Higgs boson

https://xkcd.com/1437

QuarkNet Summer Session for Teachers: The Standard Model and Beyond

Allie Reinsvold Hall

Summer 2024

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Chemistry to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. **Particle physics at colliders**
4. Beyond the Standard Model at the LHC
5. Neutrino physics
6. Dark matter and cosmology

Goal: Bring you to whatever *your* next level of understanding is and provide resources for when you teach. Not everyone is at the same level and that's okay.

Plan for today

- Loose ends from Session 2
- Discussion in breakout rooms

- Lecture: protons, neutrons, neutrinos

- 10 minute break

- Lecture: particle zoo, quark model
- Homework discussion in breakout rooms – CMS e-lab

- Final logistics, plan for next week

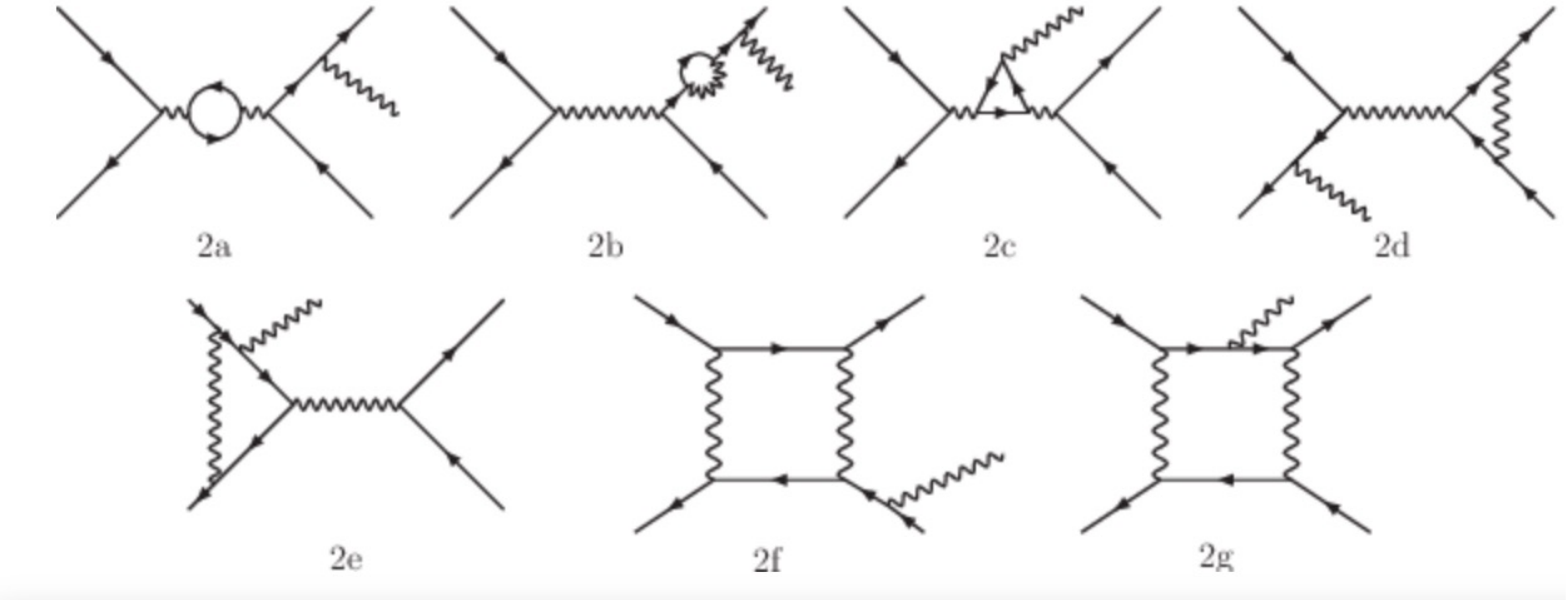
Loose ends from Session 2

- Recommendation: http://hyperphysics.phy-astr.gsu.edu/hbase/index.html
  - Physics concepts maps from Georgia State

- Feynman diagram tool: https://blog.c0nrad.io/feynman/#/
  - Lots of other good ones out there, like this "game": https://web.physik.rwth-aachen.de/user/harlander/software/feyngame/

Loose ends from Session 2

- What do the arrows mean in Feynman diagrams?
  - Time flows left to right
  - An arrow pointing right represents a **particle**
  - An arrow pointing left represents an **antiparticle**
  - All QED vertices need one arrow coming in, one going out
    - Guarantees **conservation** of electric charge



Example next-to-leading order (NLO) Feynman diagrams for

$e^+ + e^- \rightarrow e^+ + e^- + \gamma$

10.1016/j.physletb.2009.11.035

Loose ends – discussion

- How do we smash more modern physics into a general physics course? (I think I mean mostly time-wise/planning units-wise? - e.g. what do you cut of the traditional/classical stuff)
- How can we connect some of this physics to our curriculum or even other science curriculums?
- How do we use the D0 plots in the classroom in a way that the students will actually understand?

You all are better equipped to answer that than I am – time for breakout discussions!

Introduce yourself to today's group.

Add thoughts to the class google doc (link in chat)

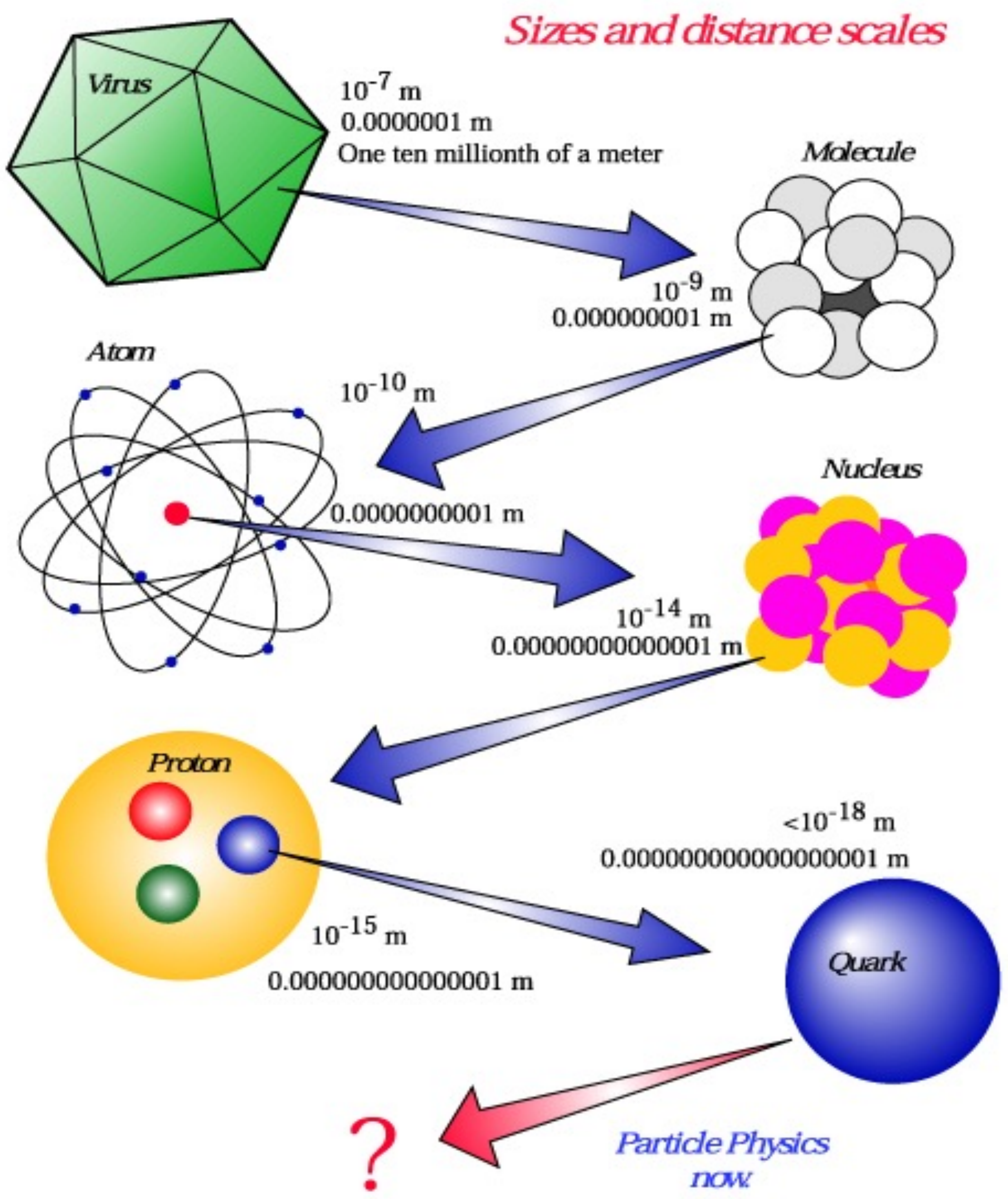
Particle Physics at Colliders

"Why God particle? The publisher wouldn't let us call it the Goddamn Particle, though that might be a more appropriate title."

- Leon Lederman, The God Particle, 1993

Why do we need accelerators?

- Recall de Broglie: $\lambda = h/p$
  - **Higher momentum** means we can probe **smaller scales**
- Recall Dirac:
  - $E^2 = p^2c^2 + m^2\,c^4$
  - **More energy** means we can create new particles of **higher mass**
- More energy available in head-on collisions → **colliders**!



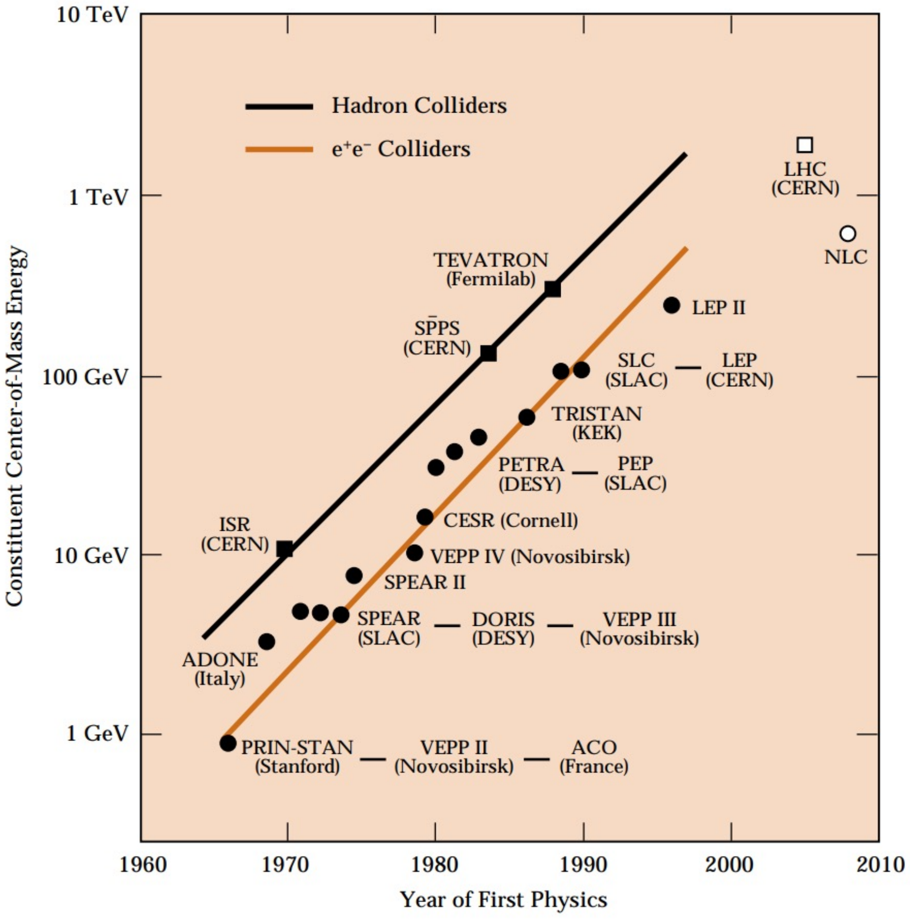
Technology drives discovery

- For the last 100 years (and foreseeable future), particle physics has been limited by the **energies** we can reach

Two general classes:

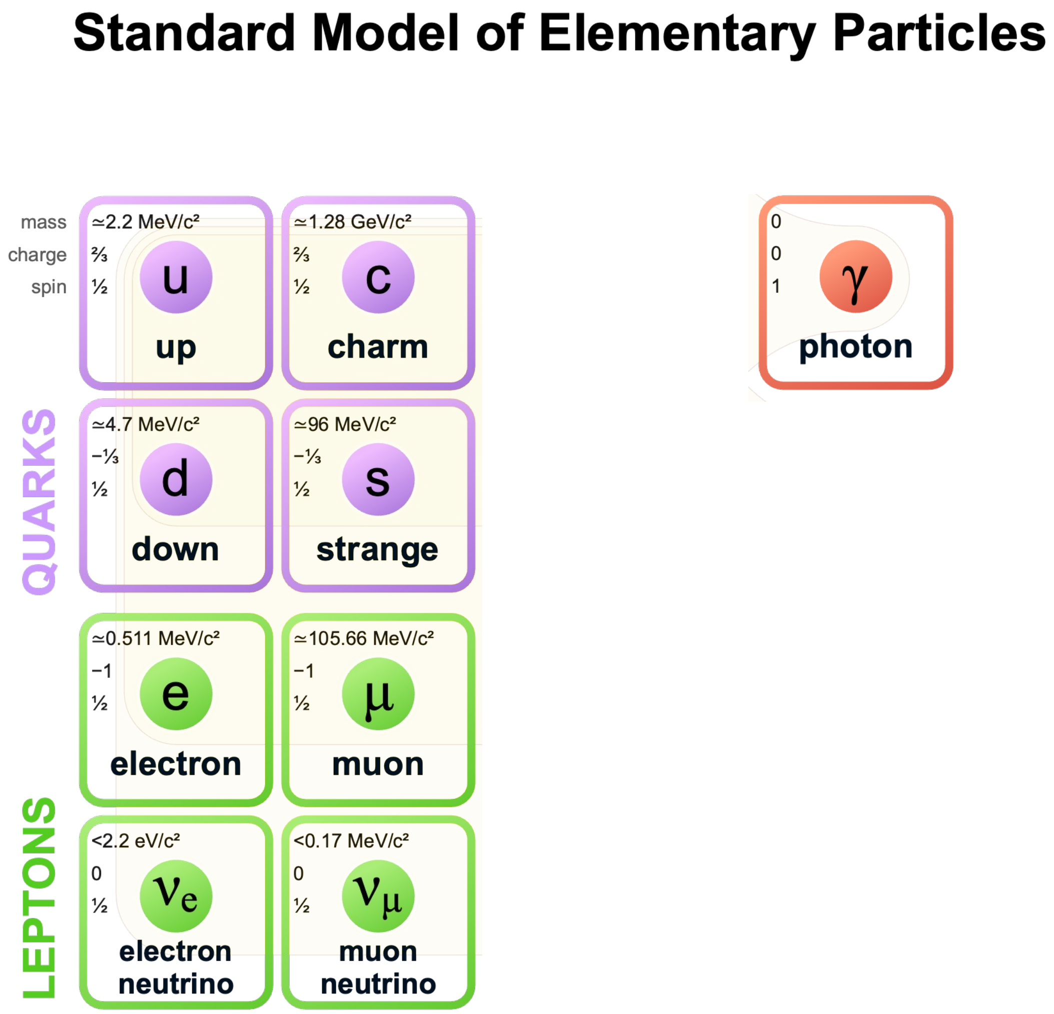
- Hadron colliders (eg proton-proton collisions at the LHC)
  - Actually quarks **within** the protons that collide
- Lepton colliders (eg e^+e^- collisions at LEP)
  - Cleaner collisions, but harder to reach high energies

- Other important property: **luminosity**
  - Essentially, the interaction **rate** of the collider



https://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf

Checkpoint: Standard Model in 1974



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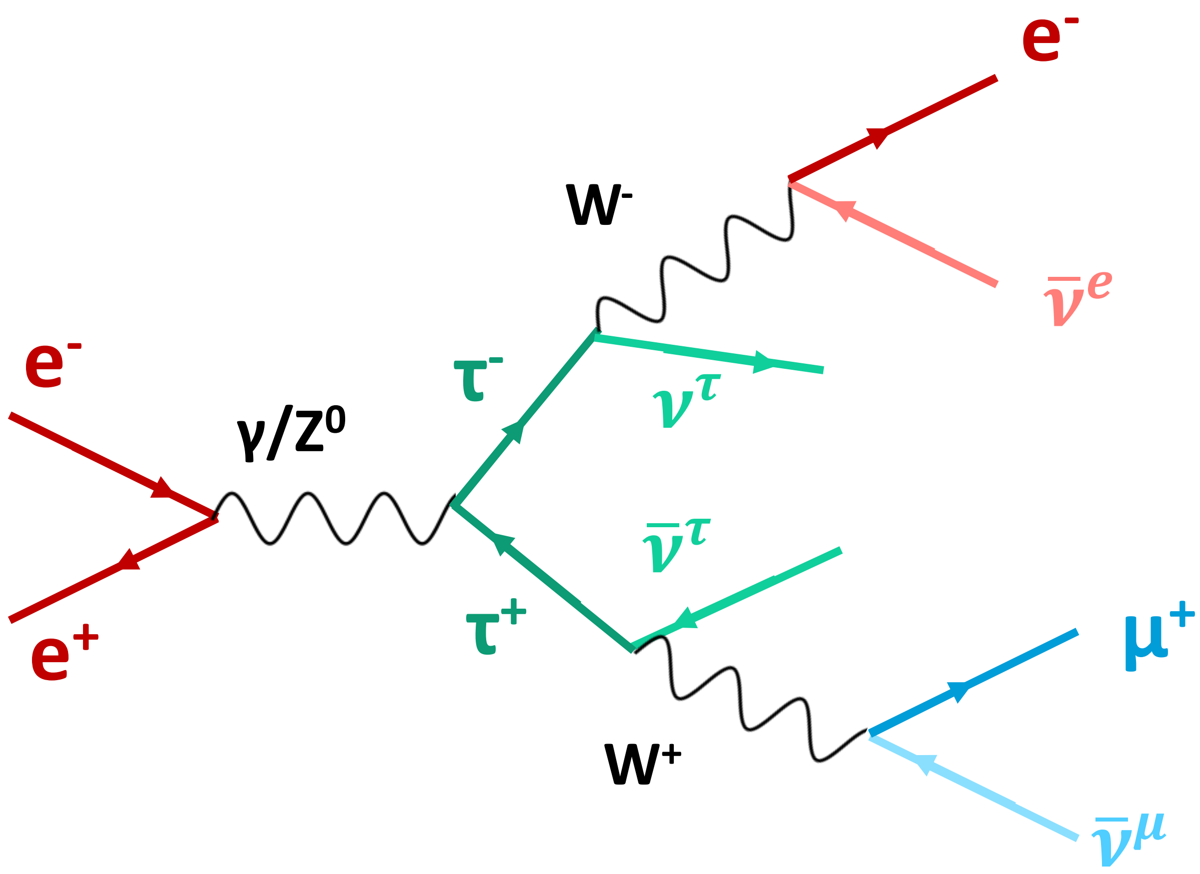
Two ***generations*** of quarks and leptons

Million-dollar question:

Are there more quarks or leptons at higher mass?

Third generation: τ lepton, 1975

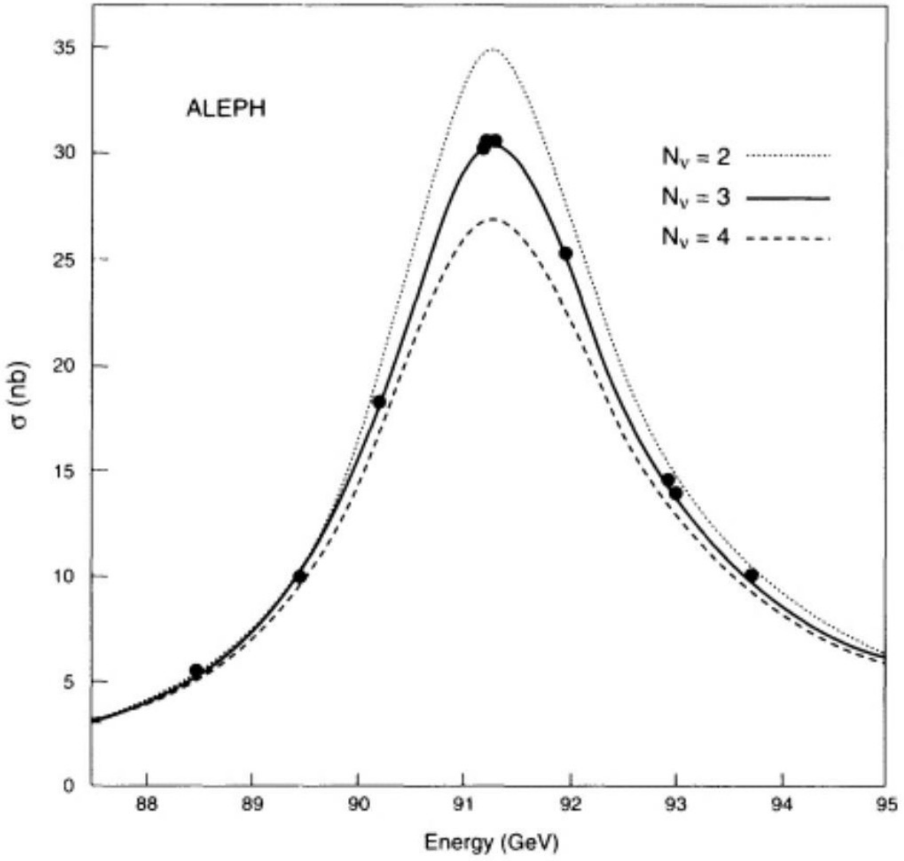
- Discovered in 1975 by Martin Perl's (1927 – 2014) group at SLAC using SPEAR
- Z boson: "neutral current"; $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ or $\tau^+\tau^-$
- $W^\pm$ bosons: "charged current"; $W^+ \rightarrow e^+\nu^e$ or $\mu^+\nu^\mu$ or $\tau^+\nu^\tau$
- Final state: 4 neutrinos, 1 electron, 1 muon
- Perl's group observed **64 events**
- Current best: $m_\tau = 1.78$ GeV
- τ can also decay "hadronically" (i.e. into hadrons)
  - Occurs 65% of the time
  - But hadrons are messier



