Particle Physics at the Large Hadron Collider

Fermilab Undergrad Lecture Series

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About Me

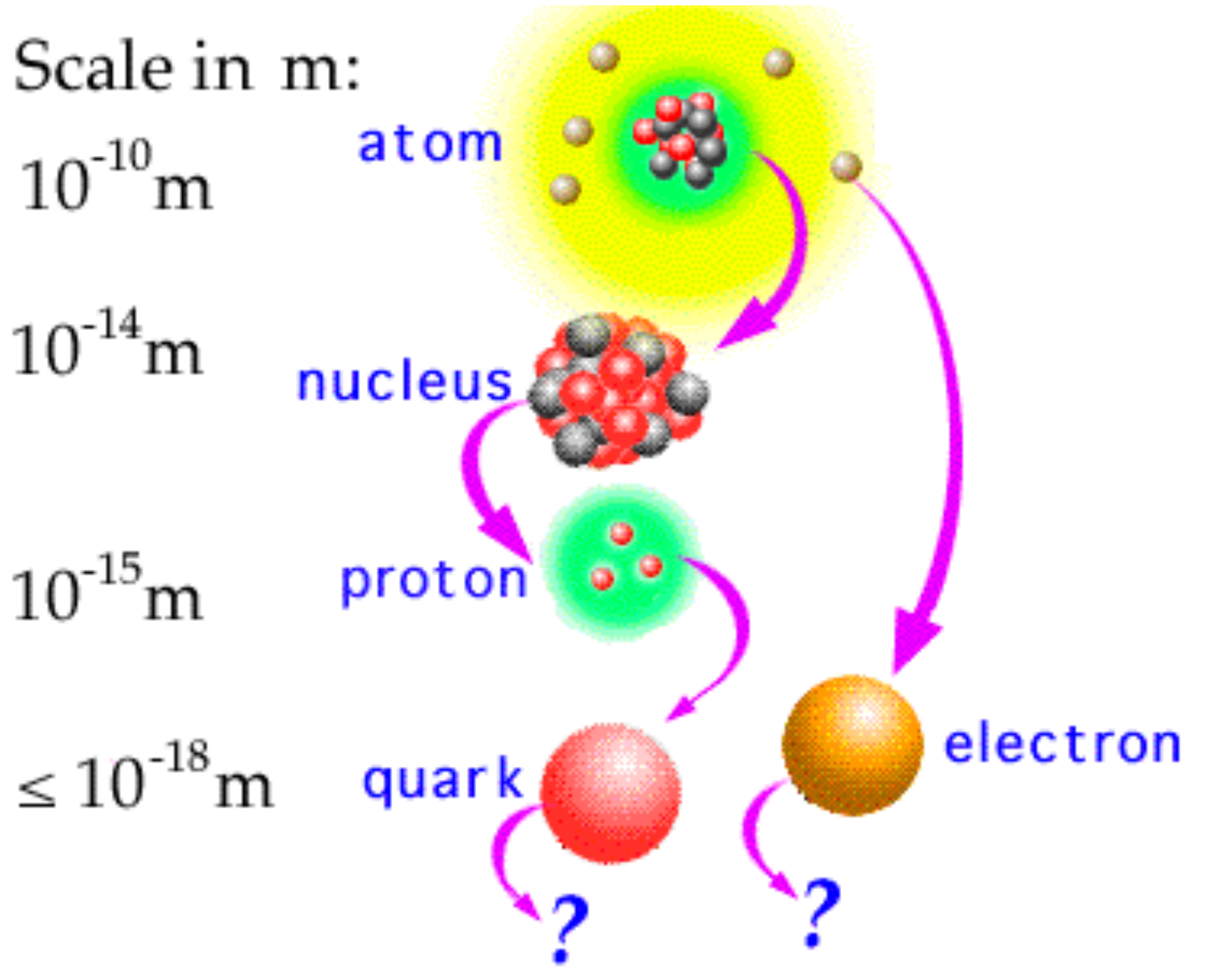
- High school in Providence, RI
- ScB from Brown in 2013
  - research & concentration in biological physics
- PhD from Harvard in 2019
  - Searches for long-lived particles
  - ATLAS Muon Spectrometer
- Now: Lederman Fellow at Fermilab with CMS
  - Searching for new physics with unconventional signatures
  - Precision timing with silicon detectors
- email: kdipetri@fnal.gov

About this lecture

- Adapted from a Saturday Morning Physics lecture for high school students
  - joint with Christian Herwig and Alexx Perloff
- We'll talk about
  - Why particle physicists use colliders
  - What questions we want to answer at the LHC
  - How the CMS and ATLAS experiments works
  - An example analysis
- Other great resources
  - CERN Summer Student Lecture Series [2019]
  - Proceedings of other intros to LHC physics
    - https://arxiv.org/abs/1004.5564
    - https://arxiv.org/abs/1611.07864
  - Physics motivation for ATLAS/CMS detector design
    - At the Leading Edge: Chapter 1

Particle physics

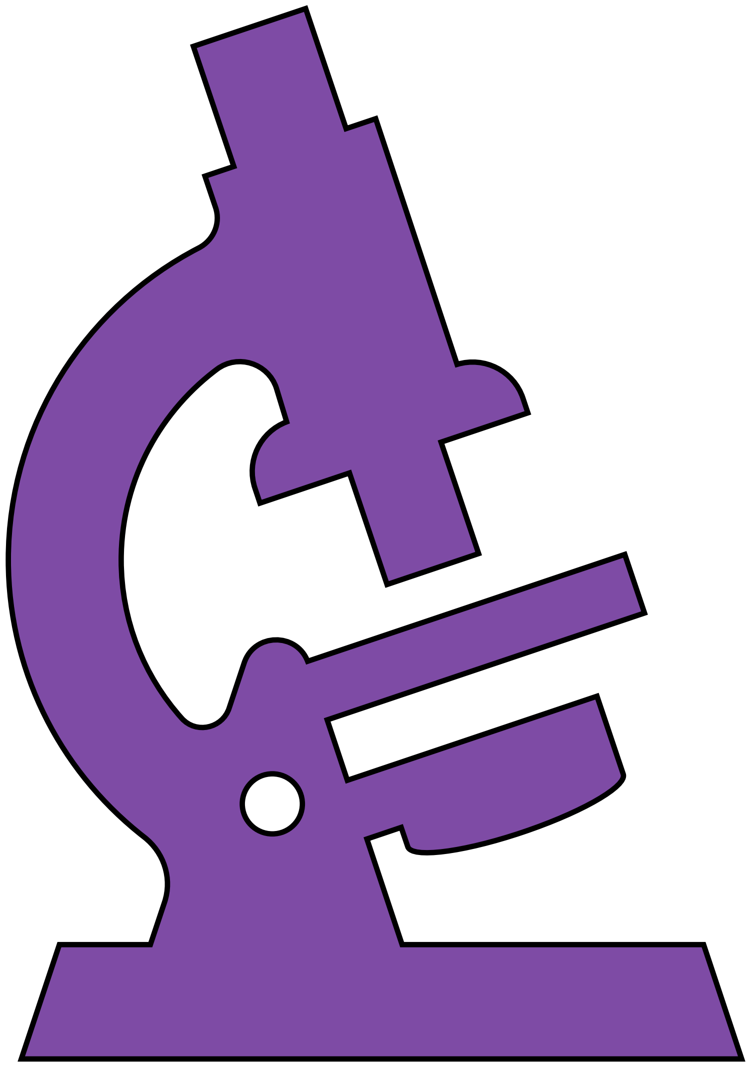
Interested in the smallest pieces of matter…
fundamental particles



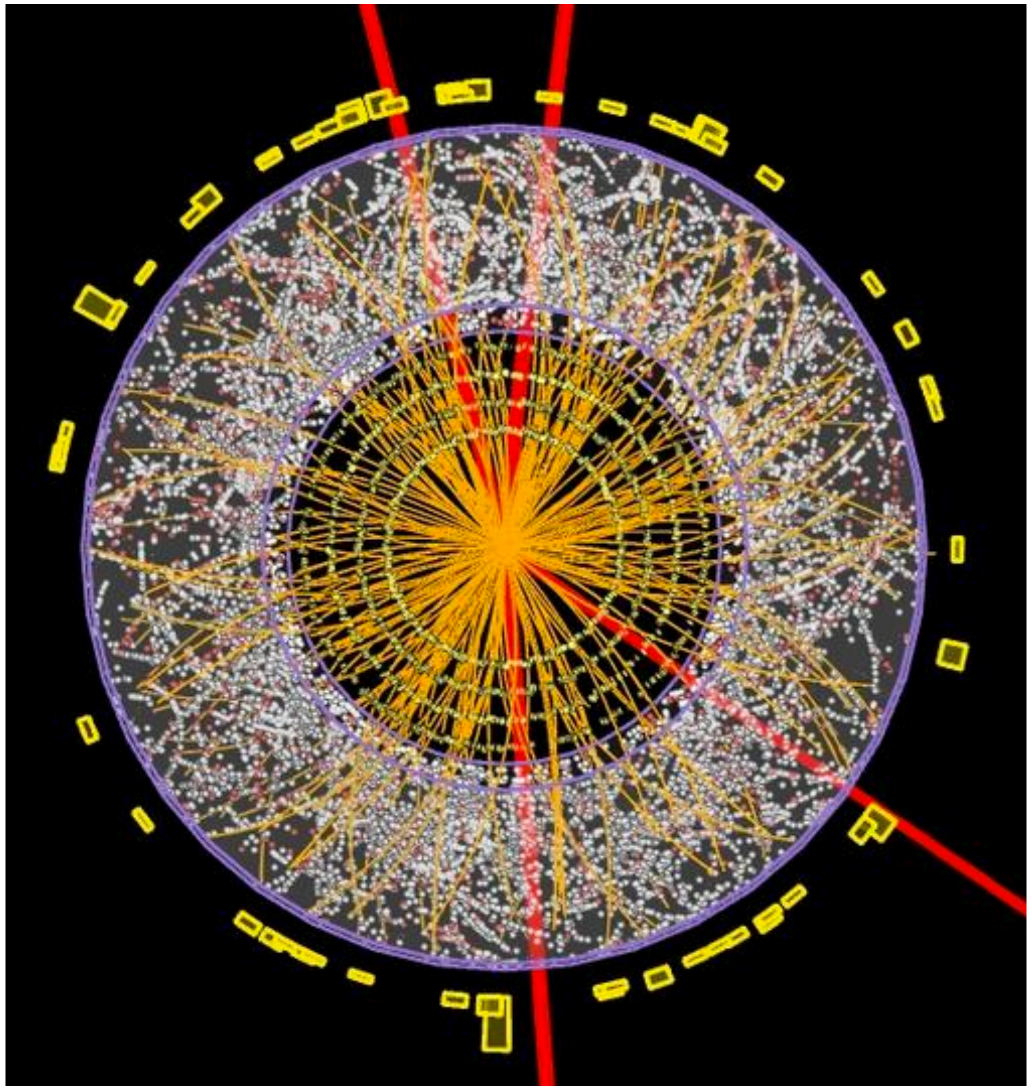
and the forces that govern these particles

How do we access small scales?

High-energy collisions access small distances



Visible light ~ 5×10^{-7} m



LHC collision ~ 10^{-19} m

Particle Colliders as a Microscope

- Quantum Mechanics tells us particles ~ waves
  - A particle with energy **E** has wavelength **λ**=**hc**/**E**
    - **c** = the speed of light
    - **h** = Planck intrinsic angular momentum (spin)
- Proton mass is 10^{-24} grams, or 1 Giga electron-volt (GeV)
  - eV = energy an electron gains over 1 volt
  - Proton wavelength is 0.2 femto-meters (10^{-15})

To accelerate an electron to 1 GeV, need a stack of AA batteries from Chicago to Geneva — the long way!

Particle Colliders as a Microscope

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- Proton mass is 10^{-24} grams, or 1 Giga electron-volt (GeV)
  - eV = energy an electron gains over 1 volt
  - Proton wavelength is 0.2 femto-meters (10^{-15})
- At the LHC, we continue a long tradition of looking to smaller scales to achieve a simpler description of nature

Periodic Table

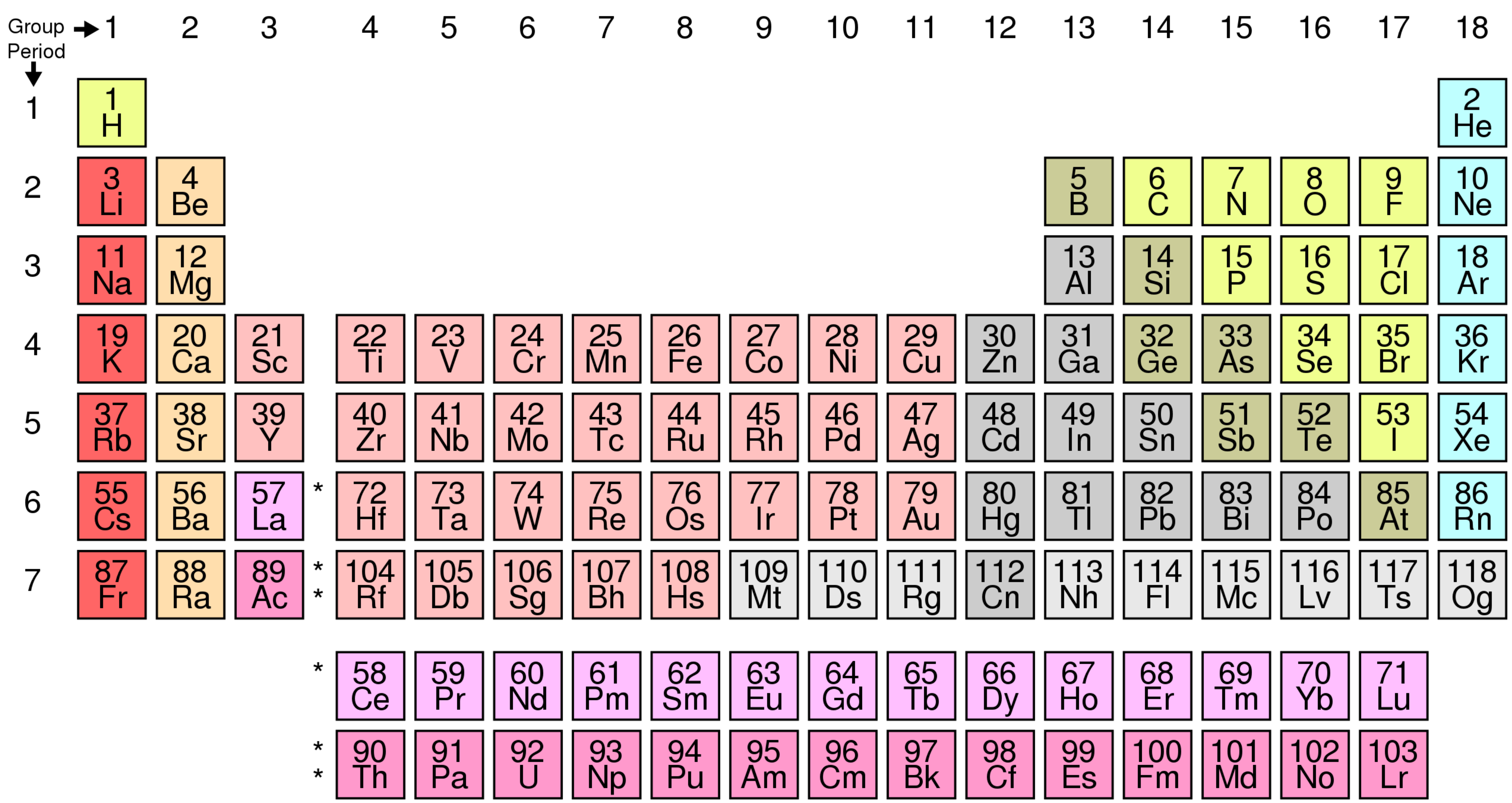
- How to understand diverse substances in everyday life?
  - Water, glass, concrete, aluminum, gasoline, …

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

- A set of fundamental (chemical) elements and prescriptions for how they may combine with each other.

Periodic Table

- How to understand diverse substances in everyday life?
  - Water, glass, concrete, aluminum, gasoline, …

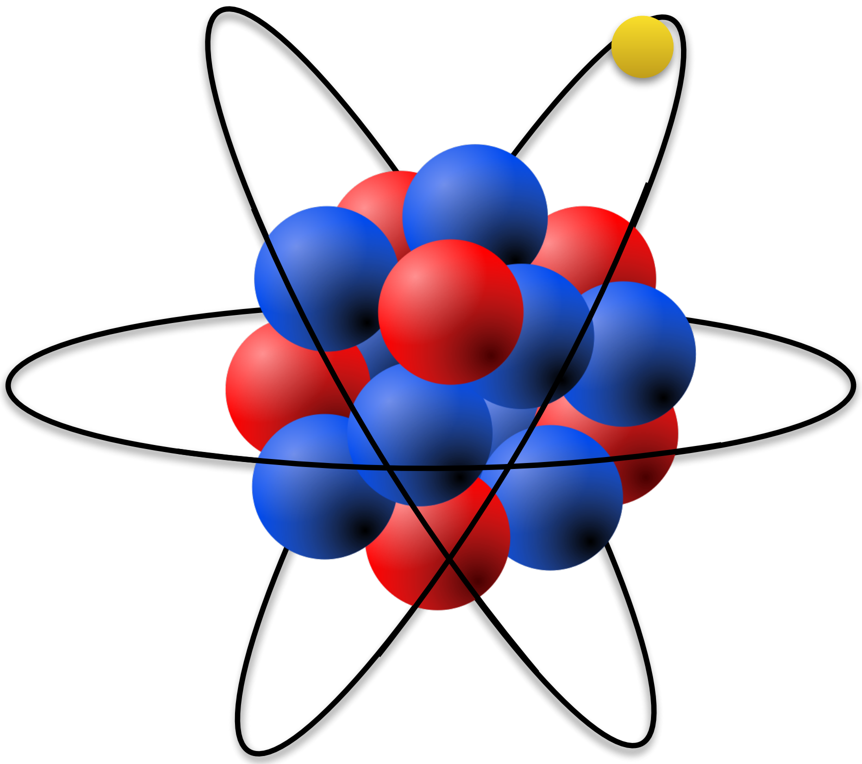


Why so many columns, rows?

Does it go on forever?

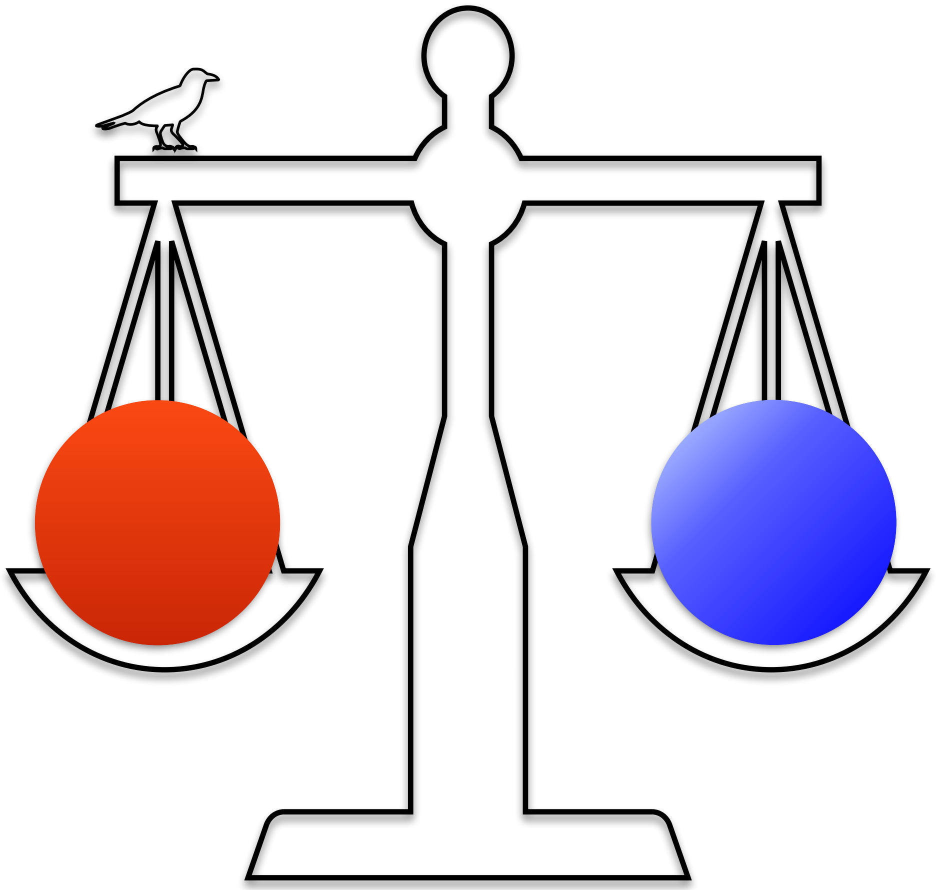
- A set of fundamental (chemical) elements and prescriptions for how they may combine with each other.

Atomic Nuclei



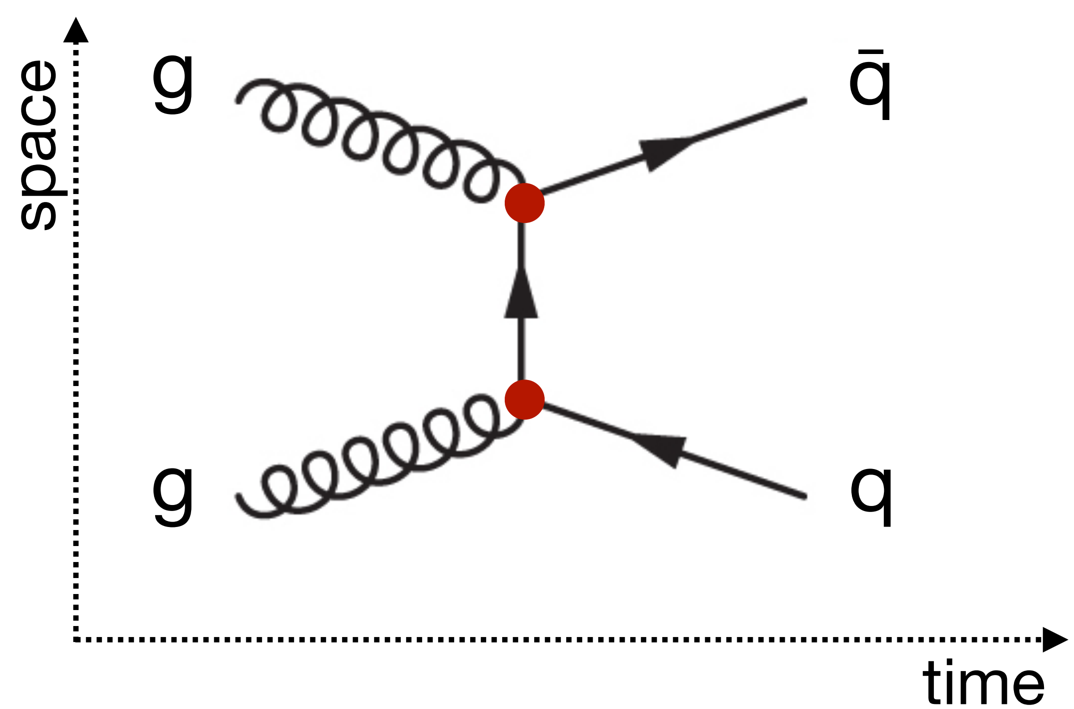
- Nuclei are just collections of protons and neutrons
  - With electrons, only need 3 ingredients for ordinary matter!

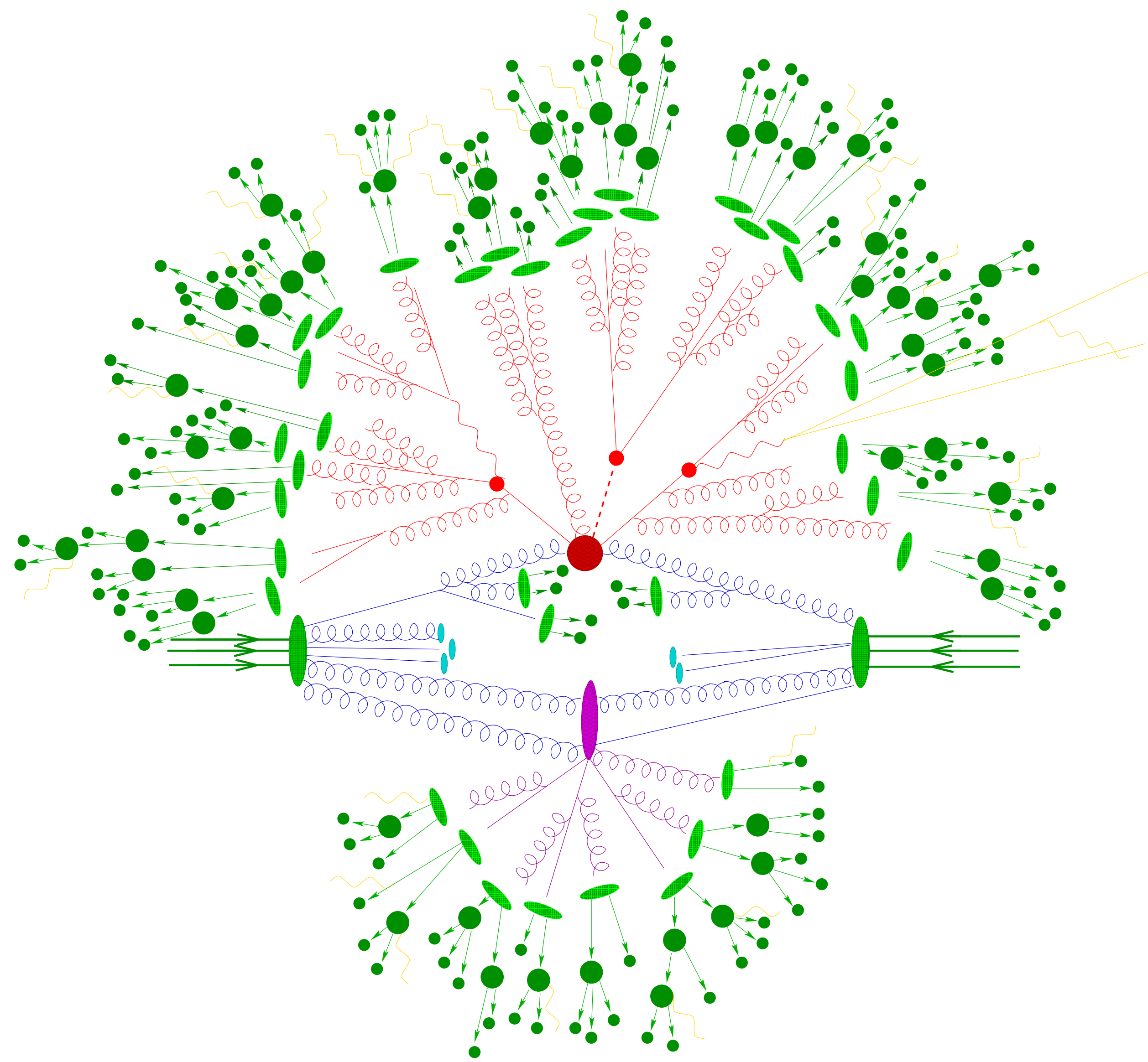
- Interesting coincidence?
  - m_{proton} = 0.9383 GeV
  - $m_{neutron}$ = 0.9396 GeV
- Hint of even deeper structure!



Simplicity = predictiveness

- Strong force: interaction structure + a single coupling
- Predicts VAST range of phenomena:
  - proton, neutron masses
  - 'excited' states
  - gluon force carrier



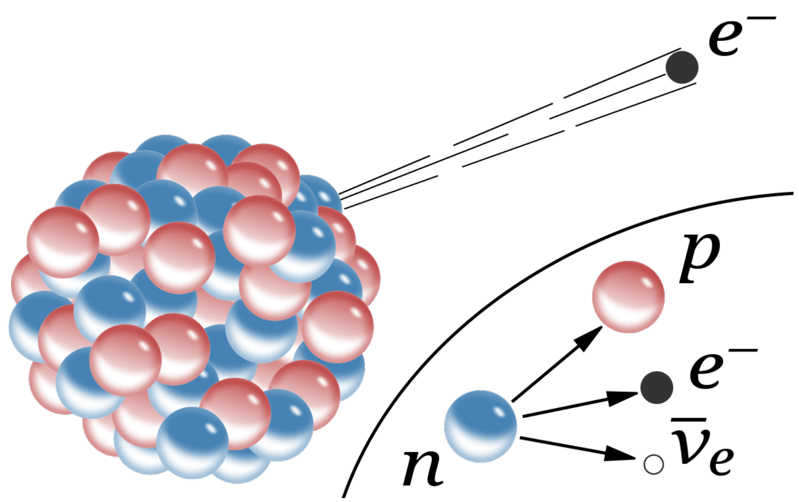


LHC collision

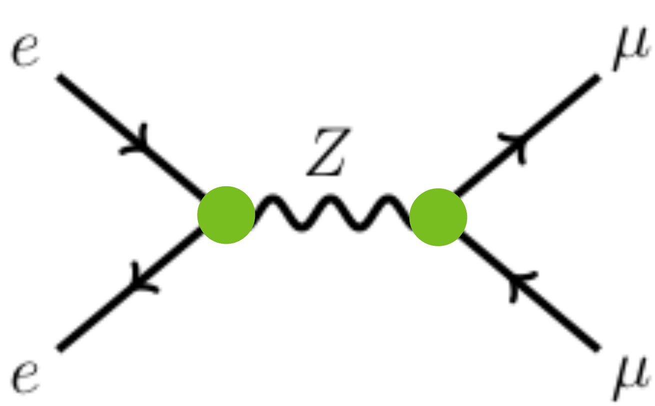
The weak force

- Similarly, weak interactions explained by a single coupling!

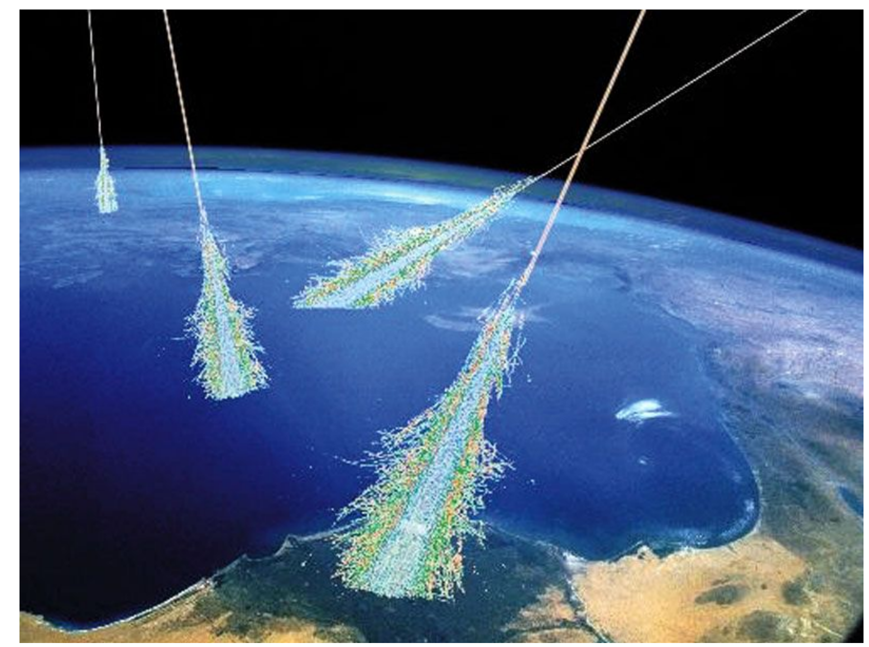
Radioactive decay

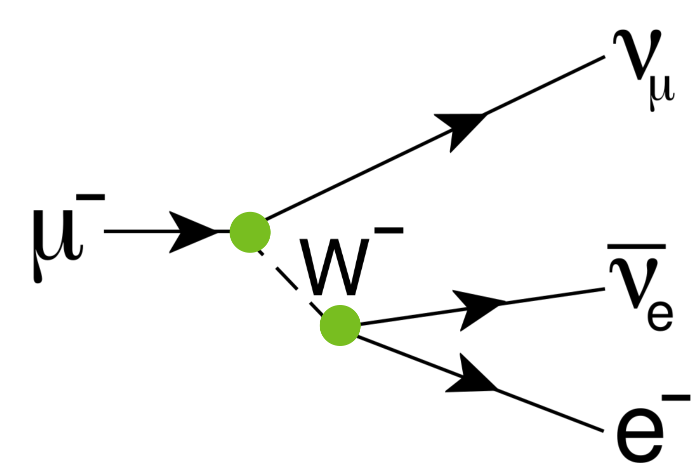


Z boson production at particle colliders



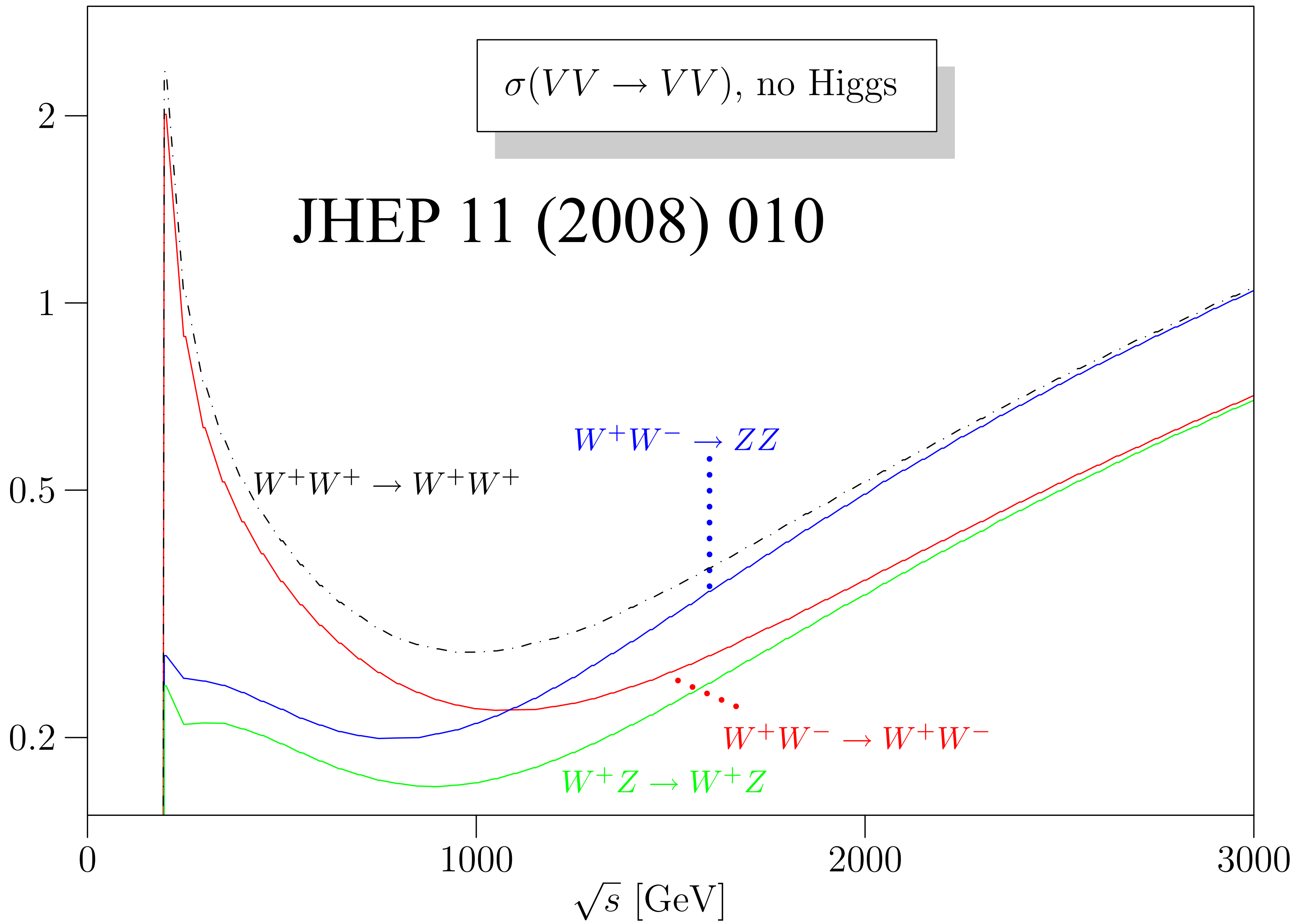
Muon decay in cosmic rays



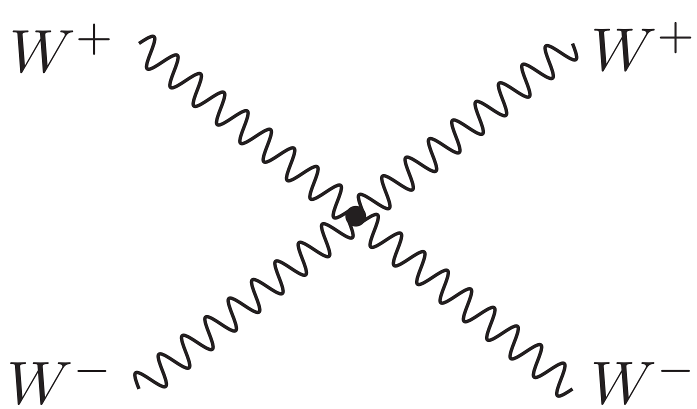


Something missing

- Particle masses not included in the theory — big hole!
- AND if we go to even smaller distances the theory breaks

