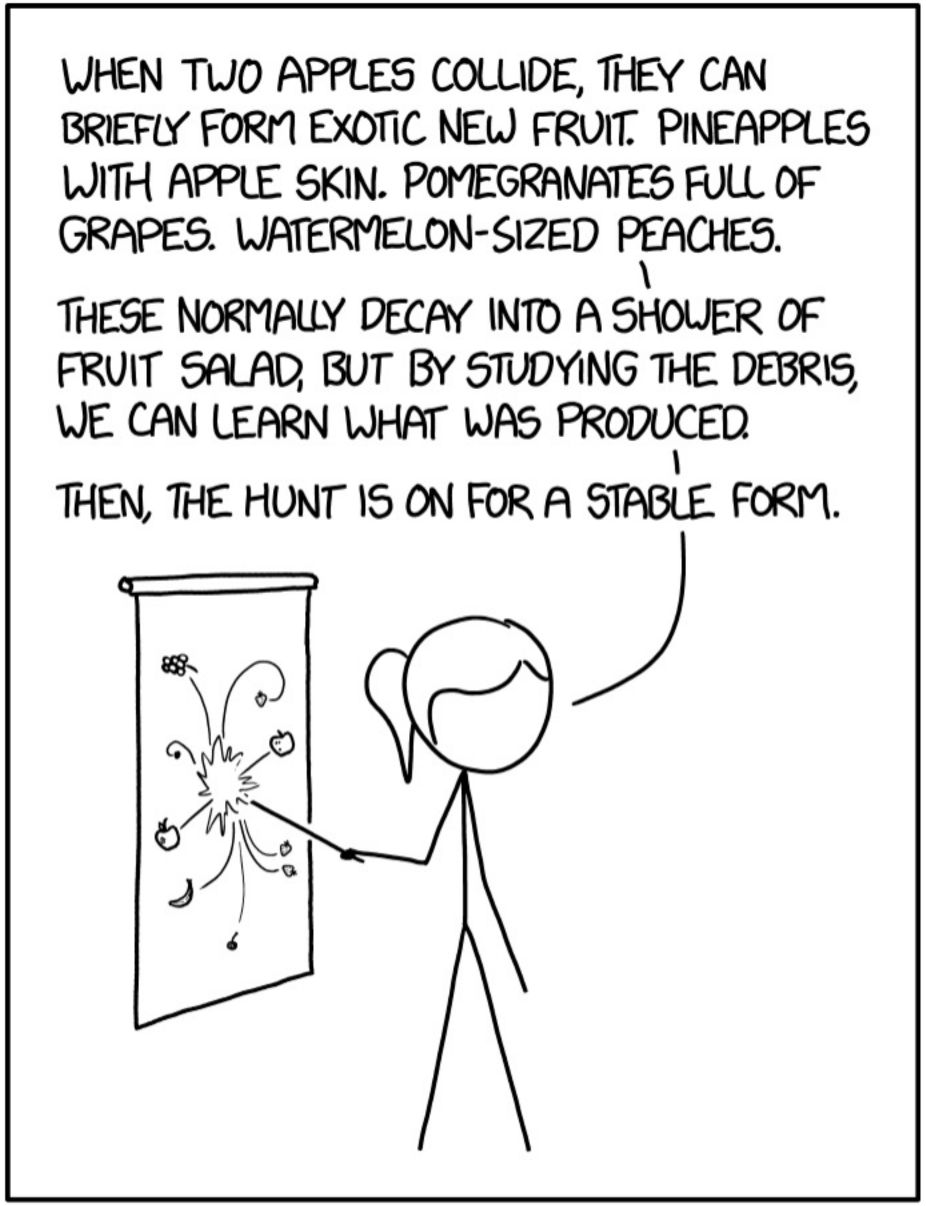
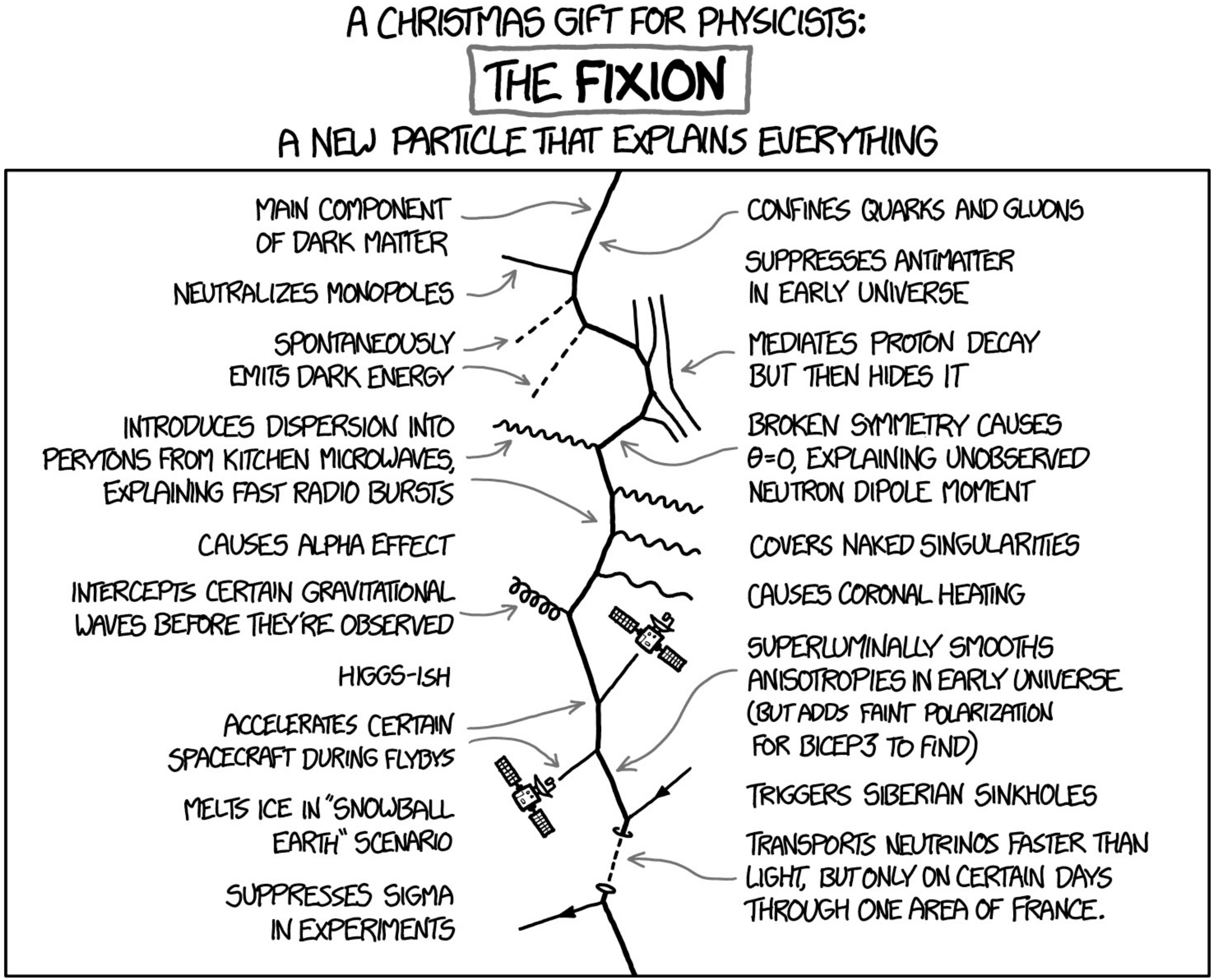
Fruit Collider

https://xkcd.com/1949



HOW NEW TYPES OF FRUIT ARE DEVELOPED

Fixion



https://xkcd.com/1621/

QuarkNet Summer Session for Teachers:
The Standard Model and Beyond

Allie Reinsvold Hall

Summer 2024

Course overview

What are the fundamental building blocks that make up our universe?

Mission: overview of the past, present, and future of particle physics

1. History of the Standard Model, Part 1: Chemistry to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. Particle physics at colliders
4. **Beyond the Standard Model at the LHC** (session webpage)
5. Neutrino physics
6. Dark matter and cosmology

Goal: Bring you to whatever *your* next level of understanding is and provide resources for when you teach. Not everyone is at the same level and that's okay.

Plan for today

- Loose ends from Session 3
- Homework discussion in breakout rooms – finding “nothing”

- Lecture

- 10 minute break

- Lecture
- Homework discussion in breakout rooms – CMS and ATLAS results

- Final logistics, plan for next week

Loose ends from Session 3

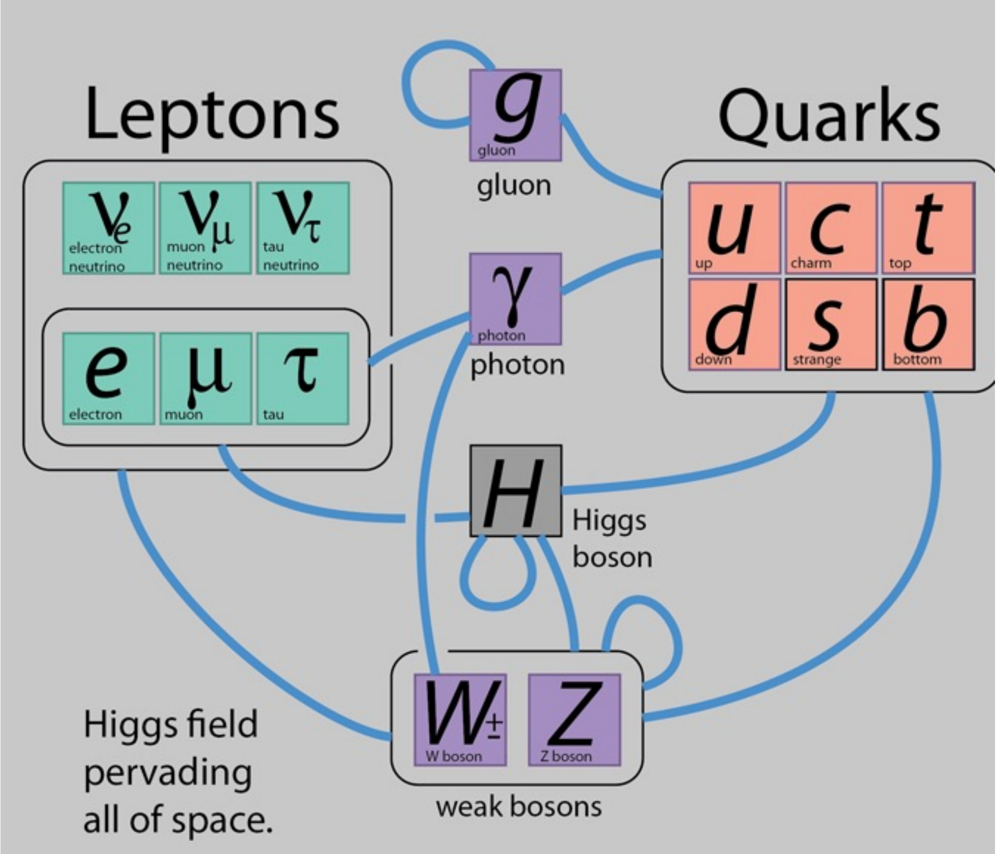
- Q: How does the neutral Z boson decay into two negatively charged electrons?
  - A: It can't! The Z actually decays into one electron and one positron (the antimatter electron), but since the electron and positron are basically the same except for charge, particle physicists are normally lazy and refer to **both** as "electrons"

- Q: What are some other ways to present the CMS data to a class? Would love some examples of how to implement this in activities or units.
  - A: Check out the resources in the QuarkNet Data Portfolio!

- Suggested reading:
  - A Tour of the Subatomic Zoo, by Cindy Schwarz
  - Six Easy Pieces by Richard Feynman
  - Fundamental: How quantum mechanics explains absolutely everything (except gravity) by Tim James

Loose ends from Session 3

- Q: How does the Standard Model predict how particles will decay?
  - A: The SM is much more than a list of particles. It also includes conservation laws, what interactions (blue lines) are allowed and the math to calculate how often each interaction occurs (**cross sections!**)



Taken from http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/particleint.html

Beyond the Standard Model at the LHC

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

Breakout discussion: Finding “nothing”

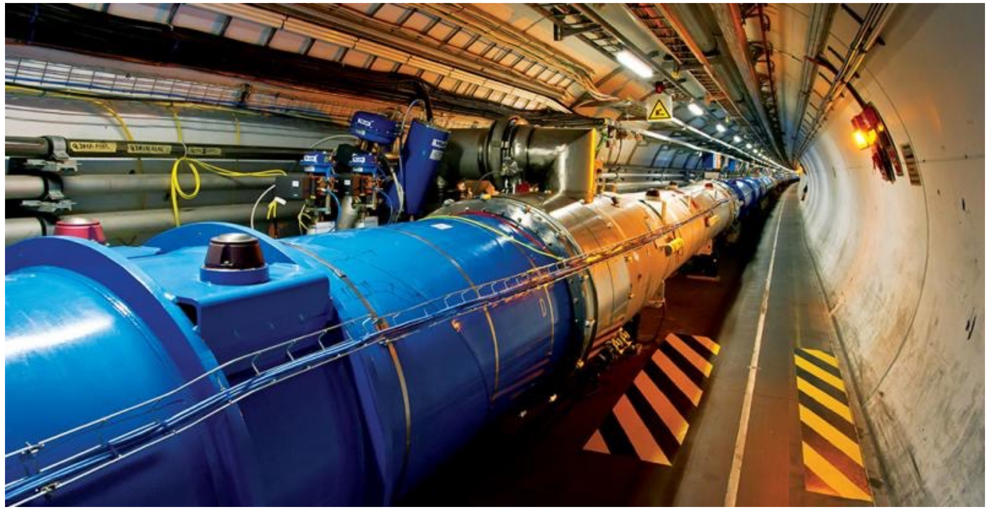
- Introduce yourself to today’s group!

