SUSY Dark Matter?

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Dark matter and physics beyond the Standard Model

- Dark matter is our best evidence for new physics beyond the Standard Model
- WIMPs are motivated by both particle physics and astrophysics.
  - Predicted in many particle theories BSM.
  - Give the right order of magnitude Ω_{DM}.

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

  - Since they must have been able to annihilate in the Early Universe, they should also produce observable signals in direct and indirect dark matter detection experiments.
- Recipe for BSM dark matter
  - invent a new model
  - invent a symmetry which guarantees a stable particle
  - fudge parameters until the lightest new stable particle is neutral and has the correct relic density

Outline

- Three generic examples of theories BSM with DM candidates
  - supersymmetry: DM = lightest superpartner.
  - extra dimensions: DM = lightest Kaluza-Klein mode.
  - Little Higgs: DM = ? (billion, gatesino, ...)
- In each case:
  - brief introduction to the model.
  - who is the DM particle?
  - why is it stable?
  - what is the preferred mass range for DM?
  - DM discovery prospects.
- How can we identify the DM particle?
  - high-energy coliders
  - astroparticle physics experiments in space (Jonathan's talk)

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)
- The superpartners are charged under a conserved R-parity
  - SM particles: $R = 0$
  - superpartners: $R = -1 \Longrightarrow$ stable LSP (DM?).
- No tree-level contributions to precision EW observables

Gaugino fraction of SUSY WIMPs

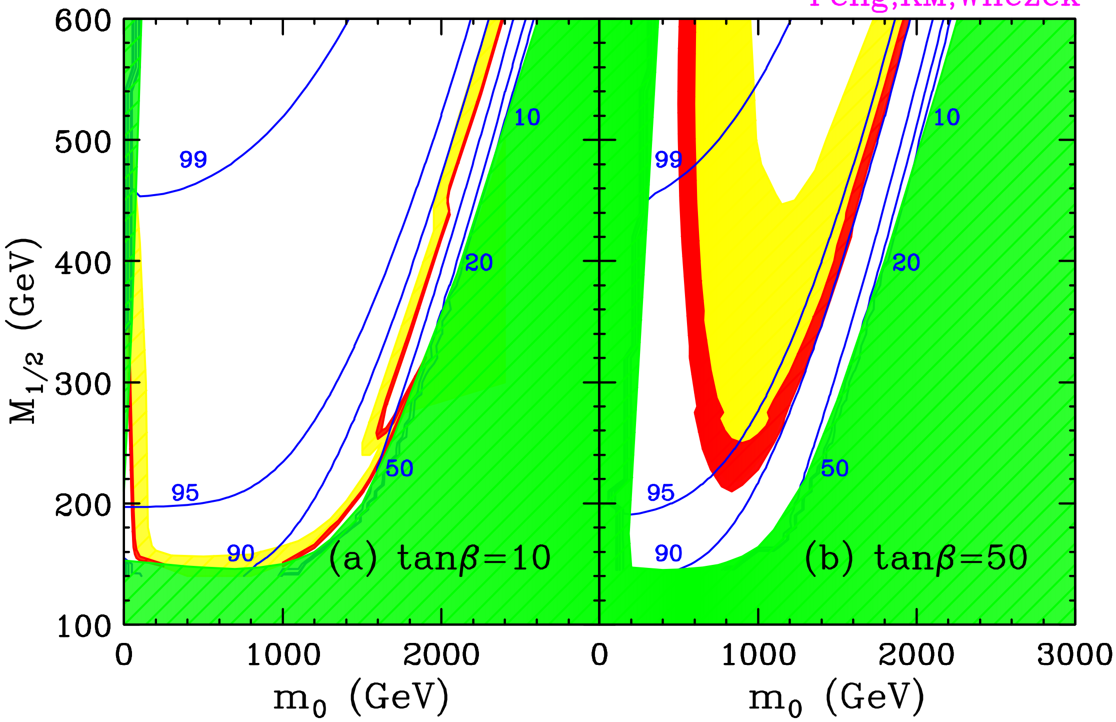
- The lightest neutralino $\tilde{\chi}_1^0$ is a mixture of $\tilde{b}^0$, $\tilde{w}^0$, $\tilde{h}_u^0$, $\tilde{h}_d^0$:

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

- Gaugino fraction R_χ of the LSP:

