

Higgs Boson: What Have We Learned

Prof. Giacinto Piacquadio

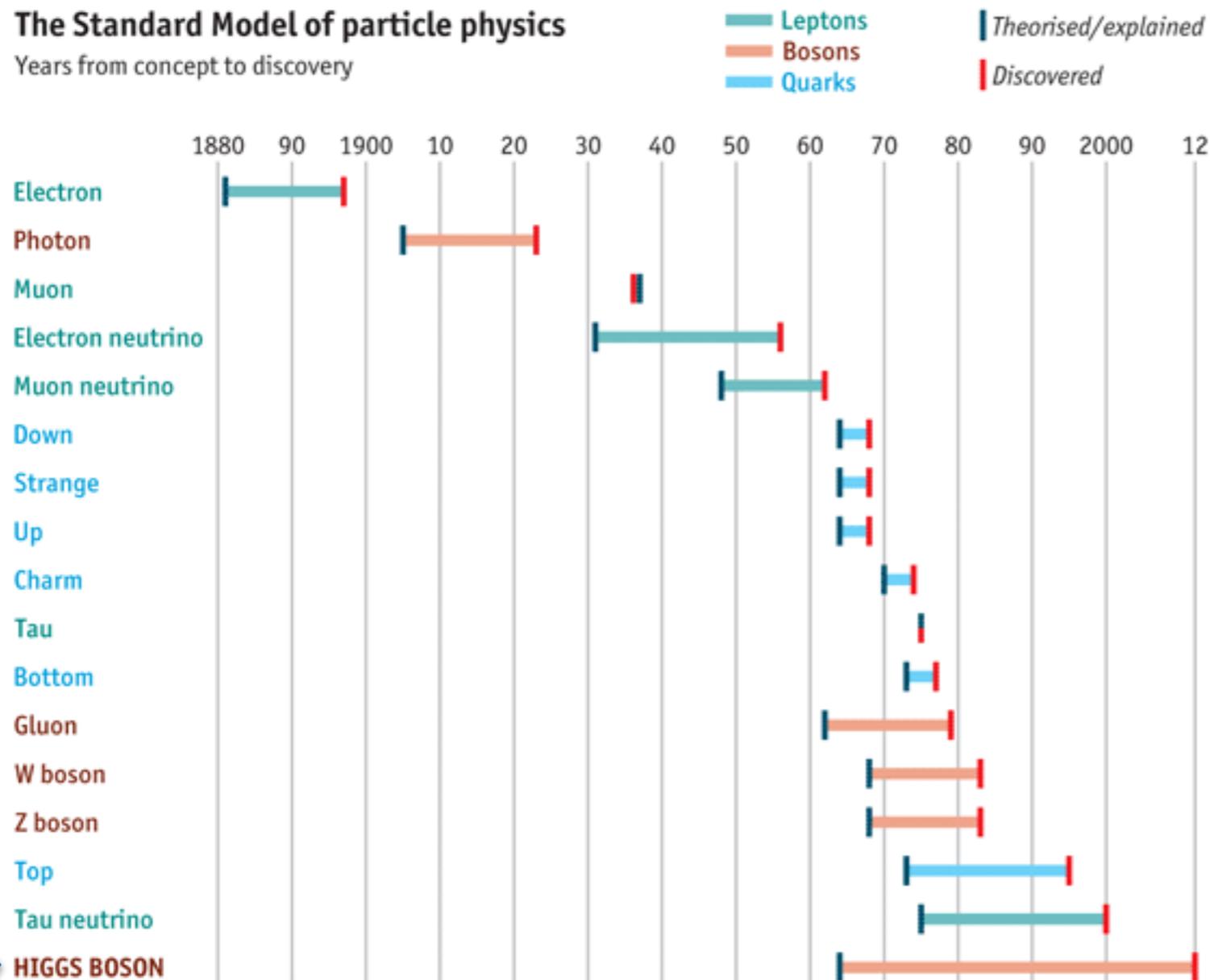
Stony Brook University

June 29th, 2022

Particle physics in 2022

The Standard Model of particle physics

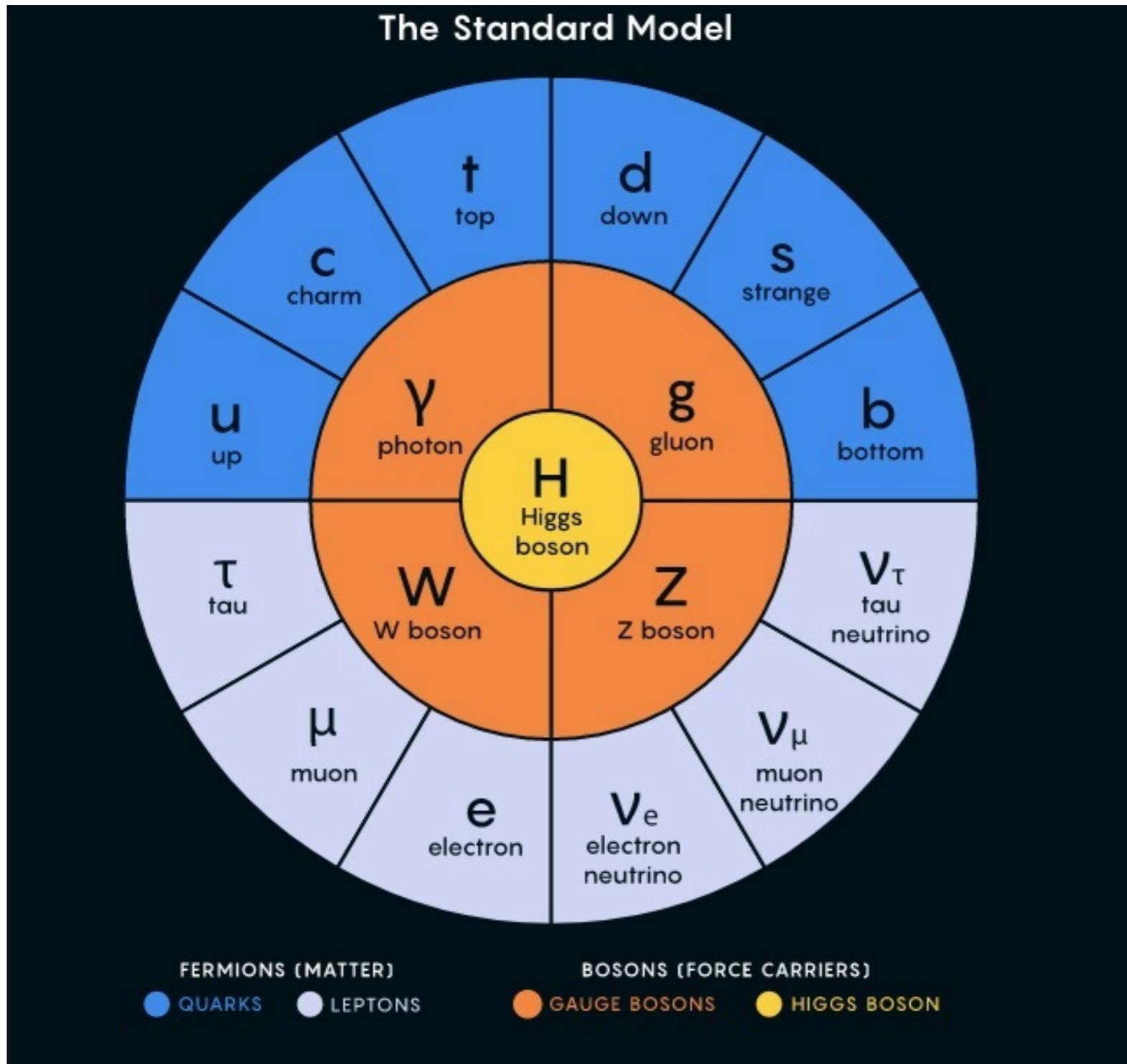
Years from concept to discovery



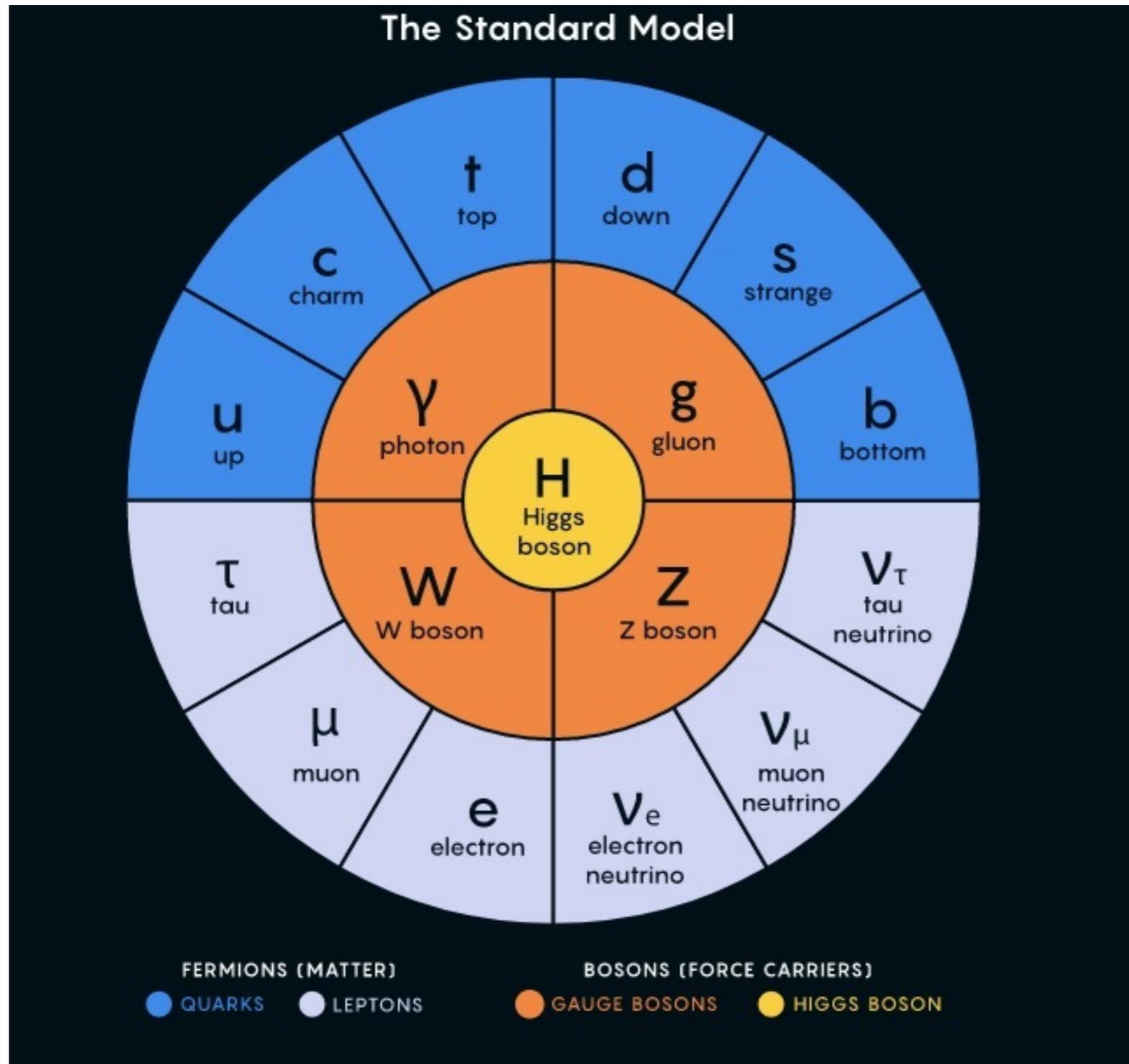
Source: *The Economist*

- Particle physicists aim at:
 - Finding all elementary constituents of matter
 - Mathematical formulation of their interaction
- More than 100 years to complete the Standard Model of Particle Physics (SM)
- The Higgs boson took >50 years from prediction (60s) to discovery (2012)!
- Next week we celebrate 10 years from the Higgs boson discovery (July 4th, 2012)!
- CERN symposium

Particle physics

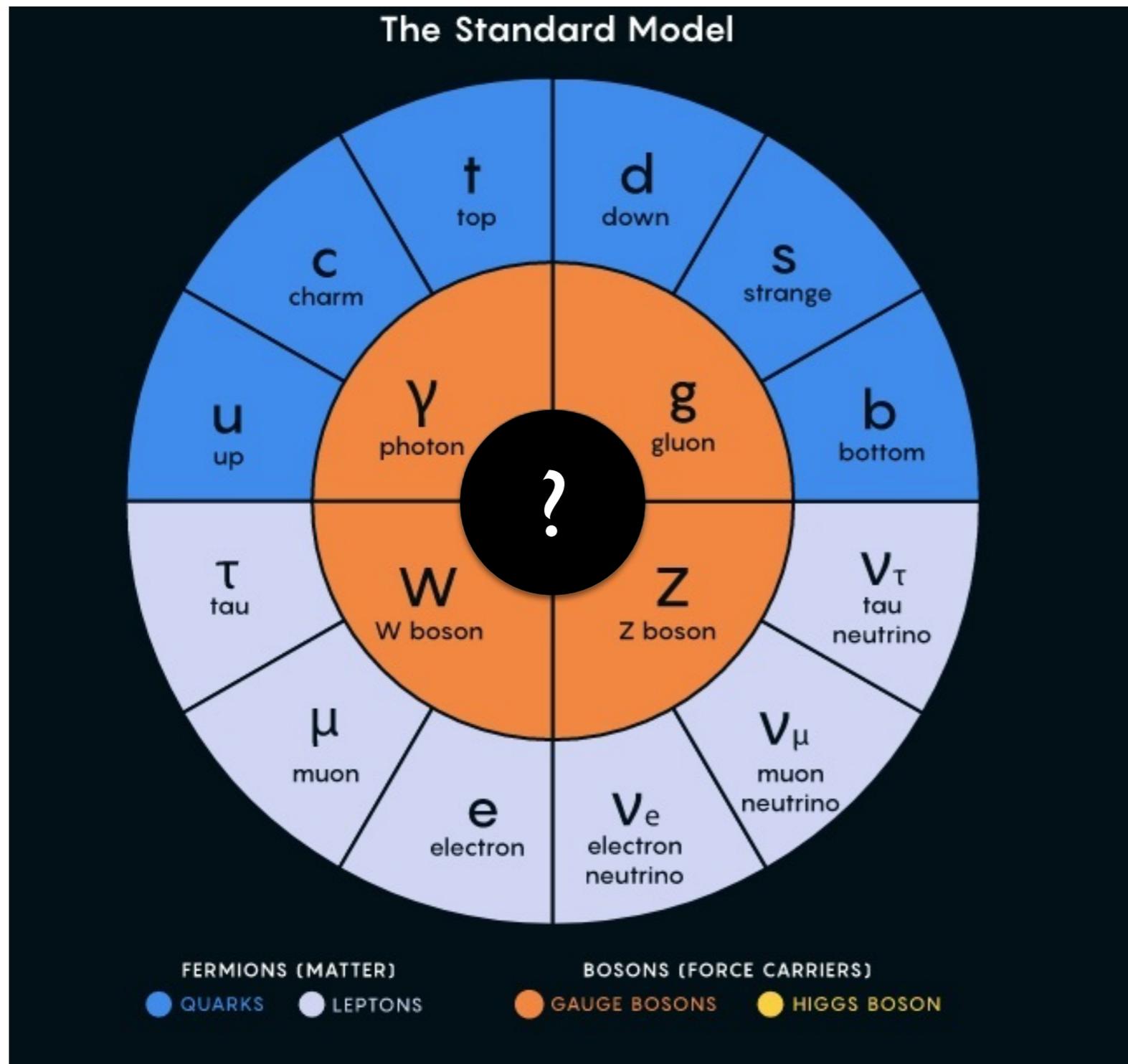


Particle physics



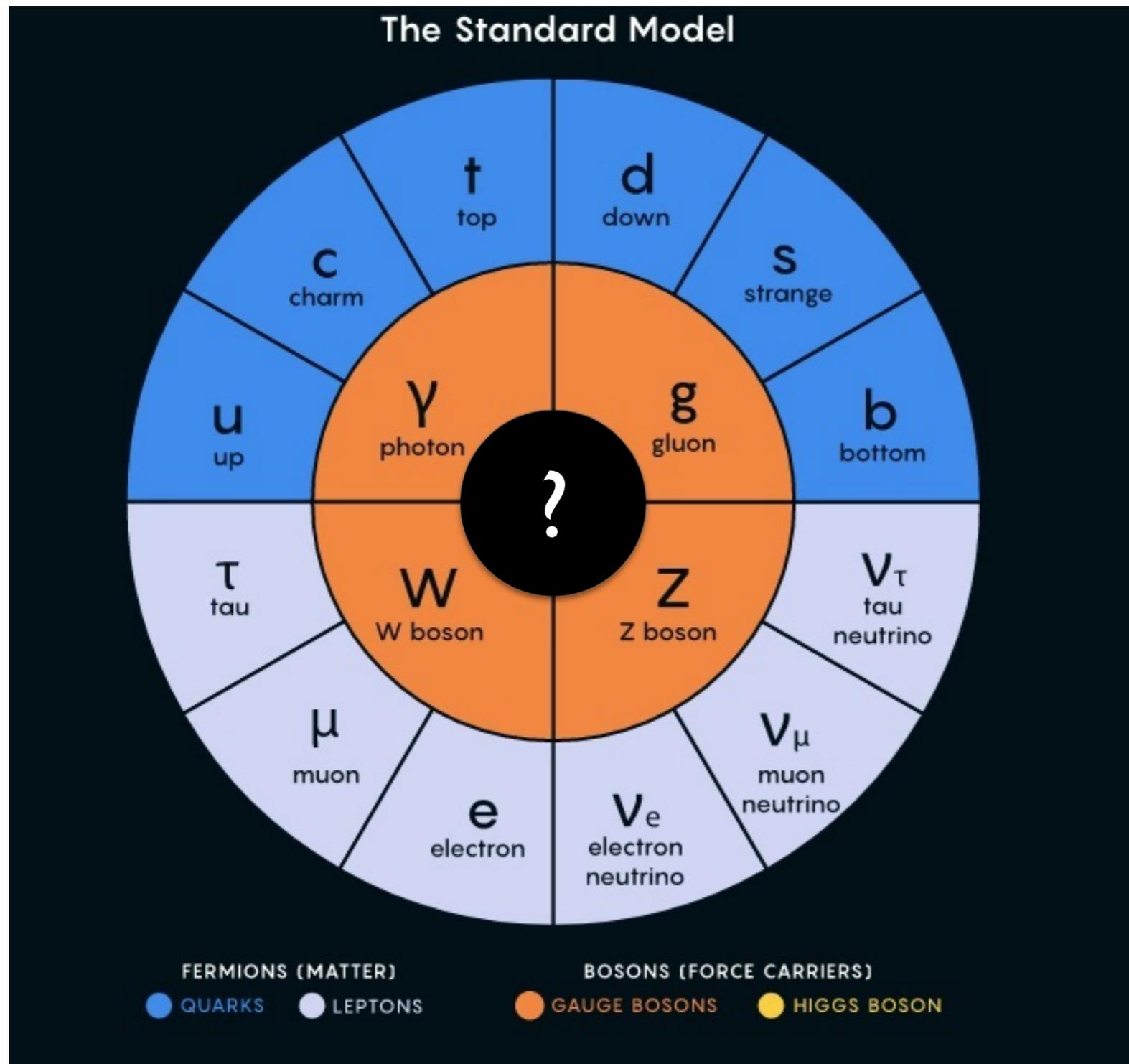
- The main goal:
 - Find all elementary constituents of matter
 - Describe/predict in a mathematically rigorous way their interactions