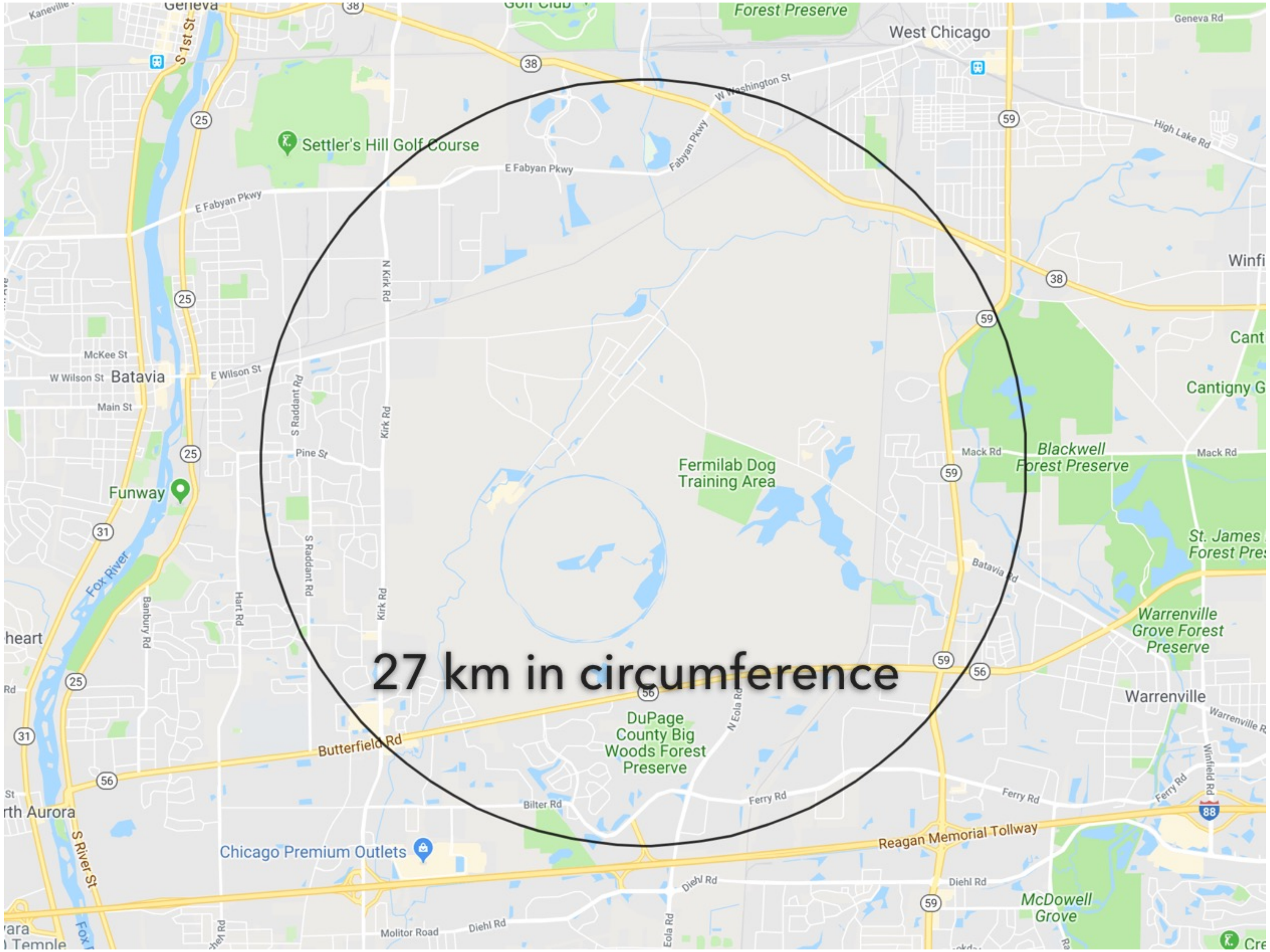
- Discuss the Gizmodo article about finding nothing: https://gizmodo.com/the-scientists-who-look-for-nothing-to-understand-every-1796309514
  - Why is it important to publish null results?
  - What is the goal of “blinding” the data?

- We’ll come back to this later today!

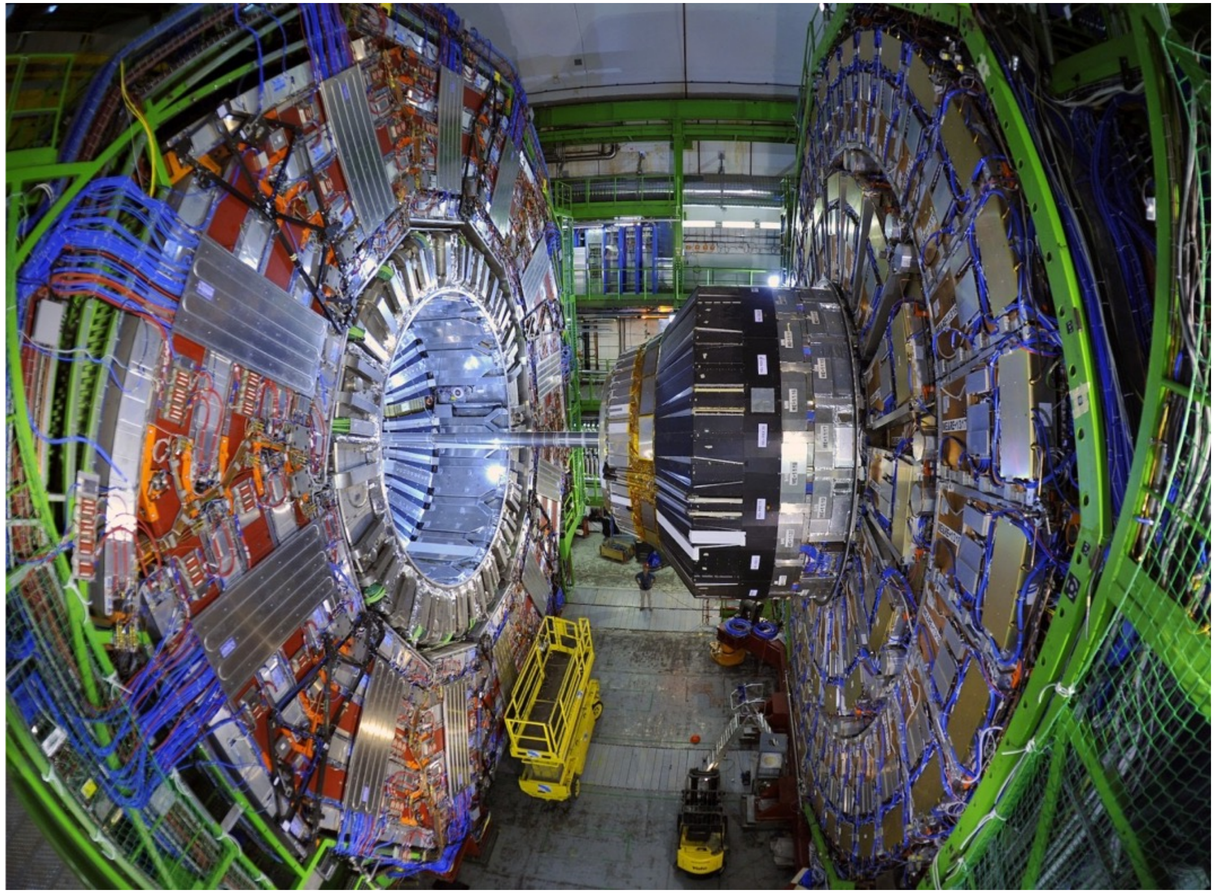
Large Hadron Collider

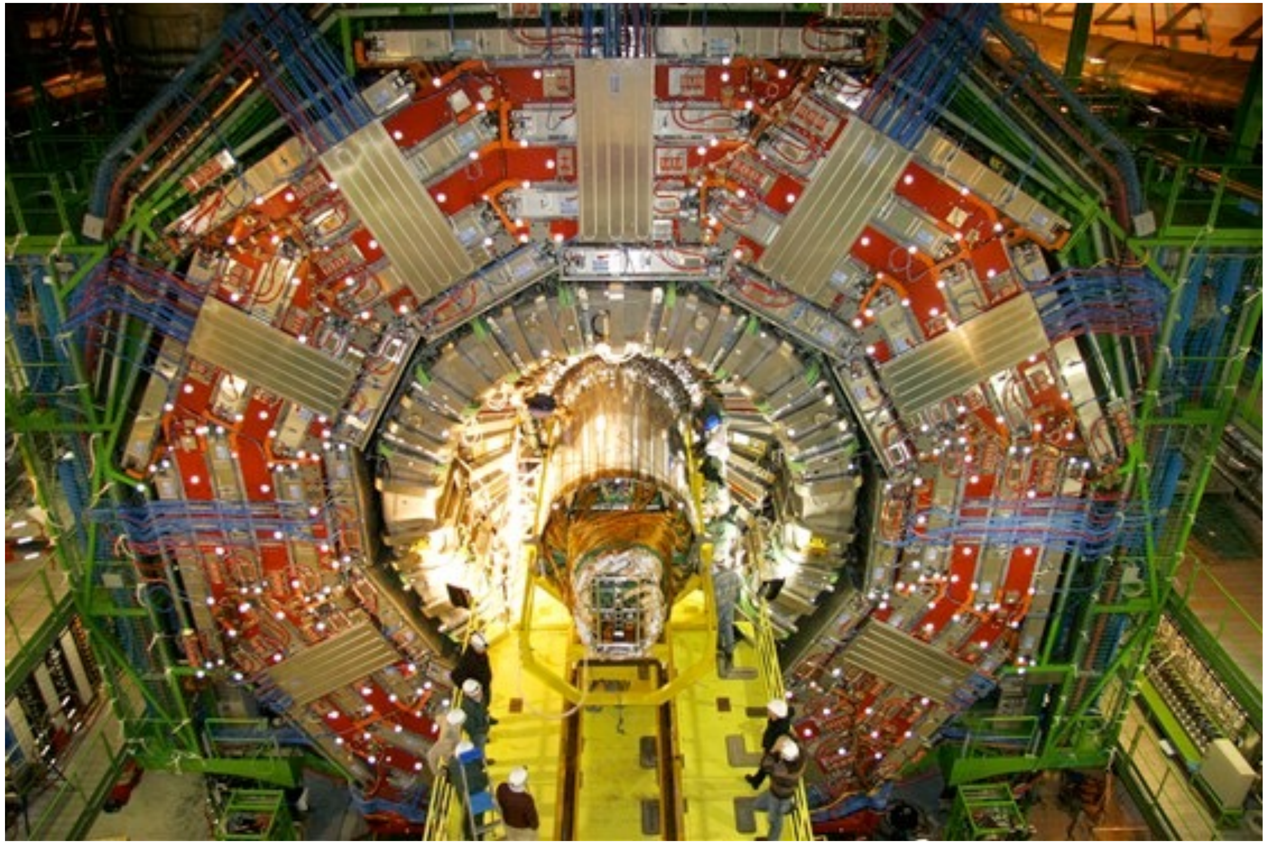
- 17 miles in circumference
- World's largest and highest energy hadron collider
    - 13.6 TeV center of mass energy
    - Beats the previous record held by the Tevatron at Fermilab
    - 1232 dipole magnets at 8.3 T




