Search for Supersymmetry at CMS

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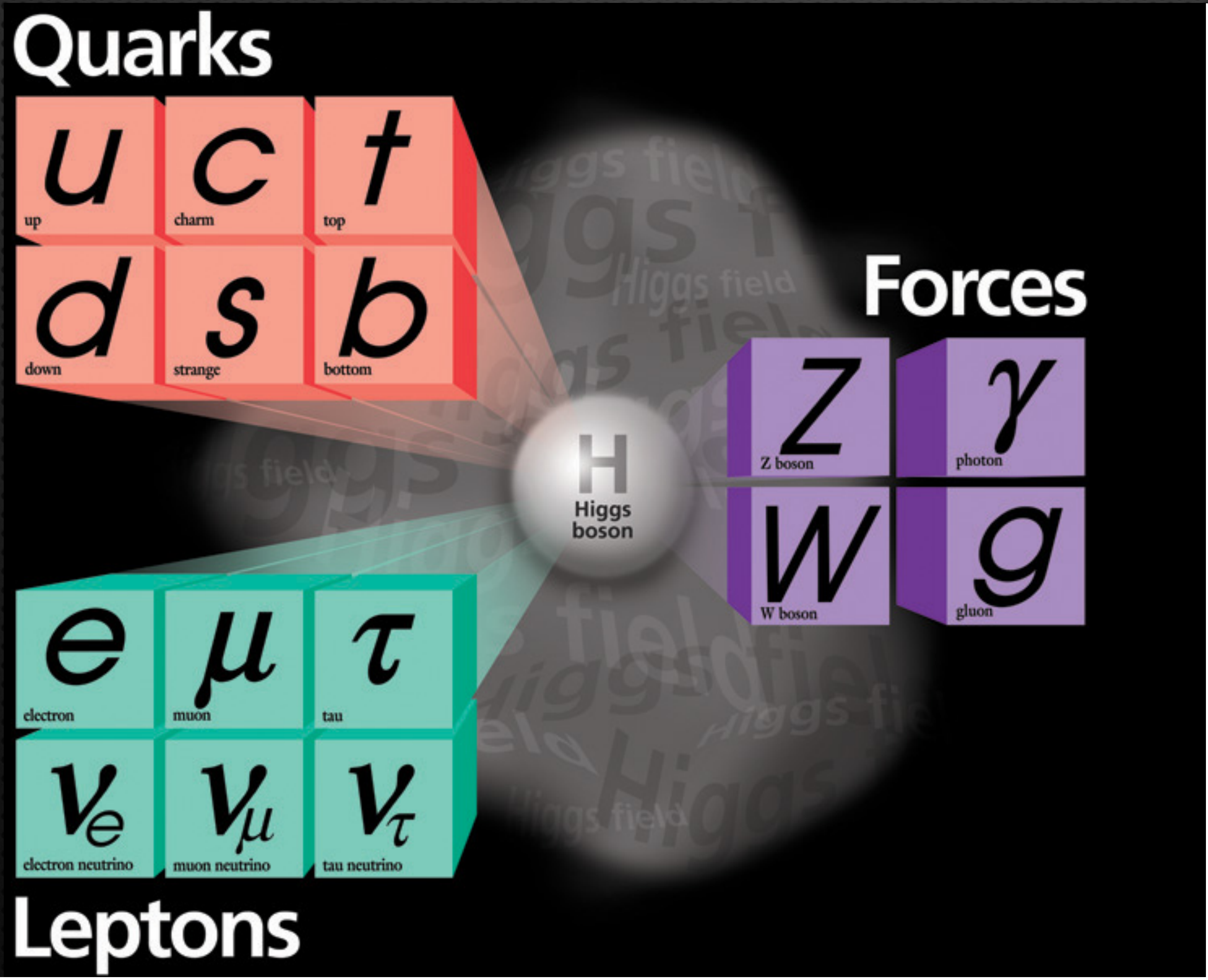
The Standard Model of particle physics (SM)

With the announcement of the Higgs boson discovery on July 4, 2012, all Standard Model particles have been observed.



But still lots of questions…

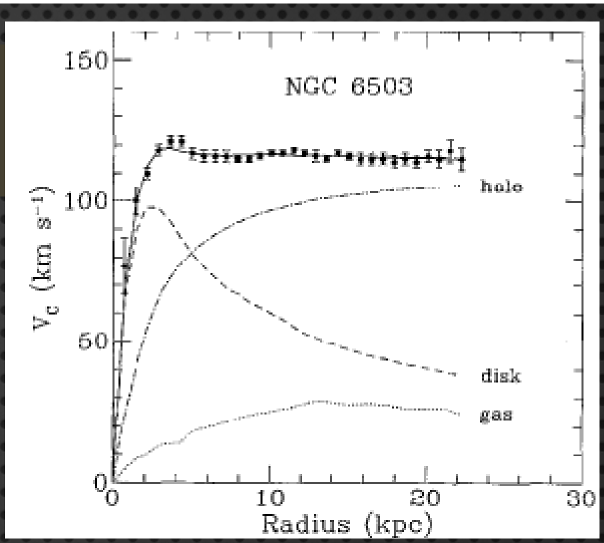
- How come the Higgs boson mass is so light?
- What is the source of dark matter?
- Is there a Grand Unified Theory?
- What is the nature of dark energy?
- What happened to all the antimatter in the universe?
- Why are there 3 generations of quarks and leptons?
- How do neutrinos get their mass?
- Are neutrinos Dirac or Majorana particles?
- What is the quantum theory of gravity?

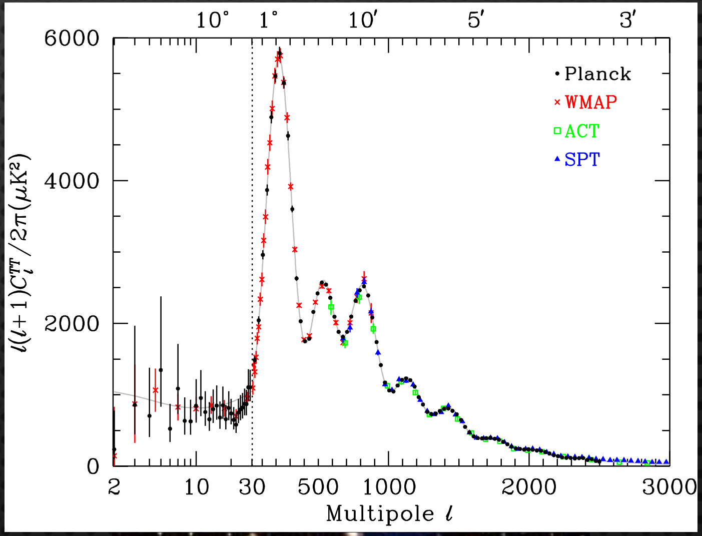
Why is the Higgs boson so light?

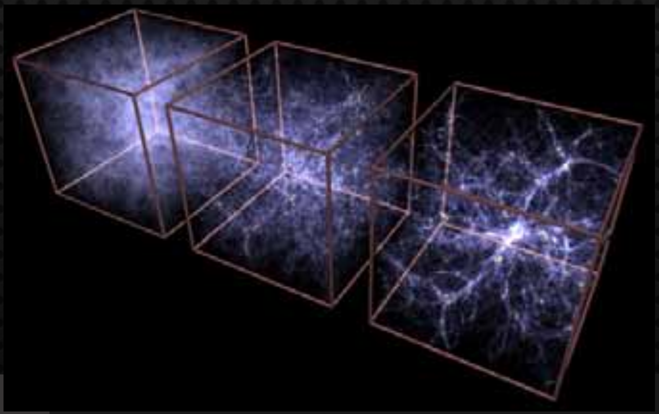
- The SM is known to work up to an energy of ~1 TeV.
- It is expected to break down before the Planck scale (10^{16} TeV) where quantum gravity should appear.
- So the SM cutoff scale, labeled Λ, should be $<10^{16}$ TeV
- Calculations of the Higgs mass in the SM contain quantum corrections that should result in a mass near Λ. So it is strange to find it at 0.1 TeV.
- Solutions to the hierarchy problem:
  - The SM is only valid to ~1 TeV and there is a new theory above ~1 TeV.
  - There is a fine tuning of the quantum corrections at the level of 1 part in 10^{16} (actually 1 part in 10^{32} since they are quadratic).

Evidence for dark matter

- Galactic rotation curves indicate invisible matter in a spherical halo.
- Cosmic microwave background finds more than normal matter.
- Gravitational lensing of Bullet Cluster shows dark matter behaves differently than ordinary matter.
- Large scale structure of the universe only makes sense with dark matter.





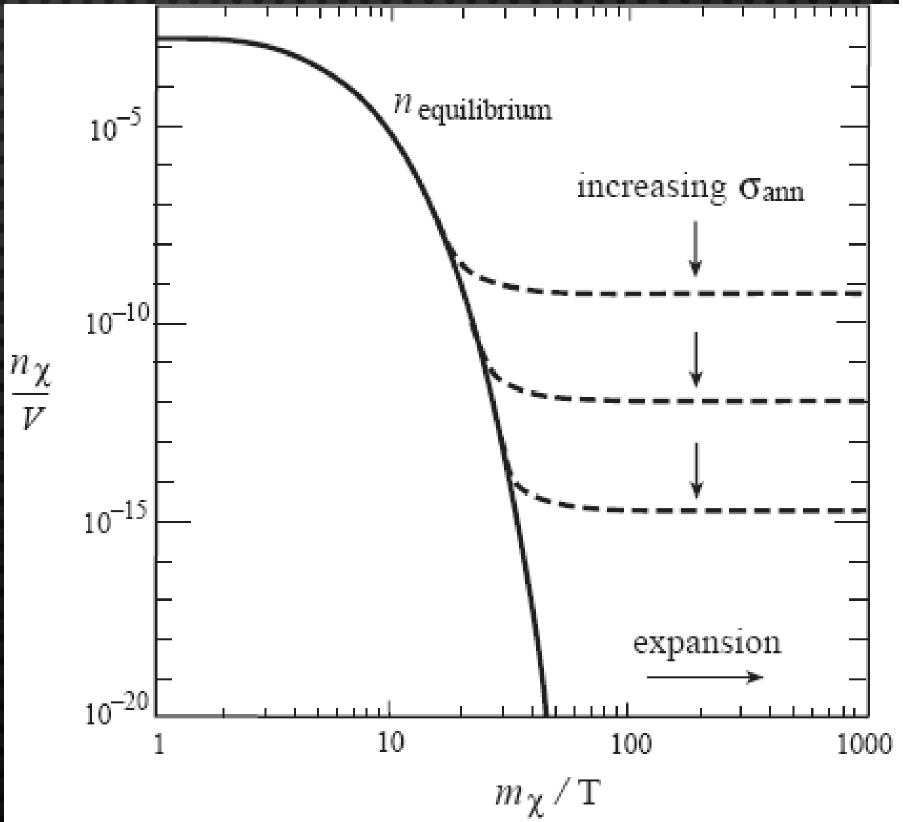


Some dark matter possibilities

- **Primordial black holes** – Created during the big bang before protons are created.
- **Axions** – Light particles with very little interaction with normal matter; Proposed to explain lack of CP violation in the strong interaction.
- **Sterile neutrinos** – Masses around keV but not coupling to the Z or other neutrinos.
- **Weakly Interacting Massive Particles (WIMPs)**
  - Interact via weak interaction (and gravity) only
  - Should have mass ~0.1–1 TeV

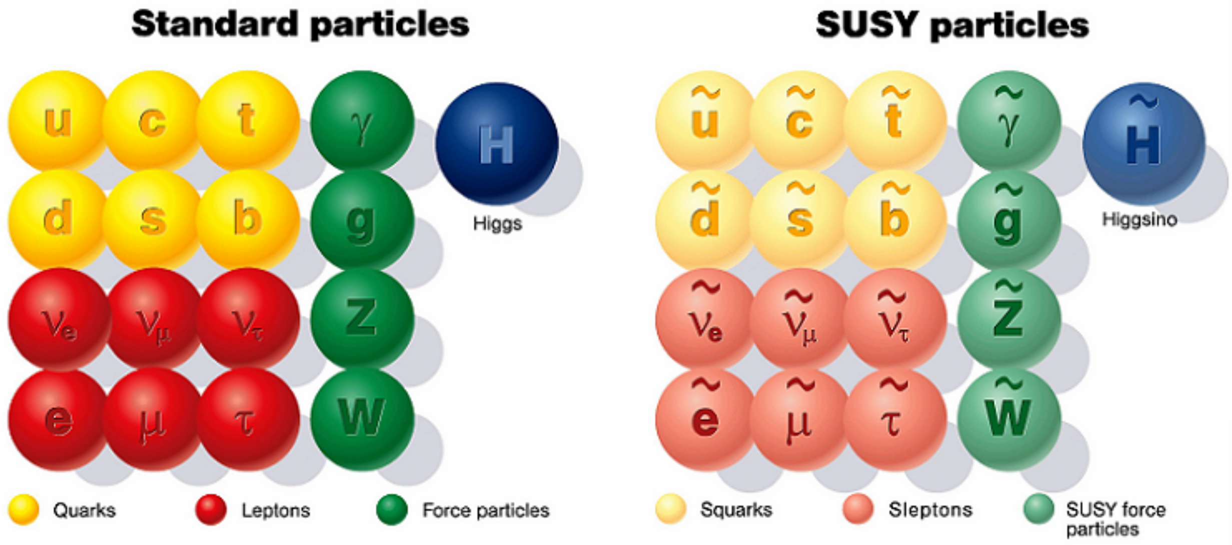
WIMPs seem to be an ideal solution

- During Big Bang, universe is cooling and expanding.
- When $T>M_\chi$, the number density of χ particles is constant as creation and annihilation is in equilibrium.
- When $T<M_\chi$, density drops off exponentially (Boltzman).
- As universe expands, particles can't find each other to annihilate: "freeze-out".
- The cross section needed to get the correct amount of dark matter is the same as the weak interaction. Called the "WIMP miracle".



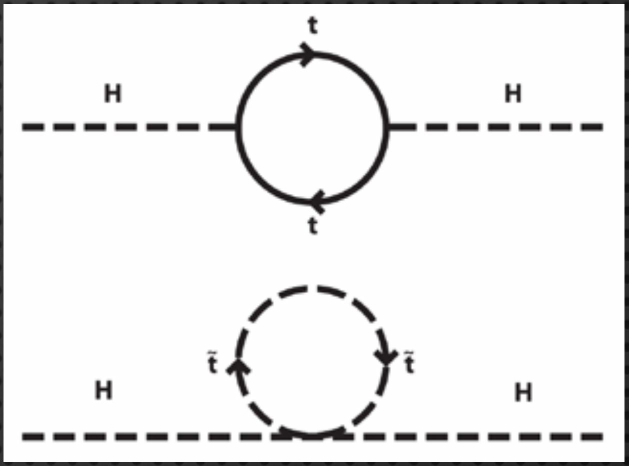
Enter Supersymmetry (SUSY)

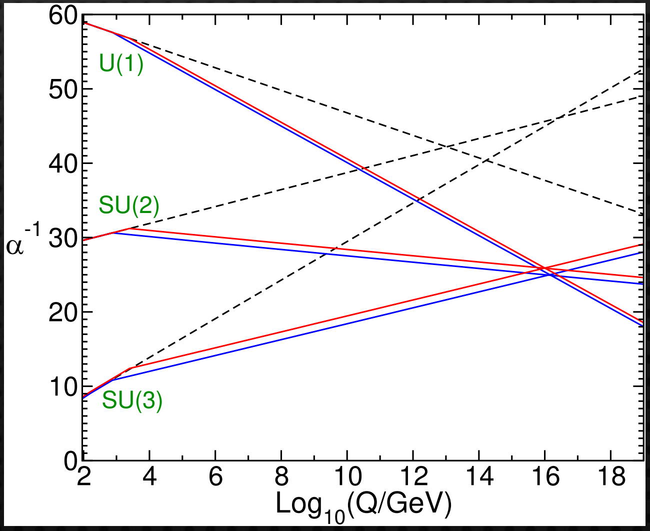
- Proposes an additional symmetry in nature between bosons and fermions.
- Each SM particle has a partner particle (sparticle) with same quantum numbers except spin differs by ½.
- Cool sparticle names like sbottom, selectron, wino.
- Consider *R*-parity conserving models today: sparticles are produced in pairs and decay to the lightest supersymmetric particle (LSP).



Three good features of SUSY

1. Can solve hierarchy problem: Quantum corrections from SM particles canceled by the sparticles.
2. Can provide a dark matter candidate. A neutral LSP will be a WIMP.
3. The strong, weak, and E&M forces have different strengths (couplings) that change (run) with energy. When the effects of SUSY are included, these couplings converge at 10^{16} GeV, keeping alive the hope for a Grand Unified Theory.



