Missing E_T – Not!

Jonathan Feng
University of California, Irvine
17 April 2009

1st Year @ the LHC
UC Riverside
West Coast LHC Theory Network

1^{st} Year @ the LHC

- What does this mean? Assume luminosity ~ 100 pb^{-1}
- Lots of SM physics, calibration of detectors, etc.
- What about new physics?
- Higgs discovery requires ~10 fb^{-1}
- Missing E_T (MET) searches require a lot, too
- Here consider alternatives to MET: “exotica”

WHY CONSIDER EXOTICA?

- Some exotica aren’t really all that exotic
- Urgent – real possibilities for 2009-10
- You have the potential to advance science

Would experimentalists have thought of this if you didn’t do this work?

— *Ed Witten*

- …and you might actually advance science

Never start a project unless you have an unfair advantage.

— *Nati Seiberg*

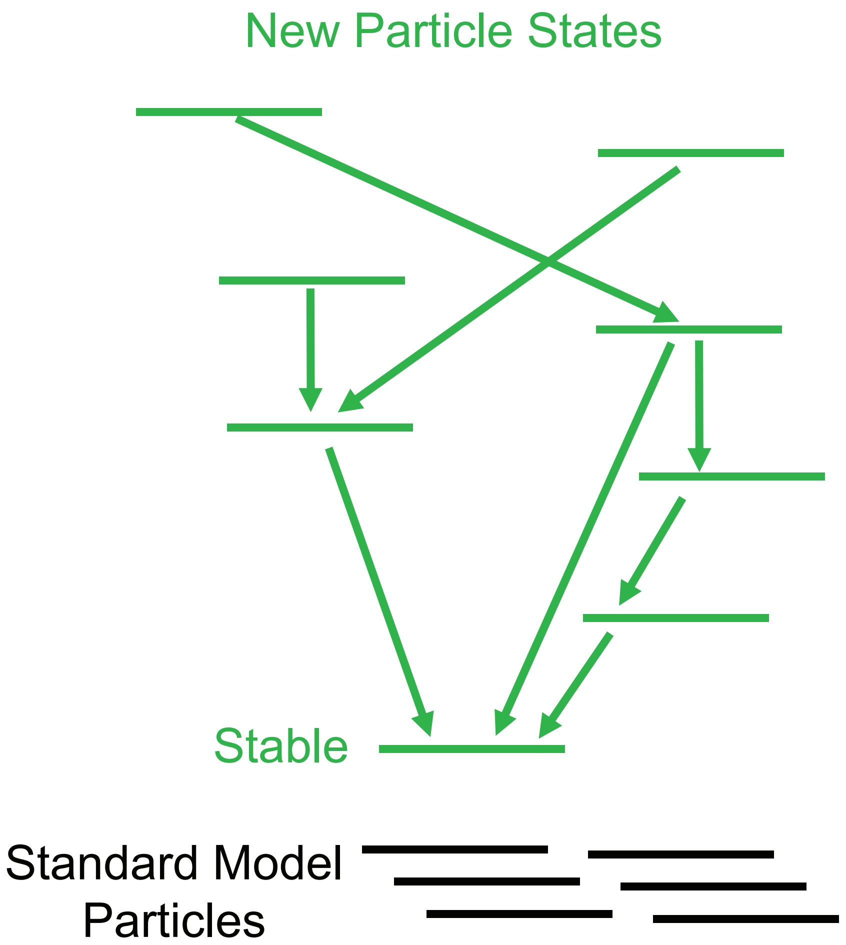
- It’s fun

If every individual student follows the same current fashion …, then the variety of hypotheses being generated…is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view … -- who will find it? Only someone who has sacrificed himself…I say sacrificed himself because he most likely will get nothing from it…But, if my own experience is any guide, the sacrifice is really not great because…you always have the psychological excitement of feeling that possibly nobody has yet thought of the crazy possibility you are looking at right now.

– Richard Feynman, Nobel Lecture

MET MYTHS

- Myth #1: Dark matter → MET at the LHC



EXAMPLES

- Supersymmetry
  - R-parity
  - Neutralino DM

Goldberg (1983); Ellis et al. (1984)

- Universal Extra Dimensions
  - KK-parity
  - Kaluza-Klein DM

Appelquist, Cheng, Dobrescu (2000)

Servant, Tait (2002)

Cheng, Feng, Matchev (2002)

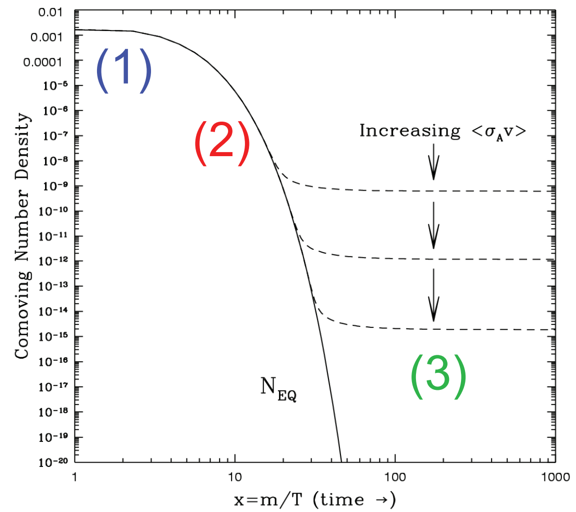
- Branes
  - Brane-parity
  - Branons DM

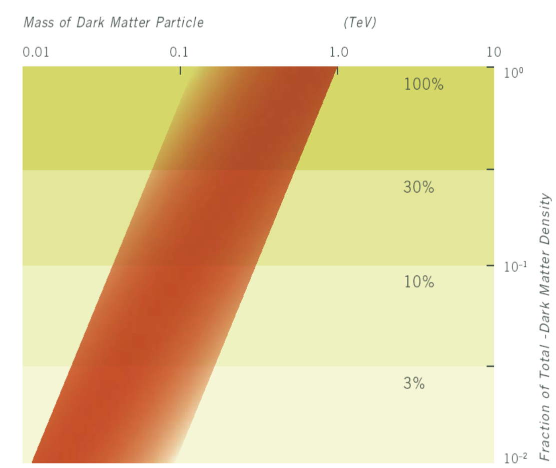
Cembranos, Dobado, Maroto (2003)

- …

COUNTER-ARGUMENTS

- Dark matter might be axions or something else, completely decoupled from weak scale physics
- But what about the WIMP miracle?
- Seems to argue for stable WIMPs and therefore MET





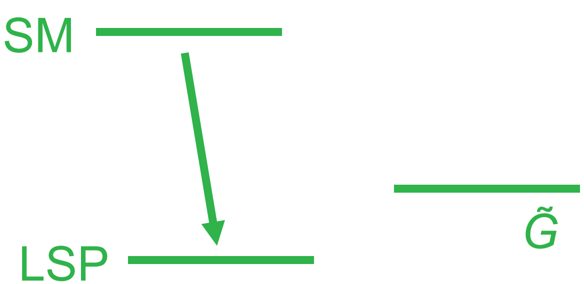
HEPAP LHC/ILC Subpanel (2006)
[band width from k = 0.5 – 2, S and P wave]

COUNTEREXAMPLE: SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

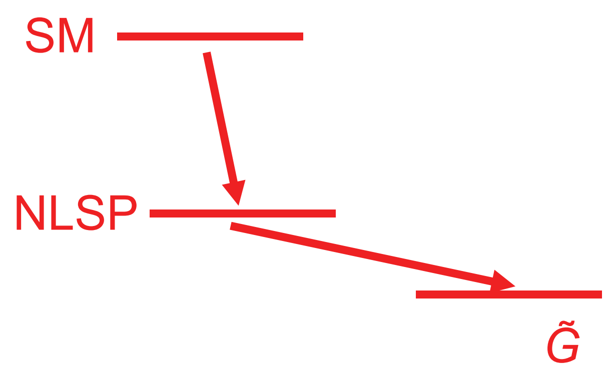
Gravitino mass ~ 100 GeV, couplings ~ M_W/M_{Pl} ~ 10^{-16}

- $\tilde{G}$ not LSP



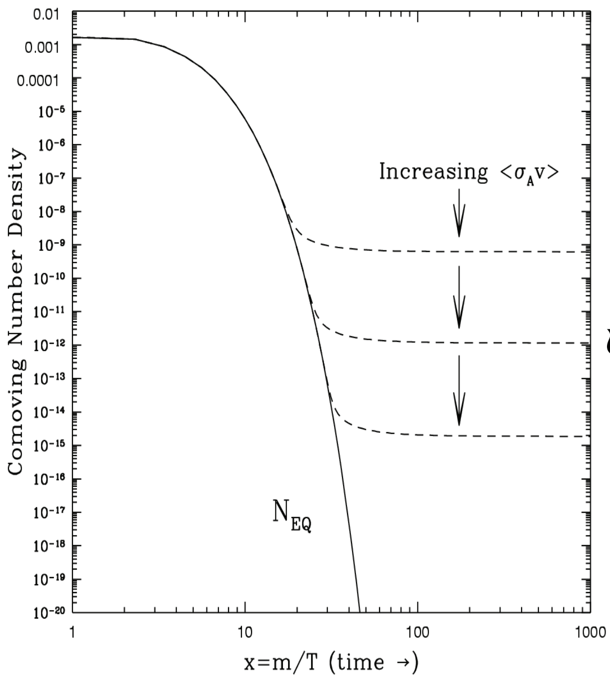
- Assumption of most of literature

- $\tilde{G}$ LSP



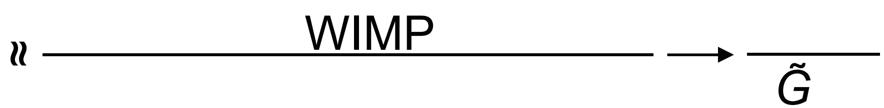
- Completely different cosmology and particle physics

