The Future of Supersymmetry

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...in recent times,

supersymmetry

has been getting a lot of bad press

Supersymmetry Bites the Dust

Where Supersymmetry Belongs: In a Coffin

SUSY in the Hospital?

Is Supersymmetry Dead?

“Supersymmetry Dealt a Blow”?

Well that about wraps it up for *SUSY*?

Truant particles turn the screw on supersymmetry

Supersymmetry takes an arrow to the knee

Is SUSY Dead Yet?

The uncertain future of SUSY

The Future of Supersymmetry

… is rooted in the present

THE CASE FOR SUSY

Aesthetic appeal of SUSY:

- only way of combining spacetime symmetry w. internal symmetry
  $\Rightarrow$ the only way to combine gravity with other interactions
- only theory which explains differentiation of bosons and fermions
  $\Rightarrow$ a consequence of the breaking of supersymmetry

Practical appeal of SUSY:

- most natural way of solving hierarchy problem
  $\Rightarrow$ pairwise cancellation of quadratic divergences
- only theory where a light Higgs boson is predicted naturally
  $\Rightarrow$ fits the 125 GeV Higgs boson perfectly
- only theory which has a natural dark matter candidate
  $\Rightarrow$and also has a 'solution' for the cosmological constant
- electroweak symmetry-breaking has a dynamical origin
- only way to get gauge coupling unification with one-step breaking

Group Theoretic Arguments

The Coleman-Mandula no-go theorem

If $\mathfrak{G}$ is a symmetry group of the S-Matrix, and the following assumptions hold:

1. For any M there are only a finite number of particle types with mass less than M,
2. Scattering occurs at almost all energies (except for perhaps some isolated set of energies),
3. The amplitudes for elastic two-body scattering are analytic functions of the scattering angle at almost all energies and angles,

then the generators of $\mathfrak{G}$ consist of only the generators of the Poincaré group $\mathfrak{P}$, and the generators of internal symmetries.

Haag–Lopuszanski–Sohnius theorem

The only way to evade the restrictions of the Coleman-Mandula theorem is to replace the Lie group of symmetries by a Z_2 graded Lie group

$\Rightarrow$ supersymmetry

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2(\sigma^\mu)_{\alpha\dot{\beta}} P_\mu$$

E

Bosons and Fermions mix freely

$\Rightarrow$ cannot be distinguished

SUSY breaks

Bosons are Bosons

Fermions are Fermions

$\Rightarrow$ cannot mix with each other

Spin-statistics theorem becomes a low-energy effect

Mass Stabilization Arguments

J. Feng
arXiv: 1302.6587

Standard Model with $f = t$:

$$m_h^2 \approx m_{h\,0}^2 - \frac{\lambda_f^2}{8\pi^2} N_c^f \int^\Lambda \frac{d^4p}{p^2} \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \Lambda^2$$

$$\mathcal{N}^0 \equiv \frac{m_{h\,\text{1-loop}}^2}{m_h^2} \sim 10^{30}$$

Supersymmetry with $f = t$:

$$m_h^2 \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \left(m_{\tilde{f}}^2 - m_f^2 \right) \ln \left(\Lambda^2 / m_{\tilde{f}}^2 \right)$$

$$m_{\tilde{f}} \lesssim 800 \text{ GeV} \, \frac{1.0}{\lambda_f} \left[\frac{3}{N_c^f} \right]^{\frac{1}{2}} \left[\frac{70}{\ln(\Lambda^2 / m_{\tilde{f}}^2)} \right]^{\frac{1}{2}} \left[\frac{\mathcal{N}_{\max}^0}{100} \right]^{\frac{1}{2}}$$

Light Higgs Boson Arguments

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta \, y_t^2 \Big[m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)$$
$$+ c_{\tilde{t}}^4 s_{\tilde{t}}^4 \Big\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2) \Big\} / m_t^2 \Big]$$

91 GeV

113 +... GeV

135 GeV max

Discovery of a 123 – 127 GeV Higgs-like boson vindicates what SUSY has always predicted

$$h^0, H^0, A^0, H^+, H^-$$

Large stop mass splitting required...

Dark Matter Arguments

Lepton number (L) and baryon number (B) conservation in the Standard Model are purely accidental – they happen because we write the minimum number of possible operators

Any bigger symmetry, such as a GUT, will automatically violate these U(1) global symmetries and lead to rapid proton decay

SUSY models lend themselves naturally to a global U(1) R-symmetry. When SUSY breaks, this remains as R-parity

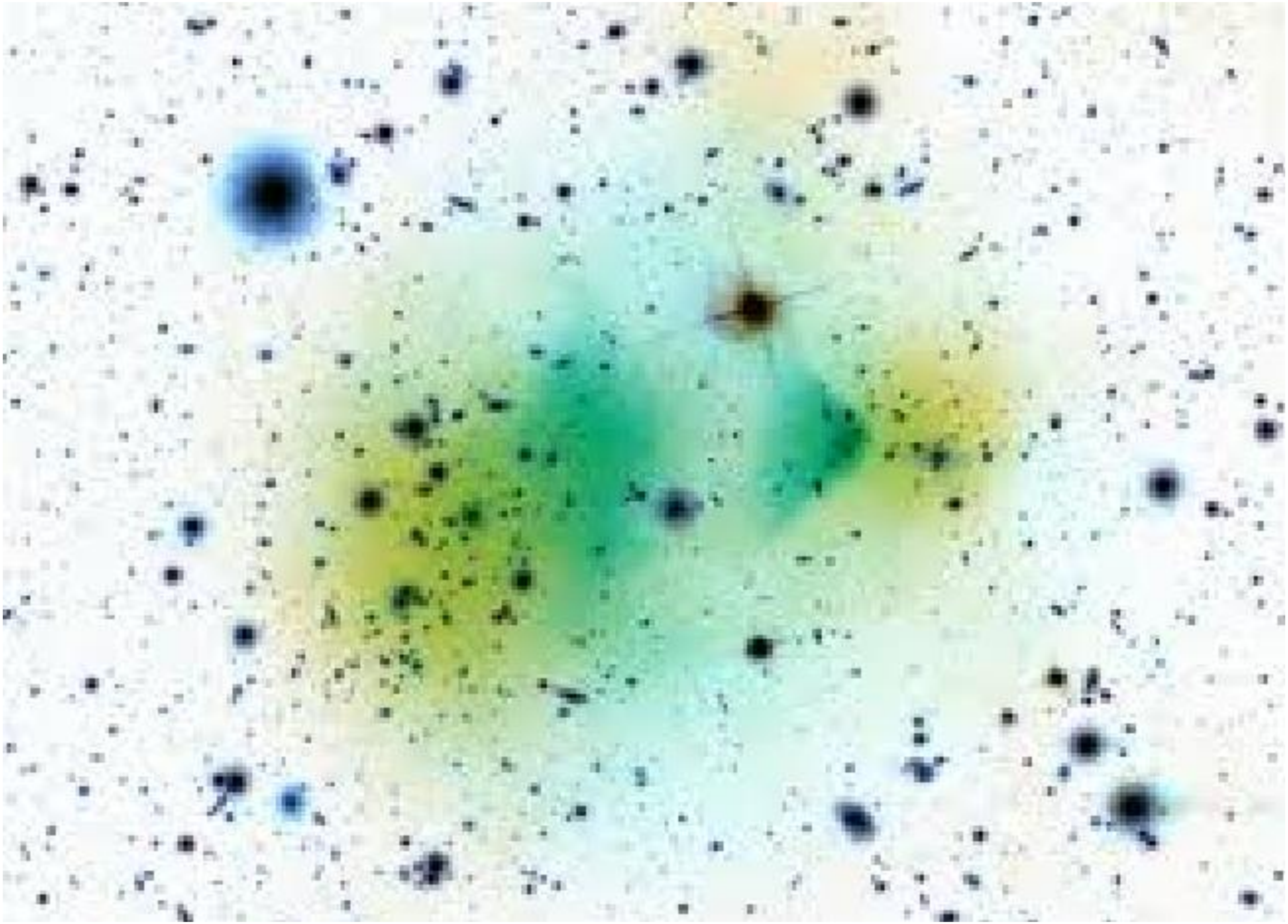
$$(-)^{L+2S+3B}$$

All SM particles have R-parity +1, all SUSY partners have -1

$\Rightarrow$The LSP is stable and weakly interacting

$\Rightarrow$ ideal WIMP for dark matter candidate

Dark matter must be WIMPS.... Bullet Cluster....



Electroweak Symmetry Breaking in SUSY

S.P. Martin
hep-ph/9709256

$$V = (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

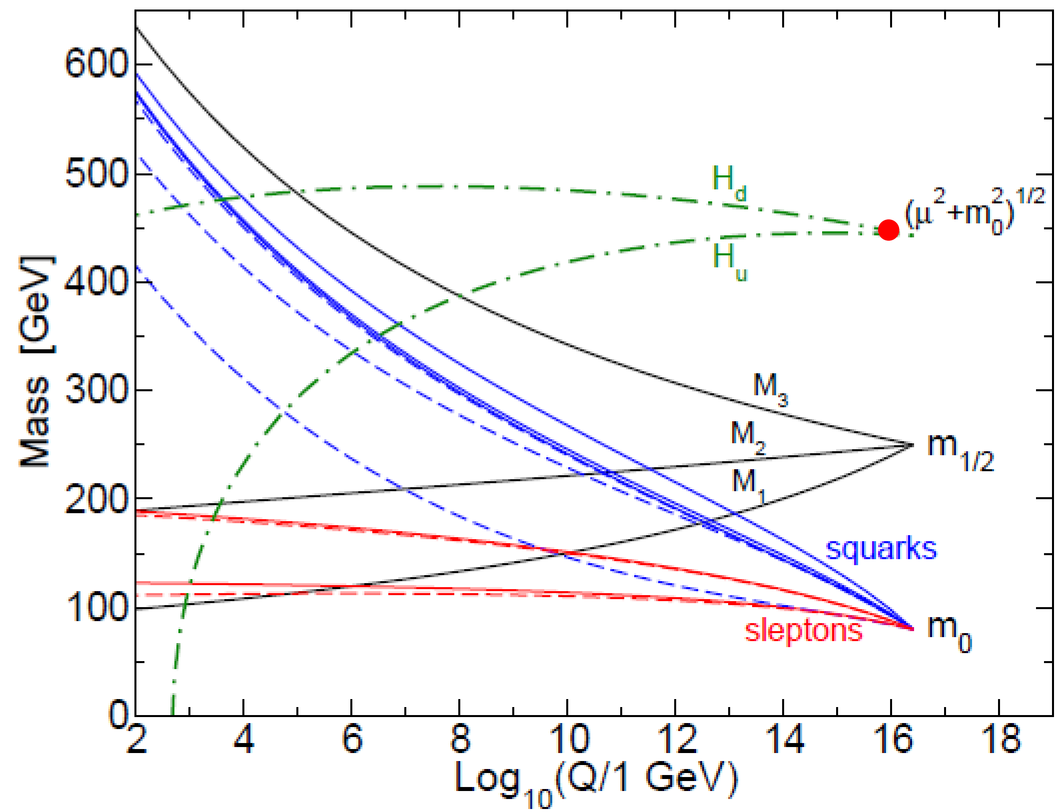
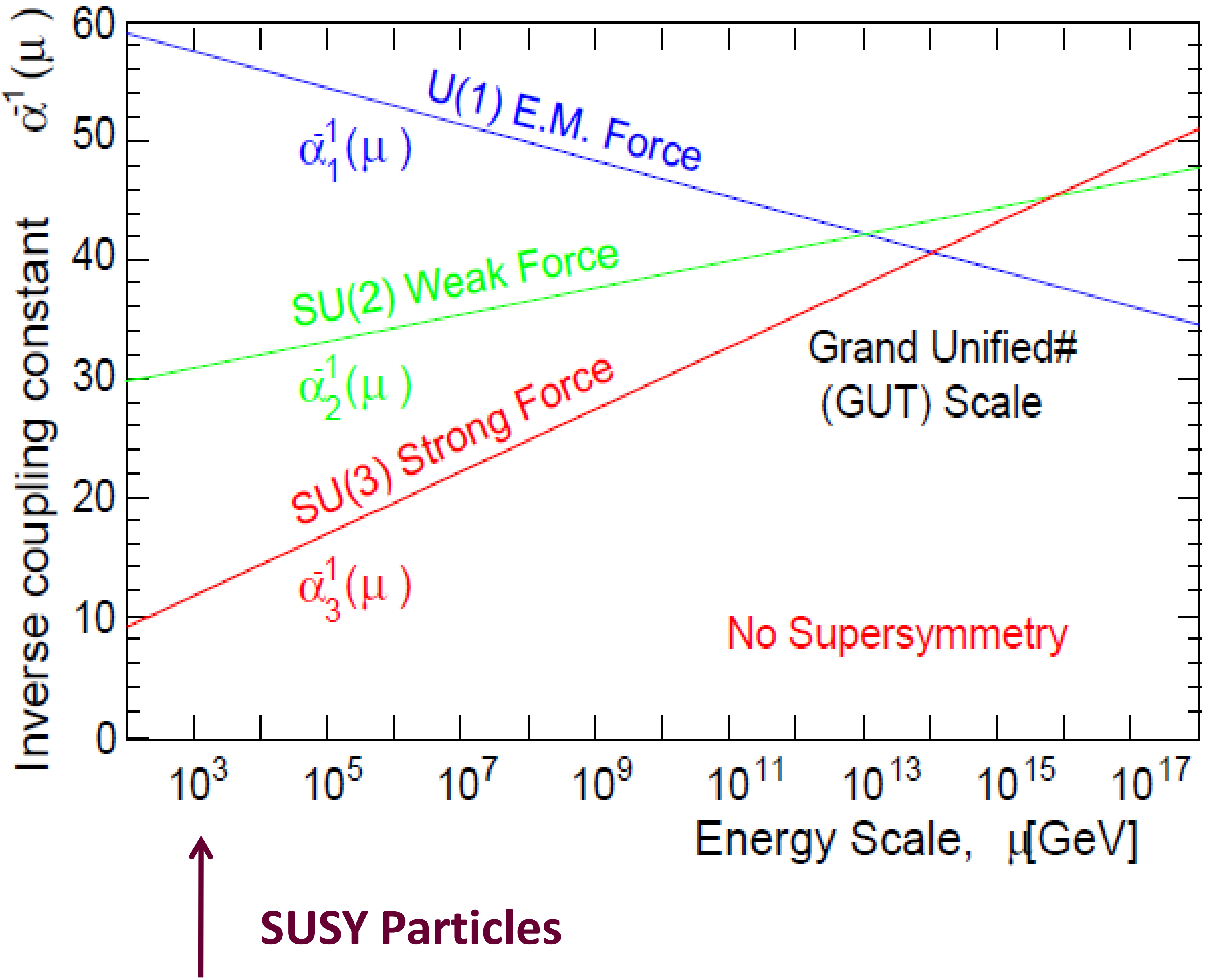


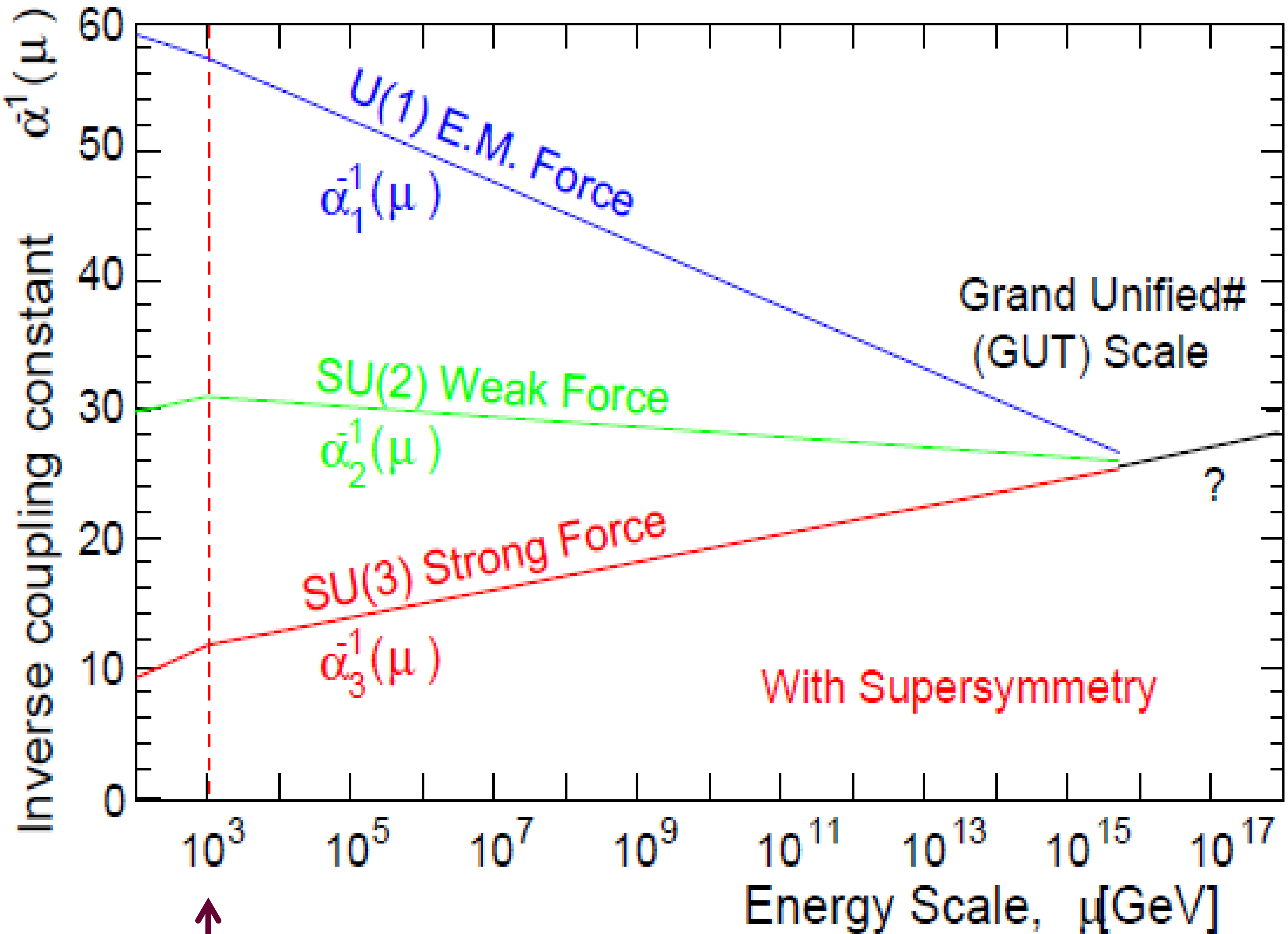
Figure 7.4: RG evolution of scalar and gaugino mass parameters in the MSSM with typical minimal supergravity-inspired boundary conditions imposed at $Q_0 = 2.5 \times 10^{16}$ GeV. The parameter $\mu^2 + m^2_{H_u}$ runs negative, provoking electroweak symmetry breaking.

