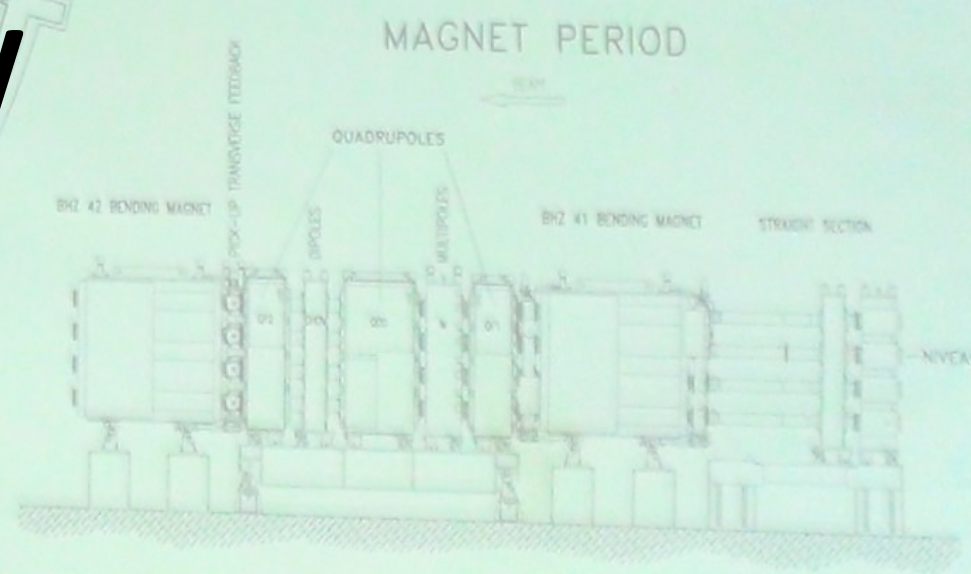


# High Energy Physics (HEP) Overview

INJECTION LINE

TRANSFER LINE and MEASUREMENT LINE



*Most slides taken from previous Quarknet presentations, particularly Jeremy's from 2020!*

PS RING

ISOLDE LINE

LINACS



# What are we looking at?

Event	XY Radius (cm)	Length Z (cm)	cos theta x	cos theta y	cos theta z	Sum E-Cal	Muon Tag
50001	-1808.48	20994.94	0.47	-0.10	-0.88	9127.05	
50001	1808.48	20994.93	-0.47	0.10	0.88	9127.05	
50002	-2801.12	16128.99	-0.21	-0.71	0.68	0.00	Hit
50002	2801.12	16128.99	0.21	0.71	-0.68	0.00	Hit
50003	-2959.26	14972.58	0.17	-0.76	-0.63	0.00	
50003	2894.38	15465.20	-0.39	0.65	0.65	0.00	
50004	-63.16	23869.40	-0.01	-0.01	-1.00	9140.57	
50004	63.16	23869.40	0.01	0.01	1.00	9140.57	
50005	-2245.86	19255.54	-0.59	0.00	0.81	0.00	
50005	2811.81	16055.31	0.64	0.36	-0.67	0.00	
50006	-3799.30	219.73	0.51	0.86	0.01	9129.13	
50006	3799.30	219.73	-0.51	-0.86	-0.01	9129.13	
50007	-3389.30	10788.96	0.03	0.89	-0.45	0.00	Hit
50007	3389.30	10788.95	-0.04	-0.89	0.45	0.00	Hit
50008	-2988.41	14742.48	0.73	-0.29	0.62	9120.09	
50008	2988.41	14742.48	-0.73	0.29	-0.62	9120.09	

What are we measuring and how do we understand what we see?

# What are the learning goals?

What is particle physics?

1

How do particle detectors work?

2

What are we seeing in the detectors?

3

How do we analyze the data?

4

# The Standard Model

A periodic table of elements with atomic numbers and symbols. The elements are color-coded by groups: H (1), He (2), Li (3), Be (4), B (5), C (6), N (7), O (8), F (9), Ne (10), Na (11), Mg (12), Al (13), Si (14), P (15), S (16), Cl (17), Ar (18), K (19), Ca (20), Sc (21), Ti (22), V (23), Cr (24), Mn (25), Fe (26), Co (27), Ni (28), Cu (29), Zn (30), Ga (31), Ge (32), As (33), Se (34), Br (35), Kr (36), Rb (37), Sr (38), Y (39), Zr (40), Nb (41), Mo (42), Tc (43), Ru (44), Rh (45), Pd (46), Ag (47), Cd (48), In (49), Sn (50), Sb (51), Te (52), I (53), Xe (54), Cs (55), Ba (56), La (57-71), Hf (72), Ta (73), W (74), Re (75), Os (76), Ir (77), Pt (78), Au (79), Hg (80), Tl (81), Pb (82), Bi (83), Po (84), At (85), Rn (86), Fr (87), Ra (88), Ac (89-103), Rf (104), Db (105), Sg (106), Bh (107), Hs (108), Mt (109), Ds (110), Rg (111), Cn (112), Nh (113), Fl (114), Mc (115), Lv (116), Ts (117), Og (118), La (57), Ce (58), Pr (59), Nd (60), Pm (61), Sm (62), Eu (63), Gd (64), Tb (65), Dy (66), Ho (67), Er (68), Tm (69), Yb (70), Lu (71), Ac (89), Th (90), Pa (91), U (92), Np (93), Pu (94), Am (95), Cm (96), Bk (97), Cf (98), Es (99), Fm (100), Md (101), No (102), Lr (103).



