LONG-LIVED HEAVY CHARGED PARTICLES AT THE LHC

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OVERVIEW

Studies of long-lived heavy charged particles (e.g., sleptons) (let's call them CHAMPs here) are

- Well-motivated – by gauge hierarchy, dark matter. No more exotic than MET
- Timely – real possibilities for the Tevatron and early years of the LHC
- Easy – just because it's easy doesn't mean it's wrong
- Fun – "If every individual student follows the same current fashion …, then the variety of hypotheses being generated…is limited…But if [the truth] lies in another direction, who will find it? Only someone who has sacrificed himself… 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

OUTLINE

- MET Myths
- Theoretical Frameworks
  - GMSB, SUGRA, AMSB, Universal Extra Dimensions, …
- Searches
  - Current Bounds, LHC Prospects
- Studies
  - Masses, Spins, Mixings, Decay

MET MYTHS

Myth #1: Dark matter → MET at colliders

Supersymmetry
- R-parity

Fayet, Farrar (1974)

- Neutralino DM

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

Universal Extra Dimensions
- KK-parity

Appelquist, Cheng, Dobrescu (2000)

- Kaluza-Klein DM

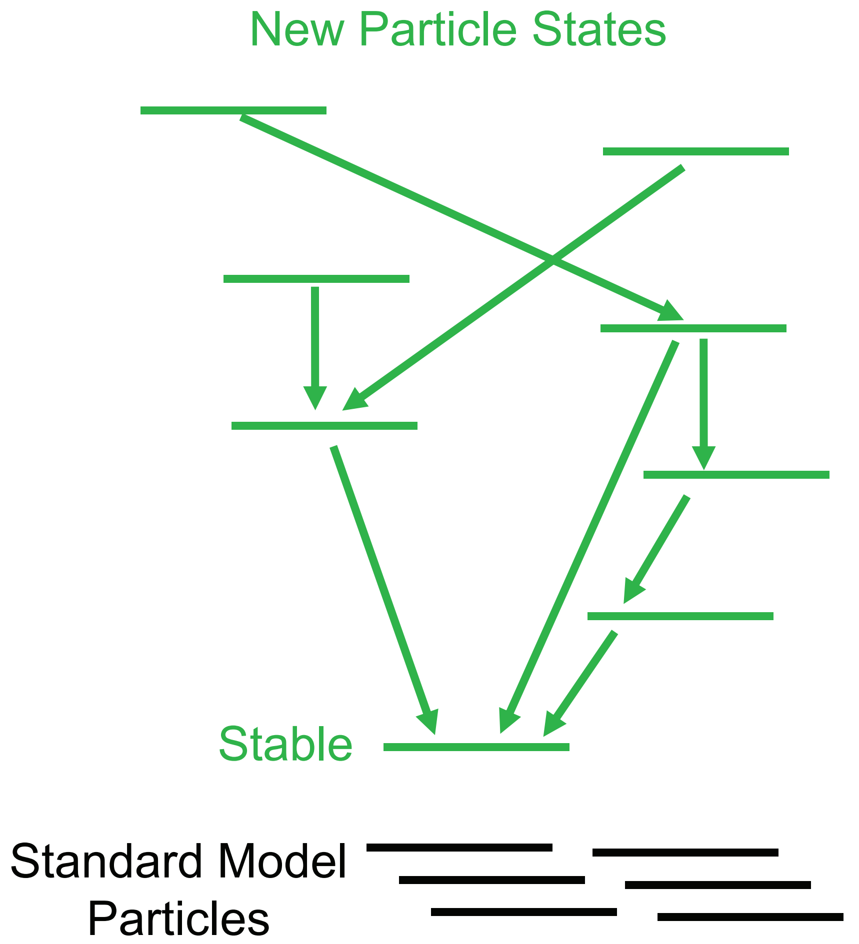
Servant, Tait (2002)

Cheng, Feng, Matchev (2002)

Branes
- Brane-parity
- Branons DM

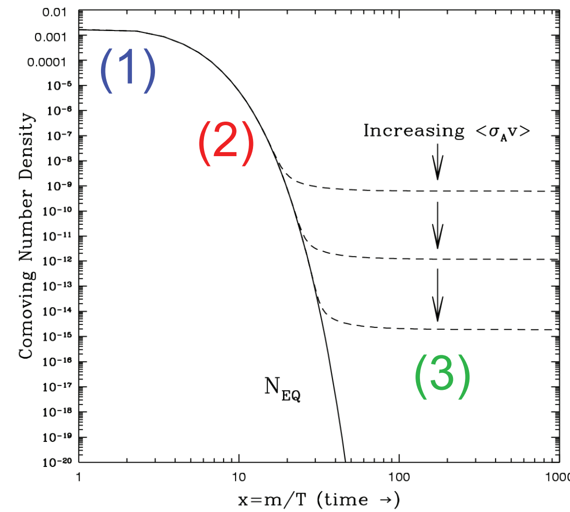
Cembranos, Dobado, Maroto (2003)

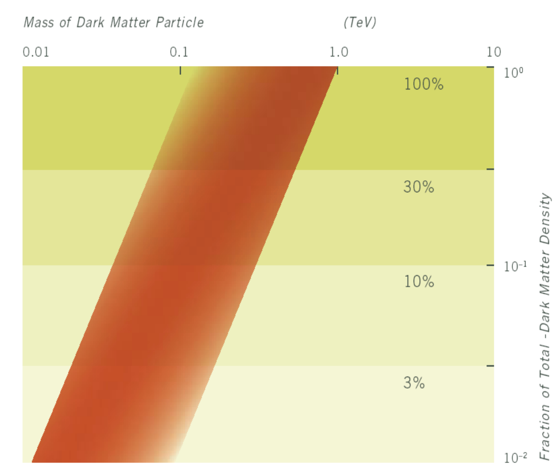
…



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





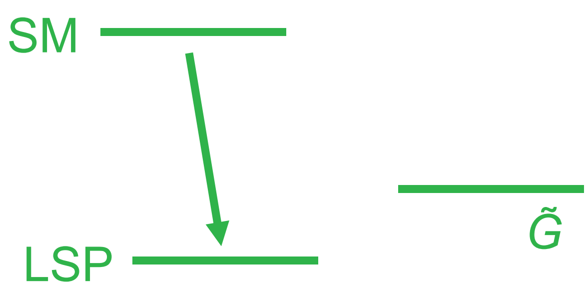
HEPAP LHC/ILC Subpanel (2006)
[band width from k = 0.5 – 2, S and P wave]

COUNTER-EXAMPLE: SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

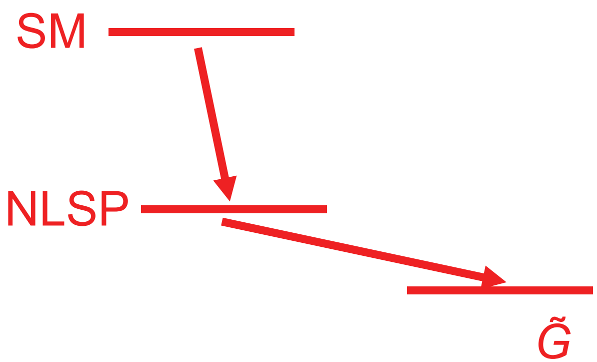
Consider supersymmetry (similar story in UED). There is a gravitino, mass ~ 100 GeV, couplings ~ M_W/M_{Pl} ~ 10^{-16}

- $\tilde{G}$ not LSP



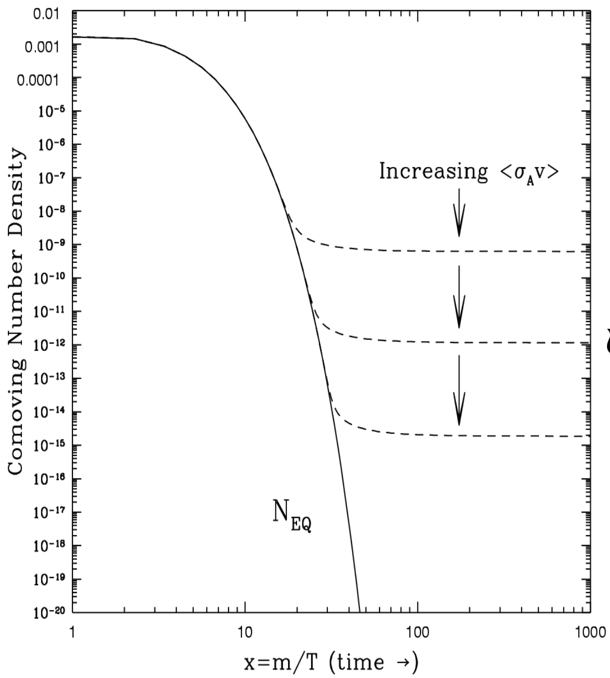
- Assumption of most of literature

- $\tilde{G}$ LSP



- Completely different cosmology and particle physics

SUPERWIMP RELICS



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

- WIMPs freeze out as usual

≈ WIMP → $\tilde{G}$

- But then all WIMPs decay to gravitinos after

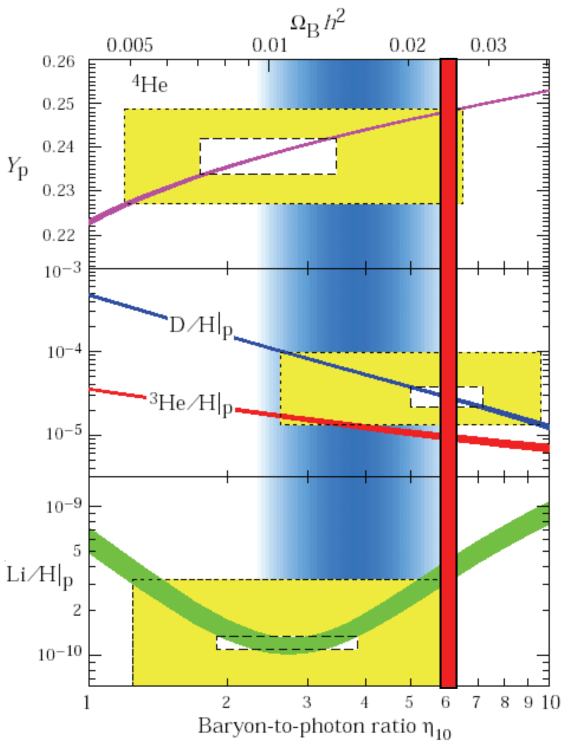
  $M_{Pl}{}^2/M_W{}^3$ ~ seconds to months

