# Last Bets for Higgs & Supersymmetry @ the LHC

*John ELLIS,*
*CERN, Geneva, Switzerland*

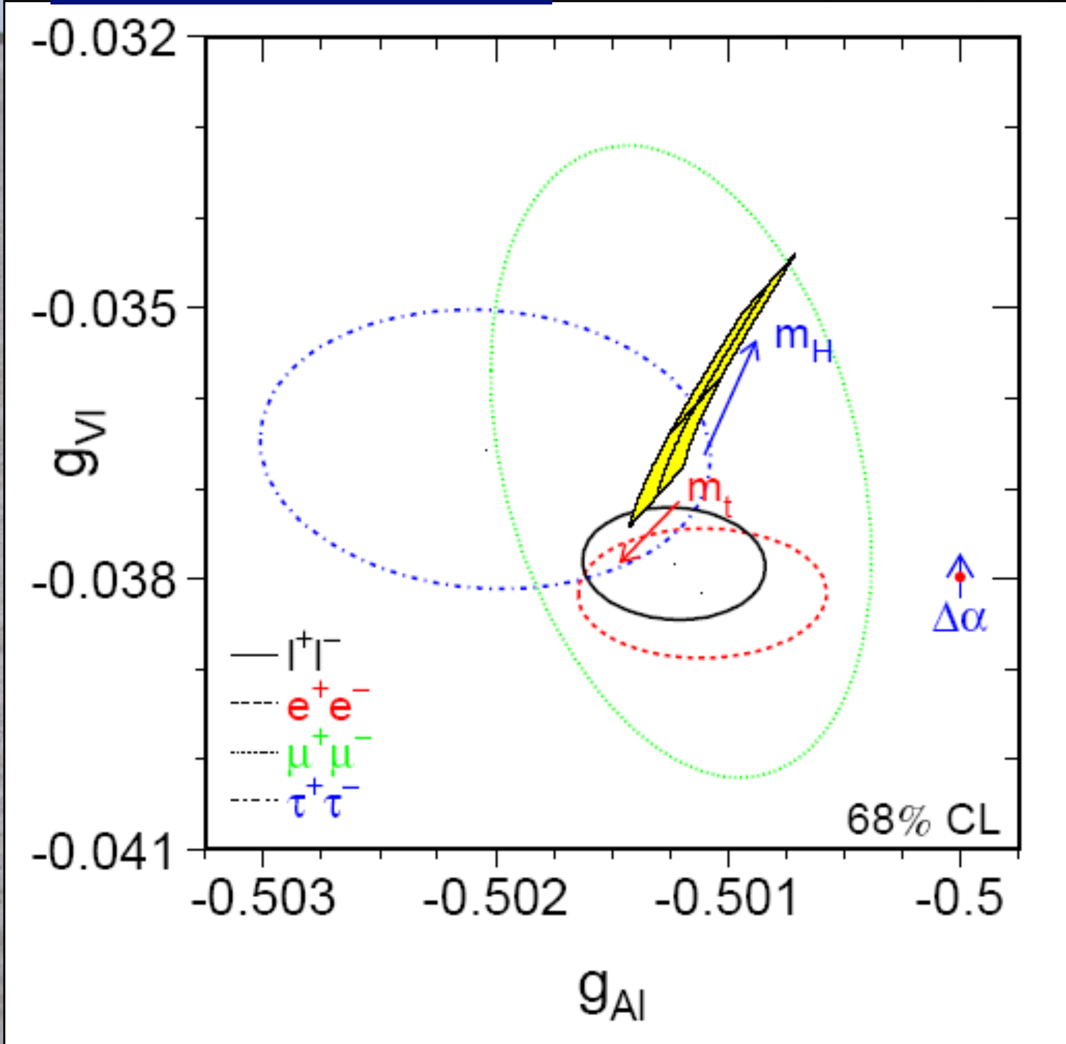
# Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing $< \sim$ 180 GeV
- Raises many unanswered questions:

  *mass? flavour? unification?*

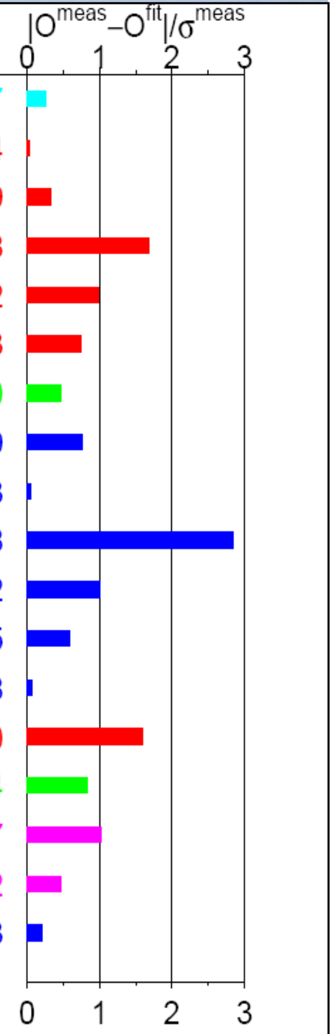
# Precision Tests of the Standard Model

## Lepton couplings




## Pulls in global fit

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02758 \pm 0.00035$ | 0.02767 |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1874 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4959 |
| $\sigma^0_{had}$ [nb] | $41.540 \pm 0.037$ | 41.478 |
| $R_l$ | $20.767 \pm 0.025$ | 20.742 |
| $A^{0,l}_{fb}$ | $0.01714 \pm 0.00095$ | 0.01643 |
| $A_l(P_\tau)$ | $0.1465 \pm 0.0032$ | 0.1480 |
| $R_b$ | $0.21629 \pm 0.00066$ | 0.21579 |
| $R_c$ | $0.1721 \pm 0.0030$ | 0.1723 |
| $A^{0,b}_{fb}$ | $0.0992 \pm 0.0016$ | 0.1038 |
| $A^{0,c}_{fb}$ | $0.0707 \pm 0.0035$ | 0.0742 |
| $A_b$ | $0.923 \pm 0.020$ | 0.935 |
| $A_c$ | $0.670 \pm 0.027$ | 0.668 |
| $A_l$(SLD) | $0.1513 \pm 0.0021$ | 0.1480 |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | $0.2324 \pm 0.0012$ | 0.2314 |
| $m_W$ [GeV] | $80.410 \pm 0.032$ | 80.377 |
| $\Gamma_W$ [GeV] | $2.123 \pm 0.067$ | 2.092 |
| $m_t$ [GeV] | $172.7 \pm 2.9$ | 173.3 |

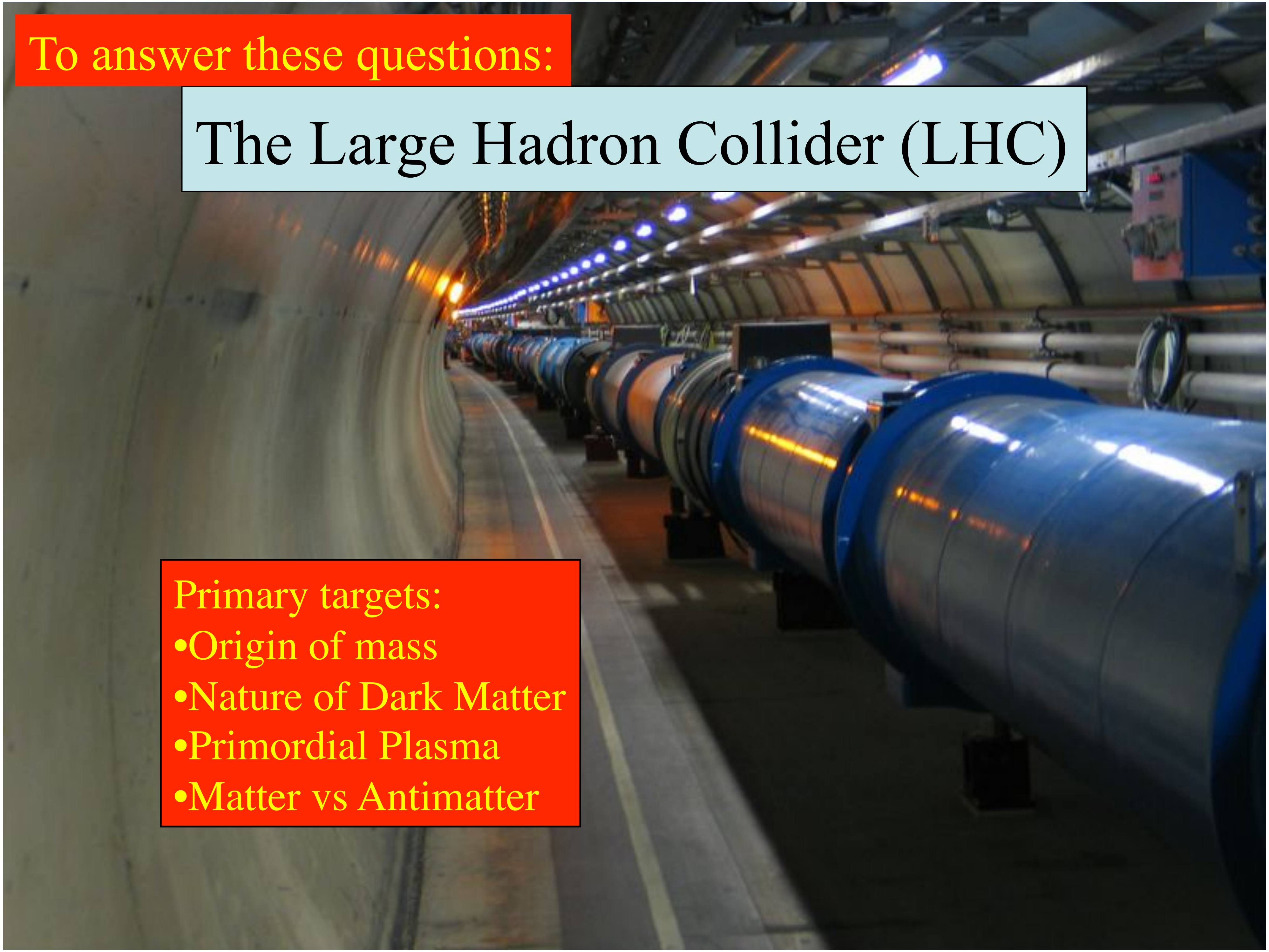


# Open Questions beyond the Standard Model

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

To answer these questions:

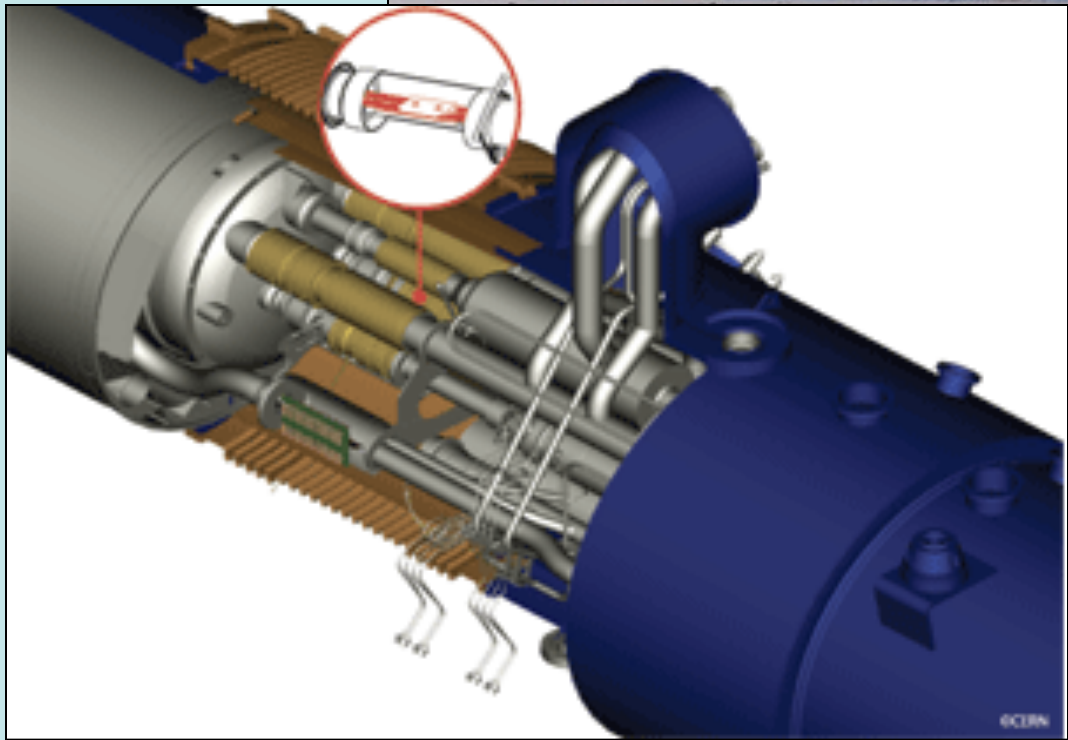
# The Large Hadron Collider (LHC)



Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

# Temporary Halt since Sept. 19th

- Electrical fault in connection between two magnets
- Ohmic heating broke cryostat, vacuum pipe
- Repairs ongoing during shutdown
- Precursor diagnostic identified
- Simple rewiring to avoid recurrence
- Relief valves being installed



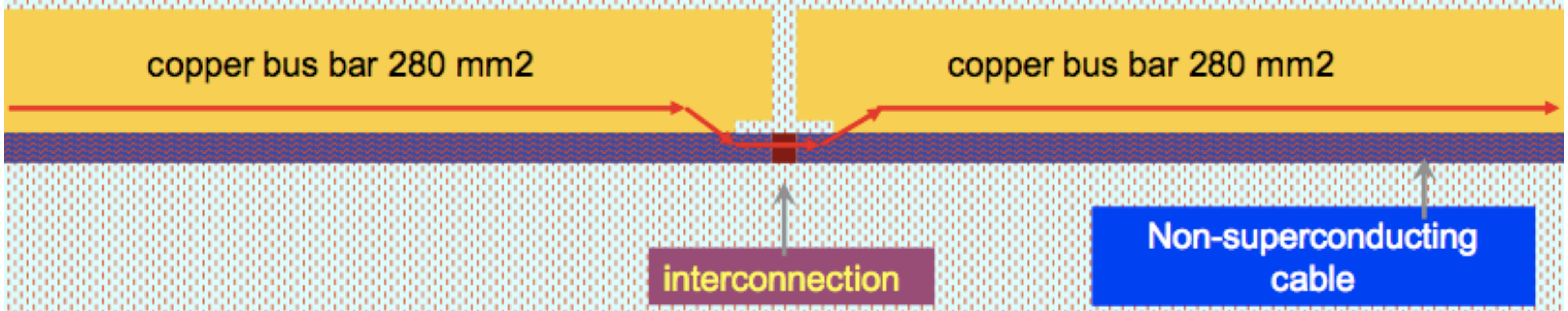
# Last repaired Magnet being lowered

# Residual Potential Issue

Current path is deviated through the sc cable (which is no longer sc). Depending on the current and length of this path, the cable can suffer thermal runaway

Magnet

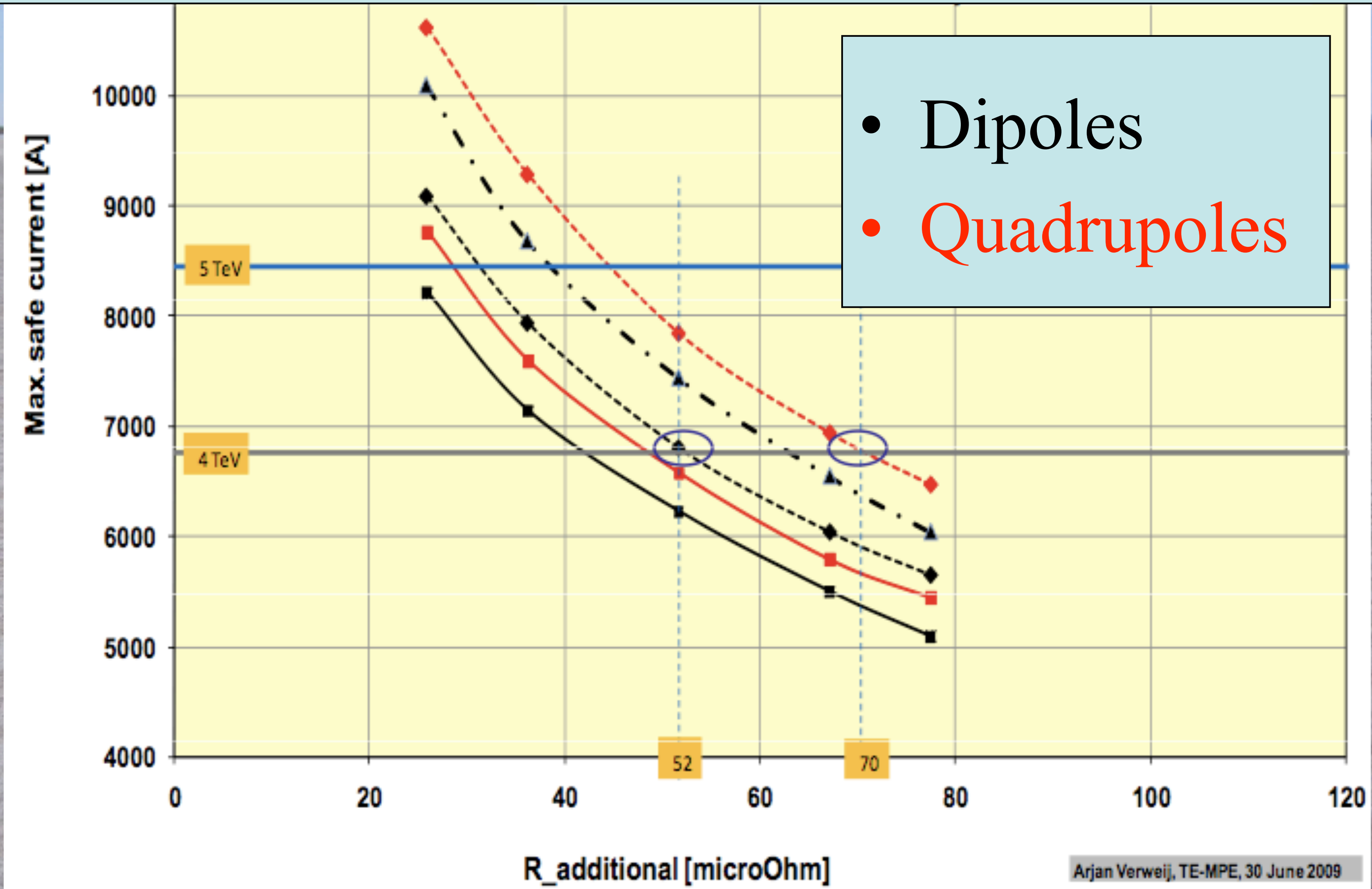
Magnet




Danger of melting the sc cable then electrical arc

Test at 80 K,
warm to 300 K if necessary

# Allowed additional Resistances



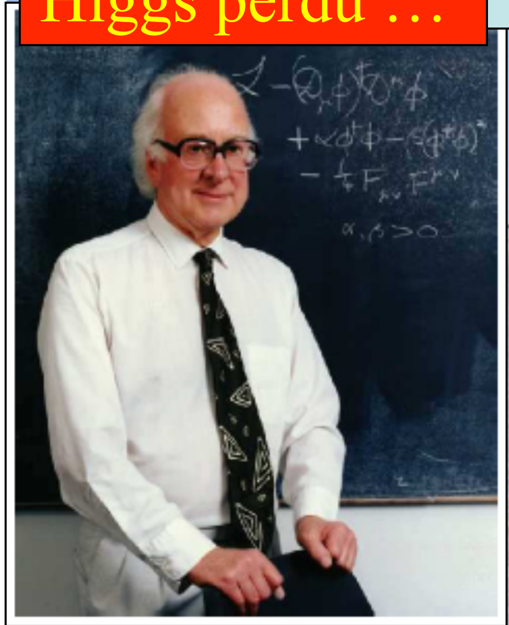

- Dipoles
- Quadrupoles

# LHC Schedule announced Aug. 6th

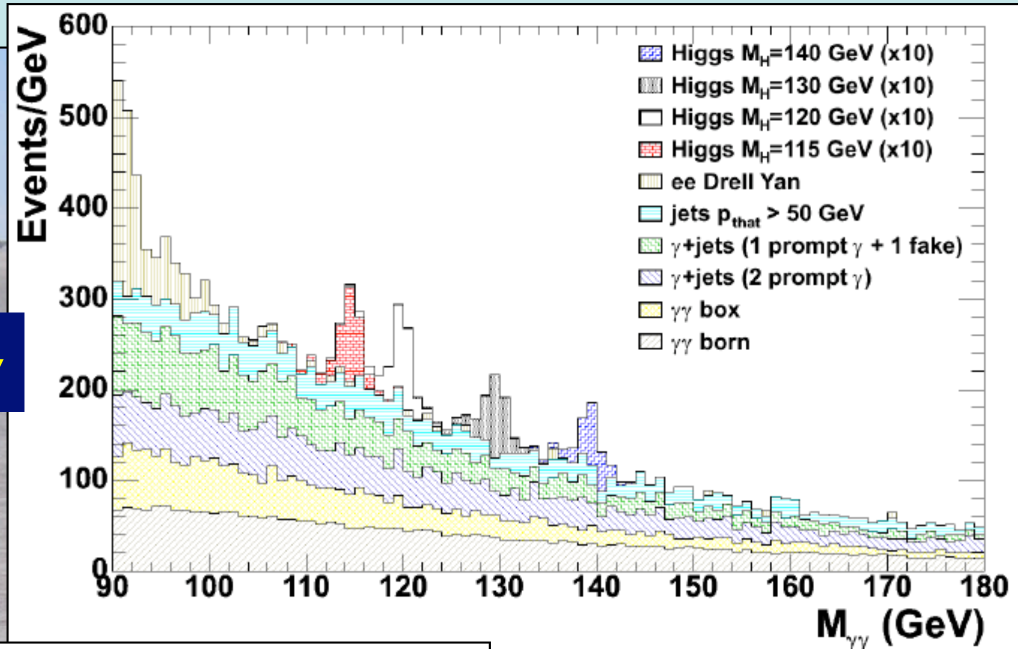
- Start run November 2009
- Continue until late 2010
  - First pp collisions, heavy-ion collisions at end
- Initially some collisions at injection energy
- Collisions at 3.5 TeV/beam within few weeks
- 5 TeV/beam after operational experience
- Work in 2010/2011 shutdown towards collisions at 7 TeV/beam

A la recherche du Higgs perdu …

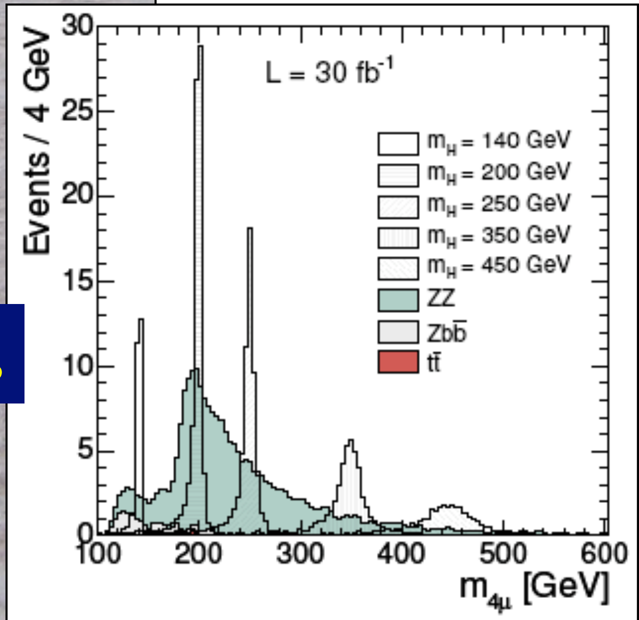
# Some Sample Higgs Signals



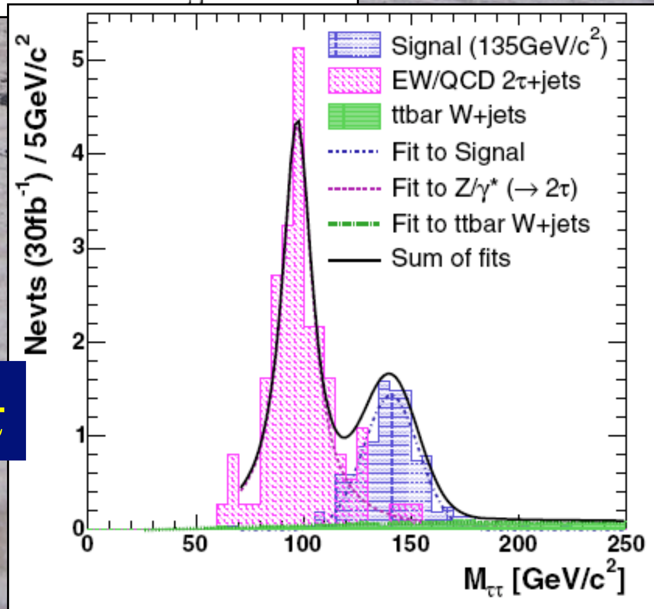
γγ



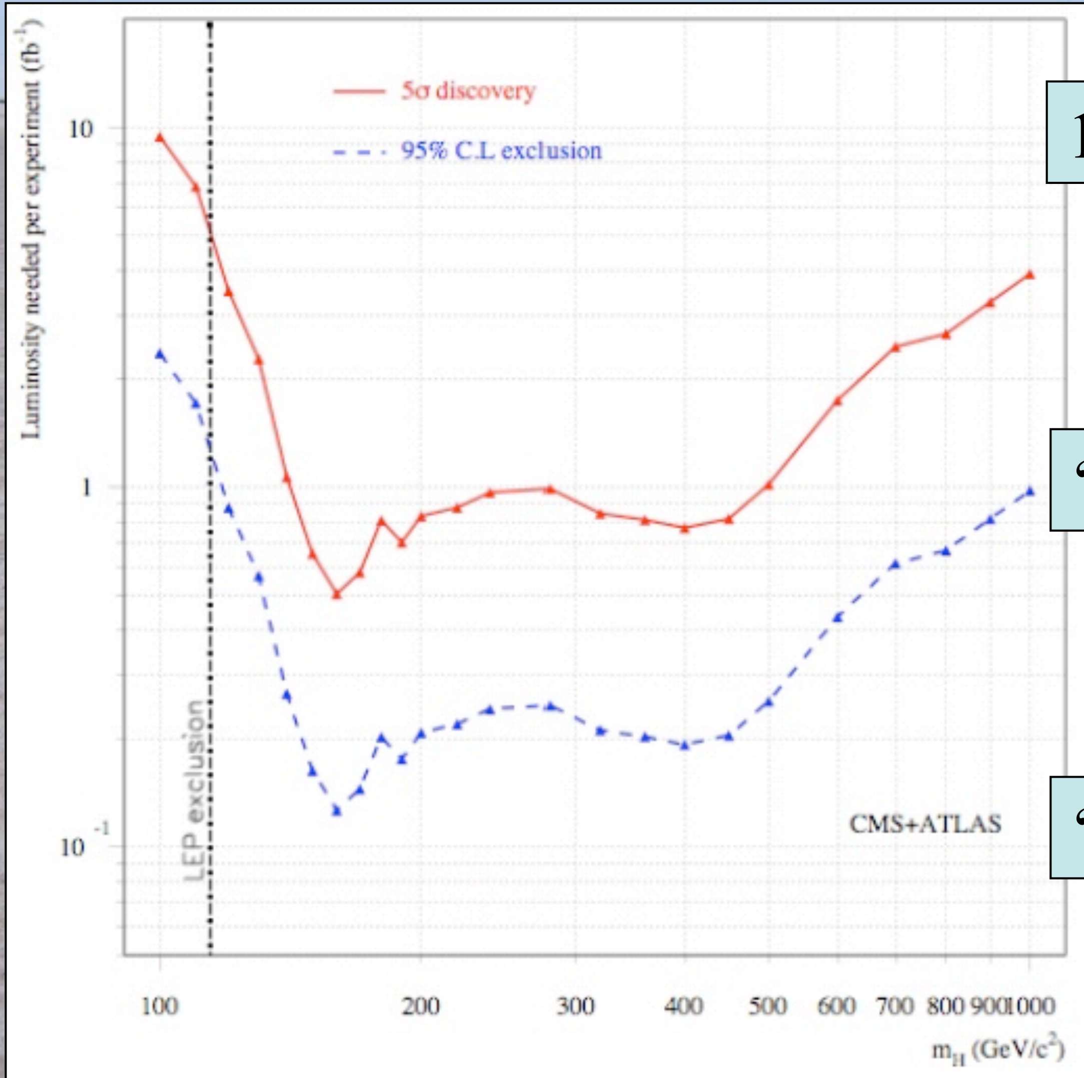

ZZ* -> 4 leptons




ττ



# When will the LHC discover the Higgs boson?




1 'year' @ $10^{33}$

'month' @ $10^{33}$

'month' @ $10^{32}$

Blaising, JE et al: 2006

# The State of the Higgs: May 2009

- Direct search limit from LEP:

  $m_H > 114.4$ GeV

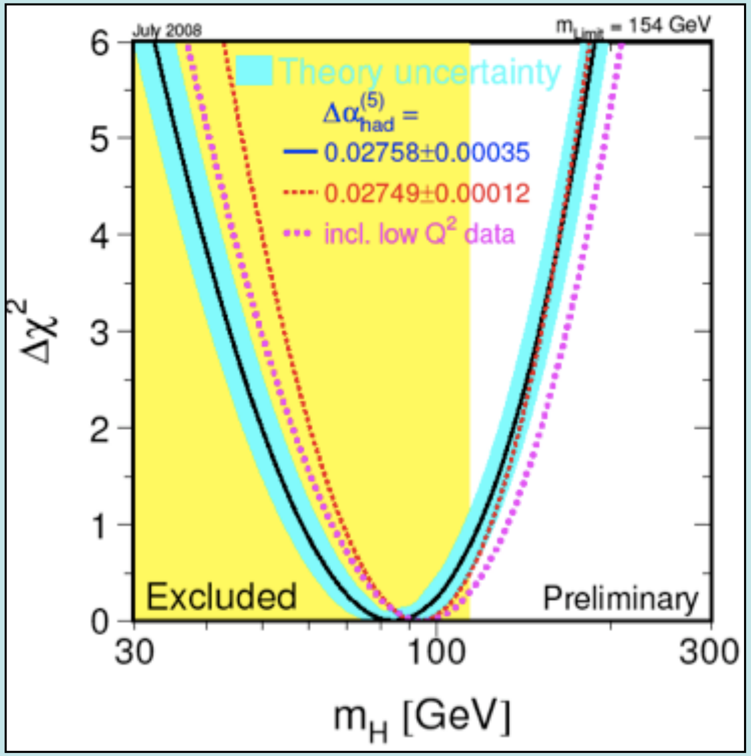
- Electroweak fit sensitive to $m_t$

  (Now $m_t = 173.1 \pm 1.3$ GeV)

- Best-fit value for Higgs mass:

  $m_H = 84^{+34}_{-26}$ GeV

- 95% confidence-level upper limit:

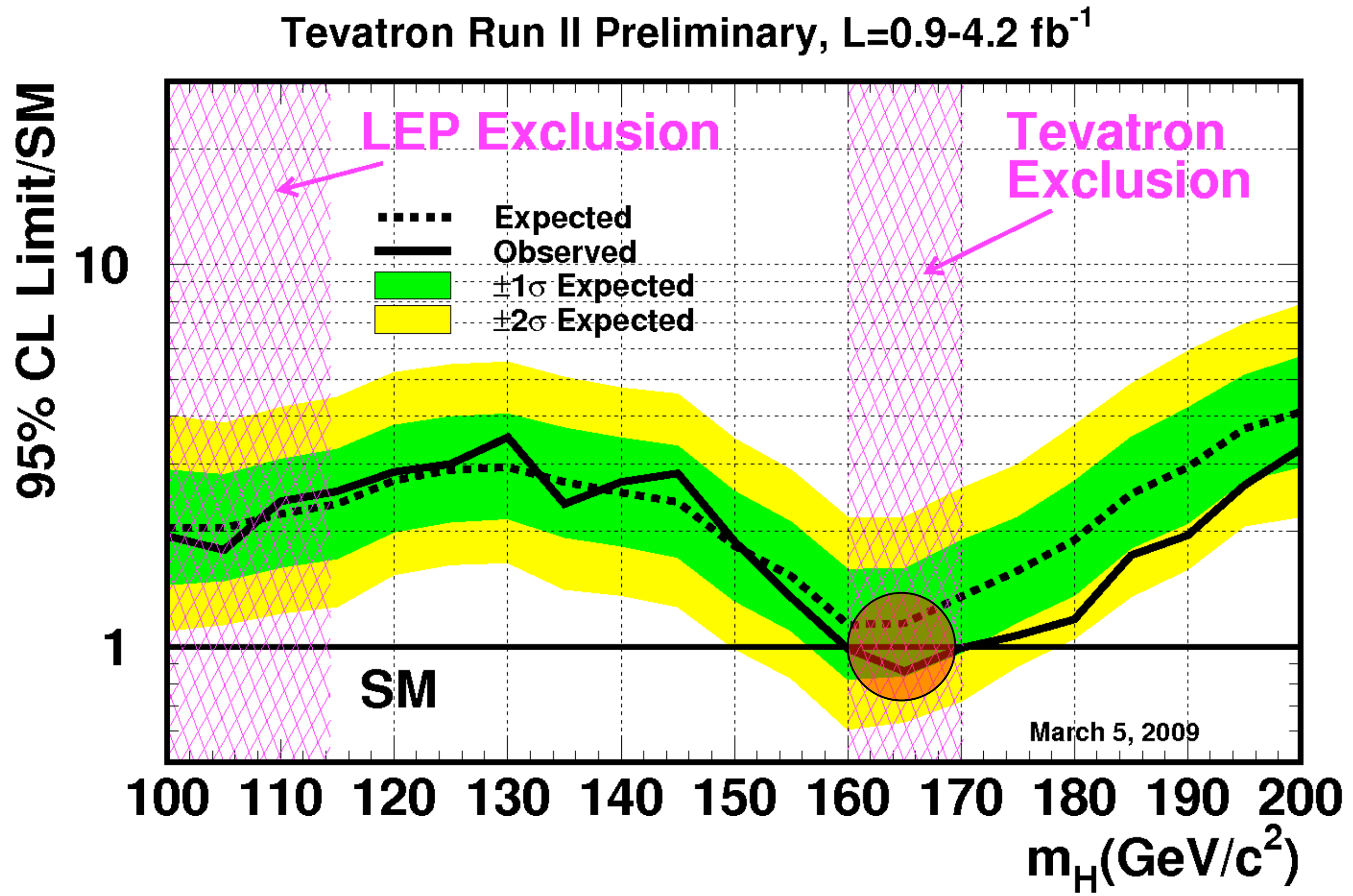



  $m_H < 154$ GeV, or 185 GeV including direct limit

- Tevatron exclusion:

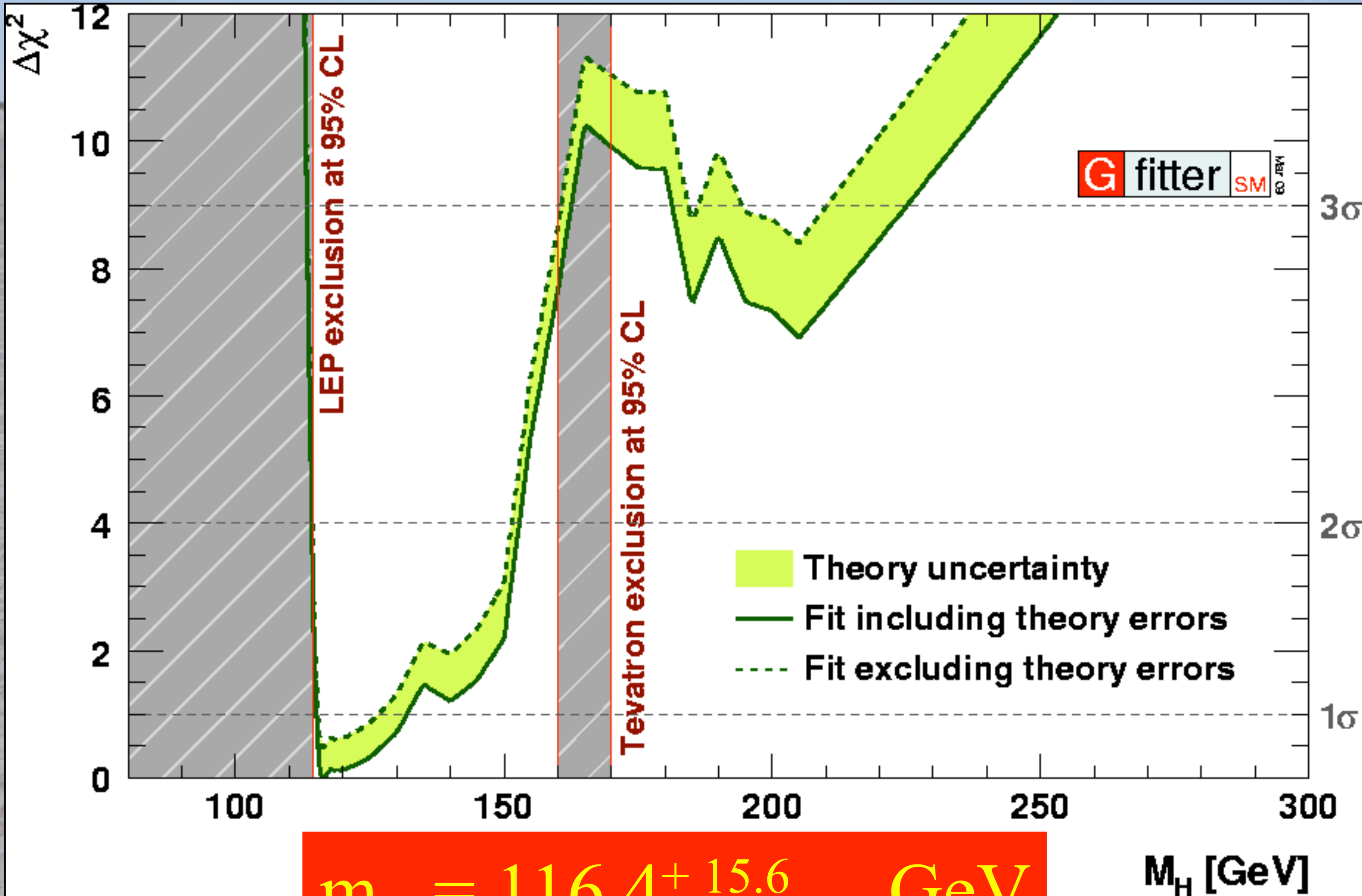
  $m_H < 160$ GeV or $> 170$ GeV

# Higgs Search @ Tevatron




Tevatron excludes Higgs between 160 & 170 GeV

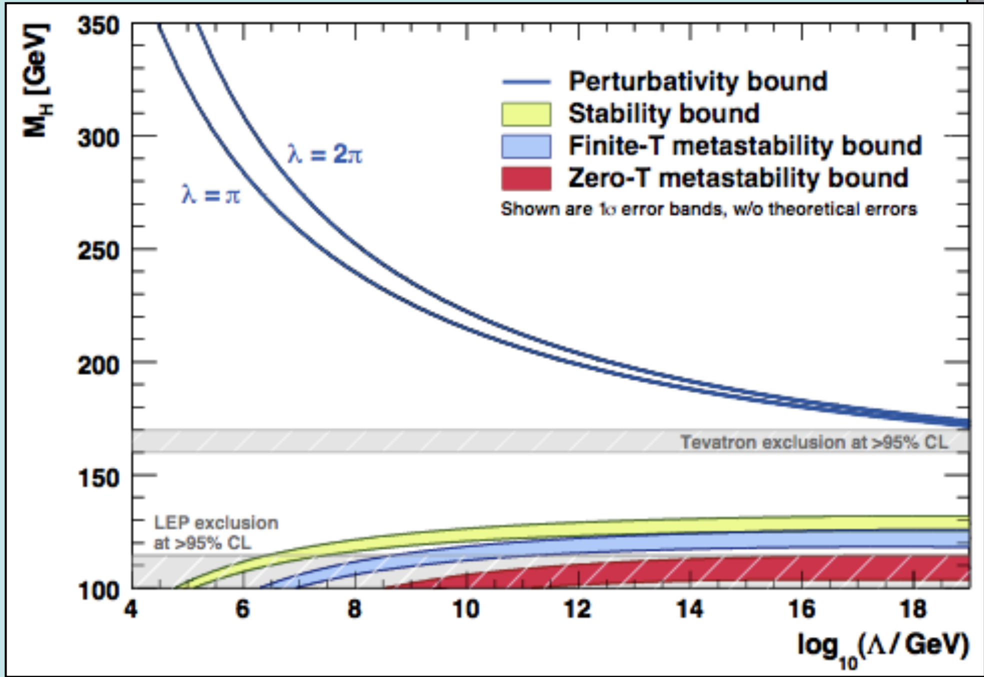
# Combining the Higgs Information




$$m_H = 116.4^{+15.6}_{-1.3}\ \text{GeV}$$

# Theoretical Constraints on Higgs Mass

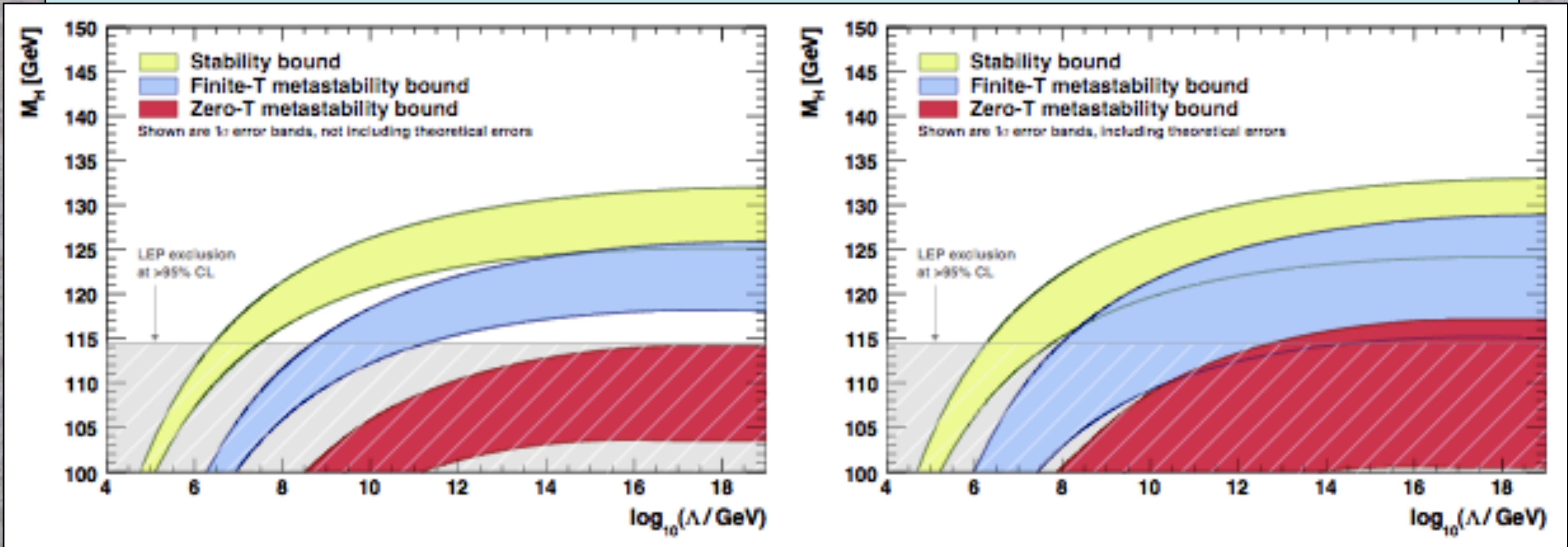
- Large → large self-coupling → blow up at low energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable




- Bounds on Higgs mass depend on Λ

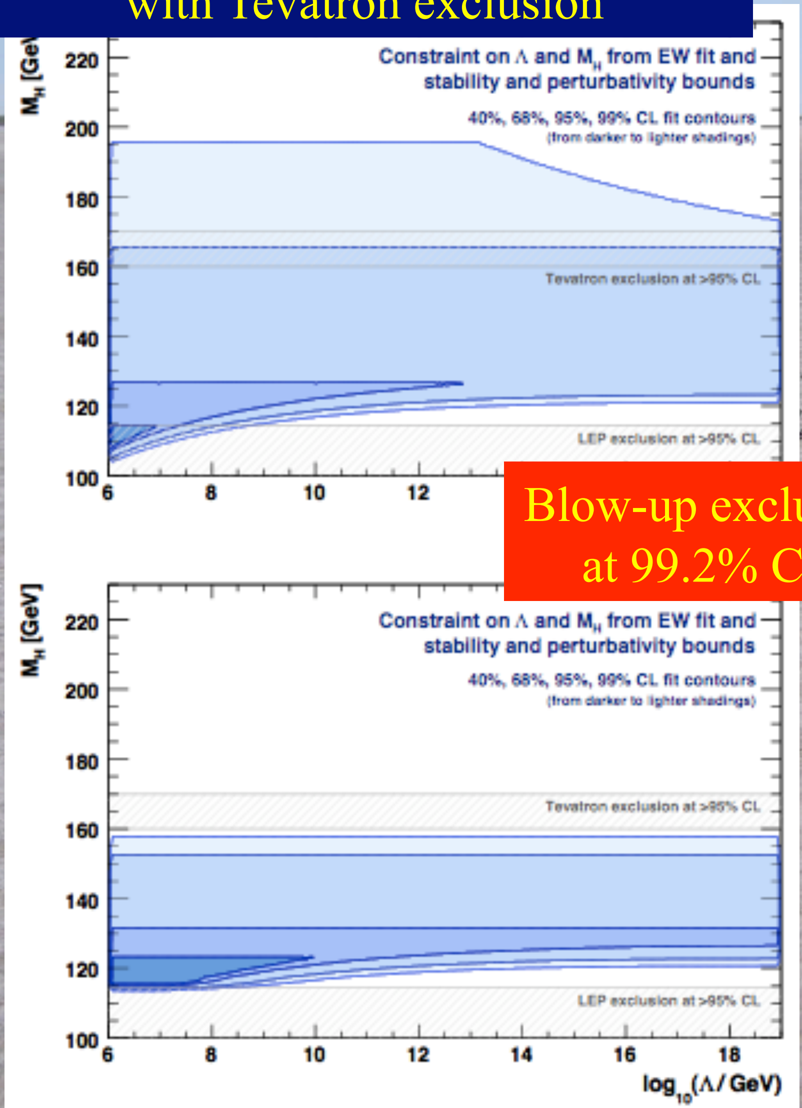
# Vacuum Stability vs Metastability

- Dependence on scale up to which Standard Model remains
  - Stable
  - Metastable at non-zero temperature
  - Metastable at zero temperature



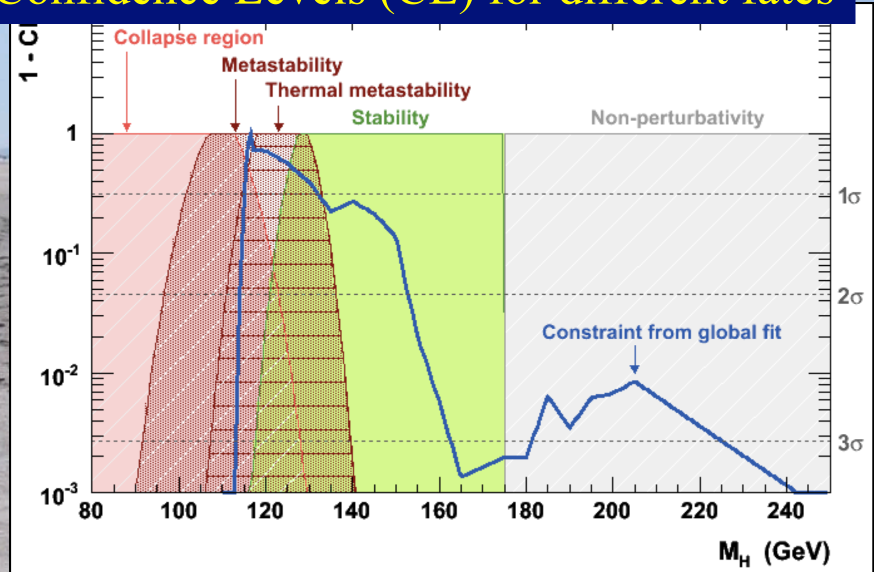
# What is the probable fate of the SM?

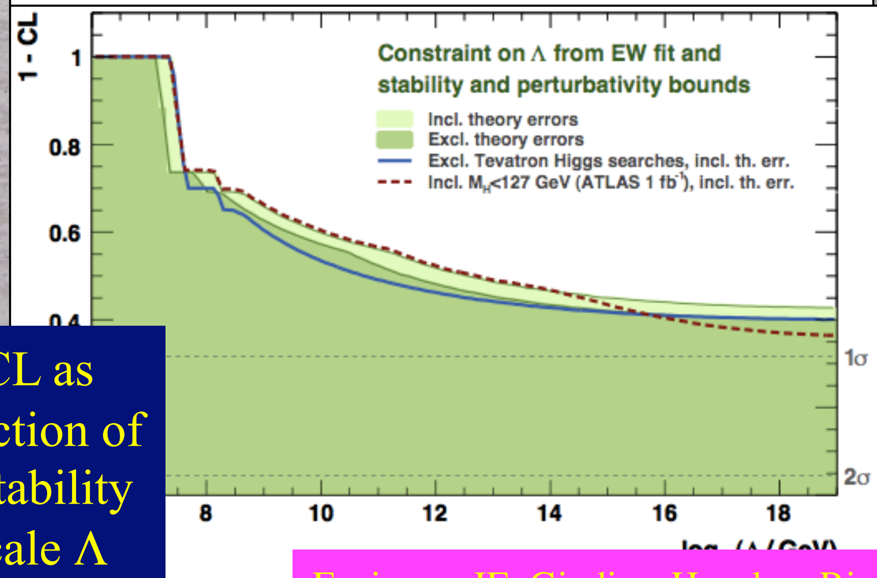
Confidence Levels (CL) without/ with Tevatron exclusion




Blow-up excluded at 99.2% CL

Confidence Levels (CL) for different fates



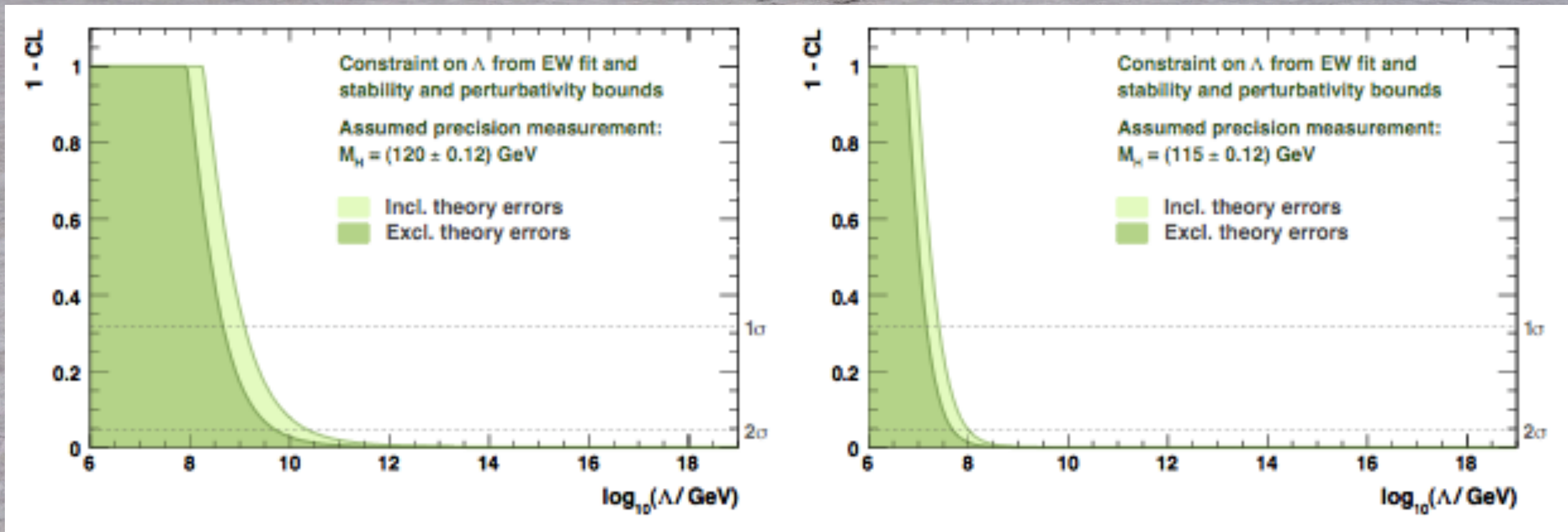




CL as function of instability scale Λ

Espinosa, JE, Giudice, Hoecker, Riotto

# The LHC will Tell the Fate of the SM

## Examples with LHC measurement of $m_H$ = 120 or 115 GeV




Espinosa, JE, Giudice, Hoecker, Riotto

# The Stakes in the Higgs Search

- How is particle symmetry broken?
- Is there an elementary scalar field?
- What is the fate of the Standard Model?
- Did mass appear when the Universe was a picosecond old?
- Did Higgs help create the matter in the Universe?
- Did a related inflaton make the Universe so big and old?
- Why is there so little dark energy?

# Theorists getting Cold Feet

- Composite Higgs model?
  conflicts with precision electroweak data
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models?
  extra 'Top', gauge bosons, 'Higgses'
- Higgsless models?
  strong WW scattering, extra D?

# The LHC Roulette Wheel

Techni colour

# The LHC Roulette Wheel

Higgsless model

# … or not to Higgs?

- Higgs must discriminate between different types of particles:
  - Some have masses, some do not
  - Masses of different particles are different
- In mathematical jargon, symmetry must be broken: how?
  - Break symmetry in equations?
  - **Or in solutions to symmetric equations?**
- Route proposed by Higgs
  - **Is there another way?**

# Where to Break the Symmetry?

- Throughout all space?
  - Route proposed by Higgs
  - Universal Higgs (snow)field breaks symmetry
- Or at the edge of space?
  - Break symmetry at the boundary?
- Not possible in 3-dimensional space
  - No boundaries
  - Postulate extra dimensions of space
- Different particles behave differently in the extra dimension(s)

# The LHC Roulette Wheel

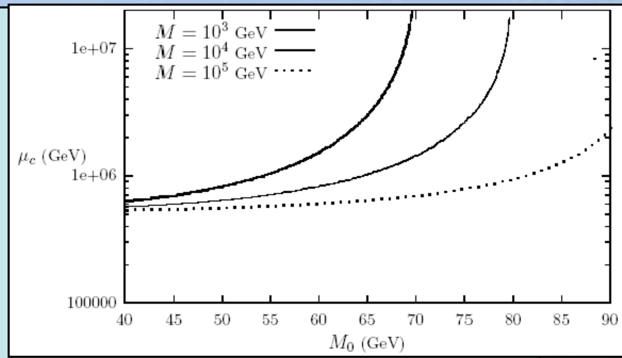
Supersymmetry

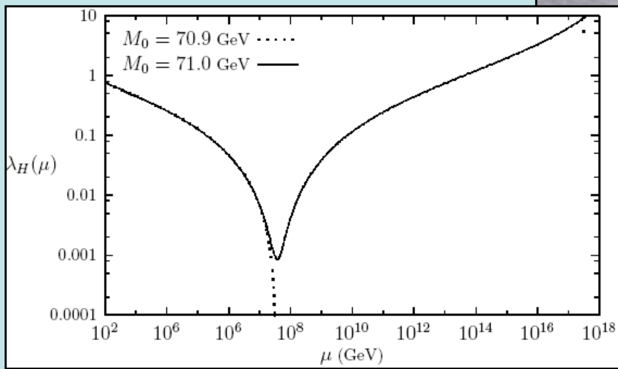
# How to Stabilize a Light Higgs Boson?

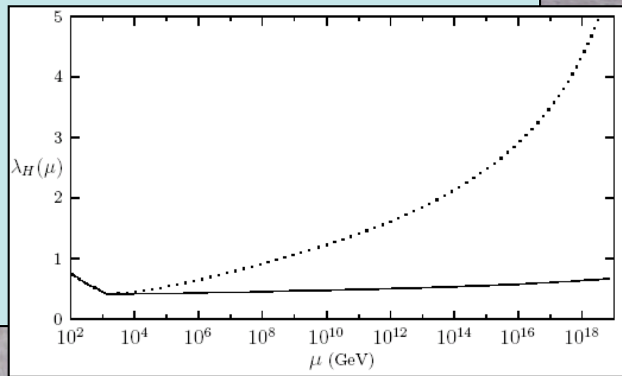
- Top quark destabilizes potential: introduce stop-like scalar:

$$\mathcal{L} \supset \; M^2|\phi|^2 + \frac{M_0}{v^2}|H|^2\,|\phi|^2$$

- Can delay collapse of potential:
- But new coupling must be fine-tuned to avoid blow-up:
- Stabilize with new fermions:
  – just like Higgsinos
- Very like **Supersymmetry!**



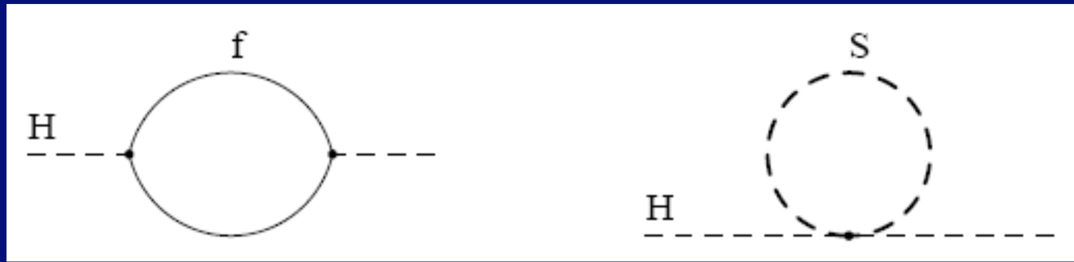




JE & D. Ross

# Loop Corrections to Higgs Mass$^2$

- Consider generic fermion and boson loops:




- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

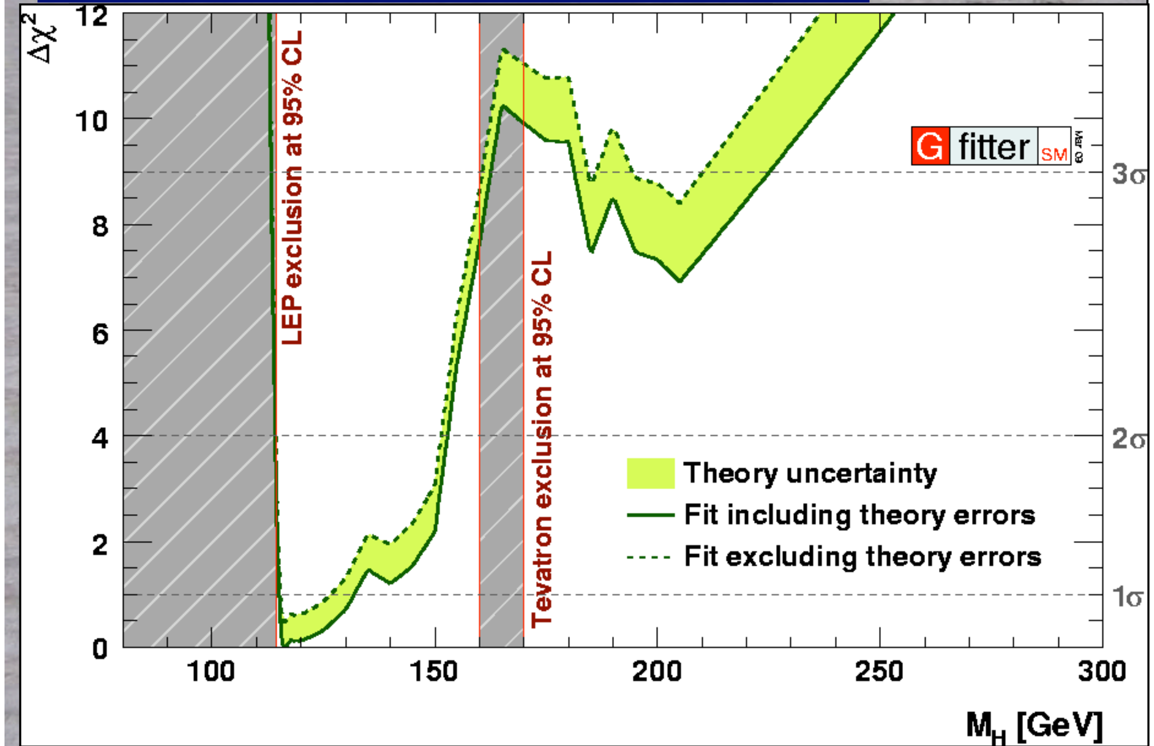
- Leading divergence cancelled if

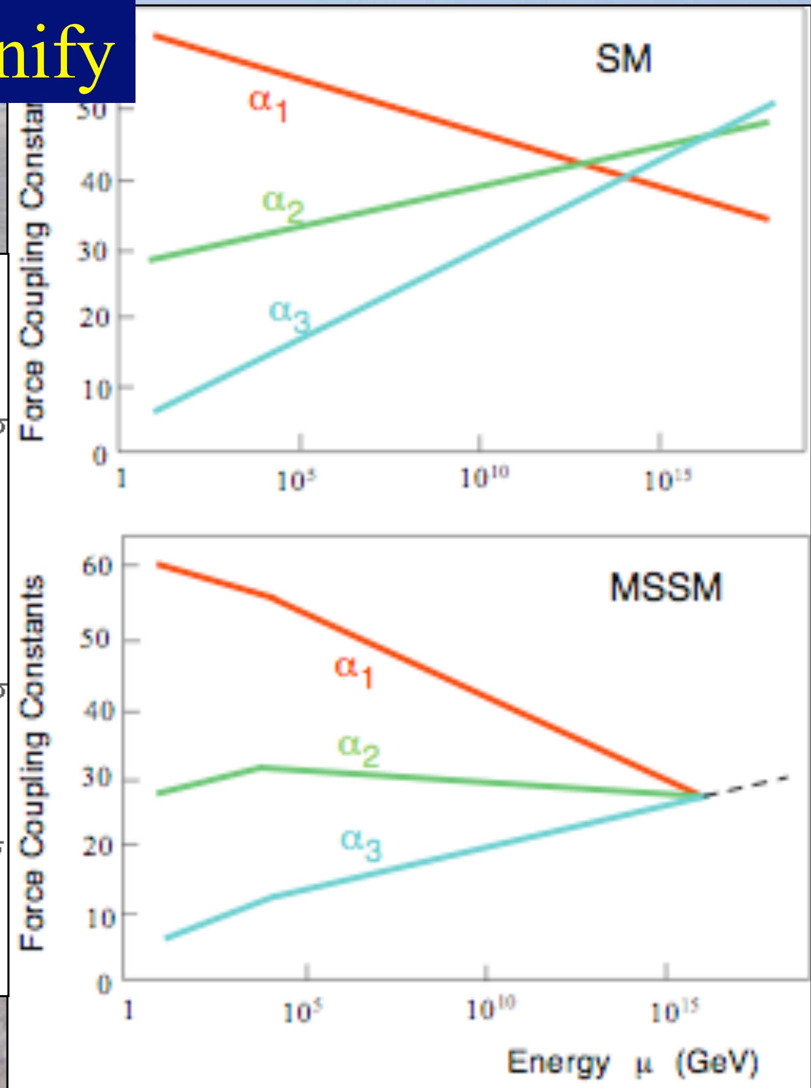
$\lambda_S = y_f^2$ x 2 Supersymmetry!

# Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV




As suggested by electroweak data

# 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 $\chi$ (partner of Z, H, $\gamma$)
  - Gravitino
    - (nightmare for astrophysical detection)

# Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 300 GeV

- Indirect constraints

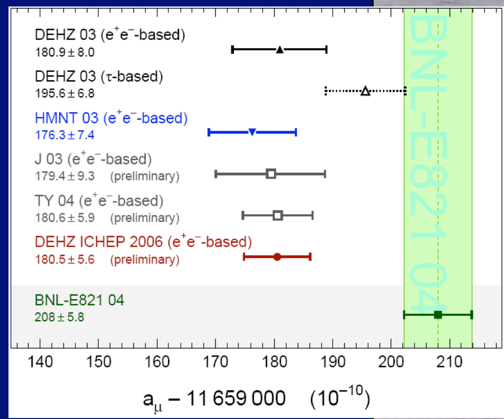
  Higgs > 114 GeV, $b \rightarrow s \gamma$

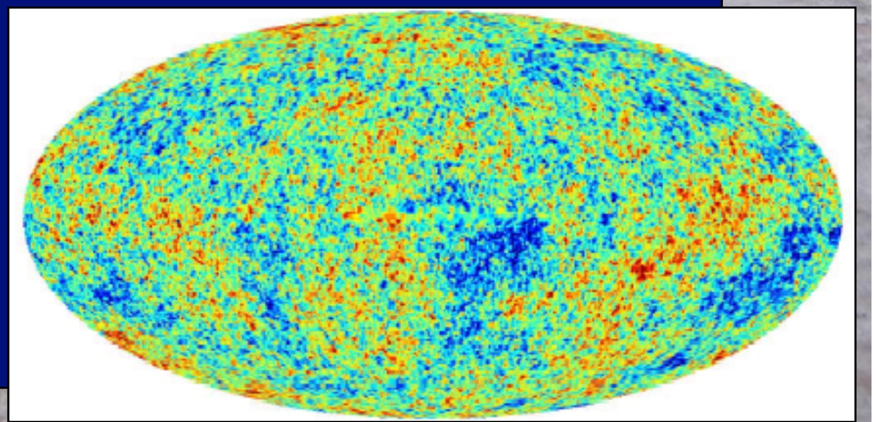
- Density of dark matter

  lightest sparticle $\chi$:

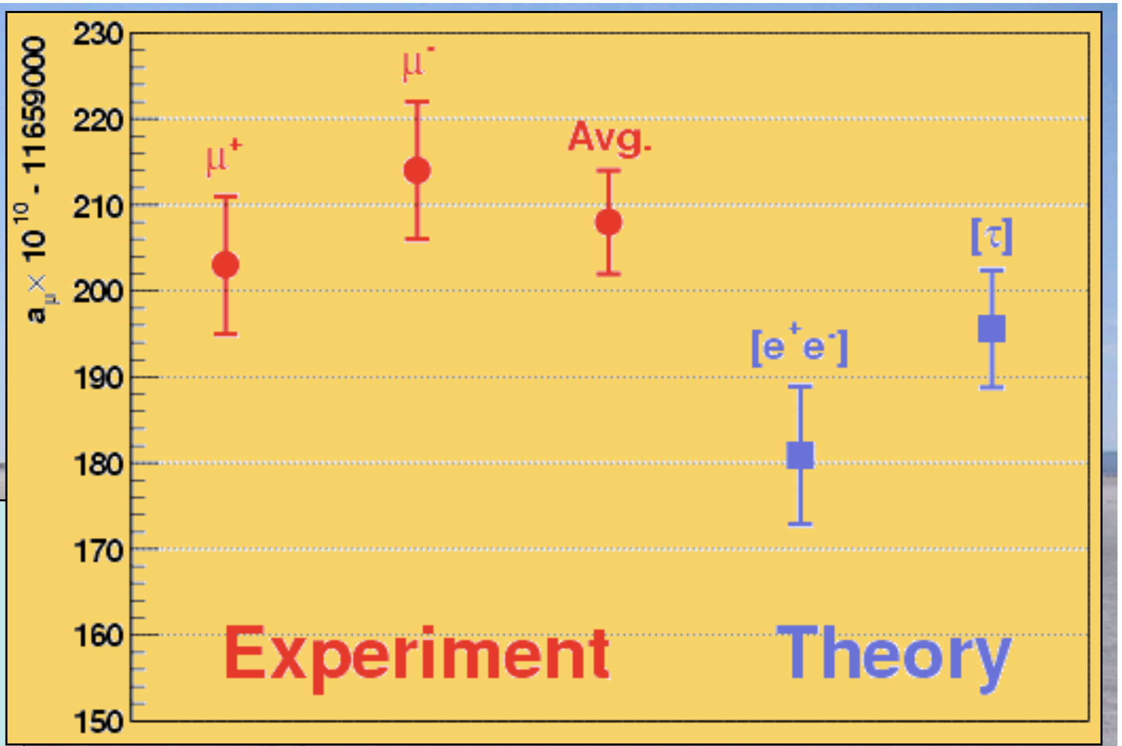
  $0.094 < \Omega_\chi h^2 < 0.124$

3.3 $\sigma$ effect in $g_\mu - 2$?

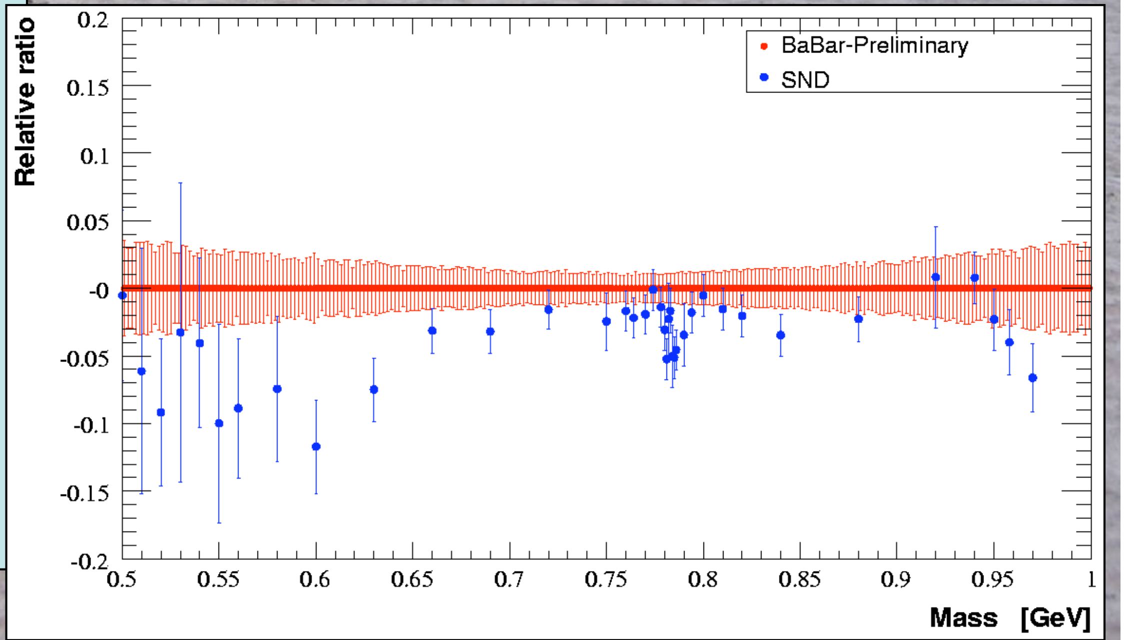


# Quo Vadis $g_\mu$ - 2?




- Older $e^+e^-$ data show discrepancy
  - now 3.4 σ
- Disagreement with τdecay data
  - discrepancy ~ 2 σ
- Look for new data from BABAR experiment



# 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 $\mu$, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  Scalar masses $m_0$, gaugino masses $m_{1/2}$,
  trilinear soft couplings $A_\lambda$, bilinear soft coupling $B_\mu$
- Assume universality? constrained MSSM = CMSSM
  Single $m_0$, single $m_{1/2}$, single $A_\lambda$, $B_\mu$: not string?
- Not the same as minimal supergravity (mSUGRA)
- Gravitino mass, additional relations

$$m_{3/2} = m_0,\; B_\mu = A_\lambda - m_0$$

# 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?

  Why not! 1 or 2 extra parameters in NUHM1,2

# Current Constraints on CMSSM

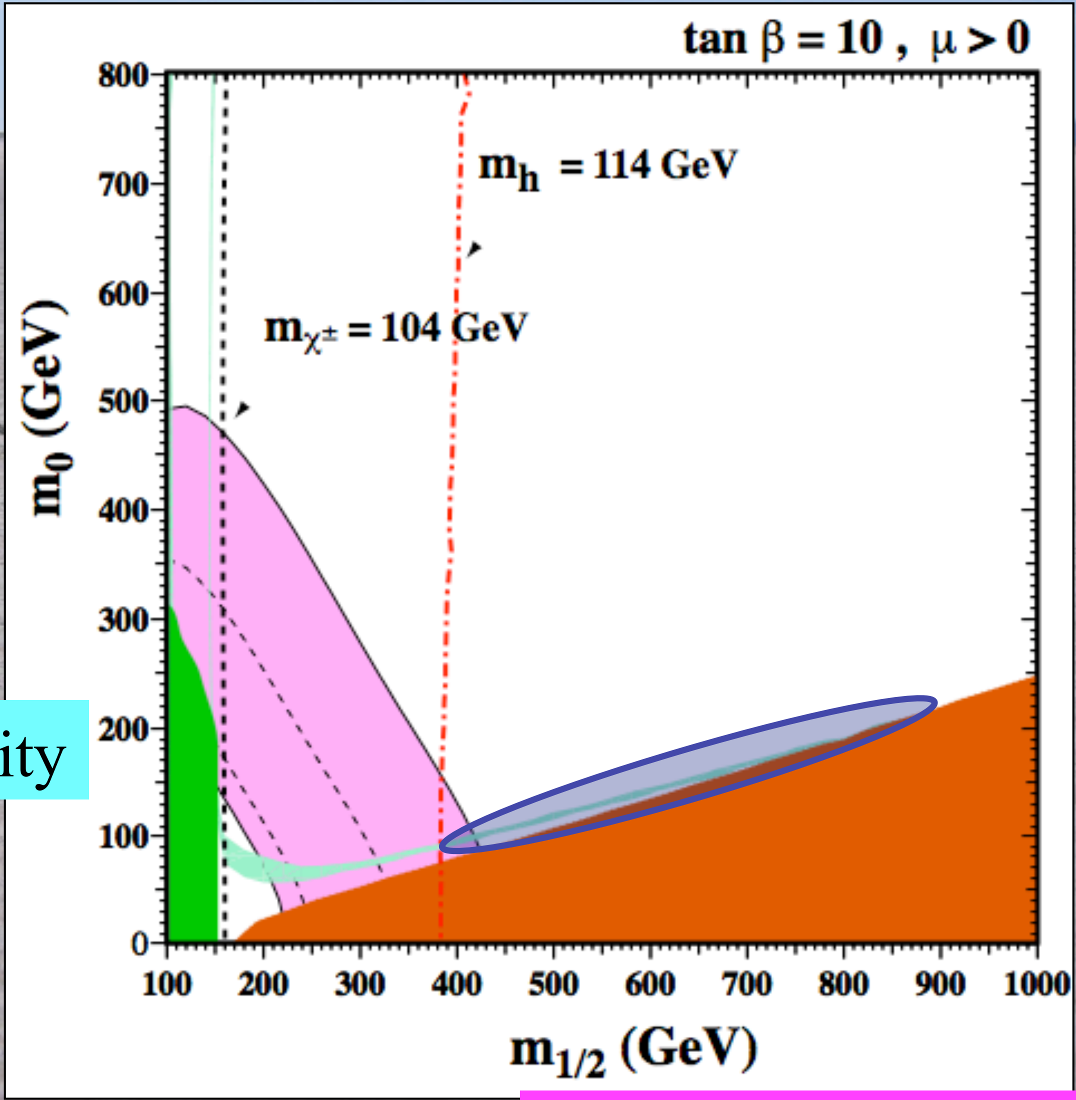
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

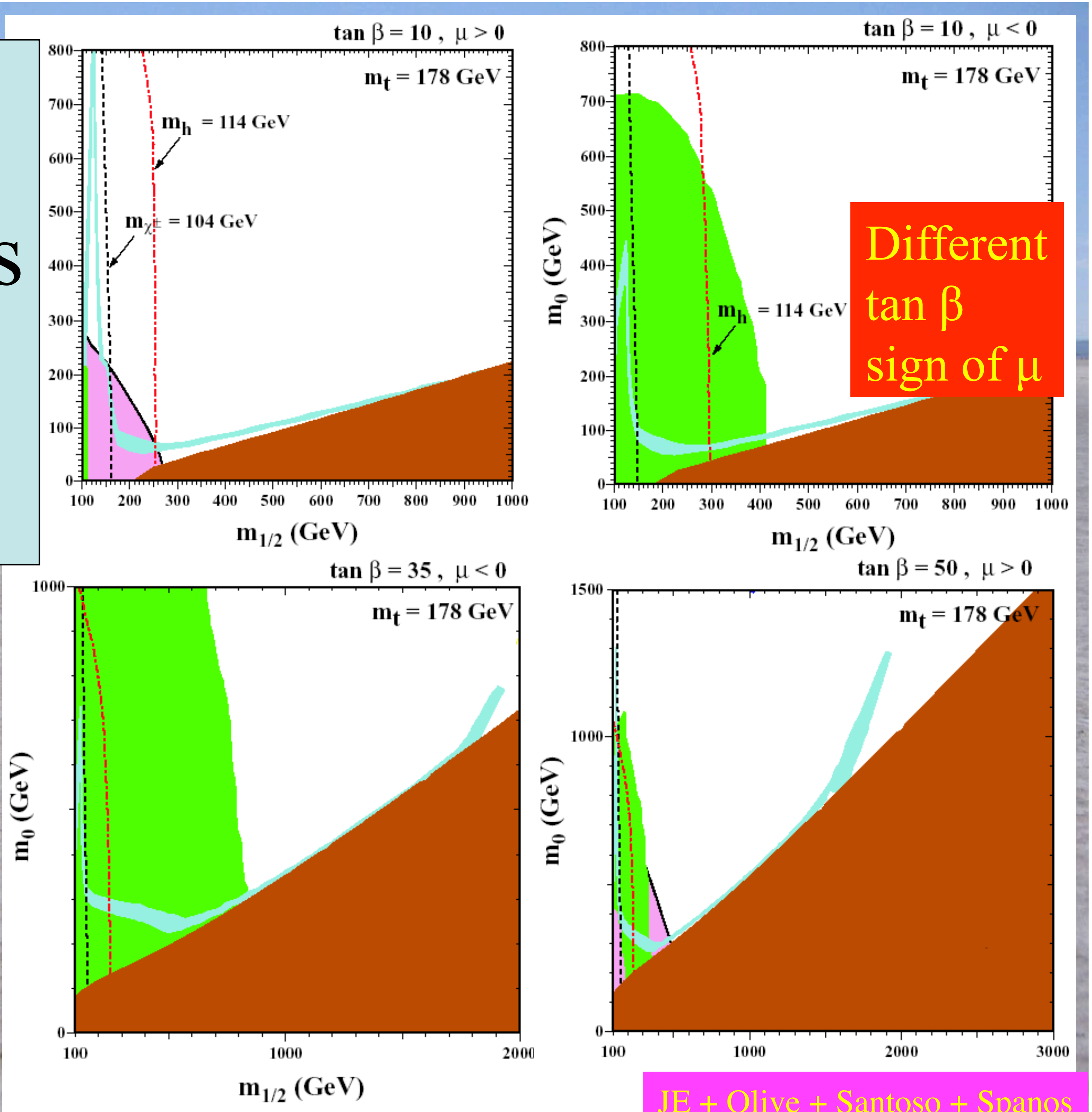
WMAP constraint on relic density

Preferred (?) by latest g - 2




JE + Olive + Santoso + Spanos

# Current Constraints on CMSSM



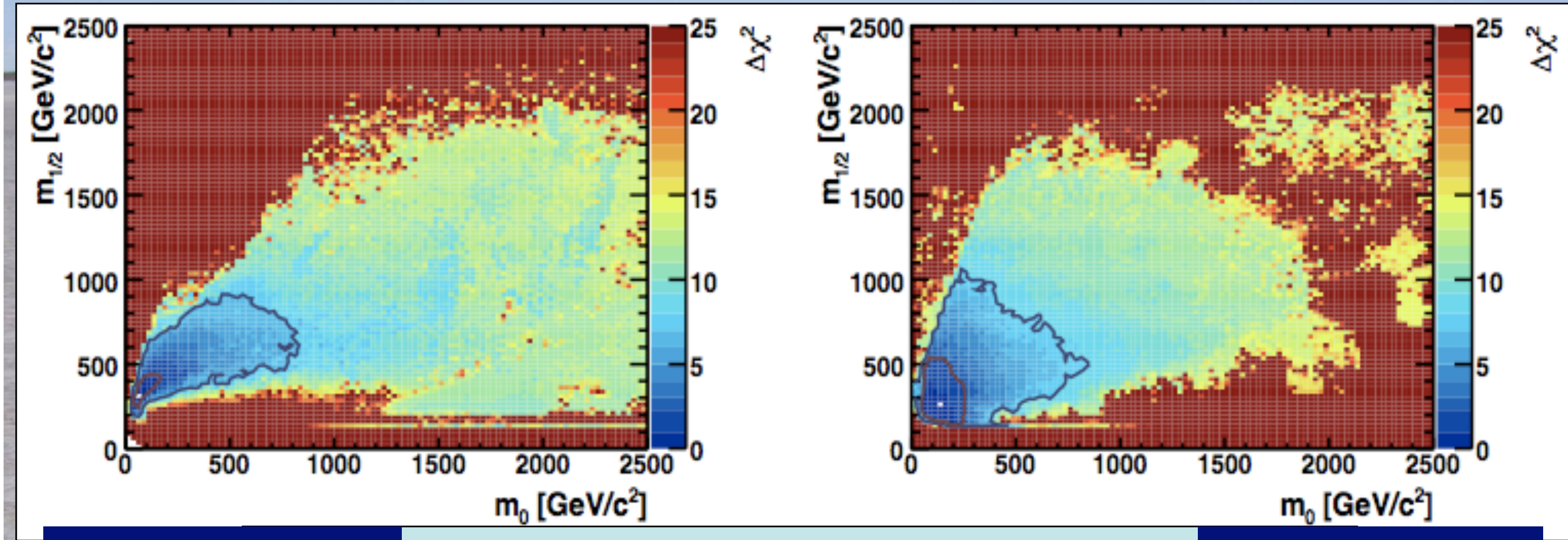

Different tan β sign of μ

Impact of Higgs constraint reduced if larger $m_t$

Focus-point region far up

JE + Olive + Santoso + Spanos

# 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

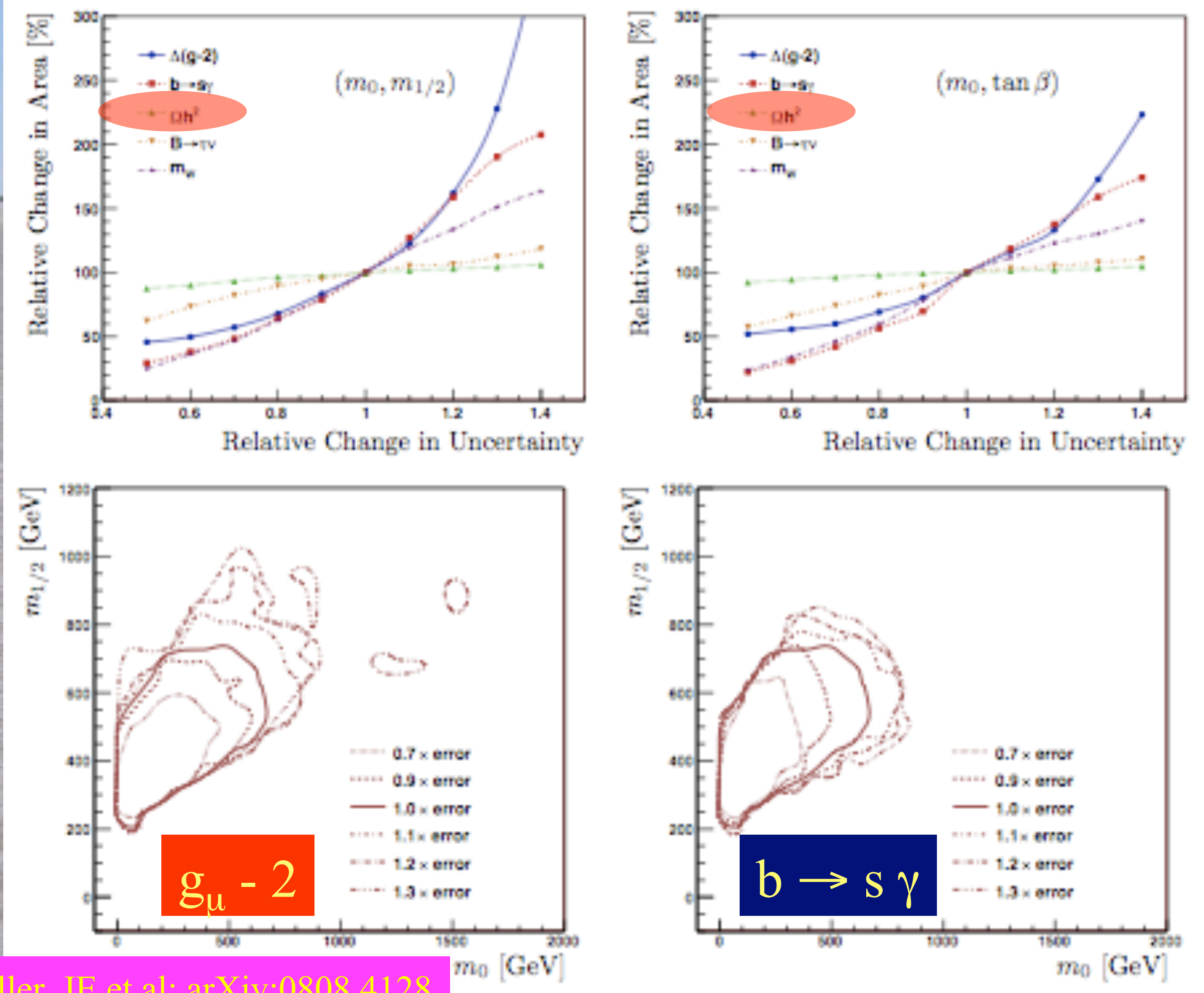
# Contributions to the Global $\chi^2$

| Observable | Best CMSSM fit | Best NUHM1 fit | Best CMSSM FP fit |
|---|---|---|---|
| $(g-2)_\mu$ | 0.44 | 0.002 | 8.4 |
| $\mathrm{BR}(B_u \to \tau\nu_\tau)$ | 0.20 | 0.41 | 0.85 |
| $M_W$ | 0.53 | 0.08 | 1.5 |
| $A_\ell(\mathrm{SLD})$ | 2.84 | 3.22 | 3.56 |
| $A_{\mathrm{fb}}(b)(\mathrm{LEP})$ | 7.61 | 7.08 | 6.74 |
| $R_\ell$ | 0.96 | 1.01 | 1.05 |
| $\mathrm{BR}^{\mathrm{SUSY}}_{b\to s\gamma}/\mathrm{BR}^{\mathrm{SM}}_{b\to s\gamma}$ | 1.16 | 0.001 | 0.95 |
| $M_h$ | 0.17 | 0 | 0 |
| $\chi^2_{\mathrm{tot}}$ | 20.6 | 18.5 | 29.8 |

Highlighted observables prefer stau coannihilation region over focus-point region, e.g., $m_W$

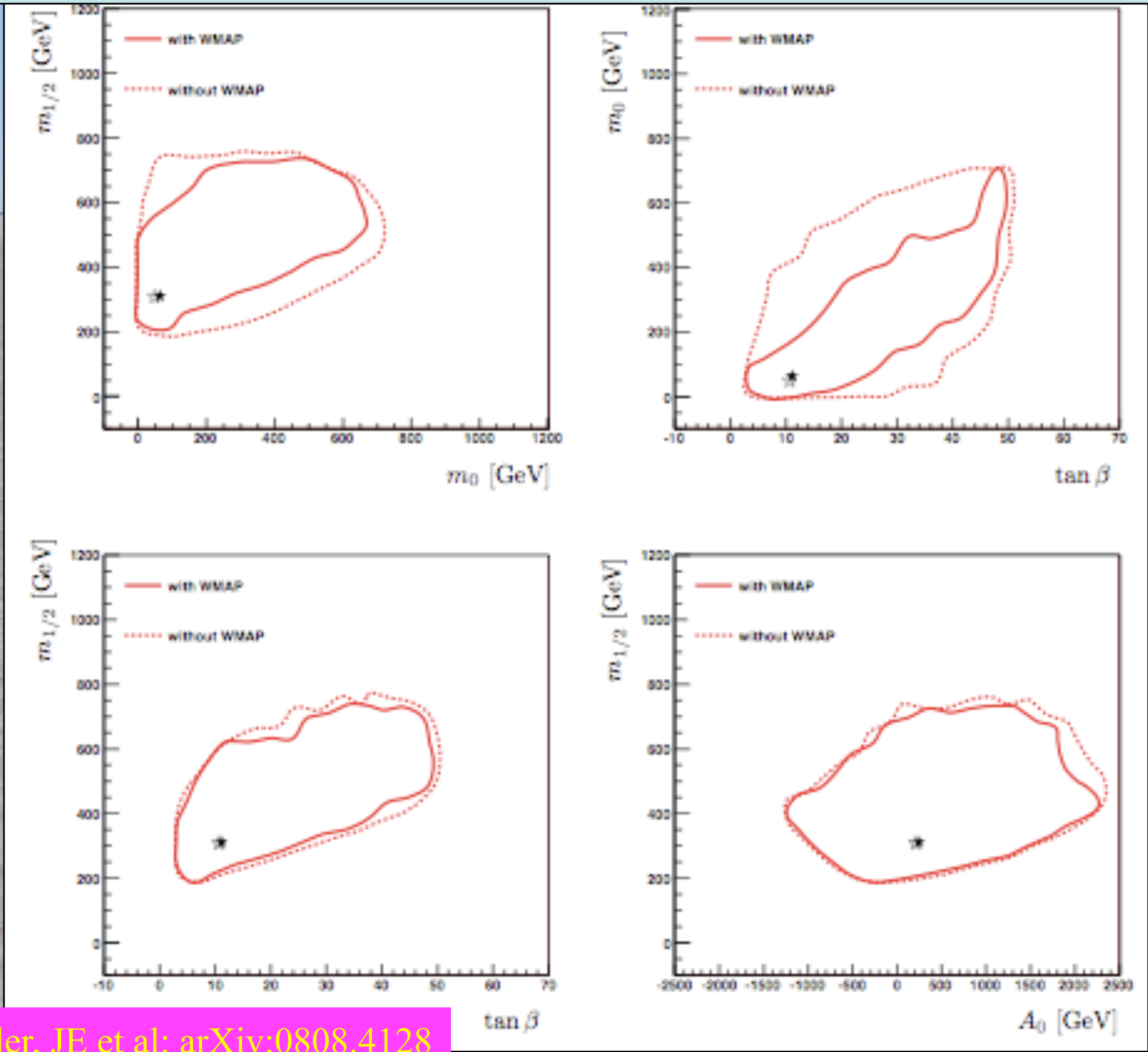
O.Buchmueller, JE et al: arXiv:0907.5568

# Sensitivities to Constraints



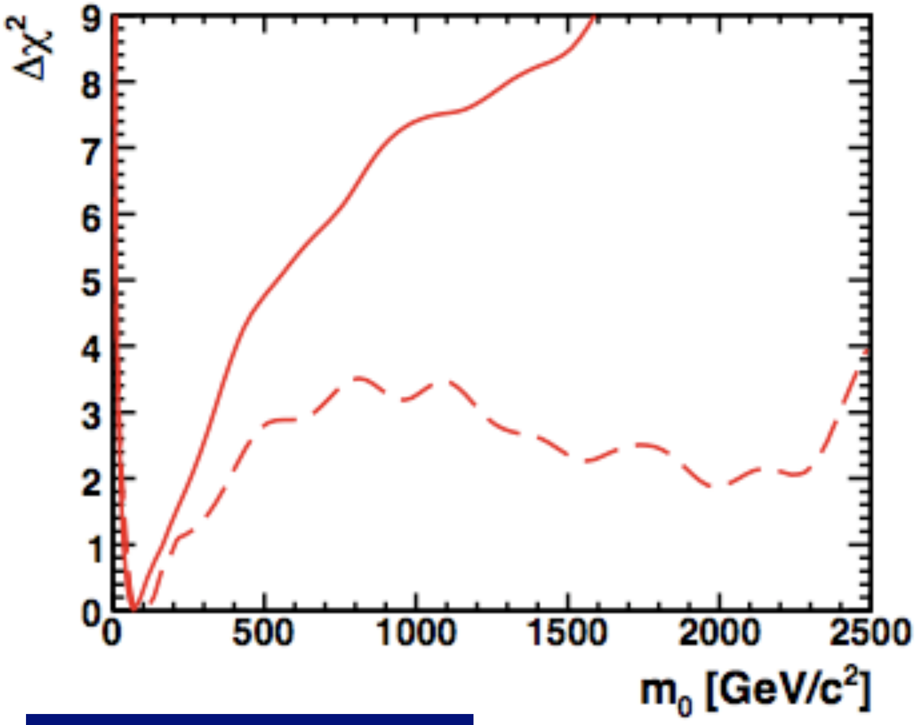

O.Buchmueller, JE et al: arXiv:0808.4128

# (In)Sensitivity to WMAP

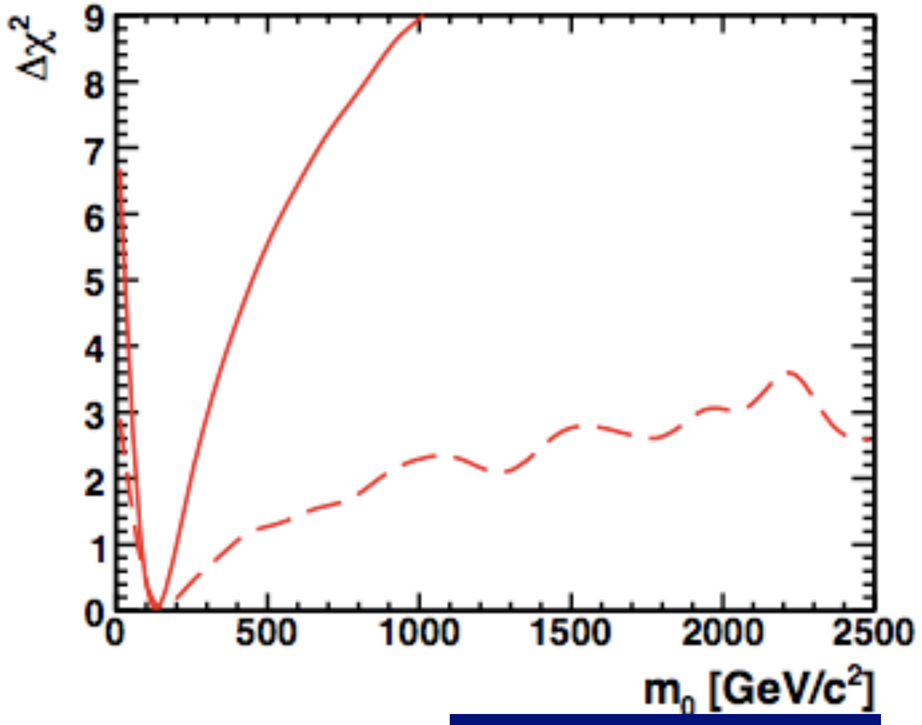



O.Buchmueller, JE et al: arXiv:0808.4128

# What Happens if $g_\mu$ - 2 Dropped?




CMSSM




NUHM1

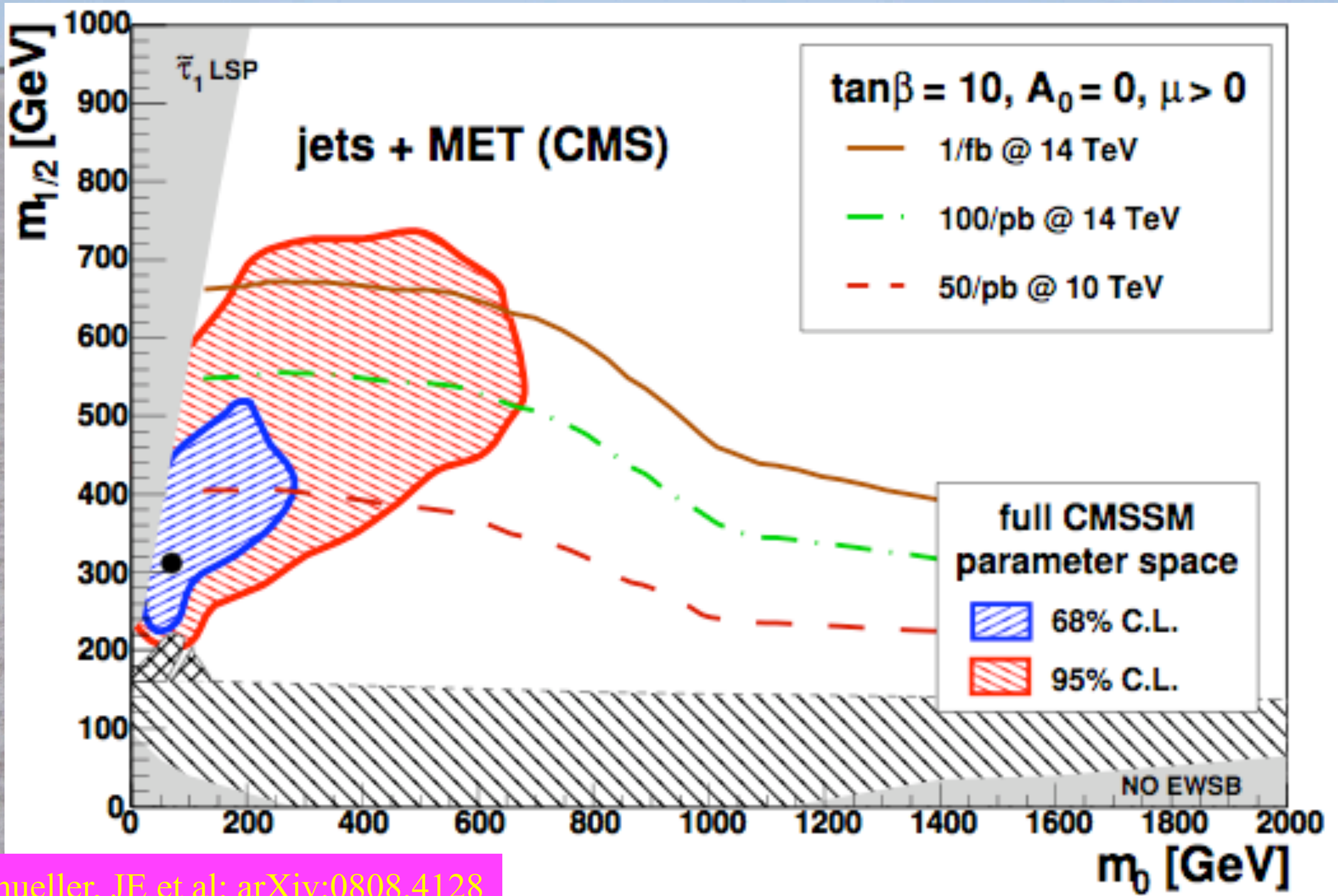
Solid lines: with $g_\mu$ - 2

Dashed lines: without $g_\mu$ - 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?

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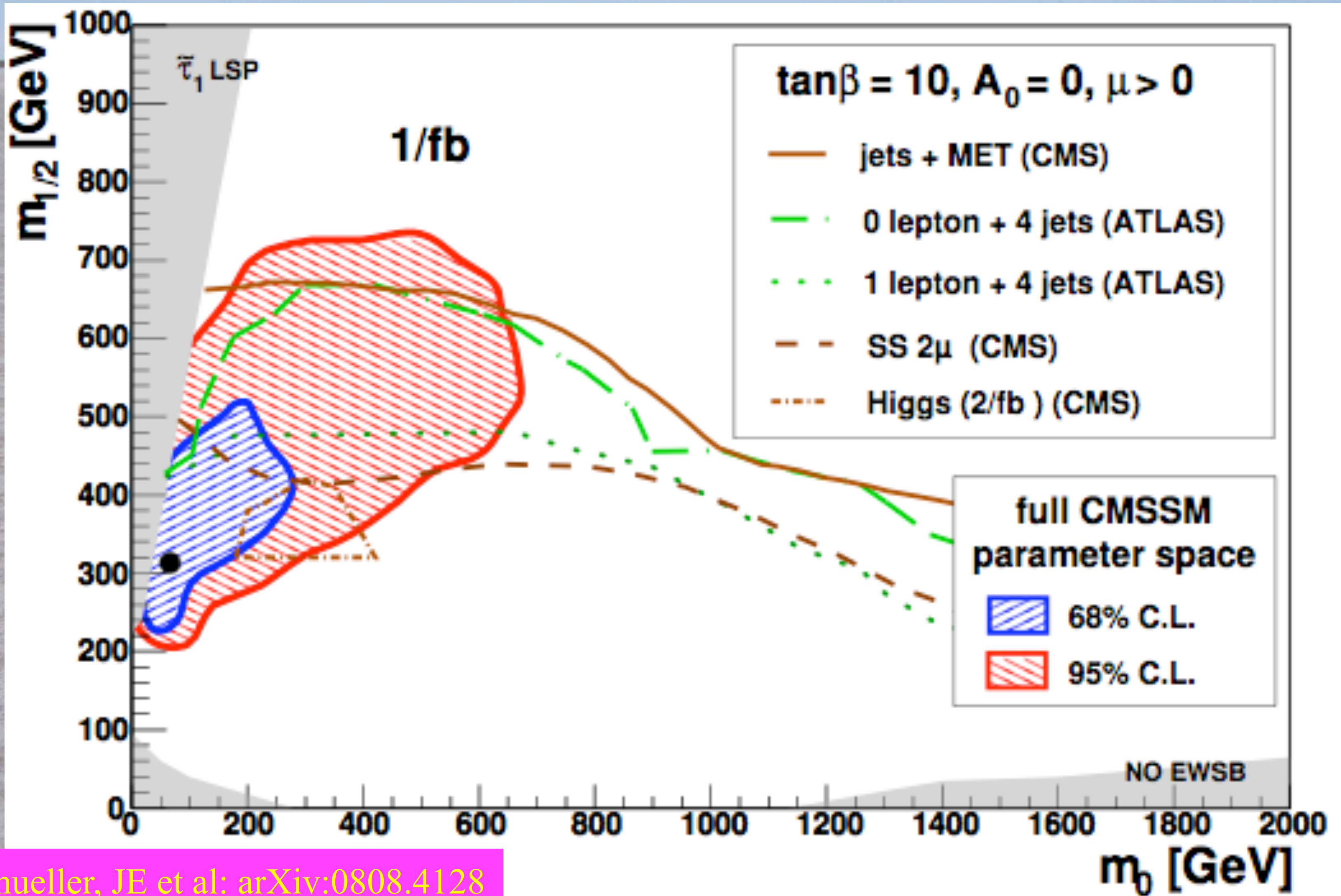
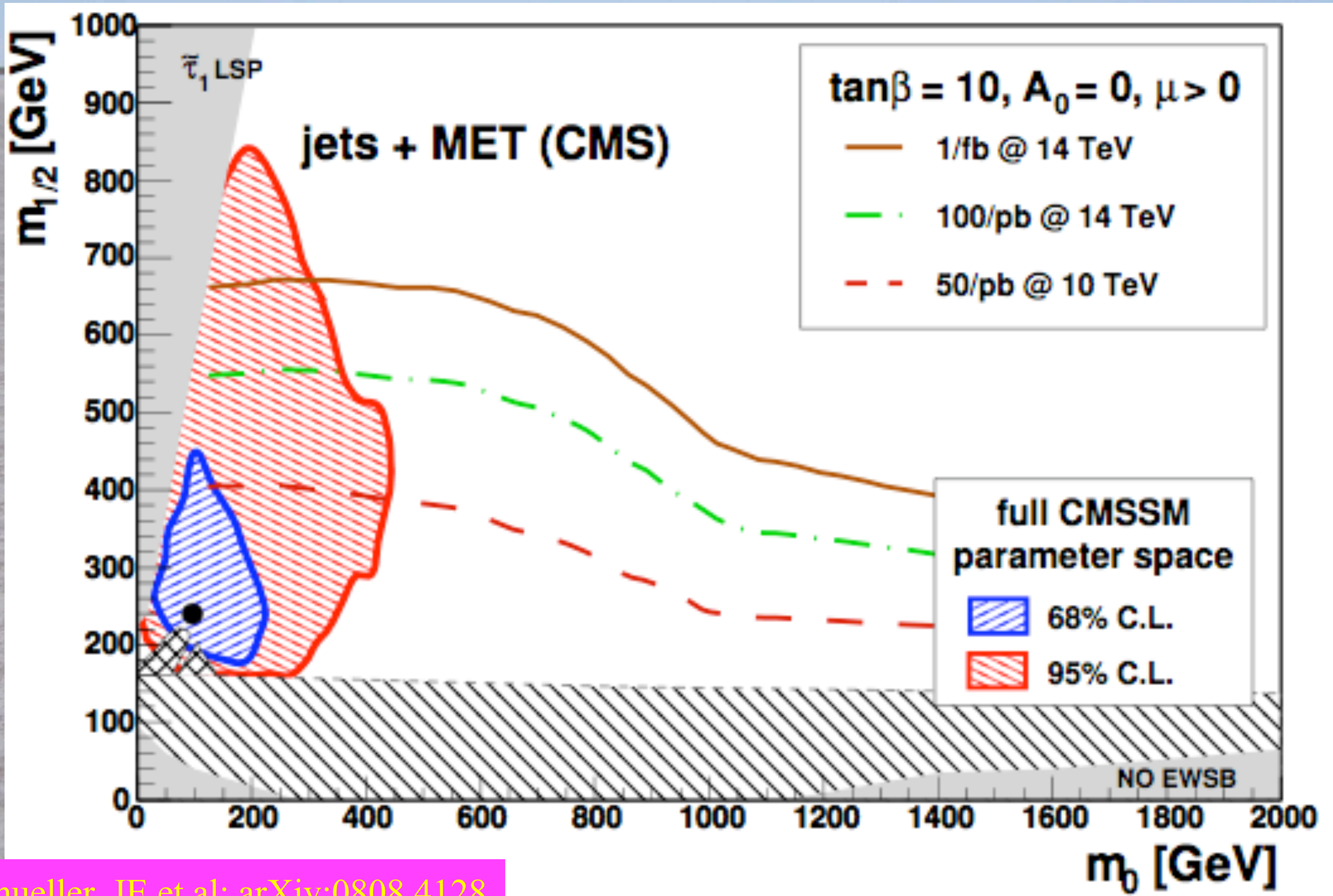
# CMSSM with 1/fb of LHC Data



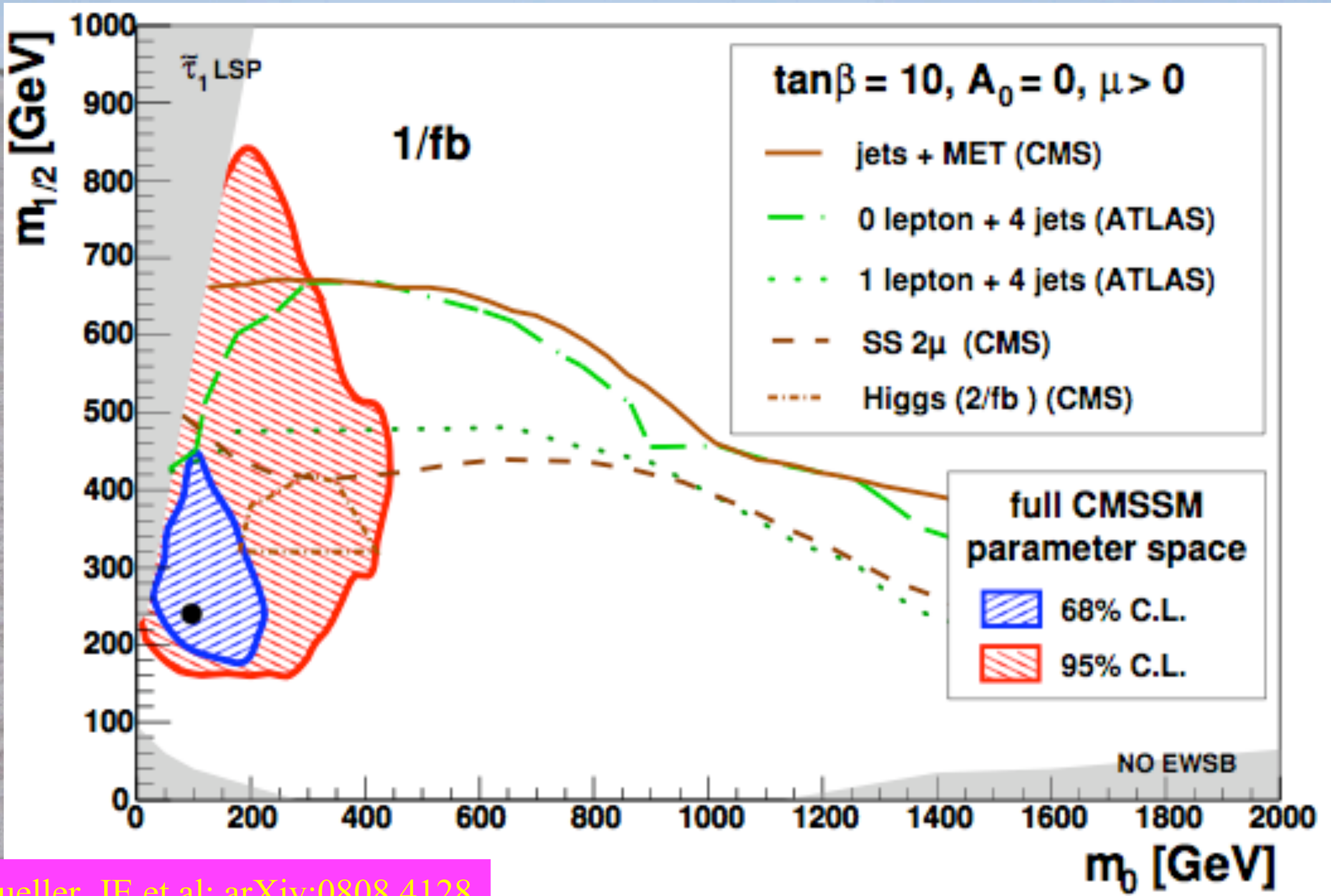

O.Buchmueller, JE et al: arXiv:0808.4128

# How Soon Might the NUHM1 be Detected?




O.Buchmueller, JE et al: arXiv:0808.4128

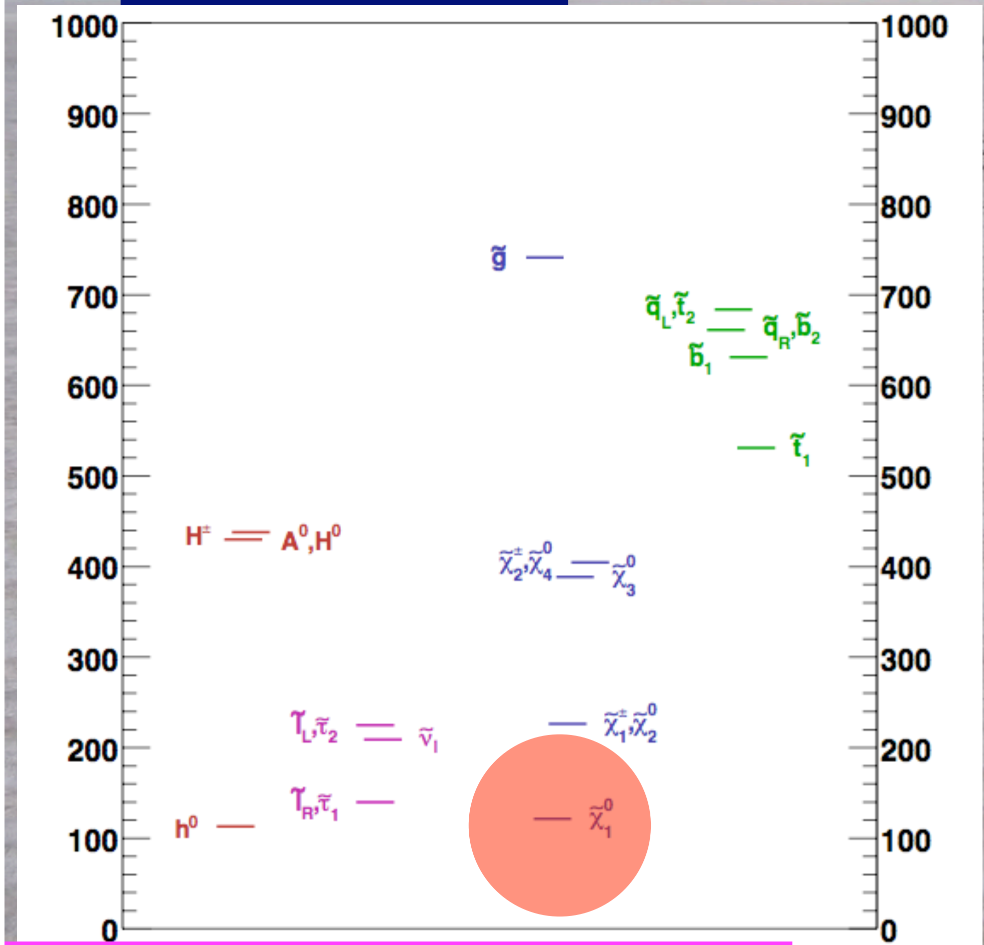
# NUHM1 with 1/fb of LHC Data



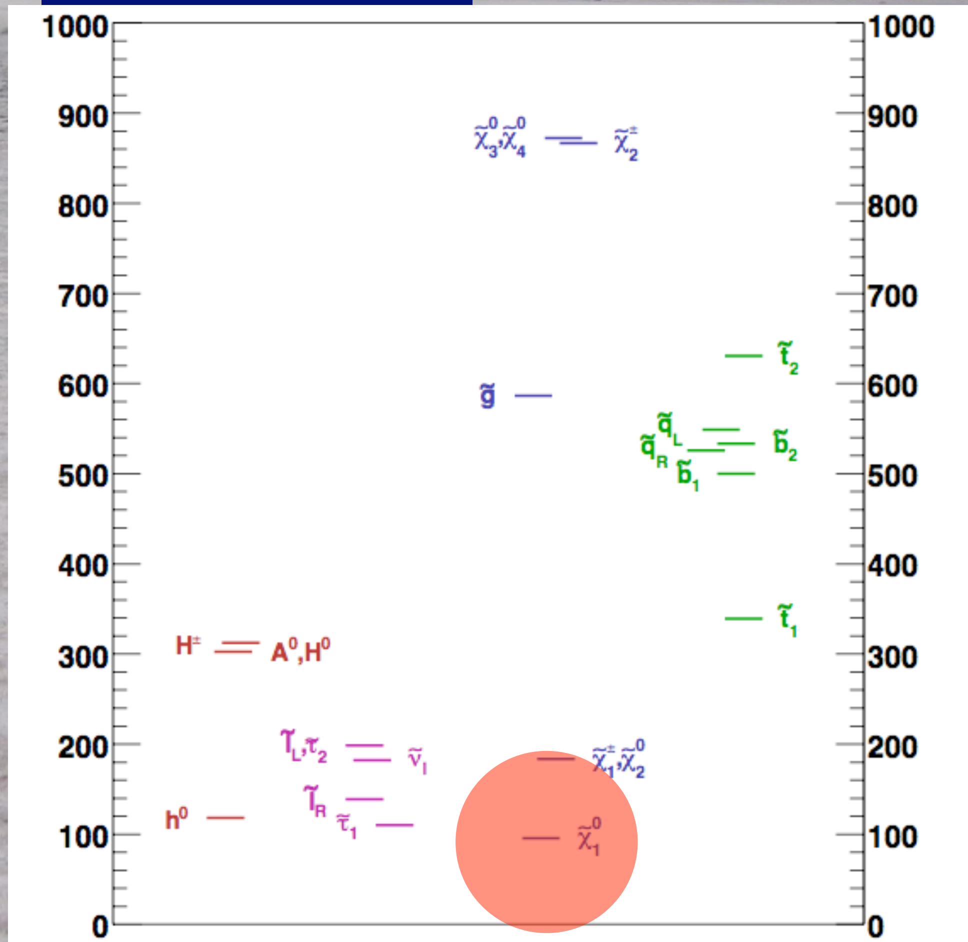

O.Buchmueller, JE et al: arXiv:0808.4128

# Best-Fit Spectra

CMSSM

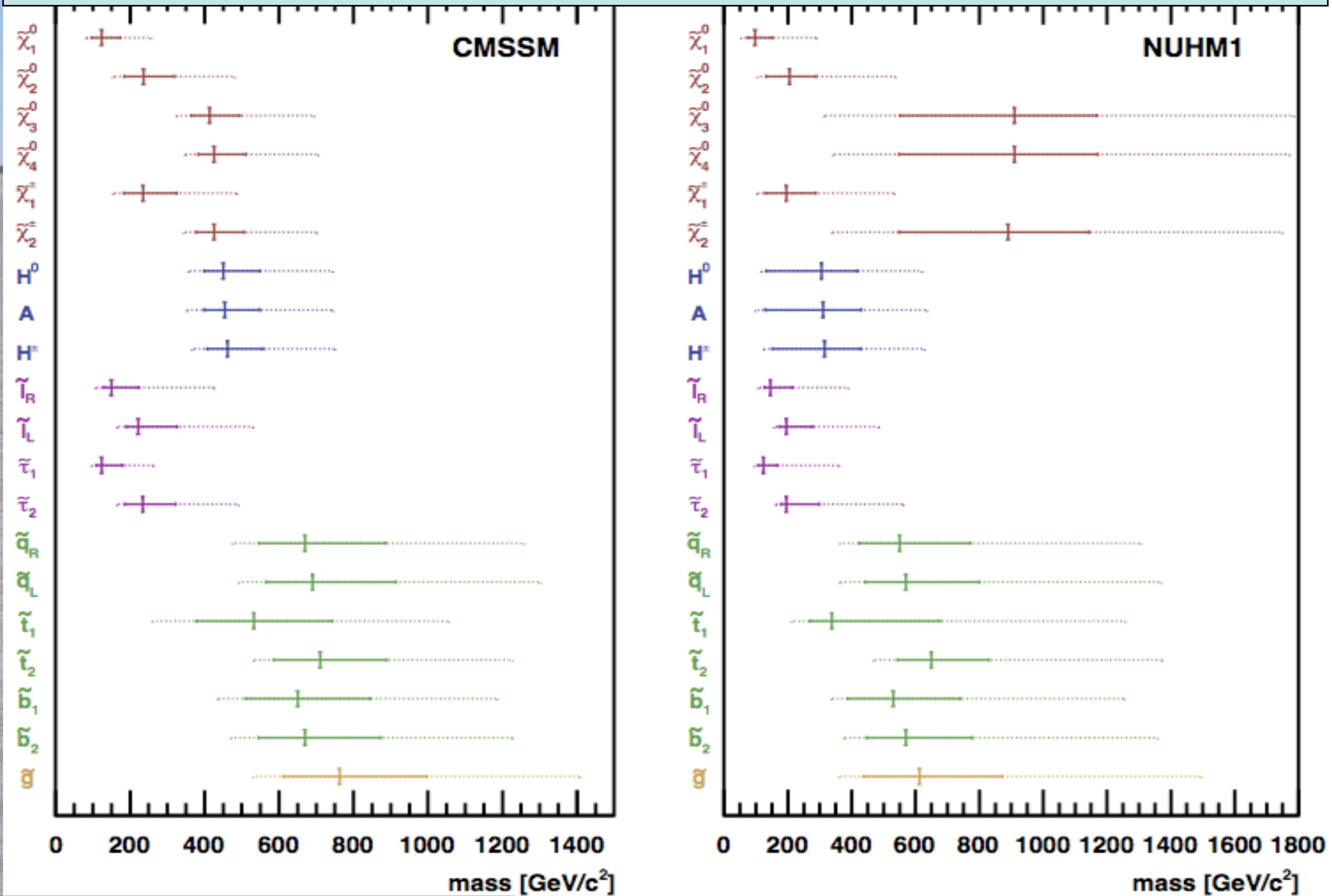



NUHM1




O.Buchmueller, JE et al: arXiv:0808.4128

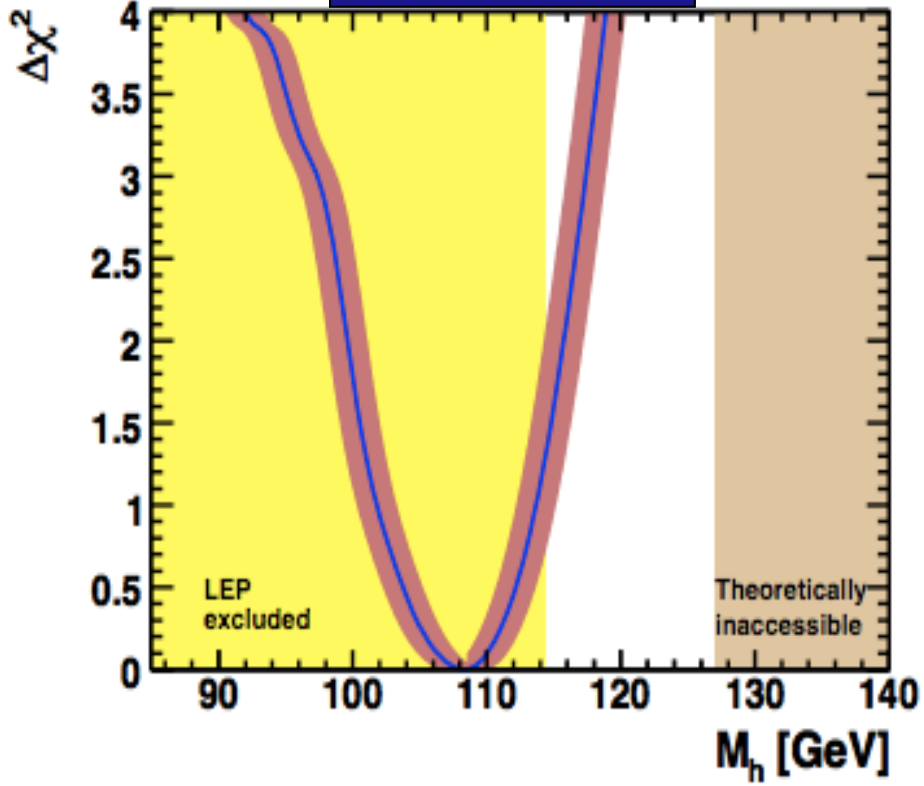
# Spectra with likely Ranges



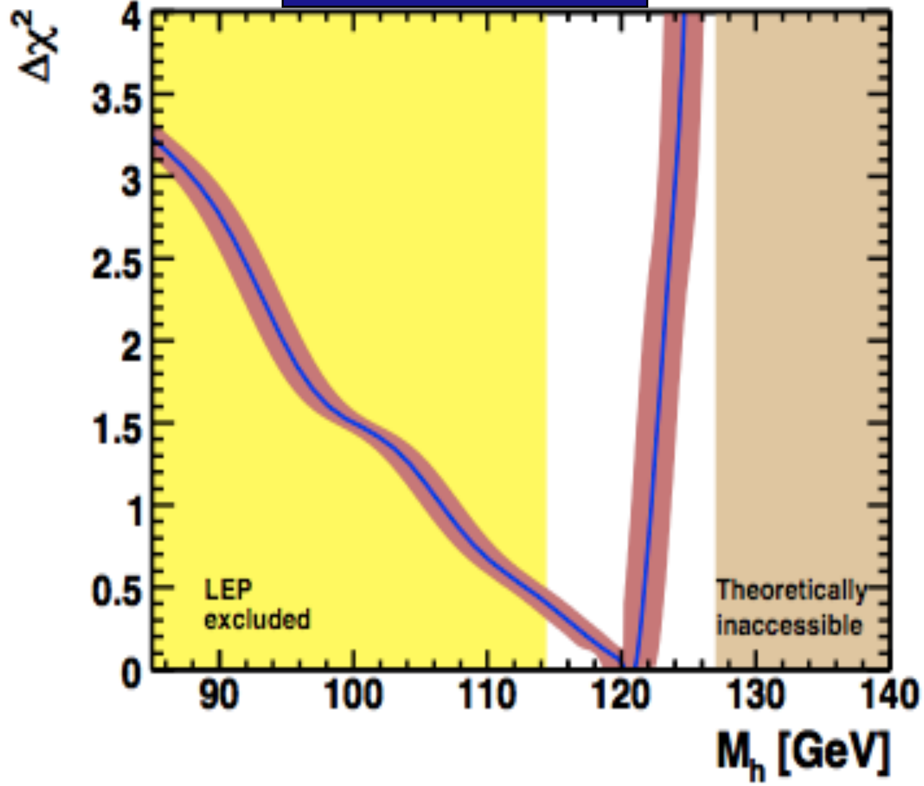

O.Buchmueller, JE et al: arXiv:0907.5568

# Likelihood Function for Higgs Mass

CMSSM

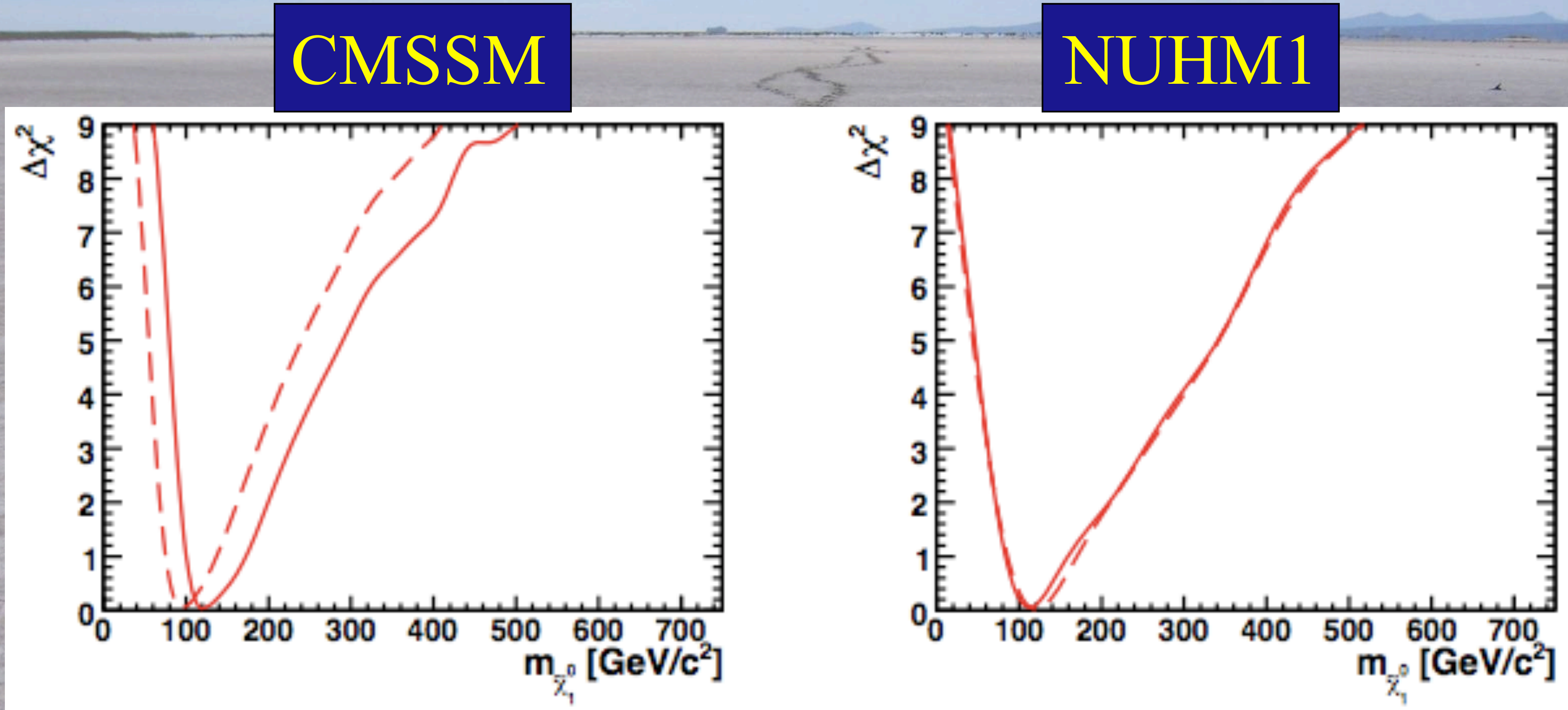



NUHM1




O.Buchmueller, JE et al: arXiv:0907.5568

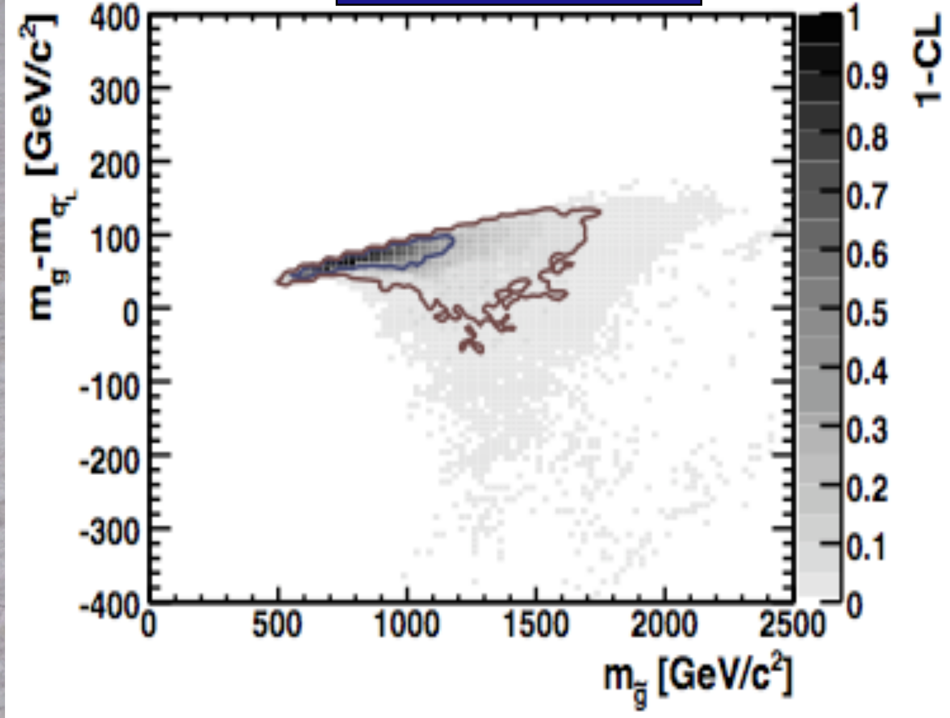
# Likelihood Function for Neutralino Mass



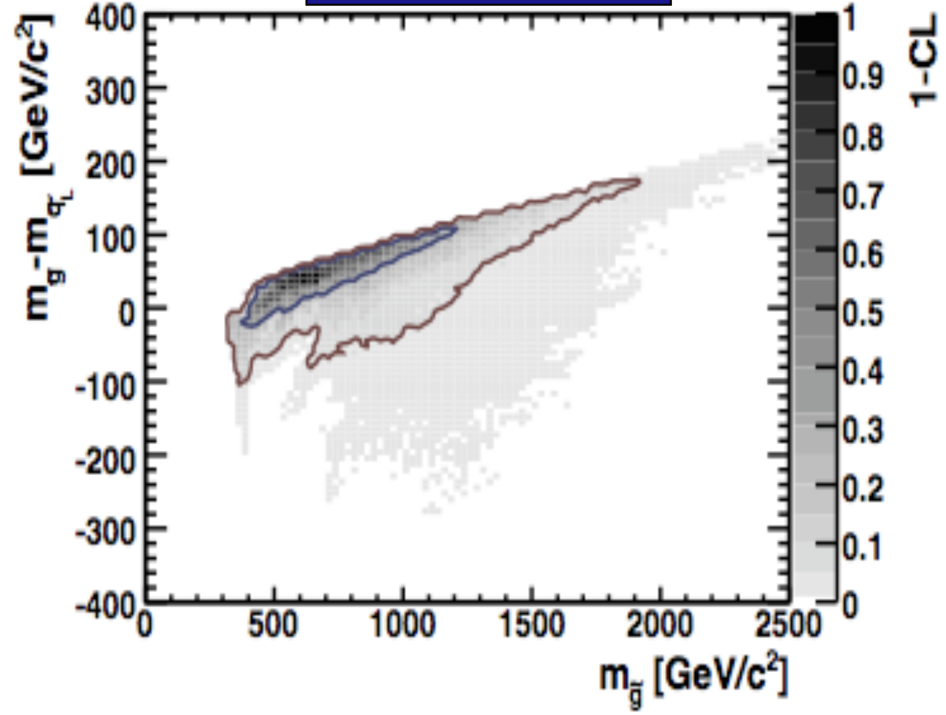

O.Buchmueller, JE et al: arXiv:0907.5568

# Correlation between Gluino & Squark Masses

CMSSM



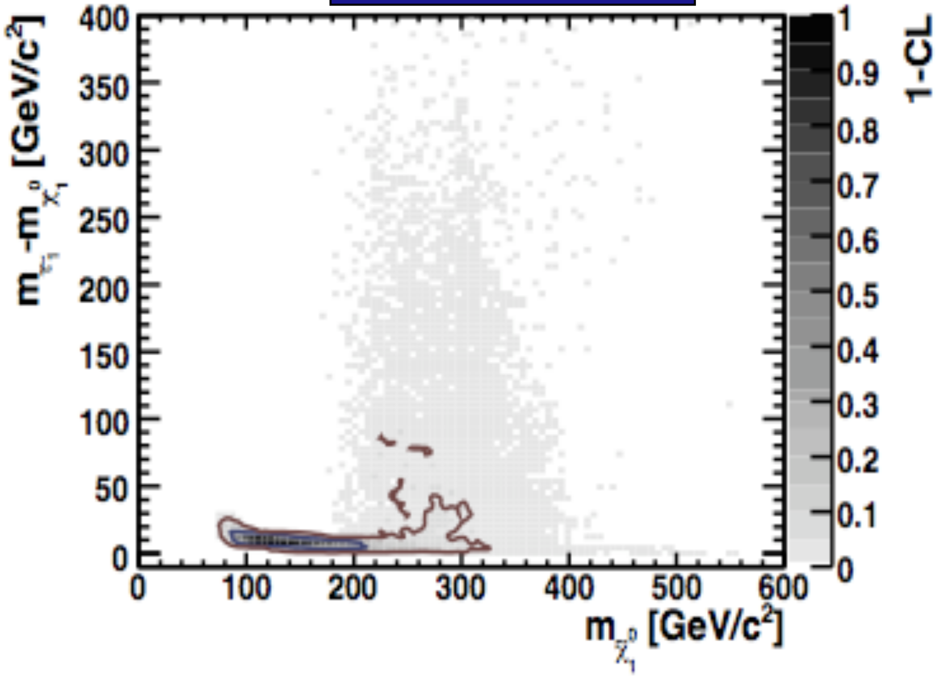

NUHM1



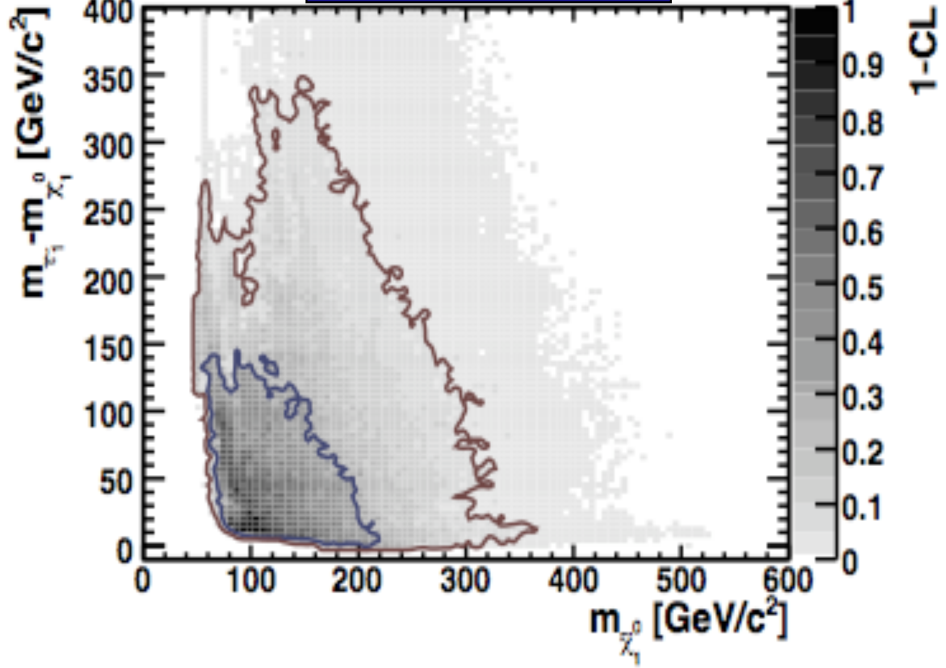

O.Buchmueller, JE et al: arXiv:0907.5568

# Correlation between Neutralino & Stau Masses

CMSSM




NUHM1

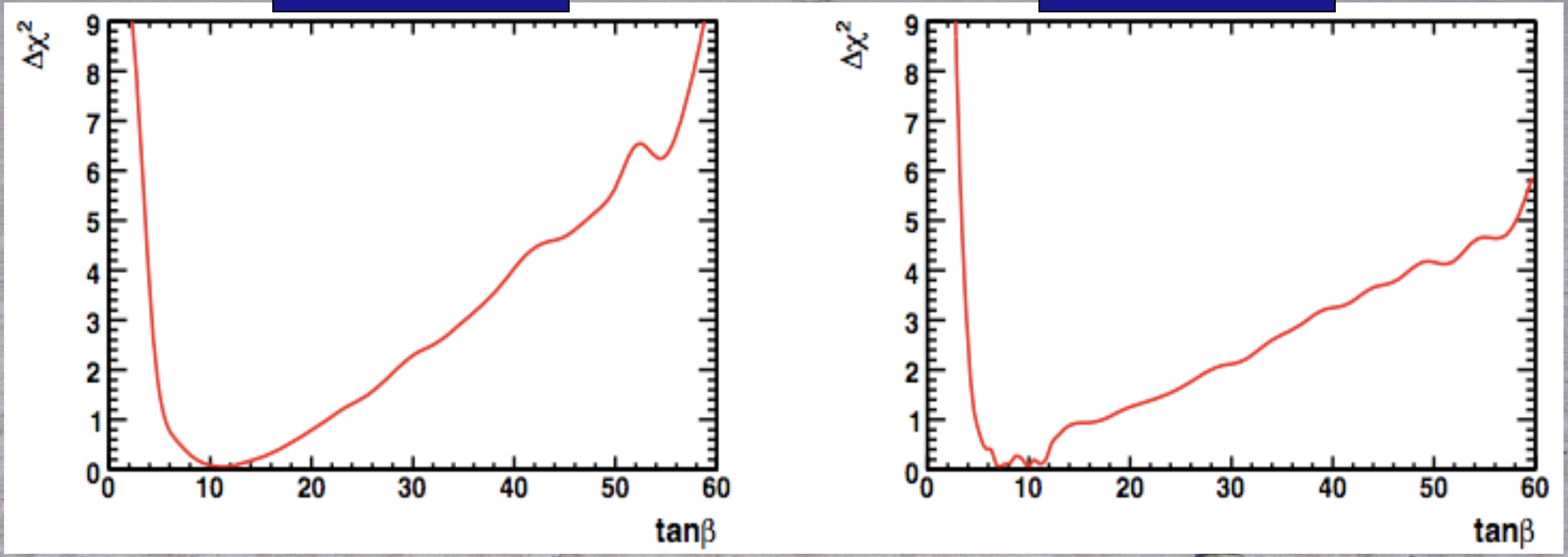



O.Buchmueller, JE et al: arXiv:0907.5568

# Likelihood Function for tan β

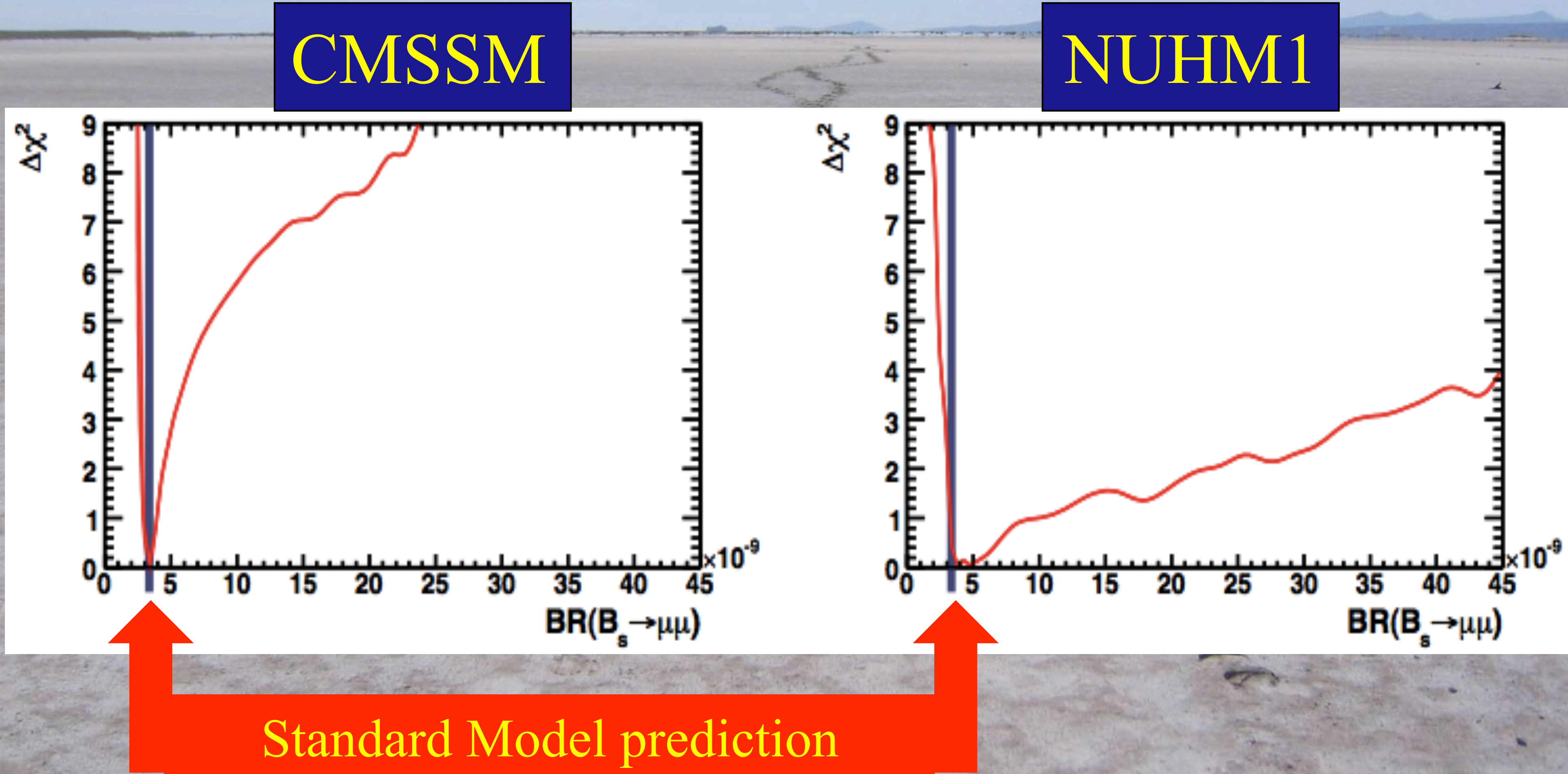
CMSSM

NUHM1



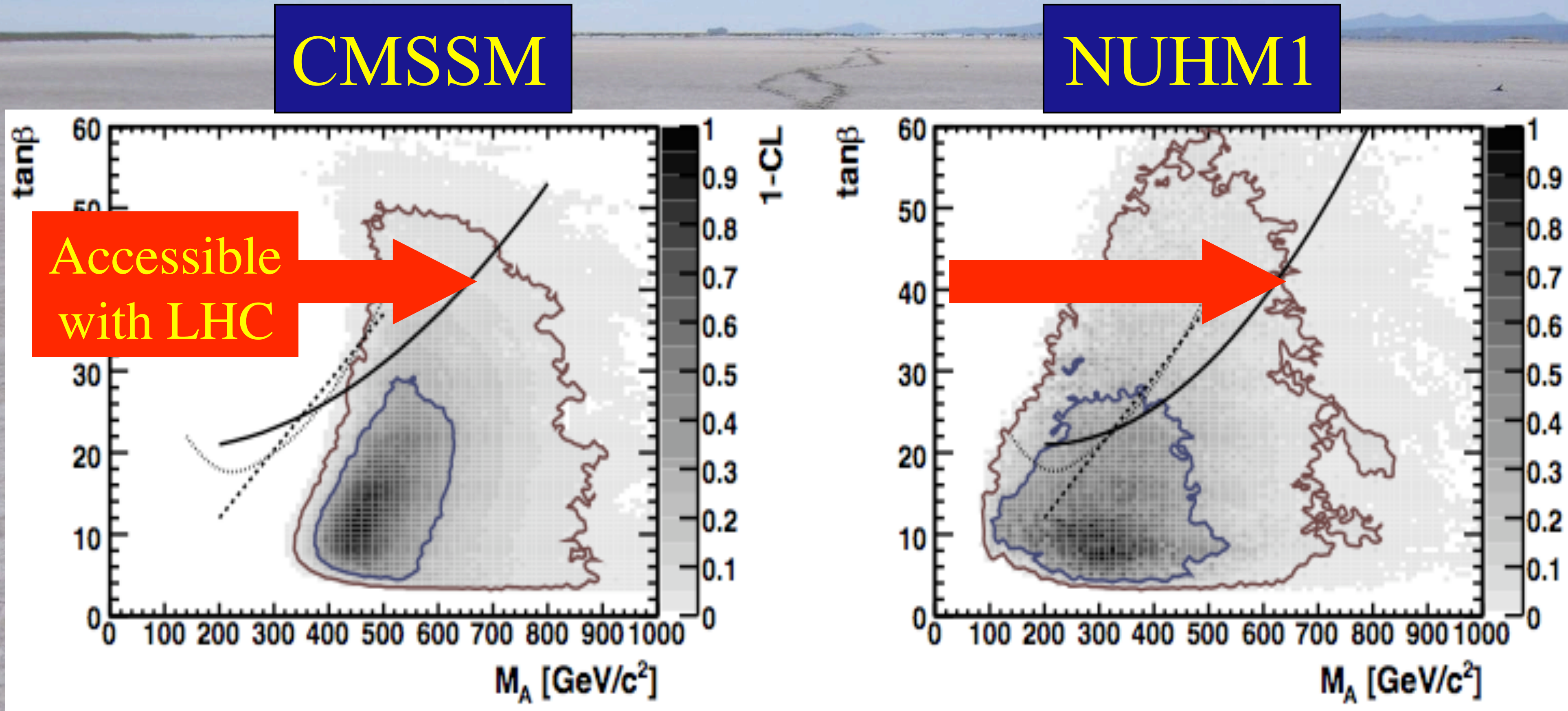

O.Buchmueller, JE et al: arXiv:0907.5568

# Likelihood Function for $B_s \rightarrow \mu^+\mu^-$




O.Buchmueller, JE et al: arXiv:0907.5568

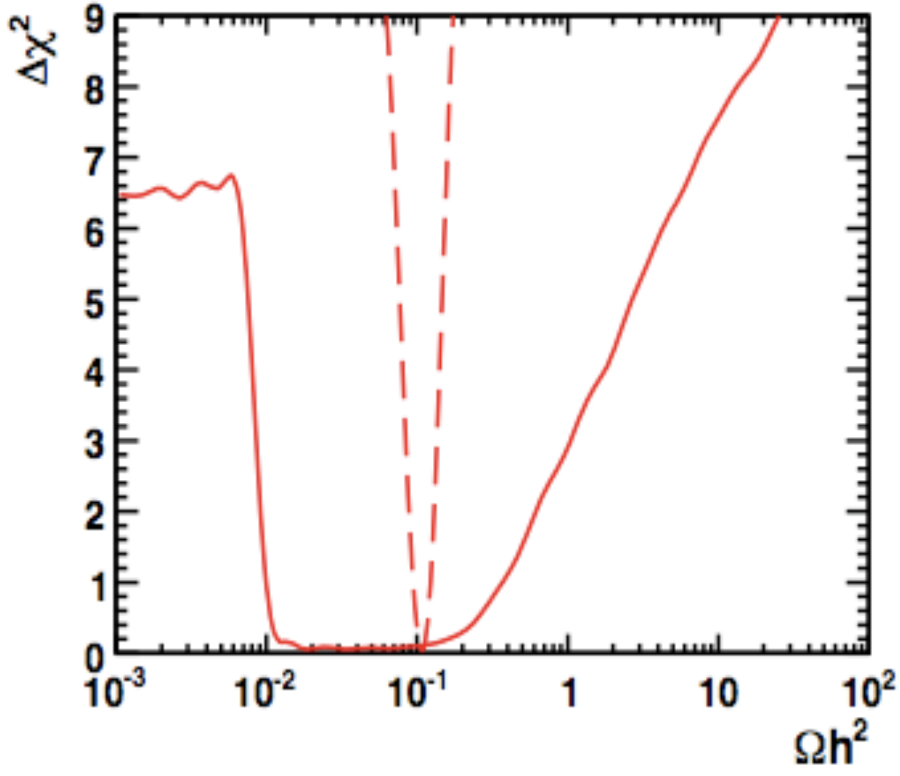
# Can the LHC find heavier Higgs Bosons?



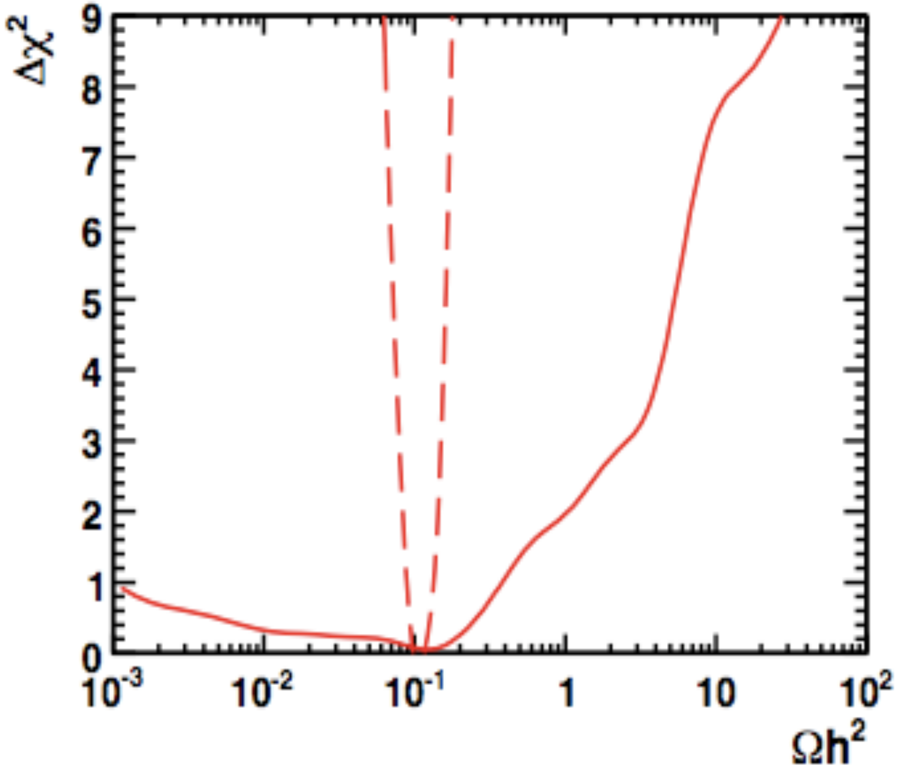

O.Buchmueller, JE et al: arXiv:0907.5568

# Predictions for Dark Matter Density

CMSSM




NUHM1




O.Buchmueller, JE et al: arXiv:0907.5568

# Strategies for Detecting Supersymmetric Dark Matter

- Annilihation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?
- Annilihation in galactic centre

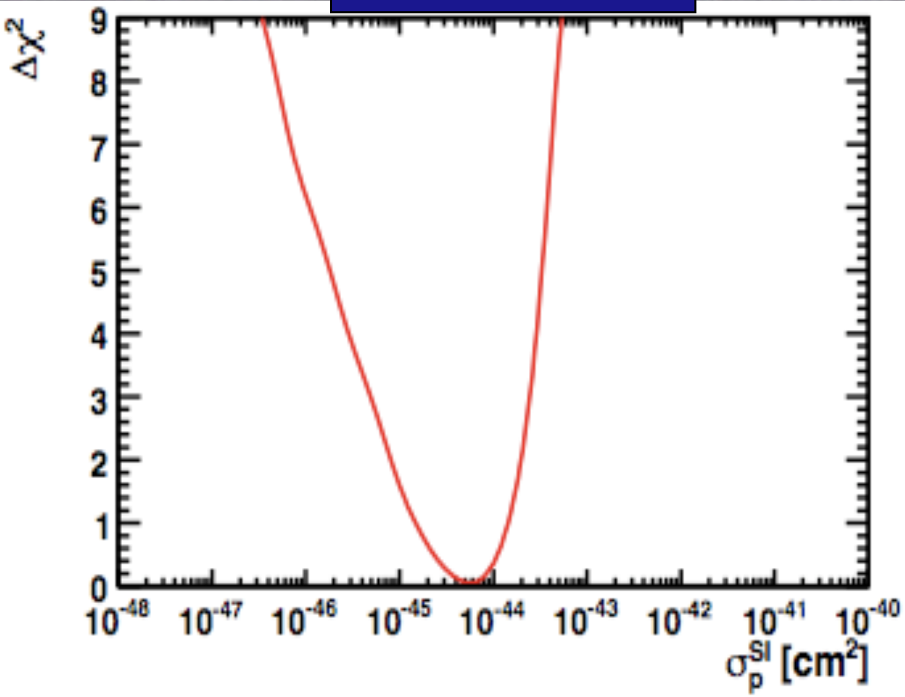
  $\chi - \chi \rightarrow \gamma + \ldots ?$
- Annilihation in core of Sun or Earth

  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$
- Scattering on nucleus in laboratory

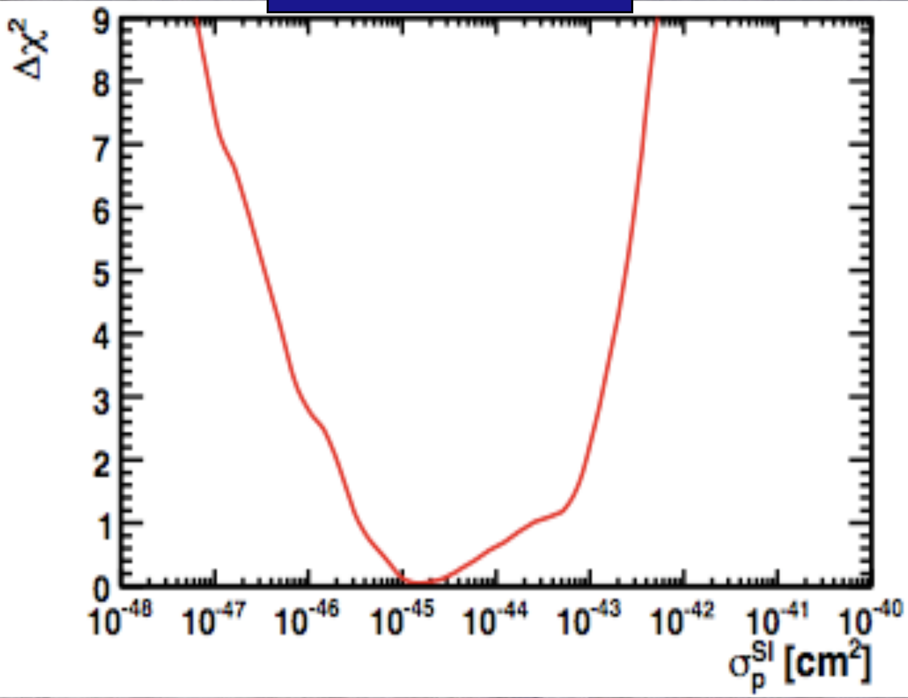
  $\chi + A \rightarrow \chi + A$

# Likelihood Function for Spin-Independent Dark Matter Scattering

CMSSM




NUHM1

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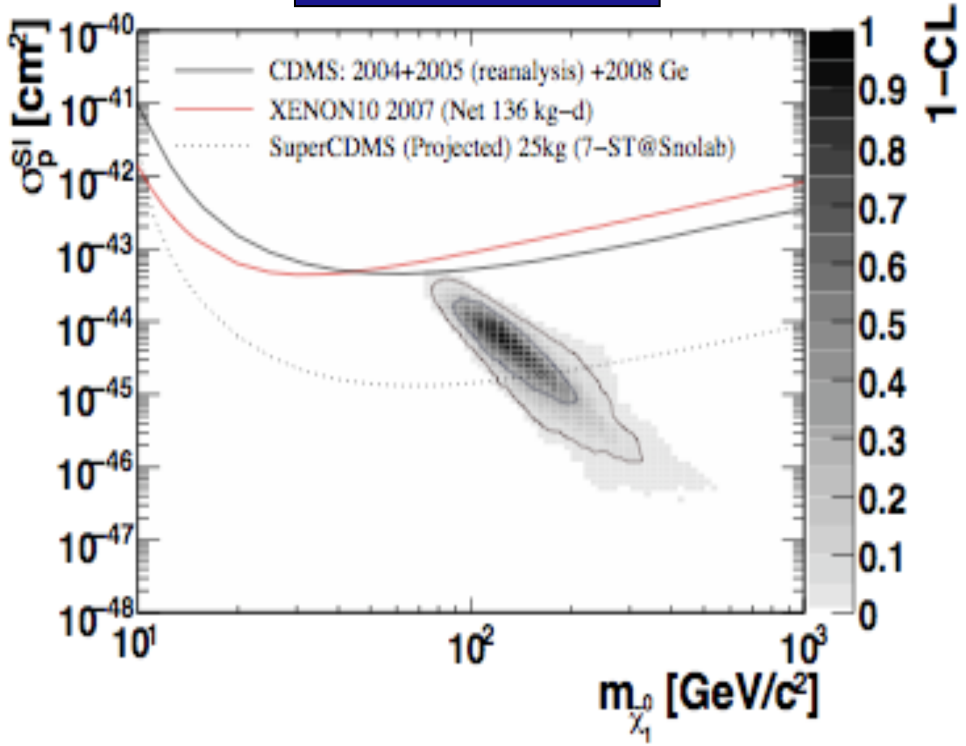
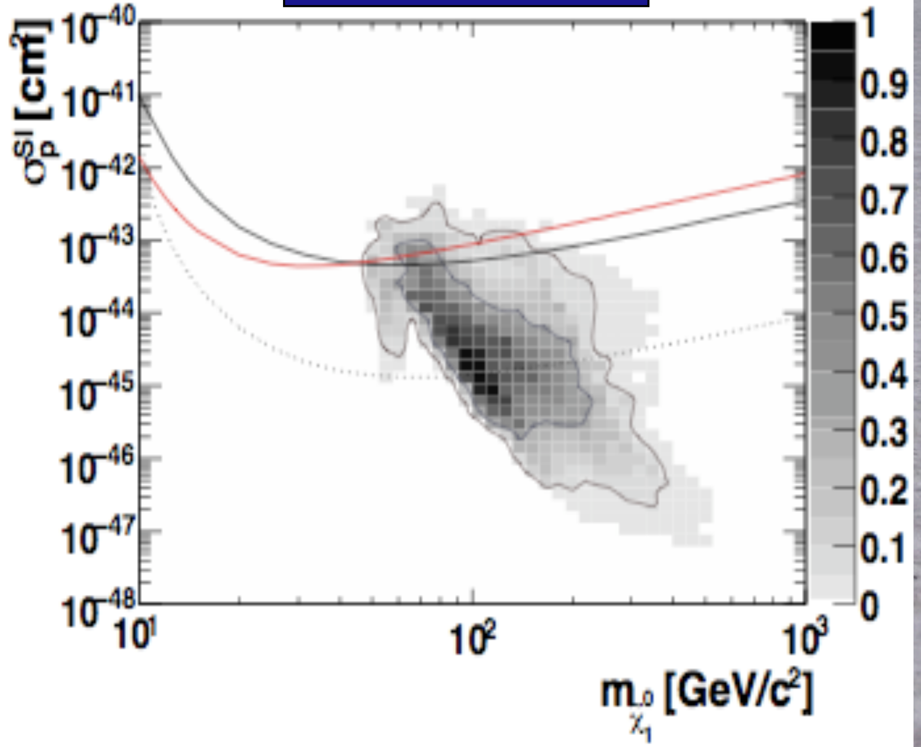
# Elastic Scattering Cross Sections

CMSSM

NUHM1

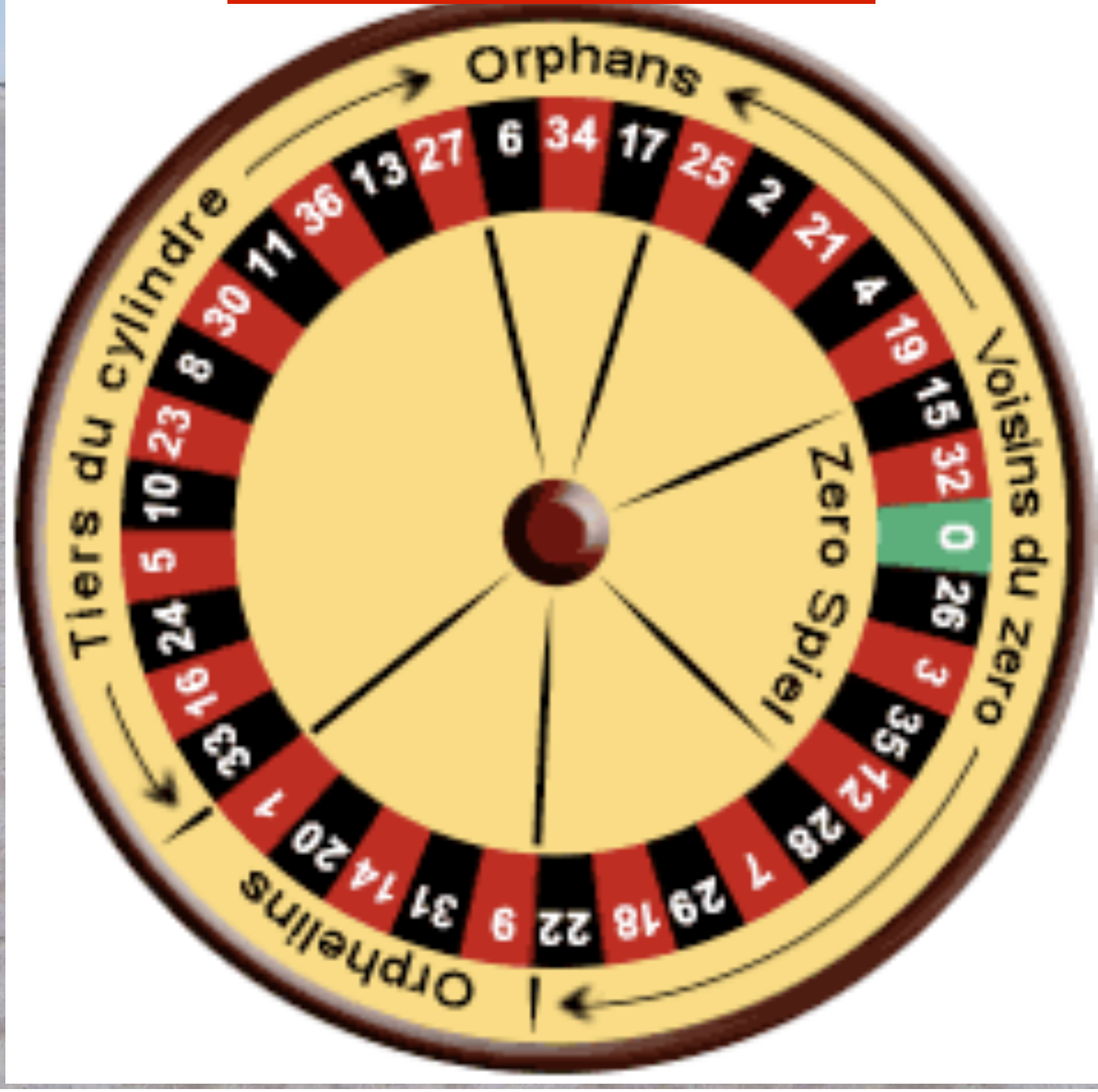


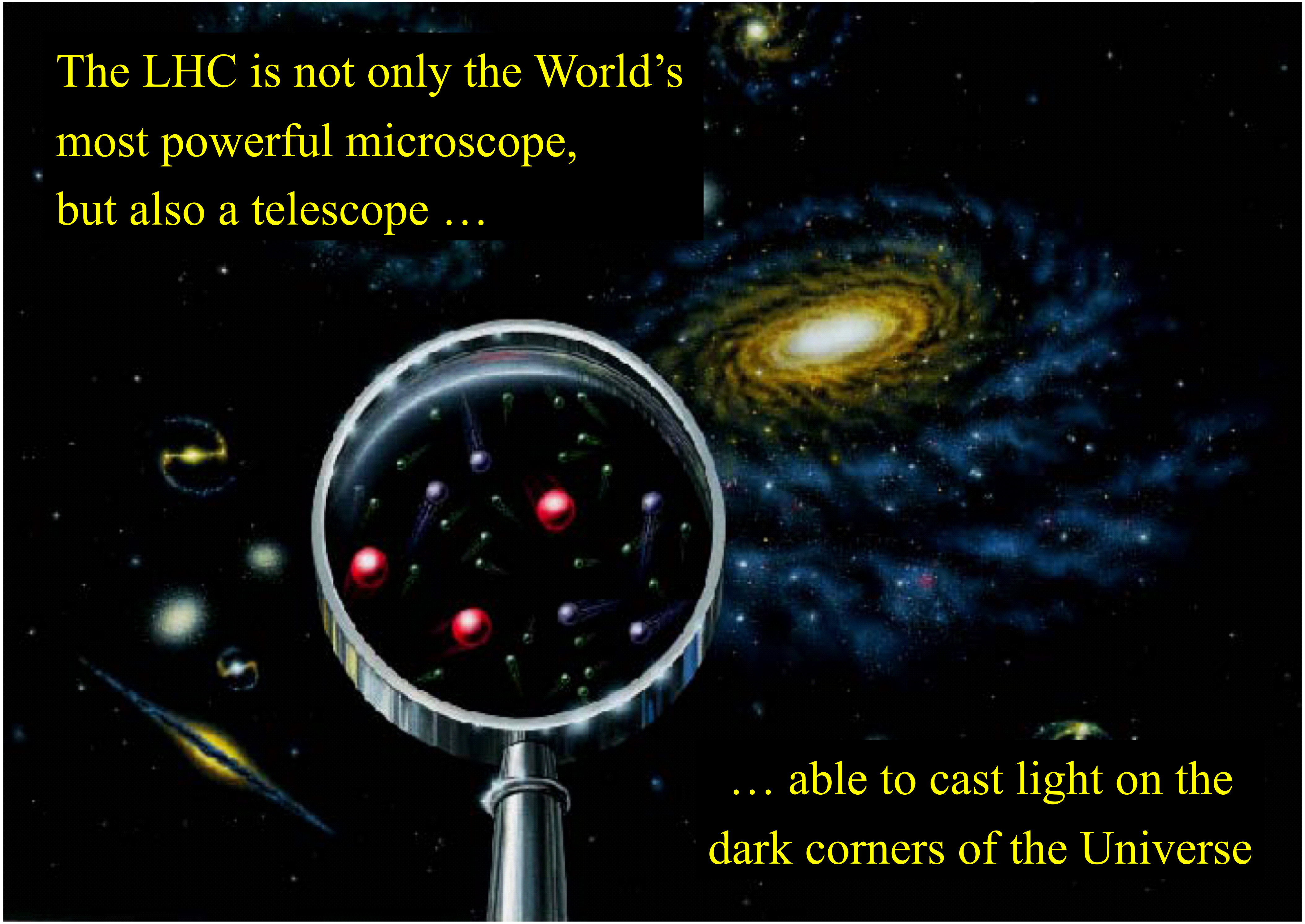

O.Buchmueller, JE et al: arXiv:0907.5568

# The LHC Roulette Wheel

Extra dimensions



The LHC is not only the World's most powerful microscope, but also a telescope …



… able to cast light on the dark corners of the Universe

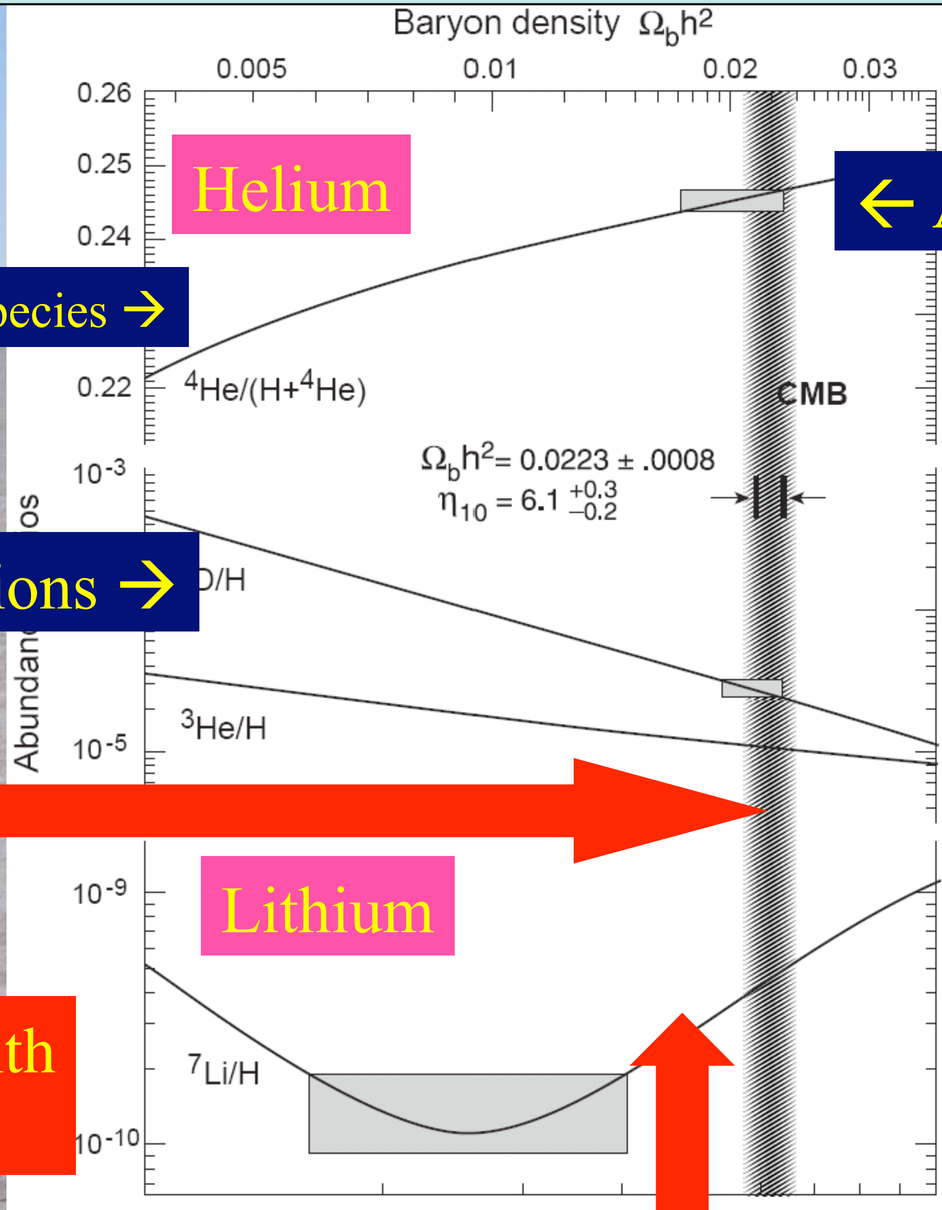
# Long-lived Supersymmetric Particle

- Inevitable in many models
  - because gravitino has gravitation-strength interactions $\sim 1/M_P$
- If neutralino is LSP:
  - Gravitino is long-lived
- If gravitino is LSP
  - Next-to-lightest sparticle (NLSP) is long-lived
- Constrained by possible effects on light-element abundances

# Making Elements in the Early Universe

- Universe contains about 24% Helium 4
  - and less Deuterium, Helium 3, Lithium 7
- Could only have been cooked by nuclear reactions in dense early Universe
  - when Universe billion times smaller, hotter than today
- Dependent on amount of matter in Universe
  - not enough to stop expansion, explain galaxies
- Dependent on number of particle types
  - number of different neutrinos measured at accelerators

# Abundances of light elements in the Universe

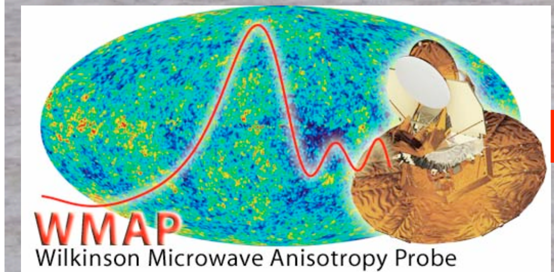



Helium

← Agree with data

Assuming 3 neutrino species →

Theoretical calculations →



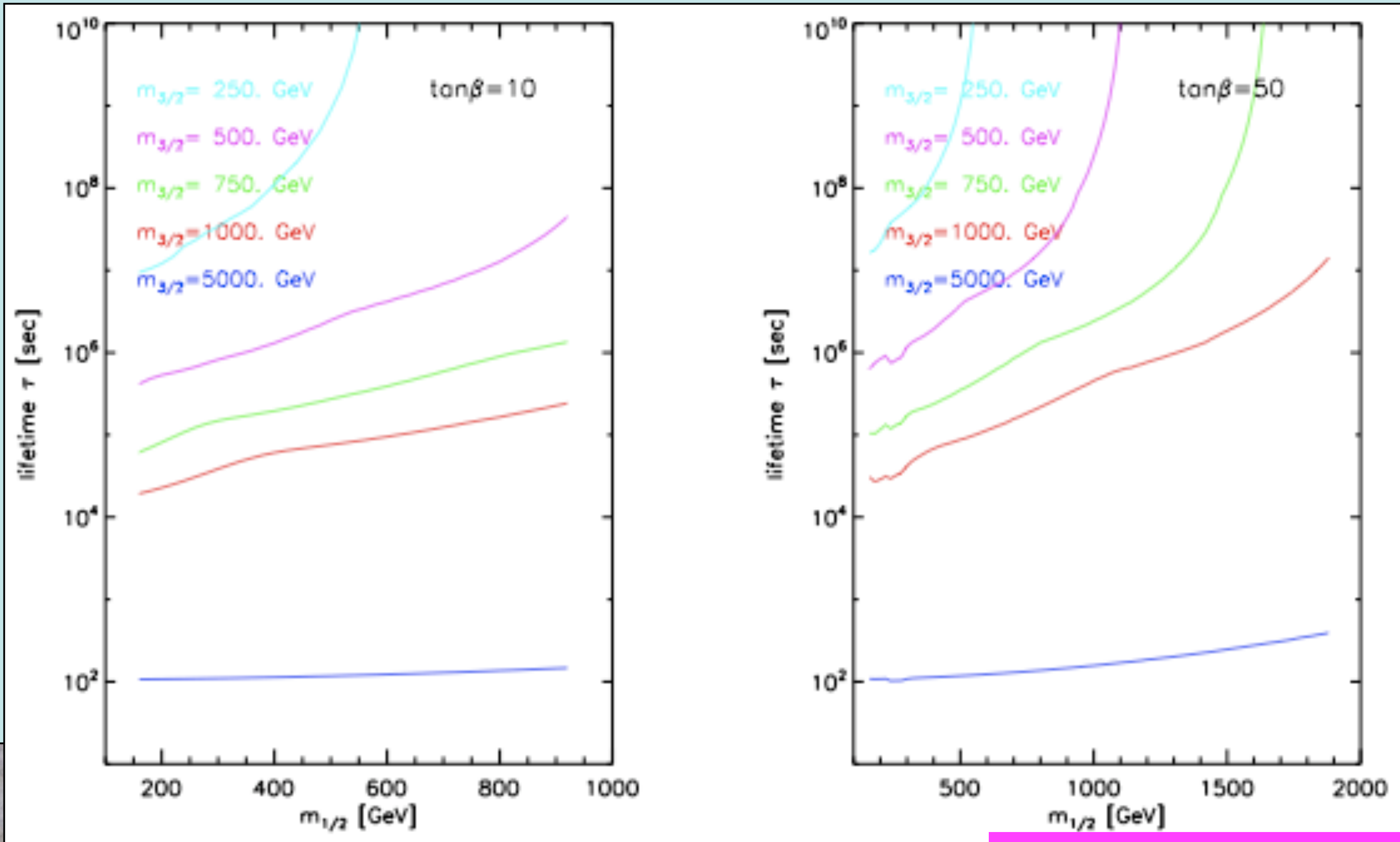

Lithium

Possible problem with abundance of $^7Li$

Not enough ordinary matter to make the Universe recollapse

# Gravitino Lifetime in CMSSM

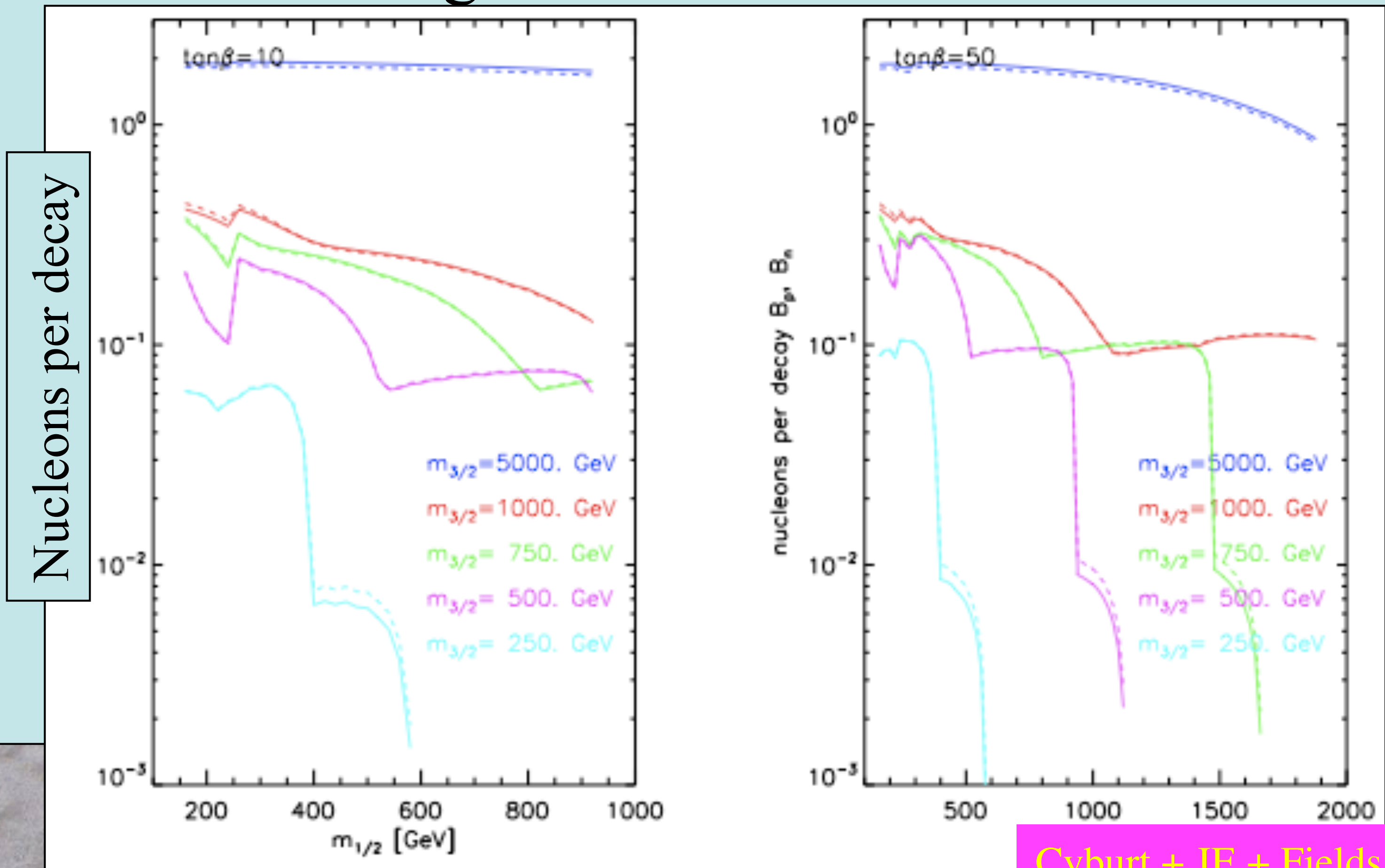
- Lifetimes along WMAP strip for different $m_{3/2}$




Cyburt + JE + Fields + Luo + Olive

# Hadronic Components of Showers Produced by Decays

- Electromagnetic and hadronic components of showers affect light-element abundances




Cyburt + JE + Fields + Luo + Olive

# Light-Element Abundances

- Deuterium abundance agrees with calculations:

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.82 \pm 0.21) \times 10^{-5}$$

- Upper limit on primordial $^3$He abundance:

$$\left(\frac{^3\mathrm{He}}{\mathrm{D}}\right)_p < 1.0$$

- $^4$He abundance agrees with calculations:

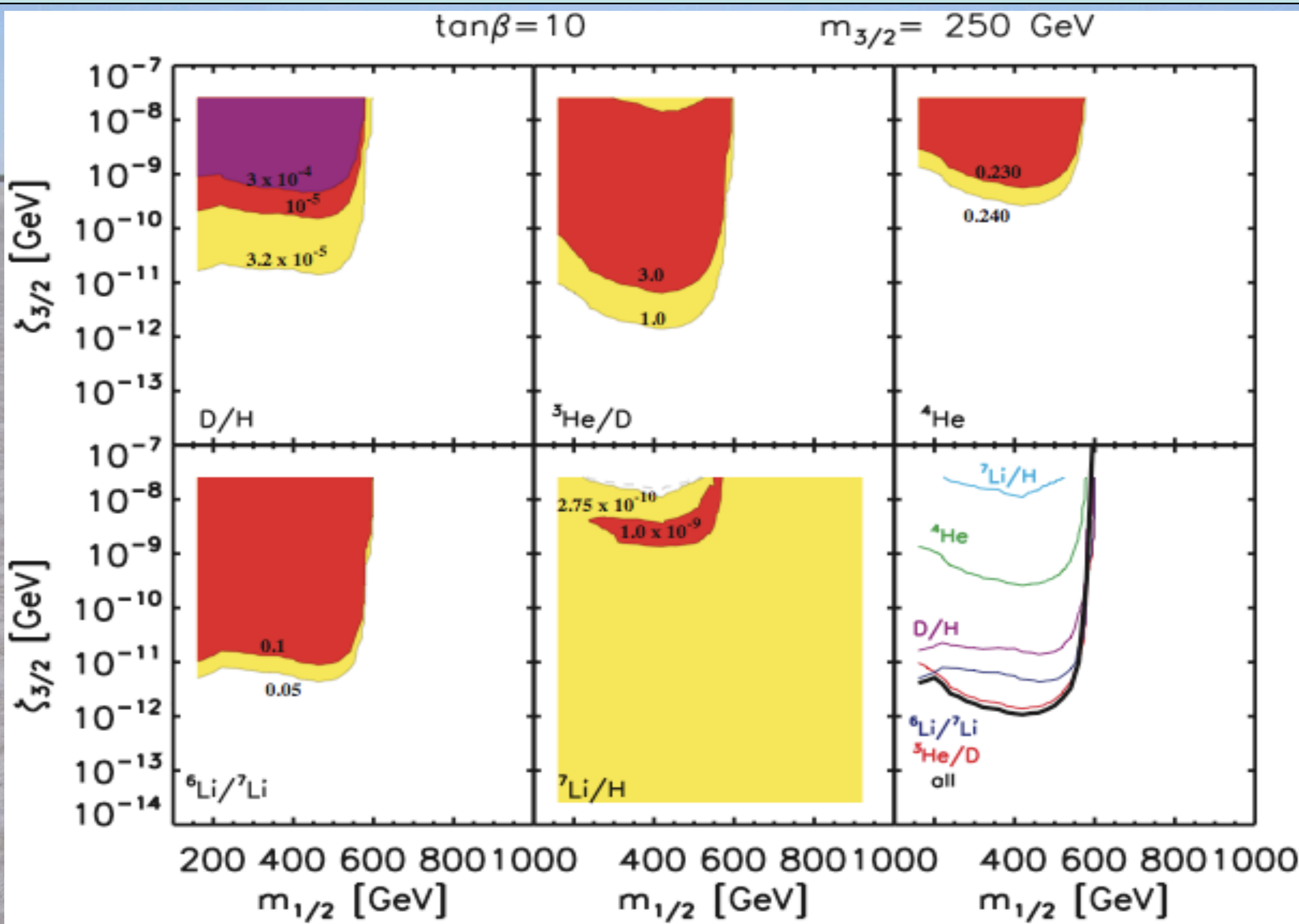
$$Y_p = 0.249 \pm 0.009$$

- **$^7$Li abundance less than predicted:**

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{gc}} = (2.19 \pm 0.28) \times 10^{-10} \qquad \frac{^6\mathrm{Li}}{^7\mathrm{Li}} \approx 0.05$$

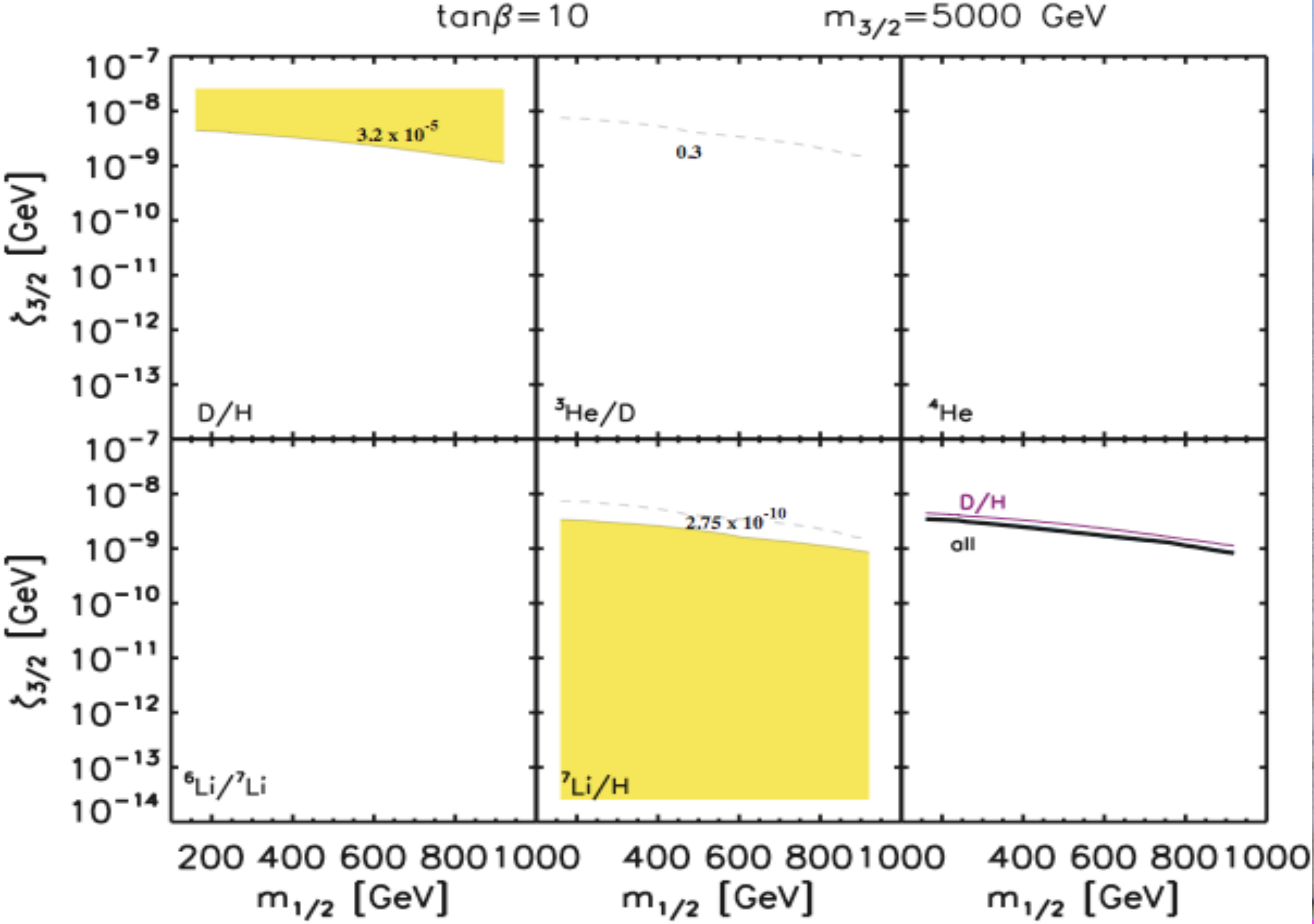
Cyburt + JE + Fields + Luo + Olive

# Constraints from Light-Element Abundances



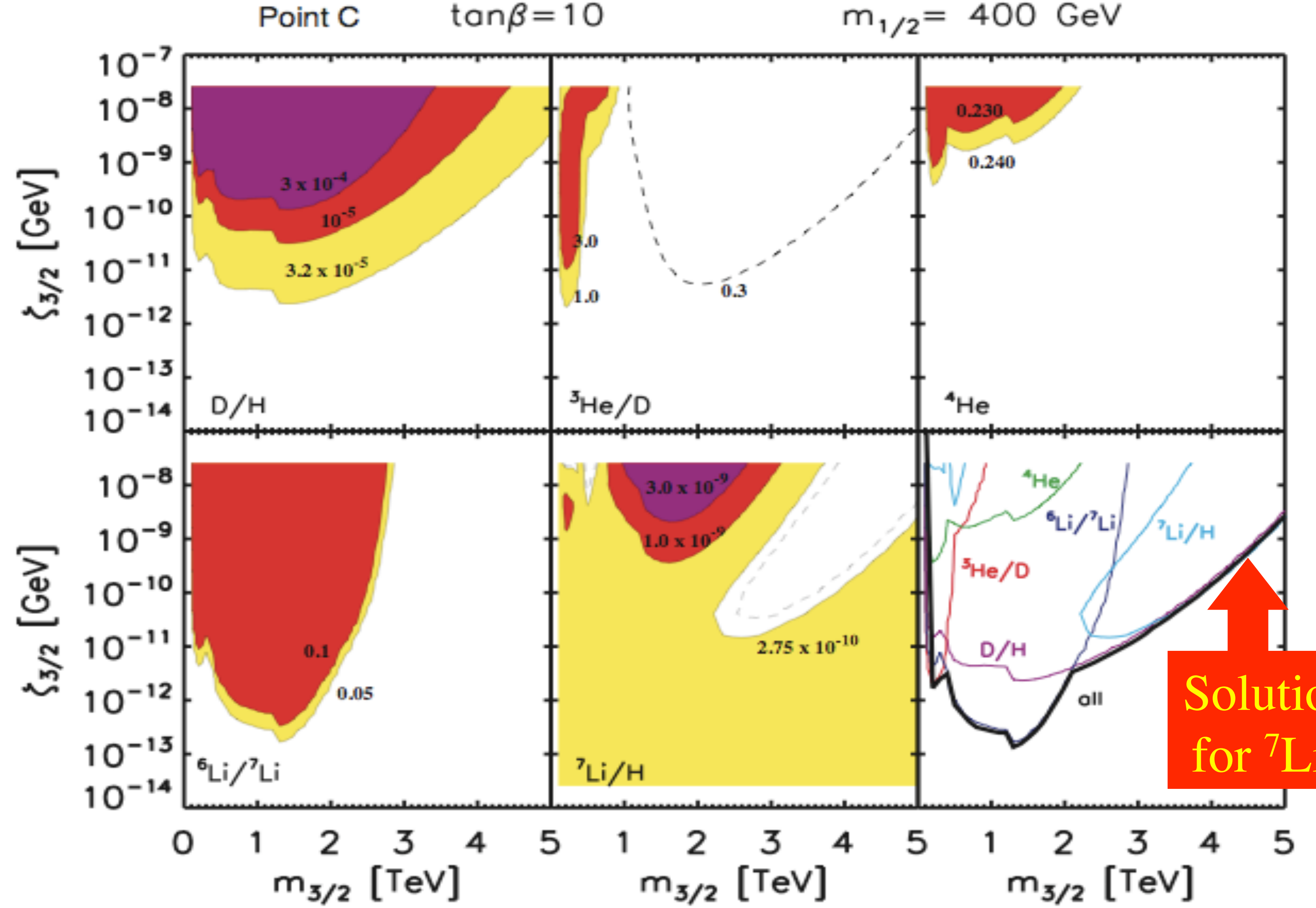

Cyburt + JE + Fields + Luo + Olive

# Constraints from Light-Element Abundances




Cyburt + JE + Fields + Luo + Olive

# Constraints from Light-Element Abundances




Solution for $^7$Li?

Cyburt + JE + Fields + Luo + Olive