	mass → $\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$1/2$	$1/2$	$1/2$	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	
					<b>GAUGE BOSONS</b>



# Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
LEPTONS		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$		
	0	0	0	$\pm 1$		
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1		
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson		

SCALAR BOSONS

GAUGE BOSONS  
VECTOR BOSONS

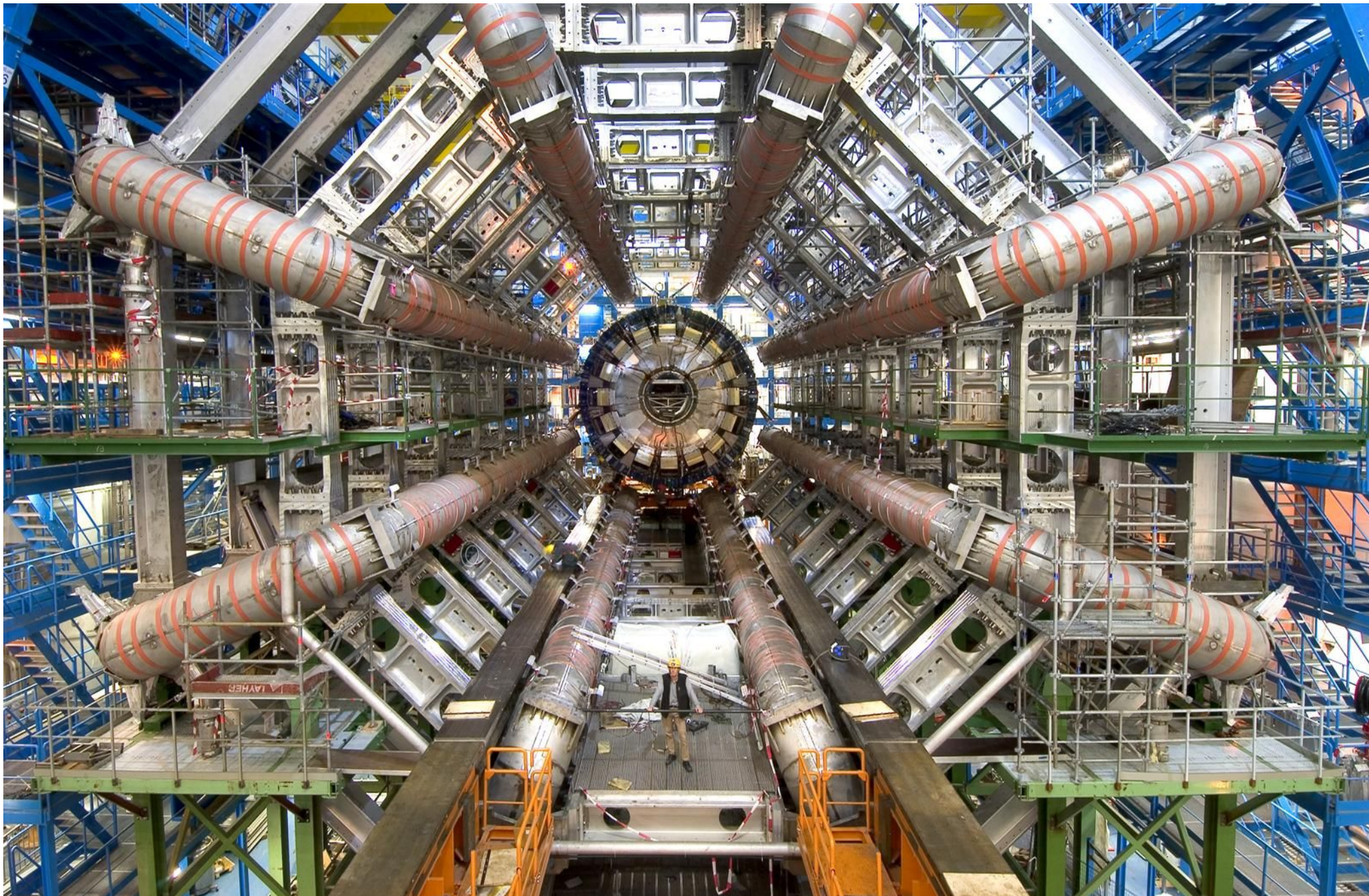
# There's more! Resources:

- [Particle Adventure](#) (good resource for students)
- [Hyperphysics particle physics topics](#) (medium difficulty between these two resources)
- [Particle Data Group PDG](#) (detailed resource, includes pamphlet you can order or use [interactive online version](#))

\*thanks Jeremy for researching these!



