LHC news and the fate of SUSY

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Outline

- Physics BSM: Motivations,
- The MSSM,
- Canonical search for SUSY at LHC,
  Recent (bad?) news from LHC,
- Other scenarios for SUSY search at LHC (Beyond MSSM),
- SUSY beyond EW realizations,
- Conclusions

1.1 New Physics: LHC and the Cosmos

- After 30-40 years of SM success (apart from ν physics), some kind of new physics is expected,
- LHC is searching for Physics Beyond the SM (BSM),
- But so far, LHC is "just" confirming the SM,
- At the same time, astro/cosmo phenomena also suggest BSM physics may be needed,
- SUSY is one of the best motivated theories BSM,
- Great expectations: LHC, CDMS, Fermi, Pamela...

1.2 Why is SUSY attractive?

- Offers the possibility to stabilize the Higgs mass and induce radiatively EWSB,
- Improves Unification and o.k. with proton decay,
- Favors a light Higgs boson, in agreement with precision analysis, i.e. $m_h \leq 180$ GeV.
- New sources of flavor and CP violation may help to get the right BAU.
- R-parity $\rightarrow$ Lightest SUSY particle is stable (LSP),
- LSP is a good Dark matter candidate.

1.3 The origins of SUSY

SUSY is a symmetry that transforms bosonic and fermionic d.of.f.,

- In the begining: Coleman-Mandula $\rightarrow$ HLS theorem (Graded Lie algebras and all that),
- SUSY was also discovered in String theory (Ramond),
- Another path to SUSY was provided by Akulov, to explain a massless neutrino,
- During the 70's lots of nice (UV) properties of SUSY-QFT's were discovered,
- But it was not clear where and how was SUSY realized in nature, (Footnote of Deser-Zumino PRL on SUGRA mentions it could be used for hadron physics!!!!!!!!!!)
- Great motivation for SUSY appeared when it was applied to solve the hierarchy problem,
- SUSY GUT's were studied first, then the MSSM,

2.1 The MSSM

The minimal extension of the SM consistent with SUSY (MSSM), is based on:

- Gauge supermultiplets
  SM Gauge Group $\longrightarrow$ gauge bosons (and gauginos),
- Chiral supermultiplets
  3 families of fermions (and sfermions),
  Two Higgs doublets (and Higgsinos),
- Soft-breaking of SUSY,
  gaugino and scalar masses,
  bilinear and trilinear terms,
- R-parity distinguish SM and their superpartners
  $\longrightarrow$ LSP is stable and good DM candidate.

2.2 SUSY braking

- SUSY breaking is assumed to take place in a hidden sector (e.g. $< F_X > \neq 0$),
- Some mediator M communicates SUSY breaking to MSSM fields,
- In Supergravity, $M = M_{pl}$ gravitation. All SUSY masses are of order gravitino mass,

(1) $$M_{susy} = \frac{< F_X >}{M_{pl}} \simeq m_{3/2} \simeq \frac{(10^{11}\, GeV)^2}{M_{pl}}$$

- In Gauge mediation, $X =$ SM gauge interactions. The gravitino mass is small,

(2) $$M_{3/2} = \frac{< F_0 >}{M} \simeq 100\, GeV\, (\frac{\sqrt{F_0}}{10^{10}\, GeV})^2$$

- Other models: anomaly, gaugino, XD,..

2.3 The MSSM particle content

	SM	Superpartners
SM Bosons	$W^{\pm}, Z, \gamma$ gluon Higgs bosons	Wino,Zino, Photino gluino Higgsinos
SM Fermions	quarks leptons neutrinos	squarks sleptons sneutrinos

Mixing of gauginos and Higgsinos $\longrightarrow$
Charginos ($\chi_i^{\pm}$, $i = 1, 2$) and
Neutralinos (χ_j^0, $j = 1, 4$),

The gravitino ($\tilde{G}$) is also part of the model,

2.4 The parameters of the MSSM

In addition to SM parameters, the MSSM includes O(100) new ones:

- Scalar masses (Sleptons, squarks, Higgs),
- Gaugino masses ($\tilde{M}_G, \tilde{M}_W, \tilde{M}_B$),
- Trilinear terms ($A_{\tilde{f}}$ for squarks and sleptons),
- From Higgs sector: $\tan\beta = v_2/v_1$ and μ,

There are some relations (at tree-level):

$$M_Z^2 = 2C_1 M_{H_1}^2 - 2t_\beta^2 M_{H_2}^2 - 2\mu^2 \quad (3)$$

with $C_1 = 1/(t_\beta^2 - 1)$,

2.5 The models (a): CMSSM

MSSM parameters are derived from models at high scale (SUGRA/GUT),

$\longrightarrow$ CMSSM = Constrained Minimal Supersymmetric Standard Model.
In the CMSSM one takes (at M_{pl}):

- Universal scalar masses (=$\widetilde{m}_0$) ,
- Universal gaugino masses (=$\tilde{m}_{1/2}$) ,
- Universal (and prop.) trilinear terms (=A_0) ,
- Also $\tan\beta = v_2/v_1$ and $sgn(mu)$,
- MSSM parameters are derived from RGE,

2.6 Mass spectrum in CMSSM

J.A. Aguilar-Saavedra et al. 11

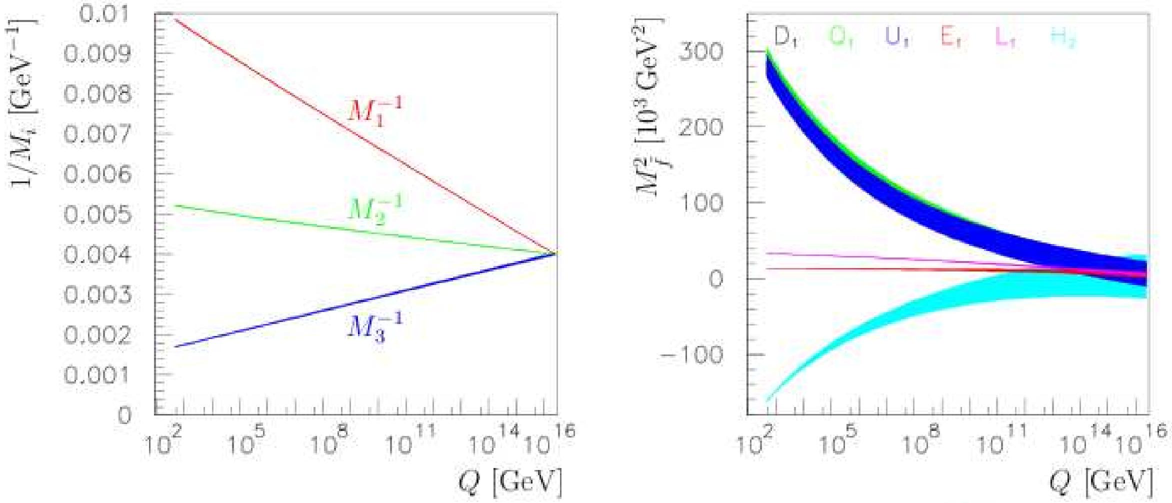


Fig. 1. *Running of the gaugino and scalar mass parameters as a function of the scale Q in SPS1a′ [56]. Only experimental errors are taken into account; theoretical errors are assumed to be reduced to the same size in the future.*

2.6 Mass spectrum in CMSSM

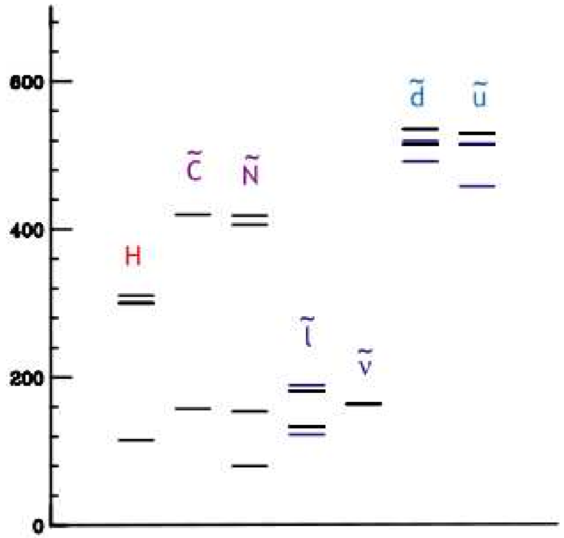


Figure 9: Illustrative spectrum of supersymmetric particles. The columns contain, from the left, the Higgs bosons, the four neutralinos, the two charginos, the charged sleptons, the sneutrinos, the down squarks, and the up squarks. The gluino, not shown, is at about 800 GeV.

