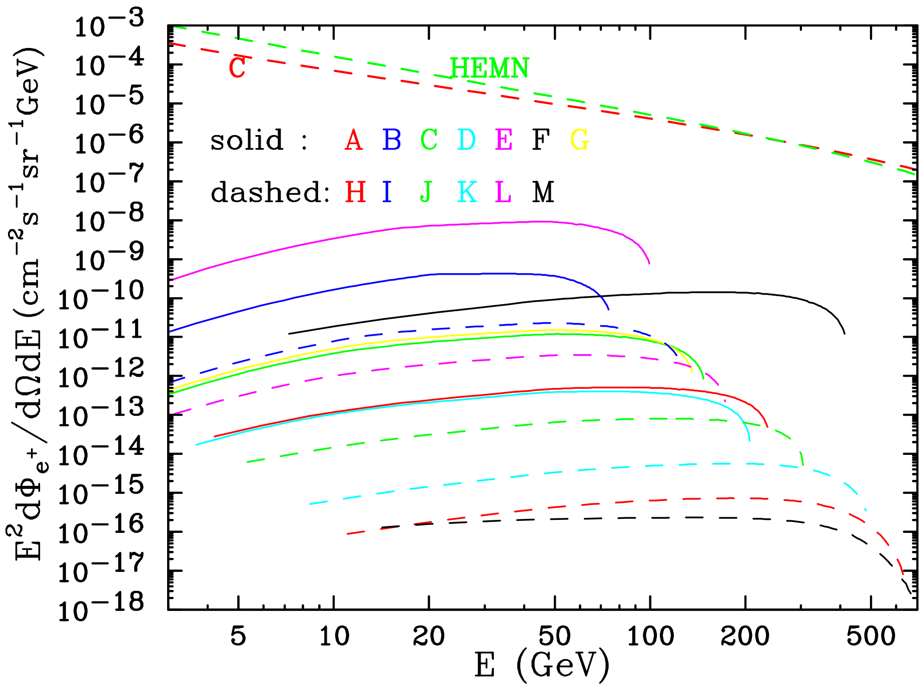
Majumdar, hep-ph/0209277

- Constructive interference: lower bound!

SUSY Dark Matter: Positron signal

- Cosmic ray positrons are an indirect signature of dark matter
- Direct annihilation $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to e^+ e^-$ helicity suppressed
- Hard e^+'s only 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



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

KK DM Indirect Detection: Positrons

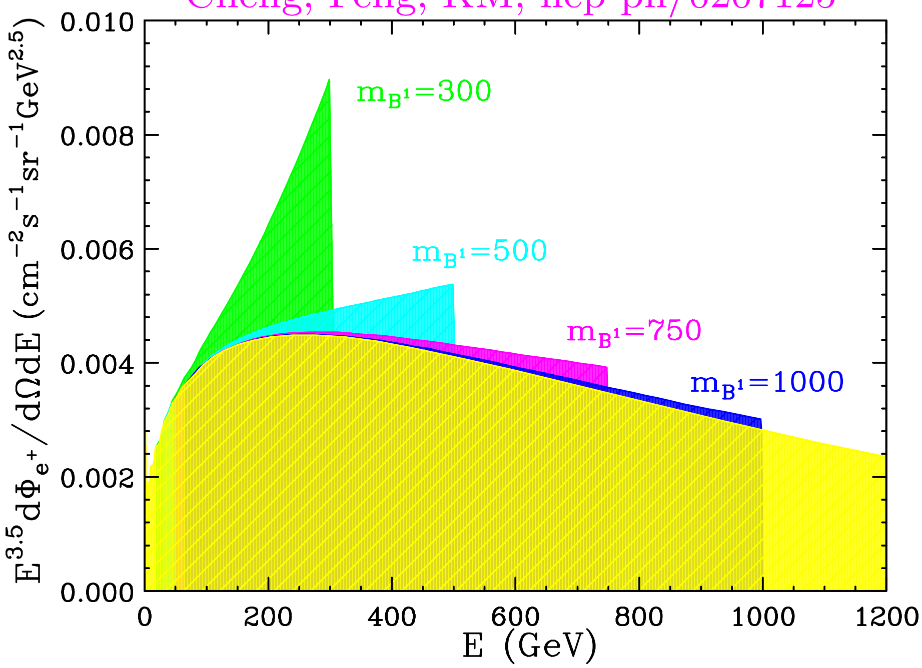
- Annihilation into fermion pairs is not helicity suppressed.