SUPERWIMP RELICS



- Suppose gravitinos $\tilde{G}$ are the LSP

- WIMPs freeze out as usual



- But then all WIMPs decay to gravitinos after
  M_{Pl}^2/M_W^3 ~ seconds to months

Like WIMPs: a particle (gravitino) naturally gets the right relic density

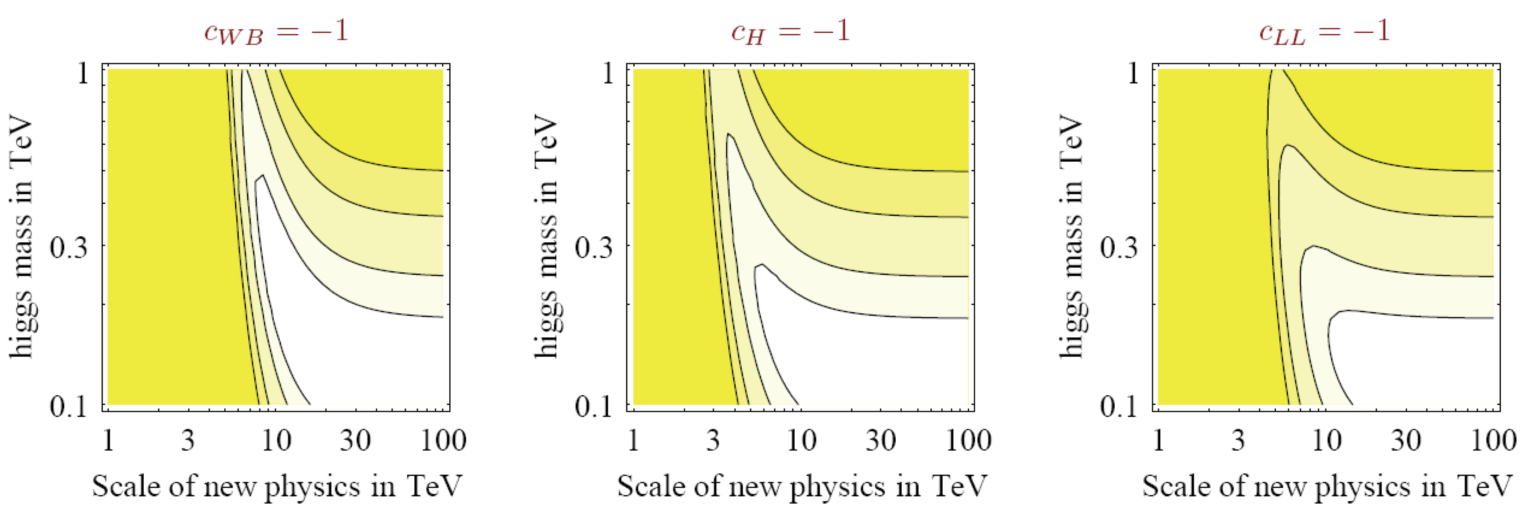
Unlike WIMPs: the WIMP can be charged, signal is CHAMP, not MET

MYTH 2: PRECISION EW → MET

- Large Electron Positron Collider at CERN, 1989-2000

- LEP and SLC confirmed the standard model, stringently constrained effects of new particles

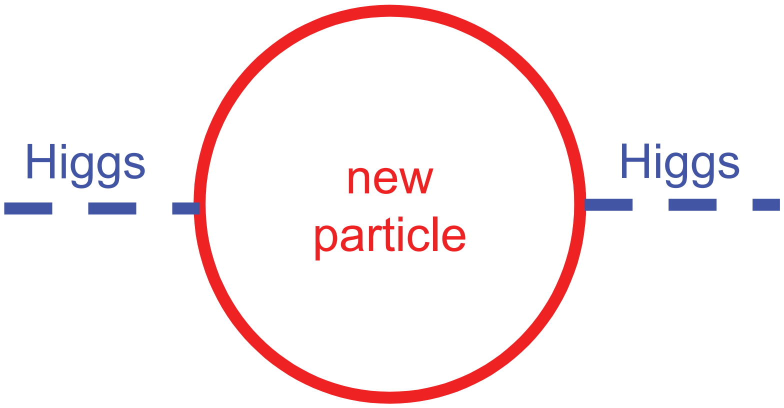
- Problem: Gauge hierarchy → new particles ~100 GeV
  LEP/SLC → new particles > 3 TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)



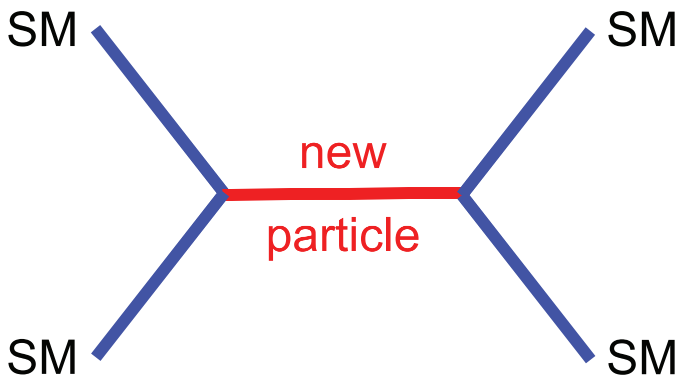
Barbieri, Strumia (2000)

LEP'S COSMOLOGICAL LEGACY

Gauge Hierarchy



Precision EW



- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

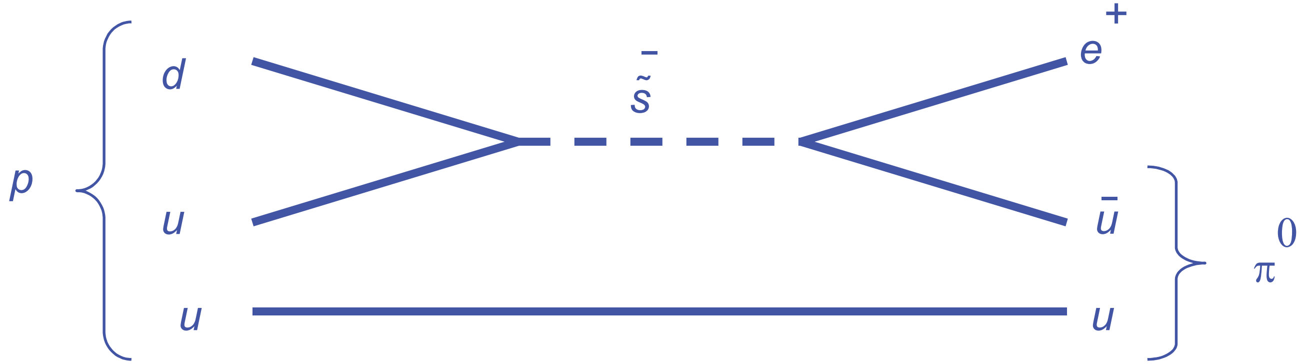
Cheng, Low (2003); Wudka (2003)

- This is a powerful argument that the LHC may make DM

- It does not necessarily imply MET, though (see superWIMPs)

MYTH 3: OTHER CONSTRAINTS → MET

- E.g., proton decay in SUSY:



- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\ R_p = 1$ at all vertices
- Consequence: the lightest SUSY particle (LSP) is stable

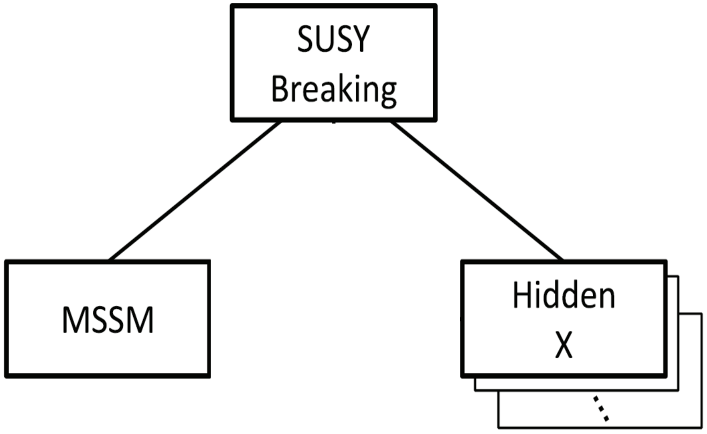
But this also does not require MET

- Even with R-parity conservation, gravitino could be the stable LSP
- R-parity might be broken: B or L conservation each forbids proton decay, don't need both
- R-parity might be broken and DM could be stabilized by another symmetry

EXAMPLE: WIMPLESS DM

Feng, Kumar (2008)

