To Higgs or not to Higgs?

That is one of the questions

being studied at the LHC

John Ellis
King's College London
(& CERN)

Open Questions beyond the Standard Model

- What is the origin of particle masses? LHC Susy

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)
- Why so many types of matter particles? LHC

  matter-antimatter difference?
- Unification of the fundamental forces? LHC Susy

  at very high energy ~ 10^{16} GeV?

  probe directly via neutrino physics, indirectly via masses, couplings
- Quantum theory of gravity? LHC Susy

  (super)string theory: extra space-time dimensions?

Why do Things Weigh?

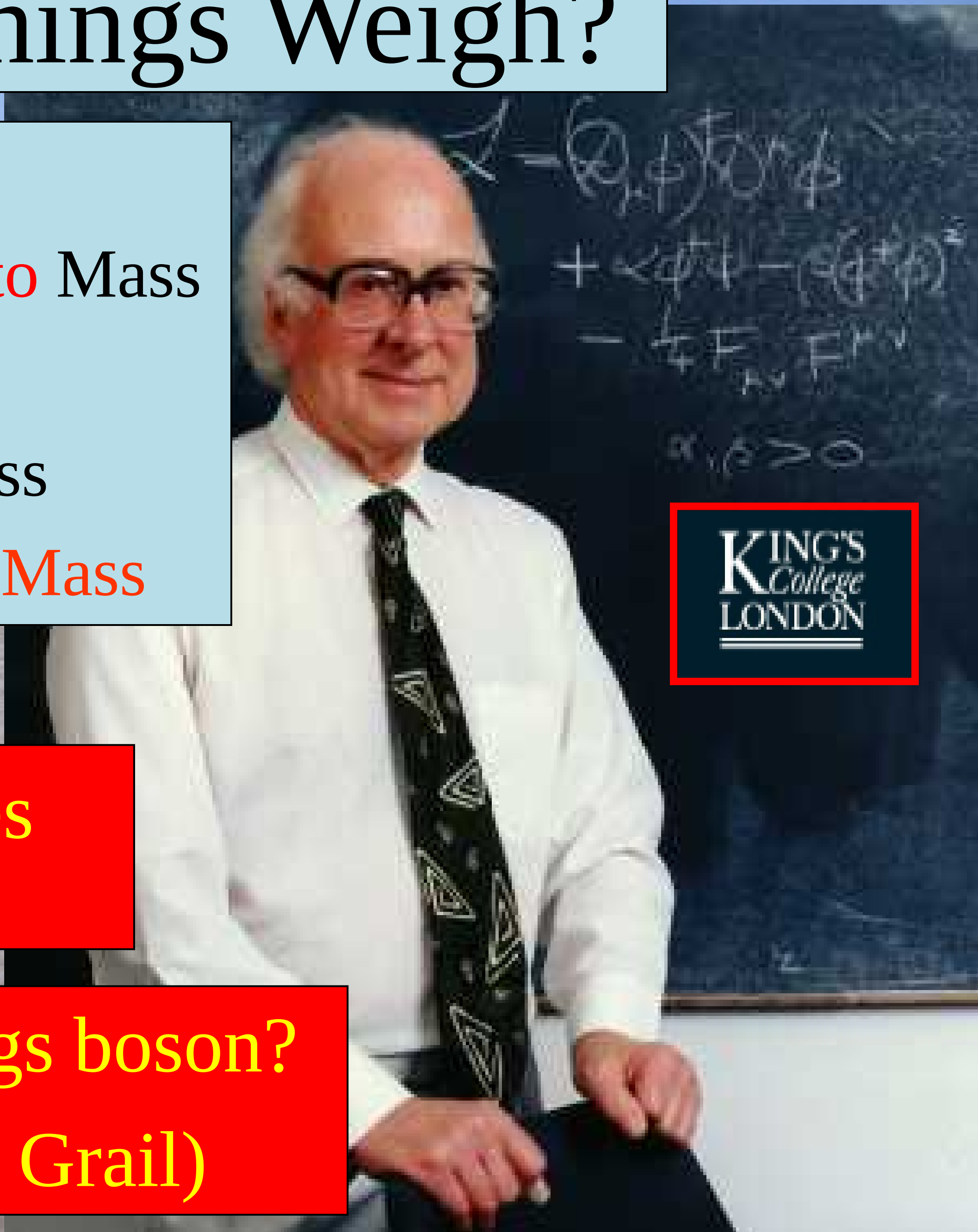
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



KING'S College LONDON

Where do the masses come from?

Are masses due to Higgs boson?

(the physicists' Holy Grail)

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

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

Englert & Brout

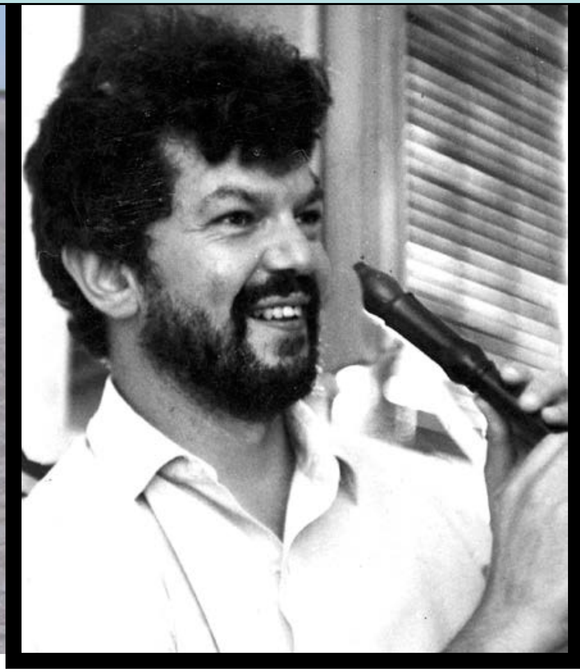


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2 (q_\mu q_\nu/q^2) \times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

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

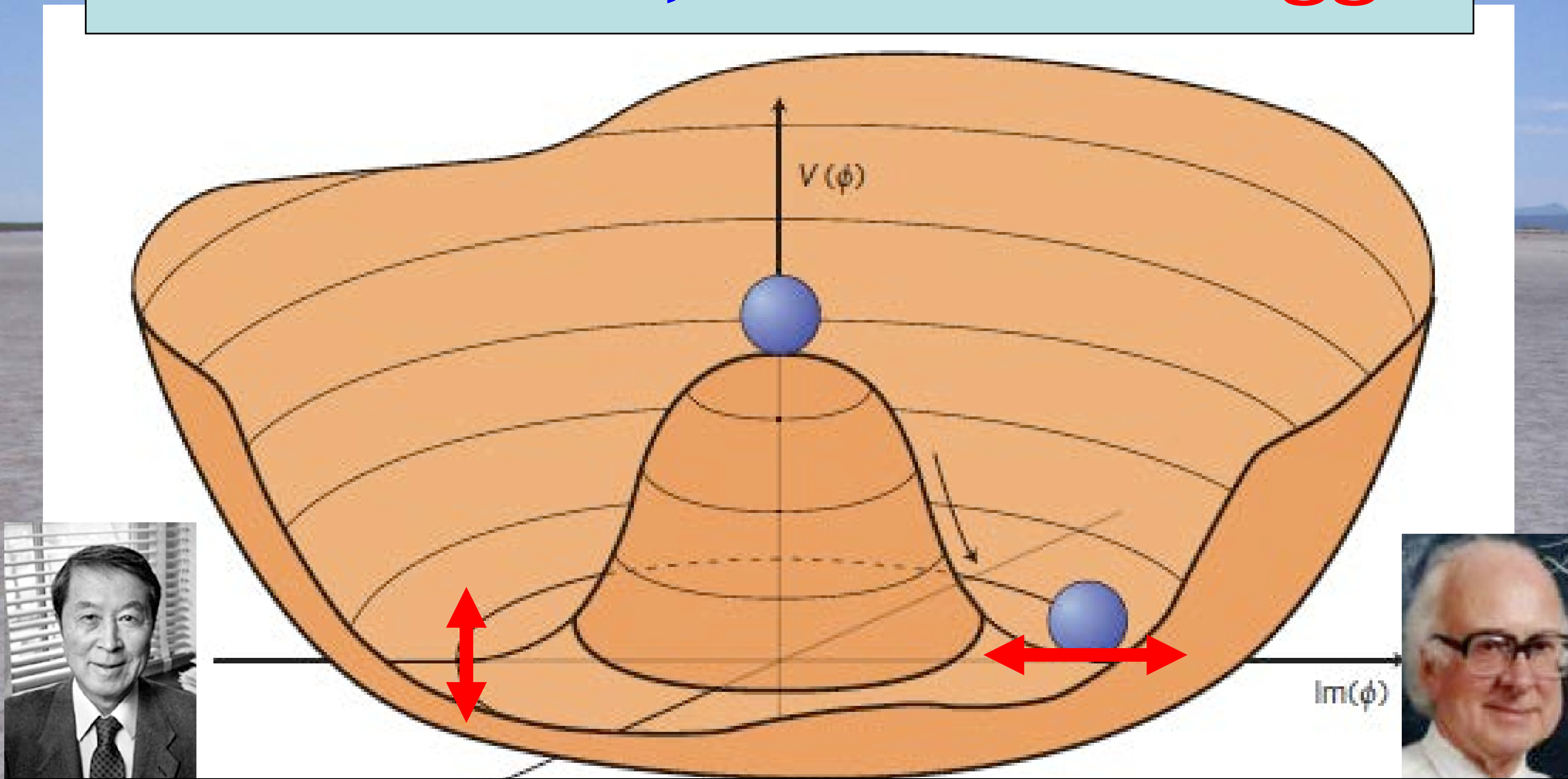
- **Higgs pointed out a massive scalar boson**

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

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**

Nambu **EB, GHK** **and Higgs**



Spontaneous symmetry breaking: massless Nambu-Goldstone boson **‘eaten’ by gauge boson**

Accompanied by massive particle

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

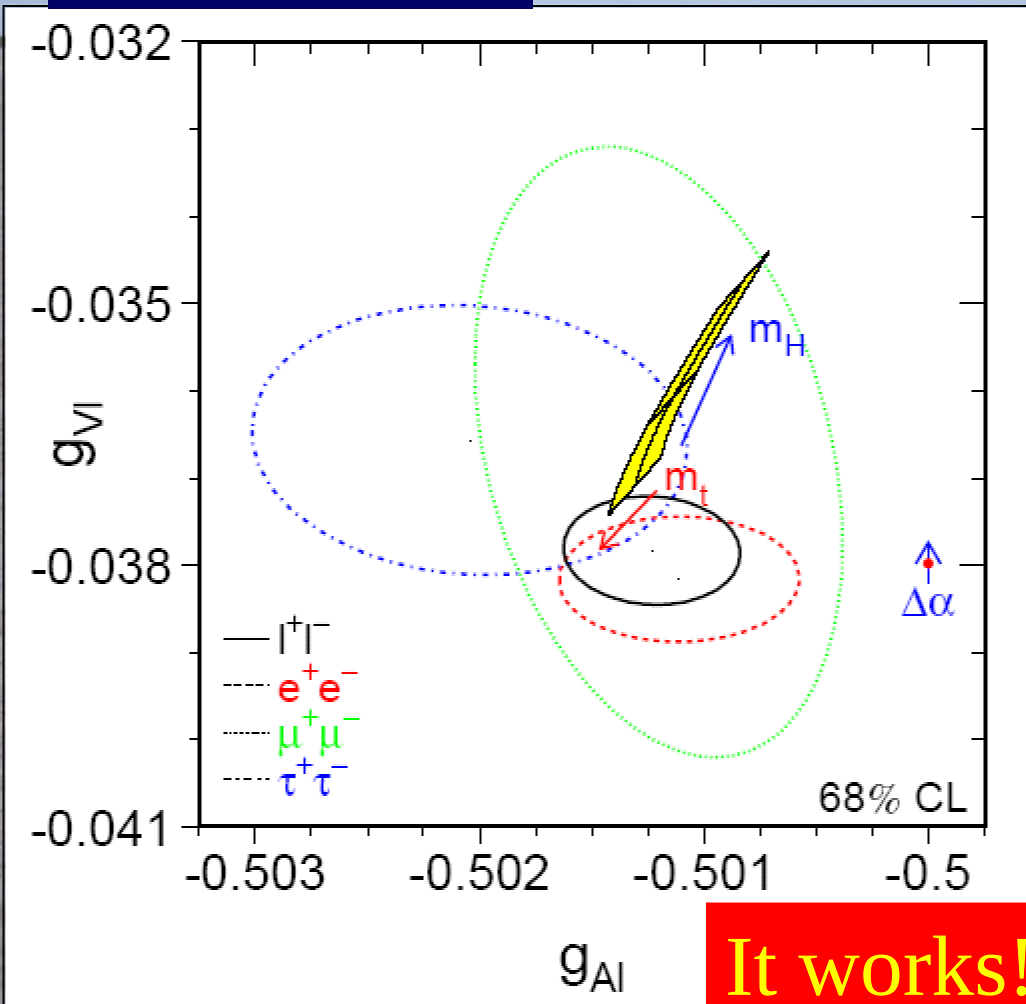
Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

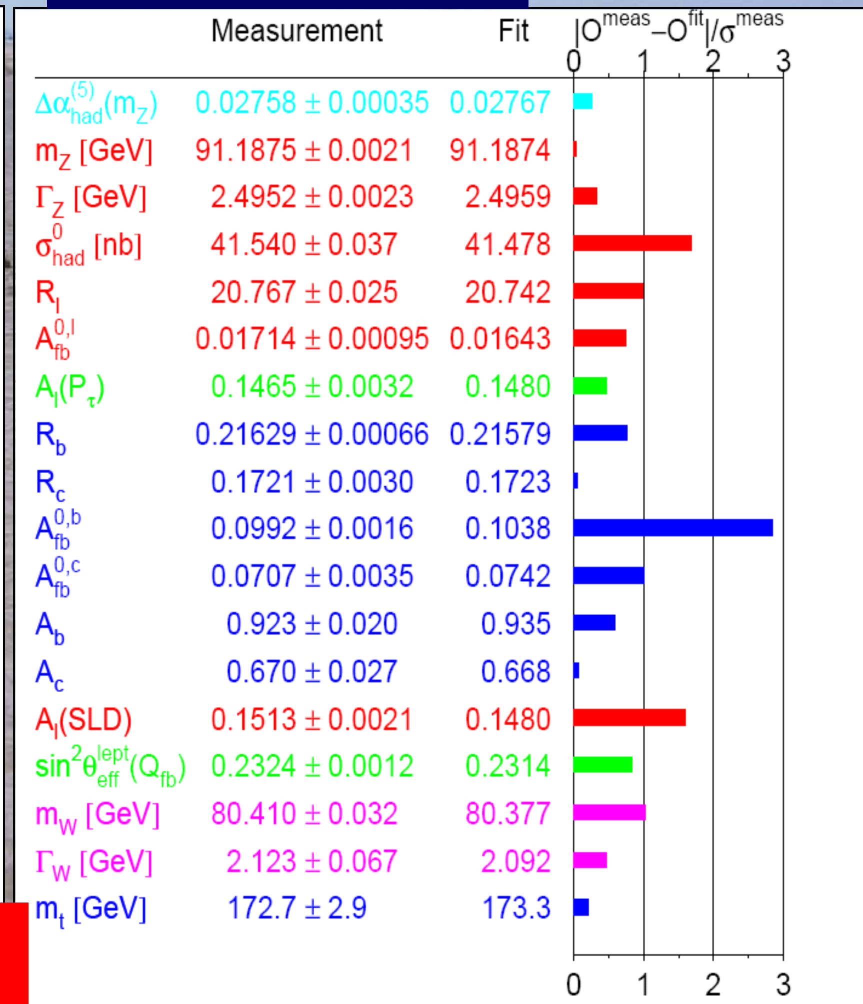
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit

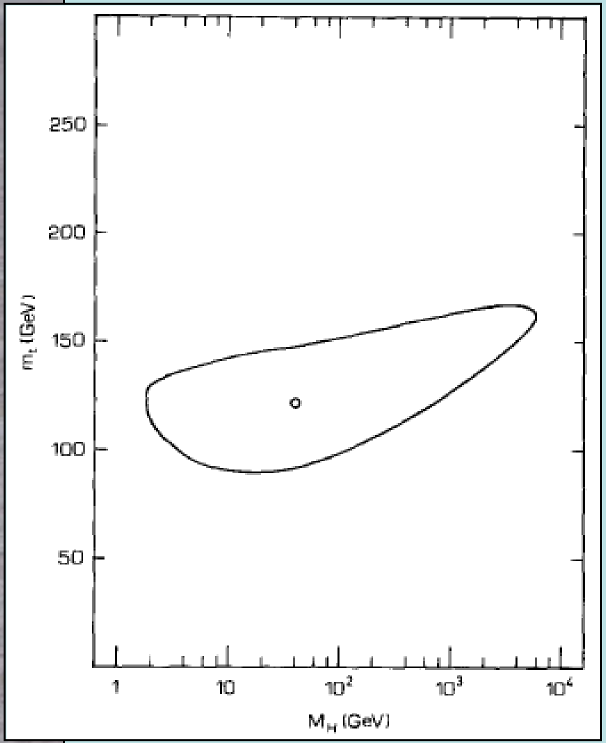


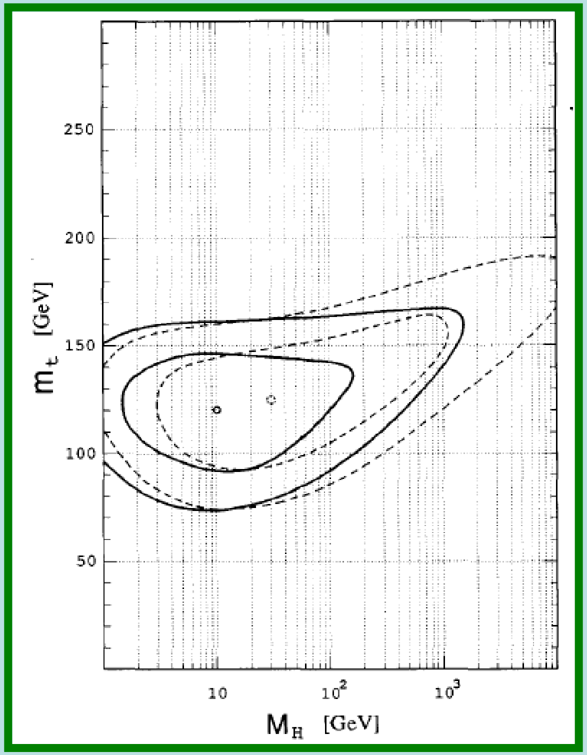
	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643	
$A_l(P_\tau)$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

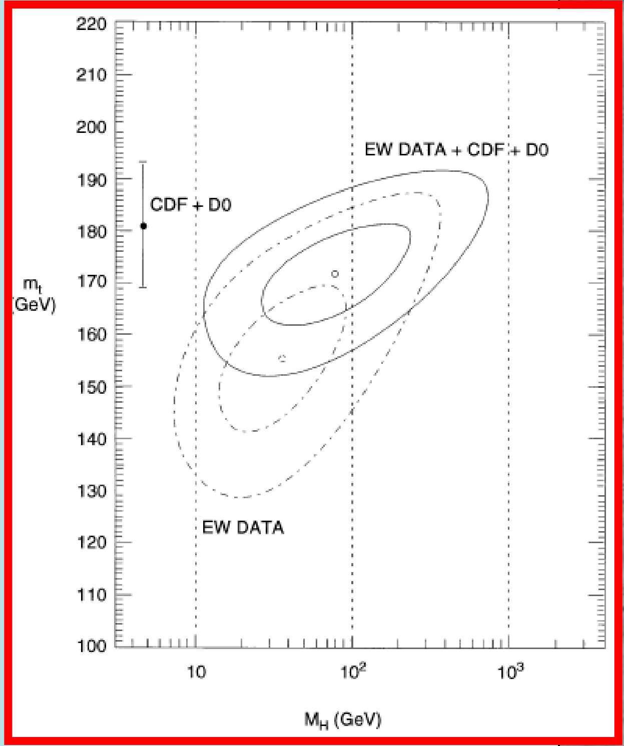
It works!

