STANDARD MODE

John Ellis, King's College London (& CERN)

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e^-_R \; , \; \mu^-_R \; , \; \tau^-_R$	$(\mathbf{1},\mathbf{2},\text{-}1)$ $(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L U_R D_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$ $u_R \; , \; c_R \; , \; t_R$ $d_R \; , \; s_R \; , \; b_R$	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

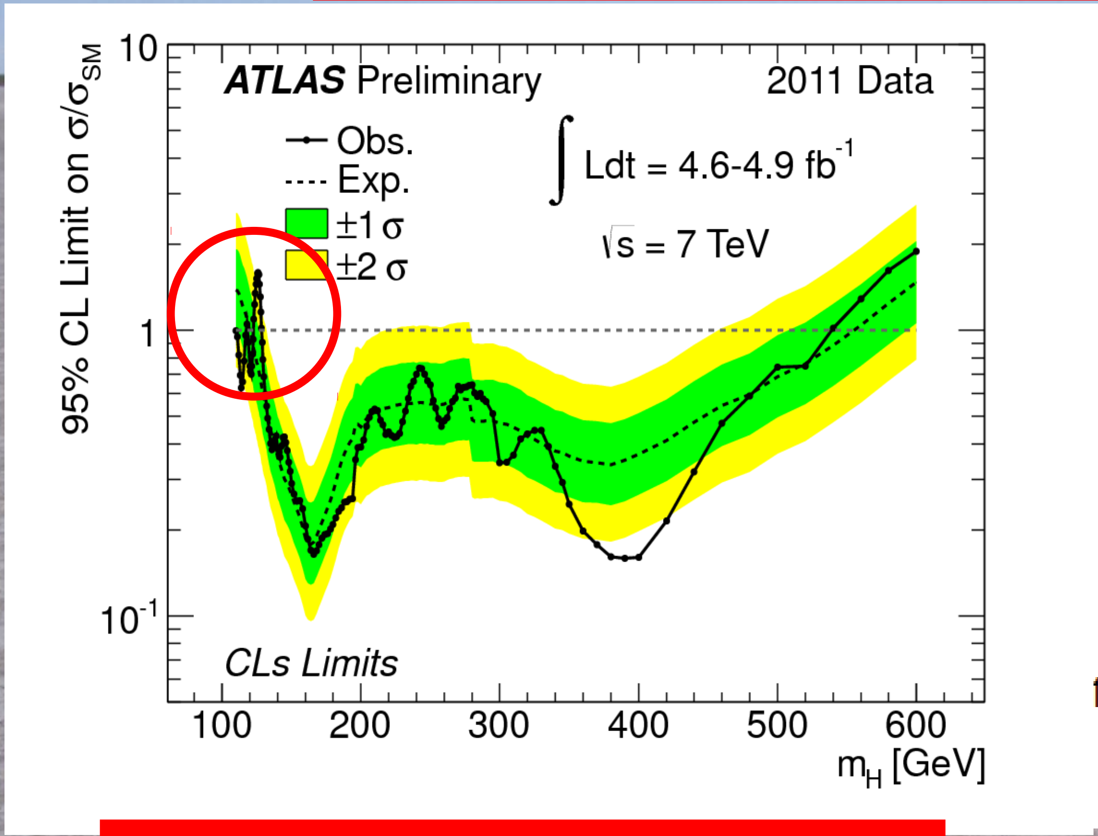
$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\ \mu\nu} && \text{gauge interactions} \\
&+ i\bar{\psi} \not{D} \psi + h.c. && \text{matter fermions} \\
&+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\
&+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential}
\end{aligned}
$$

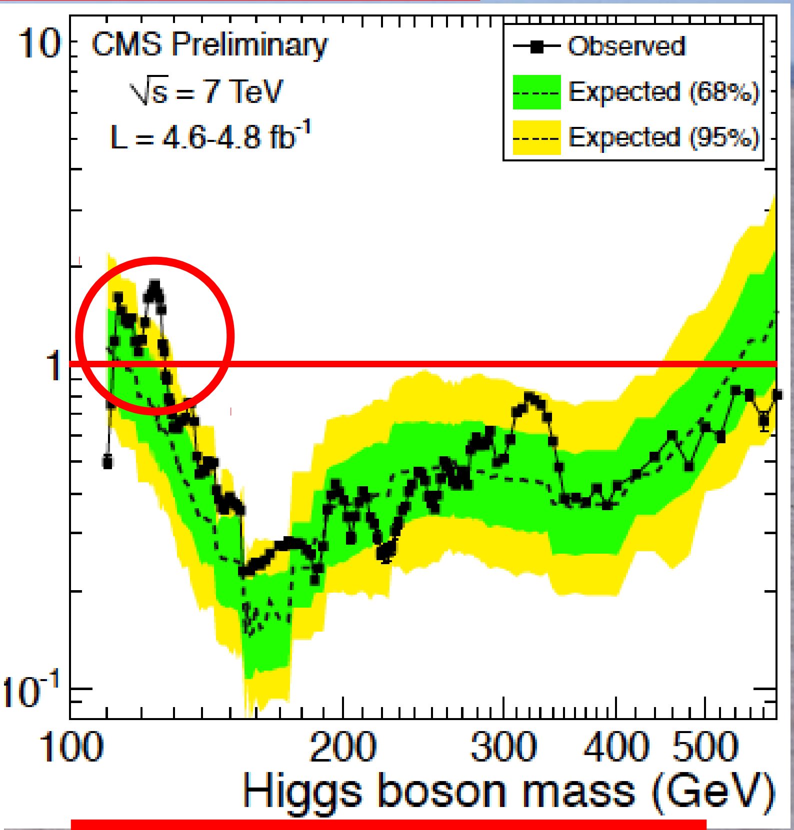
Open Questions beyond the Standard Model

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

Has the Higgs been Excluded?

Interesting hints around M_h = 125 GeV ?





ATLAS excludes

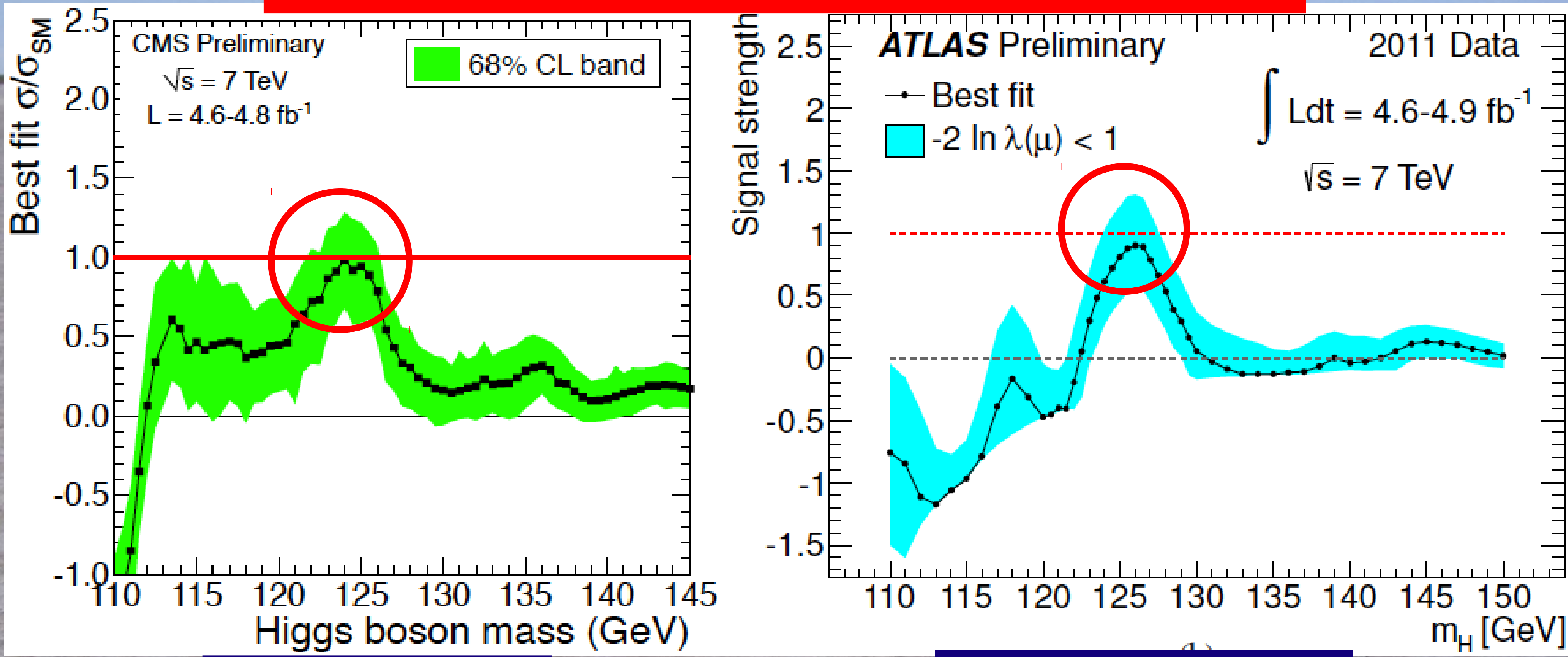
< 122.5, > 129, < 539 GeV

CMS excludes

> 127.5, < 600 GeV

Has the Higgs been Discovered?

Interesting hints around M_h = 125 GeV ?



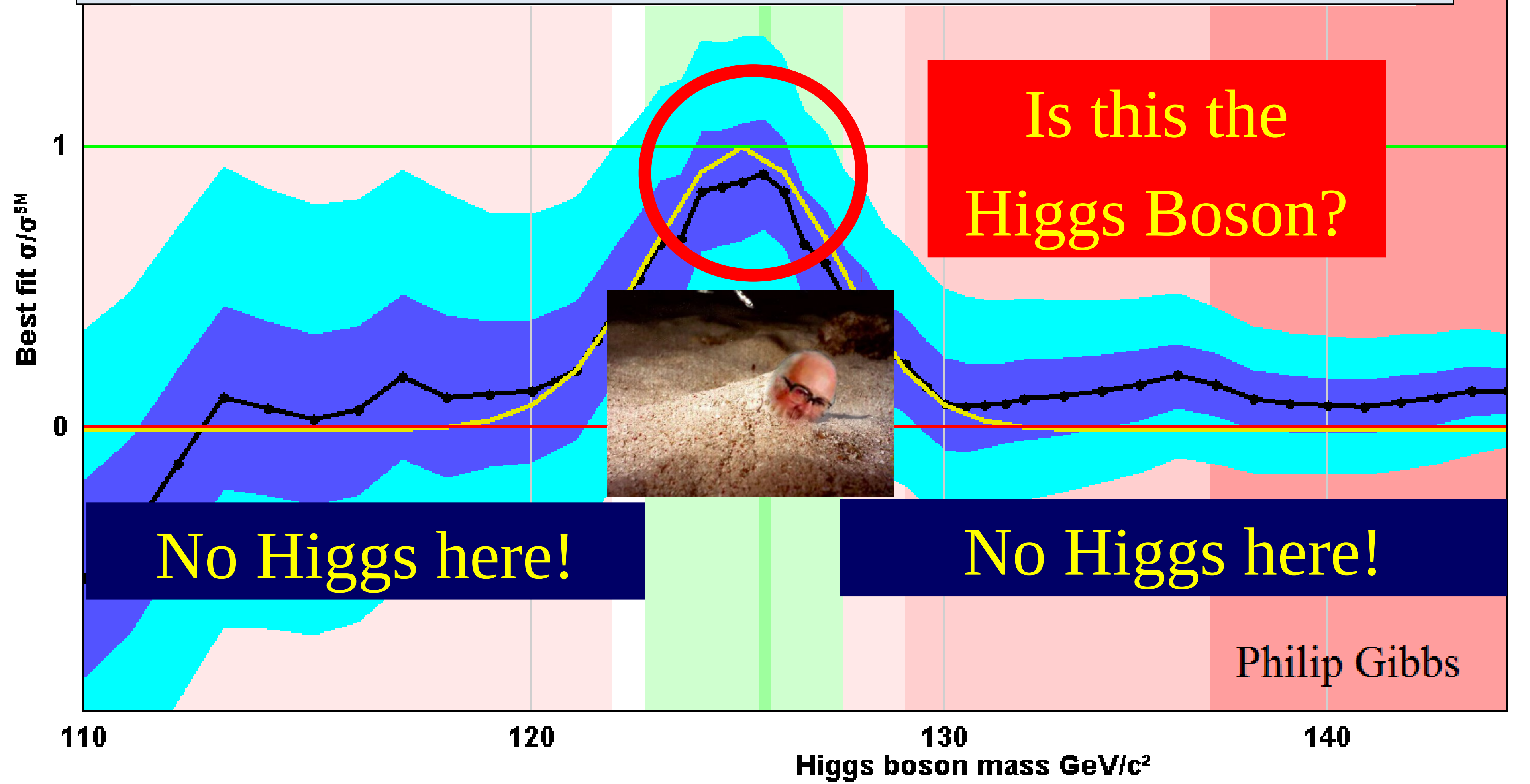
CMS prefers

< 125 GeV

ATLAS prefers

> 125 GeV

Unofficial Combination of Higgs Search Data from March 7th



The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

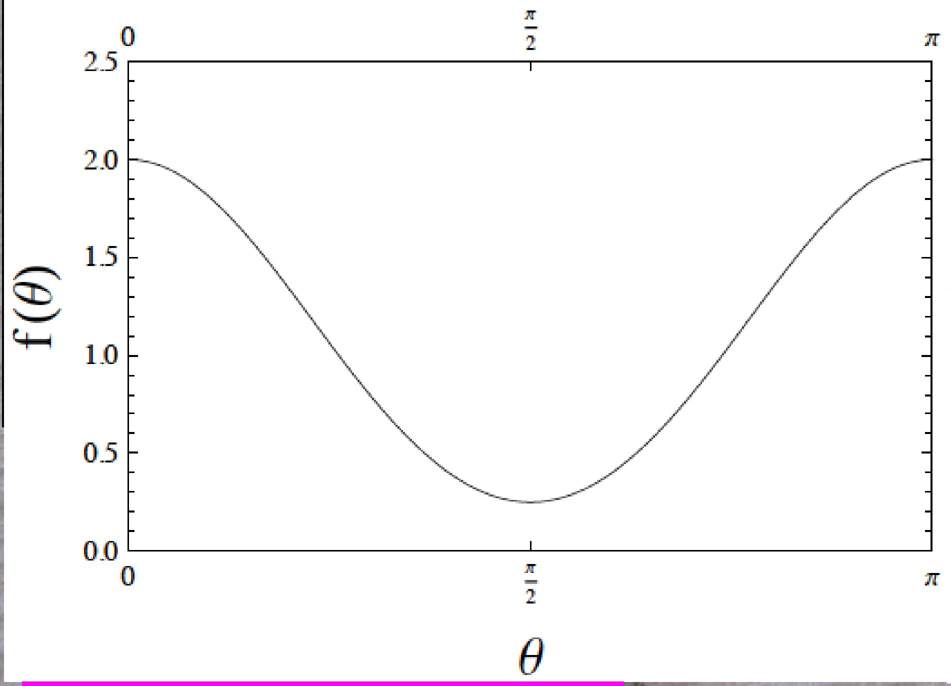
Do we already know the 'Higgs' has Spin Zero ?

- Decays into γγ, so cannot have spin 1
- 0 or 2?
- If it decays into ττ or b-bar: spin 0 or 1 or orbital angular momentum
- Can diagnose spin via
  - angular distribution of γγ
  - angular correlations of leptons in WW, ZZ decays
- Does selection of WW events mean spin 1?

Does the 'Higgs' have Spin Zero ?

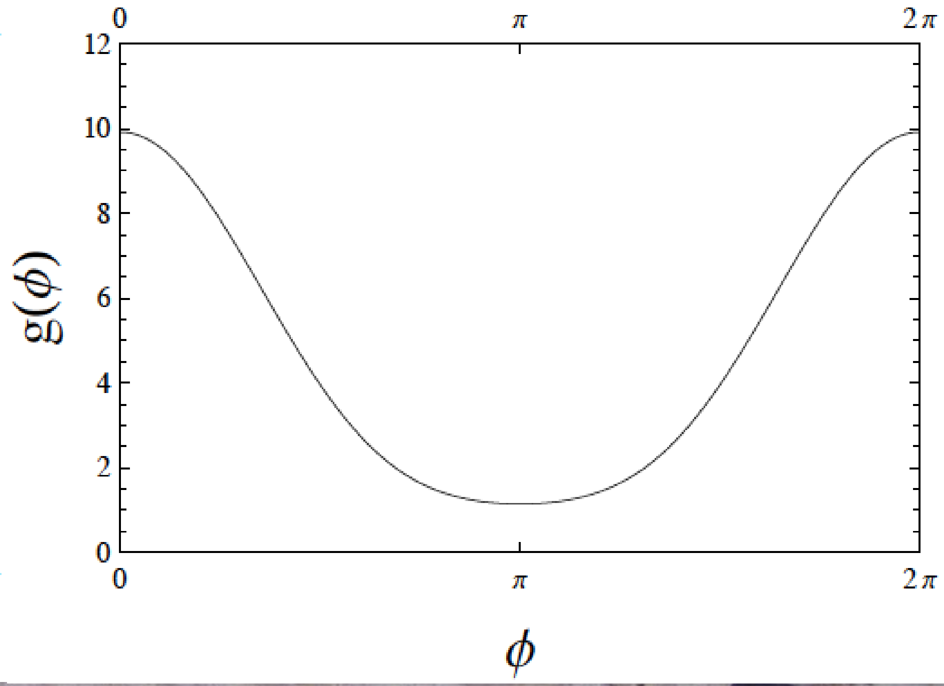
- Polar angle distribution: $X_2 \rightarrow \gamma\gamma$

  (flat for X_0)



- Azimuthal angle distribution: $X_0 \rightarrow WW$

  (flat for X_2)



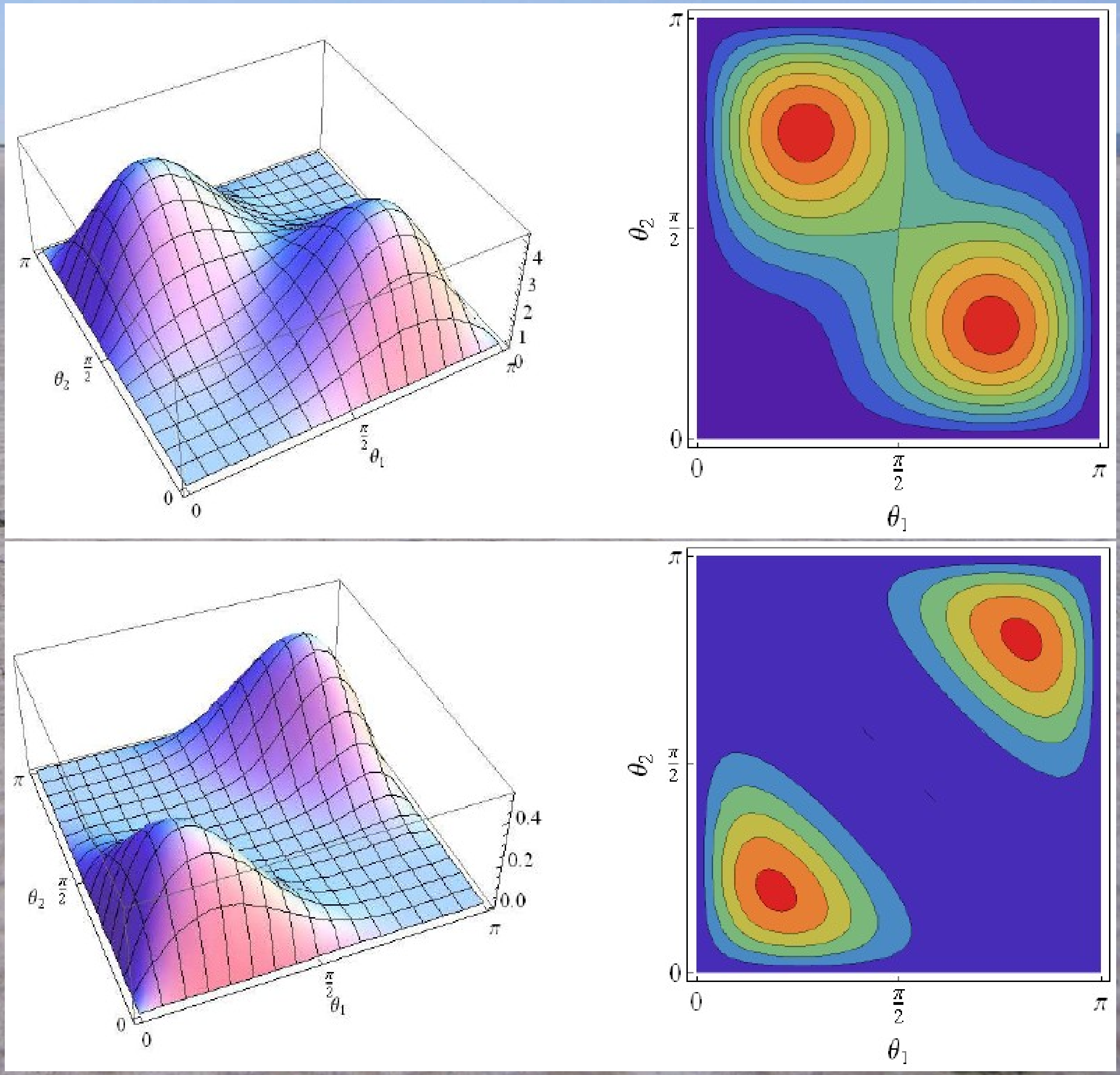
JE, Hwang: arXiv:1202.6660

Does the ‘Higgs’ have Spin Zero ?

- Polar angle distribution for $X_2 \rightarrow W^+W^-$
- Polar angle distribution for $X_0 \rightarrow W^+W^-$

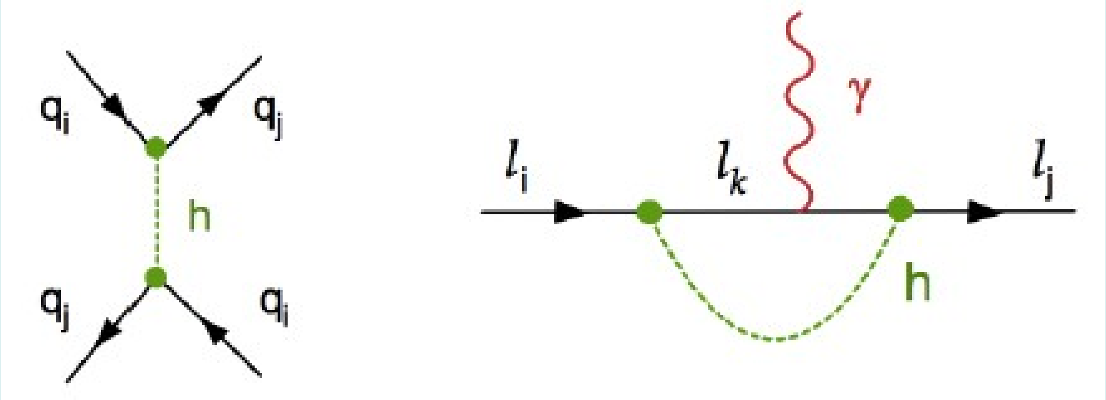
(for $\varphi = \pi$)

JE, Hwang: arXiv:1202.6660



Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



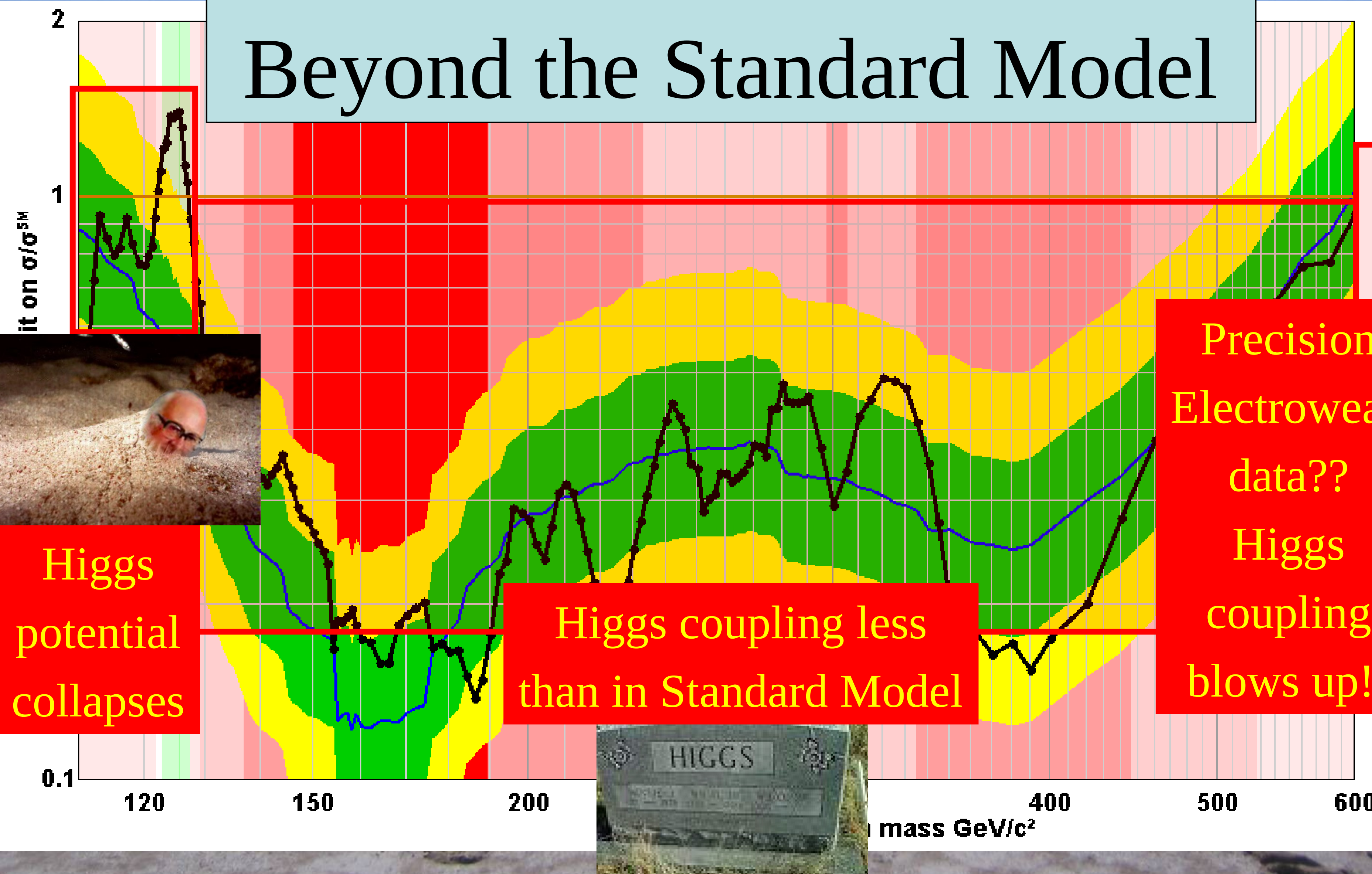
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be < 2×10^{-5}

There must be New Physics Beyond the Standard Model



Higgs potential collapses

Higgs coupling less than in Standard Model

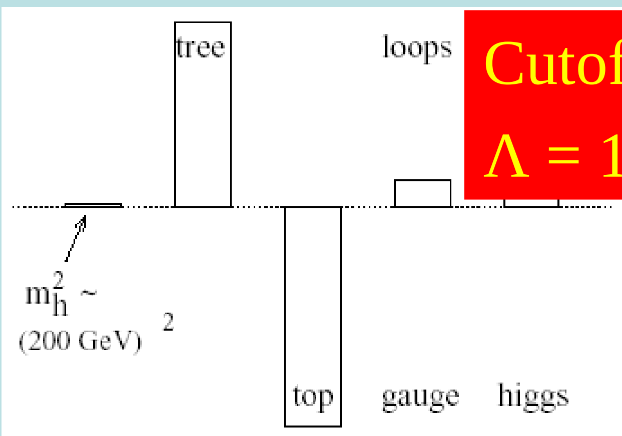
Precision Electroweak data?? Higgs coupling blows up!!

Elementary Higgs or Composite?

- Higgs field:

  $<0|H|0> \neq 0$

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off $\Lambda \sim$ 1 TeV with

Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

-Heavy scalar resonance?

-Inconsistent with

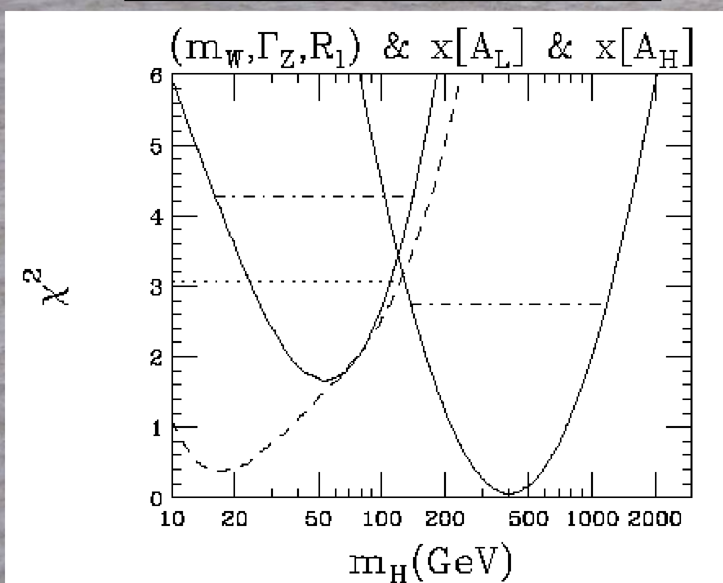
precision electroweak data?

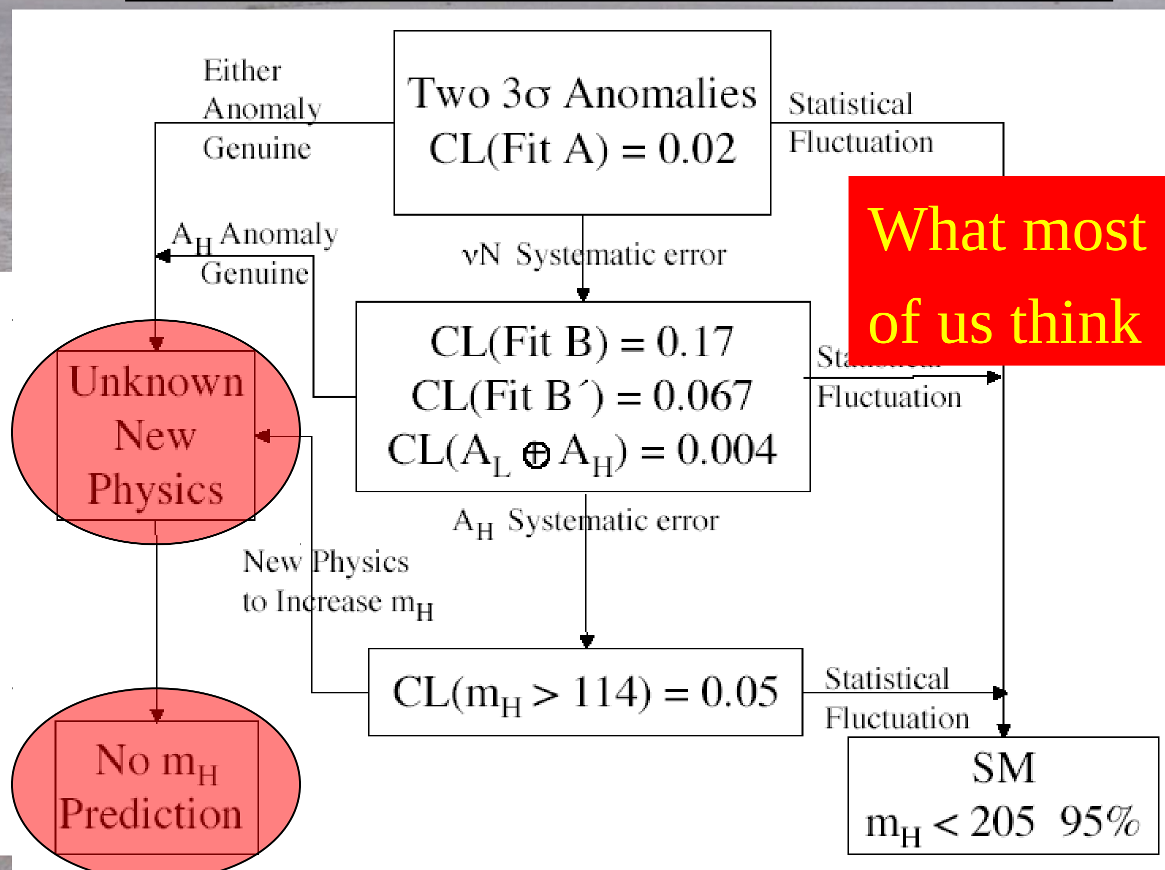
Heretical Interpretation of EW Data

What attitude towards LEP, NuTeV?

Do all the data tell the same story?

e.g., A_L vs A_H





Chanowitz

Higgs + Higher-Order Operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^p}\mathcal{O}_i^{(4+p)}$$

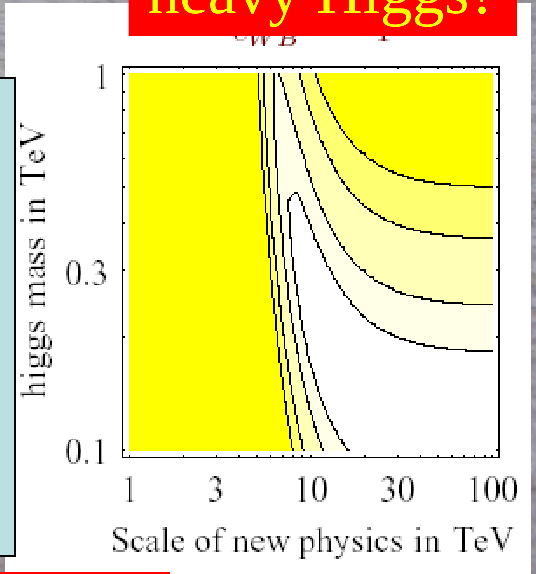
Precision EW data suggest they are small: **why?**

Corridor to heavy Higgs?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+\sigma^a H)W^a_{\mu\nu}B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H)\rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu\sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

But conspiracies are possible: m_H could be large, even if believe EW data …?

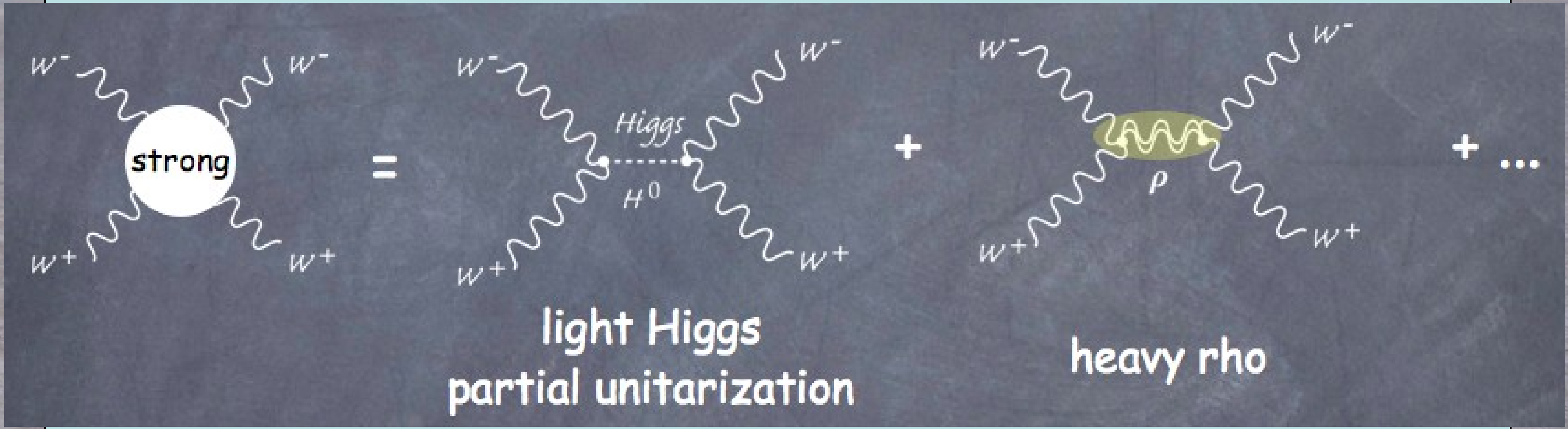


Do not discard possibility of heavy Higgs

Barbieri, Strumia

Interpolating Models

- Combination of Higgs boson and vector ρ



- Two main parameters: m_ρ and coupling g_ρ
- Equivalently ratio weak/strong scale: g_ρ / m_ρ

Grojean, Giudice, Pomarol, Rattazzi

What if the Higgs is not quite a Higgs?

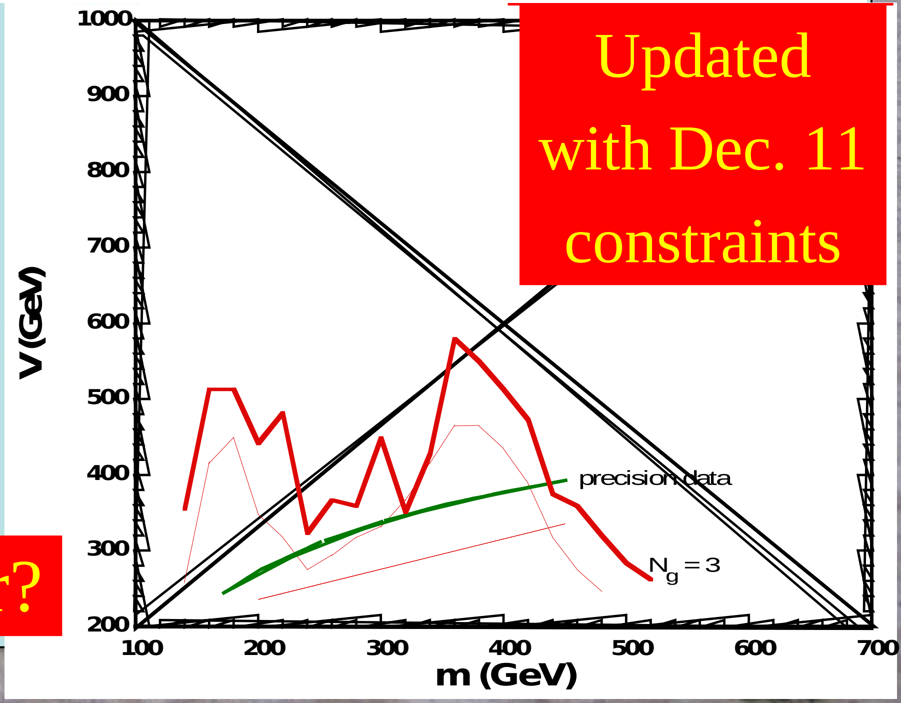
- Tree-level Higgs couplings ~ masses
  - Coefficient ~ 1/v
- Couplings ~ dilaton of scale invariance
- Broken by Higgs mass term $-\mu^2$, anomalies
  - Cannot remove μ^2 (Coleman-Weinberg)
  - Anomalies give couplings to γγ, gg
- **Generalize to pseudo-dilaton of new (nearly) conformal strongly-interacting sector**
- Pseudo-Goldstone boson of scale symmetry

A Phenomenological Profile of a Pseudo-Dilaton

- Universal suppression of couplings to Standard Model particles: a = c = v/V
- Effective potential: $\mathcal{V}(\chi) = \frac{m^2}{\gamma V^2}\left[\frac{1}{4+\gamma}\left(\frac{\chi}{V}\right)^\gamma - \frac{1}{4}\right] + \mathcal{O}\left(\frac{m^2}{V^2}\right)^2$
- Self-couplings:

$$g_{3\hat{\chi}} = (5+\gamma+\dots)\frac{m^2}{V}$$
$$g_{4\hat{\chi}} = (11+6\gamma+\gamma^2+\dots)\frac{m^2}{V^2}$$

- Γ(gg) may be enhanced
- Γ(γγ) may be suppressed



Updated with Dec. 11 constraints

Pseudo-baryons as dark matter?

Campbell, JE, Olive: arXiv:1111.4495

General Analysis of 'Less Higgs' Models

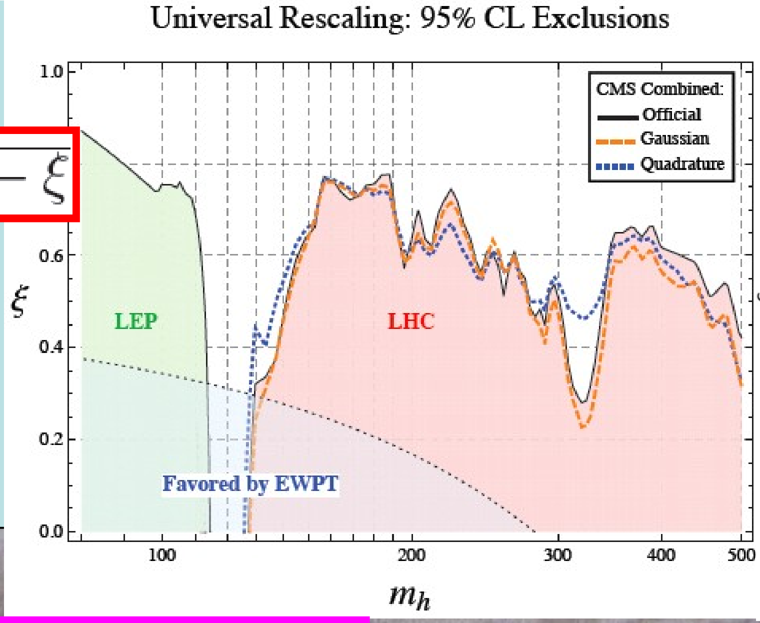
- Parameterization of effective Lagrangian:

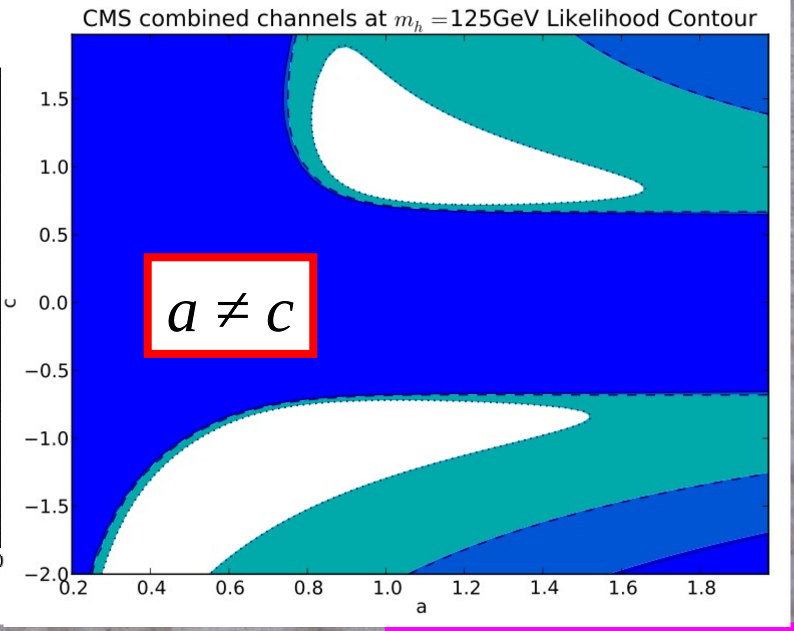
$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\frac{h}{v} + c_{2u}\frac{h^2}{v^2} + \cdots\right.$$

- Fits

$$a = c = \sqrt{1-\xi}$$





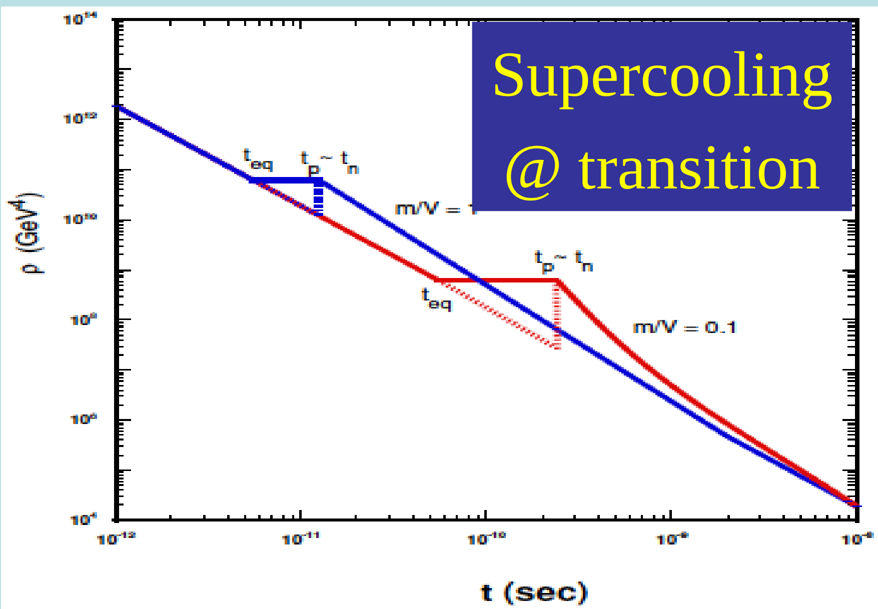
$$a \neq c$$

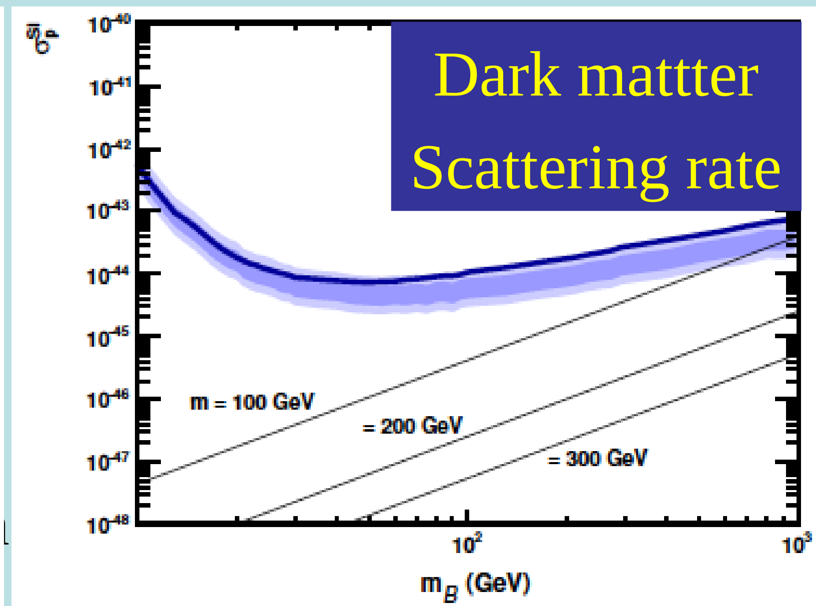
Azatov, Contino, Galloway: arXiv:1202.3415

You & JE: in preparation

Pseudo-Baryonic Dark Matter?

- Nonlinear Lagrangians have soliton solutions = baryons (à la Skyrme)
- Produced at electroweak transition (first-order)
-

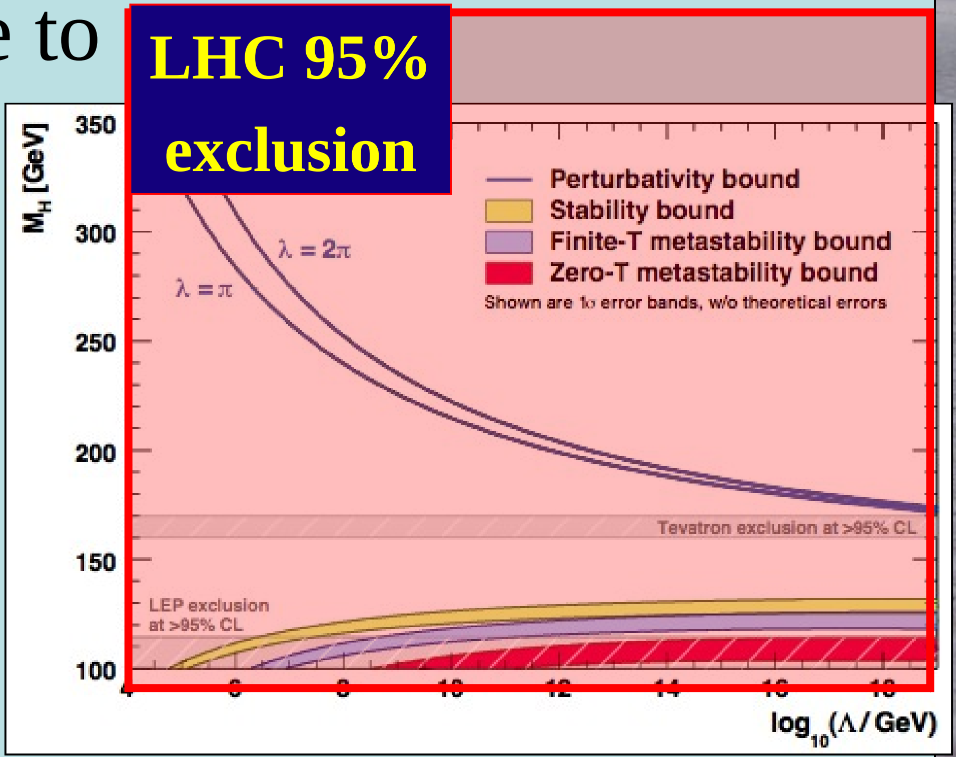




Campbell, JE, Olive: arXiv:1111.4495

Theoretical Constraints on Higgs Mass

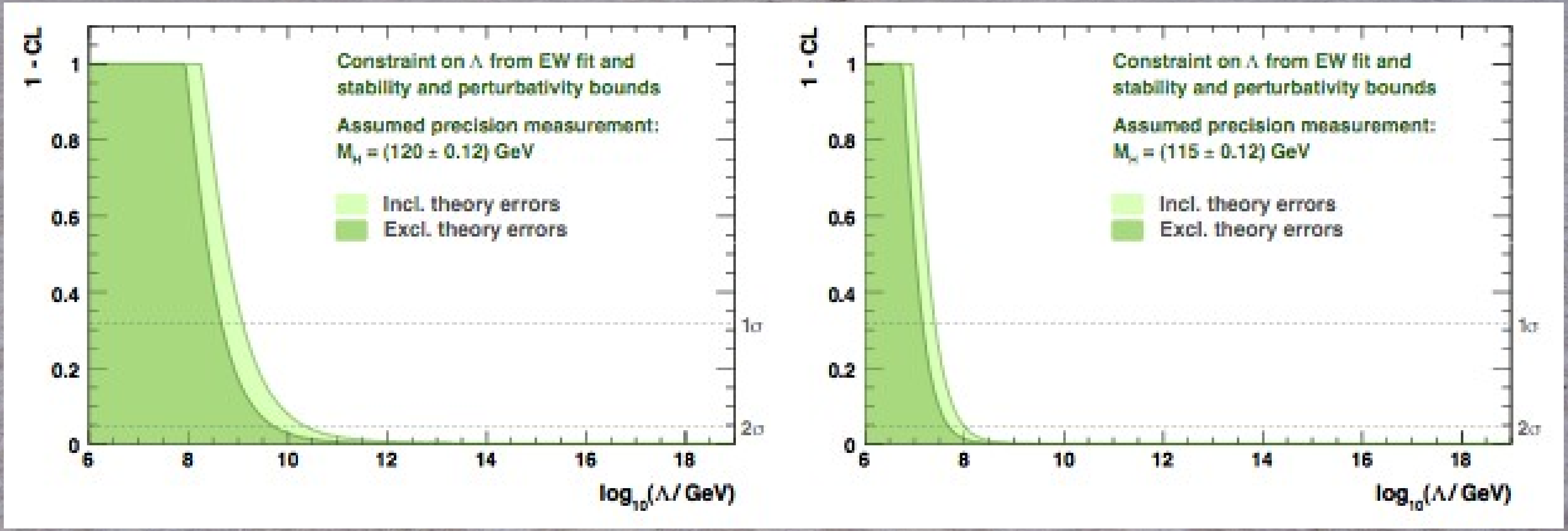
- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by supersymmetry



Espinosa, JE, Giudice, Hoecker, Riotto, arXiv0906.0954

The LHC will Tell the Fate of the SM

Examples with LHC measurement of m_H = 120 or 115 GeV



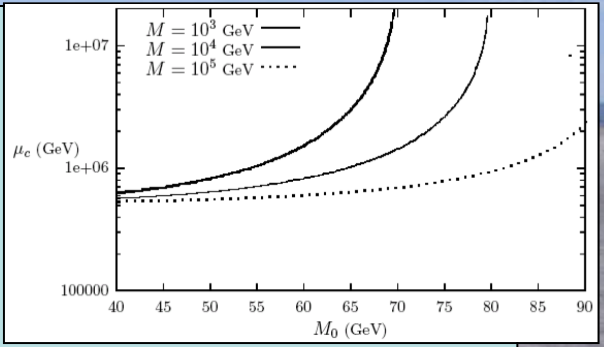
Espinosa, JE, Giudice, Hoecker, Riotto

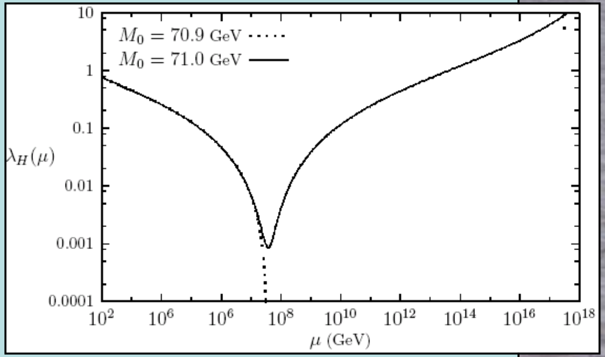
How to Stabilize a Light Higgs Boson?

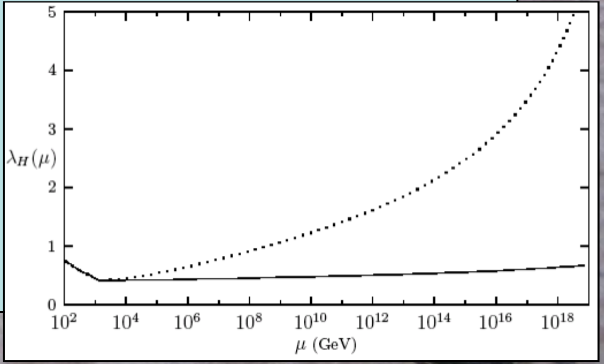
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**



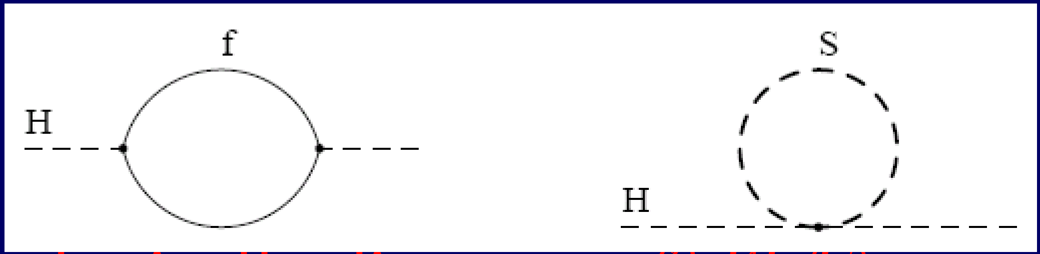




JE + D. Ross

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

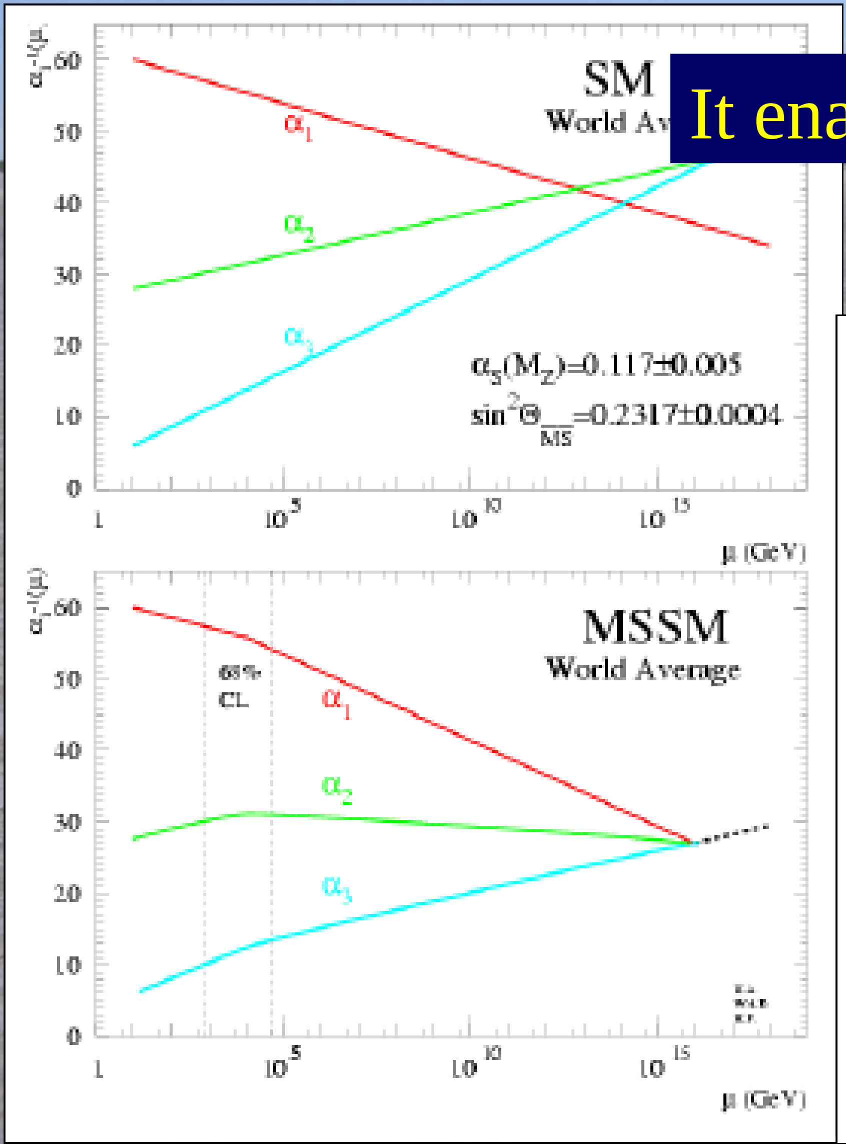
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if $\lambda_S =$ ¿ x 2

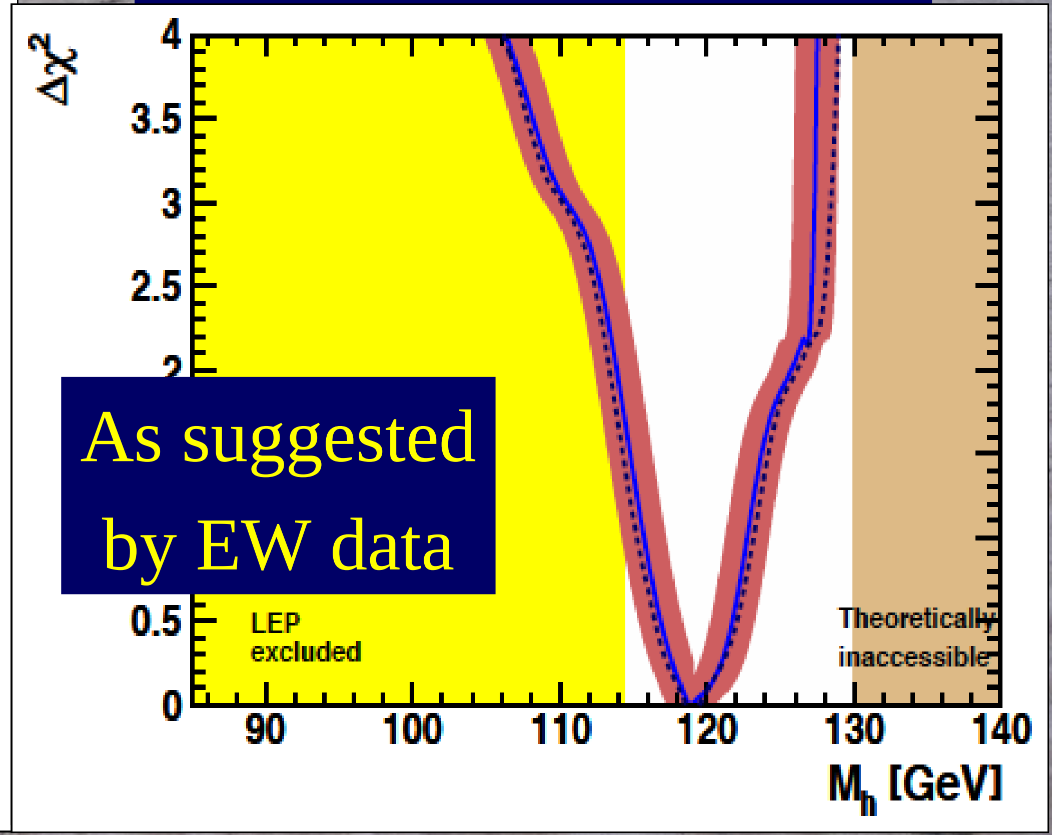
Supersymmetry!

Other Reasons to like Susy

It enables the gauge couplings to unify



It predicts m_H < 130 GeV



As suggested by EW data

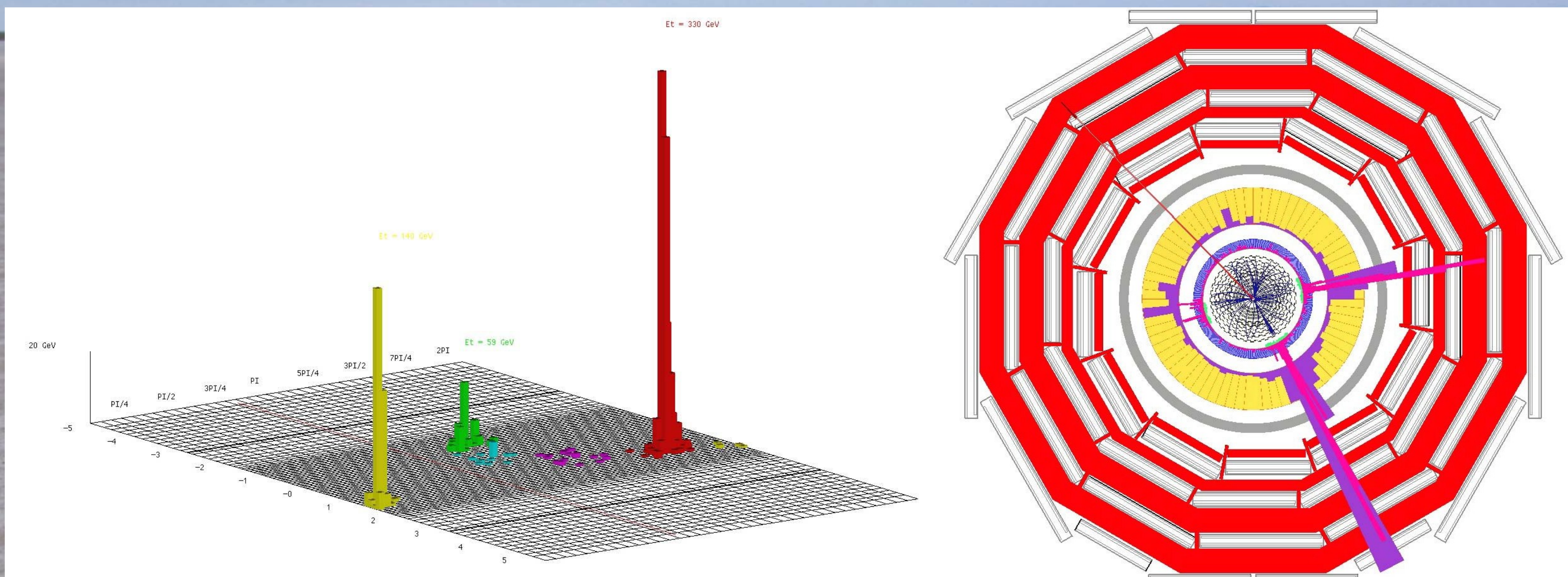
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible
Dark Matter

Supersymmetric particles ?

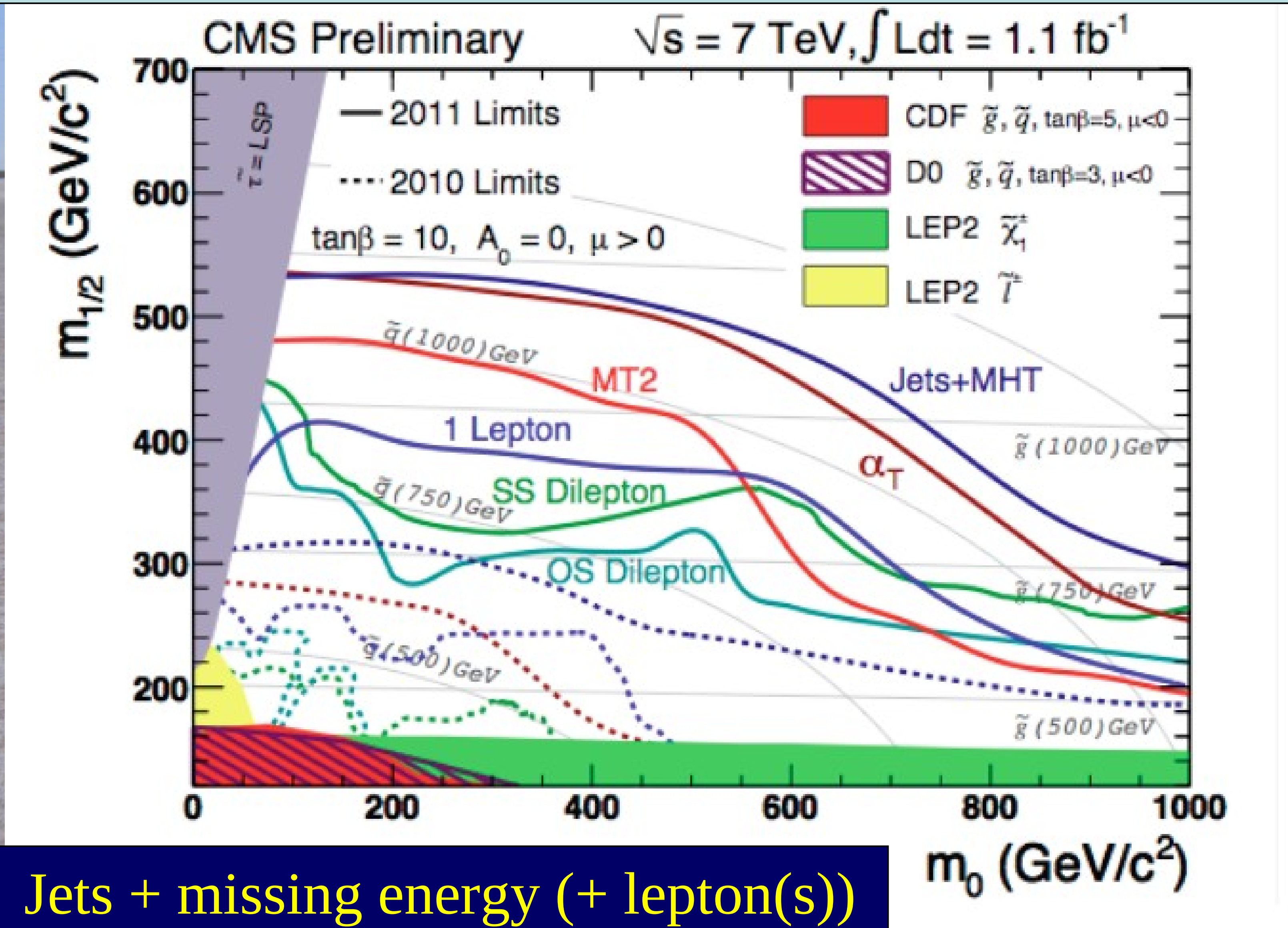
We shall look for them with the LHC

Classic Supersymmetric Signature



Missing transverse energy
carried away by dark matter particles

Supersymmetry Searches in CMS



Jets + missing energy (+ lepton(s))

Impact of LHC on the CMSSM

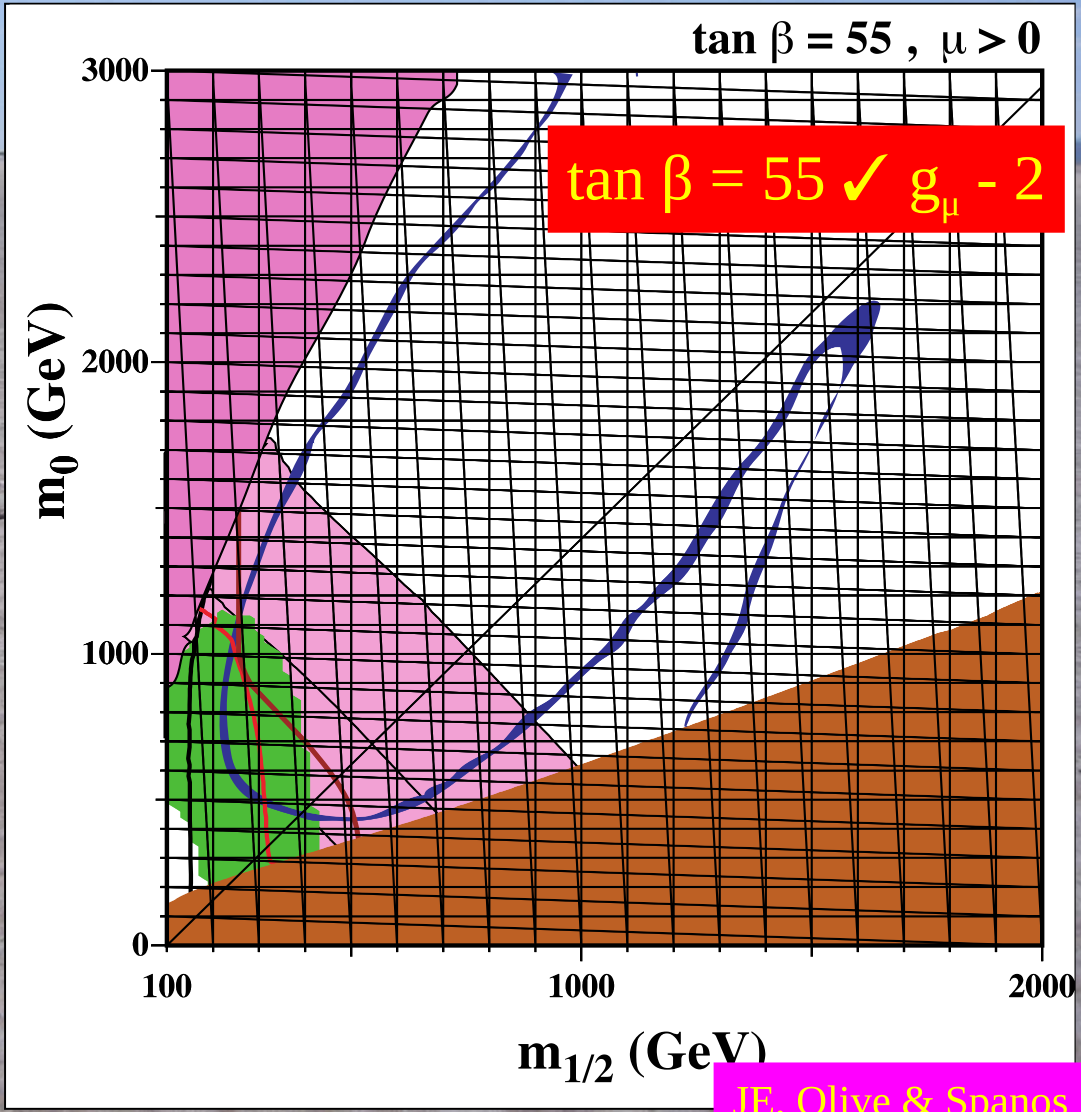
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on CDM density

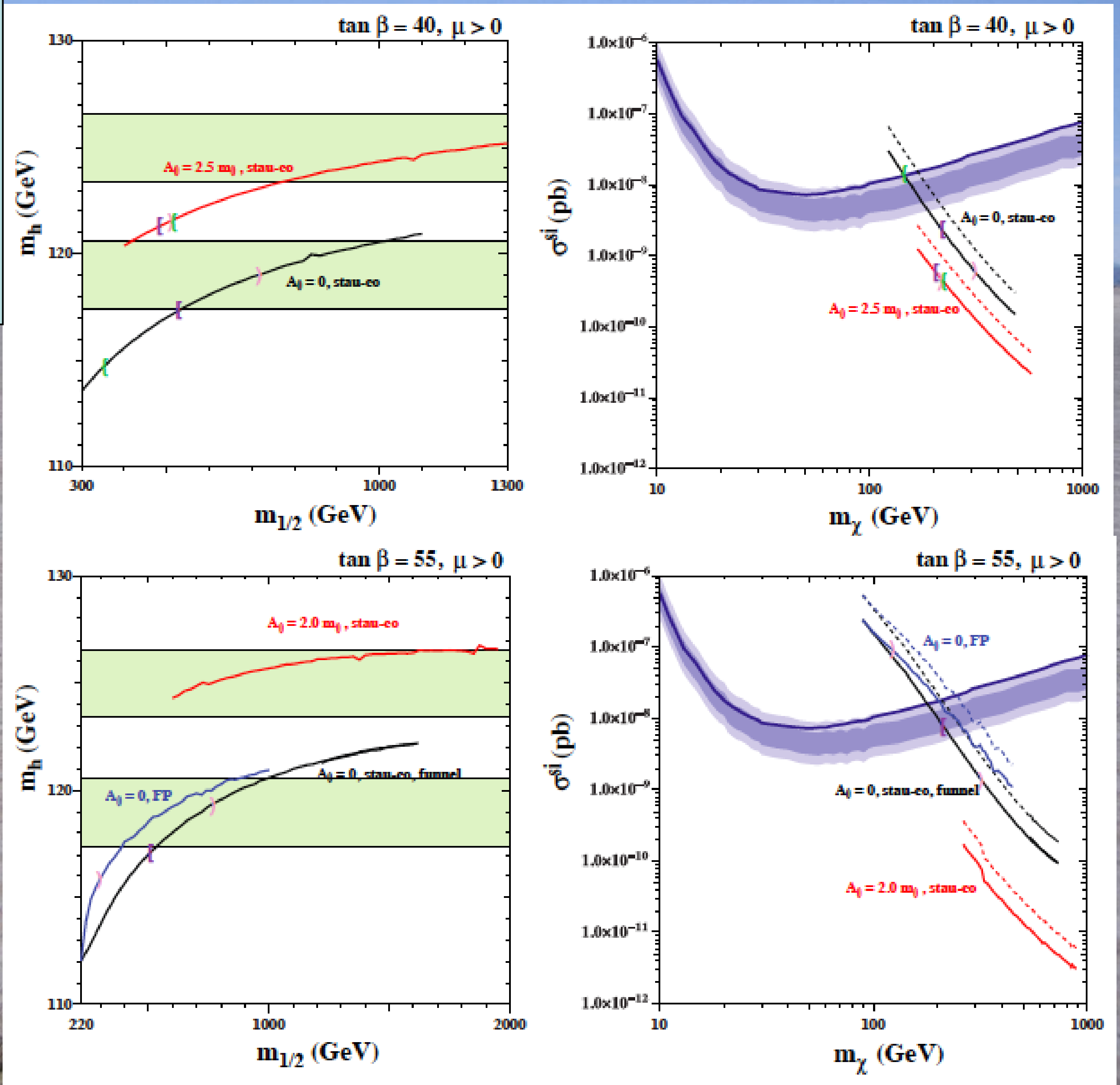
Preferred (?) by latest g - 2



JE, Olive & Spanos

Impact if m_H =125 GeV

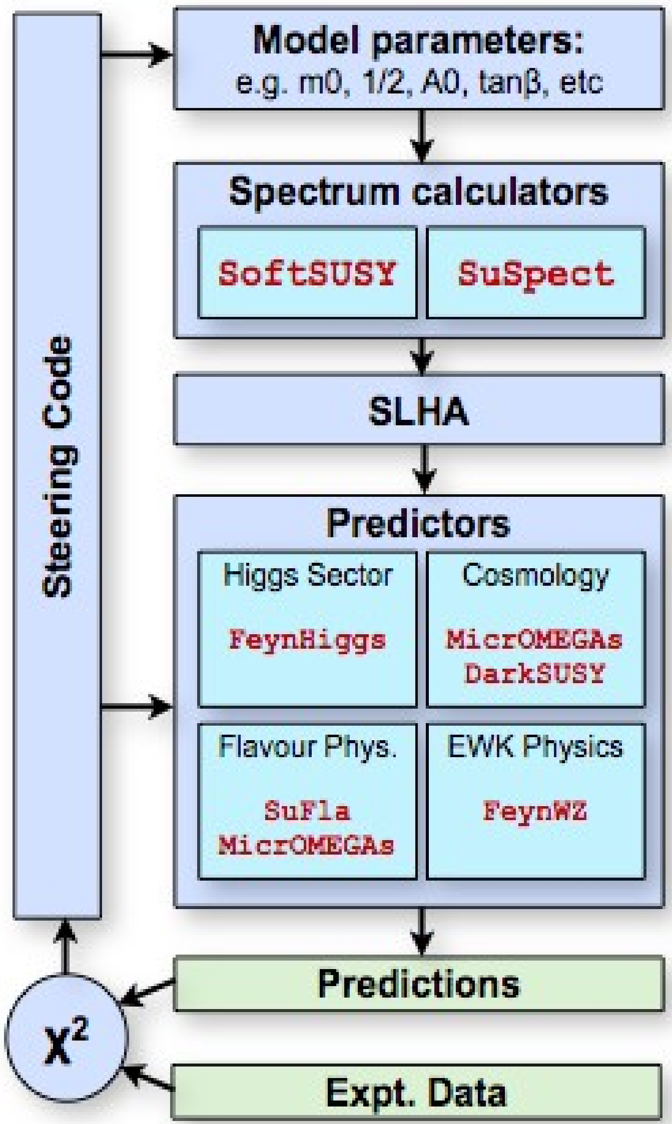
- Need large $m_{1/2}$
- Prefer big tan β
- Find small dark matter scattering rate



JE, Olive : arXiv:1202.3262

MasterCode

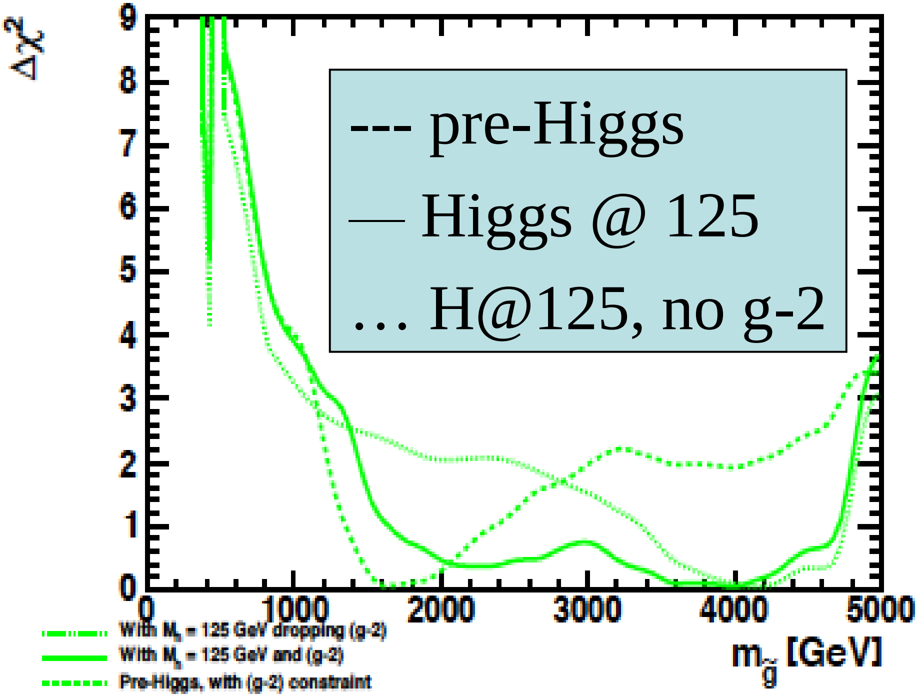
- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces



O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

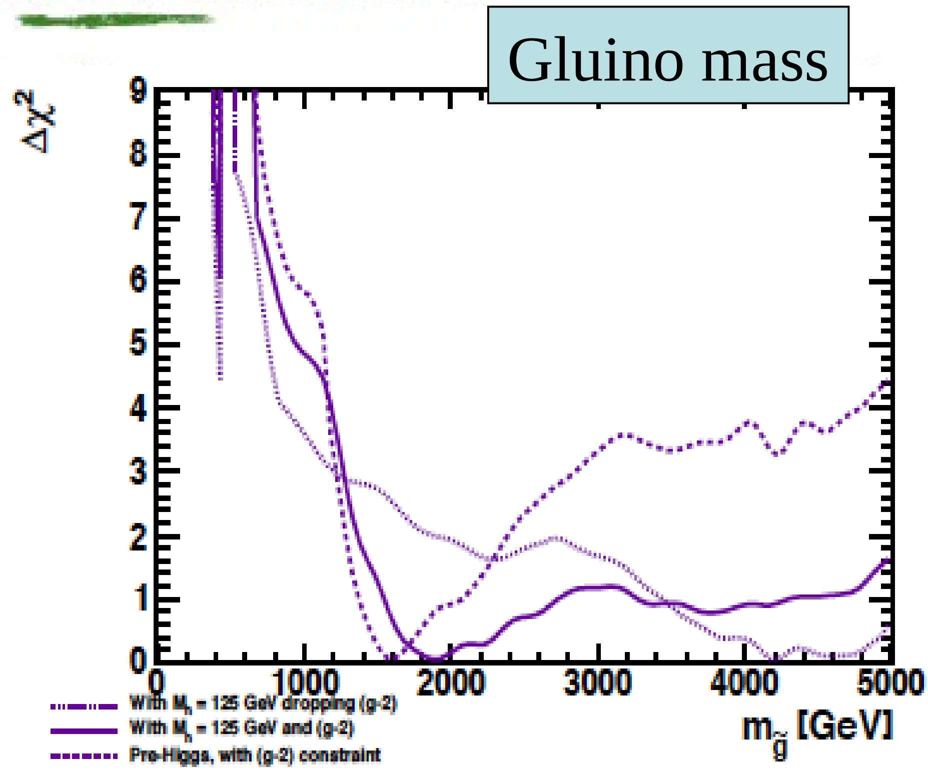
Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM

60 million points sampled



NUHM1

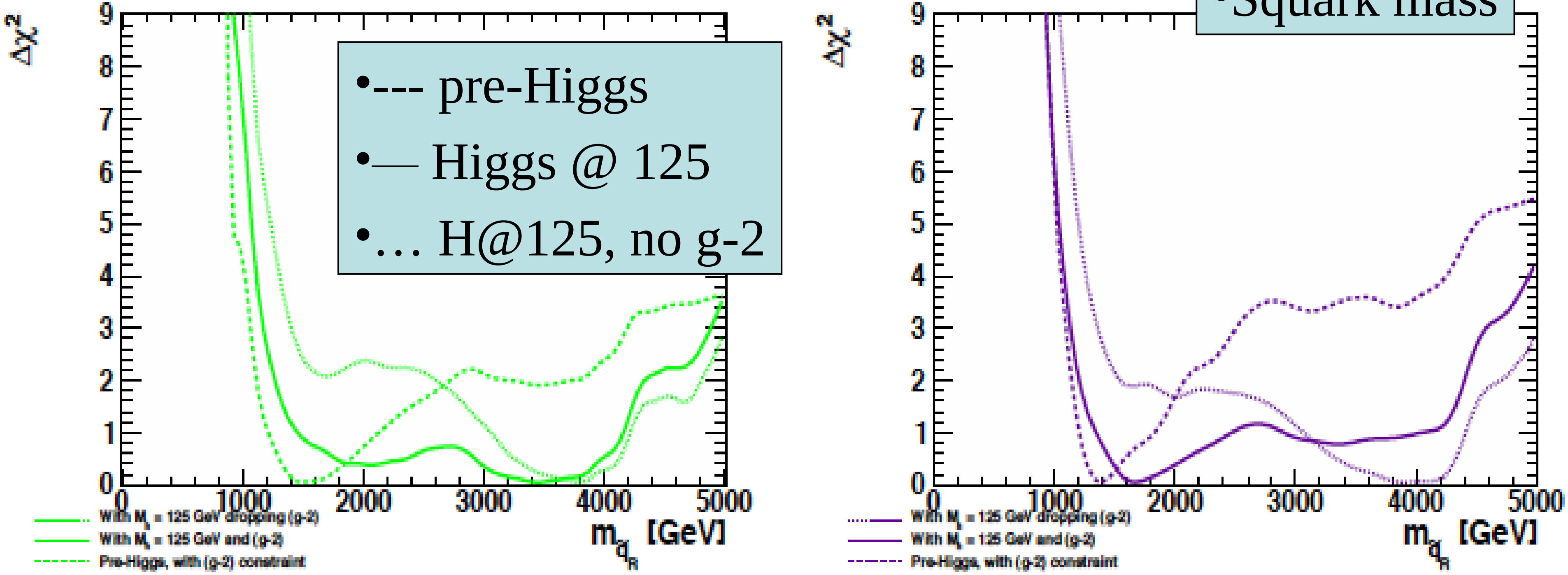
70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

Favoured values of gluino mass significantly above pre-LHC, > 2 TeV

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



- --- pre-Higgs
- — Higgs @ 125
- … H@125, no g-2

- Squark mass

CMSSM

60 million points sampled

NUHM1

70 million points sampled

- Buchmueller, JE et al: arXiv:1112.3564

- Favoured values of squark mass significantly
- above pre-LHC, > 2 TeV

Post-LHC, Post-XENON100

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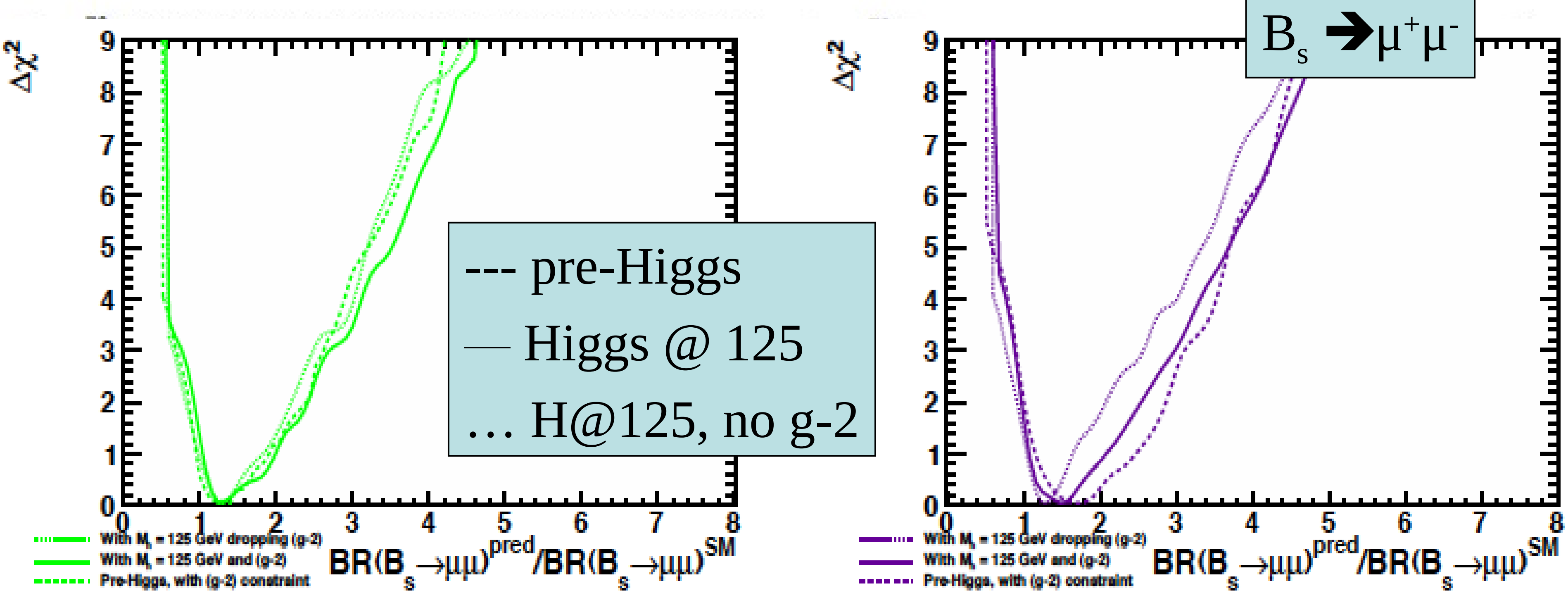


$B_s \to \mu^+\mu^-$

--- pre-Higgs

— Higgs @ 125

… H@125, no g-2

CMSSM

60 million points sampled

NUHM1

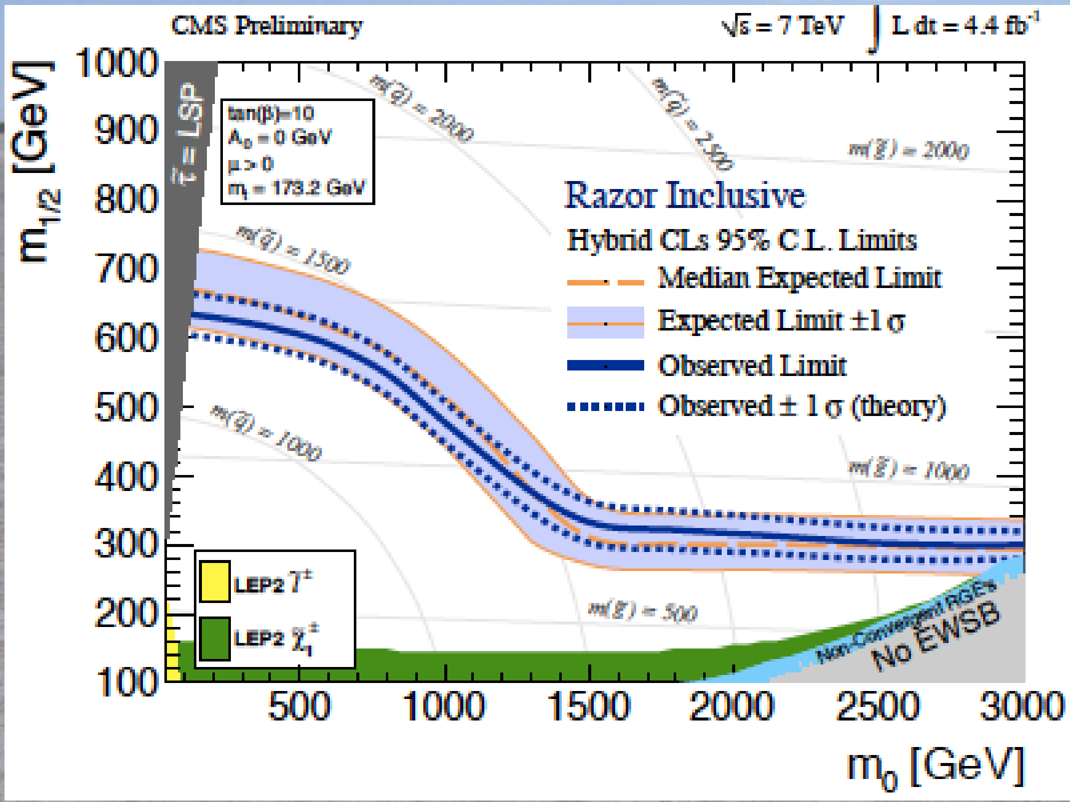
70 million points sampled

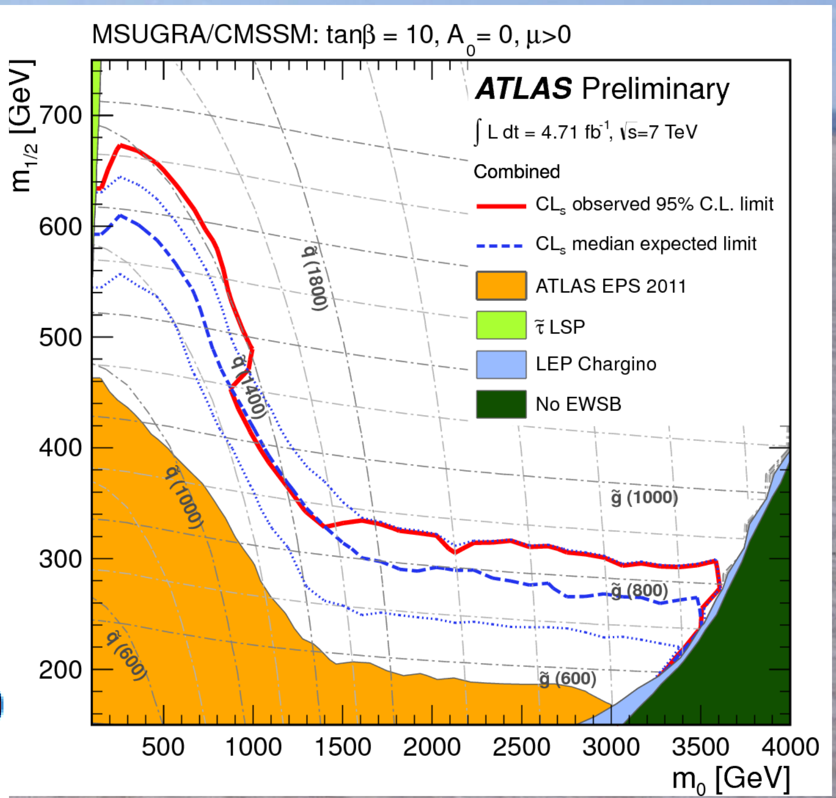
Buchmueller, JE et al: arXiv:1112.3564

Favoured values of $B_s \to \mu^+\mu^-$

above Standard Model

Searches with ~ 5/fb

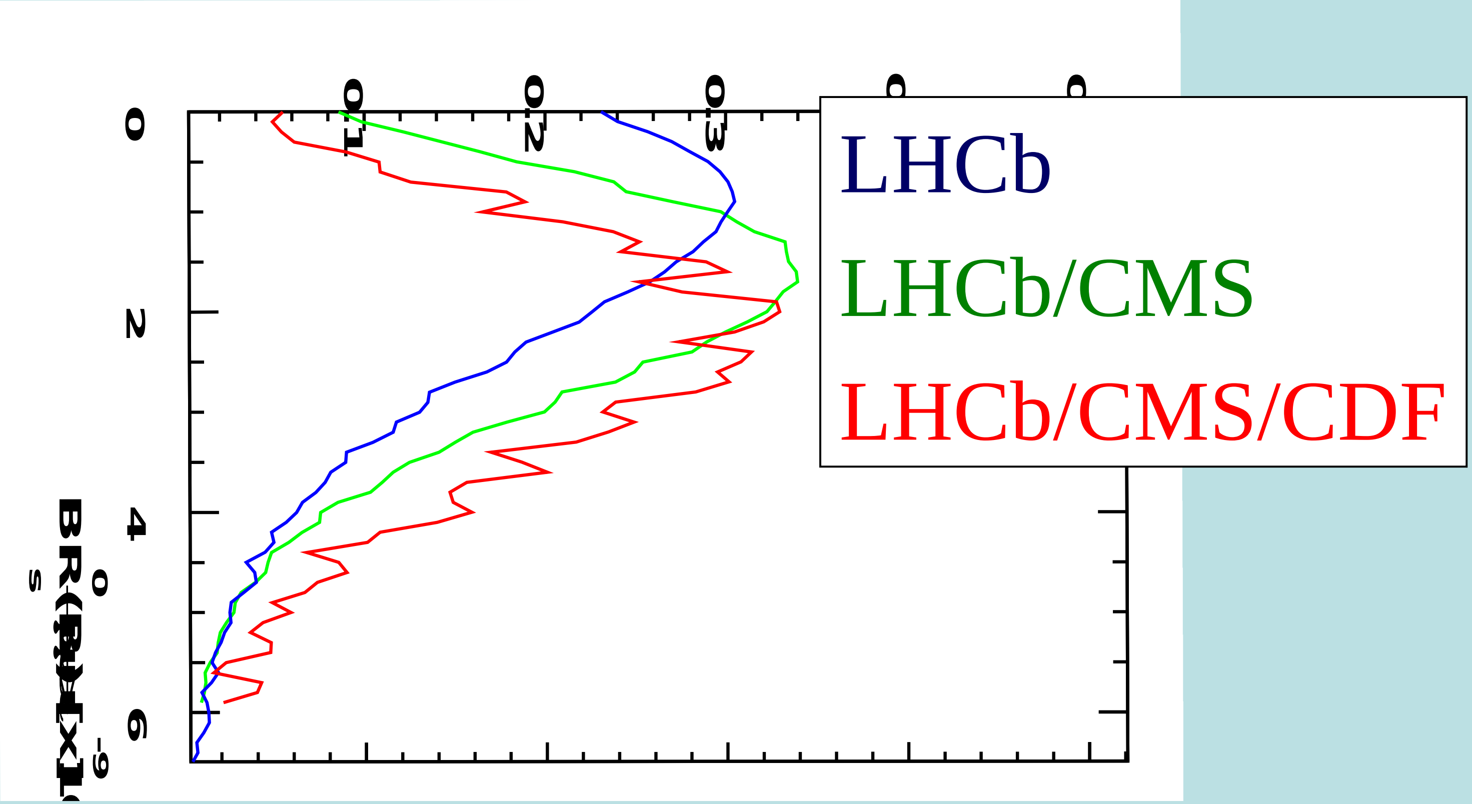




Jets + missing energy

Latest News on $B_s \rightarrow \mu^+\mu^-$

- Upper limit approaching Standard Model

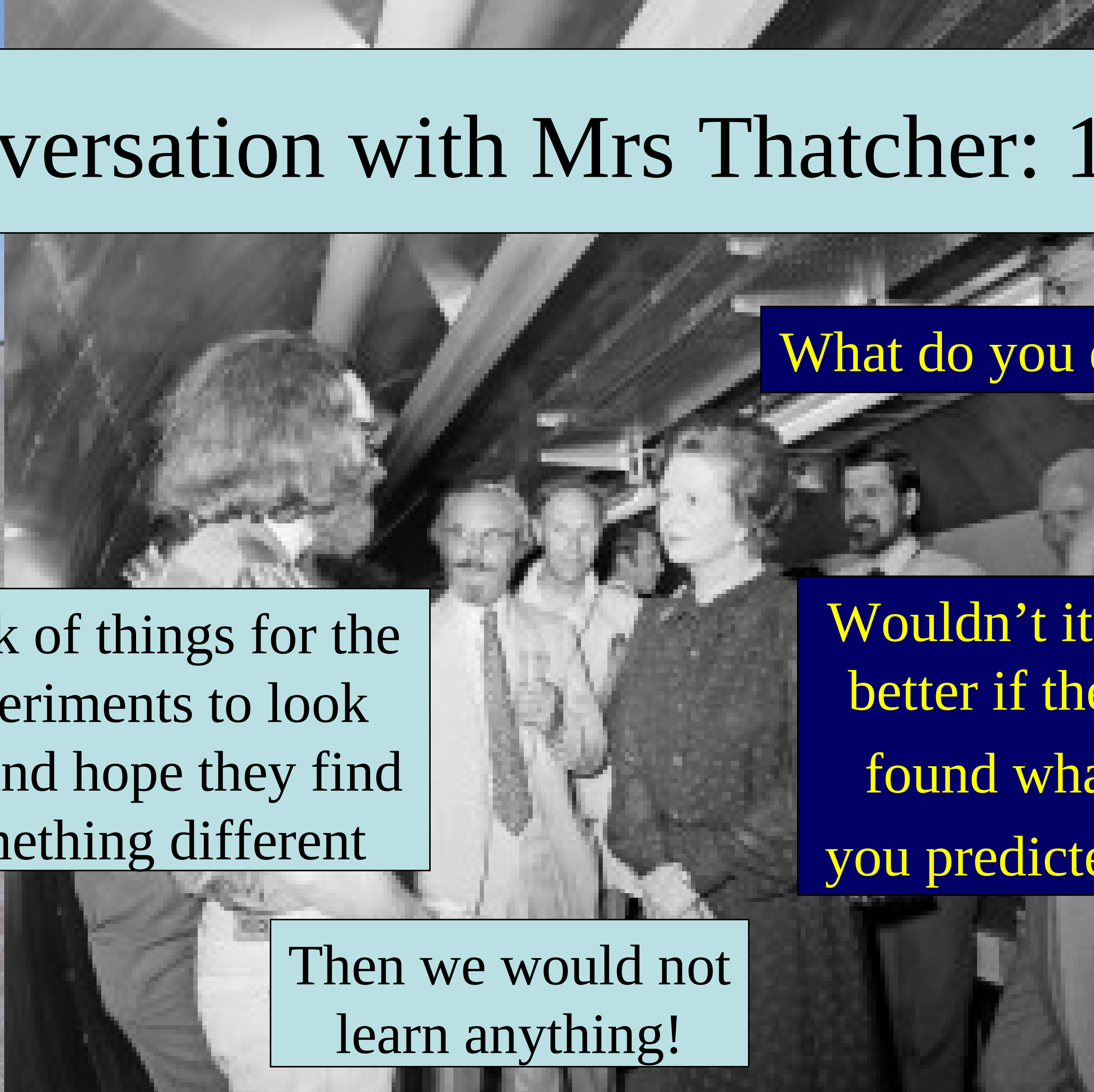


- Pressuring supersymmetric models

The Stakes in the Higgs Search

- How is gauge symmetry broken?
- Is there any elementary scalar field?
- Would have caused phase transition in the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe: electroweak baryogenesis
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old
- Contributes to today's dark energy: 10^{60} too much!

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!

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:

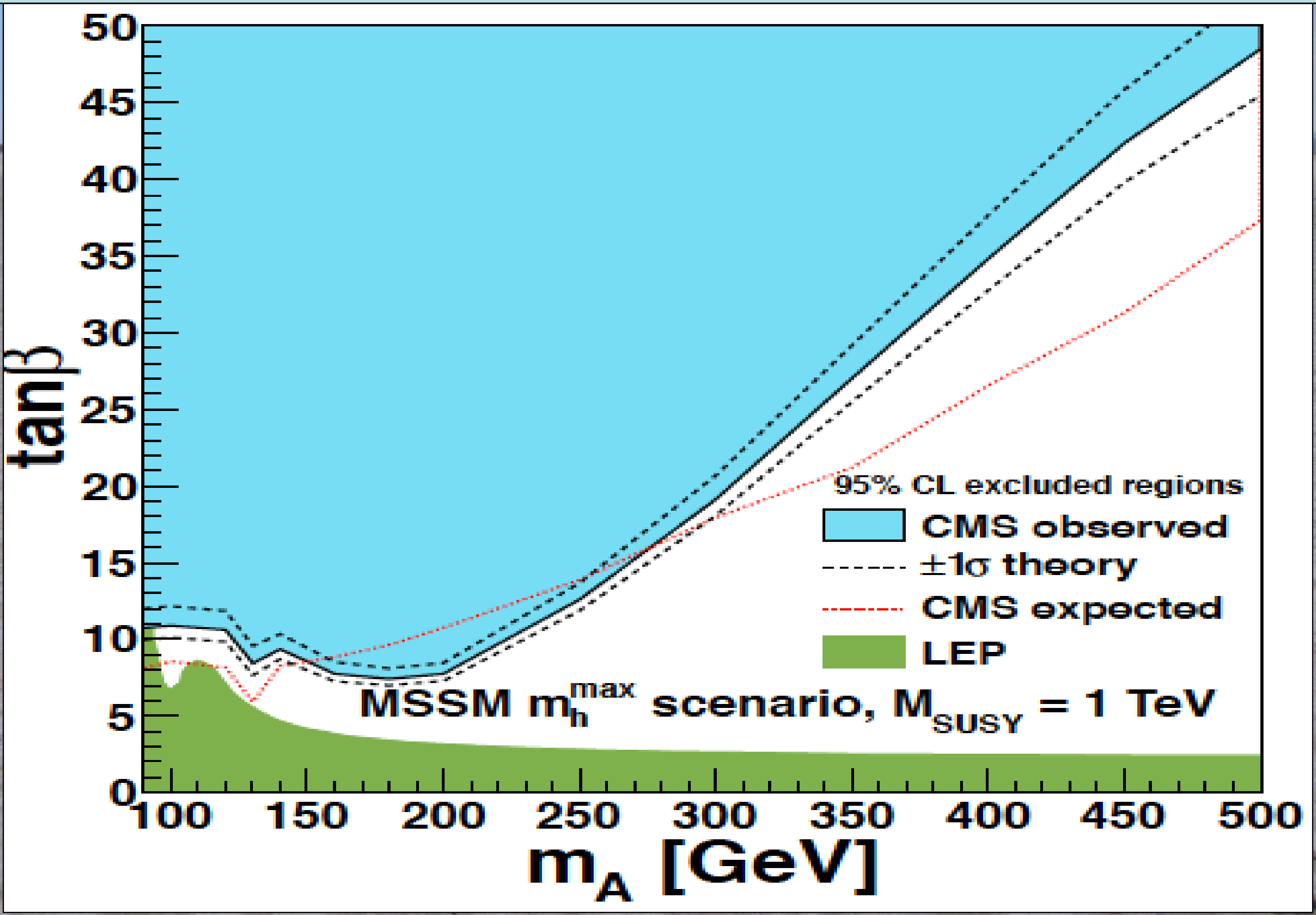
  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles
- Lightest supersymmetric particle (LSP) stable

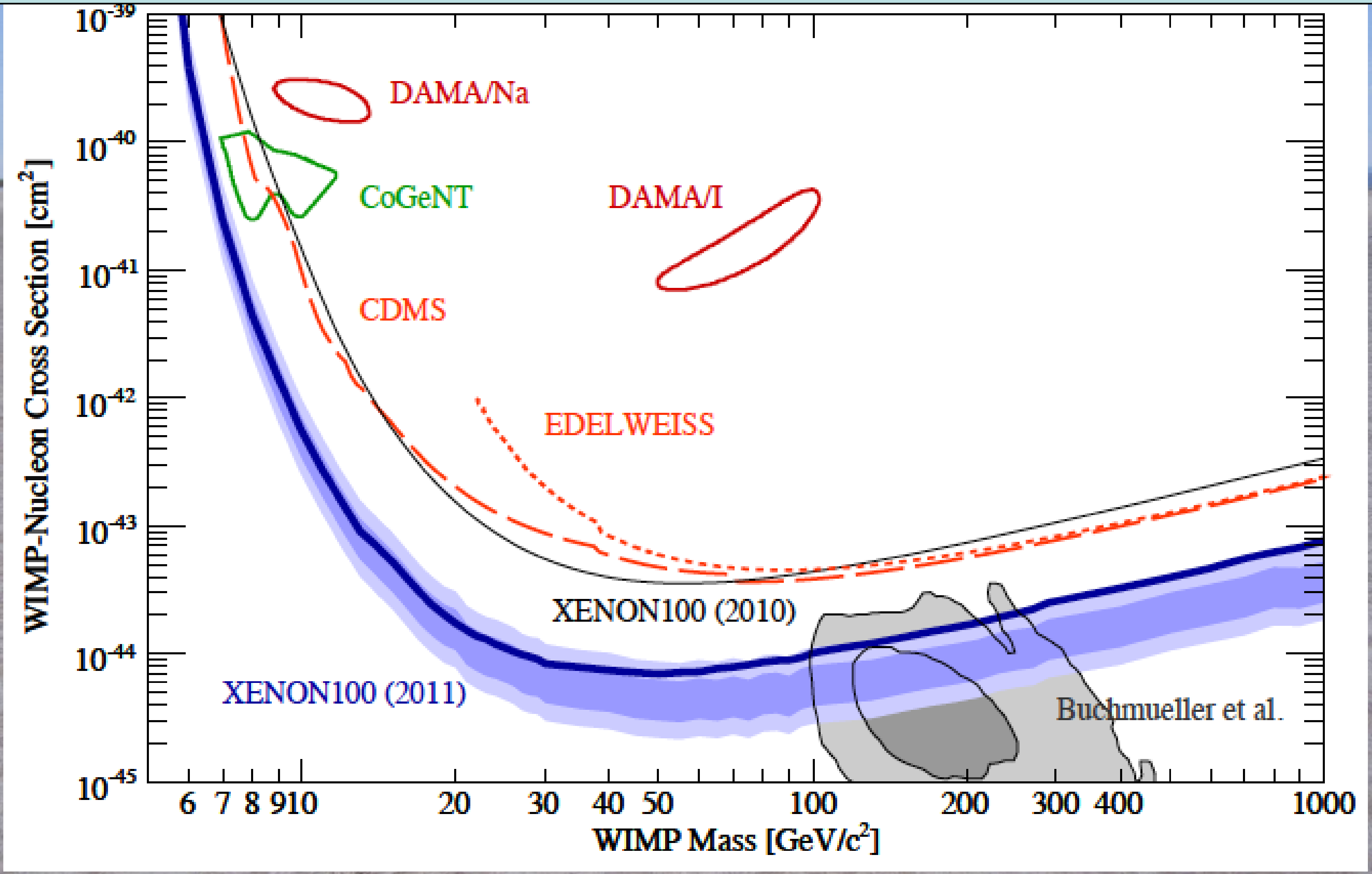
Possible Nature of LSP

- 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)

Limits on Heavy MSSM Higgses



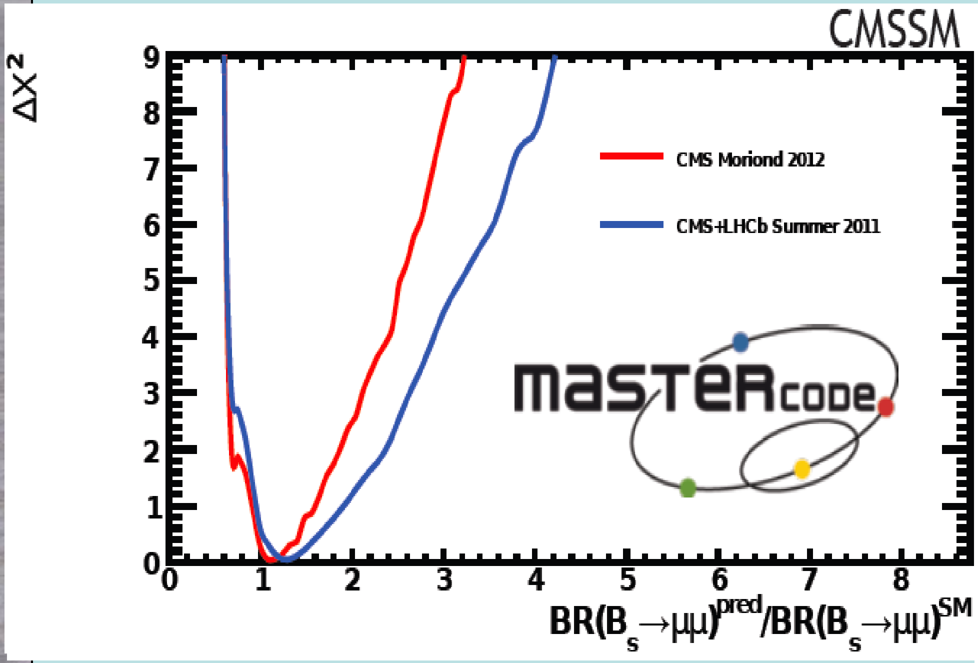
XENON100 Experiment

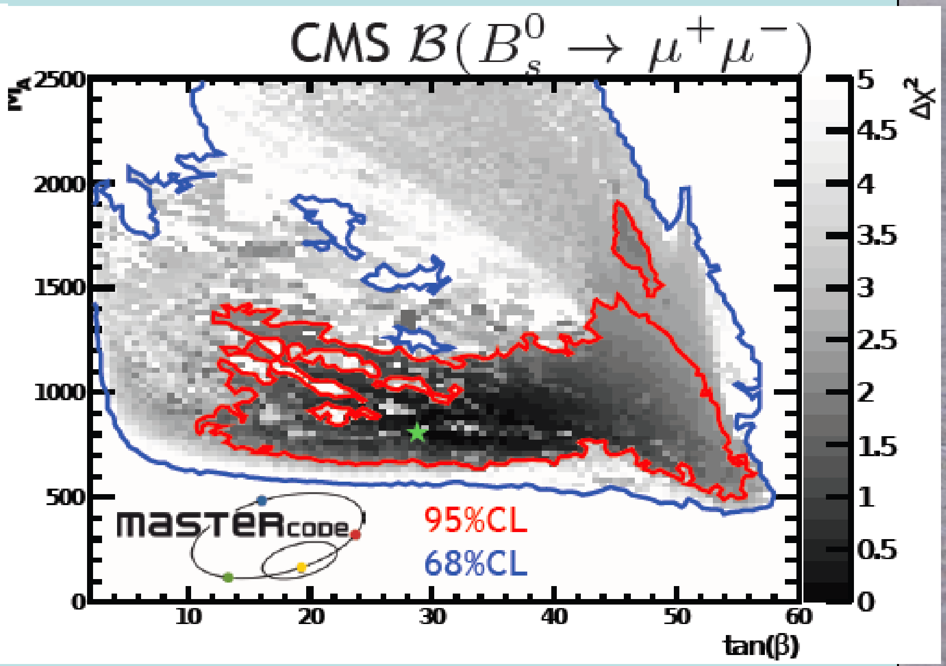


Aprile et al: arXiv:1104.2549

Latest News from LHCb: $B_s \rightarrow \mu^+\mu^-$

- LHCb upper limit approaching Standard Model



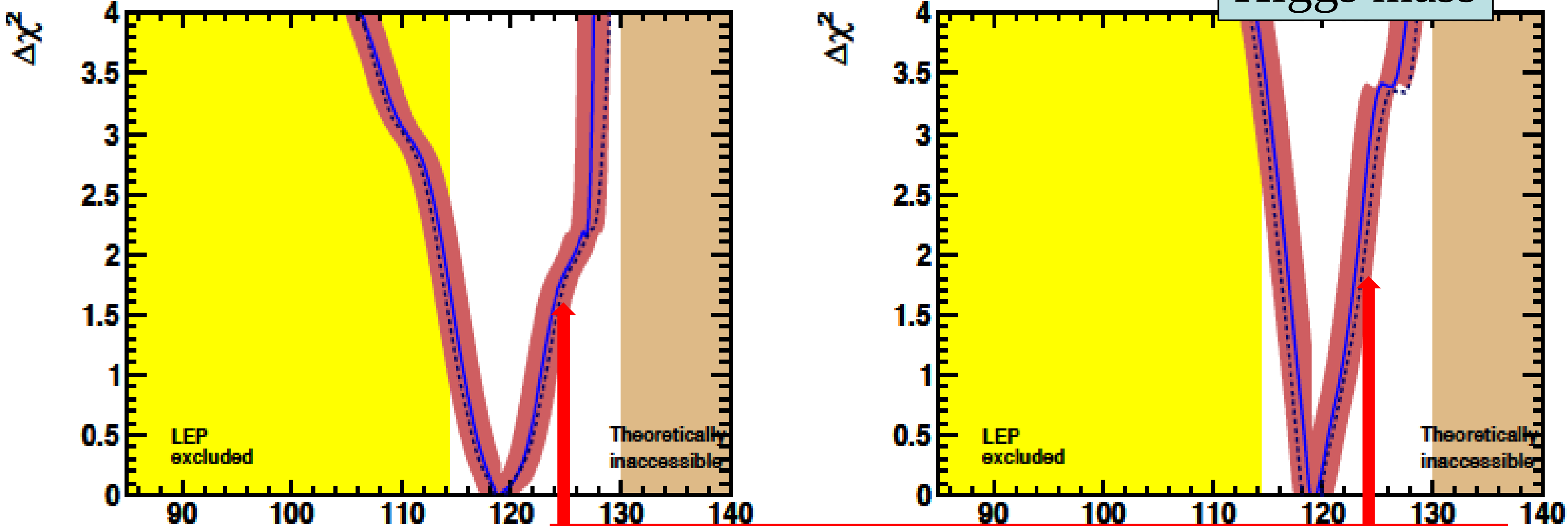


- Pressuring supersymmetric models
- Updates soon from ATLAS & CMS

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Higgs mass



χ^2 price to pay if M_h = 125 GeV is < 2

CMSSM

60 million points sampled

70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

Favoured values of M_h ~ 119 GeV:

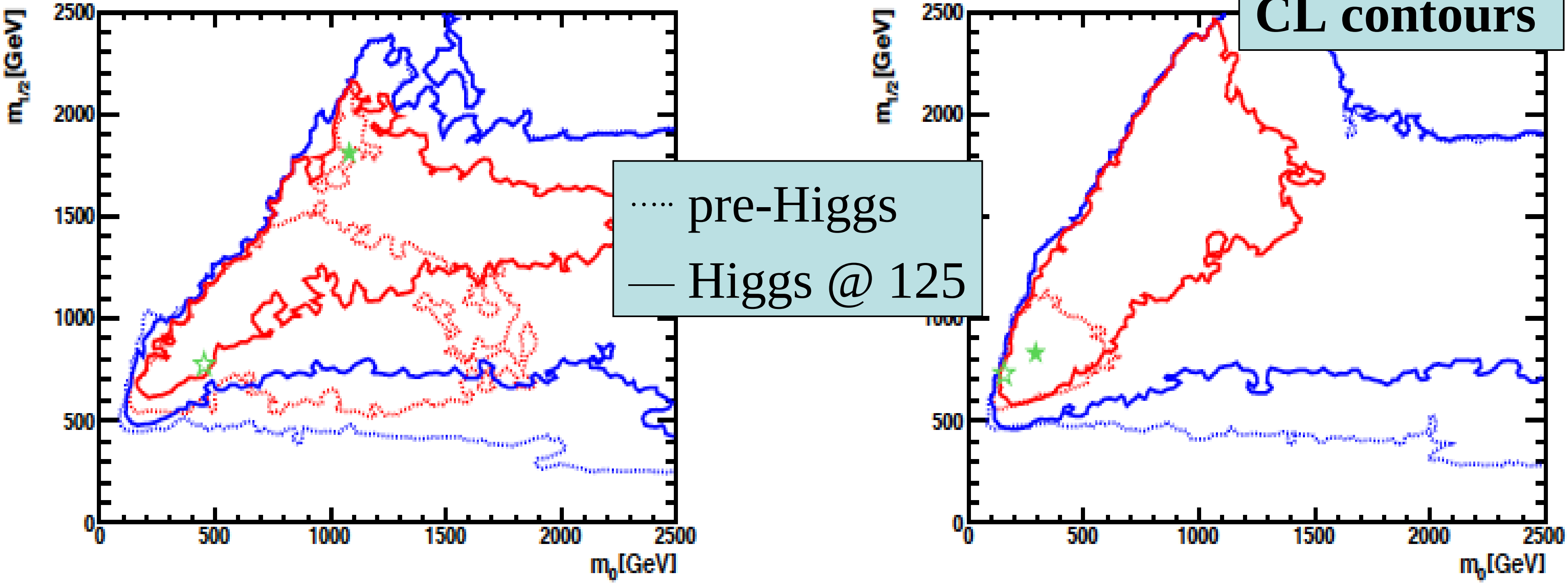
Range consistent with evidence from LHC !

Post-LHC, Post-XENON100

masterCODE

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

68% & 95% CL contours



CMSSM

60 million points sampled

NUHM1

70 million points sampled

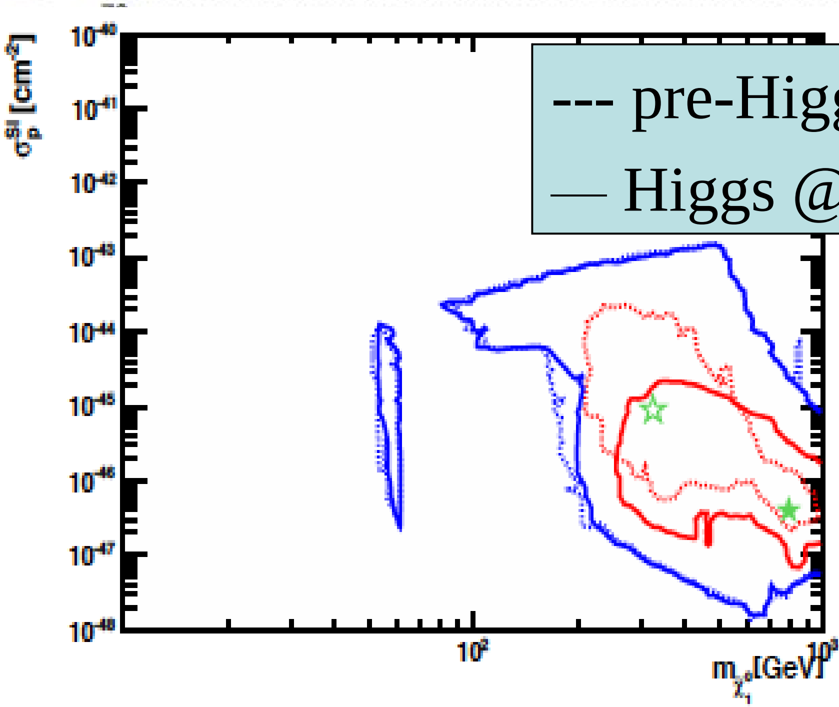
Buchmueller, JE et al: arXiv:1112.3564

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

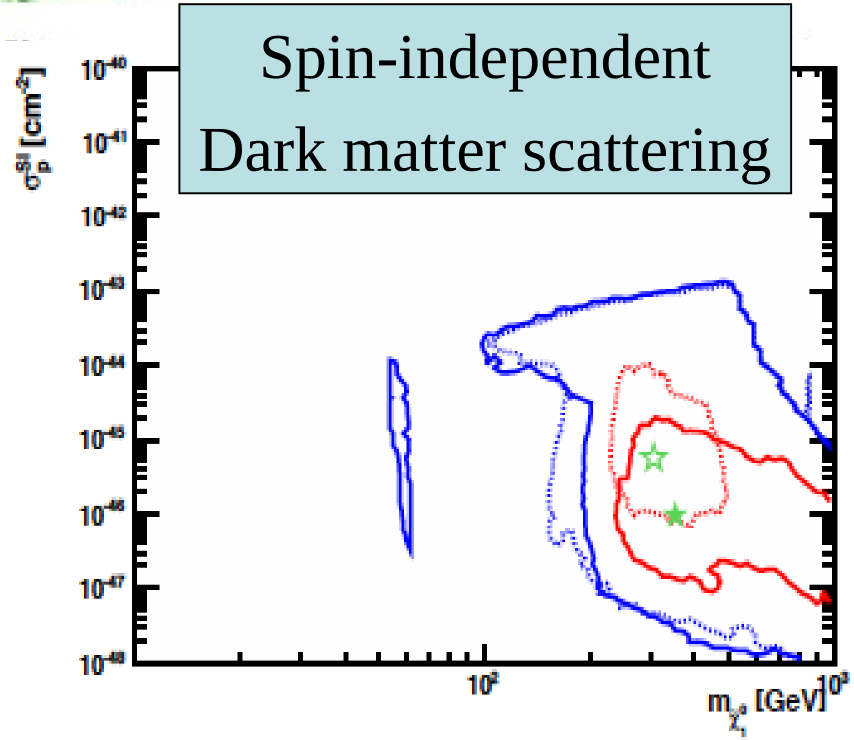
Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM

60 million points sampled



NUHM1

70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

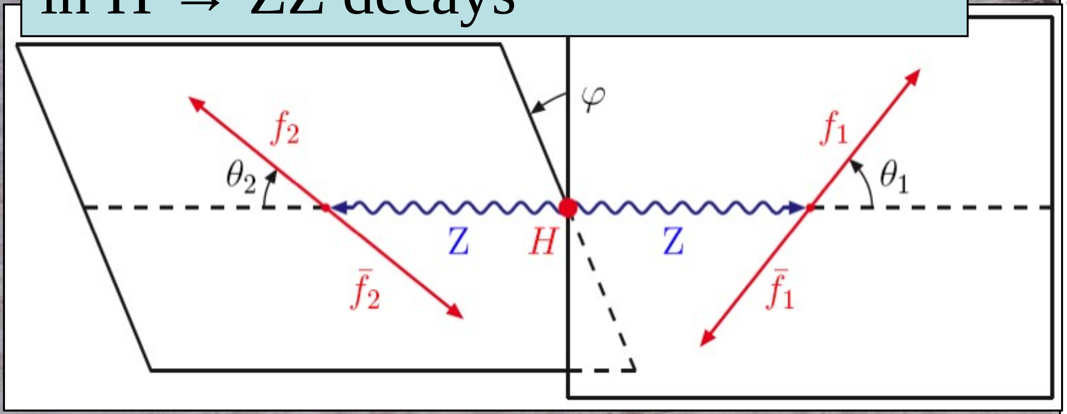
Favoured dark matter scattering rate
well below XENON100 limit

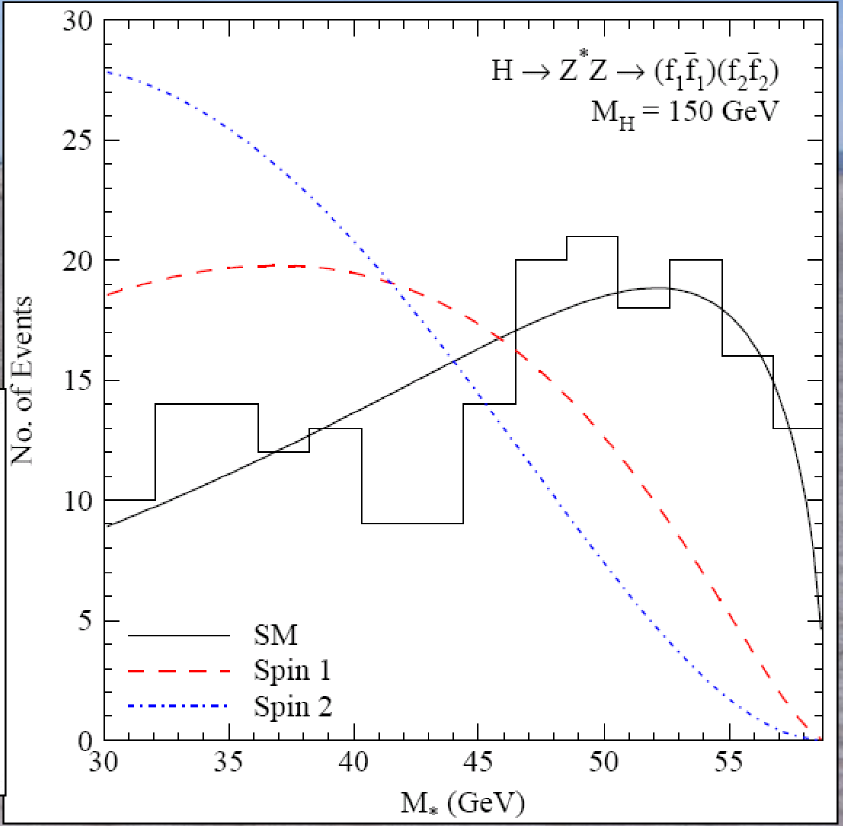
Be careful what you wish for!

The Spin of the Higgs Boson @ LHC

Low mass: if H → γγ,
It cannot have spin 1

Higher mass: angular correlations in H → ZZ decays



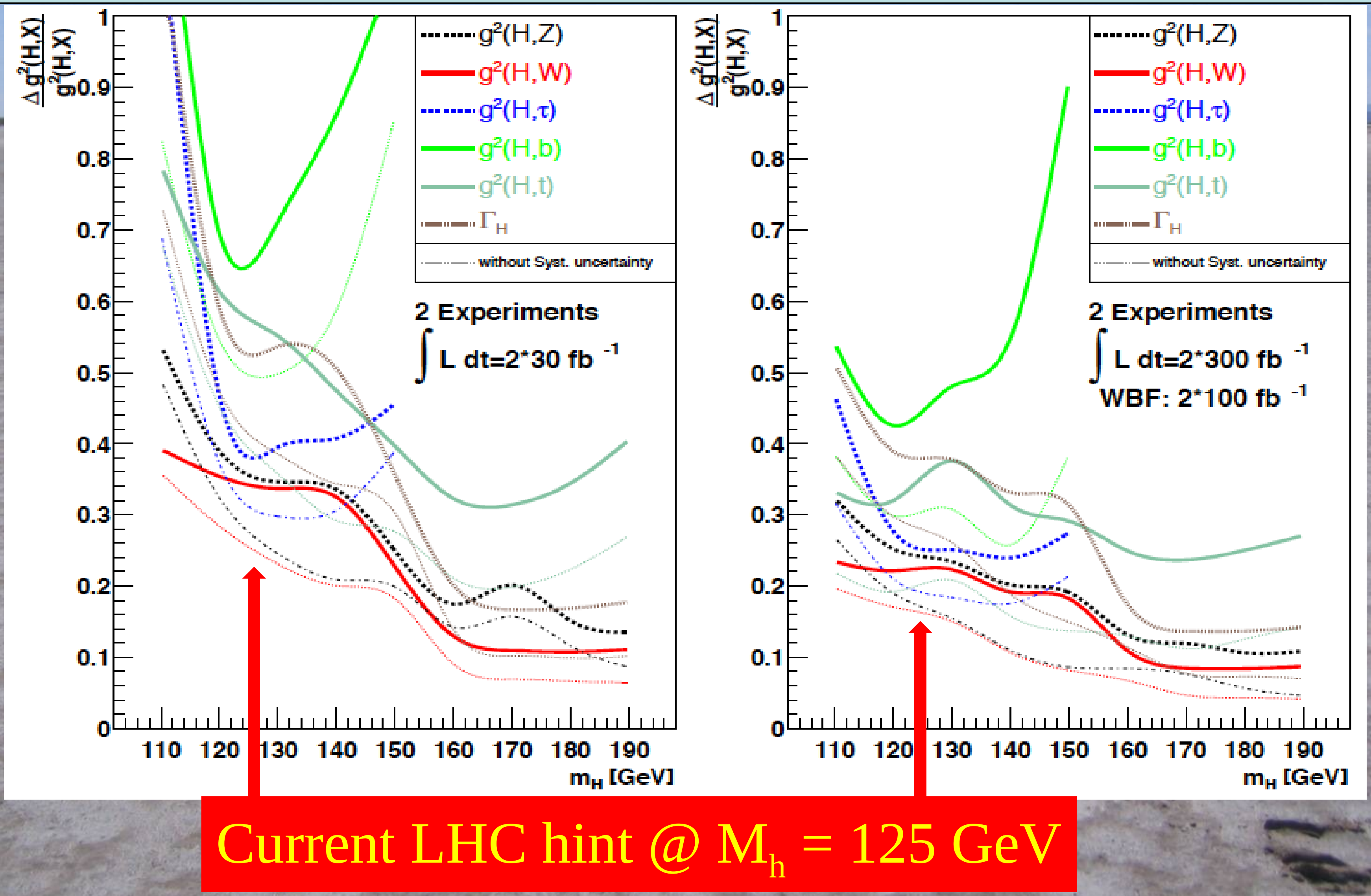


Significance for exclusion of other J^{CP} states than 0^+

ATLAS + CMS, 2 x 300 fb^{-1}

m_H (GeV)	$J^{CP} = 1^+$	$J^{CP} = 1^-$	$J^{CP} = 0^-$
200	6.5 σ	4.8 σ	40 σ
250	20 σ	19 σ	80 σ
300	23 σ	22 σ	70 σ

Measuring Higgs Couplings @ LHC



Flavour-Changing Couplings?

- Constraints on quark-flavour-changing couplings from FCNC

Operator	Eff. couplings	95% C.L. Bound $\lvert c_{\rm eff}\rvert$	95% C.L. Bound $\lvert {\rm Im}(c_{\rm eff})\rvert$	Observables
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	$c_{sd}\ c_{ds}^*$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)^2,\ (\bar{s}_L d_R)^2$	$c_{ds}^2,\ c_{sd}^2$	2.2×10^{-10}	0.8×10^{-12}	
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	$c_{cu}\ c_{uc}^*$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)^2,\ (\bar{c}_L u_R)^2$	$c_{uc}^2,\ c_{cu}^2$	1.4×10^{-9}	2.5×10^{-10}	
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	$c_{bd}\ c_{db}^*$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d\to\psi K}$
$(\bar{b}_R\, d_L)^2,\ (\bar{b}_L d_R)^2$	$c_{db}^2,\ c_{bd}^2$	1.0×10^{-8}	3.0×10^{-9}	
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	$c_{bs}\ c_{sb}^*$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar{b}_R\, s_L)^2,\ (\bar{b}_L s_R)^2$	$c_{sb}^2,\ c_{bs}^2$	2.2×10^{-7}	2.2×10^{-7}	

Eff. couplings	Bound	Constraint
$\lvert c_{sb}\rvert^2,\ \lvert c_{bs}\rvert^2$	2.9×10^{-5}	$\mathcal{B}(B_s \to \mu^+\mu^-) < 1.4 \times 10^{-8}$
$\lvert c_{db}\rvert^2,\ \lvert c_{bd}\rvert^2$	1.3×10^{-5}	$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.2 \times 10^{-9}$

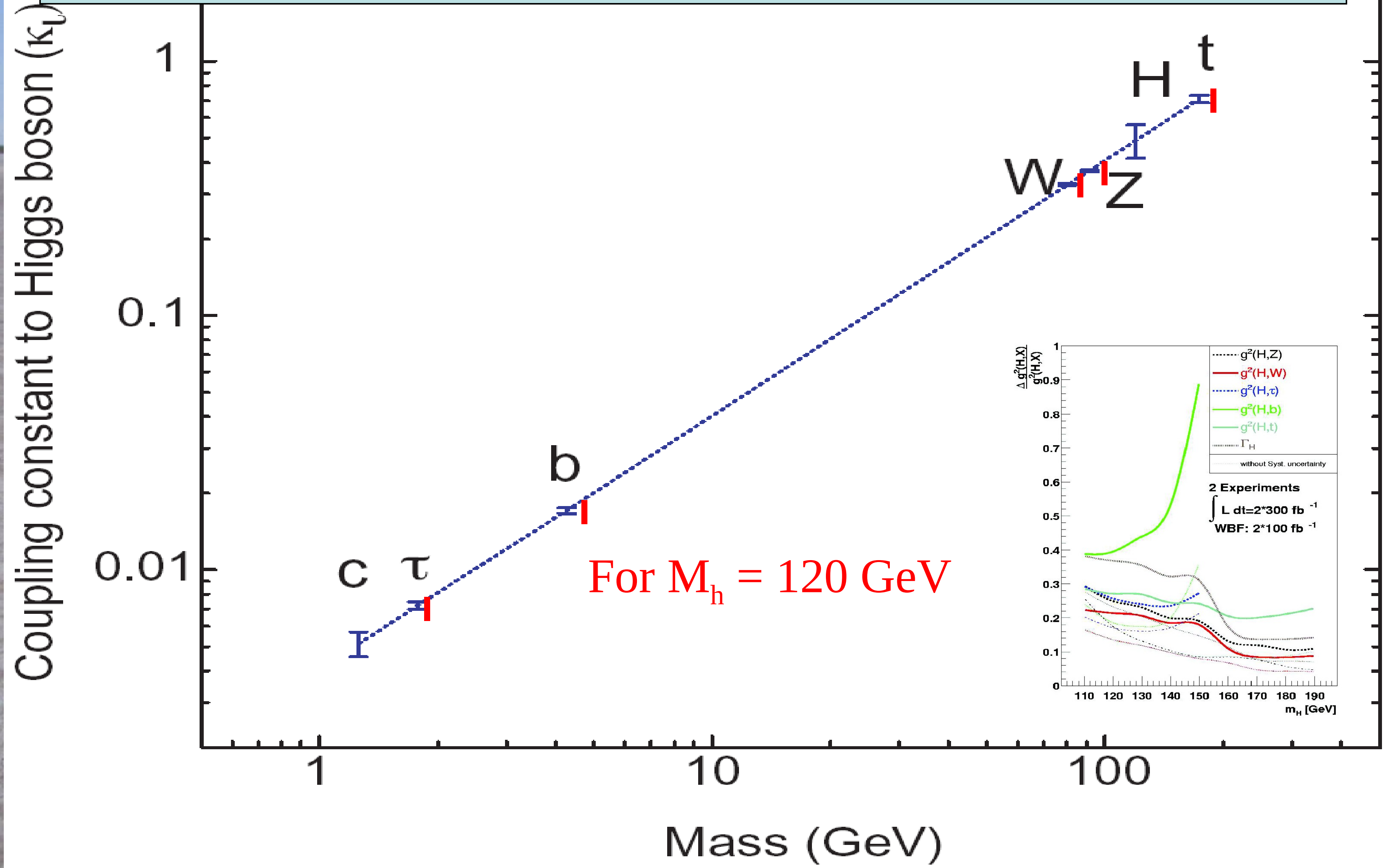
Blankenburg, JE, Isidori: arXiv:1202.5704

- Constraints on lepton-flavour-changing couplings

Operator	Eff. couplings	Bound	Constraint
$(\bar{\mu}_R\, e_L)(\bar{q}_L q_R),\ (\bar{\mu}_L\, e_R)(\bar{q}_L q_R)$	$\lvert c_{\mu e}\rvert^2,\ \lvert c_{e\mu}\rvert^2$	3.0×10^{-8}	$\mathcal{B}_{\mu\to e}({\rm Ti}) < 4.3 \times 10^{-12}$
$(\bar{\tau}_R\, \mu_L)(\bar{\mu}_L \mu_R),\ (\bar{\tau}_L\, \mu_R)(\bar{\mu}_L \mu_R)$	$\lvert c_{\tau\mu}\rvert^2,\ \lvert c_{\mu\tau}\rvert^2$	2.0×10^{-1}	$\Gamma(\tau \to \mu\bar{\mu}\mu) < 2.1 \times 10^{-8}$
$(\bar{\tau}_R\, e_L)(\bar{\mu}_L \mu_R),\ (\bar{\tau}_L\, e_R)(\bar{\mu}_L \mu_R)$	$\lvert c_{\tau e}\rvert^2,\ \lvert c_{e\tau}\rvert^2$	4.8×10^{-1}	$\Gamma(\tau \to e\bar{\mu}\mu) < 2.7 \times 10^{-8}$
$(\bar{\tau}_R\, e_L)(\bar{\mu}_L e_R),\ (\bar{\tau}_L\, e_R)(\bar{\mu}_L e_R)$	$\lvert c_{\mu e} c_{e\tau}^*\rvert,\ \lvert c_{\mu e} c_{\tau e}\rvert$	0.9×10^{-4}	$\Gamma(\tau \to \bar{\mu}ee) < 1.5 \times 10^{-8}$
$(\bar{\tau}_R\, e_L)(\bar{\mu}_R e_L),\ (\bar{\tau}_L\, e_R)(\bar{\mu}_R e_L)$	$\lvert c_{e\mu}^* c_{e\tau}^*\rvert,\ \lvert c_{e\mu}^* c_{\tau e}\rvert$		
$(\bar{\tau}_R\, \mu_L)(\bar{e}_L \mu_R),\ (\bar{\tau}_L\, \mu_R)(\bar{e}_L \mu_R)$	$\lvert c_{e\mu} c_{\mu\tau}^*\rvert,\ \lvert c_{e\mu} c_{\tau\mu}\rvert$	1.0×10^{-4}	$\Gamma(\tau \to \bar{e}\mu\mu) < 1.7 \times 10^{-8}$
$(\bar{\tau}_R\, \mu_L)(\bar{e}_R \mu_L),\ (\bar{\tau}_L\, \mu_R)(\bar{e}_R \mu_L)$	$\lvert c_{\mu e}^* c_{\mu\tau}^*\rvert,\ \lvert c_{\mu e}^* c_{\tau\mu}\rvert$		

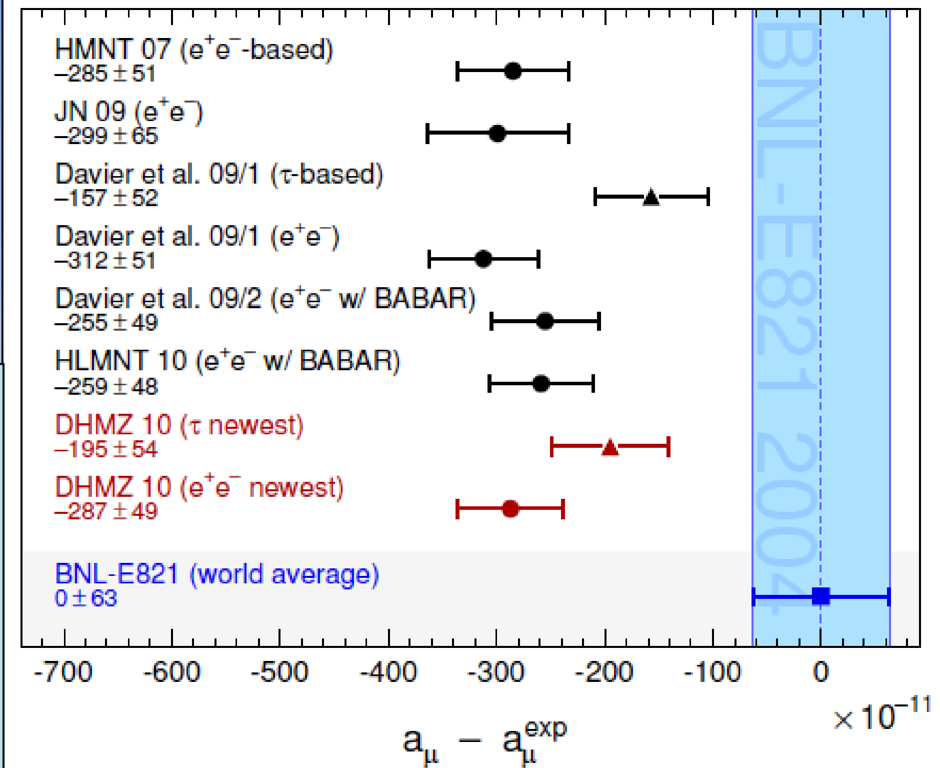
Eff. couplings	Bound	Constraint
$\lvert c_{e\tau} c_{\tau e}\rvert \quad (\lvert c_{e\mu} c_{\mu e}\rvert)$	$1.1 \times 10^{-2} \quad (1.8 \times 10^{-1})$	$\lvert \delta m_e\rvert < m_e$
$\lvert {\rm Re}(c_{e\tau} c_{\tau e})\rvert \quad (\lvert {\rm Re}(c_{e\mu} c_{\mu e})\rvert)$	$0.8 \times 10^{-2} \quad (1.4 \times 10^{-1})$	$\lvert \delta a_e\rvert < 6 \times 10^{-12}$
$\lvert {\rm Im}(c_{e\tau} c_{\tau e})\rvert \quad (\lvert {\rm Im}(c_{e\mu} c_{\mu e})\rvert)$	$1.1 \times 10^{-7} \quad (1.9 \times 10^{-6})$	$\lvert d_e\rvert < 1.6 \times 10^{-27}\ e{\rm cm}$
$\lvert c_{\mu\tau} c_{\tau\mu}\rvert$	2	$\lvert \delta m_\mu\rvert < m_\mu$
$\lvert {\rm Re}(c_{\mu\tau} c_{\tau\mu})\rvert$	2×10^{-2}	$\lvert \delta a_\mu\rvert < 4 \times 10^{-9}$
$\lvert {\rm Im}(c_{\mu\tau} c_{\tau\mu})\rvert$	8	$\lvert d_\mu\rvert < 1.2 \times 10^{-19}\ e{\rm cm}$
$\lvert c_{e\tau} c_{\tau\mu}\rvert,\ \lvert c_{\tau e} c_{\mu\tau}\rvert$	2.4×10^{-6}	$\mathcal{B}(\mu \to e\gamma) < 2.4 \times 10^{-12}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$	6.6×10^{-1}	$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c_{\tau e}^*\rvert^2$	4.7×10^{-1}	$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

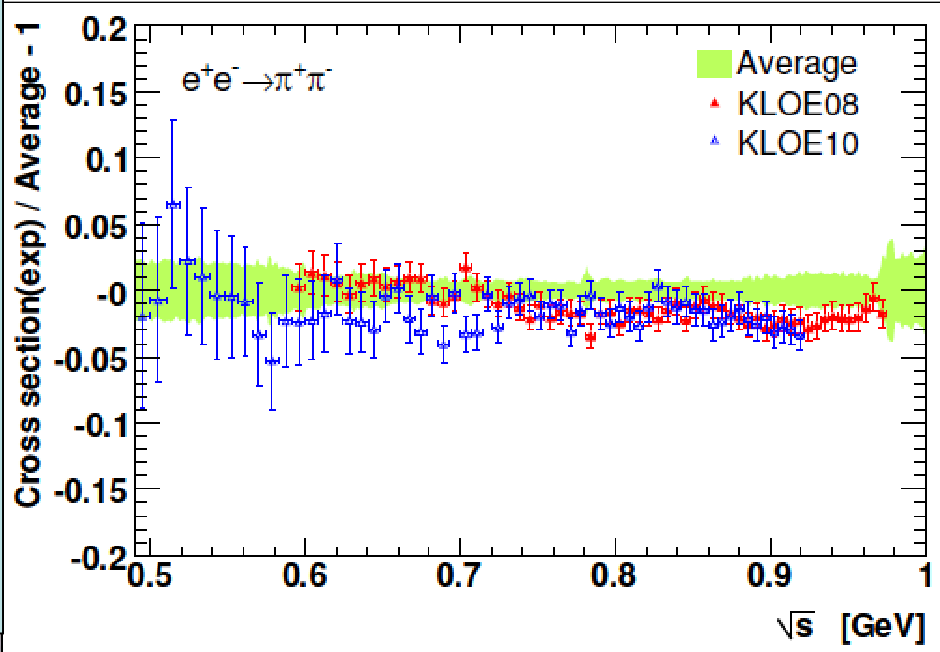
Higgs Measurements @ **LHC** & ILC



Quo Vadis g_μ - 2?

- Strong discrepancy between BNL experiment and e^+e^- data:
  - now ~ 3.6 σ
  - Better 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
- **More credibility?**





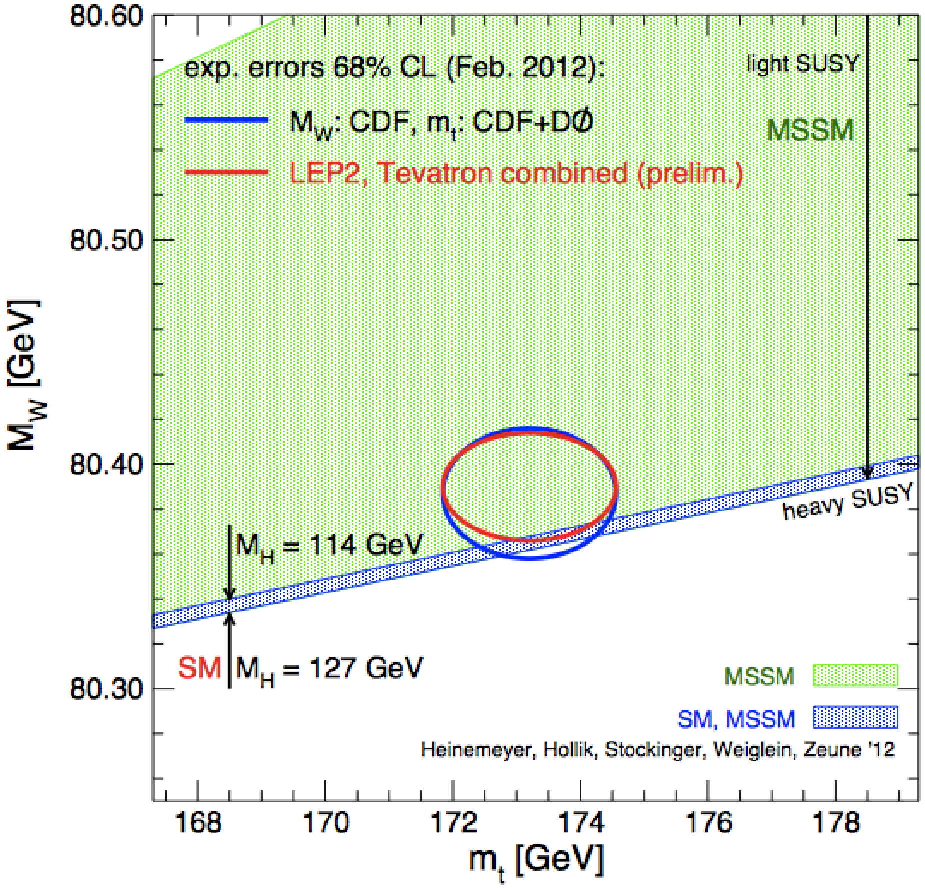
Minimal Supersymmetric Extension of Standard Model (MSSM)

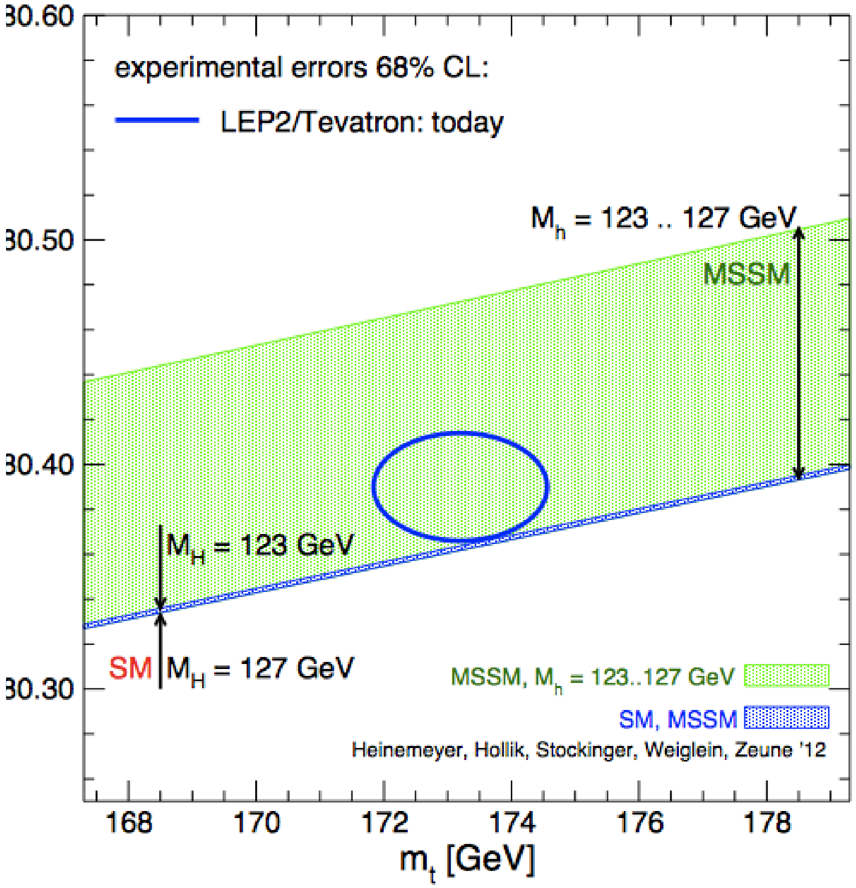
- Particles + spartners

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

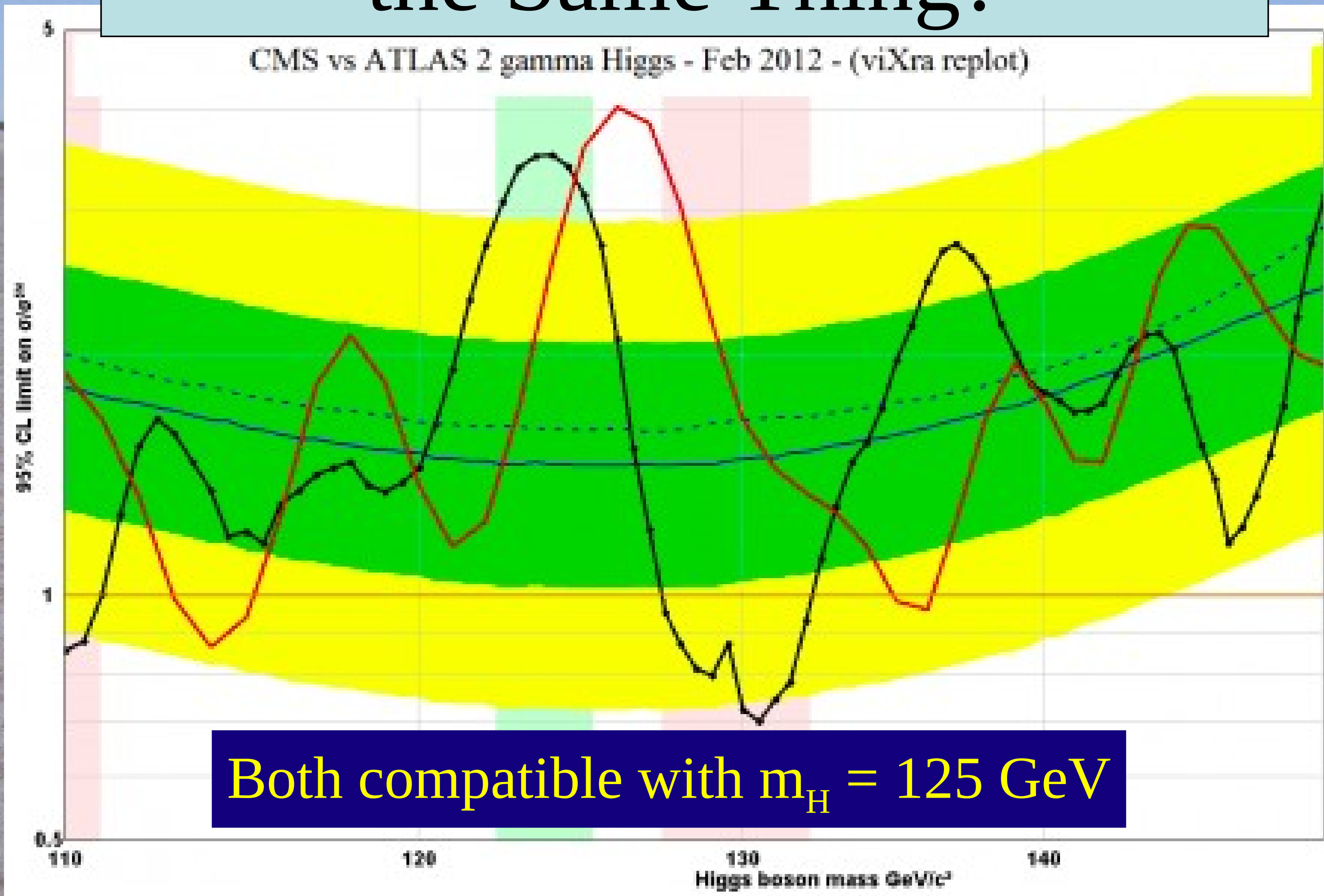
- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:
  - Scalar masses m_0, gaugino masses $m_{1/2}$,
  - trilinear soft couplings A_λ, bilinear soft coupling B_μ
- Often assume universality:
  - Single m_0, single $m_{1/2}$, single A_λ, B_μ: not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

Latest News from CDF: m_W





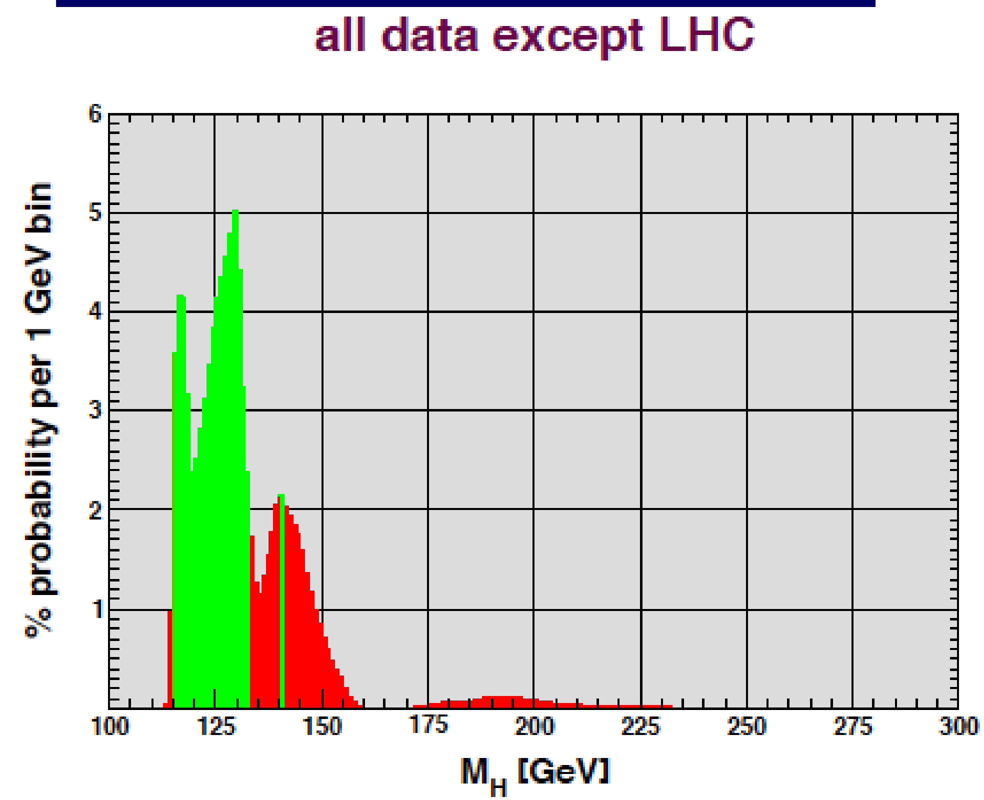
Are ATLAS & CMS seeing the Same Thing?

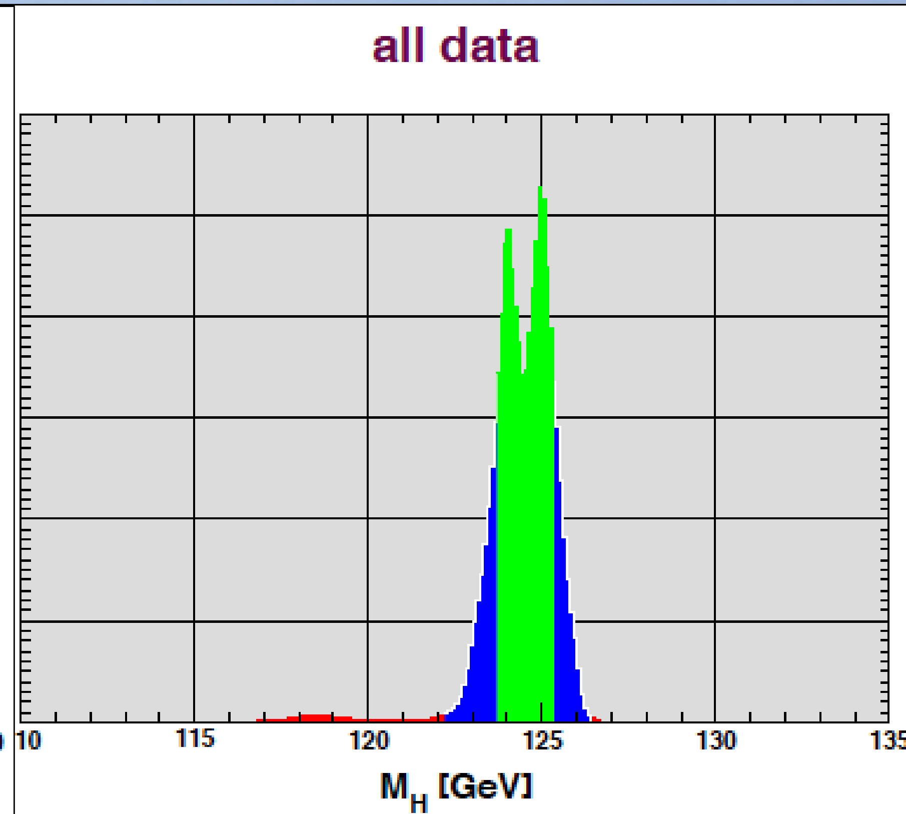


Both compatible with m_H = 125 GeV

Combining the Information from Previous Direct Searches and Indirect Data

Assuming the Standard Model



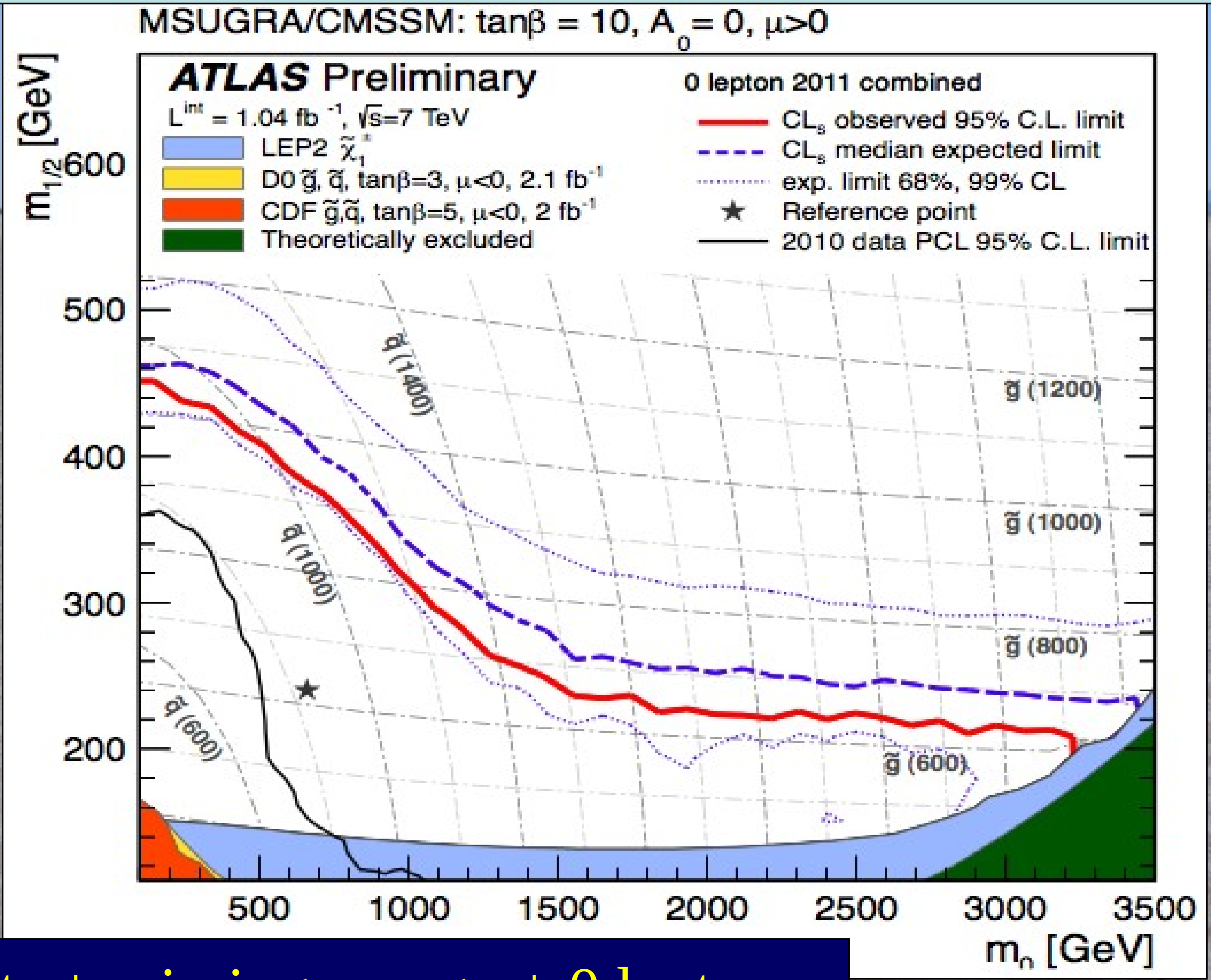


$m_H = 125 \pm 10$ GeV

$m_H = 124.5 \pm 0.8$ GeV

Erler: arXiv:1201.0695

Supersymmetry Searches in ATLAS



Jets + missing energy + 0 lepton

The Seminal Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The Englert-Brout-Higgs Mechanism

- **Vacuum expectation value of scalar field**
- Englert & Brout: June 26th 1964
- First Higgs paper: July 27th 1964
- Pointed out loophole in argument of Gilbert if gauge theory described in Coulomb gauge
- Accepted by Physics Letters
- Second Higgs paper with explicit example sent on July 31st 1964 to Physics Letters, rejected!
- Revised version (Aug. 31st 1964) accepted by PRL
- Guralnik, Hagen & Kibble (Oct. 12th 1964)

The Englert-Brout-Higgs Mechanism

Englert & Brout

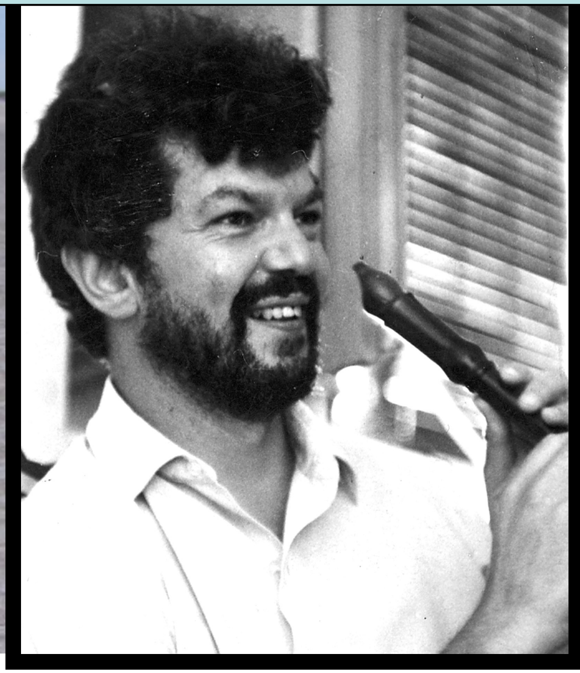


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2 (q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

Guralnik, Hagen & Kibble

We consider, as our example, a theory which was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$+ \varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$

With no loss of generality, we can take $\eta_2 = 0$, and find

$$(-\partial^2 + \eta_1^2)\varphi_1 = 0,$$

$$-\partial^2 \varphi_2 = 0,$$

$$(-\partial^2 + \eta_1^2)A_k^T = 0,$$

where the superscript T denotes the transverse part. The two degrees of freedom of A_k^T combine with φ_1 to form the three components of a

The Higgs Boson

- **Higgs pointed out a massive scalar boson**

$$\{\partial^2 - 4\varphi_0^{\,2} V''(\varphi_0^{\,2})\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^{\,2})\}^{1/2}$

- *"… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons"*
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence
- **Discussed in detail by Higgs in 1966 paper**