Particle physics



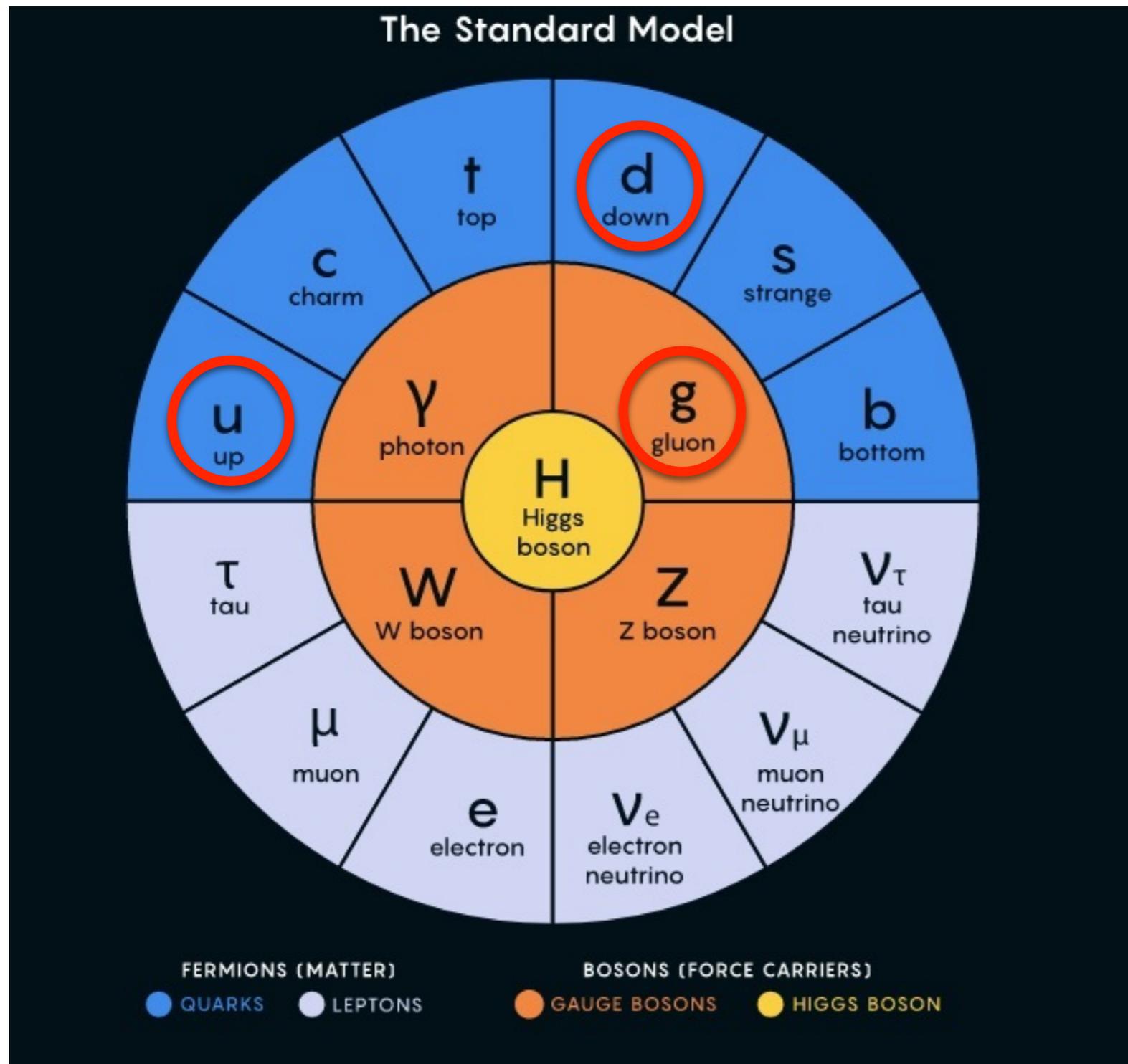
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- Until 2012, the Higgs Boson particle was missing in this picture!

Particle physics

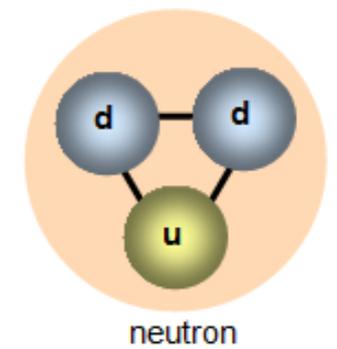
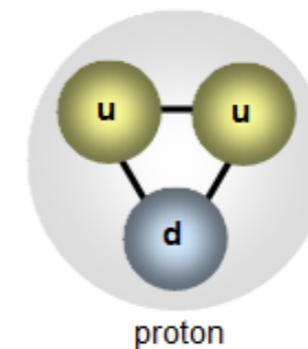


- The main goal:
 - Find all elementary constituents of matter
 - Describe/predict in a mathematically rigorous way their interactions
- Until 2012, the Higgs Boson particle was missing in this picture!
- This is not “just” another particle. The Higgs Boson is “central” to our understanding of nature.

Nature around us: nuclei

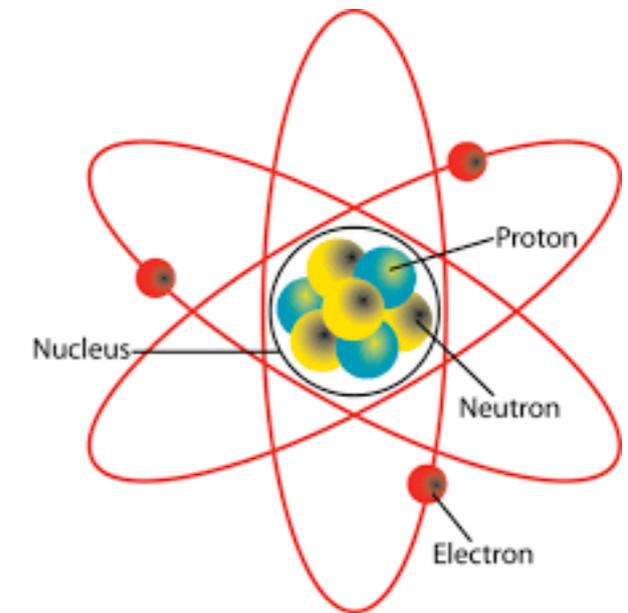
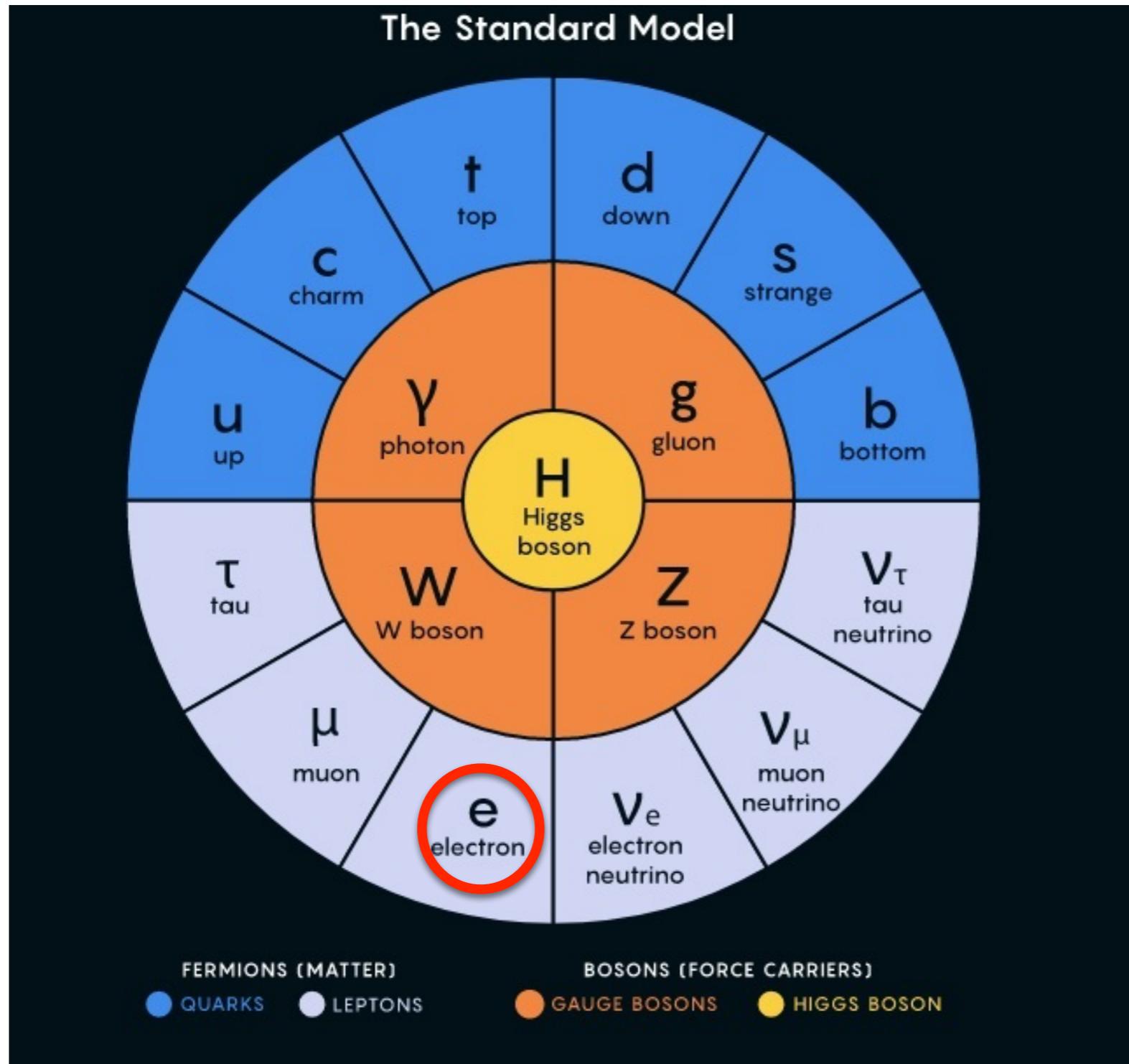


[© Keith Gibbs 2021]



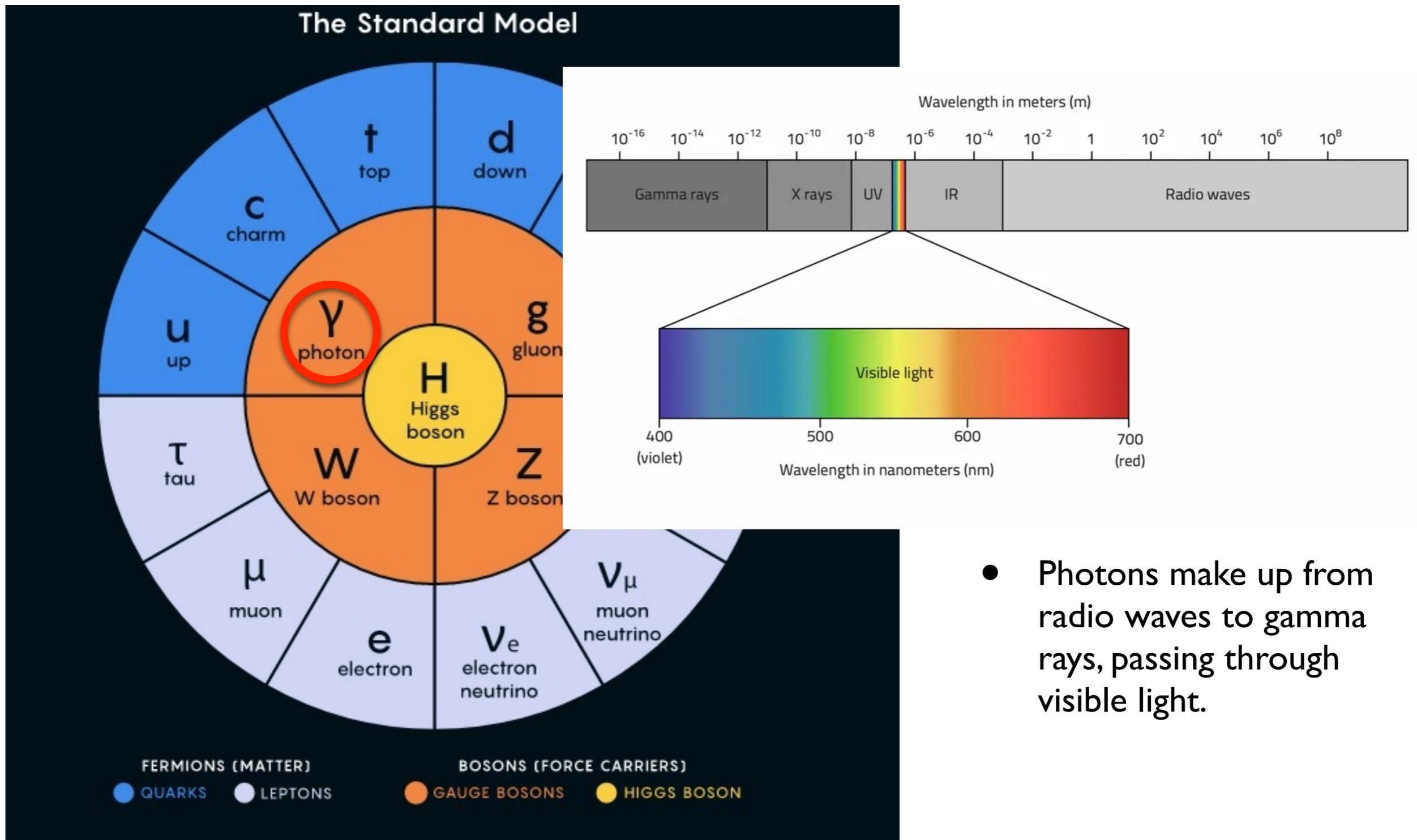
- Up and Down quarks make up the nuclei of all known elements in nature
- They are kept together by the strong force (gluons)
- Scale: 10^{-15} m (1 Fermi)

Nature around us: electrons

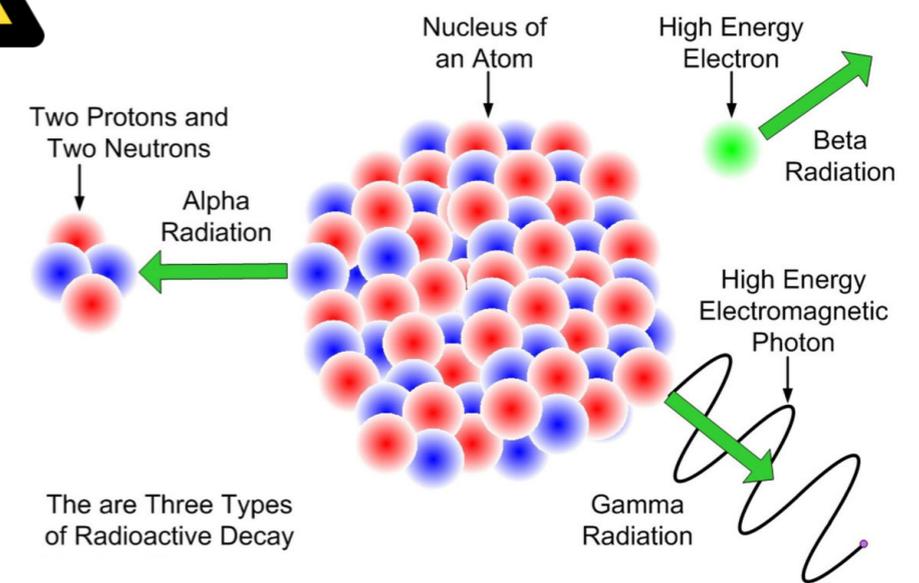
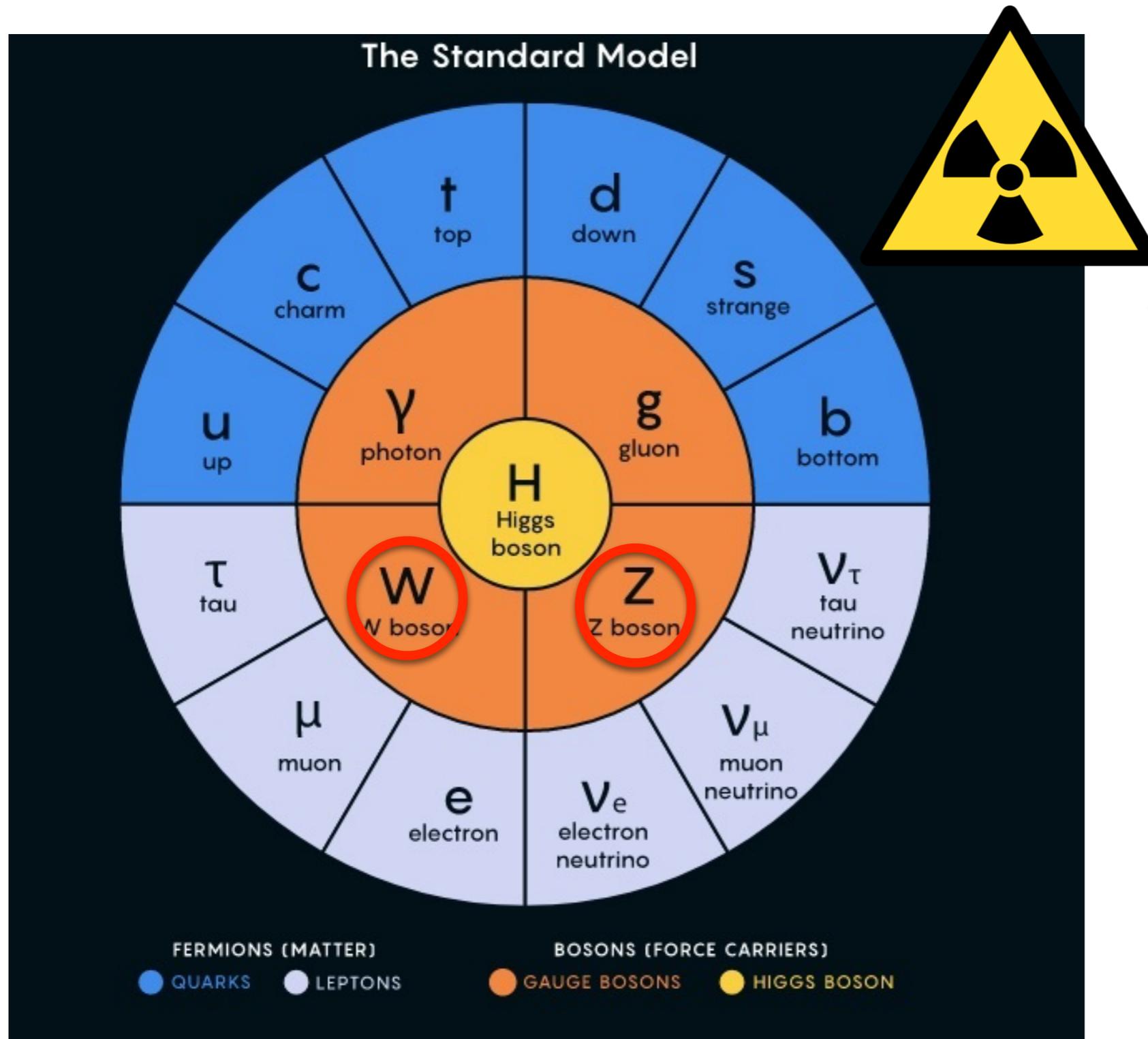


