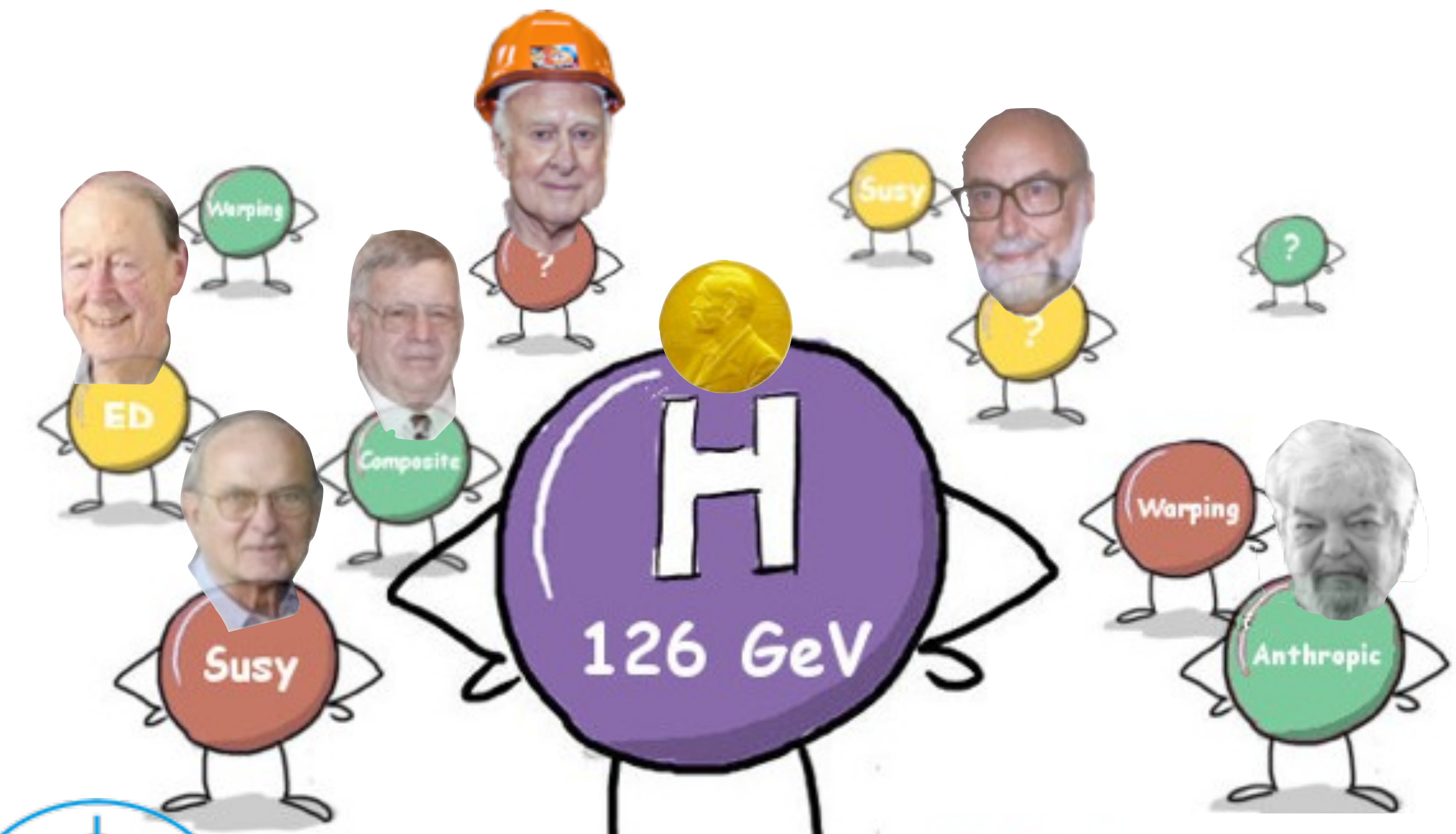
Beyond the Standard Model

CERN summer student lectures 2015



Lecture 2/5

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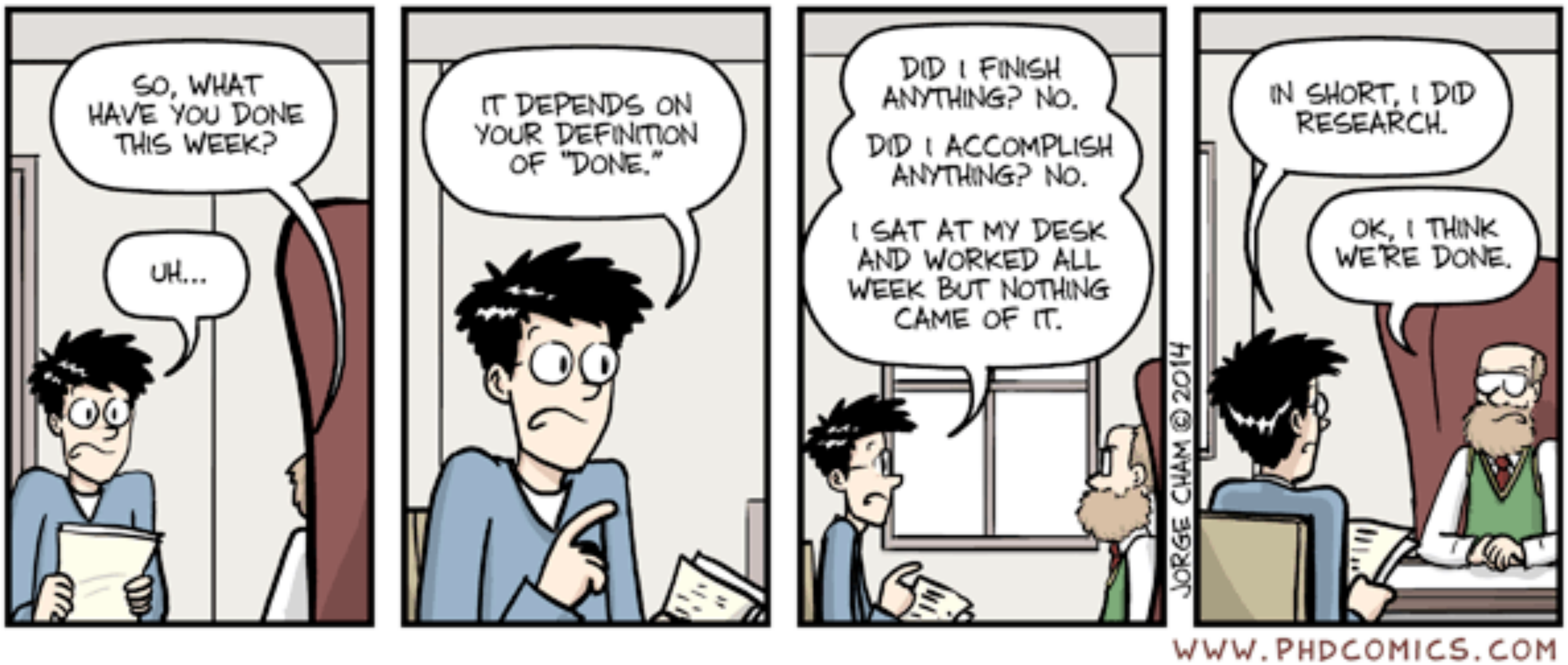
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Outline

- Monday
  - general introduction, units
- Tuesday
  - Higgs physics as a door to BSM
- Wednesday
  - Naturalness: small and large numbers in a quantum world
- Thursday
  - grand unification, proton decay
  - supersymmetry
  - extra dimensions
- Friday
  - cosmological interplay

Ask questions

Your work, as students, is to question all what you are listening during the lectures...



The Standard Model: Interactions

Even though EM is way stronger than gravity, it was unnoticed until ~ 300 years because 1-1=0

- ***gravity***

- ***electromagnetic interactions***

  (1873, Maxwell)

  tested with an accuracy of 10^{-8}

  { light, atoms, molecules }

- ***weak interactions***

  (1933, Fermi)

  tested with an accuracy of 10^{-3}

  { β decay

  $$n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e$$

  $$e^+ + e^- \xrightarrow{Z^0} D^+_{(c\bar{s})} + D^-_{(\bar{c}s)}$$
  }

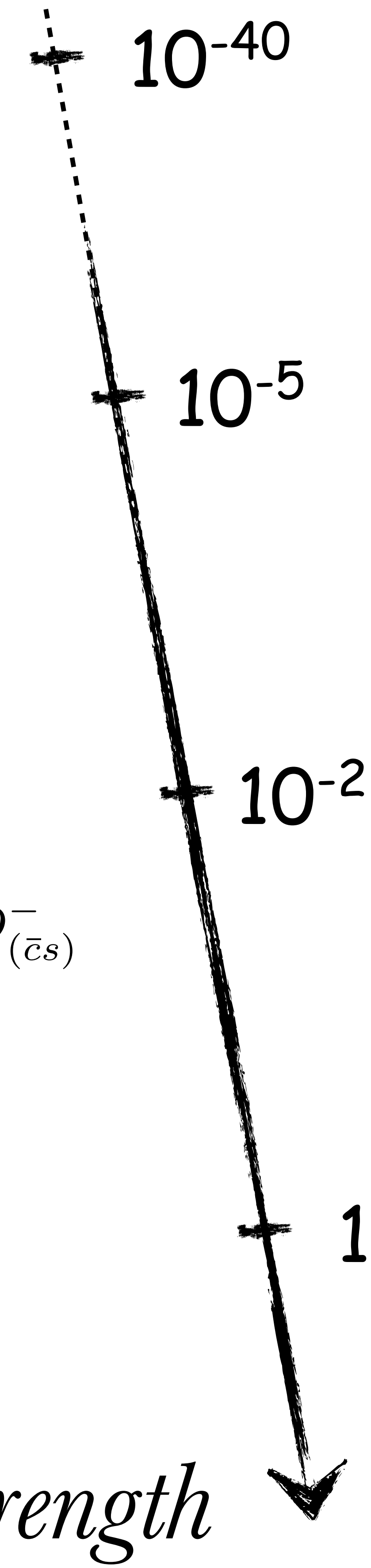
- ***strong interactions***

  tested with an accuracy of 10^{-1}

  { atomic nuclei, α decay

  $${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$
  }

(1911, Rutherford ; 1921, Chadwick and Biesler)



Gauge Theories: EM & Yang-Mills

EM U(1) $\phi \to e^{i\alpha}\phi$ but $\partial_\mu\phi \to e^{i\alpha}\,(\partial_\mu\phi) + \underbrace{i(\partial_\mu\alpha)}\,\phi$

≠0 if local transformations

EM field and covariant derivative $\partial_\mu\phi + ieA_\mu\phi \to e^{i\alpha}(\partial_\mu\phi + ieA_\mu\phi)$

if $A_\mu \to A_\mu - \frac{1}{e}\partial_\mu\alpha$

the EM field keep track of the phase in different points of the space-time

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

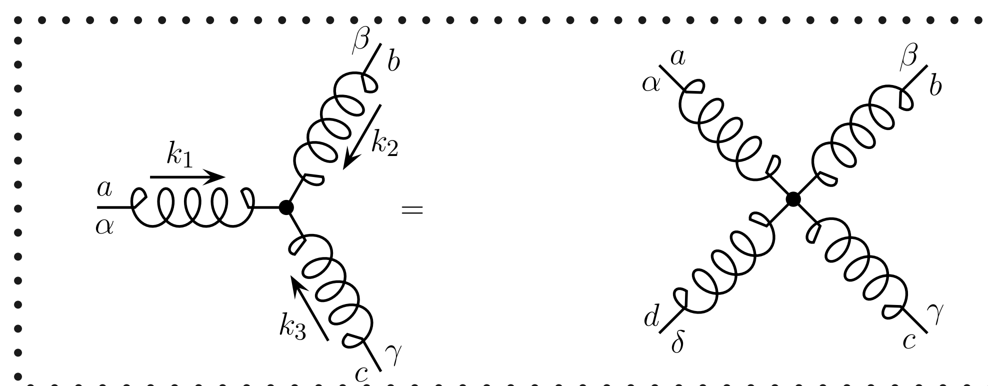
Yang-Mills : non-abelian transformations $\phi \to U\phi$

$$\partial_\mu\phi + igA_\mu\phi \to U(\partial_\mu\phi + igA_\mu\phi)$$

if $A_\mu \to UA_\mu U^{-1} - \frac{i}{g}U\partial_\mu U^{-1}$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \underbrace{ig[A_\mu, A_\nu]}$$

non-abelian int.



The Standard Model: Interactions

- $U(1)_Y$ ***electromagnetic interactions***

  ➘ Photon γ

  { light, atoms, molecules }

- $SU(2)_L$ ***weak interactions***

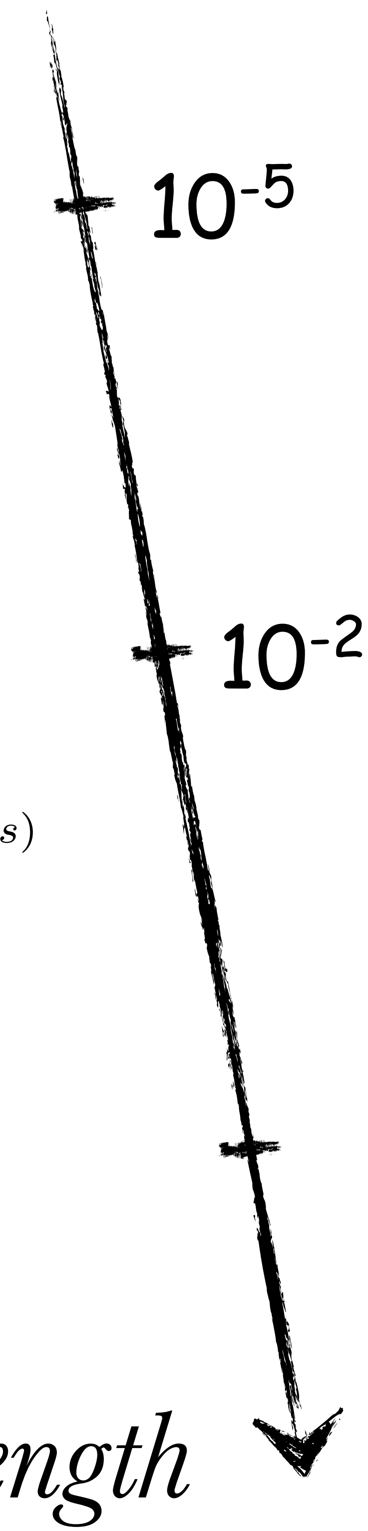
  ➘ bosons $W^\pm, Z^0$

  { β decay
  $$n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e$$
  $$e^+ + e^- \xrightarrow{Z^0} D^+_{(c\bar{s})} + D^-_{(\bar{c}s)}$$ }

- $SU(3)_c$ ***strong interactions***

  ➘ gluons g^a

  { atomic nuclei, α decay
  $$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$ }



The underlying principles of the SM

The beauty of the SM comes from the the identification of a unique dynamical principle describing the different interactions that seem so different from each others

gauge theory = spin-1

at the same time a particular and predictive structure that still leaves room for a rich variety of phenomena
(long range interaction, spontaneous symmetry breaking, confinement)

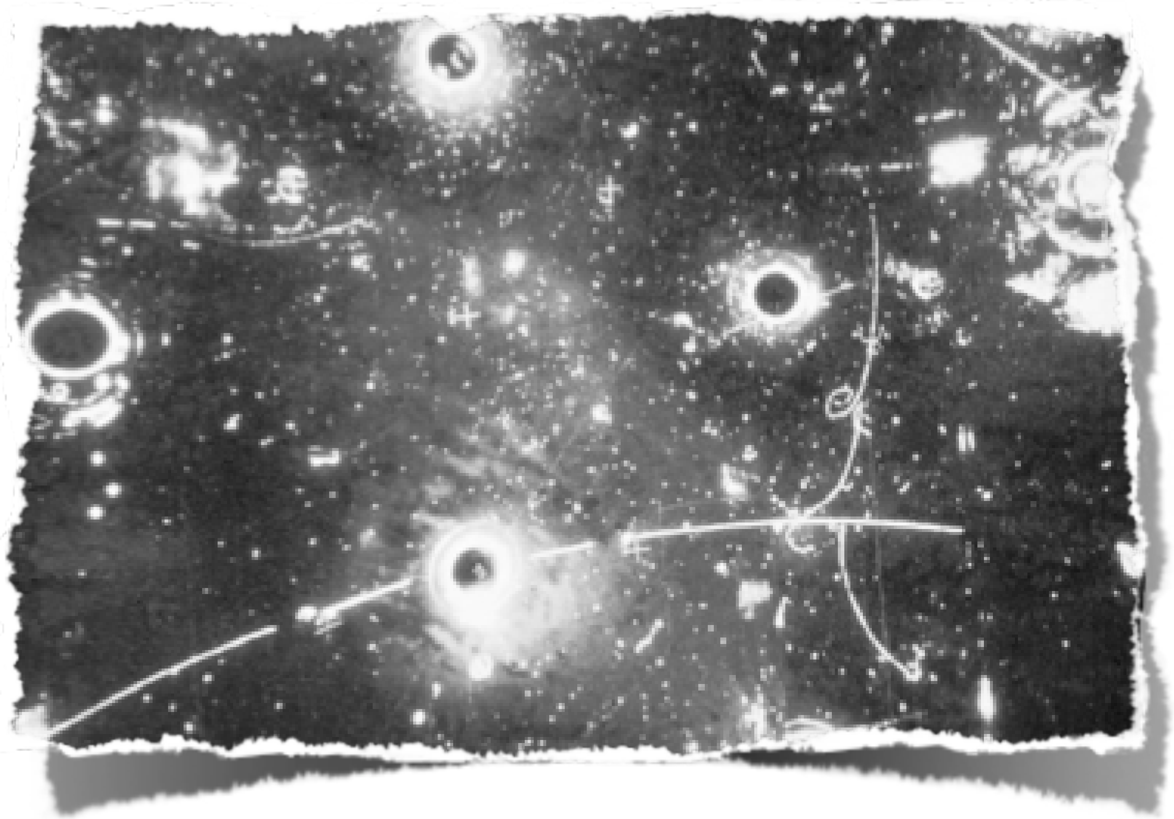
gravitation = general relativity= spin-2

much more rigid theory = unique theory

The Standard Model

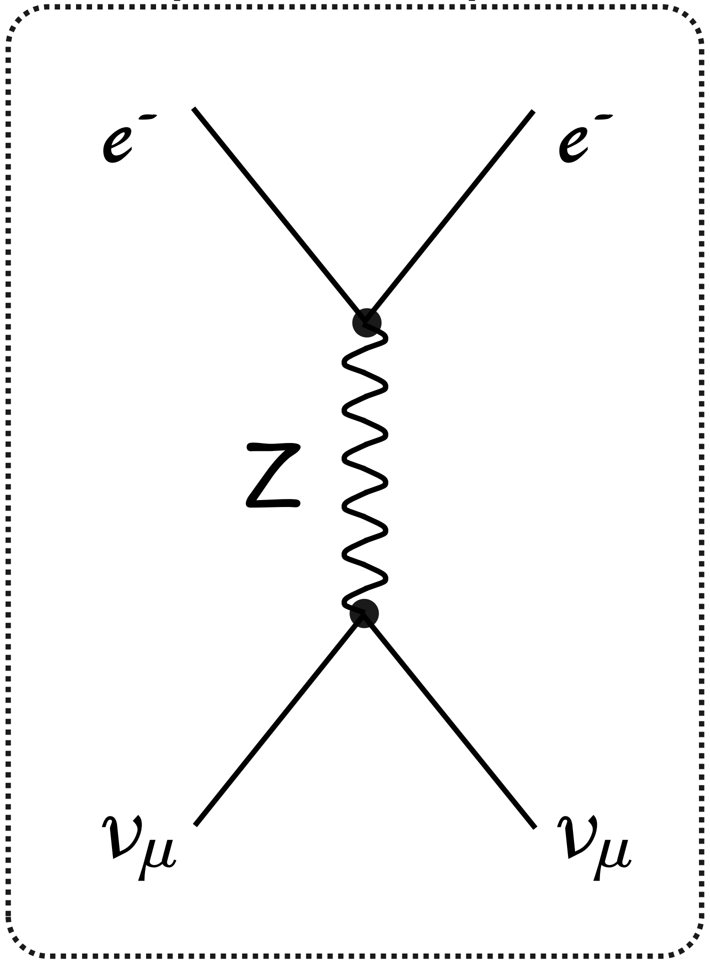
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$



[Gargamelle collaboration, '73]