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

- There is a bump! The positrons are monoenergetic at birth.

Some smearing from propagation through the galaxy.

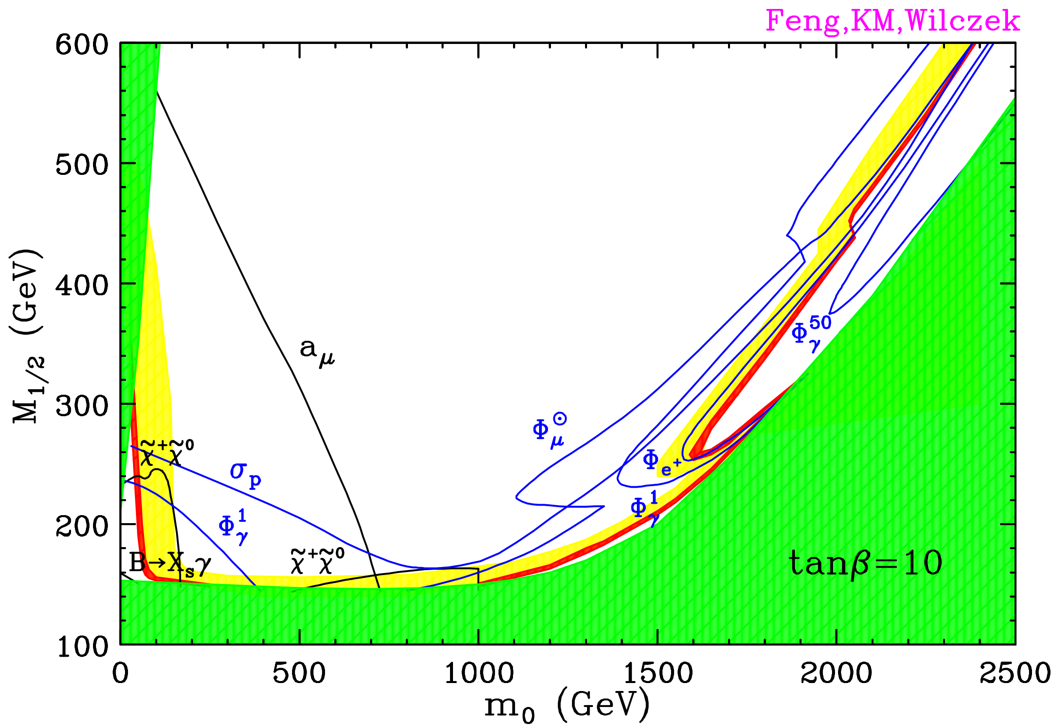
Cheng, Feng, KM, hep-ph/0207125



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

SUSY WIMP detection

- Combination of "all" pre-LHC experiments
  - Direct SUSY searches: Tevatron
  - Indirect SUSY searches: E827, B-factories
  - Direct WIMP searches: CDMS, CRESST, GENIUS
  - Indirect WIMP searches: Amanda, AMS, GLAST



- Many possible DM signals before 2007-08.

- Particle physics and astrophysics probes are highly complementary.

The particle physics/cosmology interface

- Who gets the Nobel prize for the discovery of dark matter?
- The strengths and limitations of different experiments
- Cosmology and astroparticle physics
  - direct probe of dark matter
  - unknown identity, undetermined properties, quantum numbers...
  - direct detection signal roughly bounds the mass and interaction strength
  - indirect detection signal plagued by astrophysical uncertainties; cannot fully discriminate between models
- Collider experiments
  - cannot discover the dark matter
  - missing energy signal may be due to quasistable particles Feng, Rajaraman, Takayama, hep-ph/0302215

• The full picture will only emerge from the synergy between astrophysics and particle physics probes

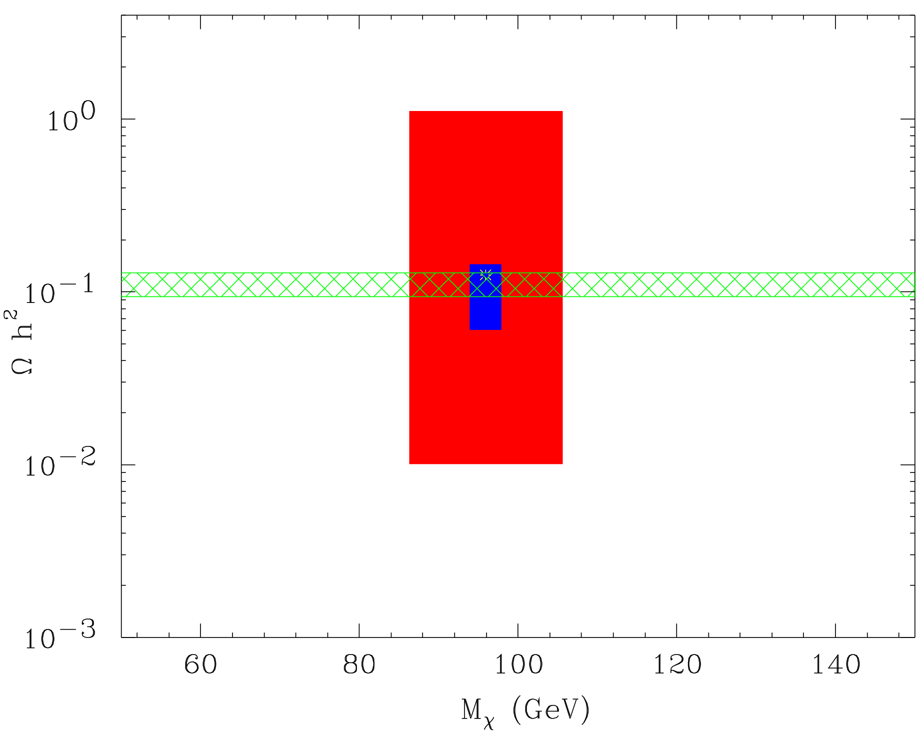
LHC vs. ILC vs. WMAP

- LCWG: Connections to Astrophysics and Cosmology (2003)

Eds.: Battaglia, Feng, Graf, Peskin, Trodden

- Typical MSUGRA benchmark:
  - $m_0 = 57$, $M_{1/2} = 250$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.
  - Similar points discussed in the LHC literature
- LHC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{q}_L$ to within 10%.

Birkedal,KM "Quantum Universe"



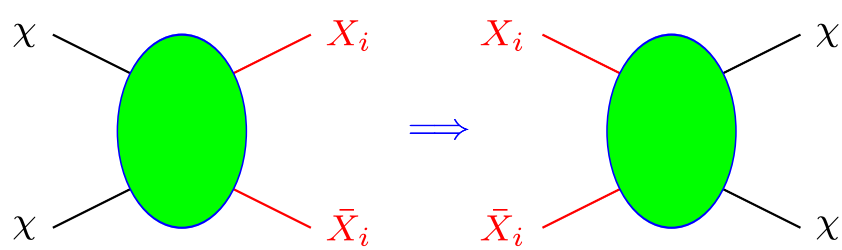
- ILC: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\ell}_L, \tilde{\ell}_R$ to within 2%. The rest above 250 GeV.

Dark matter production at colliders

- Can we predict dark matter signals at colliders?
- Expect missing energy signatures. Can we quantify?
- The DM relic abundance is governed by the annihilation cross-sections for the reactions

$$\chi + \chi \to X_i + \bar{X}_i, \qquad X_i = \{q, \ell, g, W, Z, \gamma, h\}.$$

- The inverse reaction takes place at colliders:



- $X_i = \{\mu, \tau, \nu, h, t, b\}$ channels are challenging, the rest accessible at least in principle at LHC and ILC.

Relic density calculation

- At early times, the DM particles χ are in thermal equilibrium with the SM stuff:

$$\chi\chi \leftrightarrow X\bar{X}$$

- The process of freeze-out of thermal relics is described by the Boltzmann equation

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_A v\rangle \left(n_\chi^2 - n_{eq}^2\right)$$

  - $-3Hn_\chi$ accounts for dilution due to the Hubble expansion
  - $-\langle\sigma_A v\rangle n_\chi^2$ describes depletion due to $\chi\chi \to X\bar{X}$
  - $+\langle\sigma_A v\rangle n_{eq}^2$ describes resupply due to $X\bar{X} \to \chi\chi$