- Electrons added to nuclei make up the atoms.
- Scale: 10^{-10} m (1 Angstrom)

Forces: electromagnetism



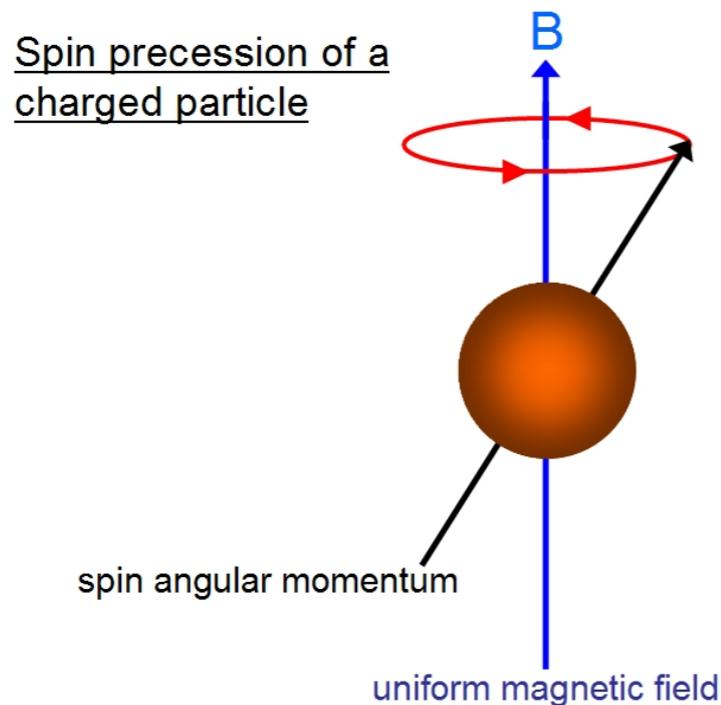
Forces: “weak” force



- Radioactive nuclear decays (happening even in our body)

A beautiful theory...

- Allows impressively precise predictions.
- Example:
 - Magnetic moment of an electron (spin=1/2 particle) in multiples of the Bohr Magneton (μ_B)

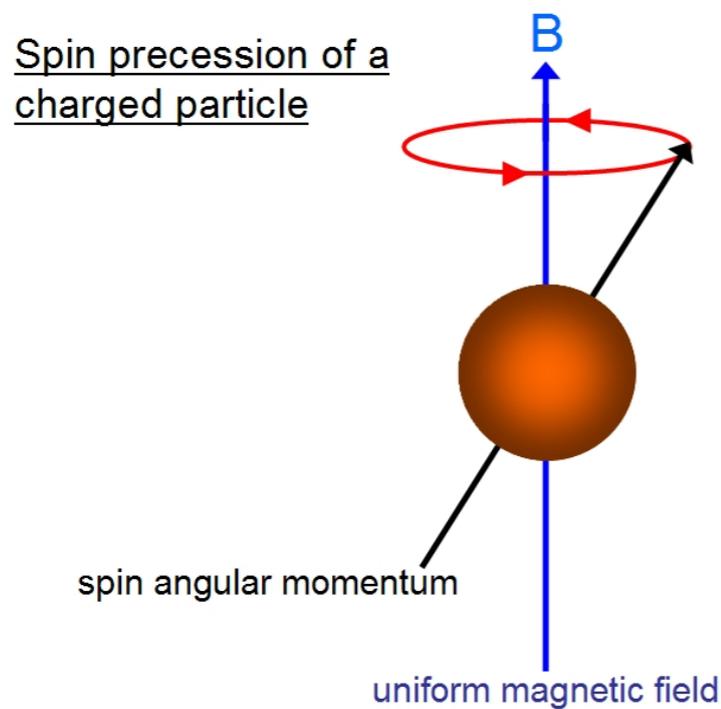


$|\mu| = iA$
 current \nearrow area enclosed by current loop

Classical	-0.5
Dirac	-1
Full theory	-1.00115965218178(77)

Most precise prediction in physics !!

...matched by incredible experimental precision...

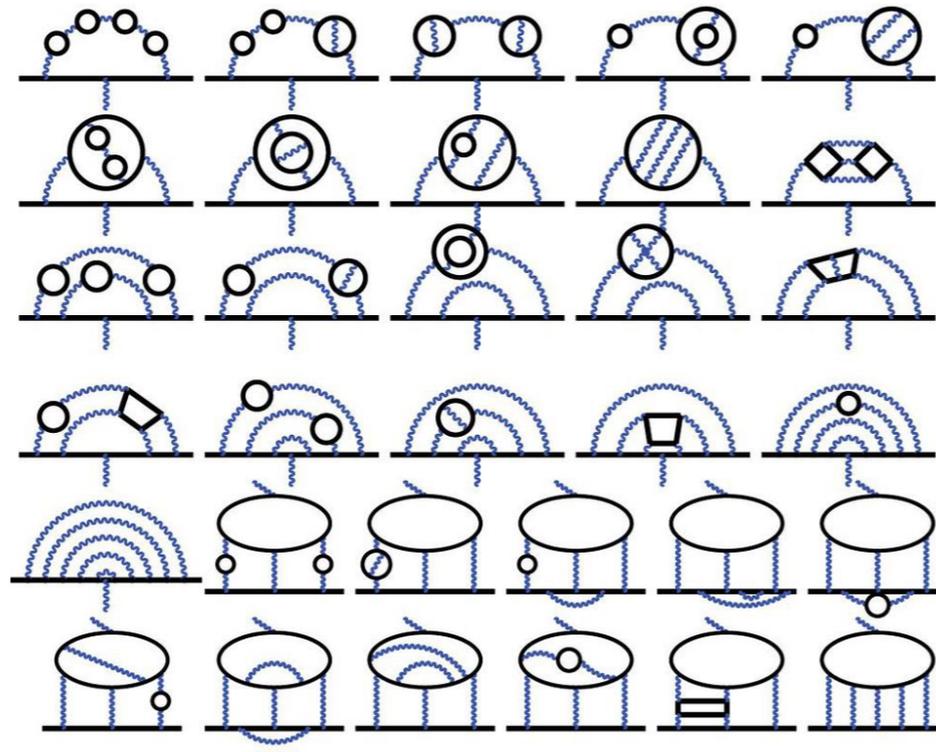


Precision $\sim 10^{-15}$

Classical	-0.5
Dirac	-1
Full theory	-1.00115965218178(77)
Measurement	-1.00115965218076(28)

...with one big problem

- To obtain super precise predictions, particle theorists compute millions of 'so-called' Feynman diagrams



- Everything works fine if they only consider a theory where all particles have no mass.
- But, if they add masses to the particles, many of these Feynman diagrams become infinite, spoiling theory predictions.



Peter Higgs's idea (1963)



A new field (“Higgs”) which permeates space.

Peter Higgs's idea (1963)



If a massive particle enters the Higgs Field...

Peter Higgs's idea (1963)



...it is slowed down by the field, i.e. it acquires mass.

The Higgs Boson

- If the Higgs Field really exists, it can also manifest itself in the form of a newly predicted fundamental particle, the **Higgs Boson**.
- So, experimental physicists have been desperately looking for this particle for decades, since proving its existence explains how elementary particles get their mass (no stable atom would exist if the electron would not have mass!)
- However:
 - The theory did not predict what the mass of the Higgs Boson would be - physicists had no clue exactly where to look for
 - Higgs Bosons are very rare - any search for the Higgs Boson turns out to be the search for a needle in a huge haystack





After 50 years, Higgs Boson Discovery announced at CERN! (July 4th, 2012)



$m_H \sim 125 \text{ GeV}$
(125 times heavier than a proton)

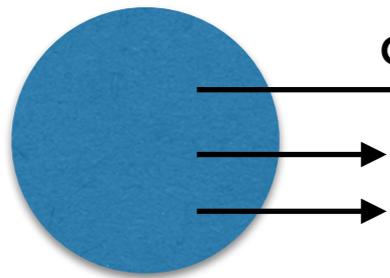
Fabiola Gianotti
(at that time ATLAS
spokesperson,
today first ever CERN
General Director for two
mandates in a row)

- Some of my colleagues/friends queued for an entire night to be in the CERN Auditorium!
- But many others (like me) were at the ICHEP conference in Melbourne, to present those results!

How did we make it?

- The most powerful accelerator and particle collider on Earth: the **LHC** (Large Hadron Collider)

E=6.5 TeV



proton

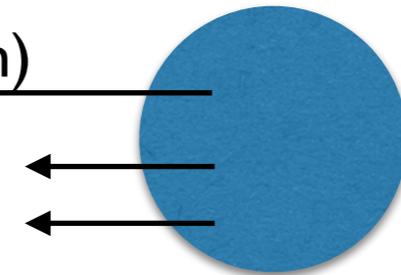
quark (or gluon)

$$E = m \cdot c^2$$



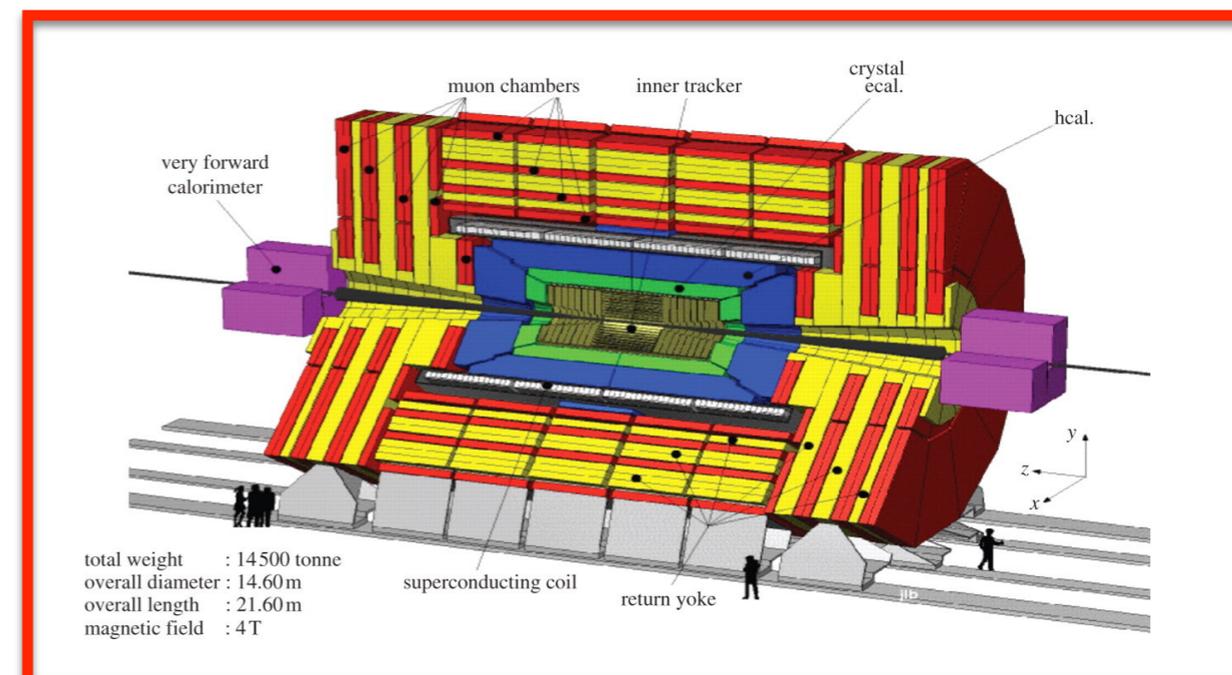
quark (or gluon)

E=6.5 TeV



proton

- Two giant and very sophisticated particle physics detectors: **ATLAS** and **CMS**
- Two collaborations of many thousands of physicists!

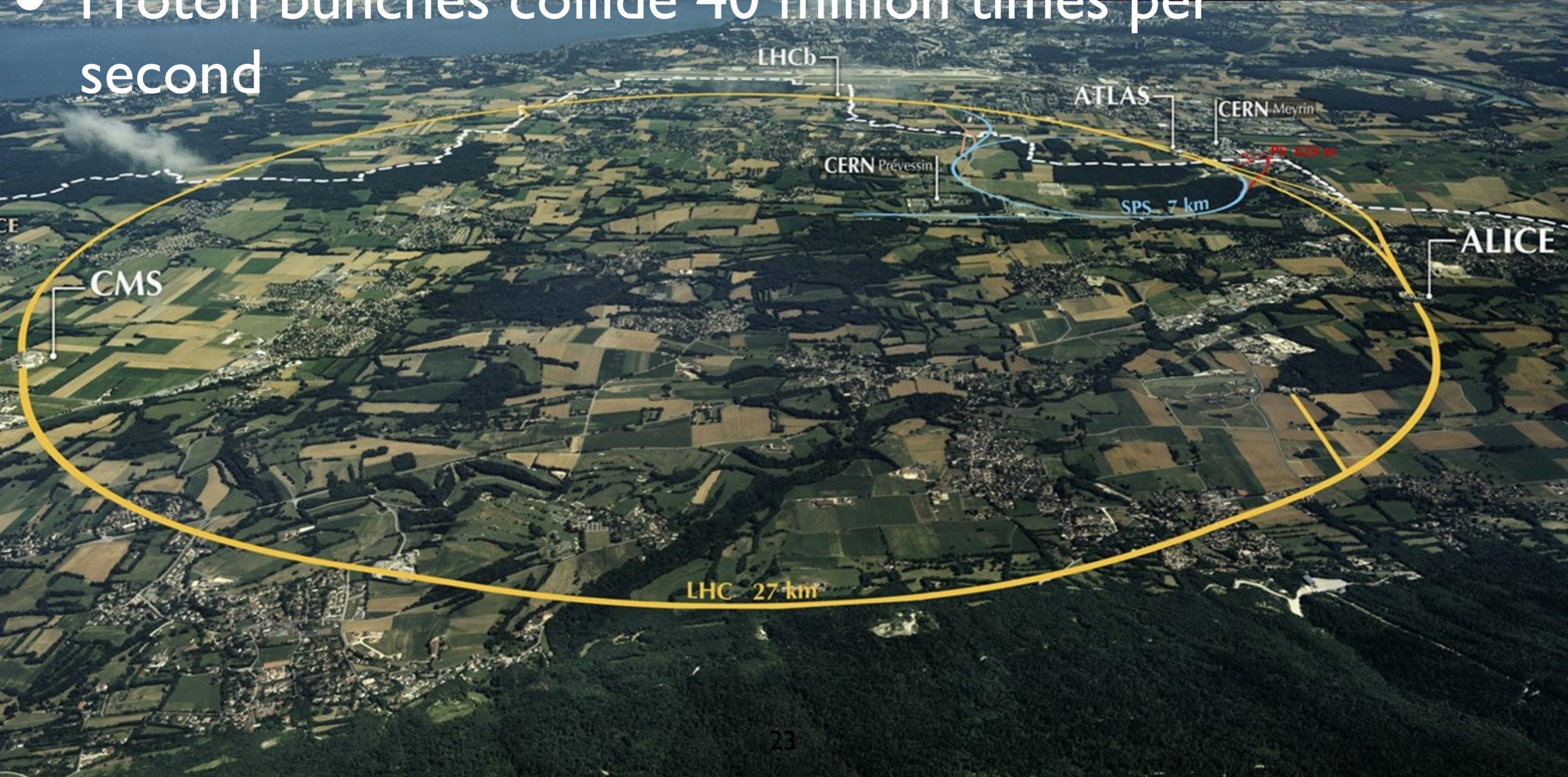


The Large Hadron Collider at CERN



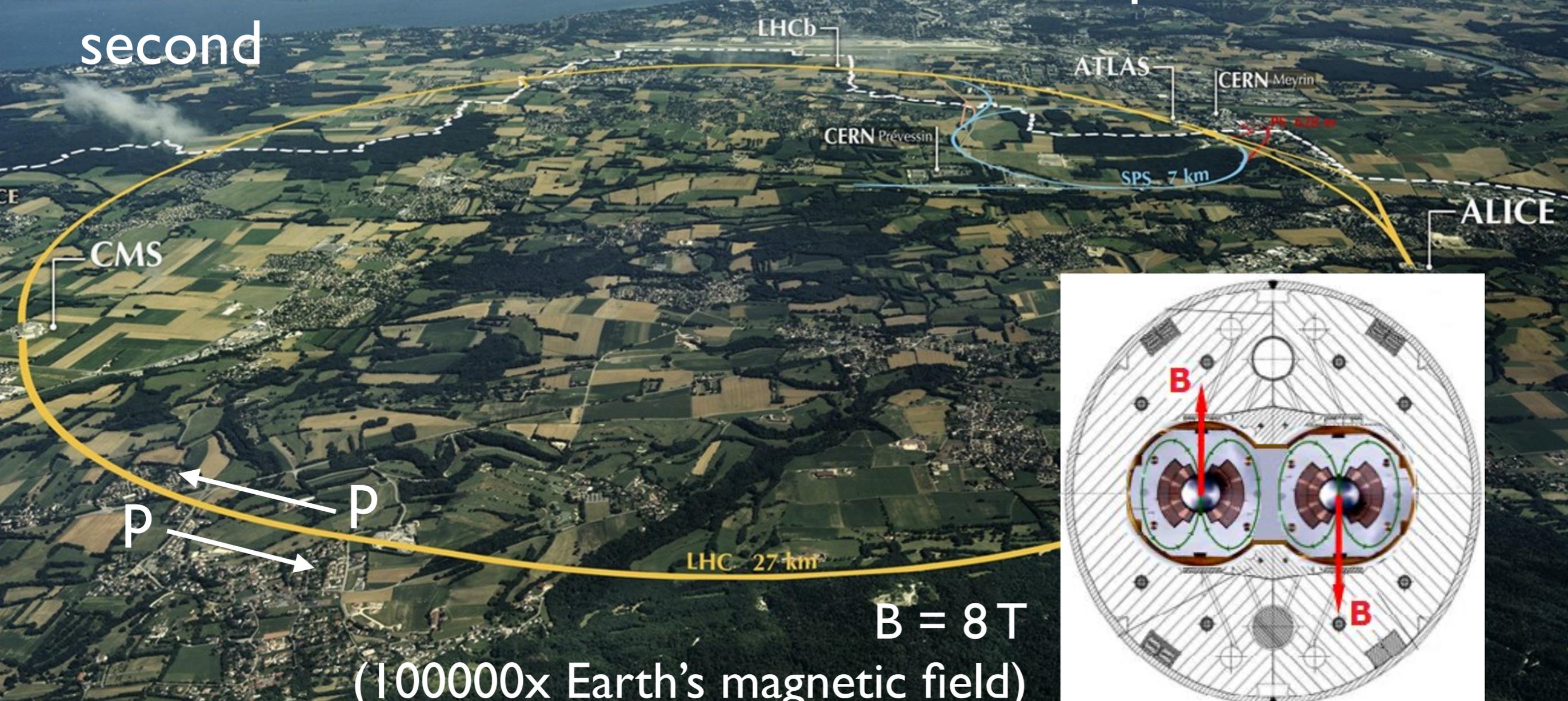
The Large Hadron Collider at CERN

- 17 miles ring, 300 feet underground
- Collision energy: 13,000x times proton mass
- Proton bunches collide 40 million times per second