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

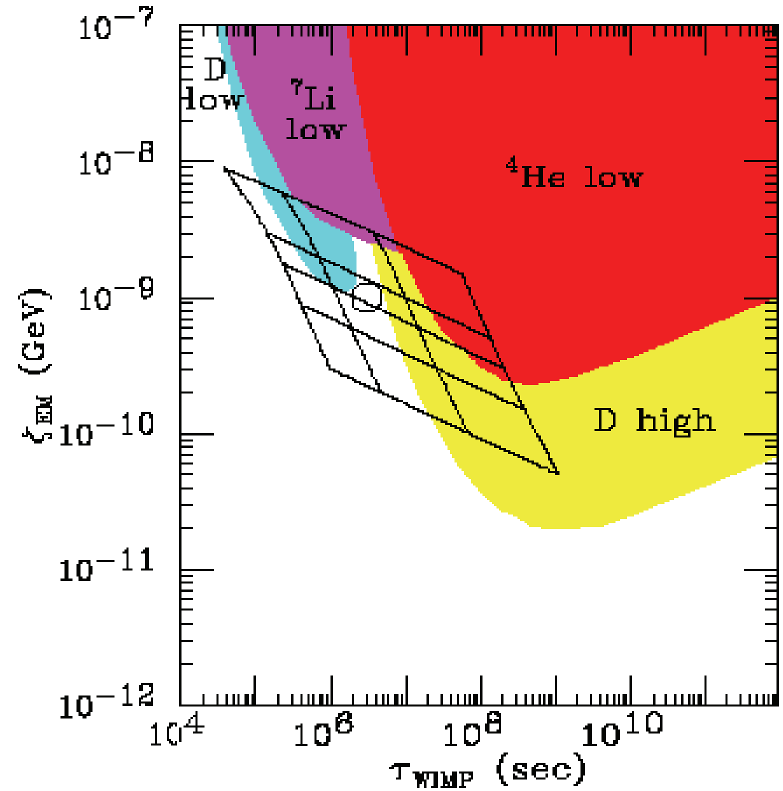
Unlike WIMPs: If WIMP is charged, signal is CHAMP, not MET

COSMOLOGY OF LATE DECAYS

Late decays impact light element abundances, CMB, …



Fields, Sarkar, PDG (2002)



Feng, Rajaraman, Takayama (2003)

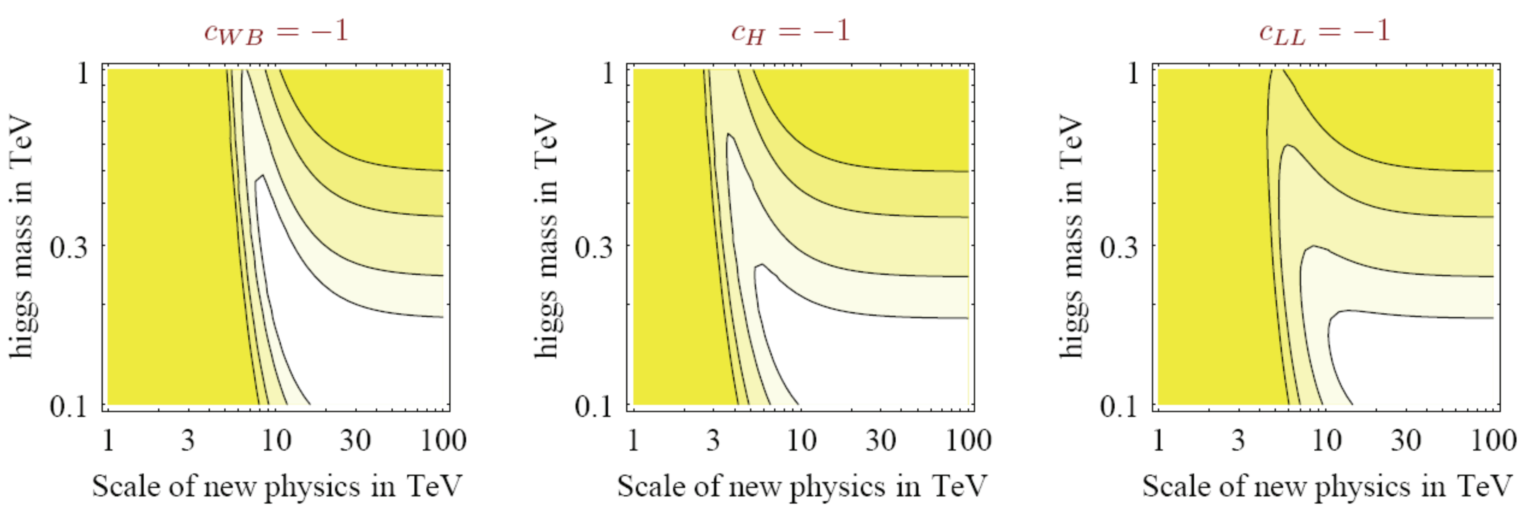
Lots of recent work, boundary of excluded region moves, but viability is not in question. In fact, these considerations strengthen the CHAMP motivation: BBN excludes $\chi \to Z \tilde{G}$, but $\tilde{l} \to l \tilde{G}$ ok

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

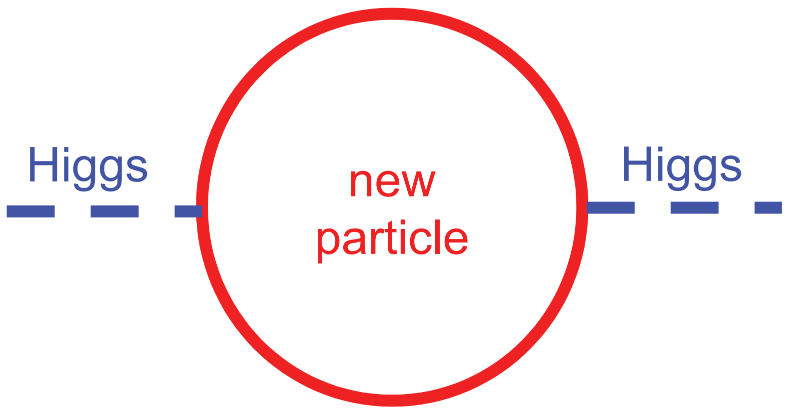
- Problem: Gauge hierarchy → new particles ~100 GeV
  LEP/SLC → new particles > 3 TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)



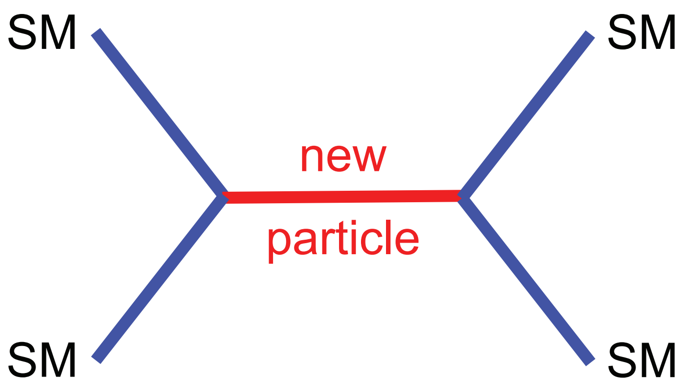
Barbieri, Strumia (2000)

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.

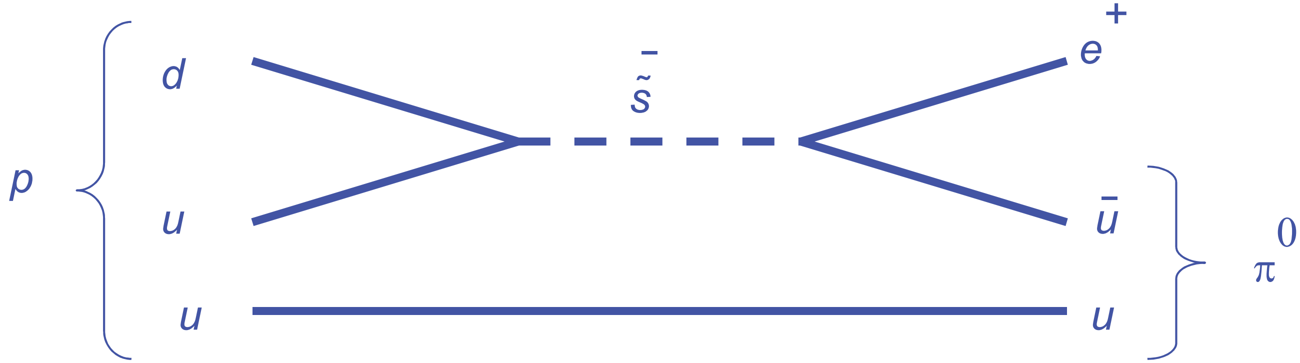
Cheng, Low (2003); Wudka (2003)

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

- But it does not necessarily imply MET (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

- R-parity might be broken
  - B (or L) conservation alone forbids proton decay
  - admittedly an unattractive possibility, as one loses dark matter and R-parity must still be nearly conserved

- R-parity might be conserved
  - See superWIMPs: gravitino could be the stable LSP, signal is CHAMPs

BOTTOM LINE

- MET is not necessarily the most motivated signature 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
- Let’s consider CHAMPs. How general are they?

THEORETICAL FRAMEWORKS

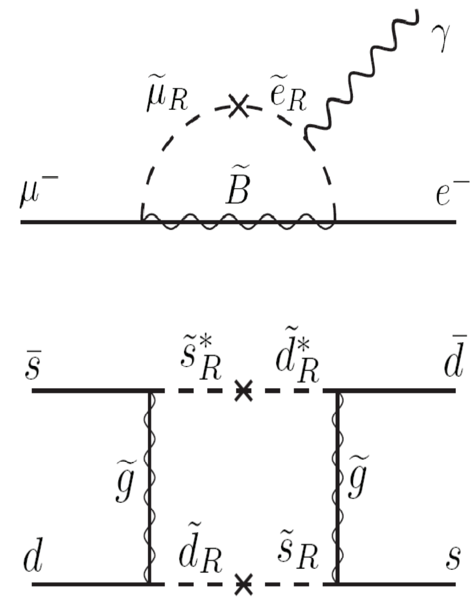
- Supersymmetry: Motivations
  - The gauge hierarchy problem
  - Force unification
  - Radiative electroweak symmetry breaking
  - Maximal extension of space-time symmetries
  - String theory

$$m_{\tilde{q}}^2 = \begin{pmatrix} \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \end{pmatrix}$$

- Flavor problem: gravitational contributions to squark and slepton masses, typically ~ gravitino mass $m_{\tilde{G}}$, generically violate flavor, CP

- These violate low energy constraints (badly)
  - Flavor: Kaon mixing, $\mu \rightarrow e\ \gamma$
  - Flavor and CP: ε_K
  - CP: neutron EDM, electron EDM

- The flavor problem motivates essentially all of SUSY model building



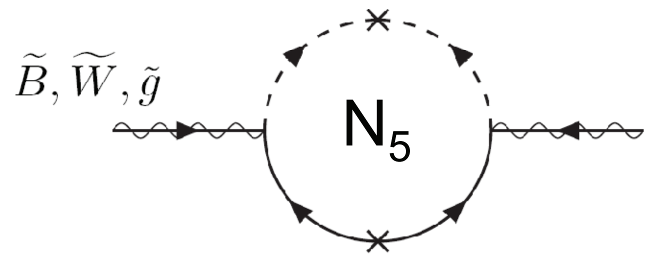
Martin (1997)

GAUGE-MEDIATED SUSY BREAKING

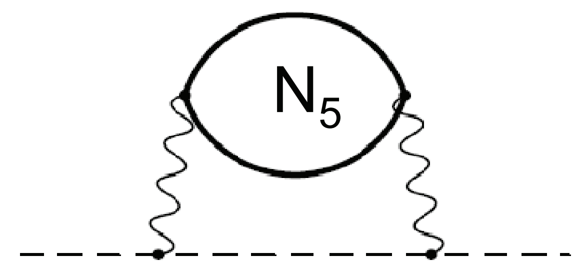
- Introduce a source of universal slepton and squark masses mediated by messenger particles
  - N_5 $5 + \bar{5}$'s
  - Mass M
- To solve flavor problem