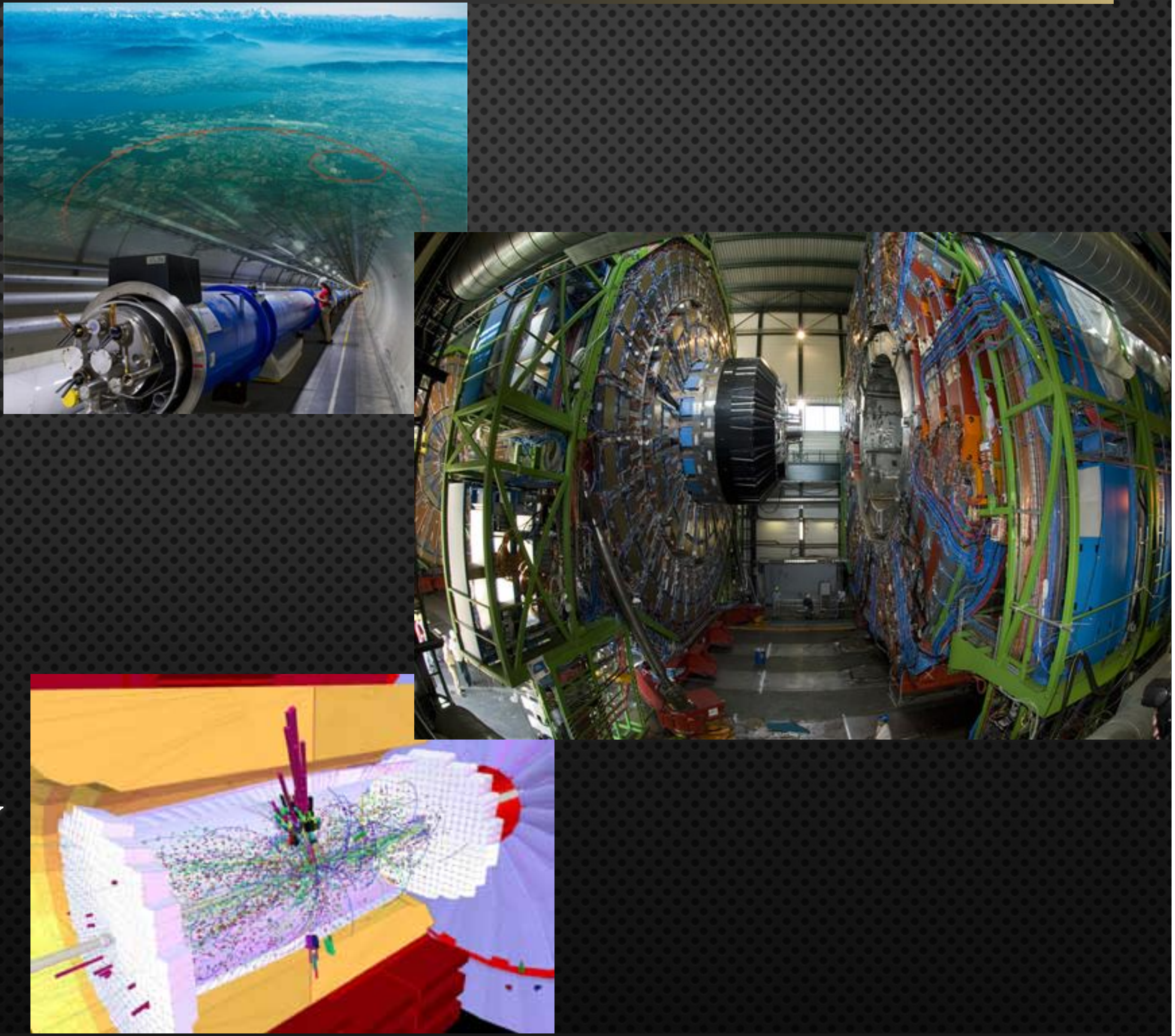


The less great features of SUSY

- SUSY itself is a well defined theory.
- If supersymmetry was a good symmetry, the sparticle masses would be the same as the particle masses.
- Since we haven't found any sparticles, there must be a symmetry breaking mechanism.
- This is no problem (already seen – electroweak symmetry breaking is what gives mass to most SM particles).
- But we have no idea how the symmetry breaking is done so this opens up all sorts of possibilities – not very predictive.
- Need to look as broadly as possible for signs of SUSY.

How do we look for SUSY?

- Need an accelerator to produce SUSY particles.
- Need a detector to record the production and decay of SUSY particles.
- Need to distinguish SUSY events from SM events.

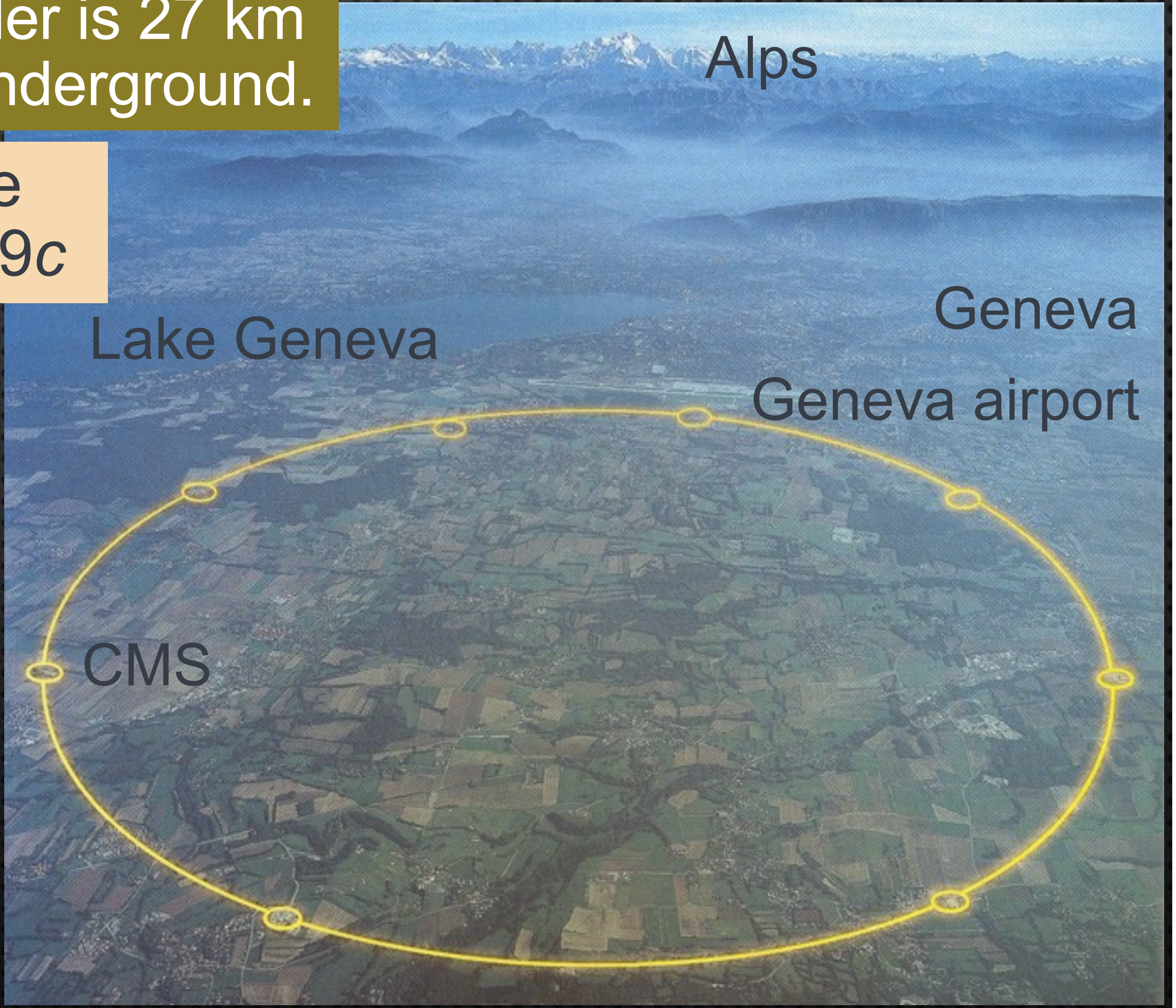


The less great features of SUSY

The Large Hadron Collider is 27 km long and 100-500 feet underground.

RF cavities accelerate protons to 0.99999999*c*

8.3 T superconducting magnets keep the protons going in circles

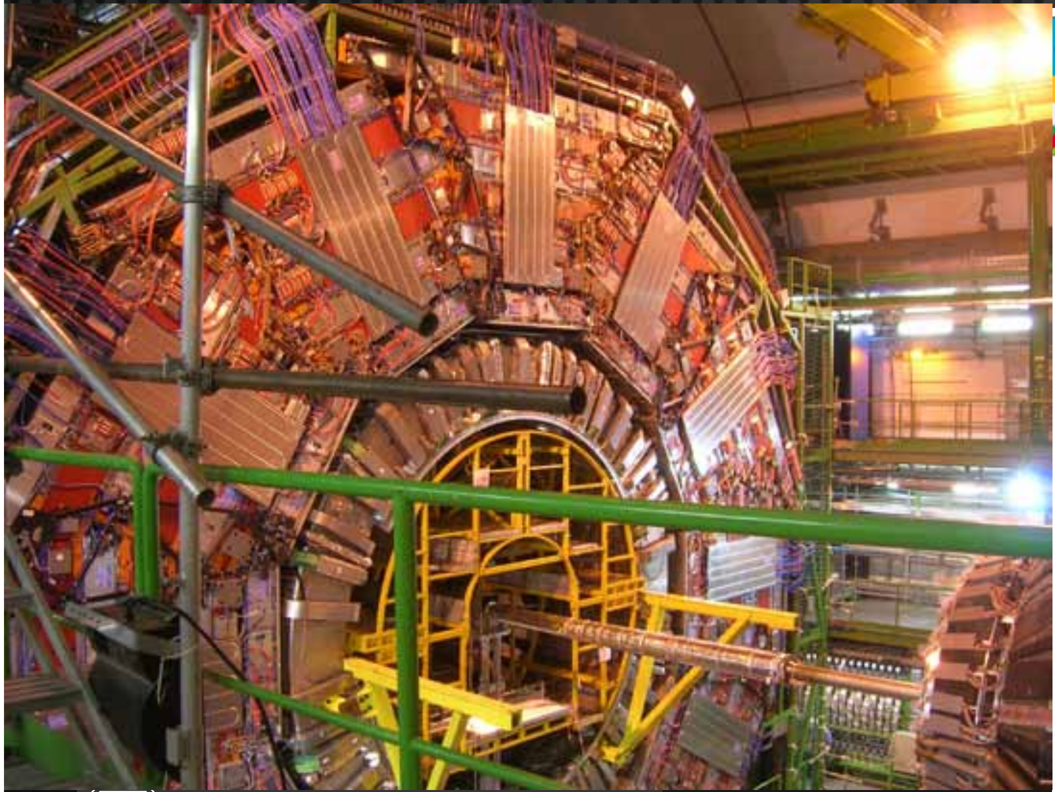


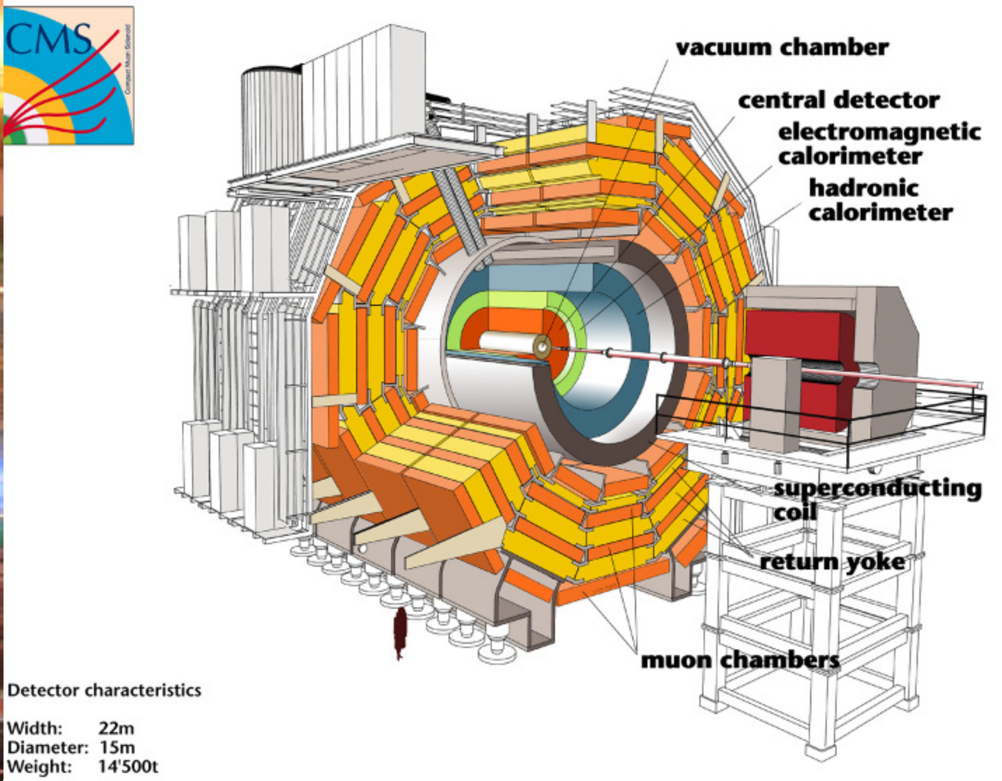
Detecting the particles

We collide protons at high energy to create new particles.
But these particles immediately decay into other particles.

Need to detect these particles to reconstruct what happened.

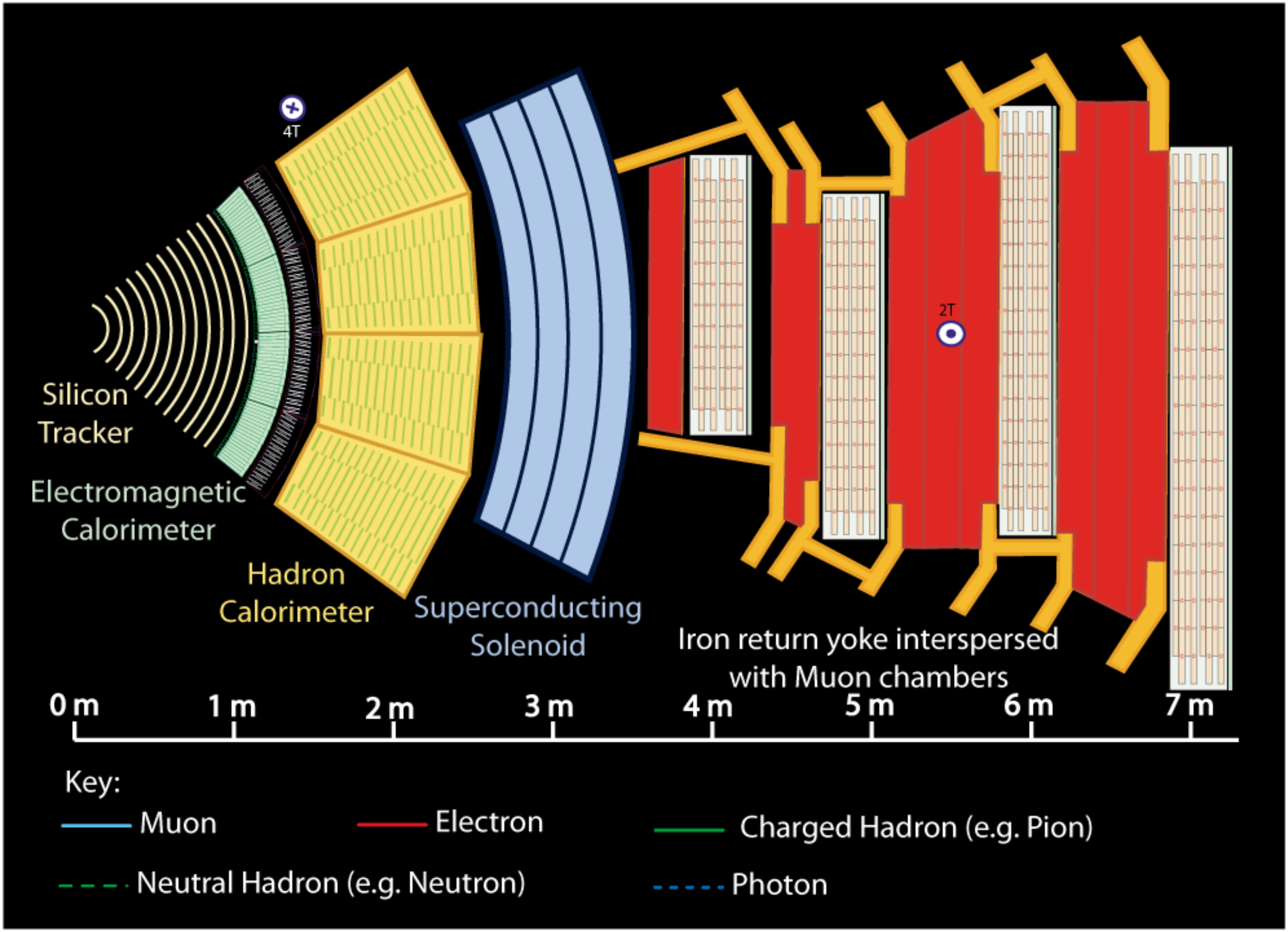
The CMS detector is in a cavern 300 feet underground.





Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t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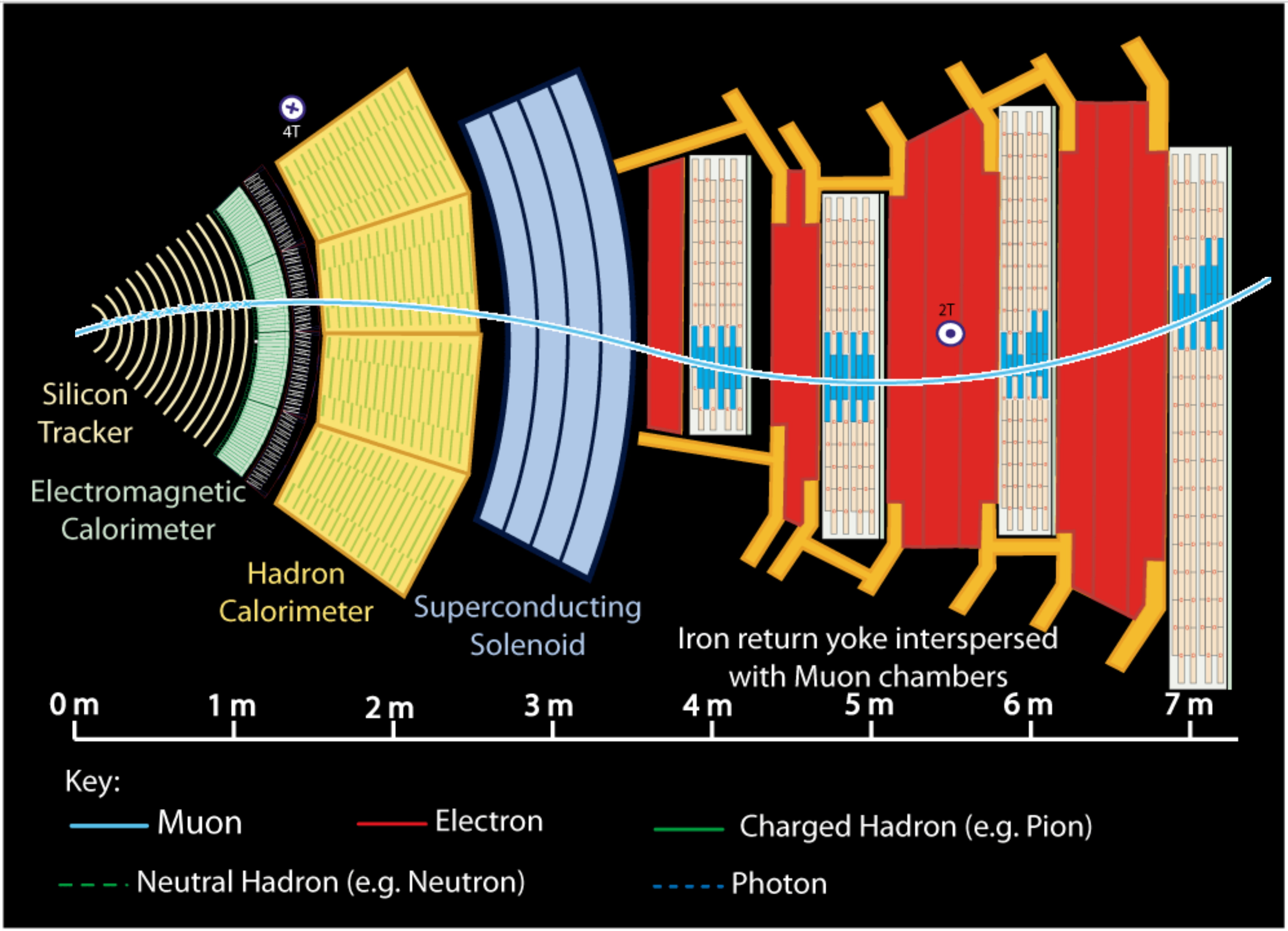
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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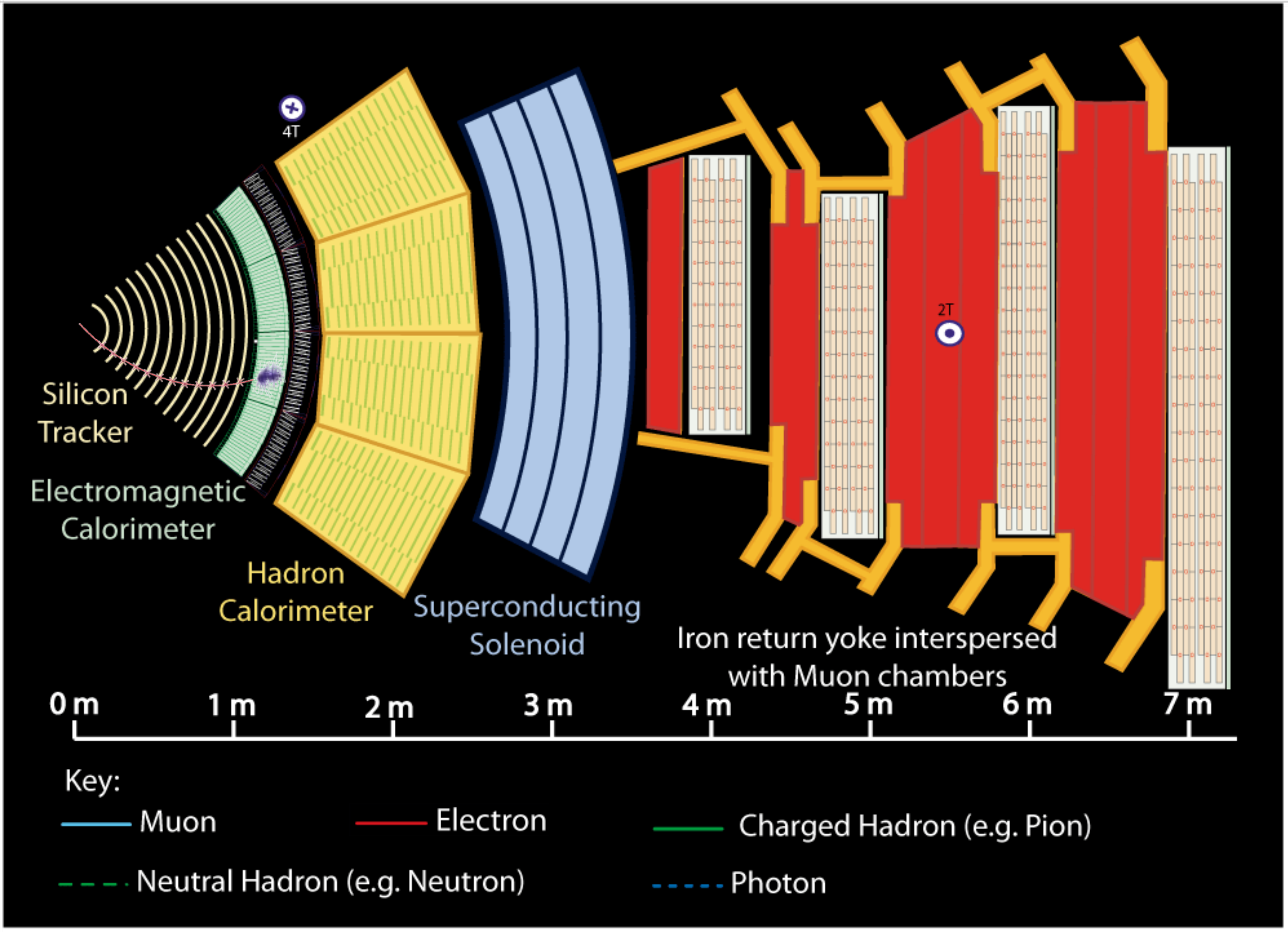
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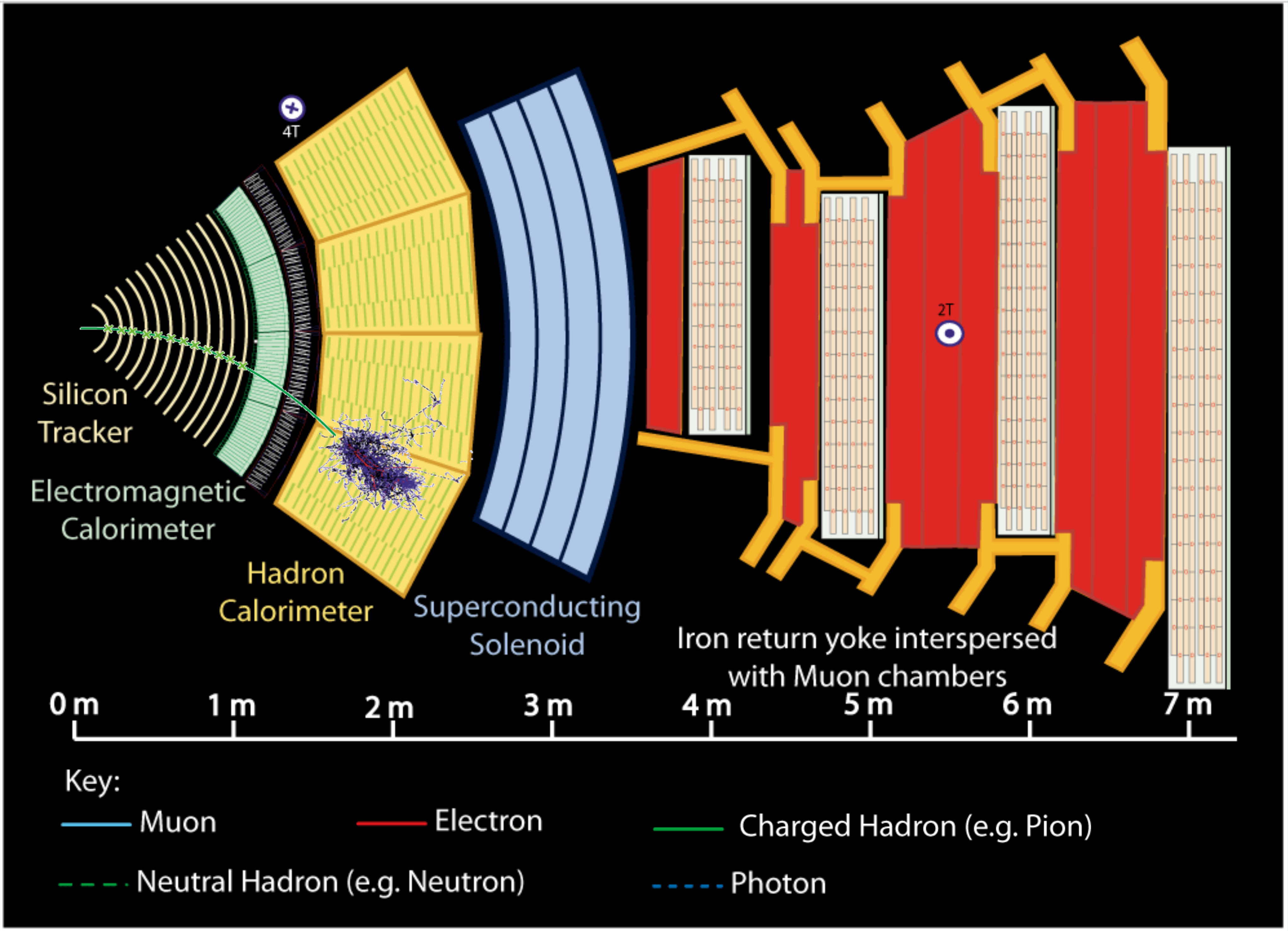
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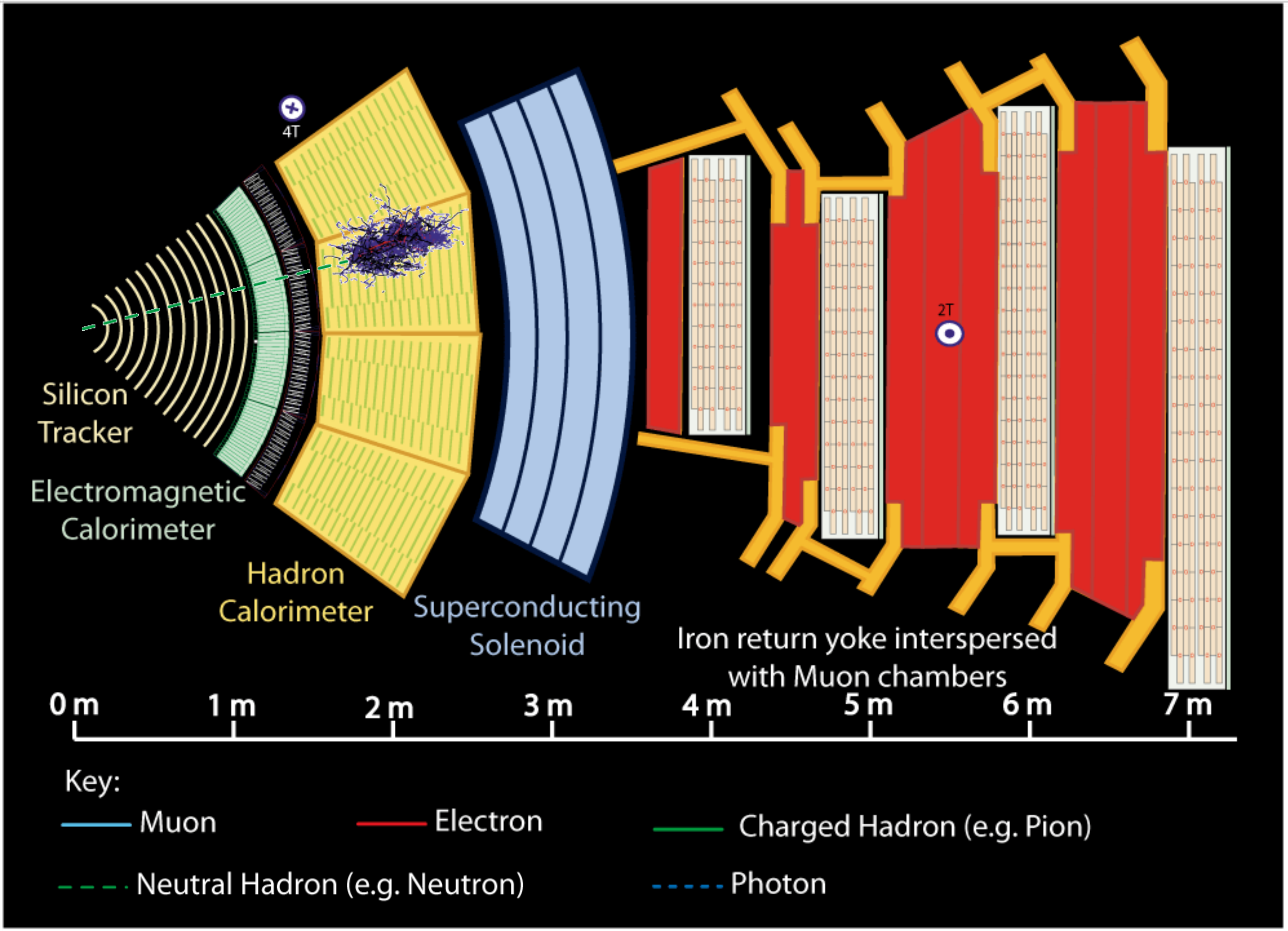
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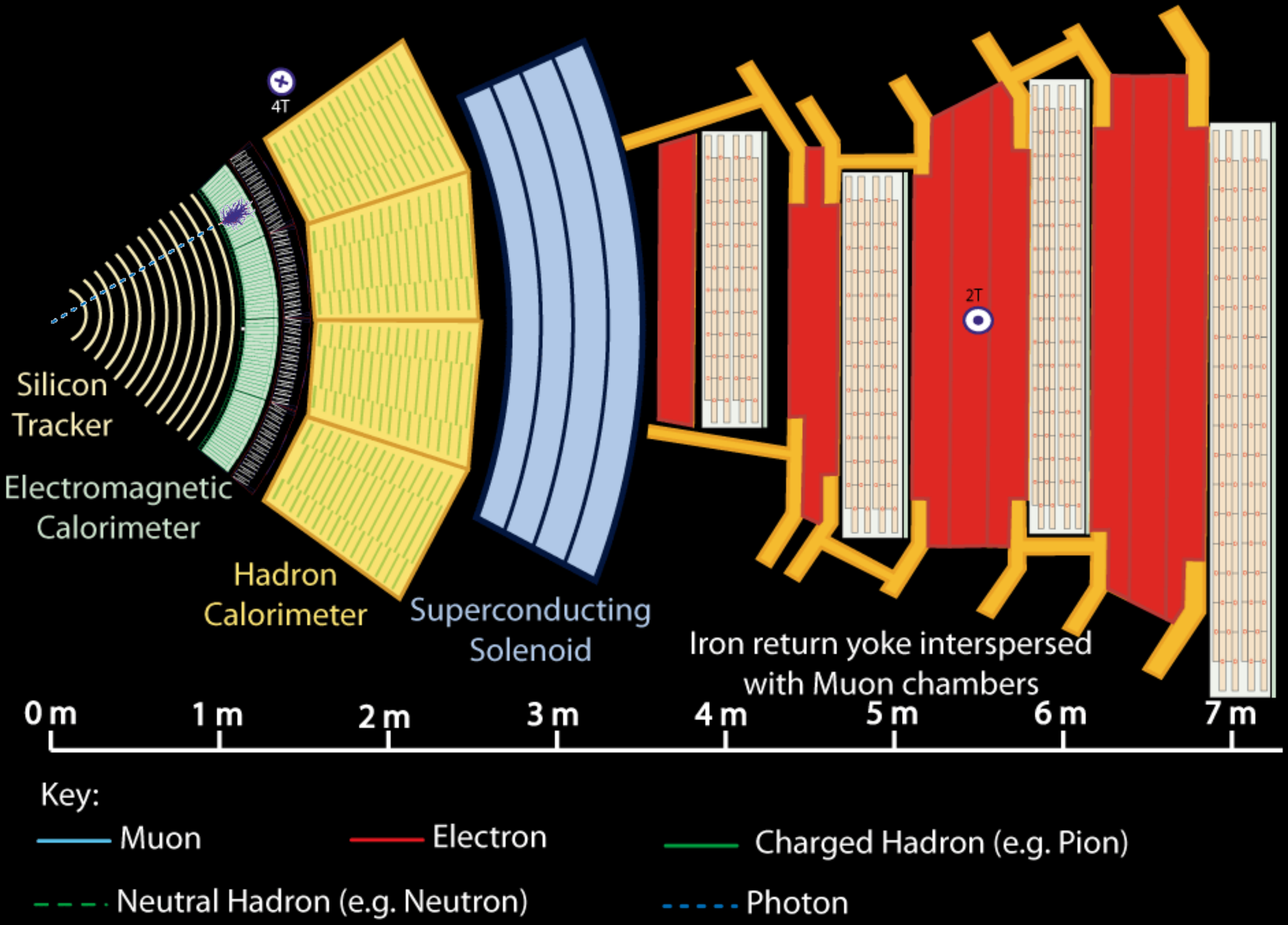
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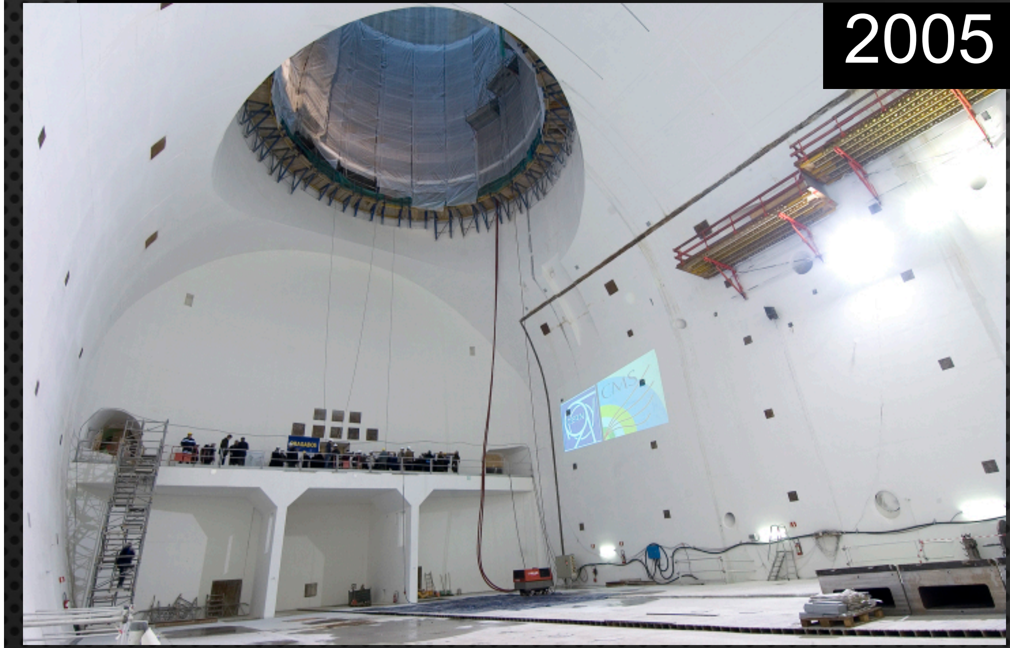
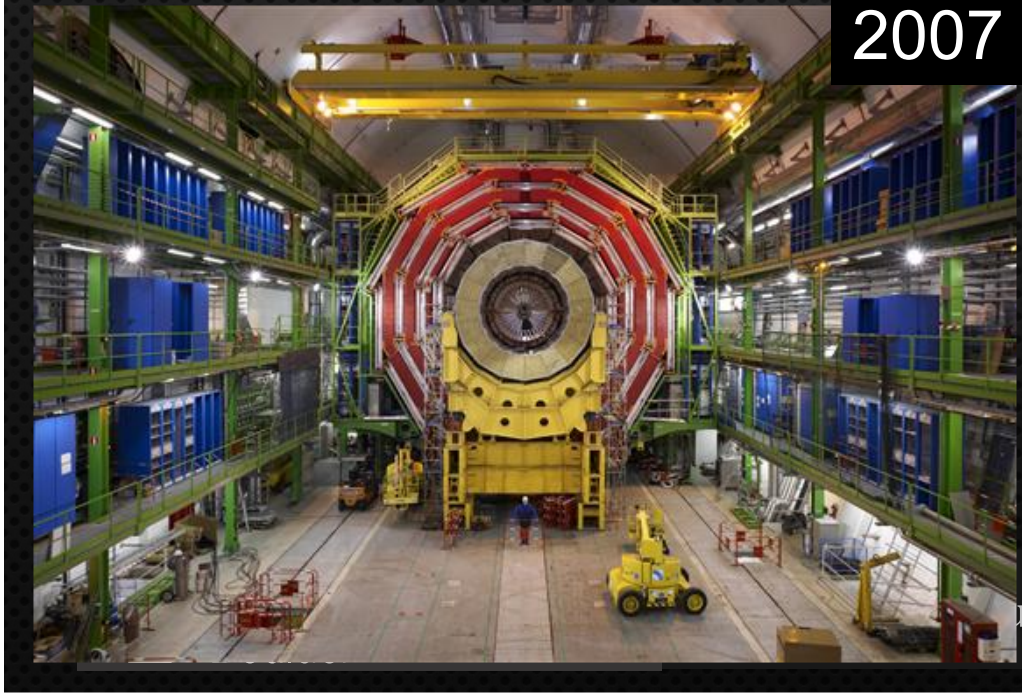
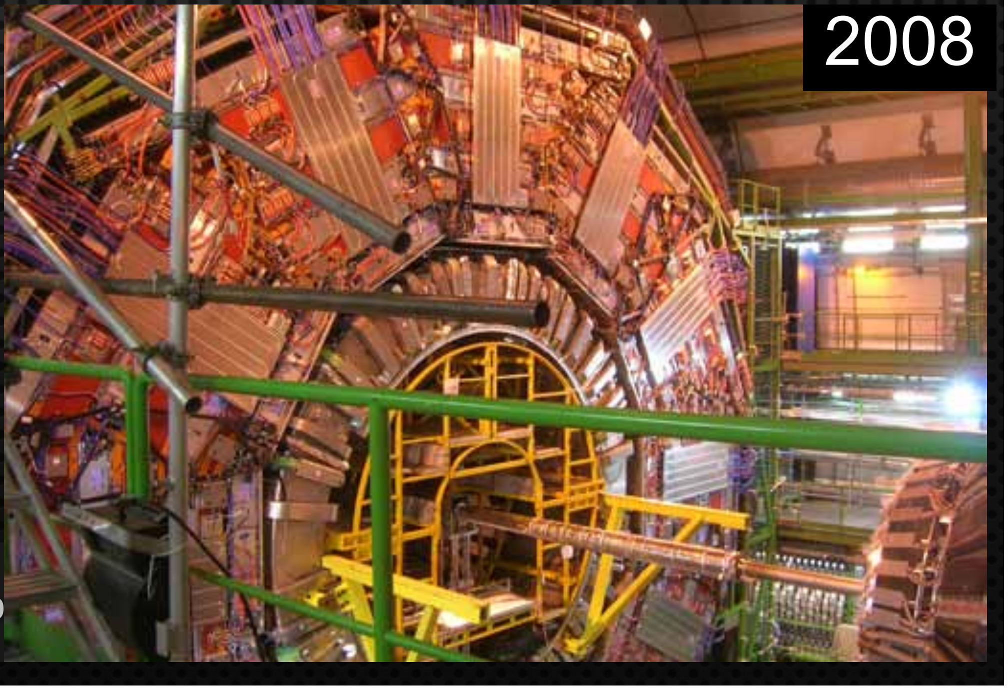
CMS assembly

