Searching beyond the Standard Model at the LHC

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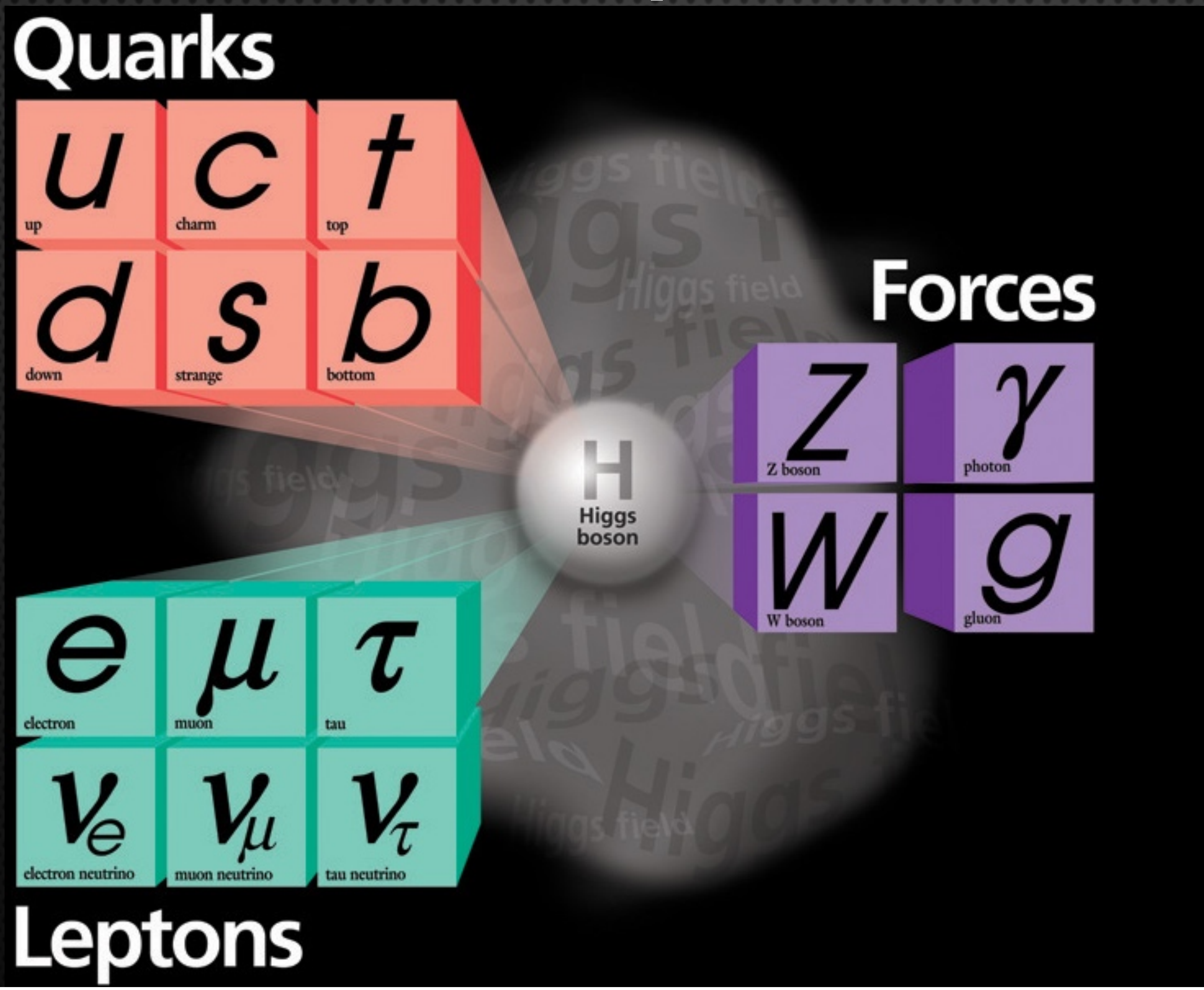
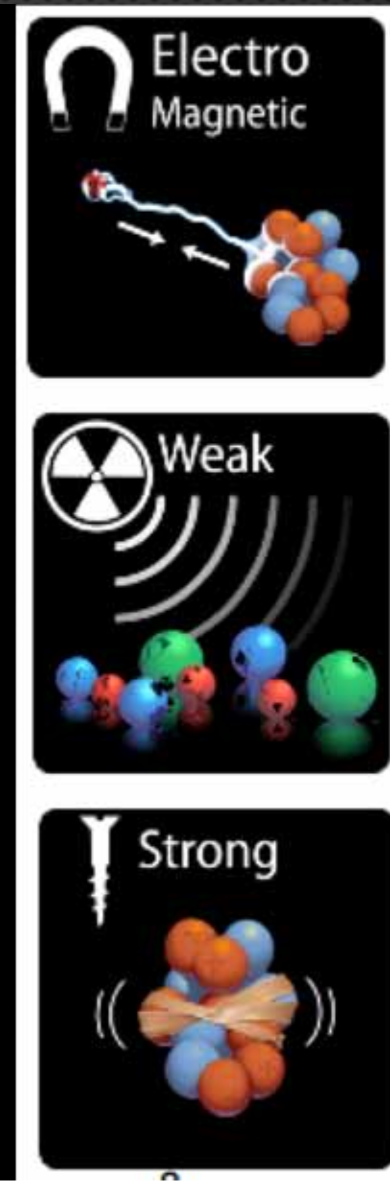
Halloween, 2018

Funding through DOE:
DE-FG02-13ER41921

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…

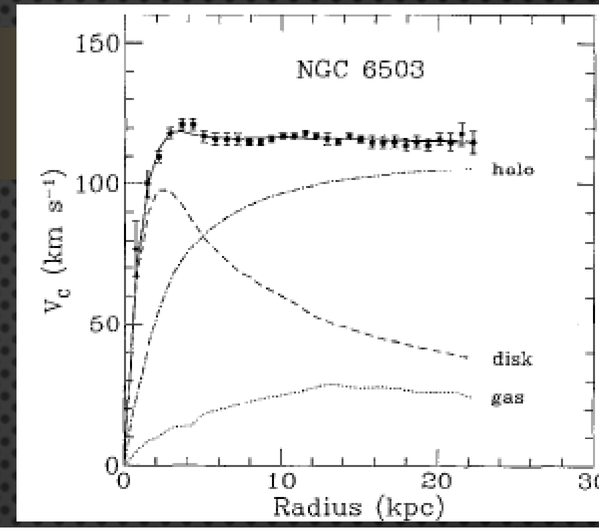
- How come the Higgs boson mass is so light?
- What is the source of dark matter?
- What is the nature of dark energy?
- What happened to all the antimatter in the universe?
- Why are there 3 generations of quarks and leptons?
- How do neutrinos get their mass?
- Are neutrinos Dirac or Majorana particles?
- Is there a Grand Unified Theory (and can we reduce the 26 parameters of the SM)?
- Are baryon and lepton number really conserved does the proton decay)?
- Why no CP violation in strong interactions?
- What is the quantum theory of gravity?

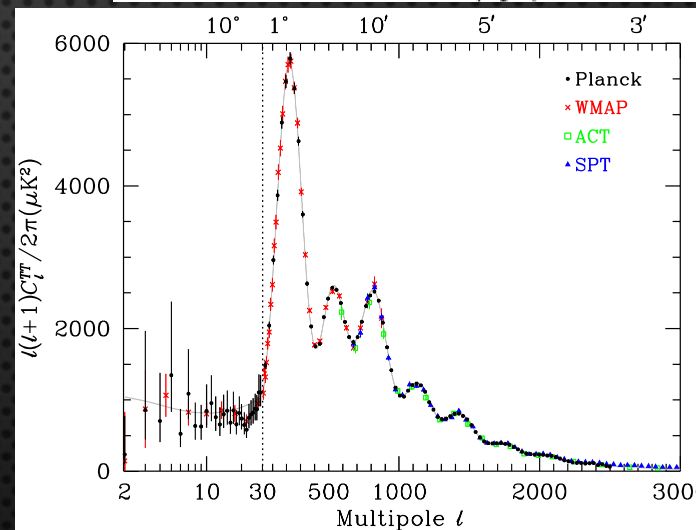
Why is the Higgs boson so light?

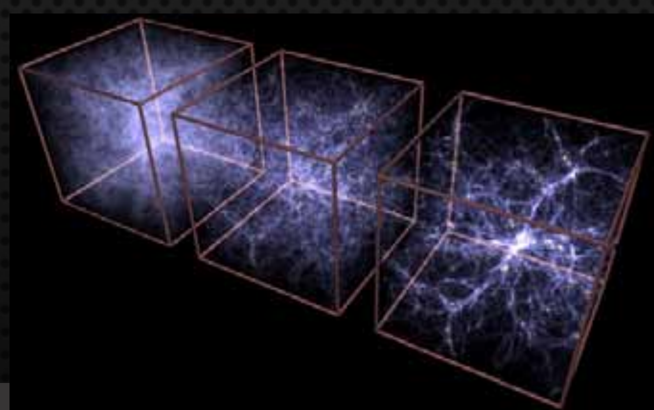
- The SM is known to work up to an energy of ~1 TeV.
- It is expected to break down before the Planck scale (10^{16} TeV) where quantum gravity should appear.
- So the SM cutoff scale, labeled Λ, should be $<10^{16}$ TeV
- Quantum corrections to the Higgs mass in the SM contain should result in a mass 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

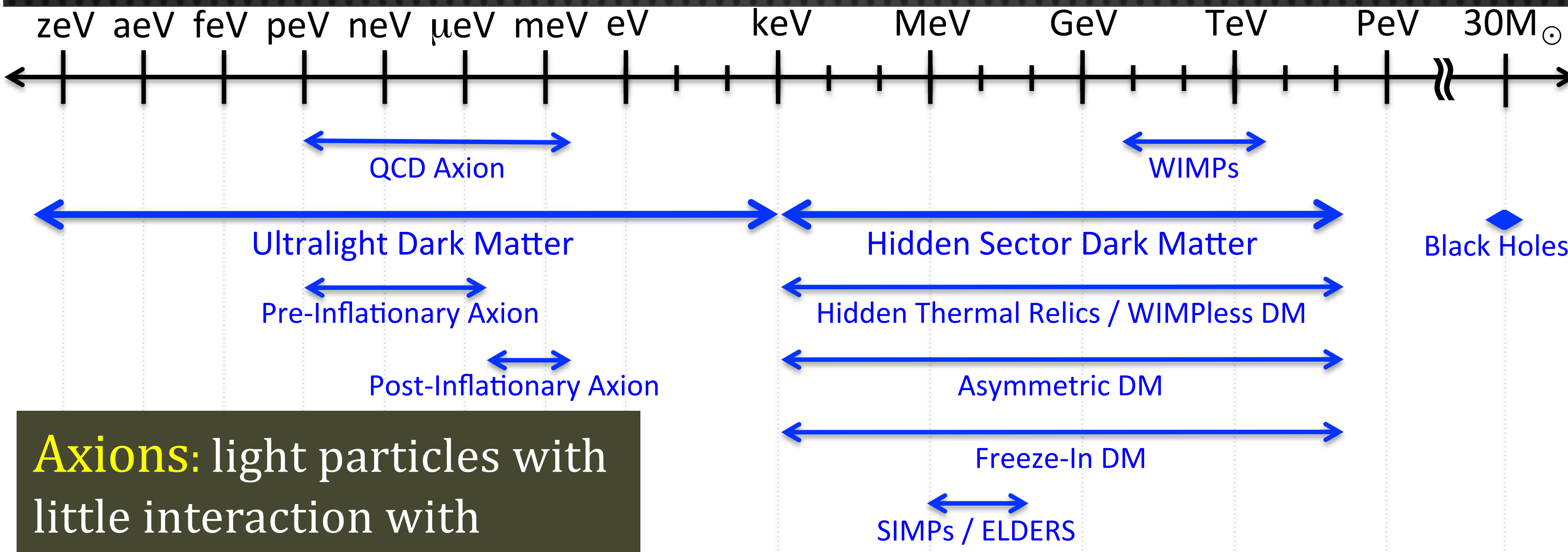
- Galactic rotation curves indicate invisible matter in a spherical halo.
- Cosmic microwave background finds more than normal matter.
- Gravitational lensing of Bullet Cluster shows dark matter behaves differently than ordinary matter.
- Large scale structure of the universe only makes sense with dark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







Many dark matter possibilities



Axions: light particles with little interaction with normal matter; originally proposed to explain lack of CP violation in strong force.

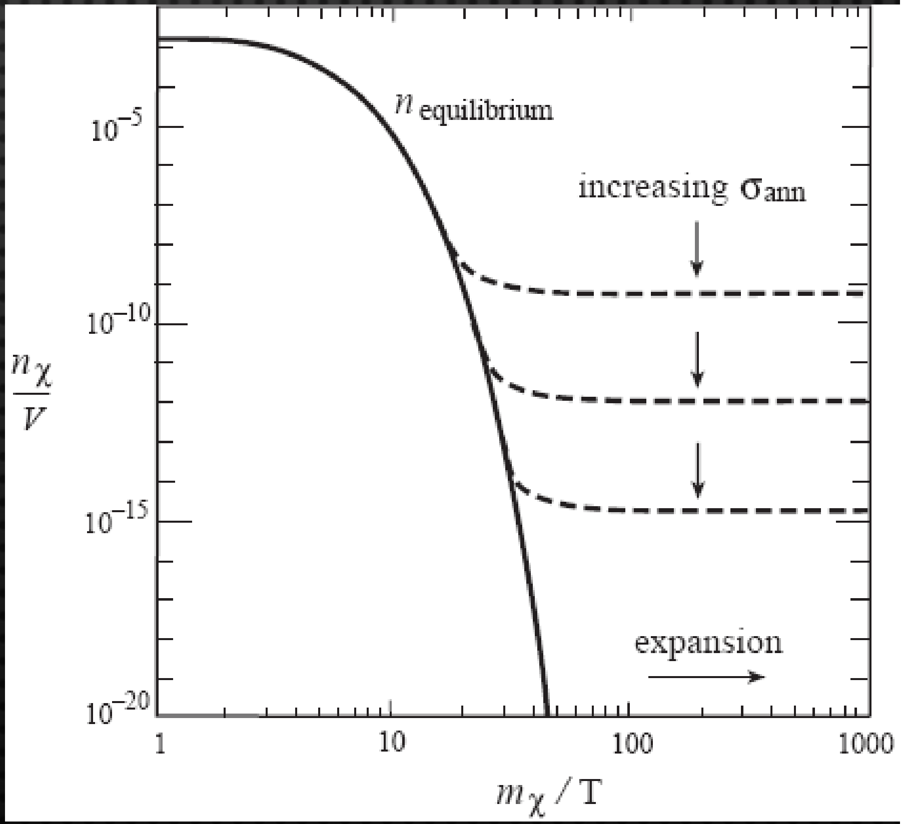
Dark sector: Particles with non-Standard Model interactions.

Sterile neutrinos: ~keV mass, no coupling to W/Z.

WIMPs: Weakly Interacting Massive Particles with mass 0.01–10 TeV that interact via weak force.

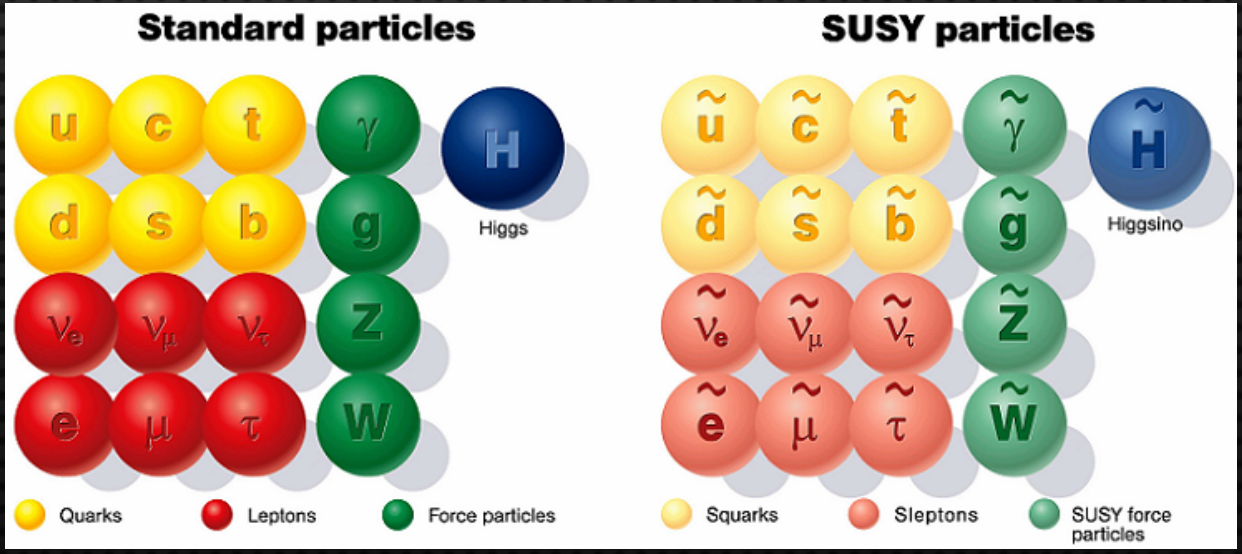
WIMPs seem to be an ideal solution

- 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 ~ weak interaction. Called the "WIMP miracle".



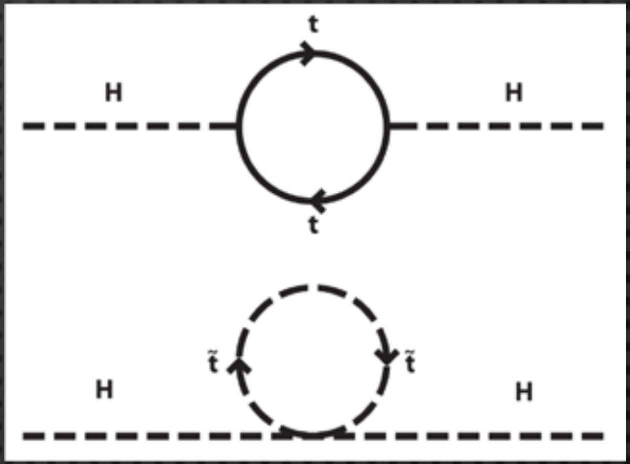
Minimal Supersymmetric Standard Model

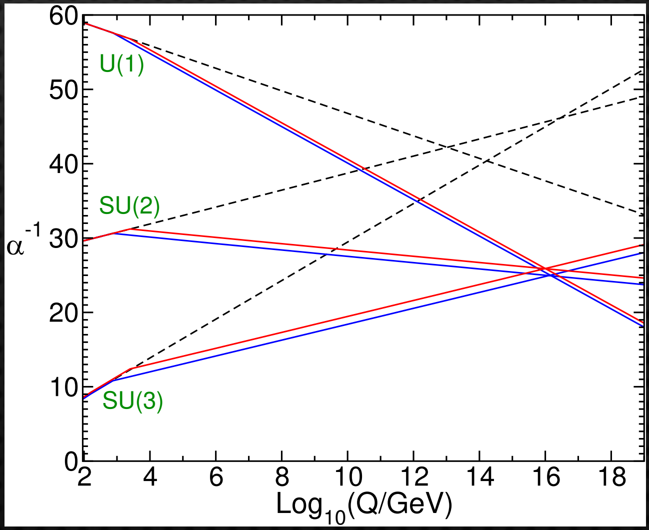
- Adds an additional symmetry (supersymmetry or SUSY) in nature between bosons and fermions
- Each SM particle has a partner particle (sparticle) with same quantum numbers except spin differs by ½
- Get cool names like sleptons, winos, sbottom
- Consider *R*-parity conserving models today: sparticles 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 (GUT).

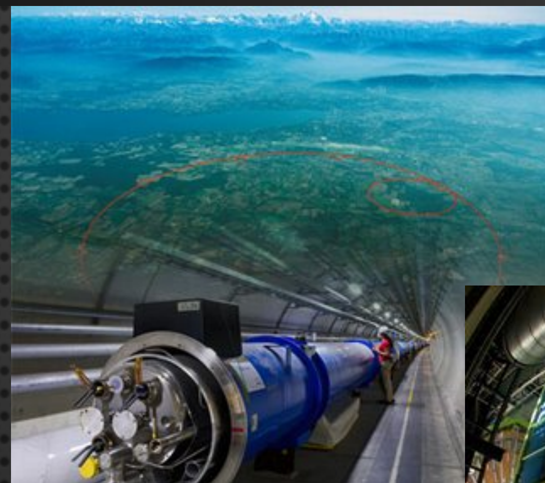




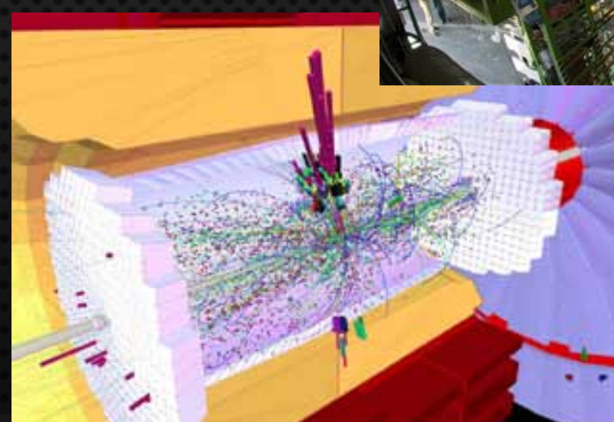
The less great features of SUSY

- 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.
- We have no idea how the symmetry breaking is done so this opens up all sorts of possibilities: 105 additional free parameters. These dictate the masses and decay patterns of the particles.

How do we look for new physics?



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

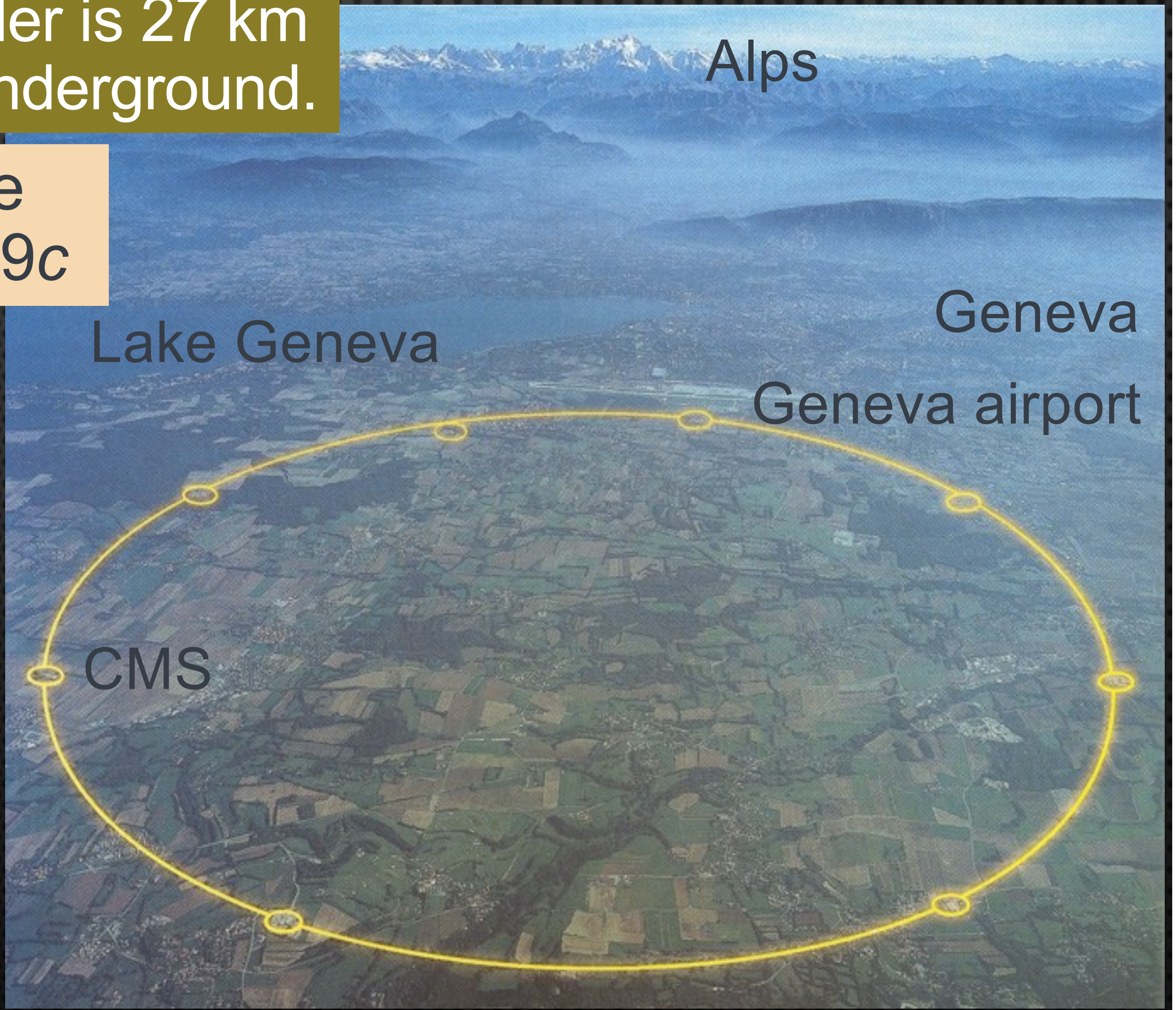


The Large Hadron Collider (LHC)

