Particle Identification

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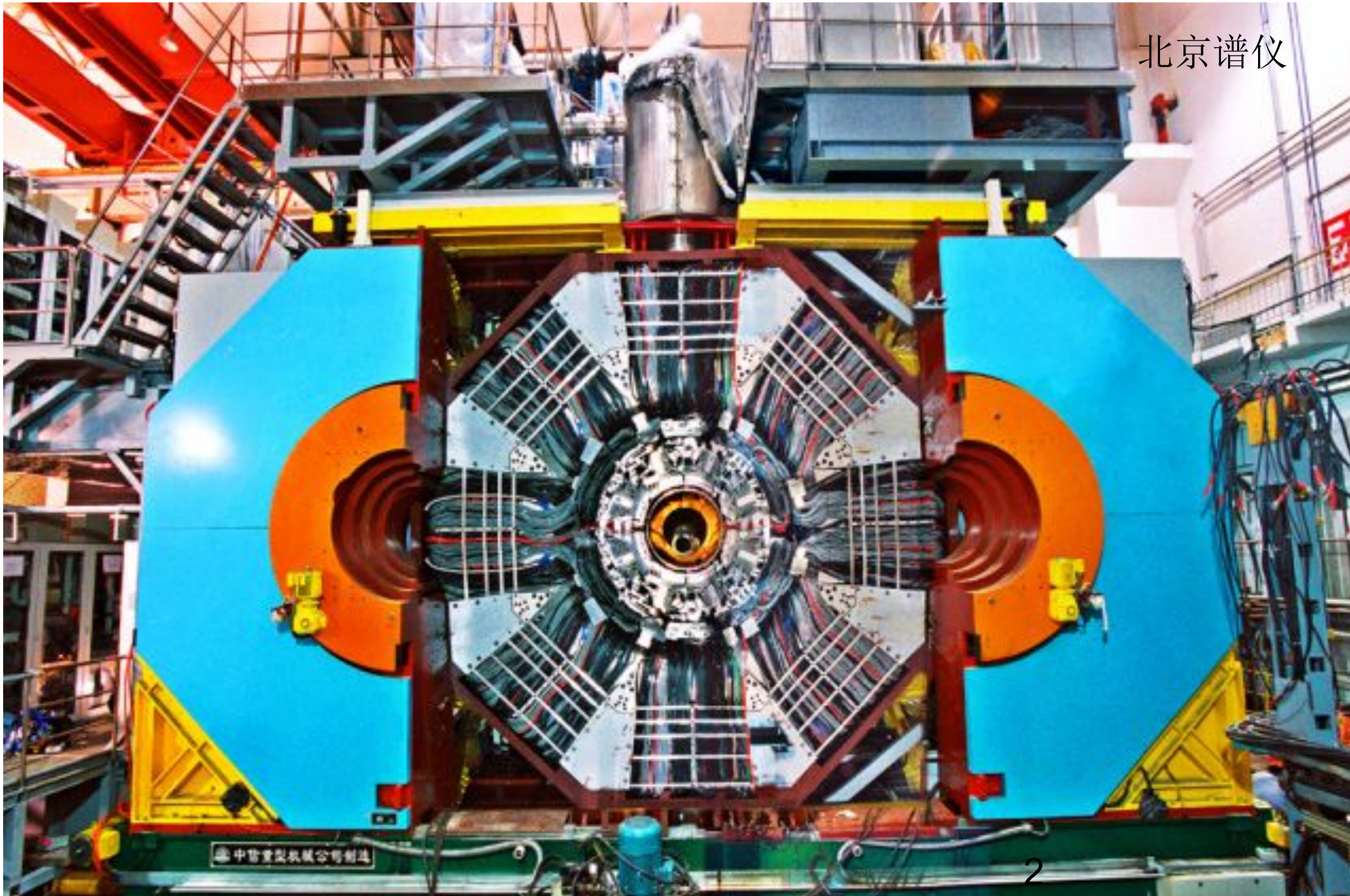
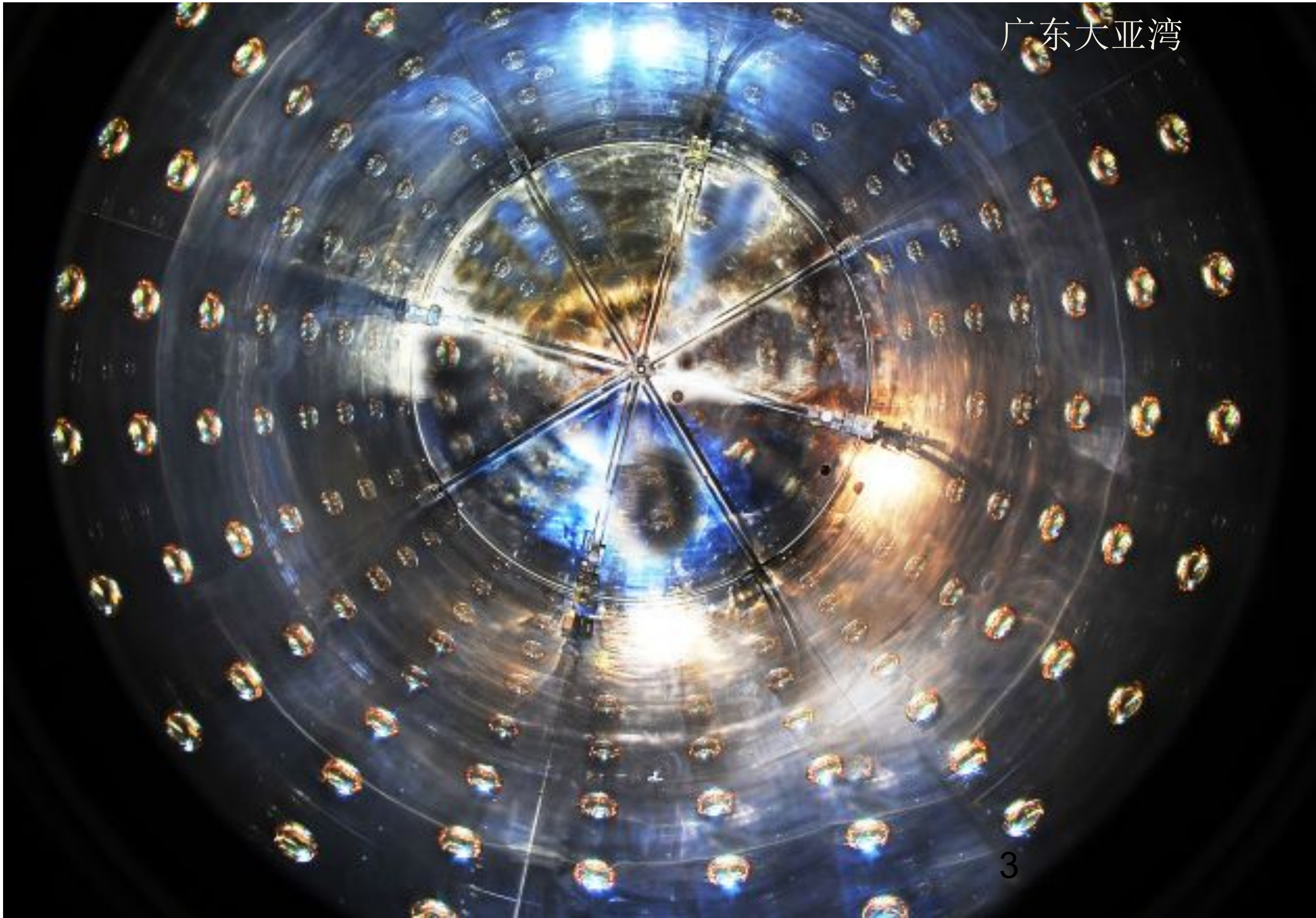
Some materials from Roger Forty's lecture

Example of high energy physics detectors



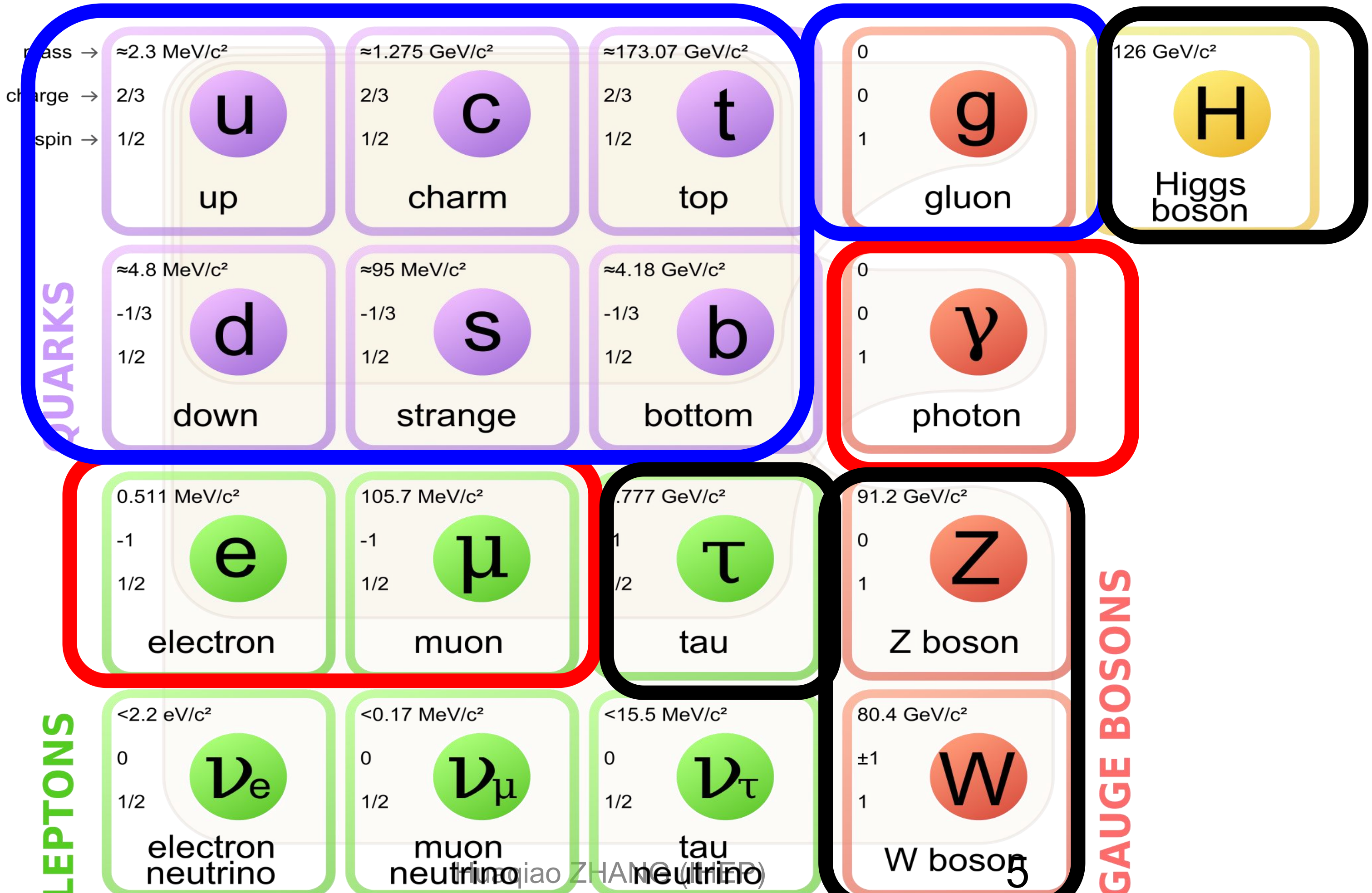
Example of high energy physics detectors



Example of high energy physics detectors

What particle to identify

- Long life time (Stable)
- Interaction with detectors => signals



Hadrons

- Instead of making do with jet reconstruction, often the physics under study requires the identification of *individual* hadrons
- Most are unstable, and decay into a few long-lived particles:

Particle	***m* [MeV]**	**Quarks**	**Main decay**	**Lifetime**	***c*τ [cm]**
$\pi^{\pm}$	140	$u\bar{d}$	$\mu\nu_{\mu}$	2.6 10^{-8} s	780
$K^{\pm}$	494	$u\bar{s}$	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2 10^{-8} s	370
K_S^0	498	$d\bar{s}$	$\pi\pi$	0.9 10^{-10} s	2.7
K_L^0	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5 10^{-8} s	1550
p	938	uud	stable	> 10^{25} years	
n	940	udd	$pe\nu_e$	890 s	2.7 10^{13}
Λ	1116	uds	$p\pi$	2.6 10^{-10} s	7.9

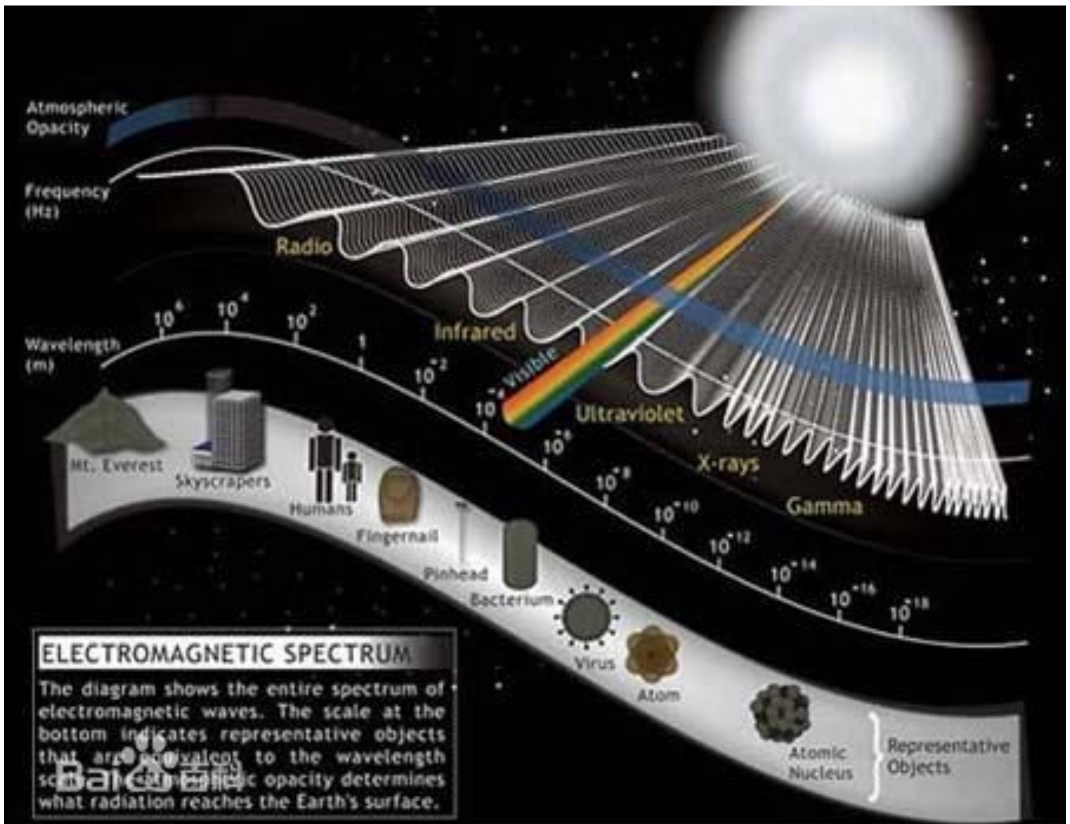
Outline

- General principle for particle identification

- Examples of High Energy physics detector
  - CMS detector
    - Photons/Electrons ID
    - Muons ID
    - Taus/jets ID
    - Others ID

例子：光子的探测

- 每个人都有的光子探测器



电磁波： 收音机
可见光： 眼睛
红外，紫外探测器等

高能物理探测的光子能量：
keV， MeV， GeV, even TeV

All particle ID are under certain conditions!!

