

Higgs boson



...WAIT. DIDN'T YOU ALREADY FIND IT A YEAR OR TWO AGO?

YES, WELL, UM.



... OK, THIS IS EMBARRASSING.

SEE, THE THING IS—



DON'T TELL US YOU LOST IT ALREADY.

LOOK. IN OUR DEFENSE, IT'S REALLY SMALL.



QuarkNet Summer Session for Teachers: The Standard Model and Beyond

Allie Reinsvold Hall

<https://quarknet.org/content/quarknet-summer-session-teachers-2020>

Summer 2020

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: Ancient Greeks to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. **Particle physics at the Large Hadron Collider (LHC)**
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.

Loose ends – questions

- What is spin?
 - Form of angular momentum
 - Inherent property of a particle
- Why is the J/ψ lifetime so long?
 - Lowest mass charm-anticharm bound state
 - Only the weak force changes quark flavors
 - Weak force is weak – takes a long time for it to act
- Are the angles in a Feynman diagram important?
 - No – angles are arbitrary
 - Actually calculating the angles is important but difficult
- Why was the energy in the D0 events not equal to the initial energy of 2 TeV?
Where did it all go?
 - Each proton has 1 TeV but at Tevatron and LHC energies, **individual** quarks interact
 - Each quark has a fraction of the total 1.0 TeV

Loose ends – teacher guides

Heisenberg uncertainty activity

- Should get slope approximately equal to $h = 6.62607004 \times 10^{-34} \text{ m}^2 \text{ kg/s}$ in proper units
- Teacher's guide:
https://quarknet.org/sites/default/files/heisenberg_teacher_%2023sep2019.pdf

D0 event displays

- Teacher's guide for missing momentum activity:
<https://quarknet.org/sites/default/files/hiddenneutrino-teacher-01Oct2019.pdf>
- Teacher's guide for top mass activity:
https://quarknet.org/sites/default/files/topquarkmass_teacher_31oct2019.pdf

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 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.

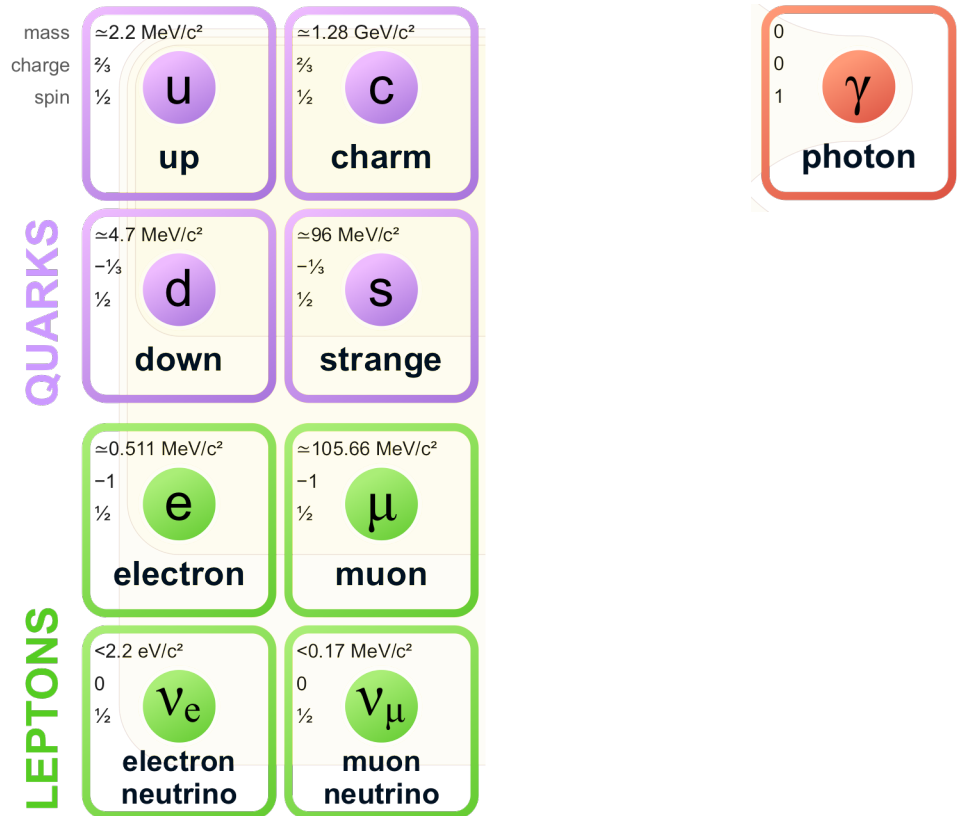
Particle Physics at the LHC

“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

Standard Model in 1974

Standard Model of Elementary Particles



Remaining questions:

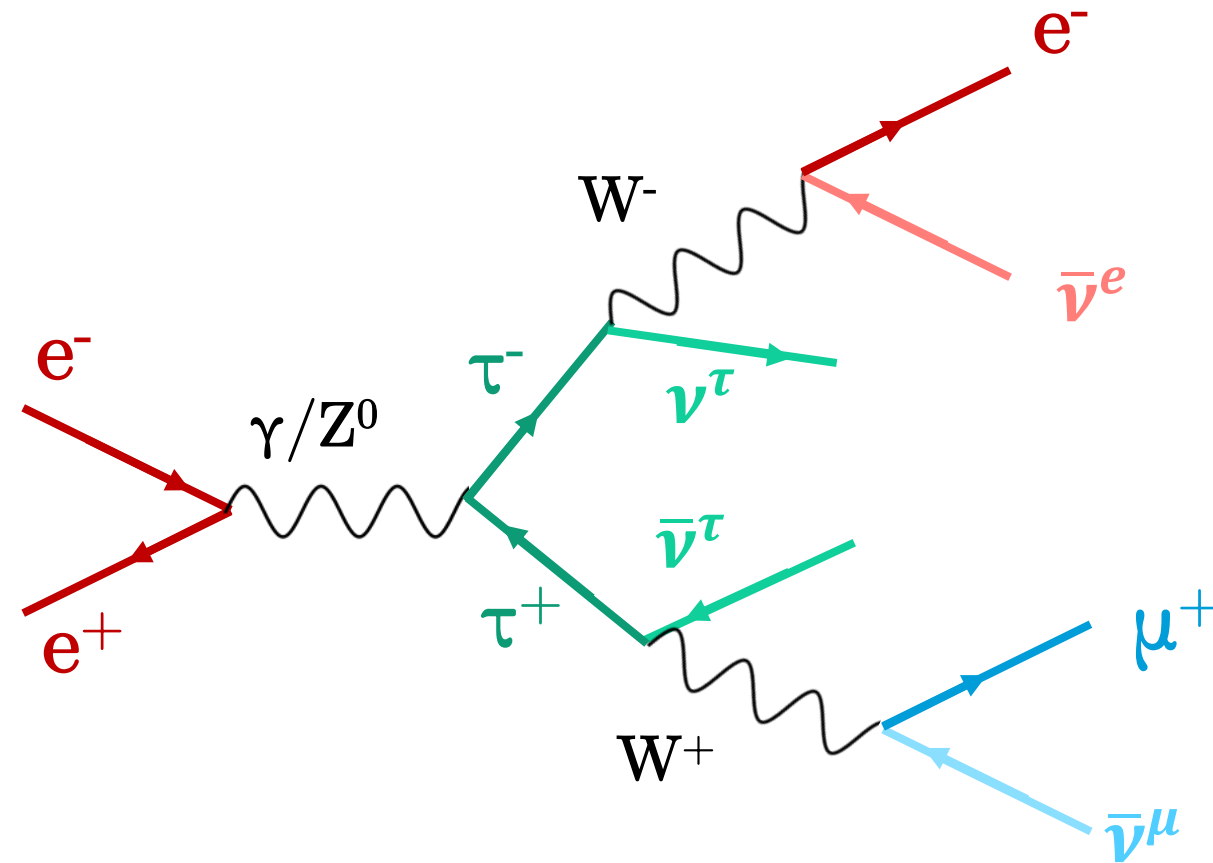
1. Are there more quarks or leptons at higher mass?
2. What about the rest of the bosons?