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

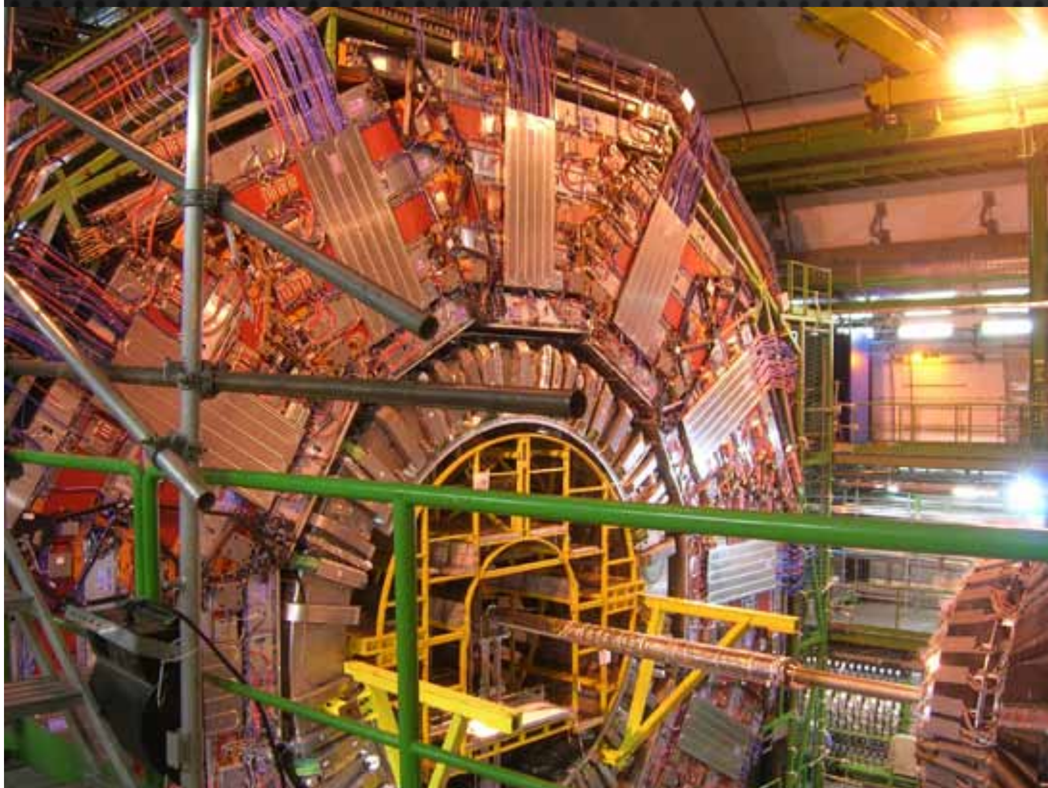


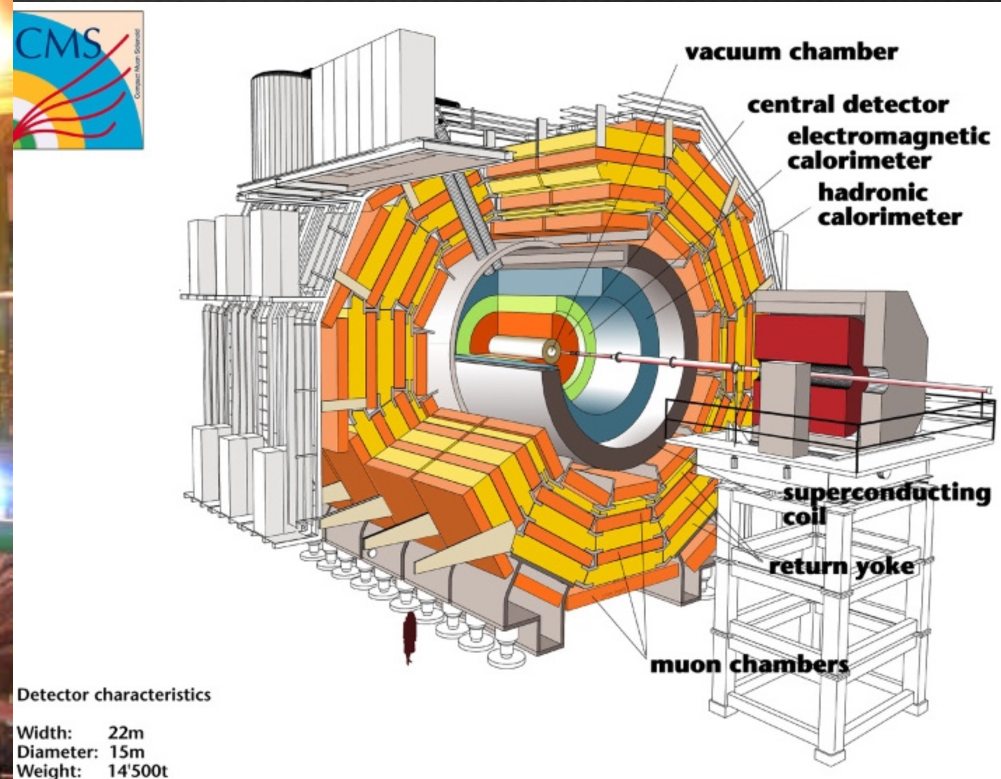
Detecting the particles

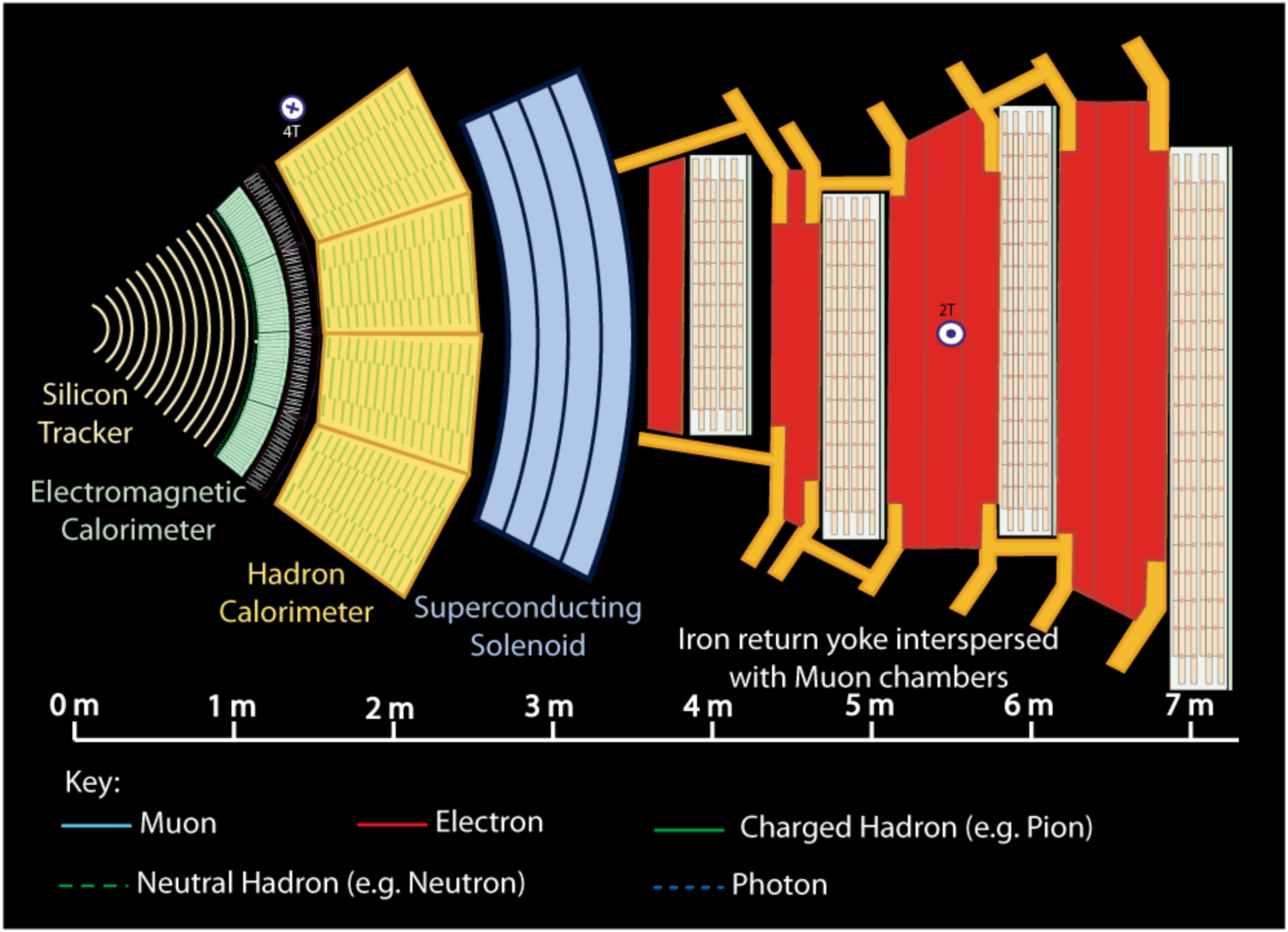
We collide protons at high energy to create new particles.
But these particles immediately decay into other particles.

Need to detect these particles to reconstruct what happened.

The CMS detector is in a cavern 300 feet underground.



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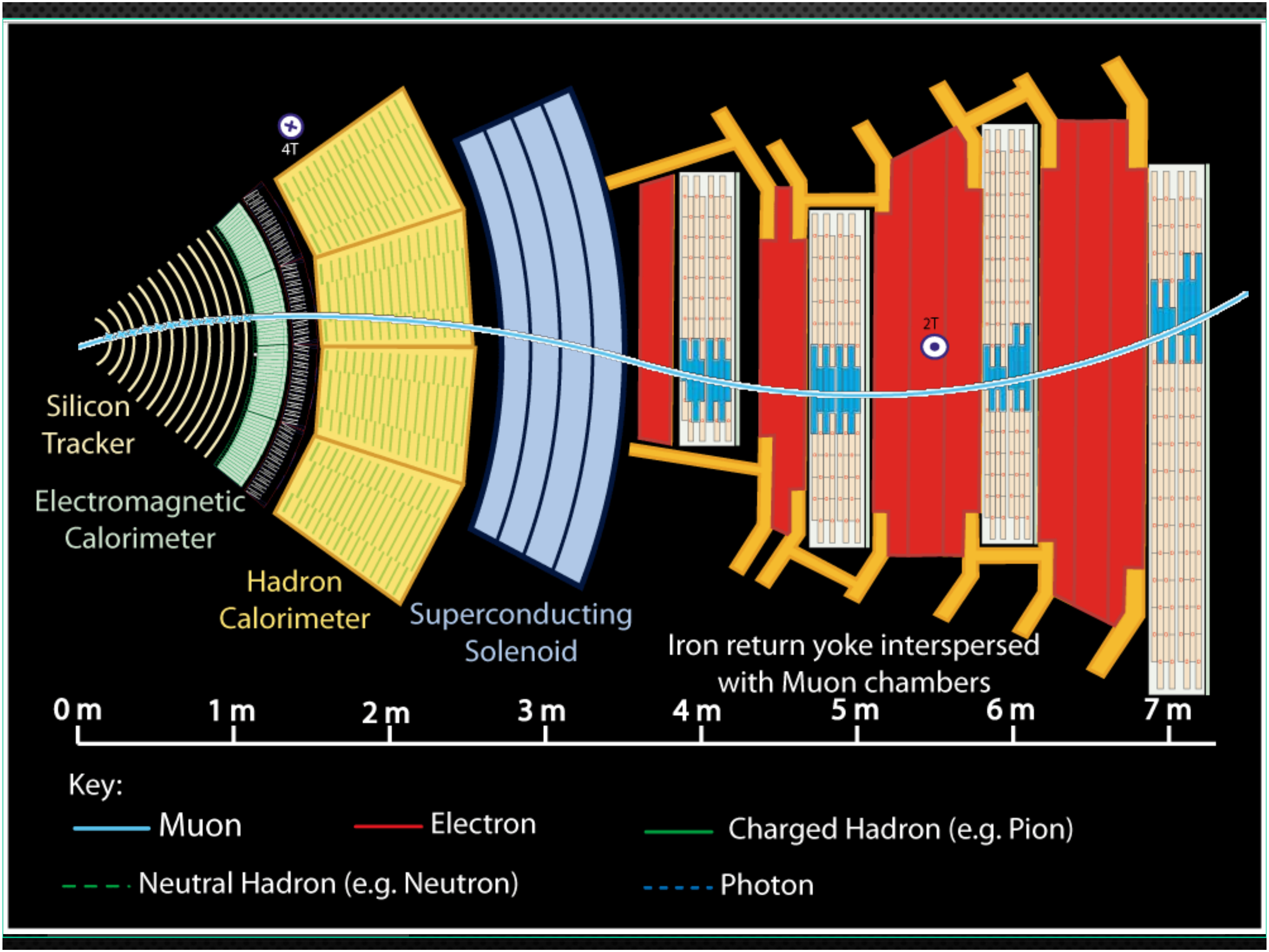
Neutral Hadron (e.g. Neutron)
Photon



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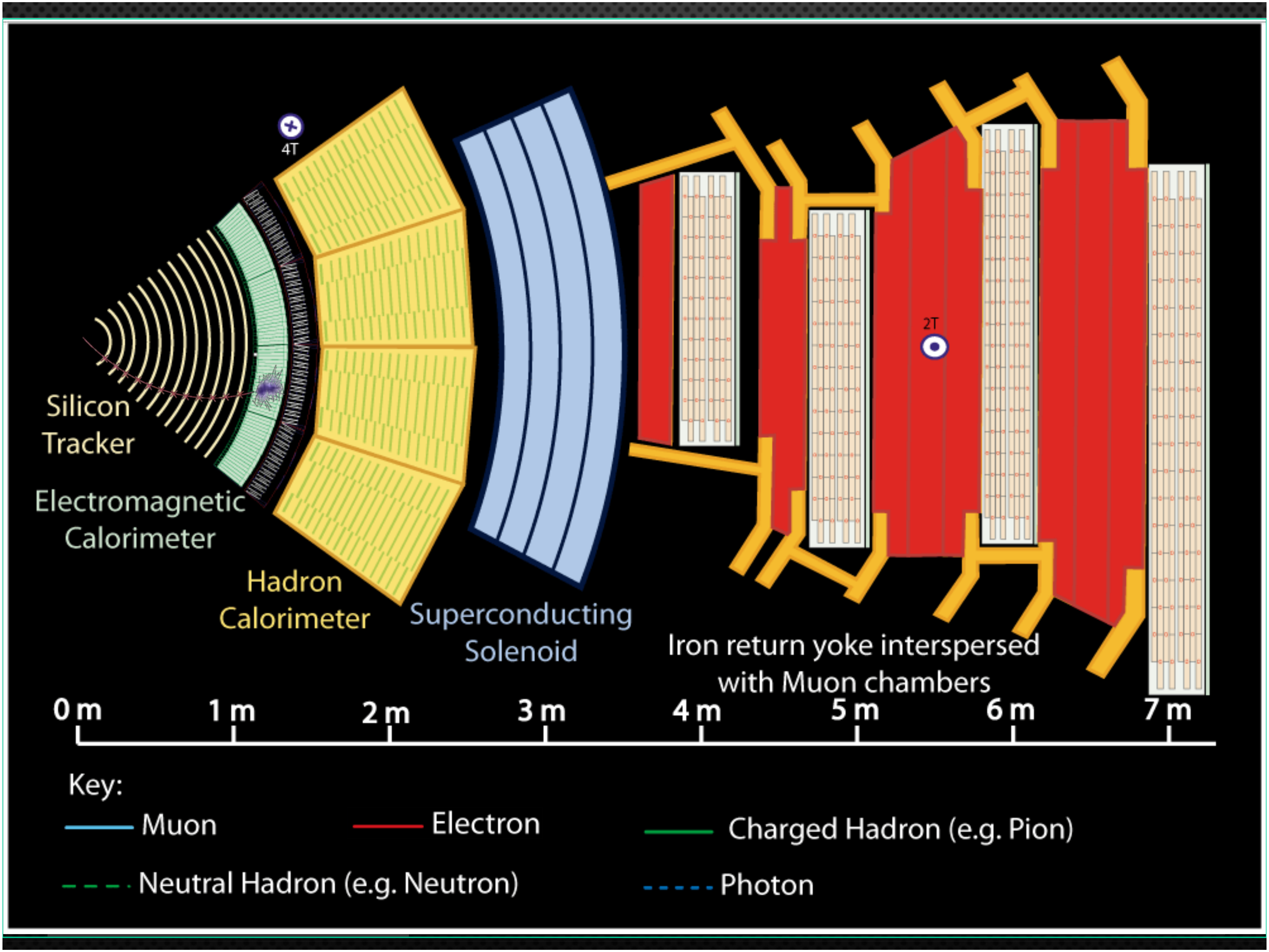
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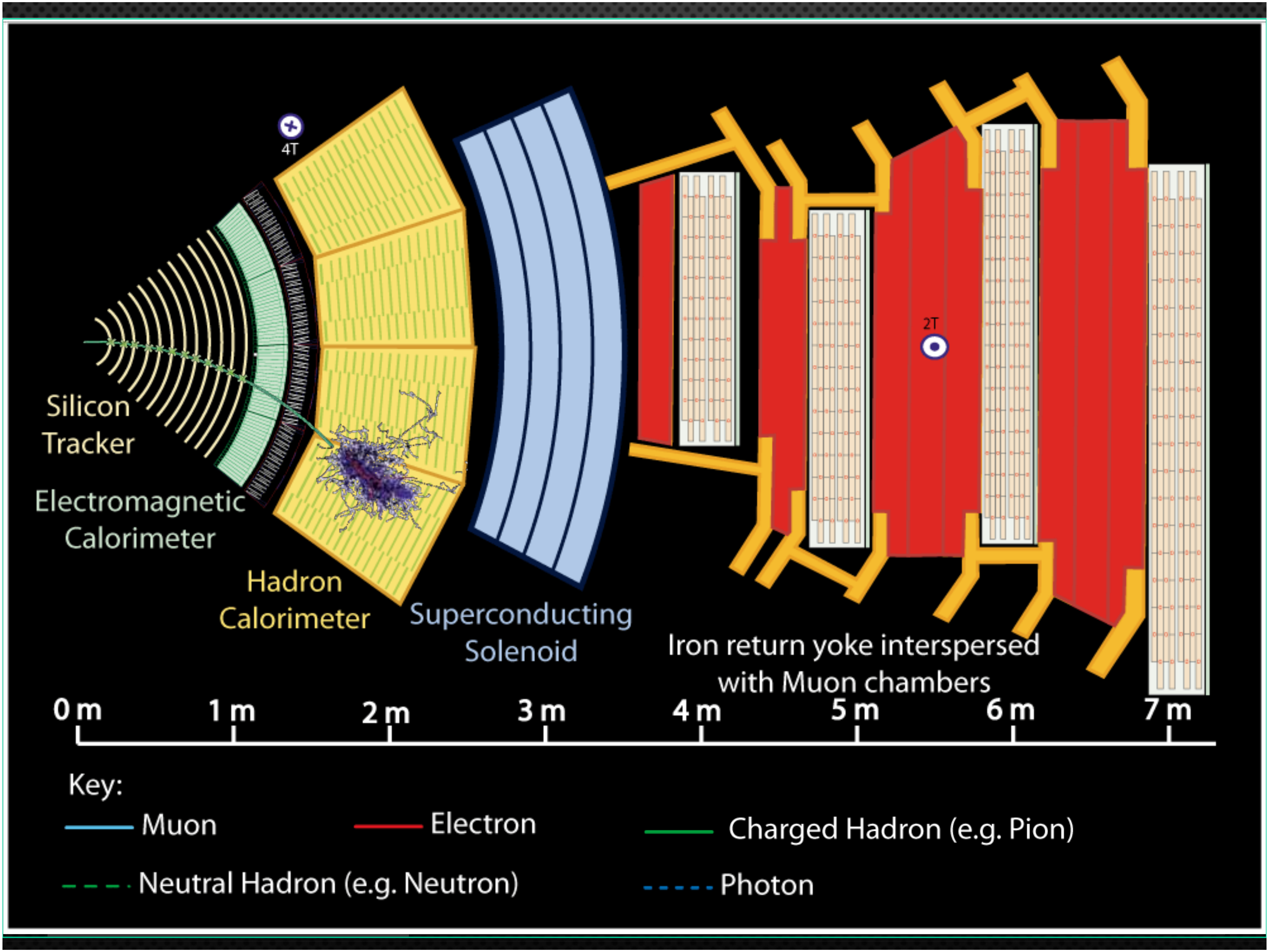
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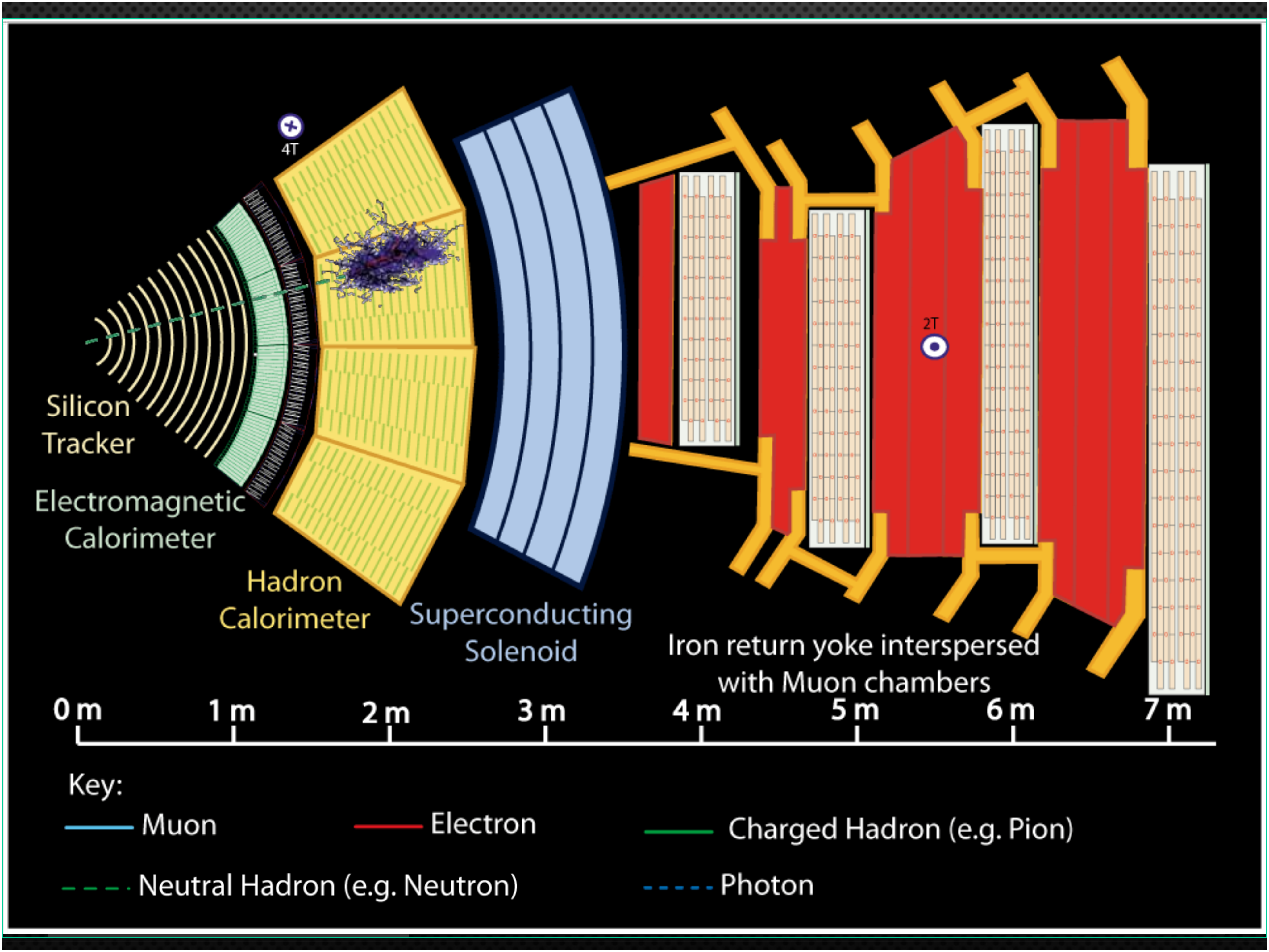
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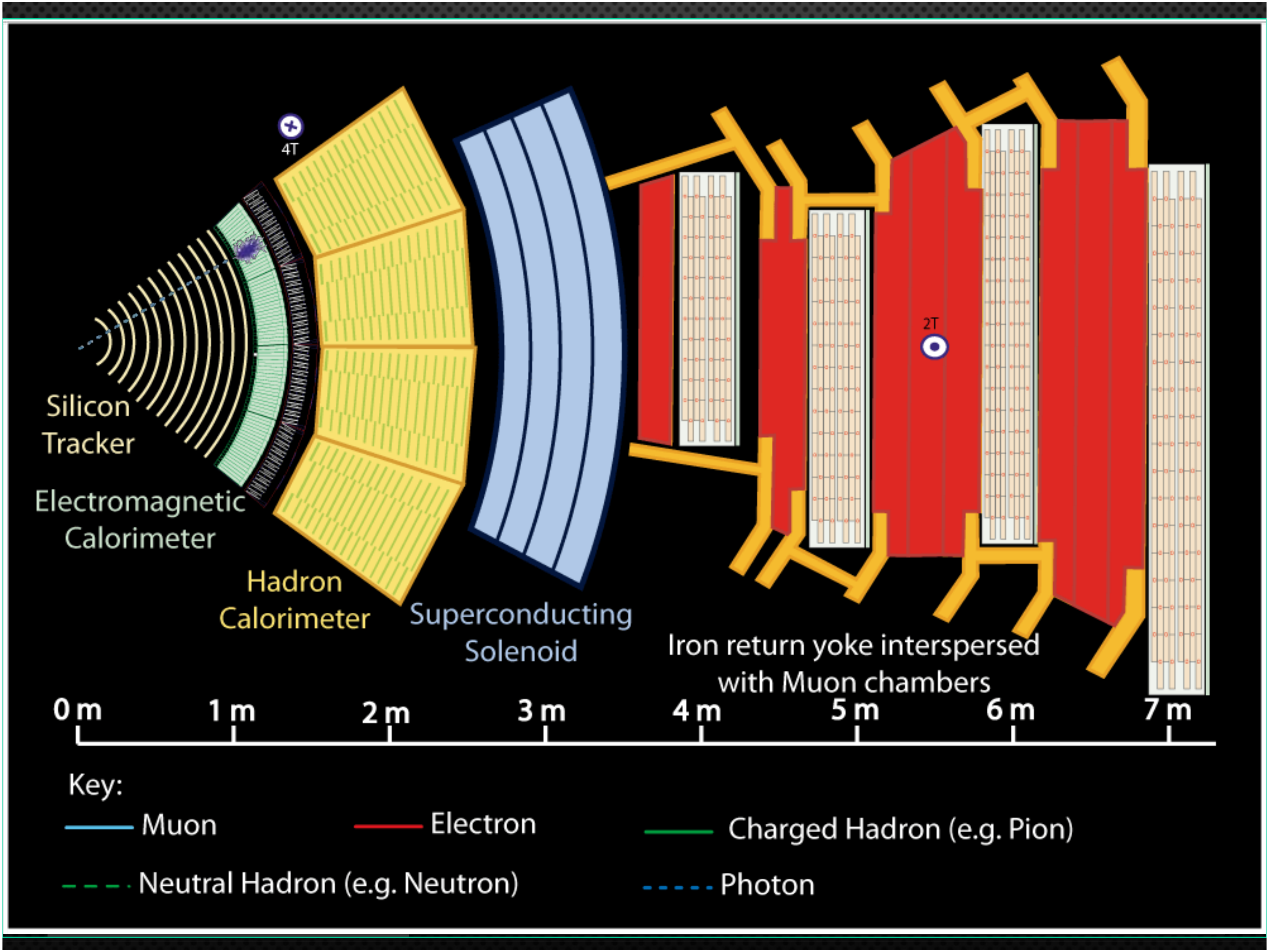
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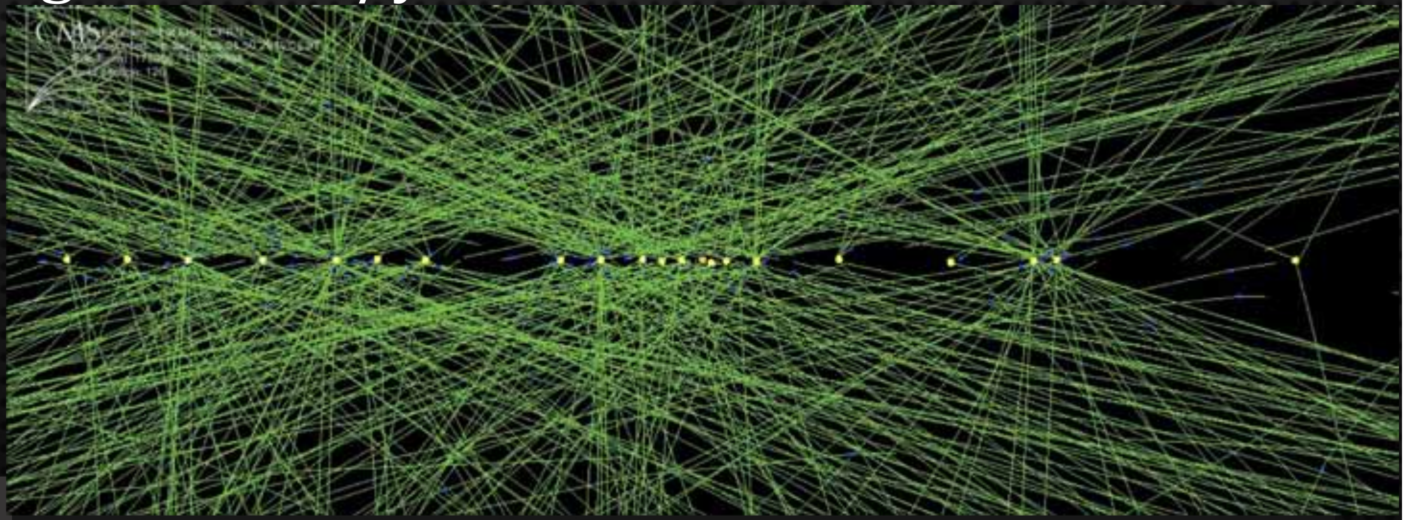
Event selection

- 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 save it if it is. Save about 1000 events/sec leading to 10 PB/year.

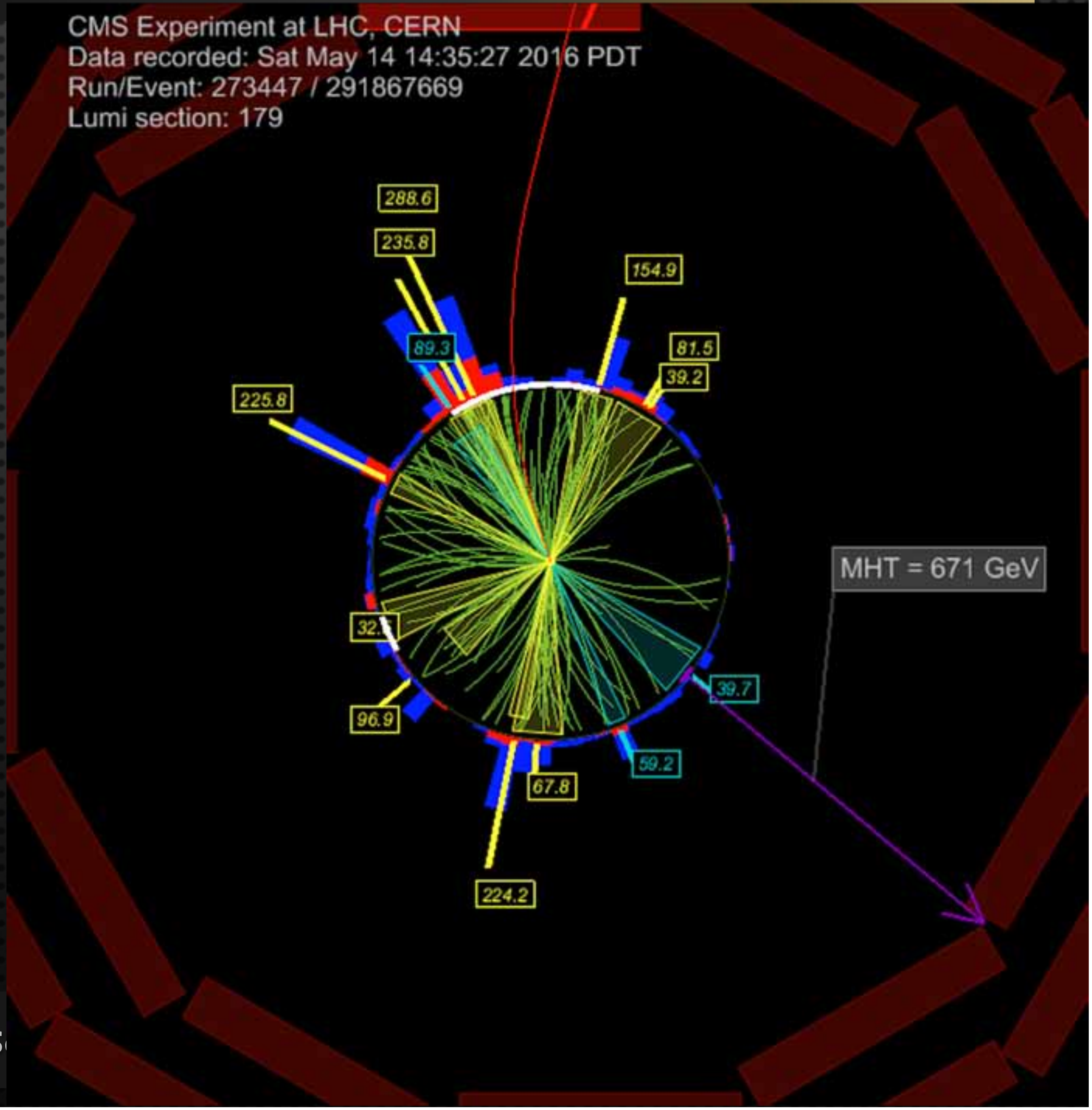


Possible SUSY event

This event contains 12 jets, 3 b-jets, and large amount of missing transverse energy. Great candidate for a SUSY event.

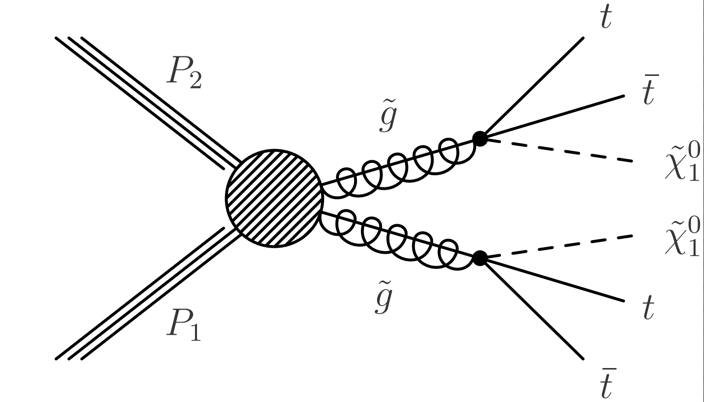
Jets come from the hadronization of quarks (and b jets from the hadronization of b quarks).

Missing transverse energy is the apparent imbalance of momentum after adding everything up.



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 (χ_1^0) , 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 ($\mathbf{N_b}$).

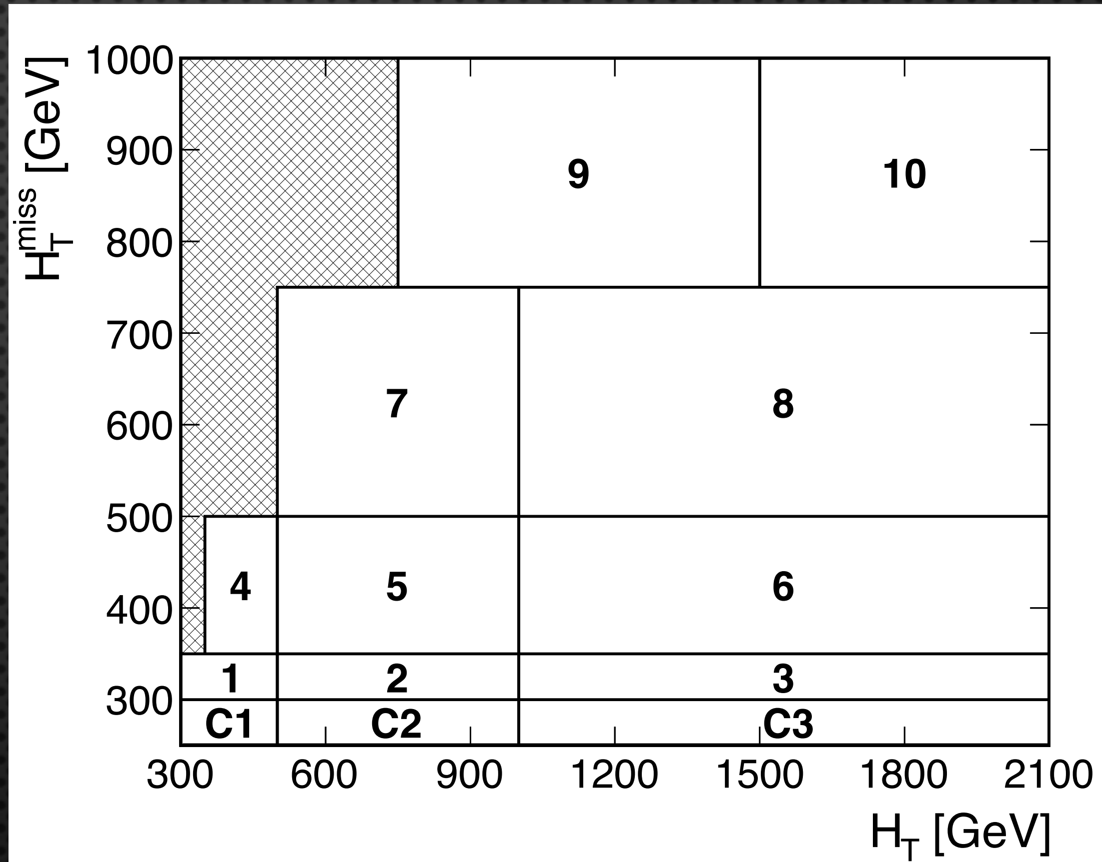
SM backgrounds

- **QCD** : Direct production of many jets with the energy of jet(s) mismeasured, leading to MHT.
- **Lost-lepton** and **hadronic τ** :Production of W+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.
- **Z→νν** : Production of Z+jets where Z decays to neutrinos, producing MHT.

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

Signal region divided into bins

- The HT-MHT plane divided into 10 bins.
- 4 bins of N_{jet}: 2, 3-4, 5-6, 7-8, 9+.
- 4 bins of N_b: 0, 1, 2, 3+.
- Total of 174 bins.



New physics can show up in particular regions so binning increases the sensitivity and flexibility of the analysis.

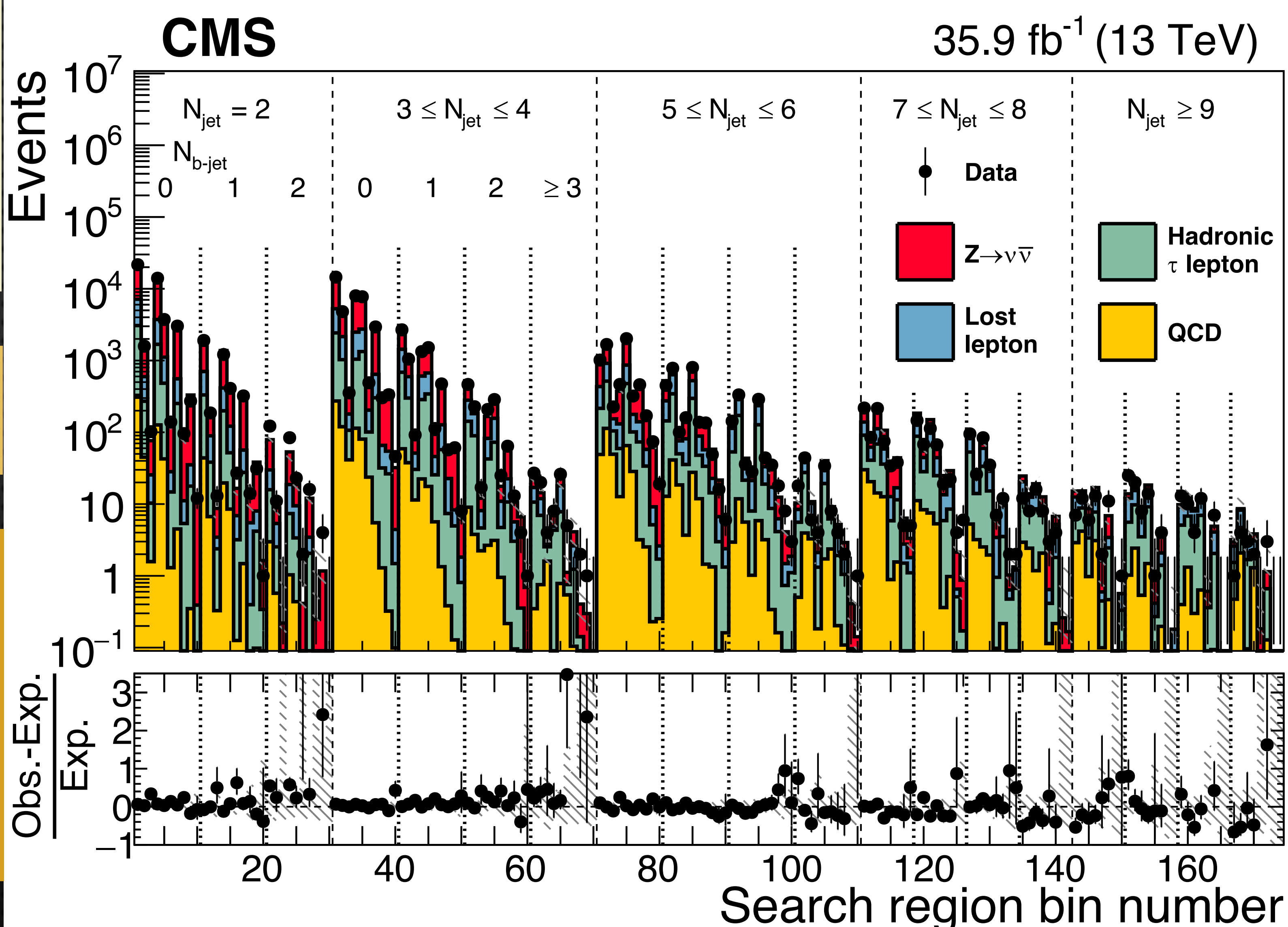
Phys. Rev. D 96 (2017) 032003

Search results

Data consistent with estimated backgrounds. No sign of new physics.

Generic search for new physics.

This plus efficiencies are provided publicly for reinterpretation by theorists.



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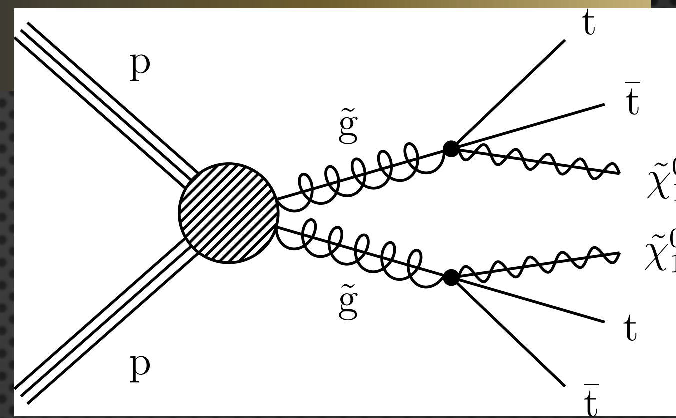
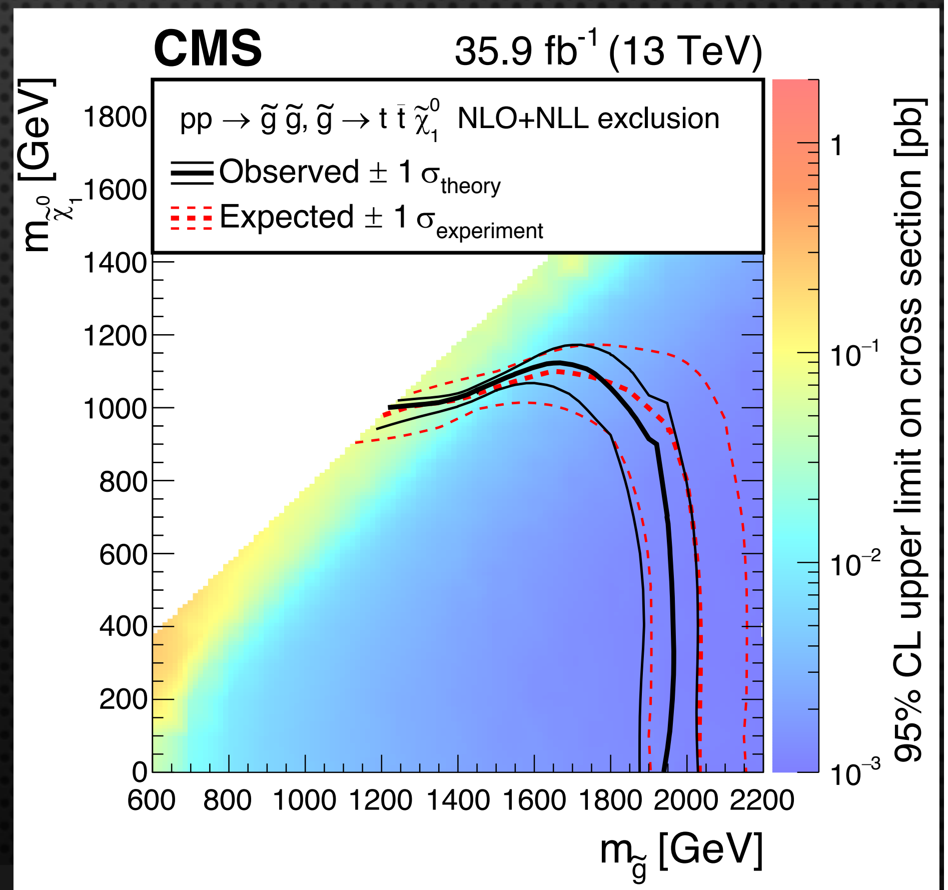
Limits on SUSY production

Simplified Models: Assume a small number of SUSY particles participate with specific decay modes. Can calculate cross sections for these models in terms of one or two masses.



Place limits on maximum cross section in 2D space of LSP mass and gluino mass.



Use calculated cross sections to determine what masses are excluded.

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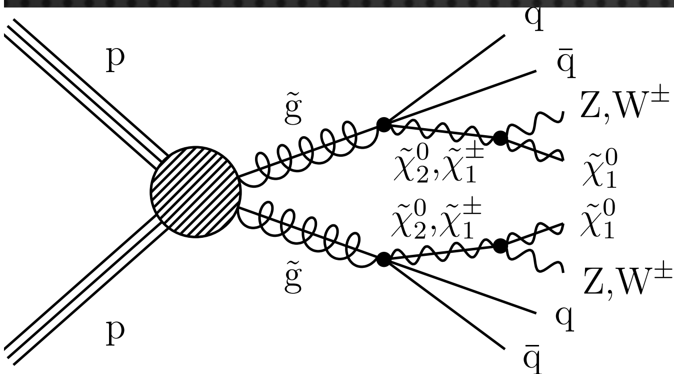
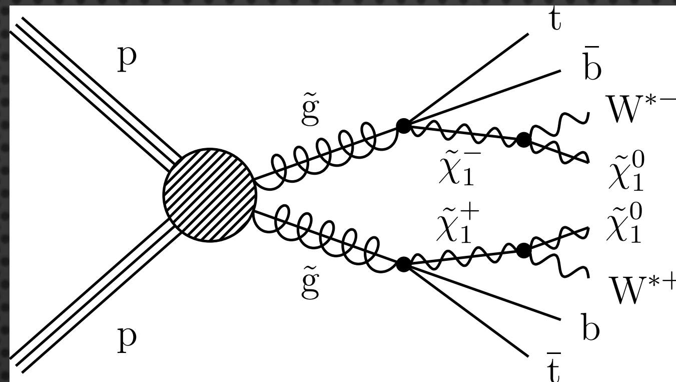
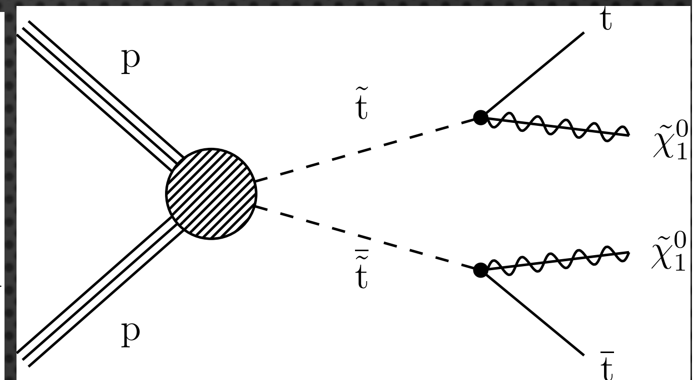
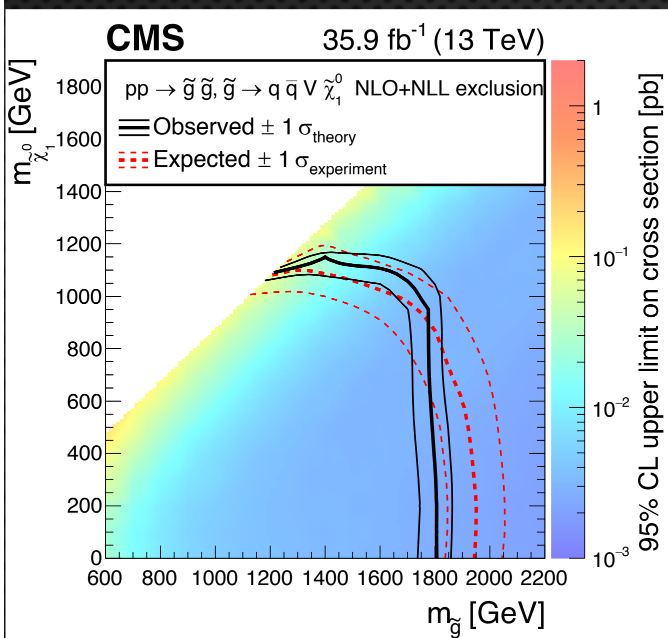
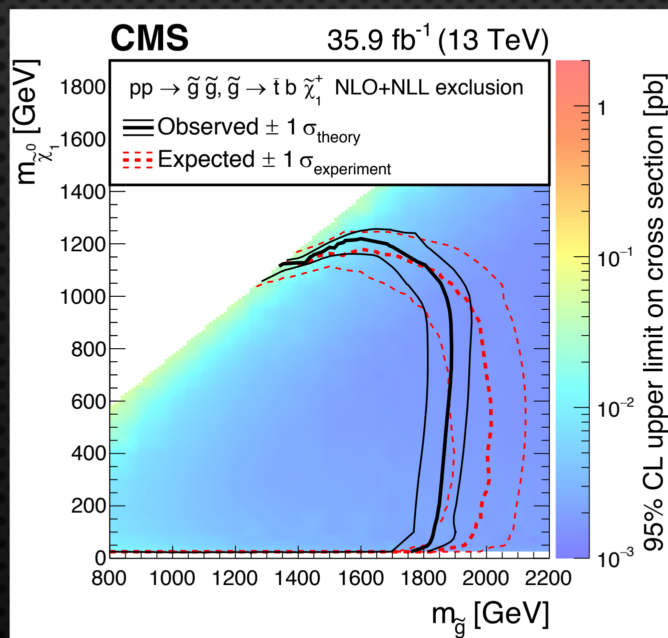
A few other simplified model limits

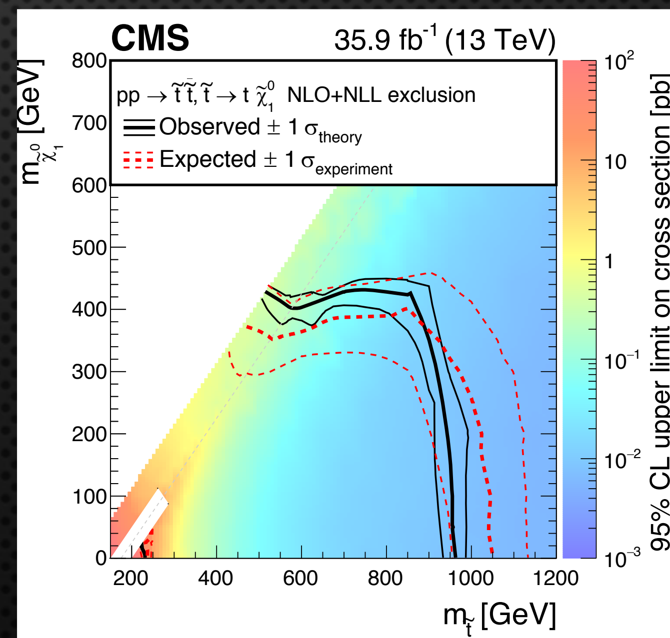






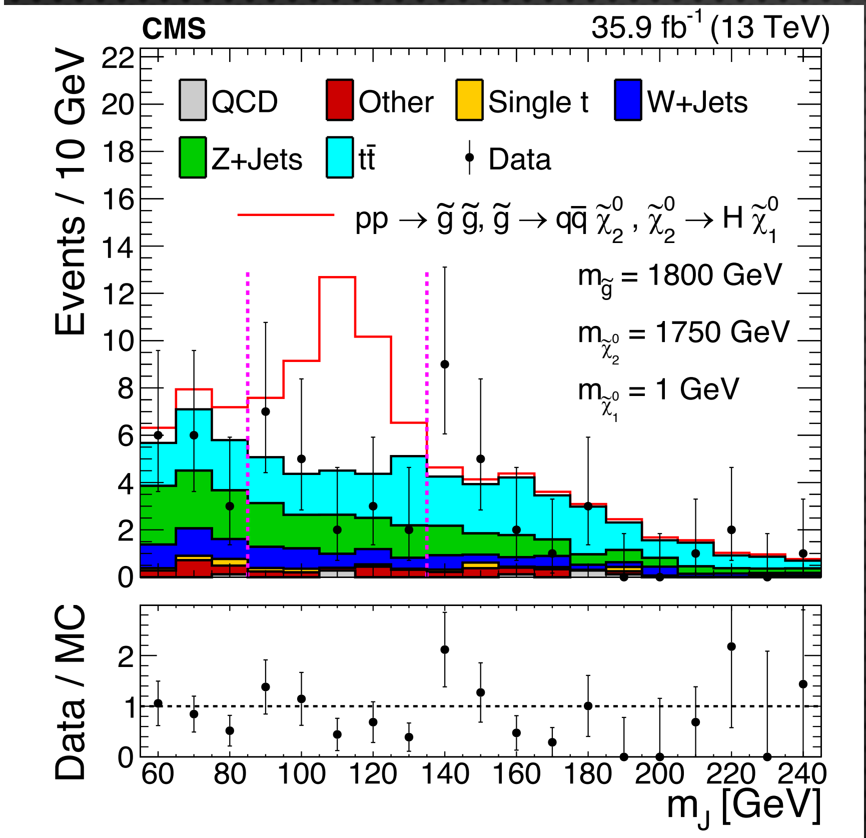




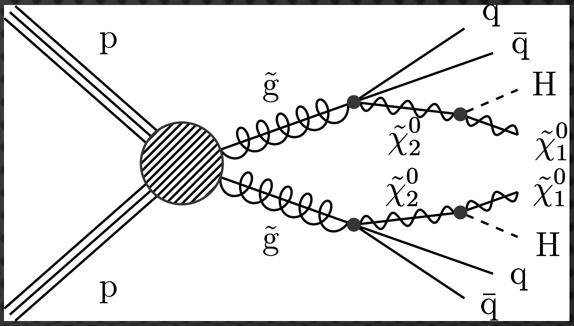


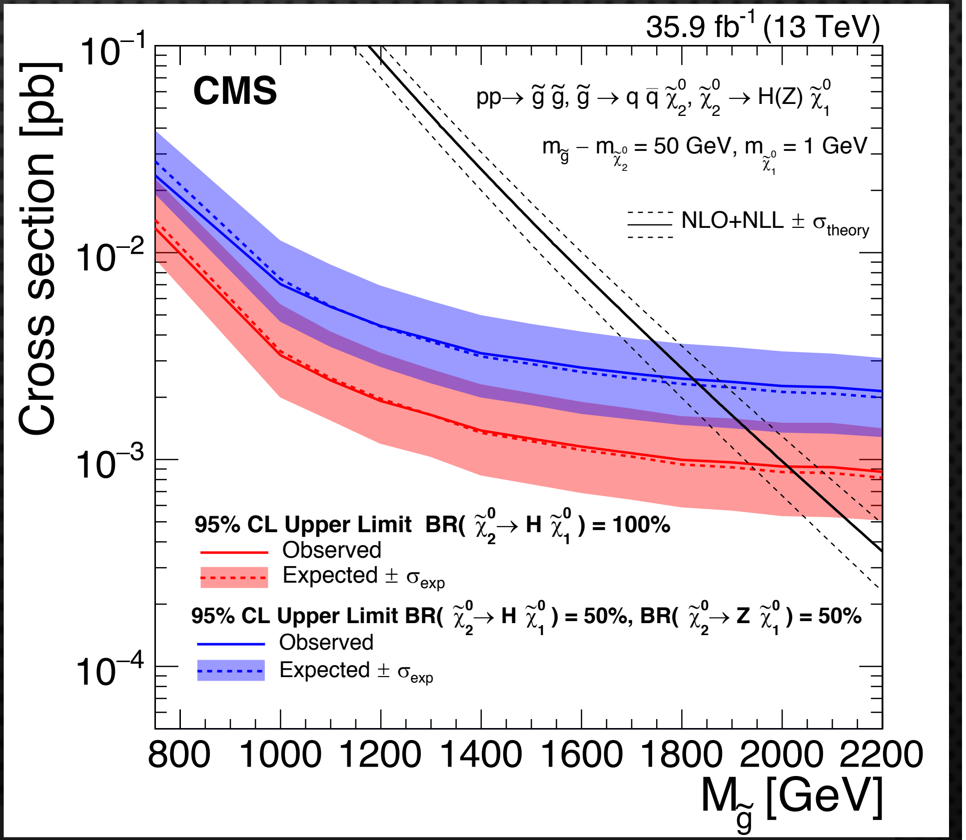
Phys. Rev. Lett. 120 (2018) 241801

Can even search using Higgs decays



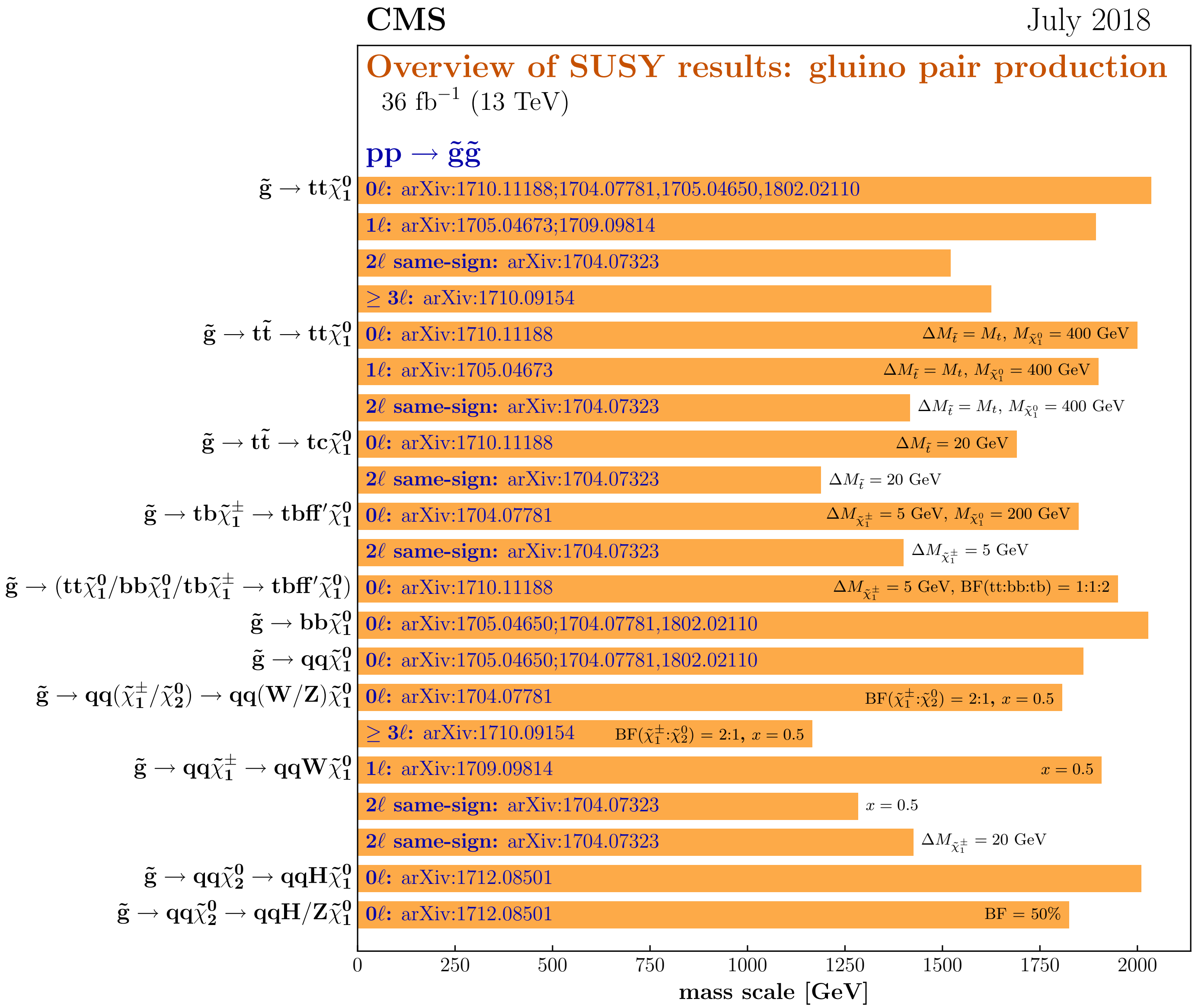
Search for high-momentum Higgs decaying into two b jets.





Place limits on gluino mass in this particular scenario.

CMS limits on gluino masses



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 sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Limits on the gluino mass from a variety of CMS searches.

Exclude masses below 1–2 TeV depending on mode.

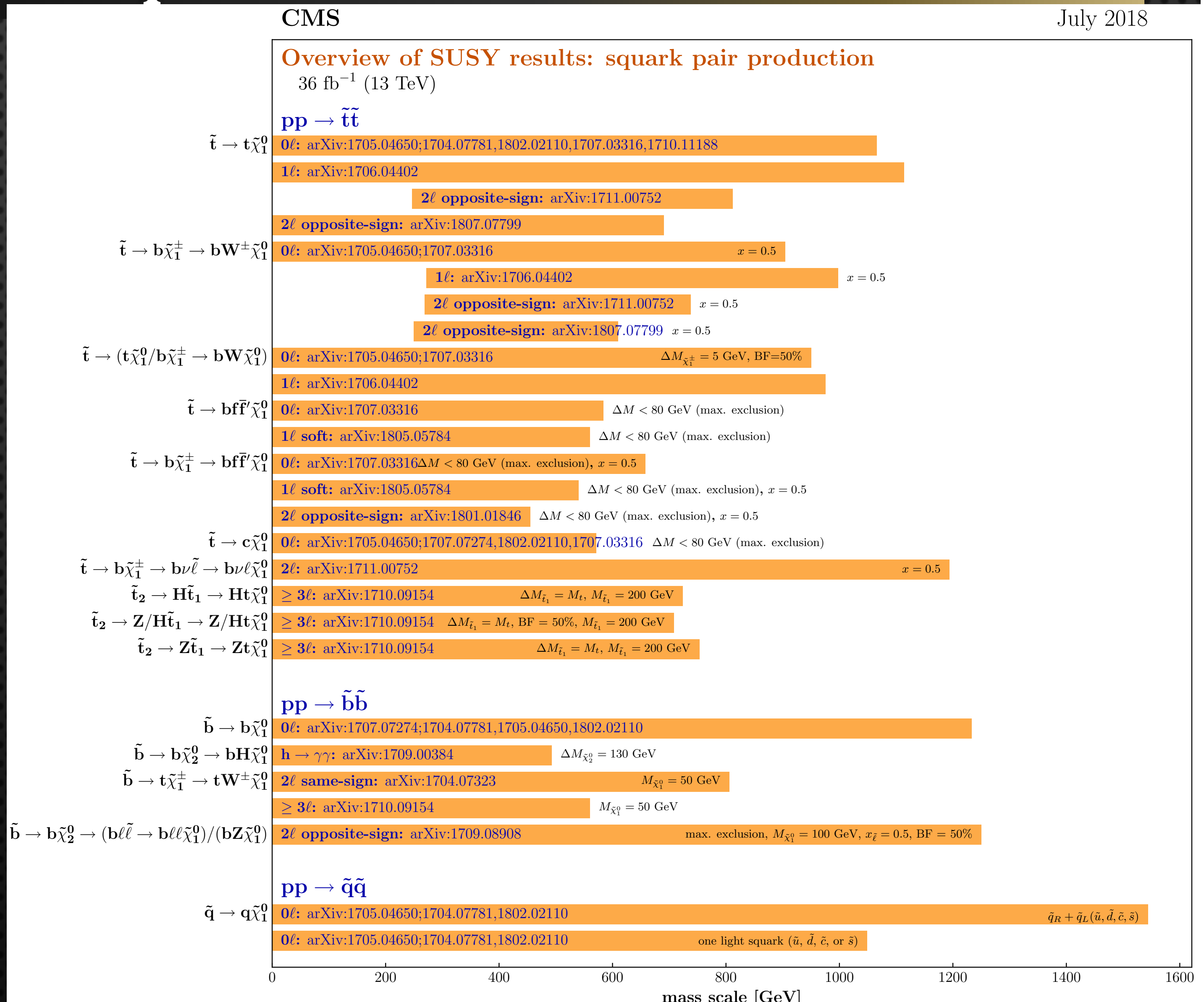
Generally represent the maximum possible excluded mass.

CMS limits on squark masses

Limits on squark masses from CMS searches.

Excluded masses range from 0.5–1.5 TeV.

Generally represent the maximum possible excluded mass.



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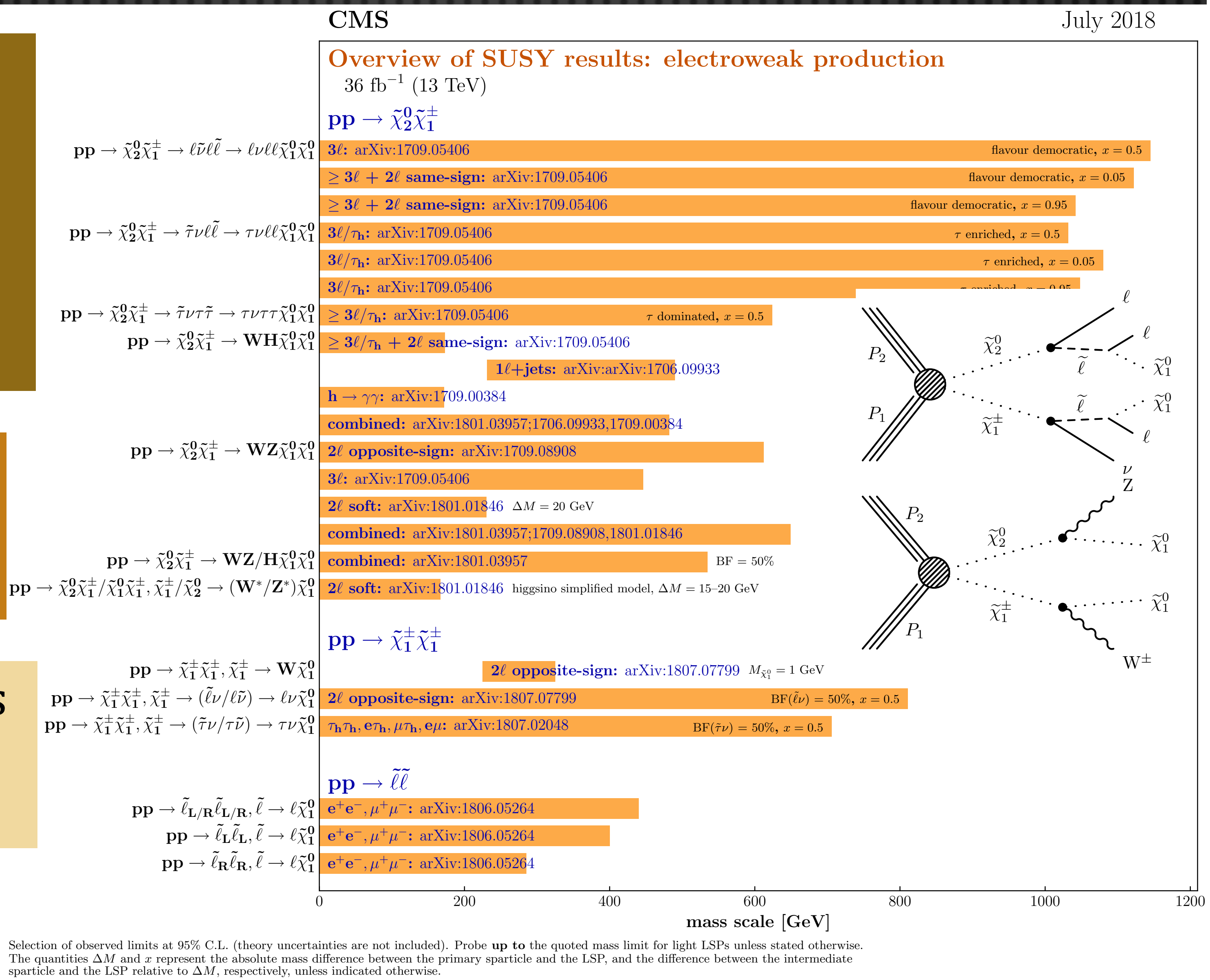
CMS limits on electroweak production

Gluino and squark production should have highest cross sections but maybe have high mass and can't be produced.

Can look for production via electroweakinos.

Smaller mass limits as cross sections are smaller.



Where do we stand with SUSY?

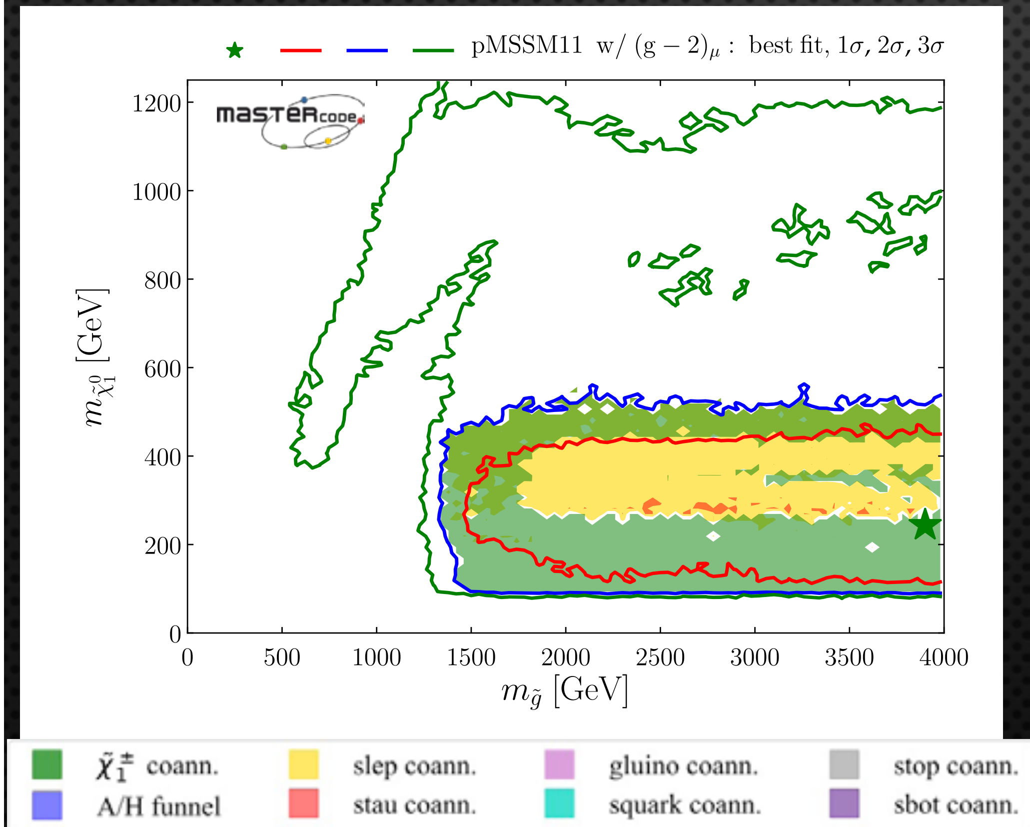
- Two common ways to simplify the SUSY parameter space:
  - Constrained MSSM (CMSSM) makes strong assumptions about universality at the GUT scale and how SUSY is broken. Some constraints not well justified. Has 4 parameters plus a sign.
  - Phenomenological MSSM (pMSSM) removes CP violating phases and sets some masses equal. About 7–19 free parameters.
- Can construct likelihood function as a function of SUSY parameters incorporating measurements from LHC, LEP, dark matter searches, cosmology, etc. to see what parameters are still viable.

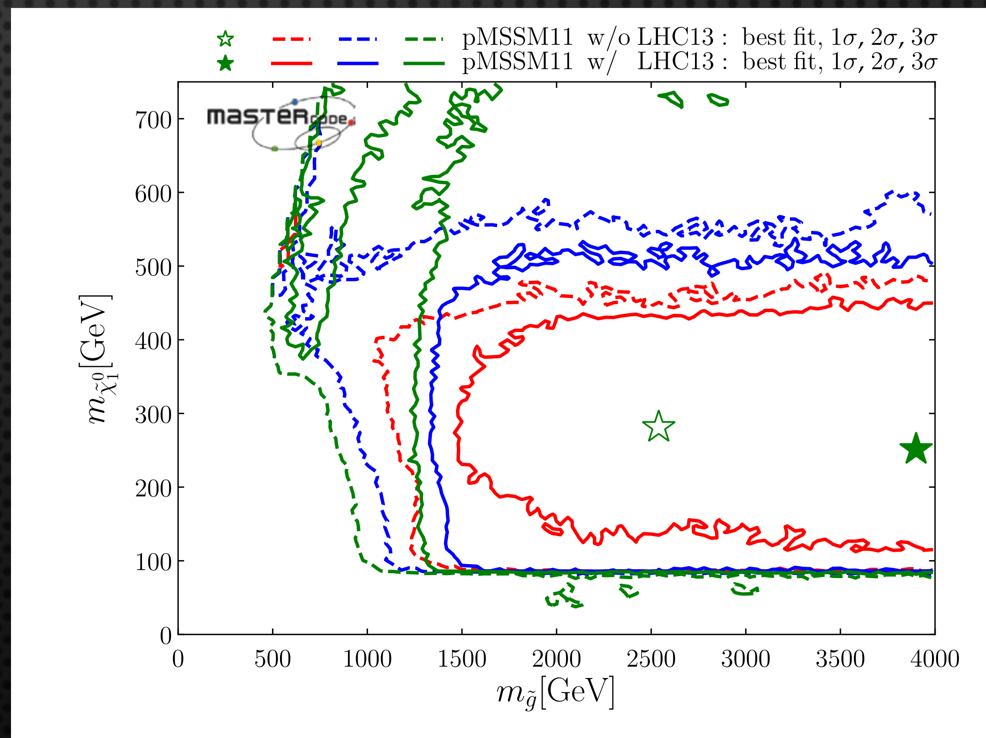
Results of 11-parameter pMSSM fit

arXiv:1710.11091

LSP vs gluino mass shows wide ranges still possible.

The addition of LHC data at 13 TeV has significantly constrained the allowed region.





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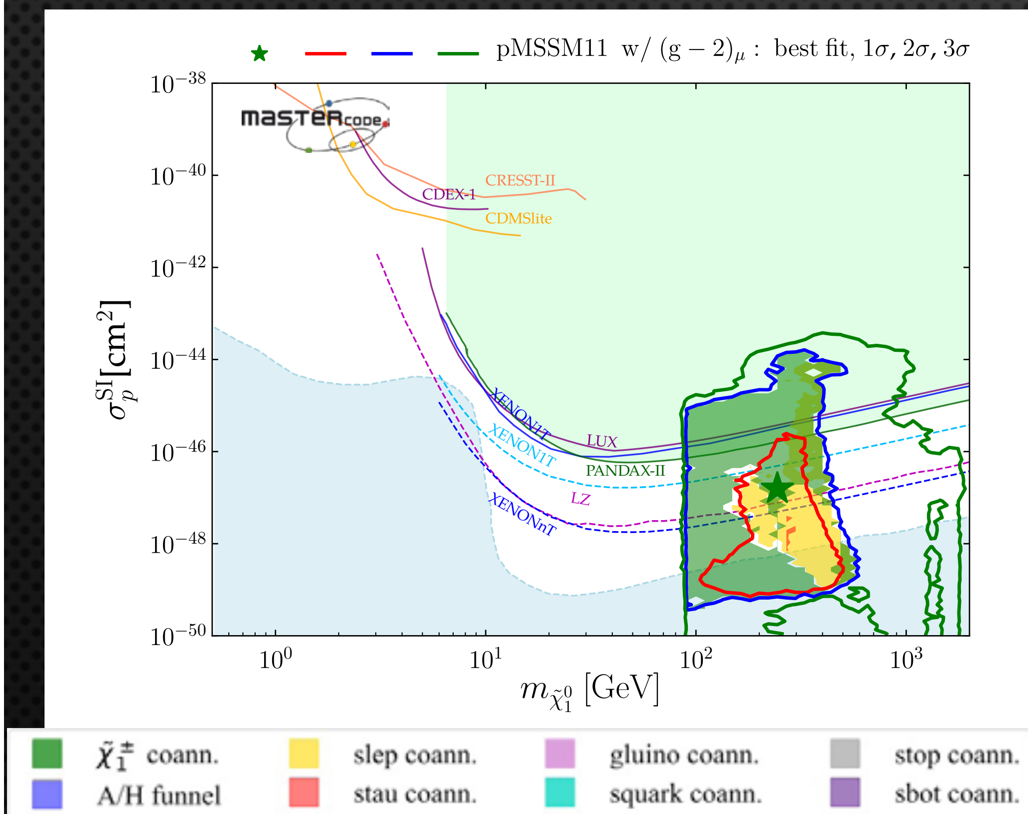
Results of 11-parameter pMSSM fit

Cross section vs mass of dark matter particle. Future direct dark matter searches can reduce allowed space.



