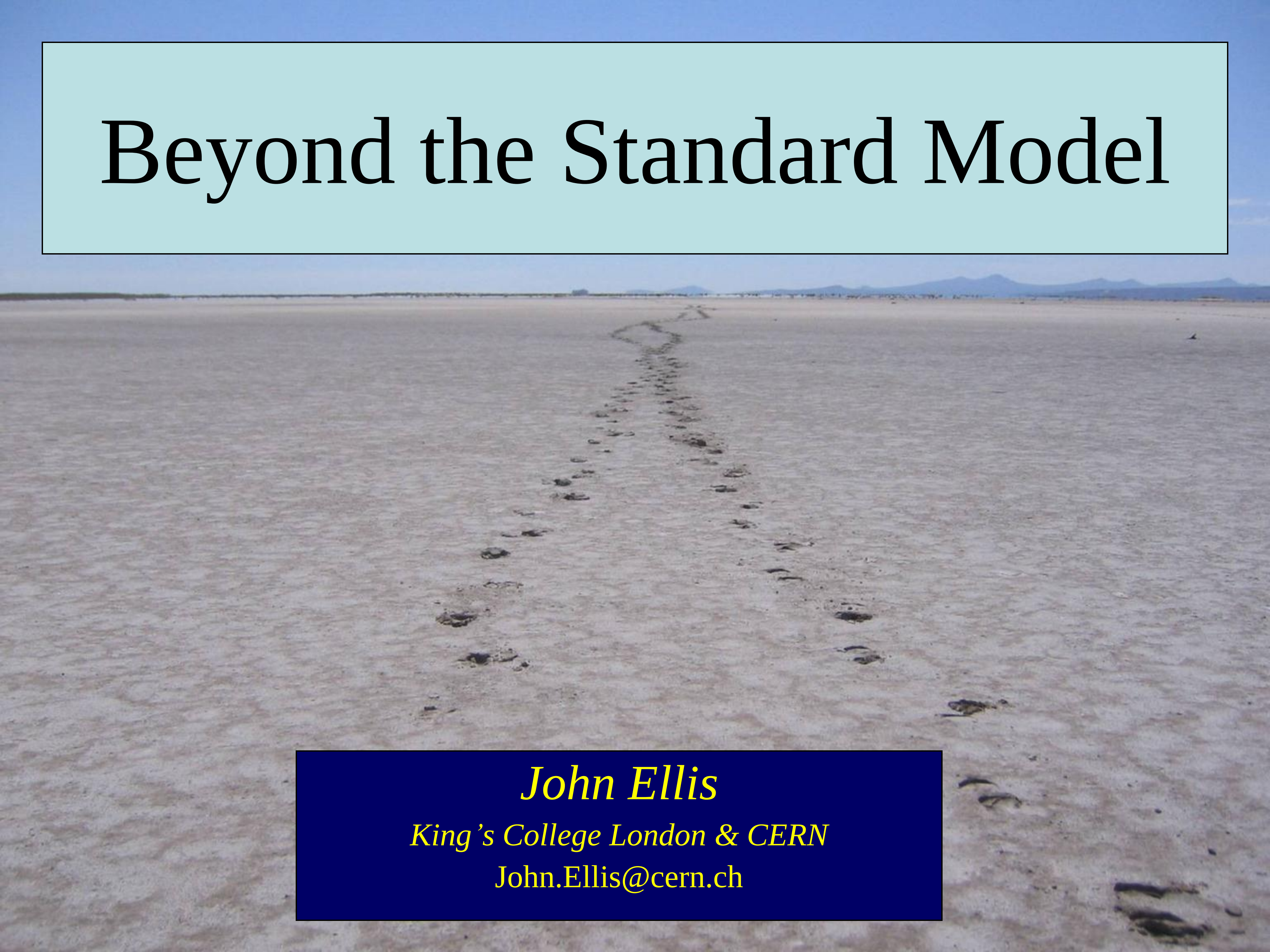
Beyond the Standard Model



John Ellis

King's College London & CERN

John.Ellis@cern.ch

Plan of the Lectures

- The Standard Model and issues beyond it
- Origin of particle masses: Higgs boson or?
- Supersymmetry
- Searches for supersymmetry: LHC & dark matter
- Extra dimensions and string theory

Beyond the Standard Model for Montañeros

M. Bustamante, L. Cieri and John Ellis
[1] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado 1761, Lima, Peru
[2] Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Pabellón 1, Ciudad Universitaria, 1428 Buenos Aires, Argentina
[3] Theory Division, Physics Department, CERN, CH 1211 Geneva 23, Switzerland

http://arXiv.org/pdf/0911.4409.pdf

Summary of the Standard Model

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

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

- Lagrangian:

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

Gauge Interactions of the Standard Model

- Three separate gauge group factors:
  - SU(3) × SU(2) × U(1)
  - Strong × electroweak
- Three different gauge couplings:
  - g_3, g_2, g'
- Mixing between the SU(2) and U(1) factors:

$$\begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$\sin^2(\theta_W) = \frac{g'^2}{g'^2 + g^2}$$

- Experimental value: $\sin^2\theta_W = 0.23120 \pm 0.00015$

Important clue for Grand Unification

Weak Interactions

- Interactions of lepton doublets: $L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$
- Charged-current interactions:

$$\mathcal{L}_{cc} = \frac{-g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \nu_{L_\alpha} \gamma_\mu l_{L_\alpha} W^\mu \ + \ h.c.$$

- Neutral-current interactions:

$$\mathcal{L}_{nc} = \frac{-g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \nu_{L_\alpha} \gamma_\mu l_{L_\alpha} Z^\mu \ + \ h.c$$

- Effective four-fermion interaction:

$G_F/\sqrt{2} = g^2/8m_W^2$

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\alpha (1-\gamma^5) \mu \bar{e} \gamma_\alpha (1-\gamma^5) \nu_e$$

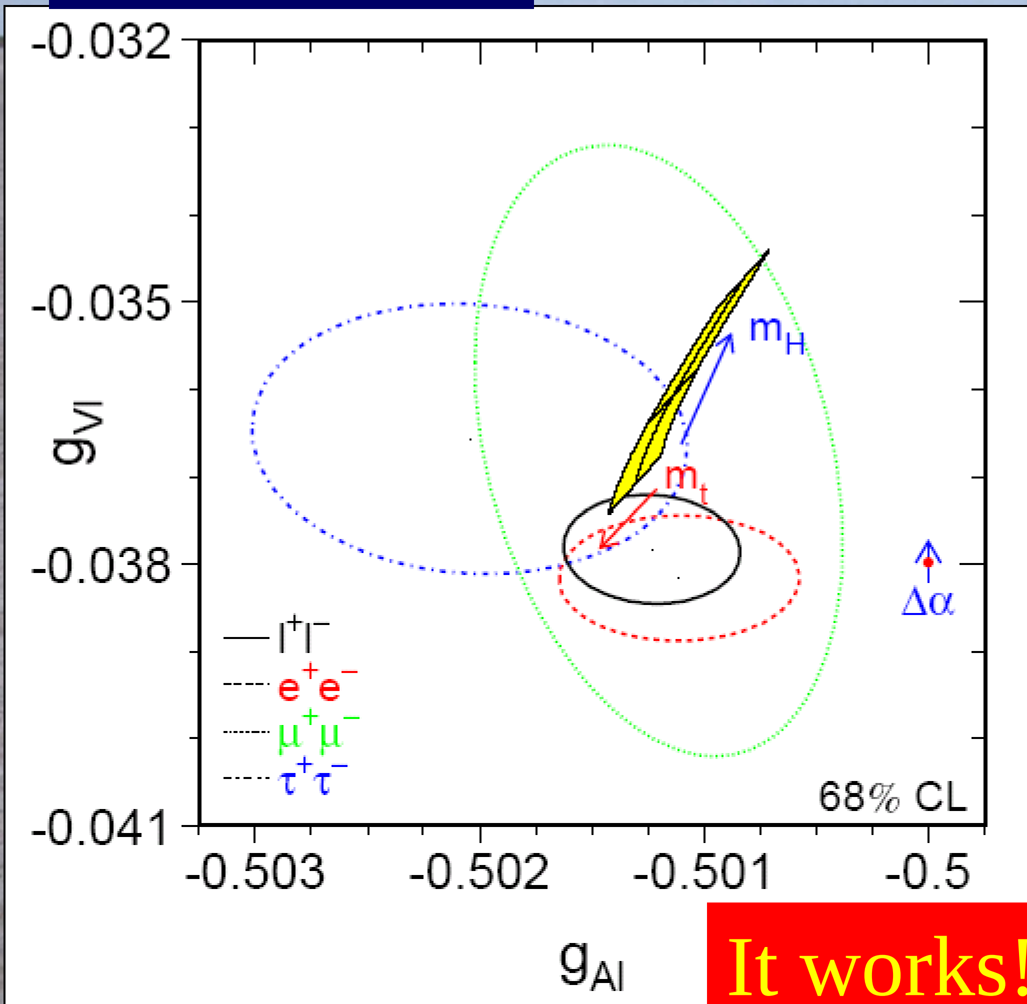
Status of the Standard Model

- 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:

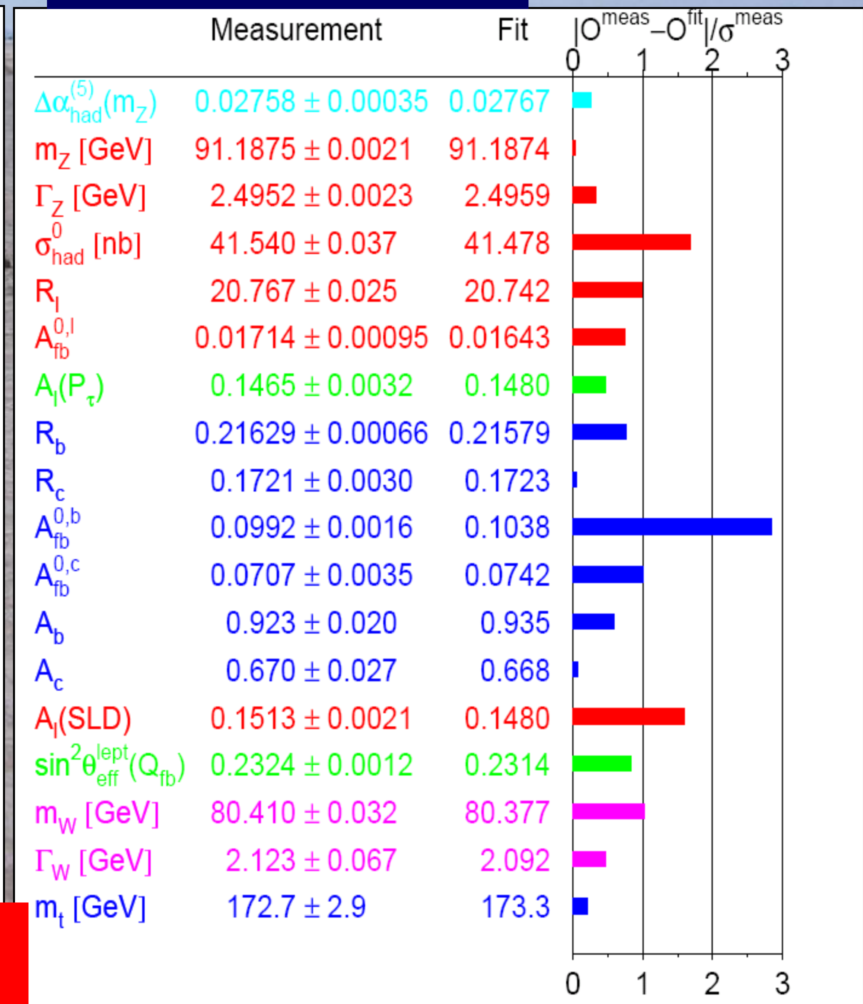
mass? flavour? unification?

Precision Tests of the Standard Model

Lepton couplings



Pulls in global fit



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	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^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	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
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	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!

Parameters of the Standard Model

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

Unification?

Flavour?

Mass?

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + other physics?

  solution at energy < 1 TeV (1000 GeV)

  Supersymmetry

- Why so many types of matter particles?

  matter-antimatter difference?

- Unification of the fundamental forces?

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

  probe directly via neutrino physics, indirectly via masses, couplings

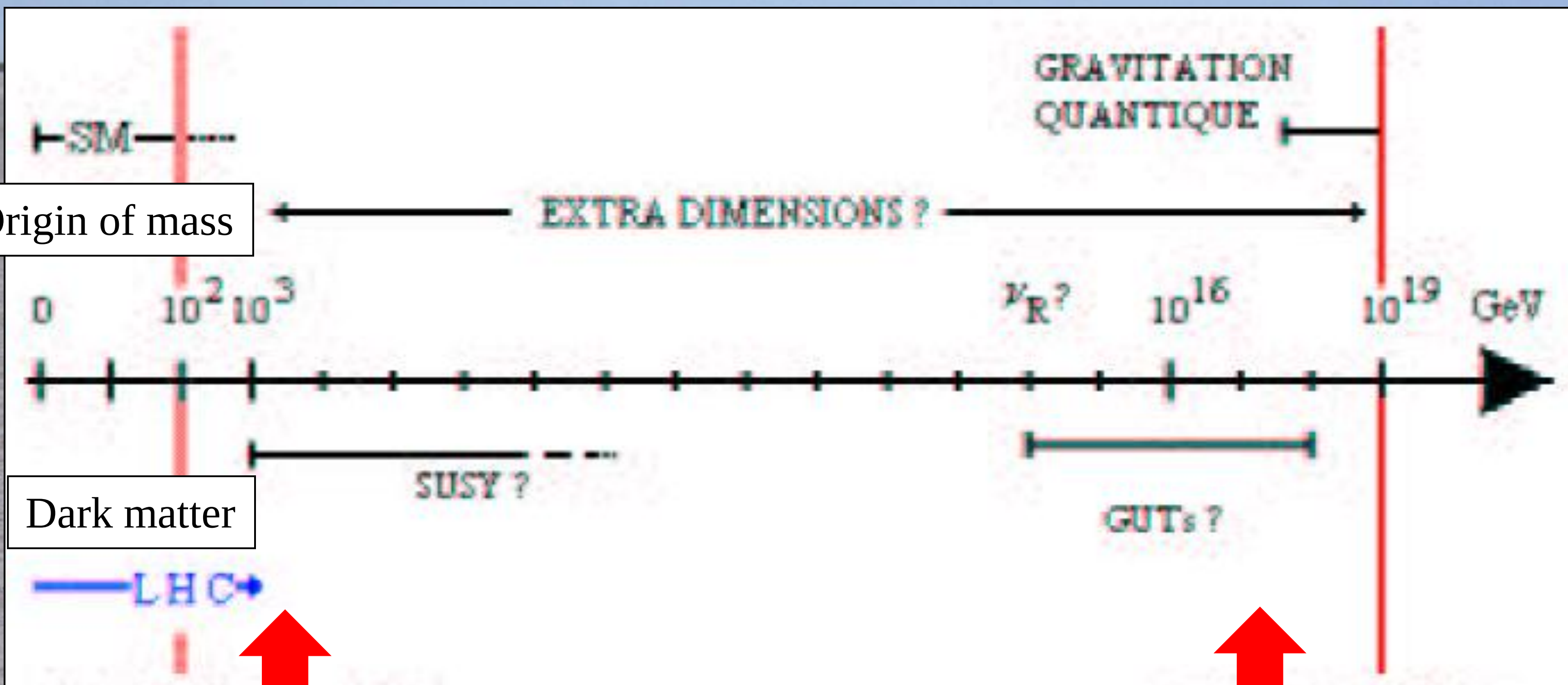
  Supersymmetry

- Quantum theory of gravity?

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

  Supersymmetry

At what Energy is the New Physics?



Origin of mass

Dark matter

A lot accessible
to the LHC?

Some accessible only indirectly:
Astrophysics & cosmology?

Why do Things Weigh?

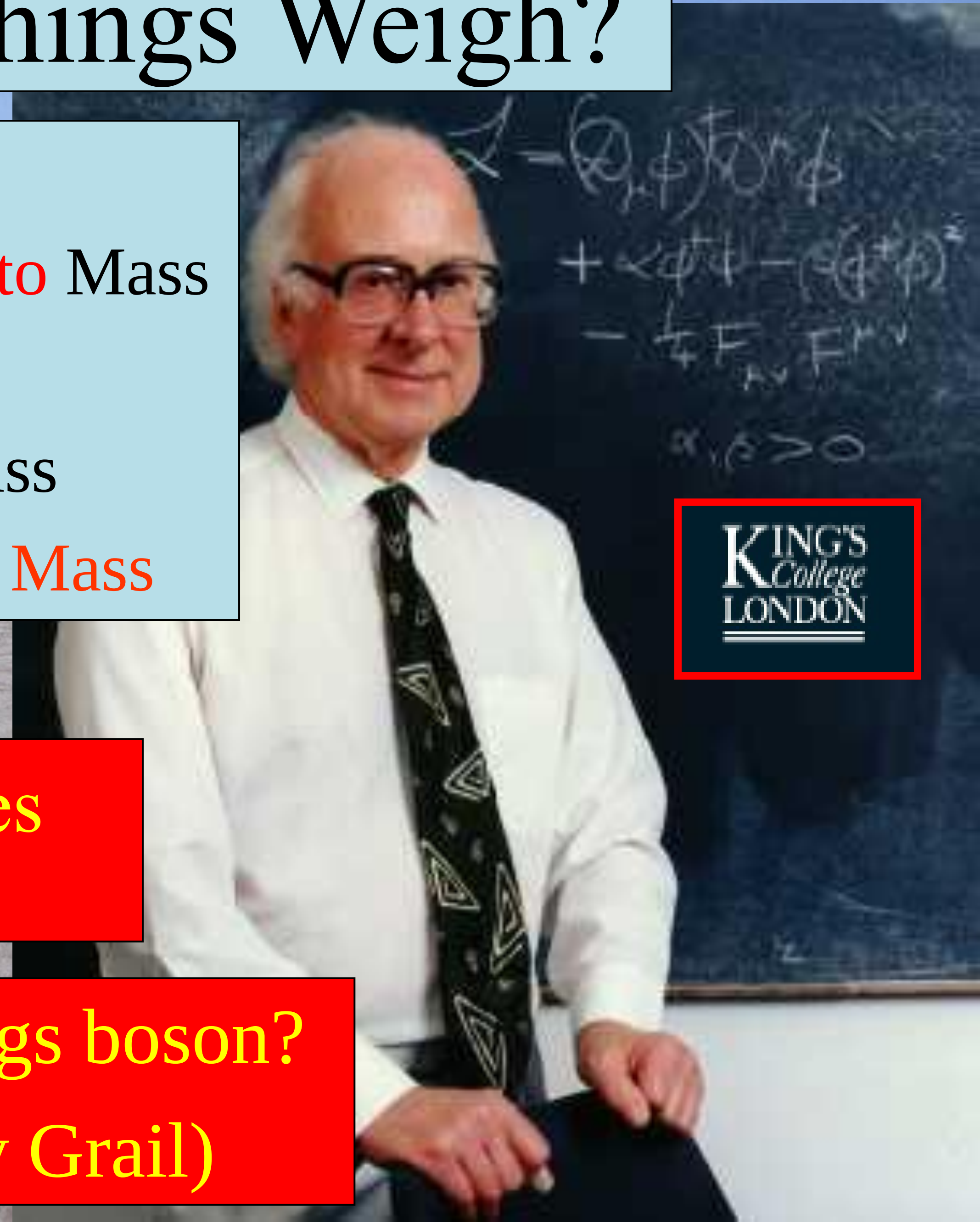
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson?

(the physicists' Holy Grail)

The Seminal Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The Englert-Brout-Higgs Mechanism

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

The Englert-Brout-Higgs Mechanism

Englert & Brout

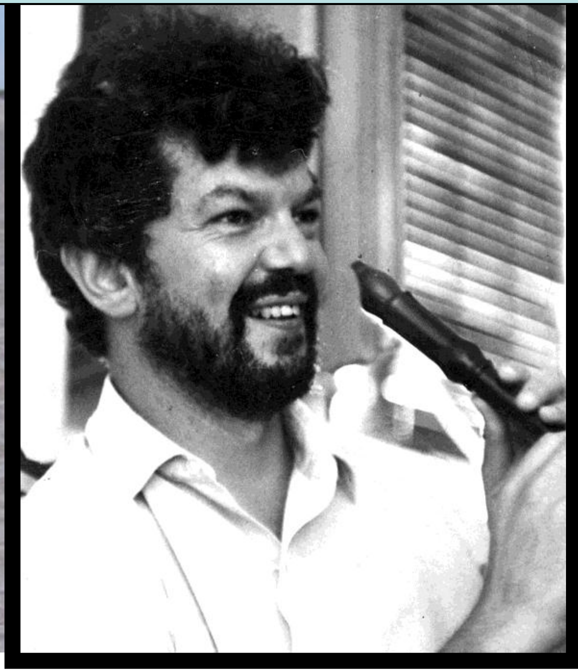


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\to (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\to -(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

Guralnik, Hagen & Kibble

We consider, as our example, a theory which was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$+\varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$

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

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

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

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

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

The Higgs Boson

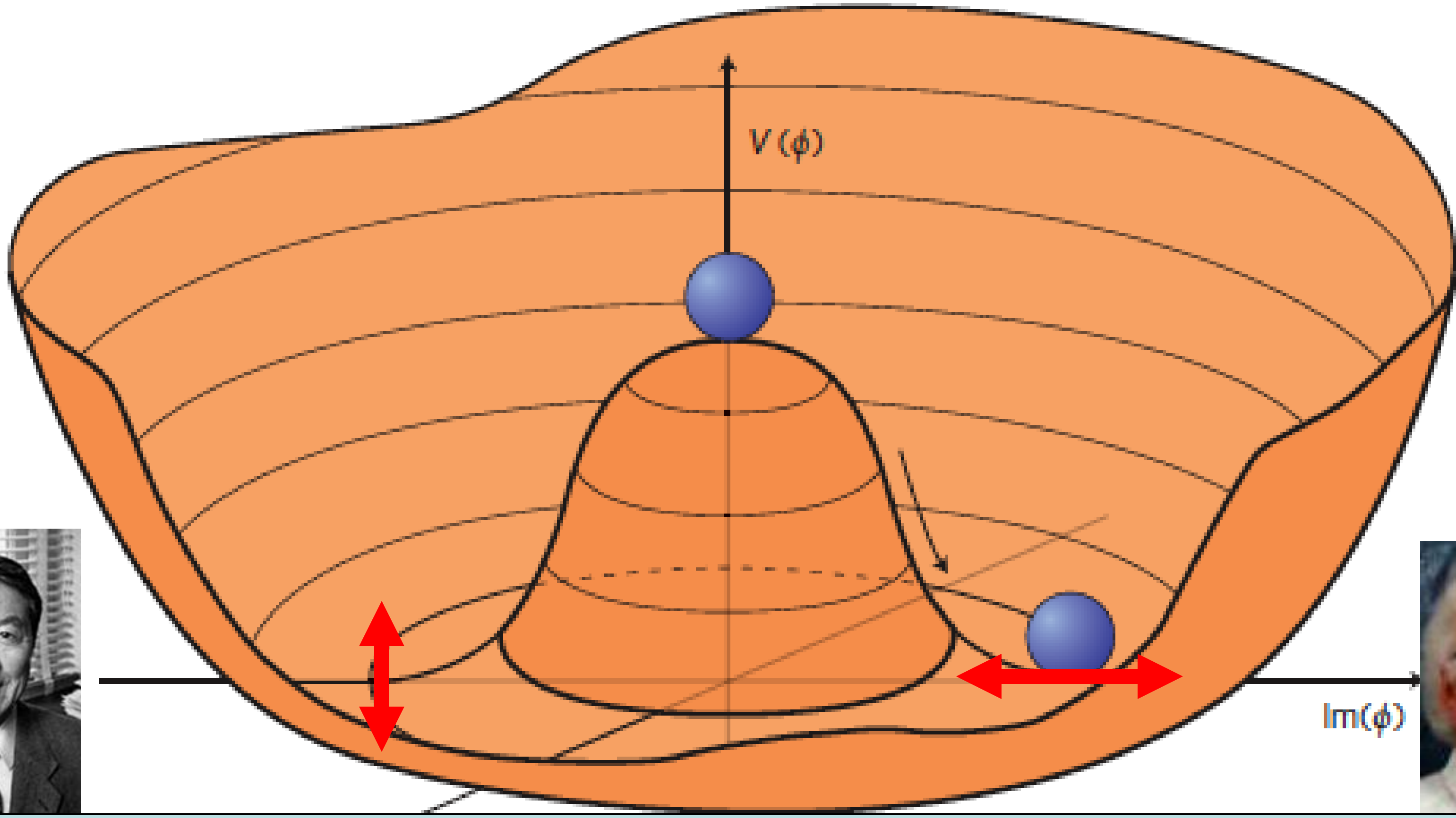
- **Higgs pointed out a massive scalar boson**

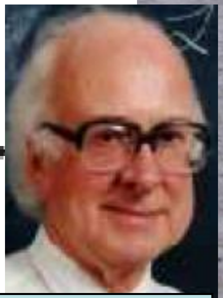
$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

- *"… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons"*
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence
- **Discussed in detail by Higgs in 1966 paper**

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





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

Accompanied by massive particle

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

How does the Higgs trick work?

Masses for 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:

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

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:

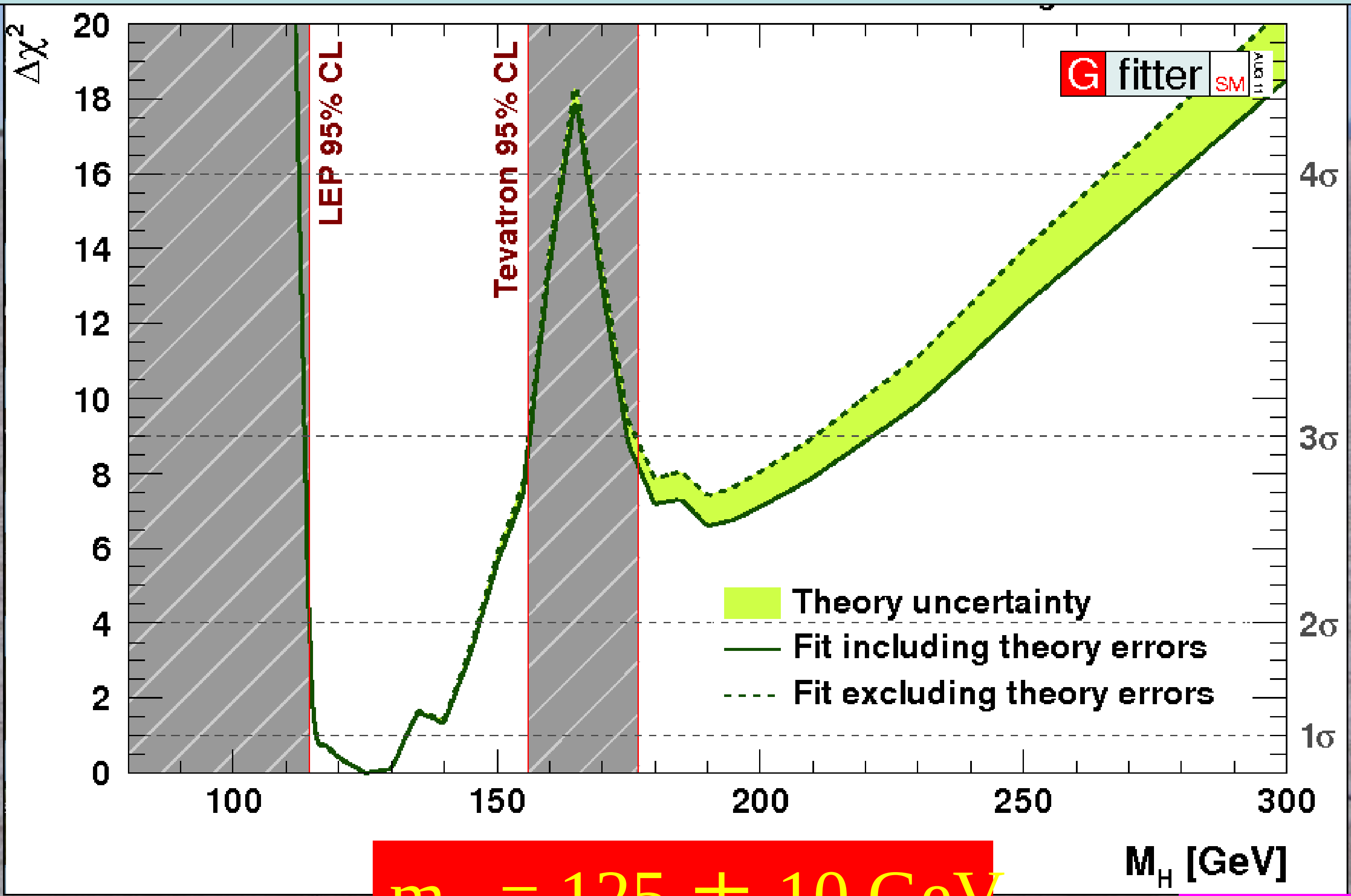
$$\frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

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

  $m_H > 114$ GeV

- No conflict!

2011: Combining Information from Previous Direct Searches and Indirect Data

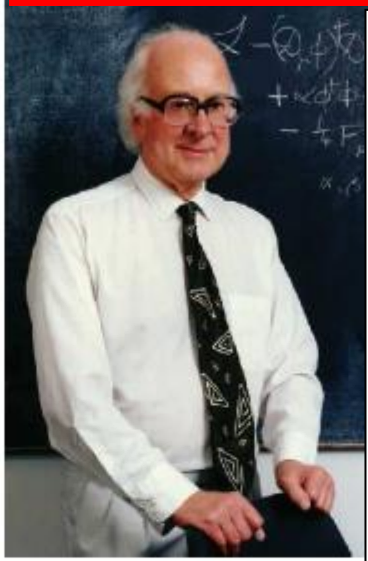


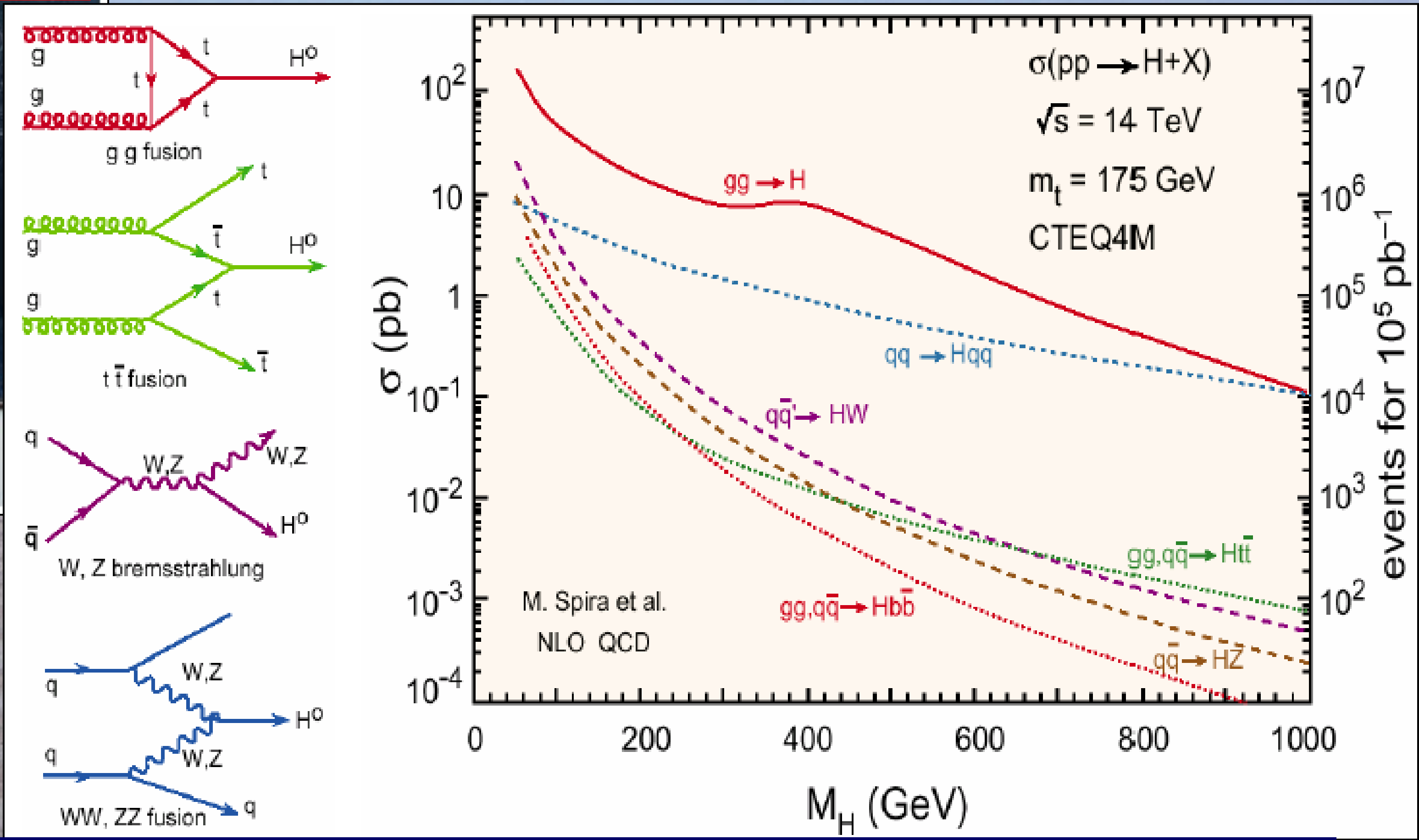
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

Higgs Production at the LHC

A la recherche du Higgs perdu …

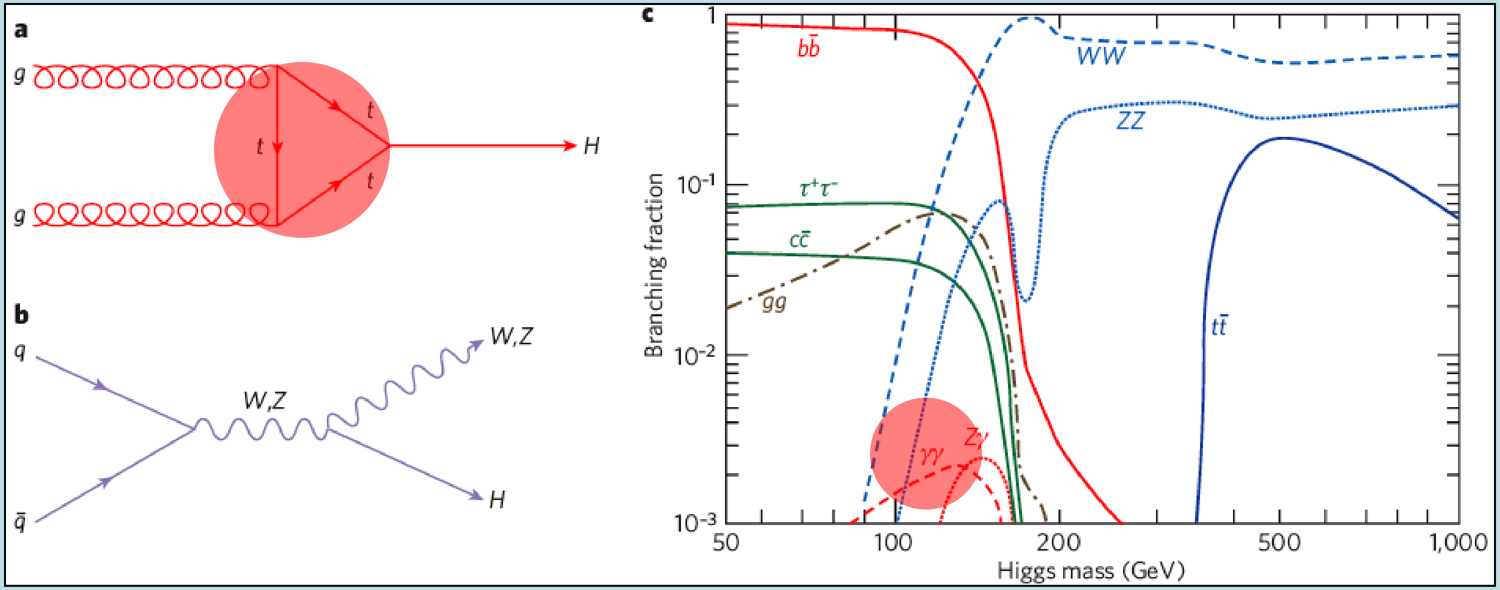




Many production modes measurable if $M_h \sim 125$ GeV

Higgs Decay Branching Ratios

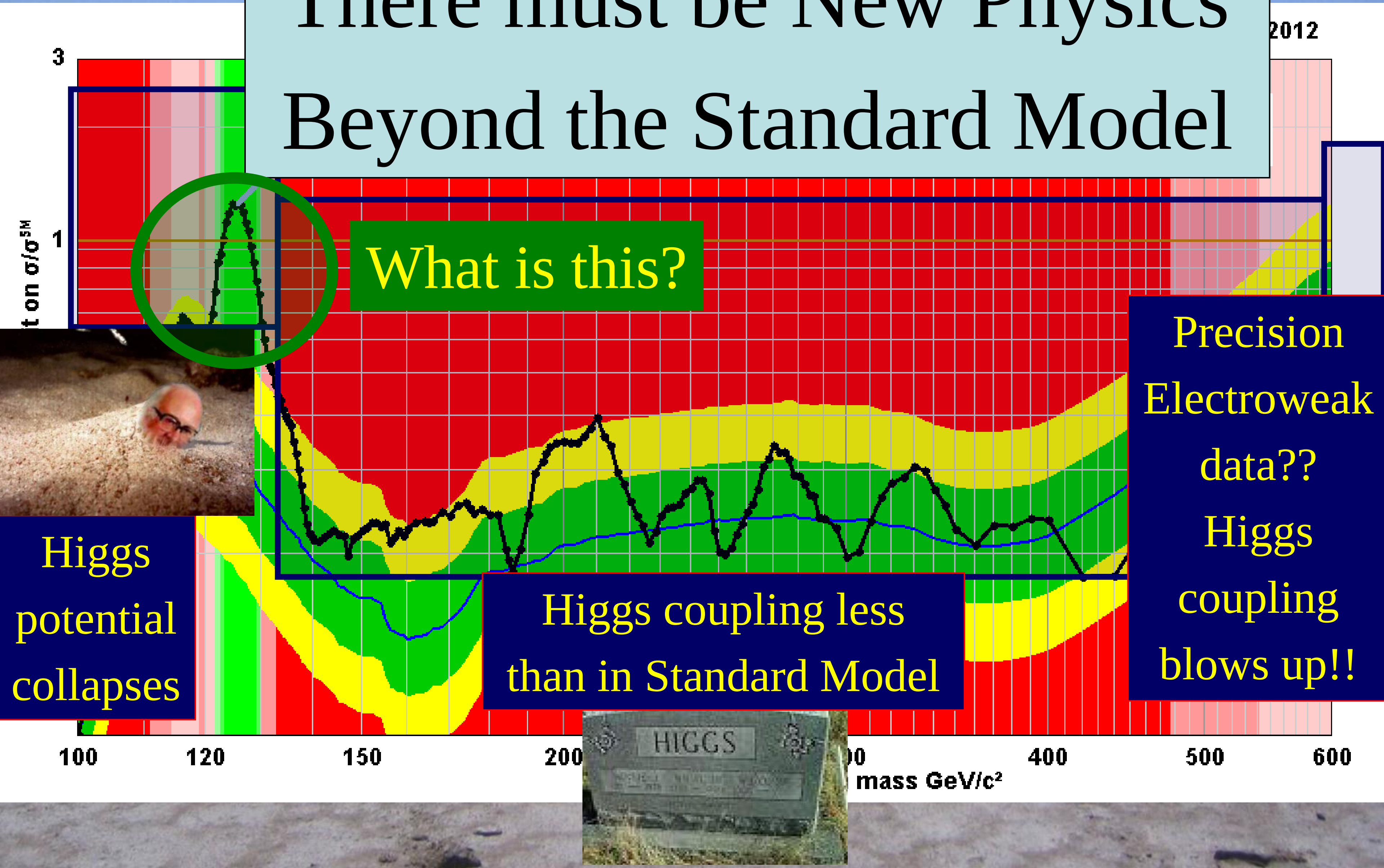
- Couplings proportional to masses (?)



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

Many decay modes measurable if M_h ~ 125 GeV

There must be New Physics Beyond the Standard Model



What is this?

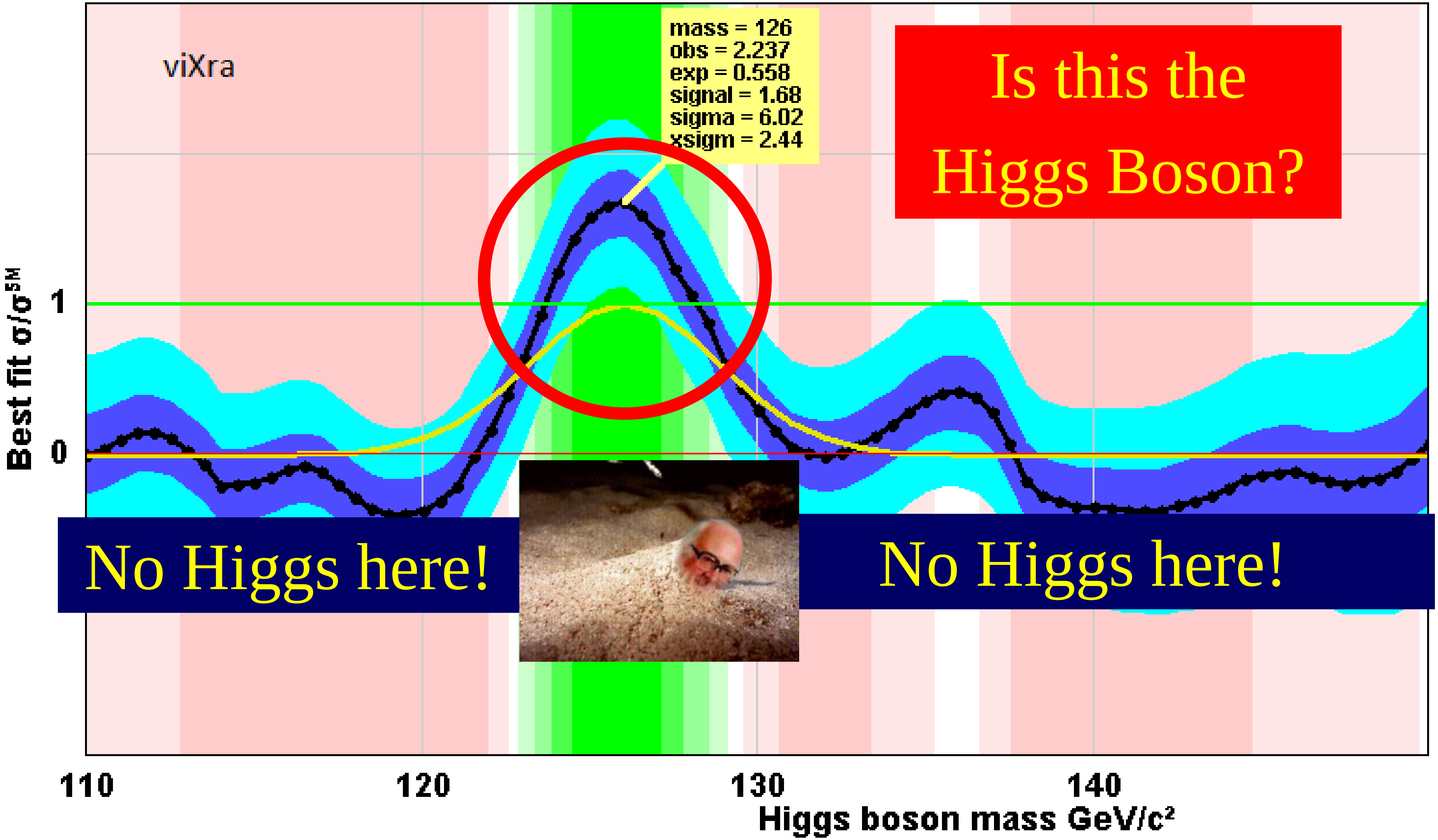
Higgs potential collapses

Higgs coupling less than in Standard Model

Precision Electroweak data??

Higgs coupling blows up!!

Unofficial Combination of Higgs Search Data from July 4th



The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

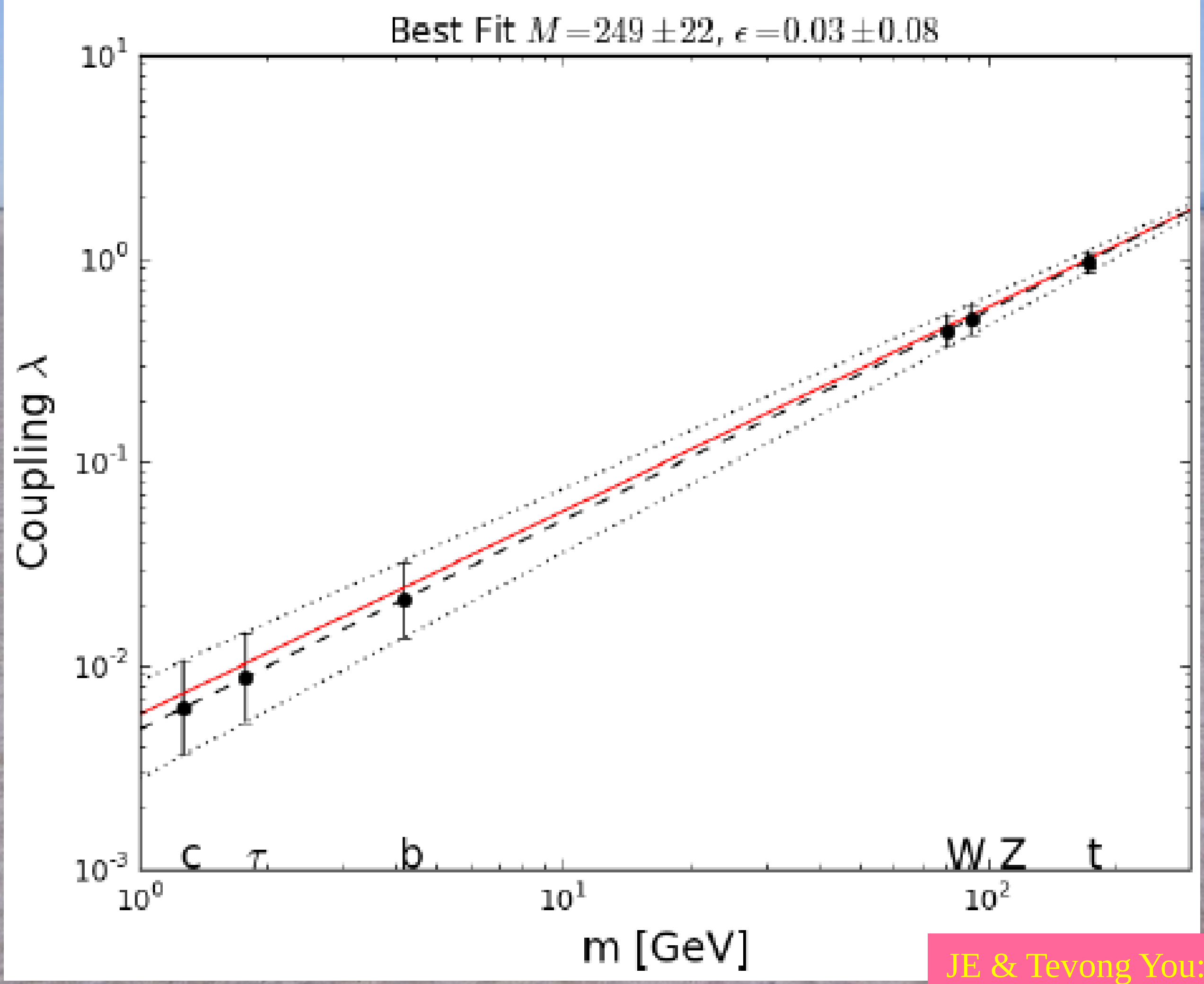
Is it the right shape?

Is it the right size?

Do we already know the 'Higgs' has Spin Zero ?

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

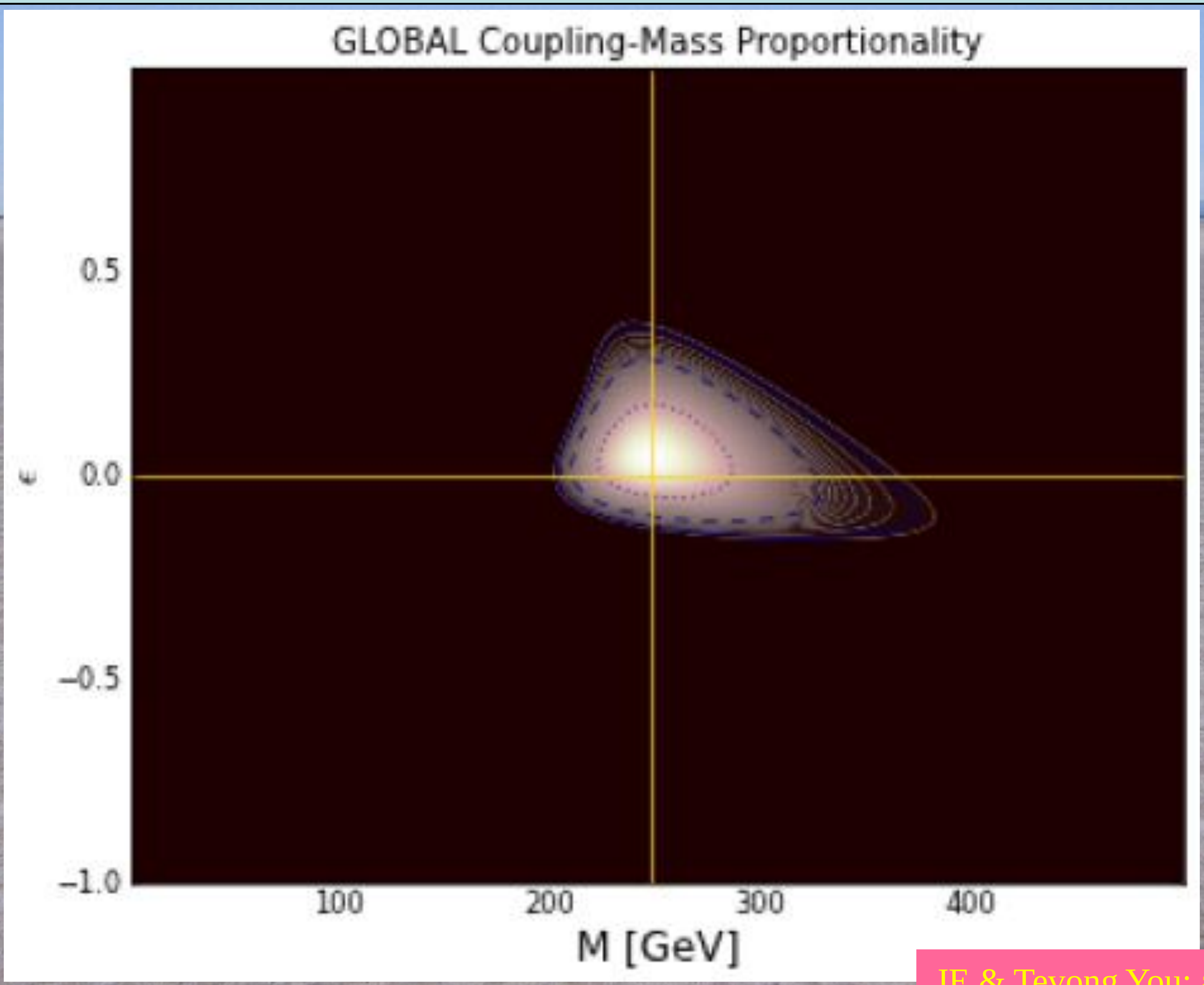
Couplings ~ Mass



JE & Tevong You: arXiv:1207.1693

Scale as expected for Higgs Boson

Couplings ~ Mass



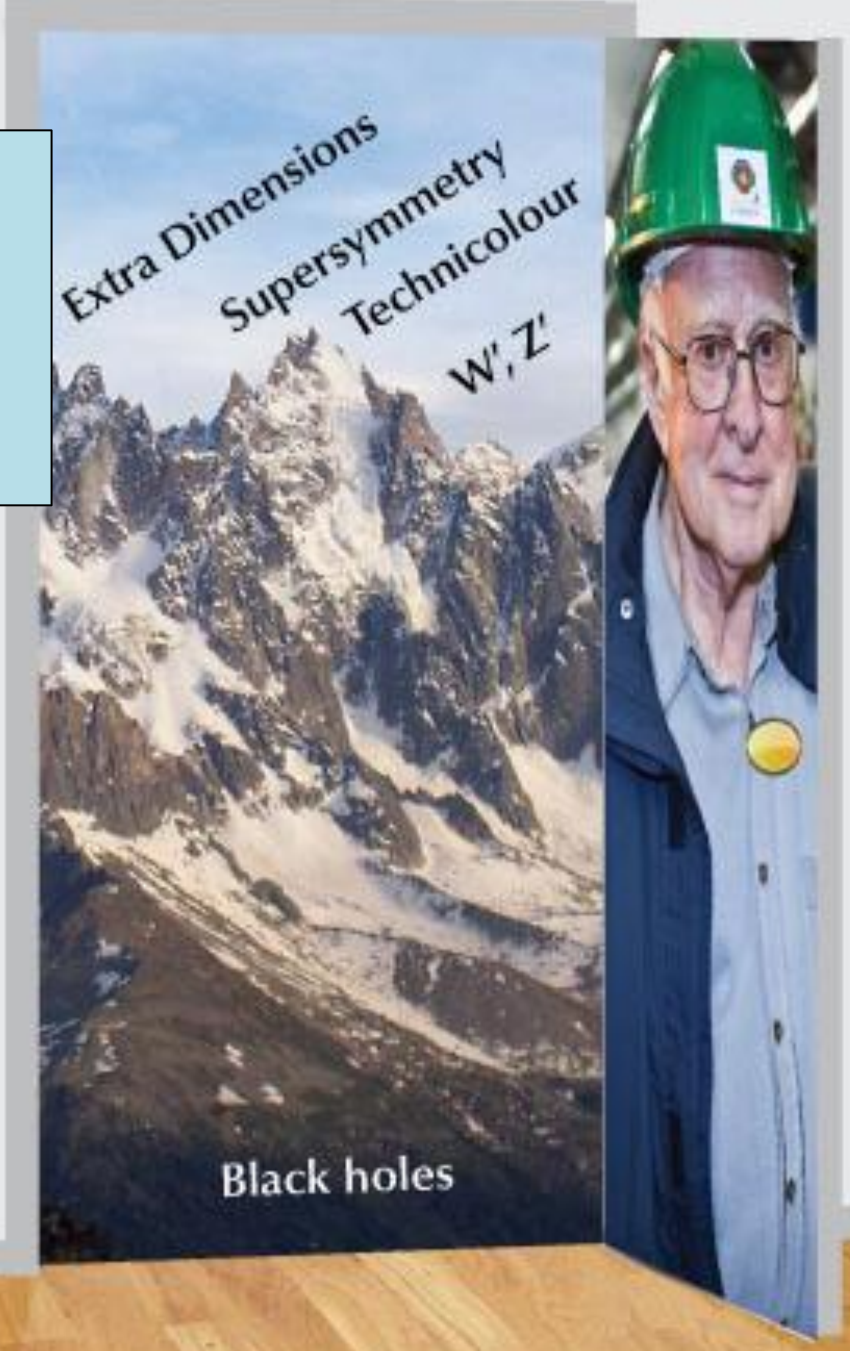
JE & Tevong You: arXiv:1207.1693

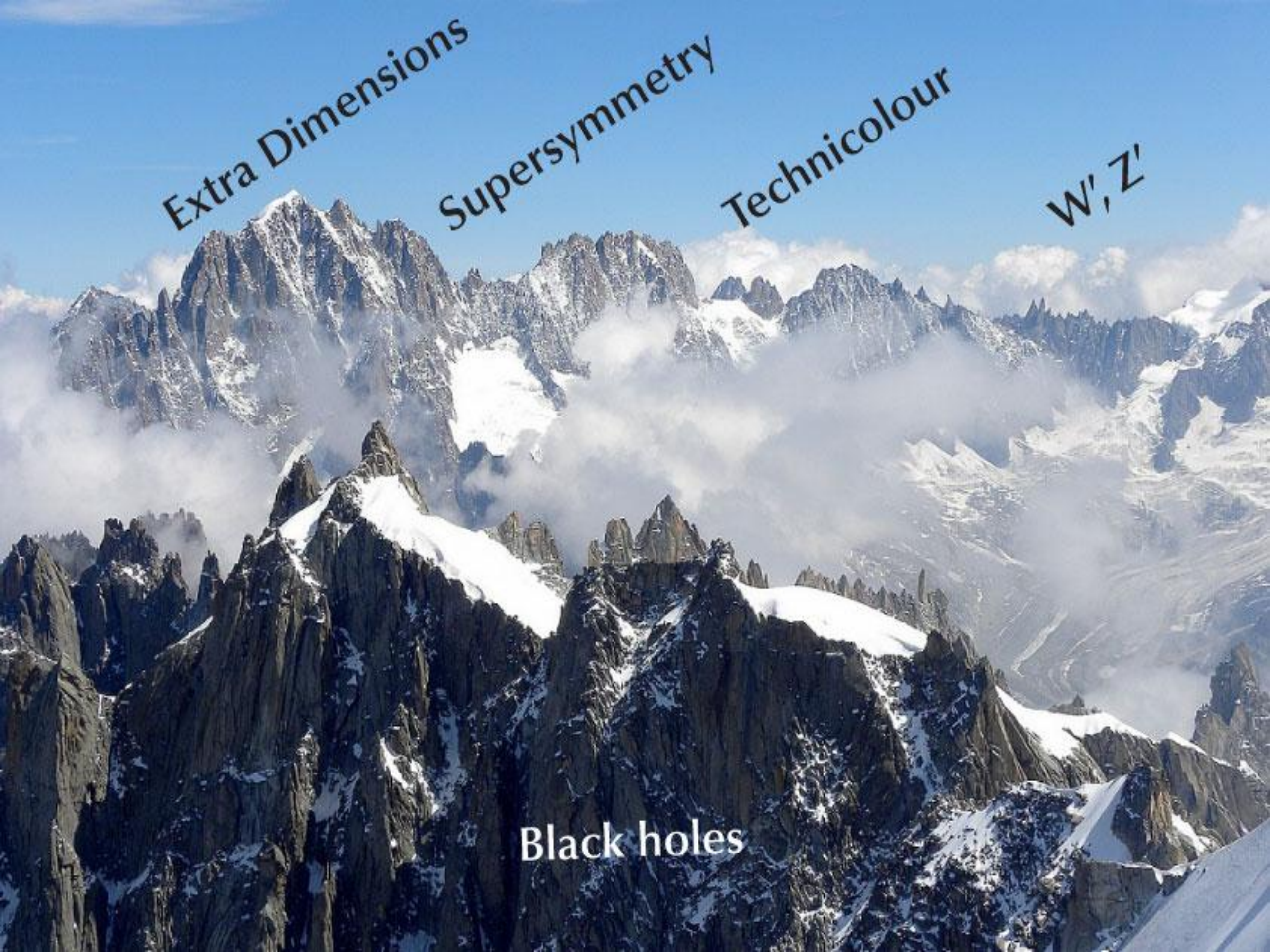
Scale as expected for Higgs Boson

Imagine a Room …

… Open The Door

What lies Beyond?



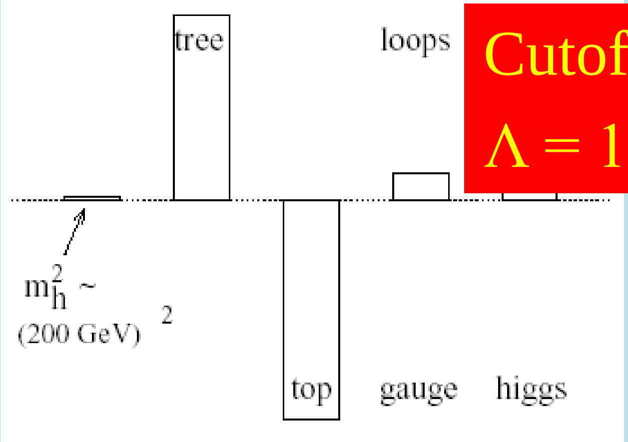

Extra Dimensions
Supersymmetry
Technicolour
W', Z'
Black holes

Elementary Higgs or Composite?

- Higgs field:

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

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off Λ ~ 1 TeV with

Supersymmetry?

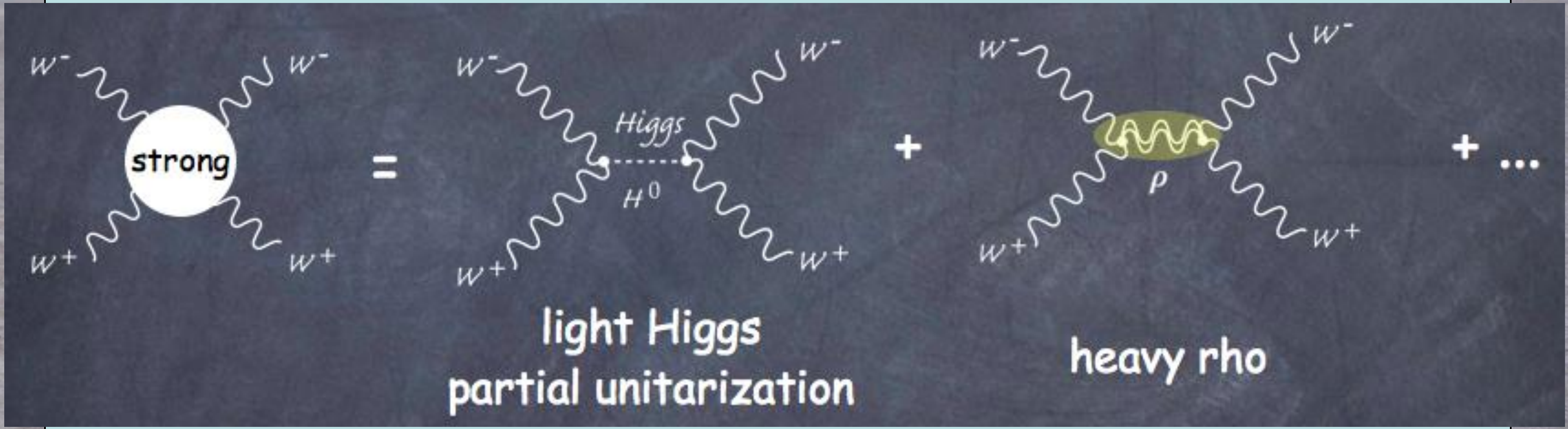
- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

- Heavy scalar resonance?
- Inconsistent with precision electroweak data?

Interpolating Models

- Combination of Higgs boson and vector ρ



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

$$g_\rho / m_\rho$$

Grojean, Giudice, Pomarol, Rattazzi

General Analysis of Generalized Higgs Models

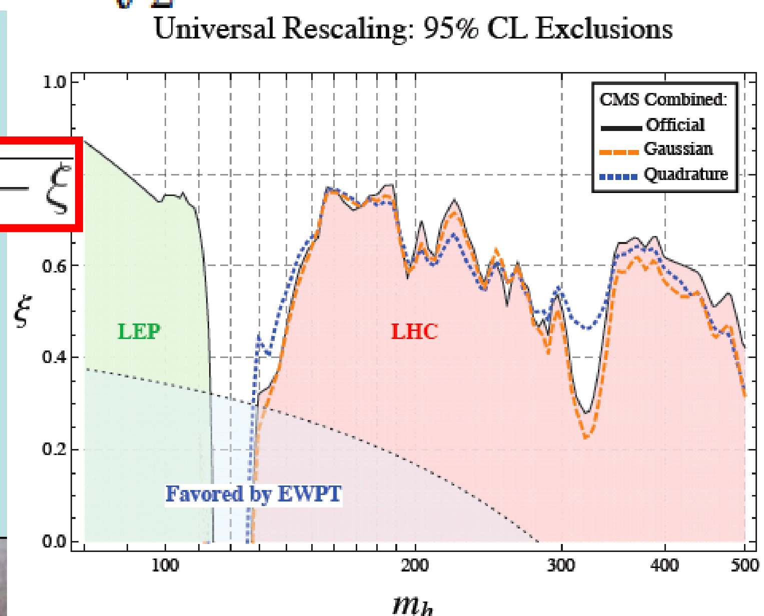
- Parameterization of effective Lagrangian:

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

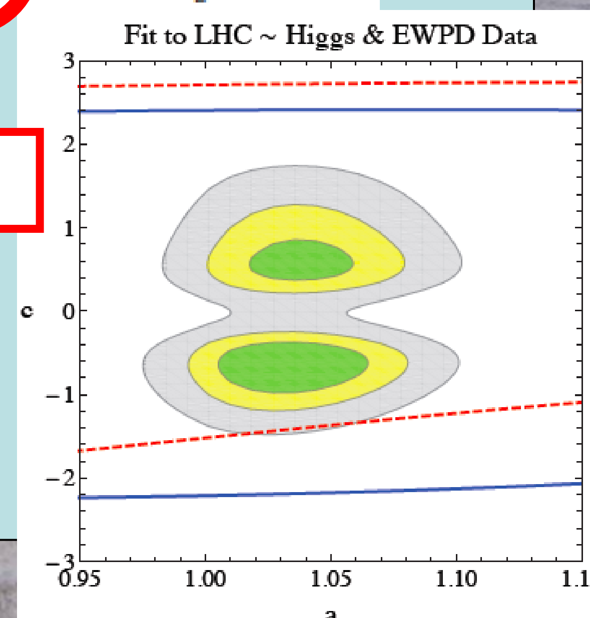
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}_L^{(i)}, \bar{d}_L^{(i)}\right)\Sigma\left(u_R^{(i)}, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right)$$

- Fits

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



$$a \neq c$$



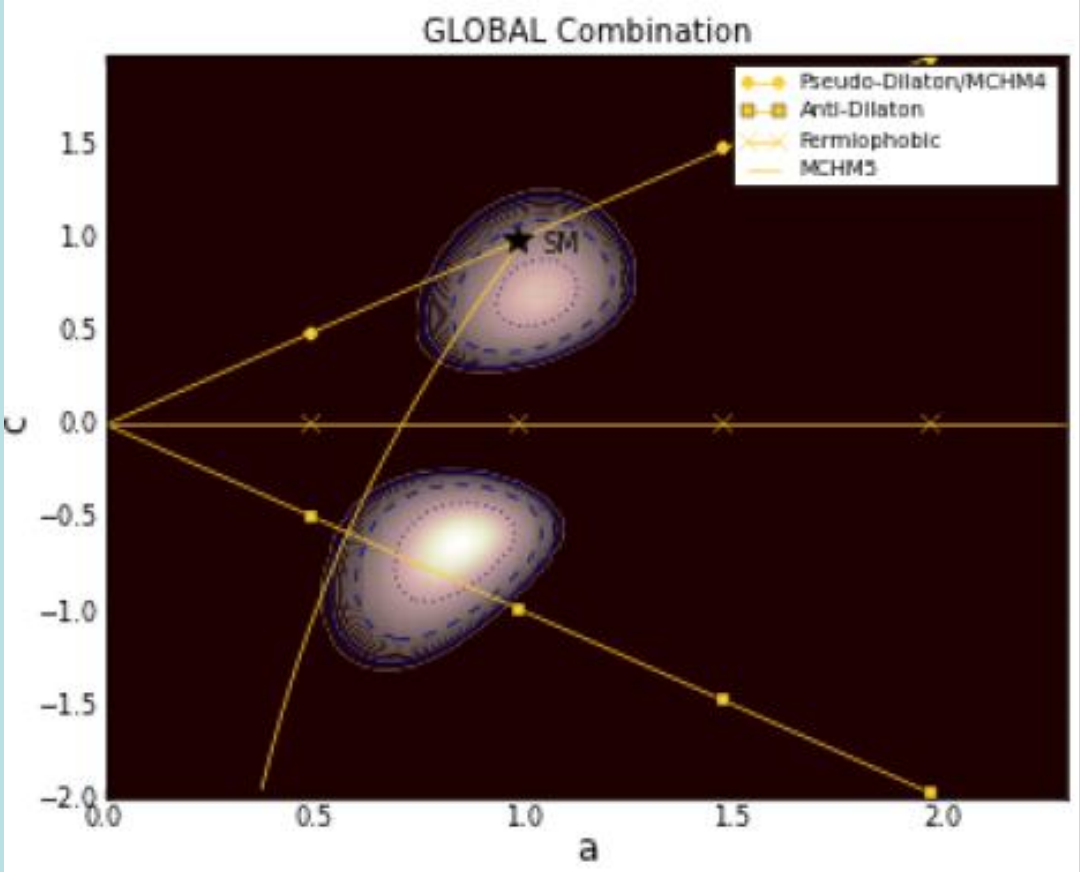
Azatov, Contino, Galloway: arXiv:1202.3415

Espinosa, Grojean, Muhlleitner, Trott: arXiv:1202.3697

Combination of LHC & Tevatron

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

Global analysis



- Standard Model: $a = c = 1$

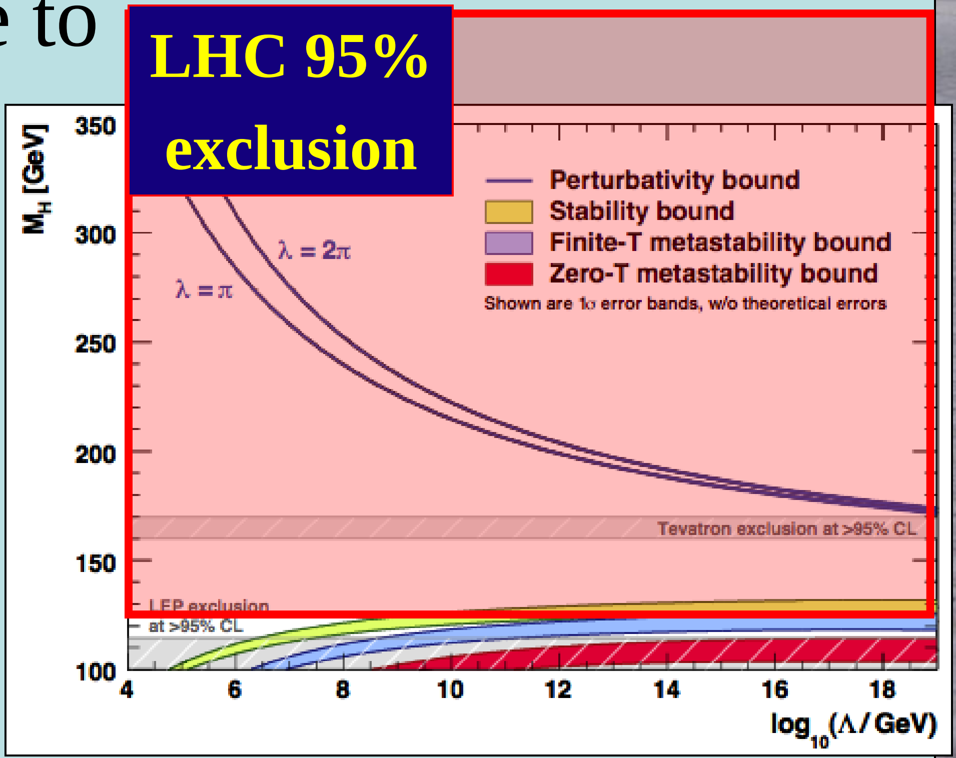
JE & Tevong You: arXiv:1207.1693

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!**

Theoretical Constraints on Higgs Mass

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



- Vacuum could be stabilized by **Supersymmetry**

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