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

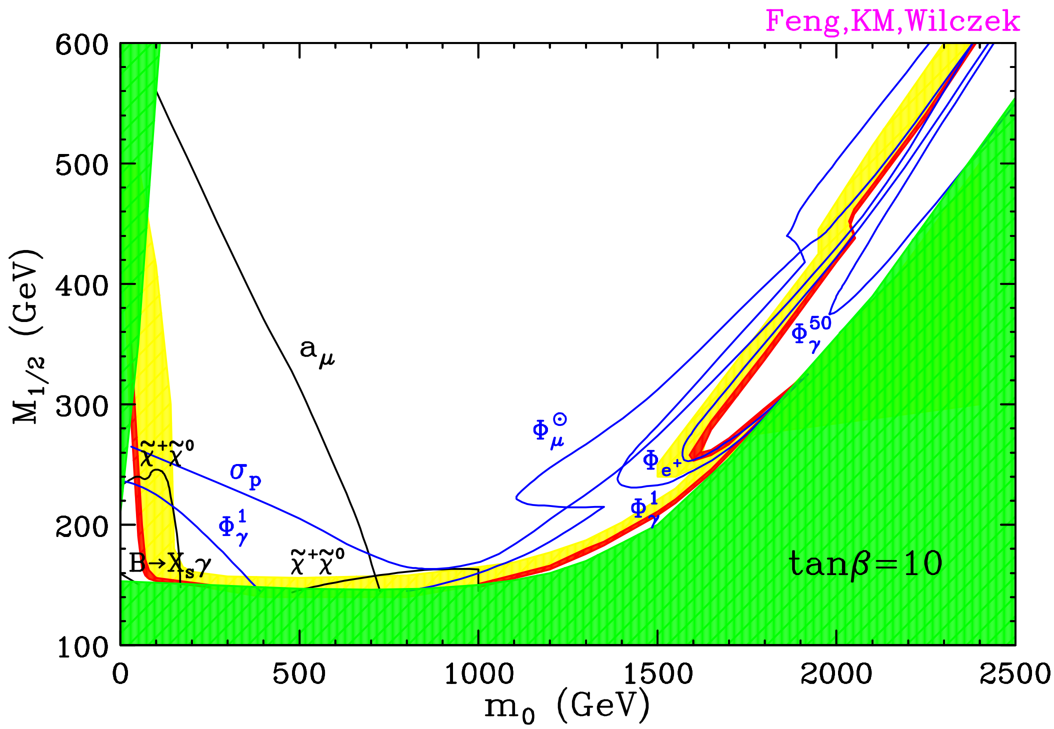
Feng,KM,Wilczek



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

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

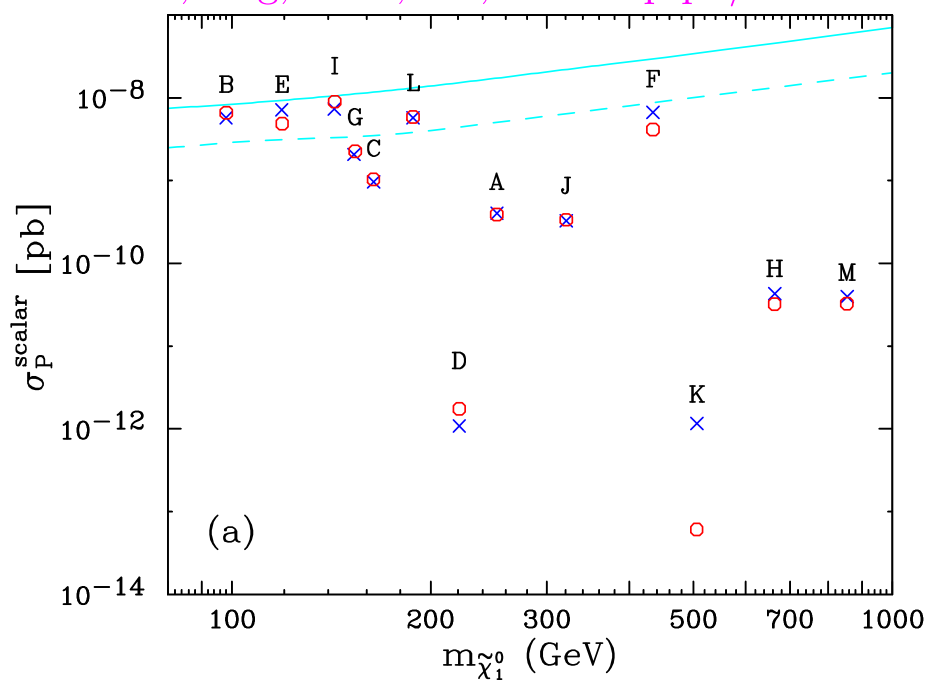


- Many possible DM signals before 2007-08.
- Particle physics and astrophysics probes are highly complementary.