2.7 The models (b): NUHM

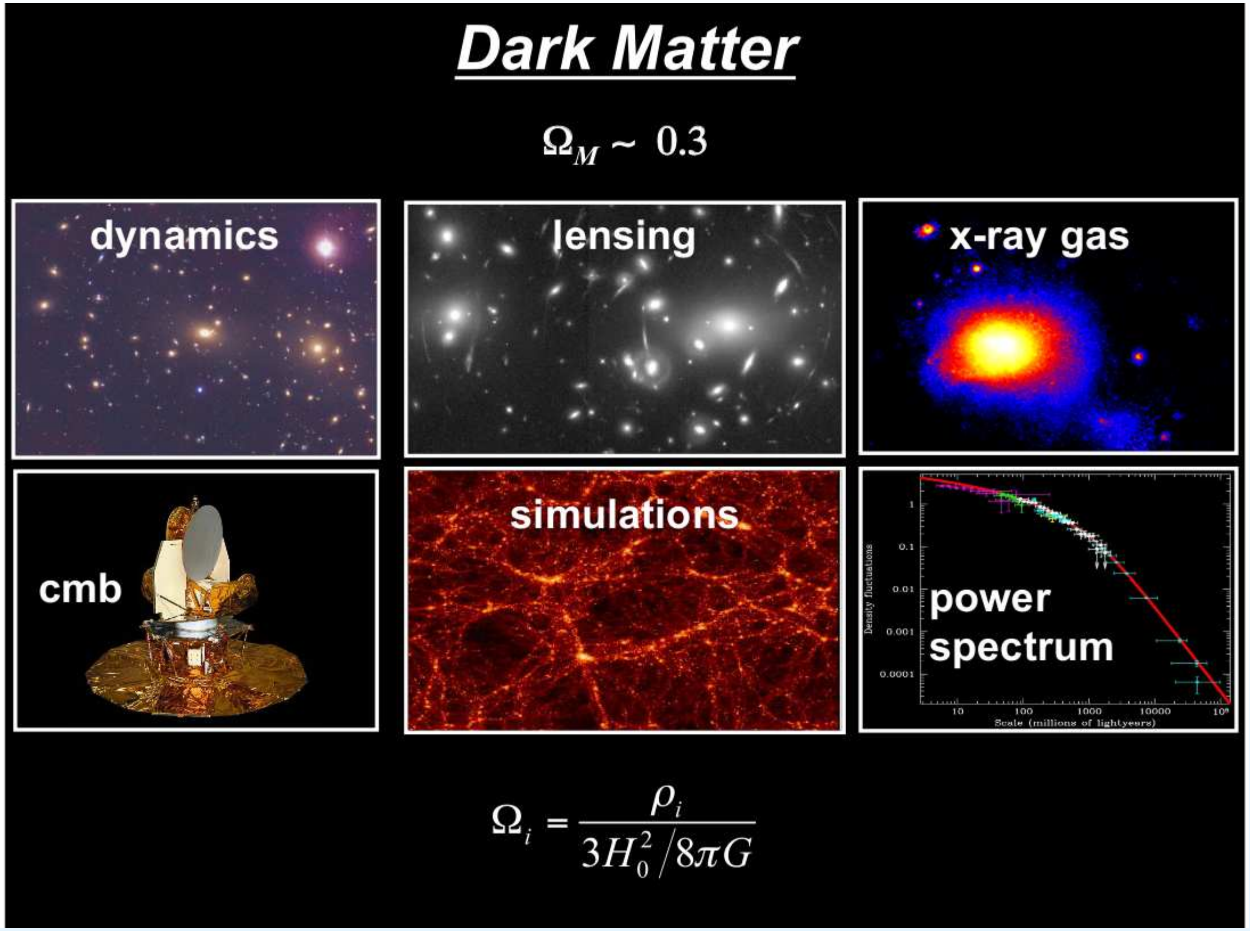
- NUHM = Non-universal Higgs Masses Model.
- Same parameters as in CMSSM, except that the Higgs masses $m_{1,2}$ are not equal to m_0.
- We can trade $m_{1,2}$ with μ and m_A, as our free parameters through the electroweak symmetry breaking condition.
- Thus the NUHM parameters are: m_0,$m_{1/2}$ A_0, $\tan\beta = v_2/v_1$, μ and m_A,.

2.8 What is the LSP?

- Most popular choice Neutralino LSP,
  - Higgsino-like, Bino-like, wino-like
- Another possibility: sneutrino LSP,
  $\tilde{\nu}_L$ is not favored by direct DM search,
  But $\tilde{\nu}_R$ is still allowed by direct DM search.
- Still another option is: Gravitino ($\tilde{\Psi}_\mu$) LSP,

LSP is a candidate for dark matter,

2.9 Dark matter

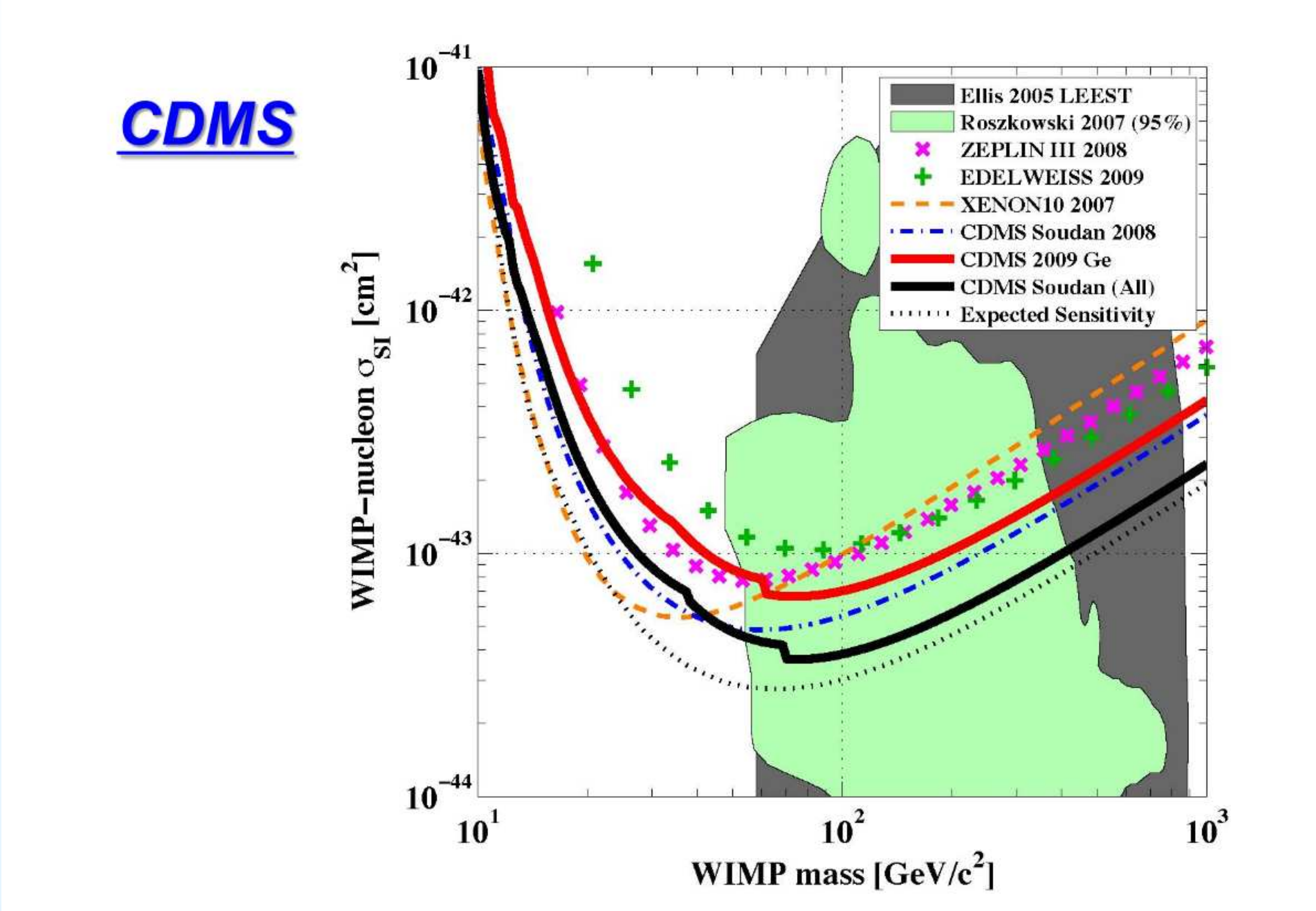


2.10 NLSP scenarios and Constraints

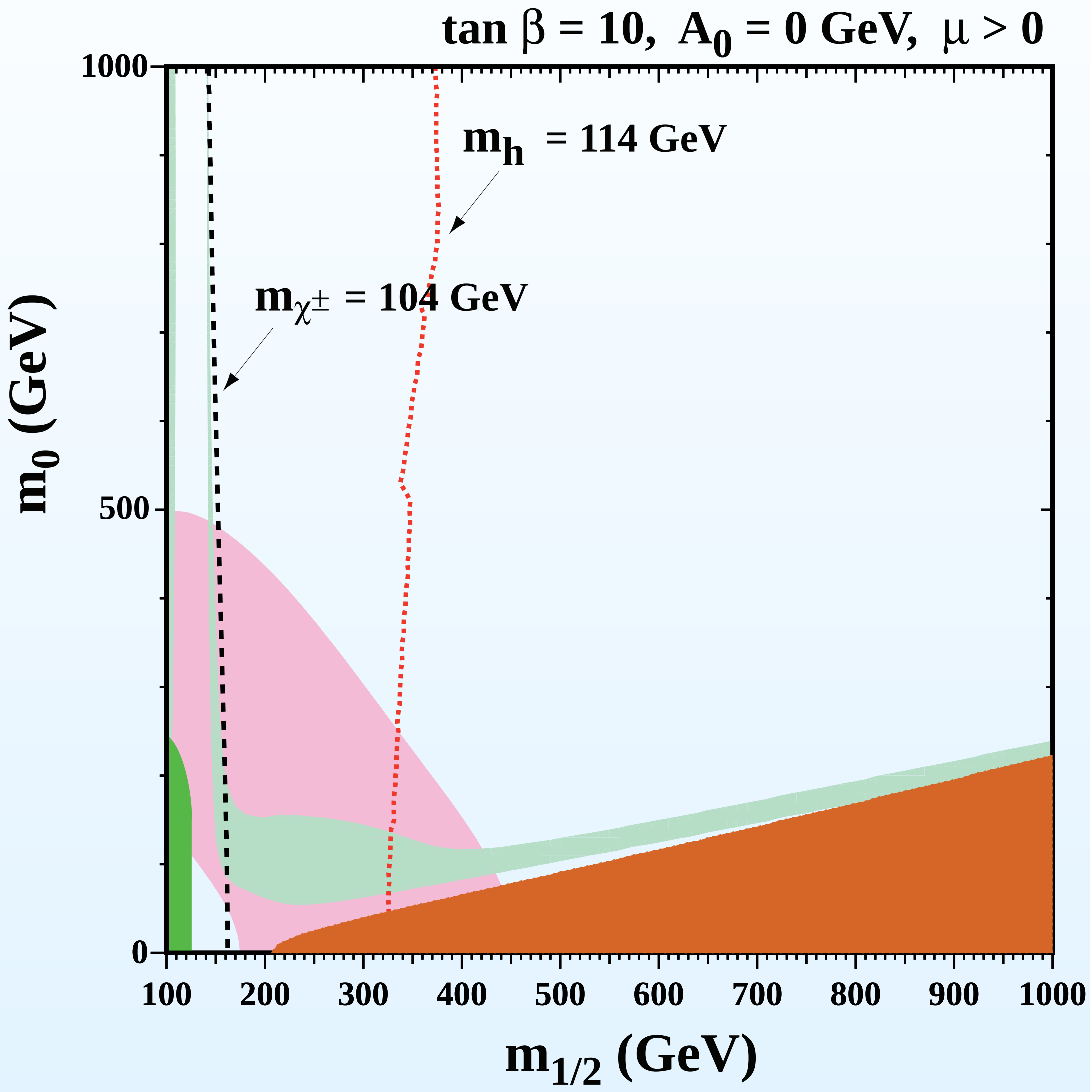
Several constraints are required for consistency of MSSM parameters:

- LEP limits on Higgs mass ($m_h \geq 114$ GeV),
- Current bounds on $b \longrightarrow s + \gamma$,
- Correct induced radiative EWSB,
- Tevatron limits on superpartners.
- Verify implications for cosmology (e.g. Relic density of DM),

2.11 Dark Matter



2.12 MSSM constraints



3.1 SUSY phenomenology at LHC

LSP (and NLSP) nature determines the signatures of SUSY at LHC.
For neutralino χ_1^0 LSP, signal of SUSY is cascade decays and missing energy ,

- Second neutralino decays: $\chi_2^0 \longrightarrow Z + \chi_1^0, h + \chi_1^0$,
- Chargino decays: $\chi_1^+ \longrightarrow W + \chi_1^0, H^+ + \chi_1^0$,
- Squark decays: $\tilde{b} \longrightarrow b + \chi_1^0$, $\tilde{t} \longrightarrow t + \chi_1^0$,
- Gluino decays: $\tilde{g} \longrightarrow q + \tilde{q}$,
- Slepton decays: $\tilde{l} \longrightarrow l + \chi_1^0$,

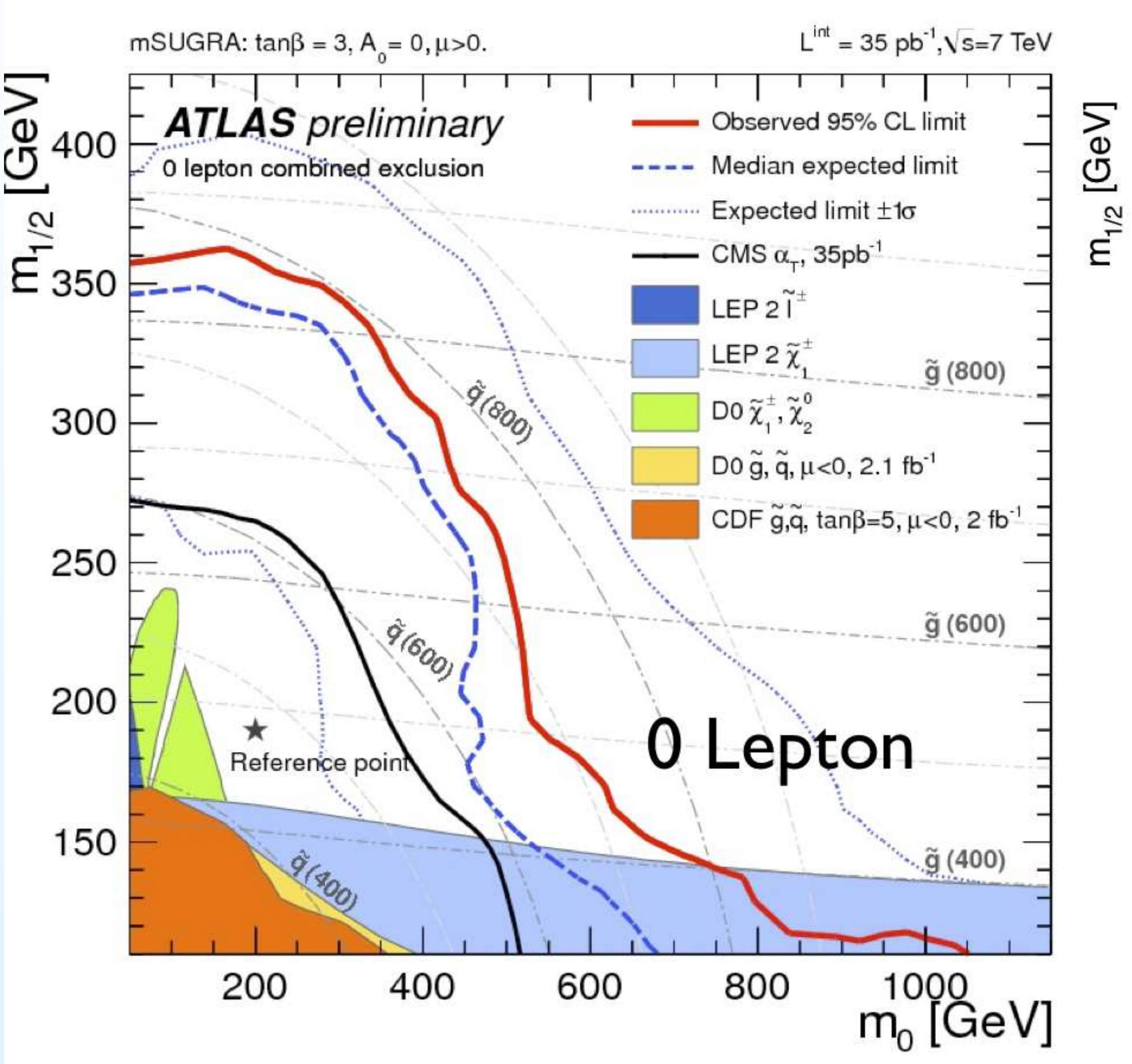
In pp collisions (LHC):

$$qq, gg \longrightarrow \tilde{q}\tilde{q}, \tilde{g}\tilde{g} \quad (4)$$

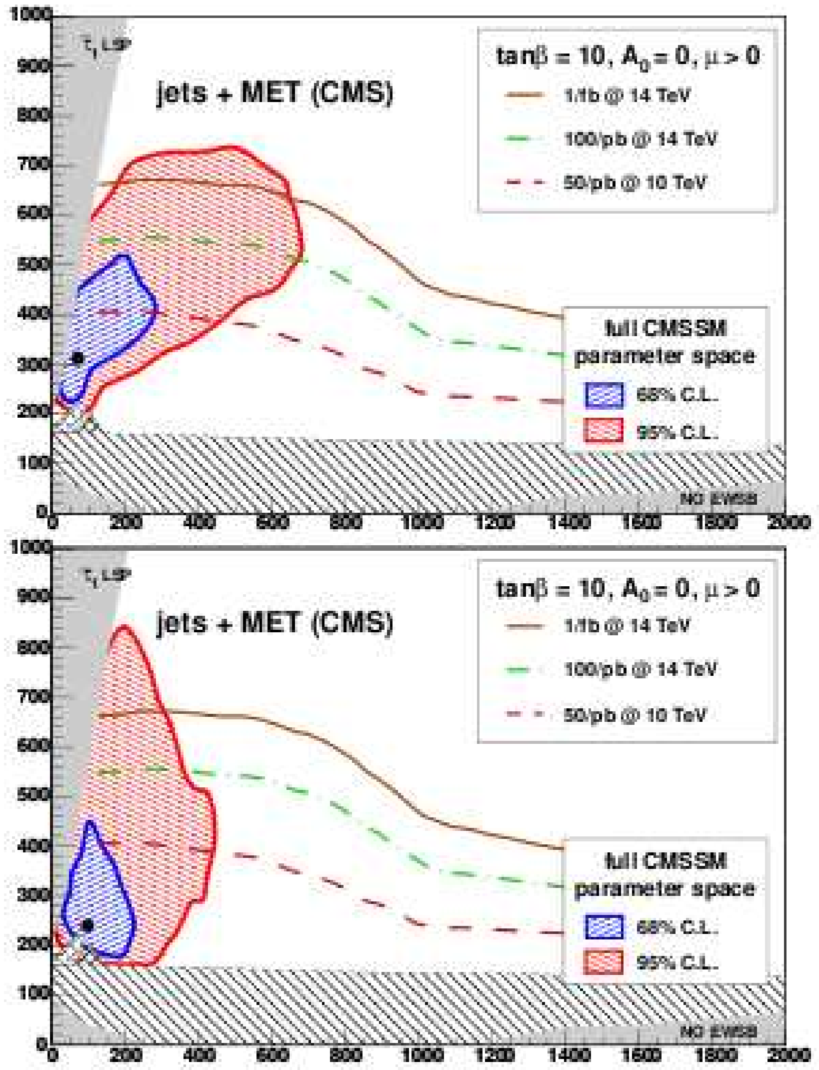
3.2 SUSY phenomenology-GMM

- Within GMM $\tilde{G} = LSP$ and it is very light ($M = O(Mev)$),
- NLSP decay into photons, e.g. $\chi_1^0 \rightarrow \tilde{G} + \gamma$,
- GMM signal includes photons plus missing energy.

3.3 Recent results from LHC



3.4 Recent results from LHC

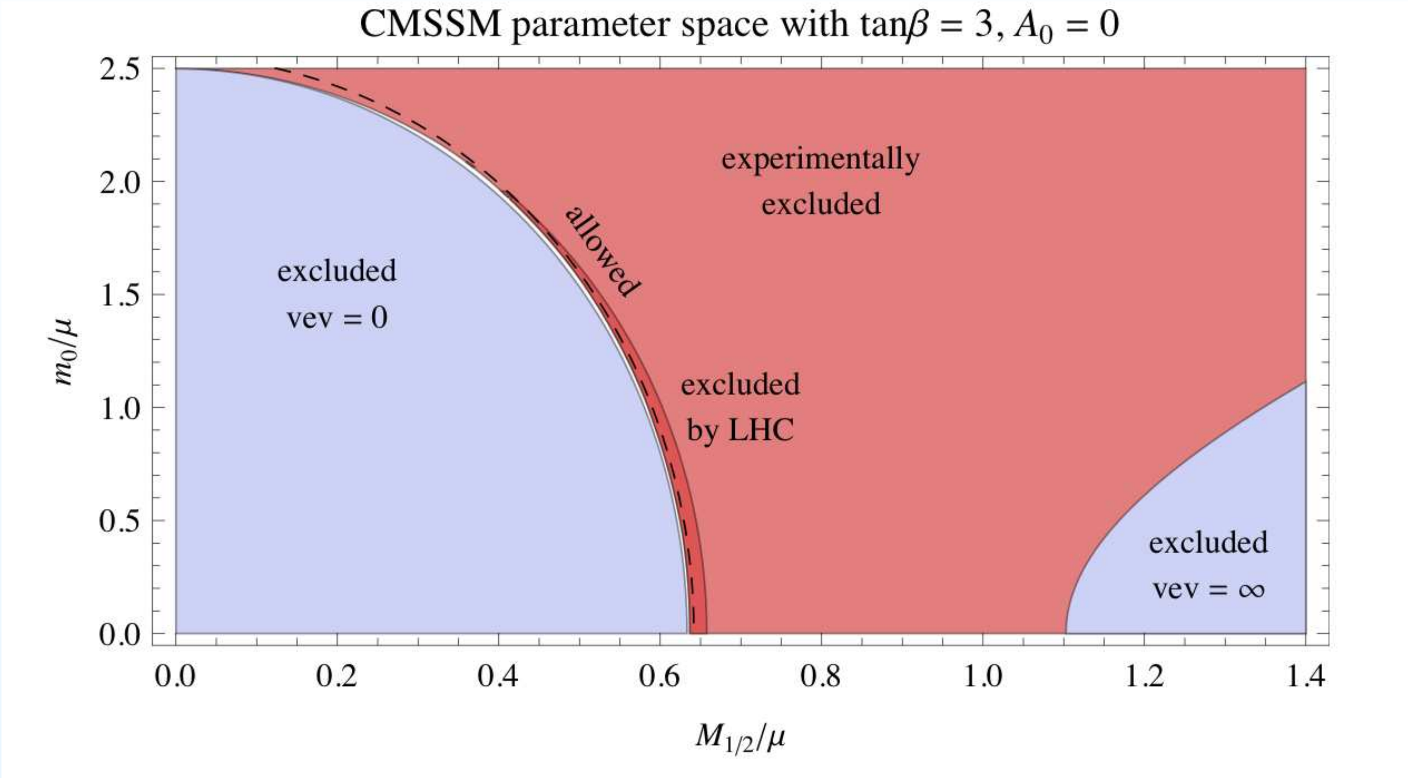


3.5 What are the bad news?

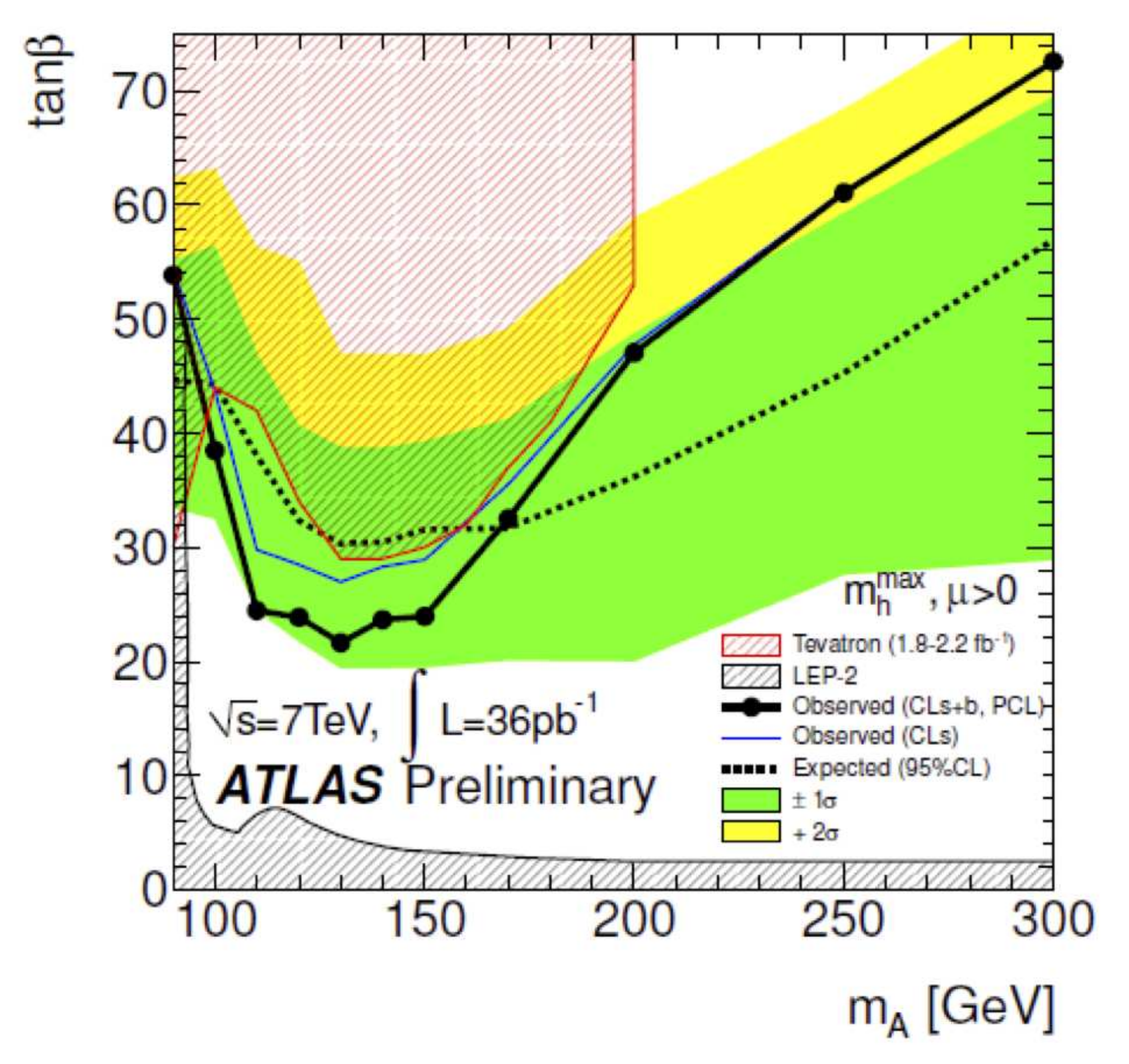
- The masses of superpartners have important implications for EWSB
- Correct radiative EWSB and LHC limits give (A. Strumia, ArXive:1101.2195 [hep-ph]):

$$M_Z^2 = 0.2m_0^2 + 0.7M_3^2 - 2\mu^2 \simeq (91GeV)^2 \times 50(\frac{M_3}{780})^2 + ... \quad (5)$$

3.6 Allowed SUSY parameters from LHC



3.7 SUSY Higgs search at LHC



4.0 SUSY searches beyond the MSSM

- Extended Higgs sector: Add an extra singlet (NMSSM), extra triplets,..
- Extra gauge symmetries: ESSM (extra $U(1)$), SUSY-LR,...
- Gravitino LSP within SUGRA models,
- Gauge mediated models,

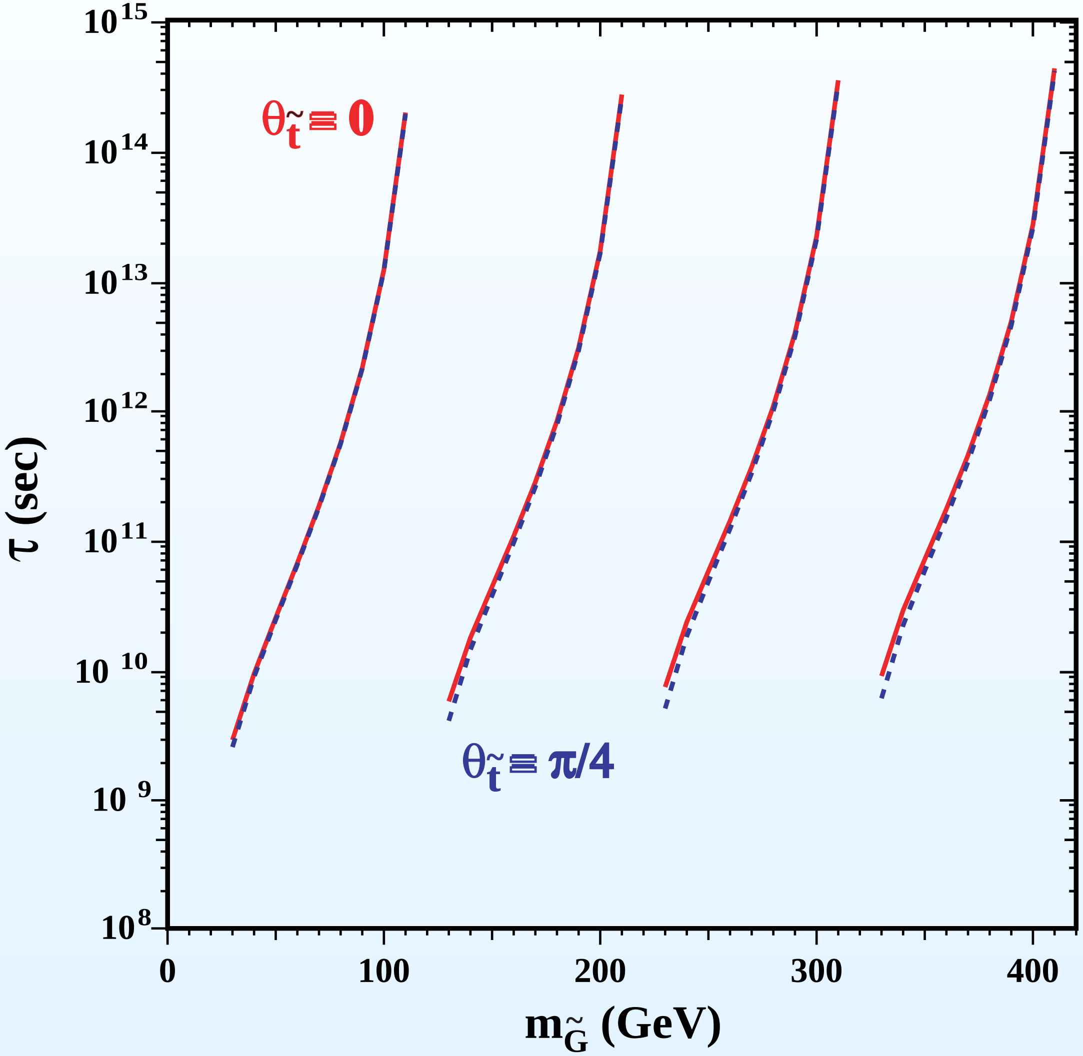
4.1 Gravitino $\tilde{\Psi}_\mu$ as LSP in SUGRA models

- One of the candidates for DM in supergravity is the gravitino.
  SUSY mass parameters are related to $O(m_{3/2})$,
  Take $m_{3/2}$ as a free parameter; lighter than other sparticle masses.
- Gravitino is a very weakly interacting particle, with coupling $\simeq 1/M_{Pl}$ (in supergravity).
  Practically undetectable. Only gravt. effect,
  The next lightest SUSY particle (NLSP) could be long lived.
- We have many possibilities for the NLSP: neutralino, stau, sneutrino, stop. Each with its own distinct phenomenology.

4.2 Stop NLSP scenario [b],

- There are regions of parameter space where stop may be NLSP,
- All constraints within this scenario are fullfilled within the NUHMM, but not within the CMSSM,
- A large life-time for stop appears in this scenario, which has very important implications,

4.3 Stop lifetime: 3-body



4.4 Implications of stop NLSP for LHC

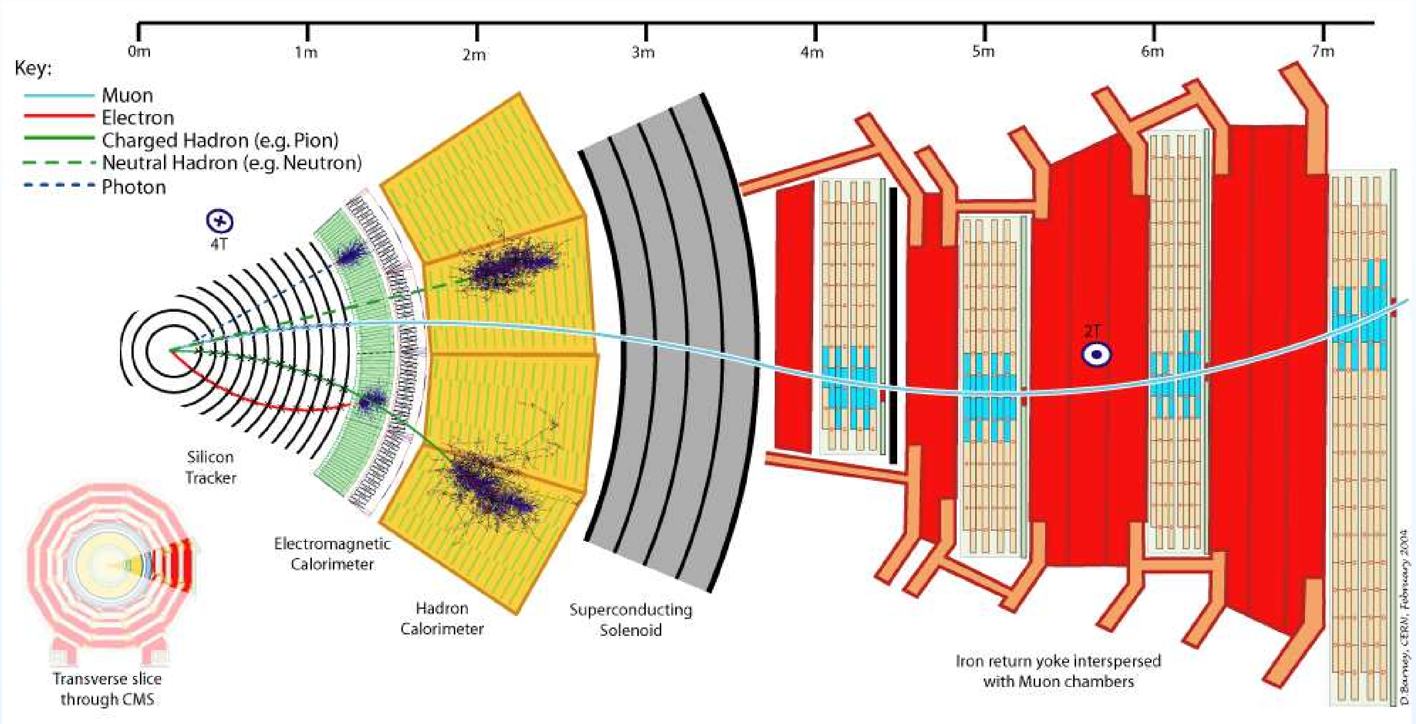
Stop NLSP will form new states, e.g. MESINOS and SBARYONS, that will constitute new signature of SUSY.

- Charged Mesinos: $\tilde{T}^{+} = (\tilde{t}_1 d)$,
- Neutral Mesinos: $\tilde{T}^{0} = (\tilde{t}_1 u)$,
- Sbarions: $\tilde{\Lambda}^{+} = (\tilde{t}_1 u d)$,
  $\tilde{\Lambda}^{0} = (\tilde{t}_1 d d)$
- One expects $\tilde{T}^{0}$ to be the lightest state,
- The charged mesinos $\tilde{T}^{+}$ decays semileptonically:
  $\tilde{T}^{+} \rightarrow \tilde{T}^{0} + e + \nu_e$ with lifetime of order 1.2 s

4.5 Implications of stop NLSP for LHC

- Limits from search for quasi-stable charged particles (Tevatron, hep-ex/0602039) can apply, $M > 220$ GeV.
- The stop hadrons will decay to the lighest state $\tilde{T}^0$, which escapes from the detectors,
- Look for novel methods to search for such states at LHC.
- Possible that LHC can go up to O(TeV) masses.

4.5b Stop NSLP and LHC

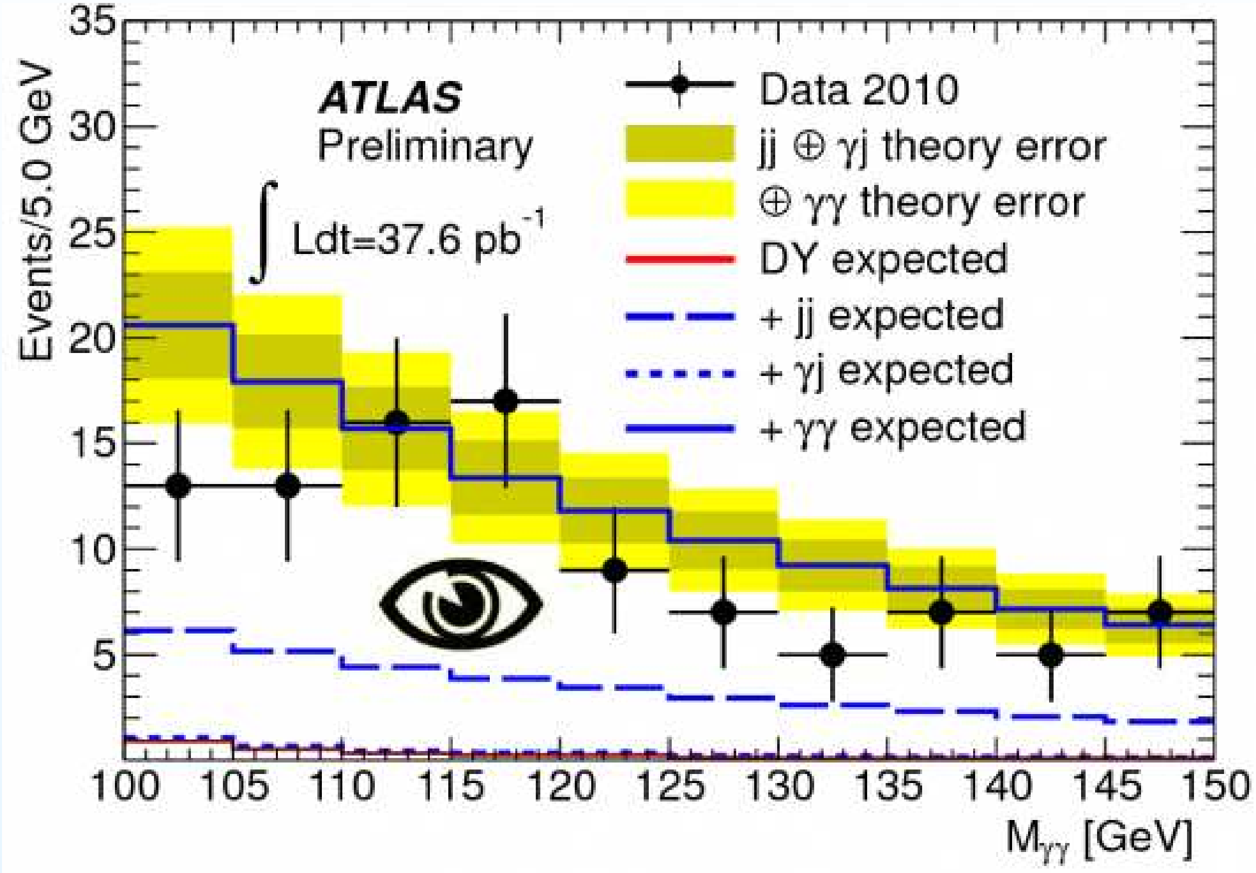


4.6 Other NLSP with gravitino LSP

From Y. Santoso et al., (ArXive:0903.2860 [hep-ph], and refs.)

- Stau (charged NLSP),
- Chargino (Charged NLSP),
- Neutralino (neutral NLSP),
- Sneutrino (neutral NLSP),

4.7 Rumor Physics and Higgs



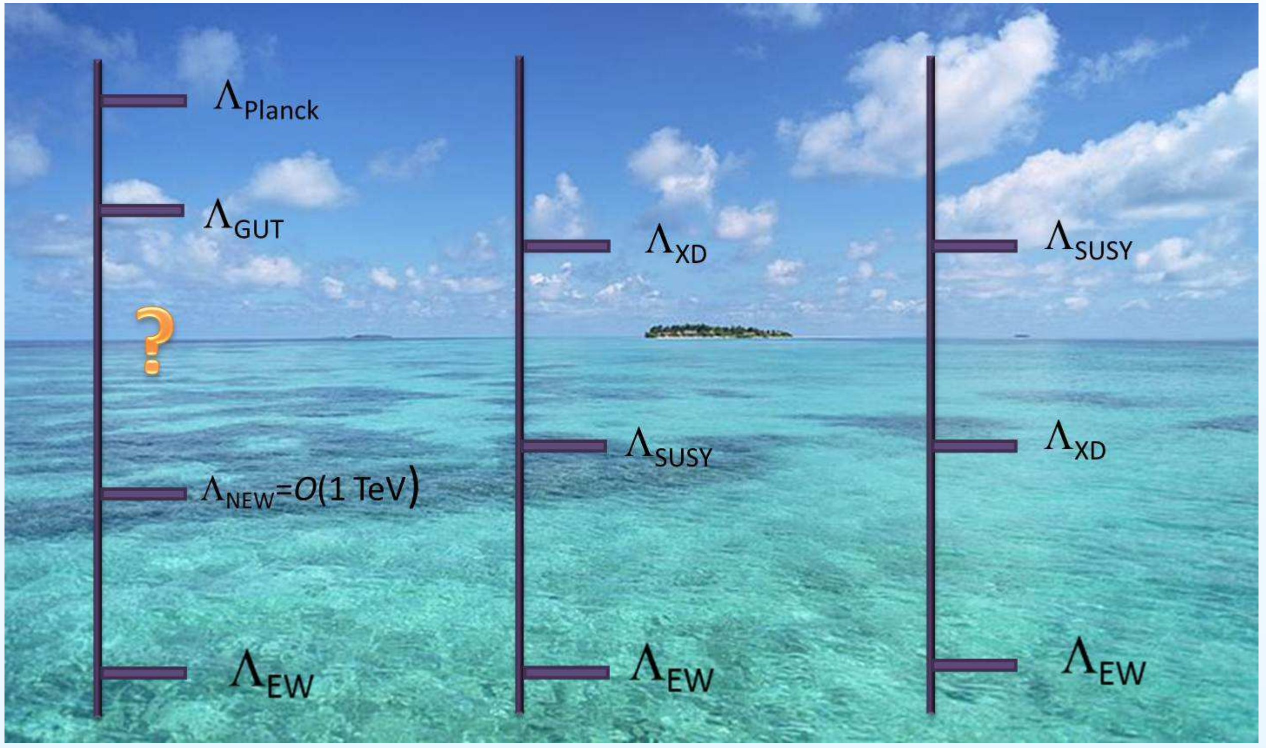
A possible explanations (DC, Gosh, Moretti, PRD68, 2003)

$$H \to \chi_1 \chi_1 \to \gamma\gamma + 2\tilde{G} \quad (6)$$

5.1 SUSY beyond the EW realization

- Current paradigm for SUSY is based on the assumption that it solves the hierarchy problem,
- But even if some other physics solves it, for instance through a composite Higgs, SUSY may play a role in the dynamics that forms the Higgs condensate.
- Furthermore, if quarks and leptons are also composite, SUSY may play a role at the underlying scale,
- Also, may be SUSY only plays a role at the planck scale (Superstring theory)

5.2 SUSY beyond EW



6.1 Conclusions

- SUSY is one very well motivated extension of the SM,
- Constraints on particular models are cominging from LHC, mSUGRA motivated scenario is in problems,
- Many other scenarios will be tested at LHC,
- Gravitino LSP is another interesting and viable scenario, Several possibilities for NLSP (stau, sneutrino, stop,..), In scenarios with stop NLSP, the large life-time of the stop $\simeq 10^8 - 10^{12}$ secs., has interesting implications for nucleosinthesis and collider physics.
- The search for SUSY is still open, and we will learn something very important from LHC: does SUSY solves the hierarchy problem?
- Even with a negative answer, some of us will keep trying to find out if some other realization of SUSY occurs in nature.

