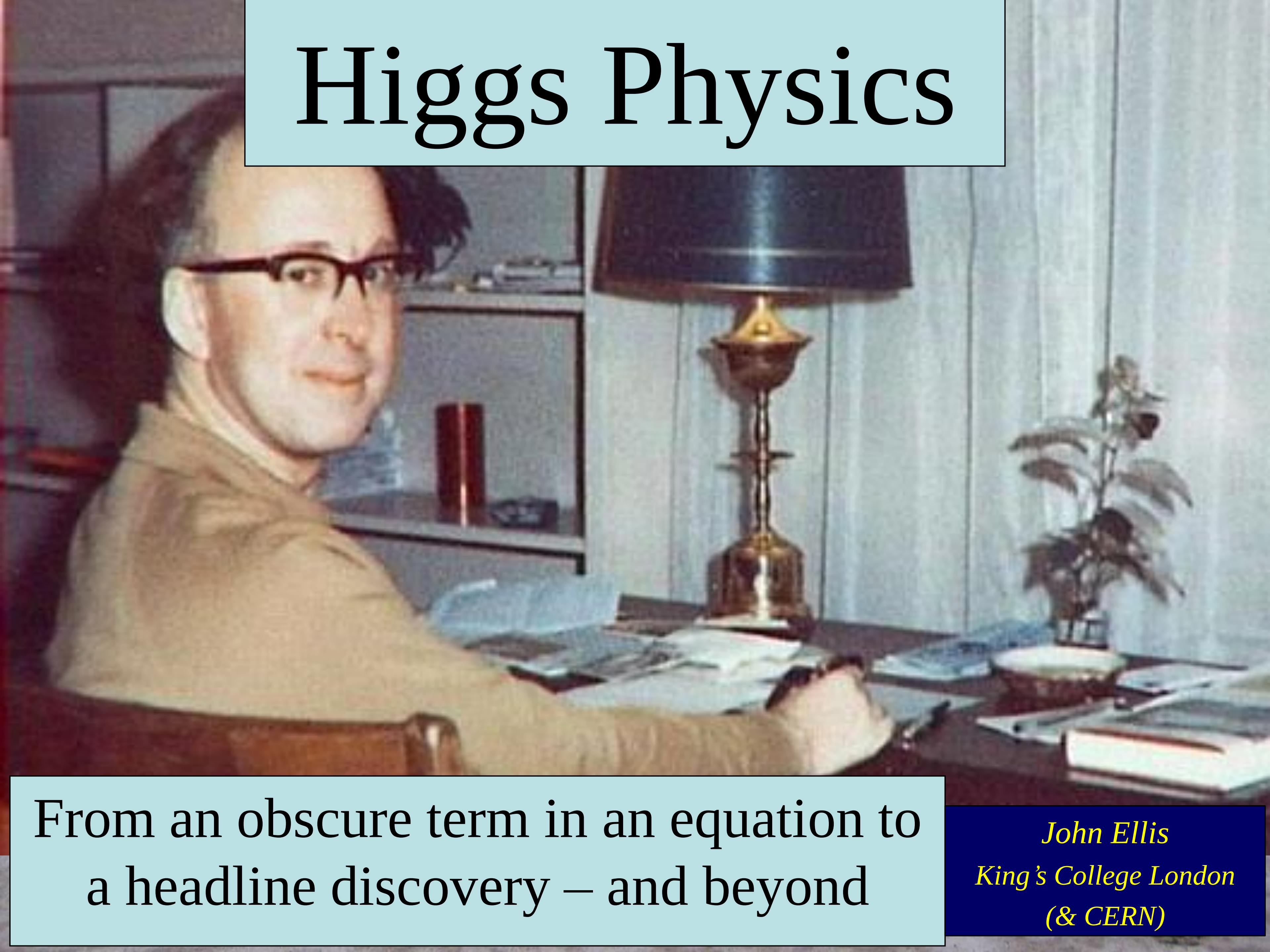
Higgs Physics



From an obscure term in an equation to a headline discovery – and beyond

John Ellis
King's College London
(& CERN)

Programme of Lectures

- Motivations and introduction
- What we know now
- The future?
  - Supersymmetric Higgses
  - Higgs factories

The Standard Model

= Cosmic DNA

The matter particles

Where does mass come from?

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Open Questions within & beyond the Standard Model

- What is the origin of particle masses?
  due to a Higgs boson?

- Why so many types of matter particles?

- What is the dark matter in the Universe?

- Unification of fundamental forces?
- Quantum theory of gravity?

To Higgs or not to Higgs?

- Need to 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?**
- This is the route proposed by Higgs
  - **Is there another way?**

Where to Break the Symmetry?

- Throughout all space?
  - Route proposed by Higgs *et al.*
  - Universal Higgs 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)

When in trouble, Theorists …

… postulate a new particle:

– QM and Special Relativity:	Antimatter
– Nuclear spectra:	Neutron
– Continuous spectrum in β decay:	Neutrino
– Nucleon-nucleon interactions:	Pion
– Absence of lepton number violation:	Second neutrino
– Flavour SU(3):	Ω^-
– Flavour SU(3):	Quarks
– FCNC:	Charm
– CP violation:	Third generation
– Strong dynamics:	Gluons
– Weak interactions:	$W^\pm$, Z^0
– **Renormalizability:**	**H**
– Dark matter:	WIMP/axion?

Completing the Holy Trinity

- Scale hierarchy possible only in theory that can be calculated over many magnitudes of energy

Renormalizable

- Theorem: (1) vectors (2) fermions (3) scalars
- Need to specify:

Cornwall, Levin & Tiktopoulos; Bell; Llewellyn-Smith

(1) group (2) representations (3) symmetry breaking

(1) = SU(3) × SU(2) × U(1) [so far]

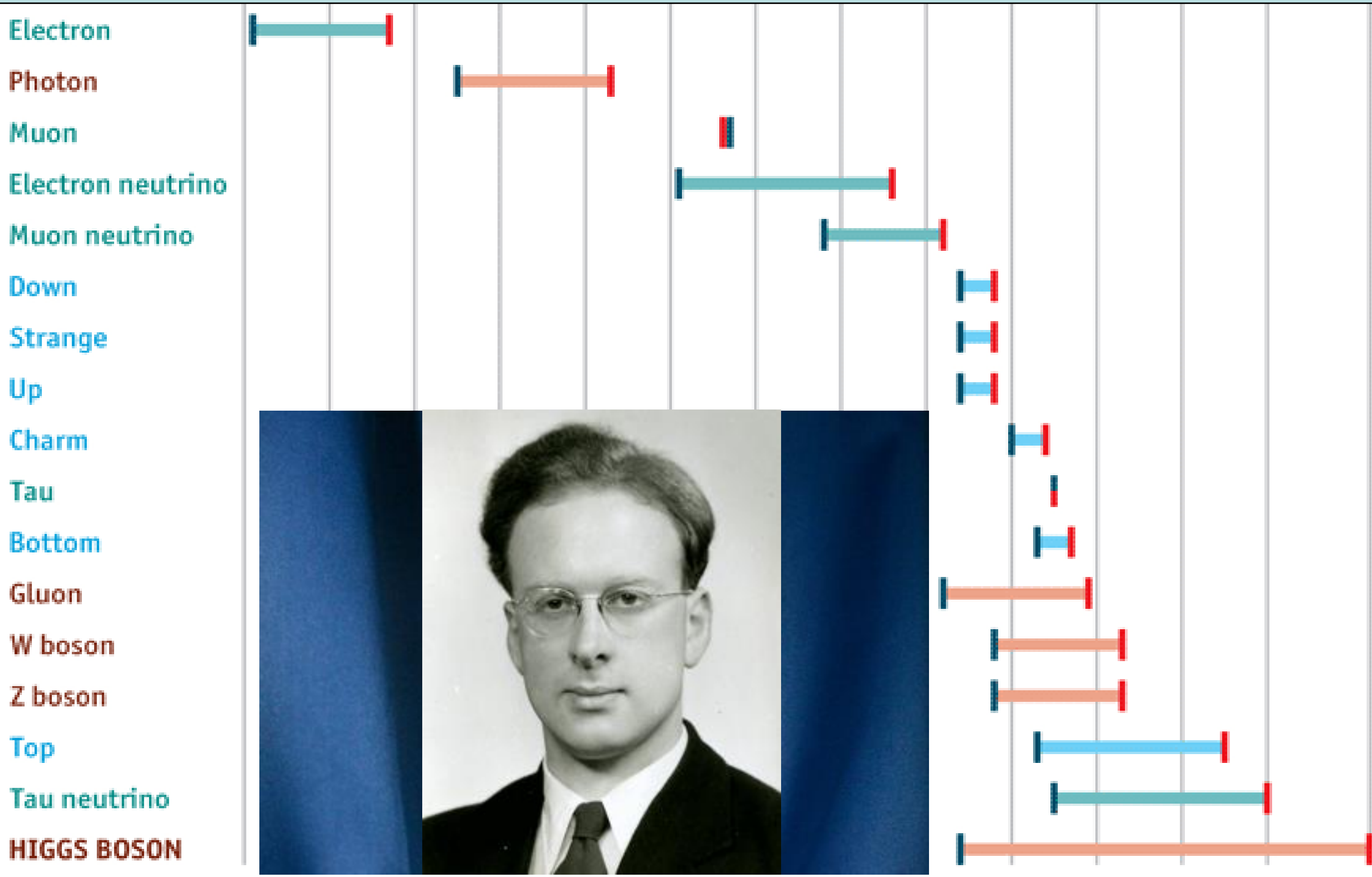
(2) = Singlets + doublets + triplets

- Finally:

(3) A scalar, mechanism of symmetry breaking

Standard Model Particles:

Years from Proposal to Discovery



Source: *The Economist*

Summary of the Standard Model

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

L_L E_R	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{2},-1)$ $(\mathbf{1},\mathbf{1},-2)$
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	$(\mathbf{3},\mathbf{2},+1/3)$ $(\mathbf{3},\mathbf{1},+4/3)$ $(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

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

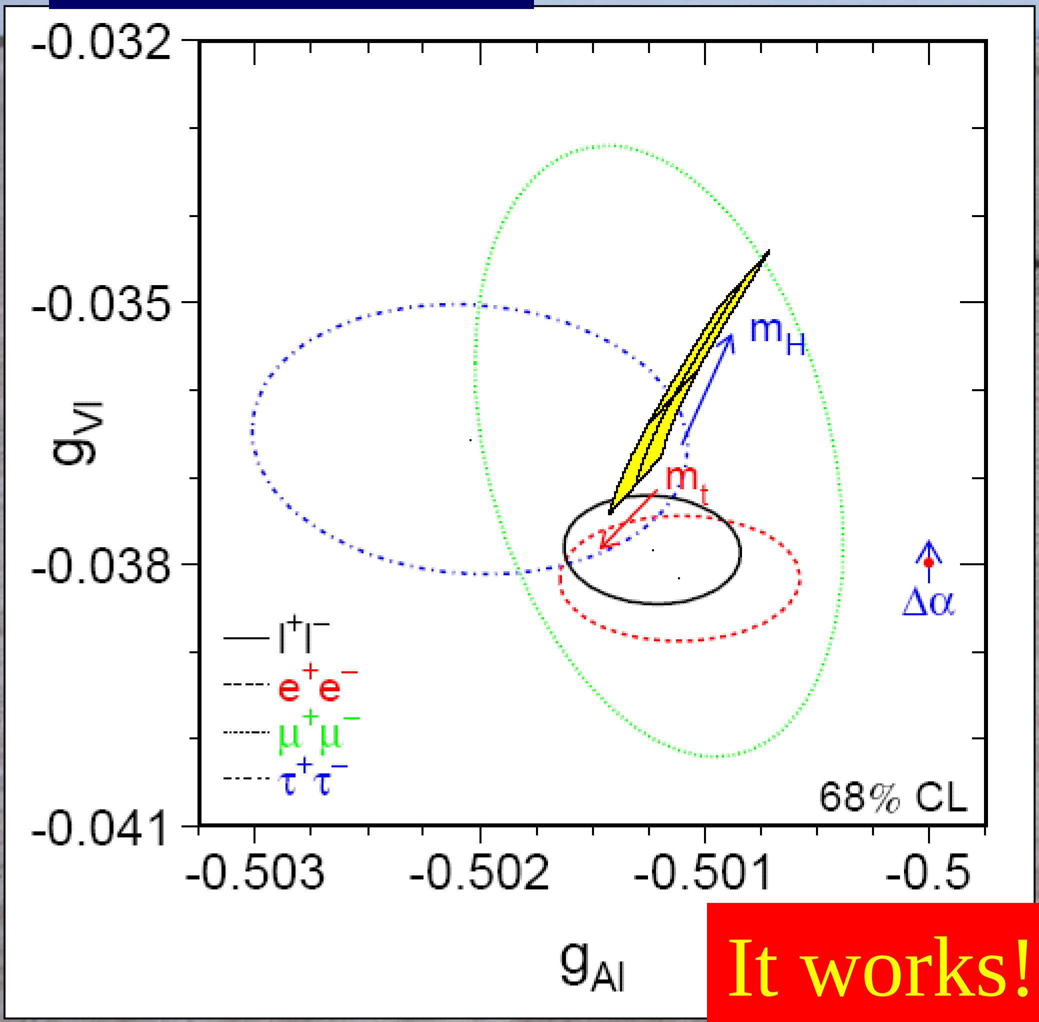
Status of the Standard Model

- 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 < ~ 180 GeV
- Raises many unanswered questions:

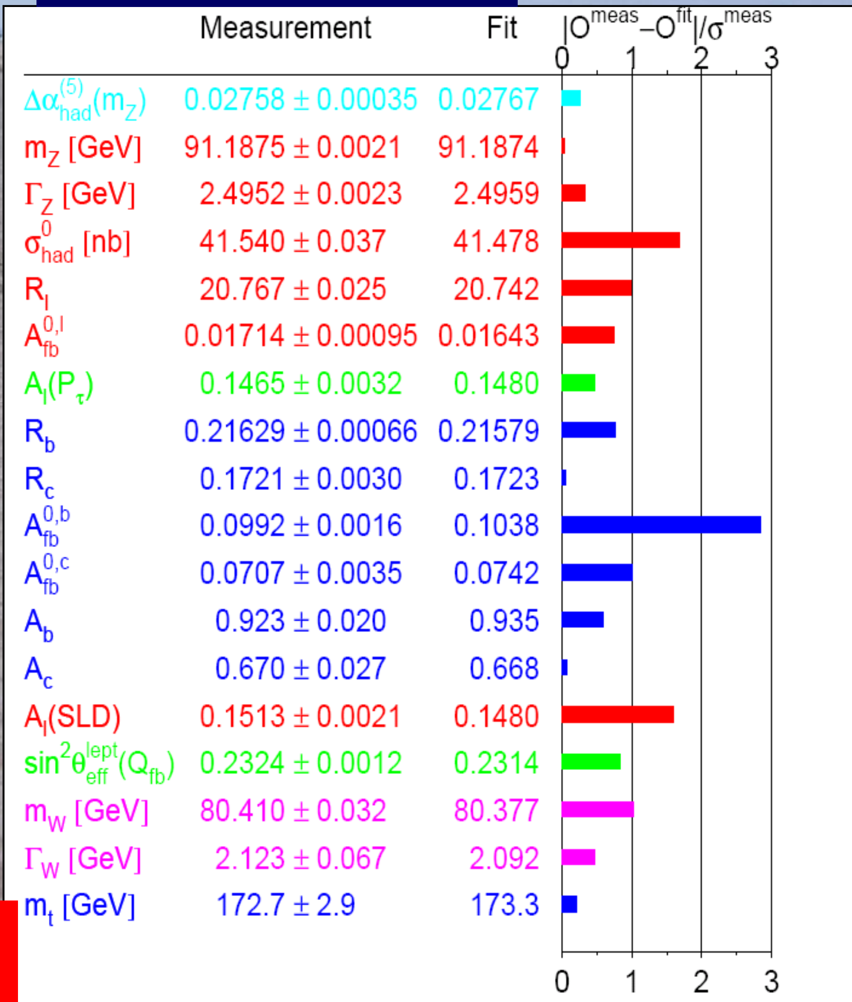
mass? flavour? unification?

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit



It works!

The Standard Model Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}$$

✓ Experiment: accuracy < %

$$\mathcal{L}_H = (D^L_\mu\phi)^\dagger(D^{L\mu}\phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d\bar{Q}_L\phi q^d_R + y_u\bar{Q}_L\phi^c q^u_R + y_L\bar{L}_L\phi l_R +$$

No direct evidence until July 4, 2012

$$D^L_\mu = \partial_\mu - igW^a_\mu T^a - iYg'B_\mu \quad , \quad D^R_\mu = \partial_\mu - iYg'B_\mu$$

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \quad .$$

The (G)AEB**H**GHKMP'tH Mechanism

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 LETTER

BROKEN SYMMETRIES AND THE MASSES OF GA

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

The only one
who mentioned a
massive scalar boson

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)

SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

The Englert-Brout-Higgs Mechanism

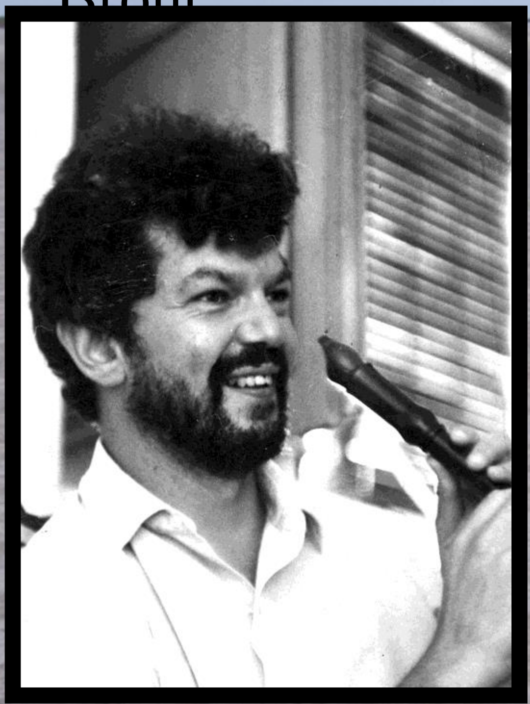
- **Vacuum expectation value of scalar field**
- Englert & Brout: June 26th 1964
- First Higgs paper: July 27th 1964
- Pointed out loophole in argument of Gilbert if gauge theory described in Coulomb gauge
- Accepted by Physics Letters
- Second Higgs paper with explicit example sent on July 31st 1964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

But the Higgs Boson

Englert & Brout

Higgs

Guralnik, Hagen & Kibble



$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

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

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be

Also Goldstone in global case

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

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

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

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

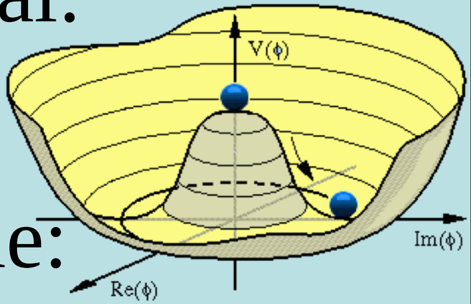
where the superscript T denotes the transverse part. The two degrees of freedom of A_k^T combine with φ_1 to form the three components of a

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) $\rightarrow -(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

The Higgs Mechanism

- Postulated effective Higgs potential:

$$V[\phi] = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$
- Couple to fermions: on-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$
- After gauging: $M_W = \frac{g\,v}{2}$

Abelian Higgs Mechanism

- Lagrangian

$$\mathcal{L} = \left(D_\mu\phi\right)^+\left(D^\mu\phi\right) - V(|\phi|) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad D_\mu = \partial_\mu - ieA_\mu$$

- Gauge transformation

$$\phi'(x) = e^{i\alpha(x)}\,\phi(x) = e^{i\alpha(x)}\,e^{i\theta(x)}\eta(x)$$

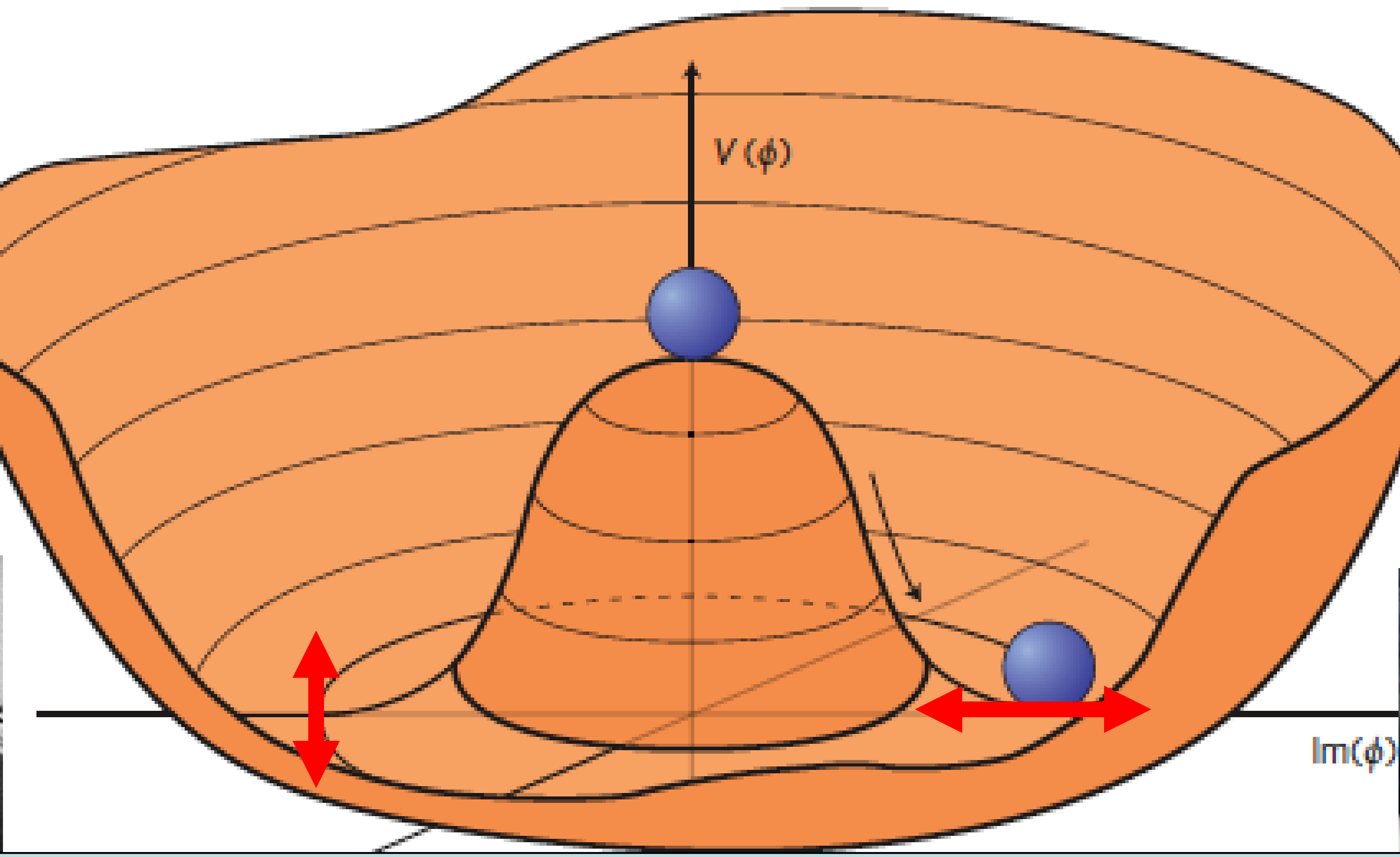
$$A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)$$

- Choose $\alpha(x) = -\theta(x)$: $\quad \phi'(x) = \eta(x)$
- Rewrite Lagrangian: $\mathcal{L} = |(\partial - ieA'_\mu)\eta|^2 - V(\eta) - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}$

$$\mathcal{L} = |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}}H)|^2 - \tfrac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - V$$

$$= \underbrace{-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + v^2e^2\,A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2}[(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots$$

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



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

Accompanied by massive particle

Masses for SM Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + i g \epsilon_{ijk} W^j_\mu W^k_\nu$ $\quad F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

- Expanding around vacuum: $\phi =< 0|\phi|0 > + \hat{\phi}$

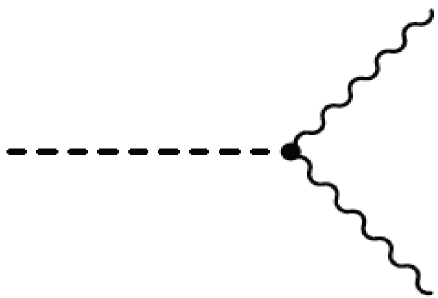
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\, W^+_\mu\, W^{\mu-} - g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu 3}$$

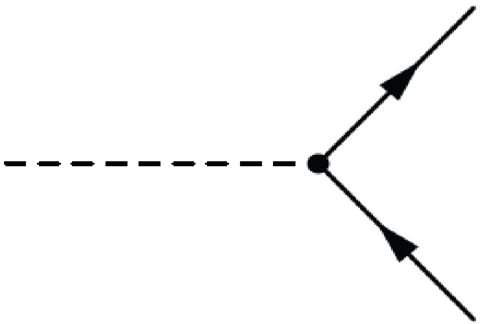
- Boson masses: 

$$m_{W^\pm} = \frac{gv}{2}$$

$$Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v\, ; \quad A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_A = 0$$

Higgs Boson Couplings





$$g_2 M_W \ , \quad g_2 \frac{M_Z}{c_W}$$

$$\frac{m_f}{v} \ = \ \frac{g_2\, m_f}{2M_W}$$

$$\Gamma(H \to f\bar{f}) \ = \ N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

$$\Gamma(H \to VV) \ = \ \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r) \left(\frac{1}{2}\right)_Z , \quad r = \frac{M_V}{M_H}$$

Why a Higgs Boson is Needed

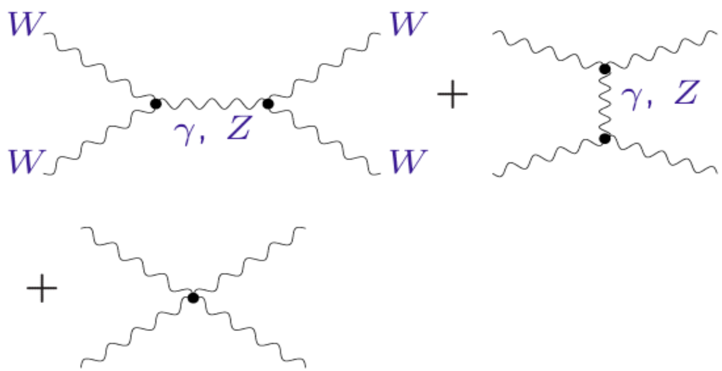
- Trouble with WW scattering: M ~ E^2

  ➔ uncontrollable infinities in loop diagrams

$W_L W_L \to W_L W_L$

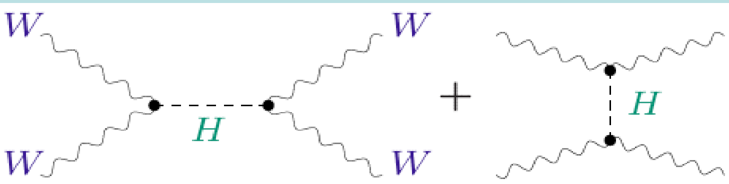
can be cancelled by scalar exchange

$\mathcal{M}_V =$



$$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$\mathcal{M}_S =$



$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$$\mathcal{M} = \mathcal{M}_V + \mathcal{M}_S$$

with HWW couplings

$$\mathcal{M} \approx \frac{M_H^2}{v^2}\left(2 + \frac{M_H^2}{s - M_H^2} + \frac{M_H^2}{t - M_H^2}\right)$$

- Similar for fermions

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

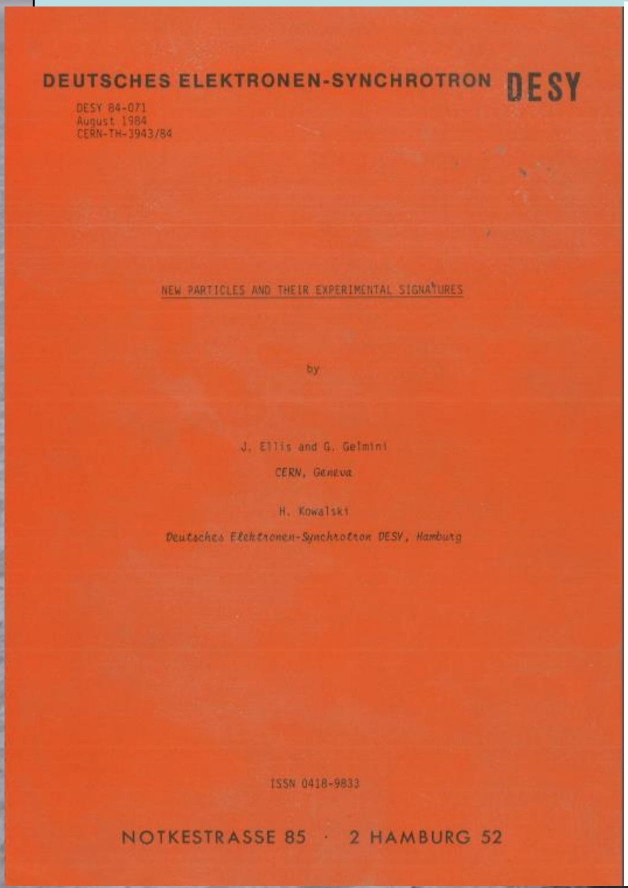
Received 7 November 1975

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.

A Preview of the Higgs Boson @ LHC

- Prepared for LHC Lausanne workshop 1984


DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 84-071
August 1984
CERN-TH-3943/84

NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES

by

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CERN, Geneva

H. Kowalski
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

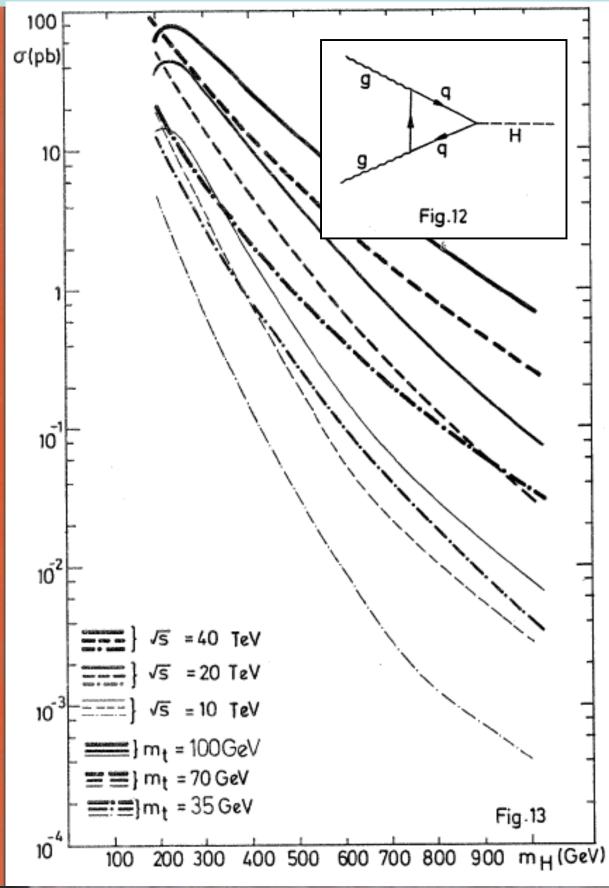


Fig.13

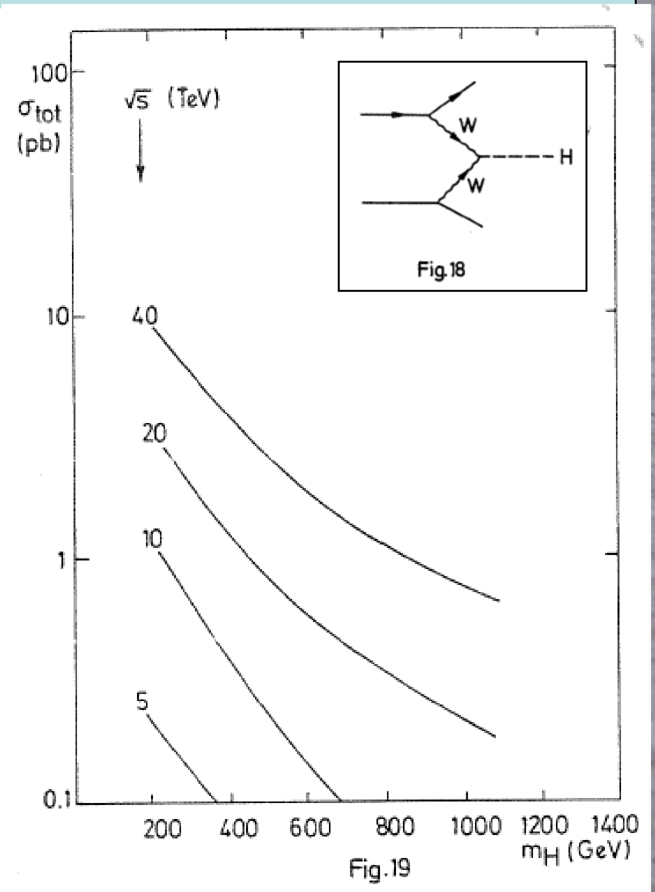


Fig.19

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

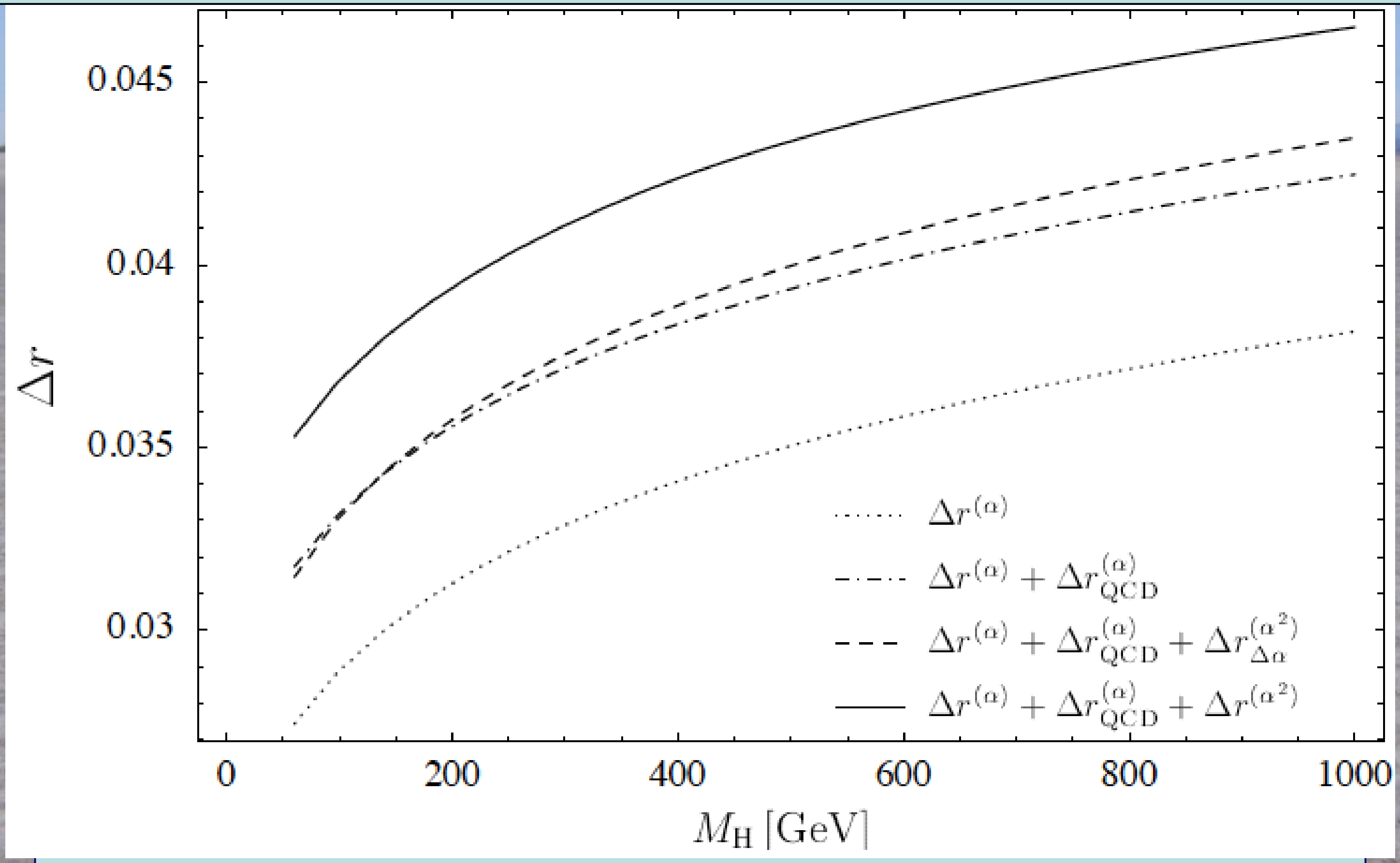
$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- Preferred Higgs mass: **$m_H \sim 100 \pm 30$ GeV**
- Compare with lower limit from direct search at LEP:

$m_H > 114$ GeV

and exclusion around **(160, 170 GeV)** at TeVatron

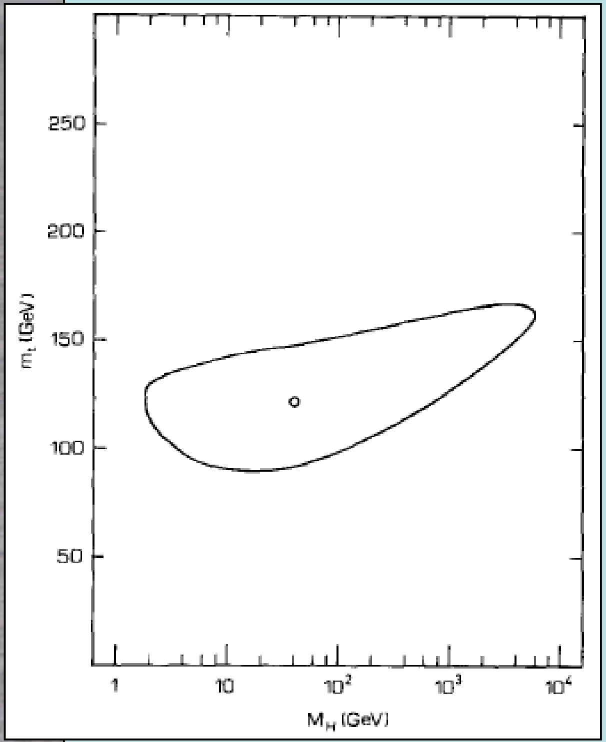
Sensitivity to Higgs Mass

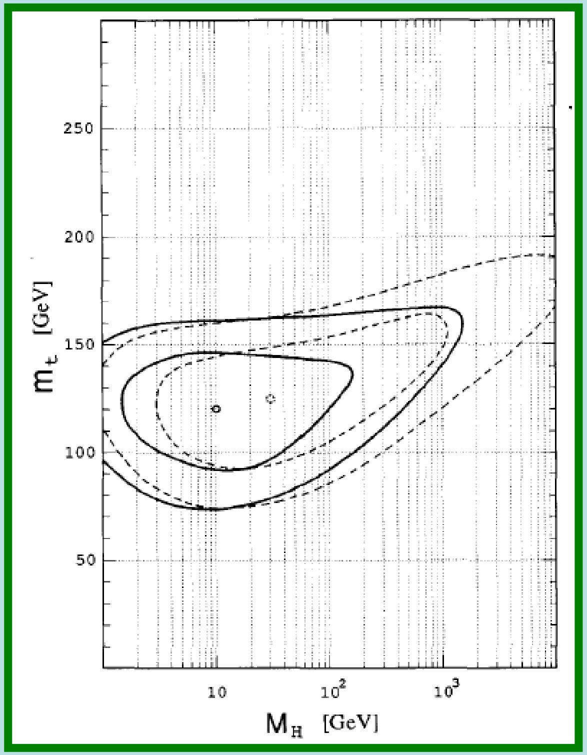


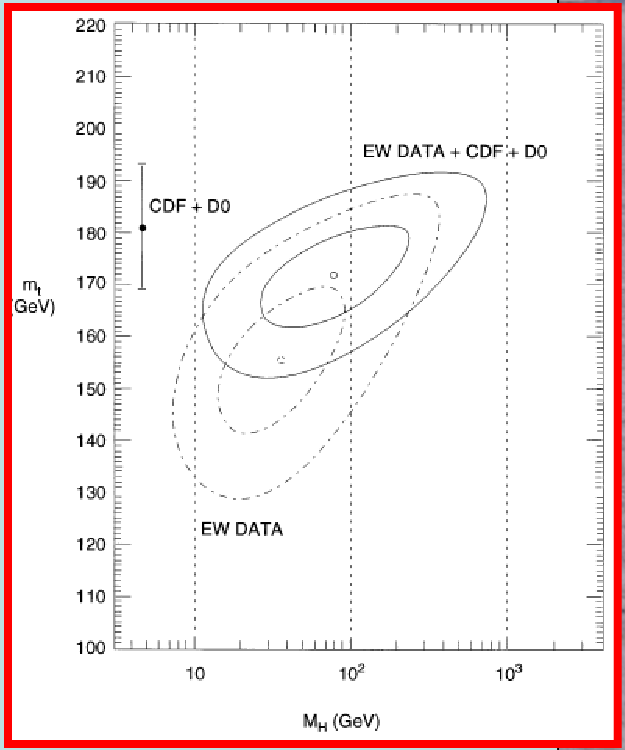
- Experimental uncertainty ΔM_W ~ 15 MeV
- Theoretical uncertainty ~ 4 MeV

Estimating the Mass of the Higgs Boson

- First attempts in 1990, **1991**







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

JE, Fogli & Lisi

The State of the Higgs: July 2011

- 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:

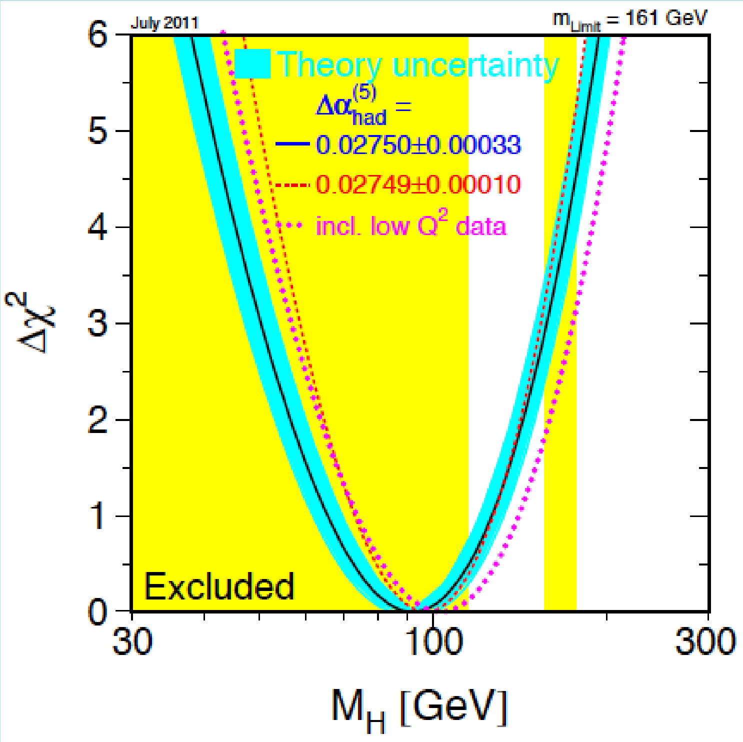
  $m_H = 94^{+29}_{-24}$ GeV

- 95% confidence-level upper limit:

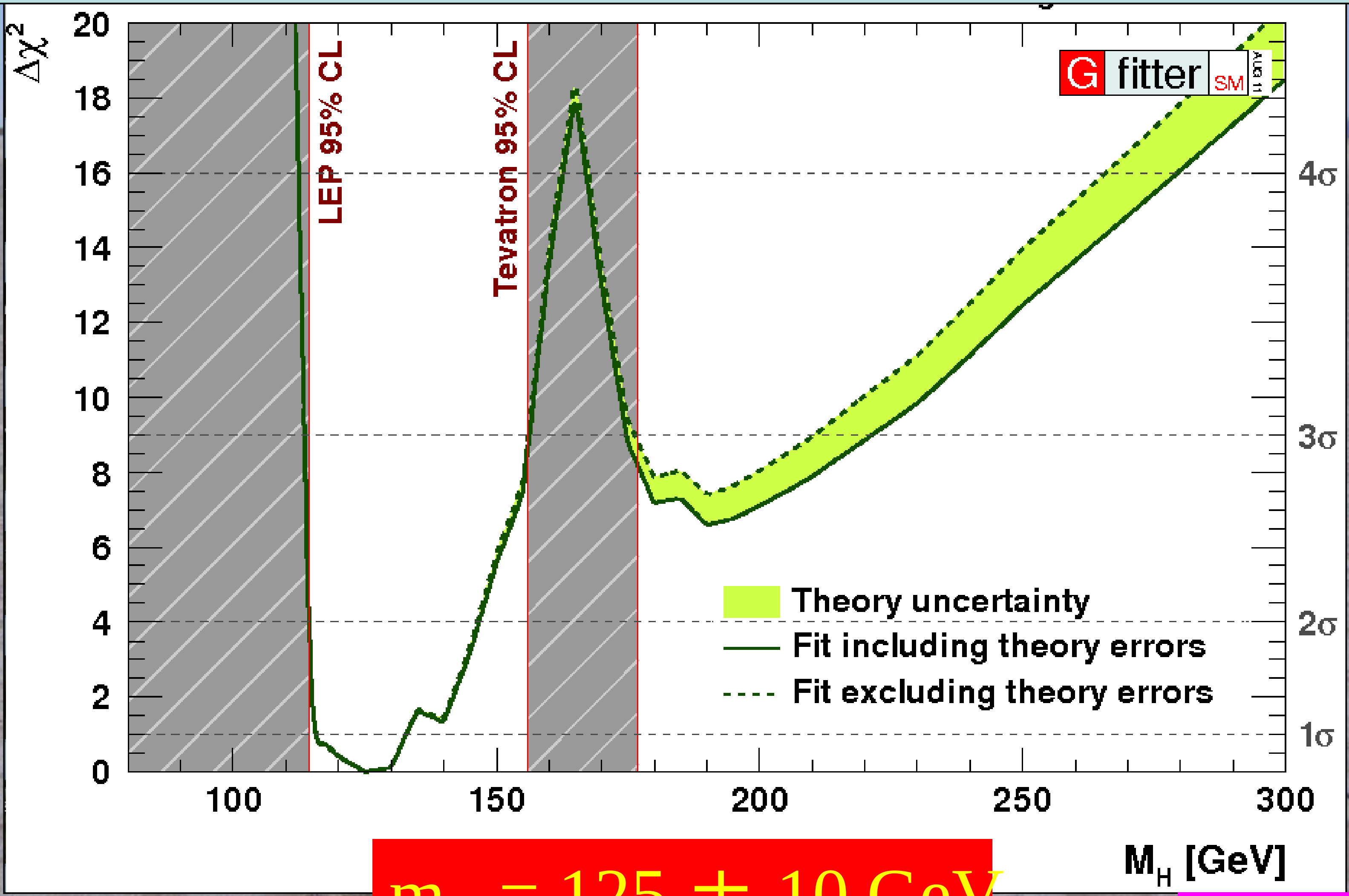
  $m_H < 161$ GeV

- Tevatron exclusion:

  $m_H < 156$ GeV or > 177 GeV



2011: Combining Information from Previous Direct Searches and Indirect Data

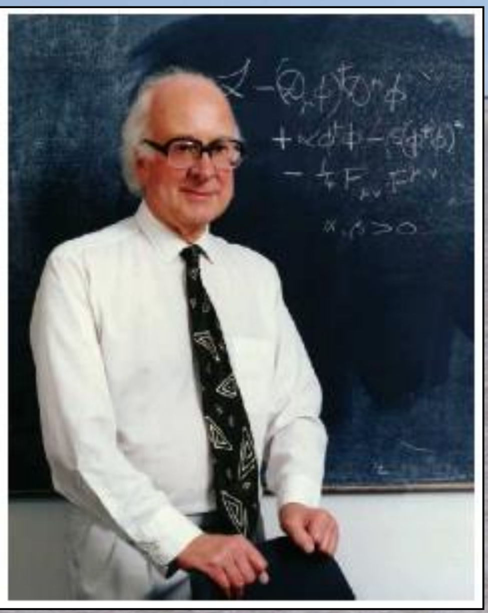


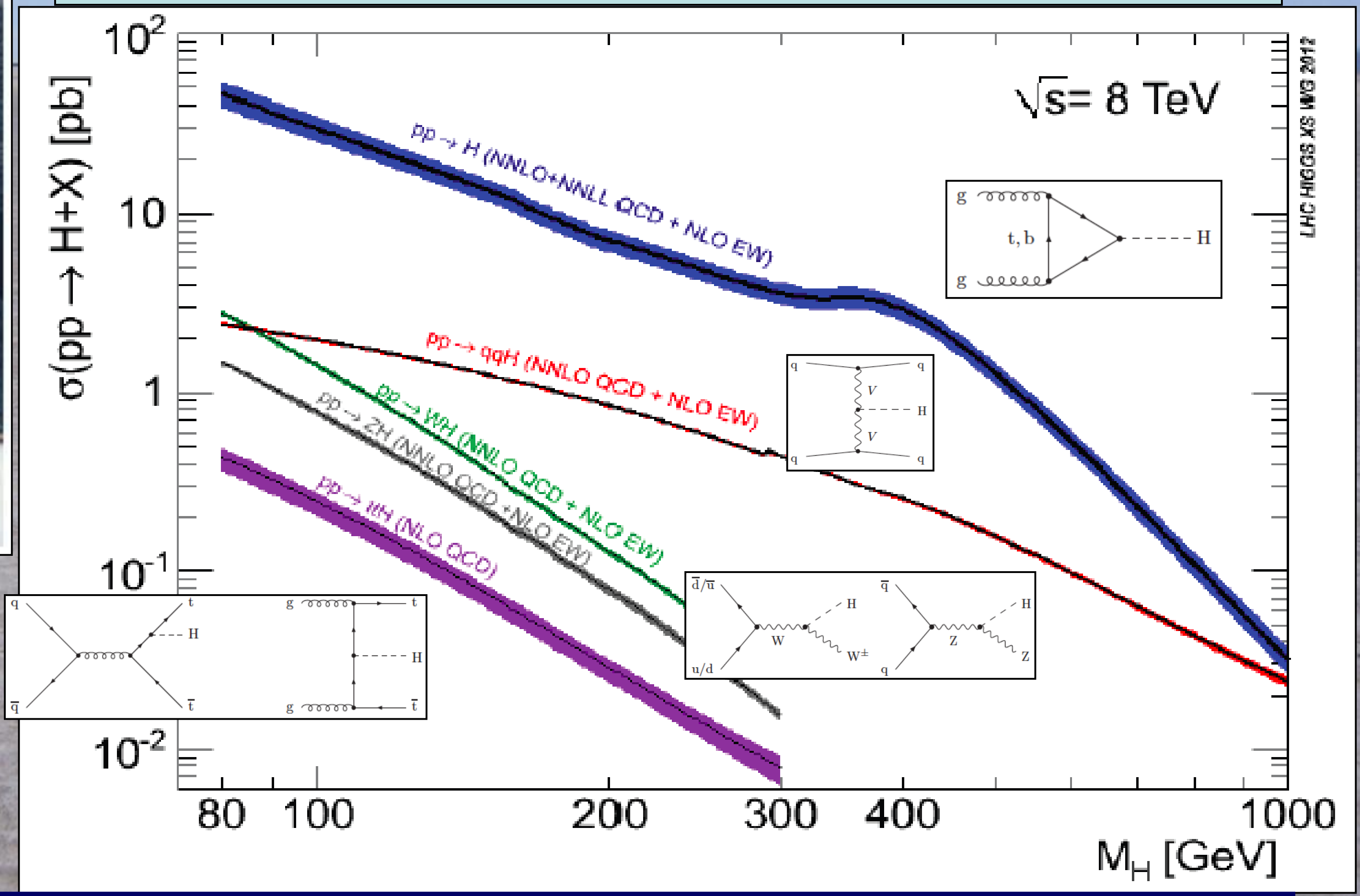
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du Higgs perdu …

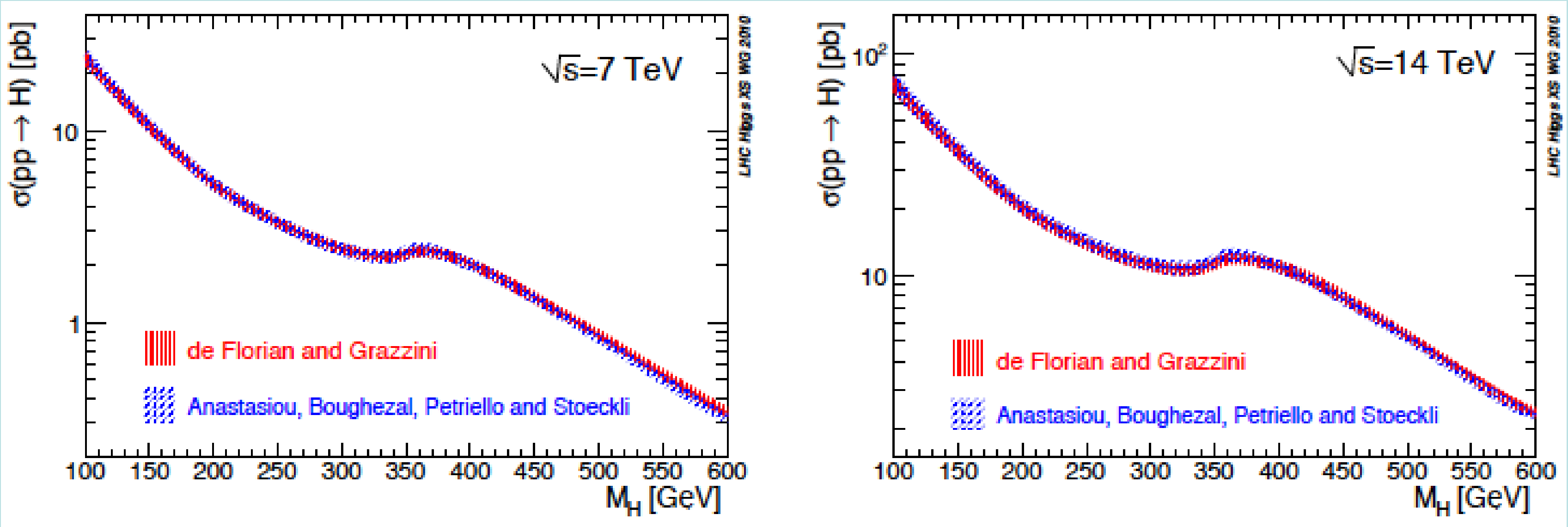
Higgs Production at the LHC





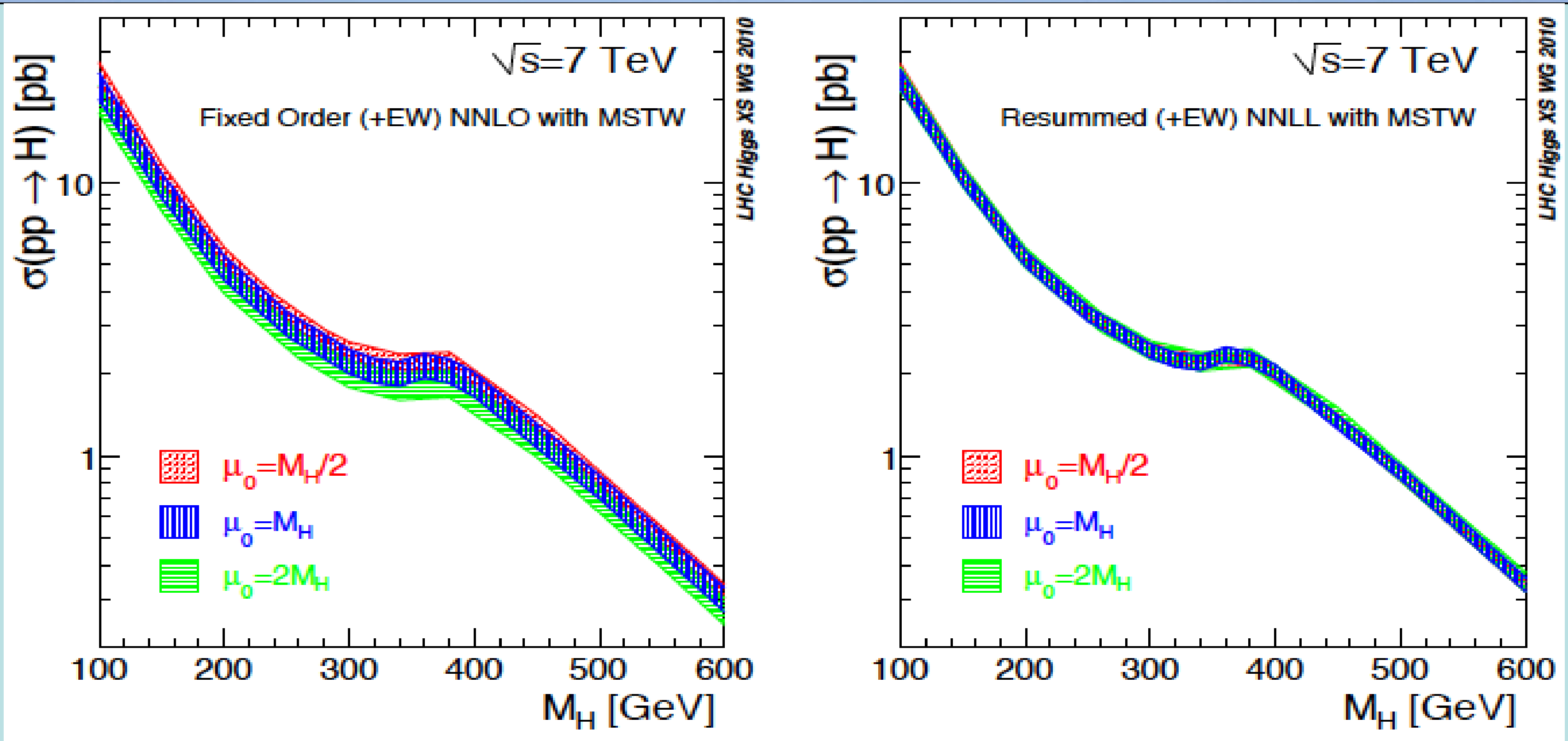
Many production modes measurable if M_h ~ 125 GeV

gg ➔Higgs Production at the LHC



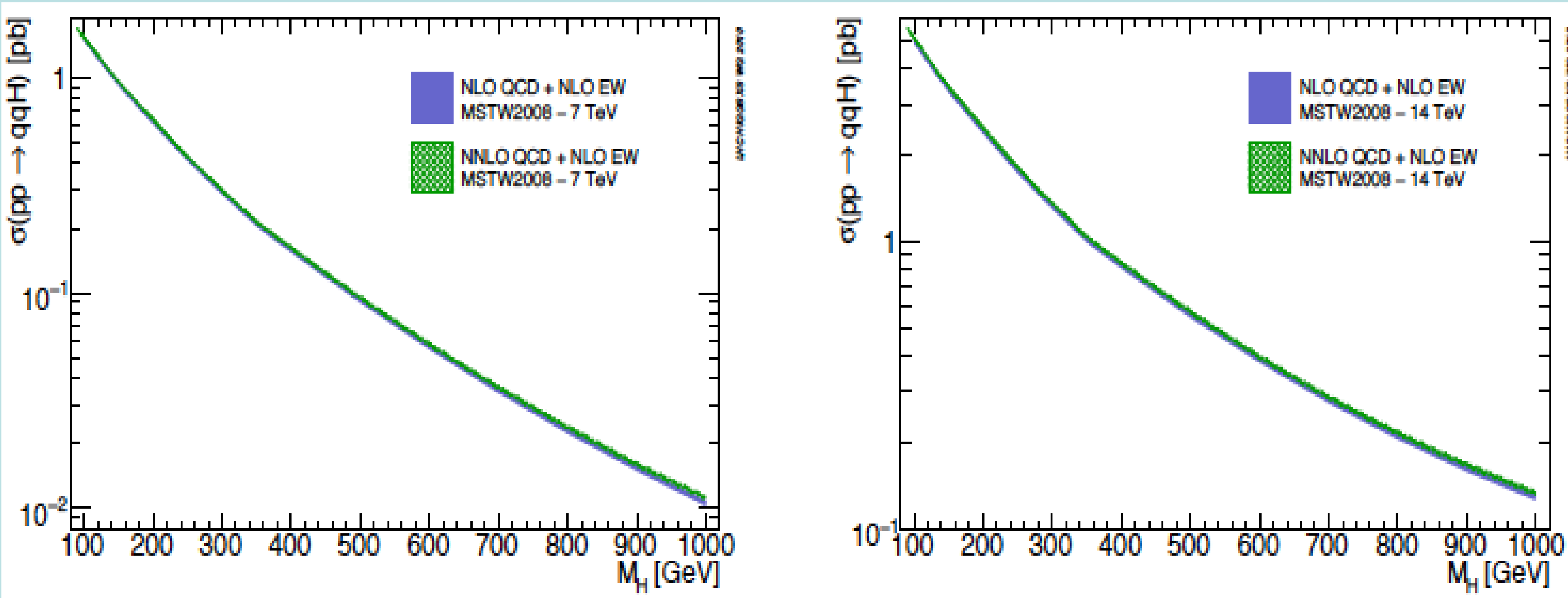
- Calculated at Next-to-next-leading order (NNLO) including leading higher-order logs (NNLL)
- Good agreement between theoretical groups
- Significant rise from 7 to 14 TeV

