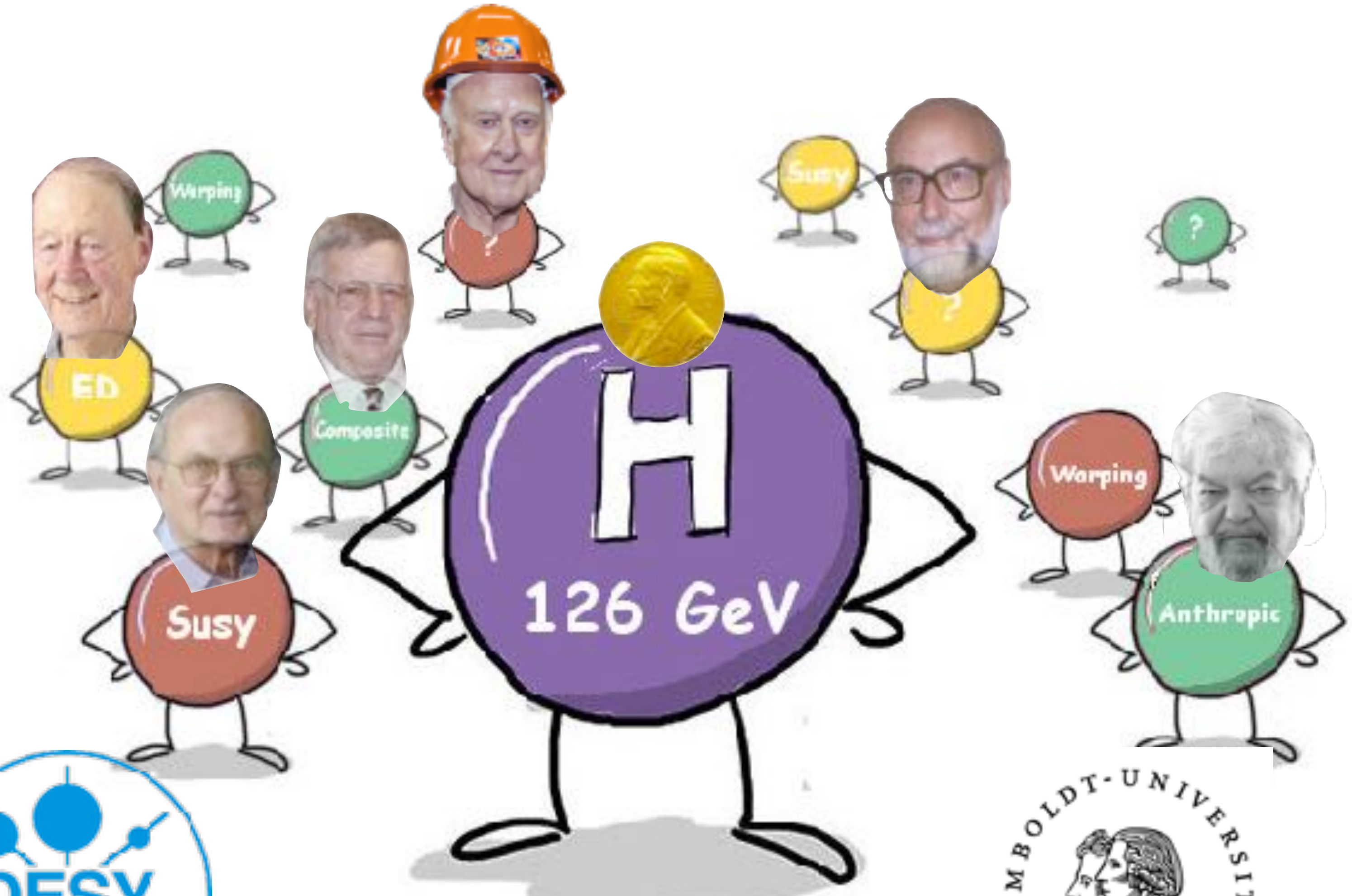
Beyond the Standard Model

CERN summer student lectures 2018



Lecture 1/4

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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 BSM is.

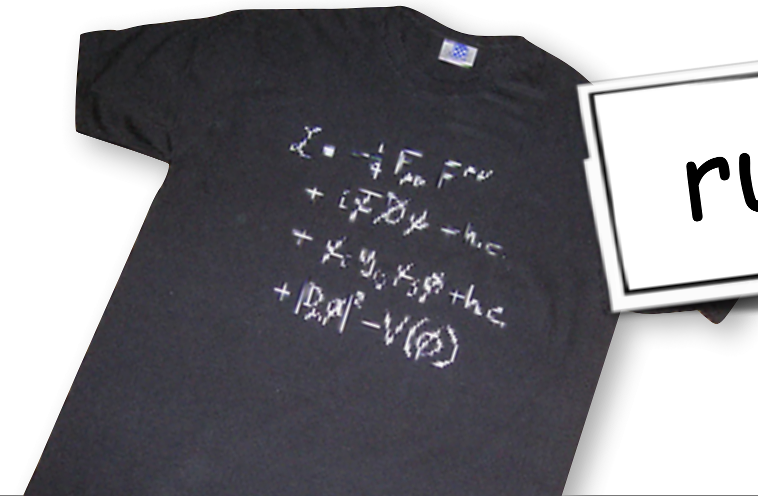
You’ll learn (maybe) what BSM could be.

“ Looking and not finding is different than not looking”

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

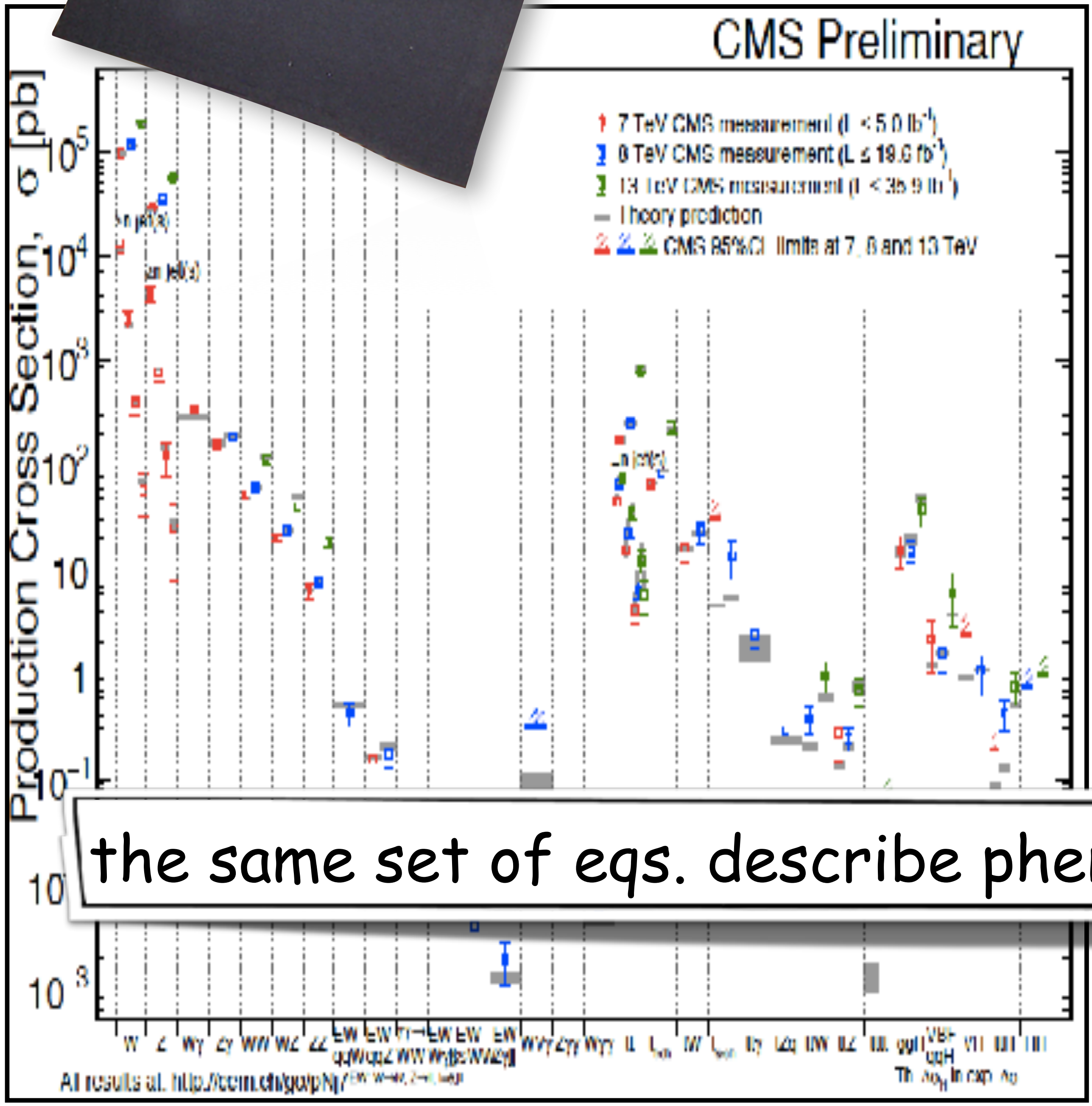
We want to learn from our failures

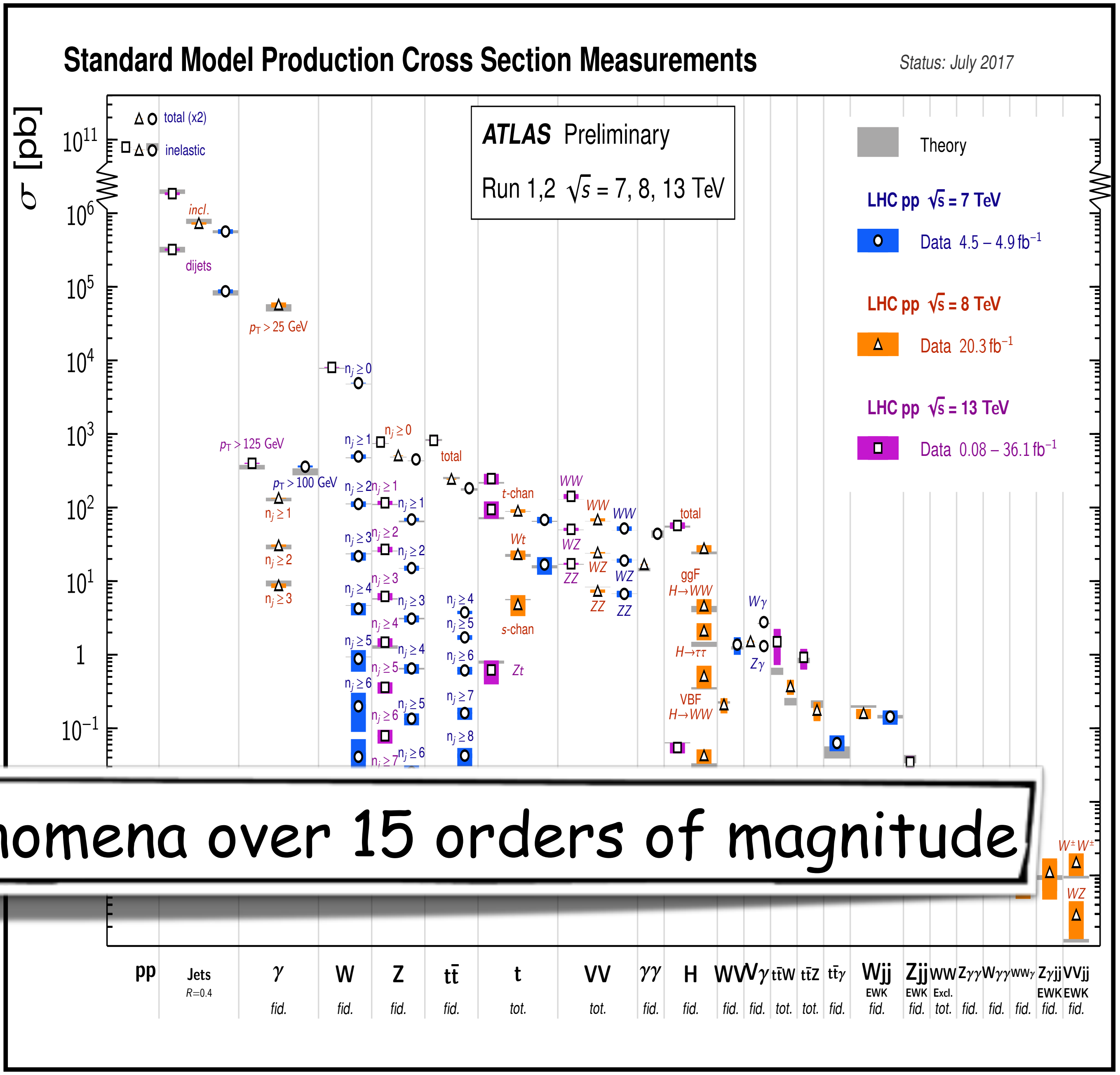
The SM and... the LHC data so far



rules the world!

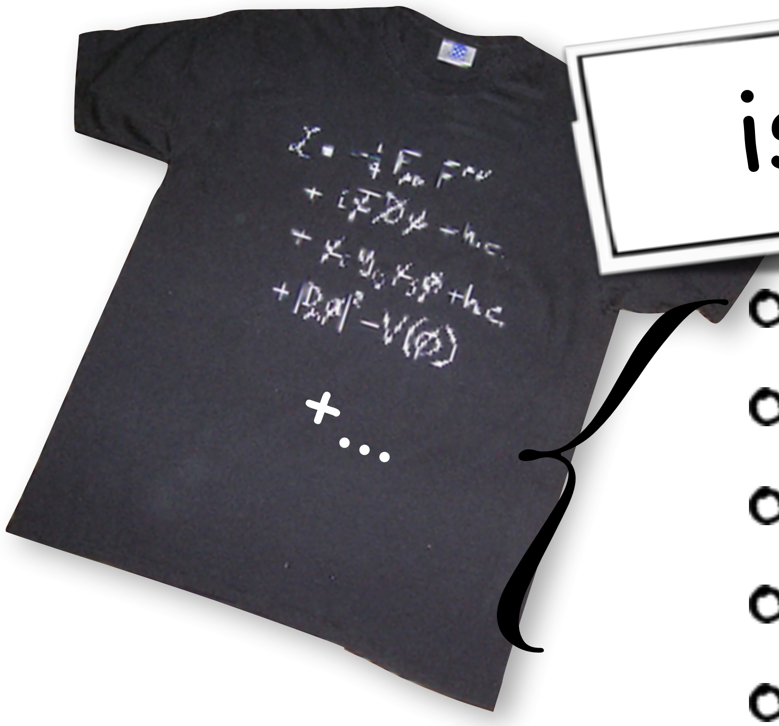
[and we, HEP practitioners, are all entitled for some royalties!]





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

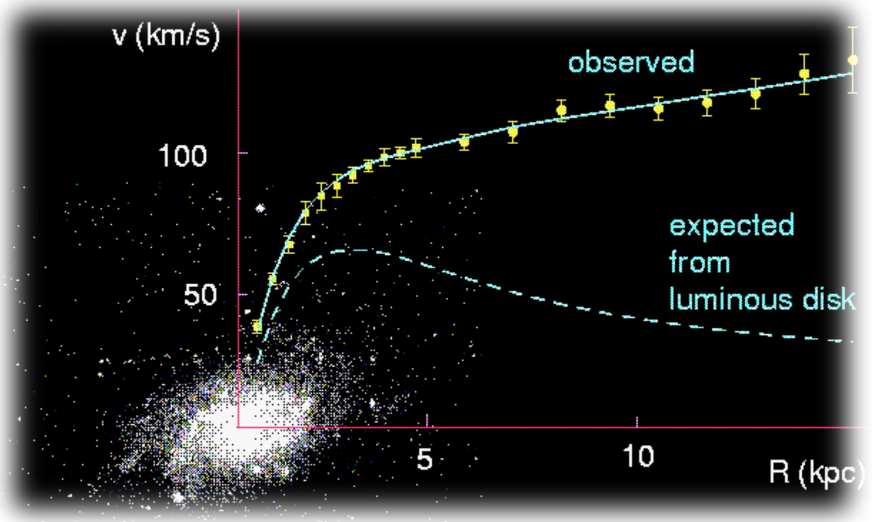
The SM and... the rest of the Universe

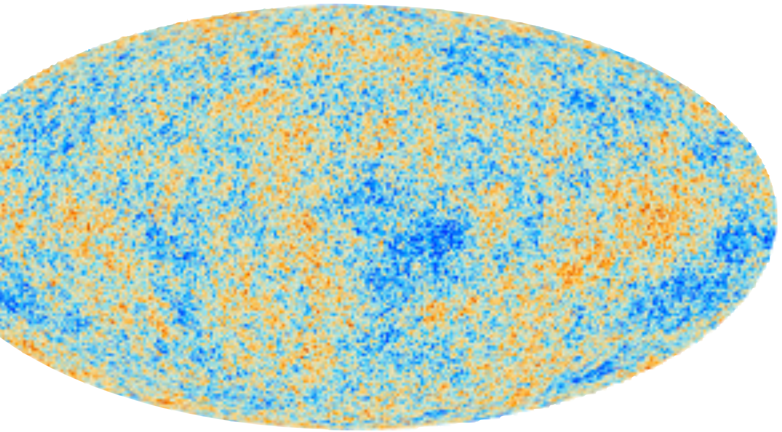


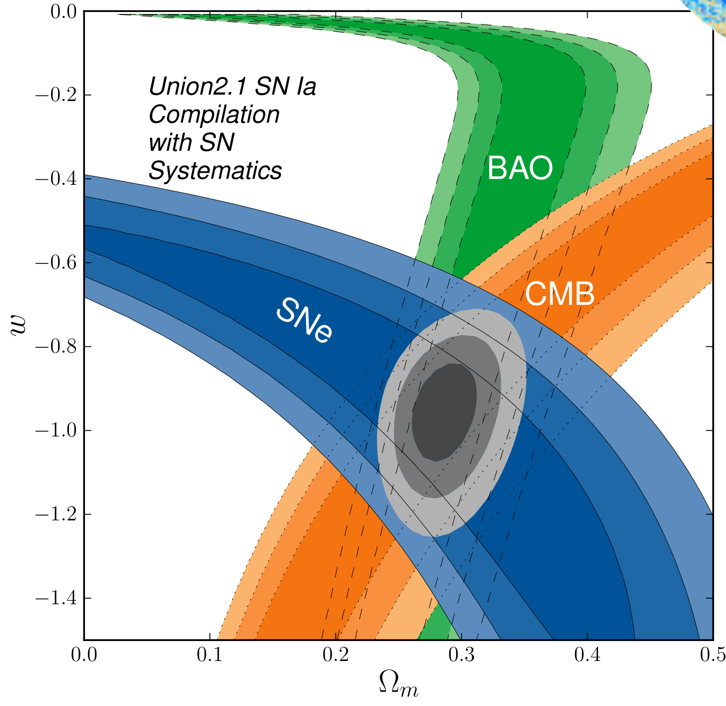
is not enough

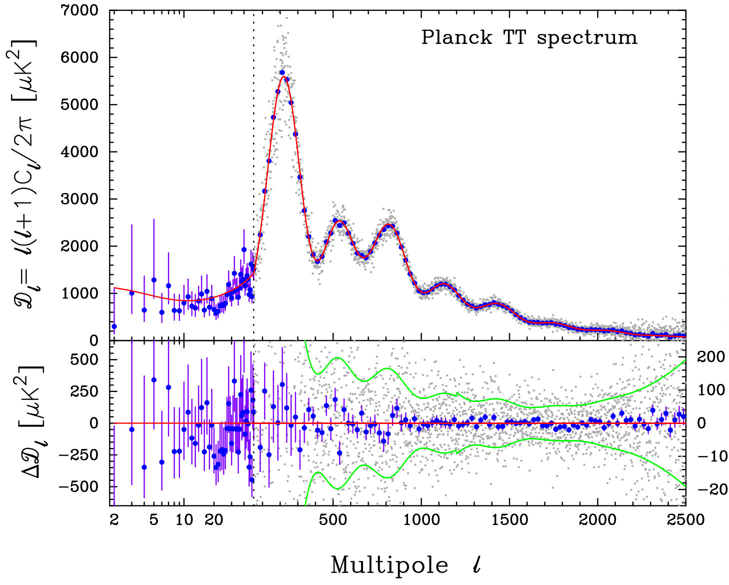
[and we all have to return our royalties!]

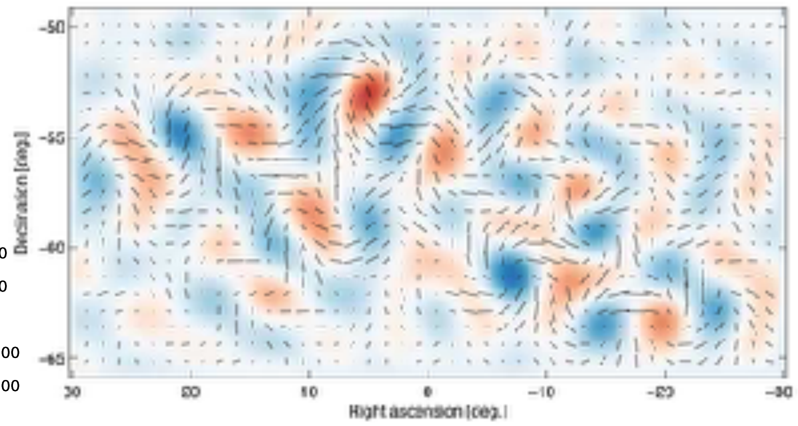
- neutrino masses
- matter-antimatter aymmetry
- Dark Matter
- Dark Energy
- Quantum gravity









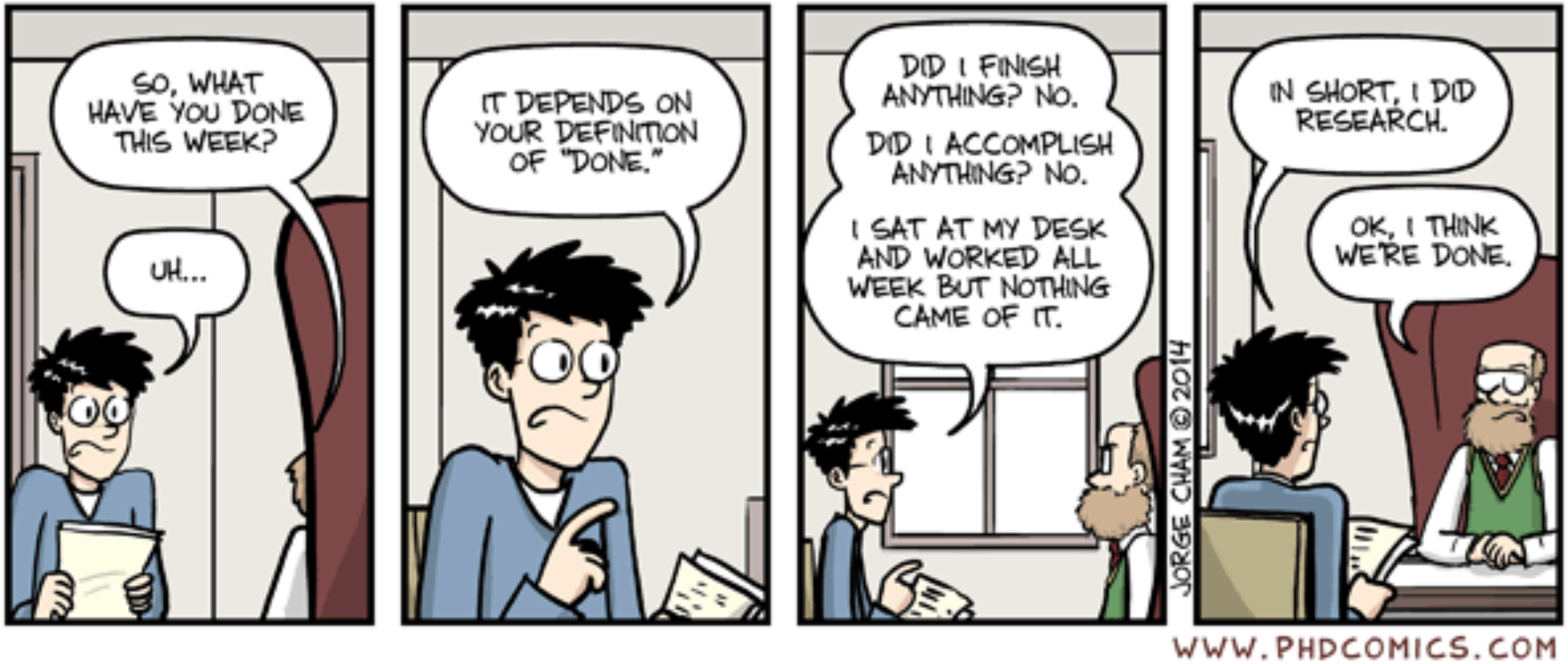


Outline

- Monday
  - General introduction
  - What kind of physics can be probed at colliders?
  - Higgs physics as a door to BSM
- Tuesday
  - Naturalness
  - Supersymmetry
  - Grand unification, proton decay
- Wednesday
  - Composite Higgs
  - Extra dimensions
  - Quantum gravity
- Thursday
  - Cosmological relaxation
  - Beyond colliders searches for new physics

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
- Undergraduate level
  - CERN summer student lectures...
- Technical accounts
  - "Journeys beyond the Standard Model" by P. Ramond CERN library link
  - Many lecture notes, e.g. TASI (@Inspire: "t TASI")

From the size of the e⁻ to anti-matter

an electron makes an electric field which carries an energy

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

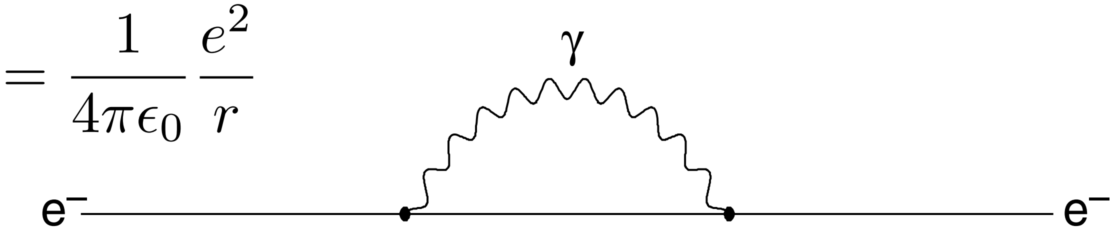
and interacts back to the electron and contributes to its mass $\delta m c^2 = \Delta E$

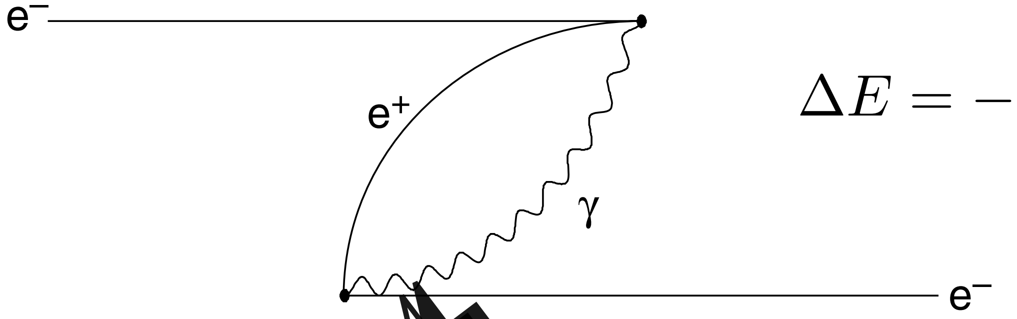
$$\delta m < m_e \quad \Rightarrow \quad r > r_e \equiv \frac{e^2}{4\pi\epsilon_0 m_e c^2} \sim 10^{-13}\ \text{m} \quad \text{i.e.} \quad E < \frac{\hbar c}{r_e} \sim 5\,\text{MeV}$$

At shortest distances or larger energies, classical EM breaks down

Quantum EM

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





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

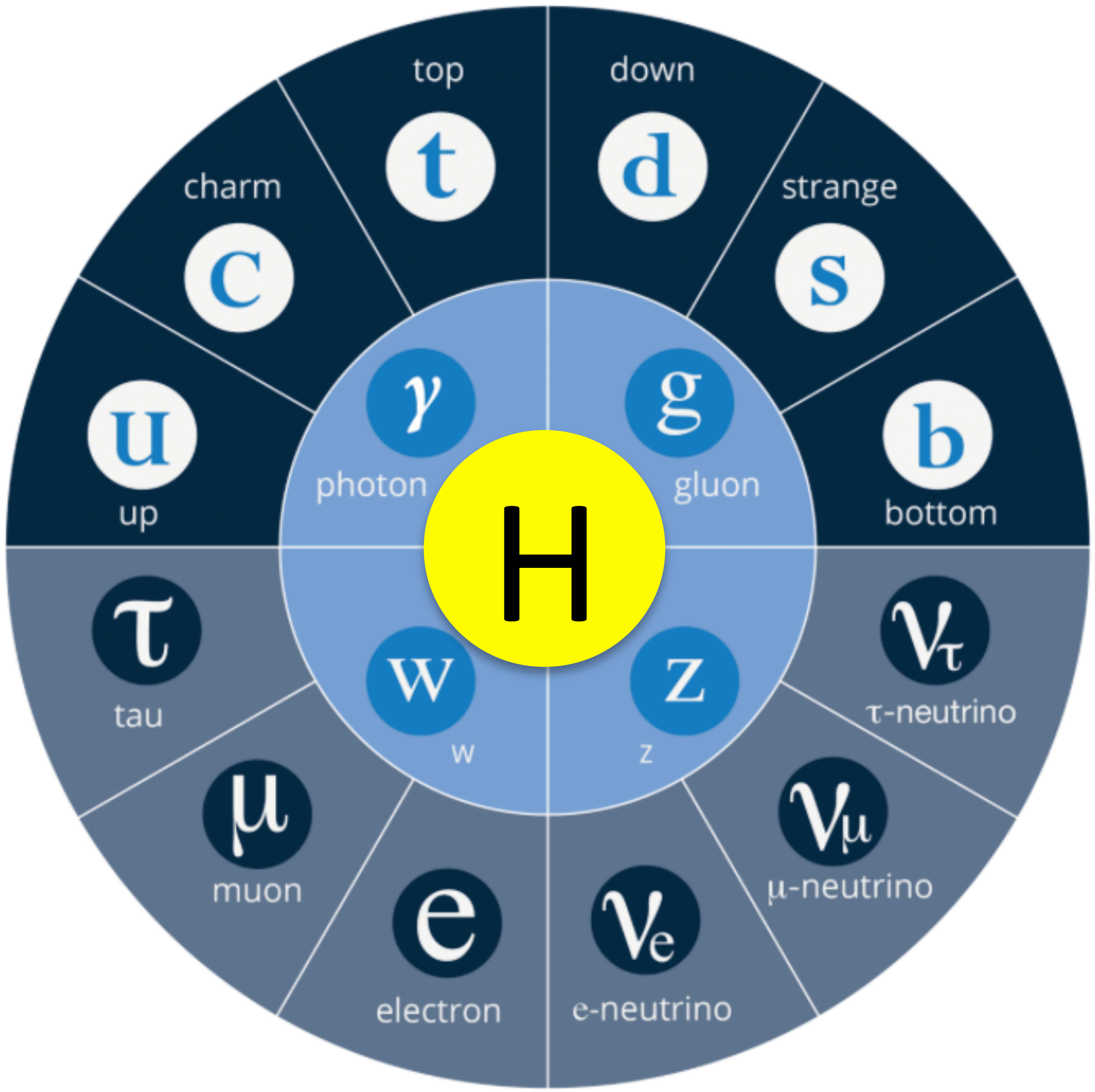
$$\Delta E = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{r m_e c}$$

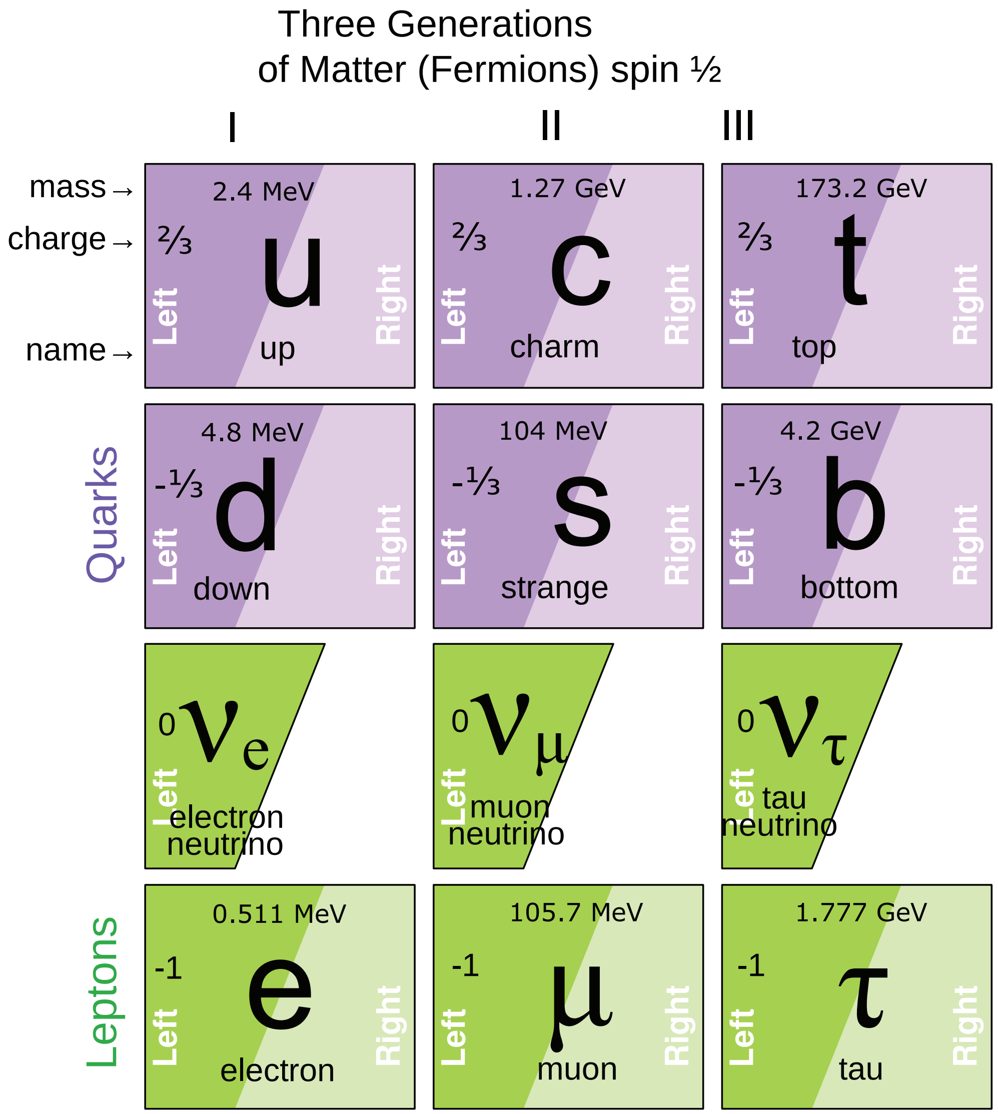
Weisskopf '39

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?~~





Three Generations
of Matter (Fermions) spin ½

		I	II	III
Quarks	mass → charge → name →	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	173.2 GeV ⅔ t top Left Right
		4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right
Leptons		0 ν_e electron neutrino Left	0 ν_μ muon neutrino Left	0 ν_τ tau neutrino Left
		0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

The Standard Model: Matter

~~How many quarks and leptons?~~

6+6=12?

6x3+6=24?

shouldn't we count different color states?

6x3x2+3x2+3=45?

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

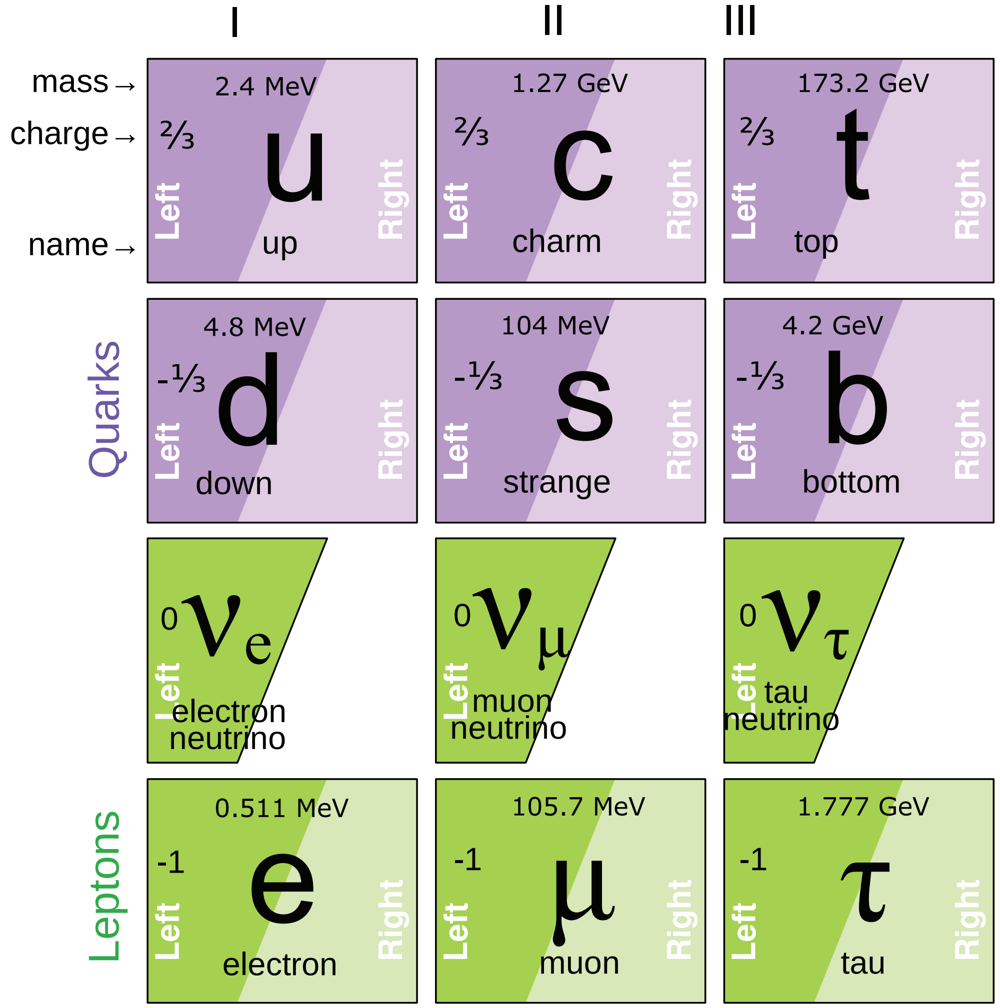
SM is a chiral theory: $e_L \neq e_R$

6x3x2+6x2=48?

are there ν_R?

are they part of the SM?

Three Generations
of Matter (Fermions) spin ½



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The Standard Model: Matter

~~How many quarks and leptons?~~

~~Is the SM theoretically consistent?~~

SM = theory based on (chiral) gauge symmetries
a symmetry is consistent with QM
iff the “sum” of the charges of the different fermions vanishes

Exercise 1: within the SM, check that
(1) $\mathrm{Tr}_L Y - \mathrm{Tr}_R Y = 0$
(2) $\mathrm{Tr}_L Y^3 - \mathrm{Tr}_R Y^3 = 0$
note that this was a priori no-guarantee to find a solution to this system of non-linear equations.
It works because EM is a vector-like theory

$$Q = T_L^3 - Y$$

Particles	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_L^i = \begin{cases} N^i = (\nu^i, \tilde{\nu}^i) \\ E_L^i = (l_L^i, \tilde{l}_L^i) \end{cases}$	1	2	1/2
$E^i = (CP(l_R^i), CP(\tilde{l}_R^i))$	1	1	-1
$Q_L^i = \begin{cases} U_L^i = (u_L^i, \tilde{u}_L^i) \\ D_L^i = (d_L^i, \tilde{d}_L^i) \end{cases}$	3	2	$-1/6$
$U_R^i = (CP(u_R^i), CP(\tilde{u}_R^i))$	$\bar{3}$	1	2/3
$D_R^i = (CP(d_R^i), CP(\tilde{d}_R^i))$	$\bar{3}$	1	$-1/3$

Exercise 2: Within the SM, the anomaly cancelation fixes the relative electric charges of the leptons and quarks. Show that with the addition of a right-handed neutrino, this ratio of electric charges is free. Still the cancelation of the anomaly imposes that the proton is electrically neutral

The Standard Model: Matter

~~The particles seen in a detector~~

Absolutely stable particles	Collider stable particles	Sort of stable particles	Displaced vertex particles
γ (m=0) (G (m=0)) (ν (m~0)) e^- (m=511keV) p (m=938MeV)	n (m=940MeV, ct=10^{14}mm) μ (m=940MeV, ct=10^{6}mm) K_L (m=500MeV, ct=10^{4}mm) $\pi^\pm$ (m=140MeV, ct=10^{4}mm) $K^\pm$ (m=500MeV, ct=10^{3}mm)	Ξ, Λ, Σ, Ω (m=1-2GeV, ct=10-100mm) K_S (m=500MeV, ct=30mm)	B, D $\Xi_{c,b}$, $\Lambda_{c,b}$ (m=2-5GeV, ct=0.1-0.5mm)

You don’t “see” most of the SM particles!
You have to infer their existence

Test: have you ever seen dinosaurs? You “reconstruct” from their decay products

Physics probed at Colliders

Colliders are best places to search for

Heavy objects

With short lifetime

That are rarely produced

That have a direct coupling to quarks/gluons or electrons

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions
Nonetheless there are compelling arguments that BSM can be seen at colliders

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

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

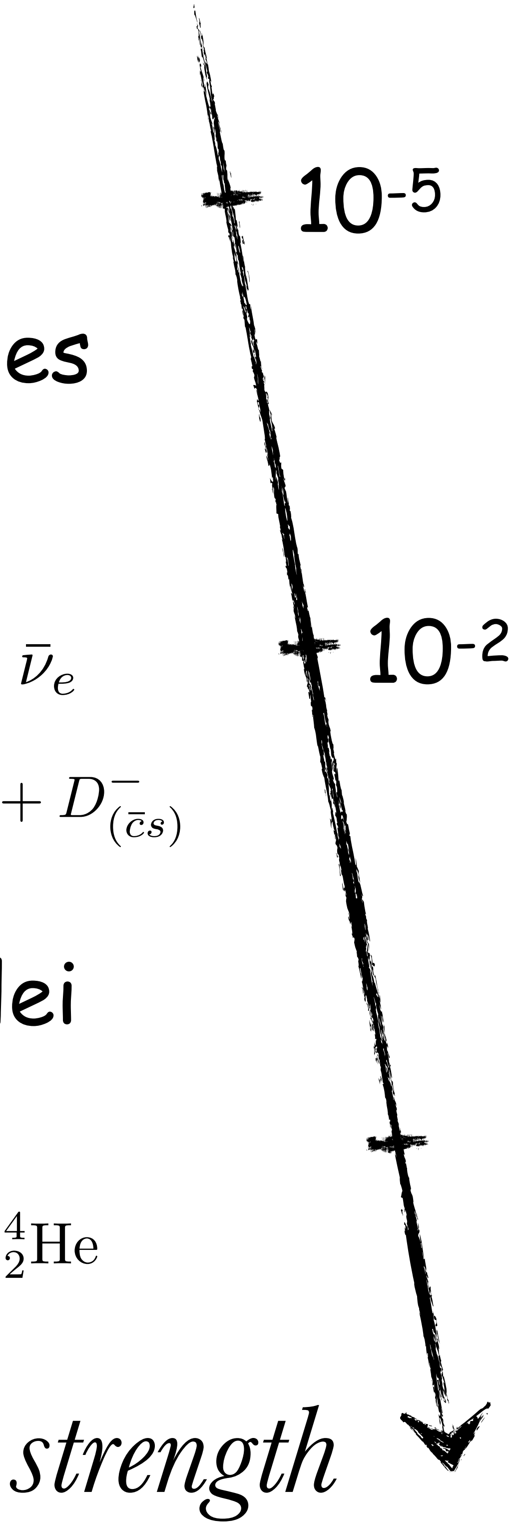
  $e^+ + e^- \xrightarrow{Z^0} D^+_{(c\bar{s})} + D^-_{(\bar{c}s)}$

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

  gluons g^a

  atomic nuclei
  α decay

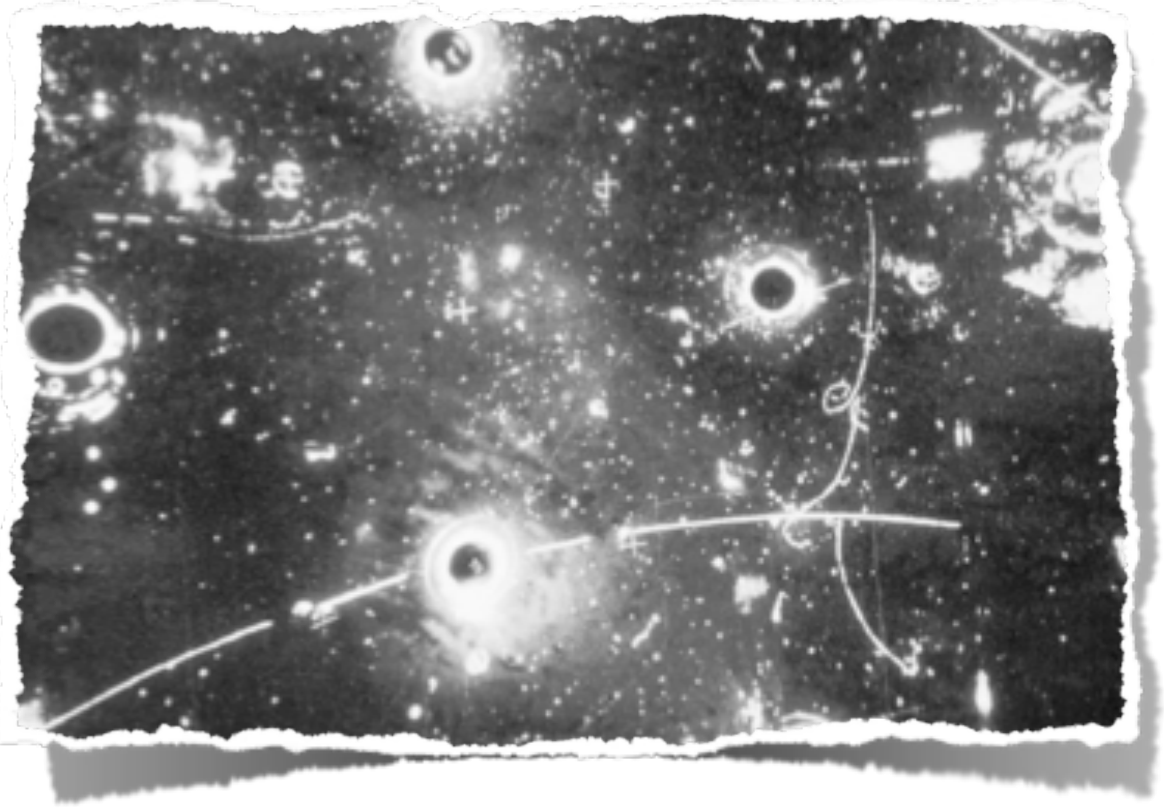
  ${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$



The Standard Model

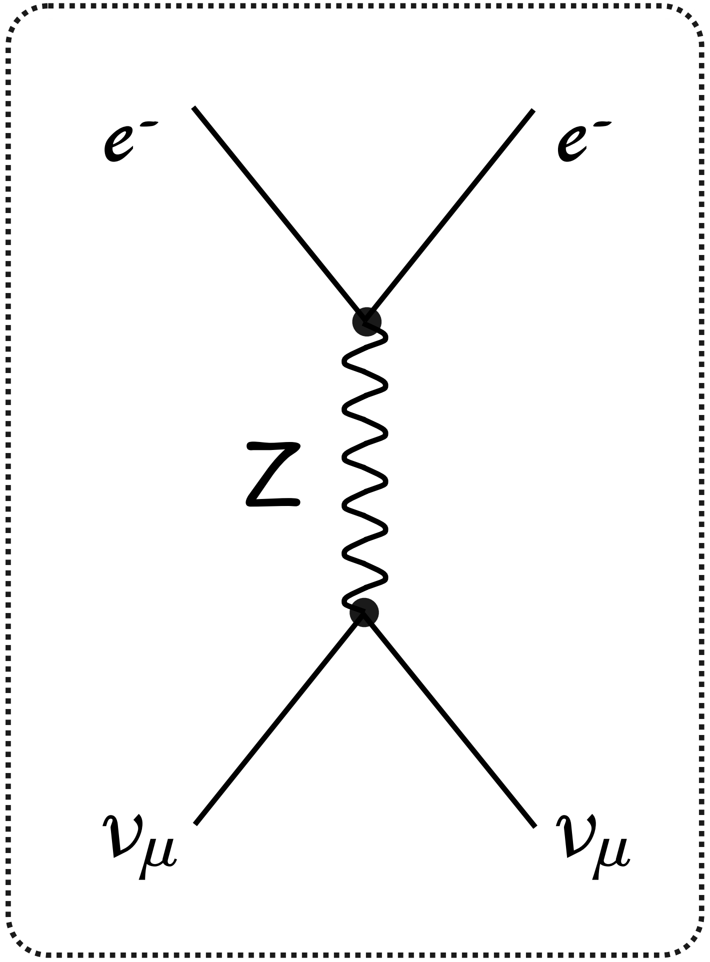
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

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



[Gargamelle collaboration, '73]

$\nu_\mu\, e^- \rightarrow \nu_\mu\, e^-$

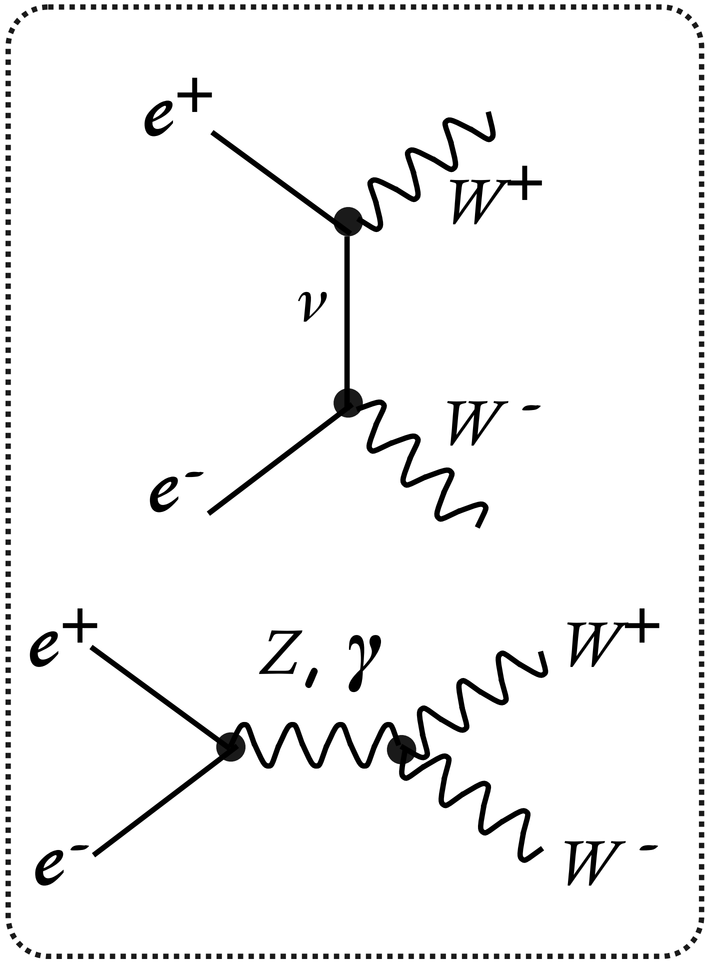


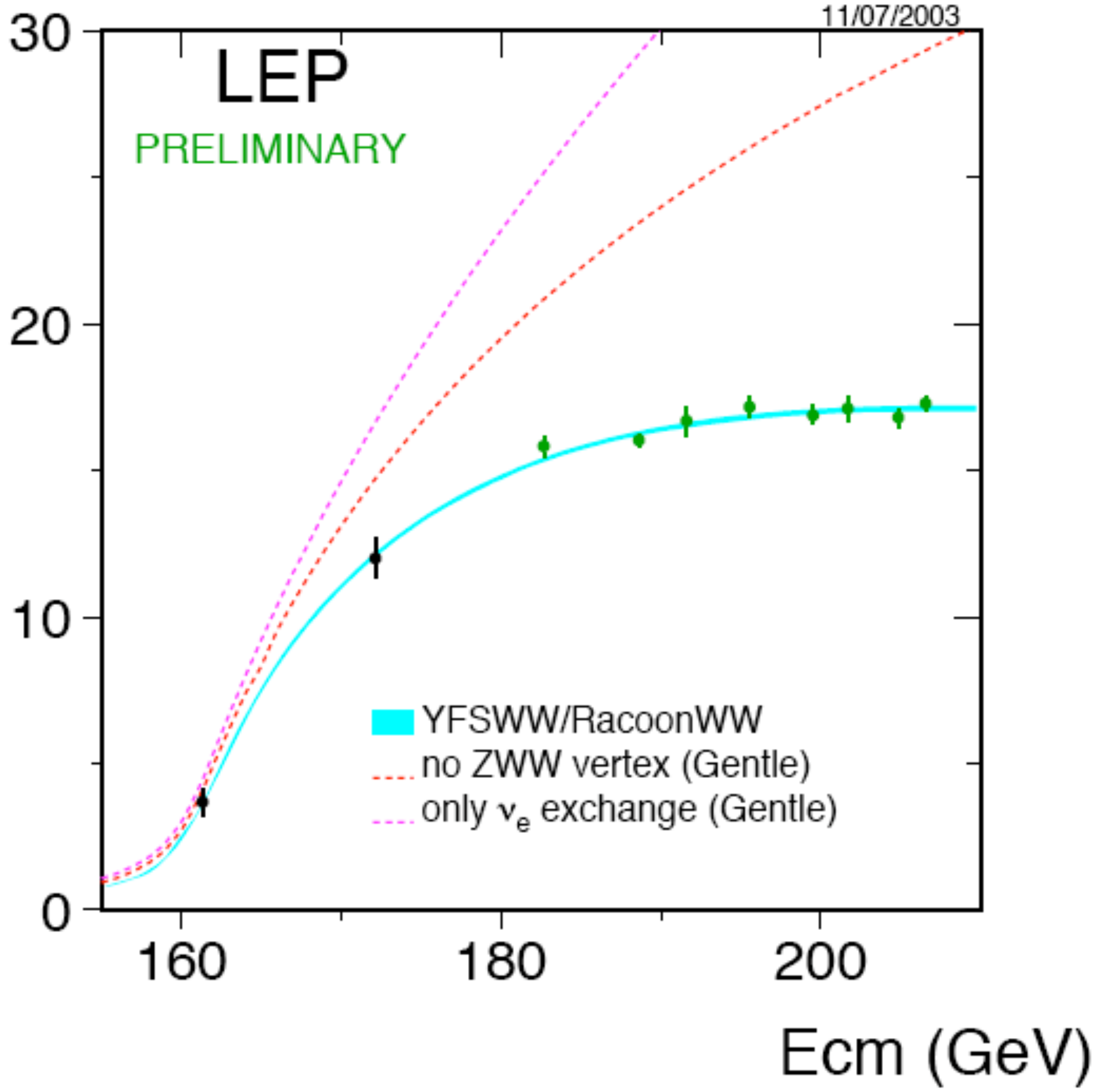
Gauge Theory as a Dynamical Principle

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

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

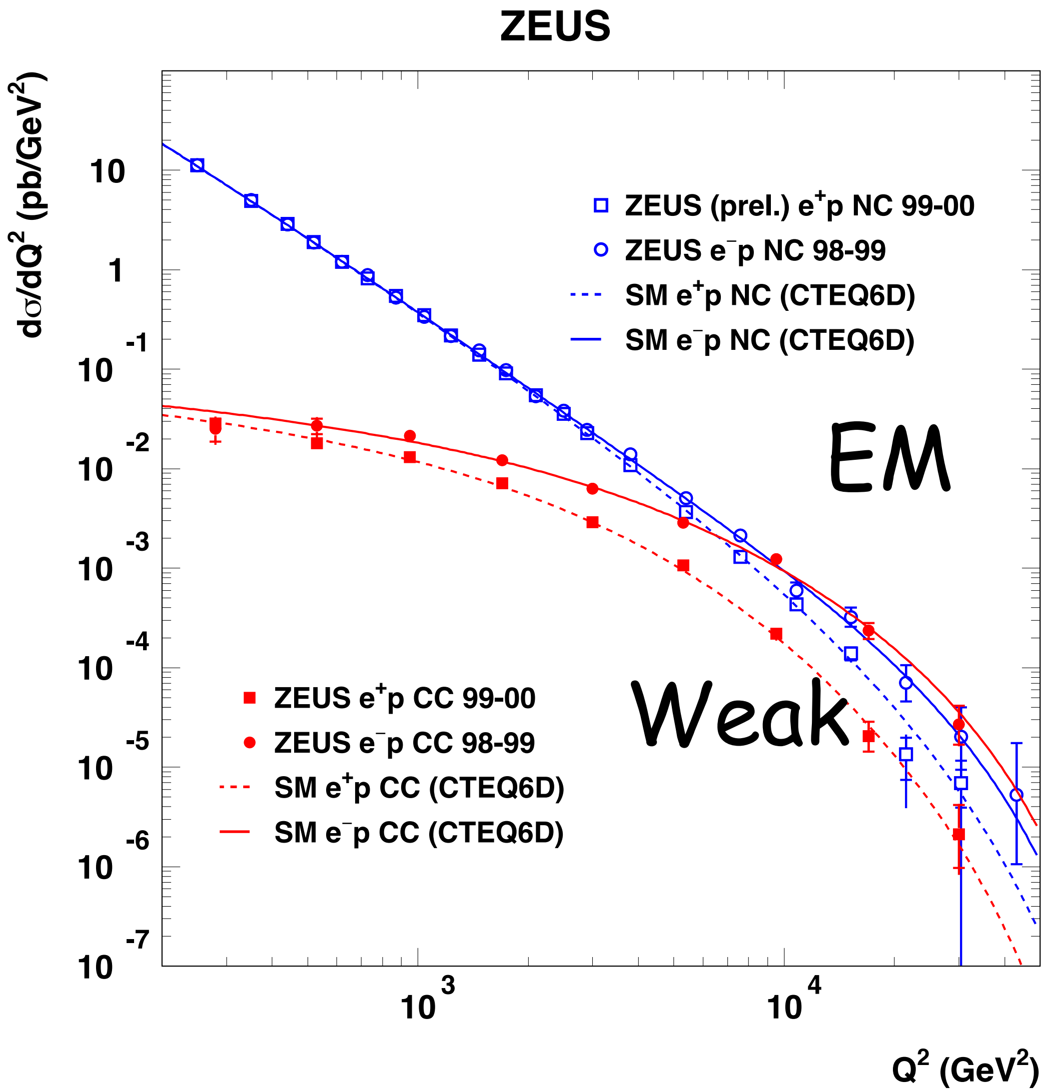
the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- ☐ $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ 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 $\delta A_\mu^a = \partial_\mu \epsilon^a + g f^{abc} A_\mu^b \epsilon^c$

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

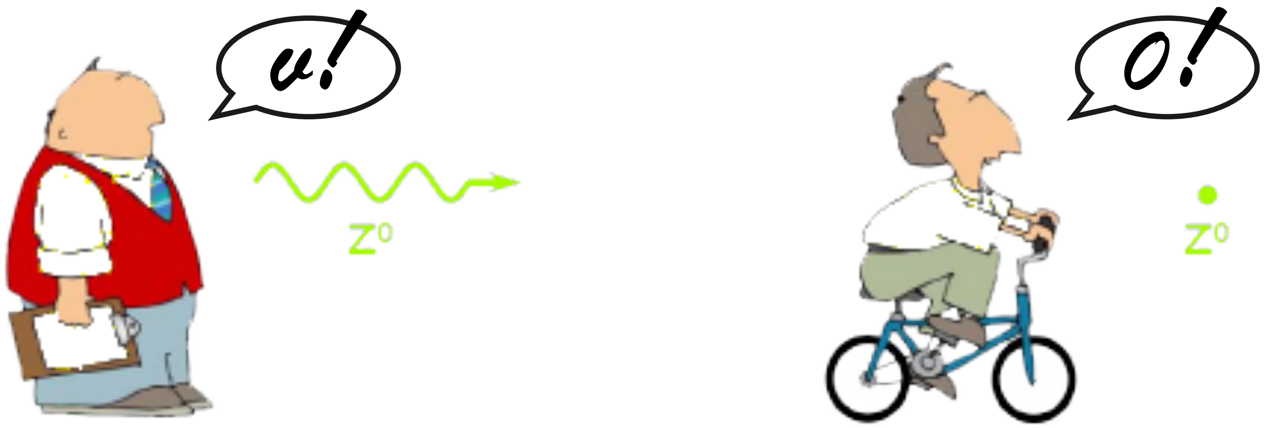
Weak forces ≈ short range

$$m_\gamma < 6 \times 10^{-17}\ \text{eV}$$
$$m_{W^\pm} = 80.425 \pm 0.038\ \text{GeV}$$
$$m_{Z^0} = 91.1876 \pm 0.0021\ \text{GeV}$$

Exercise 3:
What is the density of photons in the Universe?
What is the density of W in the Universe?

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

FOR THE EXPERTS

Indeed a massive spin 1 particle has 3 physical polarizations:

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

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

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

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

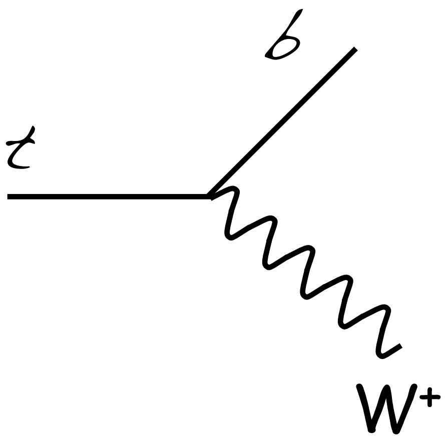
- 2 transverse: $\left\{ \begin{array}{l} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{array} \right.$
- 1 longitudinal: $\epsilon_\parallel^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

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

in the particle rest-frame, no distinction between L and T polarizations
in a frame where the particle carries a lot of kinetic energy, the L polarization "dominates"

The BEH mechanism: "V_L=Goldstone bosons"

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



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

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

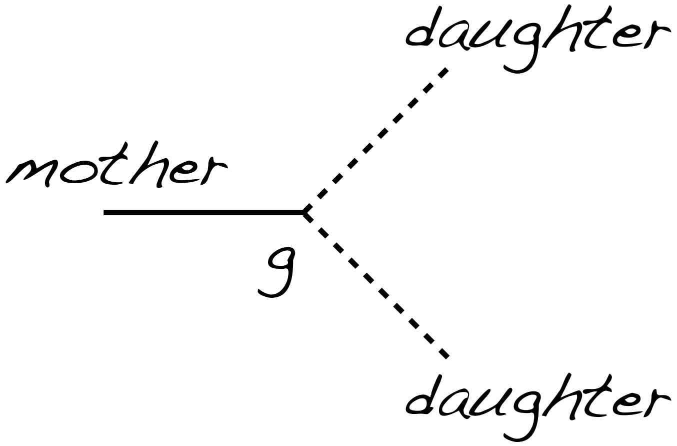
- at threshold (m

dominates the decay

Goldstone equivalence theorem
$W^\pm_L$, Z_L ≈ SO(4)/SO(3)

At high energy, the dominant degrees of freedom are W_L

~~ 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 get energy from the mother particle $\tau \ll \tau_{\rm naive}$

This is the physics that was understood at LEP
The pending question was then: is there something else?
That was the job of the LHC

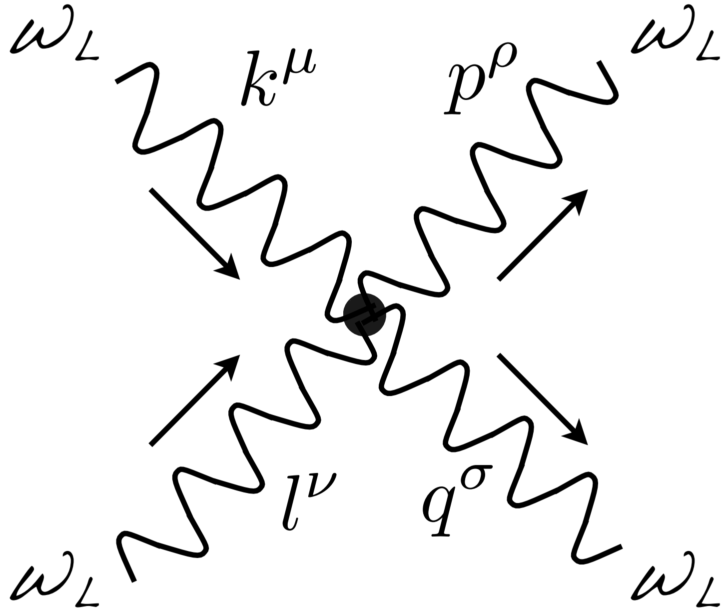
Call for extra degrees of freedom

NO LOSE THEOREM

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

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

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



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

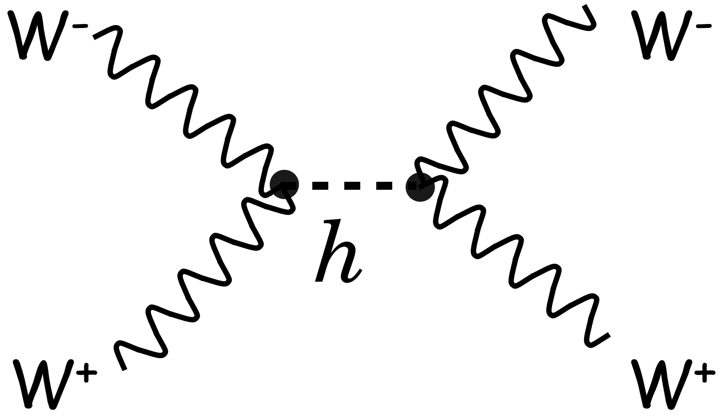
numerically: E ~ 3 TeV ⬅ the LHC was sure to discover something!

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 Higgs the name of?

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

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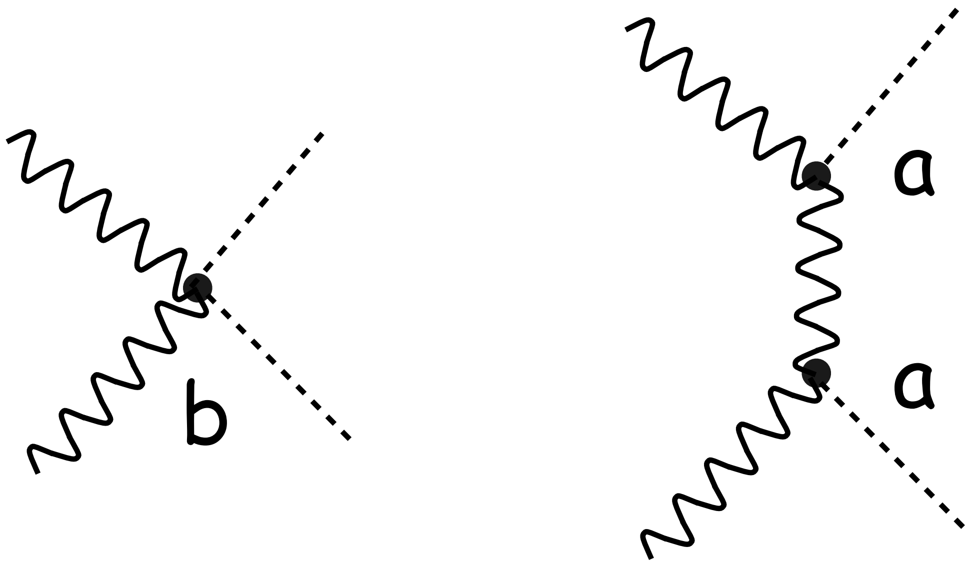
'a', 'b' and 'c' are arbitrary free couplings

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 ac=1: perturbative unitarity in inelastic WW → $\psi\ \psi$

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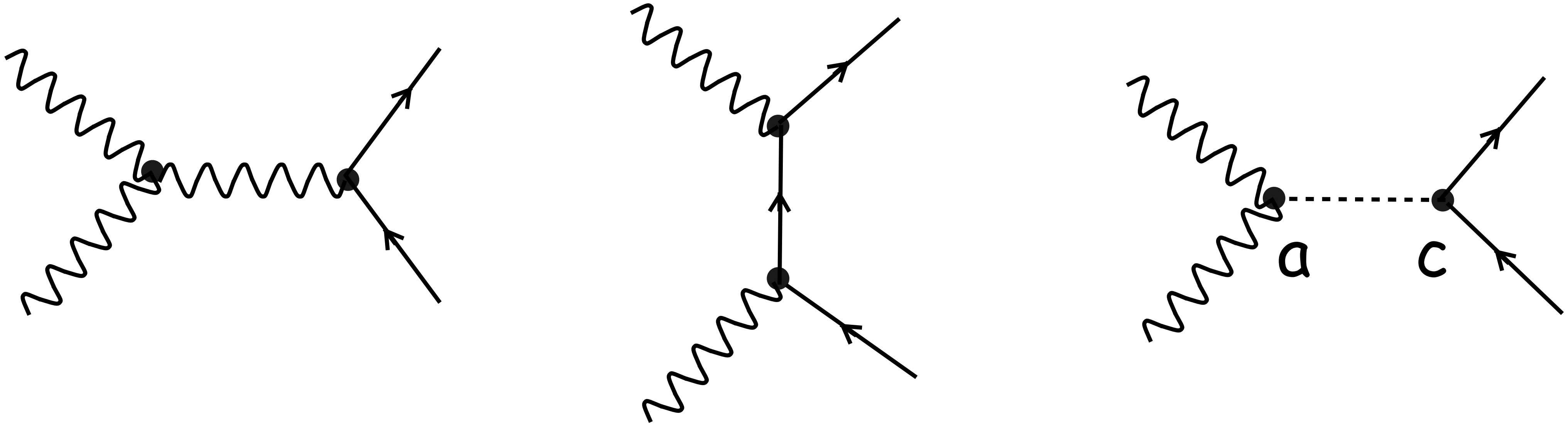

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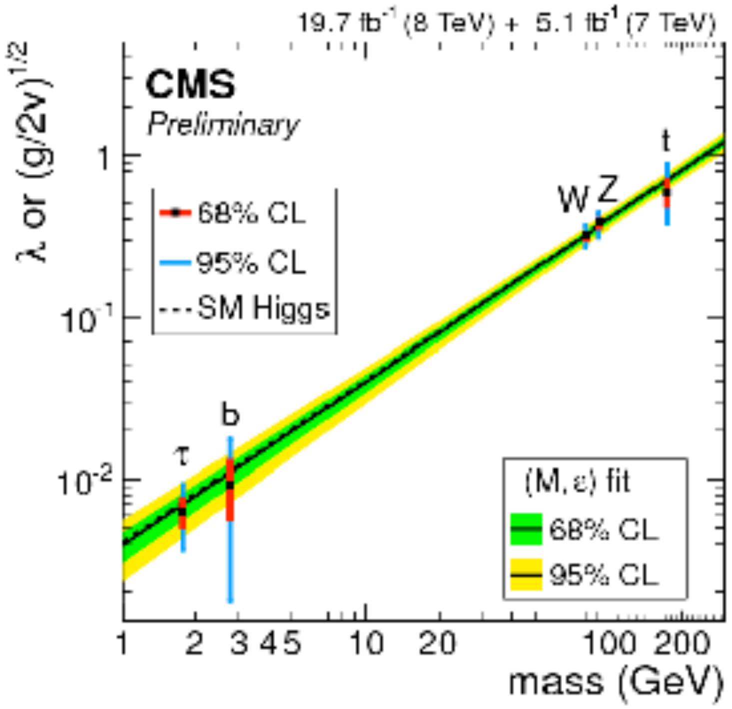


CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

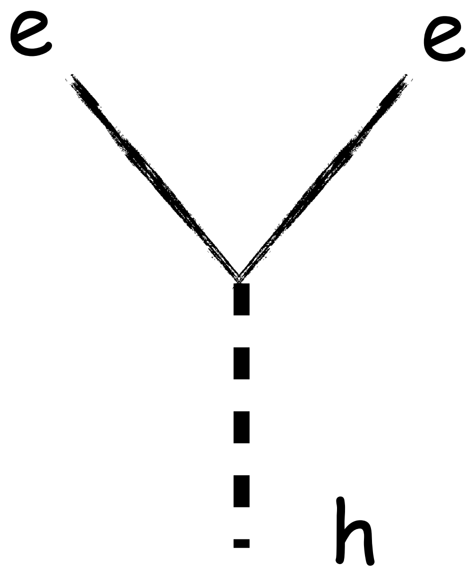
$$\lambda_\psi \propto \frac{m_\psi}{v}, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

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

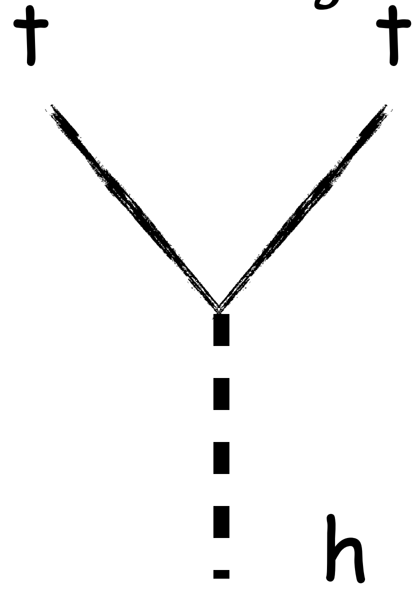
NB: the proton is not an elementary particle,
its mass doesn't measure its interaction with the Higgs substance

From electrons



probability ~ 10^{-11}

From top quarks



probability ~ 1

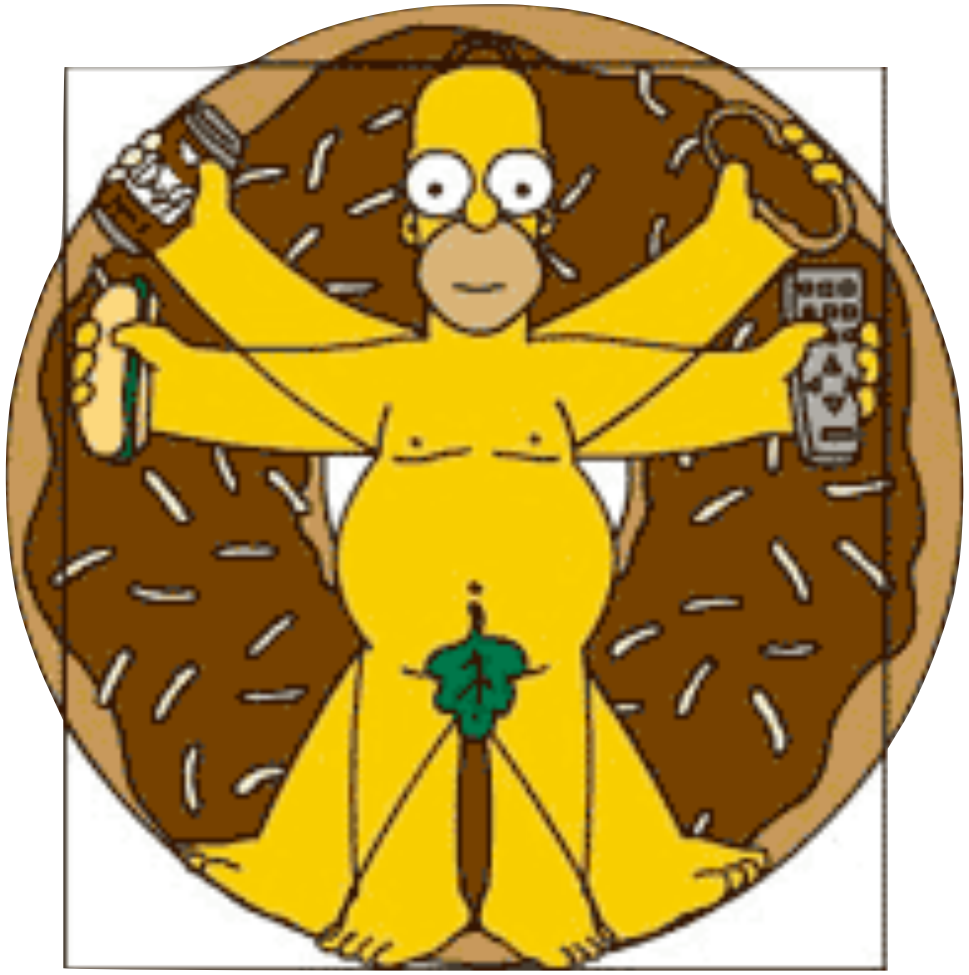
but no top quark at our disposal

Higgs boson at the LHC

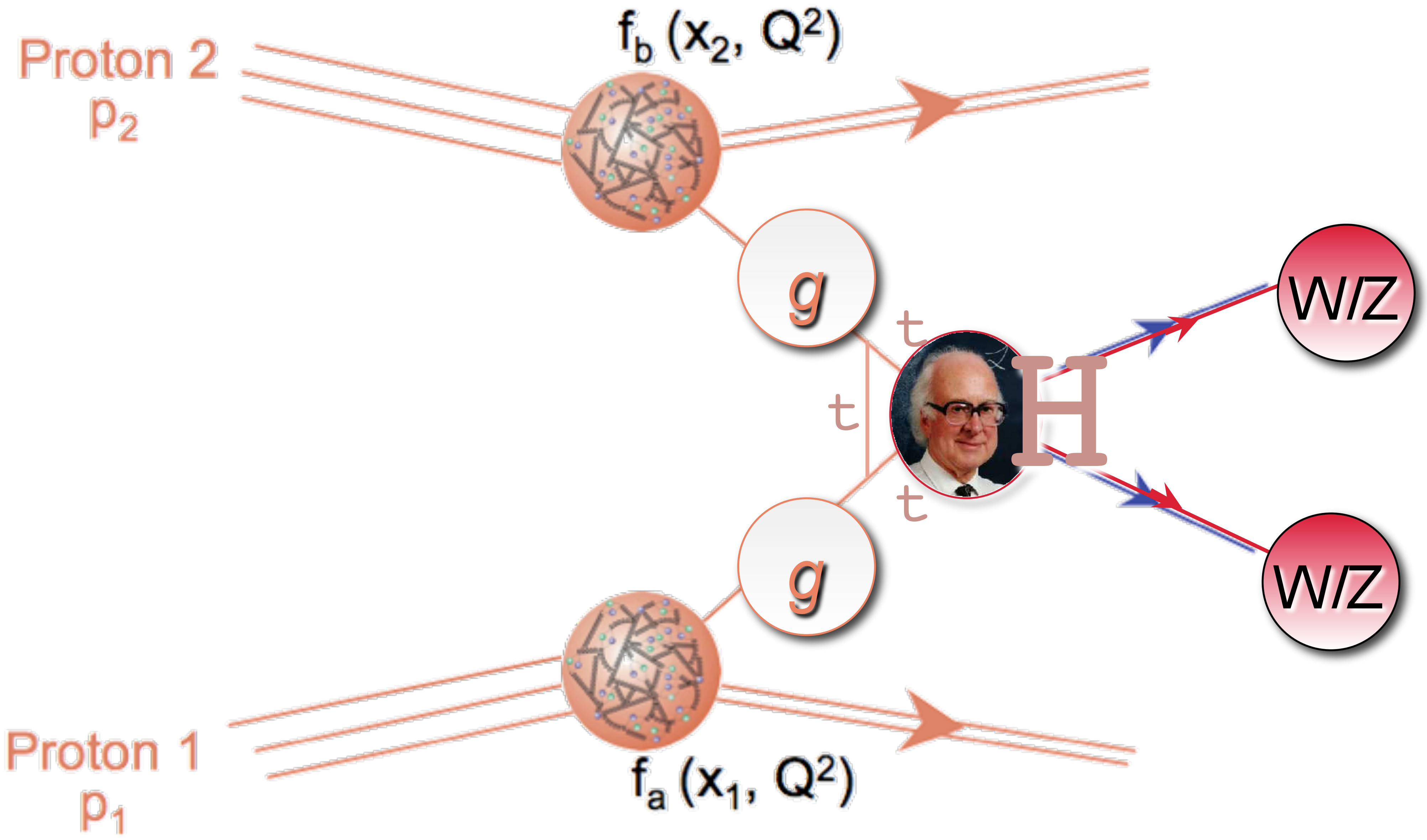
Difficult task

Homer Simpson's principle of life:

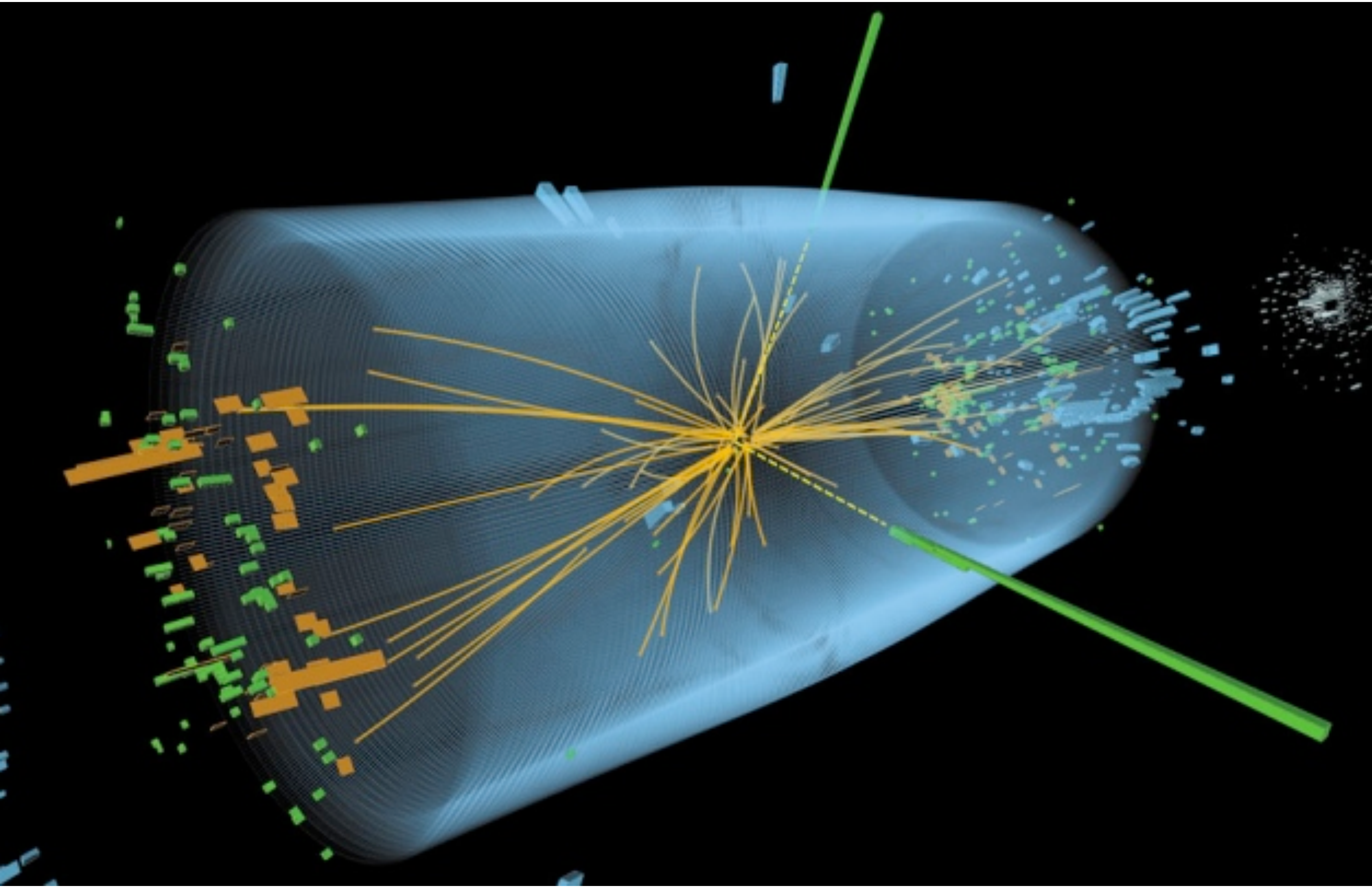
If something's hard to do, is it worth doing?



Higgs boson at the LHC



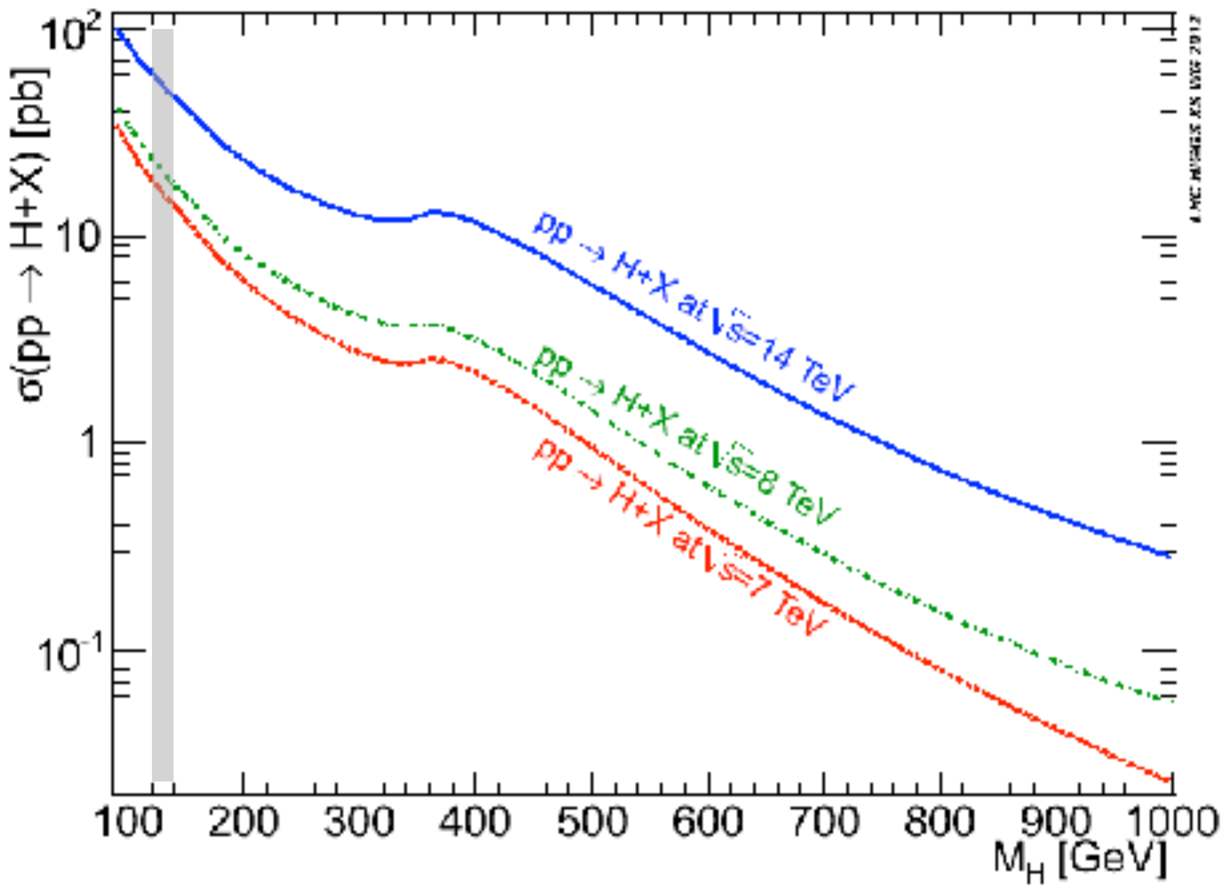
Higgs boson at the LHC



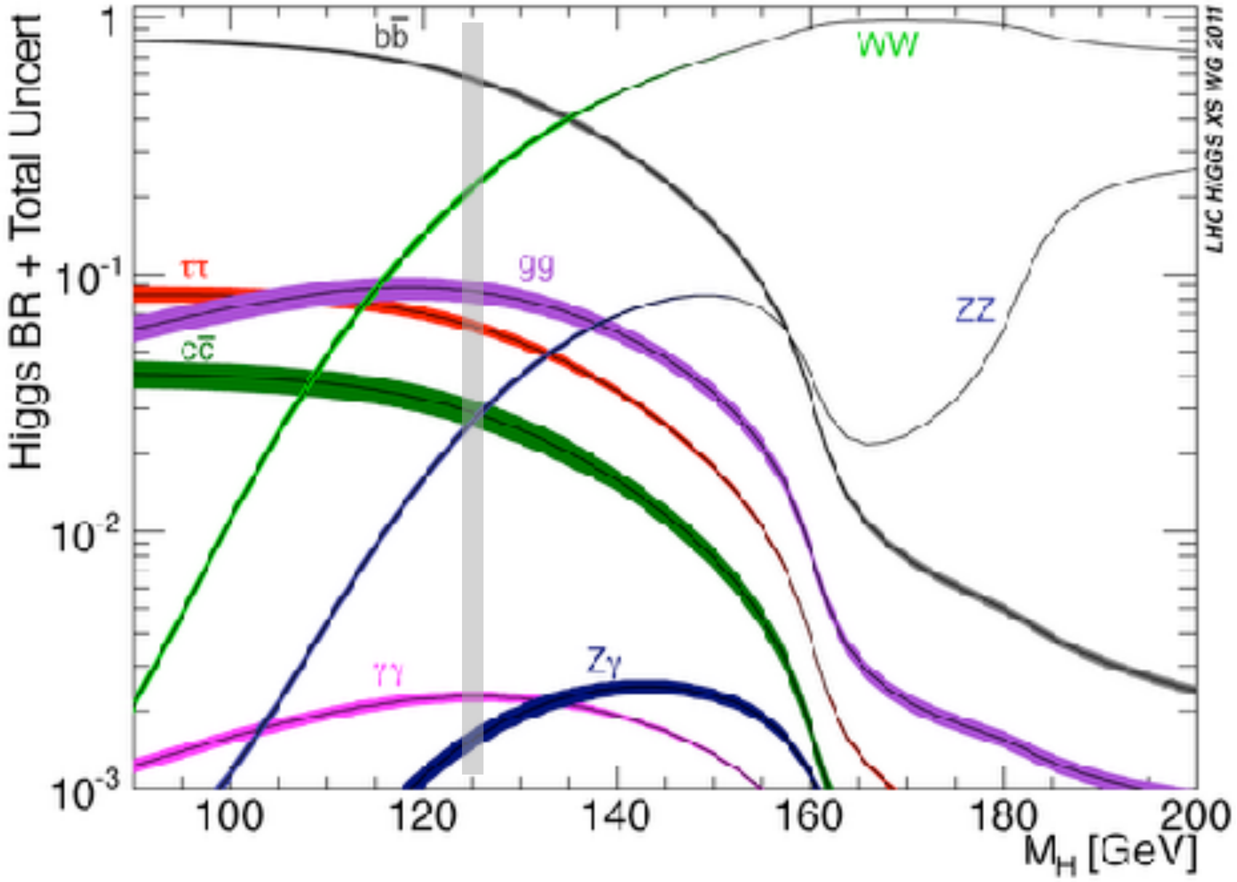
Higgs boson at the LHC

$\sigma \sim 10$ pb ⇔ 10^6 events for L=100 fb^{-1}

Higgs production



Higgs decay

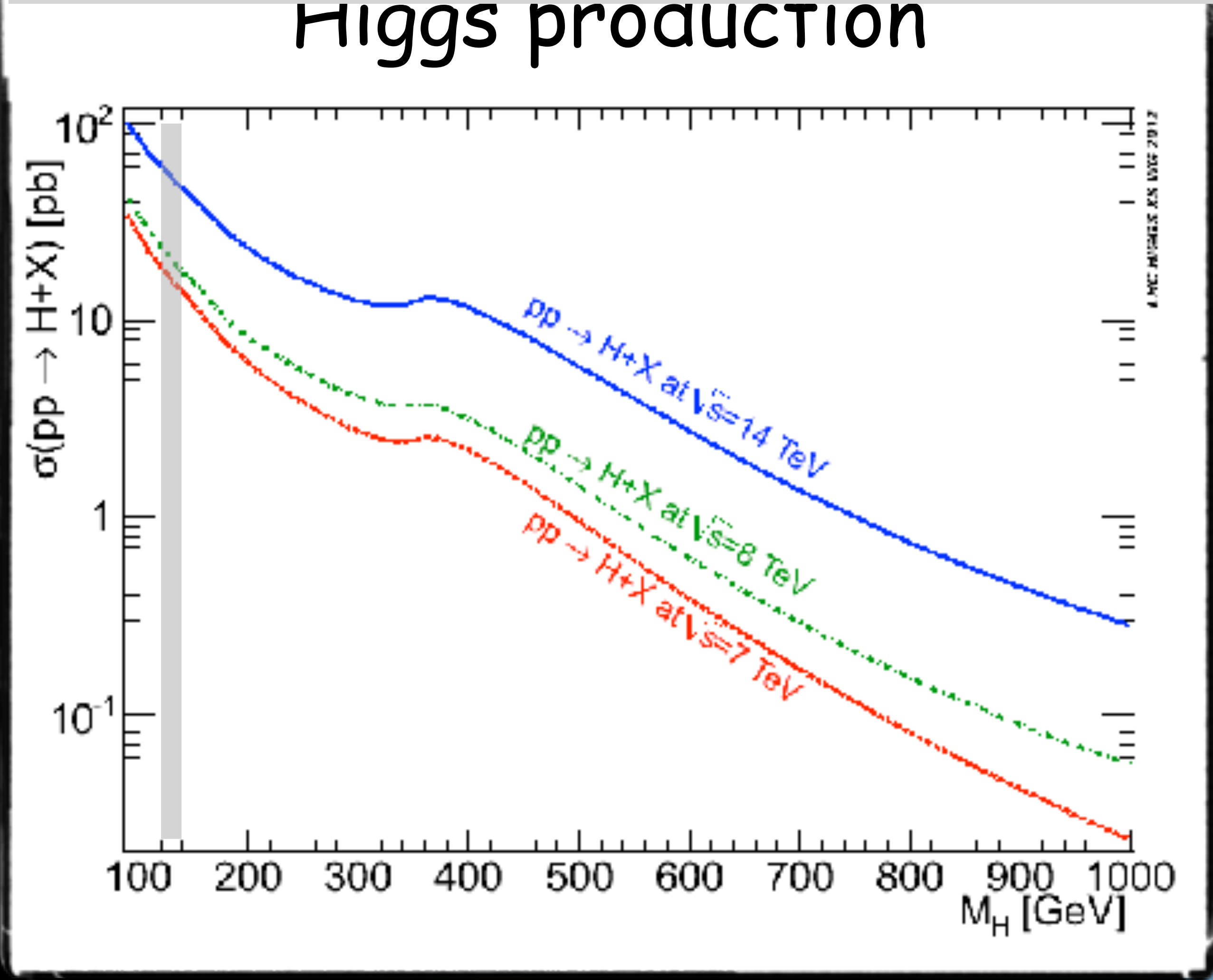


The LHC has produced 10^6 Higgs bosons out of 10^{17} pp collisions

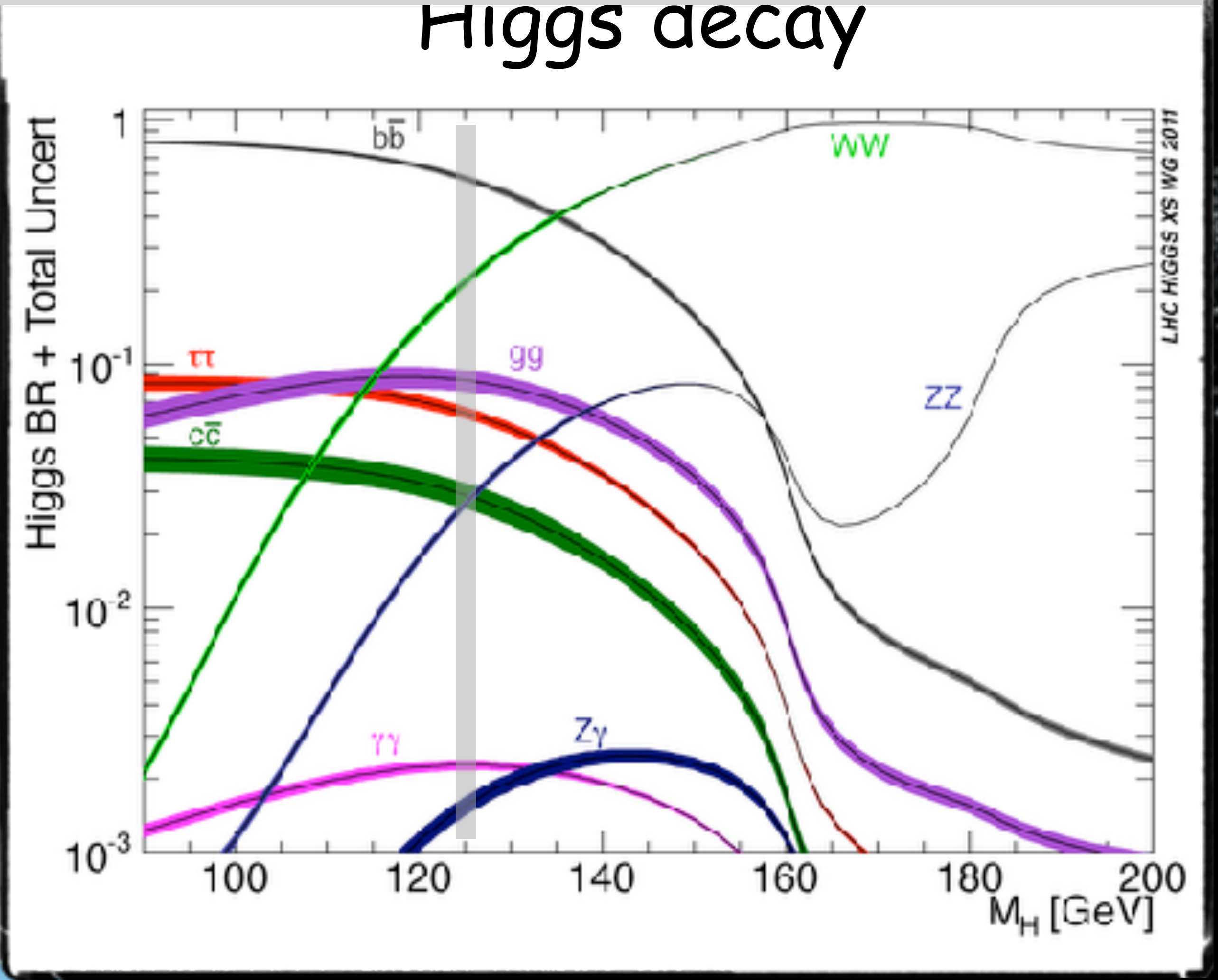
Higgs boson at the LHC

Exercise 4: The instantaneous luminosity is 10^{34}cm^{-2}s^{-1}. The LHC beams cross every 25ns. The total cross-section in 0.1b. What is the collision rate? One collision occupies about 1MB on disk. Given that you cannot record data faster than 1GB/s, what should be the trigger rate?

Higgs production



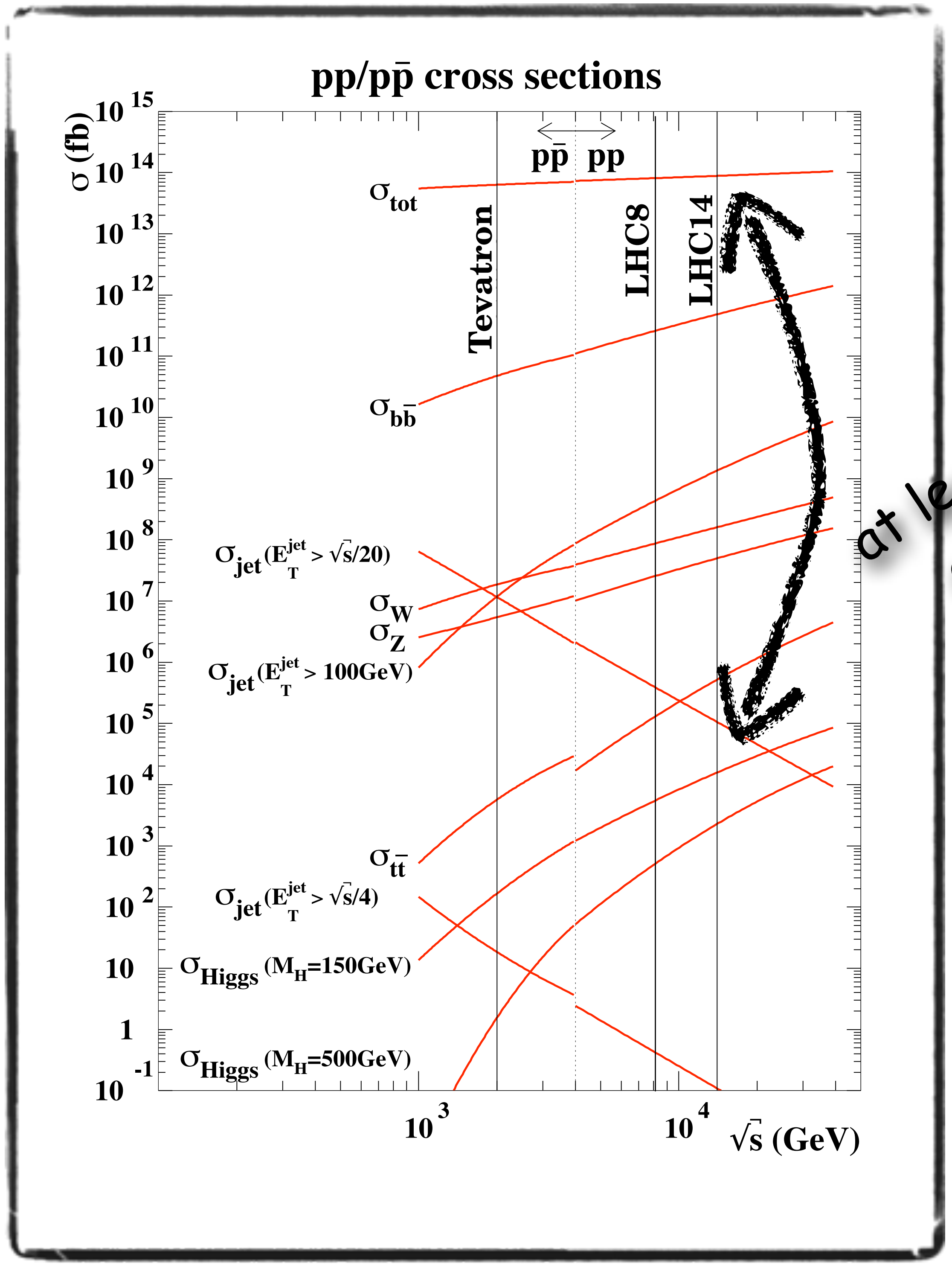
Higgs decay



The LHC has produced 10^6 Higgs bosons out of 10^{17} pp collisions

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background



at least 10 orders of magnitude

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

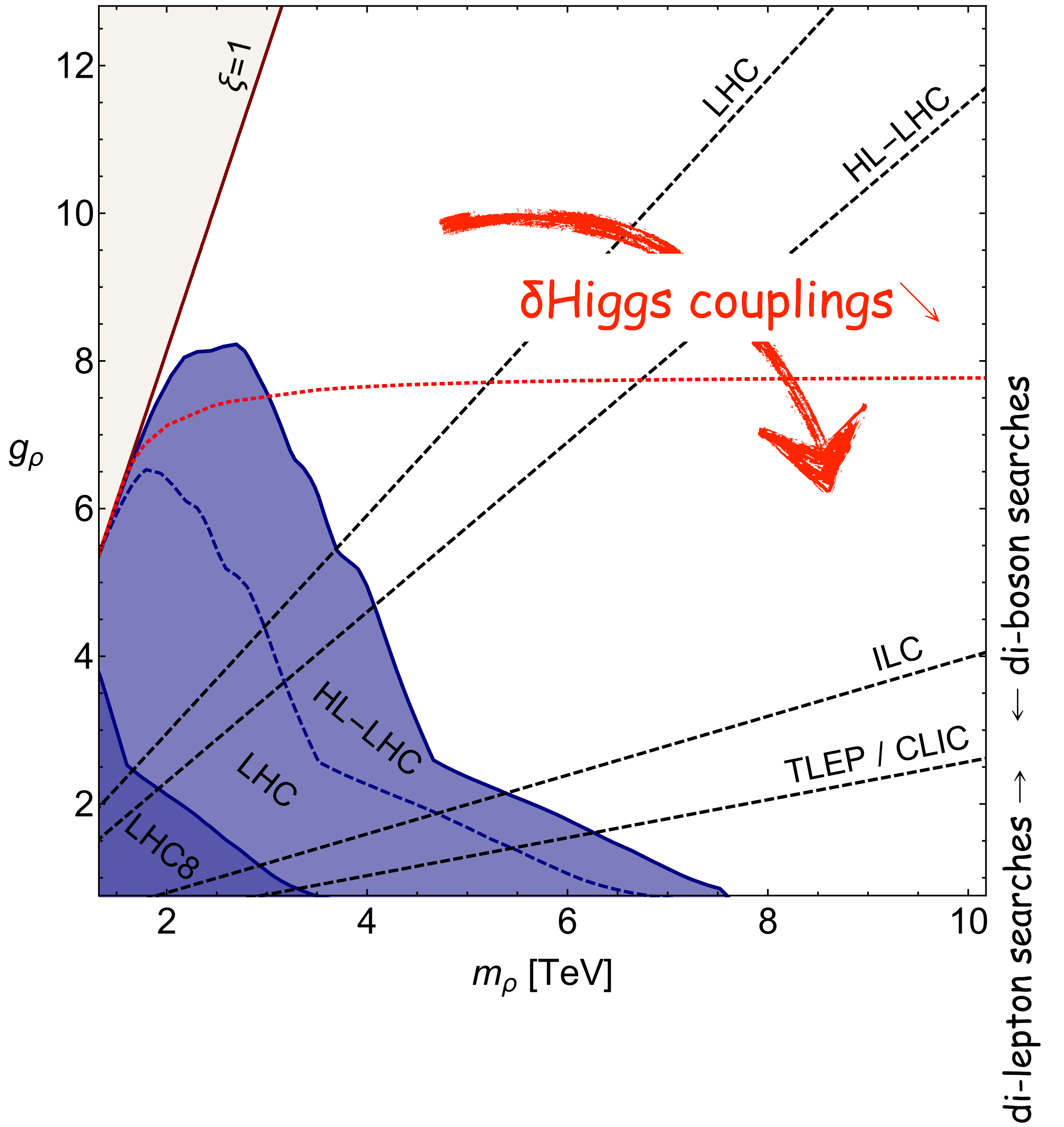
Higgs couplings = door to BSM

heavy new physics induce deformation of the Higgs couplings
(in the same way that W exchange mediate muon decay and β decay)

$$\frac{\delta g}{g} \sim \frac{g_*^2 v^2}{\Lambda_{\rm BSM}^2} \sim \left(\frac{g_*}{0.3}\right)^2 \left(\frac{1\,\rm TeV}{\Lambda}\right)^2 0.5\%$$

Higgs coupling precision measurements
are an indirect way to probe
heavy (strongly coupled) new physics
that cannot be observed directly

DY production xs of resonances decreases as $1/g_\rho^2$



Torre, Thamm, Wulzer '15