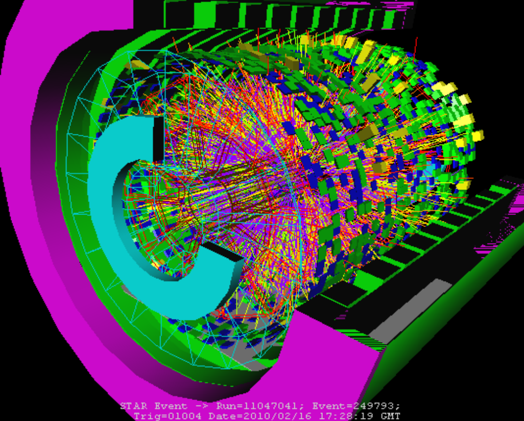

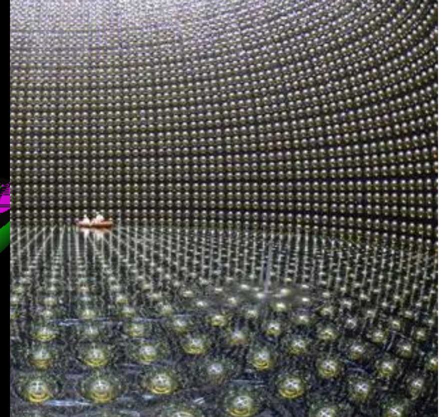

Particle Interaction with Matter and Detectors

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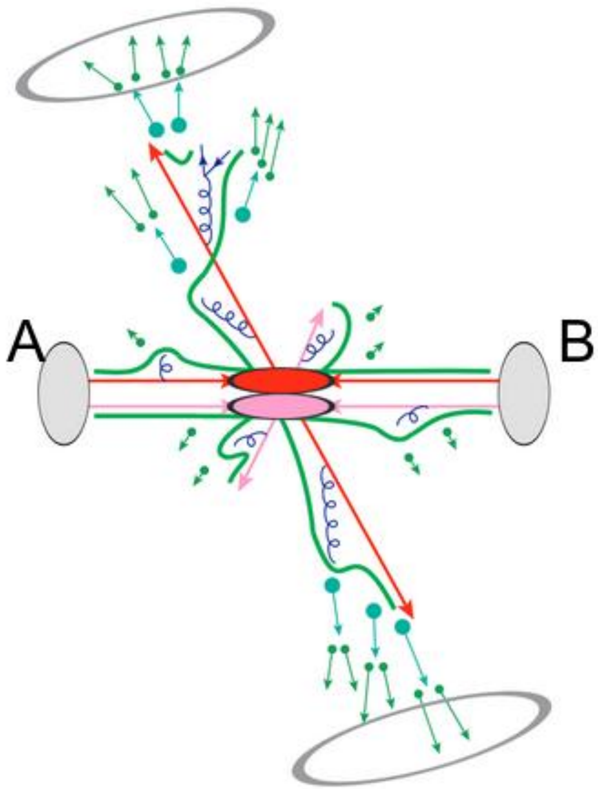
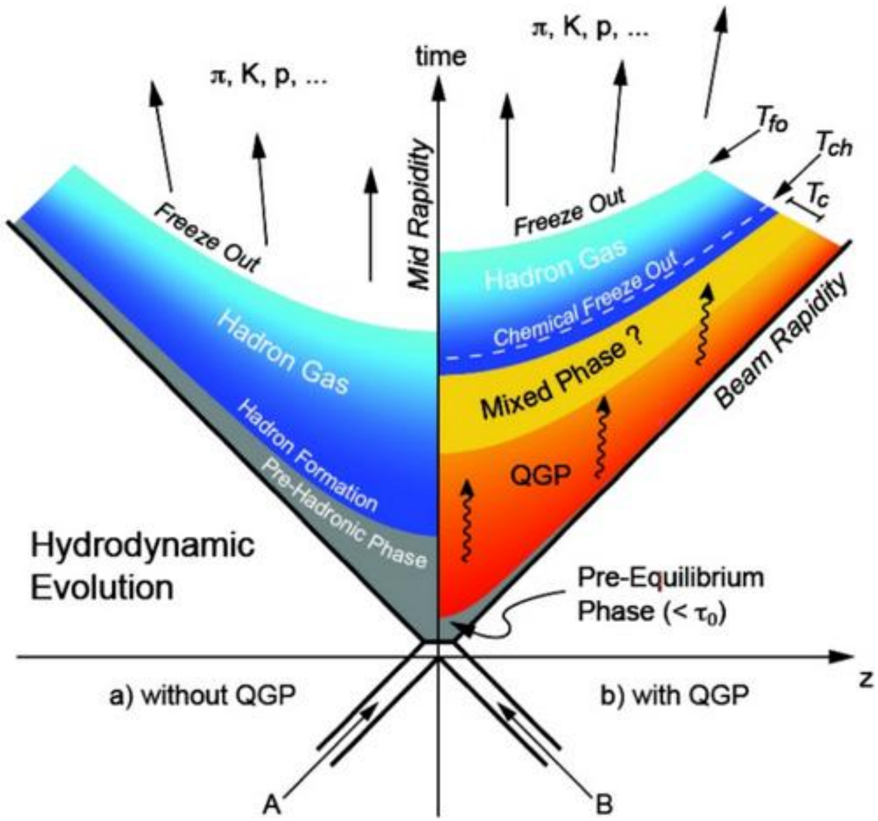
Oslo Winter School “Standard Model, Quantum Chromodynamics, Heavy Ion Collisions”
Jan. 5, 2019

Particle Production in Particle and RHI Physics





Hard interactions
- \+ Radiative cascade
- \+ Multiple interactions of initiators
- \+ Hadron formation
- \+ Hadron decays (and rescattering)
- \+ Beam spectrum & material effects

Various evolution scenarios depending on the description approach (strings, thermodynamics, hydrodynamics, hybrids)

The information about the system is carried out by particles that must be detected

Requirements for Particle Detectors

- Particle registration (detection)
- Measurement of momentum or energy
- Particle identification (e, π, K, p, …)
- Reconstruction of invariant mass via decay products

$$m_{inv}^2 = (\Sigma p_i)^2, \text{ where } p_i \text{ – four-momentum}$$

- "Missing mass" or "missing energy" for undetected particles
- Sensitivity to lifetime or decay length
  - Unstable particles (short-lived):
    - Decay via strong interaction: $\rho \to \pi^+\pi^-$ $\Gamma \approx 150$ MeV/c^2

      $\tau c = \hbar c/\Gamma \approx 1.5$ fm ($\tau \approx 10^{-23}$ s)
    - Decay via electromagnetic interaction: $\pi^0 \to \gamma\gamma$ ($\tau \approx 10^{-16}$ s)
  - Quasi-stable particles (long-lived):
    - Decay via weak interaction: $\Lambda \to p\pi^-$ ($\tau \approx 10^{-10}$ s)

Particle Interaction with Matter

There are 4 types of interactions in Nature but we use only 2 of them to detect particles:

- Strong interaction
  - Hadronic showers
- Electromagnetic interaction
  - Bremsstrahlung
  - Pair production
  - Ionization
  - Scintillation
  - Cherenkov radiation
  - Transition radiation

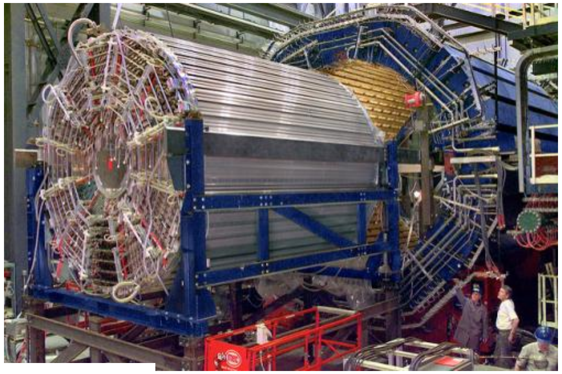
Calorimeters

Tracking detectors

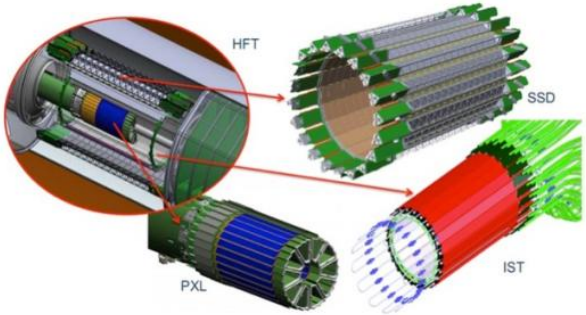
Cherenkov/TRD

Tracking detectors

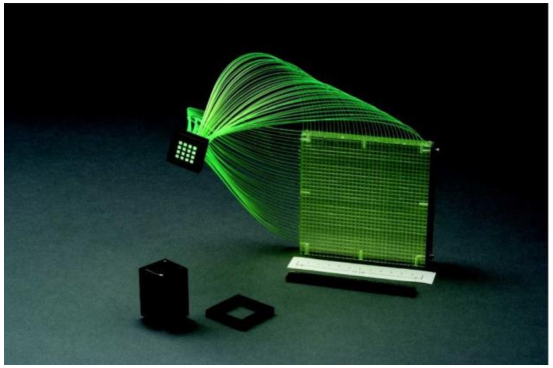
- Purpose:
  - Measurement of momentum and charge determination
  - Tracking (production position)



- Material:
  - Gaseous detectors (drift chambers, straws)
  - Solid state (silicon detectors)
  - Scintillating (fiber trackers)



- Important concepts:
  - Energy loss
  - Resolution
  - Possibility to place in a magnetic field

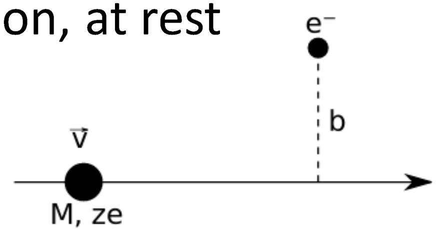


Specific Ionization Energy Loss

- Originates from the Coulomb interaction between charged particle and atom
- Dominated by inelastic collisions with electrons

$$\begin{aligned} \text{atom} + X &\rightarrow \text{atom}^+ + e^- + X && \text{ionization} \\ &\rightarrow \text{atom}^* + X && \text{excitation} \\ &\qquad \hookrightarrow \text{atom} + \gamma && \text{de-excitation} \end{aligned}$$

- Classical derivation: N. Bohr 1913
- Quantum mechanical derivation:
  - H. Bethe, Ann. d. Physik 5 (1930) 325
  - F. Bloch, Ann. d. Physik 16 (1933) 285
- *Bohr*: particle with charge *ze* moves with velocity *v* through medium with electron density n, electrons considered free and, during collision, at rest



$$\Delta p_\perp = \Delta p = \frac{2ze^2}{bv} \qquad \Delta p_{||} \text{ averages to zero}$$

$$\Delta E(b) = \frac{\Delta p^2}{2m_e} \qquad \text{energy transfer onto one electron at distance } b$$

per path length dx in the distance between b and b+db, n 2π b db dx electrons are found

Specific Ionization Energy Loss

- Diverges for b $\to$ 0

$$-\mathrm{d}E(b) = \frac{n4\pi z^2 e^4}{m_e v^2}\frac{\mathrm{d}b}{b}\mathrm{d}x$$

- b_{min} relative to heavy particle electron is located only within the Broglie wavelength

$$\Rightarrow b_{min} = \frac{\hbar}{p} = \frac{\hbar}{\gamma m_e v}$$

- b_{max} duration of perturbation should be shorter than period of electron: $b/\gamma v \leq 1/\langle \nu \rangle$

$$\Rightarrow b_{max} = \frac{\gamma v}{\langle \nu \rangle}$$

integrate over b with these limits:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} n \ln \frac{m_e c^2 \beta^2 \gamma^2}{\hbar \langle \nu \rangle}$$

electron density $n = \frac{N_A \rho Z}{A}$

average revolution frequency of electron $\langle \nu \rangle$ $\leftrightarrow$ mean excitation energy $I = \hbar \langle \nu \rangle$

Specific Ionization Energy Loss (Bethe-Bloch Equation)

- Considering quantum mechanical effects and some other corrections

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \rho \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

describes mean rate of energy loss in the range $0.1 \leq \beta\gamma \leq 1000$

$\frac{K}{A} = \frac{4\pi N_A r_e^2 m_e c^2}{A}$ with classical electron radius $r_e = \frac{e^2}{m_e c^2}$

$T_{max} \approx 2 m_e c^2 \beta^2 \gamma^2$ max. energy transferred in a single collision for $M \gg m_e$

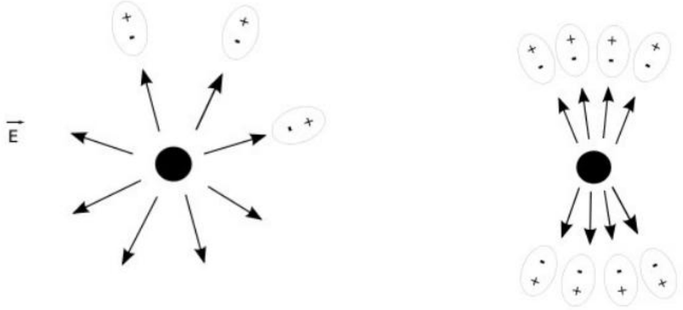
$I = (10 \pm 1) \cdot Z$ eV mean excitation energy (for elements beyond aluminum)

$\delta/2$ density correction

- with increasing particle energy → Lorentz contraction of electric field, corresponding to increase of contribution from large b with ln(βγ)

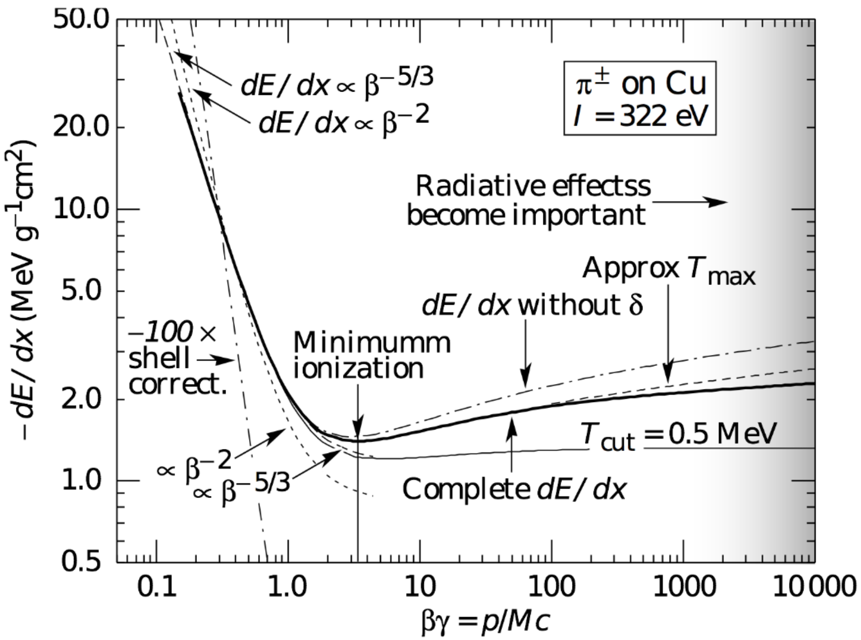
left: for small γ

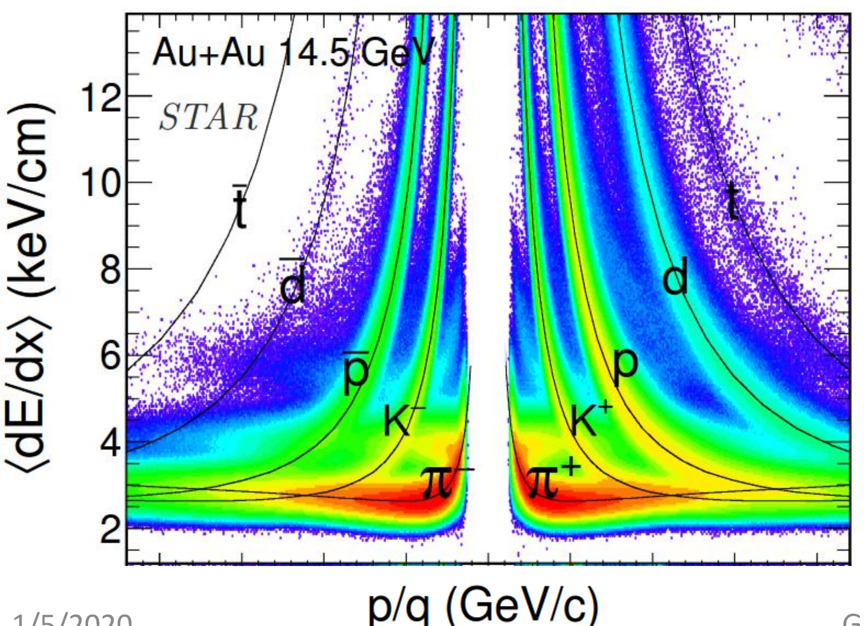
right: for large γ



- but: real media are polarized, effectively cuts off long-range contributions to logarithmic rise, term −δ/2 leads to Fermi plateau

Specific Ionization Energy Loss





- High energy limit

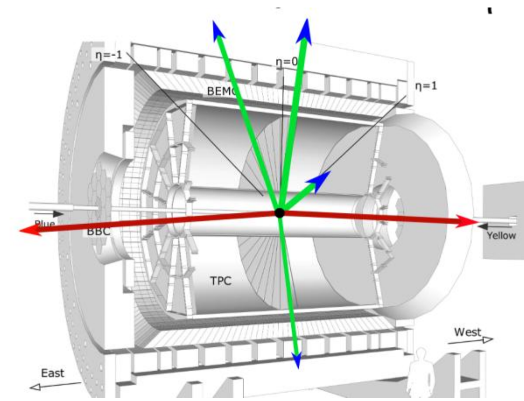
$$\frac{\delta}{2} \to \ln \frac{\hbar\omega_p}{I} + \ln \beta\gamma - \frac{1}{2}$$

with plasma energy

$$\hbar\omega_p = \sqrt{4\pi n r_e^3 m_e c^2/\alpha}$$

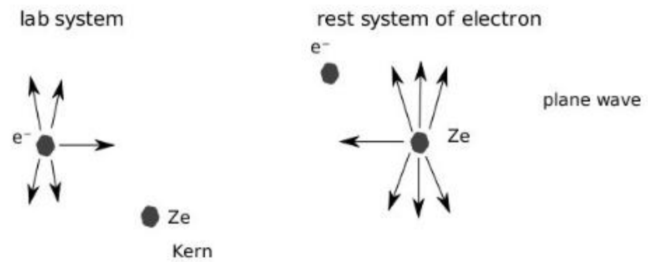
dE/dx increases more like $\ln\beta\gamma$ than $\ln\beta^2\gamma^2$ and I should be replaced by plasma energy

- Remark: plasma energy $\propto \sqrt{n}$, i.e. correction much larger for liquids and solids, leading to smaller relativistic rise
- Allows to identify different particle species in a wide momentum range



Bremsstrahlung

- QED process (Fermi 1924, Weizsäcker-Williams 1938)



- electron is hit by plane electromagnetic wave (for large v)
  E ⊥ B and both ⊥ v; quanta are scattered by electron and appear as real photons

- In Coulomb field of nucleus electron is accelerated
  amplitude of electromagnetic radiation $\propto$ acceleration $\propto$ $1/m_e c^2$

- Cross section $$\sigma_{\text{brems}} \propto \frac{Z^2\alpha^3}{(m_e c^2)^2}$$

Bremsstrahlung

- Energy loss by Bremsstrahlung – charged particle radiate photons in the Coulomb field of the nuclei of the absorber medium: $-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{\frac{1}{3}}}$
- Considering also interaction with electrons in atom:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z(Z+1)}{A} r_e^2 E \ln \frac{287}{Z^{\frac{1}{2}}} = \frac{E}{X_0}$$

$\Rightarrow$

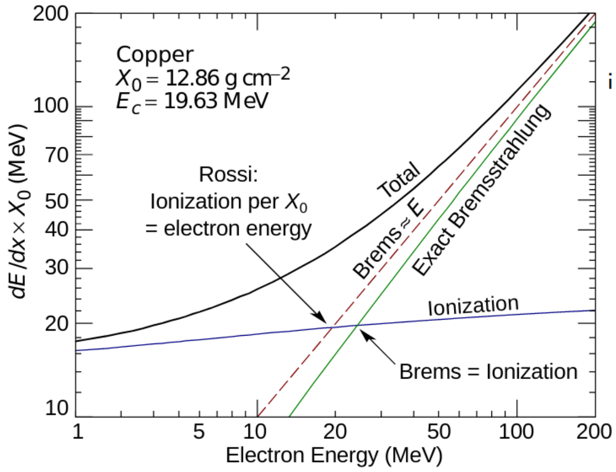
- Thus: $E(x) = E_0 \exp(-x/X_0)$

  X_0 is distance over which energy decreases to 1/e of initial value

- For mixtures: $\frac{1}{X_0} = \sum_i \frac{w_i}{X_{0i}}$ w_i weight fraction of material I
- Critical energy:

$$-\frac{dE}{dx} \text{ by ionization } \propto \ln E$$

$$-\frac{dE}{dx} \text{ by bremsstrahlung } \propto E$$



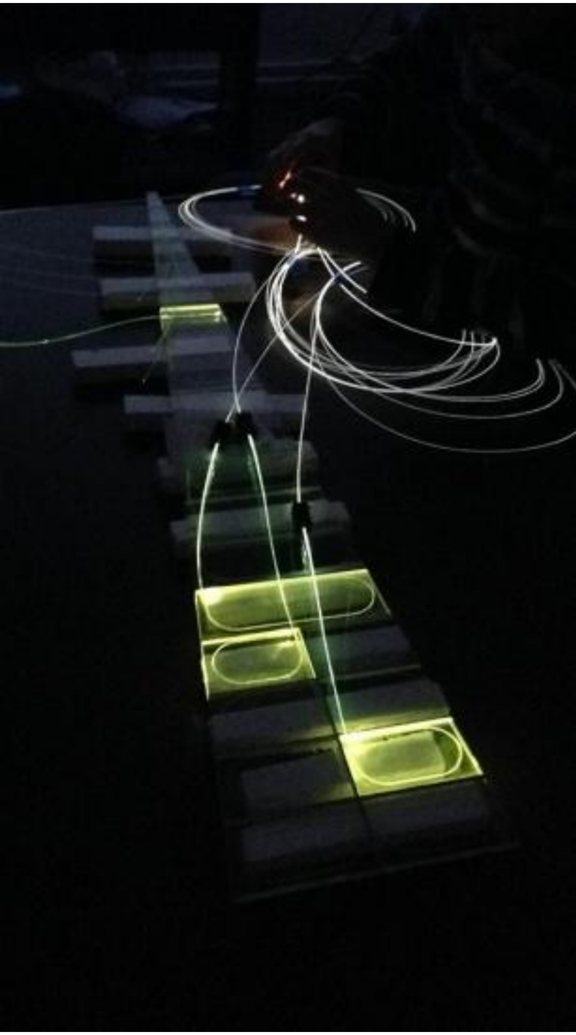
- → existence of crossing point beyond which bremsstrahlung dominates
- at critical energy E_c $\left(\frac{dE}{dx}\right)_{ion} = \left(\frac{dE}{dx}\right)_{brems}$

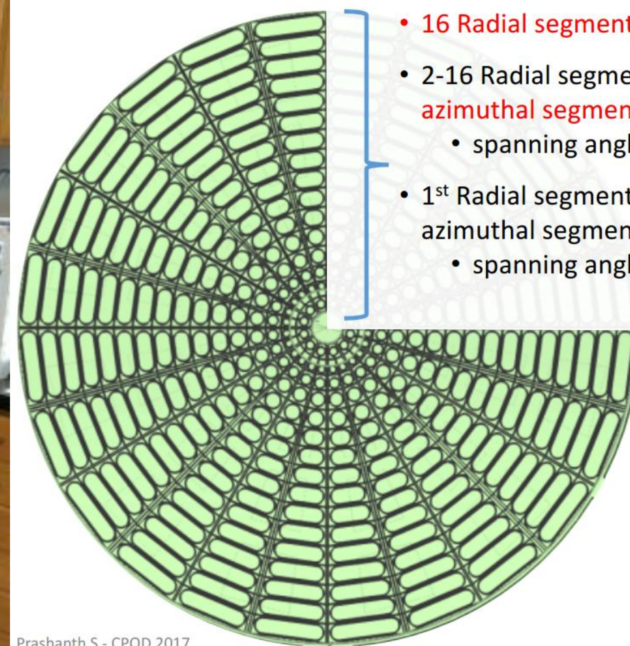
Scintillation Counters

- Principle of scintillation counter:
  - dE/dxis converted into visible light and transmitted to an optical receiver sensitivity of human eye quite good: 15 photons in the correct wavelength range within $\Delta t = 0.1$ s noticeable by human
  - scintillators make multipurpose detectors; can be used in calorimetry, time-of-flight measurements, tracking detectors, trigger or veto counters
- Scintillating materials:
  - inorganic crystals - crystal (electric insulator) doped with activator (color center) e.g. NaI(Tl) (good energy resolution but $)
  - organic crystals – aromatic hydrocarbon compounds (naphthalene, anthracene) (cheap, fast but light anisotropic output due to channeling in crystals)
  - polymers (plastic scintillators - p-Terphenyl, PBD (2-phenyl-5(4-biphenyl)-1,3,4-oxadiazole) – polymer (polystyrene, plexiglas)+ scintillator+wavelength shifter or liquid (benzene, toluene)+scintillator+wavelength shifter (fast, cheap, may be sensitive for (n,p) reactions but large energy loss, low light yield)

Sintillation Detectors

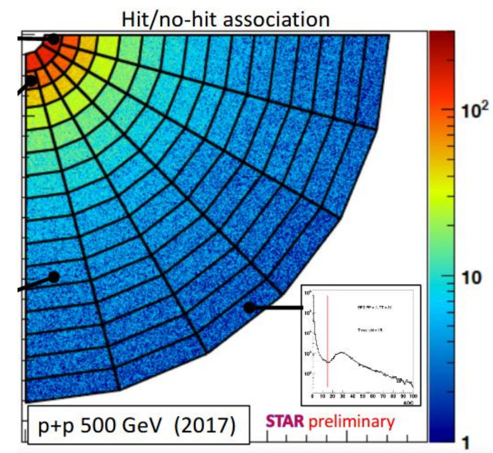
Event Plane Detector (STAR)





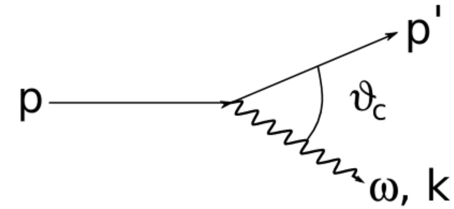
- 16 Radial segments
- 2-16 Radial segments have 24 azimuthal segments
  - spanning angle of 15^0
- 1st Radial segment has 12 azimuthal segments
  - spanning angle of 30^0

Prashanth S - CPOD 2017



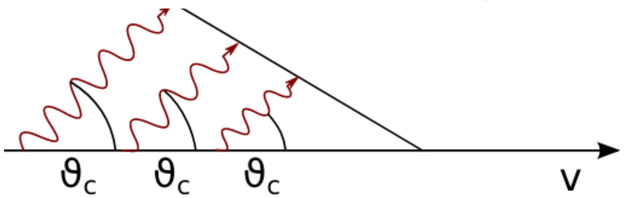
Vavilov-Cherenkov radiation

- Particle of mass, M, and velocity, β=v/c, propagates through medium with real part of dielectric constant: $\epsilon_1 = n^2 = \frac{c^2}{c_m^2}$
  in case: $\beta > \beta_{\text{thr}} = \frac{1}{n}$ or $v > c_m$



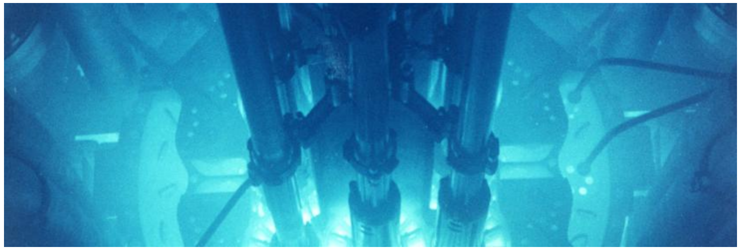
  real photons can be emitted with: $$\begin{array}{ccc} |p| & \simeq & |p'| \\ \omega & \ll & \gamma M c^2 \end{array}$$

  emission under angle: $\cos\theta_c = \frac{\omega}{k \cdot v} = \frac{1}{n\beta}$



- For distance, x, and frequency interval, dv, one can estimate number of photons, N_γ:

$$N_\gamma = x \underbrace{\frac{\alpha}{\hbar c}}_{370/\text{eV}\cdot\text{cm}} \int_{\omega_1}^{\omega_2} \underbrace{(1 - \frac{1}{\beta^2 n^2(\omega)})}_{\sin^2\theta_c} \hbar d\omega$$



for interval dω, where n(ω) varies not much, e.g. gases around visible wavelengths 300 nm< λ <600 nm and N_γ= 750 sin2θ_c/cm

typical photon energy: $\simeq 3$ eV

in water $\left.\frac{dE}{dx}\right|_{\text{cher}} = 0.5$ keV/cm $= 0.5$ keV/g/cm^2

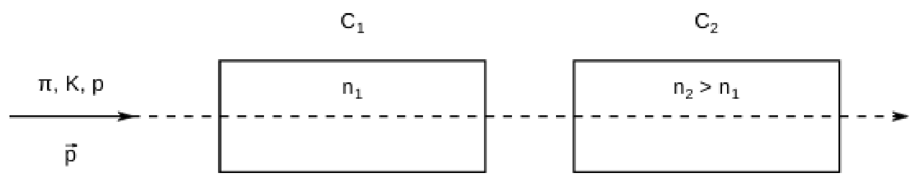
cf. ionization $\left.\frac{dE}{dx}\right|_{\text{ion}} \geq 2$ MeV/g/cm^2

→ energy loss by Cherenkov radiation negligible

	$(n-1)$	$(\beta\gamma)_{thr}$	θ_c^∞(deg)	$N_\gamma^\infty(cm^{-1})$
H_2	$0.14 \cdot 10^{-3}$	59.8	0.96	0.21
N_2	$0.3 \cdot 10^{-3}$	40.8	1.4	0.45
H_2O	0.33	1.13	41.2	165

Cherenkov Detectors

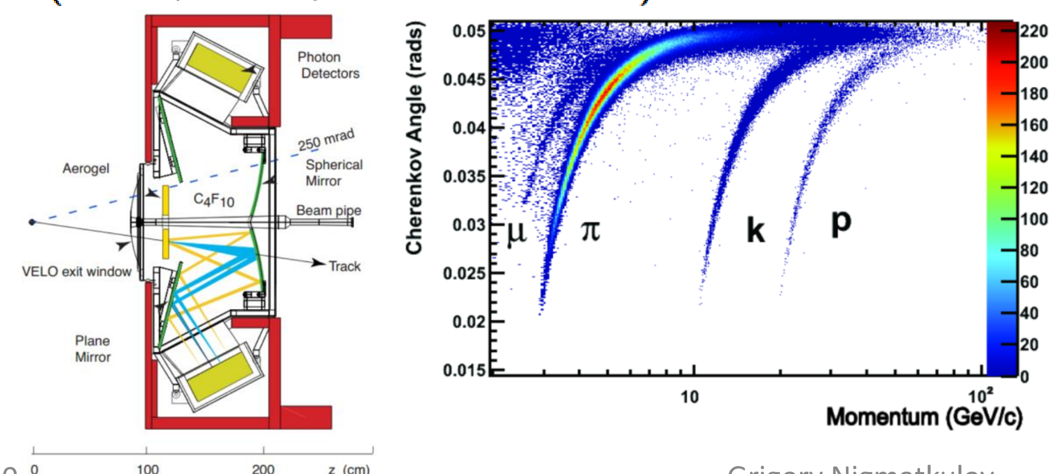
a) threshold detector: principle - if Cherenkov radiation observed $\Rightarrow \beta > \beta_{thr}$
e.g. separation of $\pi/K/p$ of given momentum p

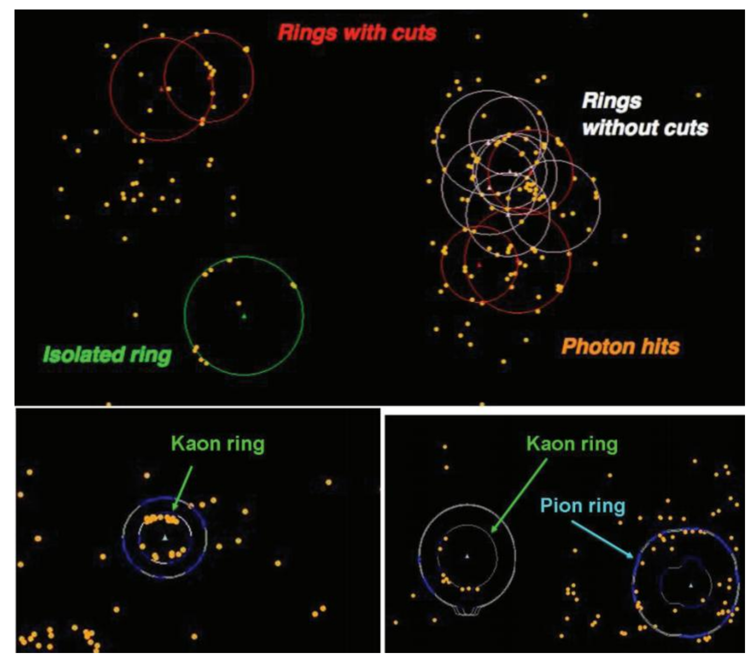


choose $\begin{matrix} n_2 \\ n_1 \end{matrix}$ such that $\begin{matrix} \beta_\pi, \beta_K > \frac{1}{n_2} & \beta_p < \frac{1}{n_2} \\ \beta_\pi > \frac{1}{n_1} & \beta_k, \beta_p < \frac{1}{n_1} \end{matrix}$

light in C_1 and C_2: π
light in C_1 and not in C_2: K
no light in C_1 and C_2: p

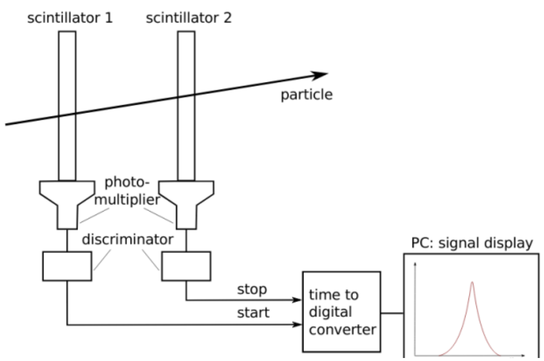
b) measurement of θ_c in medium with known $n \Rightarrow \beta$
(RICH, DIRC, DISC detectors)





Time-Of-Flight Measurements

- Time difference between two detectors with good time resolution: "start" and "stop"-counter
  - typically scintillator or resistive plate chamber, also calorimeter (neutrons)
  - coincidence set-up or put all signals as stop into TDC (time-to-digital converter) with common start (or stop) from "beam" or "interaction"
- For known distance, L, between start and stop counters, time-of-flight difference of two particles with masses $m_{1,2}$ and energies $E_{1,2}$:



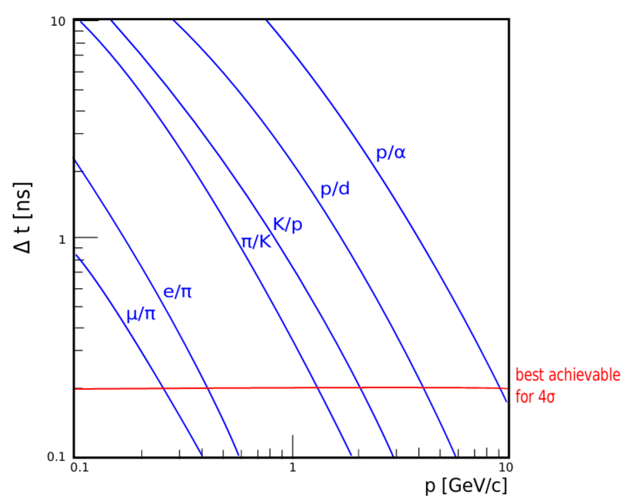
$$\Delta t = \tau_1 - \tau_2 = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$\Delta t = \frac{L}{c}\left(\sqrt{\frac{1}{1-(m_1c^2/E_1)^2}} - \sqrt{\frac{1}{1-(m_2c^2/E_2)^2}}\right)$$

limiting case: $E \simeq pc \gg mc^2$

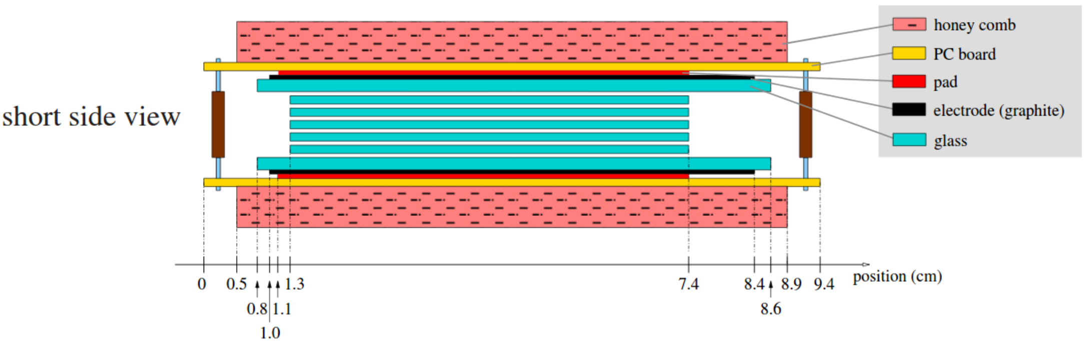
$$\Delta t = \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$

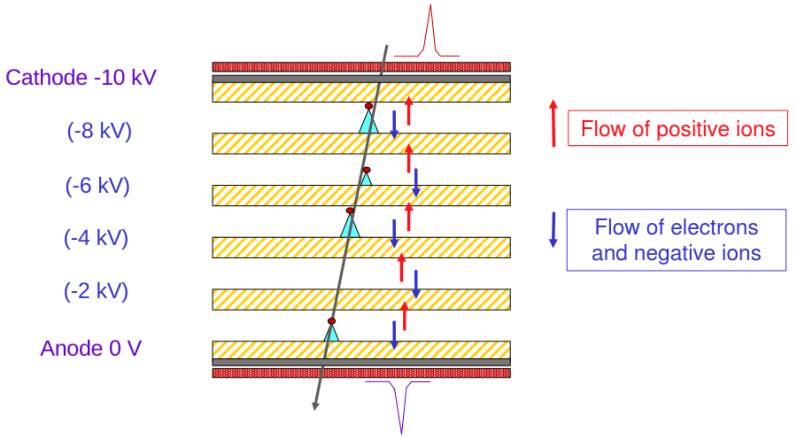
Difference in time-of-flight for $L = 1$ m

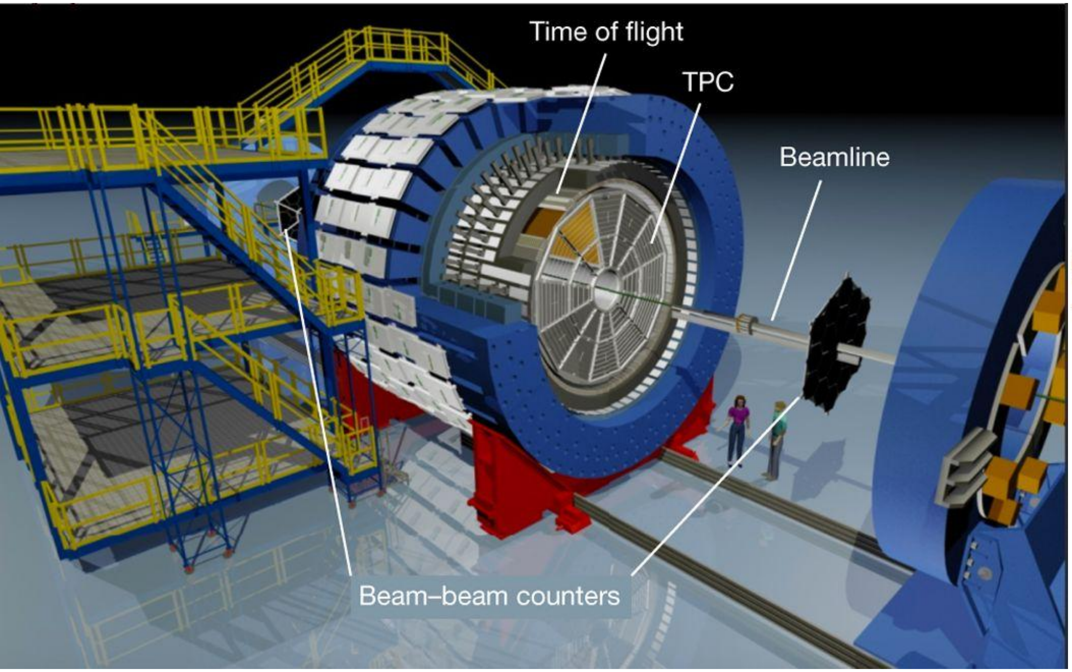


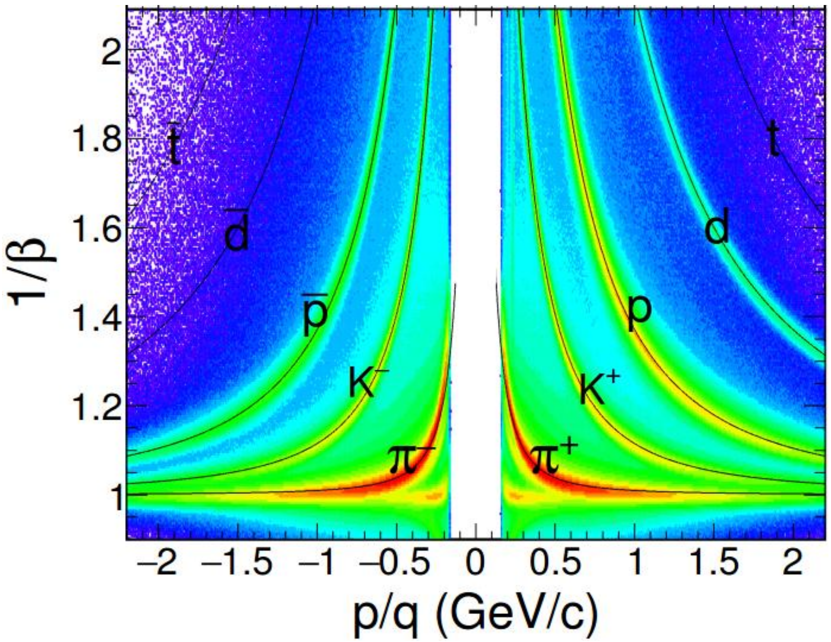
Time-Of-Flight Measurements (MRPC)

Typical Multigap Resistive Plate Chamber



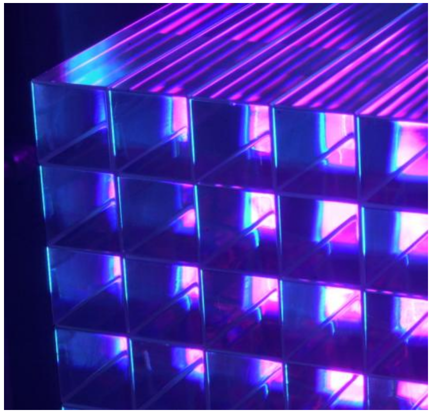


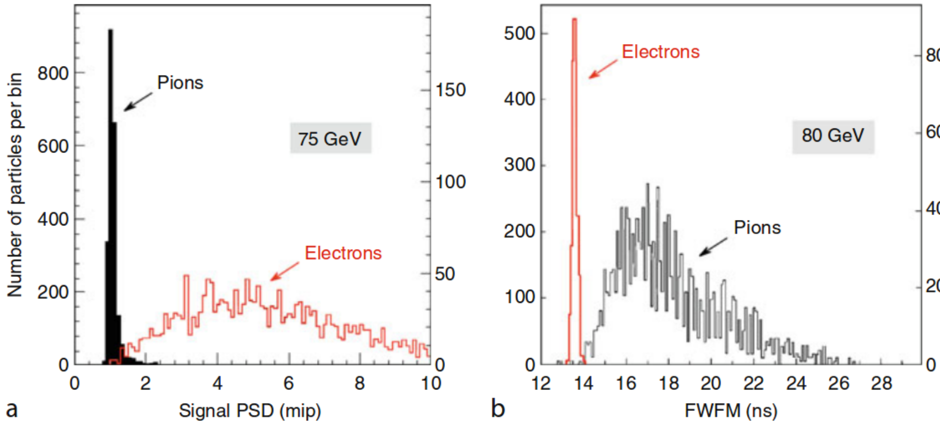




Calorimetry

- In nuclear and particle physics, calorimetry refers to the detection of particles, and measurement of their properties, through total absorption in a material
- The signals from a properly instrumented absorber may be used to measure the entire four-vector of the particles. By analyzing the energy deposit pattern, the direction of the particle can be measured. The mass of the showering particle can be determined in a variety of ways:
  – The E/p method, in which the energy measured in the calorimeter is compared with the momentum measured with a tracker in a magnetic field. This method only works for charged particles and relatively low energies.
  – By analyzing the energy deposit profile. This method is frequently used to identify electrons. Especially in calorimeters with high-Z absorber material, EM showers are much more shallow and concentrated around the shower axis than hadronic showers.
  – By measuring the time structure of the calorimeter signals





Calorimetry

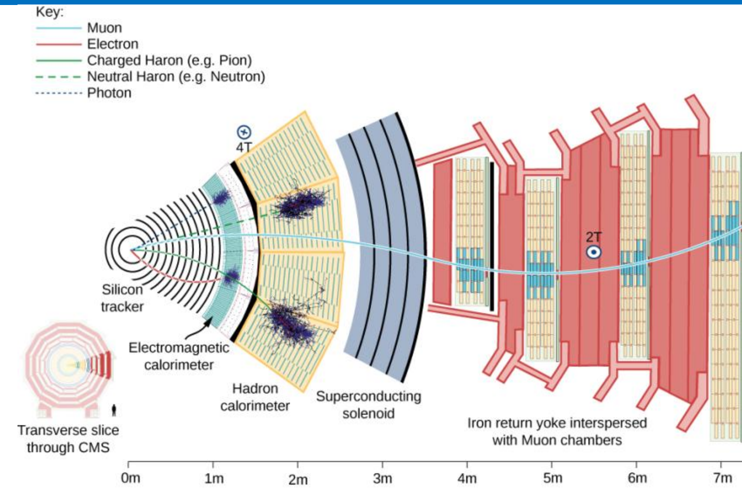
- Electromagnetic shower

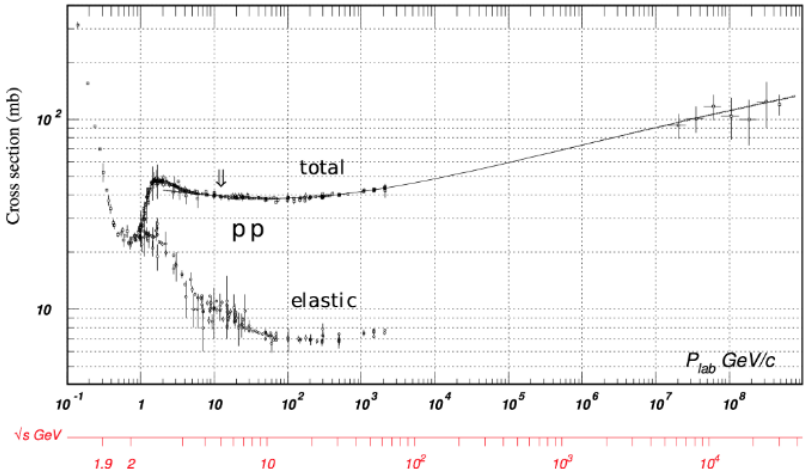
$$\gamma + \text{nucleus} \rightarrow e^{+} + e^{-} + \text{nucleus}$$
$$e + \text{nucleus} \rightarrow e + \gamma + \text{nucleus}$$

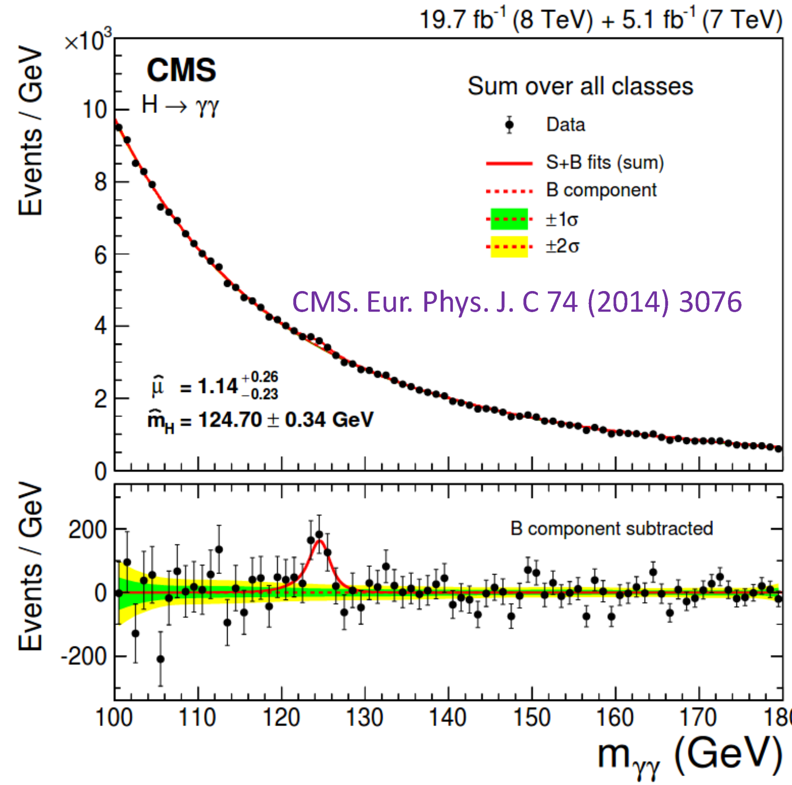
- Hadronic interactions (e.g. for protons)

Elastic	$p + N \rightarrow p + N$	σ_{el}
Inelastic	$p + N \rightarrow X$	σ_{inel}

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$







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Average nuclear interaction length: $\lambda_W = \dfrac{A}{N_A \rho \sigma_{tot}}$

For inelastic processes → absorption: $\lambda_A = \dfrac{A}{N_A \rho \sigma_{inel}}$

$$N(x) = N_0 \exp\left(-\frac{x}{\lambda_A}\right)$$

Momentum Measurements

- Deflection of track of charged particle in magnetic spectrometer
- Lorentz force → circular orbit of curvature radius, ρ, in homogeneous magnetic field: $\frac{mv^2}{\rho} = q\vec{v} \times \vec{B} = qv_\perp \cdot |\vec{B}|$

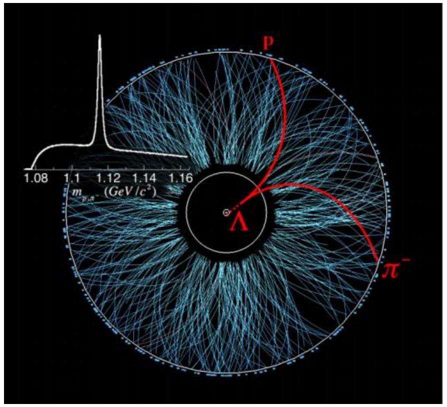
$v_\perp$: component of $\vec{v} \perp$ to $\vec{B}$

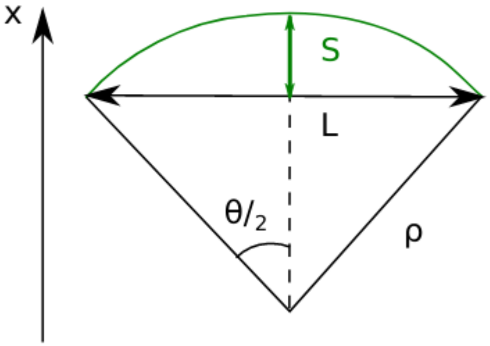
$$\rho = \frac{p^2}{qp_\perp B}$$

$p_\perp$: analogue

for $\vec{p} \perp B$: $\rho = \frac{p}{qB}$

units: for ρ in m
p in GeV/c
B in T
q in units of e





Sagitta $S = \rho - \rho\cos\frac{\theta}{2} = \rho\left(1 - \cos\frac{\theta}{2}\right)$

$= 2\rho\sin^2\frac{\theta}{4}$

for small θ $S \simeq \frac{\rho\,\theta^2}{8}$

with $\rho = \frac{p_\perp}{qB}$ and $\sin\theta/2 \simeq \theta/2 = \frac{L/2}{\rho}$

$$S = \frac{qL^2 B}{8p_\perp}$$

B in T, L in m, $p_\perp$ in GeV/c, q in e

$$S(\mathrm{m}) = \frac{0.3\,qL^2 B}{8p_\perp}$$

Summary

- Basic principles of particle interactions with matter and detection have been discussed
- One has to remember detector limitations for measurements of various physics aspects
- Detector setups usually planned for specific/dedicated physics measurements measurements