gg ➔Higgs Production at the LHC



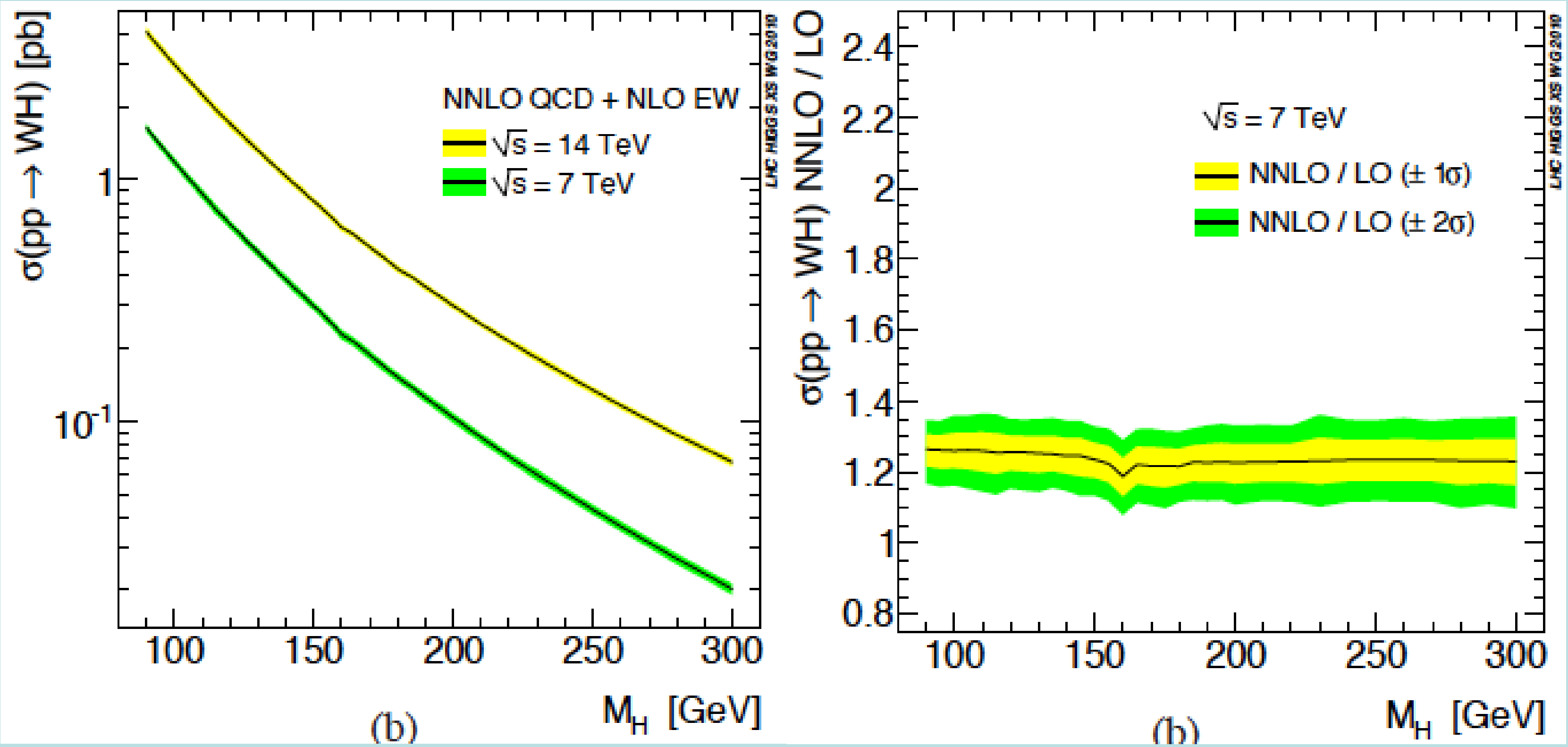
- Main remaining uncertainties:
  - Choice of renormalization scale
  - Choice of gluon parton distribution function

VBF Higgs Production at the LHC



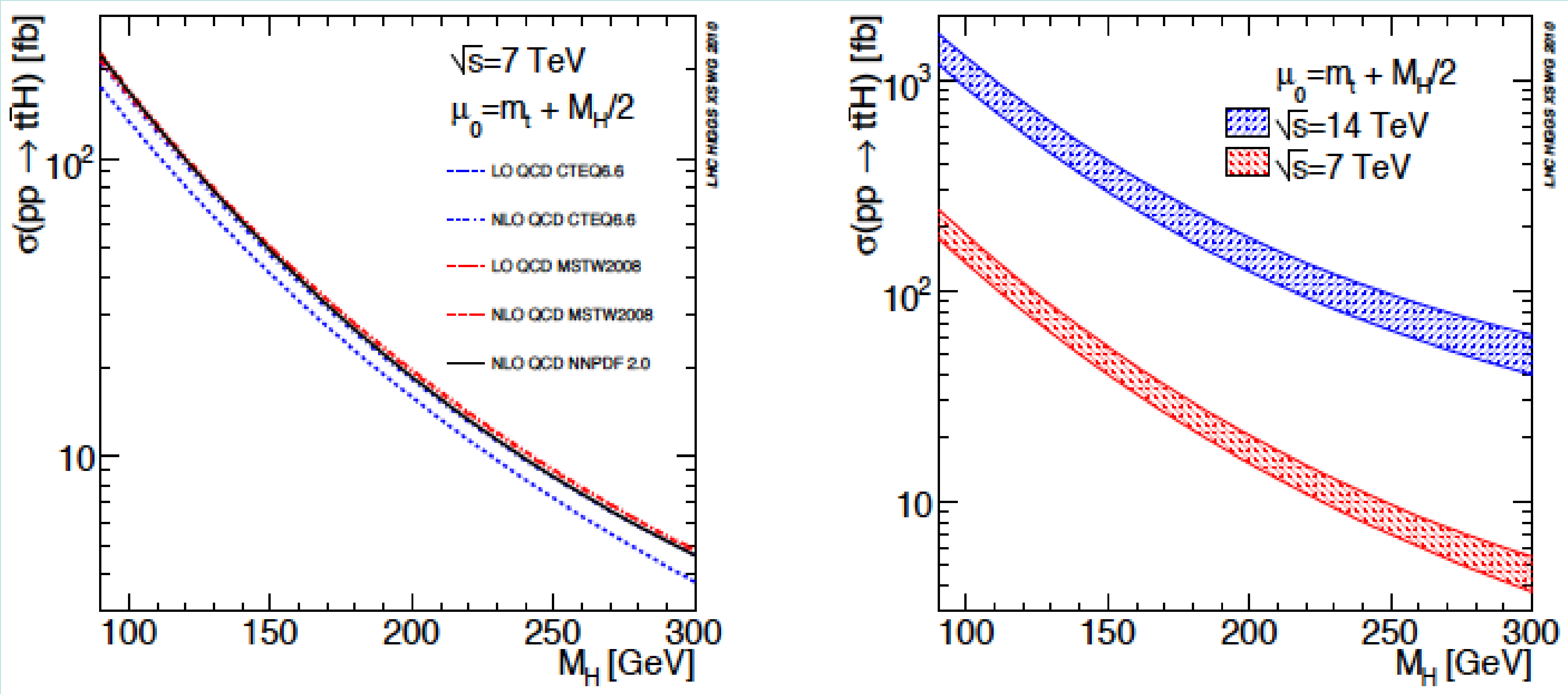
- Calculated at NNLO including electroweak corrections at NLO
- Good convergence of perturbation expansion
- Small uncertainties in quark parton dist’ns

Associated V+H Production at the LHC



- Calculated at NNLO including electroweak corrections at NLO
- Good convergence of perturbation expansion

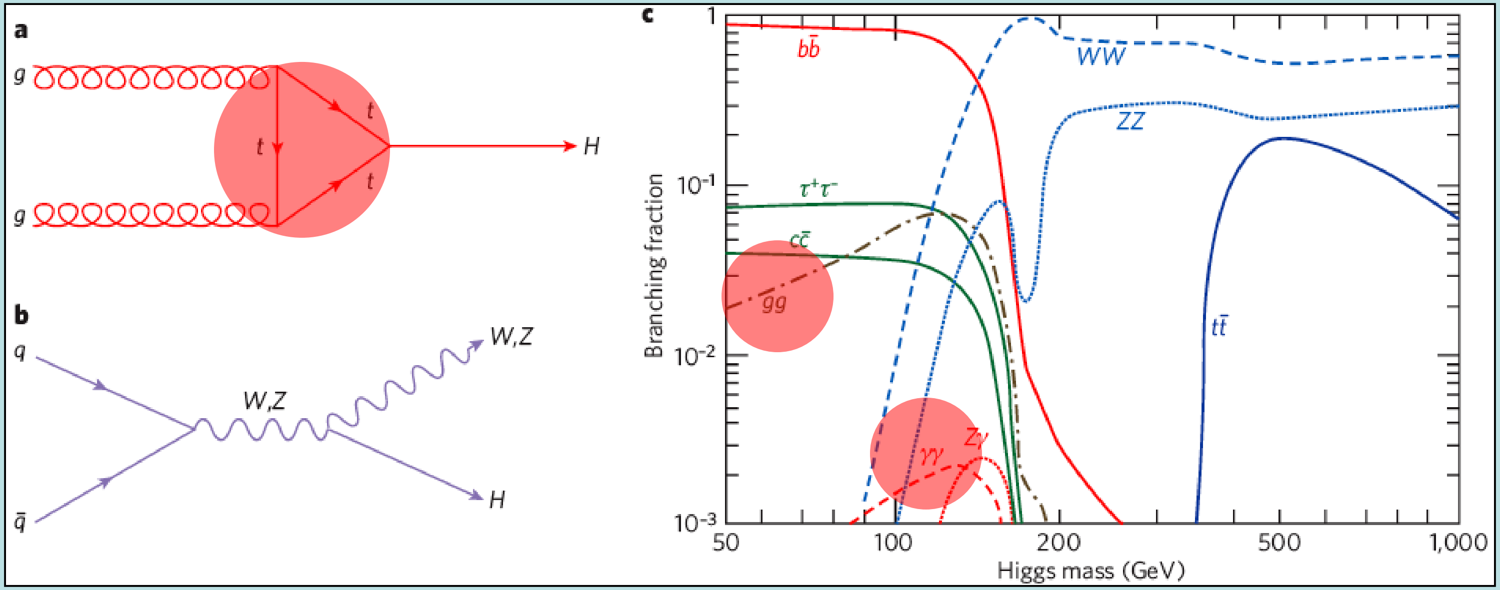
Associated $t\bar{t}$+H Production



- Calculated at NLO: uncertainties due to
  - Perturbation expansion
  - Choice of parton distributions

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

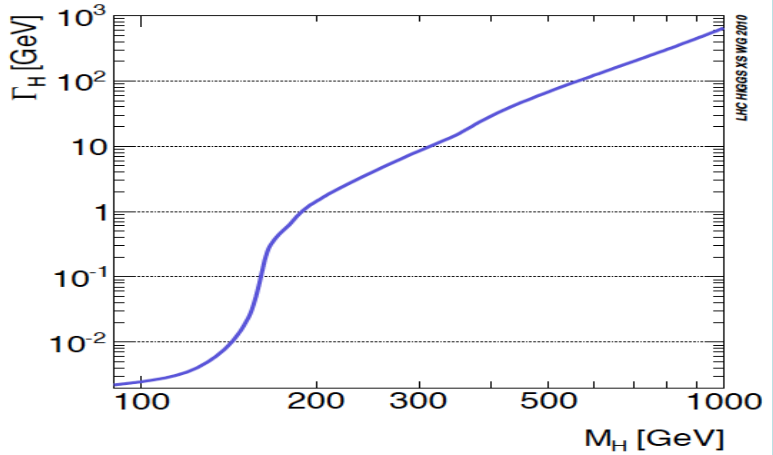
Higgs Decays

- Estimates of uncertainties in branching ratios

Partial width	QCD	Electroweak	Total
$H \to bb/cc$	~ 0.1–0.2%	~ 1–2% for $M_H \lesssim 135$ GeV	~ 1–2%
$H \to \tau\tau$		~ 1–2% for $M_H \lesssim 135$ GeV	~ 1–2%
$H \to tt$	$\sim 5\%$	$\lesssim 2$–5% for $M_H < 500$ GeV	$\sim 5\%$
		$\sim 0.1(M_H/1\ \text{TeV})^4$ for $M_H > 500$ GeV	~ 5–10%
$H \to gg$	$\sim 10\%$	$\sim 1\%$	$\sim 10\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$
		$\sim 0.17(M_H/1\ \text{TeV})^4$ for $M_H > 500$ GeV	~ 0.5–15%

- QCD @ NNNLO
- EW @ NLO
- Total decay rate

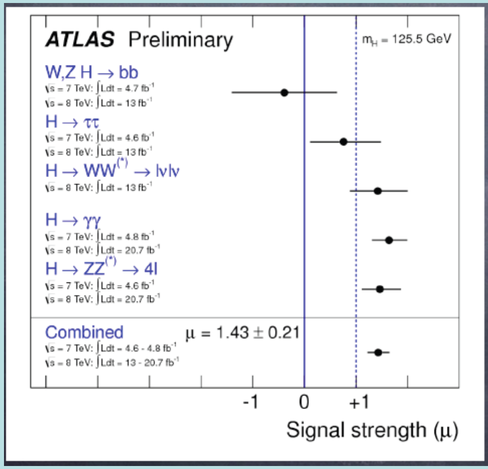
~ 4.2 MeV for 126 GeV

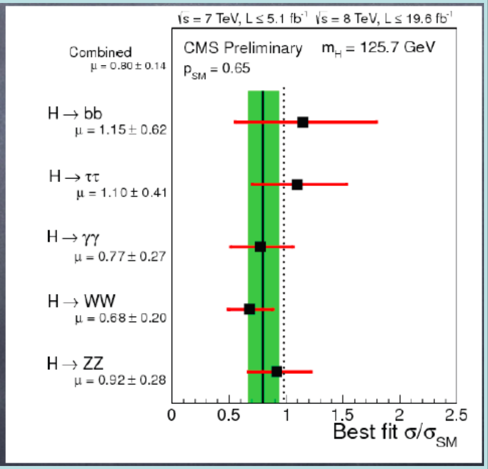


Higgsdependence Day!