1995 Nobel Prize

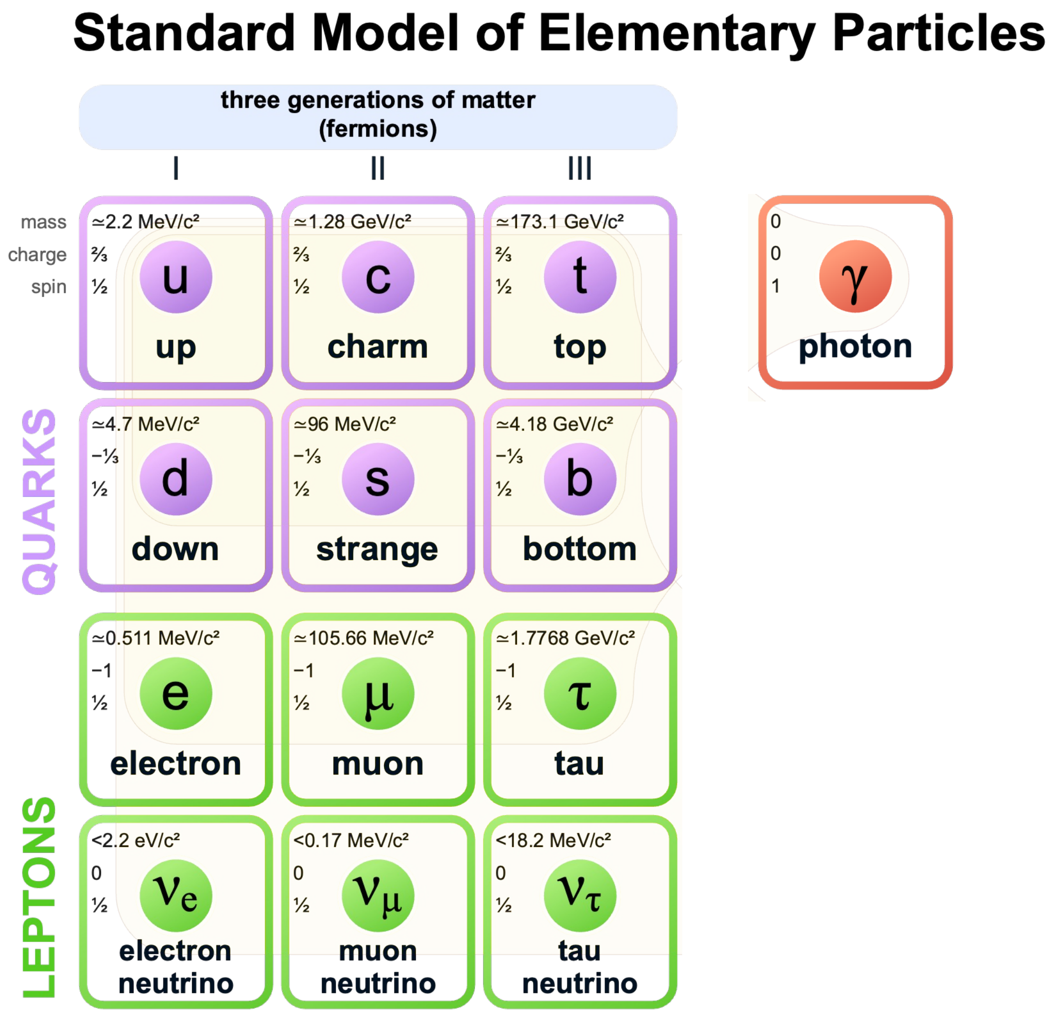
Finishing the 3rd generation

- 1977: Upsilon Υ meson discovered at Fermilab by Leon Lederman and his group
  - Υ is a bb bound state, mass 9.5 GeV
  - Bottom quark mass: 4.2 GeV
  - Similar to J/psi discovery of charm quark
- 1995: Top quark discovered at the Fermilab Tevatron by the D0 and CDF collaborations
  - Mass 173 GeV
  - Decays almost 100% of the time to Wb
- Are we done?
  - We think so… current evidence favors 3 generations
    - Measurements of the Z peak
    - Cosmology constraints from element abundances after the Big Bang



CERN/ALEPH Collaboration

Checkpoint: Standard Model



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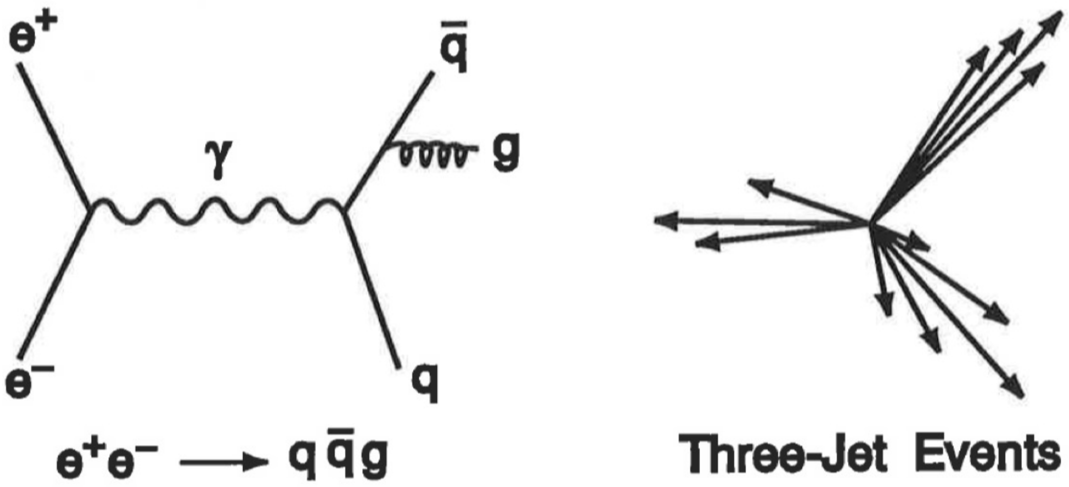
What about the bosons? Gluons

- **Gluons** are carriers of the **strong force**
- 1979 discovery: TASSO at PETRA e^+e^- collider at DESY in Germany
- Search for "3 jet events" from $e^+e^- \rightarrow qqg$
  - Jet = spray of particles from decay of quark
  - Two spin 1/2 particles (e^+e^-) cannot lead to three spin 1/2 particles
    → one jet must be from a **boson**
  - If particle decays into a jet, must have **color charge** → rules out hadrons like K, π
- Gluon's spin of 1 was experimentally confirmed a year later



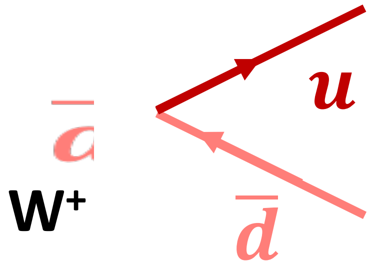
https://indico.cern.ch/event/704471/contributions/3012502/attachments/1670841/2680256/Wu.pdf

What about the bosons? W and Z

- **W and Z bosons** first proposed in 1950s as carriers of the **weak force**
- Discovered in 1983 by UA1 and UA2 Collaborations at CERN, led by Carlo Rubbia
  - Accelerator technology developed by Simon van der Meer
  - Z boson: neutral, mass of 91 GeV
  - W bosons: charge of ±1, mass of 80 GeV

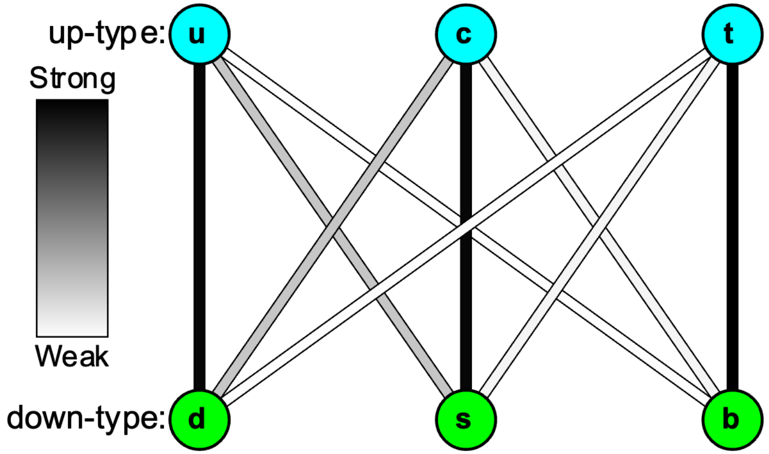
1984 Nobel Prize

- W boson changes "flavor" of quarks
  - CKM (Cabibbo, Kobayashi, Maskawa) matrix specifies strength of flavor-changing interactions between quarks
  - Predicted 3 generations back when only 2 had been observed



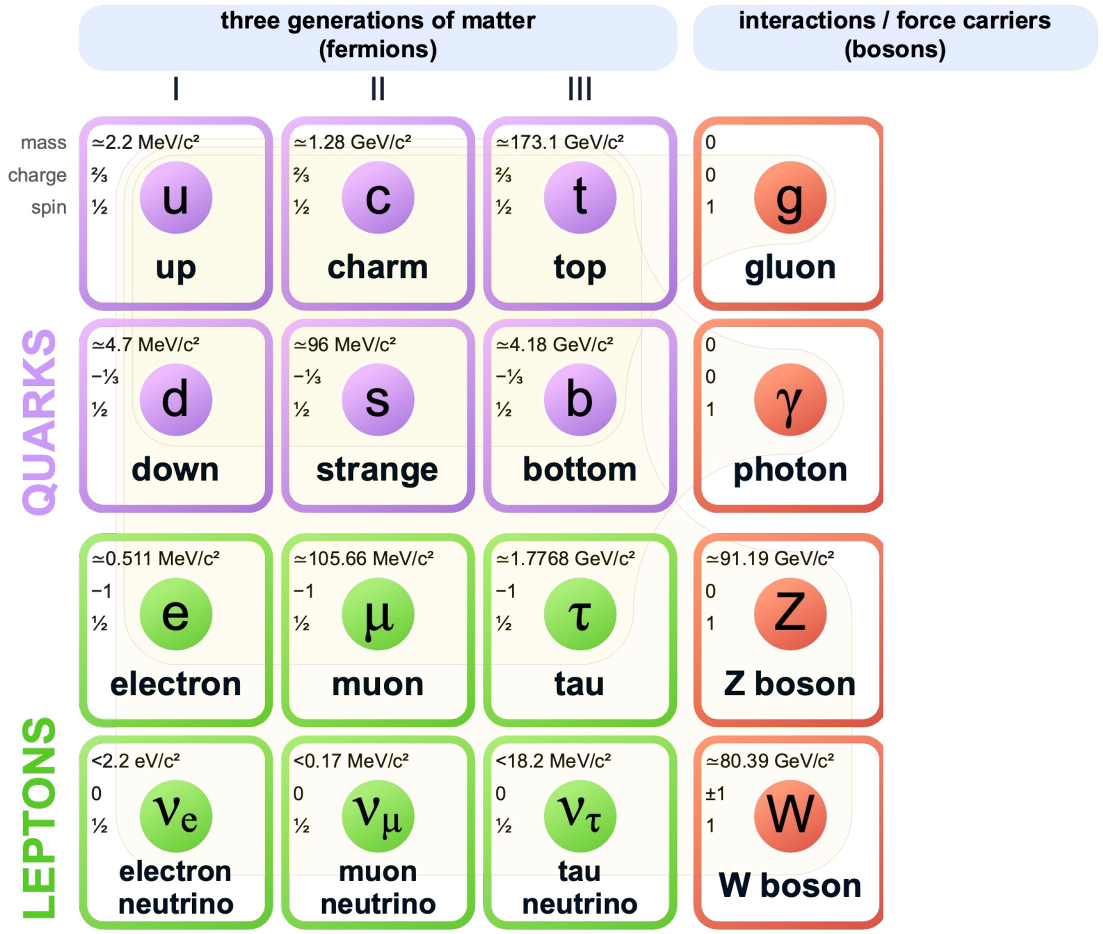
2008 Nobel Prize

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$



Checkpoint: Standard Model

Standard Model of Elementary Particles



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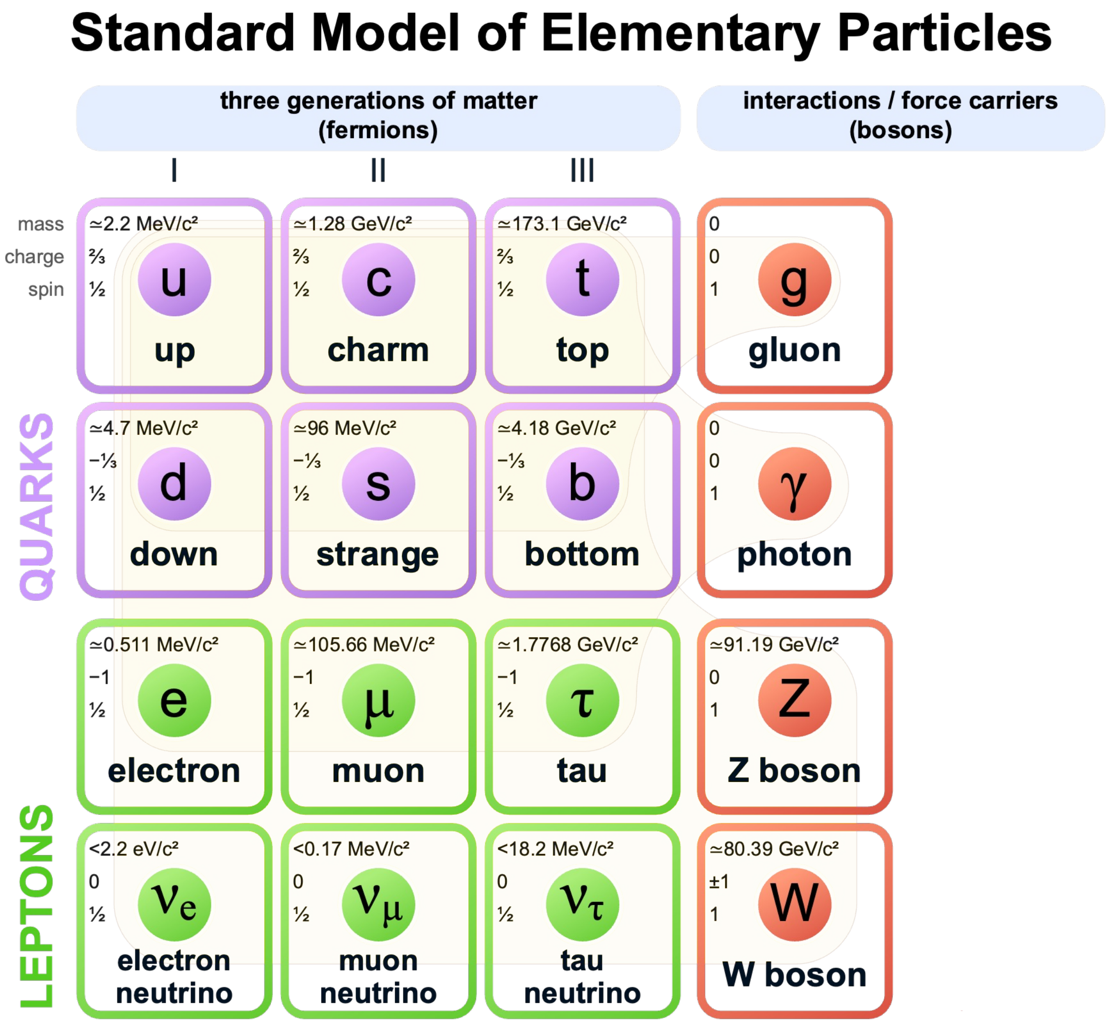
Last piece of the puzzle



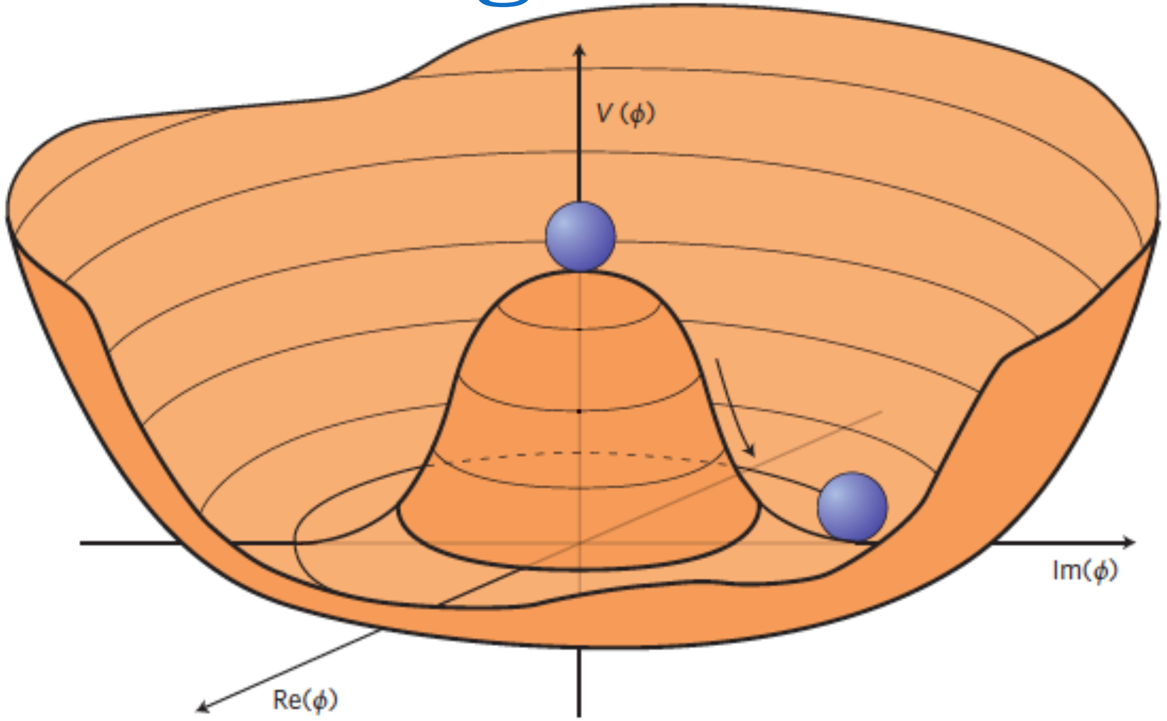
- Last missing piece = **Higgs boson**

- Higgs mechanism was developed in the 1960’s by Peter Higgs, Robert Brout, François Englert and others to explain how particles get their mass
- New particle predicted, the **Higgs boson**

https://cds.cern.ch/record/1638469/plots

Spontaneous symmetry breaking

- Start with non-zero "vaccum expectation value" (vev) for the Higgs field ϕ
- Higgs field "spontaneously" rolls to the minimum, breaking the symmetry
- 3 out of 4 degrees of freedom used to give mass to the W^+, W^-, Z^0 bosons
- Interaction with the Higgs field gives mass to the fermions
  - Higher mass = stronger interactions



<u>Before symmetry breaking</u>

- Higgs field φ at unstable maximum
- Higgs field has 4 degrees of freedom
- 4 massless bosons
- Unified electroweak force

<u>After symmetry breaking</u>

- φ at minimum
- Higgs field has 1 degree of freedom
- 3 massive gauge bosons + photon
- Separate EM and weak forces

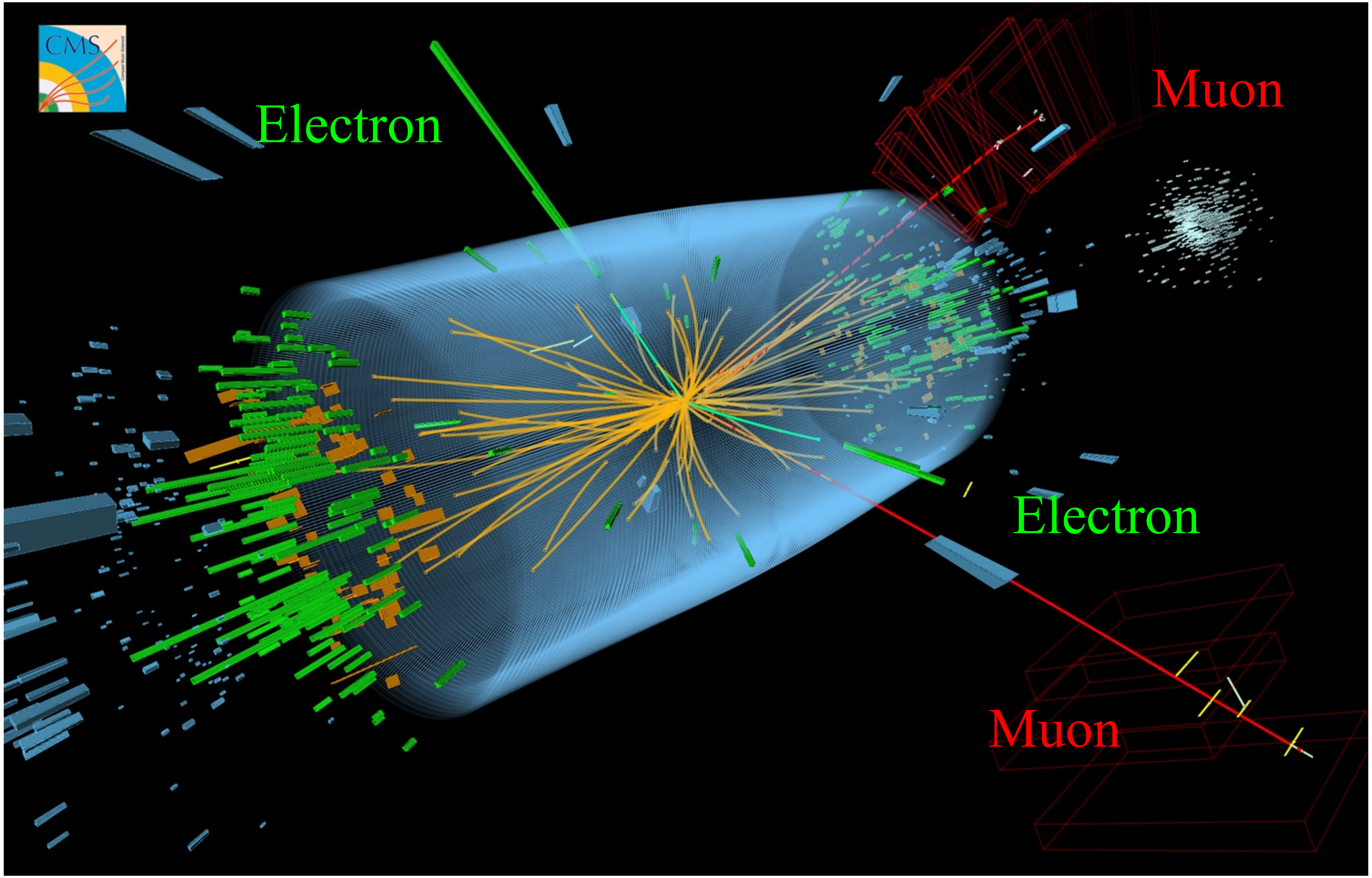
How a Higgs boson decays

- 1 in 10 billion collisions will contain a Higgs boson
- Each possible way to decay is called a decay channel
- Higher chance to decay into heavy fermions (b, τ)

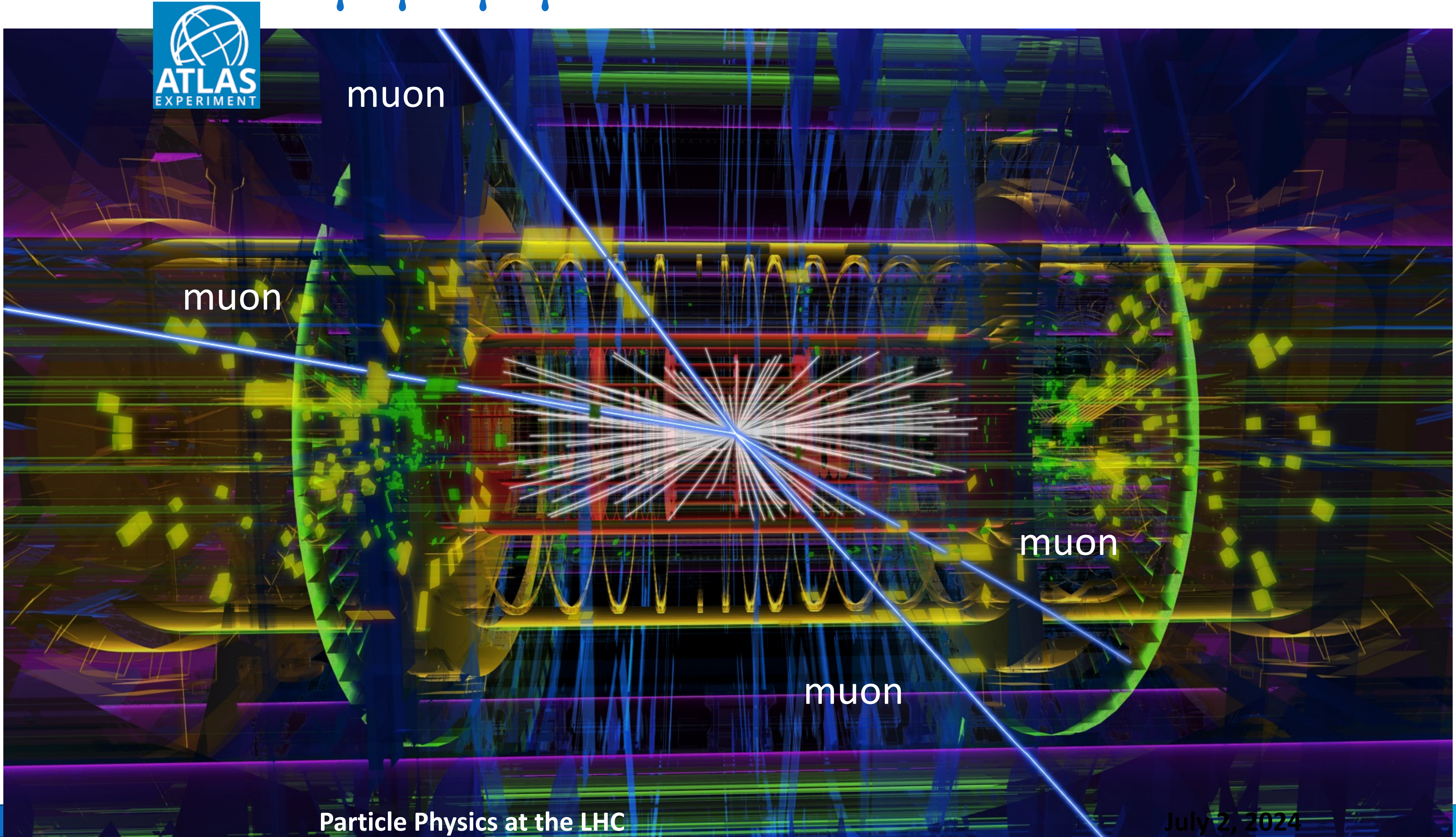
Higgs $\rightarrow b + \bar{b}$	(b quark and its antiquark)
Higgs $\rightarrow \tau^{+} + \tau^{-}$	(τ lepton and its antiparticle)
Higgs $\rightarrow \gamma + \gamma$	(two photons, also called gammas)
Higgs $\rightarrow W^{+} + W^{-}$	(W boson and its antiparticle)
Higgs $\rightarrow Z^{0} + Z^{0}$	(Two Z bosons)

- Different strategies and tools are used to search for the Higgs in each of these channels

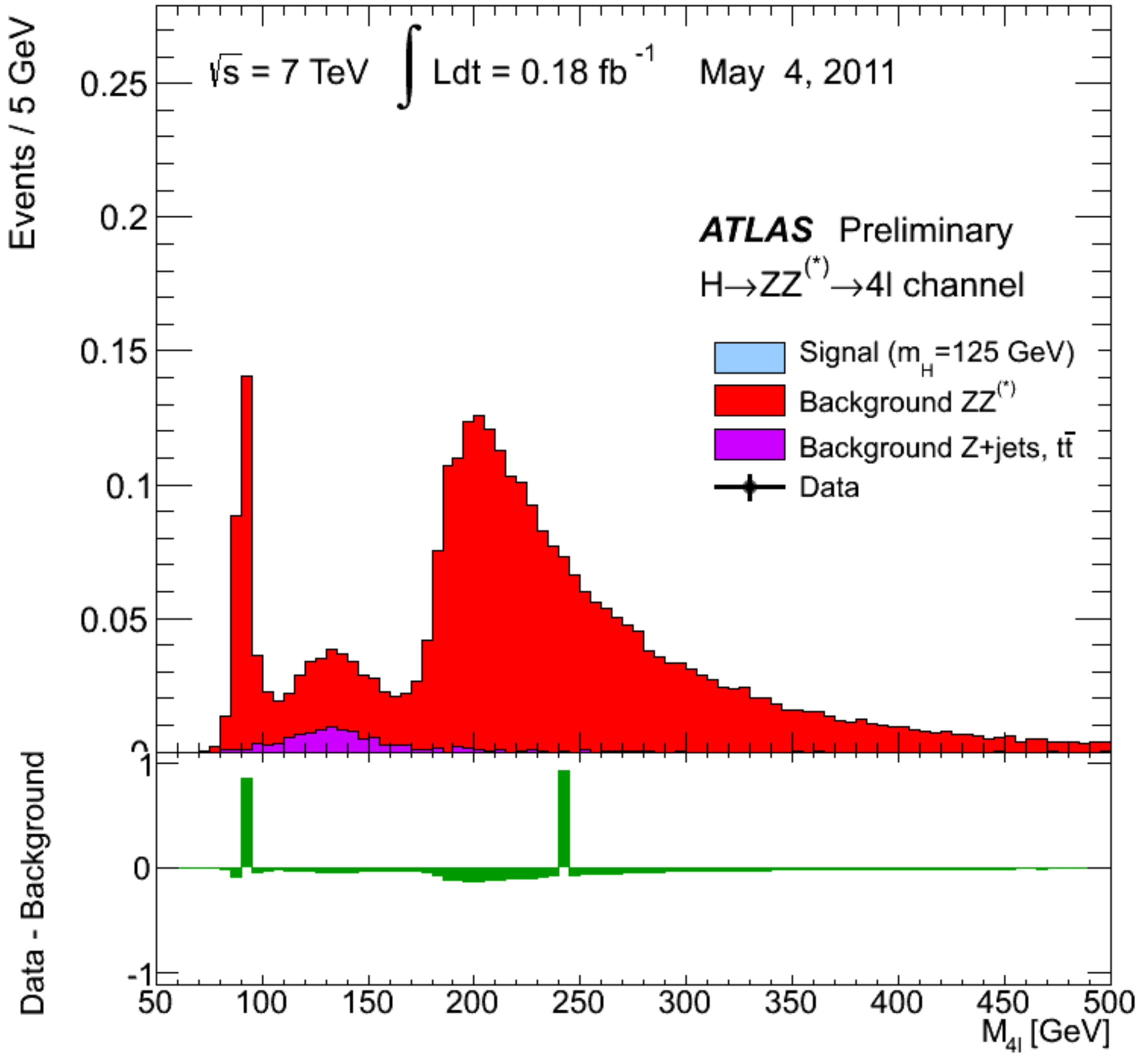
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+\mu^-$ candidate event



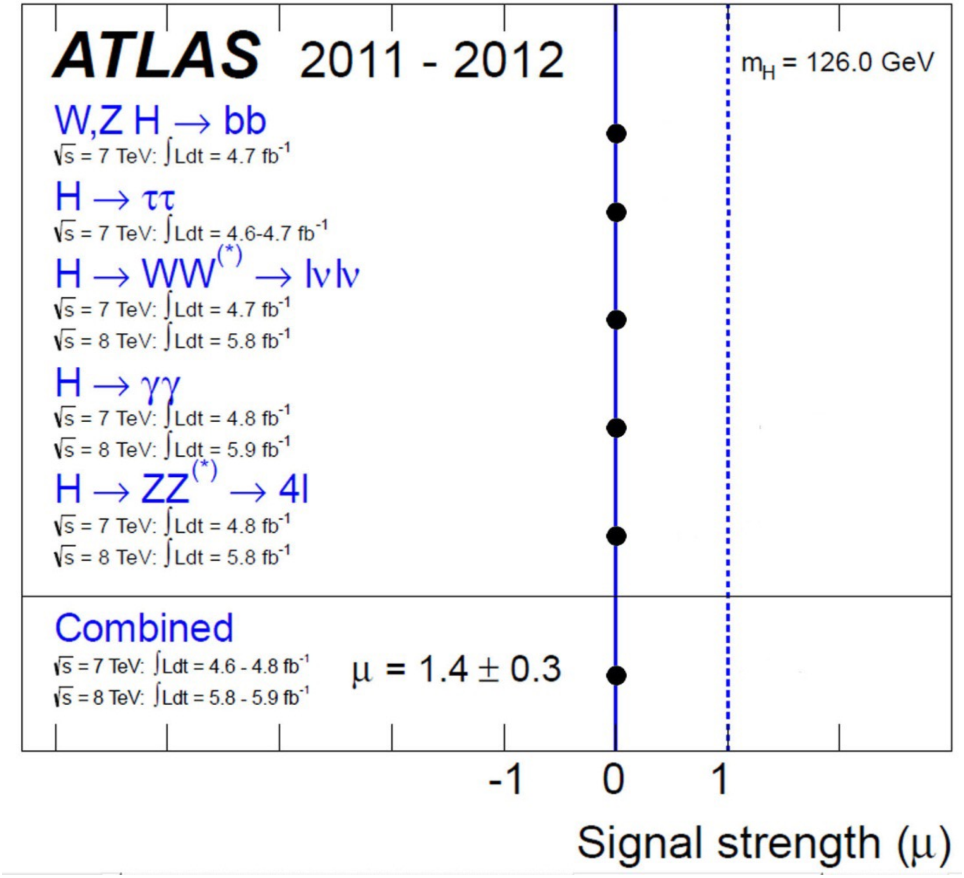
$H \to ZZ \to \mu^+\mu^- \mu^+\mu^-$ Candidate

