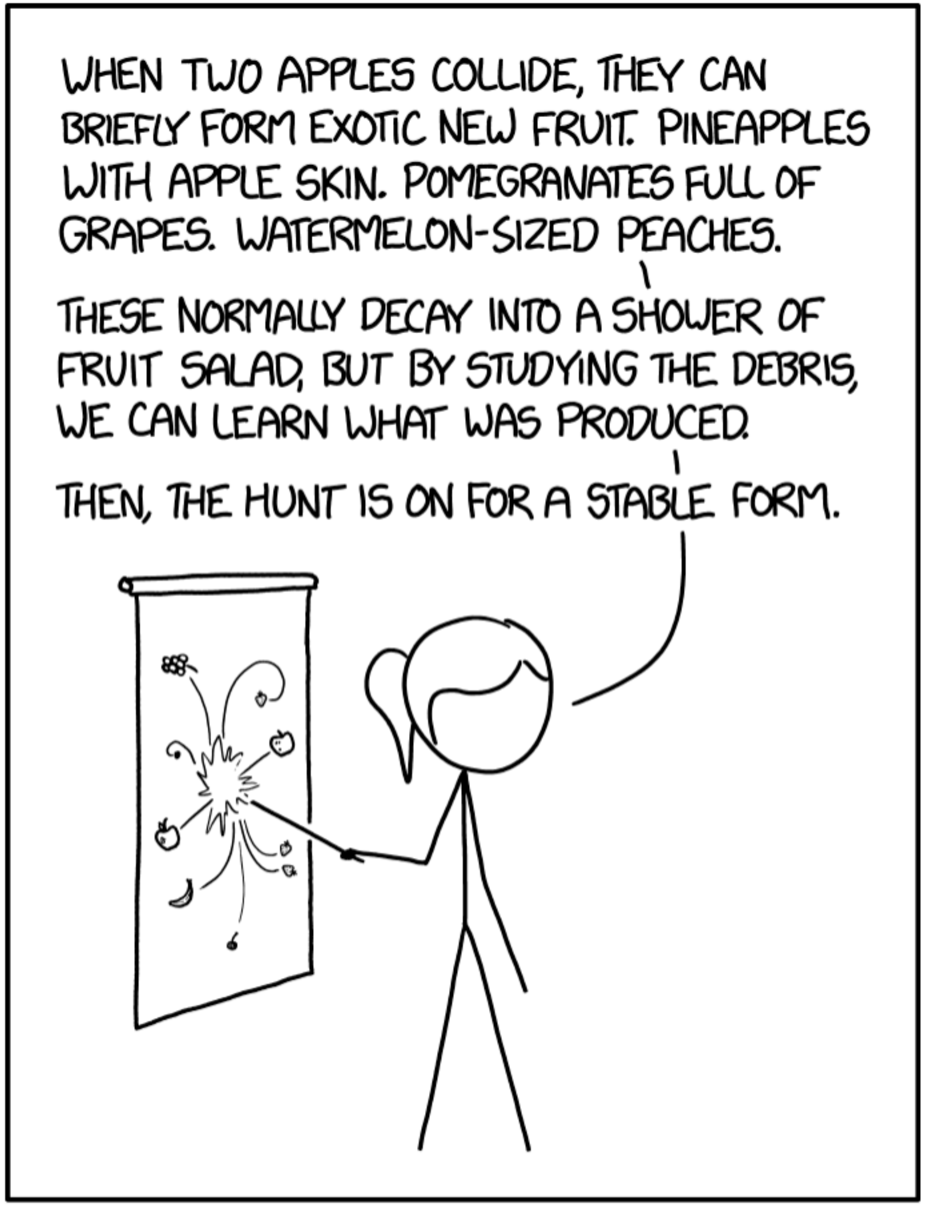
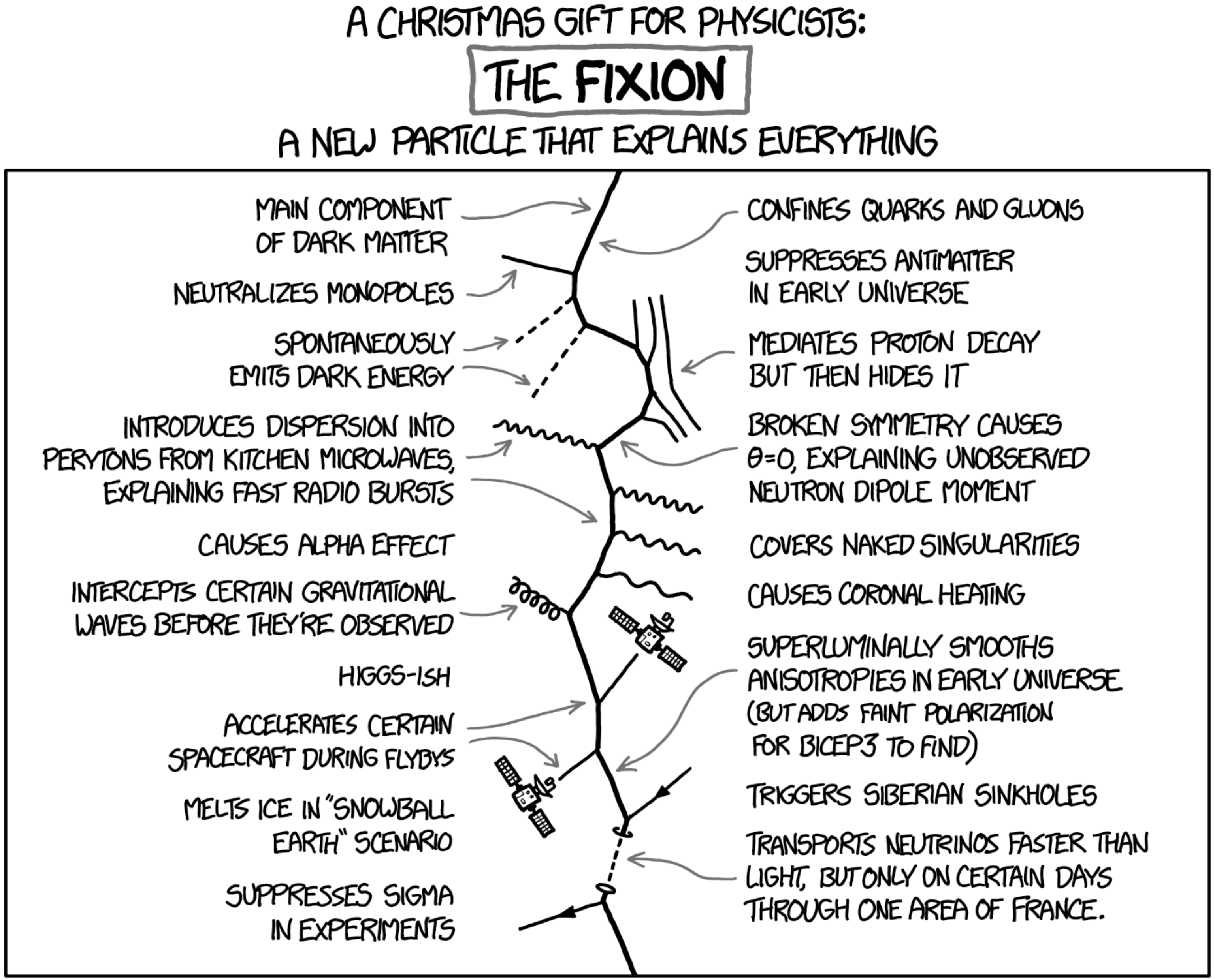
# Fruit Collider

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

https://quarknet.org/content/quarknet-summer-session-teachers-2020

Summer 2020

# 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: Ancient Greeks to Quantum Mechanics
2. History of the Standard Model, Part 2: Particle zoo and the Standard Model
3. Particle physics at the Large Hadron Collider (LHC)
4. **Beyond the Standard Model at the LHC**
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.

# Loose ends – questions

- What does "color" tell us about a particle?
  - Color is a quantum number (like spin or electric charge) that tells us how particles interact via the strong force. Can be thought of as "color charge"
- Gluons interact with particles that have color charge; photons interact with particles that have EM charge. What about W/Z bosons?
  - W/Z bosons mediate the weak interaction
  - Z boson is charged and can also interact electromagnetically
- How likely is it that the SM will someday incorporate gravity and a gravity boson?
  - Right now we don't have a good idea how, but don't underestimate human creativity
- Is the field theory explainable in layman's terms, or just in mathematics?
  - Without the math, analogies are the best we can do, but some analogies are very good
- What is the difference between a vector boson and a scalar boson?
  - Vector boson has spin 1 and a scalar boson has spin 0

# Loose ends – discussion

*"How important do you think it is to expose students to particle physics? What ages should this be done? Why?"*

*What (free/online) resources are out there for something like a crash course in graphing, linearizing, histograms, interpreting graphed data, etc?*

https://quarknet.org/data-portfolio

You all are better equipped to answer that than I am – time for breakout discussions!

Introduce yourself to today's group.

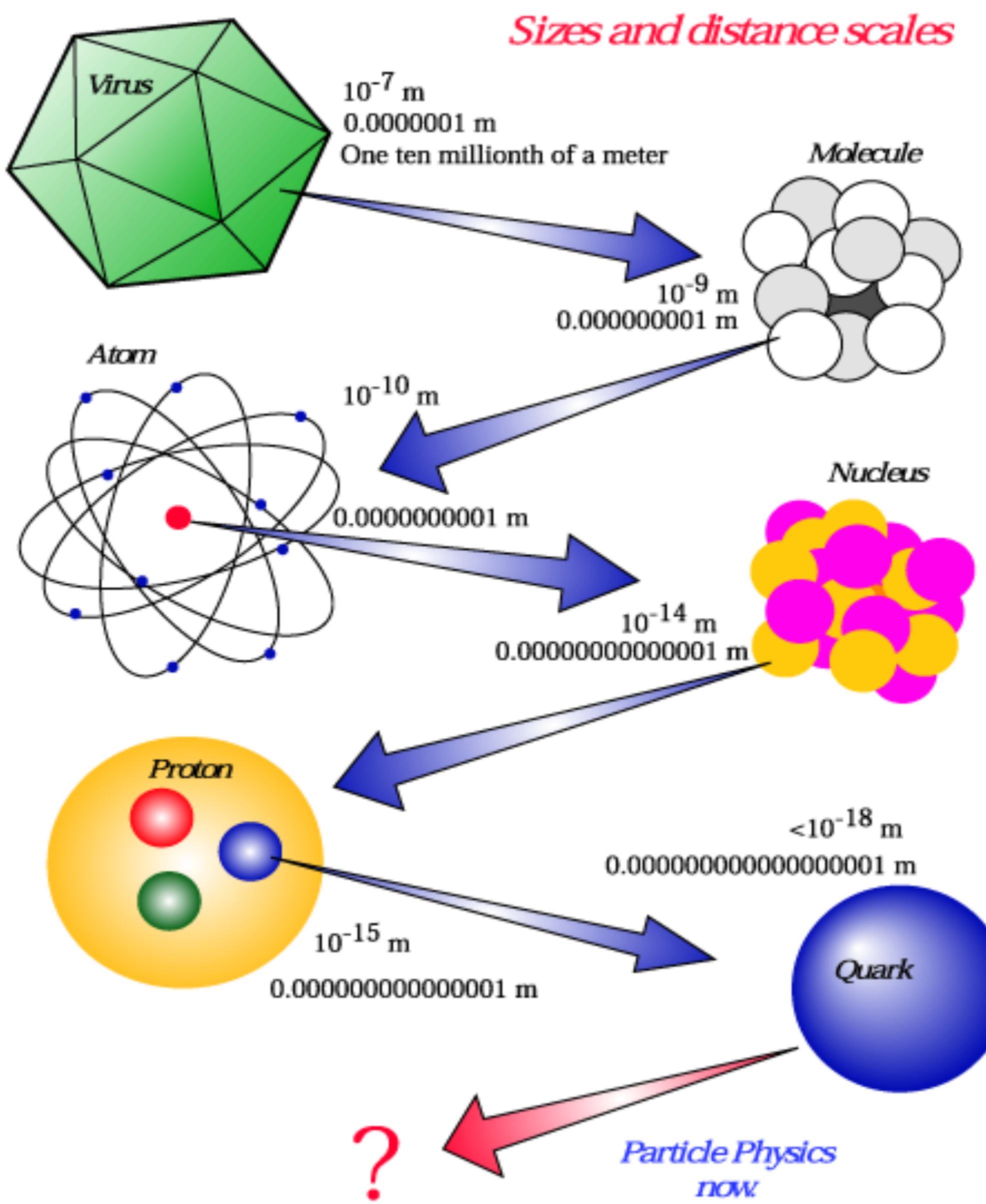
# Beyond the Standard Model at the LHC

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

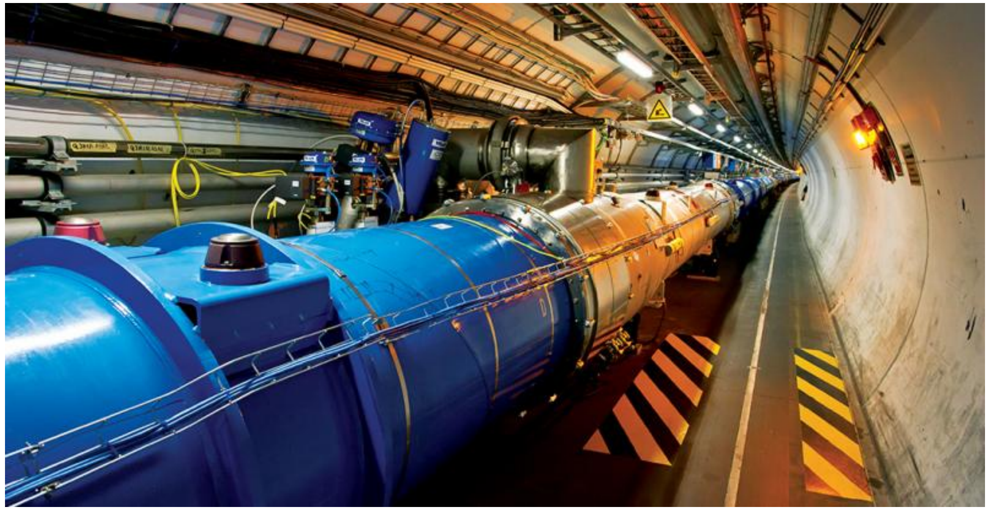
# Why accelerators?

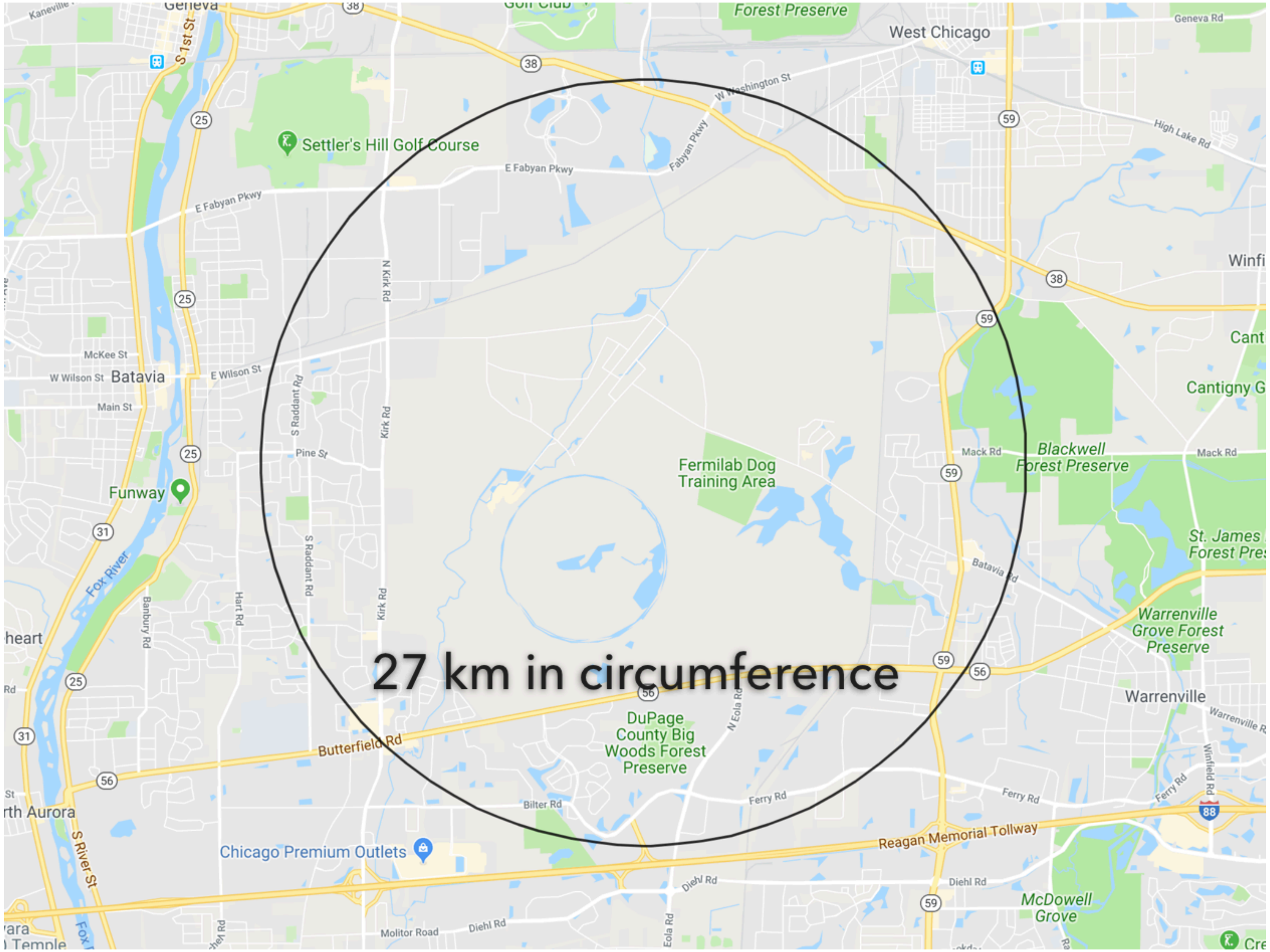
- Recall de Broglie: $\lambda = h/p$
  - Higher momentum means we can probe smaller scales
- Recall Dirac:
  - $E^2 = p^2c^2 + m^2\, c^4$
  - More energy means we can create new particles of higher mass



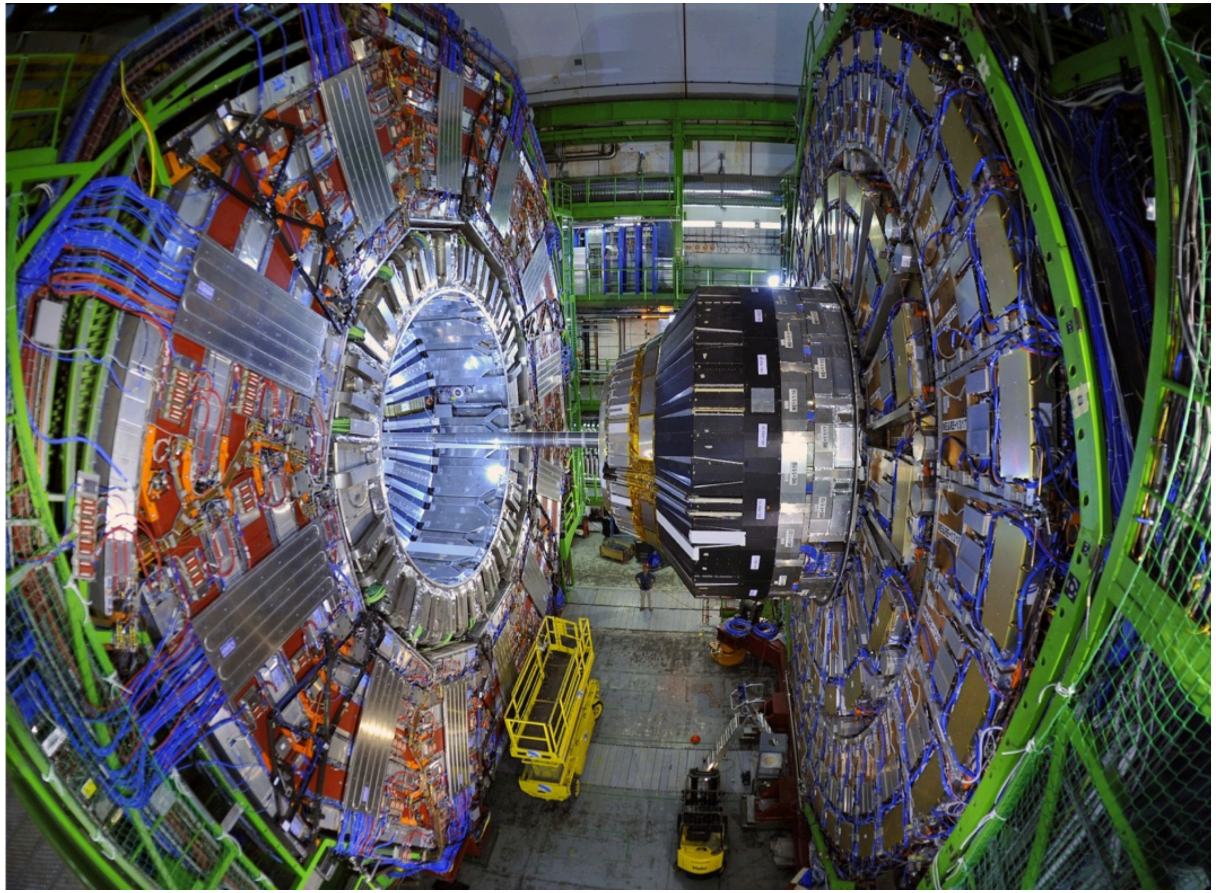
# Large Hadron Collider

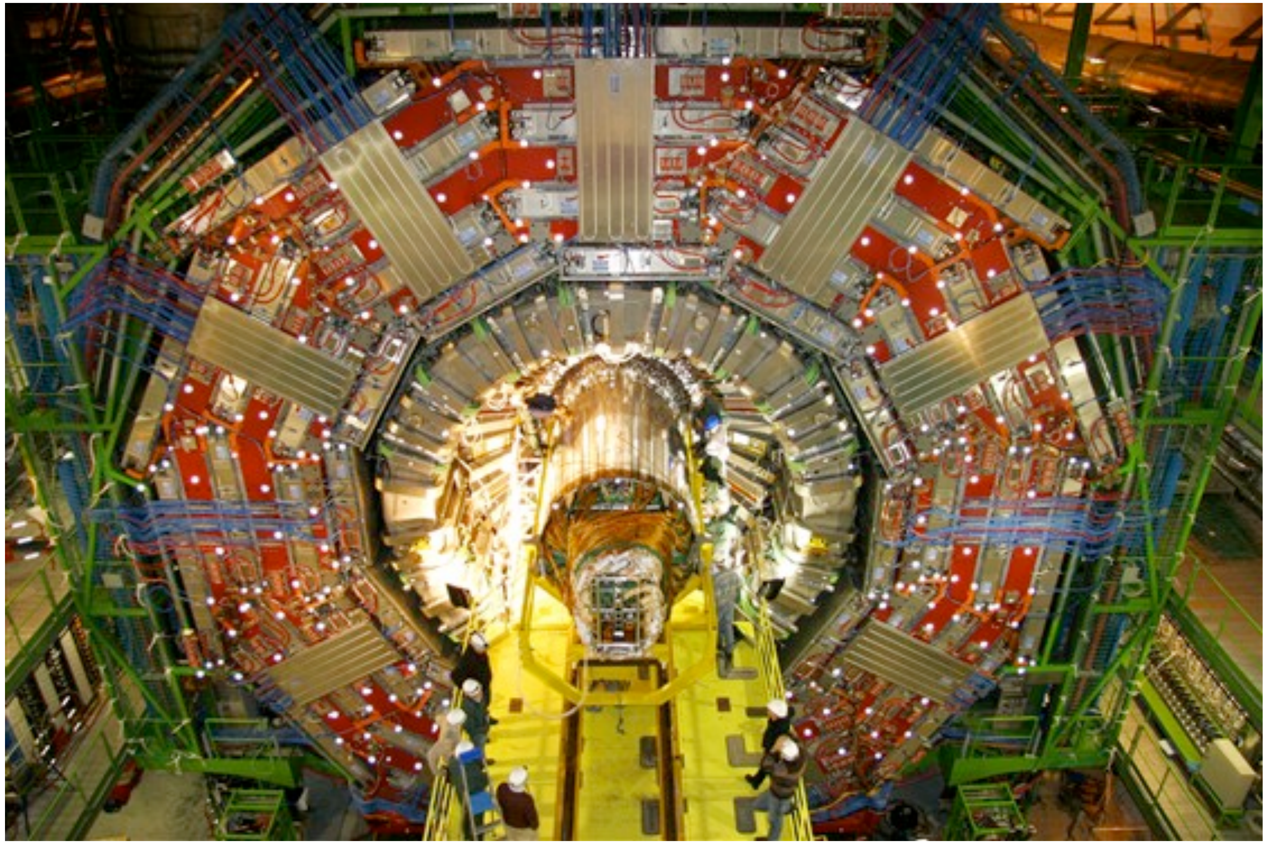
- 17 miles in circumference
- World's largest and highest energy hadron collider
  - 13 TeV center of mass energy
  - Beats the previous record held by the Tevatron at Fermilab
  - 1232 dipole magnets at 8.3 T





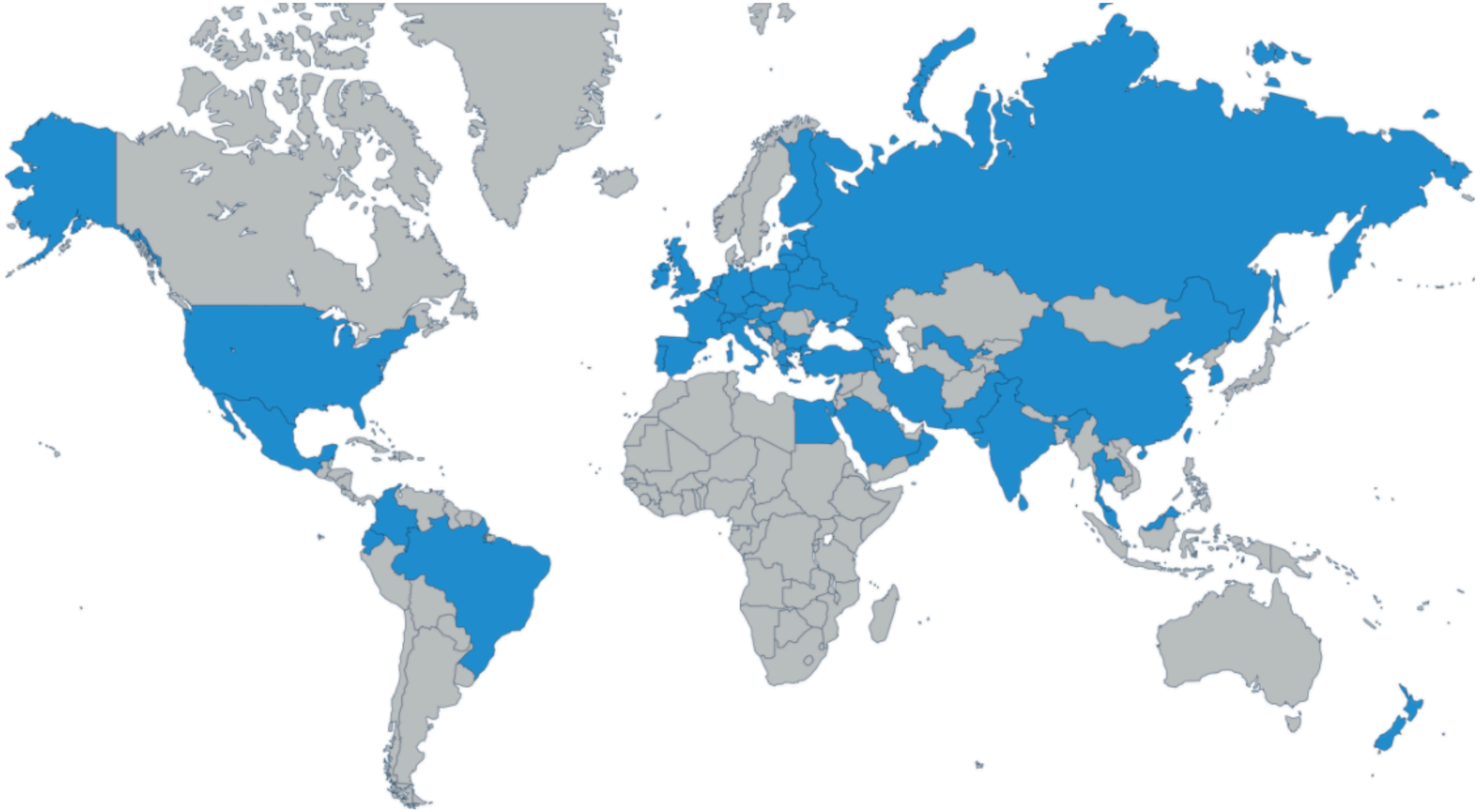
# Compact Muon Solenoid





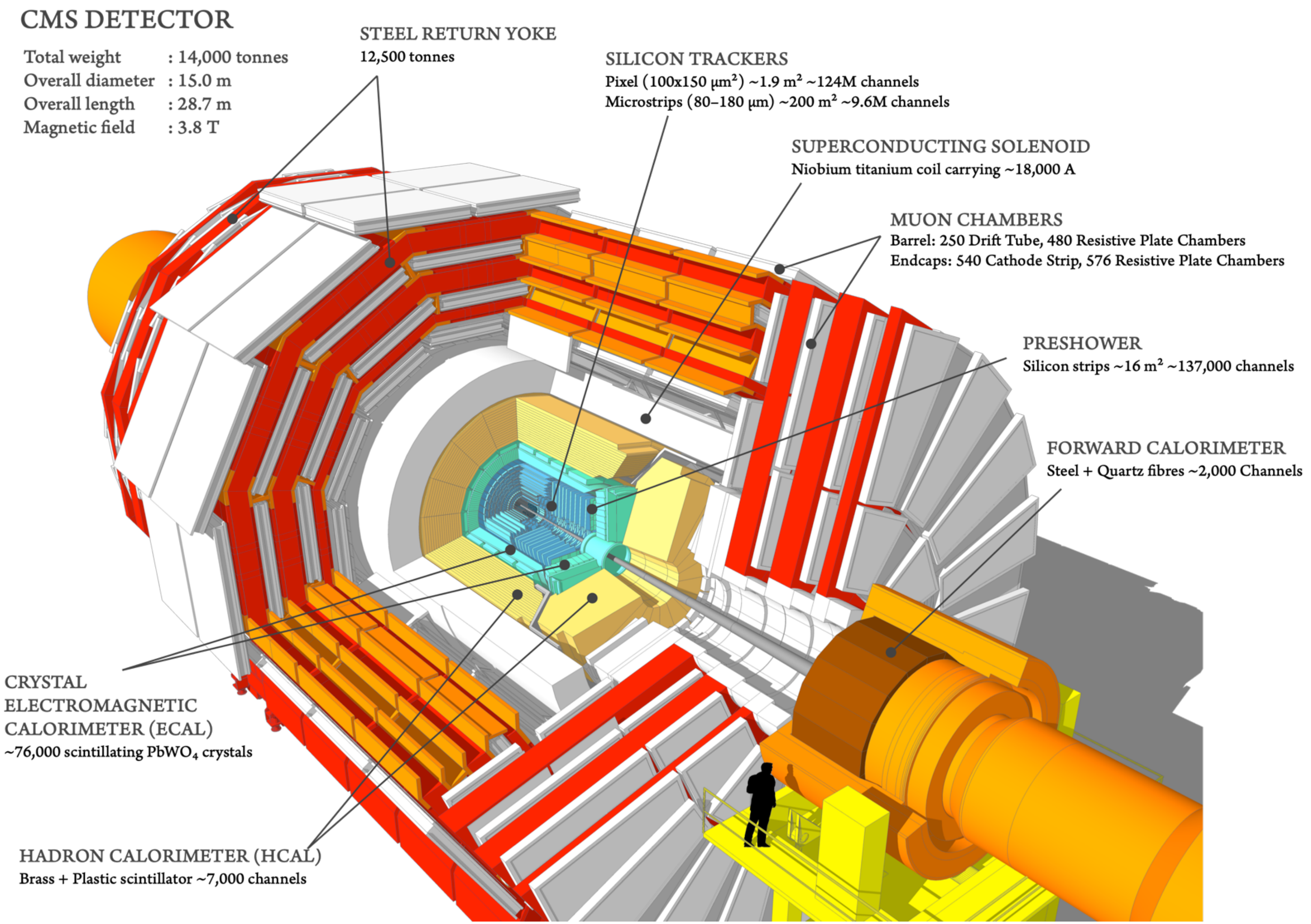
# CMS Collaboration

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



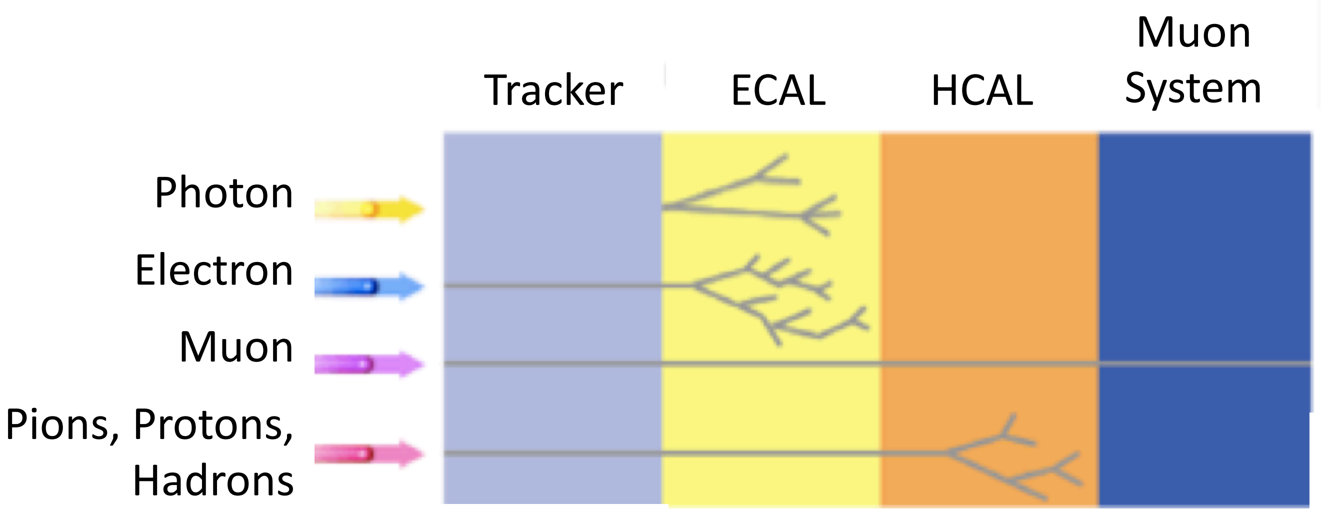
| 2942 | 1065 | 281 | 229 | 51 |
|---|---|---|---|---|
| PHYSICISTS (1036 STUDENTS) | ENGINEERS | TECHNICIANS | INSTITUTES | COUNTRIES & REGIONS |

# CMS Detector



# Particle Detection

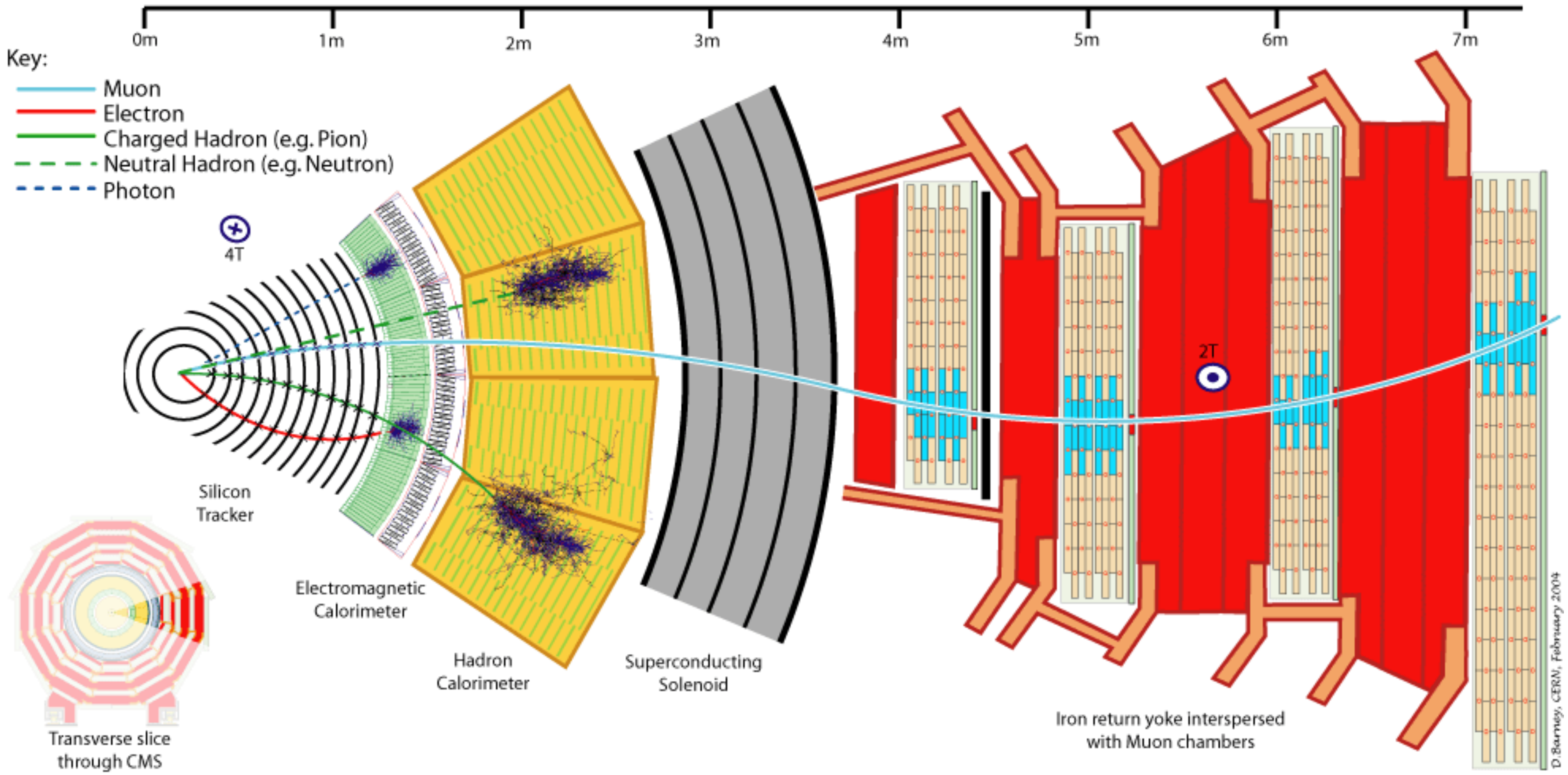
- Different types of detectors for different particles