From Discovery to Measurement

- Mass measurements: 125.6 ± 0.3 GeV
- Signal strengths ~ SM in many channels

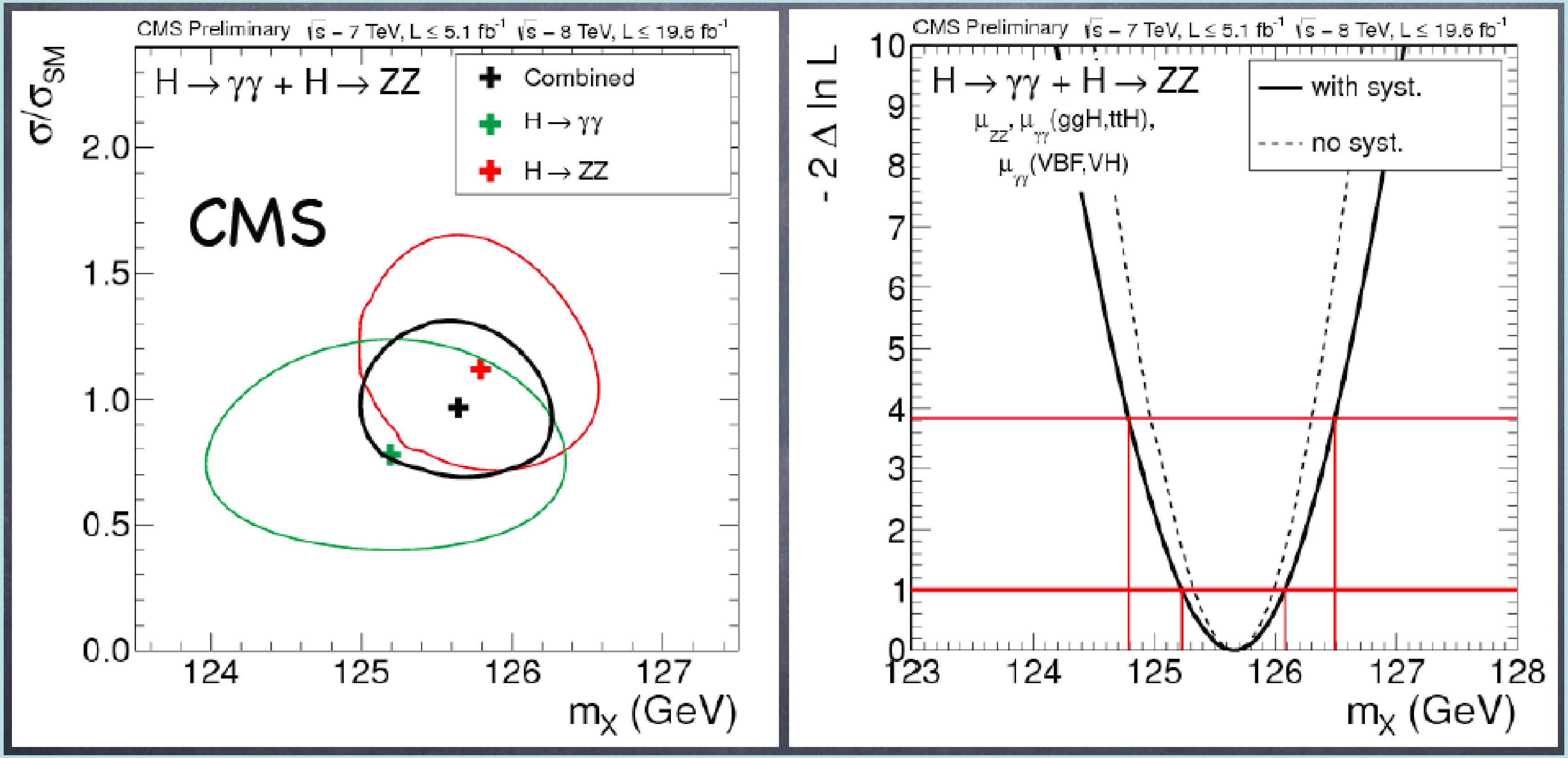




- Frontiers:
  - VBF significance 2σ in several channels, 3σ combined
  - Decay to ττ emerging, limits on ττ (μτ, eτ)
  - Decay to bbbar emerging (CMS, Tevatron)
  - Indirect evidence for ttbar coupling

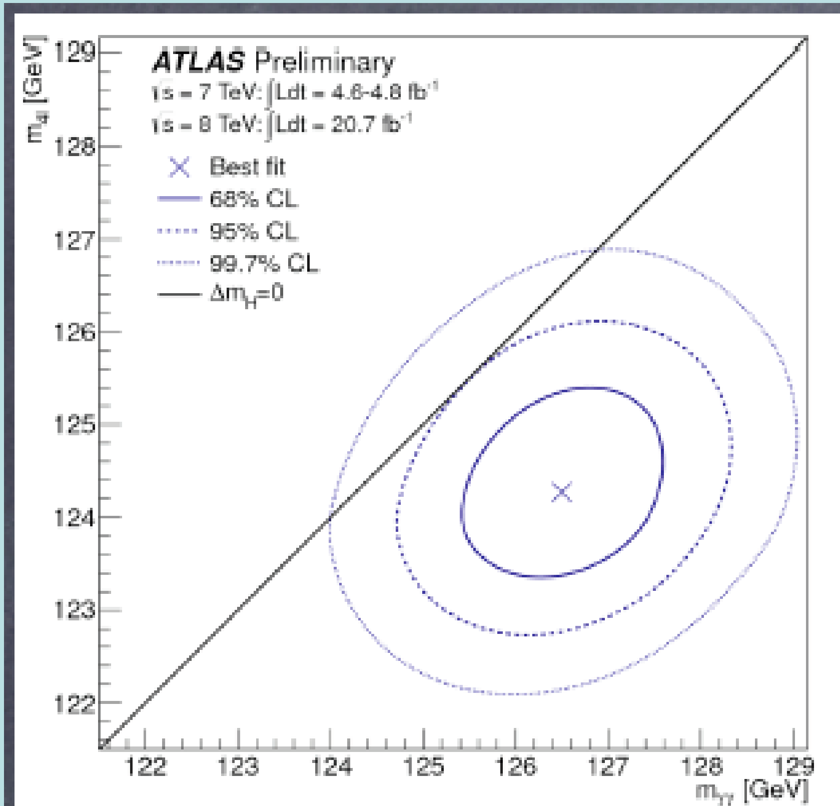
    (search for ttbar + H/W, Zγ)

