Searching for New Physics at the LHC

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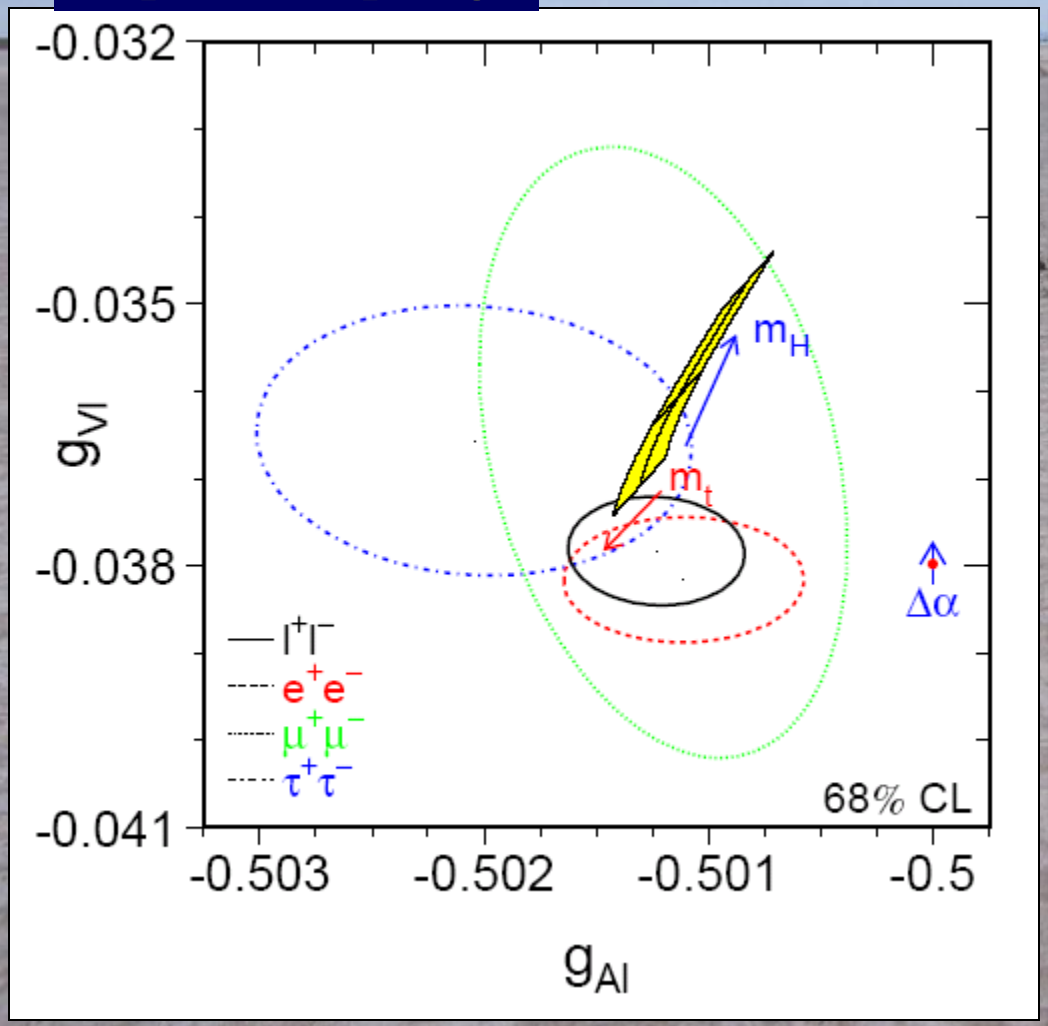
Open Questions beyond the Standard Model

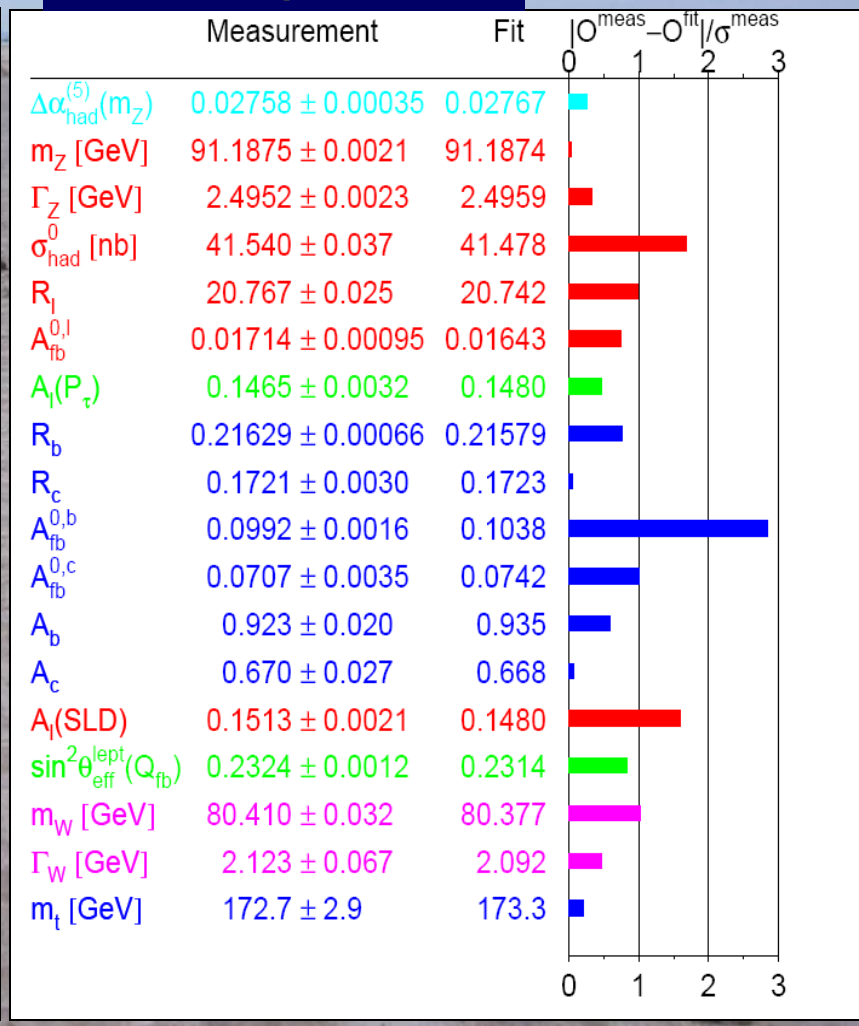
- What is the origin of particle masses? Strings
  due to a Higgs boson?
- Why so many types of matter particles? Strings
- What is the dark matter in the Universe Strings
- Unification of fundamental forces? Strings
- Quantum theory of gravity? Strings

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit



The State of the Higgs: January 2010

- Direct search limit from LEP:

  $m_H > 114.4$ GeV

- Electroweak fit sensitive to m_t

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

- Best-fit value for Higgs mass:

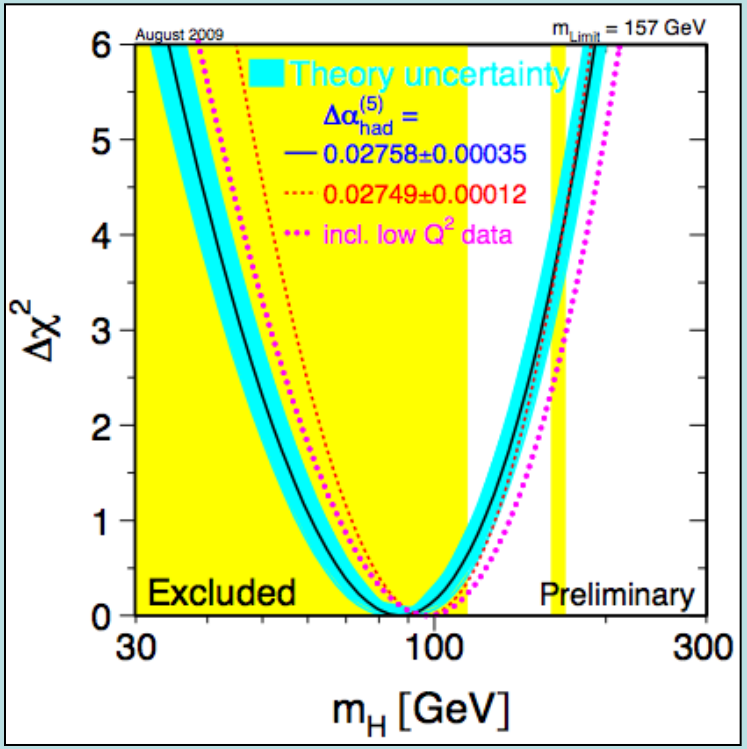
  $m_H = 89^{+35}_{-26}$ GeV

- 95% confidence-level upper limit:

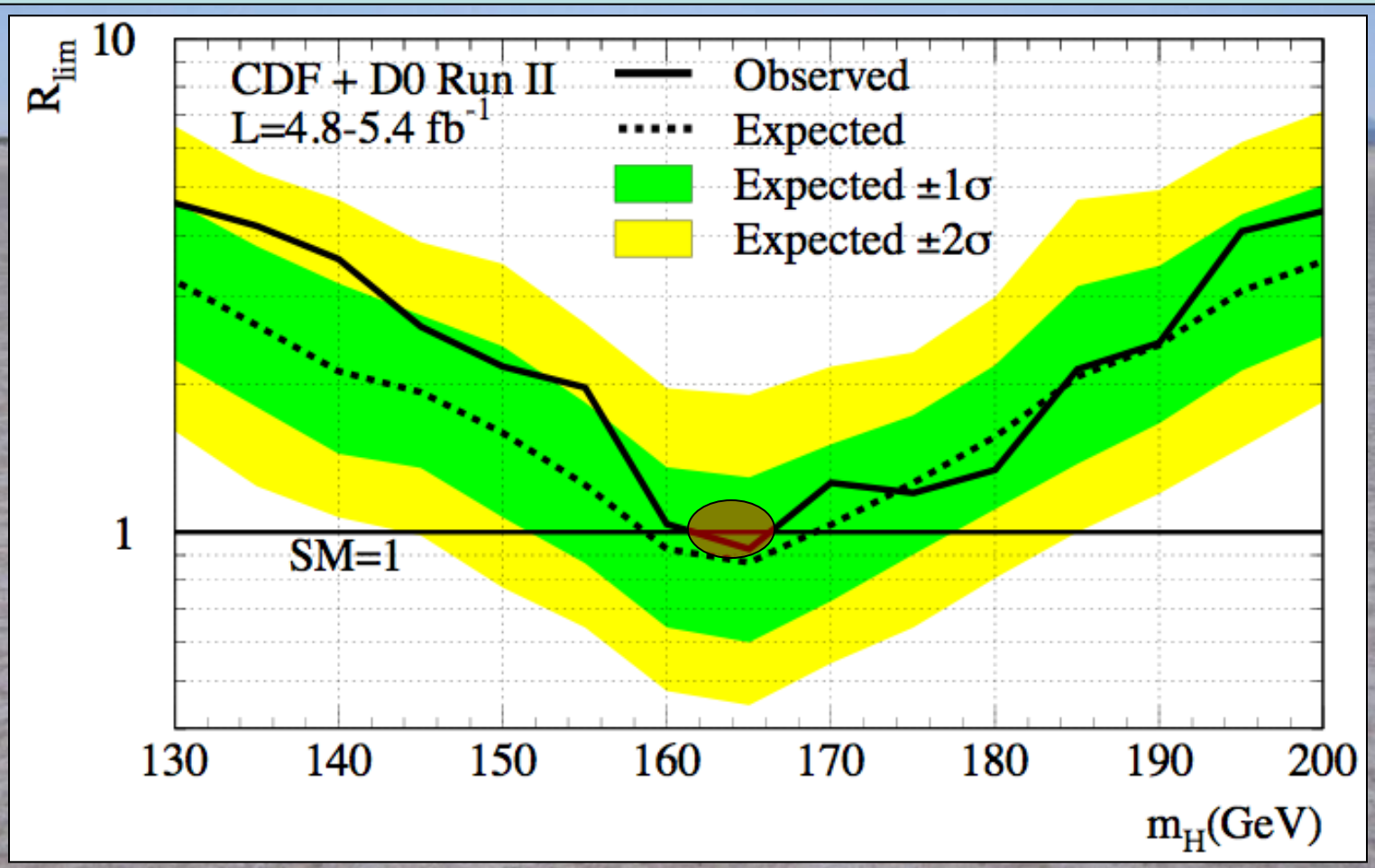
  $m_H < 157$ GeV, or 186 GeV including direct limit

- Tevatron exclusion:

  $m_H < 162$ GeV or > 166 GeV

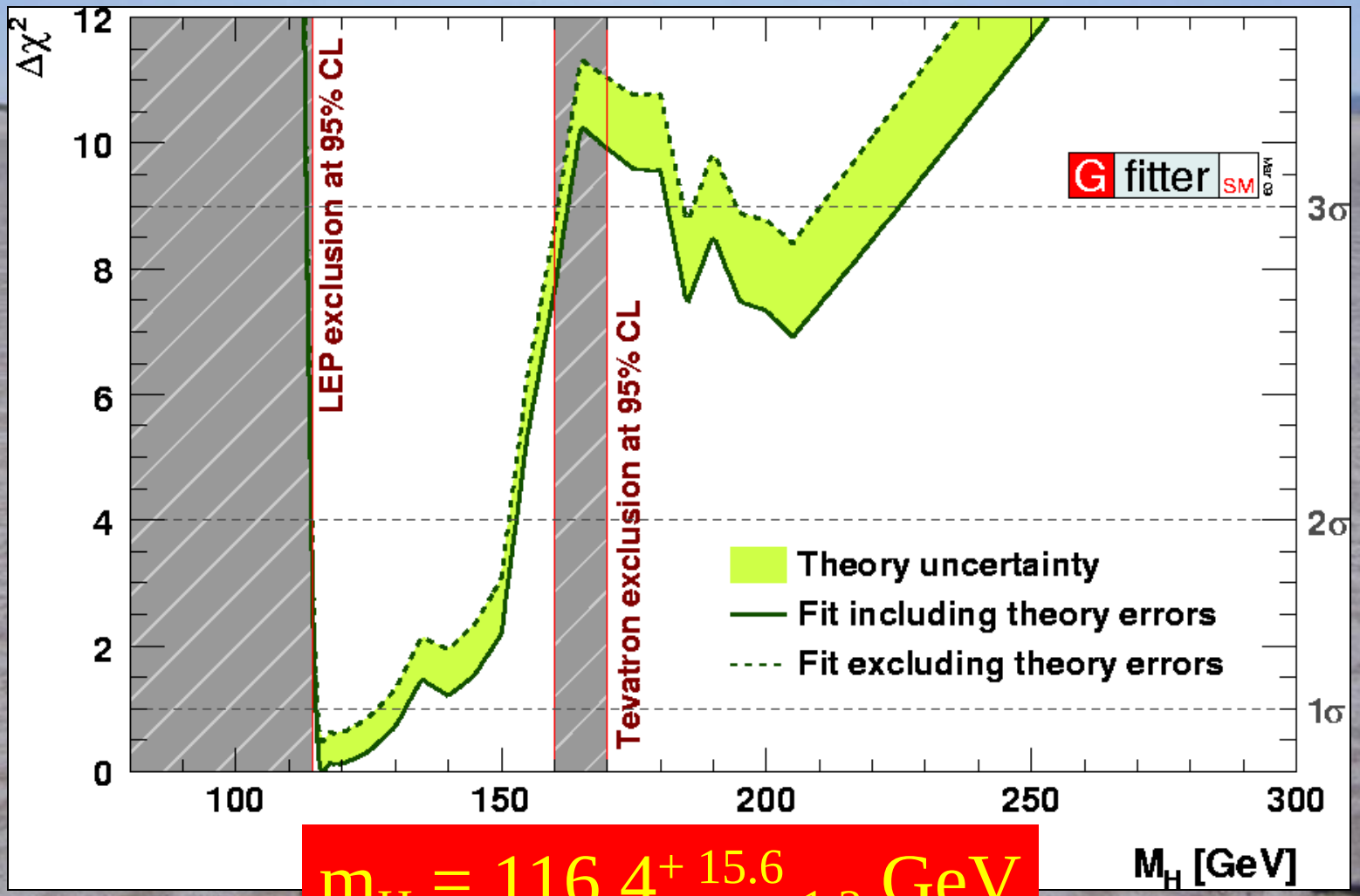


Higgs Search @ Tevatron



Tevatron excludes Higgs between 162 & 166 GeV

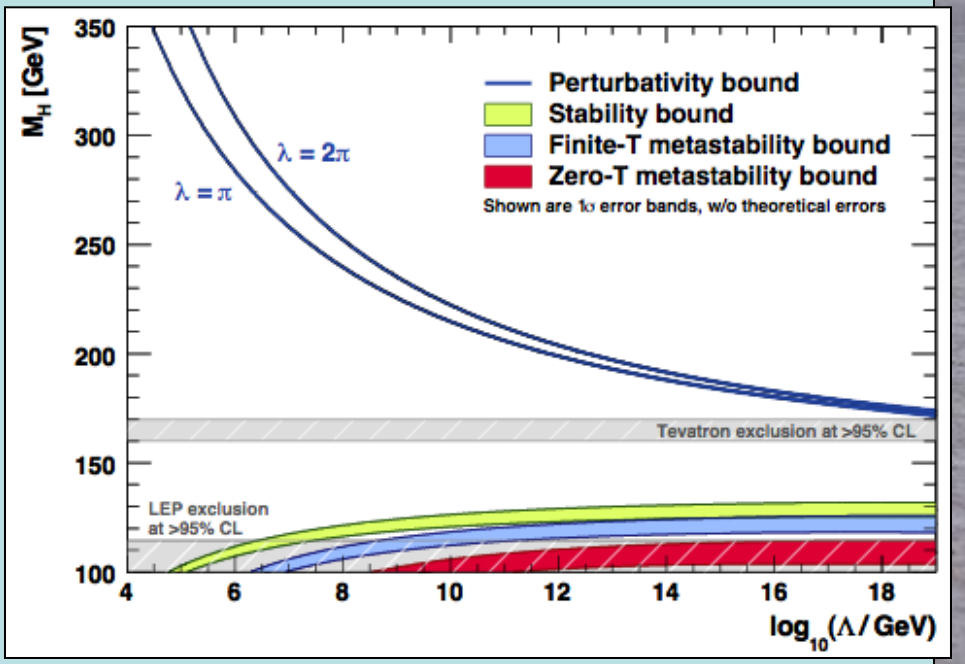
Combining the Higgs Information



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

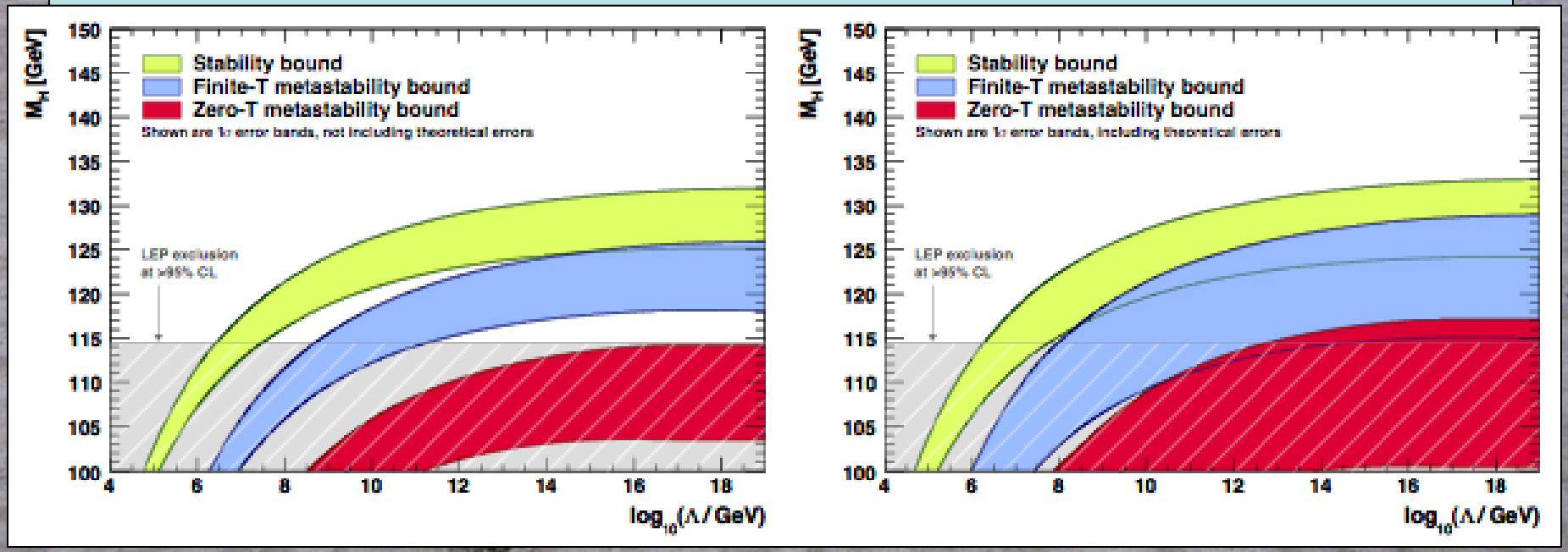
Theoretical Constraints on Higgs Mass

- 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



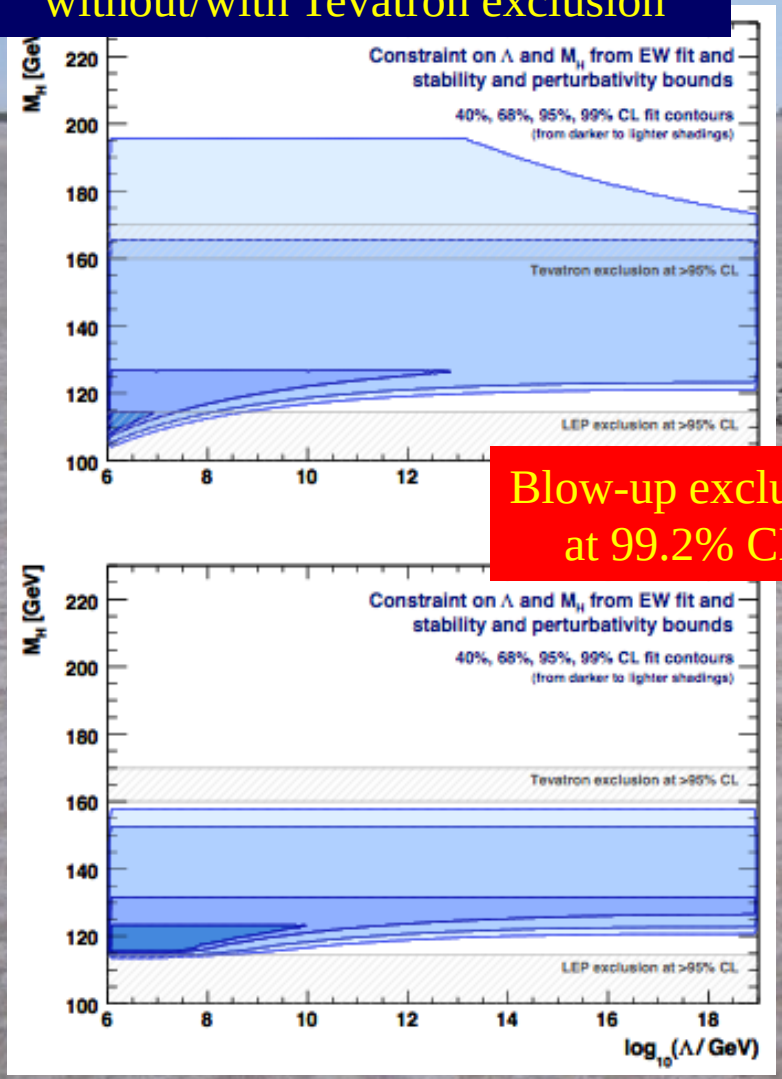
Vacuum Stability vs Metastability

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



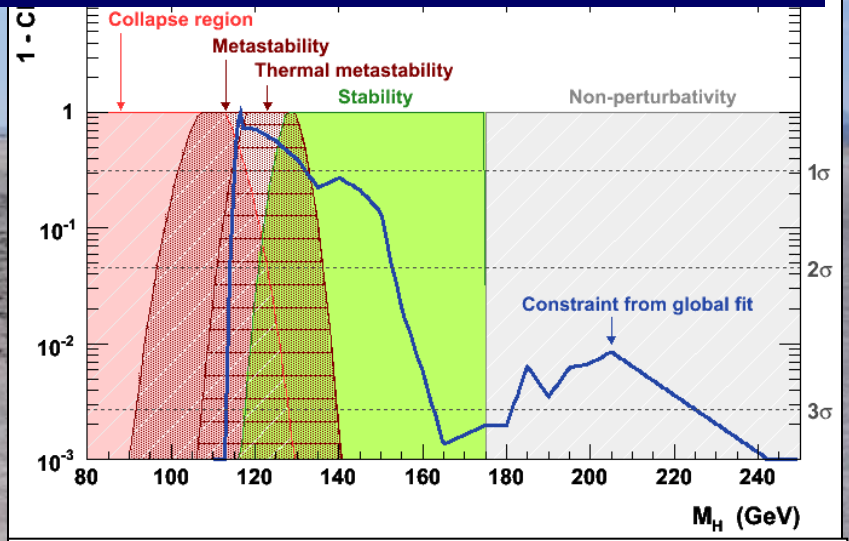
What is the probable fate of the SM?

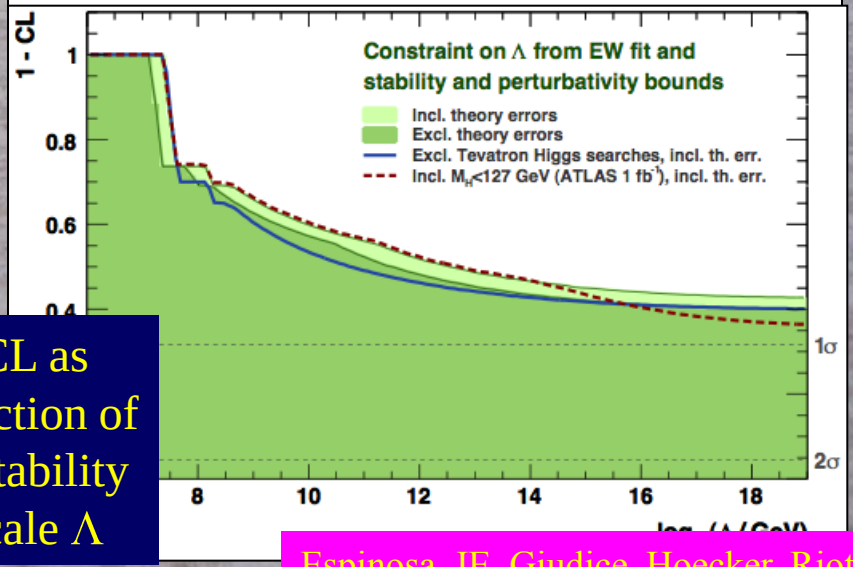
Confidence Levels (CL) without/with Tevatron exclusion



Blow-up excluded at 99.2% CL

Confidence Levels (CL) for different fates





CL as function of instability scale Λ

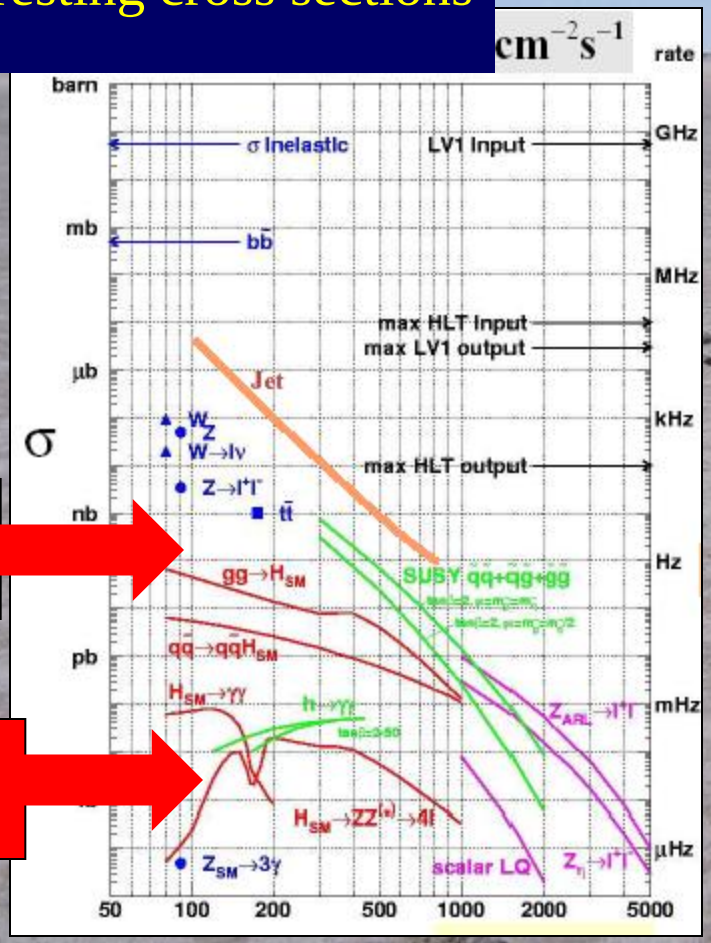
Espinosa, JE, Giudice, Hoecker, Riotto

The LHC Roulette Wheel

Standard Model

The LHC Physics Haystack(s)

Interesting cross sections



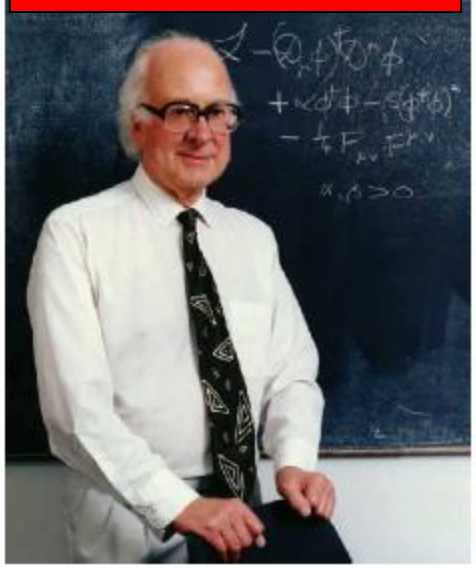
Susy

Higgs

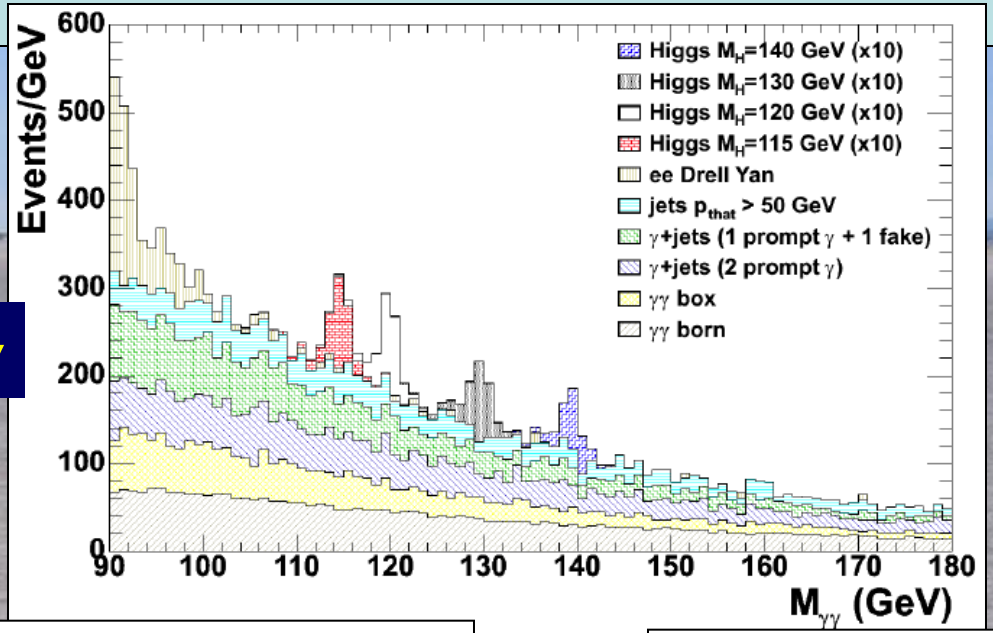
- Cross sections for heavy particles
  ~ 1 /(1 TeV)^2
- Most have small couplings ~ α^2
- Compare with total cross section
  ~ 1/(100 MeV)^2
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  ~ 1/100,000,000 m^3
- Haystack ~ 100 m^3
- Must look in ~ 100,000 haystacks

A la recherche du Higgs perdu …

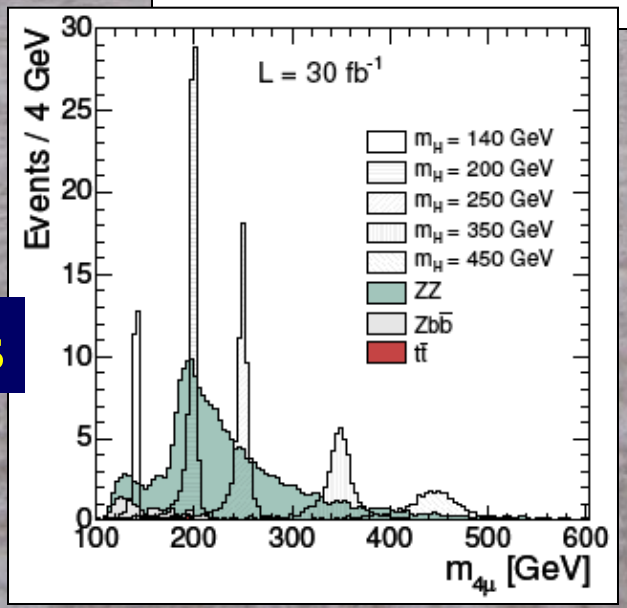
Some Sample Higgs Signals



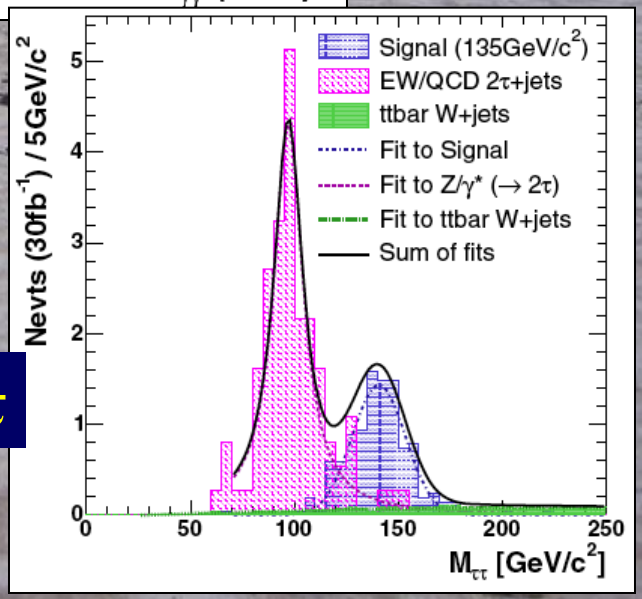
$\gamma\gamma$



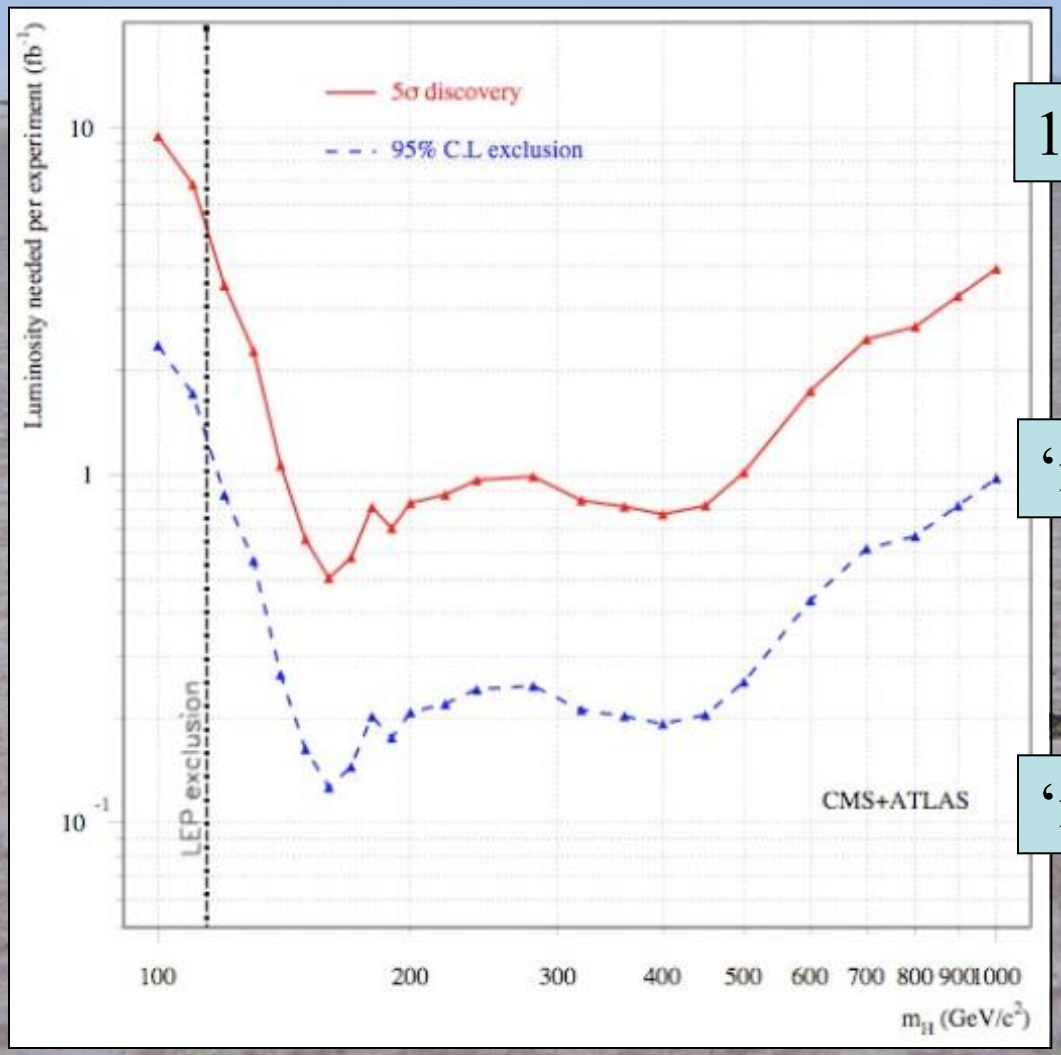
ZZ* -> 4 leptons



$\tau\tau$



When will the LHC discover the Higgs boson?