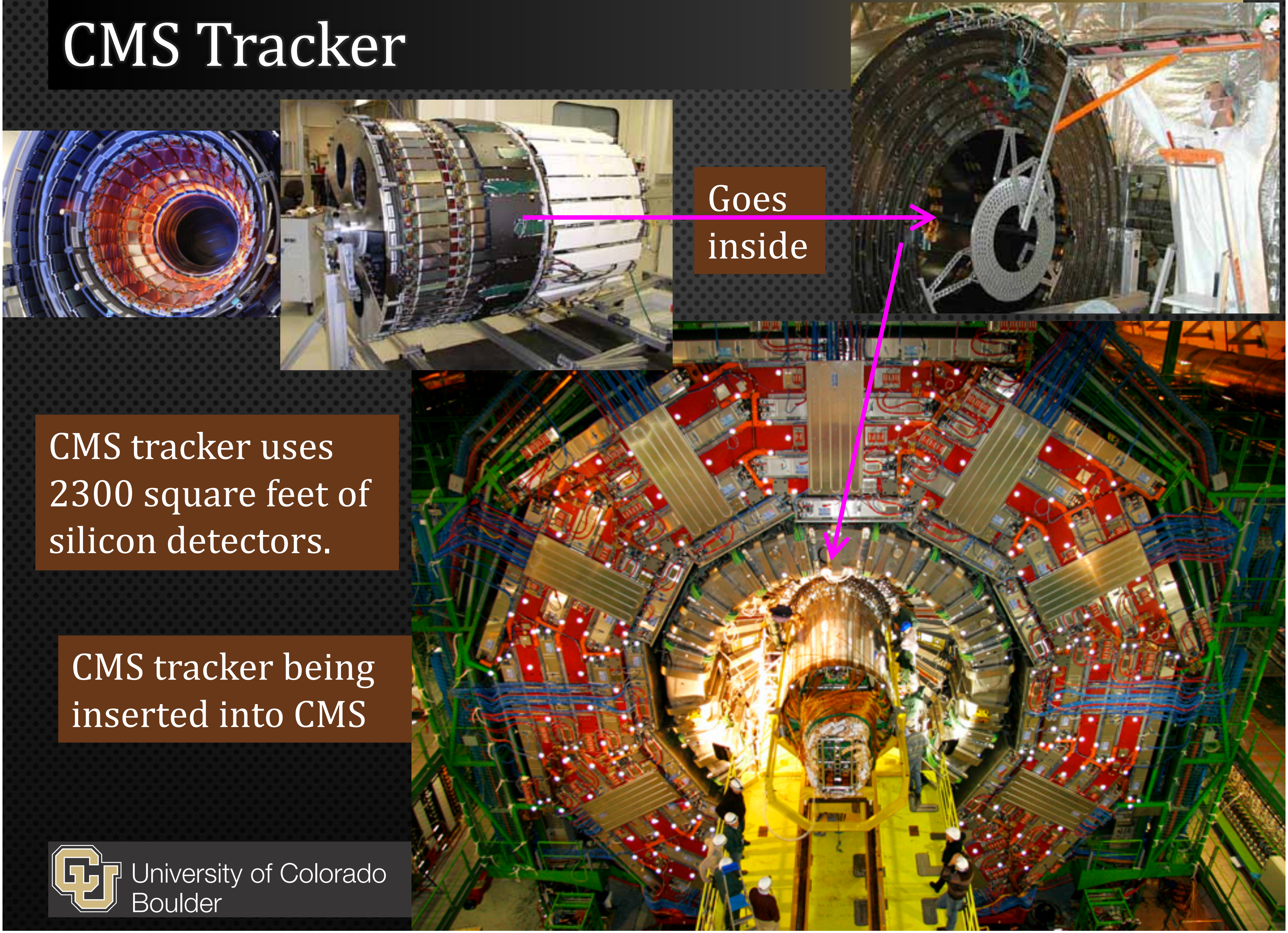

2005


2006


2007


2008

CMS Tracker



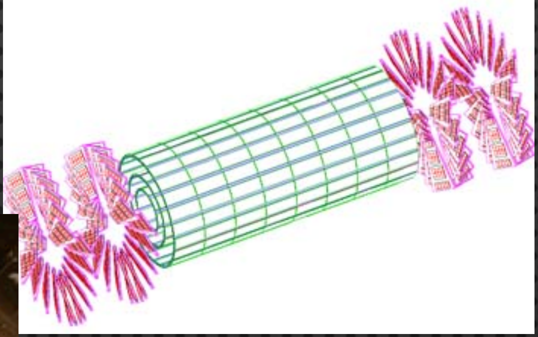
Goes inside

CMS tracker uses 2300 square feet of silicon detectors.

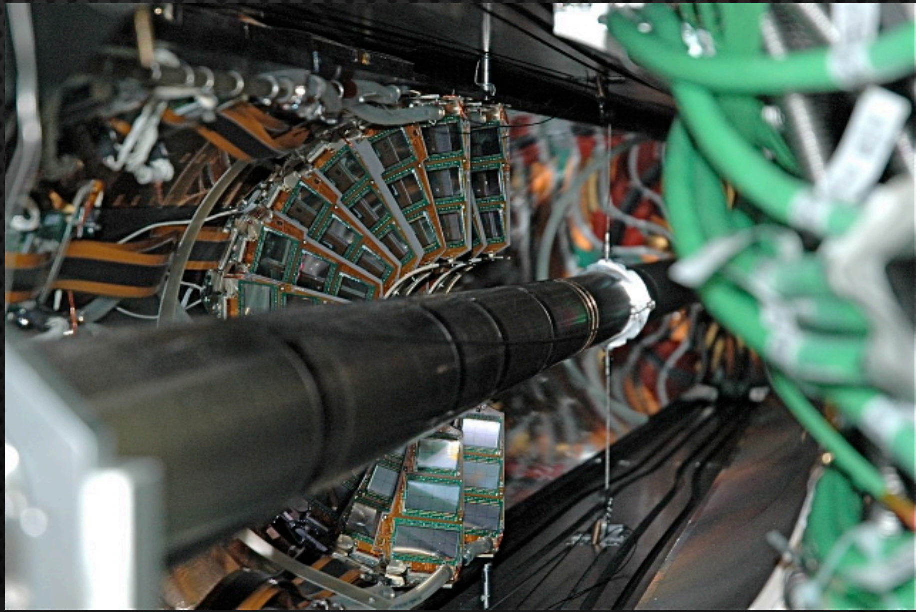
CMS tracker being inserted into CMS

CMS pixel detector

Smallest detector but the most channels. There are 66 million pixels, each 100 μm by 150 μm.

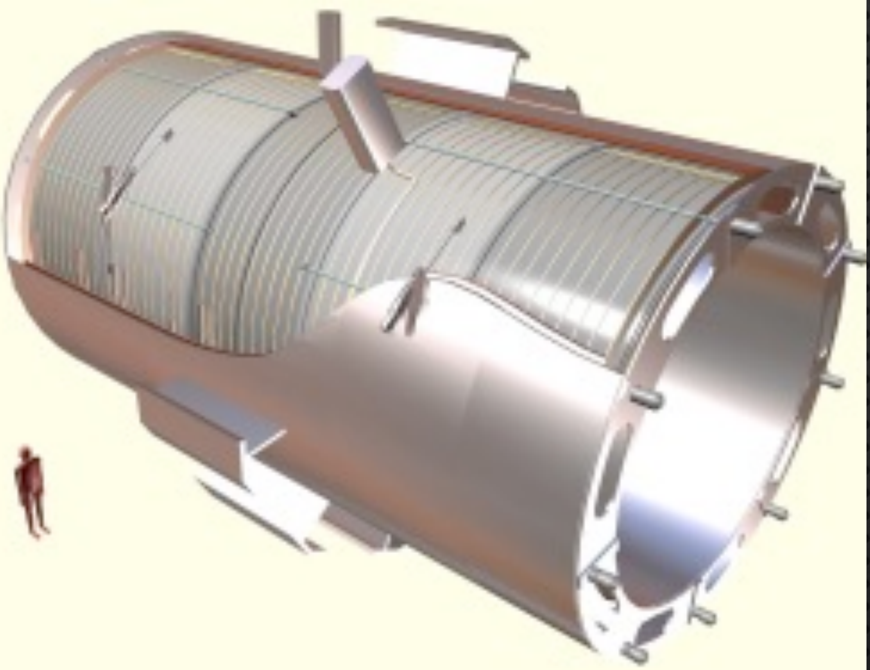


Inserting the detector



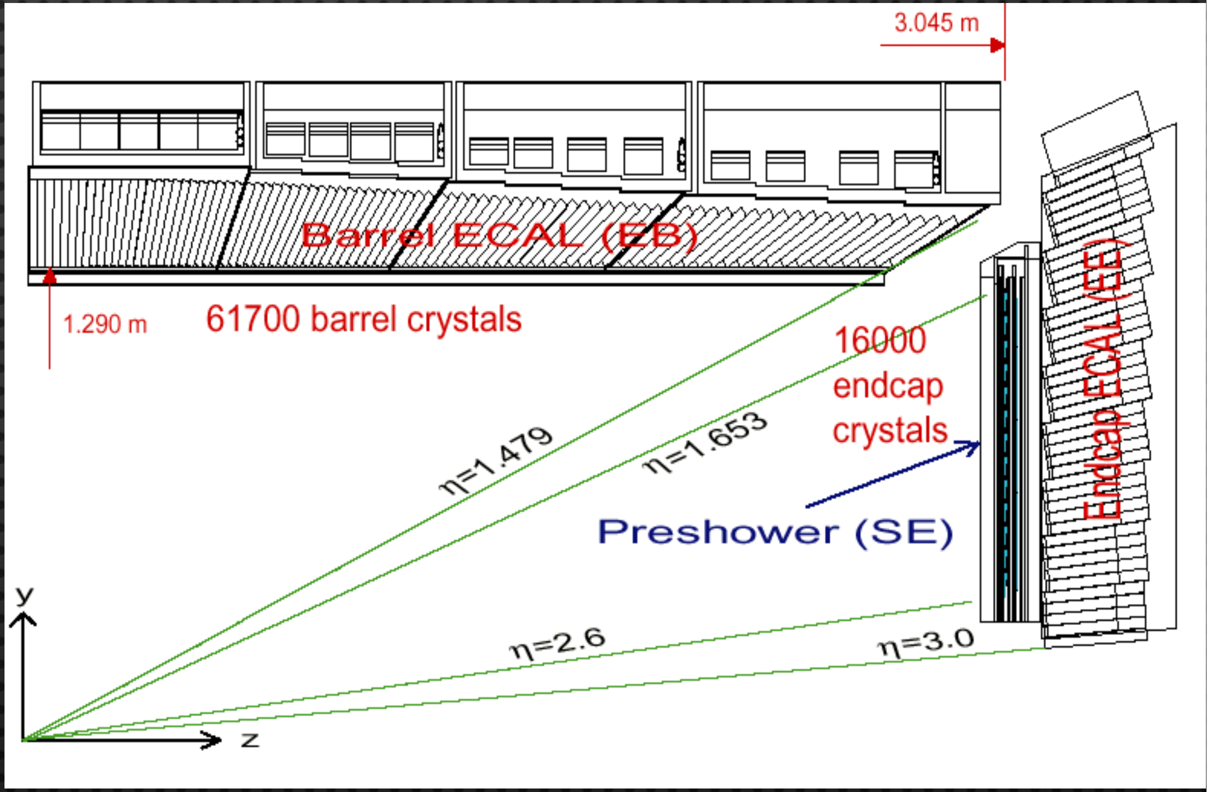
CMS Solenoid

- 3.8 tesla magnet at 4 K
- 6 m diameter and 12.5 m long (largest ever built)
- 220 t (including 6 t of NbTi)
- Stores 2.7 GJ — equivalent to 1300 lbs of TNT
- If magnet gets above superconducting temperature, energy is released as heat – need to plan for the worst
- Bends charged particles allowing tracker to measure momentum

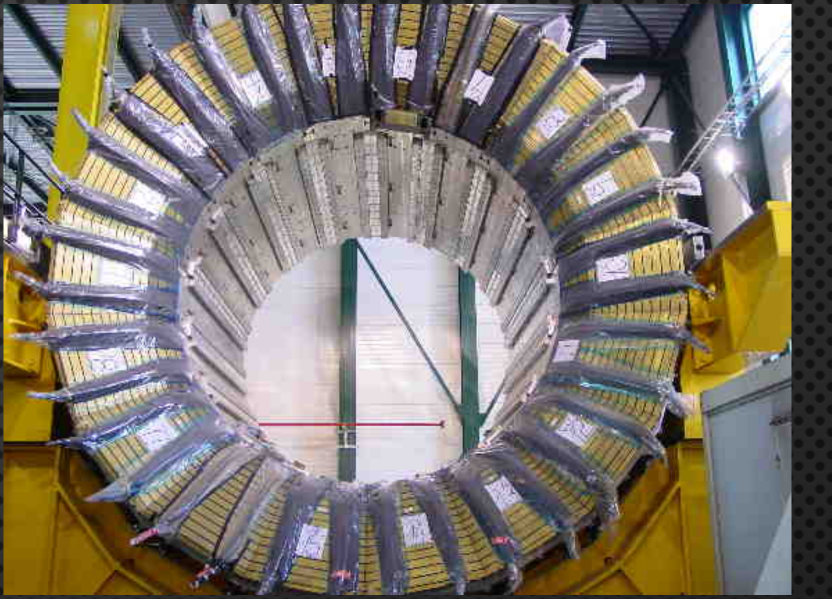


CMS Electromagnetic Calorimeter (ECAL)