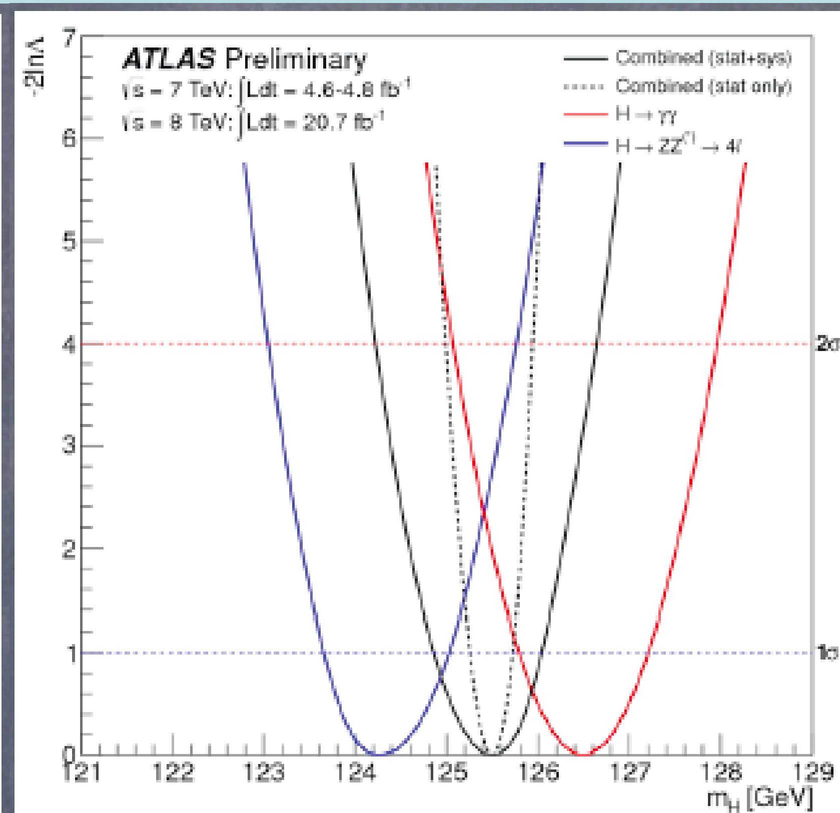
Higgs Mass Measurements



- CMS γγ and ZZ* measurements consistent

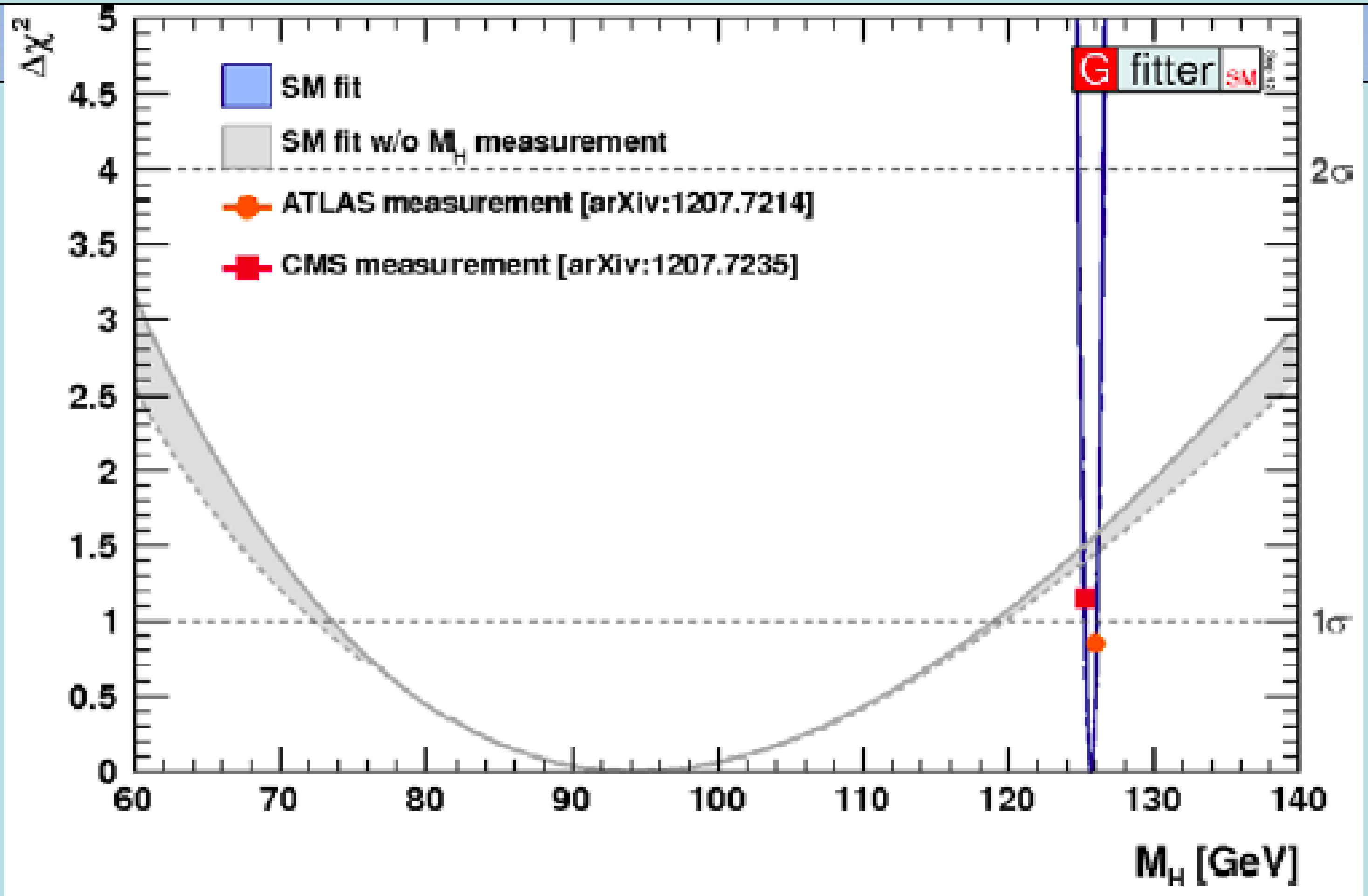
Higgs Mass Measurements





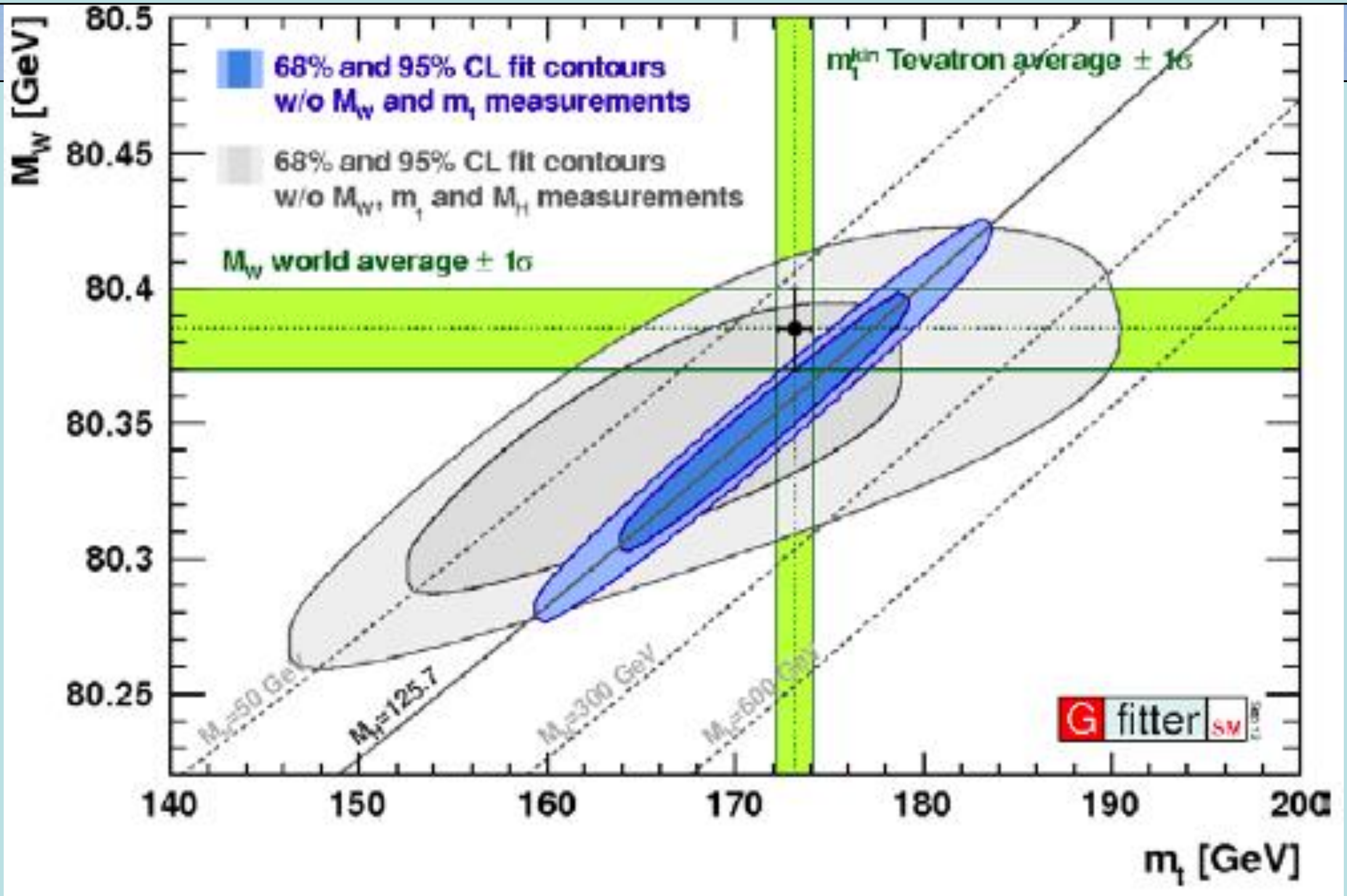
- Tension in ATLAS γγ and ZZ* measurements

Comparison with Electroweak Fit



Quite consistent: $\Delta\chi^2 \sim 1.5$

Comparison with Electroweak Fit

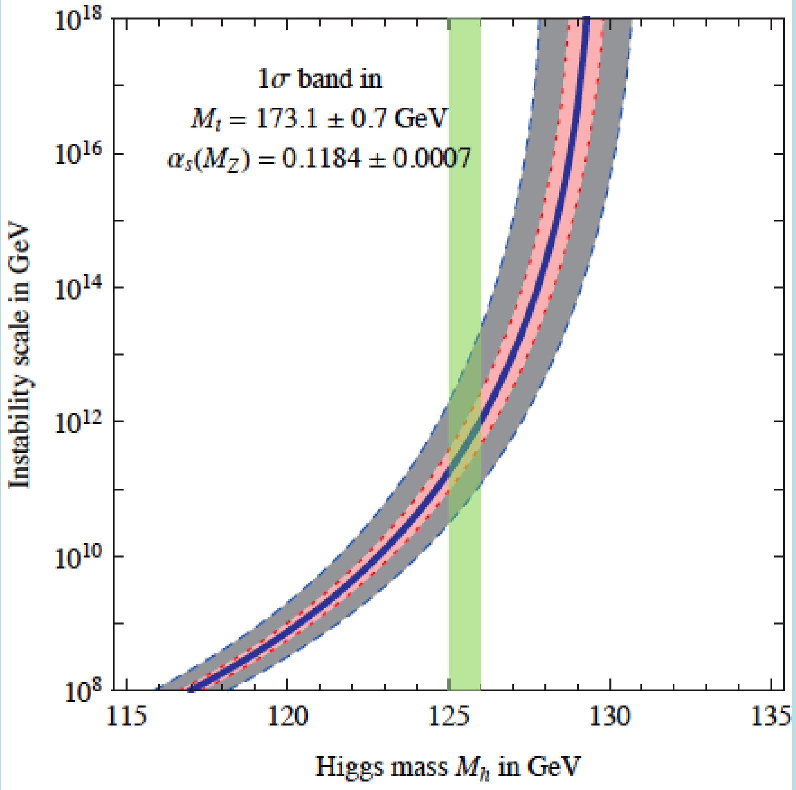


Quite consistent: $\Delta\chi^2 \sim 1.5$

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$



- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

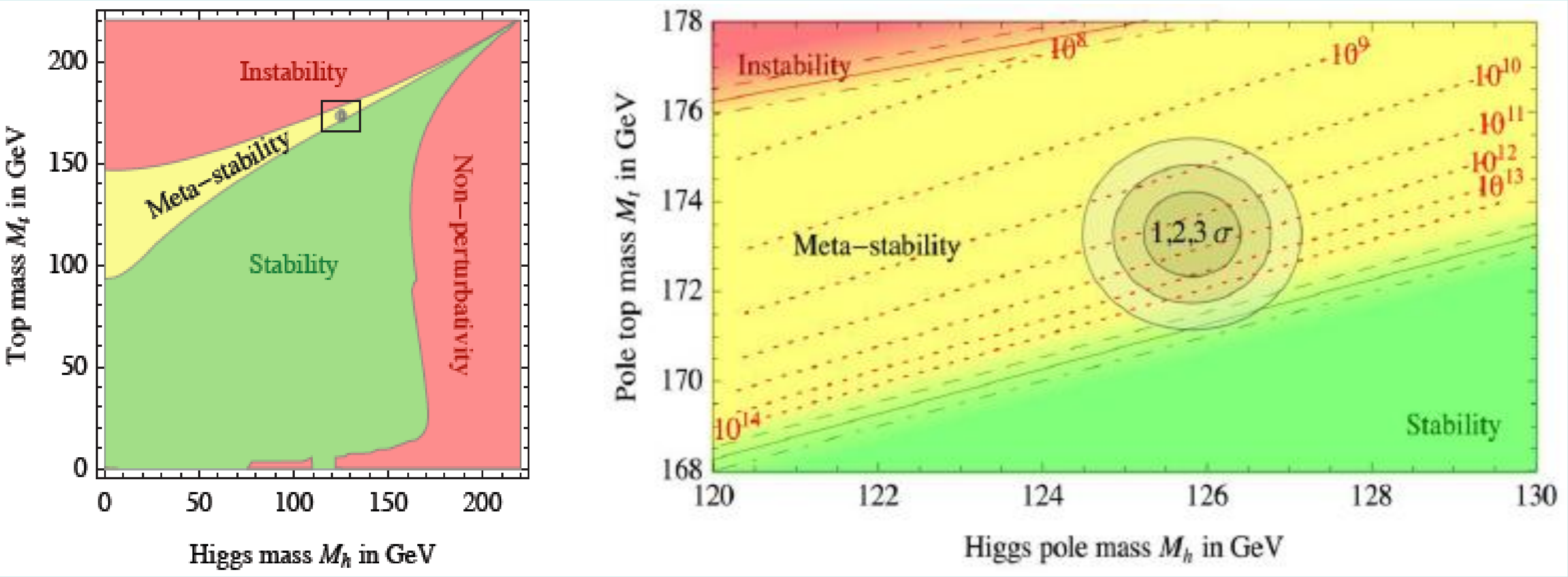
Vacuum Instability in the Standard Model

- Due to radiative corrections due to top quark

- Lifetime >> age of the Universe

Vacuum Instability in the Standard Model

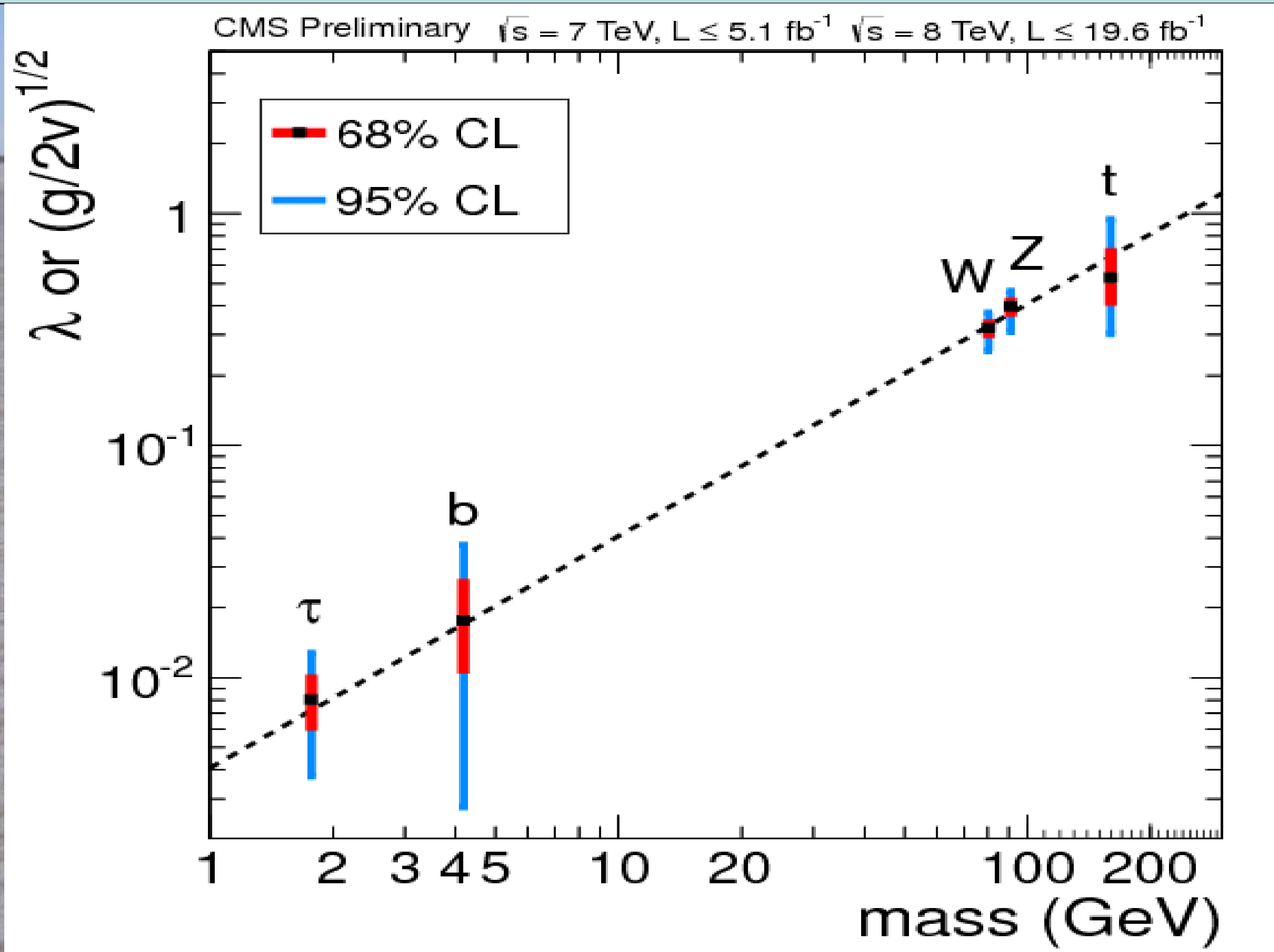
- Very sensitive to m_t as well as M_H



- Present vacuum probably metastable with lifetime >> age of the Universe

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Evidence that Couplings ~ Mass



Without Higgs …

… there would be no atoms

- Electrons would escape at the speed of light

… weak interactions would not be weak

- Life would be impossible: there would be no nuclei, everything would be radioactive

The discovery of the Higgs Boson is a big deal

'God Particle' no big Deal

- Peter Higgs as quoted in the London Times:
- *"A discovery widely acclaimed as the most important scientific advance in a generation has been "overhyped", the British scientist behind it has said."*

The Stakes in the Higgs Search

- How is gauge symmetry broken?
- Is there any elementary scalar field?
- **Likely portal to new physics**
- 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!**