1 ‘year’ @ 10^{33}

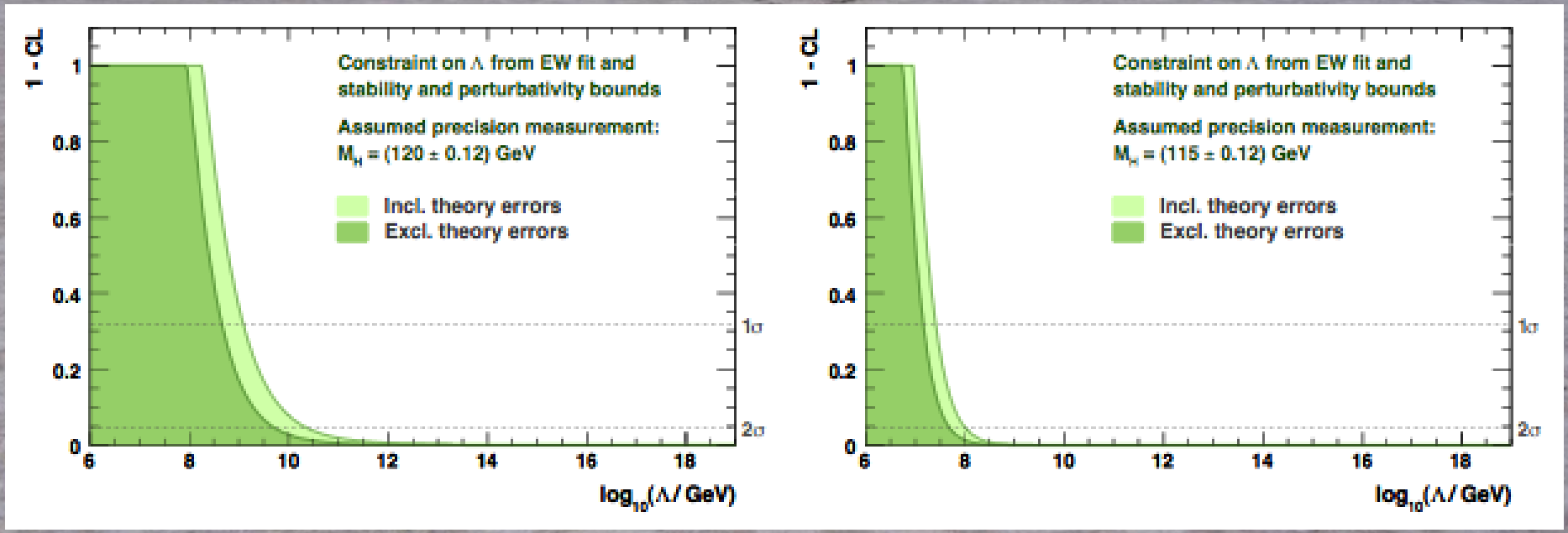
‘month’ @ 10^{33}

‘month’ @ 10^{32}

Blaising, JE et al: 2006

The LHC will Tell the Fate of the SM

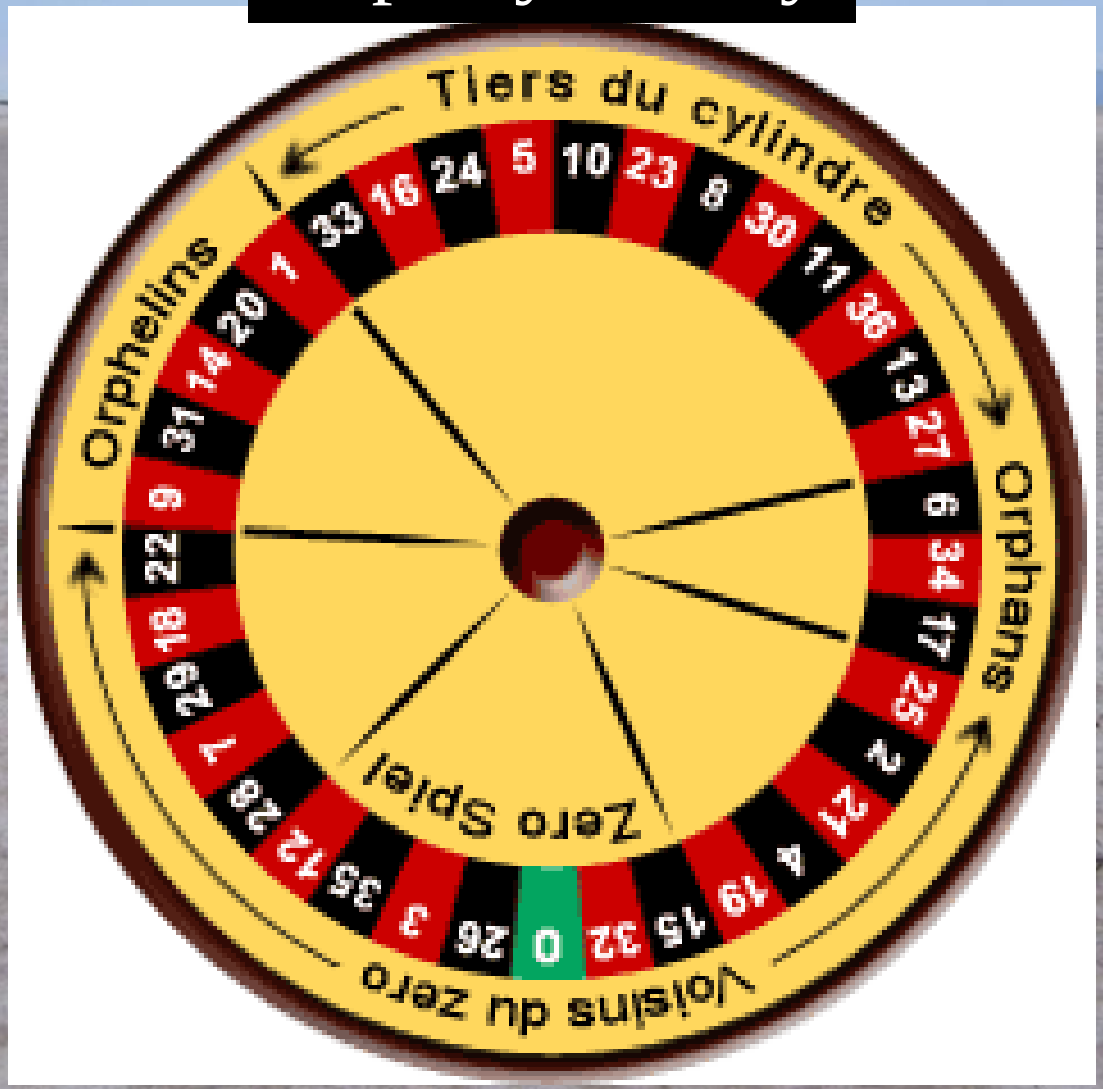
Examples with LHC measurement of m_H = 120 or 115 GeV



Espinosa, JE, Giudice, Hoecker, Riotto

The LHC Roulette Wheel

Supersymmetry



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

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

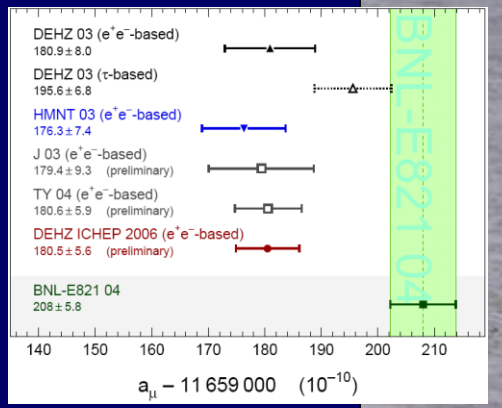
  selectron, chargino > 100 GeV

  squarks, gluino > 400 GeV

- Indirect constraints

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

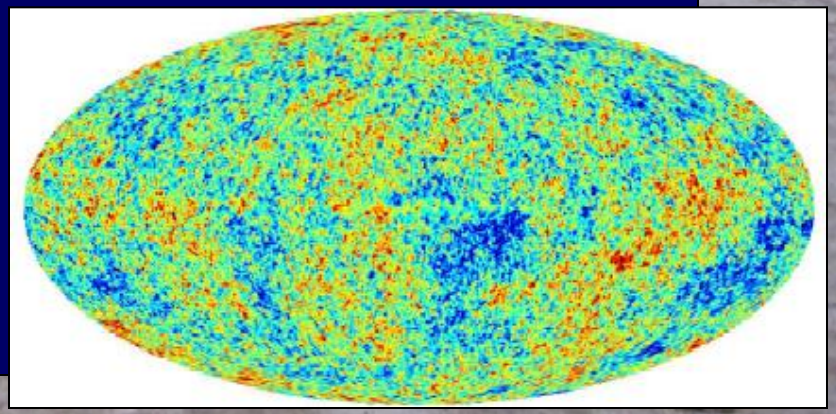
  3.3 σ effect in $g_\mu - 2$?



- Density of dark matter

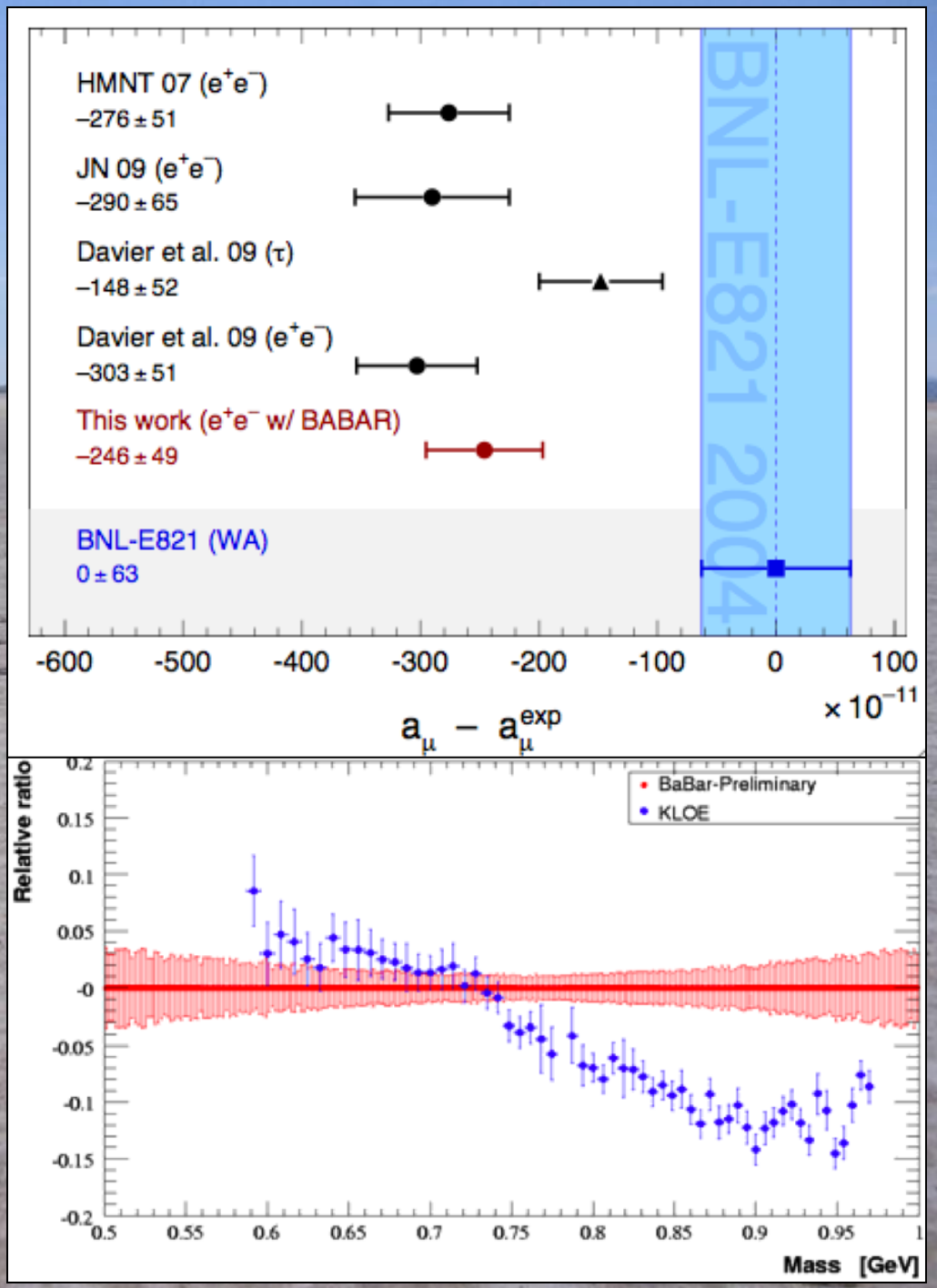
  lightest sparticle χ:

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



Quo Vadis $g_\mu - 2$?

- Older e^+e^- data show discrepancy
  - now 3.4 σ
- Disagreement with τ decay data
  - Discrepancy ~ 2 σ
- New BABAR e^+e^- data agree poorly with previous e^+e^- data
  - Intermediate between e^+e^- and τ decay data
- Combination with previous e^+e^- data yield discrepancy ~ 3.1 σ



Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

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

- 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
- Assume universality? constrained MSSM = CMSSM
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: 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?

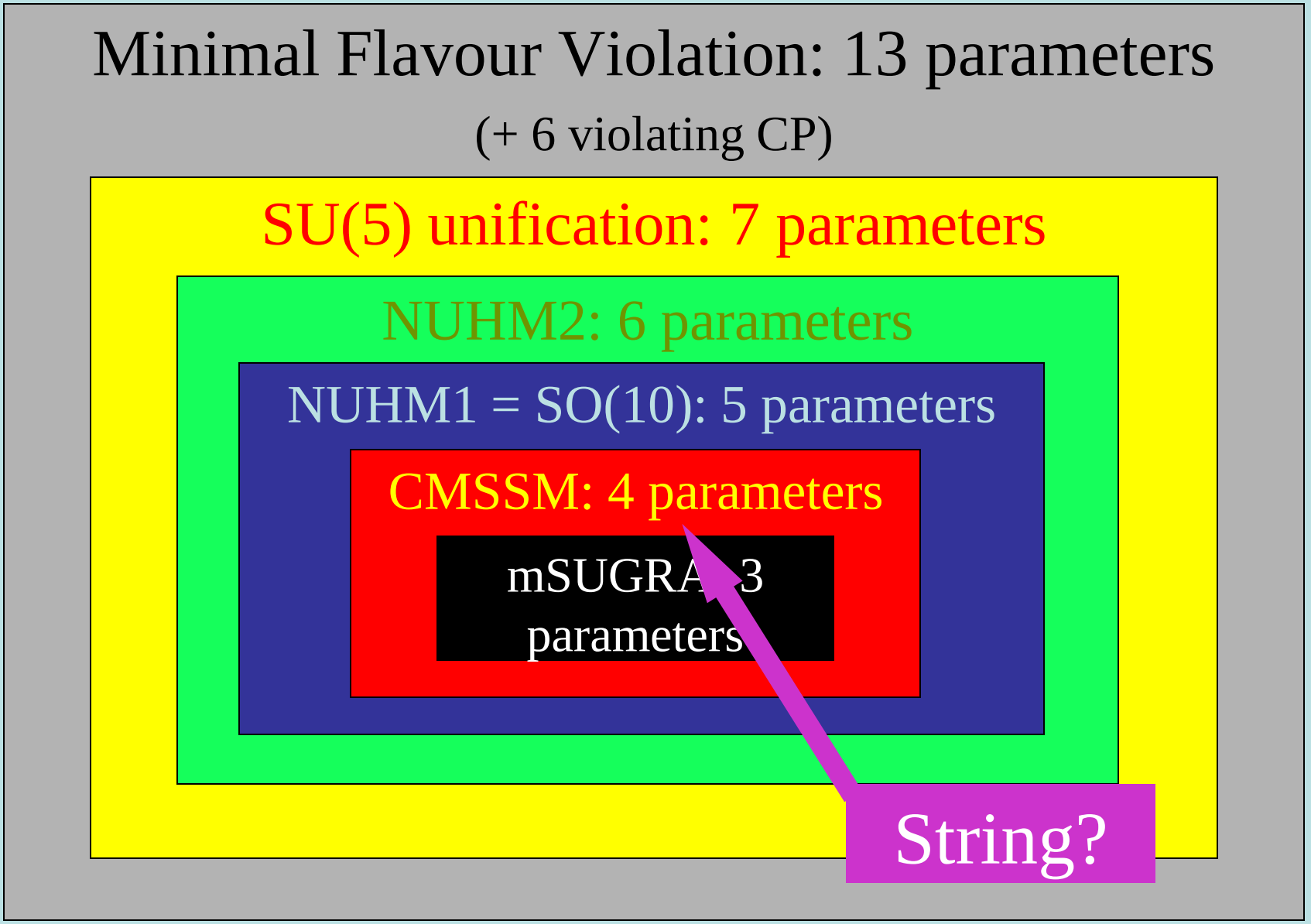
  disfavoured in various GUT models

  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

MSSM: > 100 parameters



Current Constraints on CMSSM

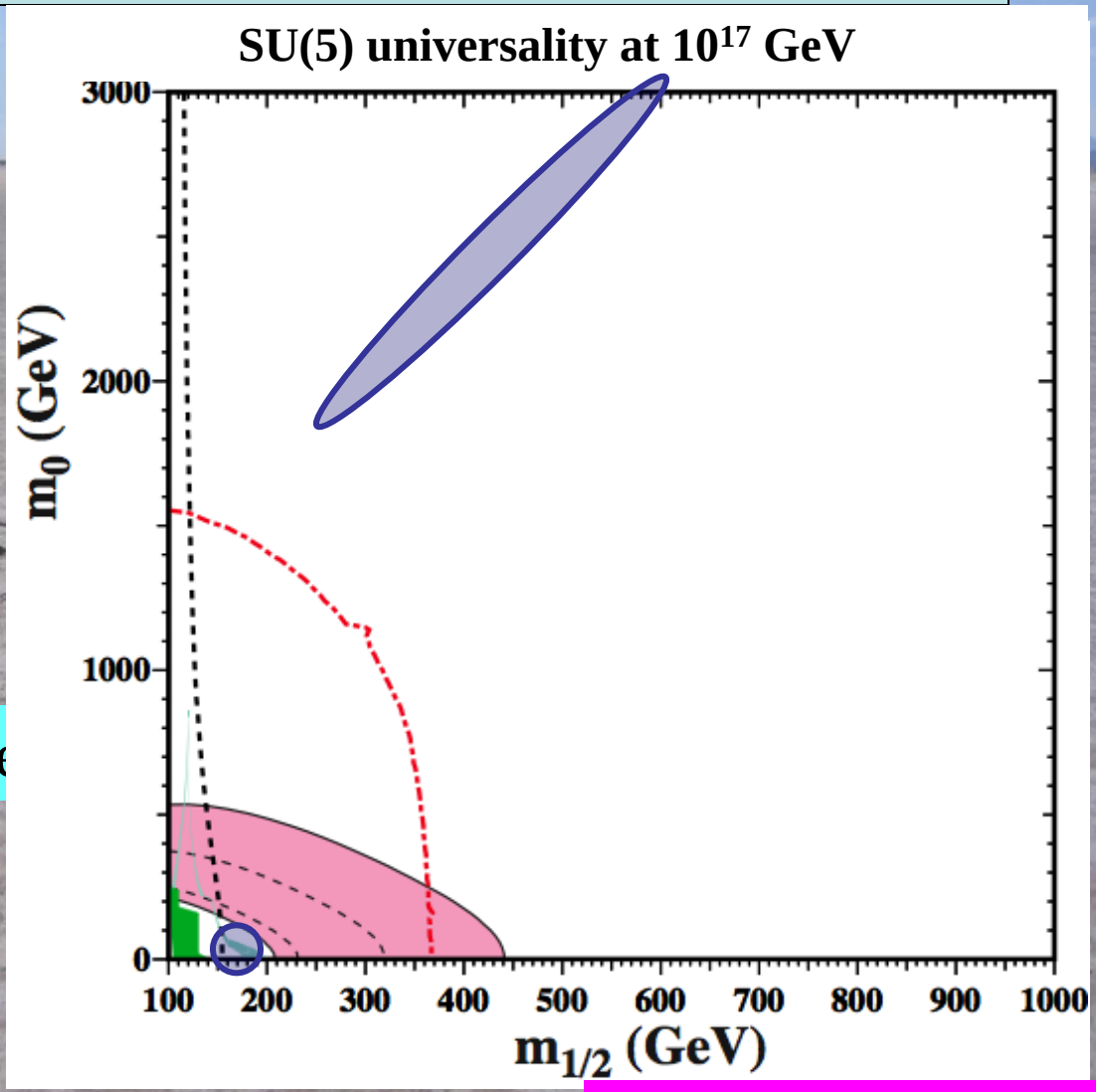
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