  $m_{\tilde{G}} << m_0 \rightarrow \text{LSP} = \tilde{G}$
- NLSP
  - Which particle: determined by N_5
  - Lifetime: determined by $F \leftrightarrow M$

$$m_{\tilde{q}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} + \begin{pmatrix} \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \\ \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 & \sim m_{\tilde{G}}^2 \end{pmatrix}$$



$$M_i(M) = N_5 \Lambda c_i \frac{g_i^2(M)}{16\pi^2}$$



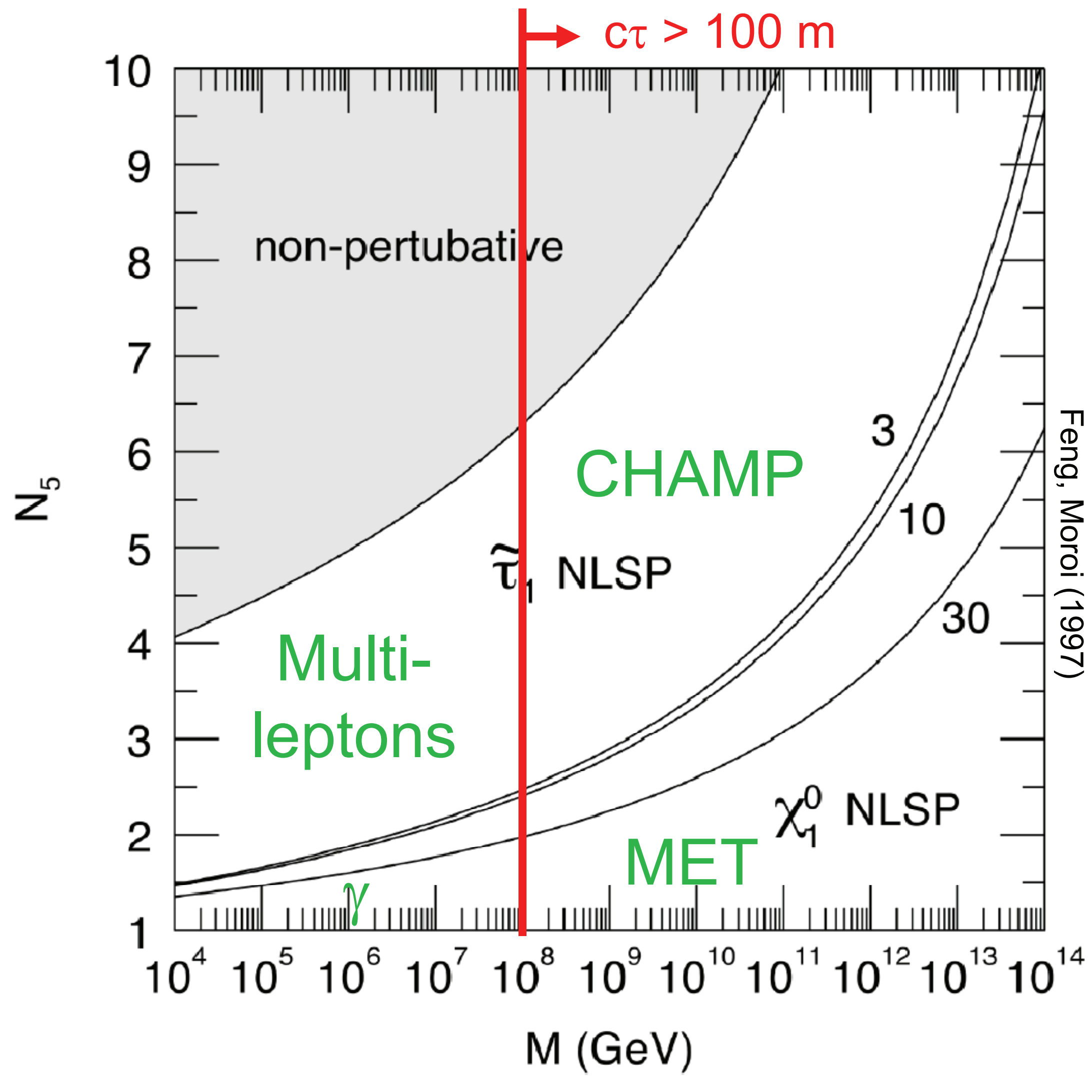
$$M_{\tilde{f}}^2(M) = 2 N_5 \Lambda^2 \sum_{i=1}^{3} C_i^f \left[\frac{g_i^2(M)}{16\pi^2} \right]^2$$

GMSB SIGNATURES

- Stau is the NLSP in much of parameter space (if $N_5 > 1$)

- Decay length shown is a lower bound: increased if SUSY breaking in other sectors

- 4 possible signatures:
  - Prompt photon
  - MET
  - Multi-leptons
  - CHAMPs



GRAVITY-MEDIATED SUSY BREAKING

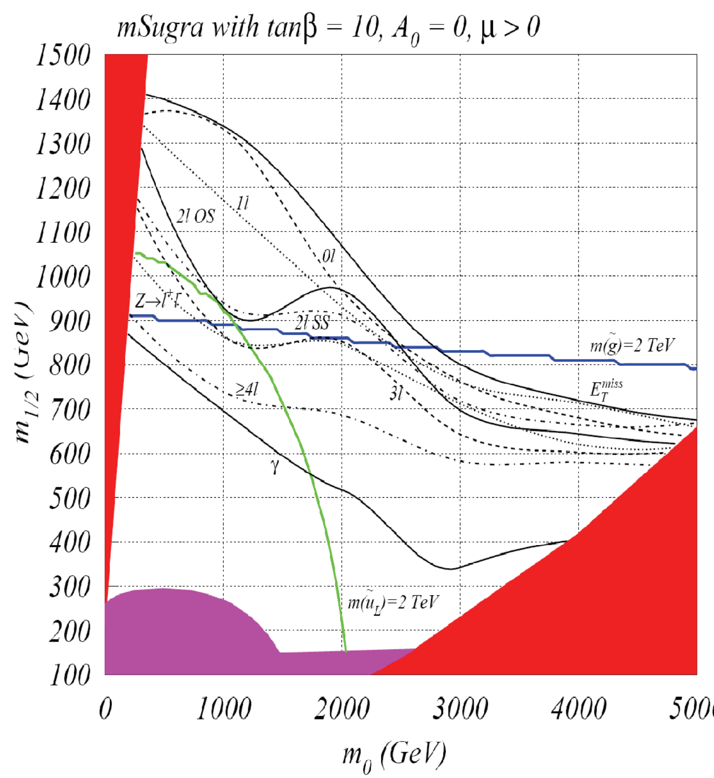
- Solve the flavor problem by fiat

$$m_{\tilde{q}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix}$$

- mSUGRA's famous 4+1 parameters:

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

- Excluded regions
  - LEP limits
  - Stau LSP
- But this is incomplete
  - Missing $m_{\tilde{G}}$
  - Assumes $m_0^2 > 0$



Baer, Balazs, Belyaev, Krupovnickas, Tata (2003)

THE COMPLETE MSUGRA

Feng, Rajaraman, Smith (2005)

- Extend the mSUGRA parameters to

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

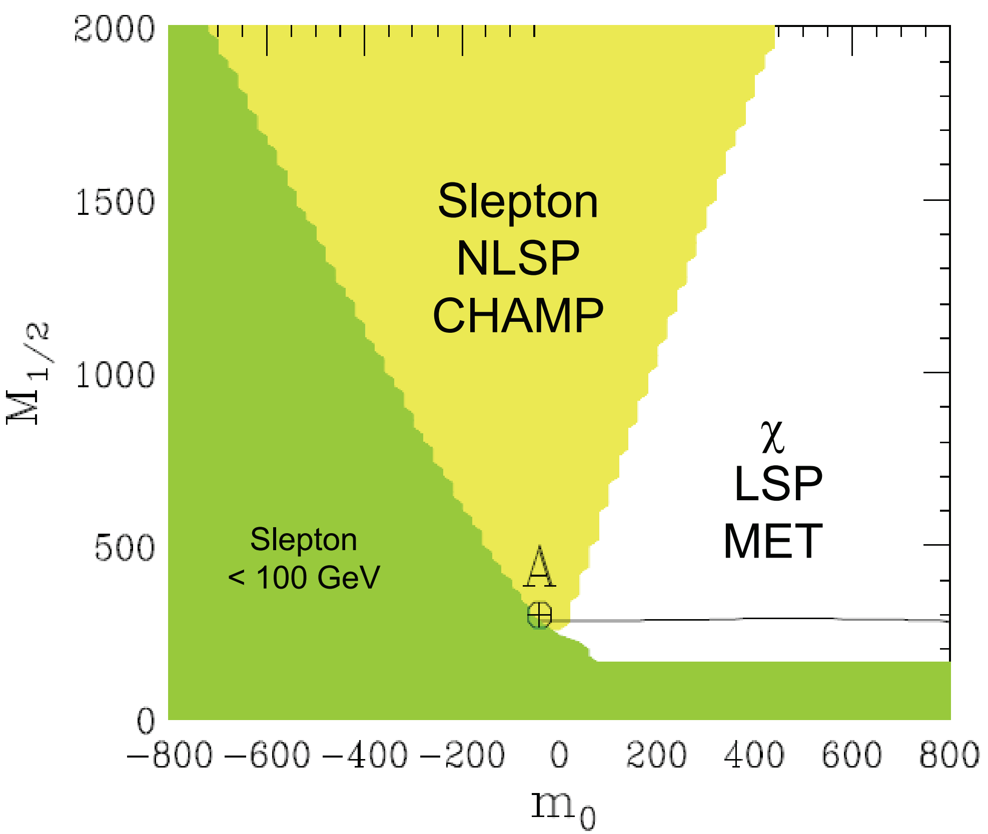
- If LSP = gravitino, then no reason to exclude stau (N)LSP region