General principle for particle identification

- Use interactions

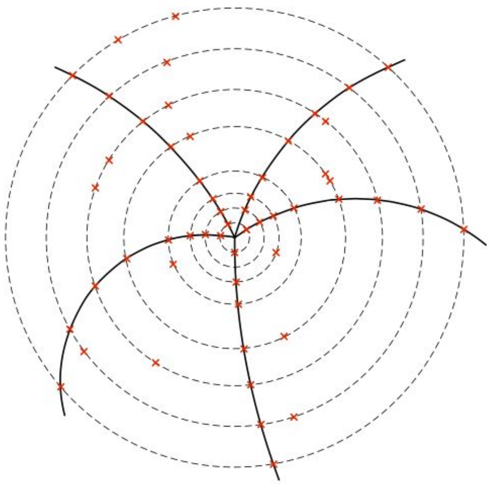
	电磁相互作用	弱相互作用	强相互作用	引力相互作用
源	电荷	弱荷	色荷	质量
作用强度	$\frac{e^2}{\hbar c} \simeq \frac{1}{137}$	$(\frac{m_p c}{\hbar})^2 \frac{G}{\hbar c} \sim 10^{-5}$	$\frac{g^2}{\hbar c} \simeq 10$	$\frac{G m_p^2}{\hbar c} \sim 10^{-38}$
力程 (m)	长程 ∞	短程 $\sim 10^{-18}$	短程 10^{-15}	长程 ∞
传递者	光子 γ	中间玻色子 $W^{\pm}$、Z^0	胶子 g	引力子(尚未发现) G
自旋宇称	1^-	$1^?$	1^-	2^+
质量(GeV)	$M_\gamma = 0$	$M_{W^\pm} = 80.4$ $M_{Z^0} = 91.2$	$M_g = 0$	$M_G = 0$
理论描述	电弱统一理论 (EW)		量子色动力学 (QCD)	几何动力学 (广义相对论)

表 1.1: 四种相互作用的性质

How to Identify particles?

- The signature of these particles
  - Interactions with material
  - Masses
  - Lifetime
  - C,P,S… quantum numbers
- Methodology
  - For charged particles:
    - Measurement of their mass
    - Interaction with absorbers
  - For neutral and stable particle
    - Interaction with absorbers
  - For unstable particles
    - Study the decay products

Charged particles ID



- **Everyone has charge**
  - *Determinate their **mass** to ID particles*
- ***p* = γ *m v***
  - momentum is measured by the check the curving in the magnet field of tracking system: pT = q B R
  - Then need to know the **velocity**

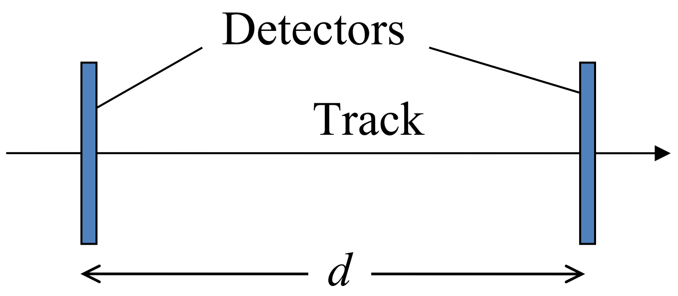
- Velocity measured by 4 main processes :
  1. **Time Of Flight** (TOF) of the particles over a fixed distance
  2. Alternatively one can look at the detail of their interaction with matter
     The main source of energy loss is via **Ionization** (*dE/dx*)
  3. If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as **Transition radiation**
  4. If a particle travels at *greater* than the local speed of light, it will radiate **Cherenkov radiation**

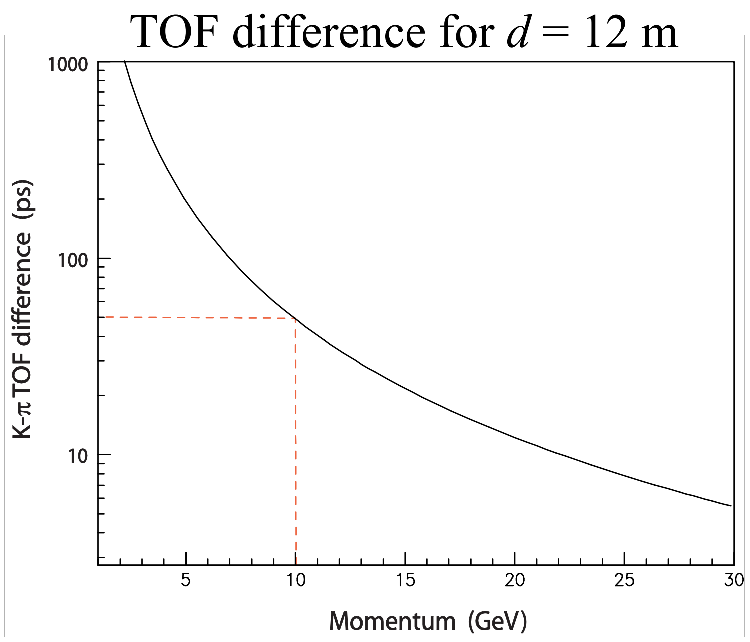
Time Of Flight

- Simple concept: measure the time difference between two detector planes
  $\beta = d / c\Delta t$
- At high energy, particle speeds are relativistic, closely approaching to *c*
- For a 10 GeV K, the time to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps

$$\delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$

- Moderr have resolution σ_t ~ 10 ns, fast enough for the LHC (bunch crossings 25 ns apart) but need σ_t < 1 ns to do useful TOF
- TOF gives good ID at low momentum
  Very precise timing required for *p* > 5 GeV