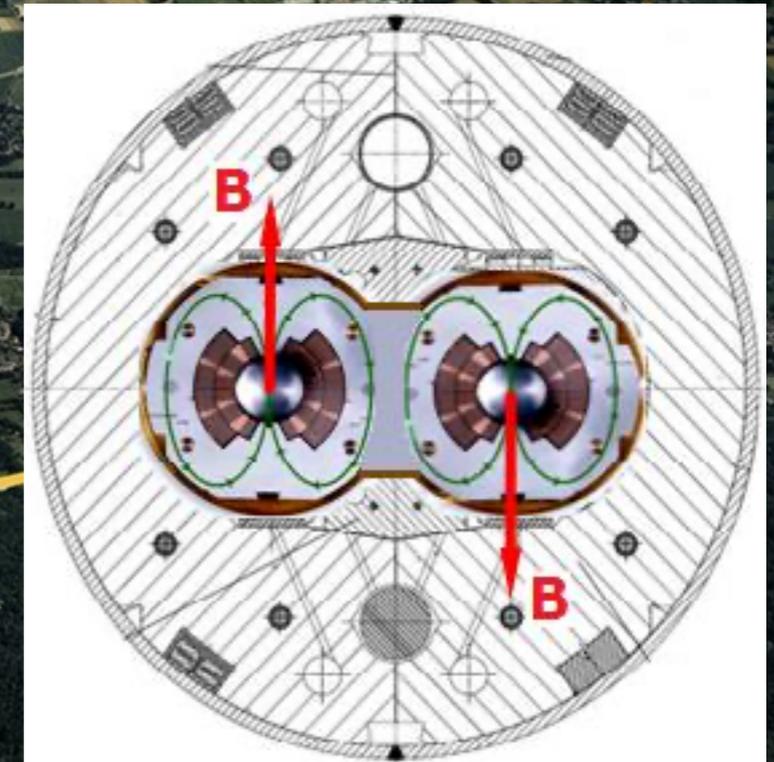
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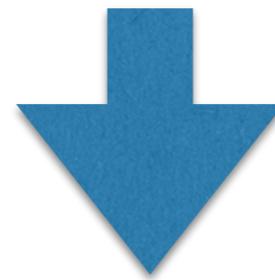
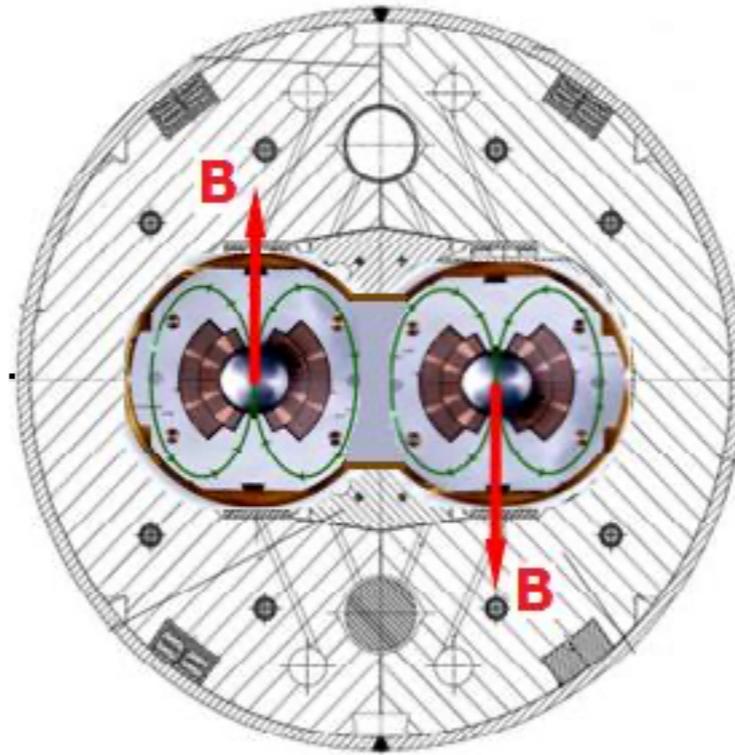


$B = 8\text{ T}$

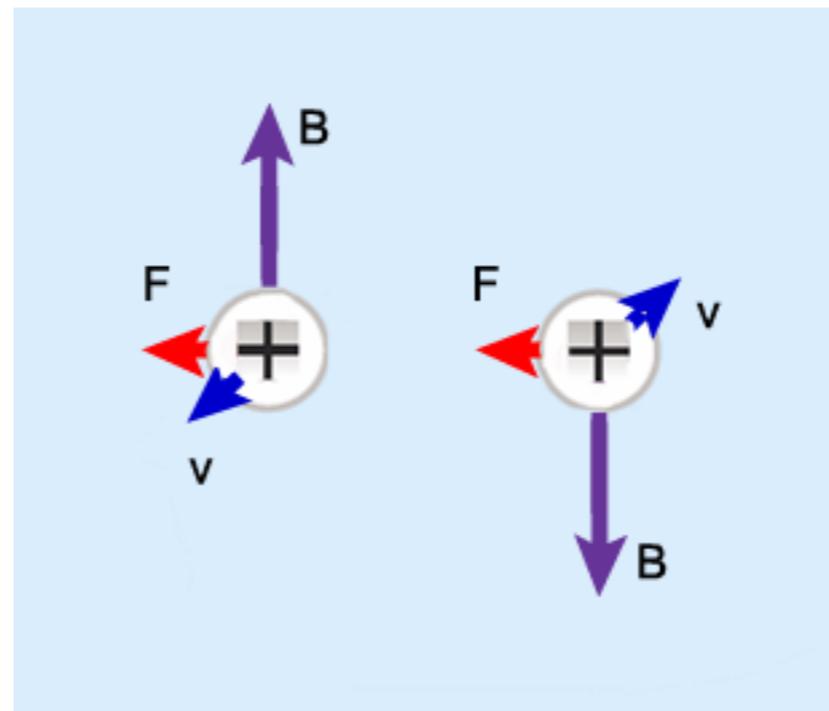
(100000x Earth's magnetic field)



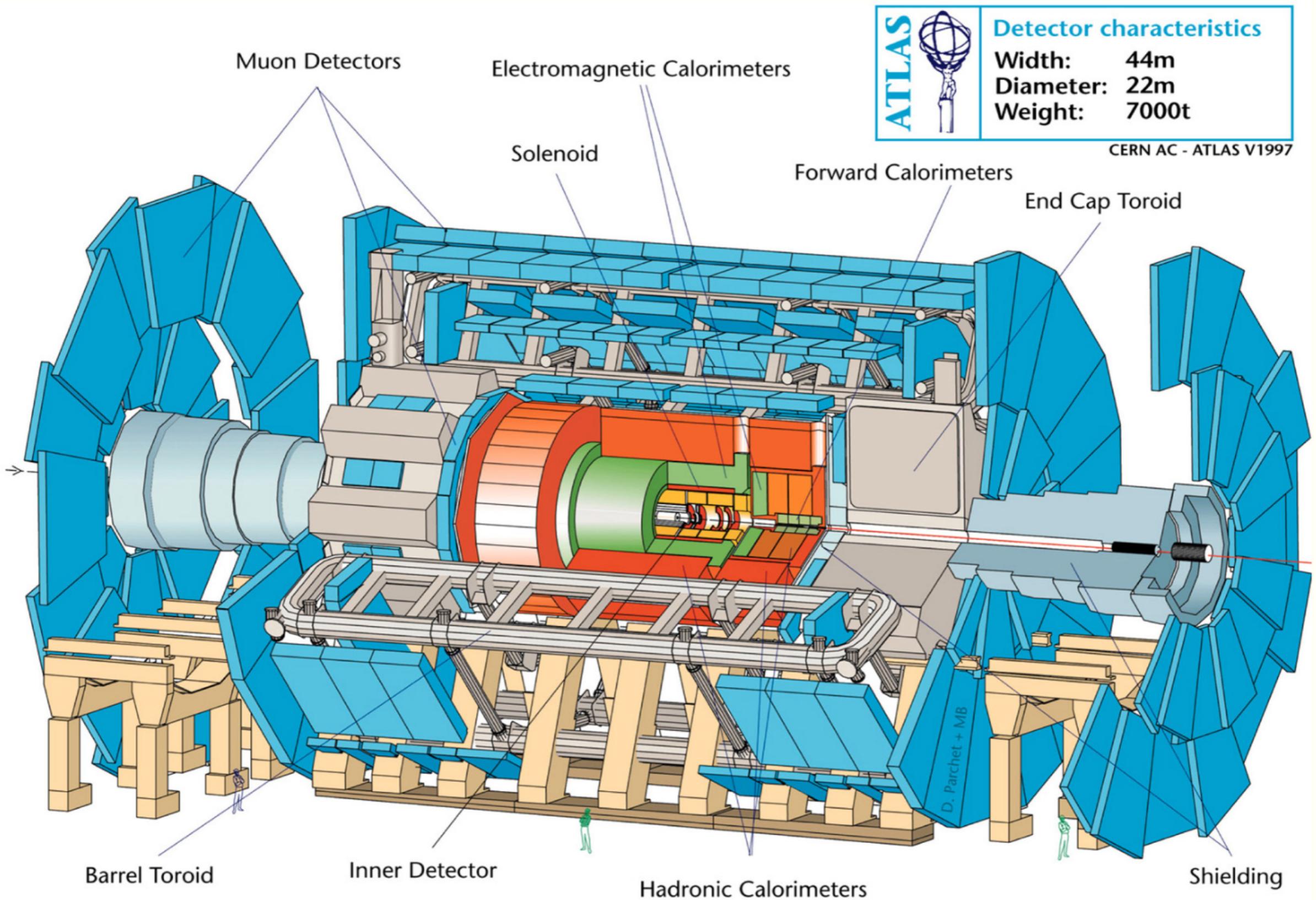
Center of ring



$$\vec{F} = q\vec{v} \times \vec{B}$$

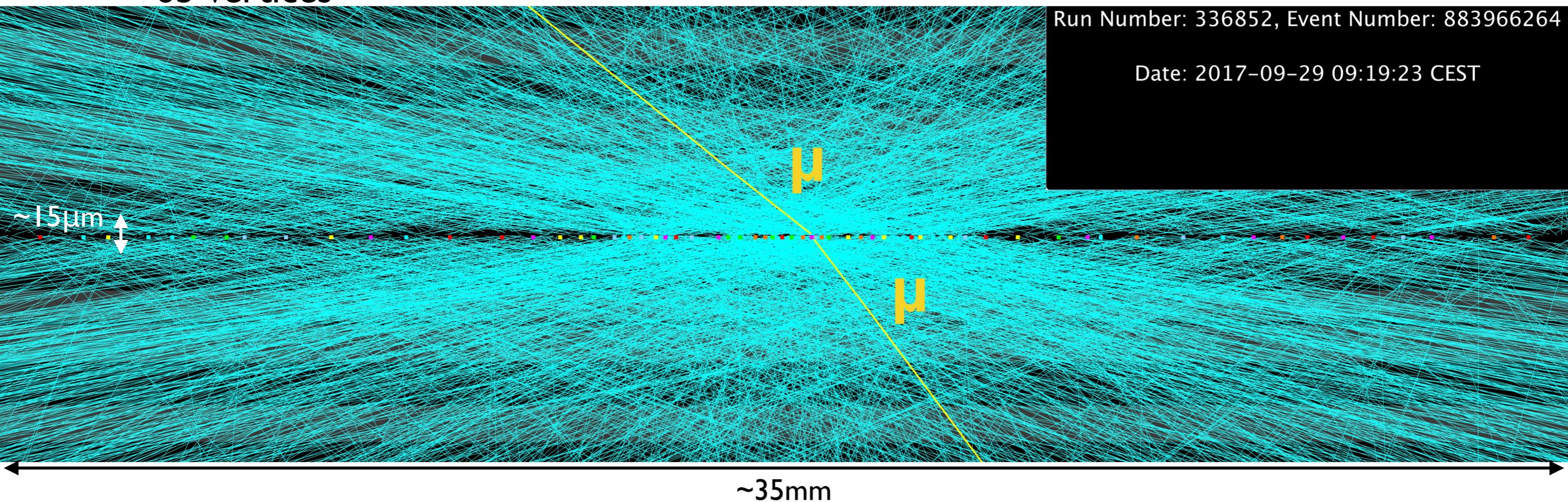


The ATLAS Detector



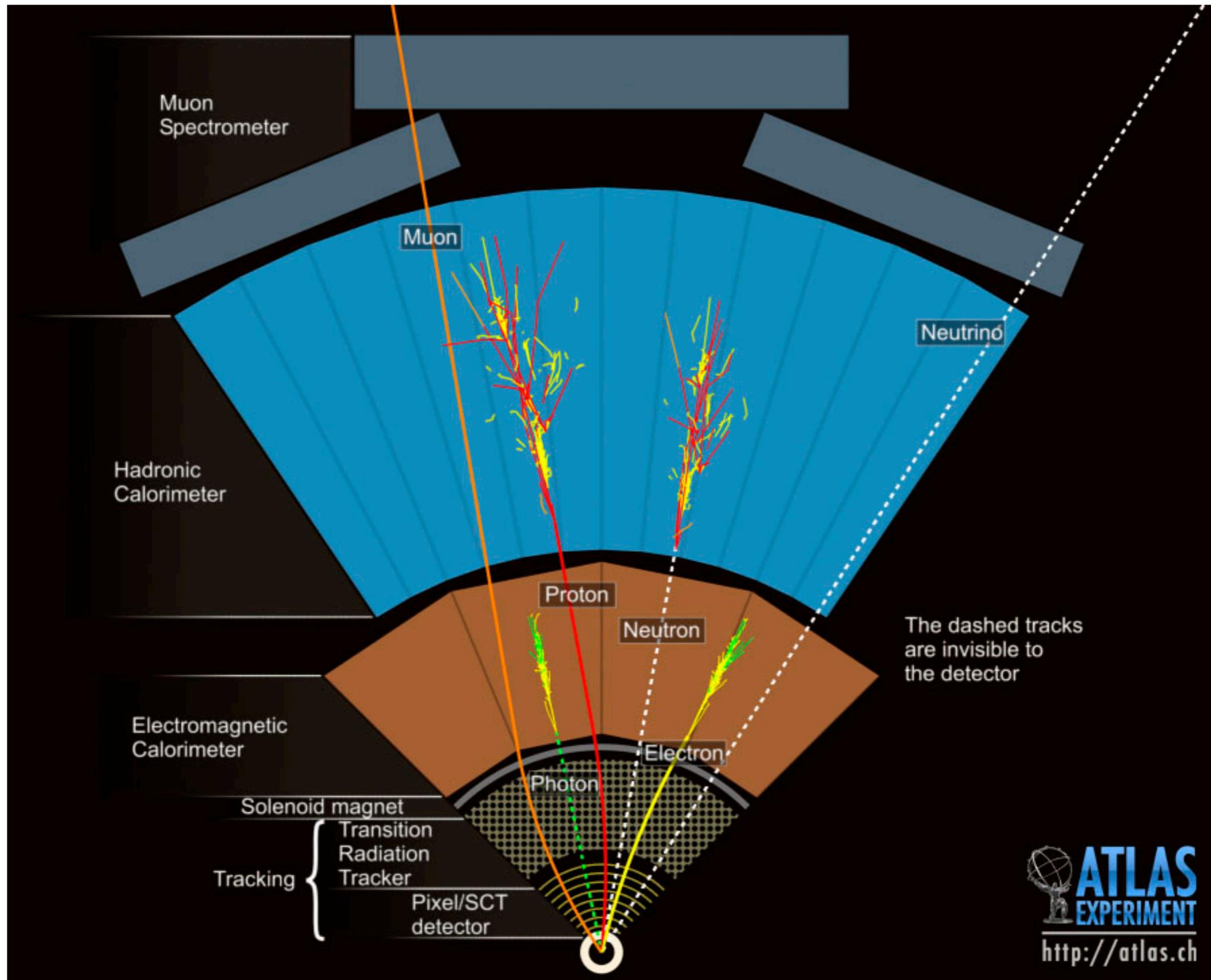
- The inner tracking detectors allow to take a “picture” of what happened at the very center of the detector during a collision:

65 vertices



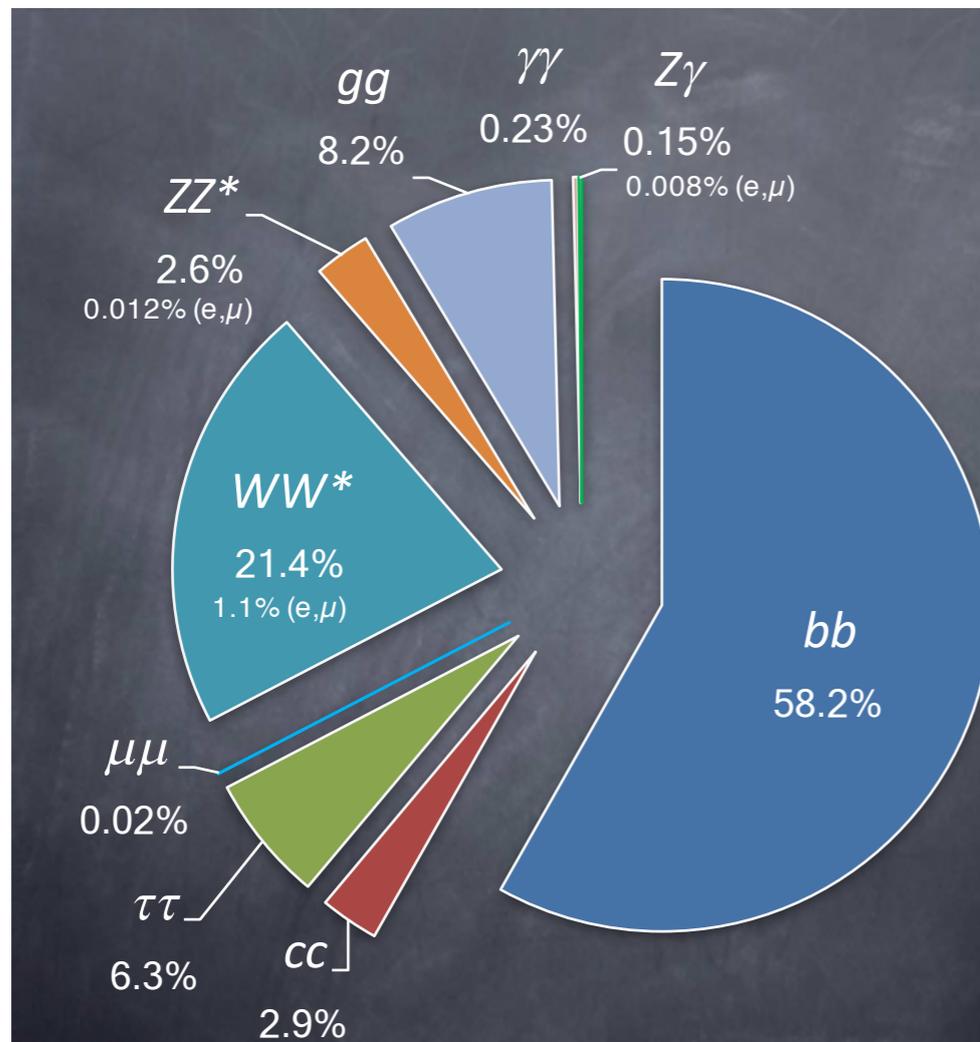
- First challenge:
 - Finding the most “interesting” event in all the noise !!

- Second challenge:
 - Find out which type of particles were produced



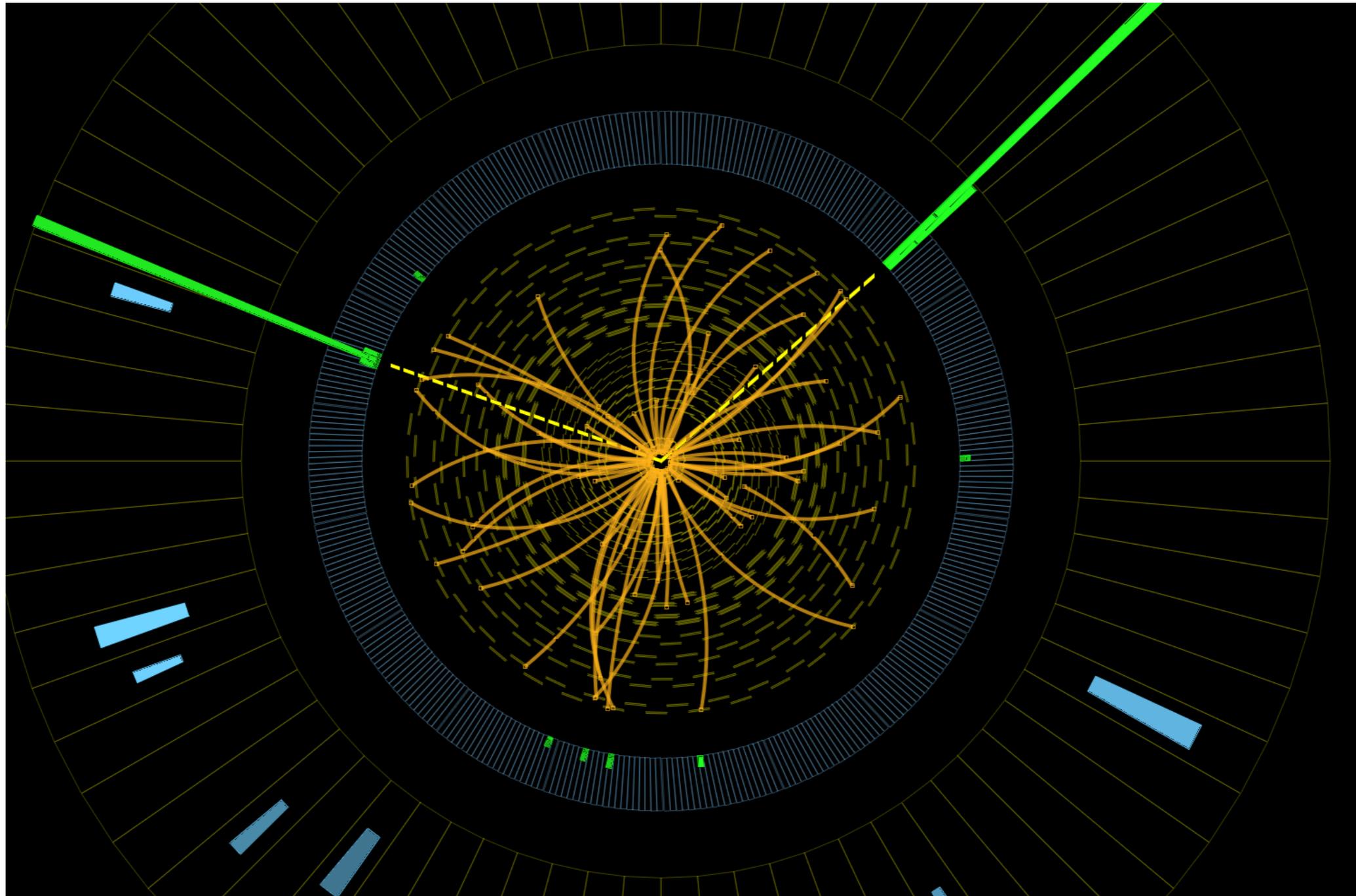
How do we “see” a Higgs Boson?

- If the theory was right, we expected around **1 every billion** of collisions at the LHC to be containing a Higgs Boson.
- However, the Higgs Boson is a very unstable particle and decays within 10^{-22} seconds. Decay means that it disappears (at the center of the detector), and its energy goes into other particles:



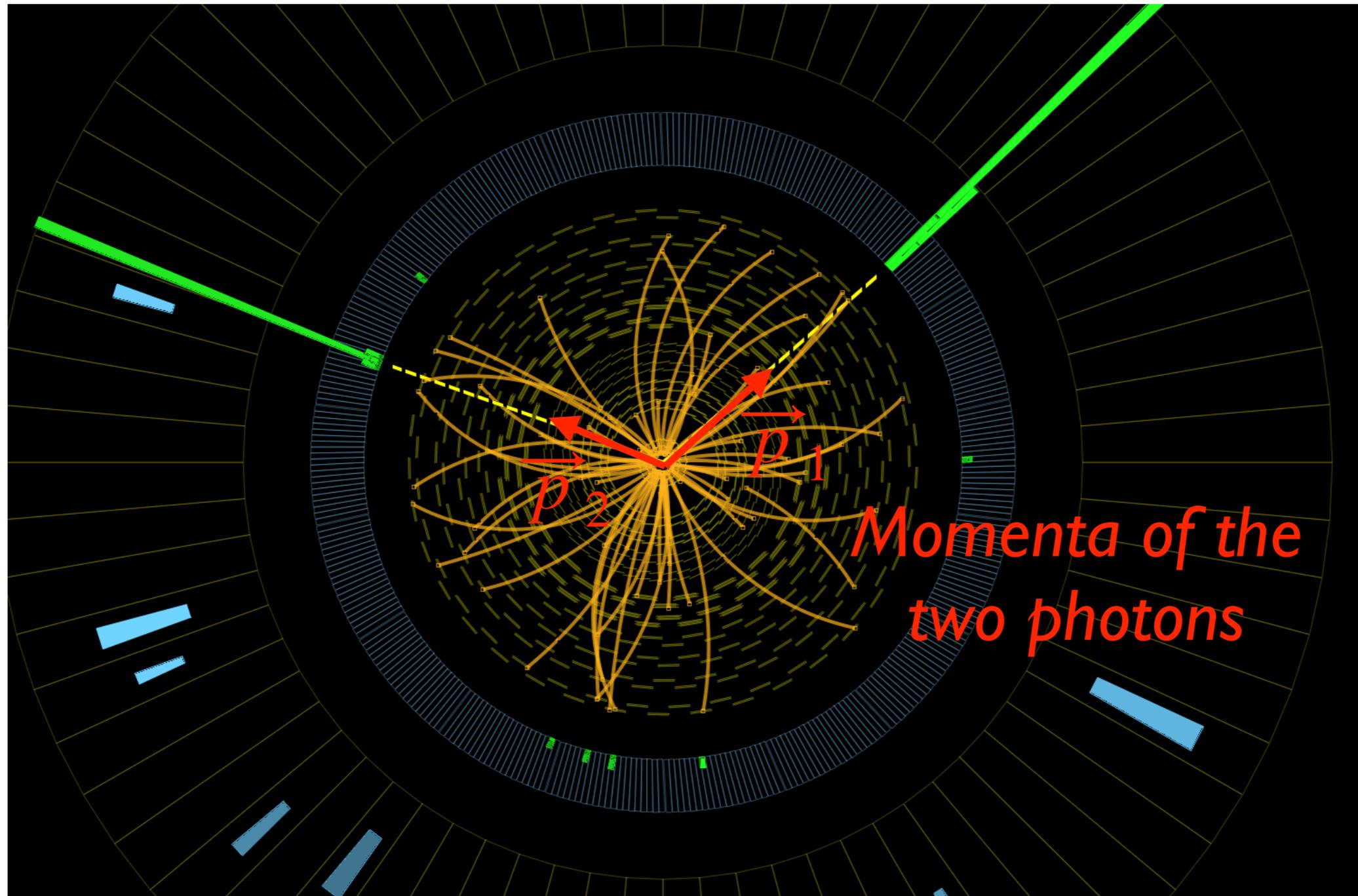
- There are a lot of ways the Higgs particle can decay!
- Next we will focus on Higgs Boson decays to two photons (light particles!)
- Yes, it is only 0.23% of the Higgs Boson decays!
- But two highly energetic light particles provide an incredibly “clean signature” in the detector...

The “diphoton” signature

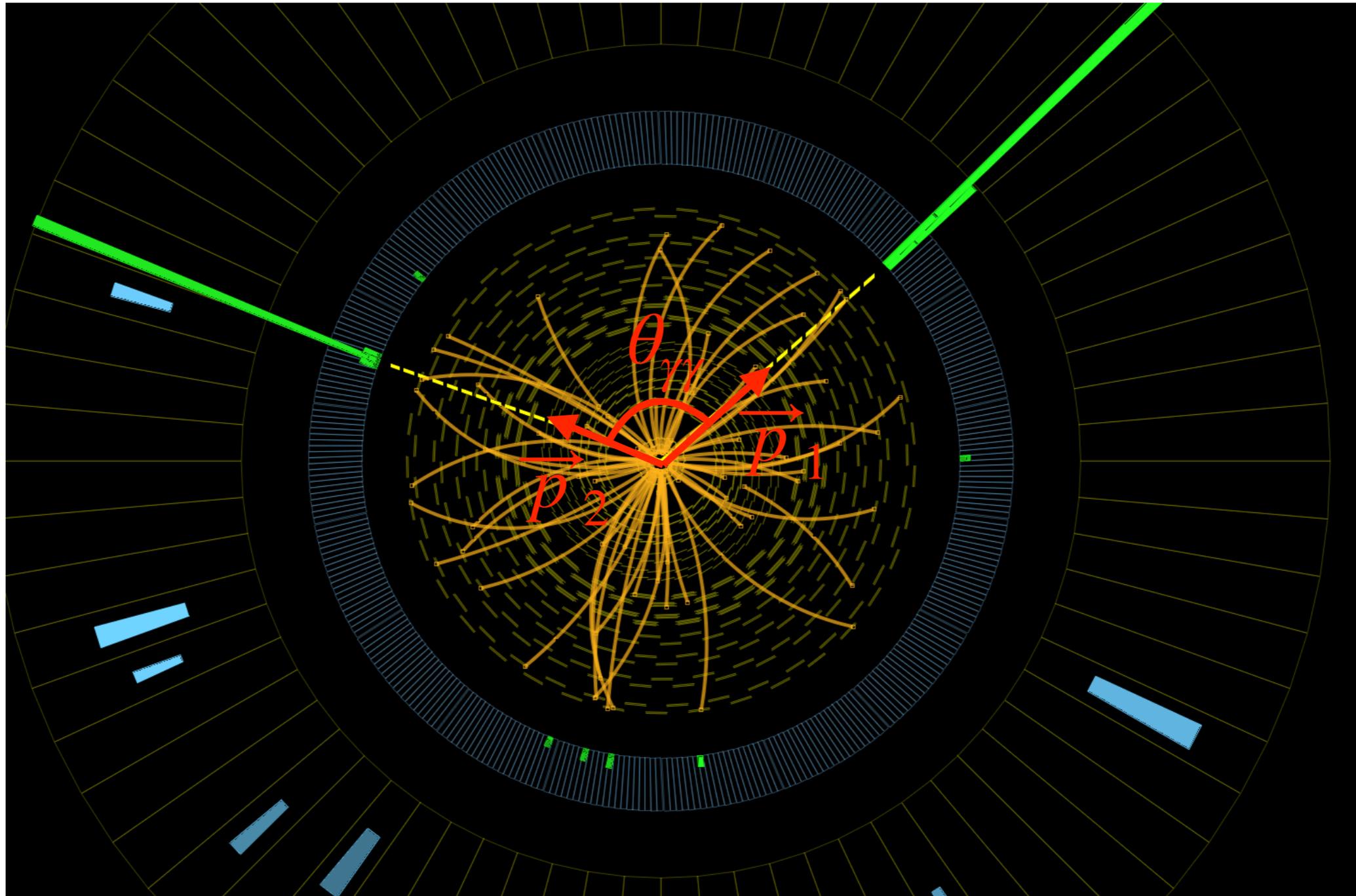


A “picture” (event display) of what was likely a Higgs Boson to di-photon decay in the CMS detector.

How do we know it was a Higgs Boson?

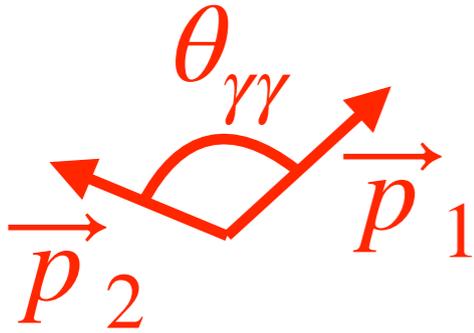


How do we know it was a Higgs Boson?



- For each di-photon event, we measure: $m_{\gamma\gamma} = 2 |\vec{p}_1| |\vec{p}_2| (1 - \cos(\theta_{\gamma\gamma}))$

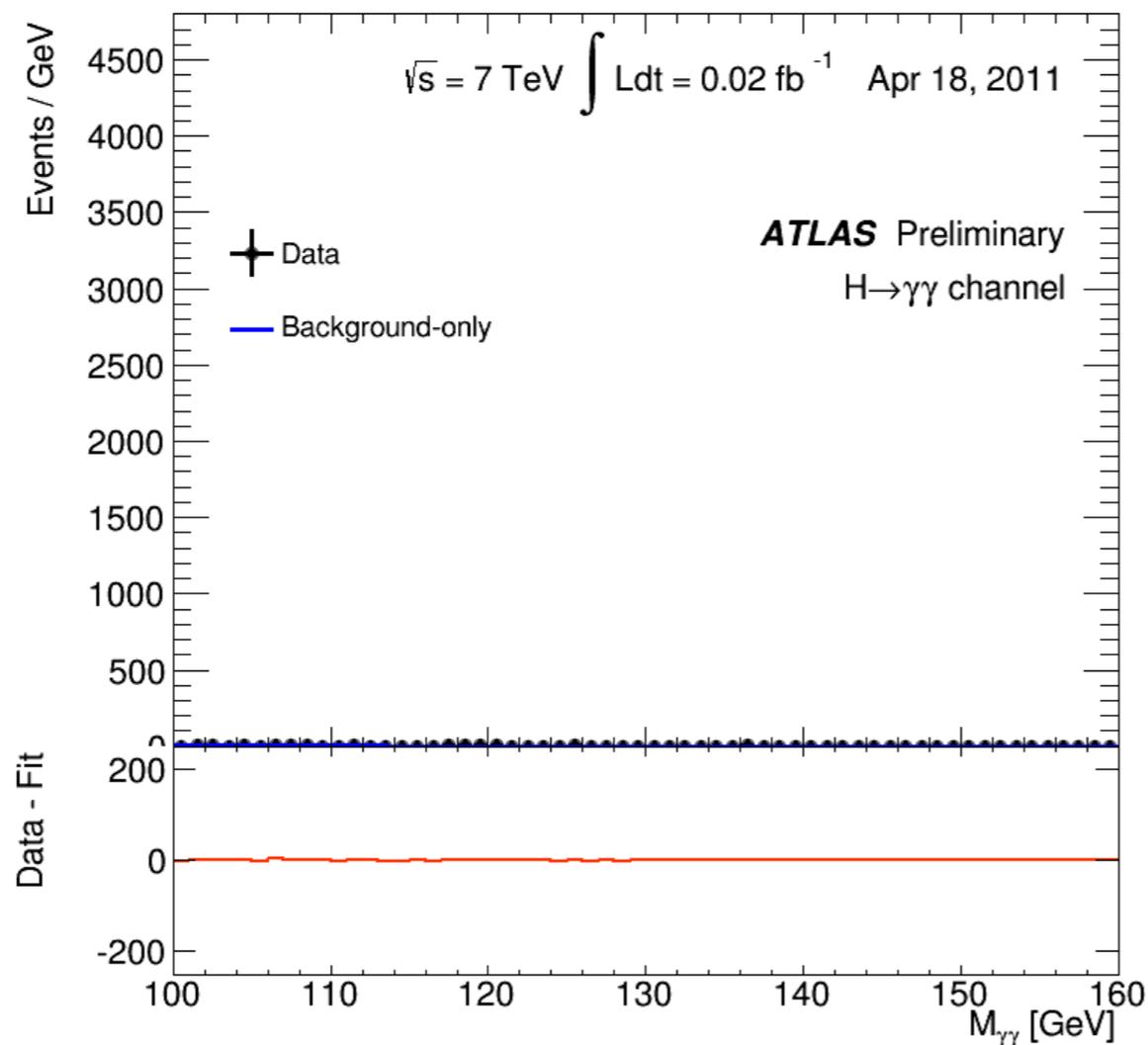
Relation based on special relativity



- Each particle, has a 4-momentum, a 4-vector with the
 - time component = energy (divided by c),
 - spacial component = spacial momentum
- $p_1^\mu = (E_1/c, \vec{p}_1)$, $p_2^\mu = (E_2/c, \vec{p}_2)$
- However for particles with no mass, like photons, the energy is equal to the absolute value of the momentum (x c):
 - $E = \sqrt{m_0^2 c^4 + |\vec{p}|^2 c^2} = |\vec{p}| c$
- The “invariant” mass of the two-particle system (with c=1) is:
 - $m_{1+2}^2 = (p_1 + p_2)_\mu (p_1 + p_2)^\mu = p_{1\mu} p_1^\mu + p_{2\mu} p_2^\mu + 2 p_{1\mu} p_2^\mu =$
 ~~$m_1^2 + m_2^2$~~ + 2 (E₁E₂ - $\vec{p}_1 \cdot \vec{p}_2$) =
 $2 |\vec{p}_1| |\vec{p}_2| (1 - \cos(\theta_{\gamma\gamma}))$
- Which gives $m_{\gamma\gamma} = 2 |\vec{p}_1| |\vec{p}_2| (1 - \cos(\theta_{\gamma\gamma}))$