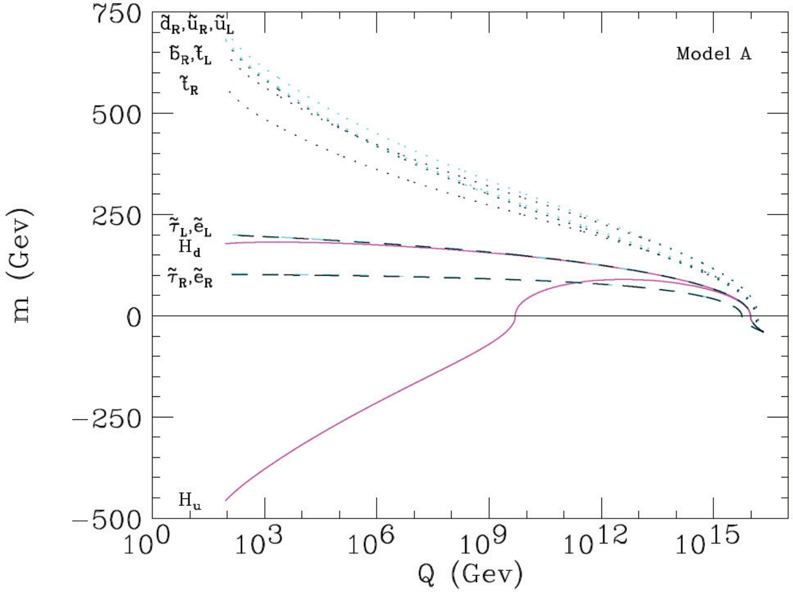
- Also include small or negative

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

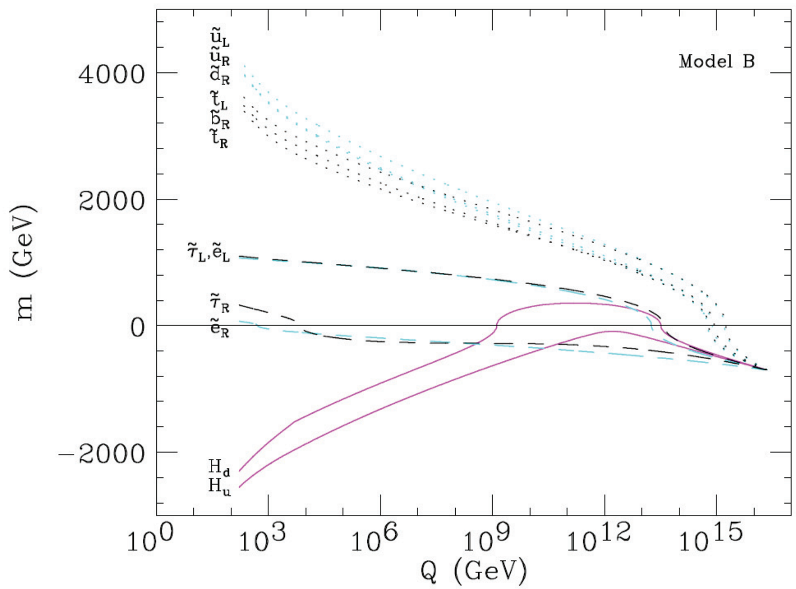
- This includes no-scale/gaugino-mediated models with $m_0 = 0$

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

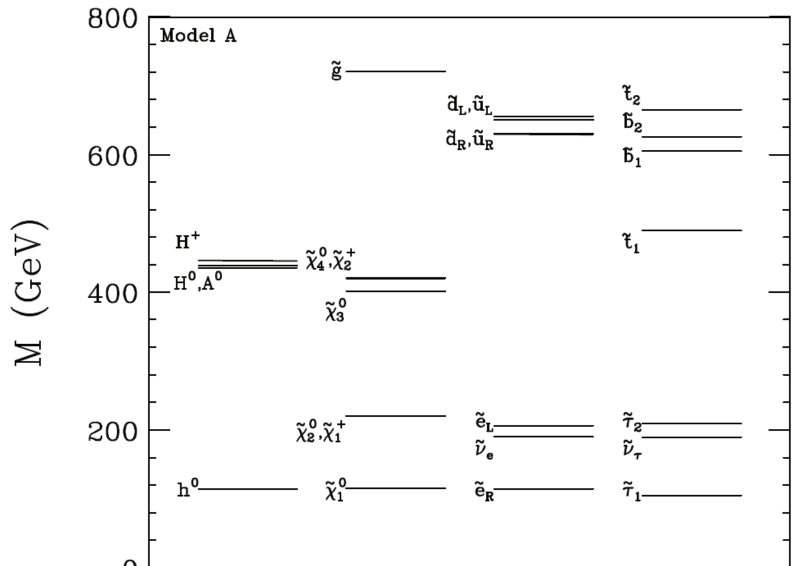




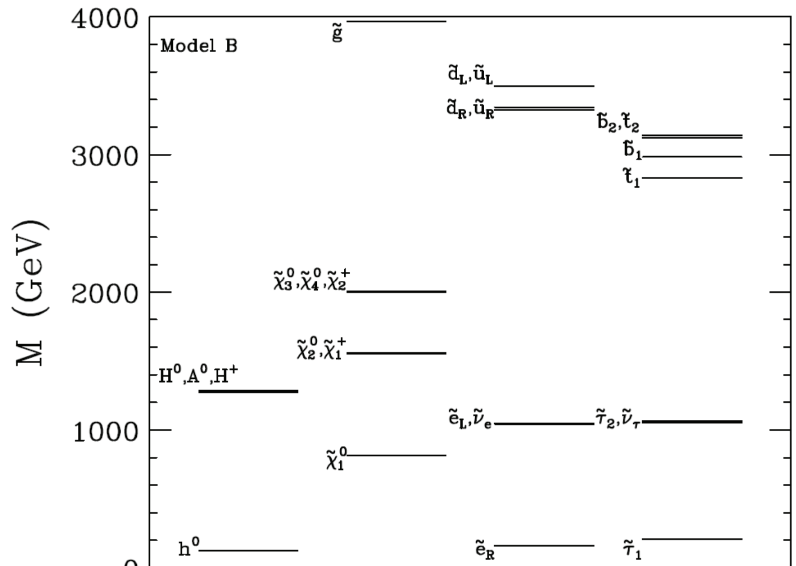
Model A
m (Gev)
Q (Gev)
$\tilde{d}_R, \tilde{u}_R, \tilde{u}_L$
$\tilde{b}_R, \tilde{t}_L$
$\tilde{t}_R$
$\tilde{\tau}_L, \tilde{e}_L$
H_d
$\tilde{\tau}_R, \tilde{e}_R$
H_u



Model B
m (GeV)
Q (GeV)
$\tilde{u}_L$
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{t}_L$
$\tilde{b}_R$
$\tilde{t}_R$
$\tilde{\tau}_L, \tilde{e}_L$
$\tilde{\tau}_R$
$\tilde{e}_R$
H_d
H_u



Model A
M (GeV)
$\tilde{g}$
$\tilde{d}_L, \tilde{u}_L$
$\tilde{d}_R, \tilde{u}_R$
$\tilde{t}_2$
$\tilde{b}_2$
$\tilde{b}_1$
$\tilde{t}_1$
H^+
H^0, A^0
$\tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^0, \tilde{\chi}_1^+$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
h^0
$\tilde{\chi}_1^0$
$\tilde{e}_R$
$\tilde{\tau}_1$

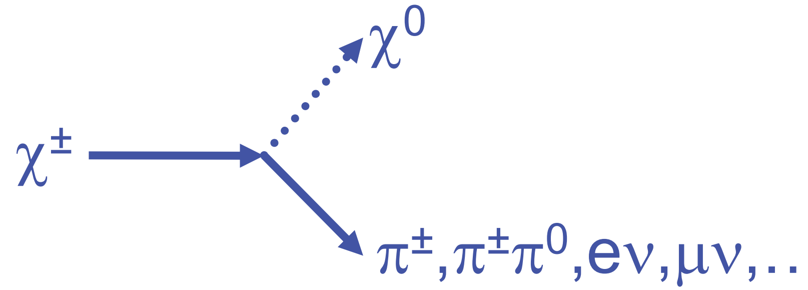


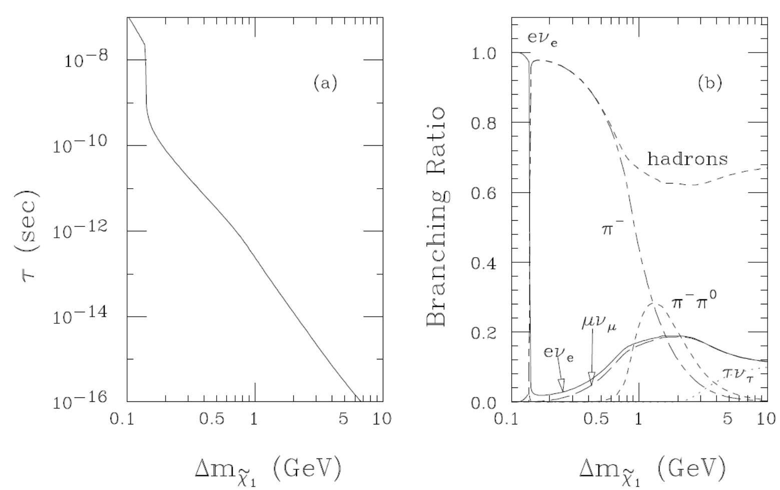
Model B
M (GeV)
$\tilde{g}$
$\tilde{d}_L, \tilde{u}_L$
$\tilde{d}_R, \tilde{u}_R$
$\tilde{b}_2, \tilde{t}_2$
$\tilde{b}_1$
$\tilde{t}_1$
$\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{\chi}_2^0, \tilde{\chi}_1^+$
H^0, A^0, H^+
$\tilde{e}_L, \tilde{\nu}_e$
$\tilde{\tau}_2, \tilde{\nu}_\tau$
$\tilde{\chi}_1^0$
h^0
$\tilde{e}_R$
$\tilde{\tau}_1$

OTHER SUSY FRAMEWORKS

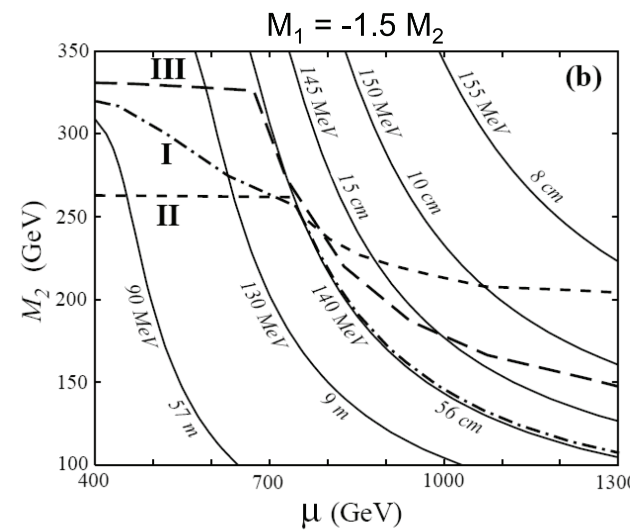
- Long-lived heavy particles may result from phase space suppression or decay through heavy virtual particles

- 2 common (but imperfect) motivations
  - Winos in AMSB (but $M_1 = 3.3\ M_2$, typically gives $c\tau$ < 10 cm)
  - Gluinos in split SUSY (unnatural)





Chen, Drees, Gunion (1999)