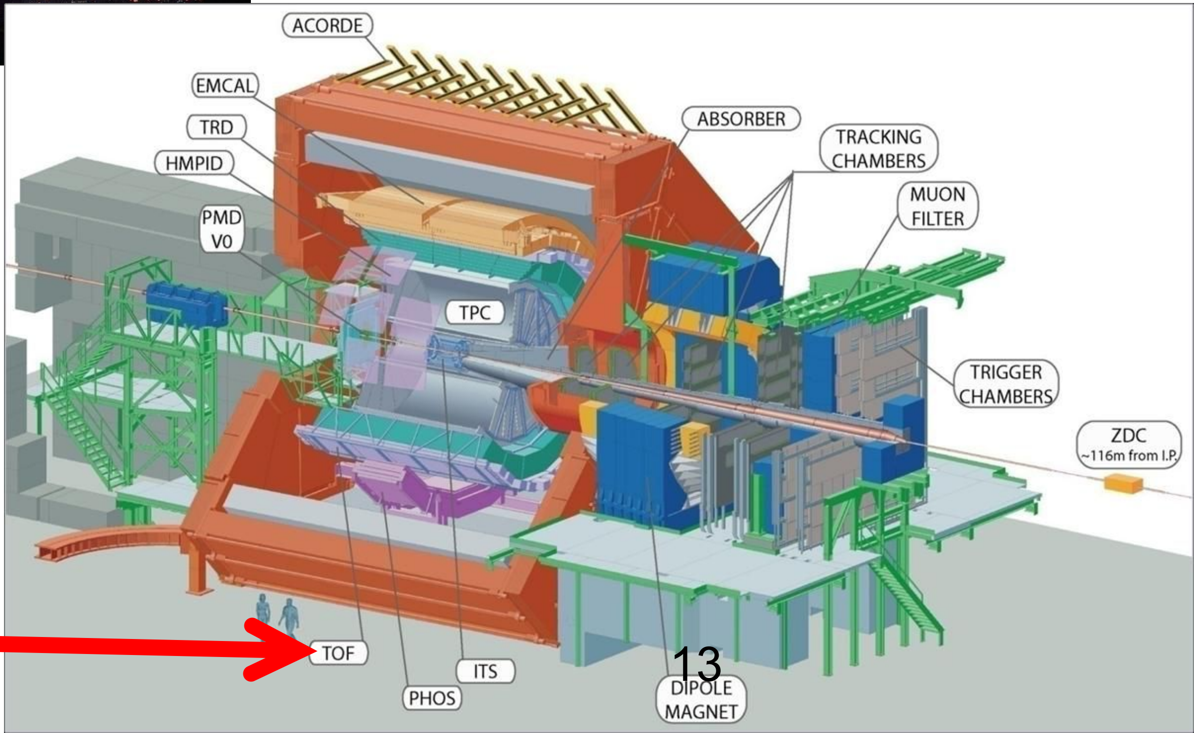




Example usage

对于远处的闪电
先看到闪电： 光波（光子）
后听到雷声： 声波（声子）

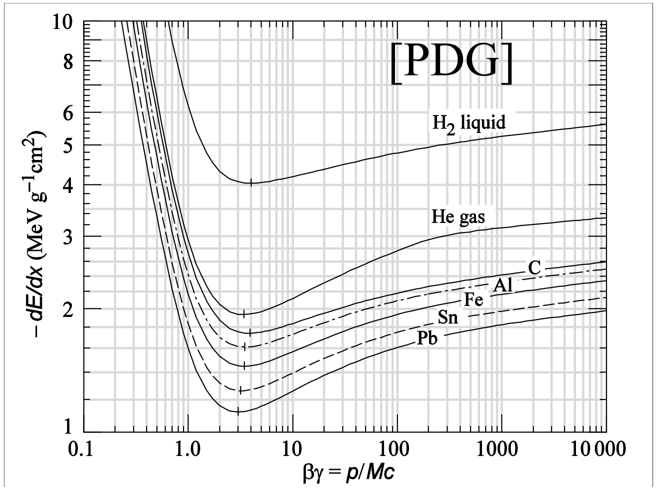
对于太近的闪电，人耳可能无法区分闪电和雷声的先后

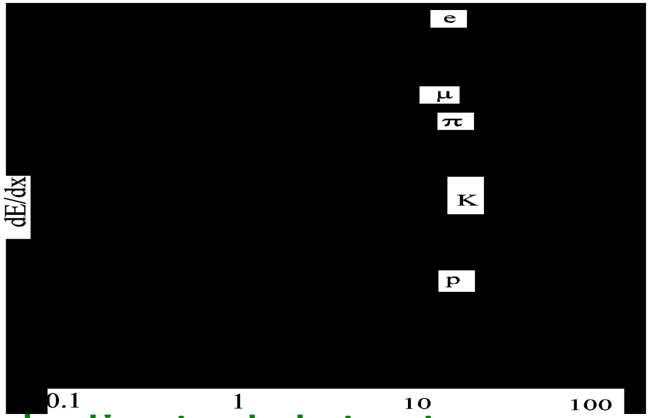


TOF在ALICE实验上的运用

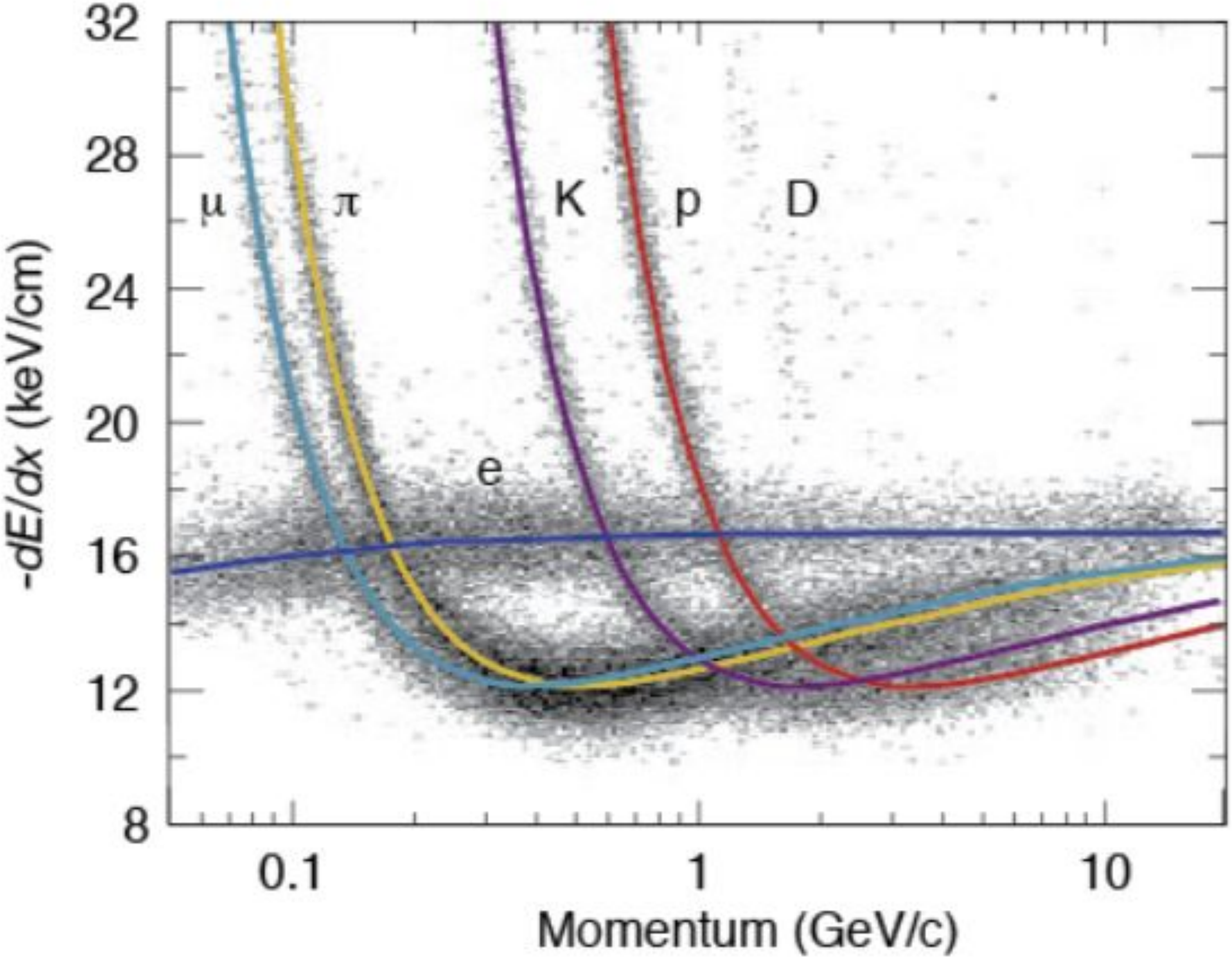
Ionization

- Charged particles passing through matter can knock out electrons from atoms of the medium: *ionization*
- Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence: $dE/dx \propto \log(\beta^2 \gamma^2) / \beta^2$
- This can be used to identify particles, particularly at low momentum where *dE/dx* varies rapidly
- *Advantage:* uses existing detectors needed for tracking (but requires the accurate measurement of the charge)
- *Note:* these techniques all provide signals for charged *leptons* e, μ as well as π, K, p
  But $m_\mu \approx m_\pi$, so they are not well separated (dedicated detectors do a better job)





Examples



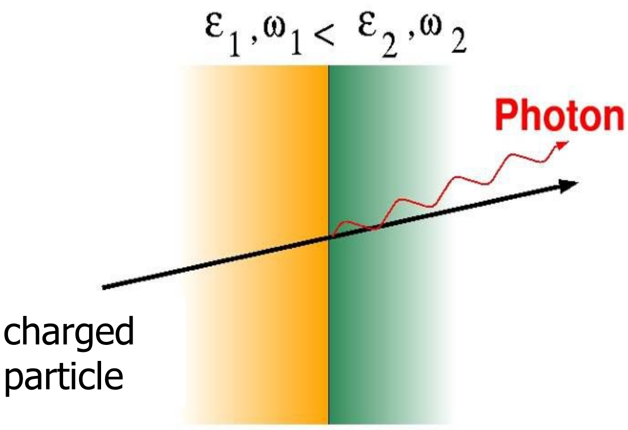
Transition radiation

- Local speed of light in a medium with refractive index n is $c_p = c/n$

- If its relative velocity $\boldsymbol{v}/c_p$ changes, a particle will radiate photons:
  1. Change of direction $\boldsymbol{v}$ (in magnetic field) $\rightarrow$ Synchrotron radiation
  2. Change of $|v|$ (passing through matter) $\rightarrow$ Bremsstrahlung radiation
  3. Change of refractive index n of medium $\rightarrow$ Transition radiation

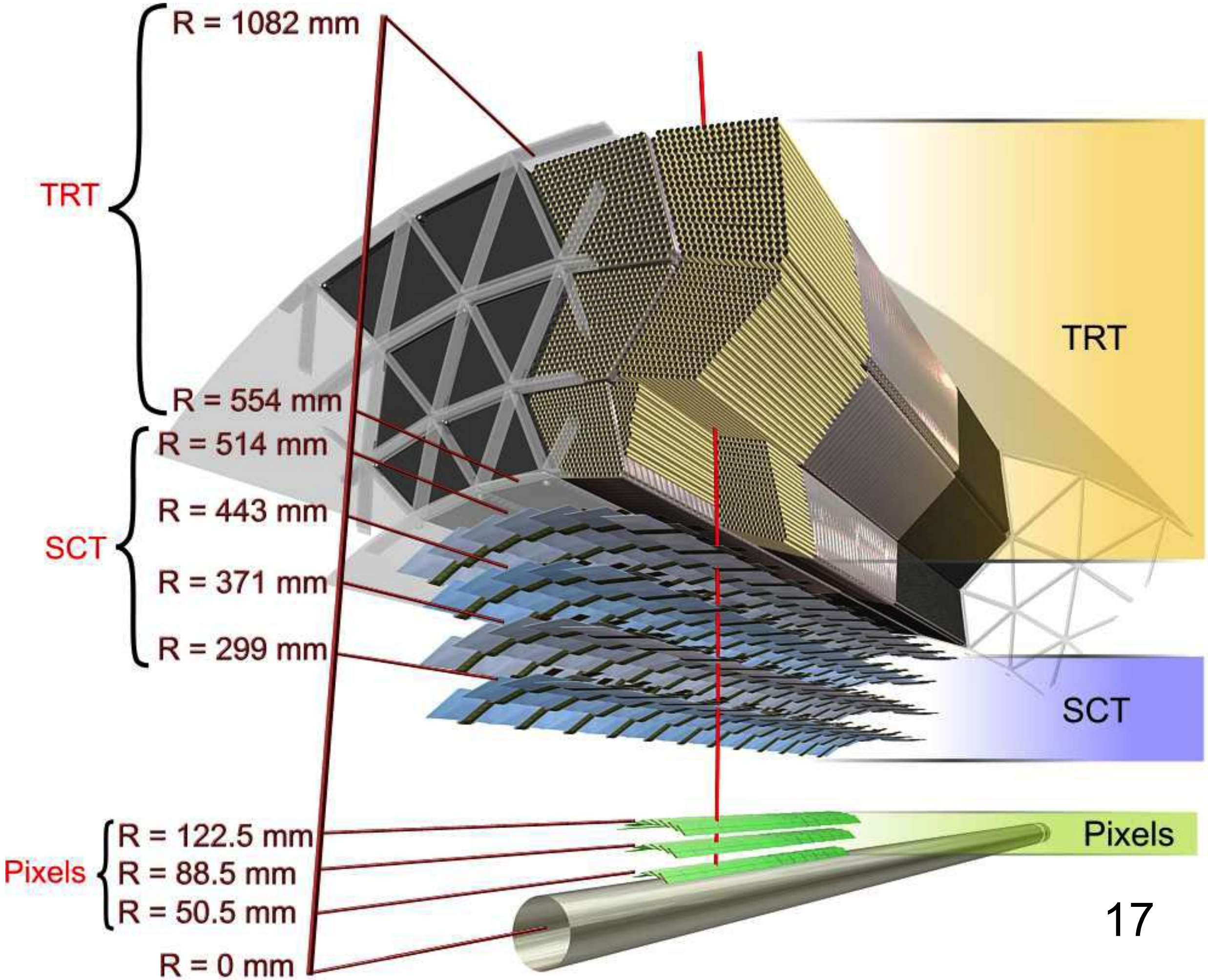
- Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)

- The energy emitted is proportional to the boost γ of the particle
  - Particularly useful for electron ID
  - Can also be used for hadrons at high energy



Example usage: ATLAS TRT

- Transition Radiation Tracker
  - Electron has faster velocity than other hadrons for same momentum

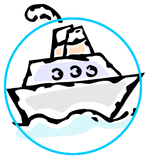


Cherenkov light

- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (he won the Nobel Prize for it in 1958)
- From Relativity, nothing can go faster than the speed of light *c* (in vacuum)
- However, due to the refractive index *n* of a material, a particle *can* go faster than the *local* speed of light in the medium $c_p = c/n$
- This is analogous to the bow wave of a boat travelling over water
or the sonic boom of an aeroplane travelling faster than the speed of sound

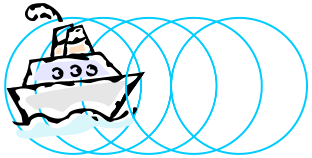
Propagating waves

- A stationary boat bobbing up and down on a lake, producing waves



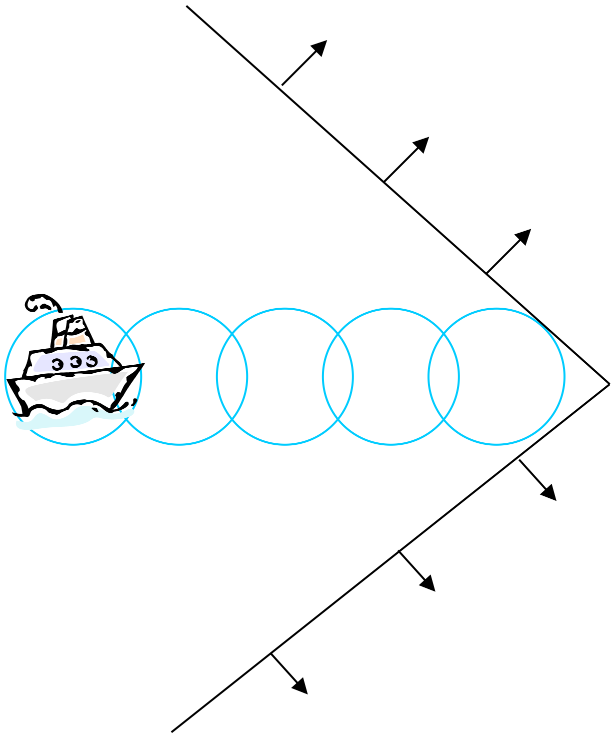
Propagating waves

- Now the boat starts to move, but slower than the waves
- No coherent wavefront is formed



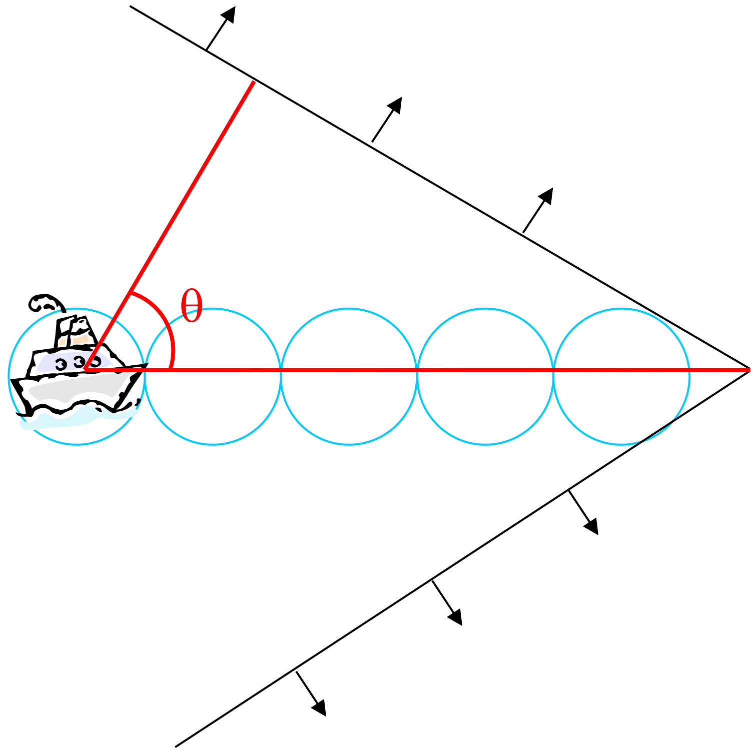
Propagating waves

- Next the boat moves faster than the waves
- A coherent wavefront is formed



Propagating waves

- Finally the boat moves even faster
- The angle of the coherent wavefront changes

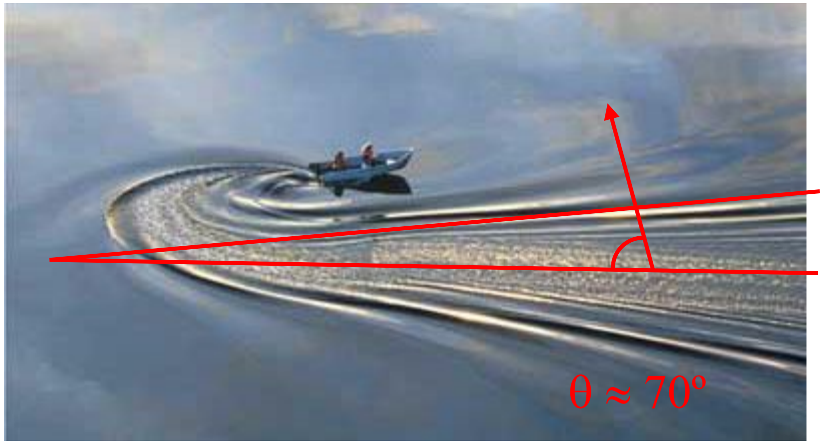


$$\cos\theta = v_{wave} / v_{boat}$$

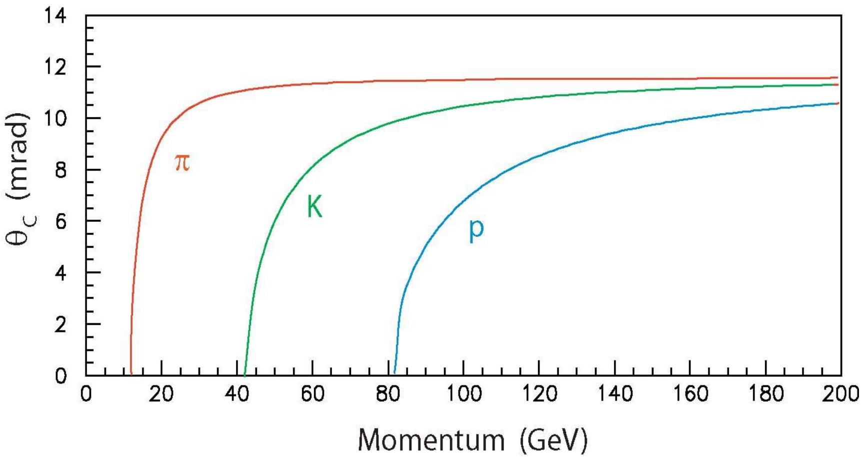
Speed calculation

- Using this construction, we can determine (roughly) the boat speed:
  θ 70°, v_{wave} = 2 km/h on water
  $\rightarrow$ $v_{boat} = v_{wave}/\cos\theta$ 6 km/h
- Cherenkov light is produced when charged particle ($v_{boat} = \beta c$) goes faster than the speed of light ($v_{wave} = c/n$)

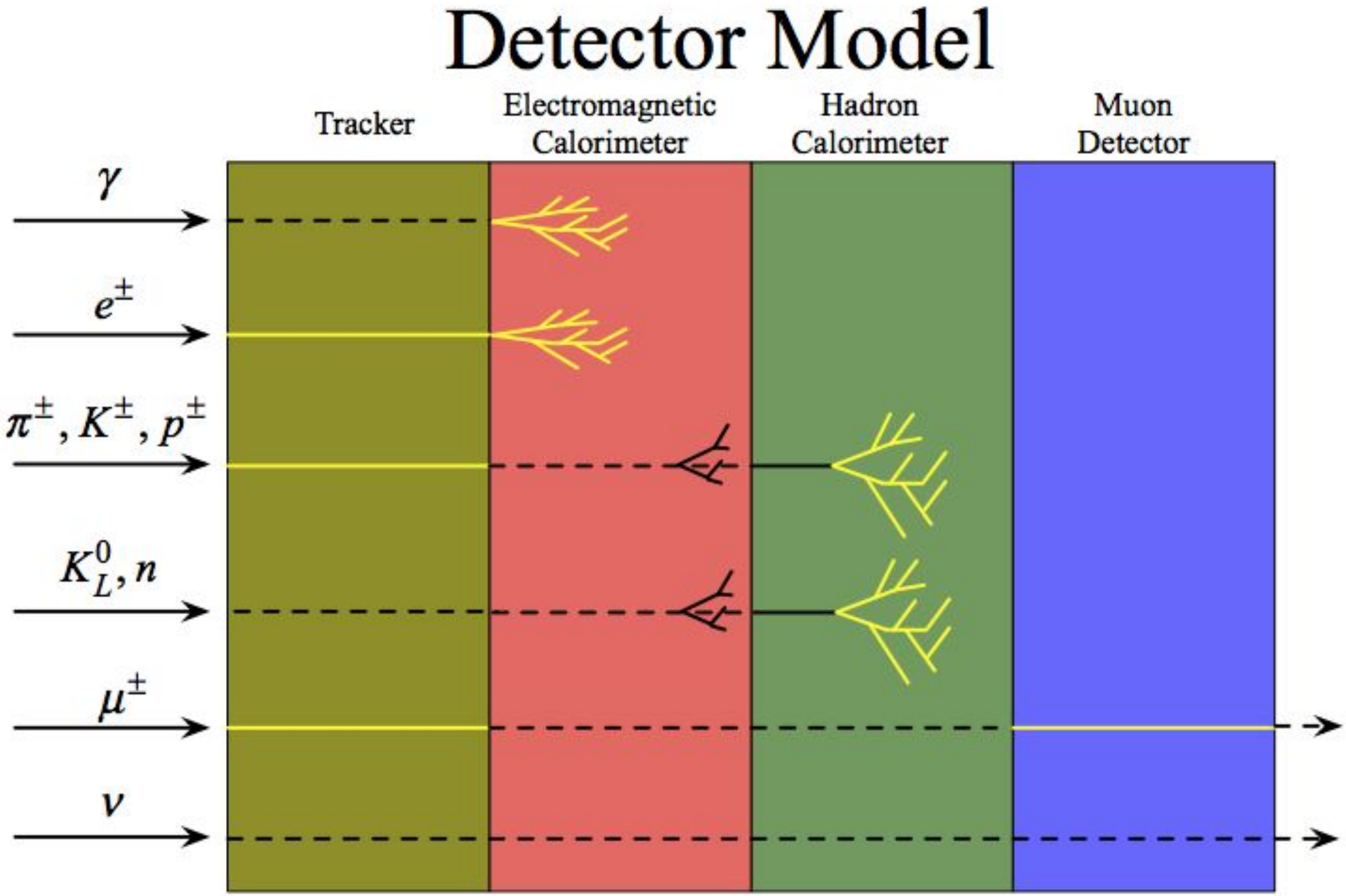
  $\rightarrow$ $\cos\theta_C = 1 / \beta n$
- Produced in three dimensions, so the wavefront forms a *cone* of light around the particle direction
- Measuring the opening angle of cone $\rightarrow$ particle velocity can be determined



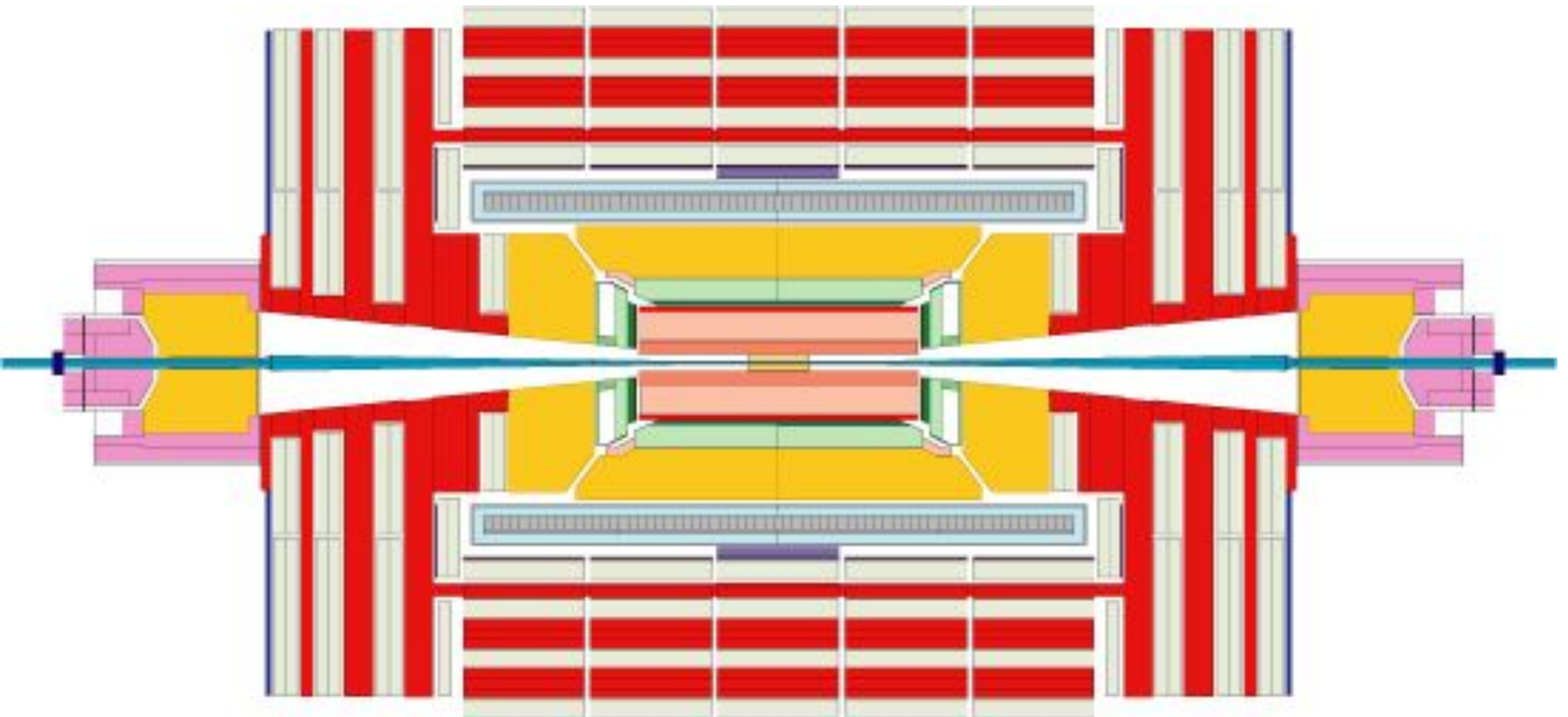
For Ne gas (n = 1.000067)



Stable particle identification

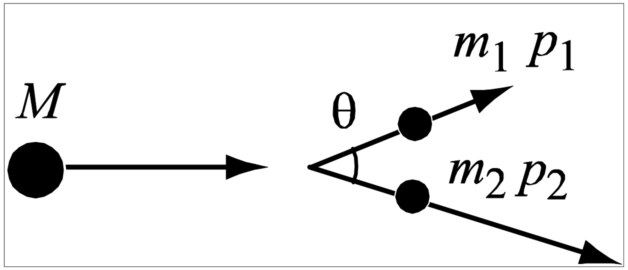


Examples: CMS detector



Unstable particle ID: two body decay

- ***$E^2 = p^2 + m^2$***
  - The full expression is $E^2 = p^2c^2 + m^2c^4$ but factors of *c* are often dropped
- Consider a particle that decays to give two daughter particles:

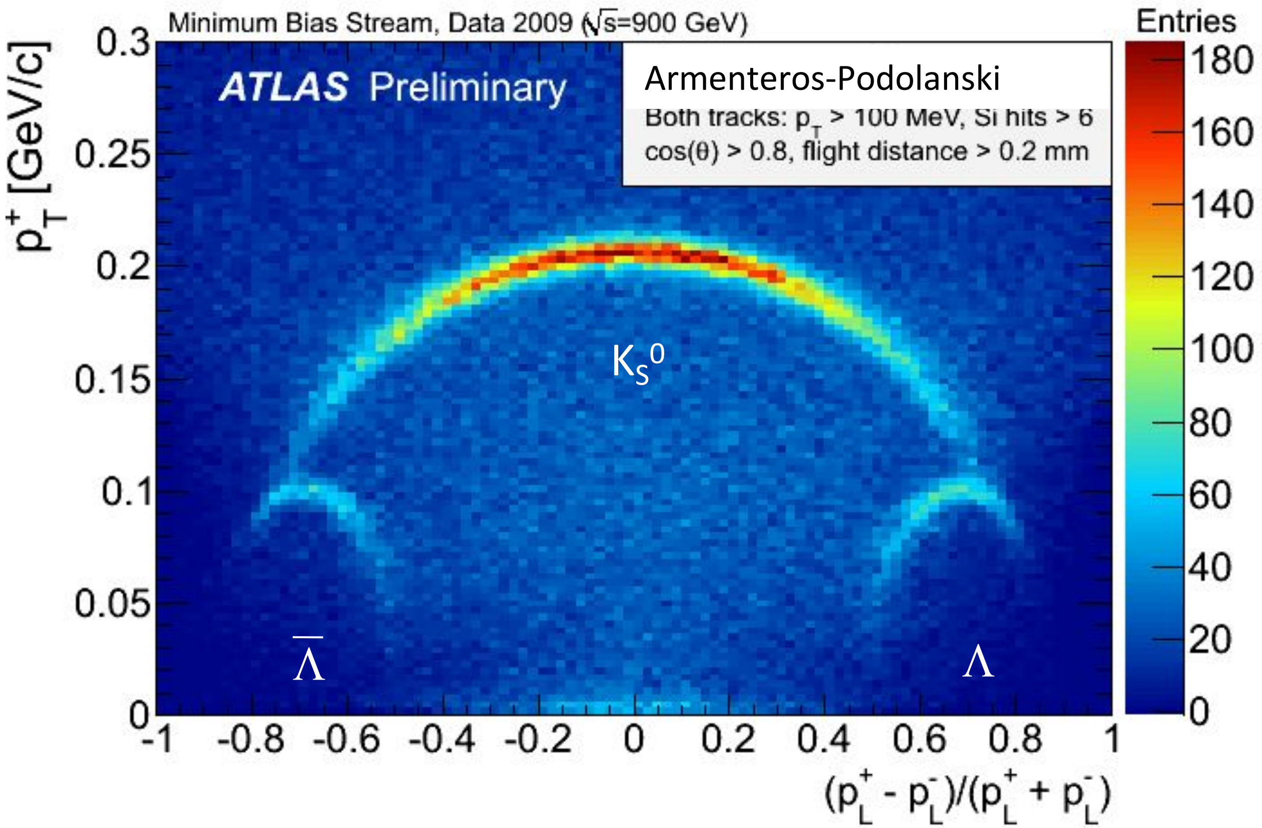


- The *invariant mass* of the two particles from the decay:
- $M^2 = m_1^2 + m_2^2 + 2(E_1E_2 - p_1p_2\cos\theta)$

- $\rightarrow$ to reconstruct the parent mass a precise knowledge of the momentum and the angle θ of decay products is needed, from the tracking system, as well as their particle type, which determines their masses m_1 and m_2

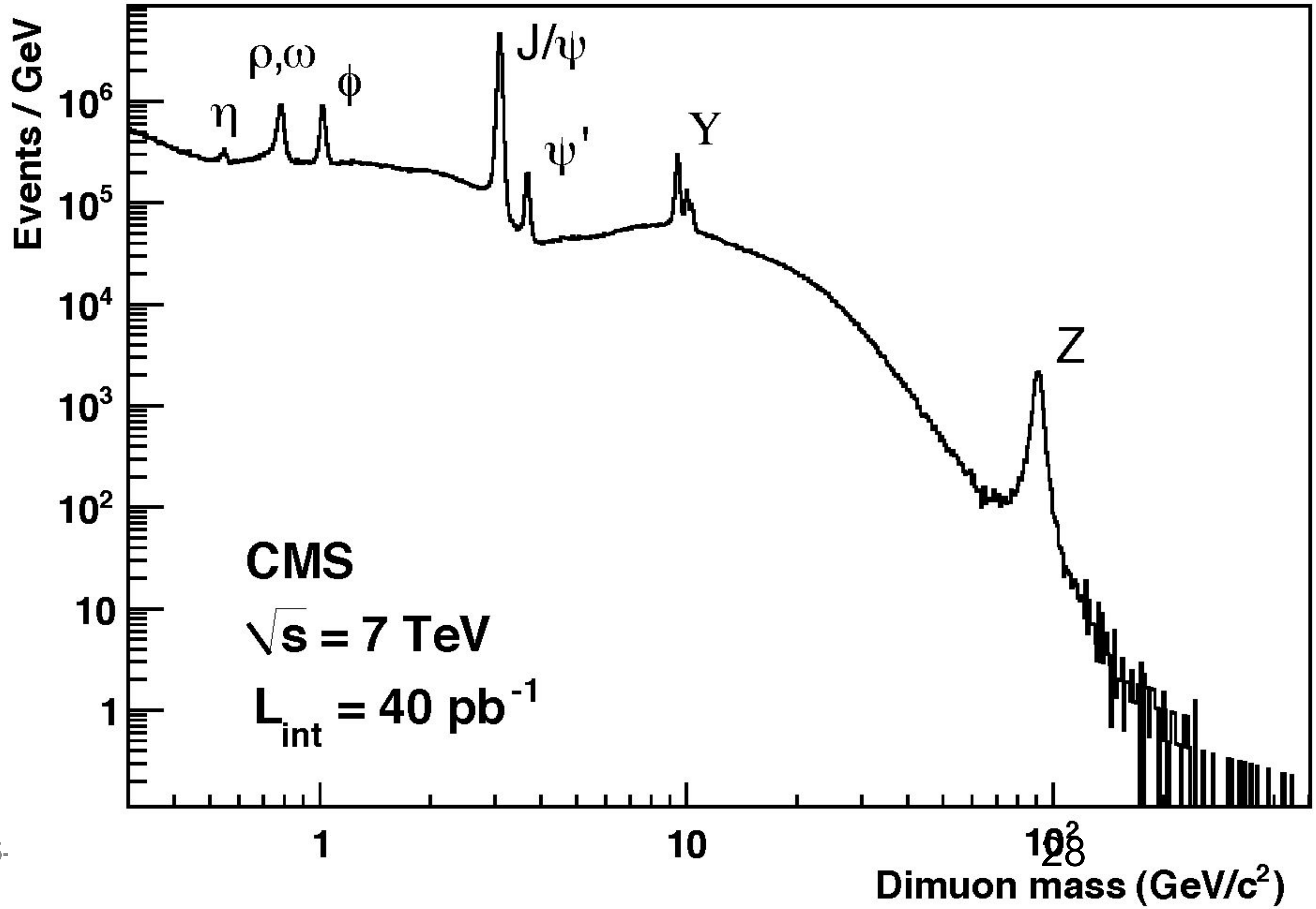
V^0 2-prong decay reconstruction

- V^0s can be reconstructed from the kinematics of their positively and negatively charged decay products, without needing to identify the π or p

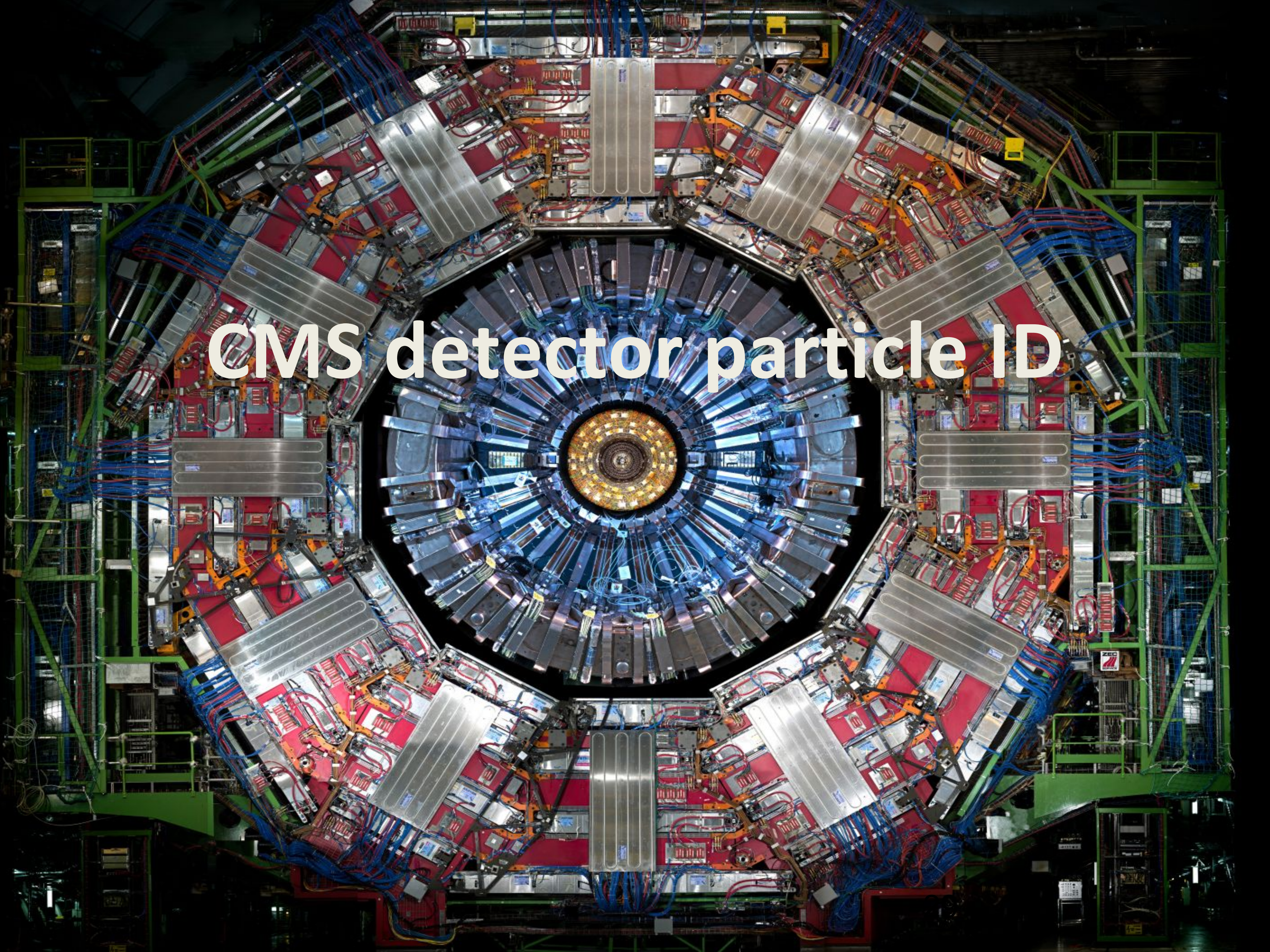


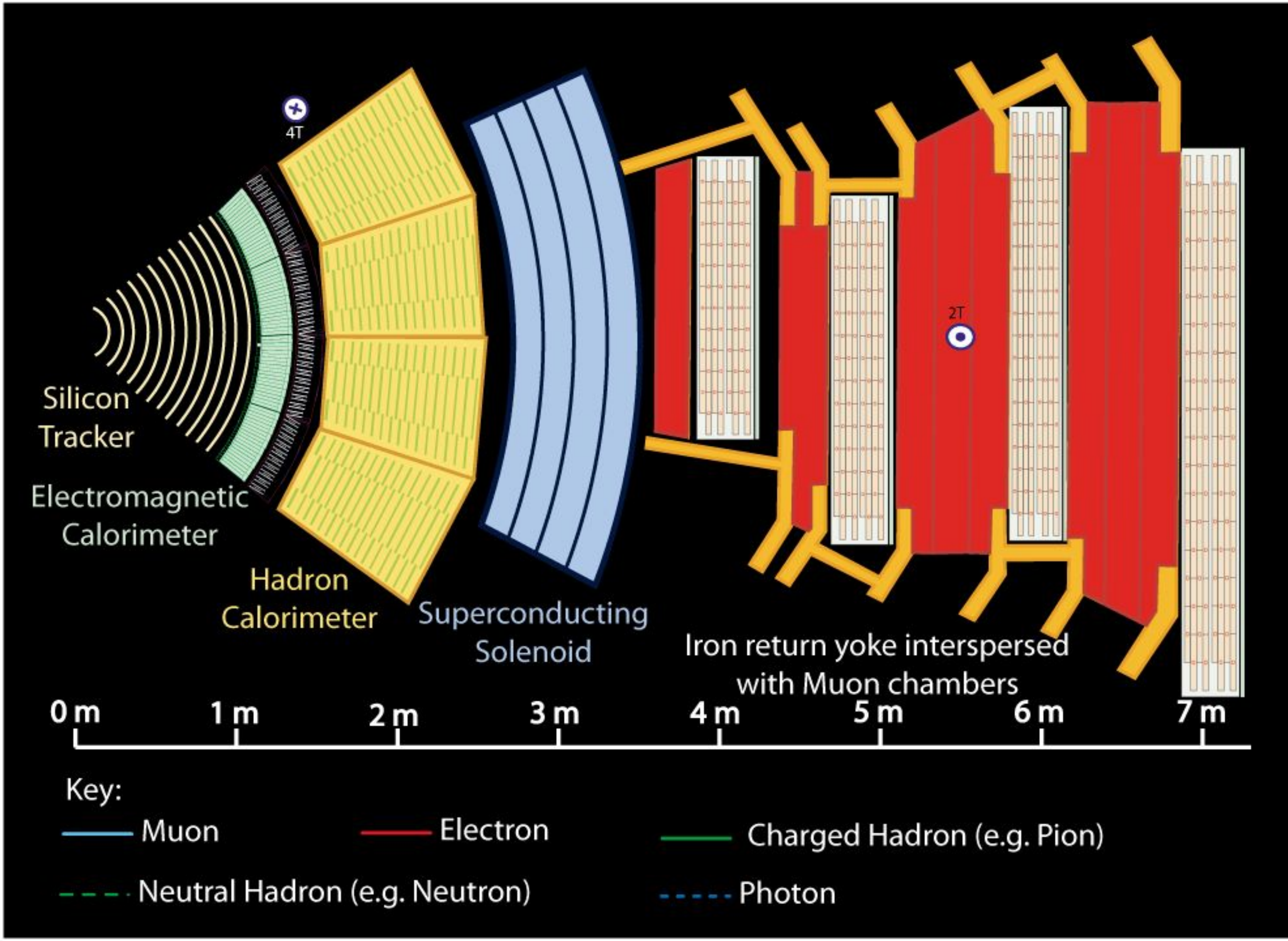
Mass reconstruction

- $M^2 = (E_1+E_2+..+E_n)^2-(p_1+p_2+..+p_n)^2$



CMS detector particle ID

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Key:
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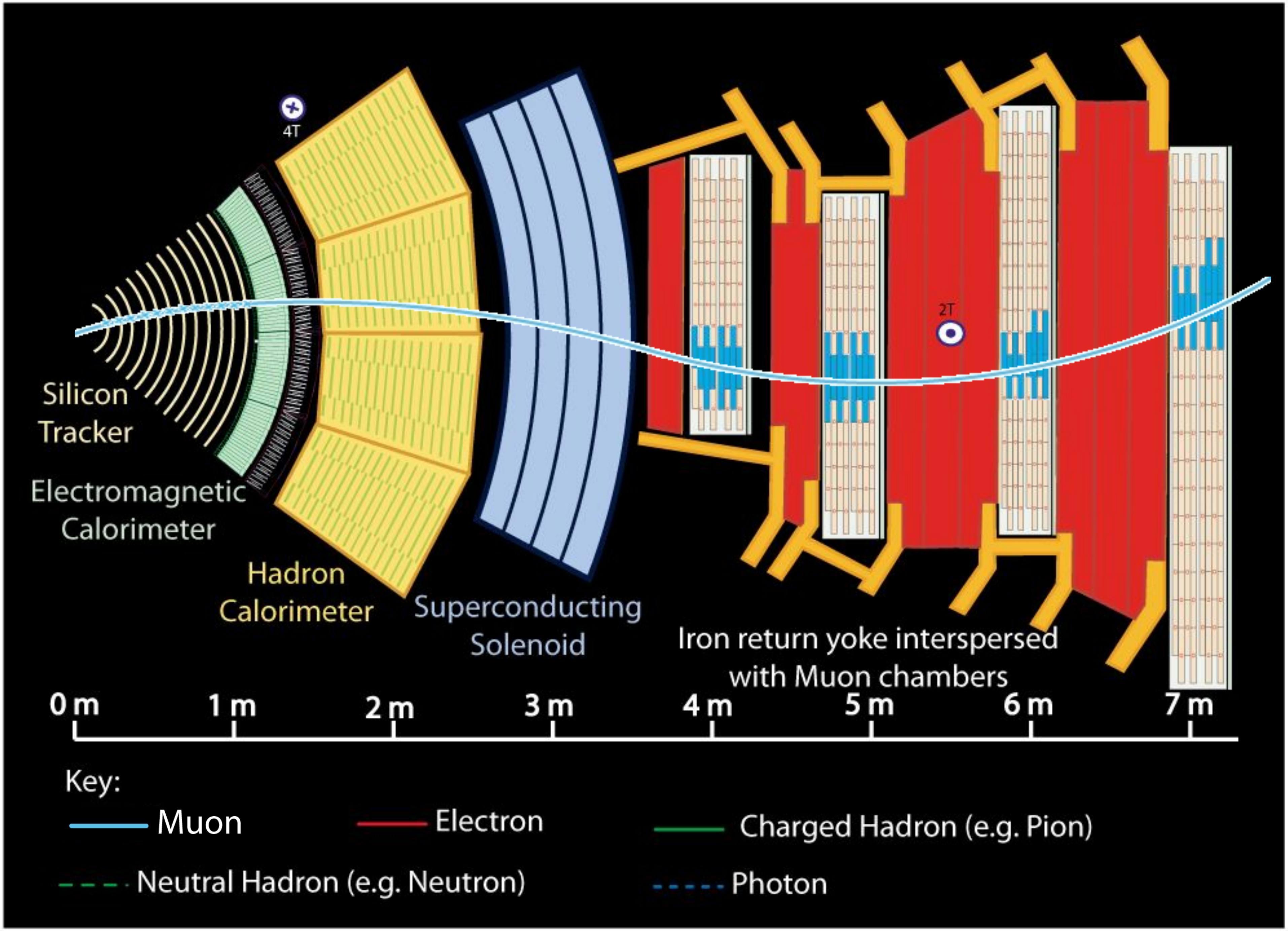
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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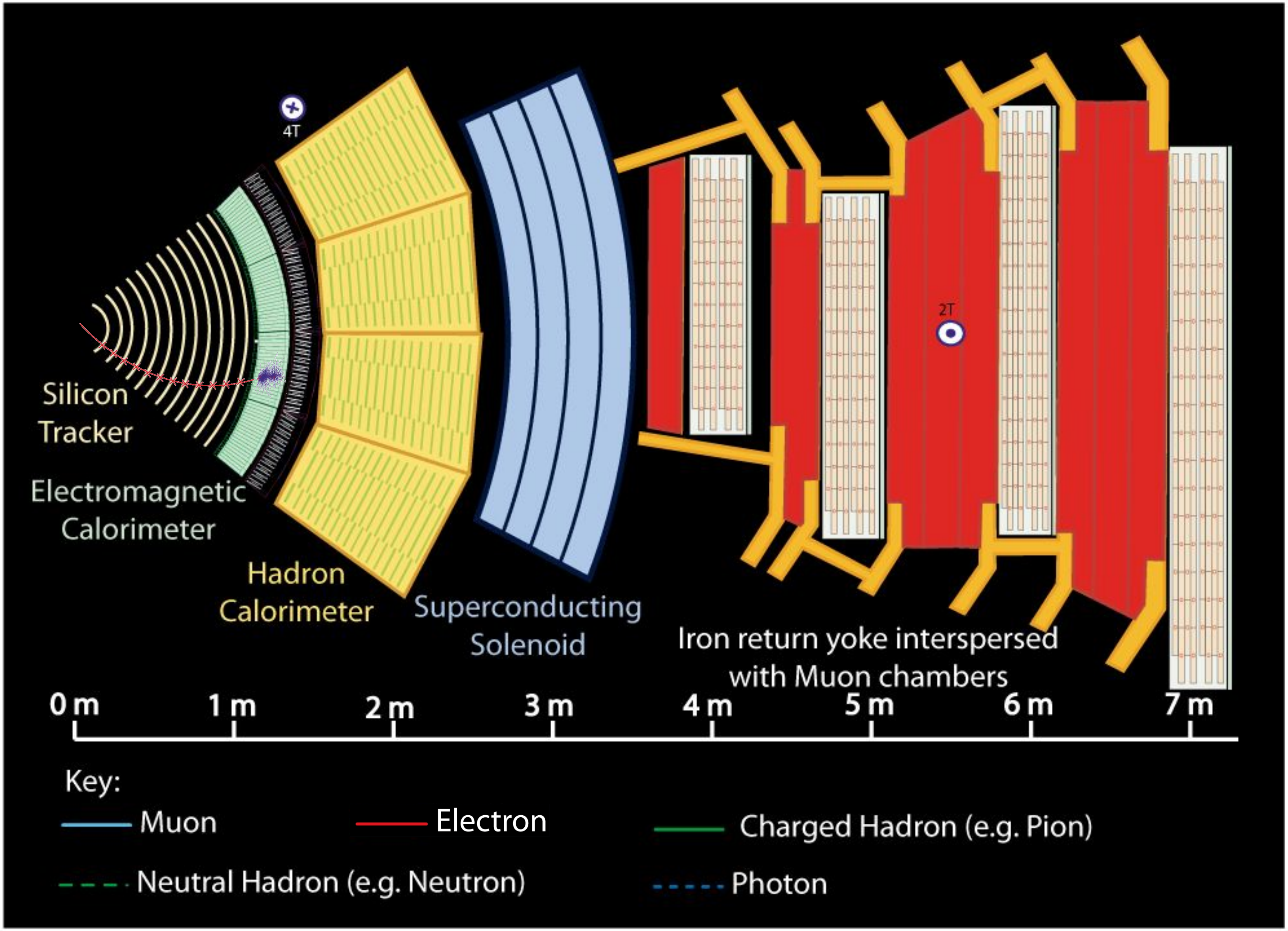

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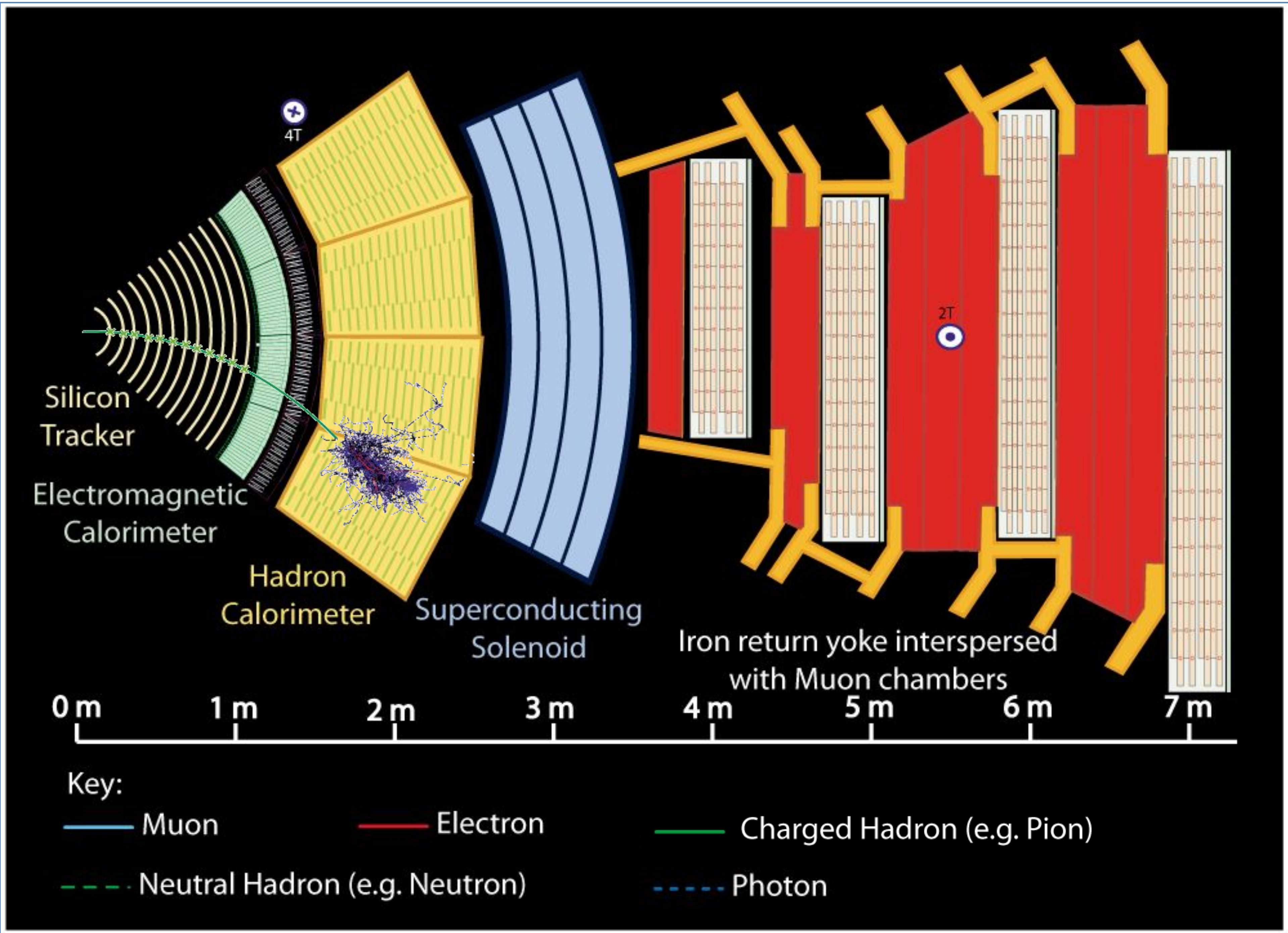
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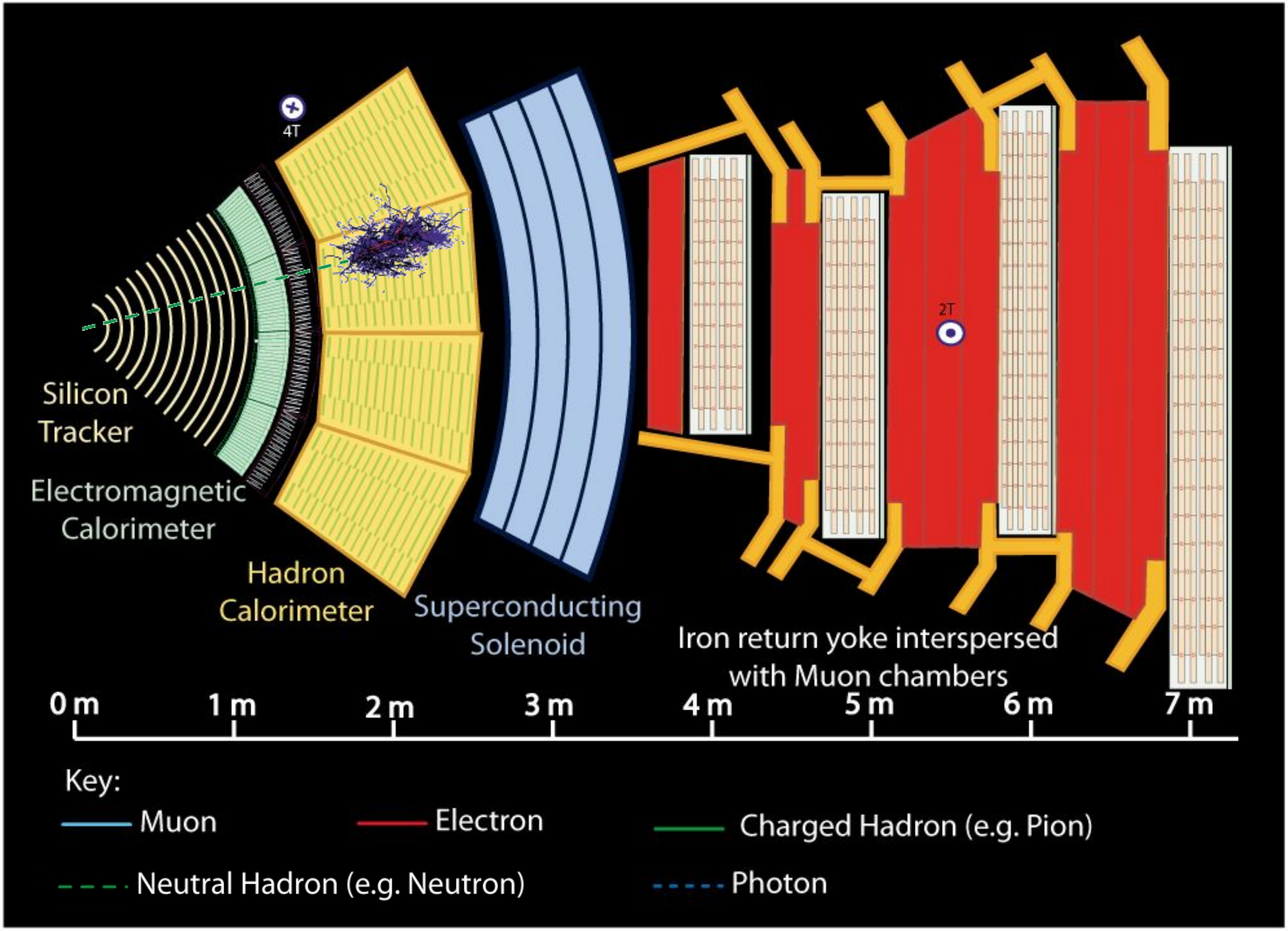
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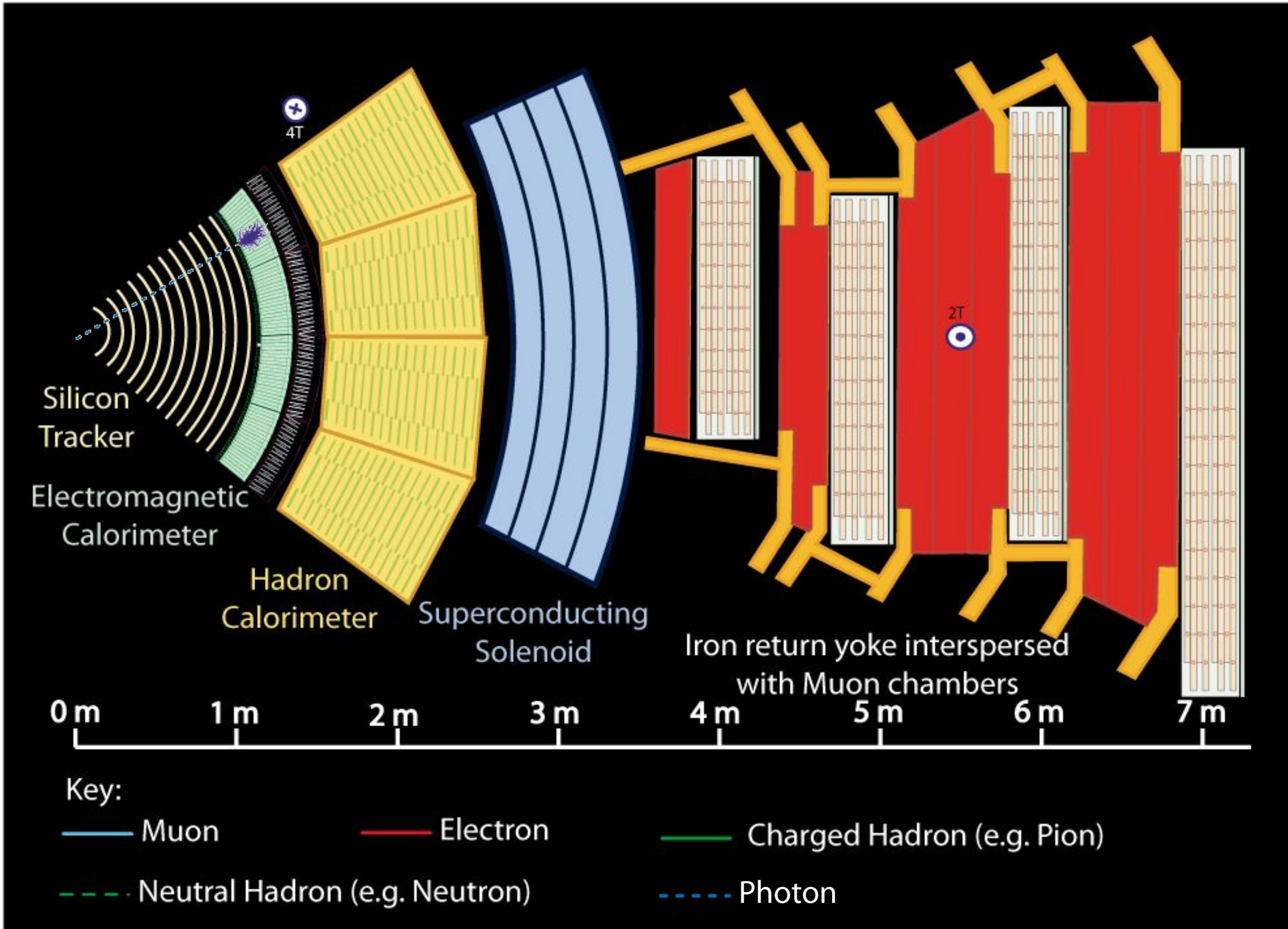

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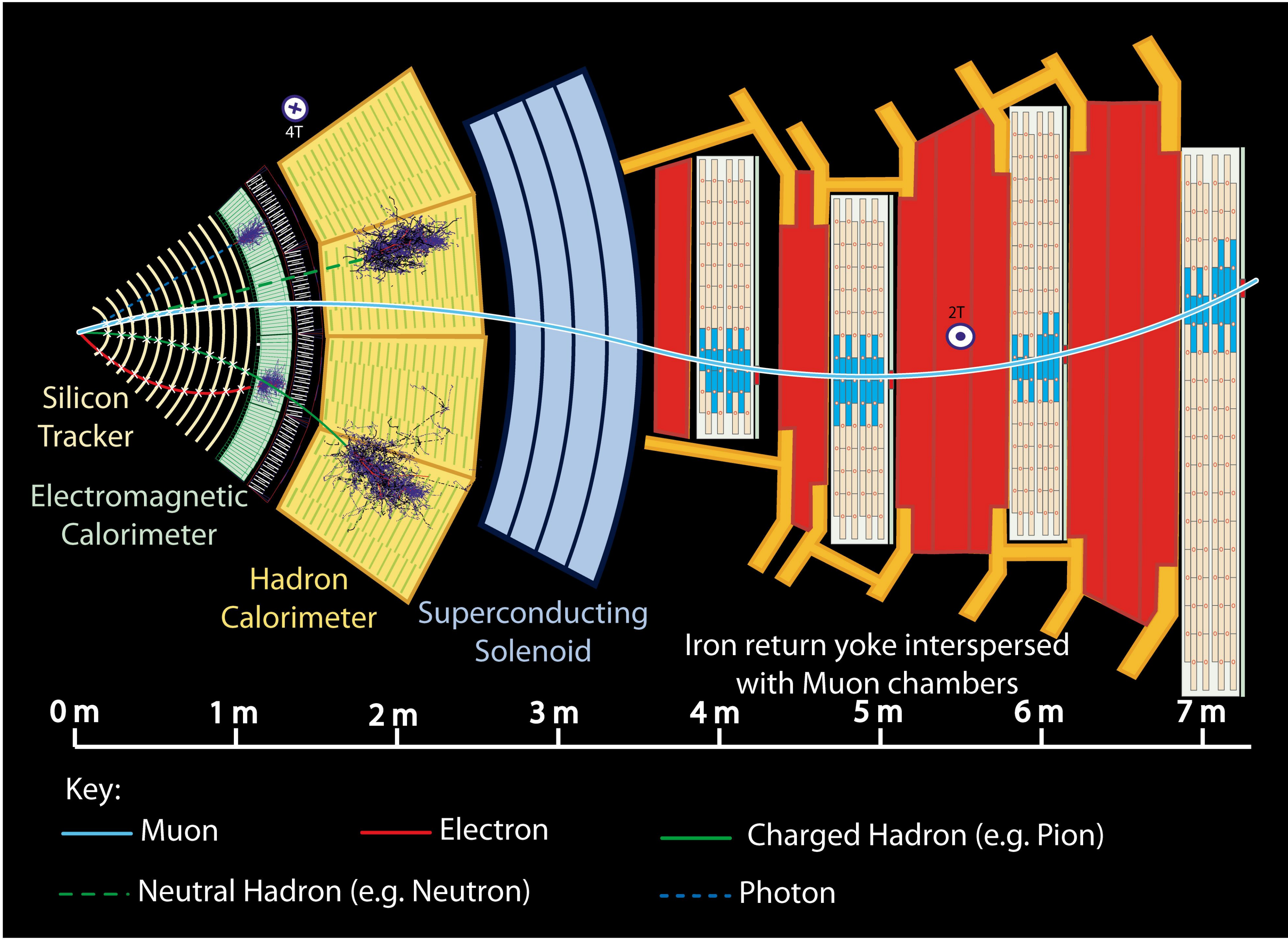
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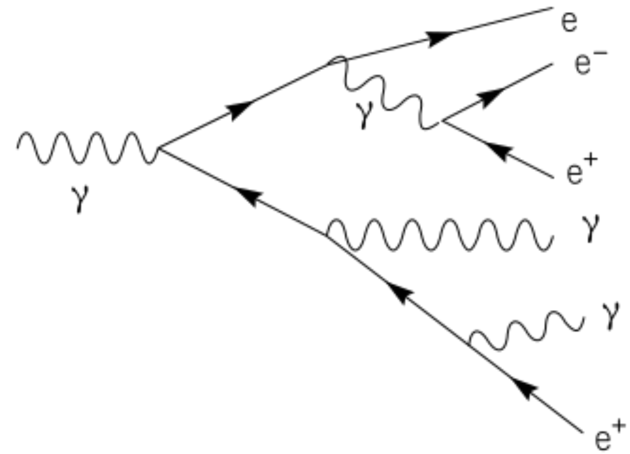
e/γ identification (1)

- When incident on matter at high energy, photons convert to e^+e^- pairs Since the electrons (and positrons) produce more photons by Bremsstahlung, a shower develops of $e^\pm$ and γ, until the energy of the incident particle has been used up
  - Special shower profile



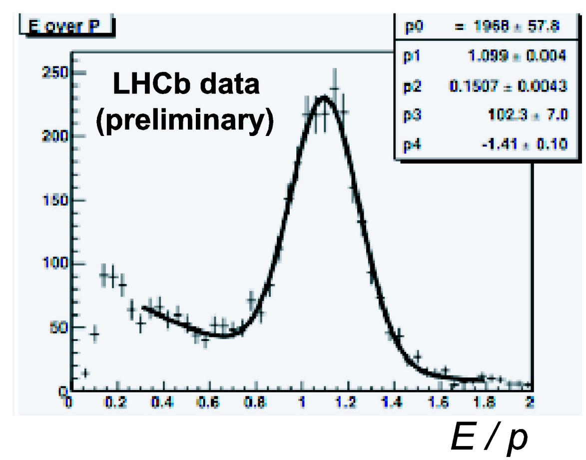
- Such showers are similar for electrons and photons Distinguished by the existence (or not) of a track associated to the shower

e/γ identification (2)

- Radiation length X_0 = mean distance to reduce energy by 1/*e*
  eg X_0 = 1.76 cm for Fe, so these *electromagnetic* showers are compact

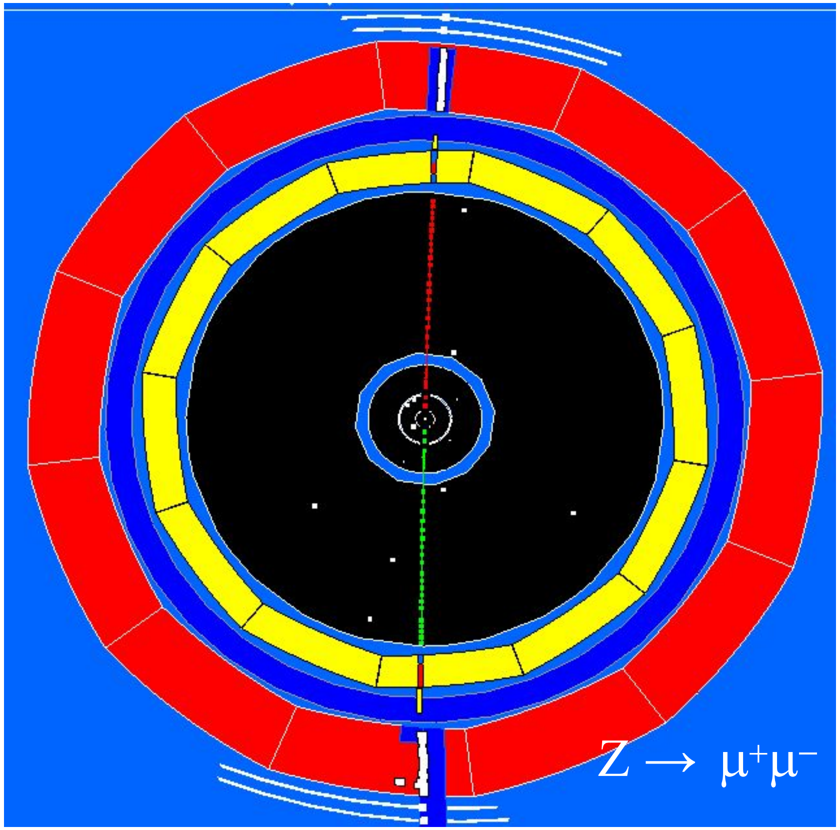
- Distinguish electron/photon by the existence (or not) of a track associated to the shower

- For the electron, *E* (energy measured in EM calorimeter) and *p* (momentum from tracker) should be equal: $E/p = 1$
- Not the case for other charged particles



Muons

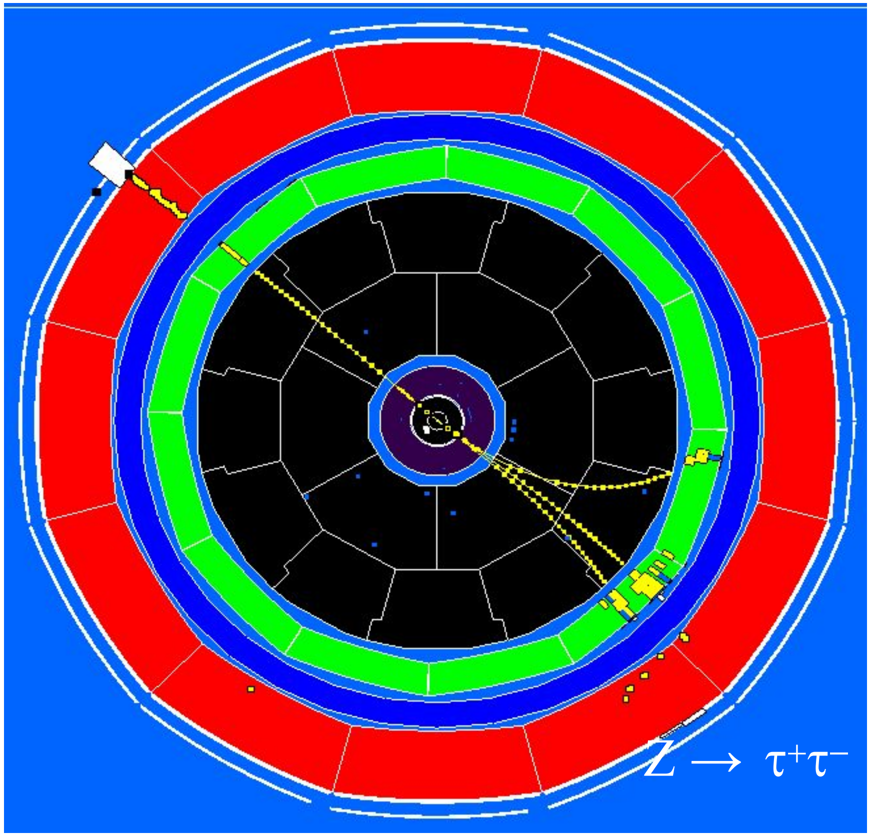
- Muons act like heavier versions of the electron, with mass 105.7 MeV
- They decay to electrons $\mu^- \to e^- \nu_e \nu_\mu$ with (proper) lifetime $\tau_\mu = 2.2\ \mu s$
- Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where *velocity* $\beta = v/c$
  boost $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$
- So a 10 GeV muon flies ~ 60 km before decay >> detector size
- effectively stable
- Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction



most penetrating charged particle

Tau leptons

- Taus are heavier still, m_τ = 1.78 GeV
- Heavy enough that can decay to many final states: $\tau^- \to \mu^- \nu_\mu \nu_\tau$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$, $\pi^- \pi^- \pi^+ \nu_\tau$, …
- Lifetime τ_τ = 0.29 ps (ps = 10^{-12} s) so a 10 GeV tau flies ~ 0.5 mm
- This is typically too short to be seen directly in the detectors
  - Instead the decay products are seen
- Accurate vertex detectors can detect that they do not come exactly from the interaction point