27 km in circumference

Compact Muon Solenoid

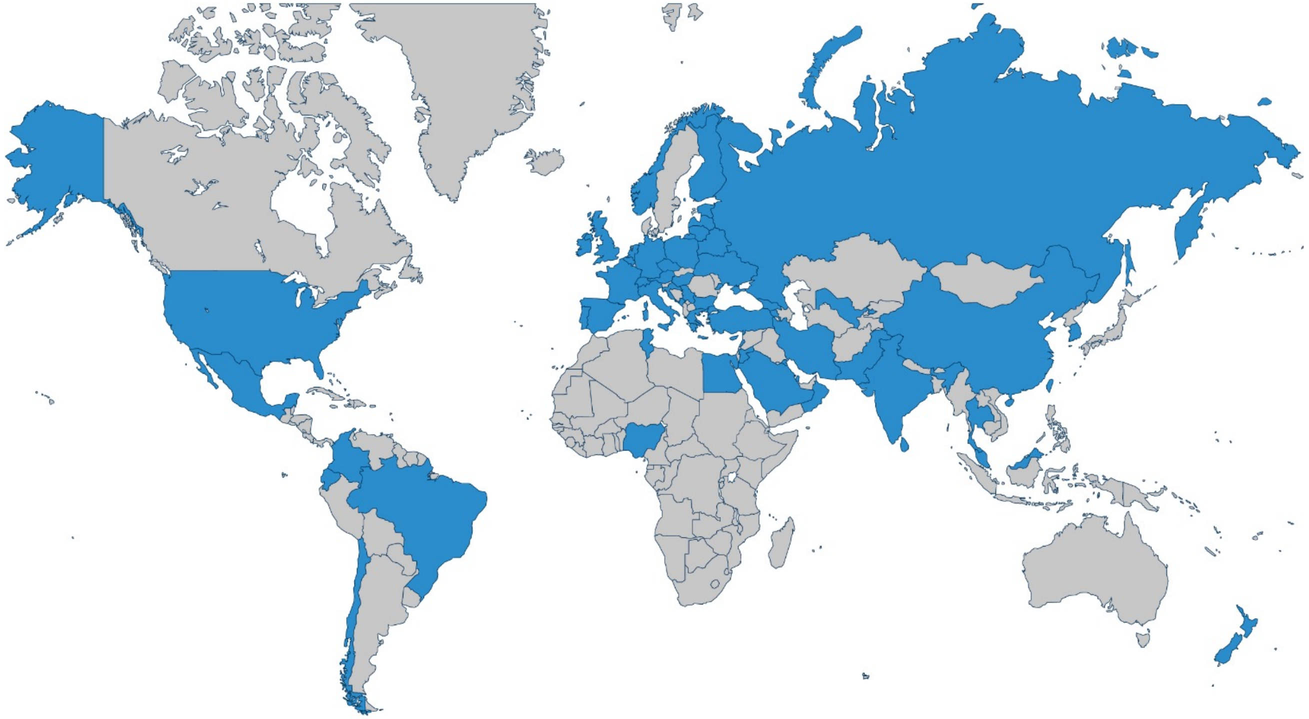




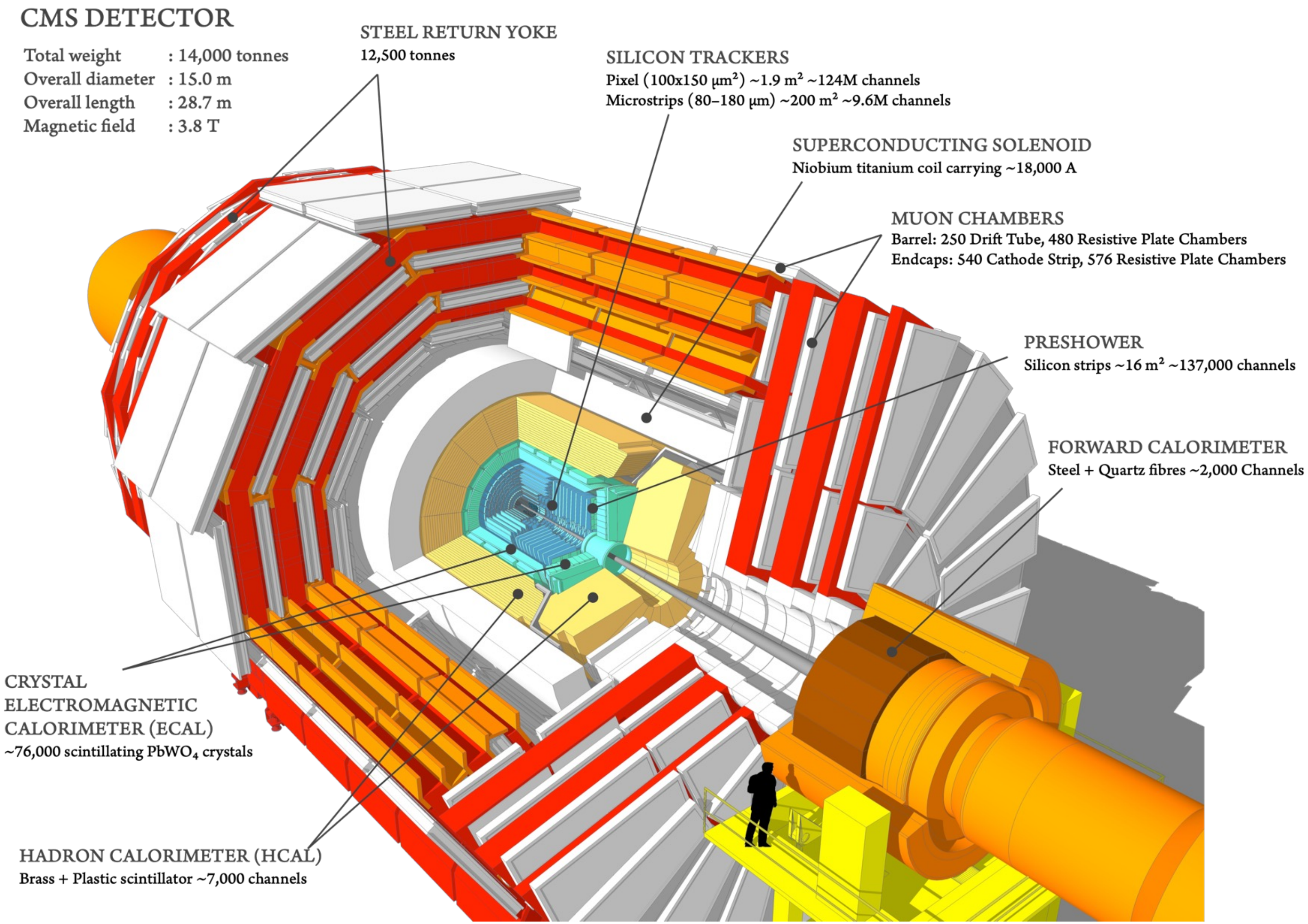
CMS Collaboration

- 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



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

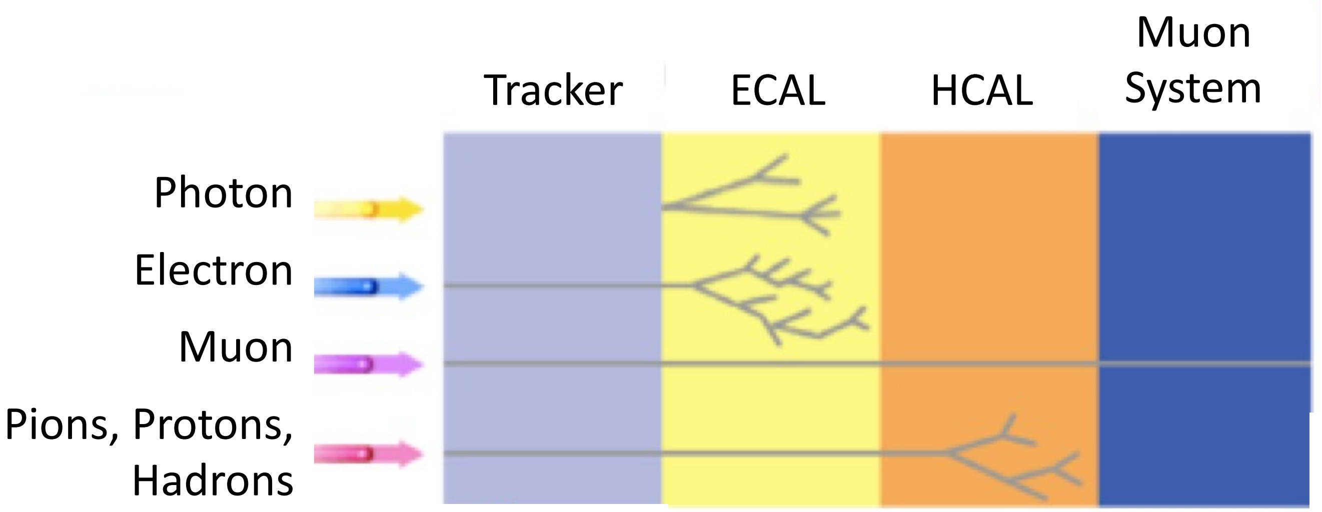
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

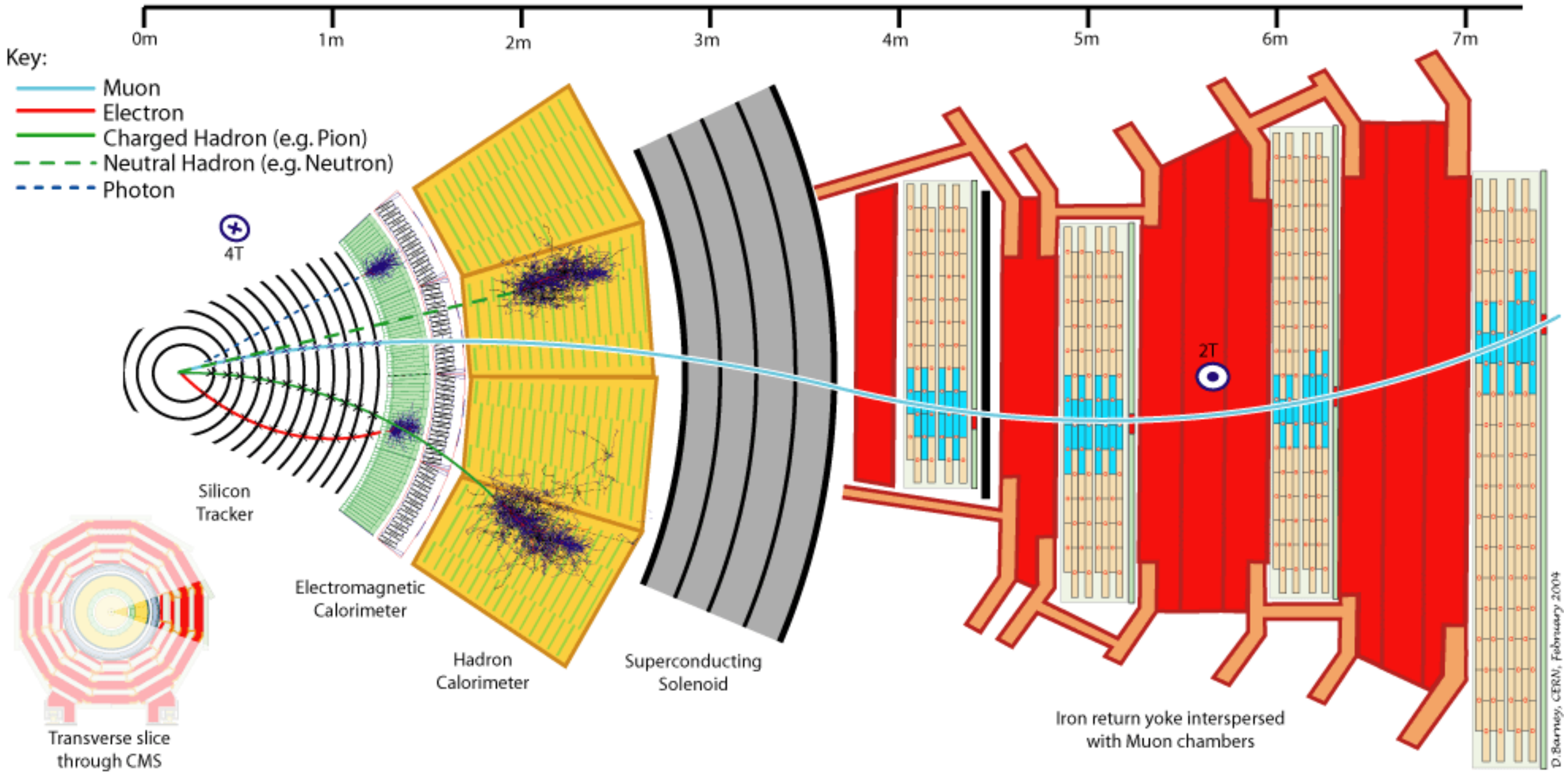
Particle Detection

- Different types of detectors for different particles



CMS Reconstruction

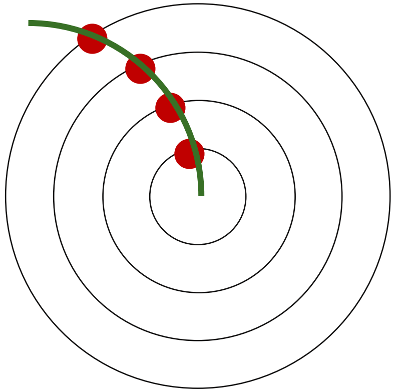
Reconstruction: identifying elementary particles by their signatures in the different sub-detectors of CMS

