The Large Hadron Collider (LHC) and the Compact Muon Solenoid (CMS) detector: WHAT and WHY

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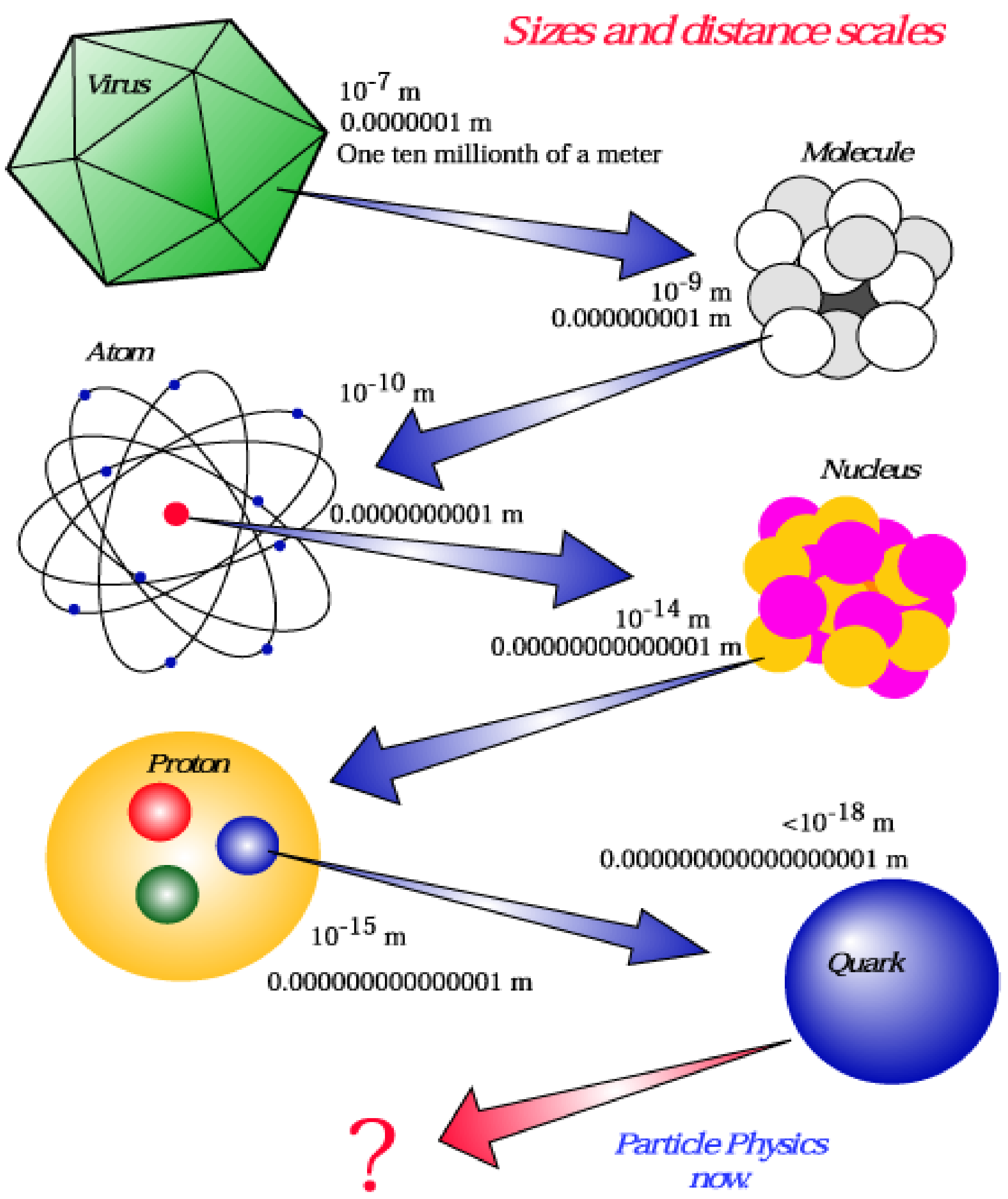
Particle accelerators

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

WHY do we need accelerators?

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



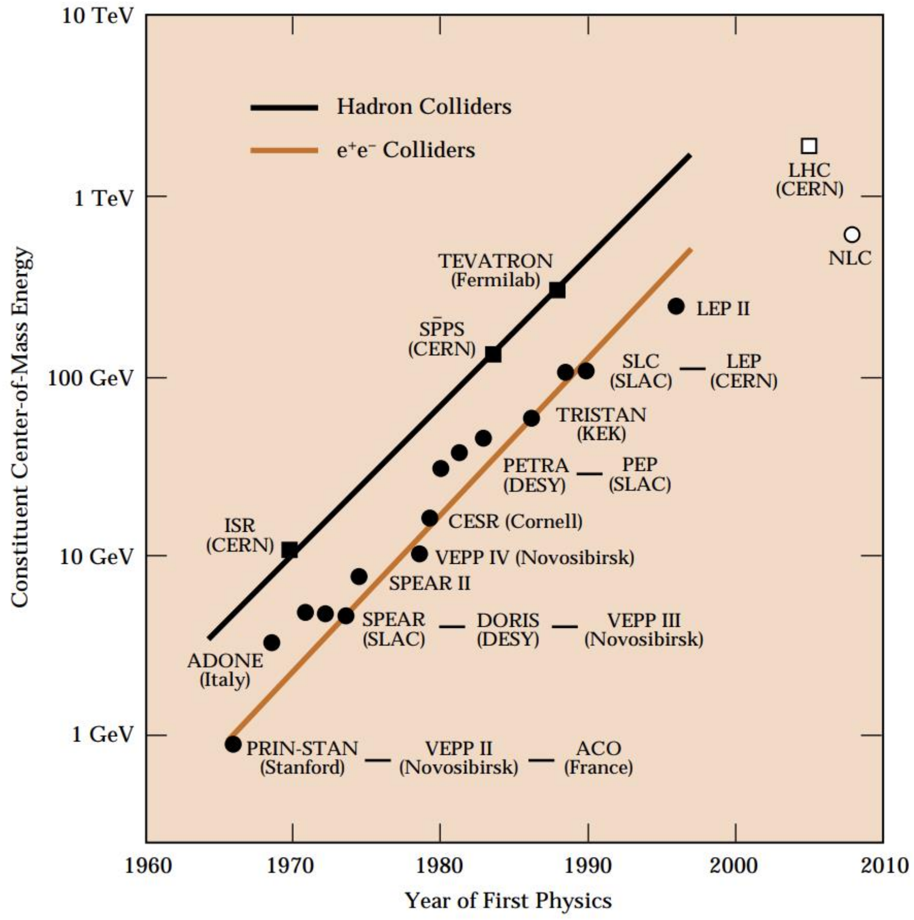
Technology drives discovery

- 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

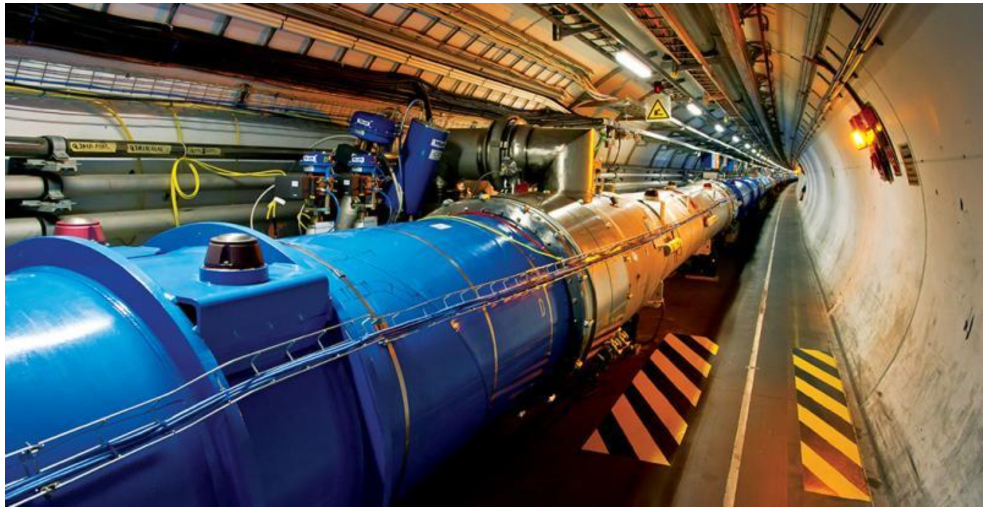
- Other important property: **luminosity**
  - Essentially, the interaction **rate** of the collider