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.

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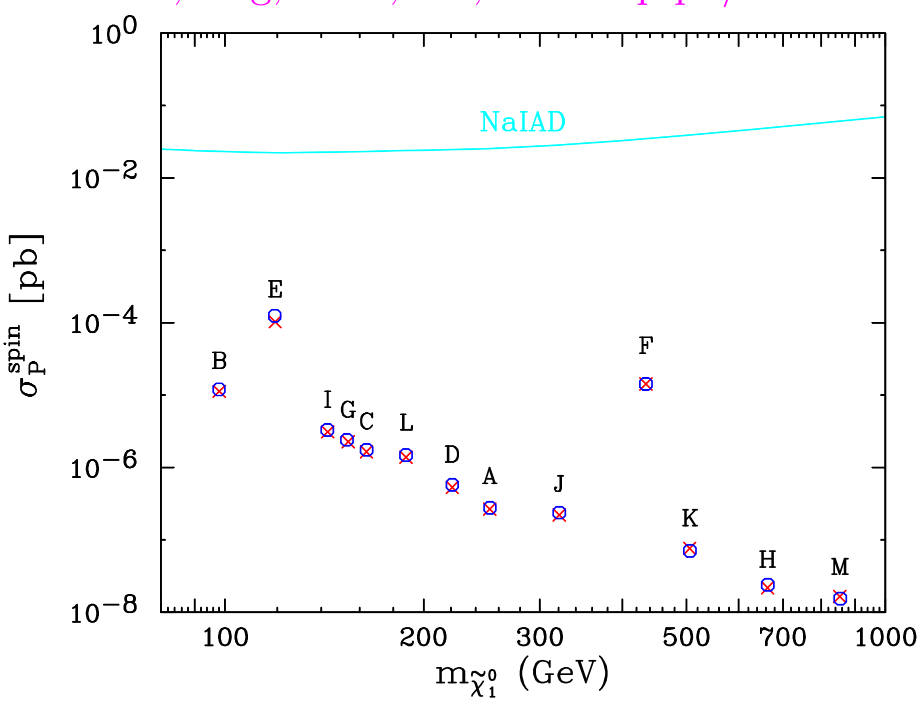


- Far below sensitivity of near-term future experiments.

Universal Extra Dimensions

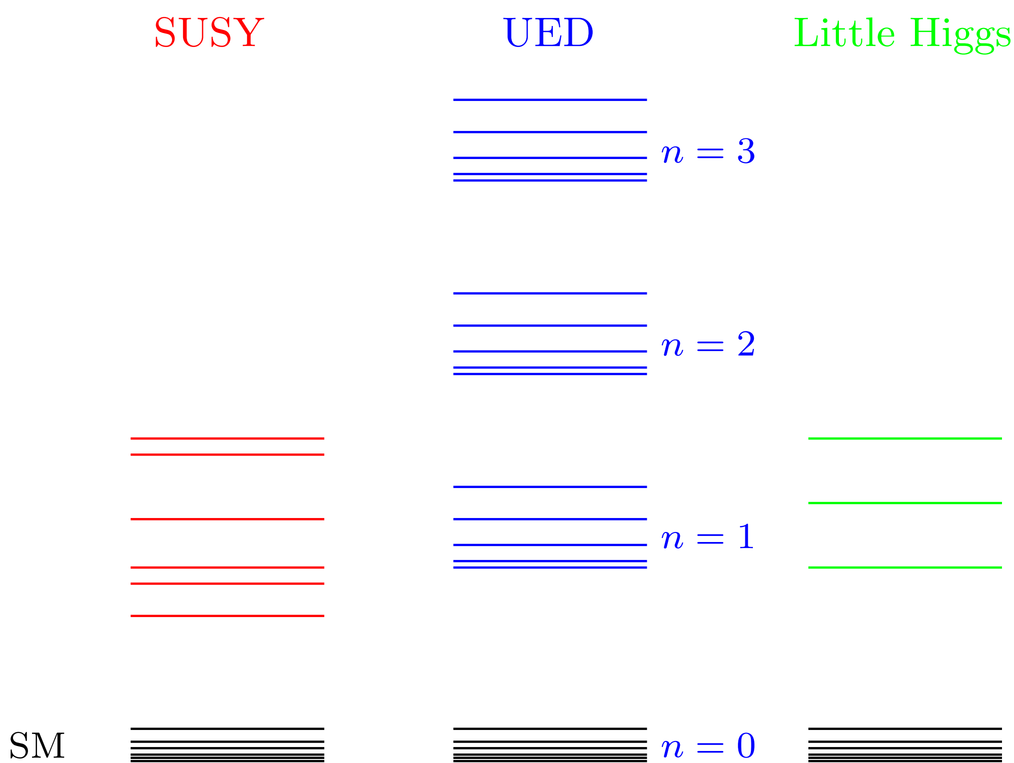
Appelquist, Cheng, Dobrescu, hep-ph/0012100

- 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

Model summary

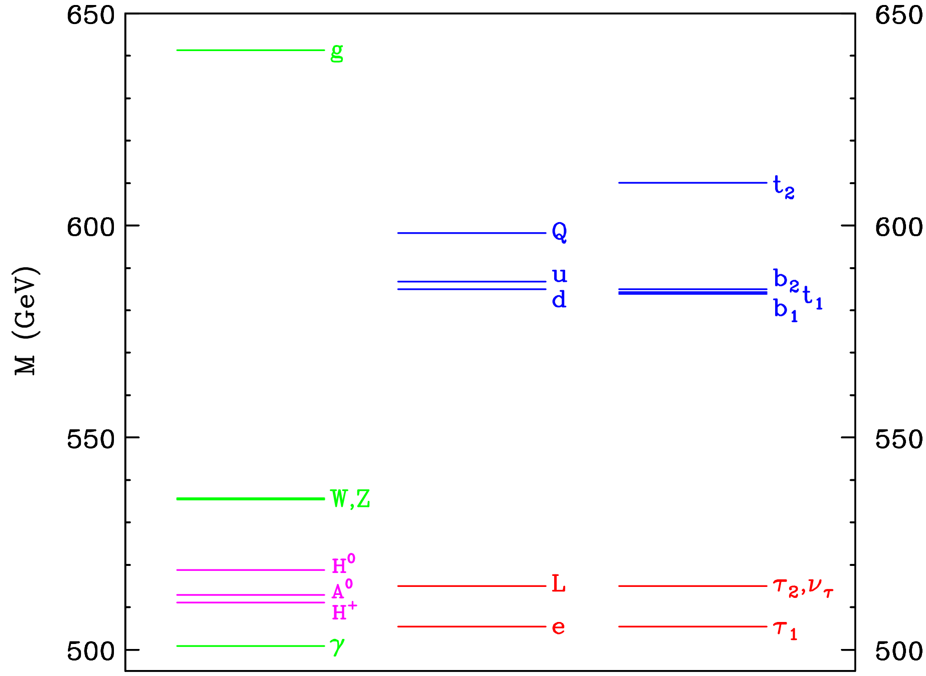


	SUSY	UED	Little Higgs
DM particle	LSP	LKP	LTP
Spin	1/2	1	0
Symmetry	R-parity	KK-parity	T-parity
Mass range	50-200 GeV	600-800 GeV	700-800 GeV

UED spectrum at level 1

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

Cheng, KM, Schmaltz, hep-ph/0204342



- Mimics (fermionic) supersymmetry!
- 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

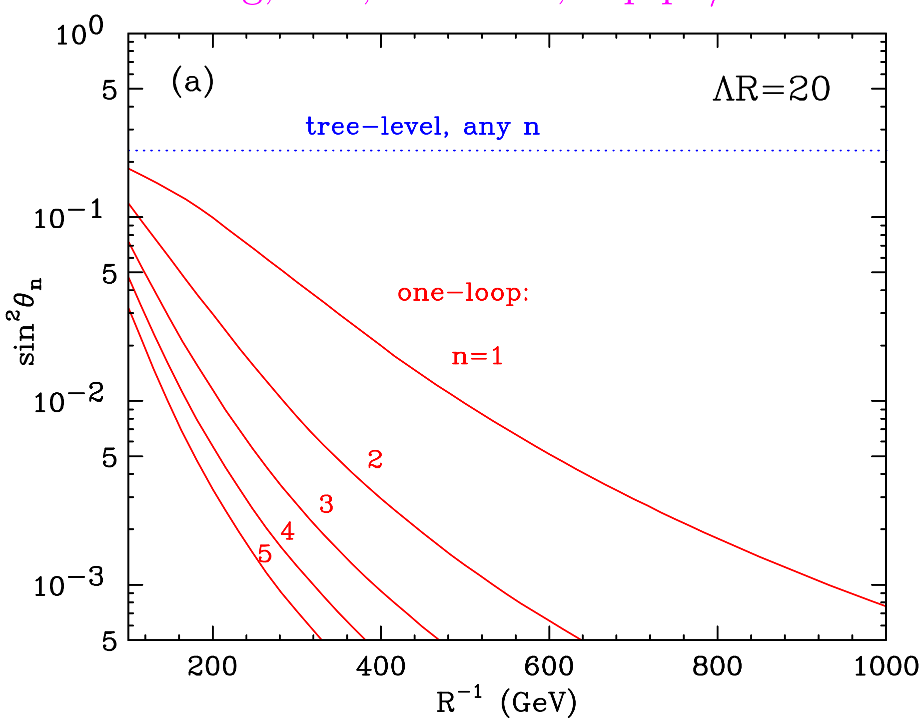
- Mass matrix for the neutral gauge bosons

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

- The Weinberg angle θ_n at KK level n

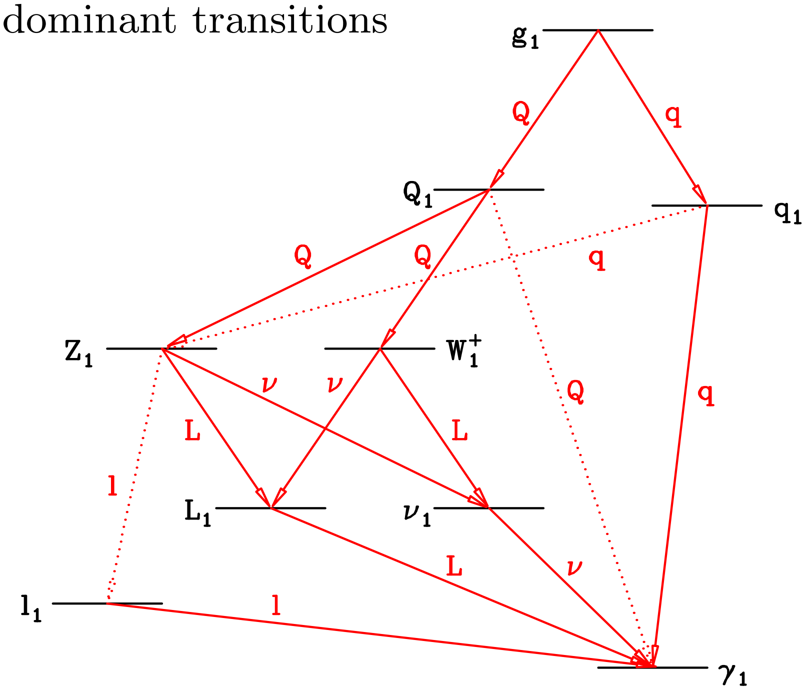
$$\gamma_n = \cos\theta_n B_n^0 + \sin\theta_n W_n^0 \approx B_n^0.$$

Cheng, KM, Schmaltz, hep-ph/0204342



Level 1 Spectroscopy

- 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 $q \to \gamma_1 q_0$
- Doublet KK quarks:

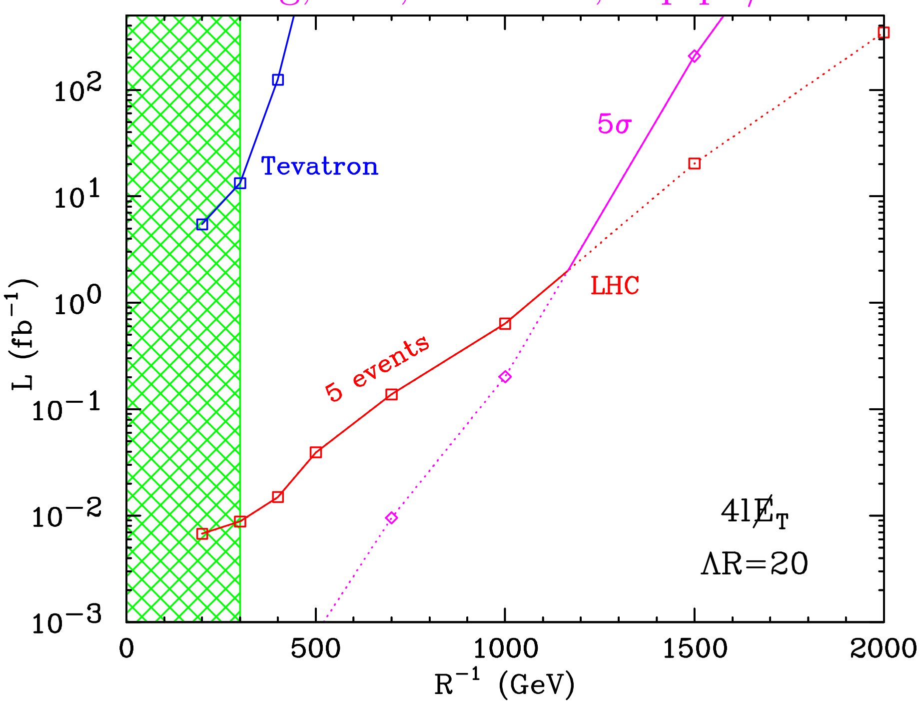
$$B(Q_1 \to W_1^{\pm} Q_0') \sim 65\% \qquad B(Q_1 \to Z_1 Q_0) \sim 33\%$$

- 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 discovery reach at the Tevatron and LHC

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

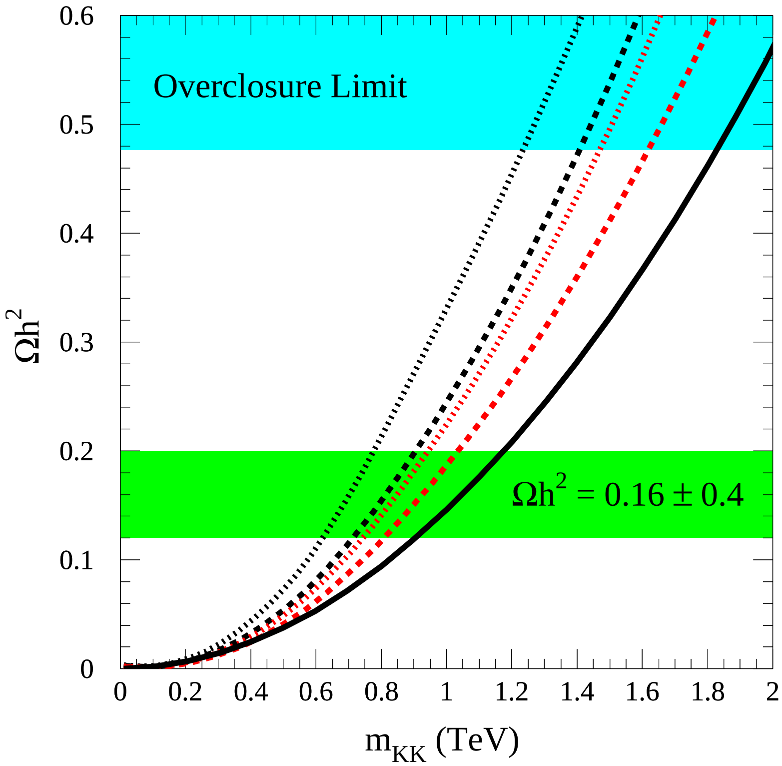
Cheng, KM, Schmaltz, hep-ph/0205314



- Typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (LHC can't measure it)

Kaluza-Klein dark matter

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



- Unlike supersymmetry: no helicity suppression

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

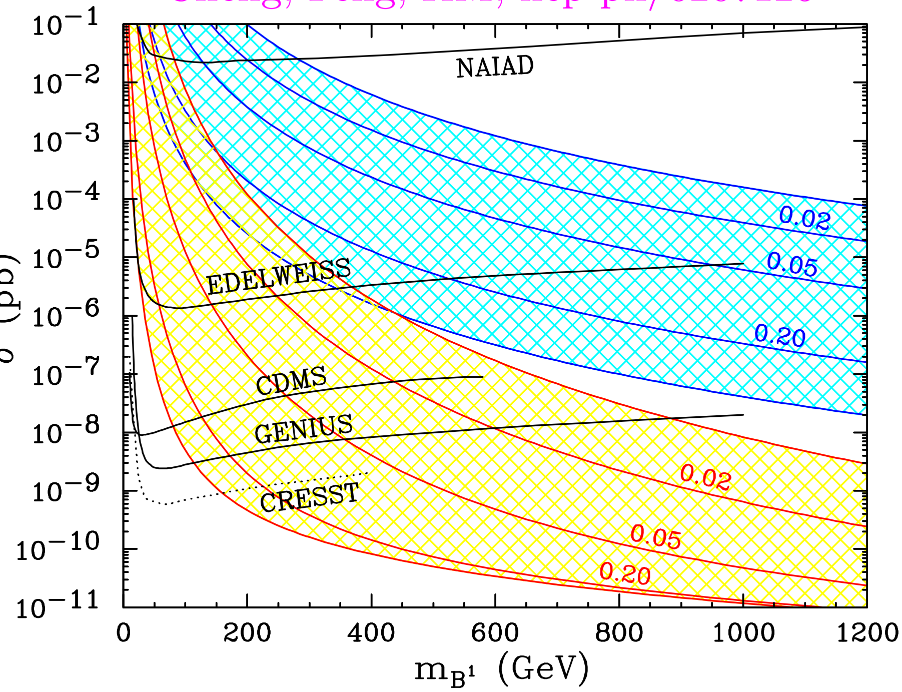
$$a = \frac{\alpha_1^2}{M_{KK}^2} \frac{380\pi}{81}; \qquad b = -\frac{\alpha_1^2}{M_{KK}^2} \frac{95\pi}{162}.$$

- Unlike supersymmetry: coannihilation lowers the bound

KK 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

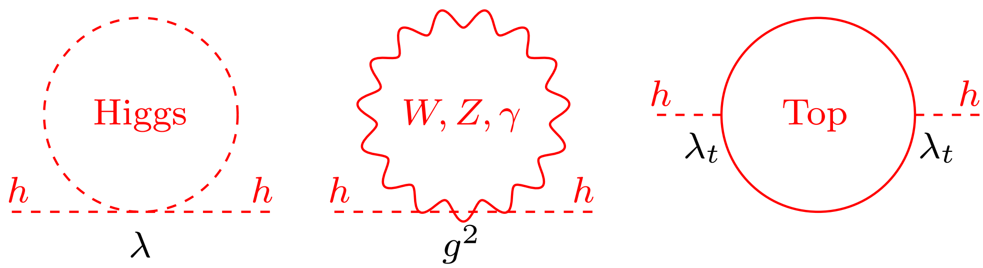
Servant, Tait, hep-ph/0209262

Majumdar, hep-ph/0209277

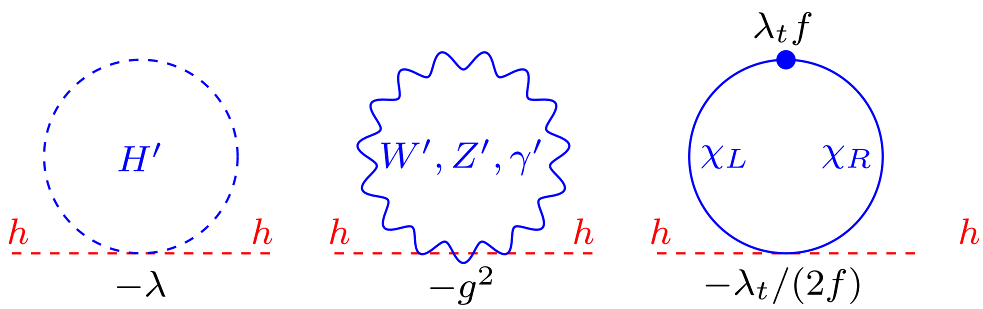
- Constructive interference: lower bound!