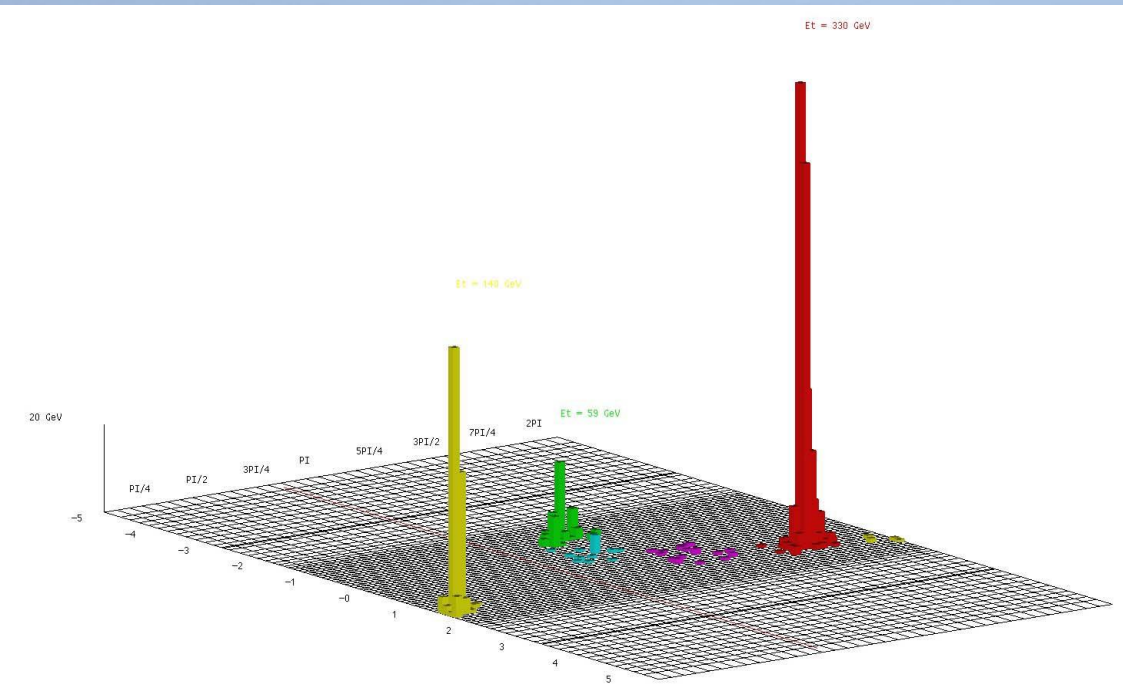
WMAP constraint on relic de

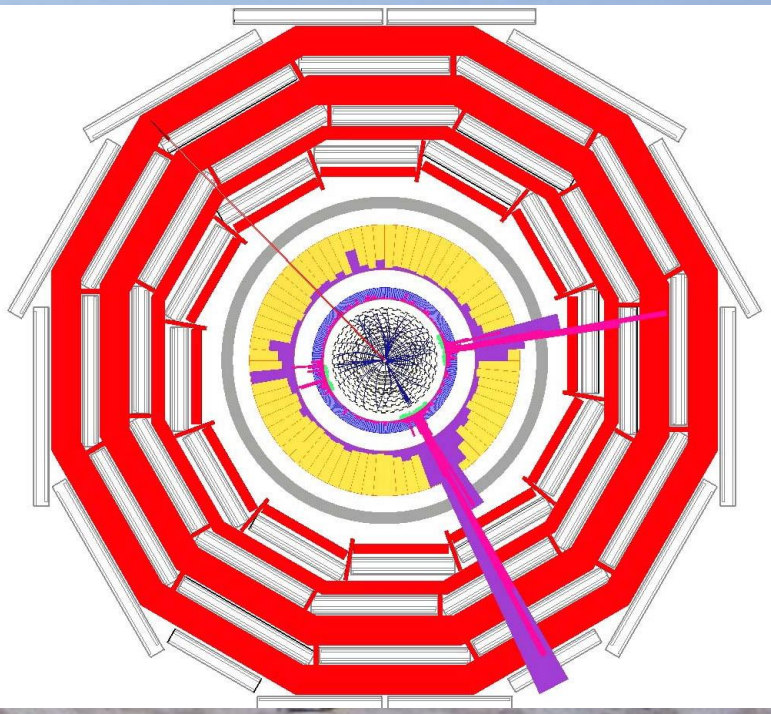
Preferred (?) by latest g - 2



JE + Mustafayev + Olive

Looking for Dark Matter





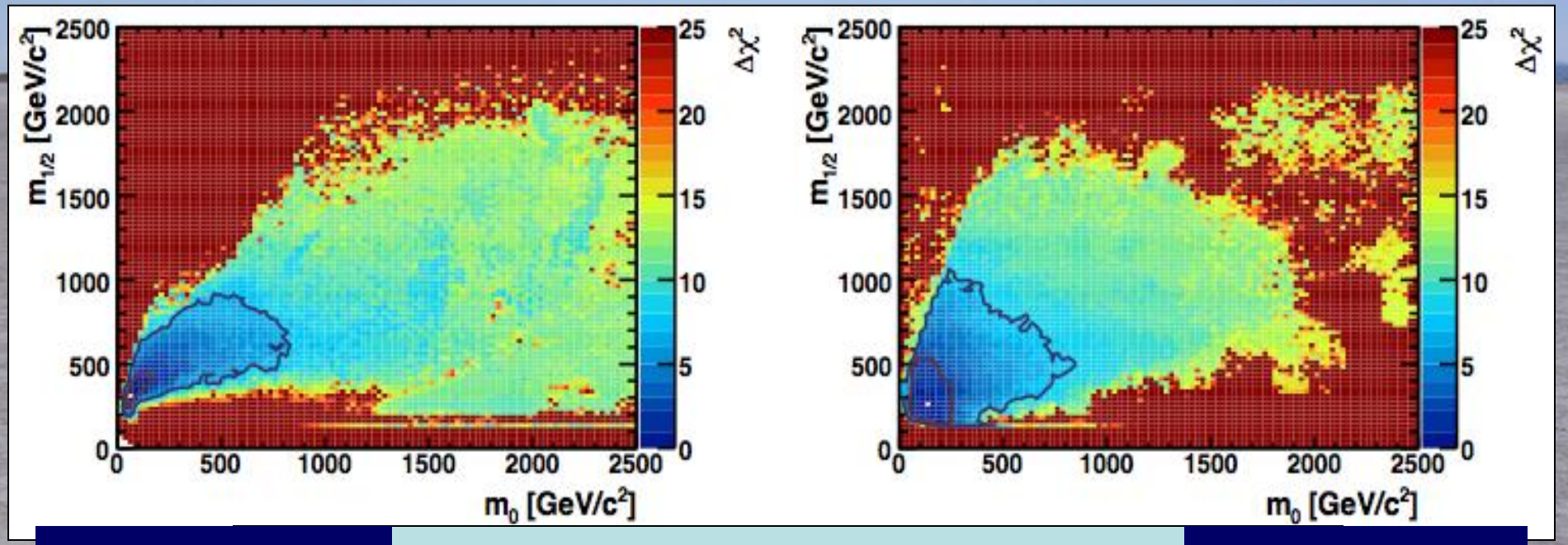
Missing energy
taken away by dark matter particles

Global Supersymmetric Fit

- 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

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

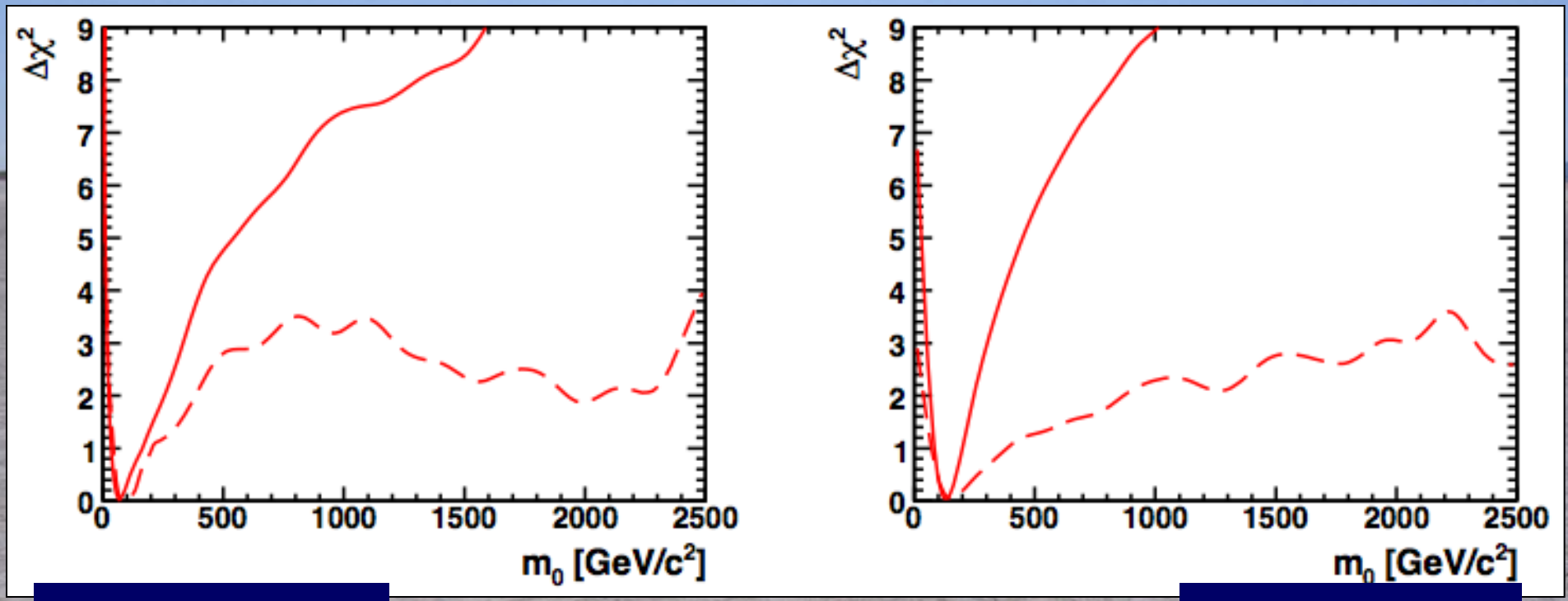
Contributions to the Global χ^2

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_ℓ	0.96	1.01	1.05
$\mathrm{BR}^{\mathrm{SUSY}}_{\mathrm{b}\to\mathrm{s}\gamma}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{b}\to\mathrm{s}\gamma}$	1.16	0.001	0.95
M_h	0.17	0	0
χ^2_{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

What Happens if g_μ - 2 Dropped?



CMSSM

NUHM1

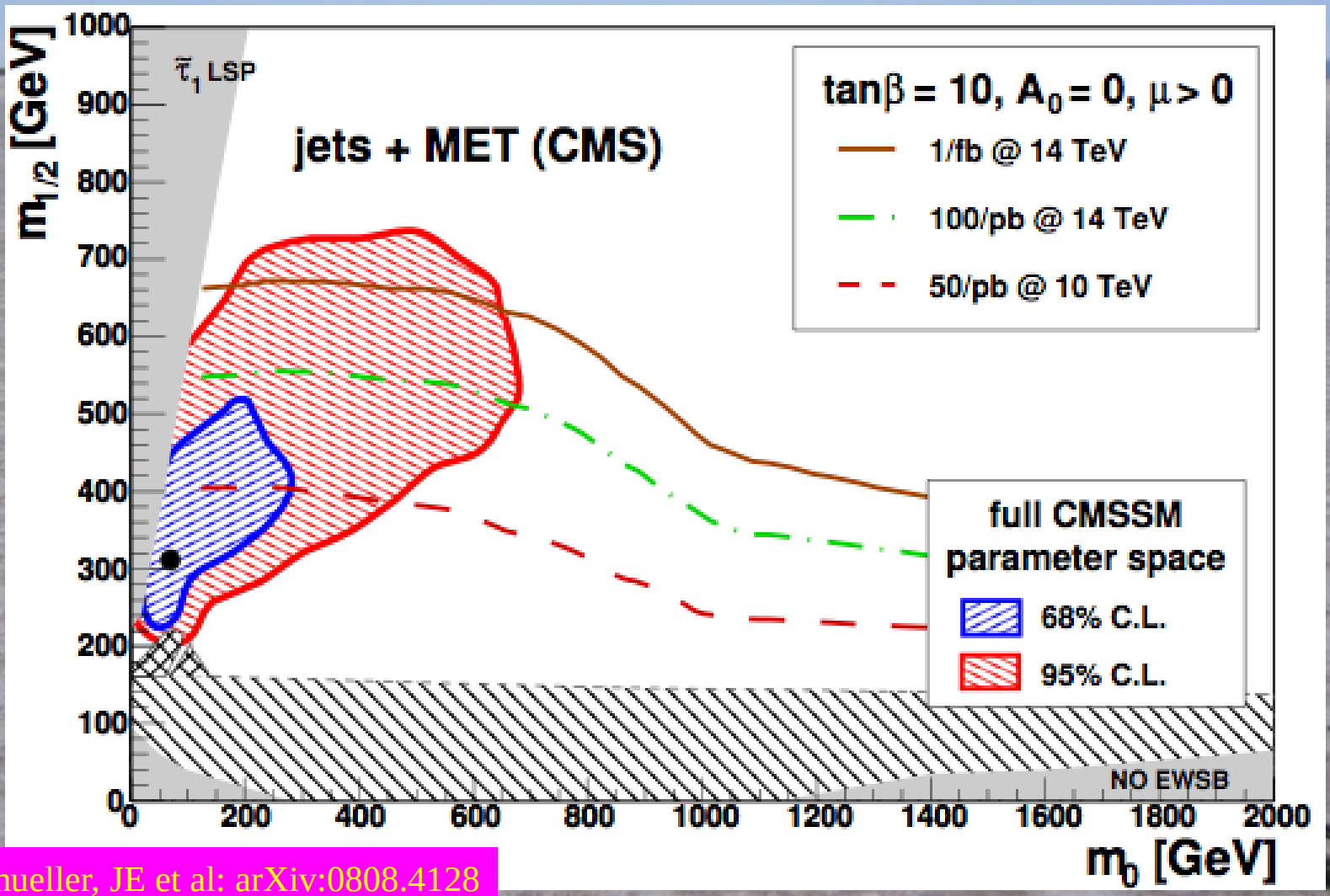
Solid lines: with g_μ - 2

Dashed lines: without g_μ - 2

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

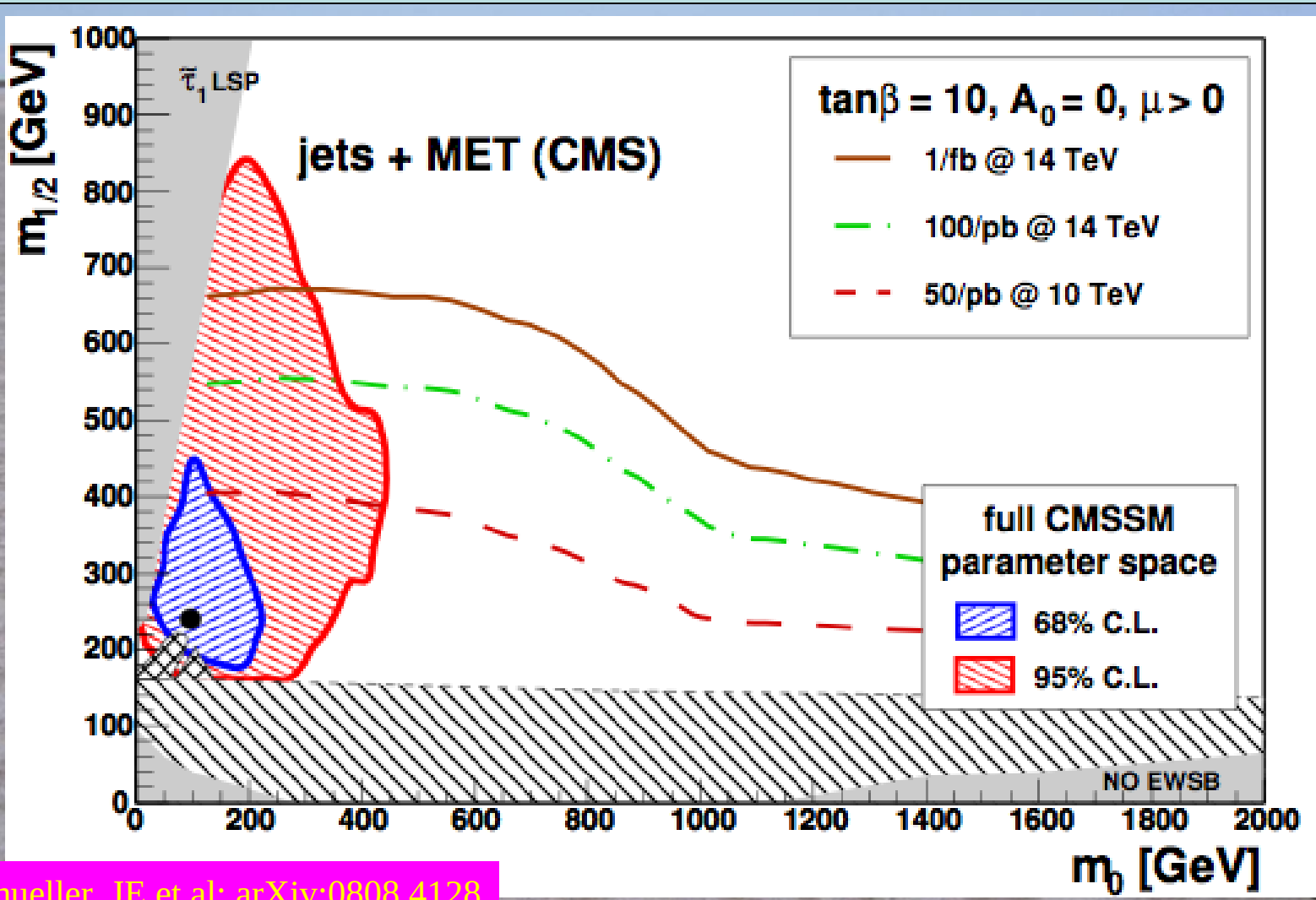
O.Buchmueller, JE et al: arXiv:0907.5568

How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

How Soon Might the NUHM1 be Detected?



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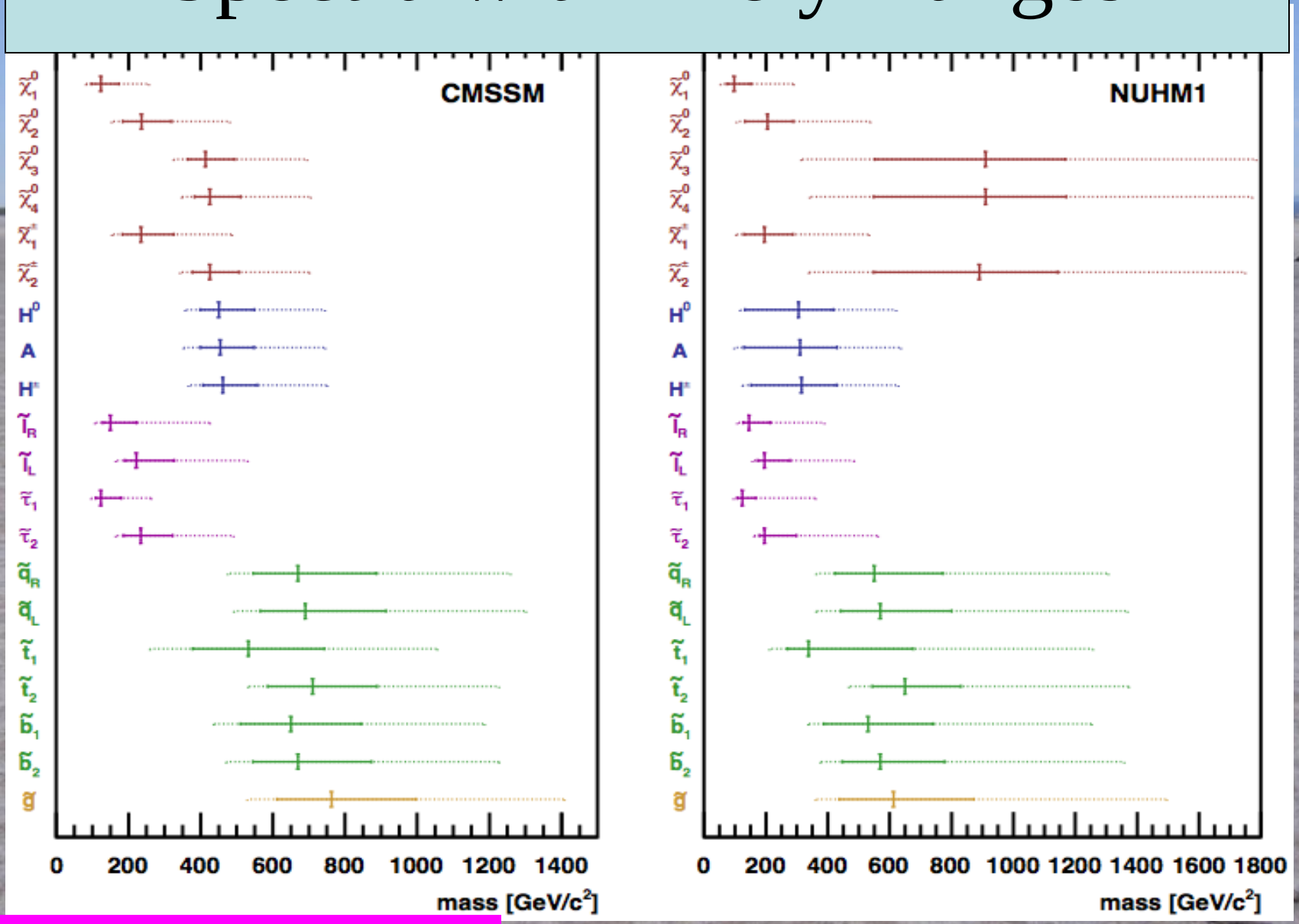
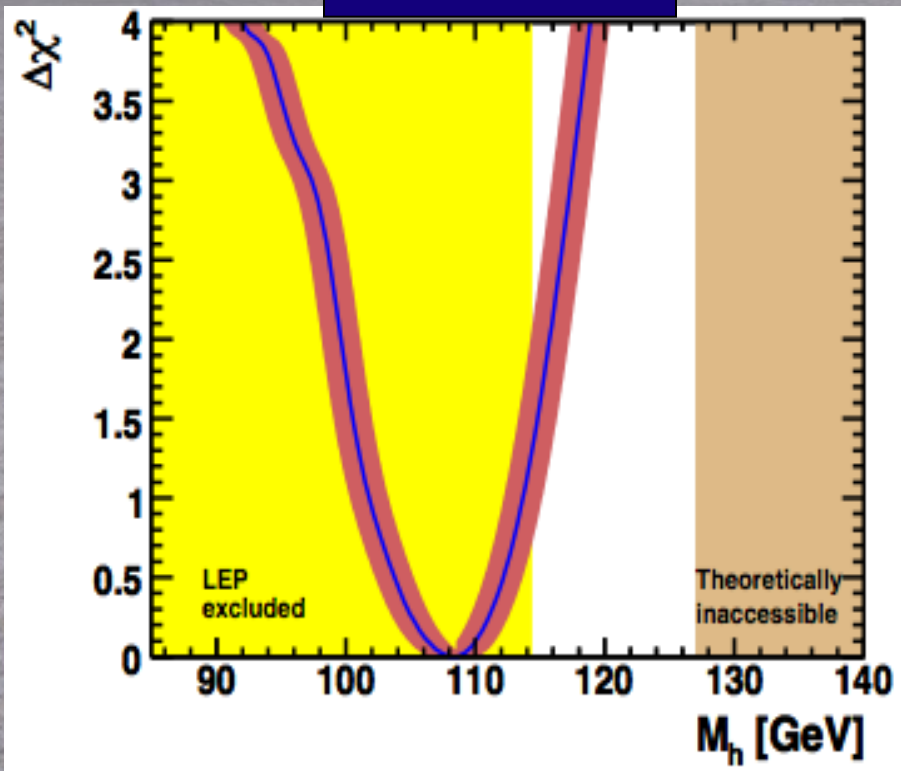
Spectra with likely Ranges