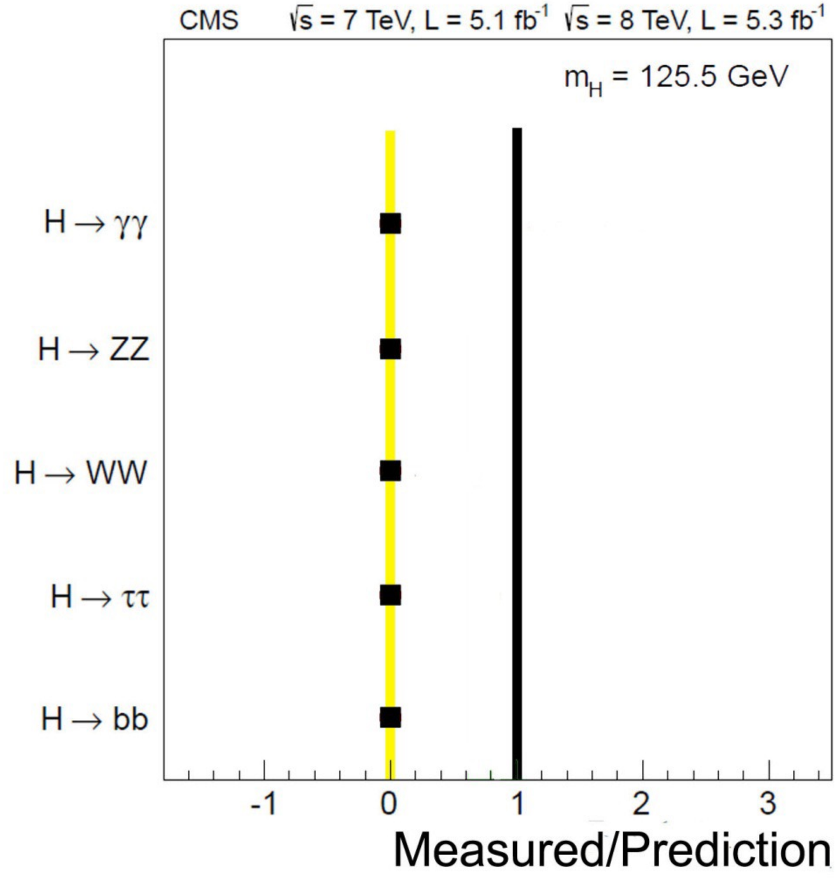


Time Evolution of Higgs Boson Data



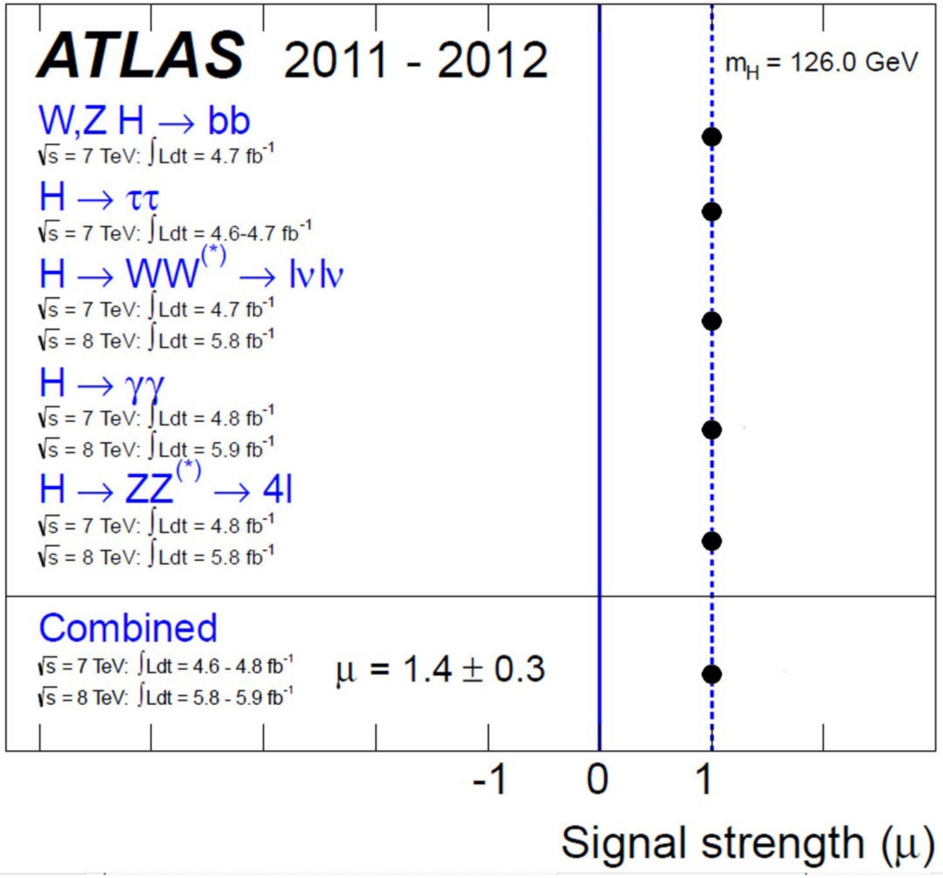
Results if no Higgs

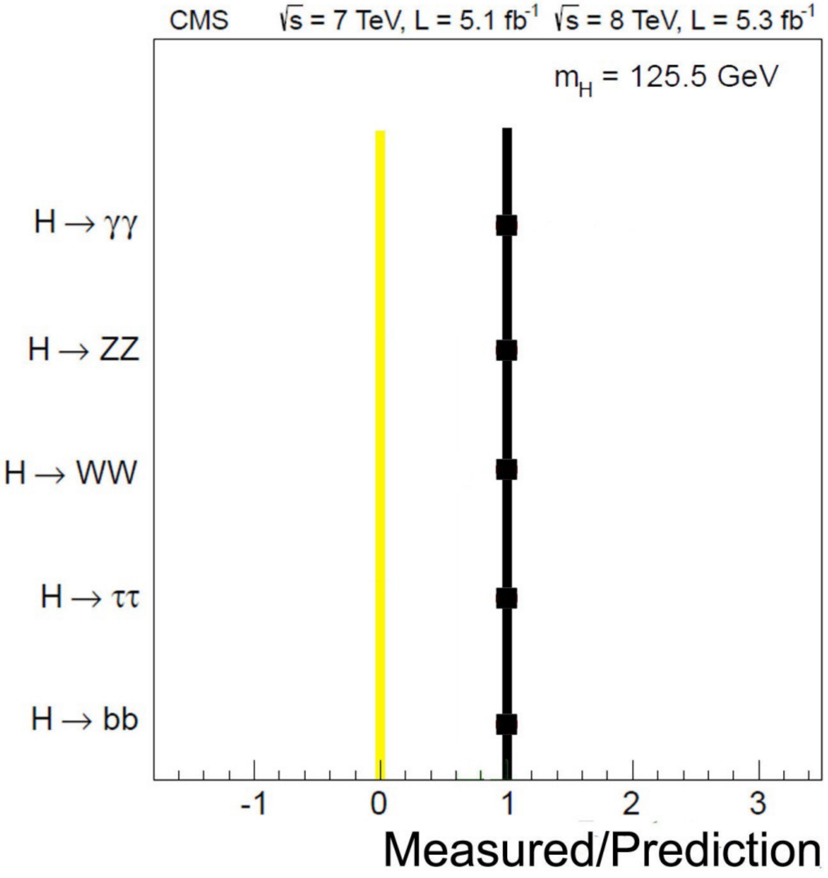




Ratio of Measurement to Standard Model Prediction

Results with Higgs





Ratio of Measurement to Standard Model Prediction

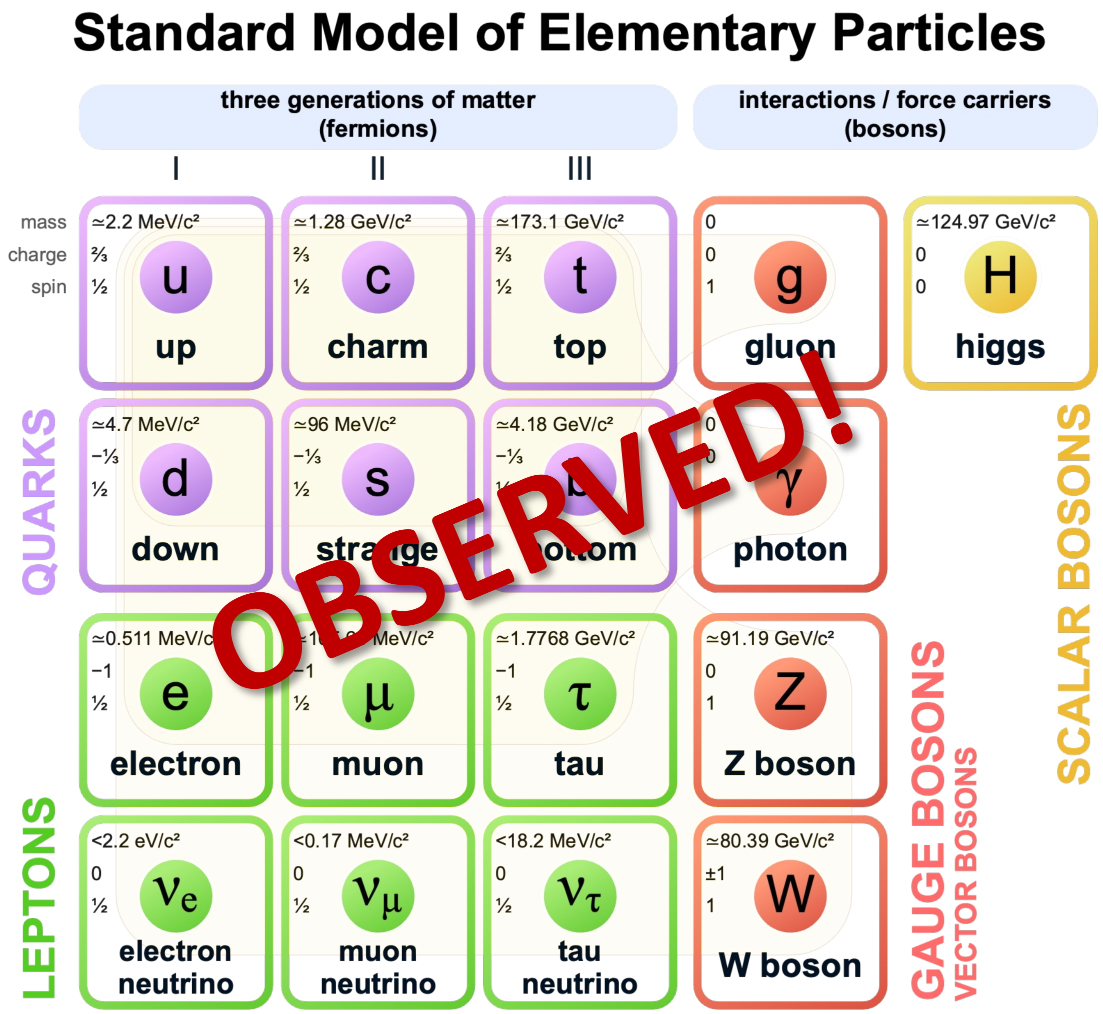
July 2012 Results

July 4, 2012: Higgs Boson discovery

- Discovered by the ATLAS and CMS Collaborations at CERN
- Higgs → two photons and Higgs → ZZ → 4 leptons

2013 Nobel Prize

Standard Model



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- Higgs boson: 2012@CERN

Homework discussion – CMS data

Lots of excellent exploration, questions and discoveries!

- Share what you did and discuss any questions you may have.
  - Discuss the physics first, but also feel free to discuss how to use this in class
- First discussion in breakout groups, then discussion as a larger group

Homework discussion – CMS data

- Are there tutorials on the e-lab?
- I was not clear as to which graph in CMS e-Lab can show that the dimuons that produce the Z have opposite charge since it is neutral.
- Why were the masses not exactly where we expected it to be? (90 vs 91.2 for the Z boson, for example)
- What are the “extra” peaks that we cannot match to particles? (for example, in the first dataset, it looks like there is a peak at 3.66 GeV if you set the bin to 0.1)

Homework assignment – lecture 4

1. Look up a recent CMS or ATLAS result that you find interesting. Make a one-slide summary to share in breakout groups next week

   https://atlas.cern/updates/briefing or https://cms.cern/cms-updates

   - What was the goal of this analysis and why is it significant? Is this a search for new physics or a precision measurement of a predicted Standard Model result?
   - What particles were used in the analysis? Does the summary describe the methods or challenges of this analysis?
   - What is the result?
2. Article about the importance of "finding nothing"

   https://gizmodo.com/the-scientists-who-look-for-nothing-to-understand-every-1796309514
3. Fill out weekly survey

- Additional, optional resources are posted to the course website
- Email me with any concerns or questions

Lecture 4: What's next?

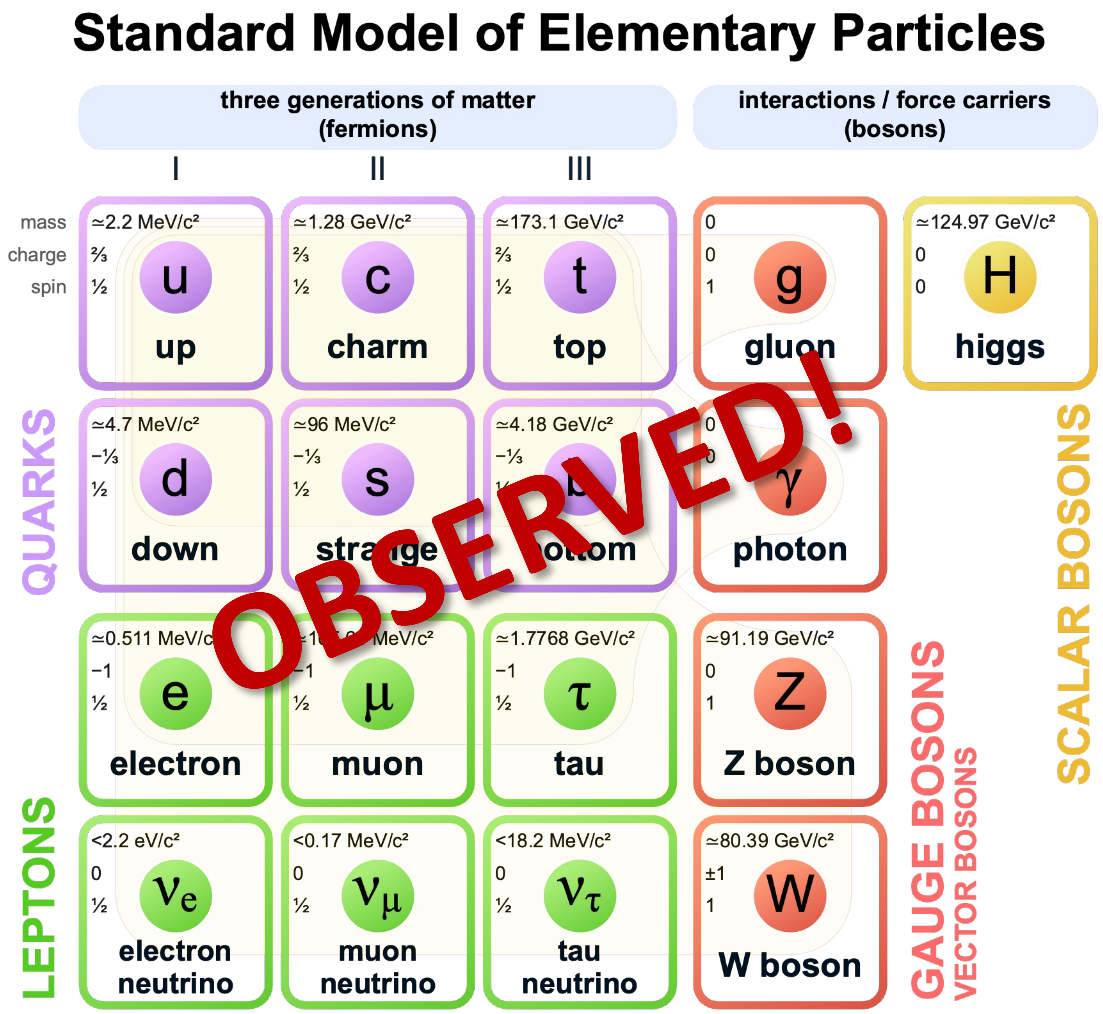
Many things left to discover and understand!

- What is dark matter?
- Is there evidence for supersymmetry?
- Why is there so much more matter than antimatter in the universe?
- Why do the different generations of quarks and leptons have such different masses?
- Why is gravity so much weaker than the other fundamental forces?