Little Higgs models

- The hierarchy problem in the SM



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



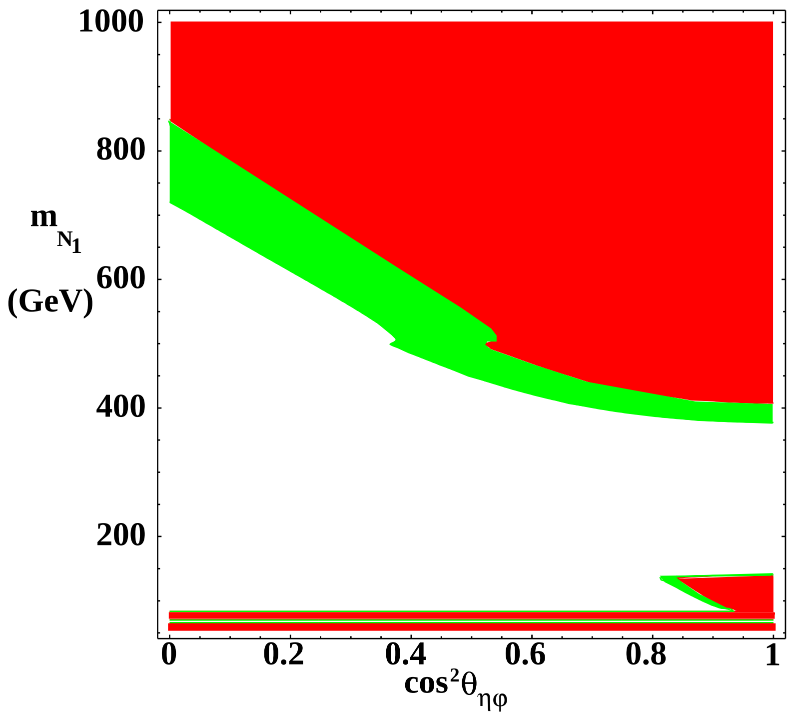
- Conserved T-parity (Cheng, Low hep-ph/0308199)
  - $T = 0$ for SM particles, $T = -1$ for new particles.
  - the lightest T-odd particle is stable.
- No tree-level contributions to precision EW observables

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-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 versus UED at a LC

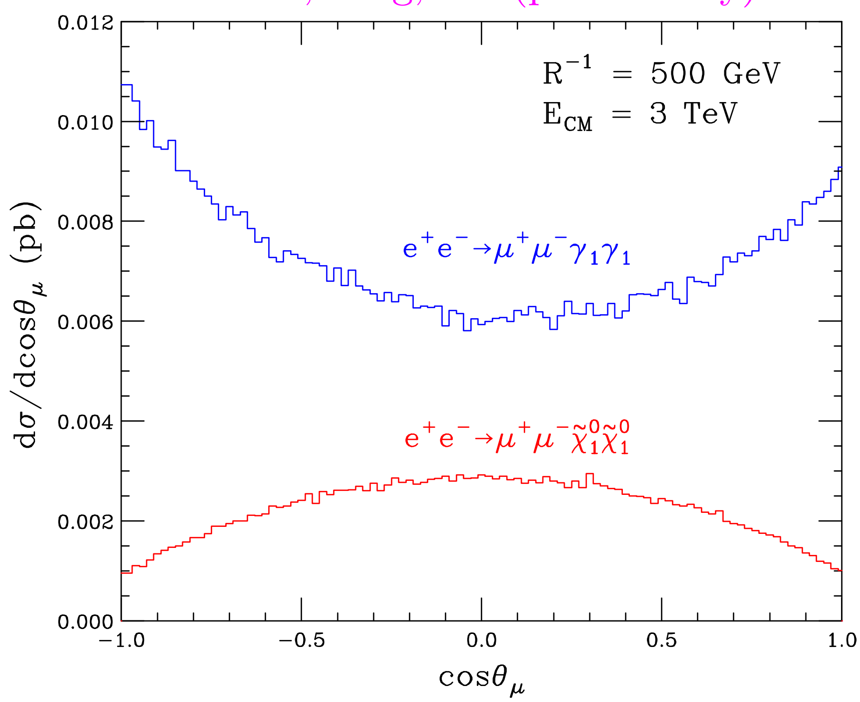
- The spin information is encoded in the angular distributions!

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.

The Message

- Recent new ideas in particle physics lead to novel alternatives for dark matter candidates. SUSY DM? Not so fast...
- Dark matter detection experiments should be prepared for surprises, avoid theory bias.
- Elucidating the nature of the dark matter can be challenging in either direct detection experiments or hadron colliders.
- Astroparticle physics experiments in space may provide important clues to the identity of the dark matter particle.