- Consider SUSY with GMSB. Suppose there are additional “hidden” sectors linked to the same SUSY breaking sector



- These sectors may have different
  - masses m_X
  - gauge couplings g_X

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

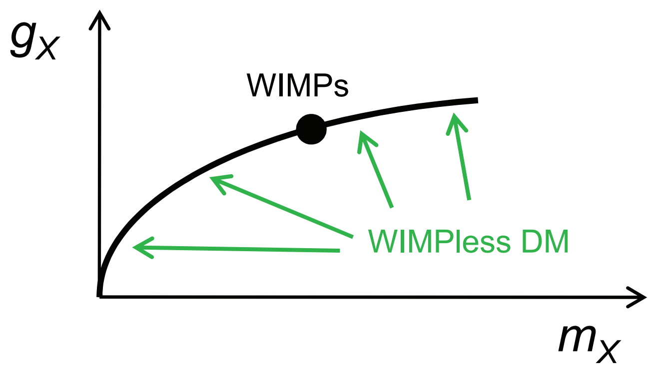
- But $m_X \sim g_X^2$ and so $\Omega_X \sim$ constant

THE WIMPLESS MIRACLE

- The thermal relic density constrains only one combination of g_X and m_X

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- These models map out the remaining degree of freedom



- This framework decouples the WIMP miracle from WIMPs, candidates have a range of masses/couplings, but always the right relic density
- The flavor problem becomes a virtue
- Naturally accommodates multi-component DM, all with relevant Ω

HIDDEN CHARGED DM

- This requires that an m_X particle be stable. Is this natural?

MSSM		Flavor-free MSSM O(1) Yukawas	
m_W	sparticles, W, Z, t	m_X	sparticles, W, Z, q, l, $\tilde{\tau}$ (or τ)
~GeV	q, l		
0	p, e, γ, ν, $\tilde{G}$	0	g, γ, ν, $\tilde{G}$

- If the hidden sector is a “flavor-free” MSSM, natural DM candidate is any hidden charged particle, stabilized by exact $U(1)_{EM}$ symmetry with no need for R_p conservation

BOTTOM LINE

- MET is just one of many possible signatures of new physics at the LHC
- Easy to think of scenarios that
  - Solve the gauge hierarchy problem
  - Have DM with naturally the right relic density
  - Are consistent with EW precision constraints
  - Are consistent with all other constraints
  - Have no MET signal at the LHC
- Consider other signatures: what do they mean for the 1st year of the LHC?

A SIMPLE MODEL

Feng, Rajaraman, Smith (2005)

- Consider the usual mSUGRA defined by

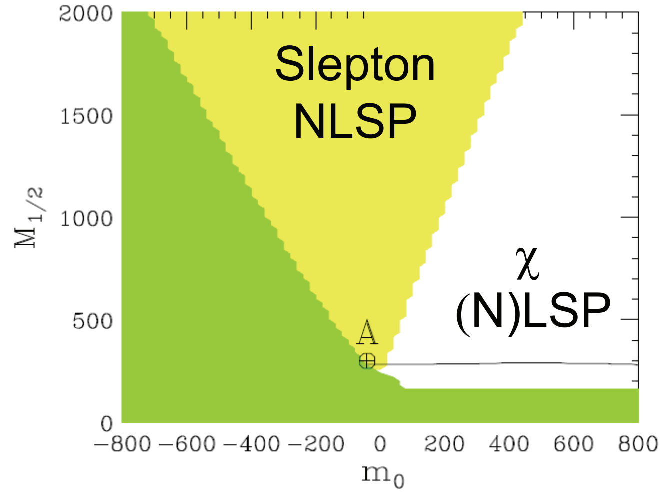
$$m_0^2, M_{1/2}, A_0, \tan\beta, \text{ sign}(\mu), \text{ and } m_{3/2}$$

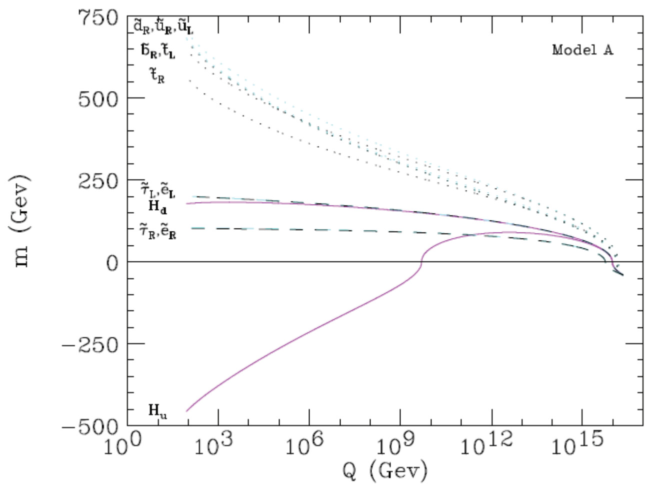
but with small or negative

$$m_0 \equiv \text{sign}(m_0^2)\sqrt{|m_0^2|}$$

- This includes no-scale/gaugino-mediated models with $m_0 = 0$

- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP





DISCOVERY POTENTIAL

Rajaraman, Smith (2008)

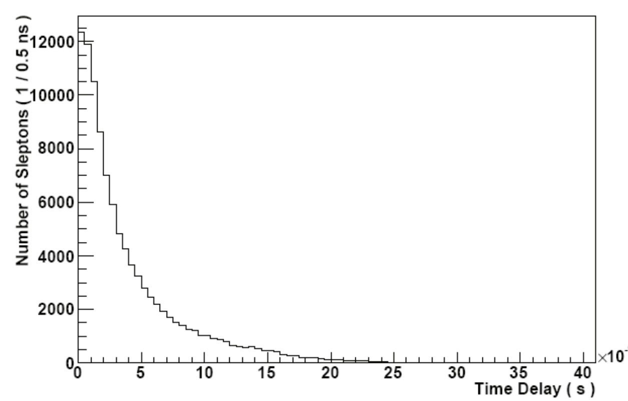
- Look for Drell-Yan slepton pair production; sleptons look like muons, but some are slow

- Require events with 2 central, isolated "muons" with
  - $m_{\mu\mu}$ > 120 GeV
  - p > 100 GeV
  - p_T > 20 GeV

- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays > 3 ns

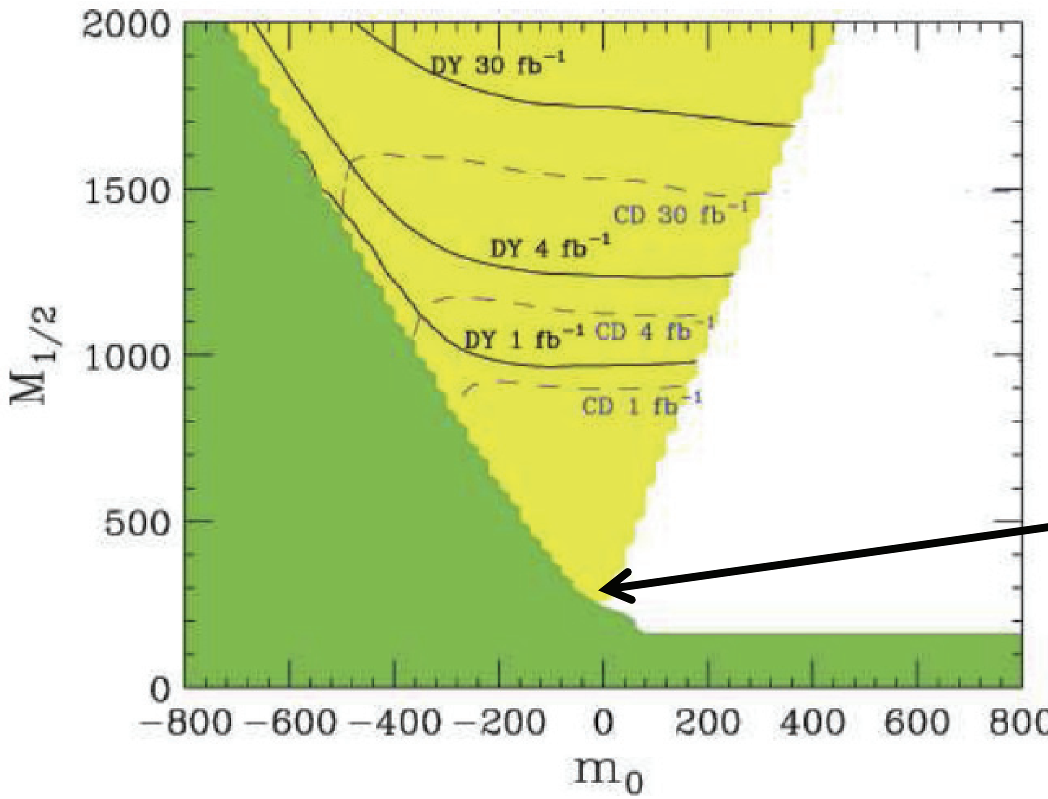
	Total cross-section	After Drell-Yan cuts
Model A	18pb	9pb
Model B	43fb	28fb
QCD	10^2mb	< 1pb
$\gamma^*/Z \to \mu\mu$	100nb	3pb
W+jet	360nb	< 40fb
Z+jet	150nb	7pb
$t\bar{t}$	800pb	430fb
WW,WZ,ZZ	2.5nb	150fb

Time delay of	0ns	1 ns	2ns	3ns	4ns	5ns
Drell-Yan; background	10pb	1.35pb	3.3fb	0.2ab	< 0.1ab	< 0.1ab
Drell-Yan; Model A	9pb	5.2pb	2.9pb	1.8pb	1.1 pb	750fb



DISCOVERY POTENTIAL

- Require 5σ signal with S > 10 events for discovery

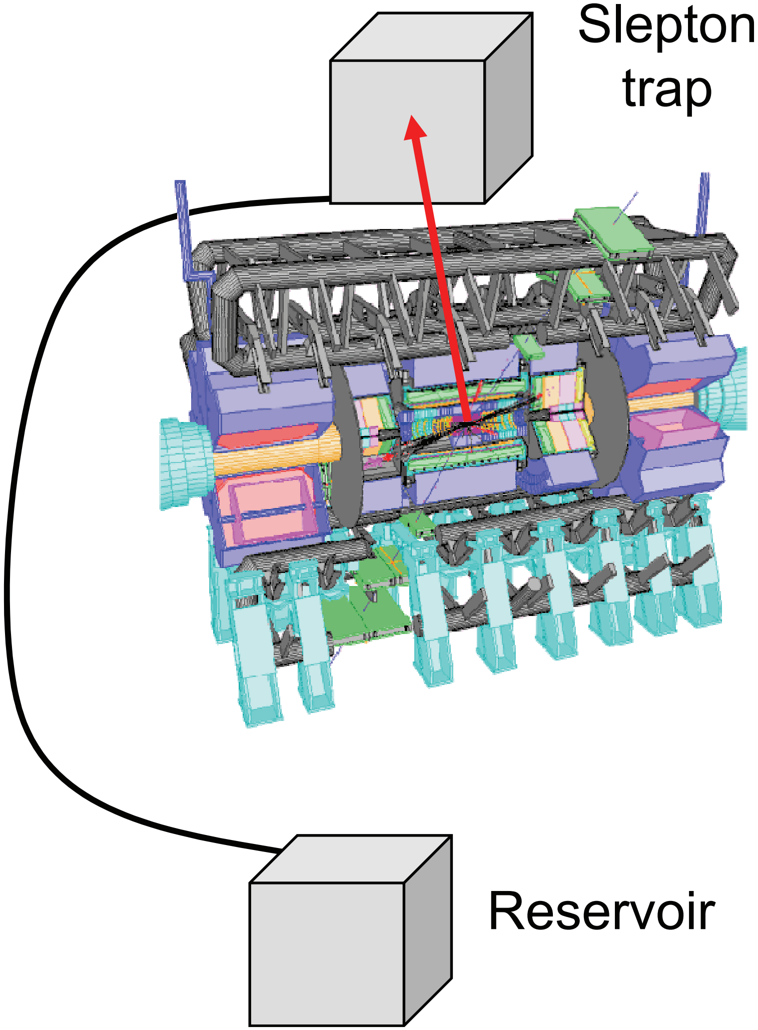


Model A discovered with 5 pb^{-1}

Slepton Trapping

- Sleptons can be trapped and moved to a quiet environment to study their decays

- Crucial question: how many can be trapped by a reasonably sized trap in a reasonable time?

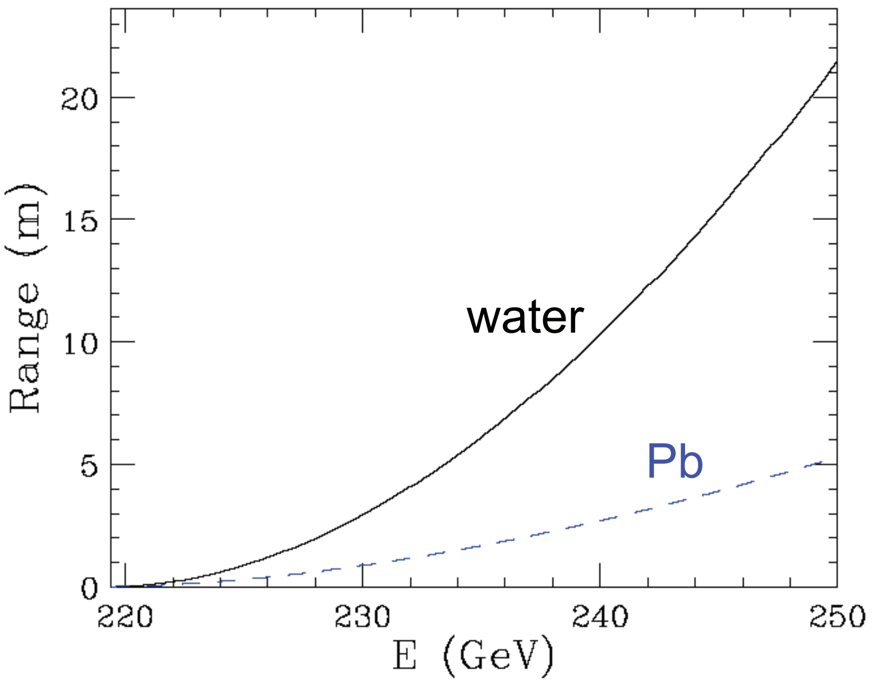


Feng, Smith (2004)
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)

Slepton Range

- Ionization energy loss described by Bethe-Bloch equation:

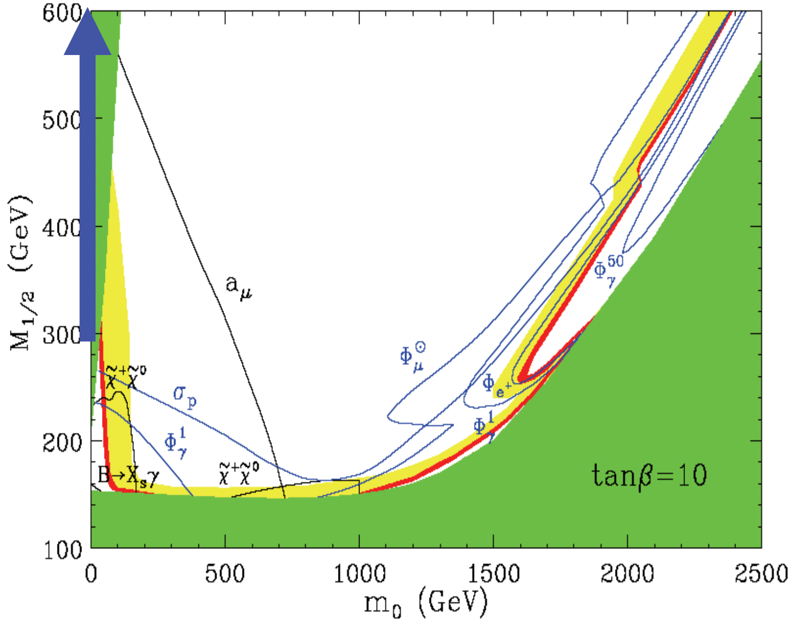
$$\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I \sqrt{1 + \frac{2 m_e \gamma}{M} + \frac{m_e^2}{M^2}}} \right) - \beta^2 - \frac{\delta}{2} \right]$$

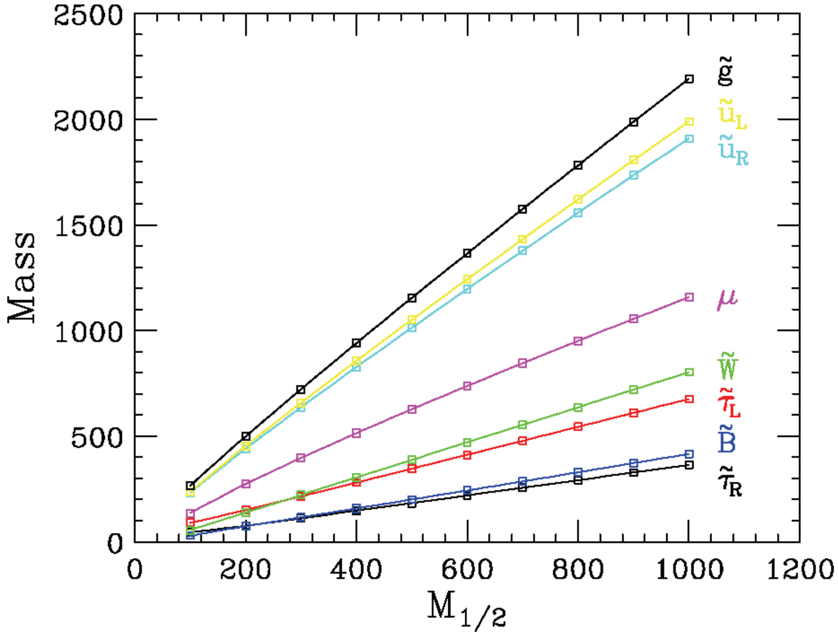


$m_{\tilde{l}}$ = 219 GeV

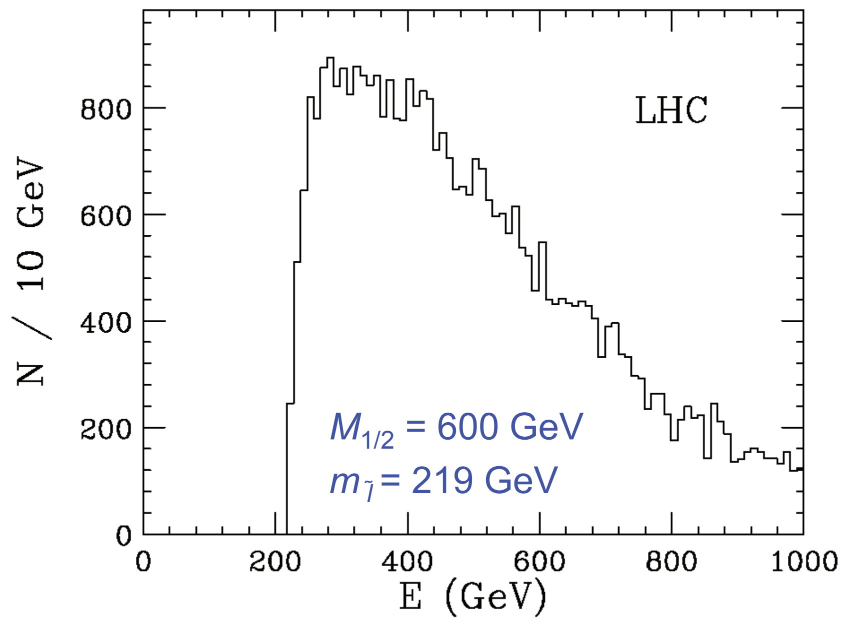
Model Framework

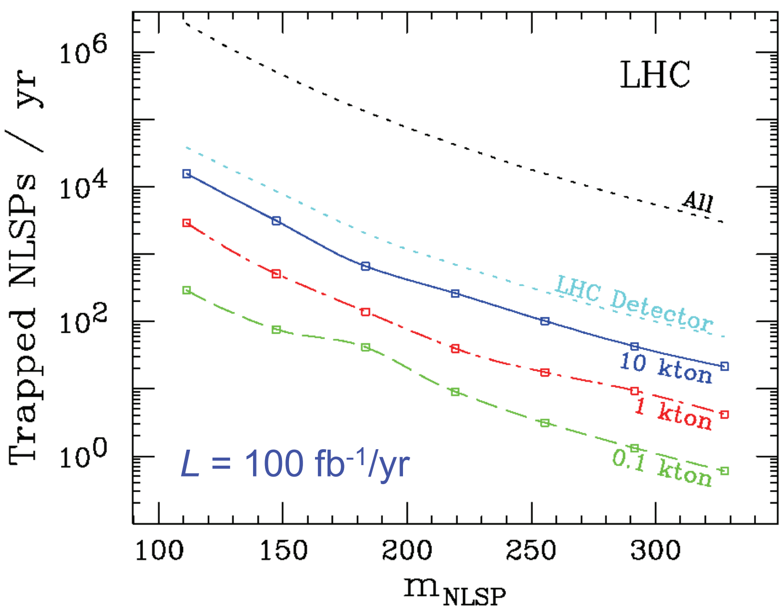
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with $m_0 = A_0 = 0$, $\tan\beta = 10$, $\mu > 0$
  $M_{1/2}$ = 300, 400,…, 900 GeV





Large Hadron Collider



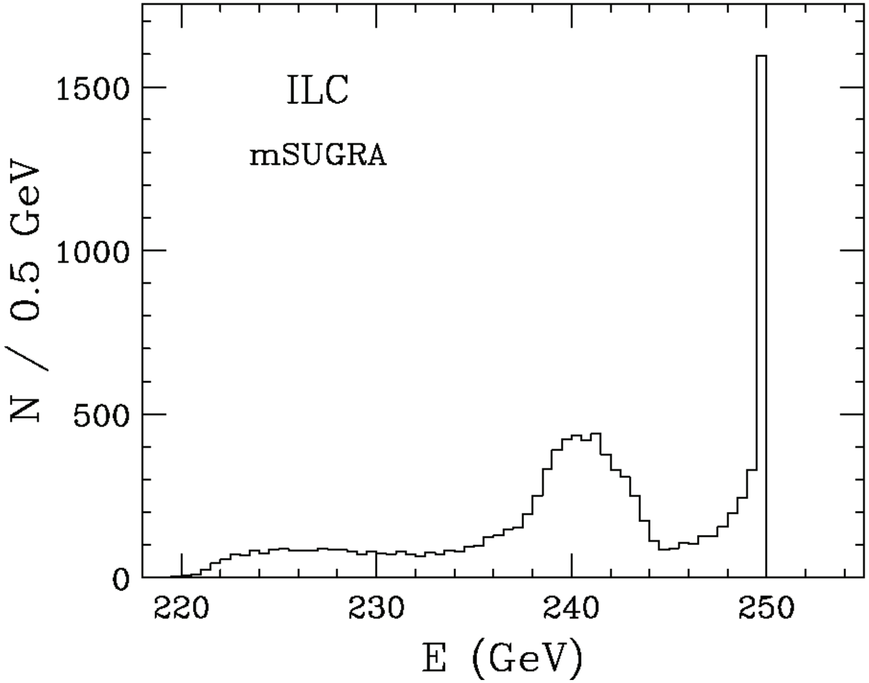


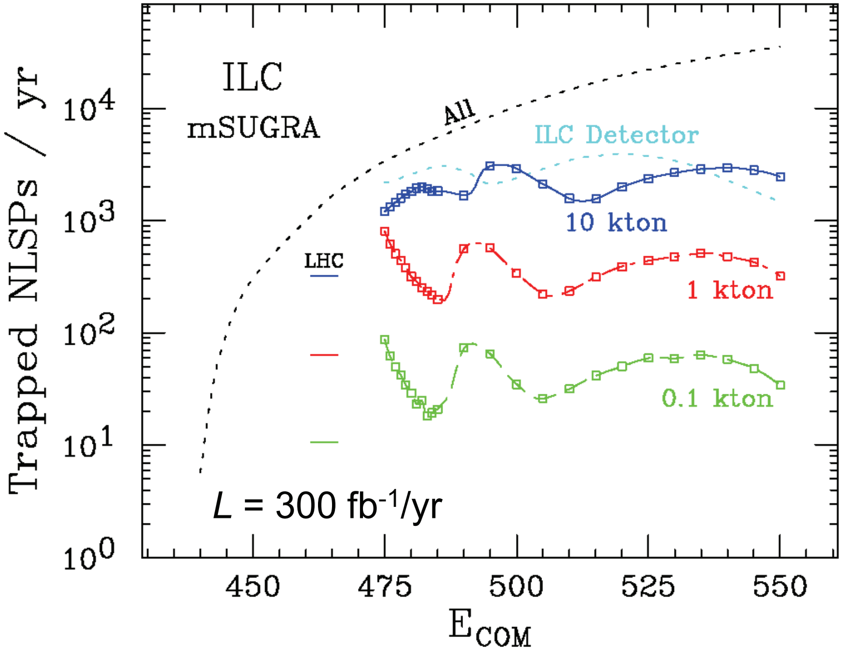
Of the sleptons produced, $O(1)$% are caught in 10 kton trap

10 to 10^4 trapped sleptons in 10 kton trap (1 m thick)

International Linear Collider

m_χ	242.9 GeV		} mSUGRA
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	227.2 GeV		
$m_{\tilde{\tau}_R}$	219.3 GeV	} NLSP only	





Sleptons are slow, most can be caught in 10 kton trap

Factor of ~10 improvement over LHC

Measuring $m_{\tilde{G}}$ and M_*

- Decay width to $\tilde{G}$:

$$\Gamma(\tilde{\ell} \to \ell \tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{\ell}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right]^4$$

- Measurement of Γ → $m_{\tilde{G}}$
  - → $\Omega_{\tilde{G}}$. SuperWIMP contribution to dark matter
  - → *F*. Supersymmetry breaking scale, dark energy
  - → Early universe (BBN, CMB) in the lab

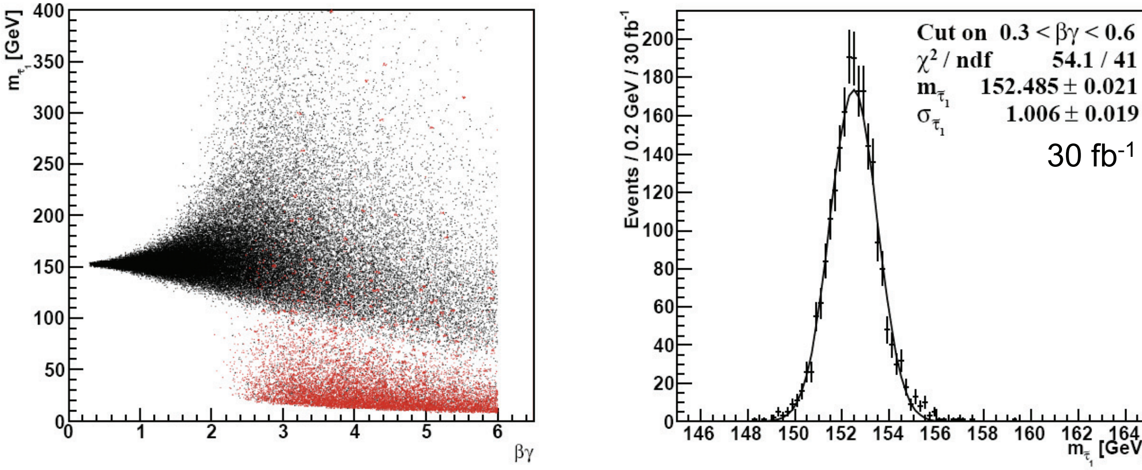
- Measurement of Γ *and* E_l → $m_{\tilde{G}}$ *and* M_*
  - → Precise test of supergravity: gravitino is graviton partner
  - → Measurement of G_{Newton} on fundamental particle scale
  - → Probes gravitational interaction in particle experiment

Hamaguchi et al. (2004); Takayama et al. (2004)

MASS DETERMINATION

- Metastable slepton masses may be measured precisely

$$m_{\tilde{\tau}_1} = \frac{p_{\text{meas}}}{\beta\gamma_{\text{meas}}}$$



Ellis, Raklev, Oye (2005)

Figure 3: Scatter plot of measured velocity $\beta\gamma_{\text{meas}}$ versus measured mass (left), with supersymmetric events in black and SM background events in red, and a corresponding plot of the measured stau mass (right) with an additional cut on the velocity of $0.3 < \beta\gamma < 0.6$.