Quarks

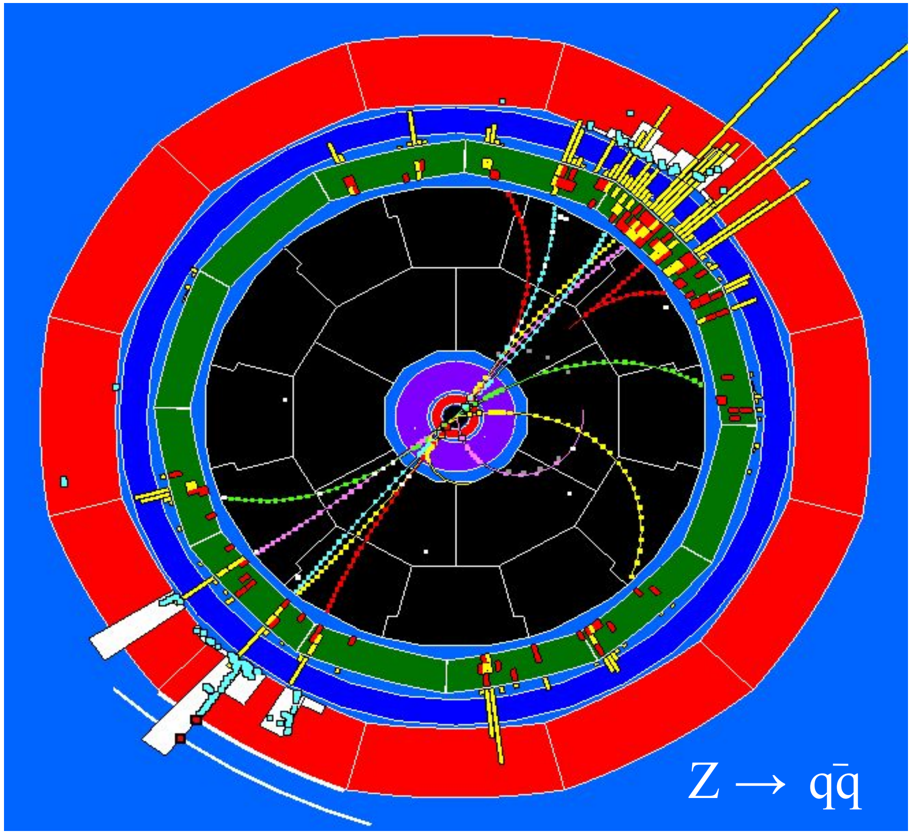
- Quarks feel the strong interaction, mediated by gluons

- Not seen in the detector, due to confinement property of QCD

- Instead, they *hadronize* into mesons (qq) or baryons (qqq)

- At high energy >> m_q
initial quark (or gluon) produces a "jet" of hadrons

- Gluon and quark jets are difficult to distinguish:
gluon jets tend to be wider, and have a softer particle spectrum



Jet reconstruction

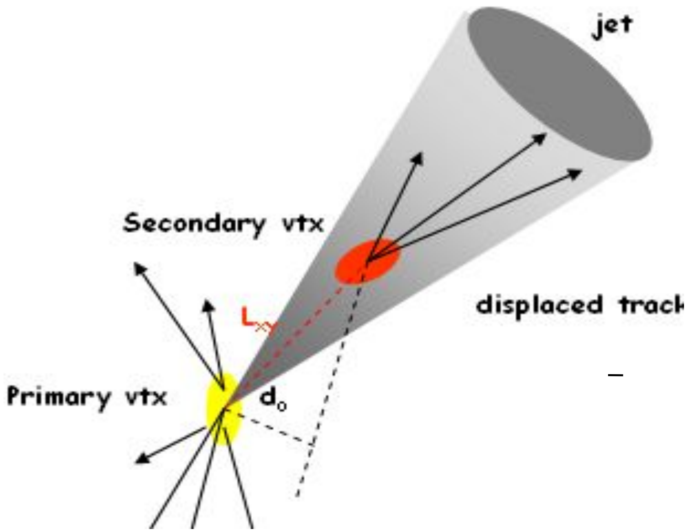
- **Jets are reconstructed by summing up the particles assigned to the jet**

- Typically check within a cone size around the direction of a "seed" particle, or by iteratively adding up pairs of particles that give the lowest invariant mass

- Different quark flavours can be separated (at least statistically) by looking for displaced tracks from b- and c-hadron decays

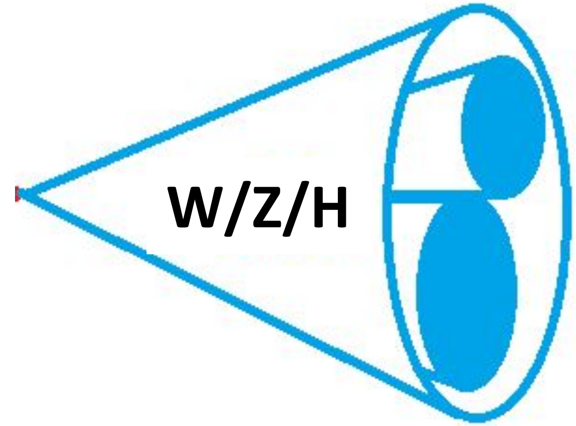
- The jet properties can be used to approximate the quark or gluon

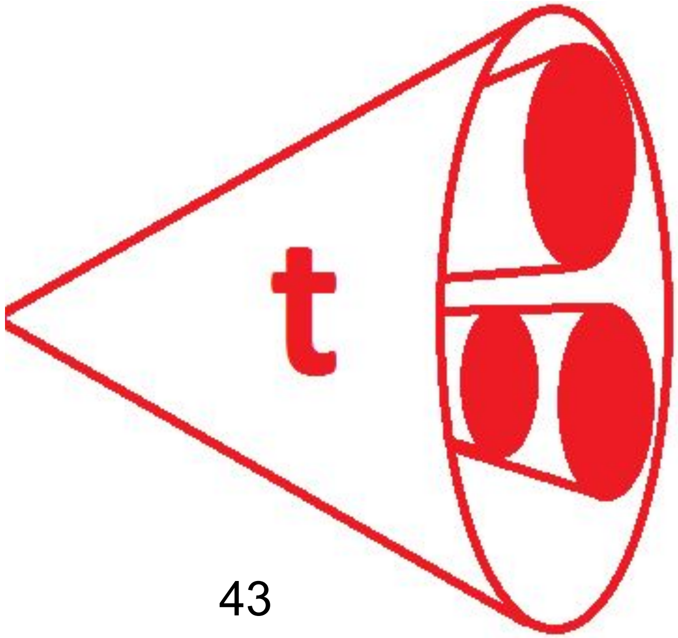
- Special alg. Used to ID b-jets: life time



Boost objects

- Highly boosted W/Z/H/t…
  - Typical Pt > ~500 GeV
  - Form a big fat jet
  - With several energy centers
  - Invariant mass
  - b-jets inside
- Very interesting for higher energy colliders (> ~13TeV)





Neutrinos

- Neutral (i.e. no track) and only weak interaction
  - pass though matter easily
- Interaction length $\lambda_{int} = A/(\rho\sigma N_A)$, cross section $\sigma \sim 10^{-38}$ cm$^2 \times E$ [GeV]
  - a 10 GeV neutrino can pass through > million km of rock
- Neutrinos are usually detected in HEP experiments through *missing energy* (applying *E* conservation to rest of the event, usually in transverse plane E_T)

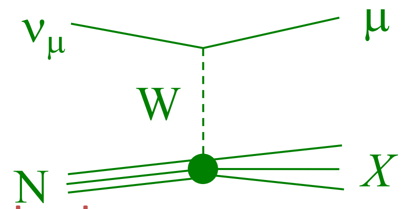
- Dedicated experiments can also identify neutrinos

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

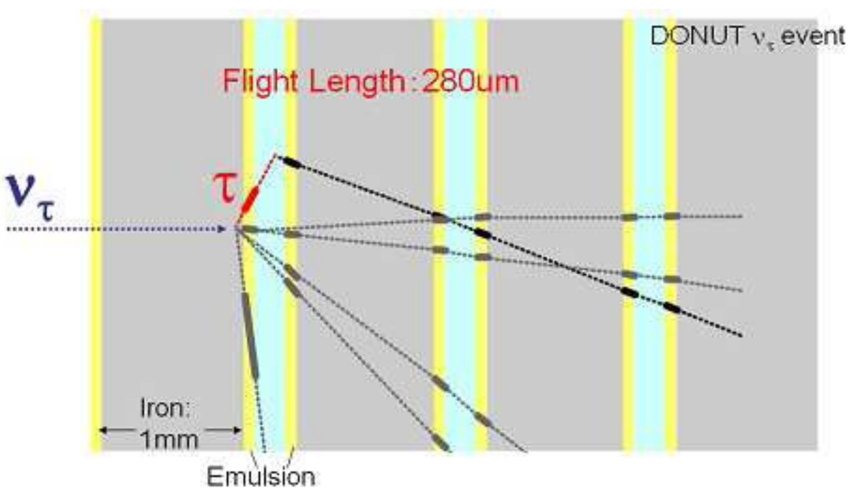
良好的屏蔽去掉其他粒子信号的可能
正负电子湮灭＋液闪捕获中子: 光子
光子探测器阵列探测到光子信号

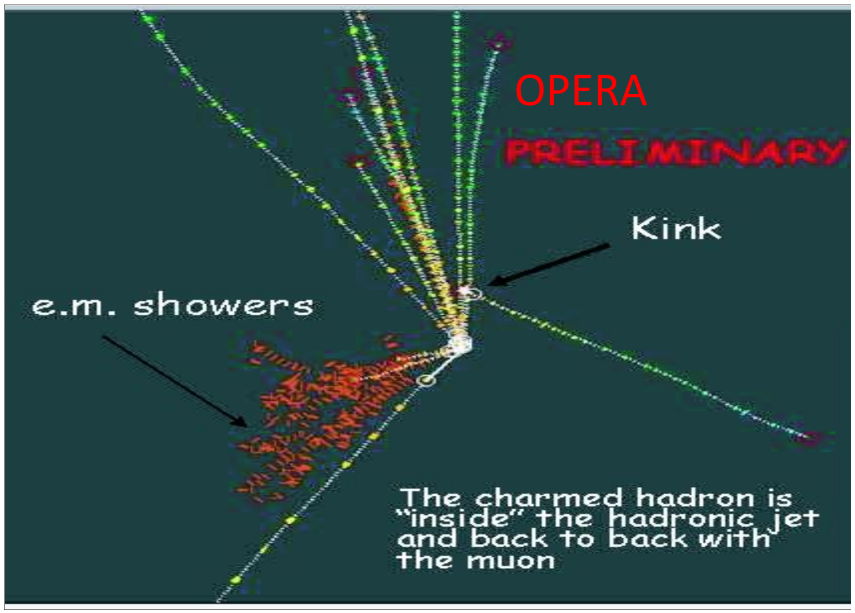
Neutrino flavours

- Can even determine the neutrino flavour (ν_e, ν_μ, ν_τ) from their charged-current interaction: $\nu_\mu N \to \mu^- X$, etc
- OPERA searches for ν_τ created by neutrino oscillation from a ν_μ beam (sent 730 km from CERN to Italy)
- Tau decay seen as track kink in a high precision emulsion detector, interleaved with lead sheets to provide the high mass of the target



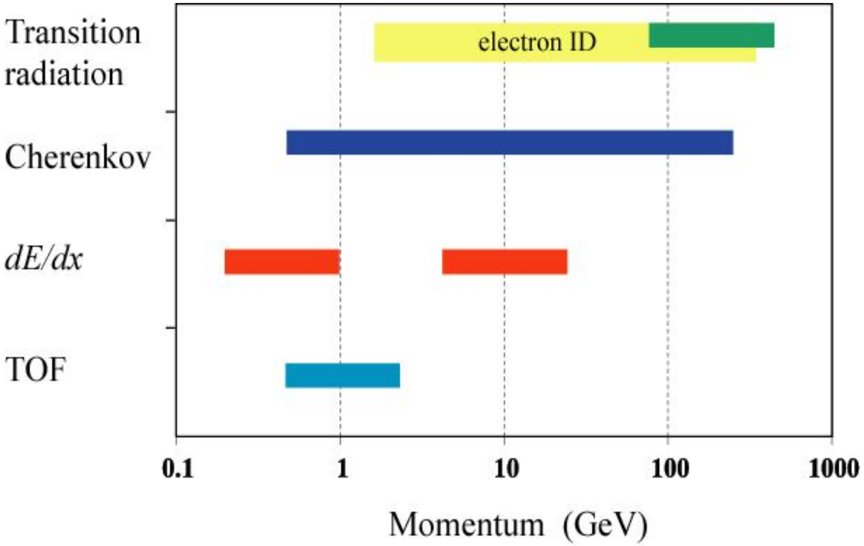
First observation of ν_τ (DONUT)





Summary

- General principle for particle ID



- Example of how CMS identify particles
    - Photons/Electrons/Muons/Taus/jets/boost objects

- Enjoy