- σ_A is the total DM annihilation cross-section:

$$\sigma_A v \equiv \sum_X \sigma(\chi\chi \to X\bar{X})v \equiv a + bv^2 + \mathcal{O}(v^4)$$

- An approximate analytical solution

$$\Omega h^2 = 0.08 \frac{1 \text{ pb}}{a + (3b - 0.75a)x_F}$$

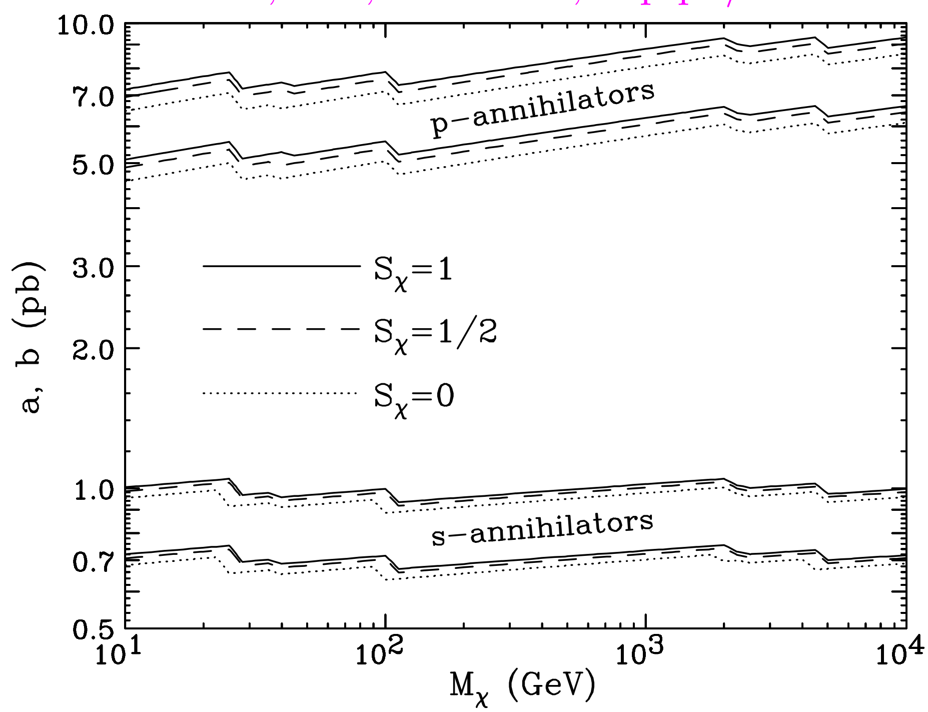
where $x_F = T_F/M_\chi \sim 0.04$, with T_F the freeze-out temperature.

What does WMAP tell us?

- Two classes of DM candidates:
  - $a \sim b$: “s-annihilators”
  - $a < bx_F << b$: “p-annihilators”

- The present amount of dark matter $\Omega_{DM} h^2 = 0.112 \pm 0.009$ tells us exactly the WIMP annihilation cross-section:

Birkedal, KM, Perelstein, hep-ph/0403004

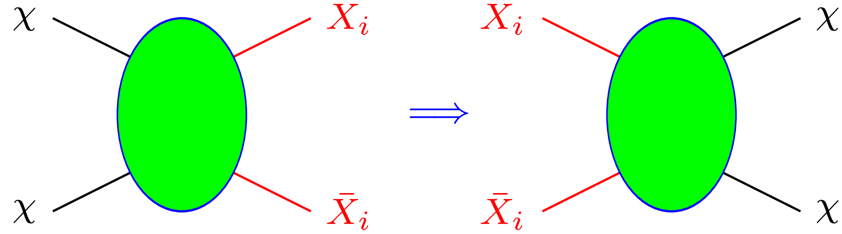


- The dependence on M_χ is only logarithmic and is offset by the change in effective number of dof in the SM at different T_F.