FLAVOR MIXINGS

- In these scenarios, all particles are observed
- Ideal settings for detailed measurements of masses and mixings
- Consider, e.g., hybrid SUSY models:
  flavor-conserving mGMSB + flavor-violating gravity-mediated masses

$$
\begin{aligned}
M^2_{\tilde{\nu}} &= m^2_{\tilde{L}} \mathbf{1} + x \tilde{m}^2 X_L \\
M^2_{\tilde{E}_L} &= m^2_{\tilde{L}} \mathbf{1} + m_E m_E^\dagger + x \tilde{m}^2 X_L \\
M^2_{\tilde{E}_R} &= m^2_{\tilde{R}} \mathbf{1} + m_E^\dagger m_E + x \tilde{m}^2 X_R \, ,
\end{aligned}
$$

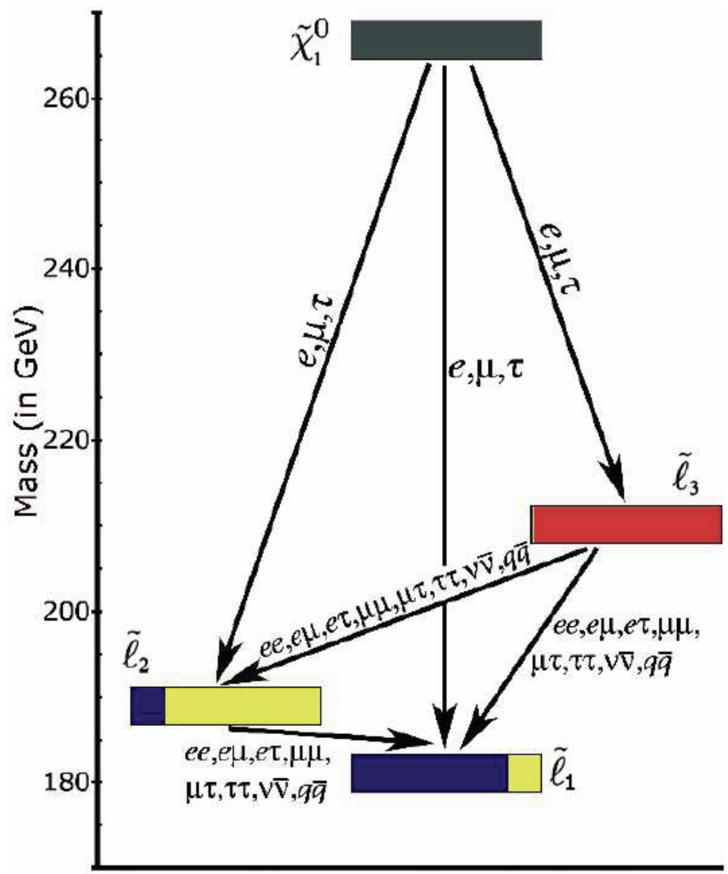
$$
X_L = \begin{pmatrix} c_{10}\lambda^{n10} & c_{11}\lambda^{n11} & c_{12}\lambda^{n12} \\ c_{11}\lambda^{n11} & c_{13}\lambda^{n13} & c_{14}\lambda^{n14} \\ c_{12}\lambda^{n12} & c_{14}\lambda^{n14} & c_{15}\lambda^{n15} \end{pmatrix}
$$

$$
X_R = \begin{pmatrix} c_{16}\lambda^{n16} & c_{17}\lambda^{n17} & c_{18}\lambda^{n18} \\ c_{17}\lambda^{n17} & c_{19}\lambda^{n19} & c_{20}\lambda^{n20} \\ c_{18}\lambda^{n18} & c_{20}\lambda^{n20} & c_{21}\lambda^{n21} \end{pmatrix}
$$

- Such models can explain the observed lepton masses and mixings; can they be tested at the LHC?

Feng, Lester, Nir, Shadmi (2007)

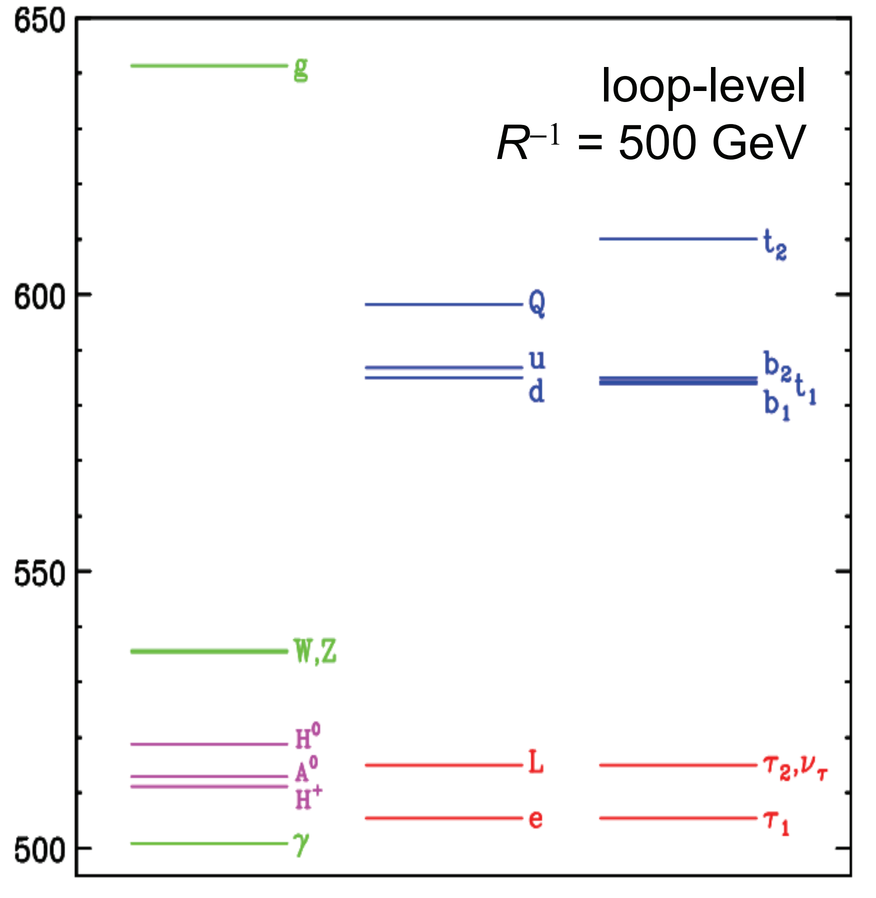
FLAVOR MIXINGS



Engelhard, Feng, Galon, Sanford, Yu (2009); see Felix's talk

ANOTHER EXAMPLE

- Universal Extra Dimensions: 5D, 5th dimension a circle with radius R
- All KK level 1 states have mass R^{-1}
- This is broken by many effects, but the lightest KK states are still highly degenerate



Cheng, Matchev, Schmaltz (2002)

UED Common Lore

- UED looks like SUSY
  - n=2 and higher levels typically out of reach
  - n=1 Higgses → A, H^0, $H^\pm$
  - Colored particles are heavier than uncolored ones
  - LKP is stable B^1 → missing energy at LHC