# CMS Reconstruction

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

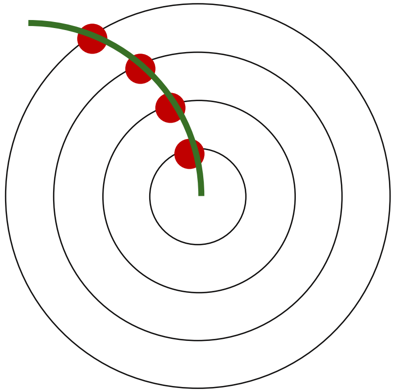
Interactive version: https://www.i2u2.org/elab/cms/graphics/CMS_Slice_elab.swf

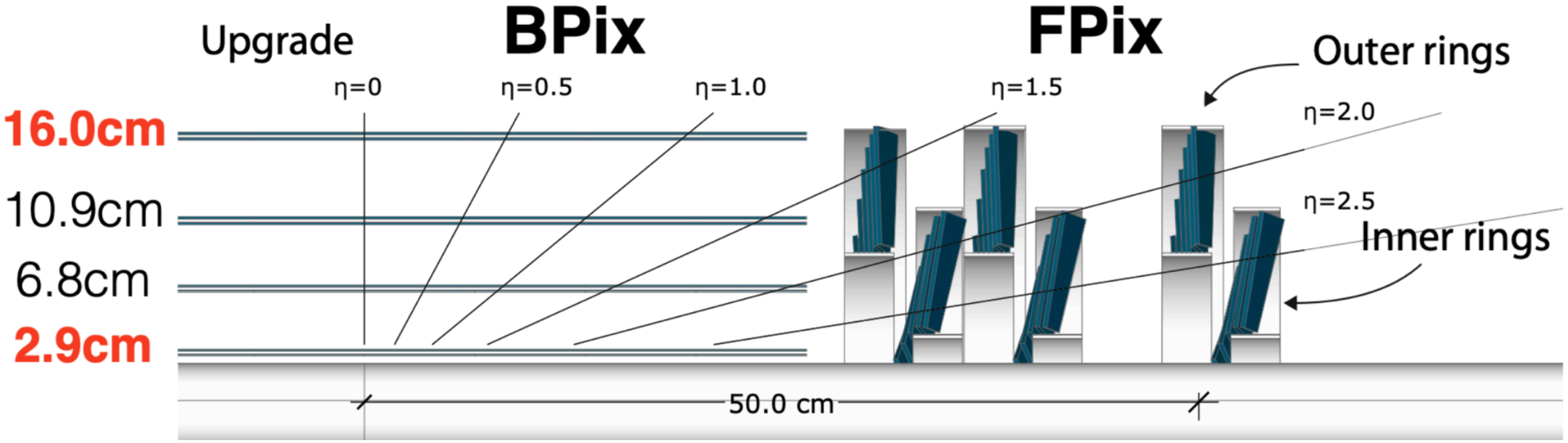


# Silicon Tracker

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

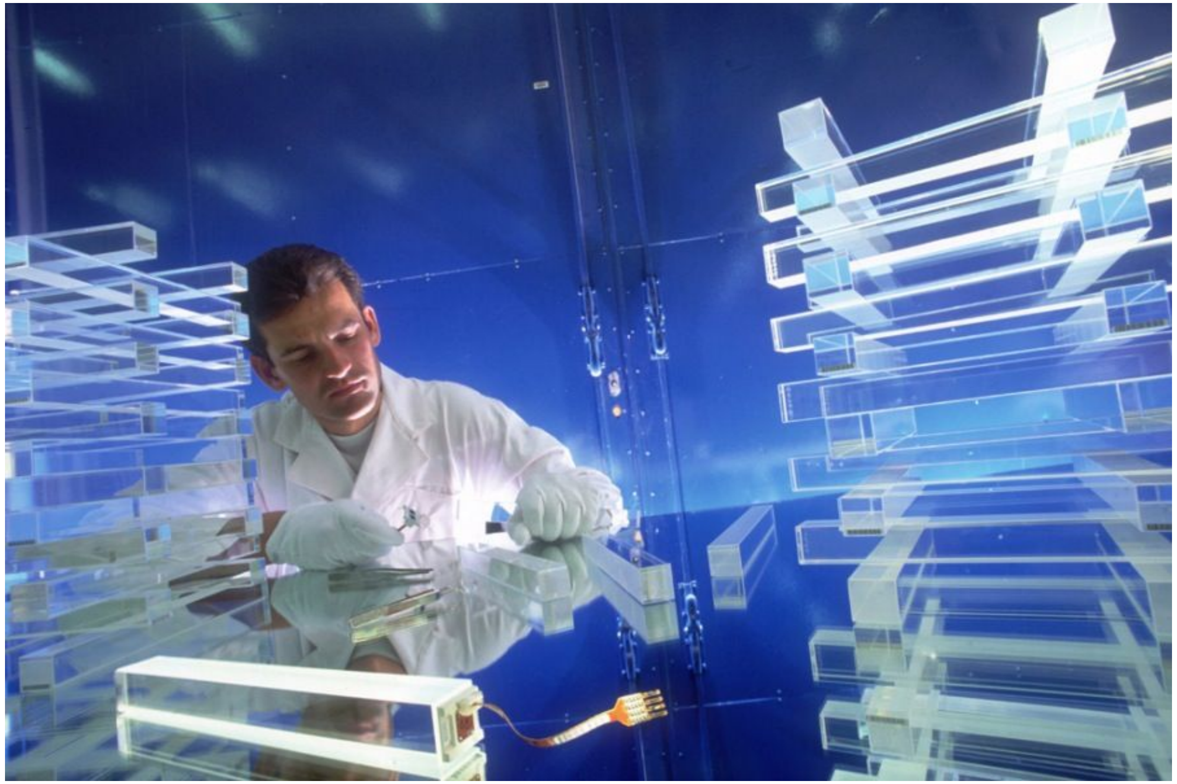
Half endcap disks for the upgraded CMS pixel detector, installed early 2017

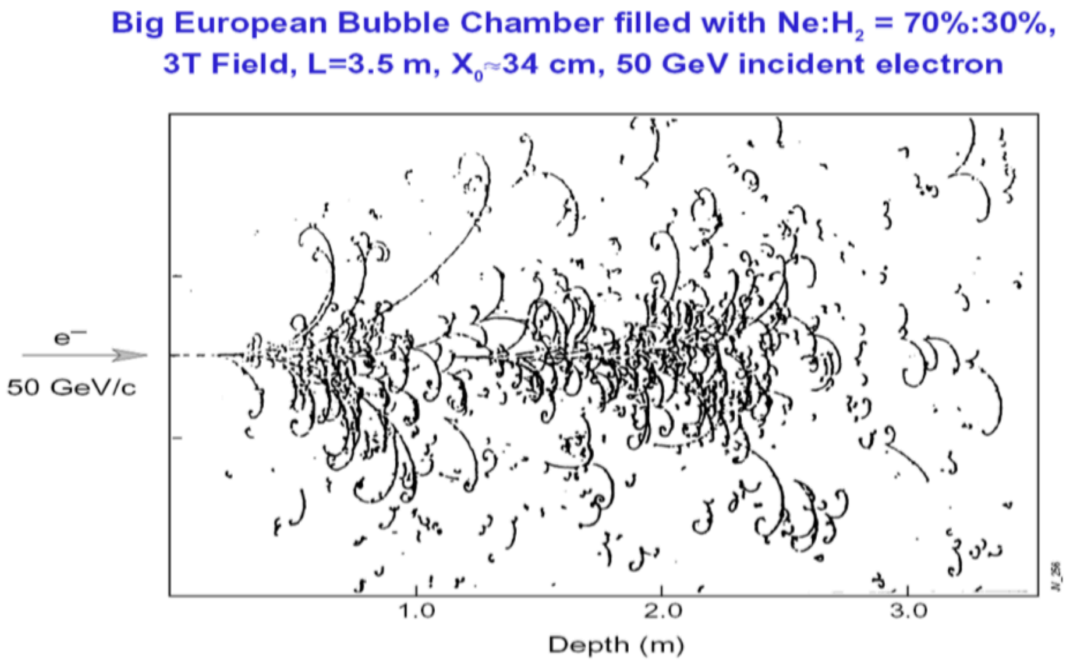




# Electromagnetic Calorimeter

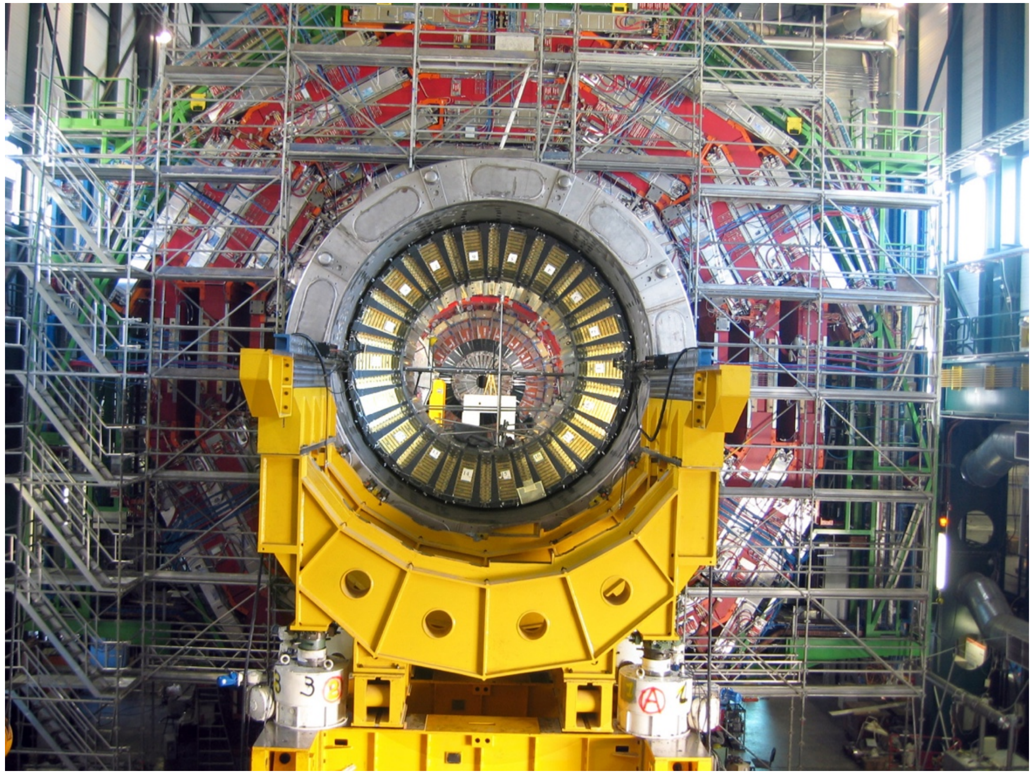
- 75,848 lead tungstate crystals in the barrel, each 2.2 x 2.2 x 23 cm
- Avalanche photodiodes used to detect the light from the scintillators
- Accurate measurement of electron and photon energies
    - Hadrons and muons pass through





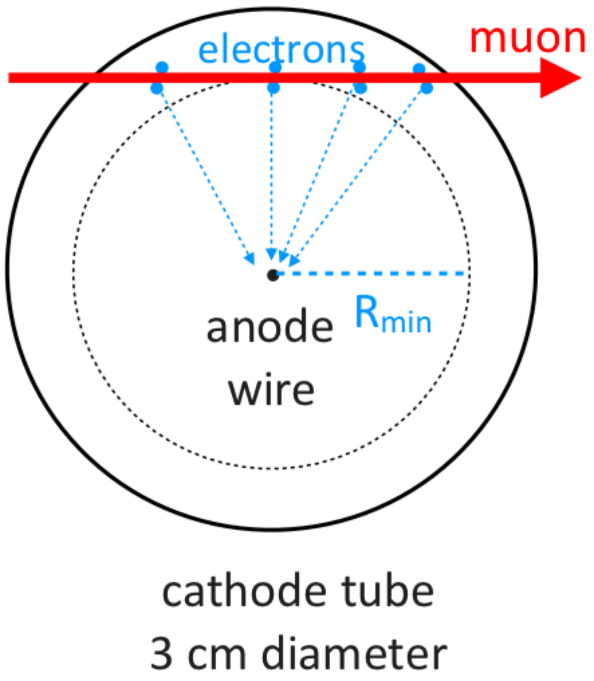
# Hadronic Calorimeter

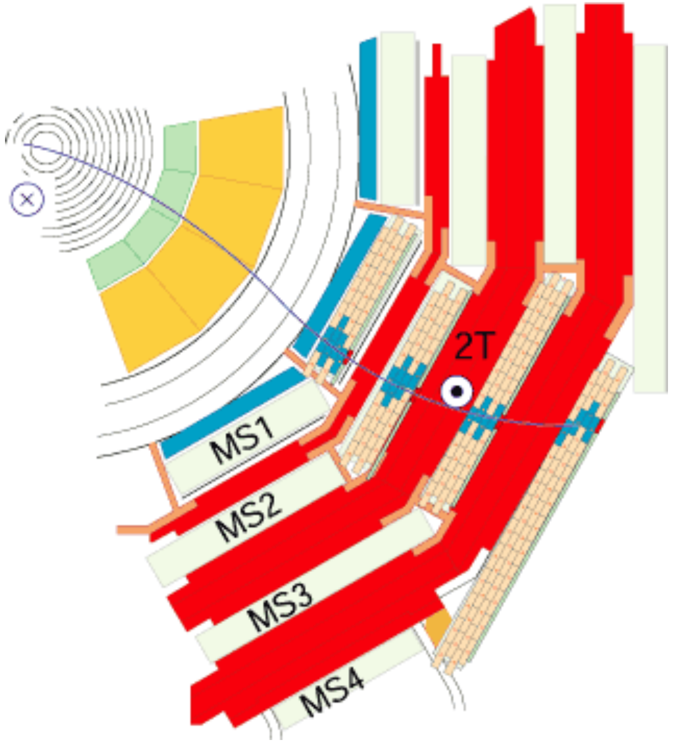
- 36 barrel wedges, each weighing 26 tons
- Repeating layers of steel and tiles of plastic scintillator
  - Steel forces the hadrons to interact and start "showering"
  - Shower energy measured ("sampled") by the scintillator



# 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

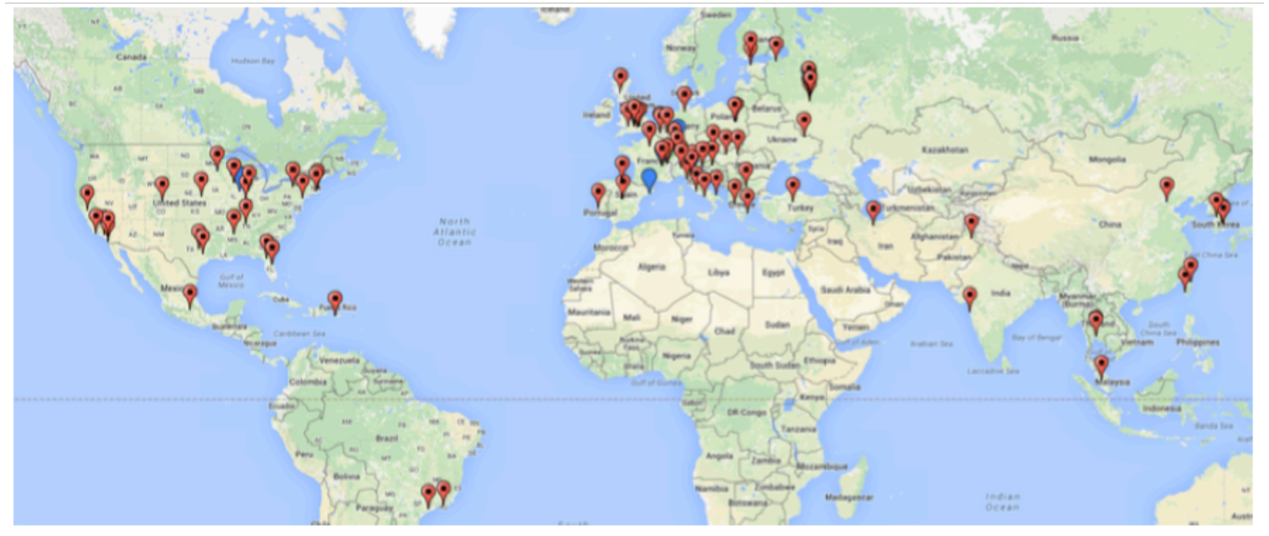
- ATLAS and CMS take data 24/7
- Collisions happen at 40 MHz
  - Too much data to keep everything!
- **Trigger** system selects 99.998% of events to throw away, 0.002% to keep
  - High stakes environment: If the trigger throws your event away, it's lost forever
  - Must decide quickly: protons collide 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