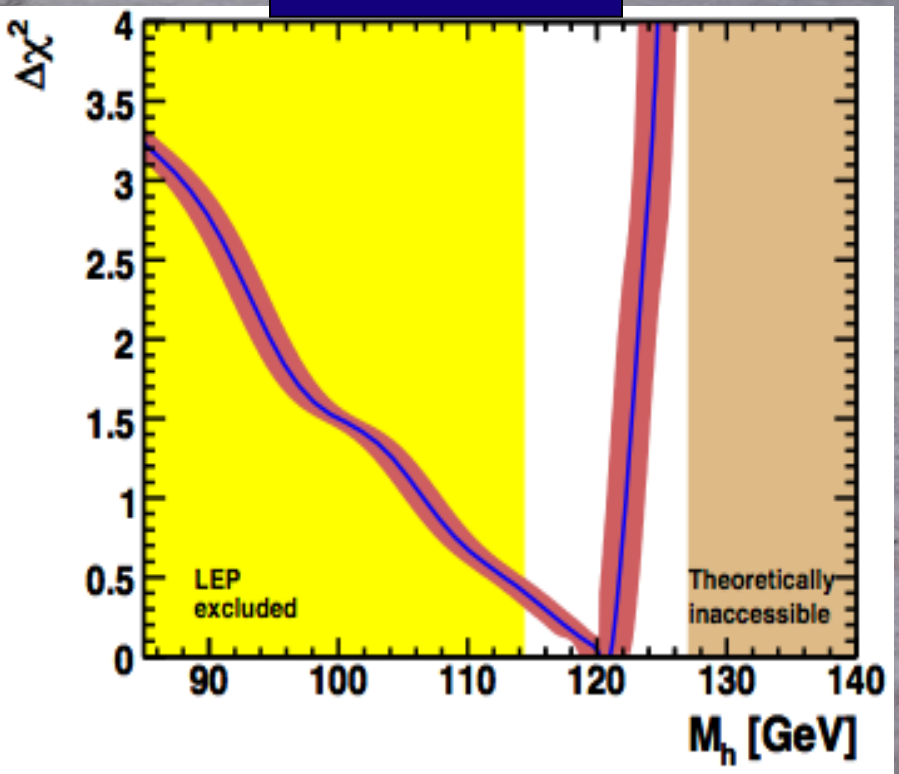
O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for Higgs Mass

CMSSM



NUHM1

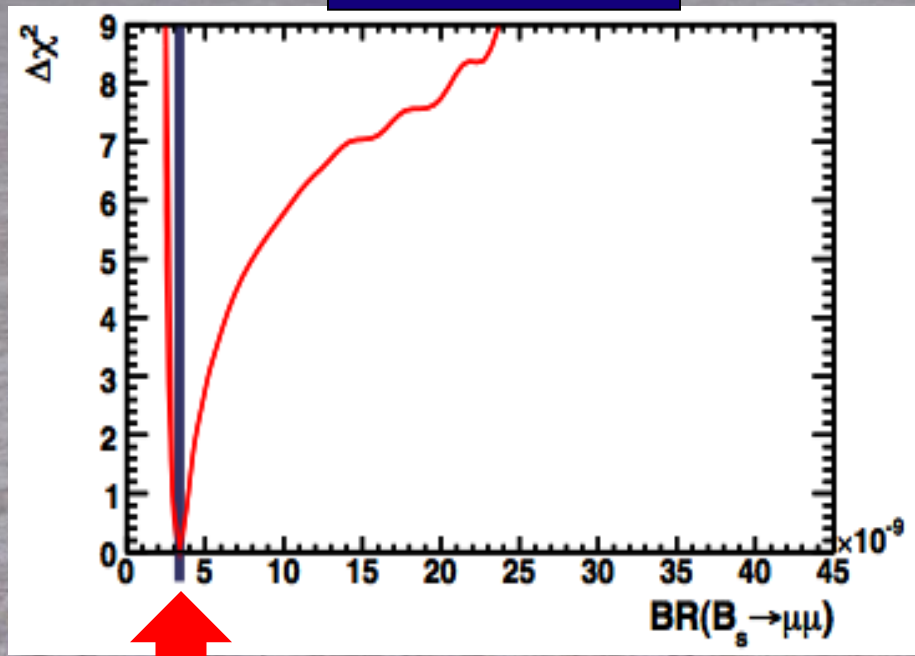


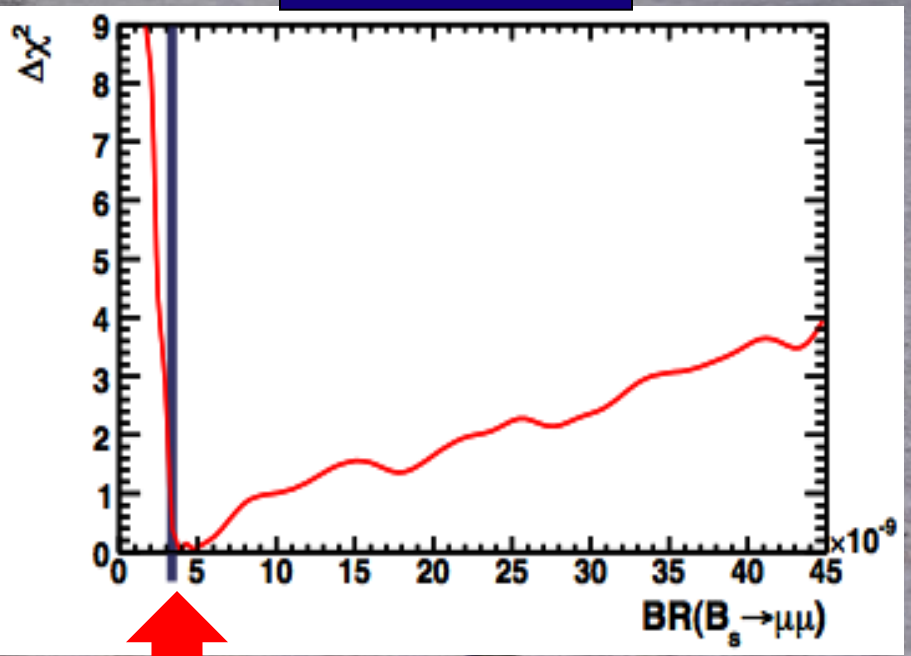
O.Buchmueller, JE et al: arXiv:0907.5568

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

CMSSM

NUHM1



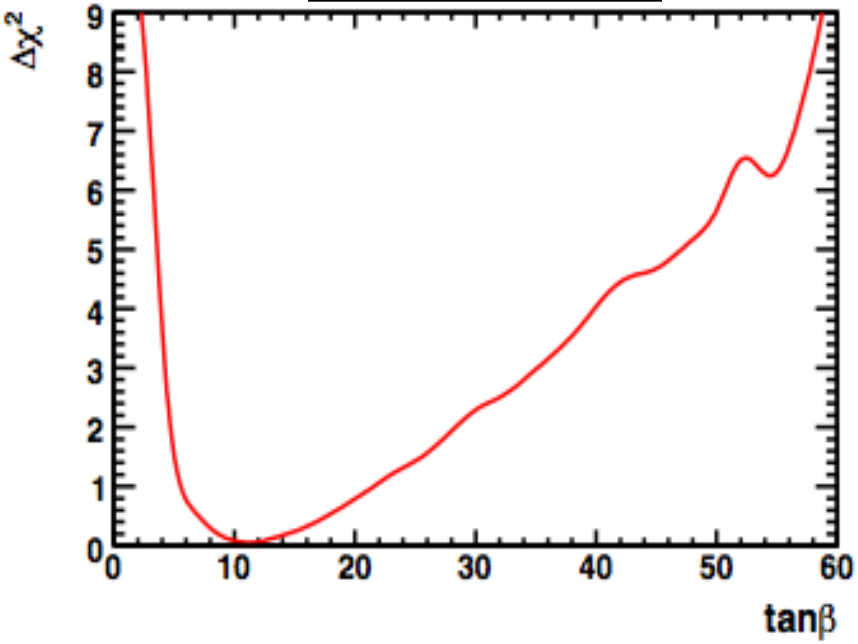


Standard Model prediction

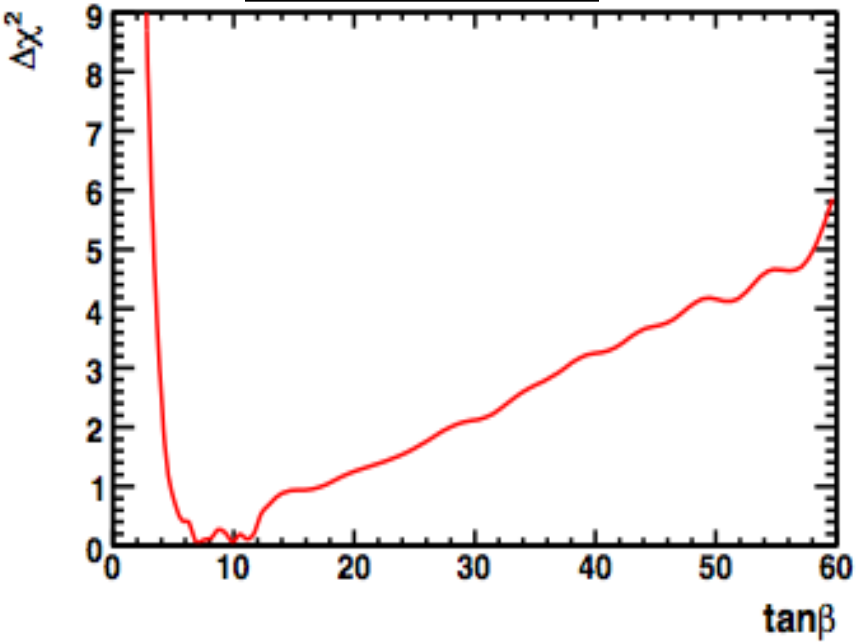
O.Buchmueller, JE et al: arXiv:0907.5568

Likelihood Function for tan β

CMSSM



NUHM1



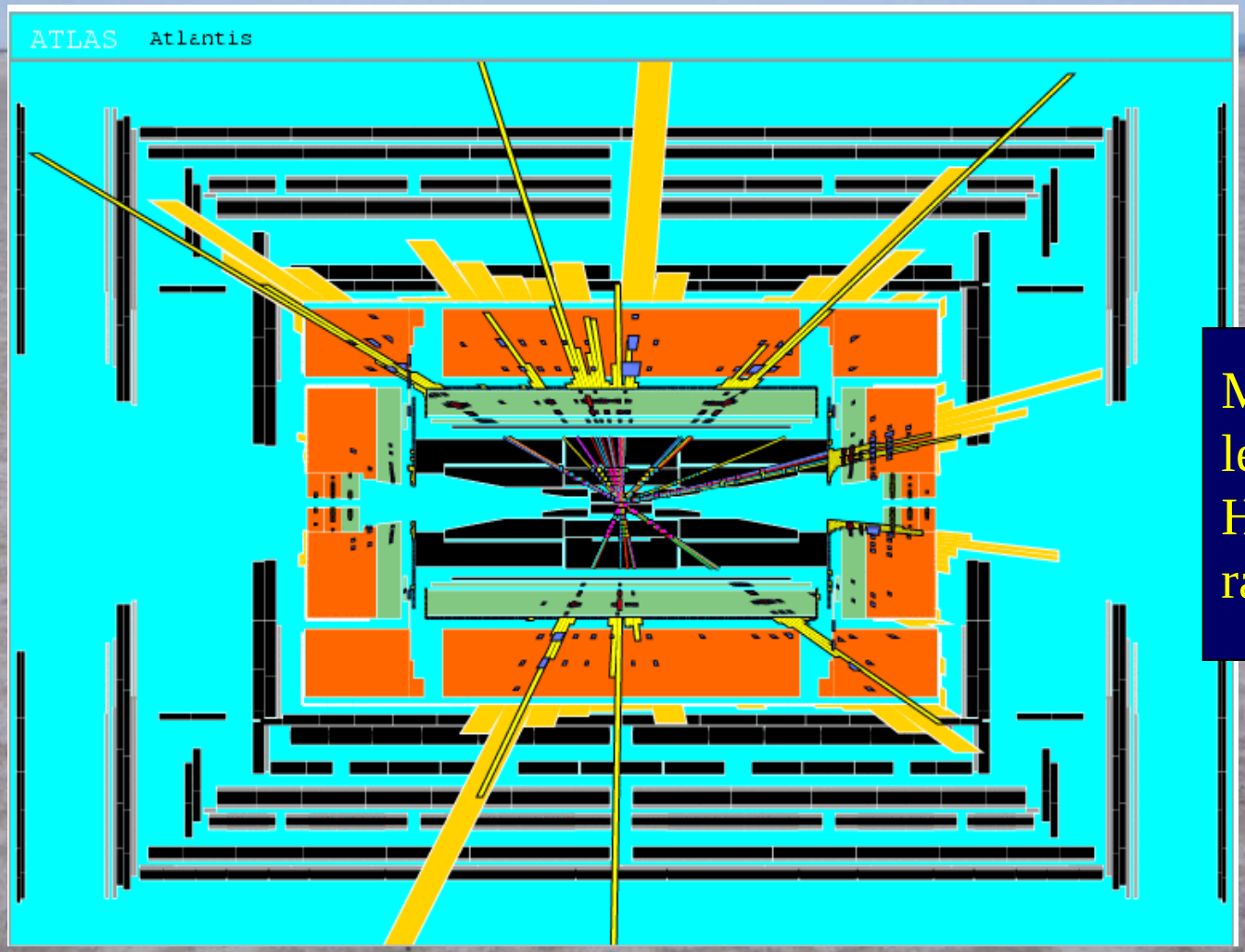
O.Buchmueller, JE et al: arXiv:0907.5568

The LHC Roulette Wheel

Extra dimensions

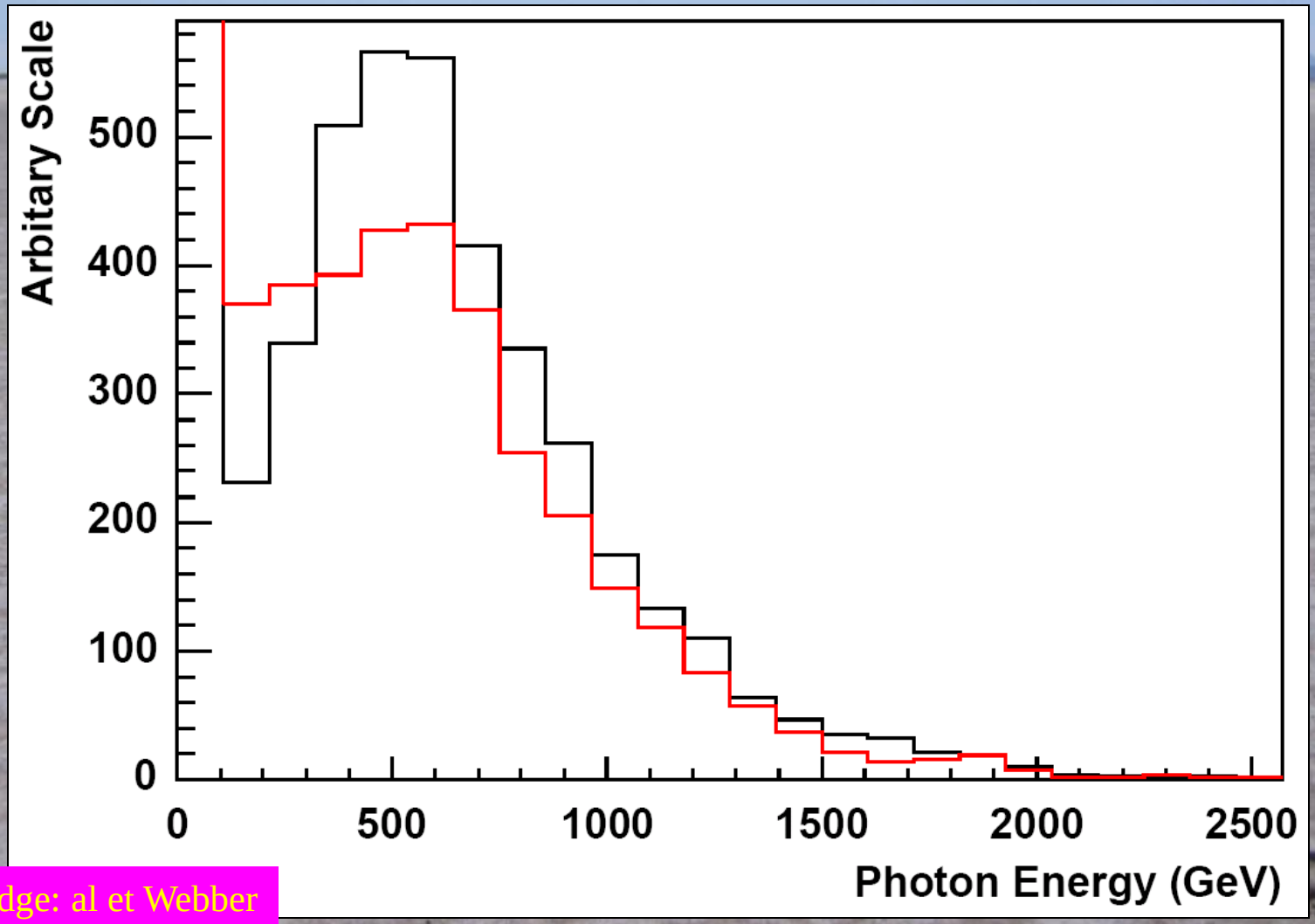
And if gravity becomes strong at the TeV scale …

Black Hole Production at LHC?



