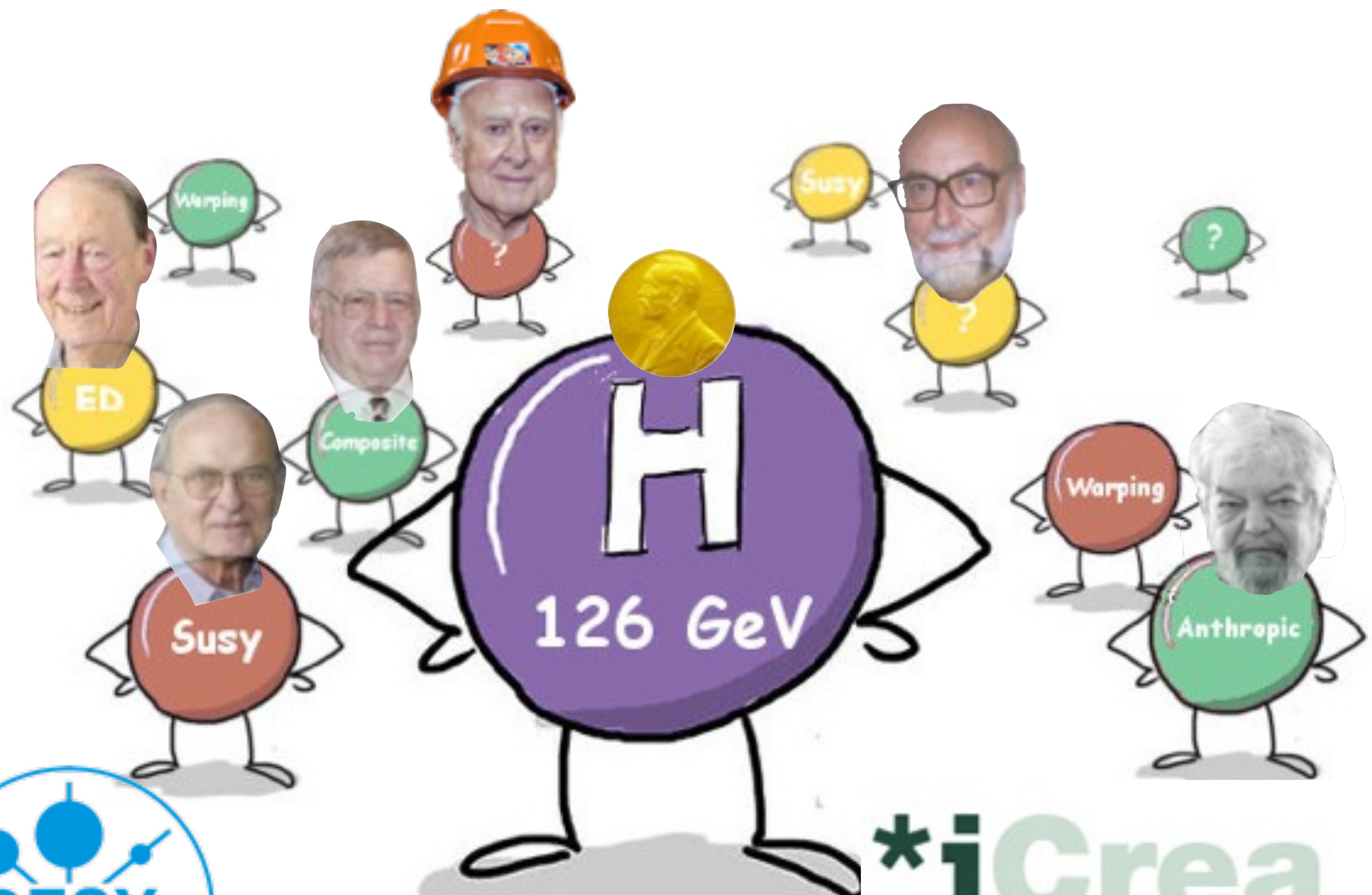
Beyond the Standard Model

CERN summer student lectures 2016



Lecture 1/4

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INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

What is physics beyond the Standard Model?

?

I don’t know. Nobody knows

If it were known, it would be part of the SM!

You won’t learn during these lectures what is BSM

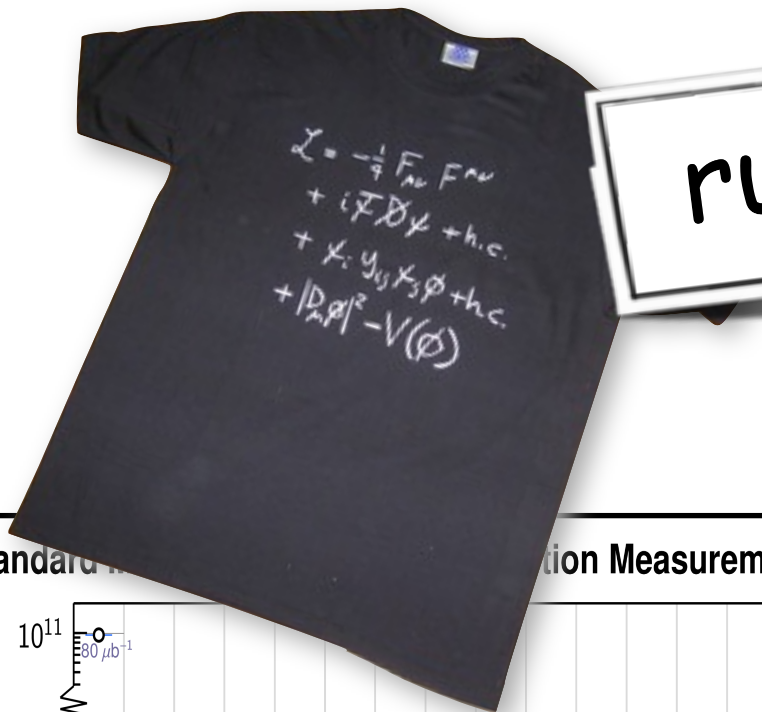
(maybe) you’ll learn what BSM could be

“Looking and not finding is different than not looking”

we’ll study the limitations/defaults of the SM as a guide towards BSM

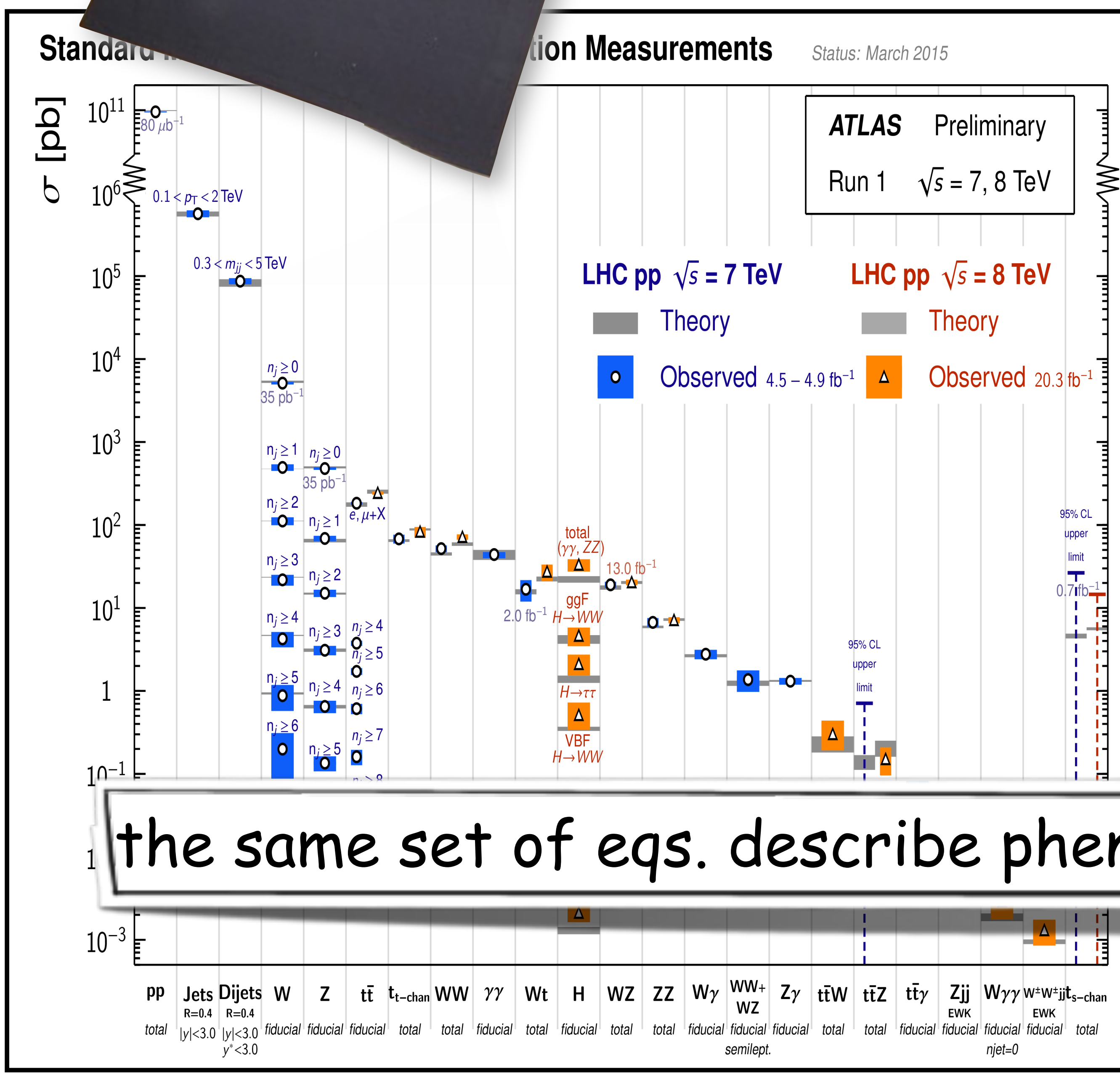
we want to learn from our failures

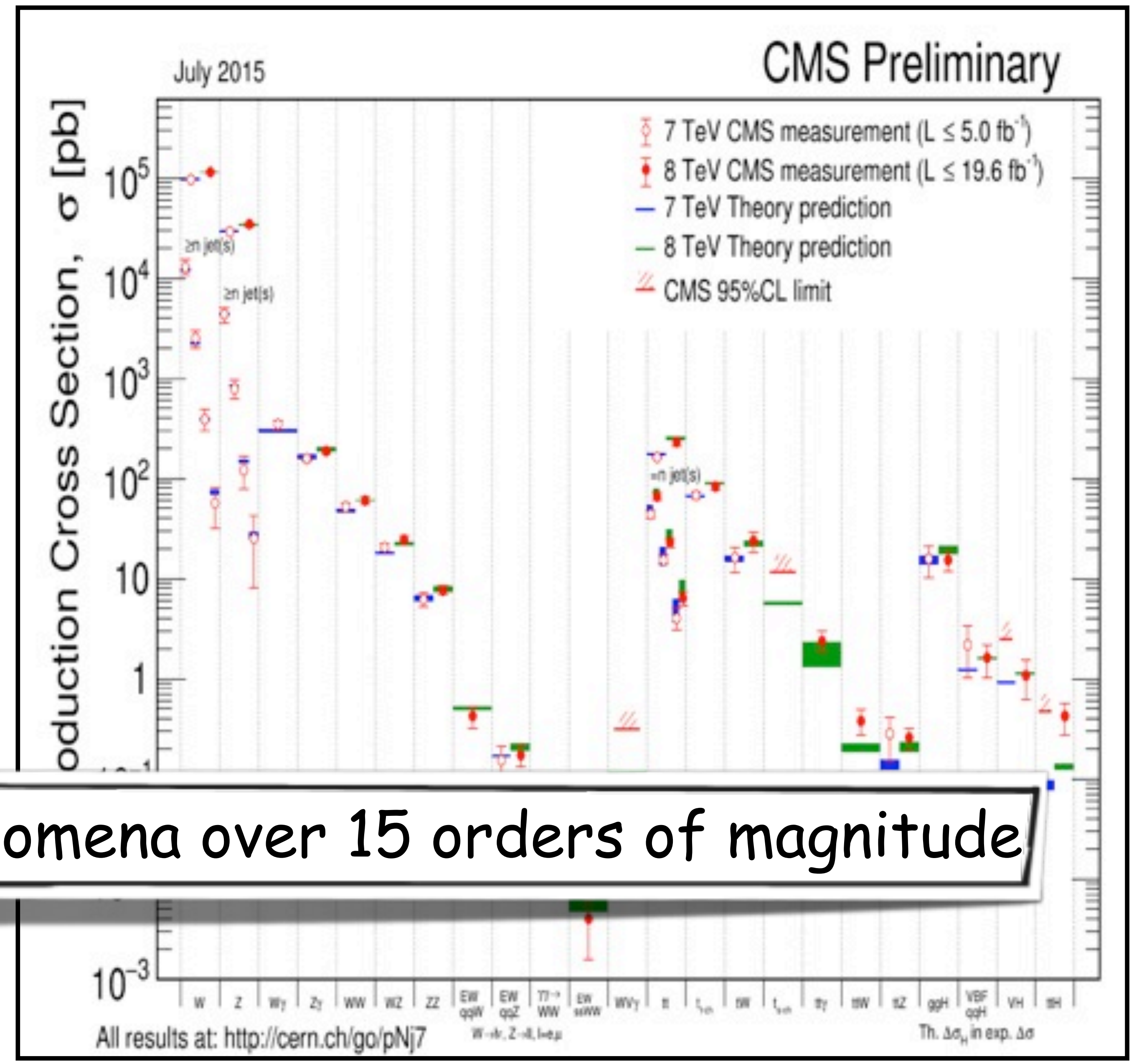
The SM and... the LHC data so far



rules the world!

[and we, HEP practitioners, are all entitled for some royalties!]





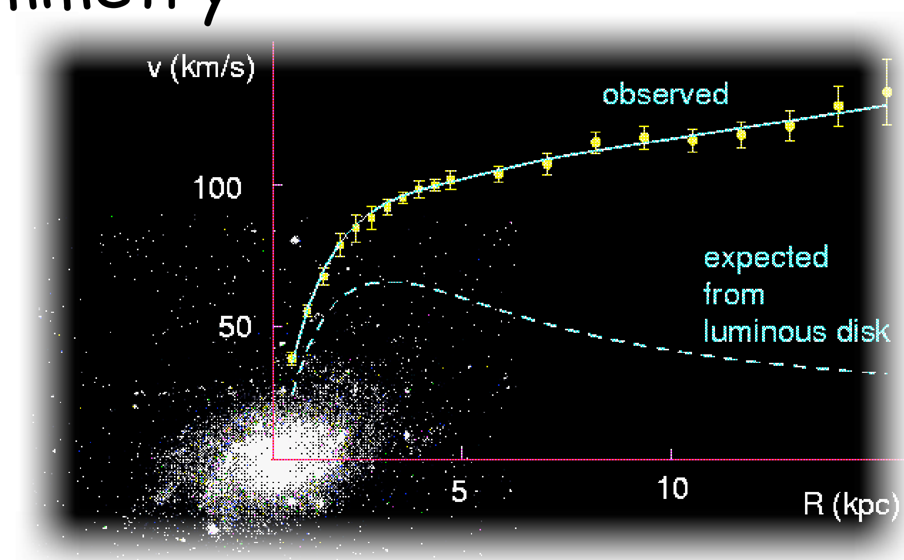
the same set of eqs. describe phenomena over 15 orders of magnitude

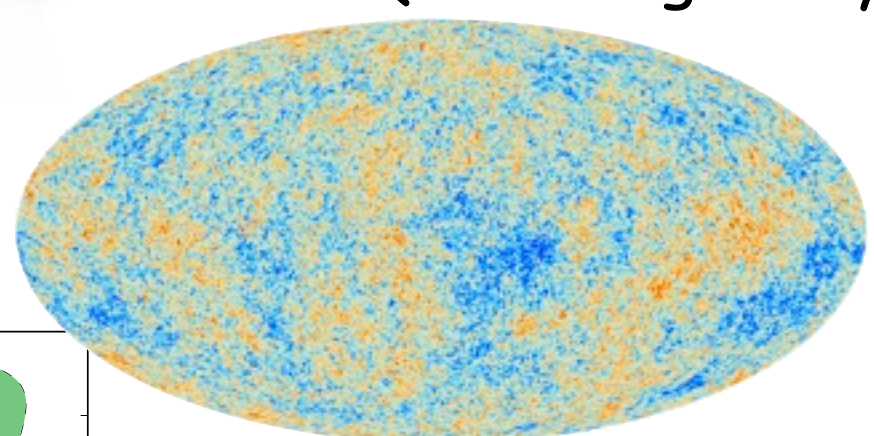
The SM and... the rest of the Universe

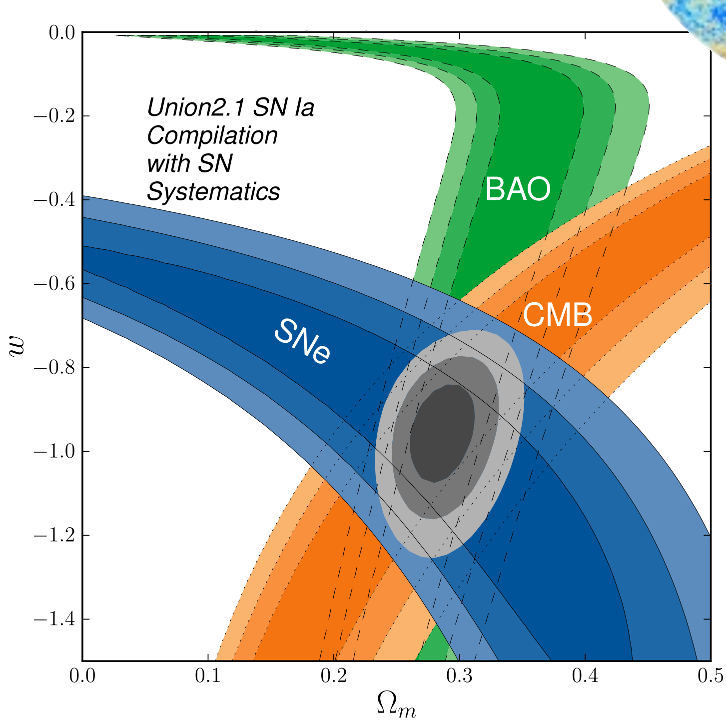
is not enough

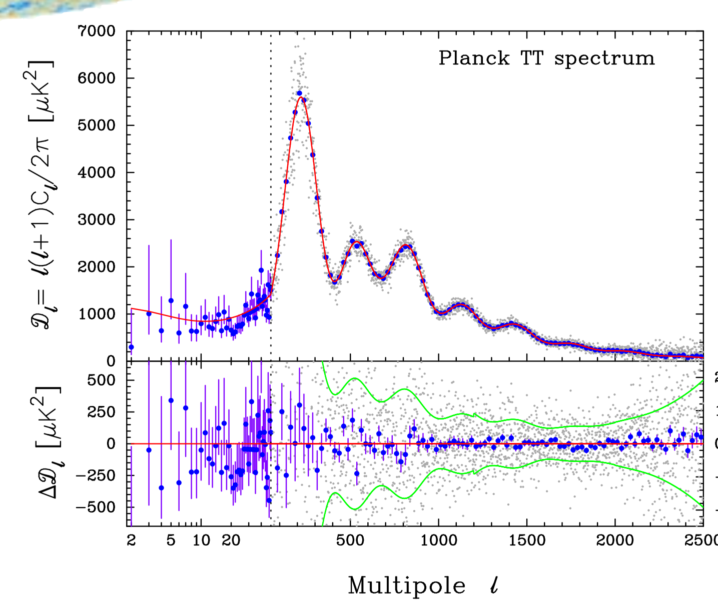
[and we all have to return our royalties!]

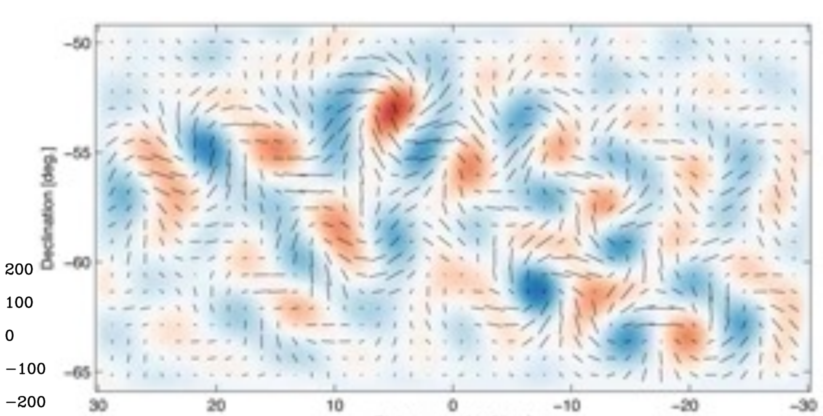
- neutrino masses
- matter-antimatter aymmetry
- Dark Matter
- Dark Energy
- Quantum gravity









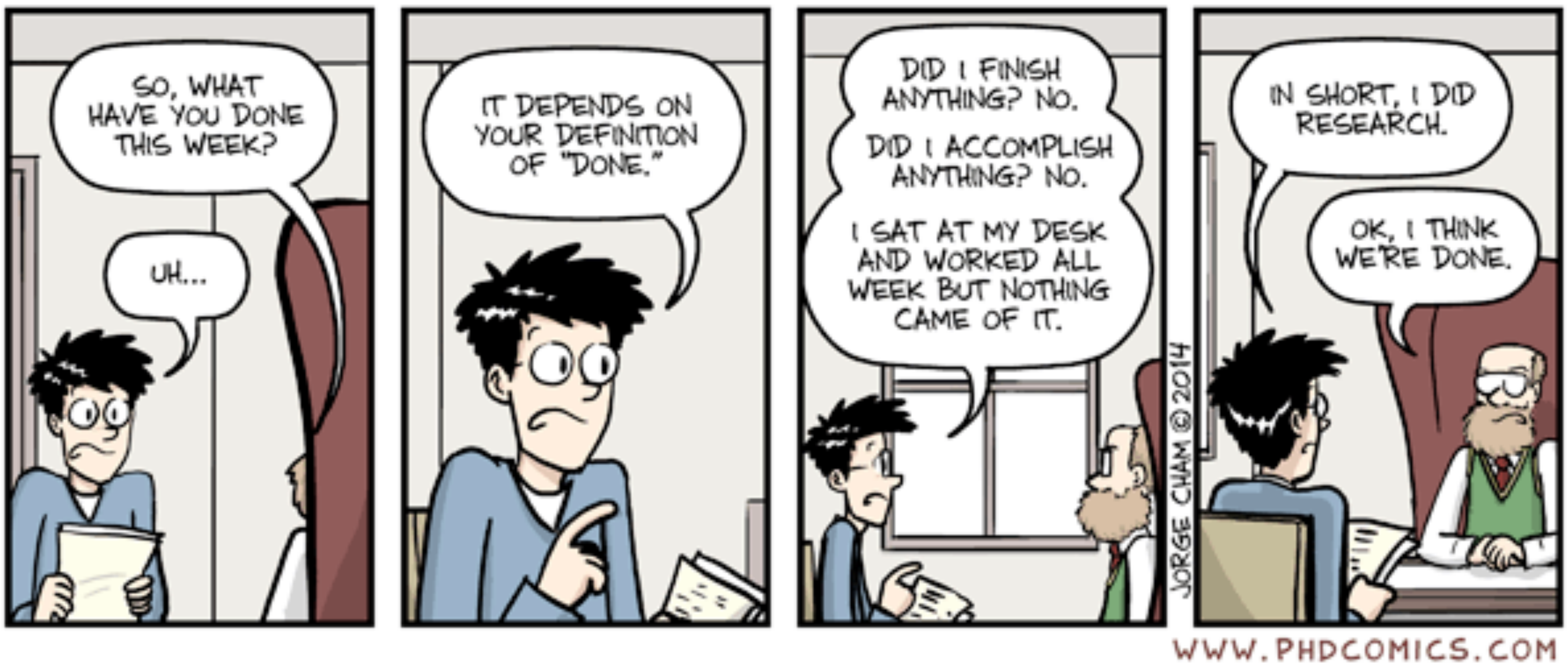


Outline

- Monday I
  - general introduction, units
  - Higgs physics as a door to BSM
- Monday II
  - Naturalness
  - Supersymmetry
  - Grand unification, proton decay
- Tuesday
  - Composite Higgs
  - Extra dimensions
  - Effective field theory
- Wednesday
  - Cosmological relaxation
  - Quantum gravity

Ask questions

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



Recommended Readings

- popular account
  - "The Zeptospace odyssey" by Gian-Francesco Giudice CERN library link
- fun physics
  - "Order-of-magnitude physics" by S. Mahajan, S. Phinney and P. Goldreich available for free online
- technical accounts
  - "Journeys beyond the Standard Model" by P. Ramond CERN library link
  - Many lecture notes, e.g. TASI (@Inspire: "t TASI")

Classical/Quantum EM & Antimatter

an electron makes an electric field which carries an energy

$$\Delta E_{\text{Coulomb}}(r) = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

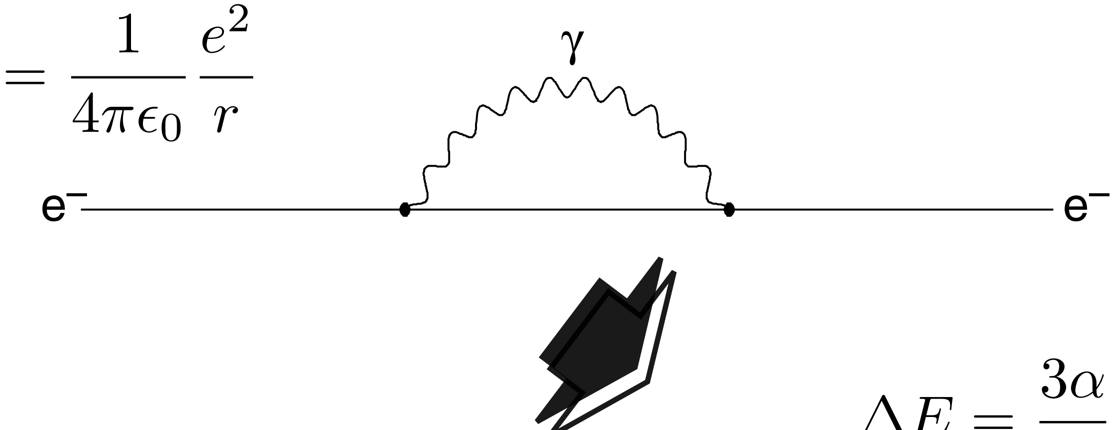
and interacts back to the electron and contributes to its mass $\delta m c^2 = \Delta E$

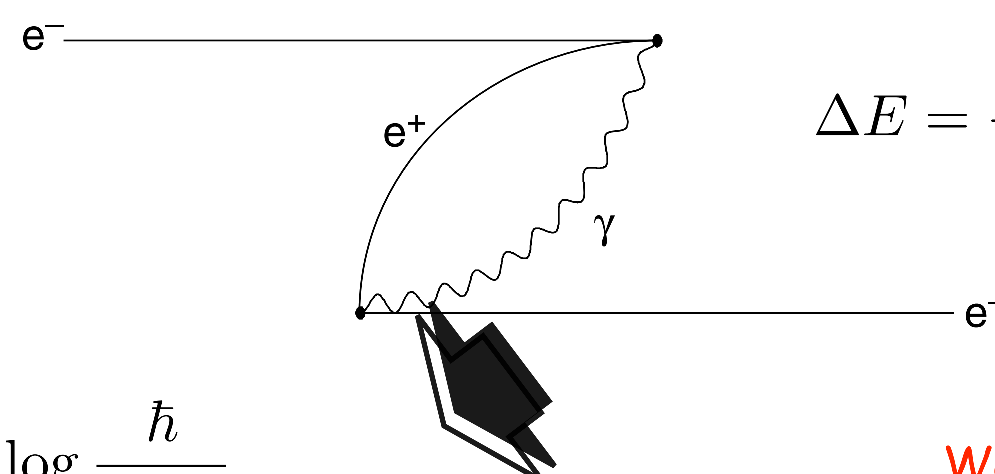
$$\delta m < m_e \quad \Rightarrow \quad r > r_e \equiv \frac{e^2}{4\pi\epsilon_0 m_e c^2} \sim 10^{-13}\ \text{m} \quad \text{i.e.} \quad E < \frac{\hbar c}{r_e} \sim 5\,\text{MeV}$$

At shortest distances or larger energies, classical EM breaks down

Quantum EM

$$\Delta E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$





$$\Delta E = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

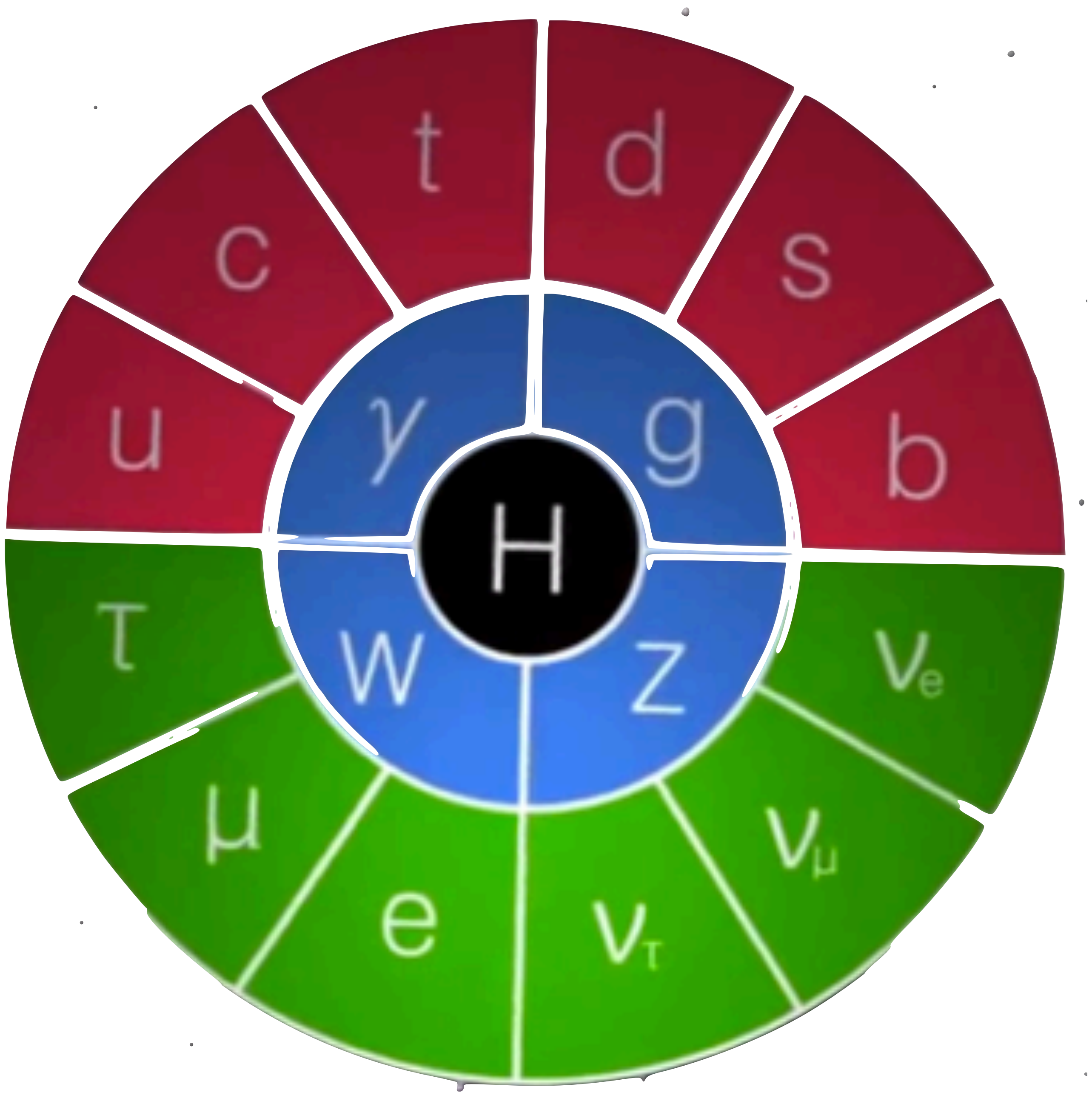
$$\Delta E = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{r m_e c}$$

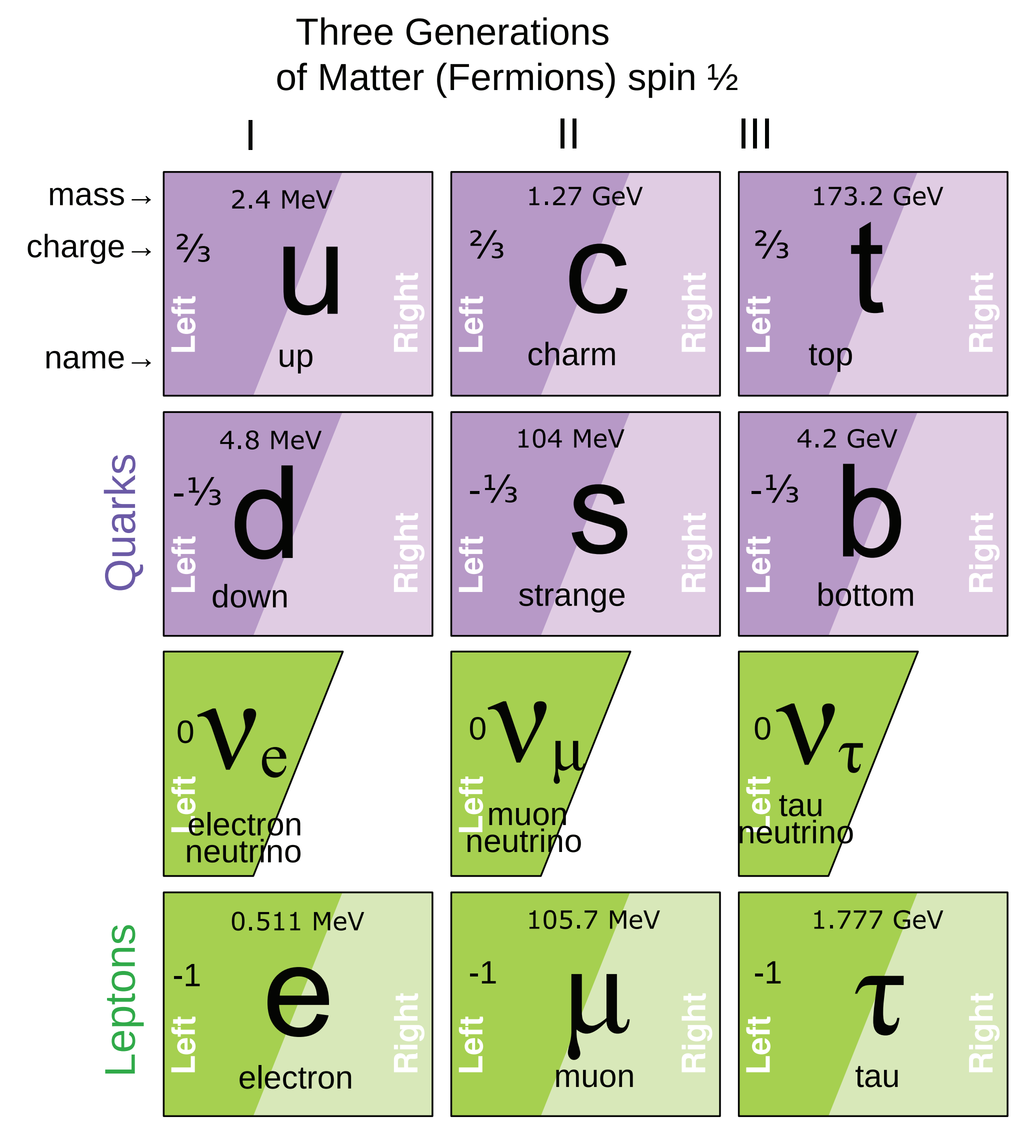
Weisskopf '39

new states ≈ softer high-energy (UV) behavior: $\delta m < 0.1 m_e \Rightarrow E < 10^{21}\,\text{GeV}$

The Standard Model: Matter

how many quarks and leptons?





an easy question... a not so simple answer!

The Standard Model: Matter

how many quarks and leptons?

$6+6=12$?

$6\times3+6=24$?

shouldn't we count different color states?

$6\times3\times2+3\times2+3=45$?

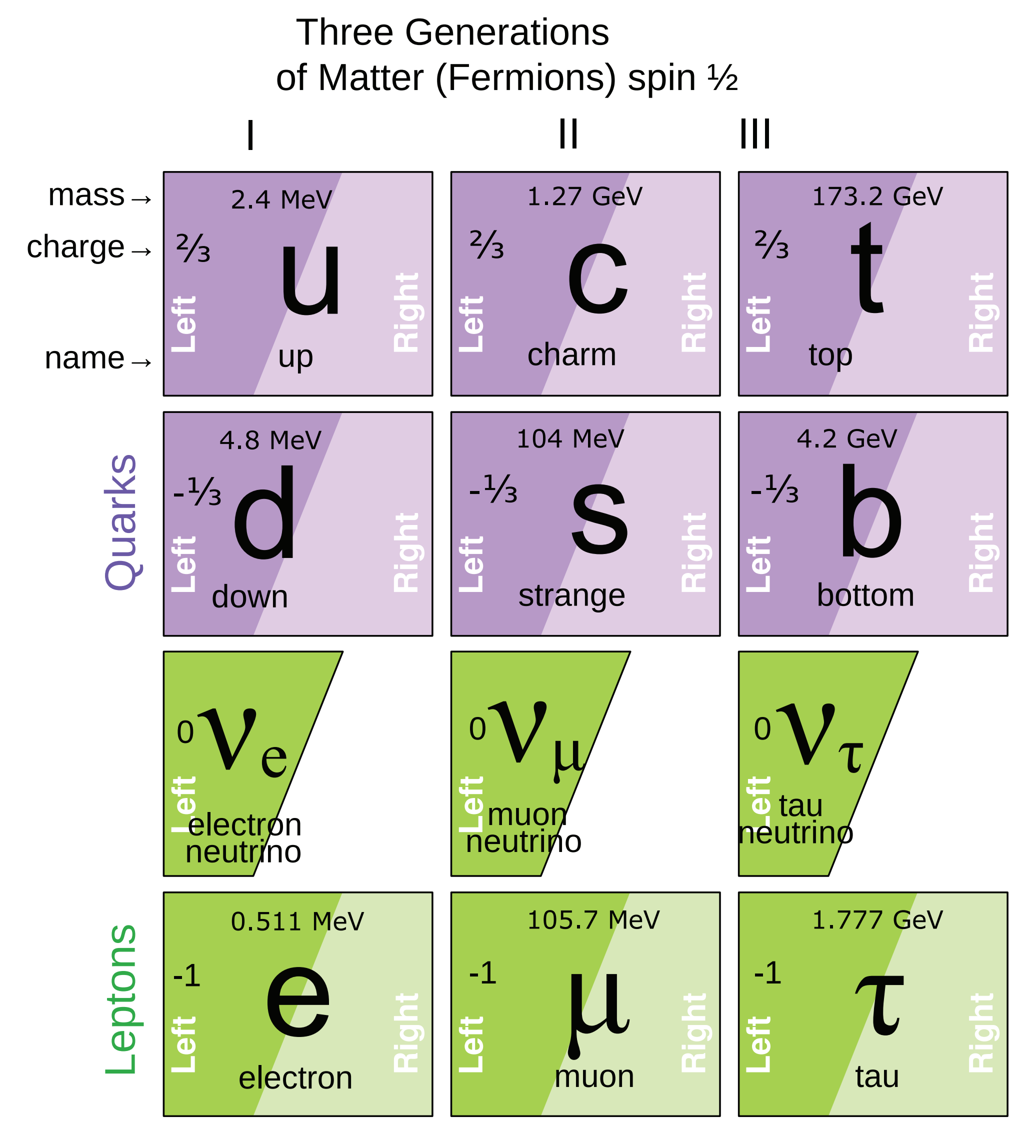
it is an accident that $e_L \sim e_R$ for QED

SM is a chiral theory: $e_L \neq e_R$

$6\times3\times2+6\times2=48$?

are there ν_R?

are they part of the SM?



an easy question... a not so simple answer!

The Standard Model: Interactions

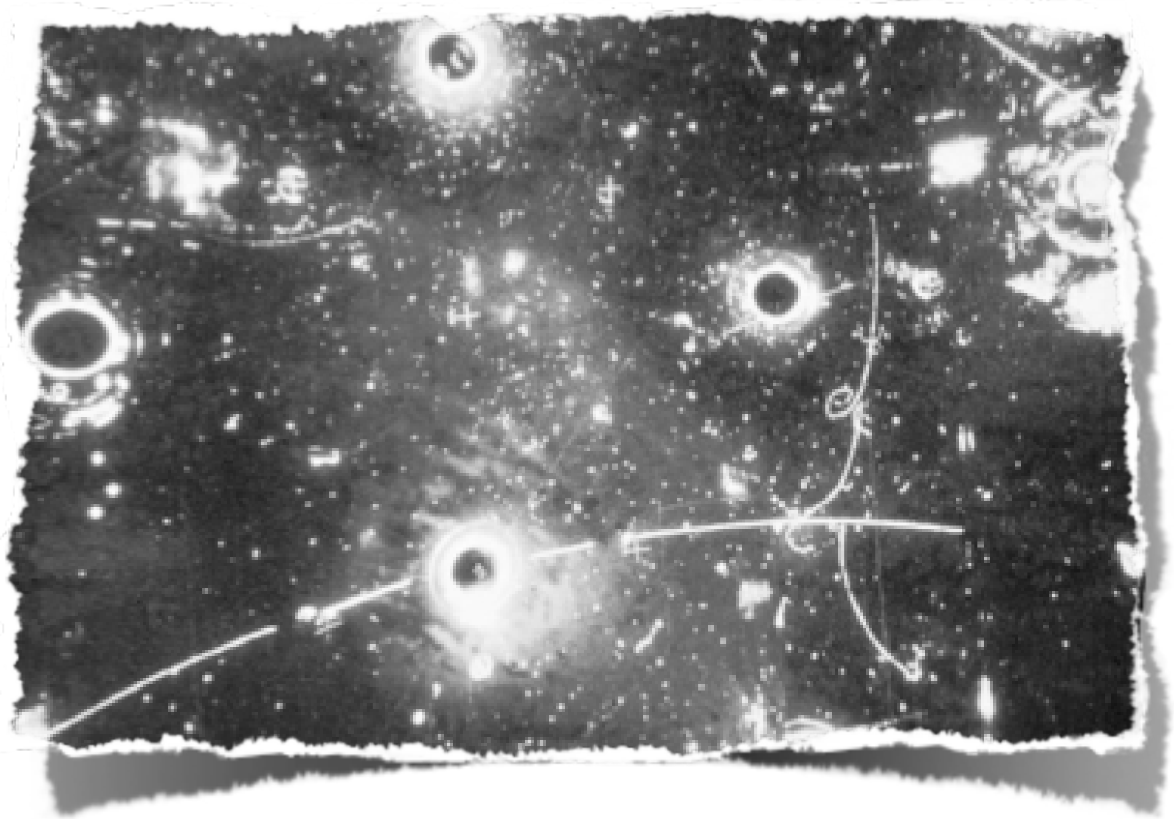
- $U(1)_Y$ ***electromagnetic interactions***
  - ➔ Photon γ
  - { light, atoms, molecules } — 10^{-5}
- $SU(2)_L$ ***weak interactions***
  - ➔ bosons $W^{\pm}, Z^0$
  - { β decay
    $n \xrightarrow{W^{\pm}} p + e^- + \bar{\nu}_e$
    $e^+ + e^- \xrightarrow{Z^0} D^+_{(c\bar{s})} + D^-_{(\bar{c}s)}$ } — 10^{-2}
- $SU(3)_c$ ***strong interactions***
  - ➔ gluons g^a
  - { atomic nuclei
    α decay
    ${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$ }

strength

The Standard Model

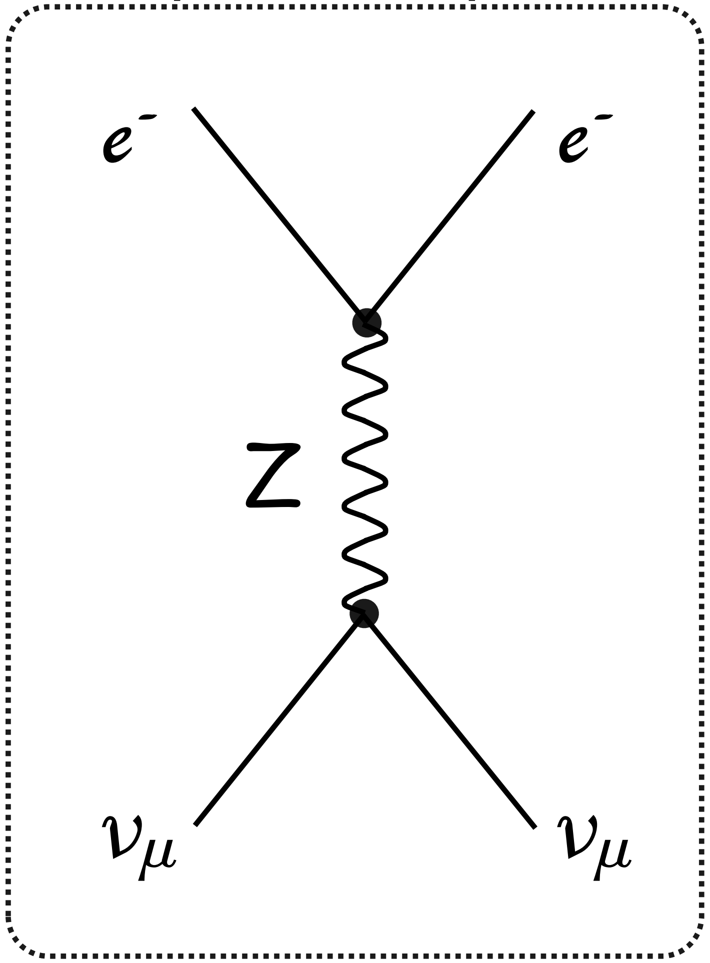
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

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



[Gargamelle collaboration, '73]

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

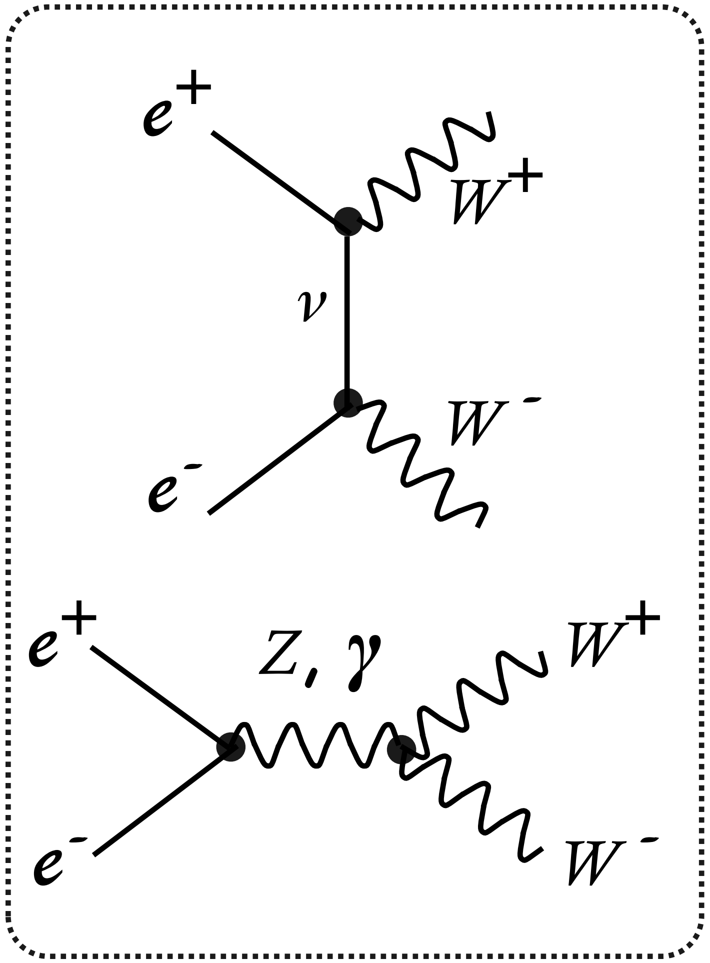


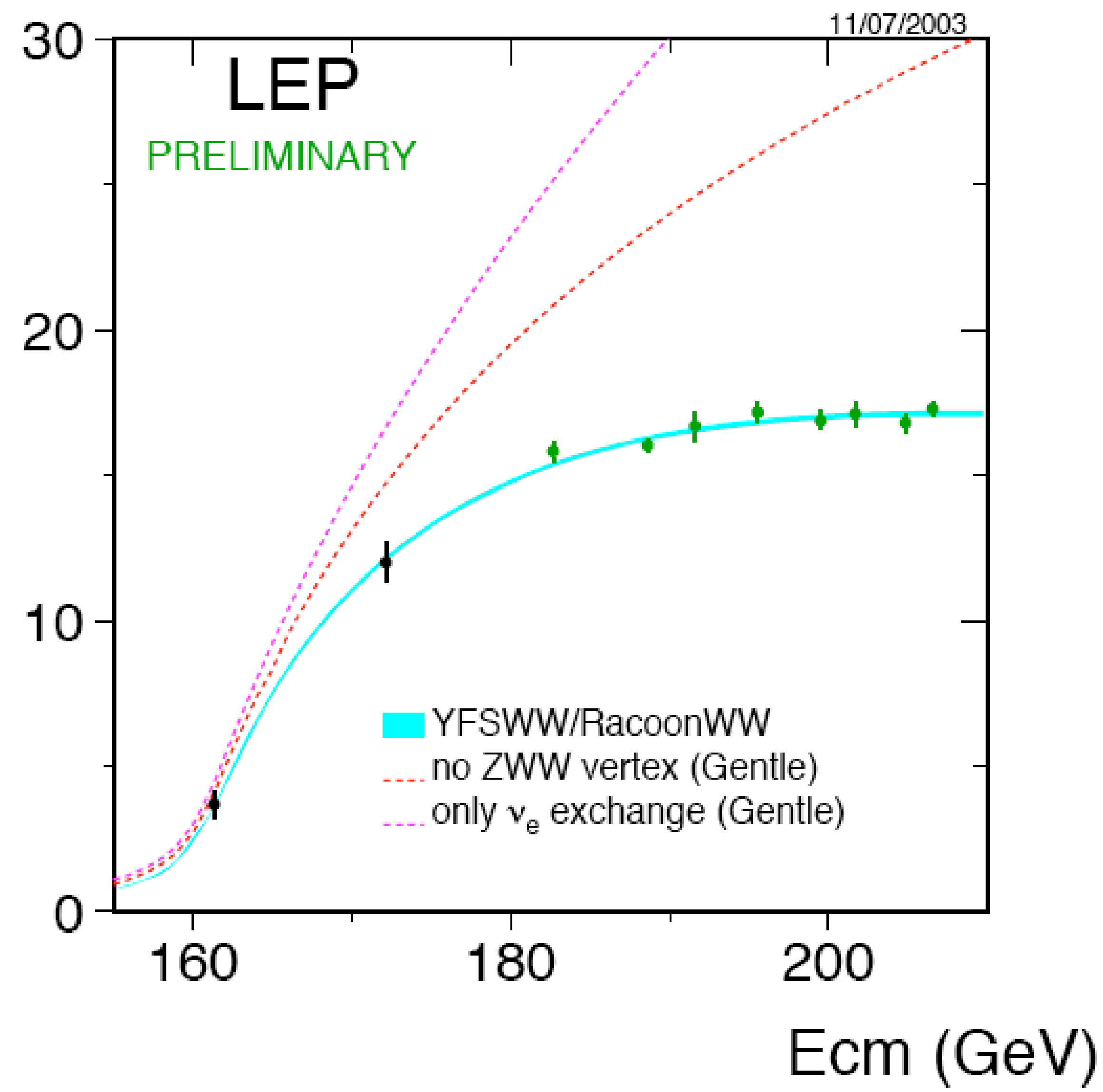
Gauge Theory as a Dynamical Principle

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

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

$e^+e^- \rightarrow W^+W^-$





The Standard Model and the Mass Problem

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

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

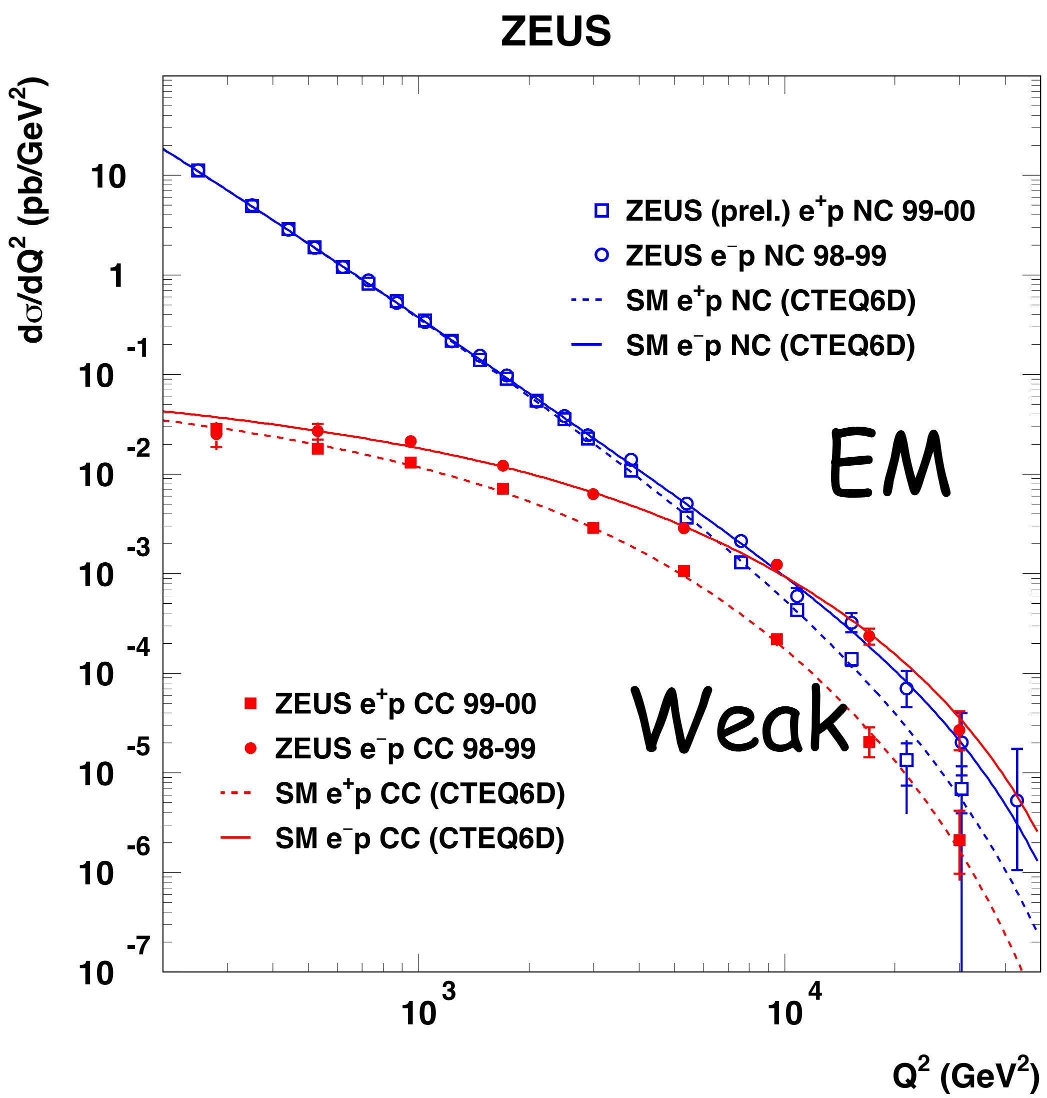
the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ 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 ⇐

Electroweak Unification

High energy (~ 100 GeV)



Low energy

This room is full of photons
but no W/Z

The symmetry between W, Z and γ
is broken at large distances

EM forces ≈ long ranges

Weak forces ≈ short range

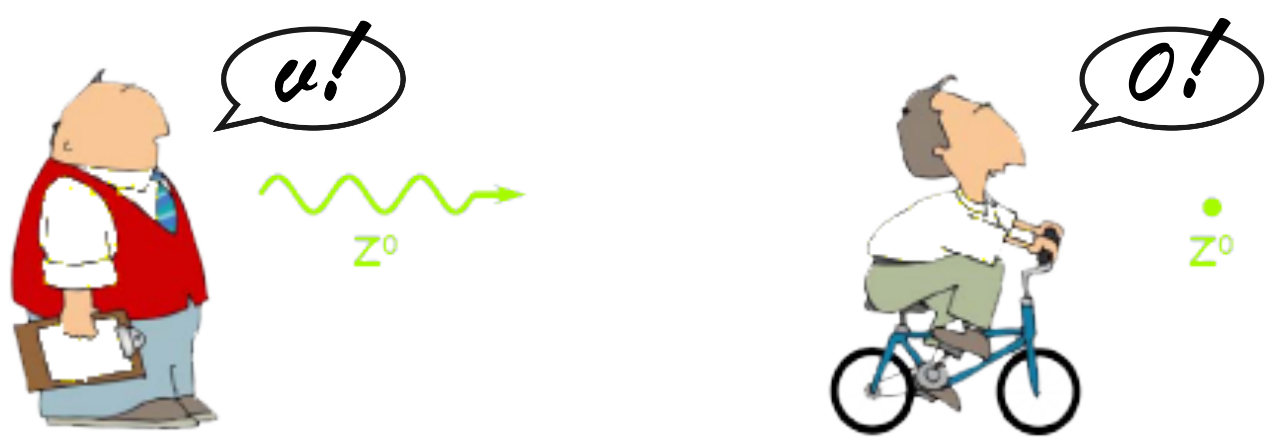
$$m_\gamma < 6 \times 10^{-17}\ \text{eV}$$

$$m_{W^\pm} = 80.425 \pm 0.038\ \text{GeV}$$

$$m_{Z^0} = 91.1876 \pm 0.0021\ \text{GeV}$$

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] 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)

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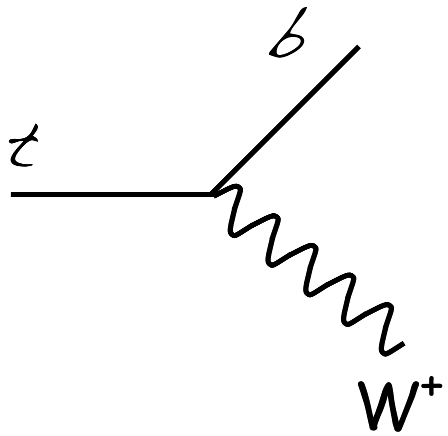
The BEH mechanism: "V_L=Goldstone bosons"

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



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

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

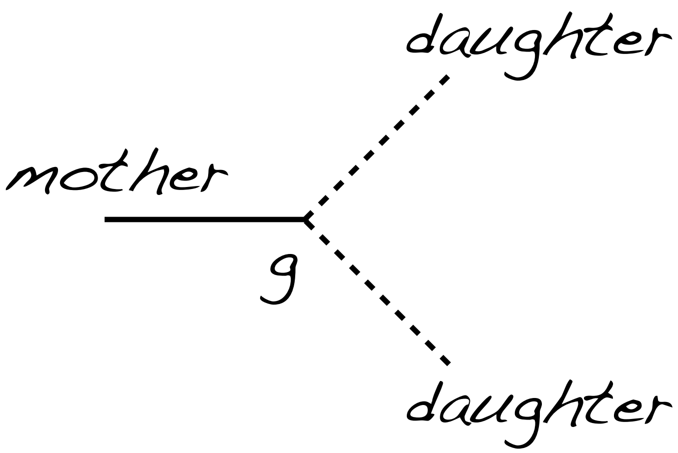
- at threshold ($m_t \sim m_W$) democratic decay
- at high energy ($m_t \gg m_W$) W_L dominates the decay

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 bosons becomes simple

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



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

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

very efficient way to suck up energy from the mother particle

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

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

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 $m_W \ll E \ll 4\pi v = \dfrac{8\pi m_W}{g}$

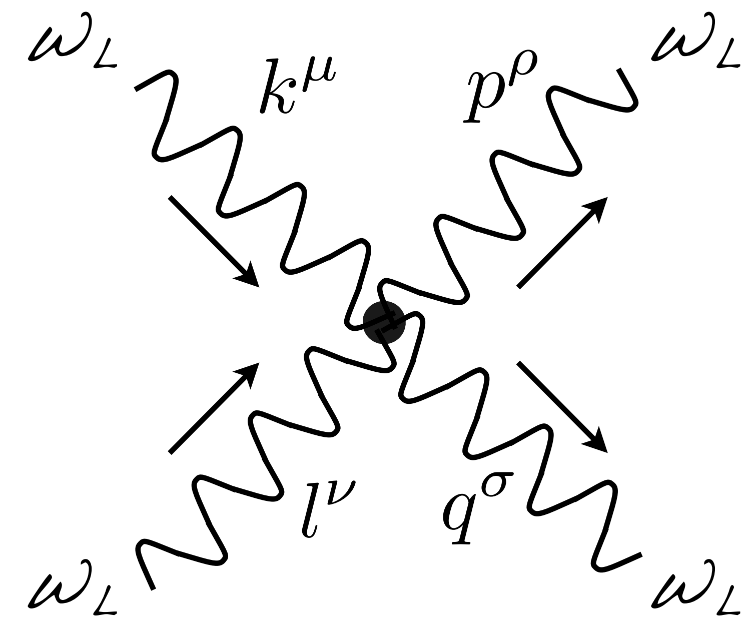
The goal of the LHC was/is to understand what comes next

Call for extra degrees of freedom

NO LOSE THEOREM

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

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



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

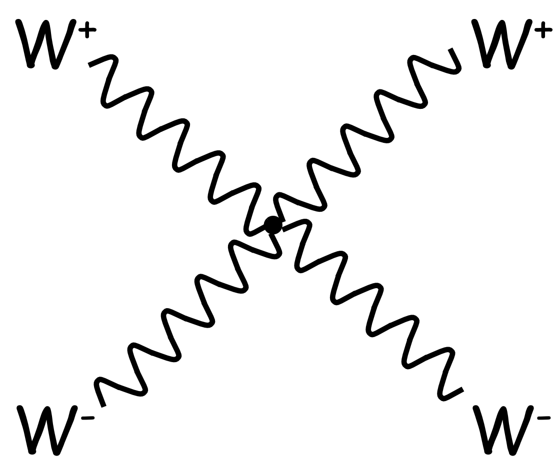
violations of perturbative unitarity around E ~ M/√g (actually M/g)

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!

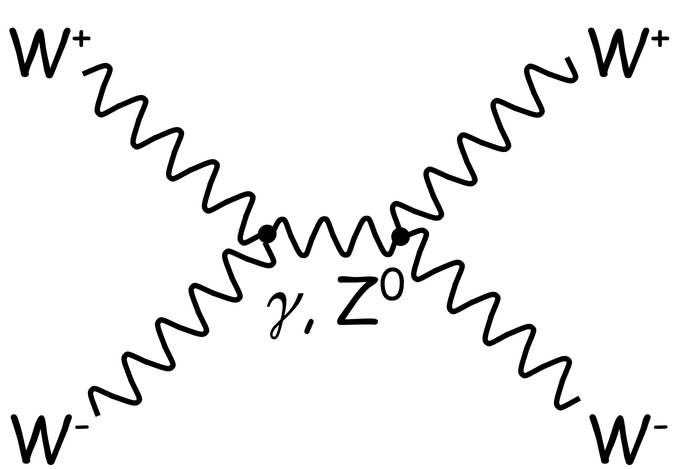
$M_W/\sqrt{(g/4\pi)}$~500GeV or $M_W/(g/4\pi)$~3TeV?

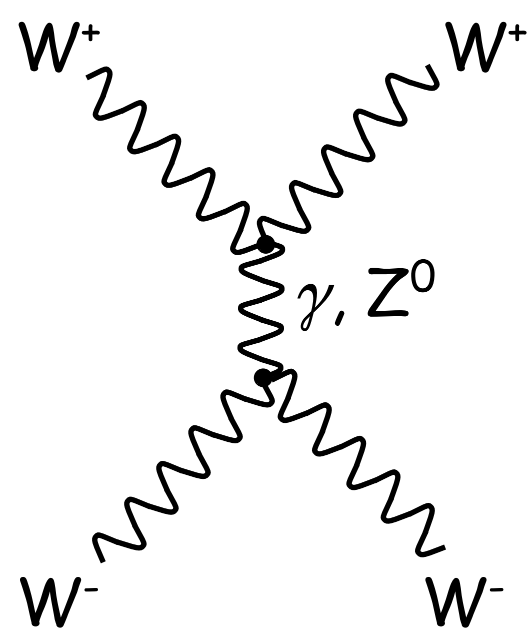
Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73



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

+





+

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

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

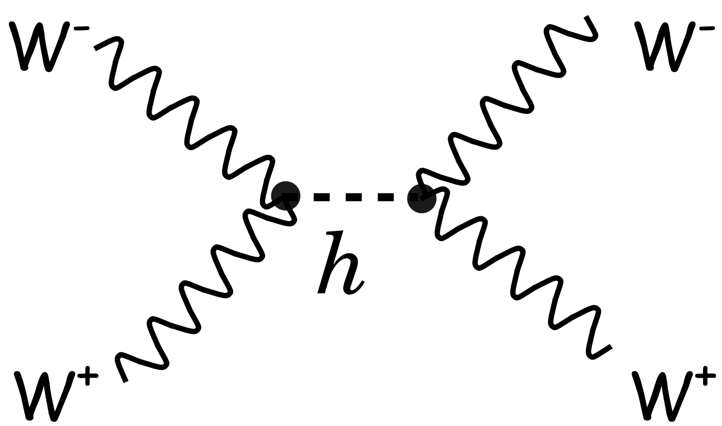
impossible to further cancel the amplitude without introducing new degrees of freedom

What is the SM Higgs?

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

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

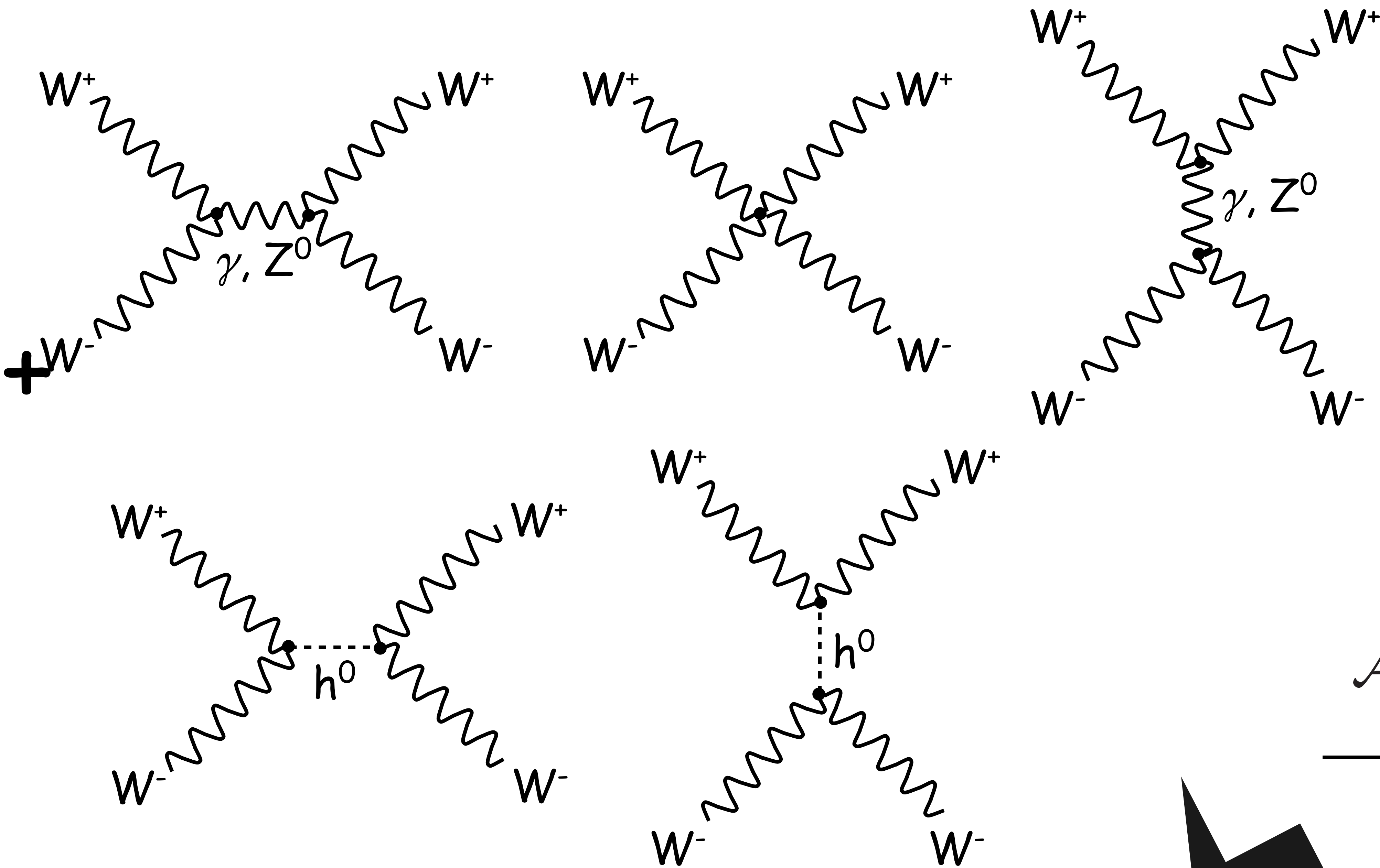
'a', 'b' and 'c' are arbitrary free couplings



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

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the SM Higgs?



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

+

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

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

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?

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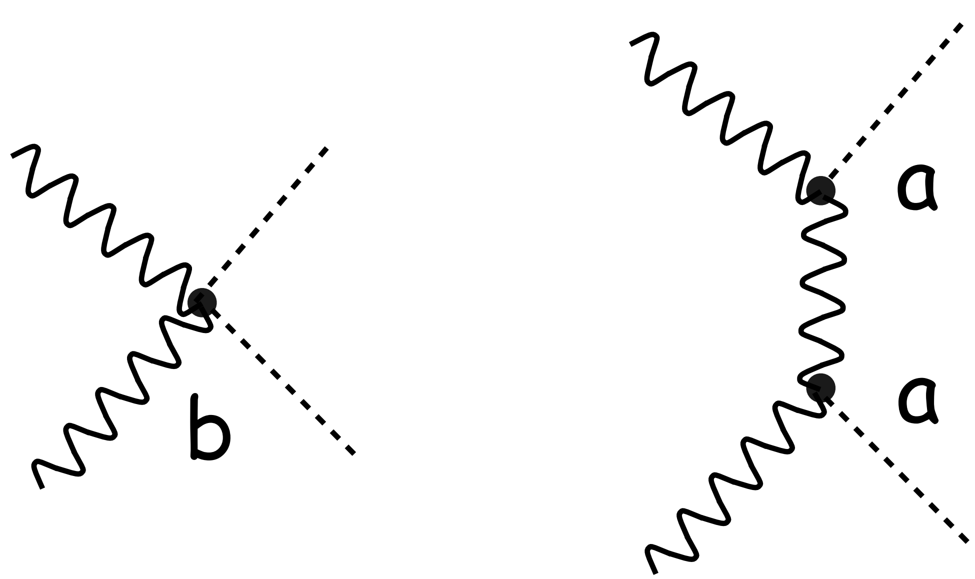
For a=1: perturbative unitarity in elastic channels WW $\to$ WW

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

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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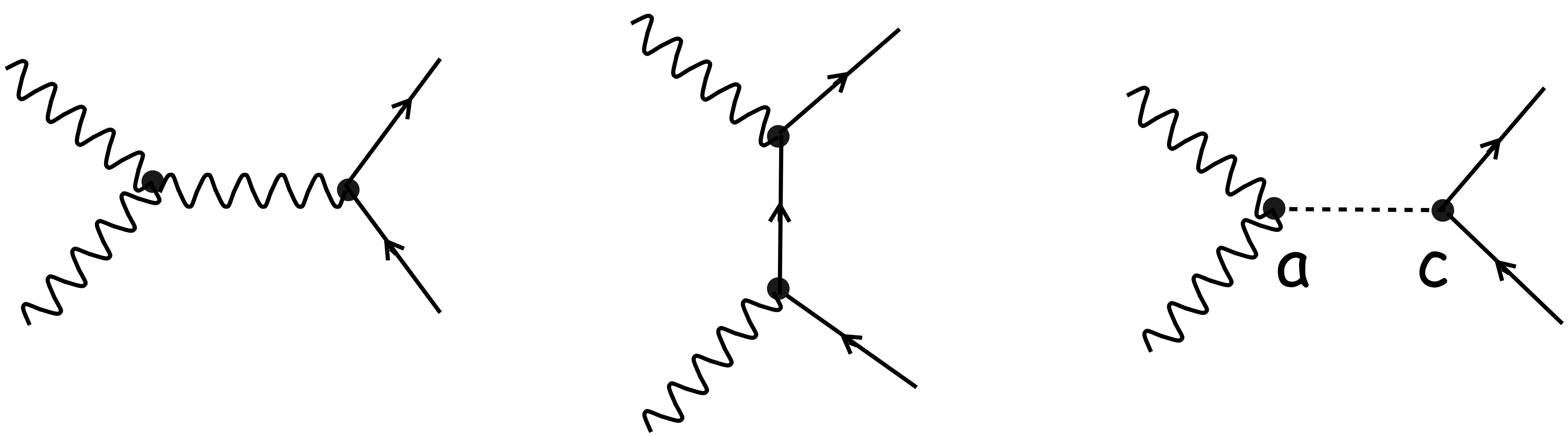

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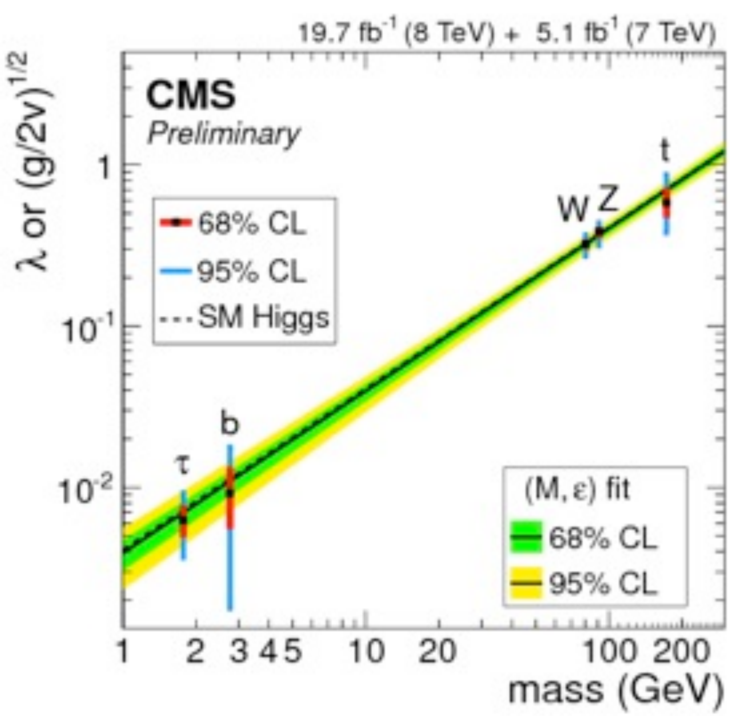


CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

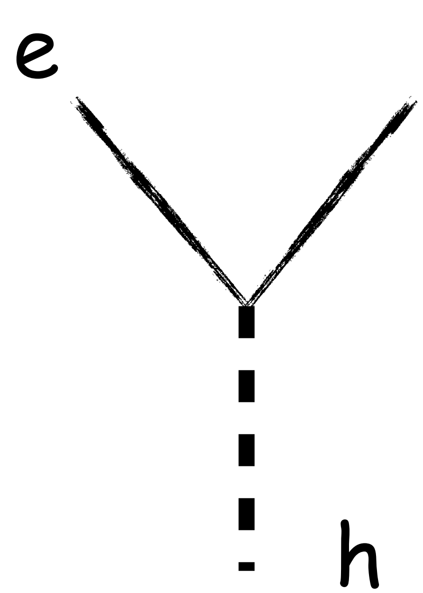
$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

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

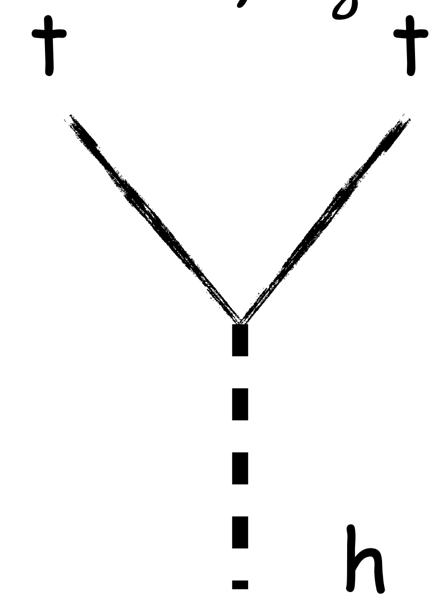
NB: the proton is not an elementary particle,
its mass doesn't measure its interaction with the Higgs substance

From electrons



probability ~ 10^{-11}

From top quarks



probability ~ 1

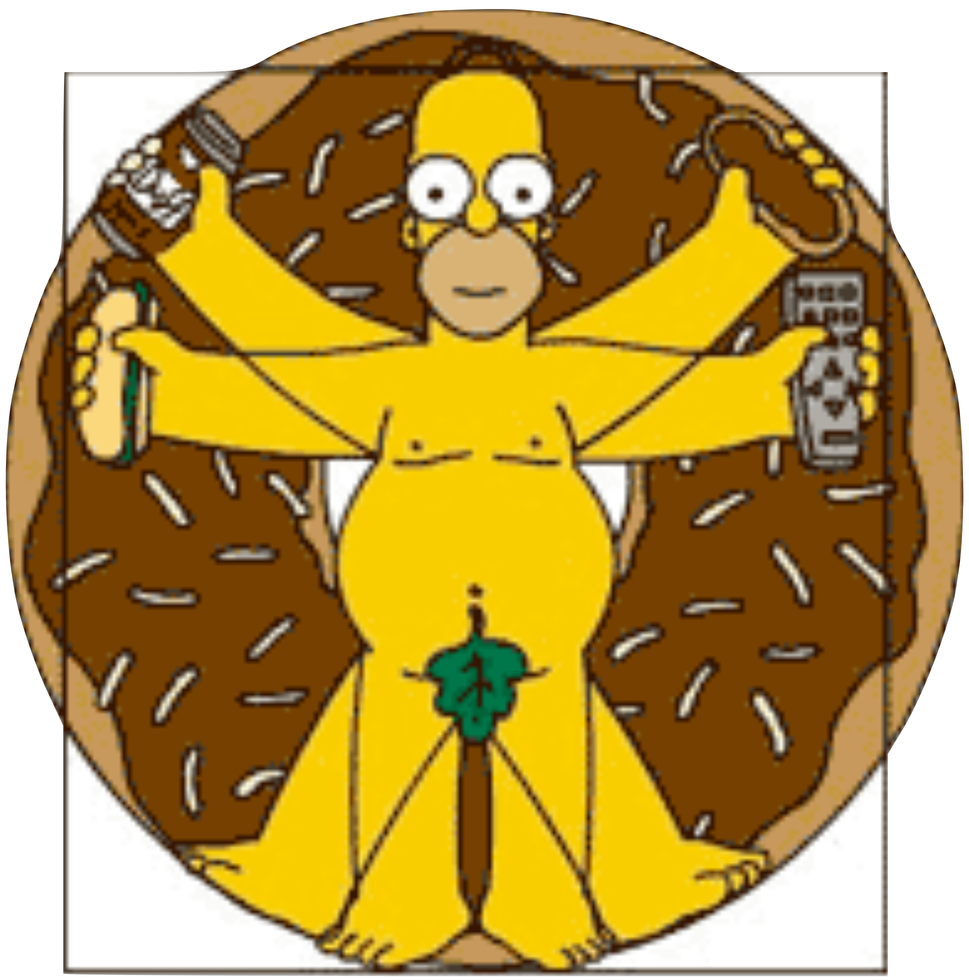
but no top quark at our disposal

Higgs boson at the LHC

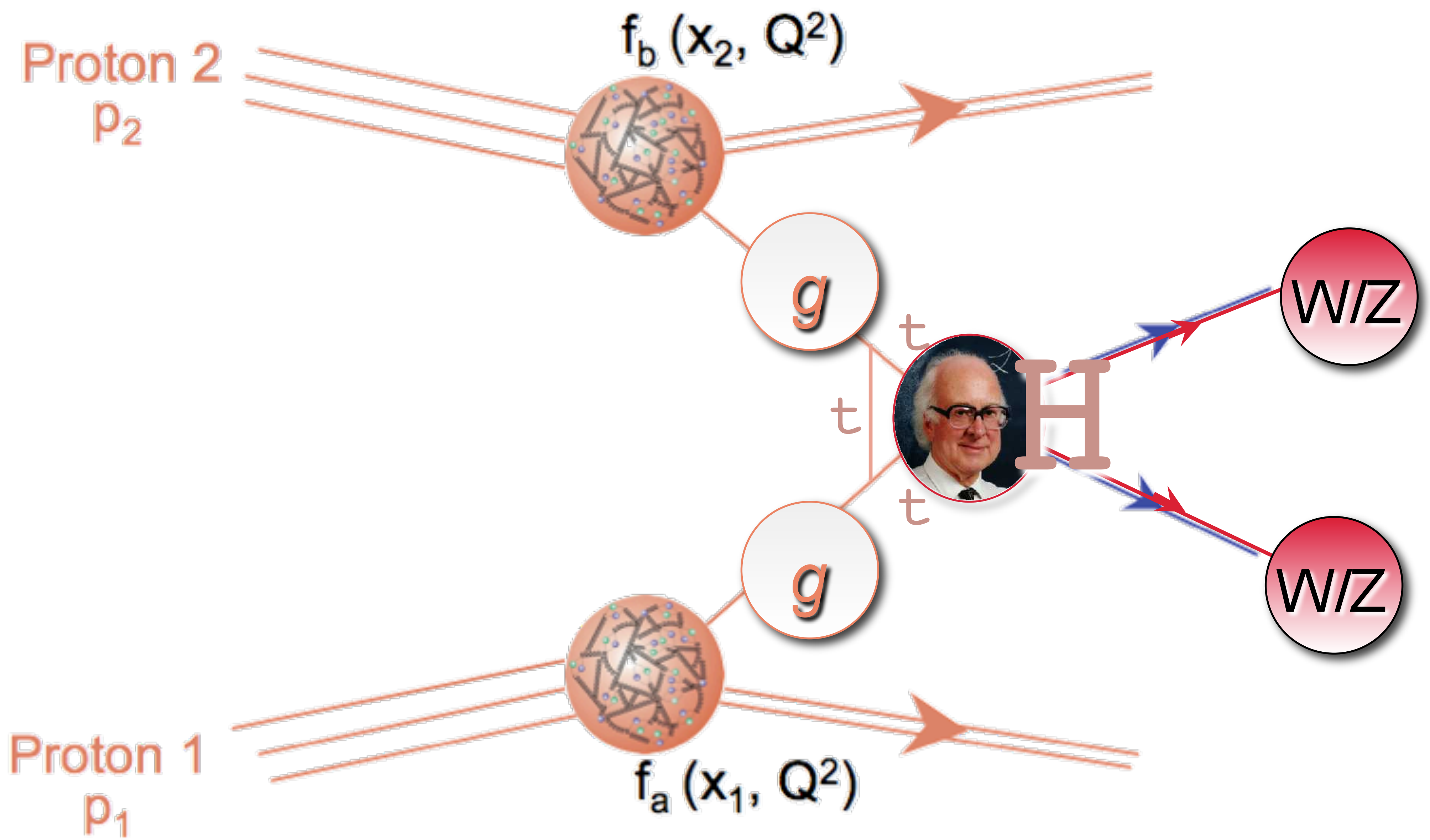
Difficult task

Homer Simpson's principle of life:

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



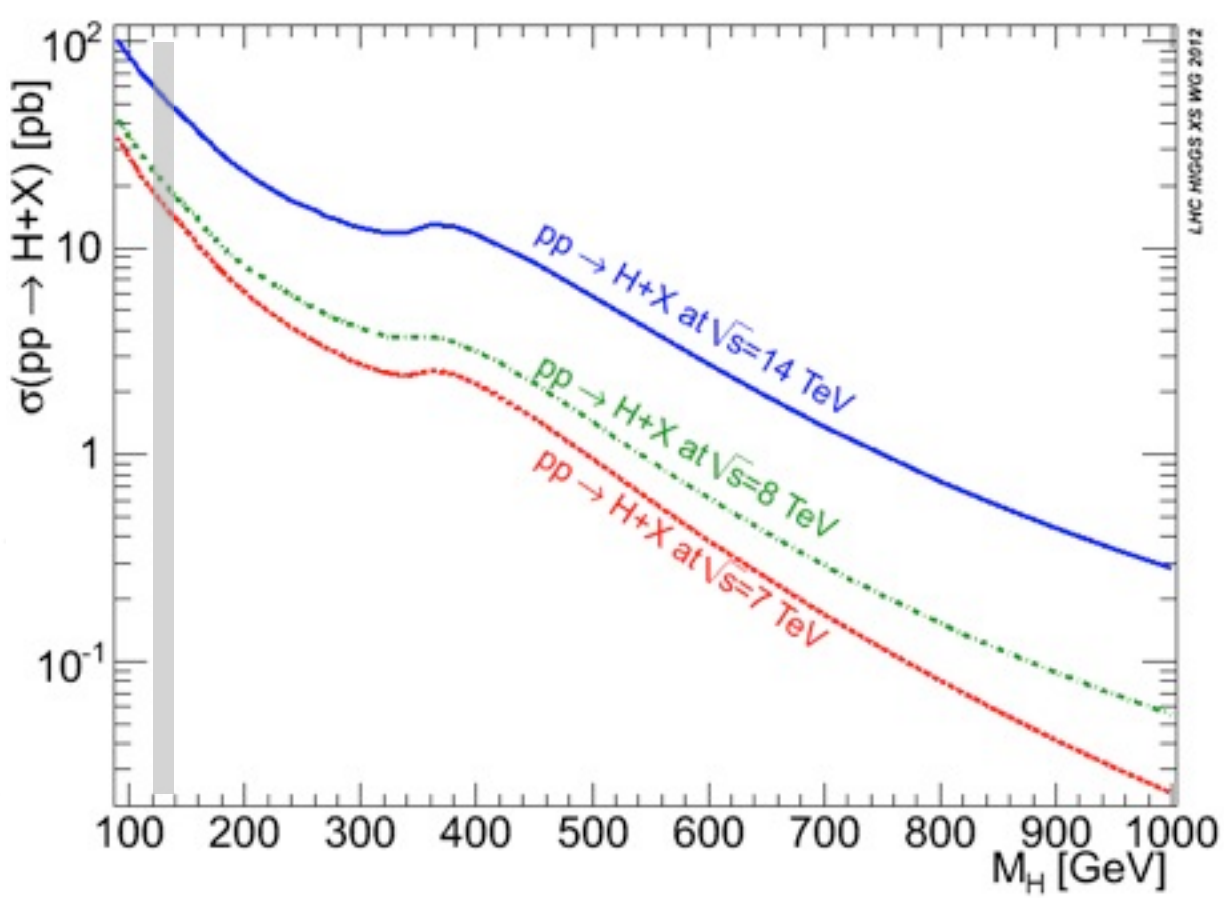
Higgs boson at the LHC



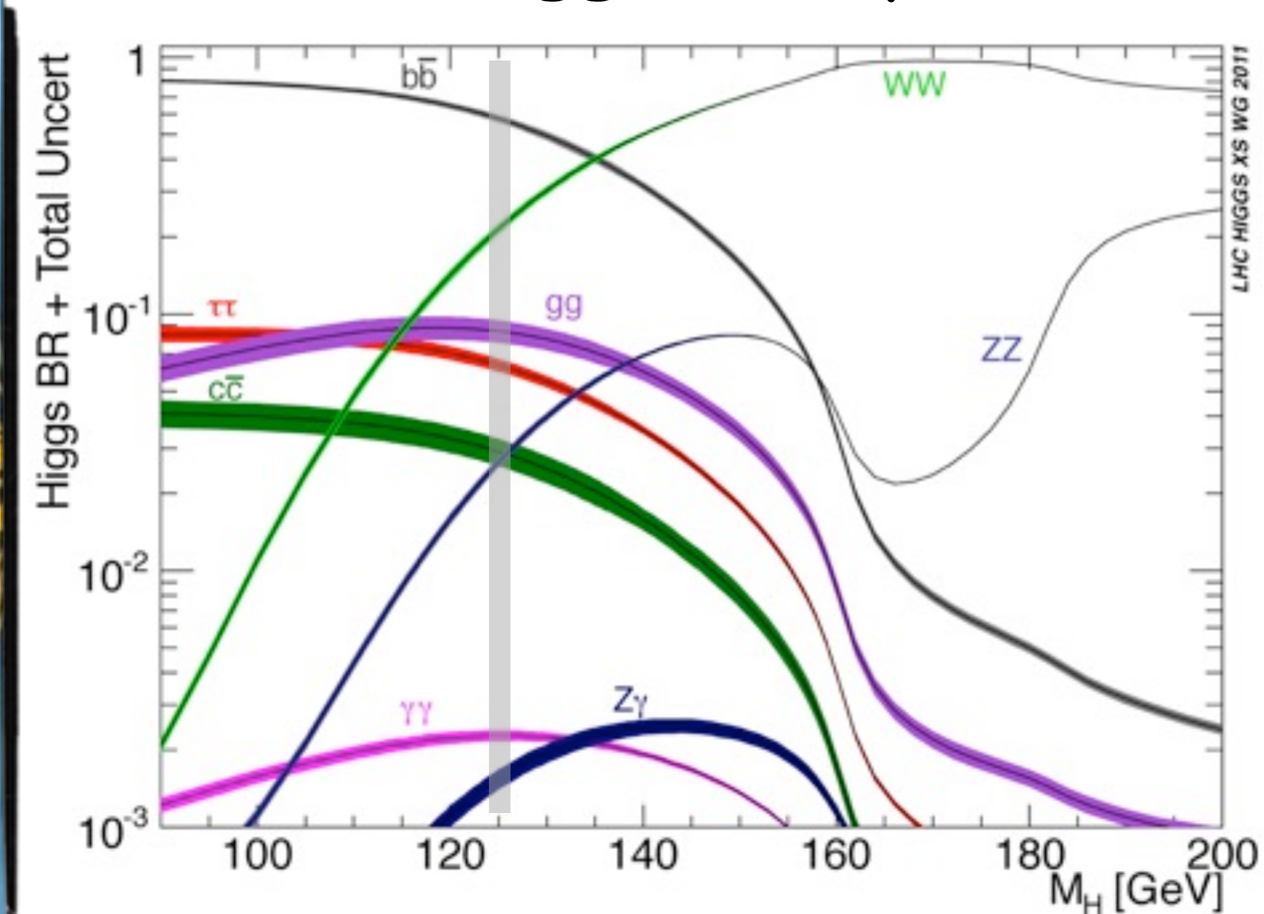
Higgs boson at the LHC

$\sigma \sim 10$ pb ⇔ 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

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

Higgs@LHC: a paradoxical triumph

The Higgs is related to some of the deepest problems of HEP

$$\mathcal{L}_{\rm Higgs} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar\psi_{Li}\psi_{Rj}H + h.c.\right)$$

- vacuum energy cosmological constant $V_0 \approx (2\times 10^{-3}\ {\rm eV})^4 \ll M_{\rm PL}^4$
- hierarchy problem $m_H \approx 100\ {\rm GeV} \ll M_{\rm Pl}$
- triviality/stability of EW vacuum
- mass and mixing hierarchy
- flavour & CP

~~ Higgs interactions ~~

gauge symmetry is the organizing principle for interactions in the gauge sector

not in the Higgs sector ⇛ many free parameters!

but they obey 3 basic structures

(1) proportionality: $g_{hff} \propto m_f \qquad g_{hVV} \propto m_V^2$

➠ test for extended Higgs sectors

(2) factor of proportionality: $g_{hff}/m_f = \sqrt{2}/v$

➠ test for extended Higgs sectors

➠ test for Higgs compositeness

(3) flavor alignment: $g_{hf_if_j} \propto \delta_{ij}$

➠ test for flavor models, origin of fermion masses