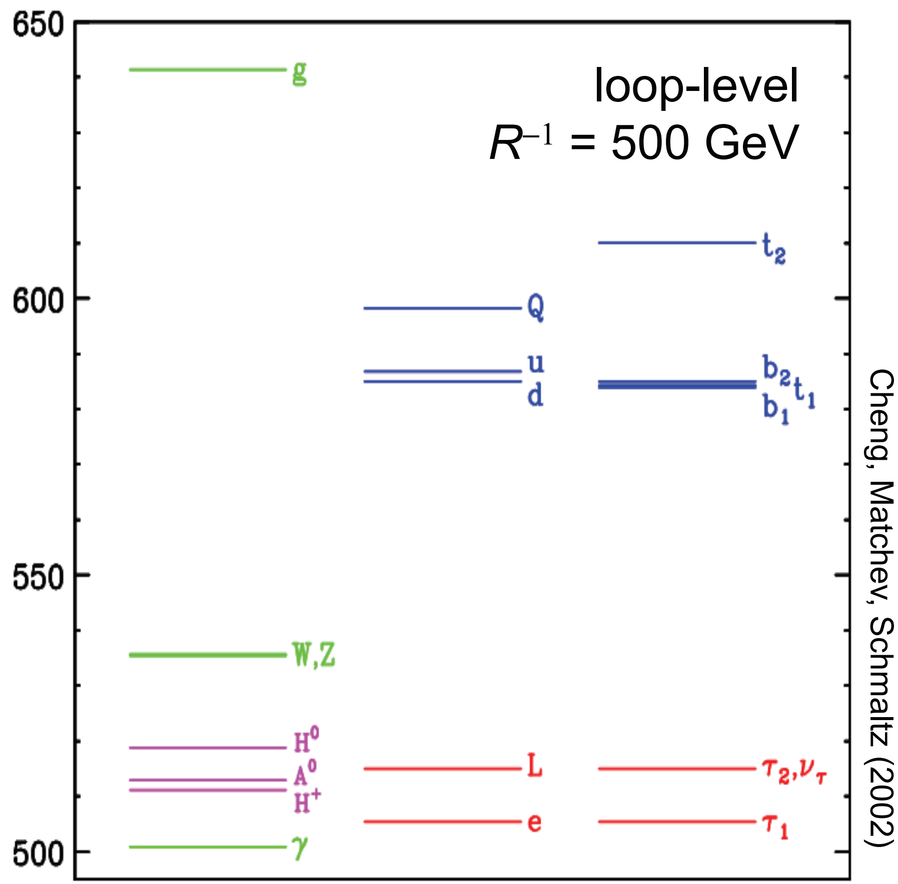


Feng, Moroi, Randall, Sstrassler, Su (1999)

UNIVERSAL EXTRA DIMENSIONS

Appelquist, Cheng, Dobrescu (2000)

- Assume 1 extra dimension, where the 5th dimension is a circle with radius R
- All Kaluza-Klein 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 → MET at LHC

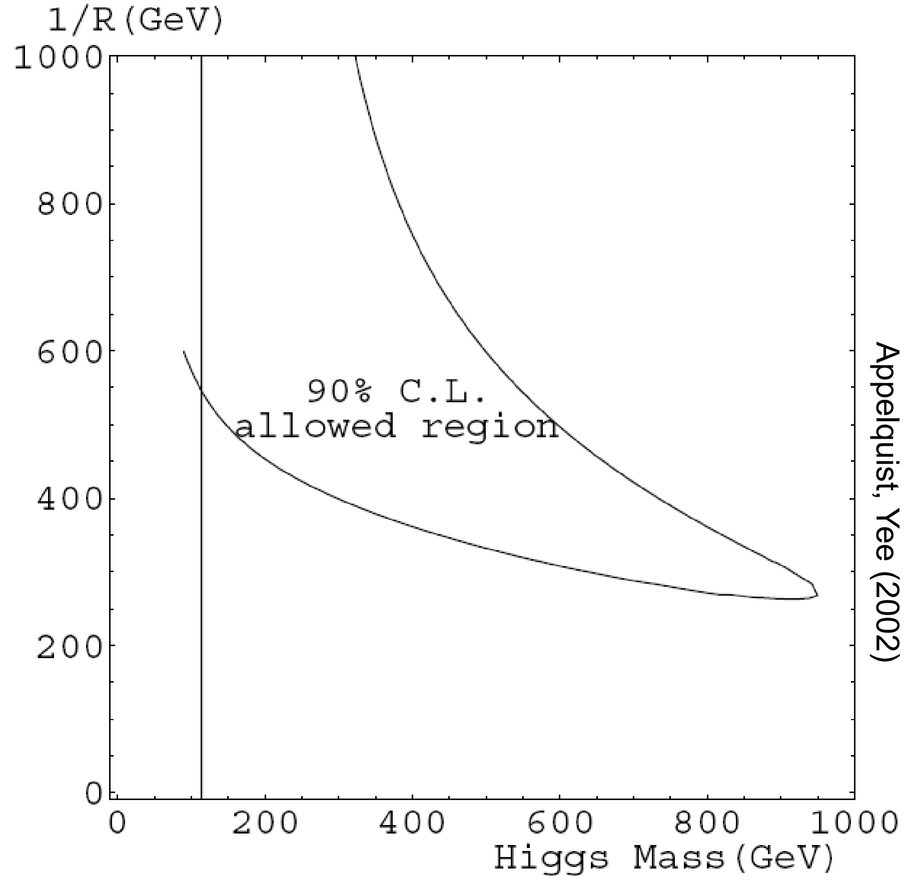
- Spectrum is more degenerate, but basically similar to SUSY

"Bosonic supersymmetry"

Cheng, Matchev, Schmaltz (2002)

BUT THERE'S MORE

- *R* is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown
- Original collider studies set m_h=120 GeV, but it can be larger (KK towers modify EW precision constraints)
- H^0, A, $H^\pm$ masses depend on m_h
- Also, there's another state in the theory: the KK graviton G^1



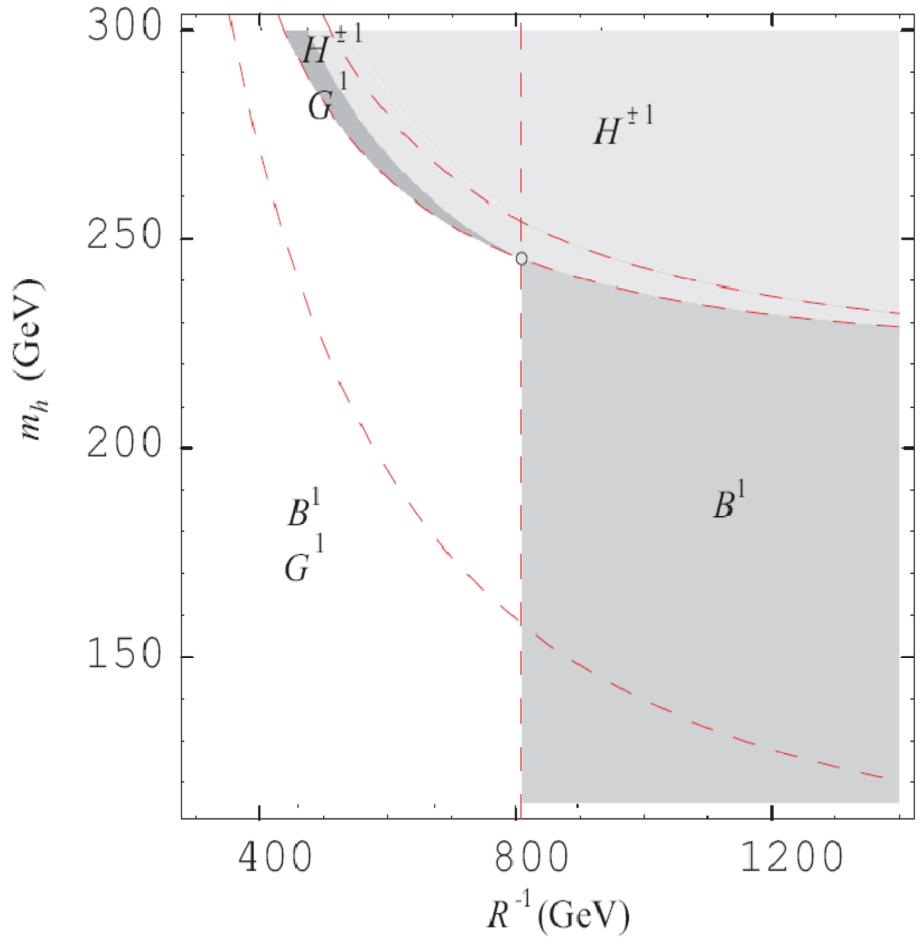
Appelquist, Yee (2002)

UED PHASE DIAGRAM

- Including the KK graviton and varying over the Higgs mass, we find several possible LKPs (and NLKPs)
- The lightest states are extremely degenerate
- One might expect degeneracies of

  $m_W^2 R \sim 10$ GeV ,

  but these are tightened by modest accidental cancelations



Cembranos, Feng, Strigari (2006)

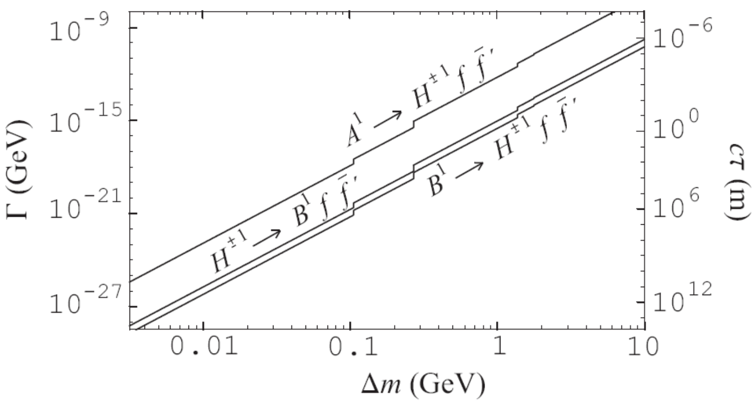
CHAMPS IN UED

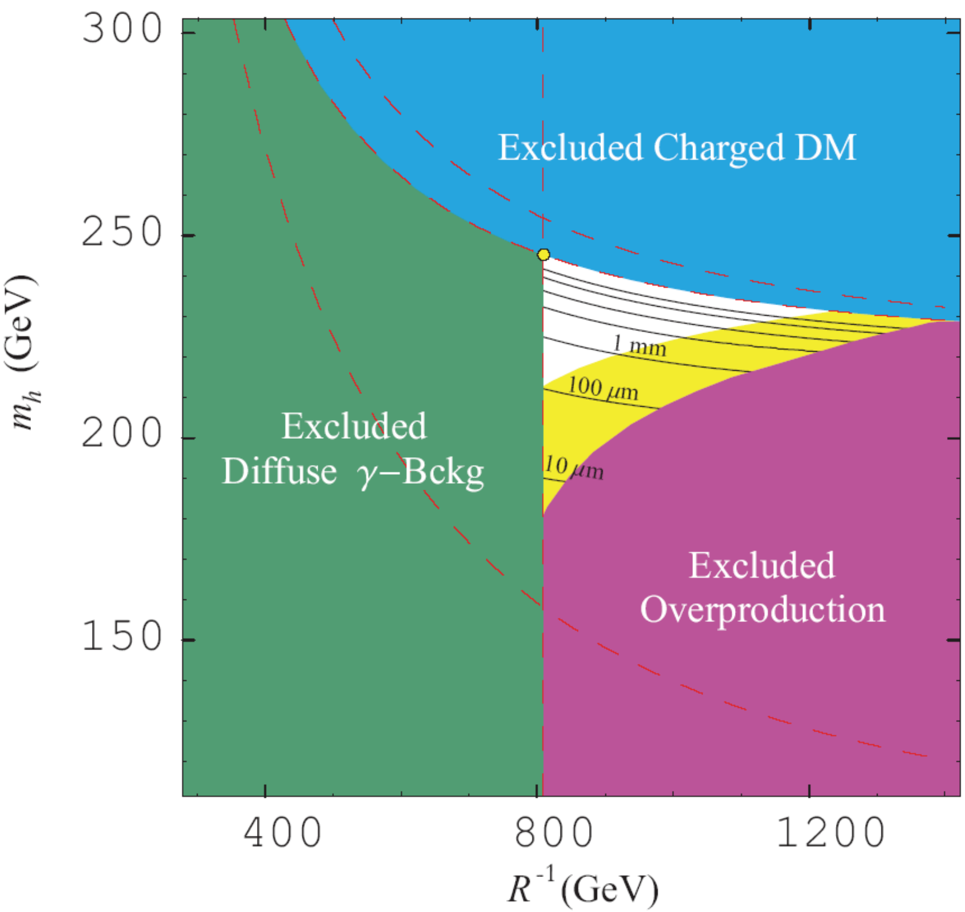
- In minimal UED, after all particle and astrophysical constraints, NLKP → LKP is