# The LHC and New Physics



□ ATLAS  
detector

How do particle detectors work?



# Generic Particle Detector

Cylinders wrapped around the beam pipe

From inner to outer . . .

Tracking

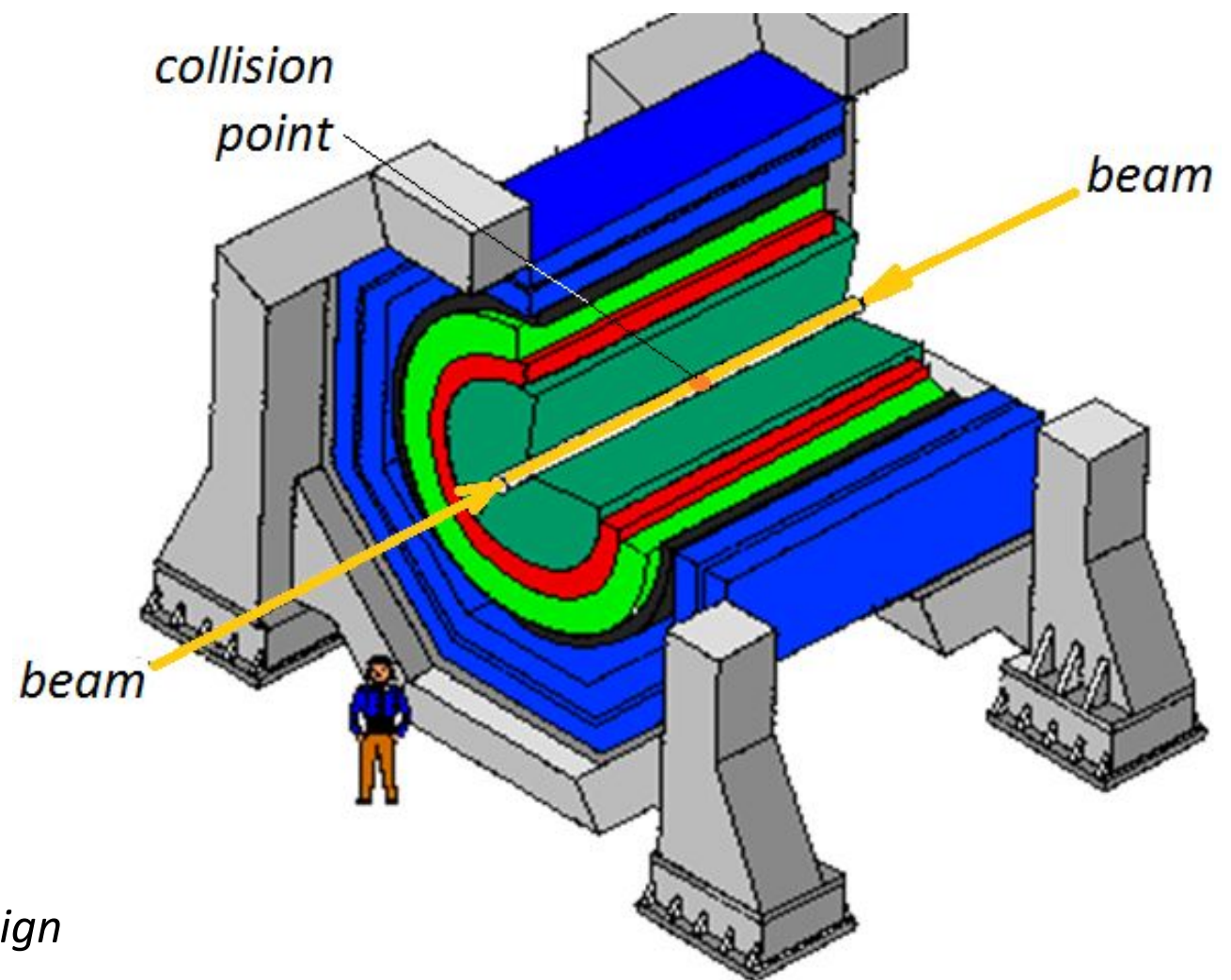
Electromagnetic calorimeter

Hadronic calorimeter

Magnet\*

Muon chamber

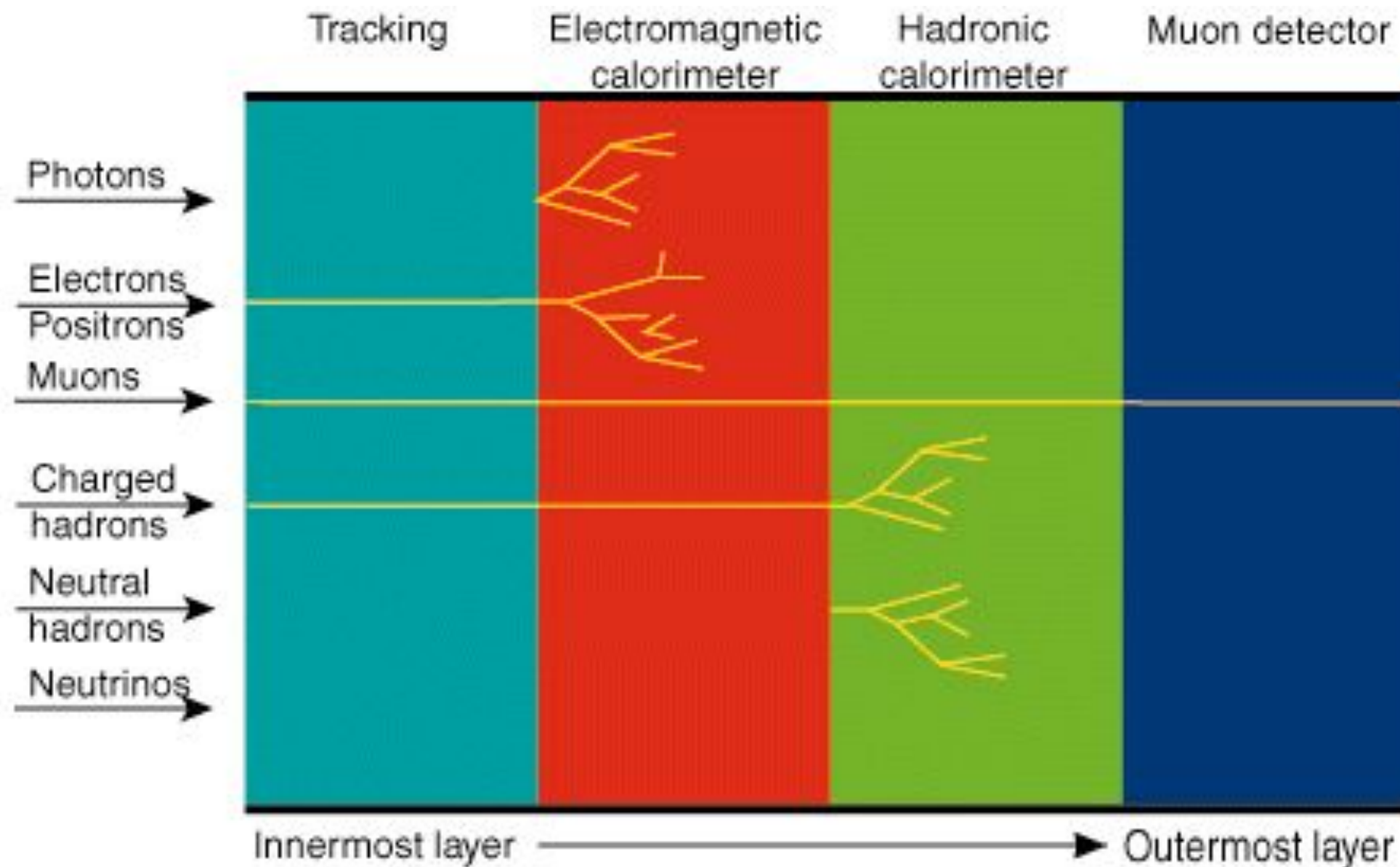
\* *location of magnet depends on specific detector design*



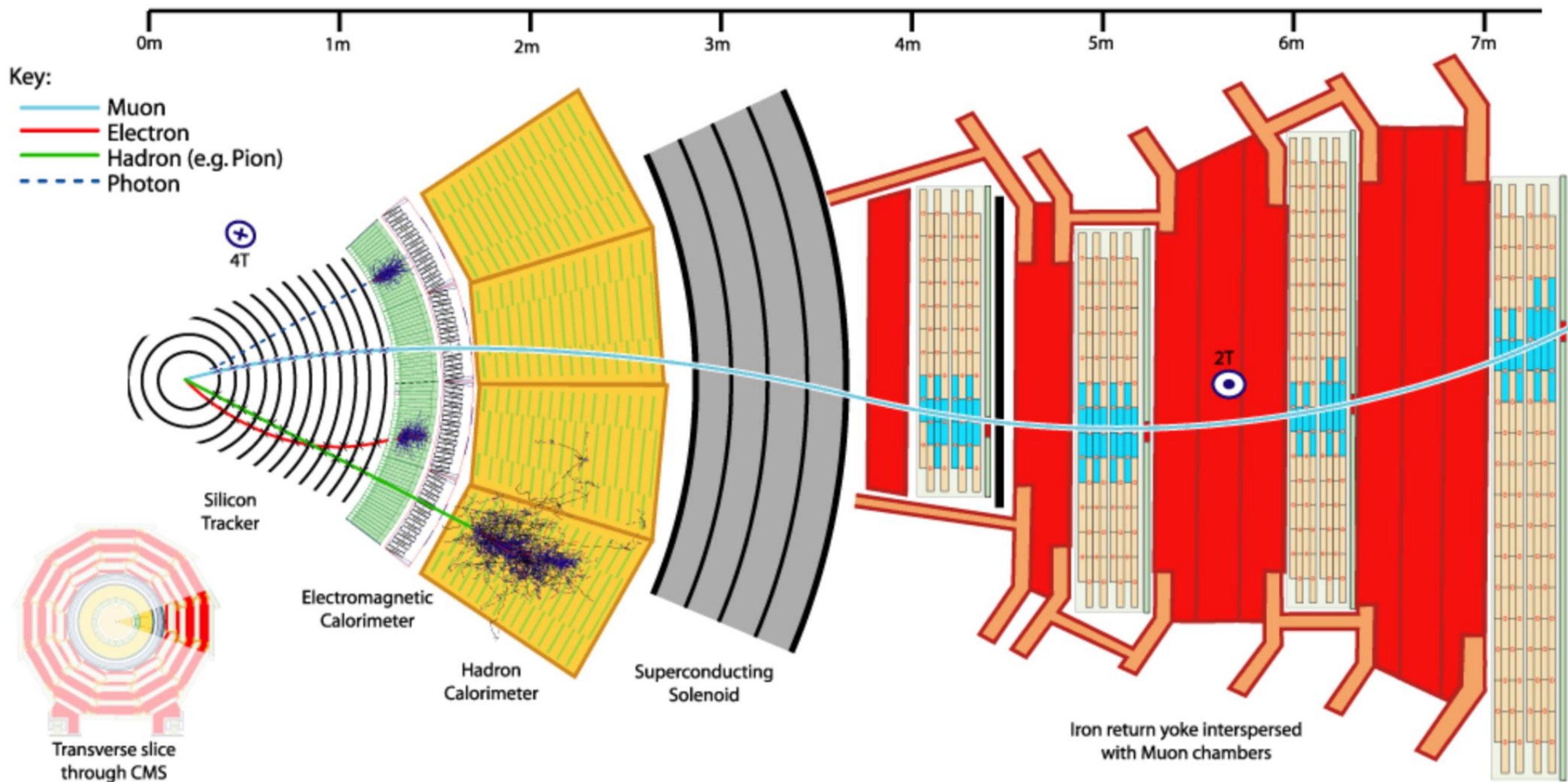


# Detector Tracks

All detectors have 4 basic layers



# Detector Tracks

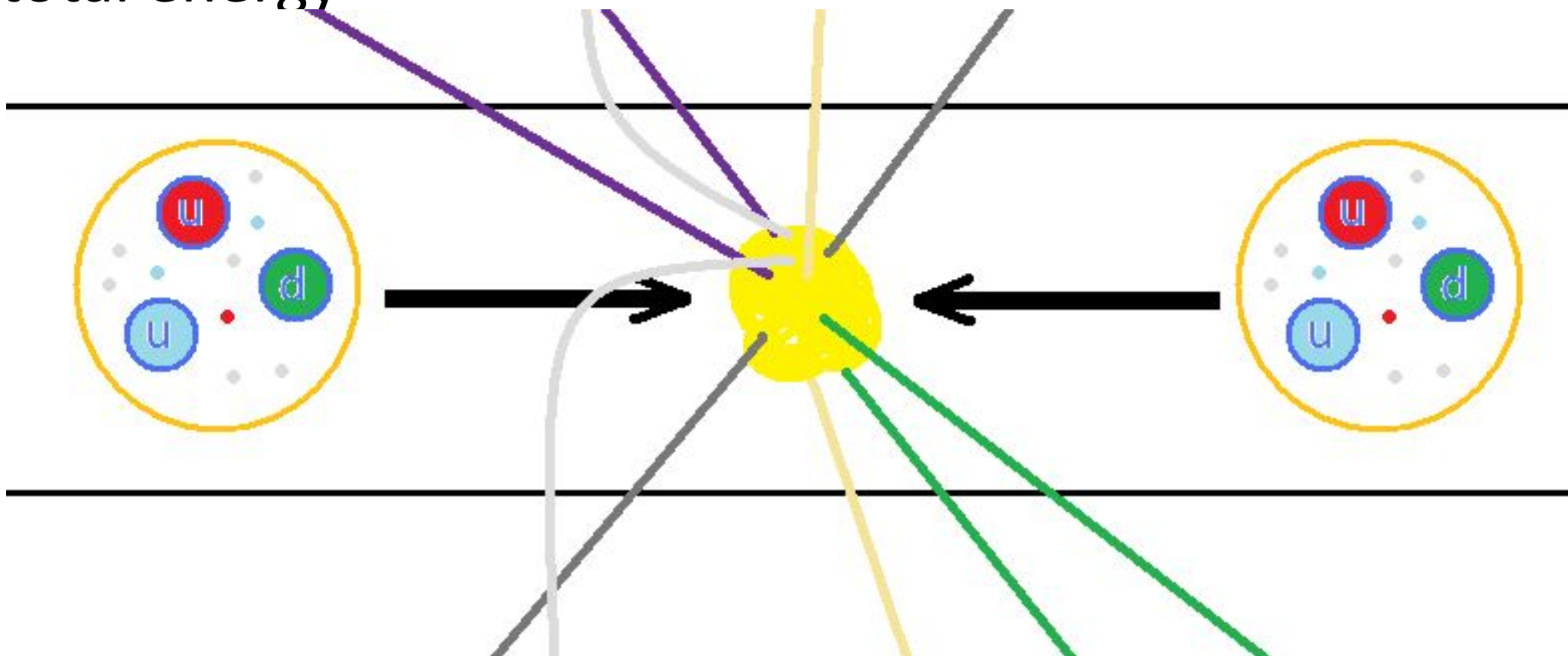




# Energy & Particle Mass

If each beam proton has energy 4 TeV....

- The total collision energy is  $2 \times 4 \text{ TeV} = 8 \text{ TeV}$
- Each particle inside a proton shares only a portion
- A newly created particle's mass ***must be*** smaller than the total energy



What are we seeing in the detectors?

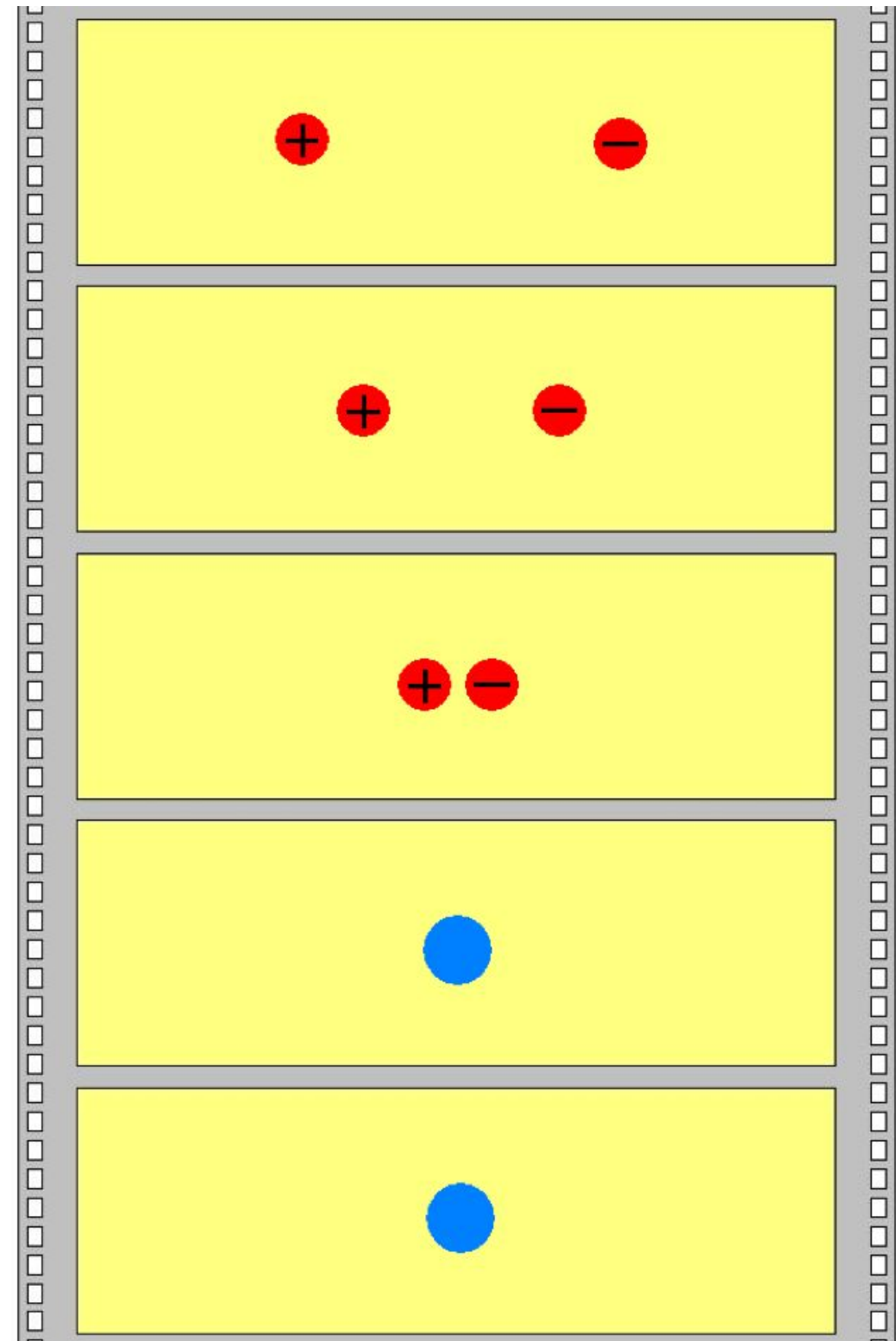
# Particle Decays

The collisions create new particles that promptly decay.

Decaying particles *always* produce lighter particles.

Conservation laws allow us to see patterns in the decays.

Ex) neutral, large blue decays into net neutral, smaller reds

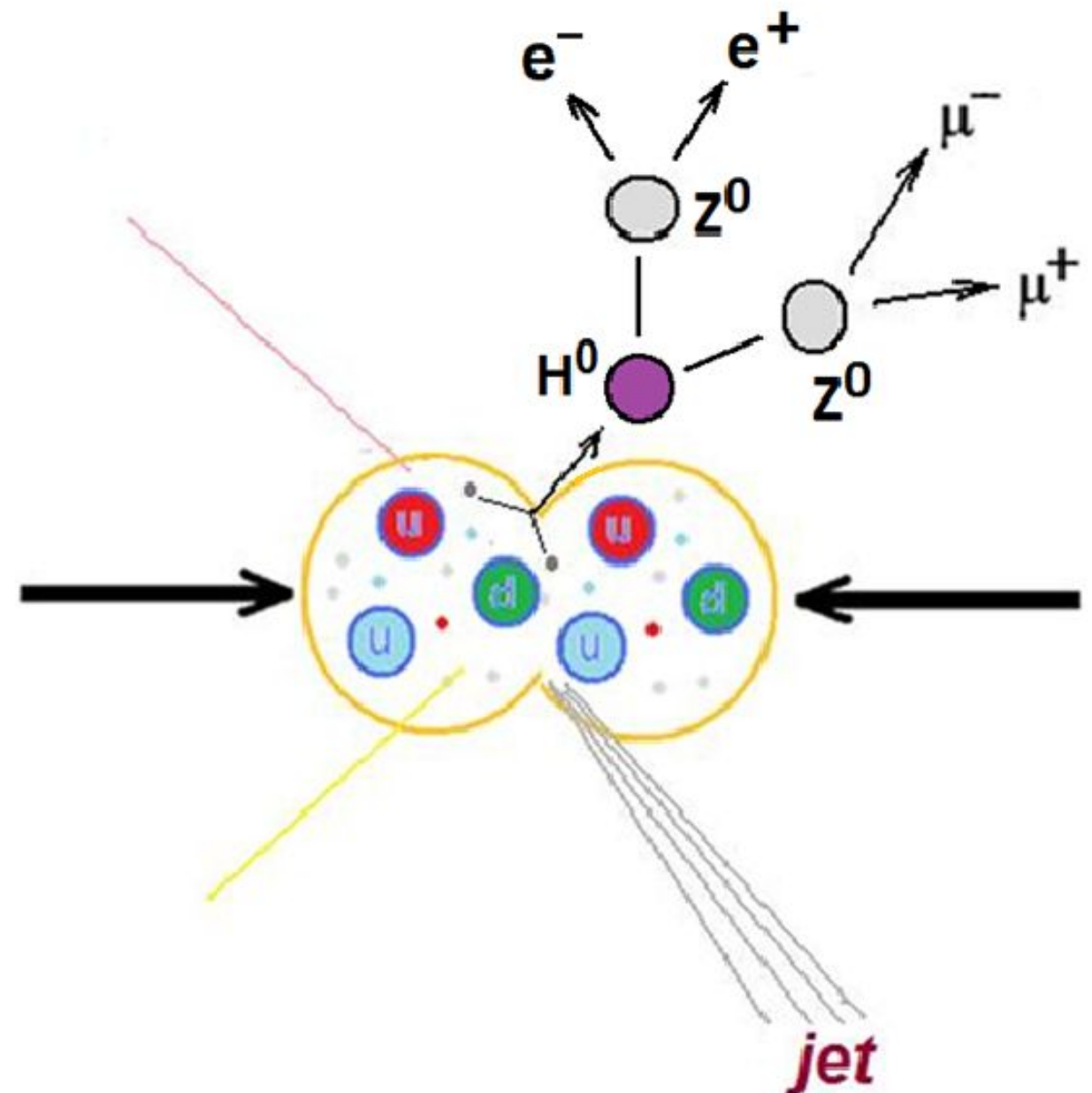




# Higgs Particle Production

The Higgs boson decays into daughter particles, sometimes including muons.

Other particles also produce muons, such as the Z boson.