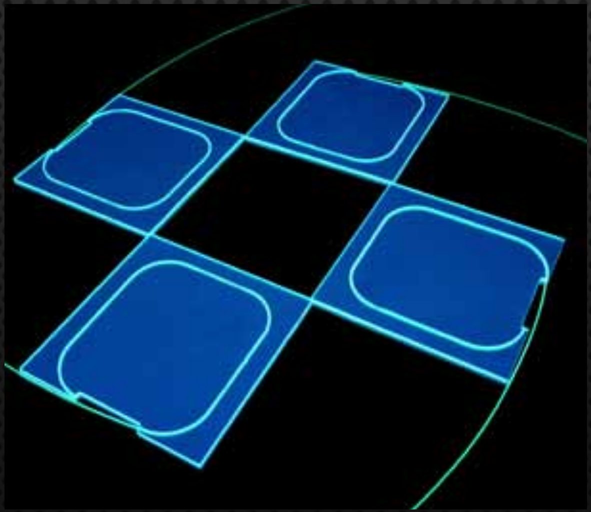
- Photons and electrons shower in high Z material
- Homogenous calorimeter
- Lead tungstate ($PbWO_4$) crystals: 2.3 x 2.3 x 23 cm^3
- Radiation hard, dense, and fast
- Low light yield & temperature sensitivity make it difficult
- Magnetic field and radiation require novel electronics APD and VPT

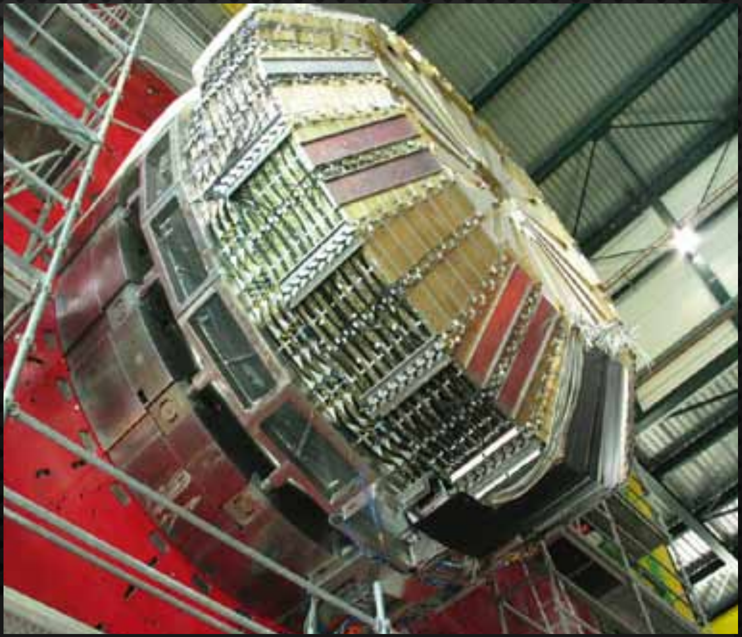


CMS Hadronic Calorimeter (HCAL)



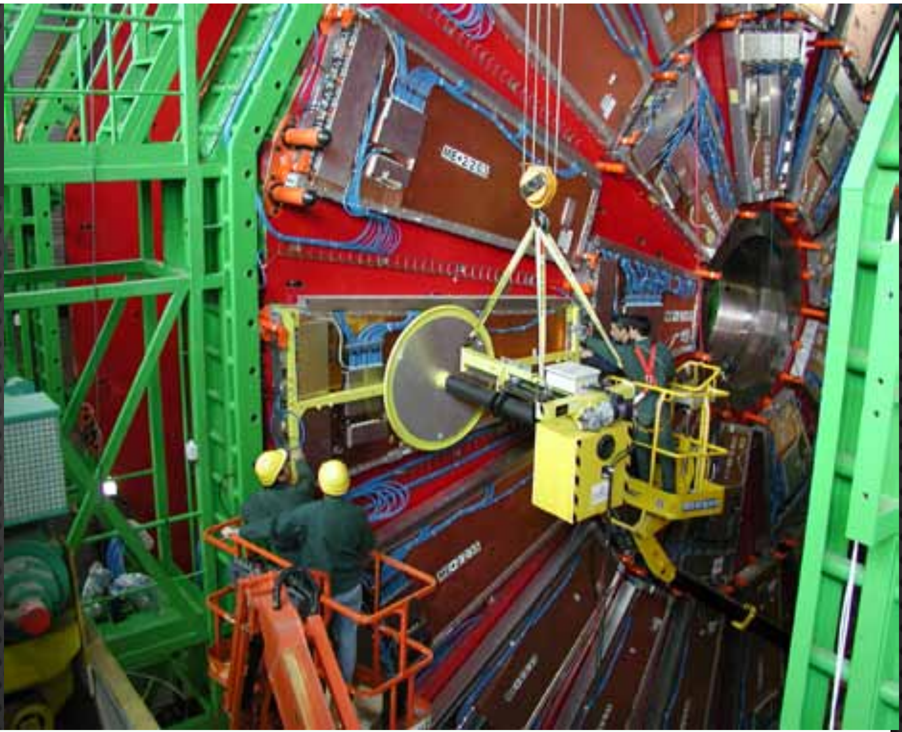
- Sampling calorimeter
- Brass absorber from Russian artillery shells (non-magnetic)
- Scintillating tiles with wavelength shifting (WLS) fiber
- WLS fiber is fed into a hybrid photo-diode (HPD) for light yield measurement

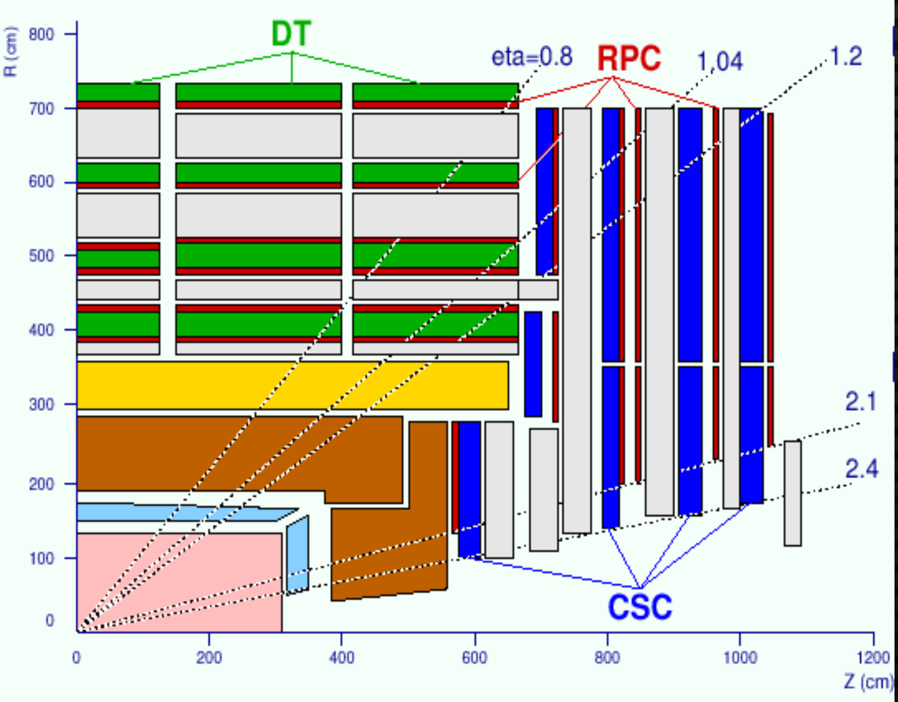




CMS Muon detector

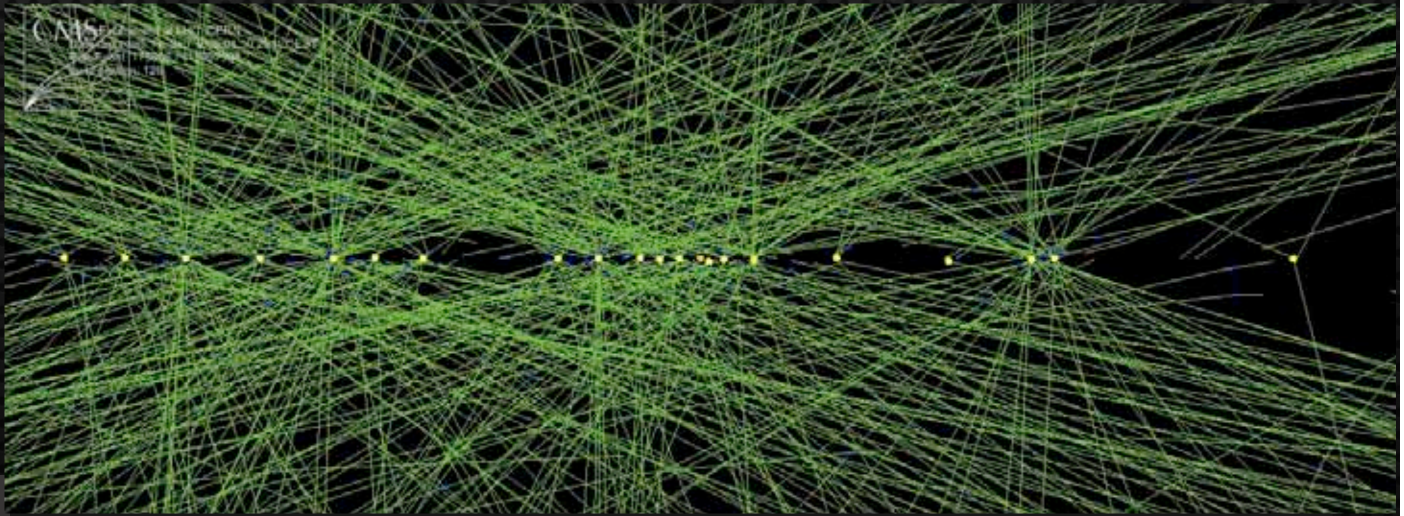
- Muons interact less than other charged particles
- Place detectors after lots of material so that what comes through must be a muon
- Add magnetic field & tracking to find momentum and link with main tracker
- 12000 t of iron is absorber and solenoid flux return
- Three tracking technologies: Drift Tube, Resistive Plate Chamber, & Cathode Strip Chamber





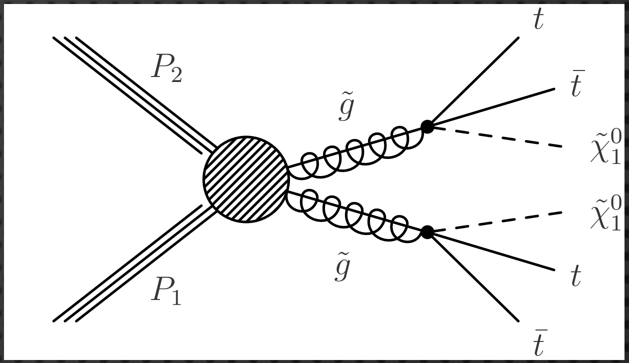
Event selection

- Proton bunches collide 40 million times per second, which results in about 40 pairs of protons colliding.
- It takes 1 MB of data to record an event.
- So we would need to record 40 TB/second to get every event. Not feasible.
- Instead, we look at a subset of the information to see if the event is interesting and only put on tape if it is. Still, we save about 1000 events/sec leading to 10 PB/year.



Search for SUSY in hadronic modes

Search for SUSY involving production via the strong interaction (larger cross section) so produce gluinos or squarks.



Always have 2 LSPs, which exit the detector undetected. In a hermetic detector, this can be seen as large missing transverse energy (**MHT**).

High mass events produce large amounts of energy seen in the detector (**HT**).

Each top quark decays to b quark (creating a b jet) and W boson (decaying to two jets 67% of time). Results in many jets ($\mathbf{N_{jet}}$) and b jets ($\mathbf{N_b}$).

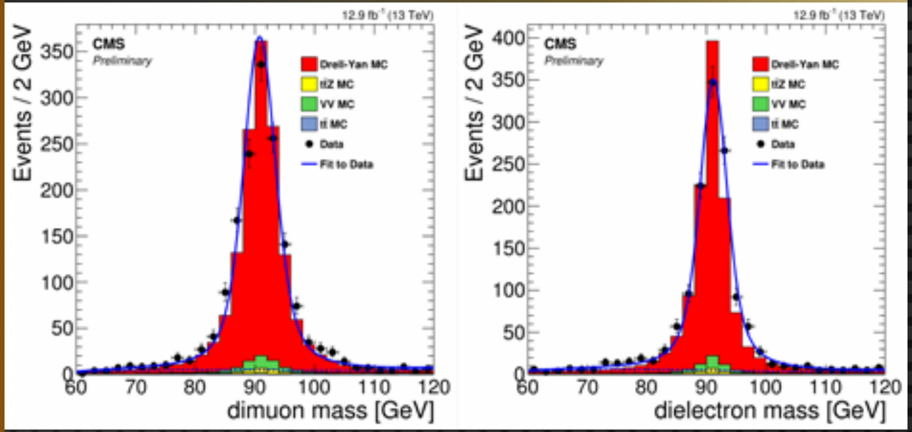
SM backgrounds for search

- **QCD** : Direct production of many jets with the energy of jet(s) mismeasured, leading to MHT.
- **Lost-lepton** and **hadronic τ** :Production of W and jets where W decays to e/μ/τ and ν. Neutrino creates MHT. Reduced by rejecting events with e/μ/τ but some may slip through. W bosons can be produced directly or from top quark decays.
- **Z→νν** : Production of Z and jets where Z decays to neutrinos, producing MHT.

These backgrounds are all estimated by using control regions (distinct from signal regions).

Estimate of Z→νν

Reconstruct Z→ee and Z→μμ events to estimate Z→νν. Just need to account for efficiency. Unfortunately, there are more Z→νν events than Z→ee + Z→μμ events so statistically limited.

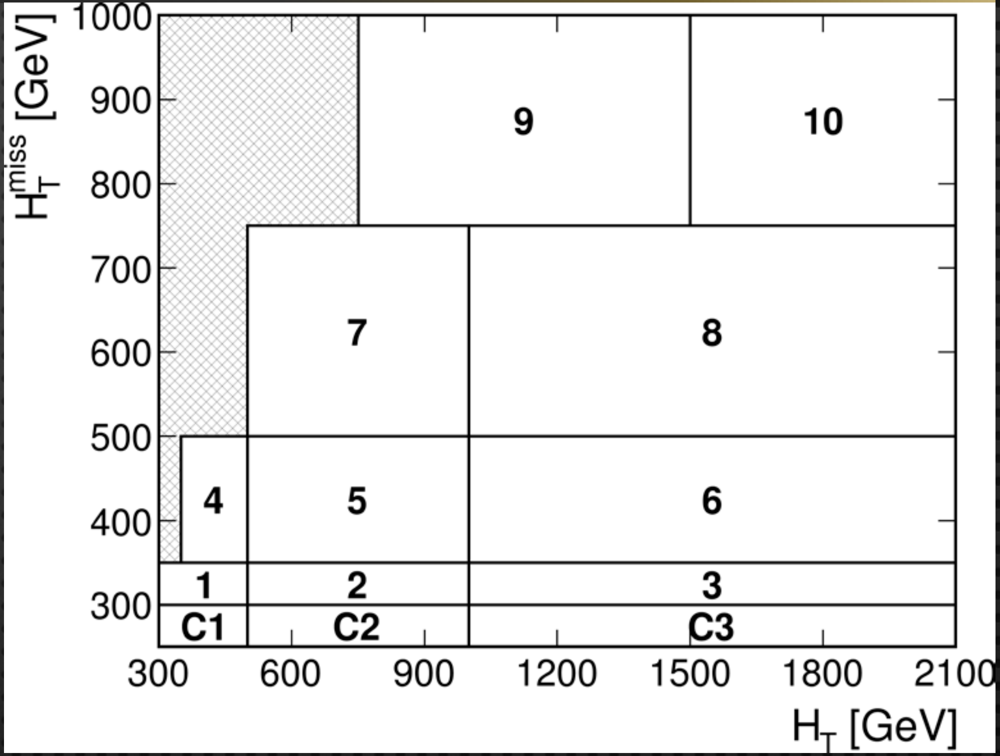


Can also use photon+jets data sample as the production of photons and Z bosons are very similar (at high energy where the mass of the Z is not relevant). Many more photon events than Z→νν so good statistical accuracy but need to carefully control for production differences.

