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
- Minimal supergravity also predicts gravitino mass
  - $m_{3/2} = m_0$, $B_\mu = A_\lambda - m_0$

Renormalization of Susy Breaking Parameters

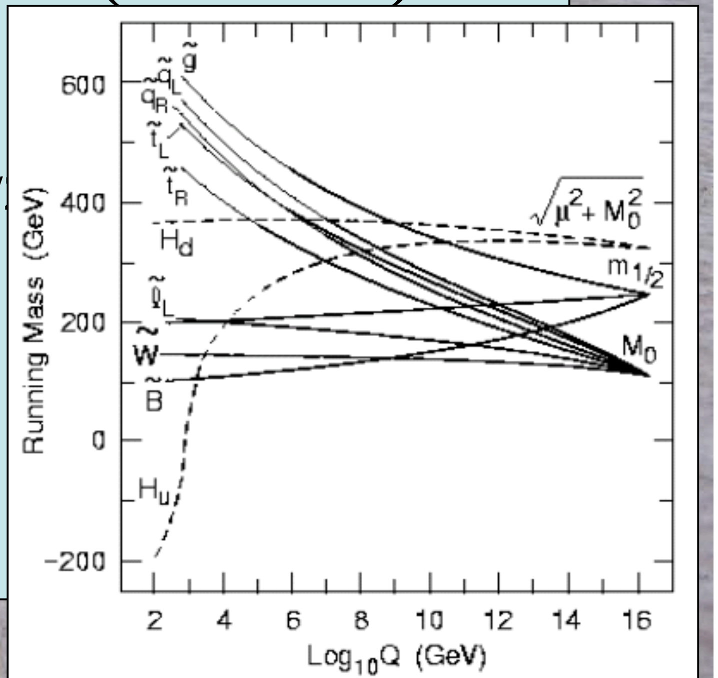
- After cancellation of quadratic divergences: renormalized logarithmically:

  gaugino masses: d $M_a/dt \sim \beta_a M_a$

  scalar masses²: $$\frac{\partial m_{0_i}^2}{\partial t} = \frac{1}{16\pi^2}[\lambda^2(m_0^2 + A_\lambda^2) - g_a^2 M_a^2]$$
- Assuming universal input parameters (CMSSM)
- Solutions at low energy scales Q:

  $$M_a (Q) = (\alpha_a / \alpha_{GUT})\ m_{1/}$$

  $$m_{0_i}^2 = m_0^2 + C_i m_{1/2}^2$$
- Gluino heavier than photino, wino
- Squarks heavier than sleptons



Mass Renormalizations

- **Assuming universality at the GUT scale**
- Gaugino masses:
  - $M_a = (\alpha_a / \alpha_{GUT})\, m_{1/2}$, e.g., $\rightarrow M_2 / M_3 = \alpha_2 / \alpha_3$
- Squark and slepton masses:
  - Squark mass^2: $m_0^2 + 6\, m_{1/2}^2$
  - Left-handed slepton mass^2: $m_0^2 + 0.5\, m_{1/2}^2$
  - Right-handed slepton mass^2: $m_0^2 + 0.15\, m_{1/2}^2$
- Minimal flavour violation (MFV):
  - Flavour mixing of squarks and sleptons induced by CKM, neutrino mixing

Electroweak Symmetry Breaking

- Could be triggered by renormalization effects:

$$\frac{\partial m^2_{0_i}}{\partial t} = \frac{1}{16\pi^2}[\lambda^2(m_0^2 + A_\lambda^2) - g_a^2 M_a^2]$$

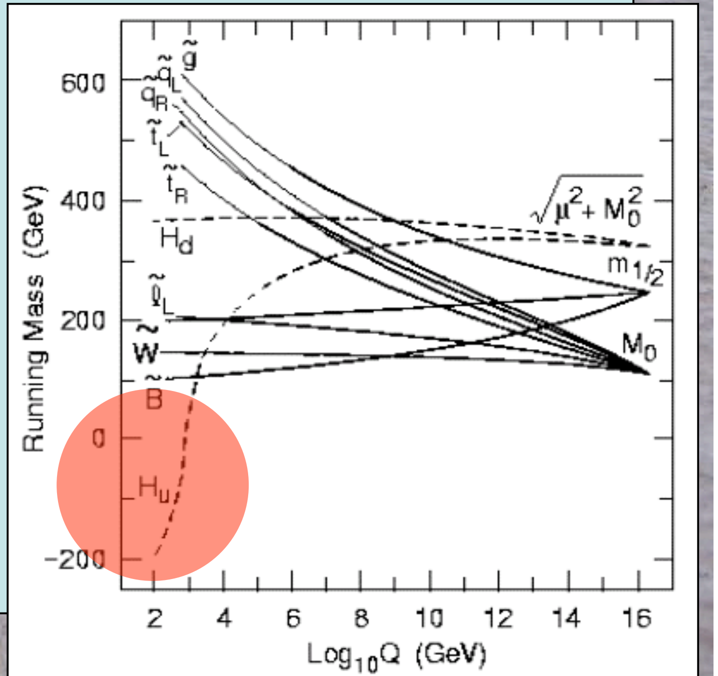
- Driven by large Yukawa coupling of top quark:

$$\frac{m_W}{m_P} = exp(\frac{-\mathcal{O}(1)}{\alpha_t}) : \quad \alpha_t \equiv \frac{\lambda_t^2}{4\pi}$$

- Higgs mass^2 → negative
- Electroweak scale

  naturally ~ 100 GeV

  for m_t ~ 60 to 200 GeV



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

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 detection)

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 300 GeV

- Indirect constraints

  Higgs > 114 GeV, b -> s γ

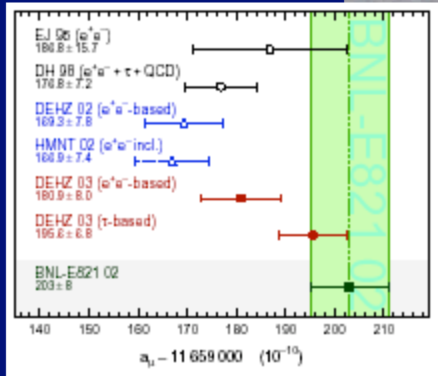
- Density of dark matter

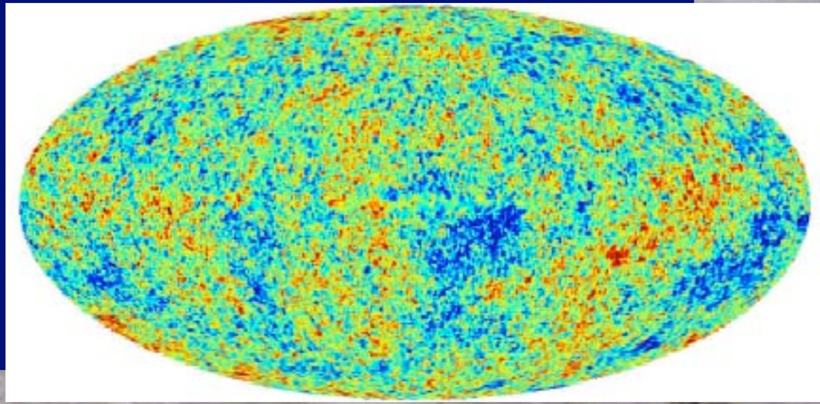
  lightest sparticle χ:

WMAP:

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

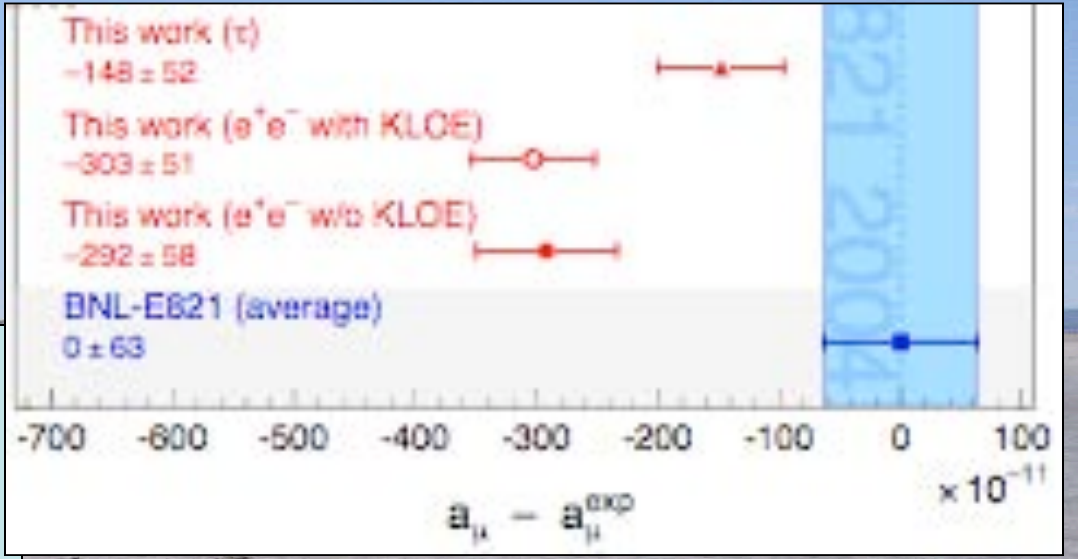
g_μ - 2

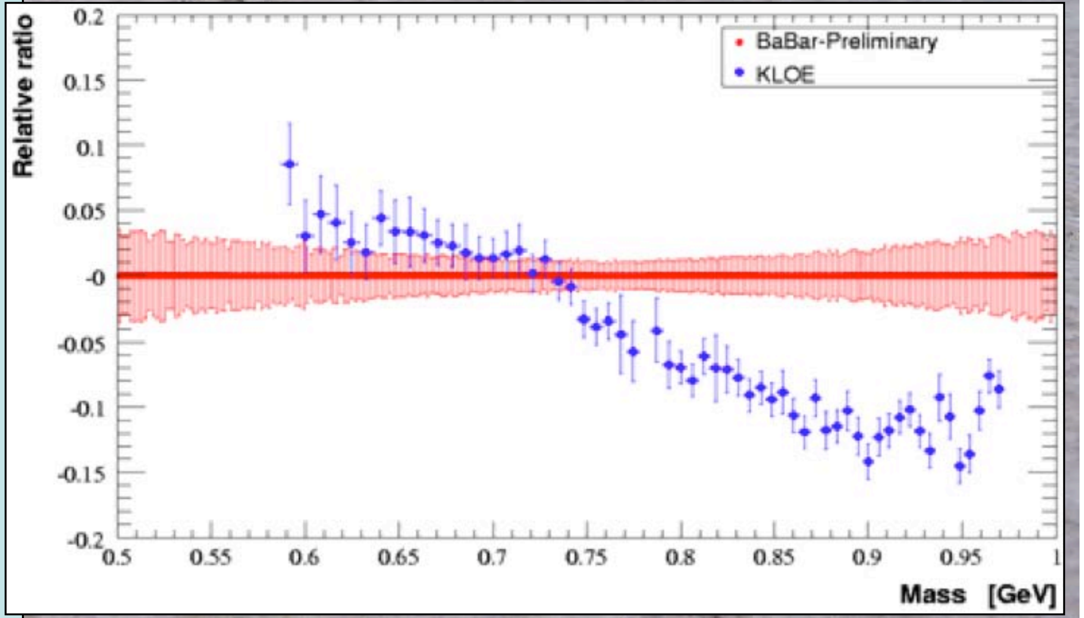




Quo Vadis g_μ - 2?