# CMS Computing

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

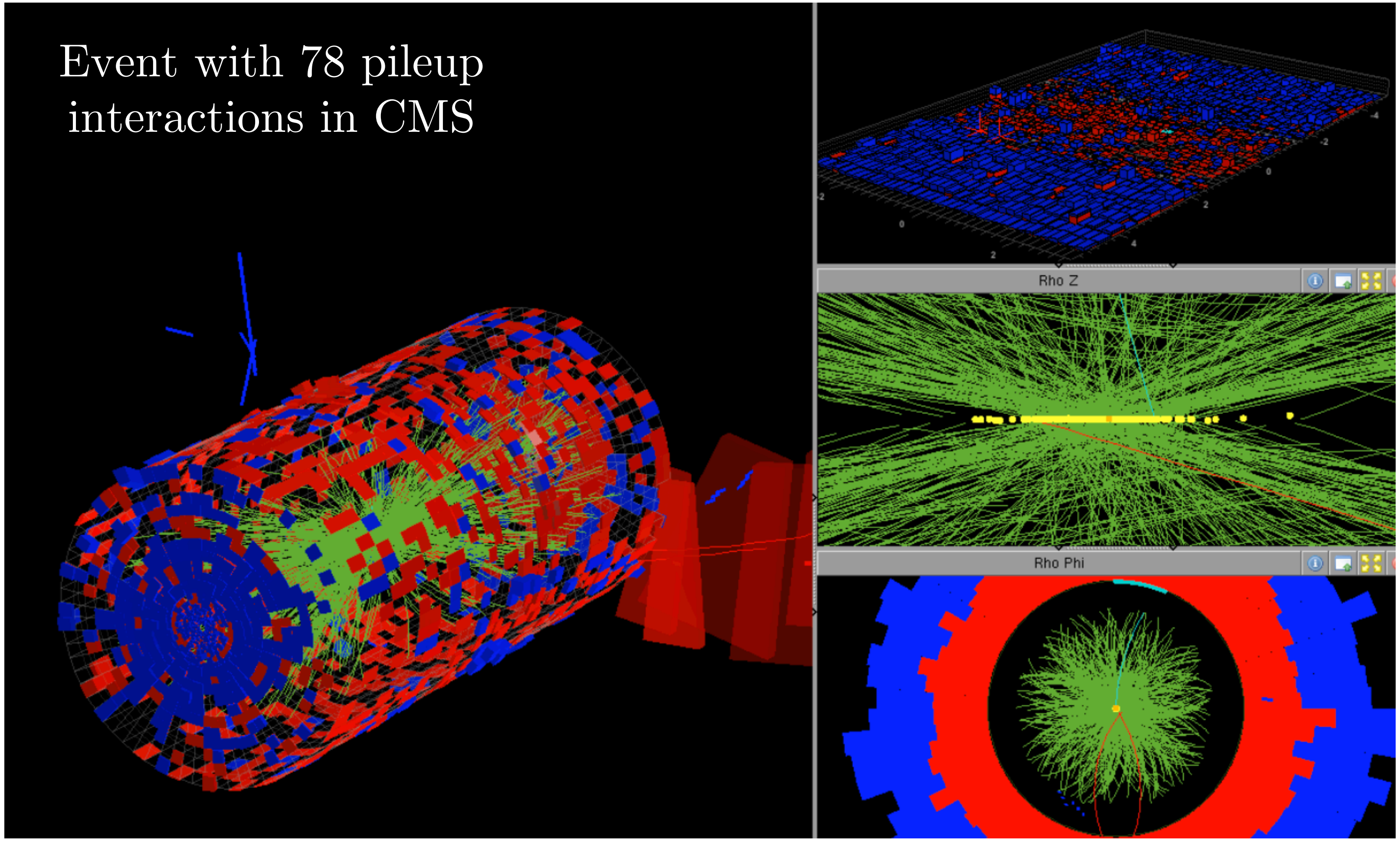
CMS Global Computing Grid



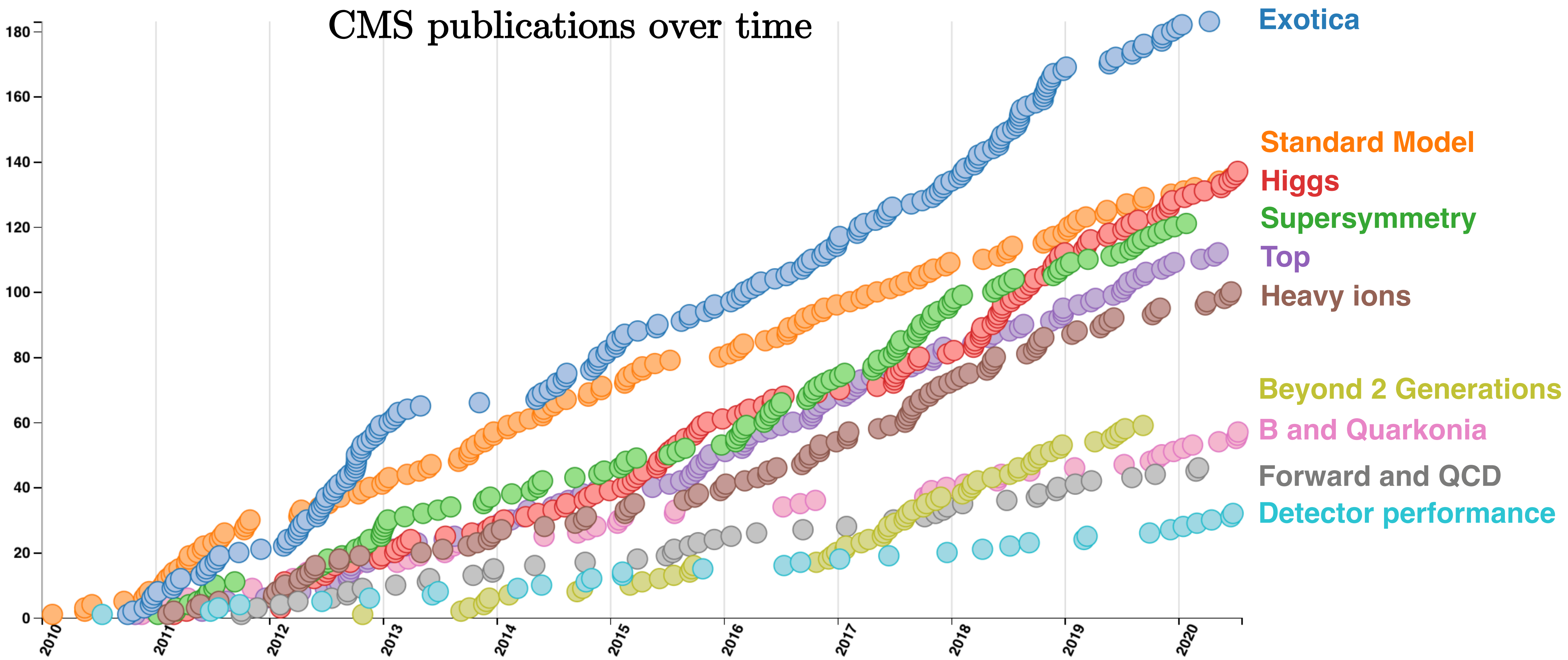
70+ sites, 200k+ CPU cores

# 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 Physics



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

# Homework discussion: CMS/ATLAS physics

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

CMS physics results: https://cms.cern/cms-updates

**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