The WIMP production cross-section

- WIMP annihilation and WIMP production at colliders are related by detailed balancing:

$$\frac{\sigma(\chi+\chi\to X_i+\bar{X}_i)}{\sigma(X_i+\bar{X}_i\to\chi+\chi)} = 2\,\frac{v_{\rm X}^2(2S_{\rm X}+1)^2}{v_\chi^2(2S_\chi+1)^2}$$



- Annihilation fractions:

$$\kappa_i = \frac{\sigma_i^{(J_0)}}{\sigma_{\rm tot}}, \qquad \sum_i \kappa_i = 1.$$

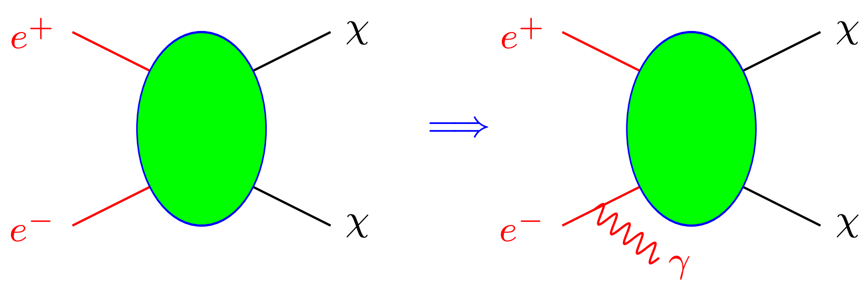
- Model-independent prediction of the WIMP production rate

$$\sigma(X_i\bar{X}_i\to 2\chi) = 2^{2(J_0-1)}\,\kappa_i\sigma_{\rm tot}\,\frac{(2S_\chi+1)^2}{(2S_{\rm X}+1)^2}\left(1-\frac{4M_\chi^2}{s}\right)^{1/2+J_0}$$

- Known parameters: $\{\sigma_{an}, S_X, s\}$
- Unknown parameters: $\{\kappa_i, M_\chi, S_\chi, J_0\}$
- Applicable only close to 2χ threshold ($v_\chi \ll 1$).
- But... no trigerrable signature!

Soft photon factorization

- What to do?
  - Give up model-independence, consider production of heavier particles (superpartners, KK-modes etc.)
  - Tag the known initial state with a soft photon/gluon



- Soft/collinear photon factorization:

$$\frac{d\sigma(e^+e^- \to 2\chi + \gamma)}{dx d\cos\theta} = \frac{\alpha}{\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin^2\theta}\,\hat{\sigma}(e^+e^- \to 2\chi)$$

where $x \equiv 2E_\gamma/\sqrt{s}$, $\hat{\sigma}$ is evaluated at $\hat{s} = (1-x)s$.

- Applicable for $E_\gamma \ll \sqrt{s} - M_\chi$.
- In specific models, we expect $\kappa_e \sim 20\% \Longrightarrow$ LC!
- Analogously, WIMP production at hadron colliders:

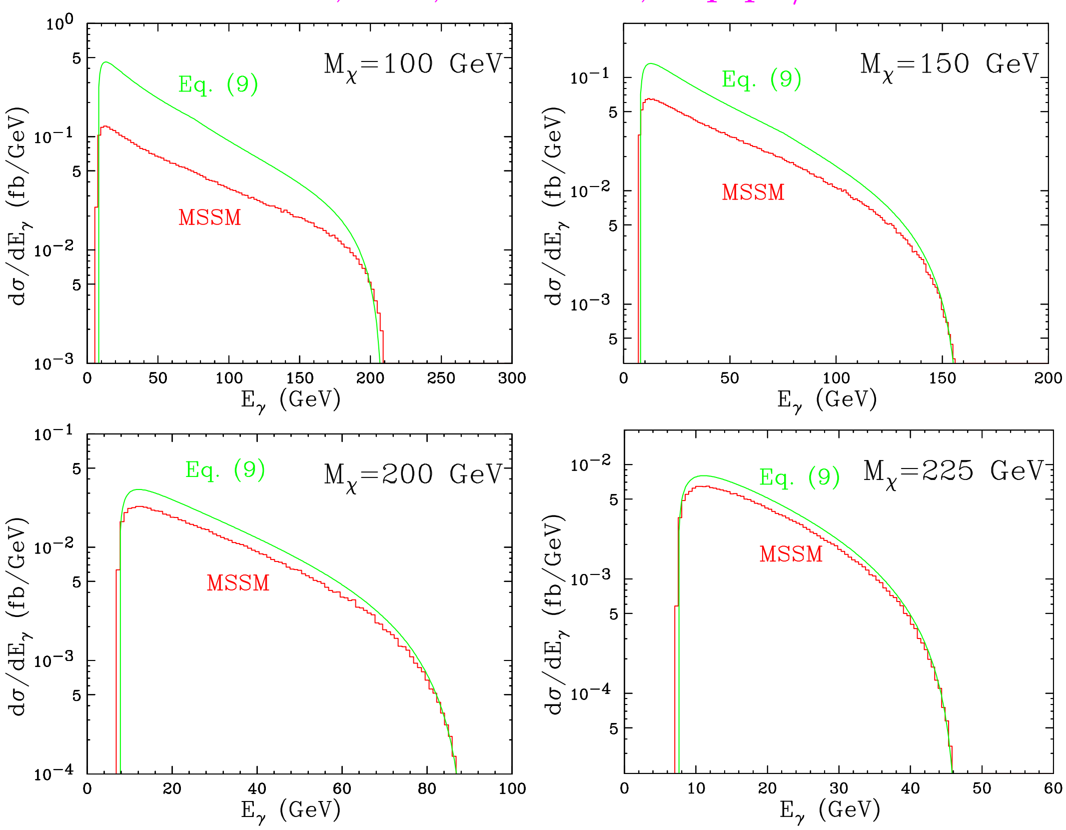
$$\sigma(q\bar{q} \to 2\chi + g) \sim \alpha_s \kappa_q \sigma_{an}, \quad \sigma(gg \to 2\chi + g) \sim \alpha_s \kappa_g \sigma_{an}$$

