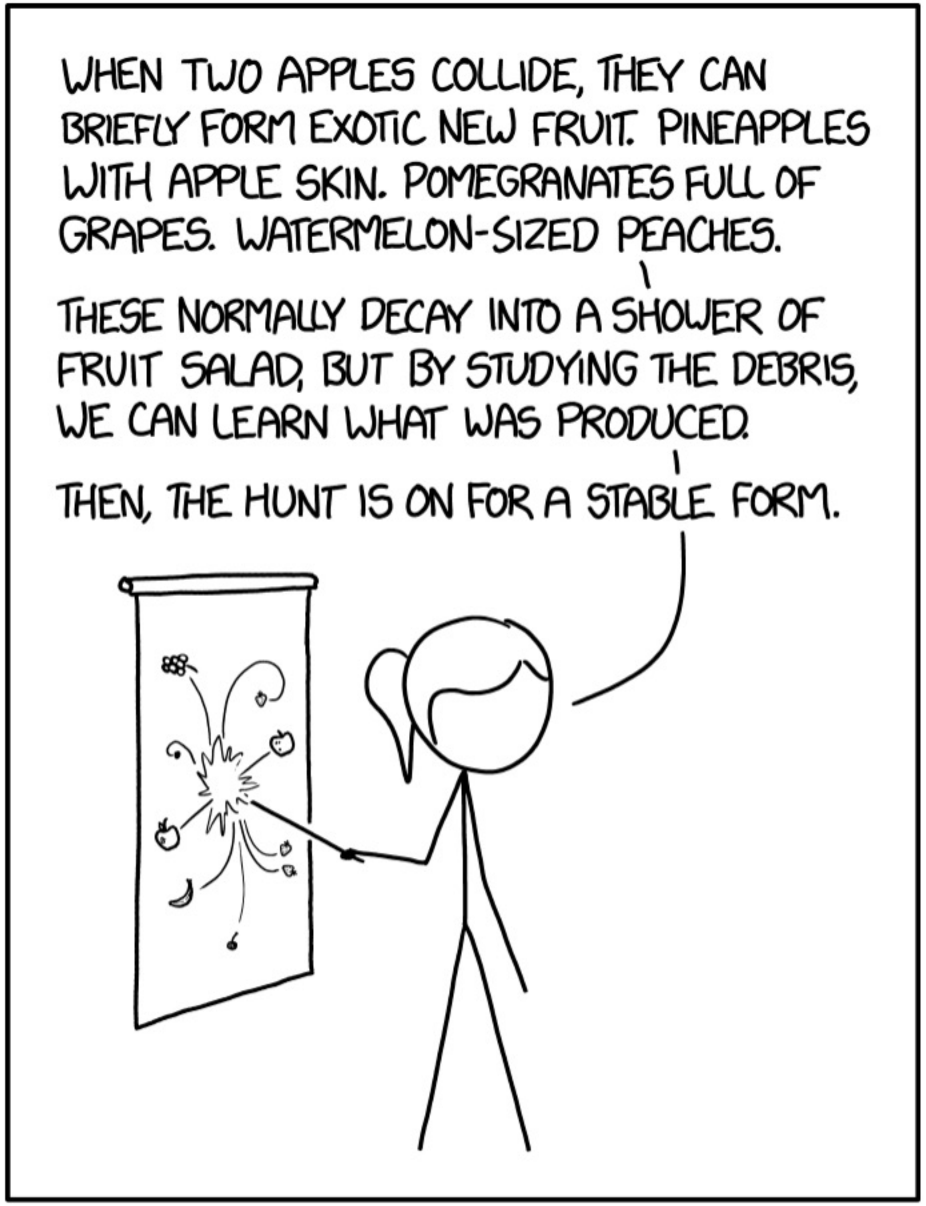
Fruit Collider

https://xkcd.com/1949

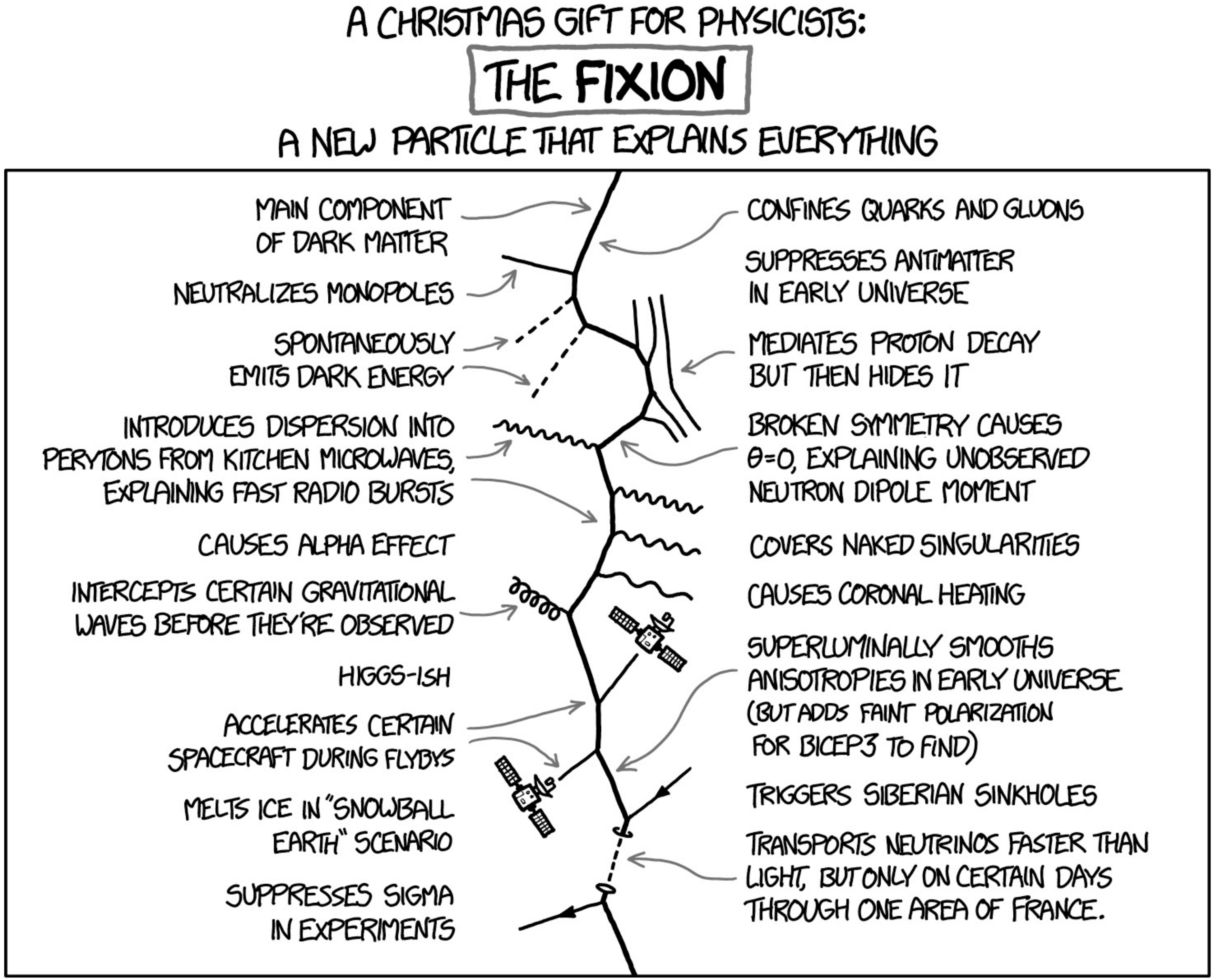


HOW NEW TYPES OF FRUIT ARE DEVELOPED

Higgs boson

https://xkcd.com/1437

Fixion



https://xkcd.com/1621/

Identifying Particles using the CMS Detector

Allie Reinsvold Hall

Asst. Prof., US Naval Academy

CUA QuarkNet Institute 2022

It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is – **if it disagrees with experiment it is wrong.** That is all there is to it.

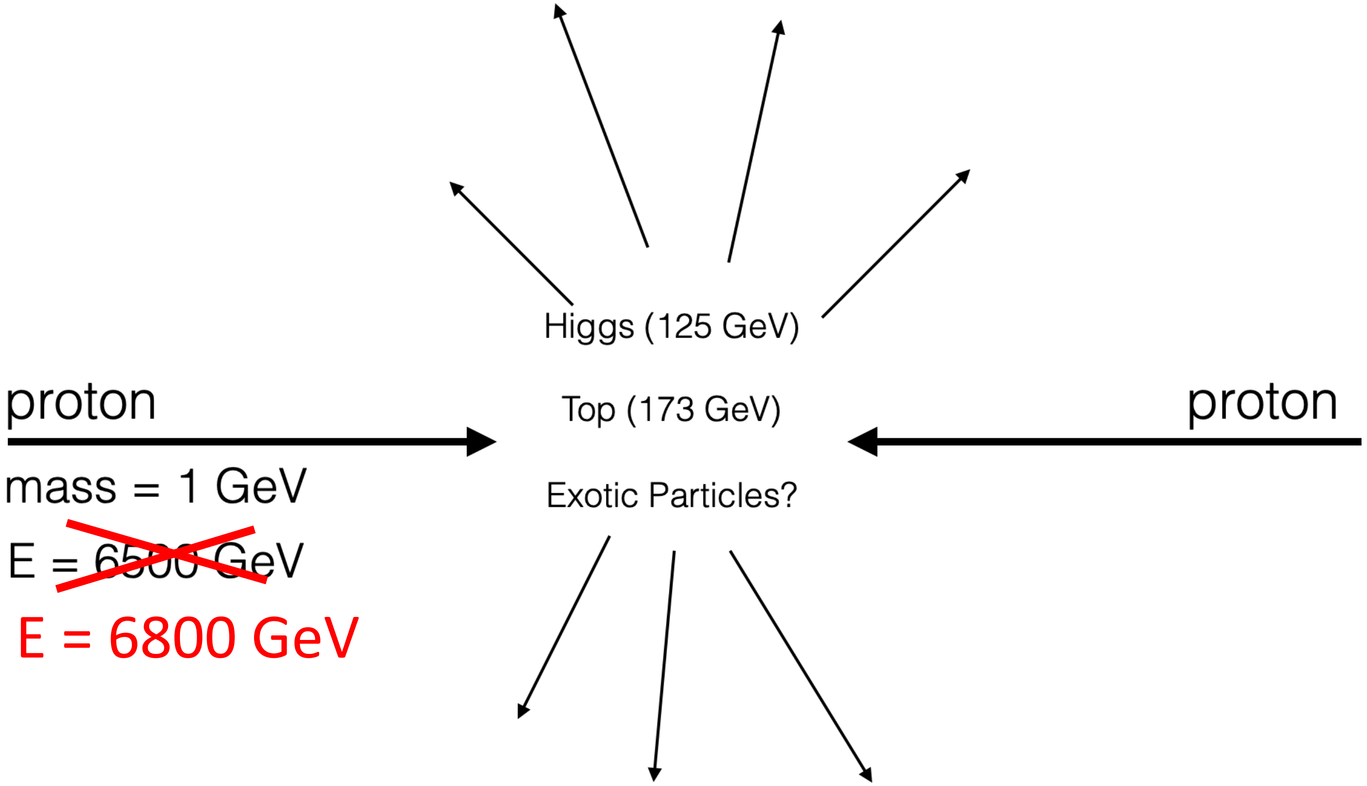
- Richard Feynman

So how do we check if “guesses” like the existence of the Higgs boson are correct?

<- Today’s talk

Why do we use colliders?

- Einstein and Dirac taught us that $\boldsymbol{E^2} = p^2c^2 + \boldsymbol{m^2}\, c^4$
- If we have **more initial energy** then we have a chance to create particles of **higher mass**
- Large Hadron Collider = highest energy collider in the world
  - Just restarted at a center-of-mass energy of 13.6 TeV!



Colliders – a biased list

- Push to bigger accelerators at higher energies

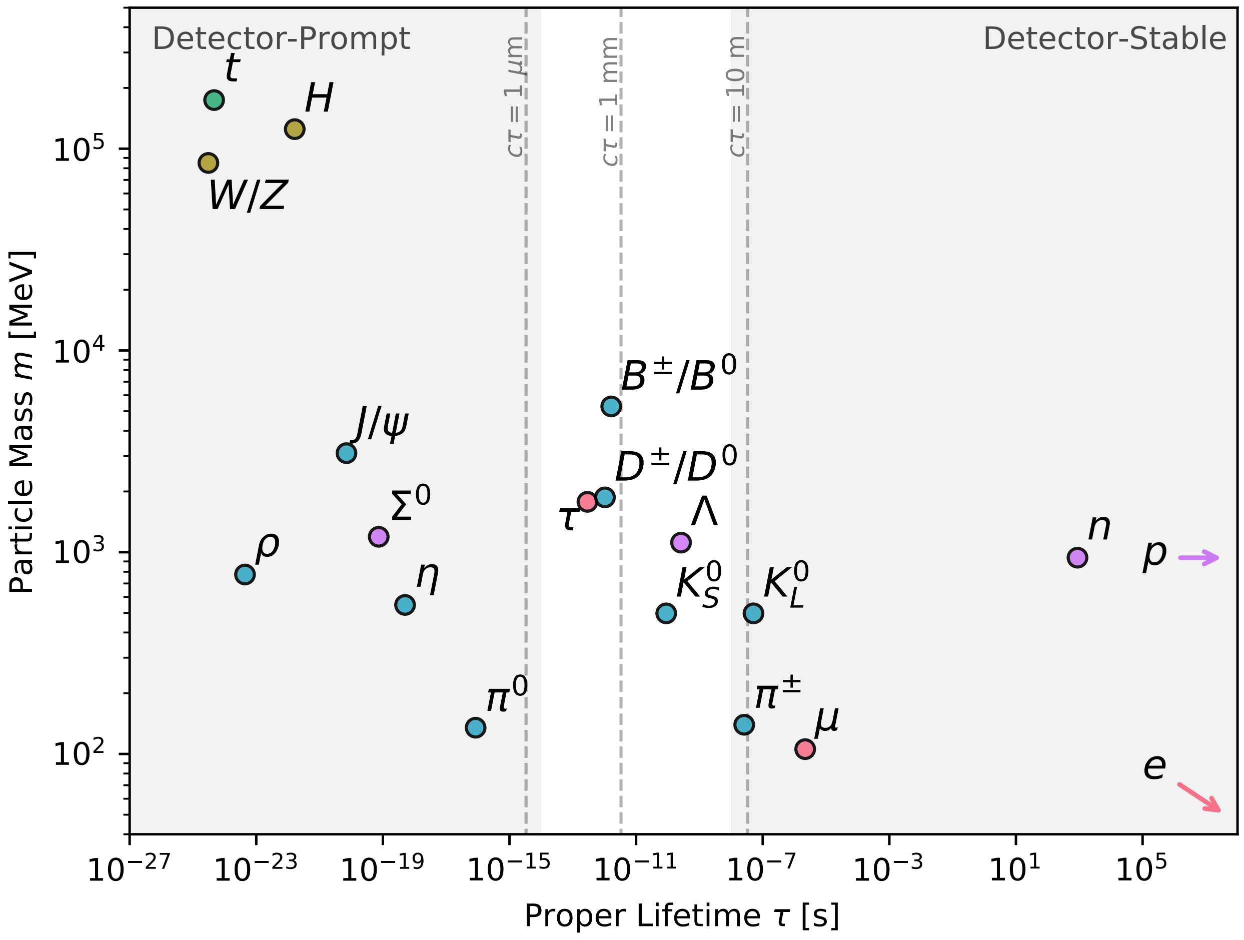
Collider	Operation	Type	Energy	Major Discoveries
Super Proton Synchrotron (SPS)	1981-1991	proton-antiproton	540 GeV	W and Z bosons, 1983
Large Electron-Positron Collider	1989-2000	electron-positron	200 GeV	Precision studies of W and Z
Tevatron	1985-2011	proton-antiproton	2 TeV	Top quark, 1995
Large Hadron Collider	2009 - Present	proton-proton	13.6 TeV	Higgs boson, 2012
The next big collider	?	Probably electrons?	?	???

Snowmass Process

- Many many discussions within the US particle physics community about what the goals and priorities should be in the next decades
  - Including studies about future proposed colliders. For example, CLIC: Compact Linear Collider, 380 GeV – 3 TeV, 11 – 50 km, proposed at CERN
- Final workshop happening now in Seattle! https://seattlesnowmass2021.net/
  - Not in Snowmass, not in 2021
- After Snowmass, a small panel of experts will draft a "P5" report summarizing priorities

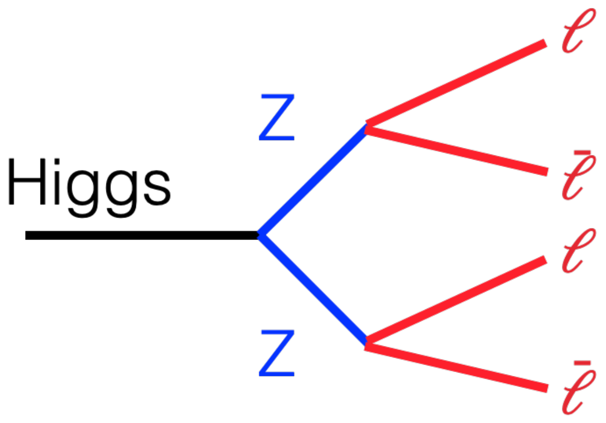
What do we actually "see" in a collision?

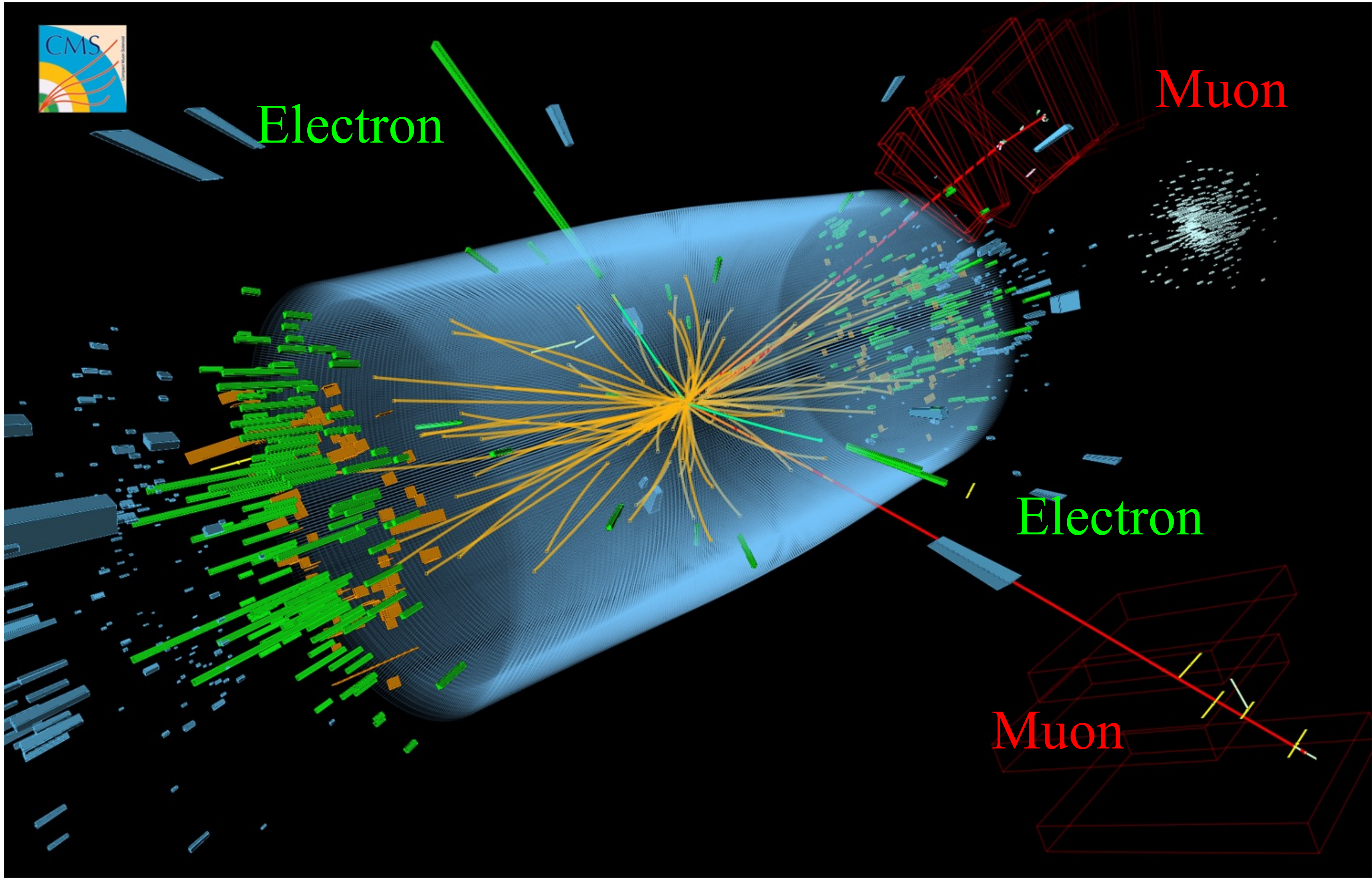
- Most particles **decay** into lighter particles
- Three categories of particles
  - Stable - lives long enough we can "see" them interact with our detector
    - Truly stable: electron, proton, photons, neutrinos
    - Stable enough for our purposes: muons, neutrons
  - Intermediate - decays slightly displaced from point of primary collision (can form a vertex)
  - Prompt - decays too quickly to detect directly
- For most particles, what we **see** are the decay products



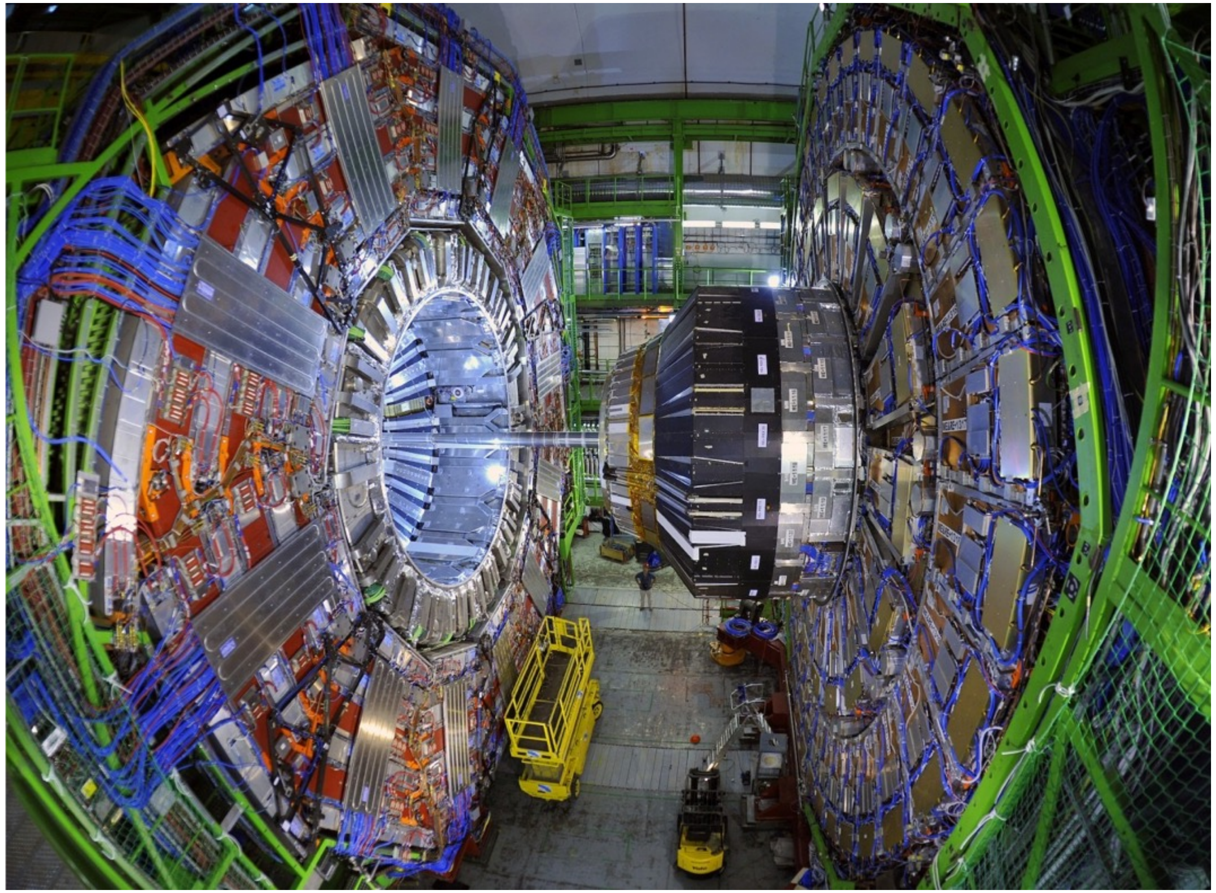
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+\mu^-$ candidate event

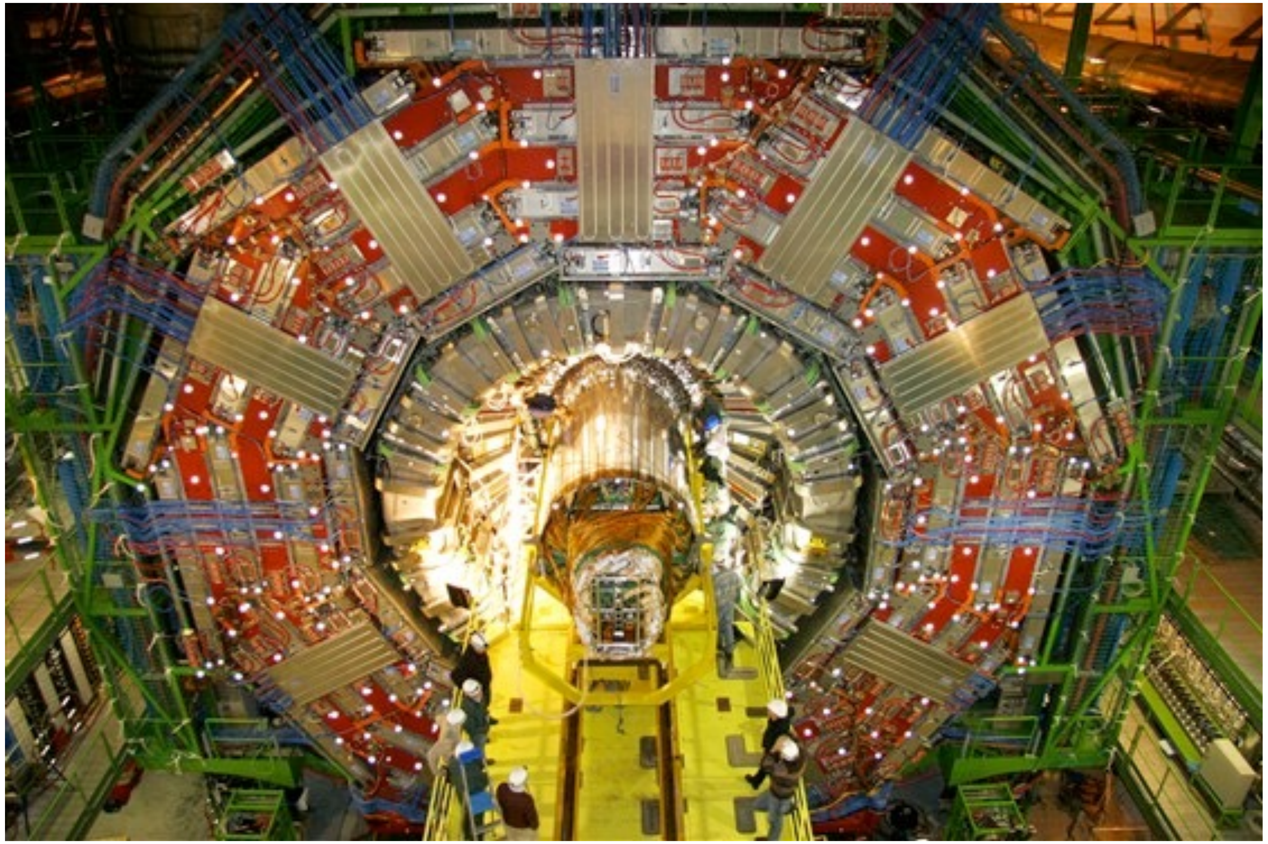
- We never see the Higgs directly, but we see what it decays into
- Our goal: identify & measure all stable particles to reconstruct what happened in a collision



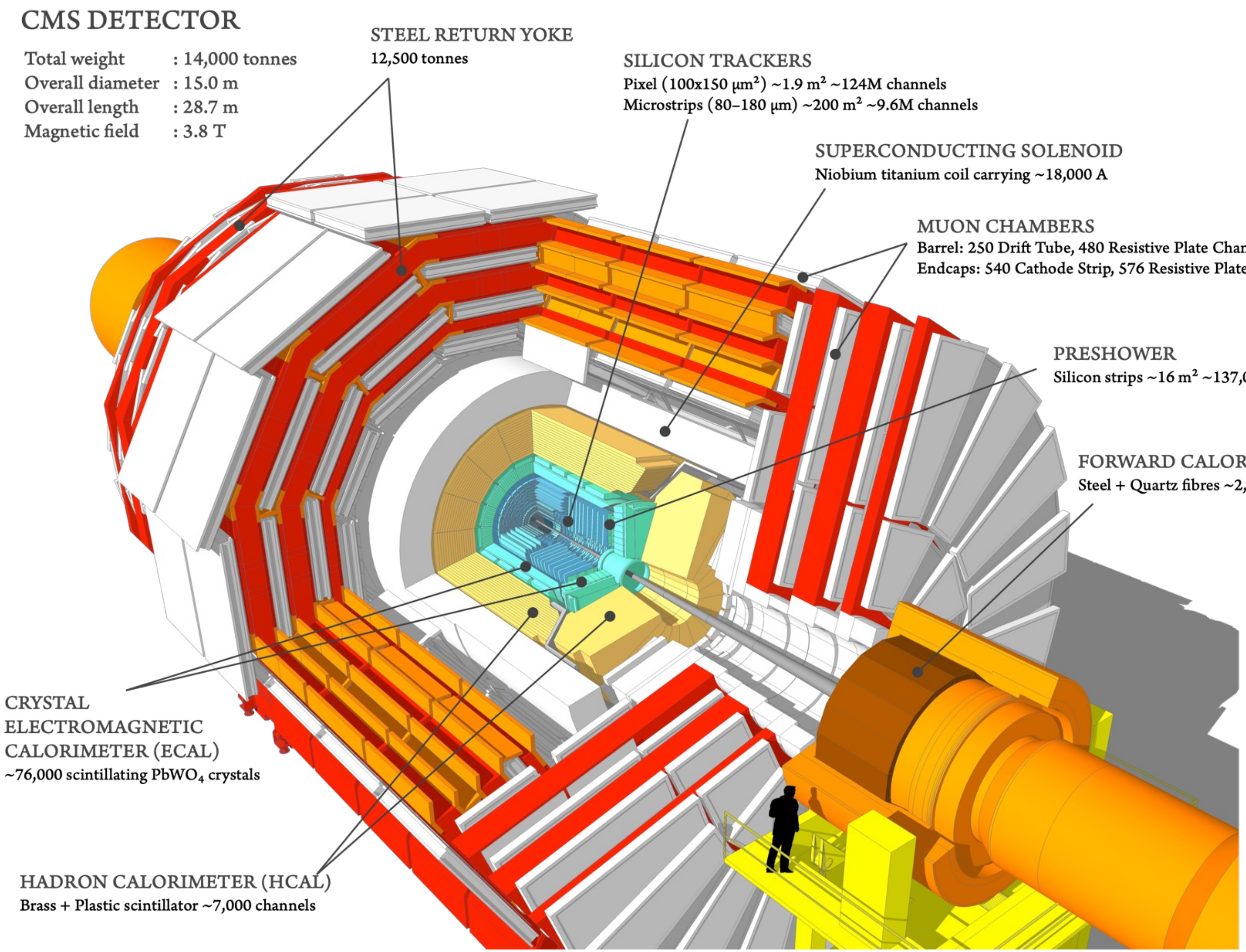


Compact Muon Solenoid





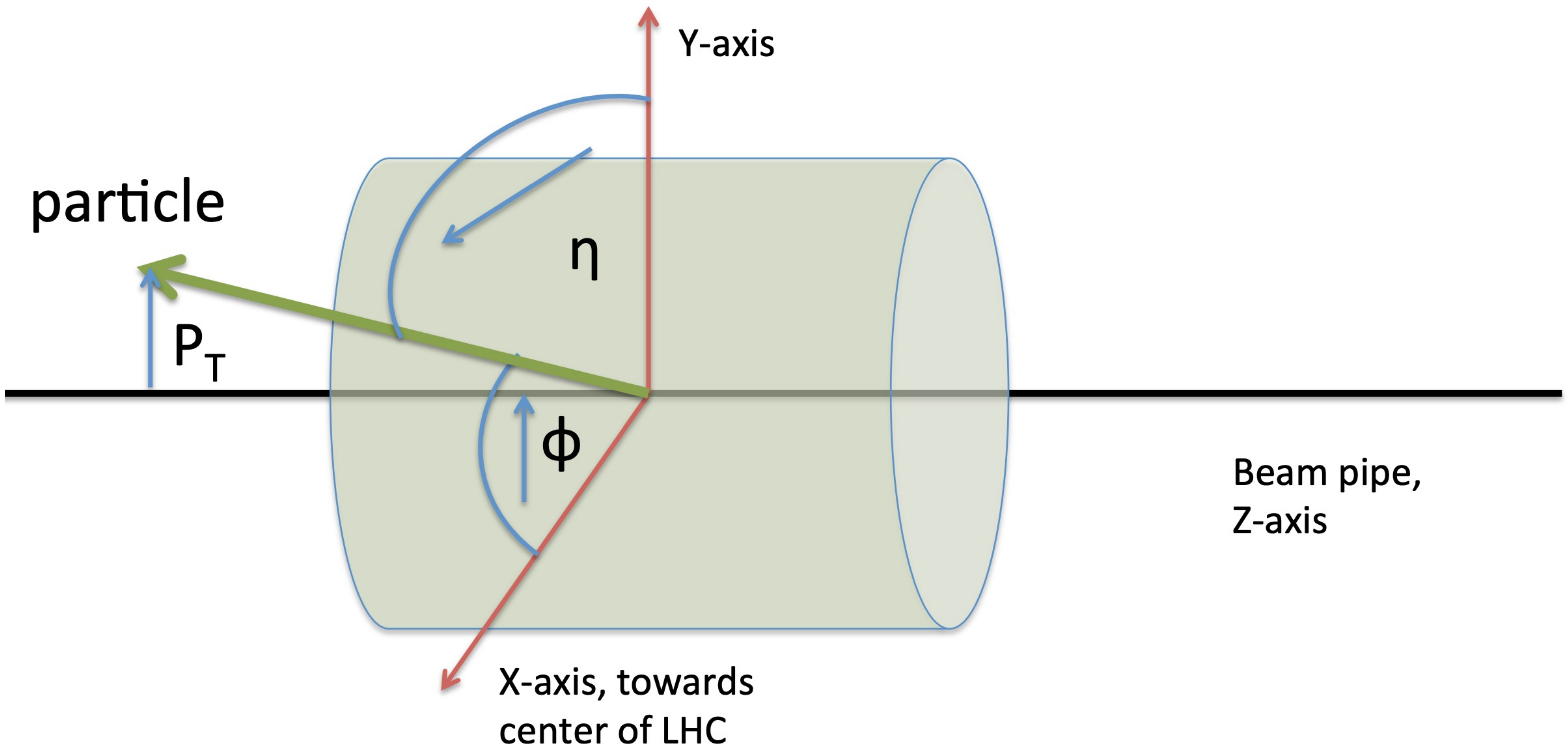
CMS Detector

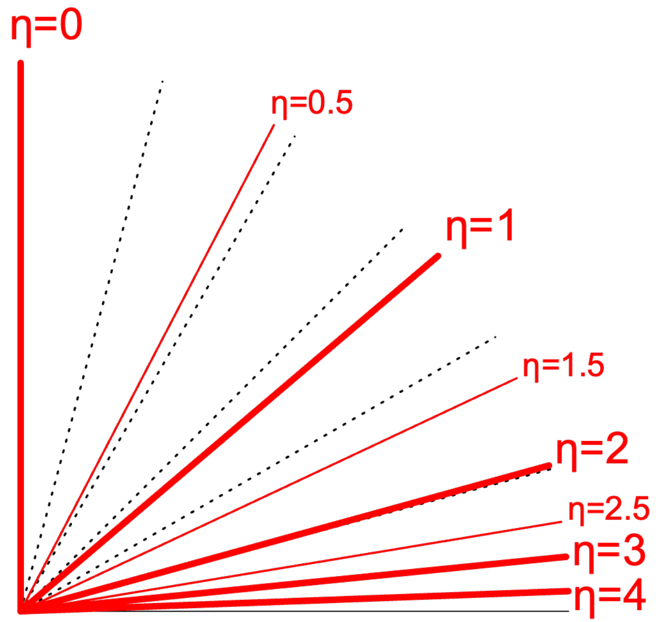


Detector geometry

Instead of (x,y,z), we use (p_T, η, ϕ) to describe the position of a particle

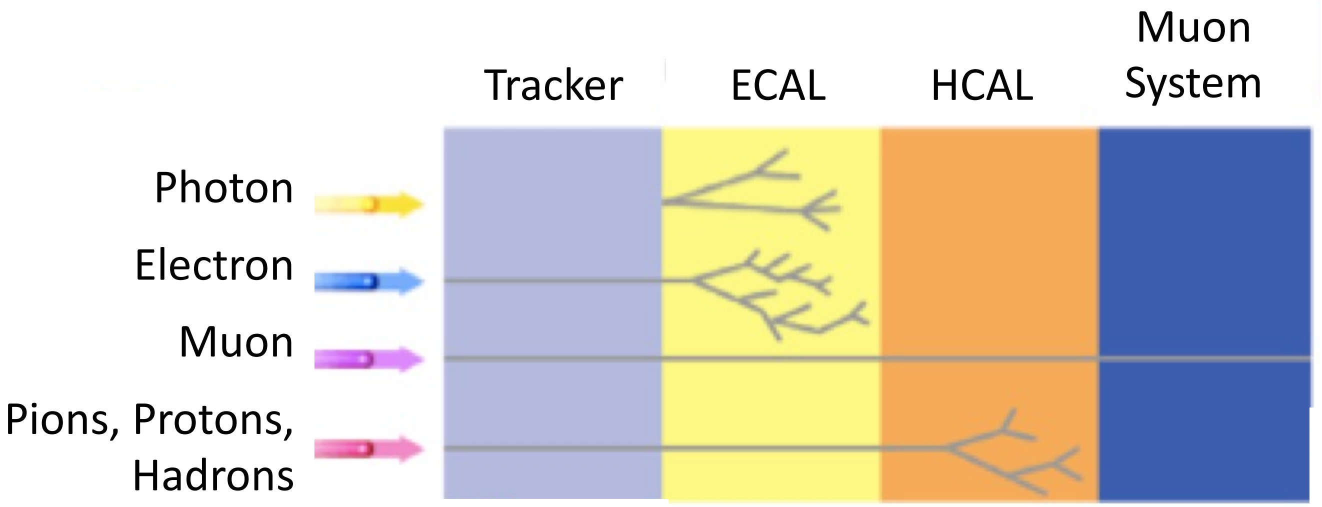
- Transverse momentum p_T is the projection of the momentum vector in the transverse (xy) plane
- Angle ϕ within the xy plane -> almost all processes should be symmetric with respect to ϕ
- Pseudorapidity η is 0 for particles produced in the xy plane and approaches ∞ for particles along the beampipe





Particle Detection

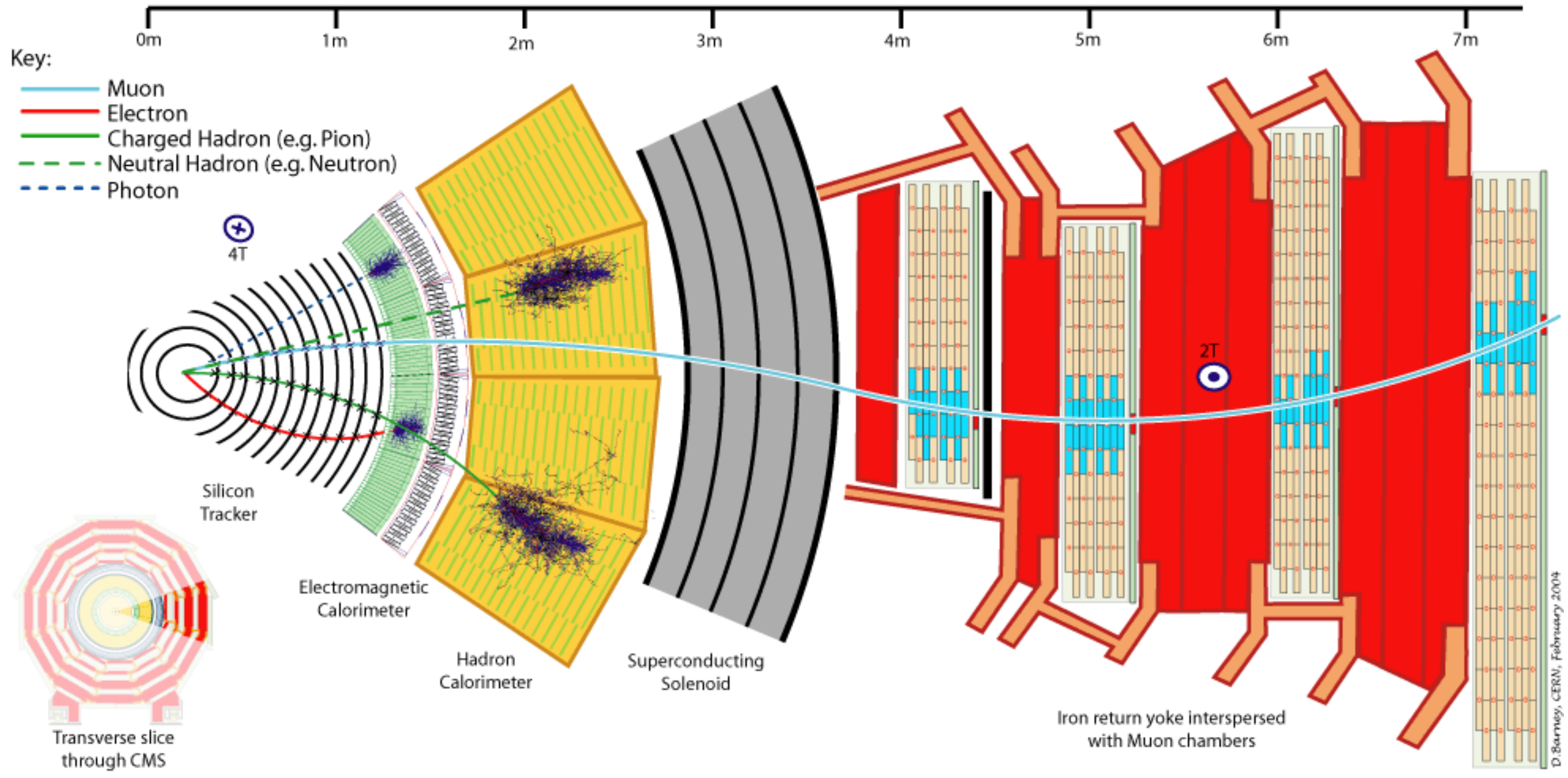
- Different types of detectors for different particles



CMS Reconstruction

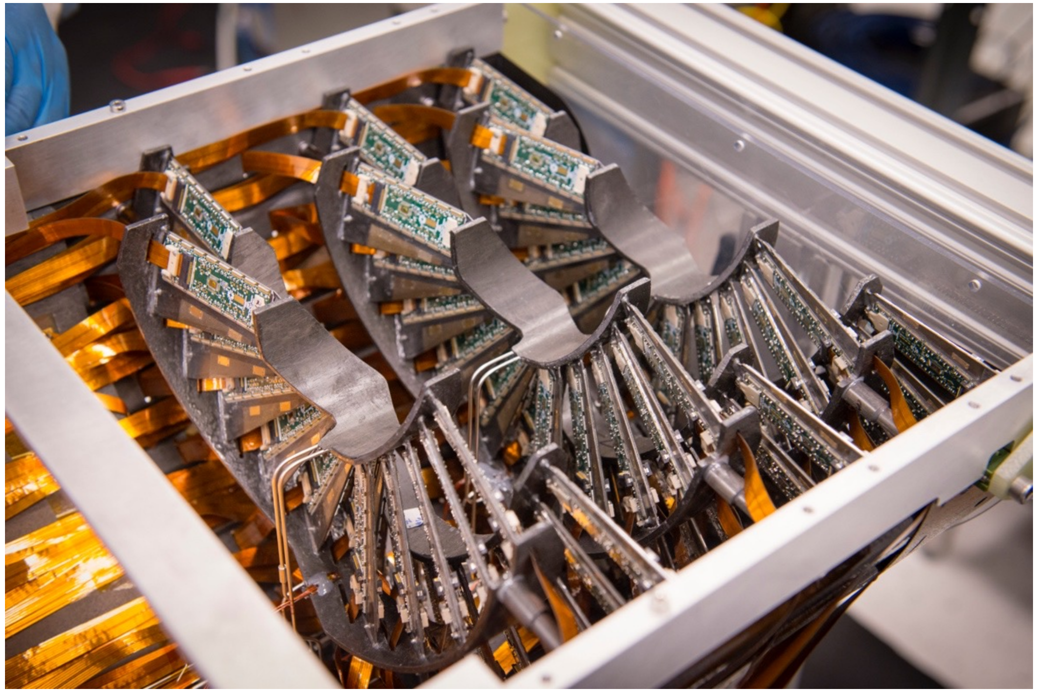
Reconstruction: identifying stable elementary particles by their signatures in the different sub-detectors of CMS

Interactive version: https://www.i2u2.org/elab/cms/graphics/CMS_Slice_elab.swf

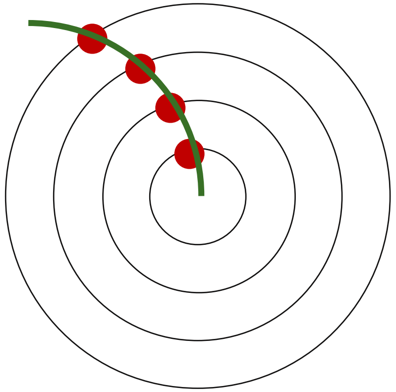


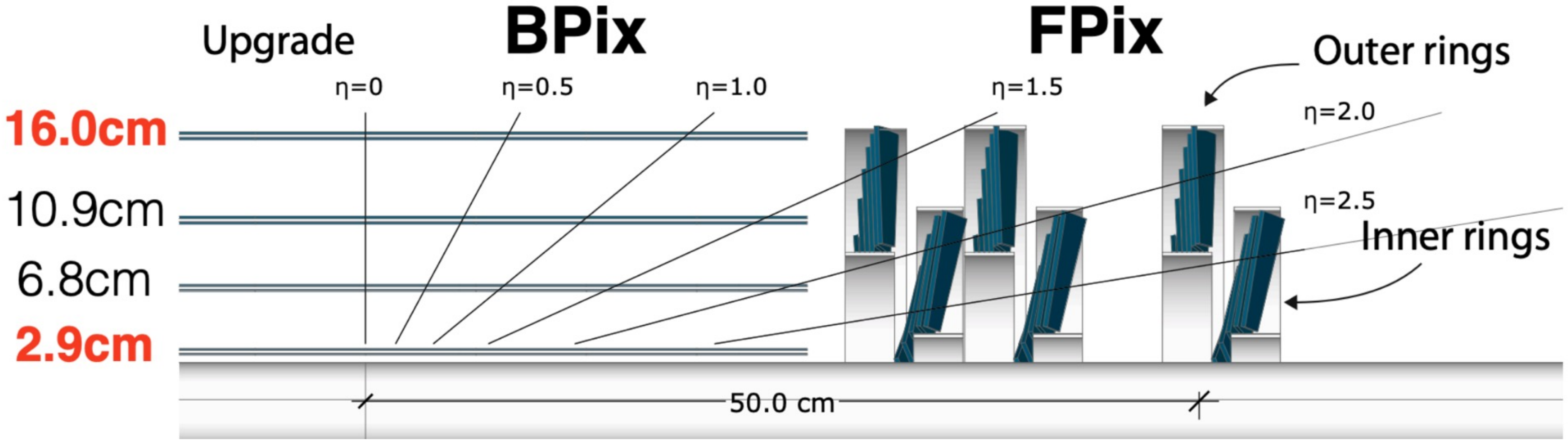
Silicon Tracker

- Precise measurement of the path of charged particles
- Silicon pixel detector: 124M channels, pixel size 100µm x 150µm
- Silicon strip detector: 10M channels, strips are 80-100µm wide, 10s of cm long
- Embedded in 3.8 T magnet
- Measuring curvature of particles lets us measure momentum



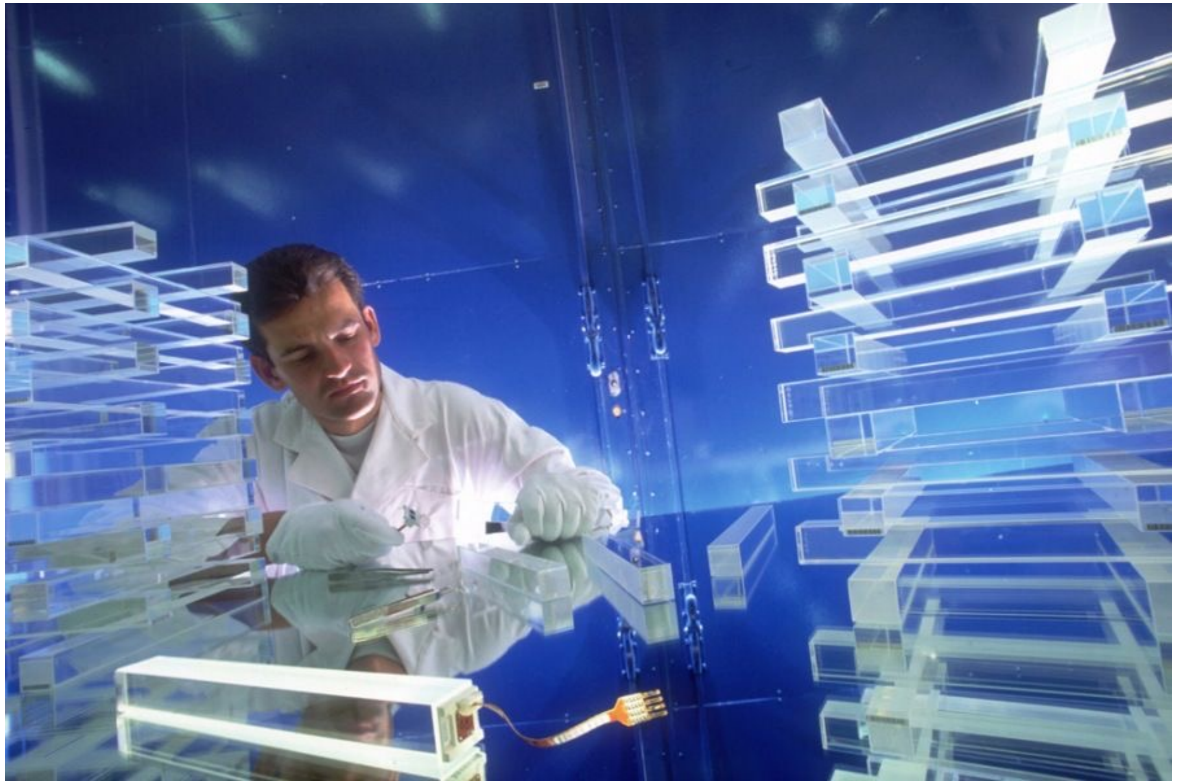
Half endcap disks for the upgraded CMS pixel detector, installed early 2017



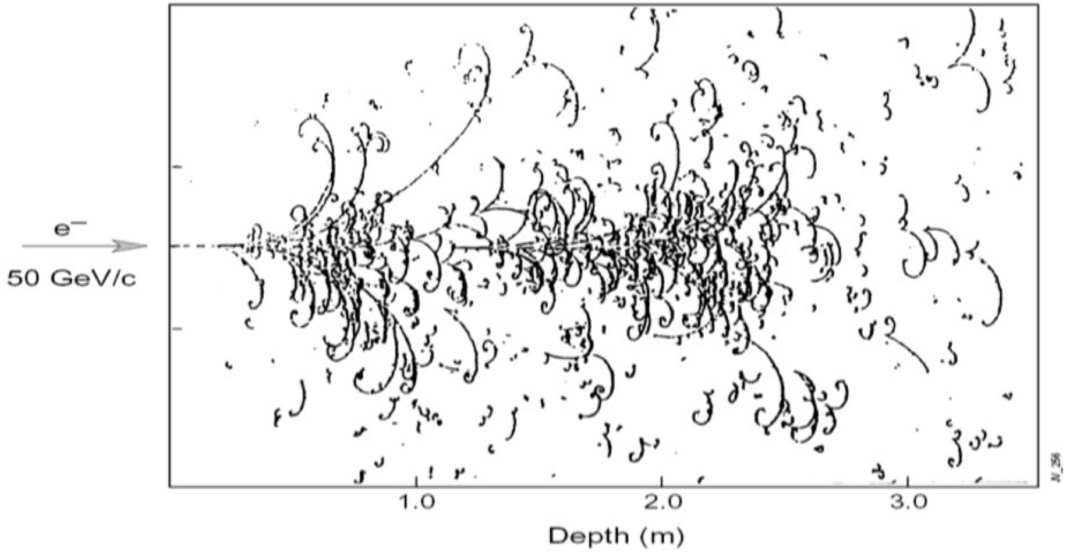


Electromagnetic Calorimeter (ECAL)

- 75,848 lead tungstate crystals in the barrel, each 2.2 x 2.2 x 23 cm
- Electrons and photons will “shower” in the crystal, and we can count the total amount of energy deposited to get an accurate measurement of the initial particle’s energy
- Not enough to stop hadrons and muons – they keep traveling through

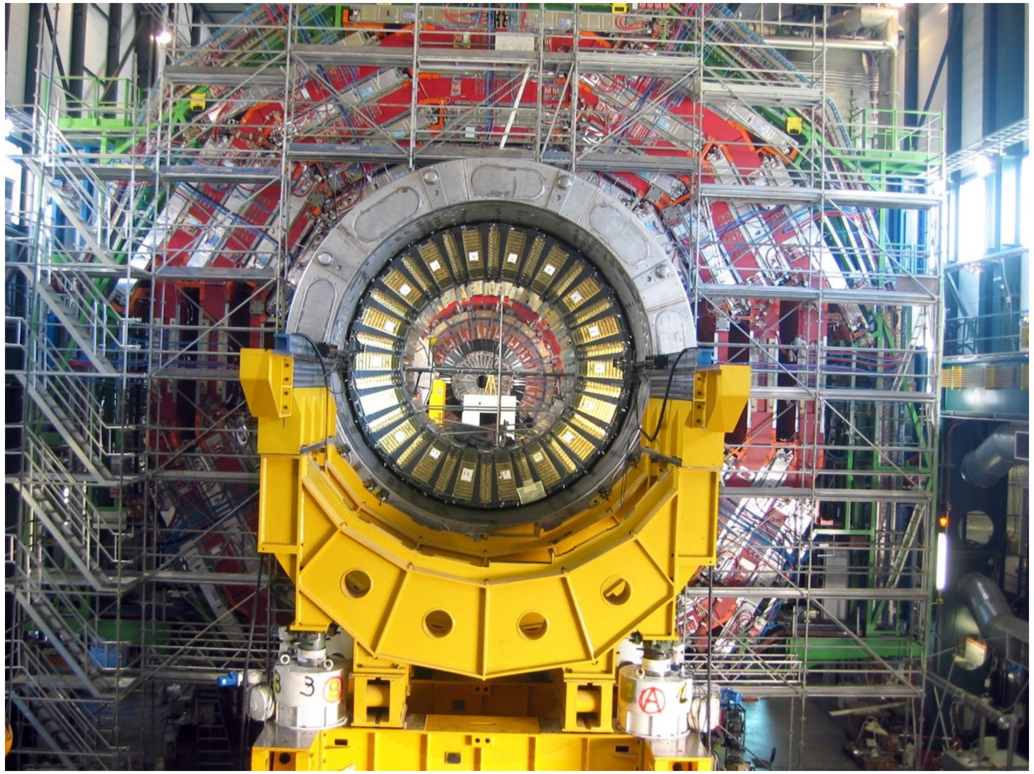


Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, $X_0 \approx 34$ cm, 50 GeV incident electron



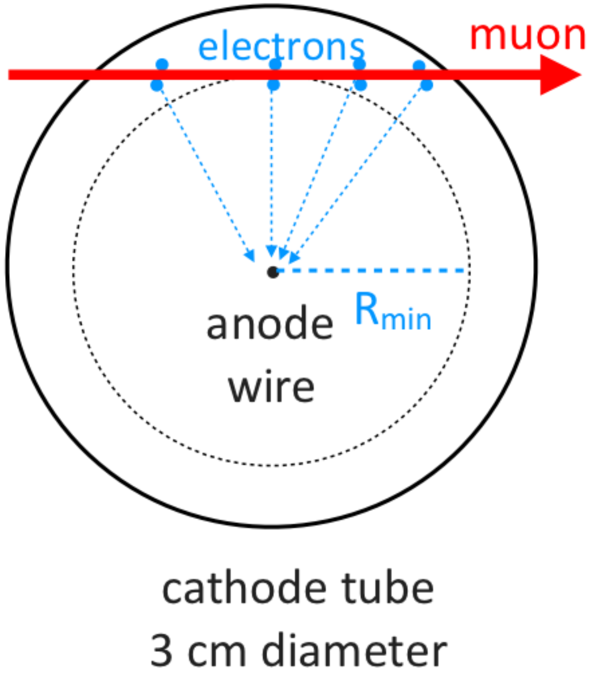
Hadronic Calorimeter (HCAL)

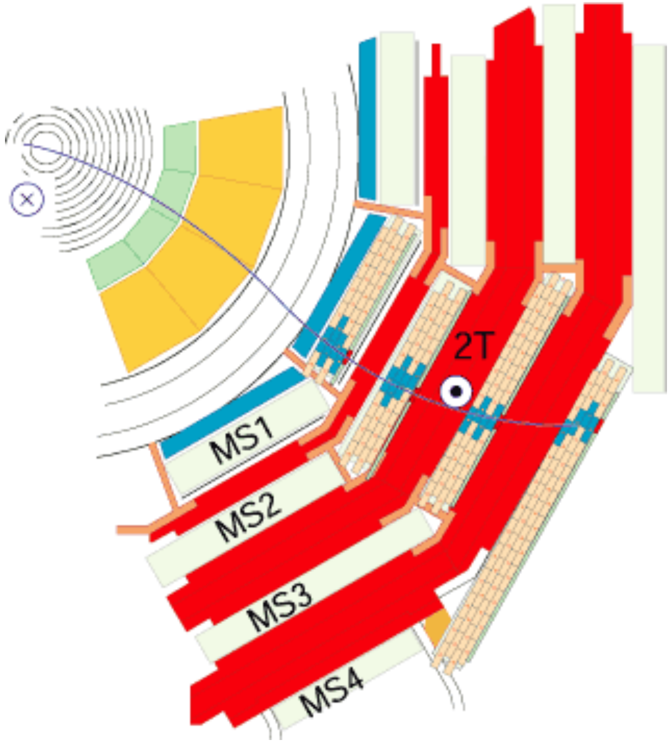
- 36 barrel wedges, each weighing 26 tons
- Repeating layers of steel and tiles of plastic scintillator
  - Steel forces the hadrons to interact and start “showering”
  - Shower energy measured (“sampled”) by the scintillator



Muon System

- Outermost detector system – muons pass through tracker, ECAL, and HCAL
- Drift tubes: muons ionize gas, electrons "drift" to anode wire
  - Timing can be used to reconstruct position of muon perpendicular to the wire
  - Cathode strip chambers, resistive plate chambers also used
- Muons also leave track in inner silicon tracker ("global" muon in e-lab)





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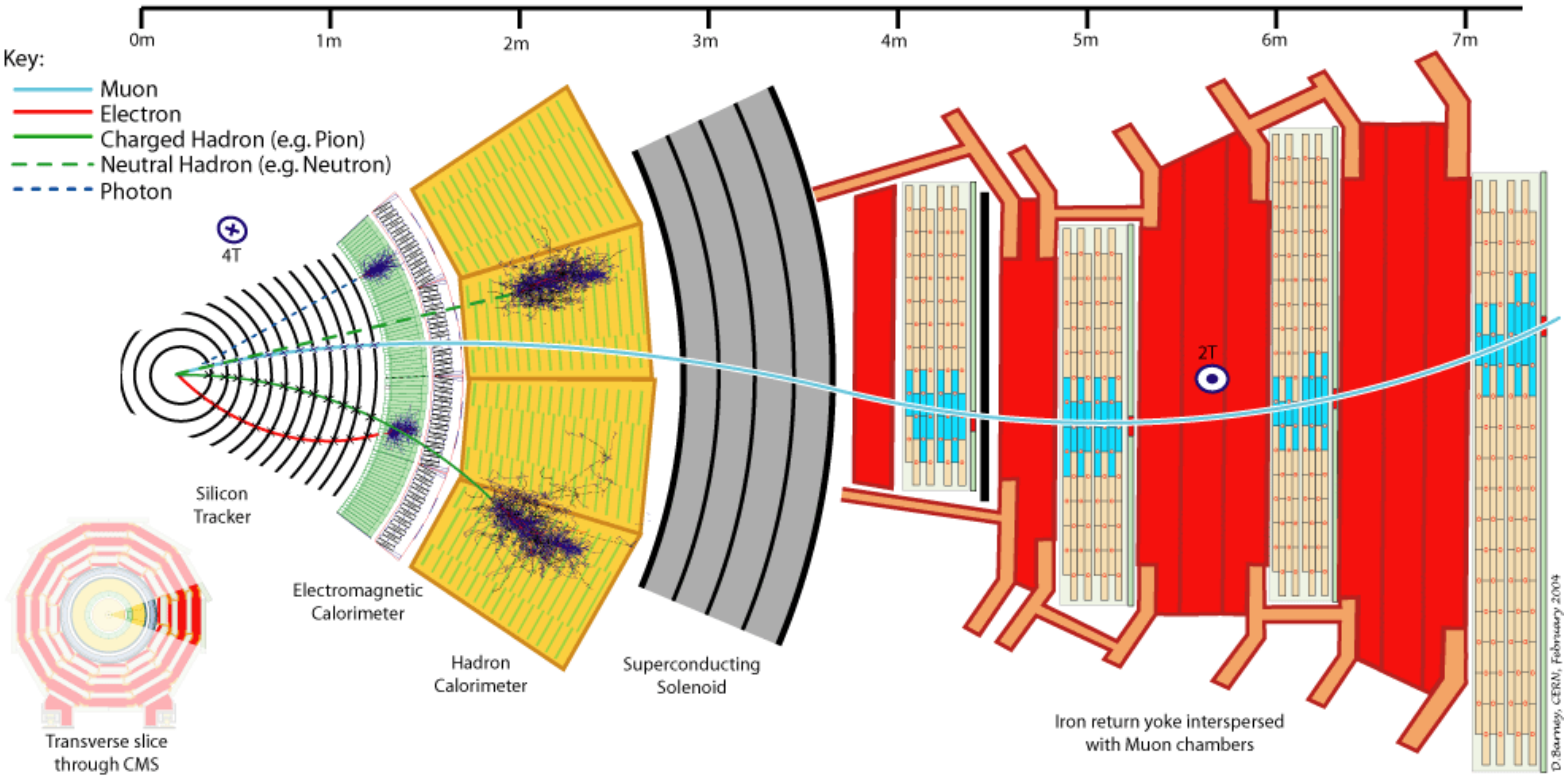
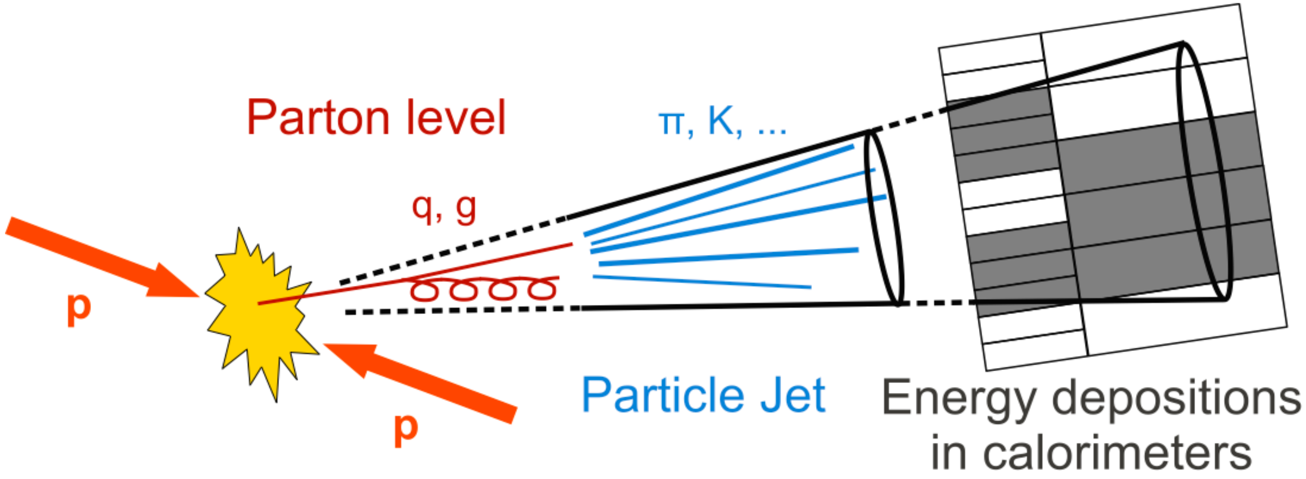


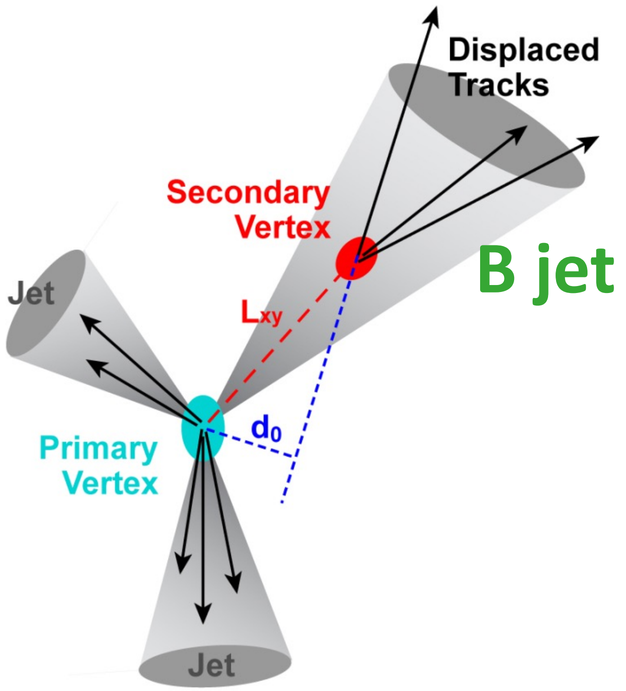
Observing quarks and gluons

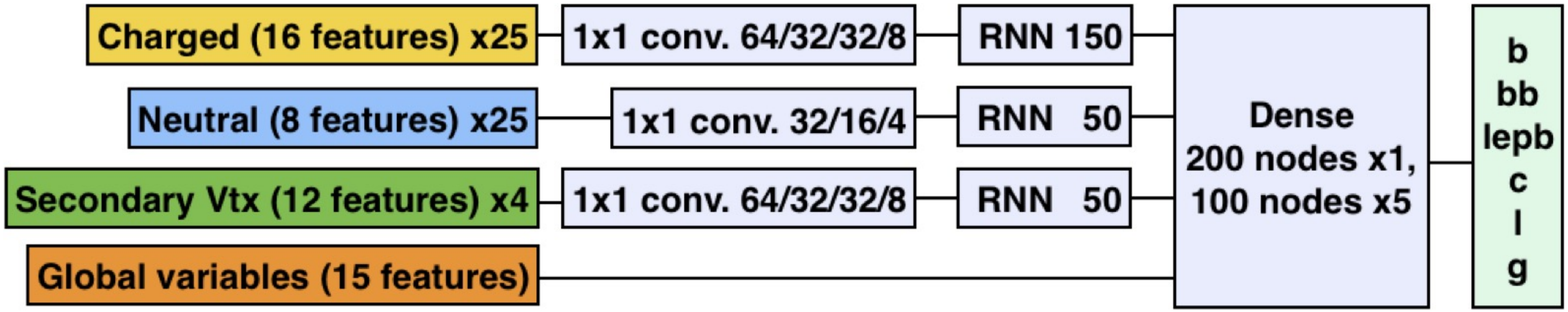
- Quarks and gluons are **color-charged particles** - Quantum Chromodynamics (QCD)
- Color-charged particles cannot be found individually; **Quarks are confined** in **color neutral** groups with other quarks
  - Baryons: 3 quarks (red+green+blue = color neutral)
  - Meson: 2 quarks (red + anti-red = color neutral)
- If a lone quark is produced in a collision, it will create a spray of hadrons known as a **jet**
  - Clustering algorithms are used to merge energy from these hadrons back into a single jet



Tagging b-quarks

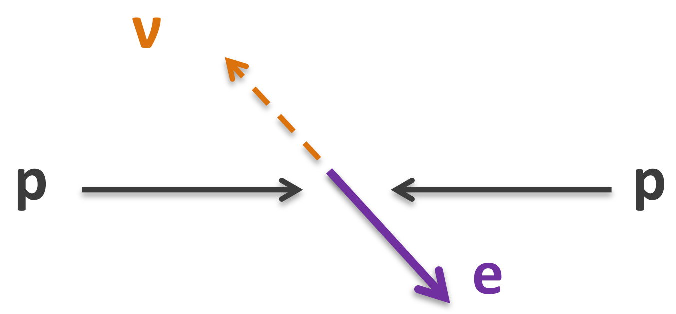
- But what type of quark or gluon created the jet? For example, can we distinguish **H→ bb events** from the much more boring **generic stuff→ two jet events**?
- B quark decays have some unique features:
  - Intermediate lifetime, so they travel some distance before decaying
  - Decays often include leptons (b -> μX)
  - B quarks have high mass, so they decay into a larger number of charged particles
- Can exploit these features in a machine learning algorithm to **tag** b-jets



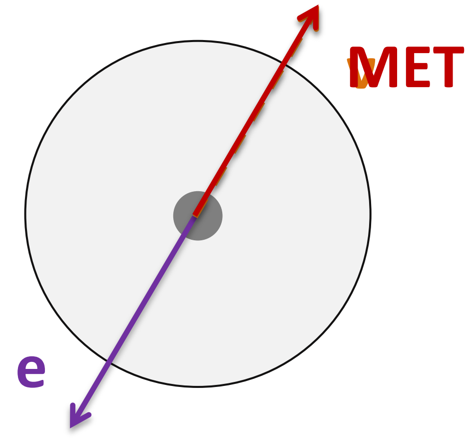


Undetectable particles and MET

- Some particles like neutrinos **ν** escape the detector without depositing energy
- Using momentum conservation, we can still "see" evidence of these invisible particles!
  - **Zero** net momentum in transverse plane **before** collision → **Zero** net momentum in transverse plane **after** collision
- "Missing" transverse energy **MET or $\vec{p}_T^{Miss}$**= $-\sum \vec{p}_T$ for all visible particles in the event



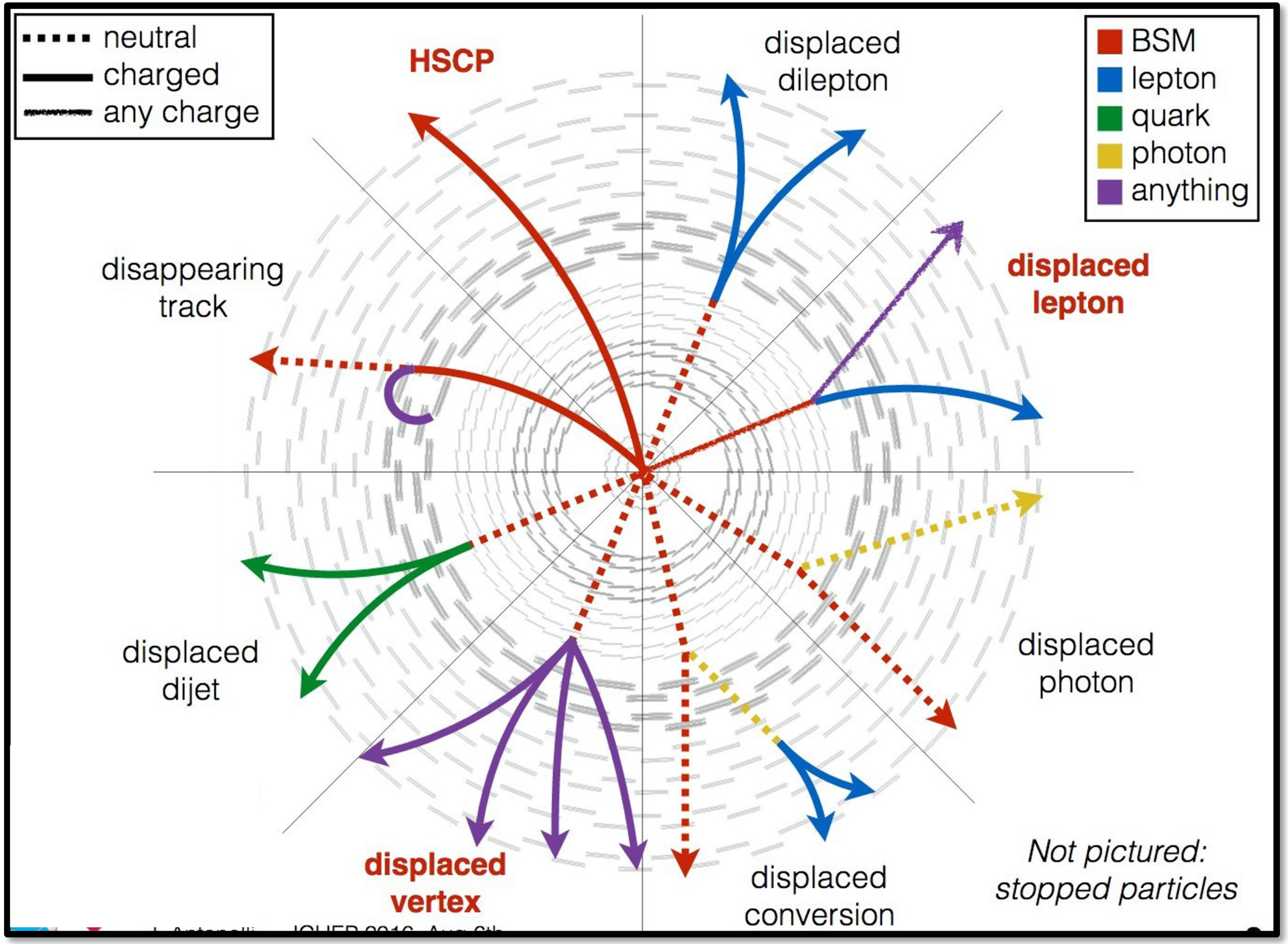
Side view



Transverse view

Possible new particles at the LHC: “exotic” signatures

- New particles like dark matter could have intermediate lifetimes and decay in the middle of the detector
- Leads to a wide range of interesting, challenging signatures to explore



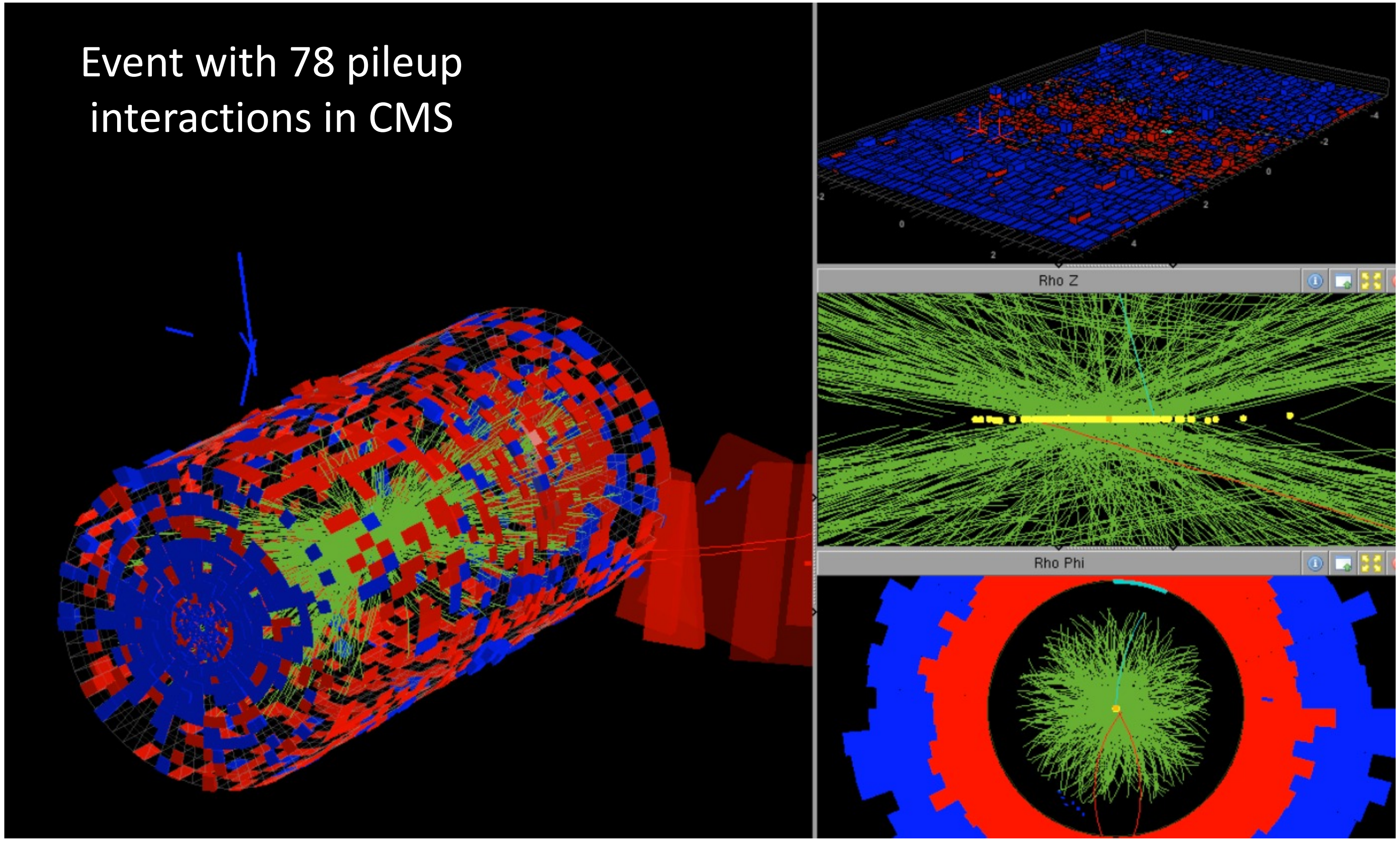
Trigger System

- ATLAS and CMS take data 24/7
- Collisions happen at 40 MHz
  - Too much data to keep everything!
- **Trigger** system selects 99.998% of events to throw away, 0.002% to keep
  - High stakes environment: If the trigger throws your event away, it's lost forever
  - Must decide quickly: protons collide every 25 ns
- Specialized hardware (FPGAs) reduces rate to 100 kHz
- Software algorithms further reduce rate to 1 kHz which is saved for later analysis

CMS control room

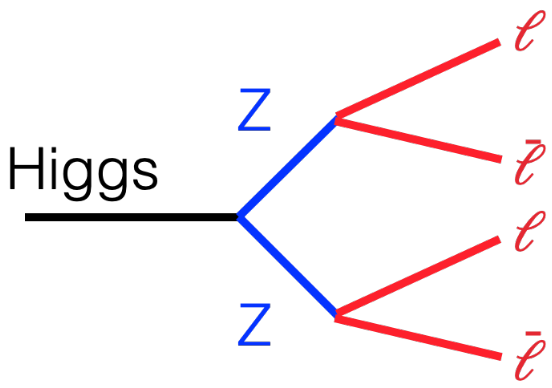
40 proton pileup

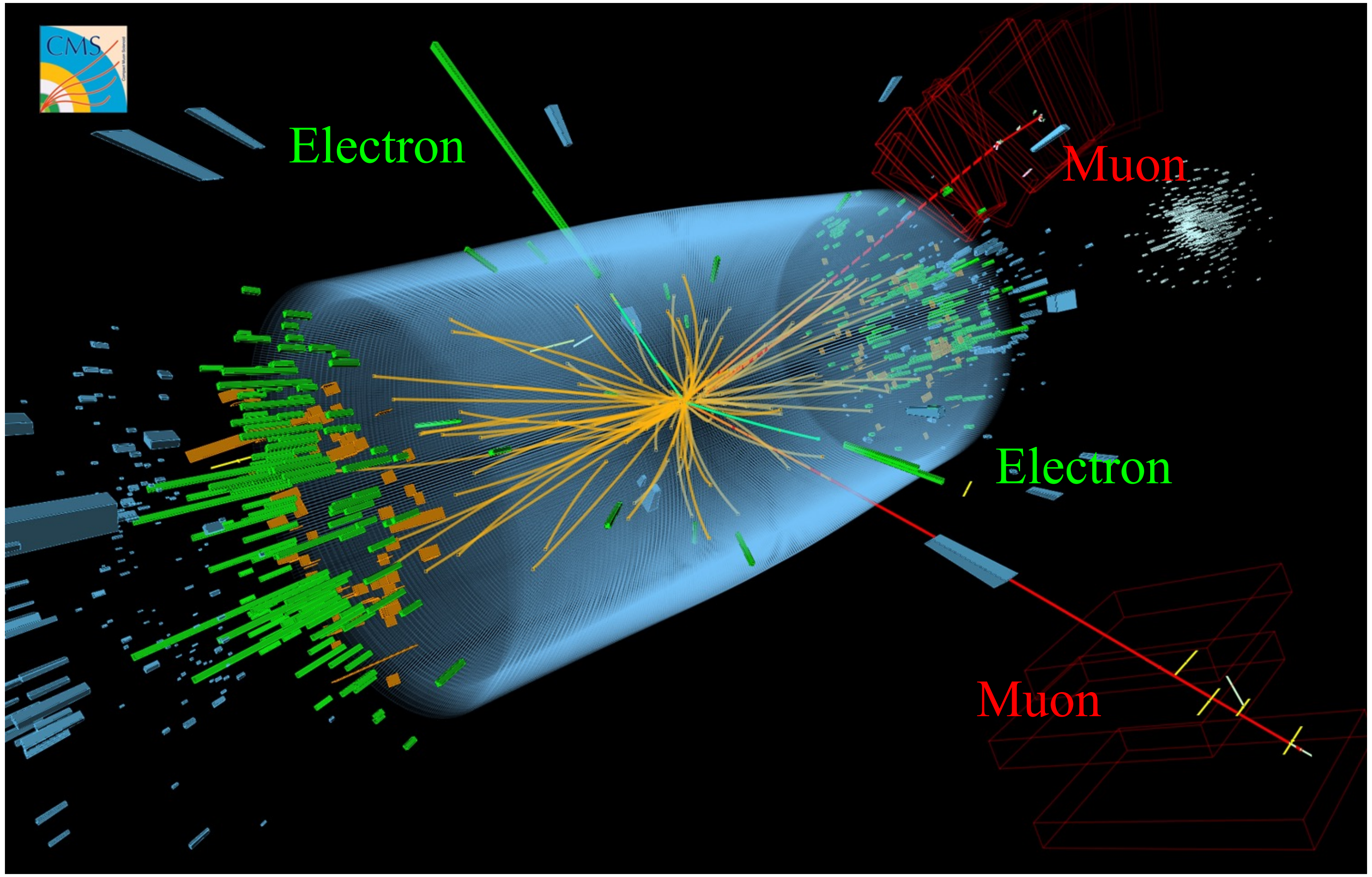
- LHC actually collides "bunches" of protons at once
  - Each with 100 billion protons
- On average, 40 pp collisions occur per bunch crossing (pileup)
  - Most are boring, low-energy interactions
  - Have to disentangle the interesting collision from the 40 pileup interactions



Conclusions

- CMS is a microscope that takes high-definition pictures of particle collisions
- Combining information from different subdetectors—tracker, ECAL, HCAL, muon system—lets us reconstruct particles that interact with the detectors—electrons, photons, hadrons, and muons
- After reconstructing “final state” particles, we can work backwards to learn about which unstable particles existed after the collision

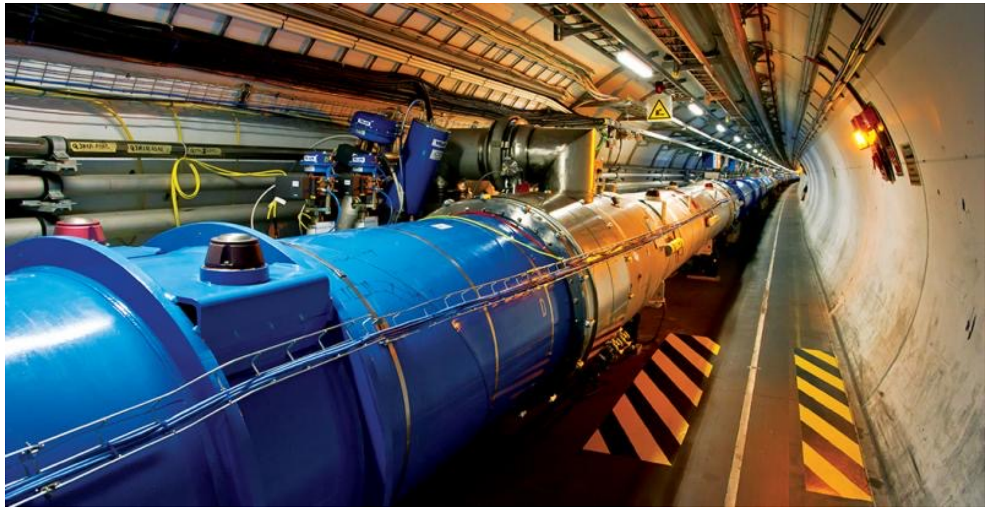


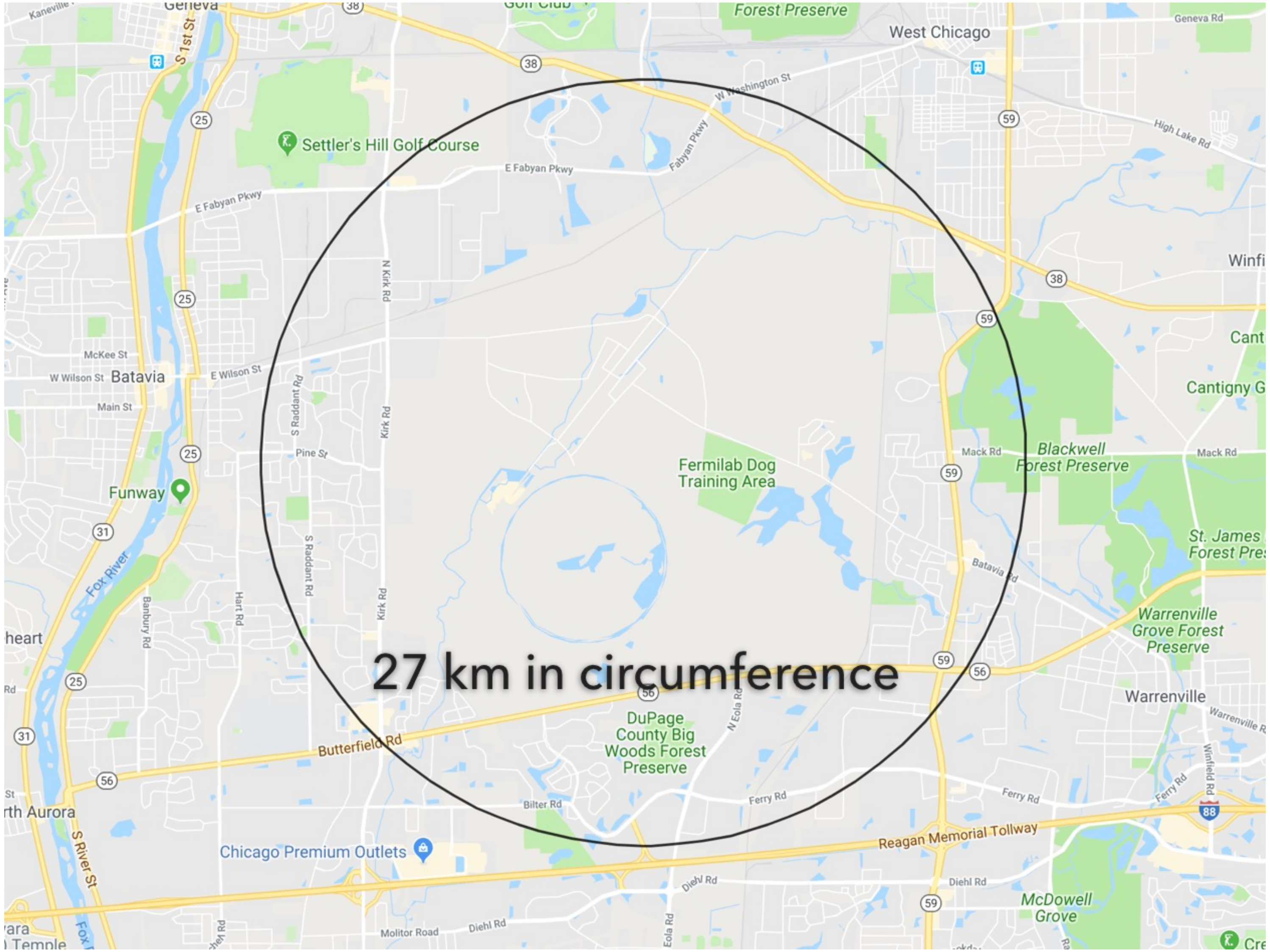


Backup

Large Hadron Collider

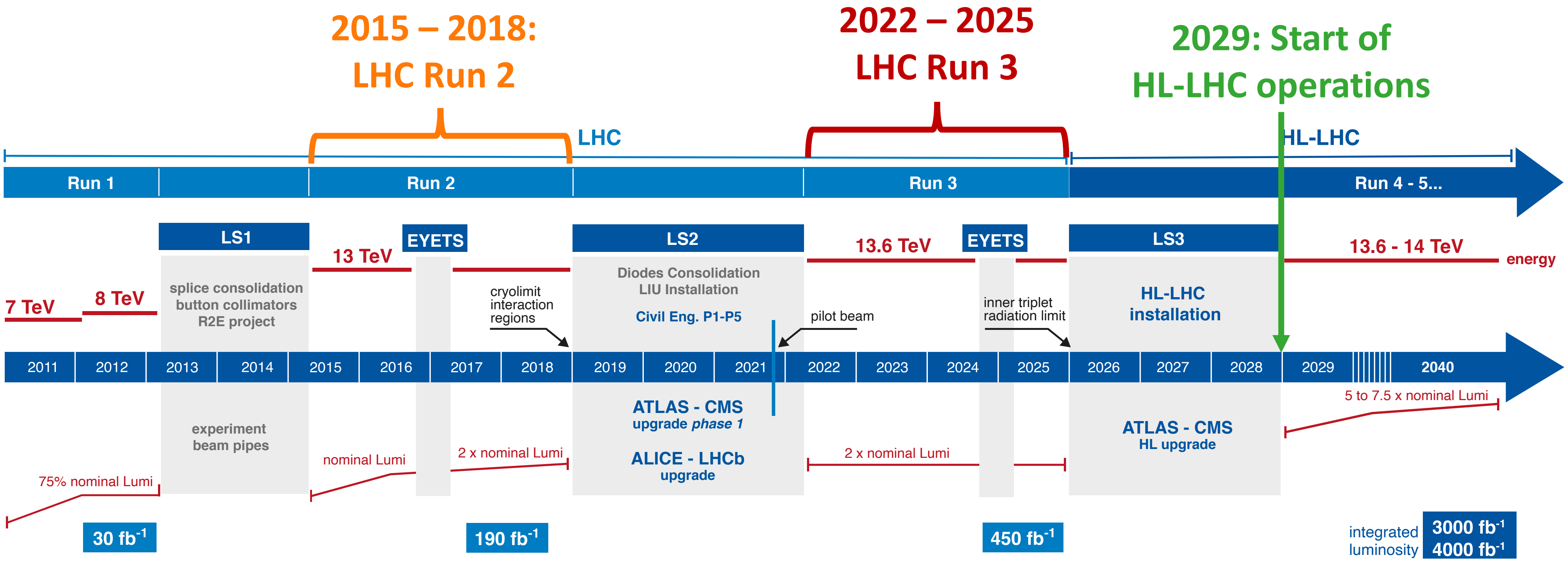
- 17 miles in circumference
- World's largest and highest energy hadron collider
  - 13 TeV center of mass energy
  - Beats the previous record held by the Tevatron at Fermilab
  - 1232 dipole magnets at 8.3 T





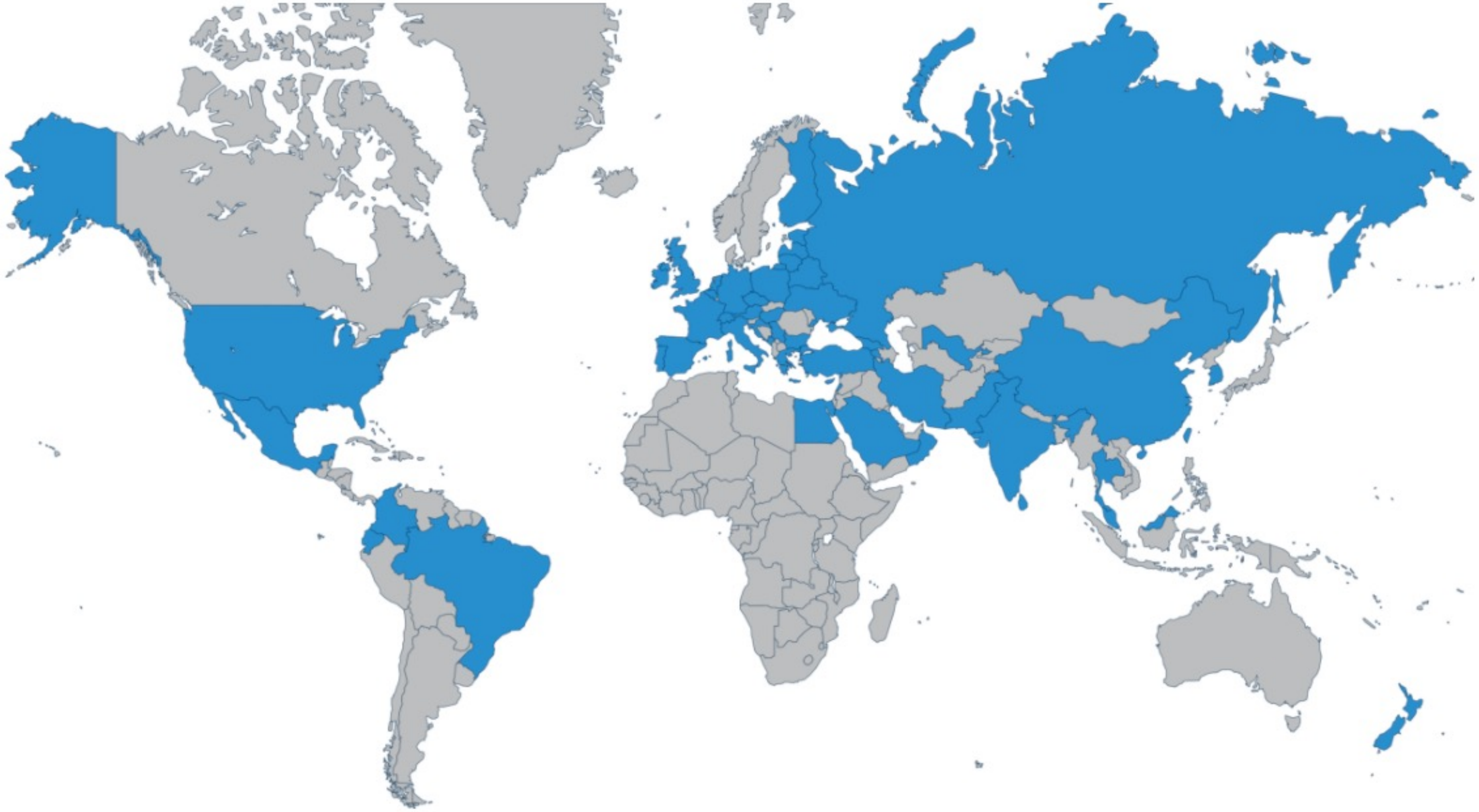
High-Luminosity LHC

- Integrated luminosity $\mathcal{L}$ is the amount of data (*pp* collisions) collected
- $\mathcal{L}$ = 160 fb^{-1} in Run 2; expected $\mathcal{L}$ > 3000 fb^{-1} during the HL-LHC
- For a process with a cross section σ of 1 fb, we expect **1** event to be produced **per** $\mathbf{fb^{-1}}$



CMS Collaboration

- Diverse institutions, nations, and skills
  - Engineers, computer scientists, technicians, scientists, postdocs, students..



2942 PHYSICISTS (1036 STUDENTS)

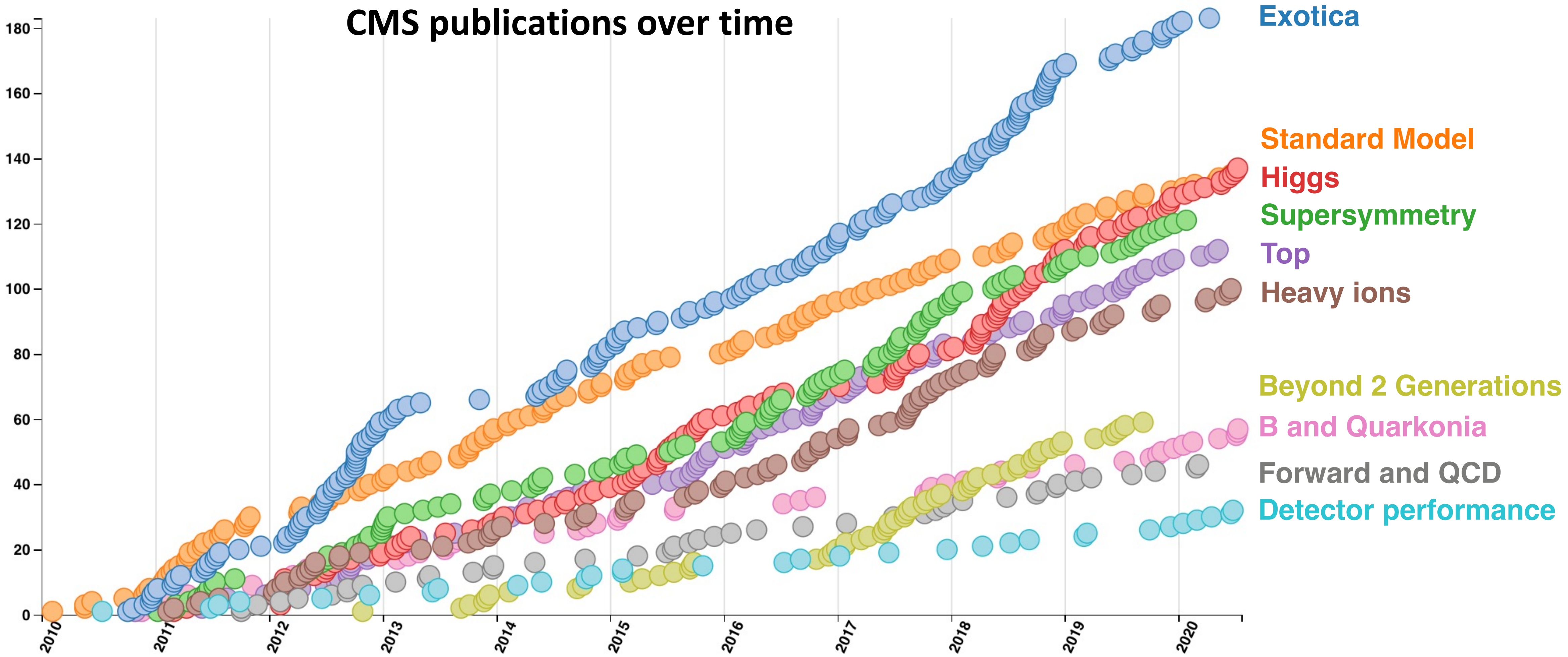
1065 ENGINEERS

281 TECHNICIANS

229 INSTITUTES

51 COUNTRIES & REGIONS

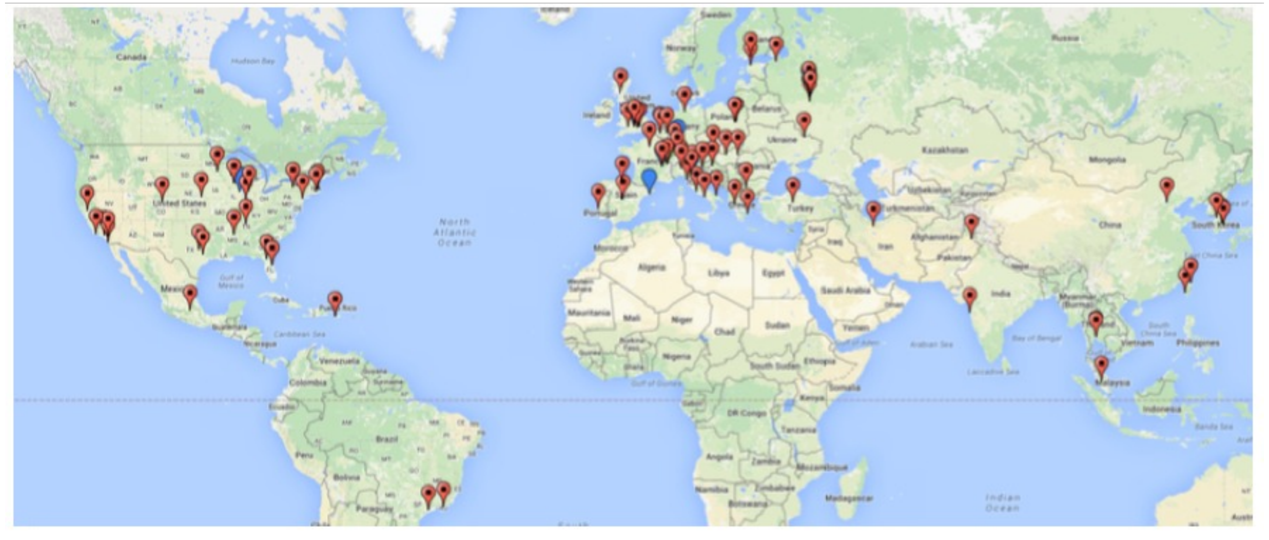
CMS Physics


CMS publications over time
180
160
140
120
100
80
60
40
20
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Exotica
Standard Model
Higgs
Supersymmetry
Top
Heavy ions
Beyond 2 Generations
B and Quarkonia
Forward and QCD
Detector performance

CMS Computing

- Still ends up with lots (PB) of data
- Stored and analyzed on “The Grid”, or the Worldwide LHC Computing Grid (WLCG) on computers from Lithuania to Nebraska, total 300k cores
- Many events: CMS needs to process **> 1 billion** events (simulated + real collisions) per month
    - Approximately 30 s/event (30x more in a decade!)

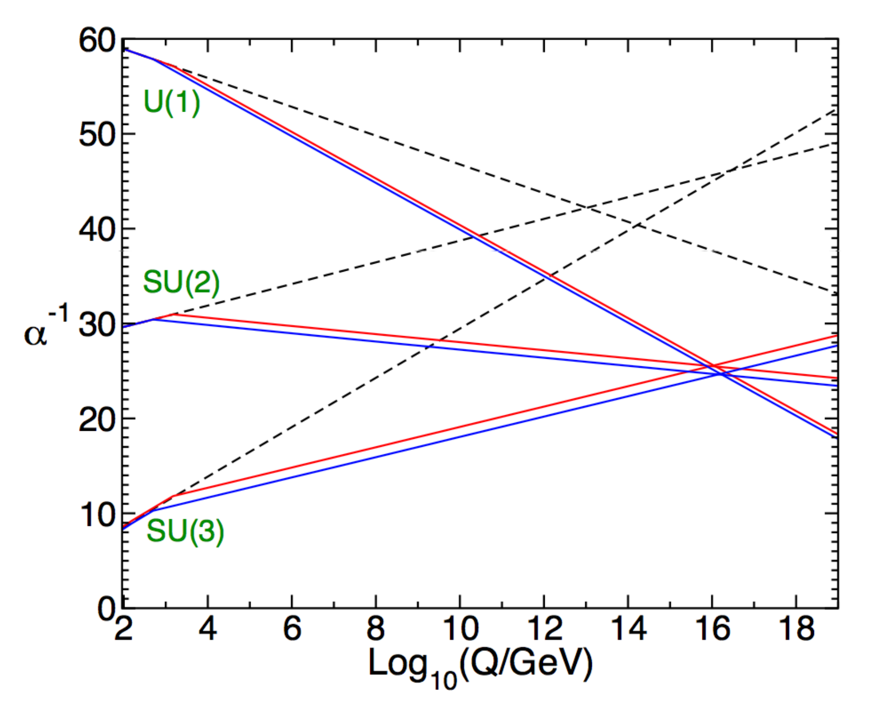
CMS Global Computing Grid



70+ sites, 200k+ CPU cores

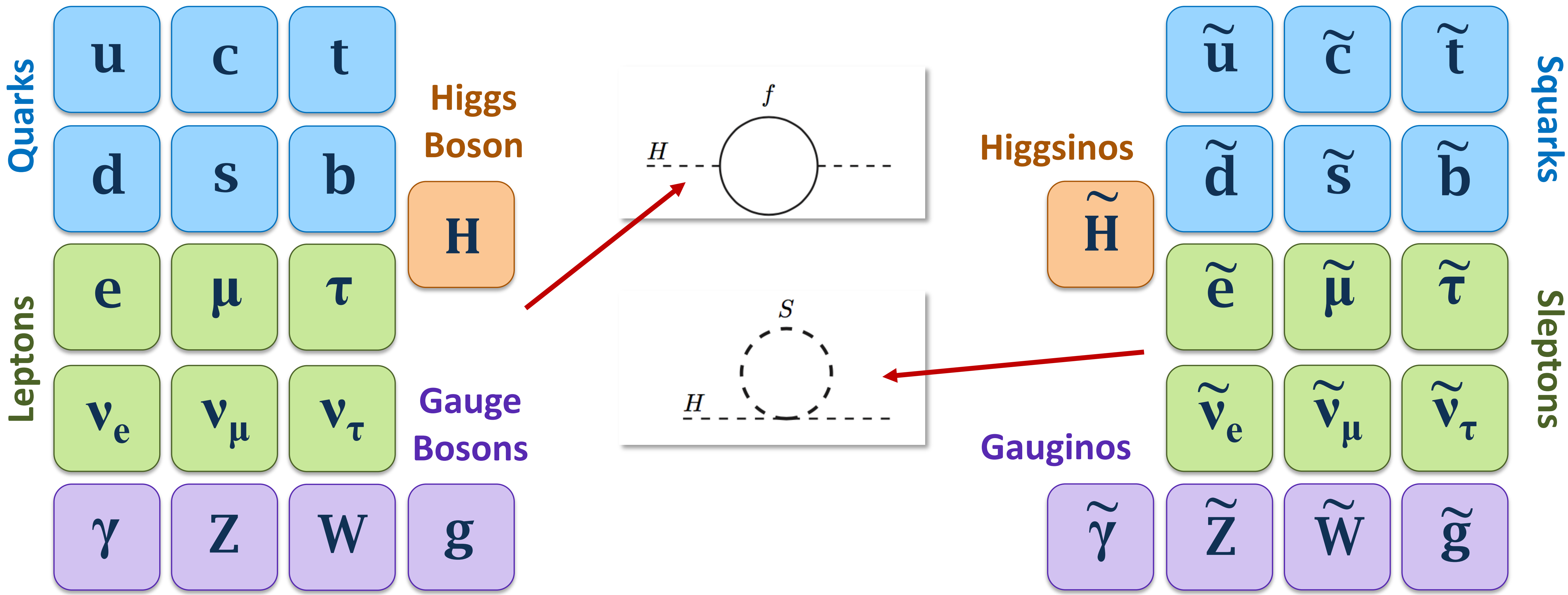
Motivations for beyond SM physics

- Hierarchy problem: one example of “fine-tuning”
  - Two extremely large values in the theory must cancel each other almost exactly
- Grand Unification theories
  - Maybe at high energies all the forces are unified into one
- Dark matter: what type of particle (if any) is it?



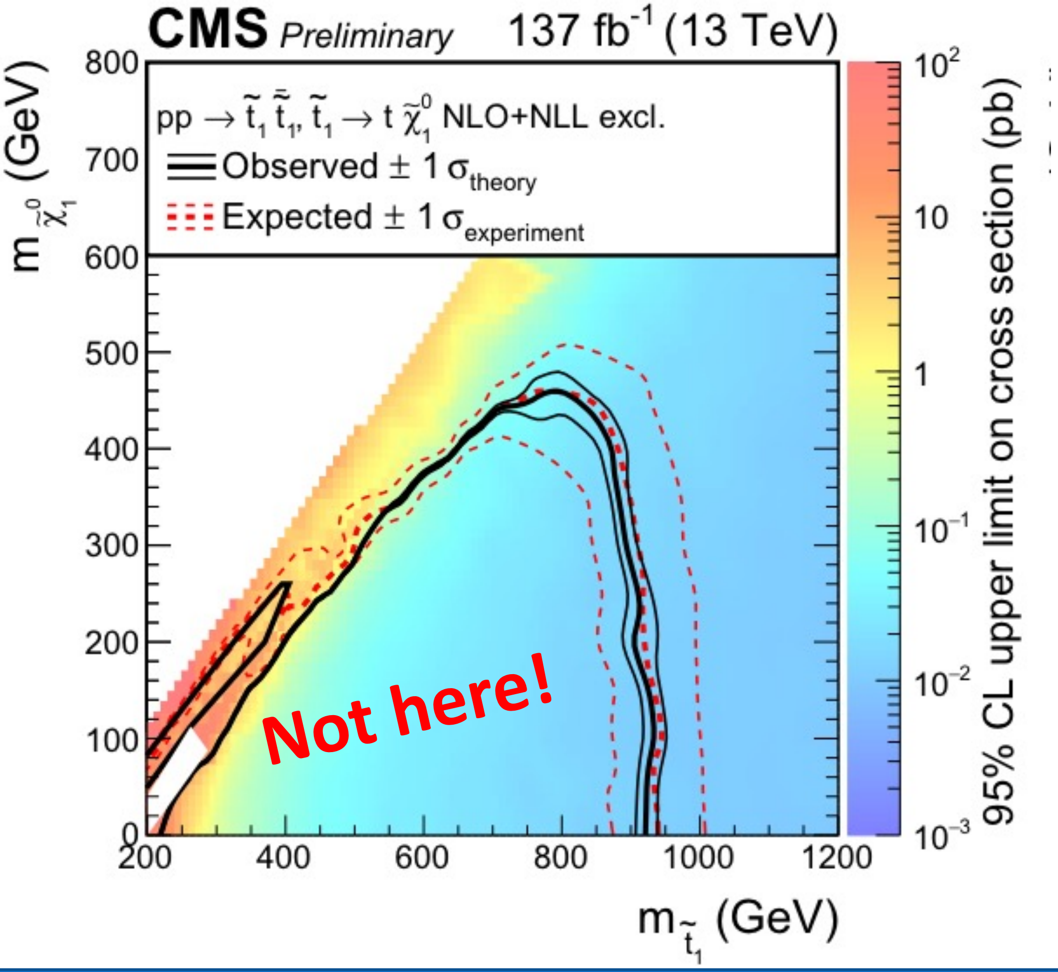
Supersymmetry (SUSY)

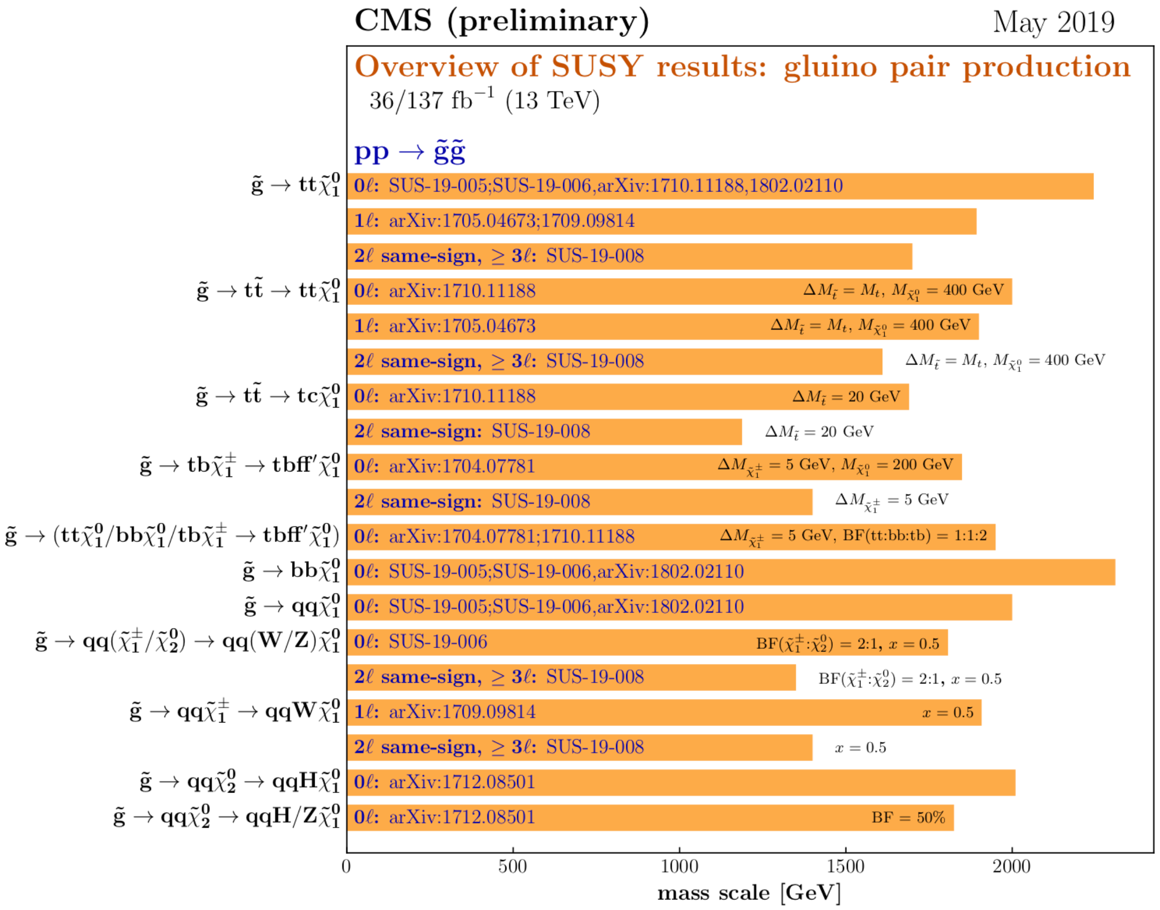
- Doubles the number of elementary particles, but solves many issues with the SM
- For each fermion, there is a superpartner boson and vice versa (symmetry!)



Supersymmetry limits

- Recall what Feynman said: "if it disagrees with experiment it is wrong"
- Limit setting (ie, looking for "nothing") forces us to develop new ideas





Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary particle and the LSP, and the difference between the intermediate particle and the LSP relative to ΔM, respectively, unless indicated otherwise.

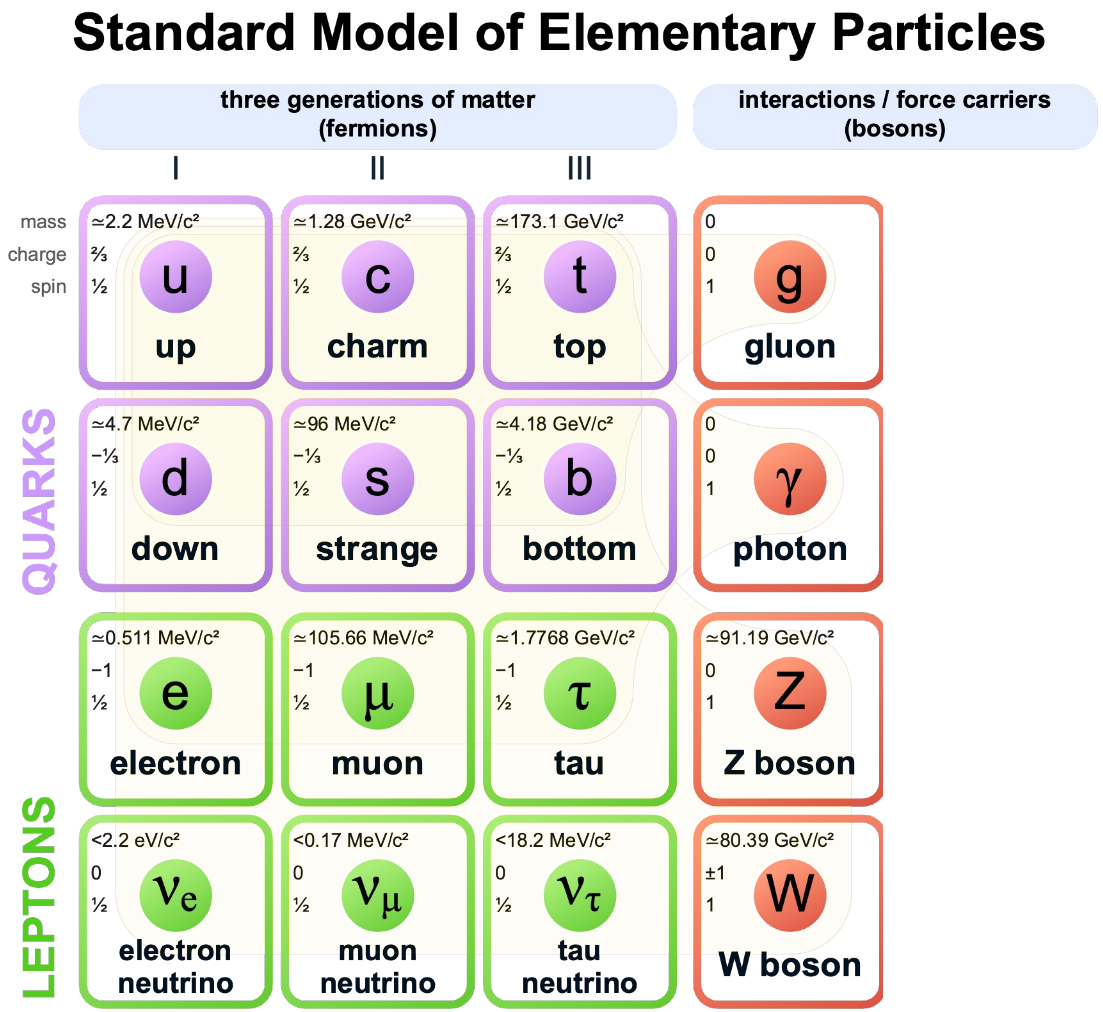
How do we do an analysis?

- Define which events are interesting for you (with help from theorists)
  - To look for a particular SUSY model, consider events with two photons plus missing transverse momentum (MET)
- Estimate how many of those events you would get from SM process
  - Use Monte Carlo simulation or similar-but-different events in data
- Use simulation to determine how many of those events you would get from SUSY
- Determine uncertainties, get other people in CMS to check your work
- Open the box! "Unblind" and see how many events CMS actually detected

Expected background events	15.6 ± 3
Expected signal events	50 ± 5
Observed events	19
Conclusion	SUSY's not home: set limits!

Expected background events	15.6 ± 3
Expected signal events	50 ± 5
Observed events	63
Conclusion	We found SUSY!

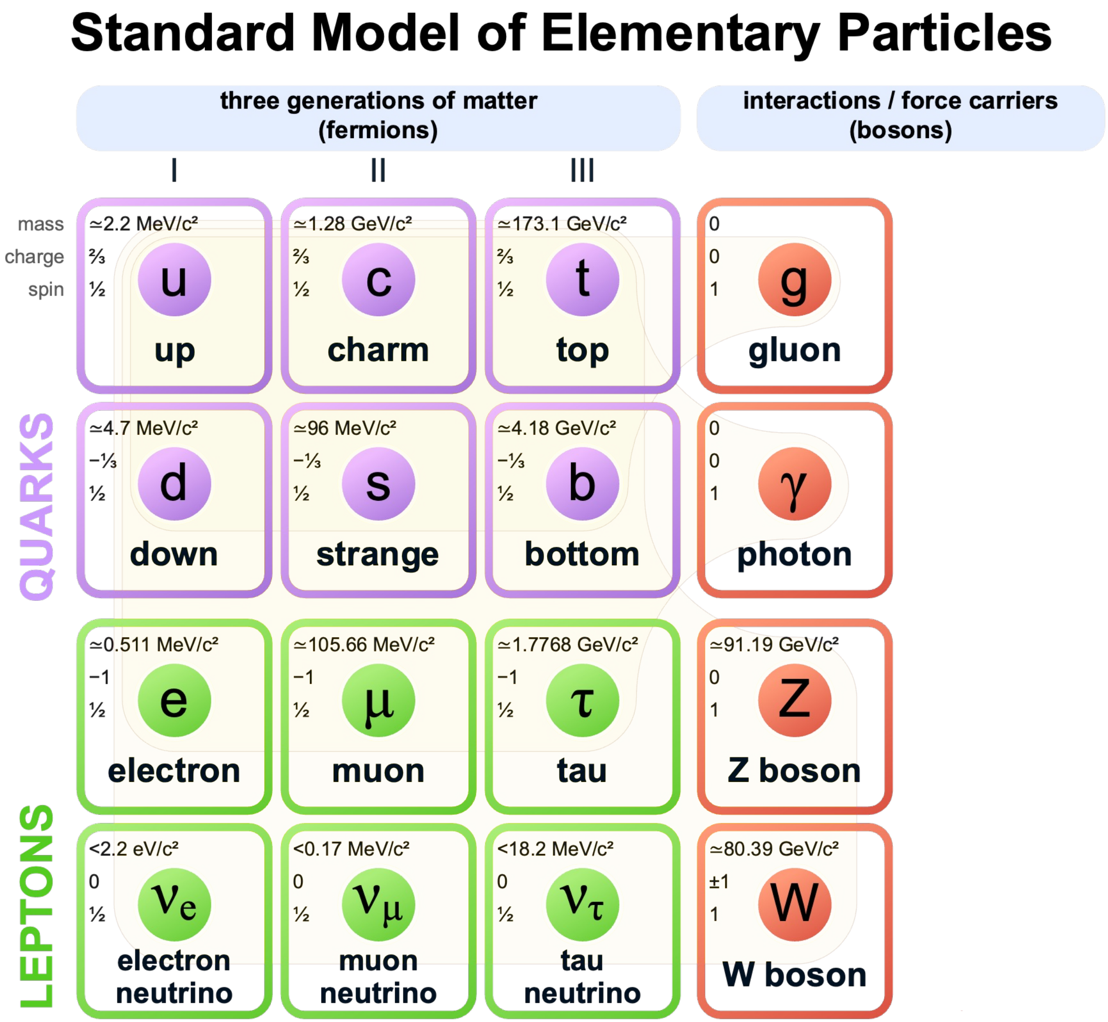
Checkpoint: Standard Model



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
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL

Last piece of the puzzle



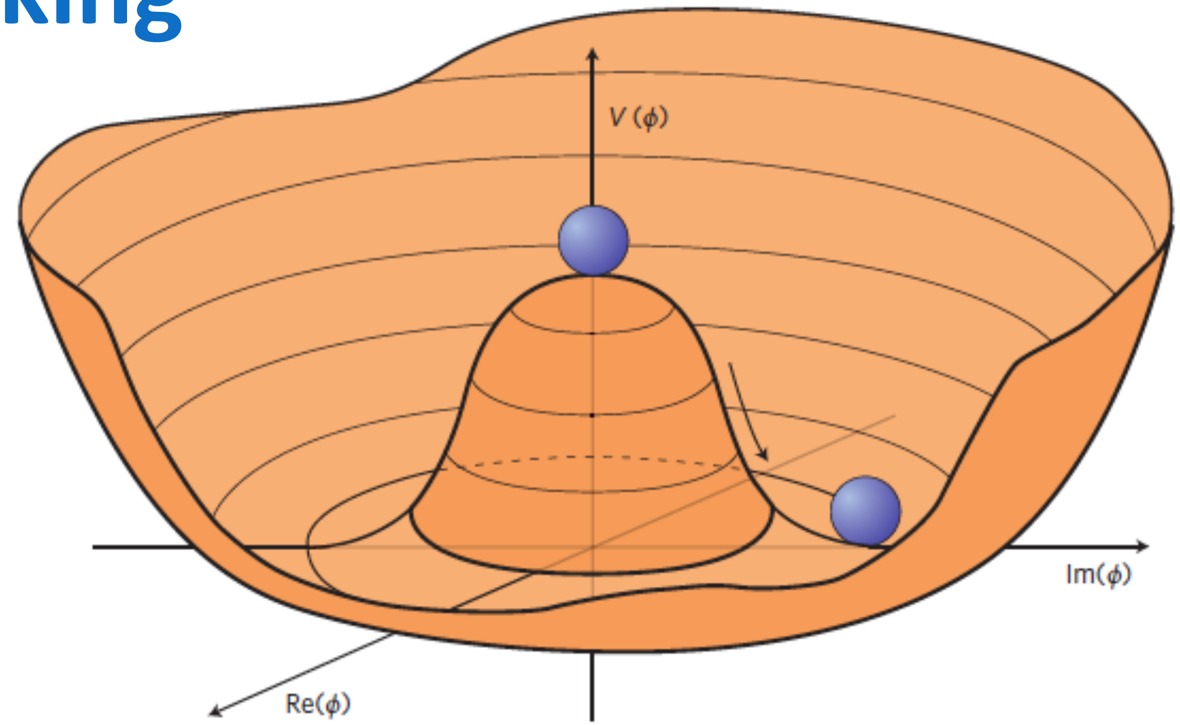
- Last missing piece = **Higgs boson**

- 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



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

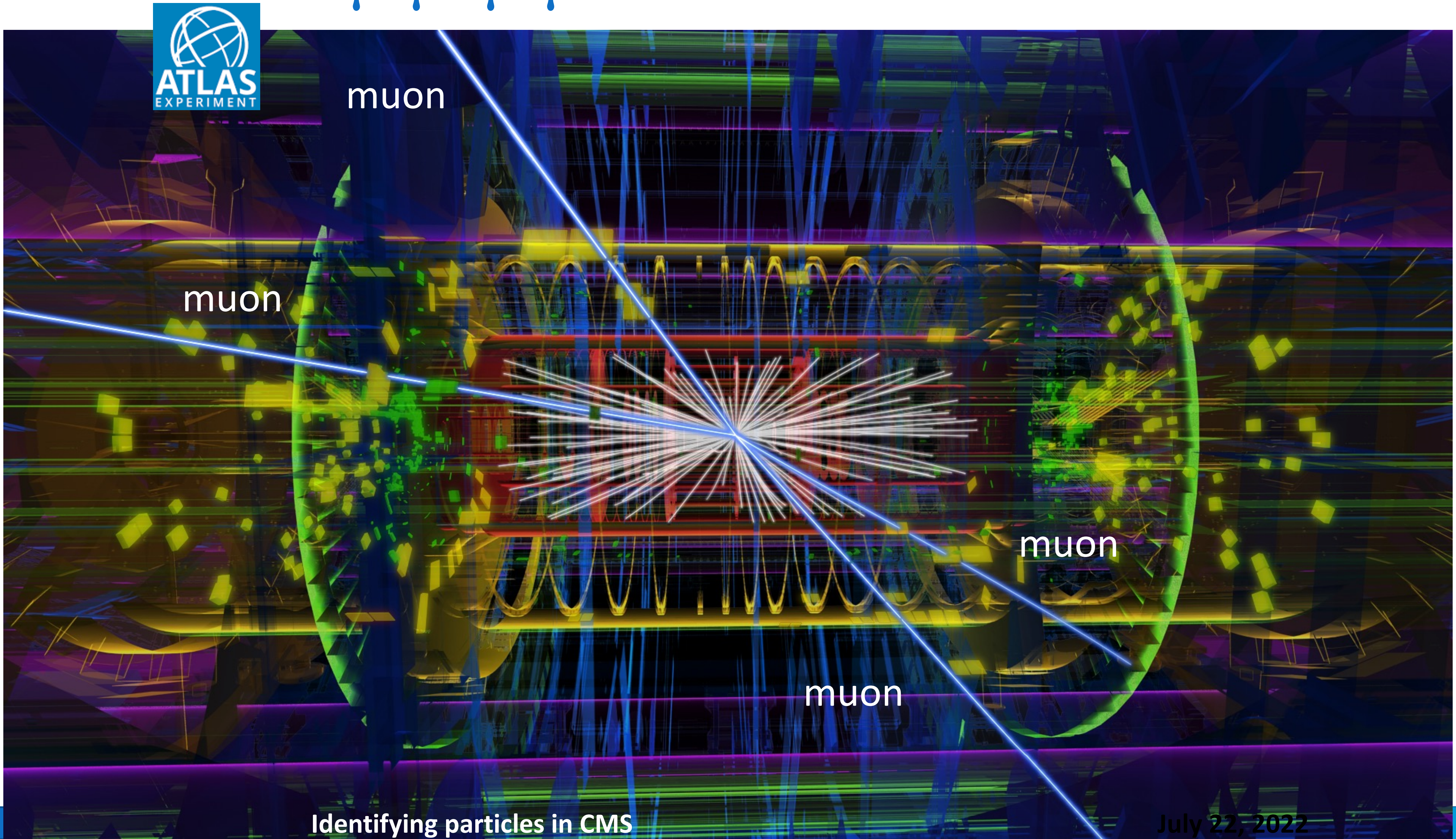
How a Higgs boson decays

- 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)

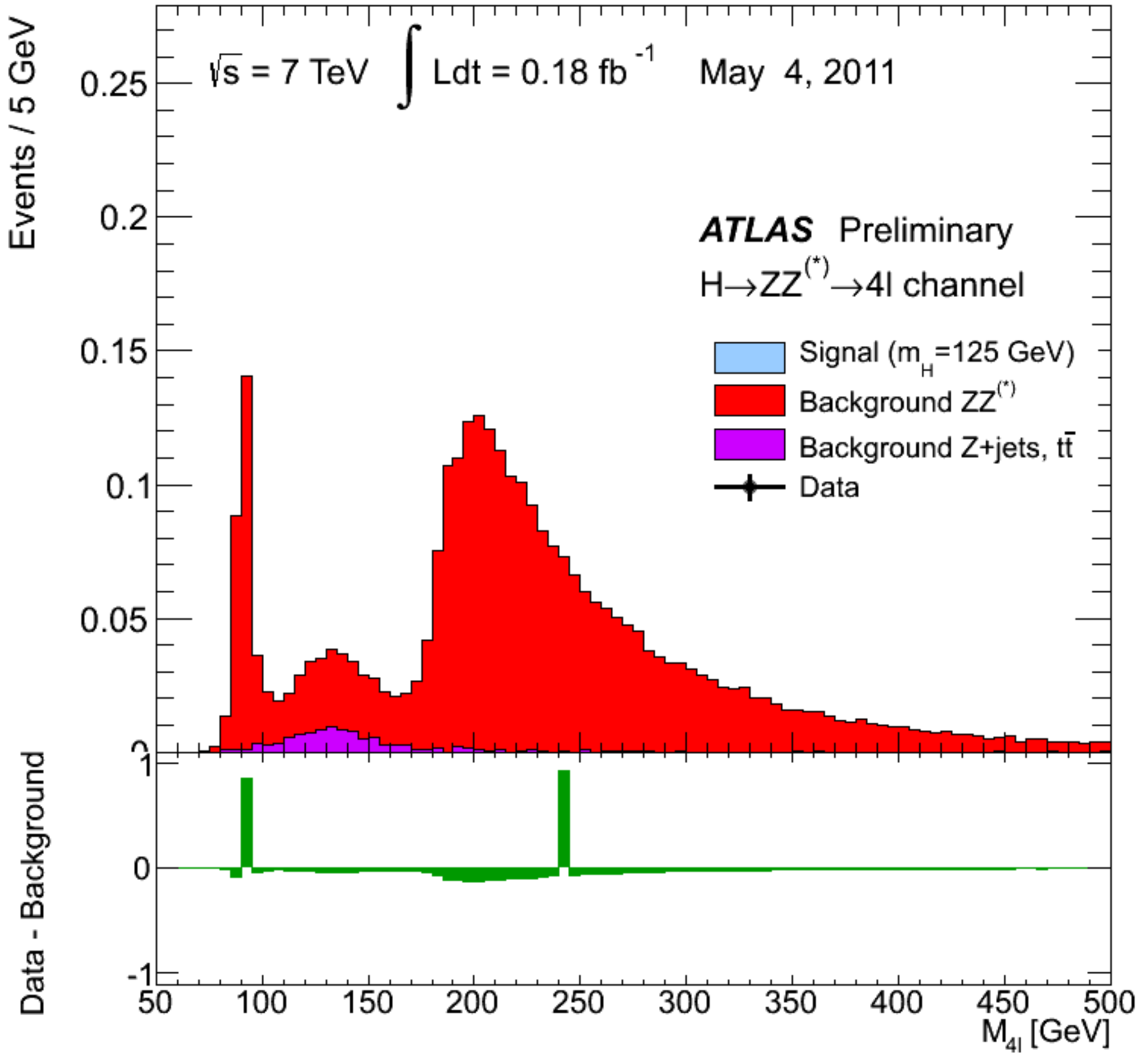
Higgs $\rightarrow b + \bar{b}$	(b quark and its antiquark)
Higgs $\rightarrow \tau^{+} + \tau^{-}$	(τ lepton and its antiparticle)
Higgs $\rightarrow \gamma + \gamma$	(two photons, also called gammas)
Higgs $\rightarrow W^{+} + W^{-}$	(W boson and its antiparticle)
Higgs $\rightarrow Z^{0} + Z^{0}$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

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

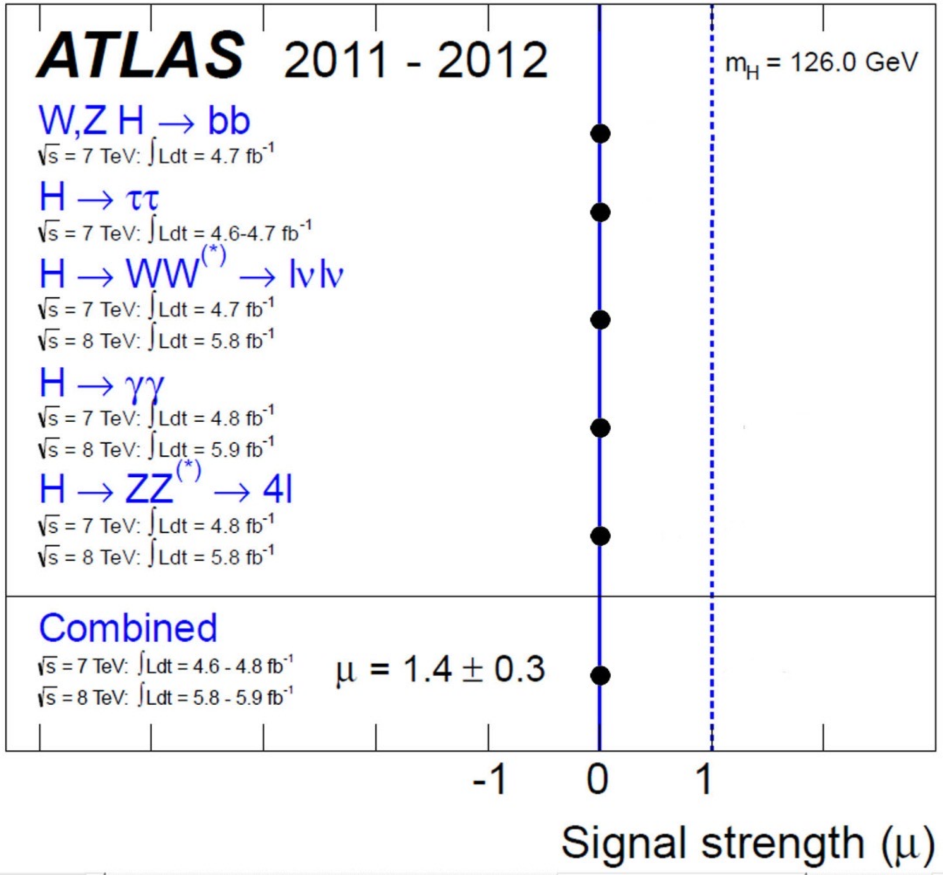
$H \to ZZ \to \mu^+\mu^- \mu^+\mu^-$ Candidate

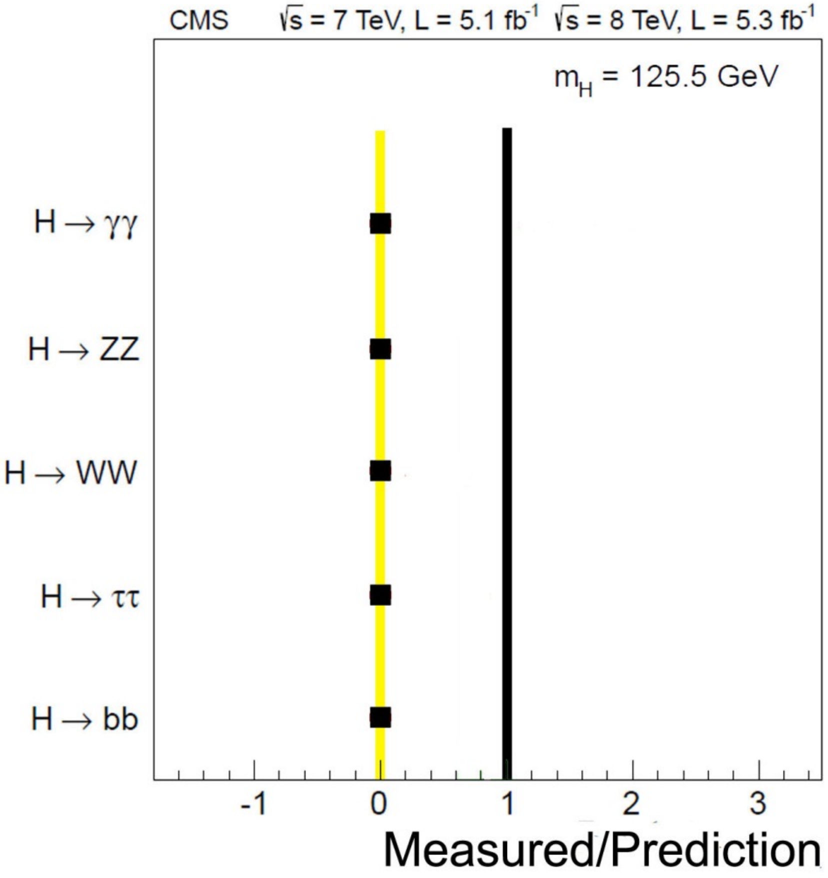


Time Evolution of Higgs Boson Data



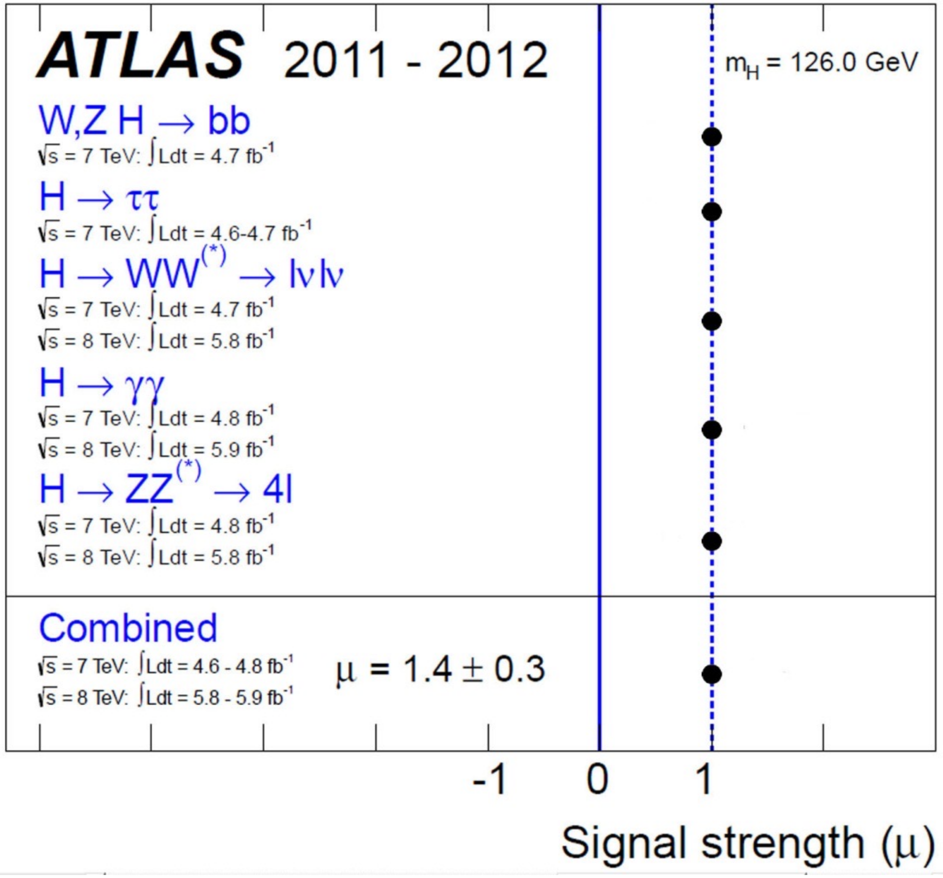
Results if no Higgs

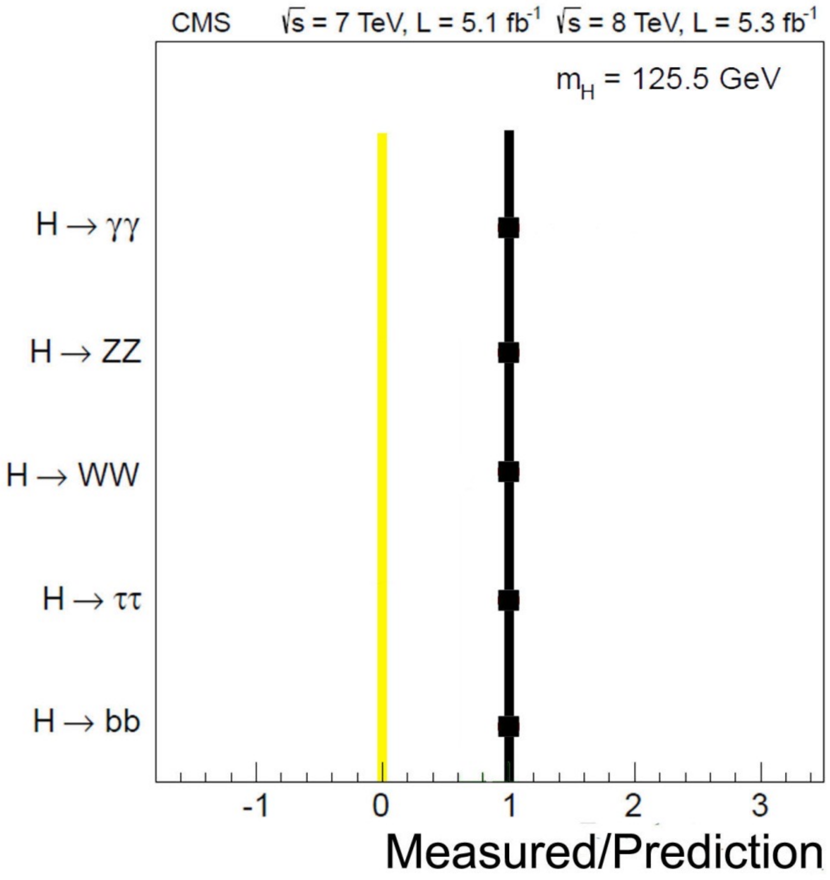




Ratio of Measurement to Standard Model Prediction

Results with Higgs





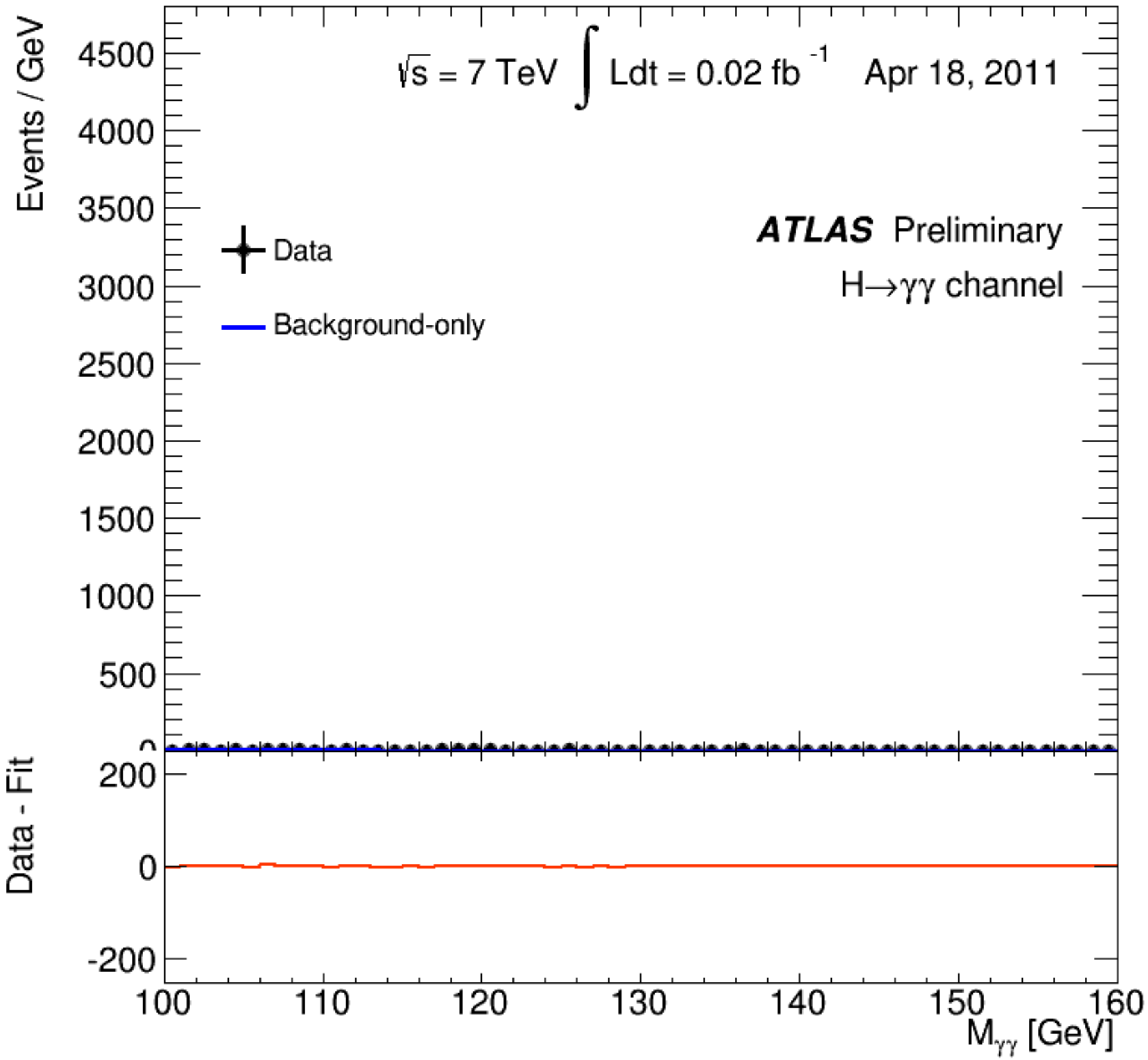
Ratio of Measurement to Standard Model Prediction

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

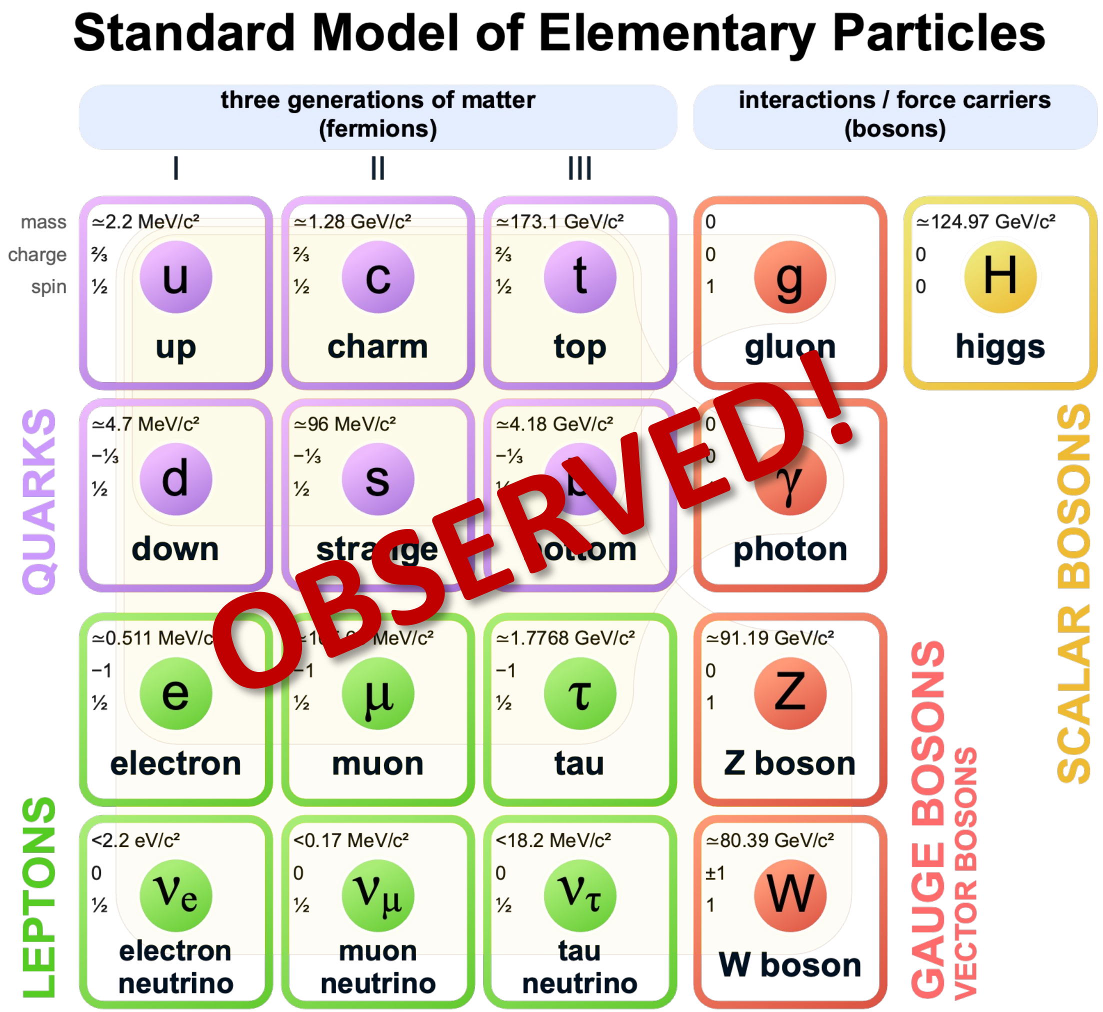


√s = 7 TeV ∫ Ldt = 0.02 fb^-1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

Future electron-positron colliders

- CLIC: Compact Linear Collider
  - 380 GeV – 3 TeV, 11 – 50 km, hosted at CERN
- ILC: International Linear Collider,
  - 500 GeV – 1 TeV, 30 – 50 km, hosted by Japan
- CEPC: Circular Electron Positron Collider
  - 240 GeV, 55 km, can be upgraded to 70 TeV pp collider, hosted by China

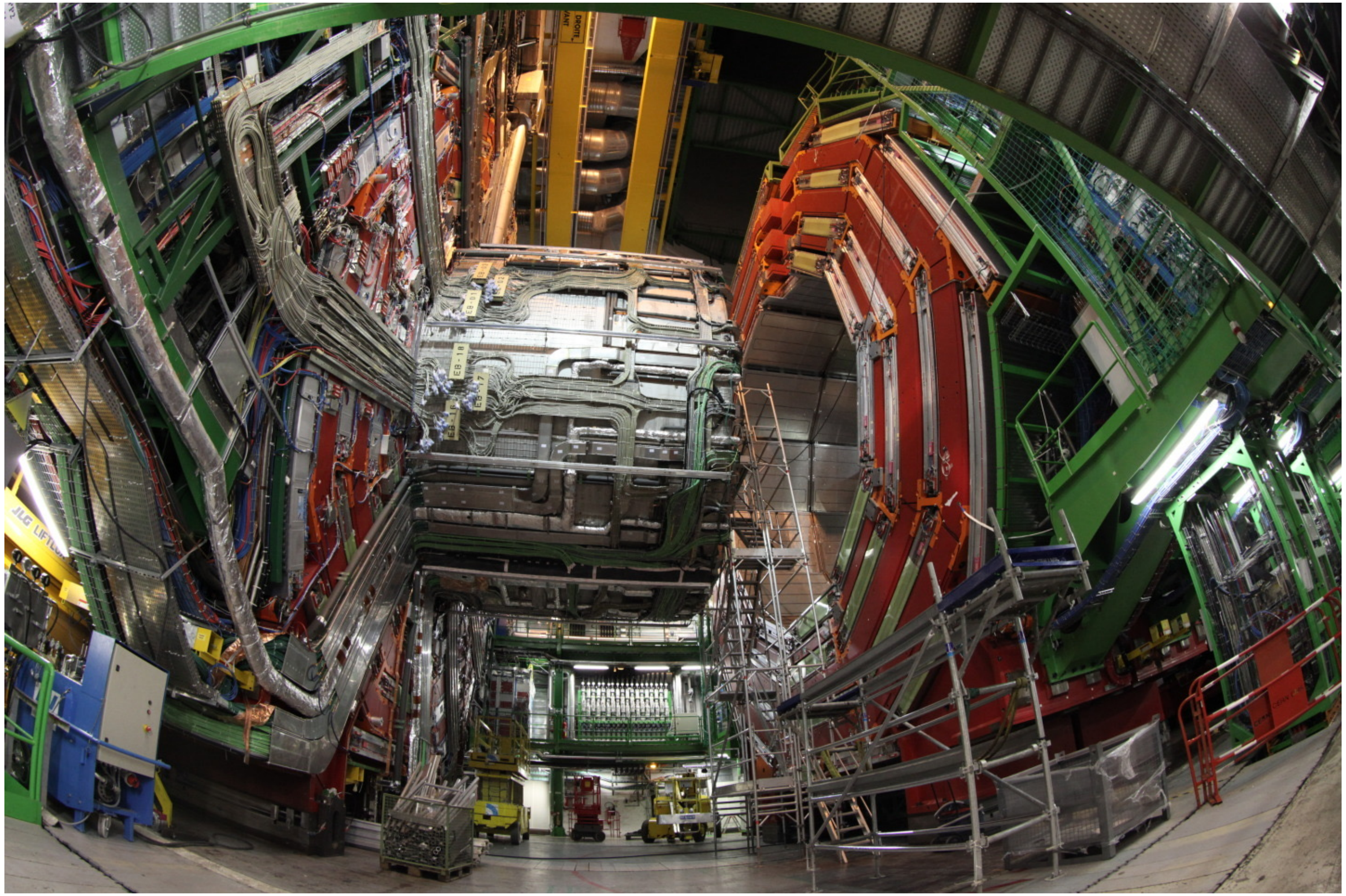
Standard Model



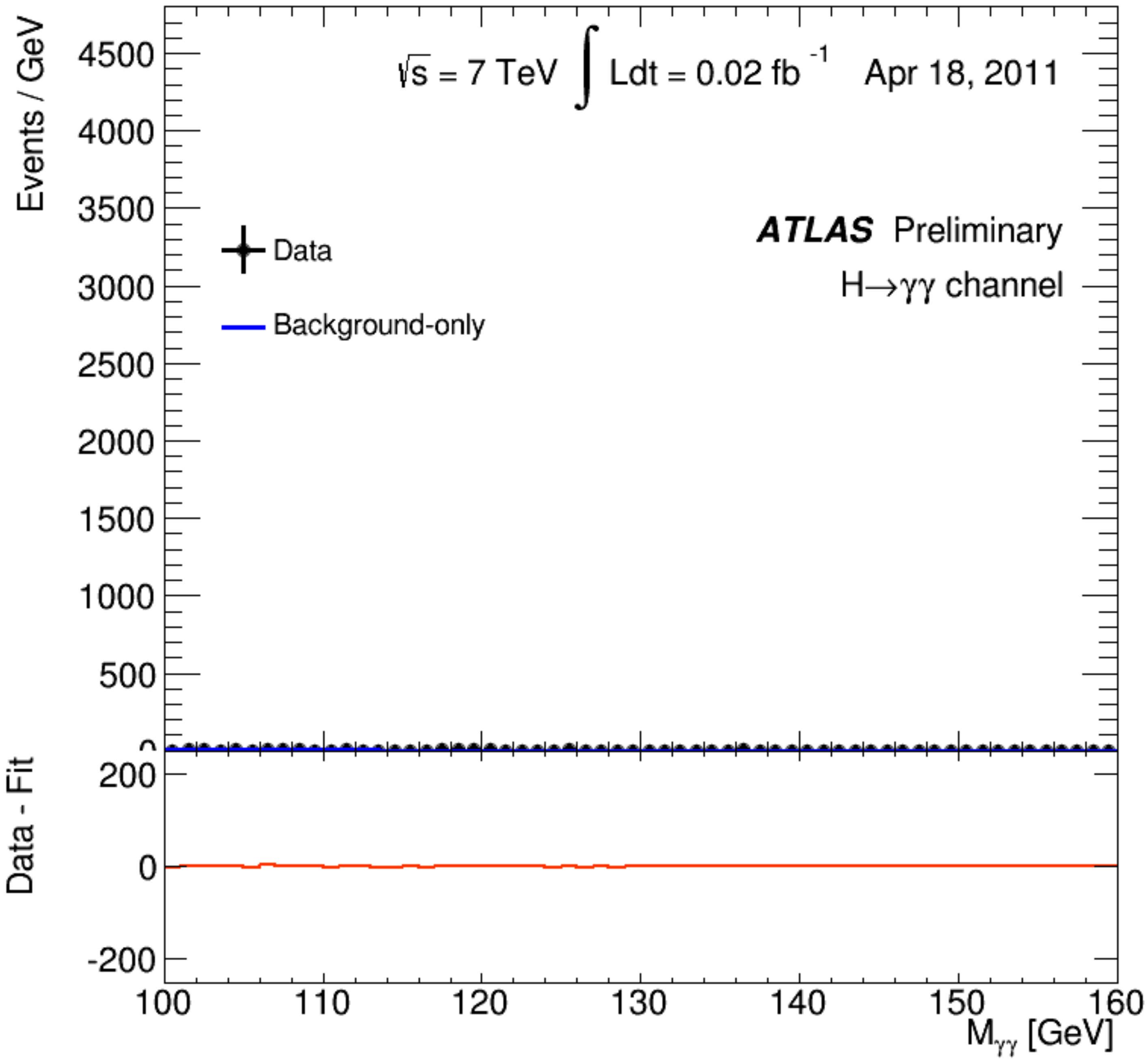
Observations:

- 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
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN

CMS Magnet



3.8 T superconducting solenoid magnet, cooled using liquid helium



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√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
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Data - Fit
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140
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160
Mγγ [GeV]

The ATLAS Detector @ the LHC