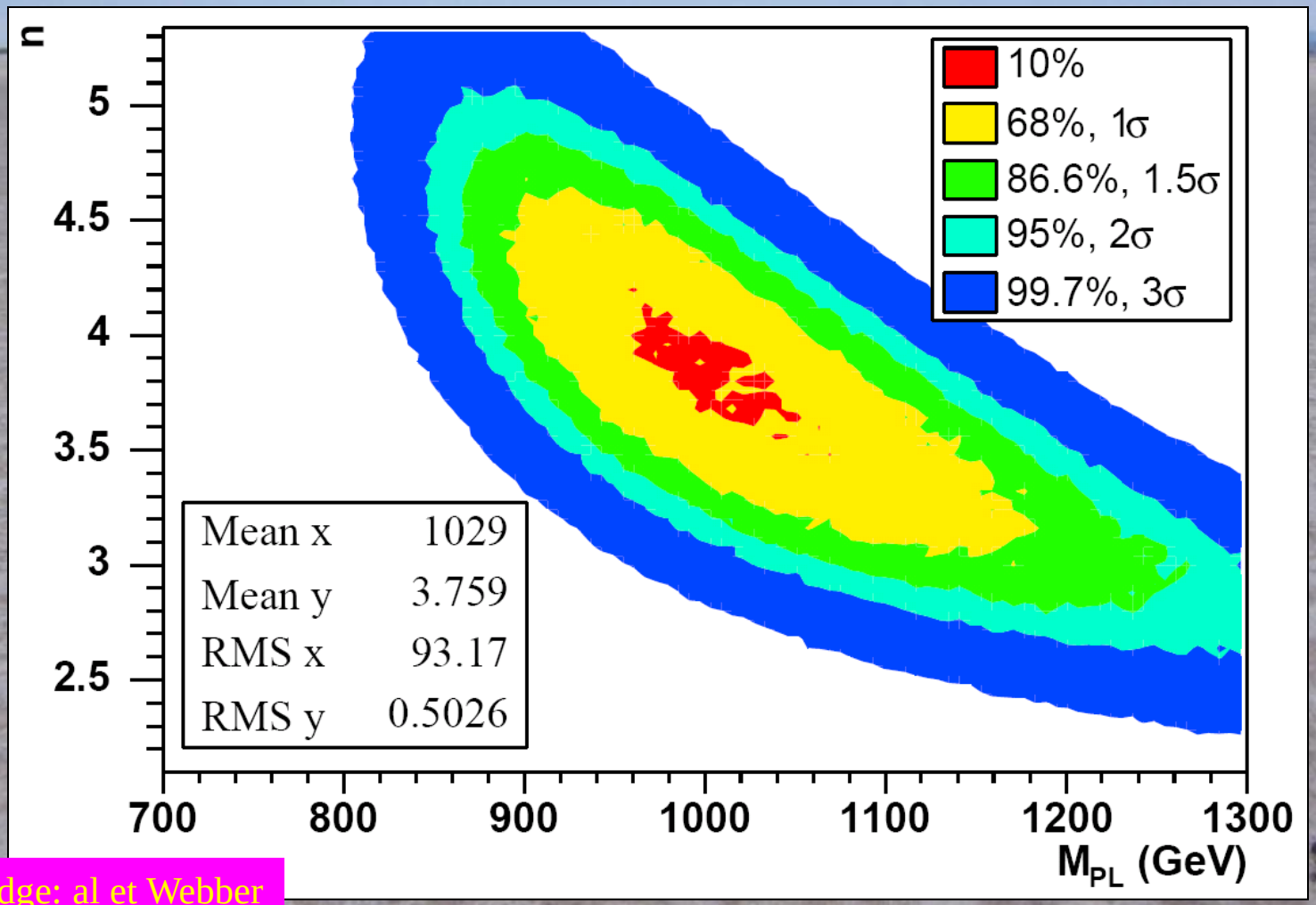
Multiple jets, leptons from Hawking radiation

Black Hole Decay Spectrum



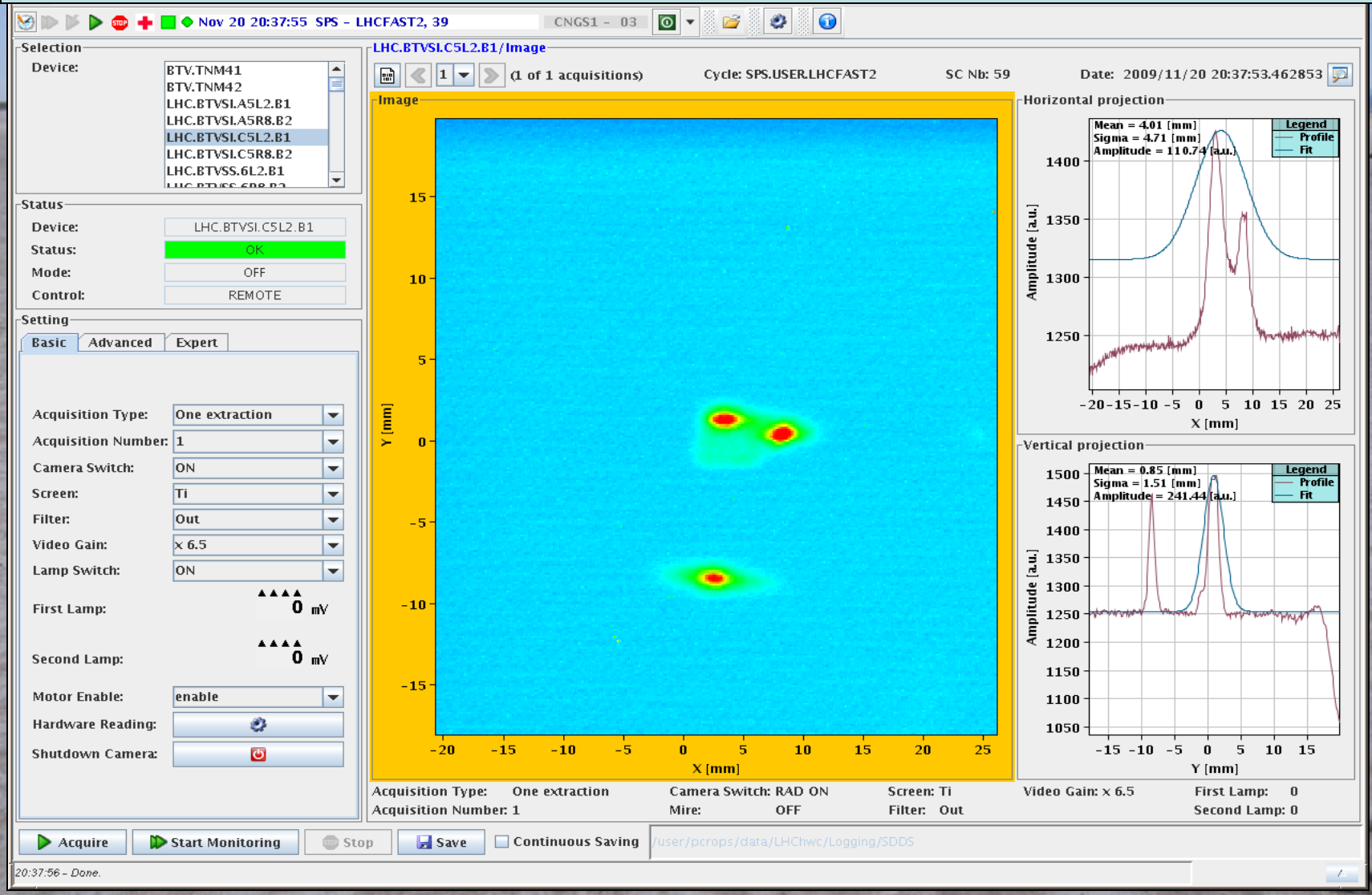
Cambridge: al et Webber

Measuring Extra Dimensions @ LHC

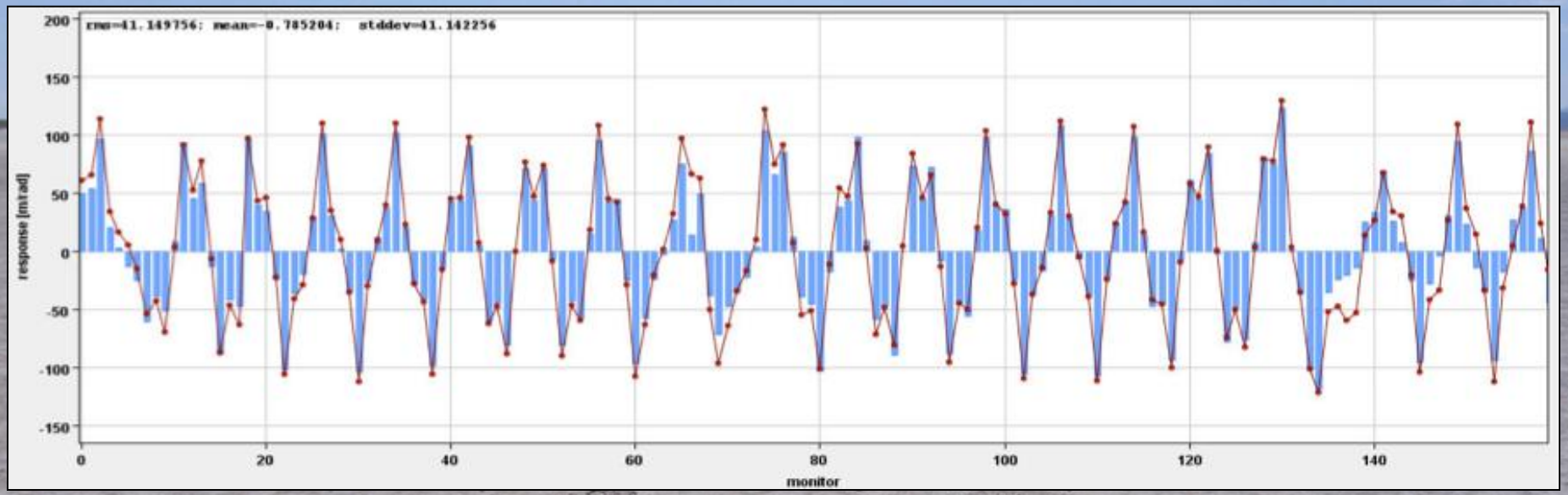


Cambridge: al et Webber

First 2009 Beam Circuits: Friday Nov. 20th @ 8.15pm

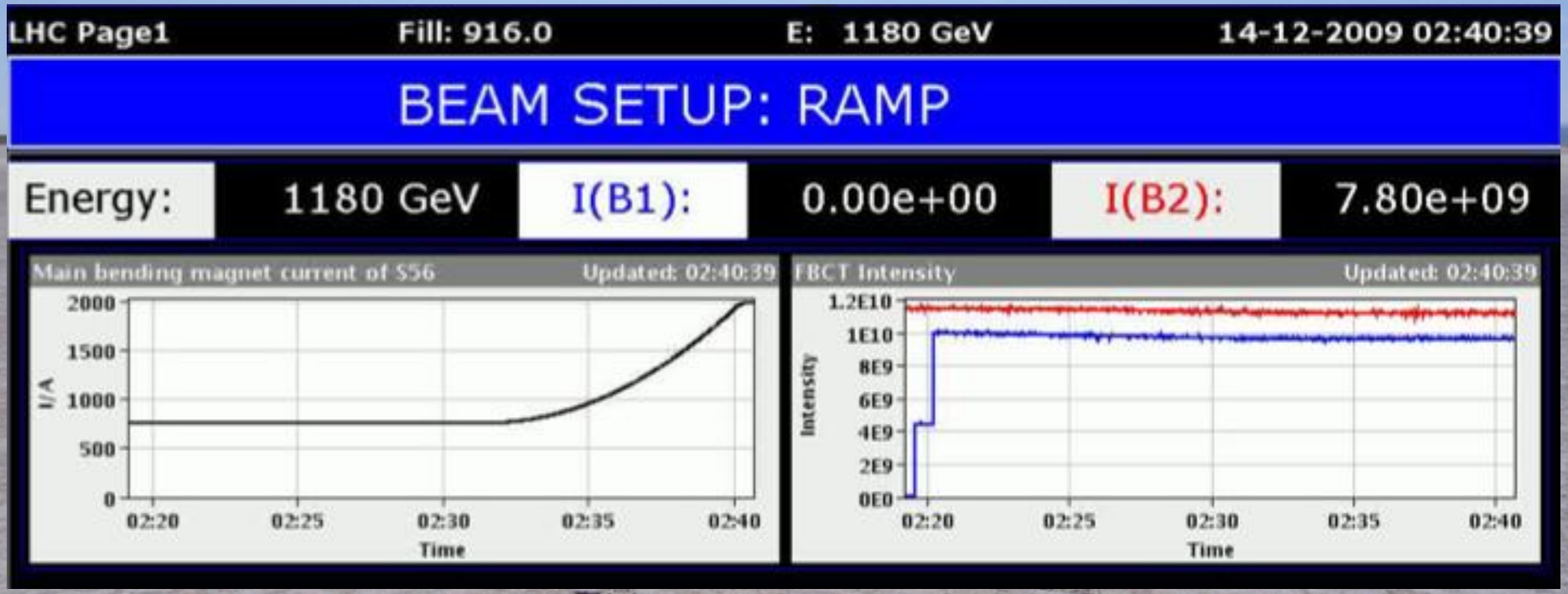


Measurements of the Beam Orbit



- Excellent agreement between measurements and model of the LHC accelerator
- The LHC is very well measured & understood

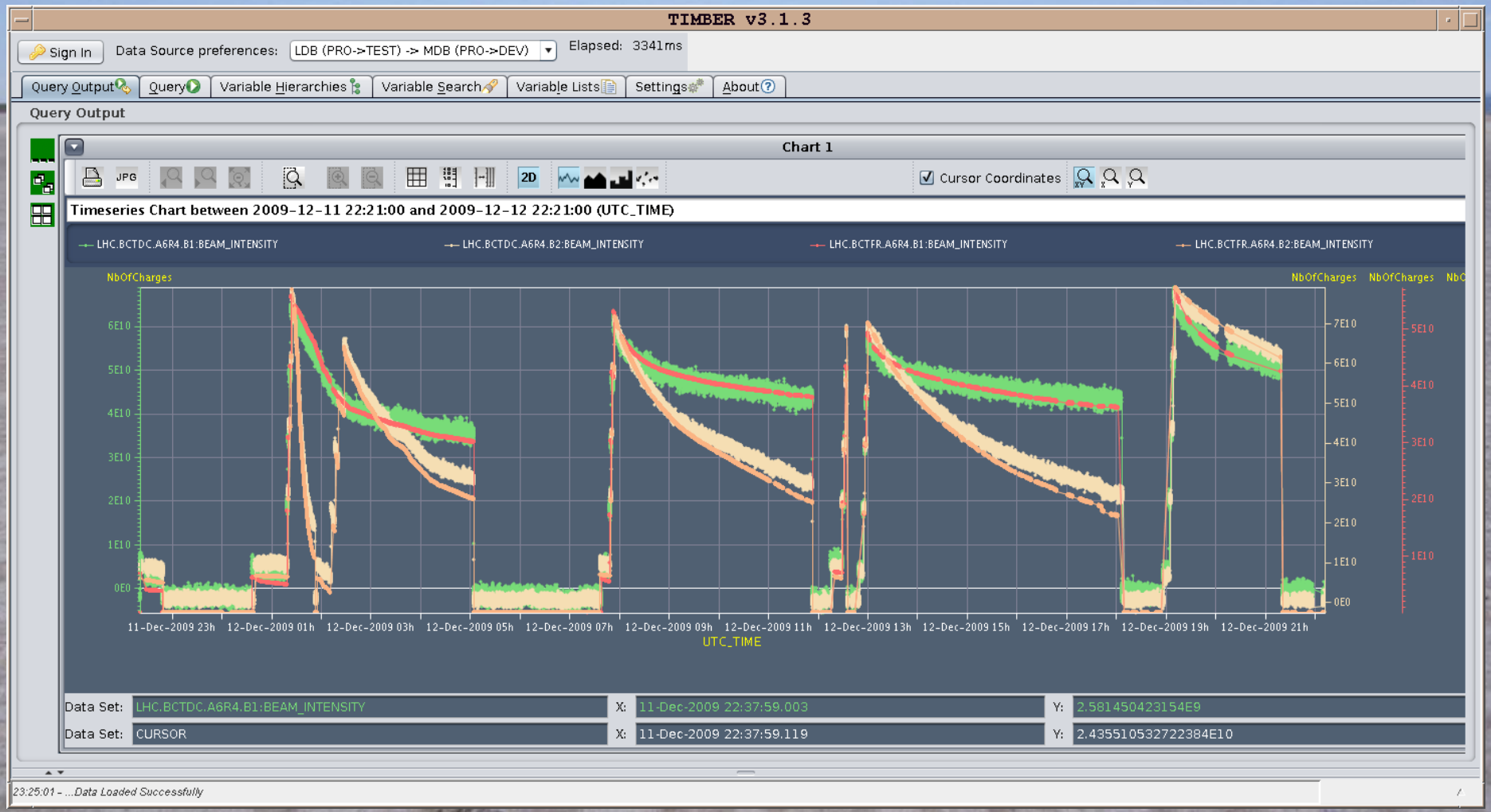
Accelerating 2 Beams to 1.18 TeV



- Smooth increase of magnet current to 2000 Amps
- Few protons lost during the acceleration

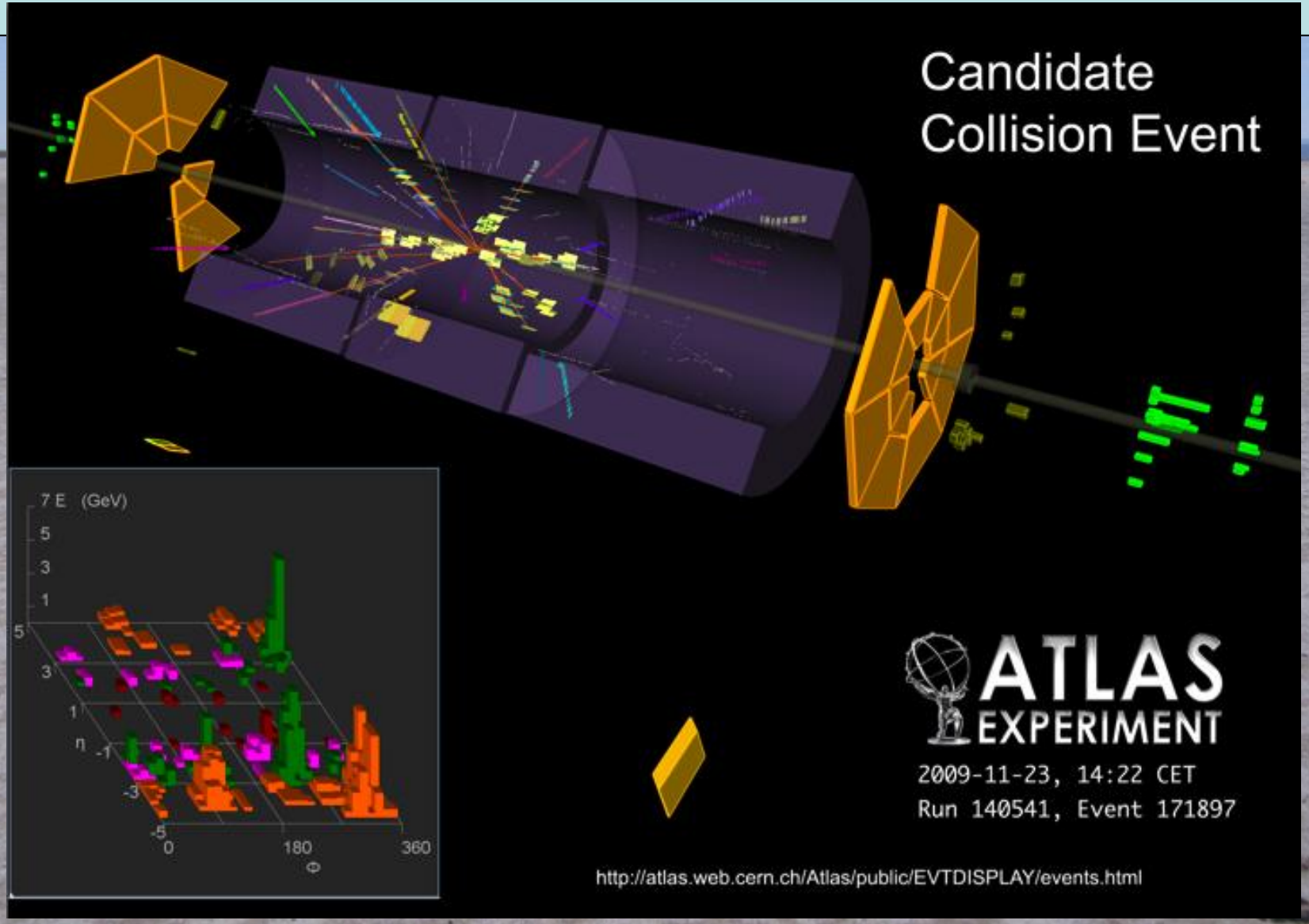
Tense Anticipation …

Colliding Beams @ 900 GeV



… and Jubilation

First LHC Collision in ATLAS



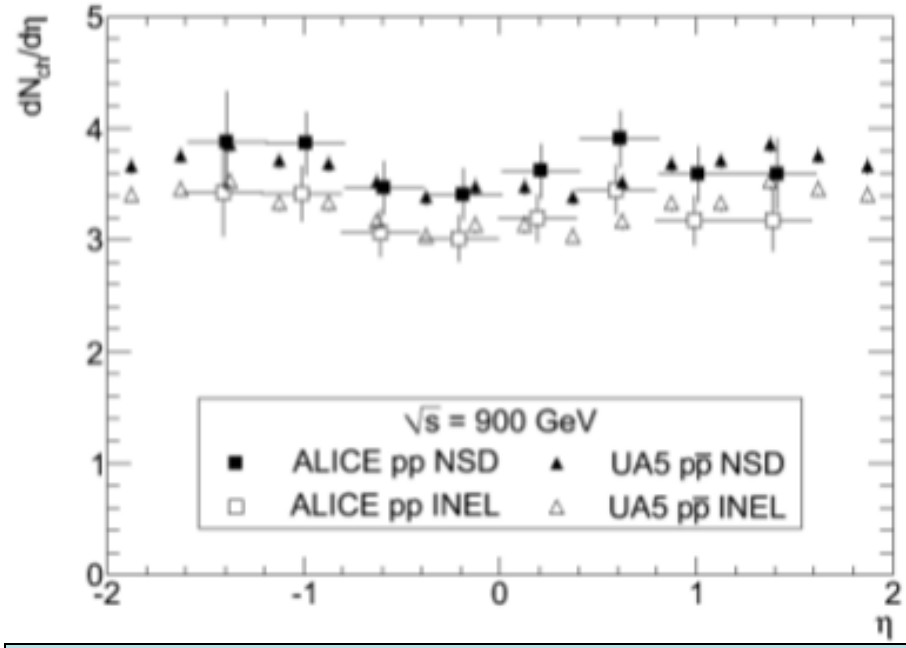
First LHC Physics Paper from ALICE

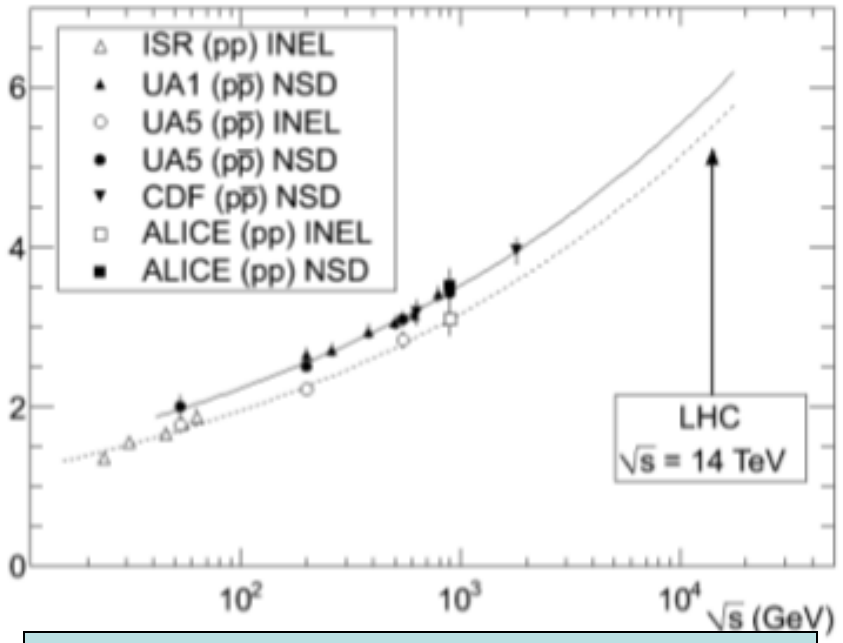
First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged particle pseudorapidity density at $\sqrt{s} = 900$ GeV

Based on 300 events from 23/11

ALICE collaboration

Experiment Model	ALICE pp	UA5 $p\bar{p}$ [3]	QGSM [26]	PYTHIA [17] (109) [18]	 (306) [27]	 (320) [28]	PHOJET [8]
INEL	$3.10 \pm 0.13 \pm 0.22$	3.09 ± 0.05	2.98	2.33	2.99	2.46	3.14
NSD	$3.51 \pm 0.15 \pm 0.25$	3.43 ± 0.05	3.47	2.83	3.68	3.02	3.61



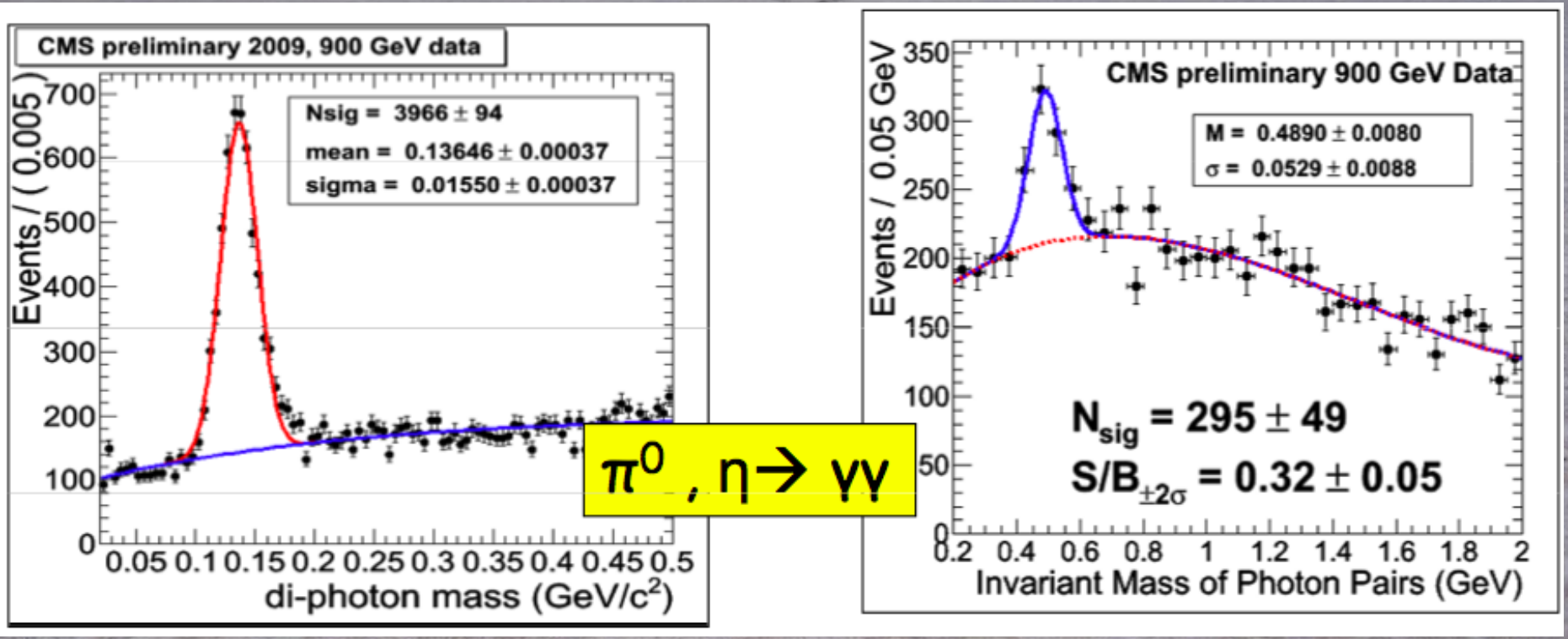


Angular distribution of produced particles

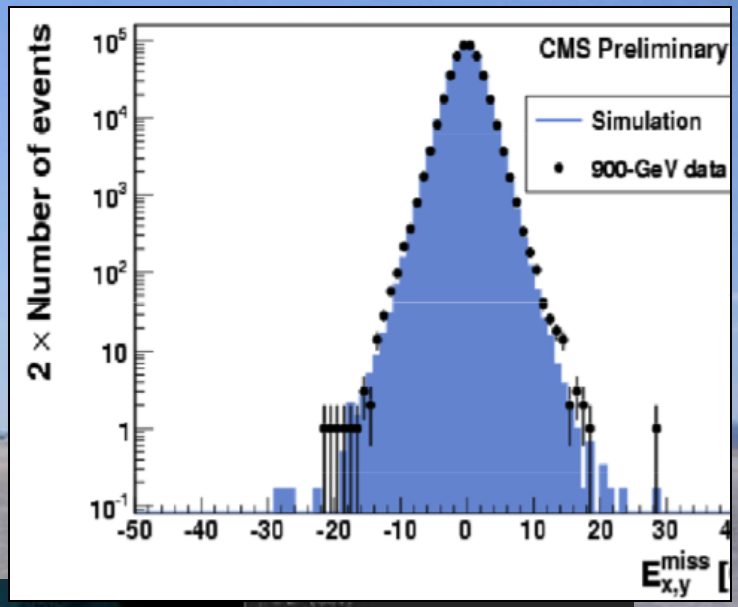
Total number of produced particles

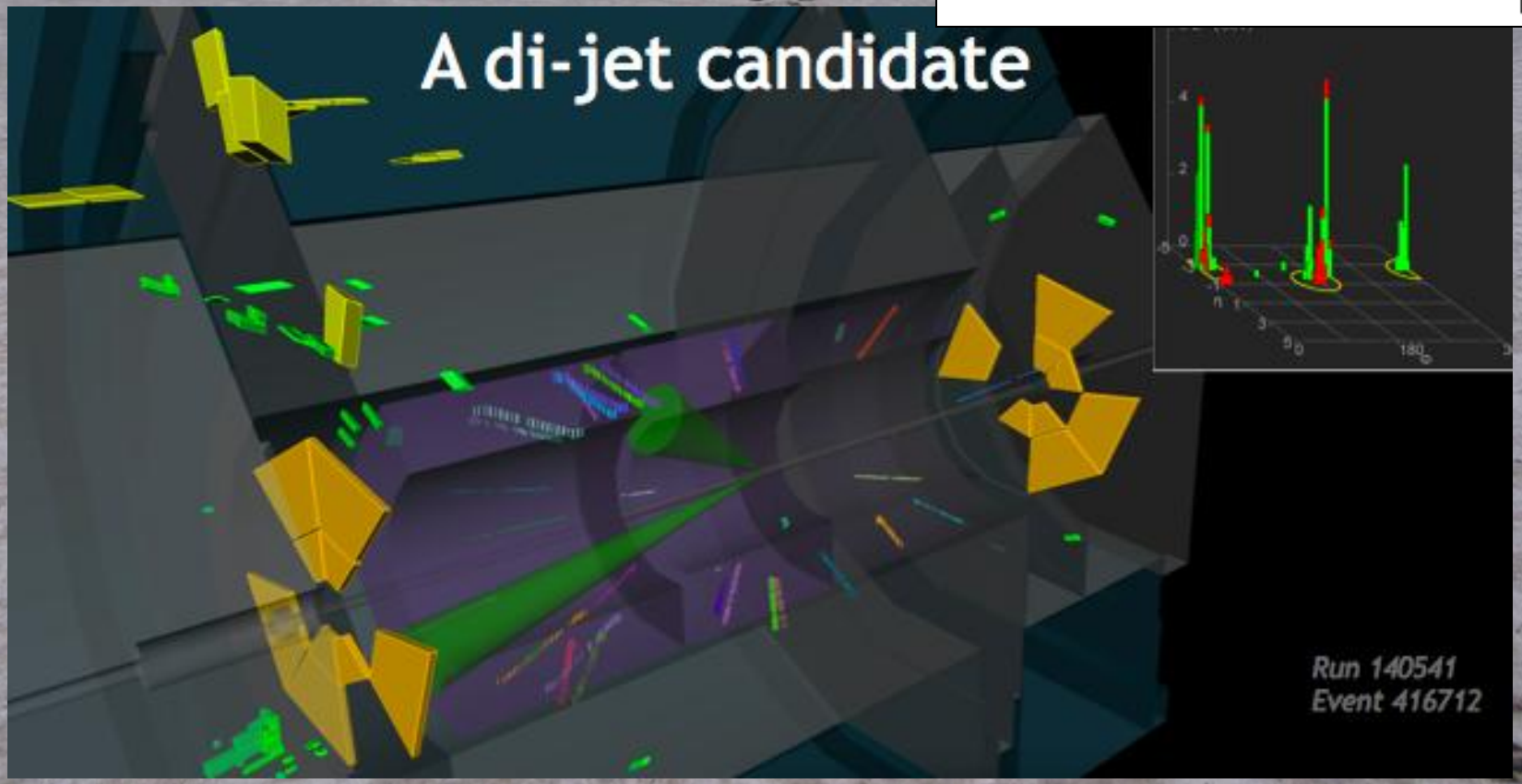
No Higgs yet!

$\gamma\gamma$ invariant mass distributions



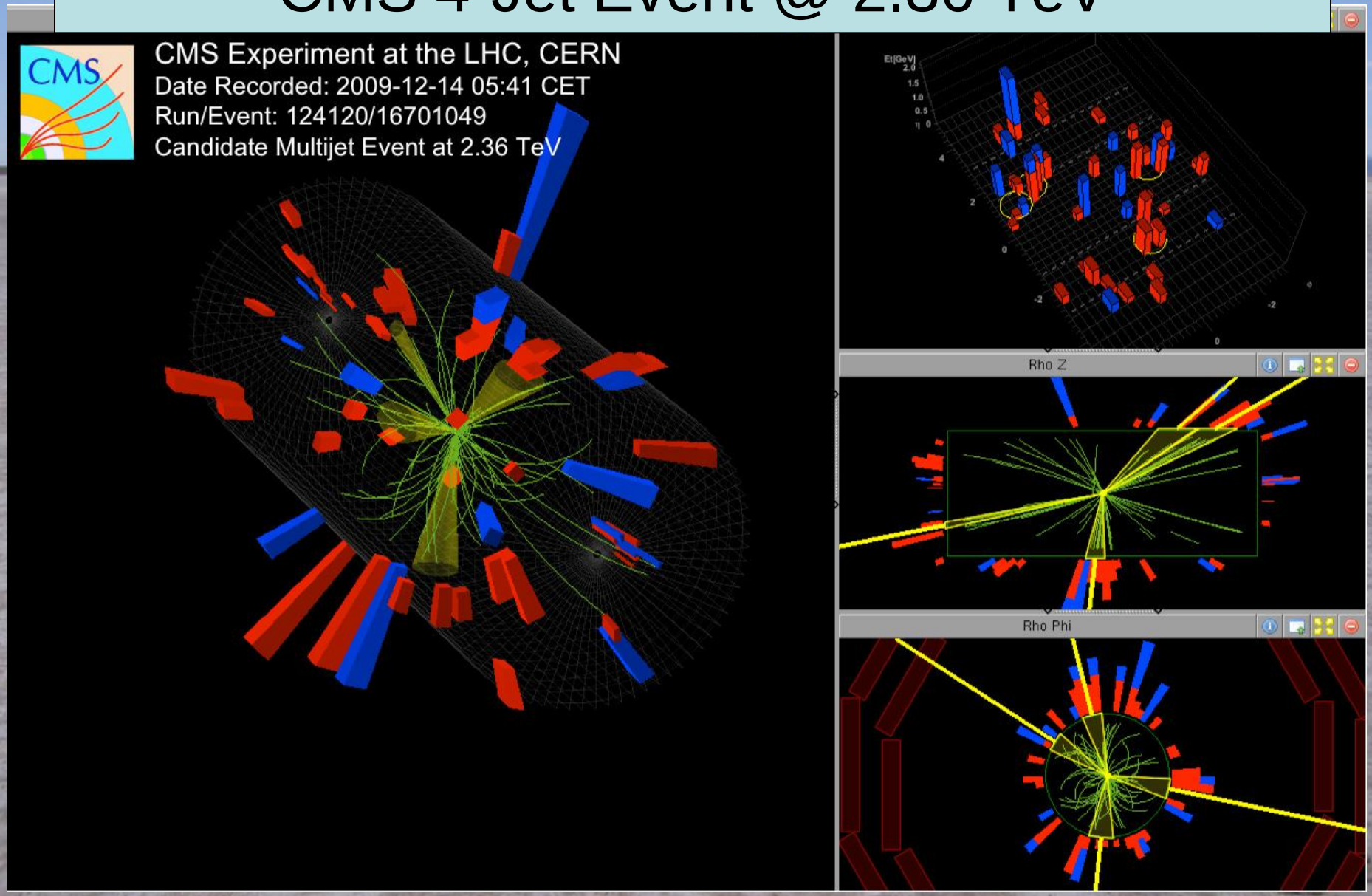
No Supersymmetry yet!





No Black Holes yet!

CMS 4-Jet Event @ 2.36 TeV

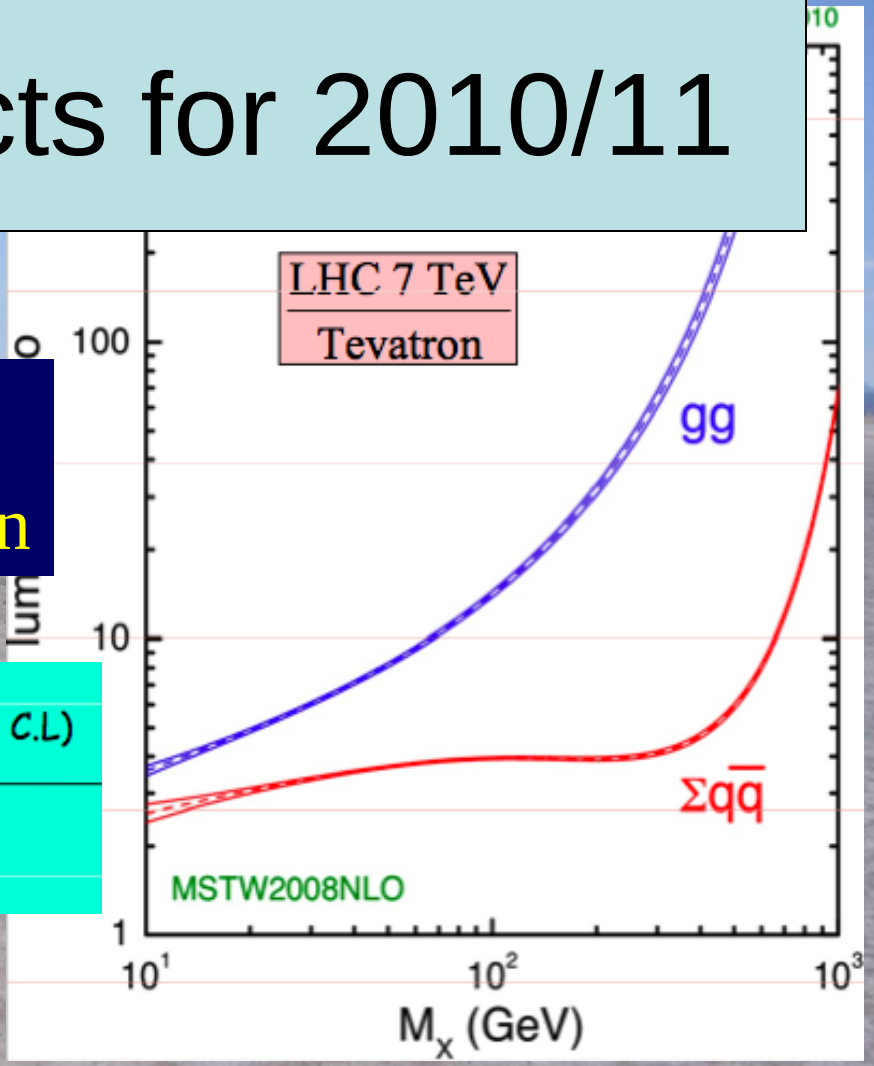


What will the Future bring?

- Default scenario:
  - 2010/2011
    - Run @ 3.5 TeV + 3.5 TeV
    - Aim for > 1/fb integrated luminosity
- Plan long shutdown before increasing energy
- At least one major upgrade:
  - Linac4, new collision insertions
- Scope of second upgrade under discussion
  - SPL? PS2? Collision insertions? Crab cavities?

Physics Prospects for 2010/11

Ratios of parton-parton luminosities @ LHC/Tevatron



SUSY ($\tilde{q},\tilde{g}$) : Tevatron limit ~ 400 GeV (95% C.L)

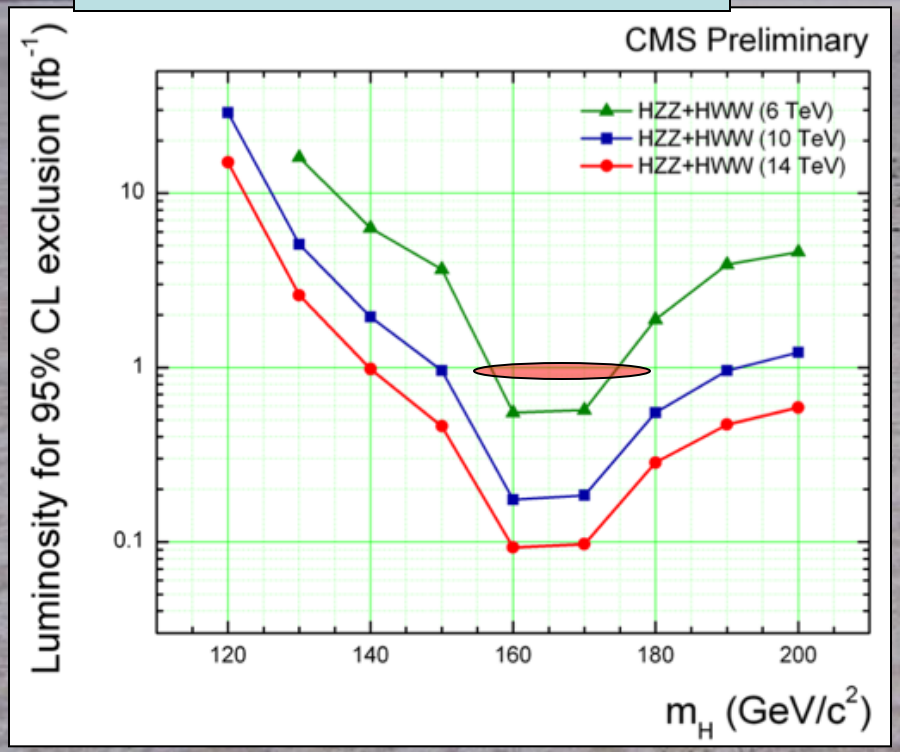
100 pb^{-1} : discovery up to ~ 400 GeV
1 fb^{-1} : discovery up to ~ 800 GeV

Higgs $\sqrt{s}$=7 TeV: H → WW, m_H ~ 160 GeV (Tevatron exclusion: 163-166 GeV)

300 pb^{-1} per experiment : ~ 3σ sensitivity combining ATLAS and CMS (similar to Tevatron)
1 fb^{-1} per experiment : could exclude 145 < m_H < 180 GeV
~ 4.5 σ combining ATLAS and CMS

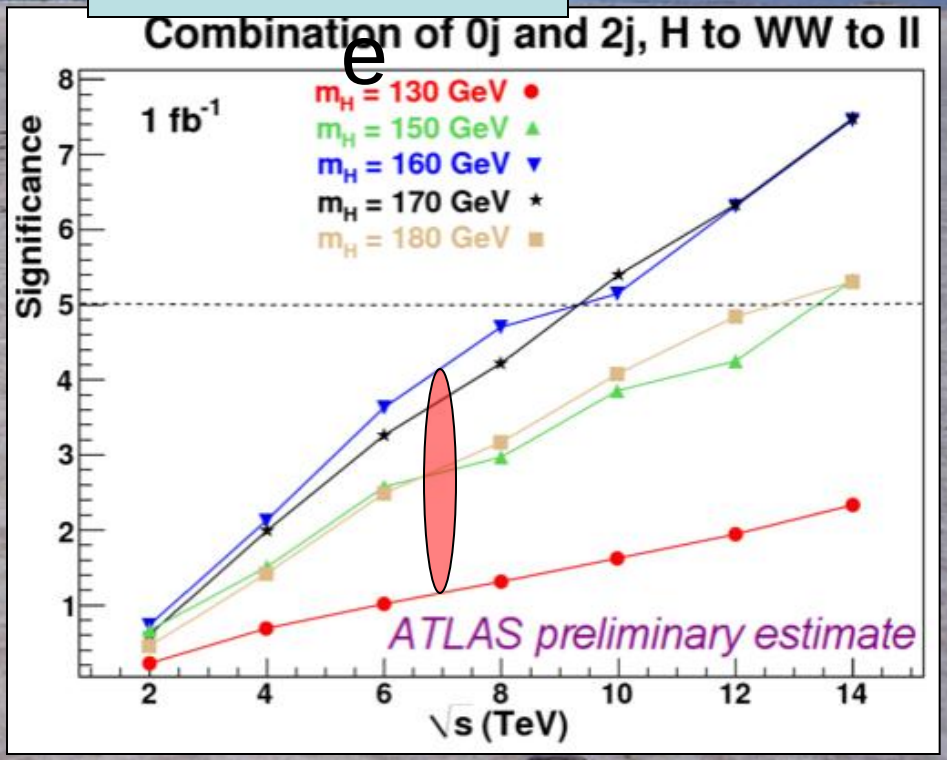
Evidence against/for the Higgs?

Exclusion region



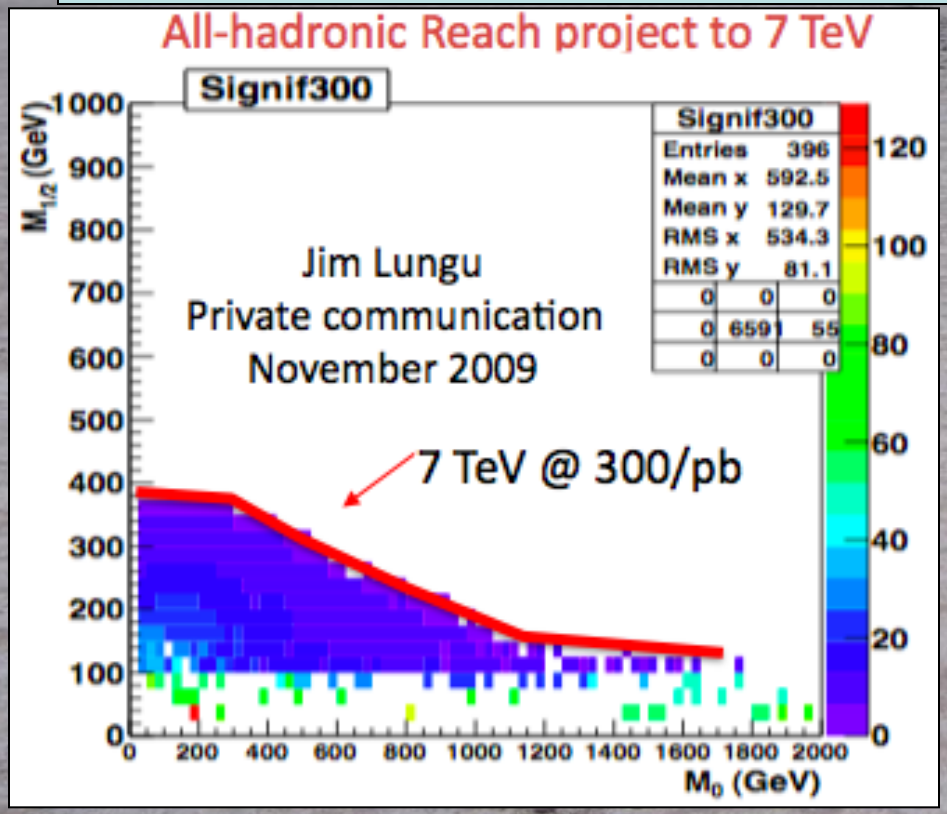
Significanc

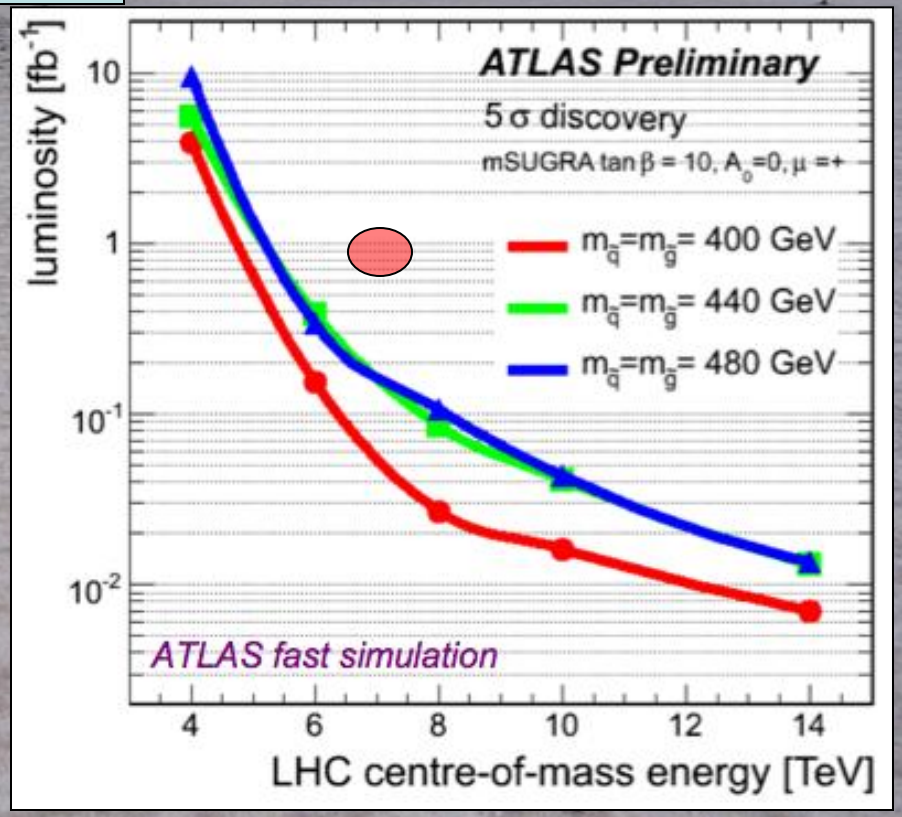
e



Discovery of Supersymmetry?

Reach for 5-σ discovery

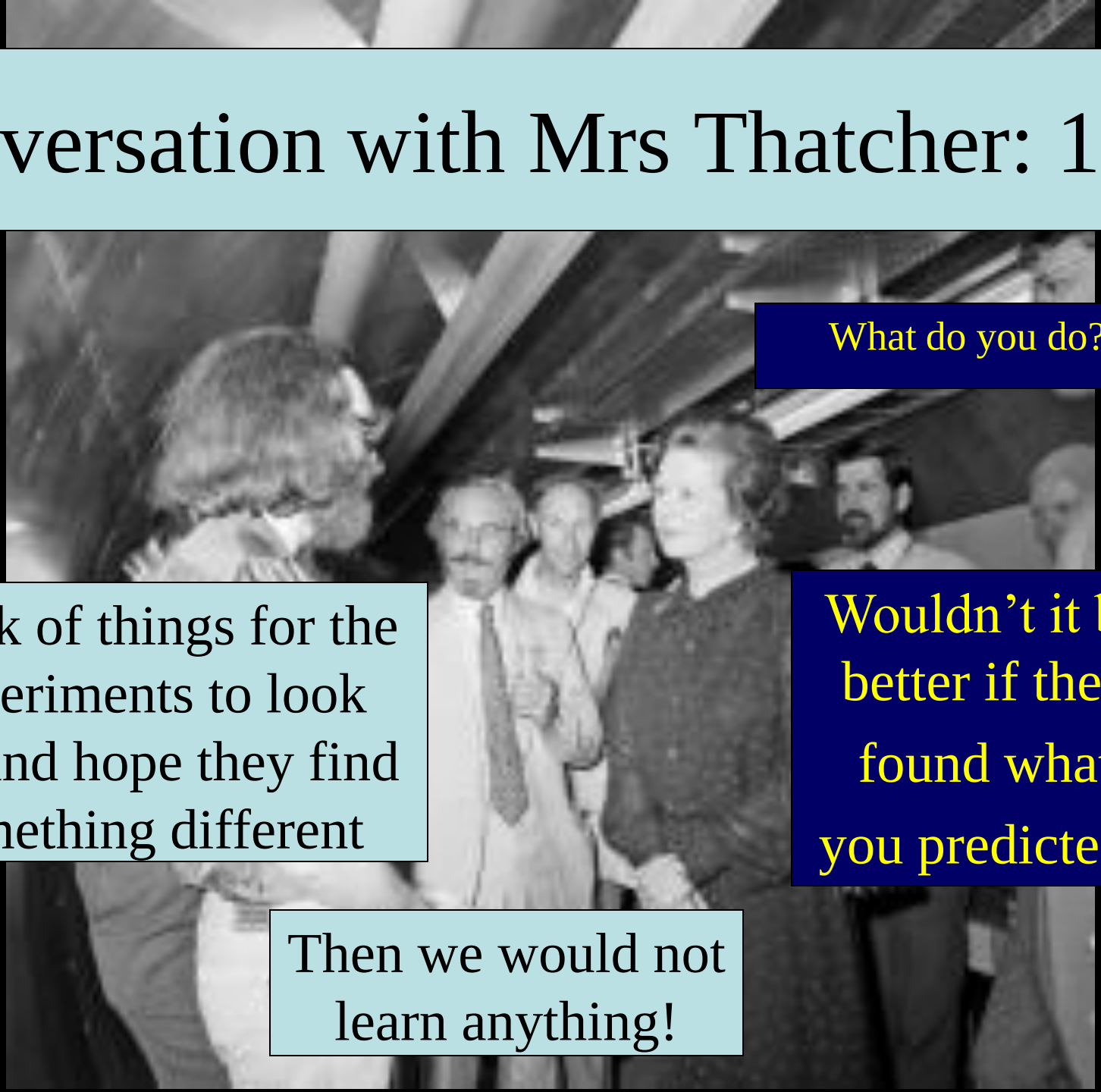




What are the Stakes for Strings?

- Is there such a thing as an elementary scalar field?
  Not if you believe Stephen Hawking
- Is there supersymmetry at an accessible energy?
  First postulated by string theorists
- If so, how is supersymmetry broken?
- Are any extra dimensions large?
- If so, what fixes their sizes?
- Does gravity become strong at TeV scale?
- If so, measure stringy grey-body factors

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!

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

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

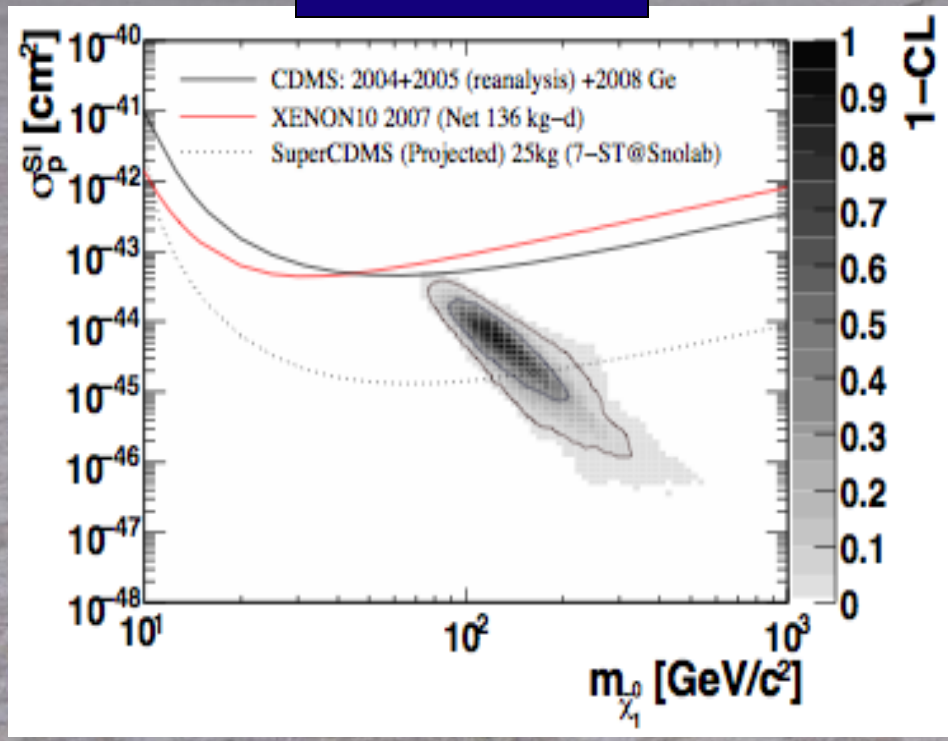
  $\chi - \chi \rightarrow \gamma + \ldots?$
- Annihilation in core of Sun or Earth

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

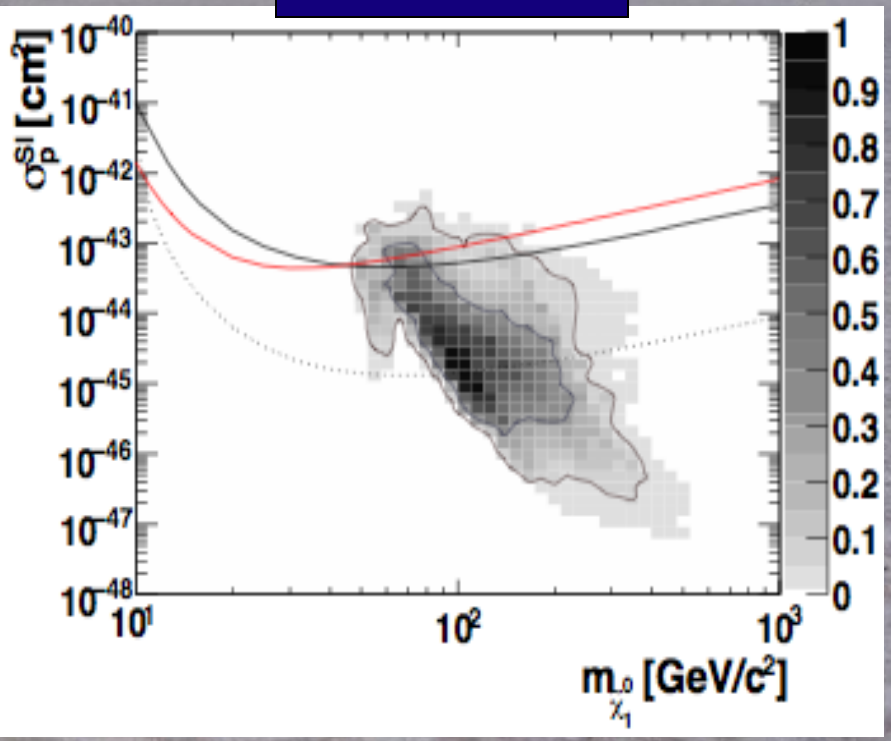
  $\chi + A \rightarrow \chi + A$

Elastic Scattering Cross Sections

CMSSM



NUHM1

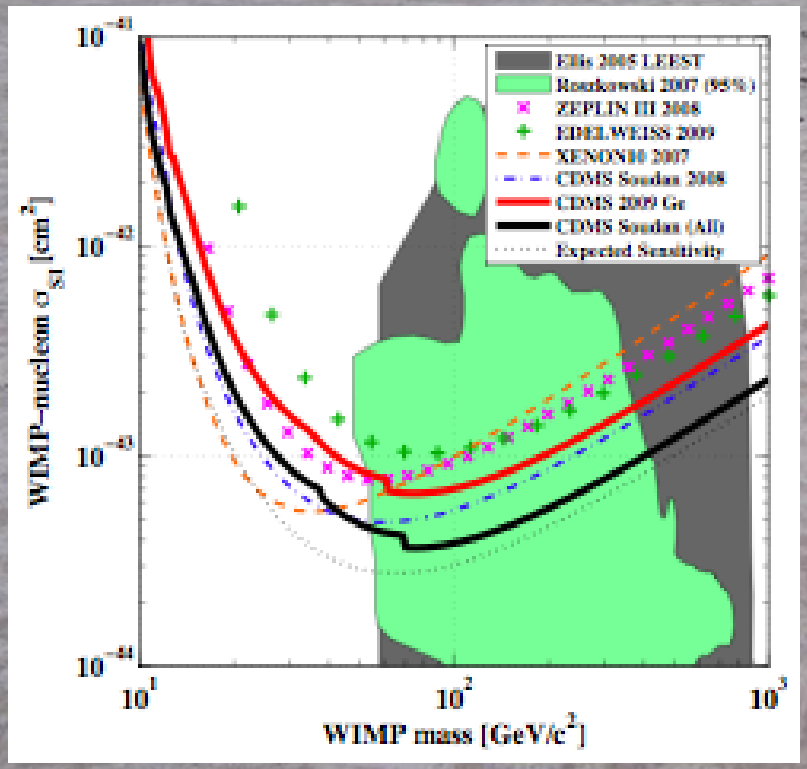


O.Buchmueller, JE et al: arXiv:0907.5568

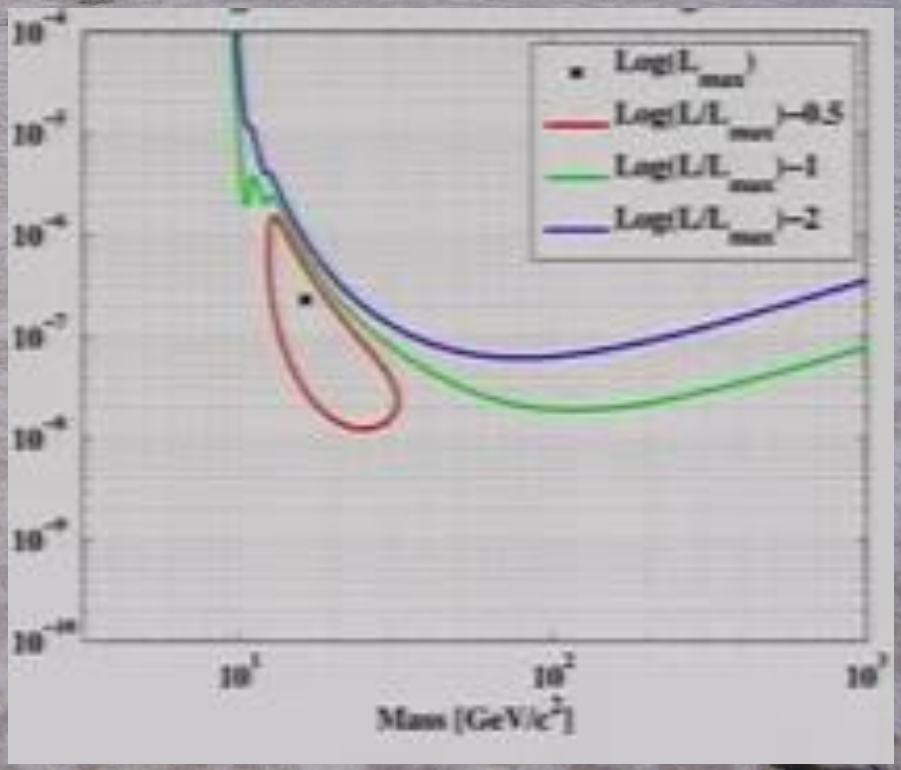
CDMS ‘Hint’?

Two events where 0.8 were expected: not significant

Published CDMS Plot



Likelihood Analysis



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?