Estimating the Mass of the Higgs Boson

- First attempts in 1990, **1991**



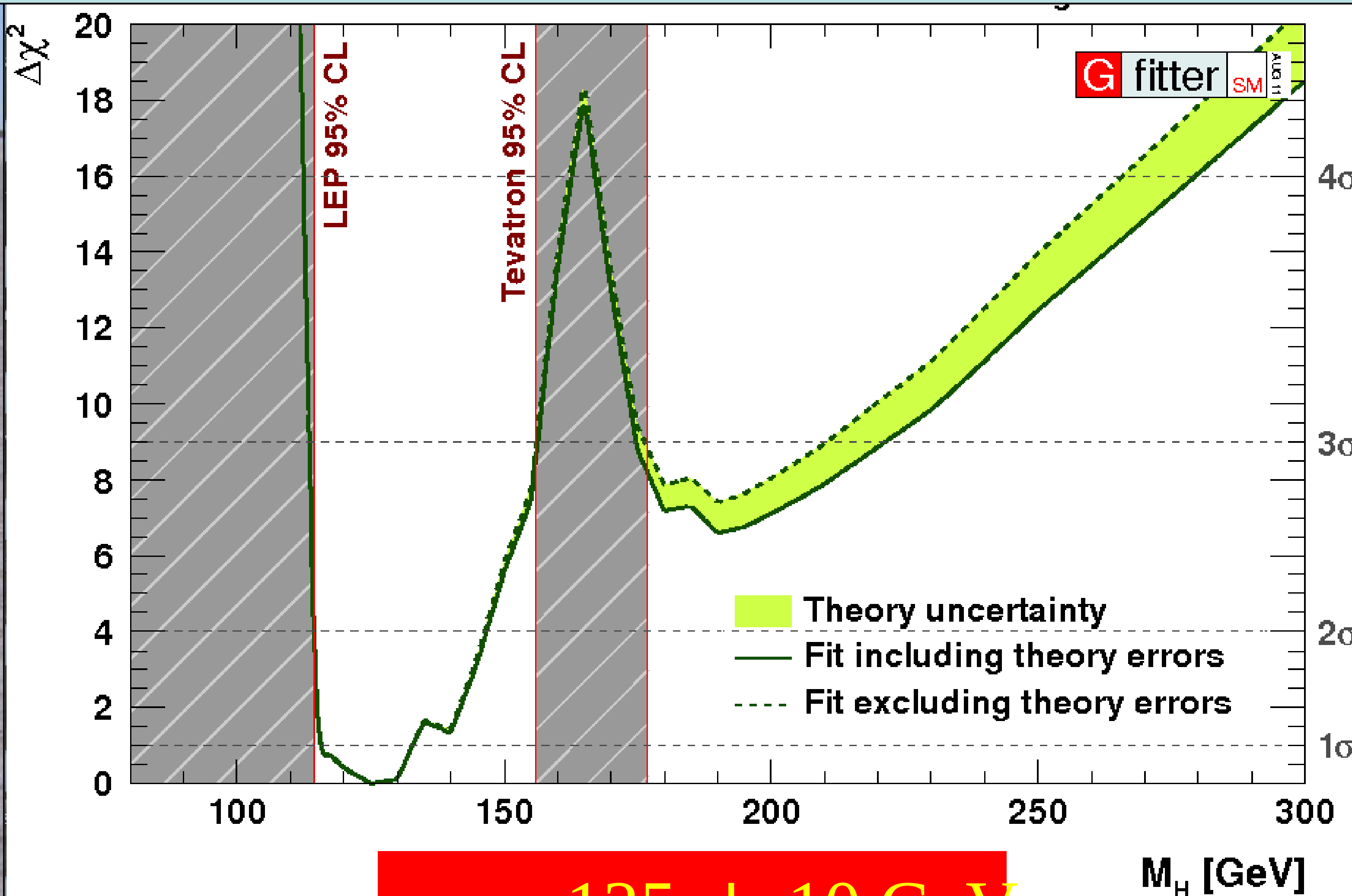




- **Easier after the discovery of the top quark**

JE, Fogli & Lisi

2011: Combining Information from Previous Direct Searches and Indirect Data

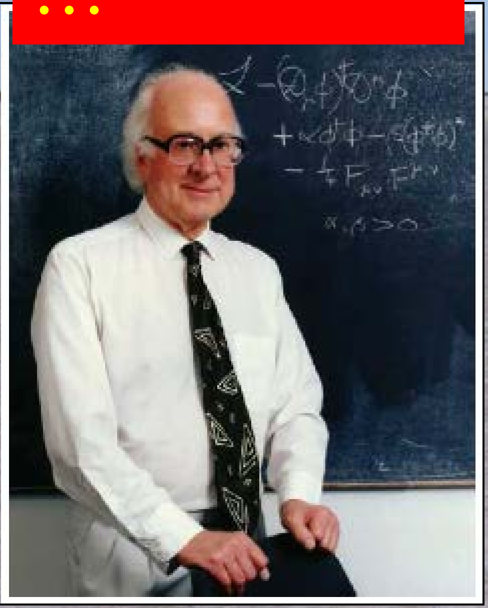


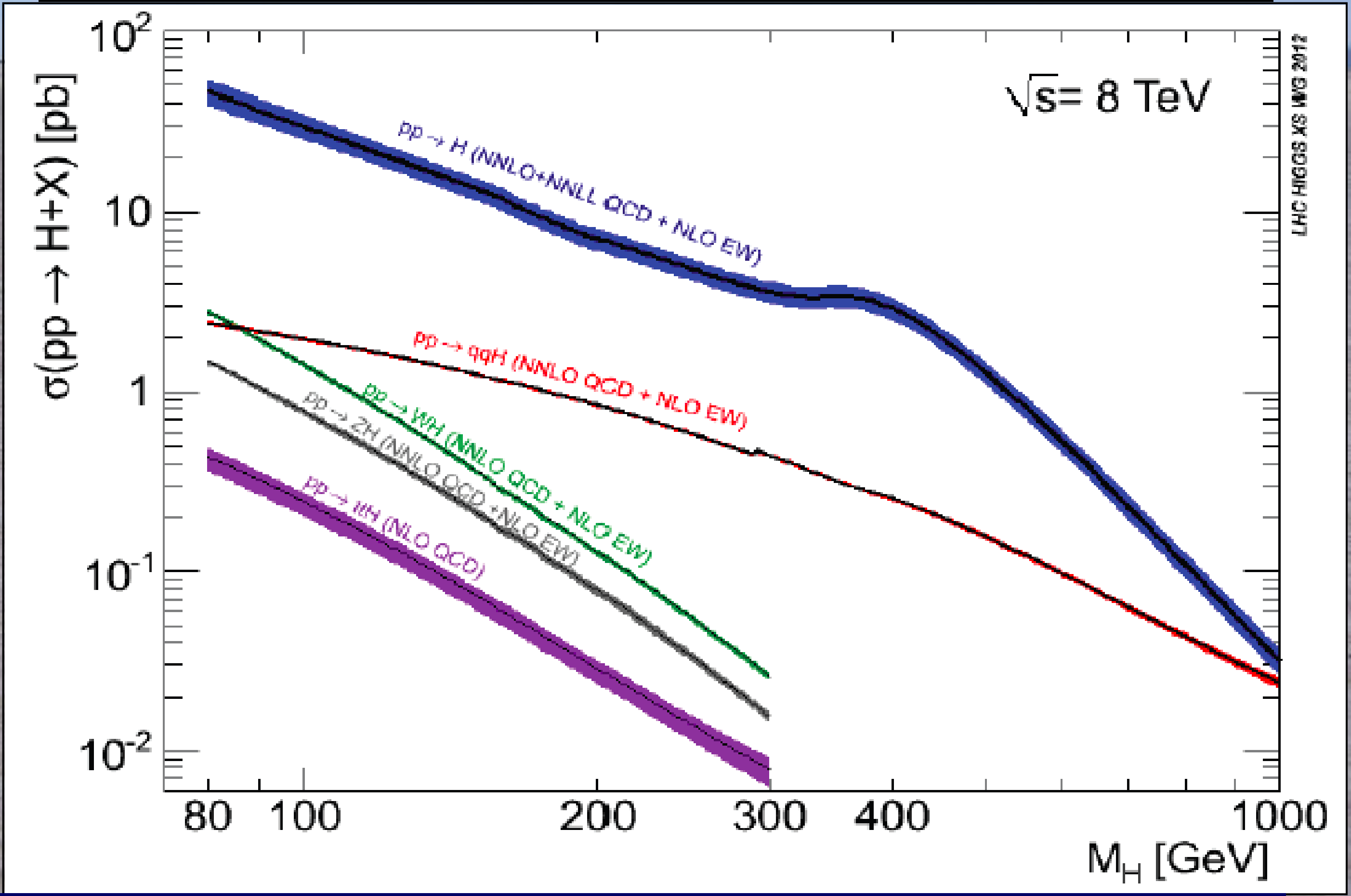
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du Higgs perdu …

Higgs Production at the LHC

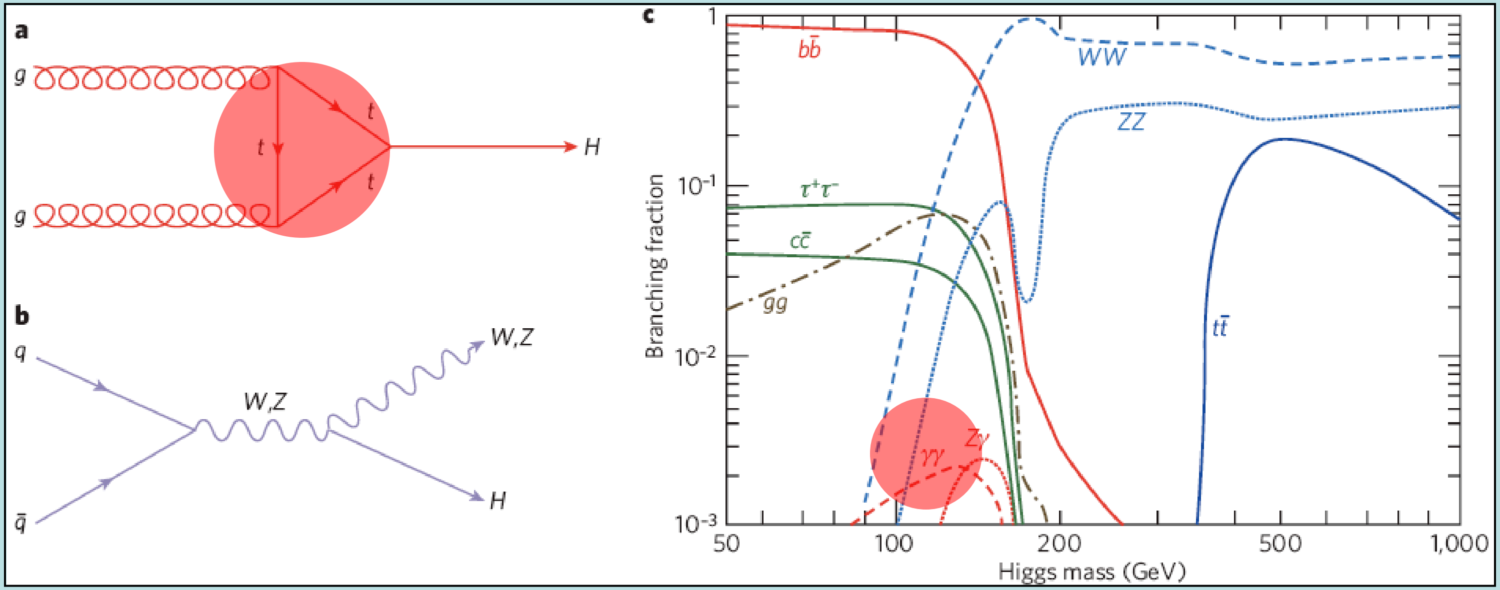




Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

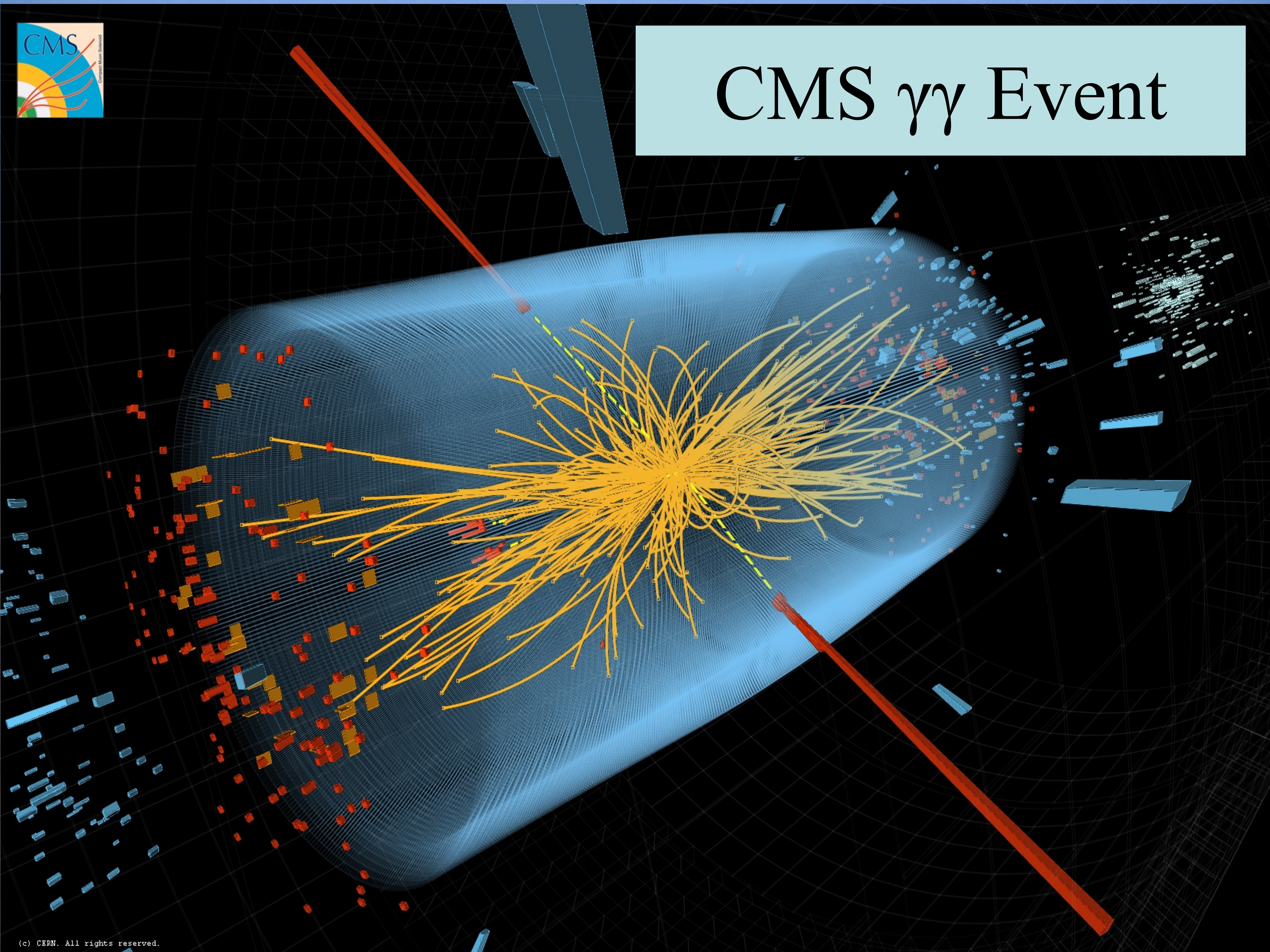
- Couplings proportional to masses (?)



- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

CMS γγ Event



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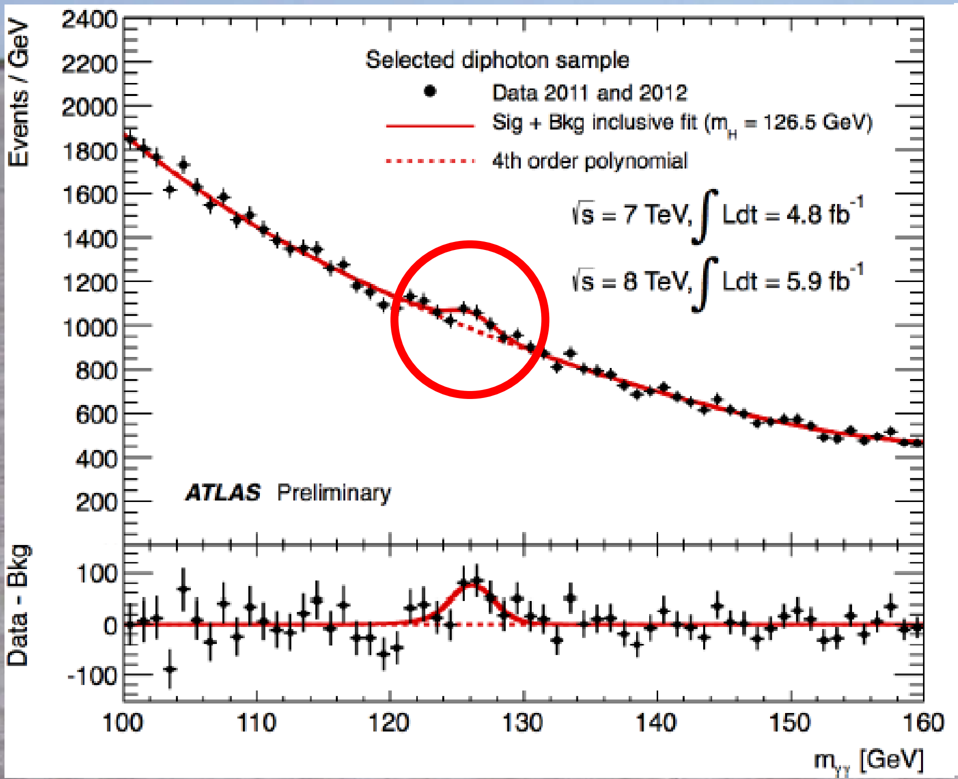
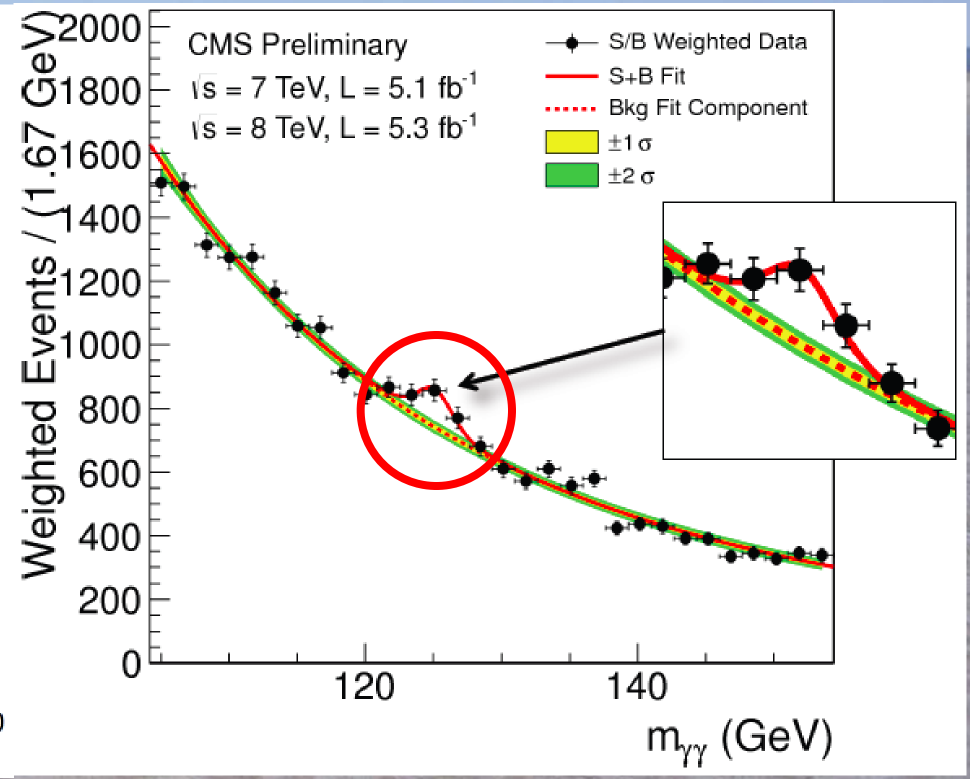
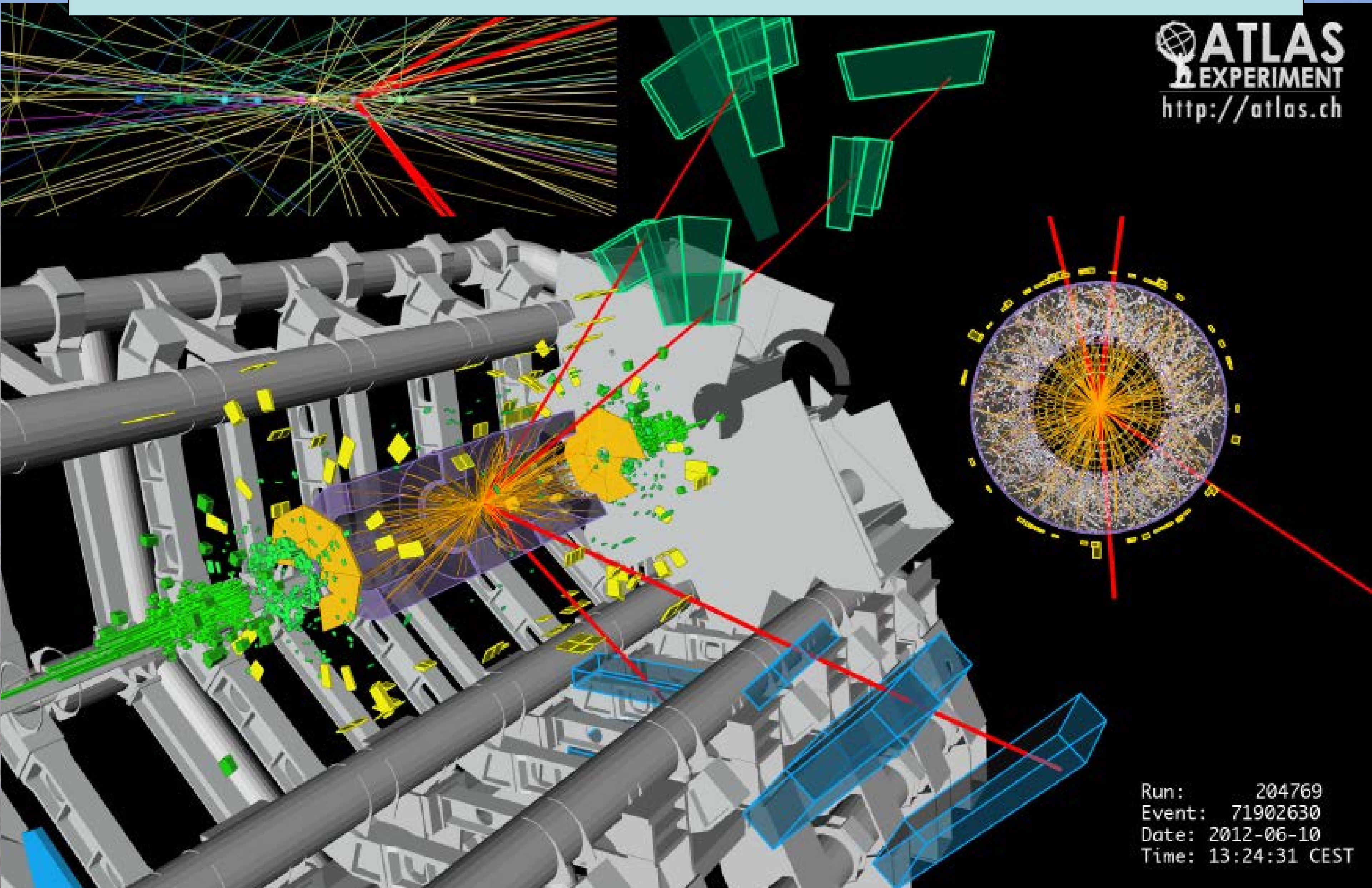
Evidence in the γγ Channel



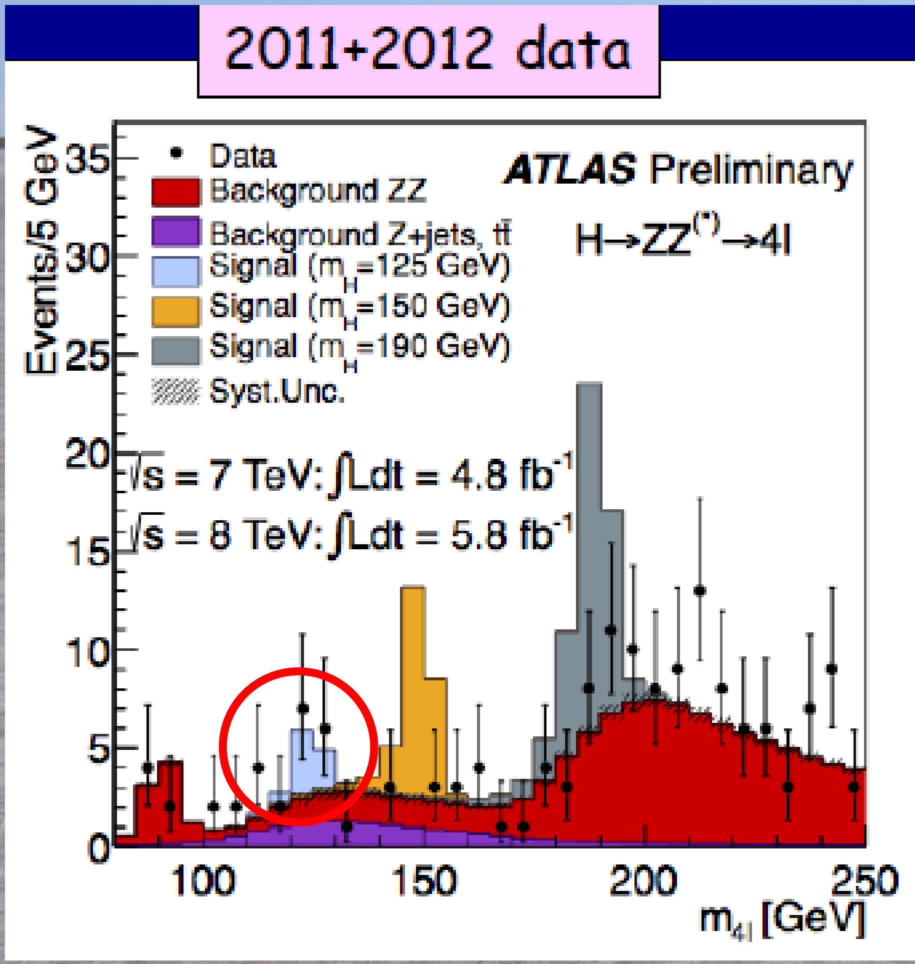


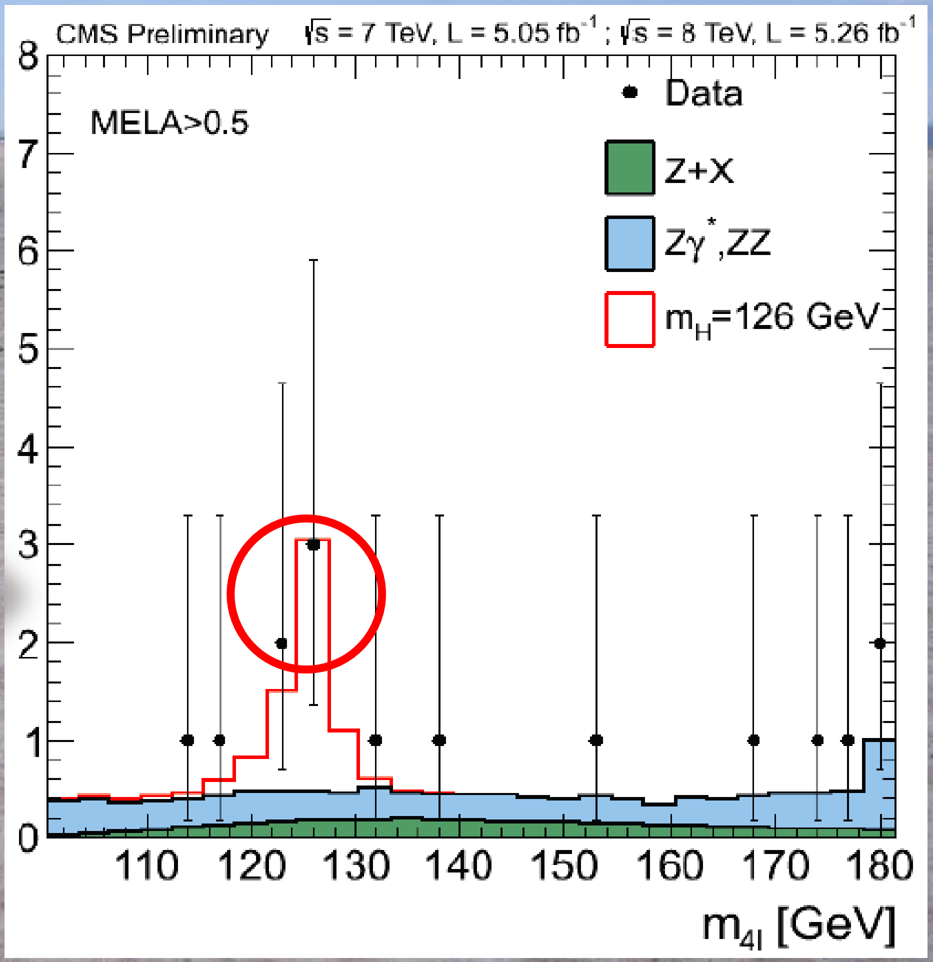
Signals around M_h = 125 GeV

ATLAS Four-Muon Event



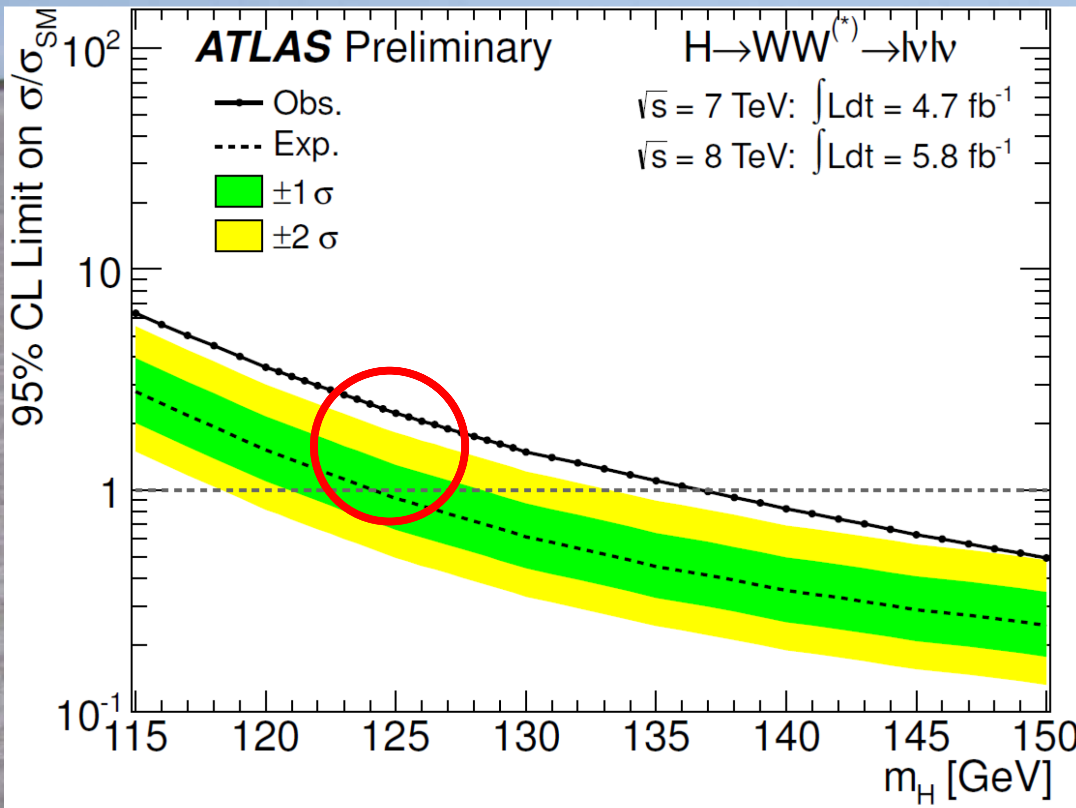
Evidence in the ZZ* Channel

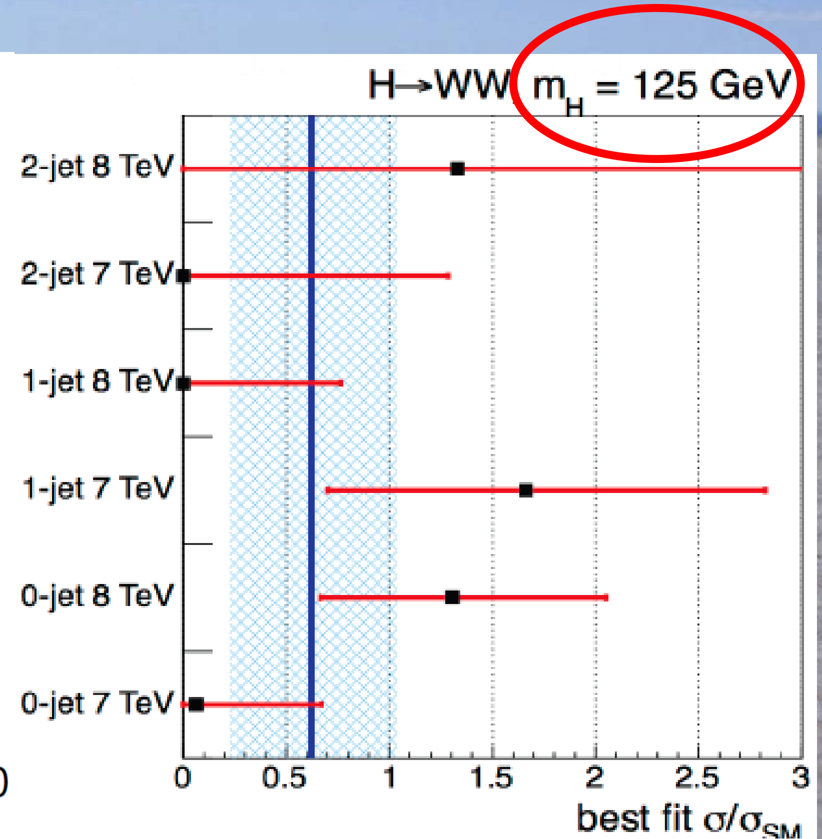




Signals around M_h = 125 GeV

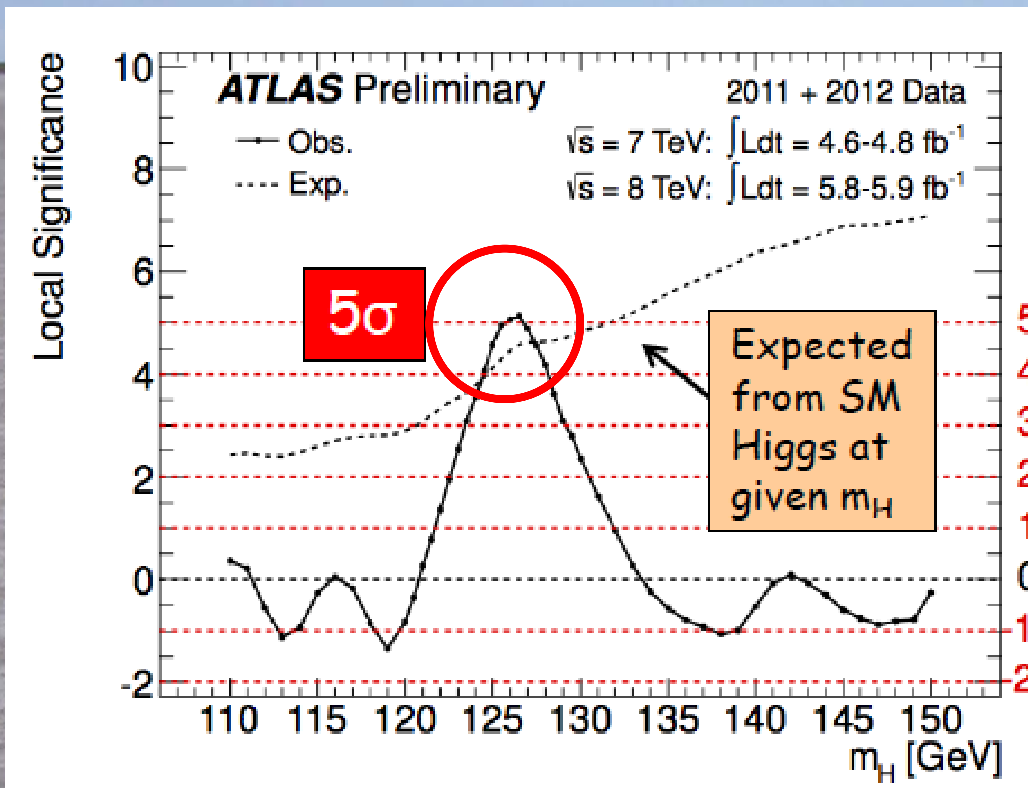
Evidence in the WW* Channel

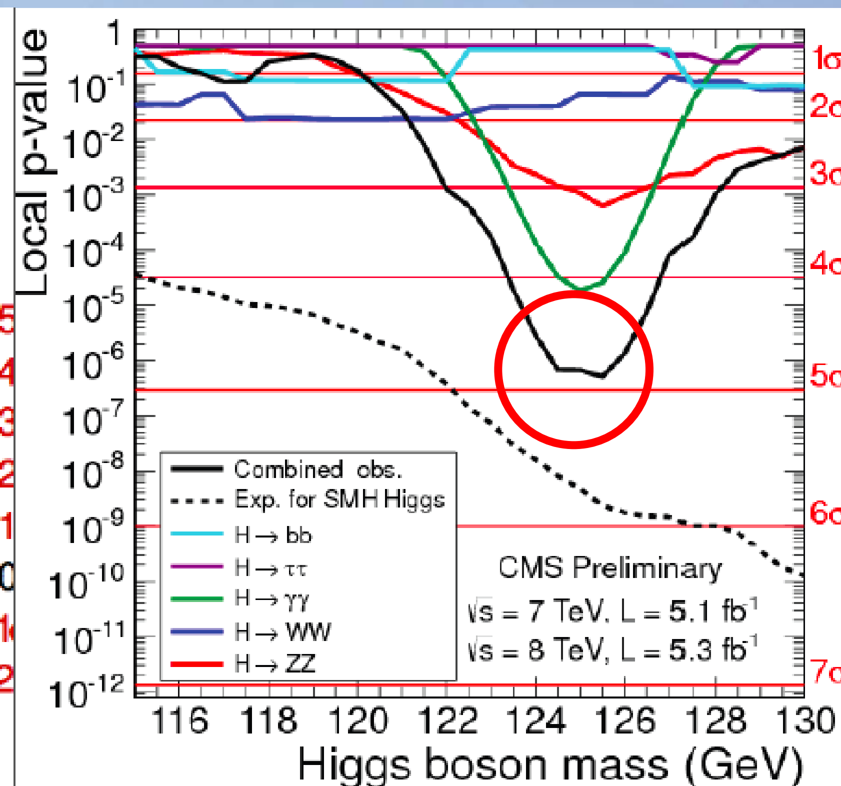




Poorer mass resolution: compatible with $M_h \sim 125$ GeV

Signal Significances

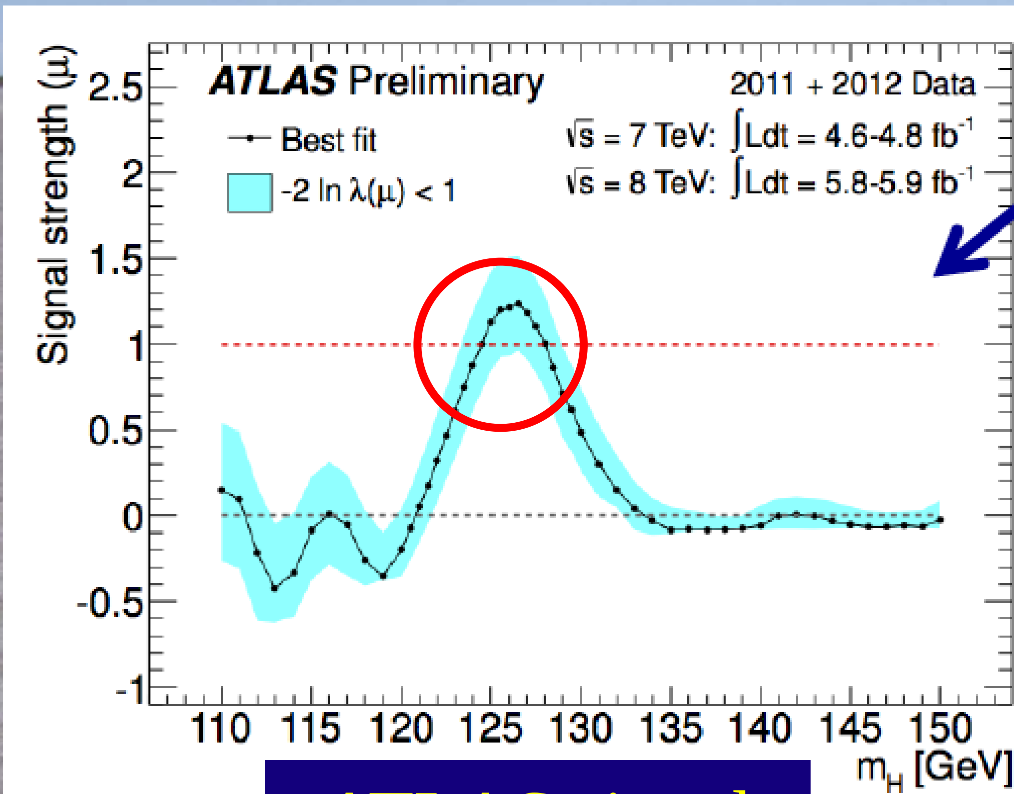


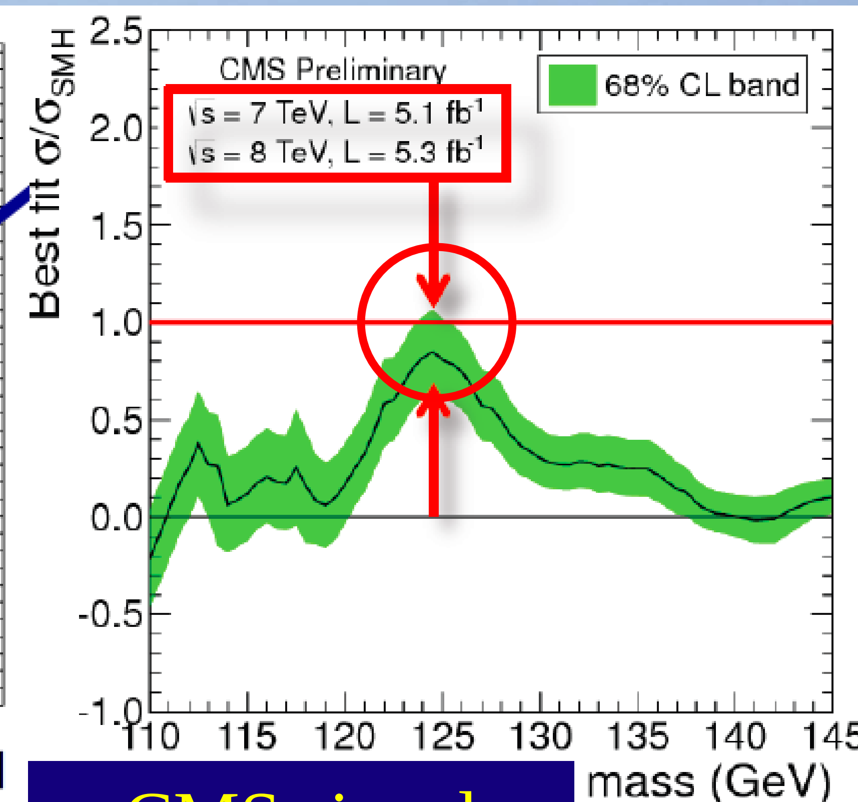


Each experiment sees ~ 5σ at M_h ~ 125 to 126 GeV

A New Particle has been Discovered

Independent discoveries around M_h = 125 to 126 GeV





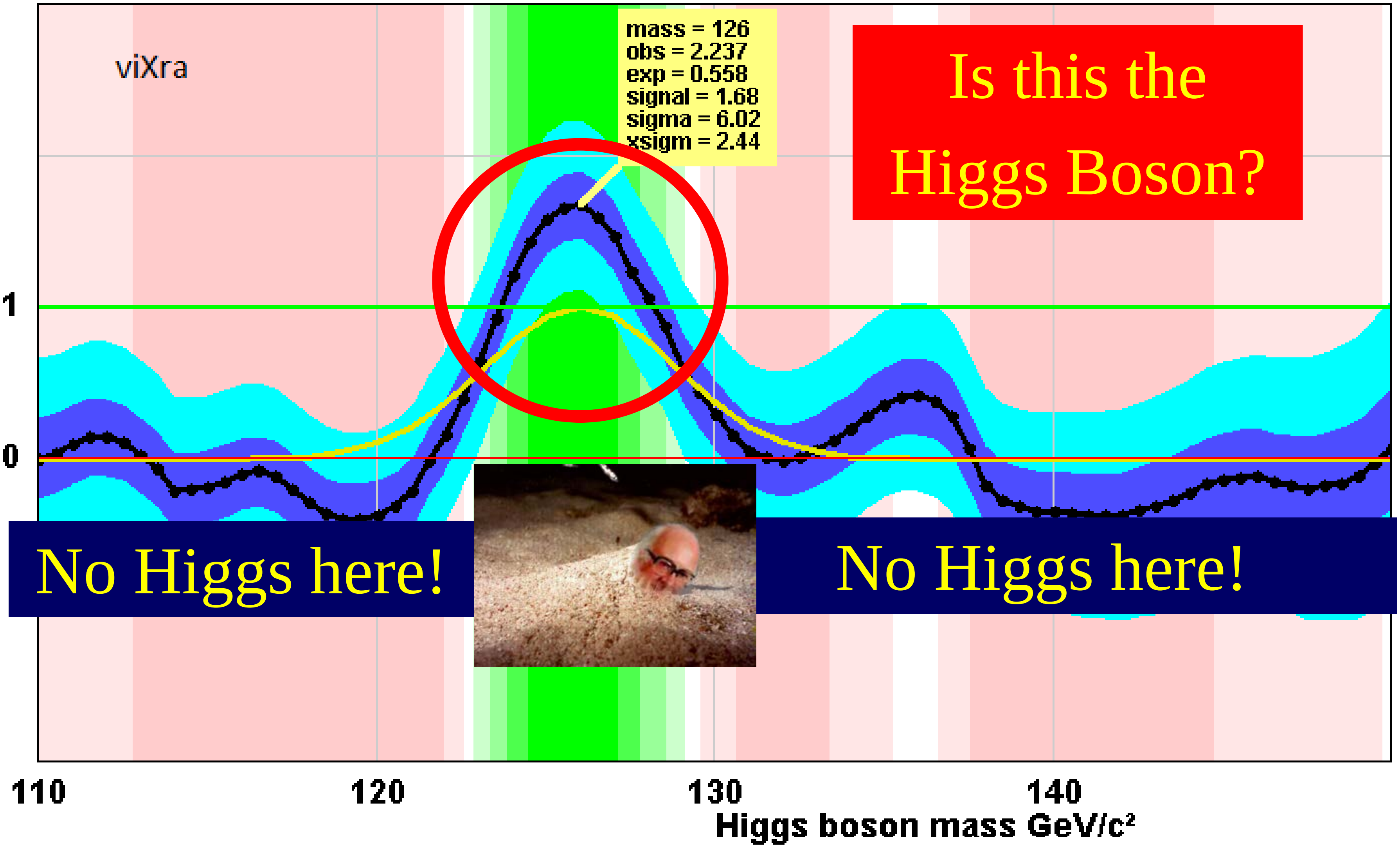
ATLAS signal

$(1.2 \pm 0.3) \times$ SM

CMS signal

$(0.8 \pm 0.2) \times$ SM

Unofficial Combination of Higgs Search Data from July 4th

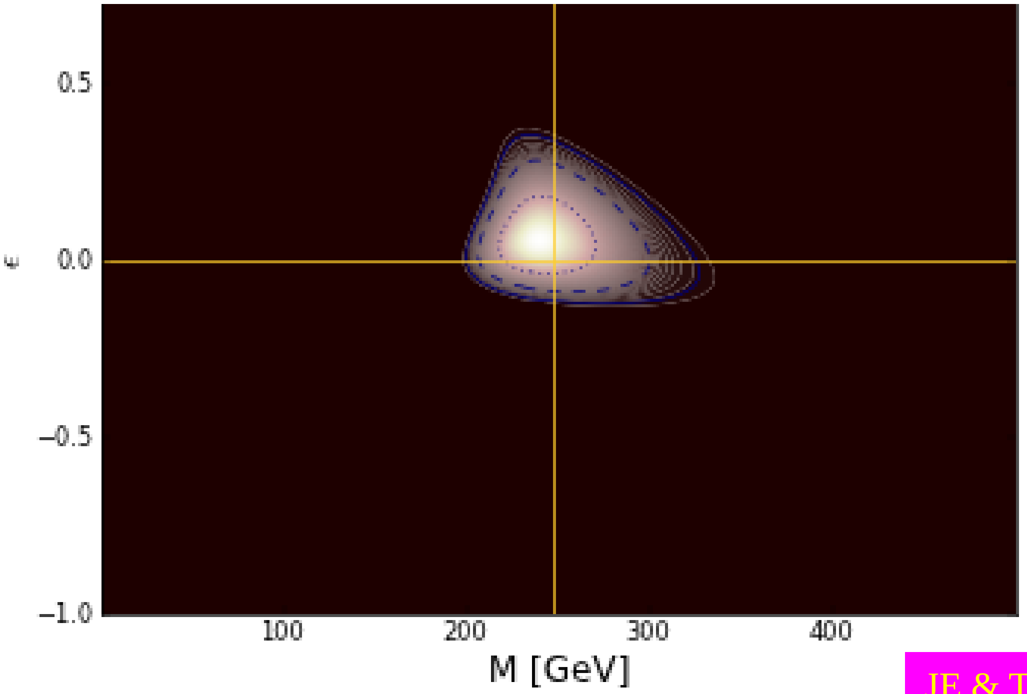


It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon},\ g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit



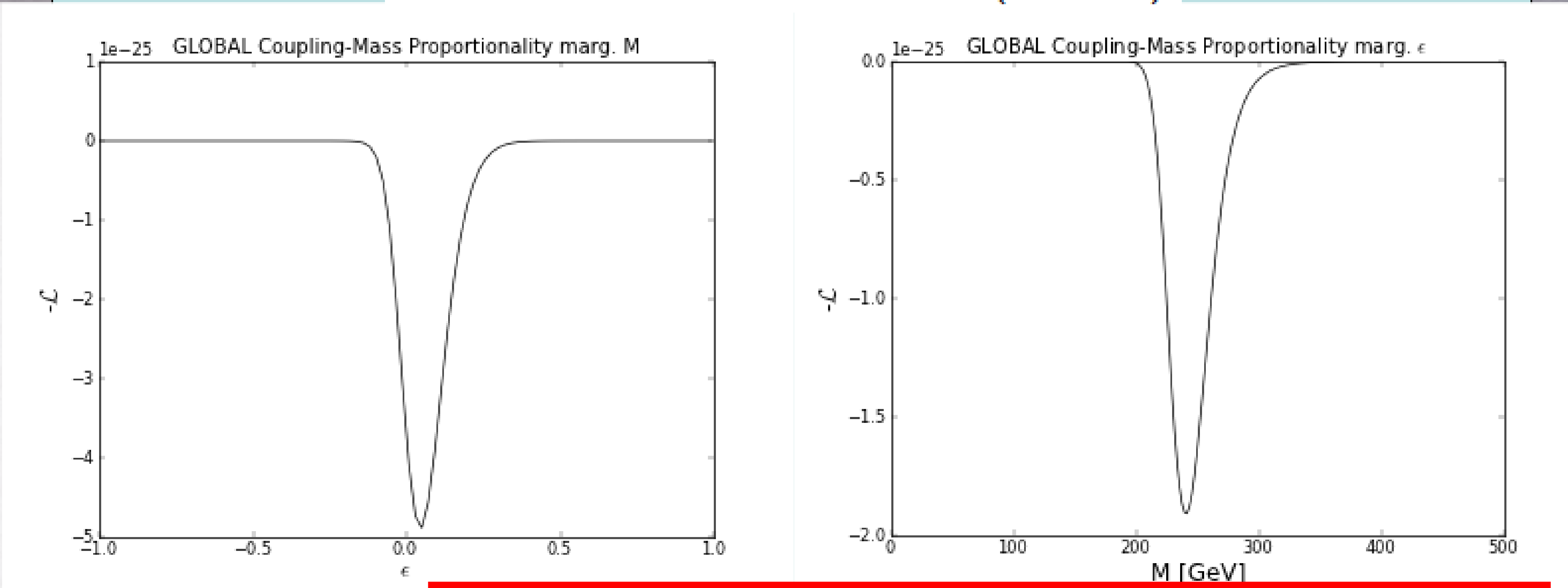
JE & Tevong You, arXiv:1207.1693

- Standard Model Higgs: ε = 0, M = v

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



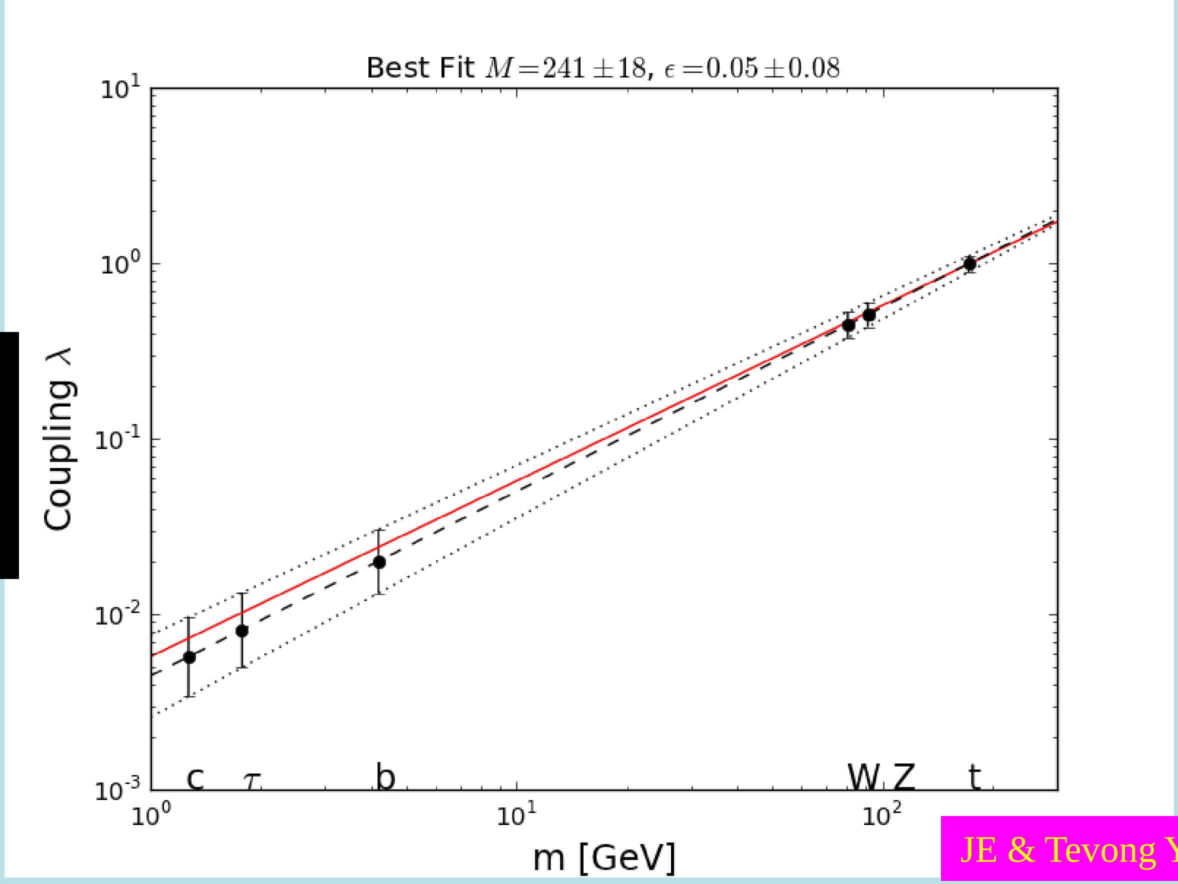
- Global fit: $\epsilon = 0.05 \pm 0.08, \quad M = 241 \pm 18 \text{ GeV}$

JE & Tevong You, arXiv:1207.1693

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

Global fit



JE & Tevong You, arXiv:1207.1693

- **Red line = SM**, dashed line = best fit

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

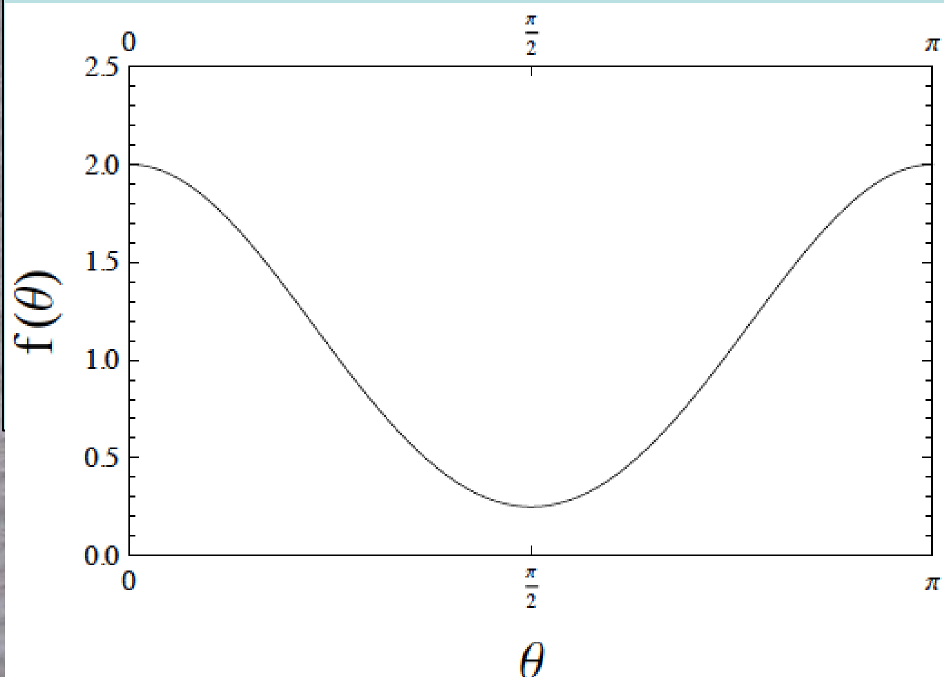
Is it the right size?

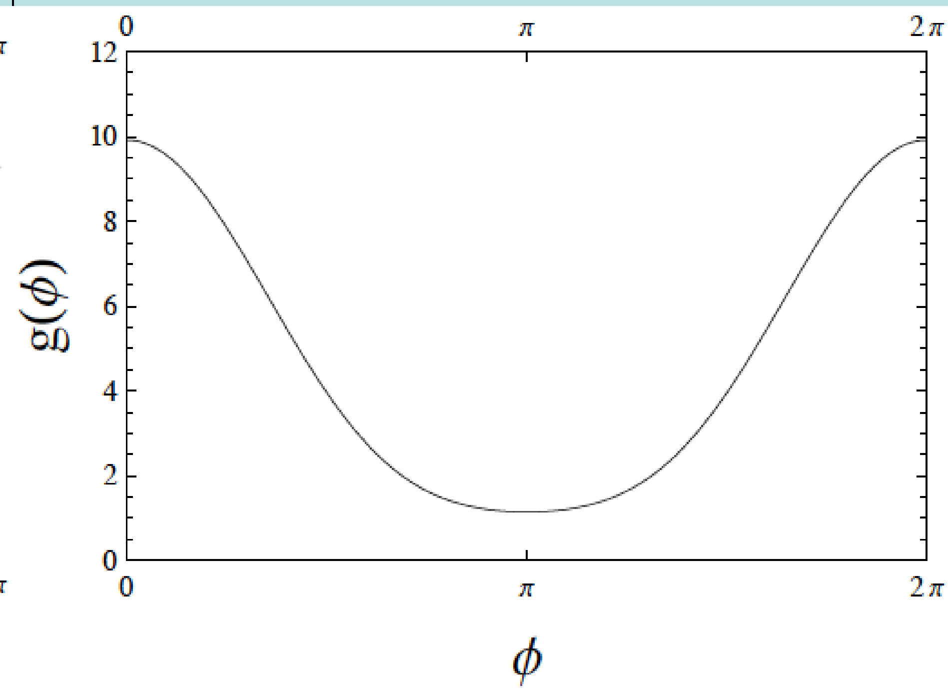
Does the ‘Higgs’ have Spin Zero ?

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

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)





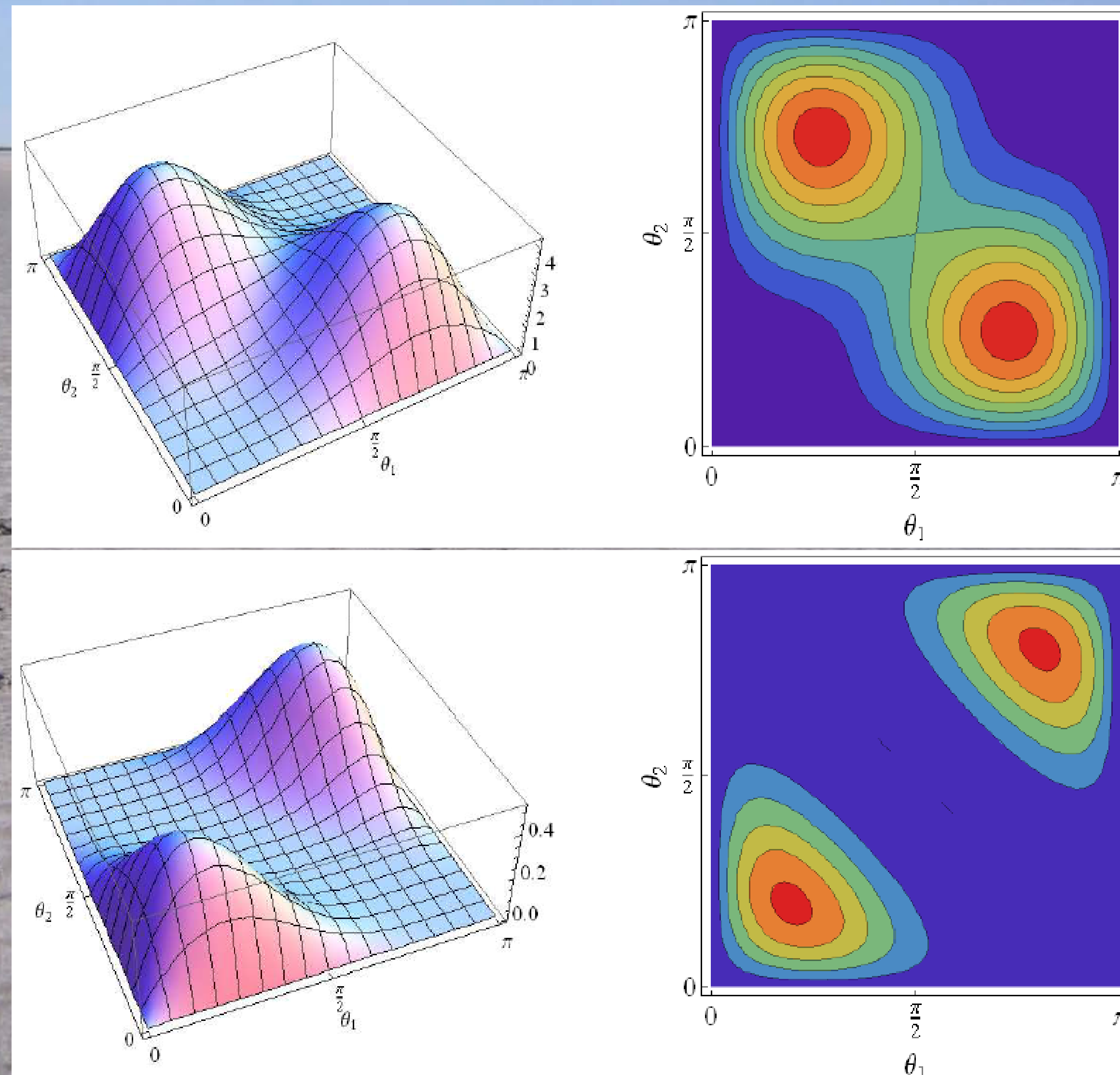
JE, Hwang: arXiv:1202.6660

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 $\varphi = \pi$)

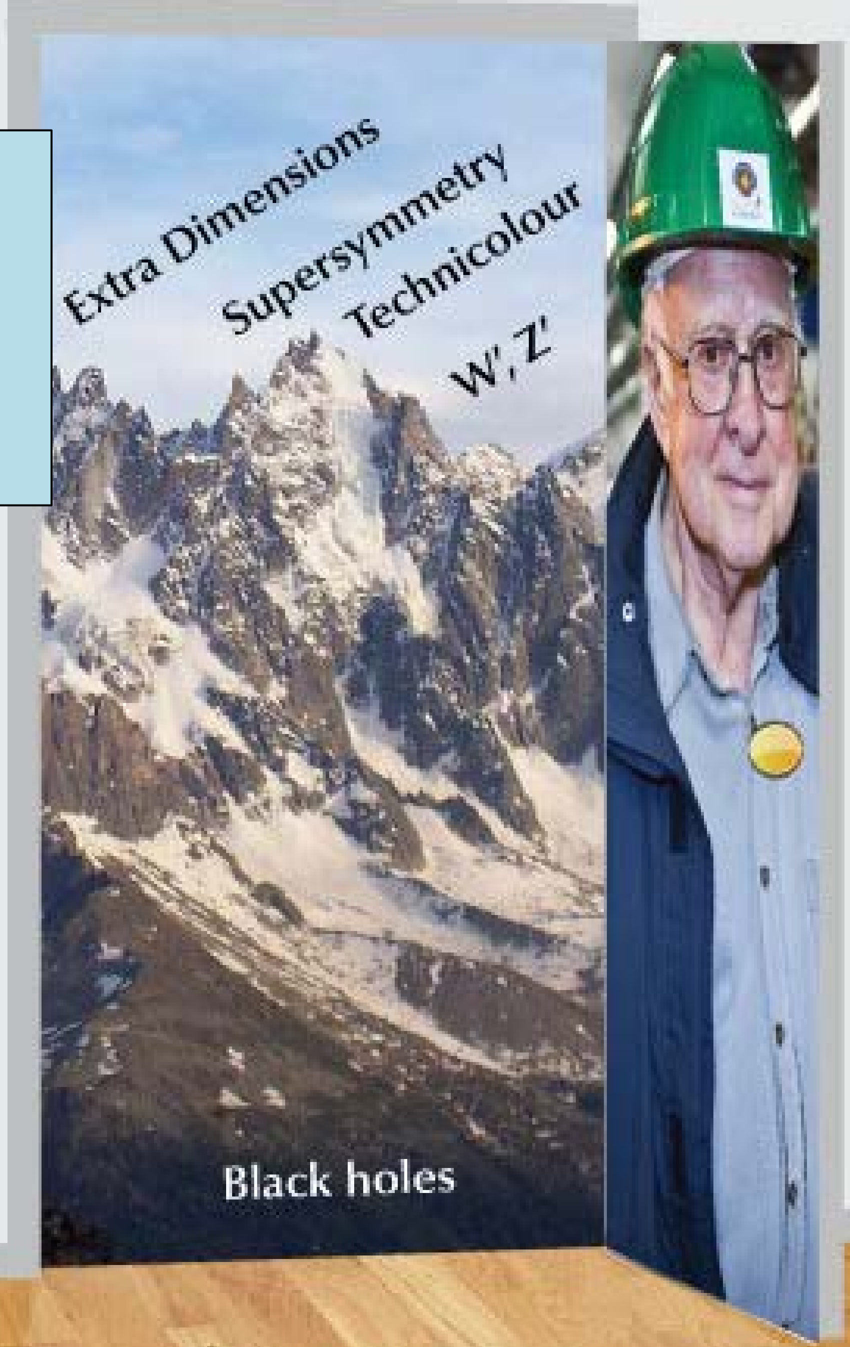
JE, Hwang: arXiv:1202.6660

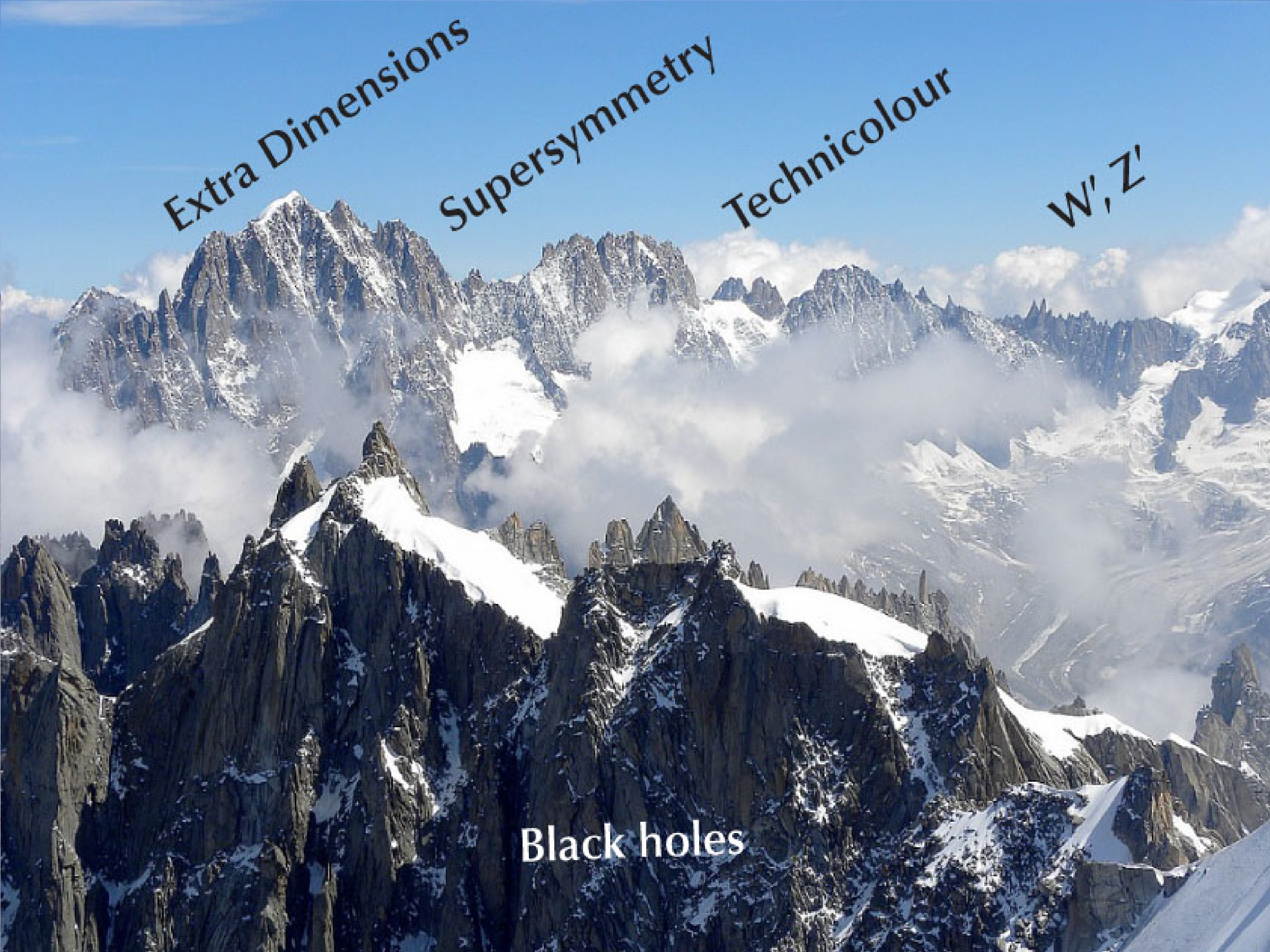


Imagine a Room …

… Open The Door

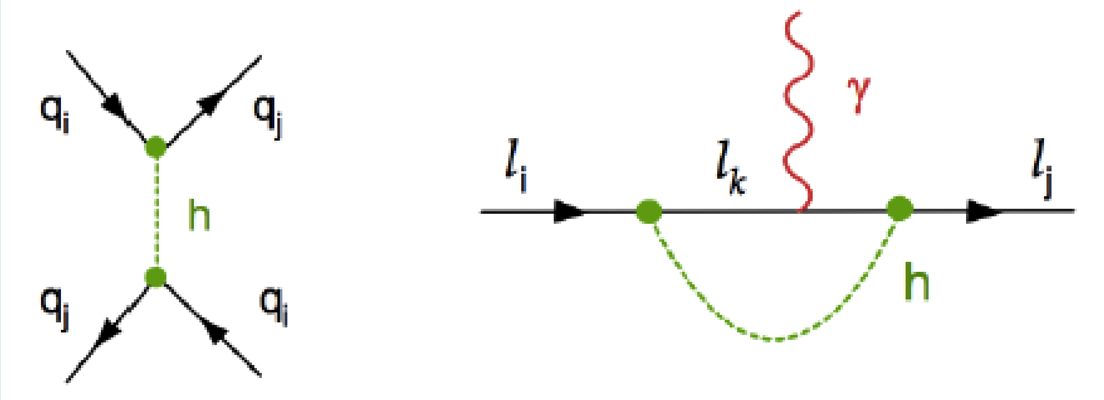
What lies Beyond?




Extra Dimensions
Supersymmetry
Technicolour
W', Z'
Black holes

Flavour-Changing Couplings?

- Upper limits from FCNC, EDMs, …



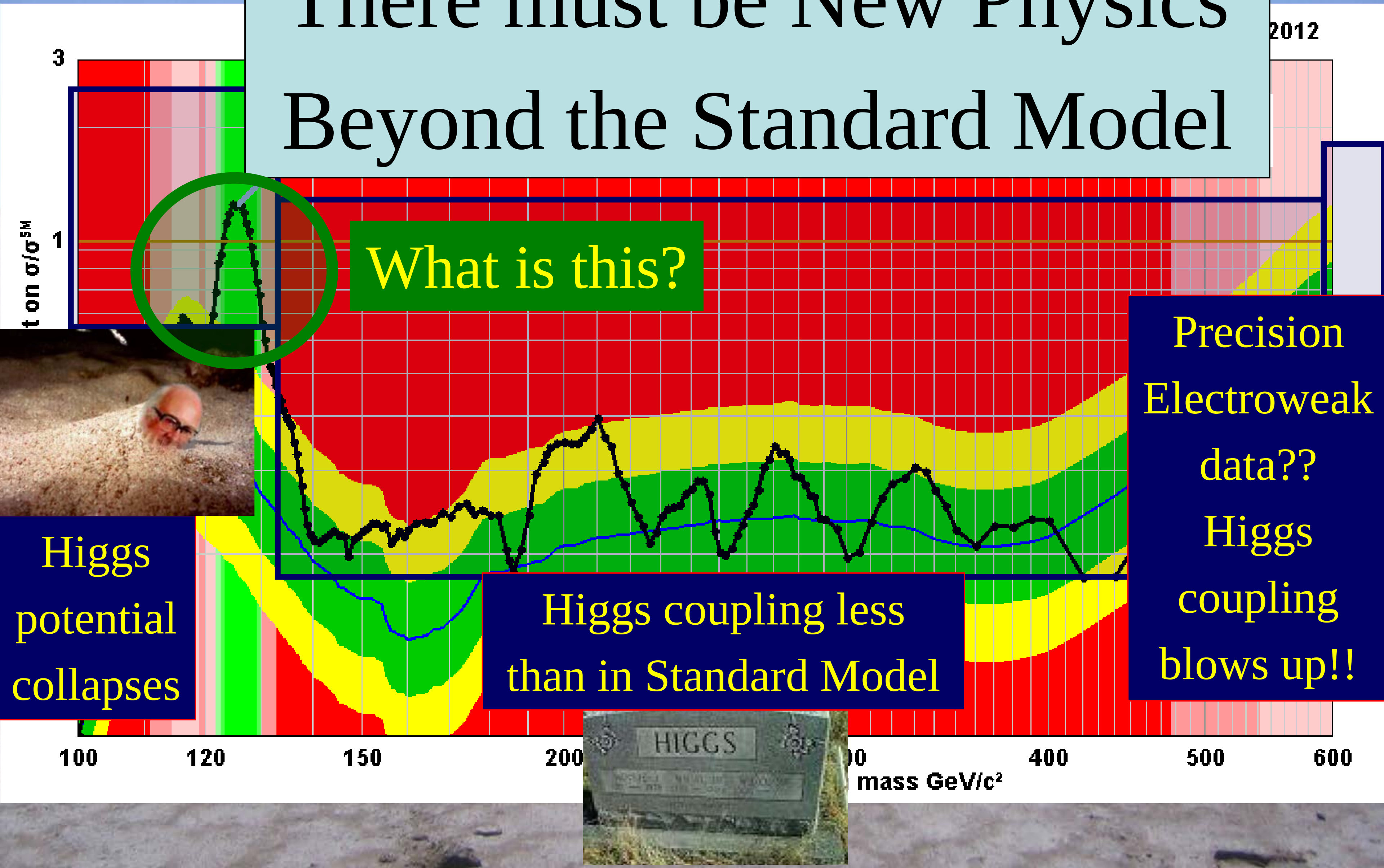
- Quark FCNC bounds exclude observability of quark-flavour-violating *h* decays
- Lepton-flavour-violating *h* decays could be large:

BR(τμ) or BR(τe) could be O(10)%

Blankenburg, JE, Isidori: arXiv:1202.5704

BR(μe) must be $< 2 \times 10^{-5}$

There must be New Physics Beyond the Standard Model



What is this?

Higgs potential collapses

Higgs coupling less than in Standard Model

Precision Electroweak data??

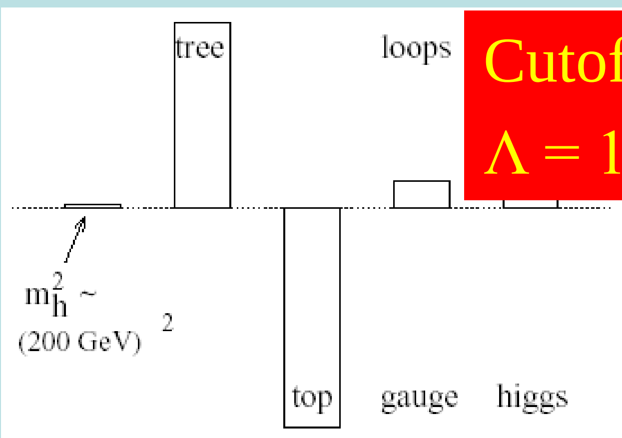
Higgs coupling blows up!!

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

$\Lambda = 10$ 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?

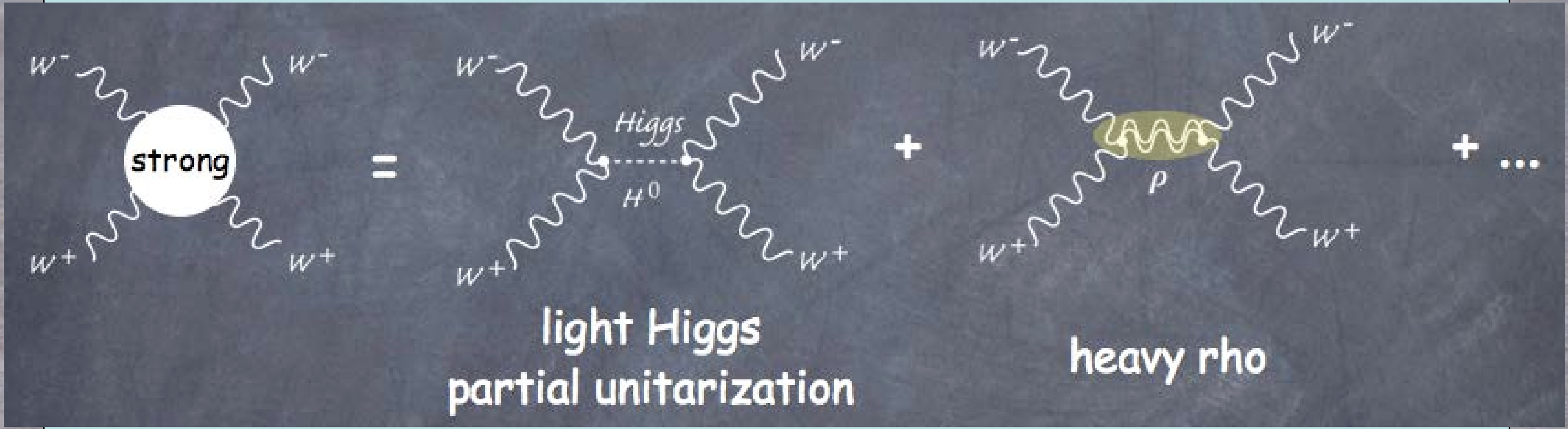
-Heavy scalar resonance?

-Inconsistent with

precision electroweak data?

Interpolating Models

- Combination of Higgs boson and vector ρ



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

$$g_\rho / m_\rho$$

Grojean, Giudice, Pomarol, Rattazzi

General Analysis of ‘unHiggs’ Models

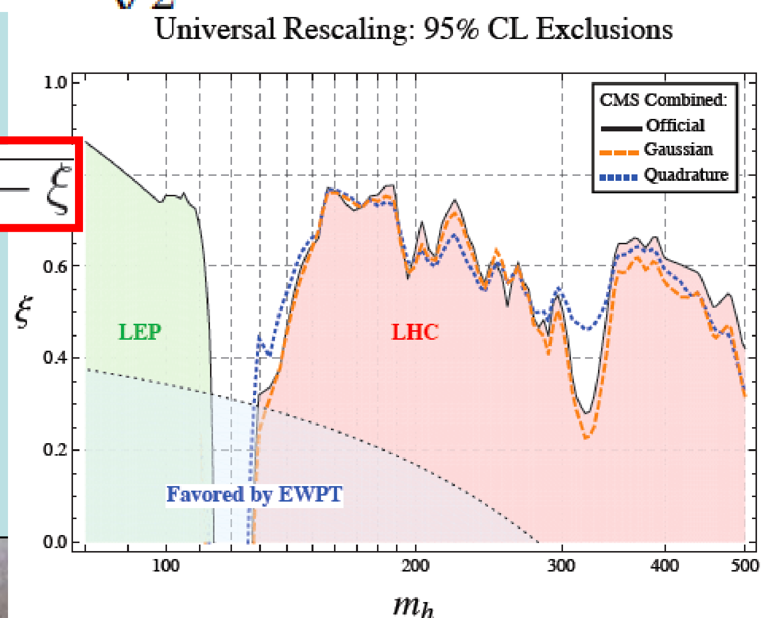
- Parametrization of effective Lagrangian:

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

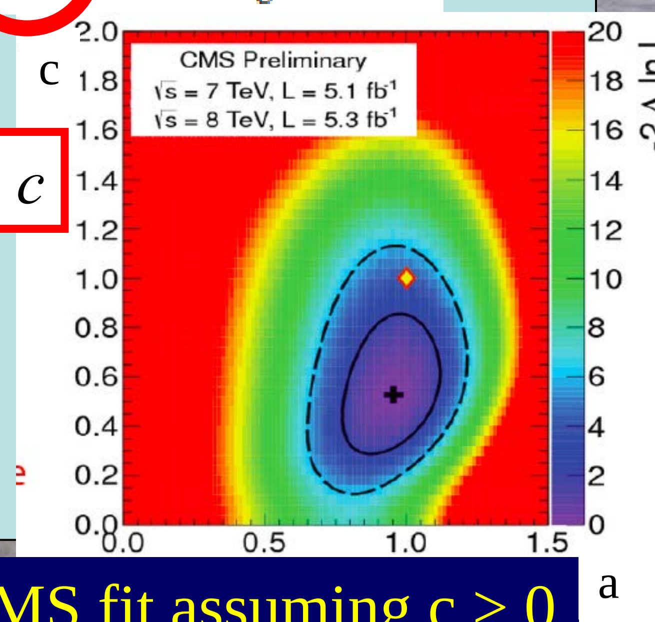
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}_L^{(i)}, \bar{d}_L^{(i)}\right)\Sigma\left(u_R^{(i)}, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right)$$

- Fits

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



$$\boxed{a \neq c}$$



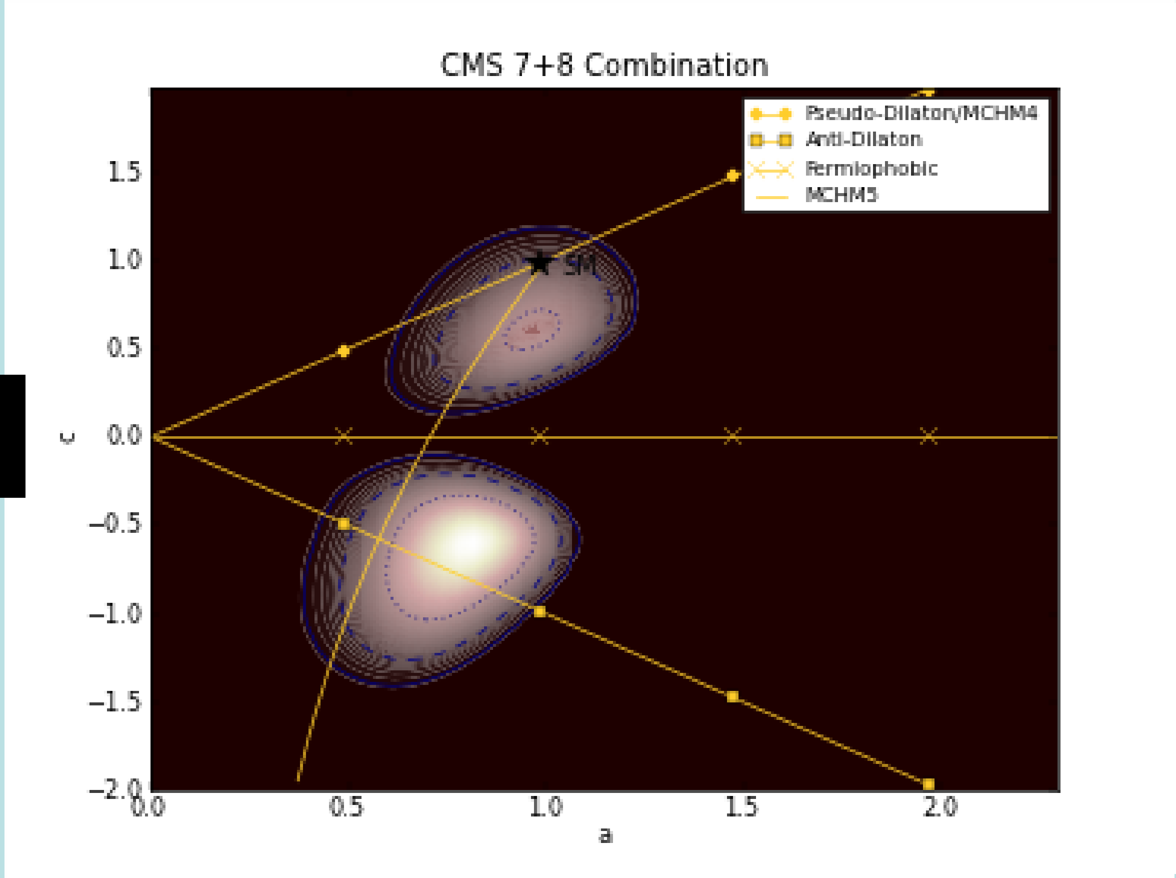
CMS fit assuming c > 0

Azatov, Contino, Galloway: arXiv:1202.3415

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

CMS



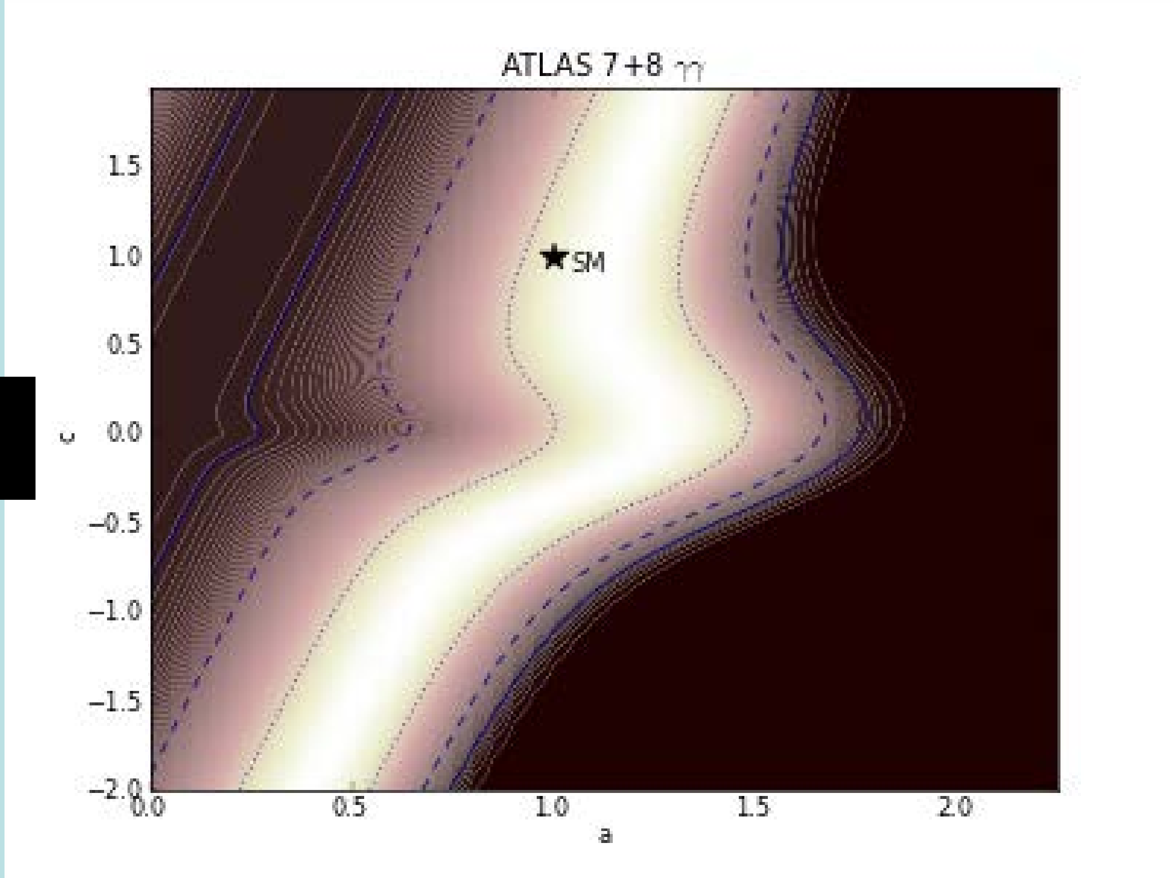
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

ATLAS



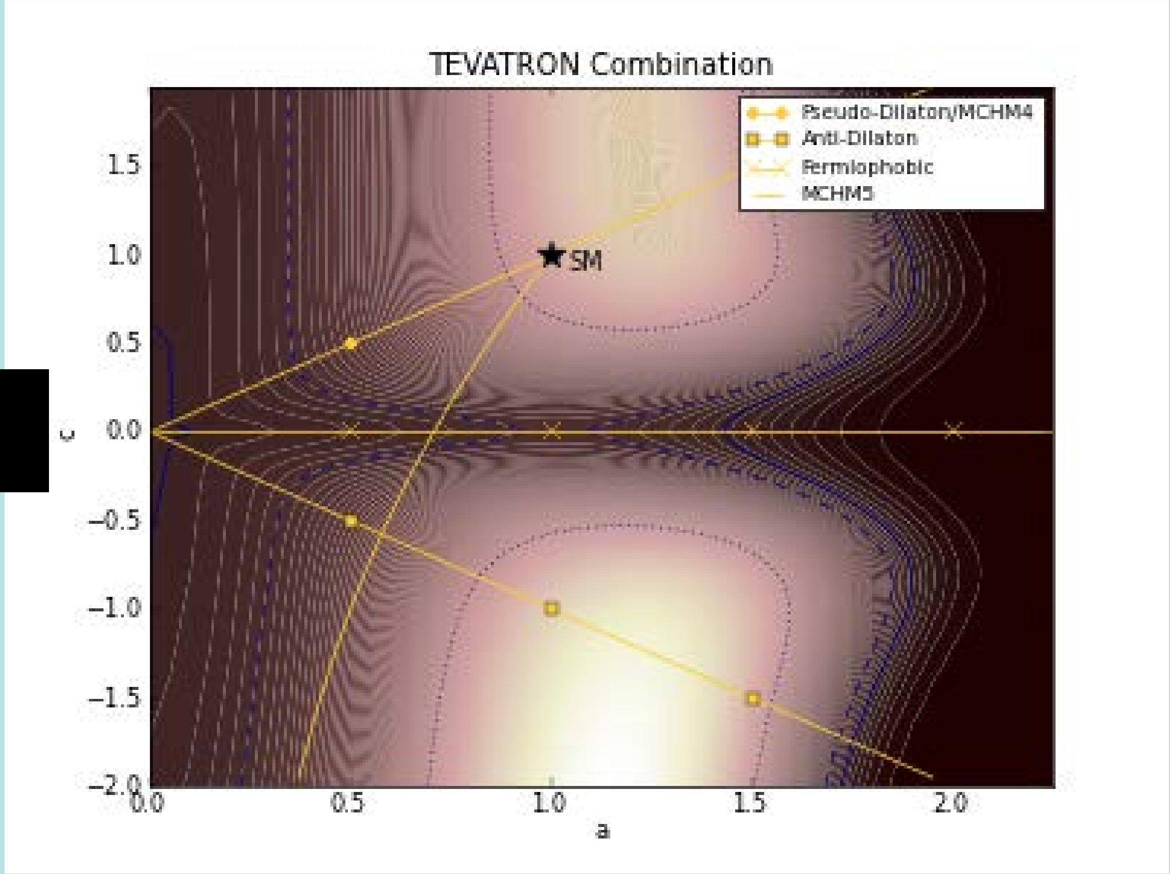
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

CDF/D0



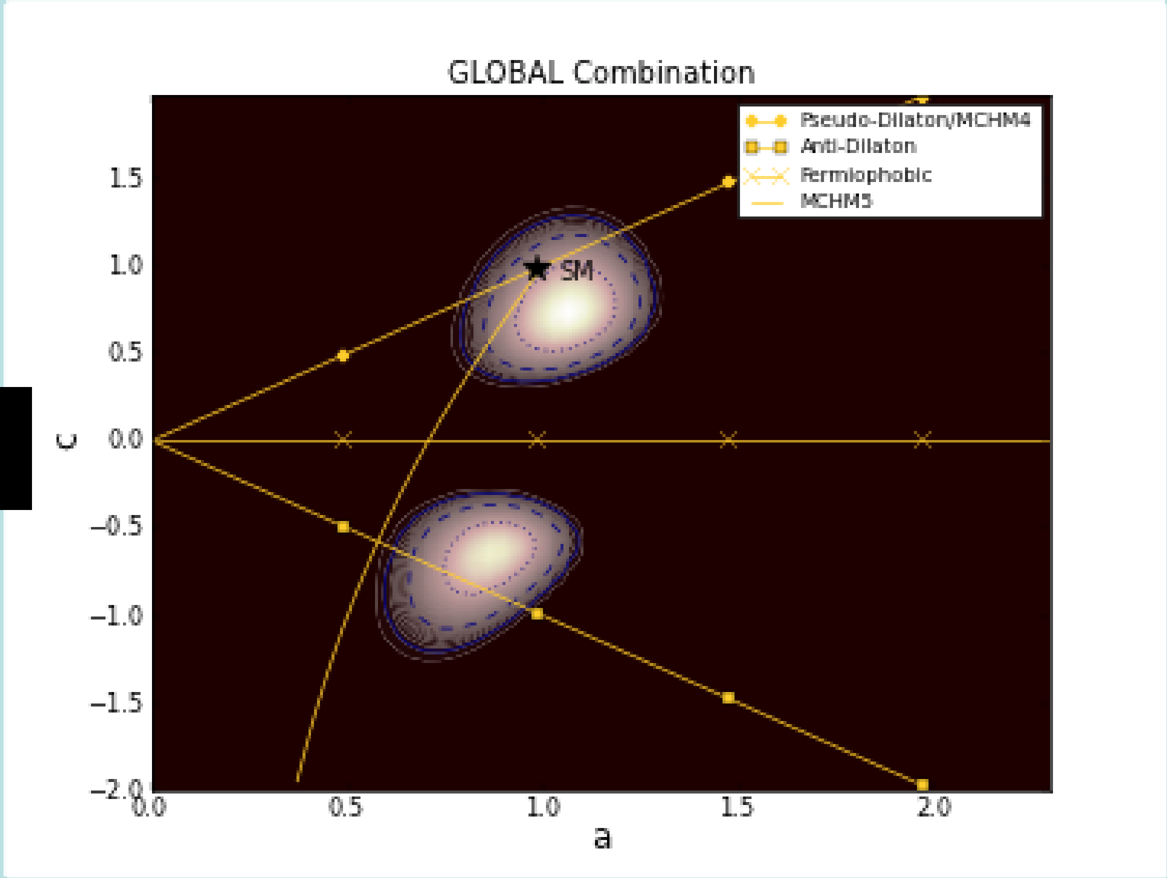
- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

Global

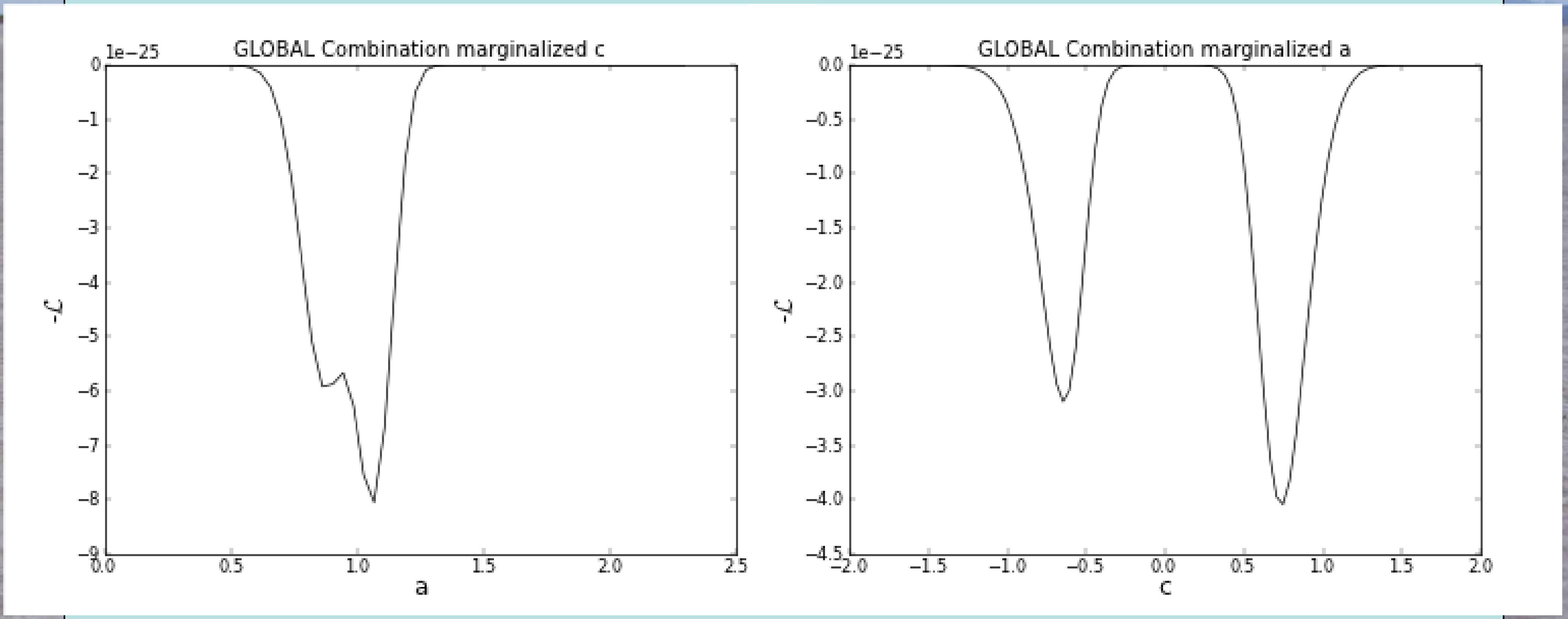


- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1207.1693

It Walks and Quacks like a Higgs

- Standard Model predicts $a = c = 1$

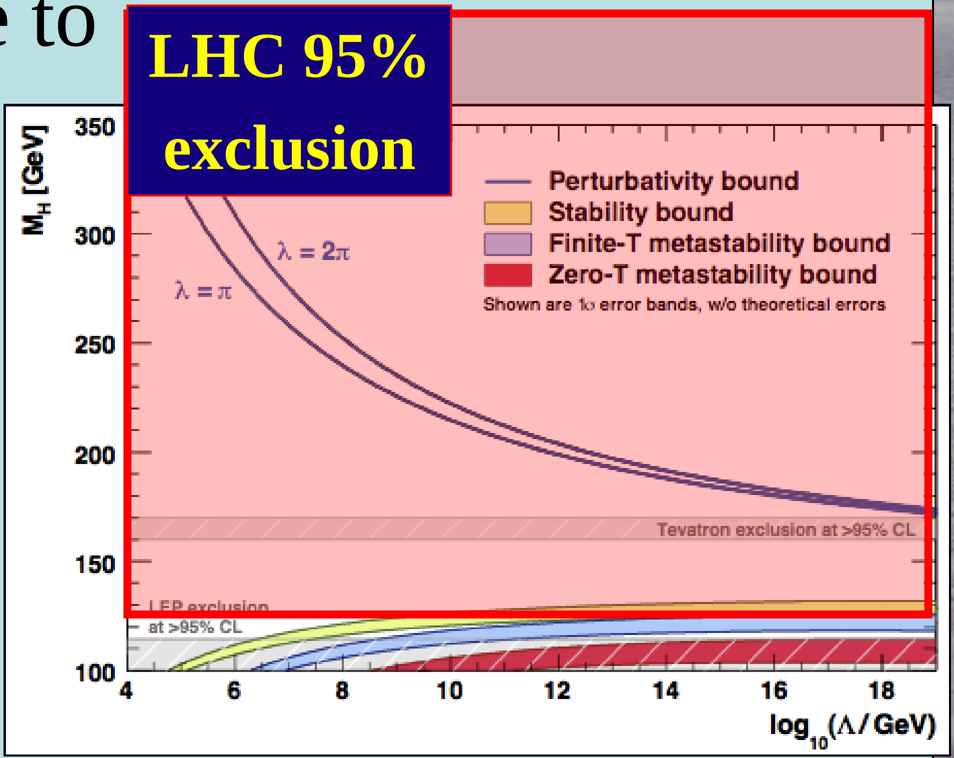


- Global fit: $a \sim 1$, $c \sim 1$

JE & Tevong You, arXiv:1207.1693

Theoretical Constraints on Higgs Mass

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



- Vacuum could be stabilized by **Supersymmetry**

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

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

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

- 2 Higgs doublets, coupling μ, ratio of v.e.v.'s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:

  Scalar masses m_0, gaugino masses $m_{1/2}$,
  trilinear soft couplings A_{λ}, bilinear soft coupling B_{μ}
- Often assume universality:

  Single m_0, single $m_{1/2}$, single A_{λ}, B_{μ}: not string?
- Called constrained* MSSM = CMSSM (* at what scale?)
- Minimal supergravity (mSUGRA) predicts gravitino mass: $m_{3/2} = m_0$ and relation: $B_{\mu} = A_{\lambda} - m_0$

Possible Nature of LSP

- No strong or electromagnetic interactions

  Otherwise would bind to matter

  Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates

  Sneutrino

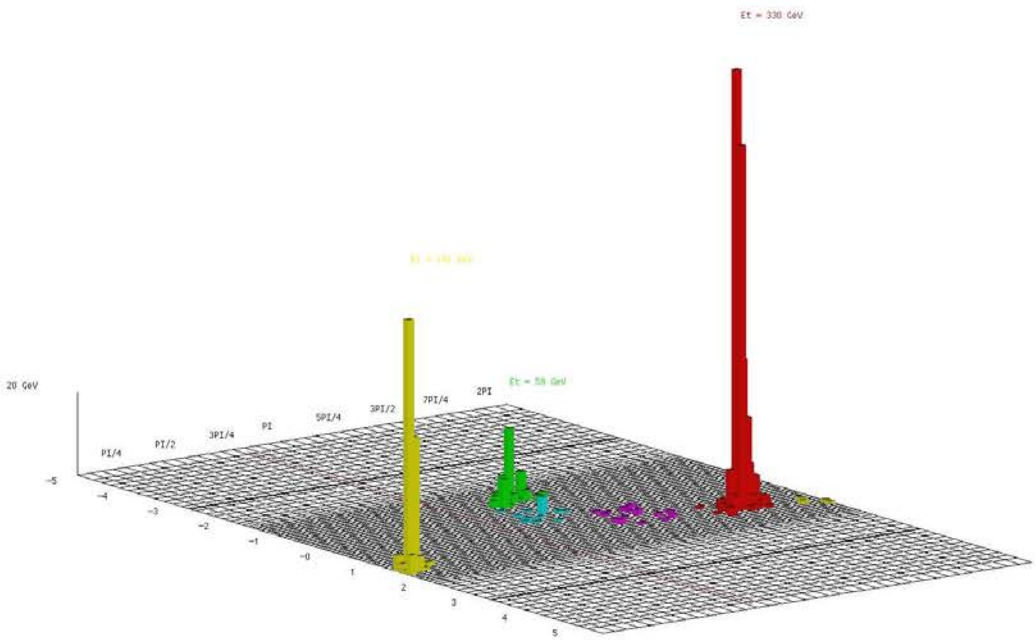
  (Excluded by LEP, direct searches)

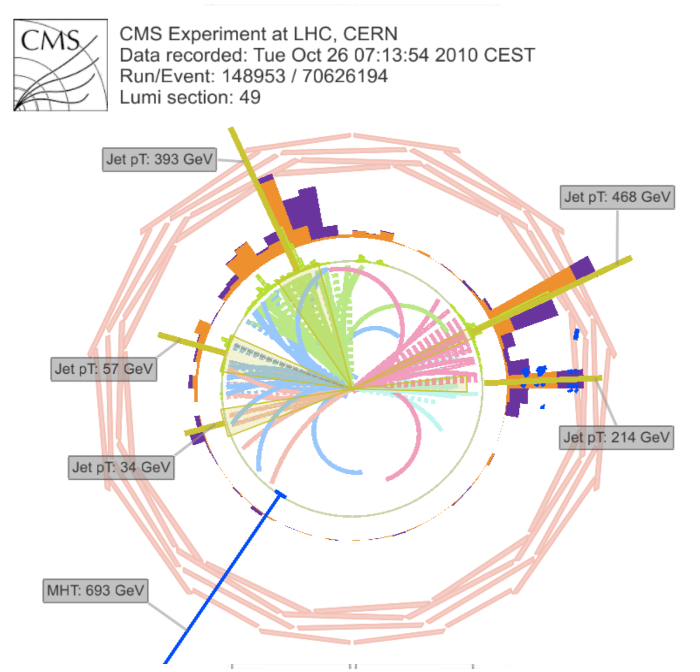
  Lightest neutralino χ (partner of Z, H, γ)

  Gravitino

  (nightmare for astrophysical detection)

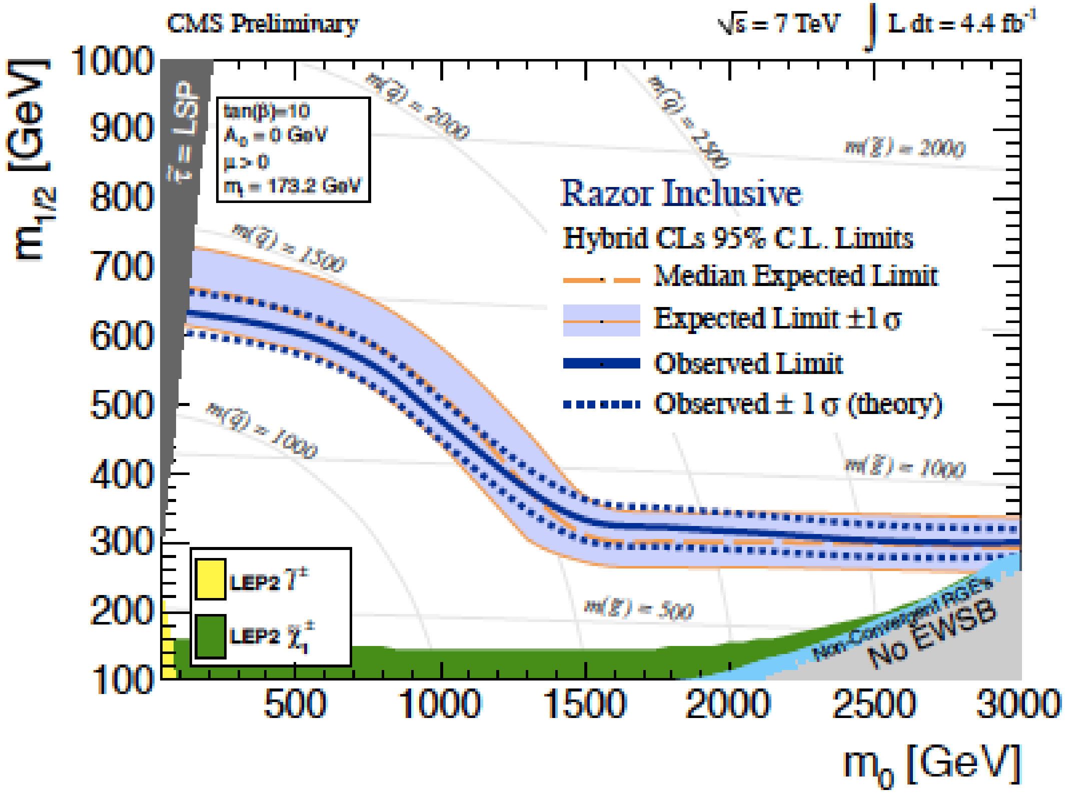
Supersymmetric Signature @ LHC

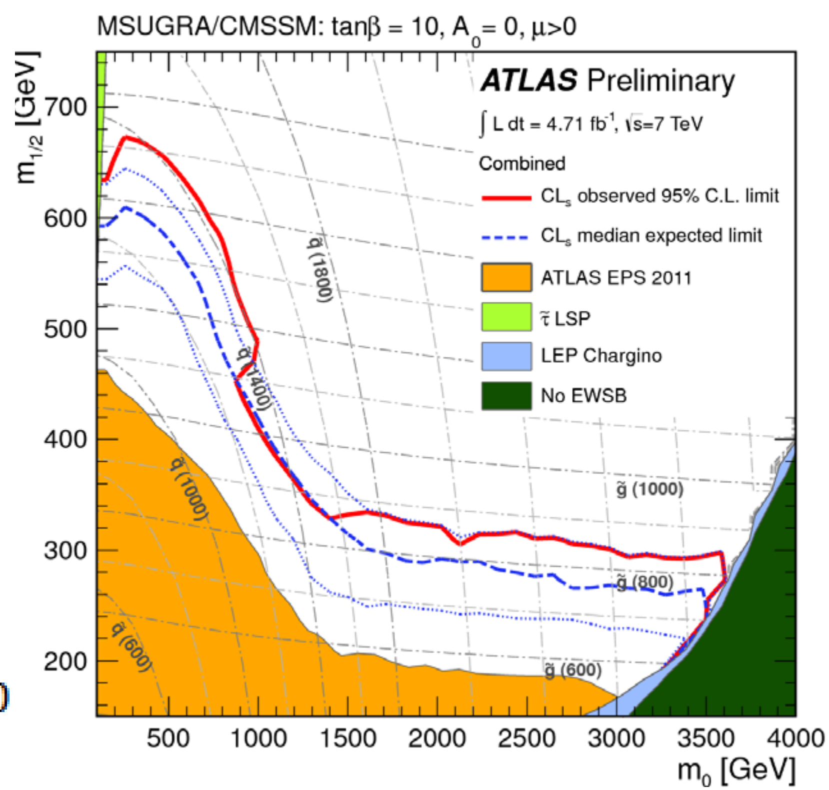




Missing transverse energy
carried away by dark matter particles

Searches with ~ 5/fb

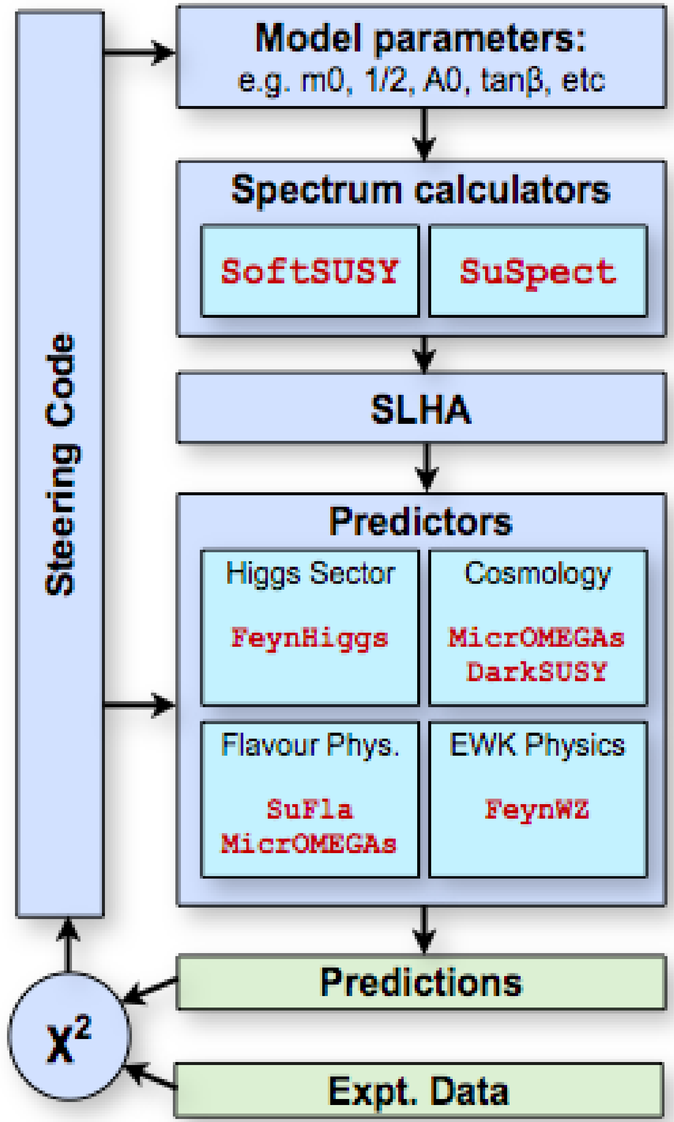




Jets + missing energy

MasterCode

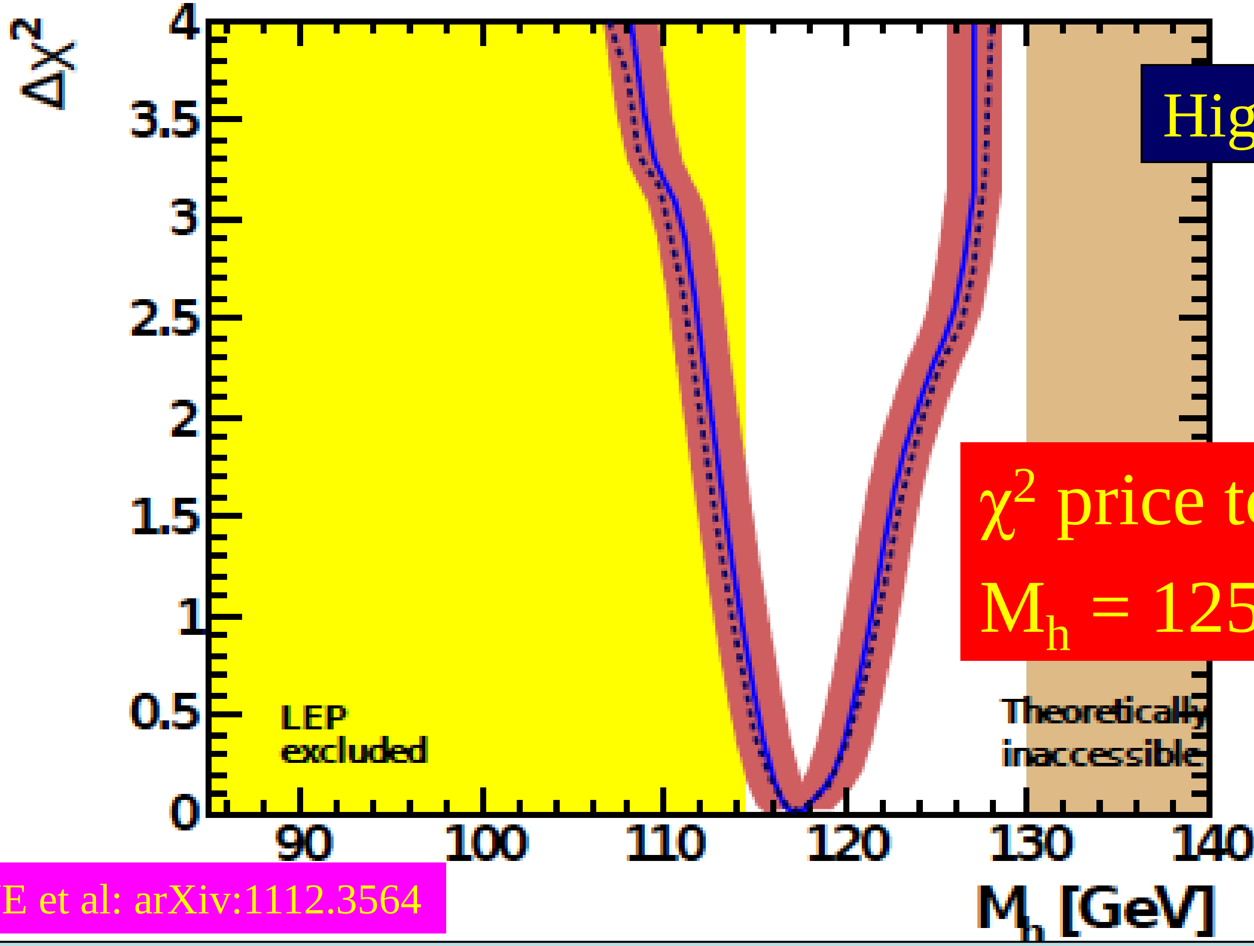
- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, 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



Higgs mass

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

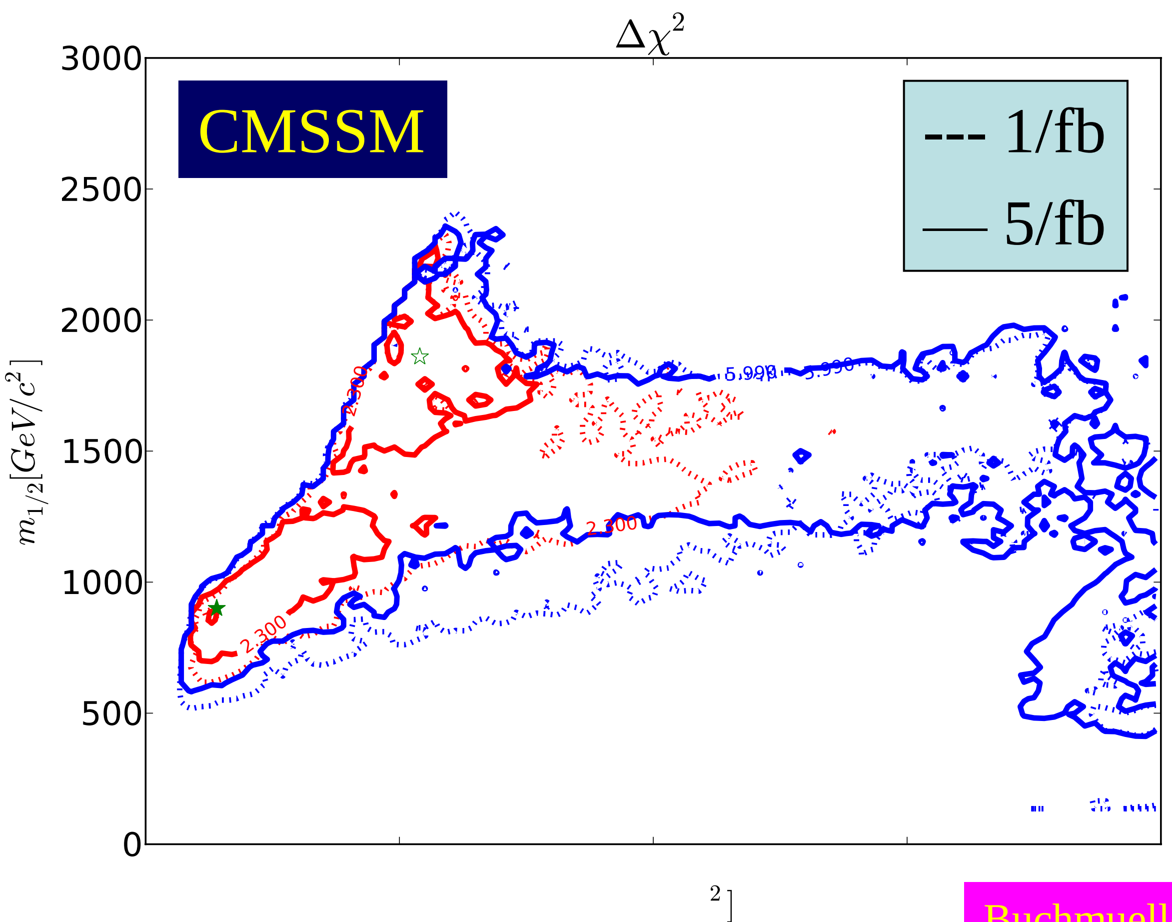
Buchmueller, JE et al: arXiv:1112.3564

Favoured values of M_h ~ 119 GeV:

Range consistent with evidence from LHC !

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 5 fb^{-1} of LHC Data



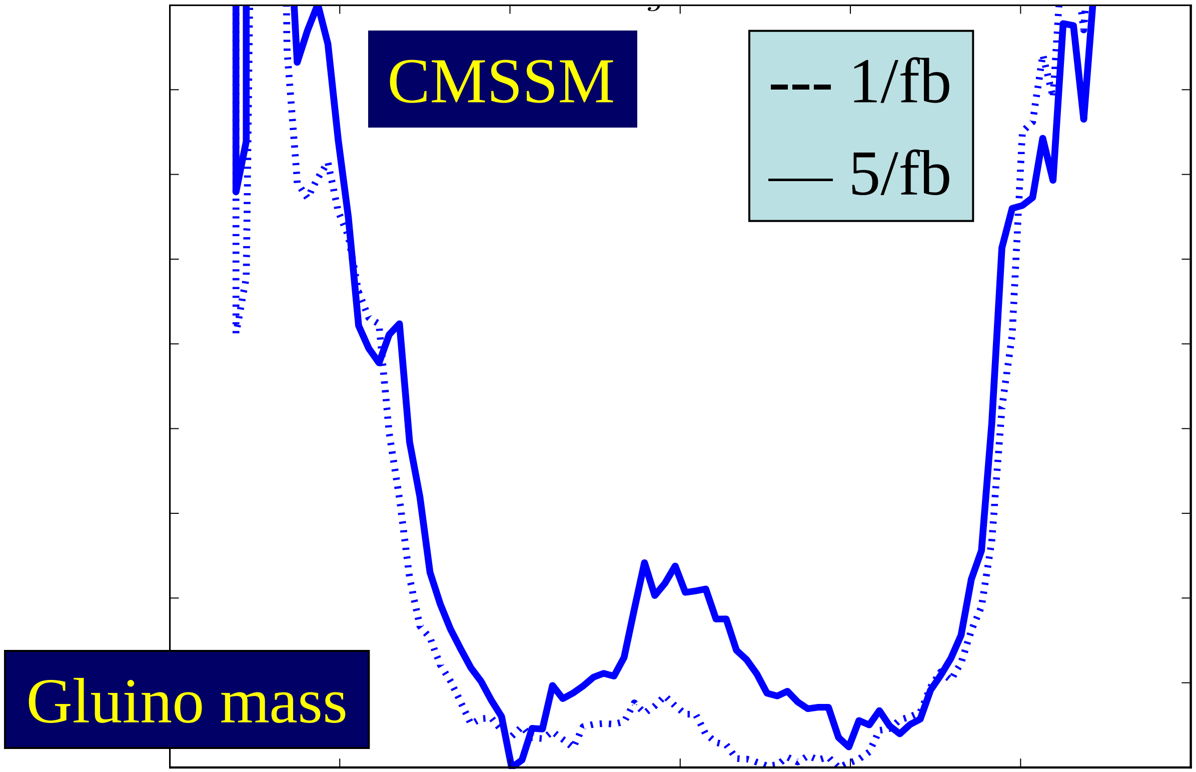
Buchmueller, JE et al: to appear

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

p-value of CMSSM ~ 10%

Post-LHC, Post-XENON100

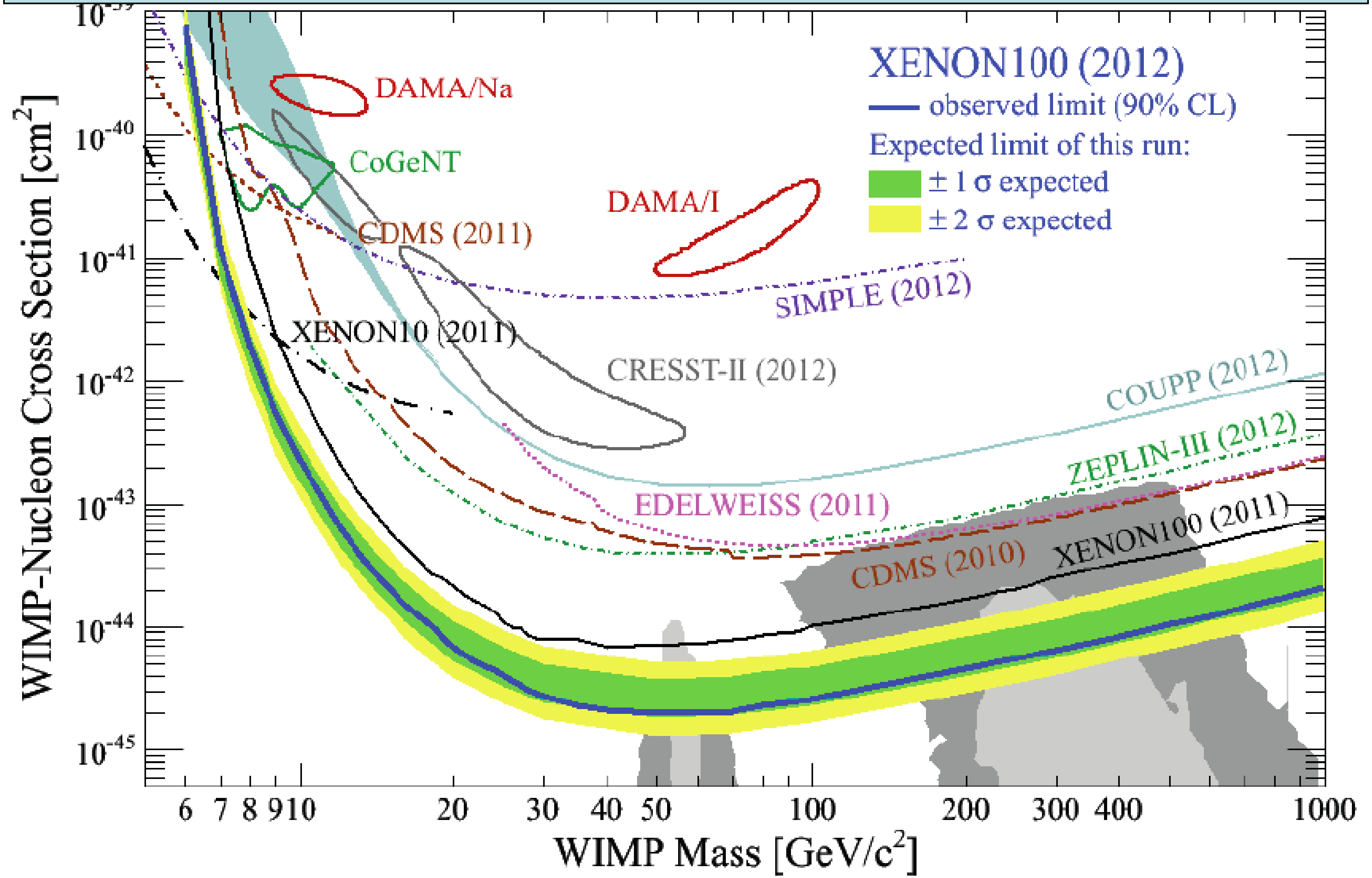
2011 ATLAS + CMS with 5 fb^{-1} of LHC Data



Buchmueller, JE et al: to appear

Favoured values of gluino mass significantly above pre-LHC, > 1.5 TeV

XENON100 & other Experiments



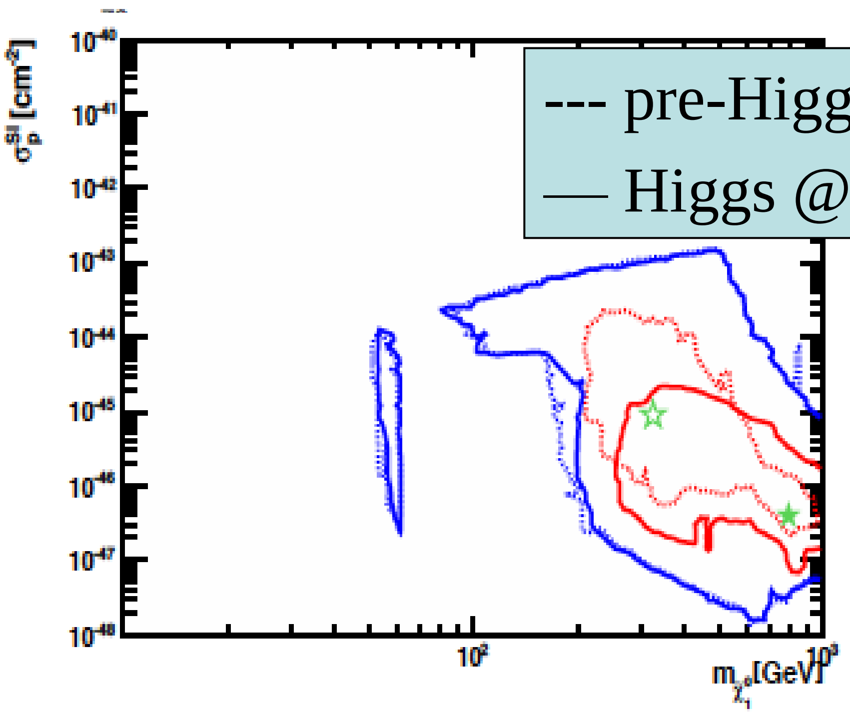
Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

Post-LHC, Post-XENON100

mastercode

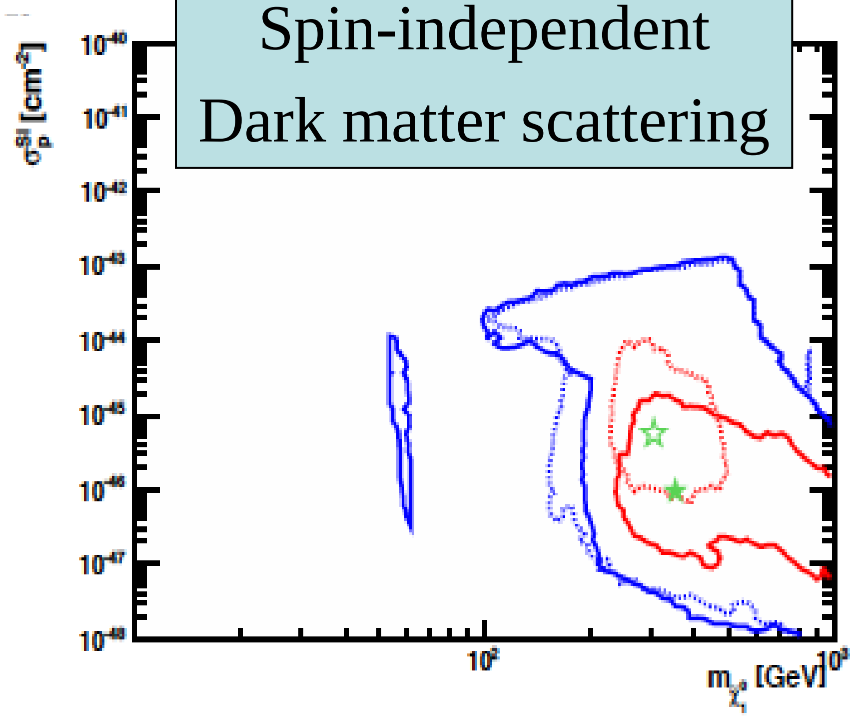
2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Spin-independent Dark matter scattering



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

Conversation with Mrs Thatcher: 1982