We could find the answers to these questions, or discover **something totally unexpected!**

End of Part 3

Overview: Standard Model



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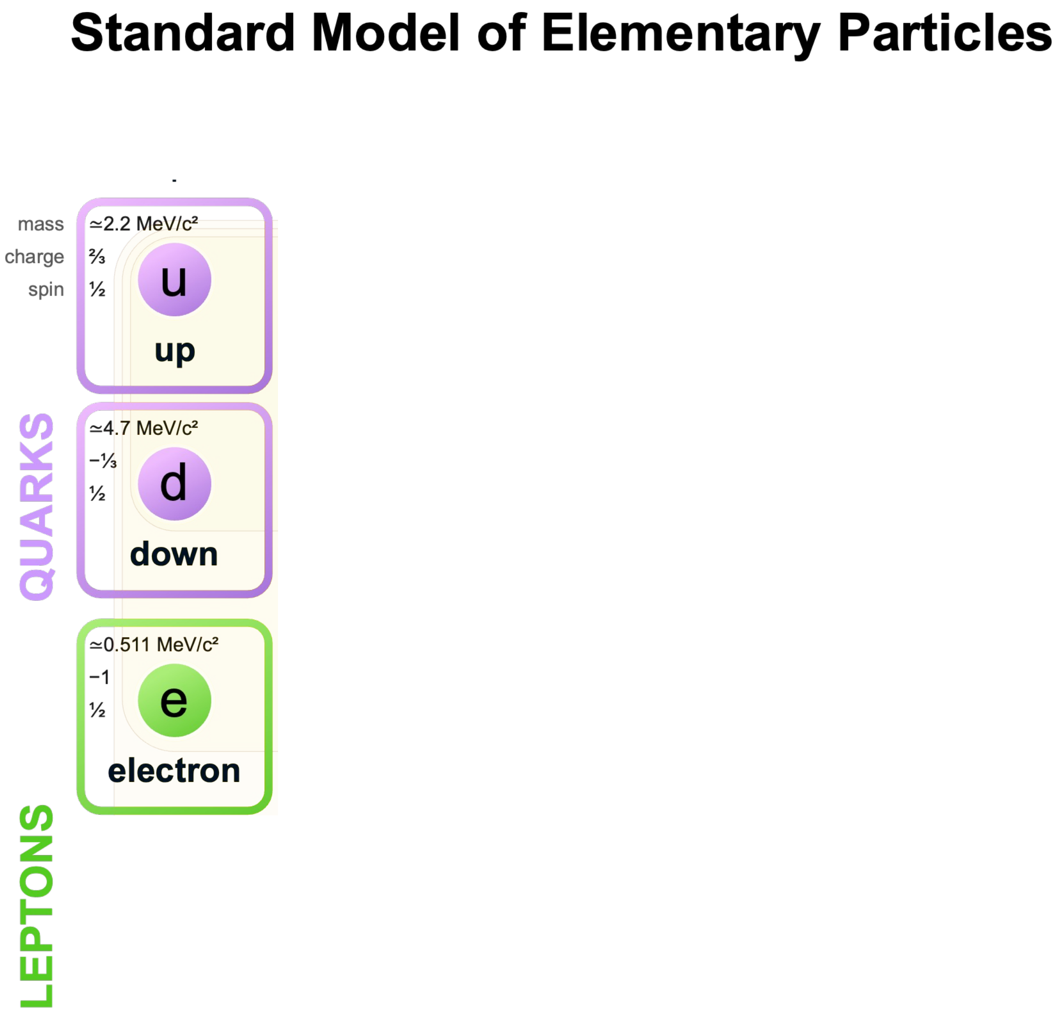
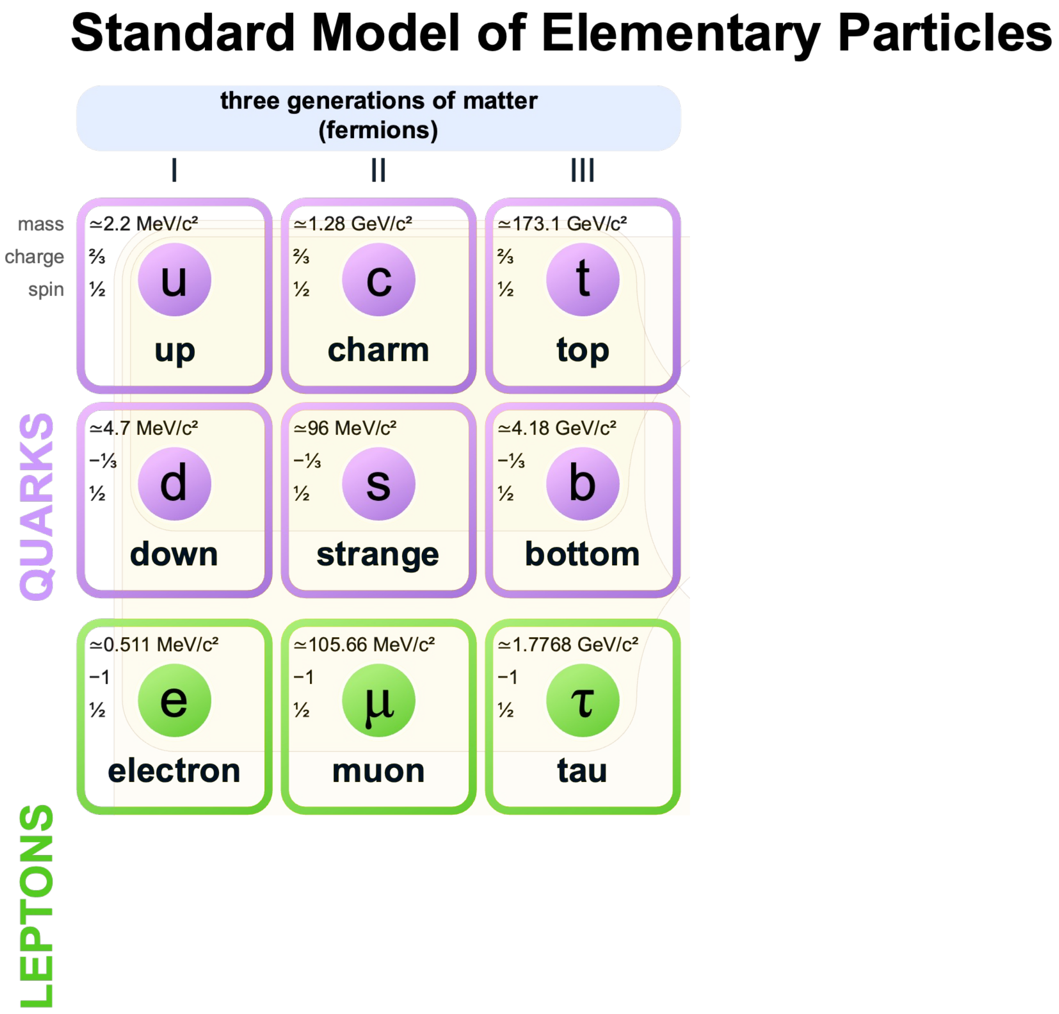
Earth's building blocks



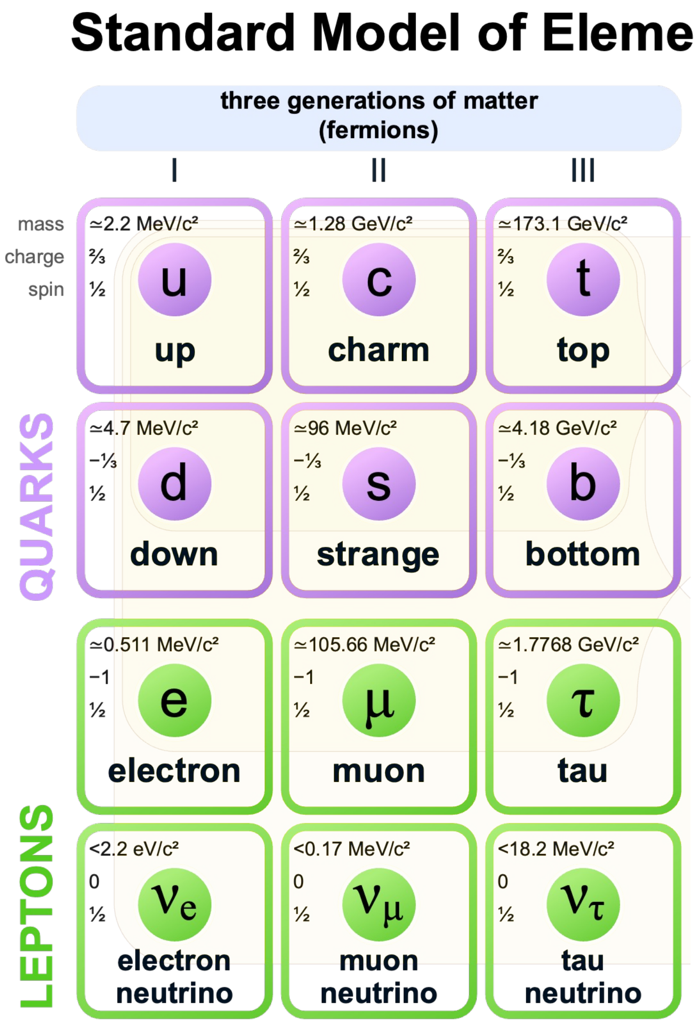
- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**

Three generations



- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier

Neutrinos

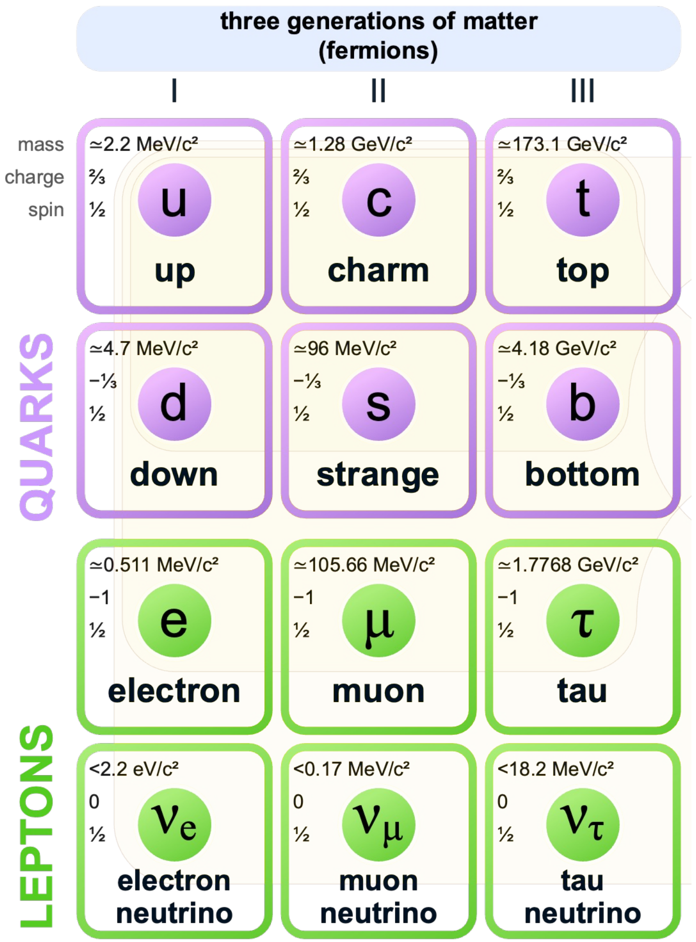


- All ordinary matter is made from **up quarks**, **down quarks**, and **electrons**
- There are three copies, or *generations*, of quarks and leptons
  - Same properties, only heavier
- Leptons also include **neutrinos**, one for each generation
  - Neutrinos have non-zero masses can **oscillate** between flavors– Lecture 5

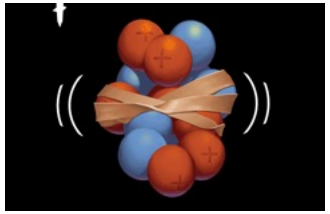
All of these *matter* particles are **fermions:** they have **half integer spin**

Force carriers

Standard Model of Elementary Particles

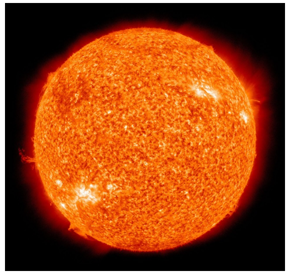


- The other group of particles in the Standard Model are **bosons:** particles with **integer spin**
- These are the force carriers



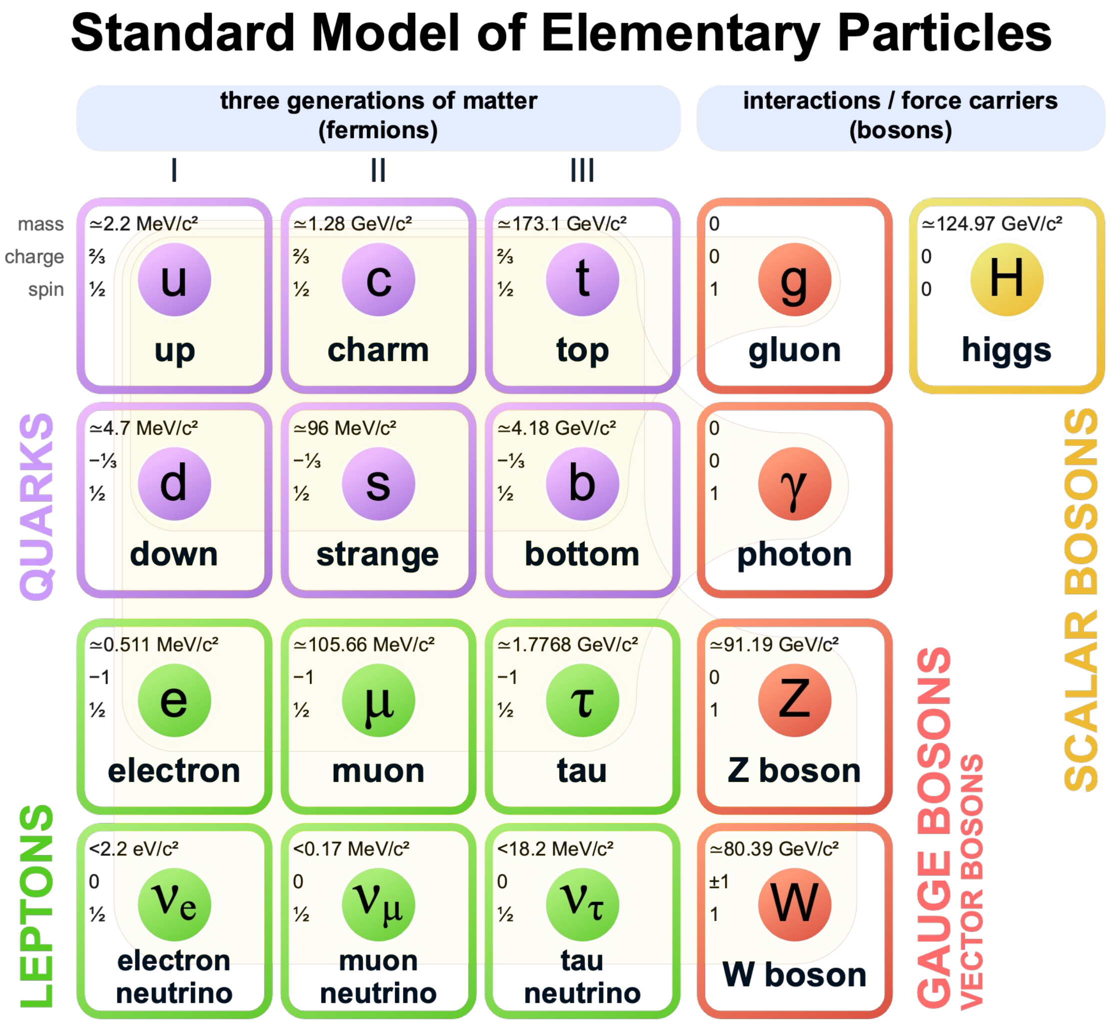
Strong force

Electromagnetic force



Weak force

Higgs boson



Higgs boson

- Spin 0: first fundamental scalar
- Higgs mechanism describes how particles get their mass

Fermions vs bosons

Fermions:

- Named for Enrico Fermi (1901 – 1954)
- Half-integer spin
- "Matter" particles (quarks, leptons, neutrinos)
- Wave functions **anticommute**
- Obey Fermi-Dirac statistics
- Exclusion principle: Identical fermions cannot occupy the same quantum state
  - Proposed in 1925 by Wolfgang Pauli (1900 – 1958)

1945 Nobel Prize

Bosons:

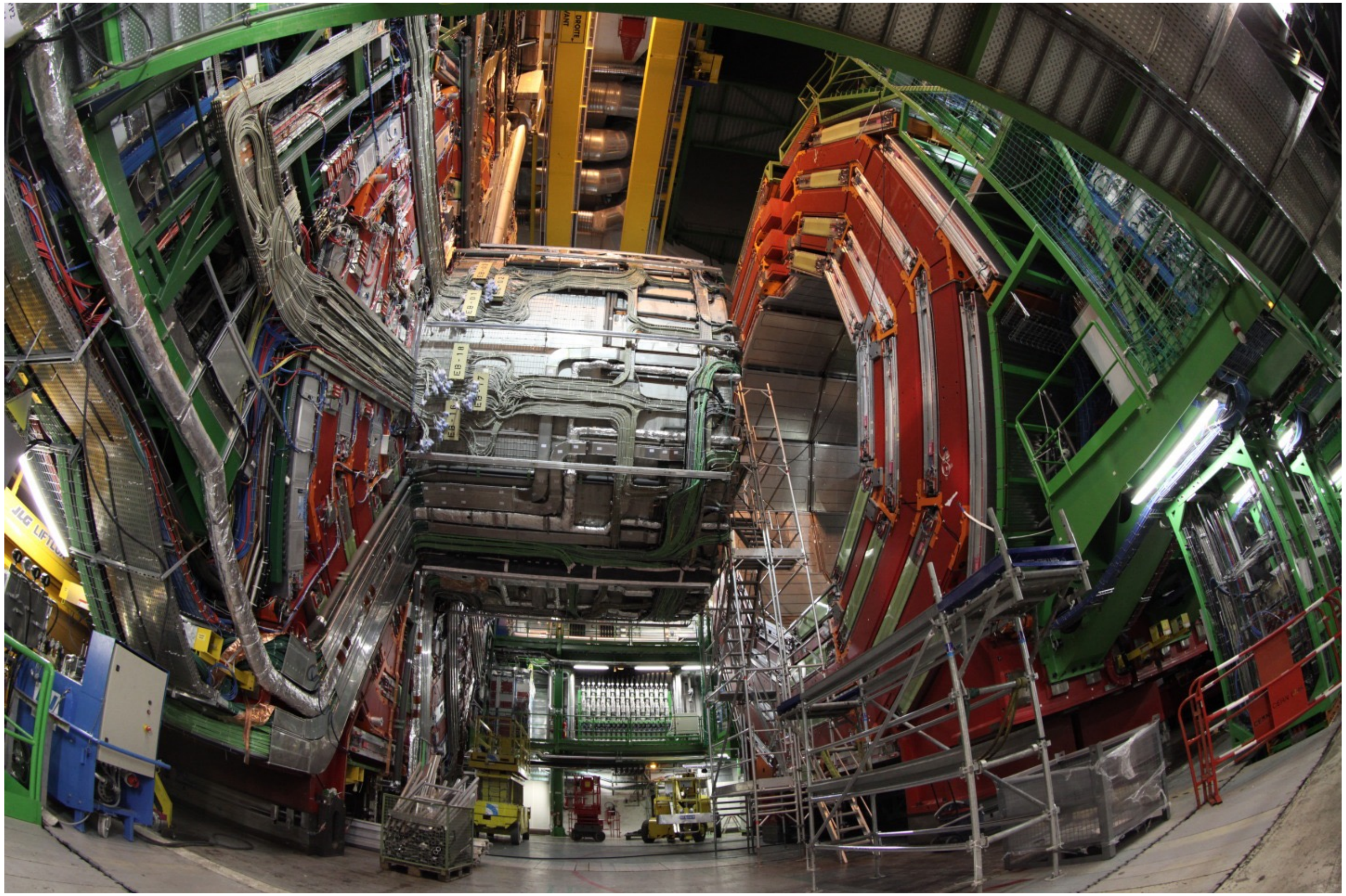
- Named for Satyendra Nath Bose (1894 – 1974)
- Integer spin
- "Force-carrying" particles (photons, gluons, W/Z bosons)
- Wave functions **commute**
- Obey Bose-Einstein statistics
- Can all be in the same quantum state – for example, lasers

Colliders – a biased list

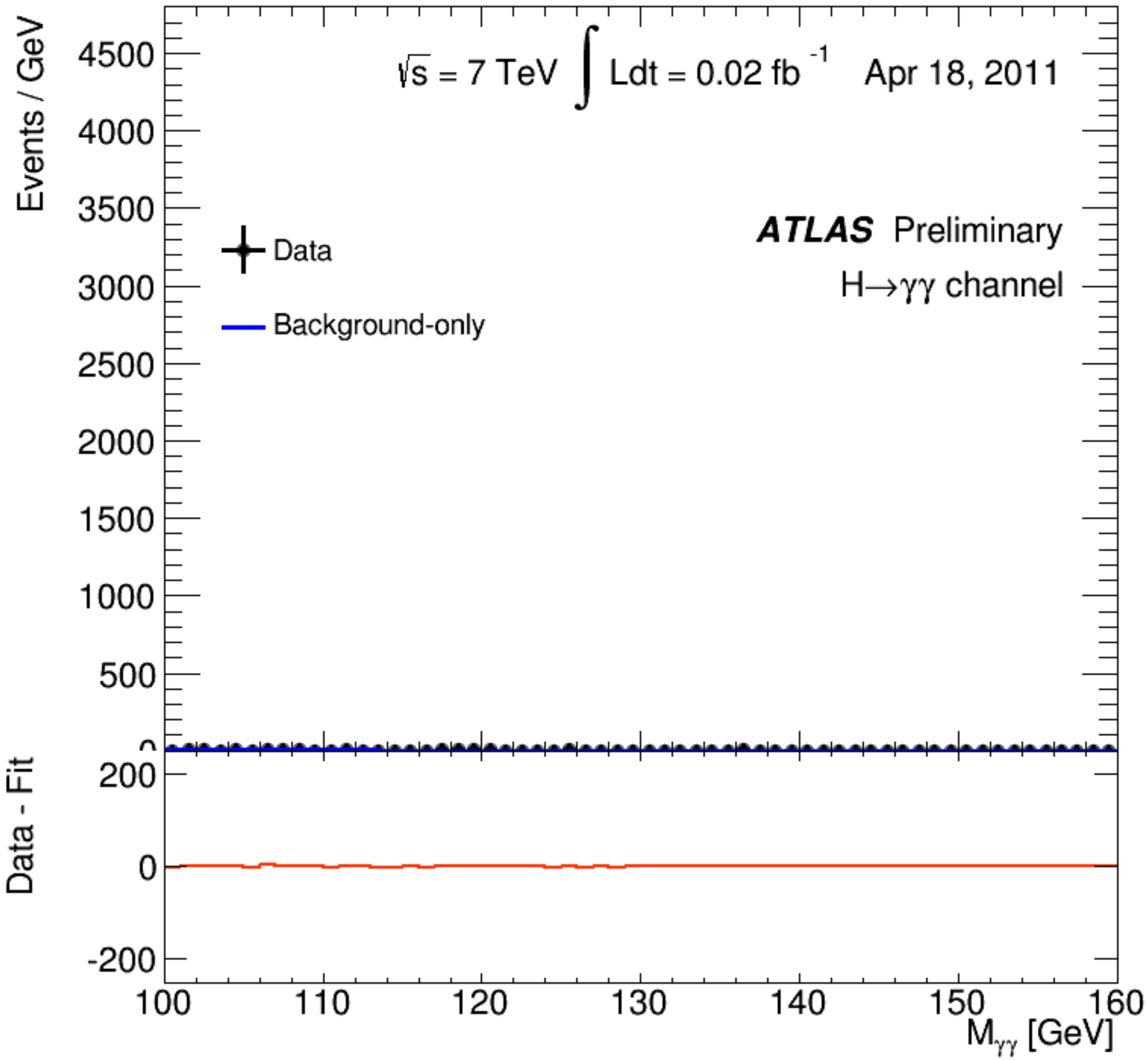
- Push to bigger accelerators at higher energies

Collider	Operation	Type	Energy	Major Discoveries
Super Proton Synchrotron (SPS)	1981-1991	proton-antiproton	540 GeV	W and Z bosons, 1983
Large Electron-Positron Collider	1989-2000	electron-positron	200 GeV	Precision studies of W and Z
Tevatron	1985-2011	proton-antiproton	2 TeV	Top quark, 1995
Large Hadron Collider	2009 - Present	proton-proton	14 TeV	Higgs boson, 2012
The next big collider	?	Probably electrons?	?	???

CMS Magnet



3.8 T superconducting solenoid magnet, cooled using liquid helium



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

The ATLAS Detector @ the LHC