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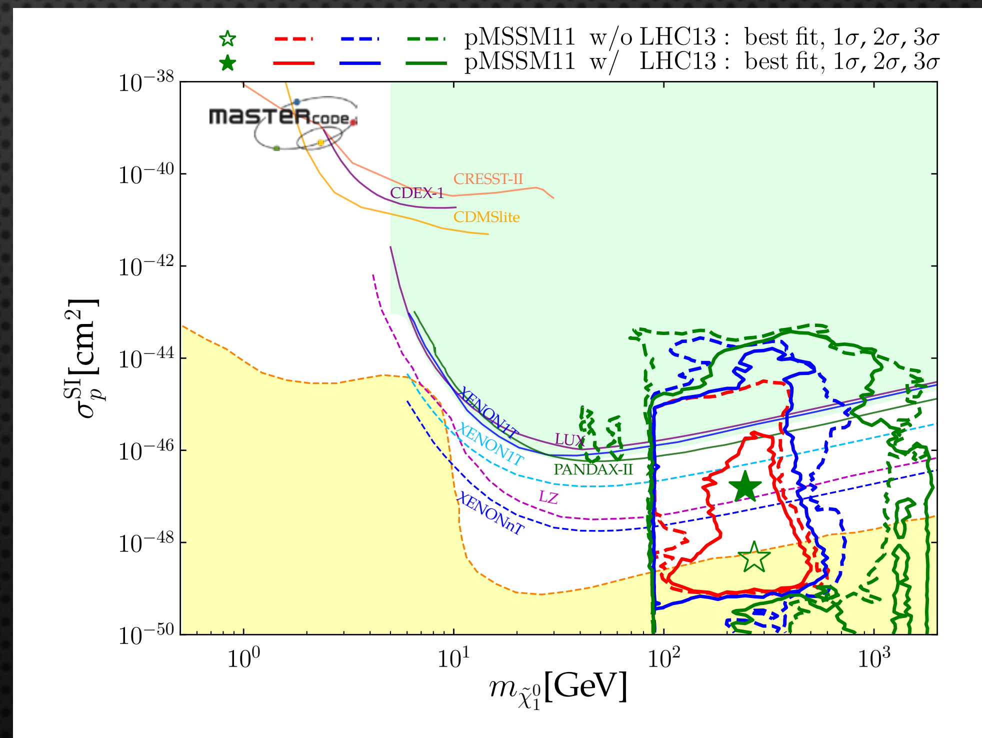
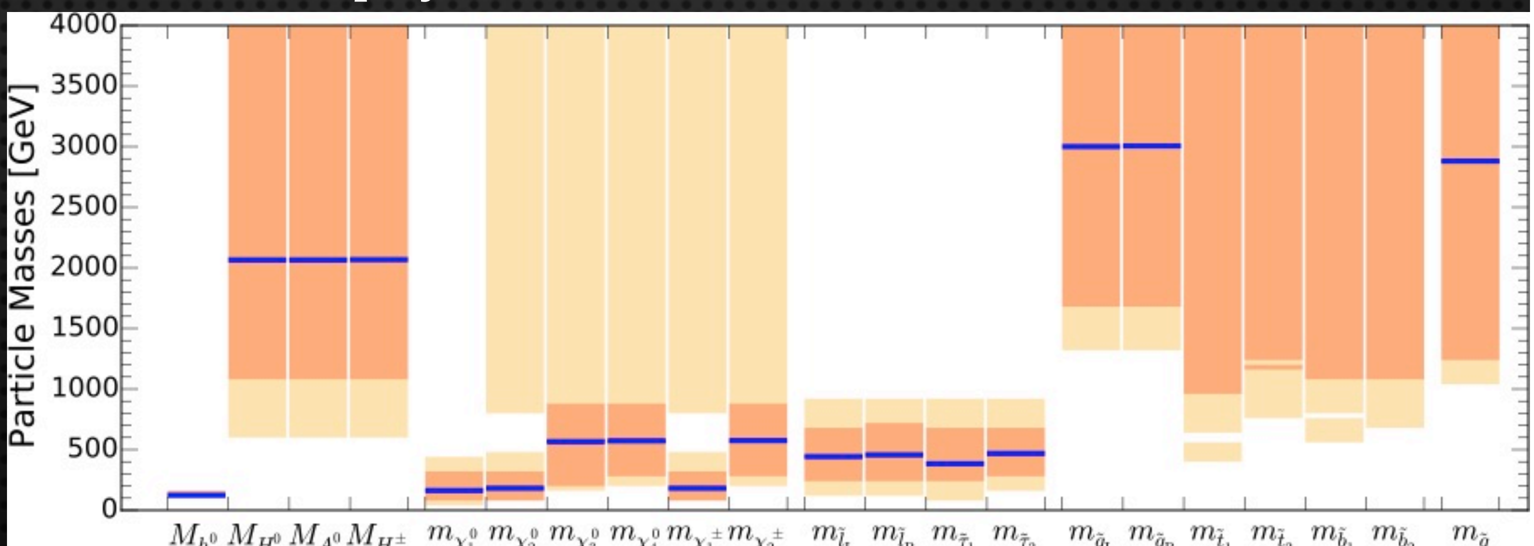


Where do we stand with SUSY?

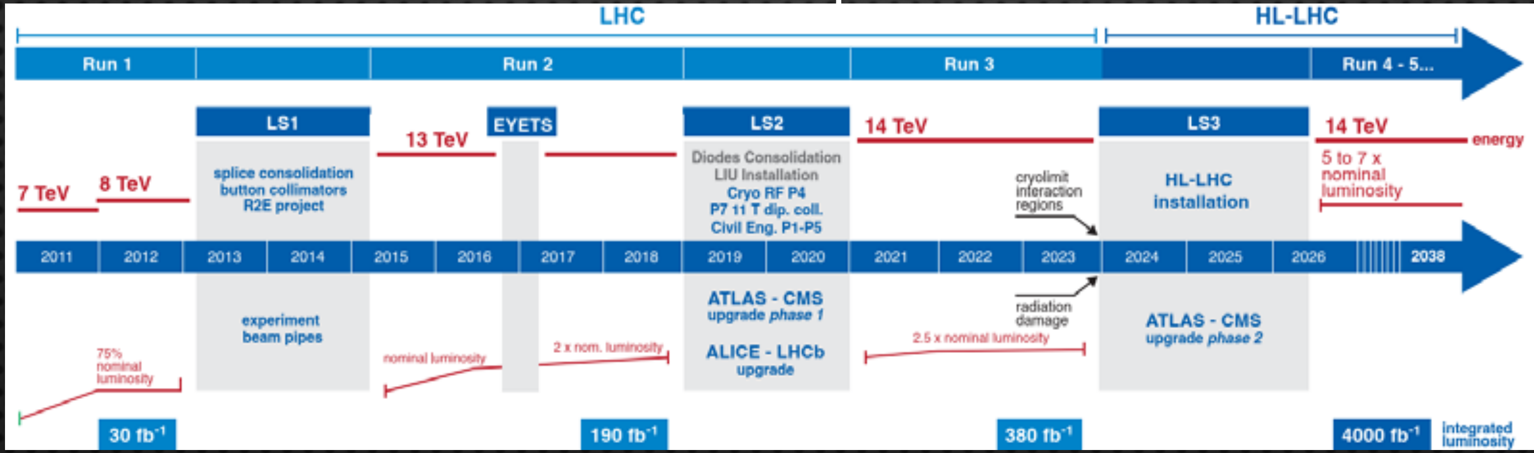
- SUSY can provide the dark matter in the universe with a wide range of mass possibilities.
- Can it still solve the hierarchy problem?
  - Many discussions about what counts as “fine-tuning”.
  - From arXiv:1407.6966, the strongest constraint on keeping fine tuning below 1% is that the gluino mass is <1.5 TeV (but this limit loosens to 2.5 GeV if new physics is at 10^7 GeV rather than the GUT scale).
  - OK so far



arXiv:1710.11091

Where do we go from here?

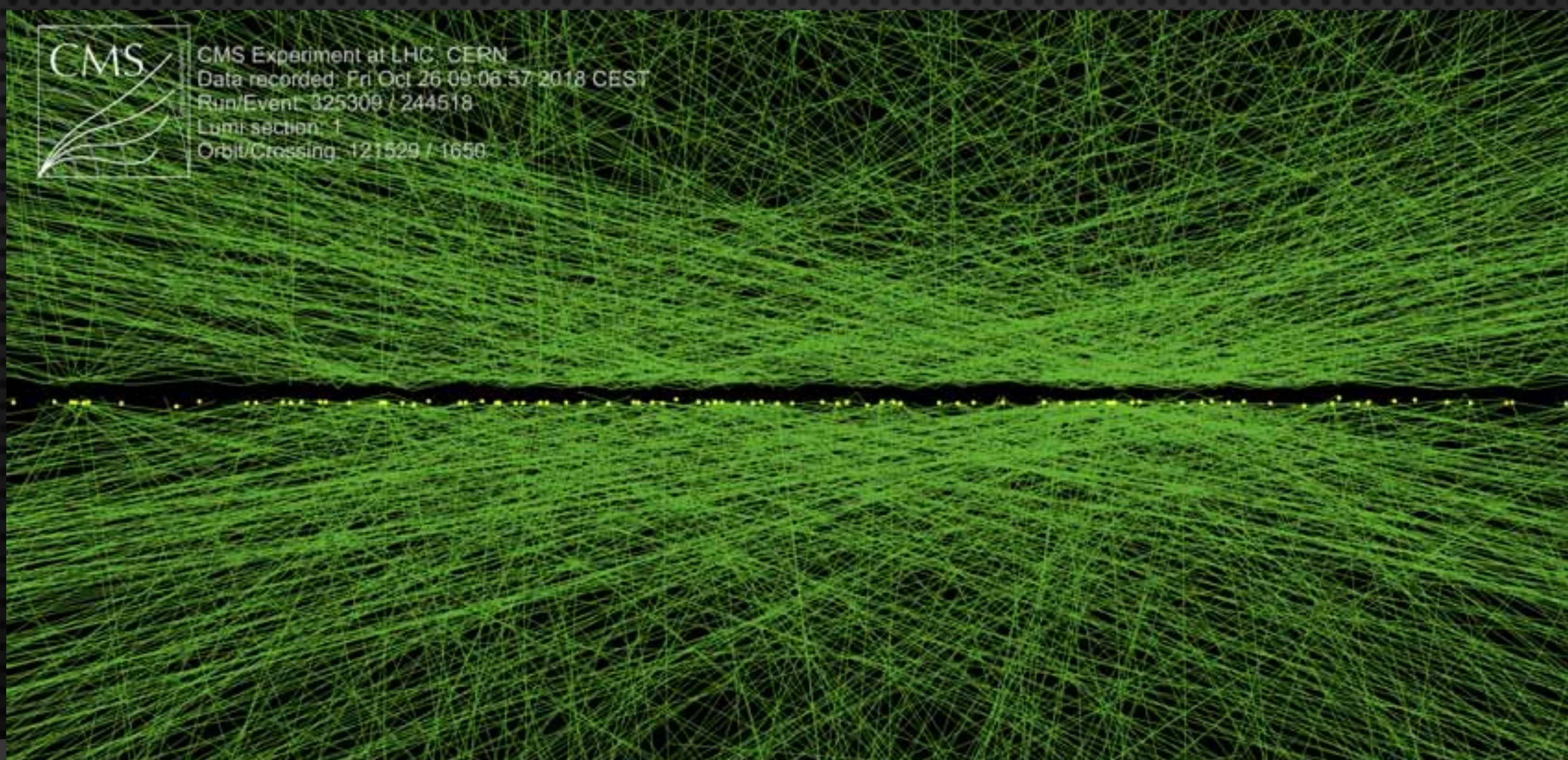
- Collect more data
  - Currently analyzing 135 fb^{-1} (about 3 times more).
  - Expect to have 300 fb^{-1} by end of 2023.
  - HL-LHC from 2026–2036 should produce additional 3000 fb^{-1}.



- Perform targeted searches in difficult to access areas, usually due to low missing transverse momentum.
  - Compressed SUSY: small mass splittings of the sparticles.
  - Stealth SUSY: hidden sector and partner masses near SM masses.
  - R-parity violating SUSY: allows sparticles to decay to SM particles.

Challenges of the HL-LHC

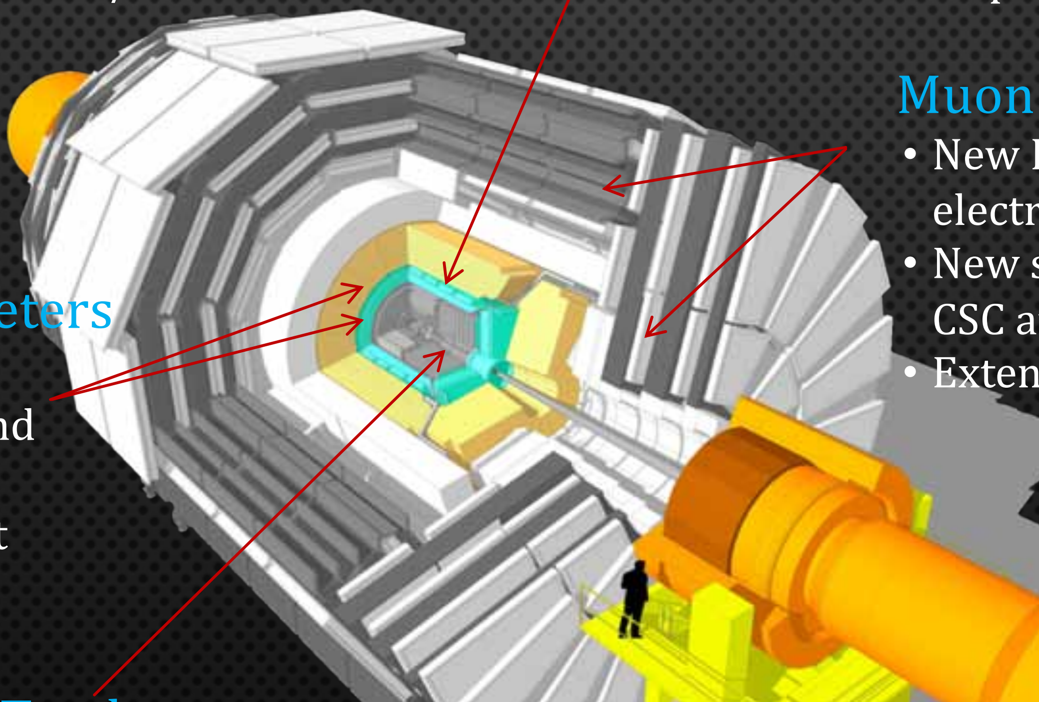
- Proton bunches collide every 25 ns. Multiple protons collide each time (pileup). Designed for pileup=25, currently at pileup=40, and HL-LHC plans for pileup=200.
- Need to move as much of offline reconstruction as possible into the trigger (which selects the events to keep).



CMS HL-LHC Upgrade Overview

Trigger/HLT/DAQ
- Track information in trigger at 40 MHz
- 12.5 μs latency
- HLT input/output 750/7.5 kHz

Barrel Calorimeter
- New FE/BE electronics for full granularity readout at 40 MHz – with improved time resolution
- Lower ECAL operating temperature



Muon systems
- New DT & CSC FE/BE electronics
- New station to complete CSC at $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

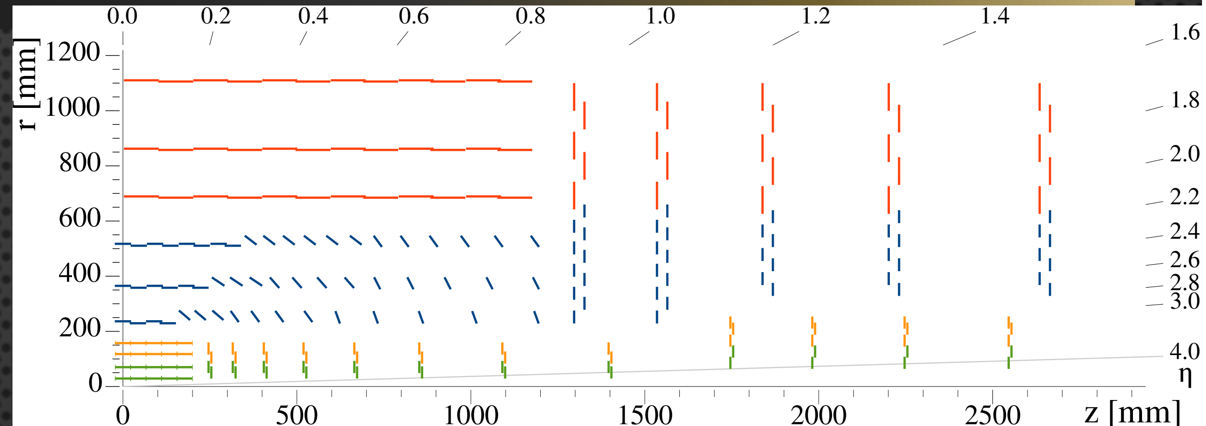
New Endcap Calorimeters
- Rad. tolerant - High granularity transverse and longitudinal
- 4D shower measurement including precise timing capability

New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout (strips) for Trigger
- Extended coverage to $\eta \simeq 3.8$

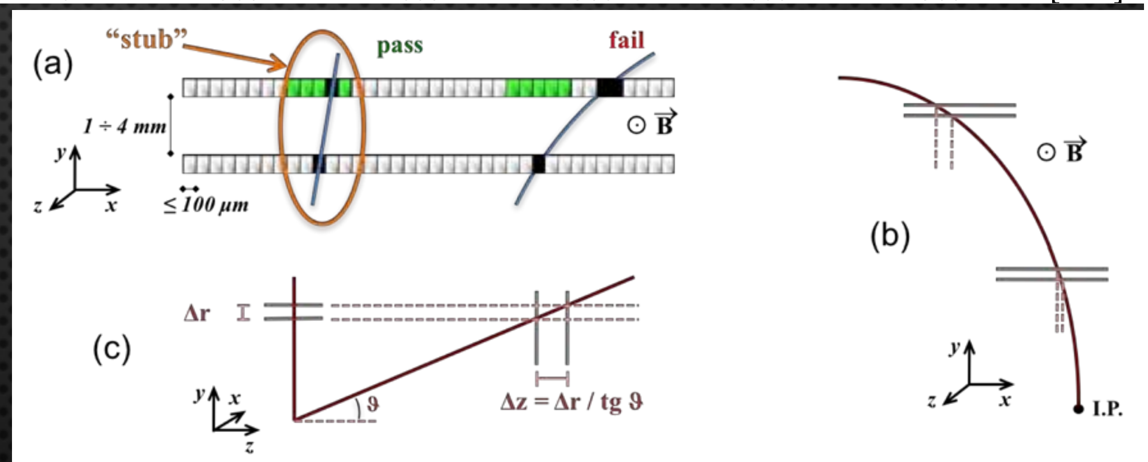
MIP precision Timing Detector
- Barrel layer: Crystal + SiPM
- Endcap layer: Low Gain Avalanche Diodes

Track trigger at Level 1

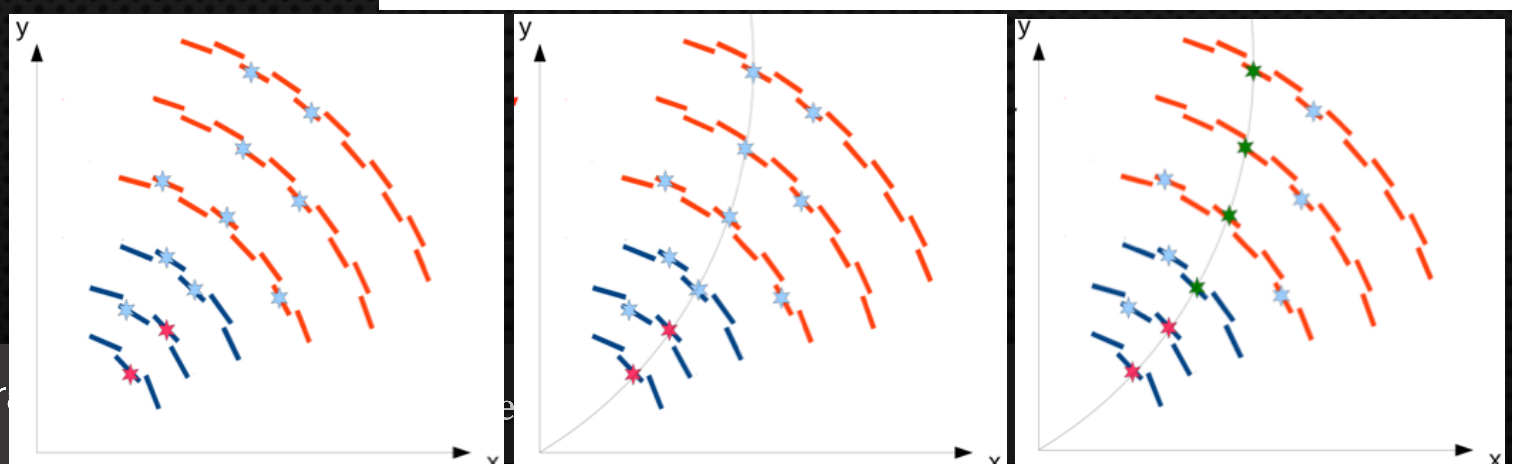
Need to reconstruct tracks in 4μs (rather than >10s on CPUs).



Tracker with double layers to only select hits with $p_T > 2$ GeV.

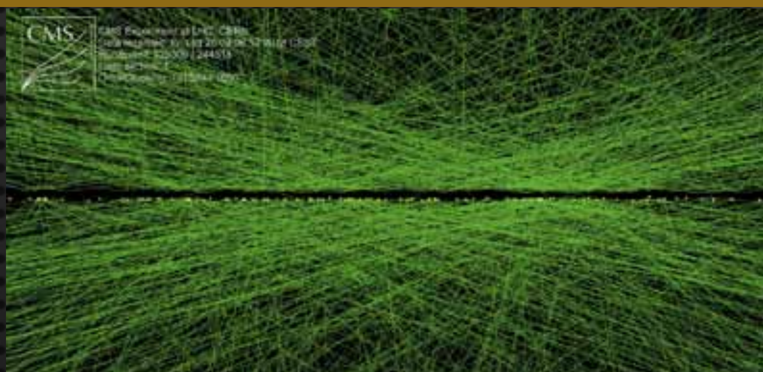


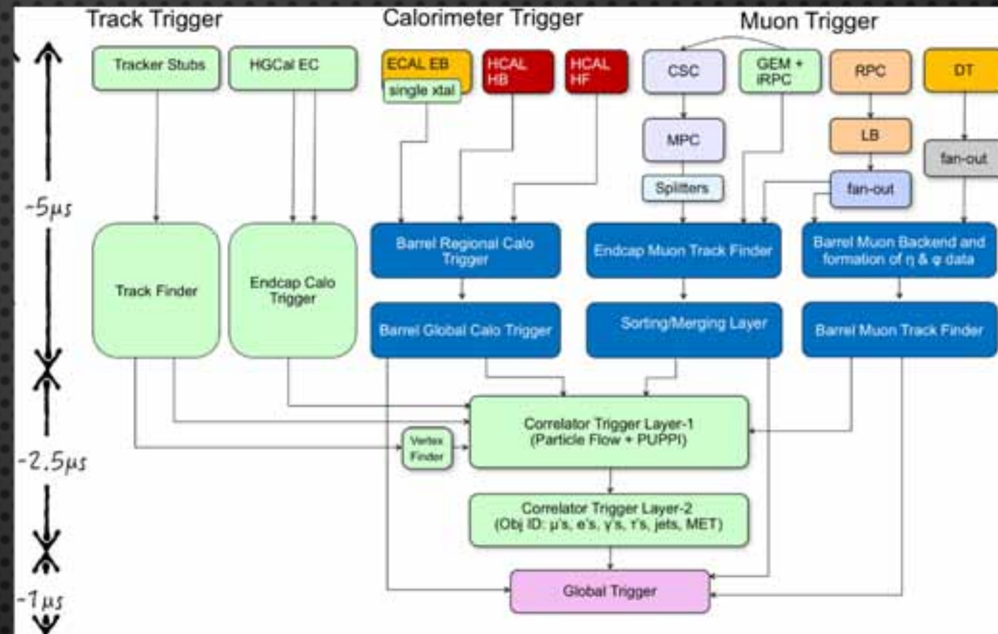
Process hits in FPGA on Track Finder boards to reconstruct and output the tracks.



HL-LHC trigger system

Vertex finder board takes tracks and finds the vertex of interest and other quantities.



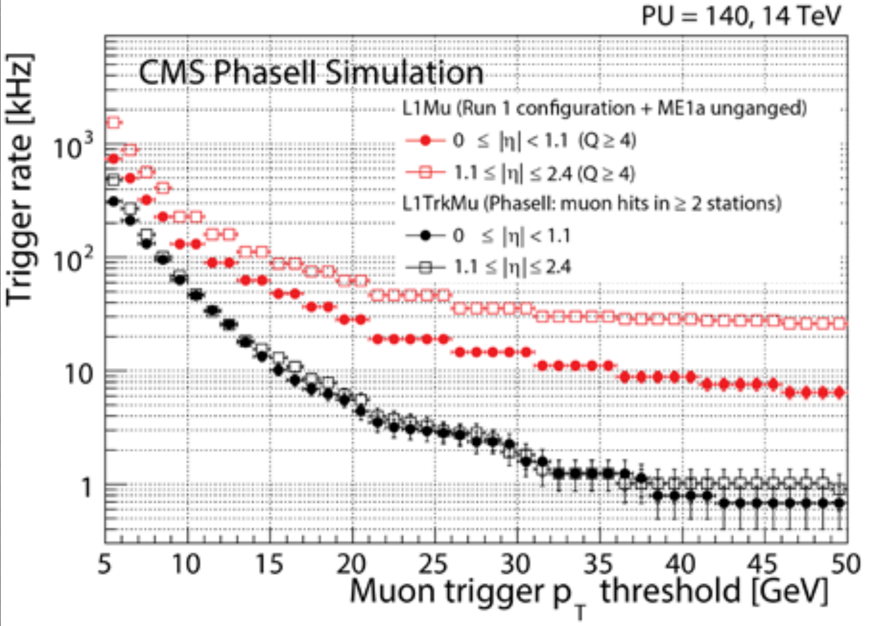


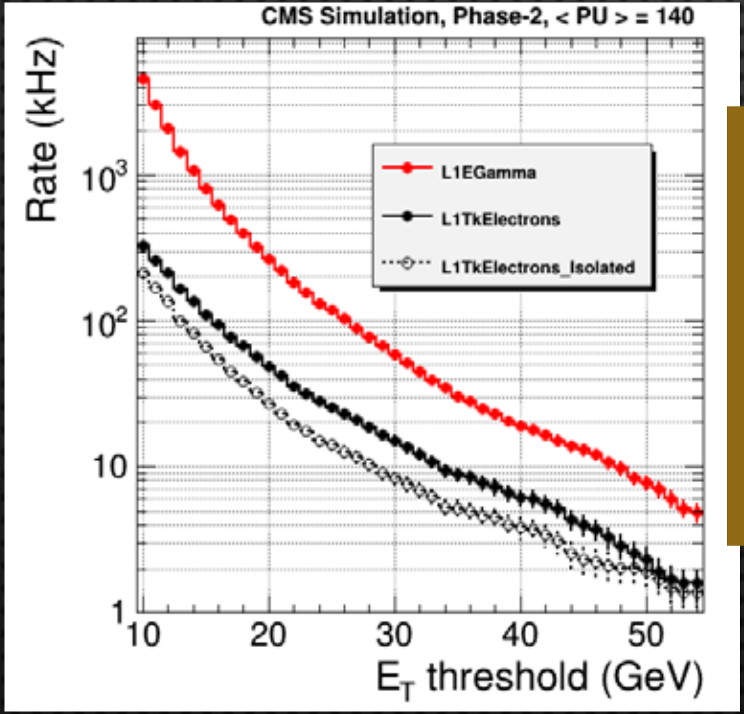
Firmware now being developed on test board at CU.

Correlator takes information from the entire detector and attempts to identify all particles from the vertex of interest. Working on the architecture of this system.

HL-LHC trigger results

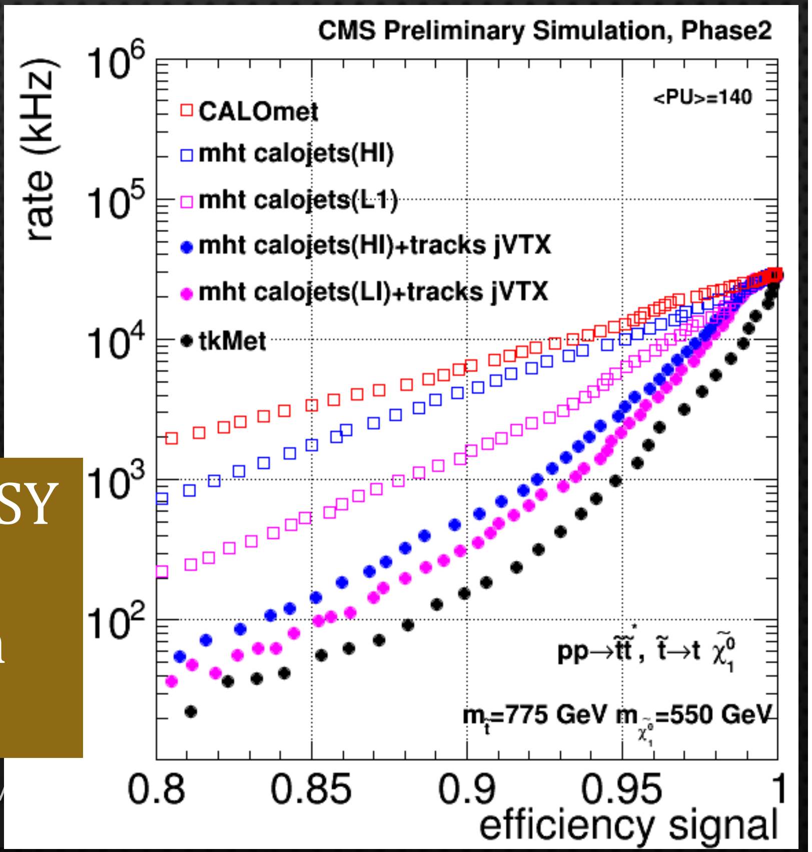
Better momentum resolution reduces muon rate by factor >10.



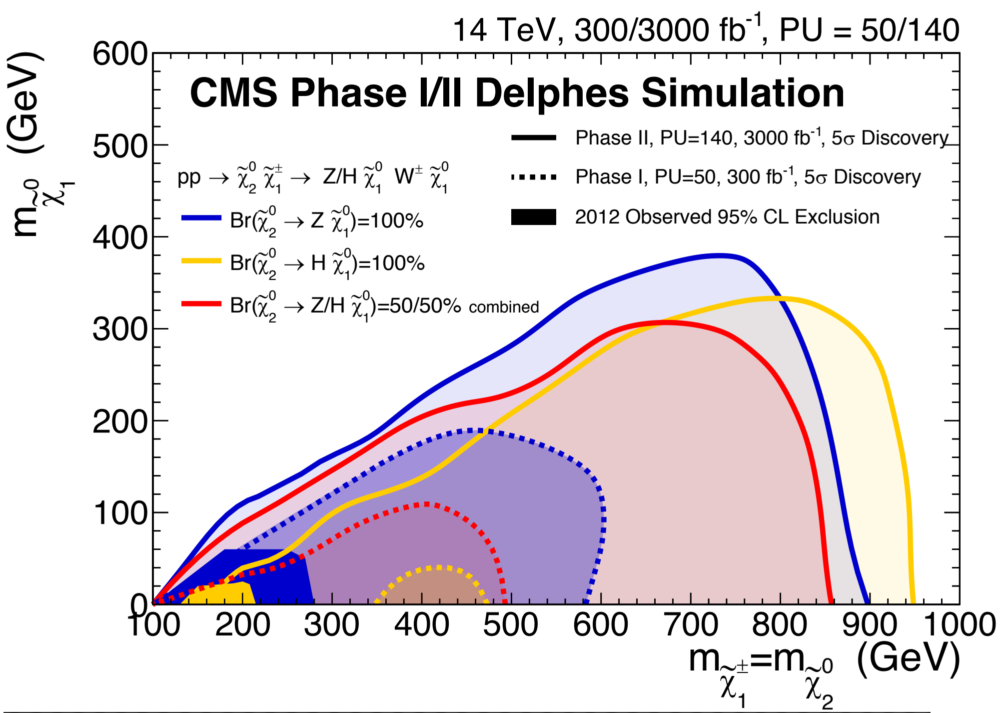


Electron rates reduced by nearly factor of 10.

Main trigger for SUSY searches allows for high efficiency with reasonable rate.

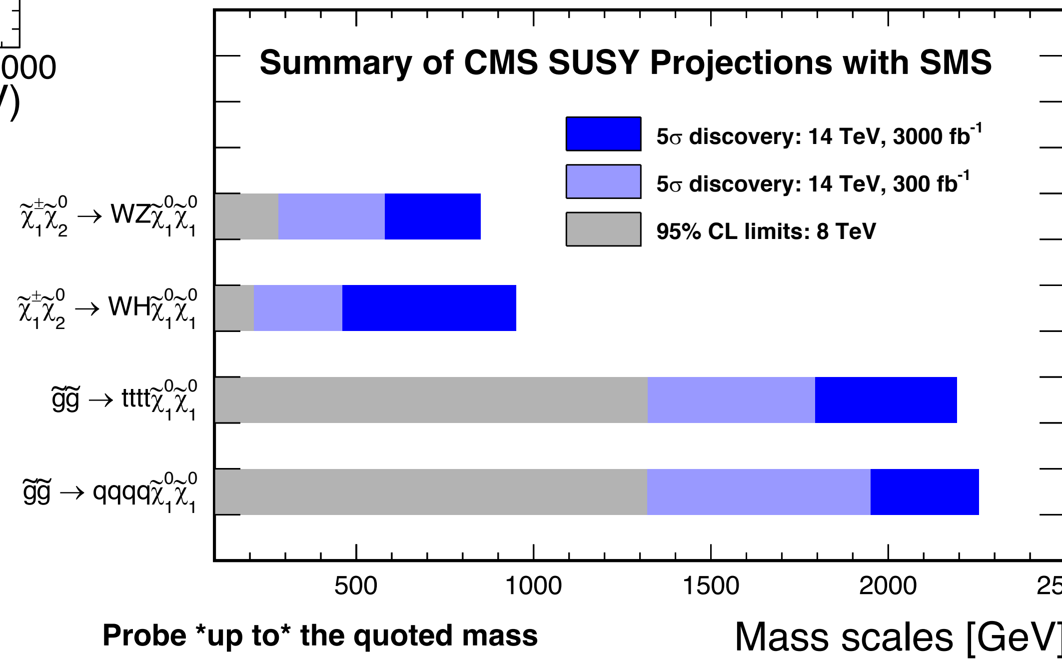


SUSY searches at HL-LHC



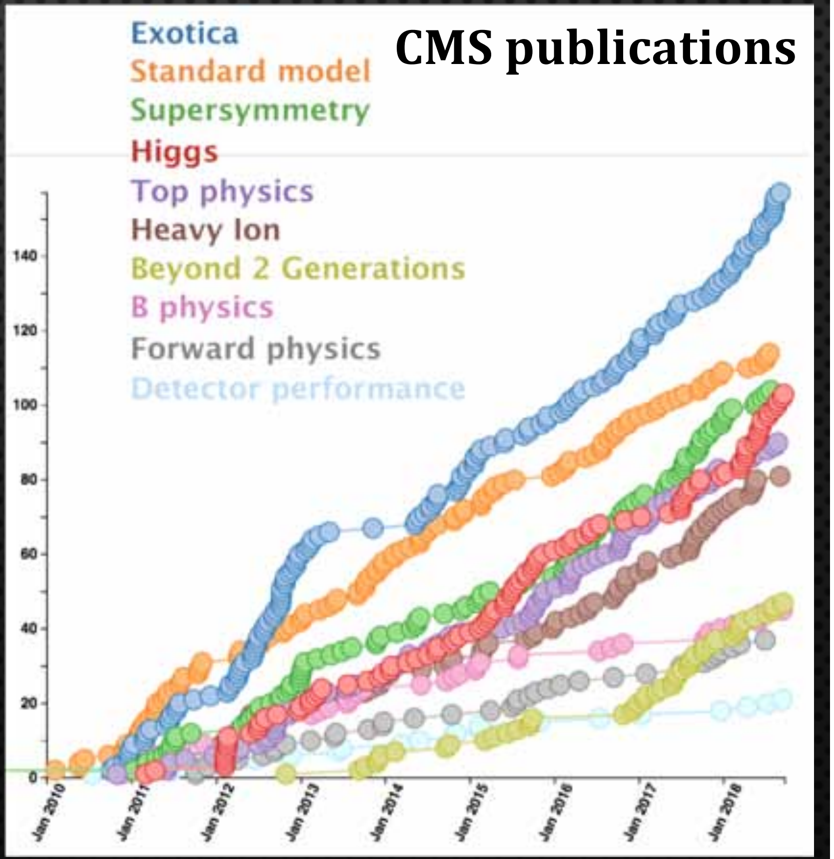
Example of improvement in discovery range for electroweak production.

Summary of discovery potential for a few SUSY possibilities.



Summary

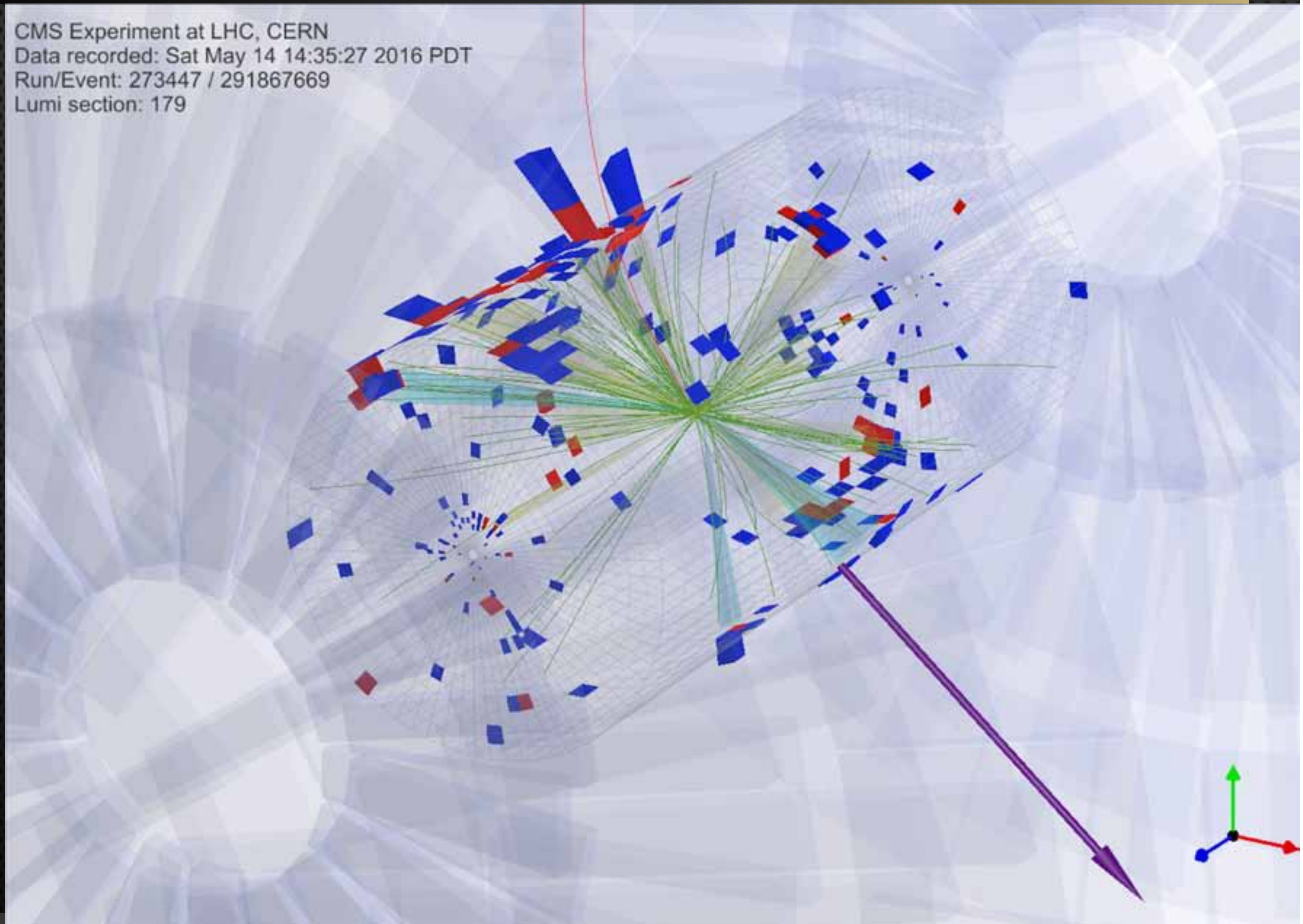
- The search for physics beyond the Standard Model is proceeding at a rapid pace.
- CMS is looking for any deviations from the Standard Model to find the way forward.
- Constraints on supersymmetry also come from other areas such as searches for dark matter and the electric dipole moment of the electron, and measurements of b-hadron decays and the anomalous magnetic dipole moment of the muon.
- There is still hope for new physics from the LHC.



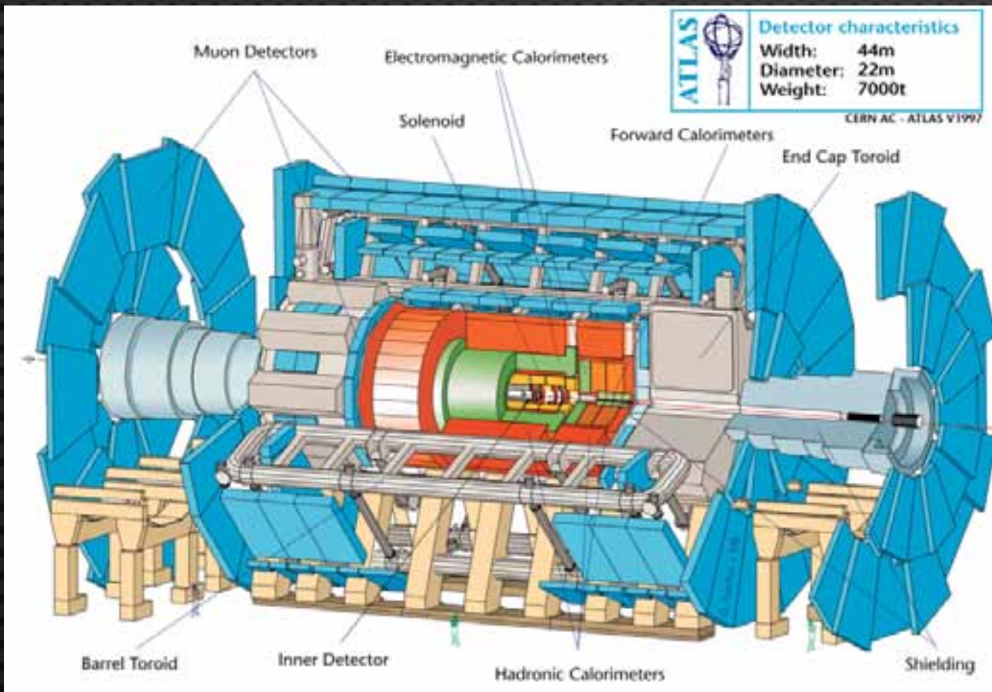
Backup

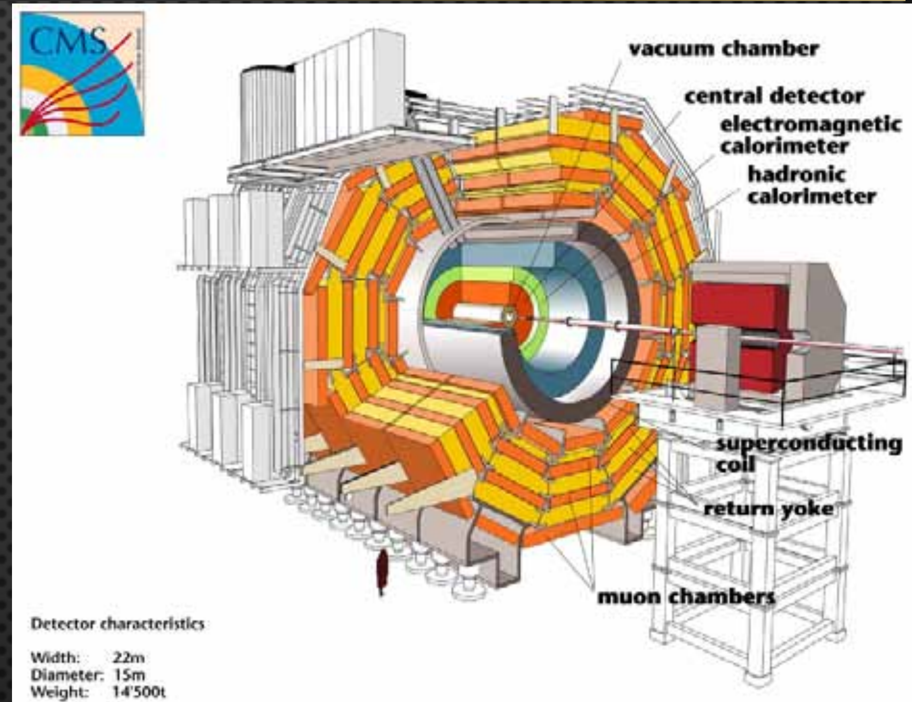
Possible SUSY event

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

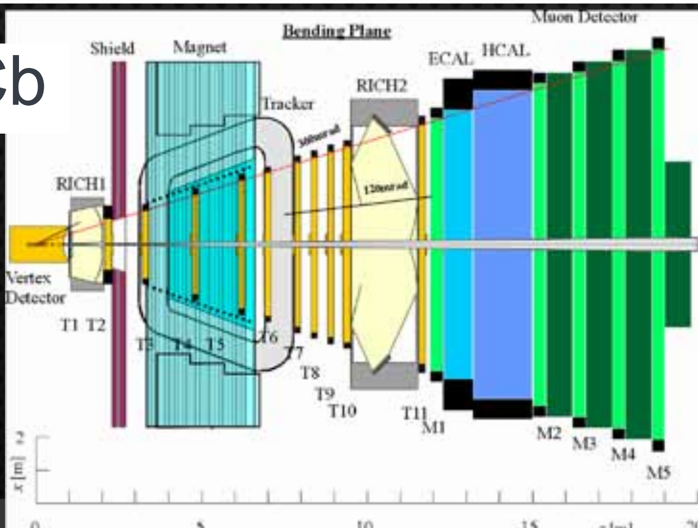


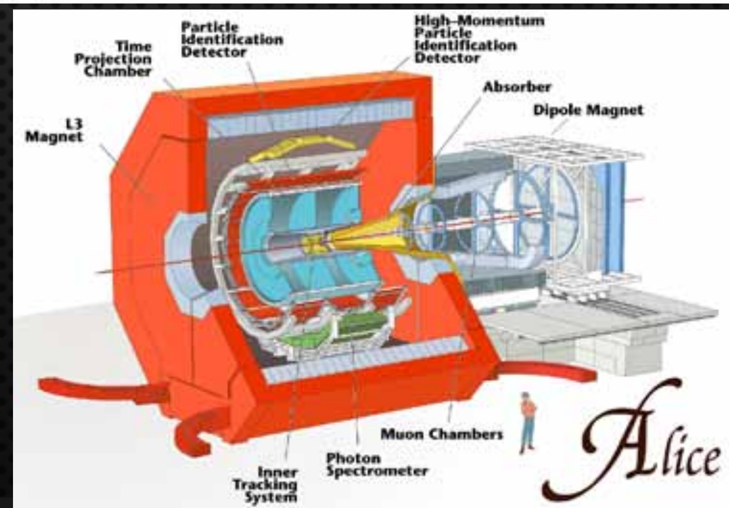
The LHC detectors



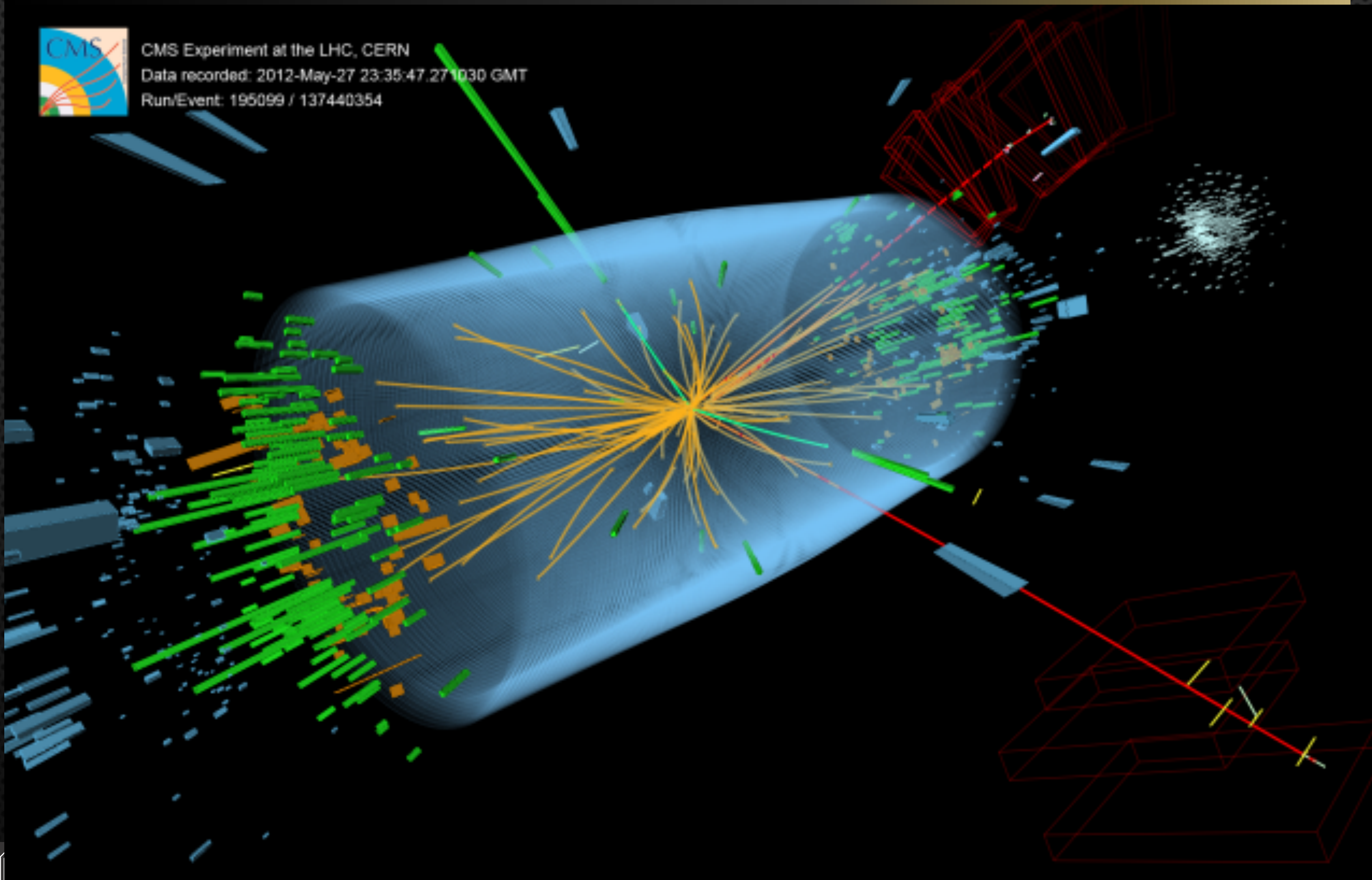


LHCb

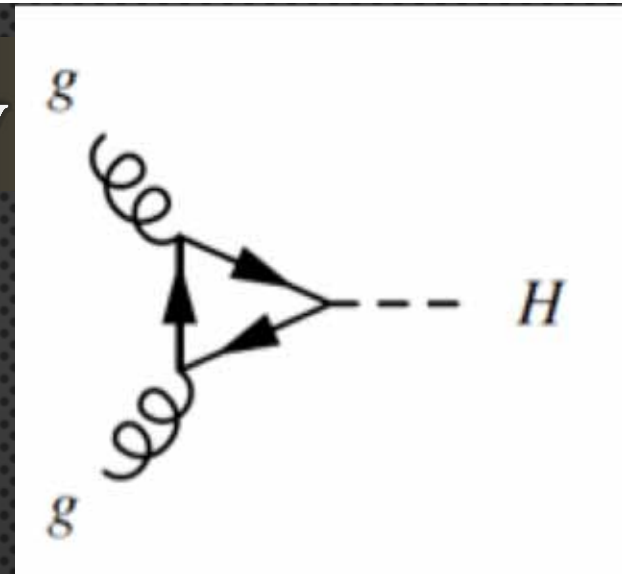




Possible Higgs decay: H→ZZ→ee$\mu\mu$

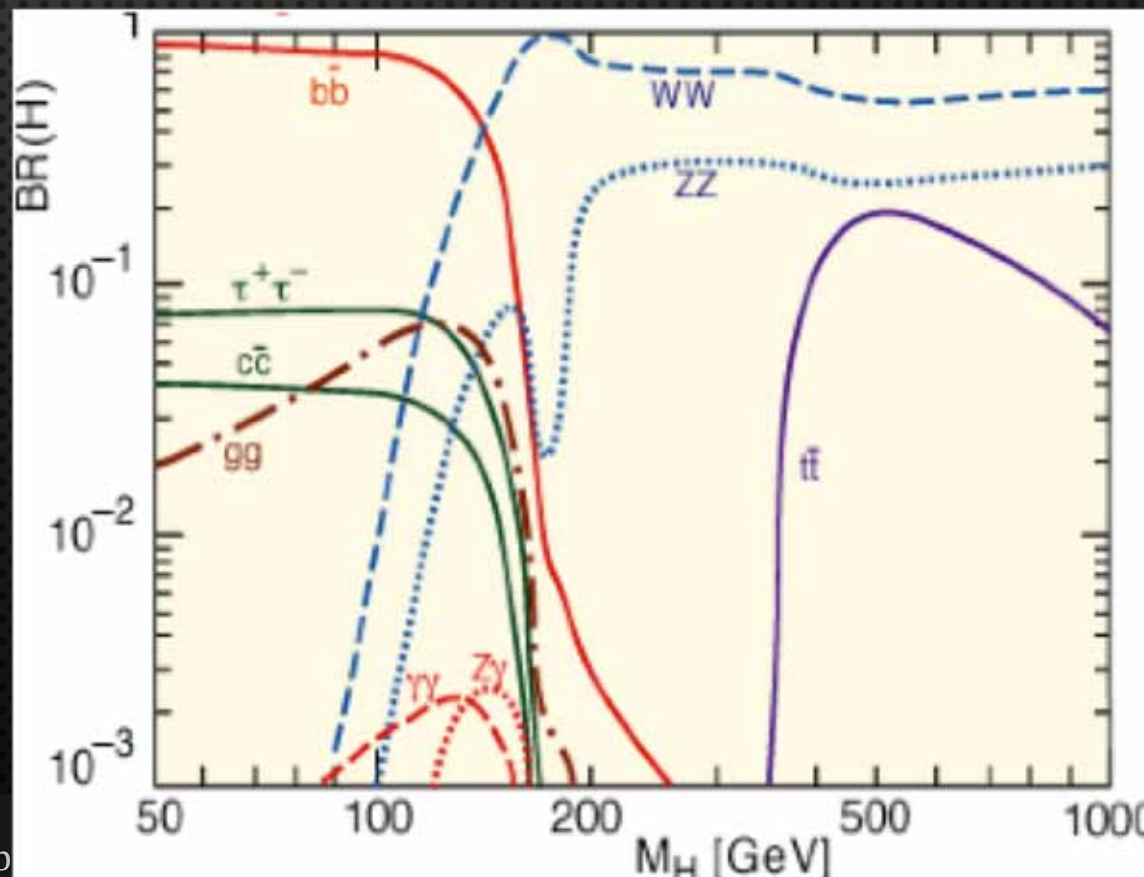


Higgs production and decay



- 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→γγ and H→ZZ are the most important.



Searching for supersymmetry

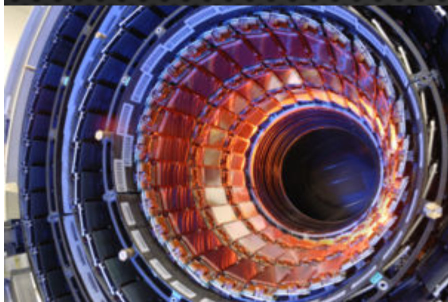
A few rules for most SUSY searches:

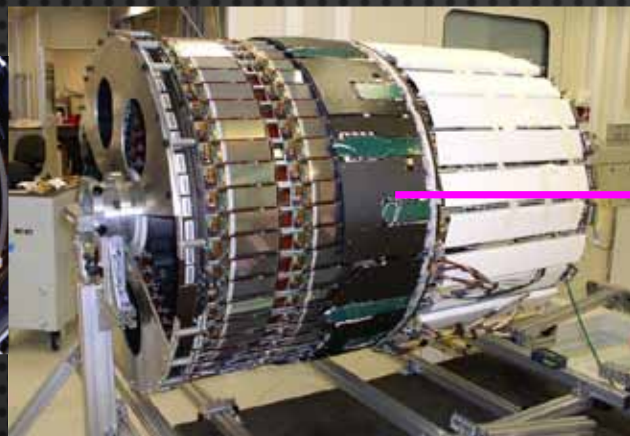
- squarks and gluinos are predominantly produced because they couple to the strong force
- SUSY particles produced in pairs (R-parity conservation)
- Decay cascades end with lightest supersymmetric particle (LSP) which escapes detection.
  - Cascades produce jets & leptons (electrons, muons, taus)
 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

These rules suggest search strategies:

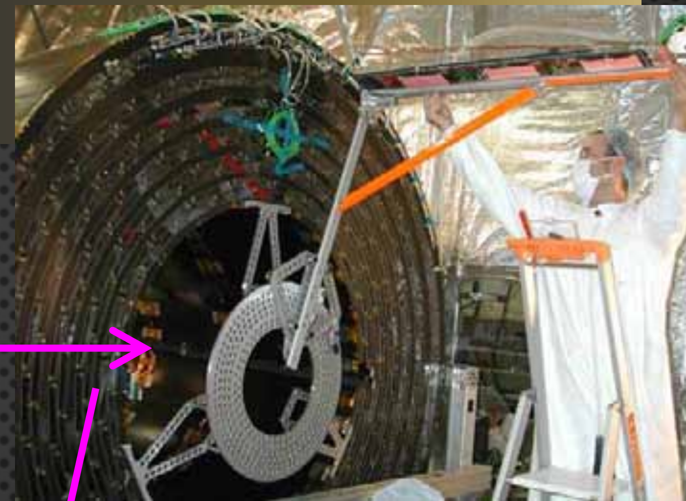
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

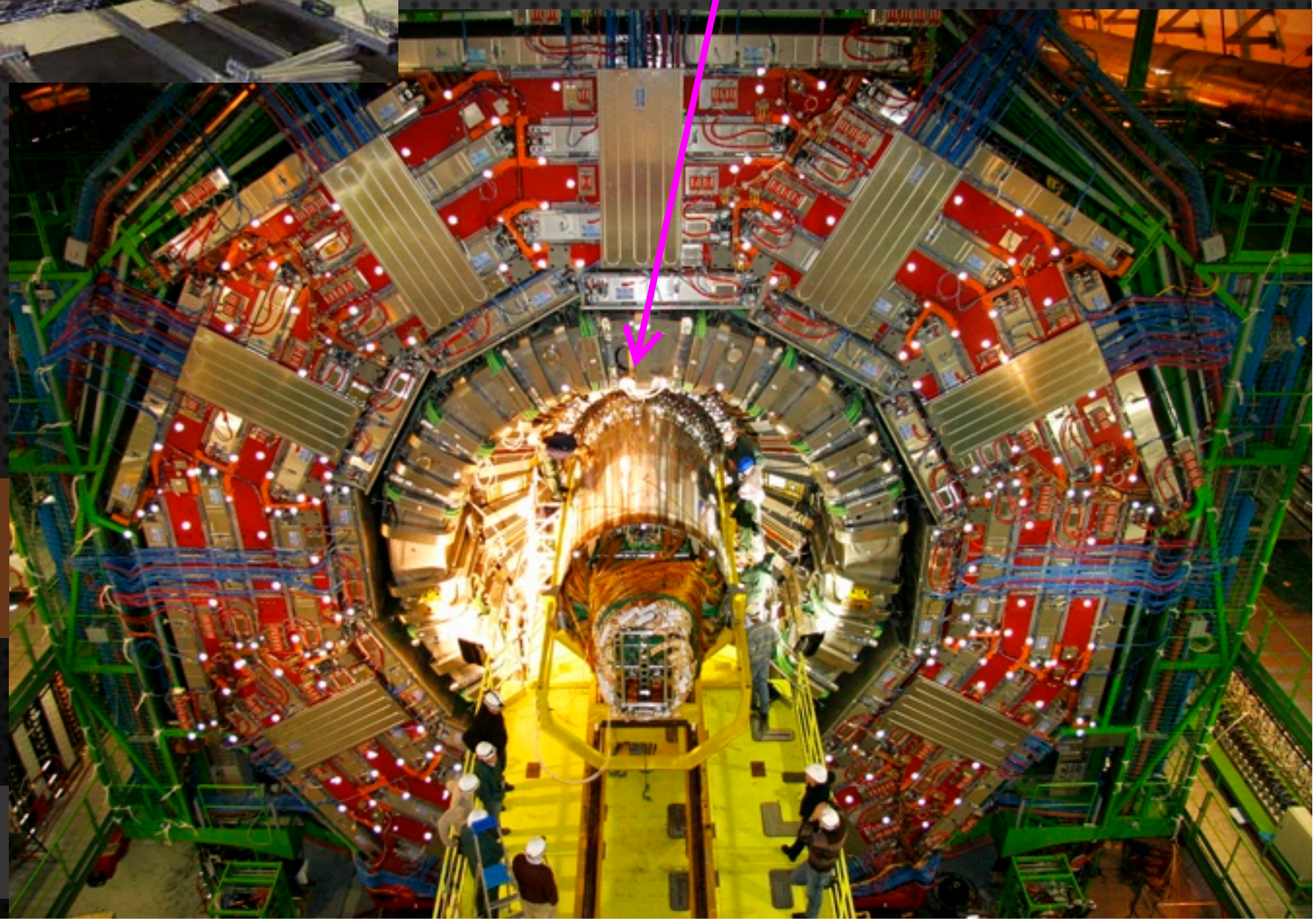
CMS Tracker





Goes inside





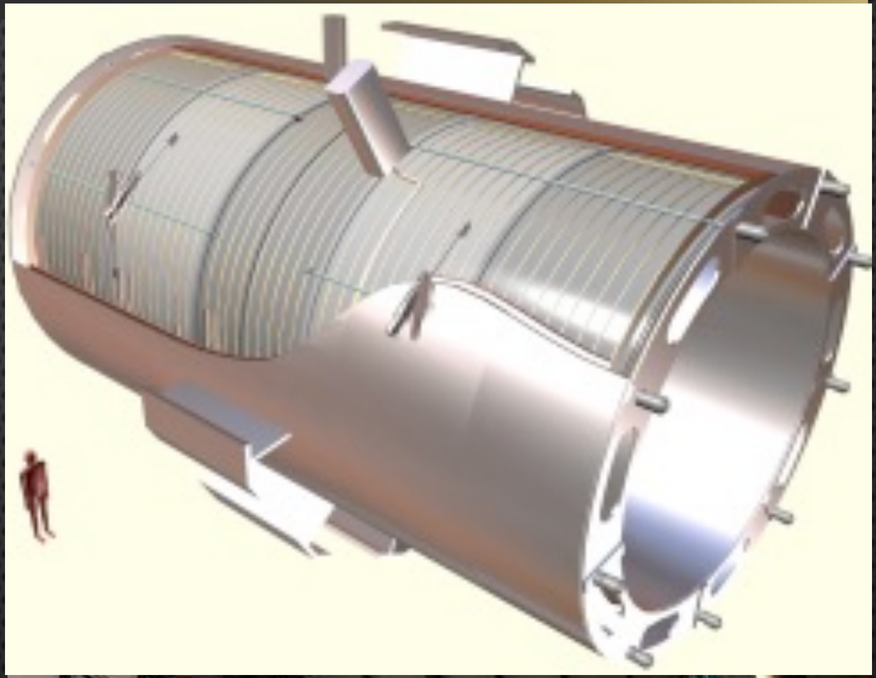
CMS tracker uses 2300 square feet of silicon detectors.

CMS tracker being inserted into CMS

University of Colorado Boulder

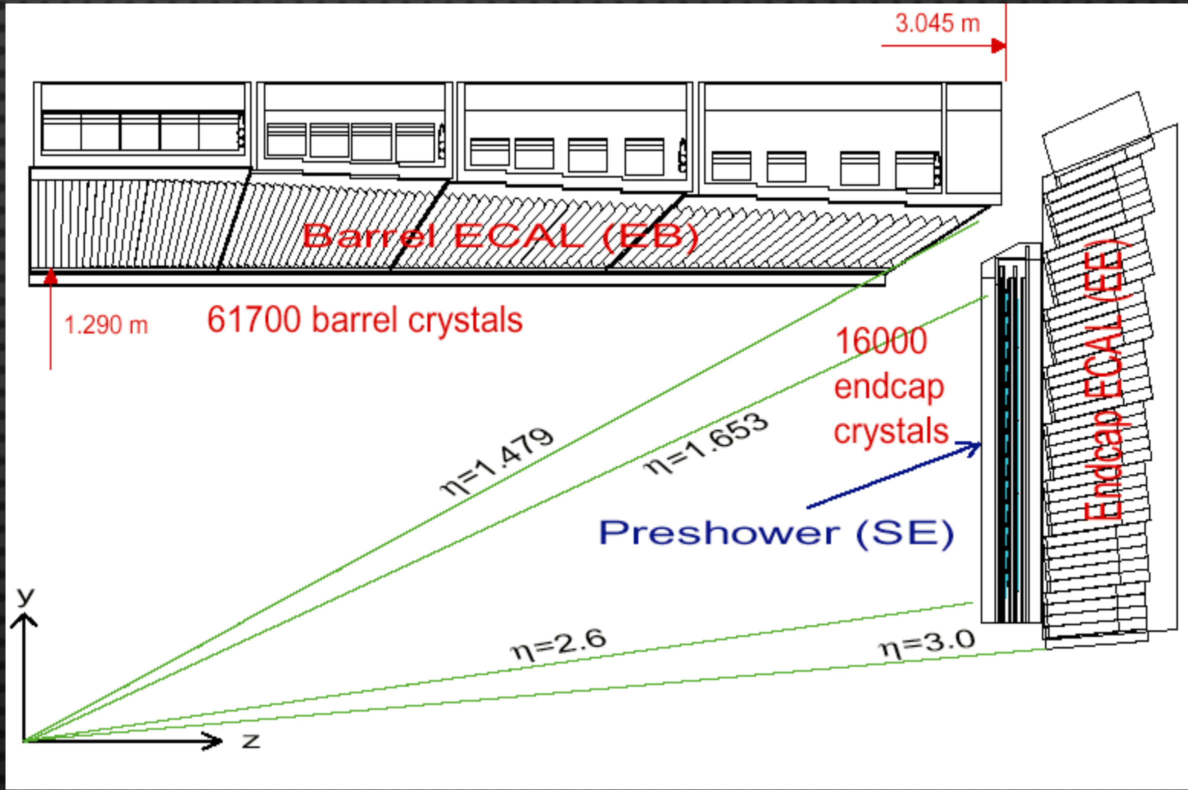
CMS Solenoid

- 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

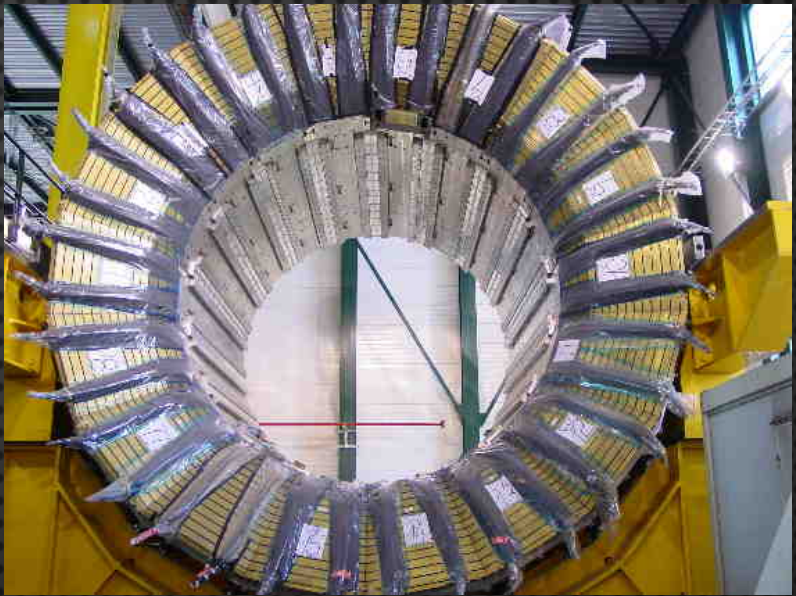


CMS Electromagnetic Calorimeter (ECAL)

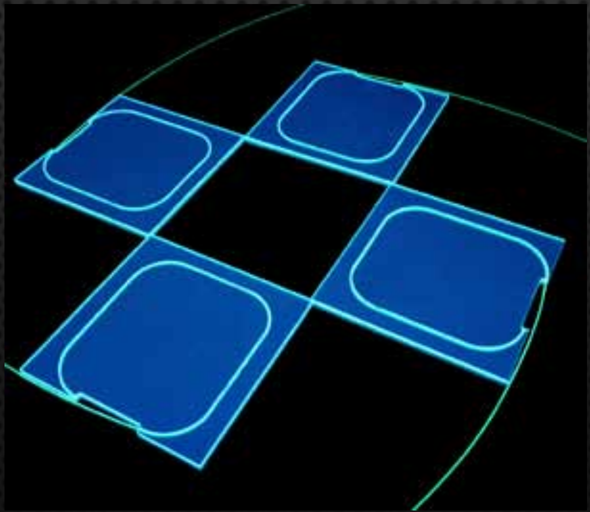
- Photons and electrons shower in high Z material
- Homogenous calorimeter
- Lead tungstate ($PbWO_4$) crystals: 2.3 x 2.3 x 23 cm^3
- Radiation hard, dense, and fast
- Low light yield & temperature sensitivity make it difficult
- Magnetic field and radiation require novel electronics APD and VPT

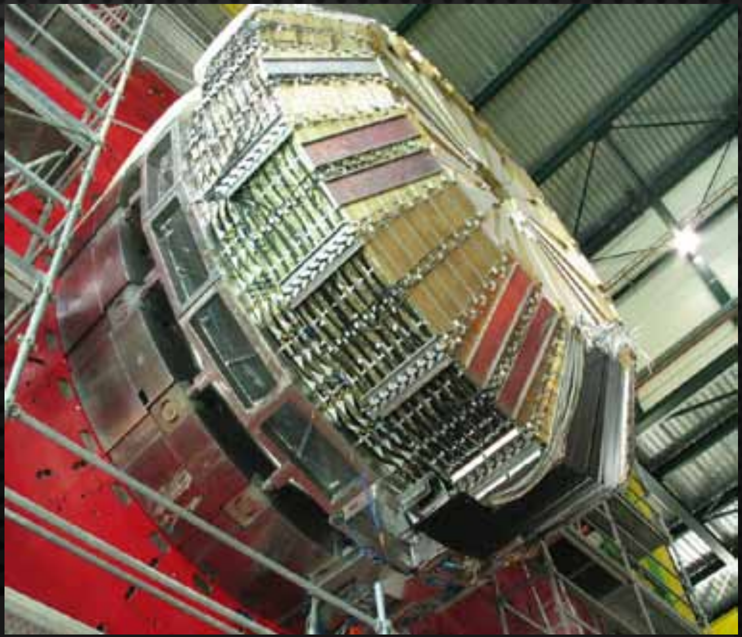


CMS Hadronic Calorimeter (HCAL)



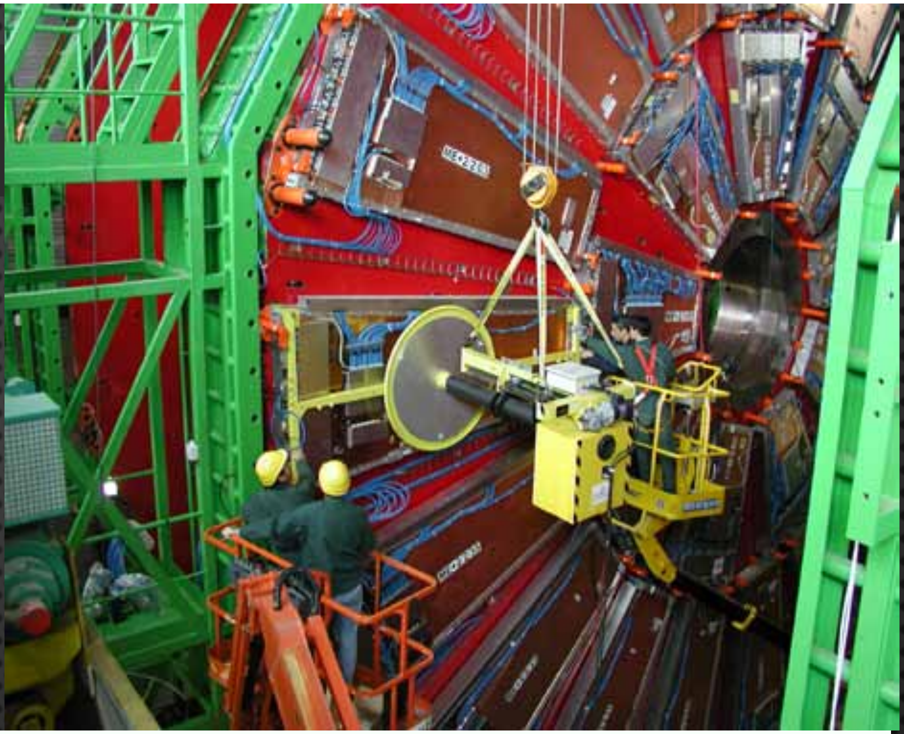
- Sampling calorimeter
- Brass absorber from Russian artillery shells (non-magnetic)
- Scintillating tiles with wavelength shifting (WLS) fiber
- WLS fiber is fed into a hybrid photo-diode (HPD) for light yield measurement

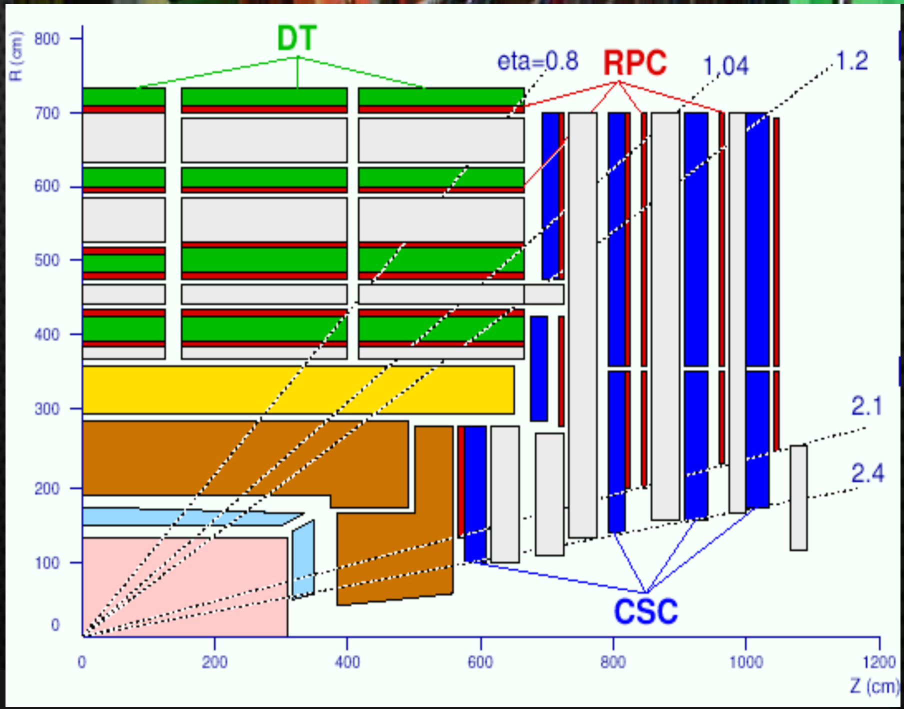




CMS Muon detector

- 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

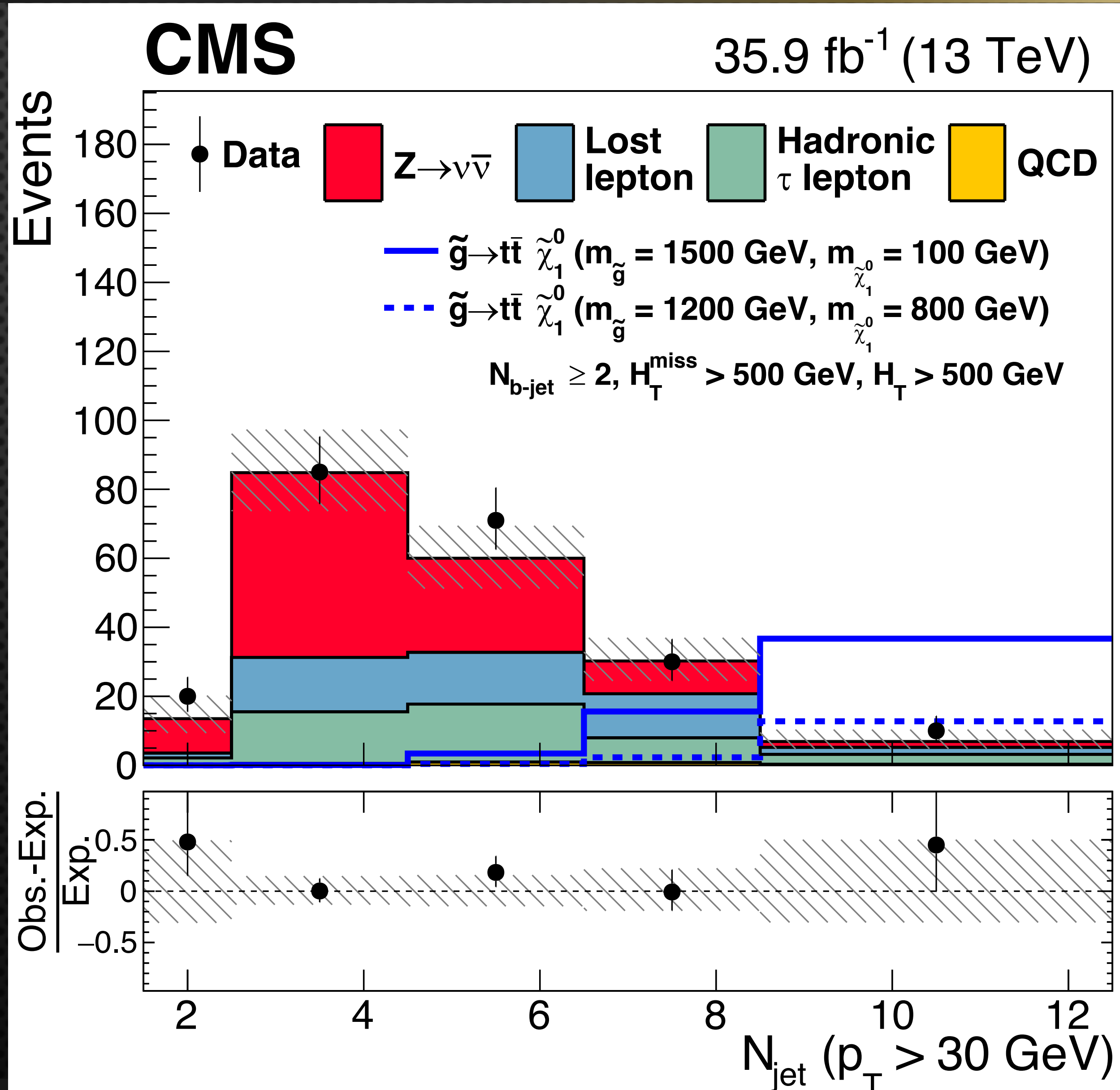




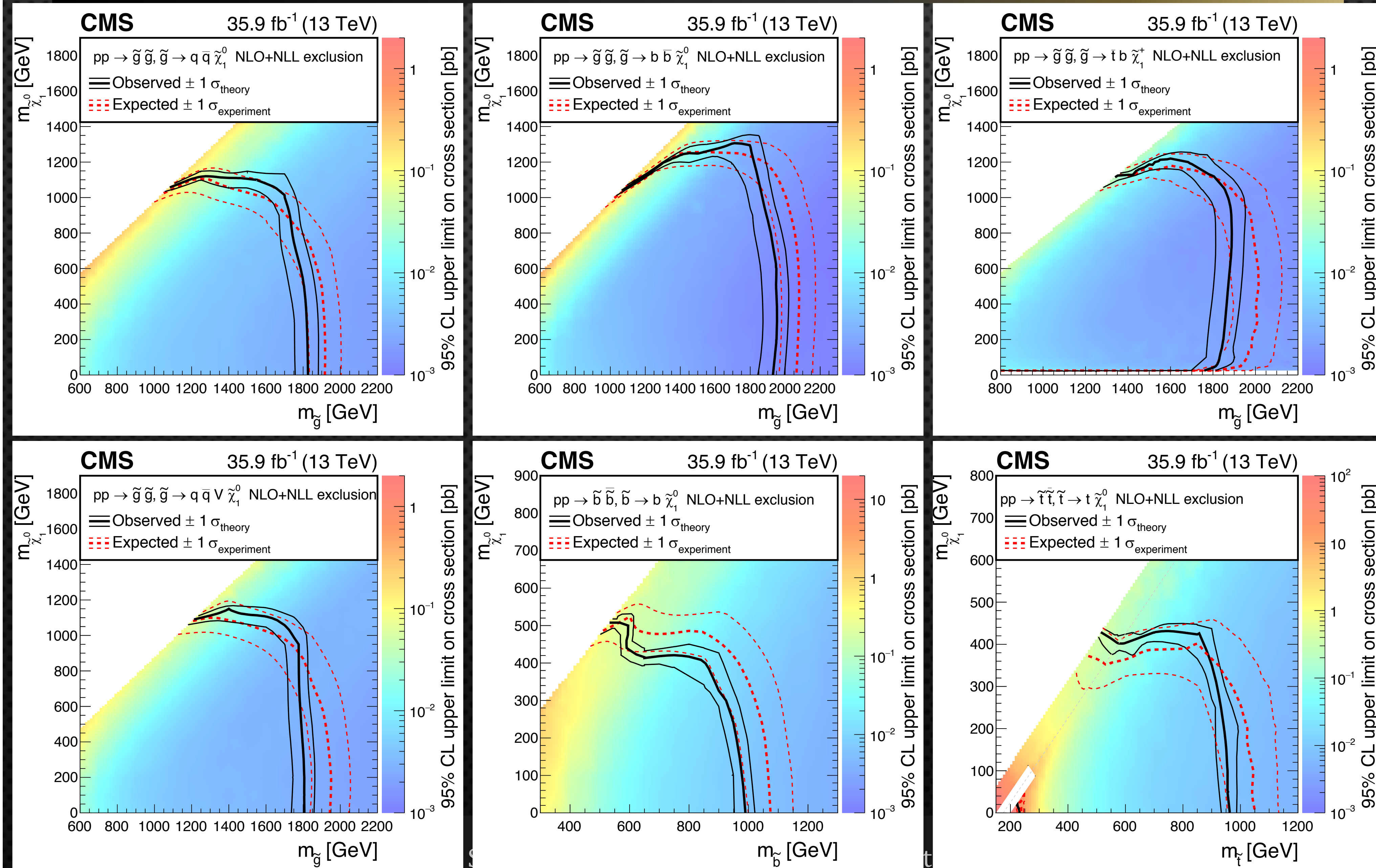
Search results

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

Still no sign of SUSY.

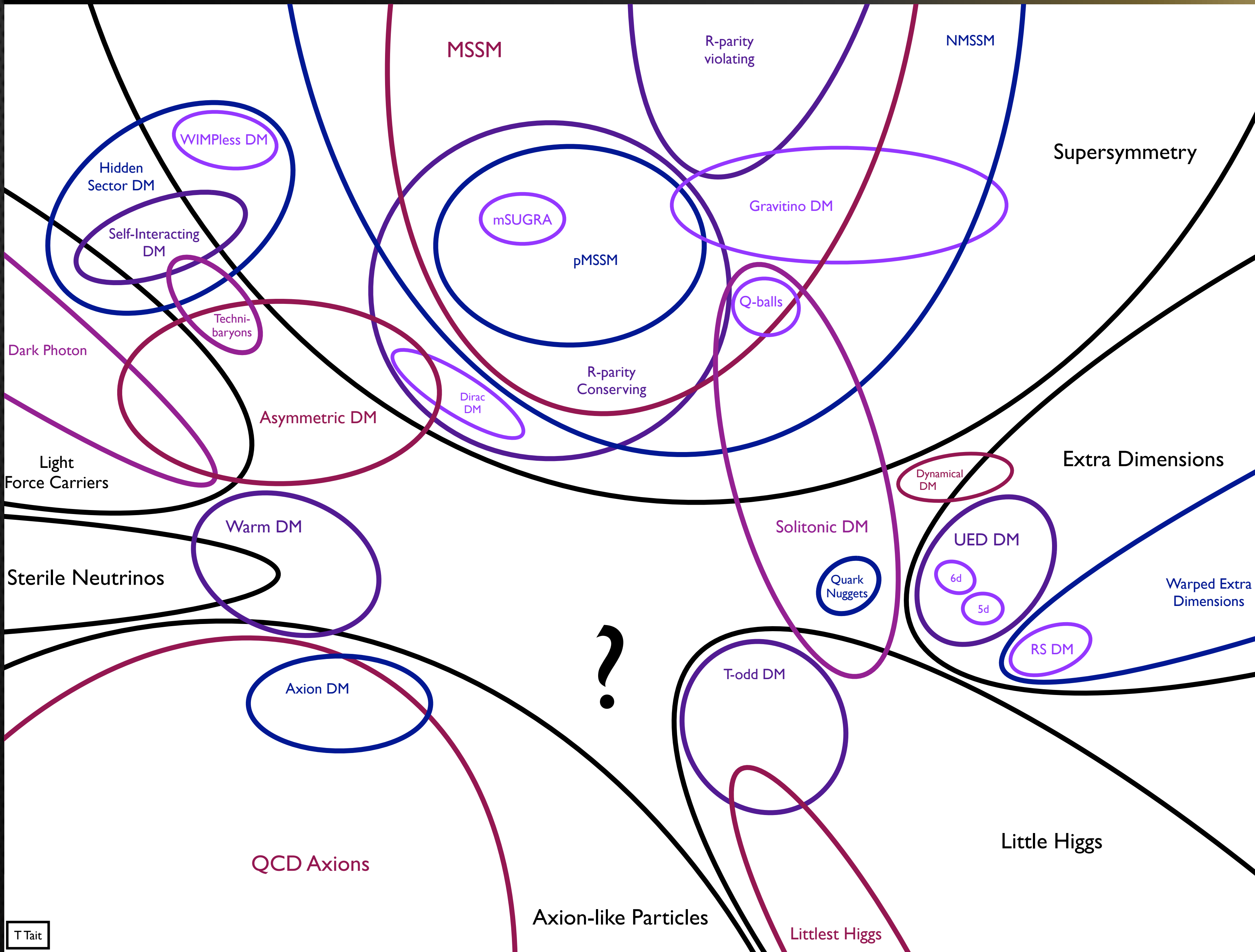


Limits from hadronic SUSY search

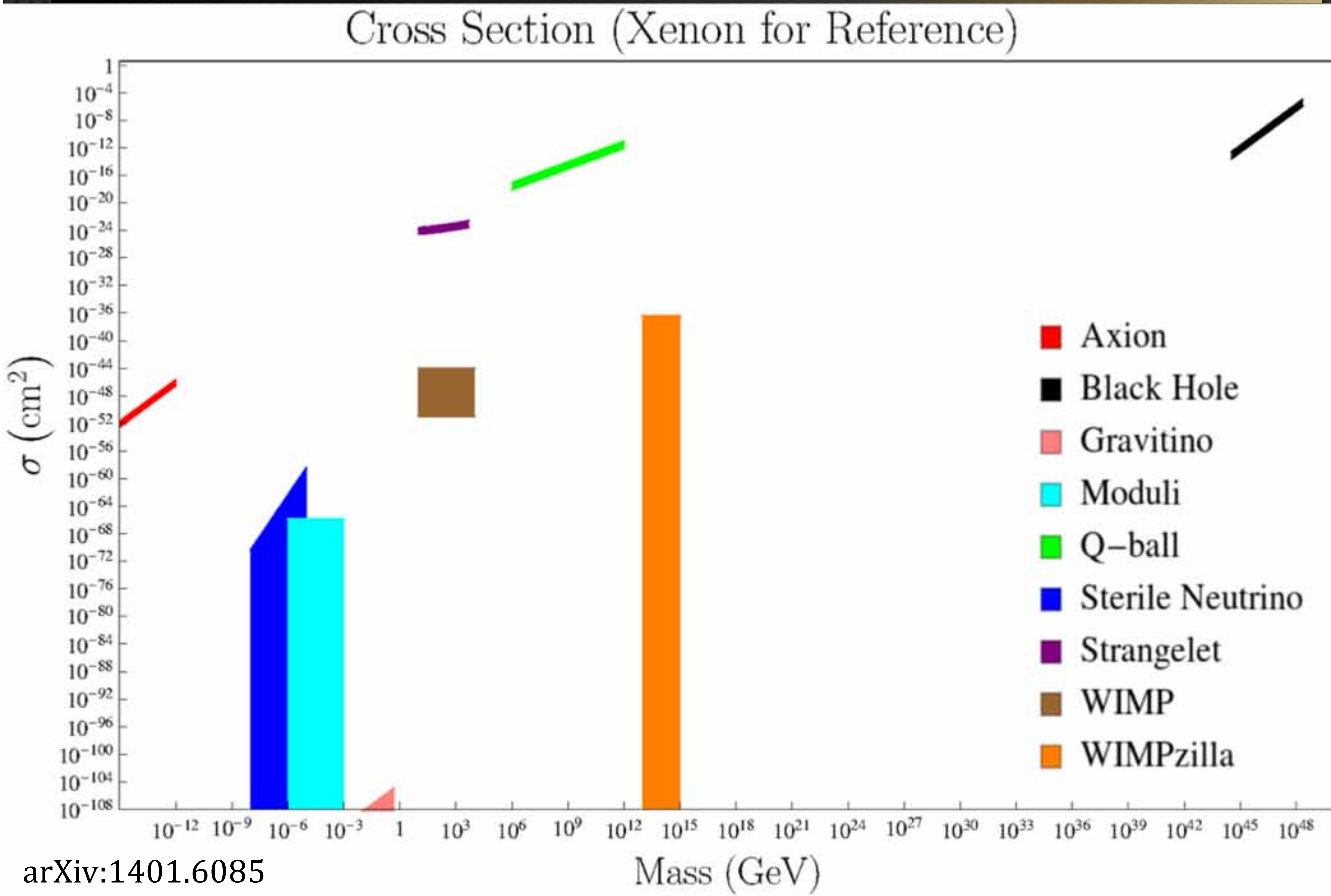


Boulder

Dark Matter candidates

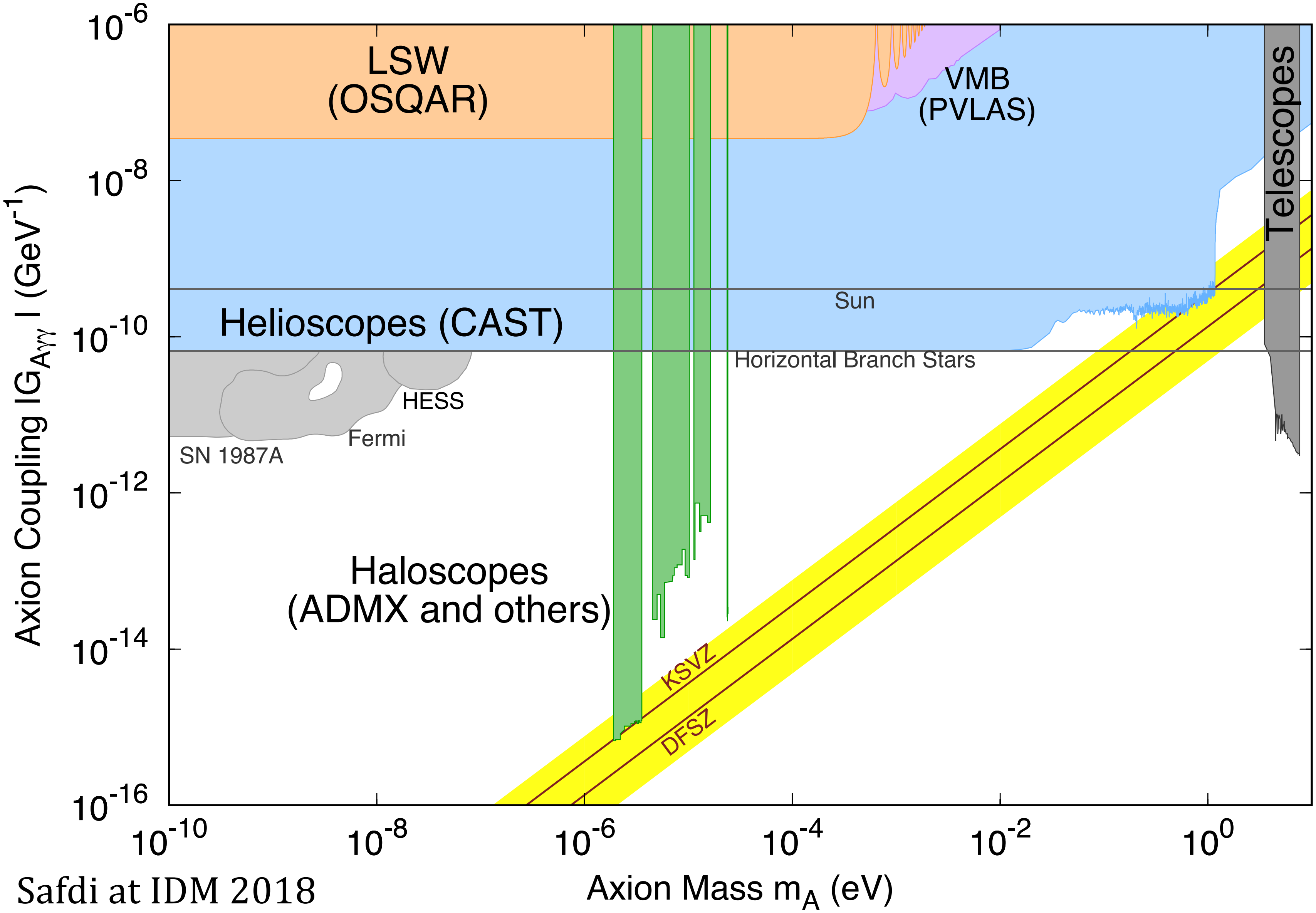


Dark matter cross section vs mass



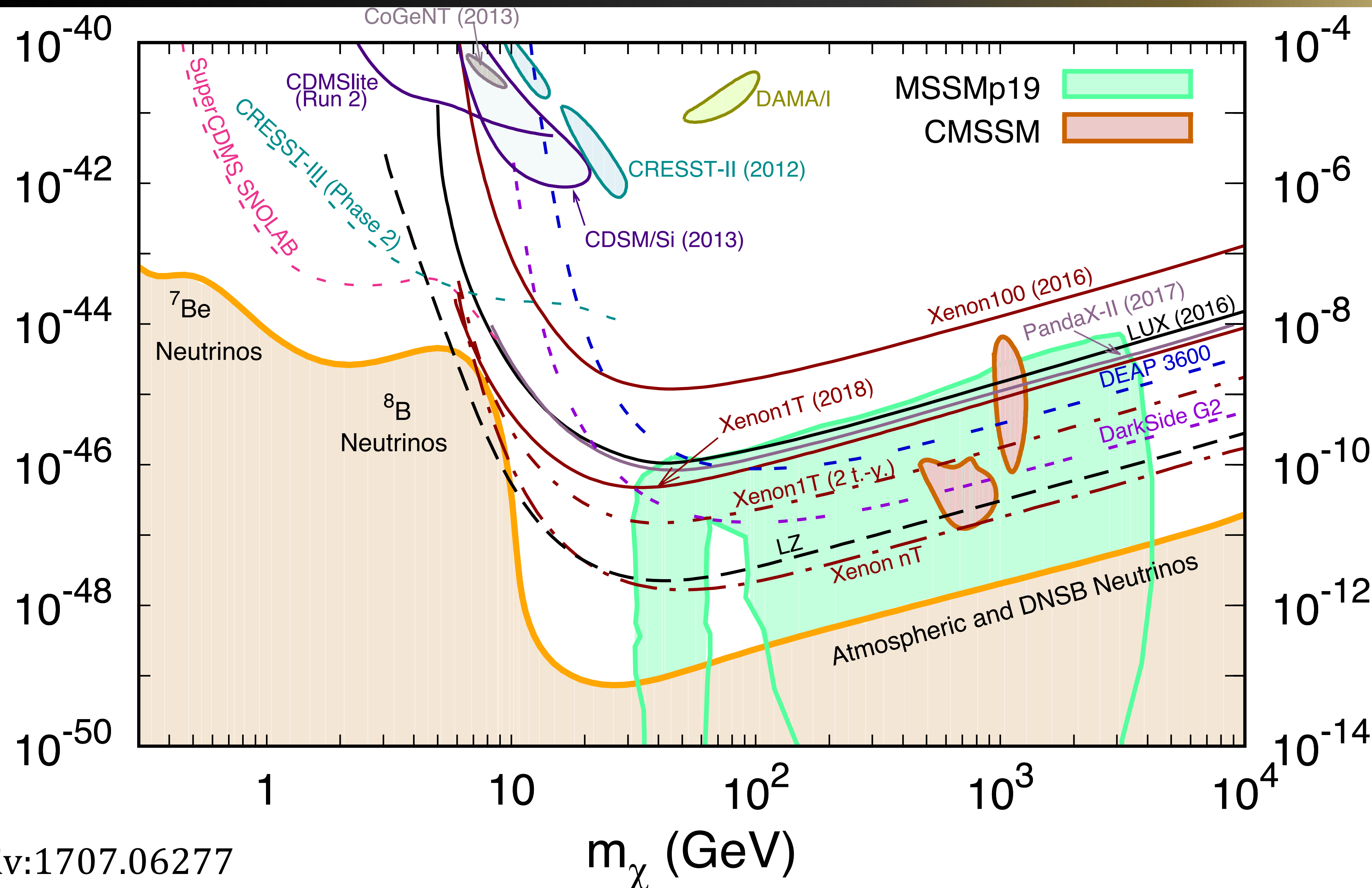
arXiv:1401.6085

Axion limits



Safdi at IDM 2018

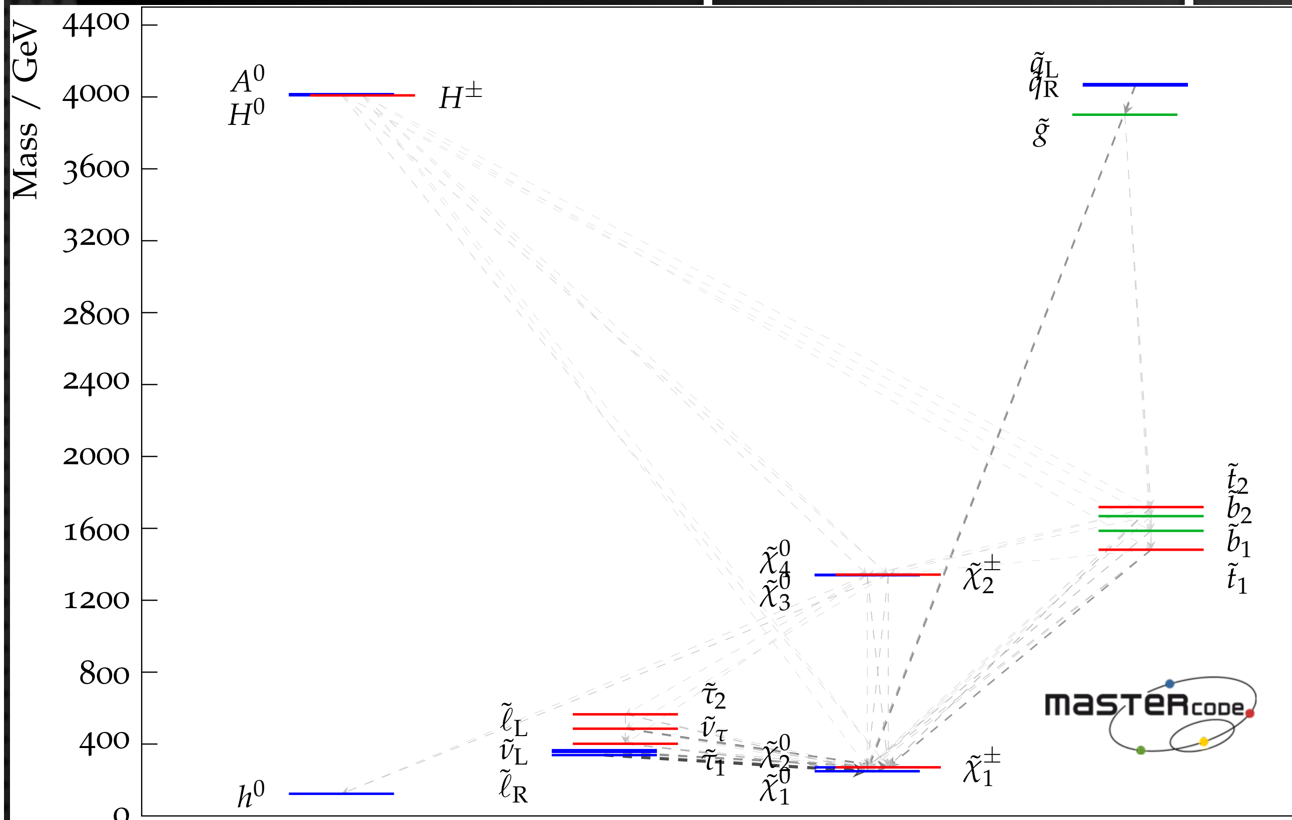
WIMP limits



arXiv:1707.06277

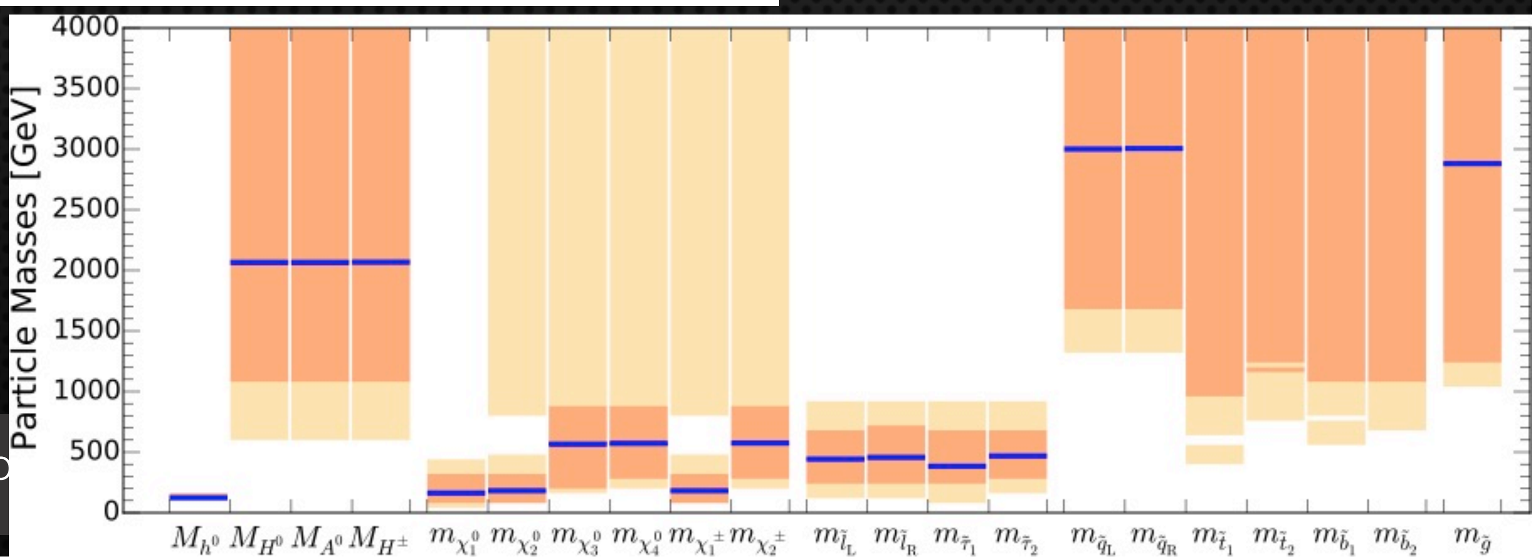
Results of 11-parameter pMSSM fit

arXiv:1710.11091



The masses and decays for the best fit.

The range of masses allowed.



University of Colo
Boulder