Gauge Coupling Unification in SUSY



SUSY Particles

Gauge Coupling Unification in SUSY



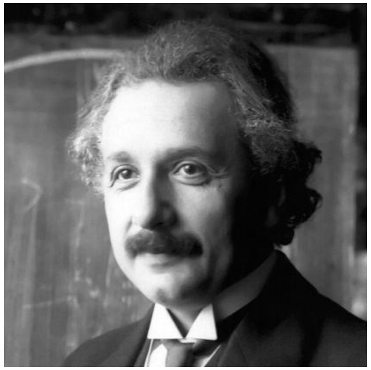
SUSY Particles

Such a beautiful theory must have truth in it somewhere

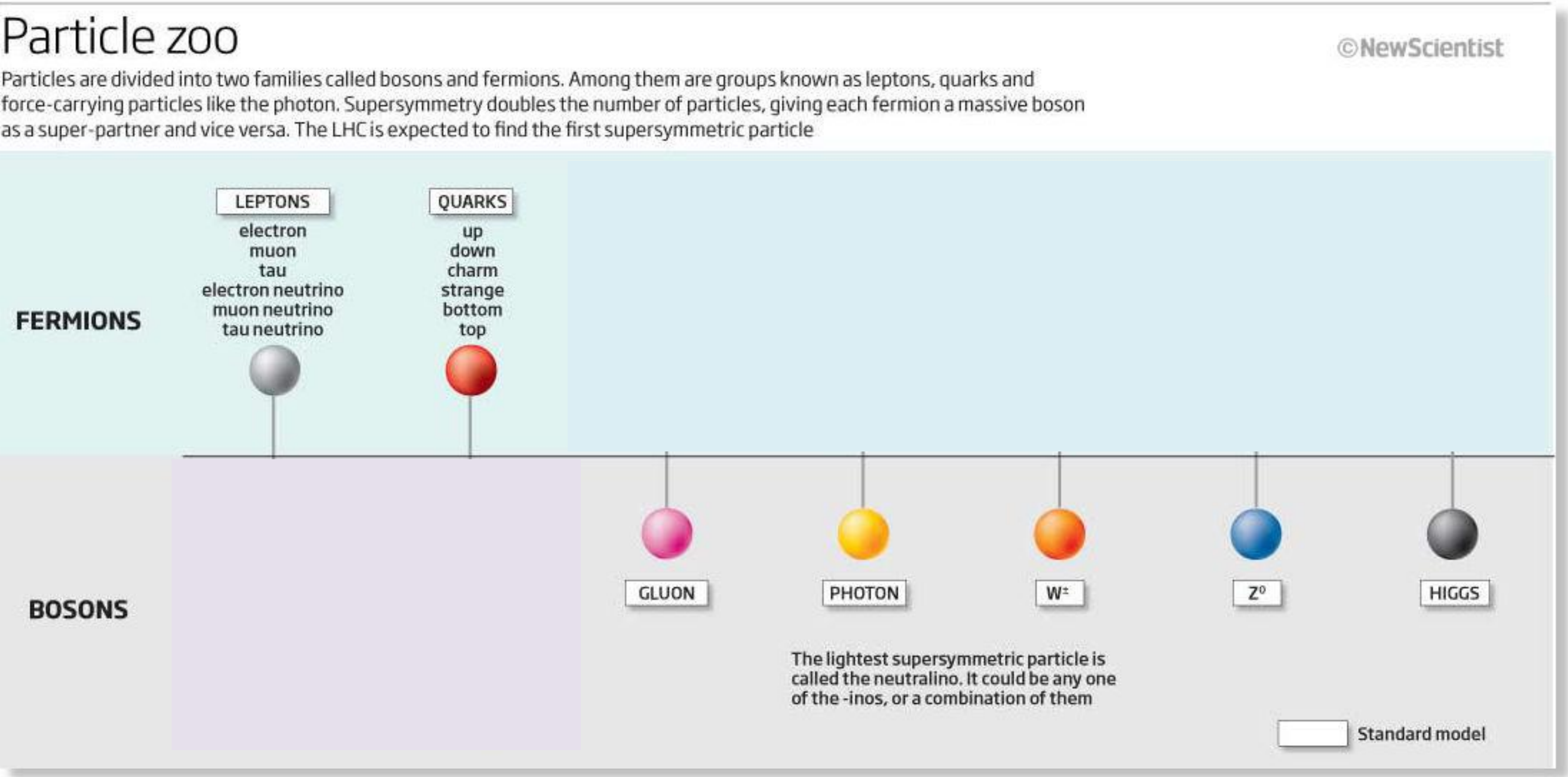
Dr. Einstein, it seems that the observations made by the British team of the recent solar eclipse in South America support your theory of general relativity.

How would you have felt if your theory had been proven wrong?

Then I would have felt sorry for the Lord.
The theory is correct.

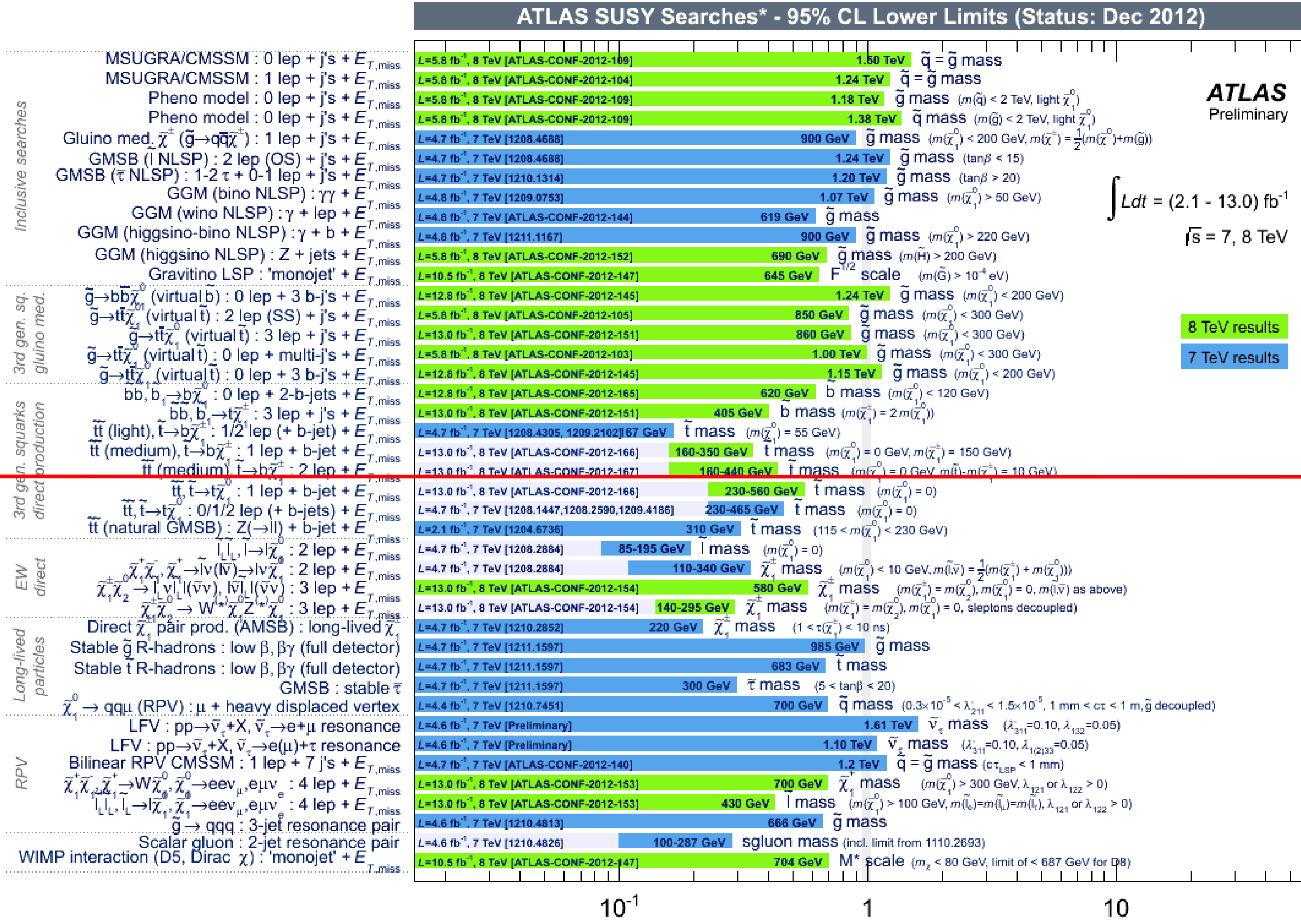


The Only Problem...



...we have no experimental evidence at all for SUSY particles

...okay, then they must be heavy...



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Little Hierarchy Problem in 3rd generation

$$m_{\tilde{f}} \lesssim 800 \text{ GeV} \left[\frac{\mathcal{N}^0_{\max}}{100}\right]^{\frac{1}{2}}$$

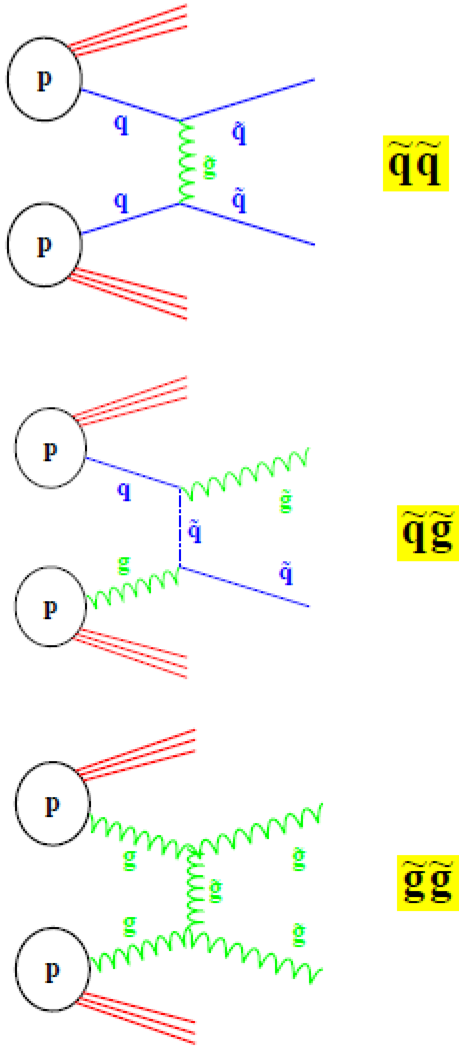
SUSY around the corner

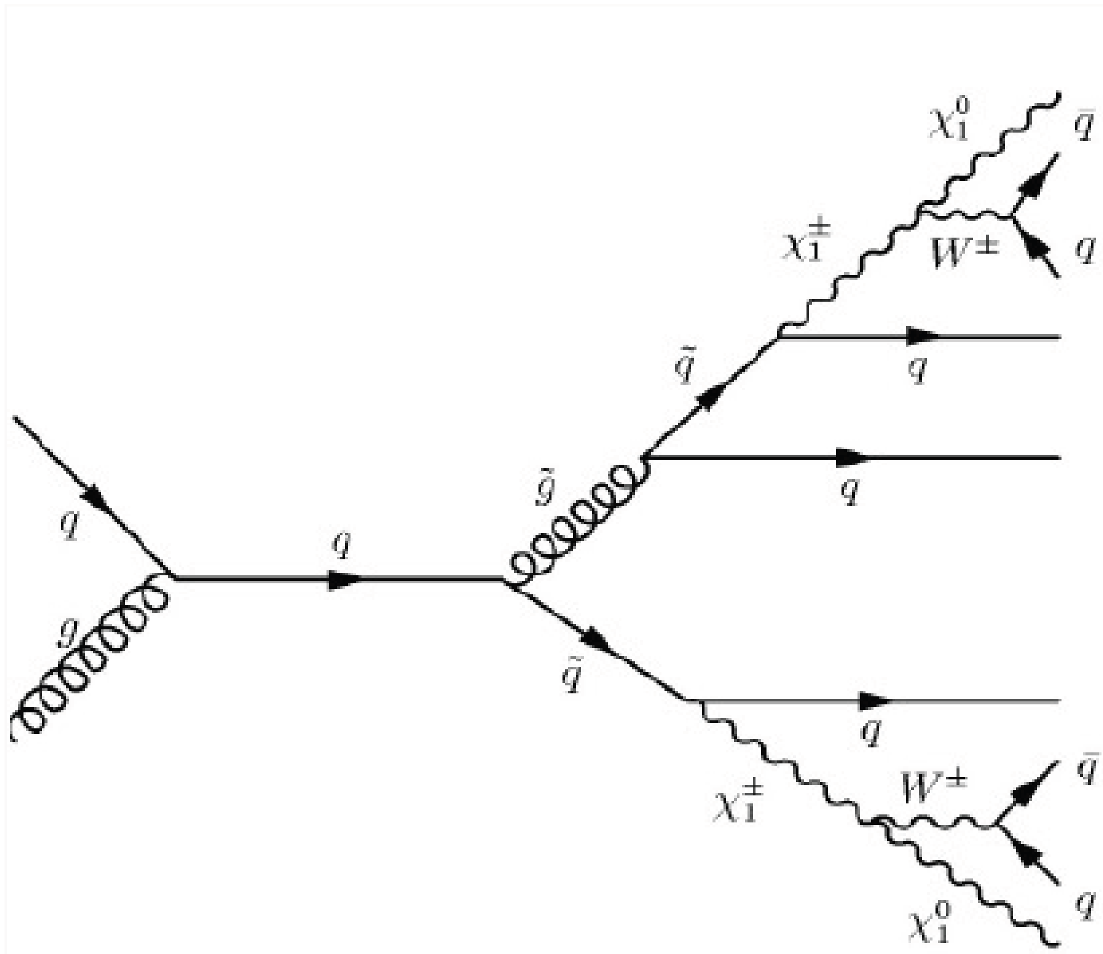
N^0	*Fine tuning level*	*Max squark mass*
10	**10%**	**253 GeV**
100	**1%**	**800 GeV**
1 000	0.1%	2.53 TeV
10 000	0.01%	8 TeV
100 000	0.001%	25.3 TeV
1 000 000	0.000 1%	80 TeV

$$\mathcal{N}^0 \equiv \frac{m^2_{h\,\text{1-loop}}}{m^2_h}$$

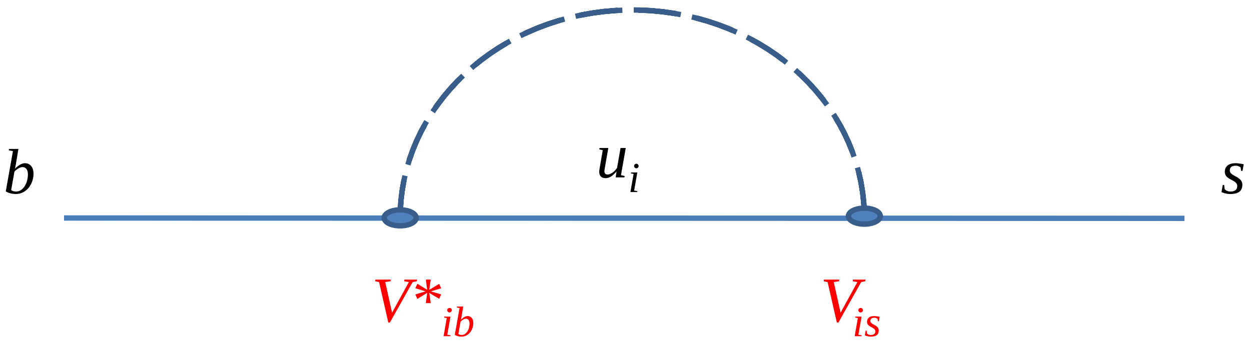
No reason to panic at this stage

Collider Searches for SUSY : missing pT





Low Energy Searches for SUSY : GIM Violation



$$\sum_i V^*_{ib} V_{is}\, f\left(\frac{m_i}{v}\right)$$

Experimental status of particle and astroparticle searches for supersymmetry

Journal of Physics: Conference Series **447** (2013) 012019

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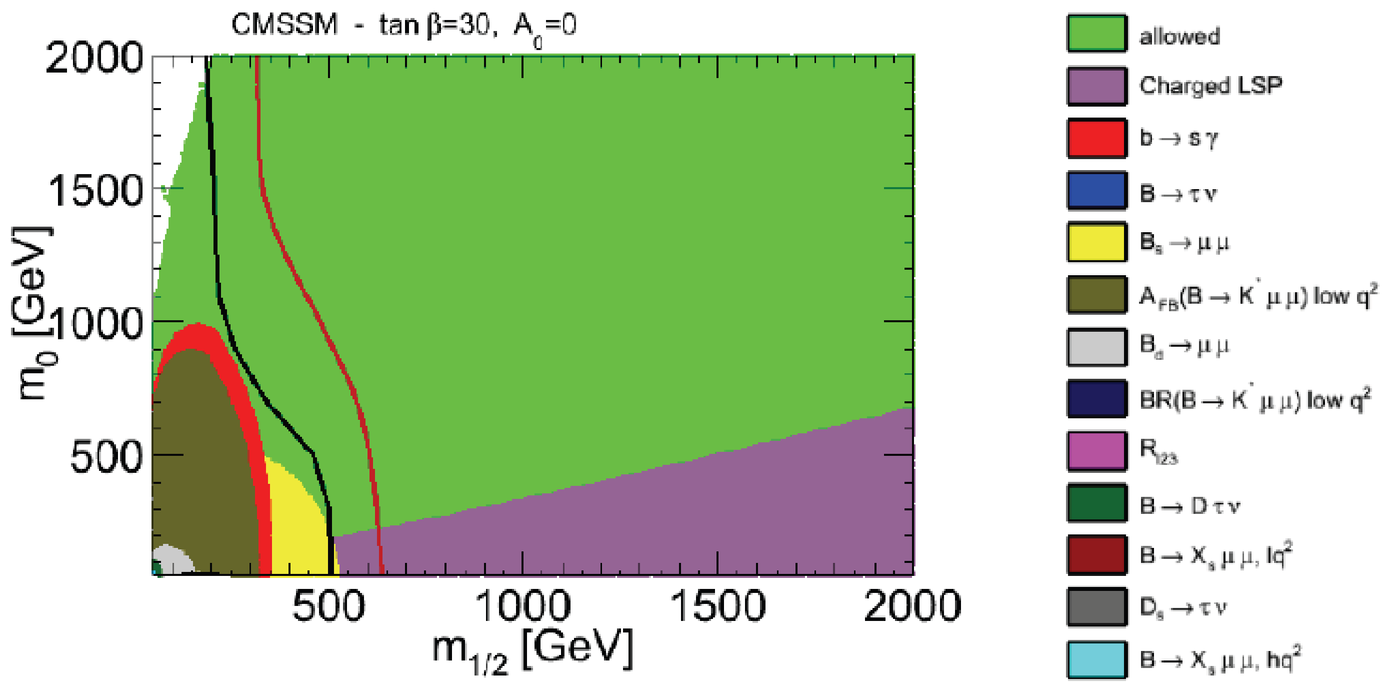
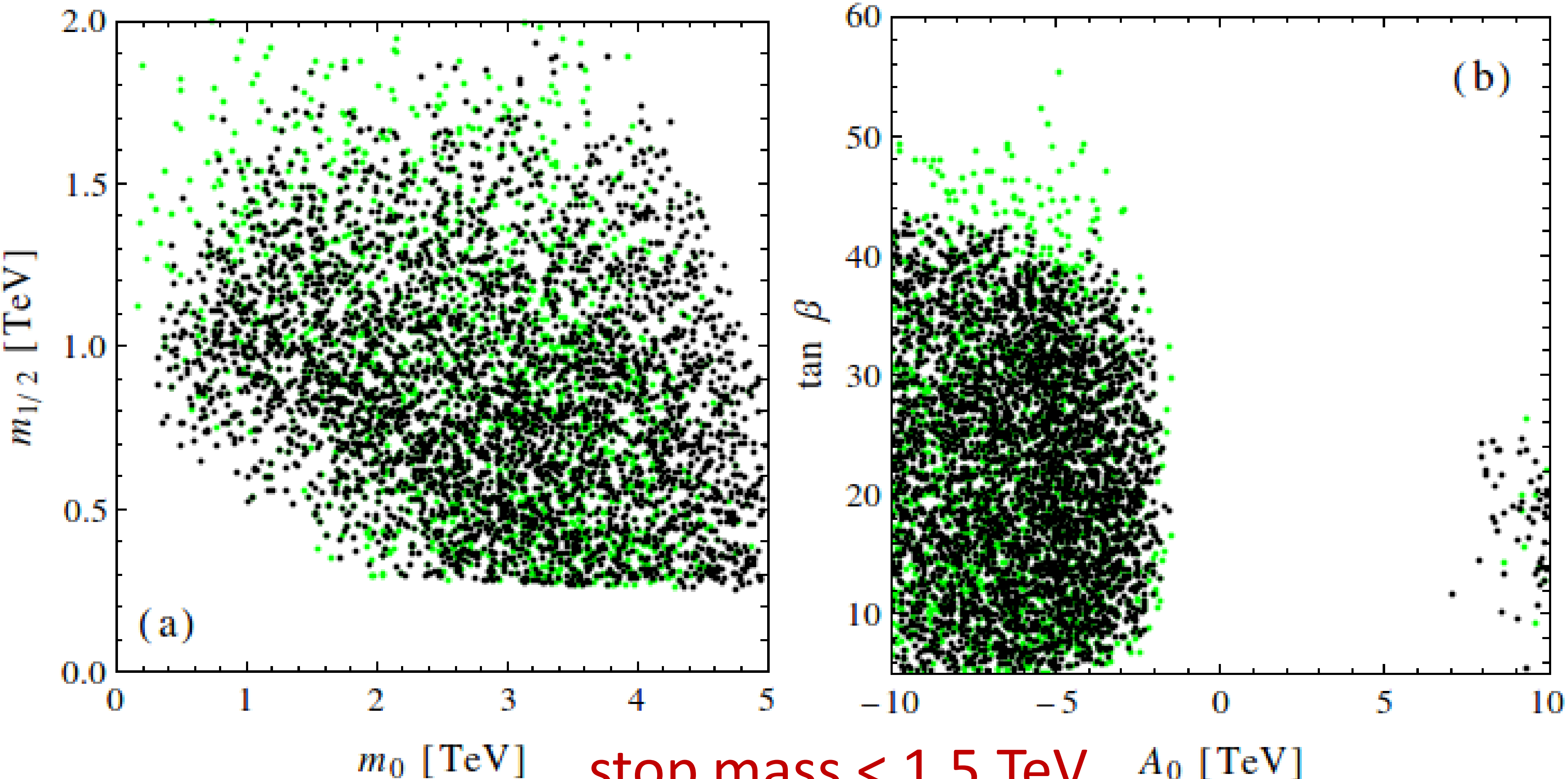


Figure 6. Constraints from flavour observables in CMSSM in the plane $(m_{1/2}, m_0)$ for $\tan\beta = 30$ and $A_0 = 0$ with the 2011 results. The black line corresponds to the CMS exclusion limit with 1.1 fb^{-1} of data [38] and the red line to the CMS exclusion limit with 4.4 fb^{-1} of data [39]. From [37].