6.2 My back pages

One important lesson from the past:

- Yang-Mills QFT’s appear in 1954 (PRD)
- As soon as Yang tried to apply them to hadron physics (the rho mesons), the problem of mass appeared
  (Pauli make him cry)
- In the 60’s, Veltman started a full systematic program to study the renormalizability of YM theories with/without mass,
  (A famous theorist told him: "You are in a forgotten corner of particple physics")
- YM with SSM were shown to be renormalizable in 1970-71 (’t Hofft- Veltman + others),
- Neutral currentswere discvered in 1973,
- Massive gauge bosons (YM) were detected in the early 80’s

Apx1.1 MSSM and Gravitino

- SUSY Algebra: $\{Q_\alpha, Q_{\dot{\beta}}\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu$,
- SUSY transf. $\delta_\epsilon F(x, \theta, \bar{\theta}) = (\epsilon\theta + \bar{\epsilon}\bar{\theta}) F(x, \theta, \bar{\theta})$
- SUGRA (Local SUSY) = Gauge theory of SUSY,
- Noether current of SUSY= Supercurrent (J^μ_α),
- Vierbein (e^a_μ) and Gravitino ($\tilde{\Psi}_\mu$) form the Supergravity multiplet.
- Thus, SUGRA includes graviton and Gravitino,

A1.2 Gravitino-MSSM interactions,

- All interactions can be derived from SUGRA lagrangian (Wess-Bagger),
- Most relevant can be identified from the fact that $\tilde{\Psi}_\mu$ couples to the supercurrent. Most relevant terms are:

  Coupling with chiral superfields:

$$L_1 = -\frac{1}{\sqrt{2}M}\tilde{D}_\nu^* \phi_i^* \tilde{\Psi}_\mu \gamma^\nu \gamma^\mu \chi_R^i + h.c.(L \rightarrow R) \tag{7}$$

  Coupling with vector superfields:

$$L_2 = \frac{i}{8M}\bar{\tilde{\Psi}}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda^a F_{\nu\rho}^a \tag{8}$$

A1.3 Relevant interactions

Stop-top-gravitino interactions:

(9) $$\tilde{t}_1^*(p)\bar{\Psi}_\mu t \rightarrow -\frac{1}{\sqrt{2}M}\gamma^\nu\gamma^\mu p_\nu(\sin\theta_{\tilde{t}}P_R+\cos\theta_{\tilde{t}}P_L)$$

and similar expression holds for the Bottom-sbottom-gravitino interaction.
Chargino-W-gravitino:

(10) $$\chi_i^-\bar{\Psi}_\mu W^-(k) \rightarrow -\frac{m_W}{M}\gamma^\nu\gamma^\mu(A_{Li}P_R+A_{Ri}P_L)$$

where: $A_{Li}=V_{i2}\sin\beta$, $A_{Ri}=V_{i2}\cos\beta$, and U,V are the matrices that diogonalize the charginos.

A.2 Stop 3BD mode: $\tilde{t}_1 \rightarrow b + W + \tilde{\Psi}_\mu$

- We shall assign the momenta for the decay as follows: $\tilde{t}_1(p) \rightarrow t^*(q)(\rightarrow b(p_2) + W(k)) + \Psi(p_1)$.
- The 3-body decay receives contributions from several intermediate states (top, sbottom and chargino).
- Decay amplitudes:

$$\mathcal{M}_t = C_t P_t(q_1)\bar{\tilde{\Psi}}_\mu p^\mu [A_{\tilde{t}} + B_{\tilde{t}}\gamma_5](q_1 + m_t)\gamma^\rho \epsilon_\rho P_L v(p_2)$$

$$\mathcal{M}_{\tilde{b}} = C_{\tilde{b}} P_{\tilde{b}}(q_2)\bar{\tilde{\Psi}}_\mu q_2^\mu [a_i P_R + b_i P_L] p^\rho \epsilon_\rho v(p_2)$$

$$\mathcal{M}_{\chi^+} = C_\chi P_\chi(q_3)\bar{\tilde{\Psi}}_\mu \gamma^\rho \epsilon_\rho \gamma^\mu [V_i + A_i\gamma_5](q_3 + m_\chi)[S_i + P_i\gamma_5] v(p_2)$$

A.3 Stop decay width

The expression for the decay width is:

$$\frac{d\Gamma}{dxdy} = \frac{g^2 m_{\tilde{t}_1}^2}{512\pi^3 \mu_W} |\mathcal{M}|^2 \tag{11}$$

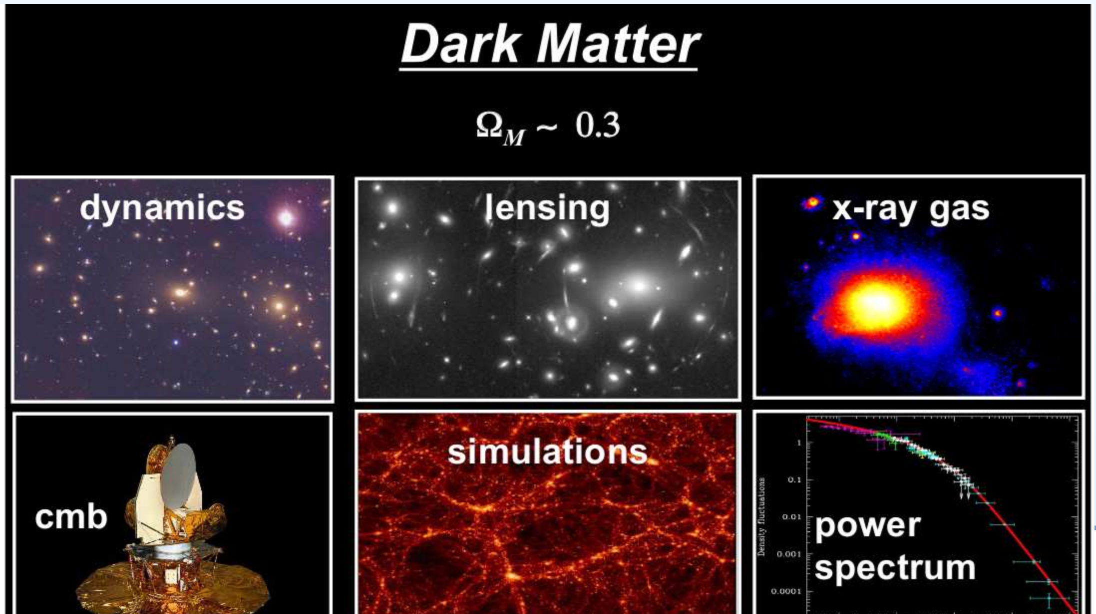
the integration limits are: $2\mu_G < x < 1 + \mu_G - \mu_W$ and $y_- < y < y_+$, where

$$y_\pm = \frac{1 + \mu_G + \mu_W - x}{2(1 + \mu_G - x)} [(2 - x) \pm (x - 4\mu_G)^{1/2}] \tag{12}$$

A.4 Dark matter (DM)

- Rotation of Galaxies,
- Dynamics of galaxie clusters,
- Flatness of the universe, i.e. $\Omega = \frac{\rho_m}{\rho_c} = 1$,
- CMB radiation spectrum,

All require DM:



A.5 What is Dark Matter??

- The relics density of DM can be estimated as:

$$\Omega h^2 \simeq \frac{3 \times 10^{-27}\, cm^3/s}{< \sigma v >} \tag{13}$$

- To get $O(10-20)\,\%$ DM, for $M_X \simeq O(m_W)$ one needs σ of weak strength (A Miracle?),
- Thus, most viable DM is a weakly interacting particle (WIMP),
- Many models beyond the SM predict stable neutral particles that could play the role of WIMPS.

3.5 Implications of stop NLSP: BBN and DM

- The presence of unstable charged particles in early universe can affect Nucleosynthesis. From Ellis et al. (astro-ph/0503023) one gets for $\tau \simeq 10^8$ secs:

$$m_{\tilde{t}_1} \frac{n_{\tilde{t}_1}}{n_\gamma} < 10^{-12} \quad (14)$$

- This implies: $\Omega_{\tilde{t}_1} h^2 < 7 \times 10^{-5}$, which can be satisfied in some regions of parameters of NUHM but not in CMSSM.
- Stop NLSP may help to alleviate the Litium problem,
- To get right gravitino abundance needs some other source, e.g. inflaton decay.