This analysis uses both methods to estimate the Z→νν background

Signal region divided into bins

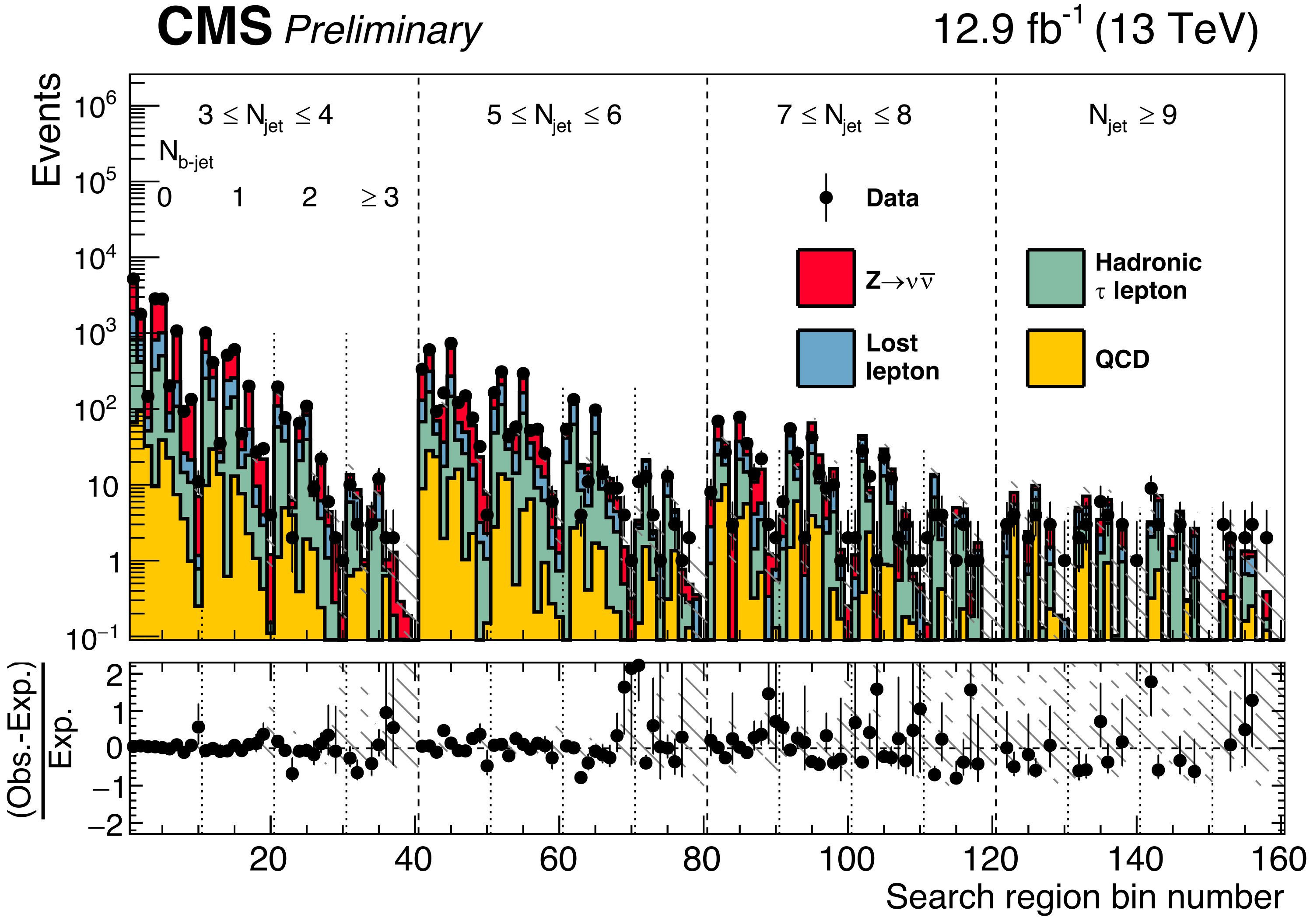
- The HT-MHT plane divided into 10 bins.
- 4 bins of N_{jet}: 3-4, 5-6, 7-8, 9+.
- 4 bins of N_b: 0, 1, 2, 3+.
- Total of 160 bins.



Binning increases the sensitivity and flexibility of the analysis.

Search results

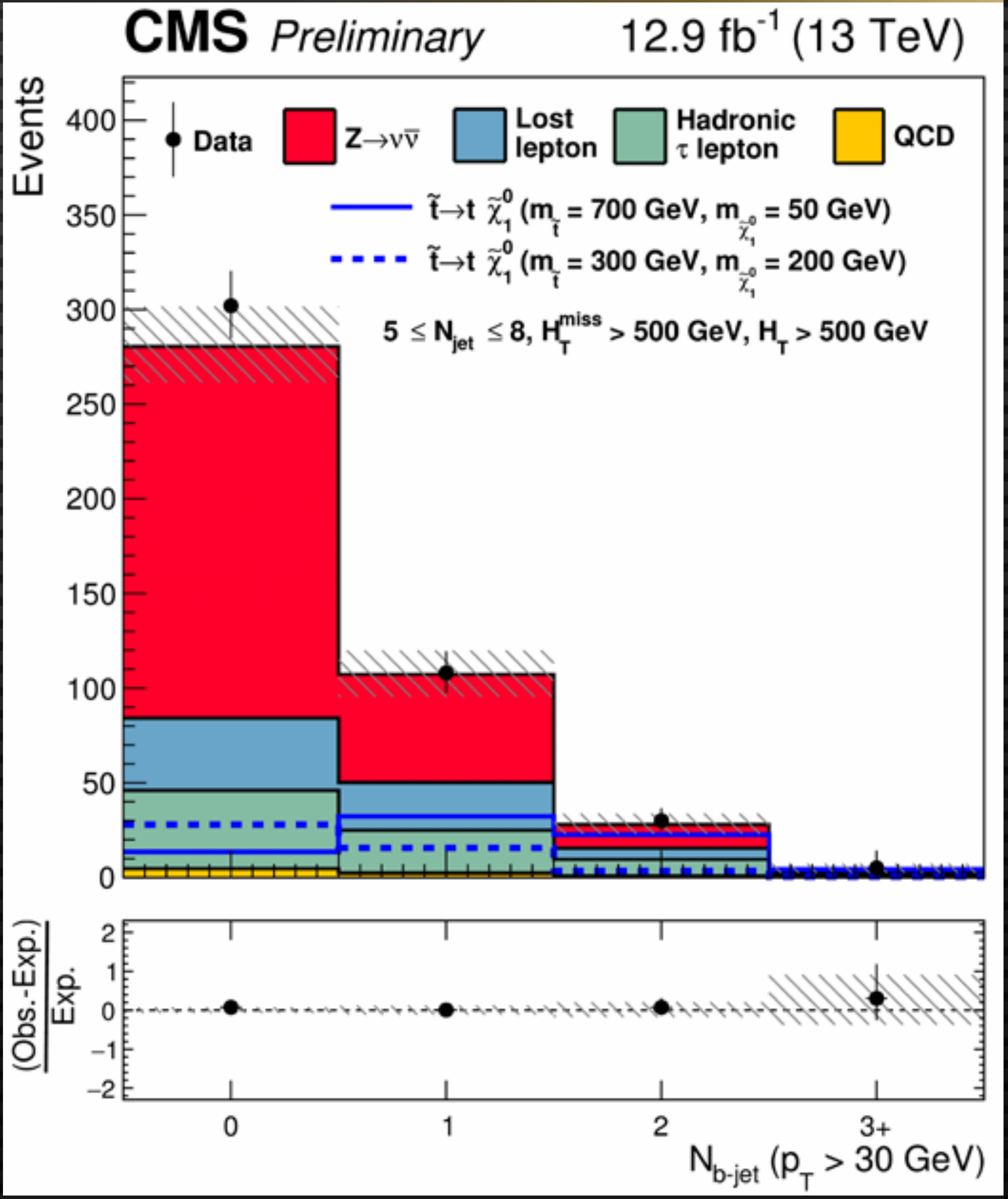
Data is consistent with estimated backgrounds. No sign of SUSY



Search results

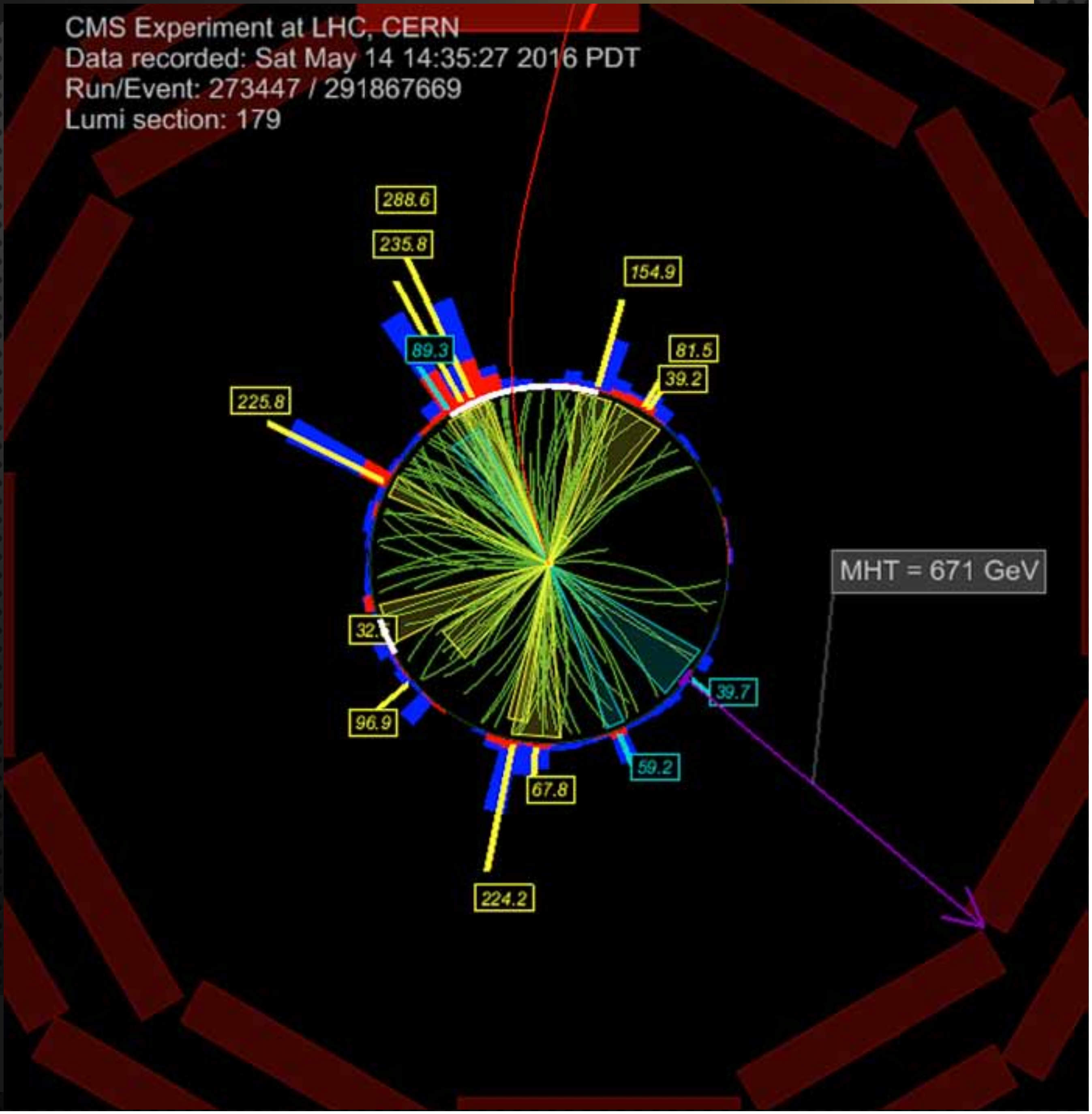
Can look in the more sensitive regions to see what a signal may look like.

Still no sign of SUSY.



Possible SUSY event

This event contains 12 jets, 3 b-jets, and large amount of missing transverse energy. Great candidate for a SUSY event (but most likely not).



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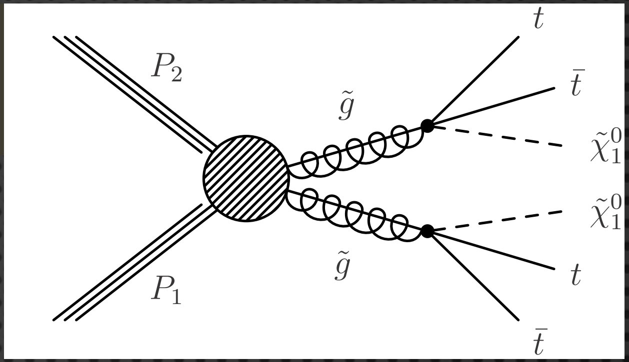
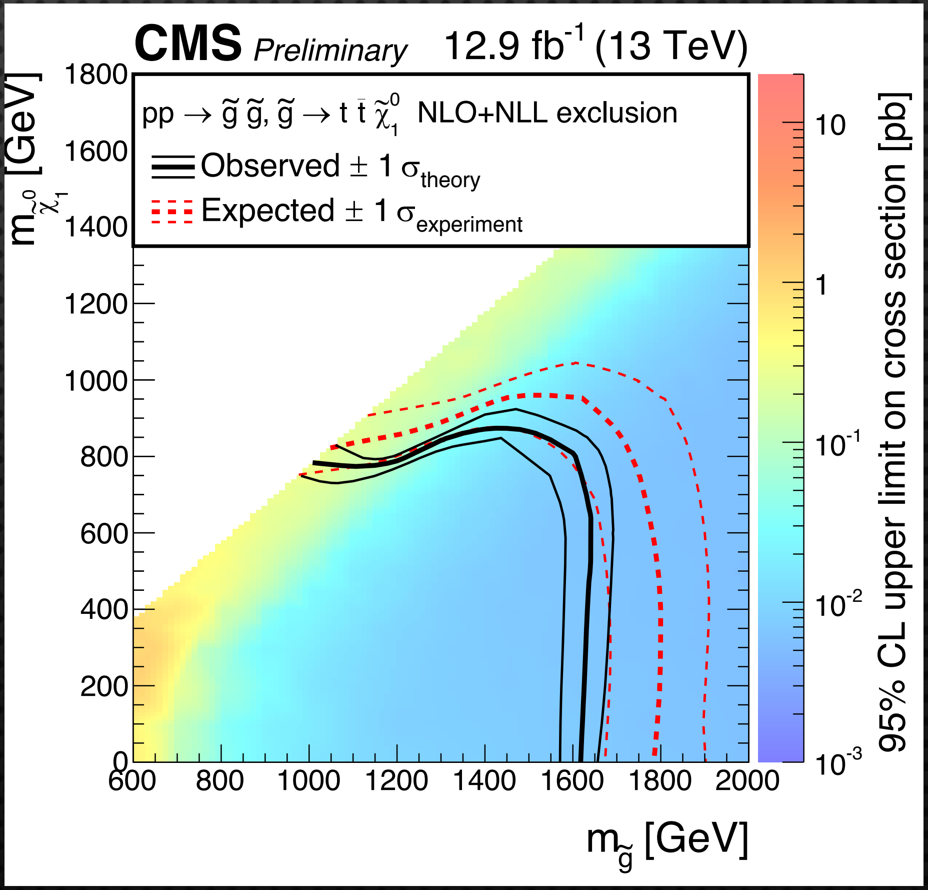
Limits on SUSY production



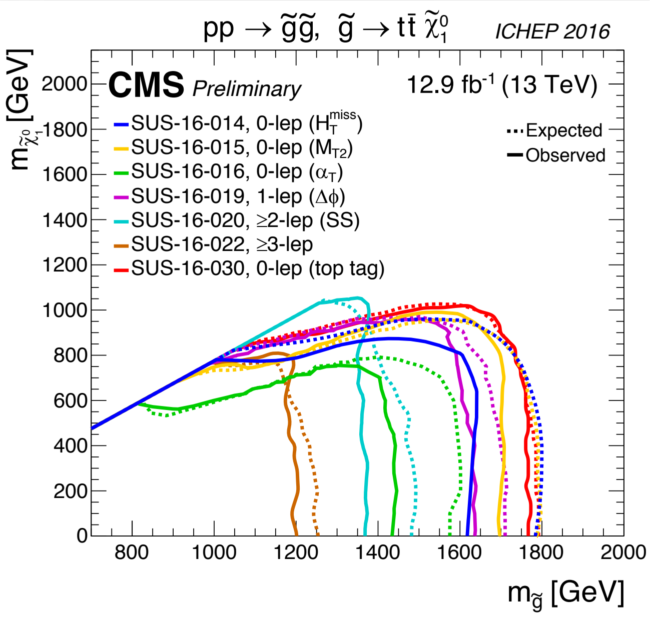
Results are presented as regions that are excluded.

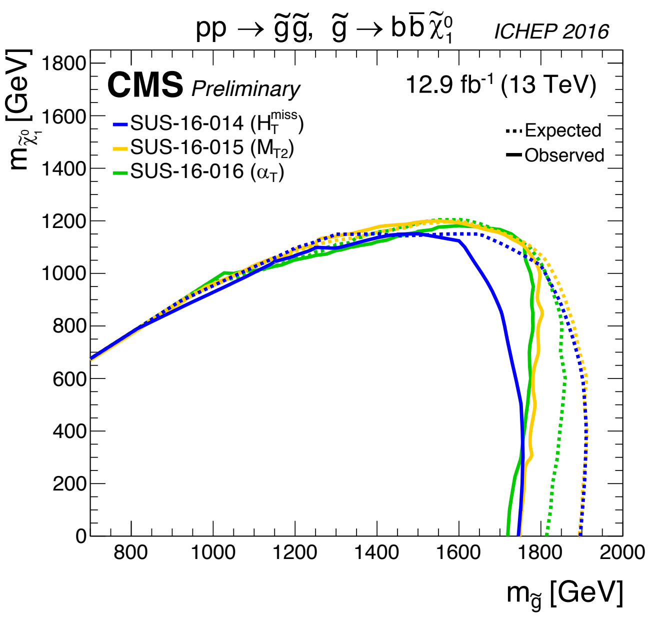
Expected limits are what would be obtained if the observed data exactly matched the prediction.

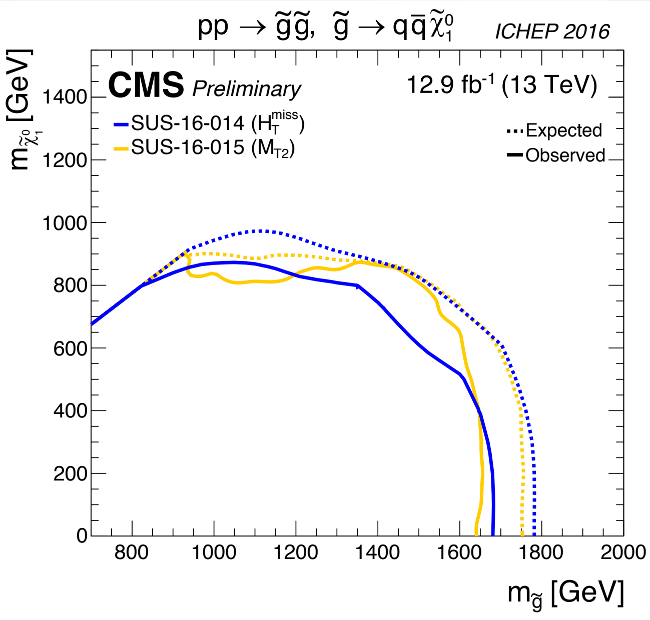
Observed limits in this case are not as good. Could be background was underestimated, statistical fluctuation, or the first sign of SUSY (probably not).

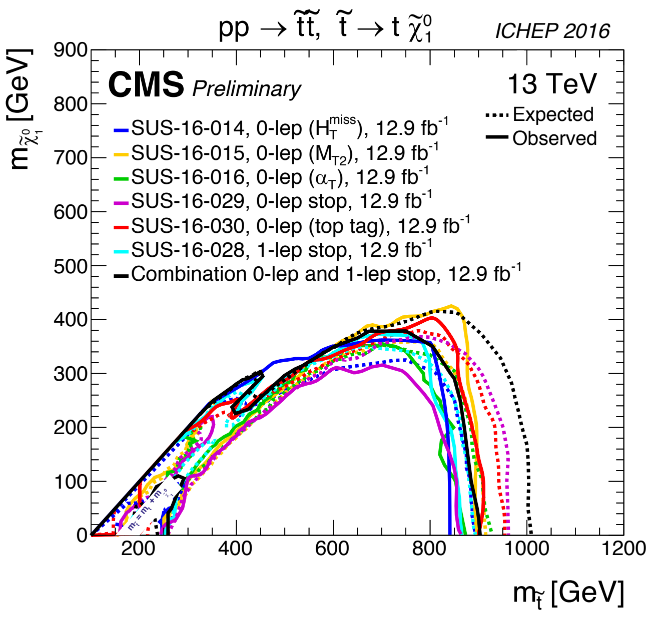


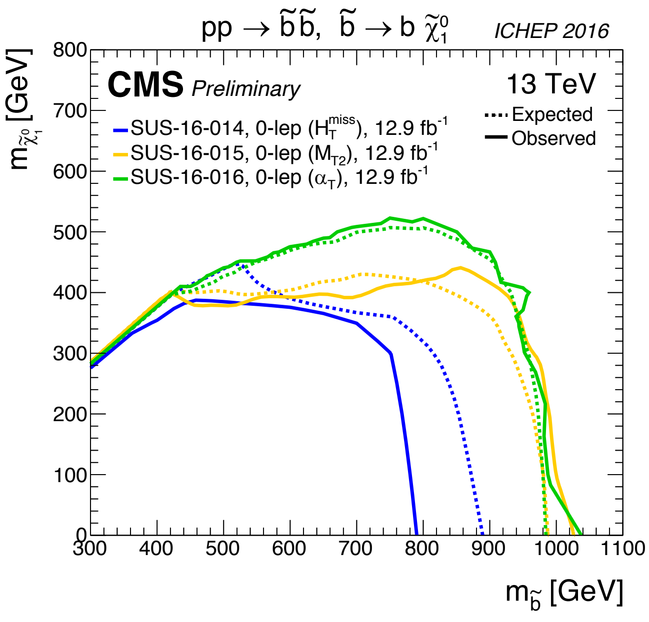
Summary of hadronic SUSY searches

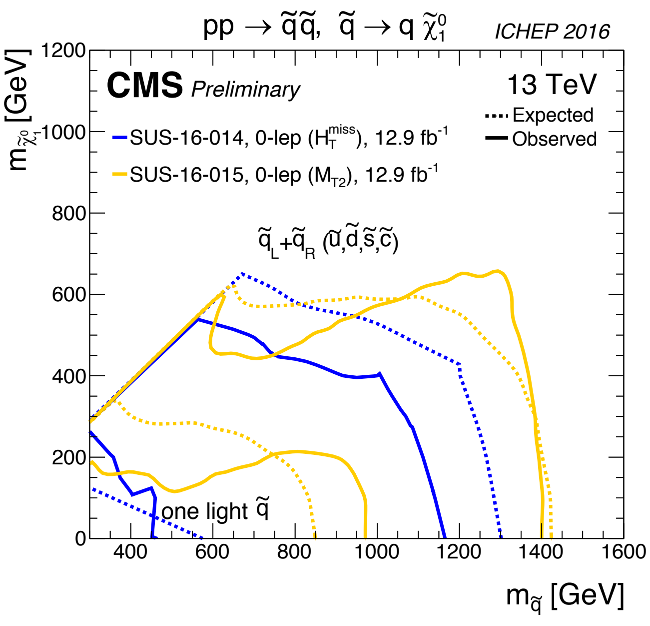






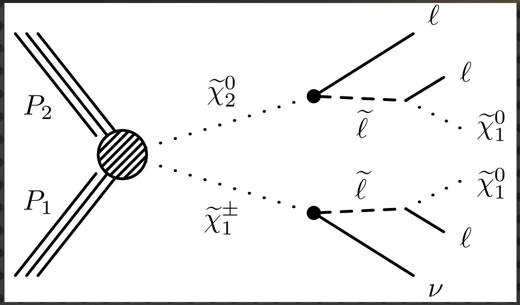


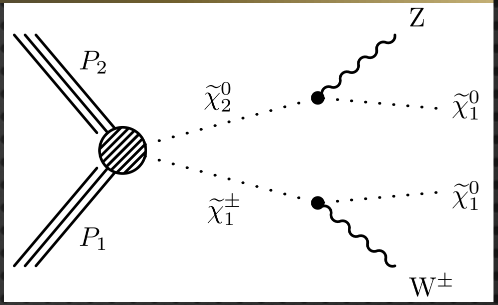


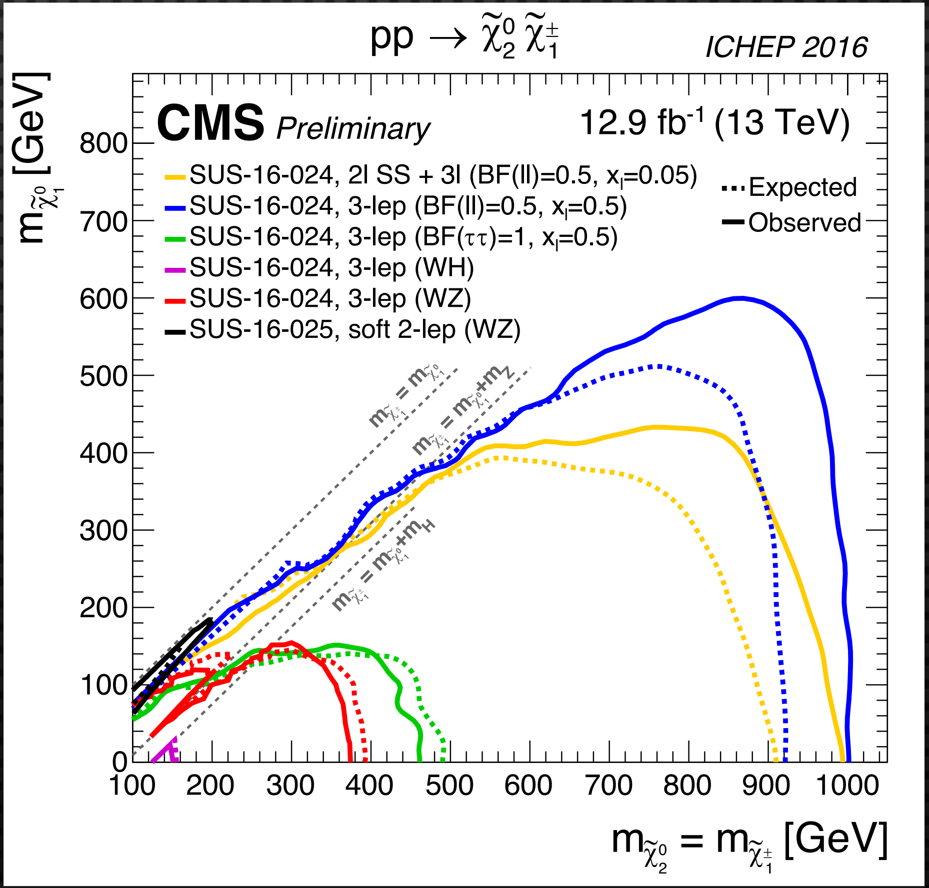


Other SUSY searches

- There are many other CMS searches for SUSY.
- These generally include some number of leptons (e/μ/τ) and/or target more specific models.
- Example of electroweak production (instead of strong production) with leptons in the final state.

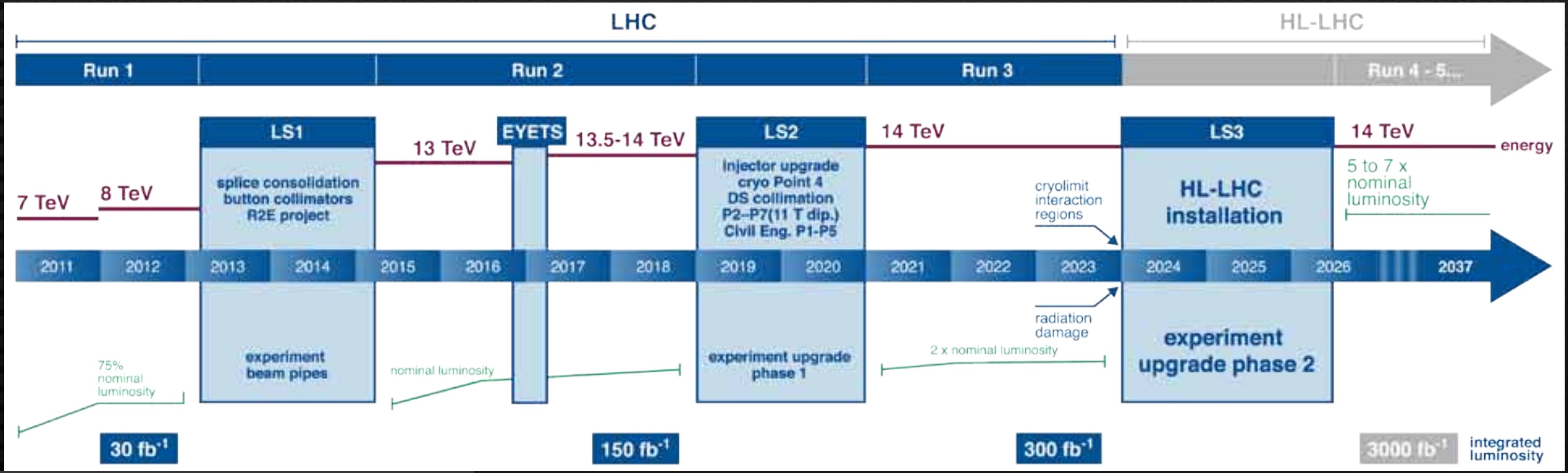






What does the future hold?

- Analyzing remaining data from 2016 (30 fb^{-1} total).
- By 2023, this will increase to 300 fb^{-1}. Will greatly expand the reach of our searches for new physics.
- After major upgrades of LHC and detectors, will collect 3000 fb^{-1} from 2026-2037 for another big increase in sensitivity. Upgrades are being designed now.
- Also expand searches to include more SUSY parameter space.



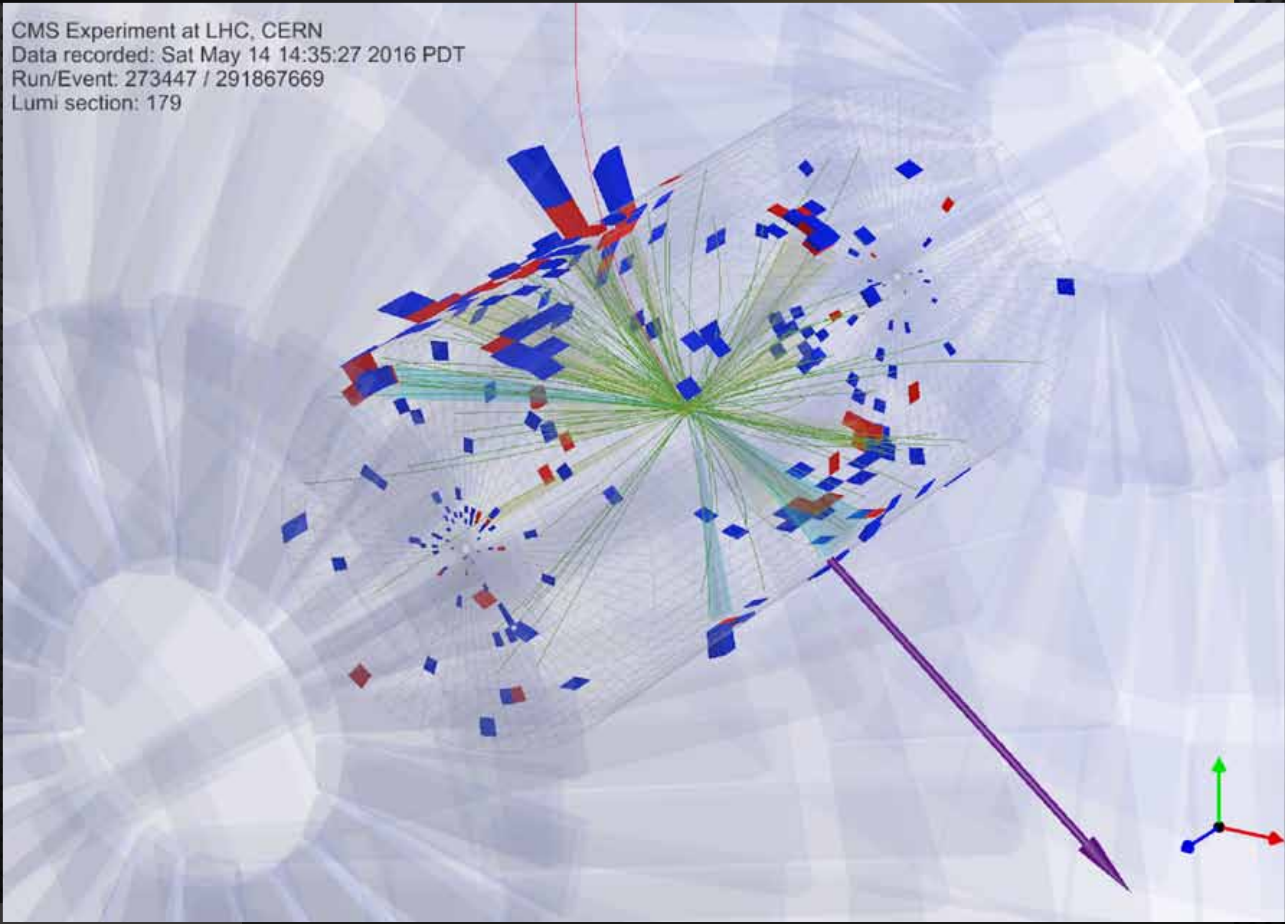
Summary

- Many people thought SUSY would have already been discovered at the LHC.
- As the mass limits increase, it becomes less of a solution to the hierarchy problem (the cancelation of quantum corrections is reduced as mass difference increases).
- SUSY is still the most popular theory but has lost some luster.
- Many other theories have been proposed, often involving some sort of extra dimension(s) to explain the weakness of gravity.
- CMS is pursuing dozens of searches to find what is beyond the Standard Model.

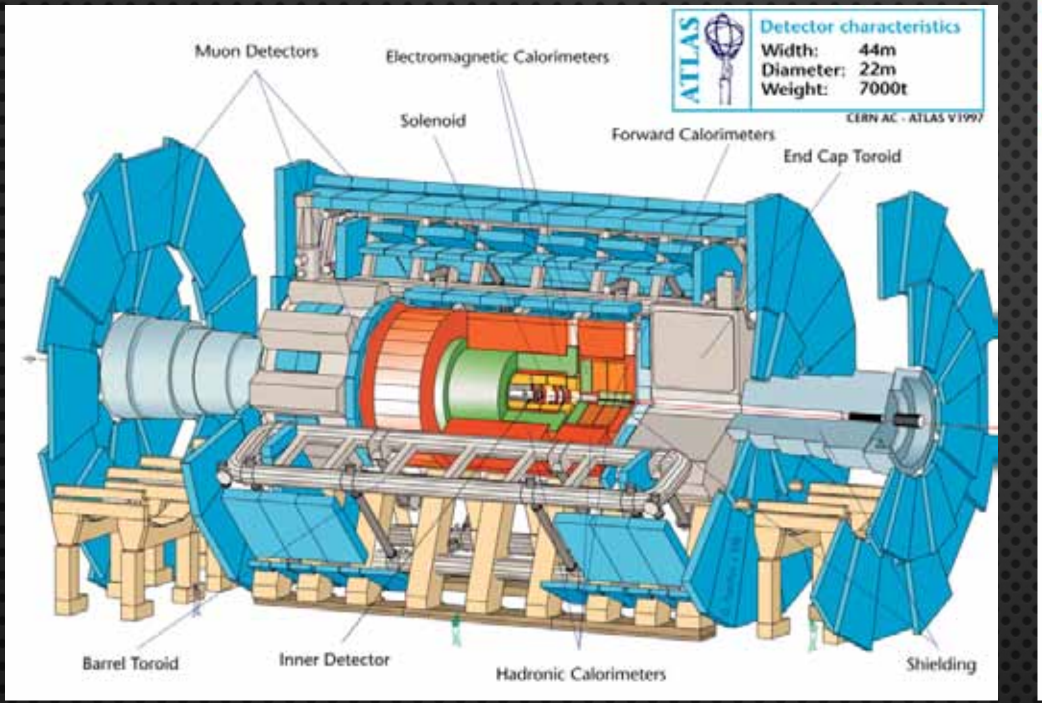
Backup

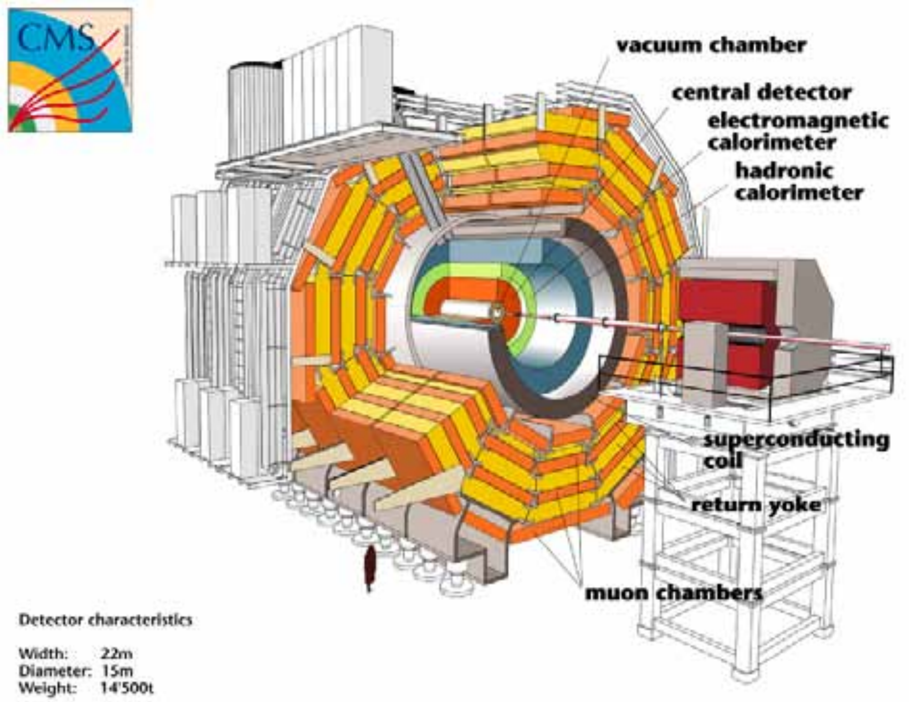
Possible SUSY event

This event contains 12 jets, 3 b-jets, and large MHT.

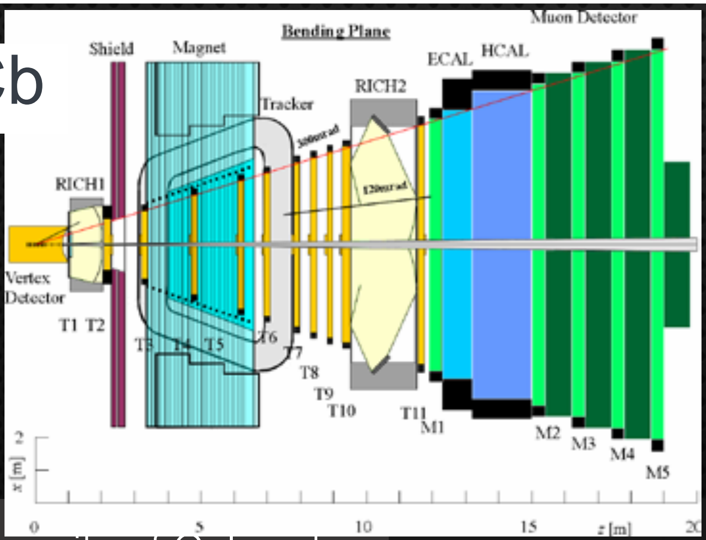


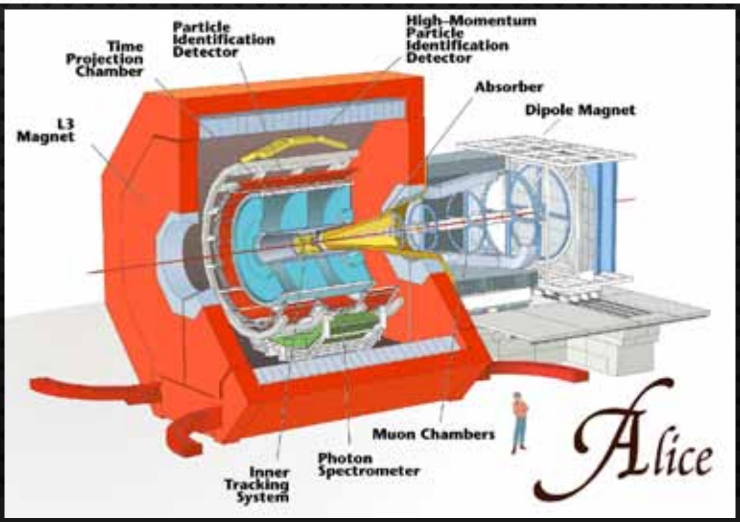
The LHC detectors





LHCb

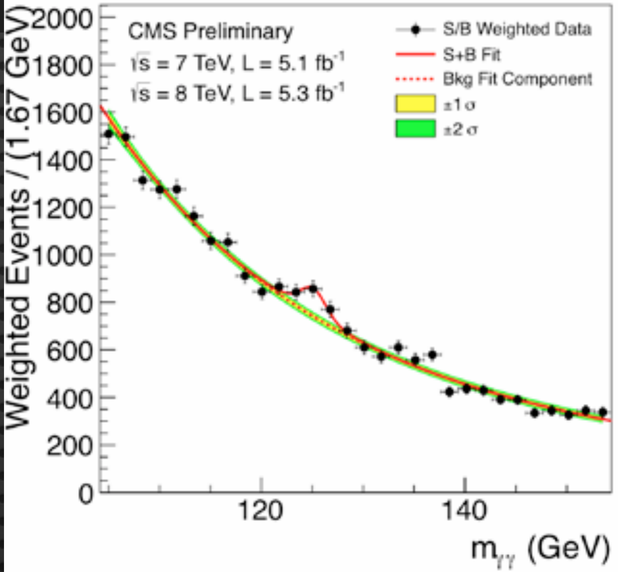


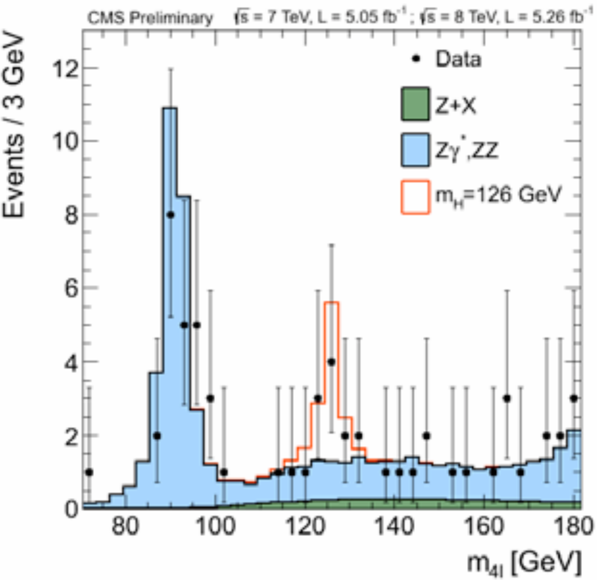


More photos to end on…

The evidence for the Higgs boson from CMS

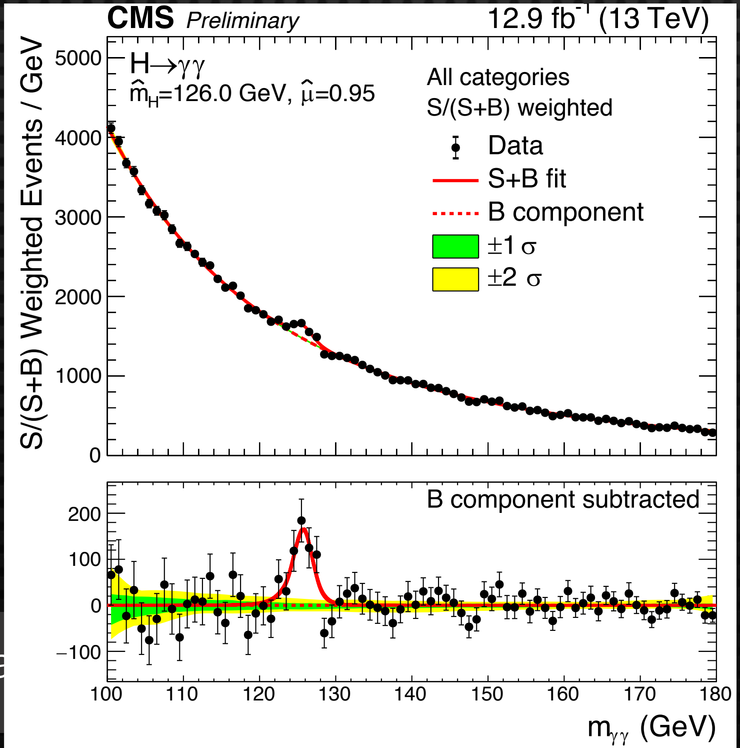
From the July 4, 2012 announcement, evidence of H→γγ and H→llll.

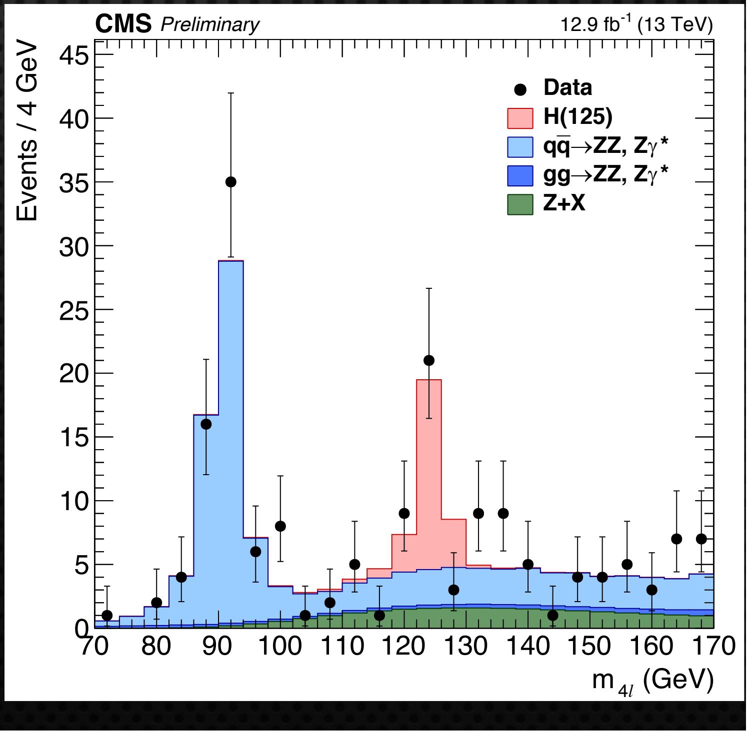




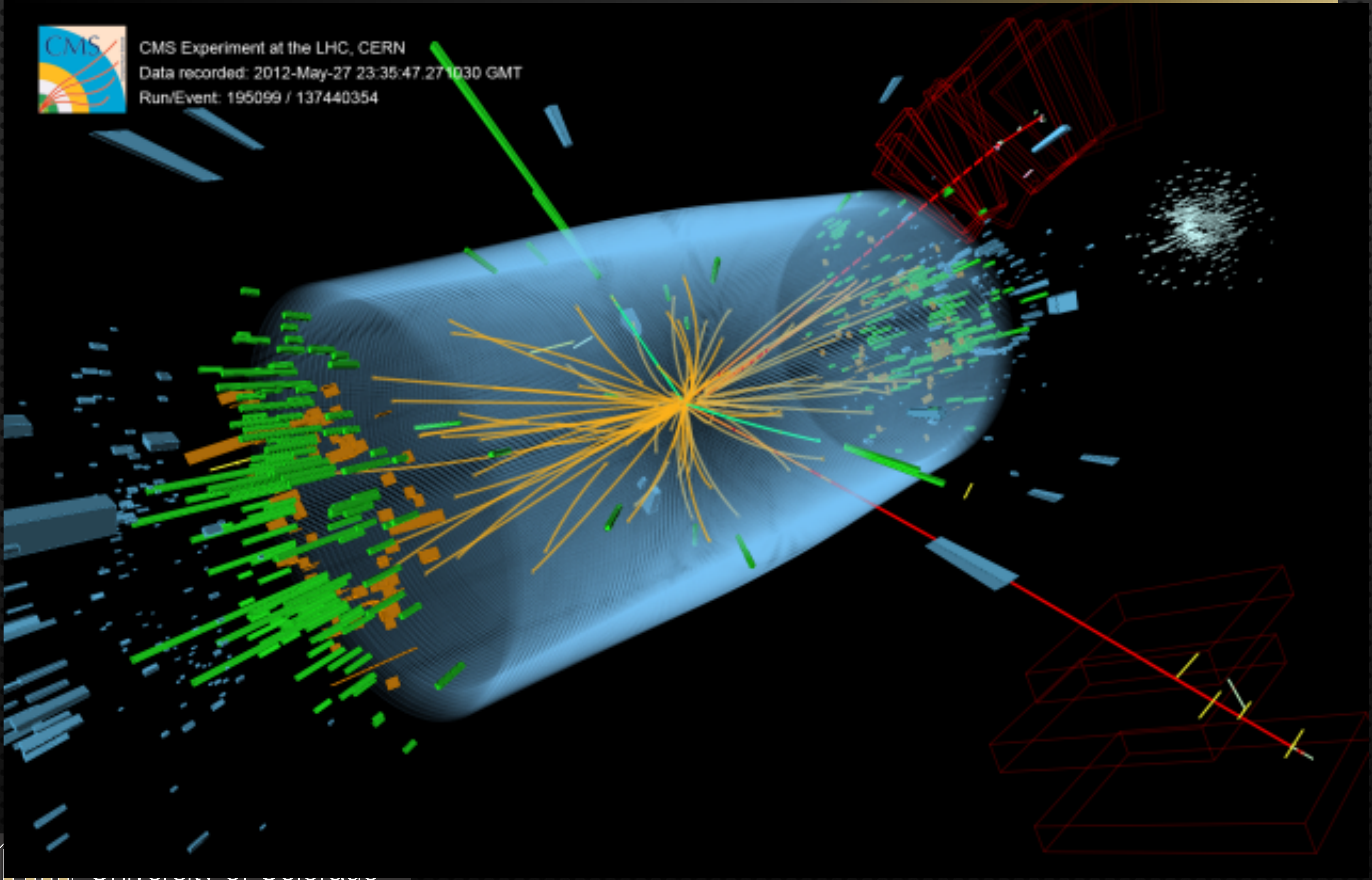
Most recent results from data collected in 2016 and shown in August.

University of Colora
Boulder



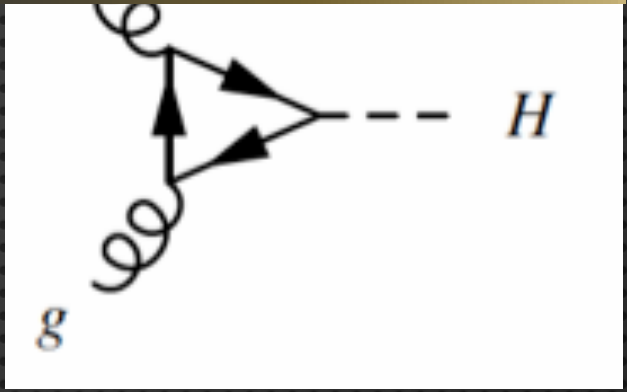


Possible Higgs decay: H→ZZ→ee$\mu\mu$

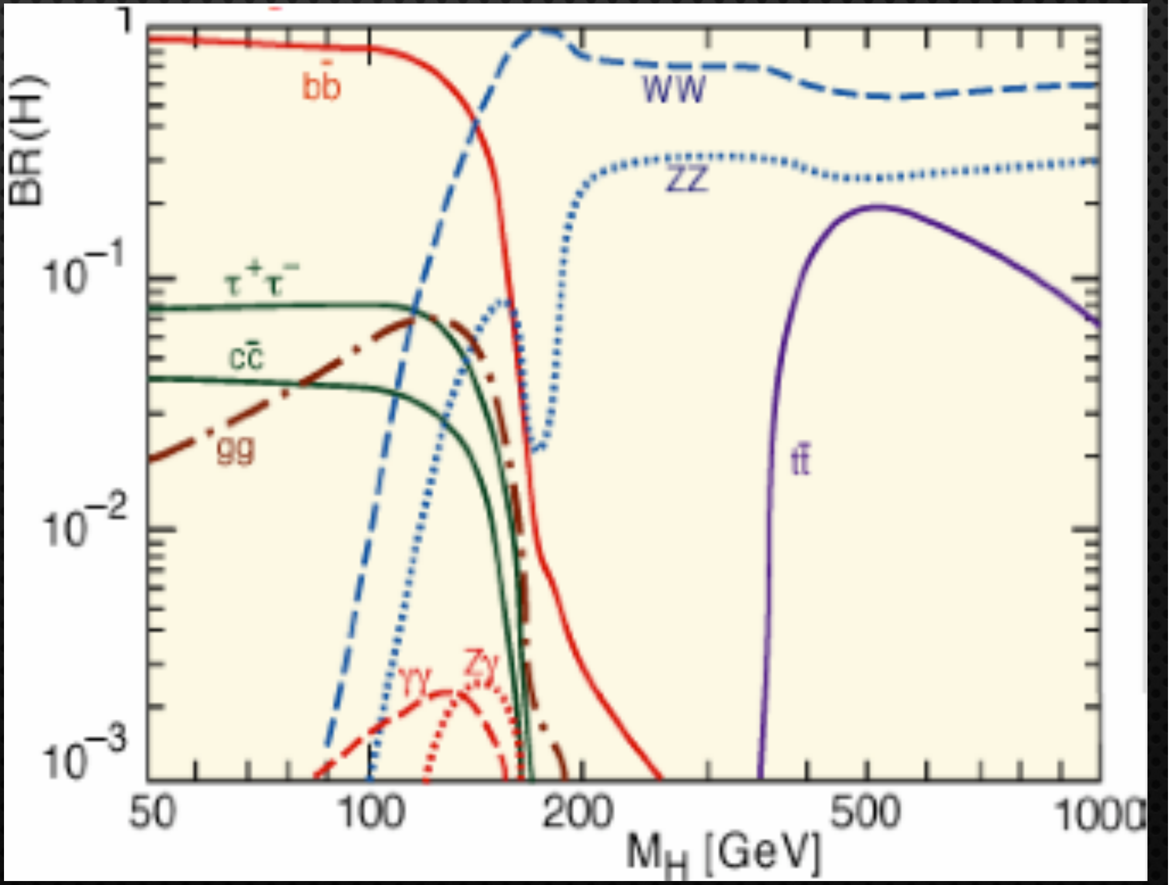


Higgs production and decay

- Two gluons inside the colliding protons fuse to make a Higgs boson.



- The Higgs is unstable so it decays into other particles, some of which also decay.
  - H→$\gamma\gamma$ and H→ZZ are the most important.



Searching for supersymmetry

A few rules for most SUSY searches:

- squarks and gluinos are predominantly produced because they couple to the strong force
- SUSY particles produced in pairs (R-parity conservation)
- Decay cascades end with lightest supersymmetric particle (LSP) which escapes detection.
  - Cascades produce jets & leptons (electrons, muons, taus)
  - The escape of LSP's results in missing energy (MET).

These rules suggest search strategies:

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET