PURDUE
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CALUMET

The Standard Model and Particle Detection with CMS

John Stupak III
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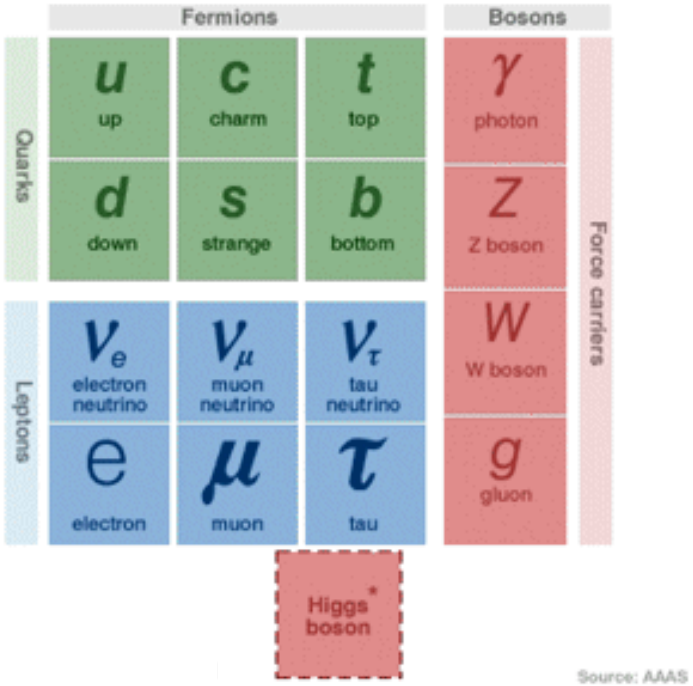
Purdue University Calumet

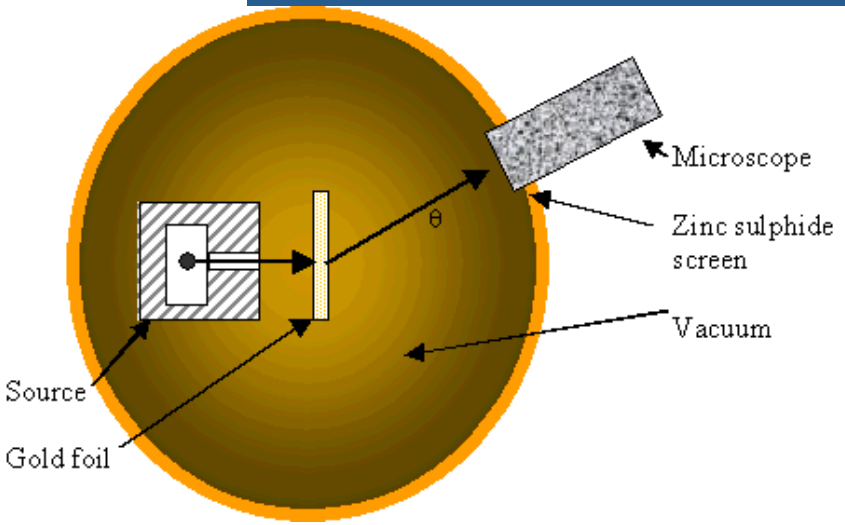
QuarkNet Masterclass
3/7/15

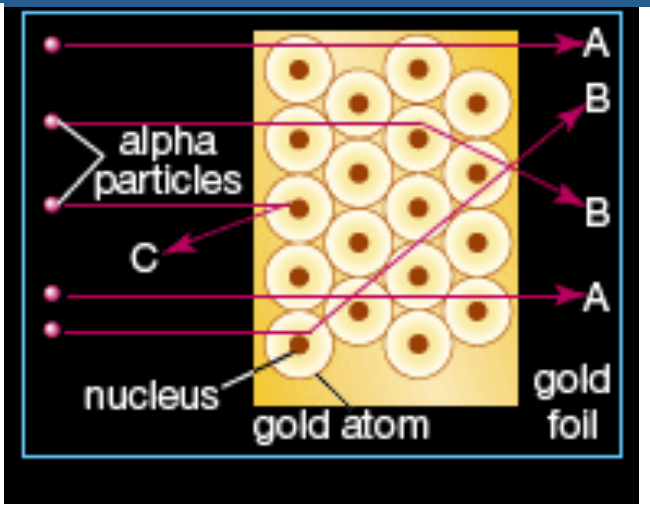
The Standard Model (review)



Rutherford: atoms are not elementary particles!

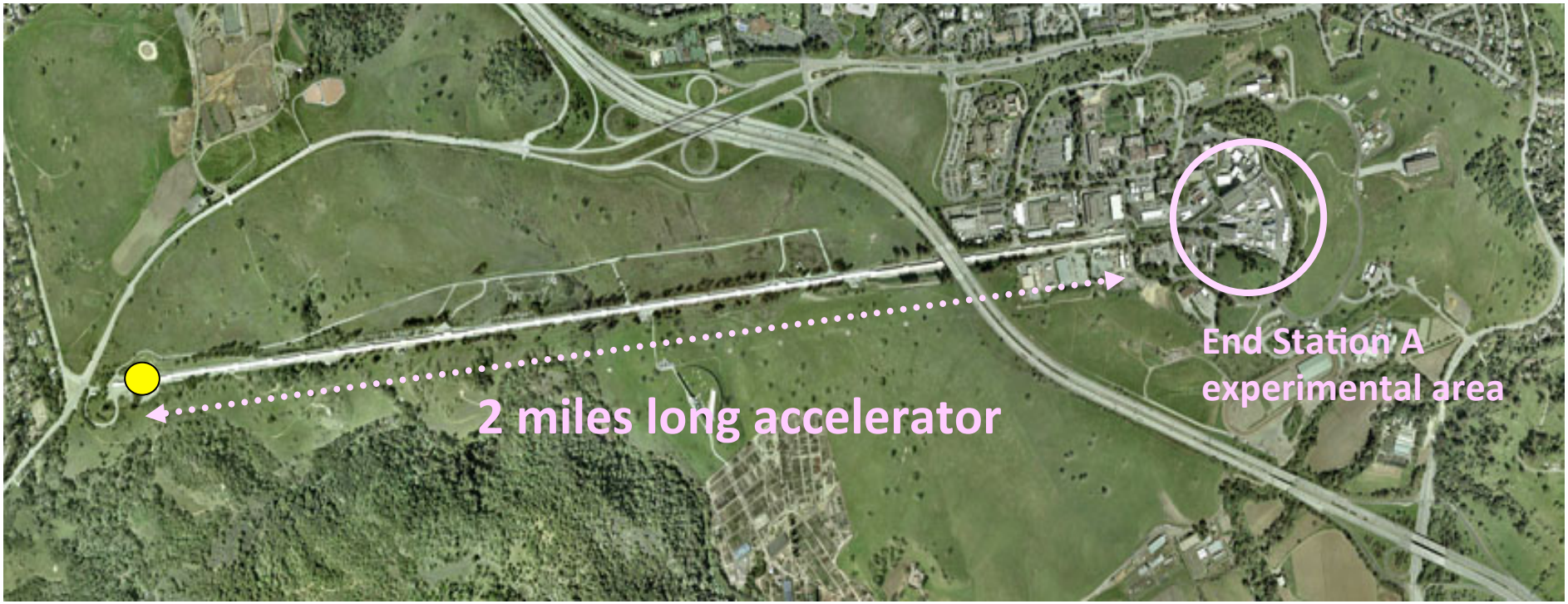
1911
Rutherford found a nucleus in the atom by firing alpha particles at gold and observing them bounce back





Precursor of modern scattering experiments at accelerator

Quarks detected within protons



Stanford (SLAC), California, late 1960s
Fire electrons at proton: big deflections seen!

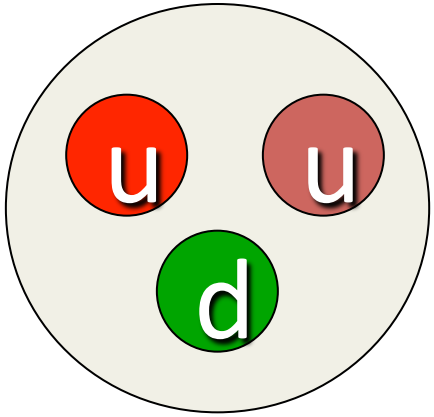
Protons and neutrons in the quark model

Quarks have fractional electric charge!

u electric charge + 2e/3

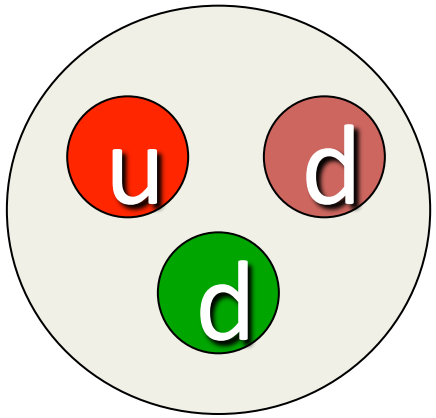
d electric charge −1e/3

proton (charge +1e)



$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

neutron (charge 0)



$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

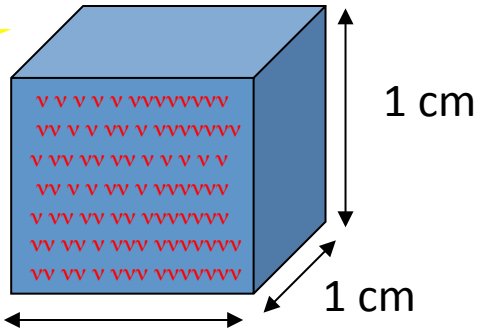
Is the whole Universe made only of quarks and electrons?

No! There are also neutrinos!

Electron, proton and neutrons are rarities!
For each of them in the Universe there is 1 billion neutrinos

Neutrinos are the most abundant matter-particles in the Universe!

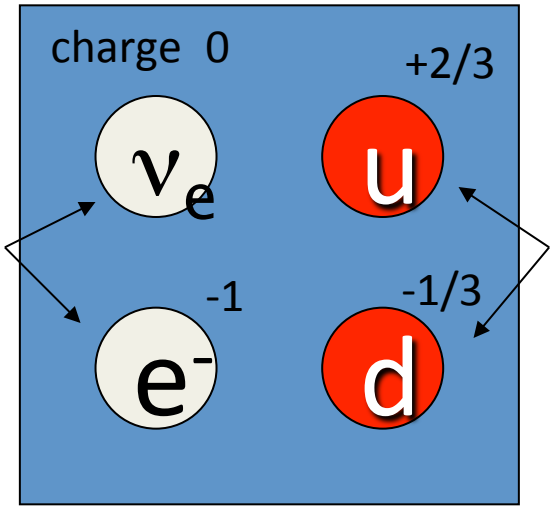
Within each cm^3 of space: ~300 neutrinos from Big Bang



Neutrinos are everywhere!
in the outer space, on Earth, in our bodies..

The particles of ordinary matter

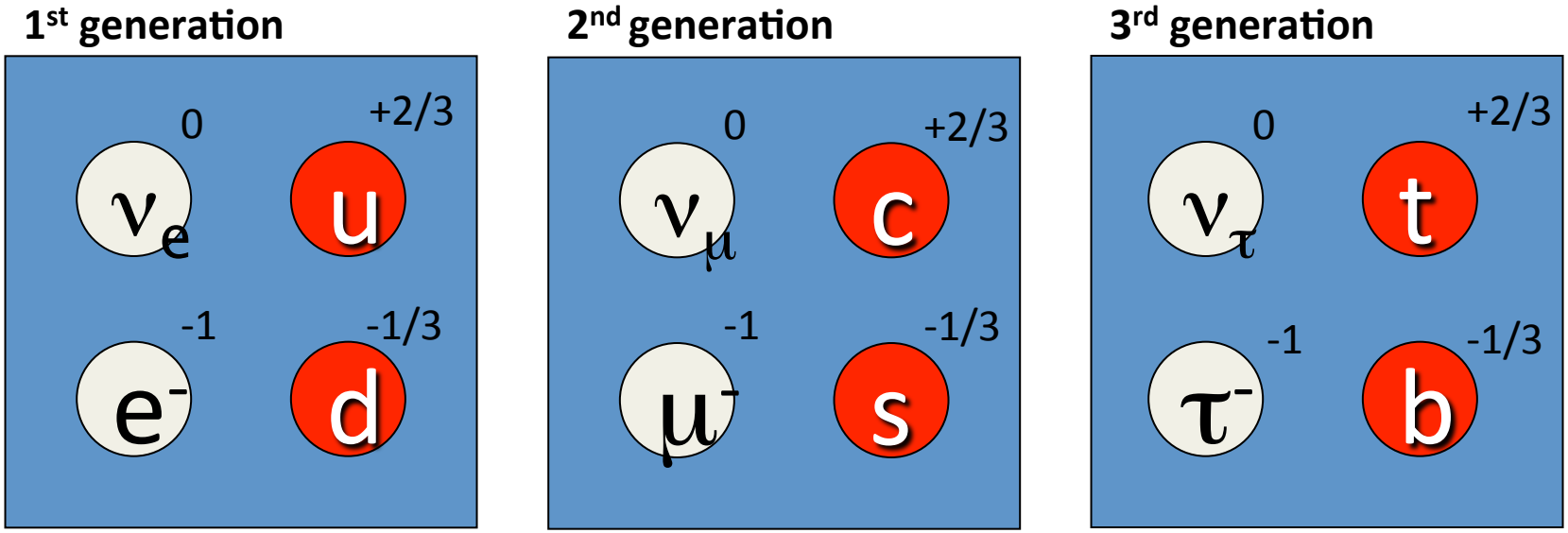
Leptons:
ν = neutrino
e = electron



Quarks:
u = up
d = down

All stable matter around us
can be described using
electrons, neutrinos, u and d quarks

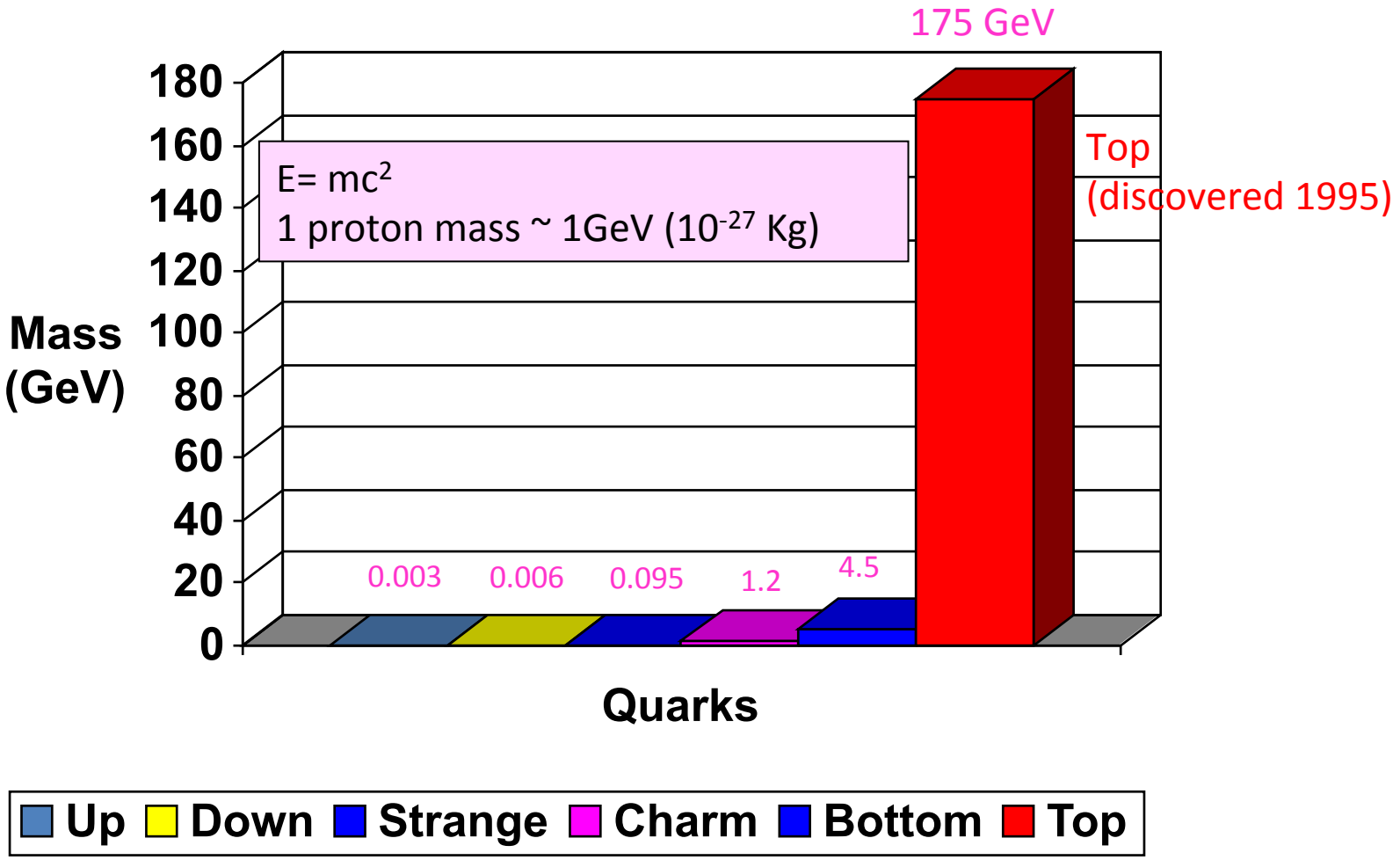
3 Families (or Generations)



3 generations in everything similar but the mass

We believe these to be the fundamental building blocks of matter

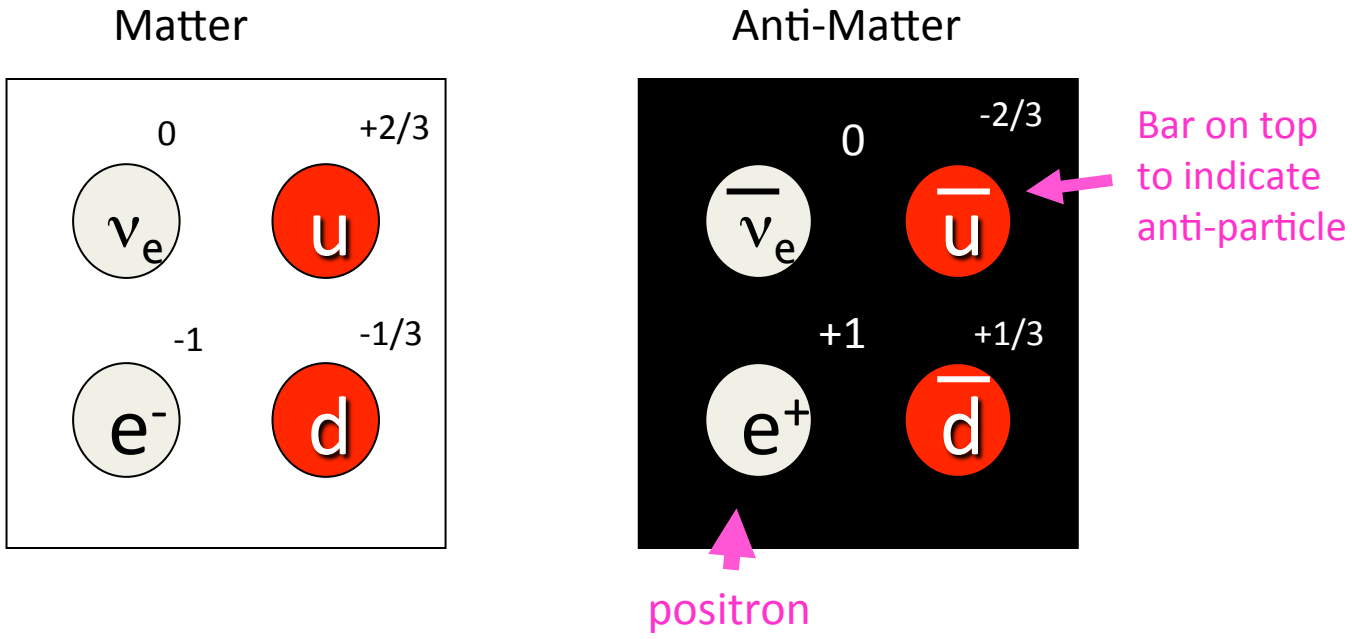
Quark masses



The mass grows larger in each successive family

Anti-matter

- For every fundamental particle of matter there is an anti-particle with same mass and properties but opposite charge

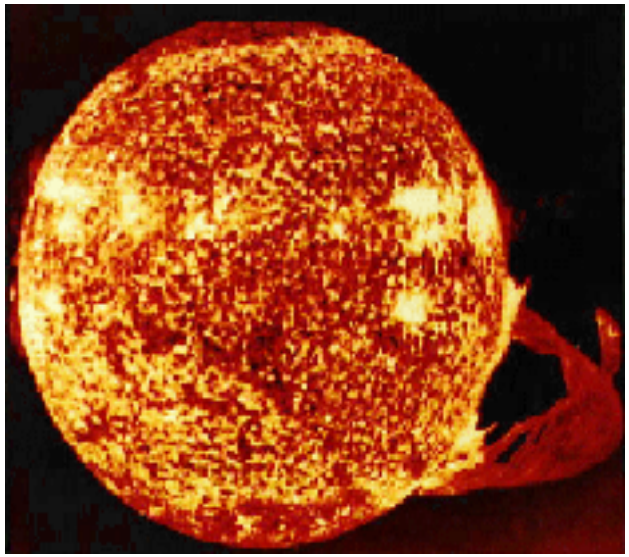


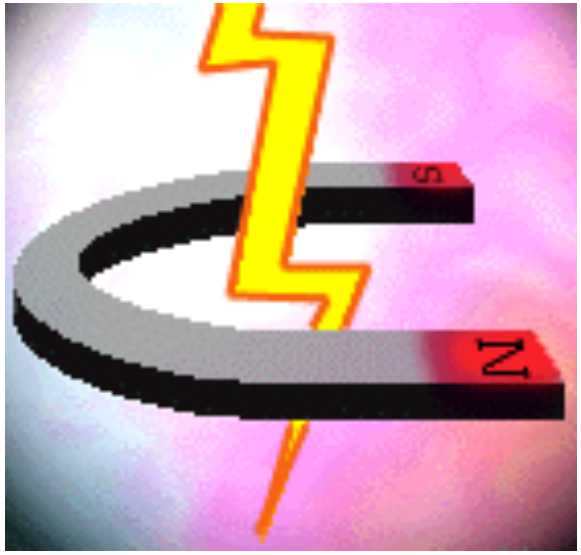
- Correspondent anti-particles exist for all three families
- Anti-matter can be produced using accelerators

The 4 forces of Nature

Weak
- Beta-decay

weak charge



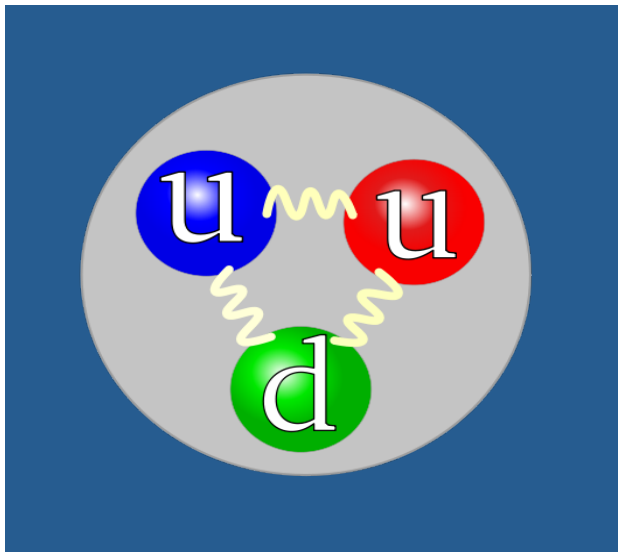


Electromagnetic
- TV, PCs
- Magnets
- e- e+ creation

Electric charge

Strong
- Quark binding

color charge

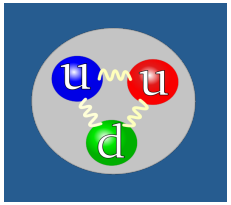
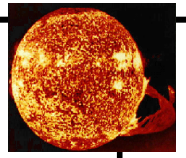


Gravity
Responsible of Keeping us well-planted on earth

mass

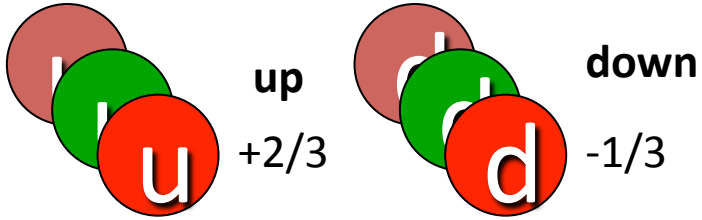
Force Carriers

Particles interact and/or decay thanks to forces
Forces are also responsible of binding particles together

Strong: gluons  Effects: Only quarks (because of their color charge)	Weak: W^+, W^-, Z^0  Effects: Leptons and quarks (only force for neutrinos)
Electromagnetic: γ Effects: Quarks and charged leptons (no neutrinos)	Gravity: graviton? Still to be discovered Effects: Negligible effects on particles

Quarks and color

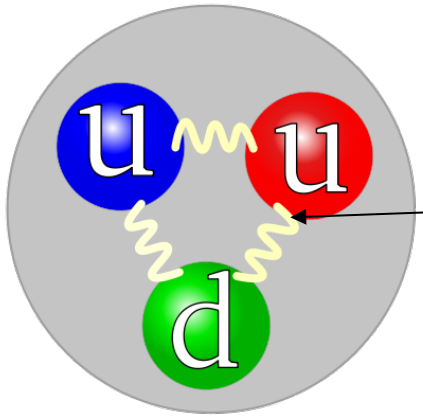
All quark flavours come in 3 versions, called "colors"



Quarks combine together to form colourless particles

-***Baryons*** (three quarks: red+ green + blue = white)

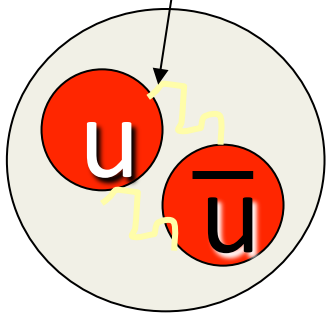
proton
p



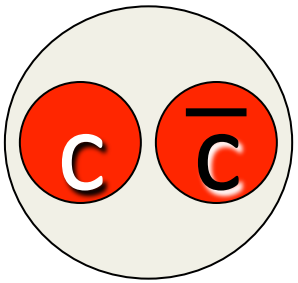
Strong forces "glue" quarks together in bound states

-***Mesons*** (quark-antiquark pair)
such as red+anti-red u-ubar state

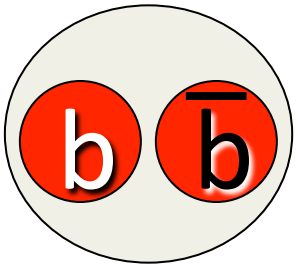
pion
π



Building more particles

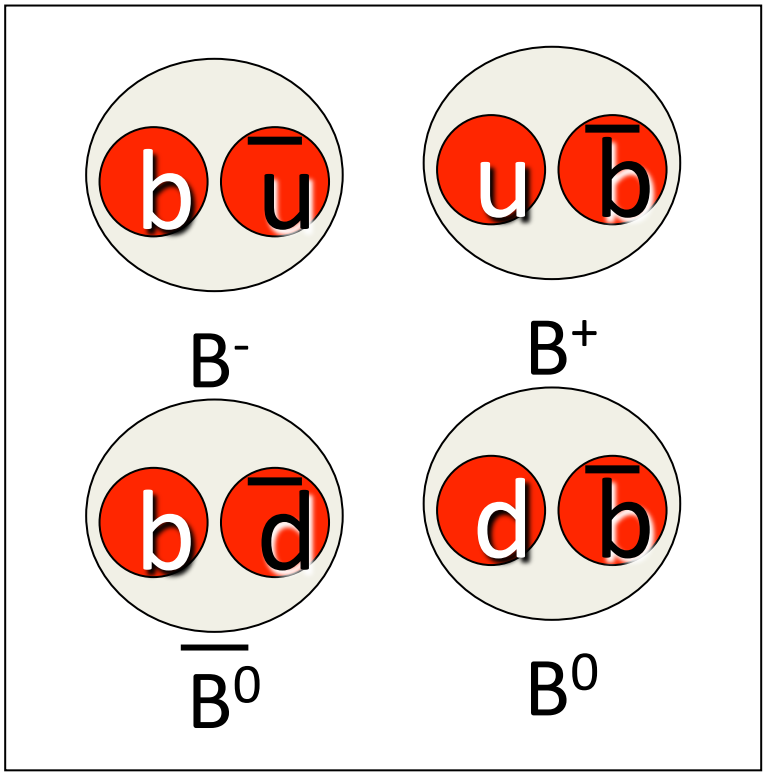


J/ψ



Υ

B mesons (bq) $^{-}$



Many more mesons and baryons…

STRANGE MESONS		CHARMED MESONS		$c\bar{c}$ MESONS		LIGHT BARYONS		BOTTOM BARYONS	
K_L^0	130	D^+	411	$\eta_c(1S)$	441	p	2212	Λ_b^0	5122
K_S^0	310	D^0	421	$\chi_{c0}(1P)$	10441	n	2112	Σ_b^-	5112
K^0		$D_0^*(2400)^+$	10411			Δ^{++}	2224		
K^+									
$K_0^*(800)^0$									
$K_0^*(800)^+$									
$K_0^*(1430)^0$									
$K_0^*(1430)^+$									
$K(1460)^0$									
$K(1460)^+$									
$K(1830)^0$									
$K(1830)^+$									
$K_0^*(1950)^0$									
$K_0^*(1950)^+$									
$K^*(892)^0$									
$K^*(892)^+$	323	$D_{s1}(2536)^+$	10433	$\eta_b(1S)$	551	Ξ^{*0}	3324^d	Ω_b^{*-}	5334
$K_1(1270)^0$	10313	$D_{s1}(2460)^+$	20433	$\chi_{b0}(1P)$	10551	Ξ^{*-}	3314^d	Ξ_{bc}^0	5142
$K_1(1270)^+$	10323	$D_{s0}^*(2317)^+$	10431	$h_b(1P)$	10555	Ω^-	3334	Ξ_{bc}^+	5242
$K_1(1400)^0$	20313			$\chi_{b0}(2P)$	110551	CHARMED BARYONS		$\Xi_{bc}^{\prime 0}$	5412
$K_1(1400)^+$	20323	BOTTOM MESONS		$\eta_b(2S)$	200551	Λ_c^+	4122	$\Xi_{bc}^{\prime +}$	5422
$K^*(1410)^0$	100313	B^0	511	$\chi_{b1}(1P)$	10553	Σ_c^{++}	4222	Ξ_{bc}^{*0}	5414
$K^*(1410)^+$	100323	B^+	521	$\Upsilon(1S)$	553	Σ_c^+	4212	Ξ_{bc}^{*+}	5424
$K_1(1650)^0$	9000313*	B_0^{*0}	10511	$h_b(1P)$	10553	Σ_c^0	4112	Ω_{bc}^0	5342
$K_1(1650)^+$	9000323*	B_0^{*+}	10521	$\chi_{b1}(1P)$	20553	Σ_c^{*++}	4224	$\Omega_{bc}^{\prime 0}$	5432
$K^*(1680)^0$	30313	B^{*0}	513	$\Upsilon_1(1D)$	30553	Σ_c^{*+}	4214		

"Young man, if I could remember the names of these particles, I would have been a botanist!"

E.Fermi to his student

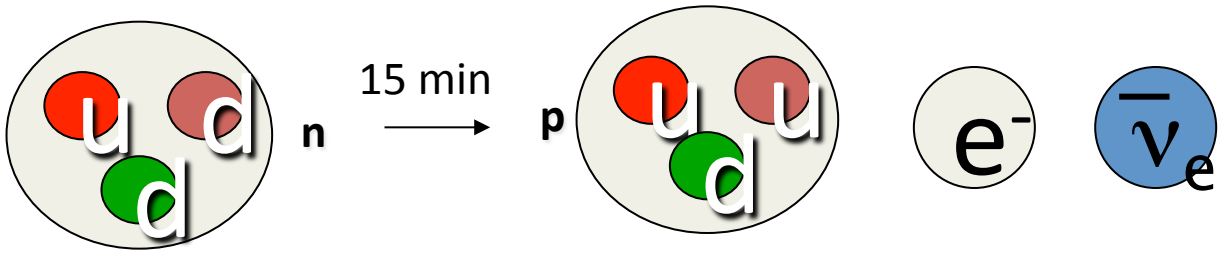
L. Lederman (both Nobel laureates)

The Particle Physicist's Bible: Particle Data Book https://pdg.lbl.gov

Most particles are not stable and can decay to lighter particles..

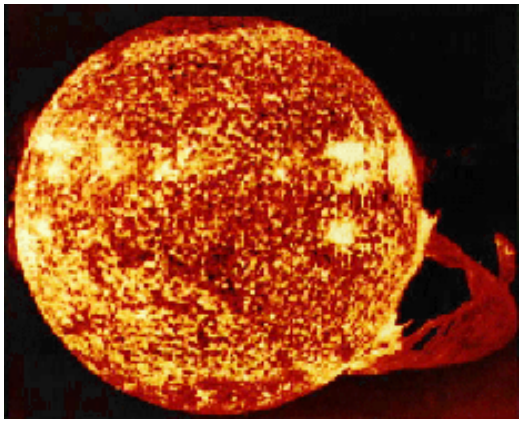
The Weak Force - Neutron b-decay

At quark level: $d \rightarrow u\ e^-\ \bar{\nu}_e$



A (free) neutron decays after 15 min

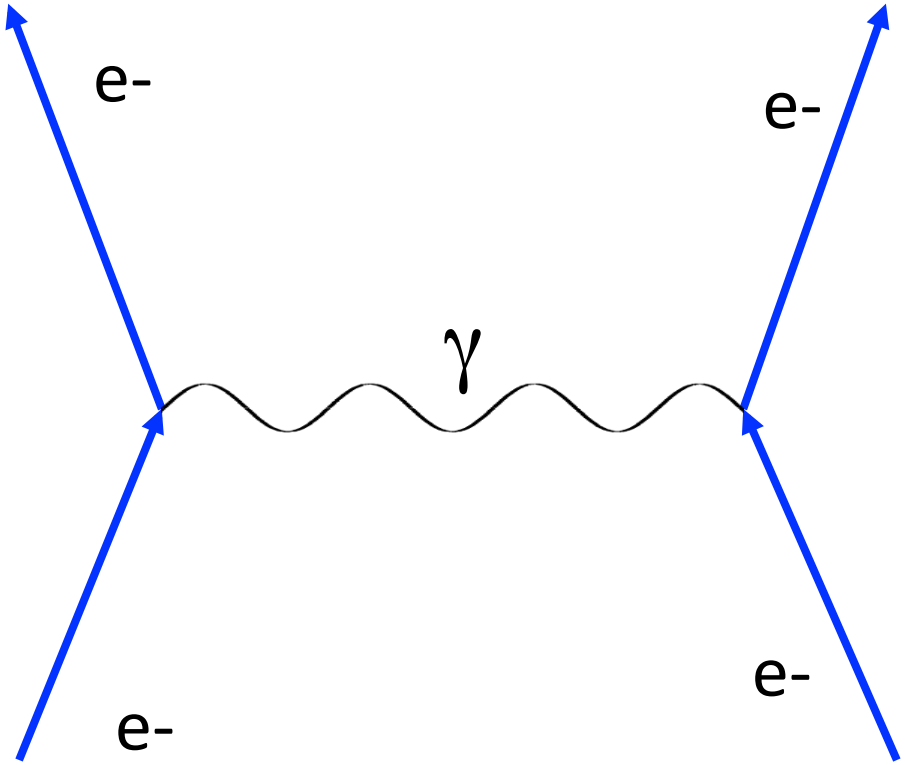
Long life time (15min is an eternity in particle physics!) ⇒ "weak"

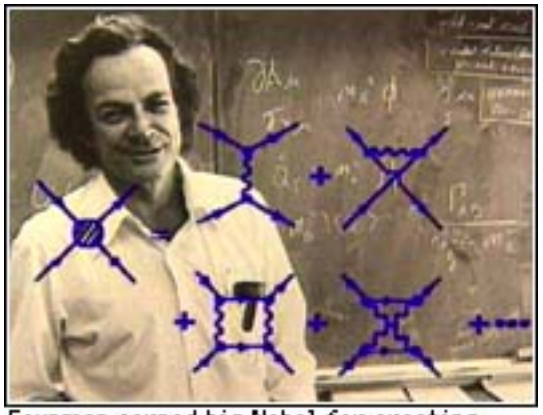


without such weak interactions the Sun would shut down!

Electromagnetic force

Photon exchange
Feynman Diagram





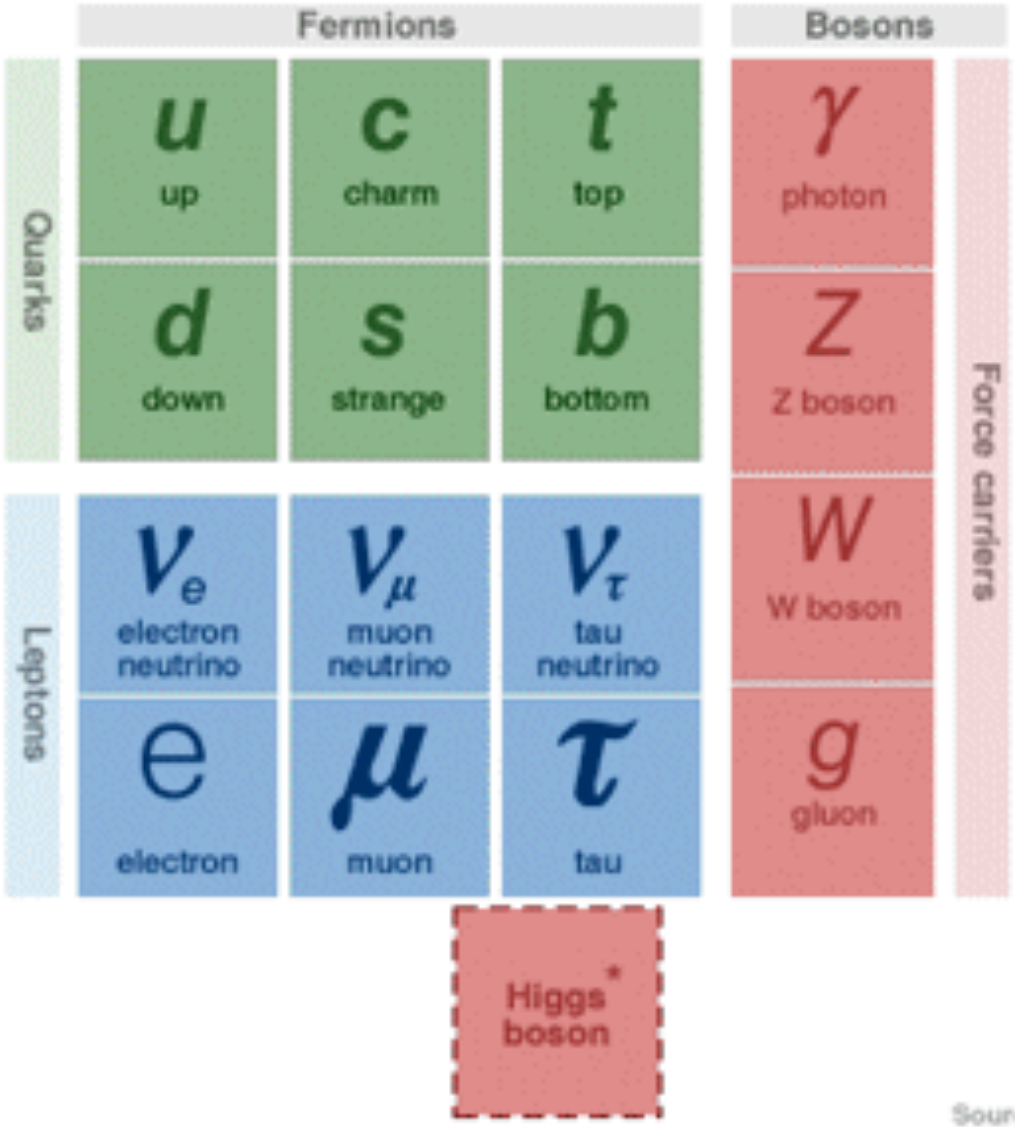
Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

time

separation

Forces are mediated by exchange of bosons

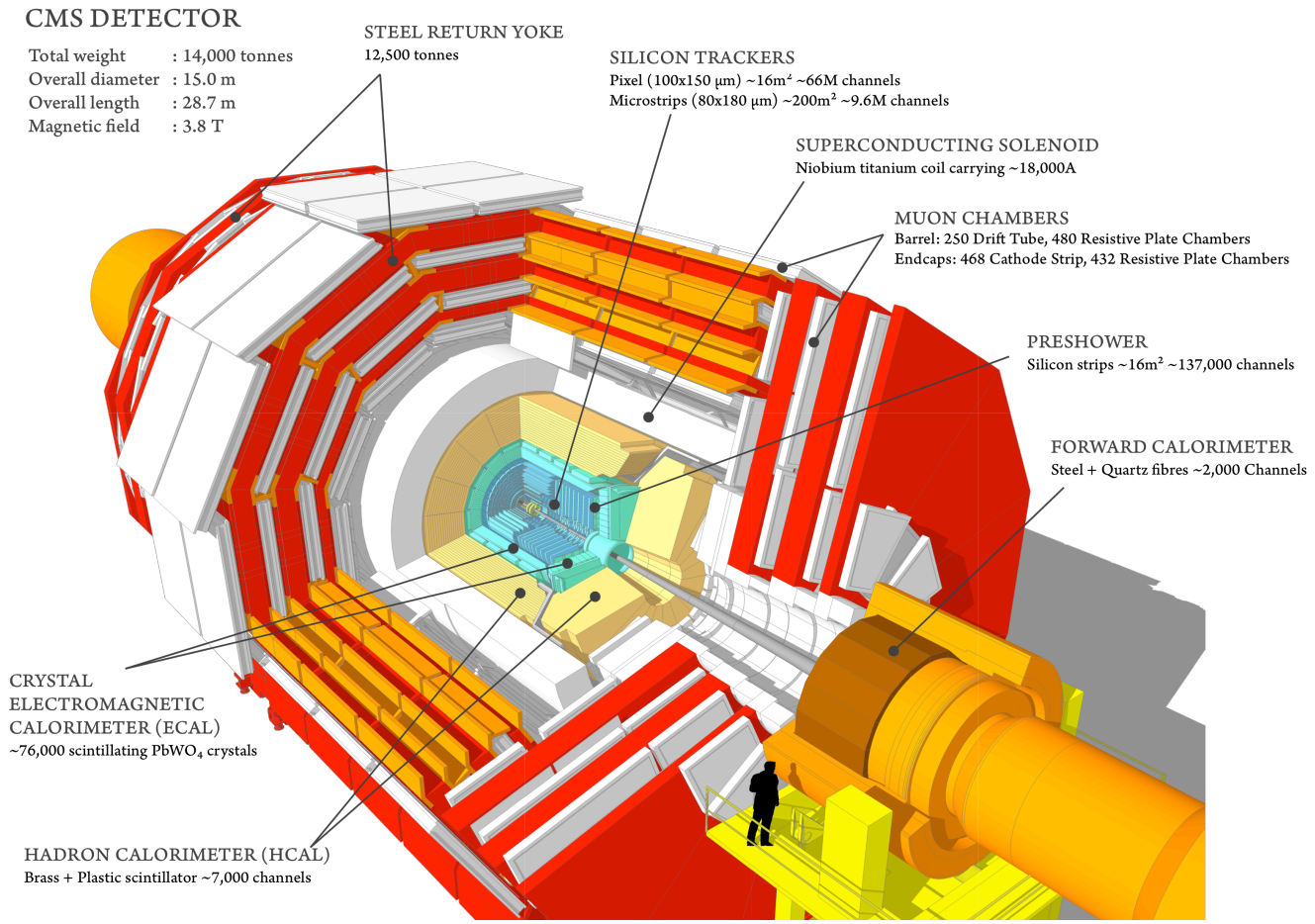
The SM (Summary)

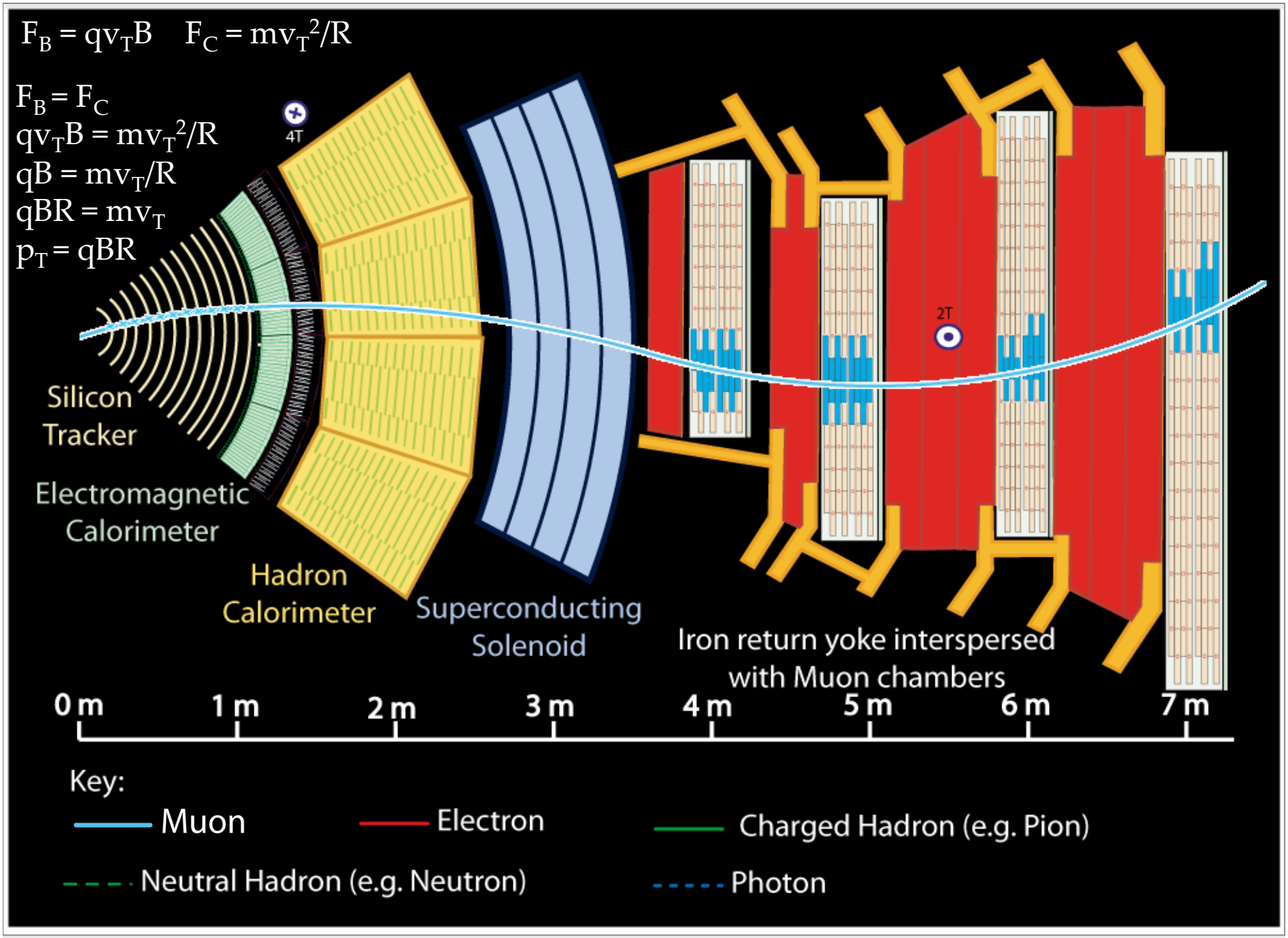


Source: AAAS

The CMS Detector

The CMS Detector

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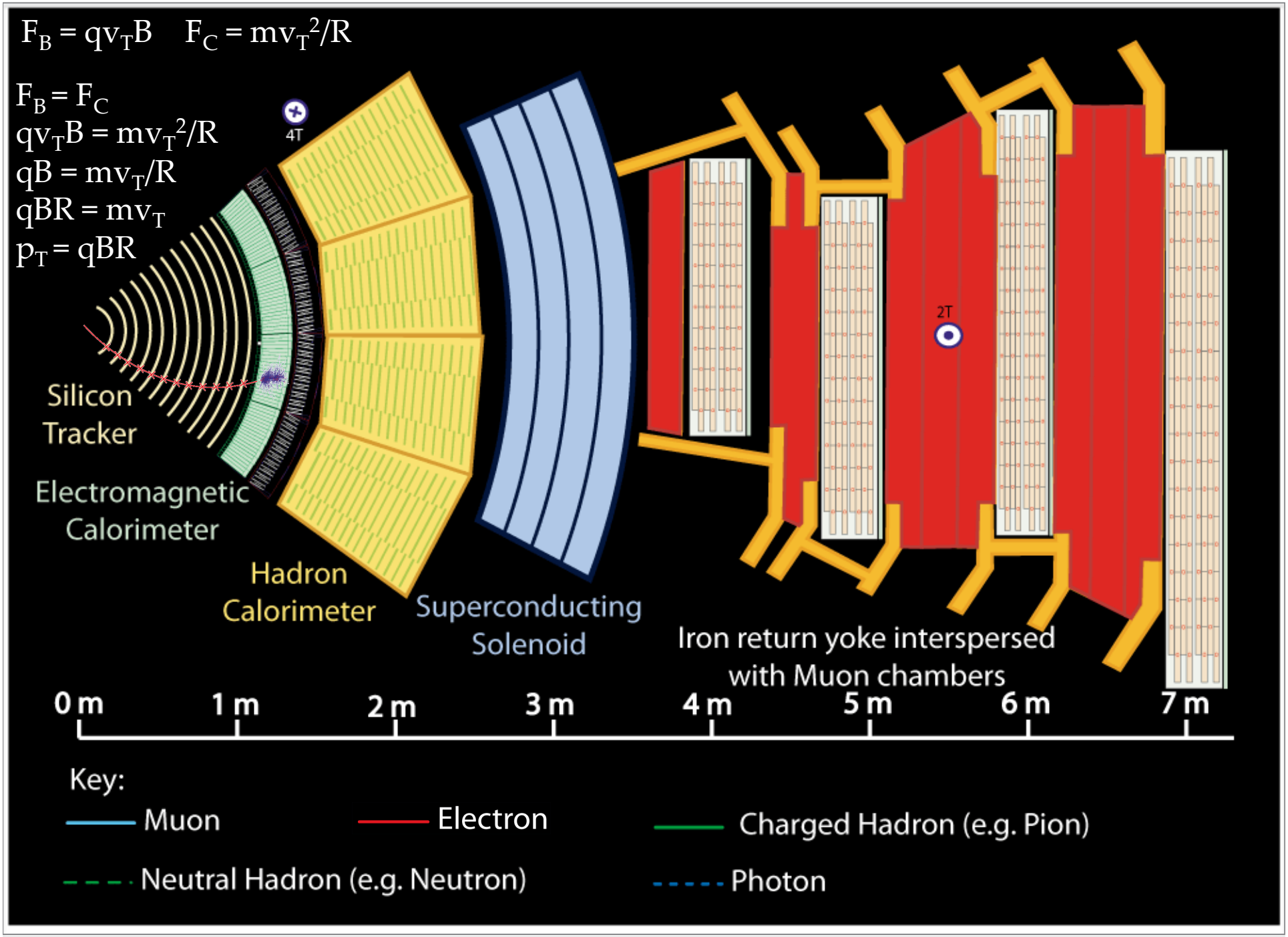
$qBR = mv_T$
$p_T = qBR$
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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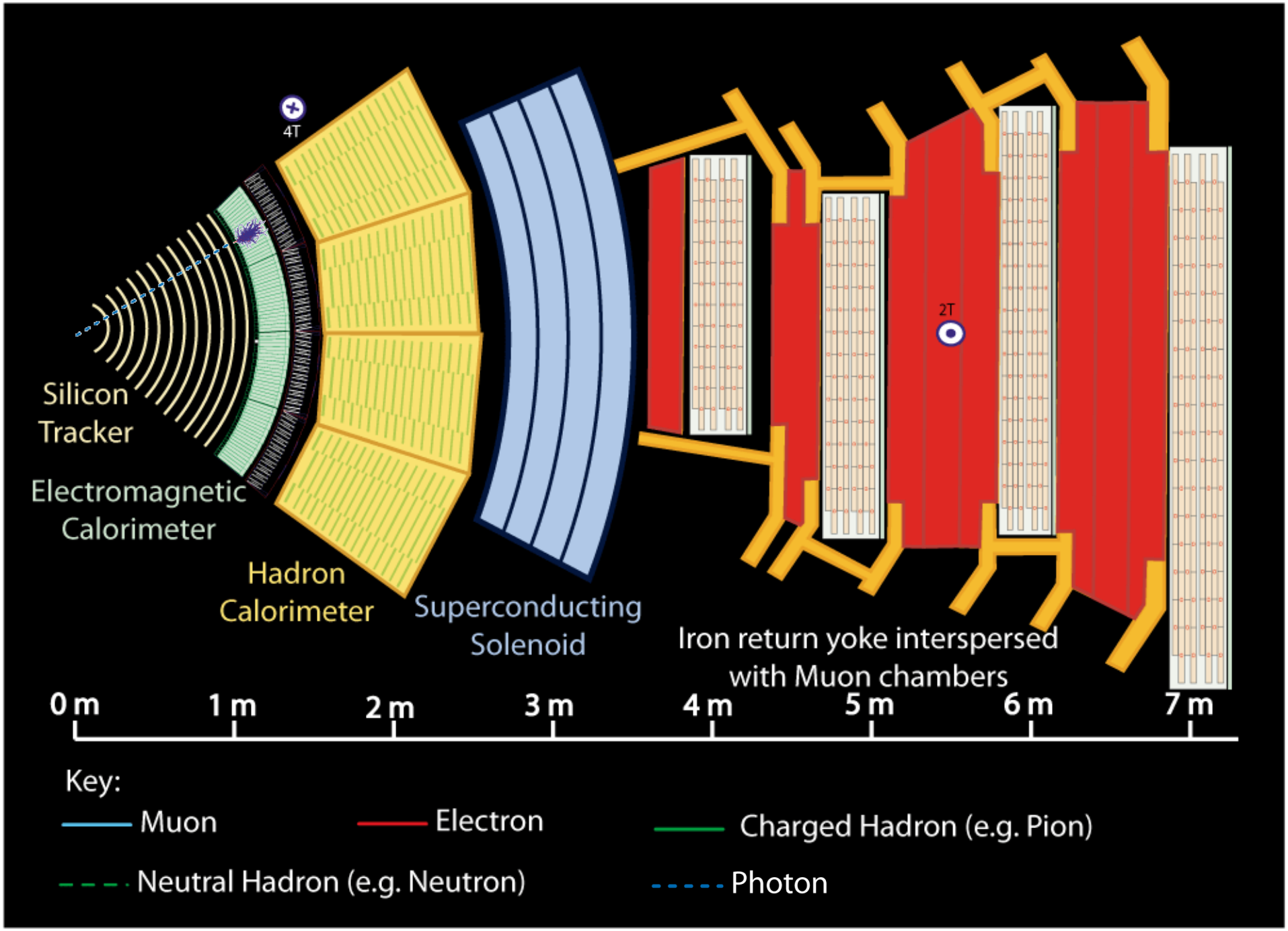
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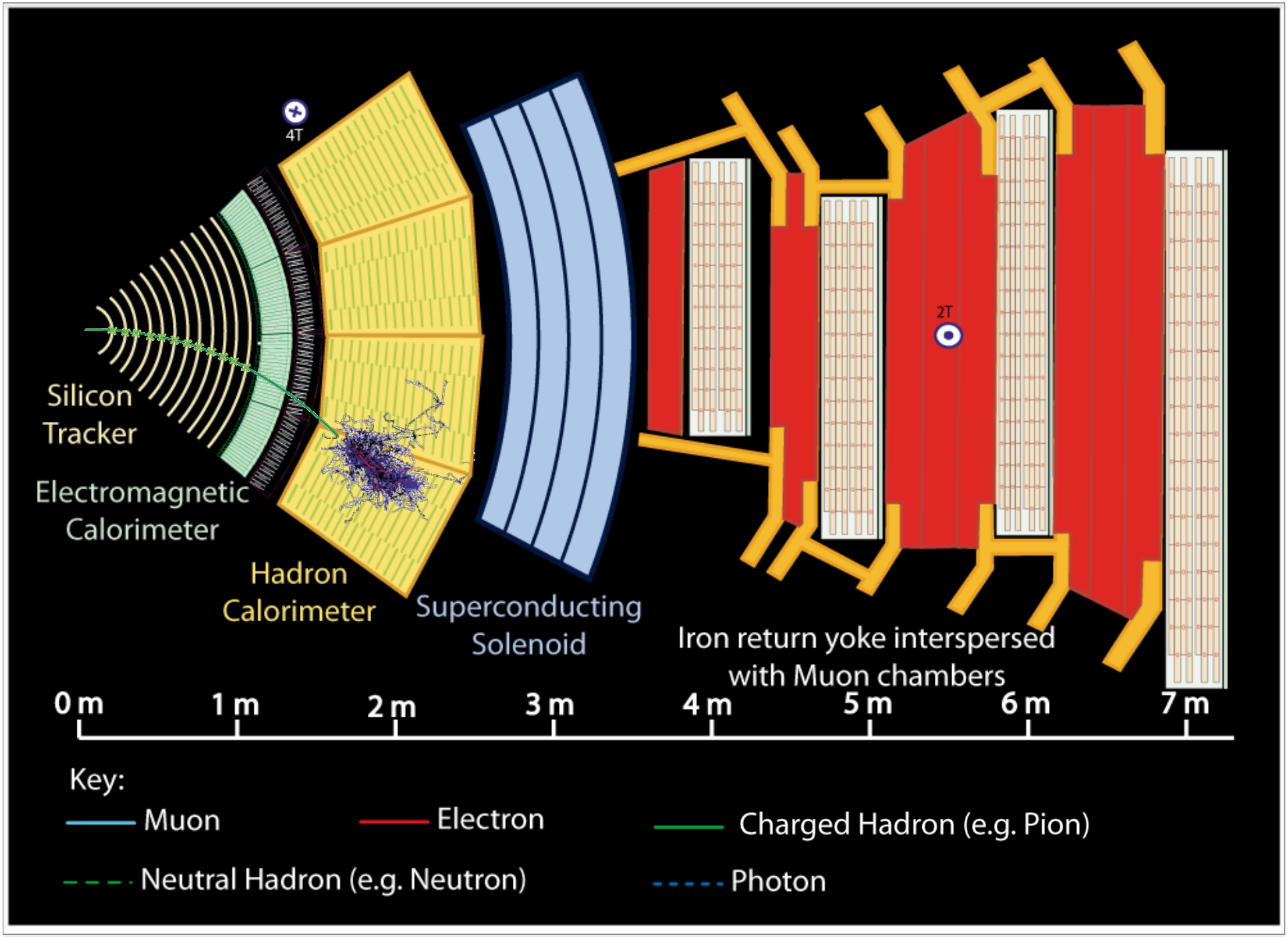
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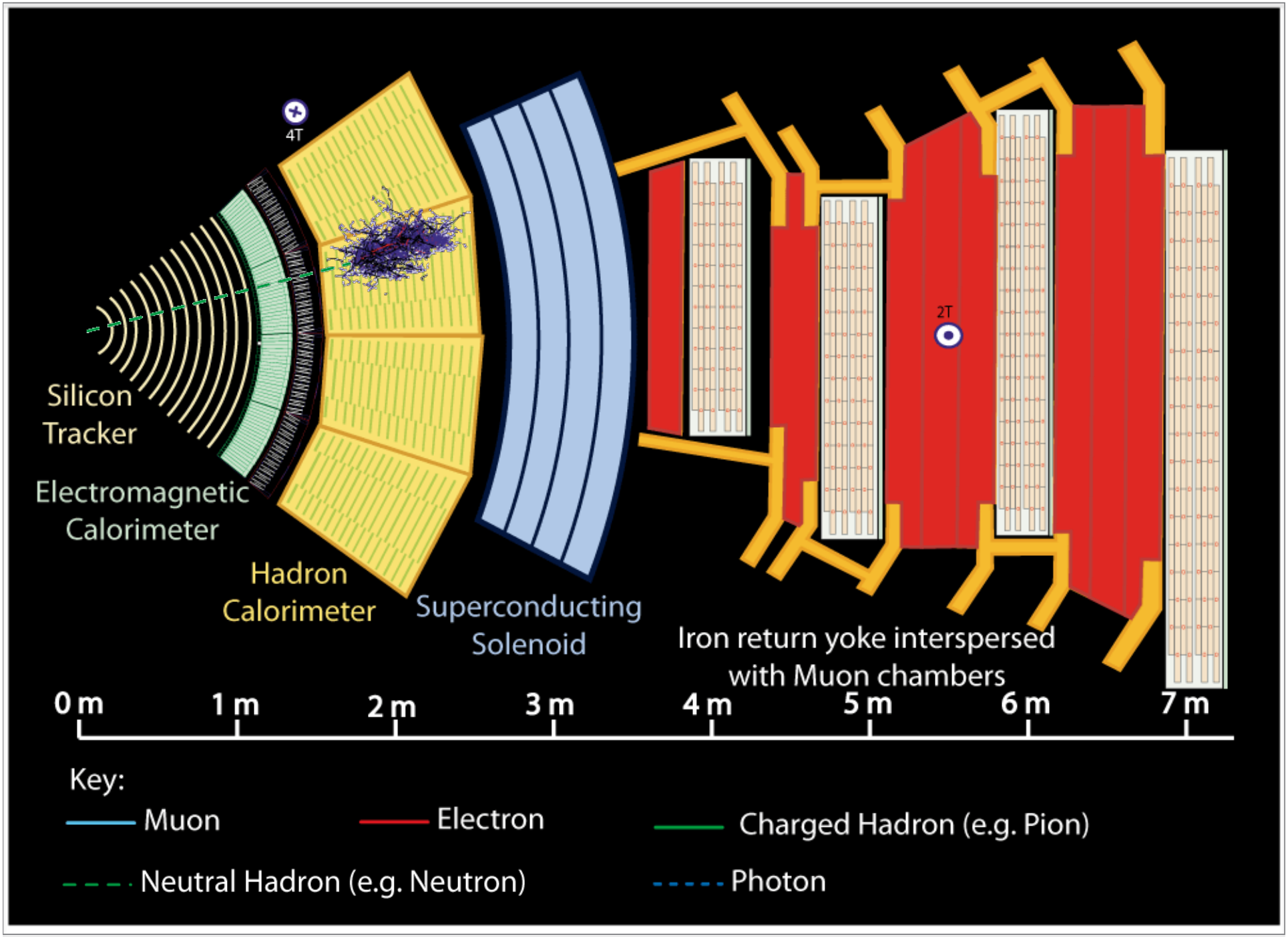
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Quarks and Jets

- Nature doesn't like free color
- What happens when a Z boson decays to a pair of u quarks?
  - Z is heavy, u quarks are light

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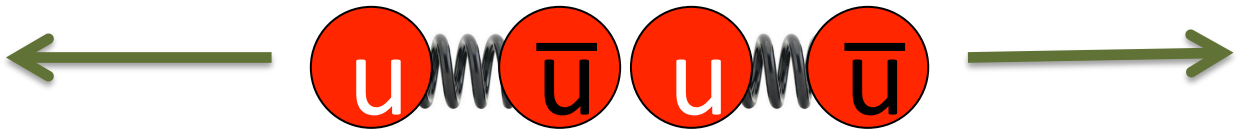

$E=kx^2=mc^2$

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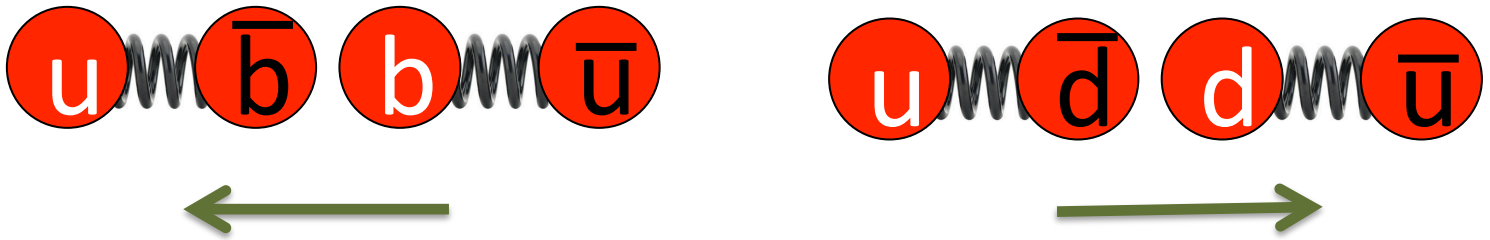

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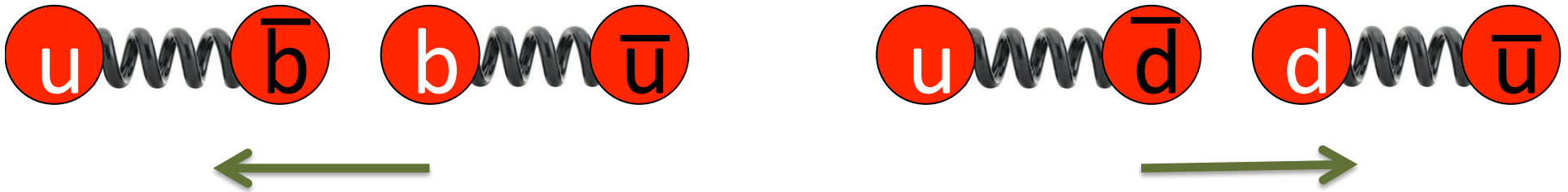

Quarks and Jets

- Nature doesn't like free color
- What happens when a Z boson decays to a pair of u quarks?
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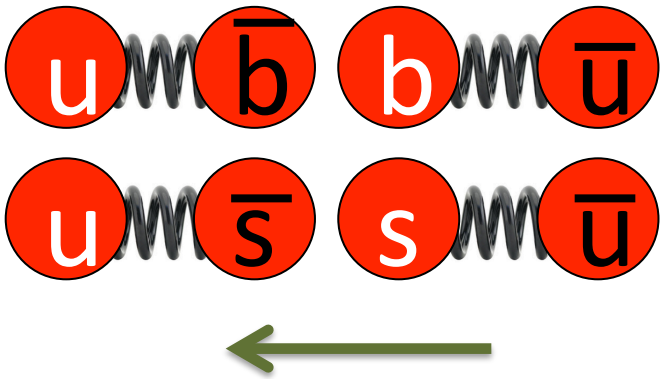

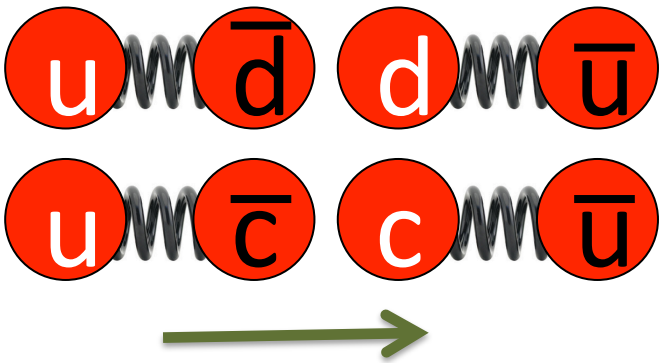

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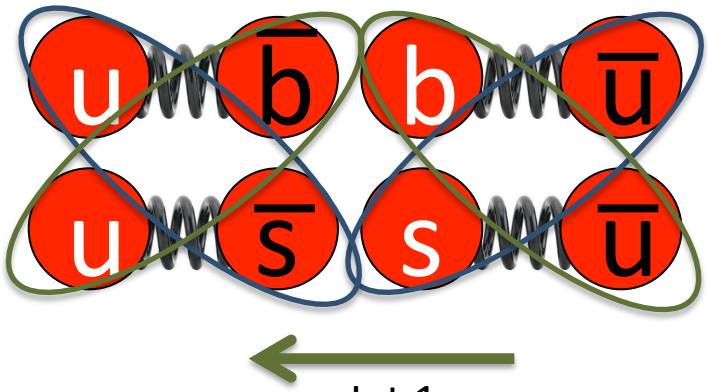
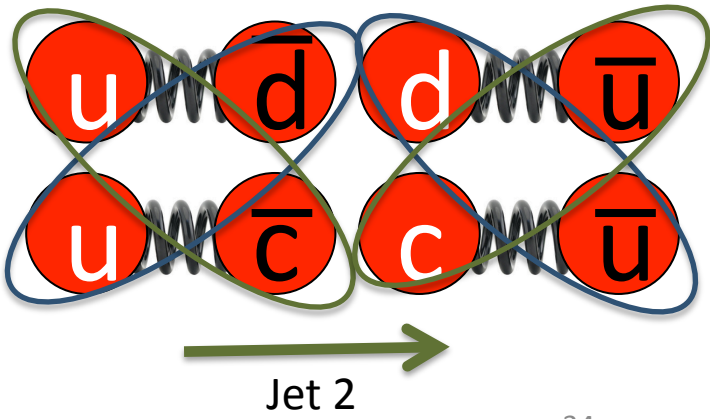
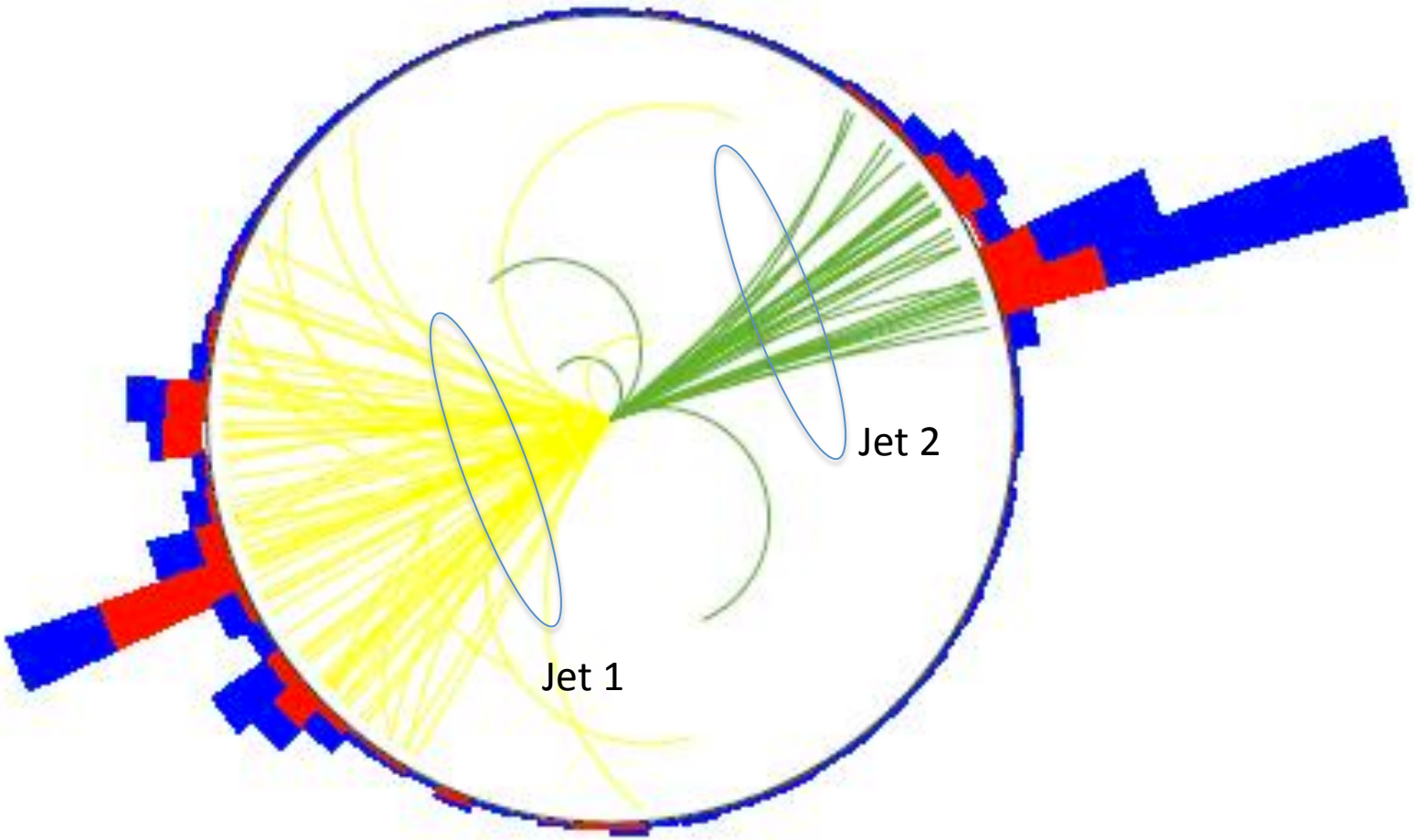




Colorless bound states eventually form

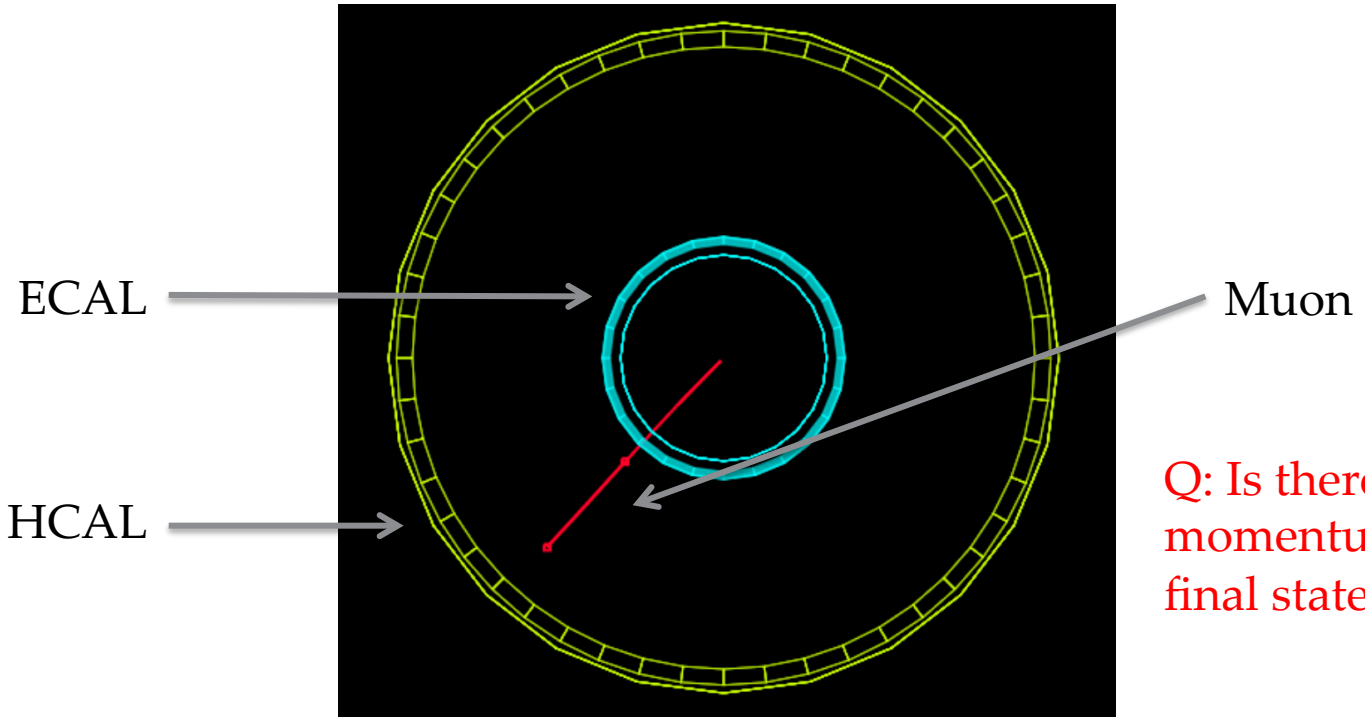
Dijet Event



Neutrinos

How do we "see" neutrinos in our detector if they don't interact?

- **With conservation of momentum!**
  - **Colliding protons (initial state) move into/out of page in this orientation**
    - **Zero momentum in the transverse plane**
    - **Final state must also contain zero net momentum in this plane**



Q: Is there net momentum in this final state?

Neutrinos

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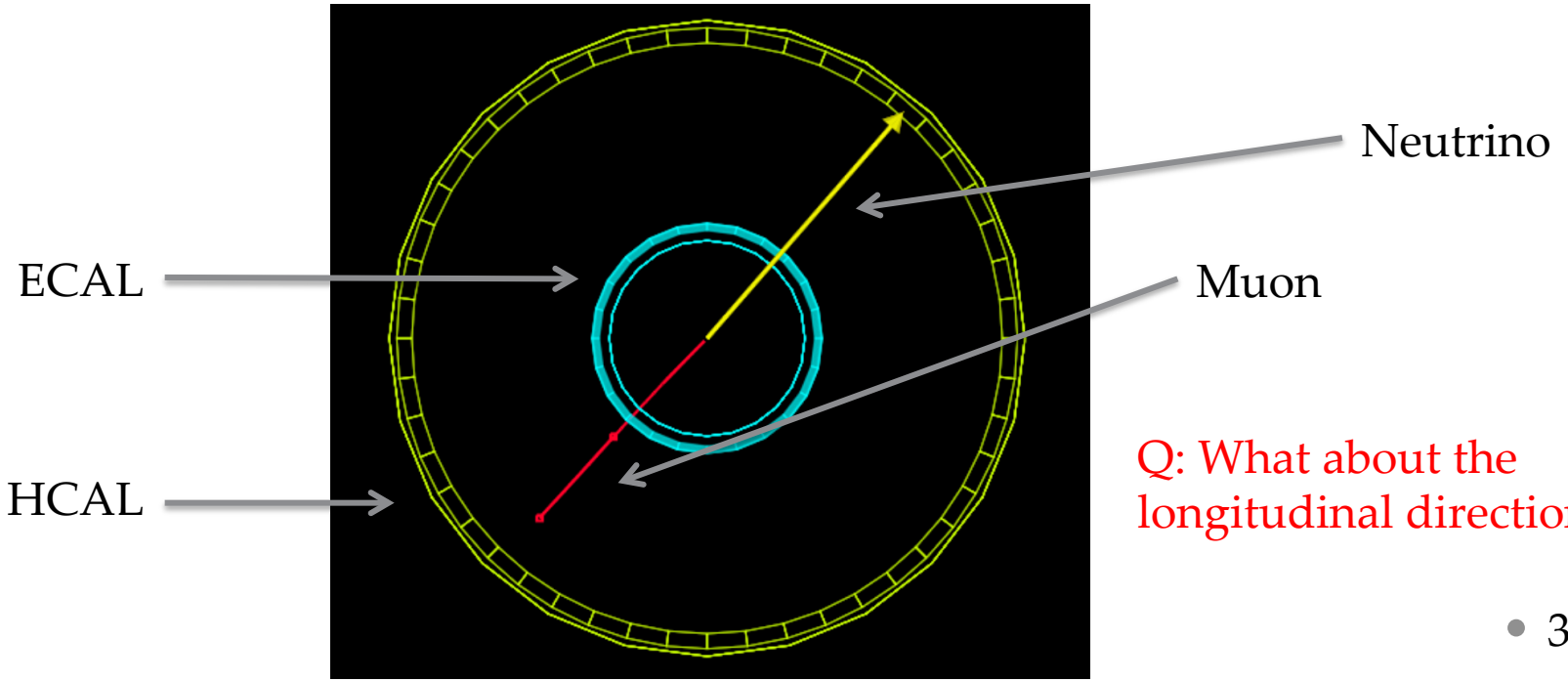


Q: What about the longitudinal direction?

Summary

These are all the particles we "see" with the CMS detector

- **Electron – track in the inner detector matched to an energy deposit in the ECAL**
- **Photon – Energy deposit in the ECAL with no matching track**
- **Muon – track in the inner detector matched to a track in the muon system**
- **Quark – spray of charged and neutral hadrons**
- **Neutrino – Transverse momentum imbalance (MET)**

But what about the others?

Why can't we "see" the τ lepton, W, Z, or even the Higgs boson?

- **They decay too quickly, before even entering the tracker**

How do we know they exist?

- **We observe their decay products!**

W boson

We will see plenty of these decays today

$W^- \rightarrow$

- $e^-\nu$ (11%)
- $\mu^-\nu$ (11%)
- $\tau^-\nu$ (11%)
- $q\bar{q}$ (66%)

These are much trickier to identify

Z boson

We will see plenty of these decays today

$Z \rightarrow$

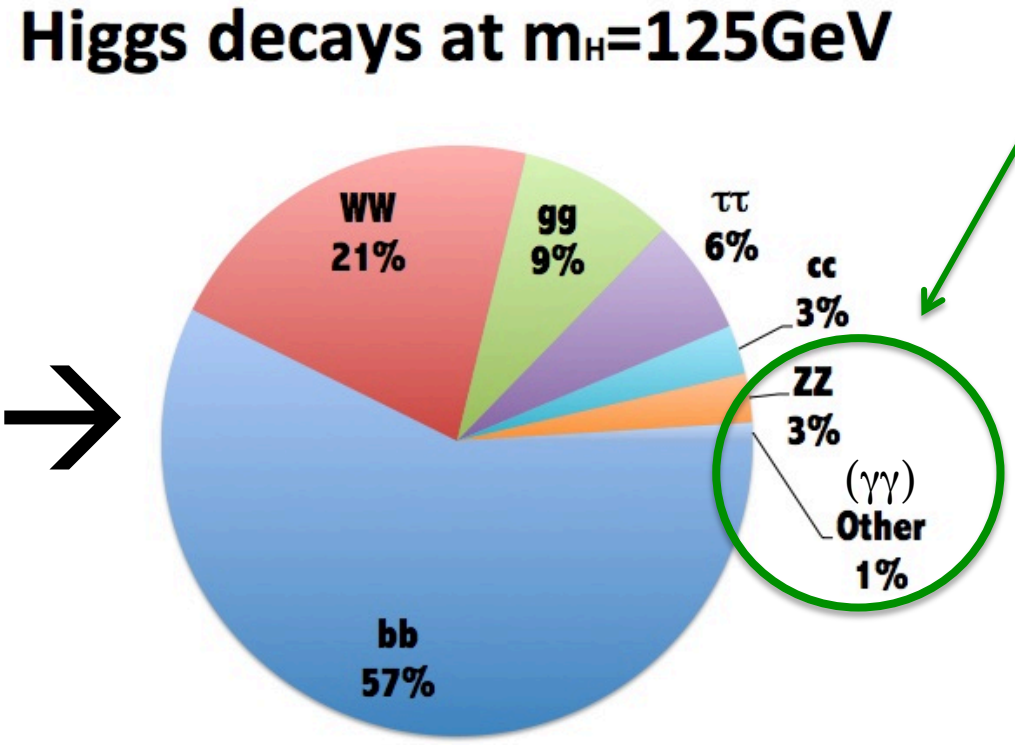
- e^+e^- (3%)
- $\mu^+\mu^-$ (3%)
- $\tau^+\tau^-$ (3%)
- $\nu\bar{\nu}$ (20%)
- $q\bar{q}$ (69%)

These are much trickier to identify

Higgs boson

We may see a few of these decays today

H →

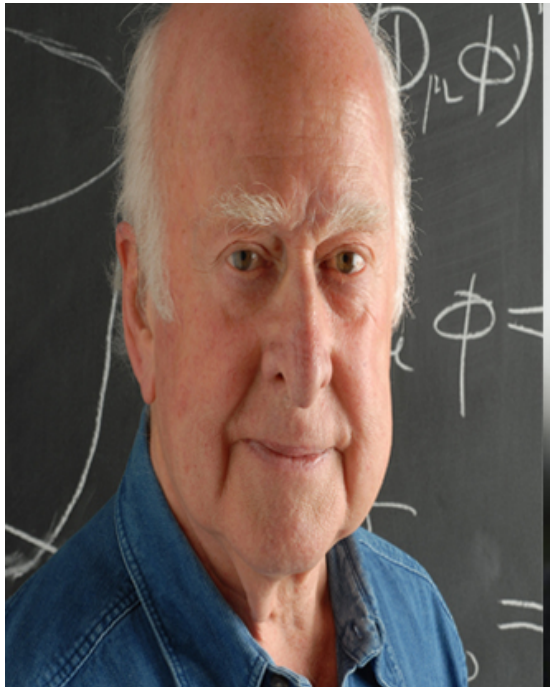


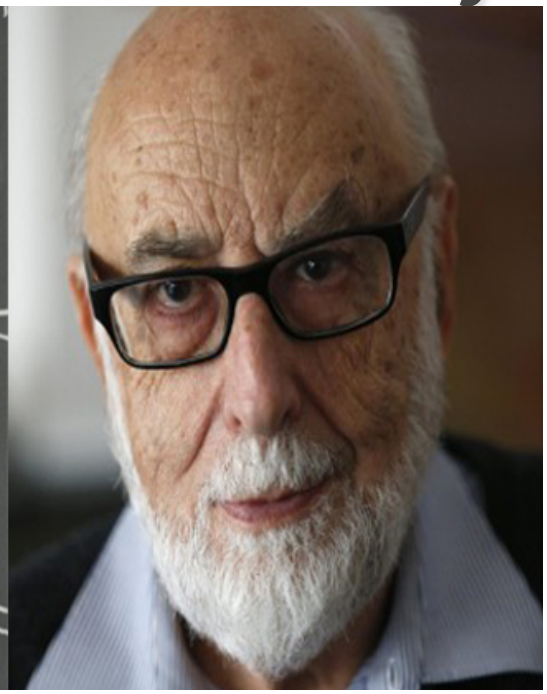
The others are much trickier to identify

Why is the Higgs special?

- Symmetry/invariance is very important in physics
  - Translation in space → momentum conservation
  - Translation in time → energy conservation
- The SM is based on a principle called "gauge invariance"
  - Requires massless W and Z bosons
- However, we observe that these particles are in fact quite massive
  - This is only possible if a very special kind of boson exists, which can give mass to these particles – The Higgs boson
    - Also gives mass to the fermions as well

2013 Nobel Prize in Physics





Peter Higgs

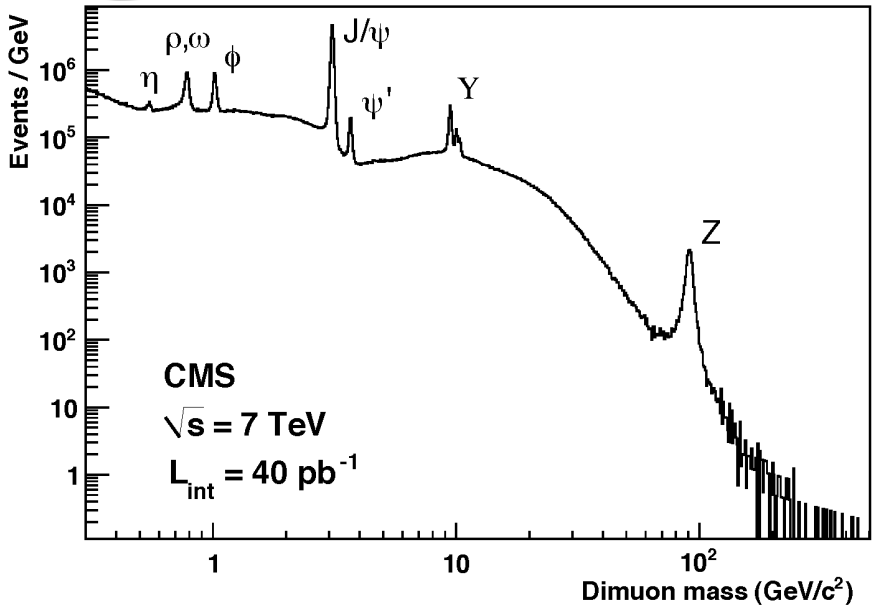
Francois Englert

CMS and ATLAS Collaborations at CERN discovered the Higgs

Purdue Calumet and CMS

- PUC is an official member both at Fermilab and CERN
- HEP Effort at PUC is led by Neeti Parashar
  - Post-doctoral Fellow
  - Undergraduate Students
  - Graduate Students
- PUC contributions to CMS were a vital part of the Higgs discovery
  - Pixel detector is an important piece of the tracker
    - Reconstructs charged particle tracks and vertices
    - Used in essentially all CMS analyses

Today's Measurement

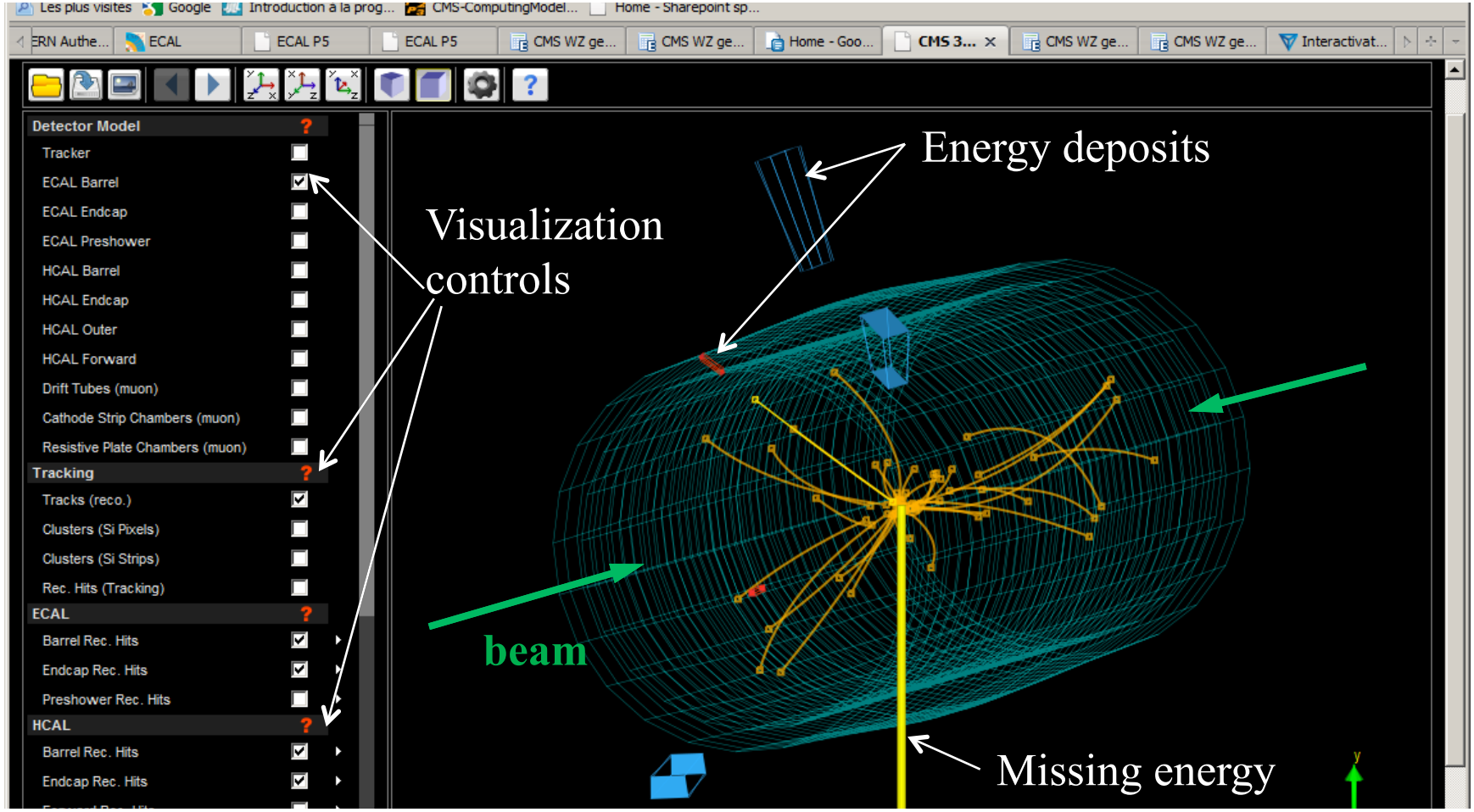


Today's measurement

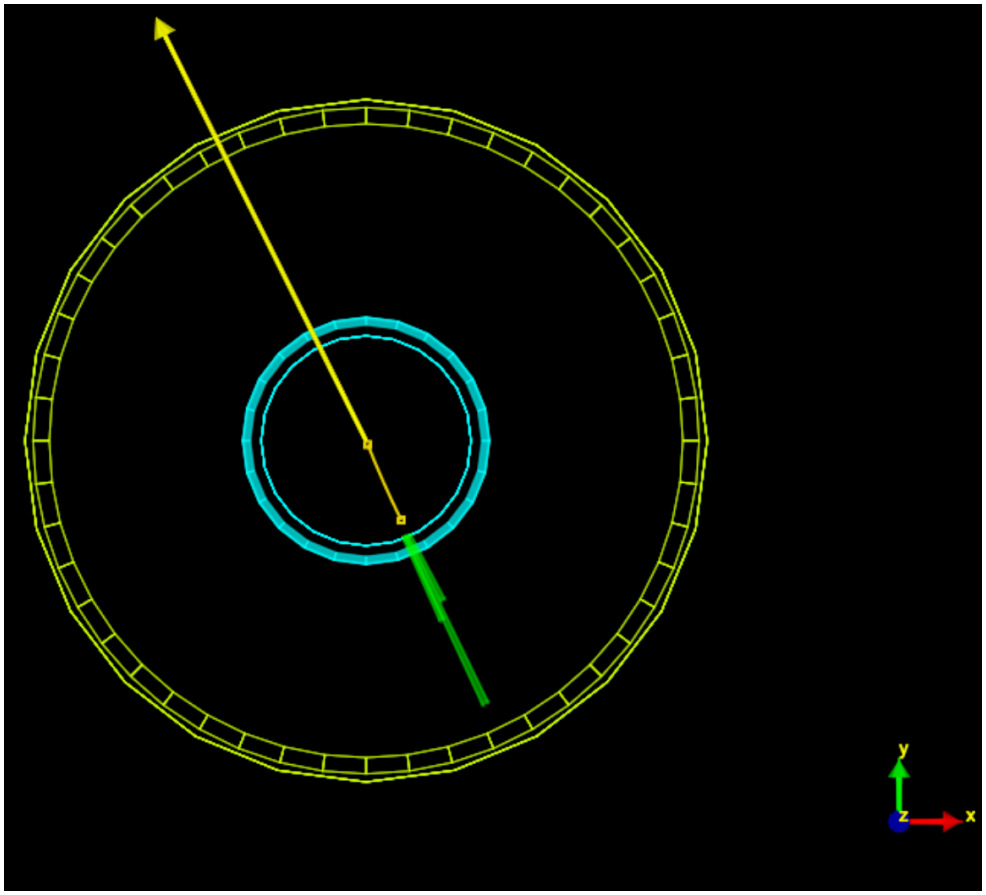
Analysis of some (real!) proton-proton collisions recorded by CMS

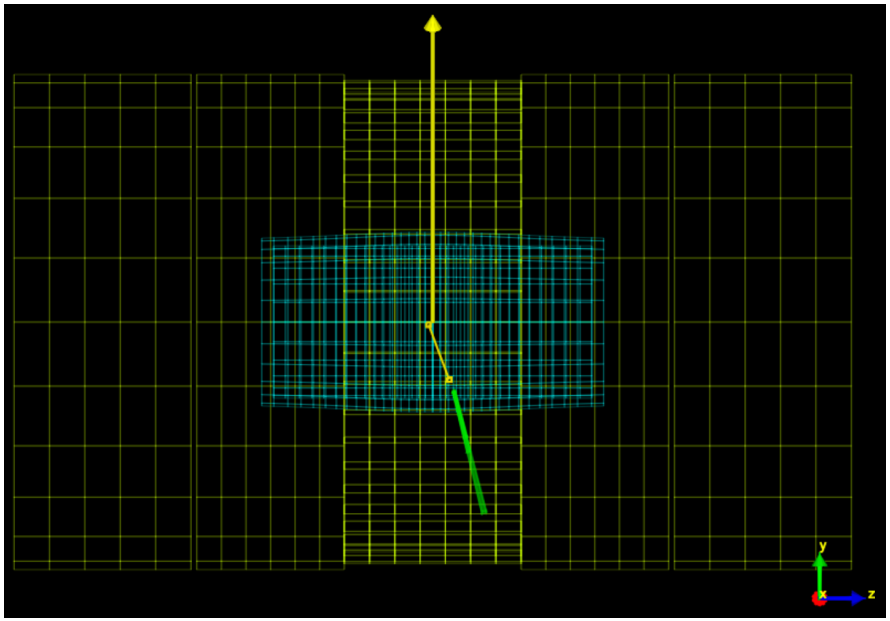
- **To identify the particles + to determine what happened during the collision**
- **Obtain an overview of some basic physical phenomena, from the analysis of a large number of events!**

Data Visualization



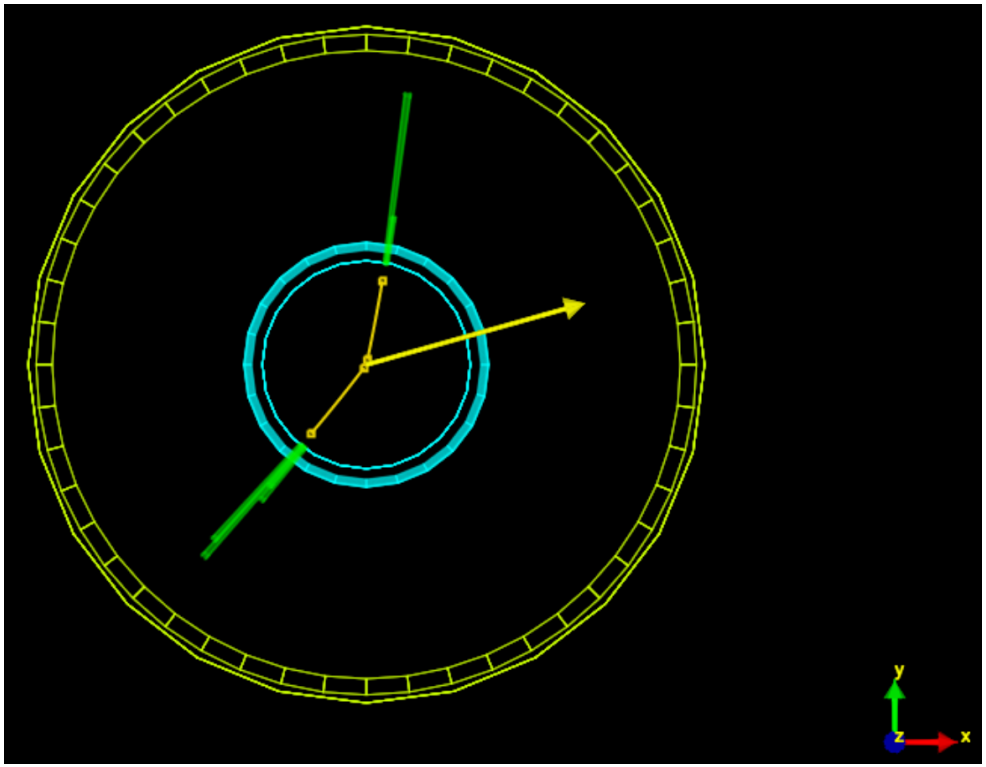
Event 1

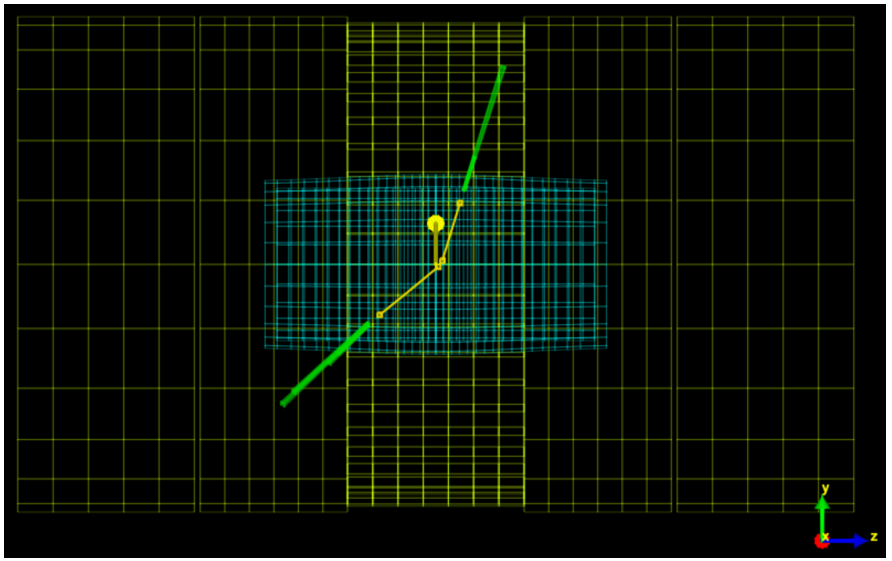




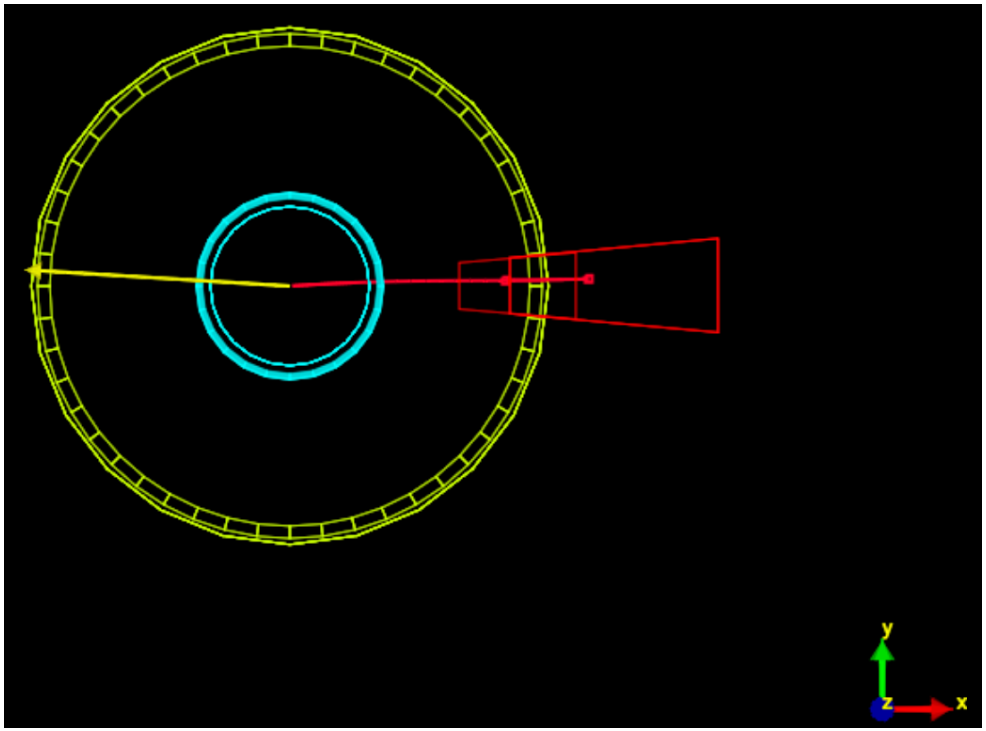
MET = 56 GeV

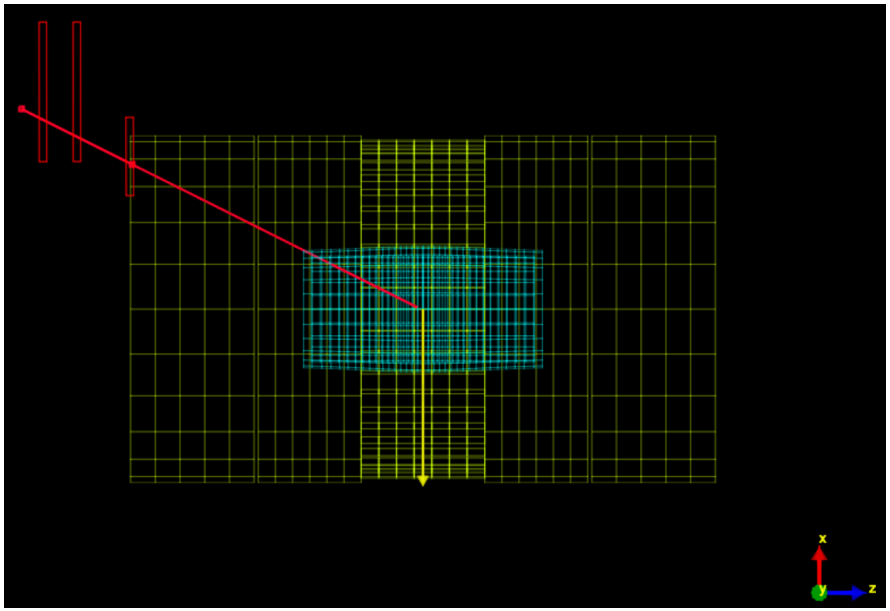
Event 2





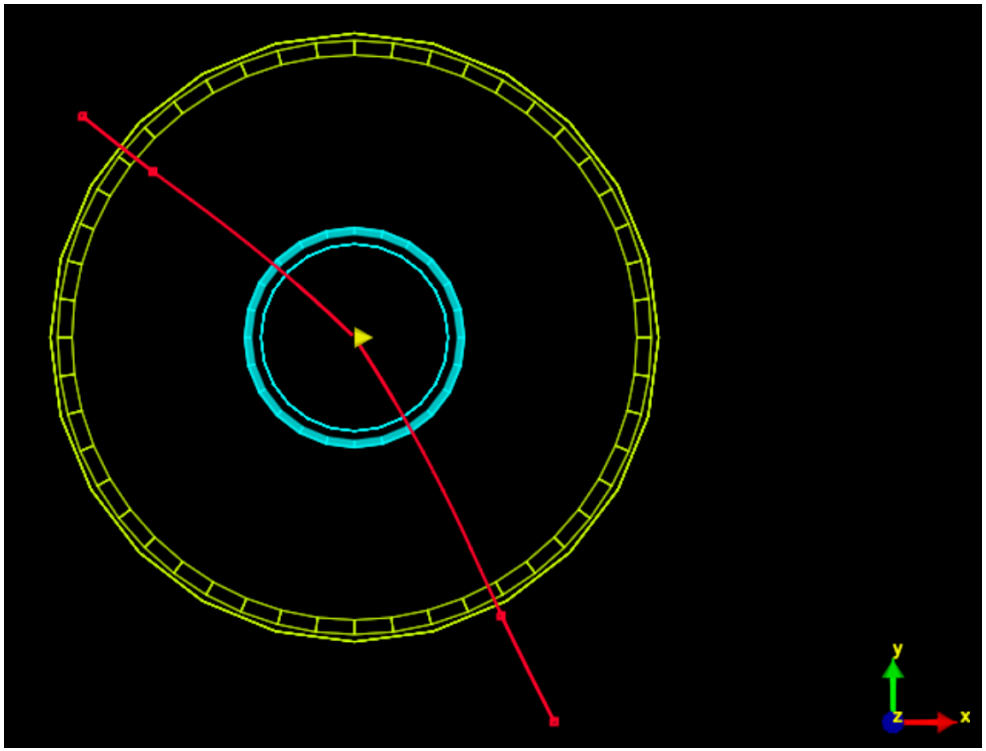
Event 3

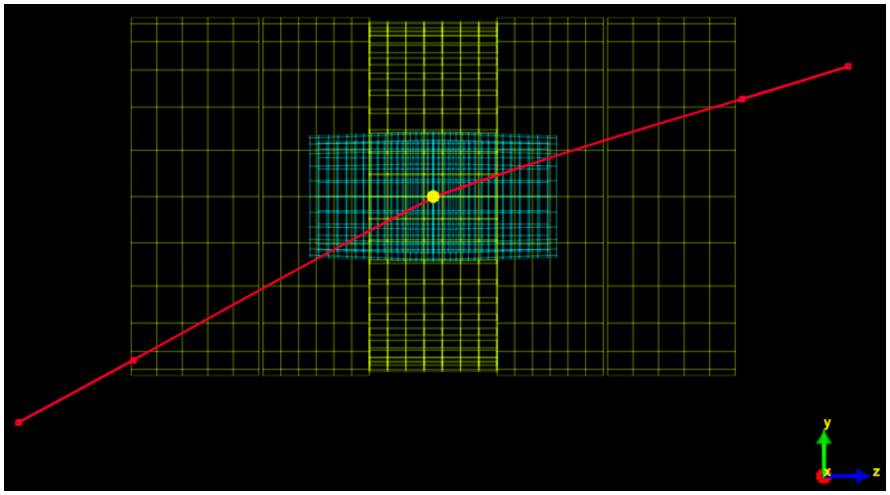




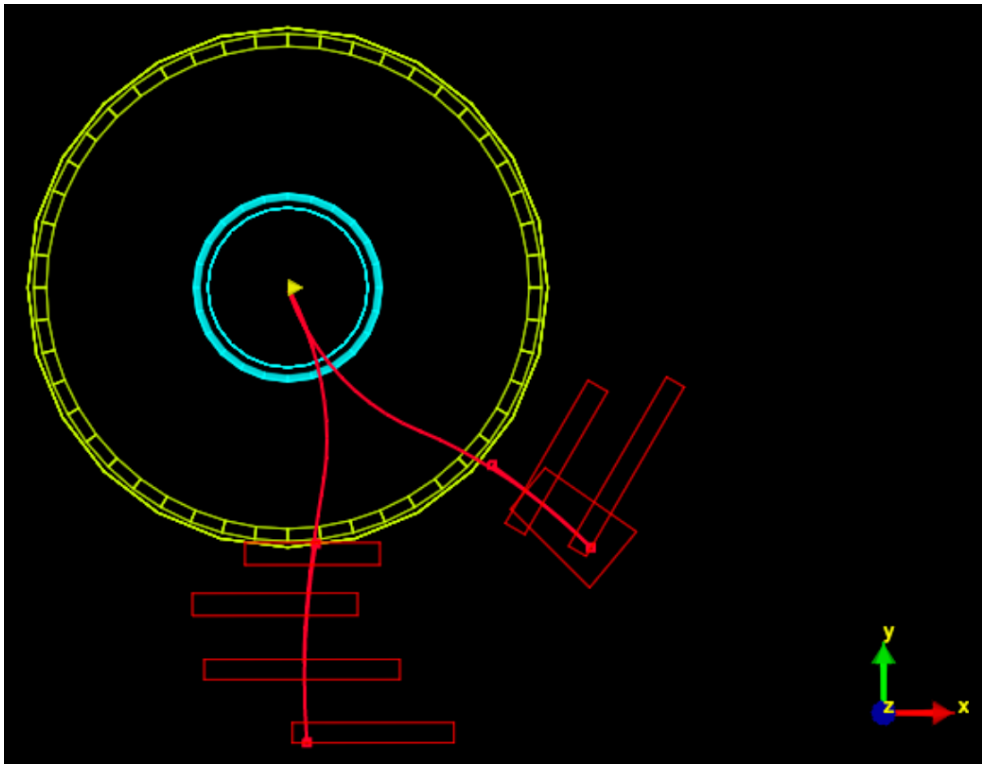
MET = 41 GeV

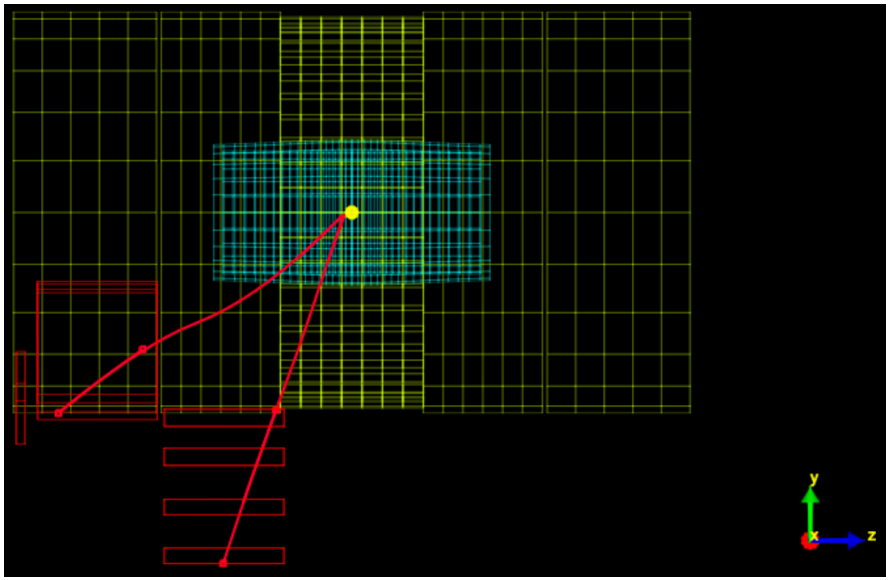
Event 4



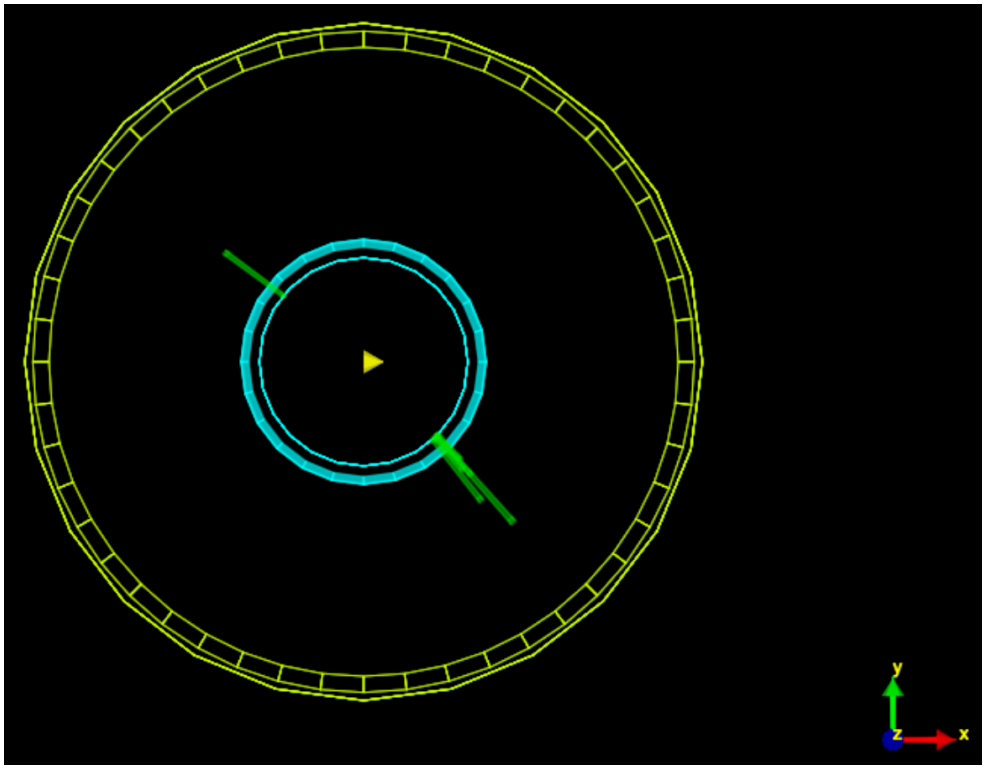


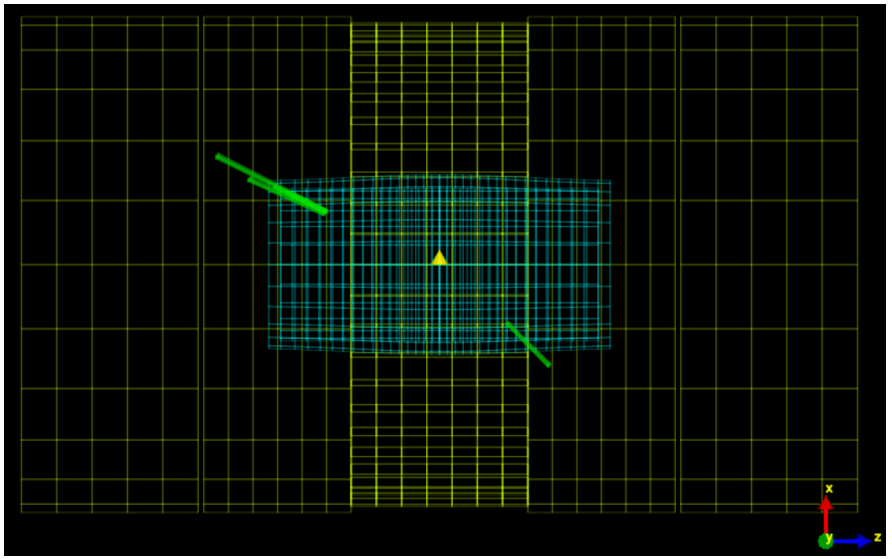
Event 5



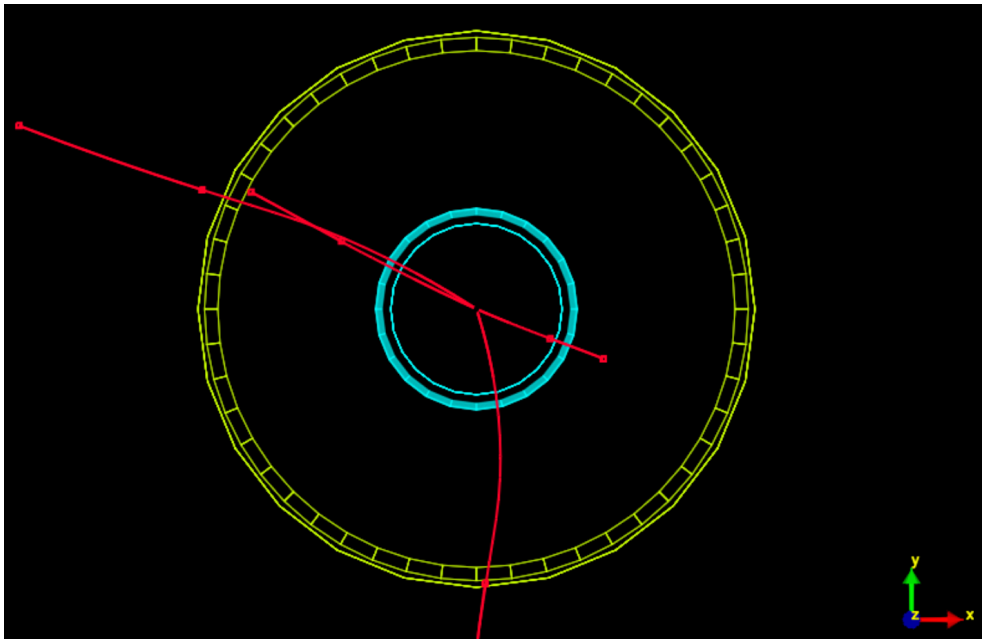


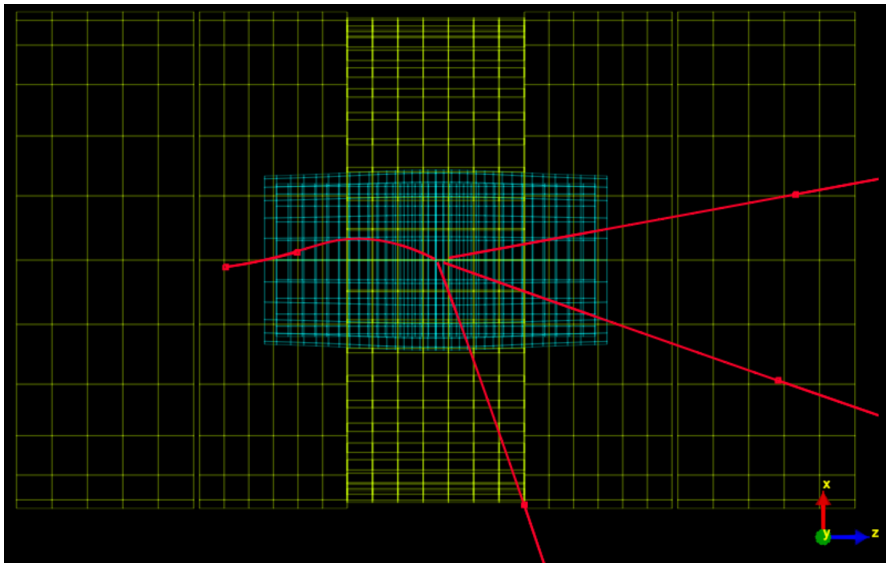
Event 6



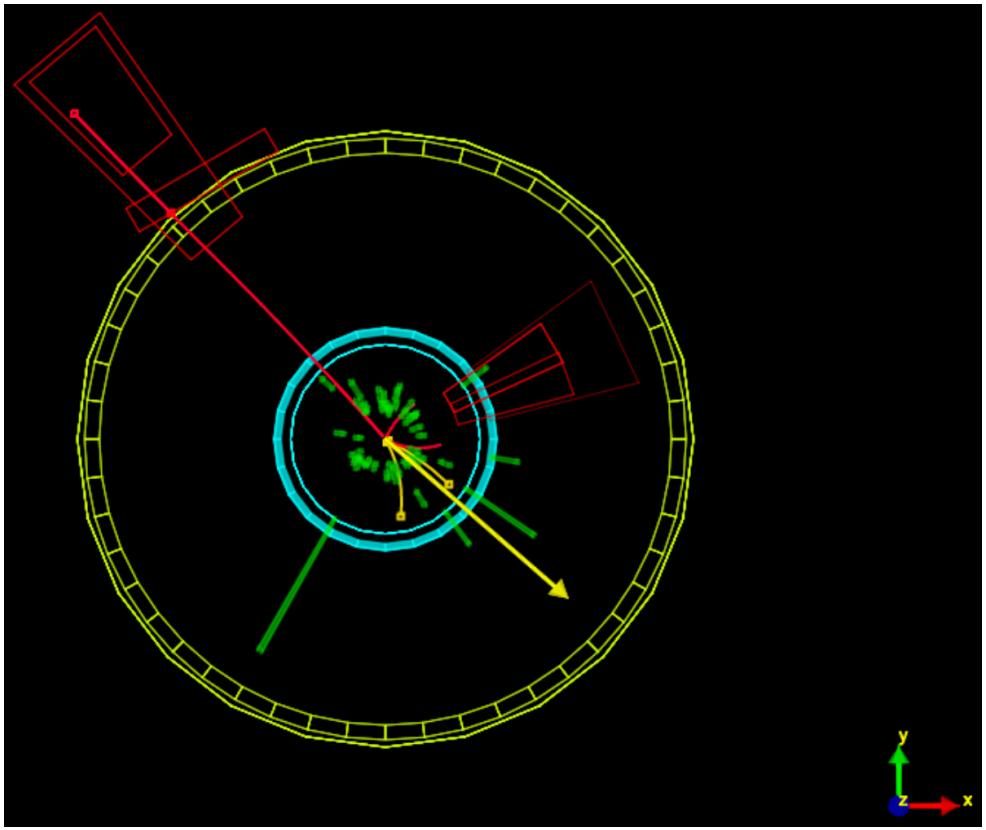


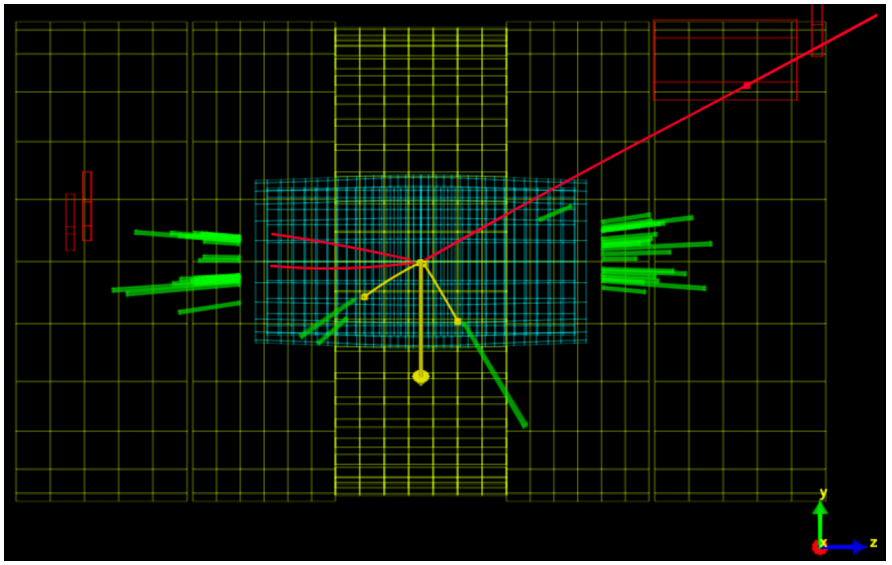
Event 7





Event 8





Objectives…

- Can we calculate the ratio W^+/W^-?
- Can we calculate the ratio e/μ in the decay of W?
- Can we visualize the mass of Z?
- Can we find any $H \rightarrow ZZ$ events?
  - $Z \rightarrow e^+ e^-$
  - $Z \rightarrow \mu^+\mu^-$

    therefore $ZZ \rightarrow e^+ e^- e^+ e^-$

    $\mu^+\mu^- \mu^+\mu^-$

    $e^+ e^- \mu^+ \mu^-$
- Can we find any $H \rightarrow \gamma\gamma$ events?

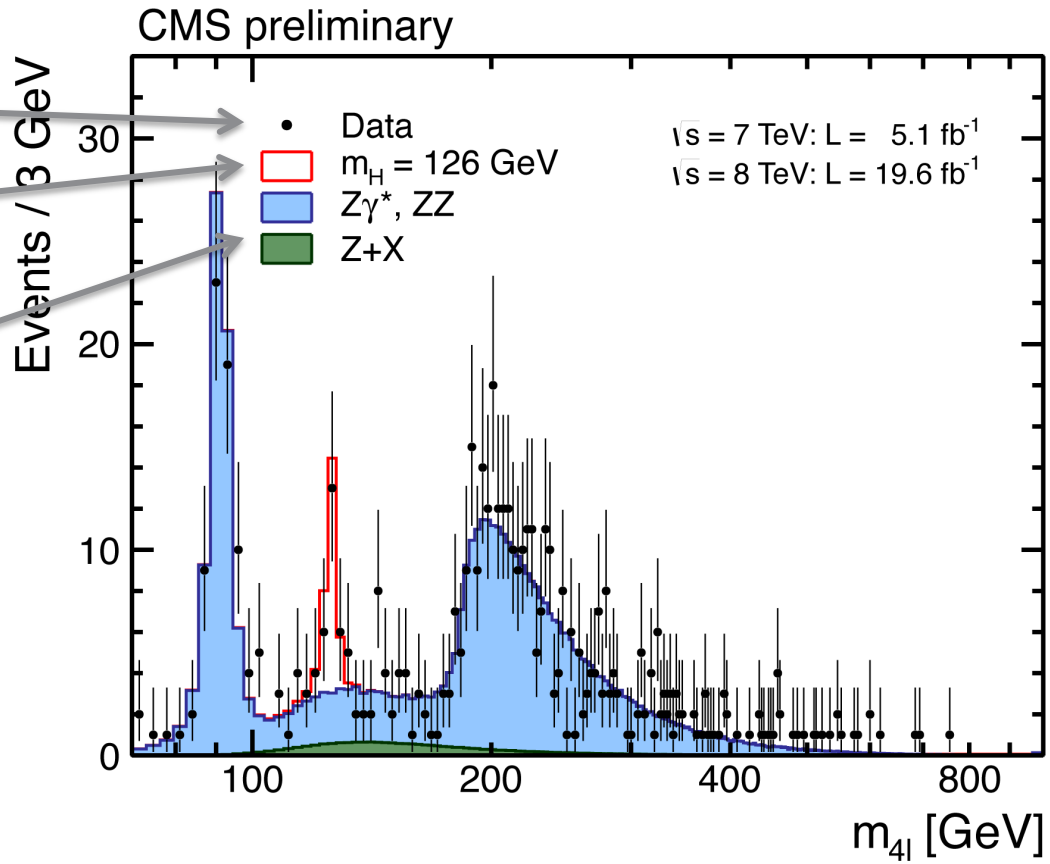
What to do with the data?

- Like real physicists, you will make a histogram to visualize the data
- Then check for any interesting resonances (bumps)

Data

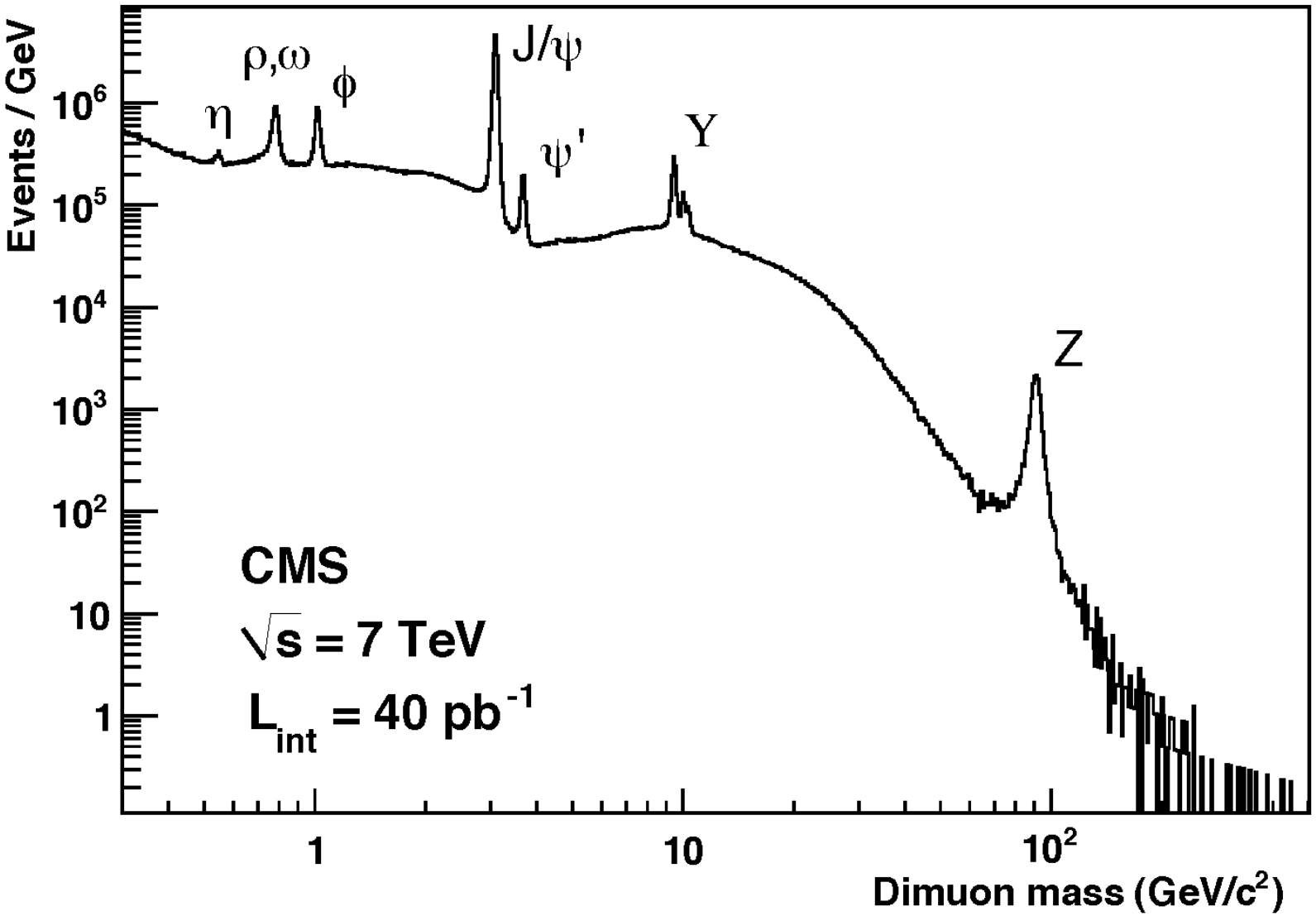
Signal prediction

Background prediction



Q: Do you see the signal in this histogram?

Dimuon Mass Distribution



More Information

- Purdue Calumet QuarkNet website: http://webs.purduecal.edu/hep/puc-cms-masterclasses/

- Cheat Sheet: http://webs.purduecal.edu/hep/files/2015/02/CMS-CHEAT-SHEET.pdf