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

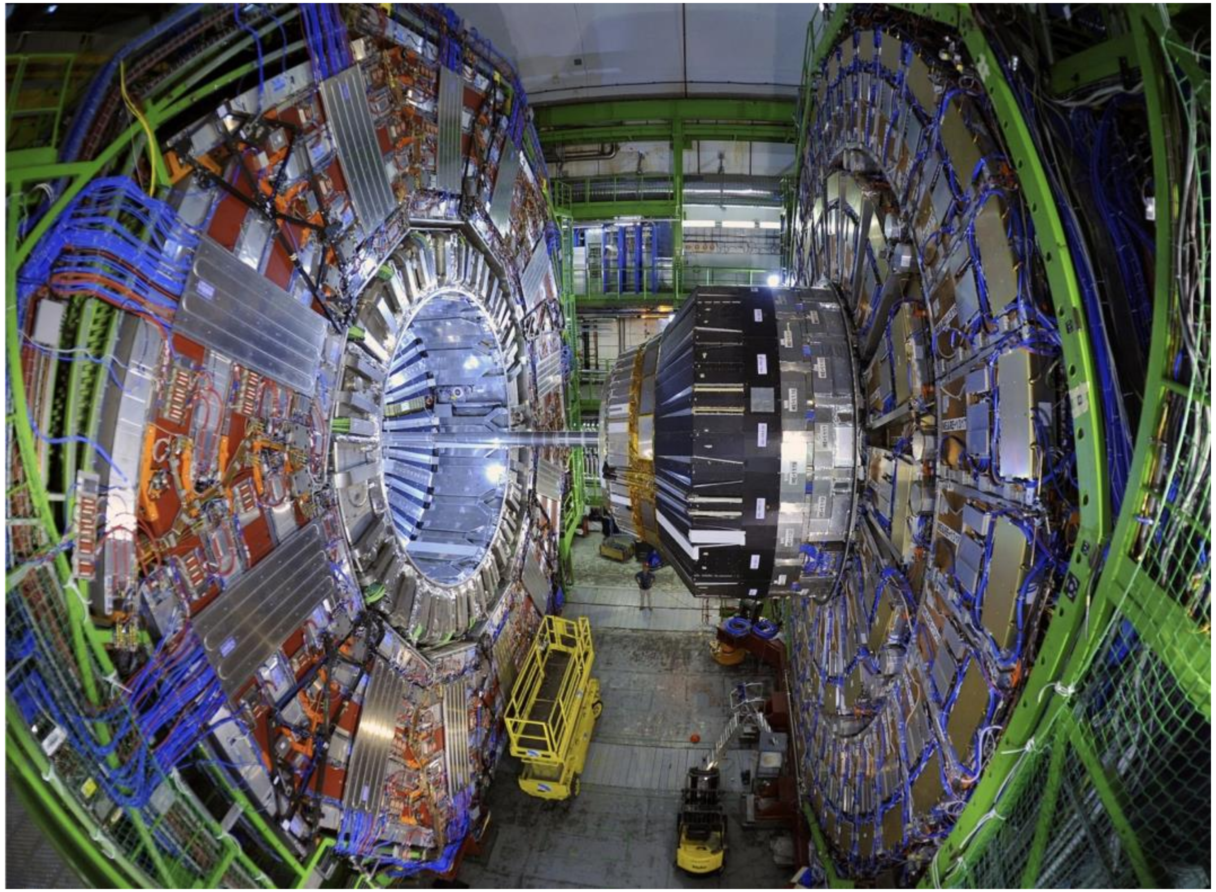
Large Hadron Collider

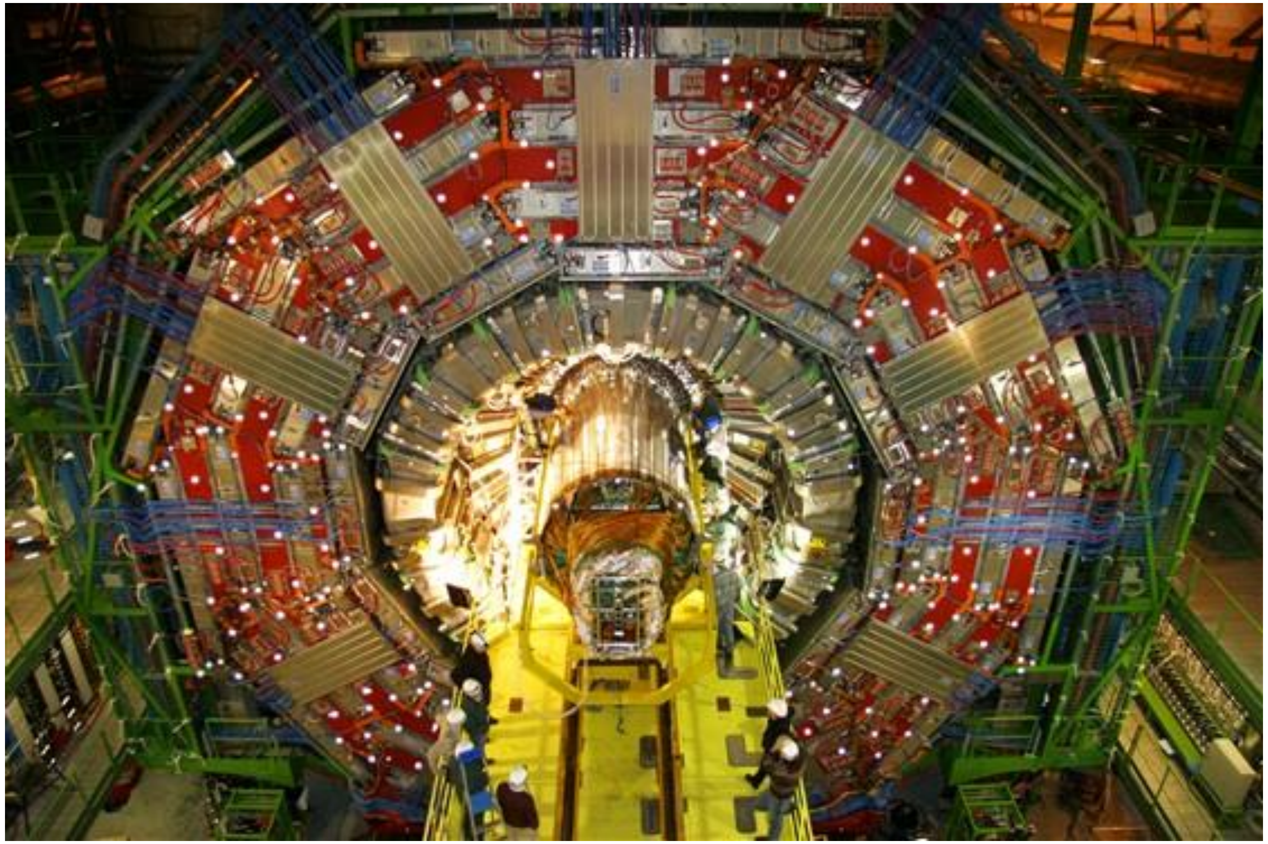
- Outside Geneva, Switzerland
- 17 miles in circumference
- World's largest and highest energy hadron collider
    - 13.6 TeV center of mass energy
    - Beats the previous record held by the Tevatron at Fermilab
    - 1232 dipole magnets at 8.3 T



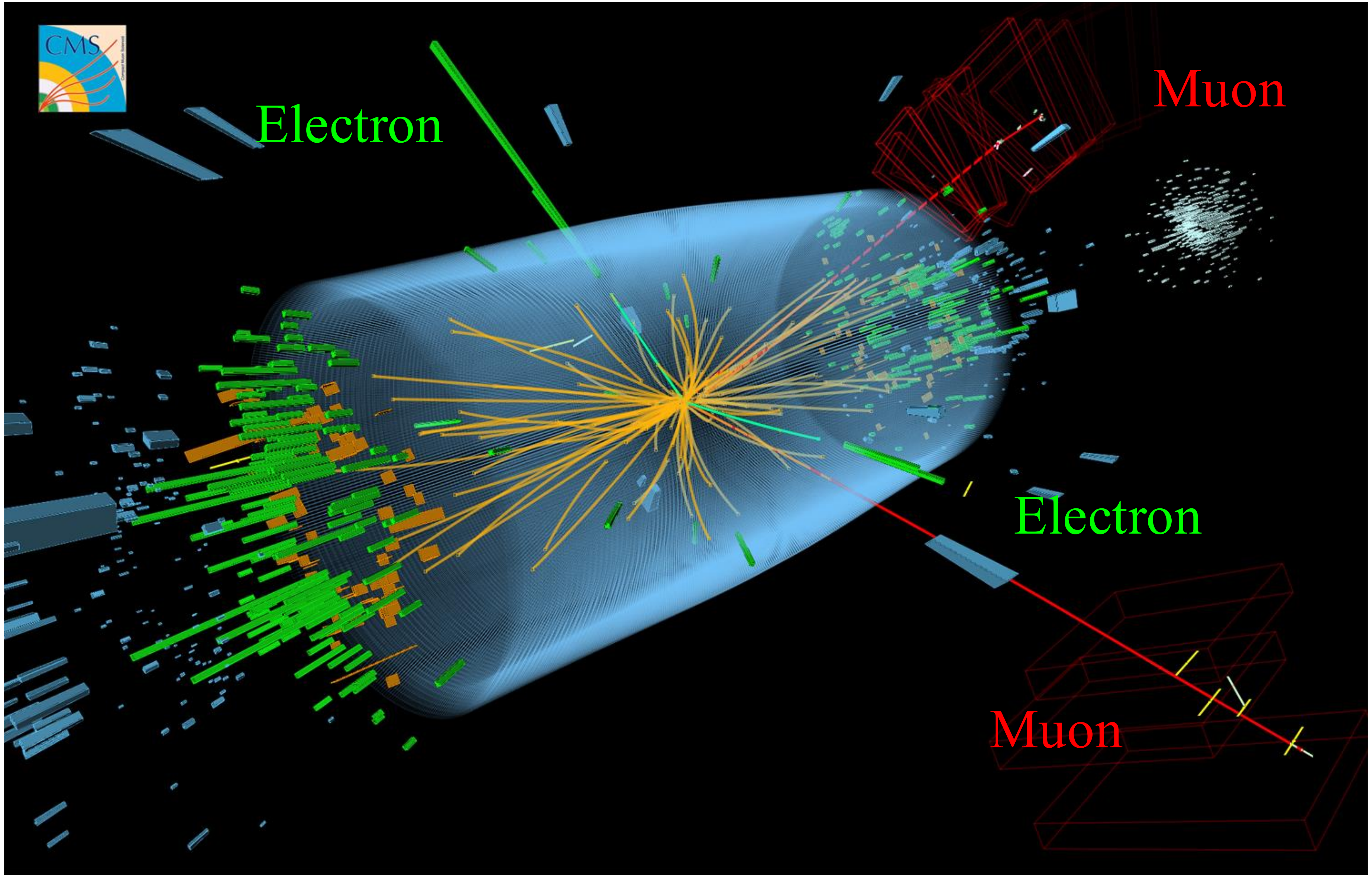
Compact Muon Solenoid

Takes pictures of collisions





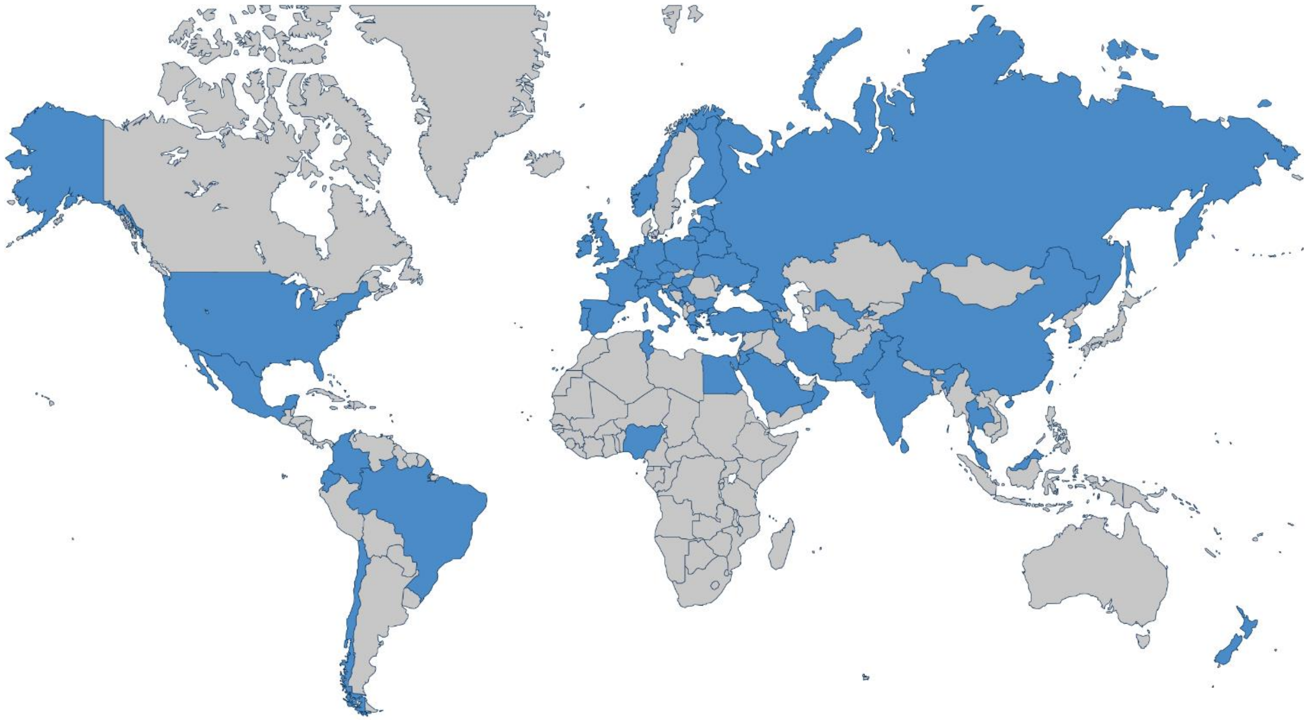
$H \to ZZ \to e^{+}e^{-}\ \mu^{+}\mu^{-}$ candidate event



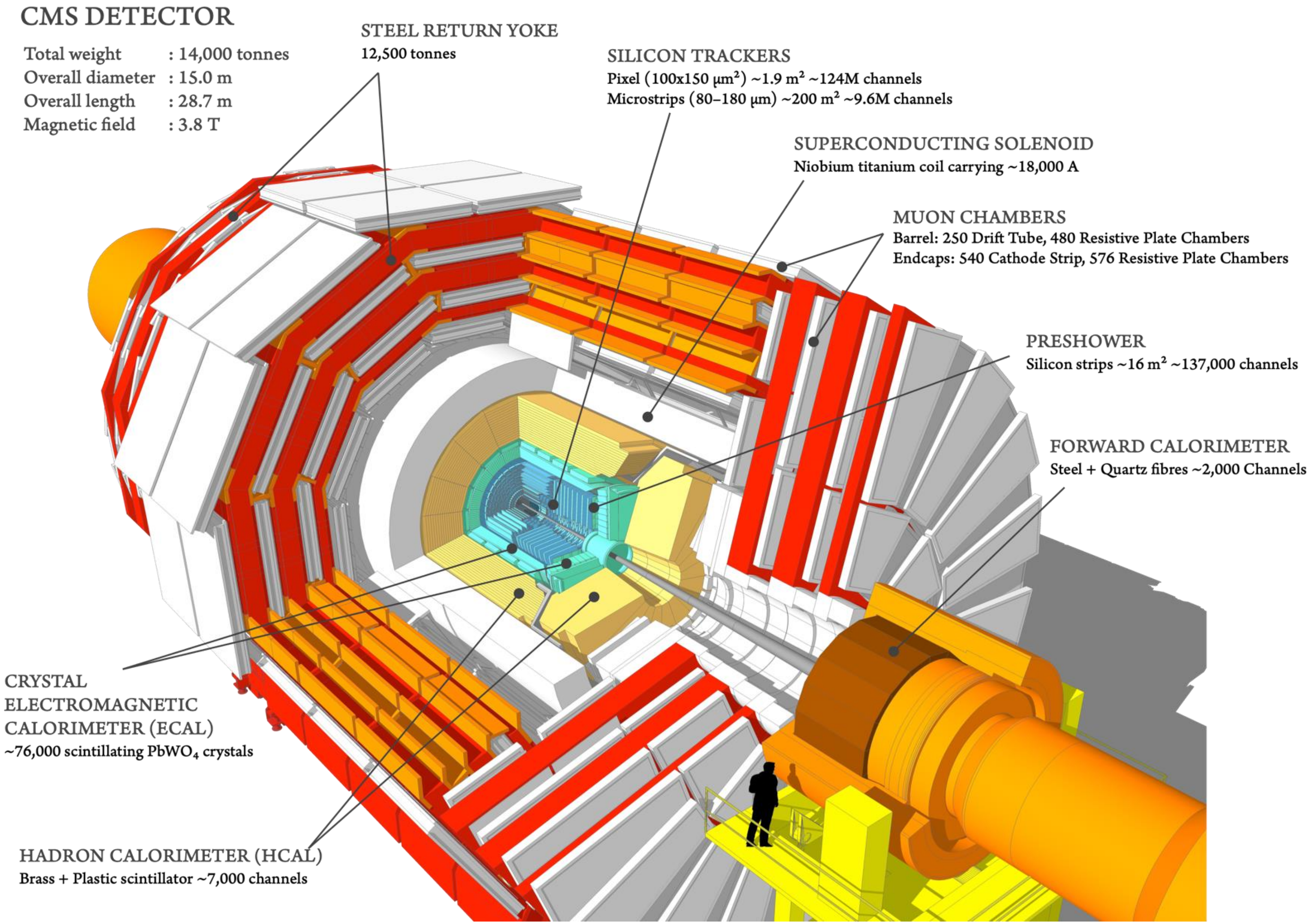
CMS Collaboration

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

3394	1102	282	247	57
PHYSICISTS (1228 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

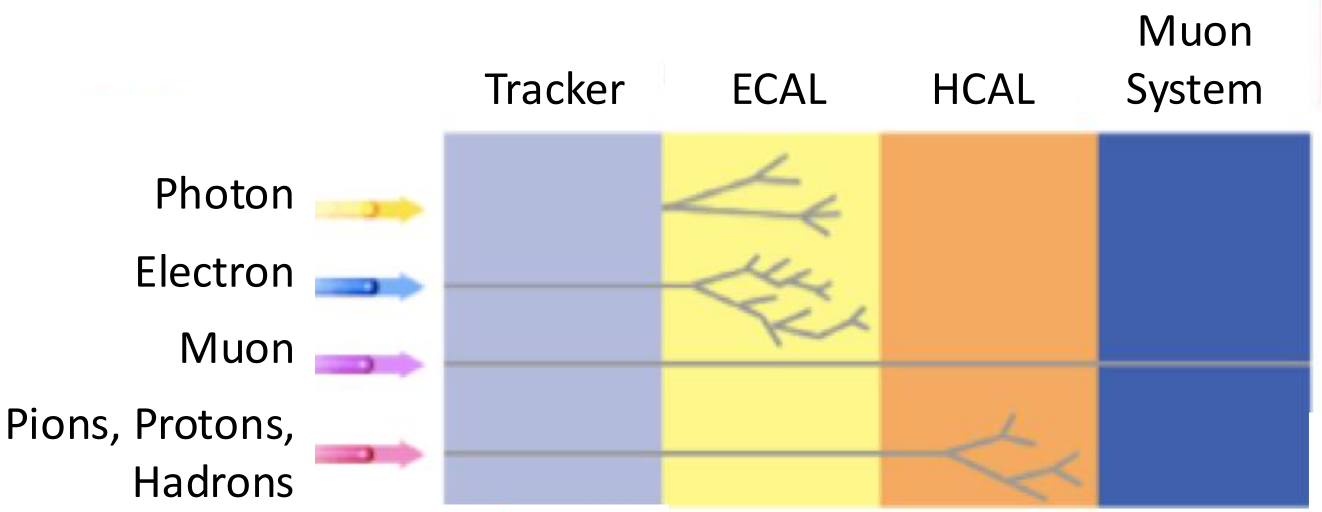


CMS Detector



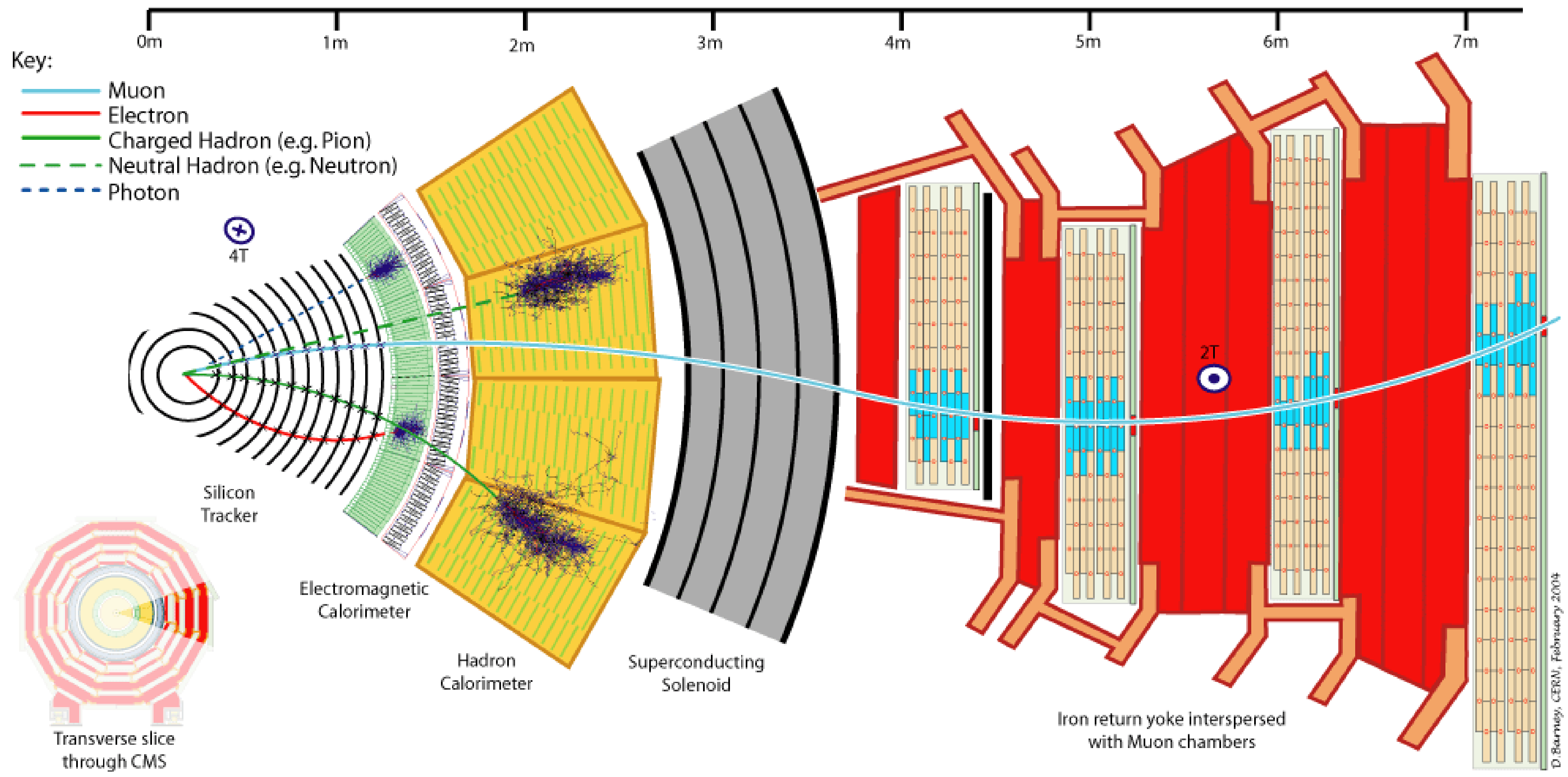
Particle Detection

- Different types of detectors for different particles



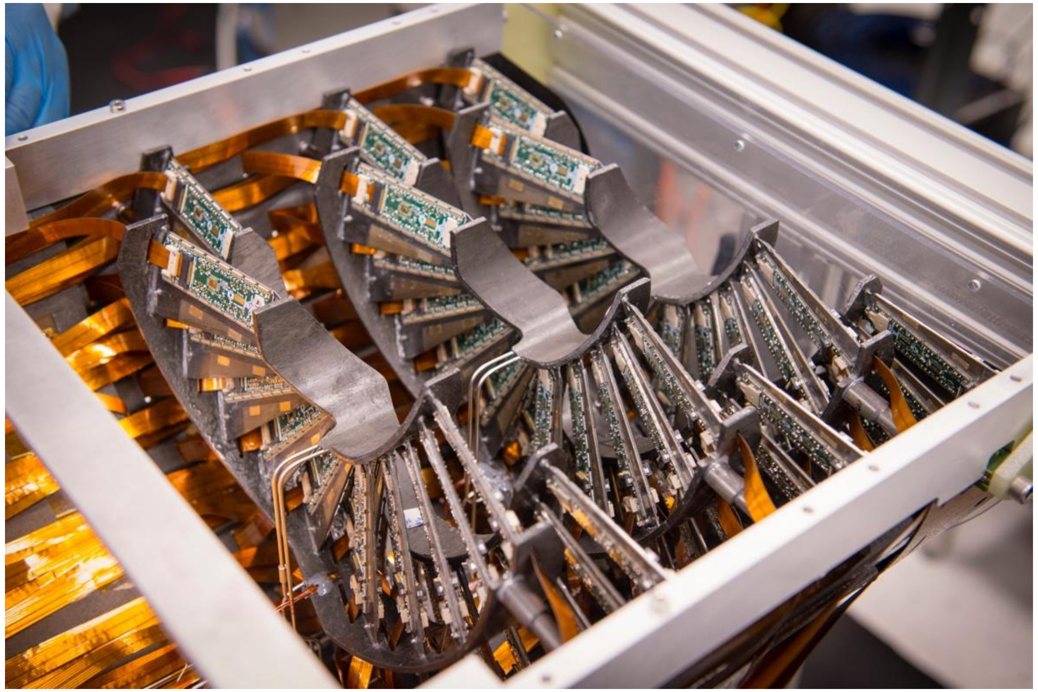
CMS Reconstruction

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

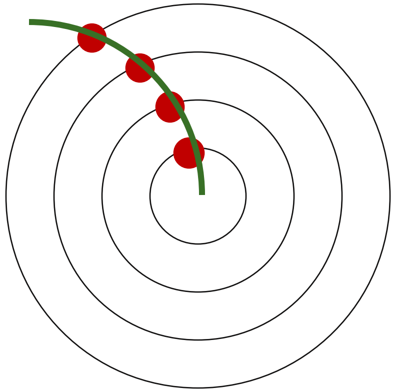


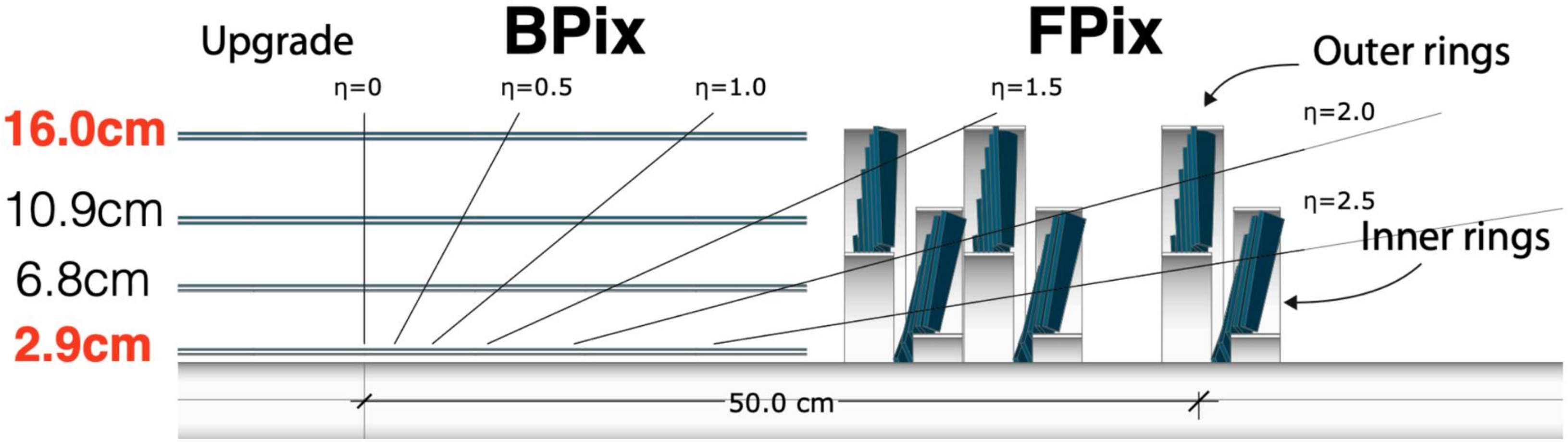
Silicon Tracker

- 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



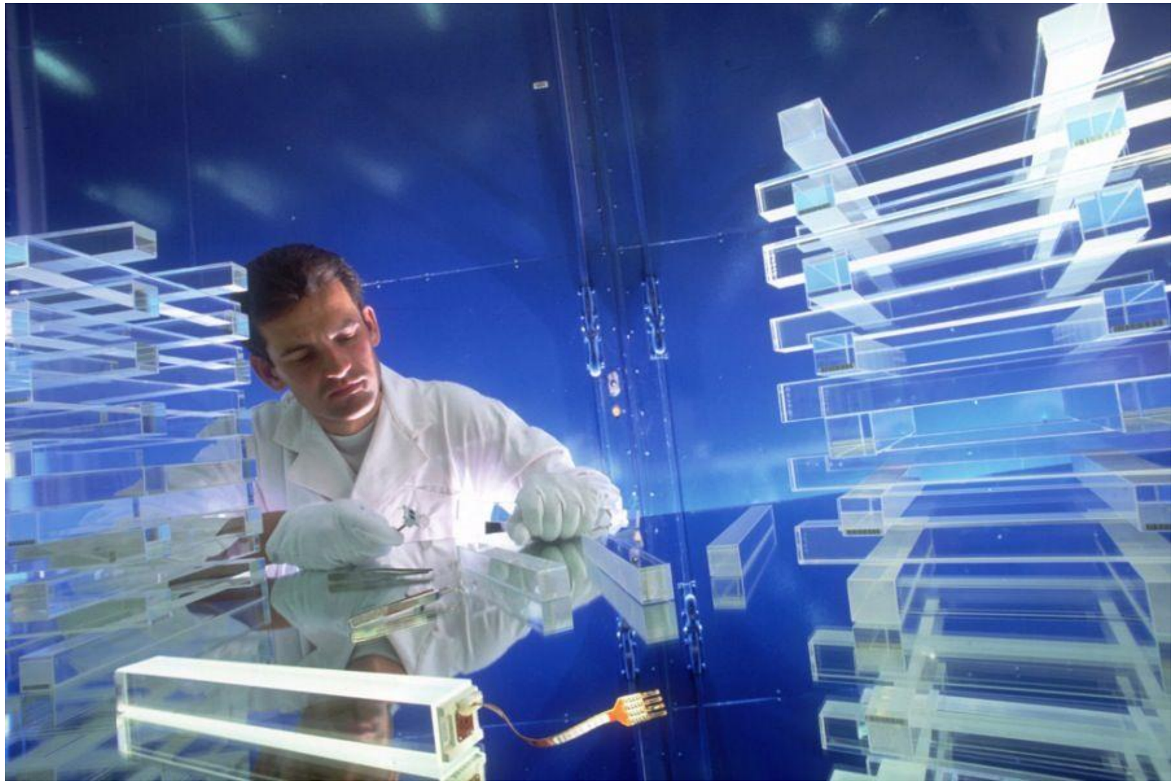
Half endcap disks for the upgraded CMS pixel detector, installed early 2017

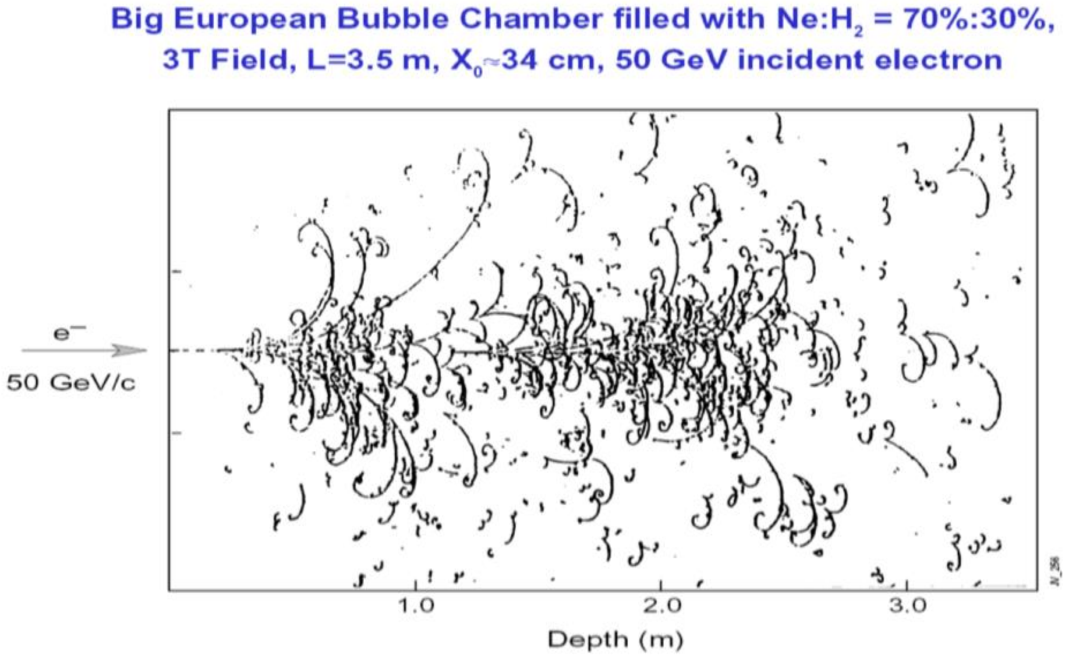




Electromagnetic Calorimeter

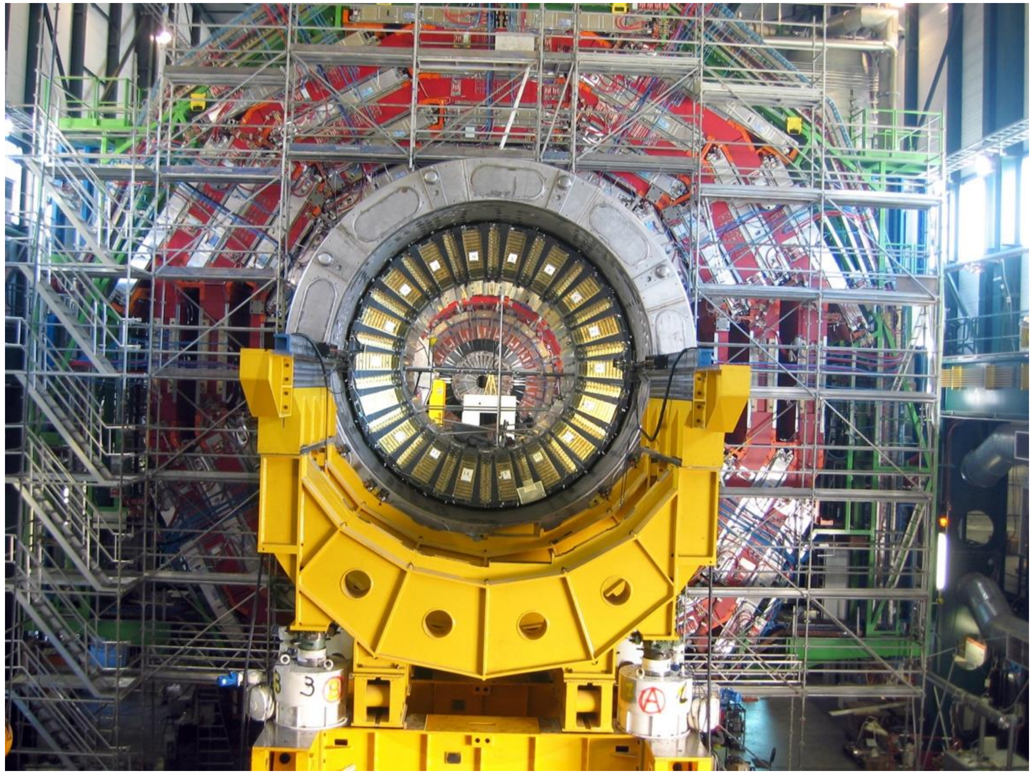
- 75,848 lead tungstate crystals in the barrel, each 2.2 x 2.2 x 23 cm
- Avalanche photodiodes used to detect the light from the scintillators
- Accurate measurement of electron and photon energies
    - Hadrons and muons pass through





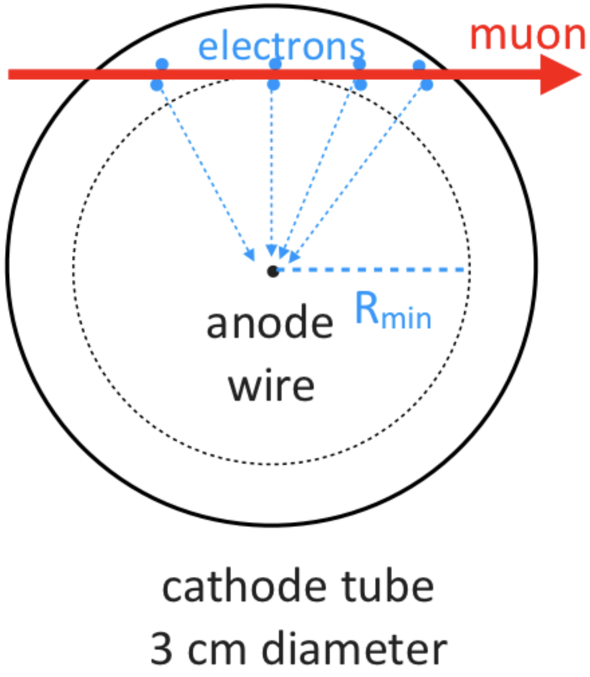
Hadronic Calorimeter

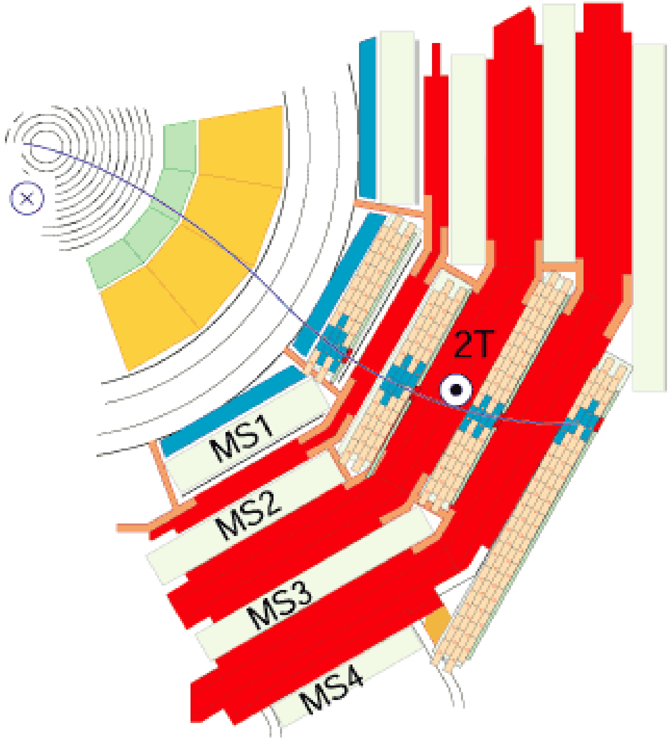
- 36 barrel wedges, each weighing 26 tons
- Repeating layers of steel and tiles of plastic scintillator
  - Steel forces the hadrons to interact and start "showering"
  - Shower energy measured ("sampled") by the scintillator



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)





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 (new in 2024!)

CMS Computing

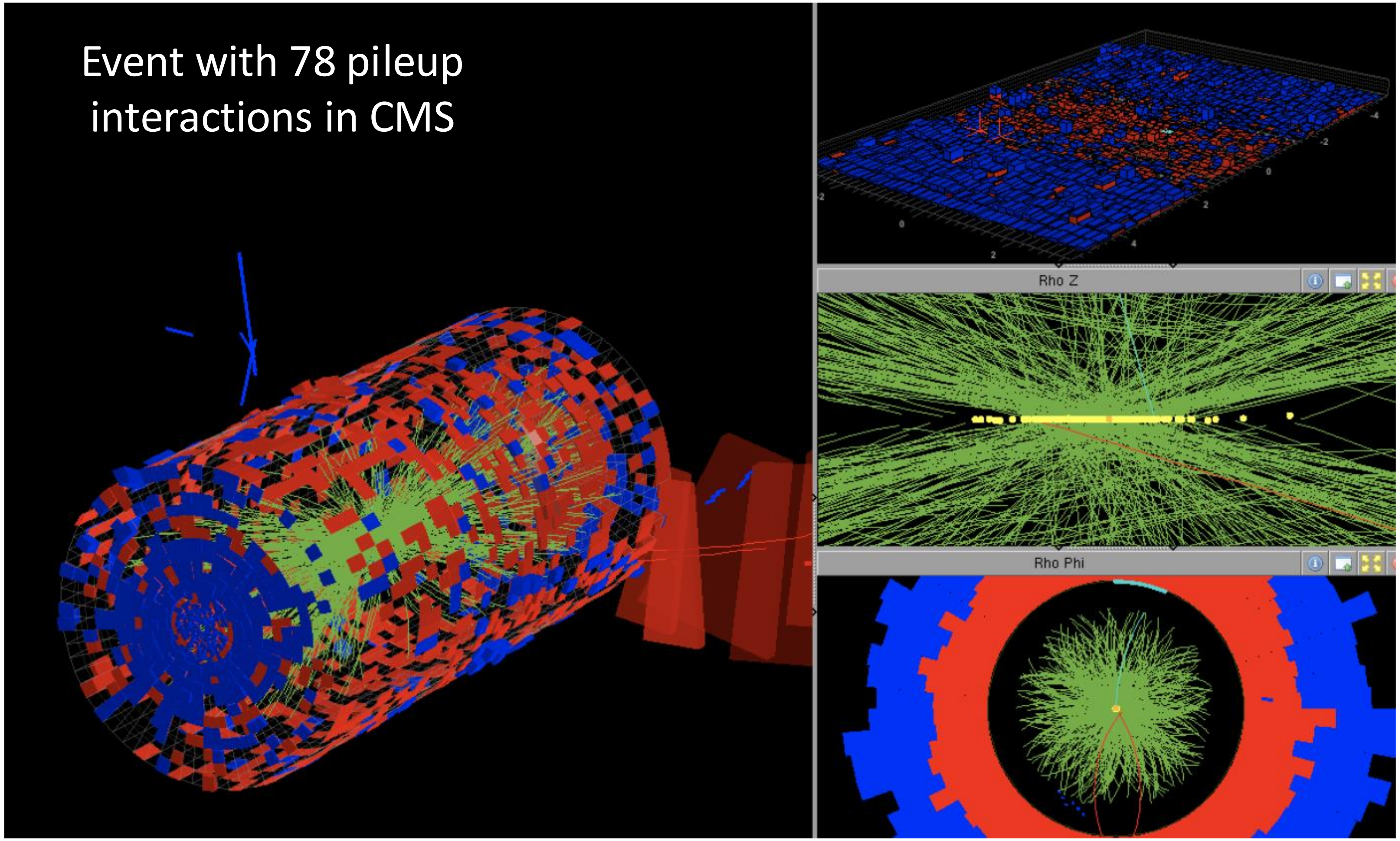
- Still ends up with lots (Petabytes, soon to be Exabytes) of data
- Stored and analyzed on “The Grid”, or the Worldwide LHC Computing Grid (WLCG) on computers from Lithuania to Nebraska, total 300k cores
- Many events: CMS needs to process **> 1 billion** events (simulated + real collisions) per month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