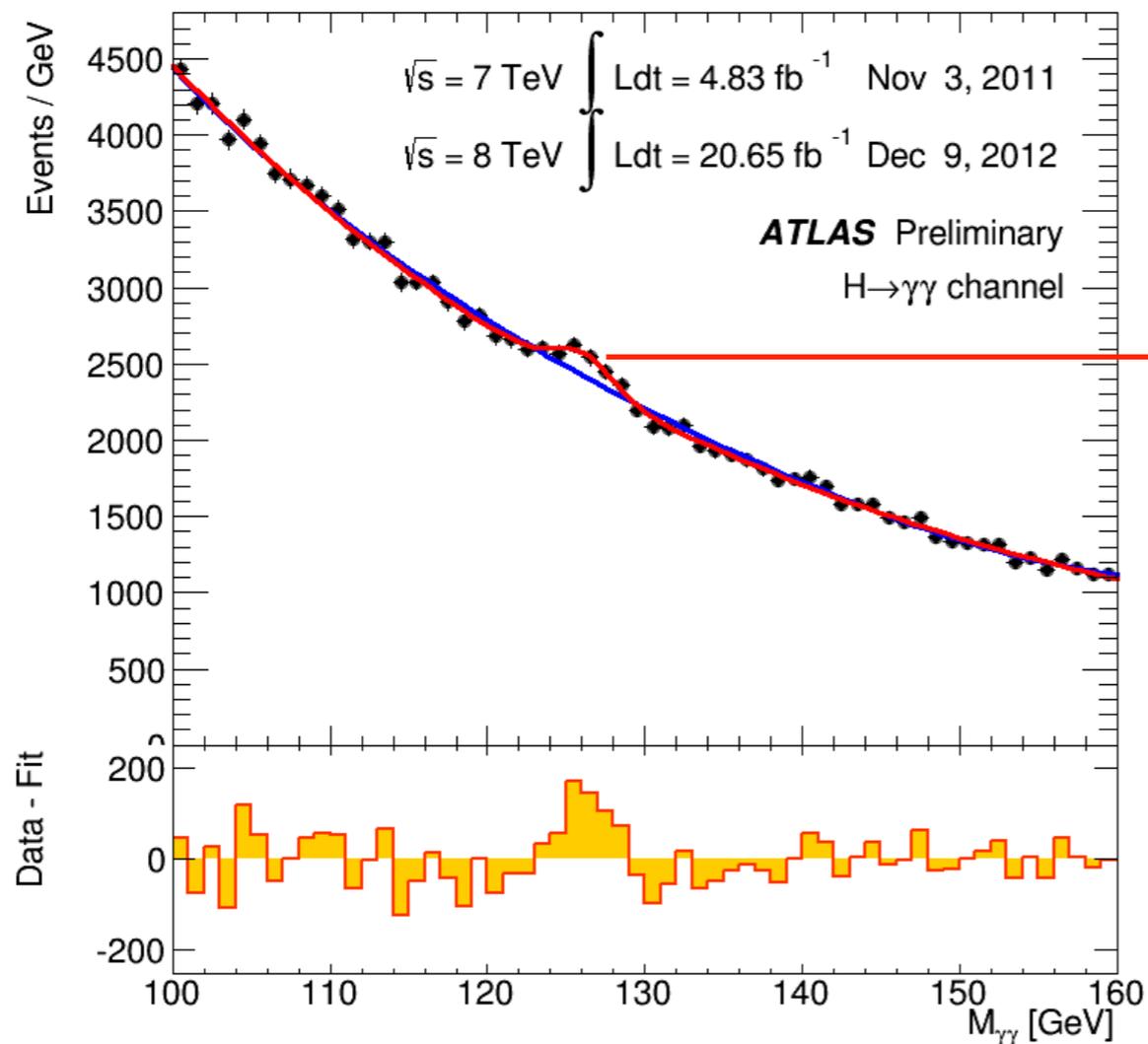
The “discovery” in a nutshell

- Select collision events with two very energetic photons
- For each event, measure $m_{\gamma\gamma}$ and add it to a histogram
- Collect as much data as you can, and look for a bump at the Higgs Boson mass!!



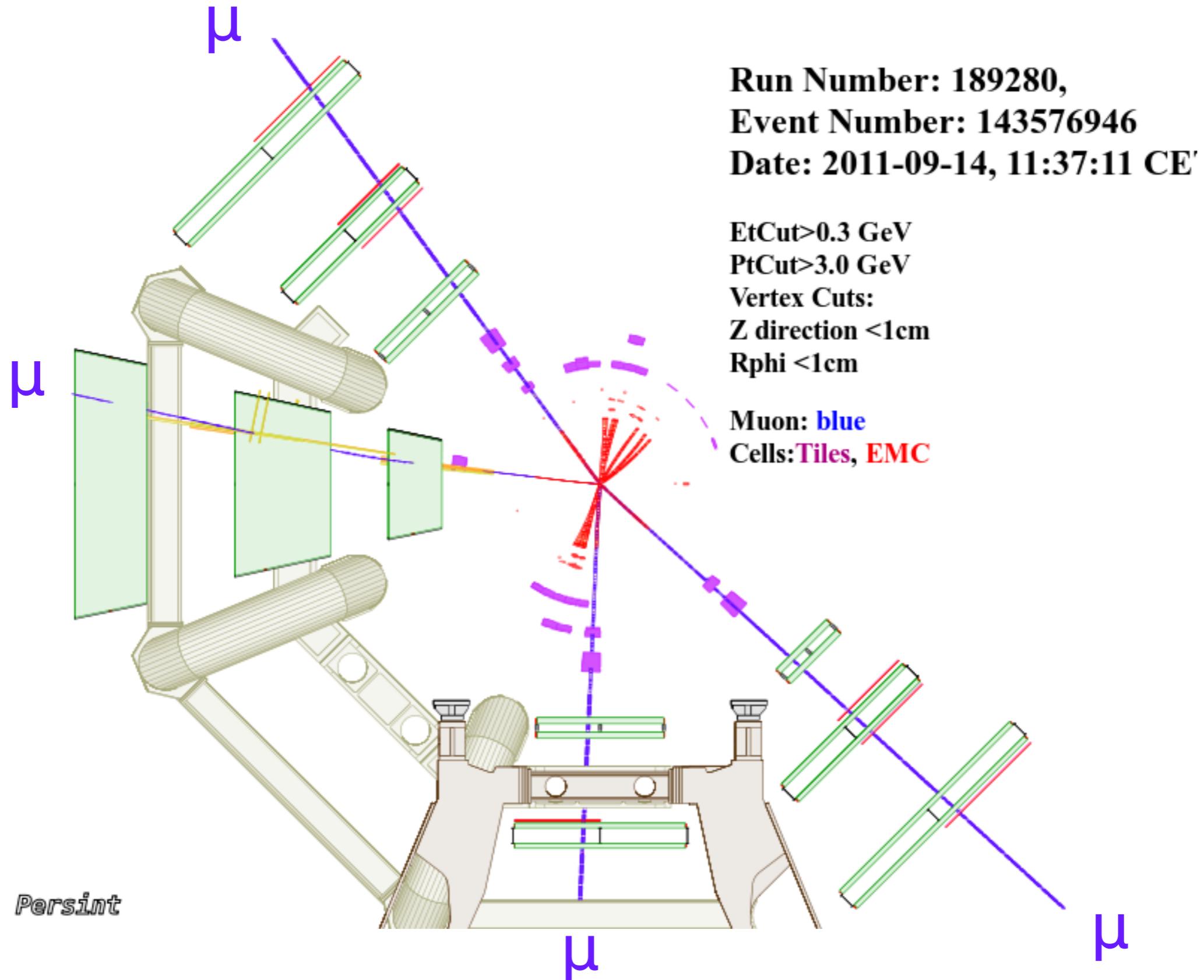
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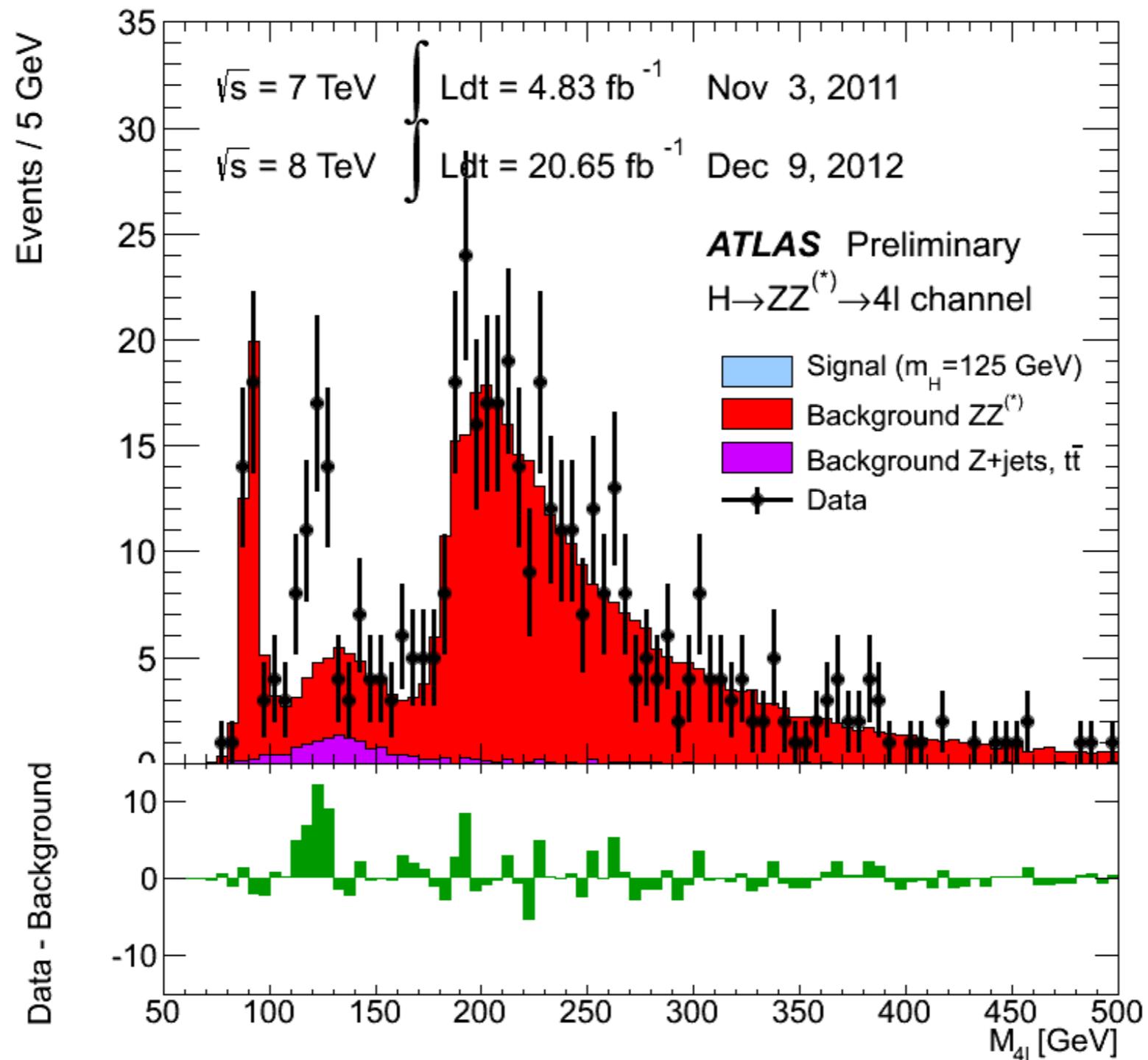


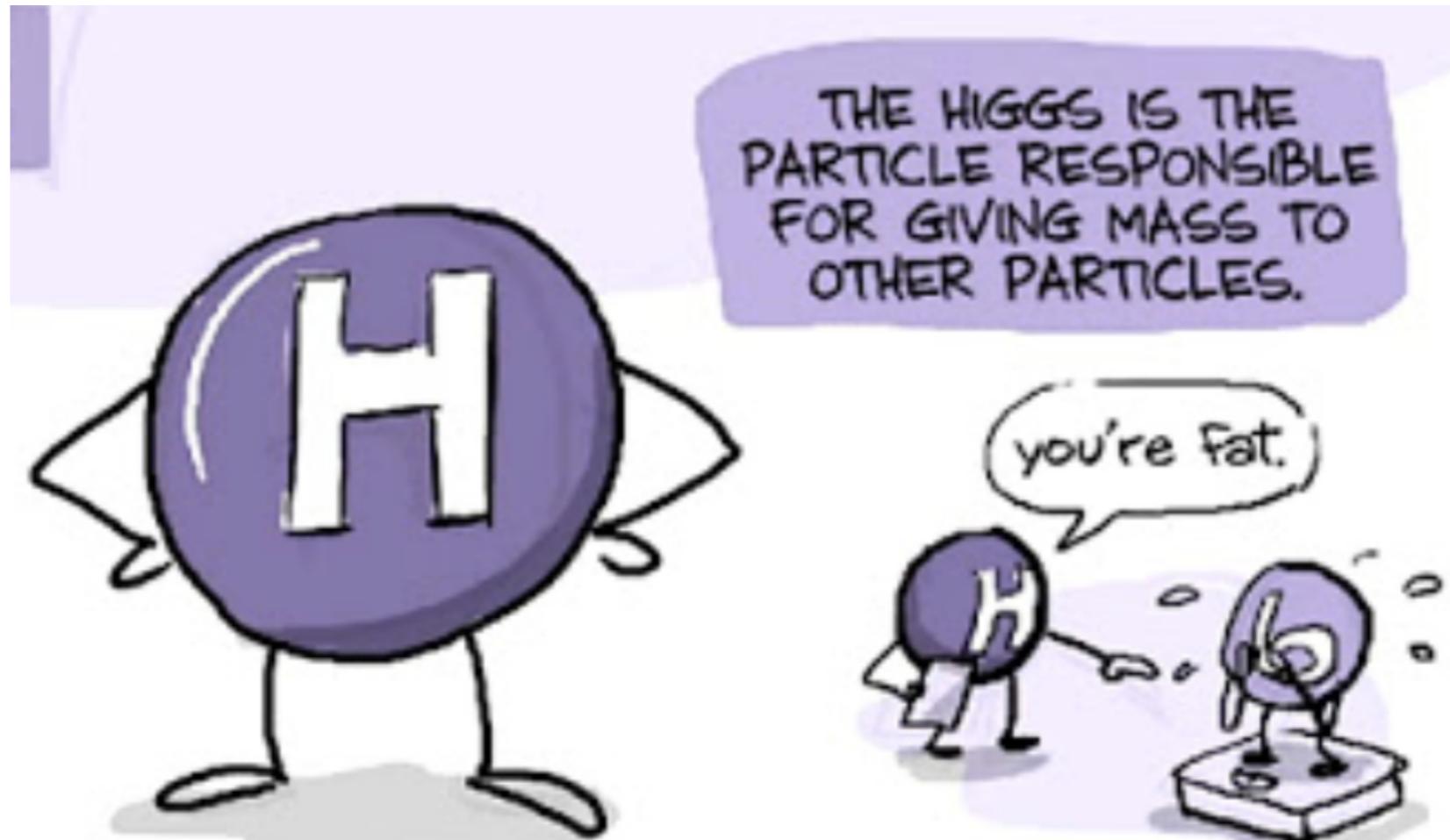
[R. Brout]
F. Englert
P. Higgs

Confirmation in decay into four leptons



Confirmation in decay into four leptons





<http://www.phdcomics.com/higgs/>

Great, we have discovered a new fundamental particle! Now what?

- When you have found something, you want to understand exactly what it is that you have found! (quote)
- Since the discovery, we are measuring in detail:

- Mass and Width
- Spin/Parity properties
- **“Coupling”** to other particles

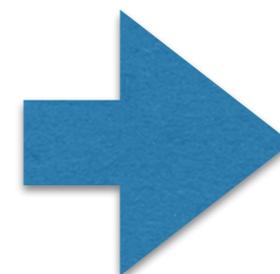
- This means how likely the Higgs boson is to interact to another particle

- To do this, many groups of physicists looked at measuring all accessible ways to **produce** a Higgs boson and to let the Higgs boson **decay**

Production

	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with tt
	✓	✓	✓	✓
	✓	✓	✓	✓
	✓	✓	✓	✓
	✓	✓	✓	✓
		✓	✓	✓

Decay



$$\mu = \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}}$$

How do theorists make predictions?