  $H^{\pm 1} \rightarrow B^1 f f'$

- Mass splitting $\Delta m < 7$ GeV

- Decay length $c\tau > 10\ \mu m$

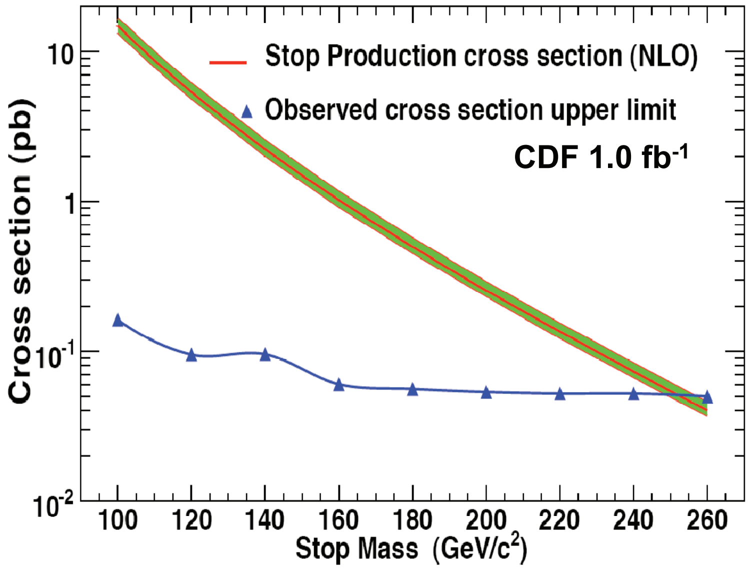




Cembranos, Feng, Strigari (2006)

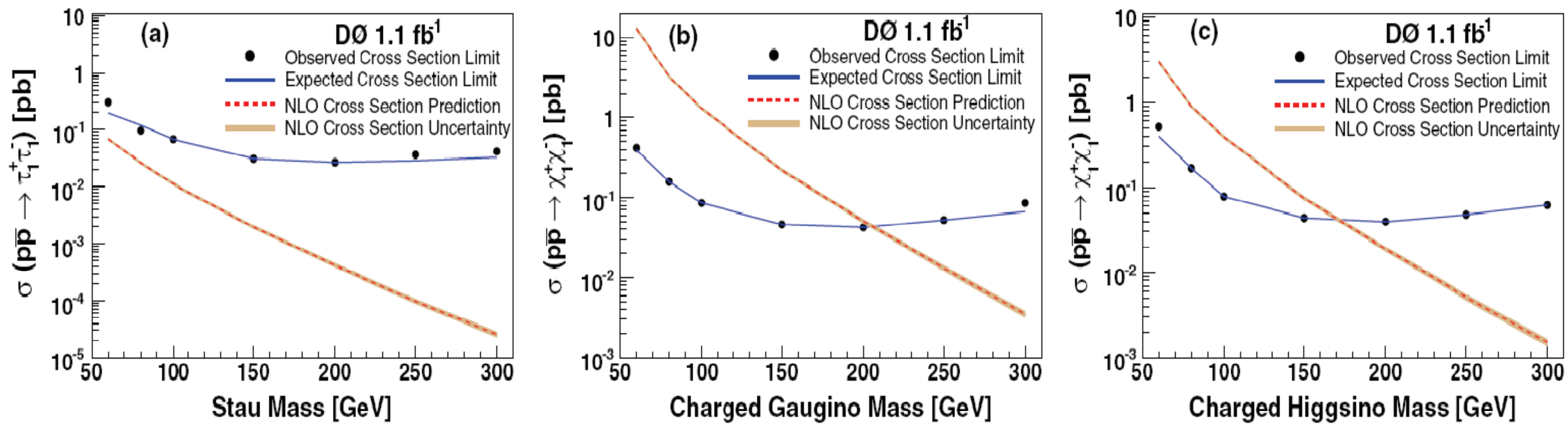
SEARCHES

- Current Bounds
  - LEP: slepton mass > 97.5 GeV, chargino > 102.5 GeV
  - CDF Run I: slepton cross section < 1 pb
  - CDF Run II: top squark mass > 249 GeV



– D0 Run II: chargino mass > 200 GeV

– D0 Run II: slepton cross section < 0.1 pb
  – assumes only Drell-Yan pair production (no cascades)
  – require 2 slow, isolated “muons”
  – about a factor of 5 from unexplored mass territory



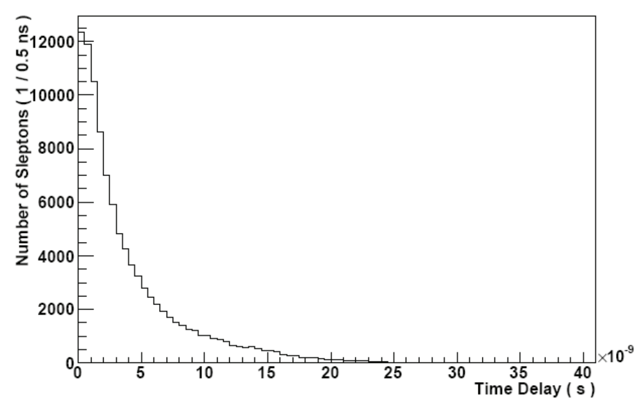
LHC DISCOVERY POTENTIAL

Rajaraman, Smith (2006)

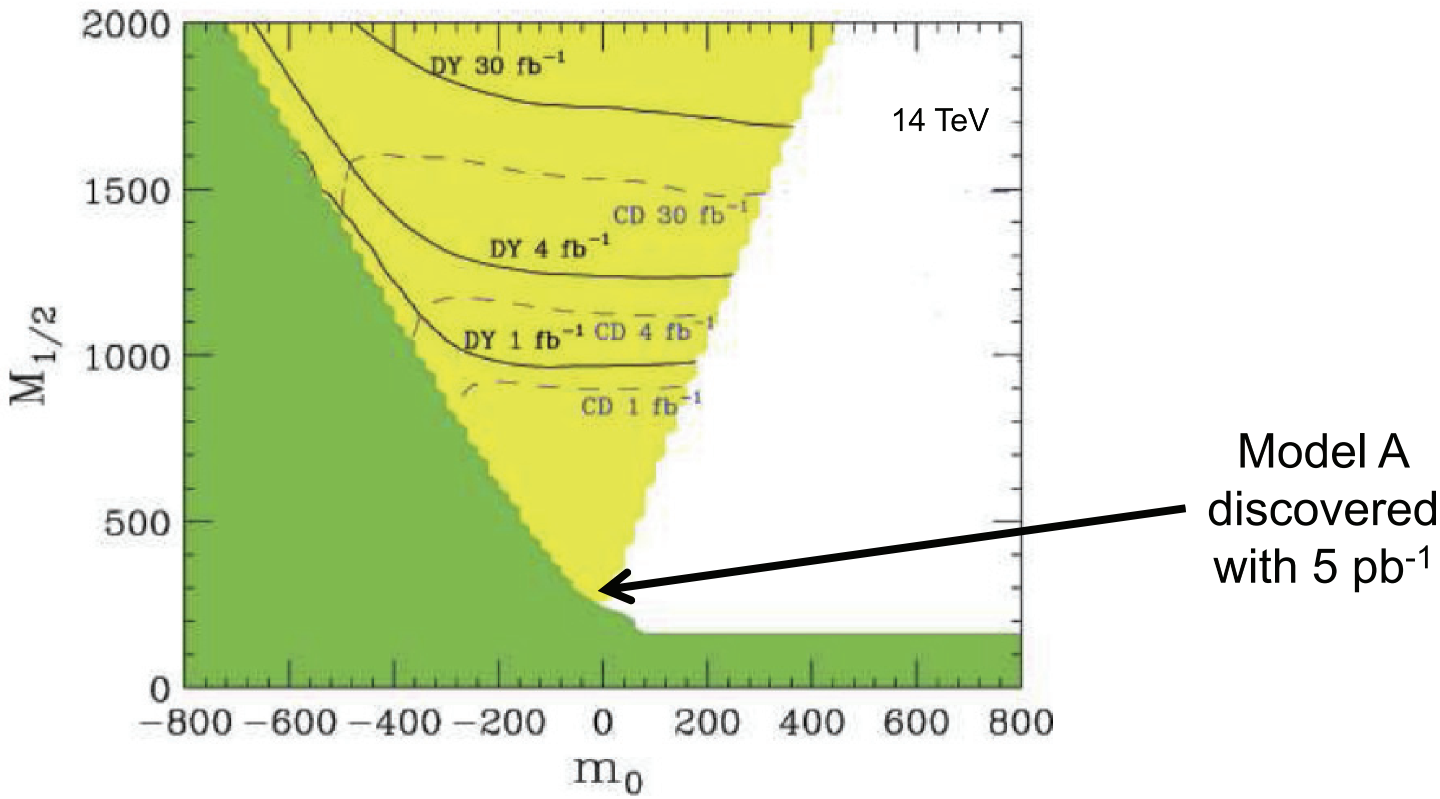
- Look for Drell-Yan slepton pair production
- Require events with 2 central, isolated "muons" with
  - p > 100 GeV
  - p_T > 20 GeV
- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays > 3 ns

	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



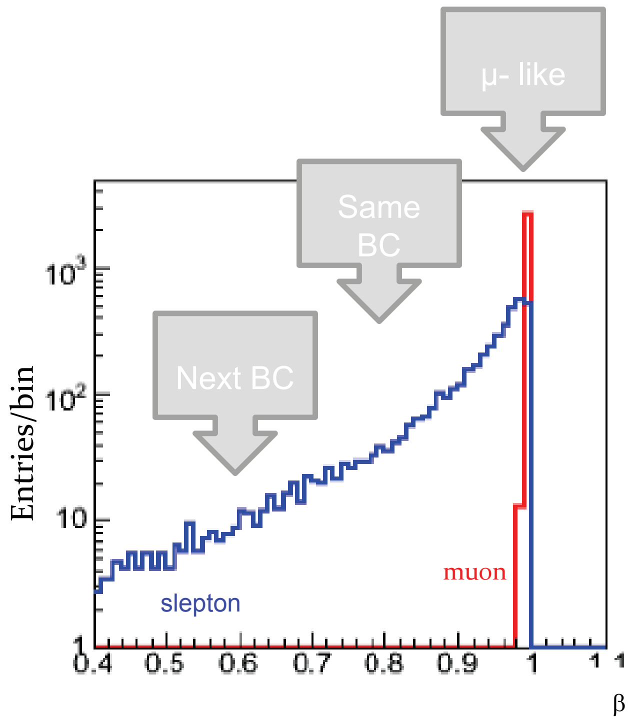
- Require 5σ signal with S > 10 events for discovery

