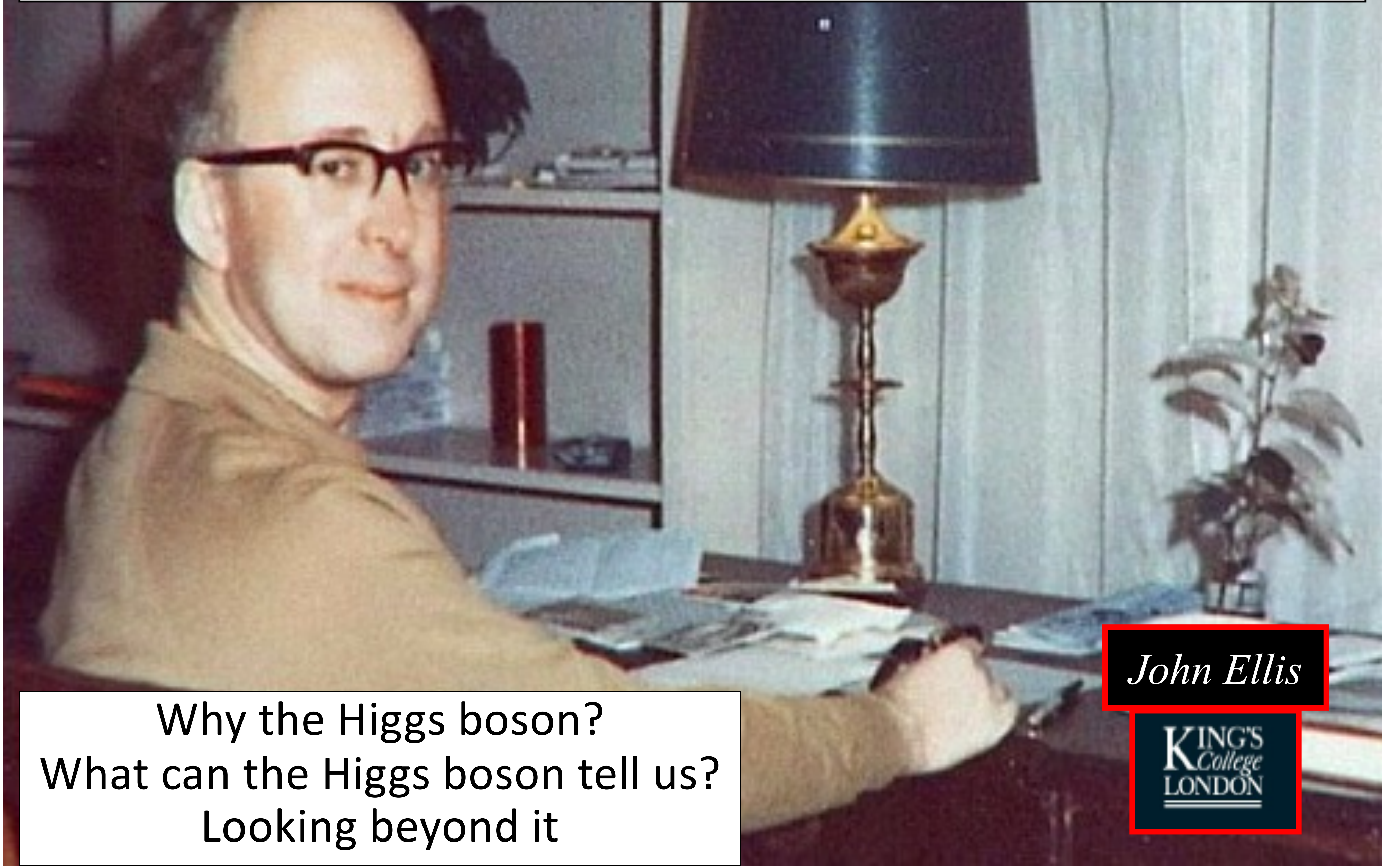
The Standard Model & Beyond

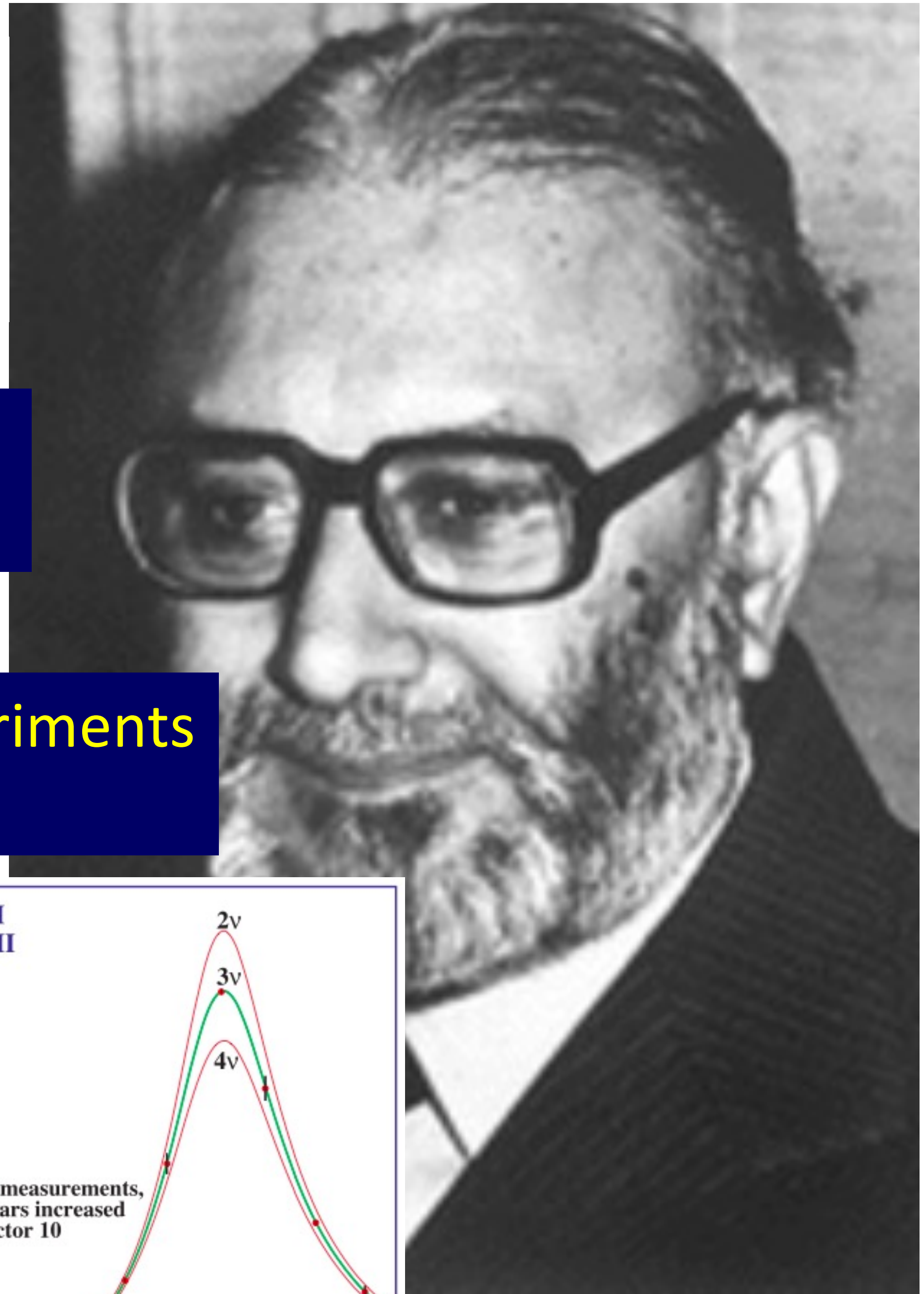


Why the Higgs boson?
What can the Higgs boson tell us?
Looking beyond it

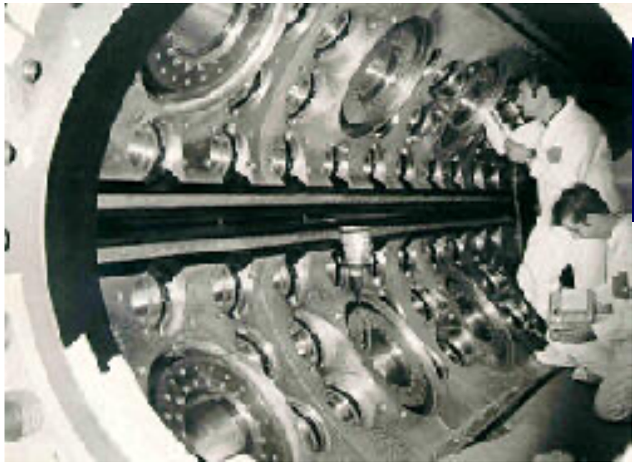
John Ellis

KING'S College LONDON

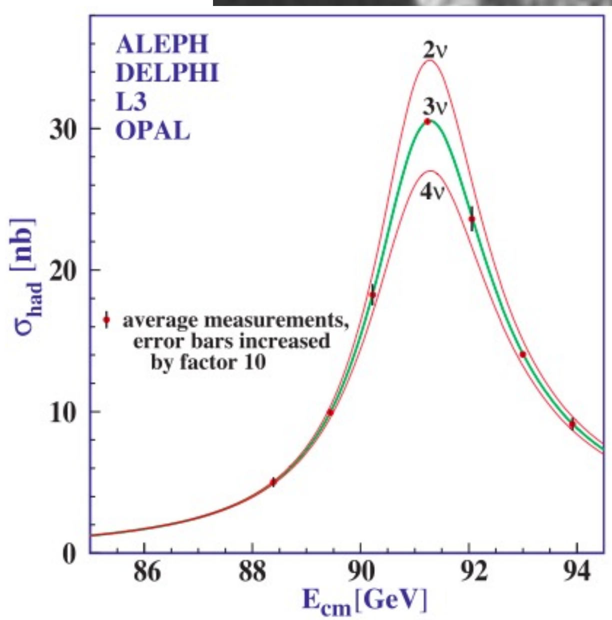
The ‘Standard Model’ of Particle Physics



Proposed byAbdus Salam, Glashow and Weinberg



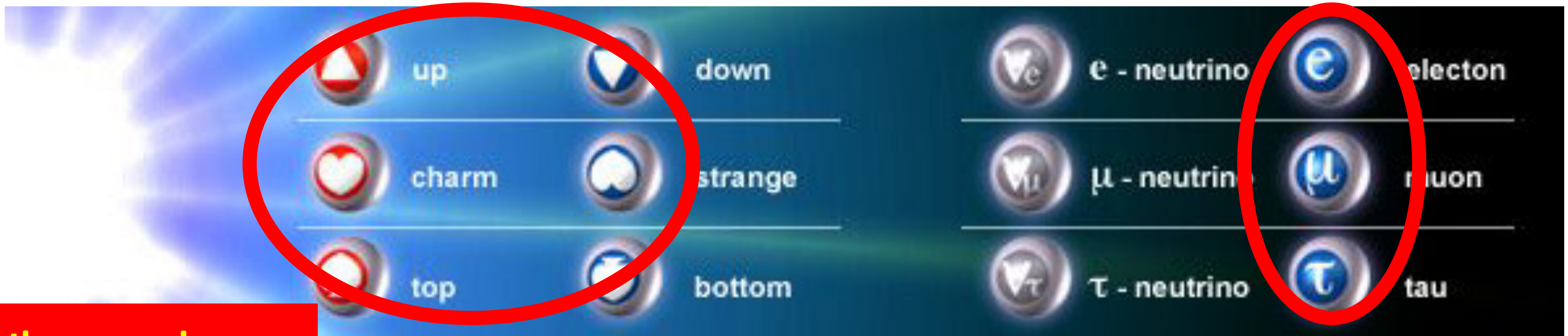
Tested by experiments at CERN



Perfect agreement between theory and experiments in all laboratories

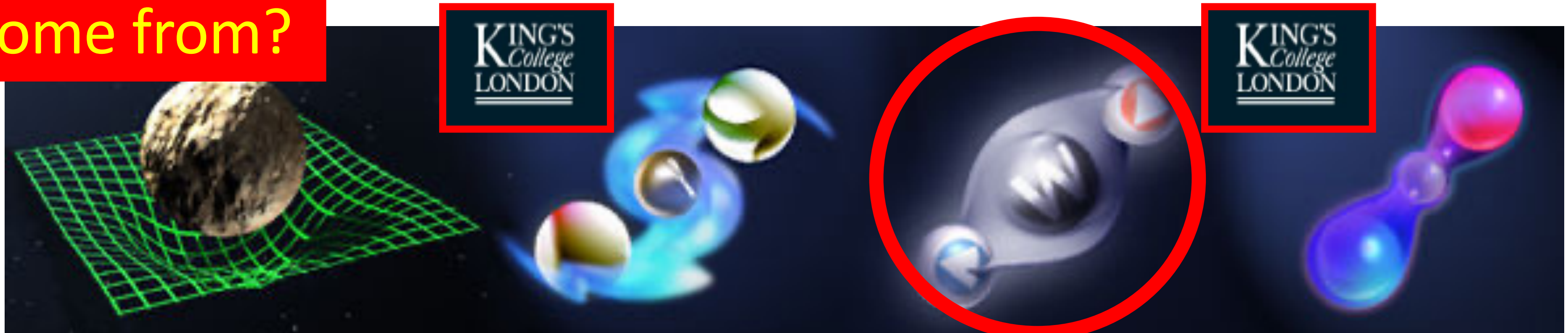
The ‘Standard Model’

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

1964

The Massive Discoverers

1964

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 ... 4

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)

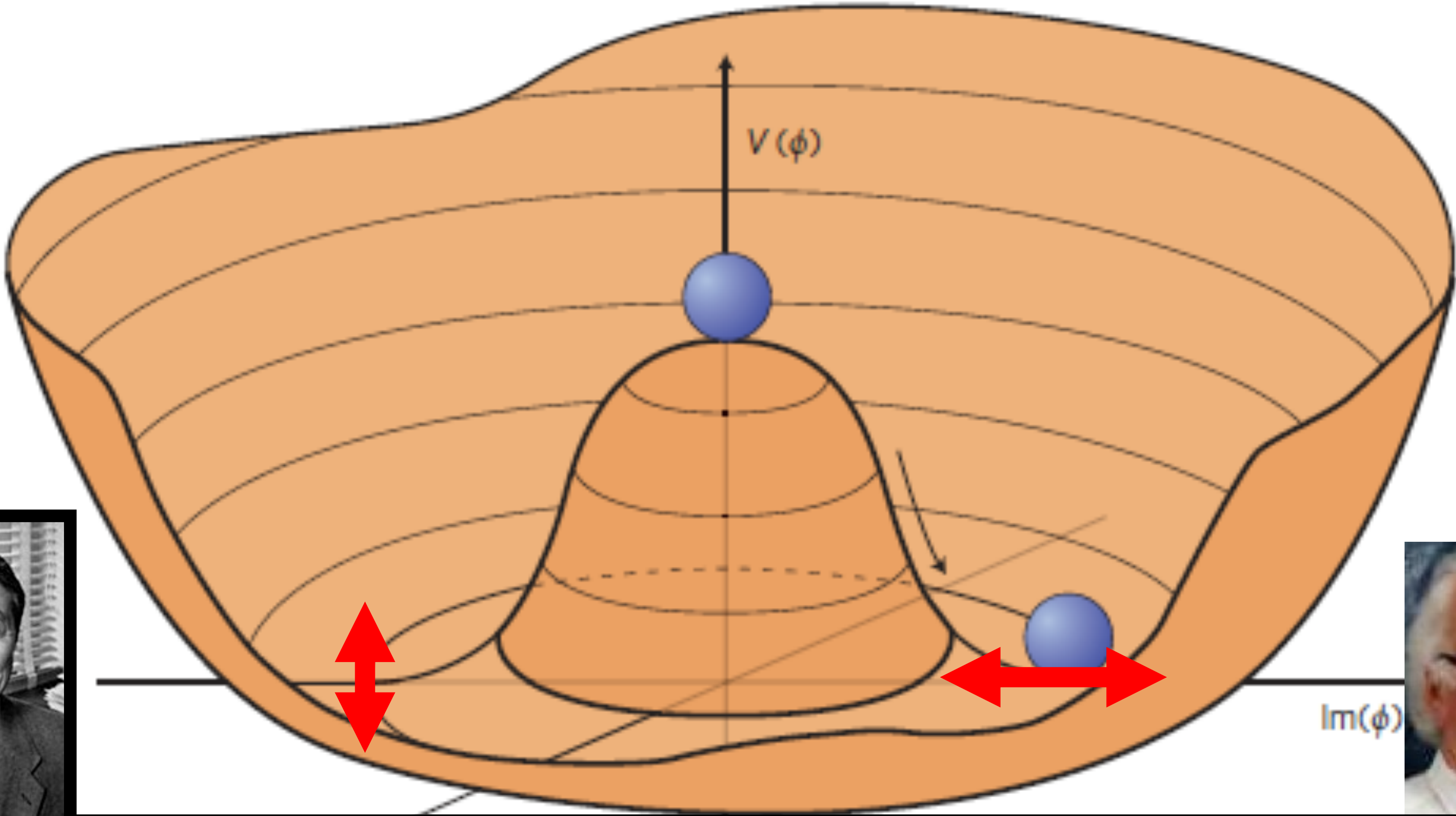
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

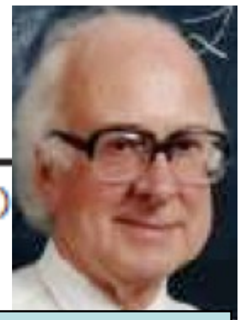
A. A. MIGDAL ...

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

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

Nambu, EB, H, GHK & Higgs





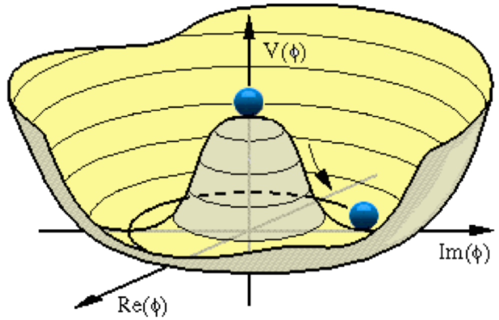
Spontaneous symmetry breaking: massless Nambu-Goldstone boson ‘eaten’ by massless gauge boson

Accompanied by massive particle

The Nambu-Goldstone Mechanism

- Postulated effective scalar 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 scalar field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \ \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$

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

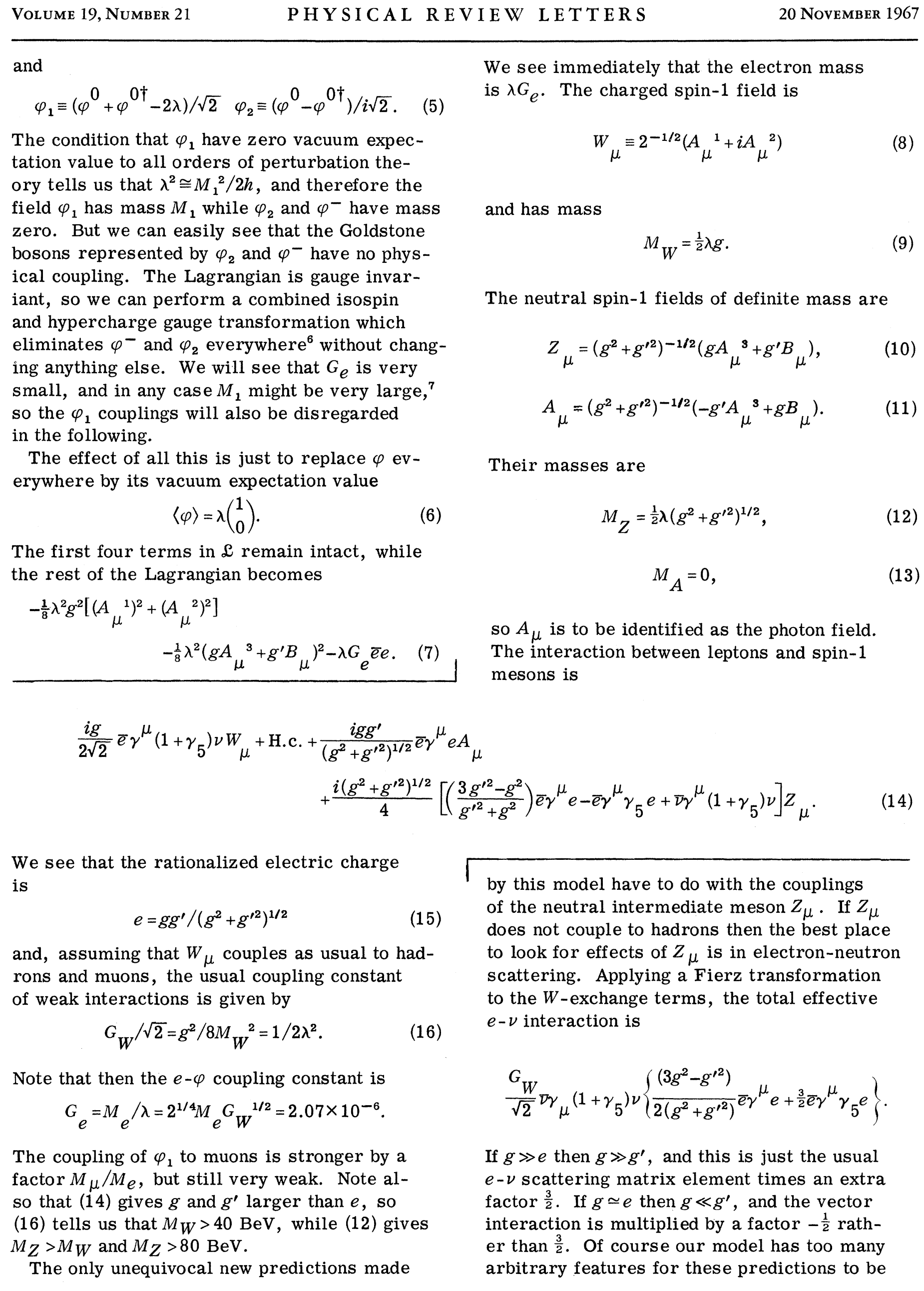
$$\mathcal{L} = |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}}H)|^2 - \tfrac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - V$$

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

1967

Weinberg: A Model of Leptons

- Electroweak sector of the Standard Model
- SU(2) x U(1)
- Mixing of Z, photon
- Neutral currents
- Higgs-lepton couplings
- No quarks



and

$$\varphi_1 \equiv (\varphi^0 + \varphi^{0\dagger} - 2\lambda)/\sqrt{2} \quad \varphi_2 \equiv (\varphi^0 - \varphi^{0\dagger})/i\sqrt{2}. \quad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2 \cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\begin{pmatrix}1\\0\end{pmatrix}. \quad (6)$$

The first four terms in $\mathfrak{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2 g^2[(A_\mu^{\ 1})^2 + (A_\mu^{\ 2})^2] - \tfrac{1}{8}\lambda^2(gA_\mu^{\ 3} + g'B_\mu)^2 - \lambda G_e \bar{e}e. \quad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu \equiv 2^{-1/2}(A_\mu^{\ 1} + iA_\mu^{\ 2}) \quad (8)$$

and has mass

$$M_W = \tfrac{1}{2}\lambda g. \quad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu^{\ 3} + g'B_\mu), \quad (10)$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu^{\ 3} + gB_\mu). \quad (11)$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \quad (12)$$

$$M_A = 0, \quad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu e A_\mu + \frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e - \bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \quad (14)$$

We see that the rationalized electric charge is

$$e = gg'/(g^2+g'^2)^{1/2} \quad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt{2} = g^2/8M_W^{\ 2} = 1/2\lambda^2. \quad (16)$$

Note that then the e-φ coupling constant is

$$G_e = M_e/\lambda = 2^{1/4}M_e G_W^{\ 1/2} = 2.07\times10^{-6}.$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be

2 citations before 1971

“Whatever the final laws of nature may be, there is no reason to suppose that they are designed to make physicists happy.”

What are we?

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

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

Tested < 0.1% before LHC

Testing now in progress

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: $\phi = <0|\phi|0> + \hat{\phi}$

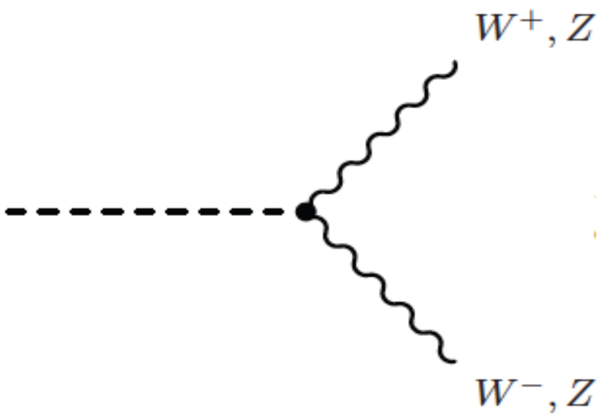
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2} W^+_\mu W^{\mu -} - g'^2 \frac{v^2}{2} B_\mu B^\mu + g\, g' v^2 B_\mu W^{\mu 3} - g^2 \frac{v^2}{2} W^3_\mu W^{\mu 3}$$

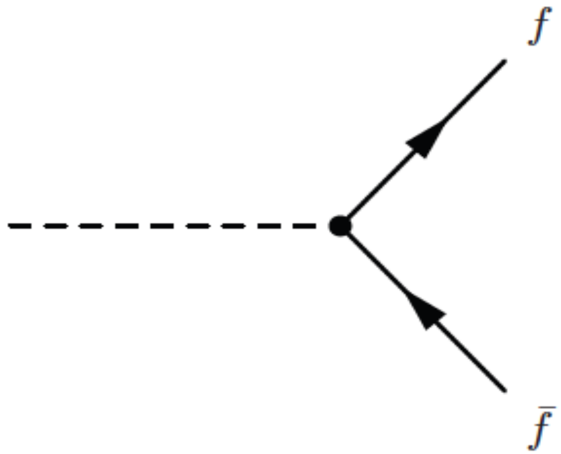
- Boson masses:

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

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

Higgs Boson Couplings





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

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

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

Weinberg 1967

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

Higgs 1966

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charged-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

Flavour?

Mass?

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.

2011

Status of the Standard Model before the LHC

- 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?

Where are the top and Higgs?

Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

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

Veltman

- Sensitivity to top mass is quadratic:

$$\frac{3G_F}{8\pi^2\sqrt{2}}m_t^2$$

- Sensitivity to Higgs mass is logarithmic:

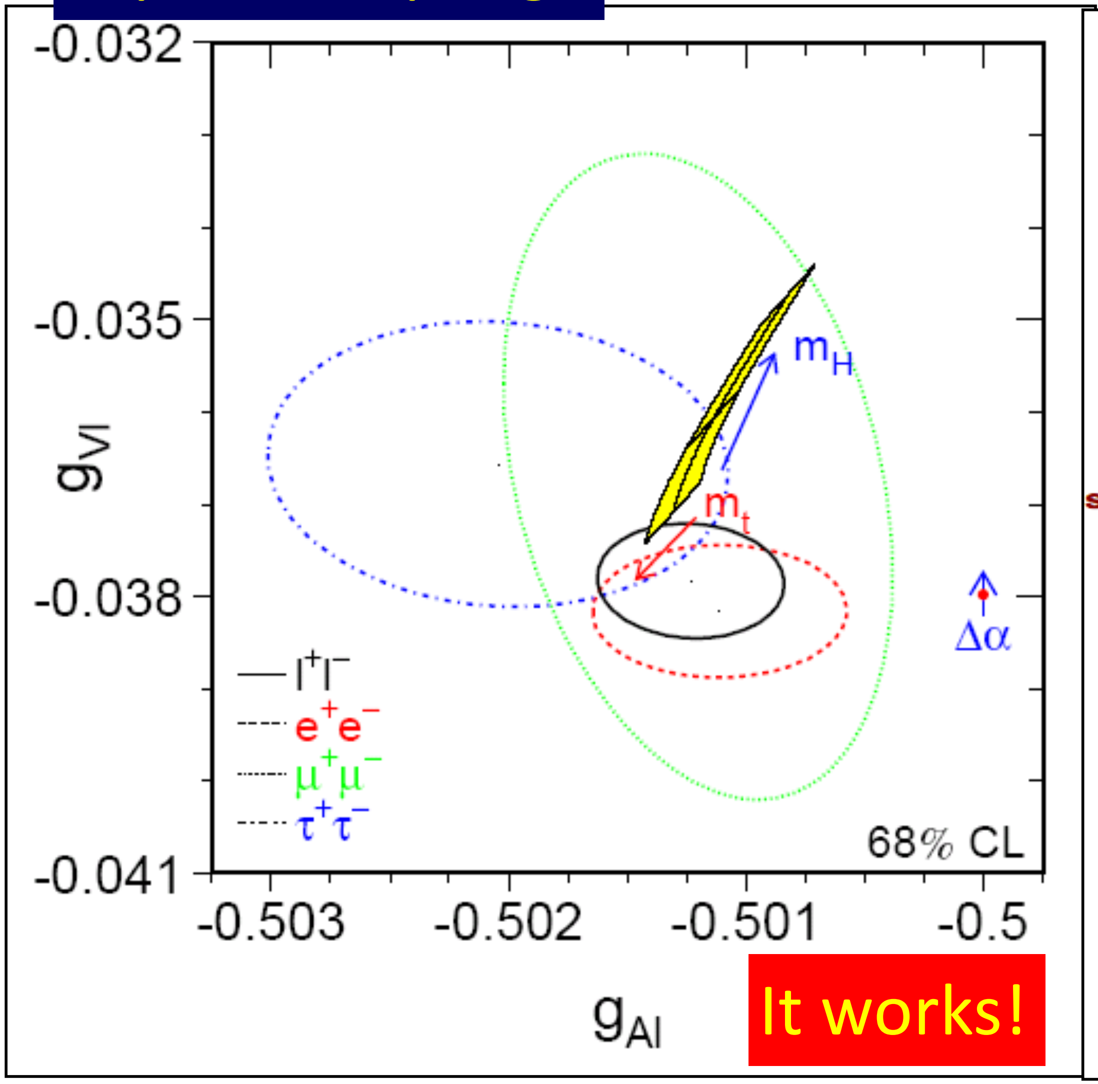
$$\frac{\sqrt{2}G_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2}+\ldots\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

$$\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$$

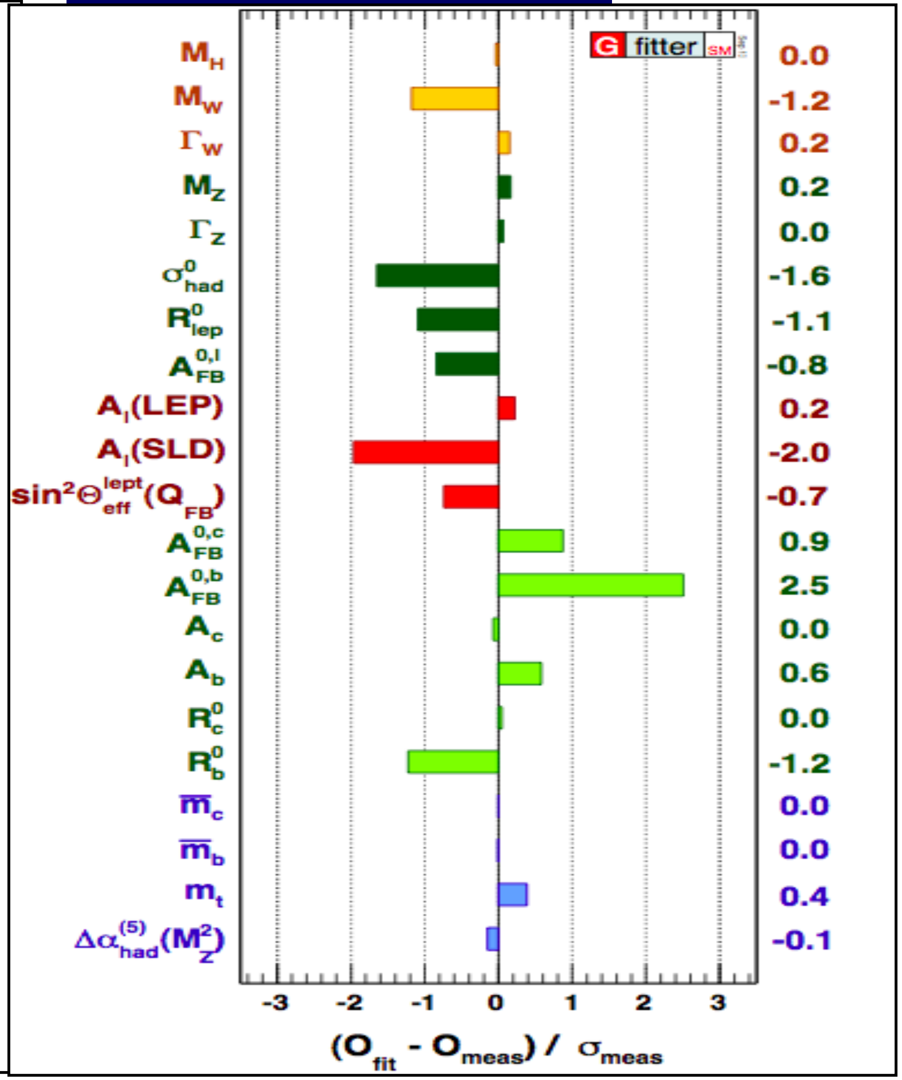
Precision Tests of the Standard Model

Lepton couplings



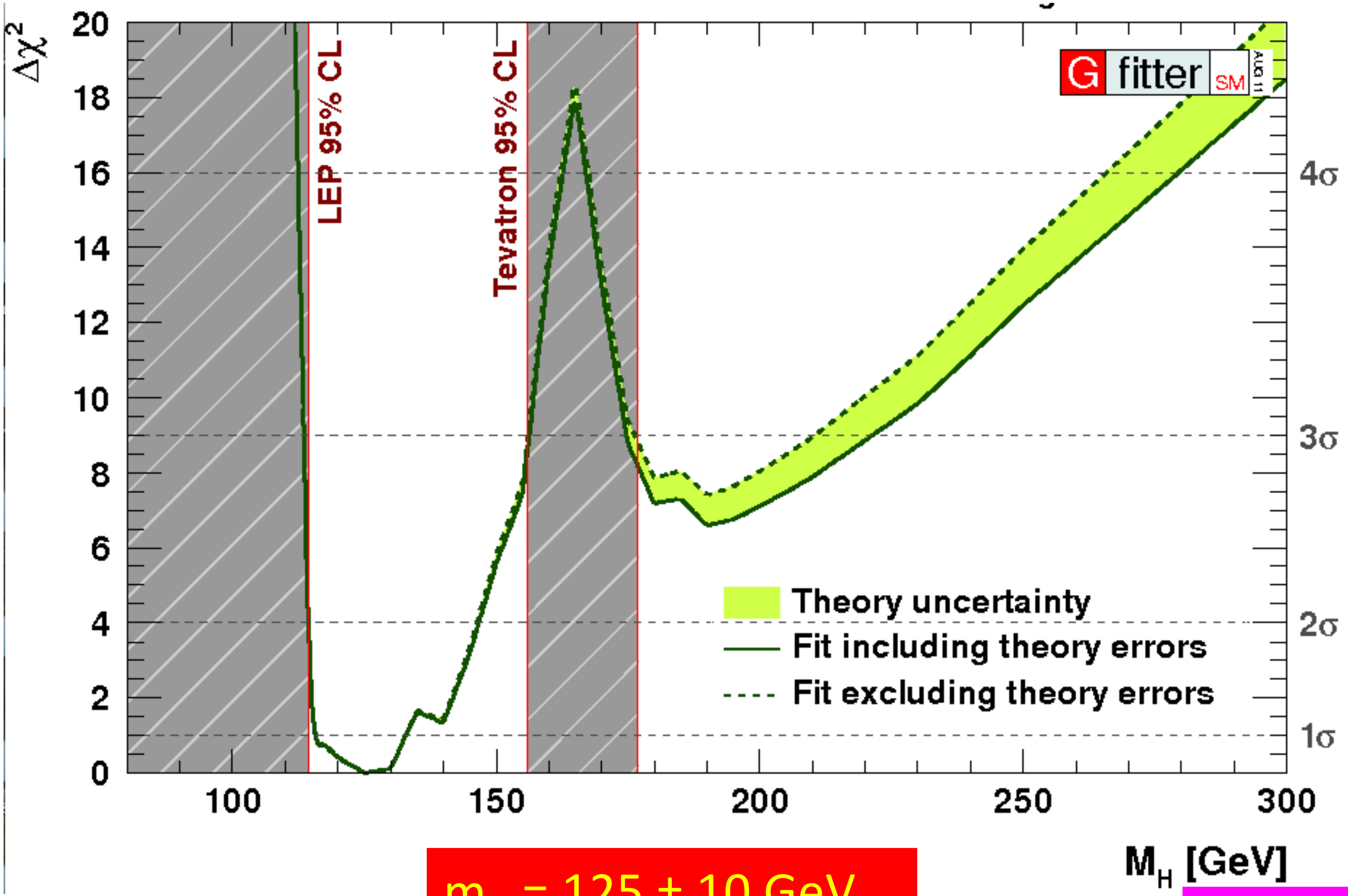
It works!

Pulls in global fit



2011

Combining Information from Previous Direct Searches and Indirect Data



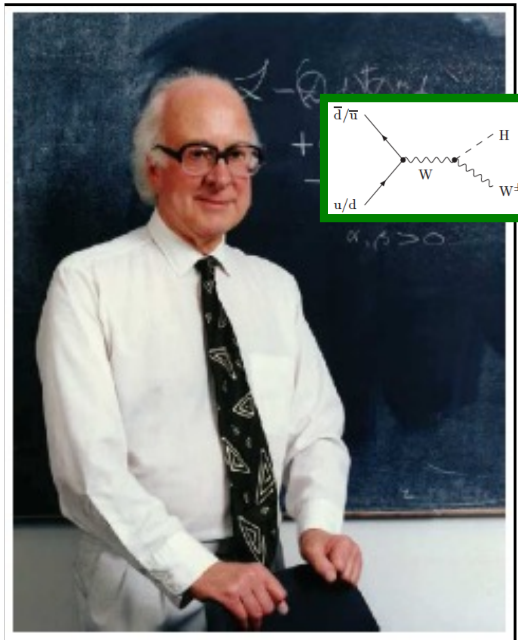
m_H = 125 ± 10 GeV

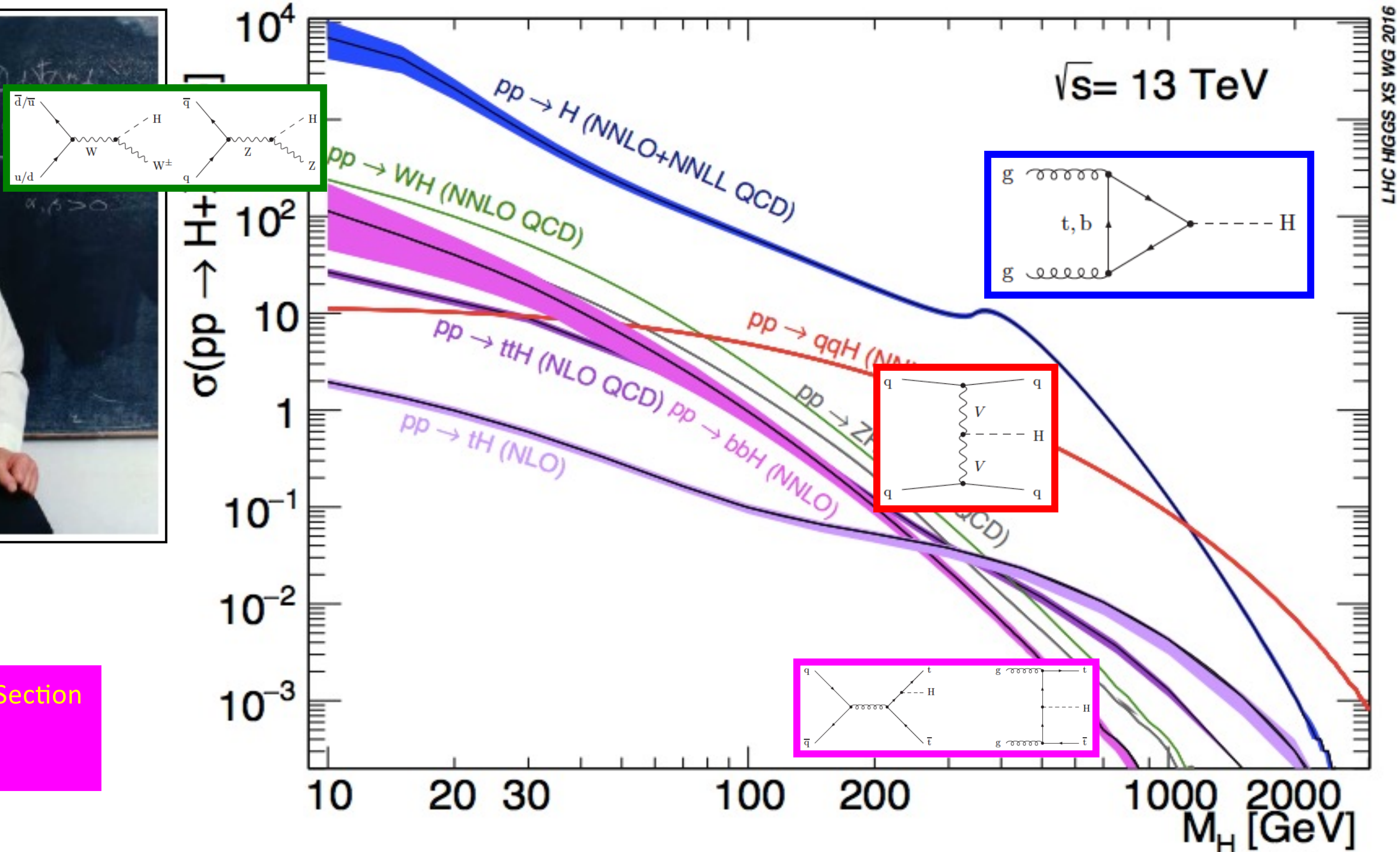
Gfitter collaboration


"… we do not want to encourage big experimental searches for the Higgs boson, but …"
EGN 1975

A la recherche du Higgs perdu …

Higgs Production at LHC



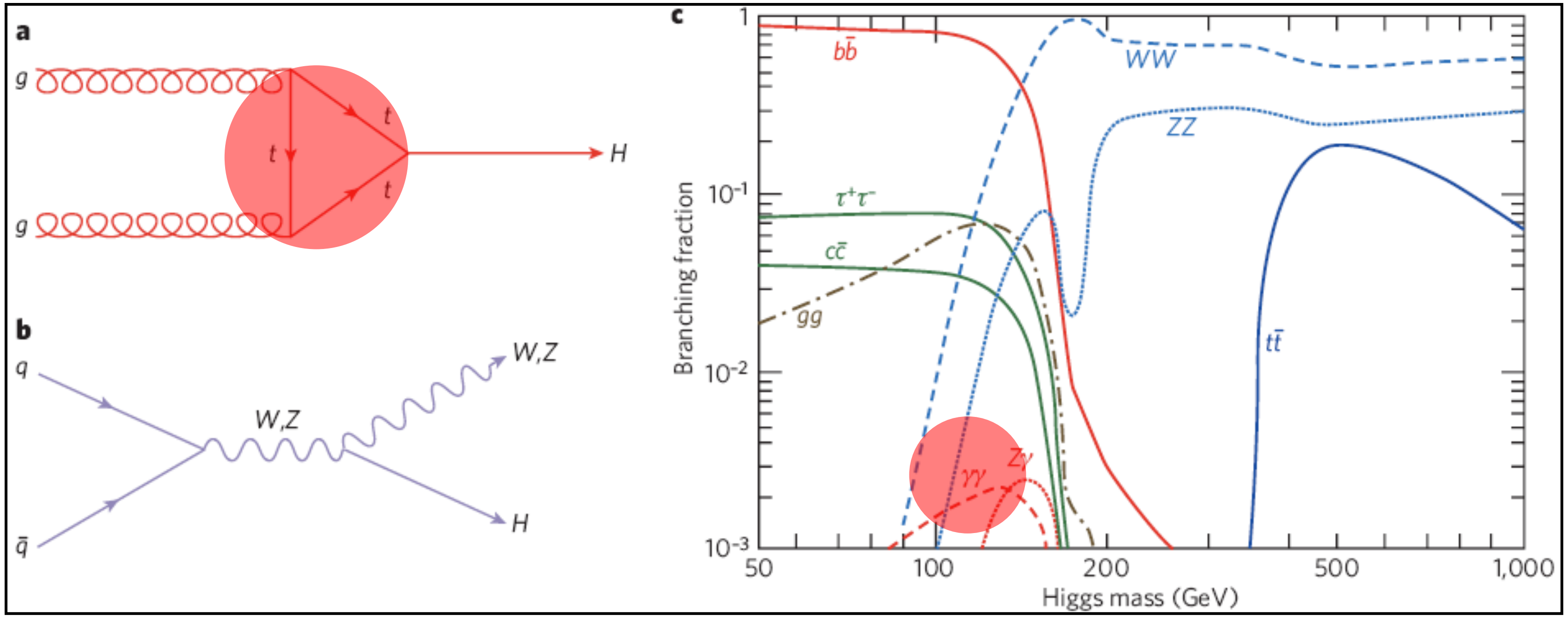


LHC Higgs Cross-Section Working Group (LHXSWG)

Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

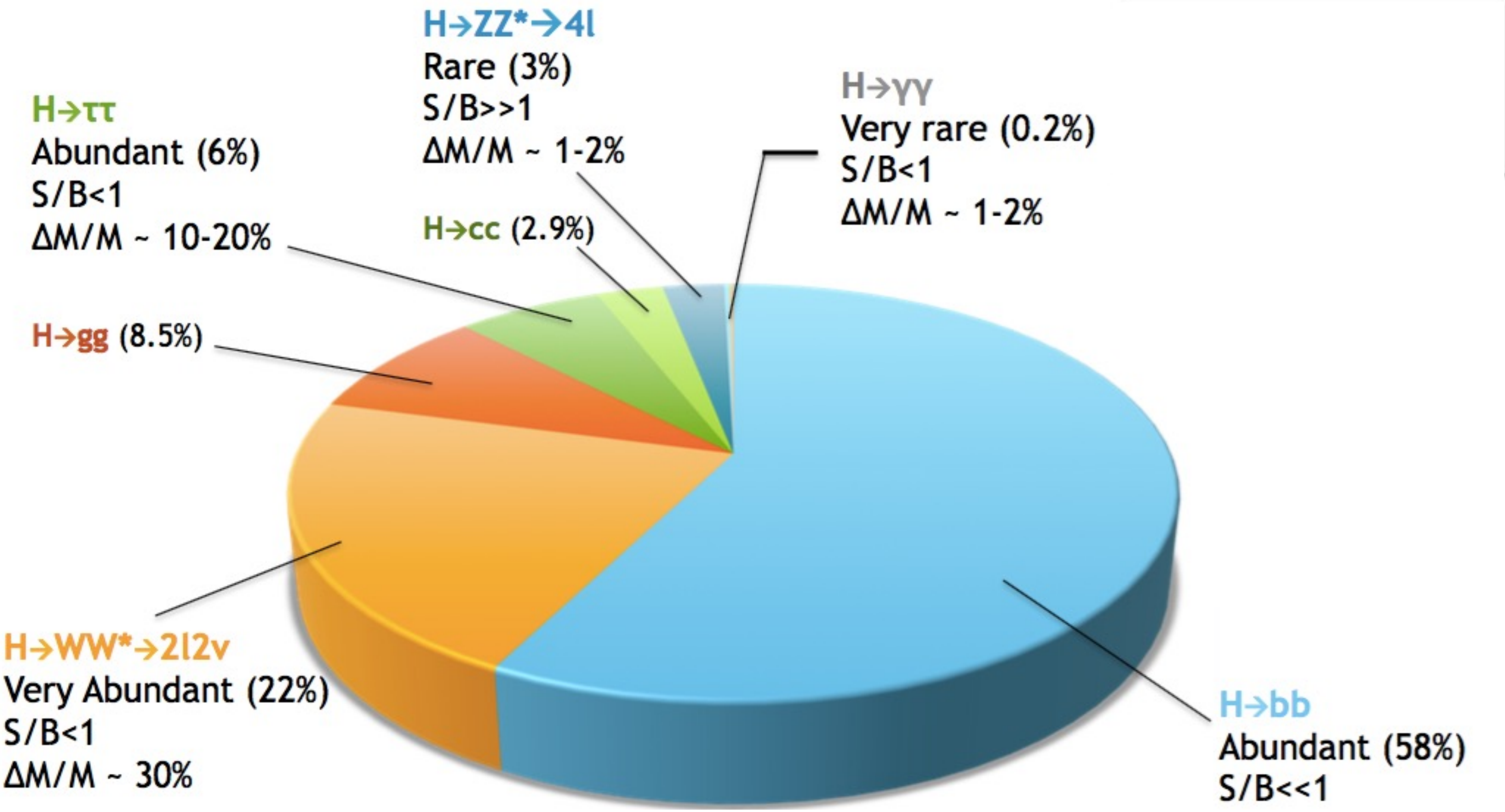
- Couplings proportional to masses (?)



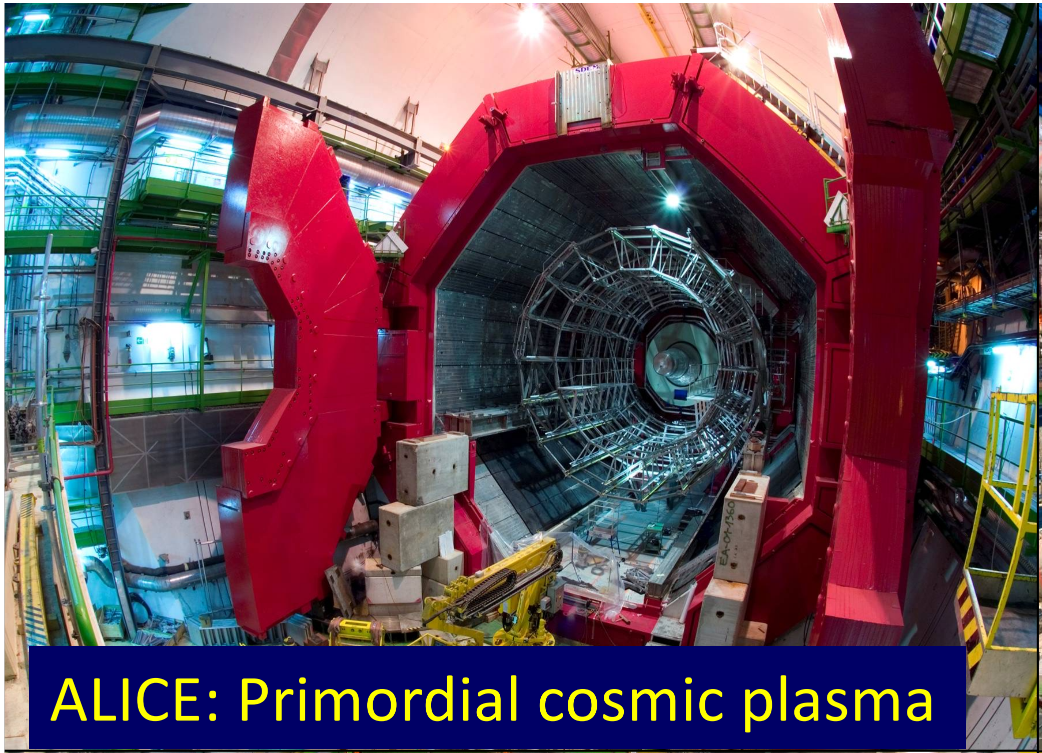
- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

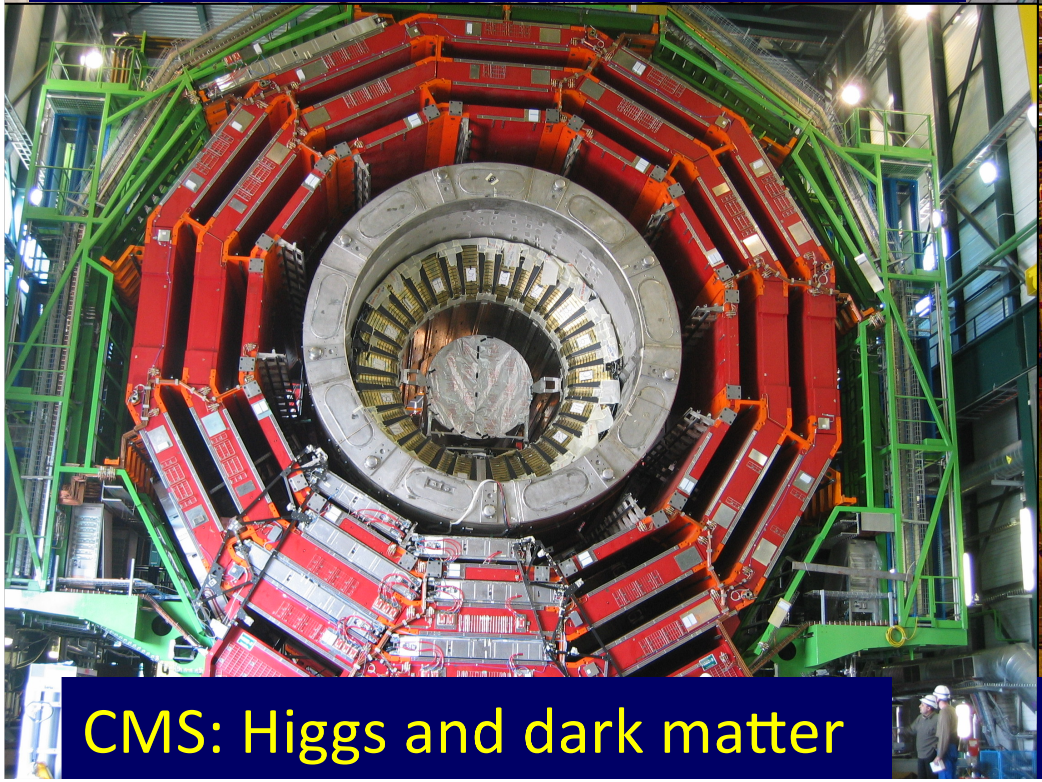
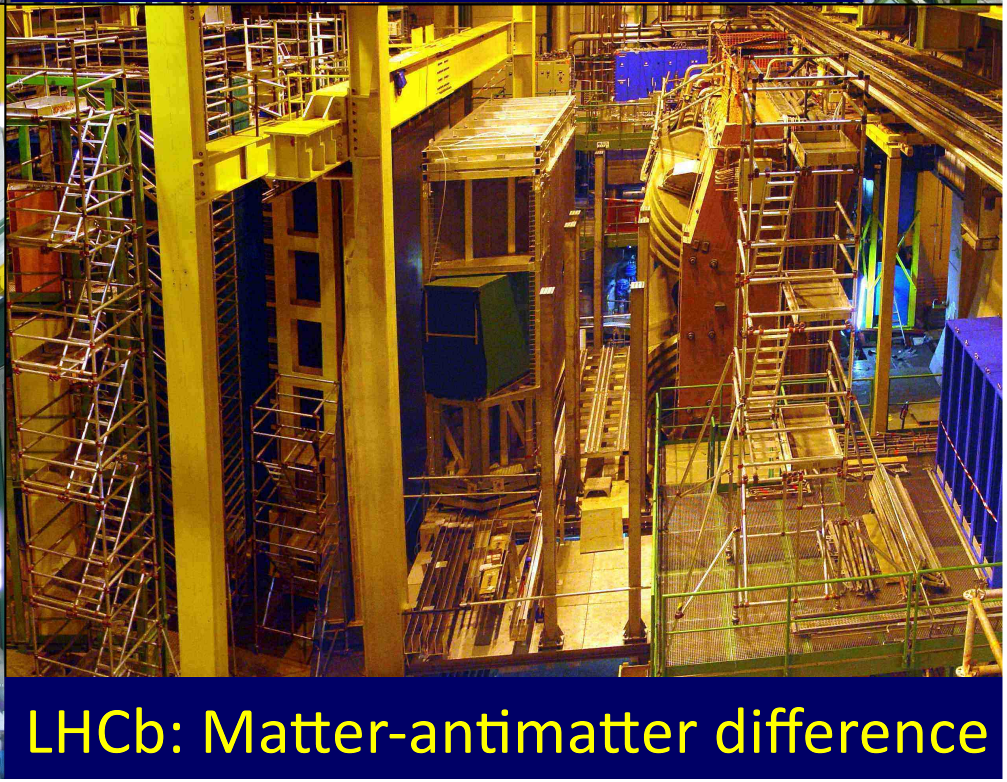
Many decay modes measurable if M_h ~ 125 GeV

What was Expected



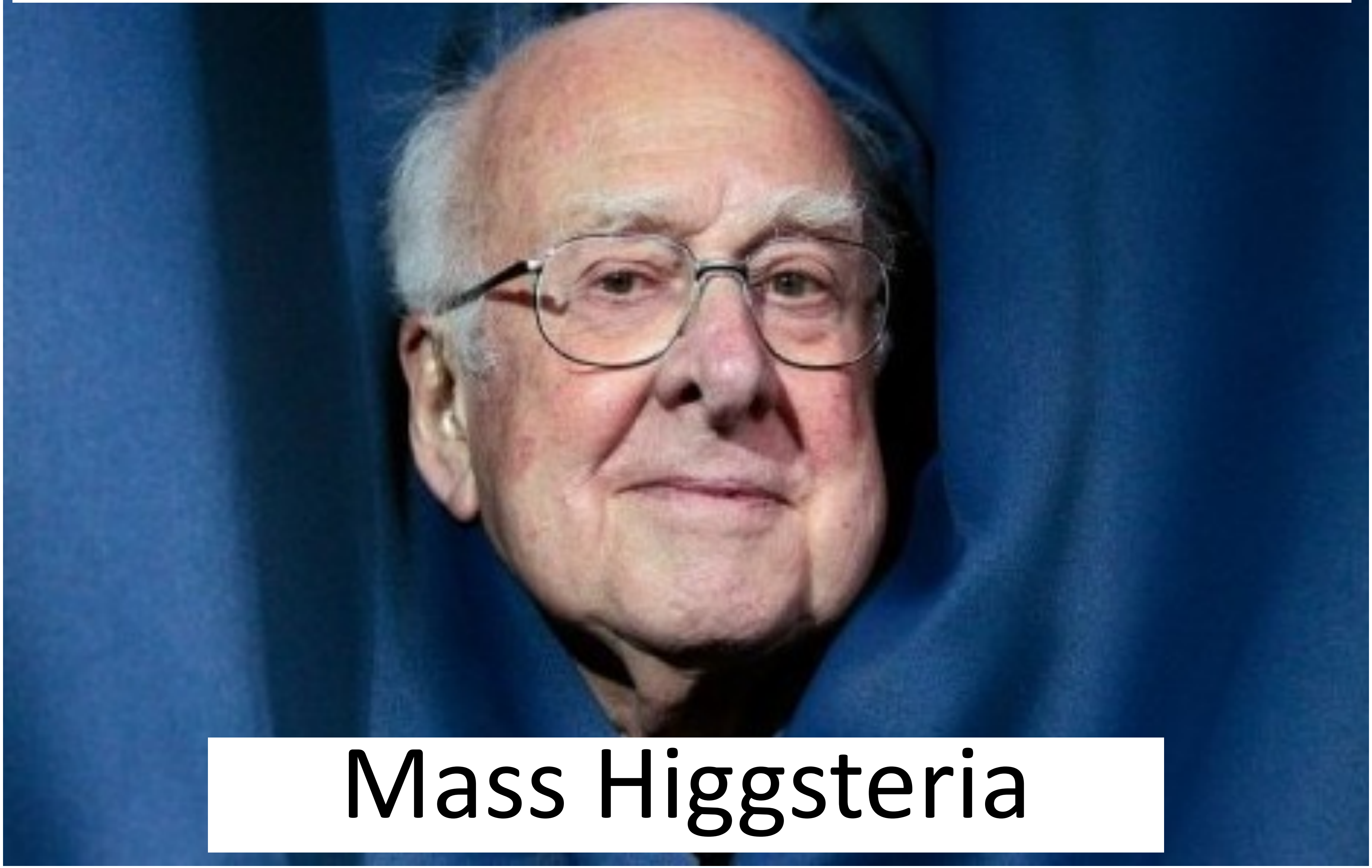
What do we know?


ALICE: Primordial cosmic plasma

ATLAS: Higgs and dark matter

CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

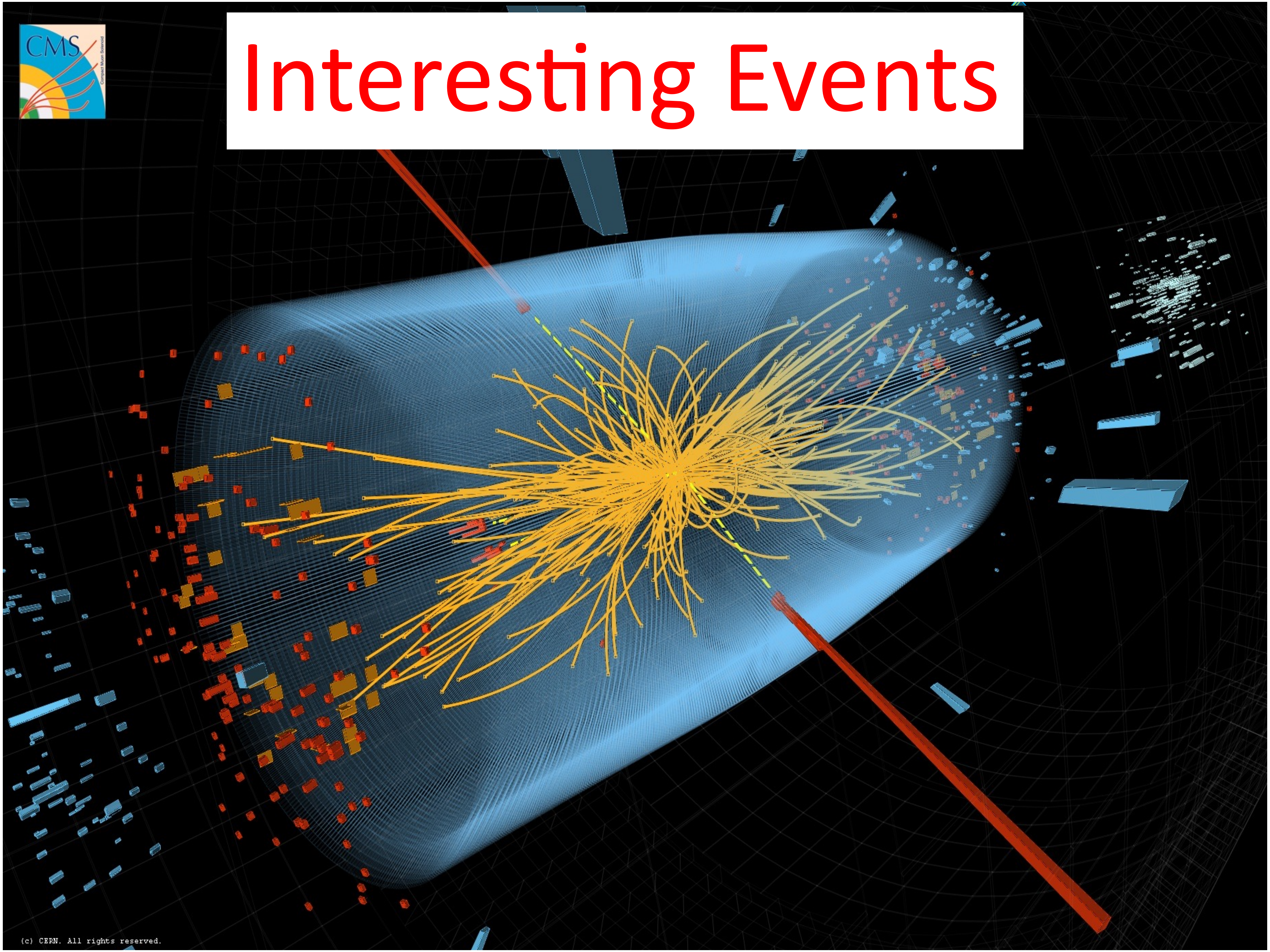
2012

The Discovery of the Higgs Boson



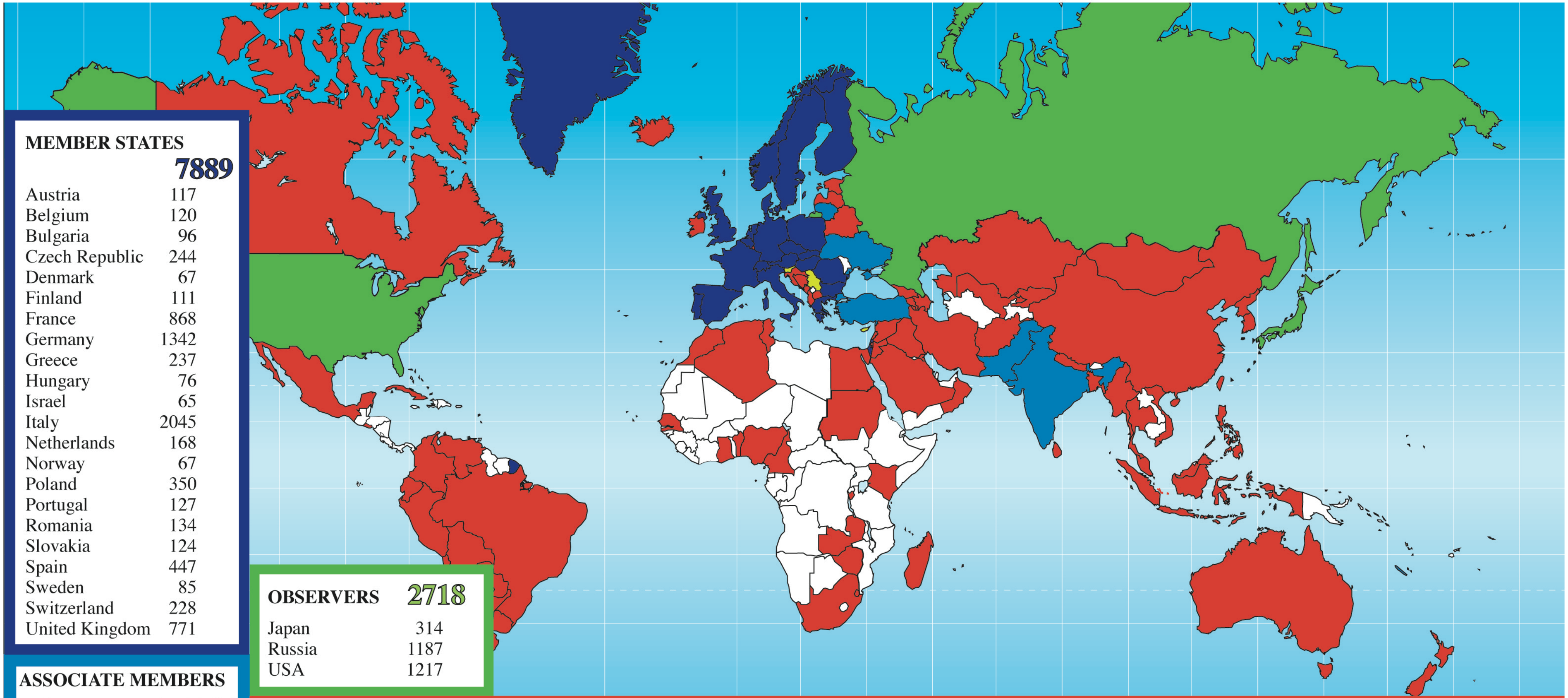
Mass Higgsteria

Interesting Events



Higgsdependence Day!

Scientists from around the World



MEMBER STATES 7889

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

ASSOCIATE MEMBERS 745

India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 118

Cyprus	26
Serbia	57
Slovenia	35

OBSERVERS 2718

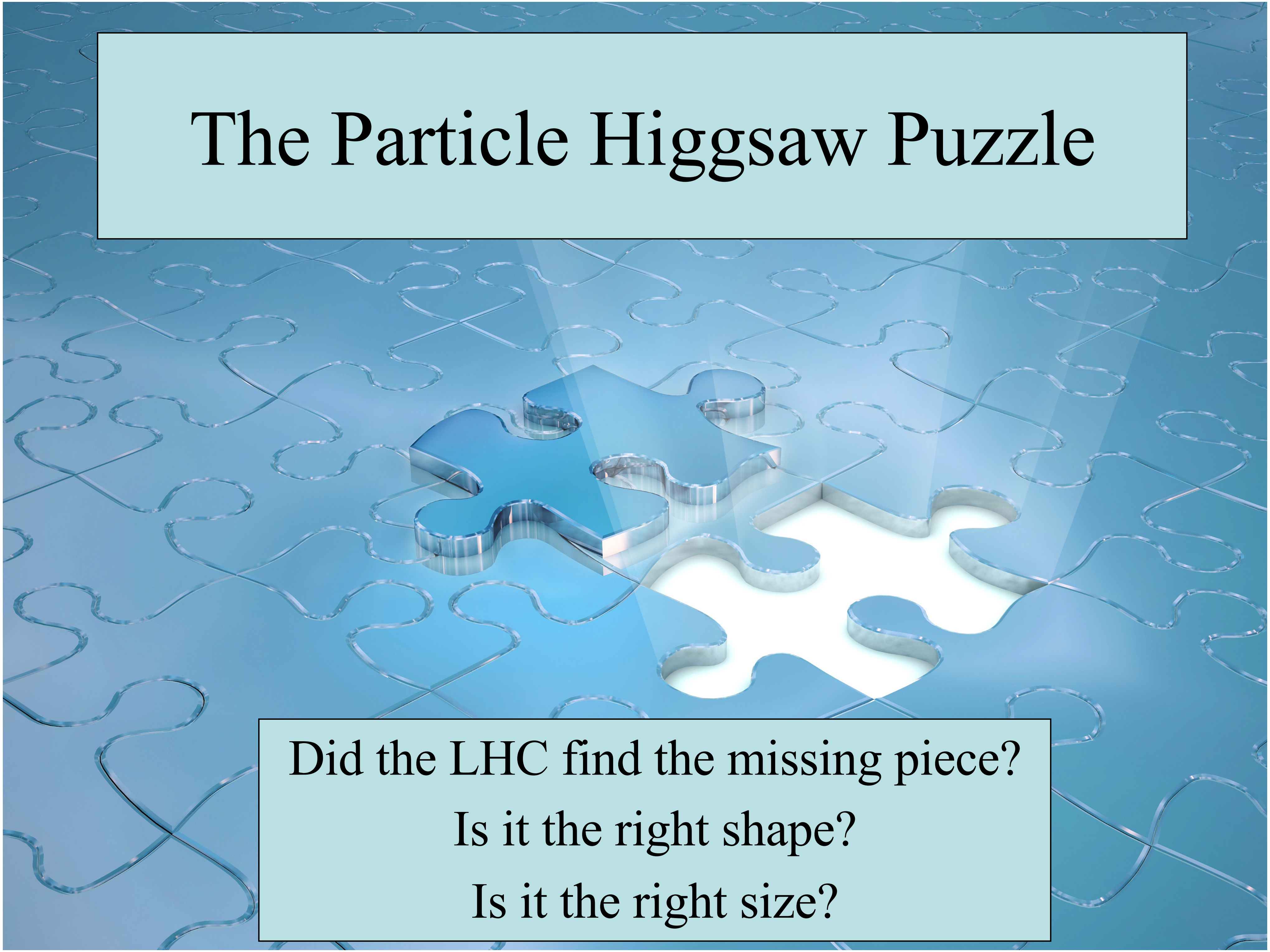
Japan	314
Russia	1187
USA	1217

OTHERS 1872

Afghanistan	1
Albania	3
Algeria	14
Argentina	27
Armenia	19
Australia	31
Azerbaijan	10
Bangladesh	11
Belarus	48
Benin	1
Bolivia	4
Bosnia & Herzegovina	2
Brazil	135
Burundi	1
Cameroon	1
Canada	161
Chile	20
China	510
Colombia	45
Croatia	41
Cuba	12
Ecuador	6
Egypt	31
El Salvador	1
Estonia	15
Georgia	46
Ghana	1
Hong Kong	1
Iceland	3
Indonesia	11
Iran	51
Iraq	1
Ireland	16
Jordan	1
Kazakhstan	5
Kenya	3
Korea Rep.	185
Kyrgyzstan	1
Latvia	2
Lebanon	23
Luxembourg	2
Madagascar	4
Malaysia	15
Malta	9
Mauritius	1
Mexico	82
Mongolia	2
Montenegro	11
Morocco	20
Myanmar	1
Nepal	10
New Zealand	5
Nigeria	3
North Korea	1
Oman	3
Palestine (O.T.).	7
Paraguay	2
Peru	7
Philippines	3
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	56
Sri Lanka	6
Sudan	1
Swaziland	1
Syria	1
Taiwan	51
Thailand	22
T.F.Y.R.O.M.	2
Tunisia	5
Uruguay	1
Uzbekistan	4
Venezuela	10
Viet Nam	13
Zambia	1
Zimbabwe	2

Russian naval shells reused in CMS
Melted down in Belarus
Supported by US

The Particle Higgsaw Puzzle

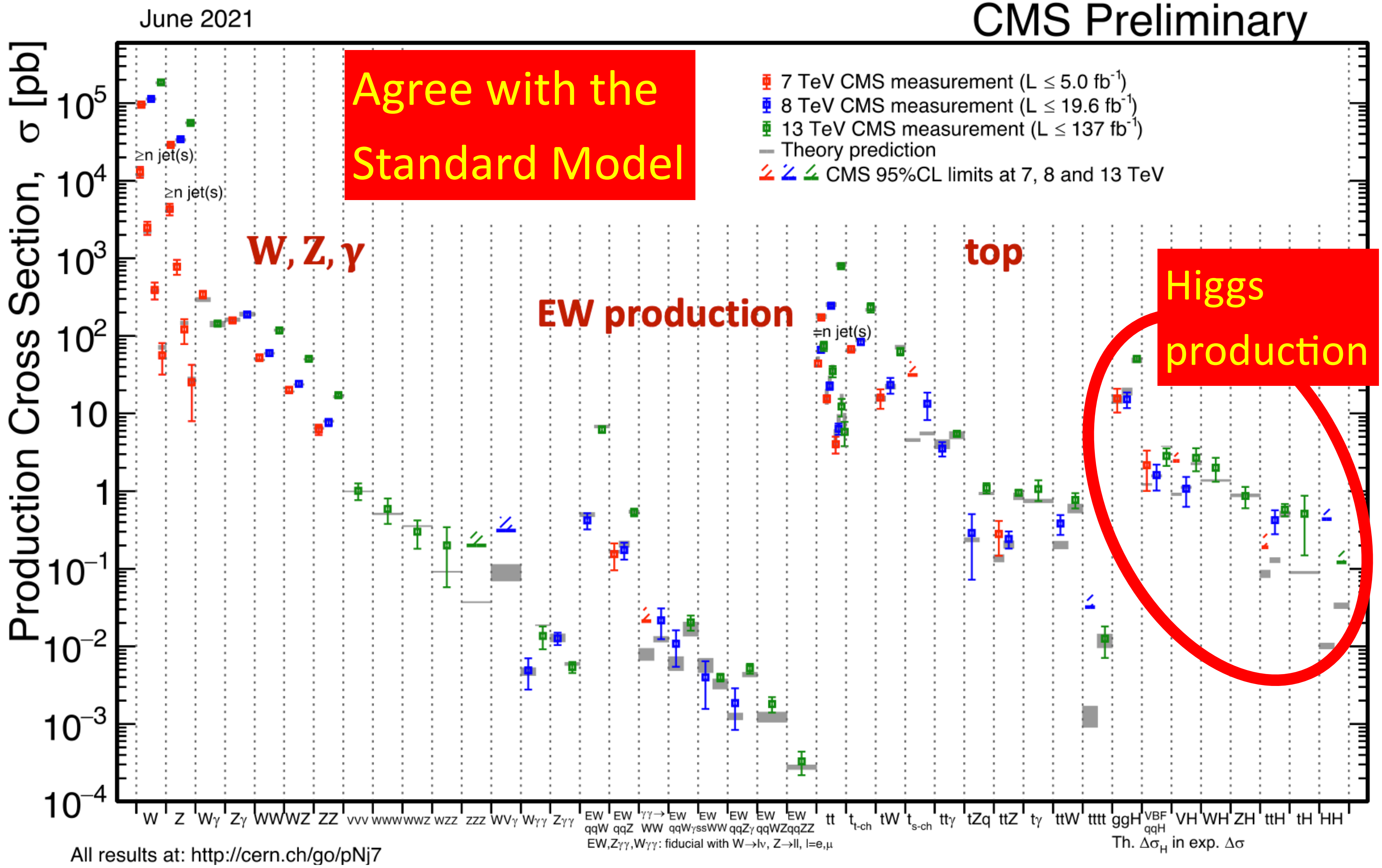


Did the LHC find the missing piece?

Is it the right shape?

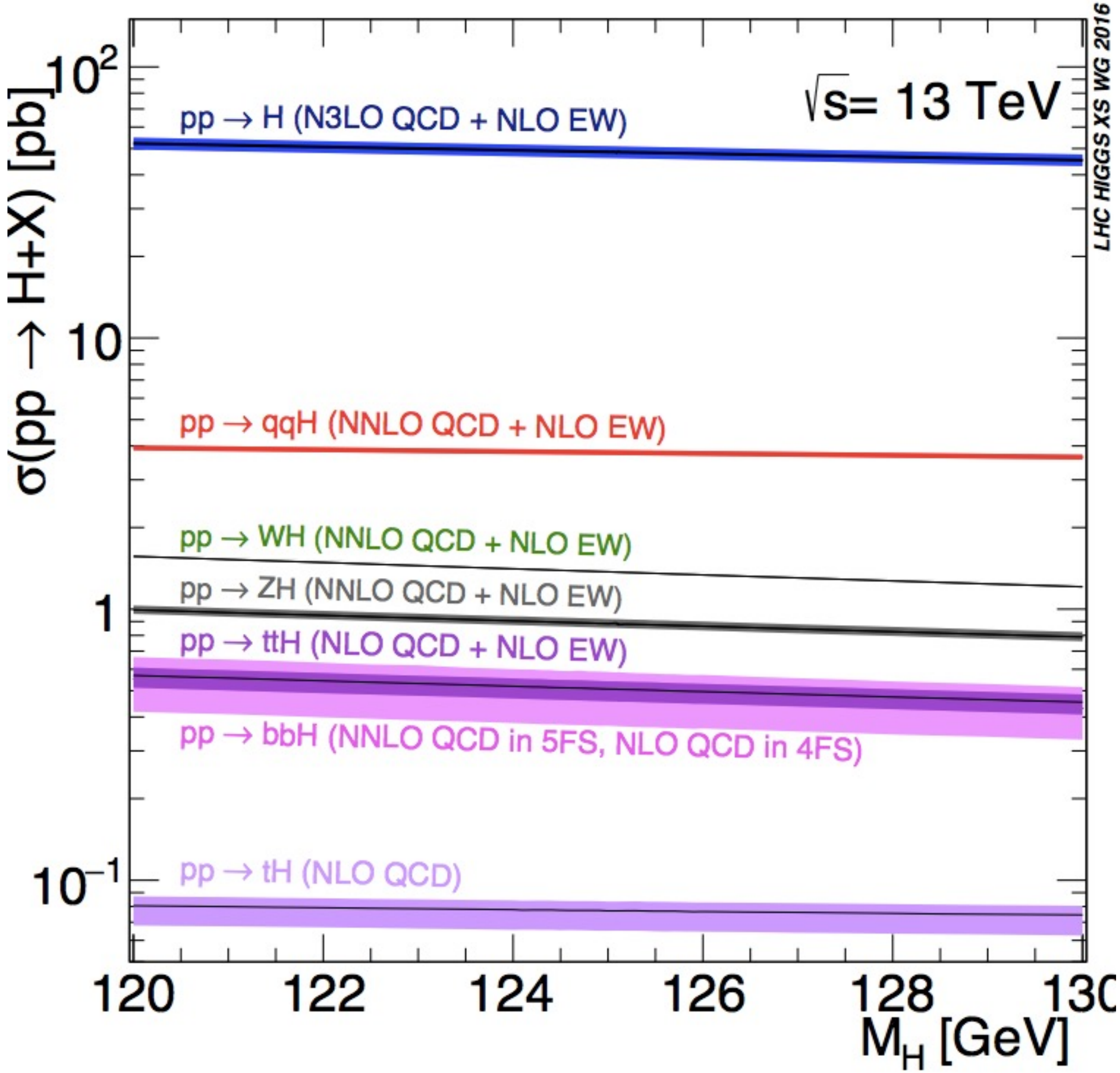
Is it the right size?

LHC Measurements



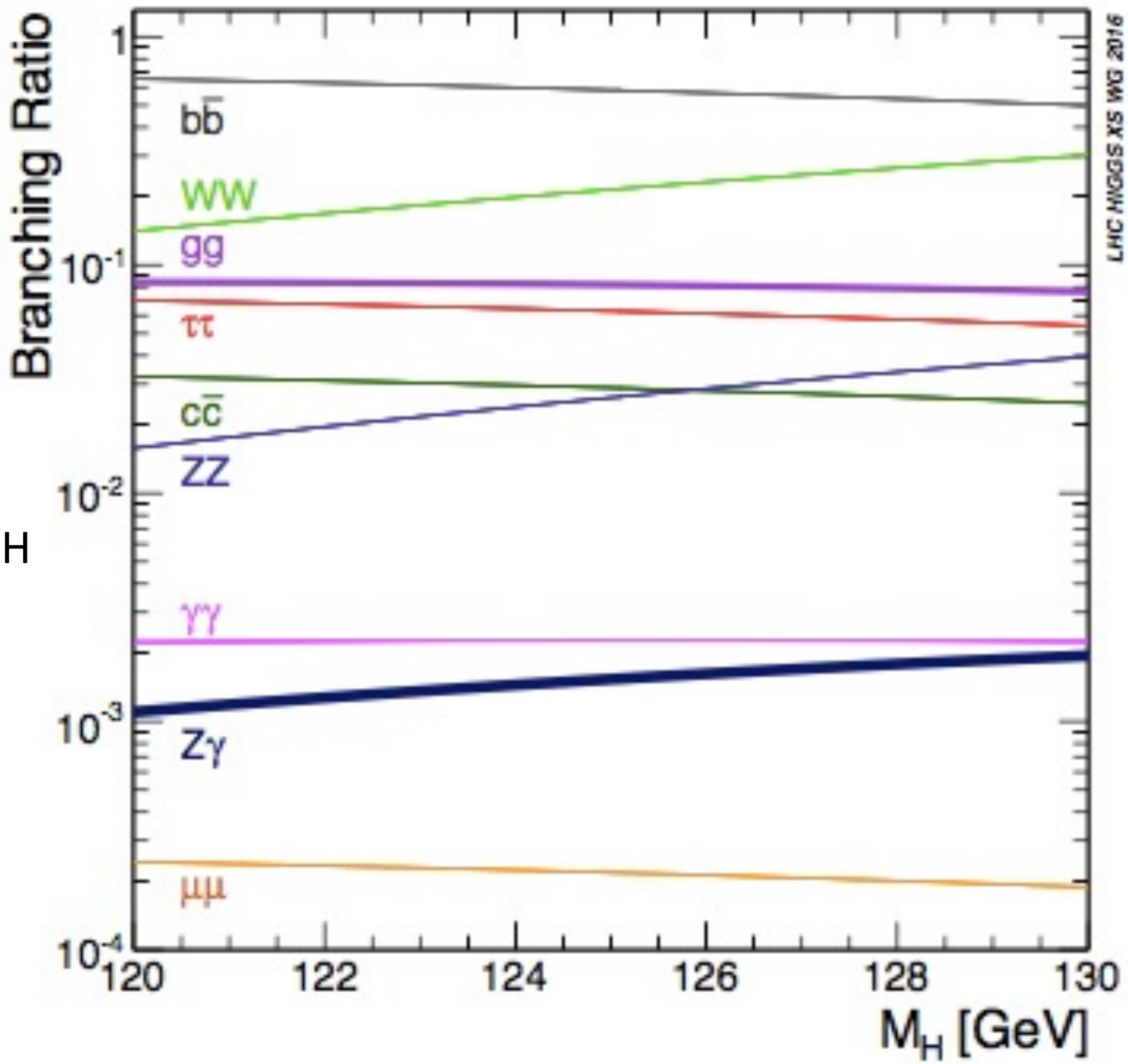
Higgs Production at the LHC

Cross sections for Higgs mass near 125 GeV



LHC Higgs Cross-Section Working Group (LHXSWG)

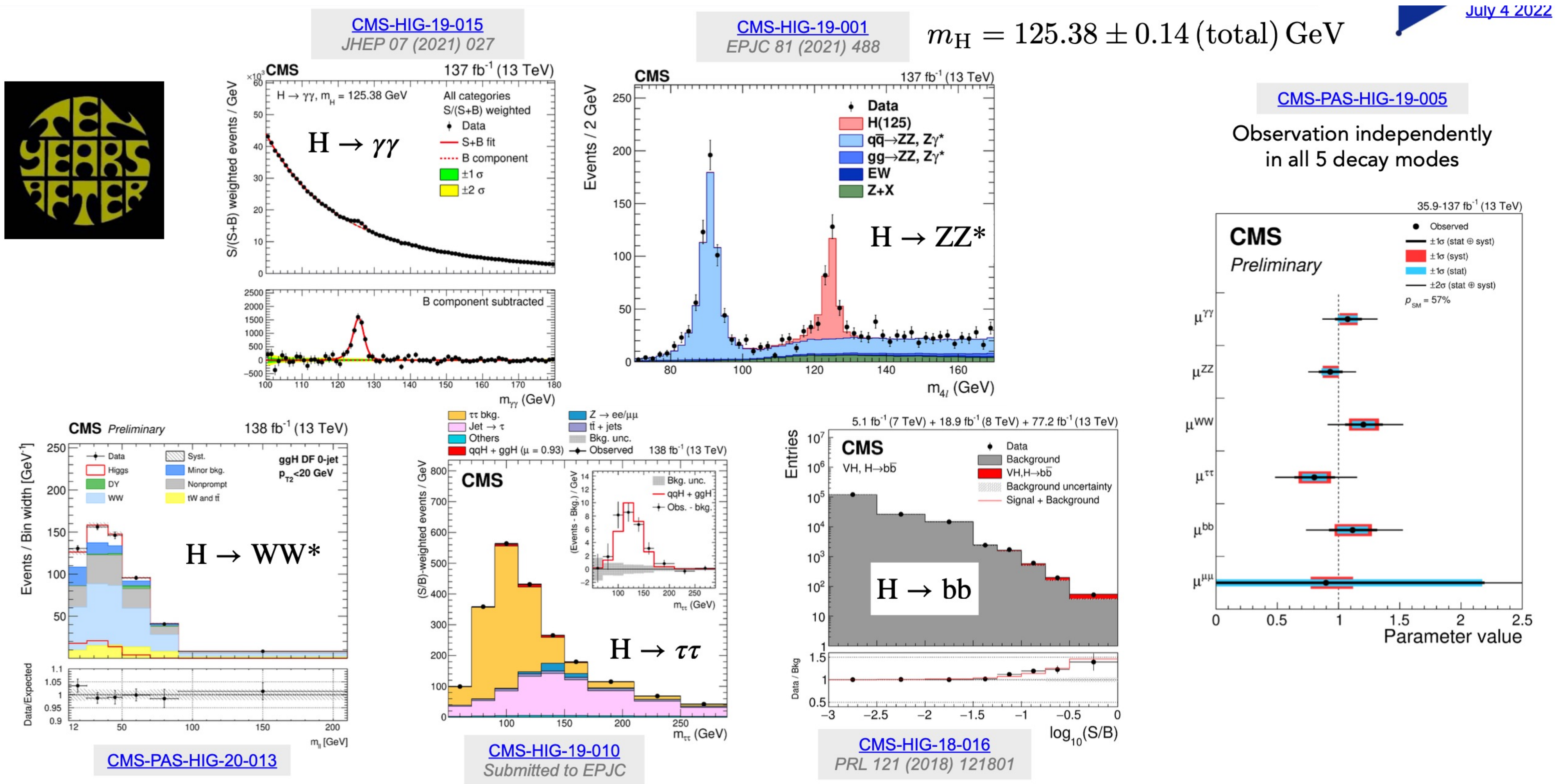
Higgs Decay Branching Ratios



Dominant decay branching ratios for m_H ~ 125 GeV

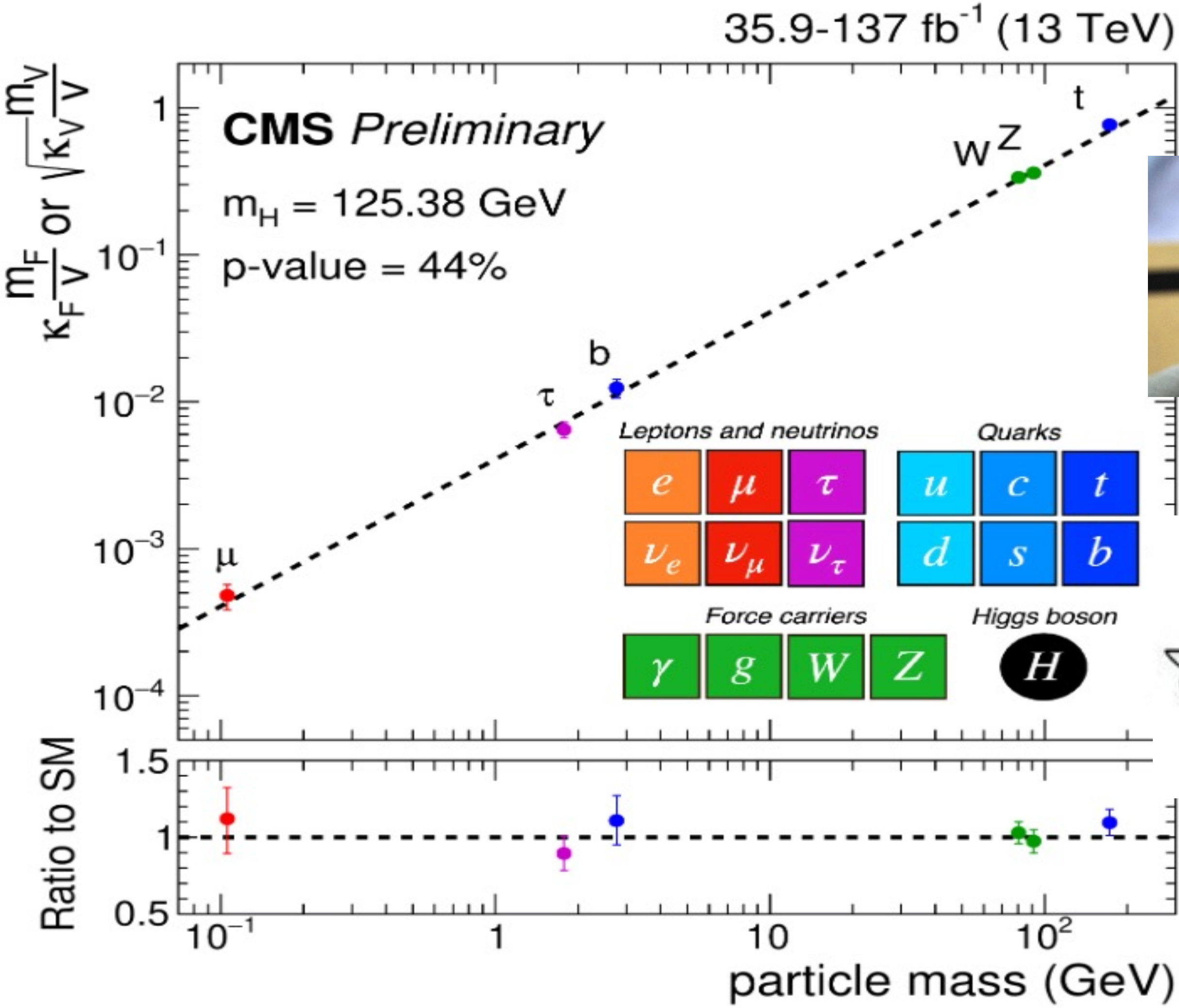
LHC Higgs Cross-Section Working Group (LHXSWG)

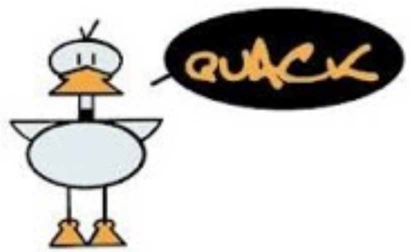
Examples of Higgs Measurements



It Walks and Quacks like a Higgs

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





Without Higgs …

… there would be no atoms

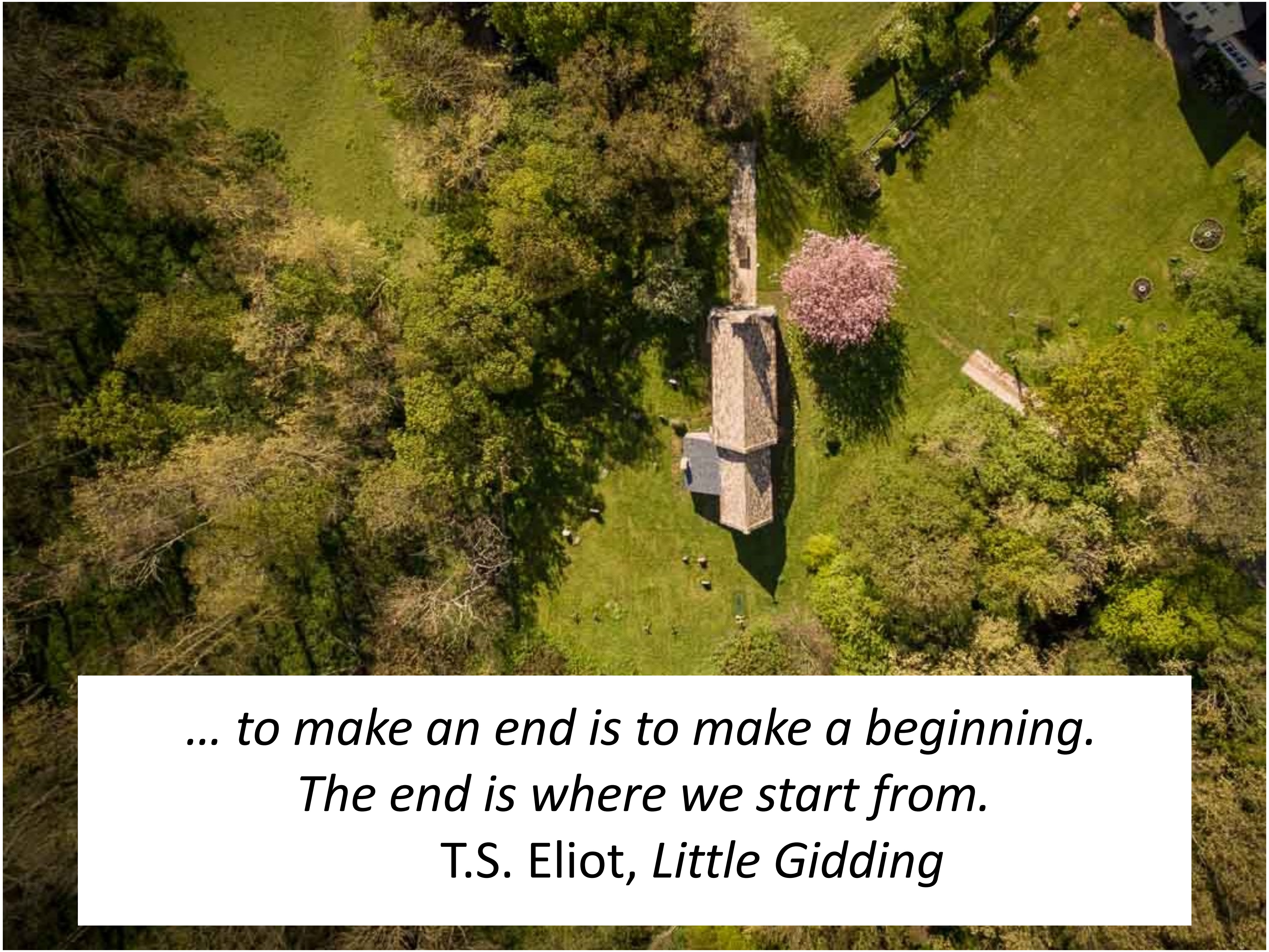
- massless electrons would escape at the speed of light

… there would be no heavy nuclei

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!



… to make an end is to make a beginning.
The end is where we start from.

T.S. Eliot, *Little Gidding*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PIERCE BROSNAN IAN FLEMING'S JAMES BOND 007
The World Is Not Enough
007
12
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LINDY HEMMING DAVID ARNOLD JIM CLARK ADRIAN BIDDLE PETER LAMONT
ANTHONY WAYE NEAL PURVIS ROBERT WADE NEAL PURVIS ROBERT WADE BRUCE FEIRSTEIN
MICHAEL G. WILSON BARBARA BROCCOLI MICHAEL APTED
GARBAGE

- « Empty » space is unstab LHC
- Dark matter LHC
- Origin of matter LHC
- Sizes of masses LHC
- Masses of neutrinos
- Inflation
- Quantum gravity
- …