- They start from the Quantum Field Theory of the Standard Model (SM Lagrangian)

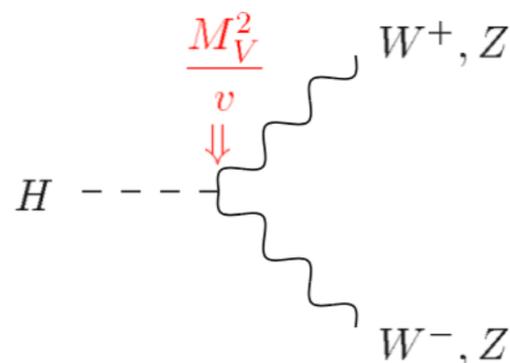
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + |D_{\mu} \phi|^2 - V(\phi) + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

- Then they compute the interaction probabilities (cross-sections or branching ratios)

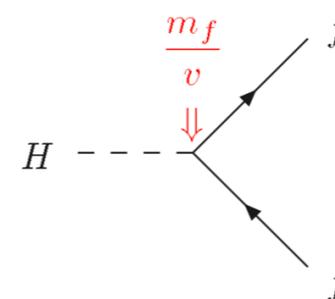
$$\sigma_{\text{Higgs}} \propto |\langle \text{Higgs} + X | H_{\text{int}} | pp \rangle|^2$$

$$\text{BR}_{ZZ} \propto |\langle ZZ | H_{\text{int}} | H \rangle|^2$$

- This selects specific Feynman diagrams out of the Lagrangian/Hamiltonian, their coefficients determine how strong the interaction is (**couplings**). For the Higgs Boson there are two categories of such diagrams:



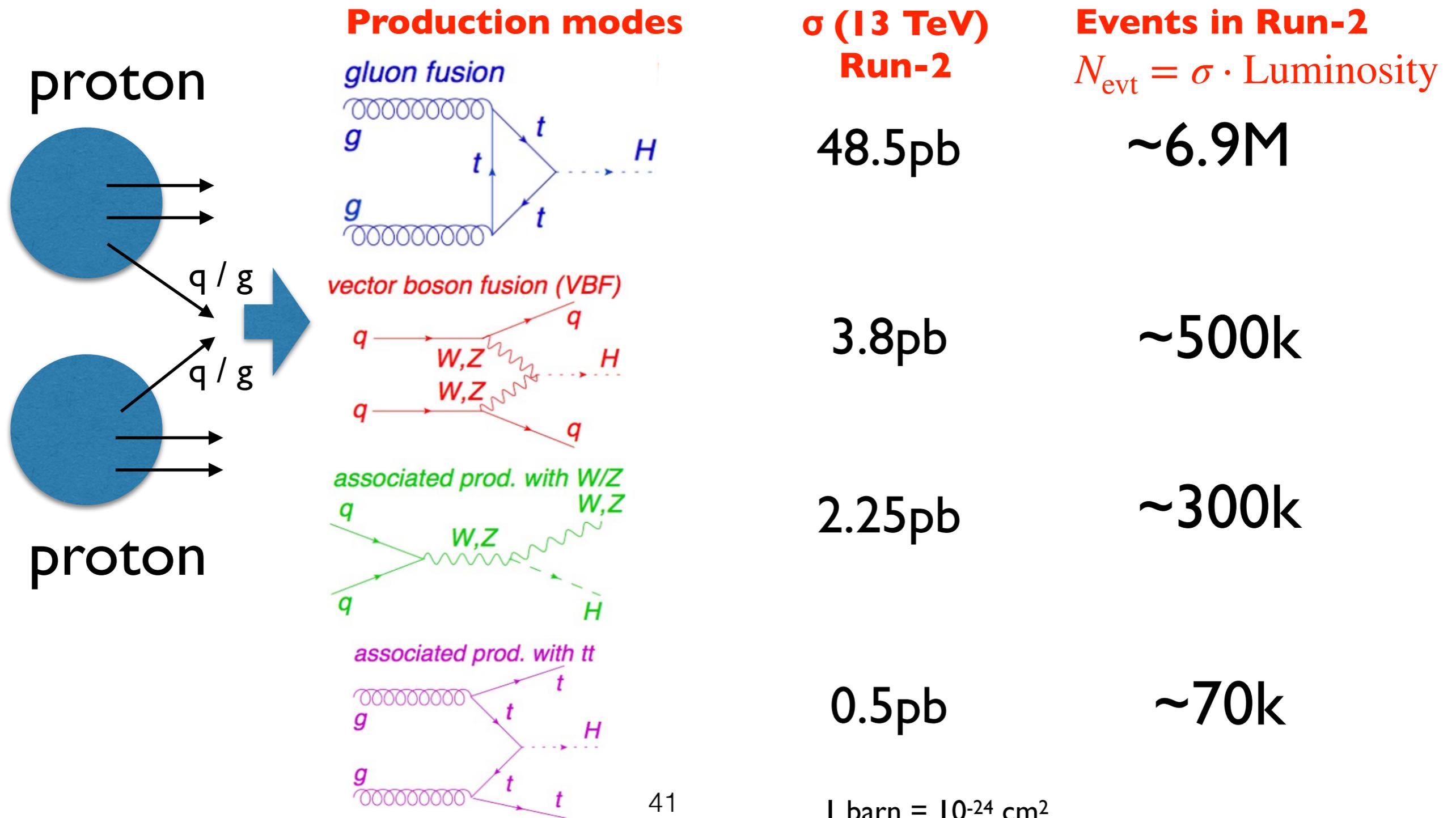
Couplings to massive vector bosons ($\propto M_V^2$)



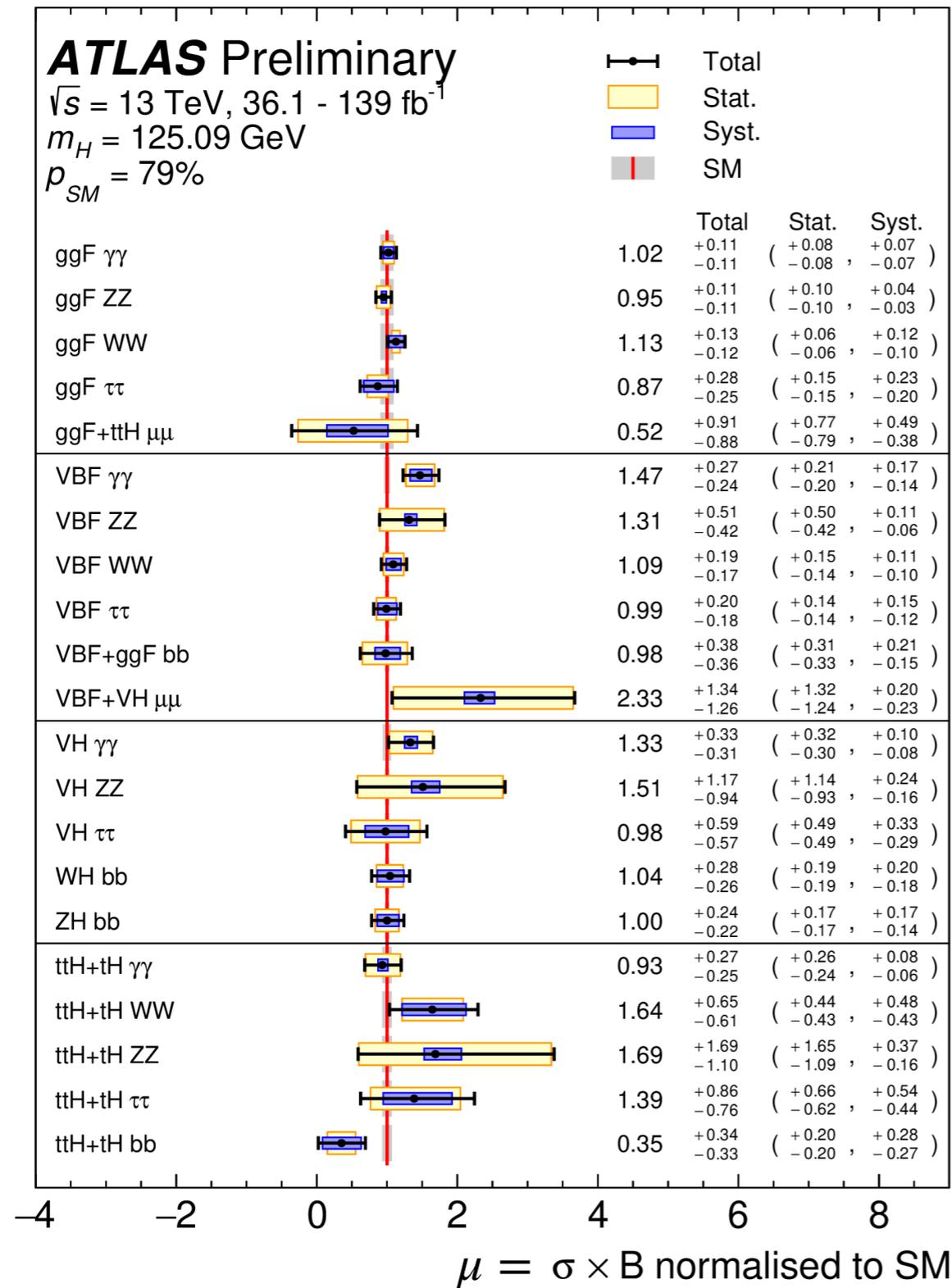
Couplings to massive fermions ($\propto M_f$)

How often is a Higgs Boson produced?

How does it look like for $\sqrt{s} \sim 13$ TeV and $m(\text{Higgs})=125$ GeV?



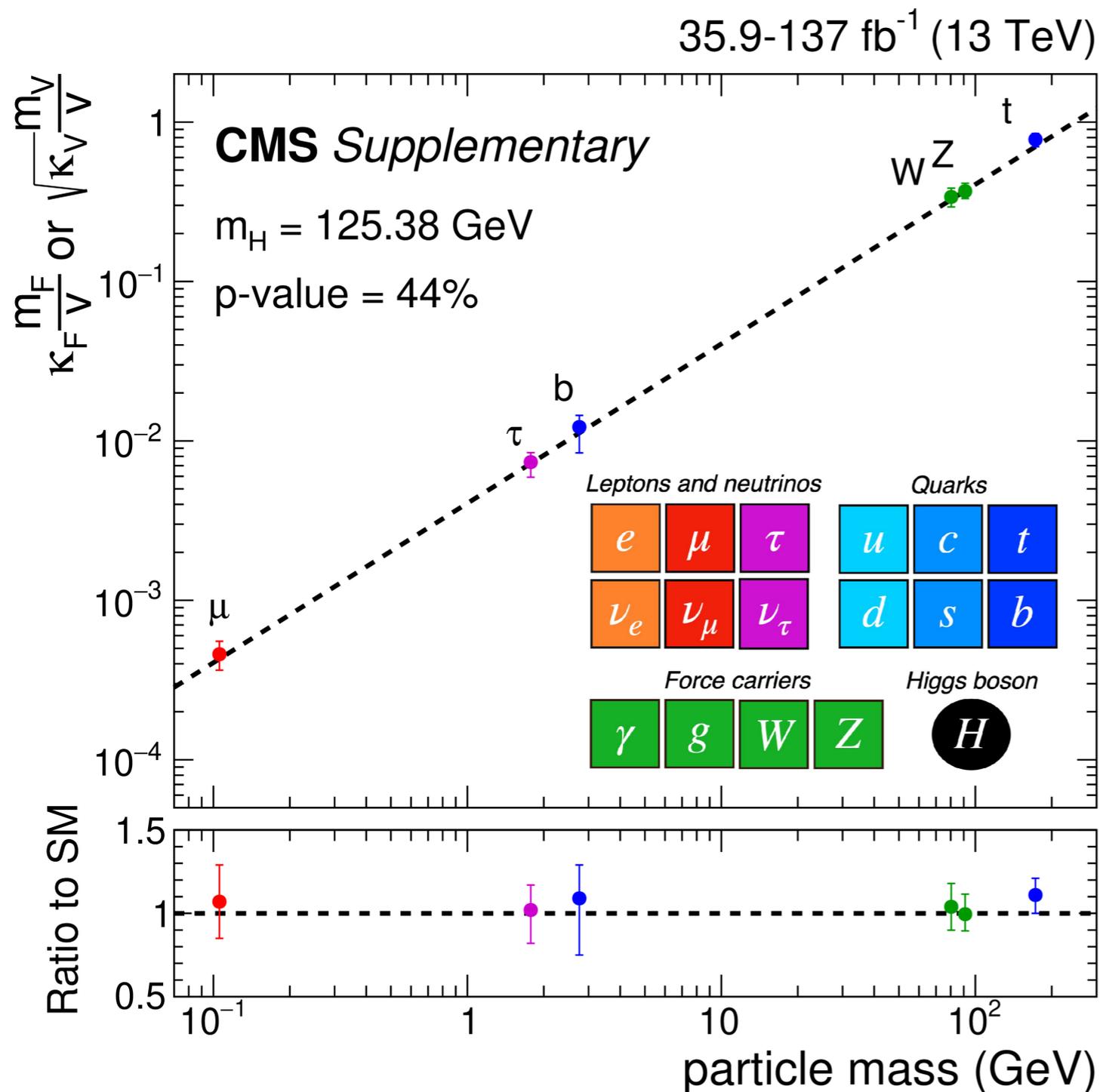
Latest Higgs boson measurements (2021)



- The precision of the measurements differs from channel to channel (**production** x **decay**)
- All measurements are compatible with the Standard Model prediction (~ 1)
- The global probability for the Standard Model to be compatible with the data is $>79\%$.
- These results can be translated into a measurement of the Higgs boson couplings (modifiers κ_j) based on **production** cross-section and **decay** branching ratios:

$$\sigma_{i \rightarrow H \rightarrow f} = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

Great, there is a new particle! Is it really the Higgs Boson predicted by Higgs?



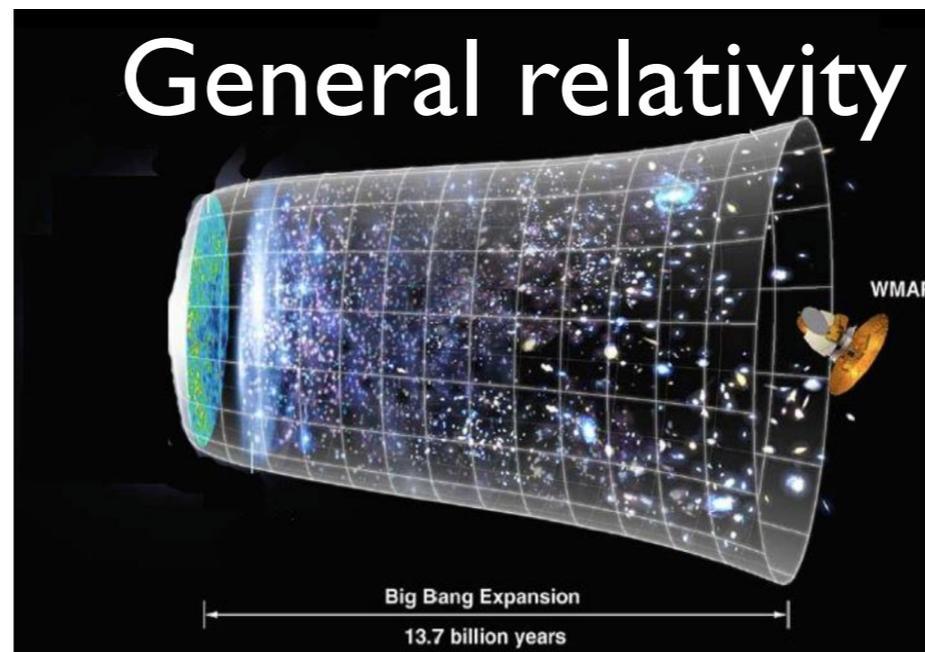
- We measured the Higgs boson couplings down to ~5-10% precision.
- So far, everything is in impressive agreement with the predictions.
- This is at the same time an incredible success, and an incredible disappointment!
- But:
 - The next big surprise could be just around the corner!

So: are we done?

Standard Model

mass	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$\approx 2.2 \text{ eV}/c^2$	$\approx 0.17 \text{ MeV}/c^2$	$\approx 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	$1/2$	$1/2$	0	
	$1/2$	$1/2$	$1/2$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

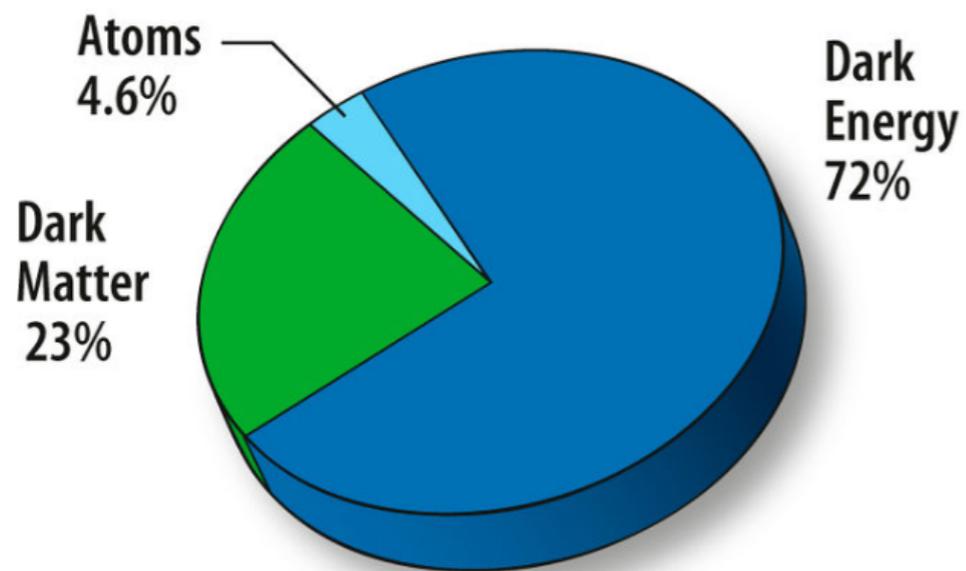
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Physics
phenomena
across
universe?

● No!



- From cosmological observations we know that the Standard Model only describes about 5% of today's universe
- **Dark Matter** (~25%) could be in the form of particles, and interacting very weakly with matter

Plenty of questions...

- In addition, the SM cannot explain:
 - Neutrino masses
 - Large matter-antimatter asymmetry observed in the universe
 - The mass hierarchy and the parameters of the SM
 - Hierarchy problem
 - Quantum theory of gravity
 - ...
 - ...
 - many many more.....

LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

2011

2012

2013

2014

2015

2016

2017

2018

2019

2020

2021

2022

2023

2024

2025

2026

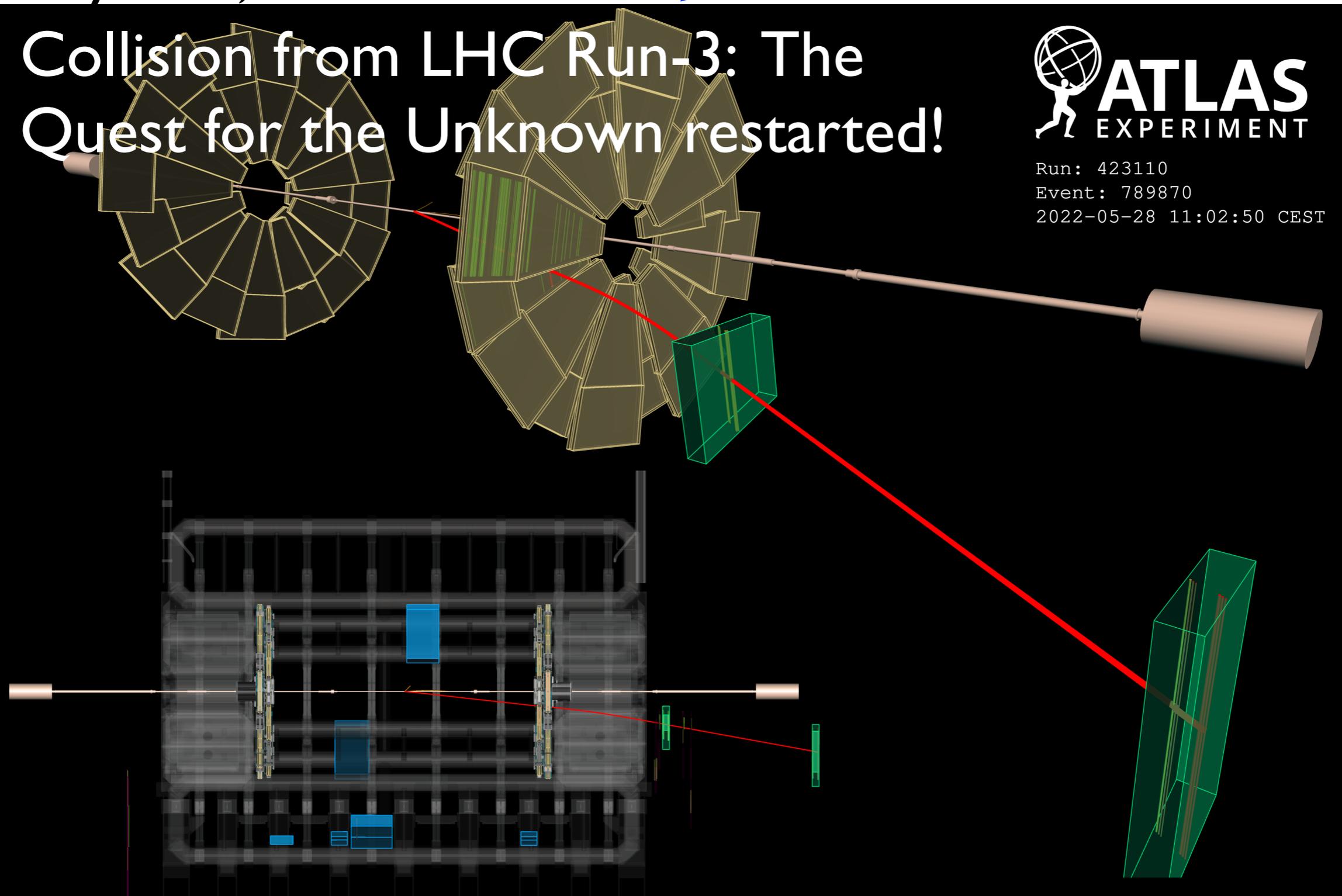
2038

May 28th, 2022

Collision from LHC Run-3: The Quest for the Unknown restarted!



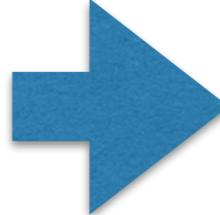
Run: 423110
Event: 789870
2022-05-28 11:02:50 CEST



Backup

SM: Challenges and successes

- Typical problem in particle physics:

• What is the probability that **{particles X}**  **{particles Y}**
turn into

- But:

- No analytic solution to the Standard Model theory exists.

- Usual solution: use **perturbation theory**

- Switch all interactions to zero, and solve the theory assuming only “free particles”
- Then compute interactions as an expansion in the fermion-boson coupling constant α

$$\text{Probability} = \alpha A_0 + \alpha^2 A_1 + \alpha^3 A_2 + \dots$$

LO NLO NNLO ...

- The number of “N” can scale \sim exponentially with the number of hours theorists dedicate to these (important) computations.

Plenty of questions...

- In addition, the SM cannot explain:
 - Neutrino masses
 - Can be added to the SM: but are they Dirac or Majorana? And what is their mass?

Plenty of questions...

- In addition, the SM cannot explain:
 - Neutrino masses
 - Large matter-antimatter asymmetry observed in the universe
 - Are sources of CP violation in SM enough? (Sakharov conditions)

Plenty of questions...

- In addition, the SM cannot explain:

- Neutrino masses
- Large matter-antimatter asymmetry observed in the universe
- The mass hierarchy and parameters of the SM

Leptons

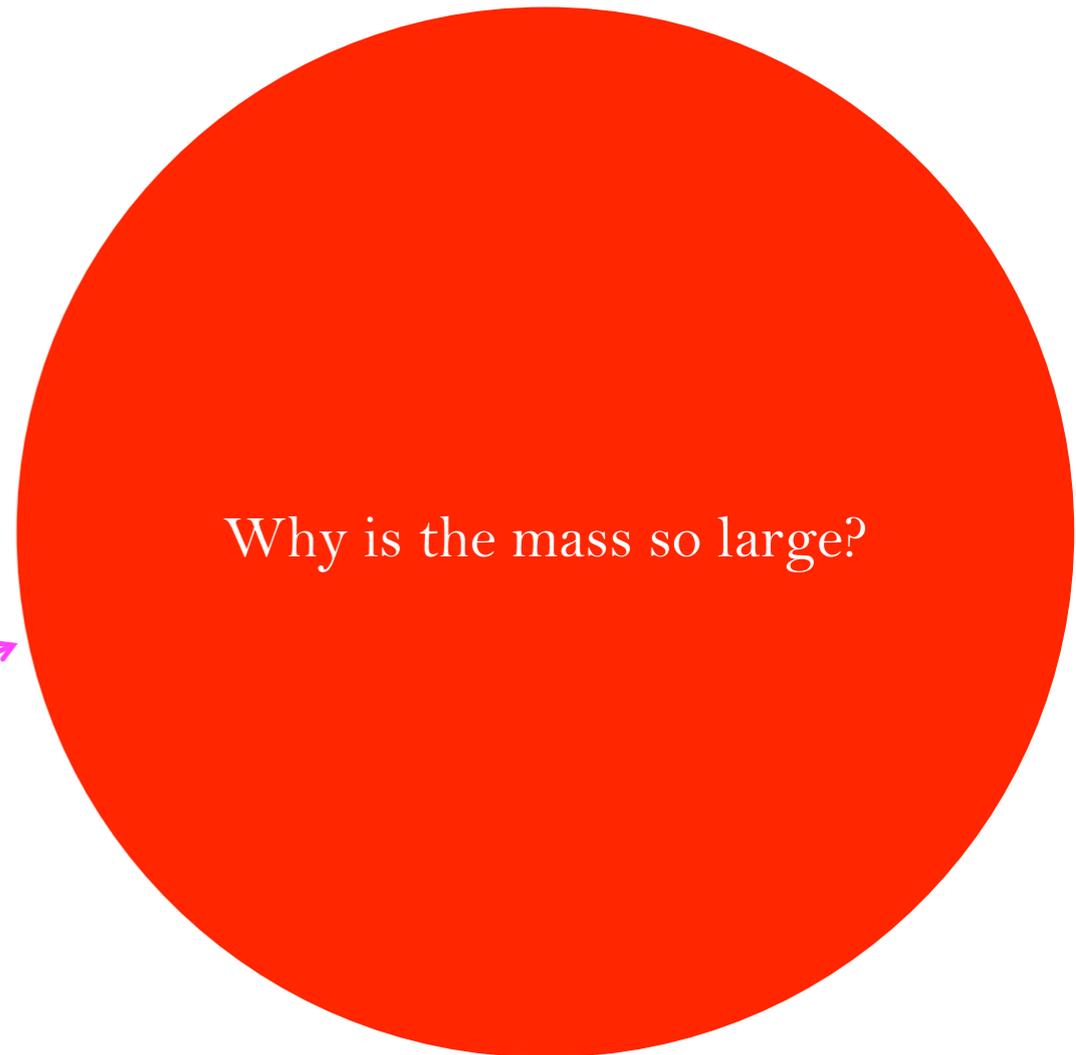
~ 0 ν_e ~ 0 ν_μ ~ 0 ν_τ

electron muon tau

Quarks

up charm top

down strange bottom



Plenty of questions...

- In addition, the SM cannot explain:
 - Neutrino masses
 - Large matter-antimatter asymmetry observed in the universe
 - The mass hierarchy and the parameters of the SM
 - Hierarchy problem

$$m_H^2 \approx m_{H,\text{bare}}^2 + \Lambda^2$$

$$\mathcal{O}(100\text{GeV}) = -\mathcal{O}(10^{19}\text{GeV}) + \mathcal{O}(10^{19}\text{GeV})$$

The physical measured mass is obtained through a huge and unnatural cancellation...

Plenty of questions...

- In addition, the SM cannot explain:
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 - The mass hierarchy and the parameters of the SM
 - Hierarchy problem
 - Quantum theory of gravity

Plenty of questions...

- In addition, the SM cannot explain:
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 - Hierarchy problem
 - Quantum theory of gravity
 - ...
 - ...
 - many many more.....

Advanced topics

- Higgs Field in QFT
(from my Graduate Particle Physics Course)

Reminder - SM interactions

Quantum Chromodynamics (QCD):

- SU(3) transformations, 8 gauge fields,
8 massless gluons, Gluon self-coupling
- T_a ($a = 1, \dots, 8$) generators of the SU(3) group
(independent traceless 3x3 matrices)
 - G_μ gluon fields
 - g = coupling constant

$$D_\mu = \partial_\mu + igT_a G_\mu^a$$

$$G_\mu^a \rightarrow G_\mu^a - \frac{1}{g} \partial_\mu \alpha_a - f_{abc} \alpha_b G_\mu^c$$

Electroweak Interaction (Glashow, Salam, Weinberg):

- SU(2)_L x U(1)_Y transformations,
4 gauge fields, ($W_\mu^1, W_\mu^2, W_\mu^3, B_\mu$)

Physical states:

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2)$$

$$Z_\mu = -\sin \theta_W B_\mu + \cos \theta_W W_\mu^3$$

$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3$$

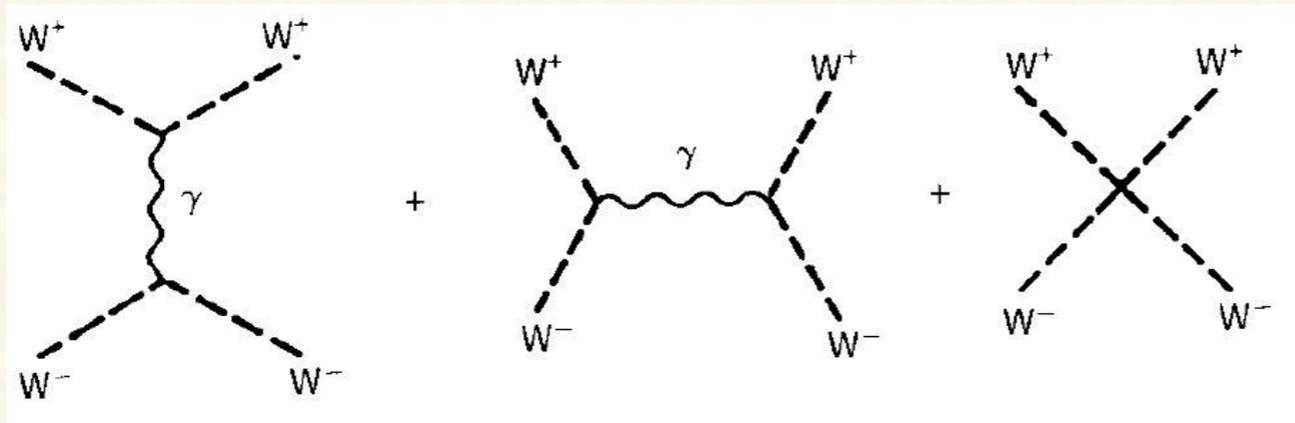
Problems at that stage:

- **Masses of the vector bosons W and Z:**

Experimental results: $M_W = 80.399 \pm 0.023 \text{ GeV} / c^2$
 $M_Z = 91.1875 \pm 0.0021 \text{ GeV} / c^2$

A local gauge invariant theory requires massless gauge fields

- **Divergences in the theory (scattering of W bosons)**



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

Solution to **both** problems:

- create mass via spontaneous breaking of electroweak symmetry
- introduce a scalar particle that regulates the WW scattering amplitude

→ **Higgs Mechanism**

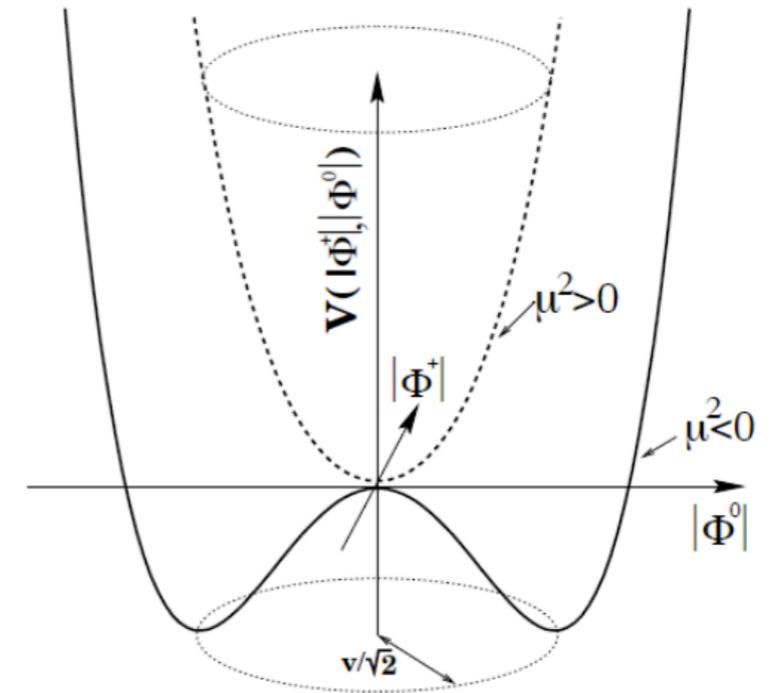
The Higgs mechanism

- Scalar fields are introduced

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Potential :

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$



- Lagrangian for the scalar fields:

$g, g' = \text{SU}(2), \text{U}(1)$ gauge couplings

$$L_2 = \left| \left(\partial_\mu + ig\mathbf{T} \cdot \mathbf{W}_\mu + ig' \frac{Y}{2} B_\mu \right) \phi \right|^2 - V(\phi)$$

- For $\mu^2 < 0, \lambda > 0$,
minimum of potential:

$$\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = v^2 \quad v^2 = -\mu^2 / \lambda$$

- Perturbation theory around
ground state:

$$\phi_0(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \Rightarrow$$

Notice that if we choose $Y/2 = 1/2$ for the Higgs doublet, then:

$$Q = \frac{Y}{2} + T_3 = \frac{Y}{2} \pm \frac{1}{2}$$

We choose $Y/2=1/2$
so that down-comp. of
Higgs field is neutral!

The Higgs mechanism (II)

(only kinetic part now)

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) = \frac{1}{2} (d^\mu h)^2 + \frac{1}{8} \left\{ \begin{bmatrix} -gW_\mu^3 + g'B_\mu & gW_\mu^1 - igW_\mu^2 \\ gW_\mu^1 + igW_\mu^2 & -gW_\mu^3 + g'B_\mu \end{bmatrix} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \right\}$$

$$M_{W^\pm} = \frac{1}{2}vg$$

$$= \frac{1}{2} (d^\mu h)^2 + \left[\frac{1}{2} g (v+h) \right]^2 W_\mu^+ W_\mu^- + \frac{1}{8} (v+h)^2 \left[\underbrace{gW_\mu - g'B_\mu}_{Z_\mu \cdot \sqrt{g^2 + g'^2}} \right]^2$$

- Massless photon:

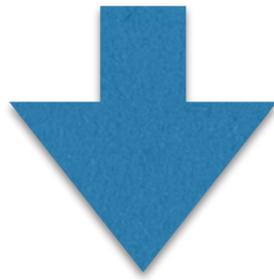
$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with} \quad M_A = 0$$

- Massive neutral vector boson:

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}} \quad \text{with} \quad M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}$$

An important relation

$$M_{W^\pm} = \frac{1}{2}vg$$



- From the M_W relation the value of the vacuum expectation value of the Higgs field can be calculated:

$$\frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \quad \rightarrow \quad v = 246 \text{ GeV}$$

where G_F = Fermi constant, known from low energy experiments (muon decay)

Higgs potential $V(\phi)$

(only potential part now)

$$V(\phi) = \mu^2 \frac{1}{2} (\sigma + h)^2 + \frac{\lambda}{4} (\sigma + h)^4 \quad \text{with } \sigma^2 = -\frac{\mu^2}{\lambda}$$

- So the Lagrangian terms (kinetic + potential) that include the Higgs terms are:

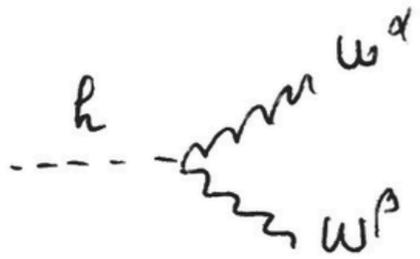
$$\mathcal{L}_H = \frac{1}{2} \left[(\partial^\mu h)^2 + 2\mu^2 h^2 \right] - \lambda h^3 \sigma - \frac{\lambda}{4} h^4 + M_W^2 \omega_+^\mu \omega_\mu^- \left(\frac{2h}{\sigma} + \frac{h^2}{\sigma^2} \right)^2 + \frac{1}{2} M_Z^2 z^\mu z_\mu \left(\frac{2h}{\sigma} + \frac{h^2}{\sigma^2} \right)$$

where $h \equiv$ neutral scalar
 \equiv Higgs boson

$$m_H^2 = -2\mu^2 = 2\lambda\sigma^2$$

- In addition to kinetic and mass term for the Higgs boson, the other terms represent interaction terms between the Higgs boson and other Standard Model particles.

Feynman diagrams



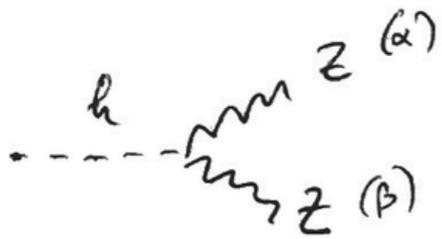
$$+ i 2 \frac{M_W^2}{v} = i g M_W g^{\alpha\beta}$$



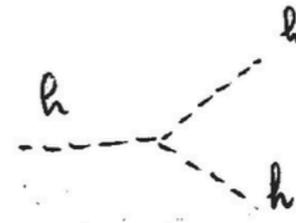
$$\frac{i}{2} g_Z^2 g^{\alpha\beta}$$

$$\downarrow$$

$$\frac{g^2}{\cos^2 \theta_W}$$



$$i 2 \frac{M_Z^2}{v} = i g_Z M_Z g^{\alpha\beta}$$



$$-i 6 \lambda = -3i \frac{m_H^2}{v}$$



$$i \frac{g^2}{2} g^{\alpha\beta}$$



$$-i 6 \lambda$$

Fermion masses

- While boson masses arise from the covariant derivatives, fermion masses need to be added "ad-hoc"

$$\mathcal{L}_{\text{YUKAWA}} = -\lambda_e \bar{L}_L \phi e_R - \lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L (i\sigma_2 \Phi^*) u_R + \text{h.c.}$$

$i\sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ *inverts up and down type components*

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$$

The first term is:

$$\frac{\lambda_e}{\sqrt{2}} [(\bar{\nu}_L, \bar{e}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} e_R + \text{h.c.}]$$

$$= \underbrace{\frac{\lambda_e v}{\sqrt{2}} (\bar{e}_L e_R + \text{h.c.})}_{\text{MASS TERM}} + \underbrace{\frac{\lambda_e}{\sqrt{2}} (\bar{e}_L e_L h + \text{h.c.})}_{\text{coupling between fermions and Higgs boson}}$$

coupling proportional to fermion mass