$\nu_\mu e^- \to \nu_\mu e^-$

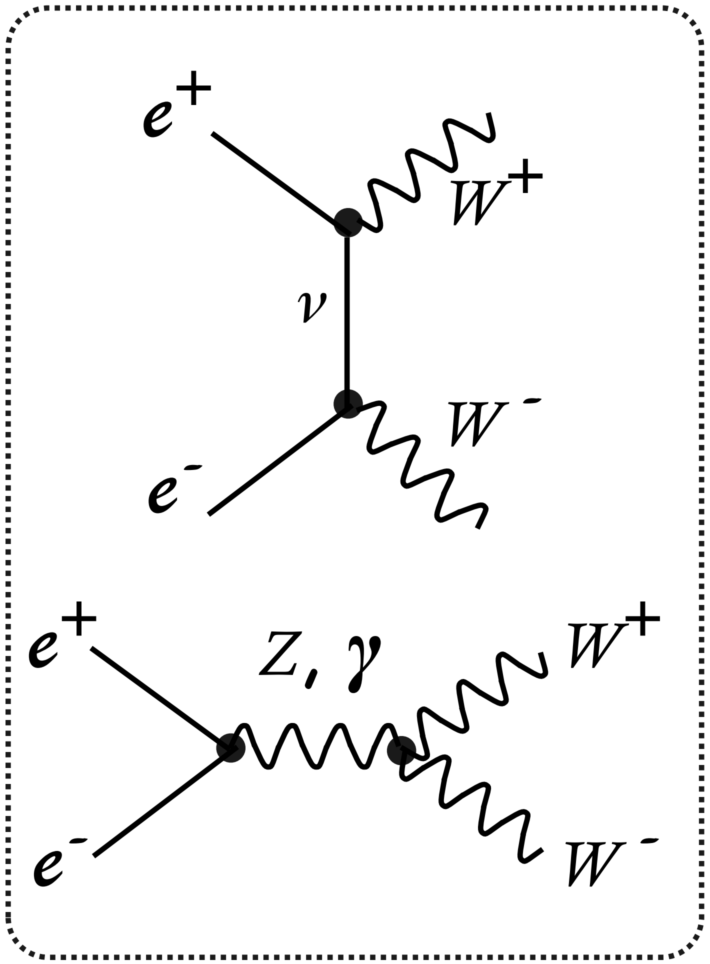


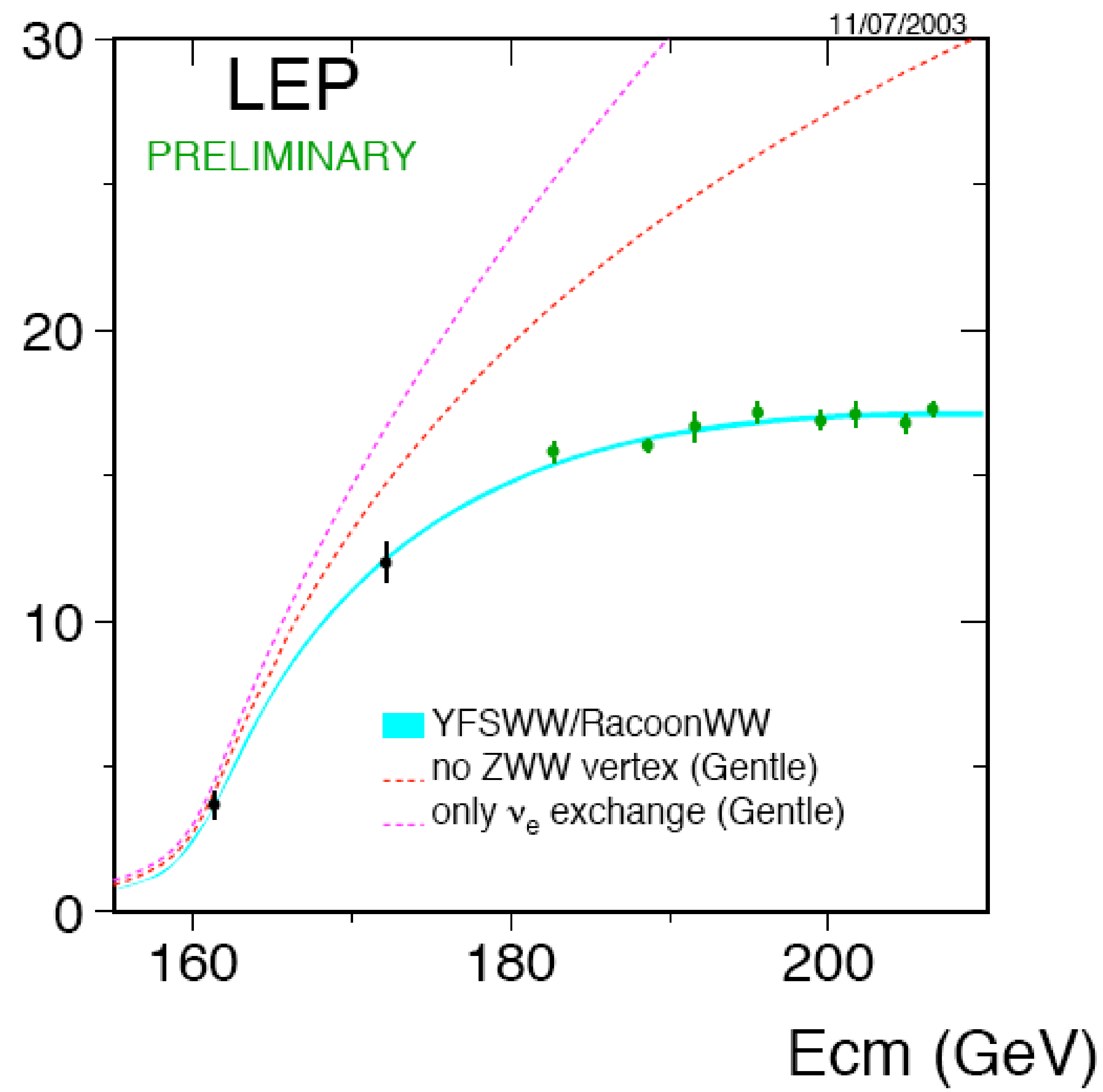
Gauge Theory as a Dynamical Principle

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$e^+e^- \to W^+W^-$





The Standard Model and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

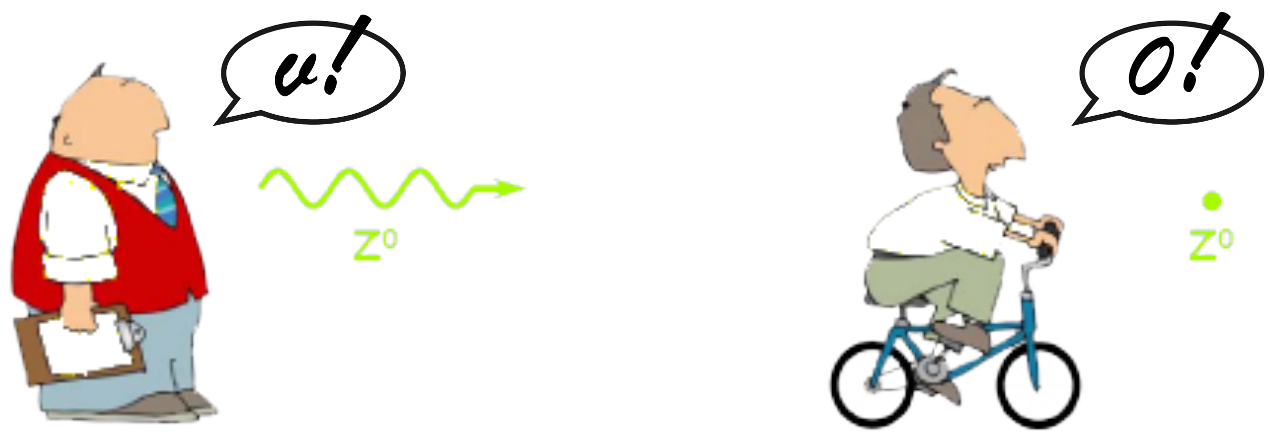
the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ is a doublet of $SU(2)_L$ but $m_{\nu_e} \ll m_e$
- a mass term for the gauge field isn't invariant under gauge transformation $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ spontaneous breaking of gauge symmetry ⇐

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{||} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M}\frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The longitudinal polarization of massive W, Z

a massless particle is never at rest: [redacted]o distinguish
(and elimin[redacted]

3=2+1

Guralnik et al '64

the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{||} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

Longitudinal polarization of a massive spin 1

a massive spin 1 particle has 3 physical polarizations:

$$k^\mu = (E, 0, 0, k)$$

with $k_\mu k^\mu = E^2 - k^2 = M^2$

$$A_\mu = \epsilon_\mu \; e^{i k_\mu x^\mu}$$

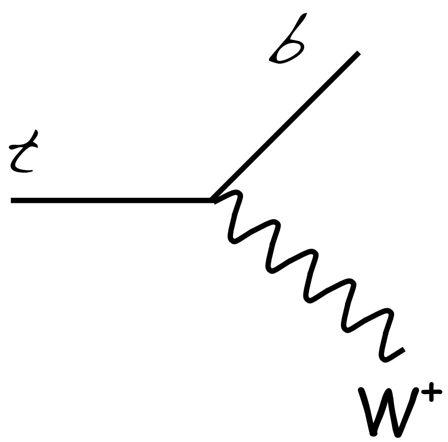
$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$
- 1 longitudinal: $\epsilon_{\parallel}^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

The BEH mechanism: "V_L=Goldstone bosons"

At high energy, the physics of the gauge boson becomes simple



$$\Gamma(t \to bW_L) = \frac{g^2}{64\pi}\frac{m_t^2}{m_W^2}\frac{(m_t^2 - m_W^2)^2}{m_t^3}$$

$$\Gamma(t \to bW_T) = \frac{g^2}{64\pi}\frac{2(m_t^2 - m_W^2)^2}{m_t^3}$$

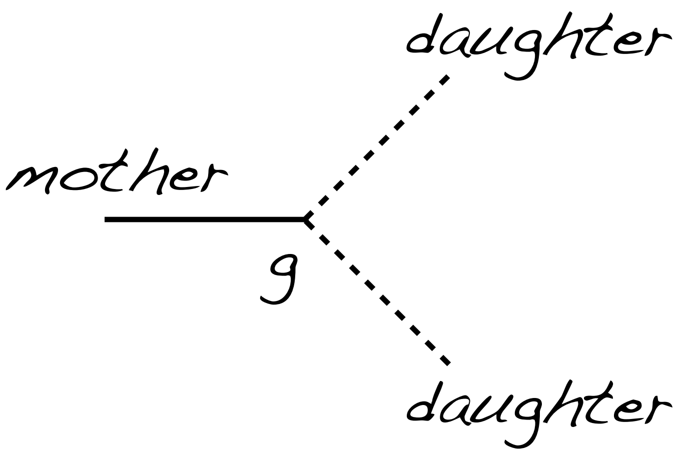
- at threshold ($m_t \sim m_W$)
  democratic decay
- at high energy ($m_t \gg m_W$)
  W_L dominates the decay

At high energy, the dominant degrees of freedom are W_L

The BEH mechanism: "V_L=Goldstone bosons"

At high energy, the physics of the gauge boson becomes simple

~~ why you should be stunned by this result: ~~



we expect: (dimensional analysis) $\Gamma \sim g^2\, m_{\text{mother}}$

instead $\Gamma \propto m_{\text{mother}}^3$ means $g \propto m$ like the Higgs couplings!

very efficient way to suck up energy from the mother particle

$$\tau \ll \tau_{\text{naive}}$$

Goldstone equivalence theorem
$W^{\pm}_L$, Z_L ≈ SO(4)/SO(3)

LEP already established the BEH mechanism
The pending question was: how is it realized?
Via a fundamental EW doublet? A la technicolor?
Is there a Higgs boson in addition to the 3 Goldstone bosons?

In other words, LEP established a simple description of the electroweak sector for E >> m_W.

This description is valid for $m_W \ll E \ll 4\pi v = \dfrac{8\pi m_W}{g}$

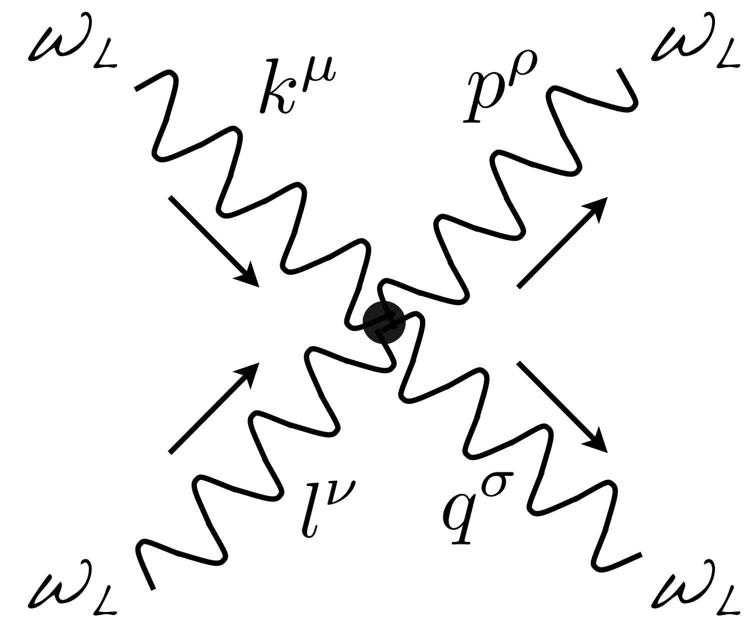
The goal of the LHC was/is to understand what comes next

Call for extra degrees of freedom

NO LOSE THEOREM

Bad high-energy behavior for the scattering of the longitudinal polarizations

$$\mathcal{A} = \epsilon^{\mu}_{\parallel}(k)\epsilon^{\nu}_{\parallel}(l) g^2 \left(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}\right) \epsilon^{\rho}_{\parallel}(p)\epsilon^{\sigma}_{\parallel}(q)$$



$$\mathcal{A} = g^2 \frac{E^4}{4M_W^4}$$

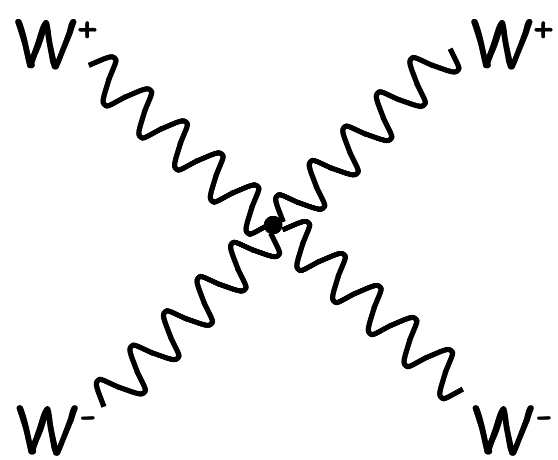
violations of perturbative unitarity around E ~ M/√g (actually M/g)

Extra degrees of freedom are needed to have a good description of the W and Z masses at higher energies

numerically: E ~ 3 TeV ⬅ the LHC was sure to discover something!

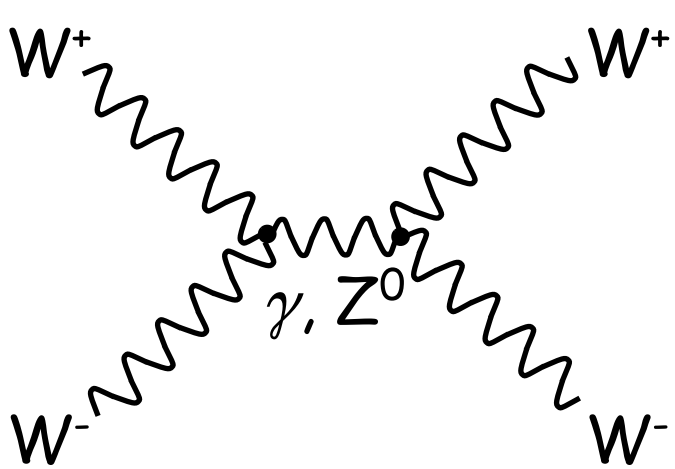
$M_W/\sqrt{(g/4\pi)}$~500GeV or $M_W/(g/4\pi)$~3TeV?

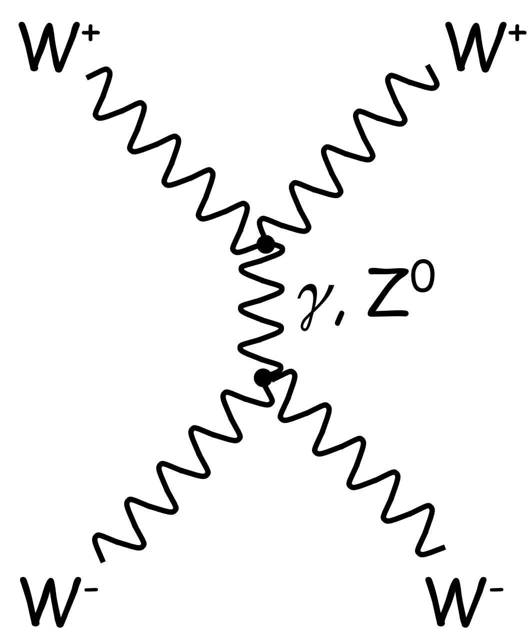
Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73



$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^4$$

+





+

$$\mathcal{A} = -g^2 \left(\frac{E}{M_W}\right)^4$$

$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^2$$

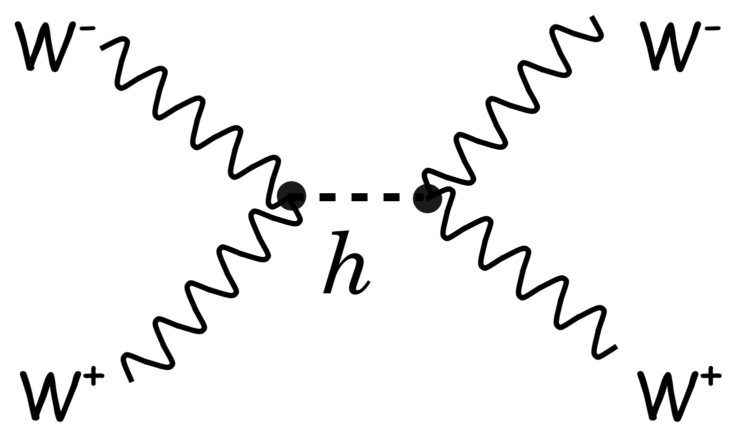
impossible to further cancel the amplitude
without introducing new degrees of freedom

What is the SM Higgs?

A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\rm EWSB} = m_W^2 W_\mu^+ W_\mu^+ \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c\frac{h}{v}\right)$$

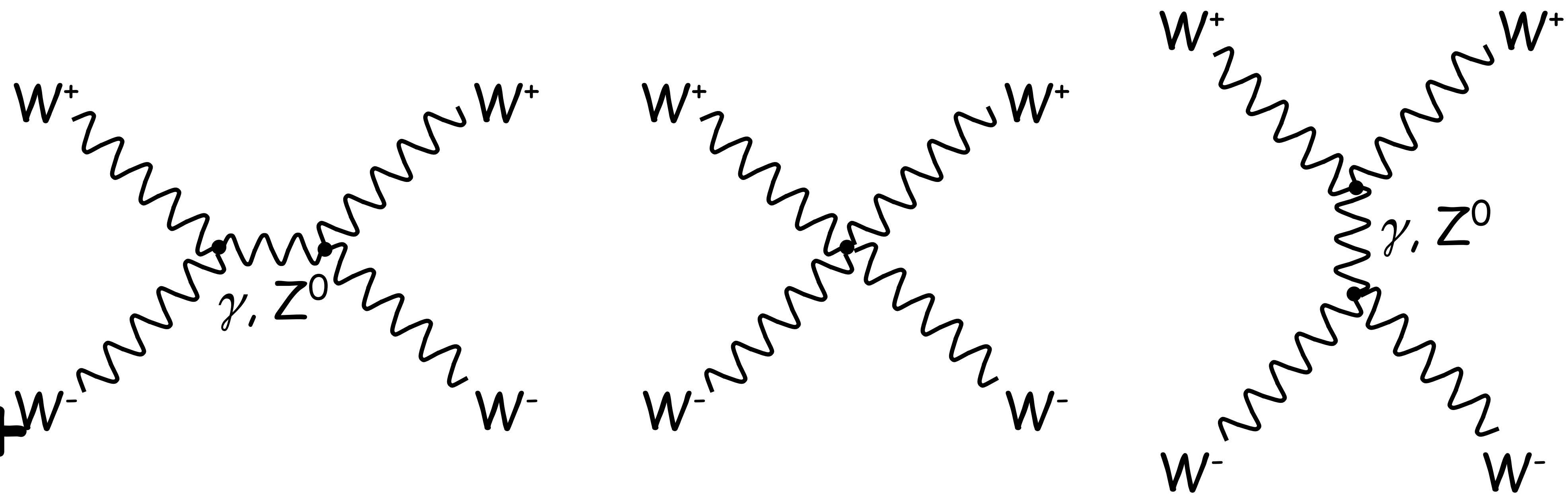
'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the SM Higgs?



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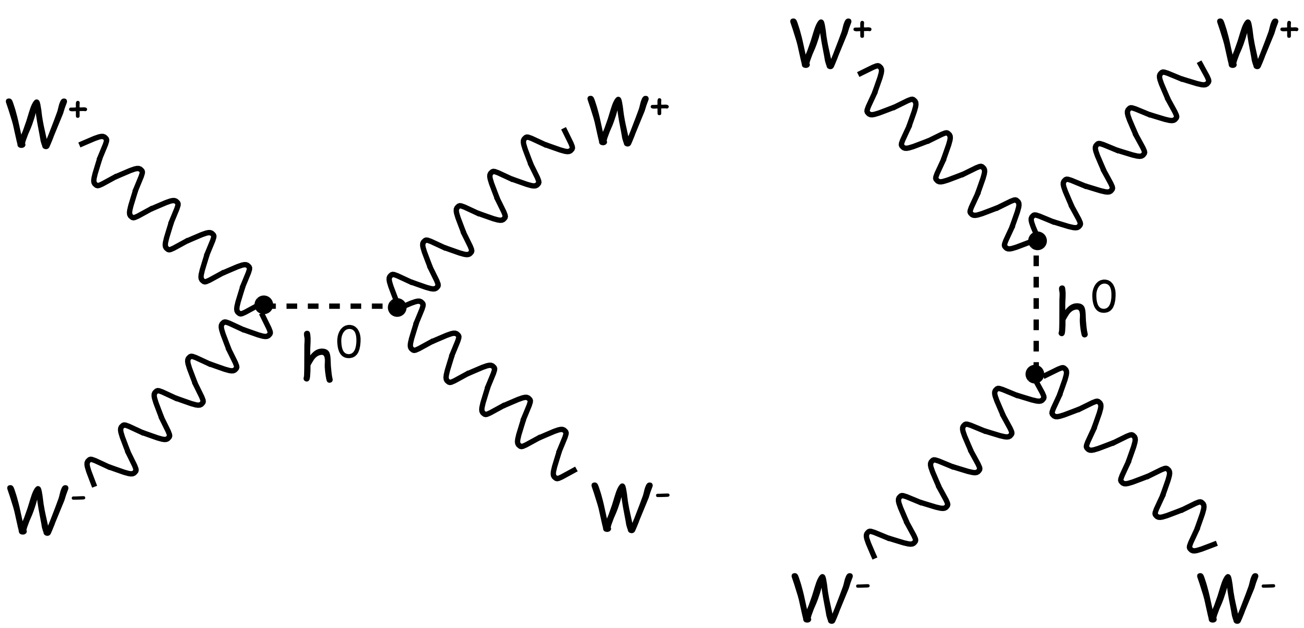
+

+



$$\mathcal{A} = -g^2 \left(\frac{E}{M_W}\right)^2$$

$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W}\right)^2$$

The Higgs boson unitarizes the W scattering
(if its mass is below ~ 1 TeV)

Lee, Quigg, Thacker '77

What is the Higgs the name of?

A single scalar degree of freedom that couples to the mass of the particles

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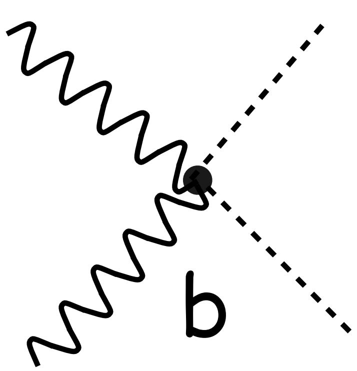
'a', 'b' and 'c' are arbitrary free couplings

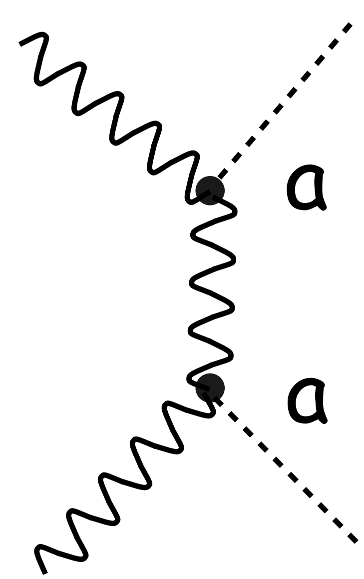
For a=1: perturbative unitarity in elastic channels WW → WW

For b = a^2: perturbative unitarity in inelastic channels WW → hh

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10





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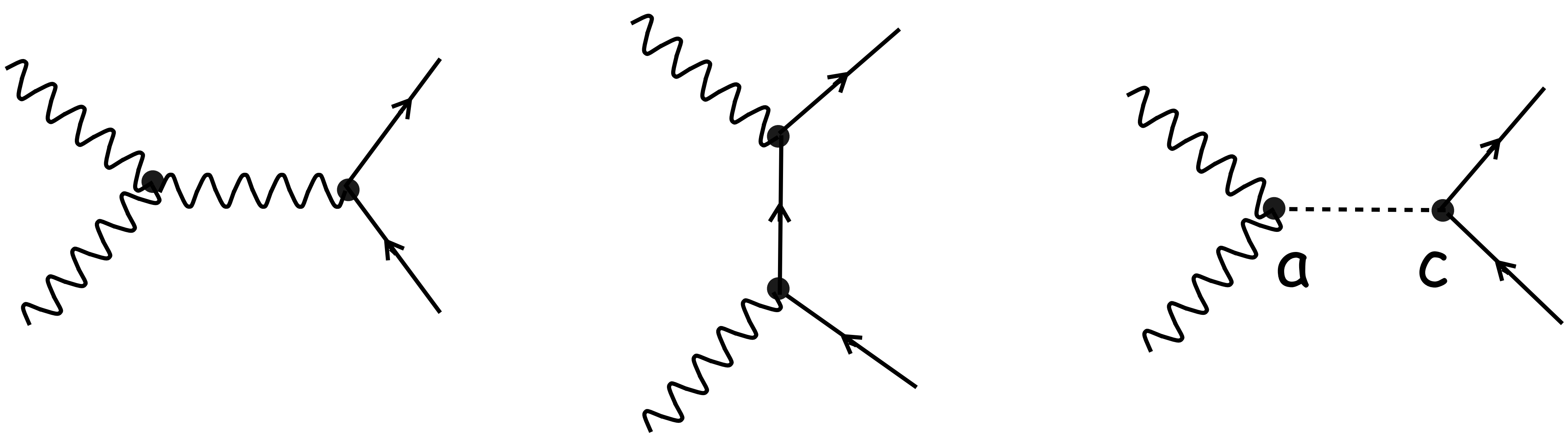
For b = a^2: perturbative unitarity in inelastic channels WW $\rightarrow$ hh

For ac=1: perturbative unitarity in inelastic WW $\rightarrow \psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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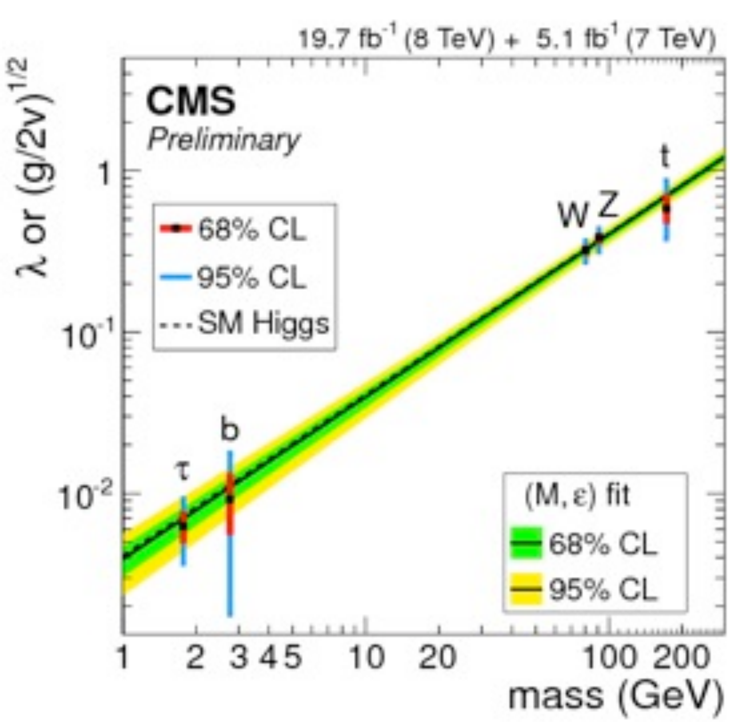


CMS PAS-HIG-14-009

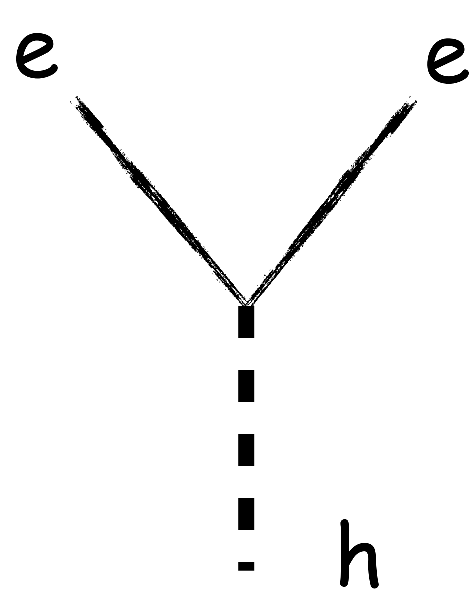
Higgs couplings are proportional to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Higgs boson at the LHC

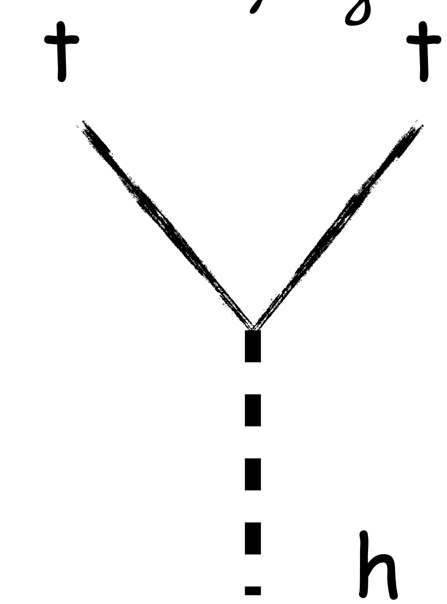
producing a Higgs boson is a rare phenomenon
since its interactions with particles are proportional to masses
and ordinary matter is made of light elementary particles
NB: the proton is not an elementary particle,
its mass doesn't measure its interaction with the Higgs substance

From electrons



probability ~ 10^{-11}

From top quarks



probability ~ 1

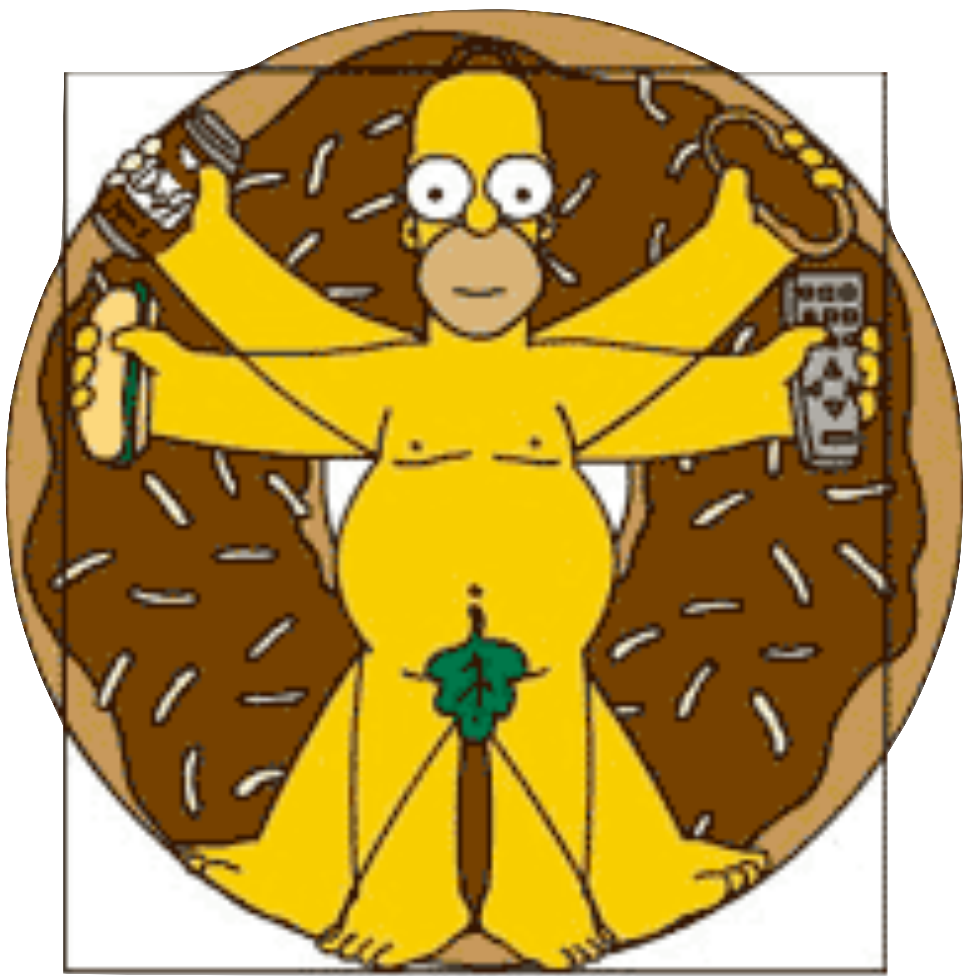
but no top quark at our disposal

Higgs boson at the LHC

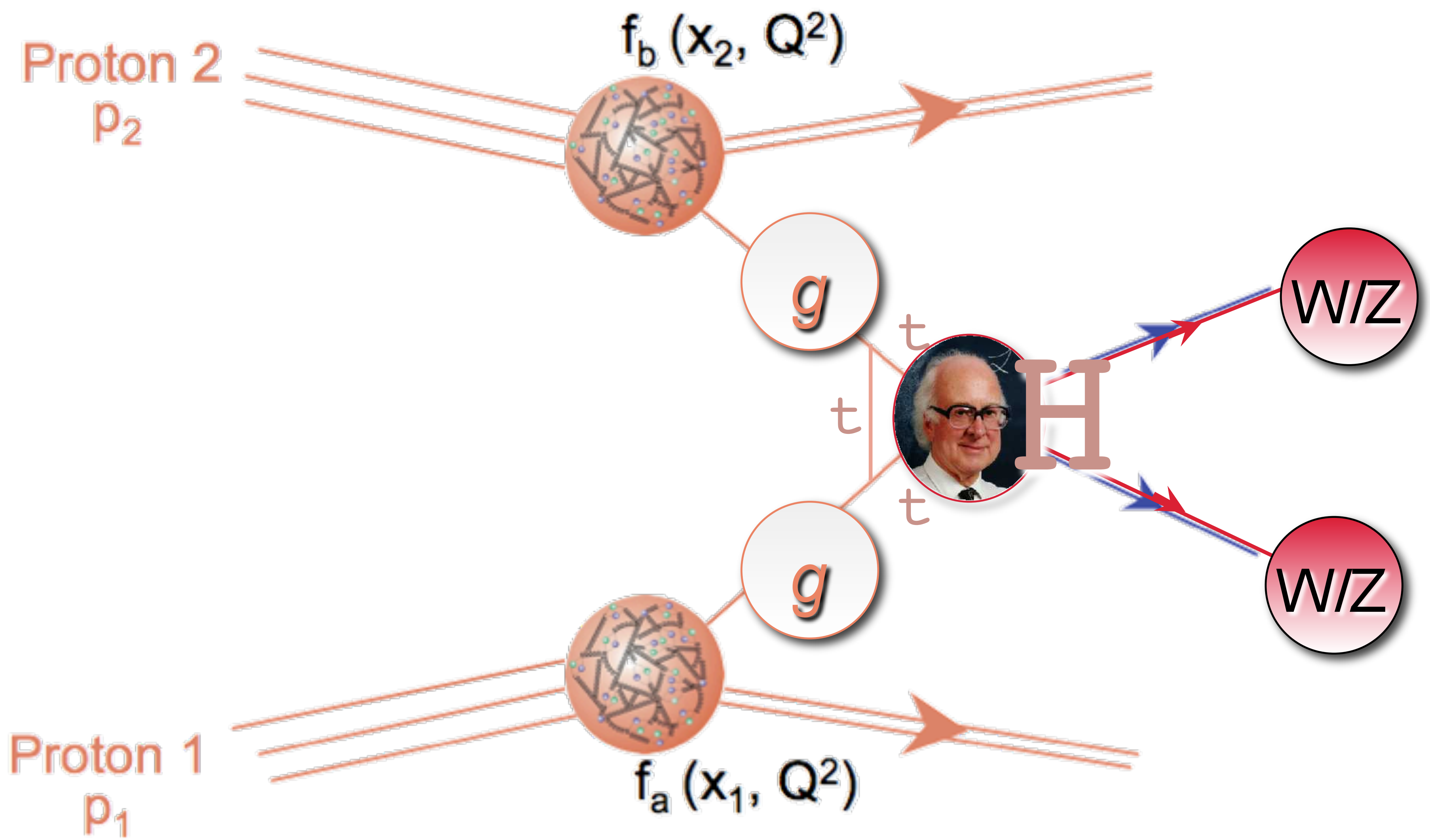
Difficult task

Homer Simpson's principle of life:

If something's hard to do, is it worth doing?



Higgs boson at the LHC



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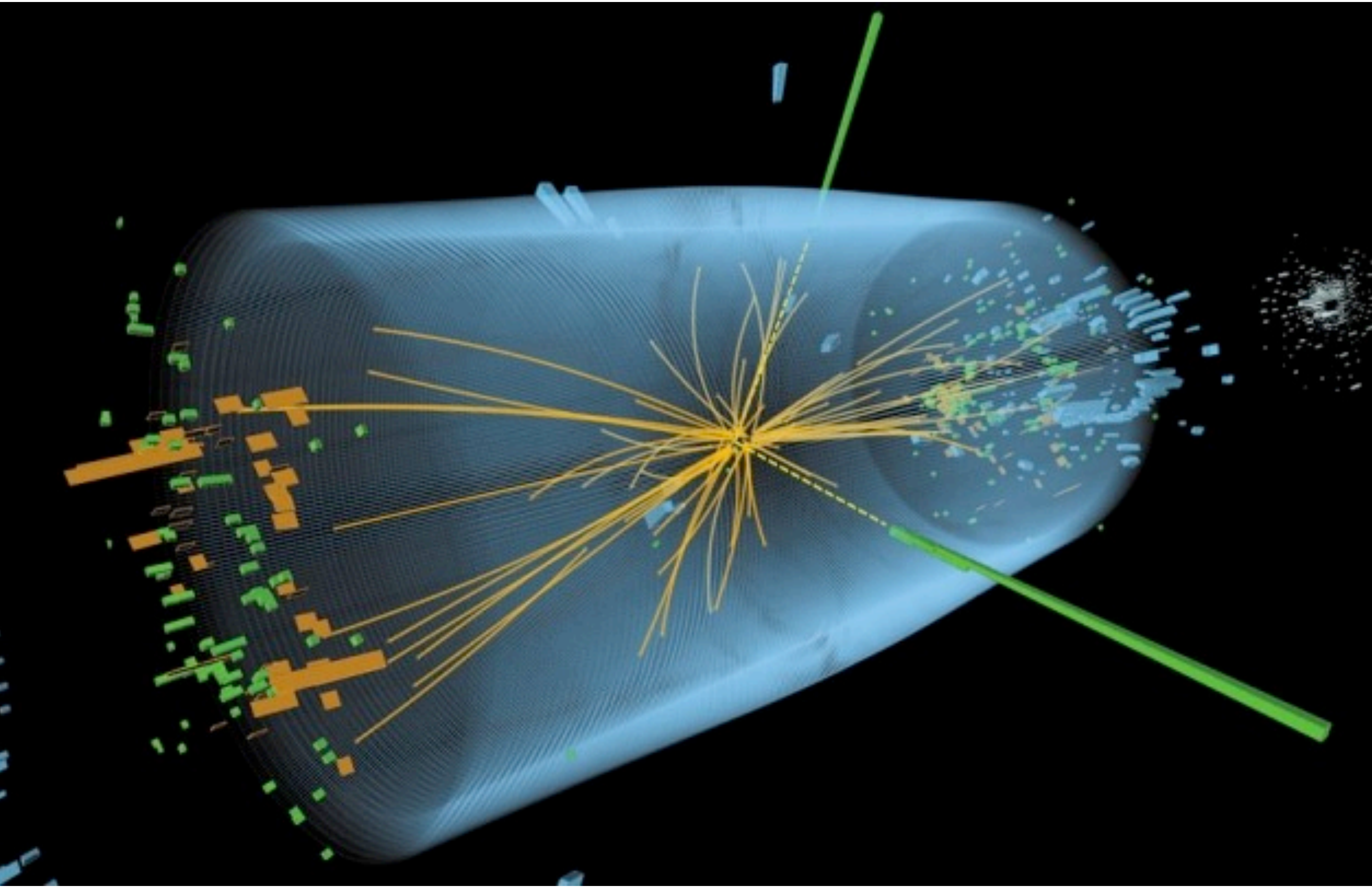
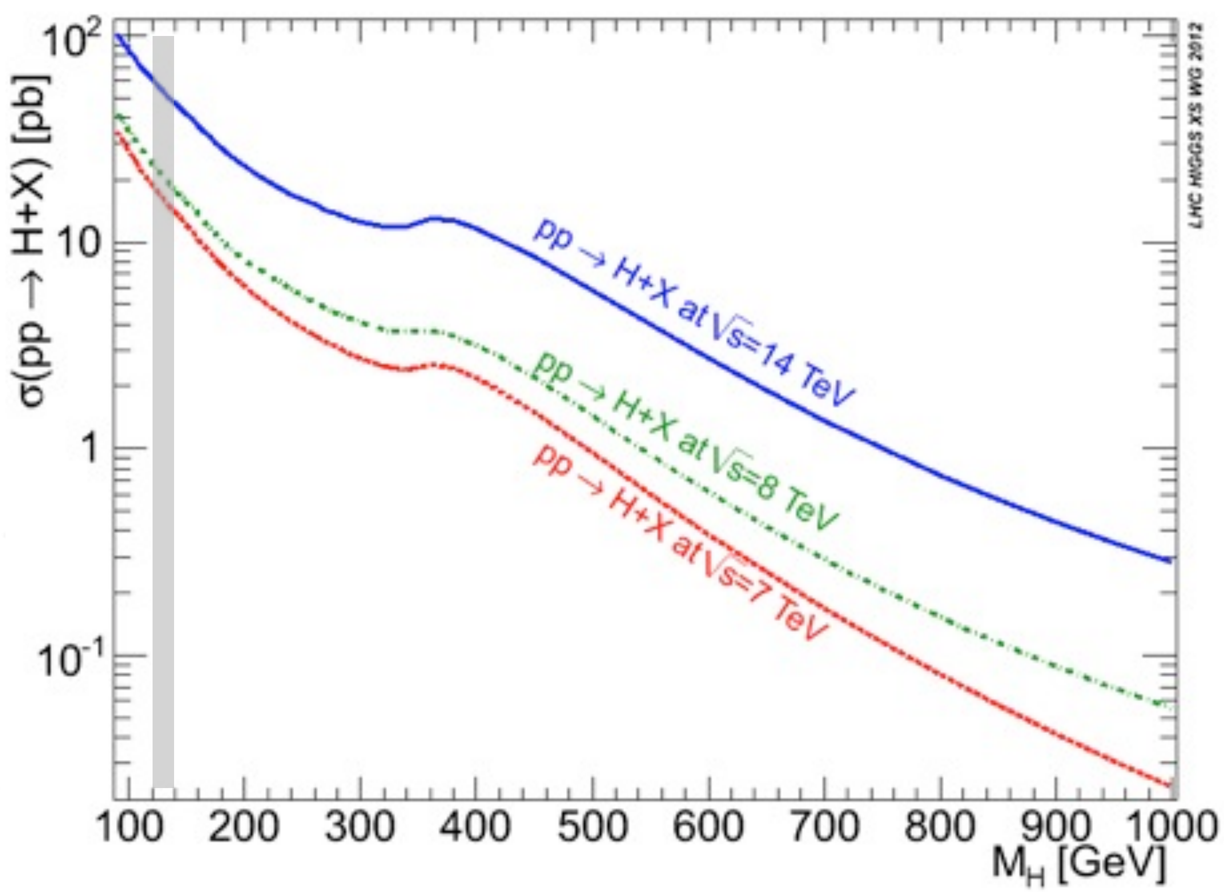


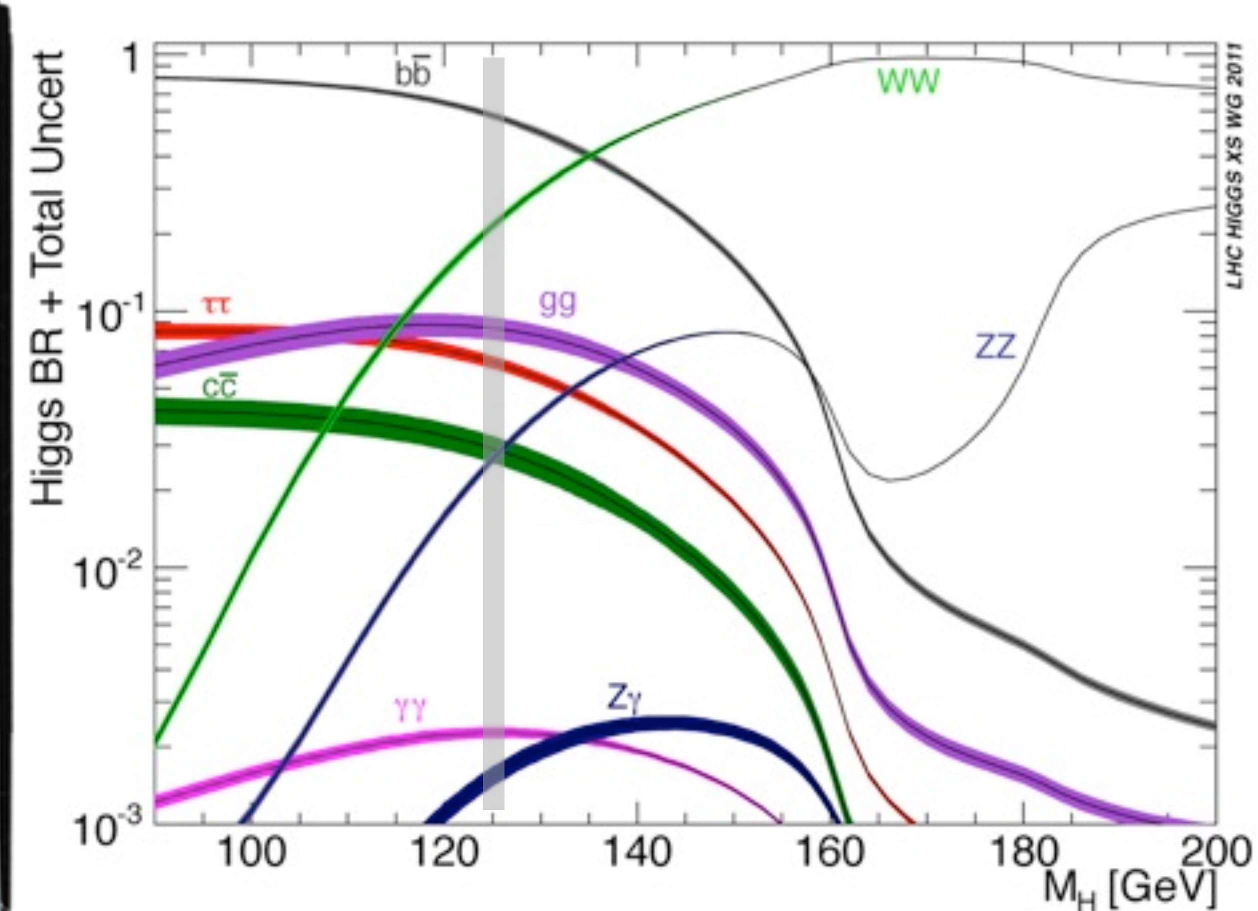
Higgs boson at the LHC

$\sigma \sim 10$ pb $\Leftrightarrow 10^5$ events for L=10 fb^{-1}

Higgs production



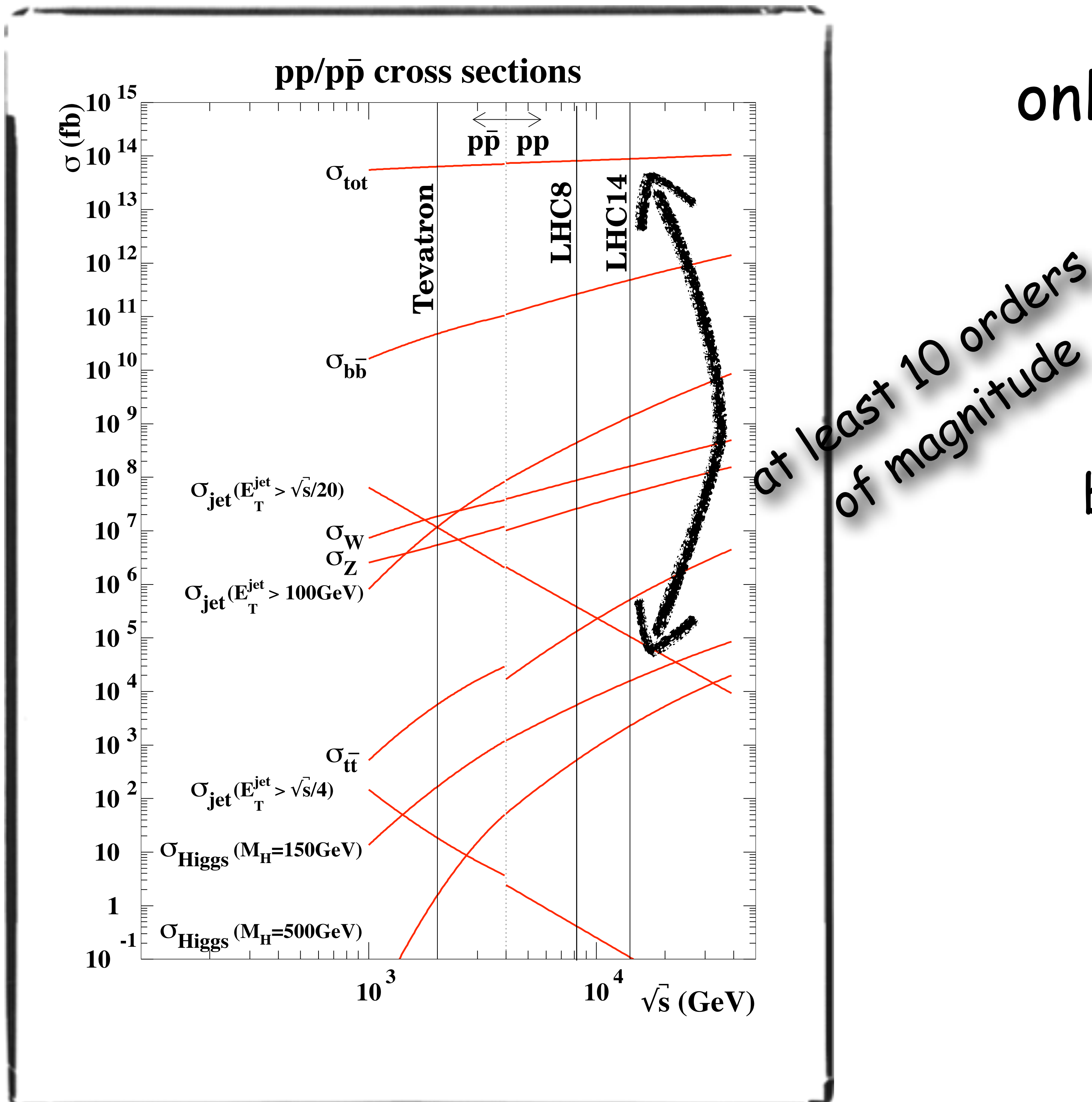
Higgs decay



The LHC has produced 10^5 Higgs bosons out of 10^{16} pp collisions

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background



only 1 out of 100 billions events are "interesting"

(for comparison, Shakespeare's 43 works contain only 884,429 words in total)

furthermore many of the background events furiously look like signal events

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background

only 1 out of 100 billions events are "interesting"

(for comparison, Shakespeare's 43 works contain only 884,429 words in total)

furthermore many of the background events furiously look like signal events

... like finding the paper you are looking for in (10^8 copies of) John Ellis' office

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}} \bar{f}_{L_i} f_{R_j} + \frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

mass ↗ higgs-fermion interactions ↖

both matrices are simultaneously diagonalizable

⇓ ⇓ ⇓

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners (*) or for non-SM Yukawa

$$y_{ij}\left(1 + c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i} H f_{R_j} = \frac{y_{ij} v}{\sqrt{2}}\left(1 + c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i} f_{R_j} + \left(1 + 3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}} h \bar{f}_{L_i} f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Higgs and Flavor

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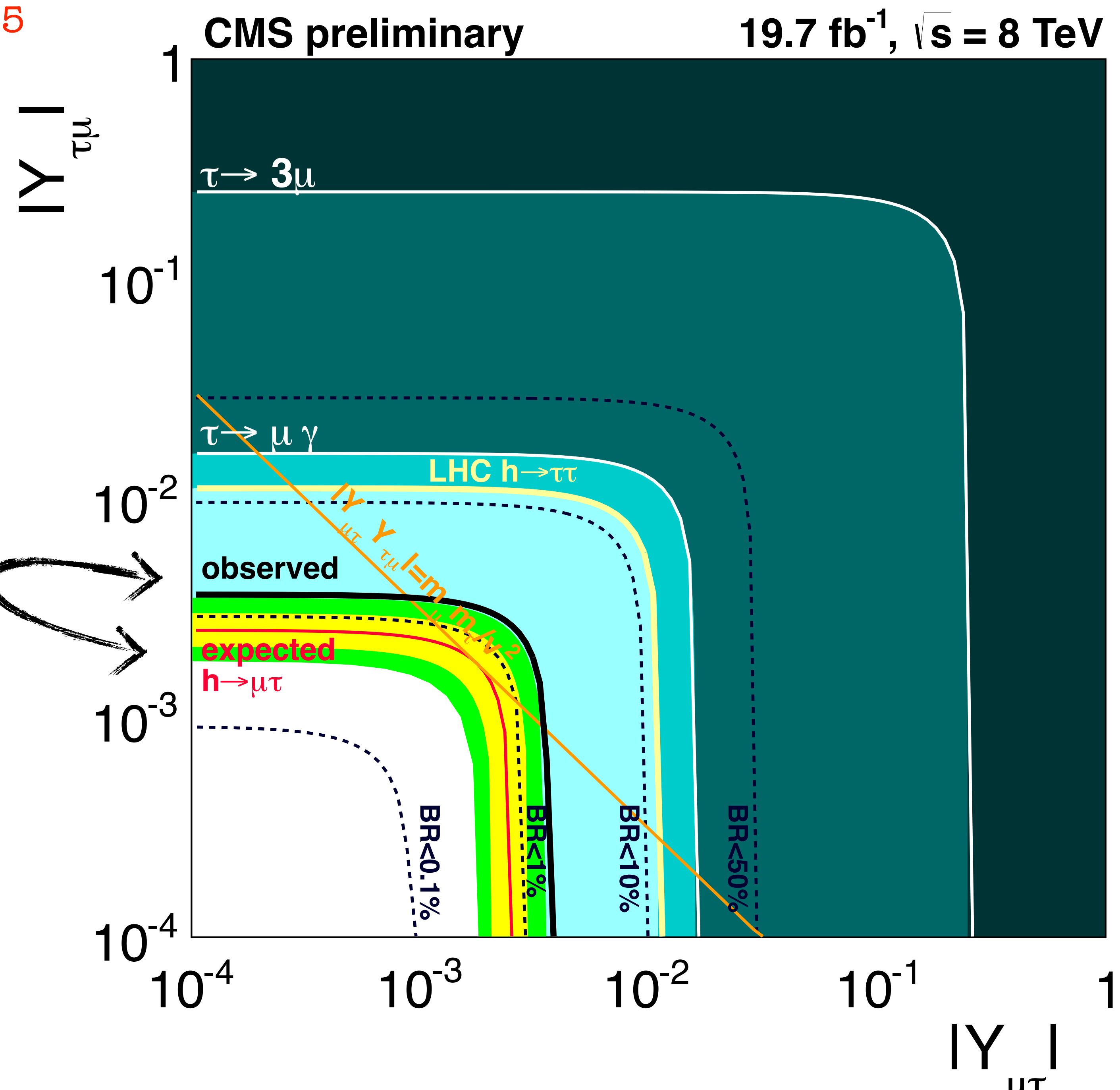
CMS-PAS-HIG-2014-005

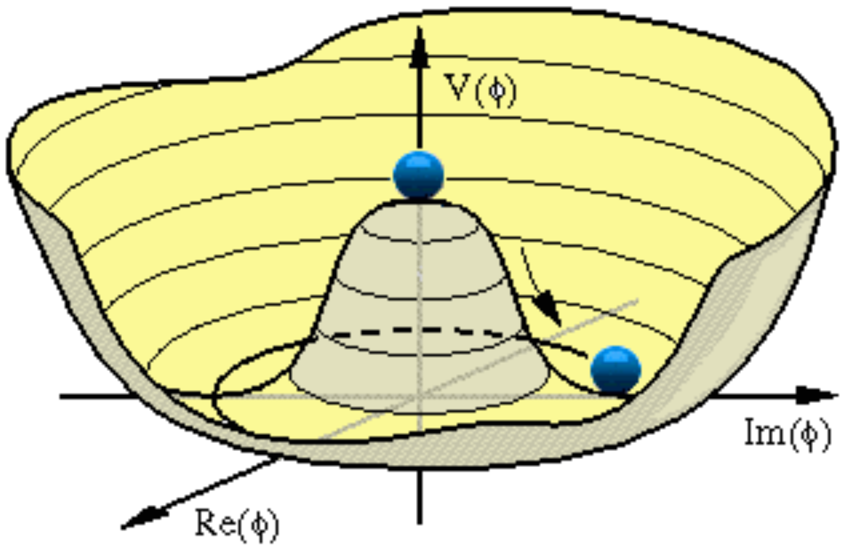


by the way: 2.3σ excess!

Off-diagonal Higgs couplings can reveal the origin of flavor

The interesting models of flavor ($Y_{ij} \approx \sqrt{(m_i m_j / v^2)}$) start being probed by the experimental data

Higgs Stability

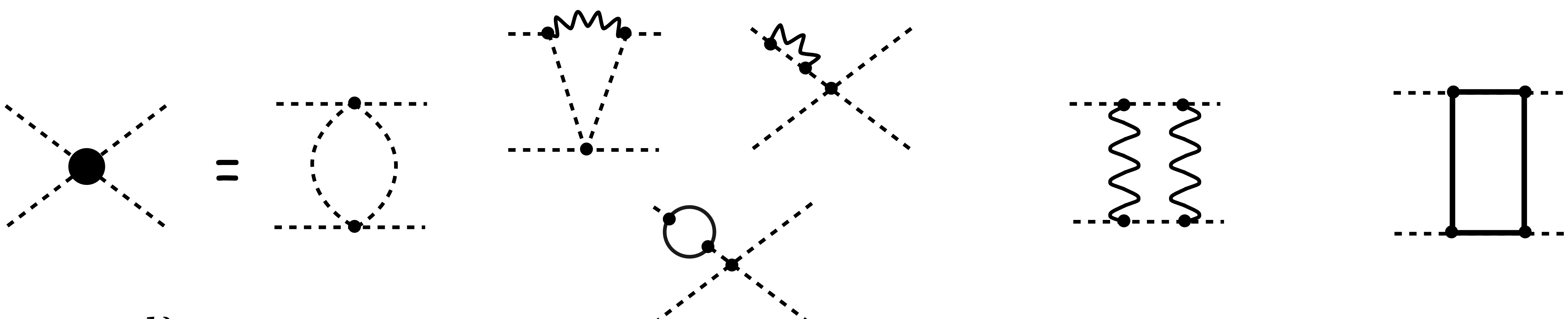


$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$

the vacuum is not empty even classically $(\hbar \to 0)$

How is Quantum Mechanics changing the picture?



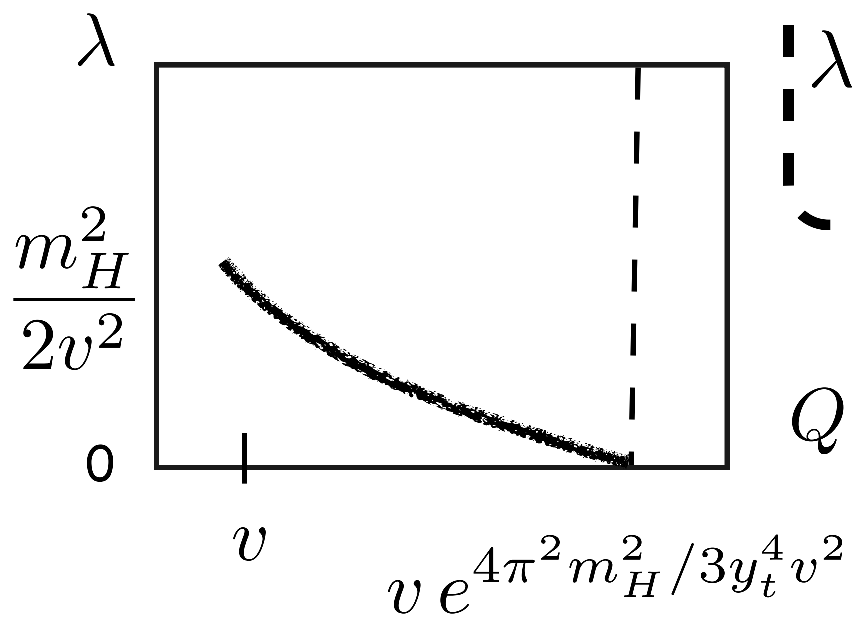
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

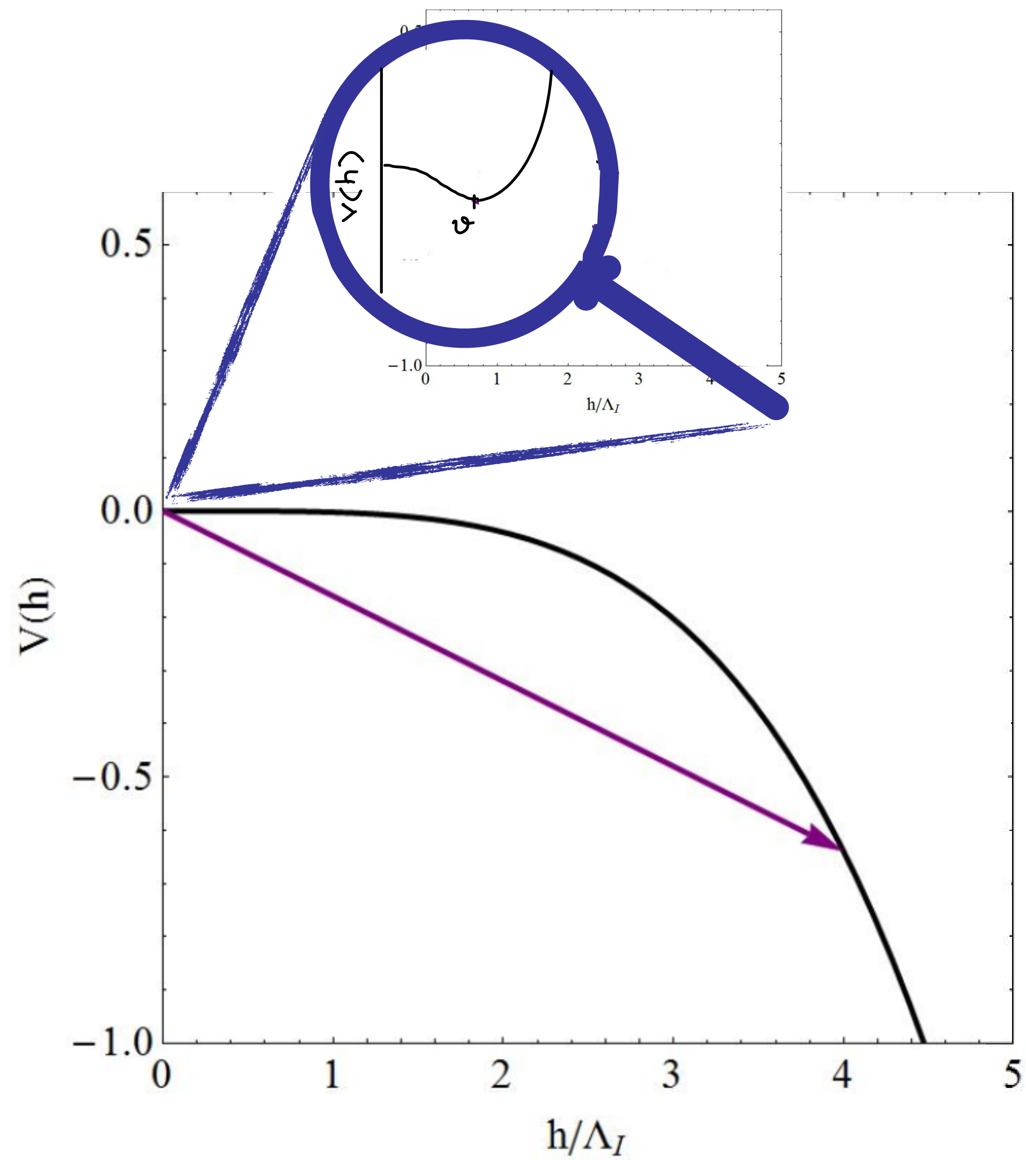
Higgs Stability

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79
Lindner '86
+...





$\lambda < 0 \;\Rrightarrow$ potential unbounded from below

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

New physics should appear before
that point to restore stability

Higgs Stability

Small mass (y_t dominated RGE)

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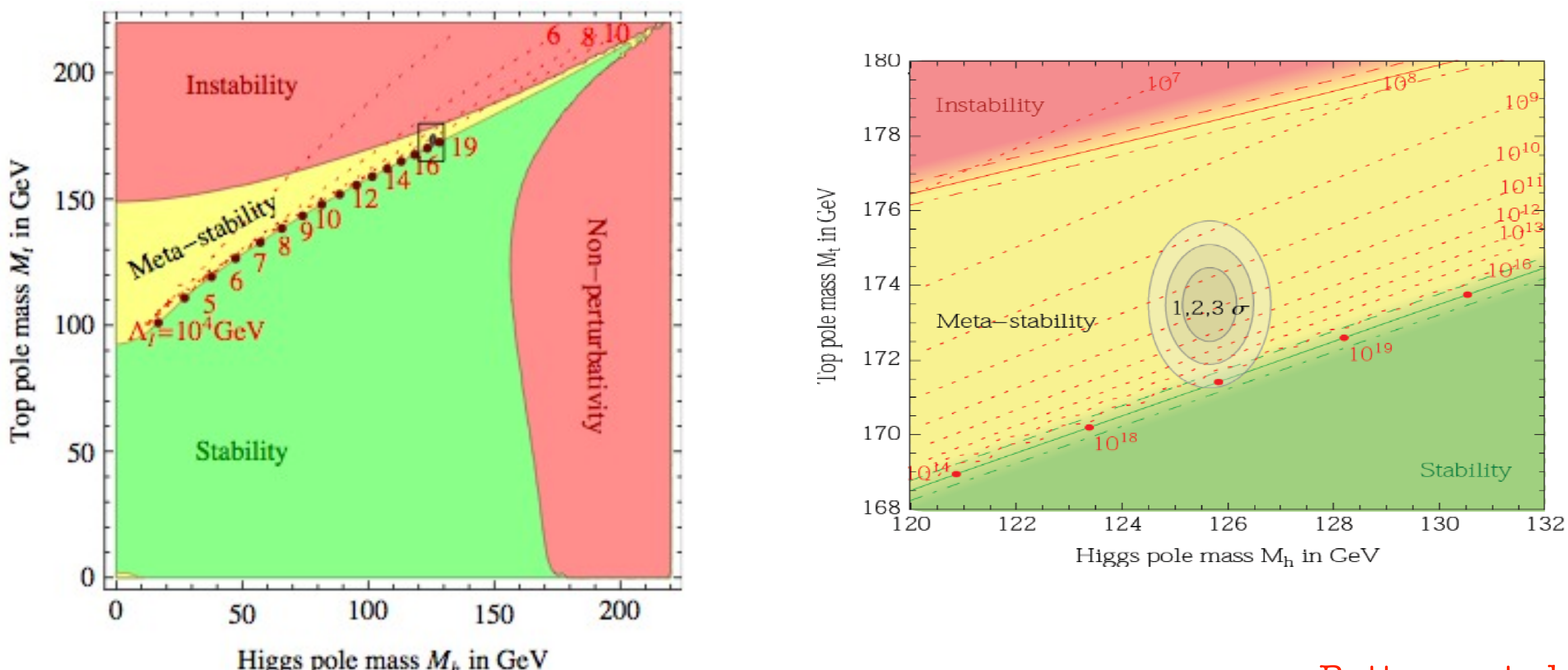

Buttazzo et al '13

HEP with a Higgs boson

"If you don't have the ball, you cannot score"

Now with the Higgs boson in their feets,
particle physicists can... play as well as Barça players

Profound change in paradigm:
missing SM particle ➪ tool to explore SM and venture into physics landscape beyond