Testing Times for Supersymmetry: Looking Under the Lamp Post

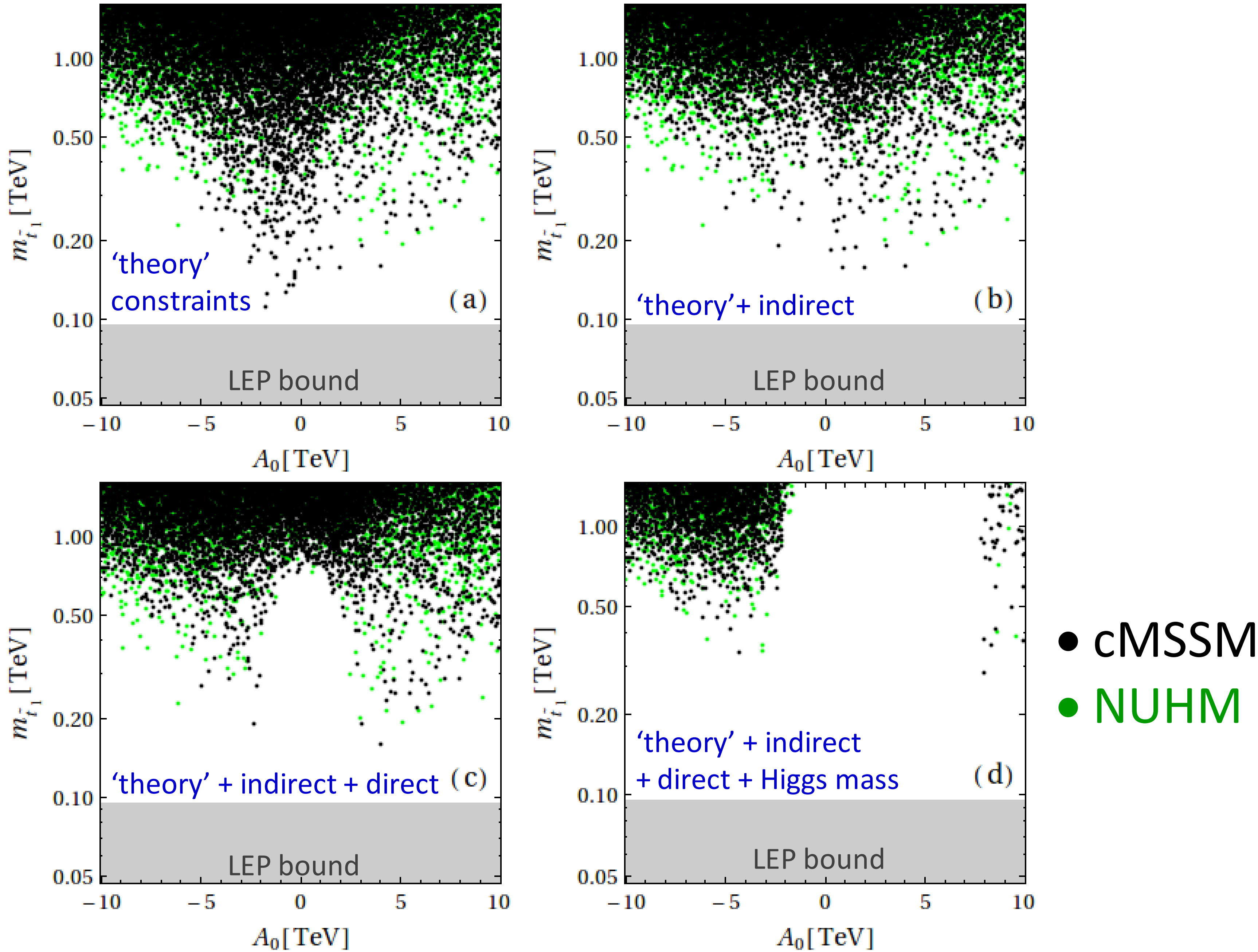
Amol Dighe,[1] Diptimoy Ghosh,[2] Ketan M. Patel,[1] and Sreerup Raychaudhuri[1]
[1] *Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400 005, India.*
[2] *INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy.*



stop mass < 1.5 TeV

● cMSSM ● NUHM

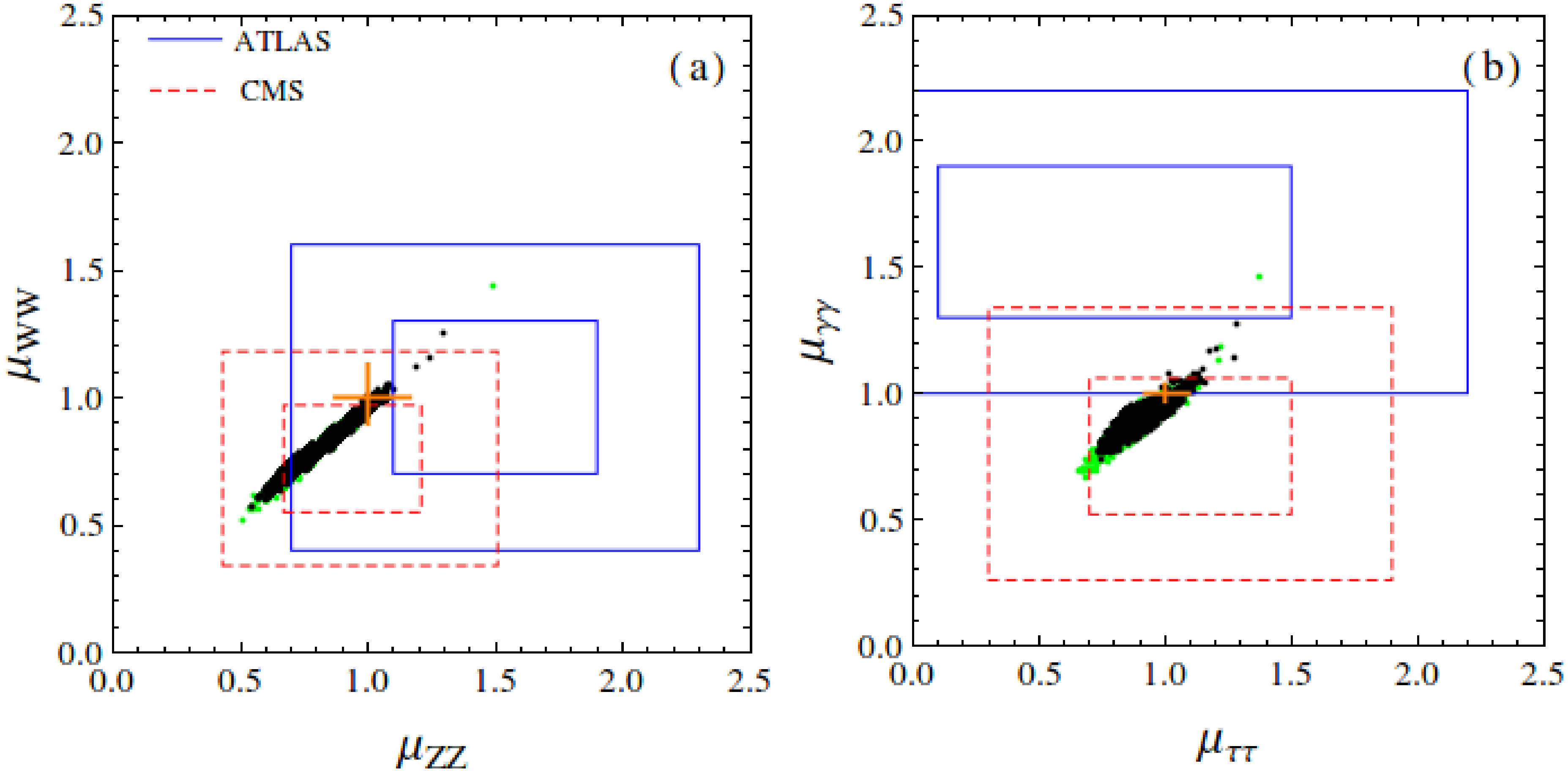
Collected constraints



CMS

ATLAS

Higgs decay constraints

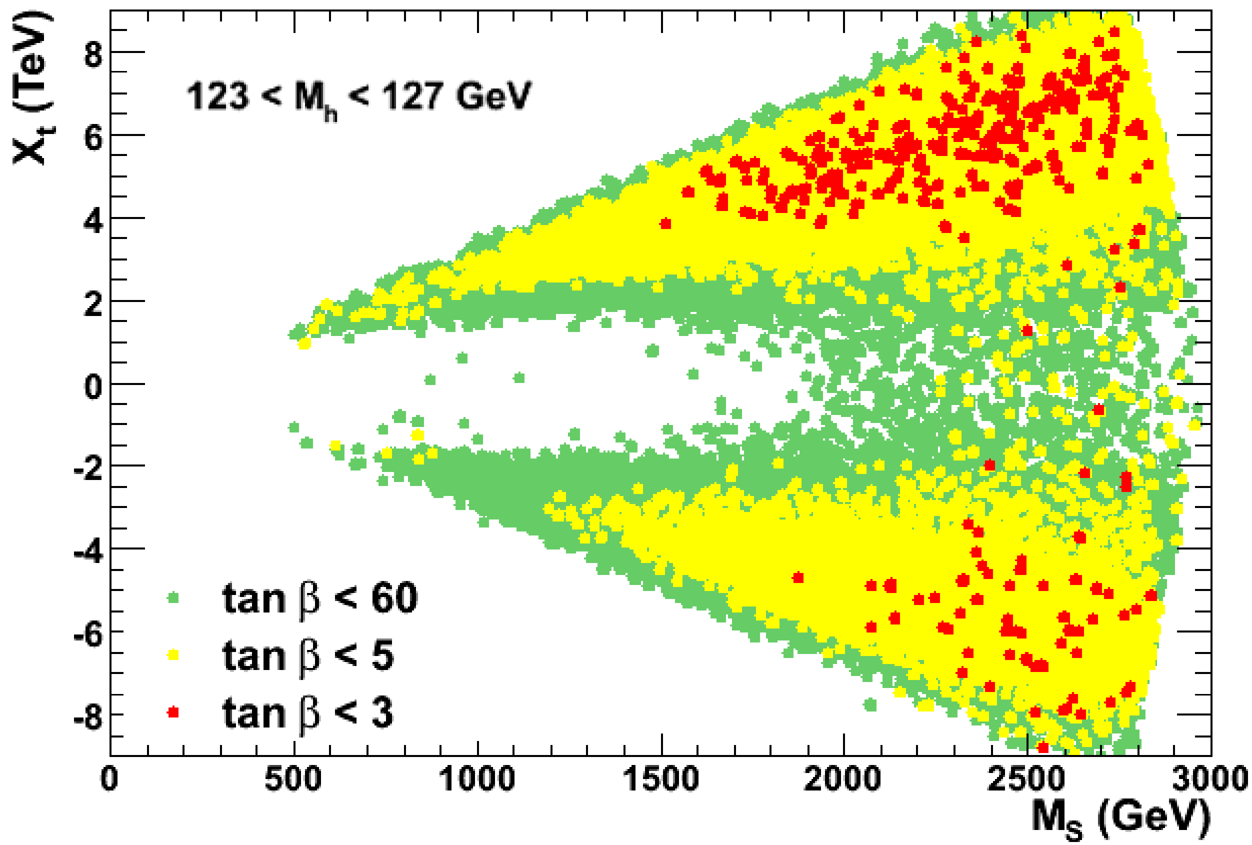


$$N_{X\bar{X}} = \mathcal{L} \times \sigma(pp \to h^0) \times \mathcal{B}(h^0 \to X\bar{X})$$

$$\mu_{X\bar{X}} \equiv \frac{N_{X\bar{X}}}{N_{X\bar{X}}^{\rm SM}} = \frac{\sigma(pp \to h^0)}{\sigma_{\rm SM}(pp \to h^0)} \times \frac{\mathcal{B}(h^0 \to X\bar{X})}{\mathcal{B}_{\rm SM}(h^0 \to X\bar{X})}$$

The pMSSM

$m_{\tilde{L}(e)_{1,2,3}}$	100 GeV – 4 TeV
$m_{\tilde{Q}(q)_{1,2}}$	400 GeV – 4 TeV
$m_{\tilde{Q}(q)_3}$	200 GeV – 4 TeV
$\|M_1\|$	50 GeV – 4 TeV
$\|M_2\|$	100 GeV – 4 TeV
$\|\mu\|$	100 GeV – 4 TeV
M_3	400 GeV – 4 Te
$\|A_{t,b,\tau}\|$	0 GeV – 4 TeV
M_A	100 GeV – 4 Te
$\tan\beta$	1 - 60
$m_{3/2}$	1 eV–1 TeV ($\tilde{G}$ LS



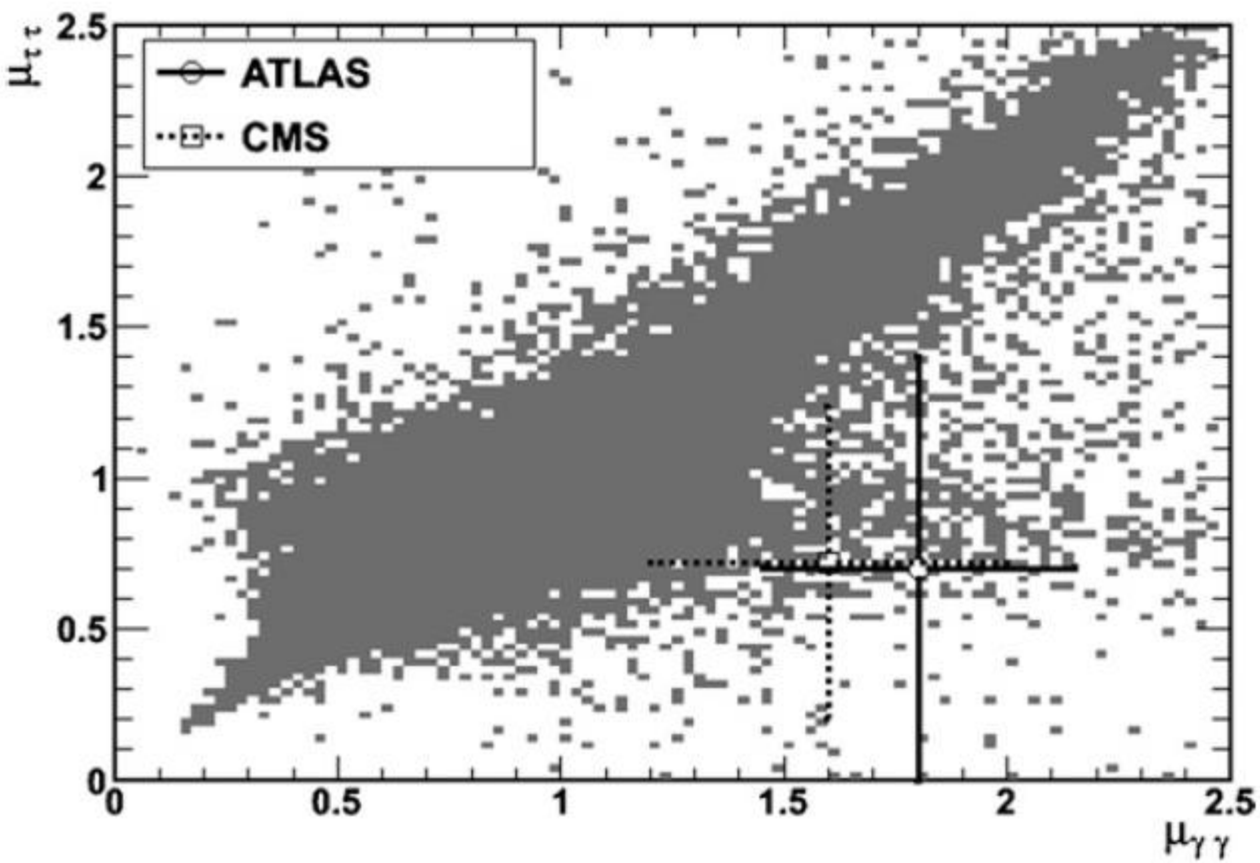
An update of the constraints on the phenomenological MSSM from the new LHC Higgs results

Alexandre Arbey [a,b,c], Marco Battaglia [d,c,*], Abdelhak Djouadi [e], Farvah Mahmoudi [f,c]

Physics Letters B 720 (2013) 153–160

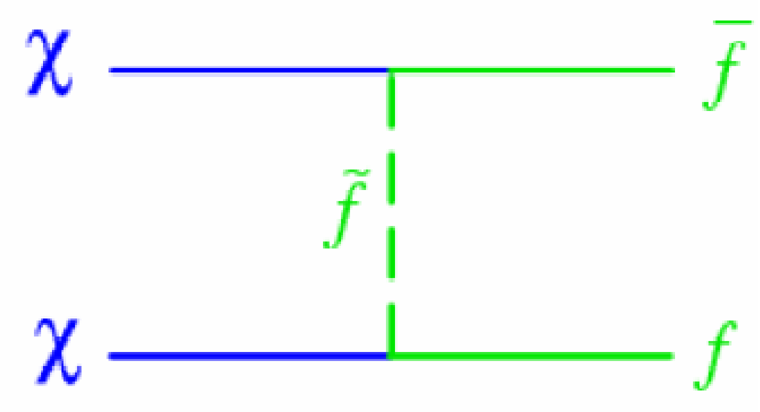
Input values for the Higgs mass and rates used for the study.

Parameter	Value	Experiment
M_h	126 ± 2 GeV	ATLAS [1] + CMS [2]
$\mu_{\gamma\gamma}$	1.71 ± 0.26	ATLAS [3] + CMS [5]
μ_{ZZ}	0.97 ± 0.26	ATLAS [4] + CMS [6]
μ_{WW}	0.85 ± 0.23	ATLAS [7] + CMS [6]
$\mu_{b\bar{b}}$	1.28 ± 0.45	
$\mu_{\tau\tau}$	0.71 ± 0.42	
$D_{\gamma\gamma}$	1.88 ± 0.46	
$D_{\tau\tau}$	0.79 ± 0.49	

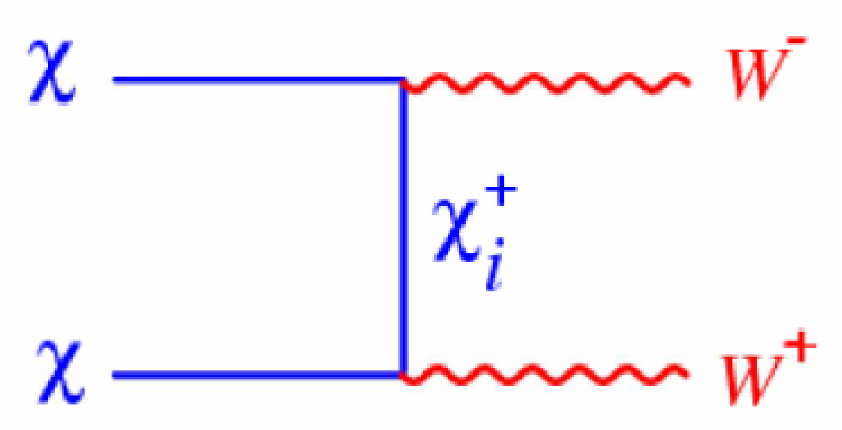


SUSY Dark Matter

…but two main classes:



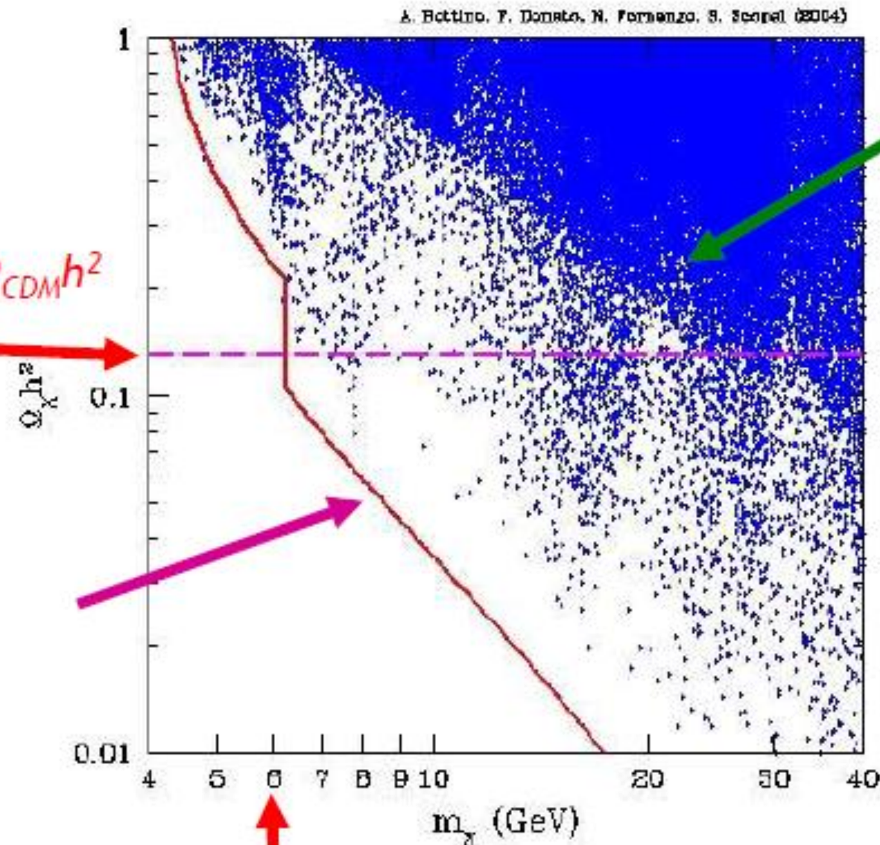
- fermion diagrams: m_f/M_W helicity suppression due to Majorana nature of neutralino



- Gauge boson diagrams: suppressed if neutralino~Bino (this is usually the case when Radiative ElectroWeak Symmetry Breaking is implemented, $|\mu|>>M_1,M_2$)

Cosmological lower bound on m_χ

A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)



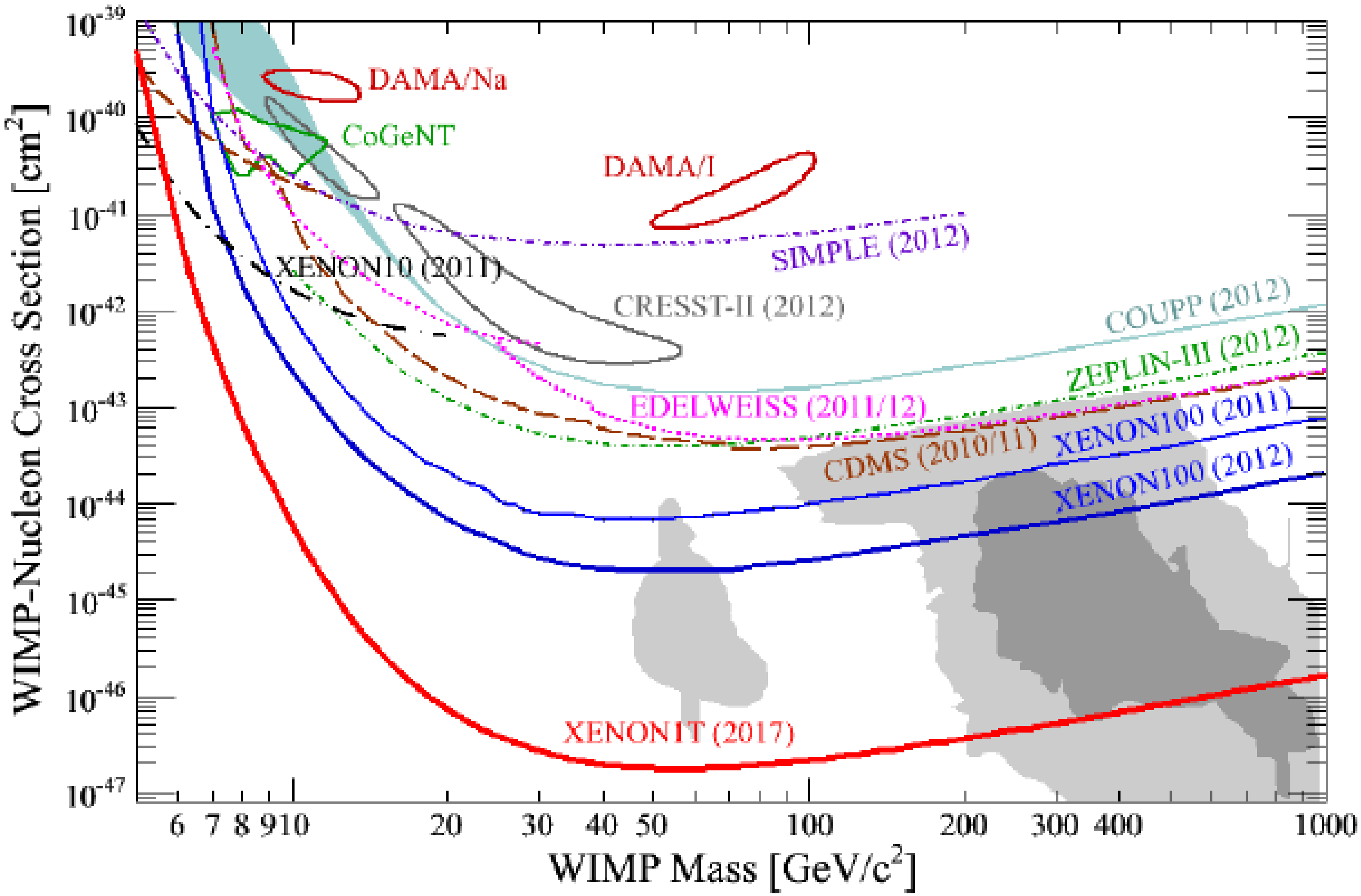
scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi \, [1 - m_b^2/m_\chi^2]^{1/4} \gtrsim 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$$

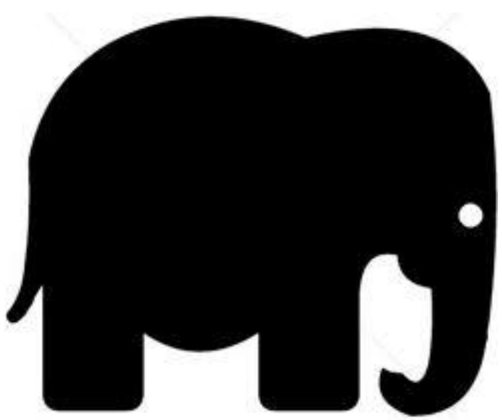
Direct Search:



P. Beltrame (on behalf of the XENON Collaboration) arXiv:1305.271

Conclusions

- Electroweak-scale SUSY remains the best BSM option
- It was not just around the corner when LHC started
- B factories have also come up with a blank
- No reason to despair yet (recall wait for the Higgs)
- We may have to live with some minor fine-tuning



Thank You