Very challenging experimentally...

How well did we do?

- Compare the analytic formula to the exact result in explicit models

Birkedal, KM, Perelstein, hep-ph/0403004



- At low v_χ, soft factorization breaks down.
- At high v_χ, higher-order terms in the velocity expansion become relevant.

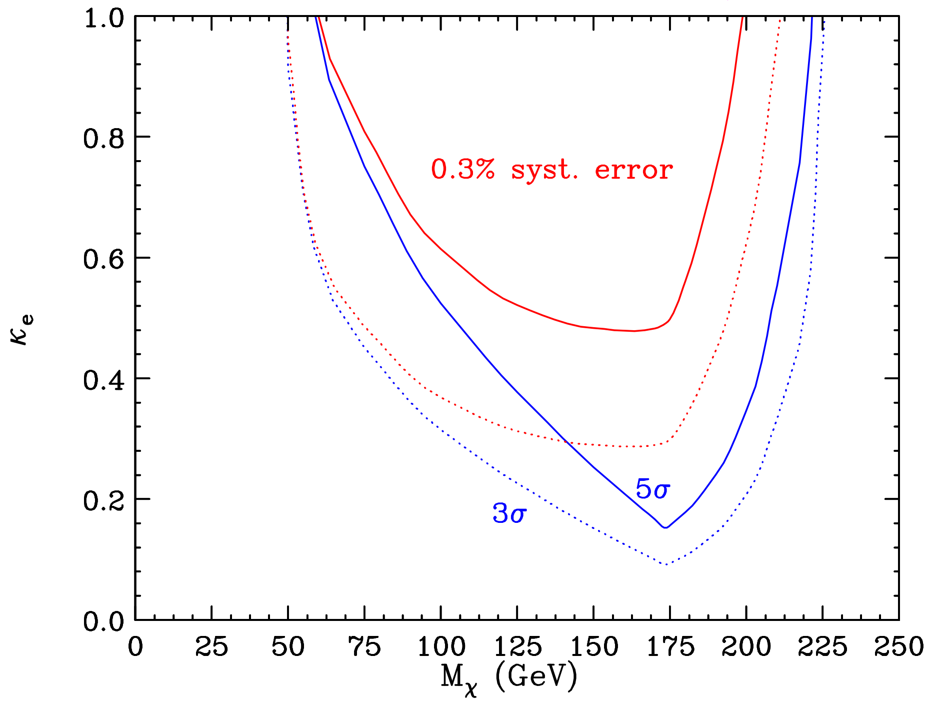
WIMP signal at a 500 GeV LC

- Discovery reach of LC500. Cuts:
  - $\sin\theta_\gamma > 0.1$, $p_{T,\gamma} > 7.5$ GeV (suppress Bhabha).
  - χ's must be non-relativistic and E_γ below threshold:

$$\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right).$$

  - No polarization. $L = 500$ fb^{-1}.