Today's class

- Finish Standard Model history (1974 – present)
 - Higgs boson theory and discovery
- Discuss LHC data analysis homework
- LHC physics
 - Accelerators
 - Particle detectors
 - Challenges

Third generation: τ lepton, 1975

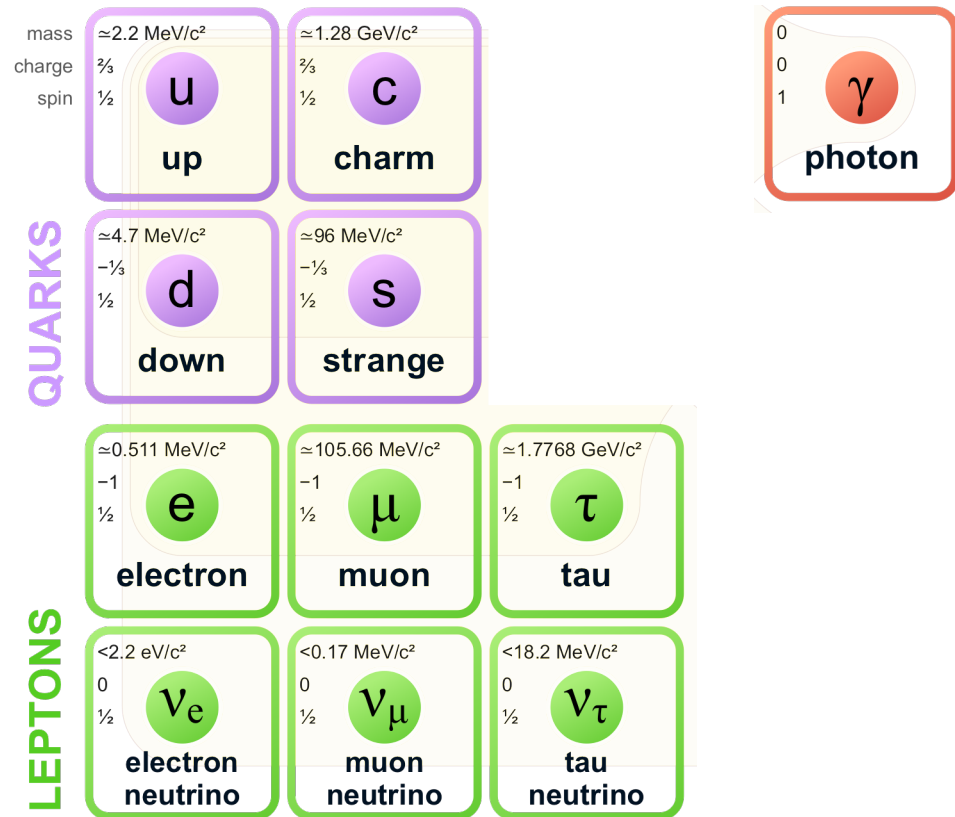
- Discovered in 1975 by Martin Perl's (1927 – 2014) group at SLAC using SPEAR
- Z boson: “neutral current”;
 $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ or $\tau^+\tau^-$
- W^\pm bosons: “charged current”;
 $W^+ \rightarrow e^+\nu^e$ or $\mu^+\nu^\mu$ or $\tau^+\nu^\tau$
- Final state: 4 neutrinos, 1 electron,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



1995 Nobel Prize

Checkpoint: Standard Model in 1975

Standard Model of Elementary Particles

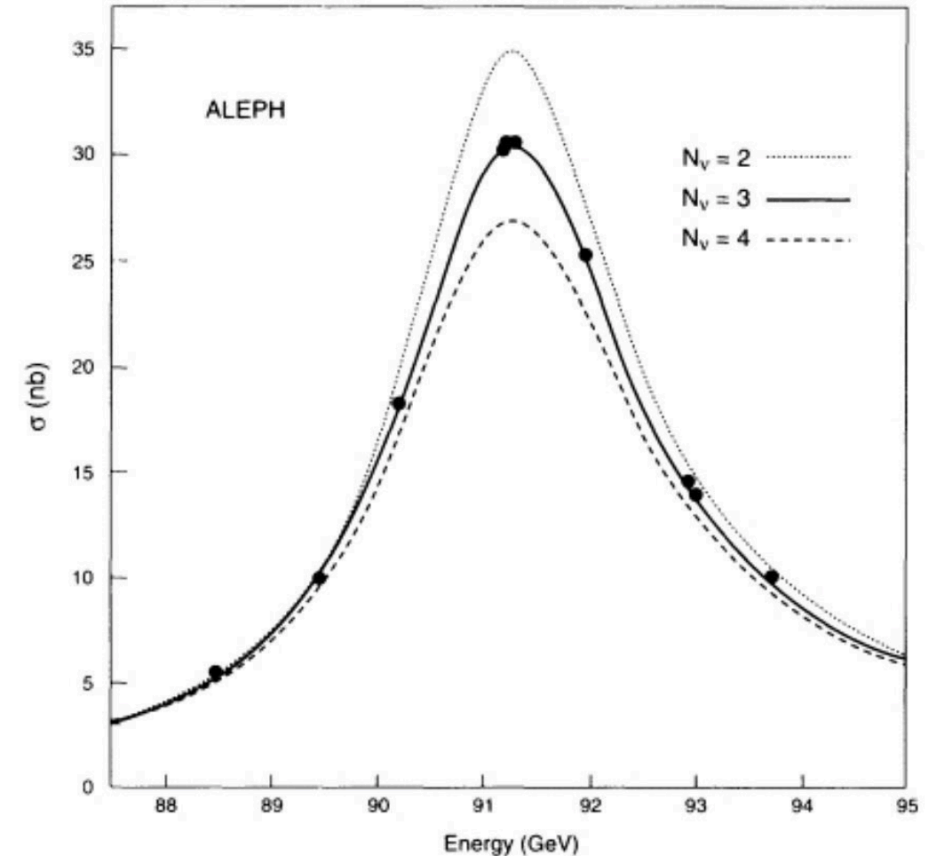


Observations:

- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- tau neutrino: 2000@FNAL

Finishing the 3rd generation

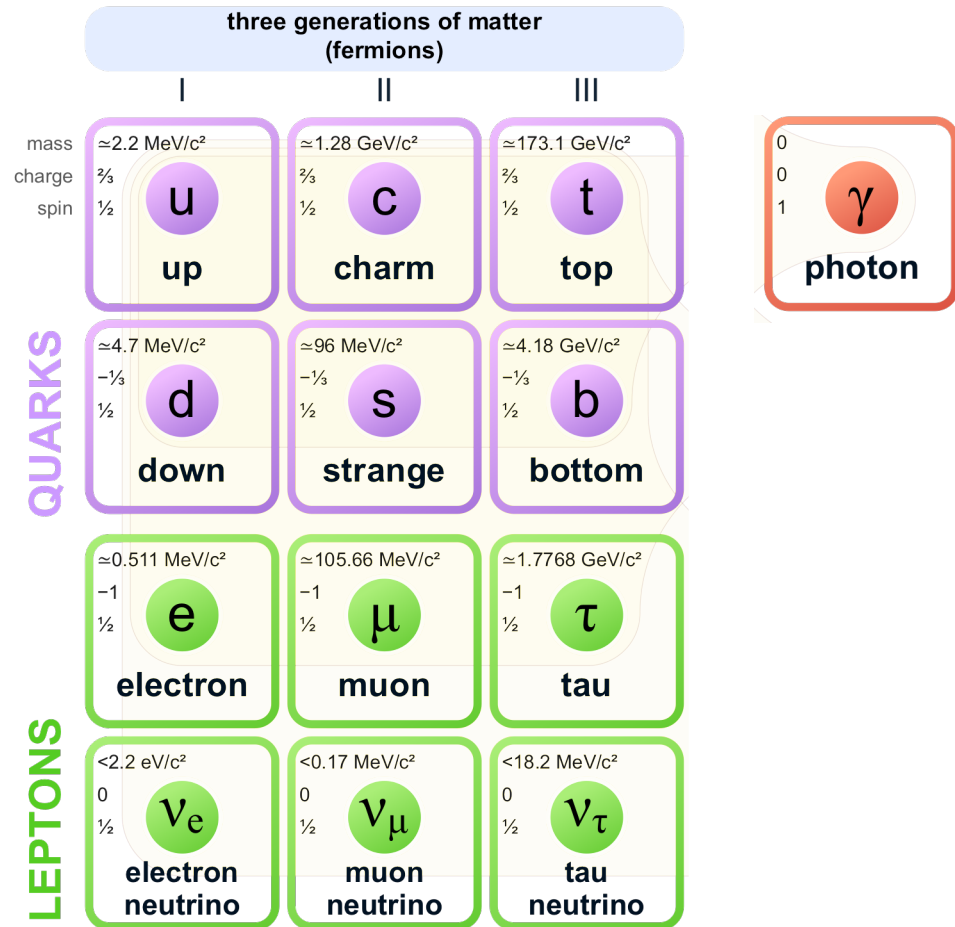
- 1977: Upsilon Υ meson discovered at Fermilab by Leon Lederman and his group
 - Υ is a $b\bar{b}$ bound state, mass 9.5 GeV
 - Bottom quark mass: 4.2 GeV
 - Similar to J/psi discovery of charm quark
- 1995: Top quark discovered at the Fermilab Tevatron by the D0 and CDF collaborations
 - Mass 173 GeV
 - 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

Standard Model of Elementary Particles

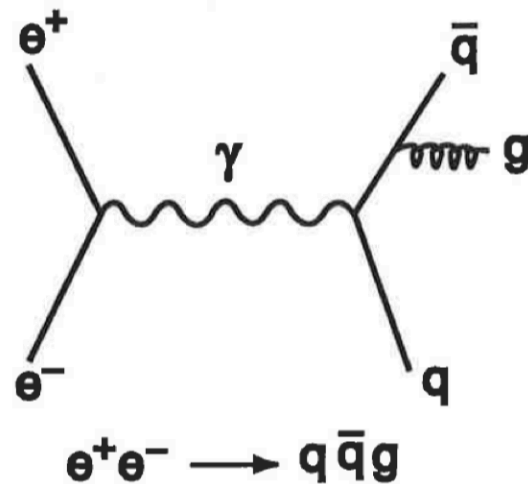


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Gluon discovery

- **1979 gluon 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 such as 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>

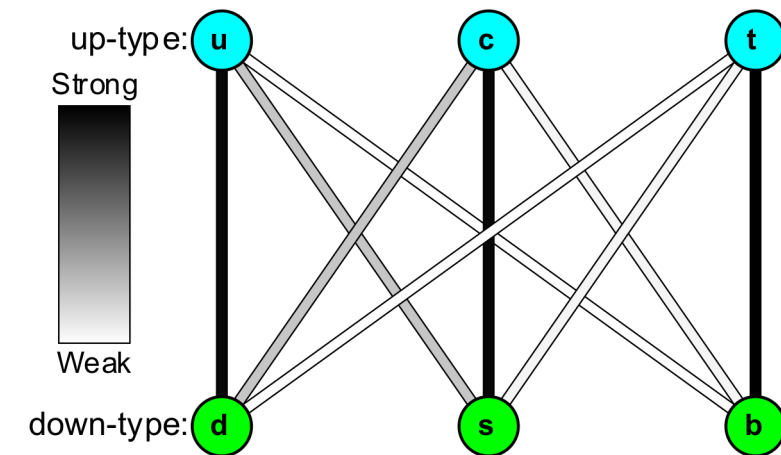
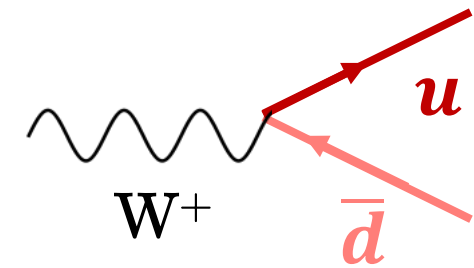
W and Z bosons

- 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
- 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

1984 Nobel Prize

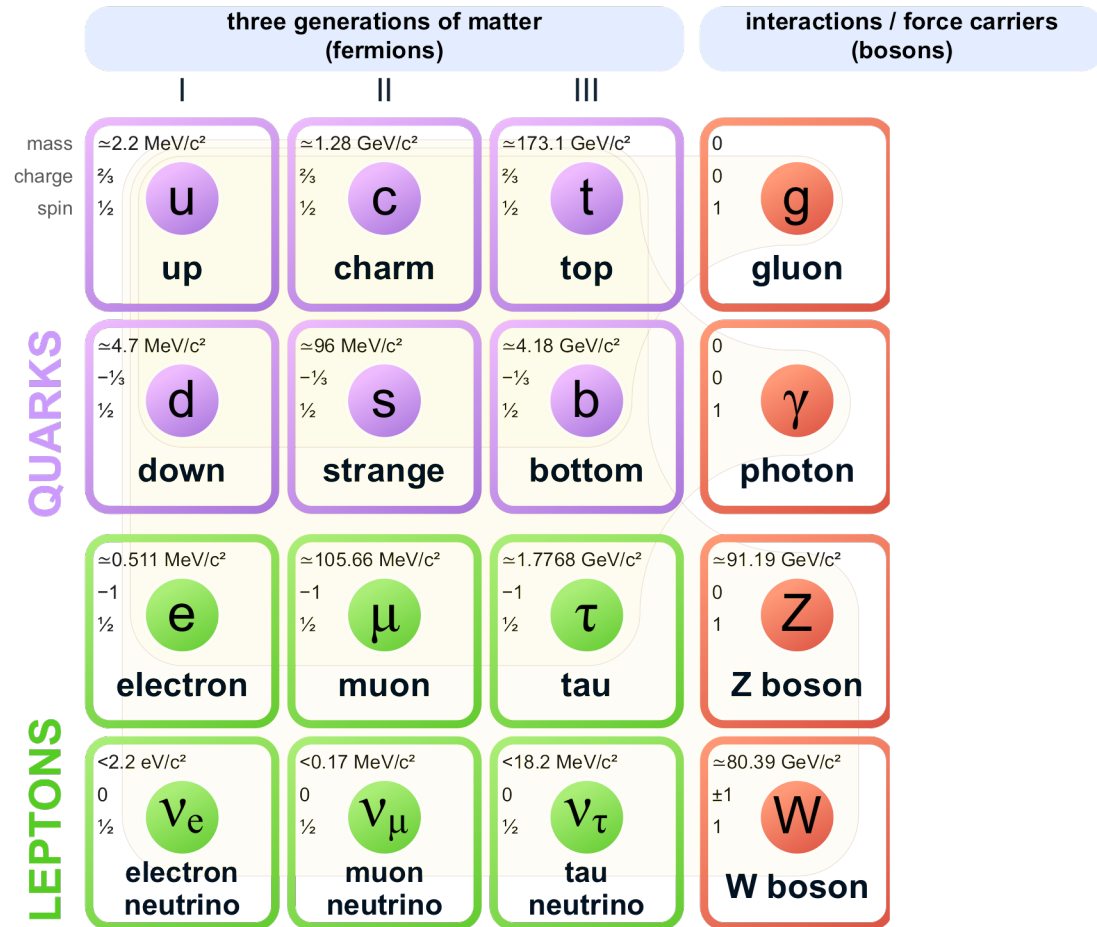
2008 Nobel Prize

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



Checkpoint: Standard Model

Standard Model of Elementary Particles



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- tau neutrino: 2000@FNAL

Last piece of the puzzle

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)
	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
QUARKS	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
	e electron	μ muon	τ tau	Z Z boson
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$

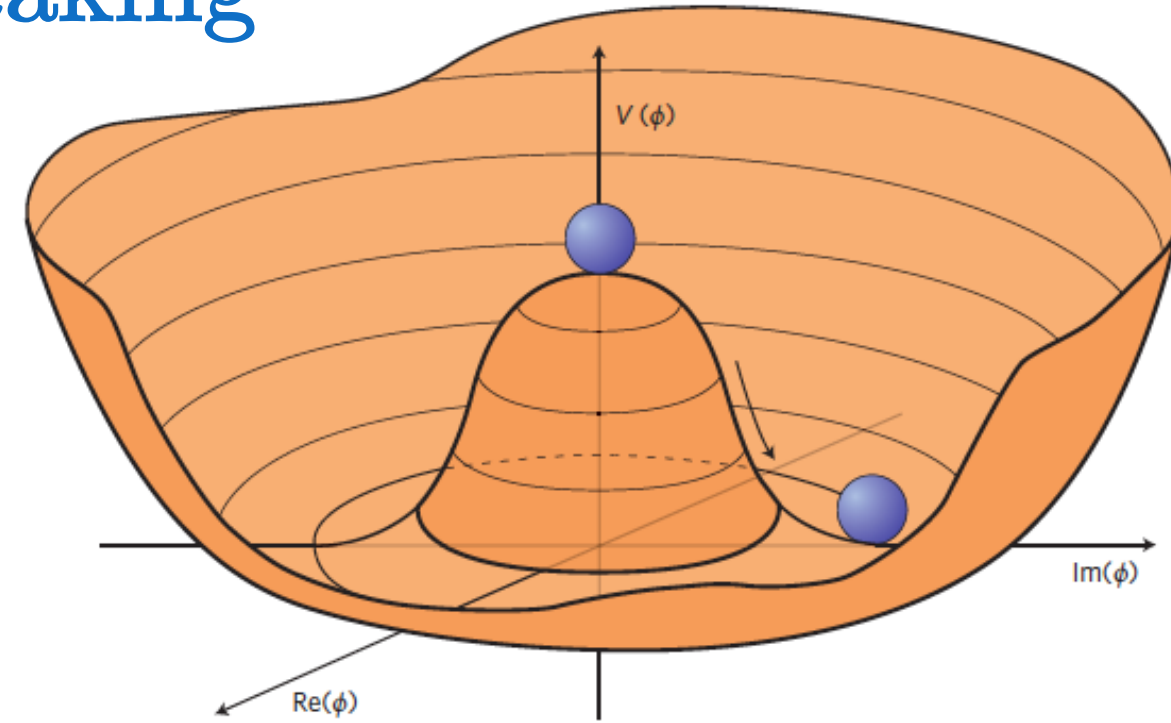
- Last missing piece = **Higgs boson**



- 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**

Spontaneous symmetry breaking

- Start with non-zero “vacuum 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



Before symmetry breaking

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

After symmetry breaking

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

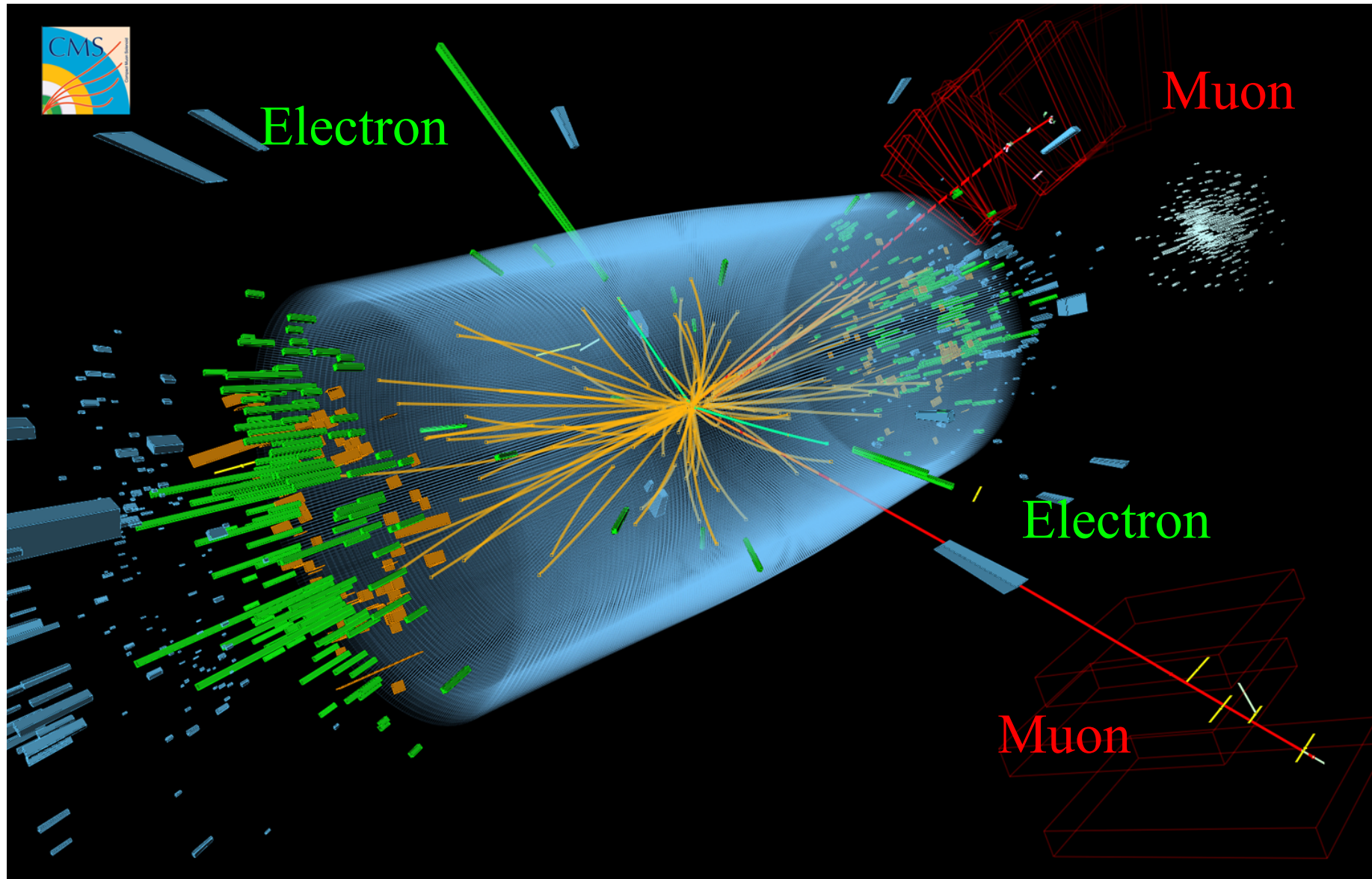
How a Higgs boson decays

- 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)

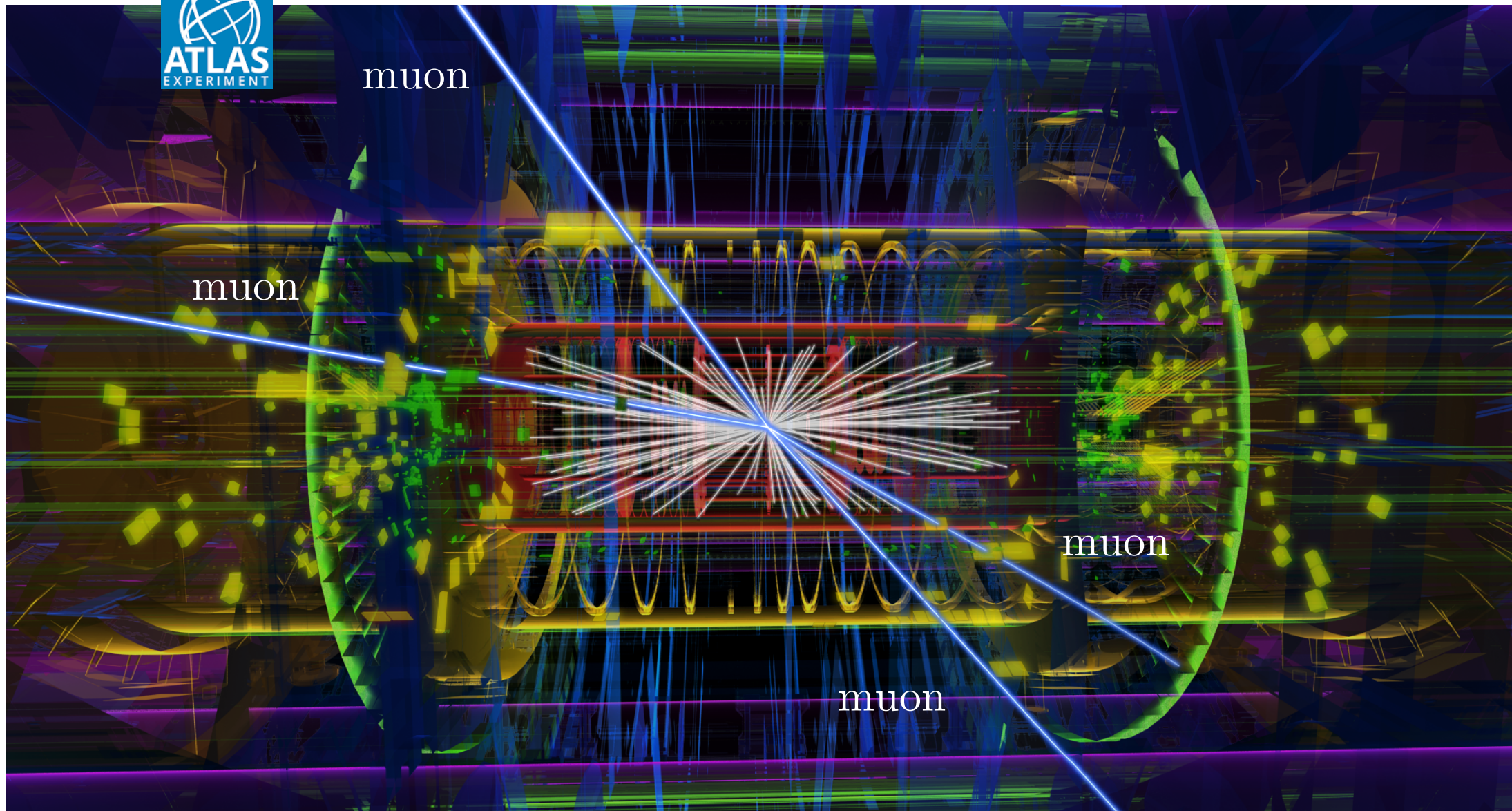
Higgs \rightarrow b + \bar{b}	(b quark and its antiquark)
Higgs \rightarrow τ^+ + τ^-	(τ lepton and its antiparticle)
Higgs \rightarrow γ + γ	(two photons, also called gammas)
Higgs \rightarrow W^+ + W^-	(W boson and its antiparticle)
Higgs \rightarrow Z^0 + Z^0	(Two Z bosons)

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

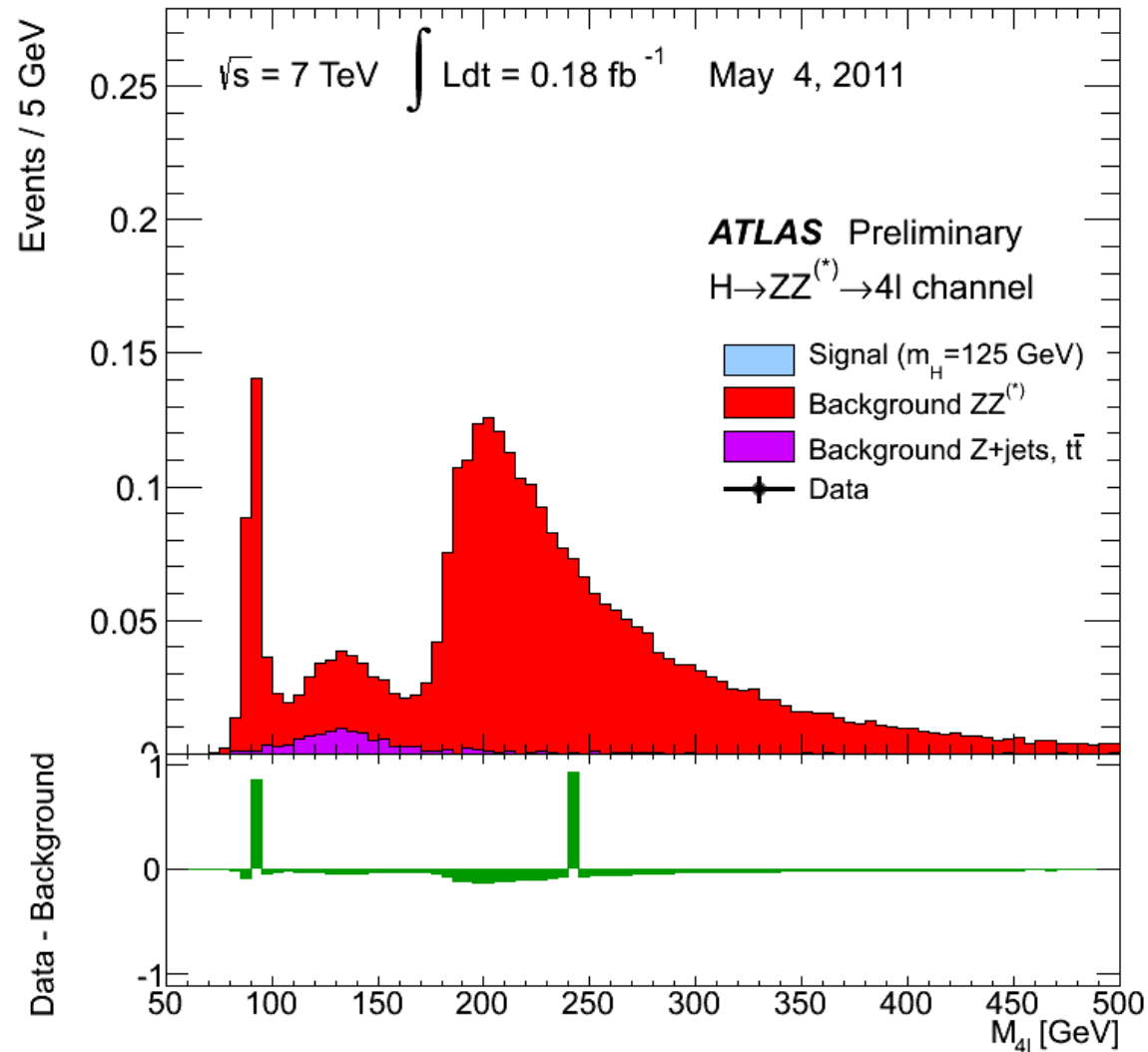
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+\mu^-$ candidate event



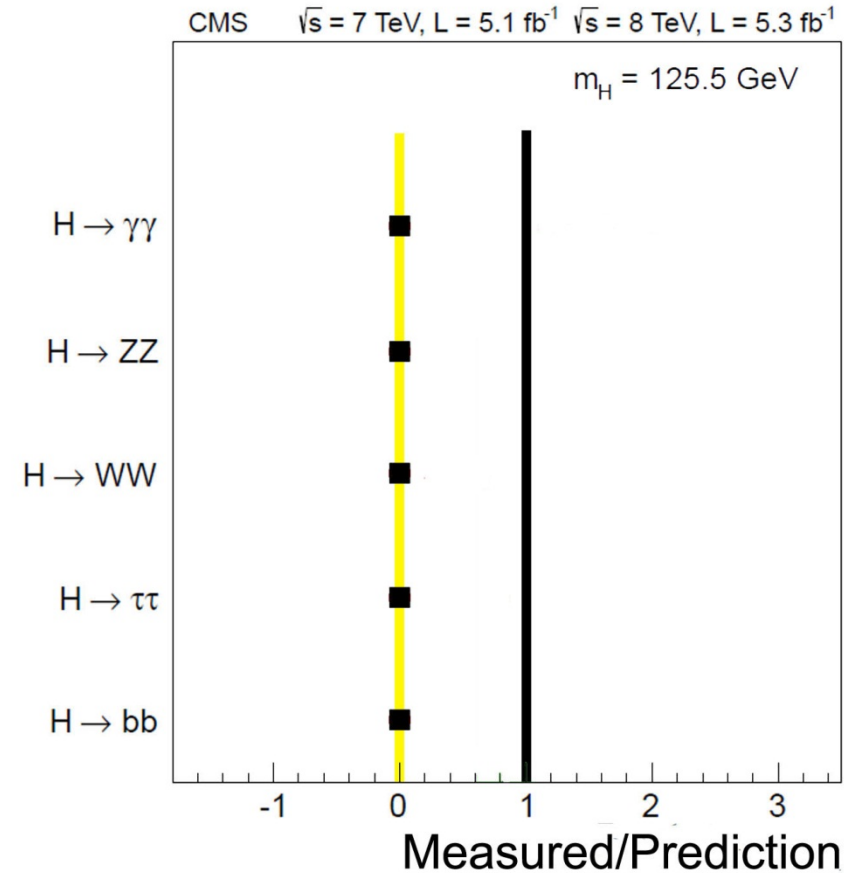
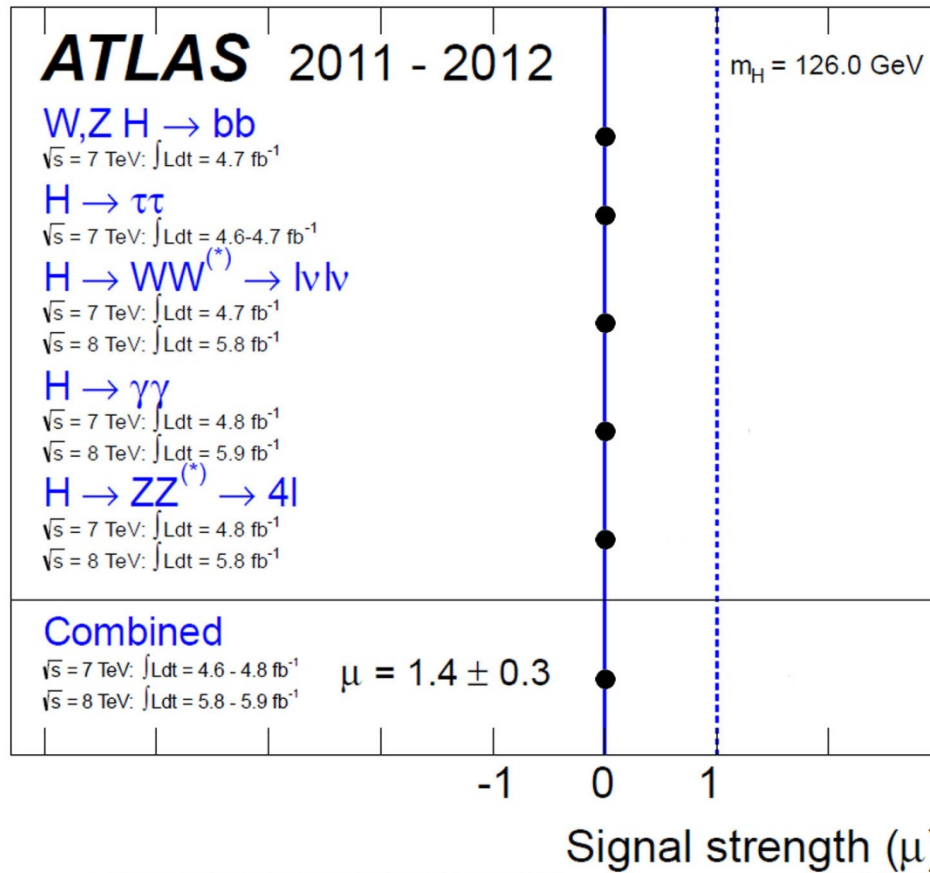
$H \rightarrow ZZ \rightarrow \mu^+\mu^- \mu^+\mu^-$ Candidate



Time Evolution of Higgs Boson Data

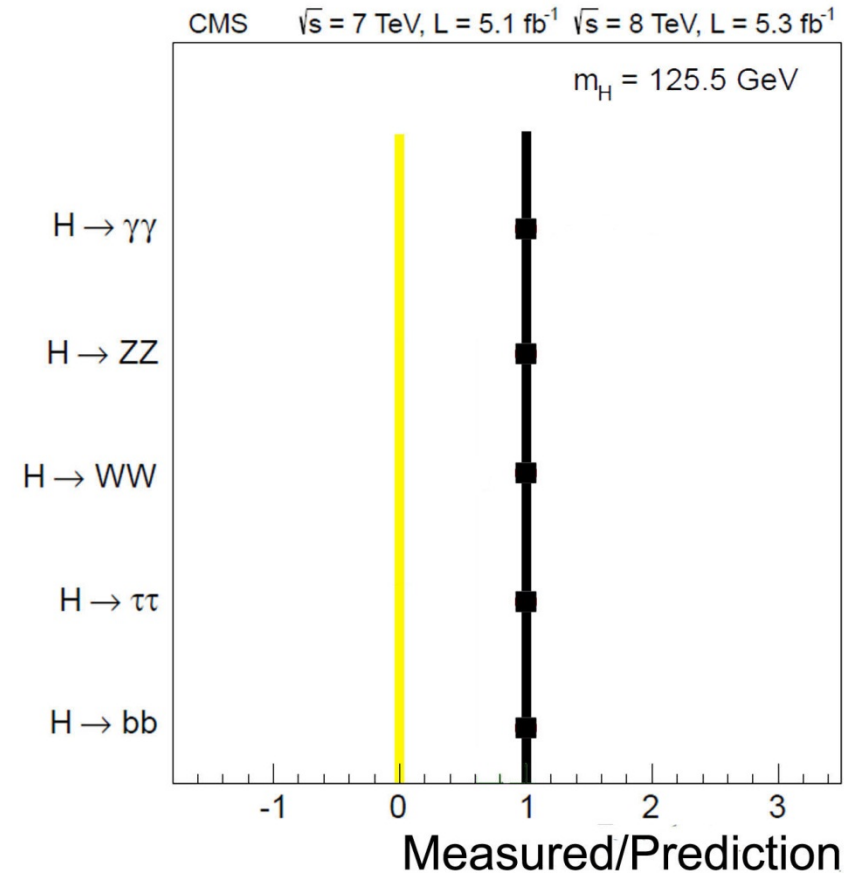
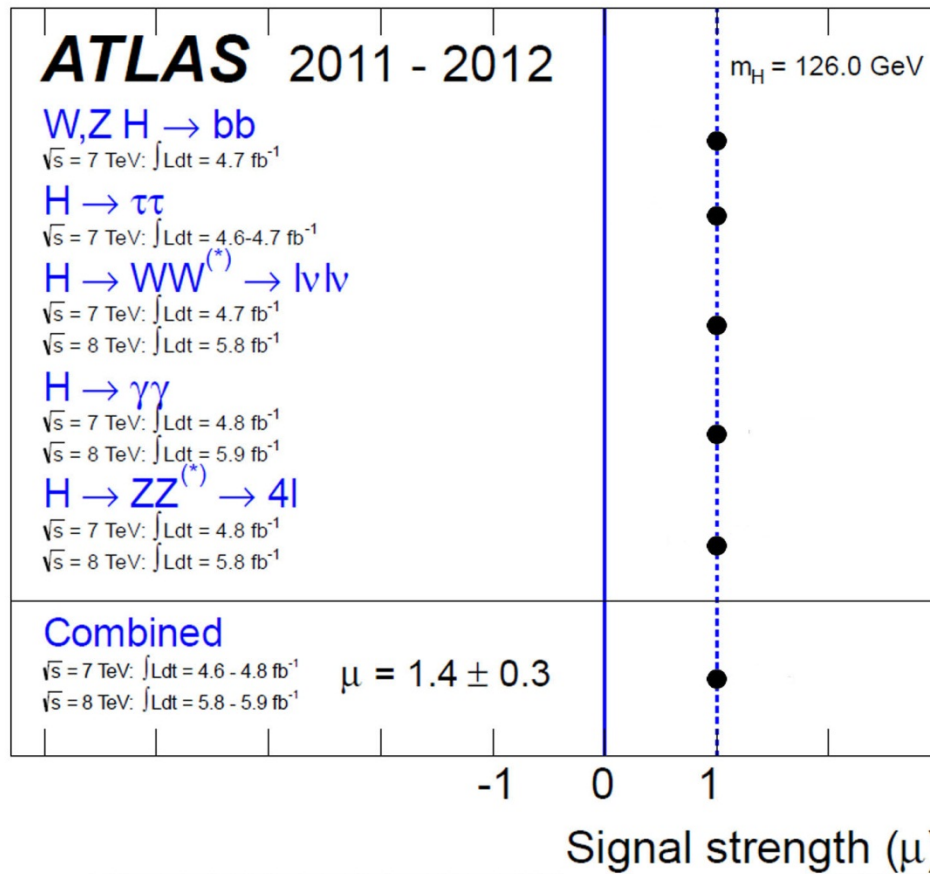


Results if no Higgs



Ratio of Measurement to Standard Model Prediction

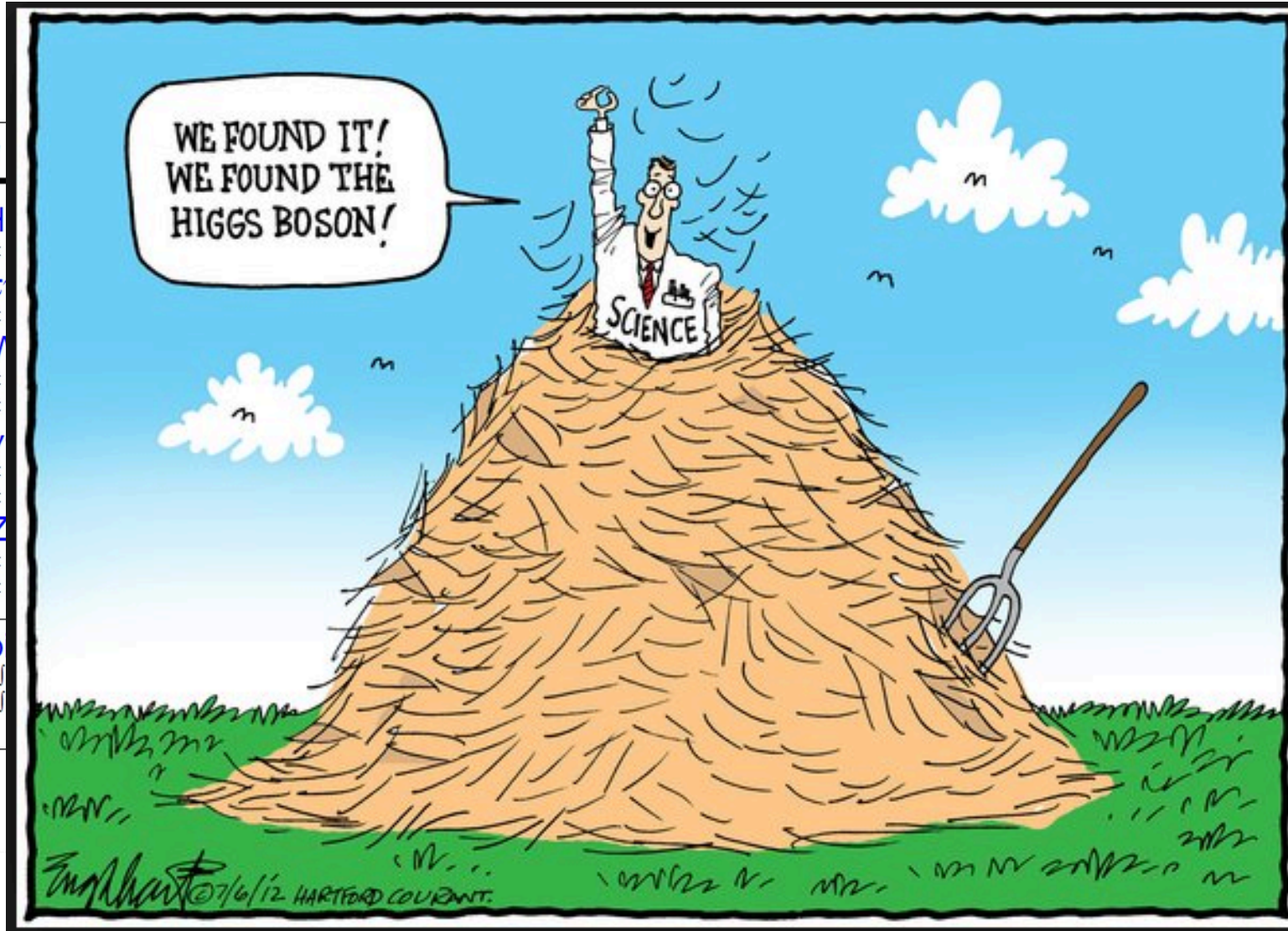
Results with Higgs



Ratio of Measurement to Standard Model Prediction

July 2012 Results

ATLAS
W,Z H
$\sqrt{s} = 7 \text{ TeV}$:
$H \rightarrow \tau$
$\sqrt{s} = 7 \text{ TeV}$:
$H \rightarrow V$
$\sqrt{s} = 7 \text{ TeV}$:
$\sqrt{s} = 8 \text{ TeV}$:
$H \rightarrow \gamma$
$\sqrt{s} = 7 \text{ TeV}$:
$\sqrt{s} = 8 \text{ TeV}$:
$H \rightarrow Z$
$\sqrt{s} = 7 \text{ TeV}$:
$\sqrt{s} = 8 \text{ TeV}$:
Comb
$\sqrt{s} = 7 \text{ TeV}$:
$\sqrt{s} = 8 \text{ TeV}$:



July 4, 2012: Higgs Boson discovery

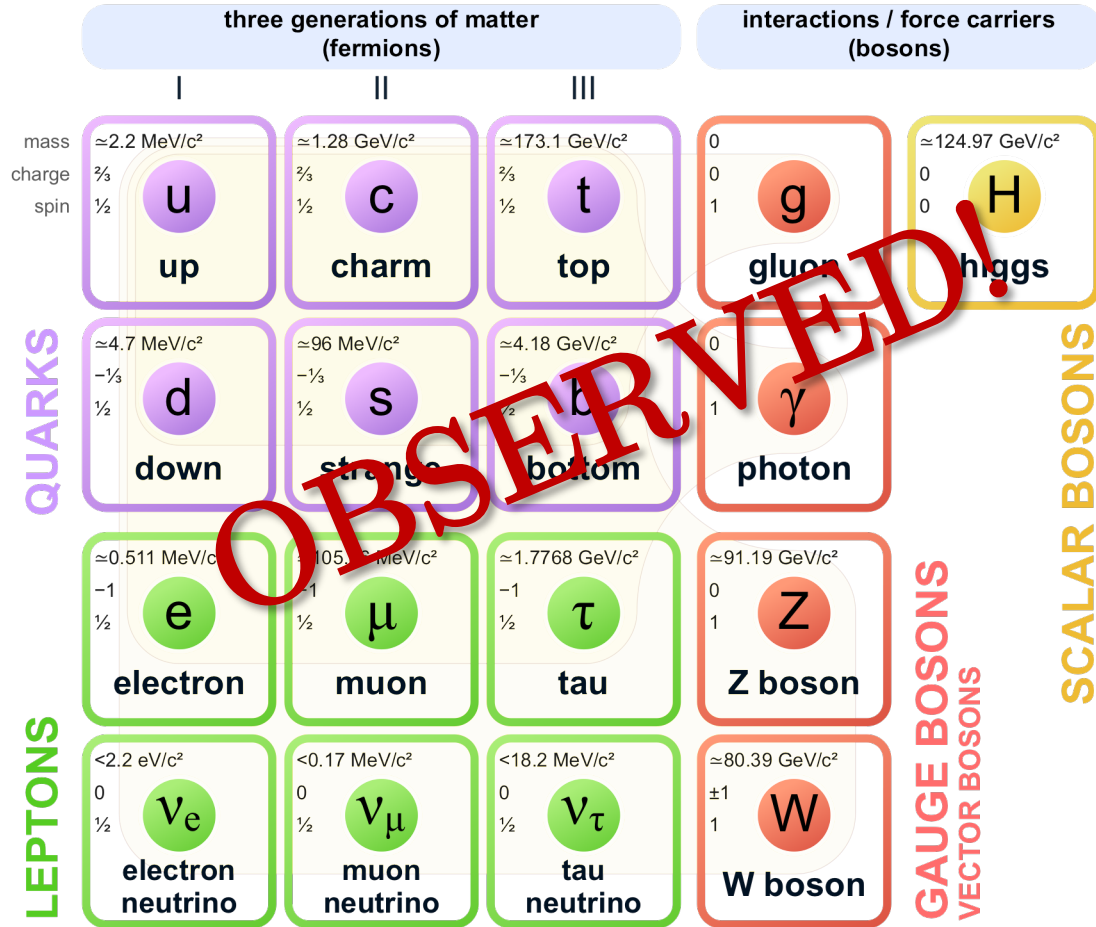
- Discovered by the ATLAS and CMS Collaborations at CERN
- Higgs \rightarrow two photons and Higgs \rightarrow ZZ \rightarrow 4 leptons

2013 Nobel Prize



Standard Model

Standard Model of Elementary Particles



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- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- 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
- 15 minutes for this 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!**

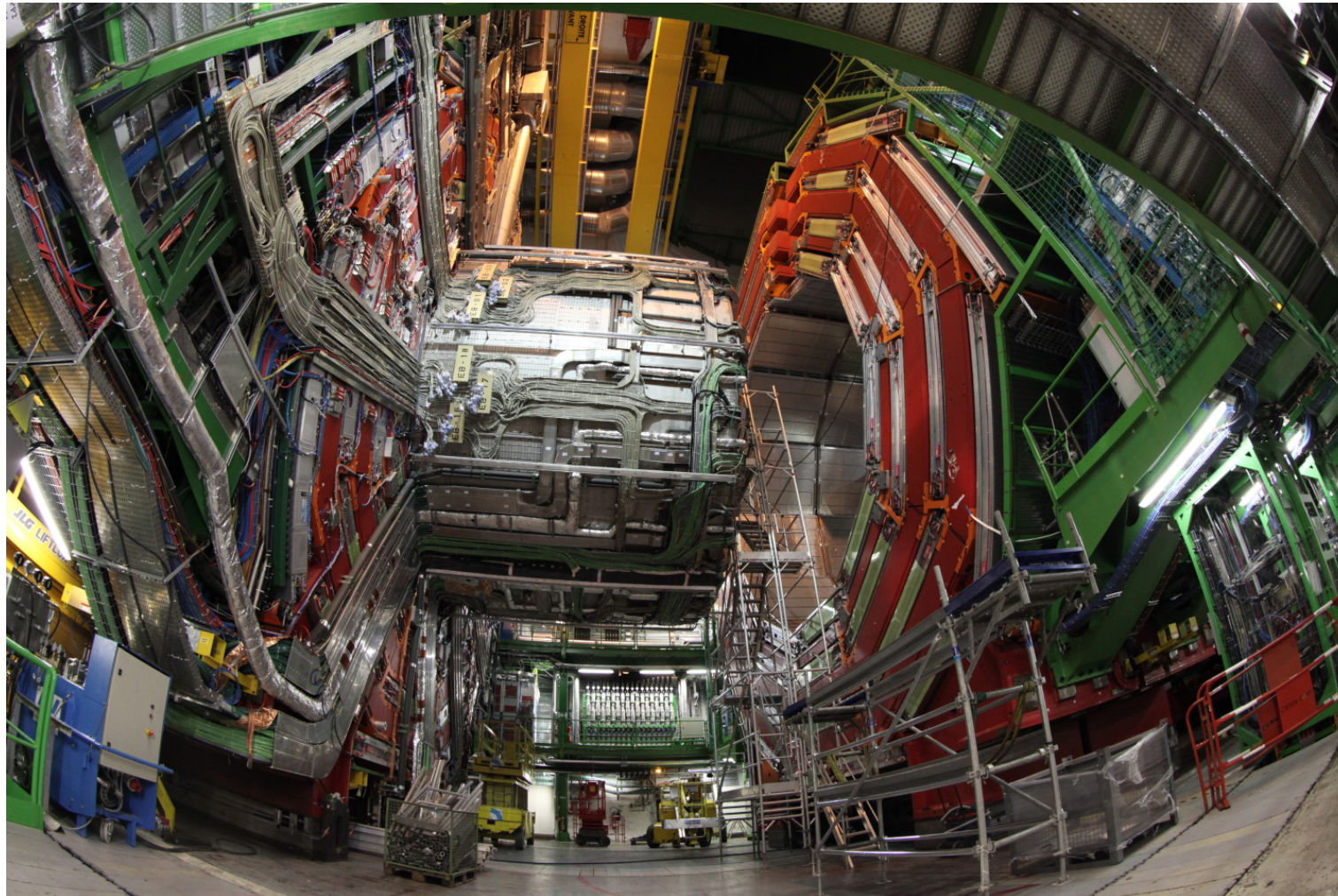
End of Part 3

Colliders – a biased list

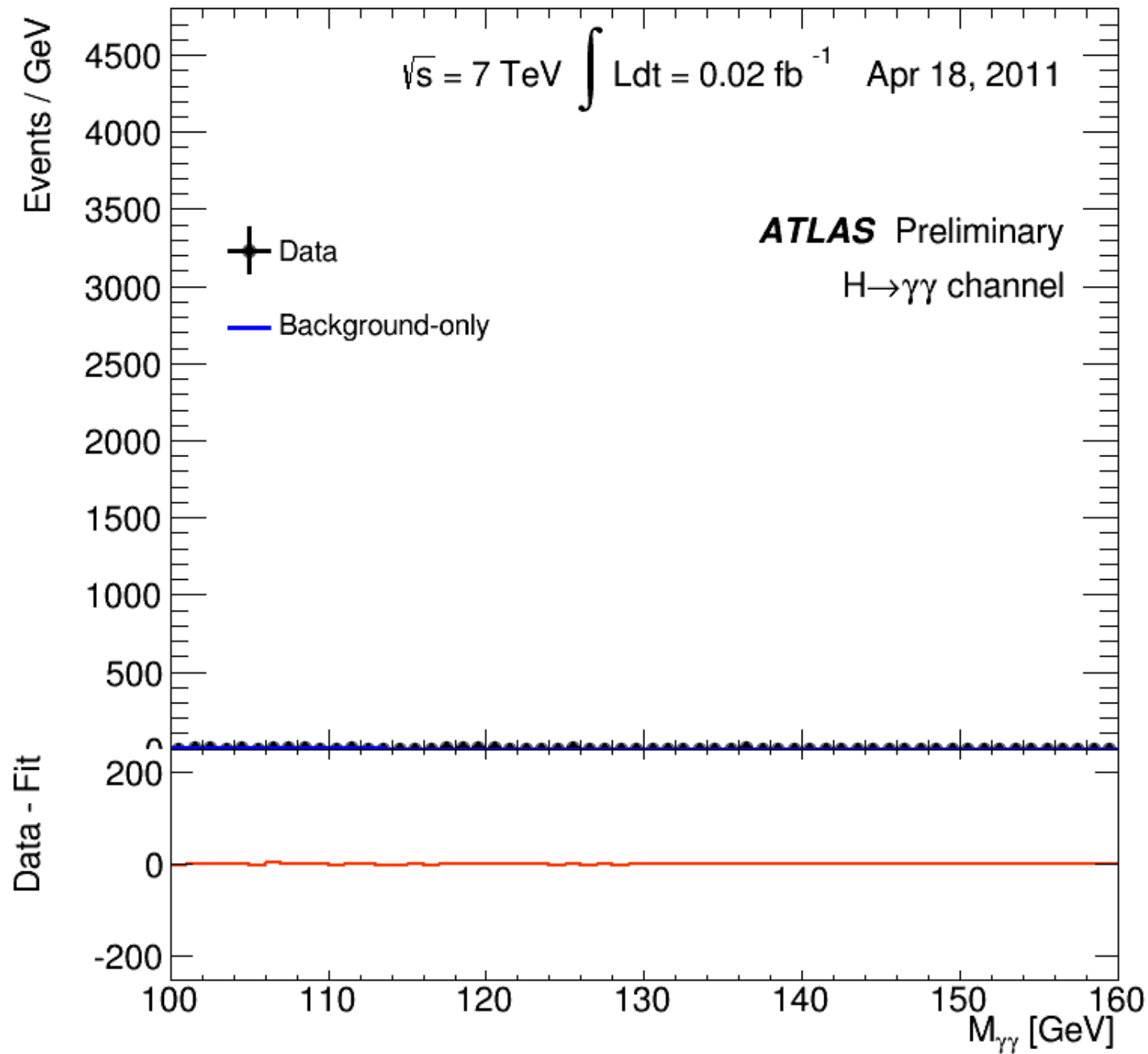
- Push to bigger accelerators at higher energies

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



The ATLAS Detector @ the LHC

