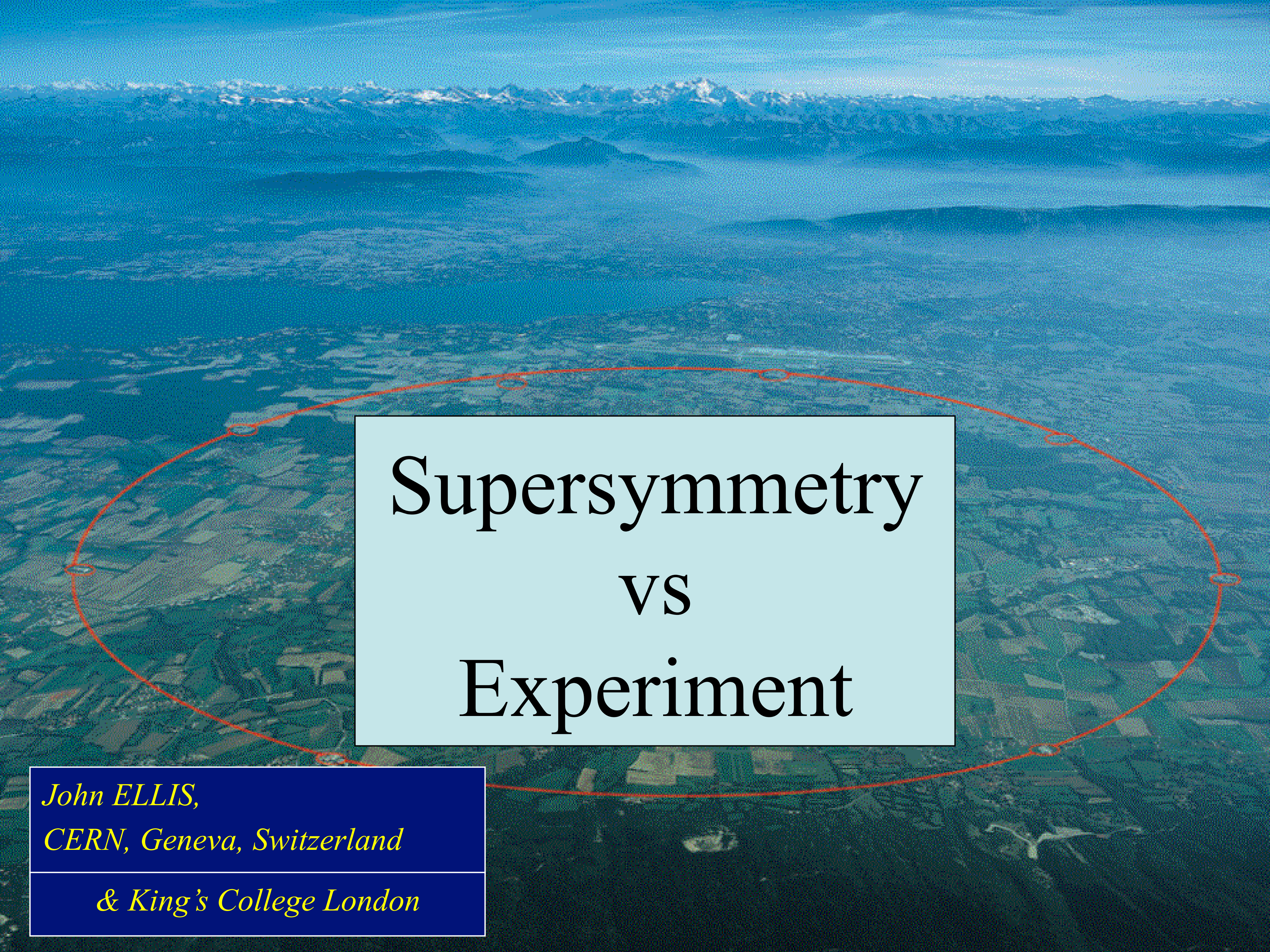


Supersymmetry vs Experiment

John ELLIS,
CERN, Geneva, Switzerland

& King's College London

A Bitino of Shistory

- 1967: Impossible to combine internal and external (Lorentz) symmetry – Coleman & Mandula
- 1971: Extend Poincaré symmetry using fernionic charges – Gol' fand & Likhtman
- 1971: Supersymmetry in 2 dimensions (for baryons in strings) – Neveu & Schwarz; Ramond
- 1973: First supersymmetric field theories in 4 dimensions: nonlinear for ν – Volkov & Akulov

renormalizable theories – Wess & Zumino

More Shistory

- 1974: No-renormalization theorems –
  Ferrara, Iliopoulos, Wess & Zumino
- 1976: Discovery of supergravity –
  Freedman, van Nieuwenhuizen & Ferrara; Deser & Zumino
- 1979/1981: Relevance to hierarchy problem –
  Maiani, Witten
- 1983: Source of astrophysical dark matter –
  Goldberg; JE, Hagelin, Nanopoulos, Olive & Nanopoulos
- 1990: Superunification of gauge couplings –
  JE, Kelley & Nanopoulos; Langacker & Luo
- 1995: LEP data favour light Higgs boson

The First 2 SUSY Papers

PHYSICAL REVIEW D VOLUME 3, NUMBER 10 15 MAY 1971

Dual Theory for Free Fermions

P. Ramond
National Accelerator Laboratory, Batavia, Illinois 60150
(Received 4 January 1971)

A wave equation for free fermions is proposed based on the structure of the dual theory for bosons. Its formal properties preserve the role played by the Virasoro algebra. Additional Ward-like identities, compatible with the equation, are shown to exist. Its solutions lie on linear trajectories. In particular, the parent is shown to be doubly degenerate, but these solutions lie on different sheets of the cut j plane.

INTRODUCTION

In spite of its obvious theoretical appeal, the dual model[1] has been denied full acceptance (credibility) because of its failure to include fermions. In this paper we present an extension of the model to encompass half-integer-spin states by making use of a structure evident in the dual theory of free bosons.[2] Namely, we found that the following view of duality led to no contradiction with existing results: Each "free" boson appearing in the theory is a state of a complex system. Its structure can be parametrized in terms of an internal motion which is periodic in an internal time coordinate so that each observable of the system is the average over a cycle of the internal motion of suitably generalized operators. In this way, operators appearing in the description of point particles in conventional theories must be thought of as averages over some internal motion when applied to a hadronic system. The system then becomes a point particle in the limit of the internal cycle going to zero. These precepts are illustrated by their application to the bosonic case in Sec. I. We use these guidelines to introduce a generalization of the Dirac matrices and postulate a Dirac wave equation for the free fermionic system. Its formal properties are studied in Sec. II. Section III will be devoted to a detailed study of its solutions.

I. BOSON CASE

In order to set the notation and illustrate the ideas behind our interpretation, it is desirable to first consider the (already known) free-boson theory. The free hadronic system is described in terms of an internal motion generated by the Nambu[3] Hamiltonian

$$H_B=\tfrac{1}{2}\sum_{n=0}^{\infty}\left[p^{(n)}\cdot p^{(n)}+\omega_n{}^2q^{(n)}\cdot q^{(n)}\right], \qquad (1.1)$$

with

$$\omega_{n+1}-\omega_n=\omega, \quad n=0,1,2,\ldots \qquad (1.2)$$

and the normal-mode coordinates are four-vector operators satisfying the usual commutation relations

$$[q_\alpha{}^{(n)},q_\beta{}^{(m)}]=[p_\alpha{}^{(n)},p_\beta{}^{(m)}]=0,$$
$$[q_\alpha{}^{(m)},p_\beta{}^{(n)}]=-ig_{\alpha\beta}\delta^{m,n}, \quad m,n=0,1,\ldots \qquad (1.3)$$

where we use $g_{\alpha\beta}=(1,-1,-1,-1)$ for the Lorentz metric. The internal system carries a total momentum

$$P_\mu=\sum_{n=0}^{\infty}p_\mu{}^{(n)} \qquad (1.4)$$

corresponding to a coordinate

$$Q_\mu=\sum_{n=0}^{\infty}q_\mu{}^{(n)}. \qquad (1.5)$$

The variable τ which describes the evolution of the internal motions is introduced by means of the Heisenberg equations

$$[H_B,f]=i(df/d\tau), \qquad (1.6)$$

where f is any operator. It is important to note that in

[1] See G. Veneziano, in Proceedings of the International School of Physics "Ettore Majorana," Erice, Italy, 1970 (unpublished).
[2] P. Ramond, National Accelerator Laboratory Report No. THY 7, 1970 (unpublished).
[3] Y. Nambu, University of Chicago Report No. EFI 69-64, 1969 (unpublished); see also L. Susskind, Yeshiva University Reports, 1969 (unpublished); S. Fubini, D. Gordon, and G. Veneziano, Phys. Letters 29B, 679 (1969).

EXTENSION OF THE ALGEBRA OF POINCARE GROUP GENERATORS AND VIOLATION OF P INVARIANCE

Yu.A. Gol'fand and E.P. Likhtman
Physics Institute, USSR Academy of Sciences
Submitted 10 March 1971
ZhETF Pis. Red. 13, No. 8, 452 - 455 (20 April 1971)

One of the main requirements imposed on quantum field theory is invariance of the theory to the Poincare group [1]. However, only a fraction of the interactions satisfying this requirement is realized in nature. It is possible that these interactions, unlike others, have a higher degree of symmetry. It is therefore of interest to study different algebras and groups, the invariance with respect to which imposes limitations on the form of the elementary particle interaction. In the present paper we propose, in constructing the Hamiltonian formulation of the quantum field theory, to use as the basis a special algebra $\mathcal{R}$, which is an extension of the algebra $\mathcal{P}$ of the Poincare group generators. The purpose of the paper is to find such a realization of the algebra $\mathcal{R}$, in which the Hamiltonian operator describes the interaction of quantized fields.

The extension of the algebra $\mathcal{P}$ is carried out in the following manner: we add to the generators P_μ and $M_{\mu\nu}$ the bispinor generators W_α and $\bar{W}_\beta$, which we shall call the generators of spinor translations. In order to obtain the algebra $\mathcal{R}$, it is necessary to find the Lorentz-invariant form of the permutation relations between the translation generators. In order not to violate subsequently the connection between the spin and statistics, we shall consider anticommutators of the operators W_α and $\bar{W}_\beta$. A generalization of the Jacobi identities imposes stringent limitations on the form of the possible commutation relations between the algebra operators. We confine ourselves to consideration of only those algebras $\mathcal{R}$, in which there are no subalgebras Q such that $\mathcal{P} \subset Q$ and $\mathcal{P} \neq Q$. This choice is governed by the fact that the remaining algebras $\mathcal{R}$ are obtained by further extending the algebras $\mathcal{R}$, and the field theories corresponding to them will have a still higher degree of symmetry.

An investigation of the albegras $\mathcal{R}$ has shown that upon spatial inversion they do not go over into themselves for any choice of the structure constants of the algebra. As a result, in a field theory that is invariant against such an algebra, the parity should not be conserved[1], and the form of the nonconservation is completely determined by the algebra itself. We shall stop to discuss one of the algebras $\mathcal{R}$:

$$[M_{\mu\nu}, M_{\sigma\lambda}]_- = i(\delta_{\mu\sigma}M_{\nu\lambda} + \delta_{\nu\lambda}M_{\mu\sigma} - \delta_{\mu\lambda}M_{\nu\sigma} - \delta_{\nu\sigma}M_{\mu\lambda}); \; [P_\mu, P_\nu]_- = 0;$$
$$[M_{\mu\nu}, P_\lambda]_- = i(\delta_{\mu\lambda}P_\nu - \delta_{\nu\lambda}P_\mu); \; [M_{\mu\nu}, W]_- = \frac{i}{4}[\gamma_\mu, \gamma_\nu]_- W; \; \bar{W} = W^+\gamma_4. \qquad (1a)$$

$$[W, \bar{W}]_+ = \gamma_\mu P_\mu; \; [W, W]_+ = 0; \; [P_\mu, W]_- = 0, \qquad (1b)$$

1982 Workshop

Ref.TH.3311/EP.82/63-CERN

SUPERSYMMETRY versus EXPERIMENT WORKSHOP

April 21-23, 1982

CERN

organized by

D.V. Nanopoulos – CERN
A. Savoy-Navarro – CEA-Saclay
Ch. Tao – CERN

Ref.TH.3311/EP.82/63-CERN
27 May 1982

Theoretical Introduction

Introduction to Supersymmetry

by

S. Ferrara

Supersymmetry is a relativistic symmetry of lagrangian field theory which relates particle fields of different statistics (bosons and fermions). The final goal of supersymmetry pratictioners is to have a unified theory encompassing all fundamental forces. This ambitious program implies, on the way, to solve the problem of quantum gravity.

The LHC Roulette Wheel

Supersymmetry

Open Questions beyond the Standard Model

- What is the origin of particle masses? due to a Higgs boson? **SUSY**
- Why so many types of matter particles? **LHC**
- What is the dark matter in the Universe? **SUSY**
- Unification of fundamental forces? **SUSY**
- Quantum theory of gravity? **String**

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity (mSUGRA) predicts gravitino mass: $m_{3/2} = m_0$ and relation: $B_\mu = A_\lambda - m_0$

Non-Universal Scalar Masses

- Different sfermions with same quantum #s?

  e.g., d, s squarks?

  disfavoured by upper limits on flavour-changing neutral interactions

- Squarks with different #s, squarks and sleptons?

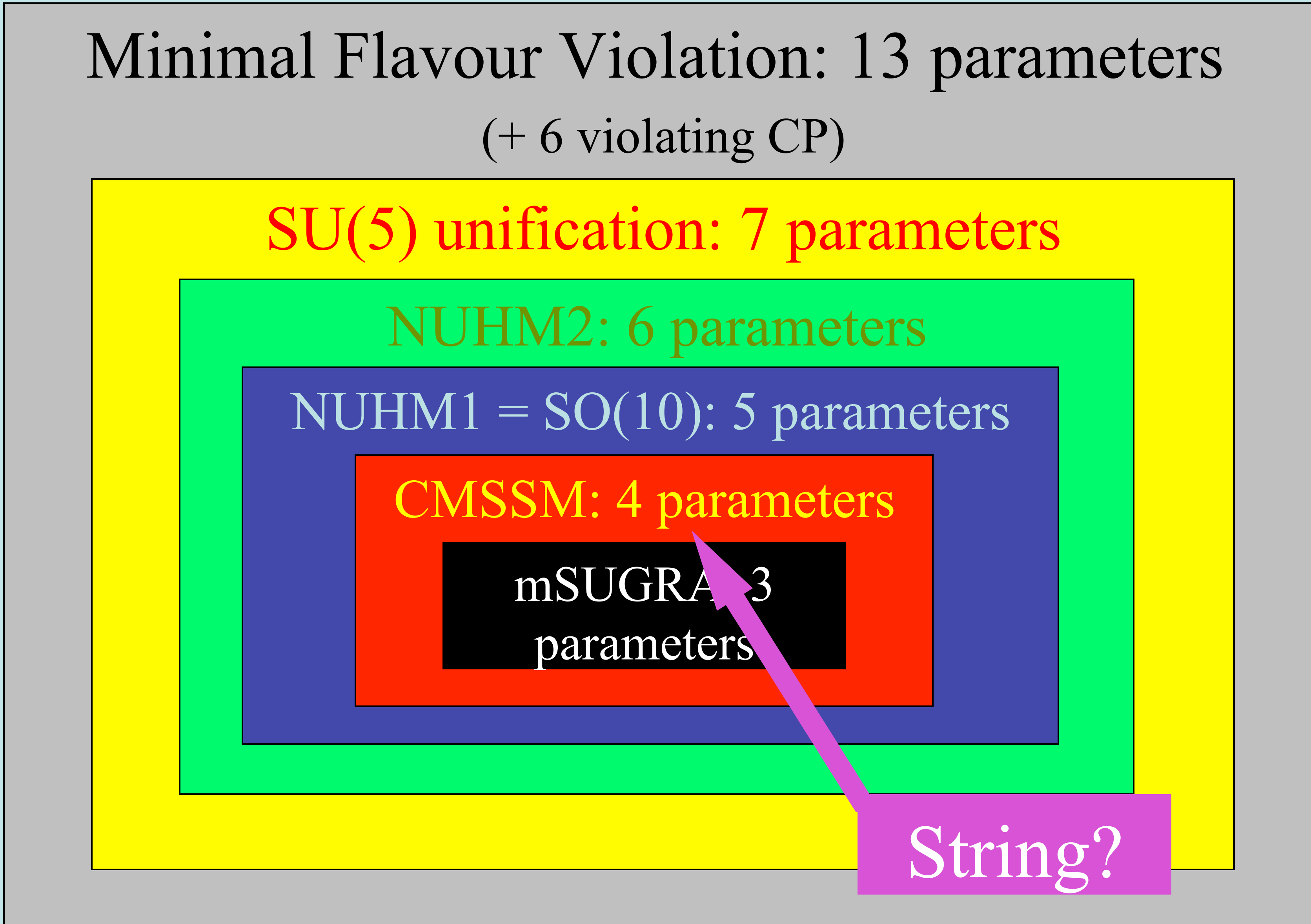
  disfavoured in various GUT models

  e.g., $d_R = e_L$, $d_L = u_L = u_R = e_R$ in SU(5), all in SO(10)

- Non-universal susy-breaking masses for Higgses?

  No reason why not! NUHM

MSSM: > 100 parameters



Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

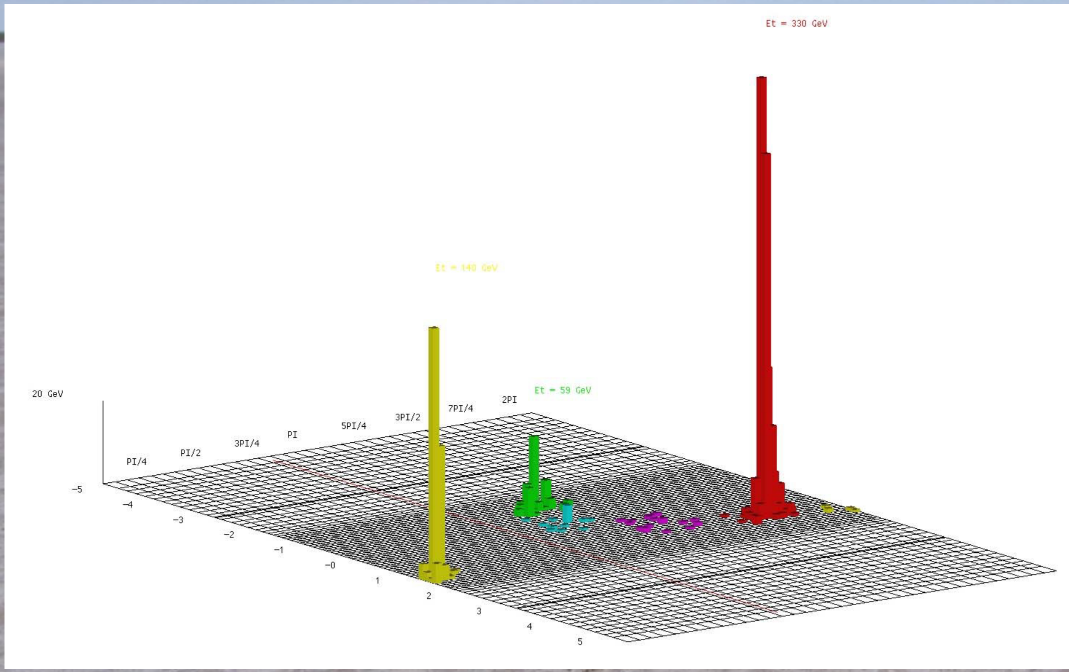
- Lightest supersymmetric particle (LSP) stable

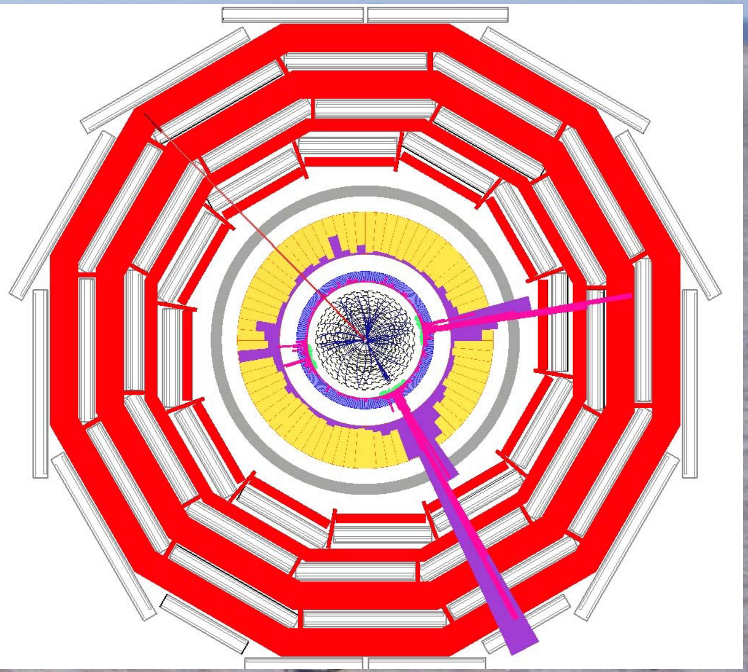
Fayet

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ (partner of Z, H, γ)
  - Gravitino
    - (nightmare for astrophysical detection)

Classic Supersymmetric Signature





Missing transverse energy carried away by dark matter particles

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 400 GeV

- Indirect constraints

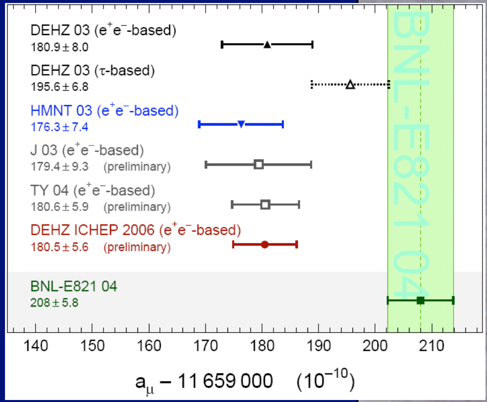
  Higgs > 114 GeV, $b \rightarrow s \gamma$

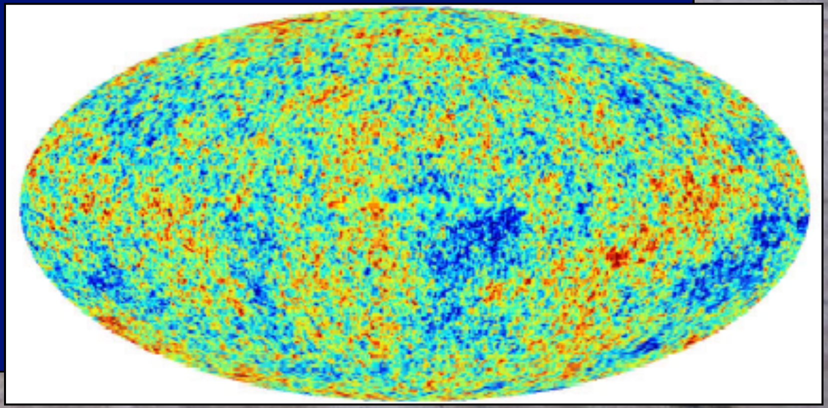
- Density of dark matter

  lightest sparticle χ:

  $0.094 < \Omega_\chi h^2 < 0.124$

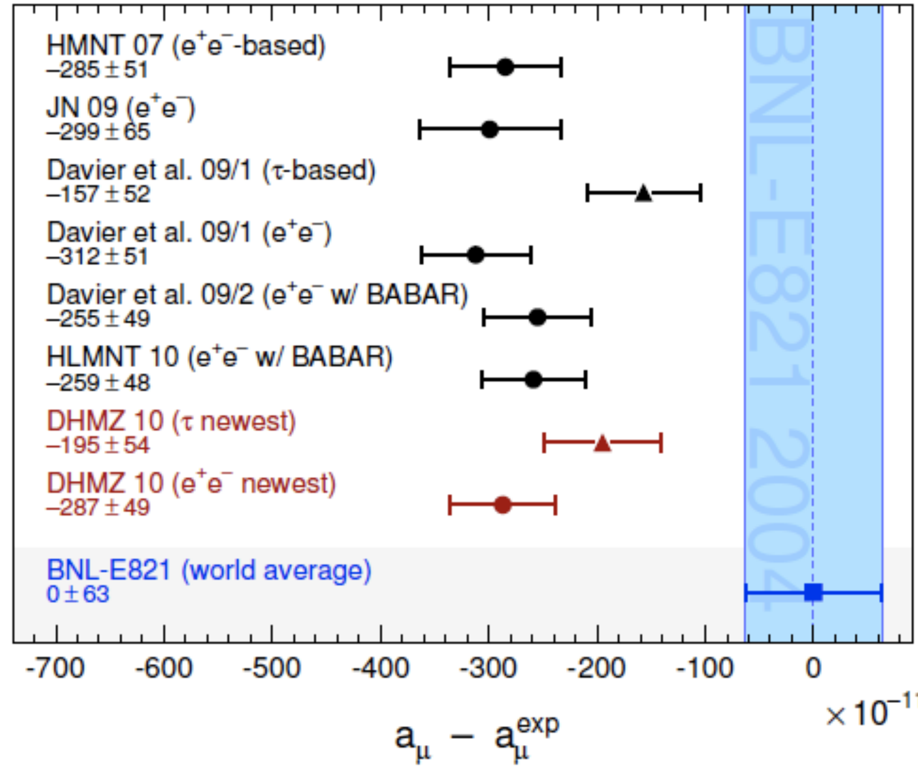
3.3 σ effect in $g_\mu - 2$?

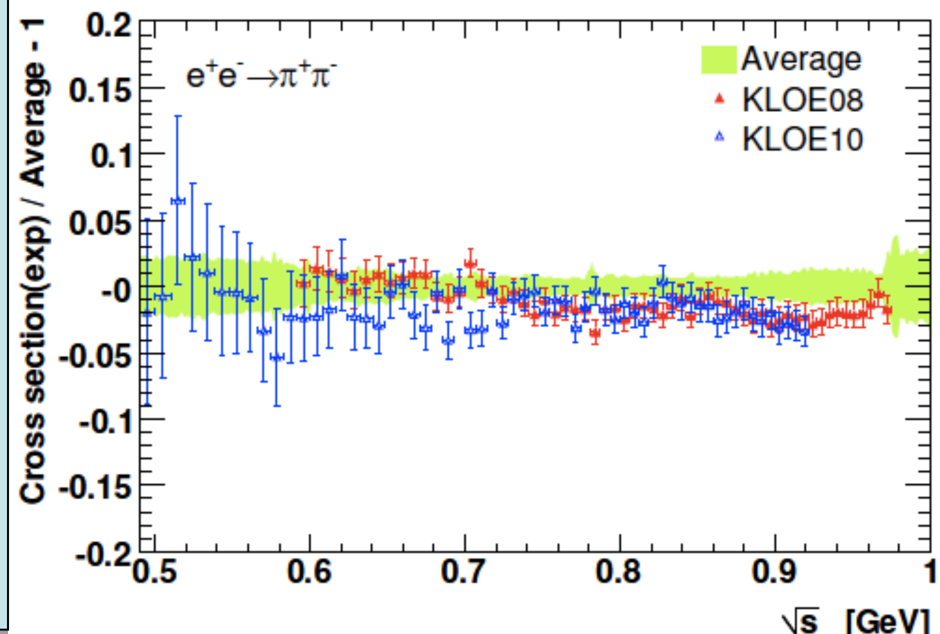




Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data:
  - now ~ 3.6 σ
- Decent agreement between e^+e^- experiments
- Increased discrepancy between BNL experiment and τ decay data
  - now ~ 2.4 σ
- Convergence between e^+e^- experiments and τ decay data?
- **More credibility?**





Pre-LHC Constraints on CMSSM

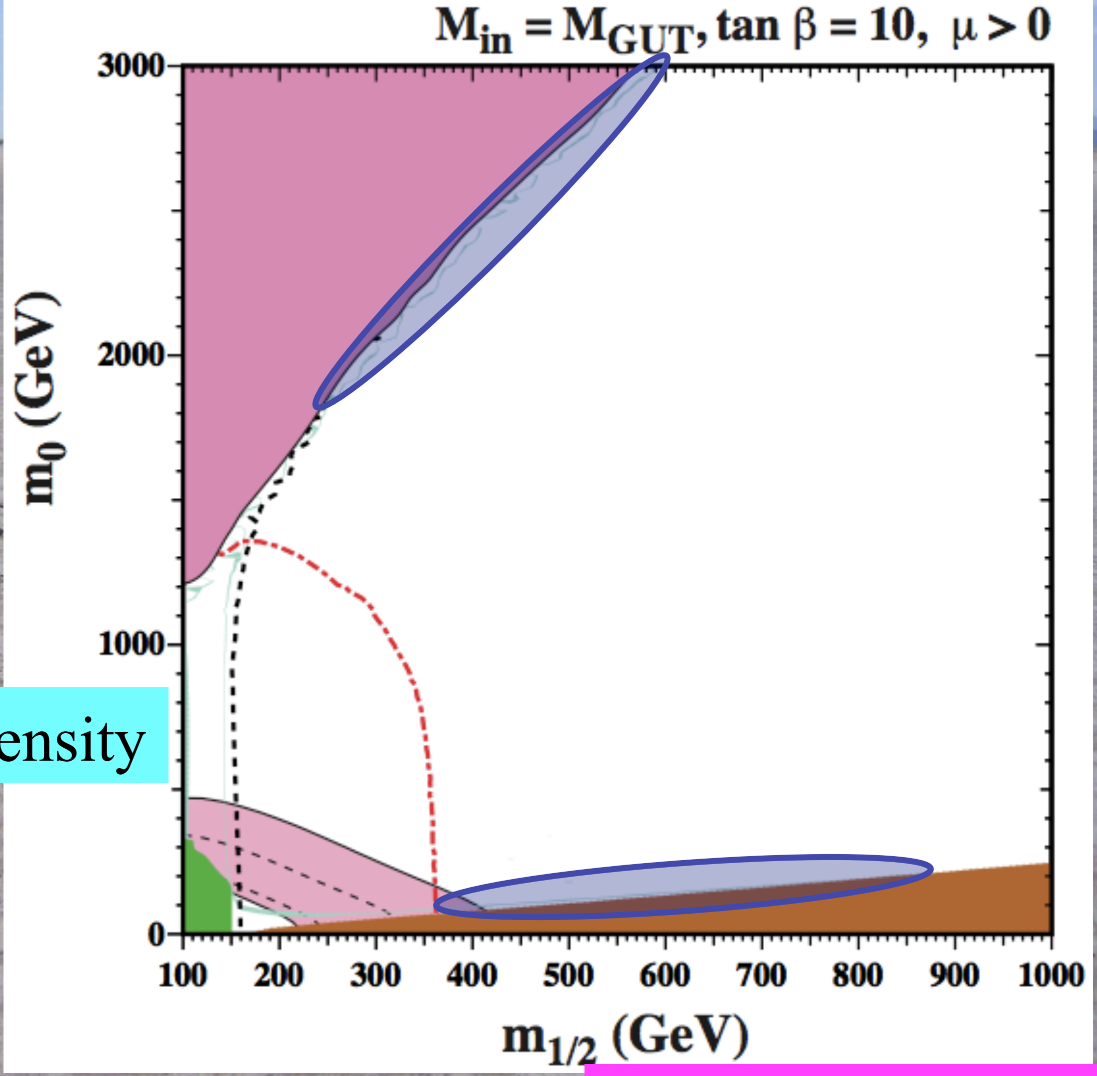
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

Preferred (?) by latest g - 2



JE + Olive + Santoso + Spanos

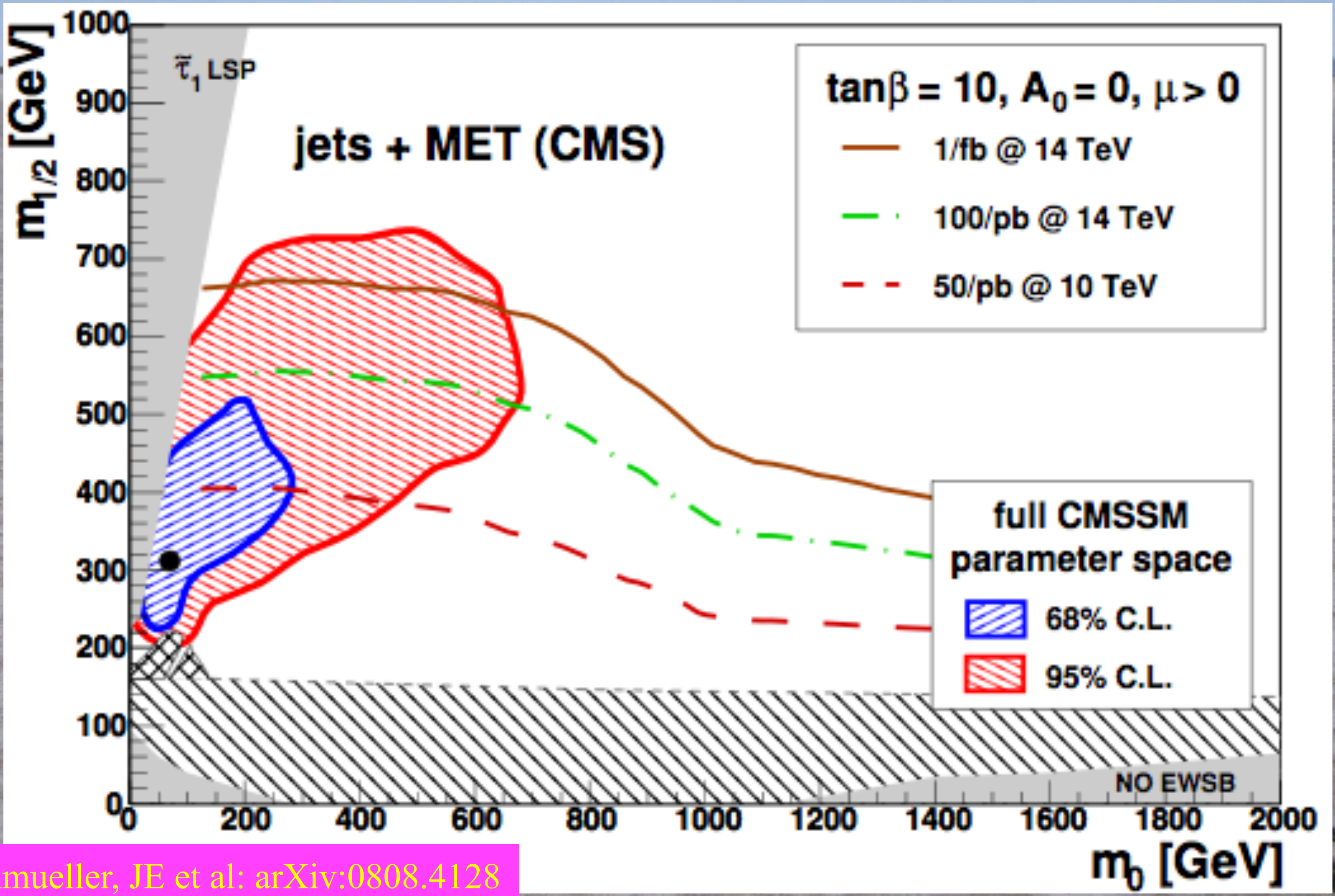
Global Supersymmetric Fits

- Frequentist approach
- Data used:
  - Precision electroweak data
  - Higgs mass limit
  - cold dark matter density
  - B decay data ($b \to s\,\gamma$, $B_s \to \mu^+\mu^-$)
  - g_μ - 2 (optional)
- Combine likelihood functions pre/post-LHC
- Analyze CMSSM, NUHM1 (VCMSSM, mSUGRA)

O.Buchmueller, JE et al: arXiv:0808.4128, 0907.5568, 0912.1036, 1011.6118, 1102.4585

Pre-LHC

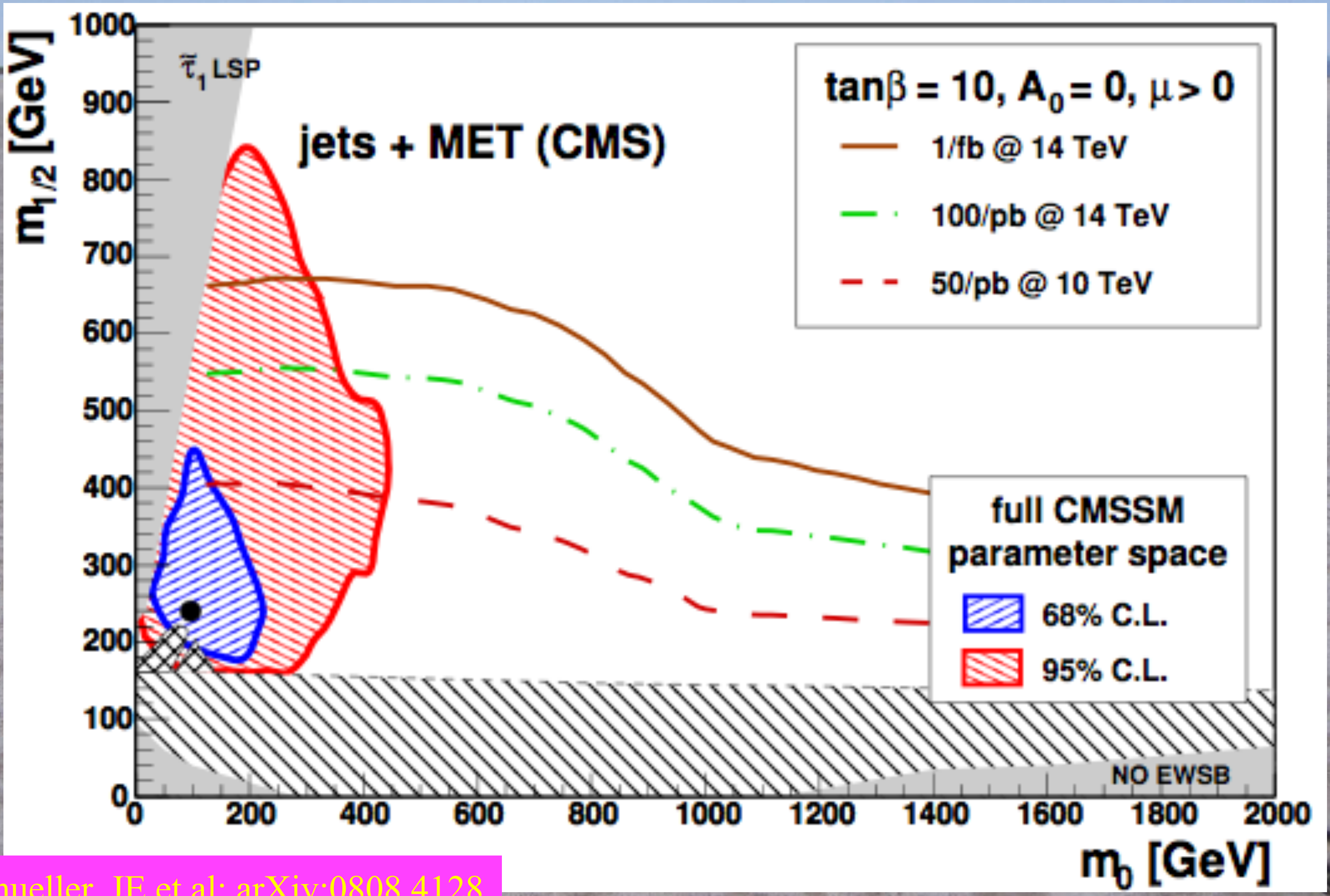
How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

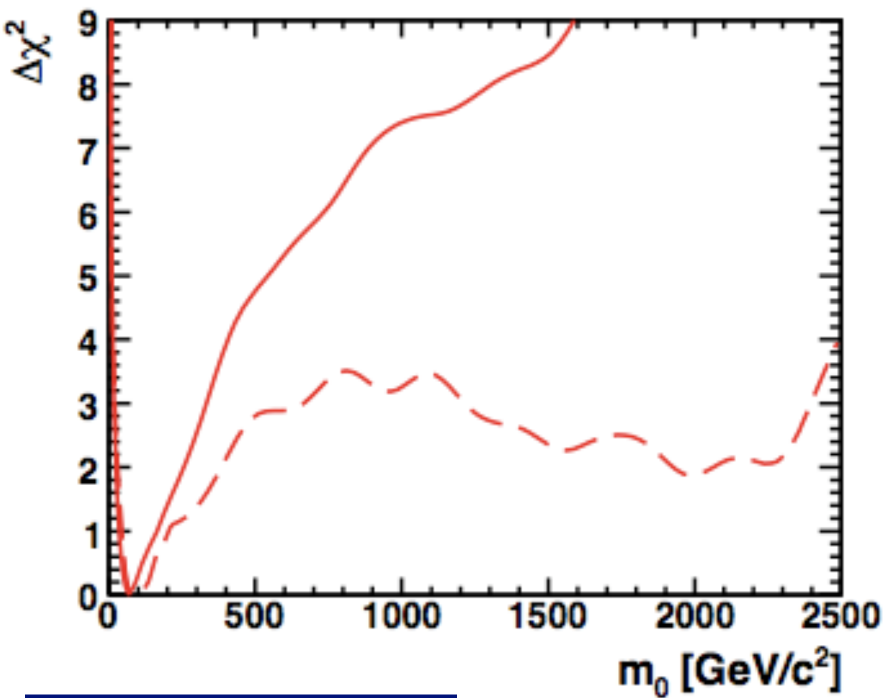
Pre-LHC

How Soon Might the NUHM1 be Detected?

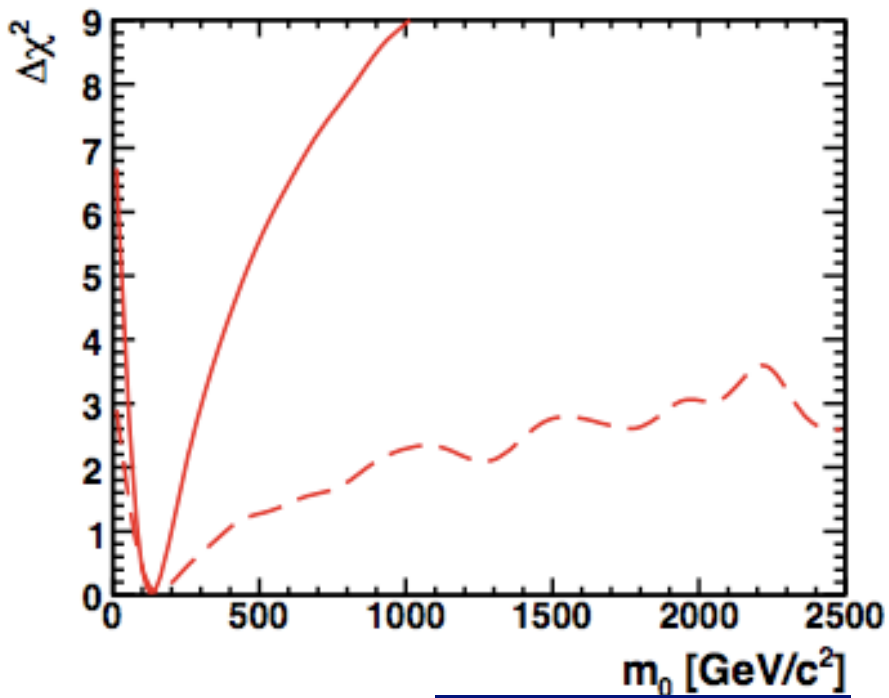


O.Buchmueller, JE et al: arXiv:0808.4128

What Happens if g_μ - 2 Dropped?



CMSSM



NUHM1

Solid lines: with g_μ - 2

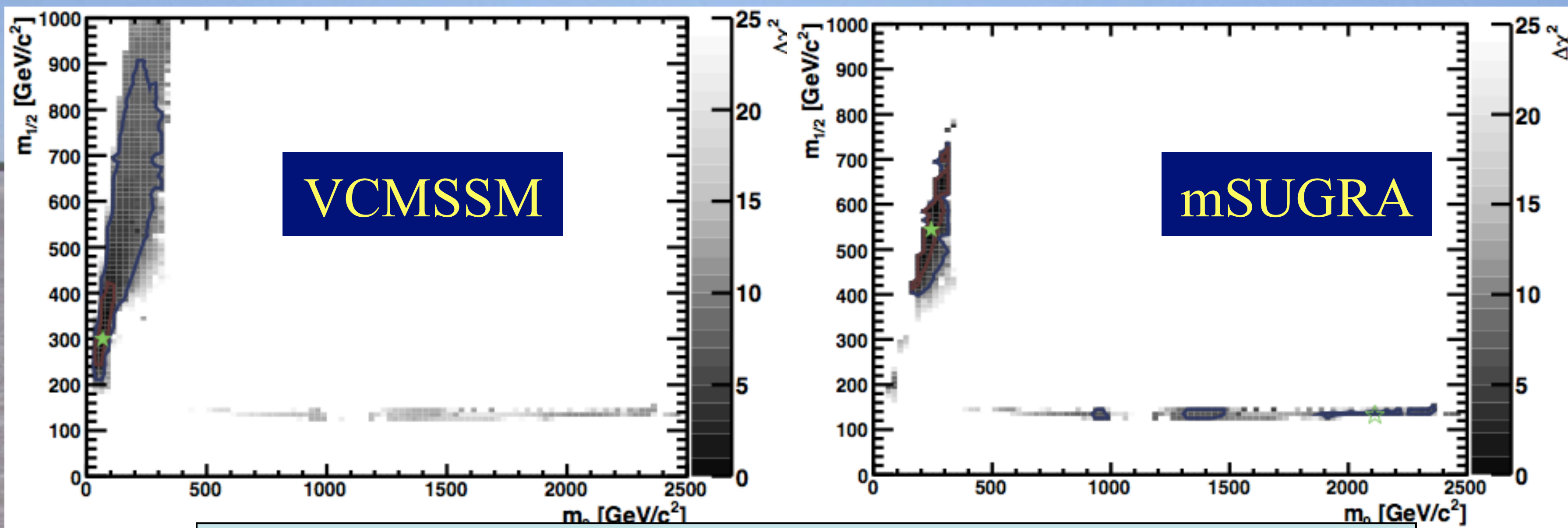
Dashed lines: without g_μ - 2

Focus-point still disfavoured, e.g., by m_W

O.Buchmueller, JE et al: arXiv:0907.5568

Pre-LHC

Frequentist Fits to VCMSSM & mSUGRA



Best-fit parameters in different models

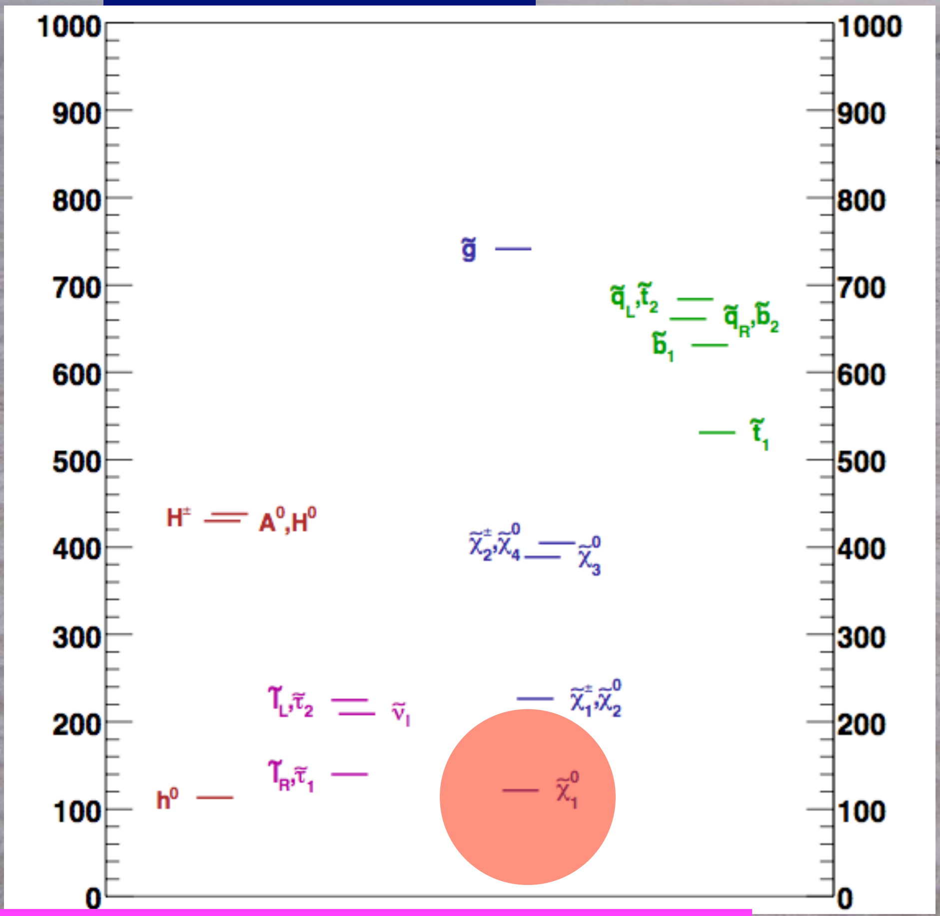
Model	Minimum χ^2	Probability	$m_{1/2}$	m_0	A_0	$\tan\beta$	M_h (no LEP)
mSUGRA	29.4	6.0%	550	230	430	28	107.7
	33.2	2.3%	130	2110	980	7	116.9
VCMSSM	22.5	31%	300	60	30	9	109.3
CMSSM	21.3	32%	320	60	-160	11	107.9
NUHM1	19.3	31%	260	100	1010	8	119.5

O.Buchmueller, JE et al: arXiv:1011.6118

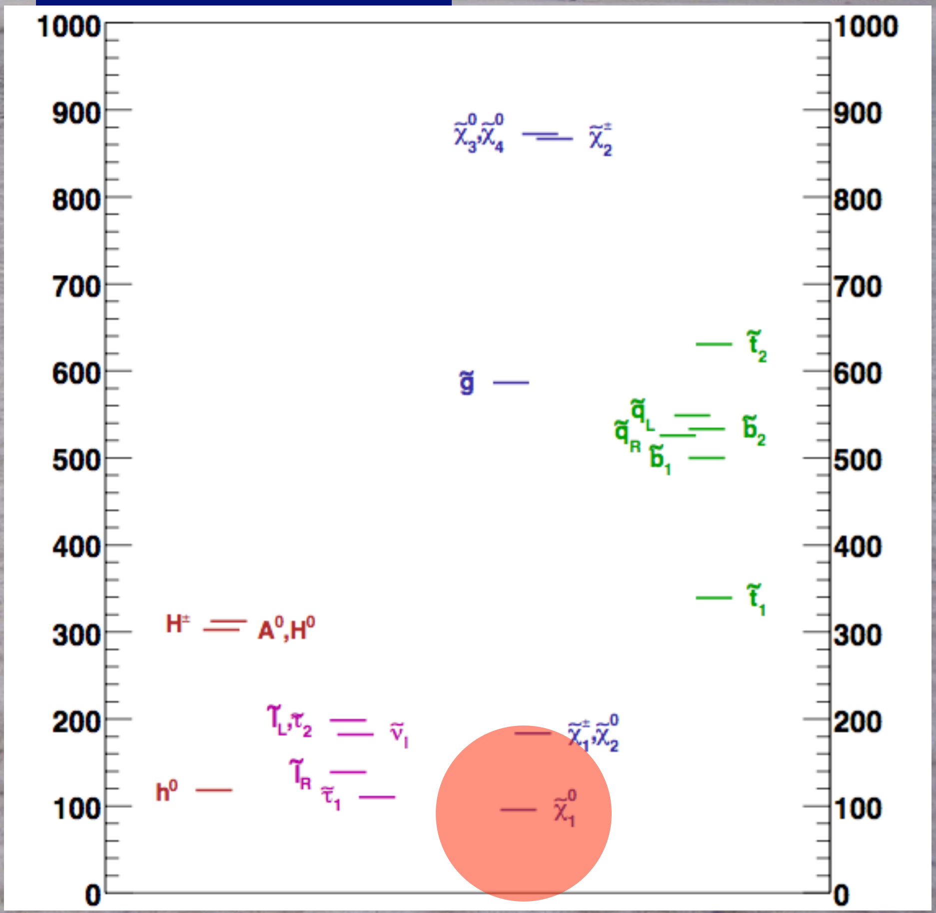
Pre-LHC

Best-Fit Spectra

CMSSM



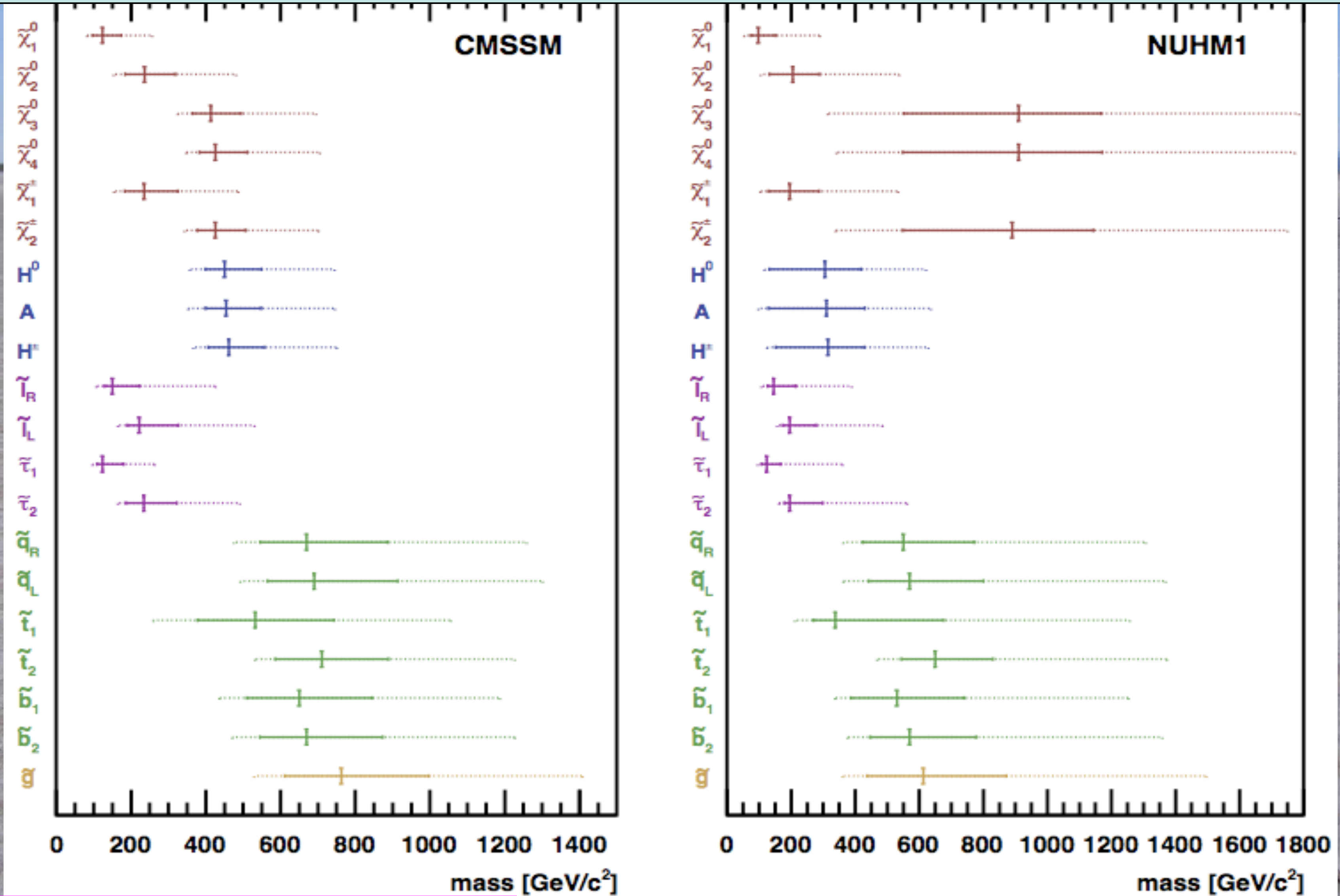
NUHM1



O.Buchmueller, JE et al: arXiv:0808.4128

Pre-LHC

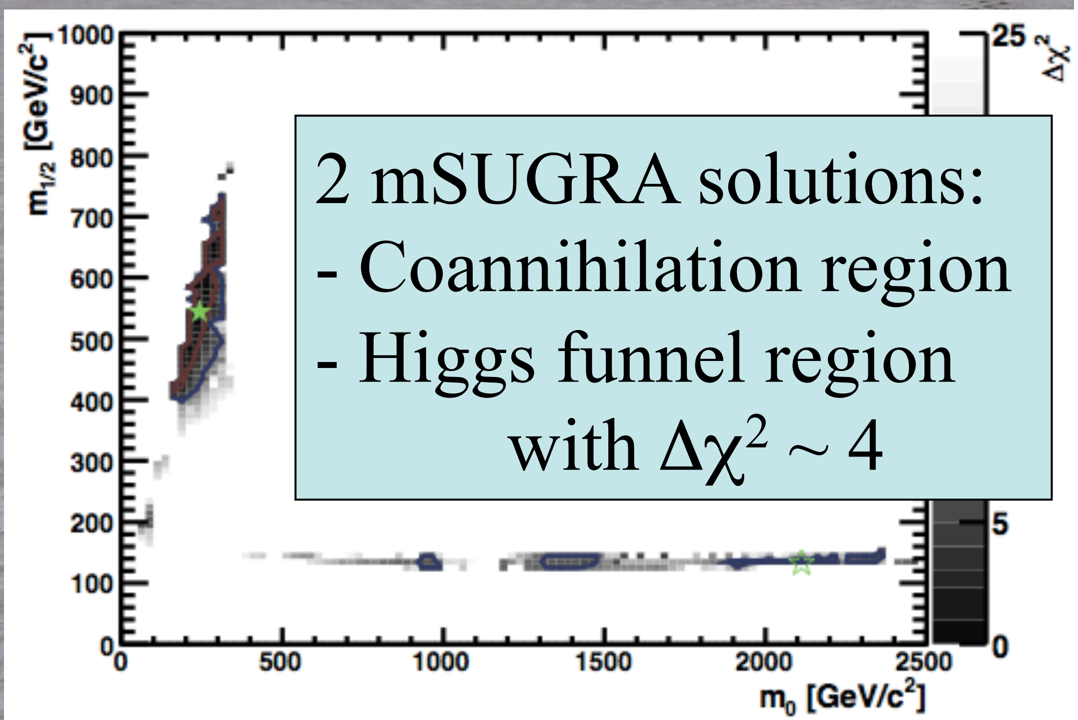
Spectra with Ranges: CMSSM & NUHM1



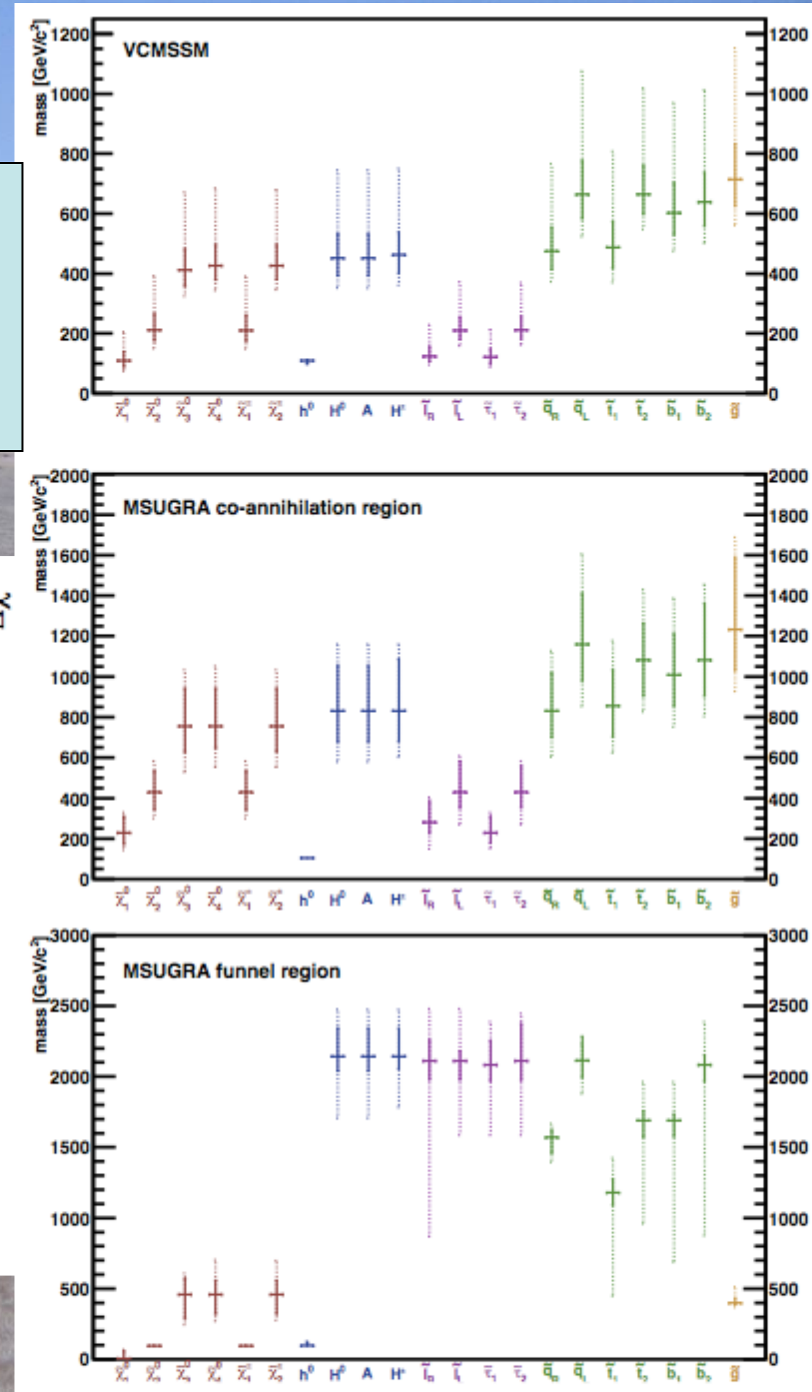
O.Buchmueller, JE et al: arXiv:0907.5568

Pre-LHC

Spectra with Ranges: VCMSSM, mSUGRA



2 mSUGRA solutions:
- Coannihilation region
- Higgs funnel region
with $\Delta\chi^2 \sim 4$

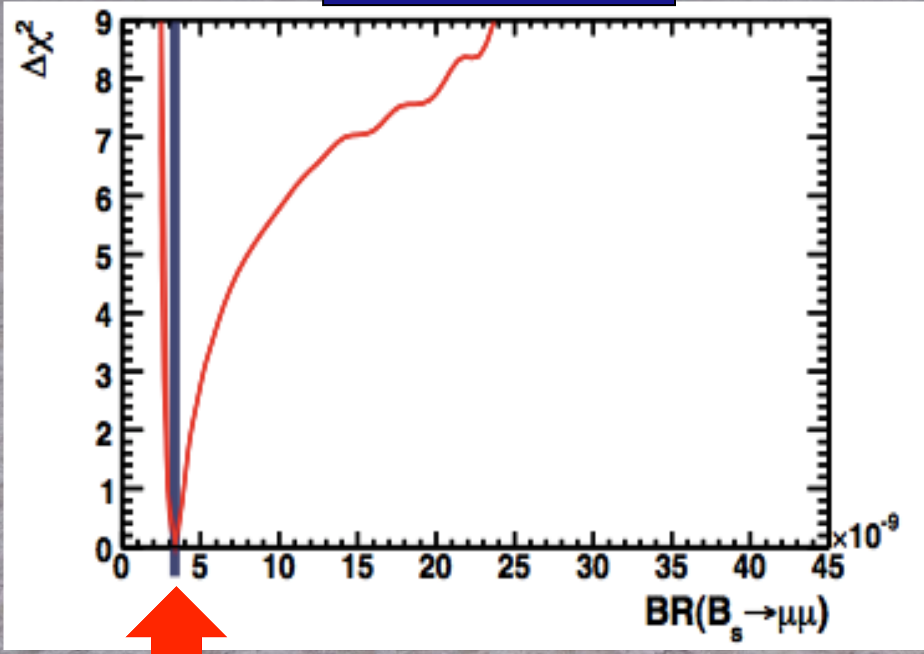


O.Buchmueller, JE et al: arXiv:1011.6118

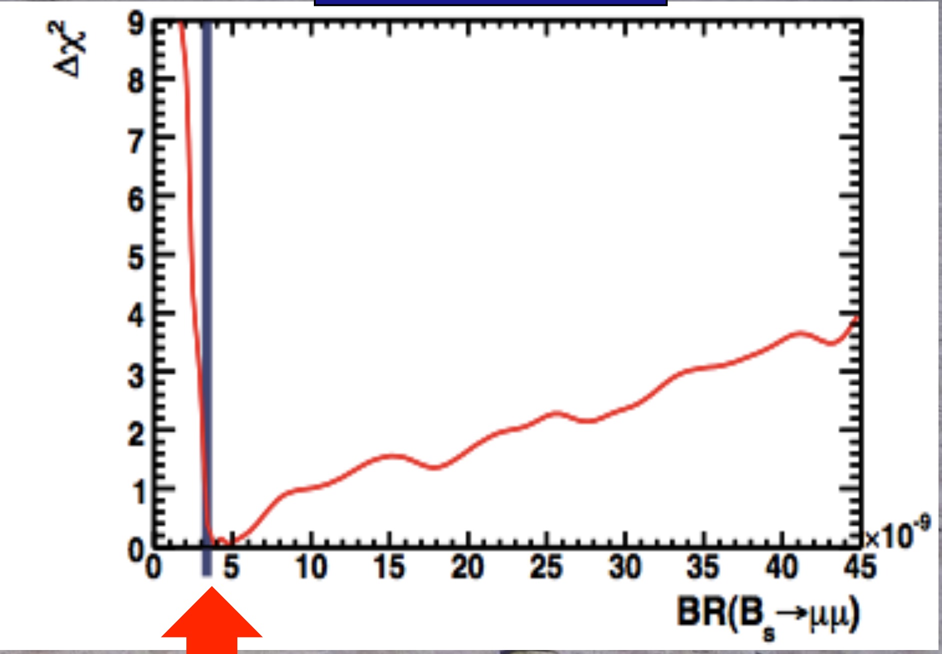
Pre-LHC

Likelihood Function for $B_s \to \mu^+\mu^-$

CMSSM



NUHM1



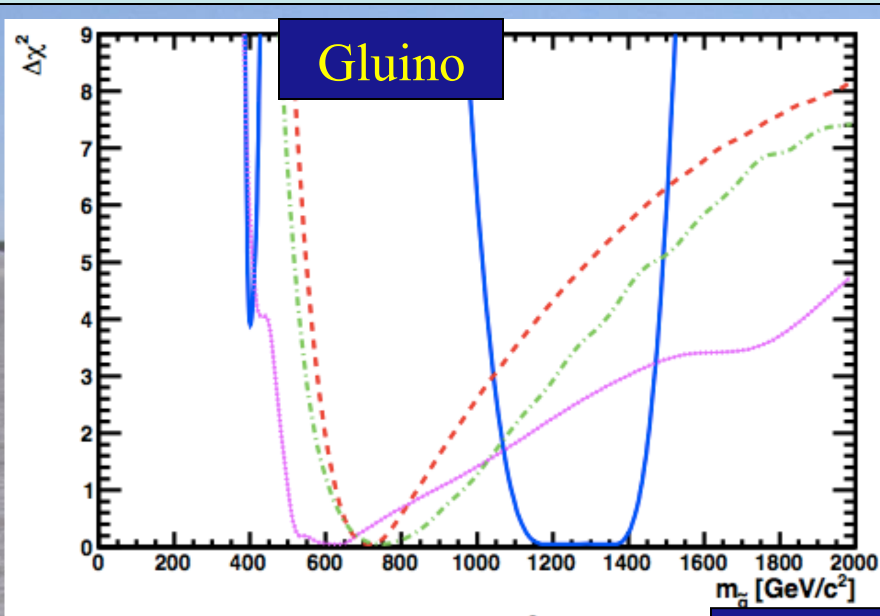
Standard Model prediction

O.Buchmueller, JE et al: arXiv:0907.5568

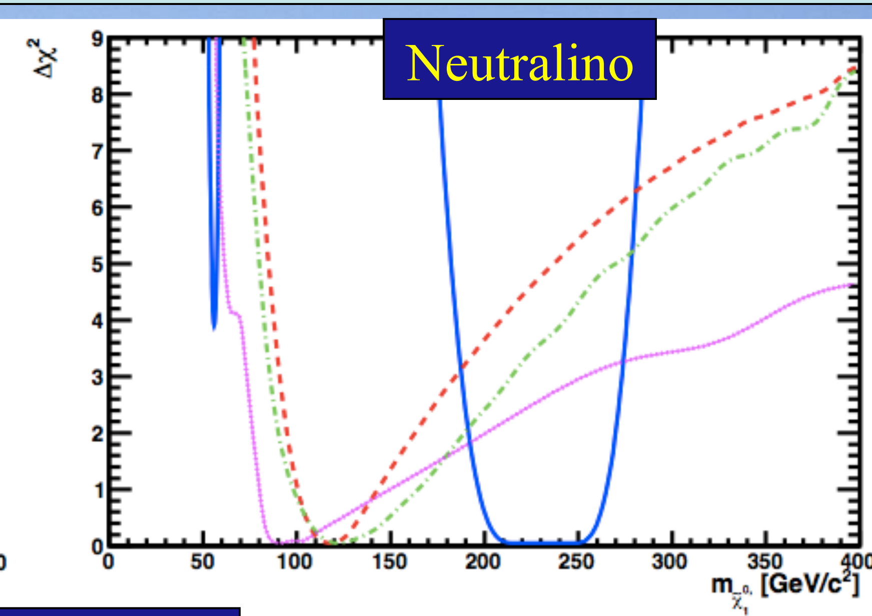
Pre-LHC

Likelihood Functions for Sparticle Masses

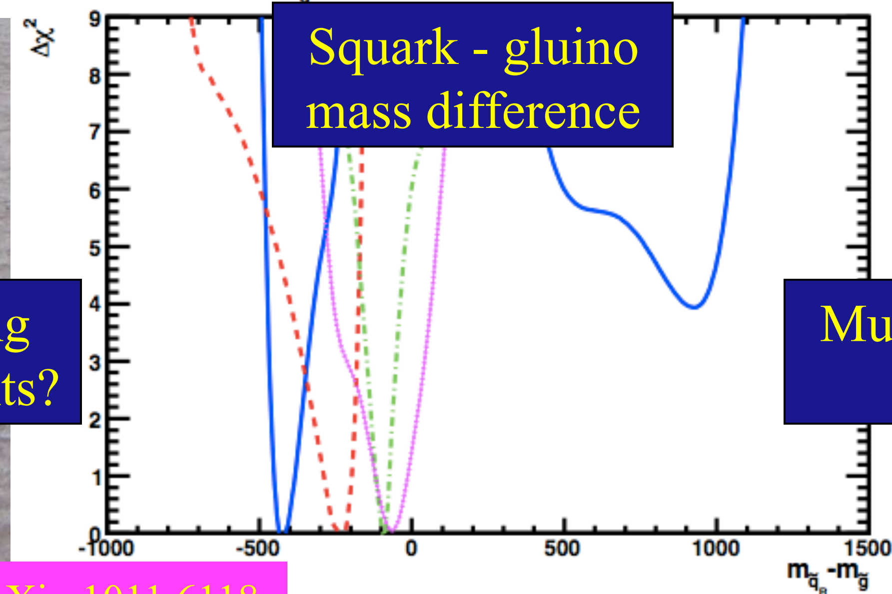
Gluino



Neutralino



Squark - gluino mass difference



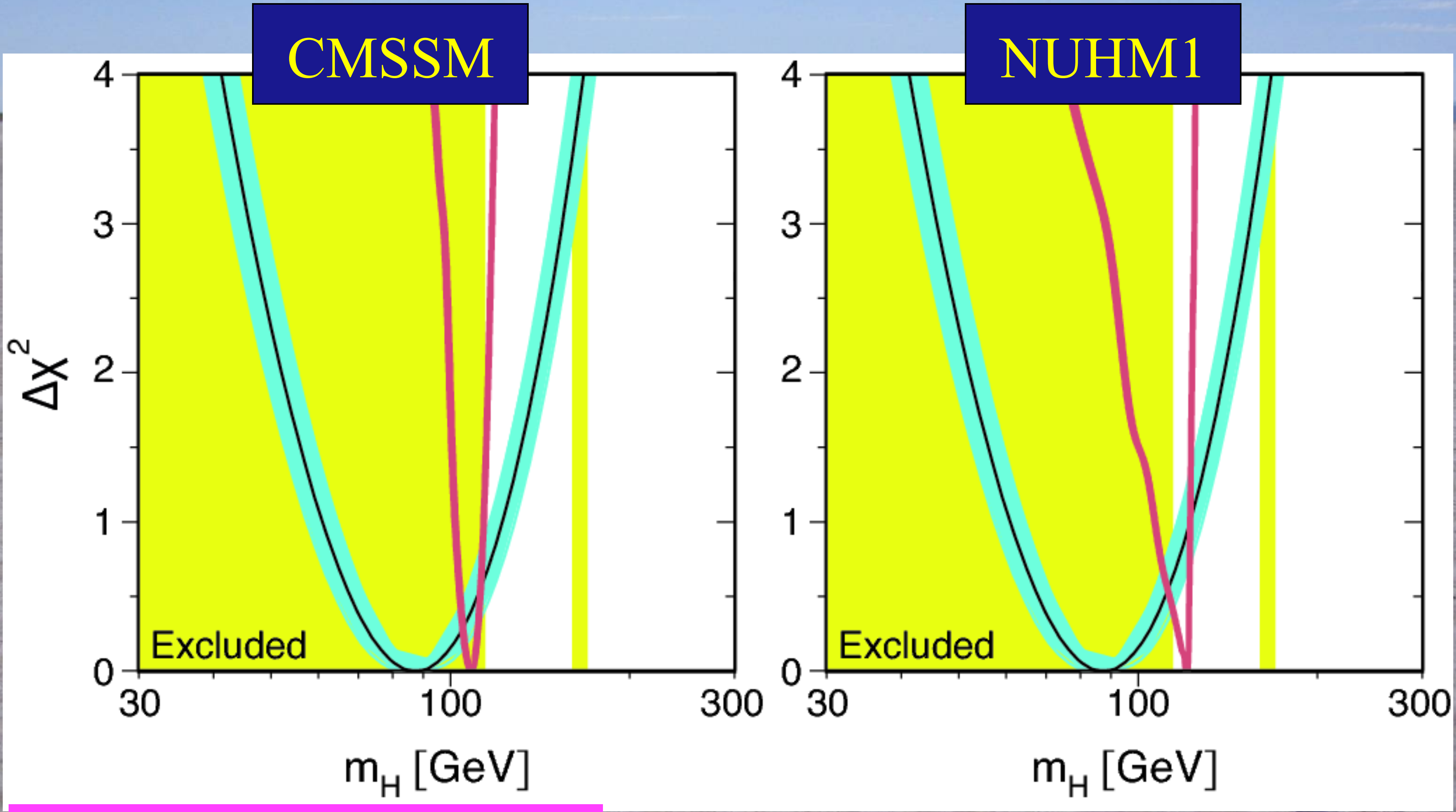
Dijet + missing energy events?

Multijet + missing energy events?

O.Buchmueller, JE et al: arXiv:1011.6118

Pre-LHC

Likelihood Function for Higgs Mass



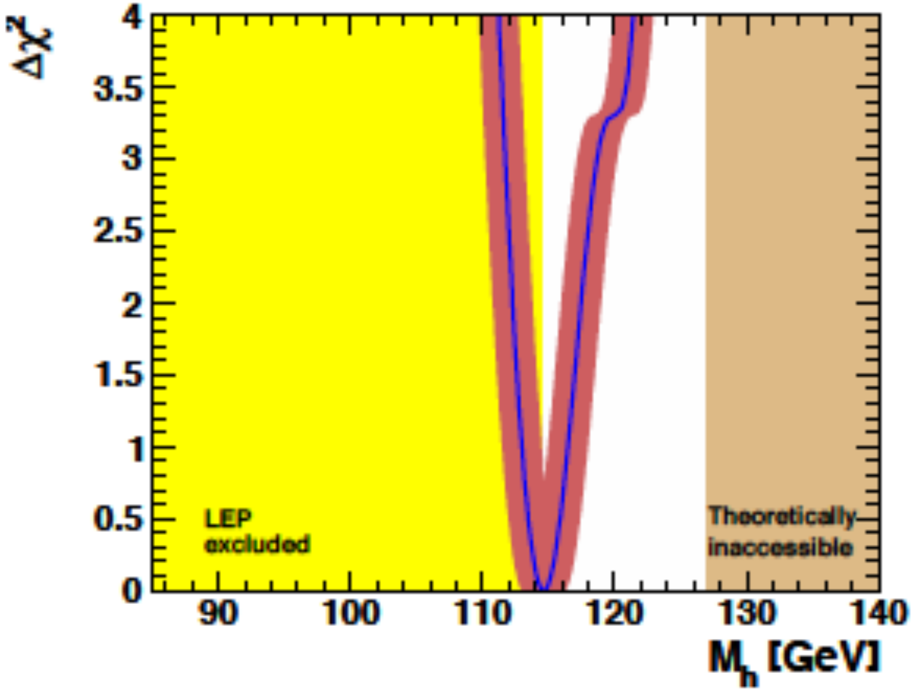
O.Buchmueller, JE et al: arXiv:0907.5568

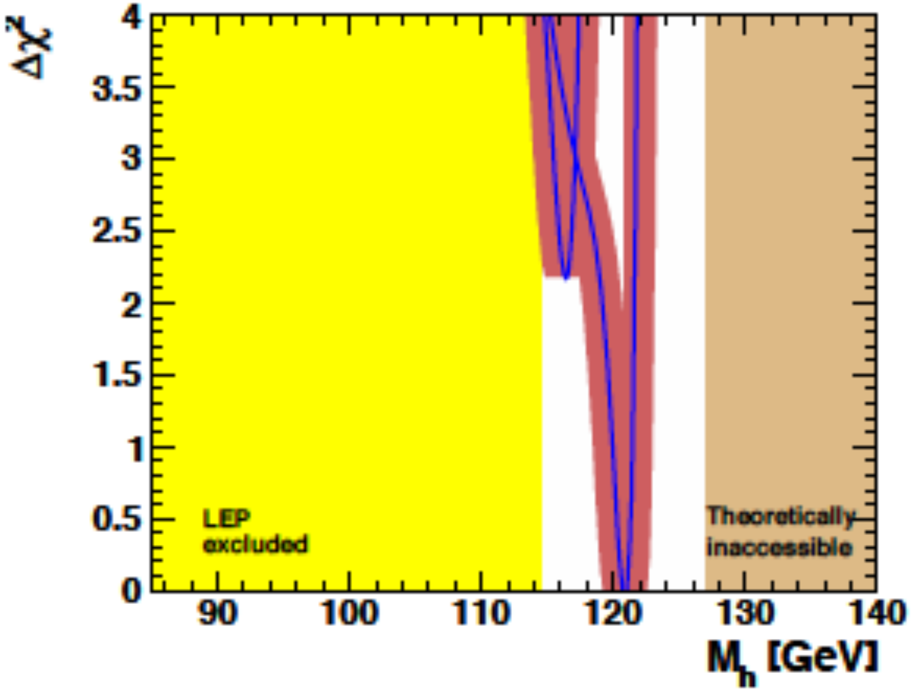
Pre-LHC

Likelihood Function for Higgs Mass

VCMSSM

mSUGRA





With LEP constraint

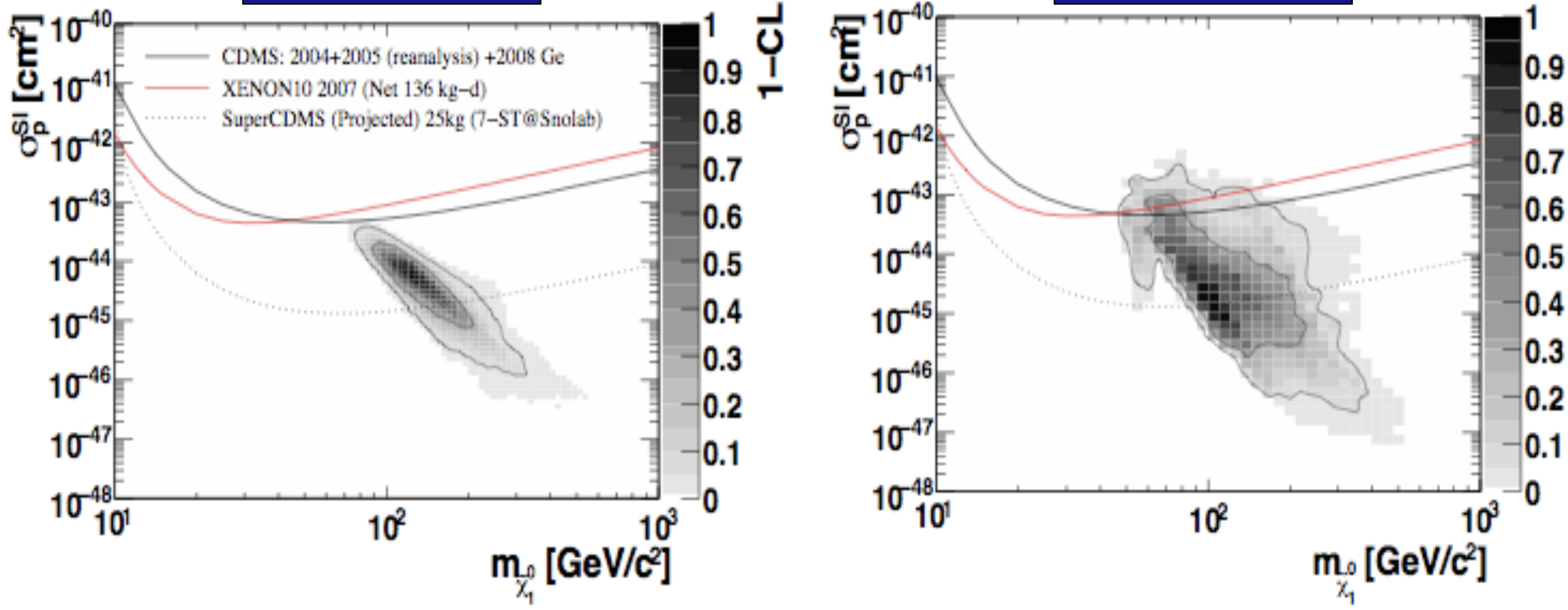
O.Buchmueller, JE et al: arXiv:1011.6118

Pre-LHC

Elastic Scattering Cross Sections

CMSSM

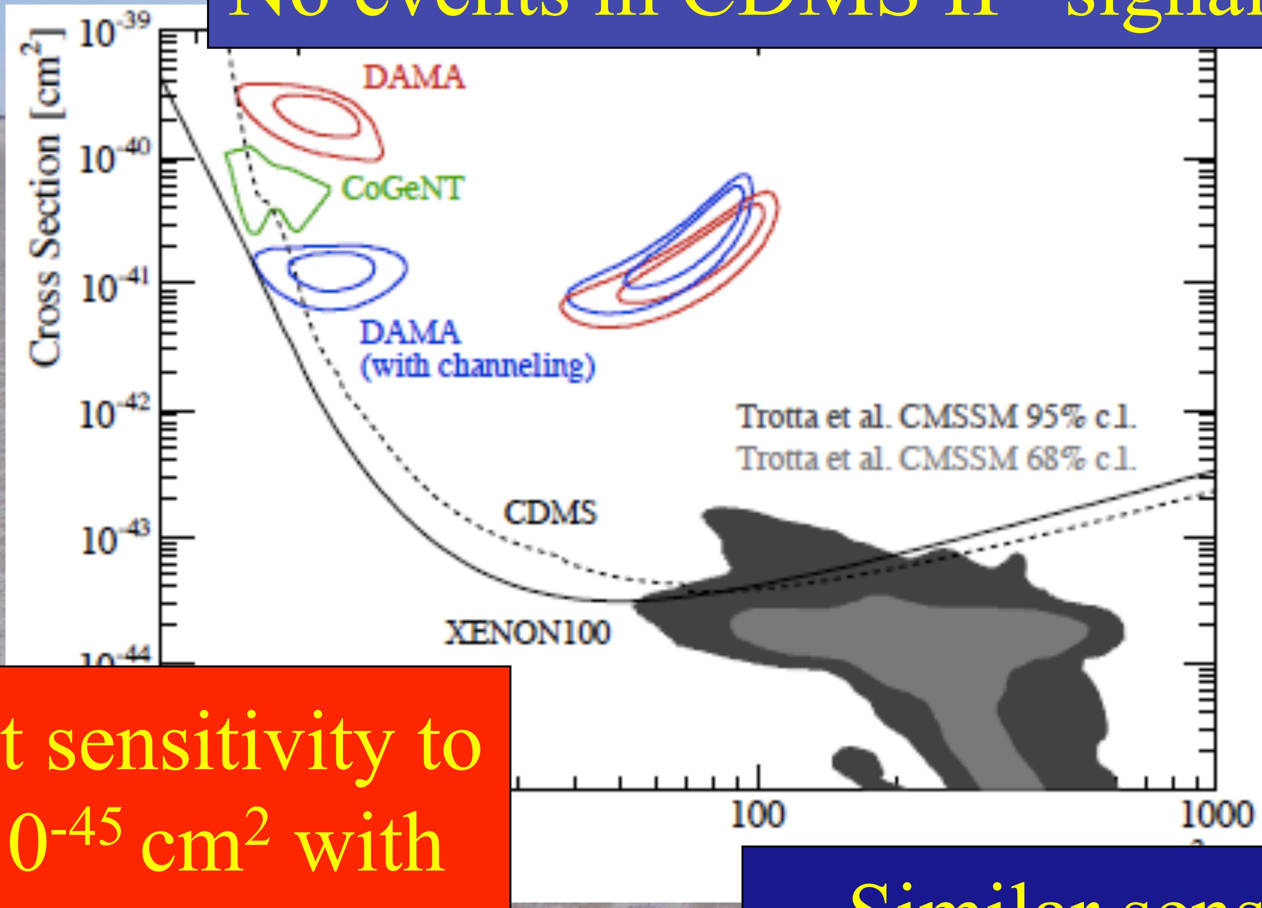
NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

Xenon100 Experiment

No events in CDMS II 'signal' region



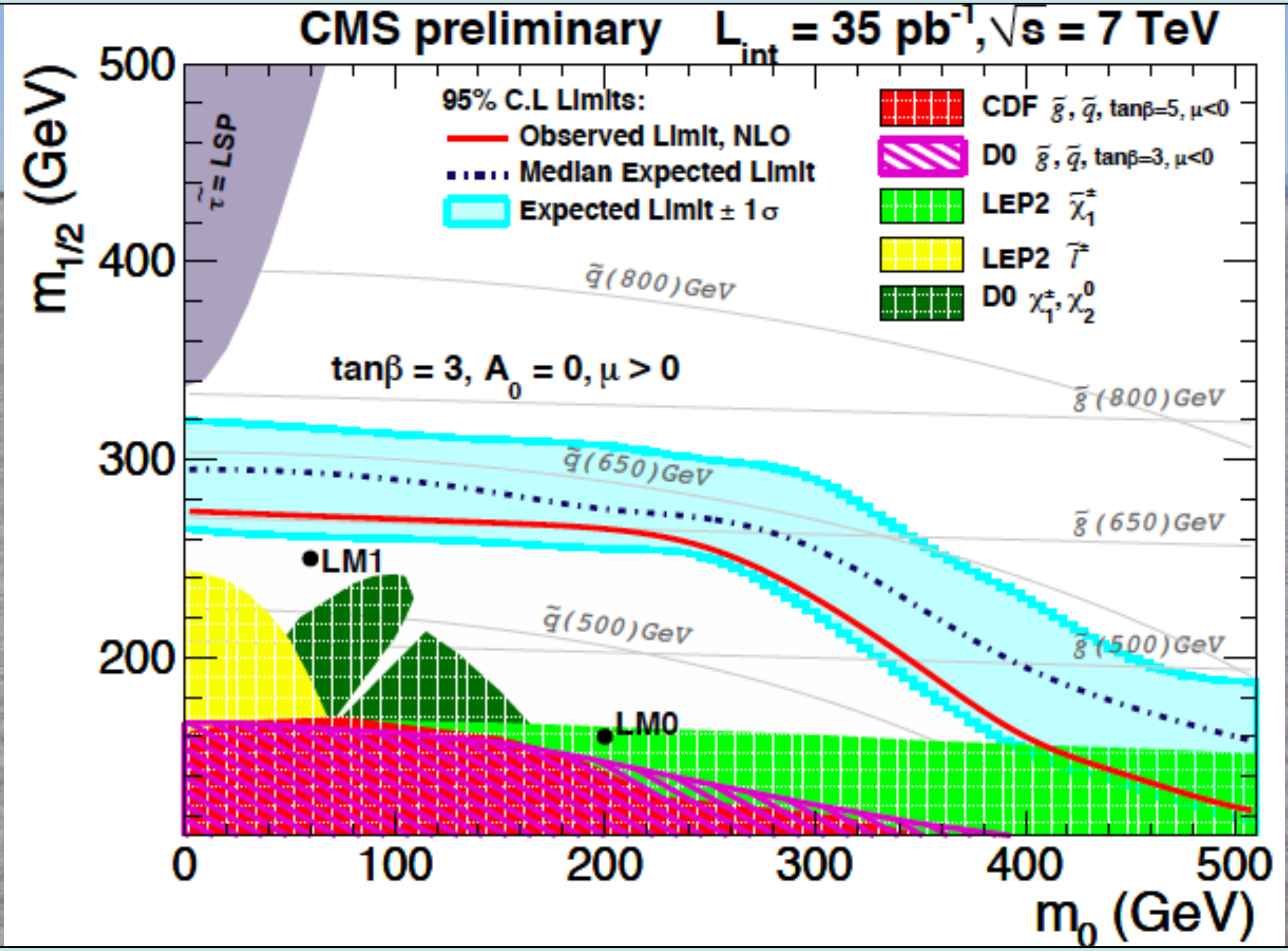
Expect sensitivity to $\sim 10^{-45}$ cm^2 with 200 days of data

Similar sensitivity with 11 days of data

Aprile et al: arXiv:1005.0380

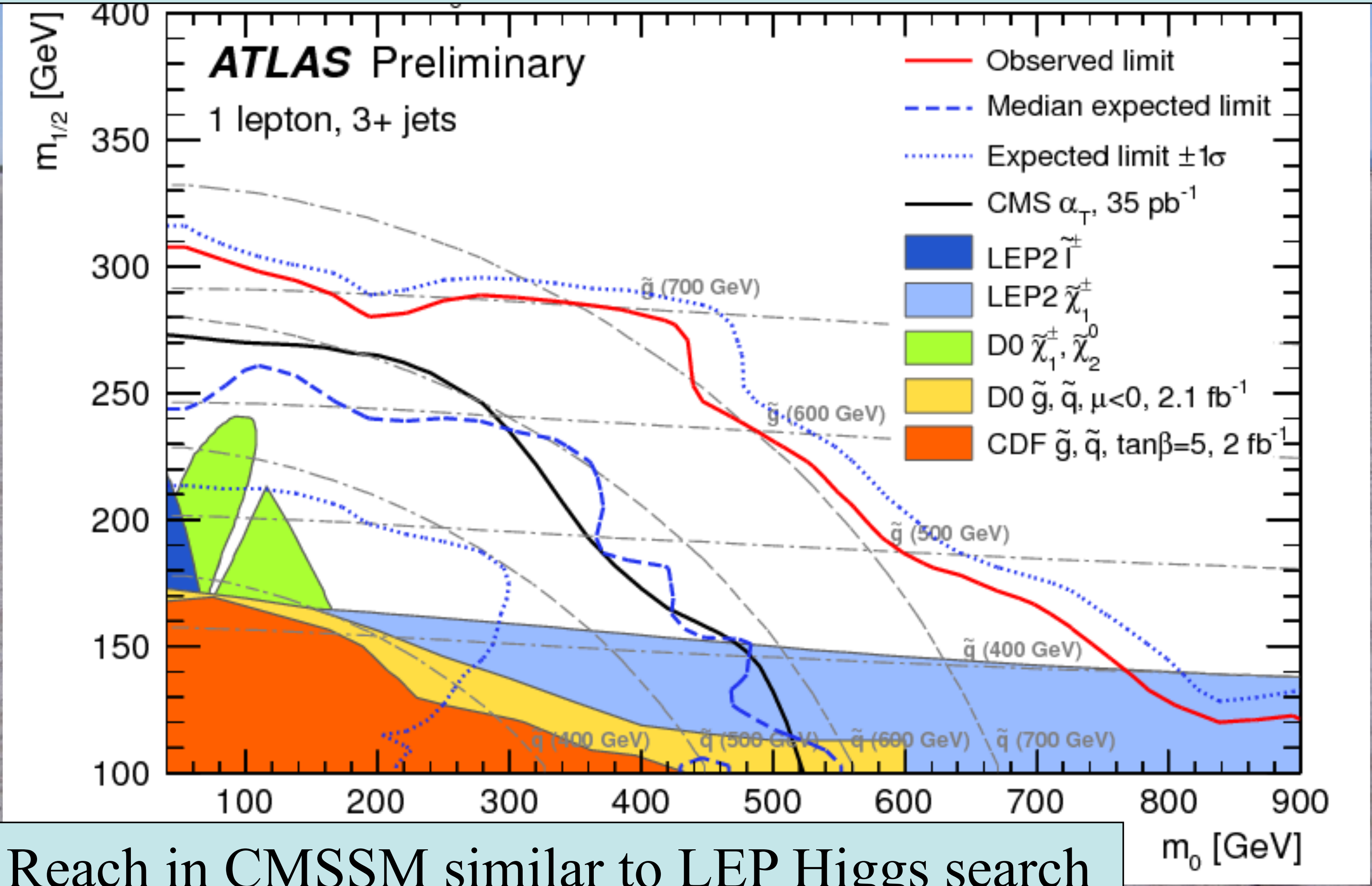
Nov. 20th 2009: Jubilation

Supersymmetry Search in CMS



Reach in CMSSM comparable to LEP Higgs search

Supersymmetry Search in ATLAS



Reach in CMSSM similar to LEP Higgs search

Impact of LHC on the CMSSM

Assuming the lightest sparticle is a neutralino

CMS

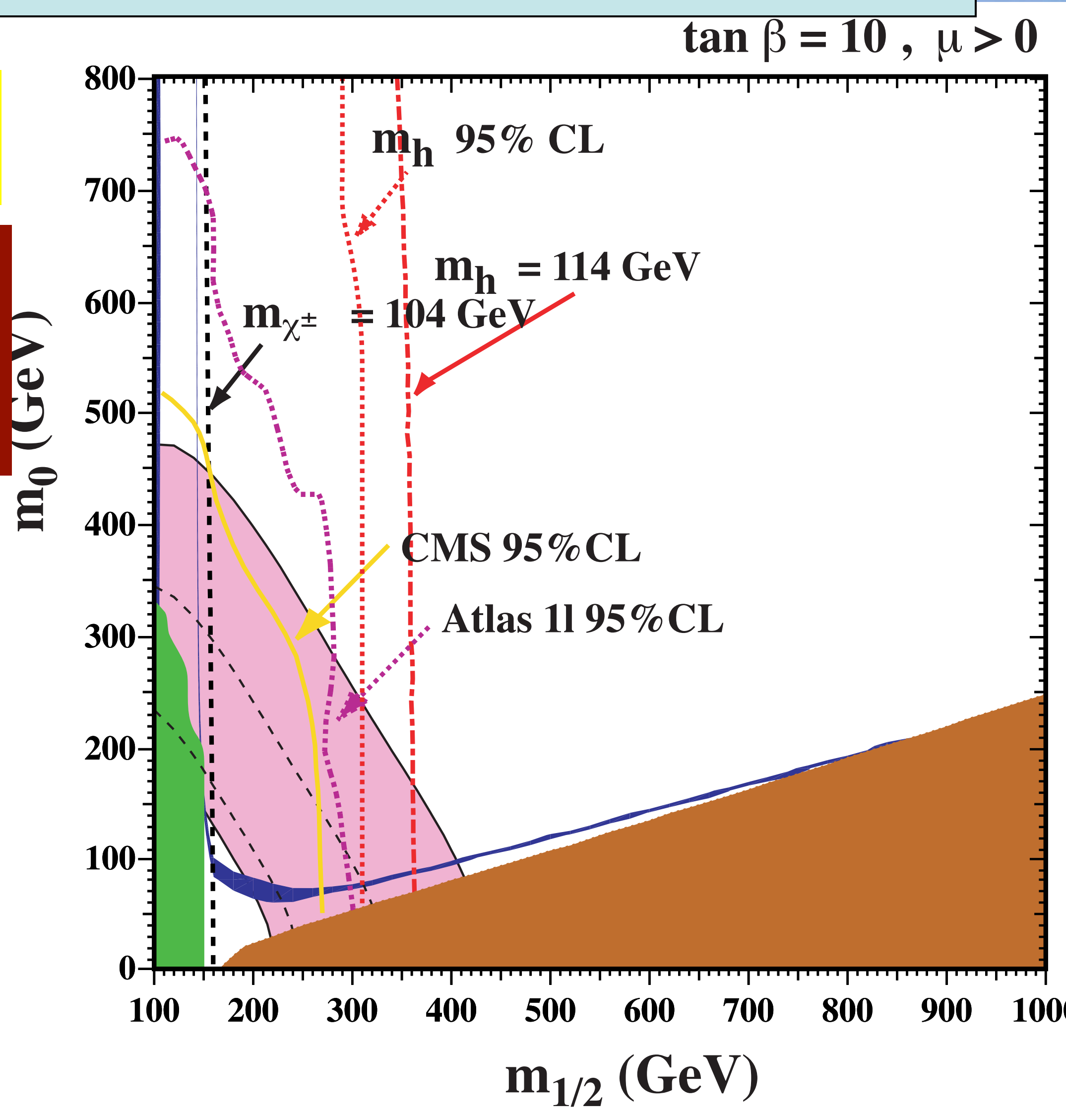
ATLAS 1 Lepton

Excluded because stau LSP

Excluded by b → s gamma

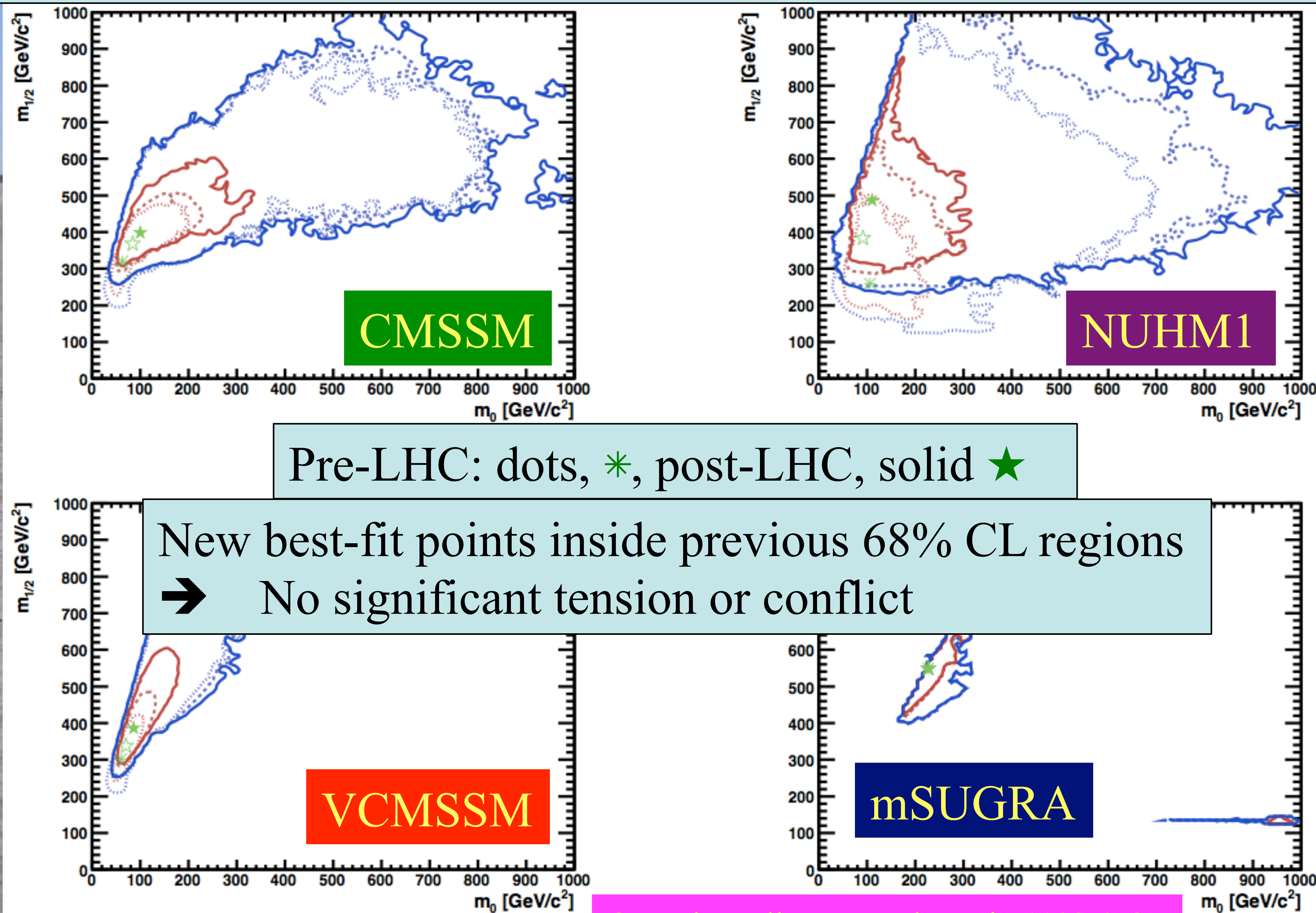
WMAP constraint on CDM density

Preferred (?) by latest g - 2



Post-LHC

$(m_0, m_{1/2})$ Planes Revisited



Pre-LHC: dots, ✳, post-LHC, solid ★

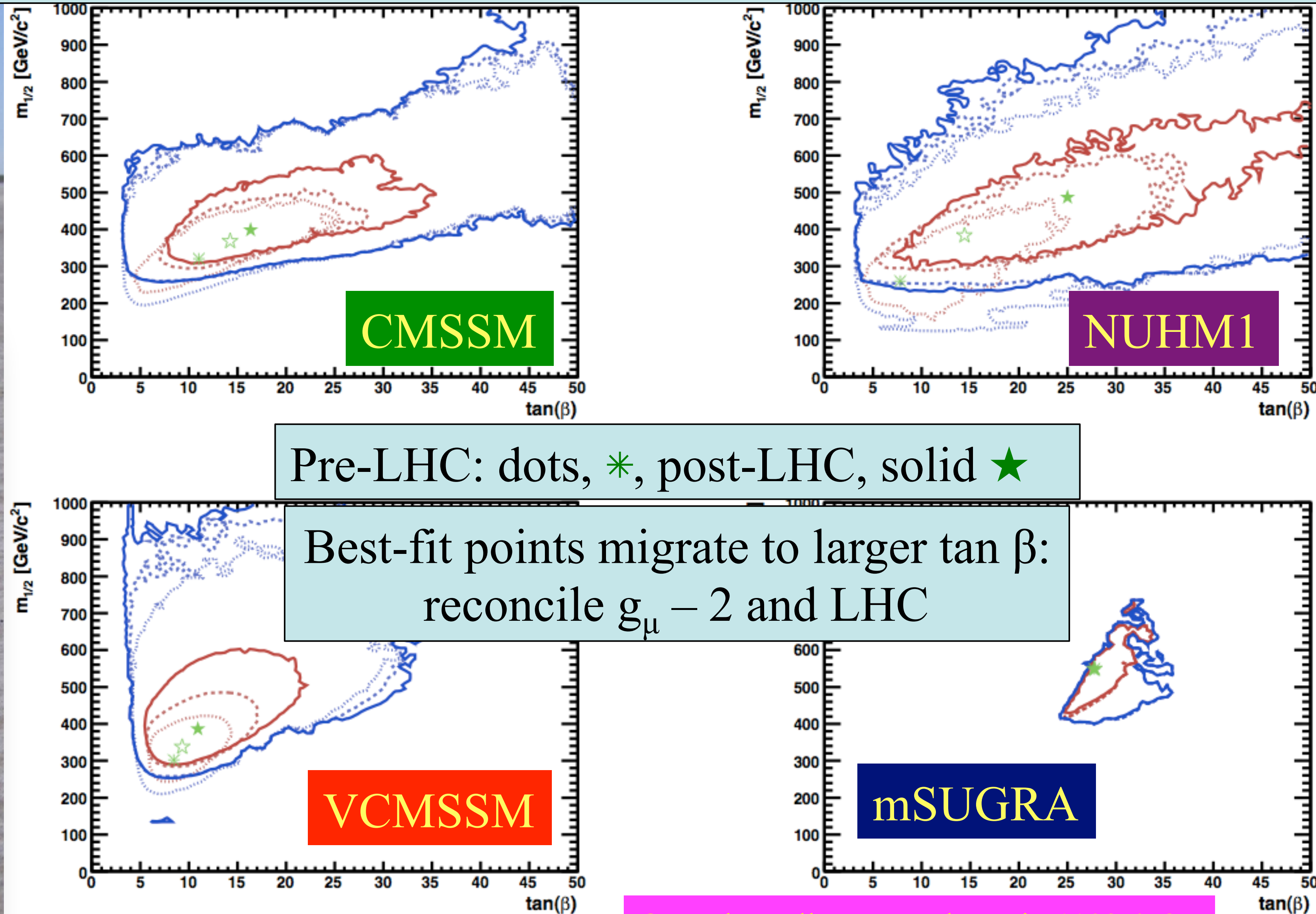
New best-fit points inside previous 68% CL regions

➔ No significant tension or conflict

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

($\tan\beta$, $m_{1/2}$) Planes Revisited



Pre-LHC: dots, ✳, post-LHC, solid ★

Best-fit points migrate to larger $\tan\beta$: reconcile $g_\mu - 2$ and LHC

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

Best-Fit Points Compared

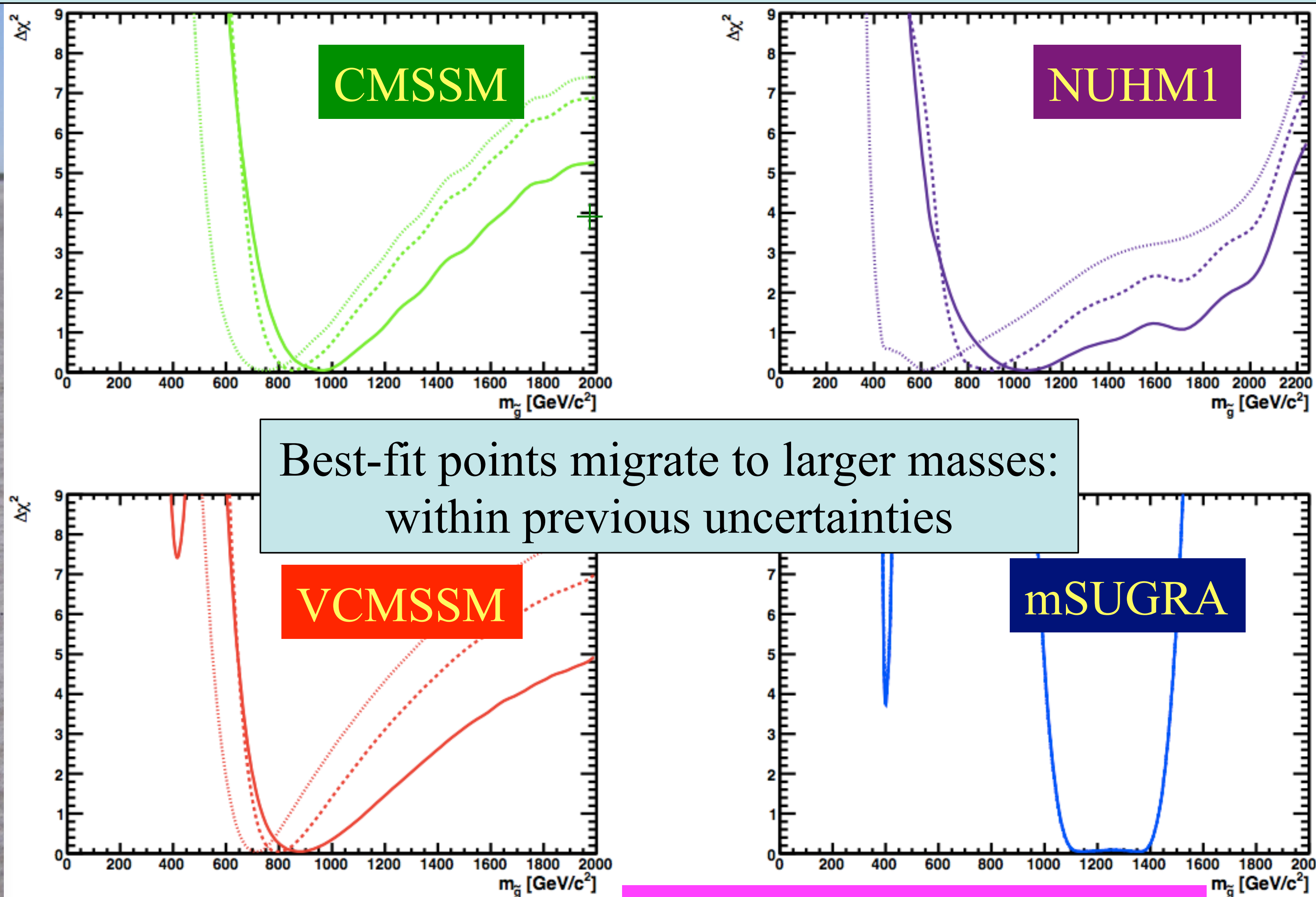
Model	Minimum χ^2	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (no LEP) (GeV)
CMSSM	(21.3)	(32%)	(320)	(60)	(-170)	(11)	(107.9)
with CMS	22.0	29%	370	80	-340	14	112.6
with ATLAS	24.9	16%	400	100	-430	16	112.8
NUHM1	(19.3)	(31%)	(260)	(110)	(1010)	(8)	(121.9)
with CMS	20.9	28%	380	90	70	14	113.5
with ATLAS	23.3	18%	490	110	-630	25	116.5
VCMSSM	(22.5)	(31%)	(300)	(60)	(30)	(9)	(109.3)
with CMS	23.8	25%	340	70	50	9	115.5
with ATLAS	27.1	13%	390	90	70	11	117.0
mSUGRA	(29.4)	(6.1%)	(550)	(230)	(430)	(28)	(107.8)
with CMS	29.4	6.1%	550	230	430	28	121.2
with ATLAS	30.9	5.7%	550	230	430	28	121.2

No significant reductions in fit probabilities:
No significant tension or conflict

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

Gluino Mass Revisited

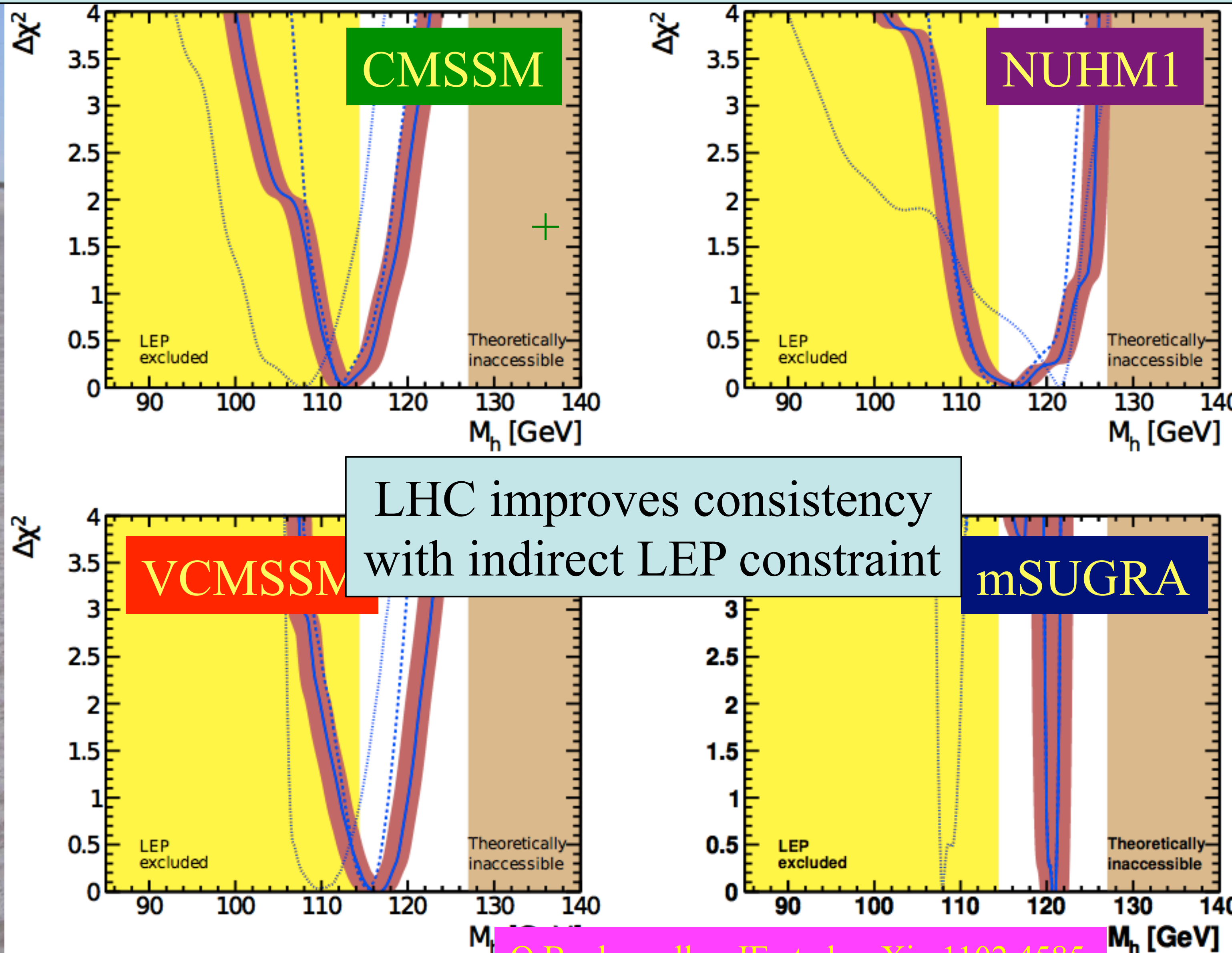


Best-fit points migrate to larger masses:
within previous uncertainties

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

Higgs Mass Revisited

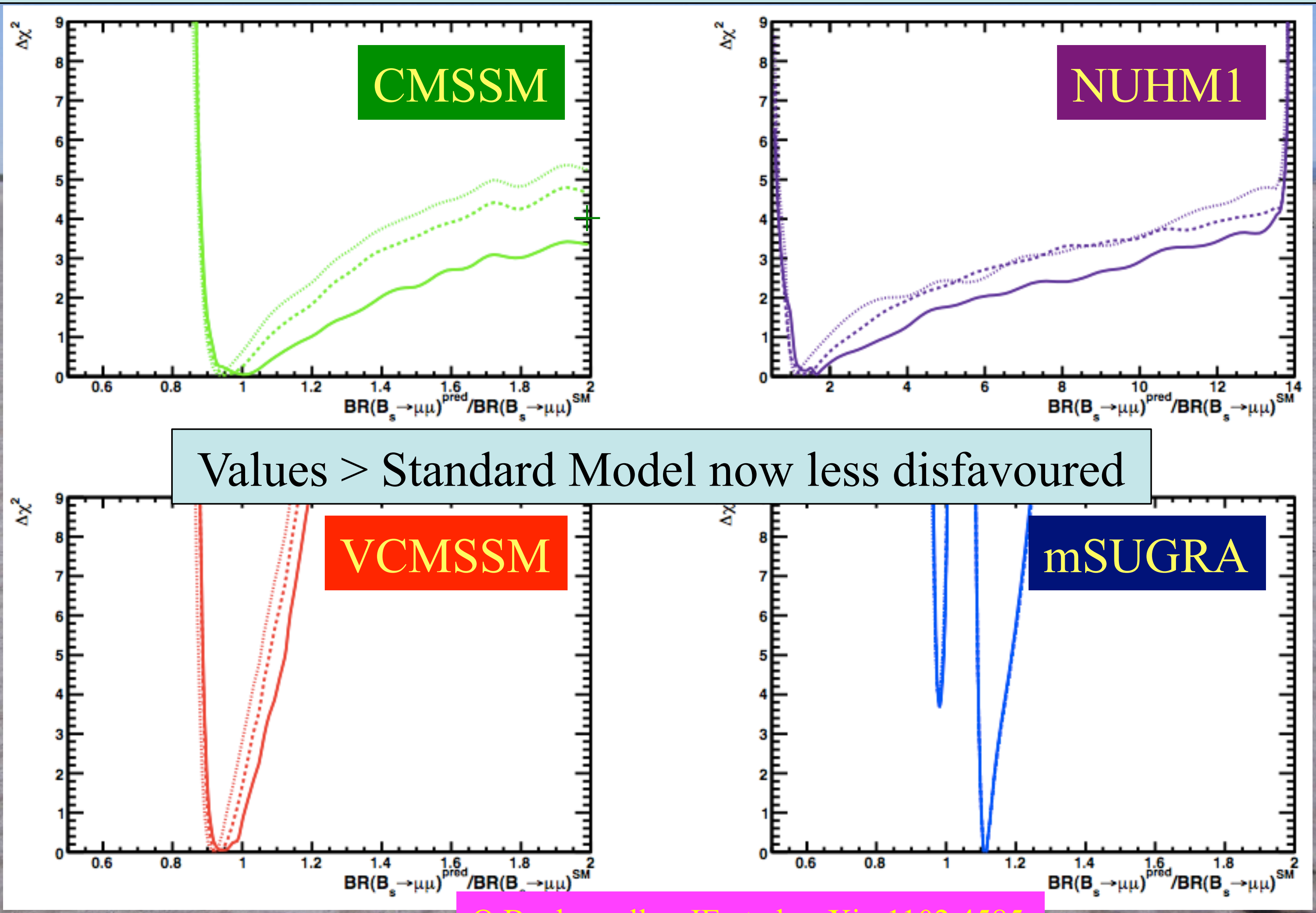


LHC improves consistency with indirect LEP constraint

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

BR($B_s \rightarrow \mu^+\mu^-$) Revisited

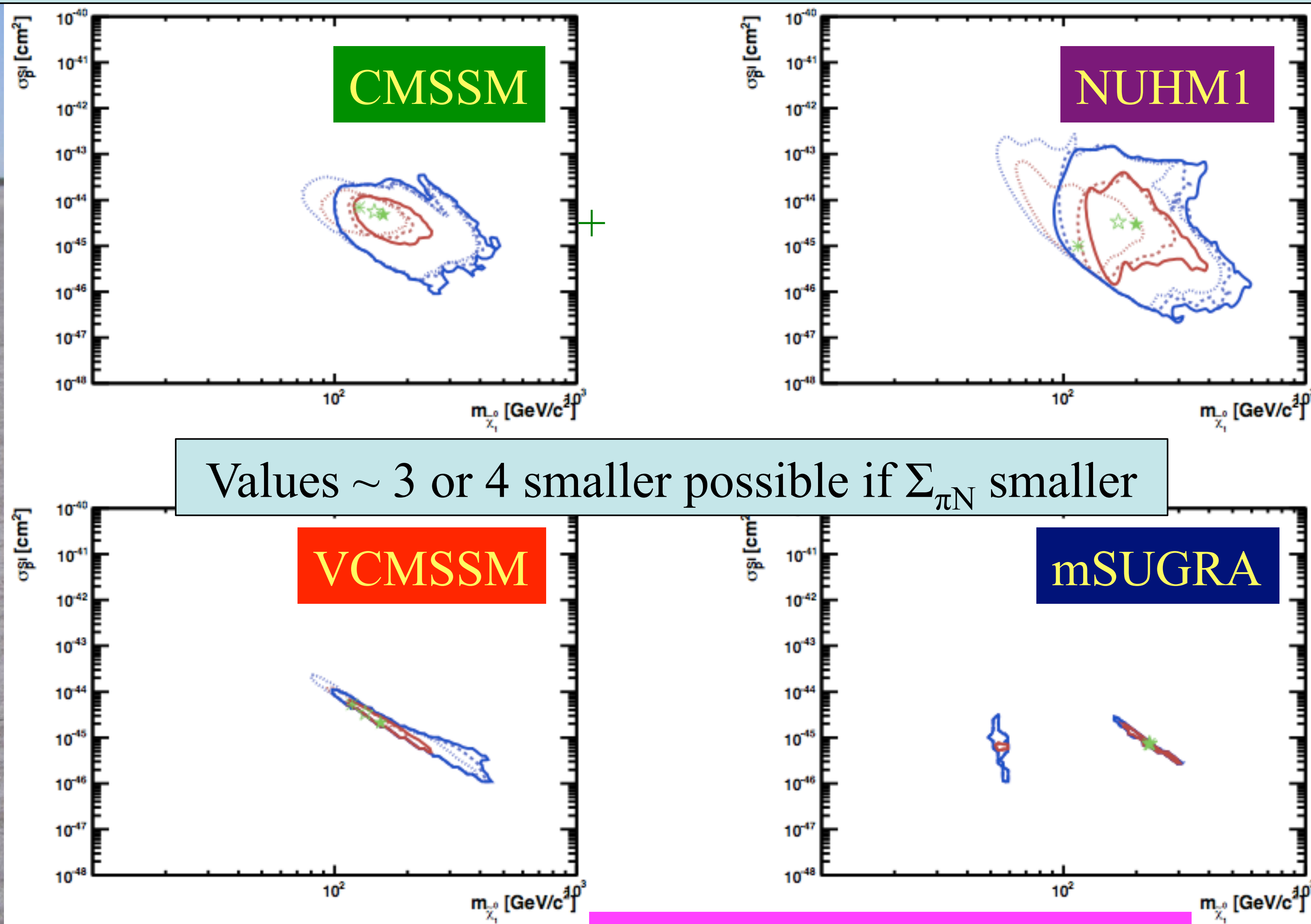


Values > Standard Model now less disfavoured

O.Buchmueller, JE et al: arXiv:1102.4585

Post-LHC

Dark Matter Scattering Revisited



Values ~ 3 or 4 smaller possible if $\Sigma_{\pi N}$ smaller

O.Buchmueller, JE et al: arXiv:1102.4585

No Issue of Fine-Tuning

- Standard measure of fine-tuning:

	Pre-LHC	After CMS, ATLAS 0l
CMSSM	100	120, 140
NUHM1	250	230, 310
VCMSSM	130	110, 140
mSUGRA	250	250, 250

- **No significant increase**

O.Buchmueller, JE et al: arXiv:1102.4585

Contrast Strumia: arXiv:1101.2195

Impact of LHC on the CMSSM

Assuming the lightest sparticle is a neutralino

CMS

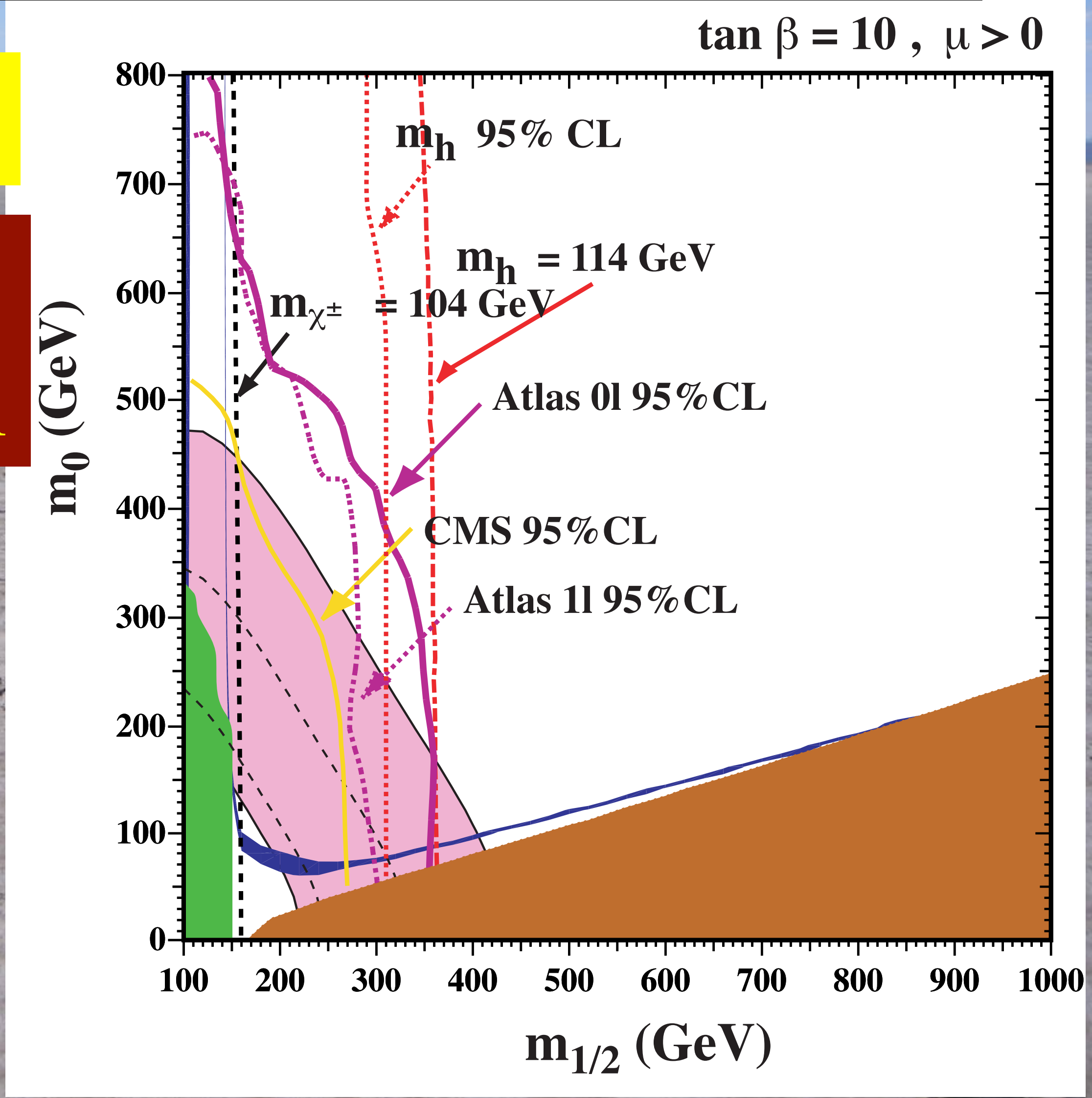
ATLAS 1 Lepton

Excluded because stau LSP

Excluded by b → s gamma

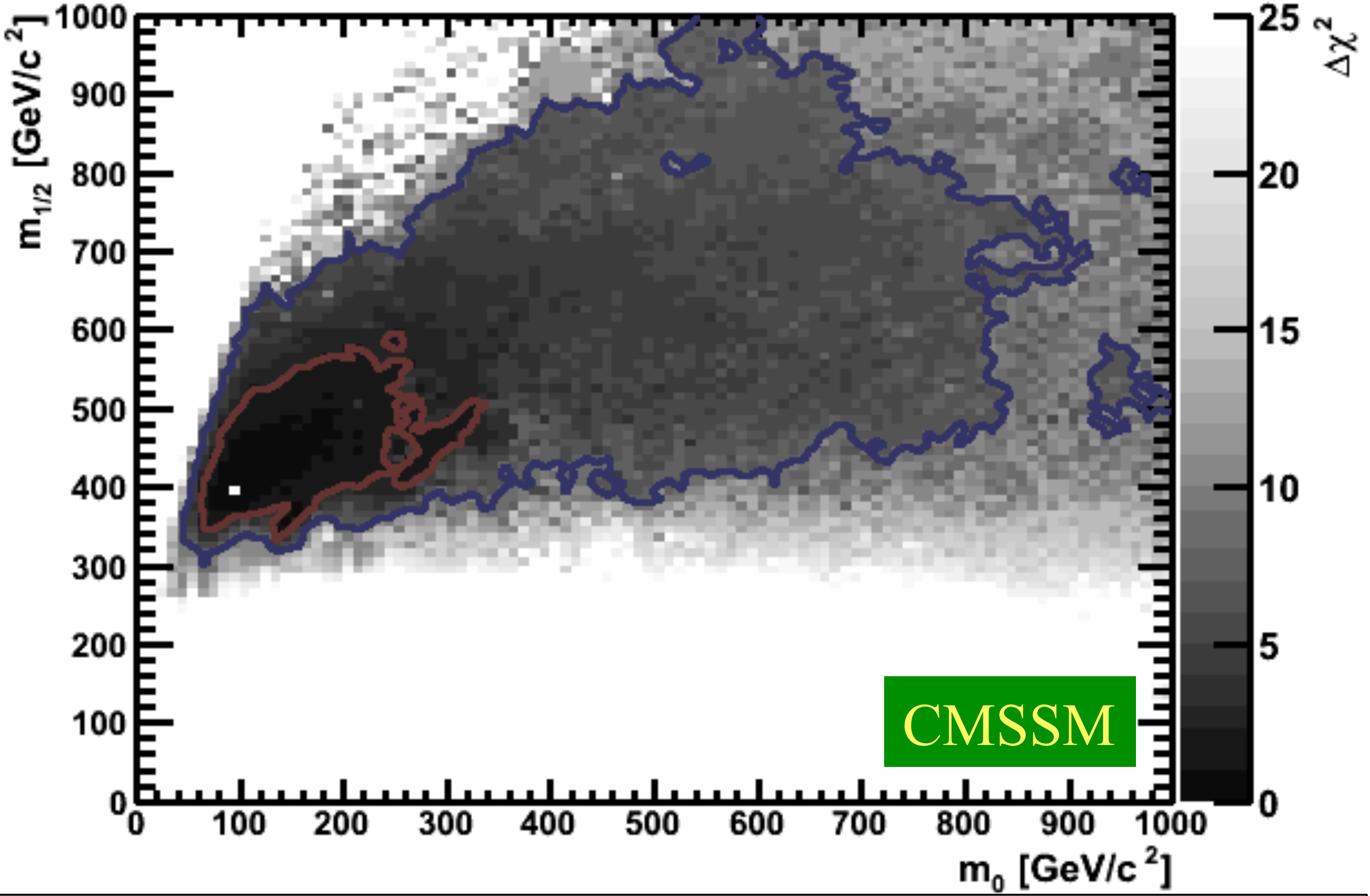
WMAP constraint on CDM density

Preferred (?) by latest g - 2



Post-ATLAS 0L

CMSSM (m_0, $m_{1/2}$) Plane Revisited



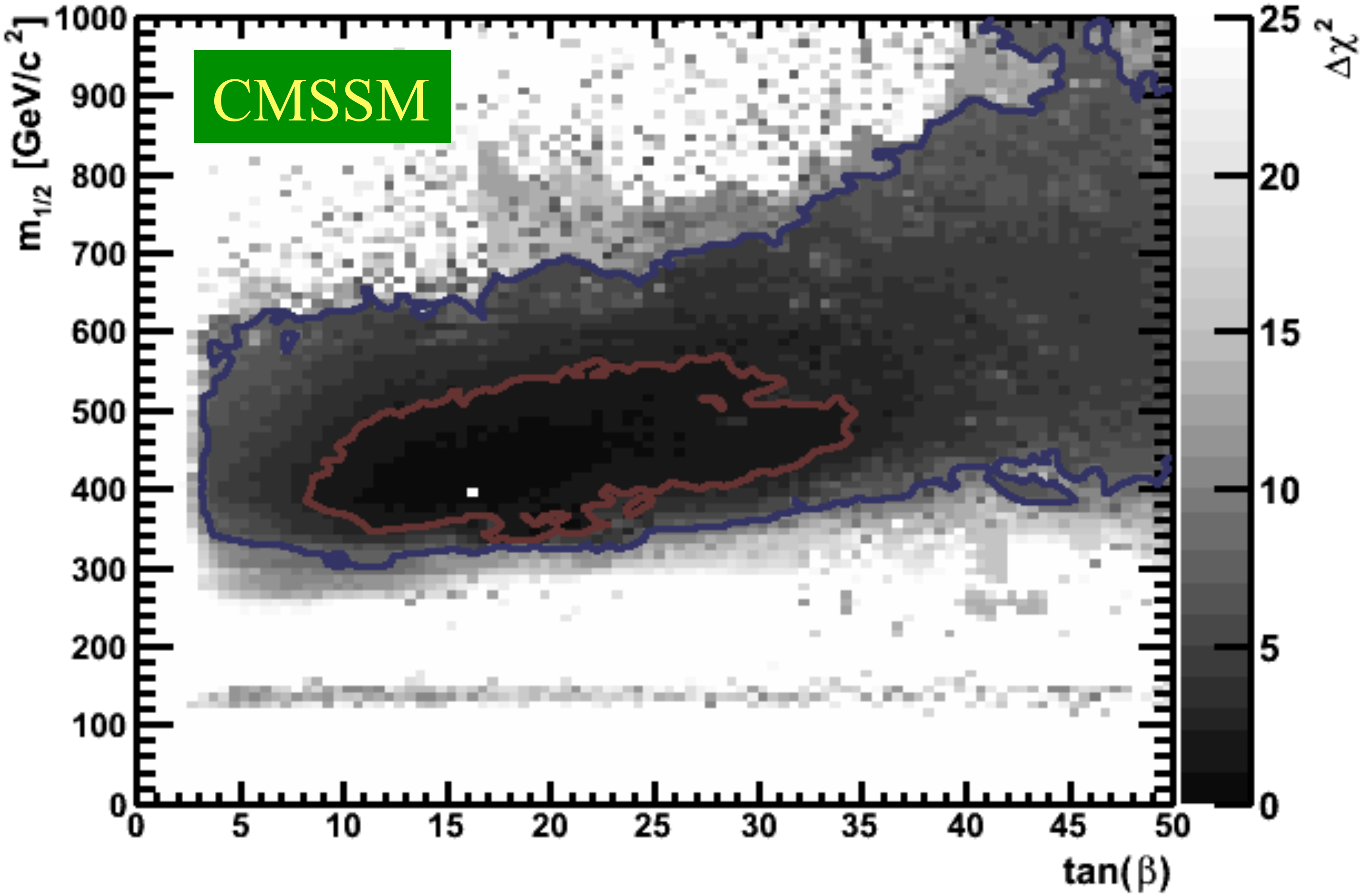
New best-fit point still inside previous 68% CL region

➔ No significant tension or conflict

O.Buchmueller, JE et al: in preparation

Post-ATLAS 0L

CMSSM (tan β, $m_{1/2}$) Plane Revisited

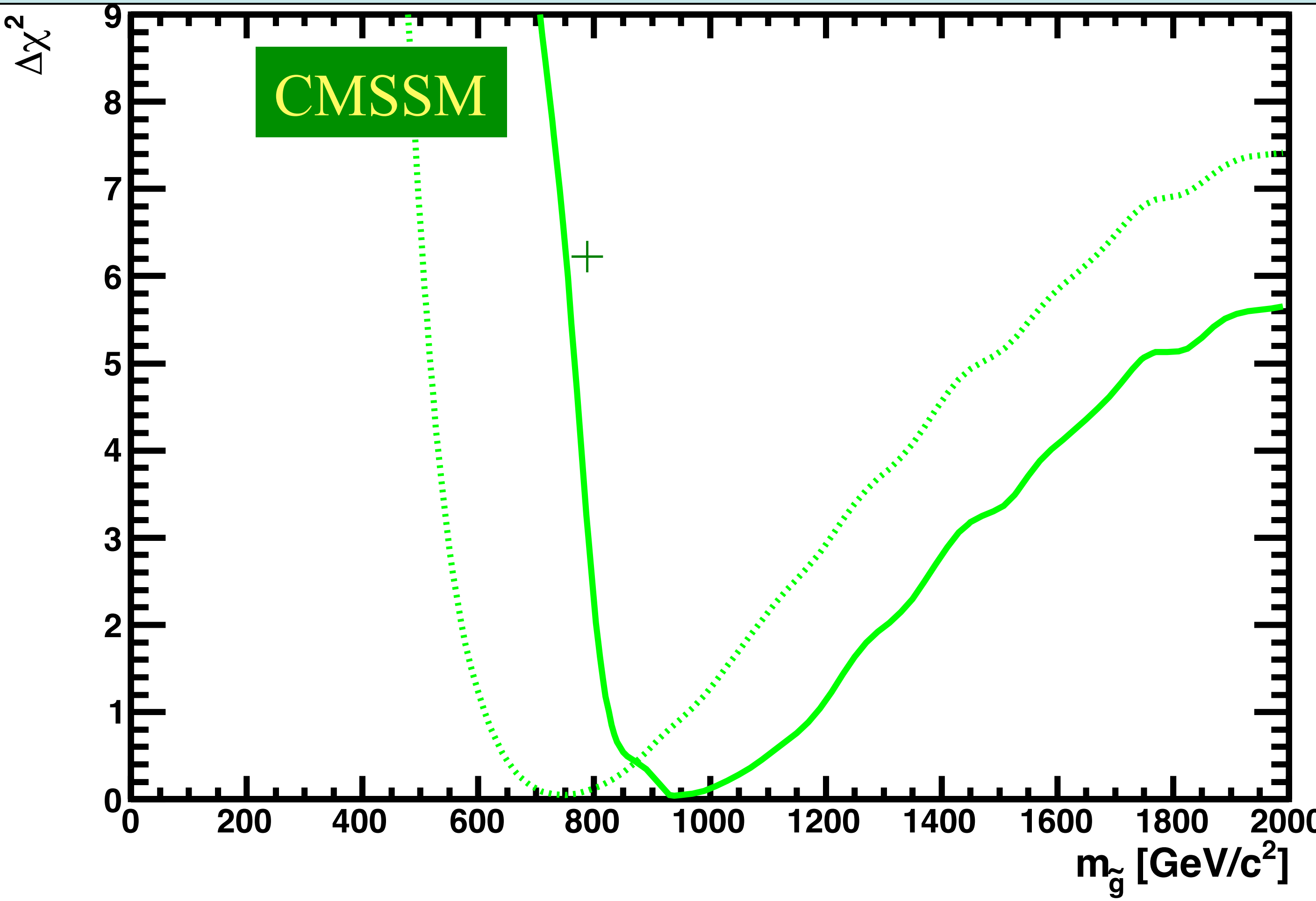


Best-fit points migrate to larger tan β: reconcile $g_\mu - 2$ and LHC

O.Buchmueller, JE et al: in preparation

Post-ATLAS 0L

CMSSM Gluino Mass Revisited

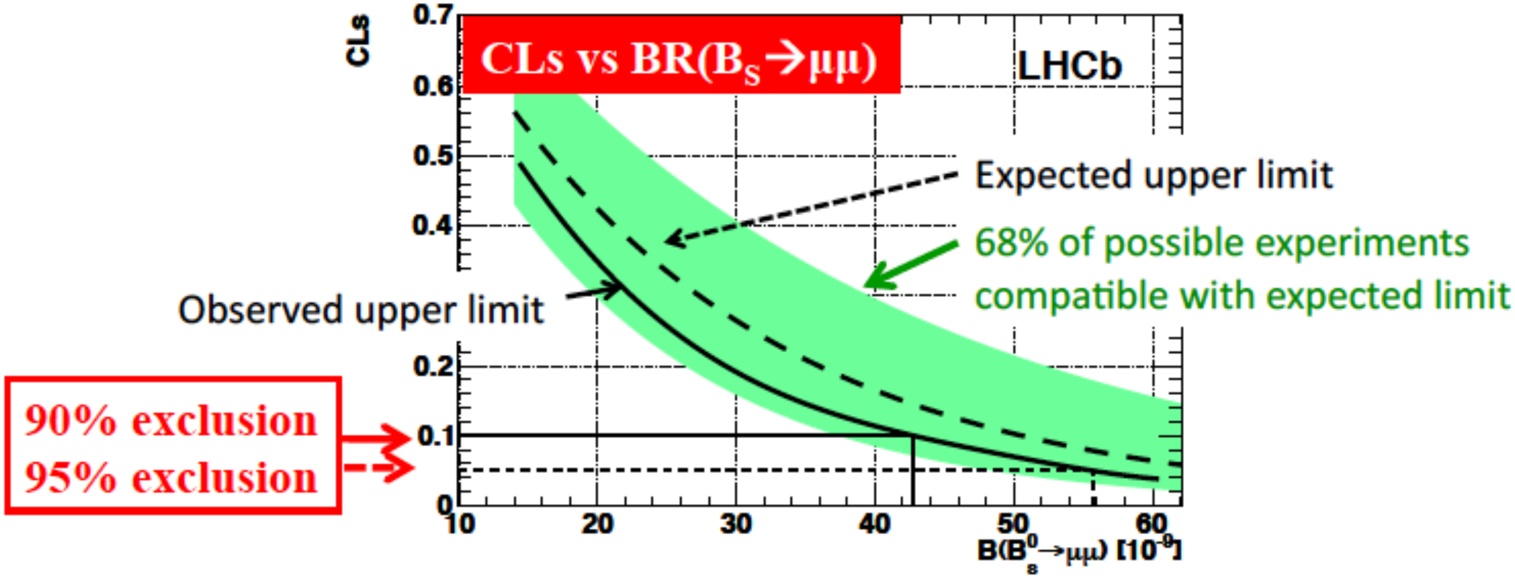


Best-fit point migrates to larger masses: within previous uncertainties

O.Buchmueller, JE et al: in preparation

Post-ATLAS 0L

NUHM1 BR($B_s \rightarrow \mu^+\mu^-$) Revisited



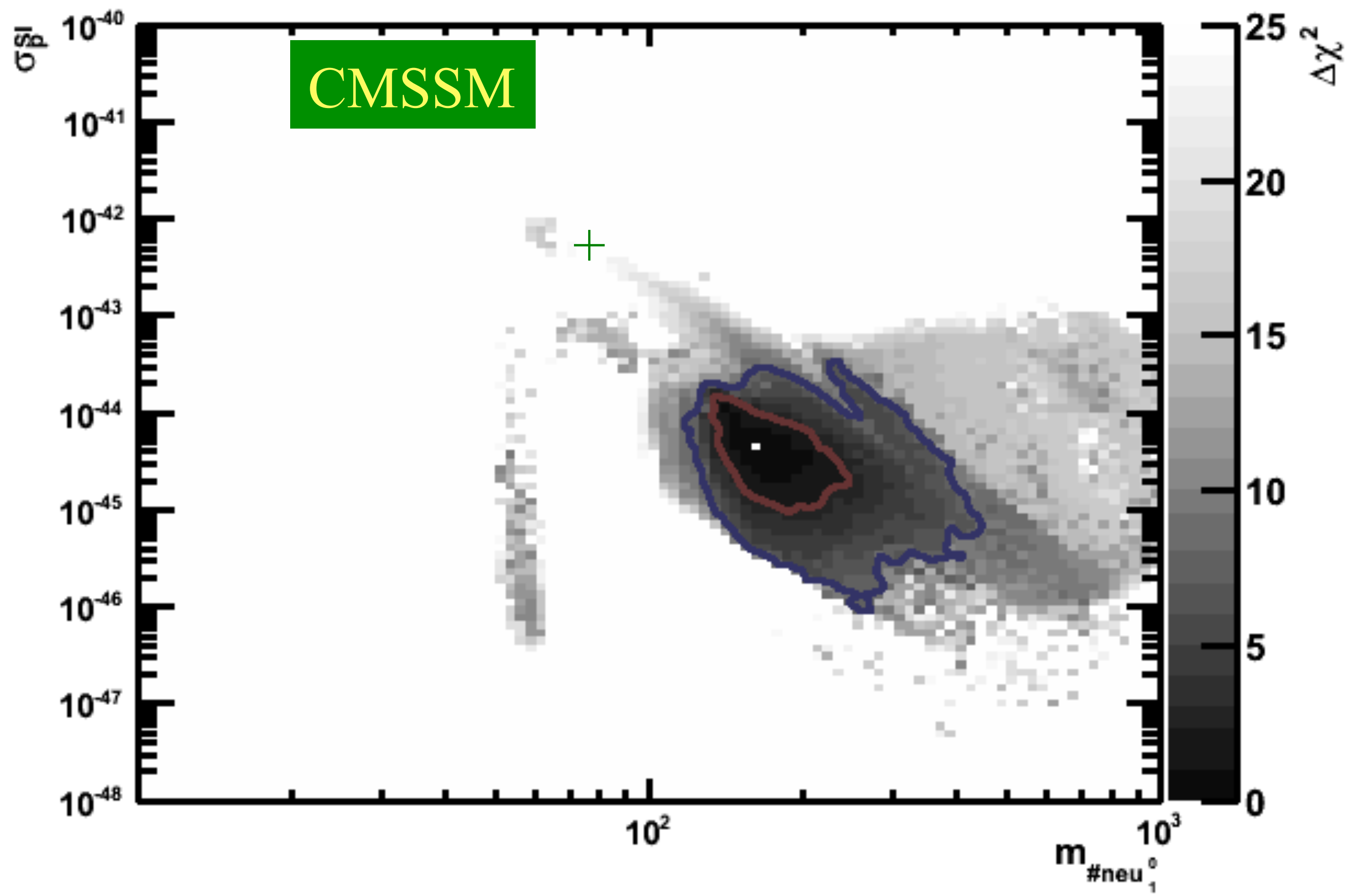
		@ 90% CL	@ 95% CL
LHCb	Observed (expected), 37 pb^{-1}	< 43 (51) $x10^{-9}$	< 56 (65) $x10^{-9}$
D0	World best published, 6.1 fb^{-1} PLB 693 539 (2010)	< 42 $x10^{-9}$	< 51 $x10^{-9}$
CDF	Preliminary, 3.7 fb^{-1} Note 9892	< 36 $x10^{-9}$	< 43 x 10^{-9}

Potential impact of LHCb, CDF and D0

O.Buchmueller, JE et al: in preparation

Post-ATLAS 0L

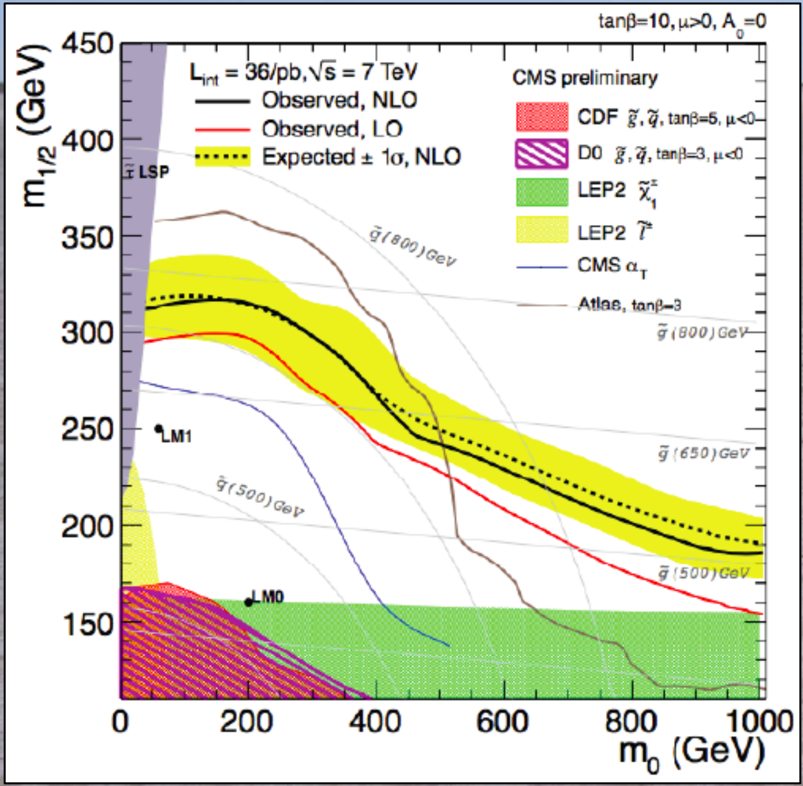
Dark Matter Scattering Revisited

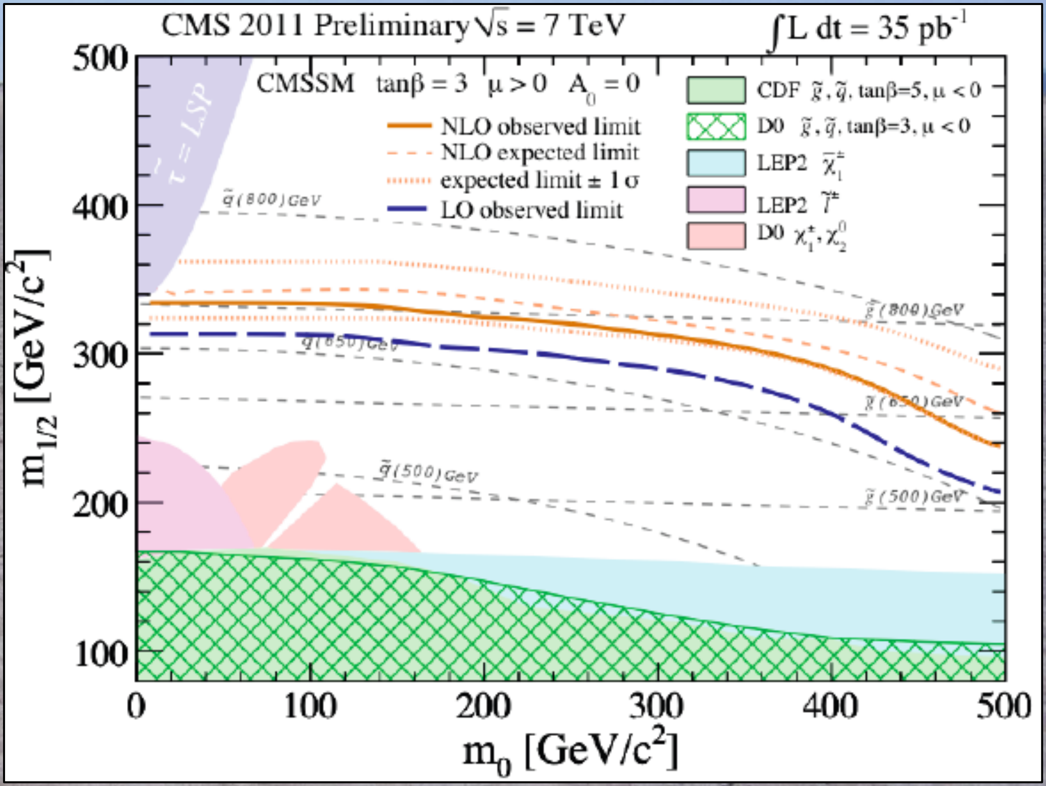


New results from Xenon100 eagerly expected

O.Buchmueller, JE et al: in preparation

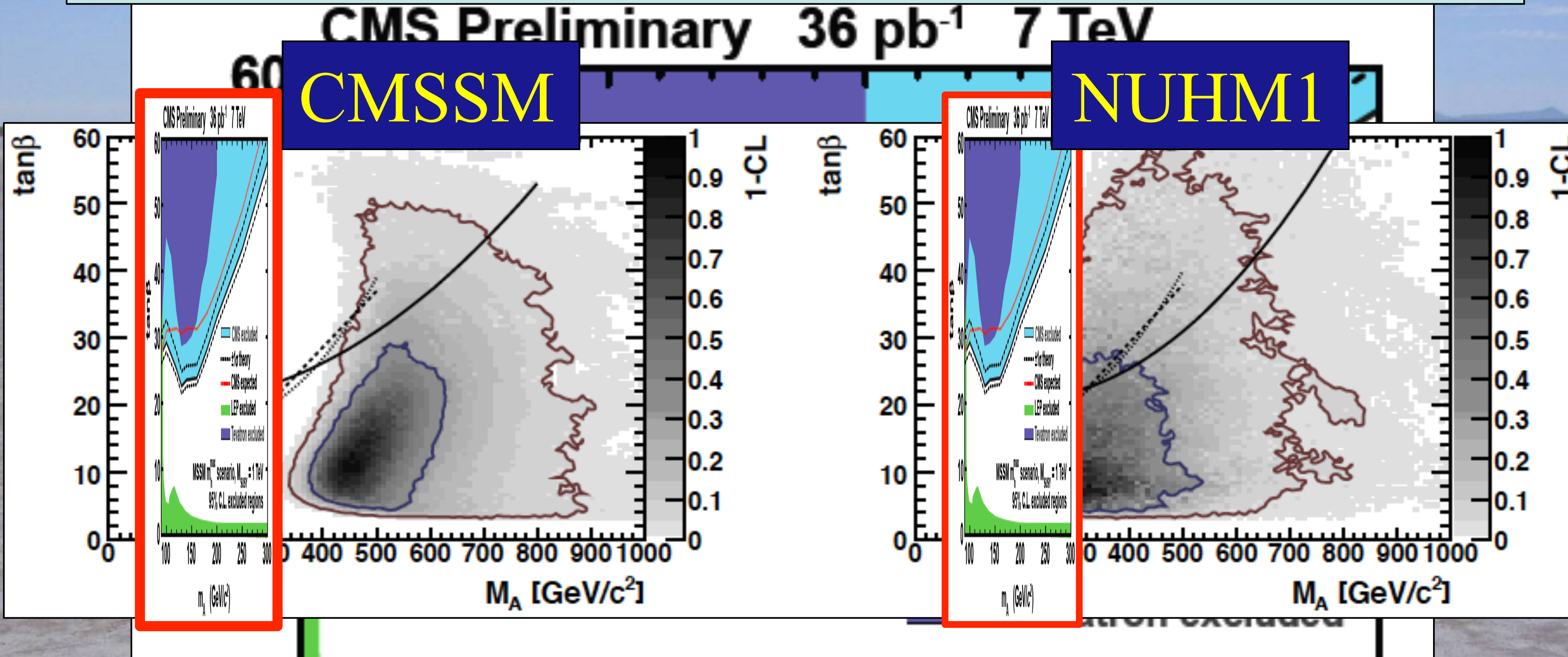
New CMS Jet + MET Analyses





Less robust for discovery: greater exclusion reach

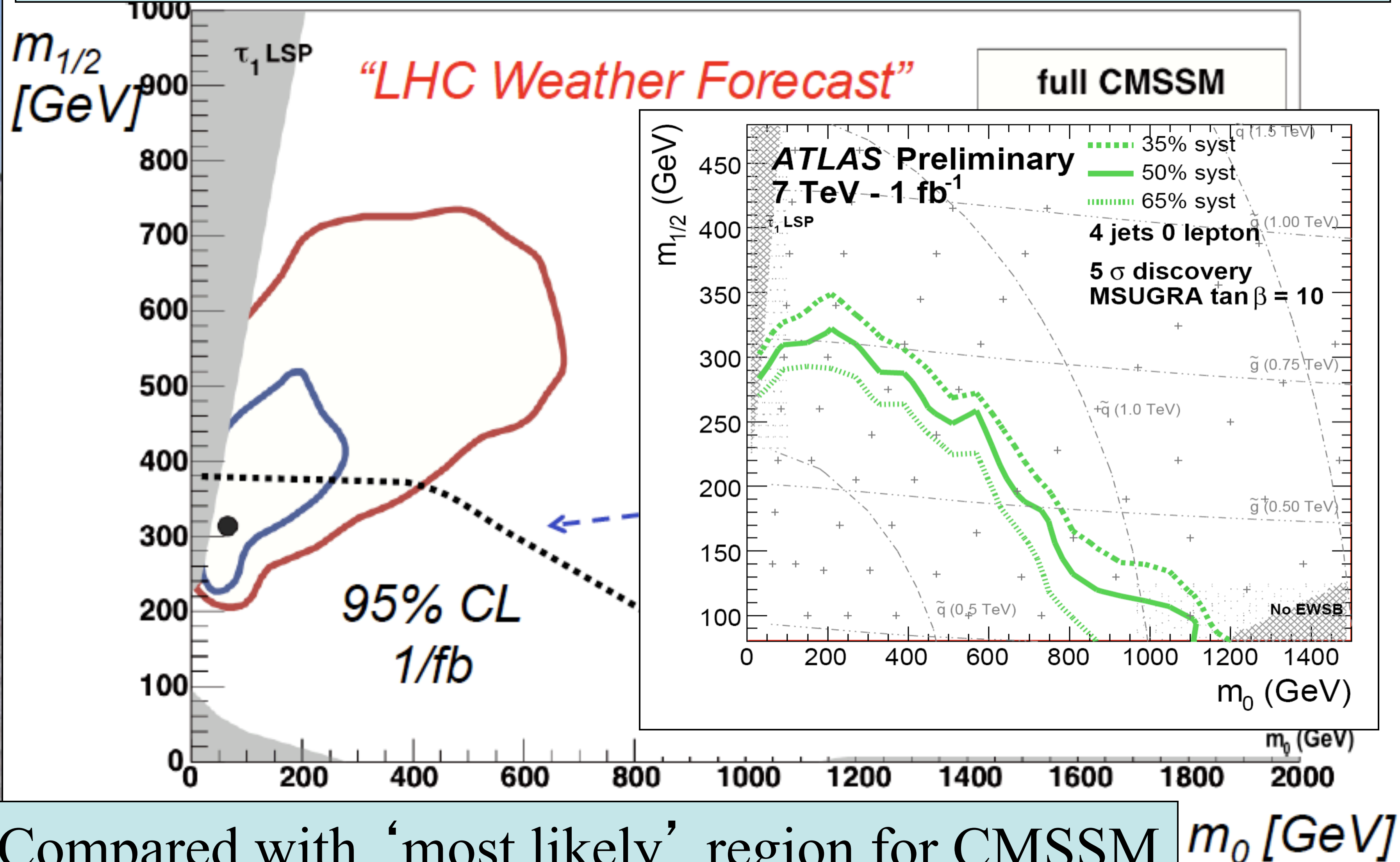
Limits on Heavy MSSM Higgses



Preferred regions in pre-LHC fits

LHC searches have little impact – so far!

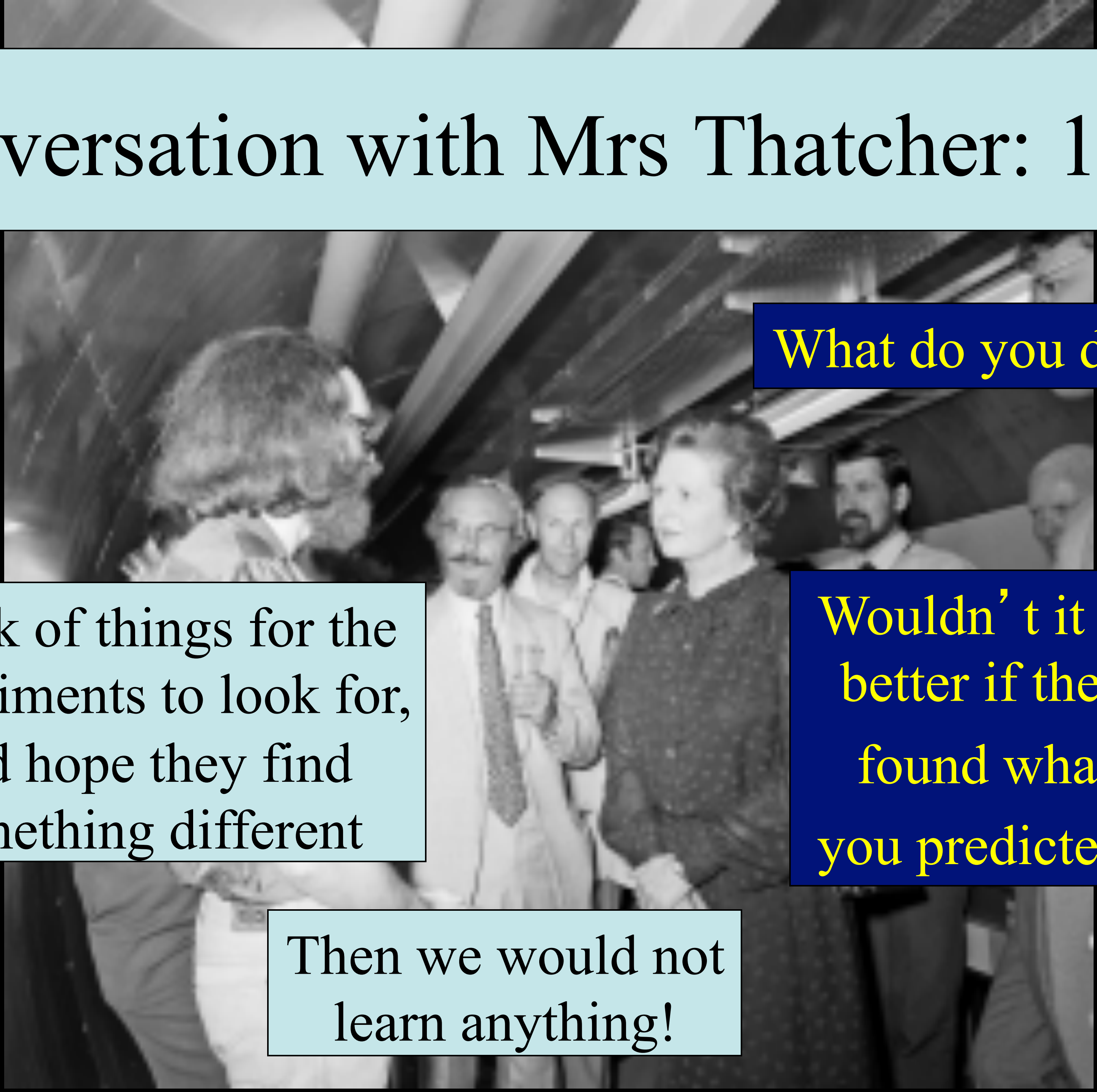
LHC Sensitivity @ 7 TeV



Compared with 'most likely' region for CMSSM

O.Buchmueller, JE et al: arXiv:0808.4128

Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn’t it be better if they found what you predicted?

Then we would not learn anything!