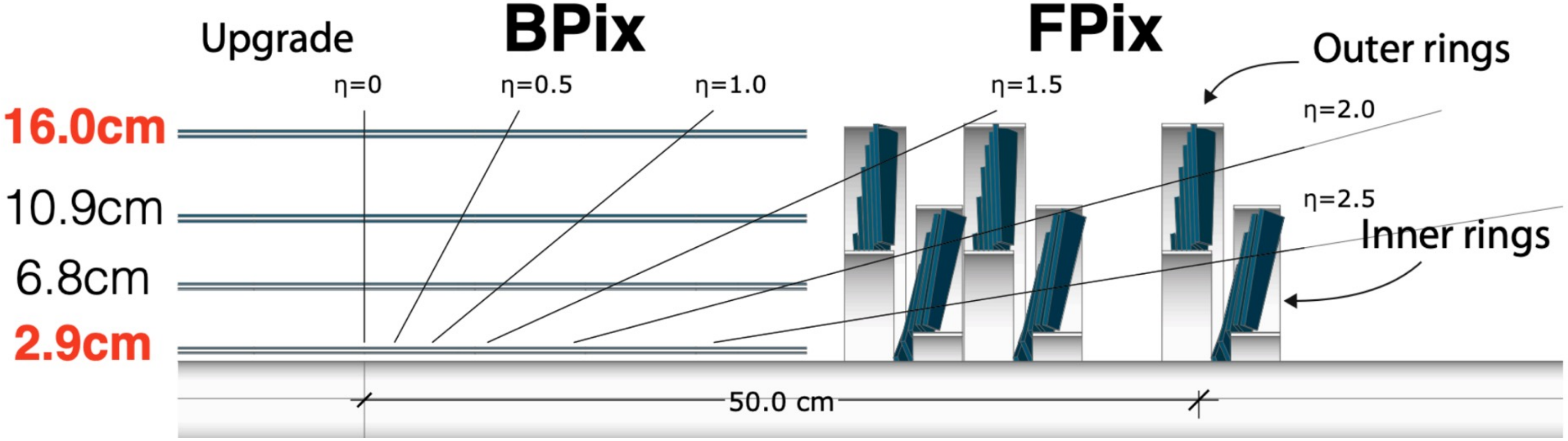


Silicon Tracker

- 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

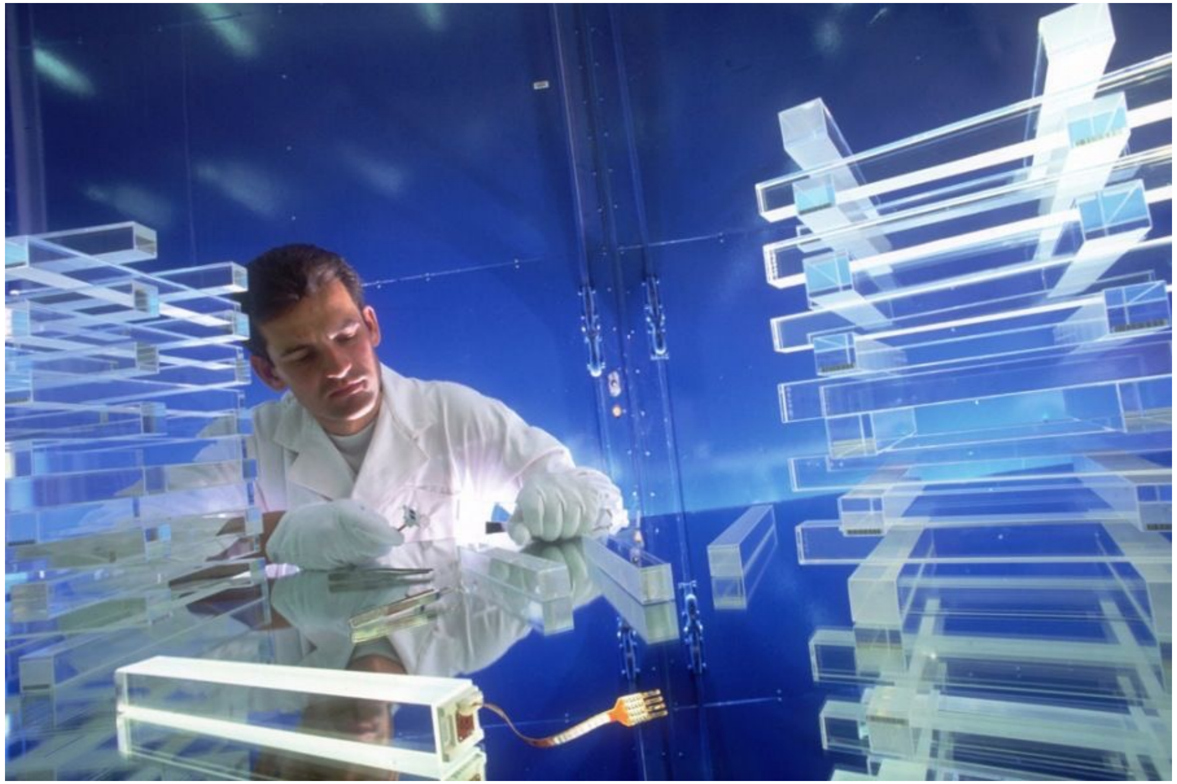
Half endcap disks for the upgraded CMS pixel detector, installed early 2017

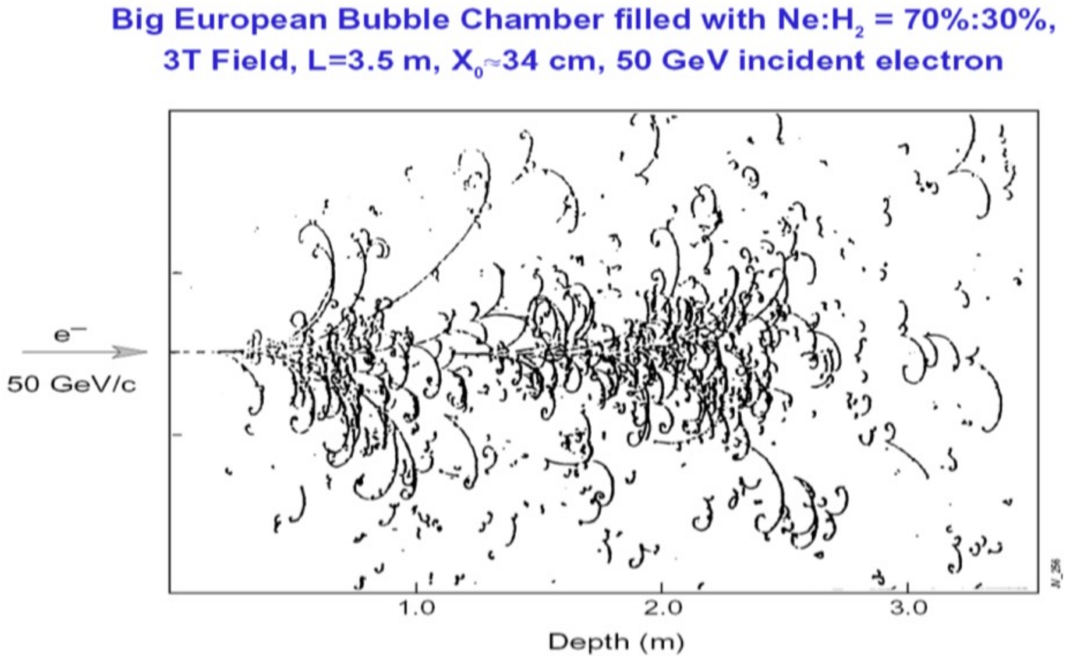




Electromagnetic Calorimeter

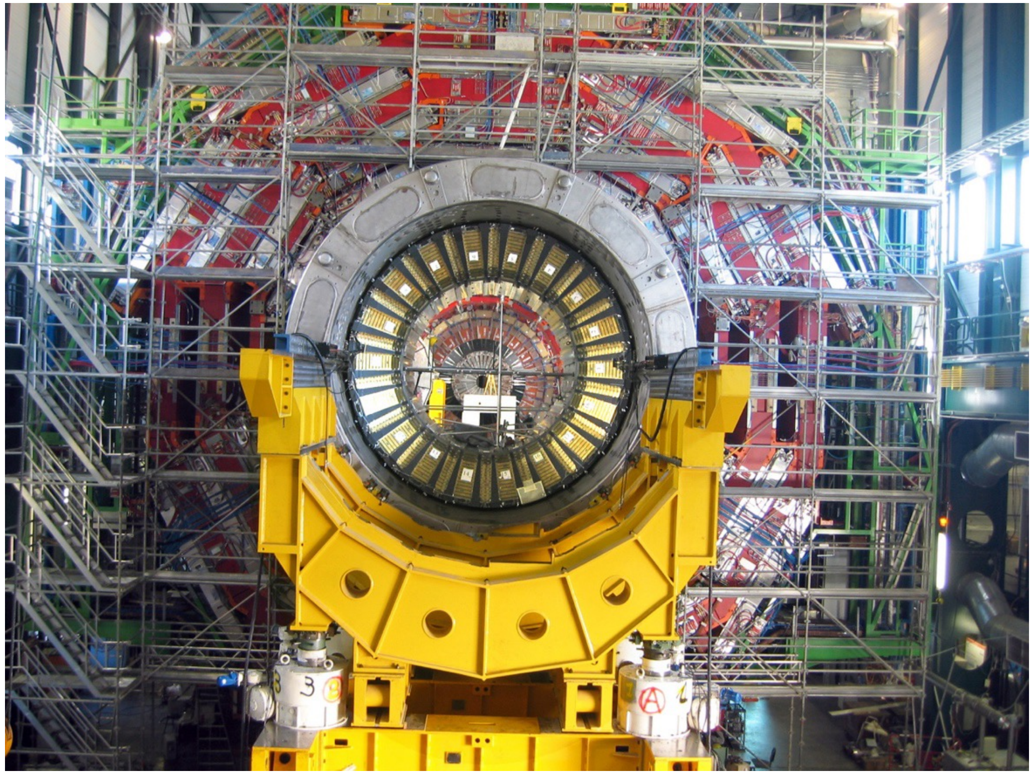
- 75,848 lead tungstate crystals in the barrel, each 2.2 x 2.2 x 23 cm
- Avalanche photodiodes used to detect the light from the scintillators
- Accurate measurement of electron and photon energies
  - Hadrons and muons pass through





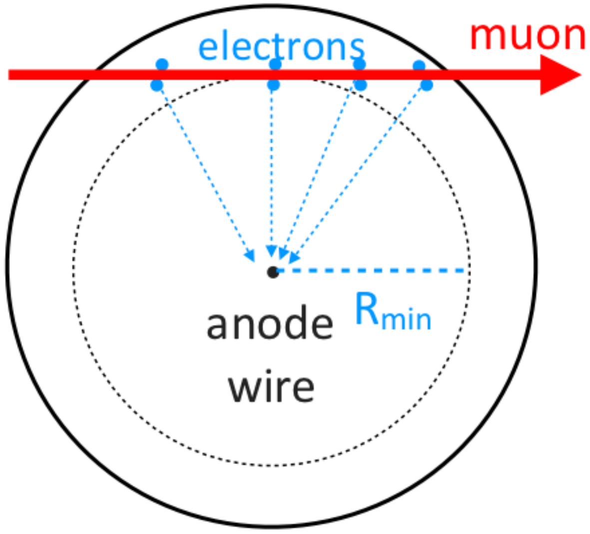
Hadronic Calorimeter

- 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

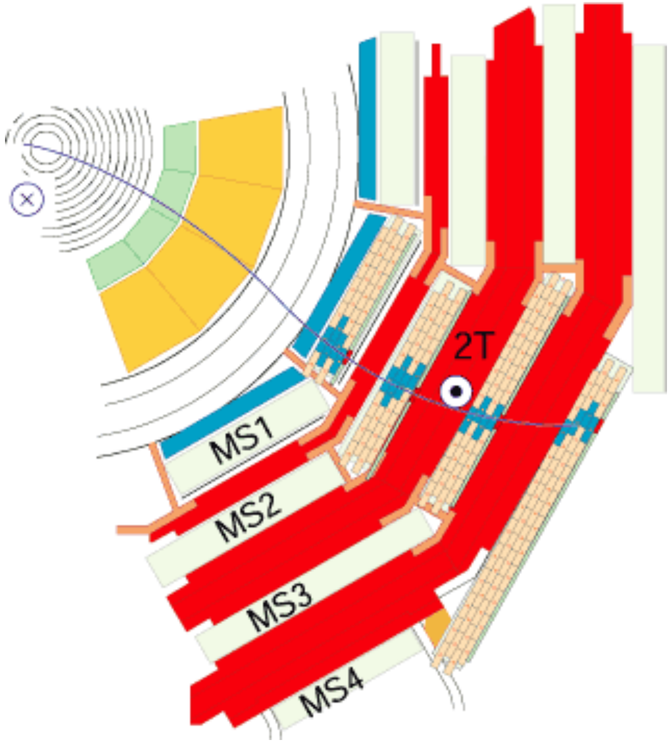


Muon System

- 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)

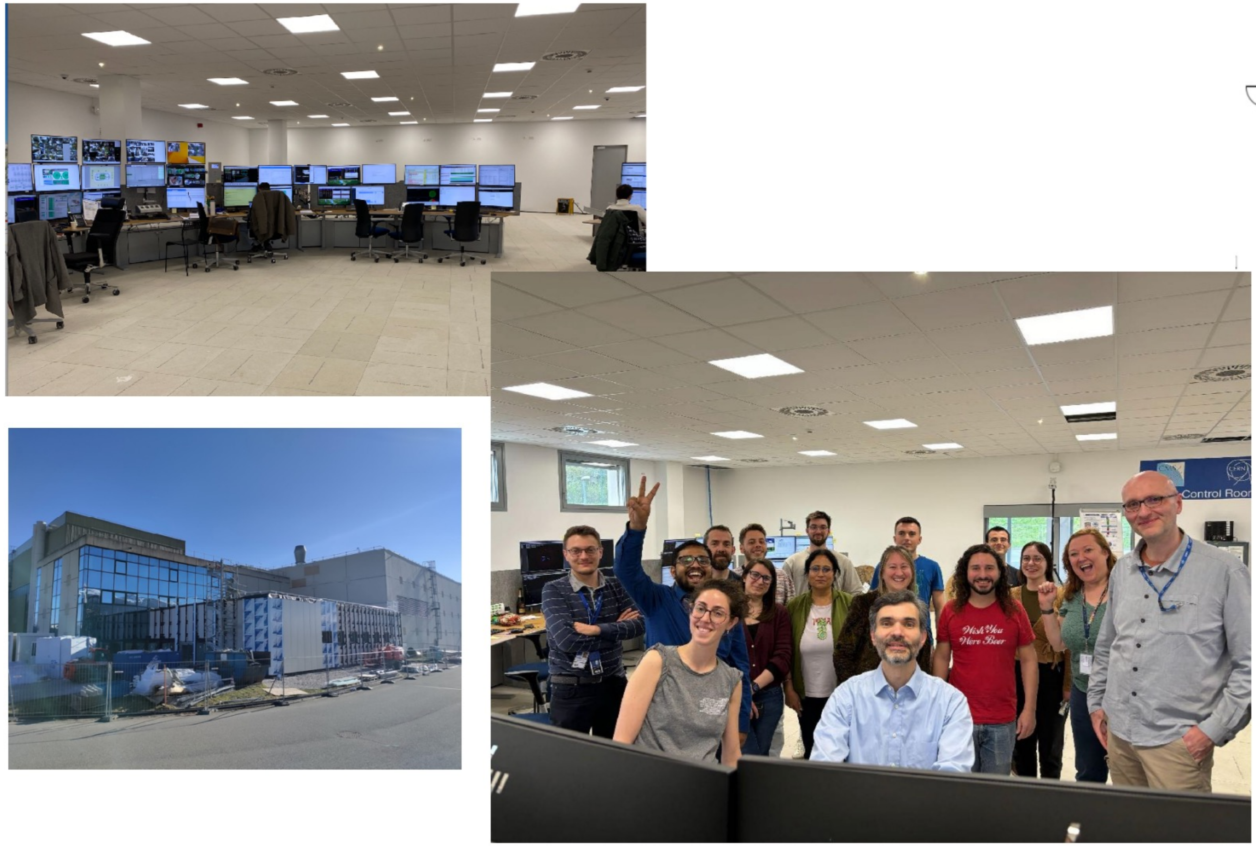


cathode tube
3 cm diameter



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

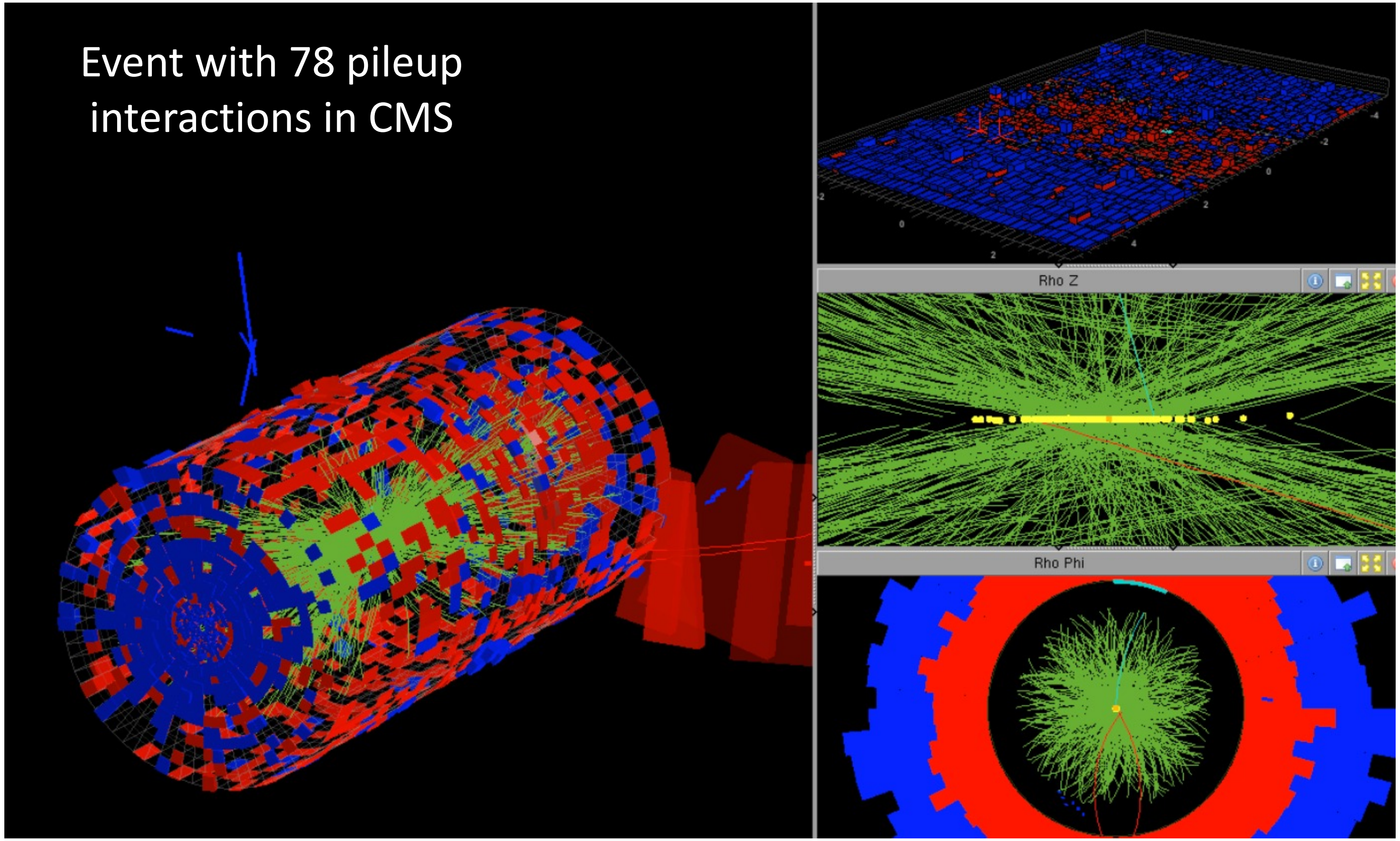
- Still ends up with lots (Petabytes, soon to be Exabytes) of data
- Stored and analyzed on “The Grid”, or the Worldwide LHC Computing Grid (WLCG) on computers from Lithuania to Nebraska, total 300k cores
- Many events: CMS needs to process **> 1 billion** events (simulated + real collisions) per month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

CMS Global Computing Grid

70+ sites, 200k+ CPU cores

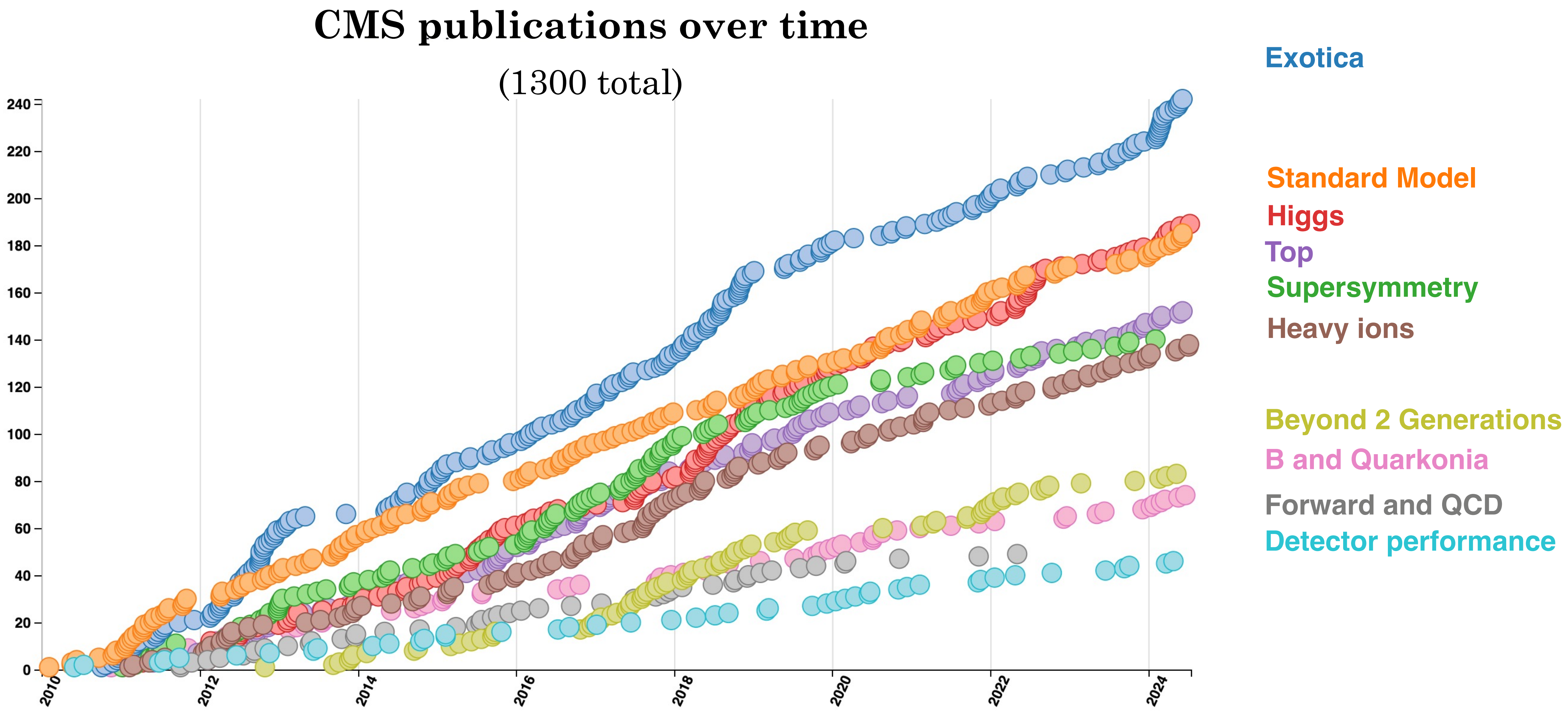
50 proton pileup

- 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



Event with 78 pileup interactions in CMS

CMS Physics


CMS publications over time
(1300 total)
240
220
200
180
160
140
120
100
80
60
40
20
0
2010
2012
2014
2016
2018
2020
2022
2024
Exotica
Standard Model
Higgs
Top
Supersymmetry
Heavy ions
Beyond 2 Generations
B and Quarkonia
Forward and QCD
Detector performance

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!

Homework: CMS/ATLAS physics

ATLAS physics results: https://atlas.cern/updates/briefing

CMS physics results: https://cms.cern/cms-updates?field_article_type_target_id=382

Presentations:

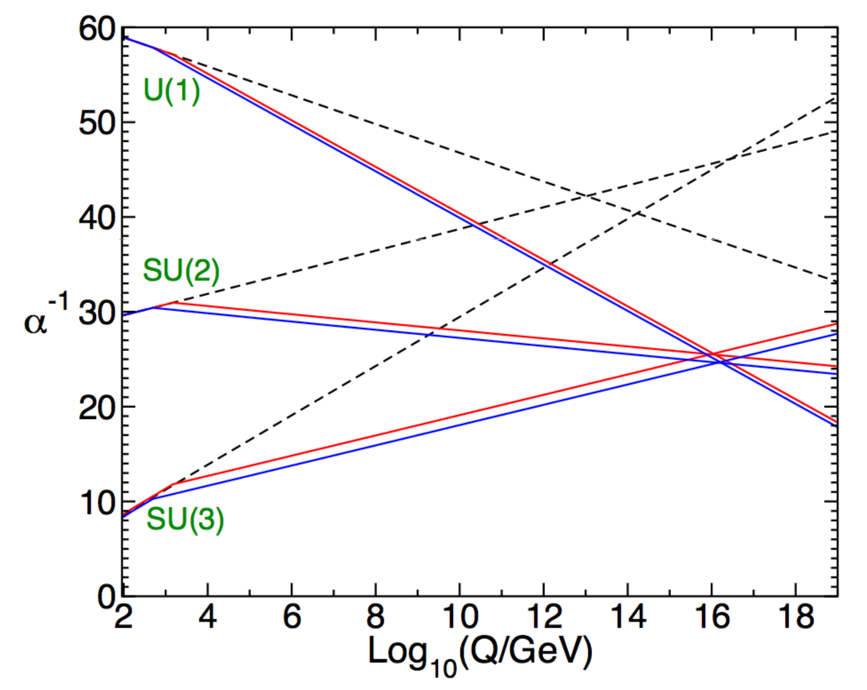
- What was the goal of this analysis and why is it significant? Is this a search for new physics or a precision measurement of a predicted Standard Model result?
- What particles were used in the analysis? Does the summary describe the methods or challenges of this analysis?
- What is the result?

Groups of 4 people, approximately twenty minutes to present and discuss

Add questions to google doc (sent in chat) for group discussion.

Motivations for beyond SM physics

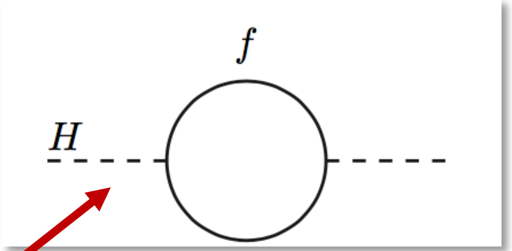
- Hierarchy problem: one example of "fine-tuning"
  - Two extremely large values in the theory must cancel each other almost exactly
- Grand Unification theories
  - Maybe at high energies all the forces are unified into one
- Dark matter: what type of particle (if any) is it?

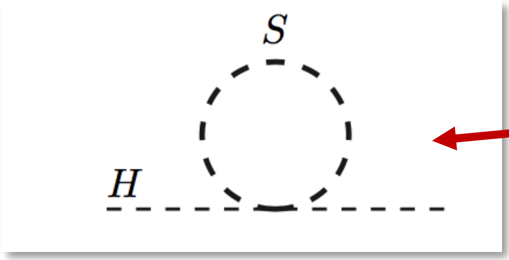


Supersymmetry (SUSY)

- 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!)

Quarks	u	c	t	**Higgs Boson**
	d	s	b	H
Leptons	e	μ	τ	
	ν_e	ν_μ	ν_τ	**Gauge Bosons**
	γ	Z	W	g

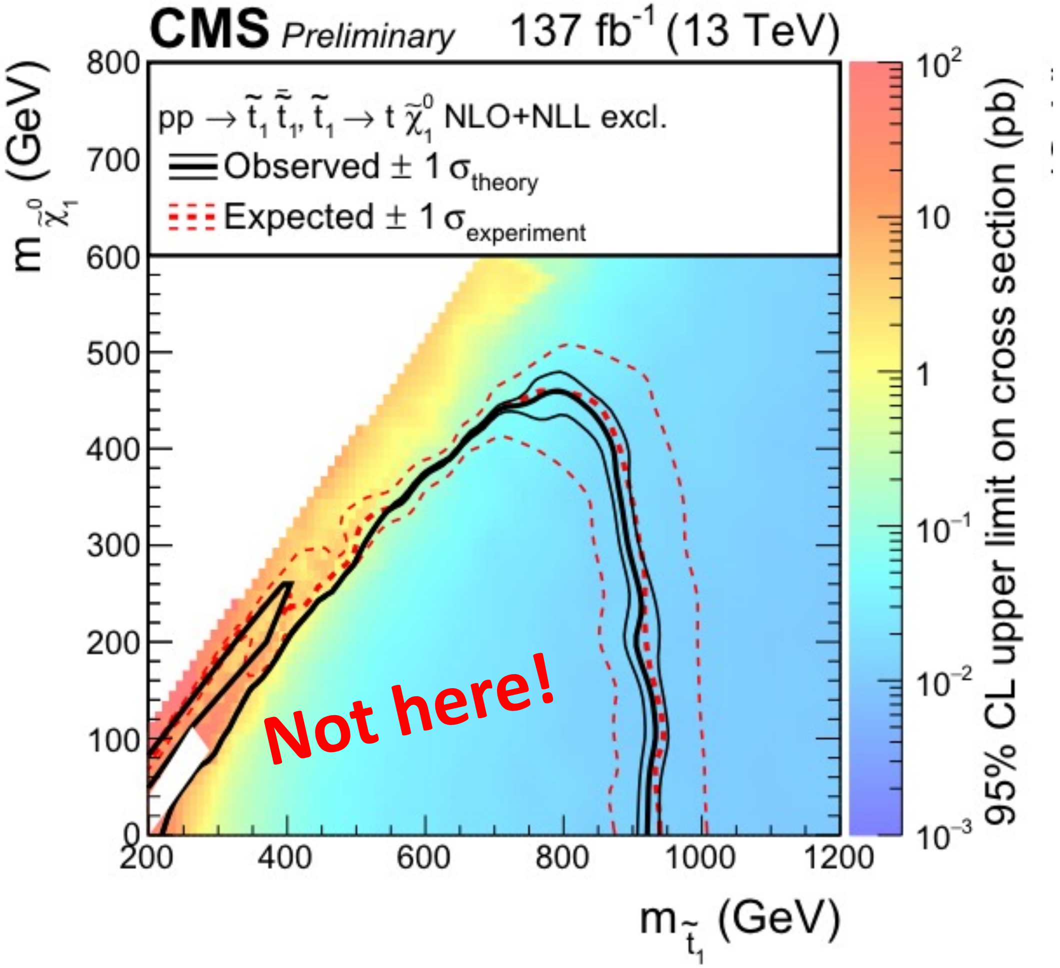


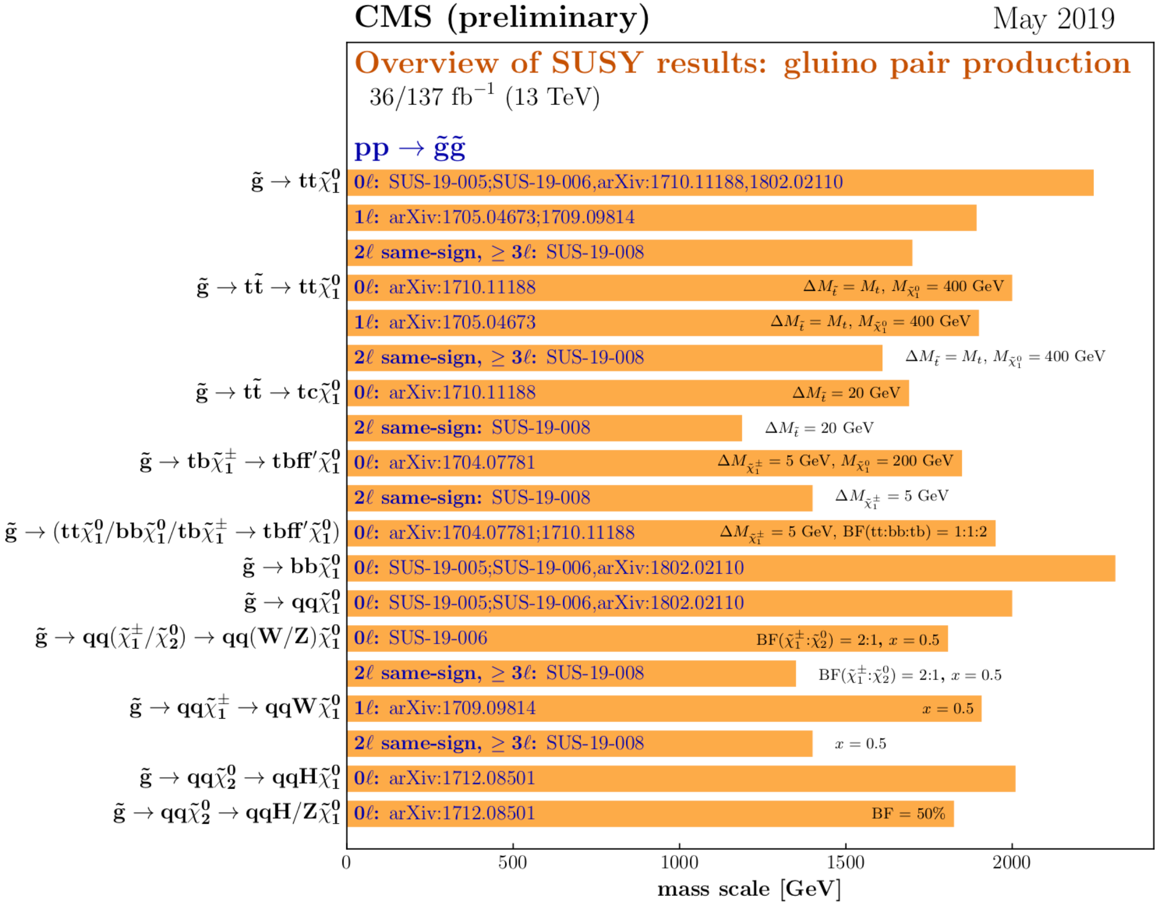


	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	**Squarks**
Higgsinos	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	
$\tilde{H}$	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	**Sleptons**
Gauginos	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	
$\tilde{\gamma}$	$\tilde{Z}$	$\tilde{W}$	$\tilde{g}$	

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

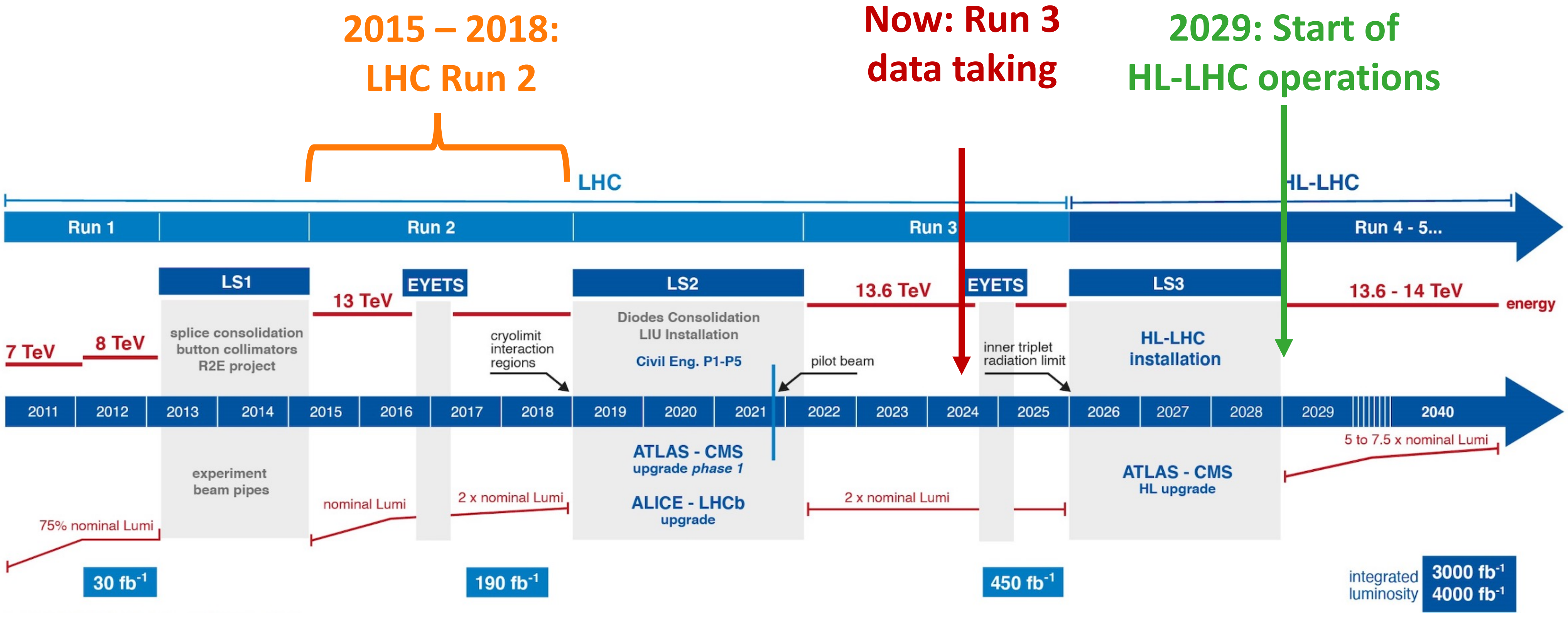




Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary particle and the LSP, and the difference between the intermediate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

High-Luminosity LHC

- Integrated luminosity $\mathcal{L}$ is the amount of data (*pp* collisions) collected
- $\mathcal{L}$ = **450 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}**



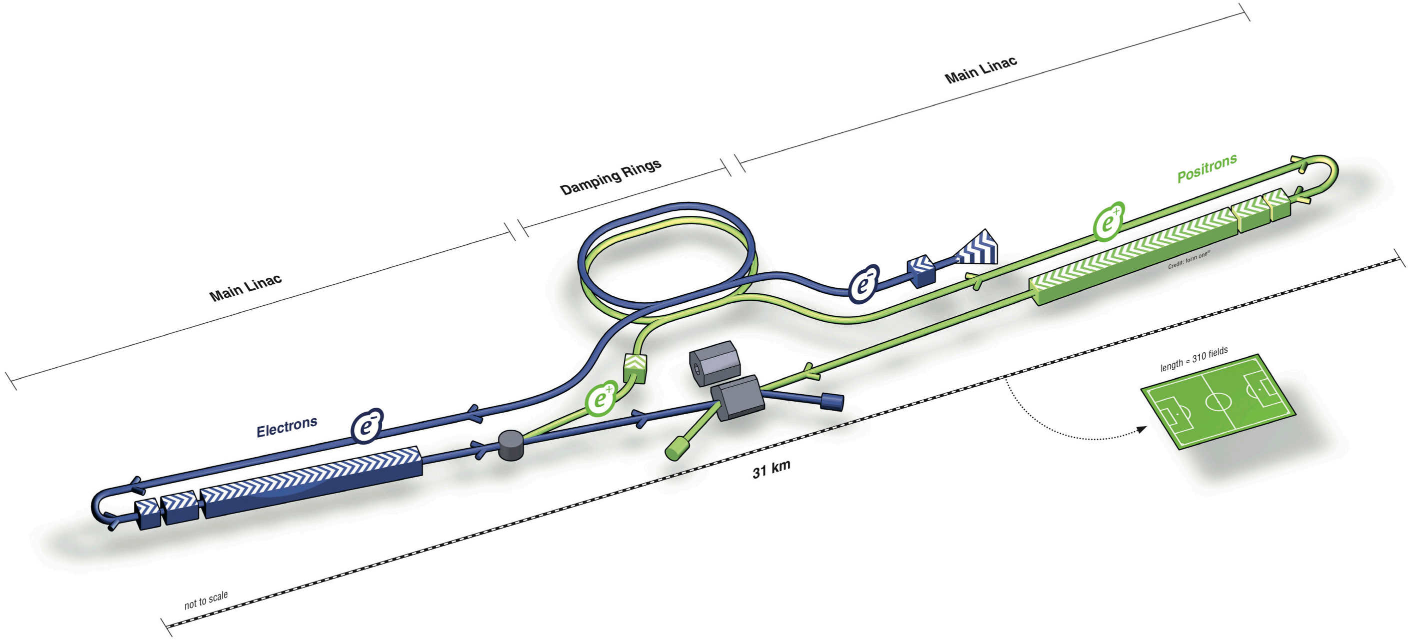
2015 – 2018: LHC Run 2

Now: Run 3 data taking

2029: Start of HL-LHC operations

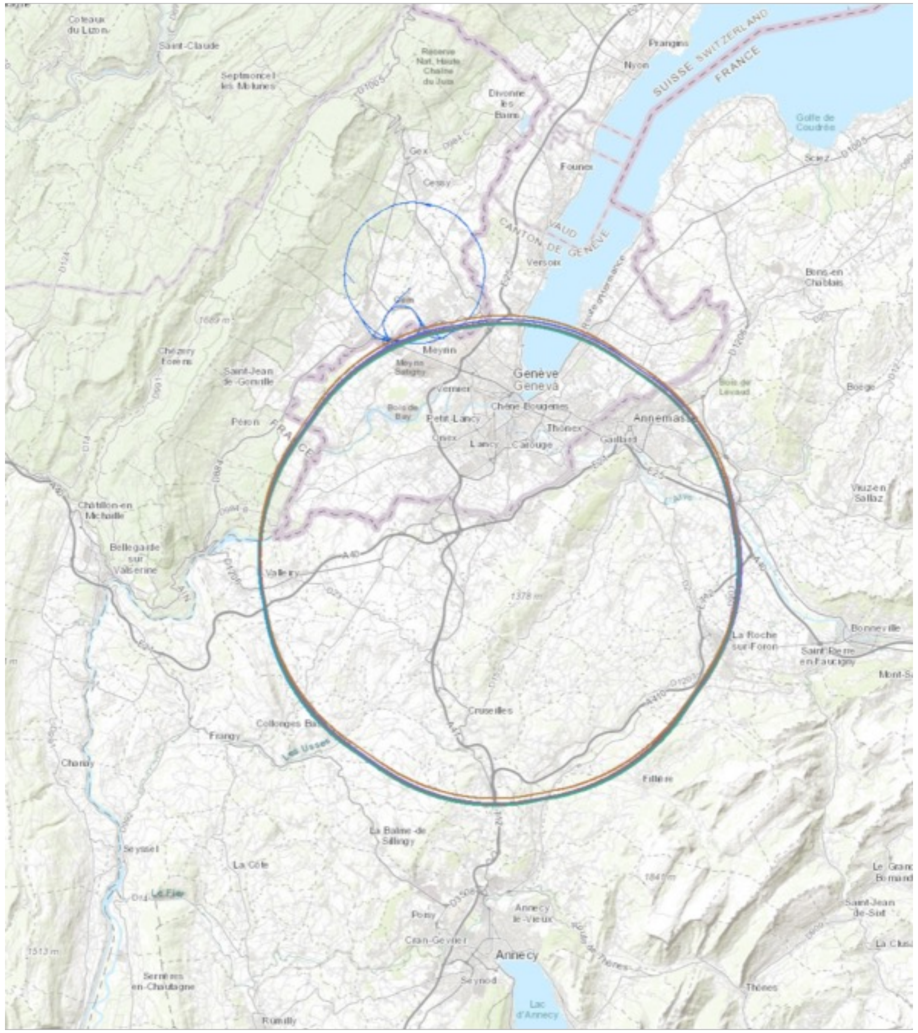
Future electron-positron colliders

- 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



Conclusions

- 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
- By setting limits, we make important claims on what nature *isn't* like
- It takes a village – lots of people with lots of different expertise

- Future colliders are being discussed now with even greater discovery potential

Homework assignment – lecture 4

A. Read this overview article about neutrino physics in the US

B. Watch this (5 minute) video to investigate how a compound pendulum can be used to understand neutrino oscillations and be prepared to discuss

Bonus points if you decide to build your own coupled pendulum (example instructions here)

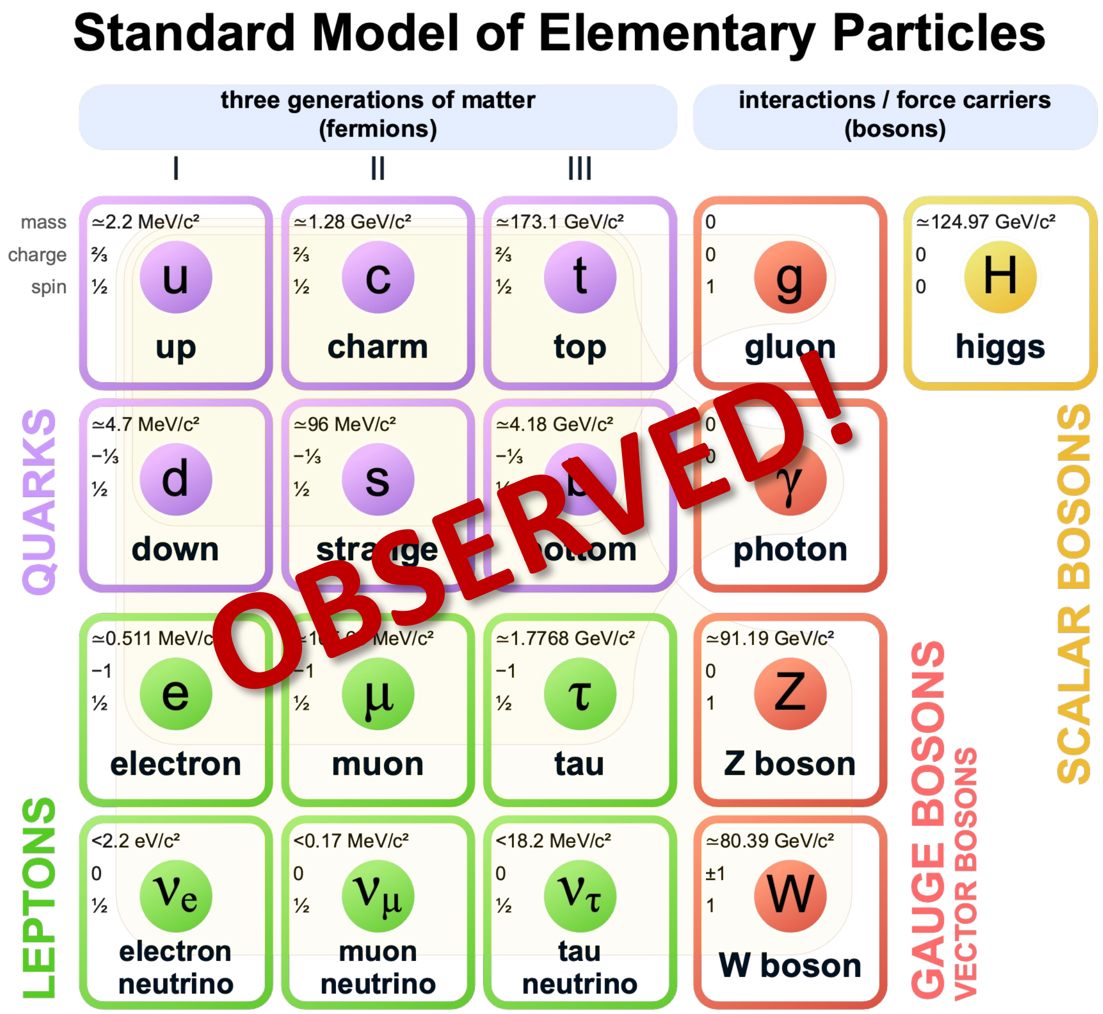
C. Do the **Signal and Noise** activity from the QuarkNet data portfolio. Start with the student guide, and write down your answers somewhere. Example answers can be found in the teacher's guide to this activity.

D. Fill out the weekly course survey (link sent via email

- Additional, optional resources are posted to the course website for session 5
- Email me with any concerns or questions

End of Part 4

Standard Model



Observations:

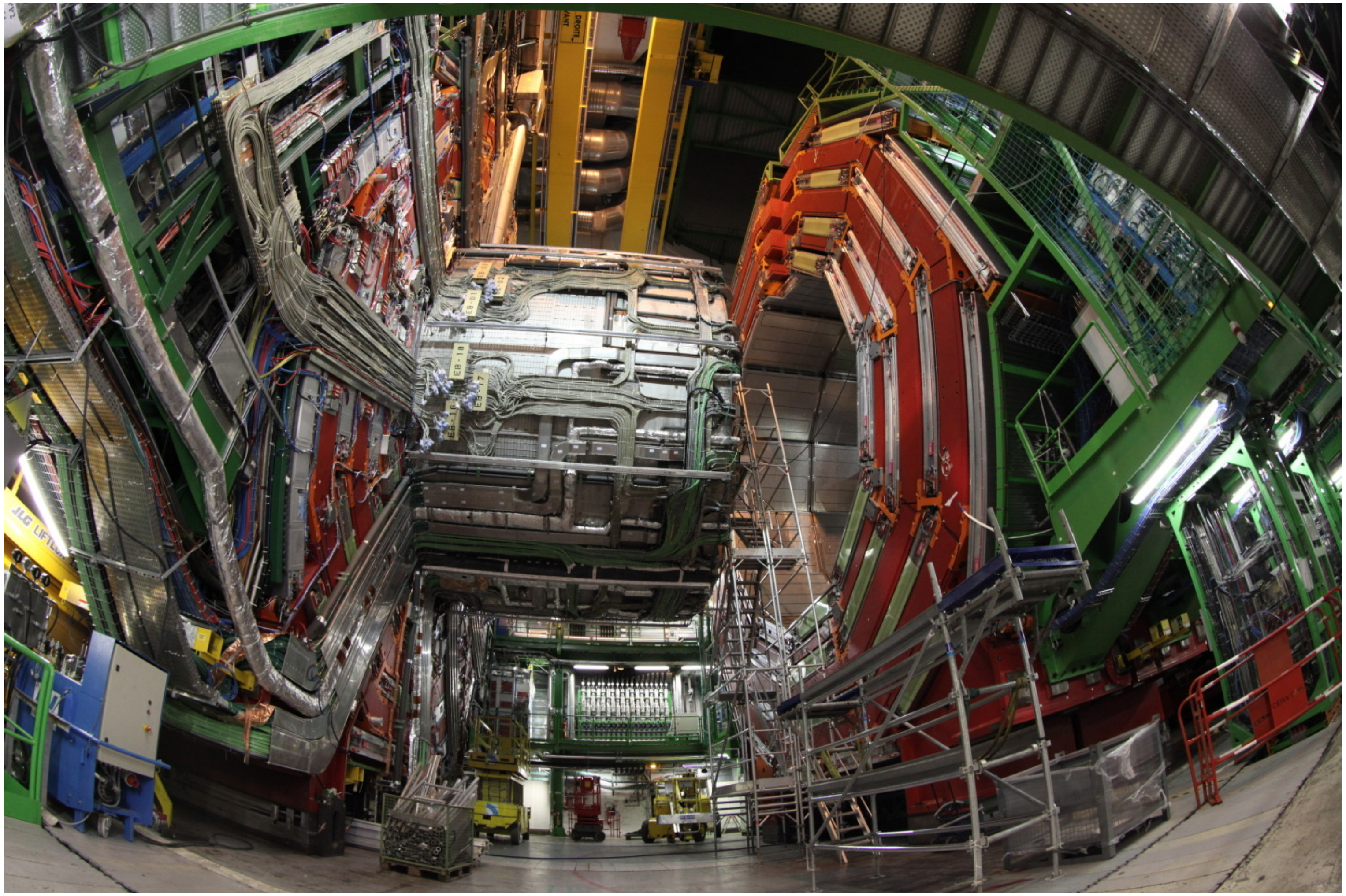
- electron: 1897 by JJ Thomson
- muon: 1937 by Anderson & Neddermeyer
- electron neutrino: 1956 by Cowan & Reines
- muon neutrino: 1962@BNL
- up, down, strange quark: 1968@SLAC
- charm quark: 1974@SLAC, BNL
- tau lepton: 1975@SLAC
- bottom quark: 1977@FNAL
- gluon: 1979@DESY
- W and Z bosons: 1983@CERN
- top quark: 1995@FNAL
- tau neutrino: 2000@FNAL
- Higgs boson: 2012@CERN

Colliders – a biased list

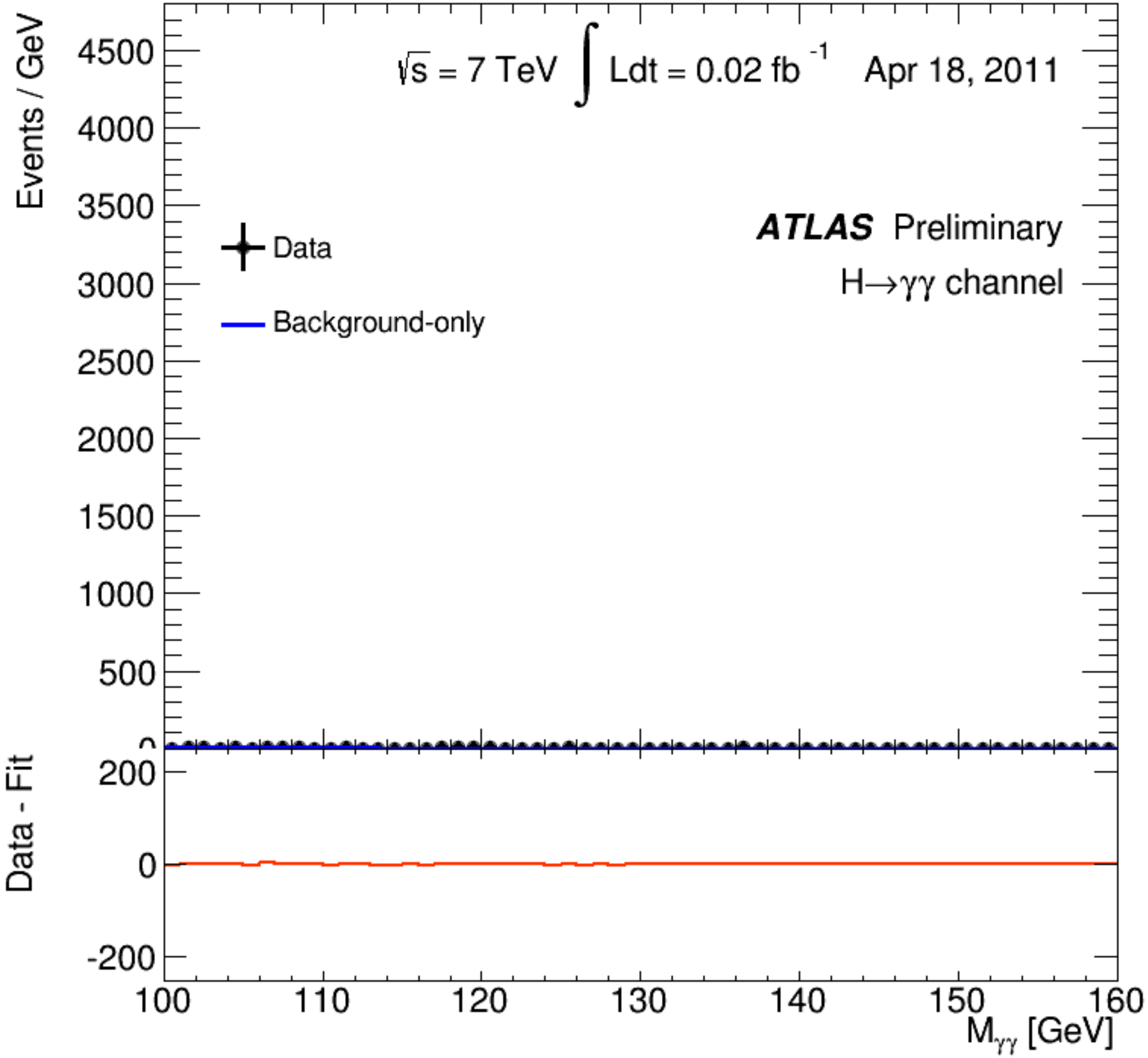
- Push to bigger accelerators at higher energies

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?	?	???

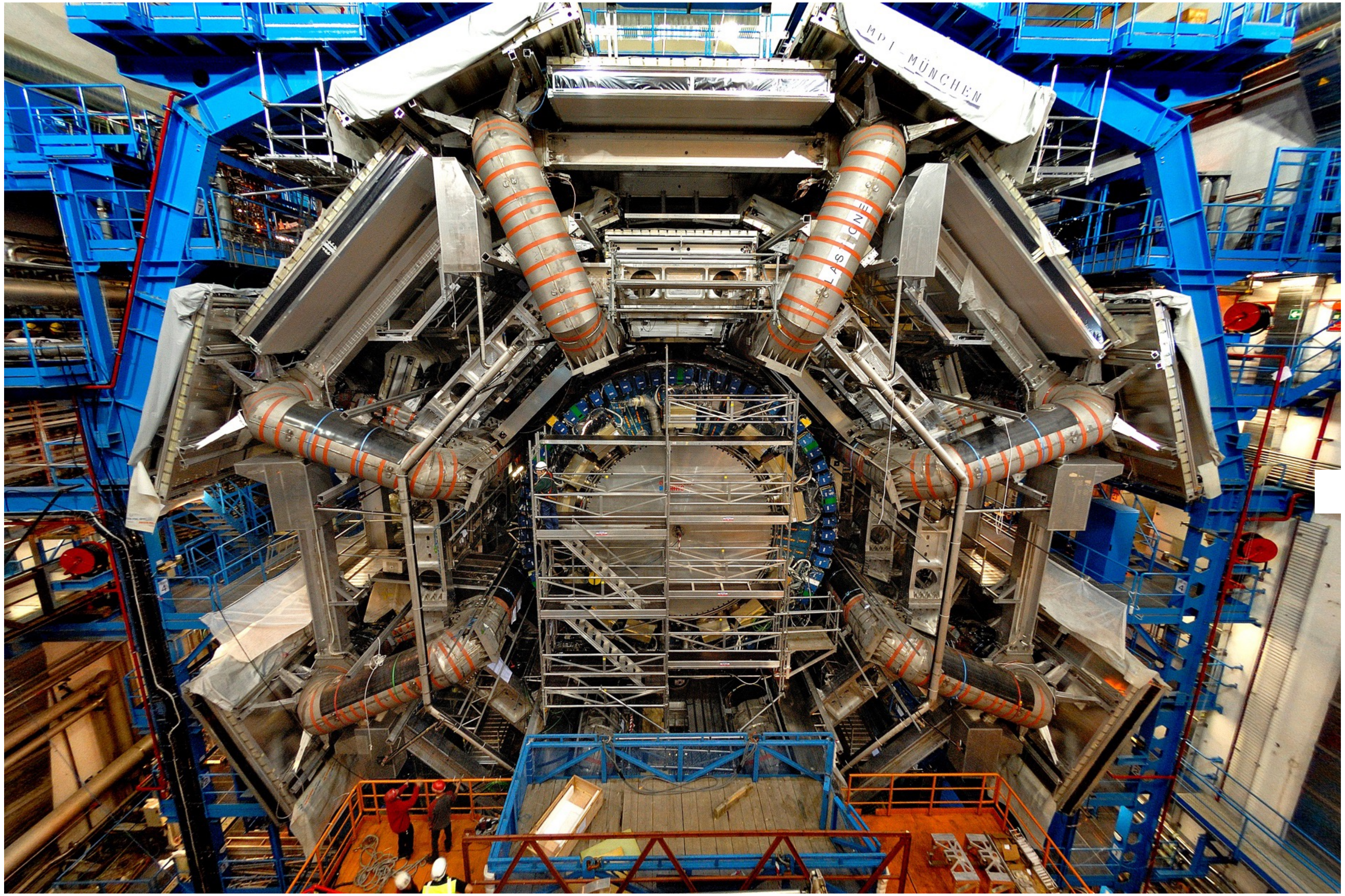
CMS Magnet



3.8 T superconducting solenoid magnet, cooled using liquid helium

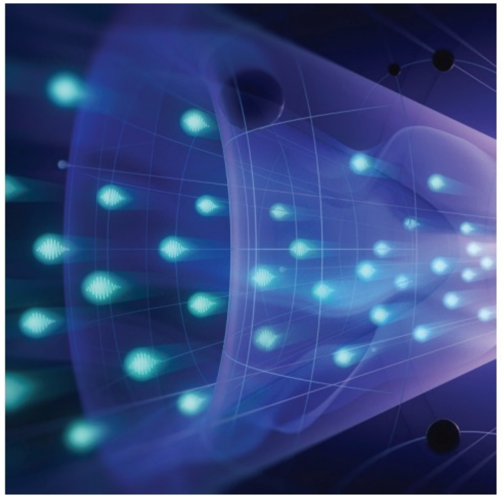

Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb $^{-1}$ Apr 18, 2011
Data
Background-only
ATLAS Preliminary
$H\rightarrow\gamma\gamma$ channel
Data - Fit
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]

The ATLAS Detector @ the LHC



Snowmass and P5: deciding what's next

- Community exercise to



Decipher the Quantum Realm

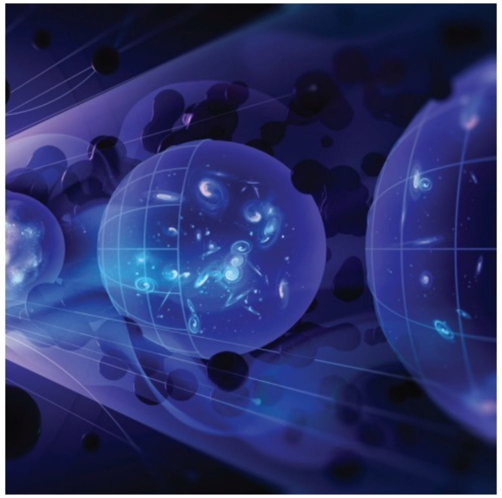
Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution