The Standard Model & Beyond

Not only the Higgs discovery – though that is important!

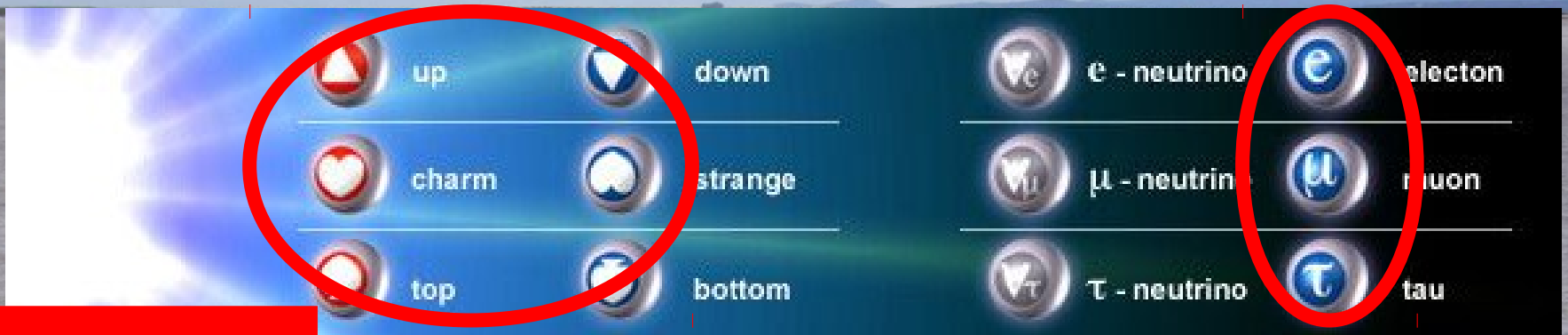*John Ellis*

KING'S *College* LONDON

Programme of Lectures

- The road to the Higgs discovery
- Characterizing the new particle
- What else?
  - Supersymmetry?
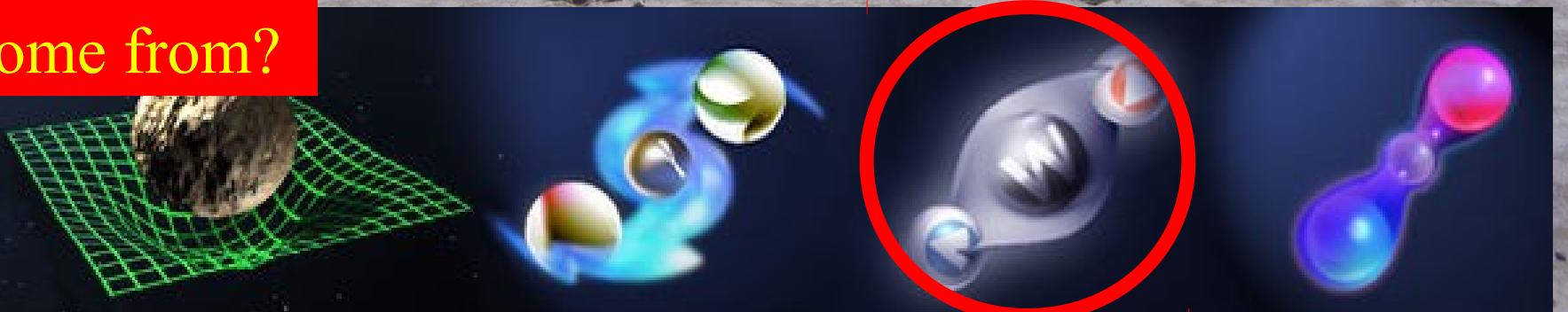 - Future accelerators?
  - Cosmological inflation?

JE "Higgs Physics": arXiv:1312.5672

The Standard Model

= Cosmic DNA

The matter particles

up	down	e - neutrino	electon
charm	strange	μ - neutrino	muon
top	bottom	τ - neutrino	tau

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)

Standard Model Particles: Years from Proposal to Discovery

Source: *The Economist*
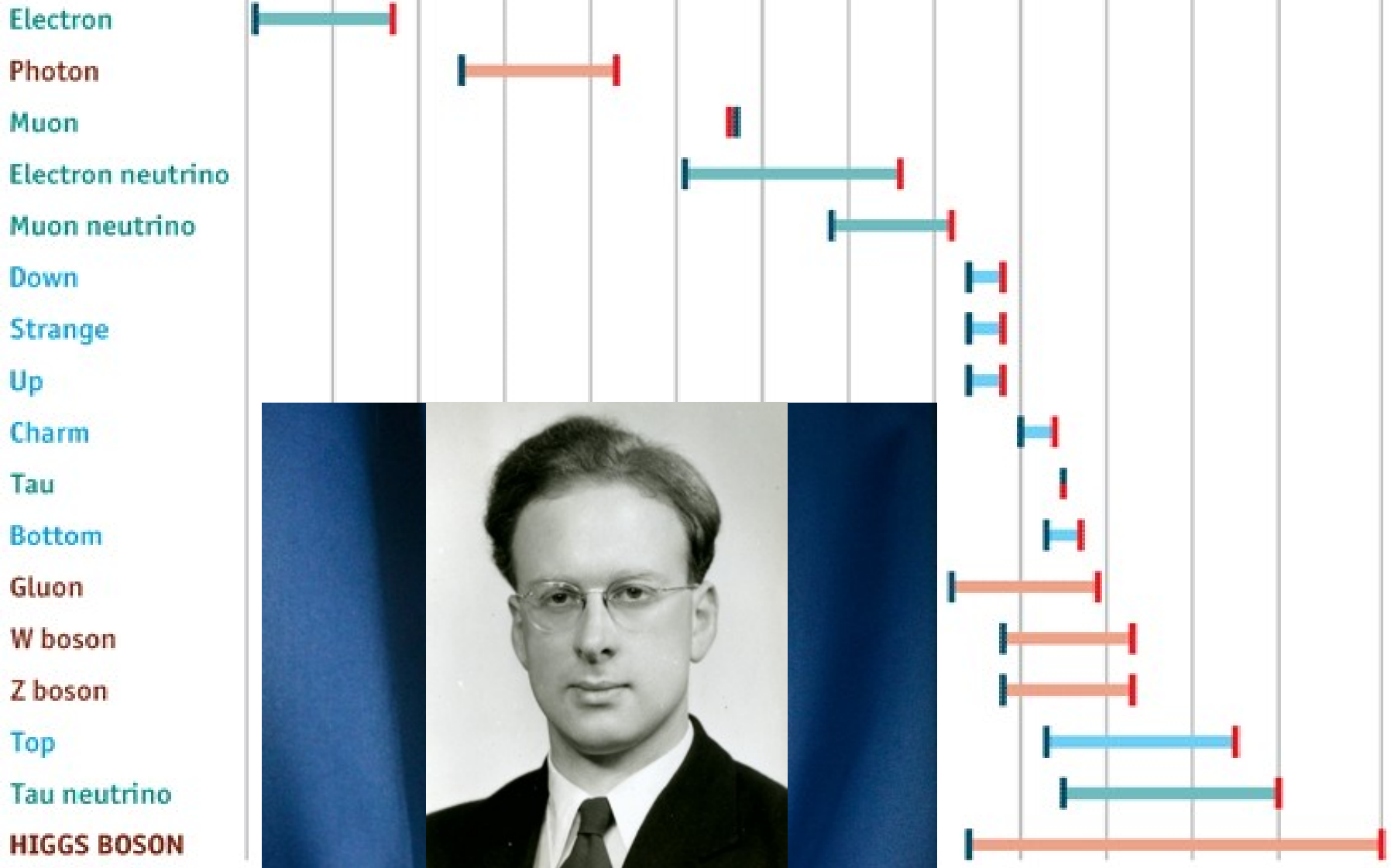
Summary of the Standard Model

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

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

- Lagrangian:

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

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?

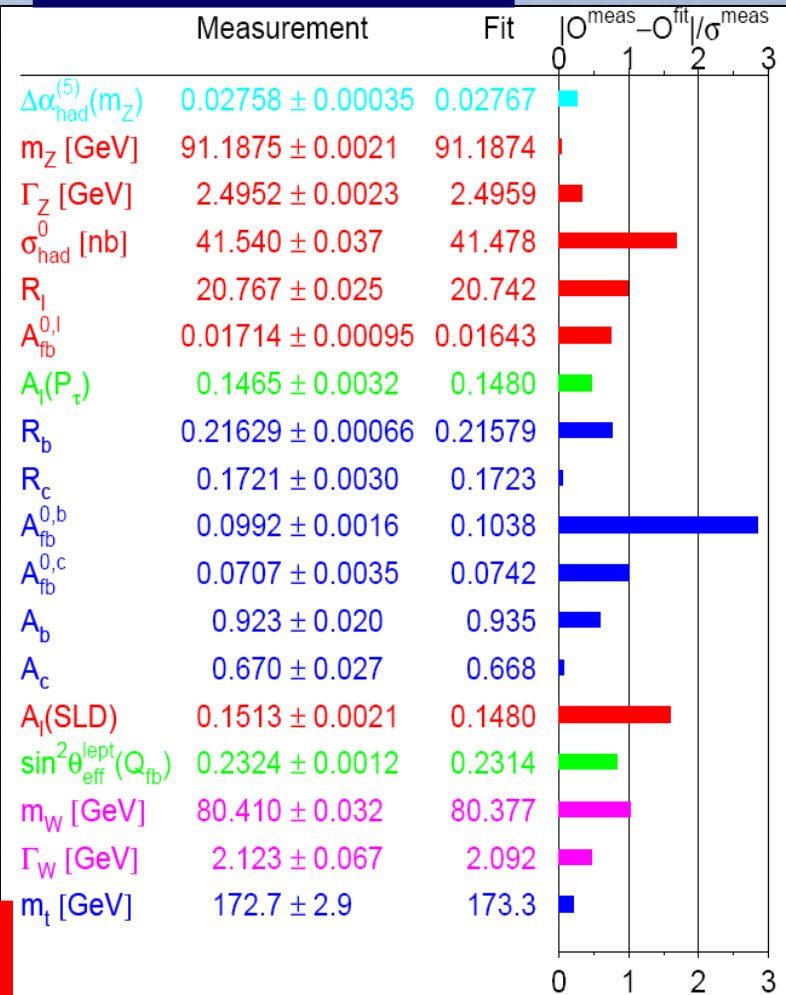# Precision Tests of the Standard Model

	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$
			0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	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!

The Standard Model Lagrangian

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

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

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

✓ Experiment: accuracy < %

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

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi^c q_R^u + y_L \bar{L}_L \phi l_R +$$

No direct evidence until July 4, 2012

$$D_\mu^L = \partial_\mu - ig W_\mu^a T^a - iY g' B_\mu \quad , \quad D_\mu^R = \partial_\mu - iY g' B_\mu$$

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

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

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BROKEN SYMMETRIES AND THE MASSES OF GAU...

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 A. ...

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

J. Expe...

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

- Guralnik, Hagen & Kibble (Oct. 12th 1964)

But the Higgs Boson

Englert & Brout

Higgs

Guralnik, Hagen & Kibble

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

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

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

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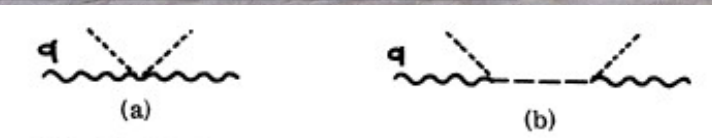
FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu} \langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2 (q_\mu q_\nu/q^2) \times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

The Higgs Mechanism

- Postulated effective Higgs potential:

$$V[\phi] = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$
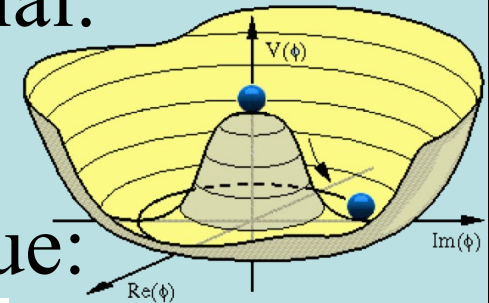
- Minimum energy at non-zero value:

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

- 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

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

- 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 $\alpha(x) = -\theta(x)$: $\qquad \phi'(x) = \eta(x)$

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

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

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

Nambu EB, H, GHK and Higgs
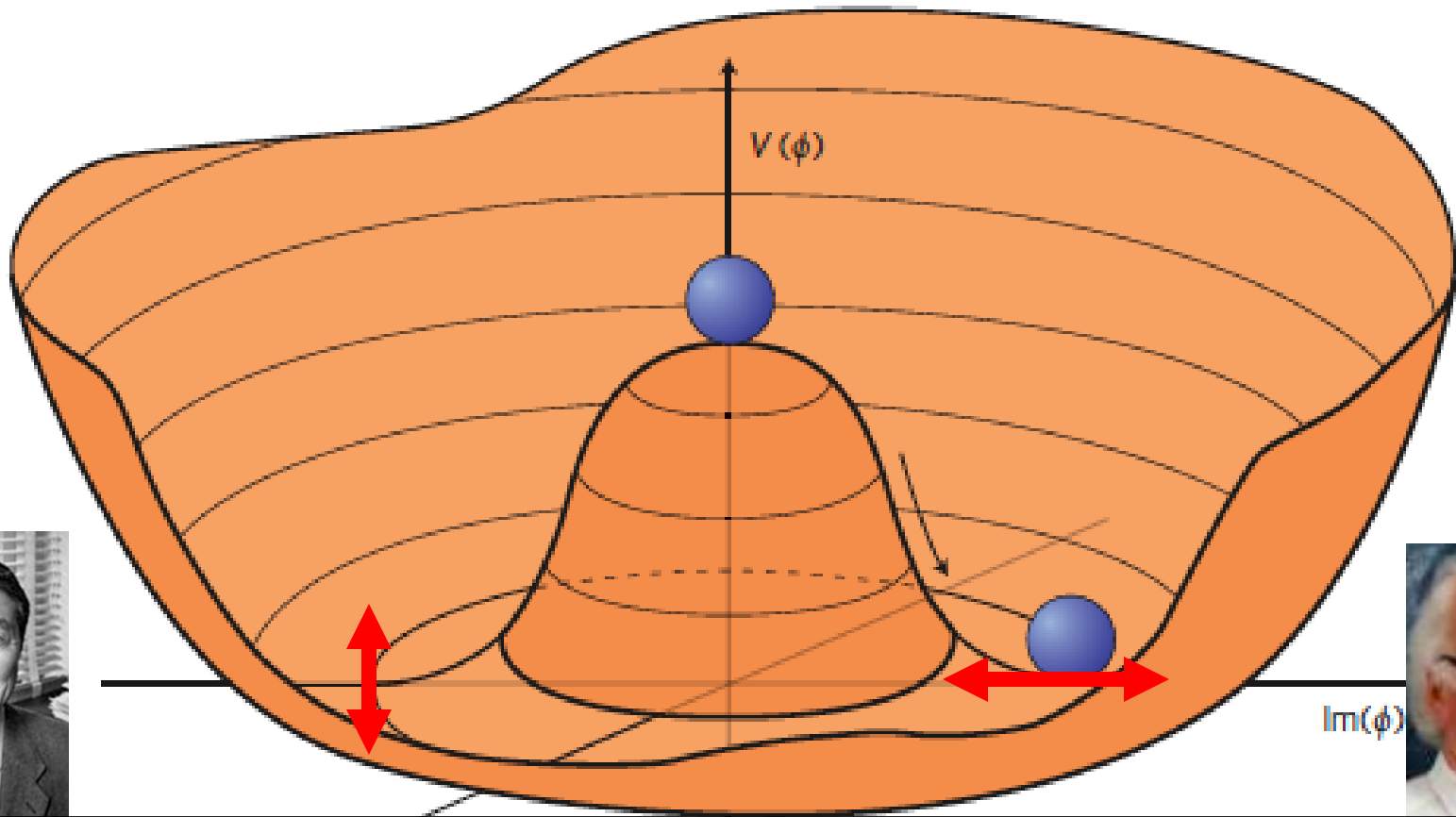
Spontaneous symmetry breaking: massless Nambu-Goldstone boson **'eaten' by massless gauge boson**

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

- 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:

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

Higgs Boson Couplings

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

$$\frac{m_f}{v} \ = \ \frac{g_2 \, m_f}{2 M_W}$$
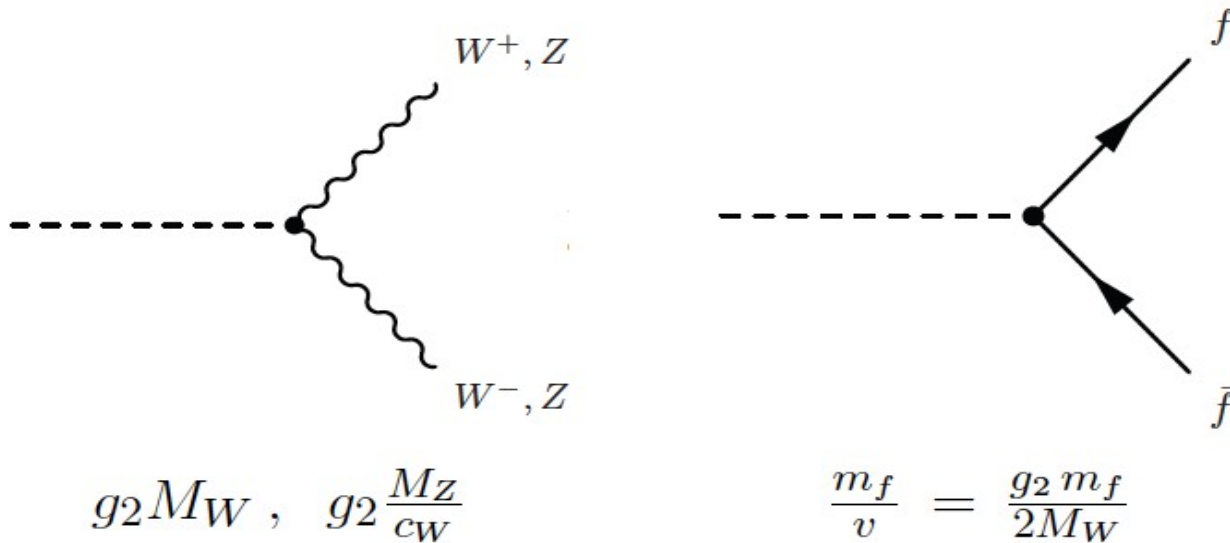
$$\Gamma(H \to f\bar{f}) \ = \ N_c \frac{G_F M_H}{4\pi\sqrt{2}} m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