- Older e^+e^- data show discrepancy
  - now 3.4 σ
- Disagreement with τ decay data
  - Discrepancy ~ 2 σ
- New BABAR e^+e^- data apparently disagree with previous e^+e^- data
  - Agree with τ decay data
- Soon to be finalized?





Current Constraints on CMSSM

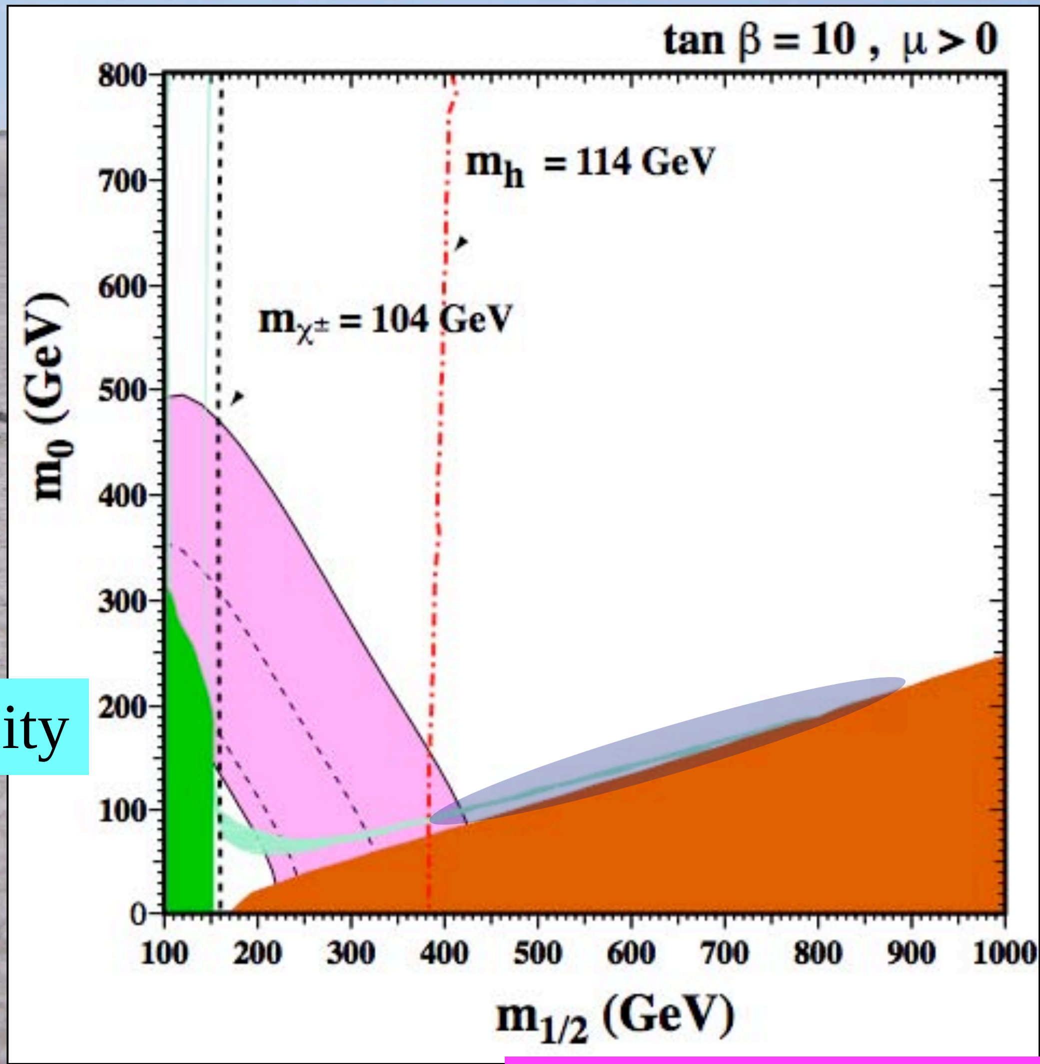
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

