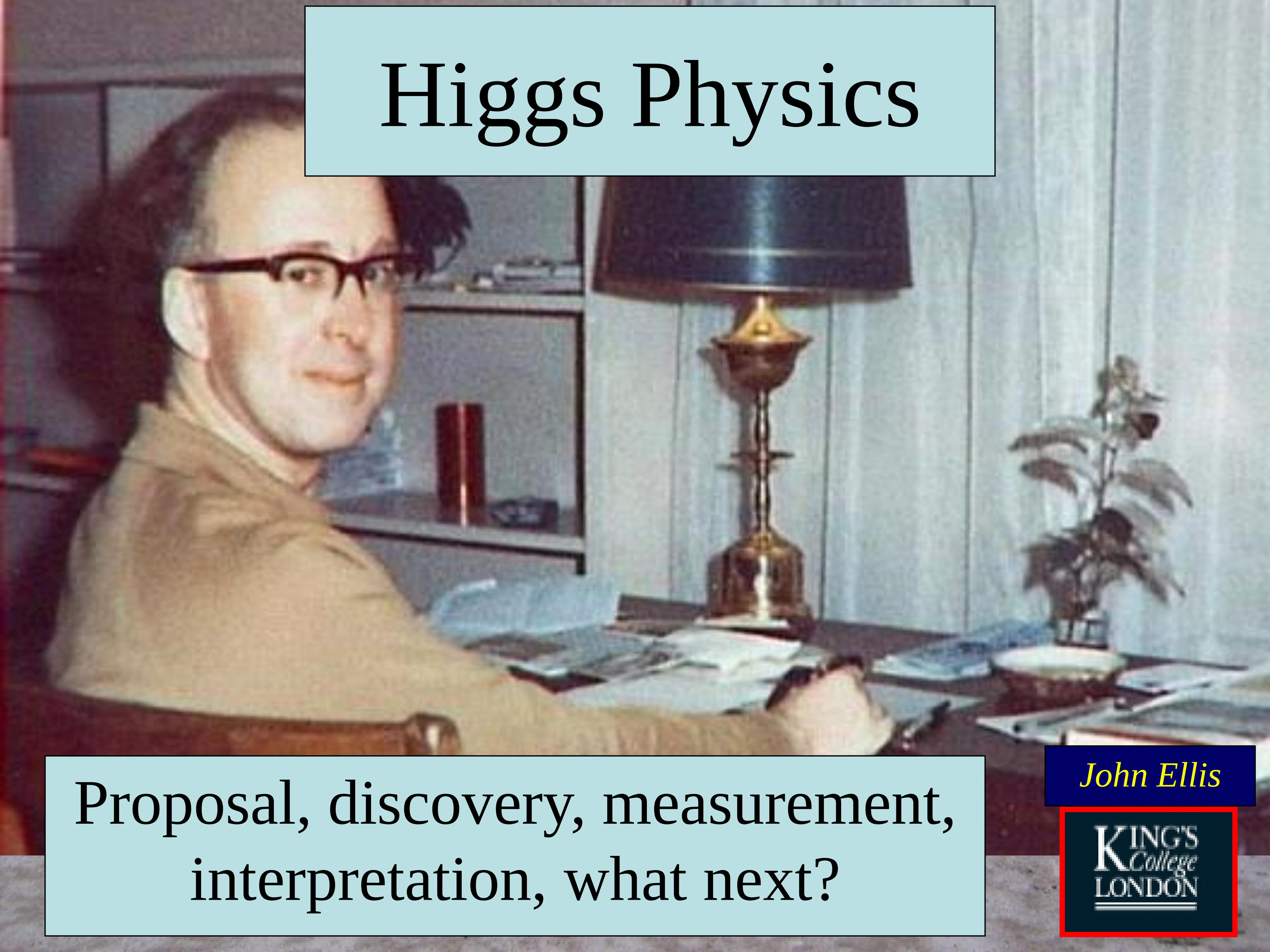


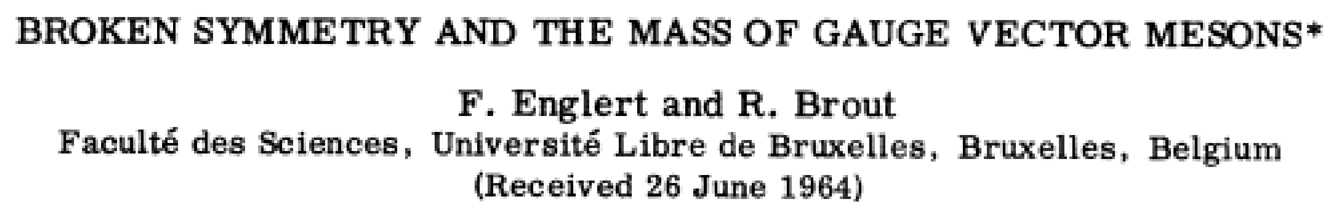
Higgs Physics

Proposal, discovery, measurement, interpretation, what next?

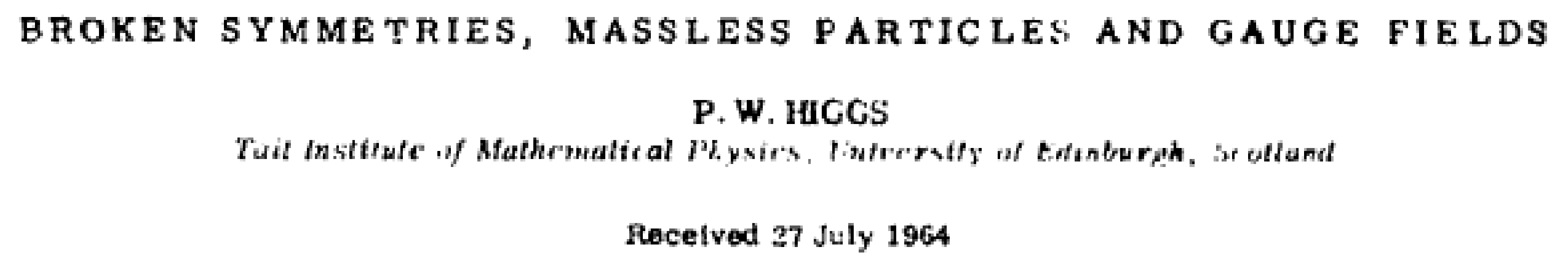
John Ellis

KING'S College LONDON

The (G)AEBHGHKMP’tH Mechanism

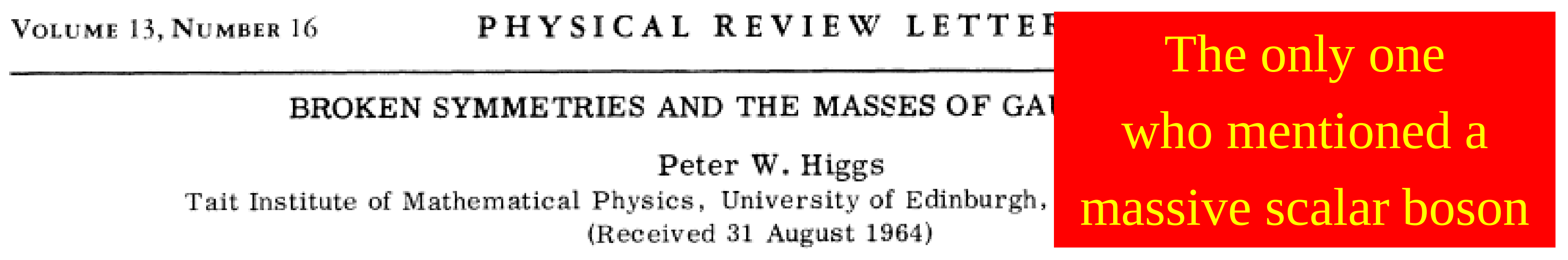

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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

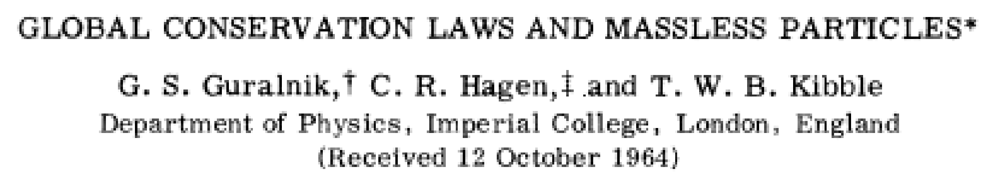
Received 27 July 1964


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTE

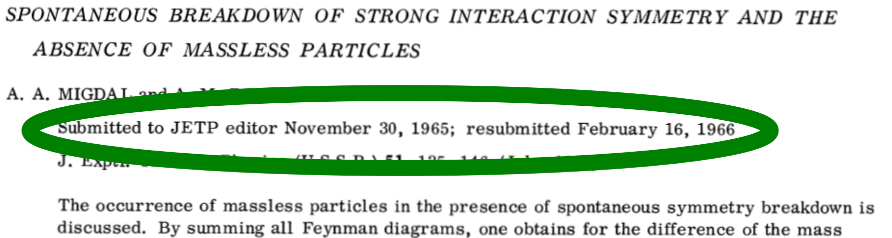
BROKEN SYMMETRIES AND THE MASSES OF GA

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 and

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

J. Exptl.

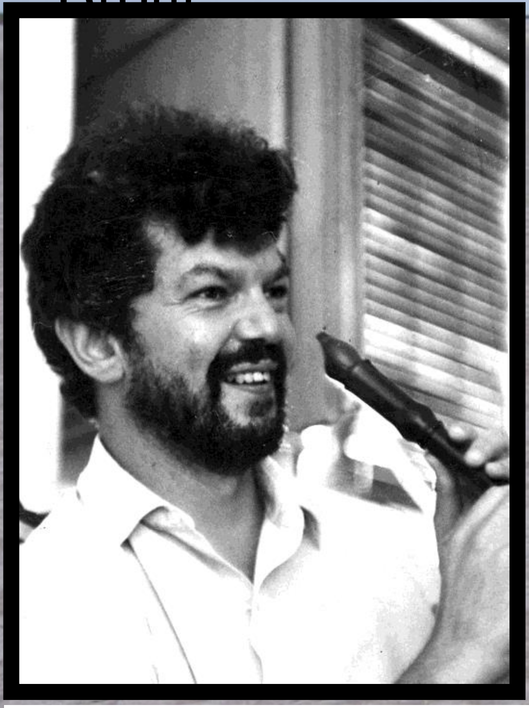
The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

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

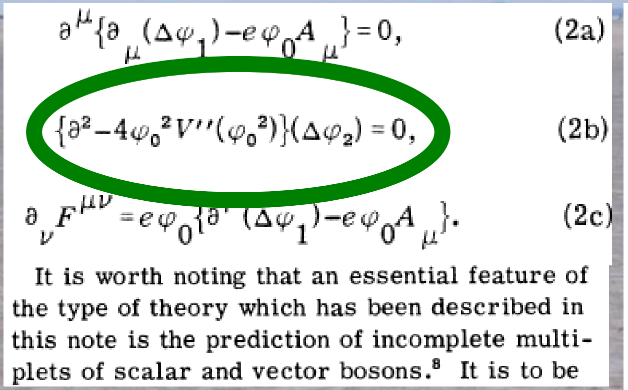
Englert & Brout



(a) (b)

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) → $(2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) → $-(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

Higgs



$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \tag{2a}$$

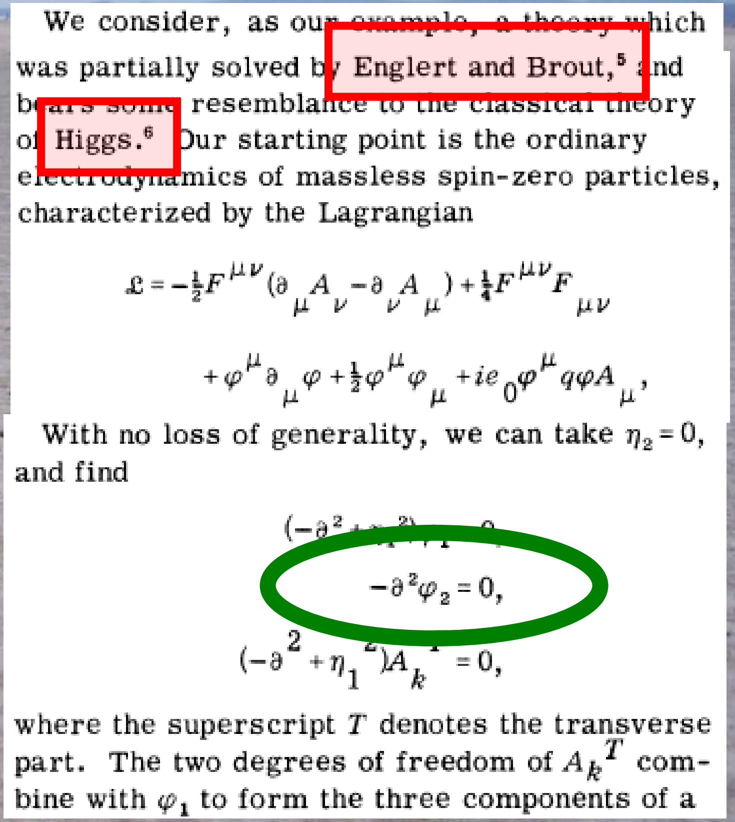
$$\{\partial^2-4\varphi_0{}^2V''(\varphi_0{}^2)\}(\Delta\varphi_2)=0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \tag{2c}$$

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

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

$$\mathfrak{L}=-\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu-\partial_\nu A_\mu)+\tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}$$
$$+\varphi^\mu\partial_\mu\varphi+\tfrac{1}{2}\varphi^\mu\varphi_\mu+ie_0\varphi^\mu q\varphi A_\mu,$$

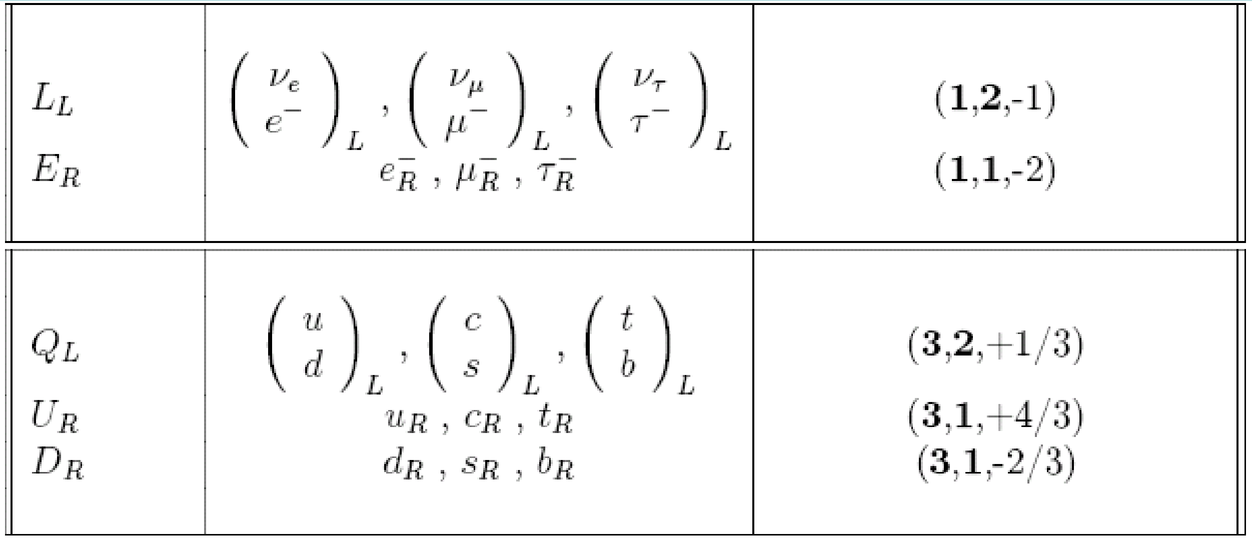
With no loss of generality, we can take $\eta_2=0$, and find

$$(-\partial^2+\eta_1^2)\varphi_1=0,$$
$$-\partial^2\varphi_2=0,$$
$$(-\partial^2+\eta_1^2)A_k^T=0,$$

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

Summary of the Standard Model

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



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

- Lagrangian:

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

gauge interactions

matter fermions

Yukawa interactions

Higgs potential

Untested before 2012

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 < %

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

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

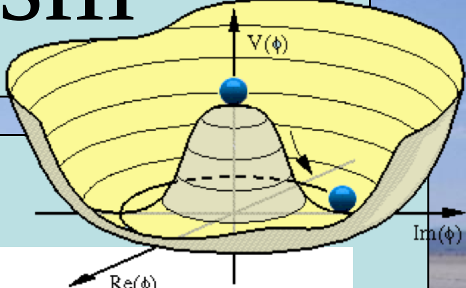
No direct evidence until July 4, 2012

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

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

1964

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

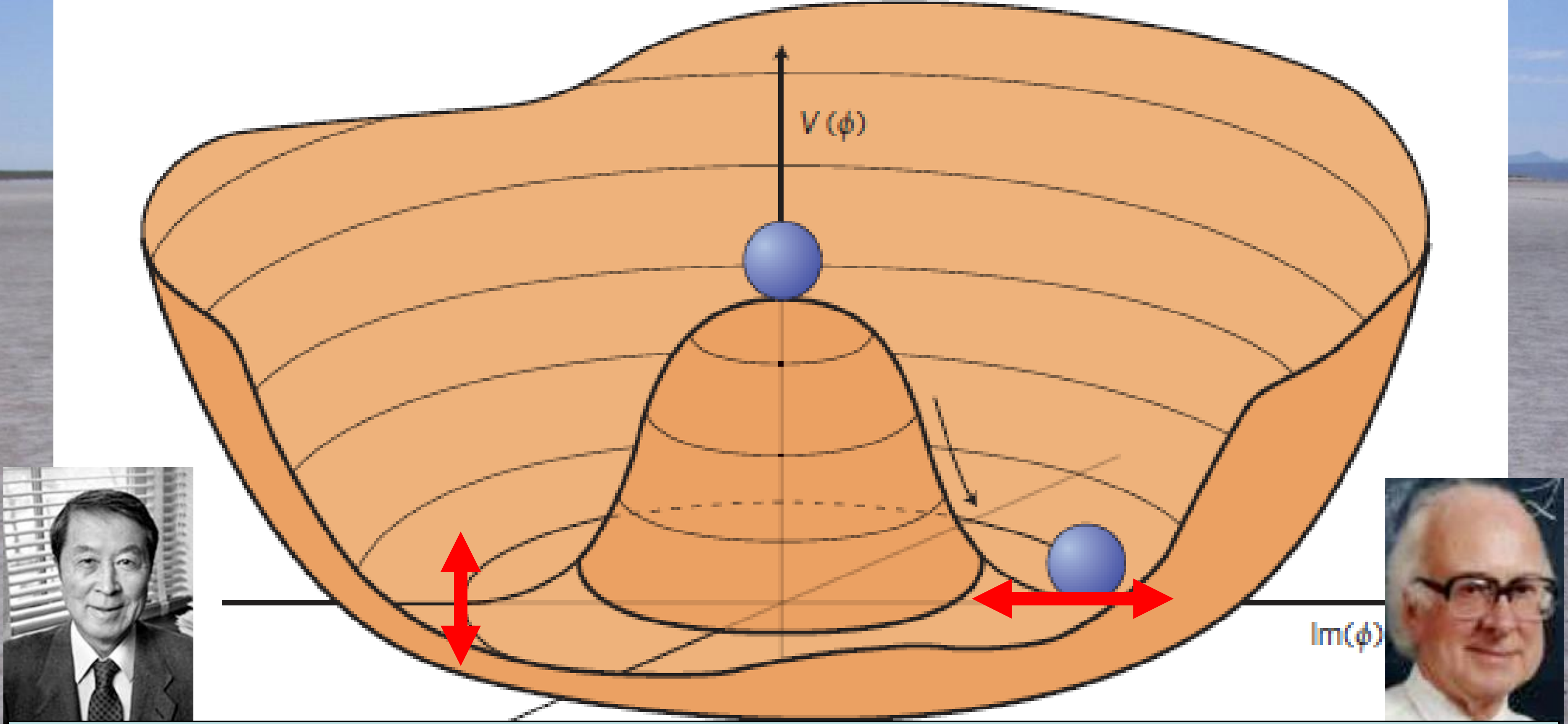
$$\phi'(x) = e^{i\alpha(x)}\, \phi(x) = e^{i\alpha(x)}\, e^{i\theta(x)} \eta(x)$$

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

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

$$\begin{aligned} \mathcal{L} &= |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}} H)|^2 - \tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - V \\ &= \underbrace{-\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + v^2 e^2\, A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2}[(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots \end{aligned}$$

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



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

Accompanied by massive particle

1967

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

- Kinetic term for Higgs field:

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

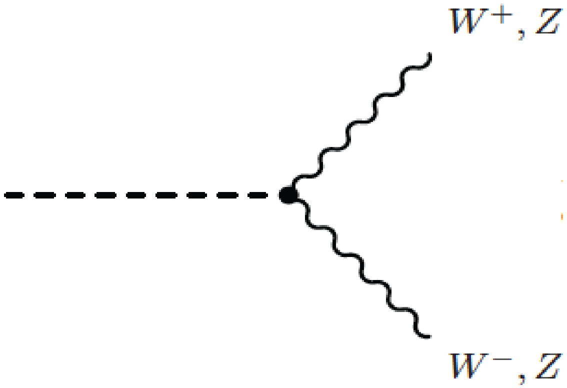
- Expanding around vacuum: $\phi =< 0|\phi|0 > + \hat{\phi}$

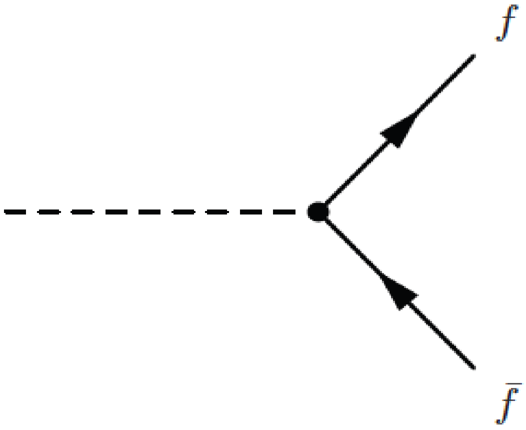
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\; W^+_\mu\, W^{\mu-} - g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu 3}$$

- Boson masses: 

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

Higgs Boson Couplings





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

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

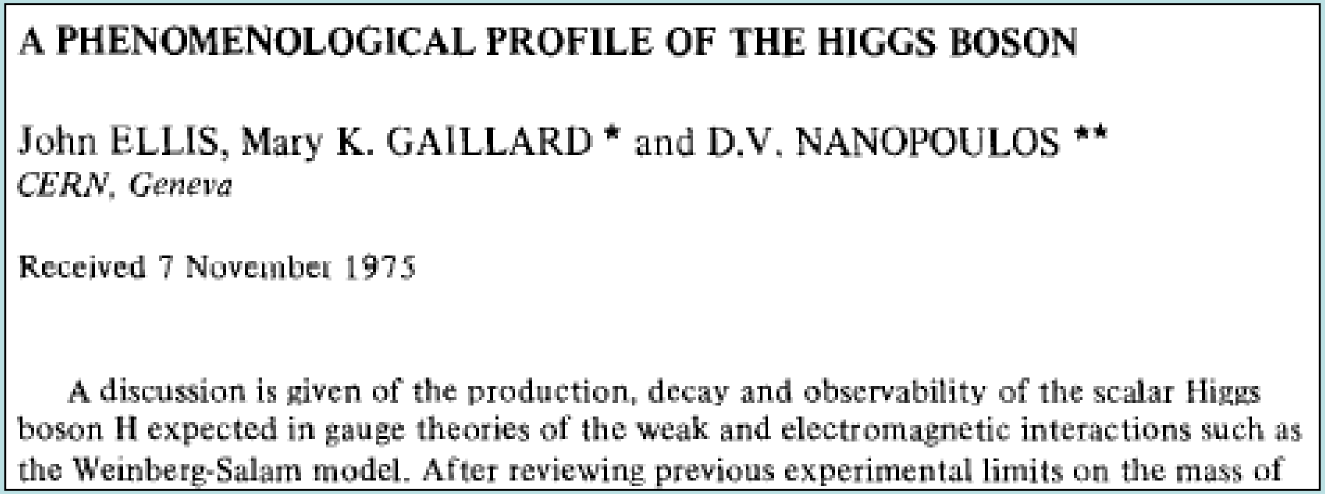
$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

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

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

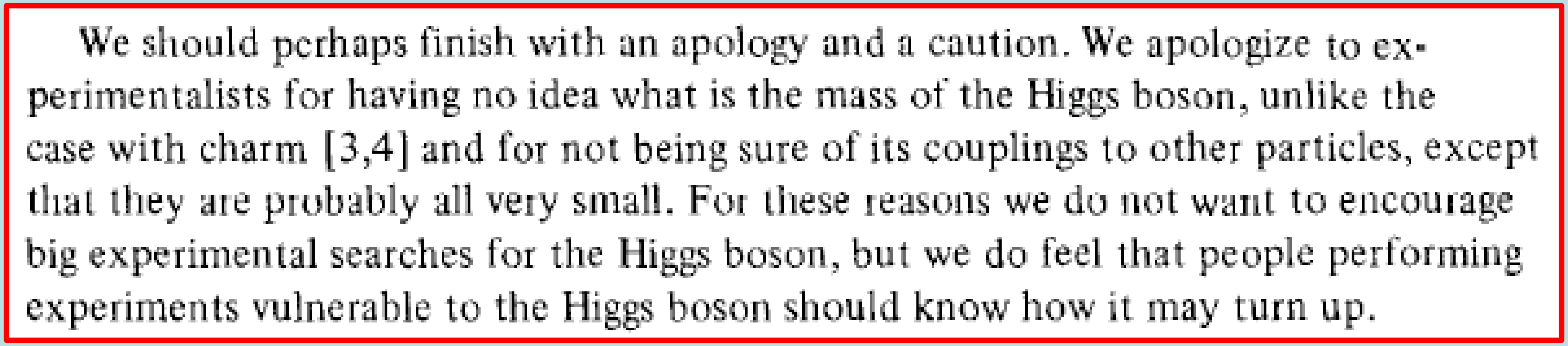


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

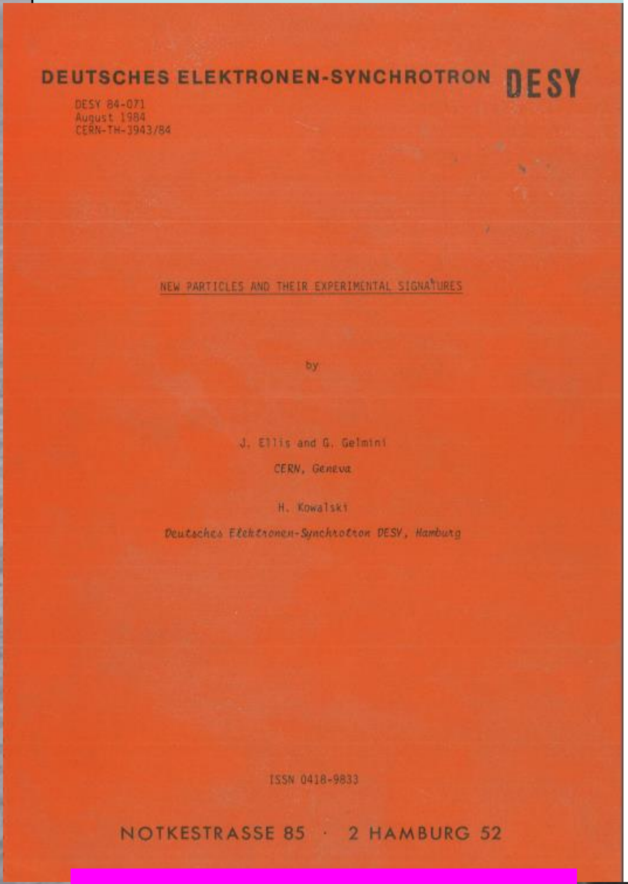


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

1984

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

J. Ellis and G. Gelmini
CERN, Geneva

H. Kowalski
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

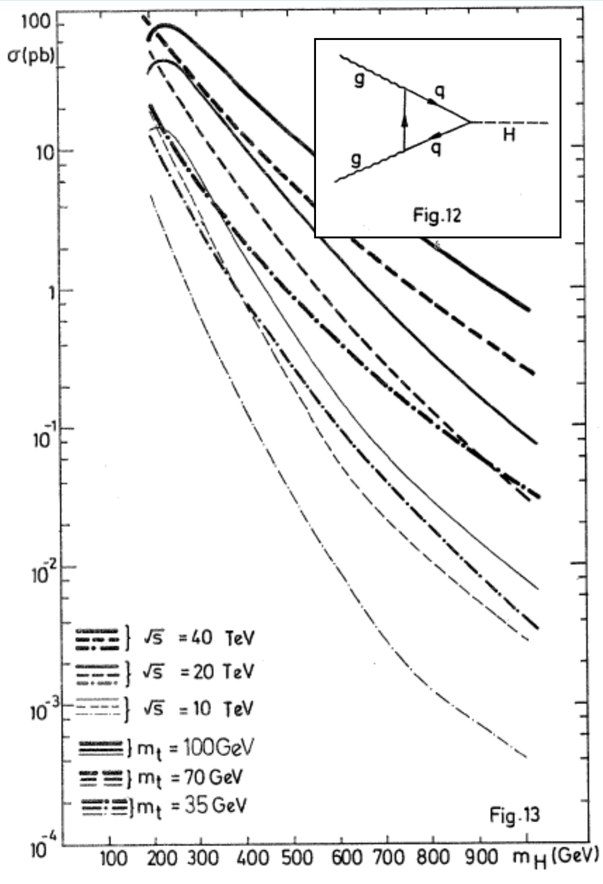


Fig.13

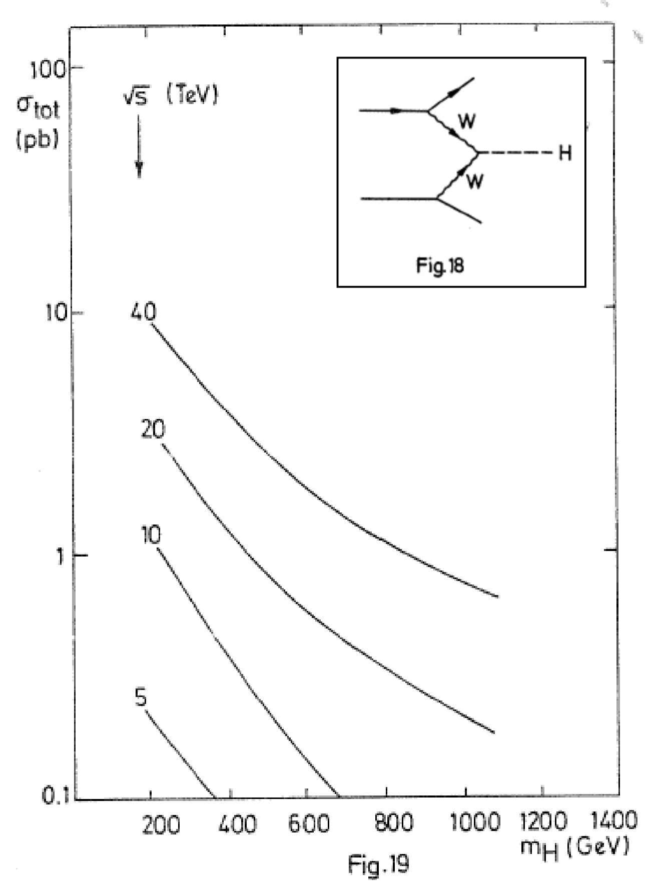


Fig.19

JE, Gelmini & Kowalski, 1984

Status of the Standard Model

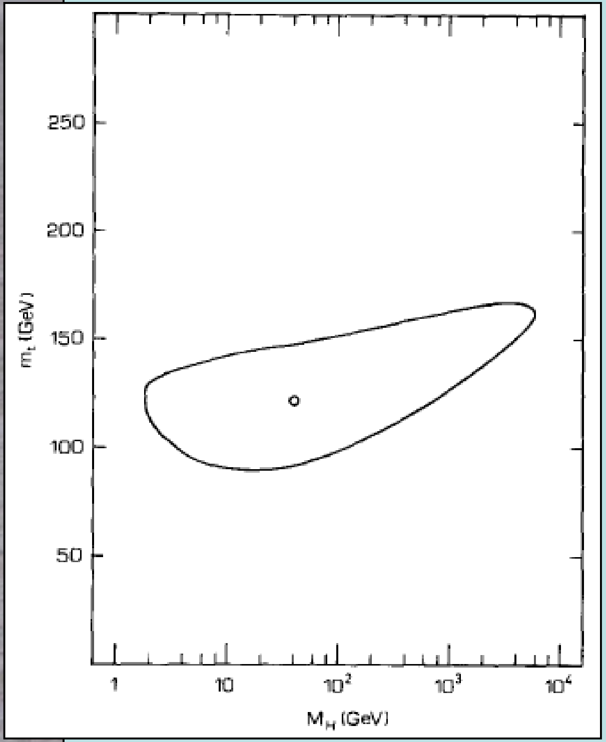
- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing $< \sim 180$ GeV
- Raises many unanswered questions:

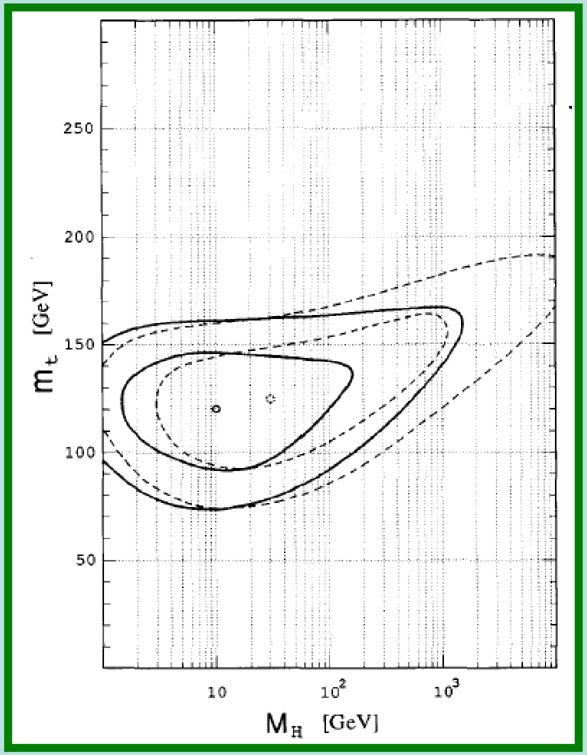
mass? flavour? unification?

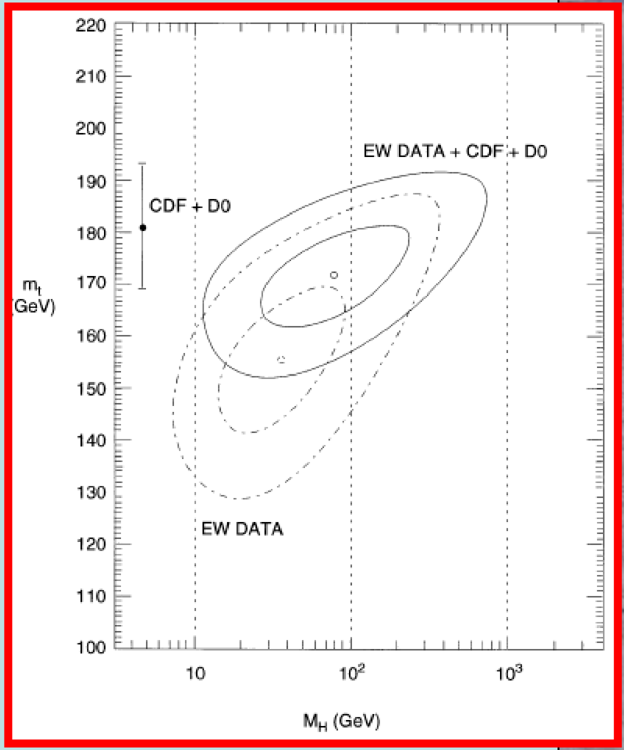
1990

Estimating the Mass of the Higgs Boson

- First attempts in 1990, **1991**





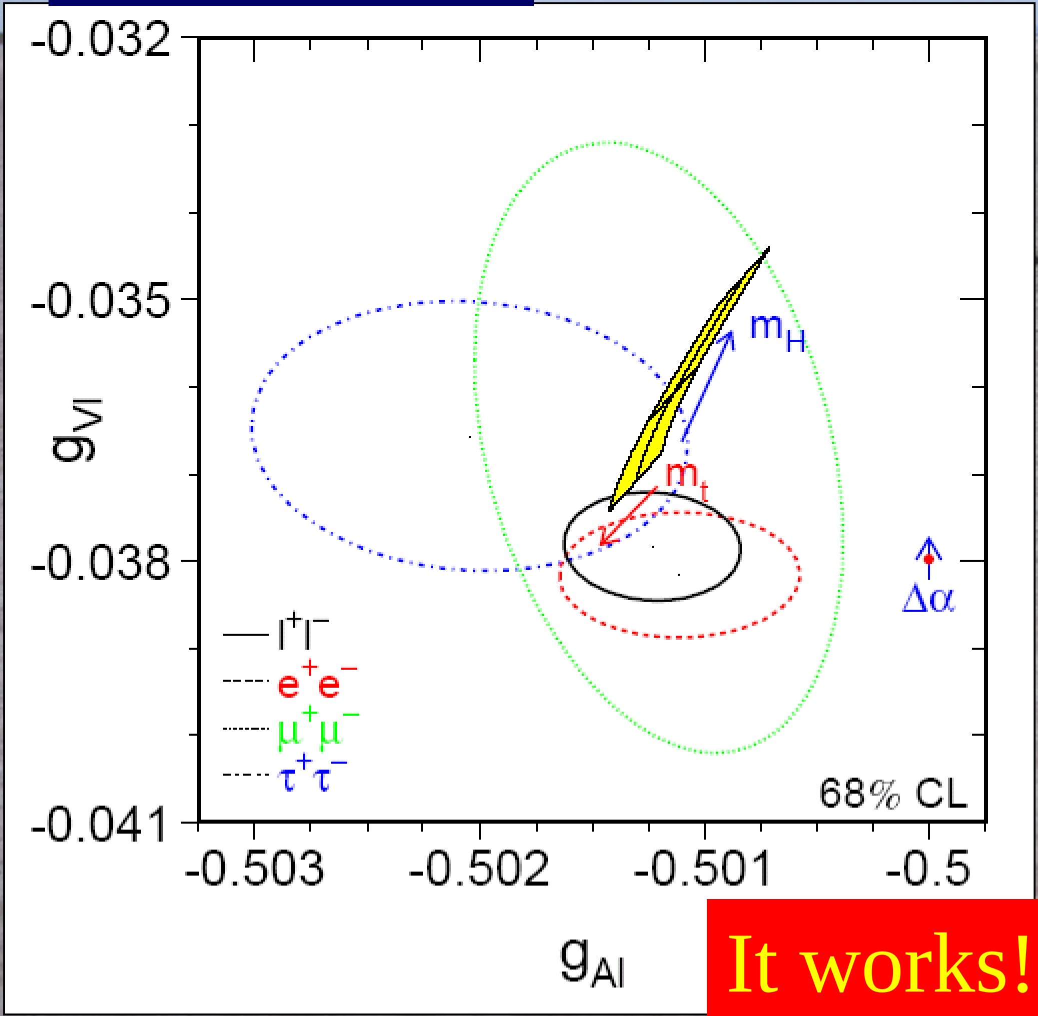


- **Easier after the discovery of the top quark**

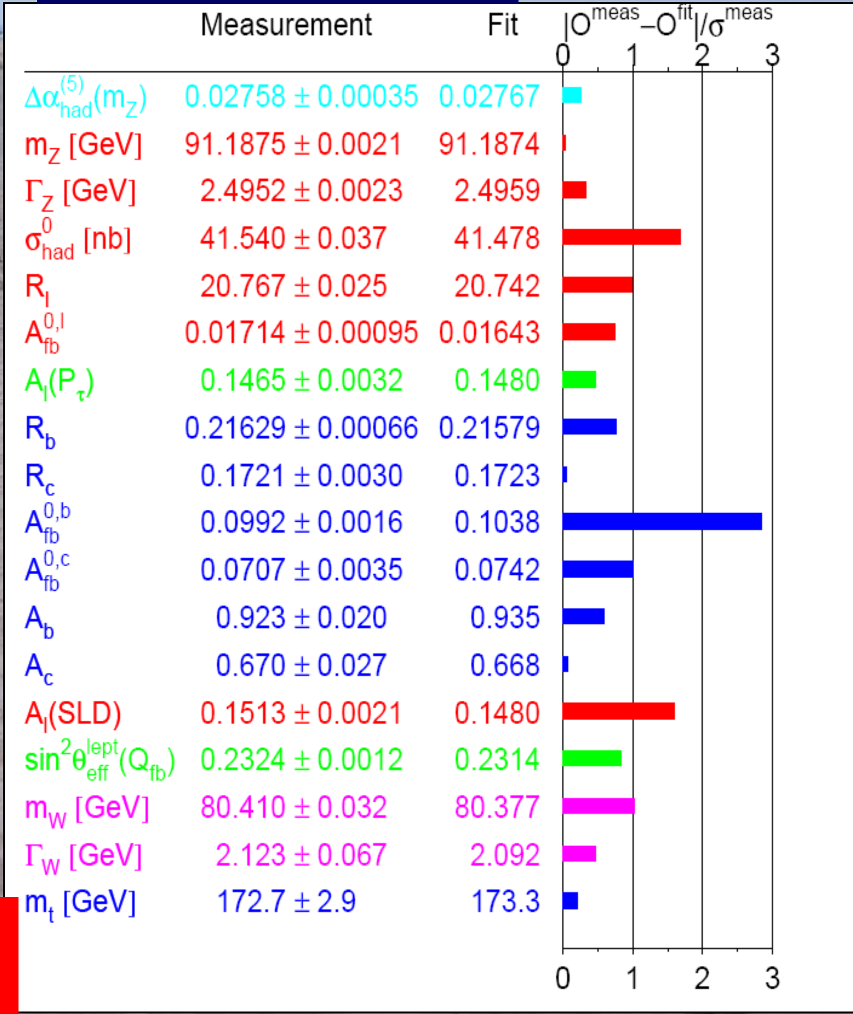
JE, Fogli & Lisi

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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!

2011

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:

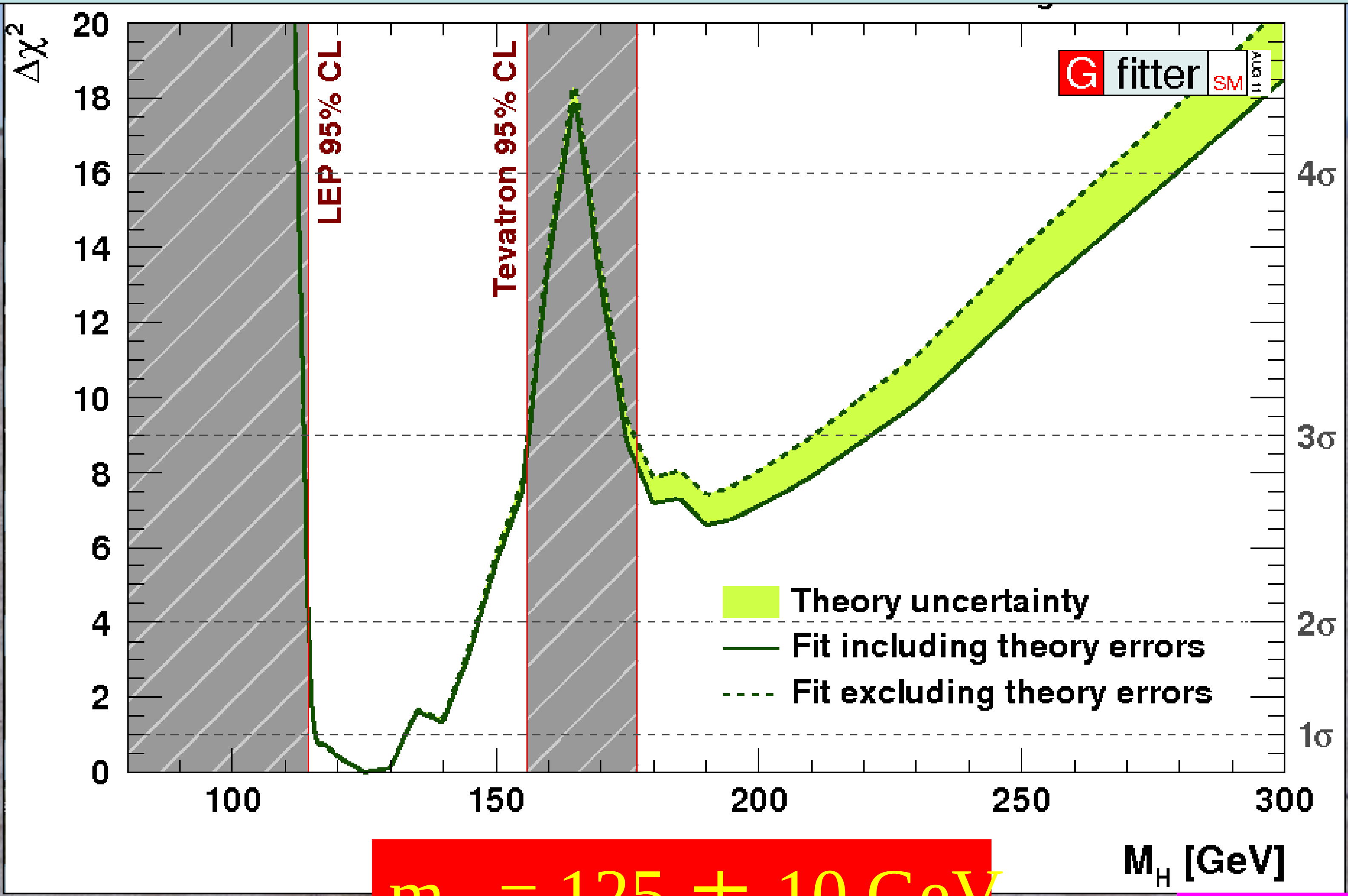
$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- 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

2011: Combining Information from Previous Direct Searches and Indirect Data

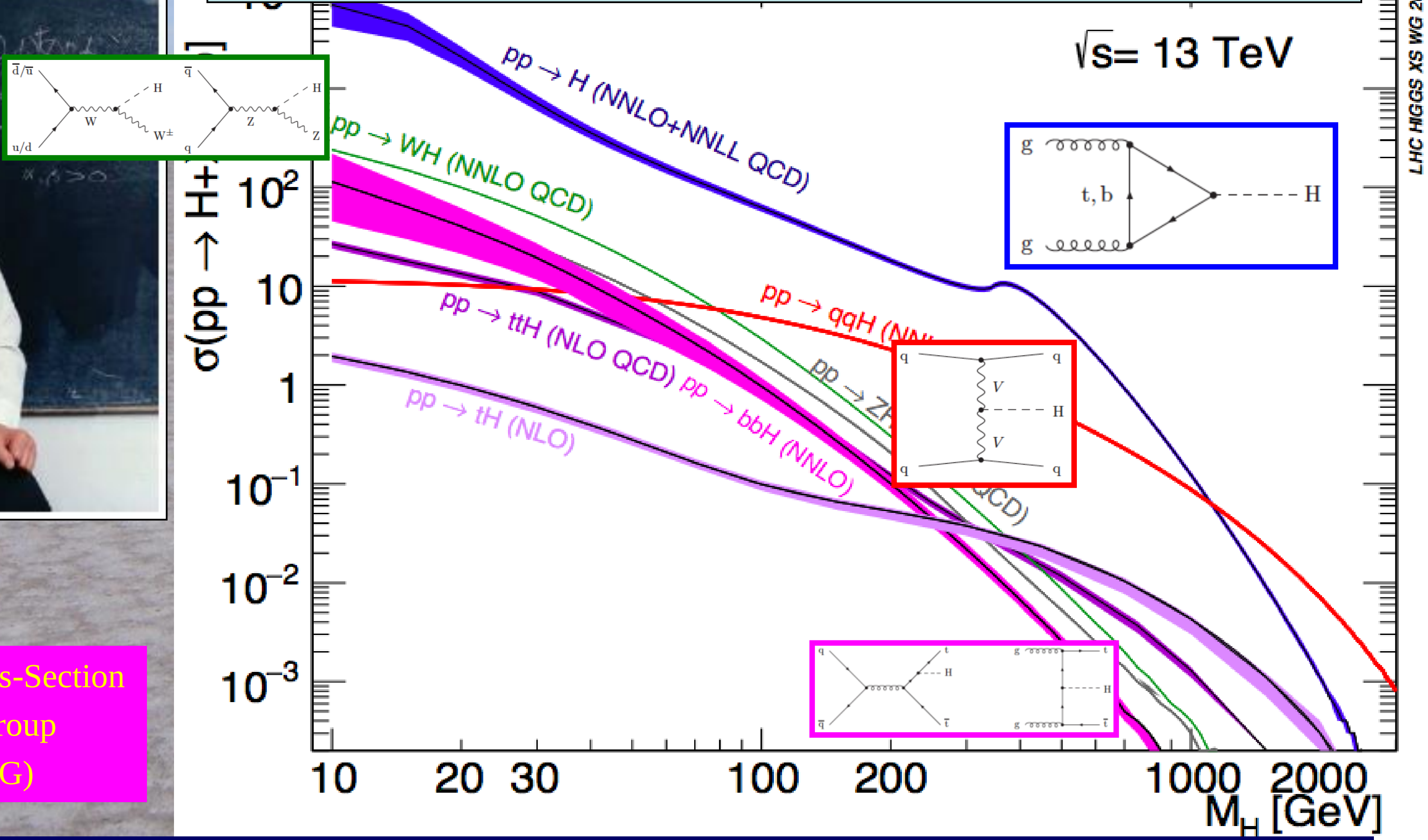


$m_H = 125 \pm 10$ GeV

Gfitter collaboration

A la recherche du
Higgs perdu …

Higgs Production at the LHC

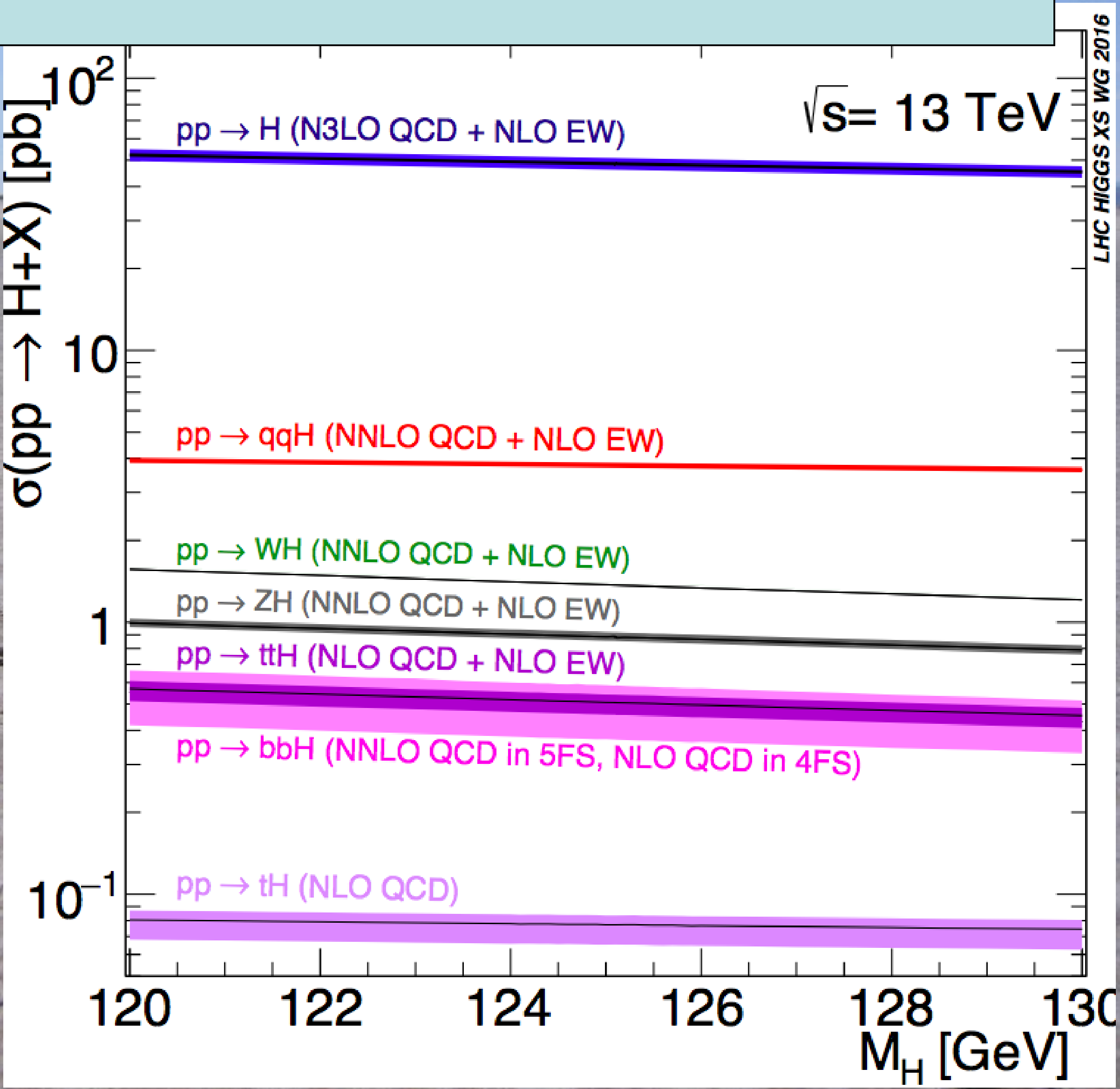


LHC Higgs Cross-Section
Working Group
(LHXSWG)

Many production modes measurable if M_h ~ 125 GeV

Higgs Production at the LHC

Cross sections for Higgs mass near 125 GeV



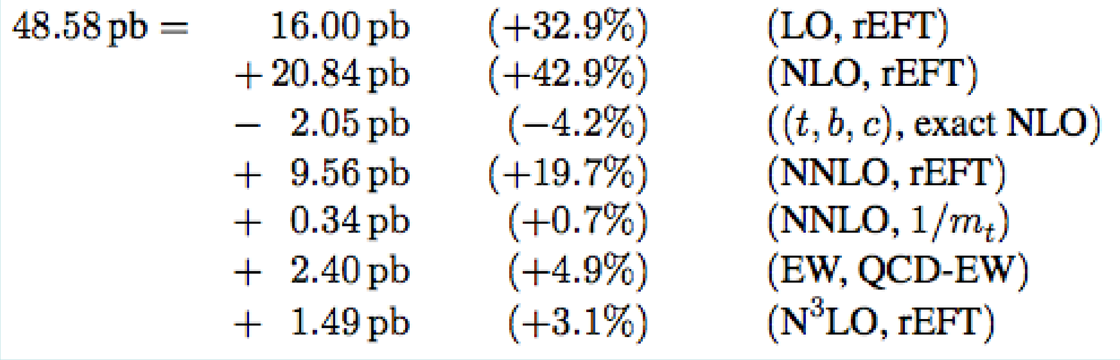
LHC Higgs Cross-Section Working Group (LHXSWG)

gg ➔Higgs Production at the LHC

- Calculated at Next-to-Next-to-Next-to-Leading Order (N^3LO) in limit of heavy t quark:

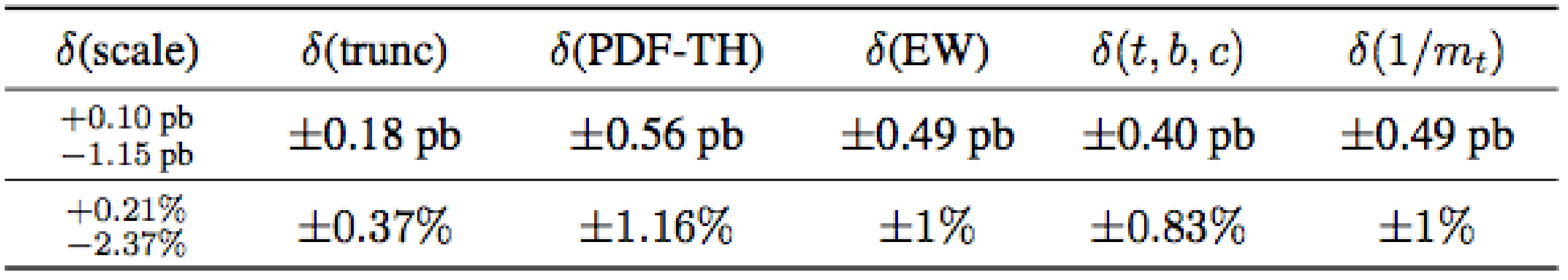
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF+}\alpha_s)$$

- Contributions at different orders:



$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\ \ 2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\ \ 9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\ \ 0.34\,\text{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)
	$+\ \ 2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\ \ 1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)

- Breakdown of theoretical uncertainties:



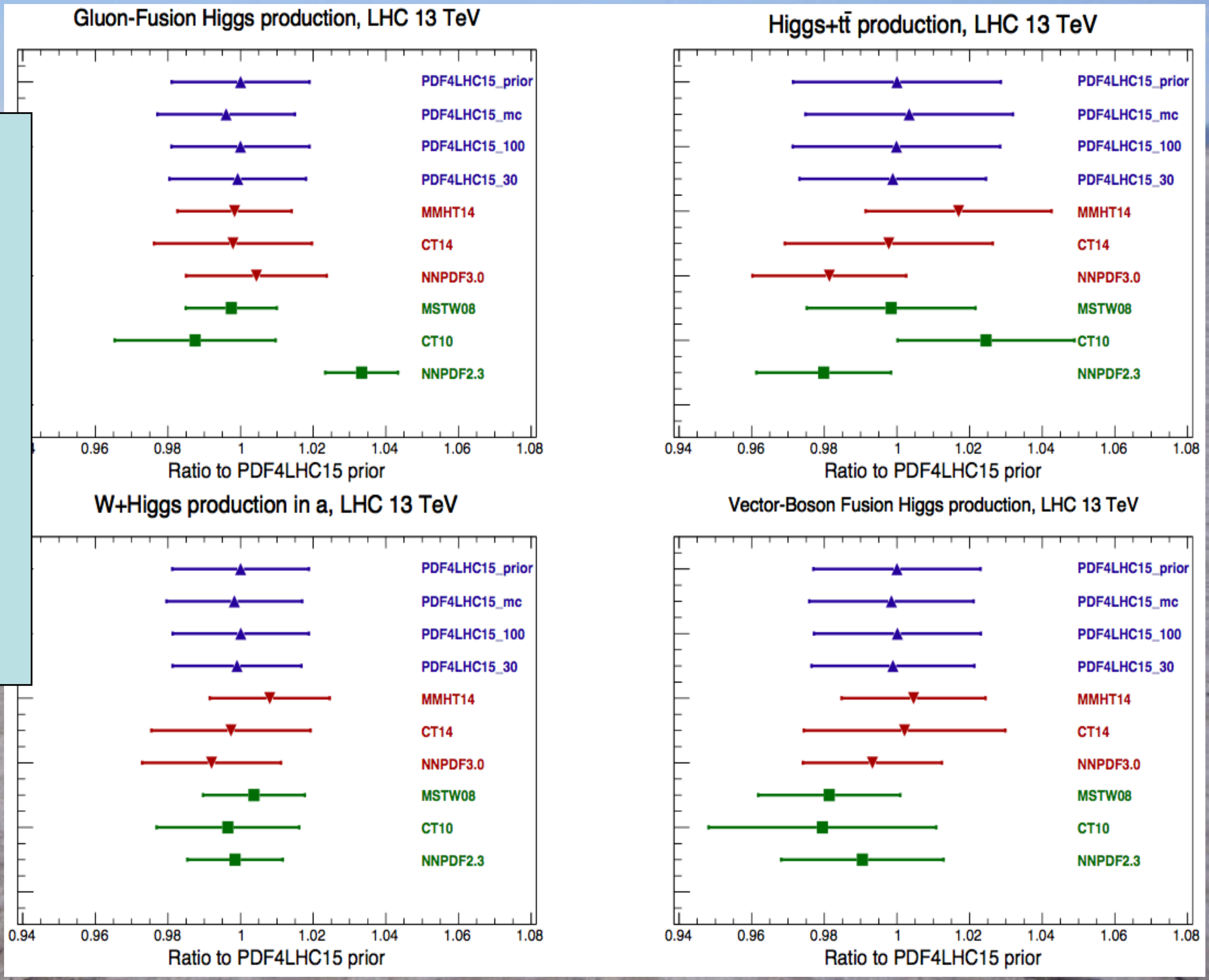
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\,\text{pb}}_{-1.15\,\text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

Dependences on Parton Distributions

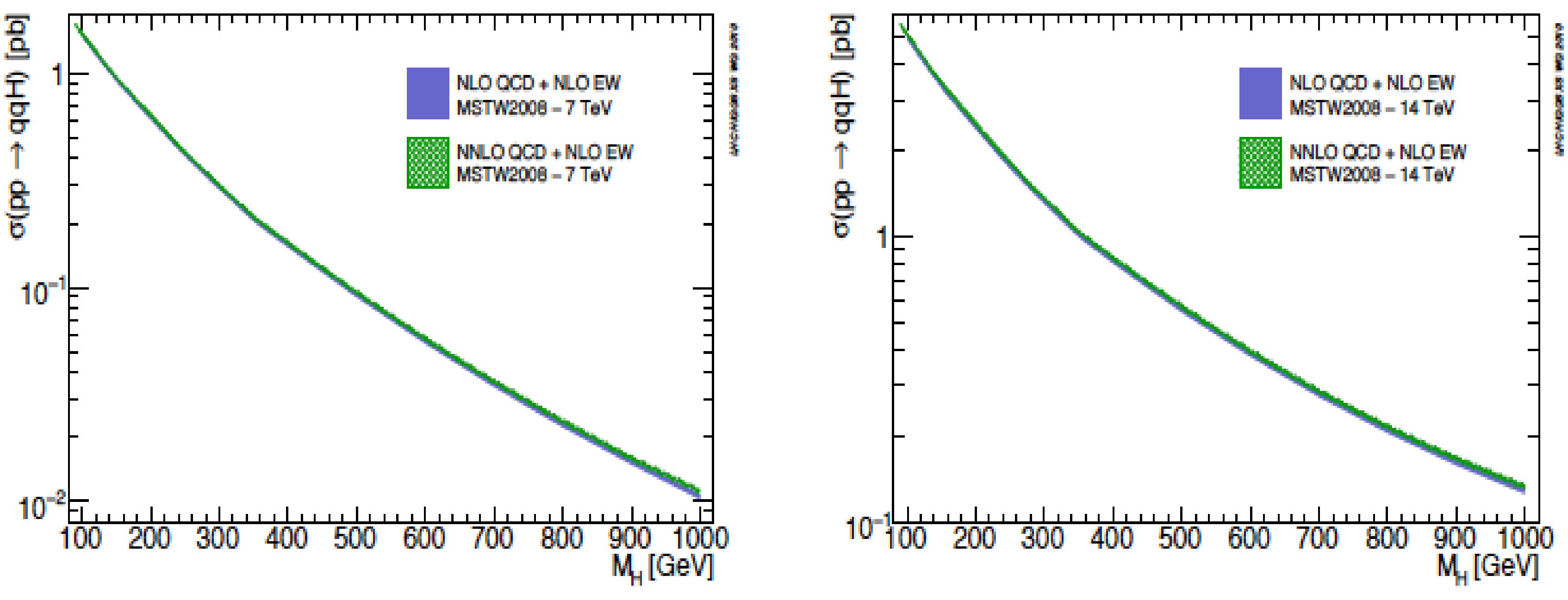
Uncertainties now ~ 2 %,

Similar uncertainties in gg➔H, ttH from α_s

LHC Higgs Cross-Section Working Group (LHXSWG)