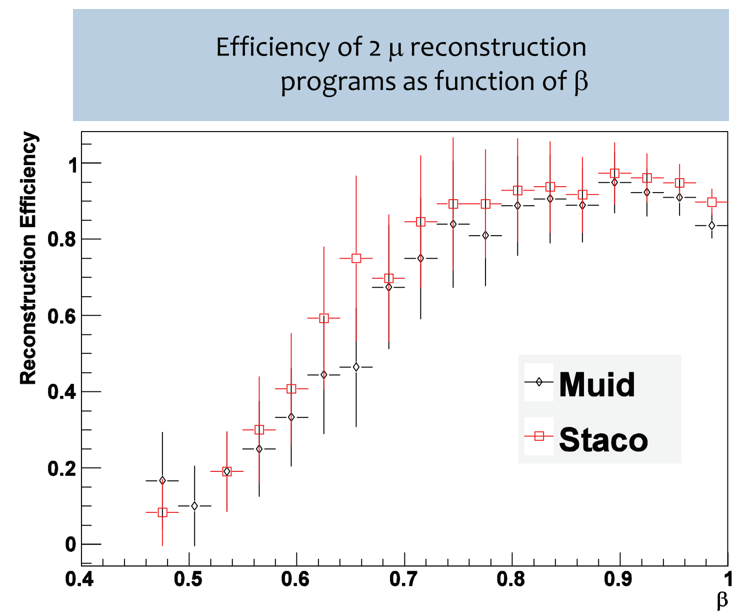


- Model A is “best case scenario”
- Lesson: *Very* early on, the LHC will probe new territory

CMS/ATLAS ANALYSES

- Ongoing work on CHAMP search and reconstruction
  - ATLAS (Tarem et al.): added ToF calculation to level 2 trigger to improve reconstruction efficiency
  - CMS (Rizzi): studied both dE/dx and ToF (Analysis Note (2006))



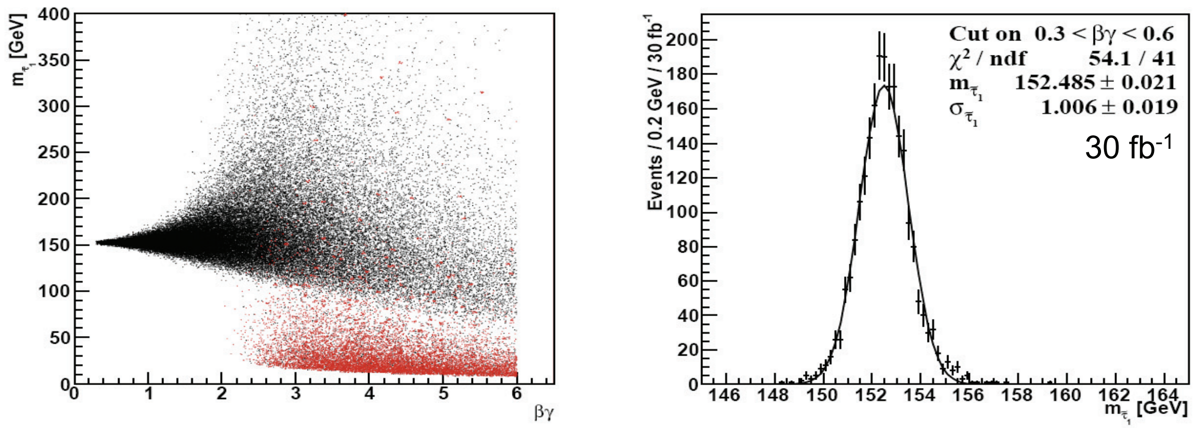


Tarem, Bressler, Nomoto, De Mattia (2008)

PRECISION STUDIES

- CHAMP masses may be measured precisely

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



Ellis, Raklev, Oye (2005)

Figure 3: Scatter plot of measured velocity $\beta\gamma_{\rm meas}$ 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 $0.3 < \beta\gamma < 0.6$.

- CHAMP spins determined by reconstructing the angular distribution of Drell-Yan production in the COM frame

Rajaraman, Smith (2007)

FLAVOR MIXINGS

- In CHAMP scenarios, all particles are observed, ideal for detailed measurements of masses and mixings

- Consider, e.g., hybrid SUSY models:
  flavor-conserving mGMSB + flavor-violating gravity-mediated masses

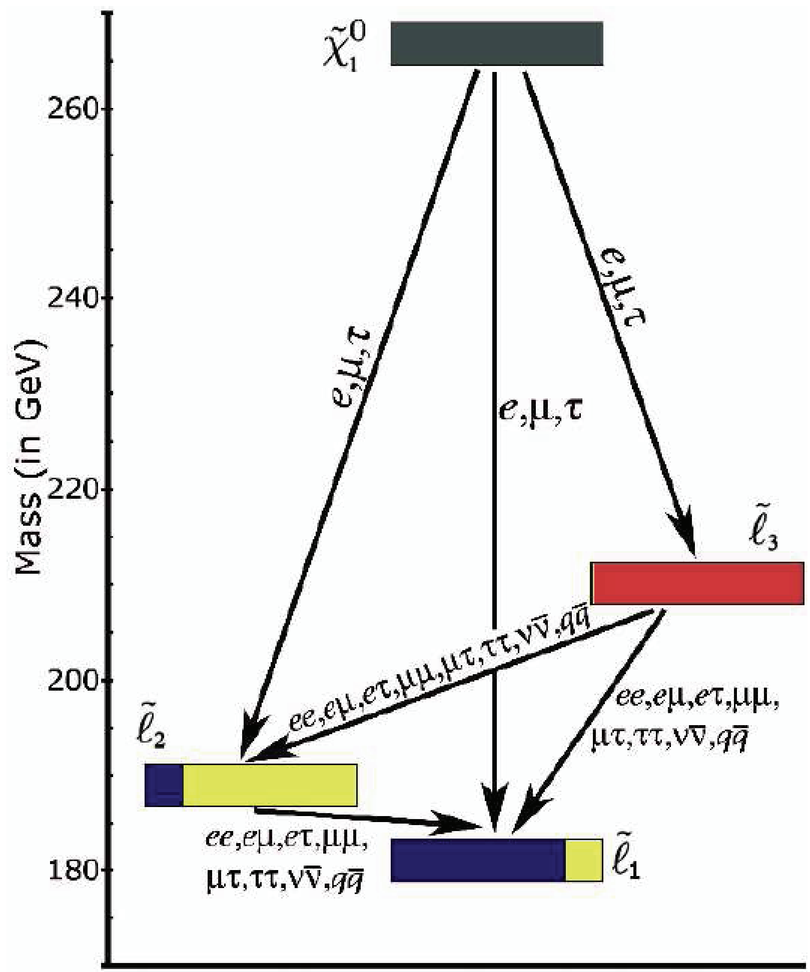
$$
\begin{aligned}
M^2_{\tilde{\nu}} &= m^2_{\tilde{L}} \mathbf{1} + x \tilde{m}^2 X_L \\
M^2_{\tilde{E}_L} &= m^2_{\tilde{L}} \mathbf{1} + m_E m_E^\dagger + x \tilde{m}^2 X_L \\
M^2_{\tilde{E}_R} &= m^2_{\tilde{R}} \mathbf{1} + m_E^\dagger m_E + x \tilde{m}^2 X_R \ ,
\end{aligned}
$$

$$
X_L = \begin{pmatrix} c_{10}\lambda^{n_{10}} & c_{11}\lambda^{n_{11}} & c_{12}\lambda^{n_{12}} \\ c_{11}\lambda^{n_{11}} & c_{13}\lambda^{n_{13}} & c_{14}\lambda^{n_{14}} \\ c_{12}\lambda^{n_{12}} & c_{14}\lambda^{n_{14}} & c_{15}\lambda^{n_{15}} \end{pmatrix}
$$

$$
X_R = \begin{pmatrix} c_{16}\lambda^{n_{16}} & c_{17}\lambda^{n_{17}} & c_{18}\lambda^{n_{18}} \\ c_{17}\lambda^{n_{17}} & c_{19}\lambda^{n_{19}} & c_{20}\lambda^{n_{20}} \\ c_{18}\lambda^{n_{18}} & c_{20}\lambda^{n_{20}} & c_{21}\lambda^{n_{21}} \end{pmatrix}
$$

- Such models can explain all observed lepton masses and mixings in terms of a few horizontal symmetry charges; can they be tested at the LHC?

Feng, Lester, Nir, Shadmi (2007)



Engelhard, Feng, Galon, Sanford, Yu (2009)
Feng, French, Galon, Lester, Nir, Sanford, Shadmi, Yu (2009)

CHAMP TRAPPING

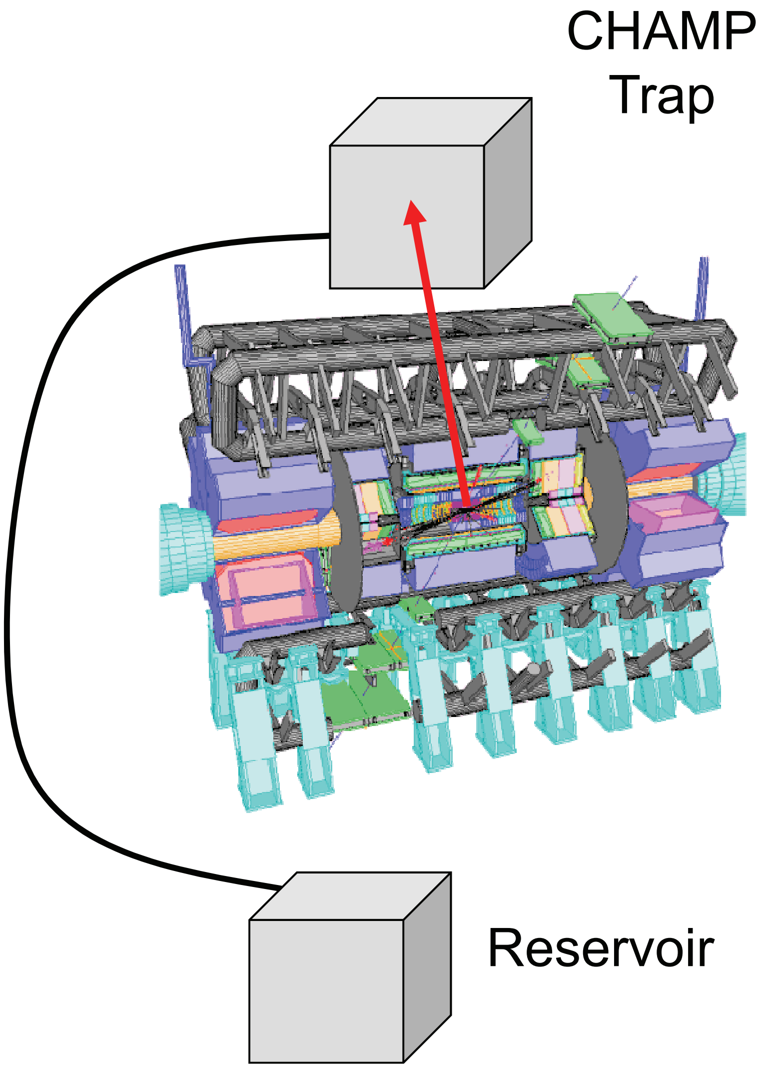
- CHAMPs can be trapped and moved to a quiet environment to study their decays

- Can catch 1000 per year in a 1m thick water tank

Feng, Smith (2004)

- Alternatively, can try to catch uncorrelated-with-beam-crossing decays from CHAMPs in detector, or mine for CHAMPs in detector hall walls

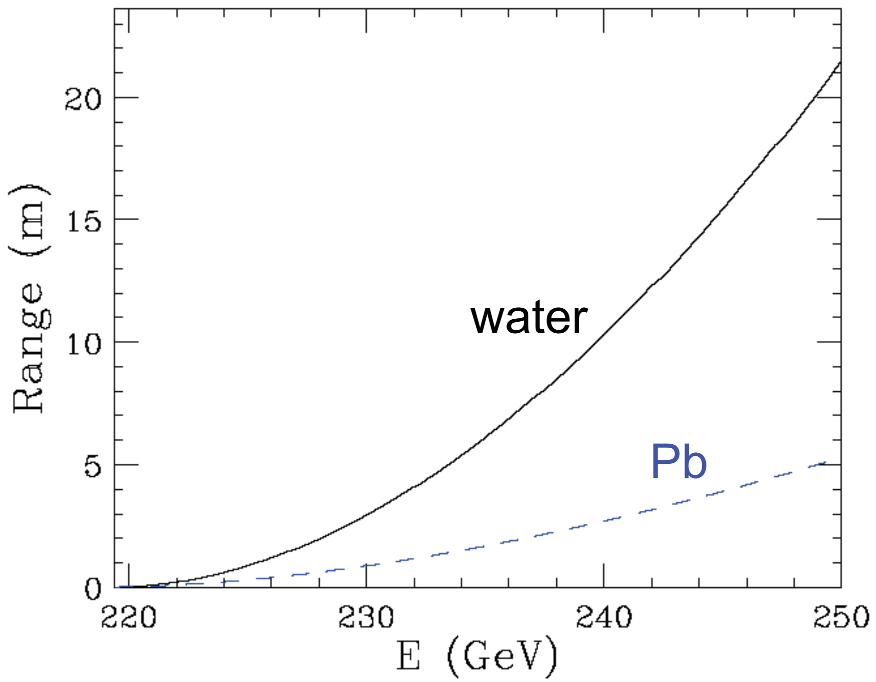
Hamaguchi, Kuno, Nakawa, Nojiri (2004)
De Roeck et al. (2005)



SLEPTON RANGE

- Ionization energy loss described by Bethe-Bloch equation:

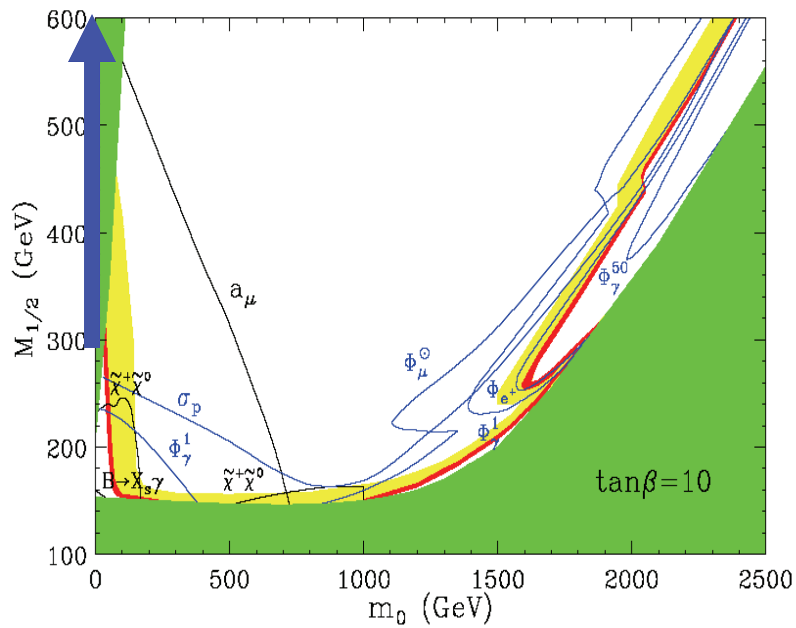
$$\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_ec^2\beta^2\gamma^2}{I\sqrt{1+\frac{2m_e\gamma}{M}+\frac{m_e^2}{M^2}}}\right)-\beta^2-\frac{\delta}{2}\right]$$

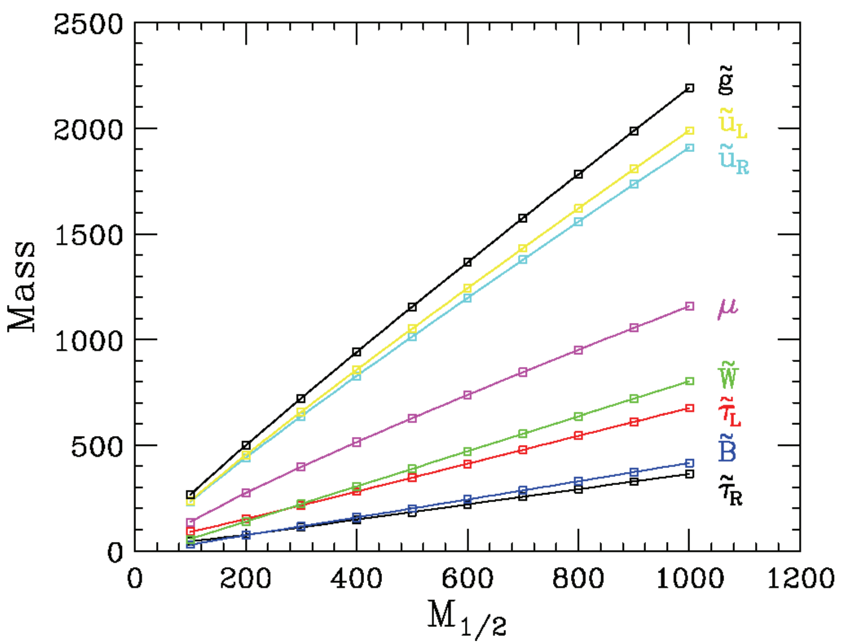


$m_{\tilde{l}}$ = 219 GeV

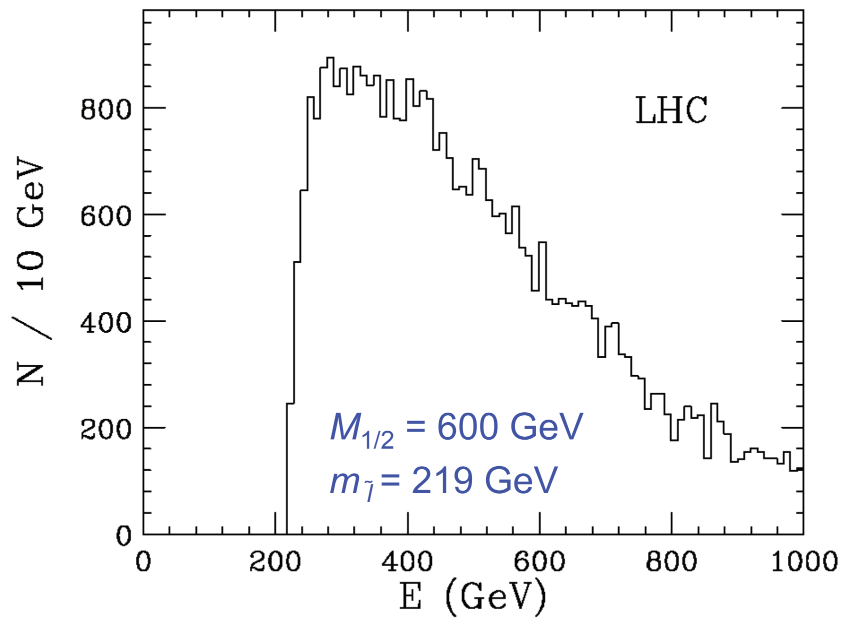
MODEL FRAMEWORK

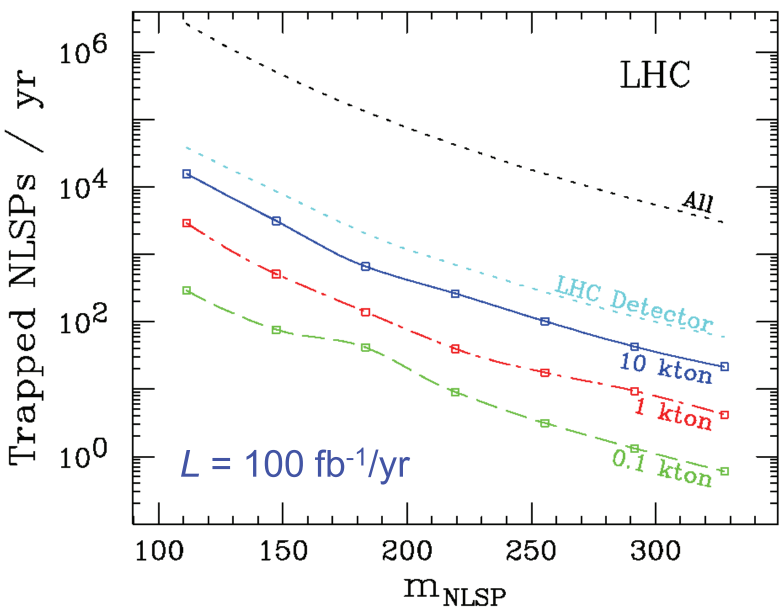
- Results depend heavily on the entire SUSY spectrum
- Consider mSUGRA with m_0=A_0=0, tanβ = 10, μ>0
  $M_{1/2}$ = 300, 400,…, 900 GeV





LHC





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)

IMPLICATIONS FROM CHAMP DECAYS

$$\tau(\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^5} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2}\right]^{-4}$$

- Measurement of τ , $m_{\tilde{l}}$ and E_l → $m_{\tilde{G}}$ and G_N
  - Probes gravity in a particle physics experiment!
  - Measurement of G_N on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines $\Omega_{\tilde{G}}$: SuperWIMP contribution to dark matter
  - Determines F : supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

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

CONCLUSIONS

- Long-lived heavy charged particles (CHAMPs) are motivated by gauge hierarchy and dark matter, just like MET
- CHAMPs are far more promising in the early years at the LHC – 100 pb^{-1} is probably sufficient to say many interesting things
- There are several simple frameworks for investigating this possibility
- If found, physics at the LHC may be much easier and interesting than many people think