CMS Global Computing Grid

70+ sites, 200k+ CPU cores

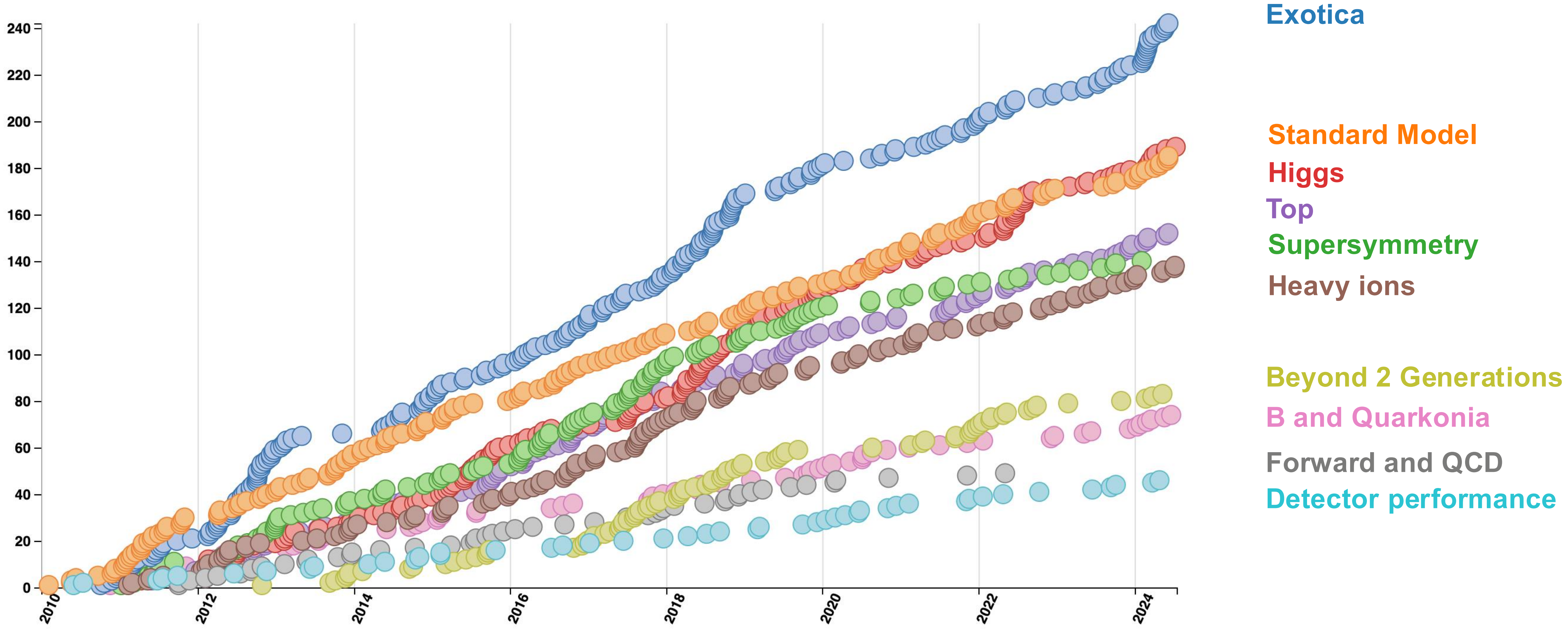
50 proton pileup

- Collide “bunches” of protons at a time
  - 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



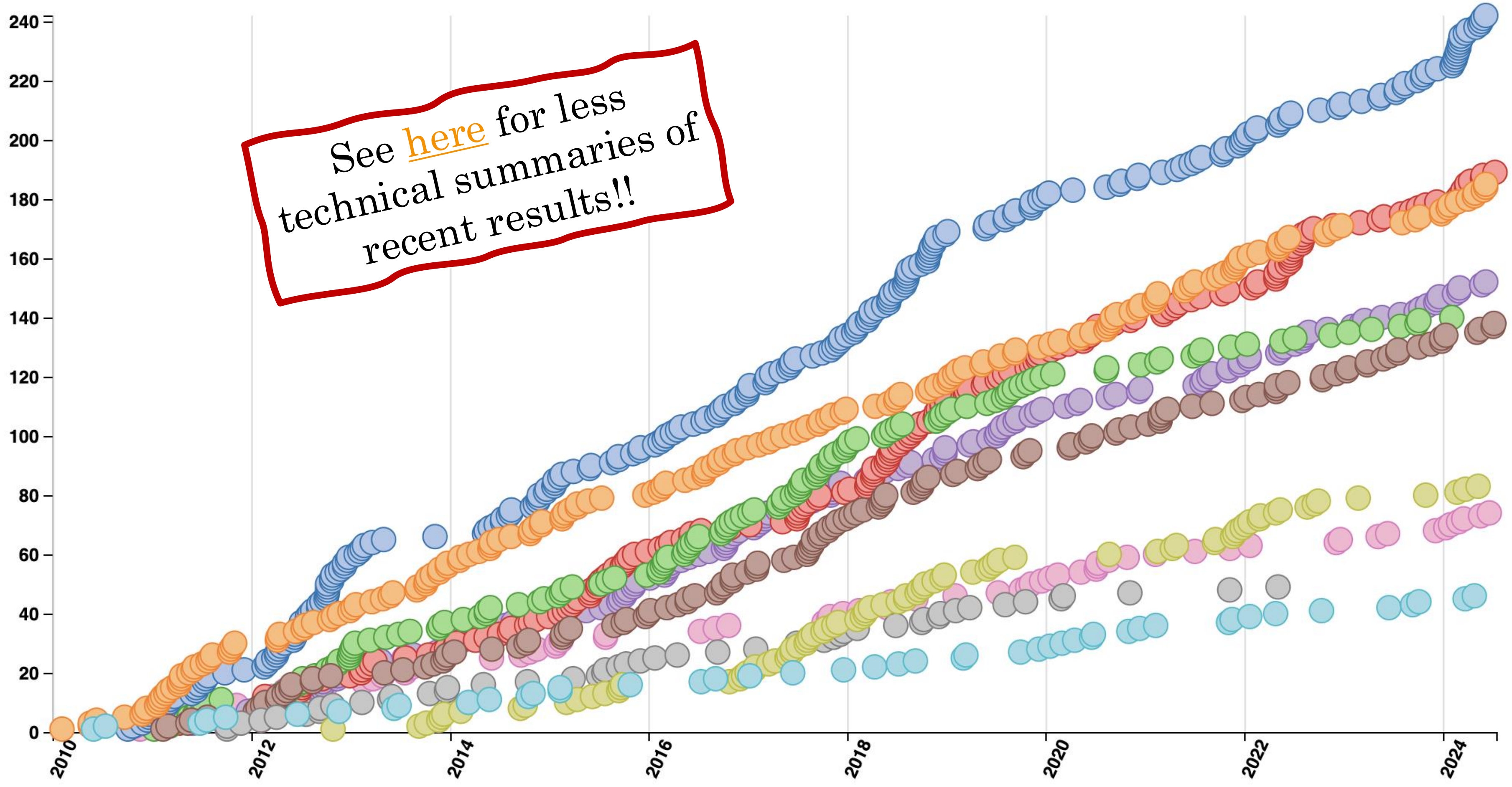
CMS publications over time

Over 1300 total



CMS publications over time

Over 1300 total



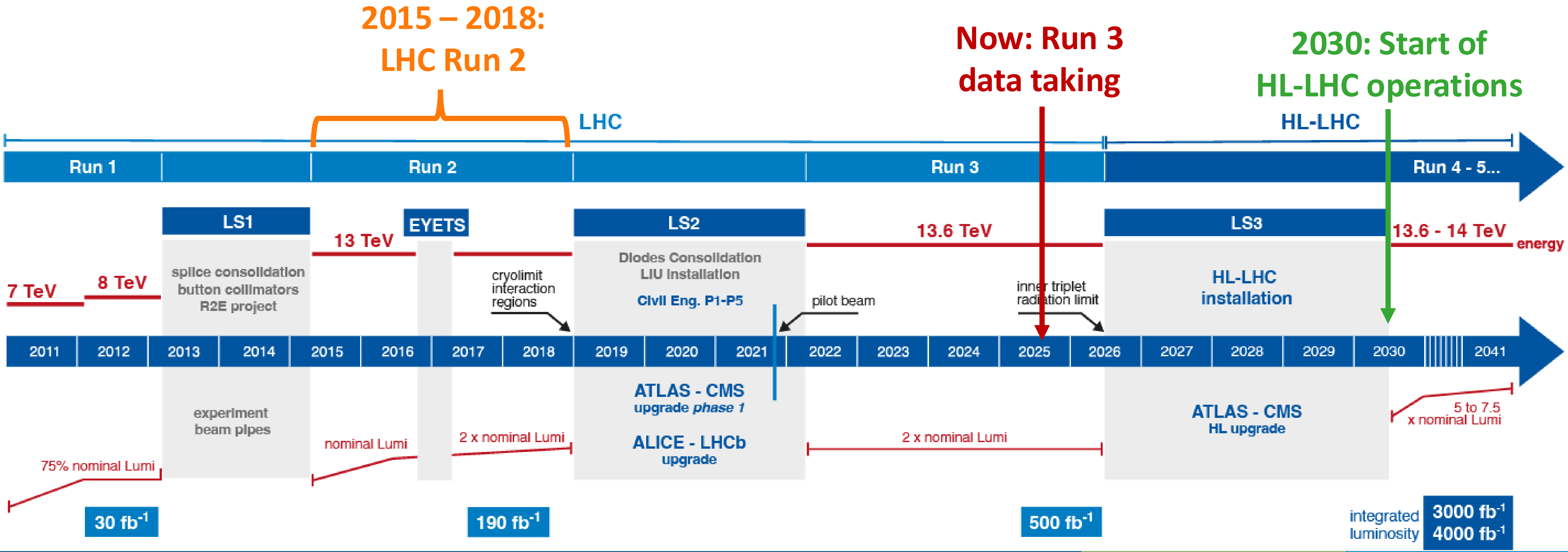
Exotica

Standard Model
Higgs
Top
Supersymmetry
Heavy ions

Beyond 2 Generations
B and Quarkonia
Forward and QCD
Detector performance

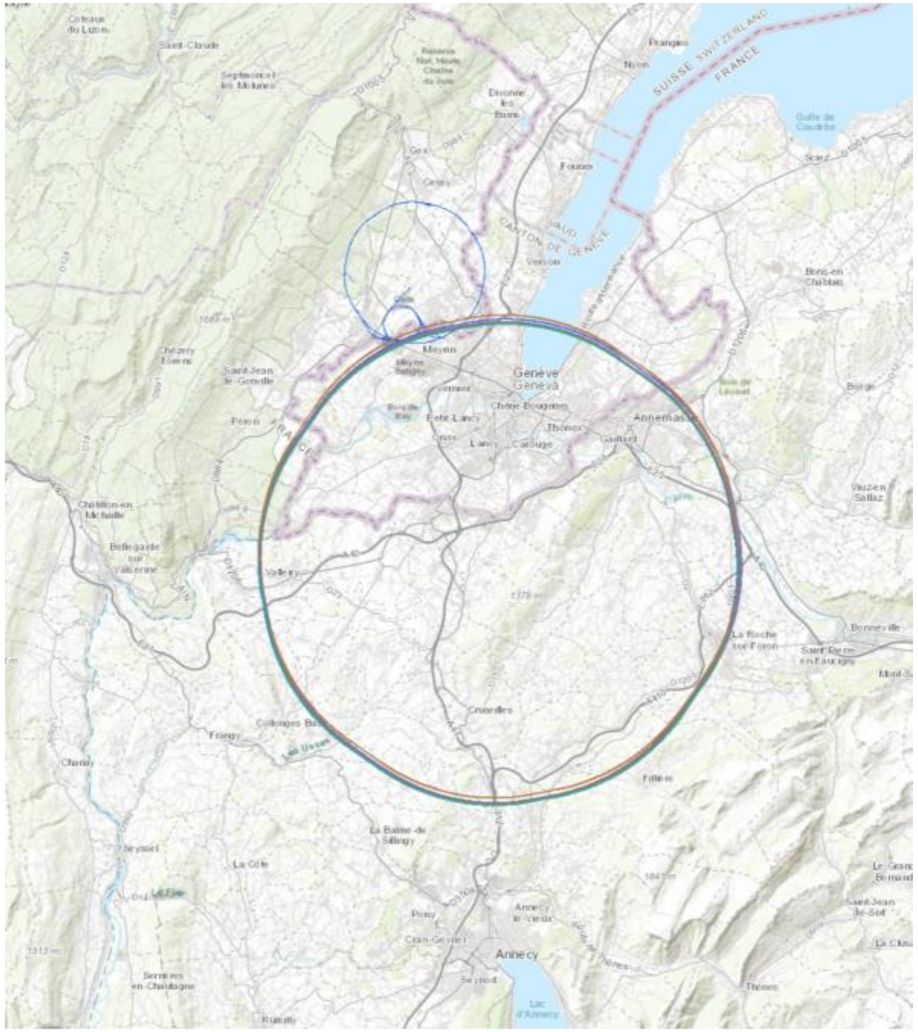
High-Luminosity LHC

- Integrated luminosity $\mathcal{L}$ is the amount of data (*pp* collisions) collected
- $\mathcal{L}$ = **500 fb^{-1}** in Run 3; 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 fb^{-1}**



Not done yet…

- Colliders such as the LHC are a powerful tool to probe the Standard Model and new physics
- Huge variety of physics searches performed using the CMS dataset
  - But lots of data still to collect and analyze
- By setting limits, we make important claims on what nature *isn't*
- It takes a village – lots of people with lots of different expertise
- Future colliders are being discussed now with even greater discovery potential

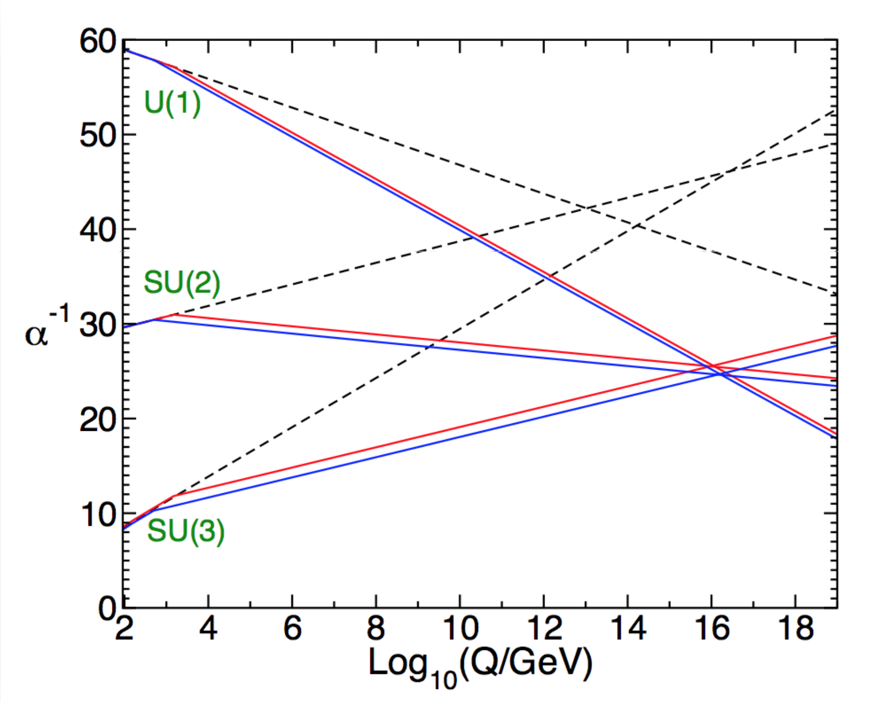


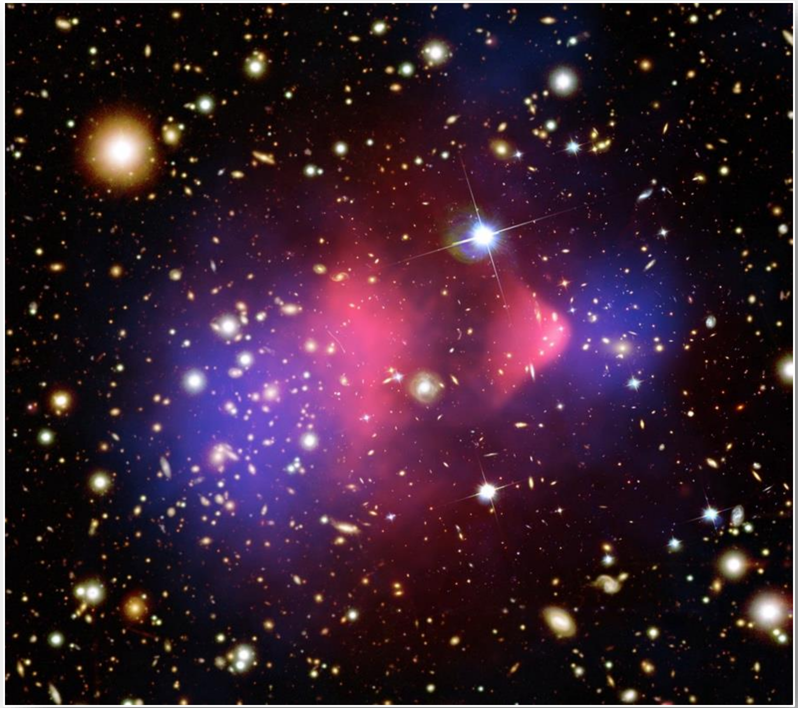
FCC-hh, proposed 100 TeV collider

Thank you!

Motivations for beyond SM physics

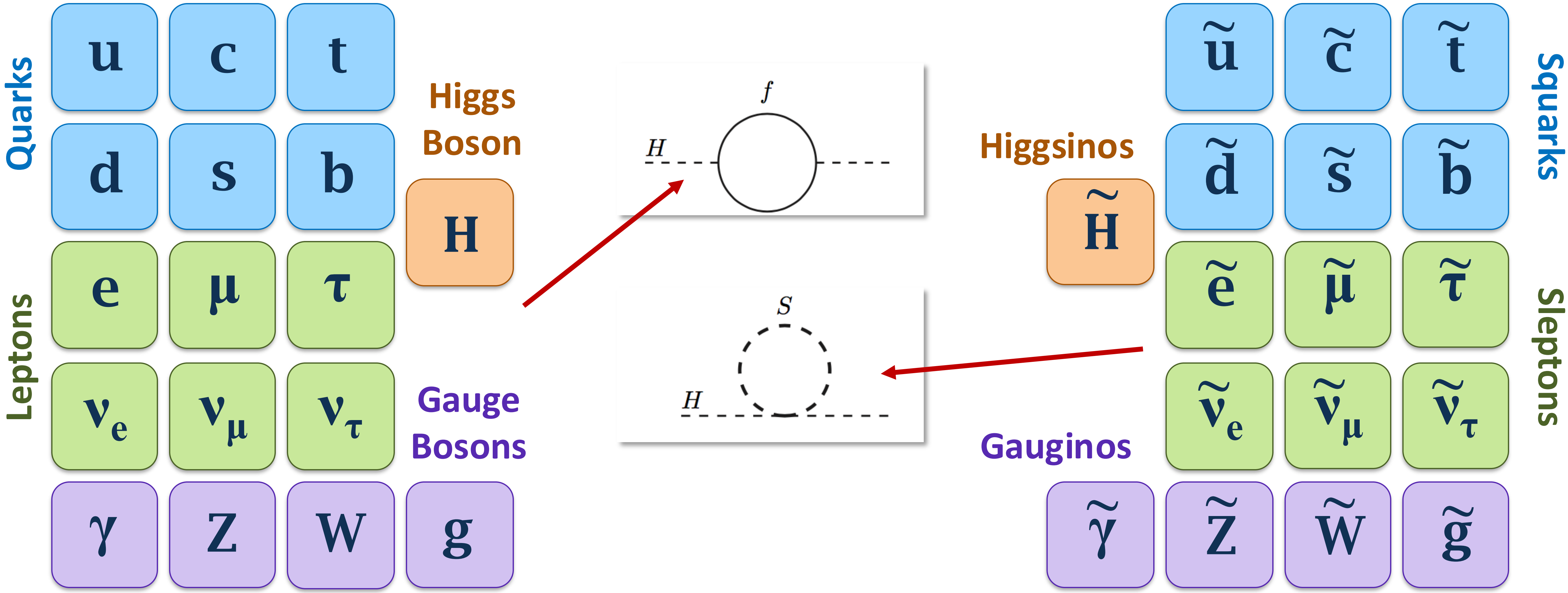
- Hierarchy problem: one example of "fine-tuning"
  - Two extremely large values in the theory must cancel each other almost exactly
- Grand Unification theories
  - Maybe at high energies all the forces are unified into one
- Dark matter: what type of particle (if any) is it?





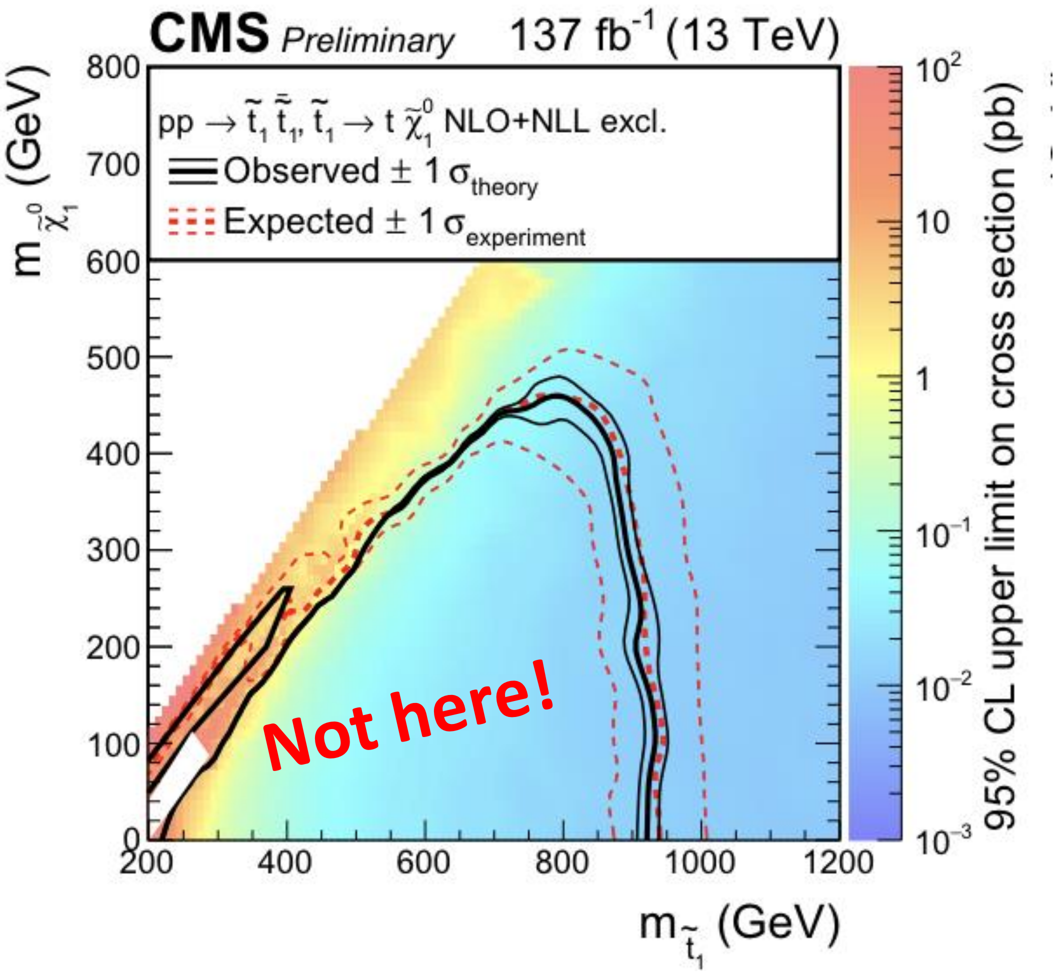
Supersymmetry (SUSY)

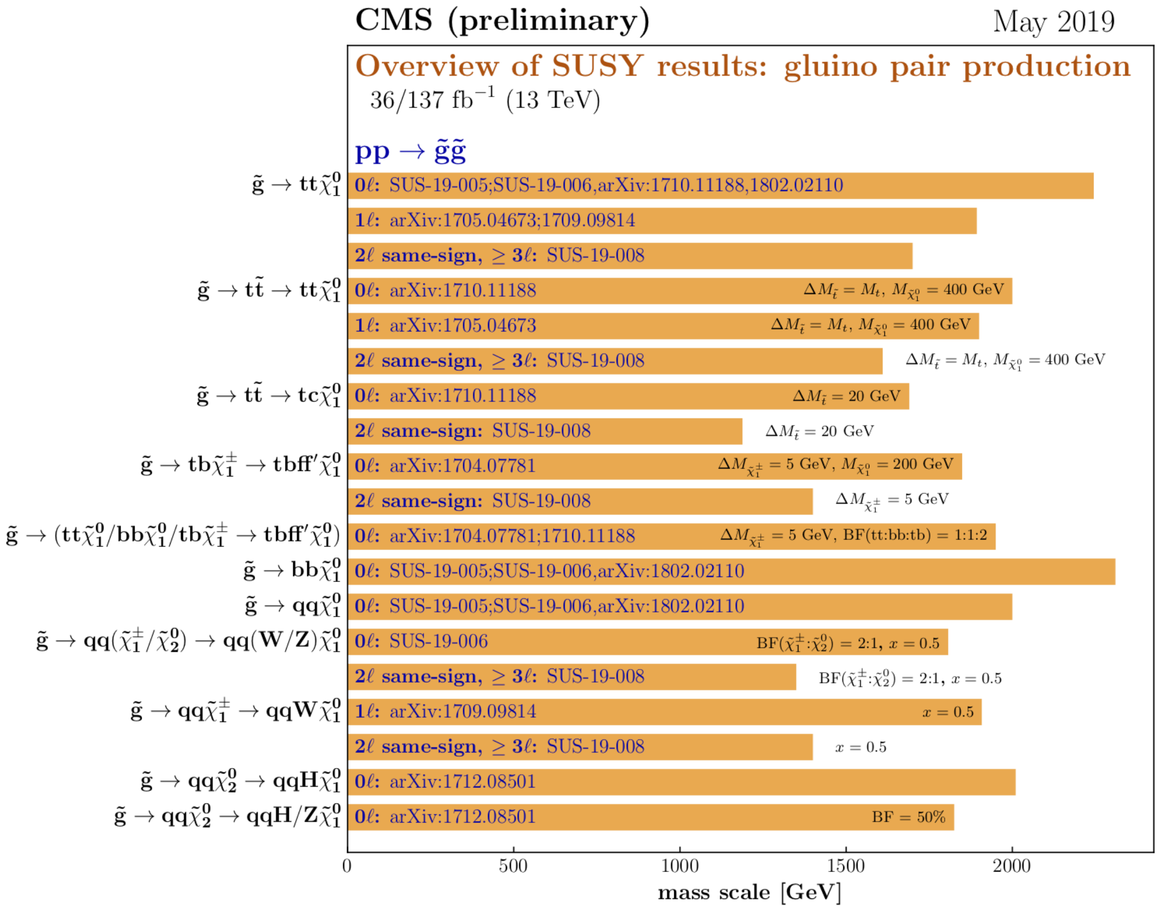
- Doubles the number of elementary particles, but solves many issues with the SM
- For each fermion, there is a superpartner boson and vice versa (symmetry!)



Supersymmetry limits

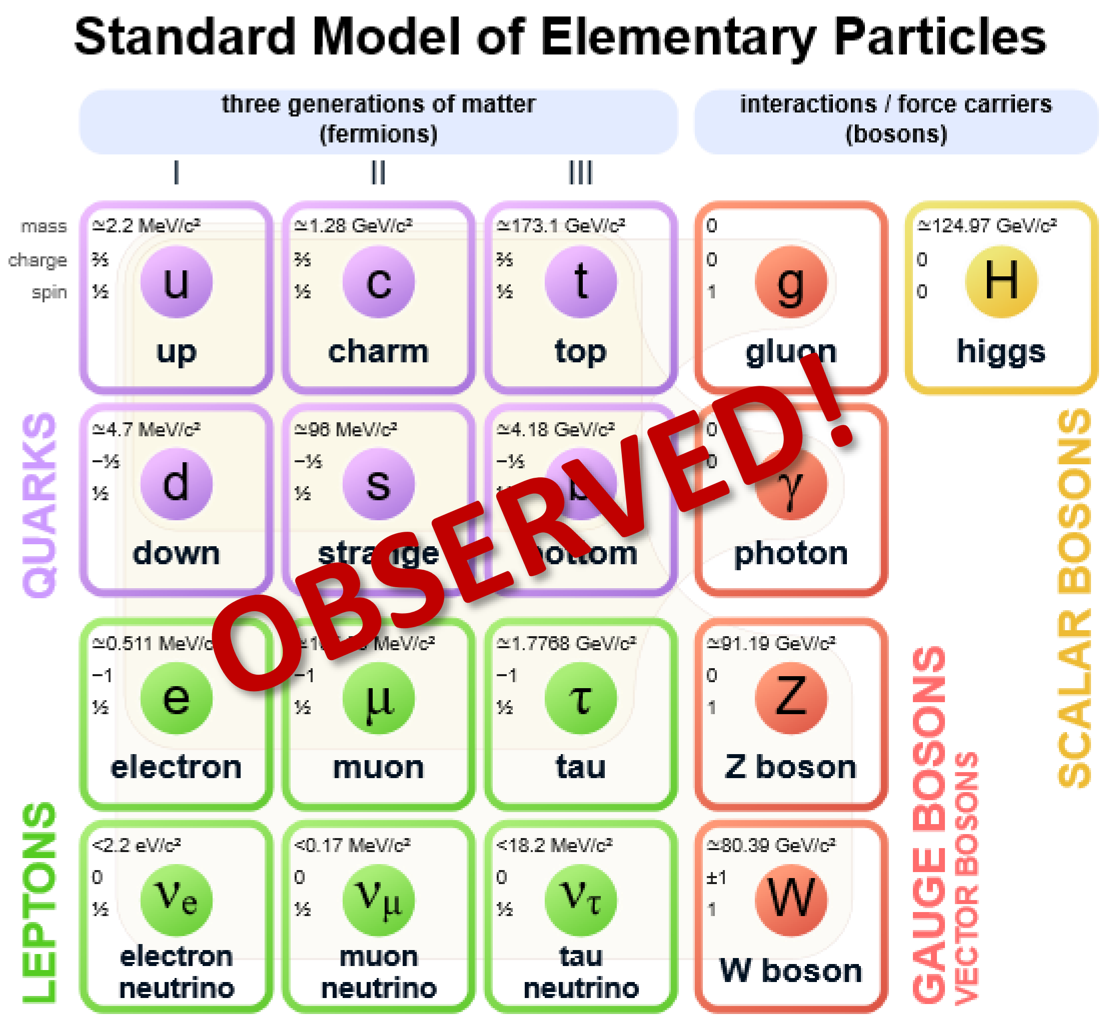
- Recall what Feynman said: “if it disagrees with experiment it is wrong”
- Limit setting (ie, looking for “nothing”) forces us to develop new ideas





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.

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

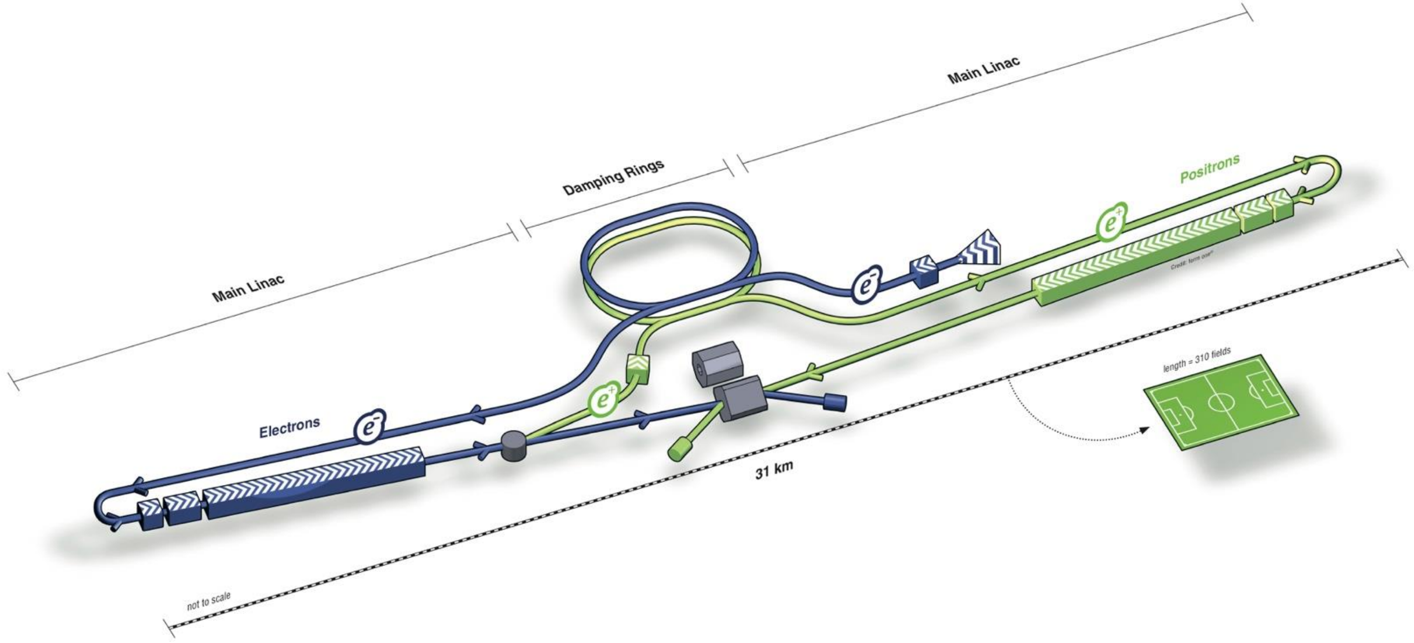
Colliders – a biased list

- 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?	?	???

Future electron-positron colliders

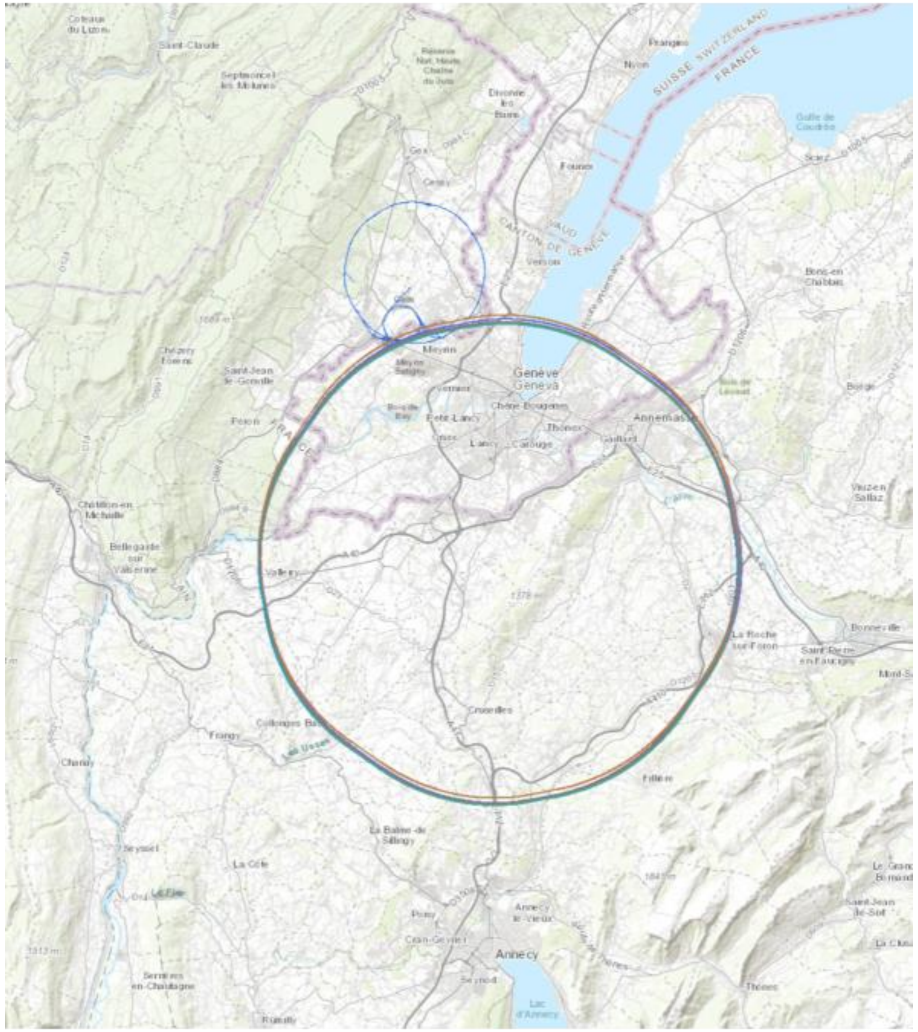
- FCC-ee: Future Circular Collider
  - 100 GeV – 360 GeV, 91 km, hosted at CERN
- ILC: International Linear Collider,
  - 500 GeV – 1 TeV, 30 – 50 km, hosted by Japan
- CEPC: Circular Electron Positron Collider
  - 240 GeV, 55 km, can be upgraded to 70 TeV pp collider, hosted by China



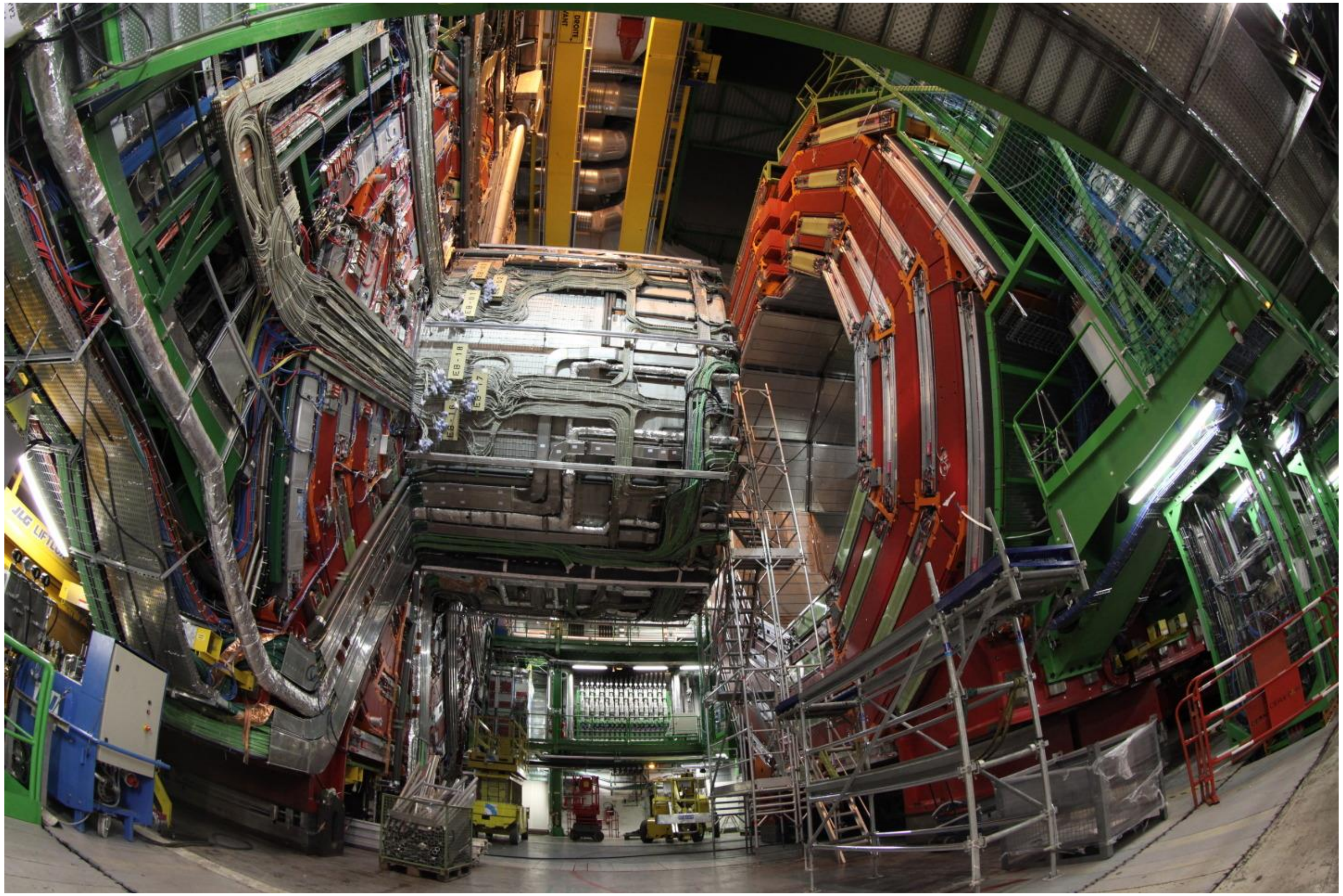
Future hadron collider: FCC-hh

- FCC-hh: hosted by CERN
  - Use the same 91 km tunnel as FCC-ee
  - Reach center-of-mass energy of **100 TeV**
    - Compared to current 13.6 TeV of LHC
- Timeline:
  - FCC-ee runs for 15 years, starting in mid 2040s
  - FCC-hh runs for 25 years, starting in early 2070s

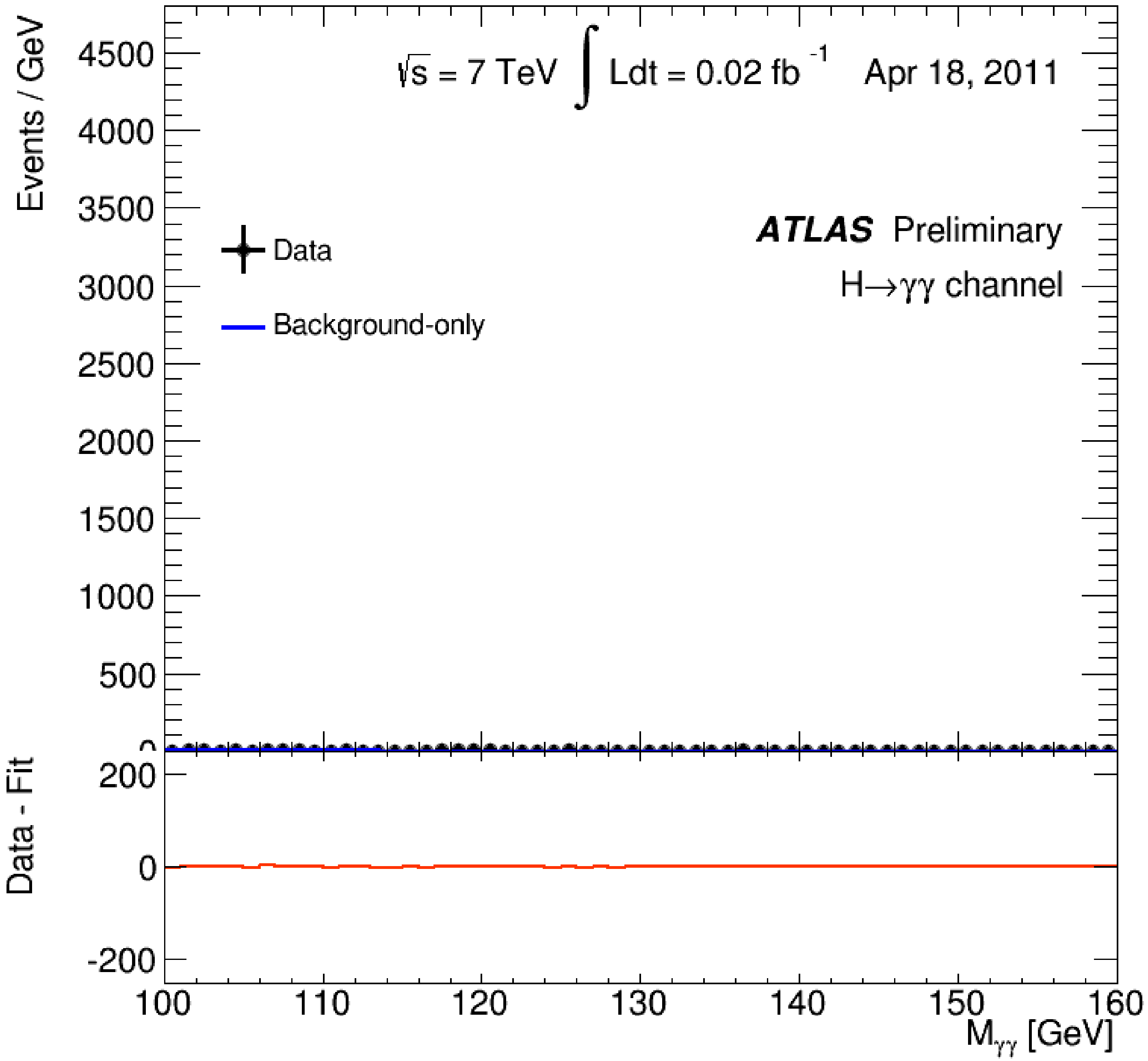
- Context: LHC was first proposed in 1984, first data taken in 2010, and HL-LHC will run until 2040



CMS Magnet

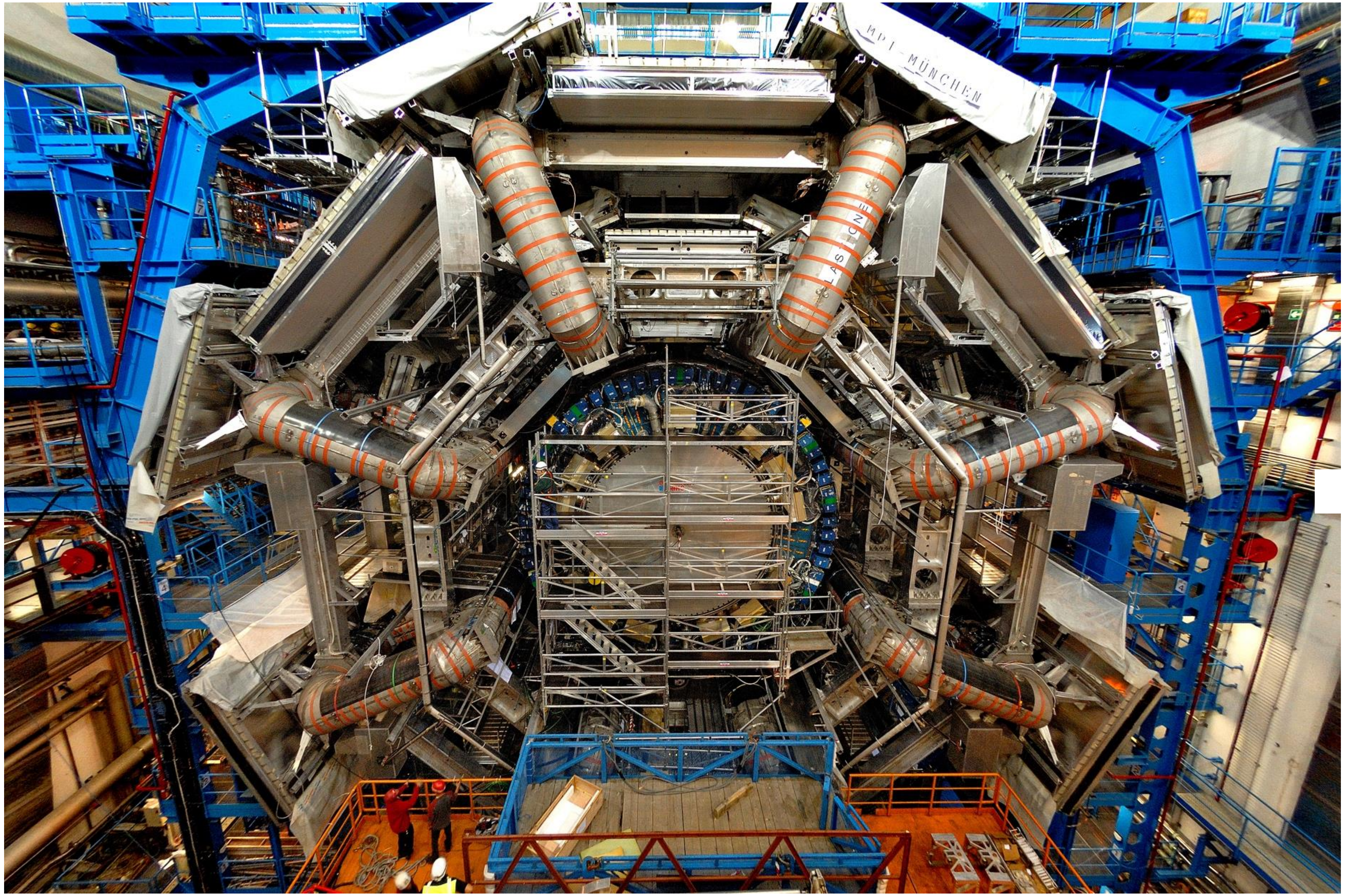


3.8 T superconducting solenoid magnet, cooled using liquid helium



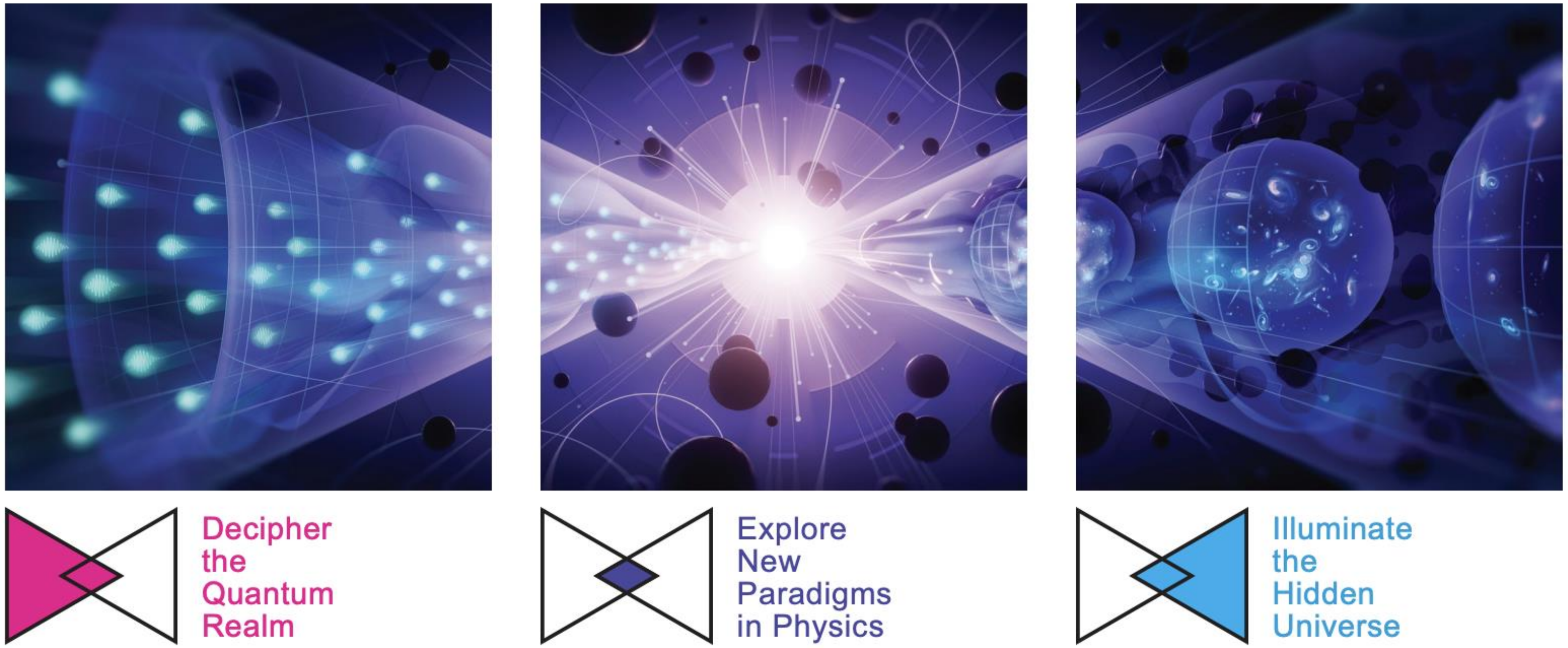
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

The ATLAS Detector @ the LHC



Snowmass and P5: deciding what’s next

- Community exercise to



Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

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!