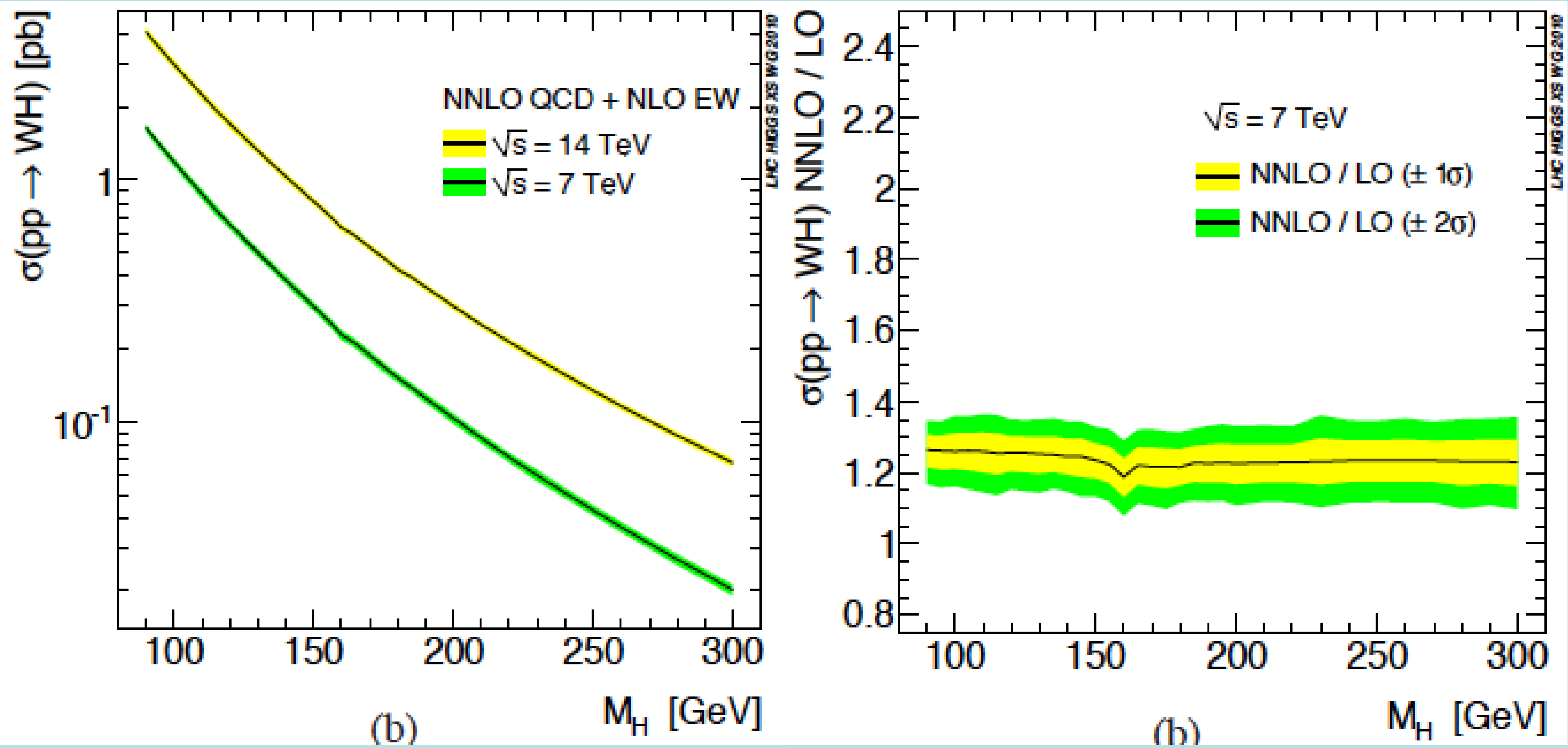


VBF Higgs Production at the LHC



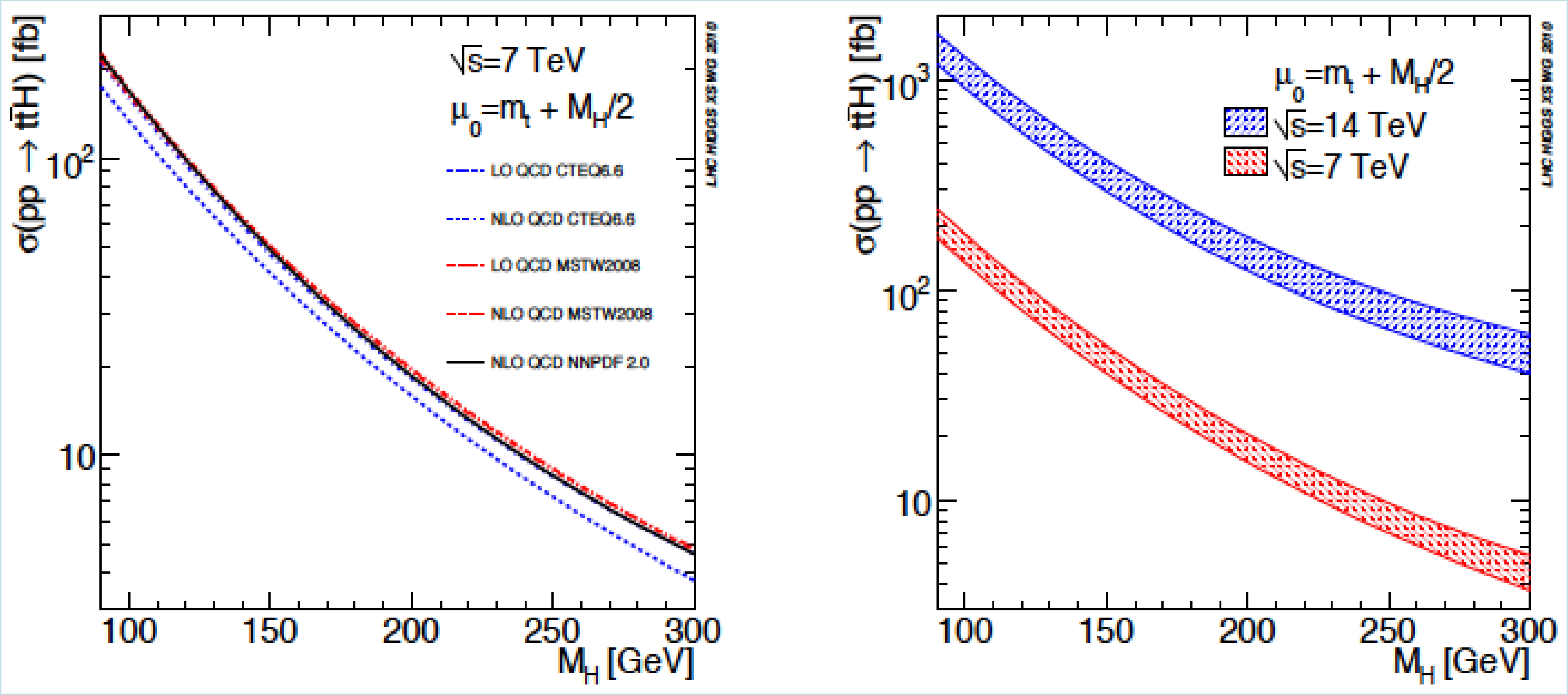
- Calculated at NNLO including electroweak corrections at NLO
- Good convergence of perturbation expansion
- Small uncertainties in quark parton dist’ns

Associated V+H Production at the LHC



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

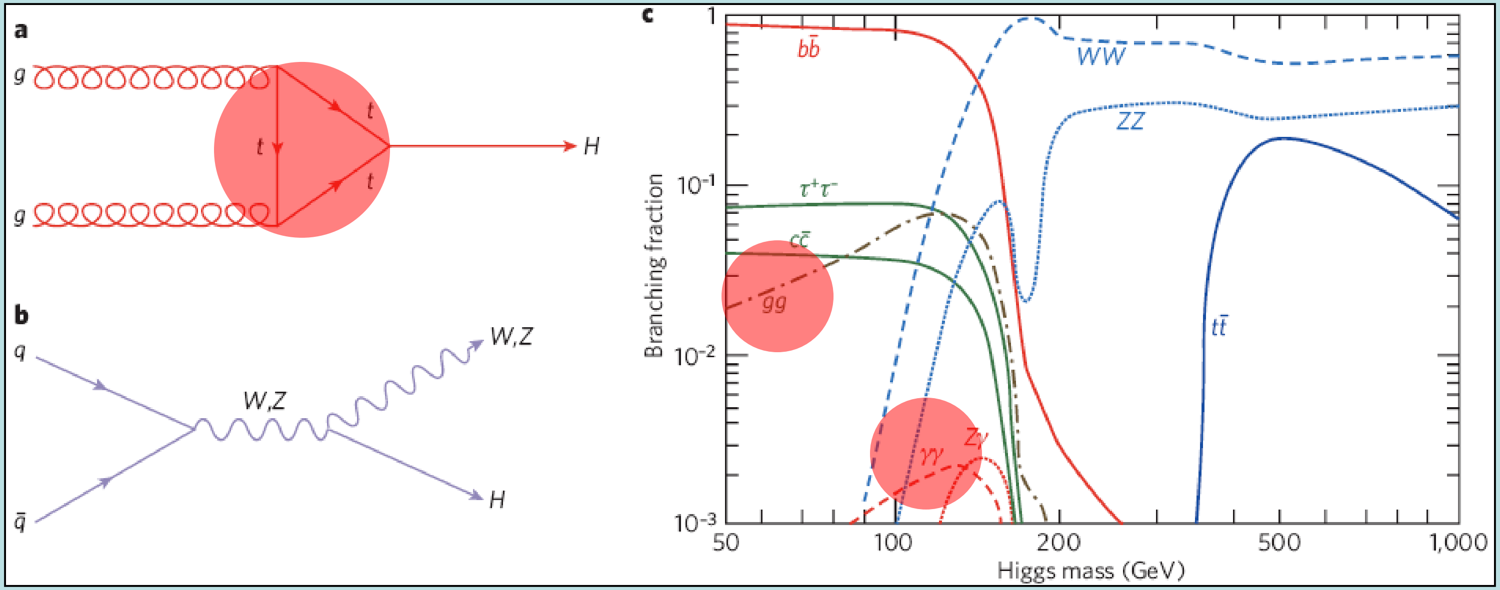
Associated $t\bar{t}$+H Production



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

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)

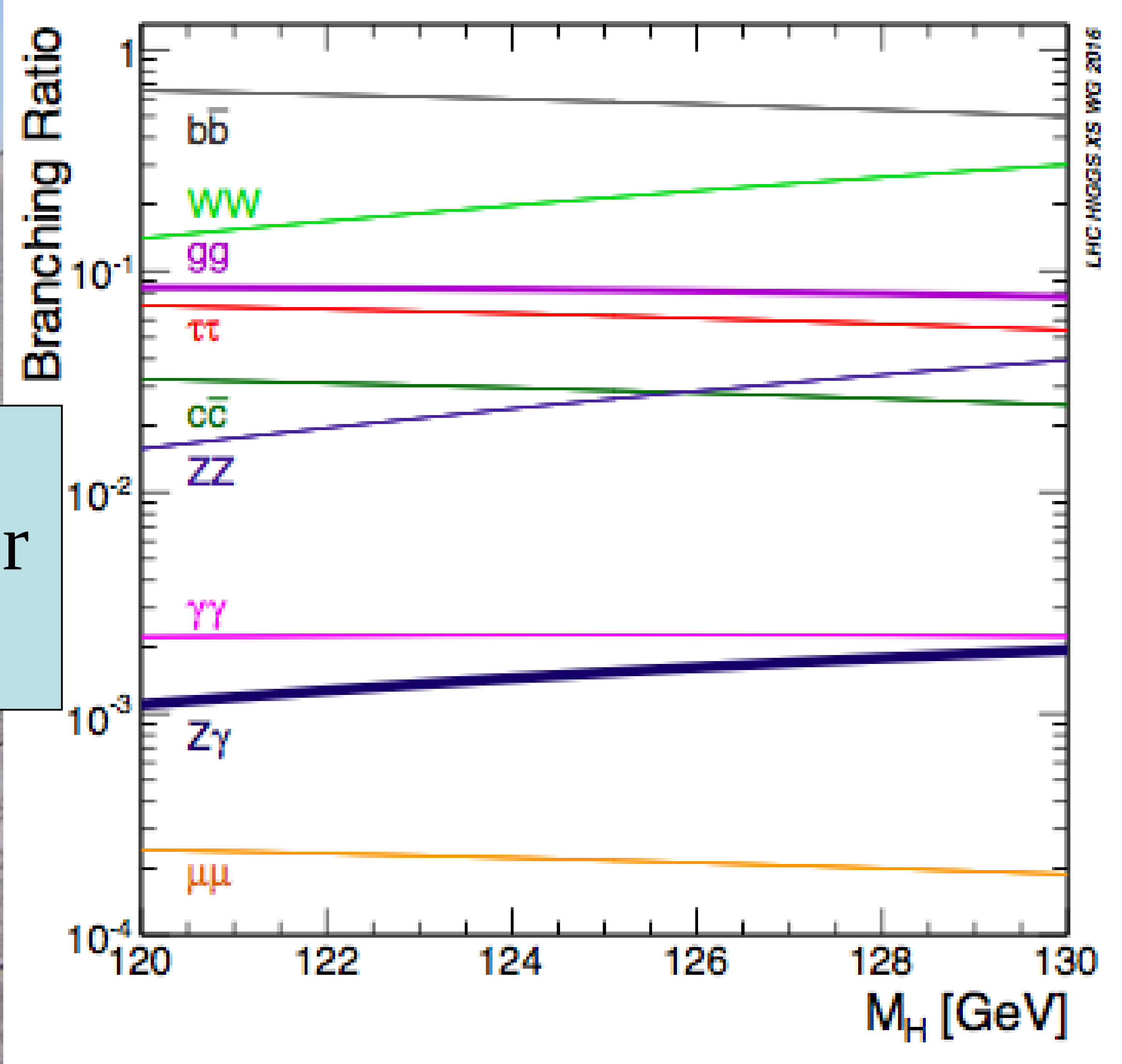


- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

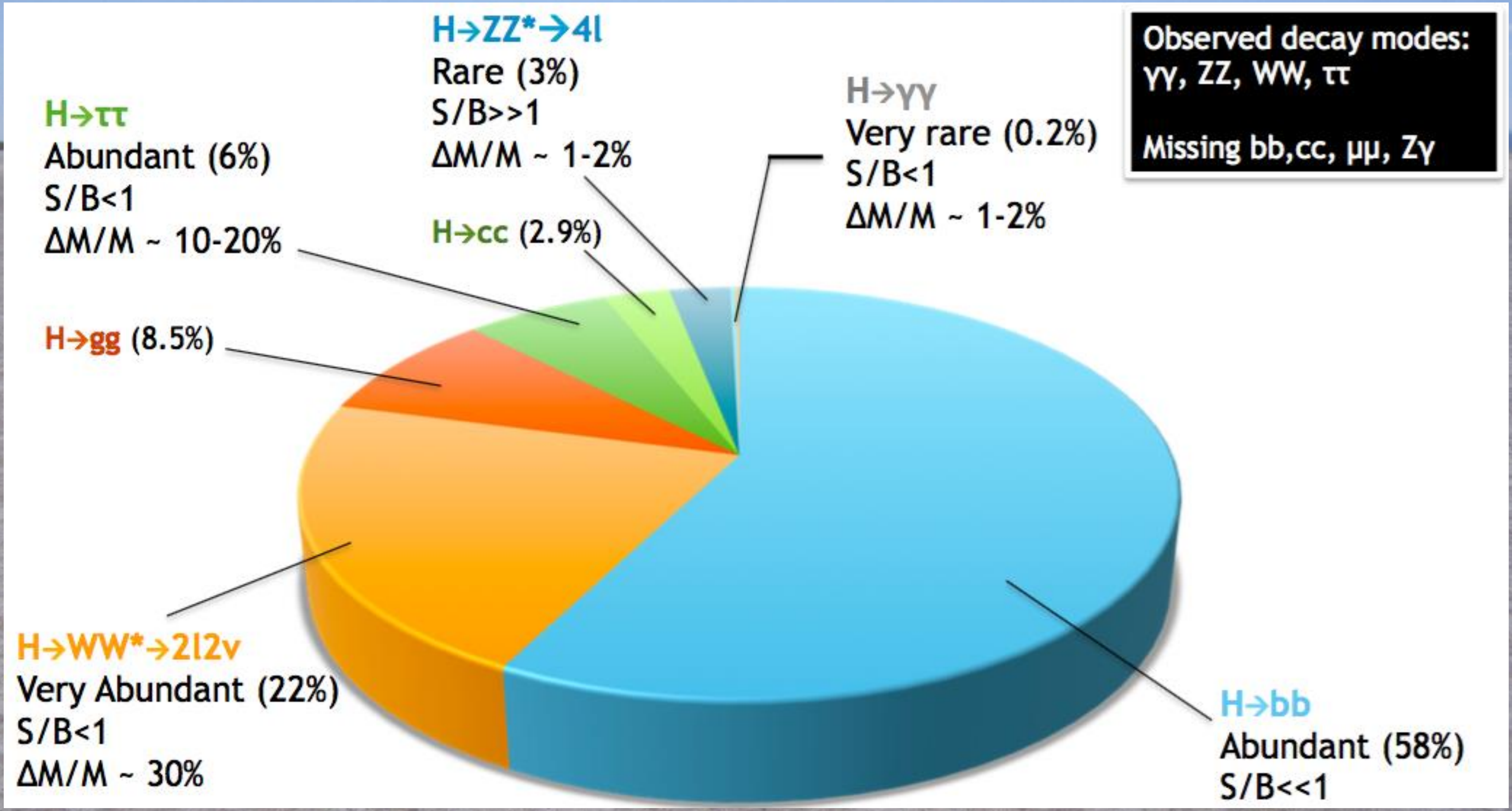
Higgs Decay Branching Ratios

Dominant decay branching ratios for $m_H \sim 125$ GeV



LHC Higgs Cross-Section Working Group (LHXSWG)

What we Expect



What do we know?

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!**

Higgs champagne in Singapore

The wait is over

Champagne bottle, 2012

In 1964, Robert Brout, François Englert, Gerald Guralnik, Carl Richard Hagen, Tom Kibble and Peter Higgs put forward a bold new idea to explain how fundamental particles acquire mass. Higgs suggested that if they were right, a new particle should exist.

On the evening of 3 July 2012, Higgs shared this bottle of champagne with his friends, theoretical physicist John Ellis and former CERN Director-General Chris Llewellyn Smith. The next day, CERN announced the discovery of the particle he had proposed almost five decades earlier, the Higgs boson.

Peter Higgs at the University of North Carolina, 1965.

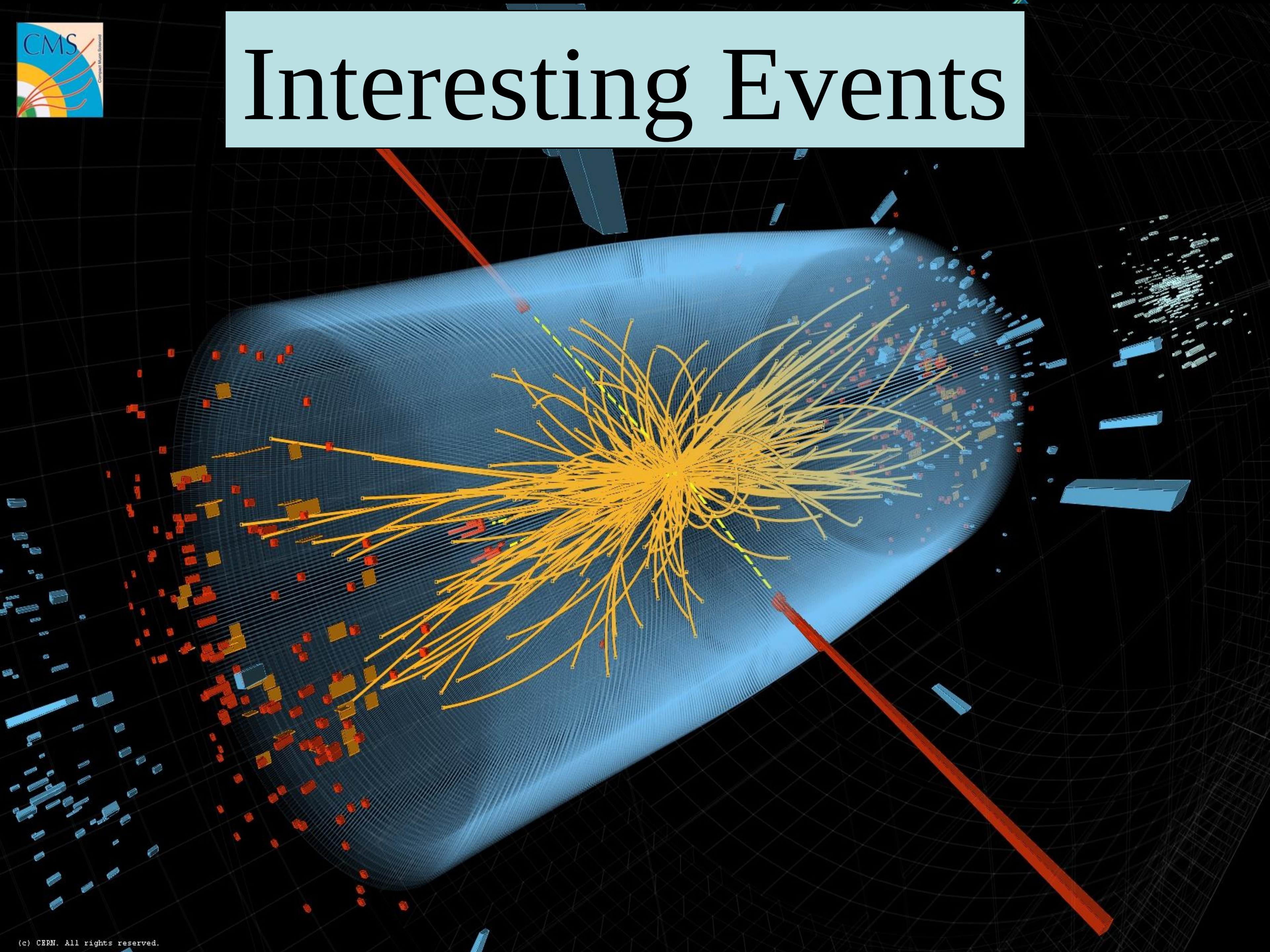
Inside atoms

Rutherford – Bohr atomic models, 1926

In the early 20th century, the electron was the only subatomic particle known. When Ernest Rutherford and his team at Manchester discovered that atoms had another particle at their centre – later named the 'nucleus' – a new theory was needed to describe the atom's inner structure.

These models, showing rings of electrons orbiting a nucleus, depict the atomic theory proposed by Rutherford in 1911 and revised by Niels Bohr in 1913. This planetary structure became the classic image of the atom in popular culture.

Interesting Events



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Higgsdependence Day!

July 4th 2012
The Higgs discovery

International Herald Tribune

Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Oil Backed Up, Iranians Put It On Idled Ships

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

The Economist

A giant leap for science

Finding the Higgs boson

The Gazette

'God particle' discovery has scientists giddy. Page A2

EL PAIS

Hallada la partícula clave para a comprensión del universo

Milhares de moradores de bairros sociais em risco de perderem RSI

"Partícula de Deus" existe, mas a história não acaba aqui

Le boson de Higgs, particule manquante pour expliquer l'Univers, vient d'être découvert

MK

ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ

AD ALGEMEEN DAGBLAD

EINDELIJK GELIJK NA 48 JAAR

Frankfurter Allgemeine

Masse macht's

CHINA DAILY

IMPORTANT MATTER

Scientists claim to have discovered 'God particle'

THE TIMES OF INDIA

Big bang moment: Scientists may have found 'God particle'

THE HINDU

Elusive particle found, looks like Higgs boson

CERN physicists hail evidence of game-changing discovery of subatomic particle

CORRIERE DELLA SERA

La particella che può svelare i segreti dell'universo

gazeta WYBORCZA.PL

BOSKA MASA

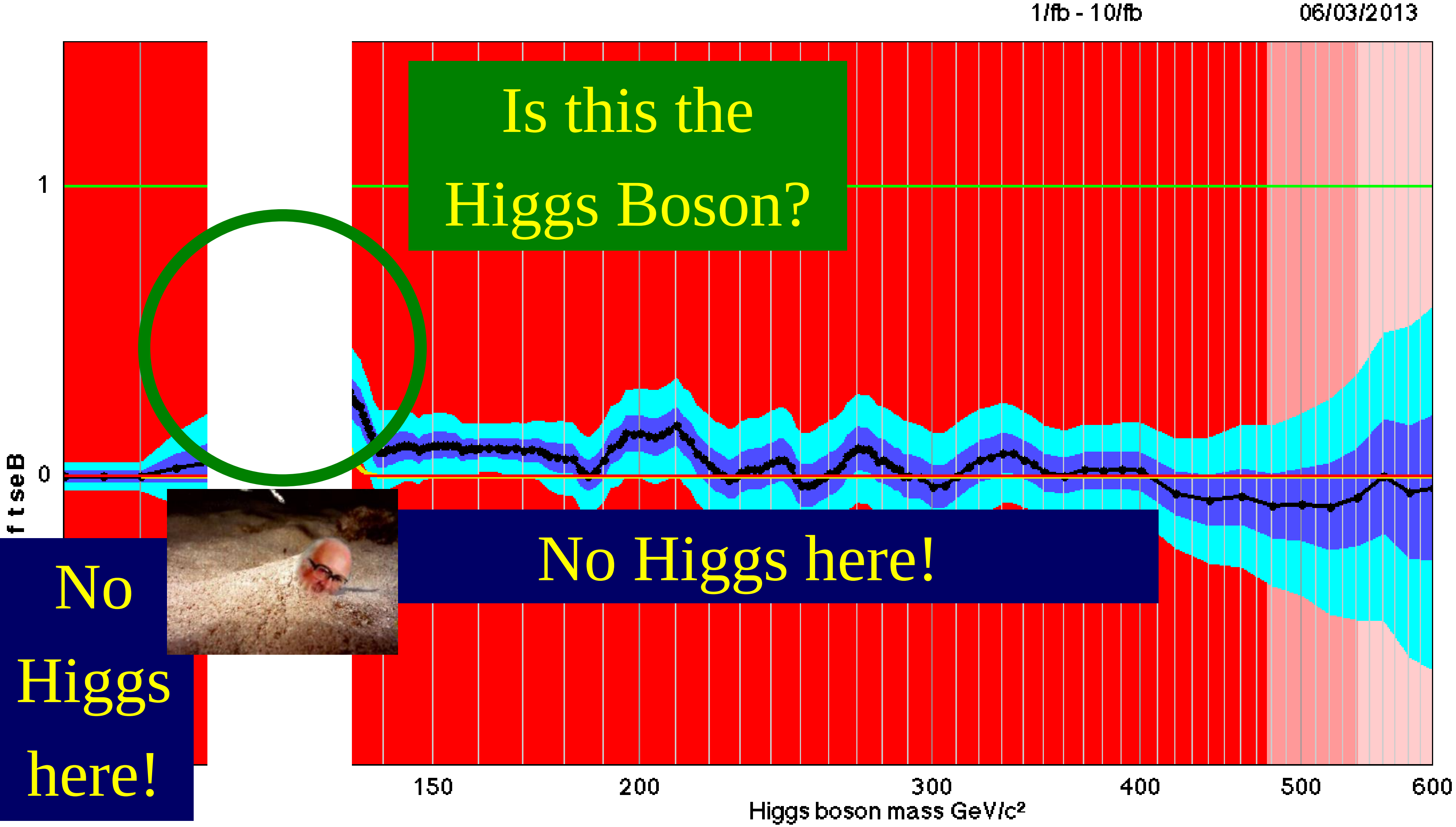
Cząstkę Higgsa fizycy najpierw wymyślili, potem szukali 40 lat

আনন্দবাজার পত্রিকা

বিজ্ঞানের 'ঈশ্বর' দর্শন

'পেয়েছি, যা খুঁজছিলাম'

Unofficial Combination of Higgs Data



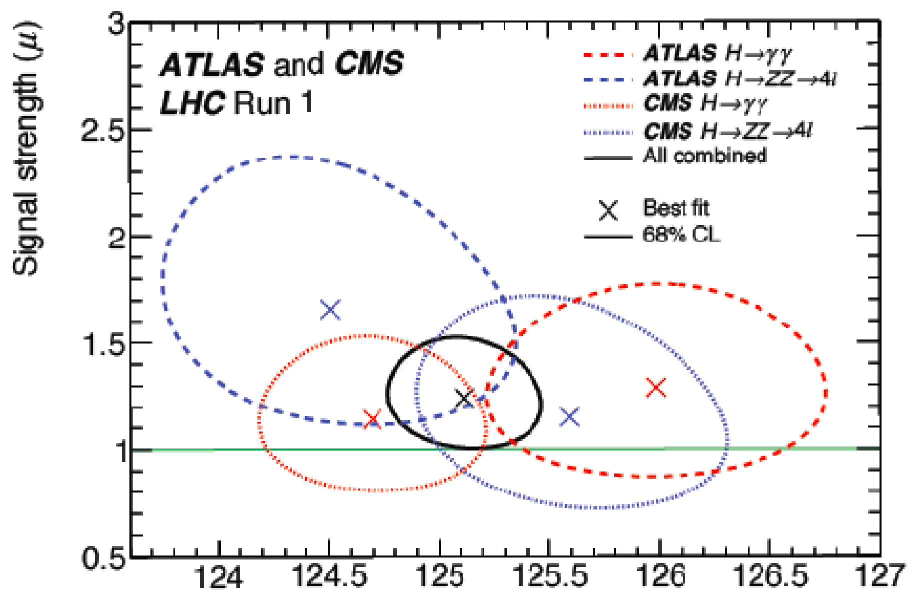
Is this the Higgs Boson?

No Higgs here!

No Higgs here!

Higgs Mass Measurements

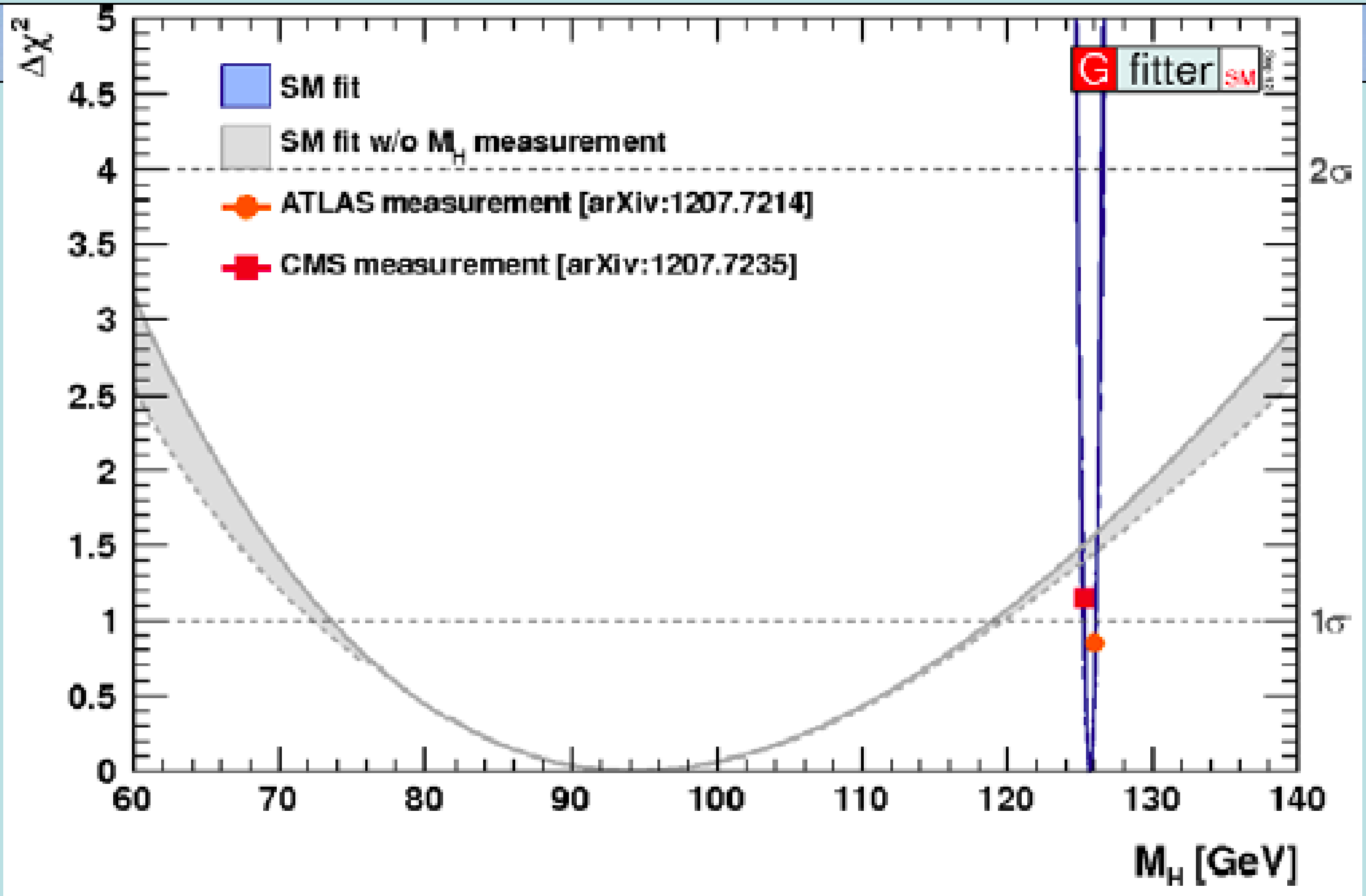
- ATLAS + CMS ZZ* and γγ final states



$125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$

- Statistical uncertainties dominate
- Allows precision tests
- **Crucial for stability of electroweak vacuum**

Comparison with Electroweak Fit



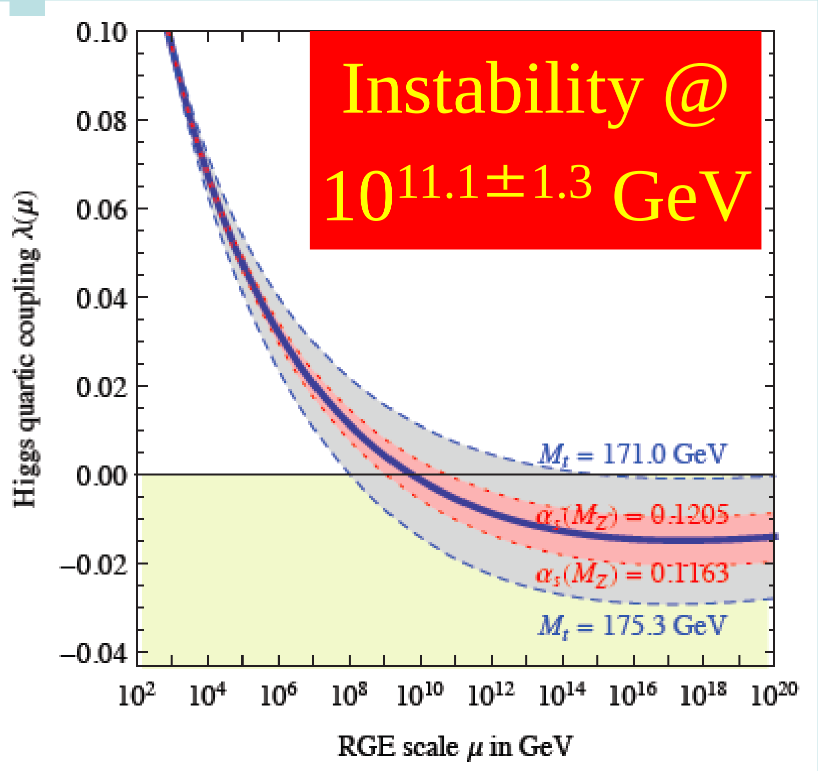
Quite consistent: $\Delta\chi^2 \sim 1.5$

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



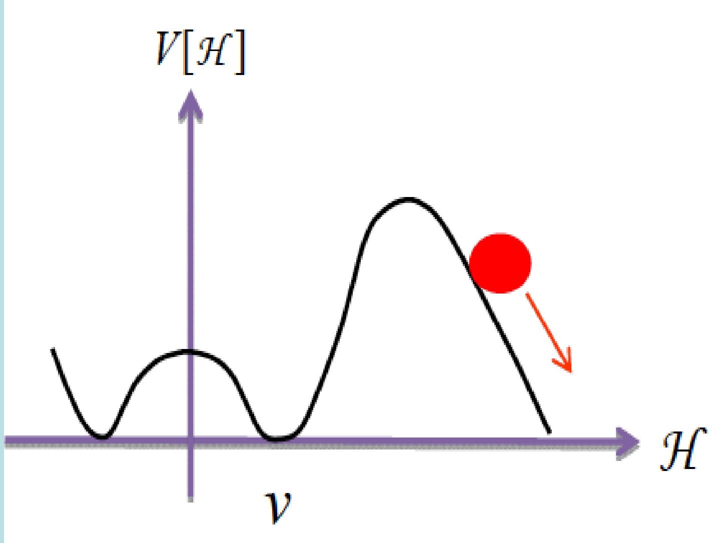
Instability @ $10^{11.1 \pm 1.3}$ GeV

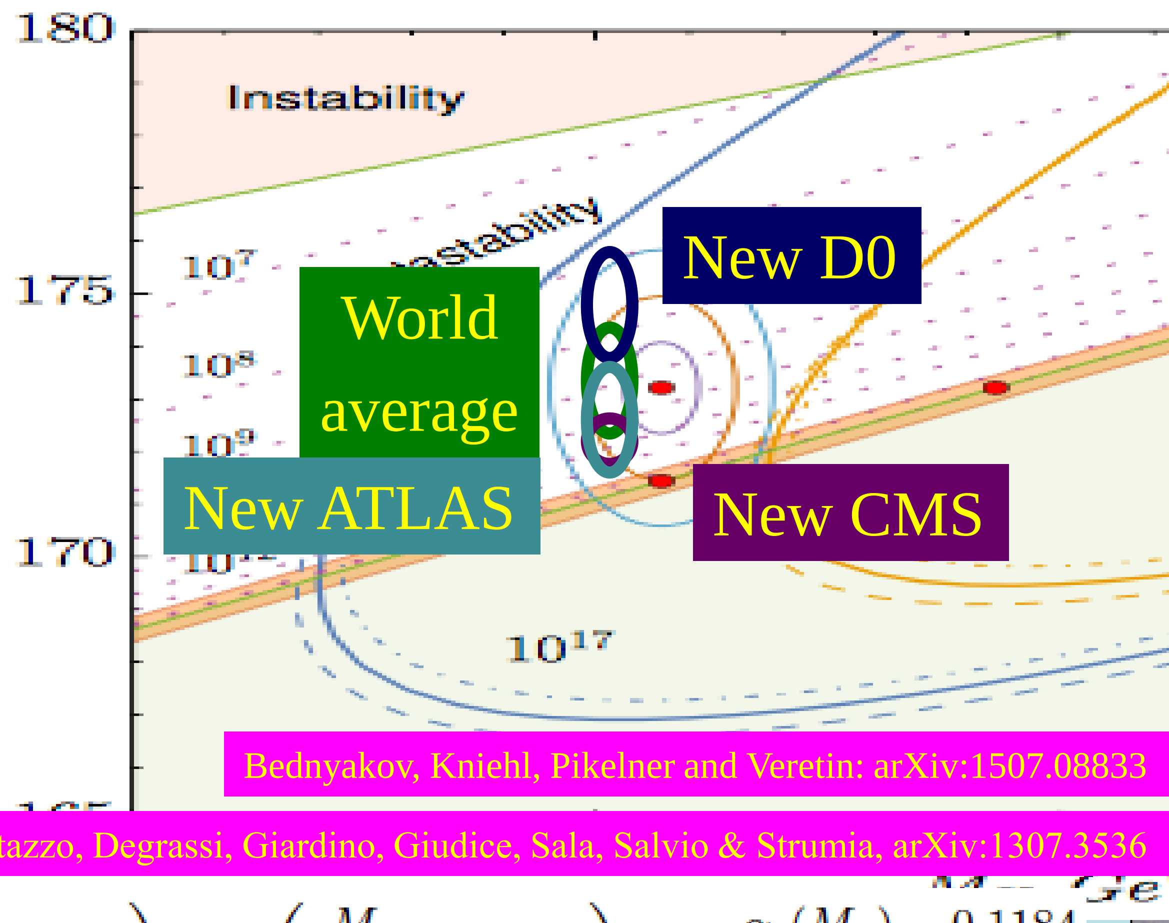
- Vacuum could be stabilized by **Supersymmetry**

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

Vacuum Instability in the Standard Model

- Very sensitive t





New D0

World average

New ATLAS

New CMS

Bednyakov, Kniehl, Pikelner and Veretin: arXiv:1507.08833

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Instability scale

$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$

Hard QCD: the Top Mass

- Basic parameter of SM; **stability of EW vacuum?**
- World average:

$m_t = 173.34 \pm 0.76$ GeV

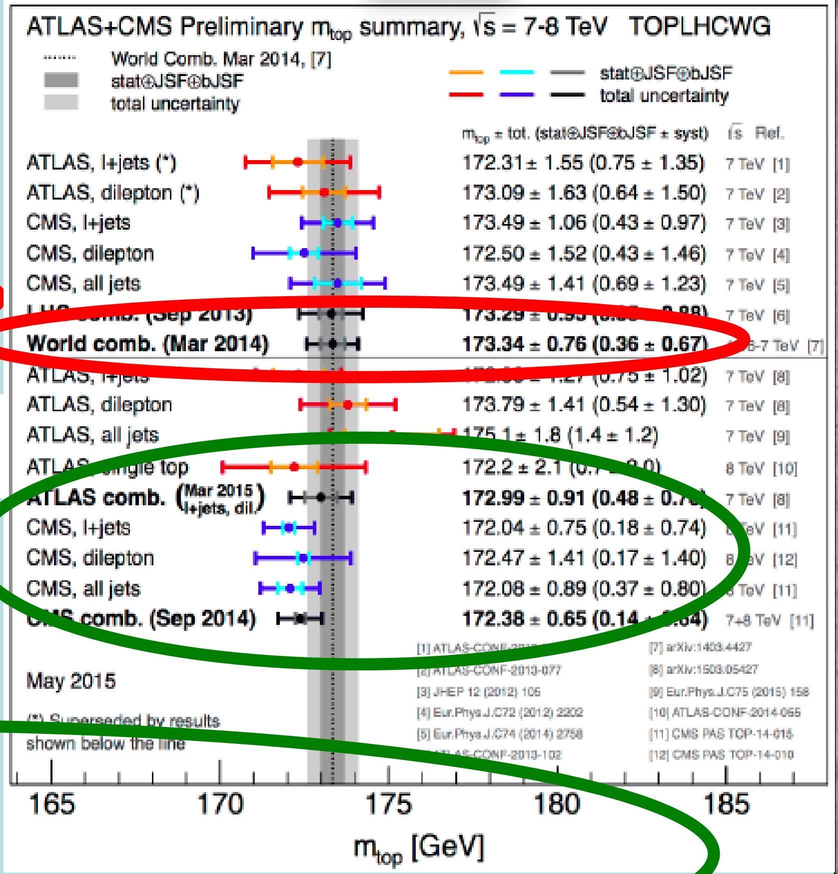
- **Running → pole mass OK?**

$$+\,7.557 + 1.617 + 0.501 + 0.195)$$

- Monte Carlo mass ✓?
- New measurements:

ATLAS: 172.99±0.91 GeV

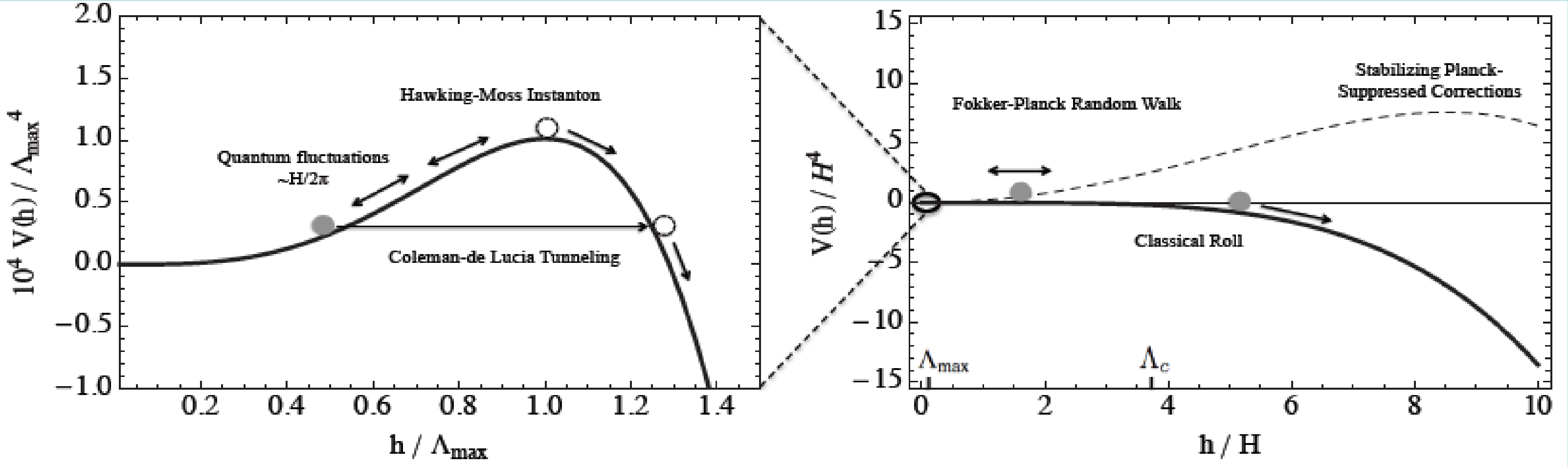
CMS: 172.38±0.65, D0: 174.98±0.58±0.49 GeV



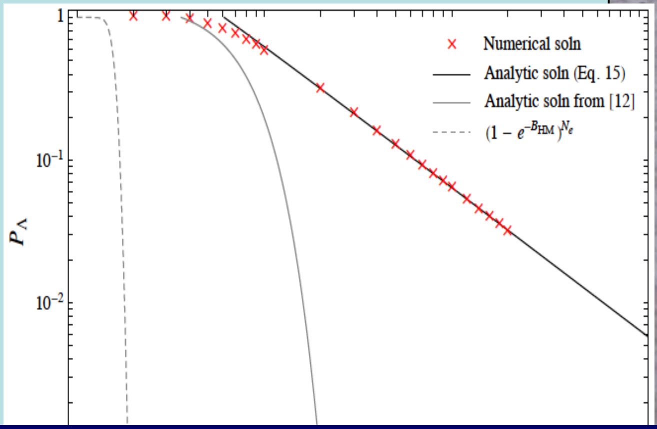
Instability during Inflation?

Hook, Kearns, Shakya & Zurek: arXiv:1404.5953

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Do AdS regions eat us?
  - – Disaster if so
  - – If not, OK if more inflation



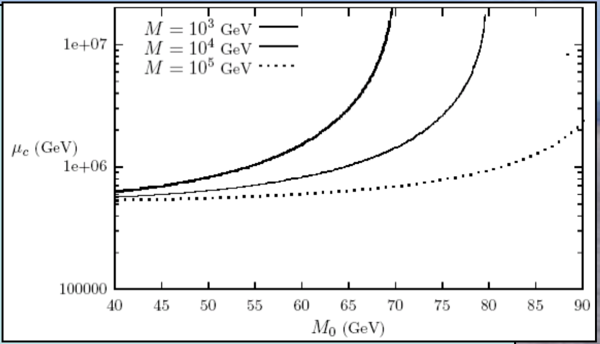
Stabilize vacuum with some physics beyond the SM?

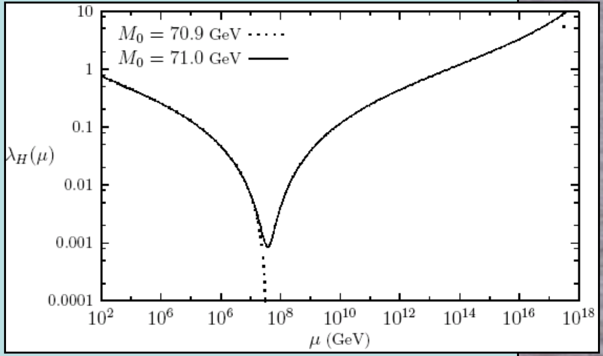
How to Stabilize a Light Higgs Boson?

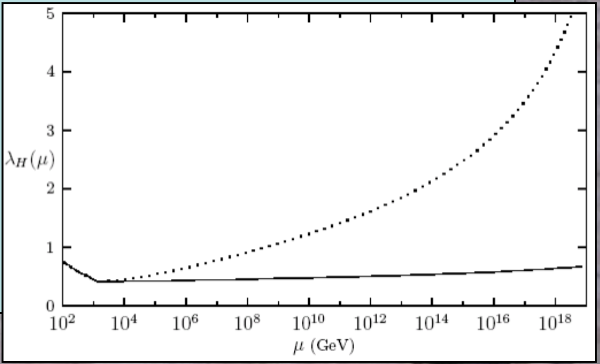
- Top quark destabilizes potential: introduce stop-like scalar:

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

- 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!**

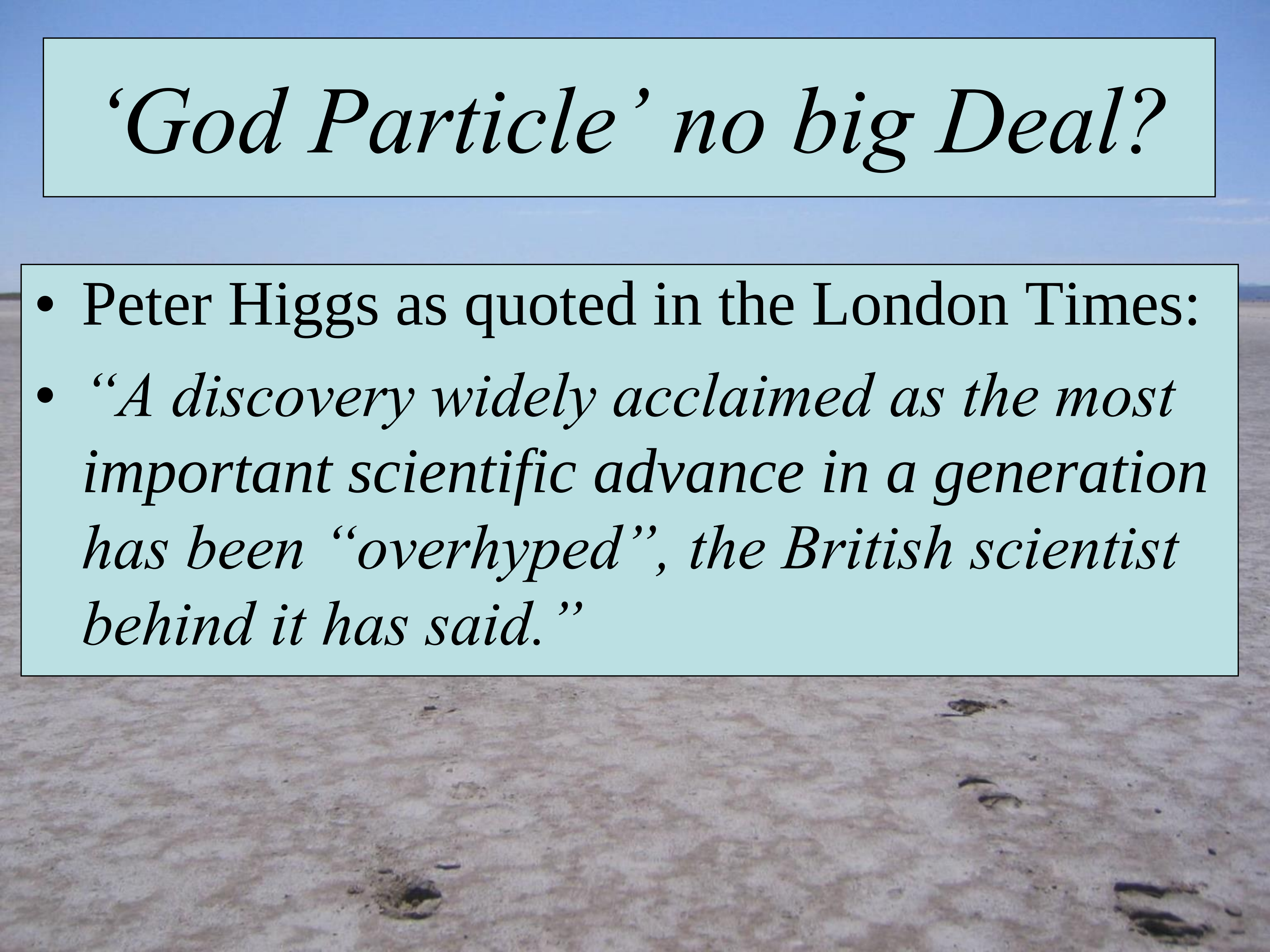






JE + D. Ross

‘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.”*

Without Higgs …

… there would be no atoms

- Electrons would escape at the speed of light

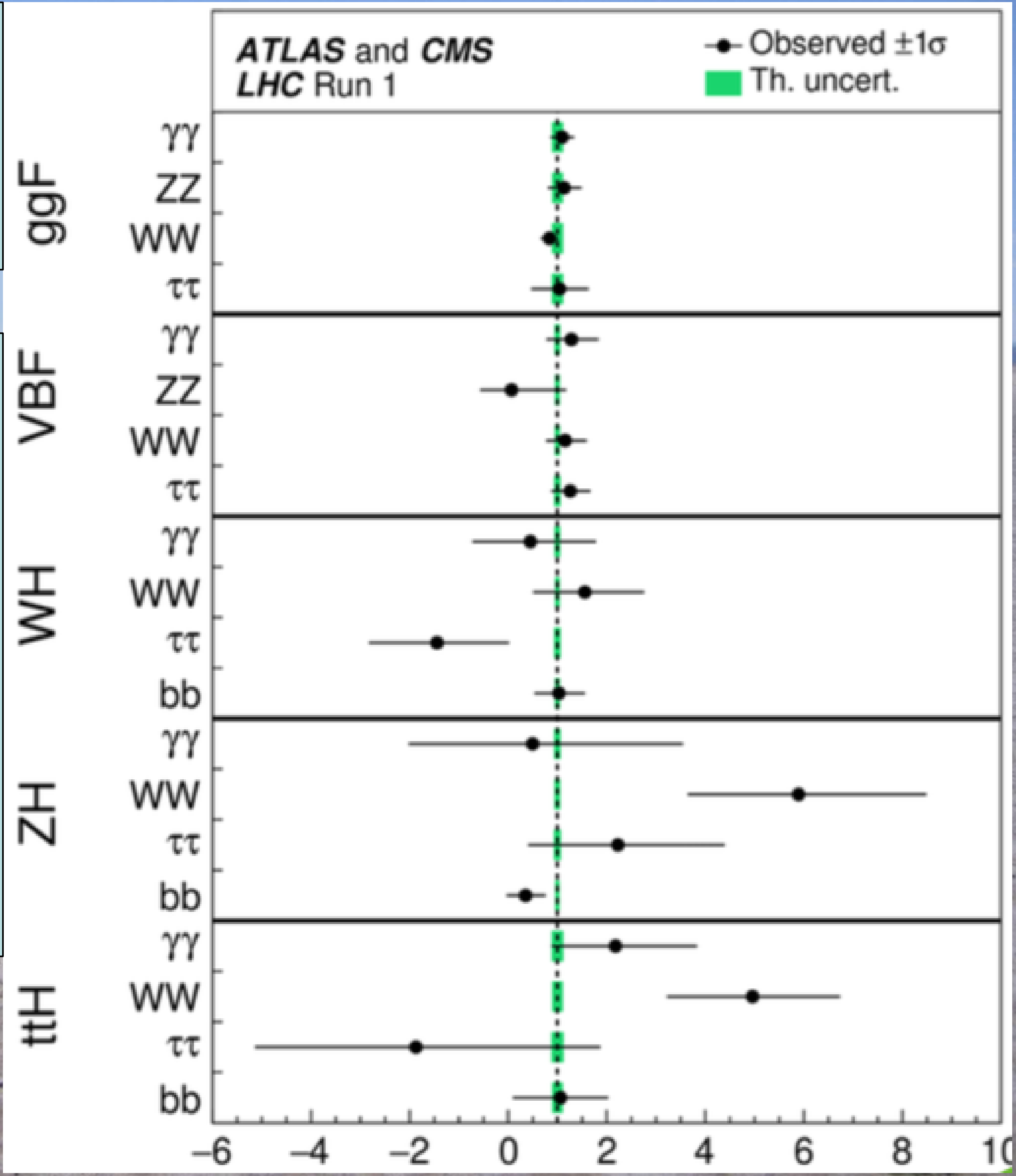
… weak interactions would not be weak

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

The discovery of the Higgs Boson is a big deal

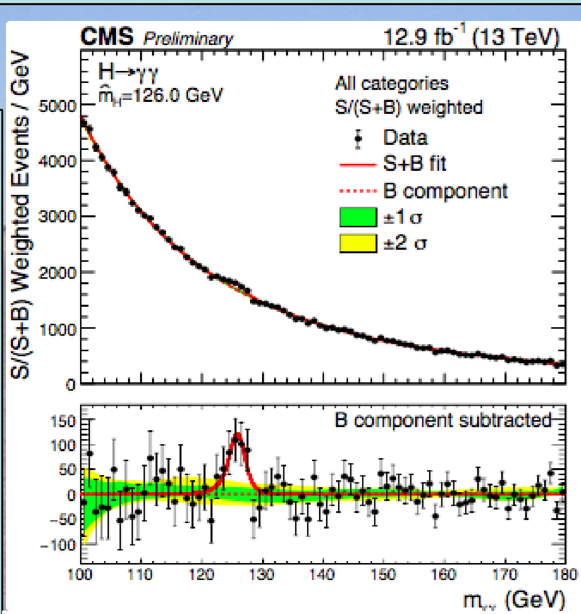
Measurements in Run 1

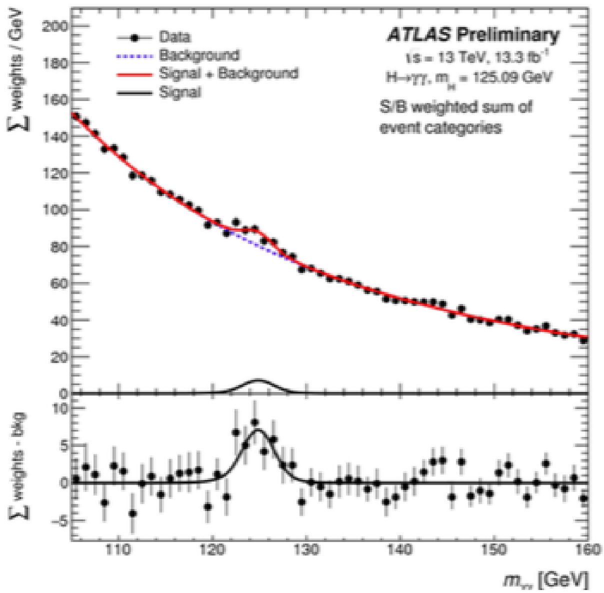
- Open questions:
  - H➔bb?
    - 2.6σ @ LHC
    - 2.8σ @ FNAL
  - H➔➚μ?
  - ttH production?
  - tH production?

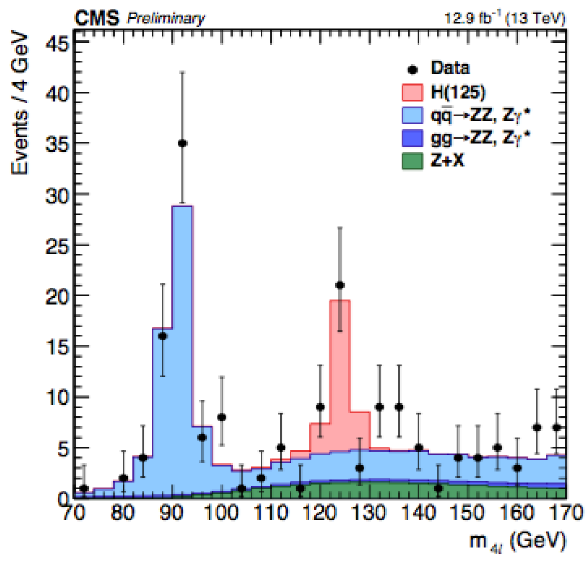


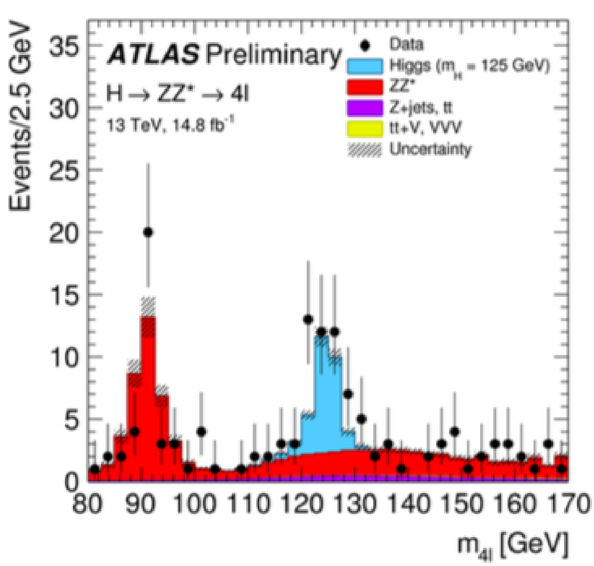
Measurements in Run 2

- Measurements in γγ and ZZ* final states
- 10σ significance
- Cross-section agrees with theory
- Searching for ttH, H➔μμ and tH



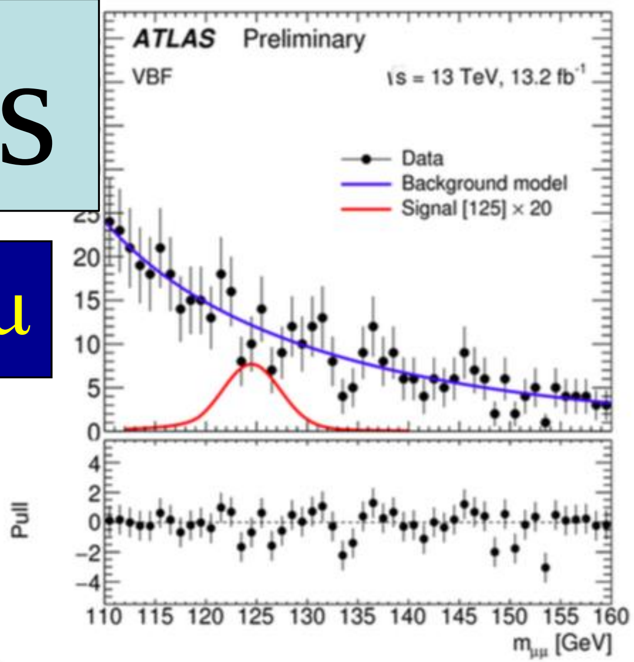






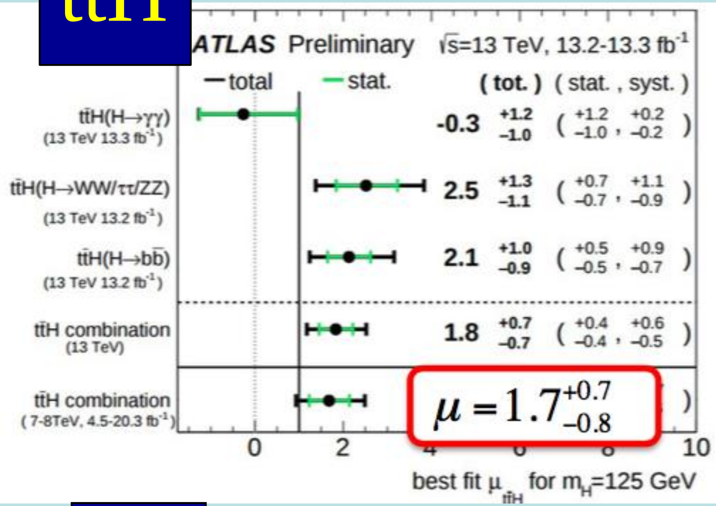
The Next Frontiers

H→μμ

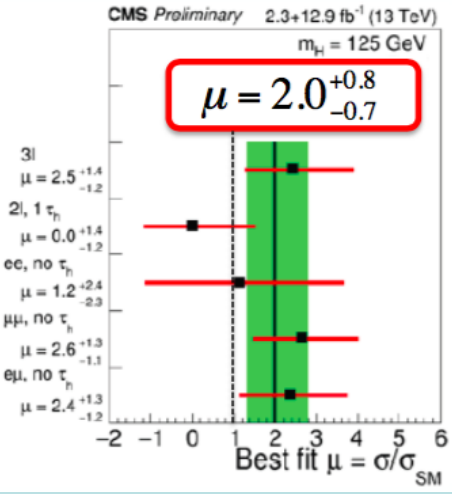


ATLAS	Upper limit x SM (expected)
Run 1	7.1 (7.2)
Run 2	4.4 (5.5)
Combined Run 1 and Run 2	3.5 (4.5)

ttH



$$\mu = 1.7^{+0.7}_{-0.8}$$



$$\mu = 2.0^{+0.8}_{-0.7}$$

tH

CMS	Upper limit x SM (expected)
SM	113.7 (98.6)
	6.0 (6.4)

Opposite sign of t Yukawa coupling