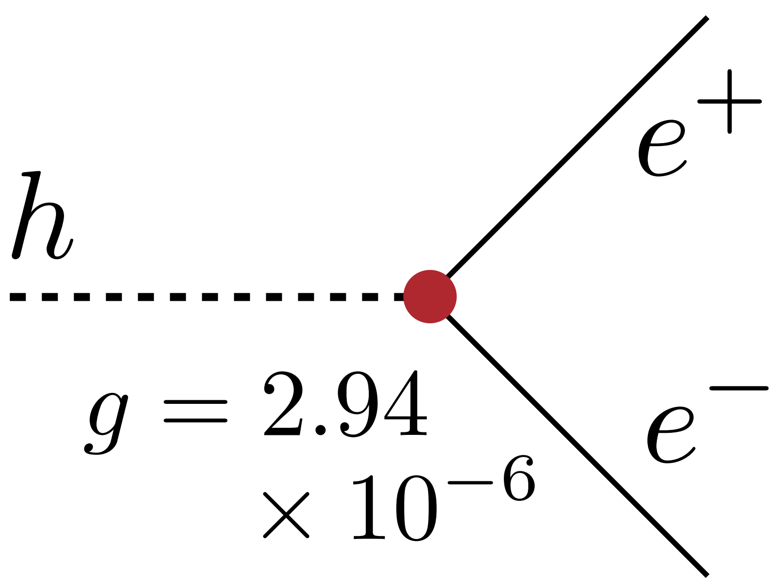


At high energies
Predict probabilities
> 1 !!!

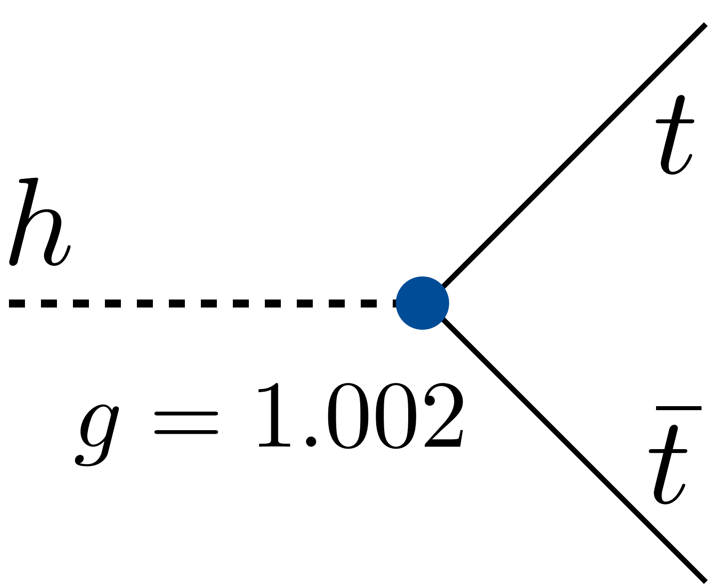


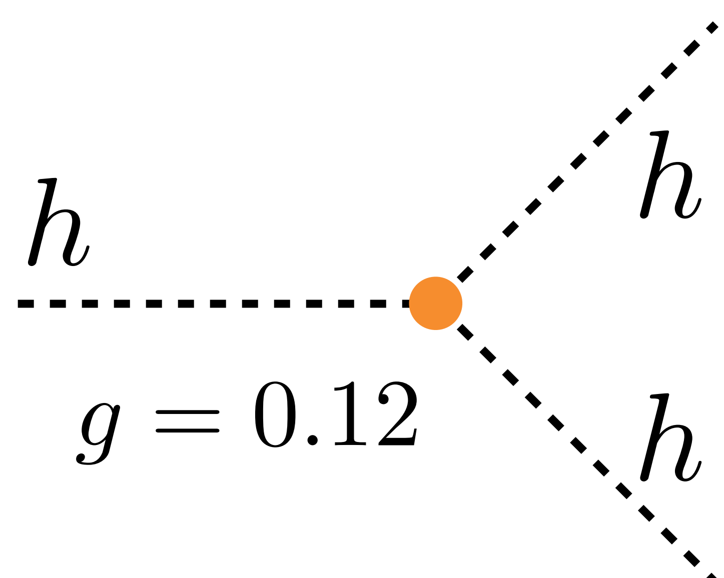
Introducing the Higgs boson

- The Higgs field: couples to ALL massive particles.
    - Electron mass originates from a Higgs-electron coupling



Each particle has a different mass, which means a DIFFERENT coupling for EVERY SINGLE PARTICLE!





Why so many new couplings?

Measure them!

Beyond the Higgs?

- Many questions revolve around the Higgs — the newest and least-understood component of the Standard Model
  - Why are there so many different masses/couplings, and with such different sizes?
  - Is there only one Higgs boson?
  - Is the Higgs a fundamental particle or a composite, like the proton?
  - Is the Higgs also responsible for neutrino masses?
  - Does the Higgs respect the known symmetries of nature?
  - How does dark matter fit into this picture??
  - …
- Higgs is a fundamentally unique particle within the SM!

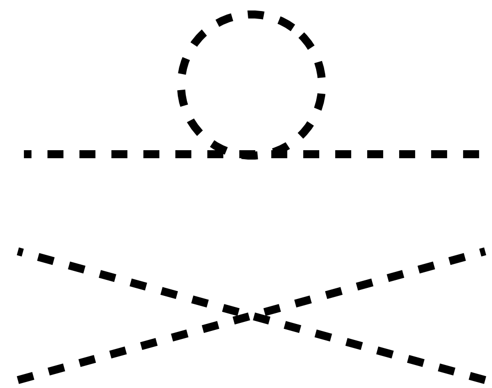
Breaking the Higgs

- So far, we've made progress by asking "what happens to our model at shorter distances?" E.g. looking
  - At substances' chemical structure
  - Inside the atom
  - Inside the nucleus
  - At high-energy W boson scattering
- Can we also "break" current theory of the Higgs?
  - Yes!

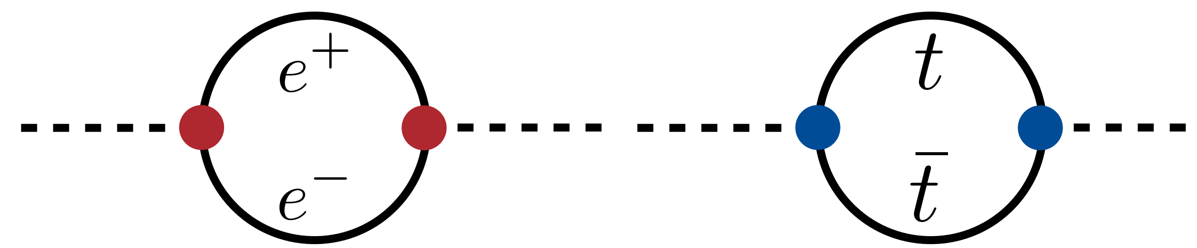
The hierarchy puzzle

- Can calculate Higgs mass. Find two contributions:

Higgs mass =



\+

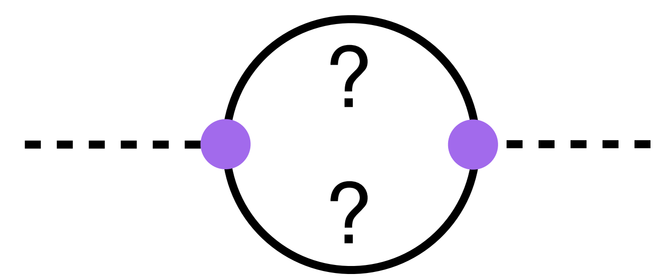


measured!
125 GeV

a few terms
~ 100 GeV

contributions proportional from each massive particle

undiscovered particles too!



- E.g. a 10^{16} GeV graviton wants to "pull up" the Higgs mass to 10^{16} GeV, but we observe it as 125 GeV. Why??

A new symmetry?

- Suggests a new *mechanism* to keeps Higgs light
- Supersymmetry is one possible answer
  - Idea: every SM particle gets a copy, with equal and opposite contribution to Higgs mass

- Experimental question: where are the super-partners?
  - Expect their masses to be near the Higgs.
  - We can look for these new particles at the LHC!

And there are even more questions

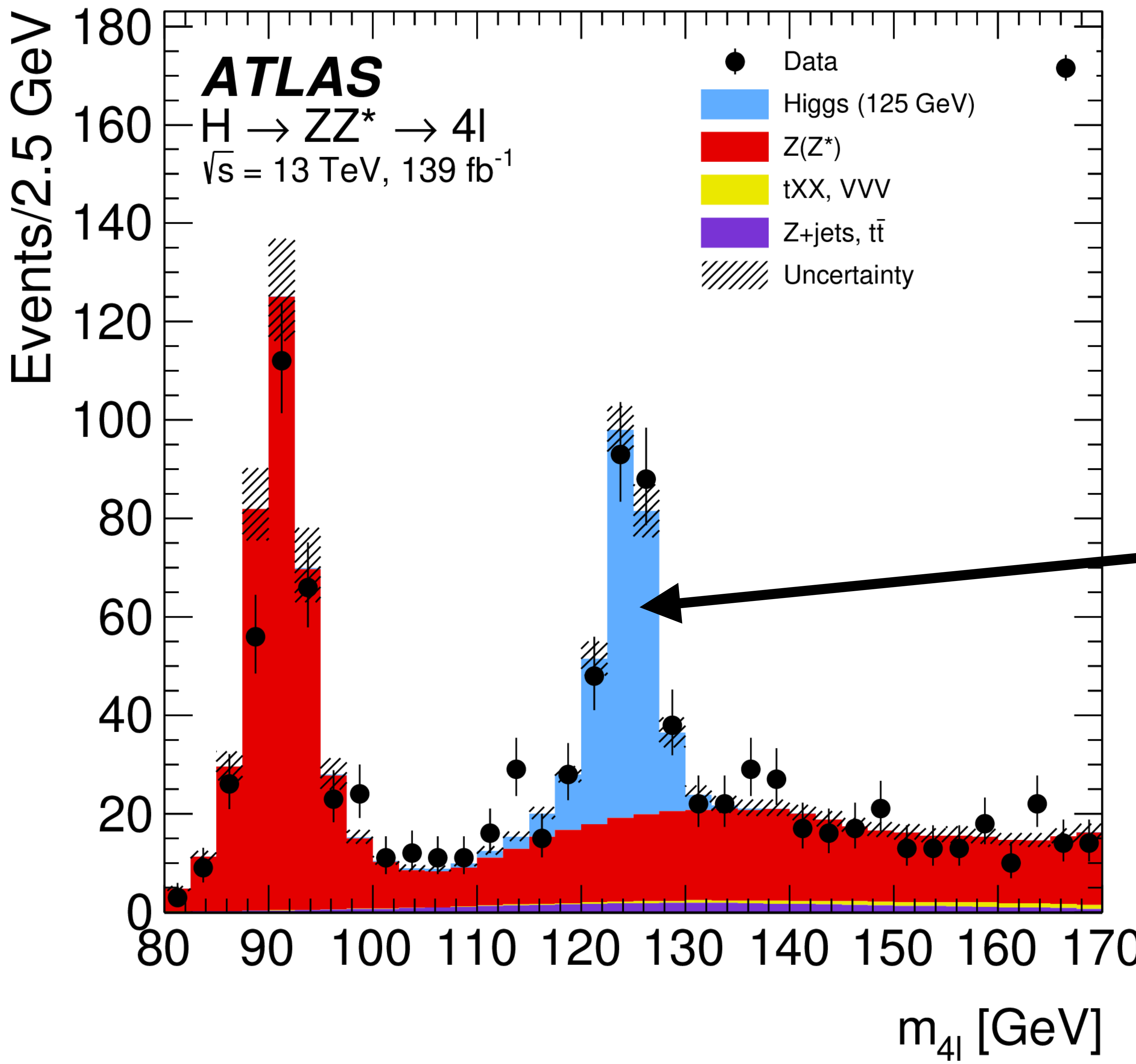
- If we just think about the Standard Model
    - why are there three generations of quarks and leptons?
    - are all leptons the same?
    - why is there more matter than anti-matter in the universe?
    - What is dark matter? Can we make dark matter particles in colliders?
    - What about gravity?
    - ….
- A high energy collider is a generic way to probe all of these questions!

How to do physics at the LHC

The easy way…

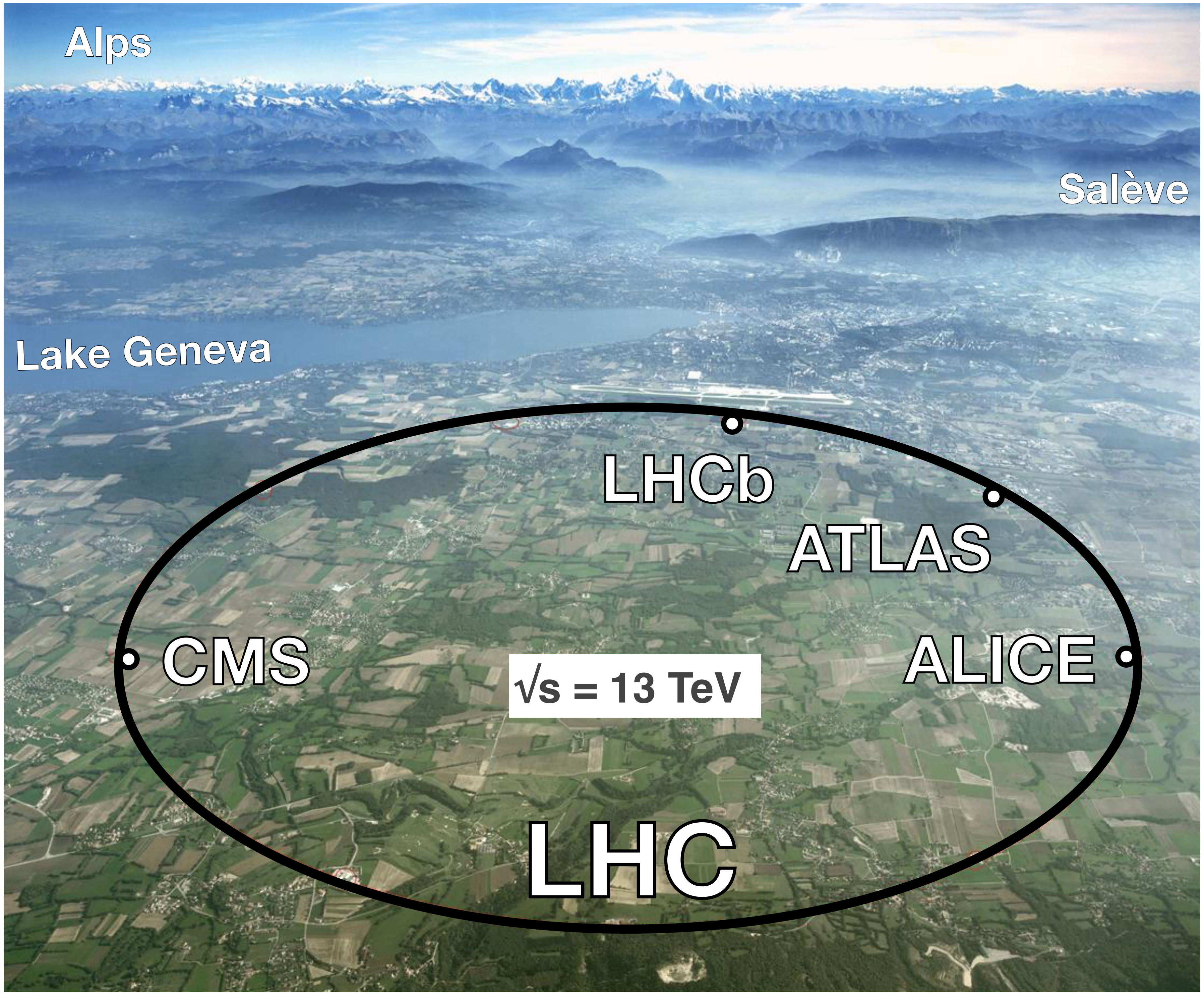
Example: How to find a Higgs

arXiv:2004.03969



The Higgs!

The Large Hadron Collider



The LHC =
source of particles

27 km circumference

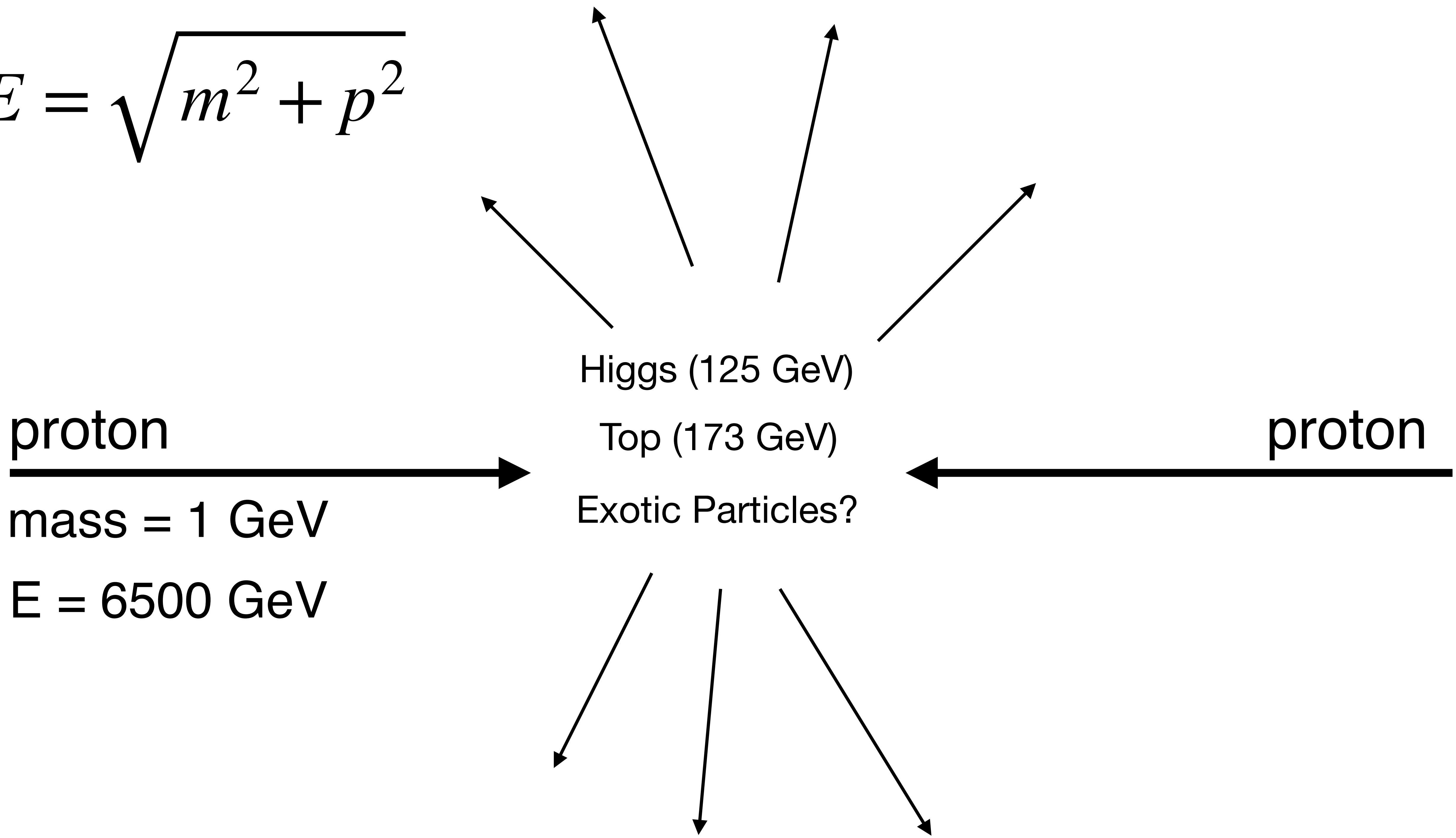
protons travel at
99.999 999 99%
the speed of light

Lives on the border of Geneva, Switzerland & France

Making heavier particles

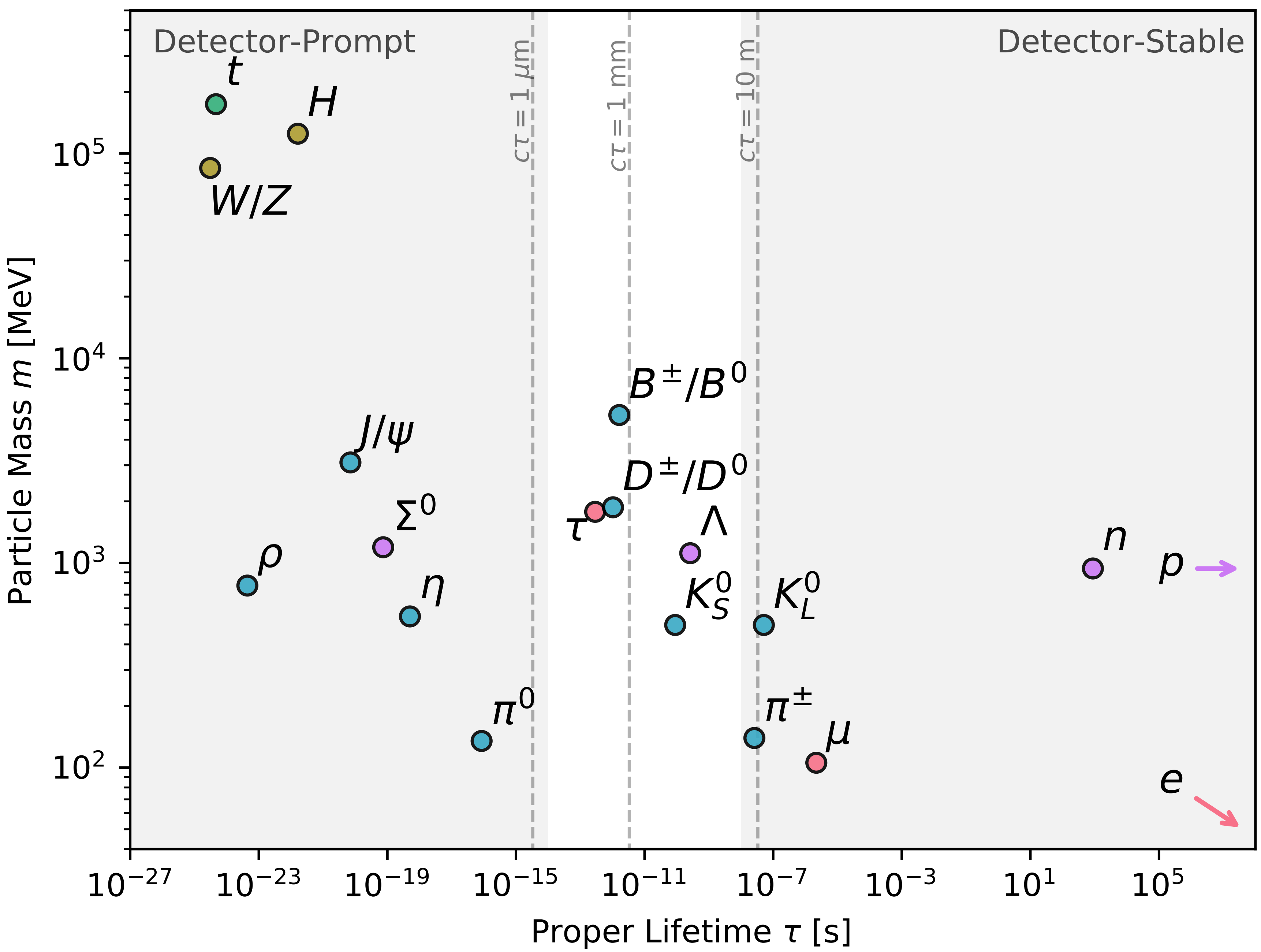
LHC = Highest energy collider in the world

$$E = \sqrt{m^2 + p^2}$$



We don’t see the Higgs, it decays…

Three categories of particles, based on lifetime

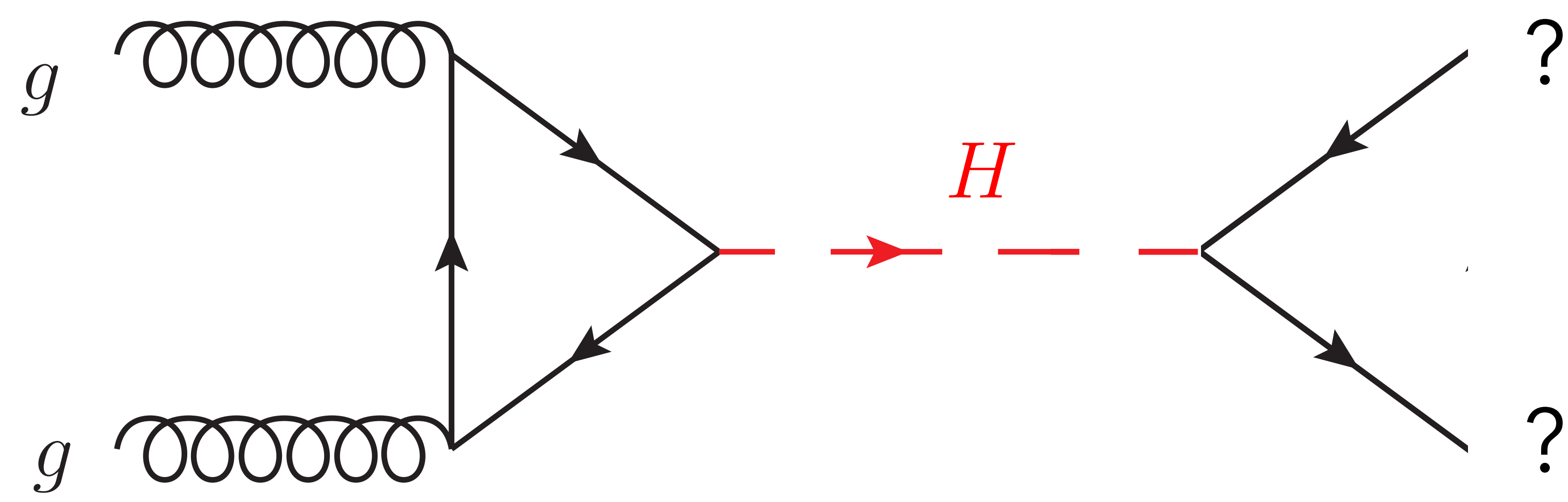


How does the Higgs decay?

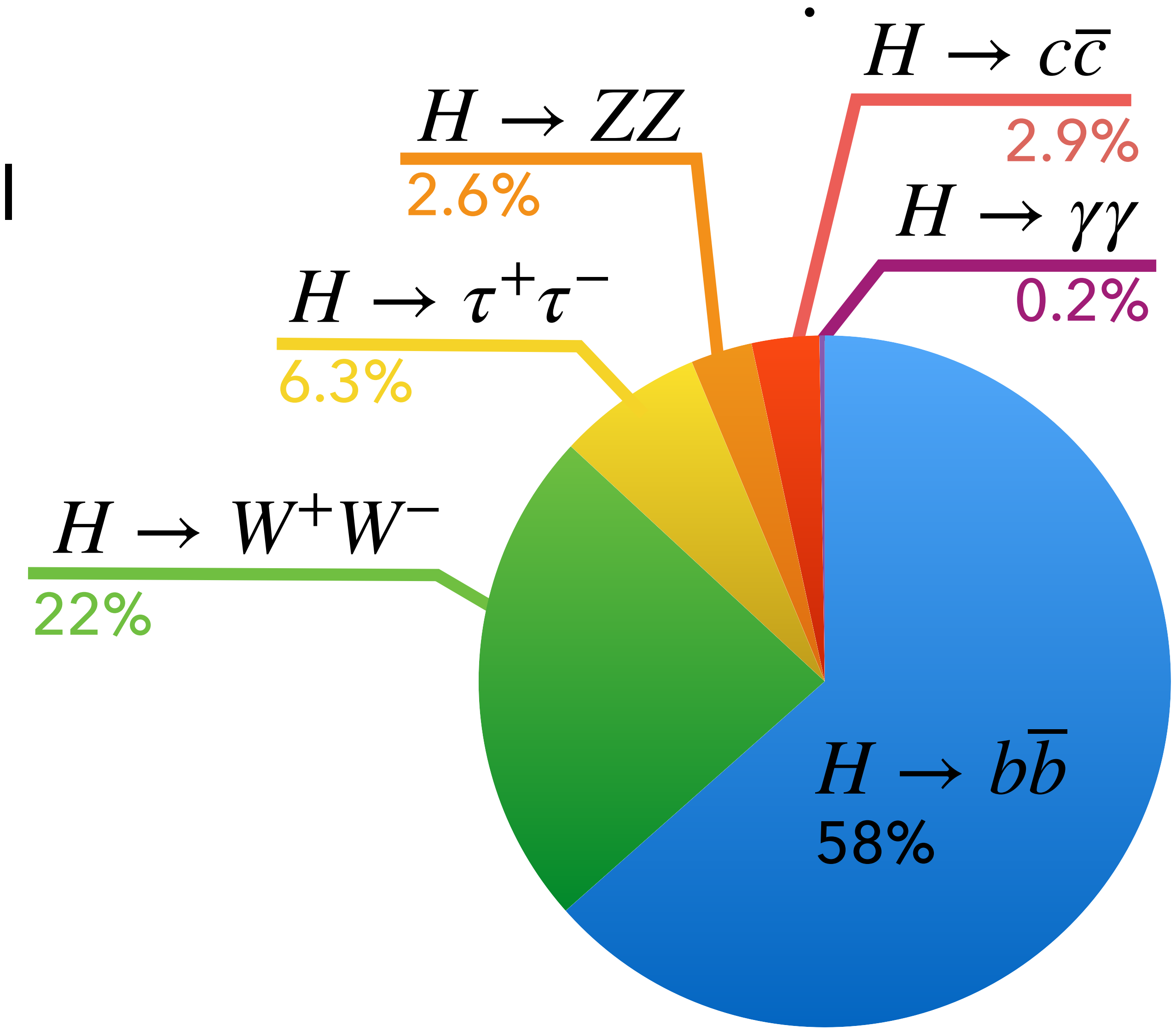
produce

detect

(87%)

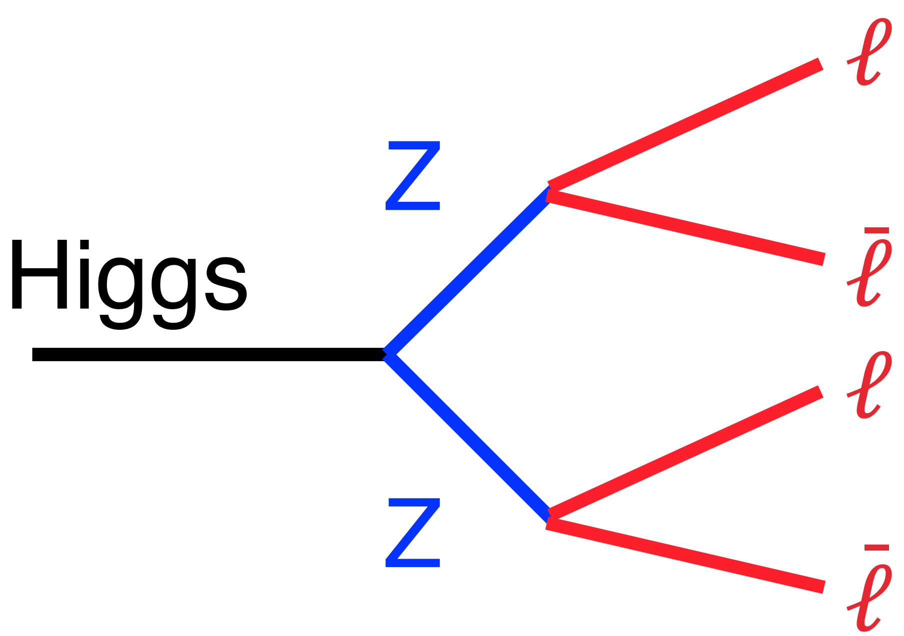


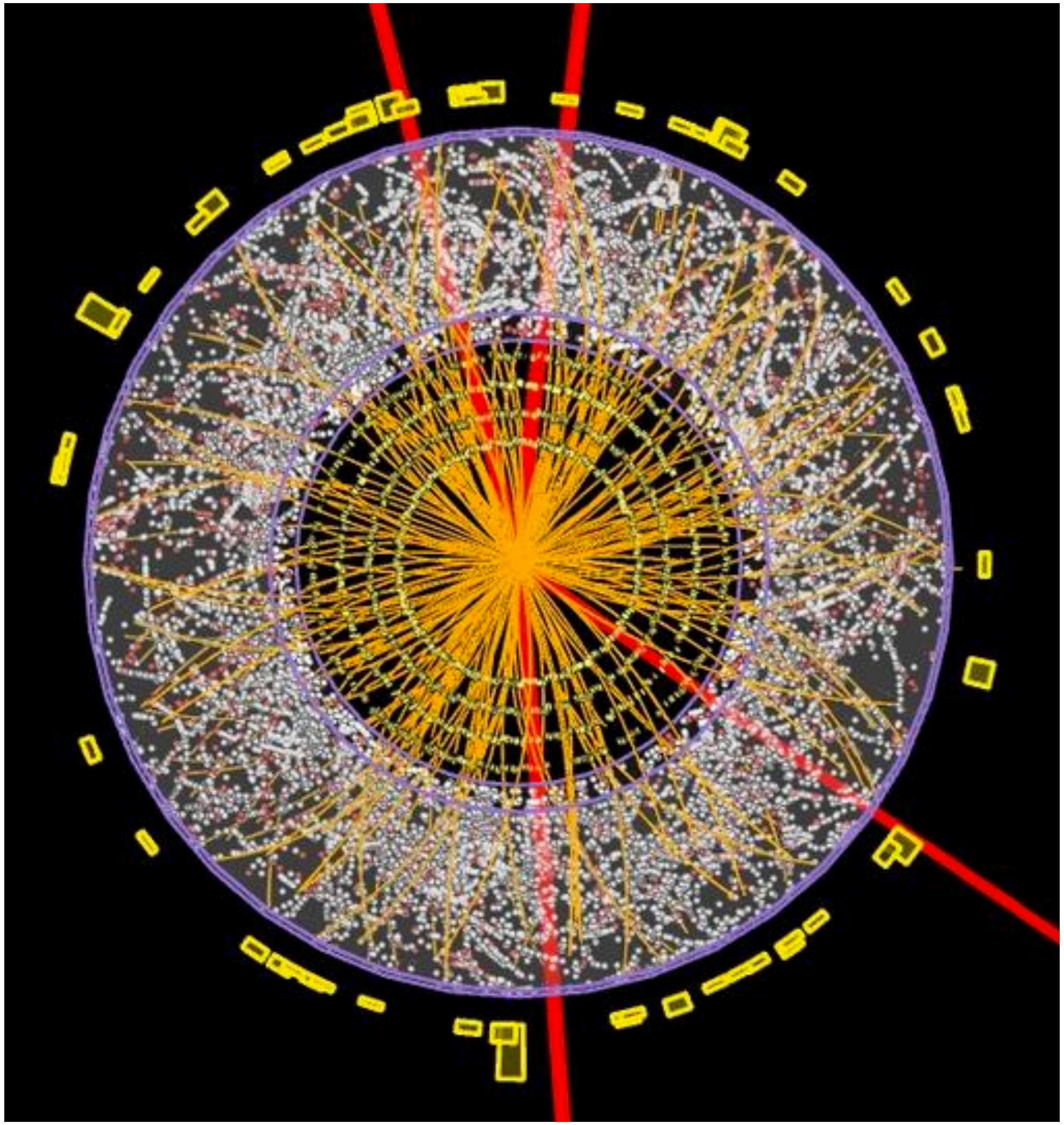
- H→γγ and **H→ZZ** have small rate but are very “clean”
- H→bb is large, but more difficult due to large backgrounds



What we see in the detector

Means we never see the Higgs
Just it's decay products

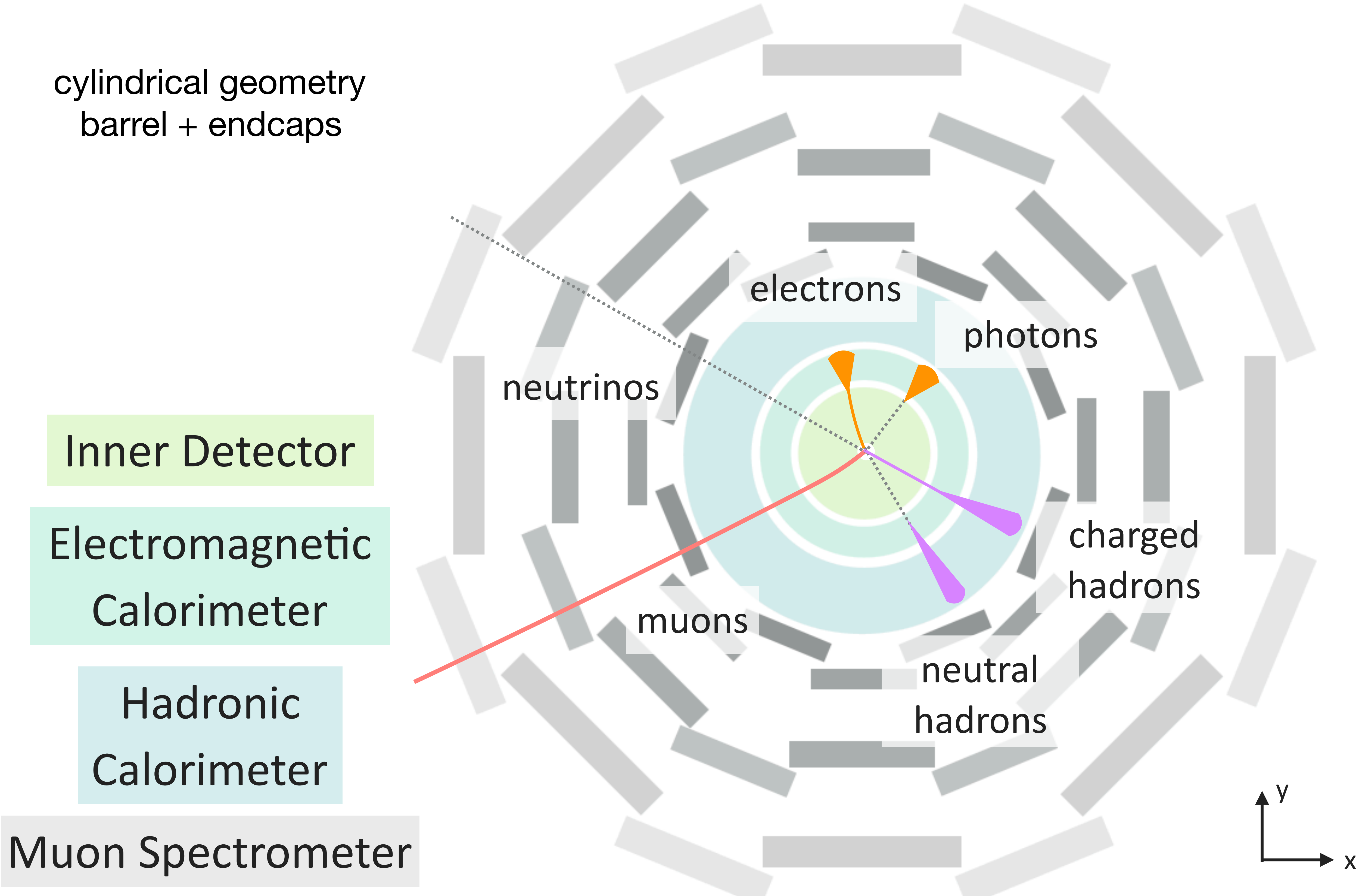




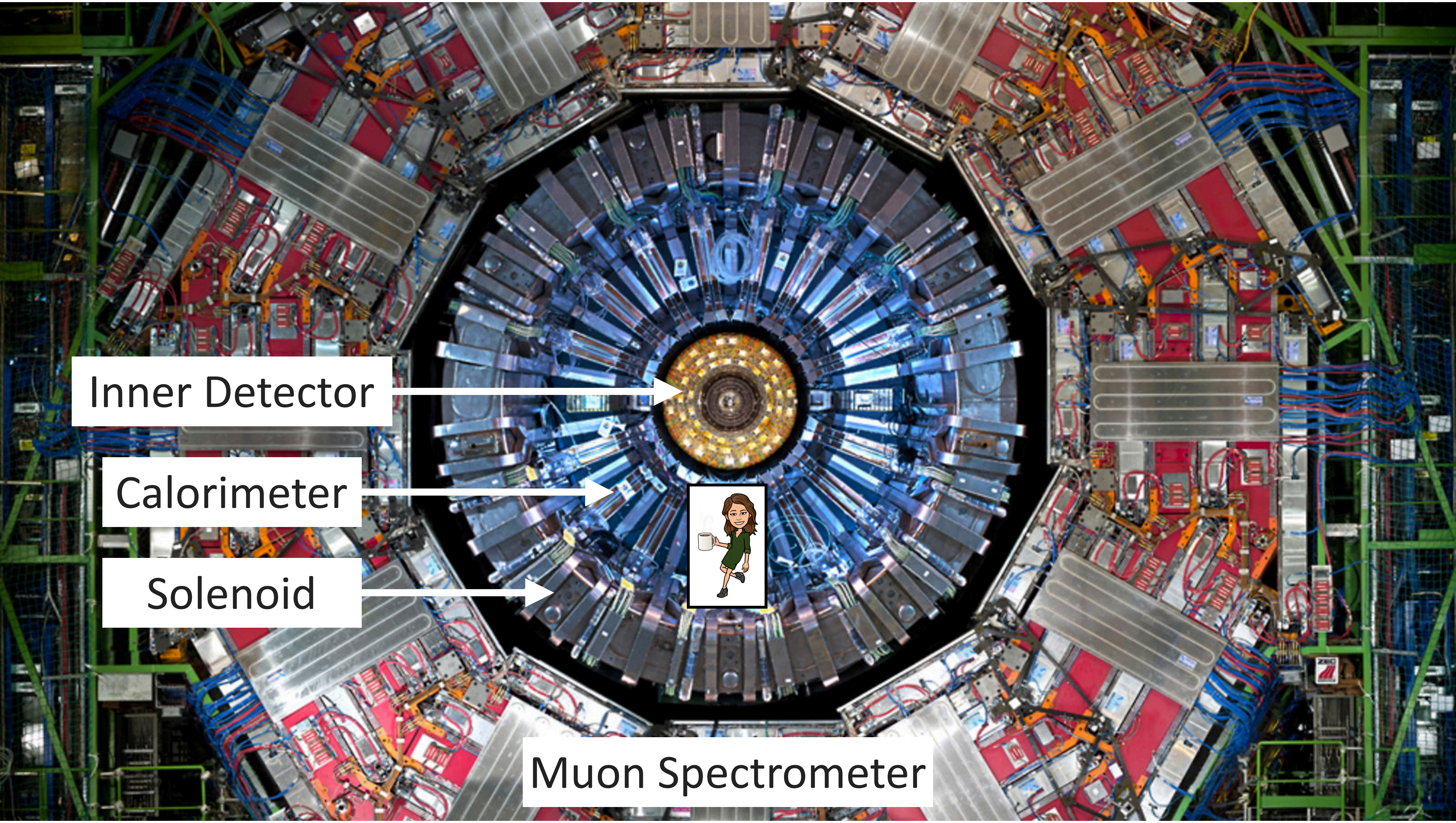
Our goal: identify & measure
all detector stable particles

How we identify our particles

cylindrical geometry
barrel + endcaps



A real detector!



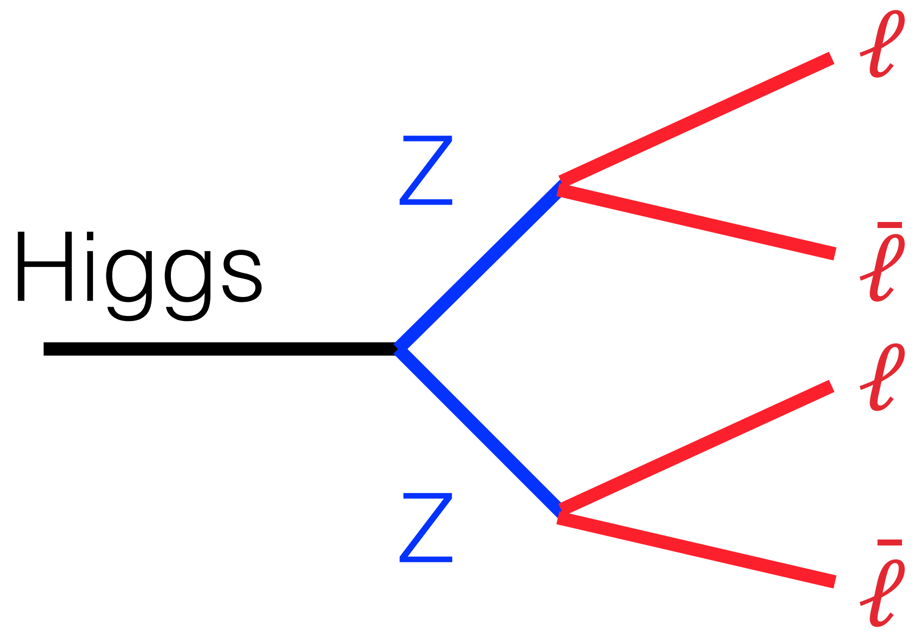
Then we make a Higgs

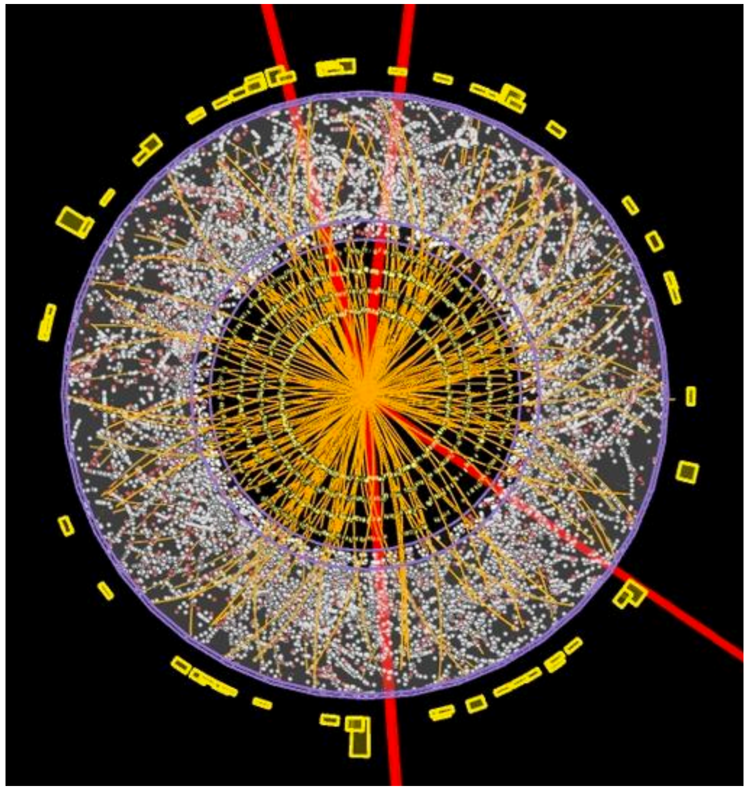
Select events with 4 leptons (e or μ)

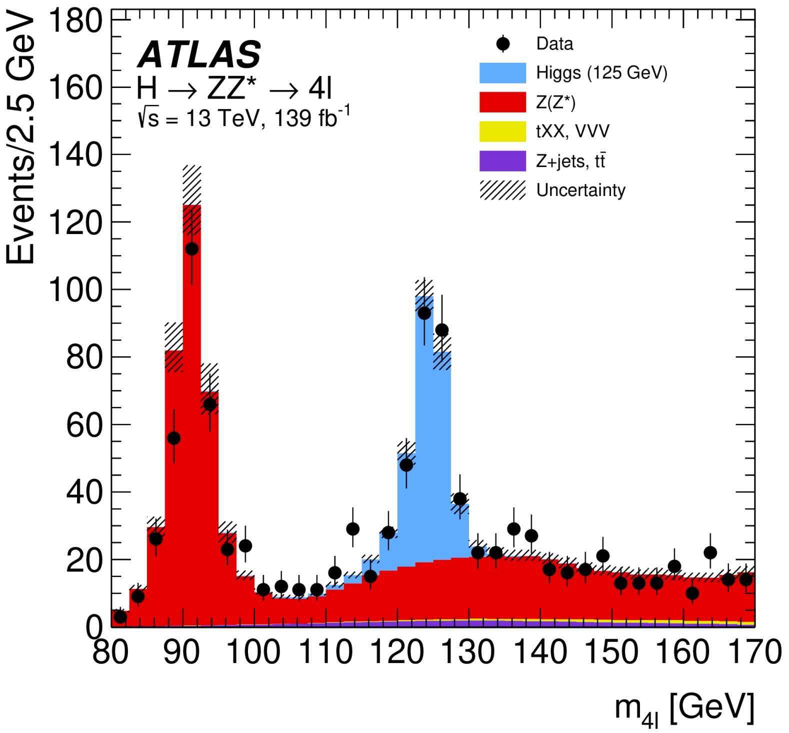
Identify pairs of leptons from Z bosons

Compute the Higgs mass

Fill histogram → see a bump!





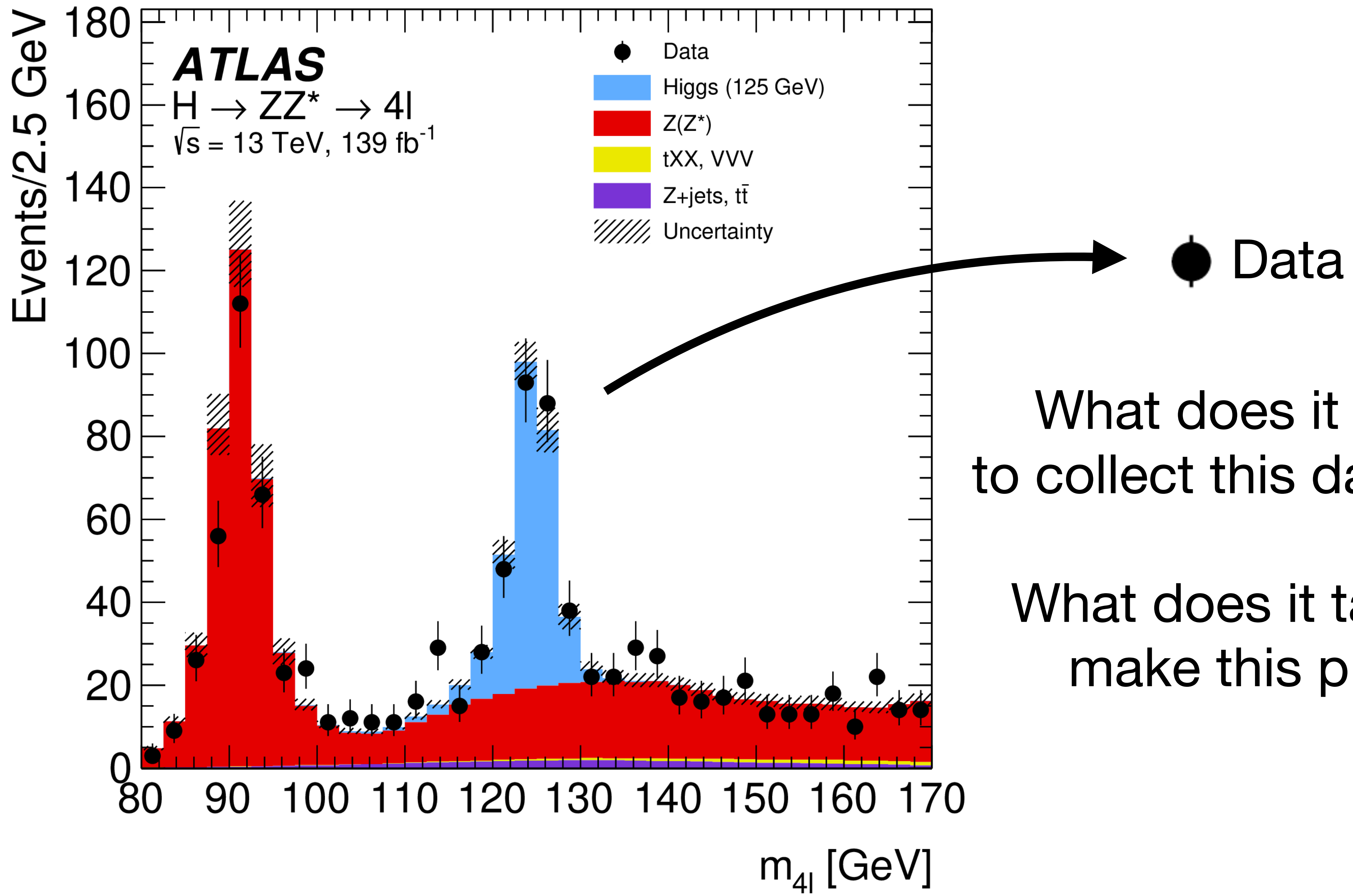


Challenge #1

The Detector

Example: How to find a Higgs

arXiv:2004.03969



What does it take to collect this dataset?

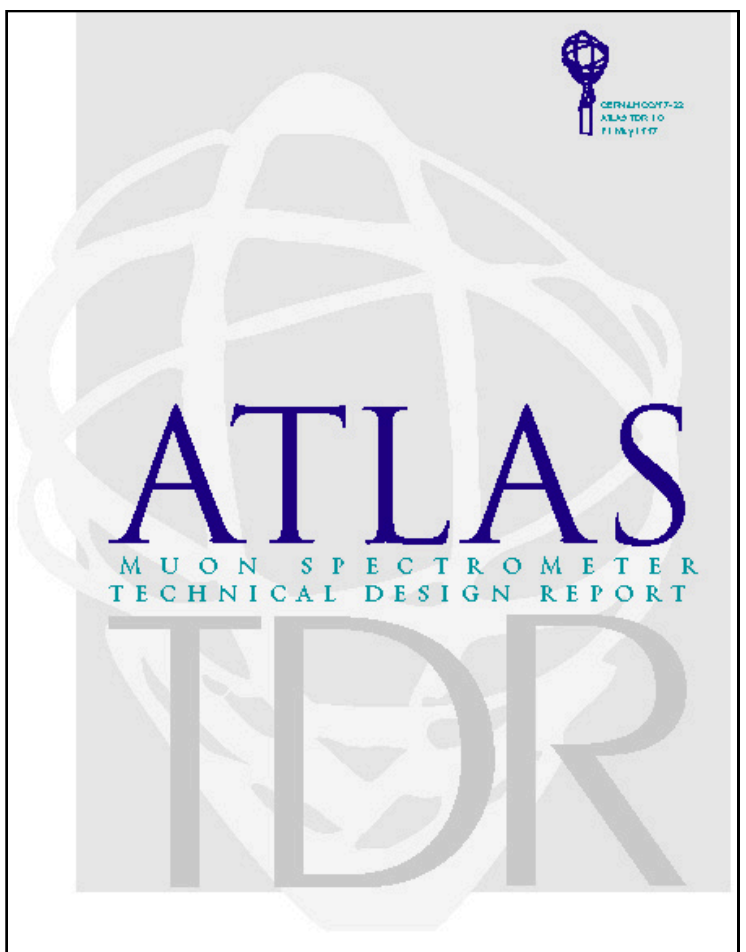
What does it take to make this plot?

It’s hard work to make a detector

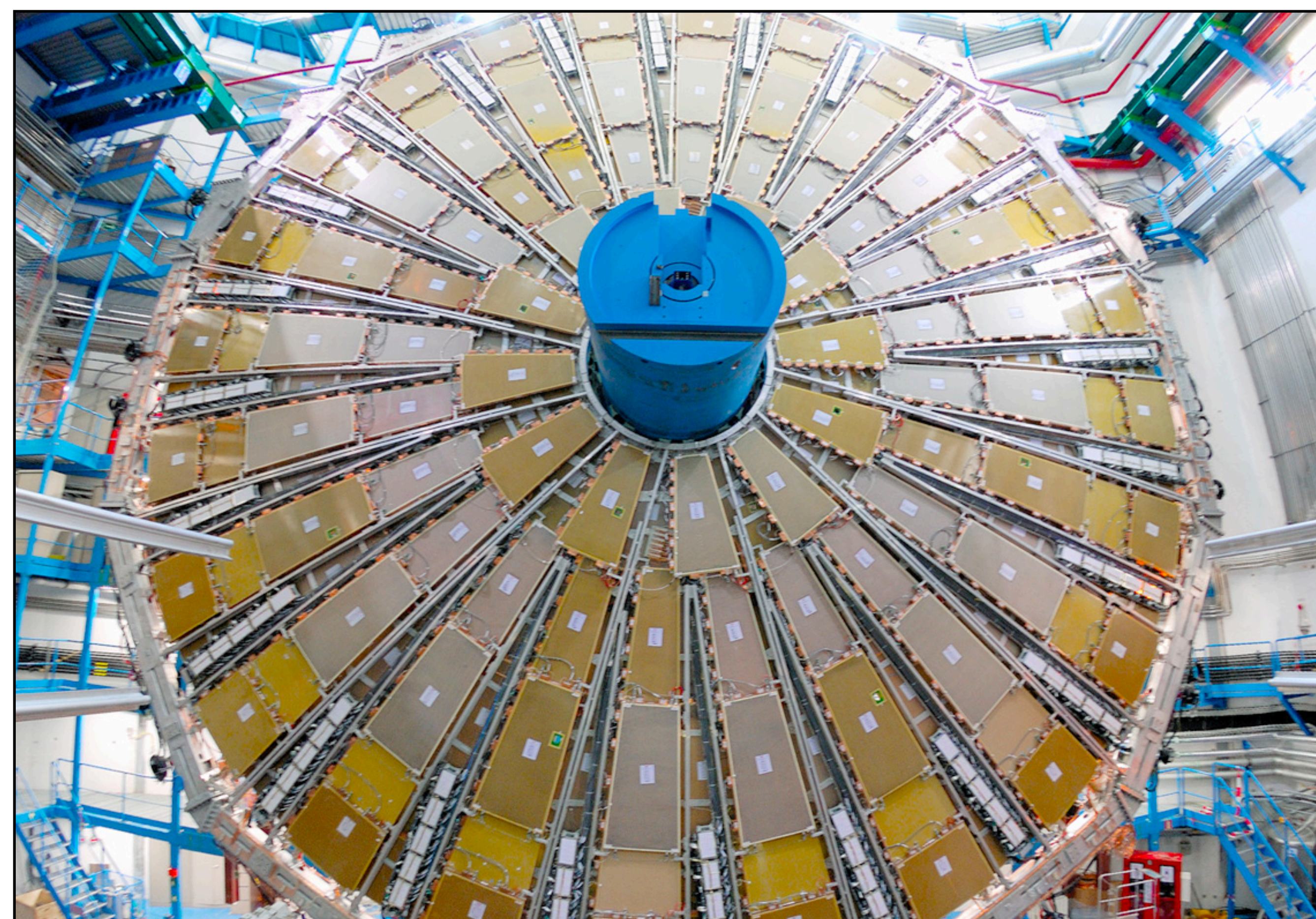
~complete design — installation

1997 → 2008

hundreds? of people to build ATLAS Muon Spectrometer



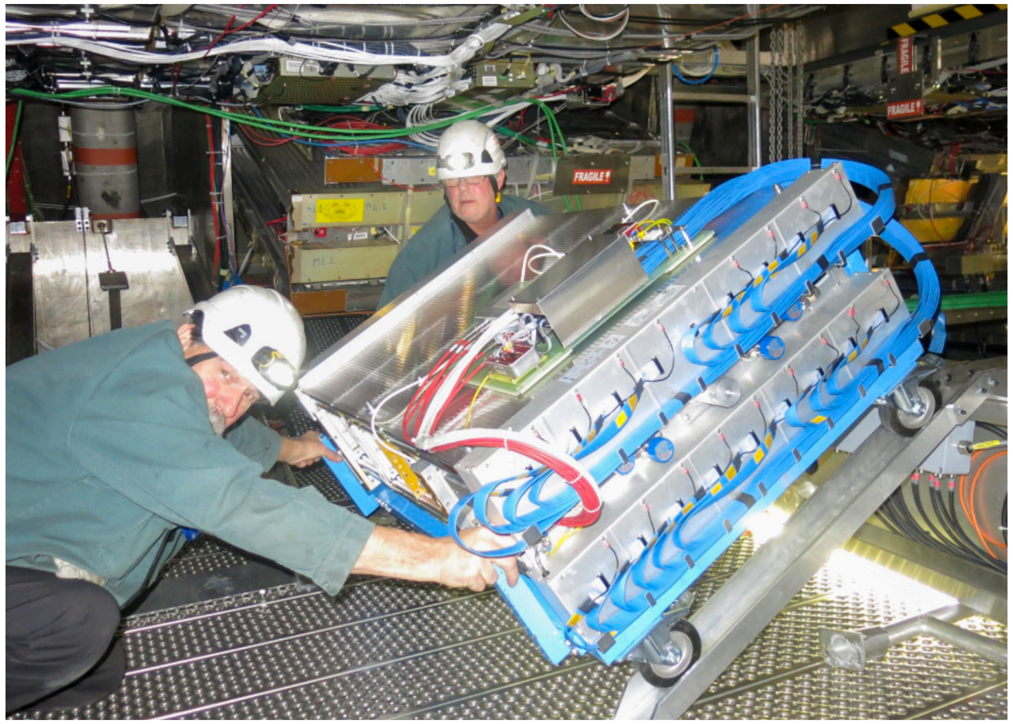
20 m

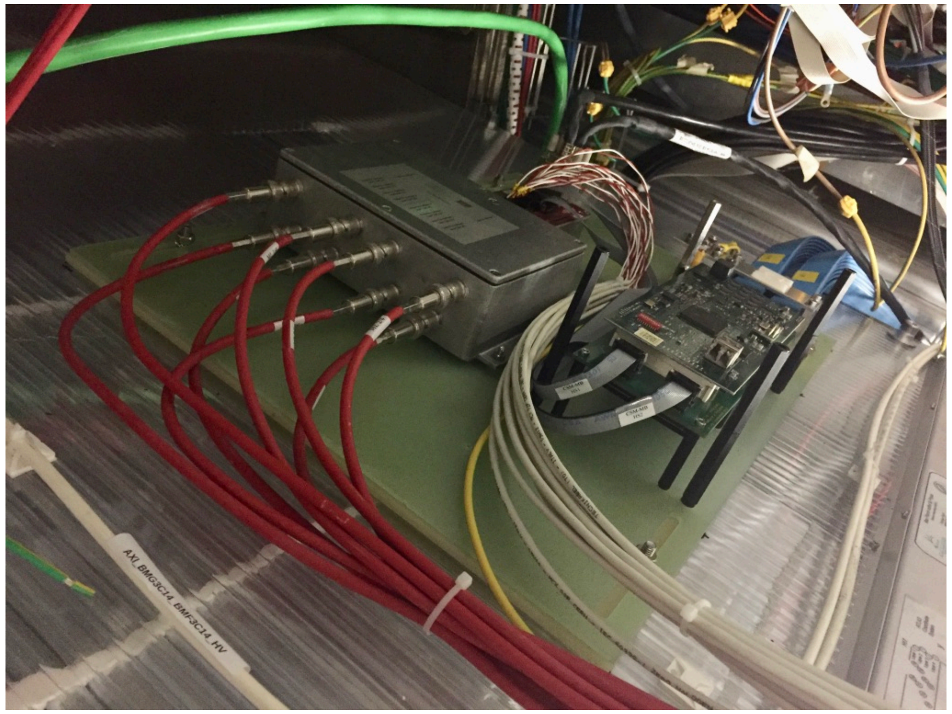


Even installing one chamber is hard

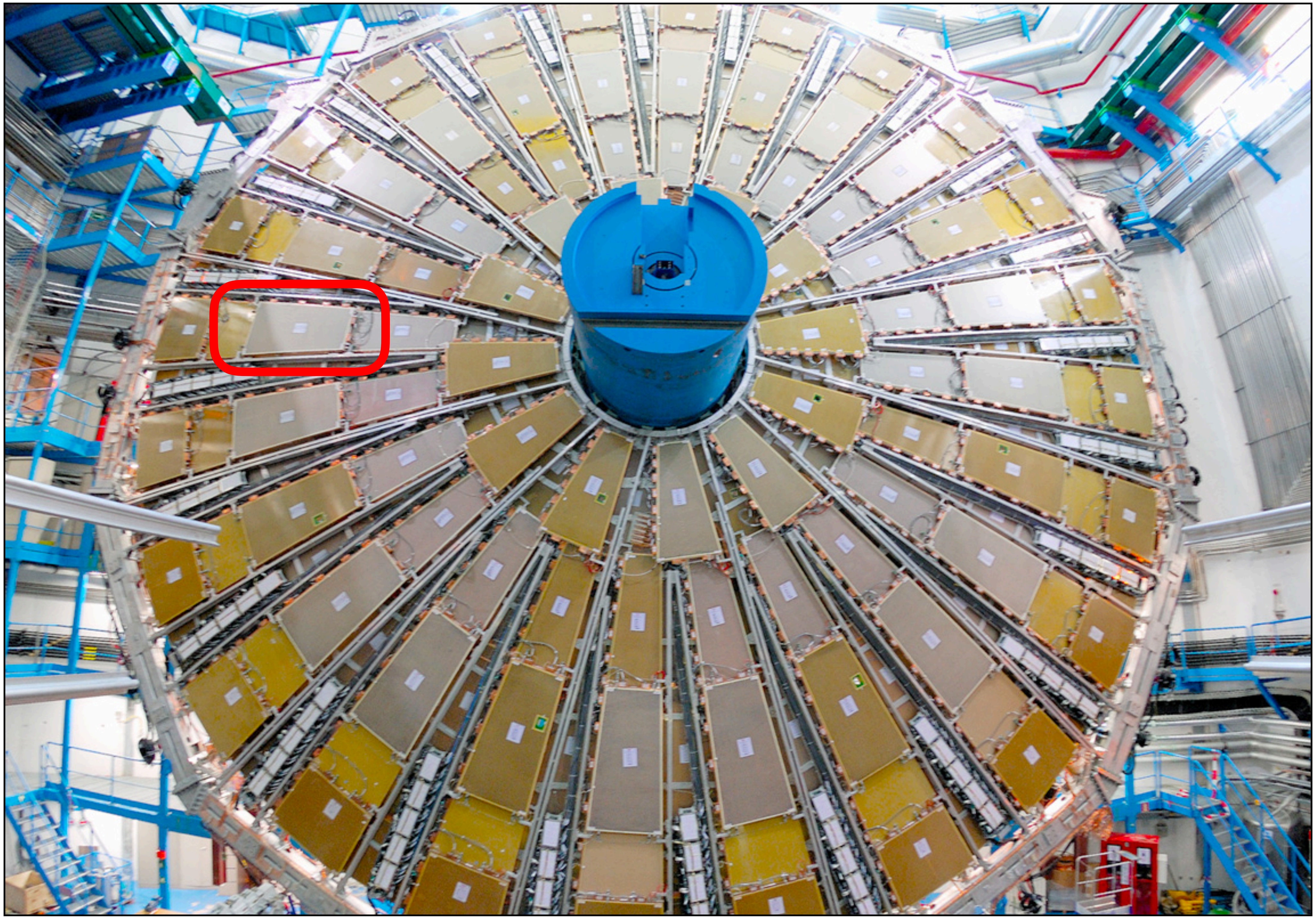
It probably takes 2 weeks per chamber
to go from the surface inside ATLAS/CMS
to be fully connected and turned ON

if nothing breaks…



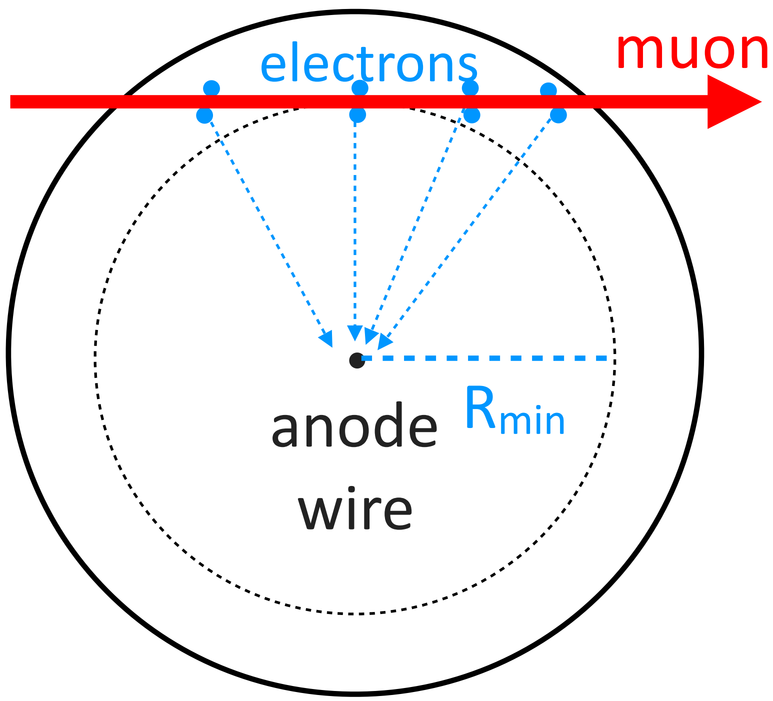


There are thousands of chambers

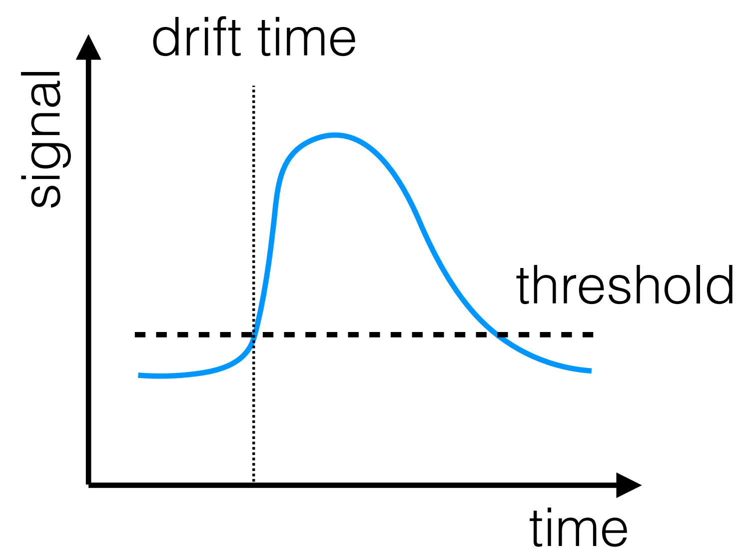


How a detector works

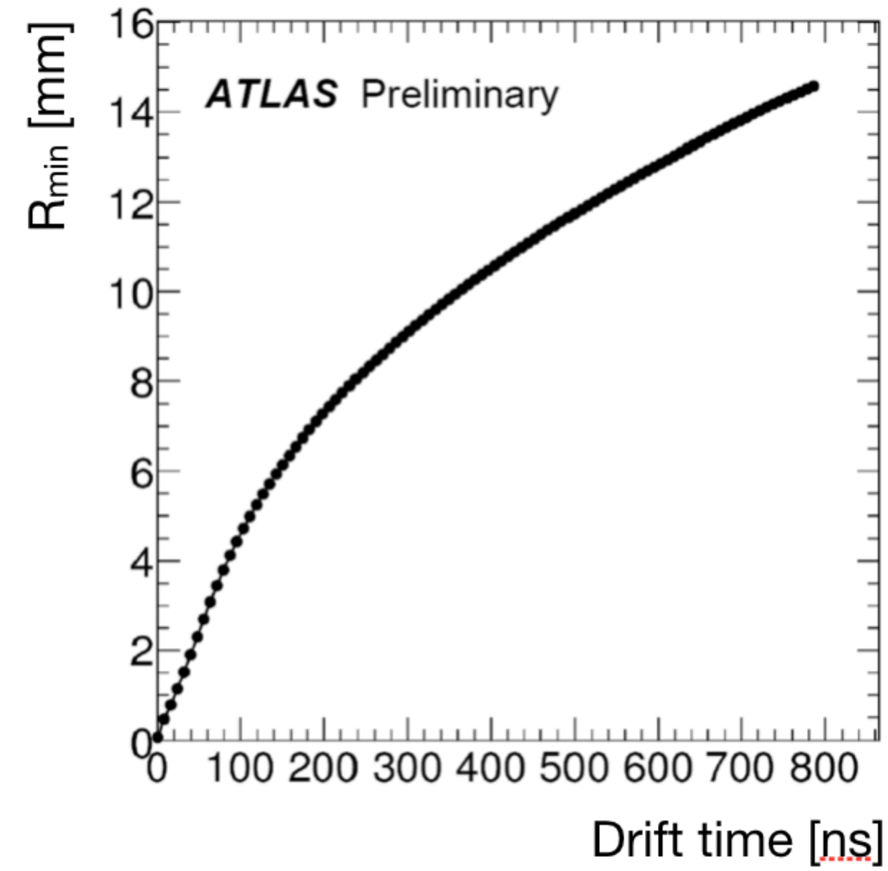
Muon chambers are made up of drift tubes
a single drift tube → position measurement



cathode tube
3 cm diameter



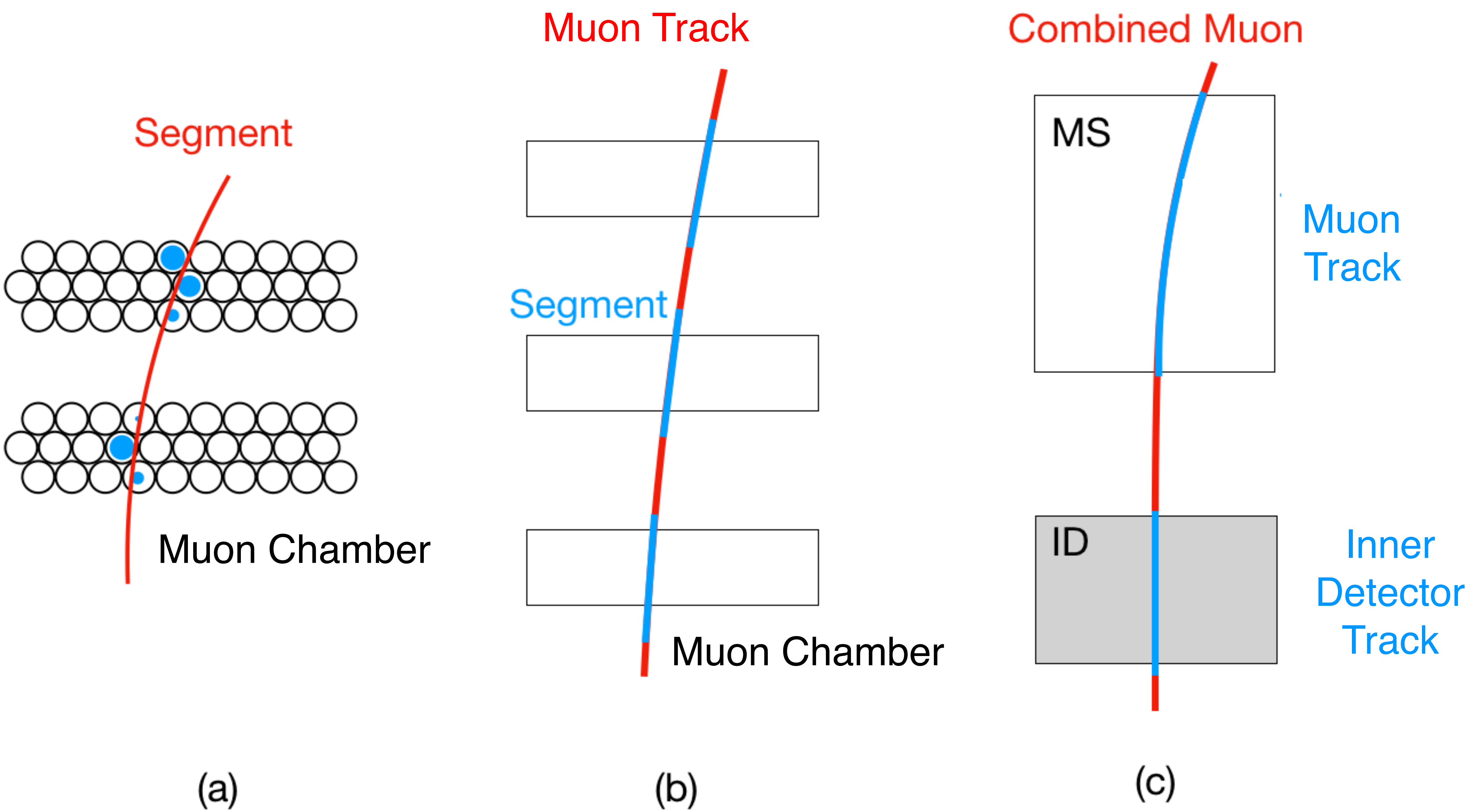
after some electronics
signal shaping



ATLAS has 300,000 muon drift tubes
The entire ATLAS detector has 100 million electronic channels!

Reconstructing particles

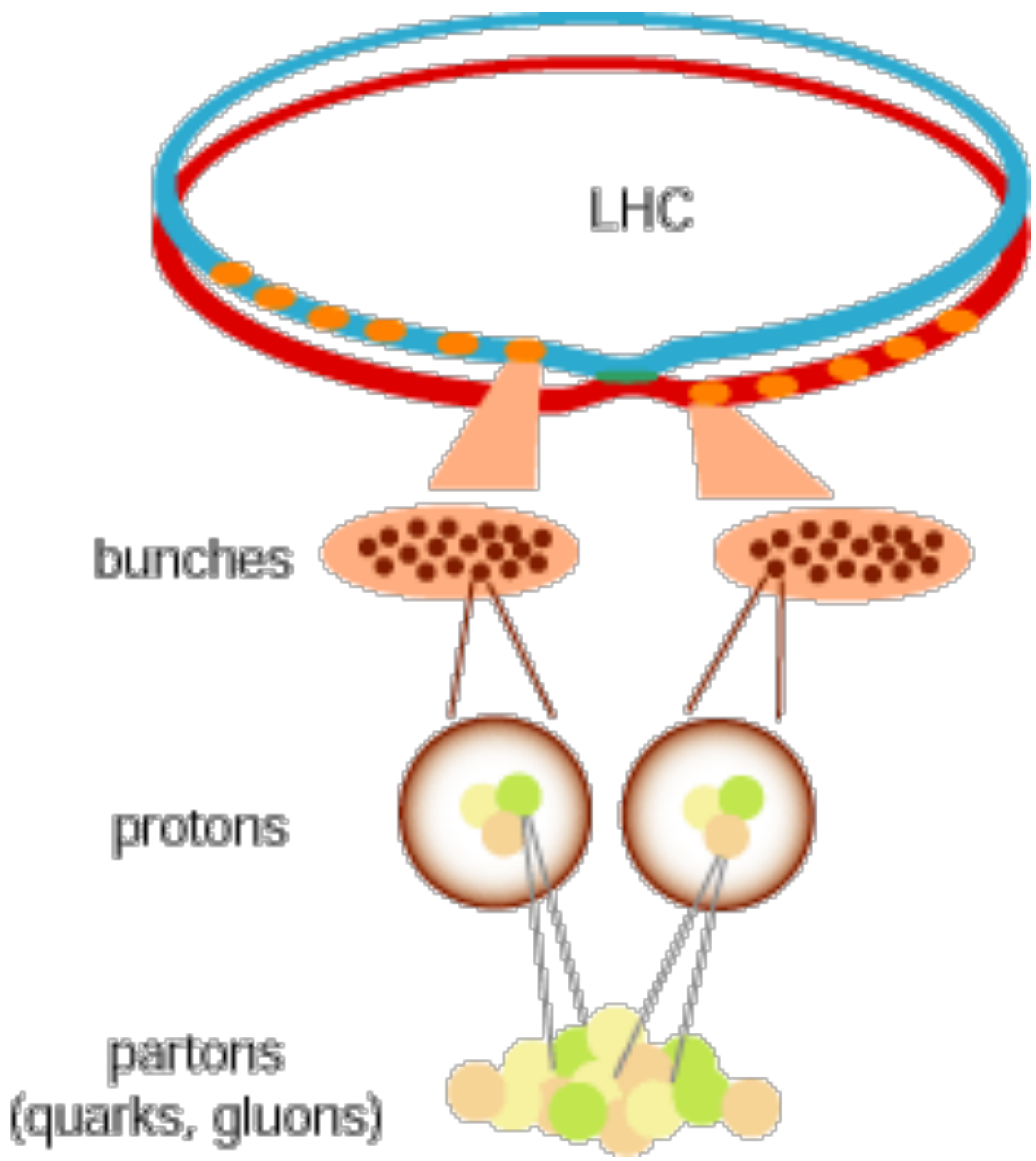
Then we take our signals and reconstruct them into muons



Challenge #2

The Event Rate

LHC makes MANY collisions



~3200 bunches of protons
in LHC ring

bunches cross every 25 ns
40 million crossings per second

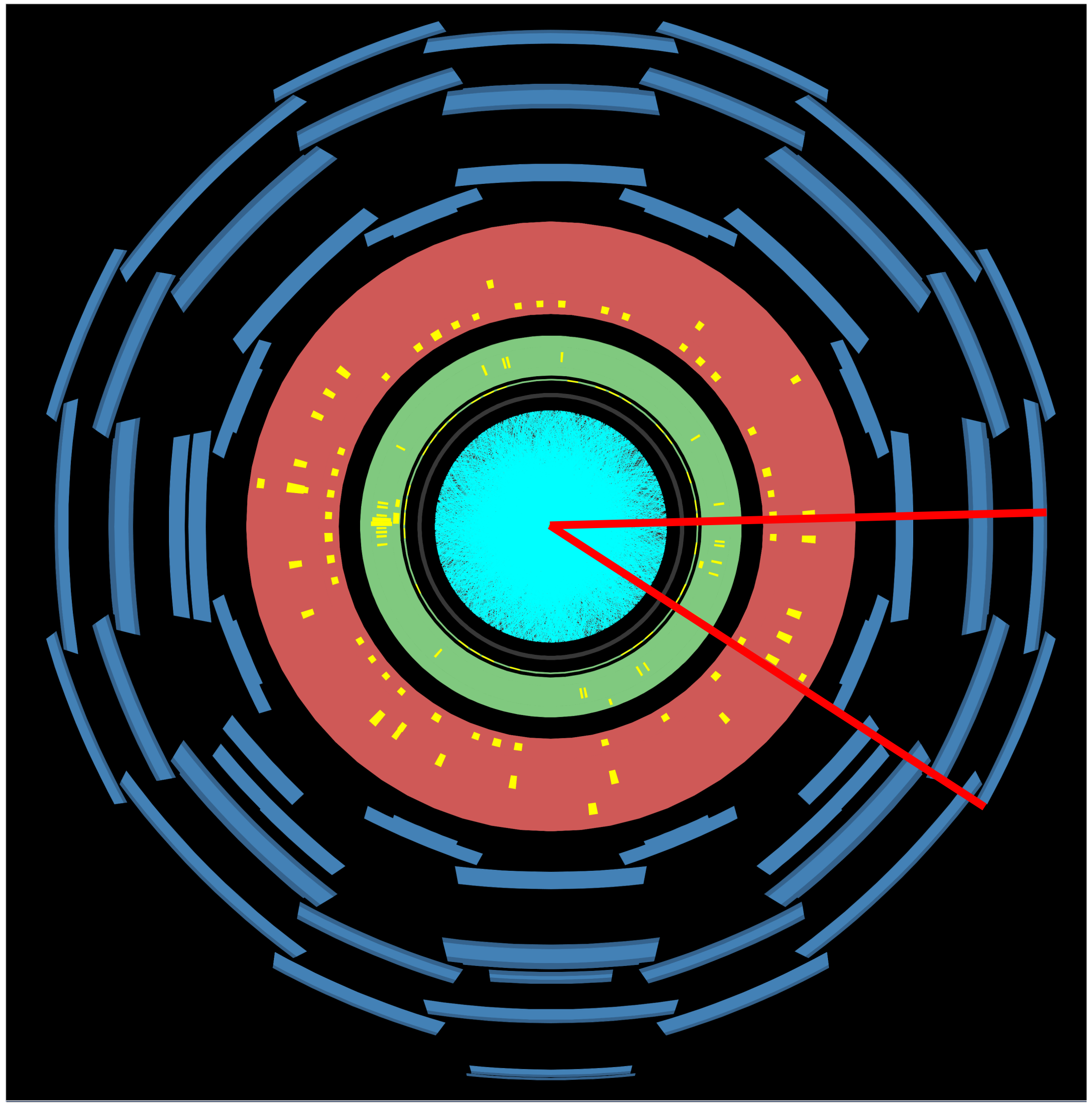
each bunch contains ~100 billion protons

we get ~50 pp-collisions per crossing
or 2 billion collisions per second

Only one of these is a Higgs!

The trigger challenge

If we saved every LHC event
in an hour we'd accumulate
as much data as as one year of
Facebook uploads



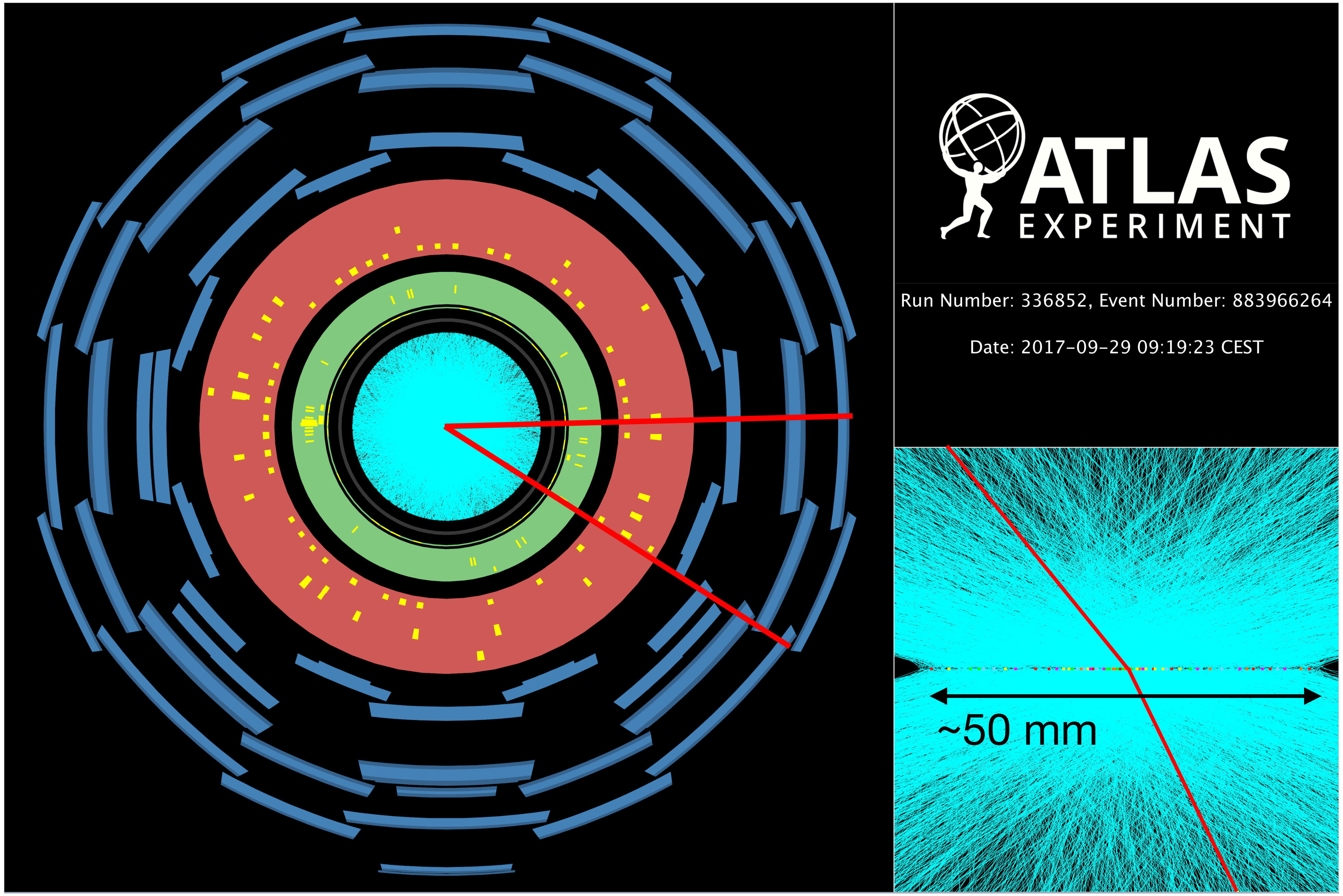
We can only save one thousand
events (or crossings) per second

Can only select ~1 in a million collisions
And we need to do it quickly!

how can we pick out the interesting events?

The pile-up challenge

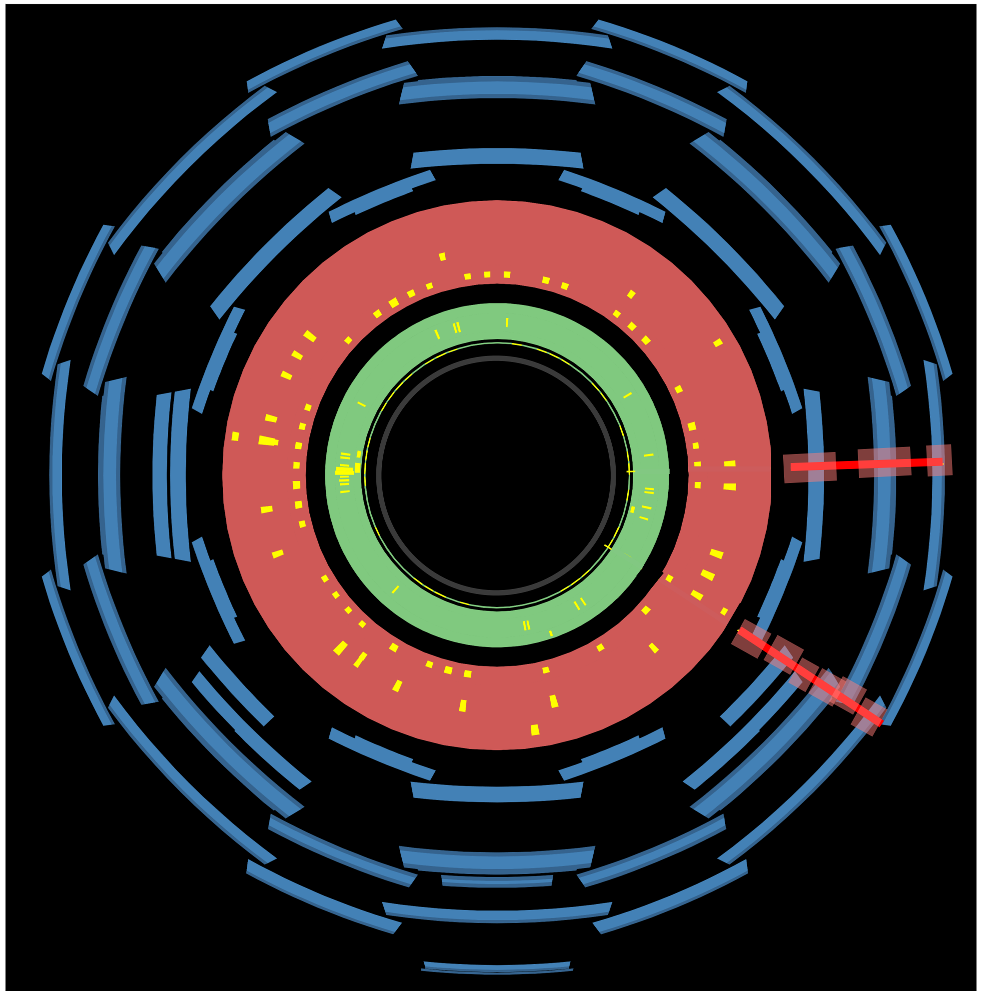
LHC events are busy!



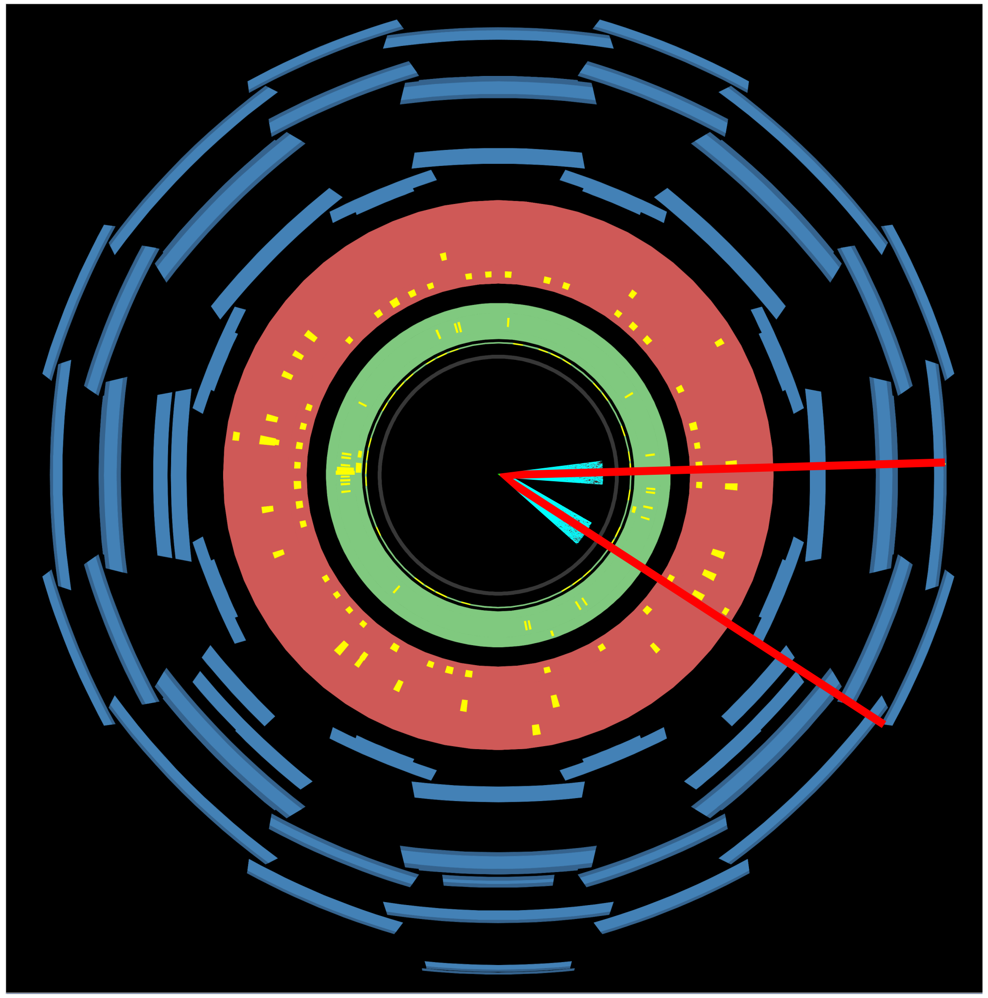
A 2017 Z→μμ candidate,
with 65 additional “pile-up” vertices

Trigger = two step process

Step 1.
coarse muon and
calorimeter information
decision time: 3.2 μs
keeps 1/400 crossings



Step 2.
nearly full detector in
region of interest
decision time: 200 ms
keeps 1/100 crossings



No room for error!

Data taking is a high stakes environment

If the trigger throws your event away, it's lost forever

If something goes wrong with your detector
can't use that data for physics

ATLAS and CMS take data 24/7

8 shifters in the Control Room

~30 people reachable by phone

Teams of experts who work to maintain detectors

Teams of experts who work to maintain computers

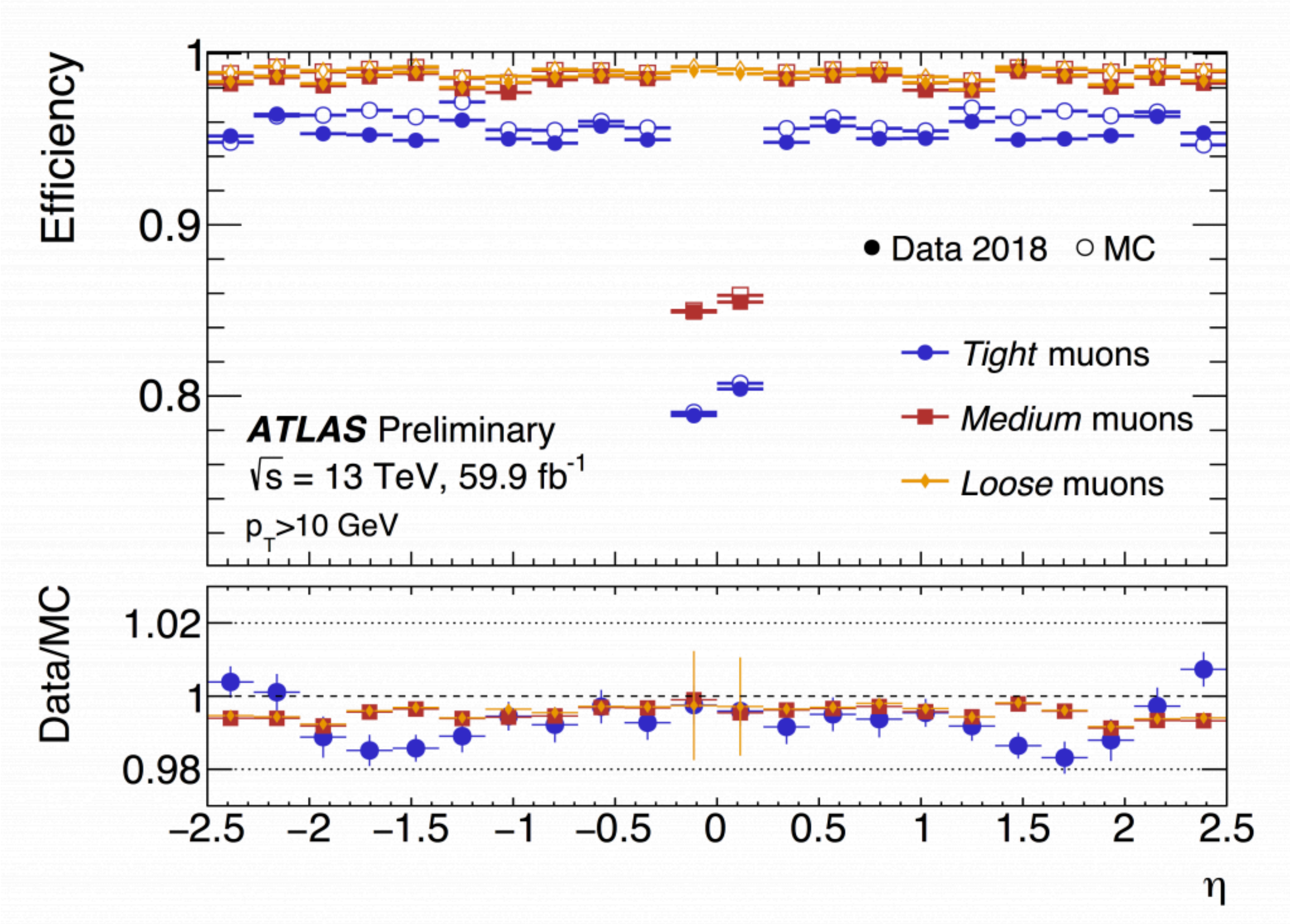
The work doesn’t stop there

After data taking

Quantify detector performance

Make projections to ensure detectors will keep working

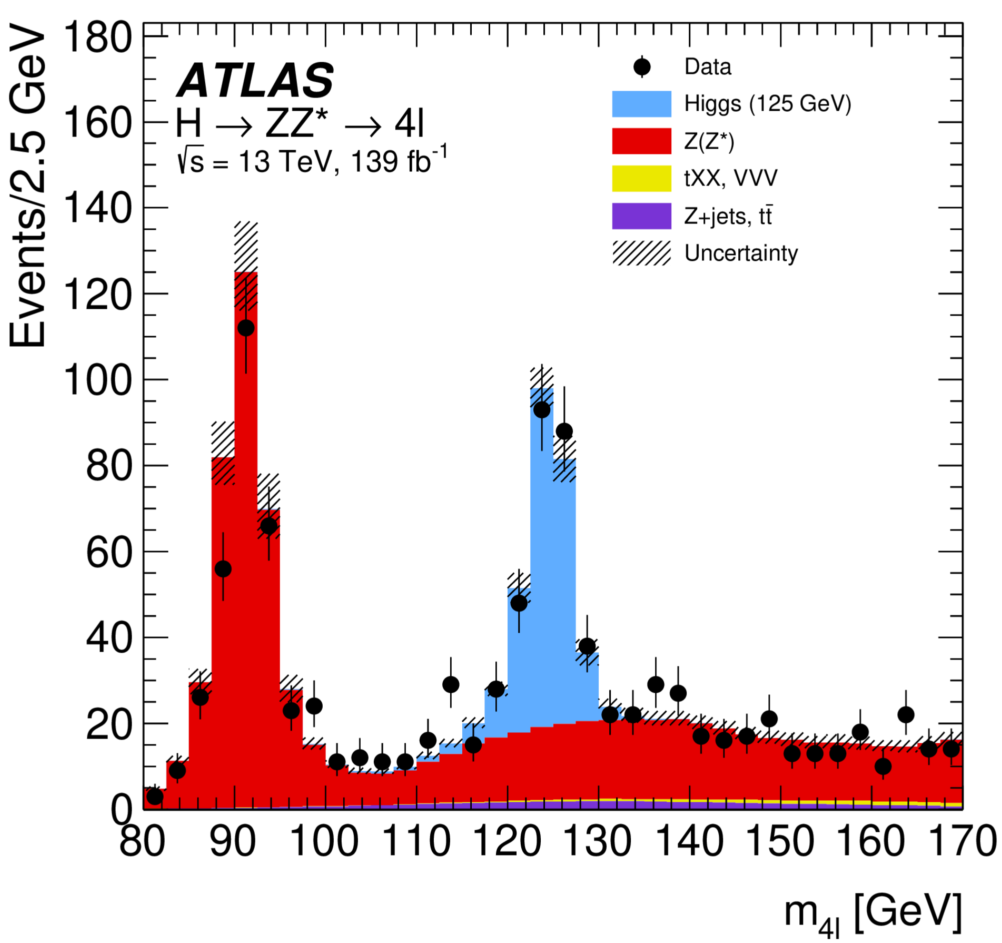
Ensure good agreement between predictions & data



Finally our data is ready for physics

And it's not just used for one Higgs measurement
measure top quark mass
study properties of W/Z bosons
look for new exotic particles!

Every analysis we do is incredibly rewarding
and tells us something new about particle physics



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What's next?

- High Luminosity LHC
  - we've only collected 5% of the LHC's data so far
  - improvements to the ATLAS and CMS detectors
  - could we discover a new rare process or a particles with challenging signatures?
- Next machine is likely to be a lepton collider
  - Future Circular Collider
  - Compact Linear Collider
  - Internaltional Linear collider
  - Muon Collider???
- We should know more soon!
  - European Strategy Report comes out tomorrow
  - US Snowmass process is ongoing

Conclusions

- Standard Model is not the complete picture of the universe
- High energy particle colliders are
  - one of the most effective ways to look for new particles
  - and to do measurements which try to “break” the Standard Model
- Being a scientist at the Large Hadron Collider means
  - you have MANY wonderful collaborators
  - working together on fun detector, trigger, and analysis challenges
- The future is bright: new physics could be lurking just around the corner!