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

Why a Higgs Boson is Needed

- Trouble with WW scattering: $M \sim E^2$

  ➔ uncontrollable infinities in loop diagrams

  can be cancelled by

  scalar exchange

$W_L W_L \rightarrow W_L W_L$

$\mathcal{M}_V = $ [diagram] $+$ [diagram] $+$ [diagram]

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

$\mathcal{M}_S = $ [diagram] $+$ [diagram]

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

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

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
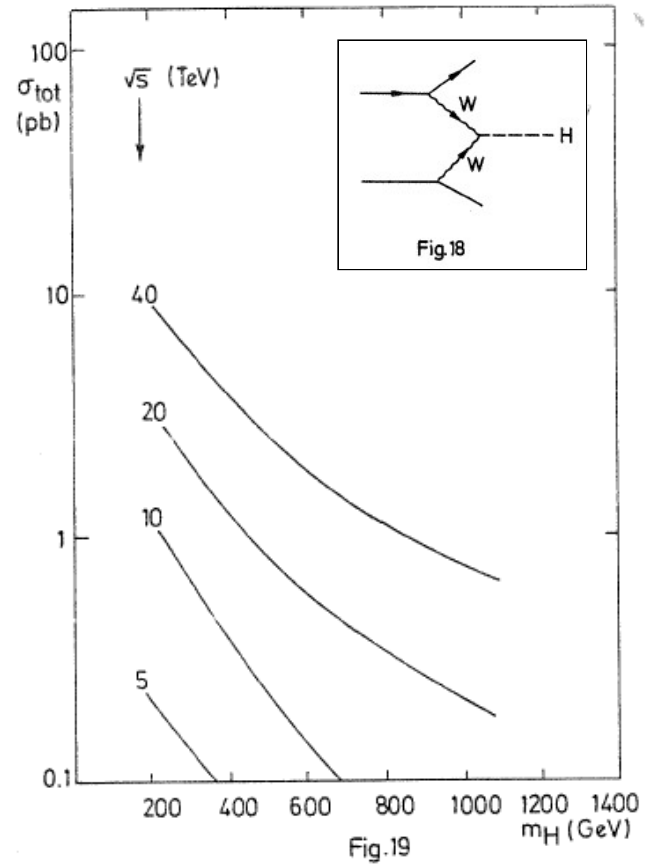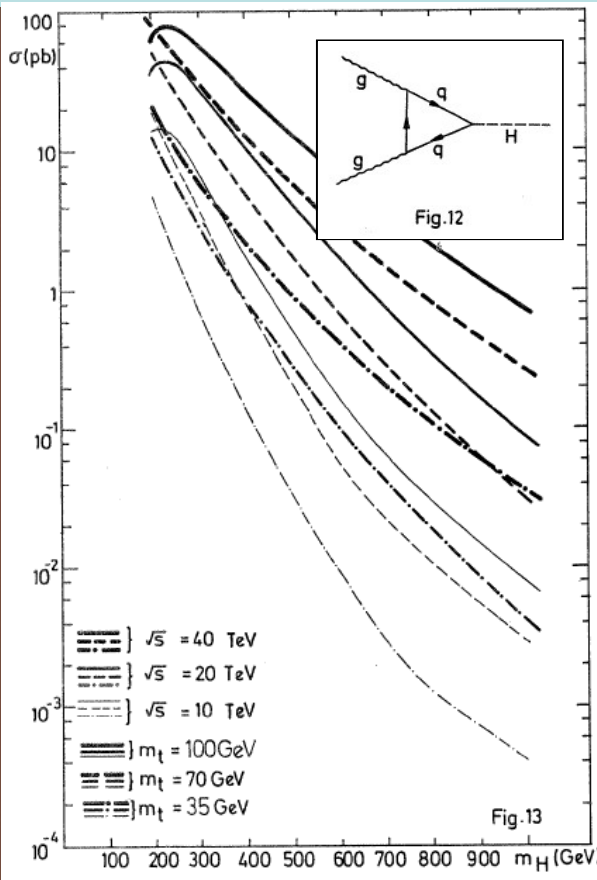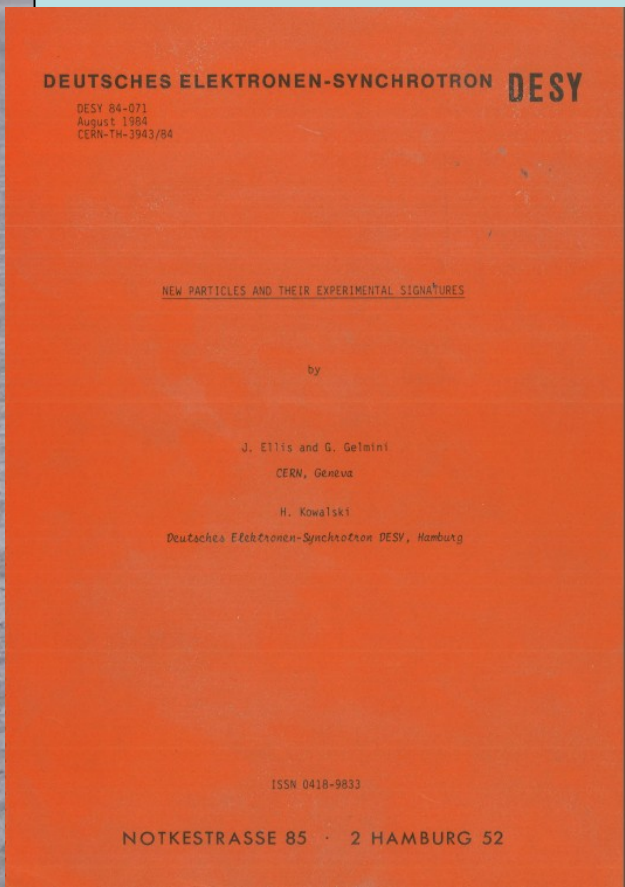
Constraints on Higgs Mass

- 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:

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

- 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

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
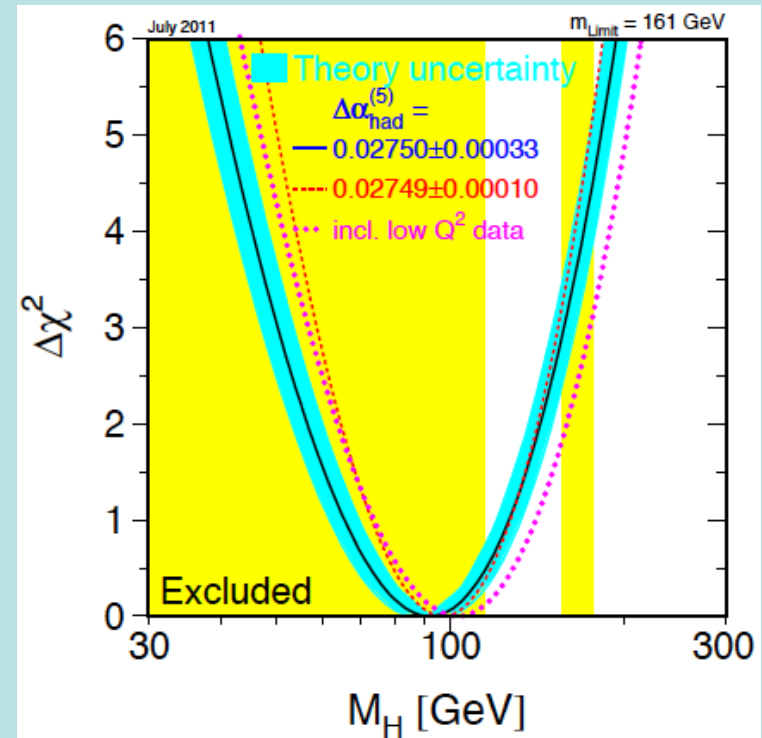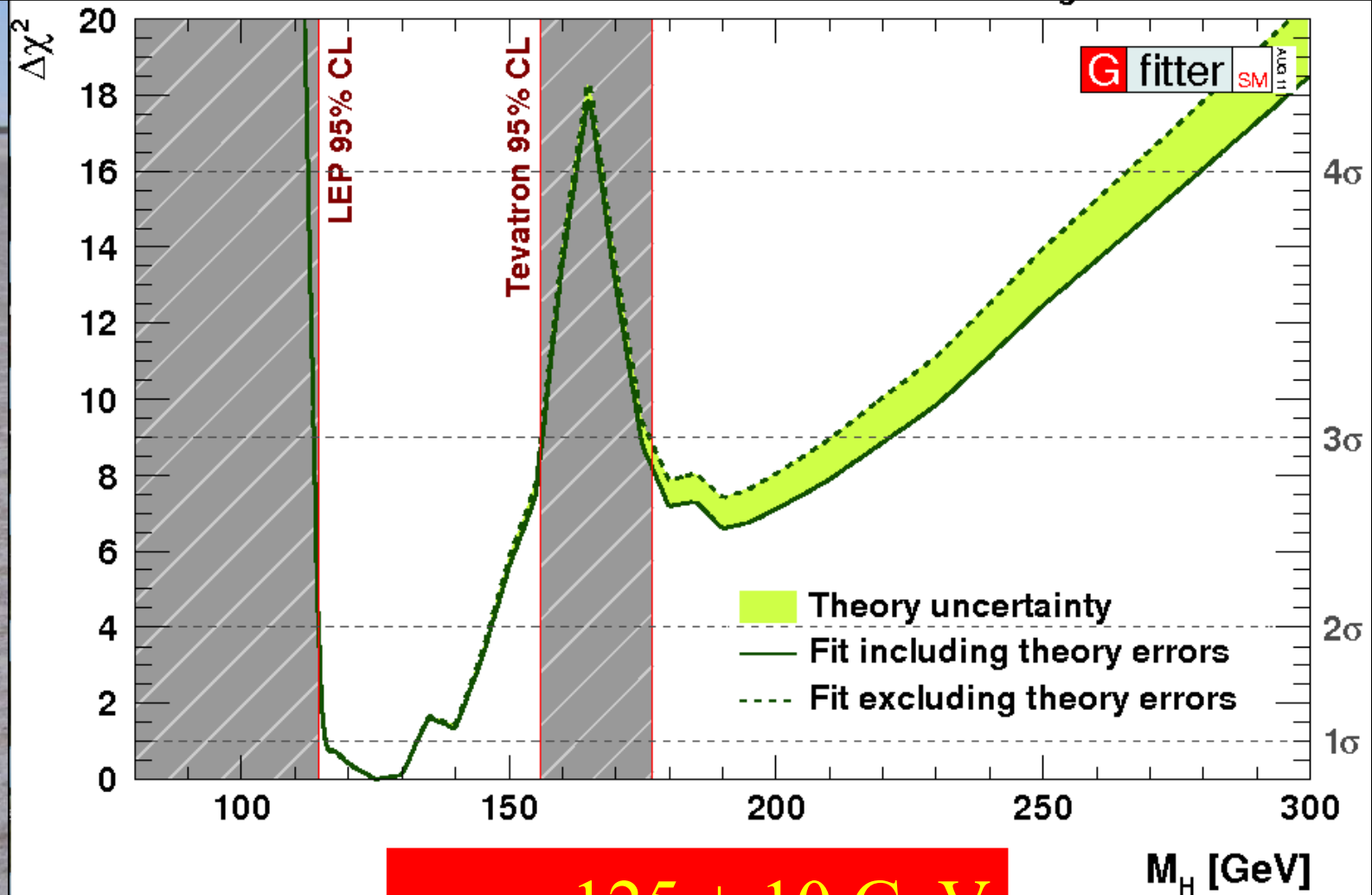
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

Higgs Production at the LHC
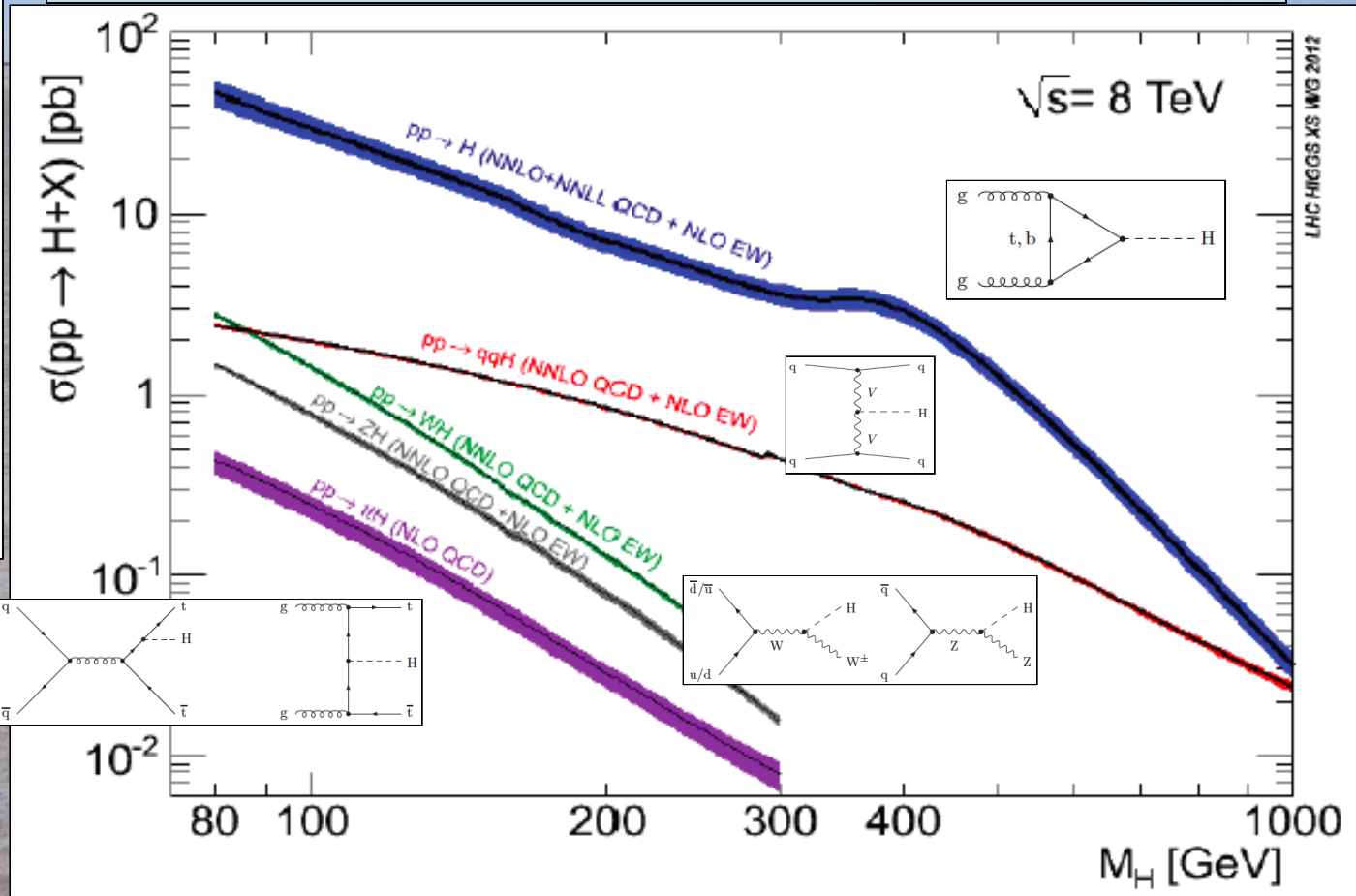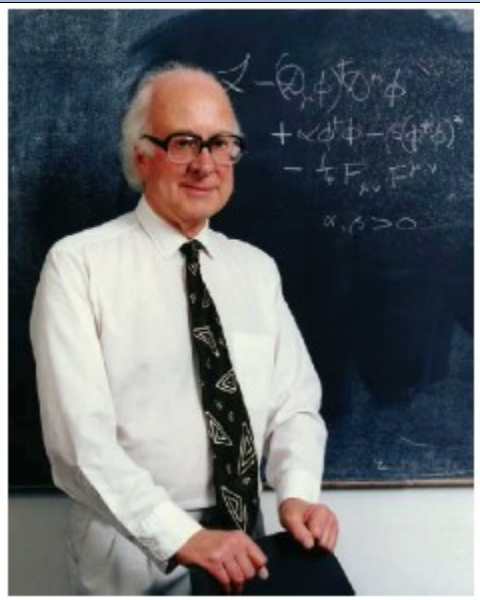
Many production modes measurable if $M_h \sim 125$ GeV

gg ➔ Higgs Production at the LHC
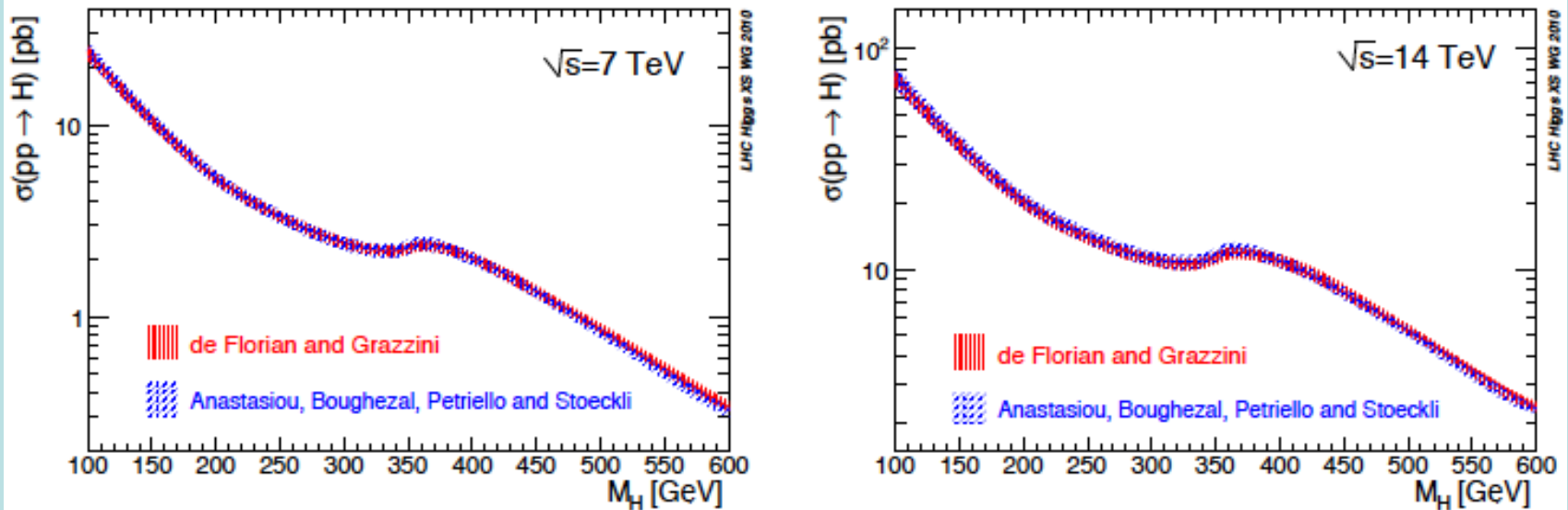
- Calculated at Next-to-next-leading order (NNLO) including leading higher-order logs (NNLL)

- Good agreement between theoretical groups
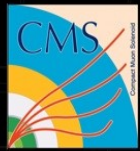
- Significant rise from 7 to 14 TeV

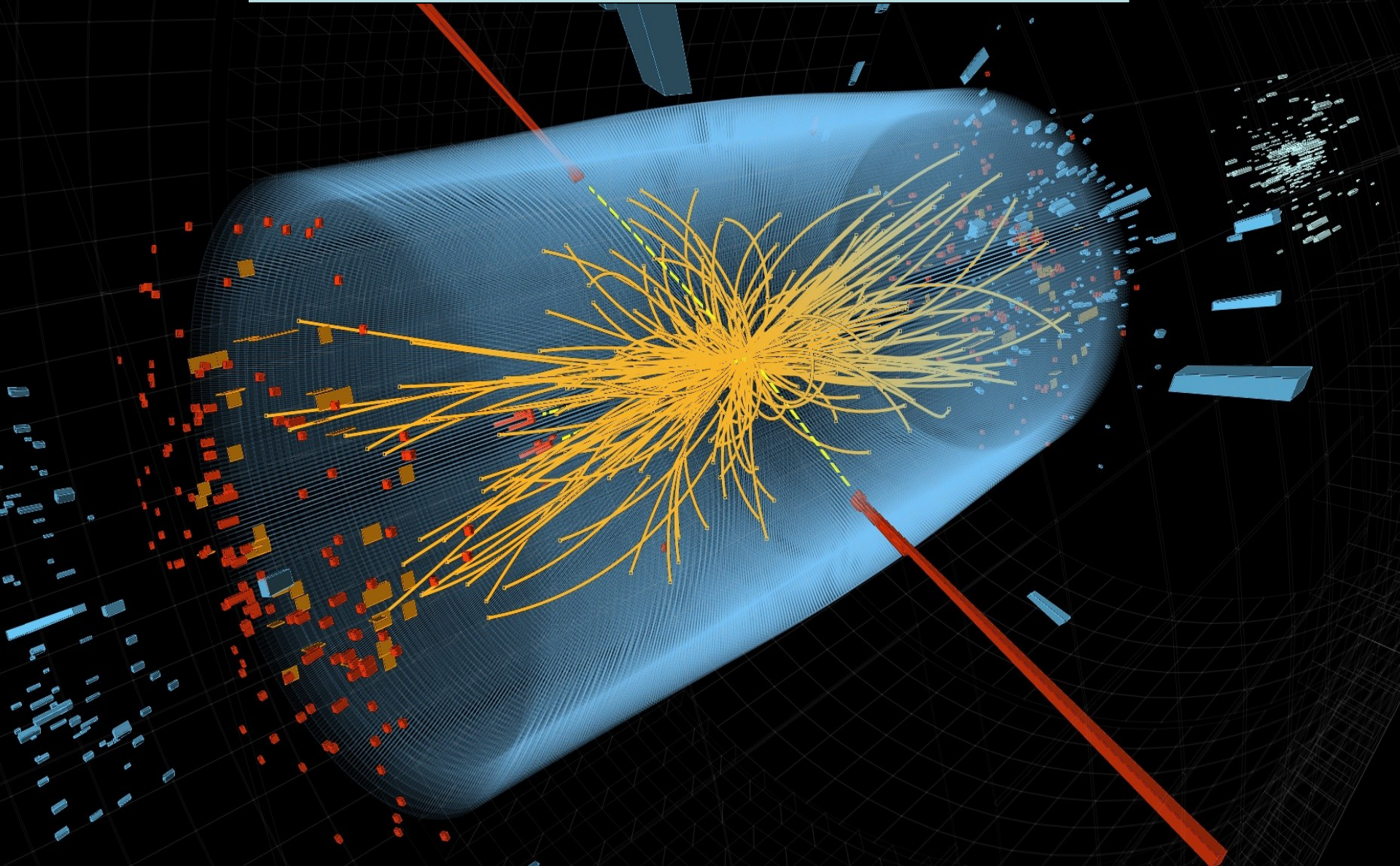# Higgs Decay Branching Ratios

- Couplings proportional to masses (?)
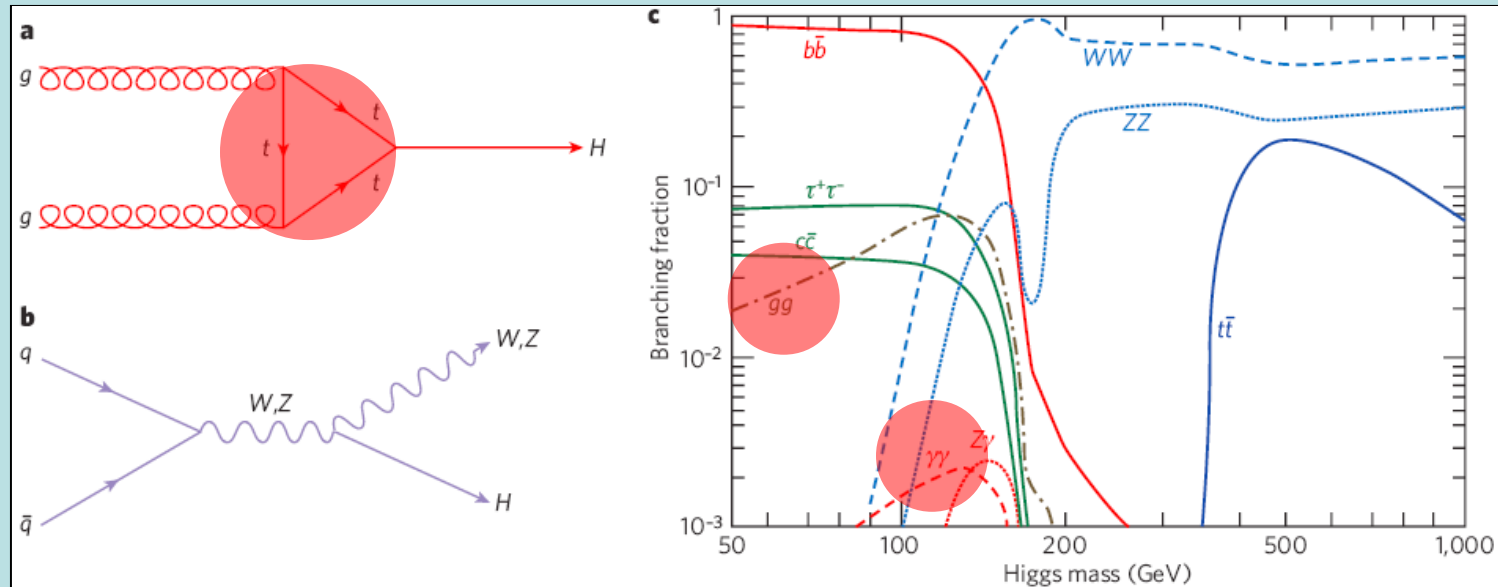
- Important couplings through loops:
  – gluon + gluon $\rightarrow$ Higgs $\rightarrow \gamma\gamma$
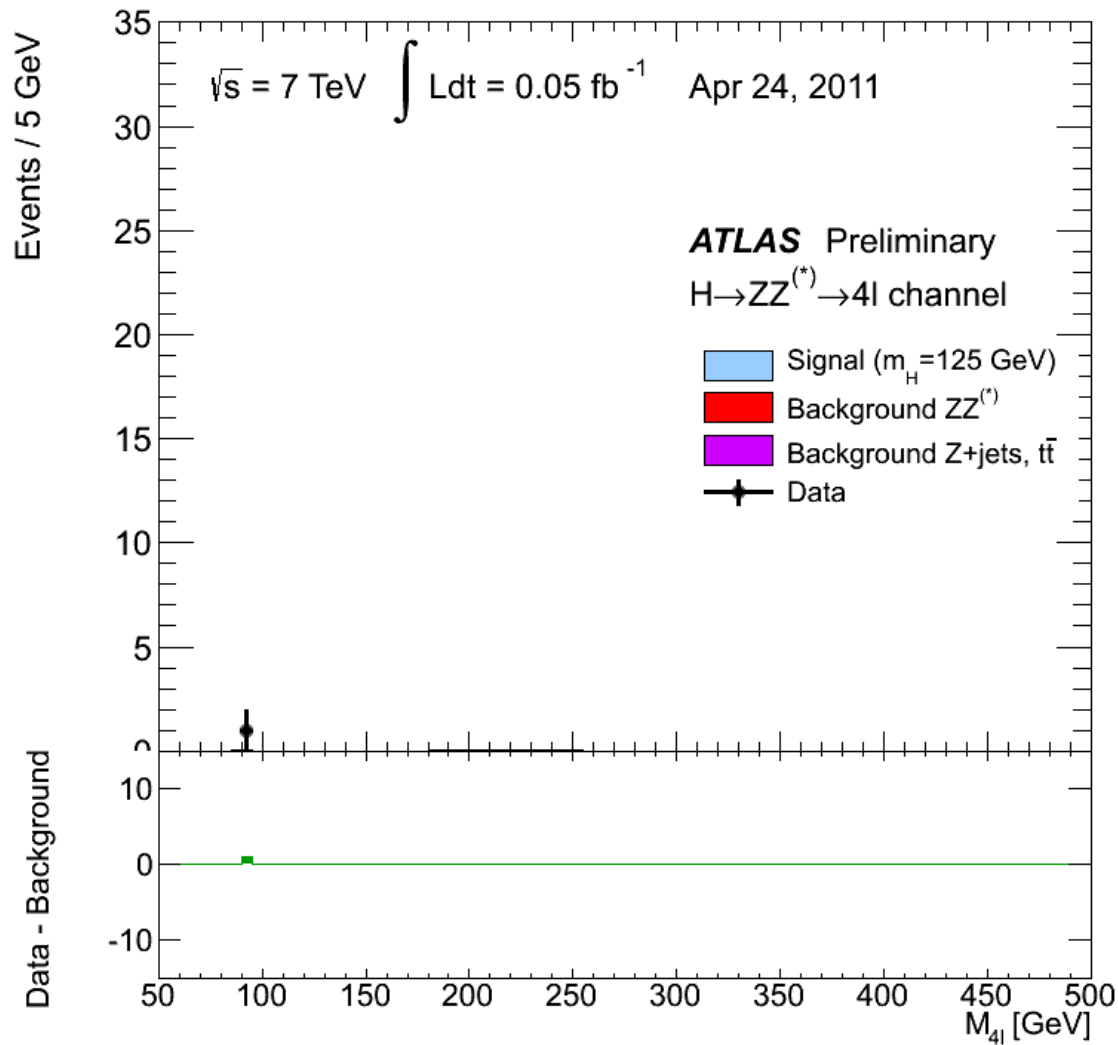
Many decay modes measurable if $M_h \sim 125$ GeV

Interesting Events

Higgsdependence Day!

•How the Higgs Signal has Grown

Unofficial Combination of Higgs Data