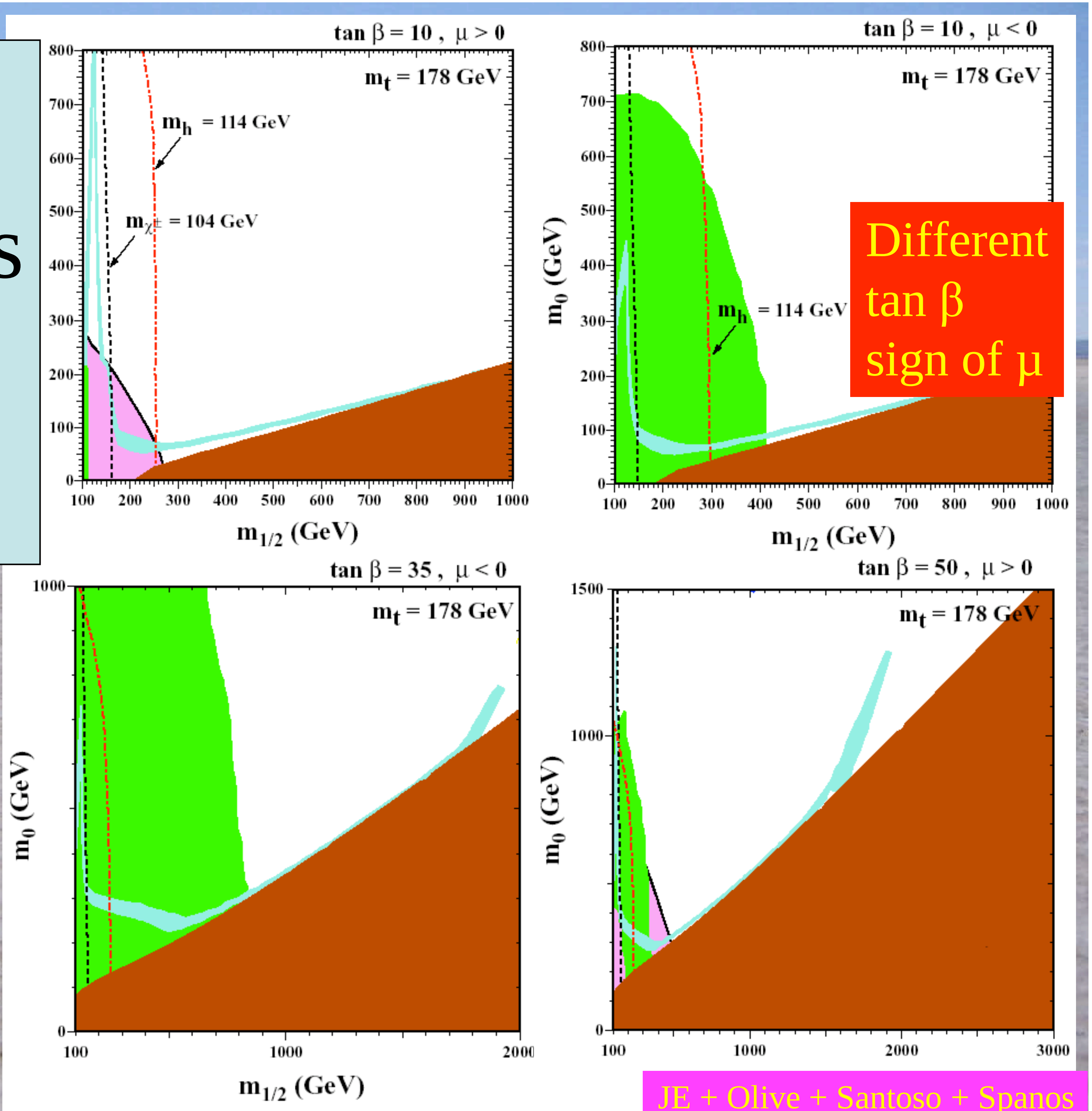
WMAP constraint on relic density

Preferred (?) by latest g - 2



JE + Olive + Santoso + Spanos

Current Constraints on CMSSM



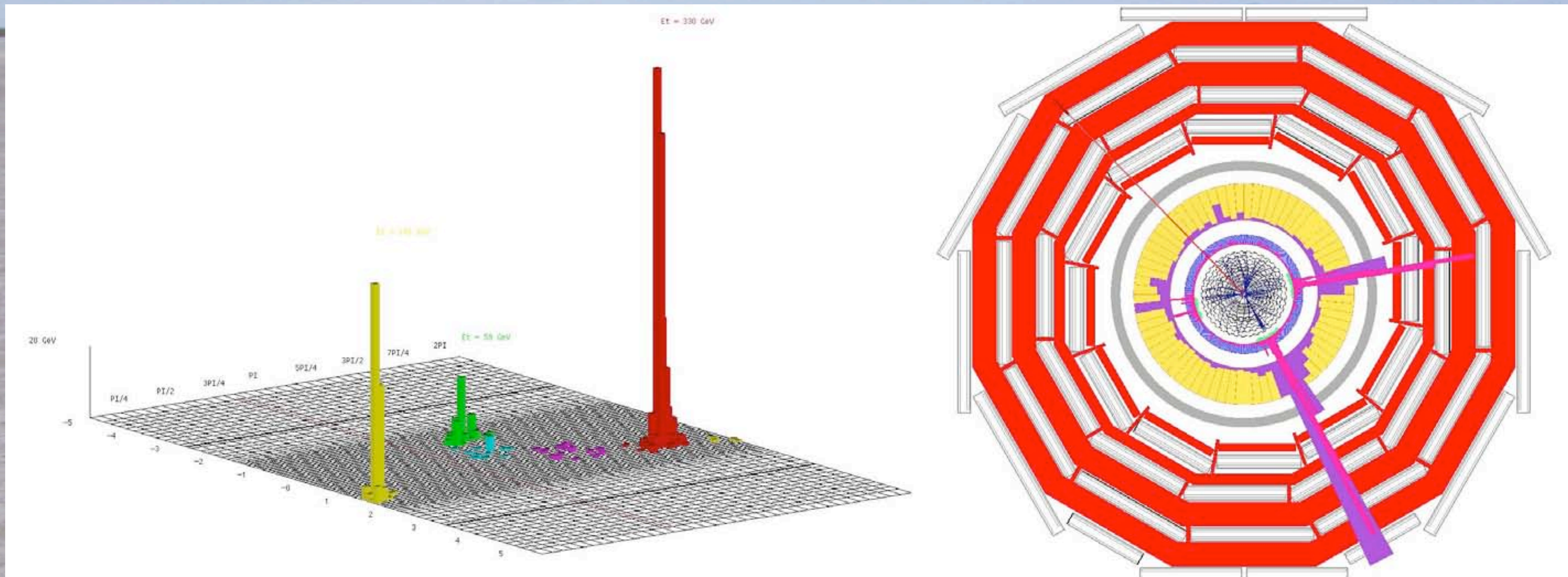
Different $\tan\beta$
sign of μ

Impact of Higgs constraint reduced if larger m_t

Focus-point region far up

JE + Olive + Santoso + Spanos

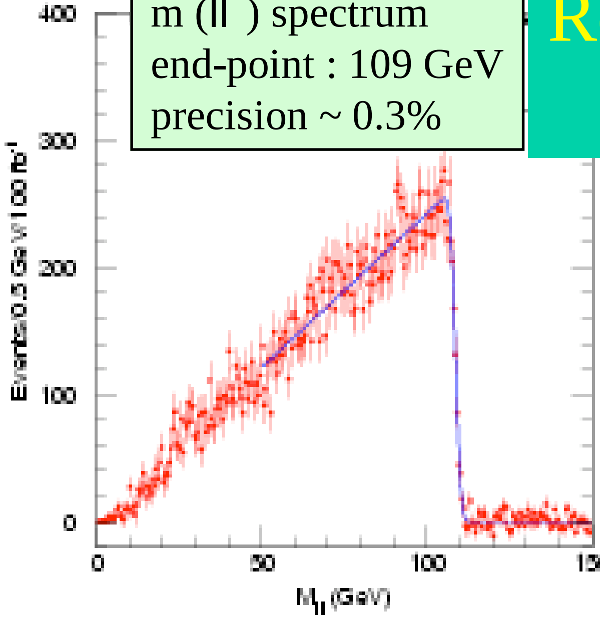
Classic Supersymmetric Signature



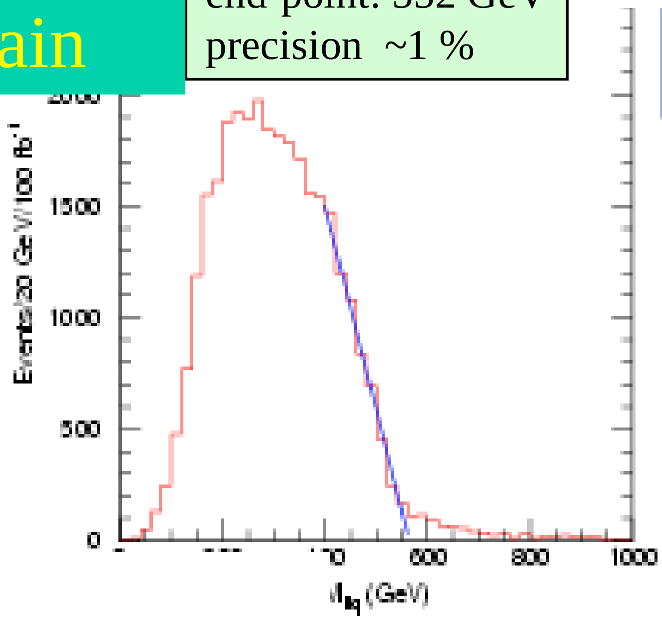
Missing transverse energy
carried away by dark matter particles

Reconstruction of `Typical' Sparticle Decay Chain

m (ll) spectrum
end-point : 109 GeV
precision ~ 0.3%



m (ll j)^{min} spectrum
end-point: 552 GeV
precision ~1 %

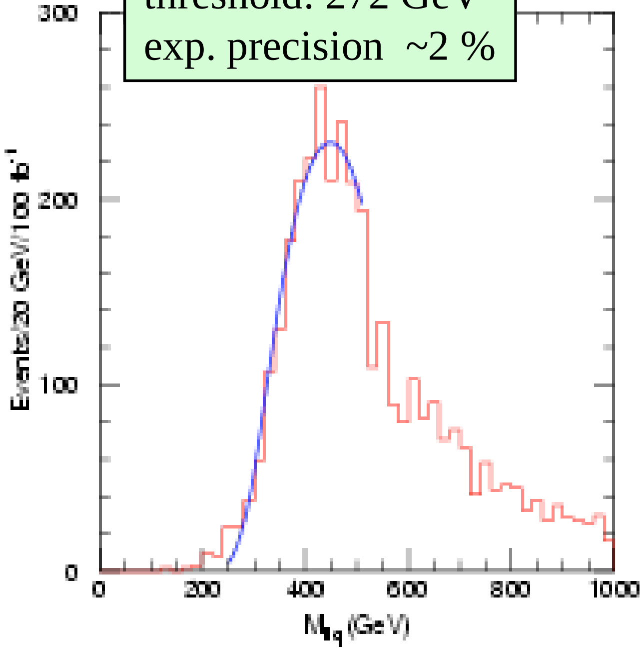


$\tilde{q}_L \rightarrow q\ \chi^0_2$

$\quad \hookrightarrow \tilde{l}_R\ l$

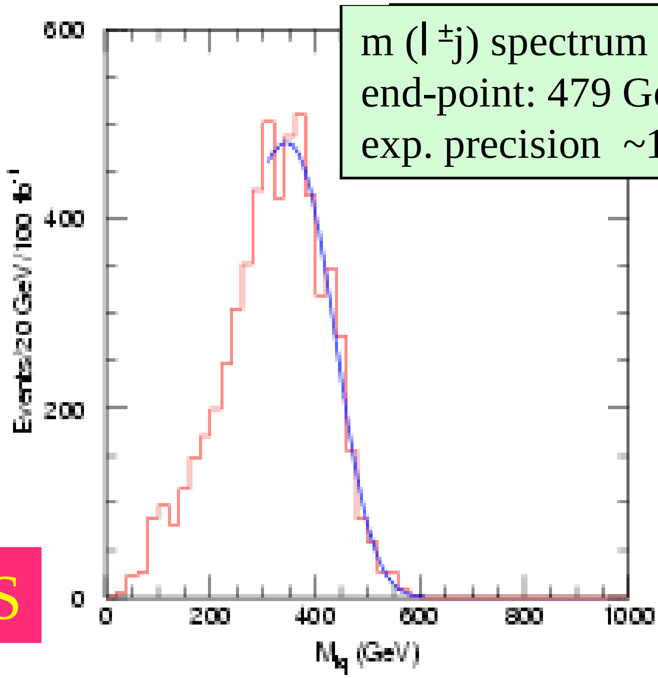
$\qquad \hookrightarrow l\ \chi^0_1$

m (ll j)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %



M_{squark} = 690
$M_{\chi^0_2}$ = 232
$M_{slepton}$ = 157
$M_{\chi^0_1}$ = 121
(GeV)

m (l $^{\pm}$j) spectrum
end-point: 479 GeV
exp. precision ~1 %



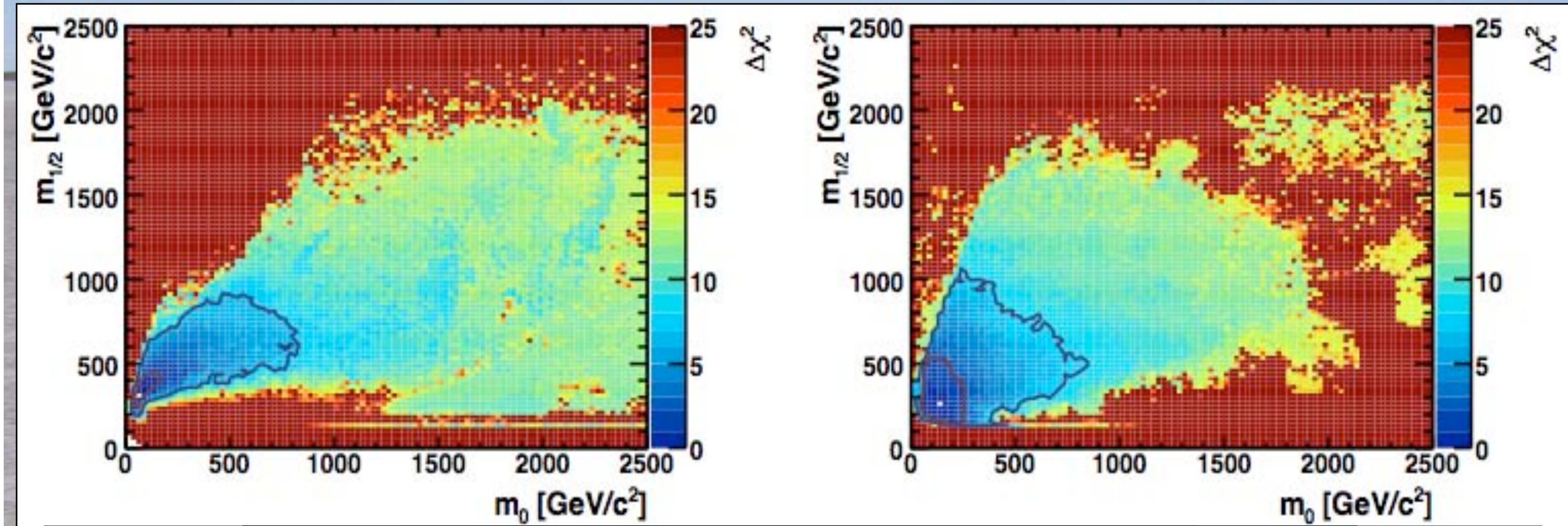
ATLAS

Global Fit to Supersymmetry

- Precision electroweak data
- Cold dark matter density, g_μ - 2
- Use frequentist approach to calculate global likelihood function
- Apply to CMSSM and NUHM1
- Relatively light sparticles favoured