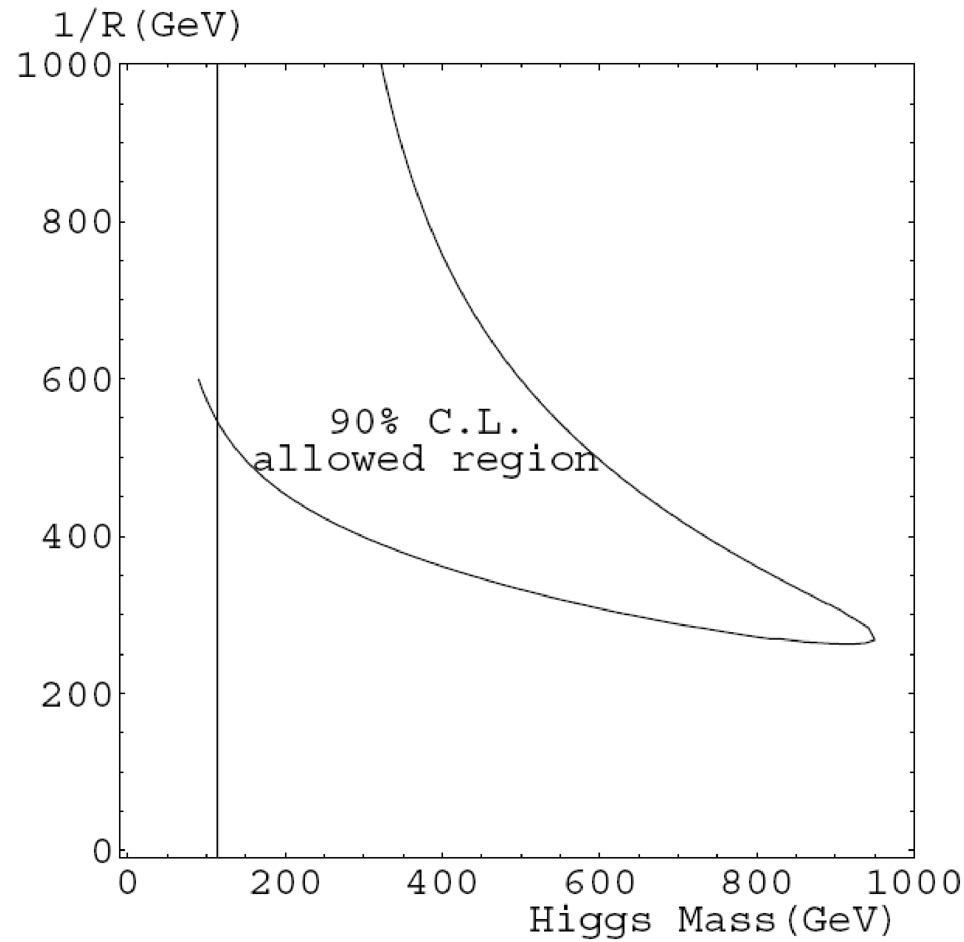
- Spectrum is more degenerate, but basically similar to SUSY

"Bosonic supersymmetry"

Cheng, Matchev, Schmaltz (2002)

But Wait, There's More

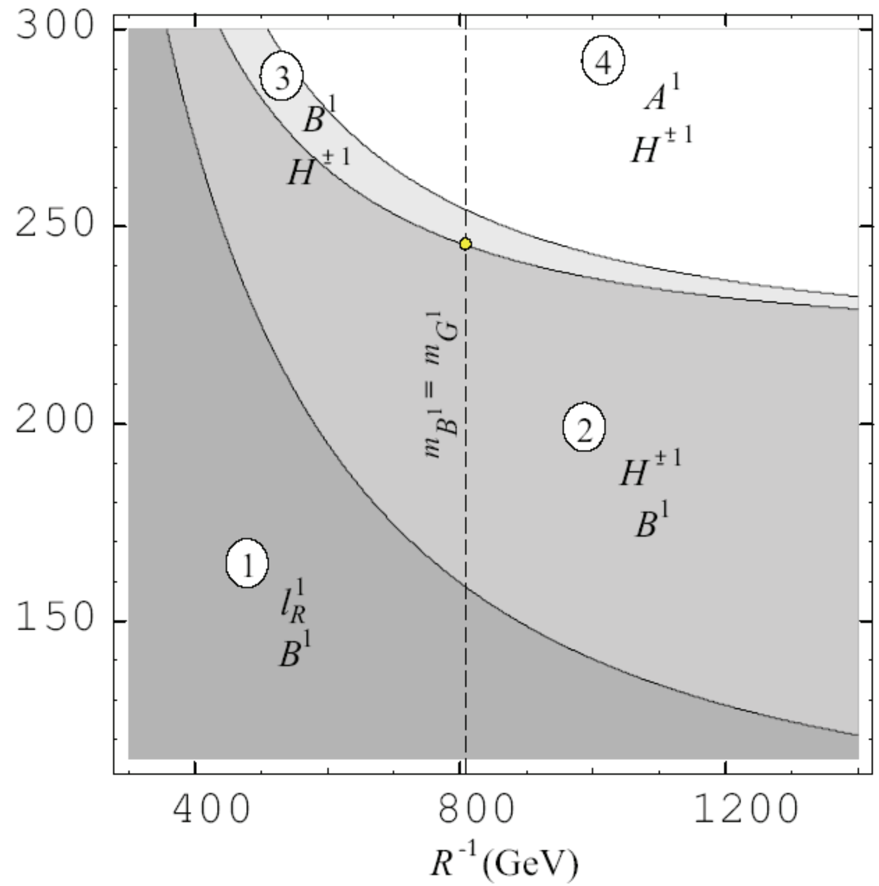
- R is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown
- These studies set m_h=120 GeV, but it can be larger
- H^0, A, $H^\pm$ masses depend on m_h



Appelquist, Yee (2002)

Collider Phase Diagram

- Then there are 4 (NLKP, LKP) phases
- Note: m_h=120 GeV lies entirely in Phase 1

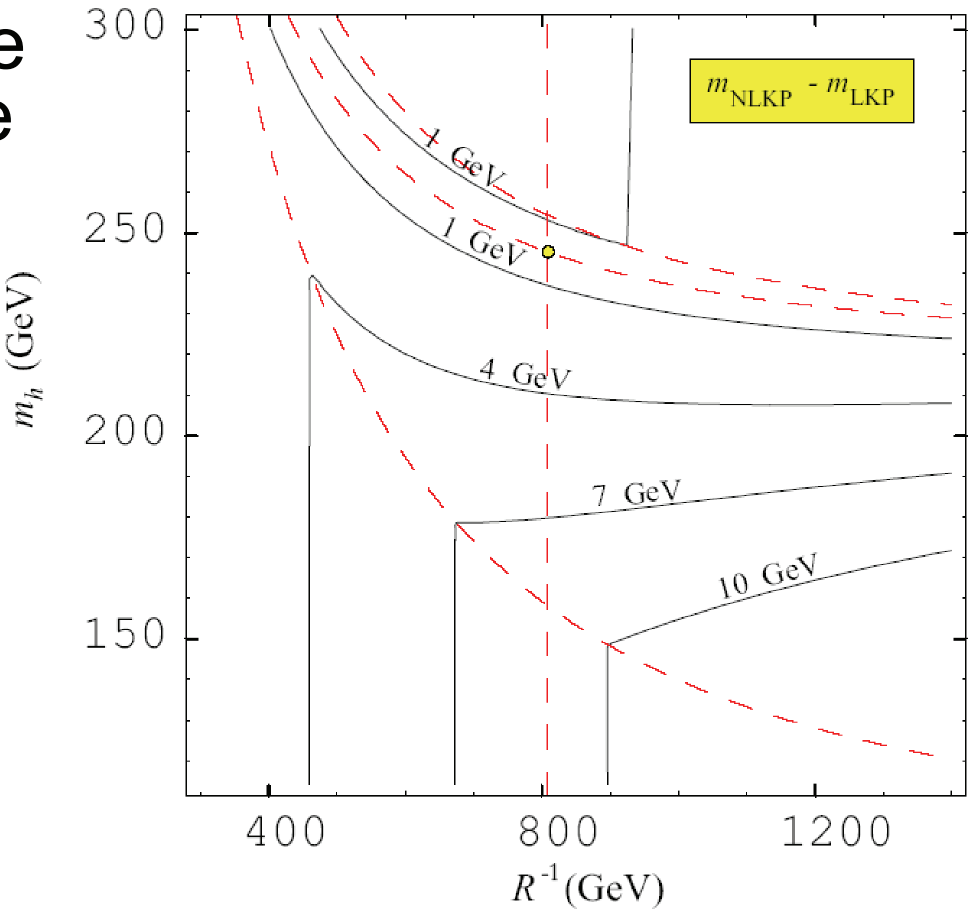


Cembranos, Feng, Strigari (2006)

Degeneracies

- The lightest states are extremely degenerate
- One might expect degeneracies of

  $m_W^2 R^{-1} \sim 10$ GeV
- Modest accidental cancelations tighten the degeneracies

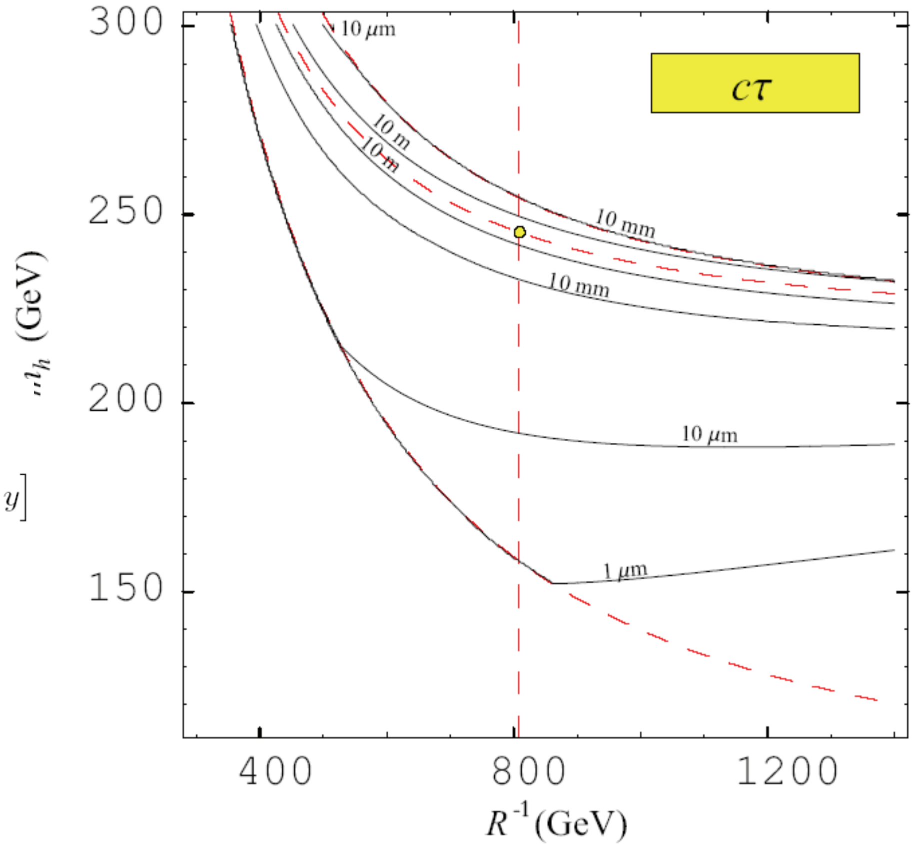


Cembranos, Feng, Strigari (2006)

NLKP Decays

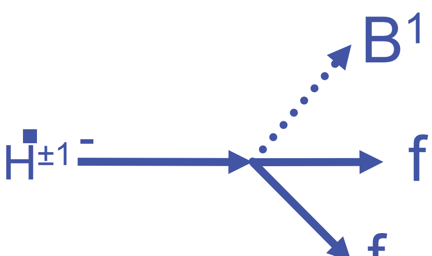
- This leads to long decay lengths: microns to 10 m

$$\Gamma(H^{\pm 1} \to B^1 f \bar{f}') = \frac{N_C g^2 g'^2}{49152\pi^3} \frac{M^5}{m_W^2 m_1^2} \times$$
$$\left[(1-y)(1+y+73y^2+9y^3)+12y^2(3+4y)\ln y\right]$$
$$\approx \frac{N_C \alpha^2}{80\pi \sin^2\theta_W \cos^2\theta_W} \frac{(\Delta m)^5}{m_W^2 M^2}$$
$$\simeq 1.96 \times 10^{-16} \text{ GeV } N_C \left[\frac{\Delta m}{\text{GeV}}\right]^5 \left[\frac{\text{TeV}}{M}\right]^2$$
$$\simeq \left[1.01 \text{ m} \frac{1}{N_C} \left[\frac{\text{GeV}}{\Delta m}\right]^5 \left[\frac{M}{\text{TeV}}\right]^2\right]^{-1},$$

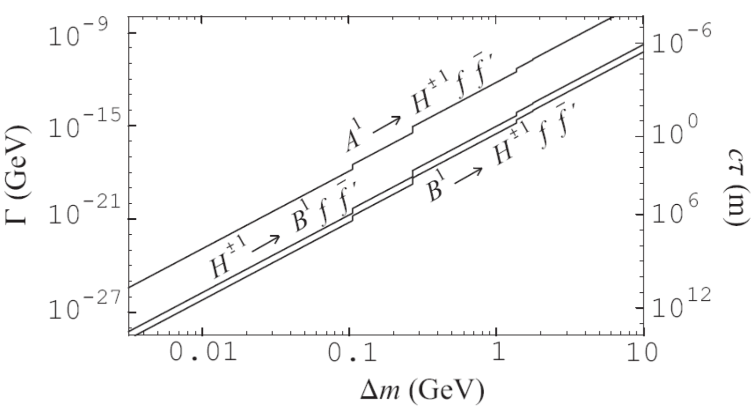


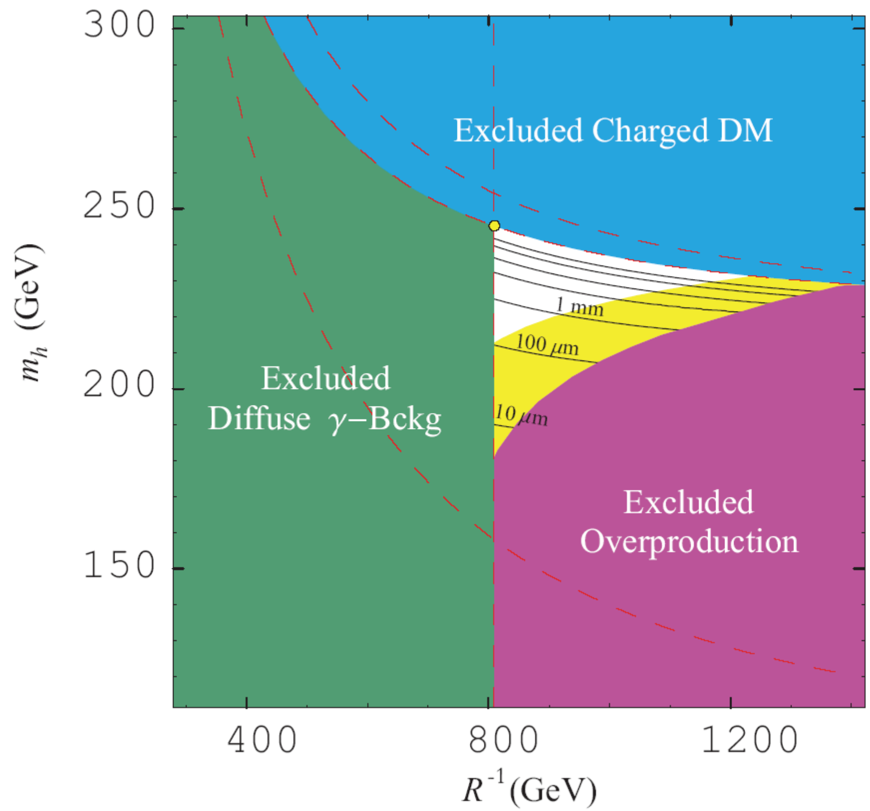
PHASE SPACE SUPPRESSED: NATURAL

- In minimal UED, after all particle and astrophysical constraints, NLKP → LKP is



  - Δm < 7 GeV
  - decay length > 10 μm

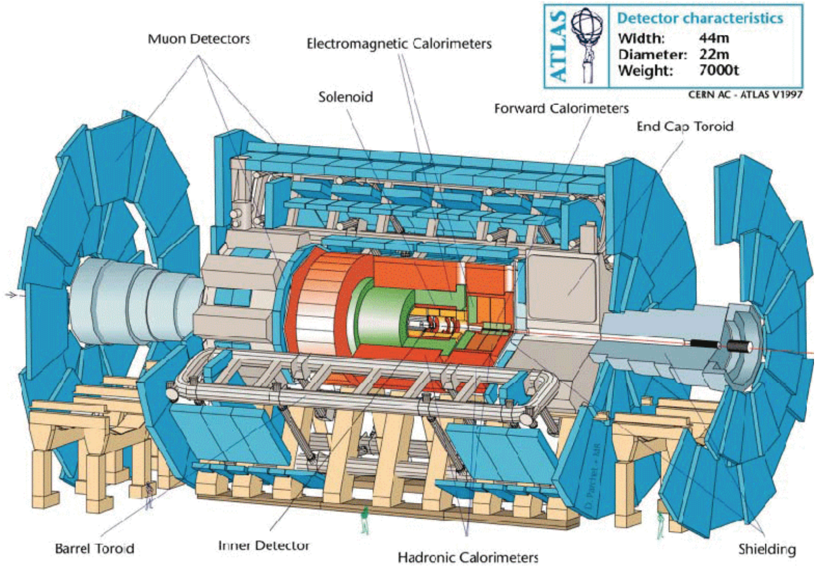




Cembranos, Feng, Strigari (2006)

LHC Signals

- Kinks: $H^{\pm} \rightarrow B^1\ e\ \nu$
- Displaced vertices: $H^{\pm} \rightarrow B^1\ u\ d$
- Vanishing tracks: $H^{\pm} \rightarrow B^1\ (e)\ \nu$
- Highly-ionizing tracks : $H^{\pm}$
- Time-of-flight anomalies: $H^{\pm}$
- Appearing tracks: $A \rightarrow H^{\pm}\ e\ \nu$
- Appearing tracks: $A \rightarrow H^{\pm}\ (e^{\pm})\ \nu$
- Impact parameter: $A \rightarrow H^{\pm}\ (e^{\pm})\ \nu$
- …
- Decays in vertex detectors, trackers, calorimeters, muon chambers, outside detector are all possible.



CONCLUSIONS

- Missing E_T is not the only interesting signal of new physics, especially in the near term
- Metastable charged (and neutral) particles are found in many models with many particle and cosmological features
- If found, physics at the LHC may be much easier and interesting next year than many people think