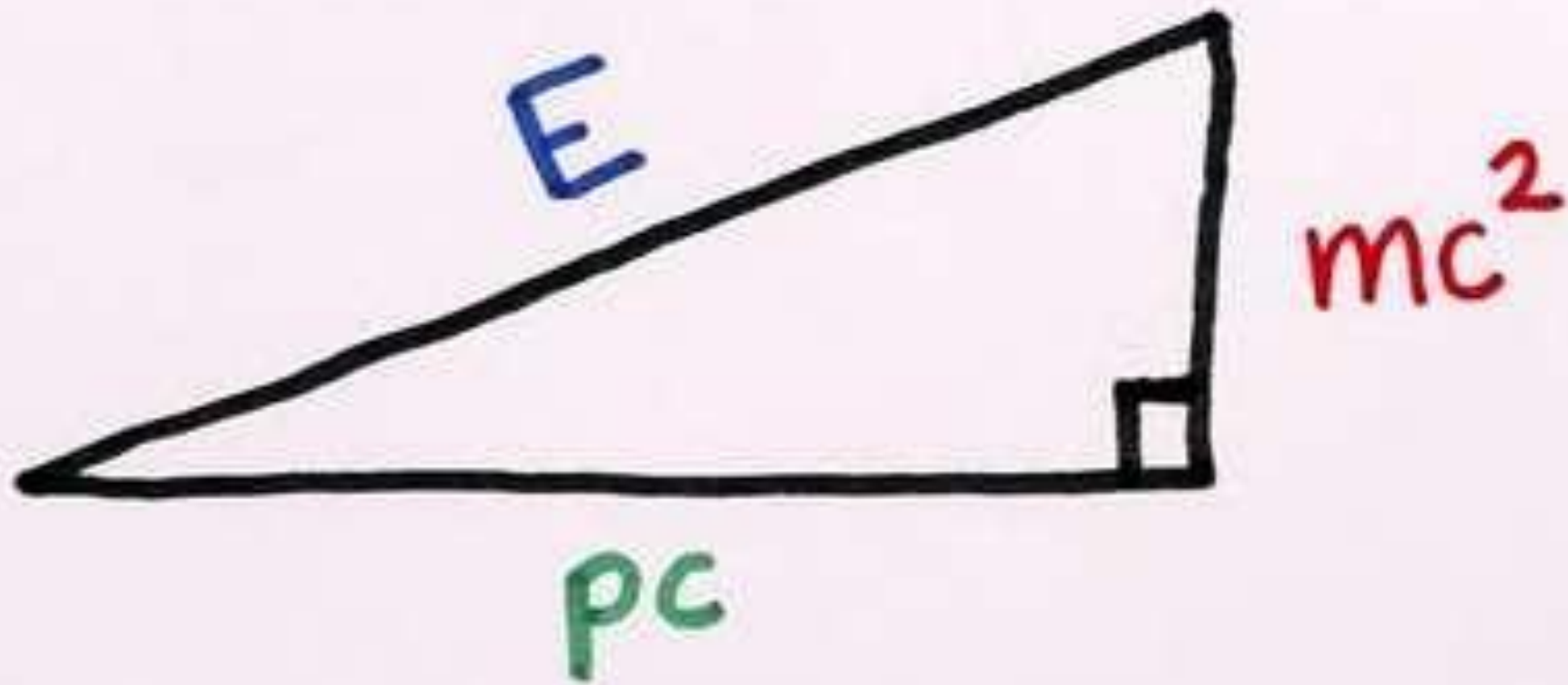
# Still more resources!

CERN detector overview, good for students

Detailed presentation on detector physics, includes historical overview

[https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L1\\_Introduction\\_HEPdetectors.pdf](https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L1_Introduction_HEPdetectors.pdf)





$$E^2 = (mc^2)^2 + (pc)^2$$

# *A Word About Units*

<u>Qty</u>	<u>Formula</u>	<u>SI Unit</u>	<u>HEP Unit</u>
Energy	$K \sim mv^2$	Joule	GeV
Mom.	$p = mv$	J/speed	GeV/c
Mass	$m$	J/speed <sup>2</sup>	GeV/c <sup>2</sup>

Make  $c = 1$  and  $E = p = m$ , everything in GeV



The famous [Einstein relationship](#) for energy

$$E = mc^2$$

can be blended with the [relativistic momentum](#) expression

$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

to give an alternative expression for energy.

The combination **pc** shows up often in relativistic mechanics. It can be manipulated as follows:

$$p^2 c^2 = \frac{m_0^2 v^2 c^2}{1 - \frac{v^2}{c^2}} = \frac{m_0^2 \frac{v^2}{c^2} c^4}{1 - \frac{v^2}{c^2}}$$

and by adding and subtracting a term it can be put in the form:

$$p^2 c^2 = \frac{m_0^2 c^4 \left[ \frac{v^2}{c^2} - 1 \right]}{1 - \frac{v^2}{c^2}} + \frac{m_0^2 c^4}{1 - \frac{v^2}{c^2}} = -m_0^2 c^4 + (mc^2)^2$$

which may be rearranged to give the expression for energy:

$$E = \sqrt{p^2 c^2 + (m_0 c^2)^2}$$

Note that the  $m$  with the zero subscript is the rest mass, and that  $m$  without a subscript is the effective [relativistic mass](#).

$$E^2 = p^2 c^2 + m_0^2 c^4$$

Let's make  $c = 1$

$$E^2 = p^2 + m_0^2$$

$$m = \sqrt{E^2 - p^2}$$