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

The $(m_0, m_{1/2})$ Planes in the CMSSM and the NUHM1



CMSSM

Low $(m_0, m_{1/2})$ preferred

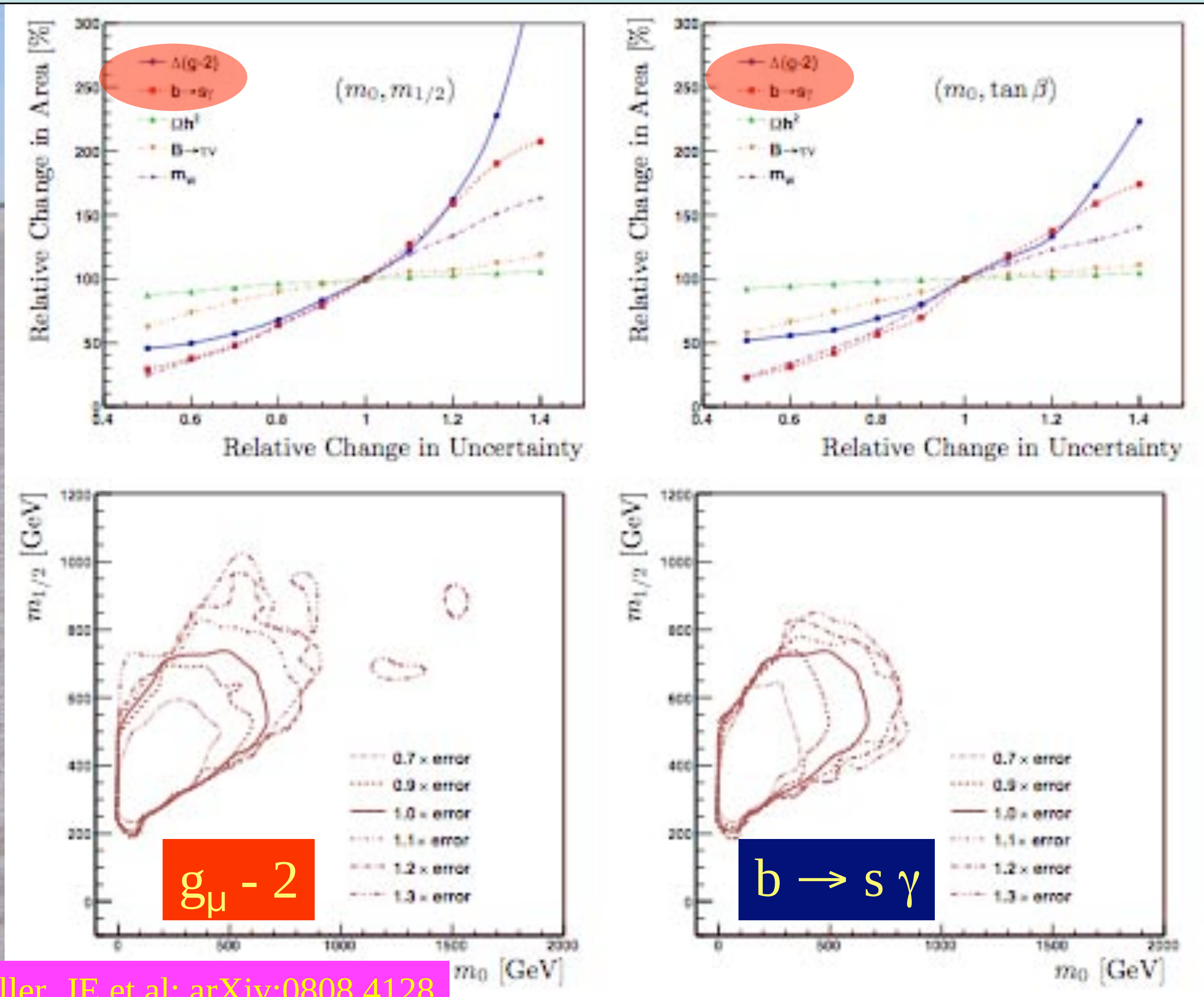
NUHM1

[stau coannihilation region]

Focus-point region disfavoured

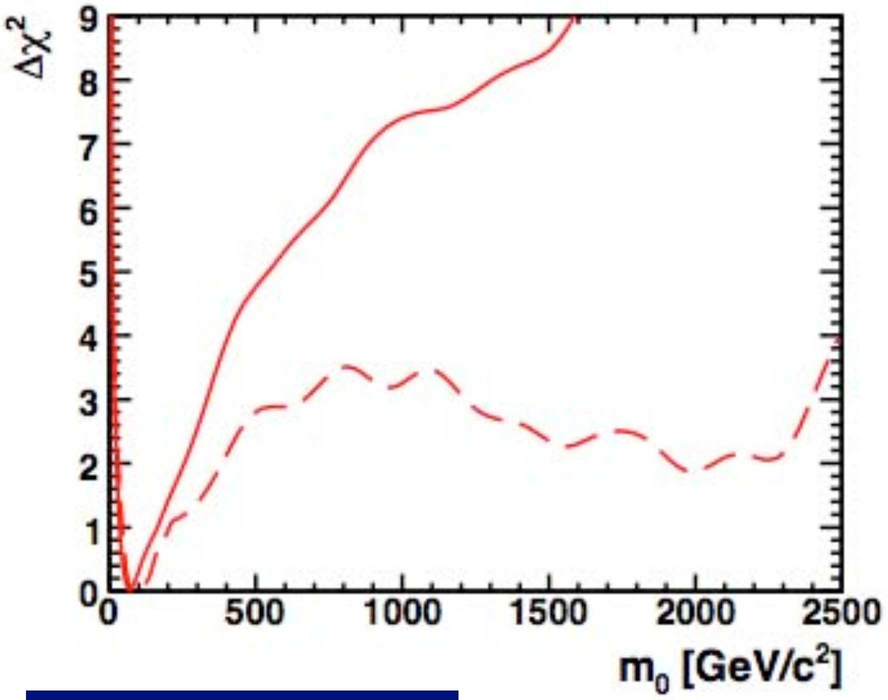
O.Buchmueller, JE et al: arXiv:0907.5568

Sensitivities to Constraints

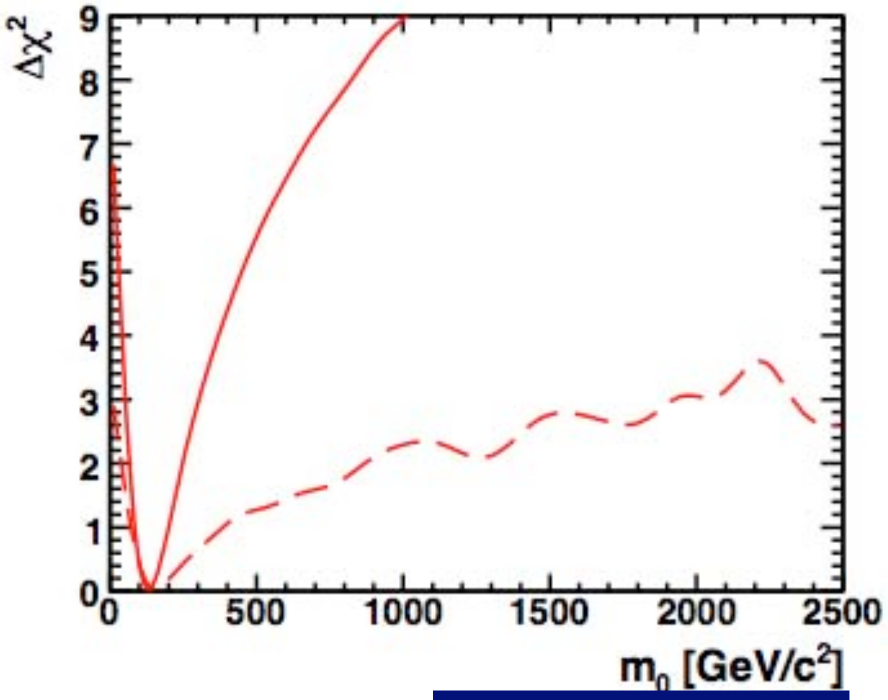


O.Buchmueller, JE et al: arXiv:0808.4128

What Happens if g_μ - 2 Dropped?



CMSSM



NUHM1

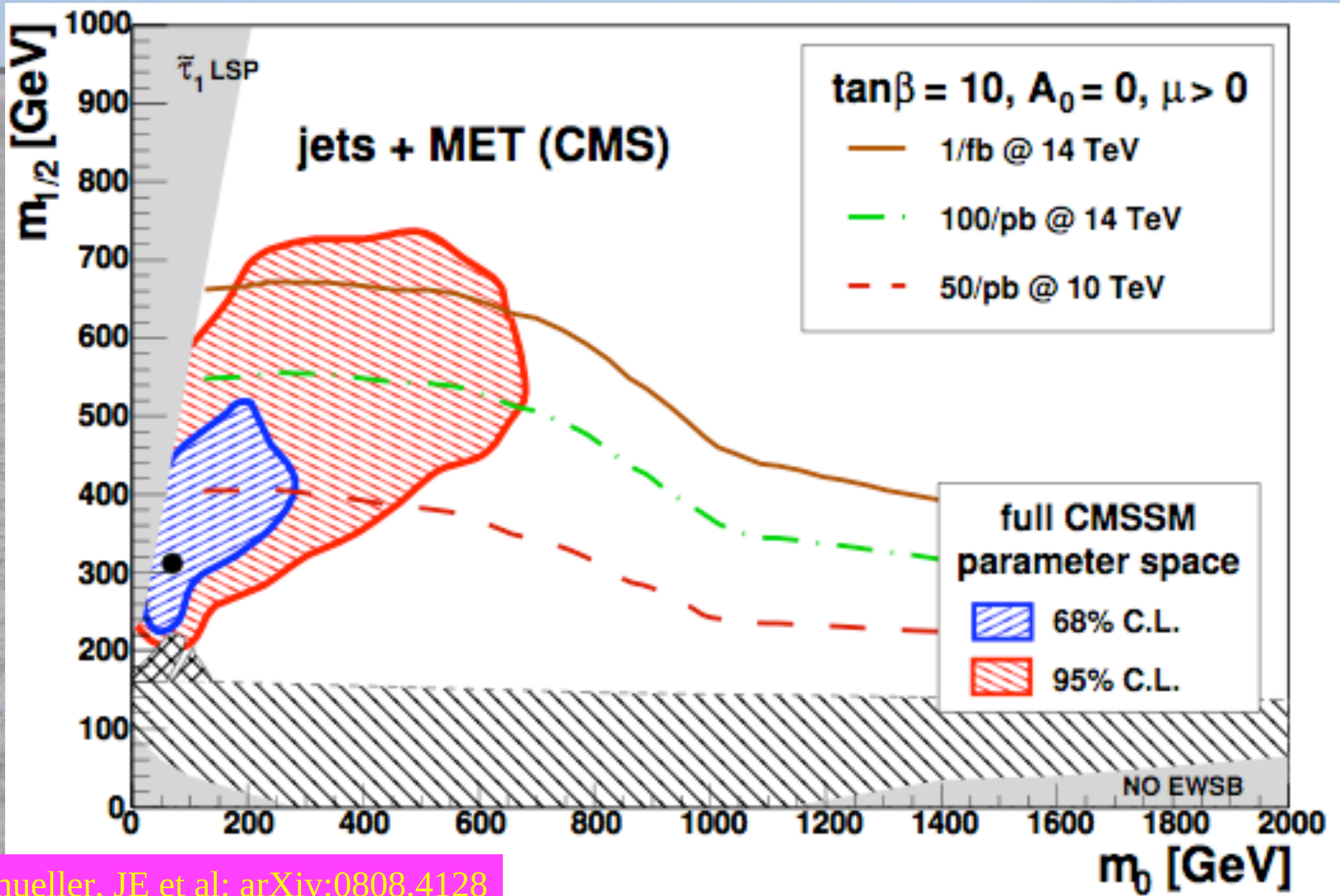
Solid lines: with g_μ - 2

Dashed lines: without g_μ - 2

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

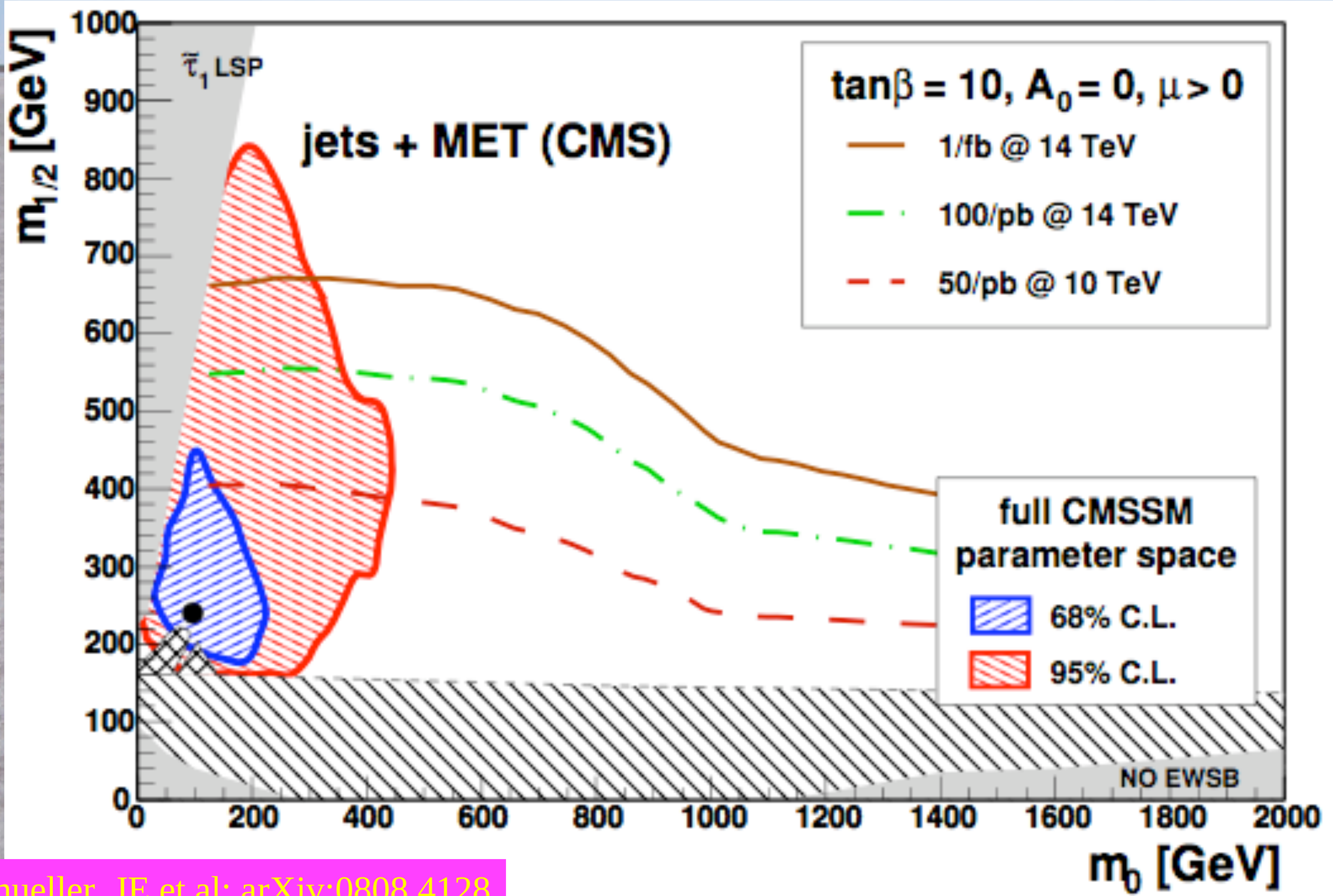
O.Buchmueller, JE et al: arXiv:0907.5568

How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

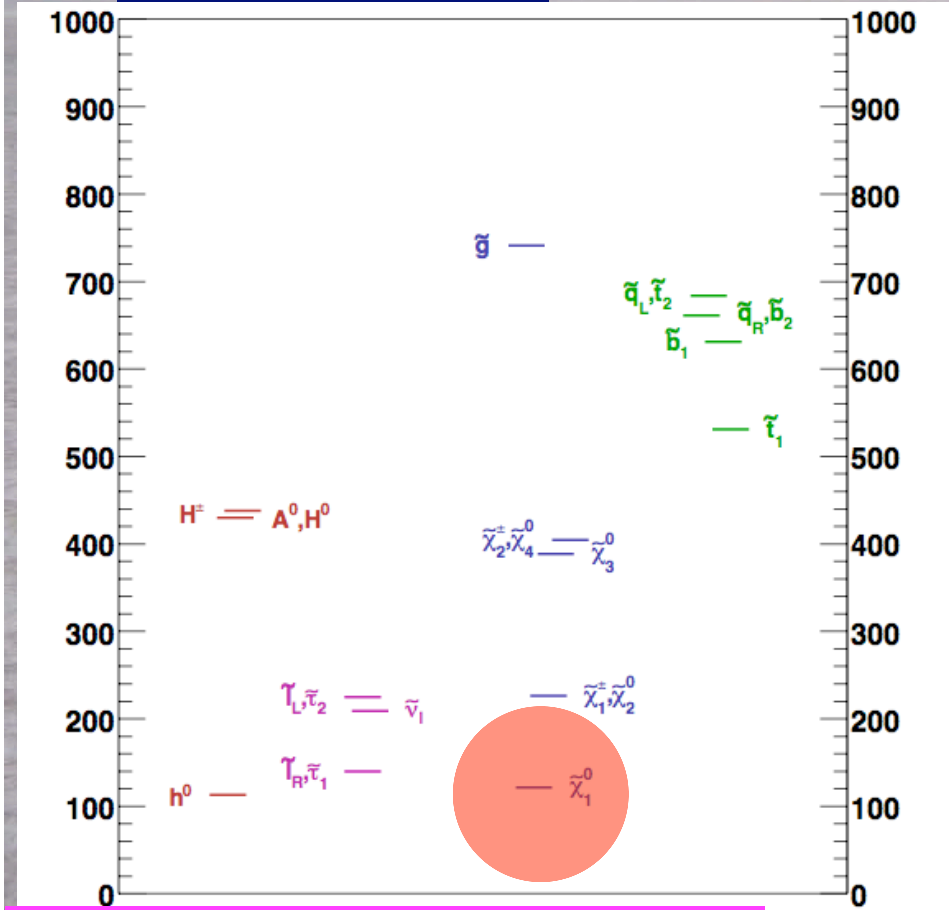
How Soon Might the NUHM1 be Detected?



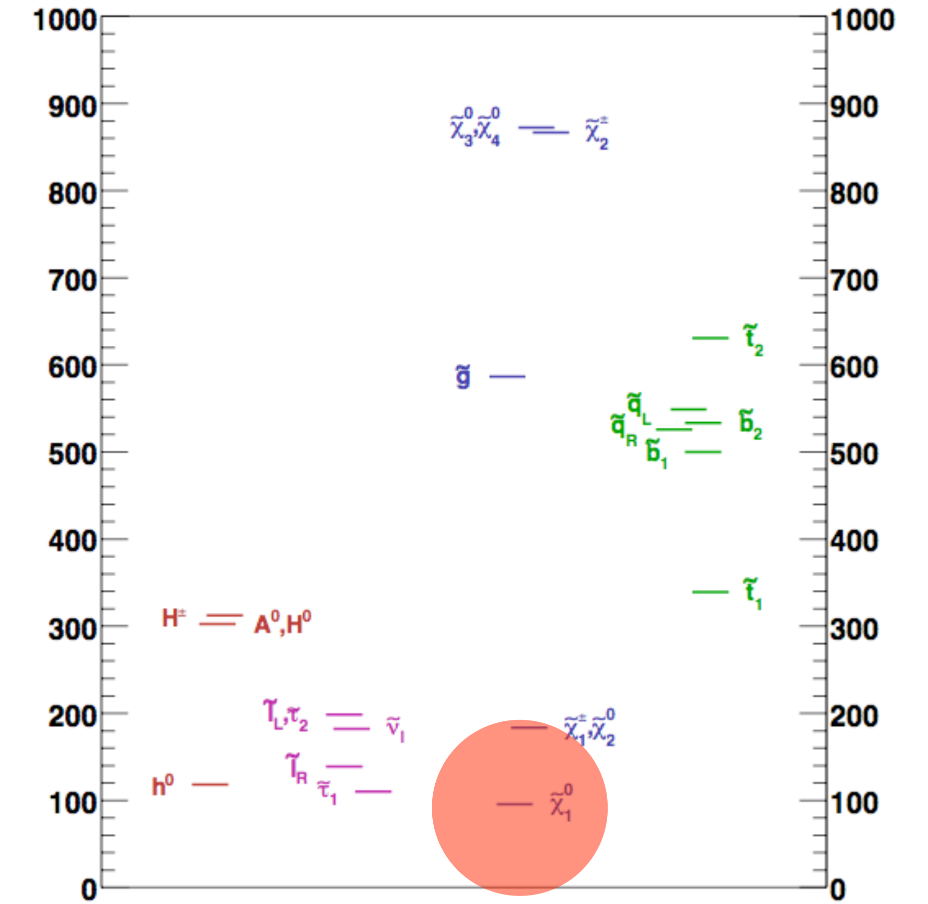
O.Buchmueller, JE et al: arXiv:0808.4128

Best-Fit Spectra

CMSSM

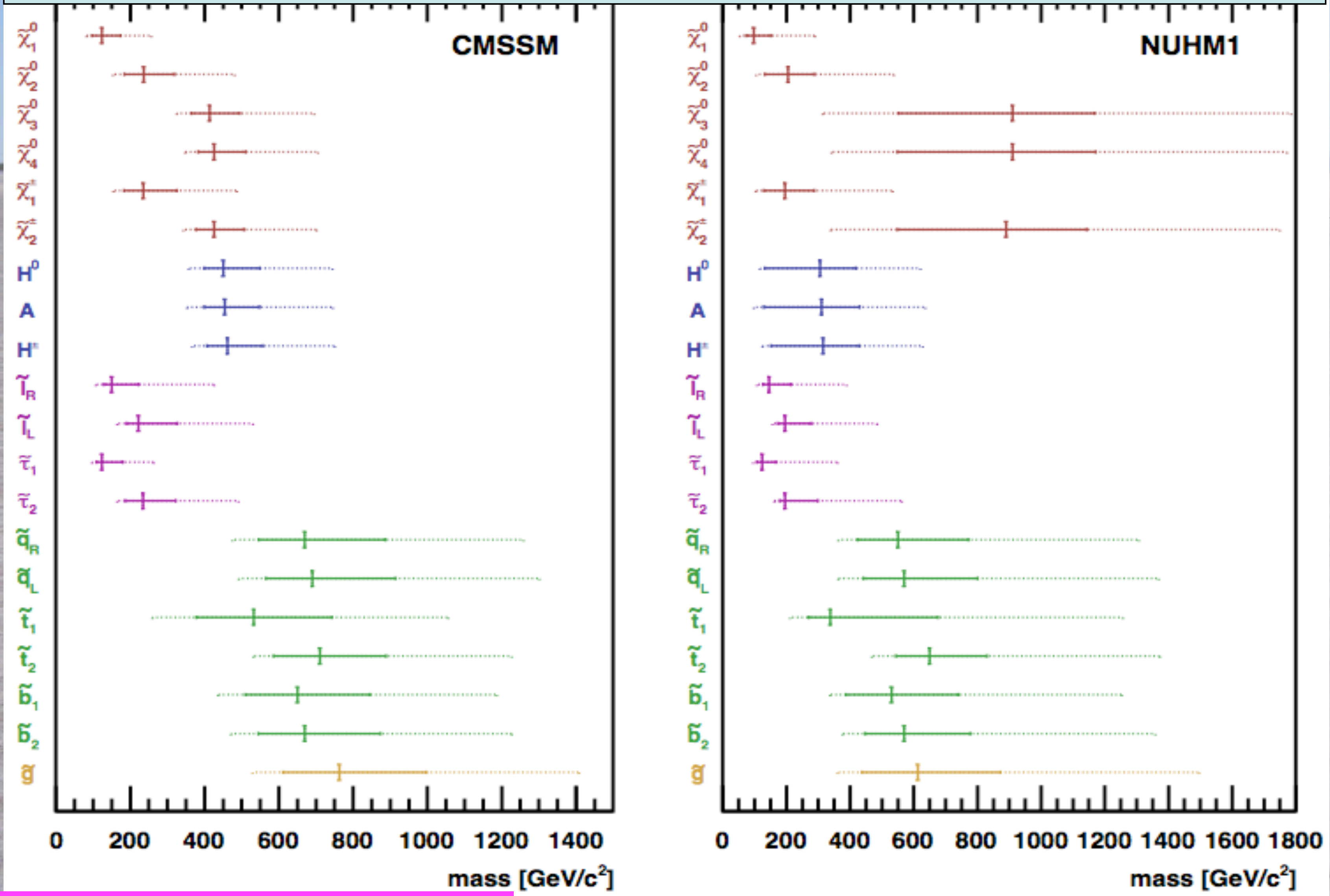


NUHM1



O.Buchmueller, JE et al: arXiv:0808.4128

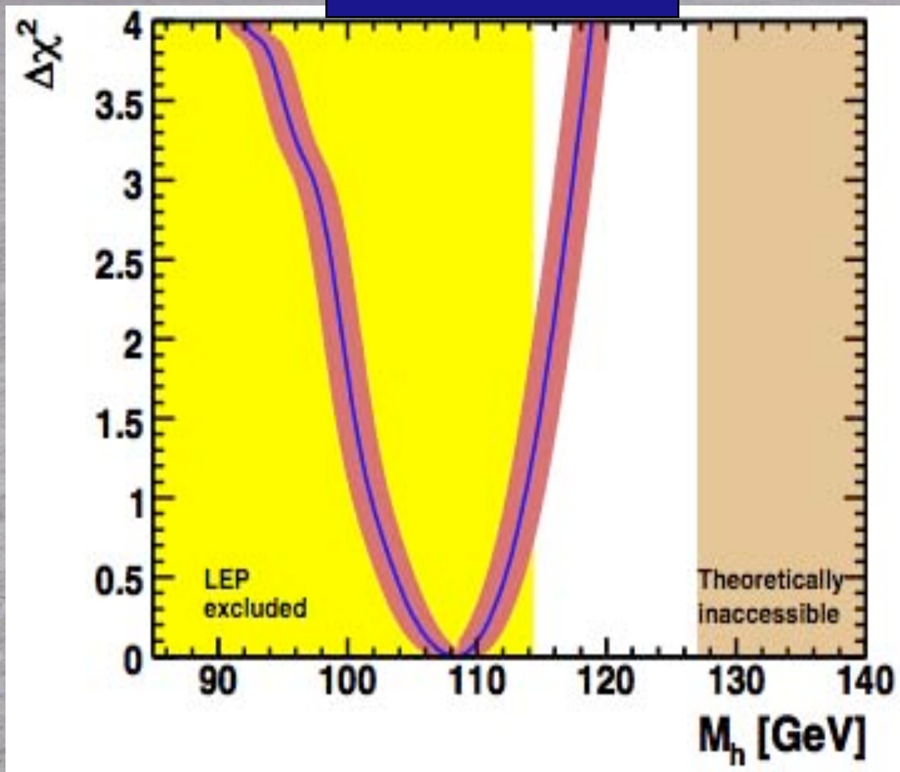
Spectra with likely Ranges



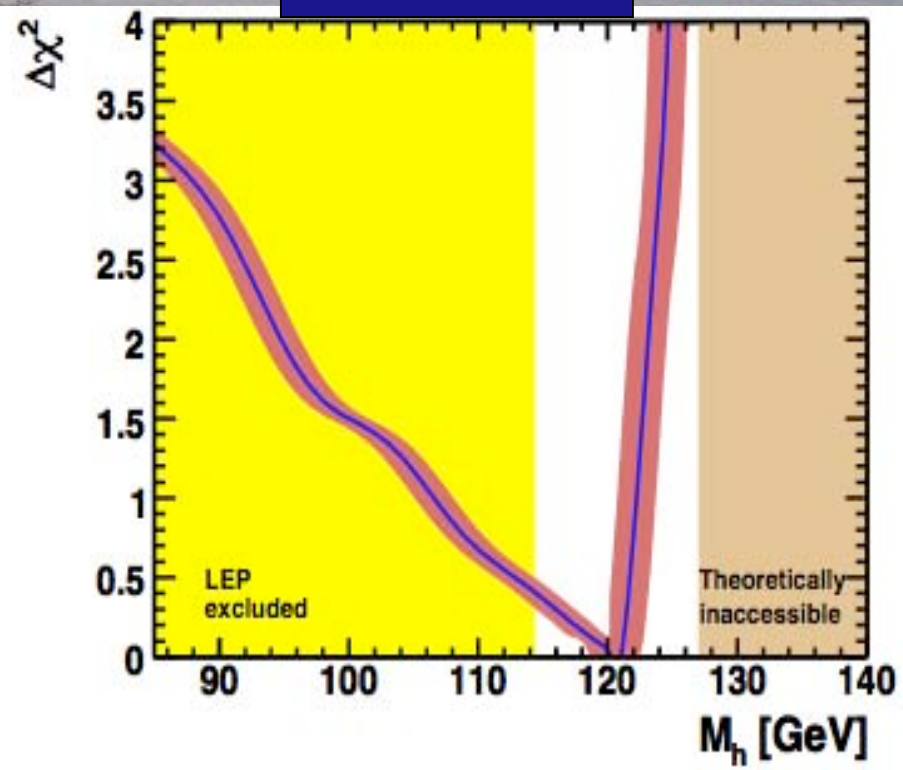
O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for Higgs Mass

CMSSM



NUHM1

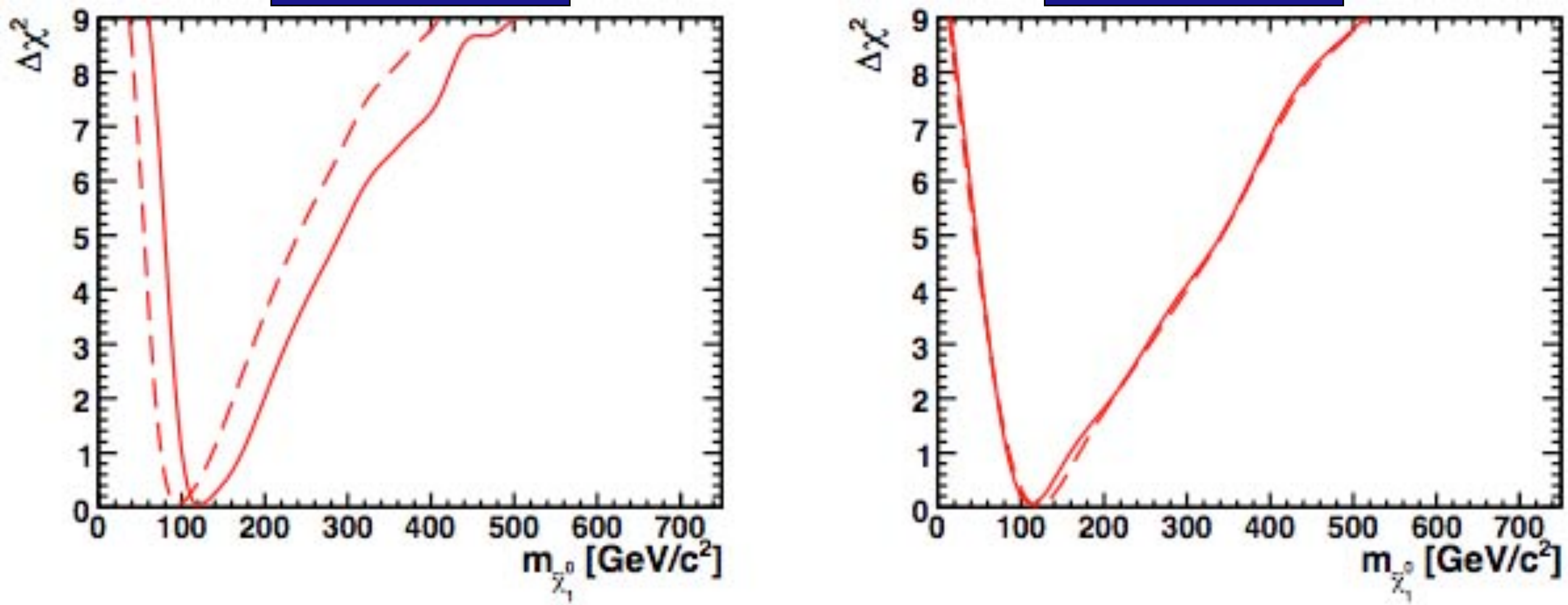


O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for Neutralino Mass

CMSSM

NUHM1

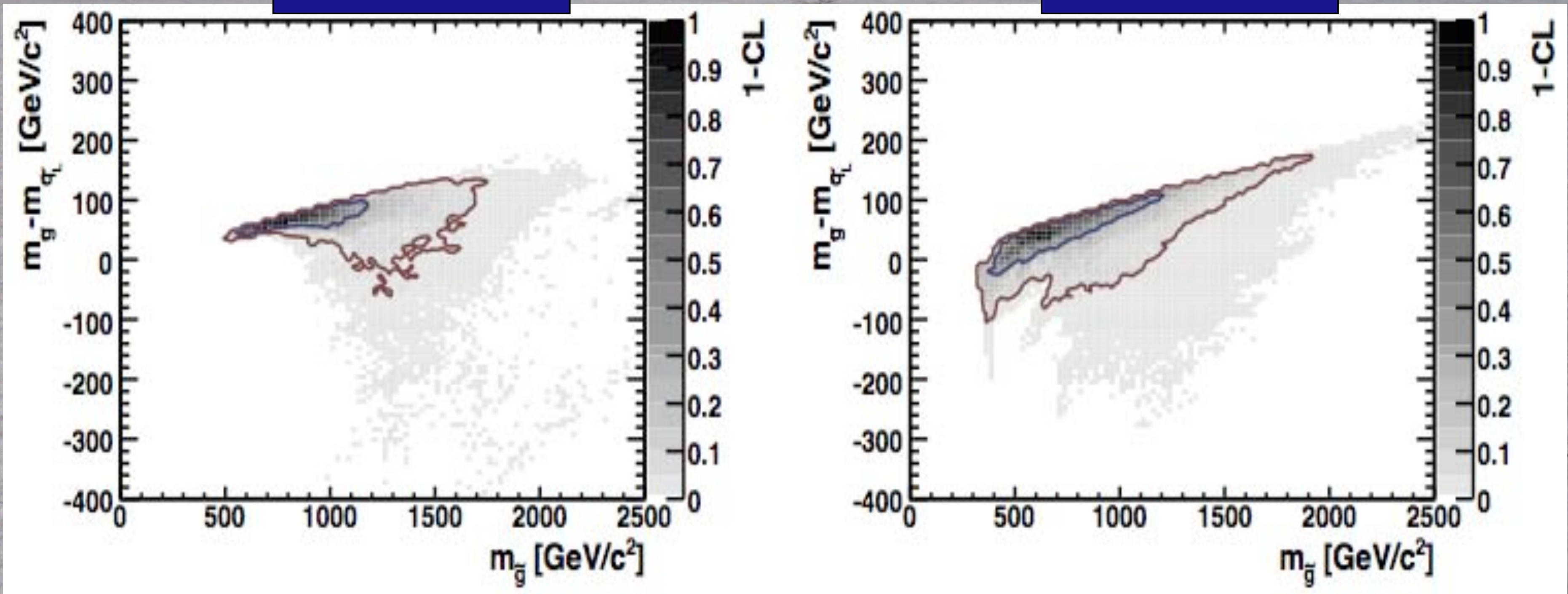


O.Buchmueller, JE et al: arXiv:0907.5568

Correlation between Gluino & Squark Masses

CMSSM

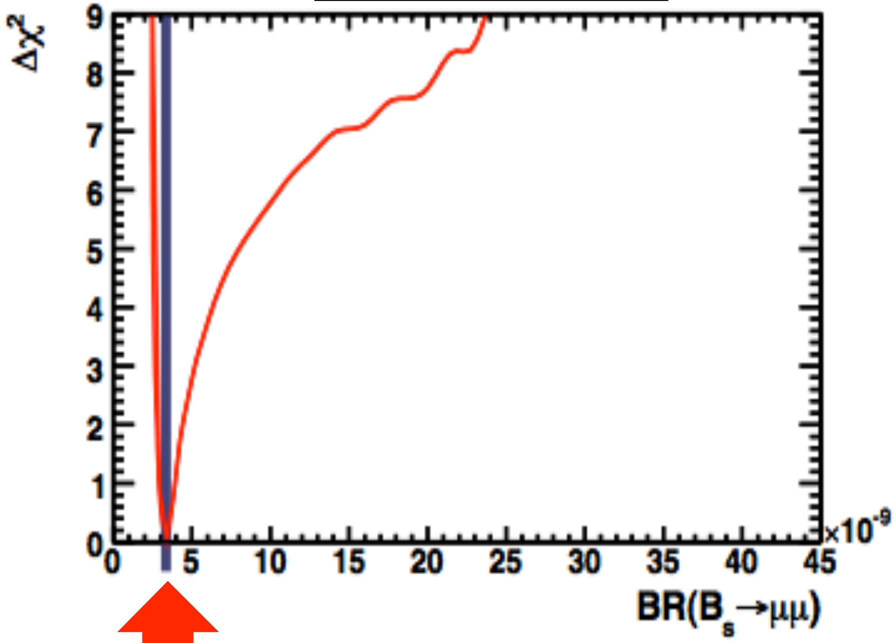
NUHM1



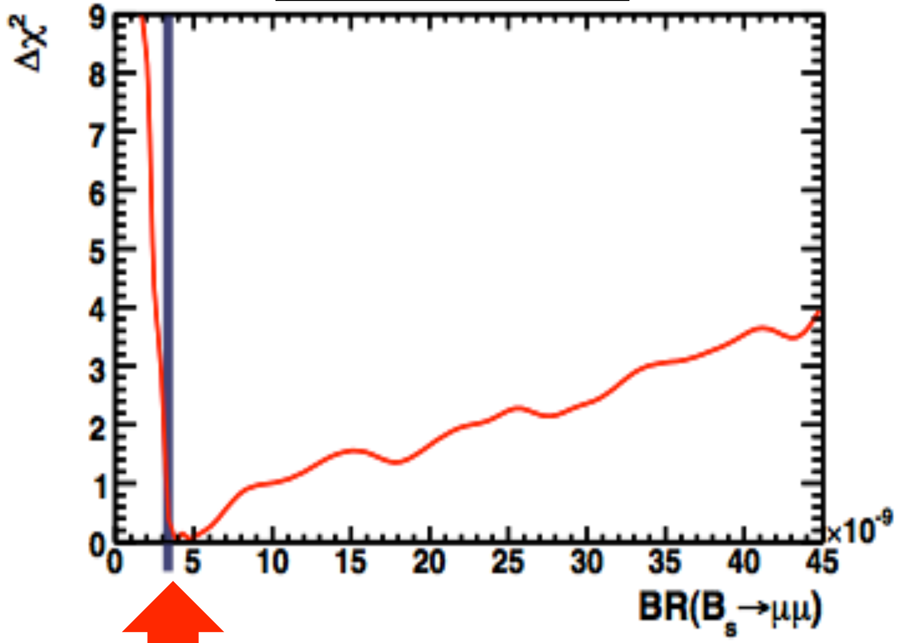
O.Buchmueller, JE et al: arXiv:0907.5568

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

CMSSM



NUHM1

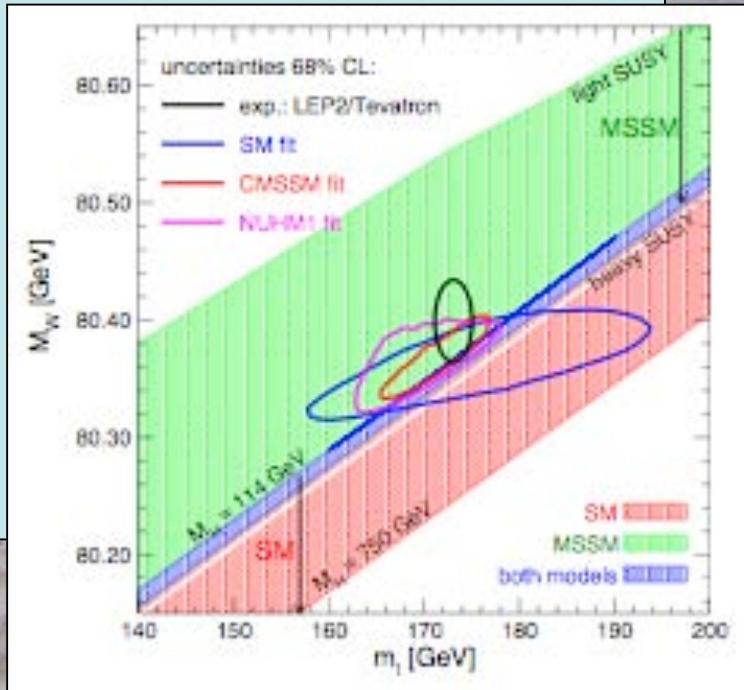


Standard Model prediction

O.Buchmueller, JE et al: arXiv:0907.5568

Precision Electroweak Data

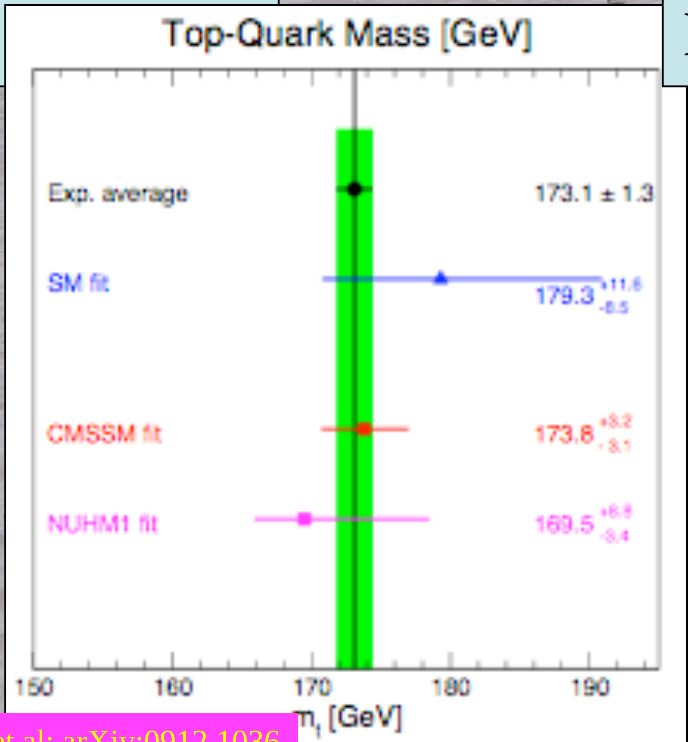
- Revisit indirect information on m_t & m_H
- On the one hand:
  - Restricted range of $m_H < 130$ GeV possible
- On the other hand:
  - Corrections due to sparticles?
- Narrower range of m_t?
- Larger values of m_W?



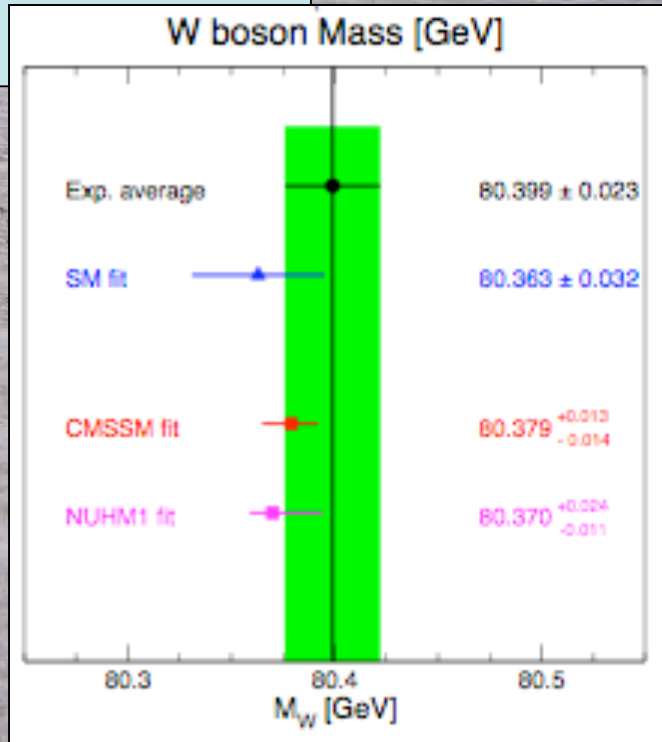
O.Buchmueller, JE et al: arXiv:0912.1036

Precision Electroweak Data

Measurement of m_t
Fits to m_t in
Standard Model
CMSSM (red)
NUHM1



Measurement of m_W
Fits to m_W in
Standard Model
CMSSM (red)
NUHM1



O.Buchmueller, JE et al: arXiv:0912.1036

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in core of Sun or Earth

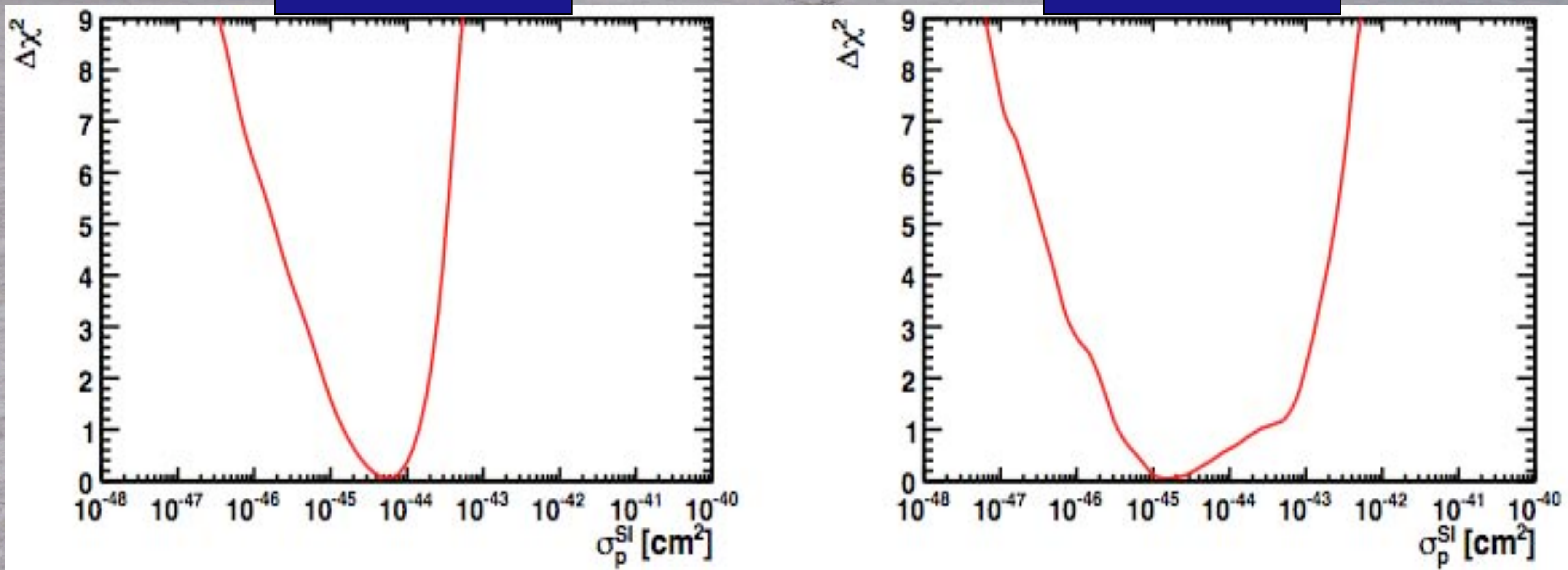
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

Likelihood Function for Spin-Independent Dark Matter Scattering

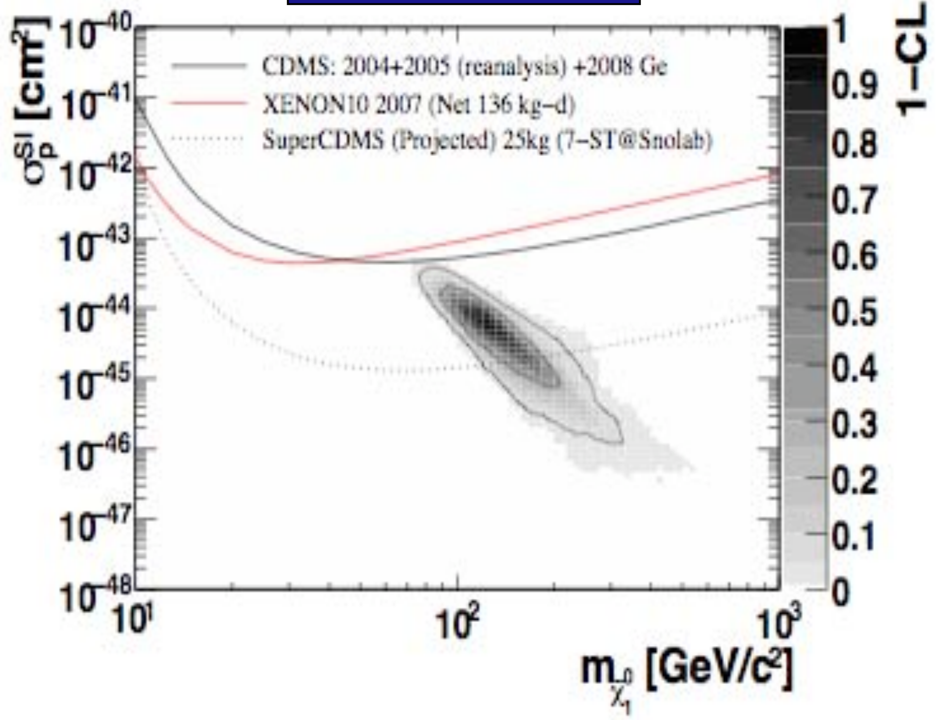
CMSSM NUHM1



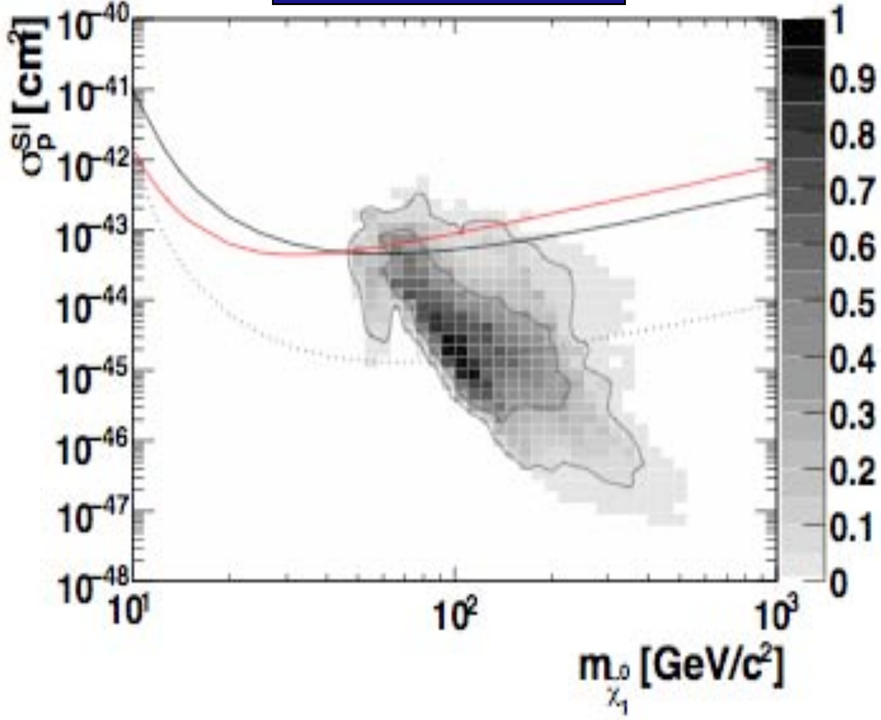
O.Buchmueller, JE et al: arXiv:0907.5568

Elastic Scattering Cross Sections

CMSSM



NUHM1

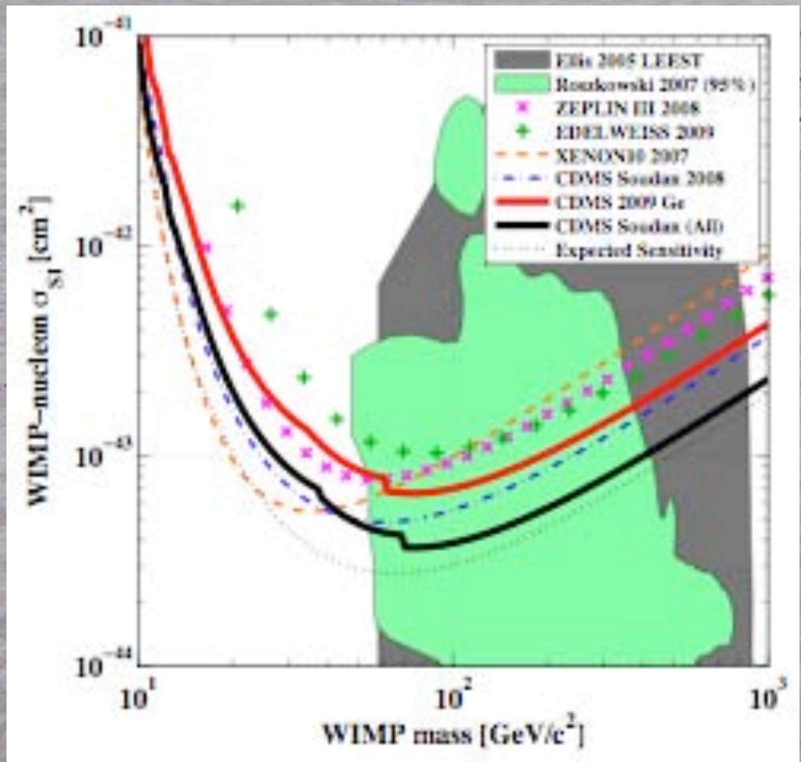


O.Buchmueller, JE et al: arXiv:0907.5568

CDMS 'Hint'?

Two events where 0.8 were expected: not significant

Published CDMS Plot



Likelihood Analysis