Birkedal, KM, Perelstein, hep-ph/0403004

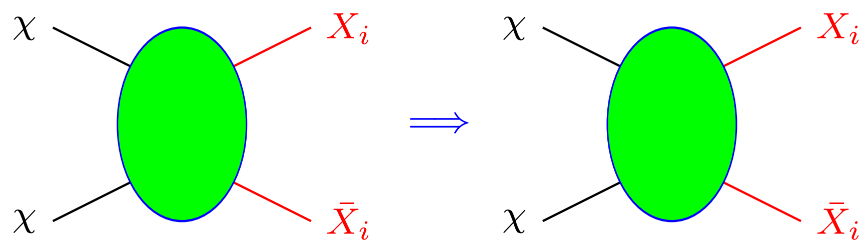


- In SUSY $\kappa_e \sim 25\%$. Polarization would help.

Indirect detection of dark matter: a model-independent approach

- The DM relic abundance is governed by the annihilation cross-sections for the reactions

$$\chi + \chi \to X_i + \bar{X}_i, \qquad X_i = \{q, \ell, g, W, Z, \gamma, h\}.$$

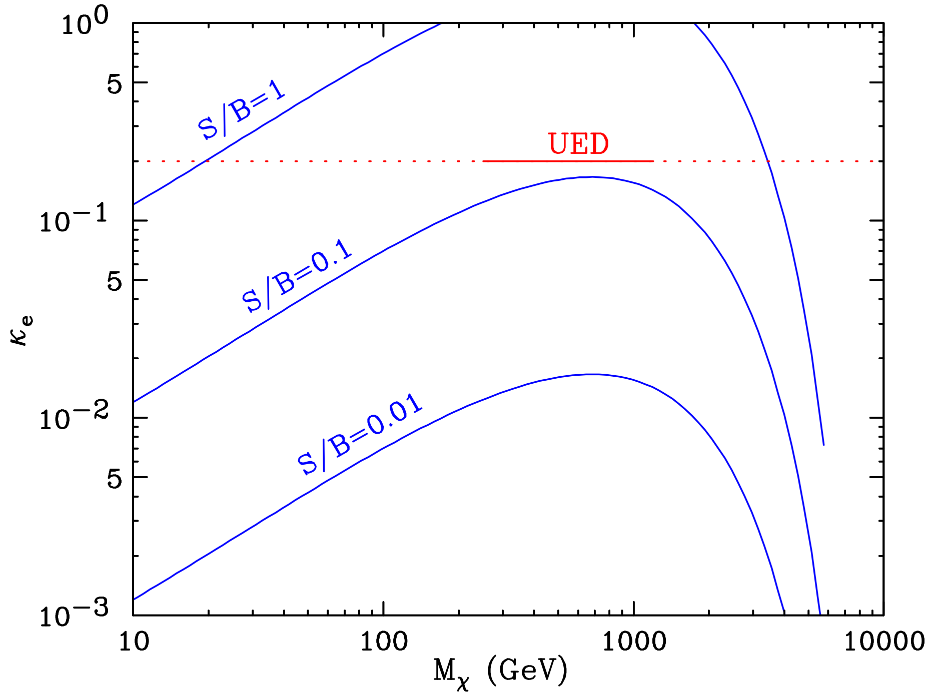


- The same annihilation reaction is happening right now:
  - neutrinos from the Sun/Earth
  - antimatter cosmic rays
  - high energy photons from the galactic center
- Model-independent indirect DM signals (KM,Perelstein,Spray)

Indirect WIMP signals: positrons

- A model-independent prediction for the positron peak rate due to DM annihilations $\chi\chi \to e^+e^-$ in the halo:

KM,Perelstein,Spray (preliminary)



- In UED $\kappa_e \sim 25\%$. In SUSY much smaller.
- Similar predictions can be made for secondary positrons in
  - $\chi\chi \to \tau^+\tau^- \to e^+e^-...$
  - $\chi\chi \to W^+W^- \to e^+e^-...$
  - $\chi\chi \to ZZ \to e^+e^-...$

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 particle in a collider?

- Elucidating the nature of the dark matter will require both dark matter and collider experiments.

- Dark matter detection experiments should be prepared for surprises, avoid theory bias.

- WMAP implies model-independent, guaranteed and experimentally challenging rates for missing energy signals of DM at colliders.