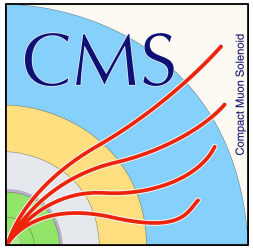


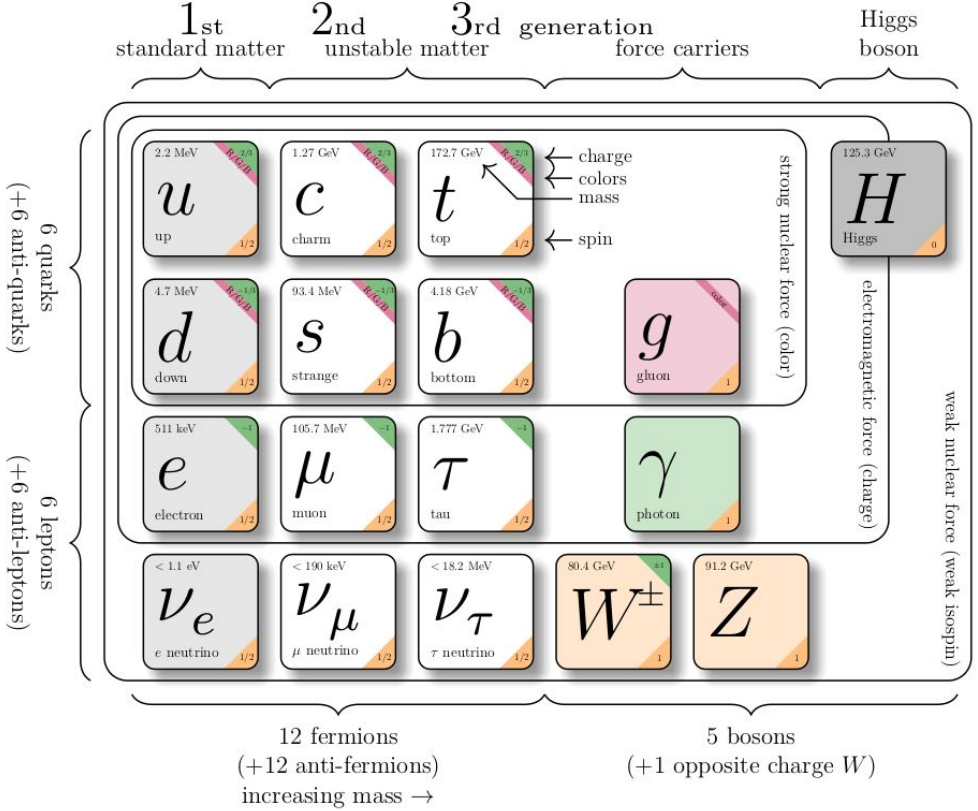
Fermilab

Colliders

Creating and *studying* the *heaviest* particles

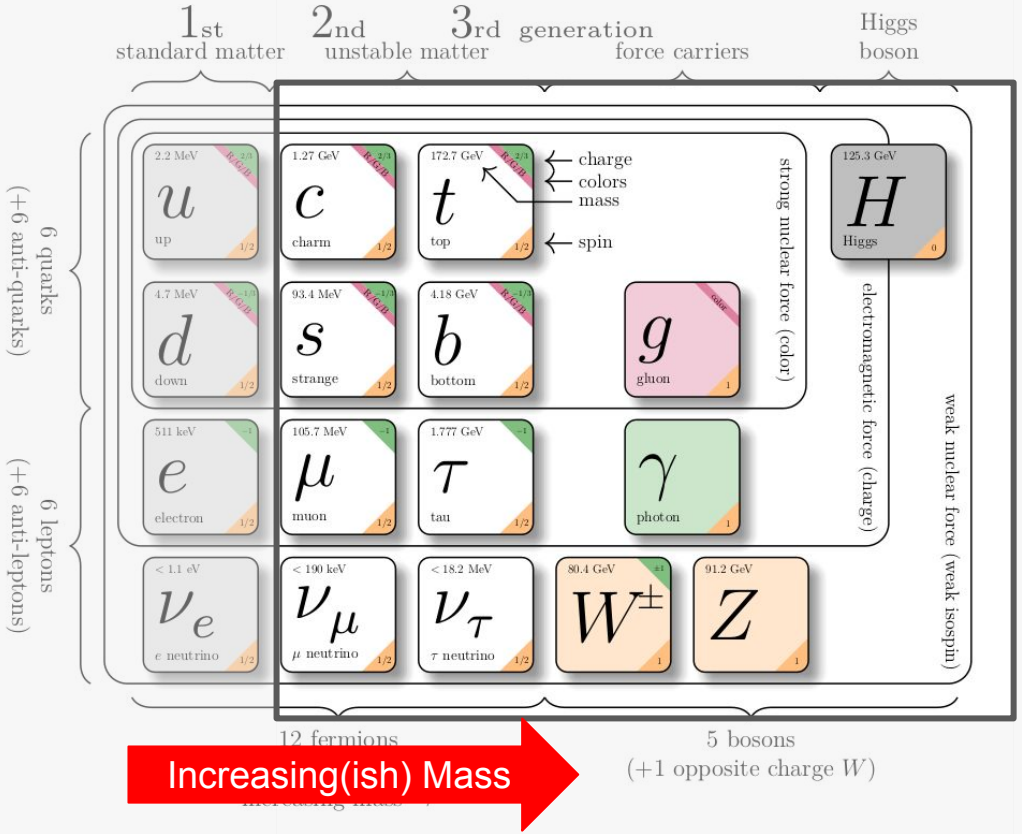
Grace E. Cummings, TRAC 26 June 2024

Why a *Collider*?

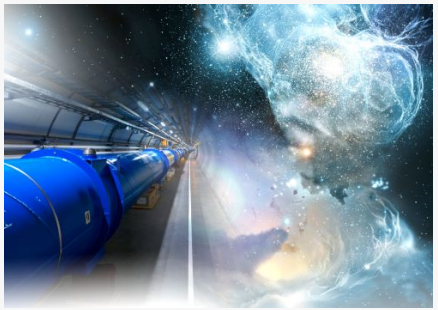


Why a ~~Collider~~? So you want to study heavy stuff

The rest is accessible most easily at accelerators and colliders



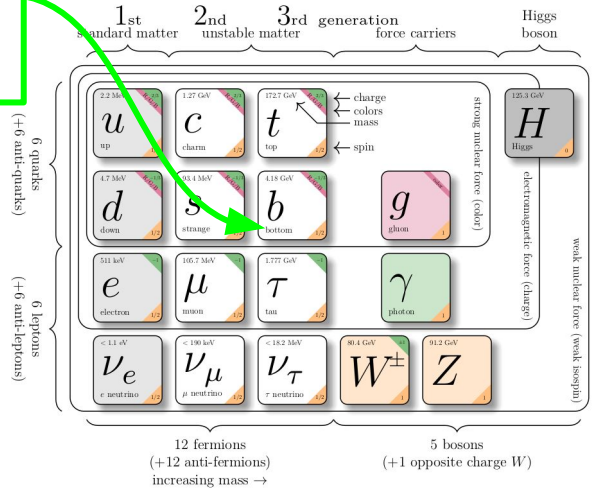
$$E^2 = \left(mc^2\right)^2 + (pc)^2$$



Need accelerators!

Bigger energies -> Bigger particles

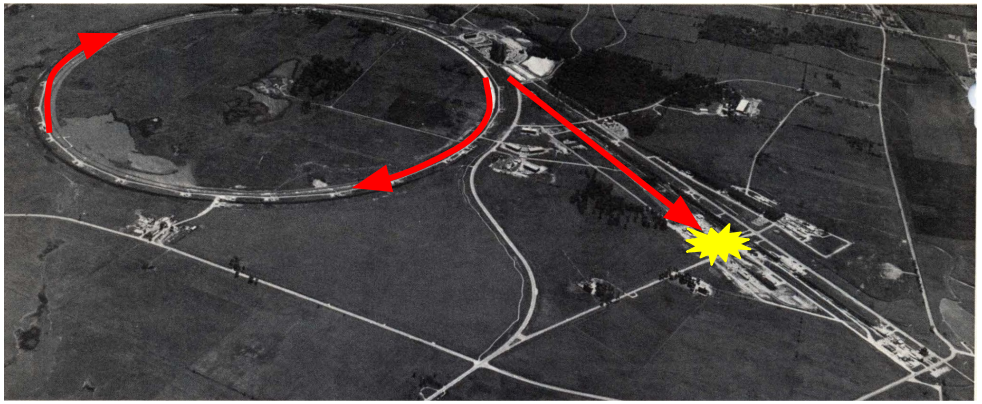
Bottom Quark, 4.18 GeV



OBSERVATION OF A DIMUON RESONANCE AT 9.5 GeV
IN 400 GeV PROTON-NUCLEUS COLLISIONS

S. W. Herb, D. C. Hom, L. M. Lederman,
J. C. Sens,† H. D. Snyder, and J. K. Yoh
Columbia University
New York, New York 10027*

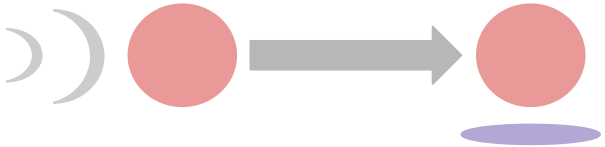
and



Bottom ("Beauty") quark discovered at Fermilab's E288 **Fixed Target** Experiment

Limitations of fixed target

400 GeV → ? → Bottom Quark, 4.18 GeV



$$\sqrt{s} \sim \sqrt{2E_{beam}m_{particle}}$$

Available energy (with some caveats)

OBSERVATION OF A DIMUON RESONANCE AT 9.5 GeV
IN 400 GeV PROTON-NUCLEUS COLLISIONS

S. W. Herb, D. C. Hom, L. M. Lederman,
J. C. Sens,† H. D. Snyder, and J. K. Yoh
Columbia University
New York, New York 10027*

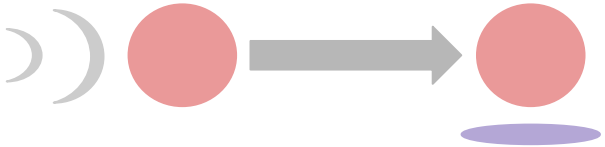
and

Limitations of fixed target

400 GeV

?

Bottom Quark, 4.18 GeV



$$\sqrt{s} \sim \sqrt{2E_{beam} m_{particle}}$$

Available energy (with some caveats)

OBSERVATION OF A DIMUON RESONANCE AT 9.5 GeV

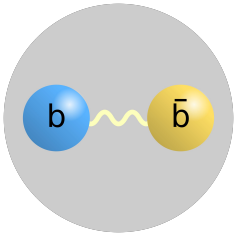
IN 400 GeV PROTON-NUCLEUS COLLISIONS

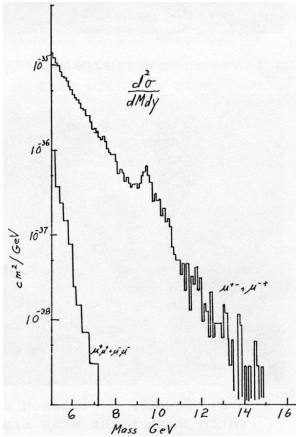
S. W. Herb, D. C. Hom, L. M. Lederman,
J. C. Sens,† H. D. Snyder, and J. K. Yoh
Columbia University
New York, New York 10027*

and

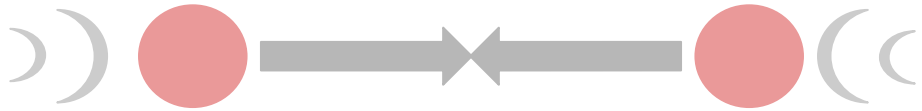
Naively, ~28 GeV available

Actually discovered the Υ@ ~9.5 GeV





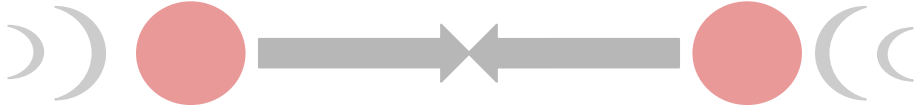
And this brings us to colliders!



All of the energy in both beams can be used!

$$\sqrt{s} = E_{beam1} + E_{beam2}$$

And this brings us to colliders!



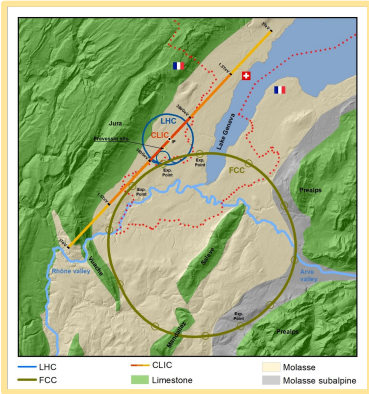
All of the energy in both beams can be used!

$$\sqrt{s} = E_{beam1} + E_{beam2}$$

Unfortunately, they are a bit harder to build!

Circular v. Linear

proposed future linear and circular colliders at cern

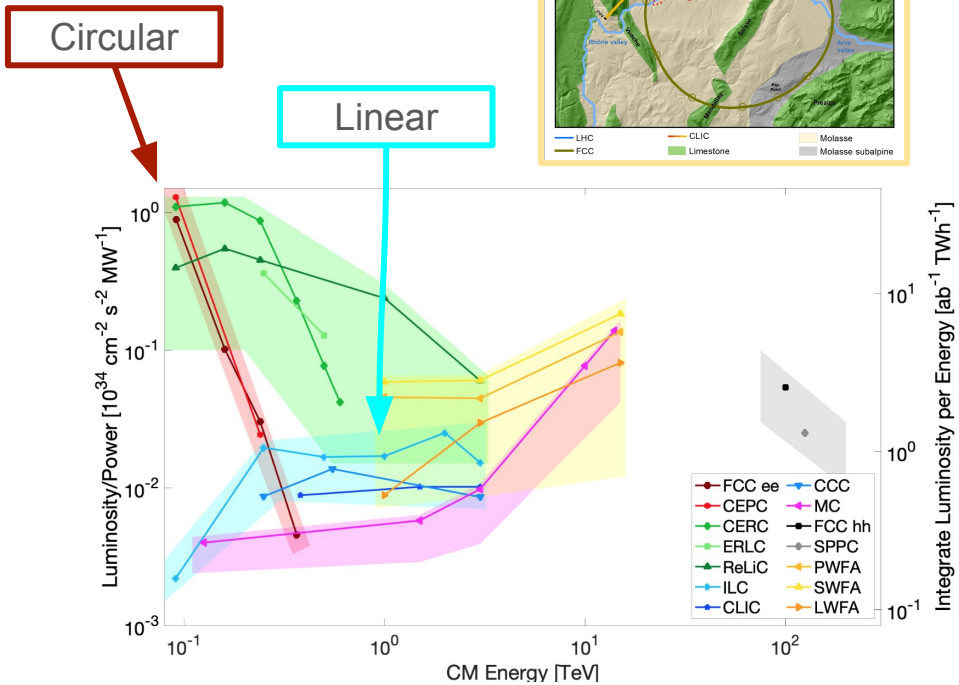


Circular

- Recycle the beam
- Smaller footprint/more acceleration reps
- Need adjustable, strong magnets
- Synchrotron radiation

Linear

- One shot beam
- Fewer strong magnets
- No synchrotron radiation



Circular v. Linear

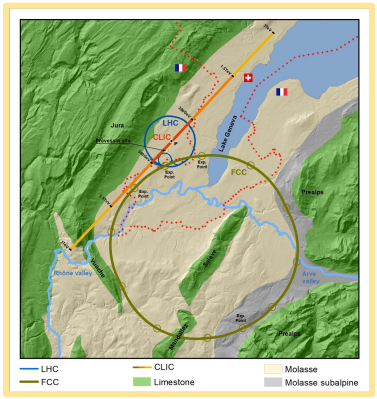
Circular

- Recycle the beam
- Smaller footprint/more acceleration reps
- Need adjustable, strong magnets
- Synchrotron radiation

Linear

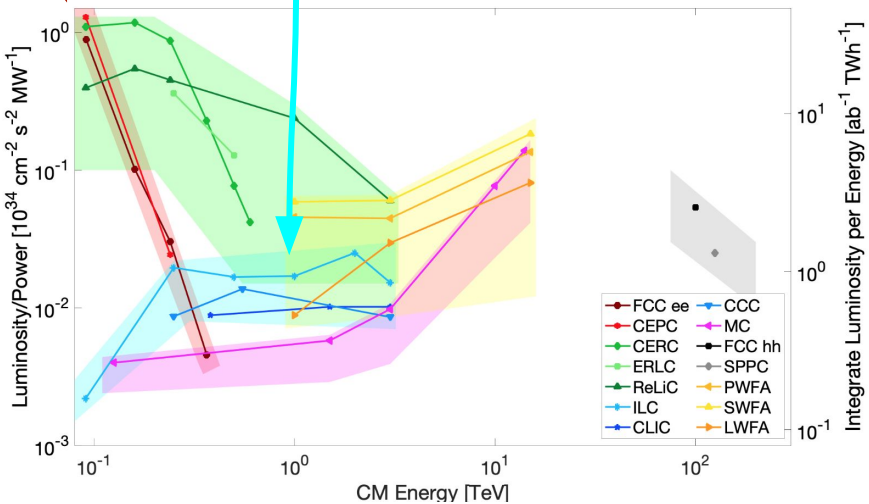
- One shot beam
- Fewer strong magnets
- No synchrotron radiation

proposed future linear and circular colliders at cern

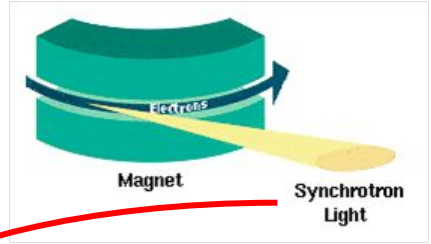


Circular

Linear



Hadron Colliders - natural for highest energies

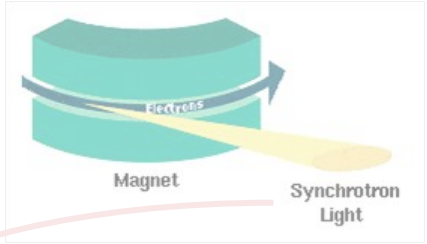


$$P_\gamma = \frac{q^2 c}{6\pi\varepsilon_0}\frac{\beta^4\gamma^4}{\rho^2},$$

$$\gamma = \frac{E}{mc^2}$$

Higher mass, less loss!

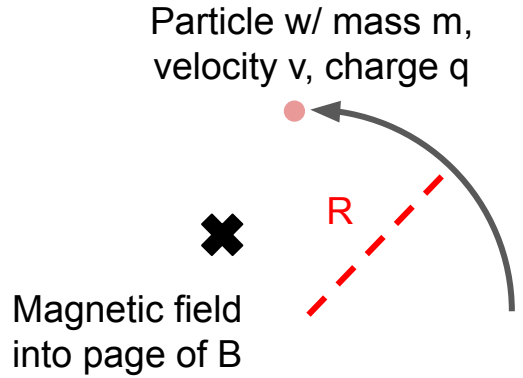
Hadron Colliders - naturally difficult



$$P_\gamma = \frac{q^2 c}{6\pi\varepsilon_0}\frac{\beta^4\gamma^4}{\rho^2},$$

$$\gamma = \frac{E}{mc^2}$$

Higher mass, less loss!

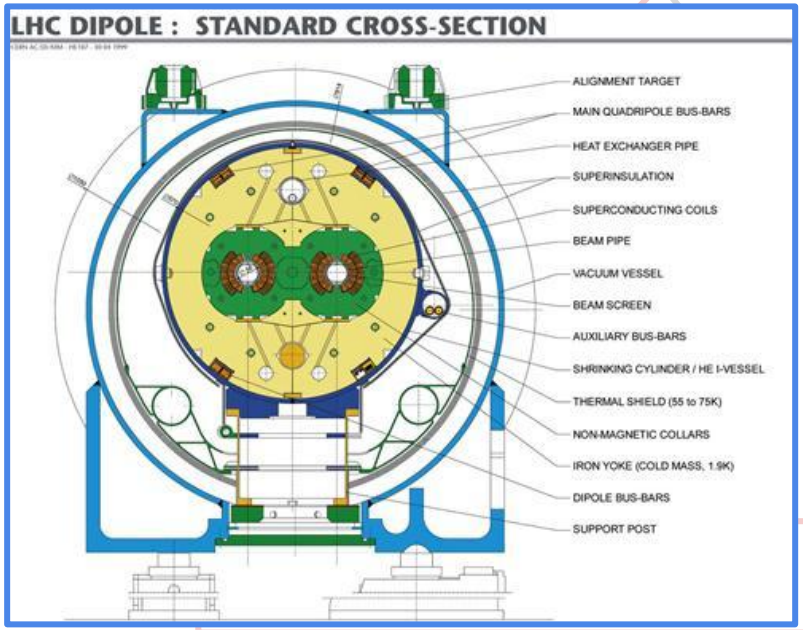


$$R = \frac{mv}{qB}$$

For same radius, higher mass means higher magnetic field!

Hadron Colliders naturally dif

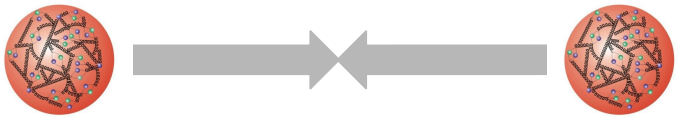
Magnet tech ultimately limits energy reach! (in reasonable sized tunnels)



LHC Dipole magnets are super complicated! ~8 T and need to be cooled to 1.9 K

Complications of hadron colliders

Complications of hadron colliders



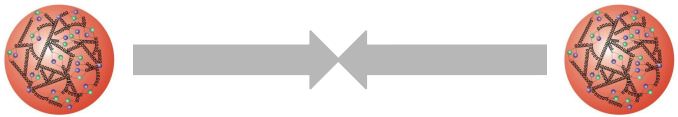
Actually colliding quarks + gluons inside the protons - each carry a fraction of the total energy

Don’t actually get full energy of accelerated proton

(Unknown initial state along direction motion)* important later

Lots of other crap in the collision

Complications of hadron colliders



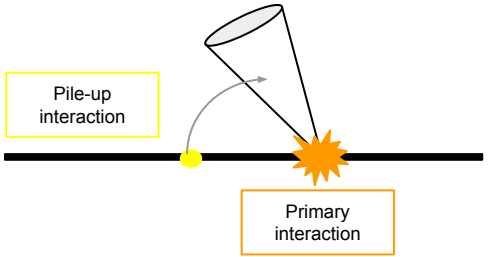
Don’t actually get full energy of accelerated proton

(Unknown initial state along direction motion)* important later

Actually colliding quarks + gluons inside the protons - each carry a fraction of the total energy

Also collide bunches, so we get “pile-up” - interactions from other particles in the bunch, but not interesting

Lots of other crap in the collision

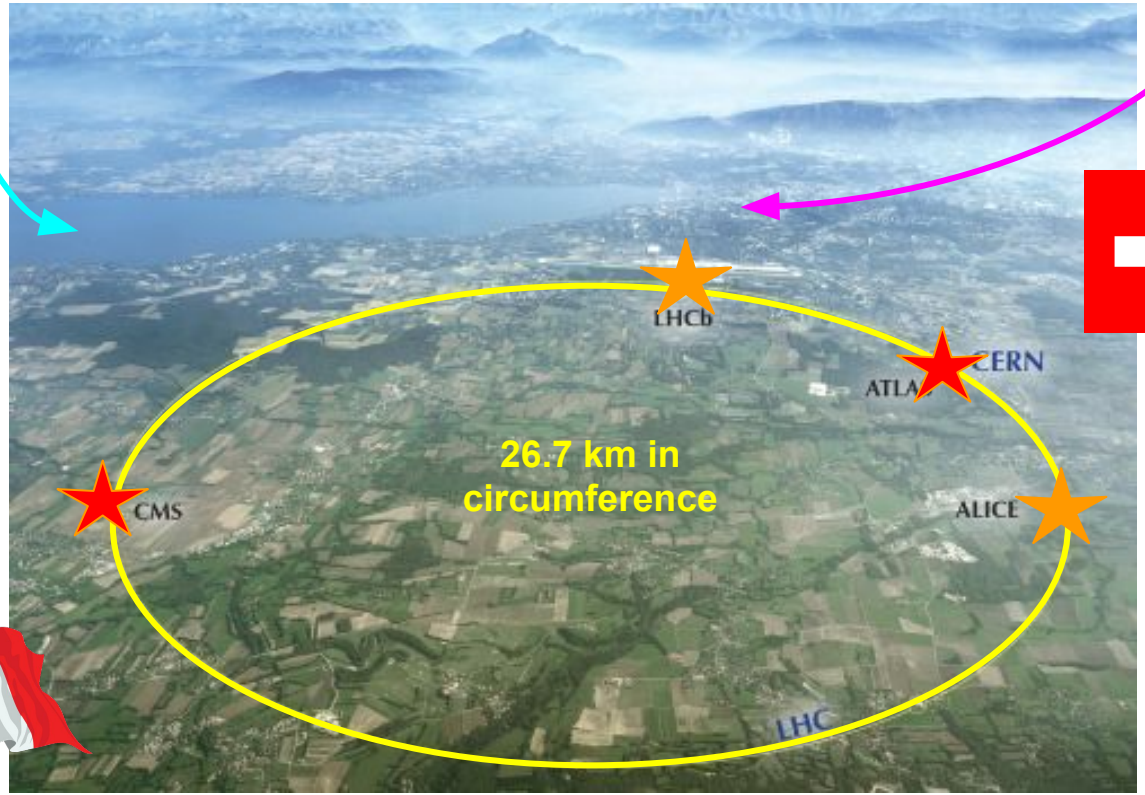


The Large Hadron Collider

The Large Hadron Collider (LHC)

Geneva, Switzerland

Lac Léman (Lake Geneva)

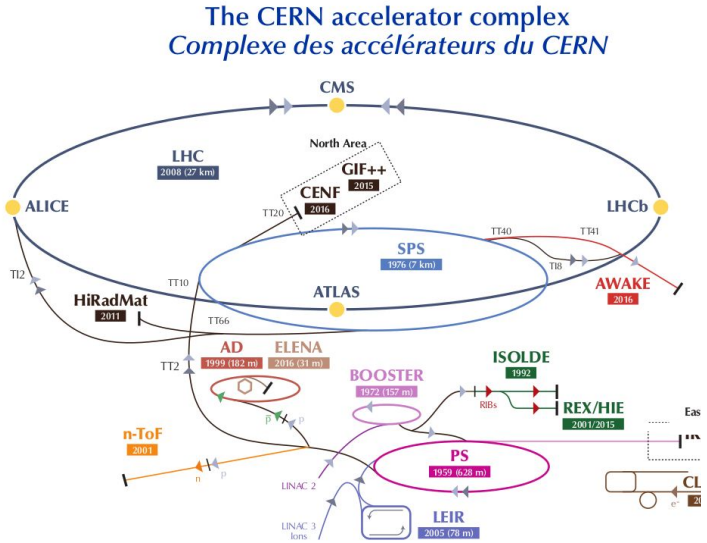


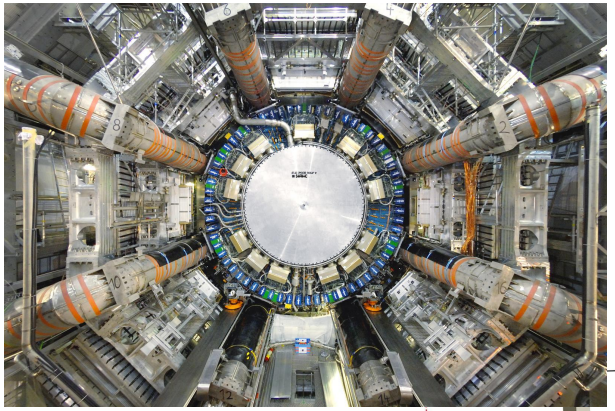
Partially in Switzerland!

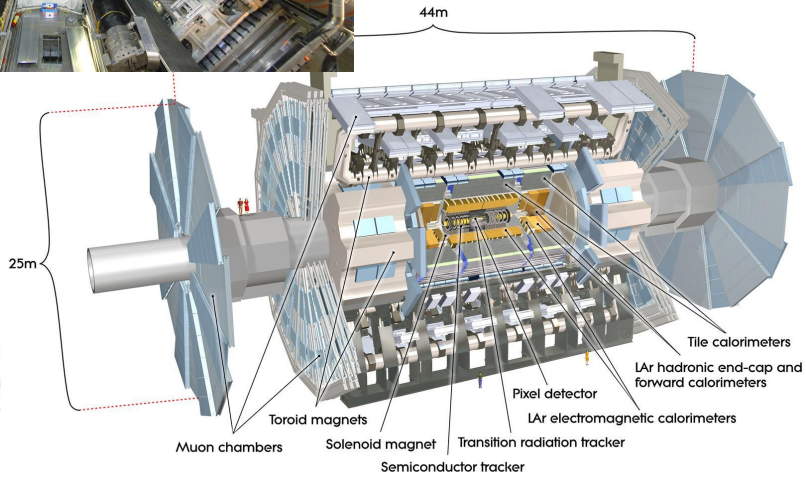
Partially in France!

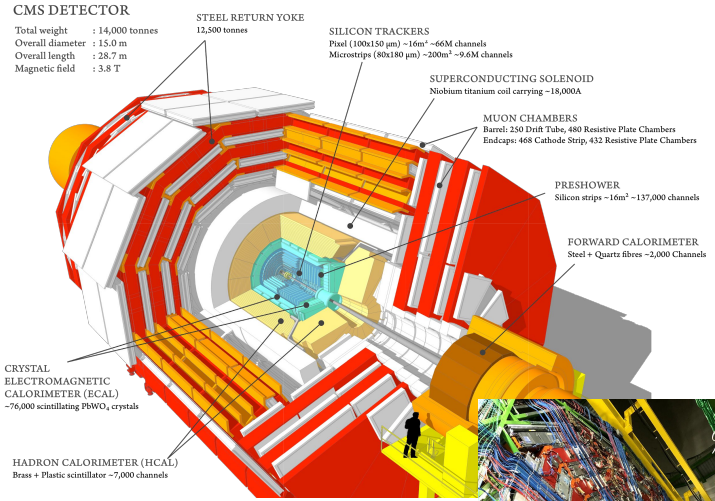
A ~13 TeV Collider

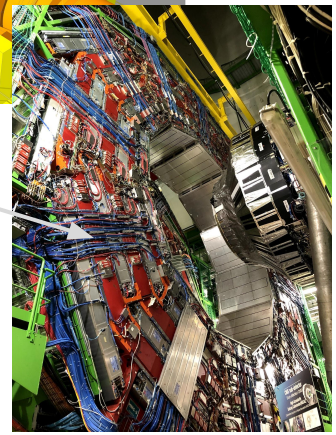
- Final stage of the CERN accelerator chain
  - Largest energy achievable in LEP tunnel (26.7 km in circumference)
- 2, 6.8 TeV **proton** beams
- 4 collision points
  - 2 high luminosity collision points w/ general purpose detectors
  - 2 specialized detectors
- 25 ns bunch spacing



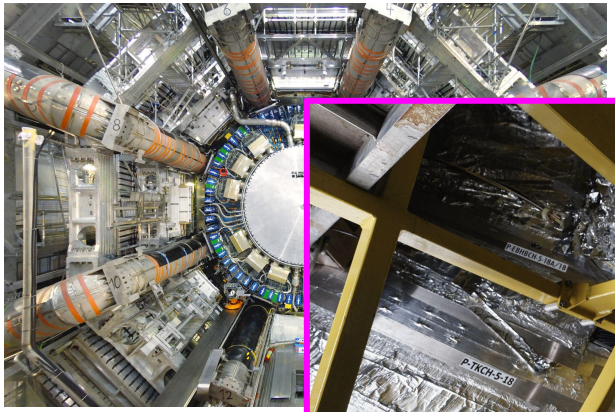


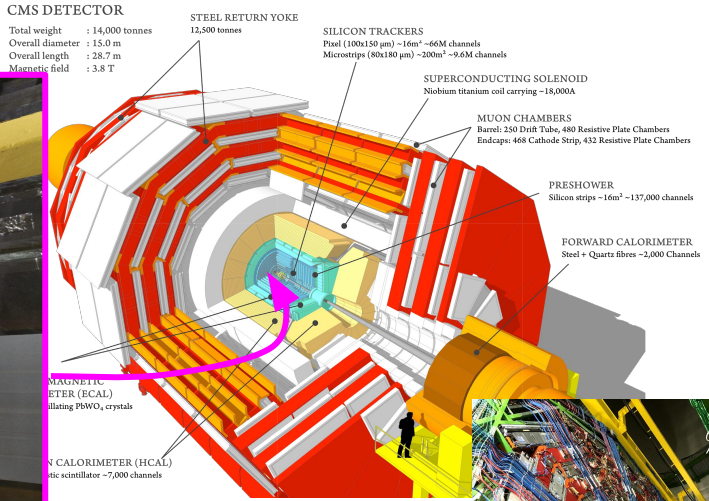


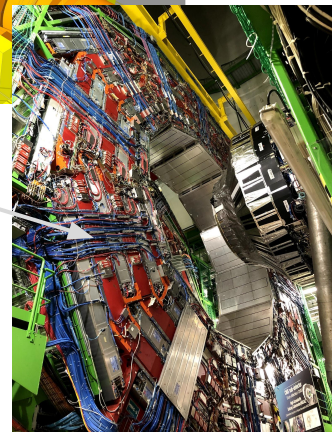


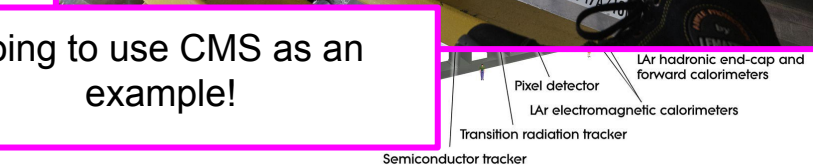


General Purpose Experiments





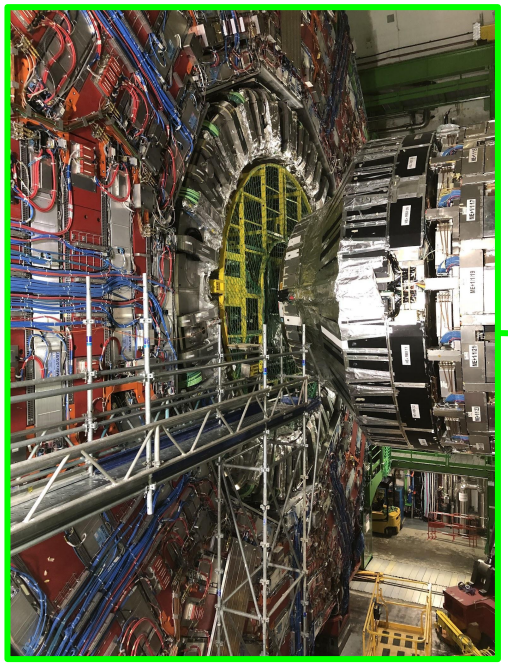


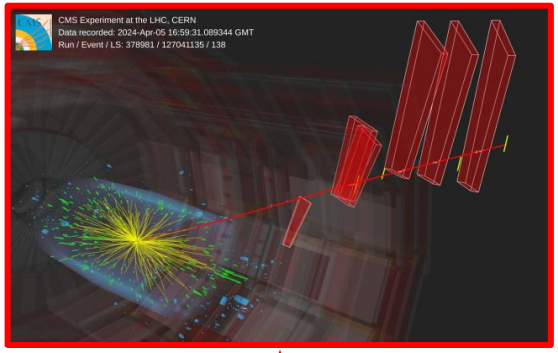


Going to use CMS as an example!

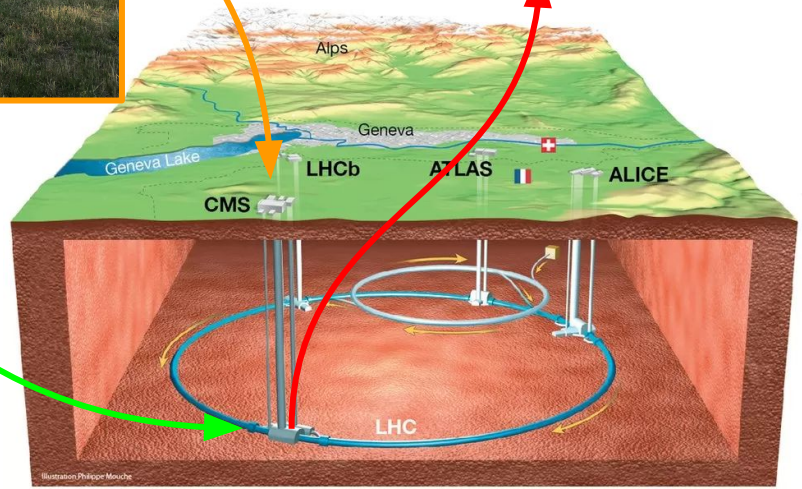
General Purpose Experiments

The CMS Experiment at the LHC

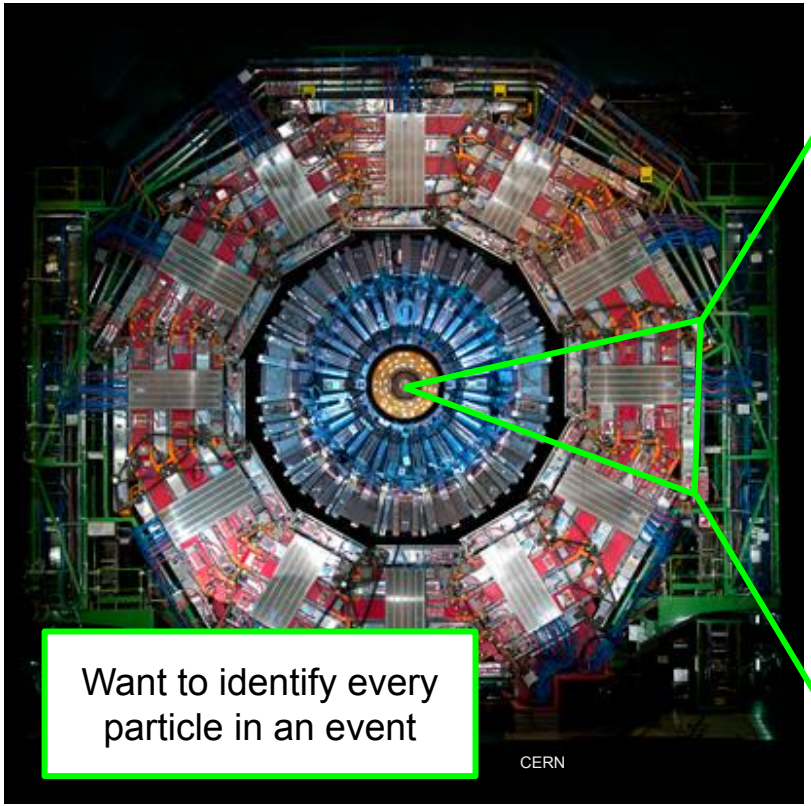


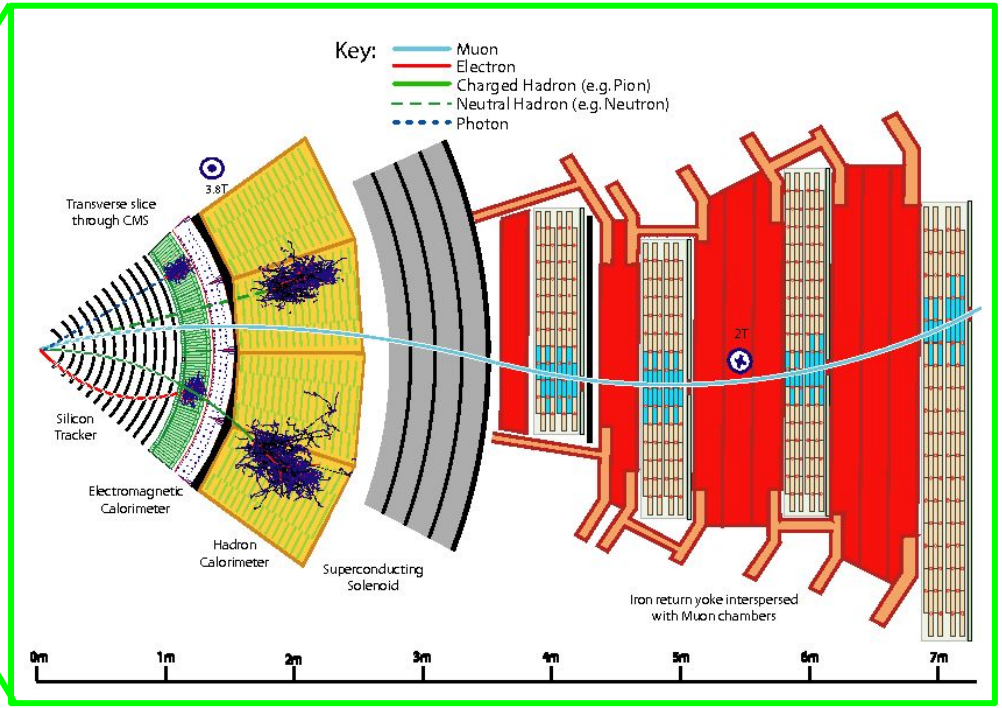


General purpose, discovery machine!

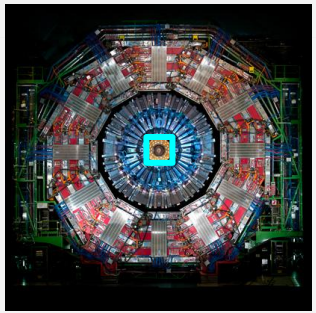


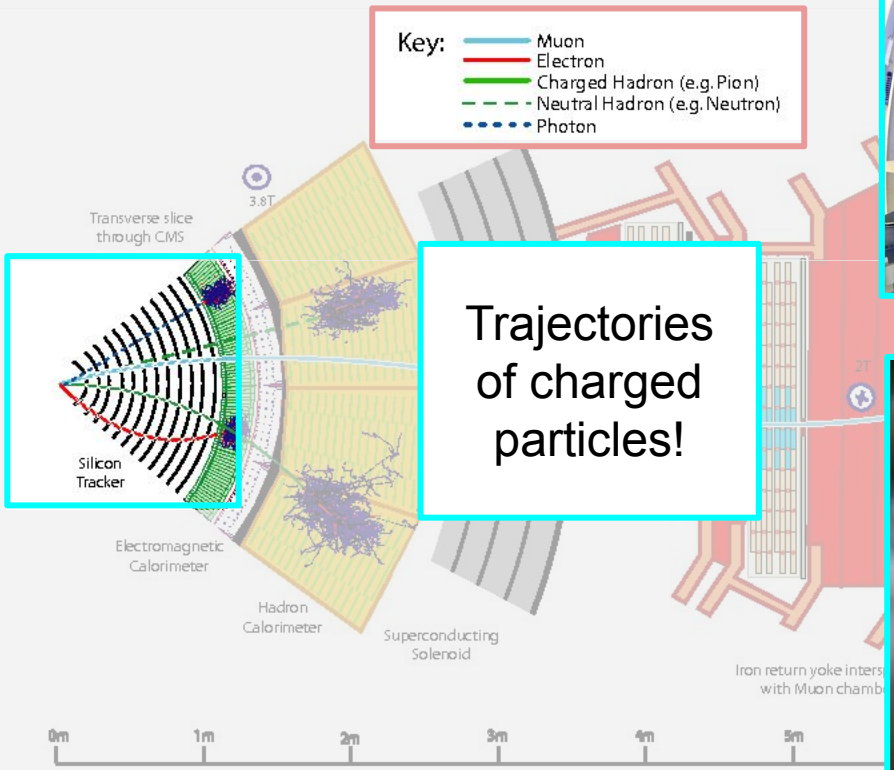
Compact Muon Solenoid Experiment



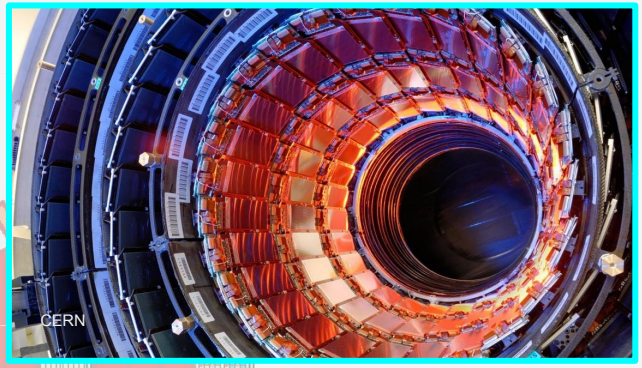


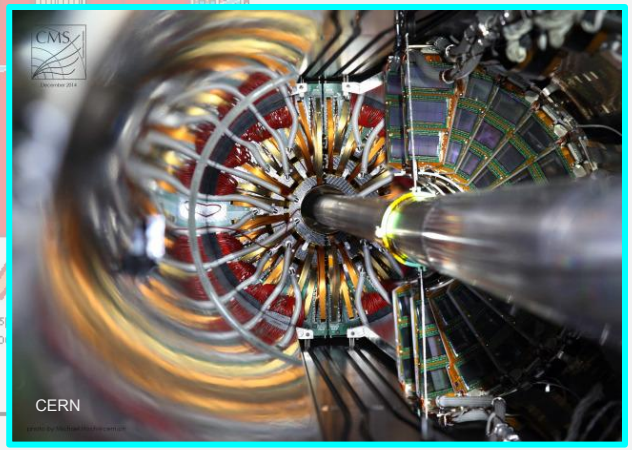
CMS at the LHC - Silicon Tracker



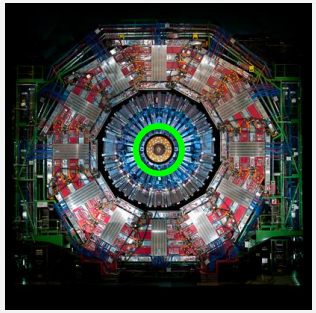


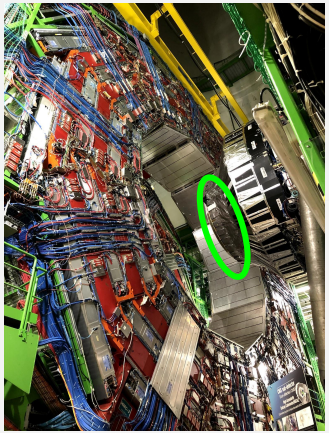
Trajectories of charged particles!

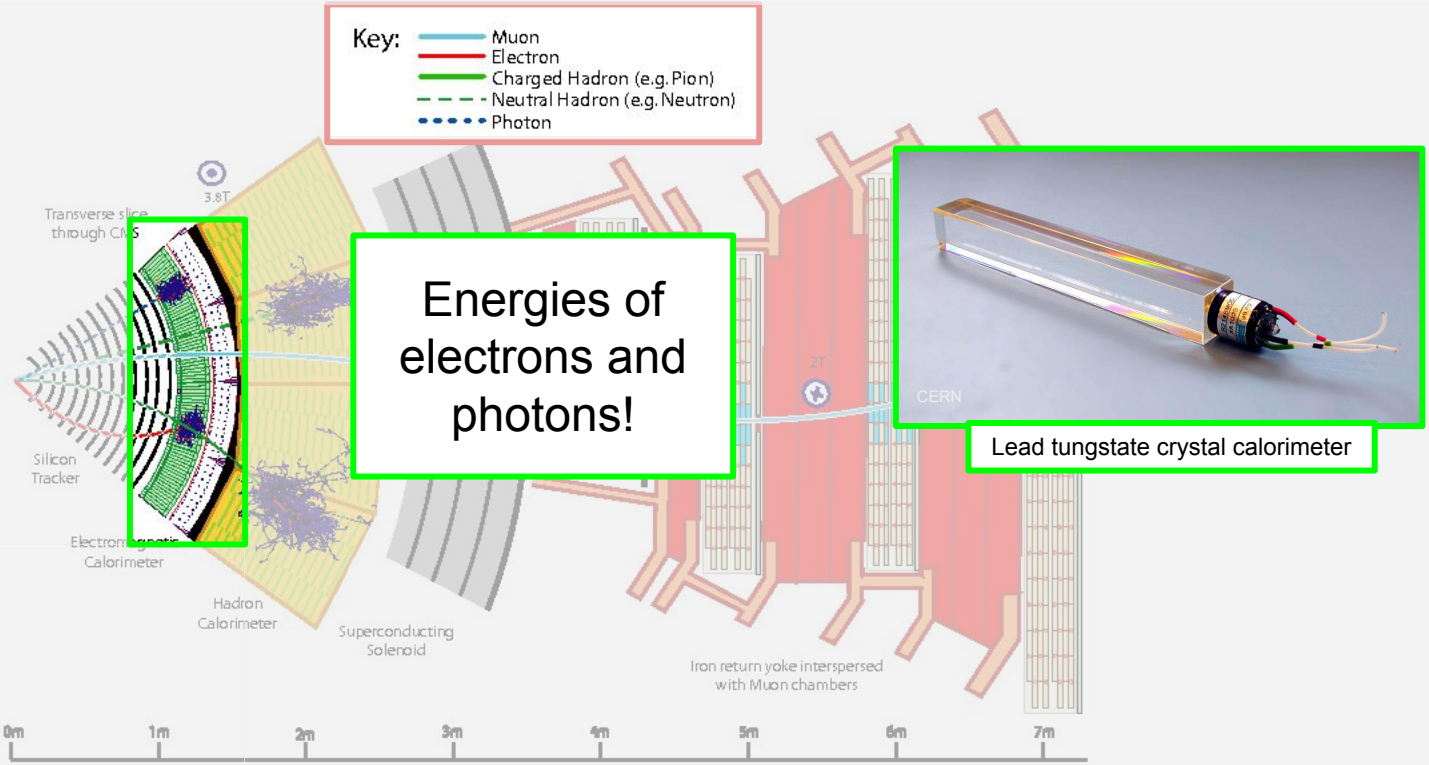




CMS - Electromagnetic Calorimeter (ECAL)



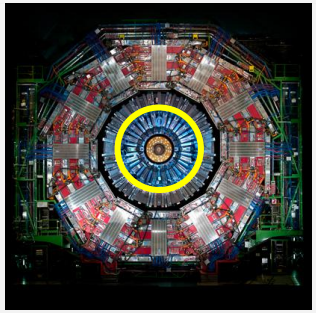


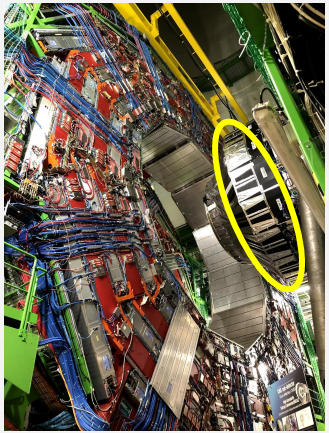


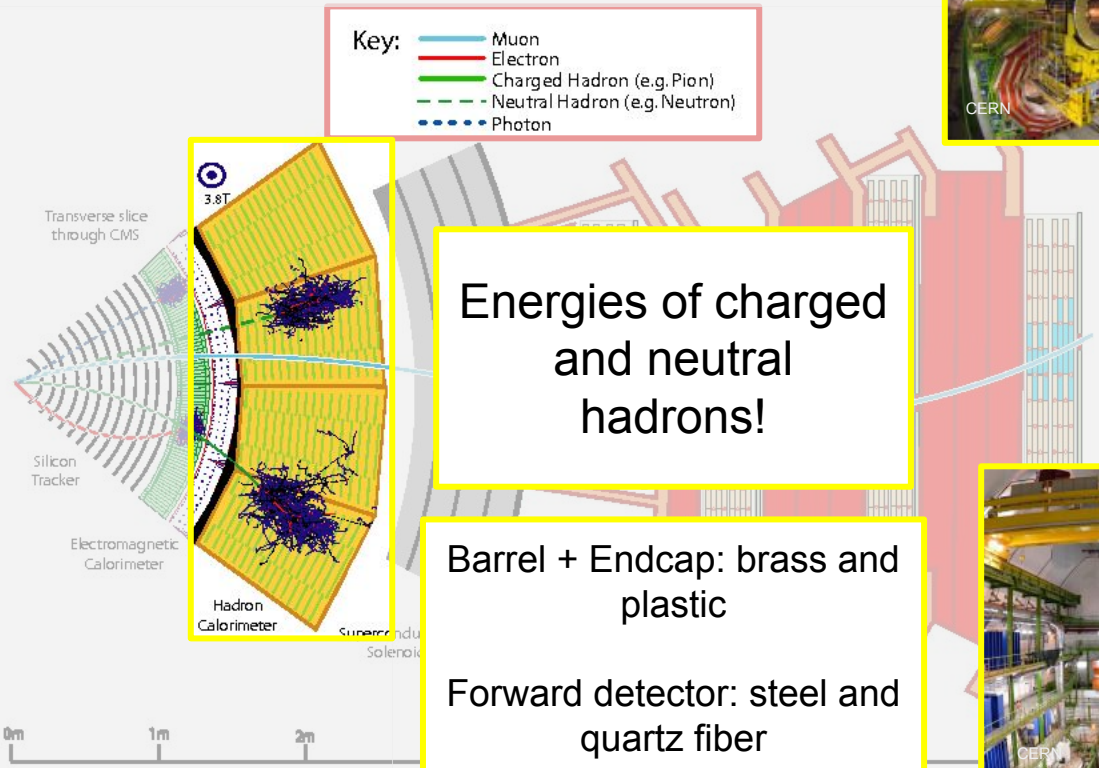
Energies of electrons and photons!

Lead tungstate crystal calorimeter

CMS - Hadron Calorimeter (HCAL)





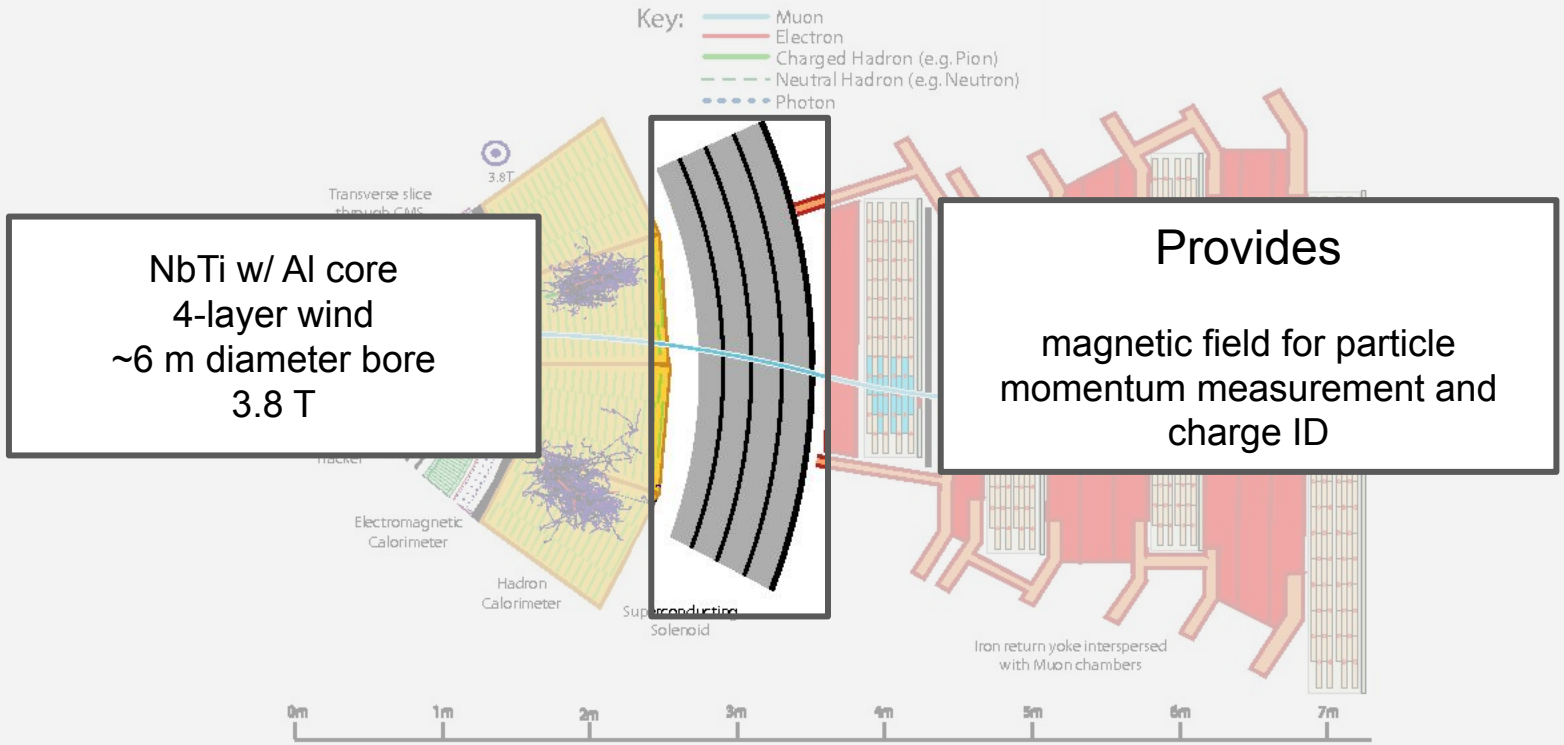


Energies of charged and neutral hadrons!

Barrel + Endcap: brass and plastic

Forward detector: steel and quartz fiber

CMS at the LHC - Superconducting Solenoid

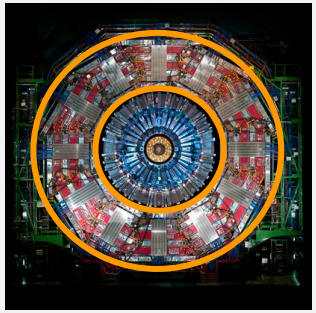


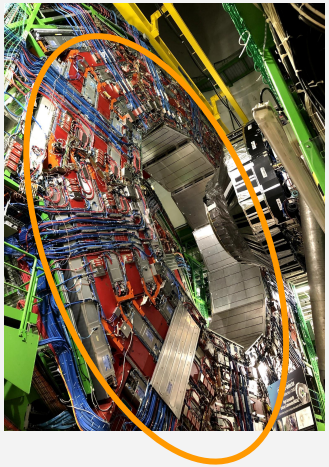
NbTi w/ Al core
4-layer wind
~6 m diameter bore
3.8 T

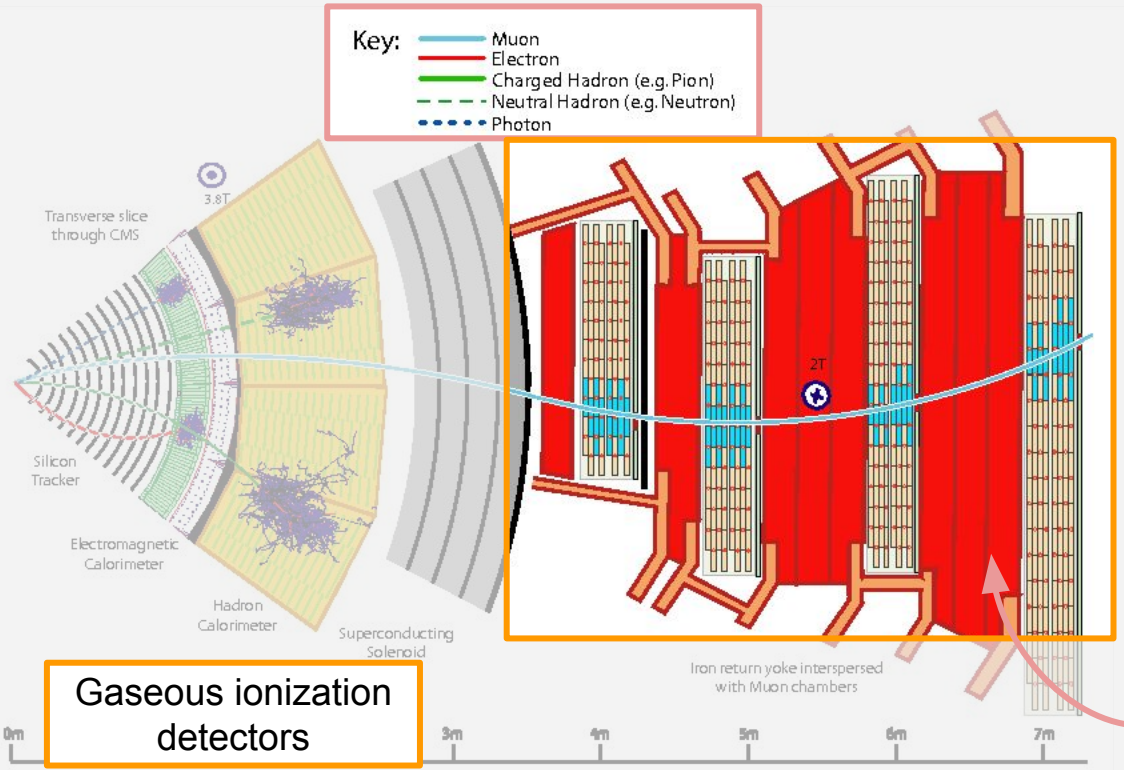
Provides

magnetic field for particle momentum measurement and charge ID

CMS at the LHC - Muon System and Flux Return





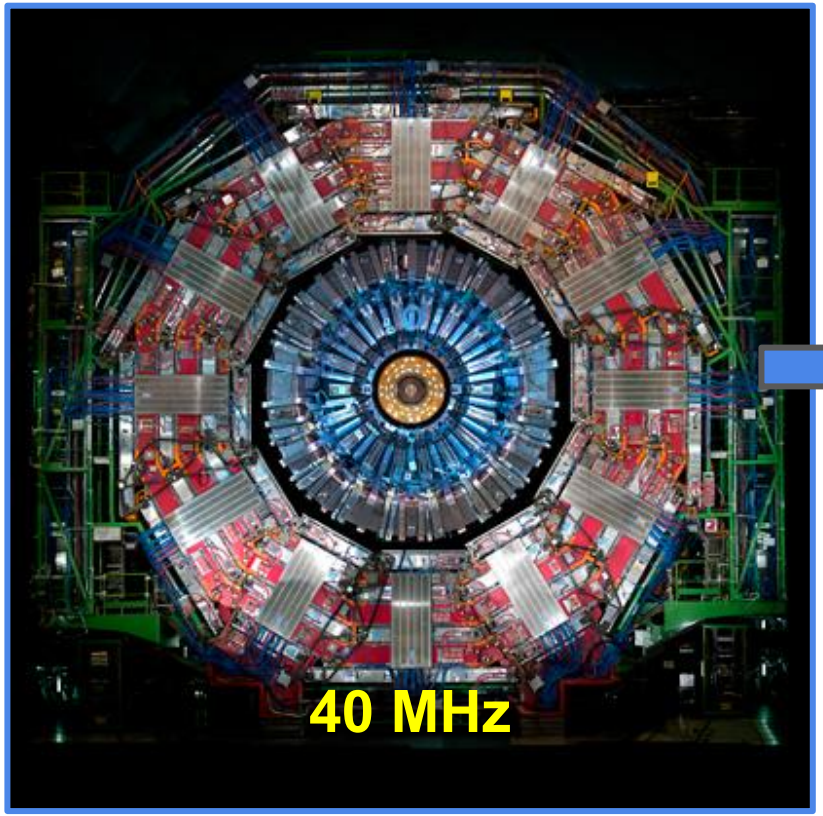


Muon trajectories and particle ID

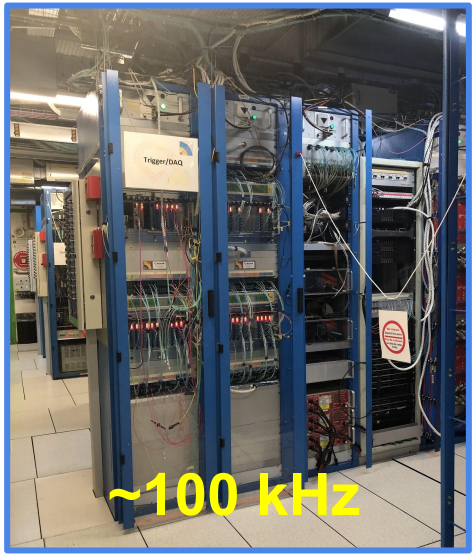
Gaseous ionization detectors

Iron for magnetic flux return

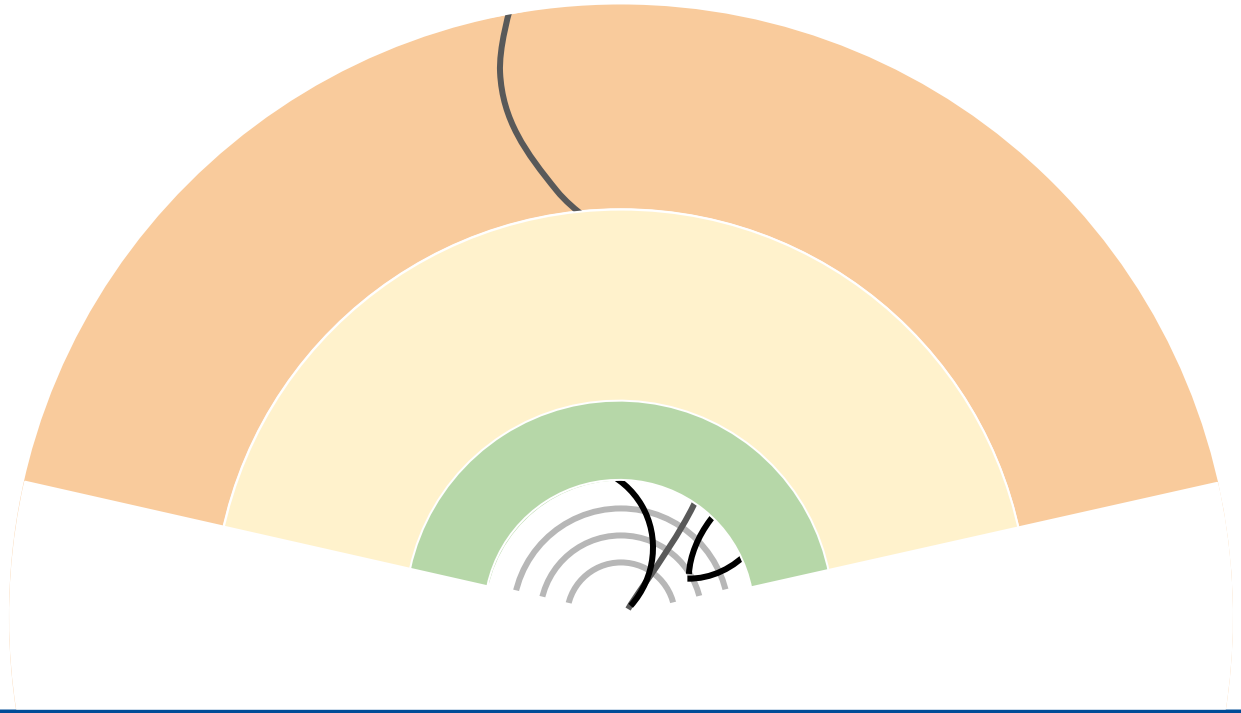
CMS at the LHC - Trigger



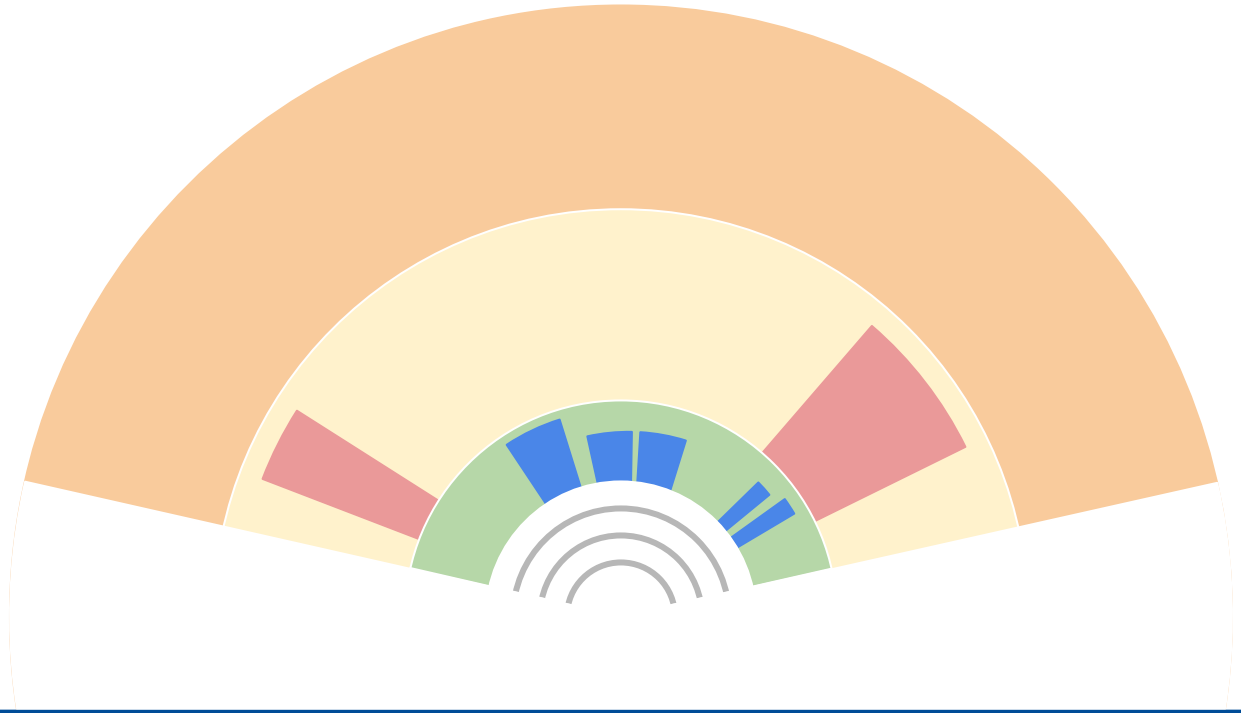
Stairs to counting room



Reconstructing particles

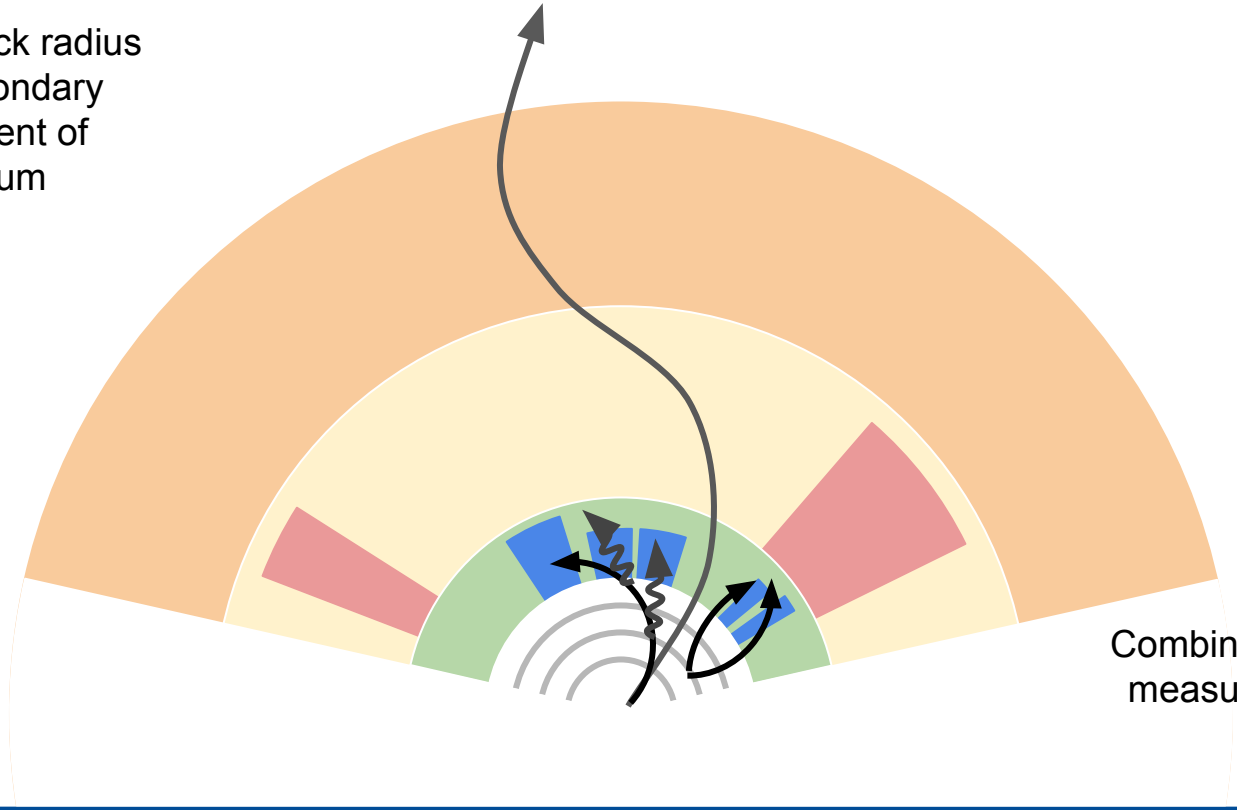


Reconstructing particles



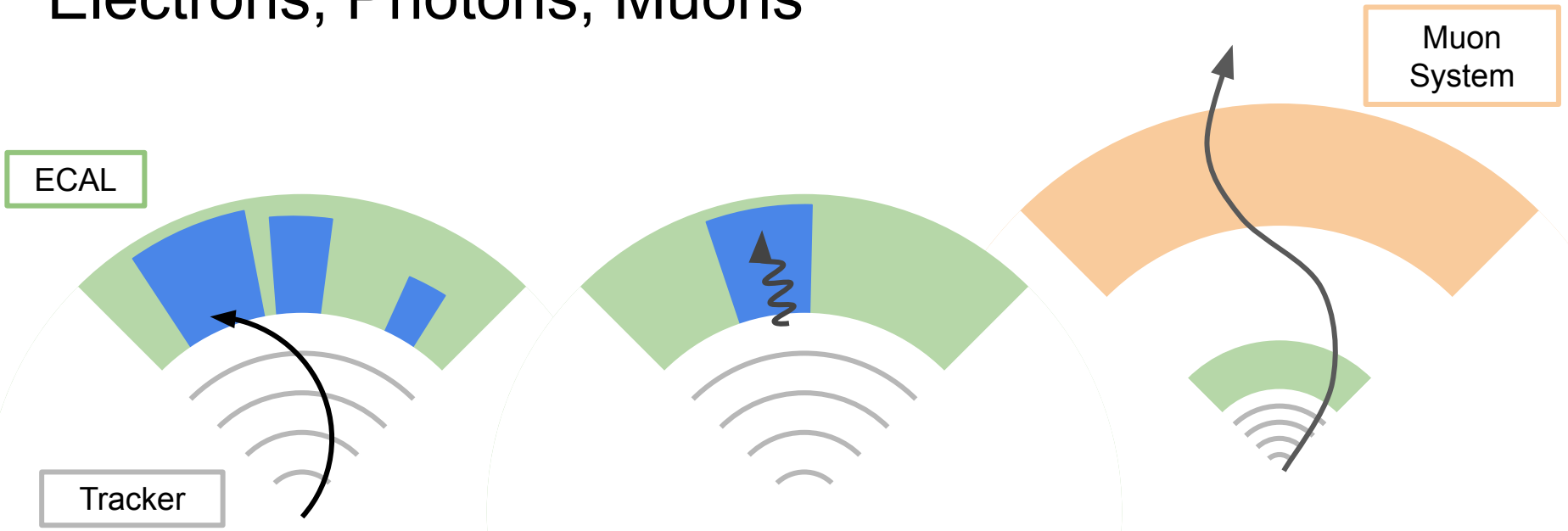
Reconstructing particles

Measuring track radius gives a secondary measurement of momentum



Combining complementary measurements improves resolution!

Electrons, Photons, Muons

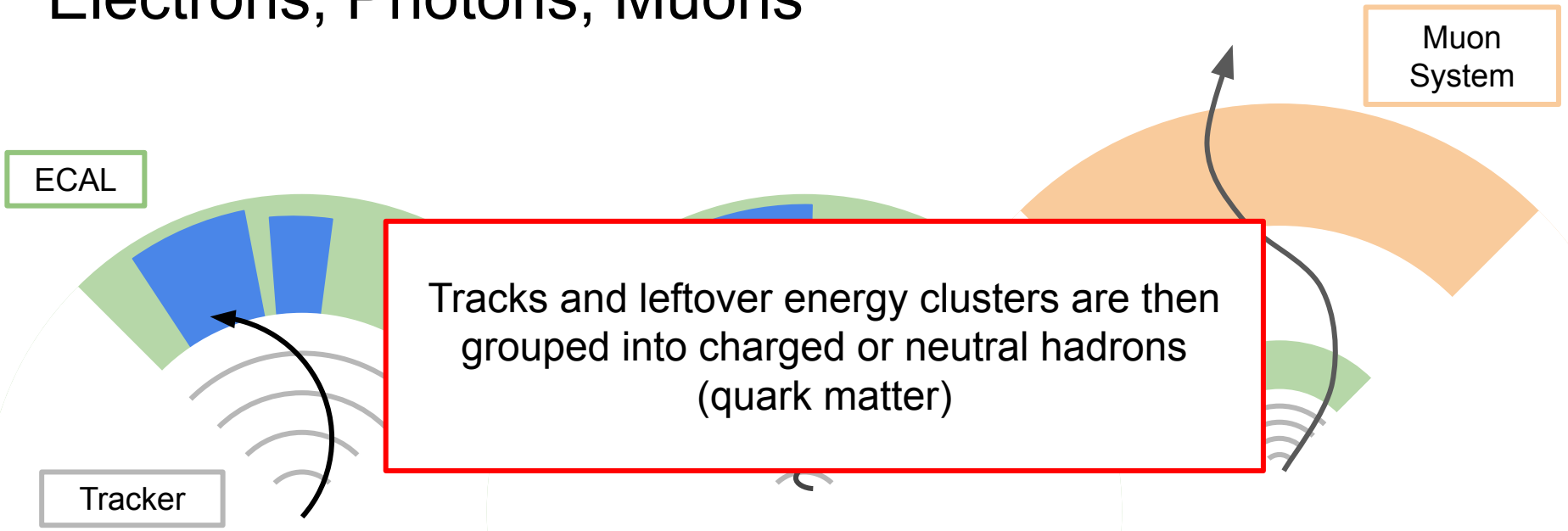


Electrons are made of tracks and energy clusters

Photons are made of energy clusters w/out tracks

Muons are made of tracks in the tracker and the muon system

Electrons, Photons, Muons



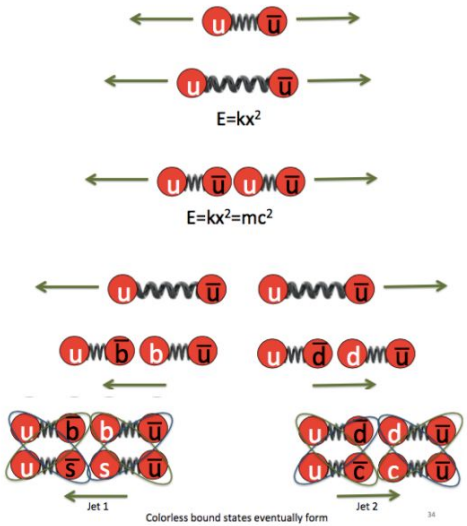
Electrons are made of tracks and energy clusters

Photons are made of energy clusters w/out tracks

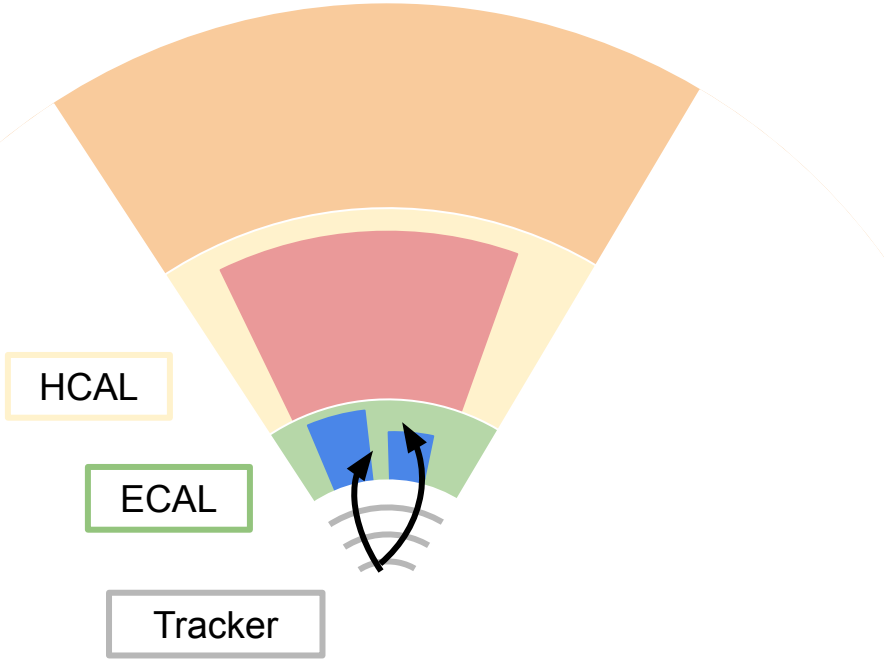
Muons are made of tracks in the tracker and the muon system

Jets

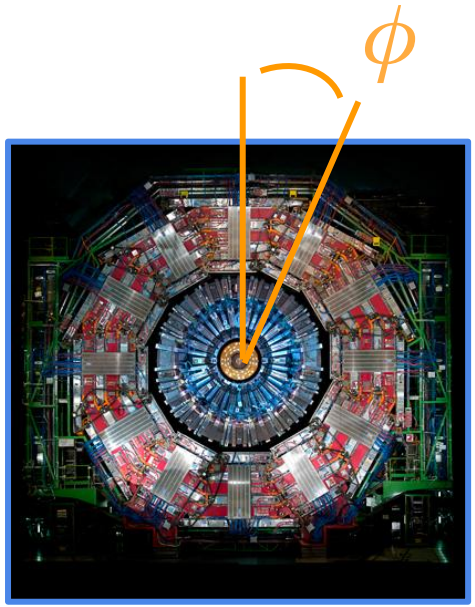
Quarks hadronize, forming lots of bound states as they shower!



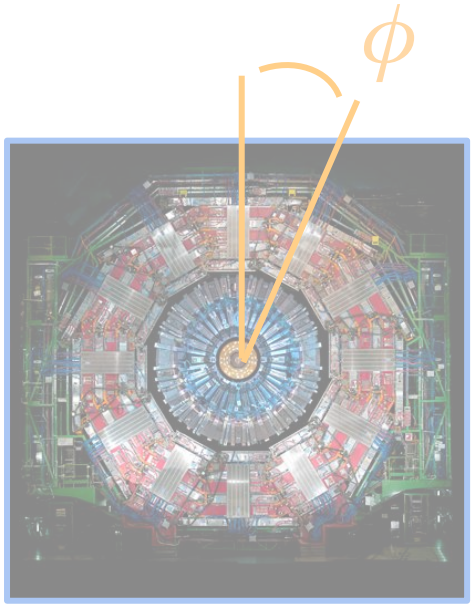
jets → collections of hadrons and other particles grouped to **reconstruct a quark** – they have all subsystems!

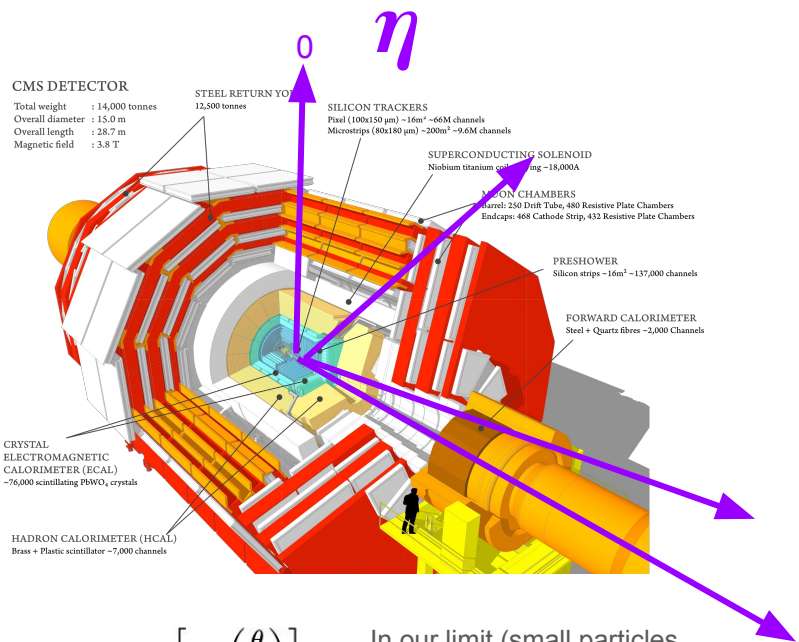


Relativistic Kinematics



Relativistic Kinematics

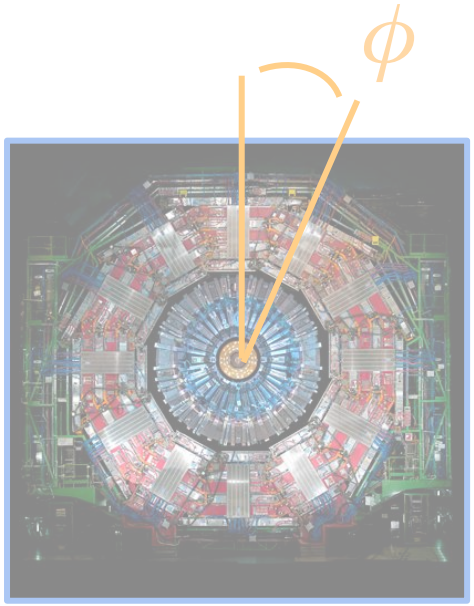


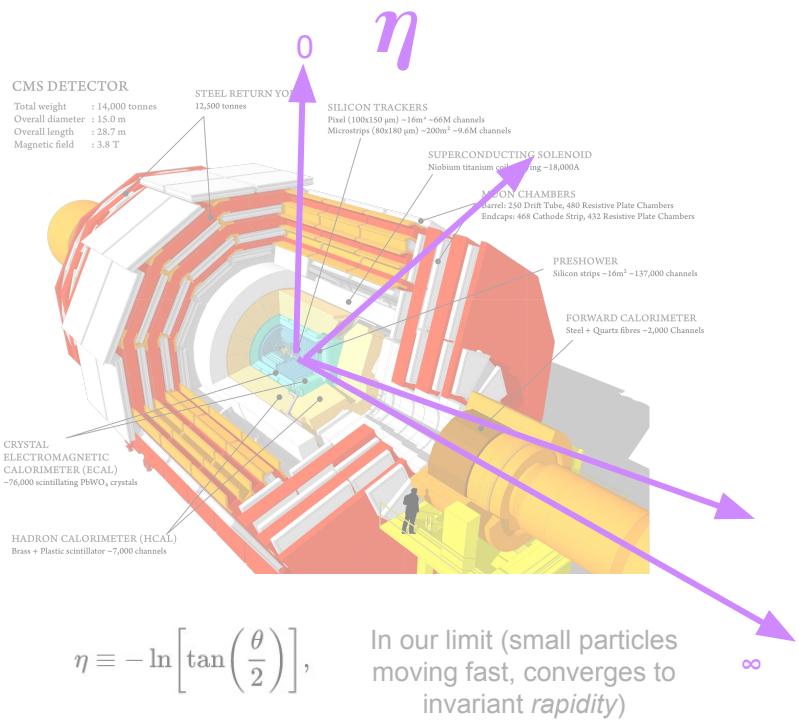


$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

In our limit (small particles moving fast, converges to invariant *rapidity*)

Relativistic Kinematics





$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

In our limit (small particles moving fast, converges to invariant *rapidity*)

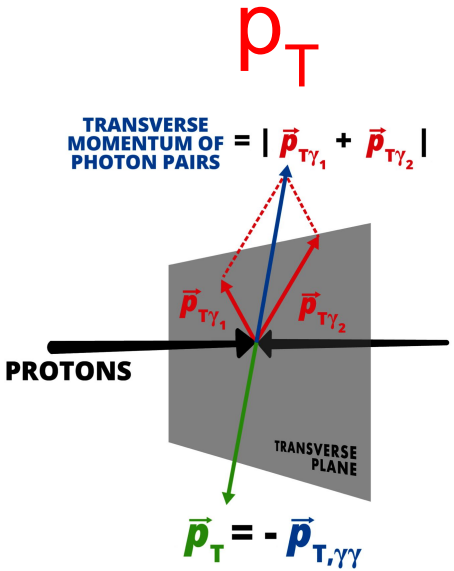
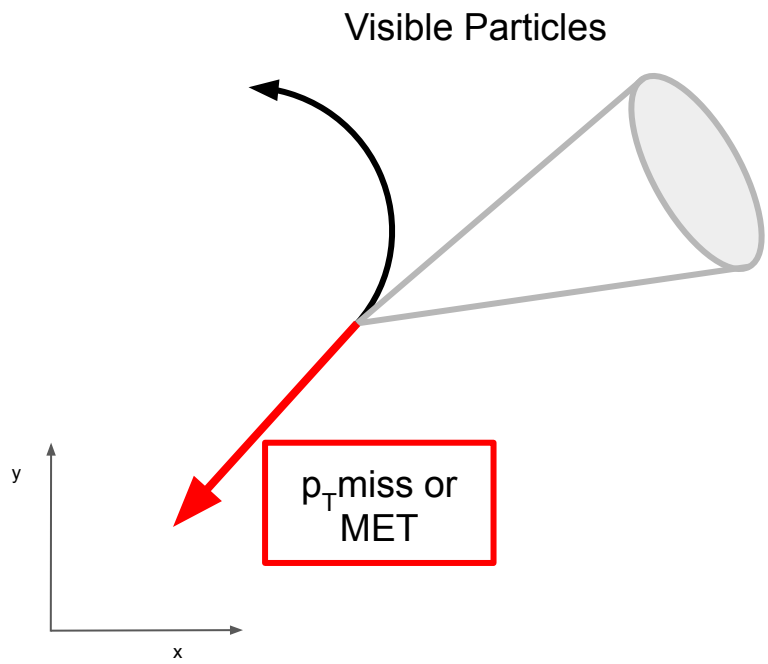


Image: ATLAS

Transverse momentum, since we do not know momentum along beam!

Final, sneaky object- Missing Transverse Momentum

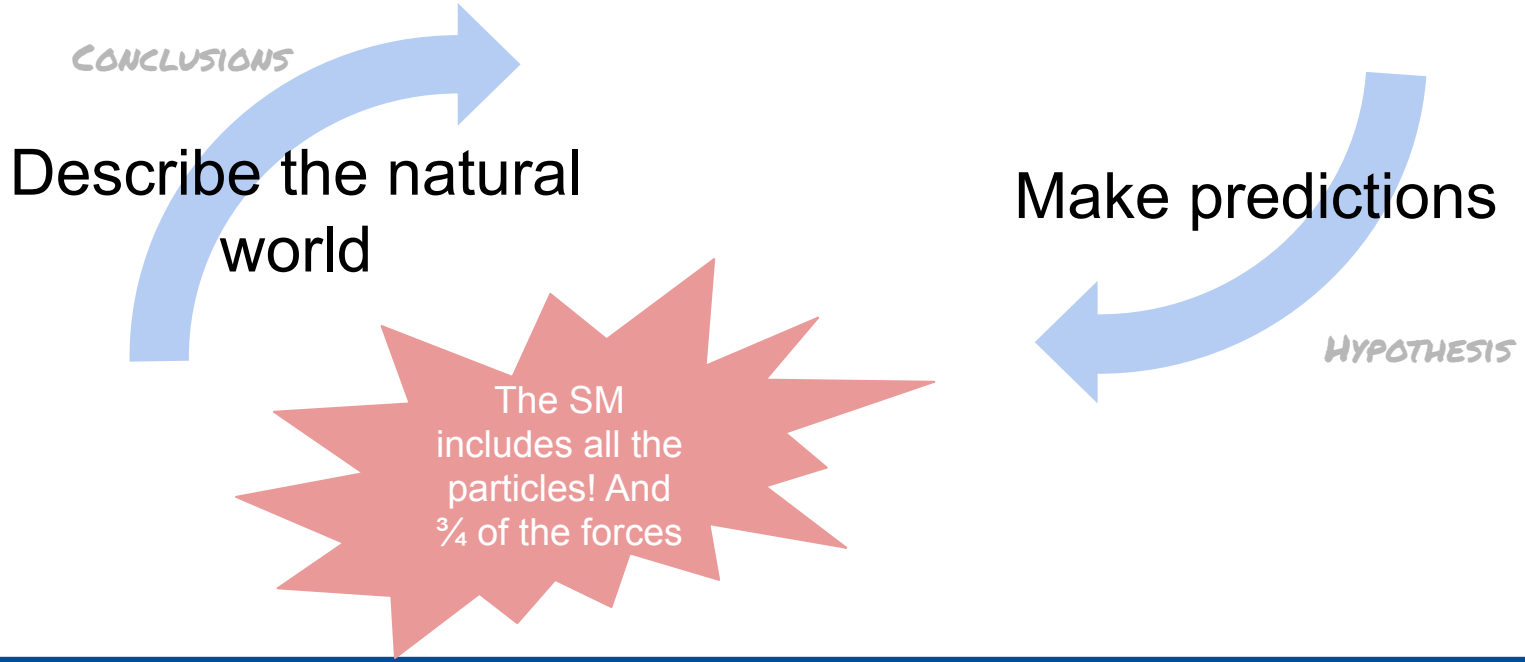
- Momentum imbalance in the transverse plane of the detector
  - momentum carried away by **invisible particles**



Physics at colliders

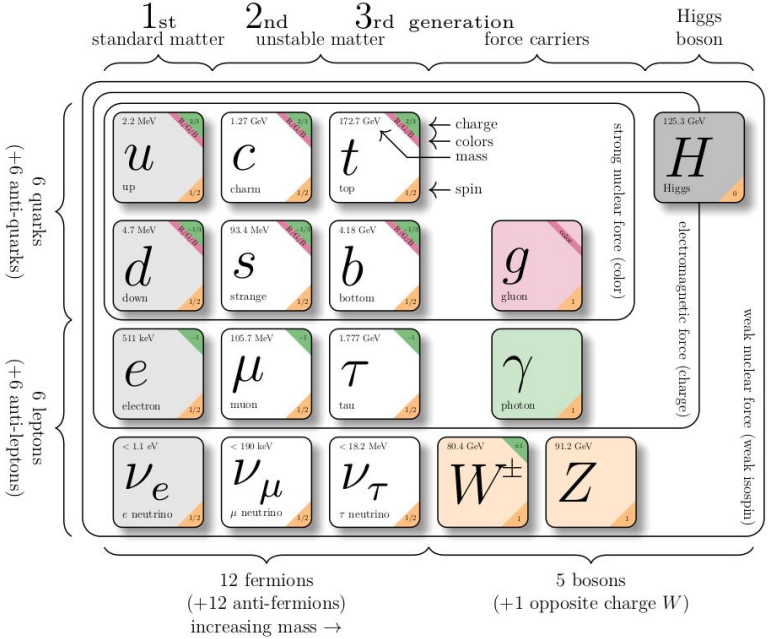
What makes a good scientific model

A good model must:



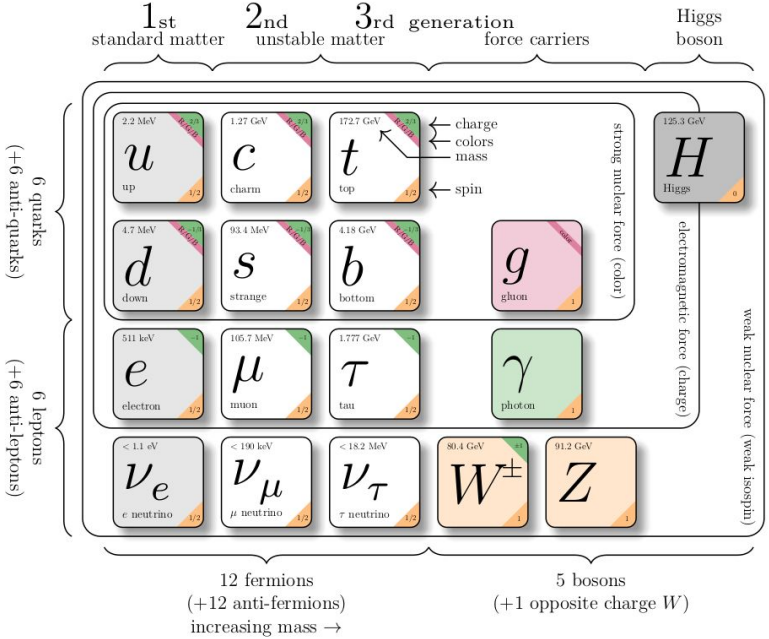
Collider physics

All of this can be made…



Collider physics is probabilistic

All of this can be made…



… at any time!

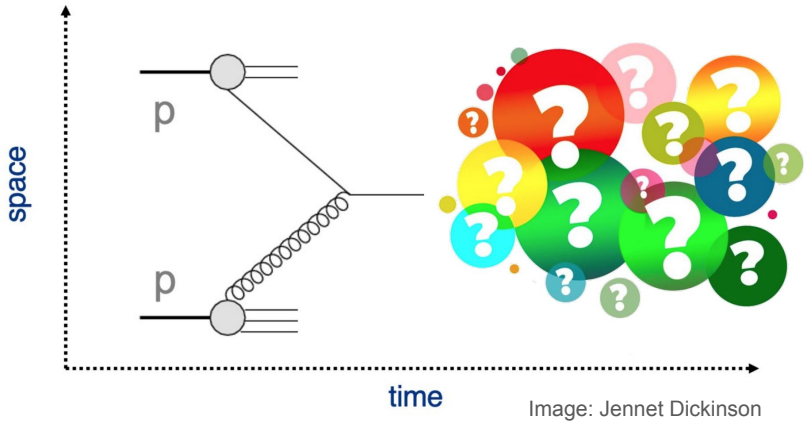
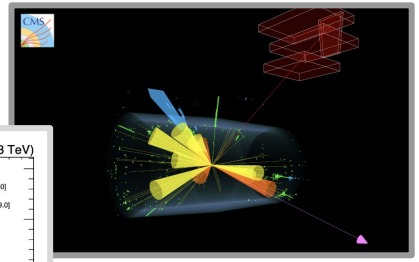


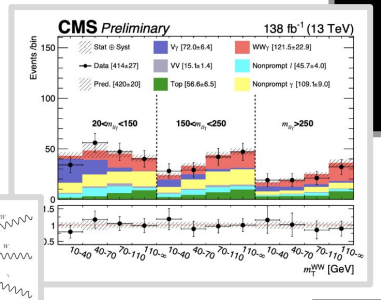
Image: Jennet Dickinson

Physics Menu

Standard Model Measurement

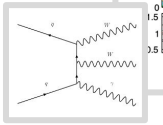
Observations of rare decays, precision measurements





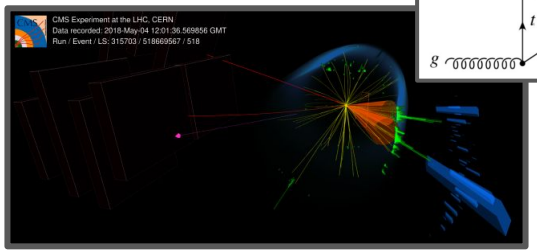
WWγ

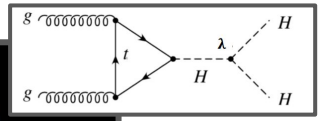
SMP-22-006



4 Top production!

TOP-22-013



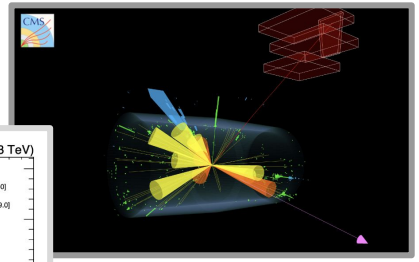


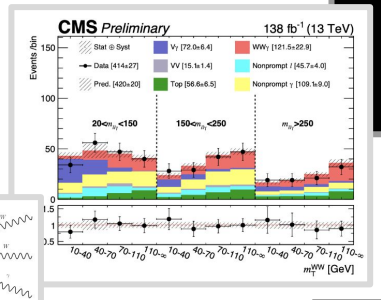
Di-higgs on on the horizon!

Physics Menu

Standard Model Measurement

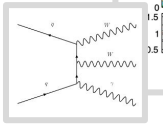
Observations of rare decays, precision measurements





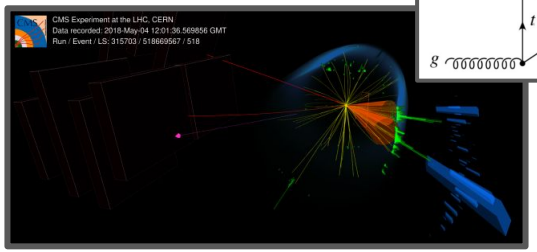
$WW\gamma$

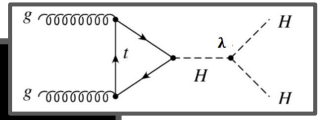
SMP-22-006



4 Top production!

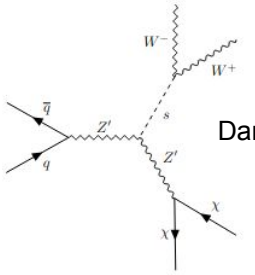
TOP-22-013



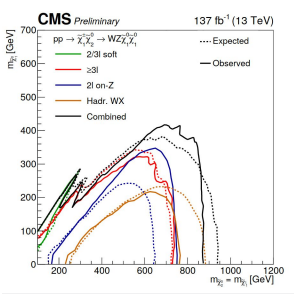


Di-higgs on on the horizon!

Beyond the Standard Model Searches

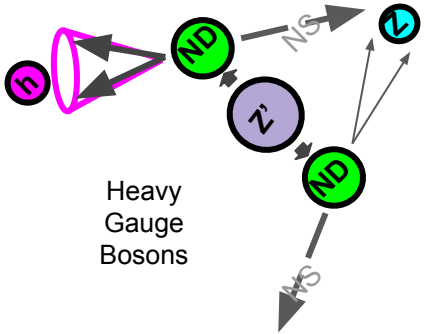


Dark Matter



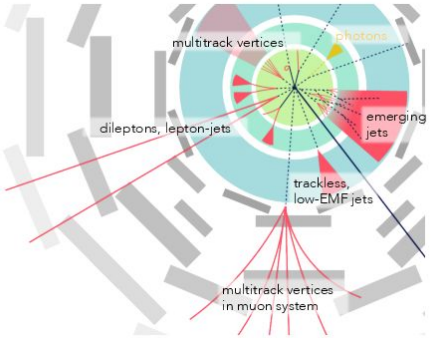
SUSY

SUS-21-008



Heavy Gauge Bosons

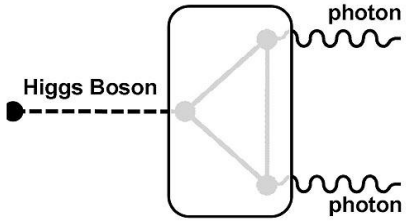
Long Lived particles



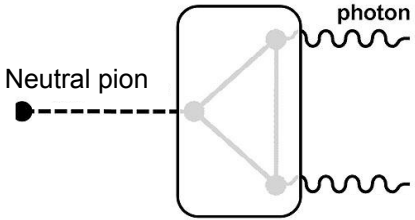
Heather Russell

Search analysis – bare bones

Signal

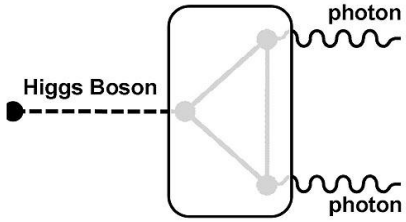


Background
(example)

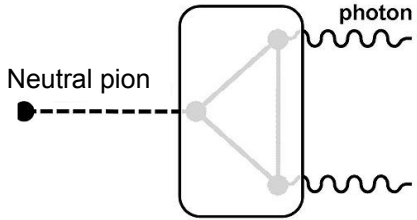


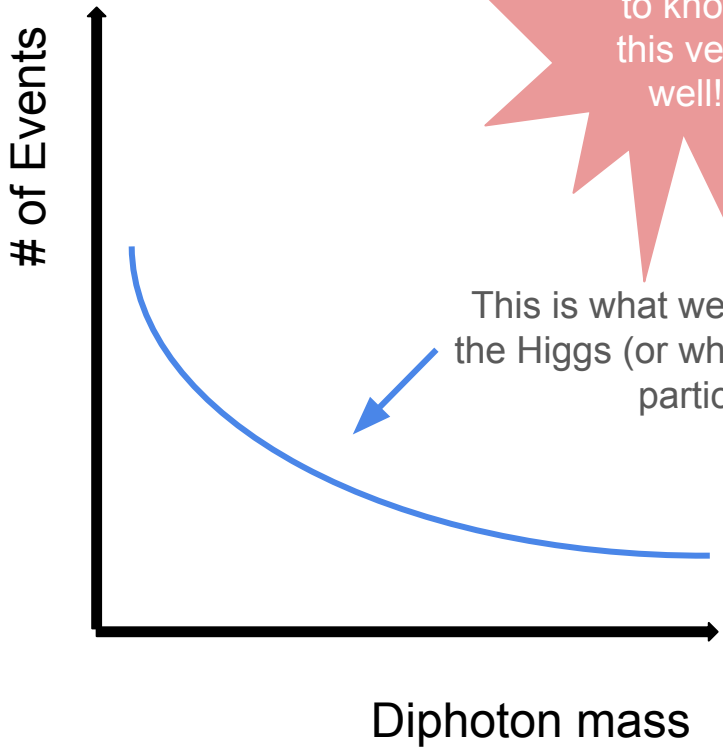
Search analysis – bare bones

Signal



Background
(example)



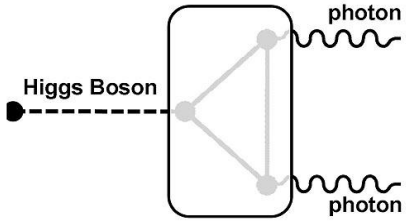


You have to know this very well!

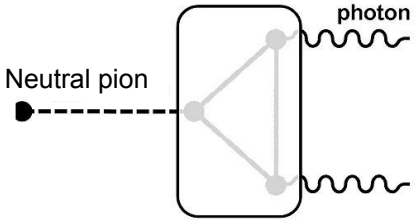
This is what we expect without the Higgs (or whatever your new particle is)

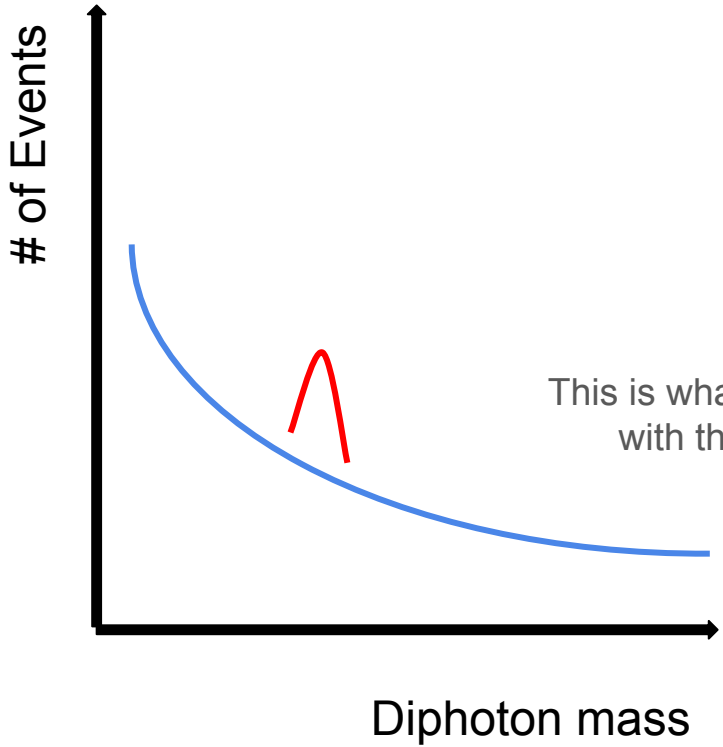
Search analysis – bare bones

Signal



Background
(example)

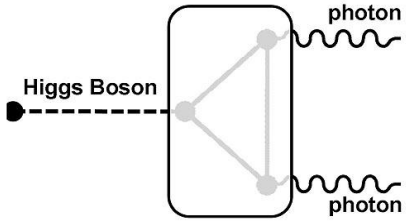




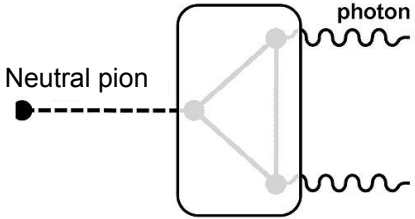
This is what we expect with the Higgs

Search analysis – bare bones

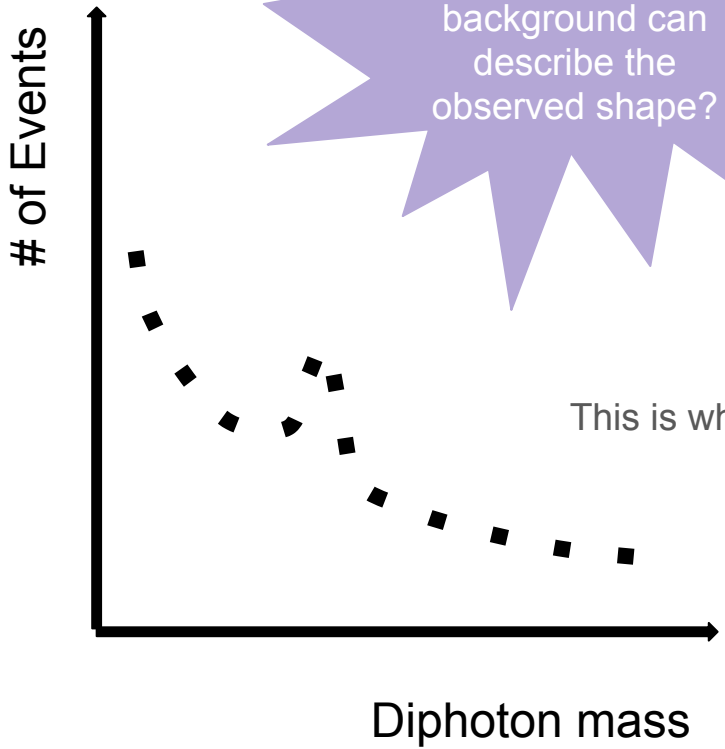
Signal



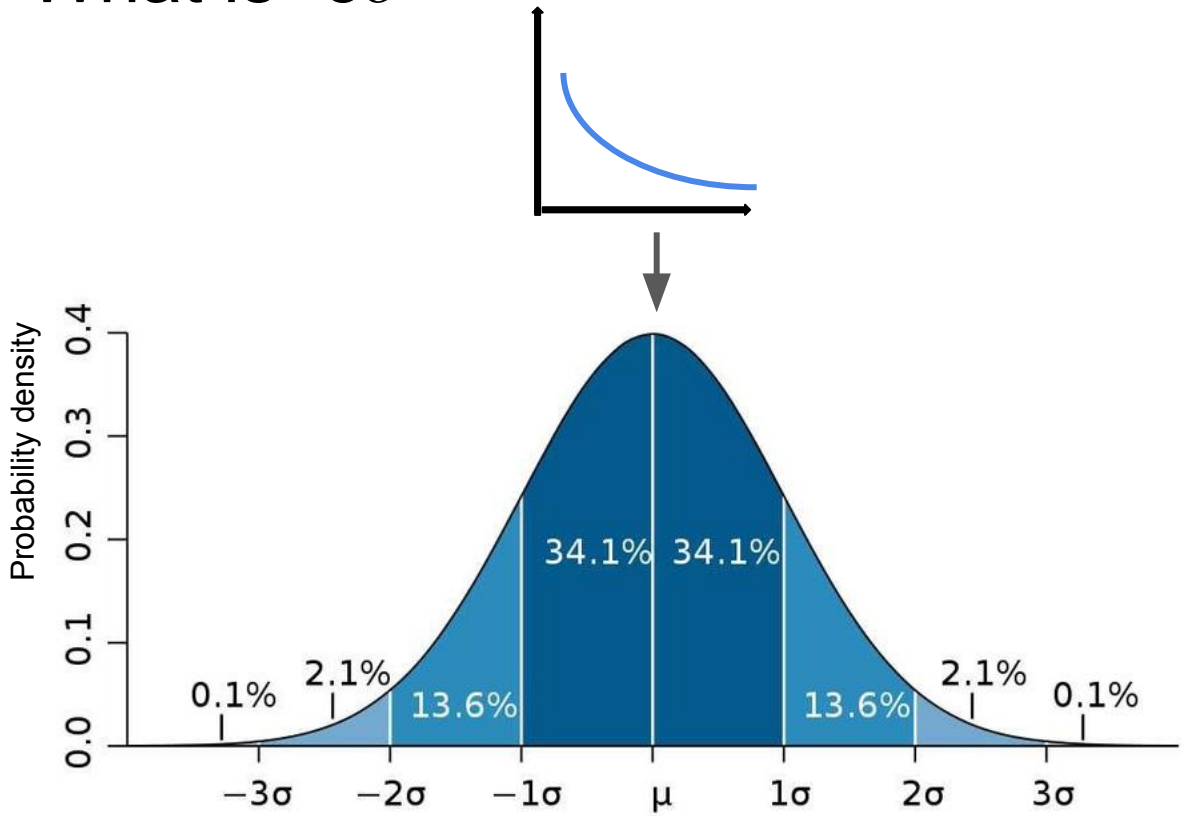
Background
(example)



How likely is it the background can describe the observed shape?

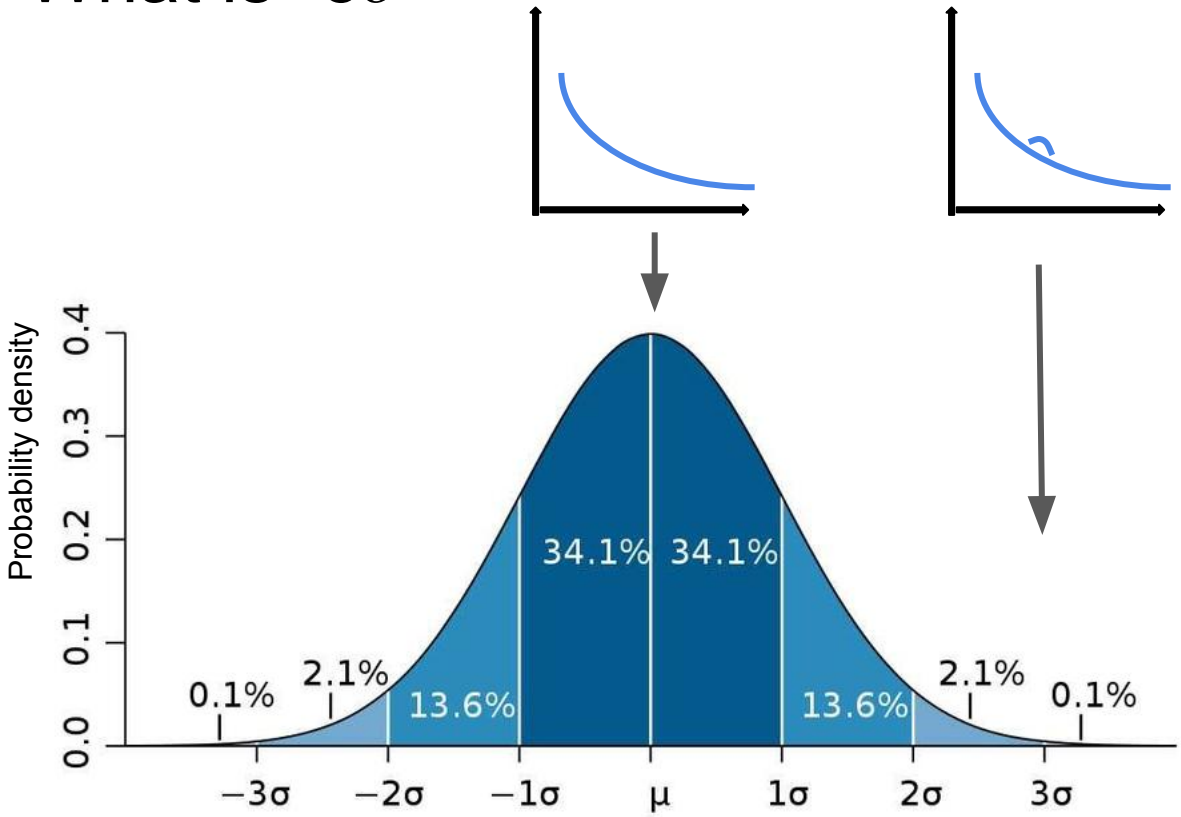


What is “5σ”



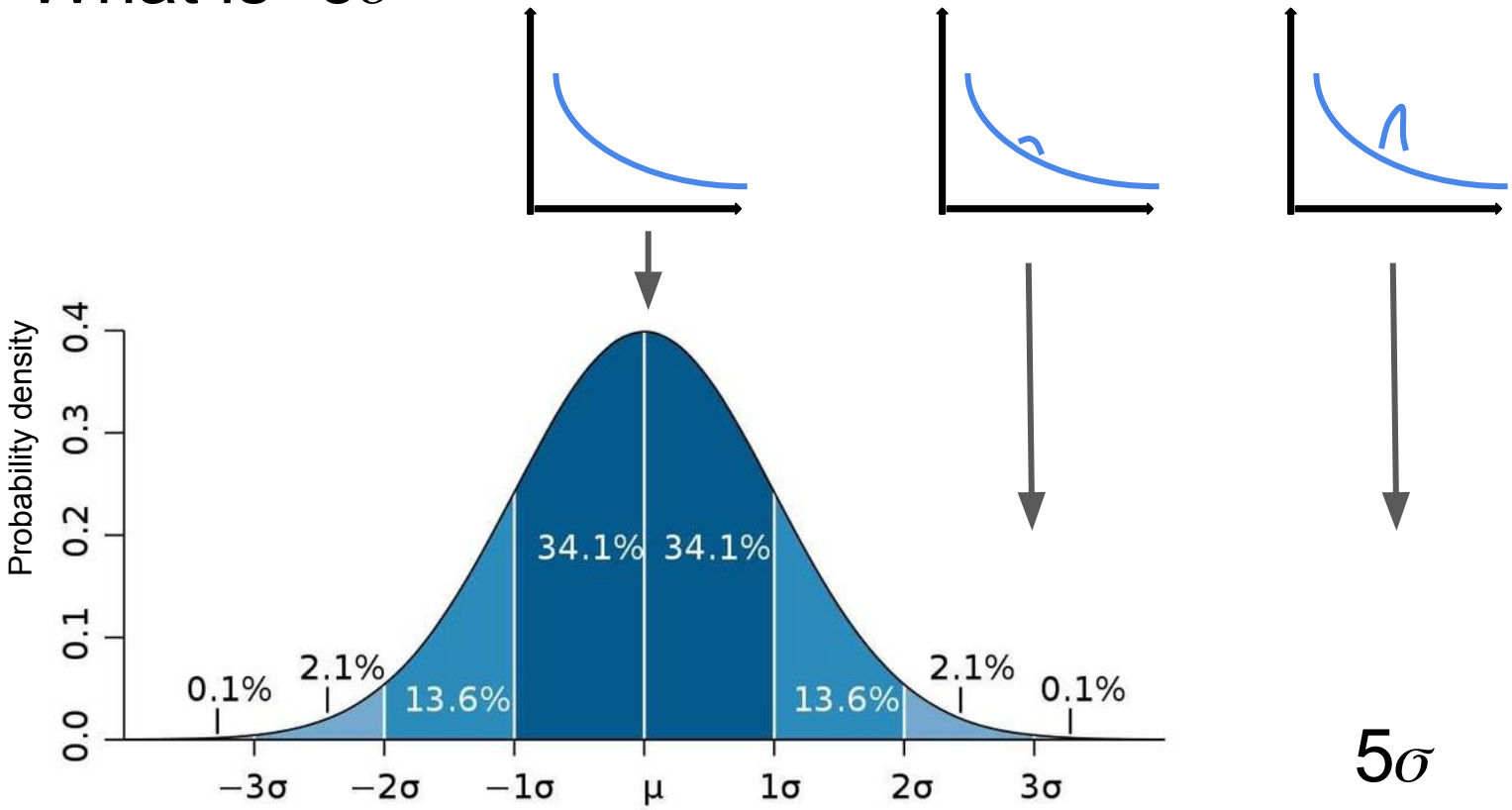
https://news.mit.edu/2012/explained-sigma-0209

What is “5σ”



https://news.mit.edu/2012/explained-sigma-0209

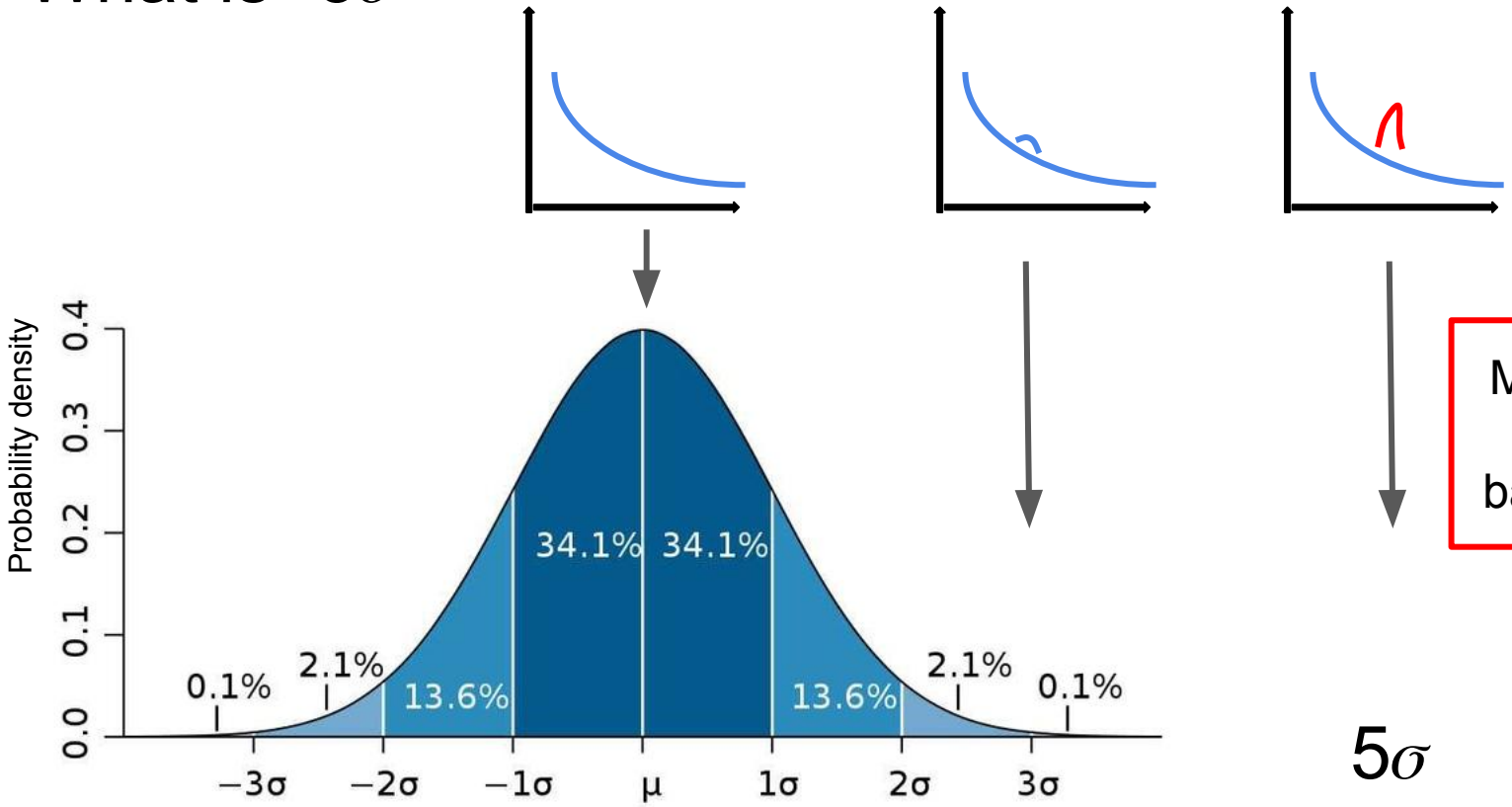
What is “5σ”



5σ

https://news.mit.edu/2012/explained-sigma-0209

What is “5σ”

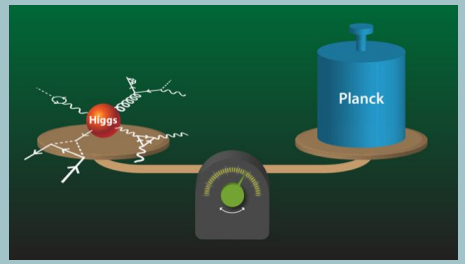


https://news.mit.edu/2012/explained-sigma-0209

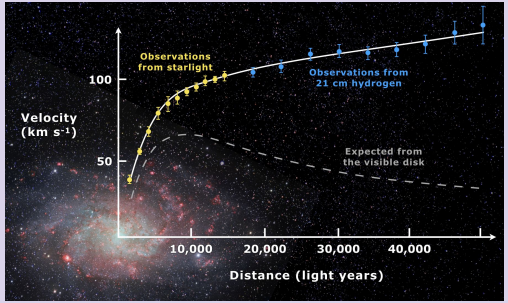
Must not be your background!

5σ

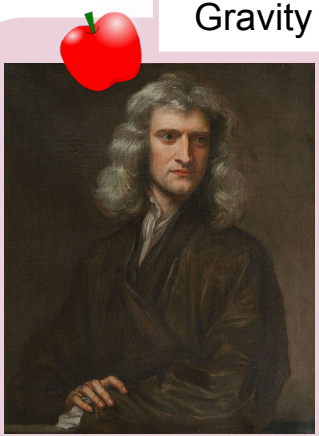
Hierarchy

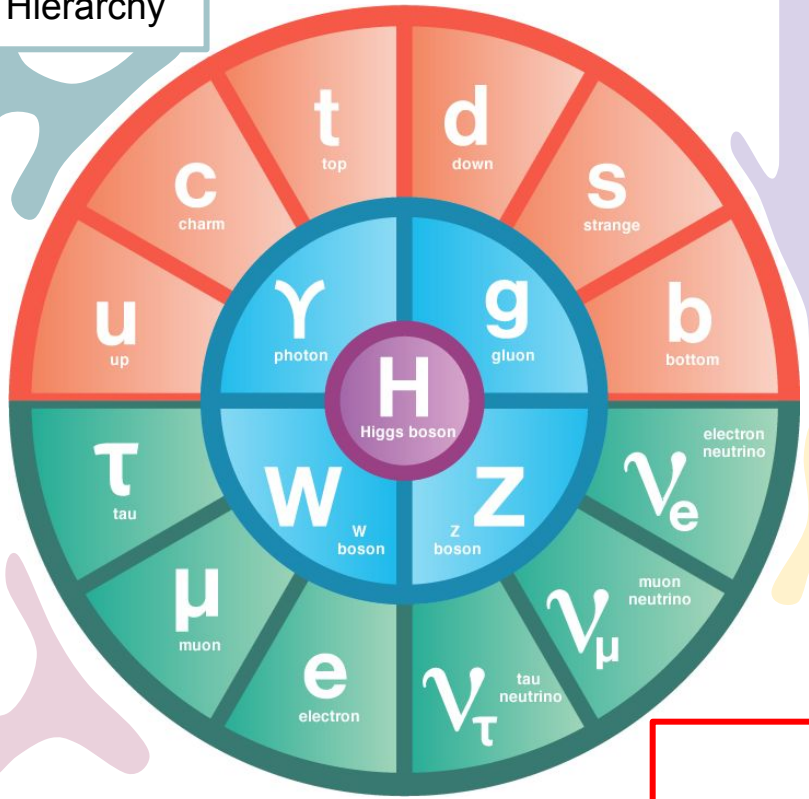


Dark matter

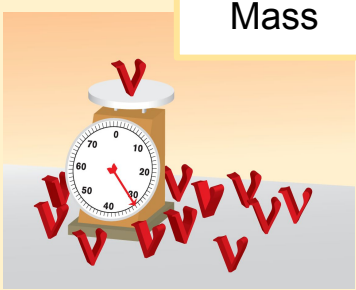


Gravity





Neutrino Mass

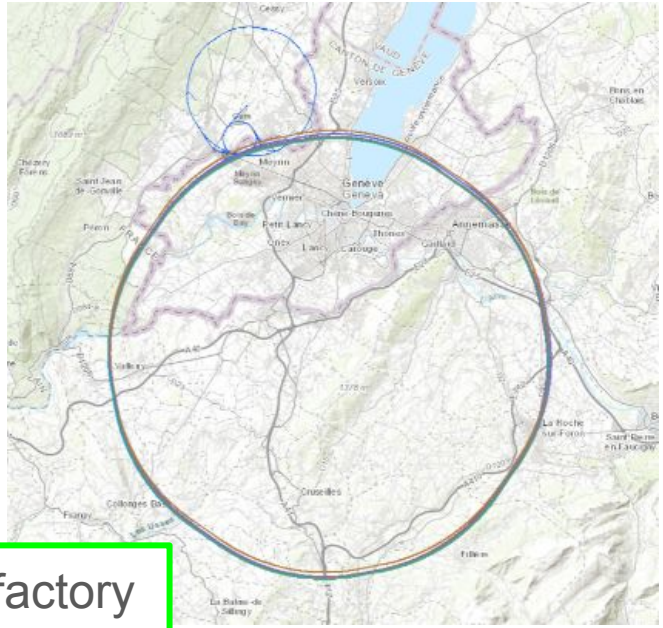


SO MANY SHORTCOMINGS!

Future colliders

Future colliders - Lepton Machines

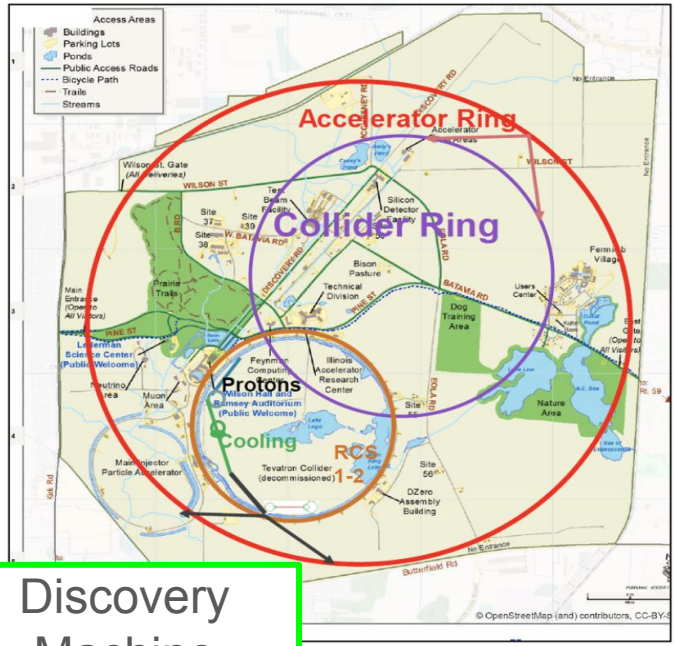
Future Circular Collider e+e- (FCCee)



Higgs factory

arXiv:2203.08310

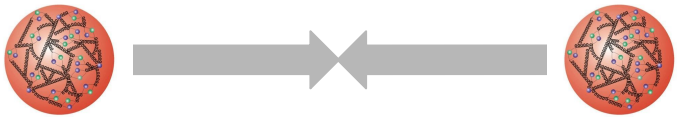
Muon Collider



Discovery Machine

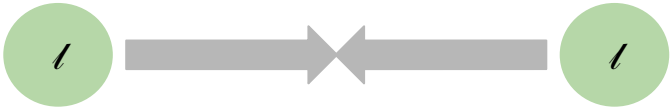
2209.01318

Complications of hadron colliders



Actually colliding quarks + gluons inside the protons - each carry a fraction of the total energy

Benefits of lepton colliders!



Completely know initial state – can use full momentum, not just pT

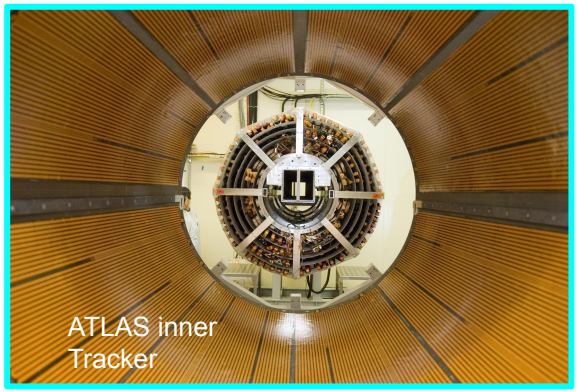
Fundamental!

Clean collisions!

Leads to different detector design!

Future Trackers

LHC needs silicon

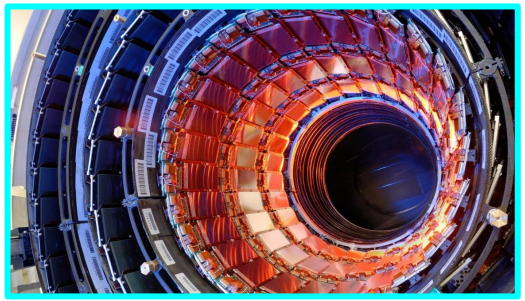


Radiation tolerance and occupancy!

FCCee → Wire Tracker

Ultra-light for best resolution

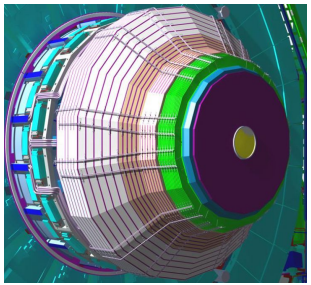
Muon collider probably needs silicon

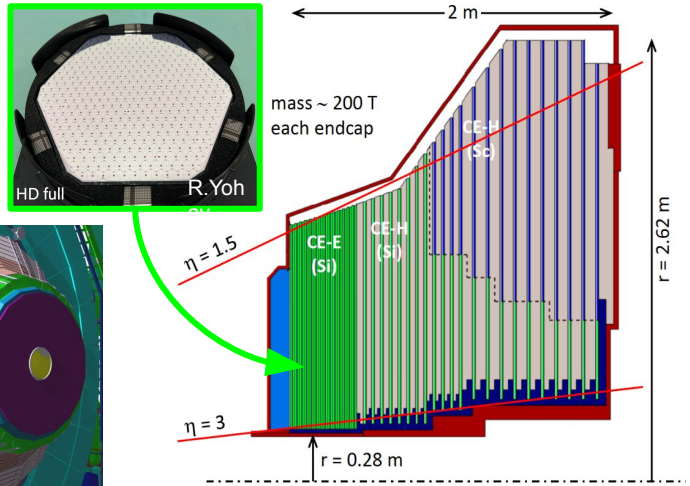


Radiation tolerance and occupancy!

Future Calorimeters

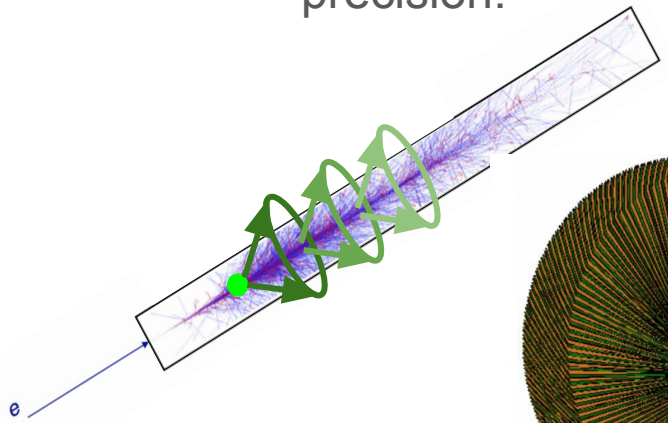
LHC needs high granularity

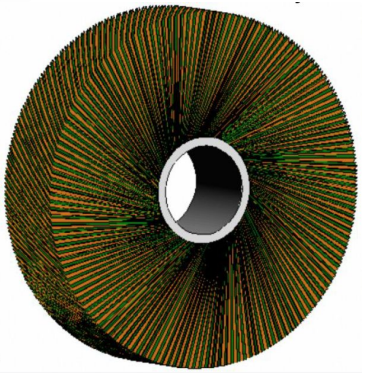


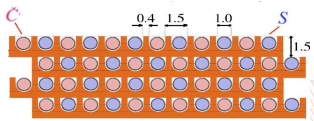


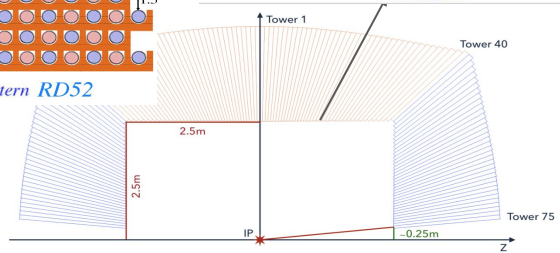
Radiation tolerance and
pile-up mitigation

Lepton colliders need precision!









Summary

- Collider physics offers a wealth of possibilities
  - Varied and rich physics opportunities
    - SM Measurement
    - New physics reach
  - Diverse instrumentation requirements
    - High rate and radiation environments now
    - Precision environments in the future
- Collider design ultimately driven by outside factors
  - How much land can you buy
  - How strong of magnets can you build
  - How much energy can you afford
- Really at a turning point → not sure what the future holds!

back-up