JENNIFER2 SUMMER SCHOOL ON PARTICLE PHYSICS AND DETECTORS

~~6-15~~ 20-27 July 2020

~~KEK, Tsukuba, Japan~~ REMOTE

Particle Detectors 03

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Jennifer2 Summer School
20-27 July 2020

INFN

Belle II

Università di Pisa
Dipartimento di Fisica
"Enrico Fermi"

Outline

01

- Introduction
- A tour of particle-matter interactions
  - Heavy charged particles
  - Electron and positrons
  - Hadrons
  - Neutrinos

02

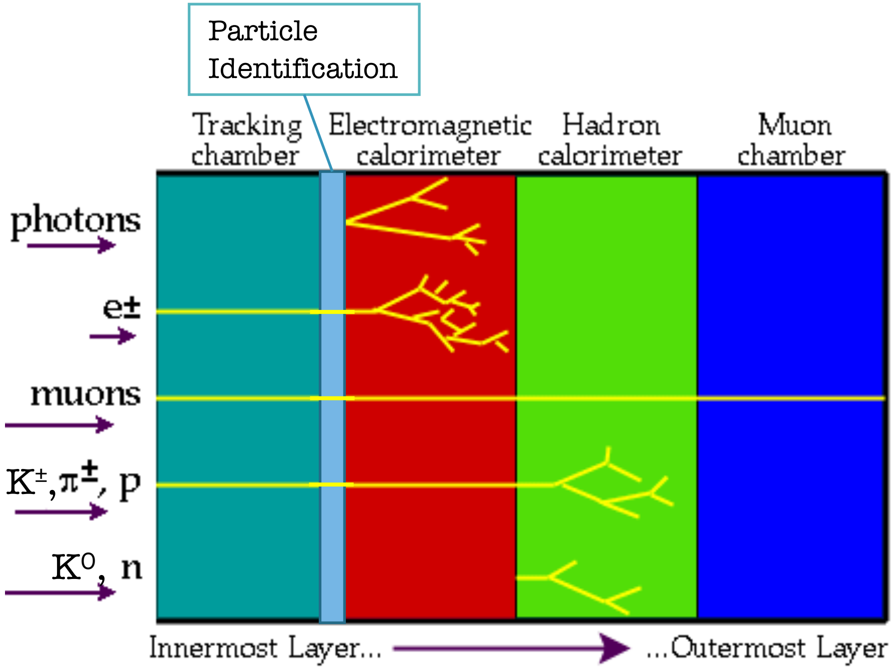
- Detector technologies
  - Gas ionization detectors
  - Semiconductor detectors
  - Scintillators and photodetectors

03

- Modern detector systems
  - Tracking/vertexing
  - Particle identification
  - Calorimetry
- Conclusion

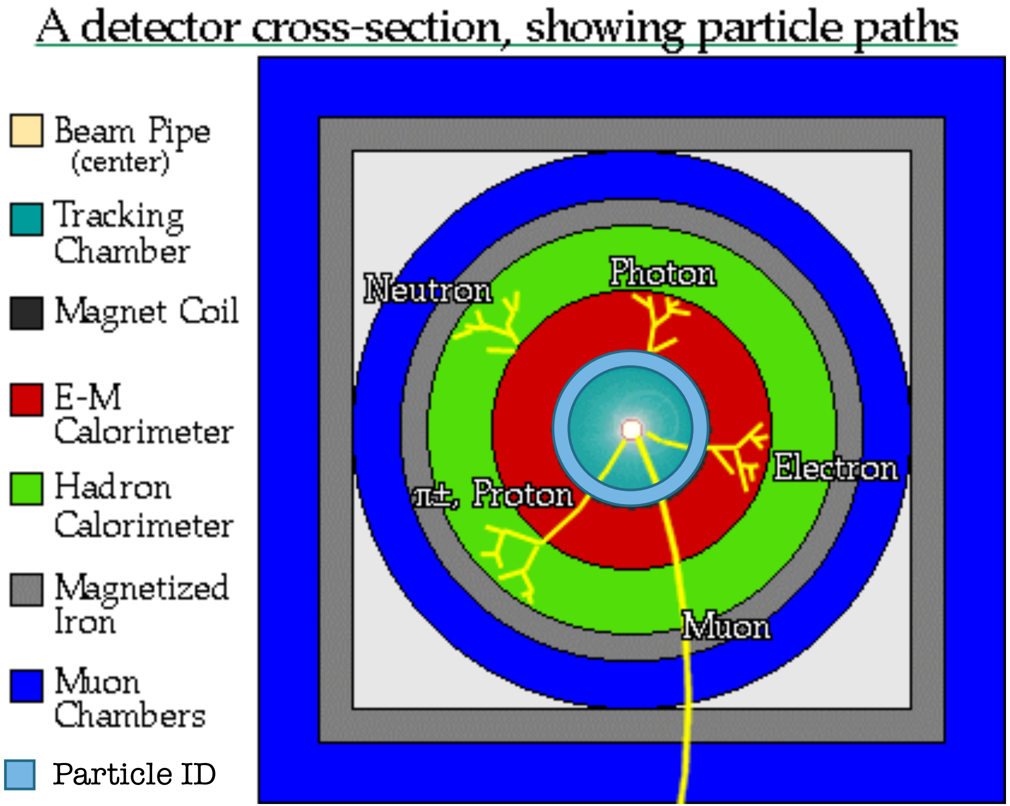
Modern detectors @ accelerators

- Tracking:
  - Silicon detectors (pixel, strips)
  - Gas detectors (MPGD, drift, …)
- Particle ID
  - Time of flight (scintillator)
  - Cherenkov radiator
- Calorimeters
  - Scintillating crystals/liquid
  - Sandwich heavy material (Pb, Fe) and detector
- Muon chamber
  - Absorber (Fe) and large area detectors

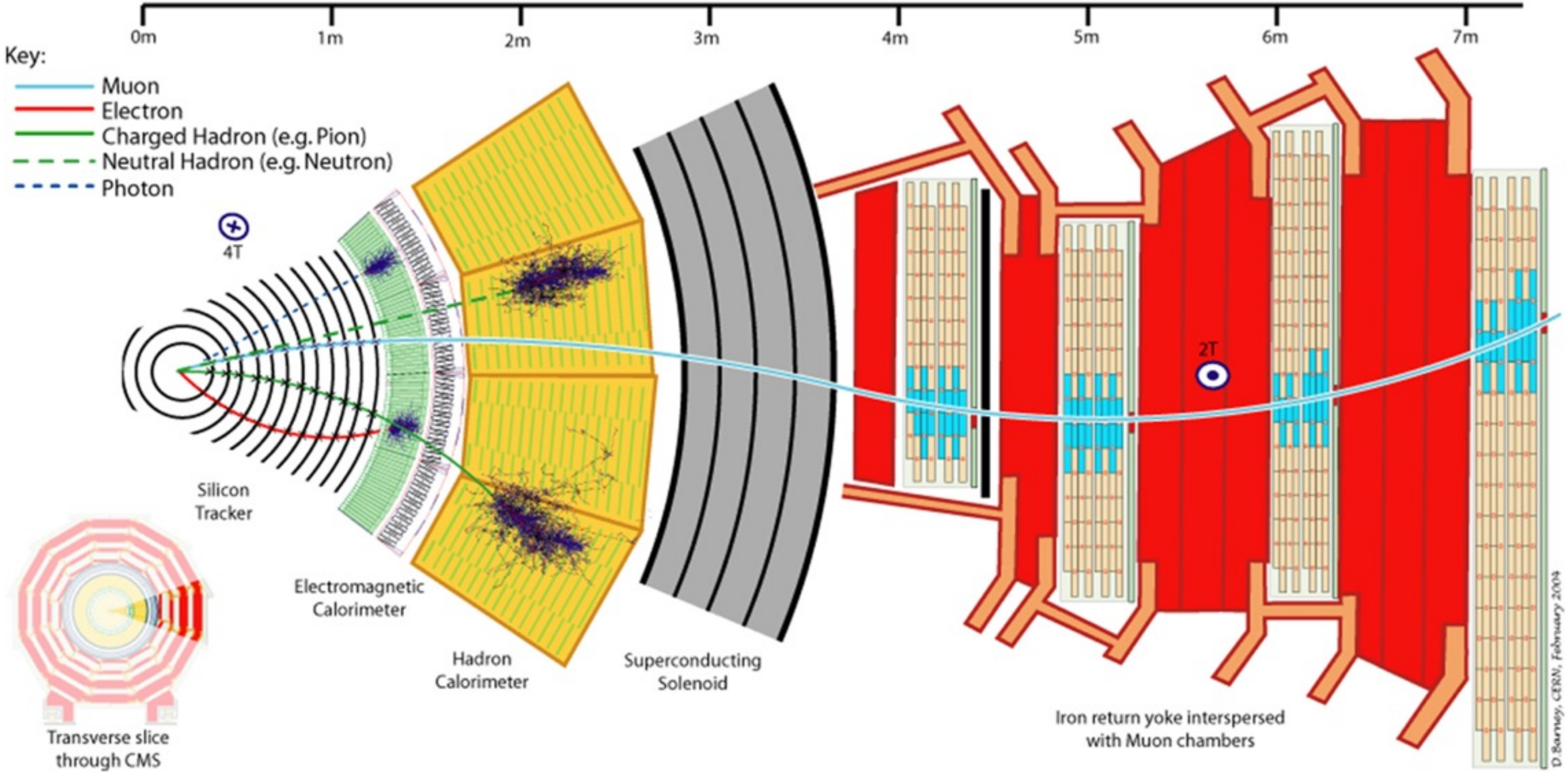


Collider detector scheme

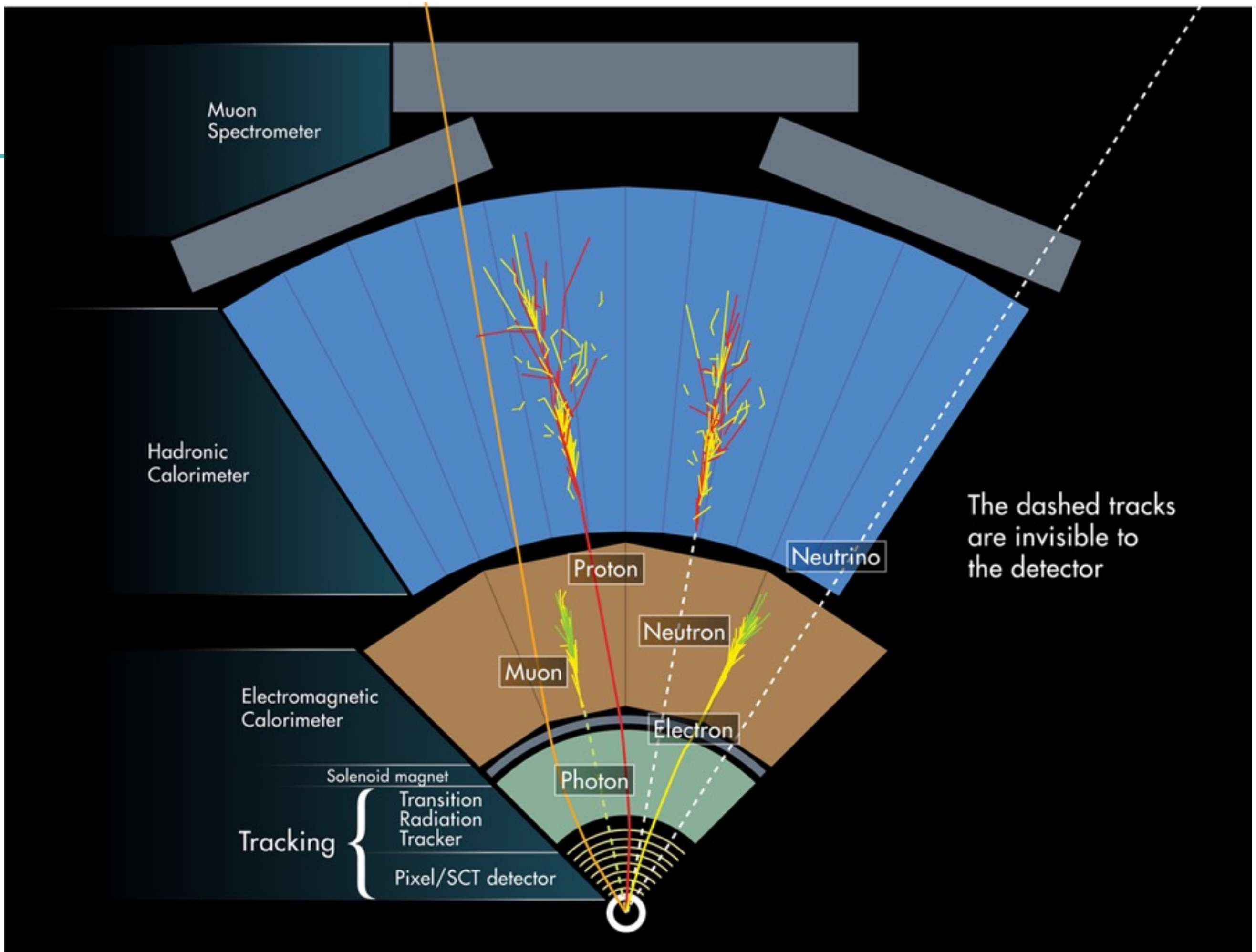
- Cylindrical shape
- Exact structure depends on experiment
- Radius 1-10m
- Called 4π detectors because cover as much as possible of the solid angle



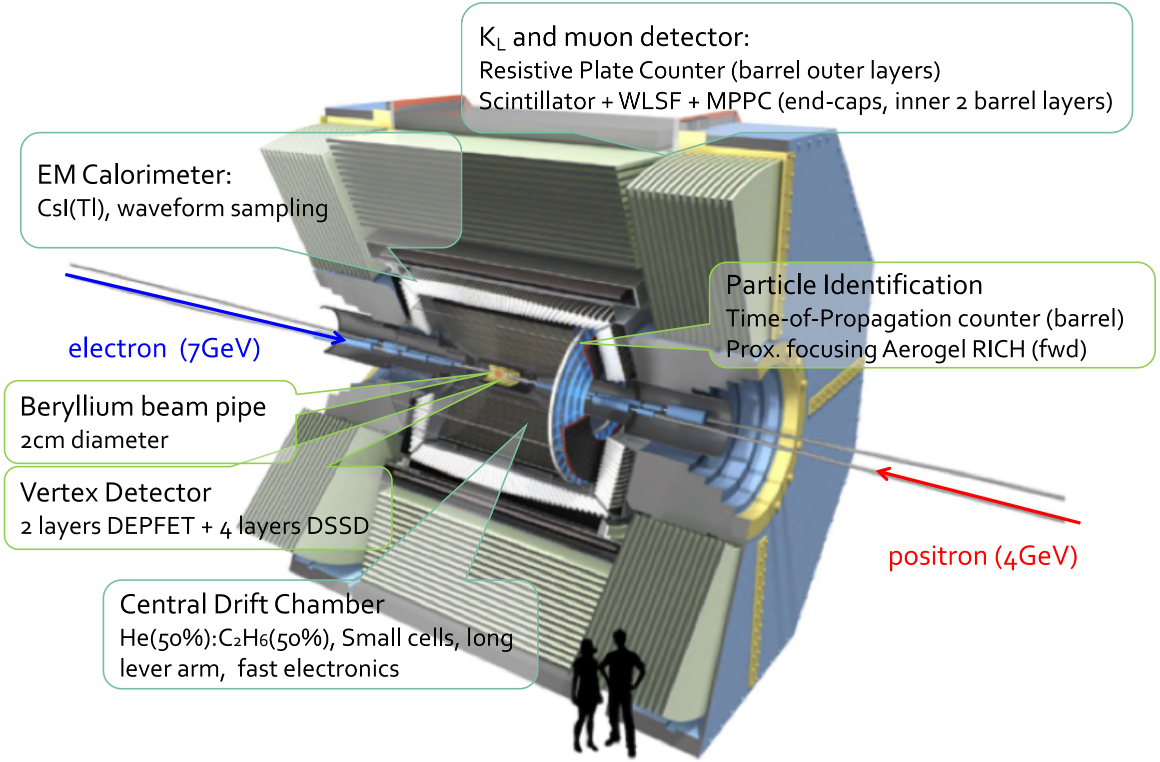
CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

ATLAS


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector

BELLE II

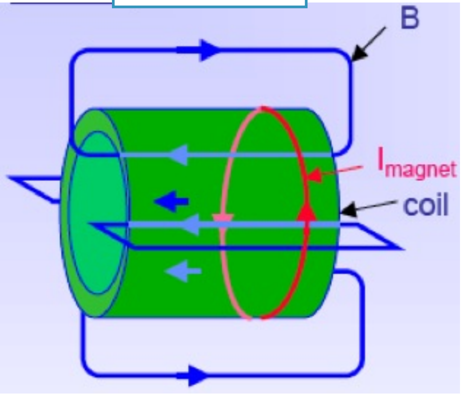


K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
EM Calorimeter:
CsI(Tl), waveform sampling
Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)
electron (7GeV)
Beryllium beam pipe
2cm diameter
Vertex Detector
2 layers DEPFET + 4 layers DSSD
positron (4GeV)
Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

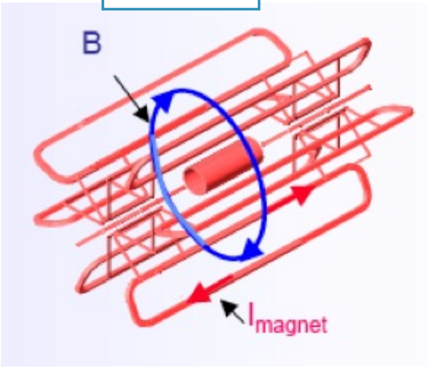
Magnets

- A high magnetic field is essential for momentum measurement (0.5 – 4 T)
- Obtaining such a magnetic field in a large volume is very challenging and requires a superconducting magnet
- Solenoid (most experiments)
  - Large homogenous field inside
  - Opposite field in return yoke
  - Large material and cost
- Toroid (ATLAS)
  - Large field on large volume
  - Relatively low material
  - Non-uniform field
  - Complex structural design

Solenoid



Toroid



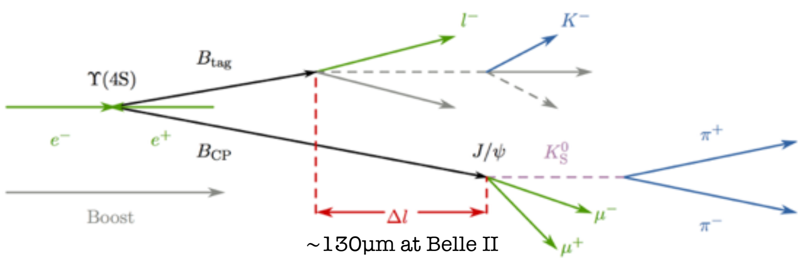
Electronics, Trigger, Data acquisition

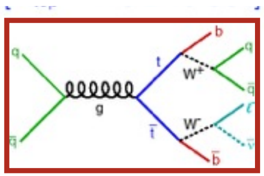
- Electronics: amplification and digitization of signals coming from the detectors
  - Essential to extract very tiny signals from a lot of noise
- Trigger: very fast decision logic to select events
  - Essential to extract interesting events out of the large number of background events
- Data acquisition: combine data from different sub-detectors and transfer to permanent storage
  - Complex real time system to process and transfer large amounts of data
- Will not cover these topics for lack of time.
- Technologically very challenging

Tracking and vertexing

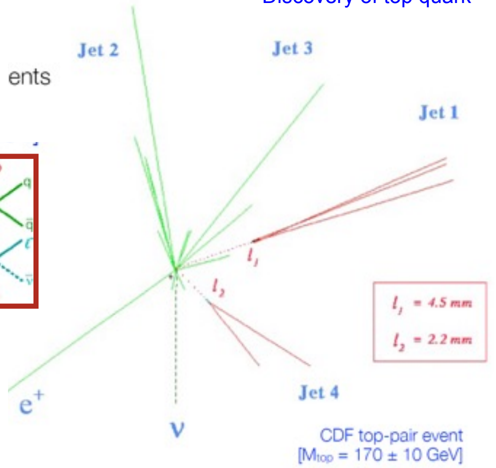
Tracking / vertexing

- Measure precisely the trajectory of charged particle
  - Determine momentum and sign of charge through curvature in magnetic field
- Extrapolate tracks to interaction point to determine:
  - primary vertex position (where the main interaction happened)
  - secondary vertices positions (where unstable particles decayed)





Discovery of top quark

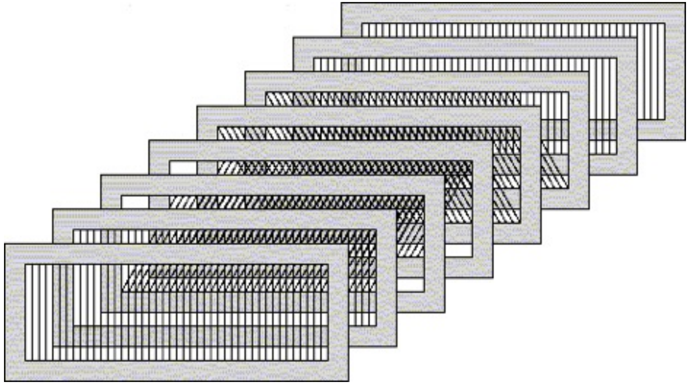


Important parameters for tracking

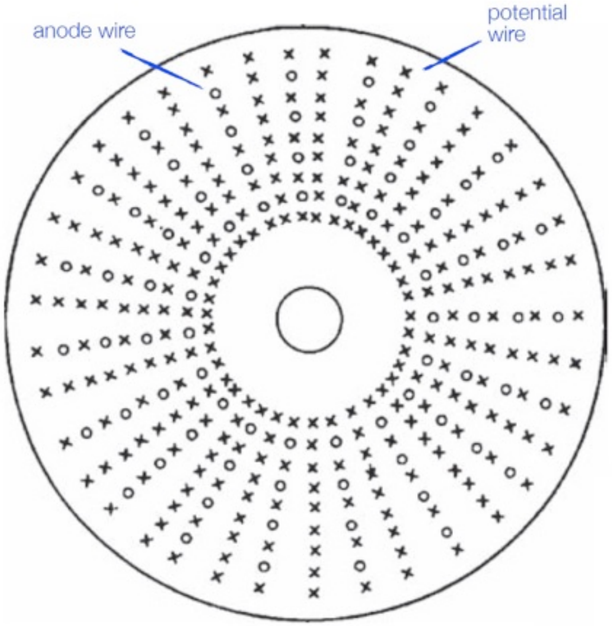
- Point resolution: the spatial resolution on measurement points
  - Range from a few μm (pixels) to mm (gas detectors)
- Number of measurement points along the trajectory
  - Tradeoff between precision, material, cost, complexity
- Magnetic field
  - Necessary for momentum measurement. The higher the momentum, the higher magnetic field is needed
- Amount of material
  - Multiple scattering limits resolution,

Gas Tracking detectors

Tracking at fixed target experiments:
Multi-layer MWPC or drift chamber

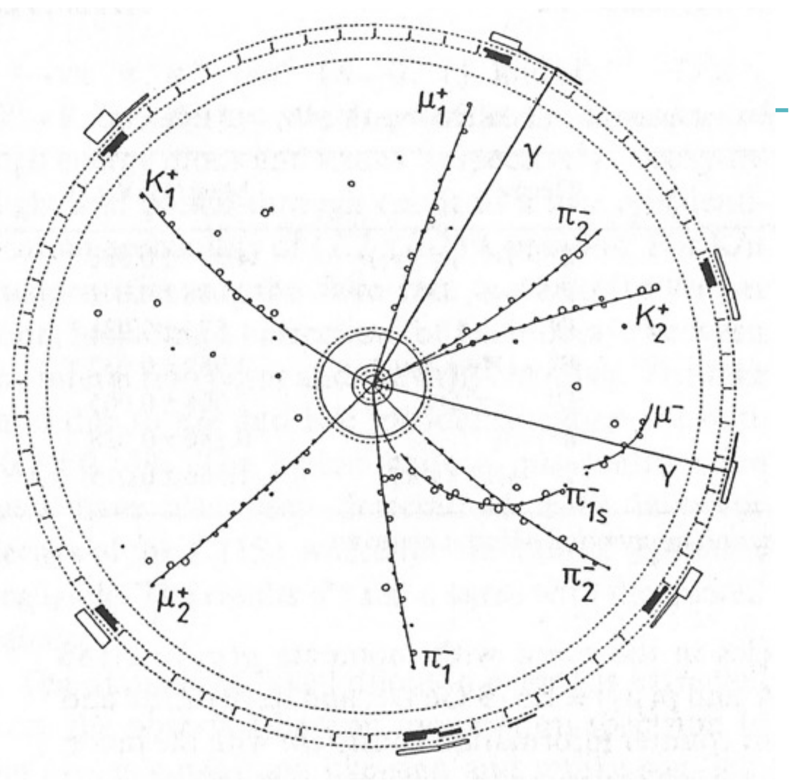


Tracking at collider experiments:
cylindrical drift chamber



Drift chamber event

- First fully reconstructed $B^0\overline{B}$ mixing event @ ARGUS at DESY, 1987

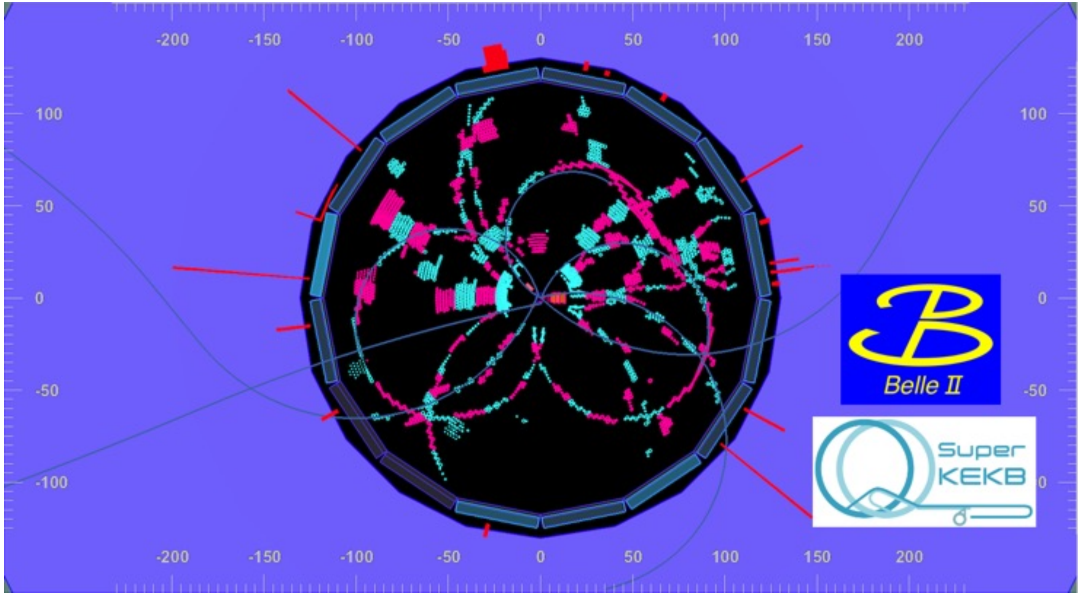


$$1)\ B_1^0 \to D_1^{*-}\mu_1^+\nu_1,\ D_1^{*-} \to \pi_1^-\overline{D}^0,\ \overline{D}^0 \to K_1^+\pi_1^-$$

$$2)\ B_2^0 \to D_2^{*-}\mu_2^+\nu_2,\ D_2^{*-} \to \pi^0 D^-,\ D^- \to K_2^+\pi_2^-\pi_2^-$$

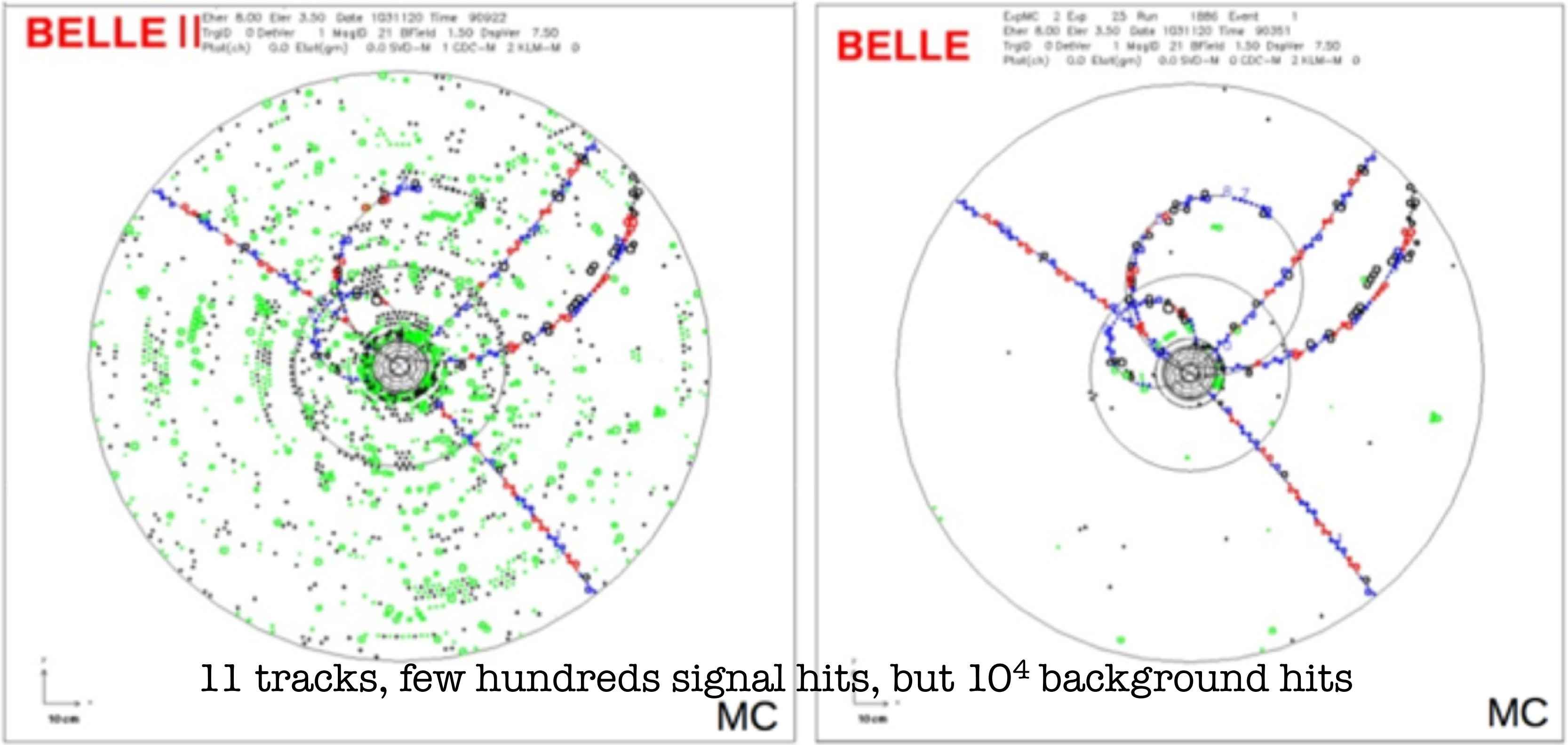
An event from Belle II's first evening, 2019

$$e^+e^- \rightarrow \gamma^* \rightarrow B\overline{B}$$



A candidate $e^+e^- \rightarrow B\overline{B}$

Backgrounds



11 tracks, few hundreds signal hits, but 10^4 background hits

Silicon tracking detectors

- Drift chambers provide a continuous gas volume with many measurement points obtained from the wires
- Silicon detector provide one measurement point per detector. Only few points because of cost and material (typical number for $300\mu m$ thick silicon is $0.3\% X_0$ per layer).
- Point resolution is in general better: $5 - 20\mu m$
- Cylindrical arrangement around the interaction region

Technologies:

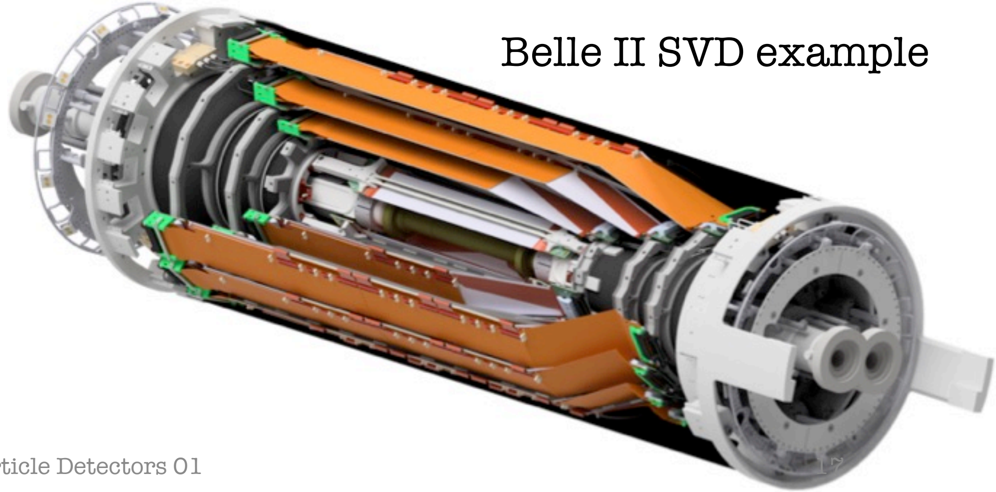
Inner layers: pixels

- Hybrid pixels, CCDs, DEPFETS

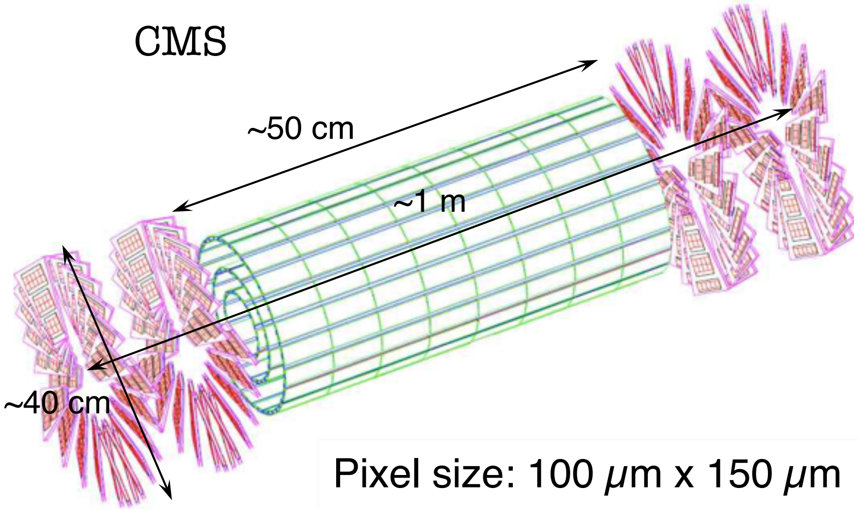
Outer layers strips

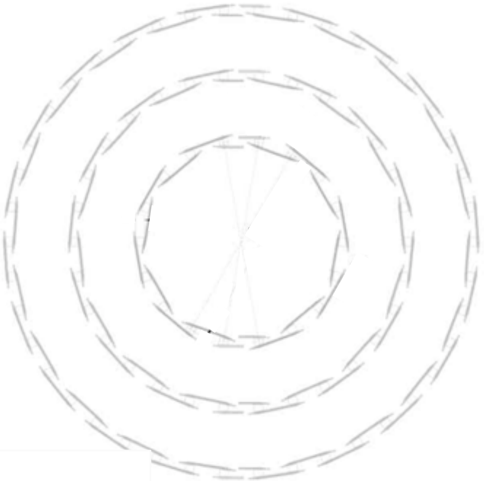
- Single sided or double sided

Belle II SVD example



CMS

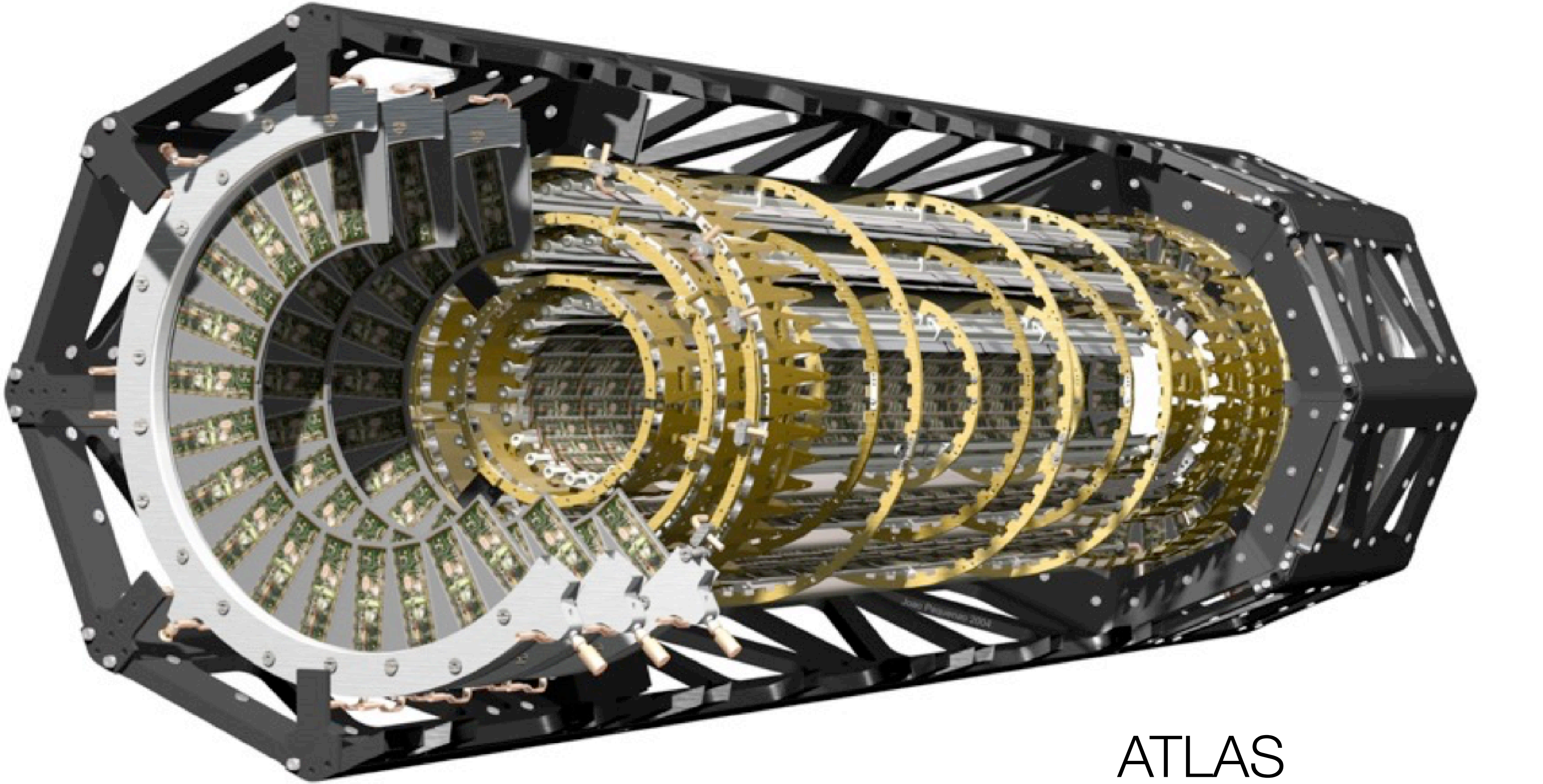




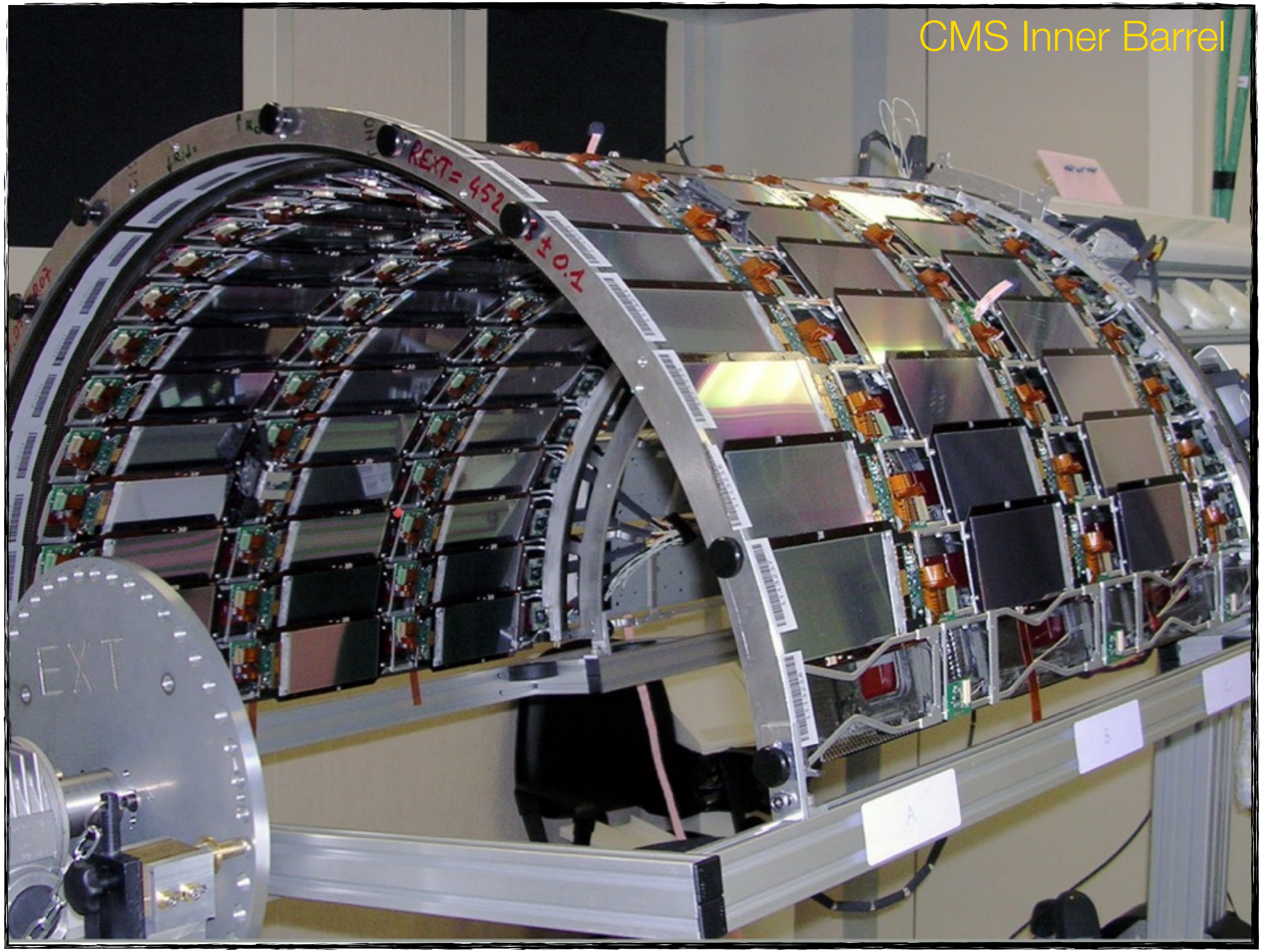
Pixel size: 100 μm x 150 μm

Barrel Pixel:
3 barrel layers at *r* of 4.3, 7.3, 10.4 cm
11520 chips (48 million pixels)

Forward Pixel:
4 disks at *z* of ±35.5 and ±46.5 cm
4320 chips (18 million pixels)
Modules dilted by 20^{o} for better charge sharing

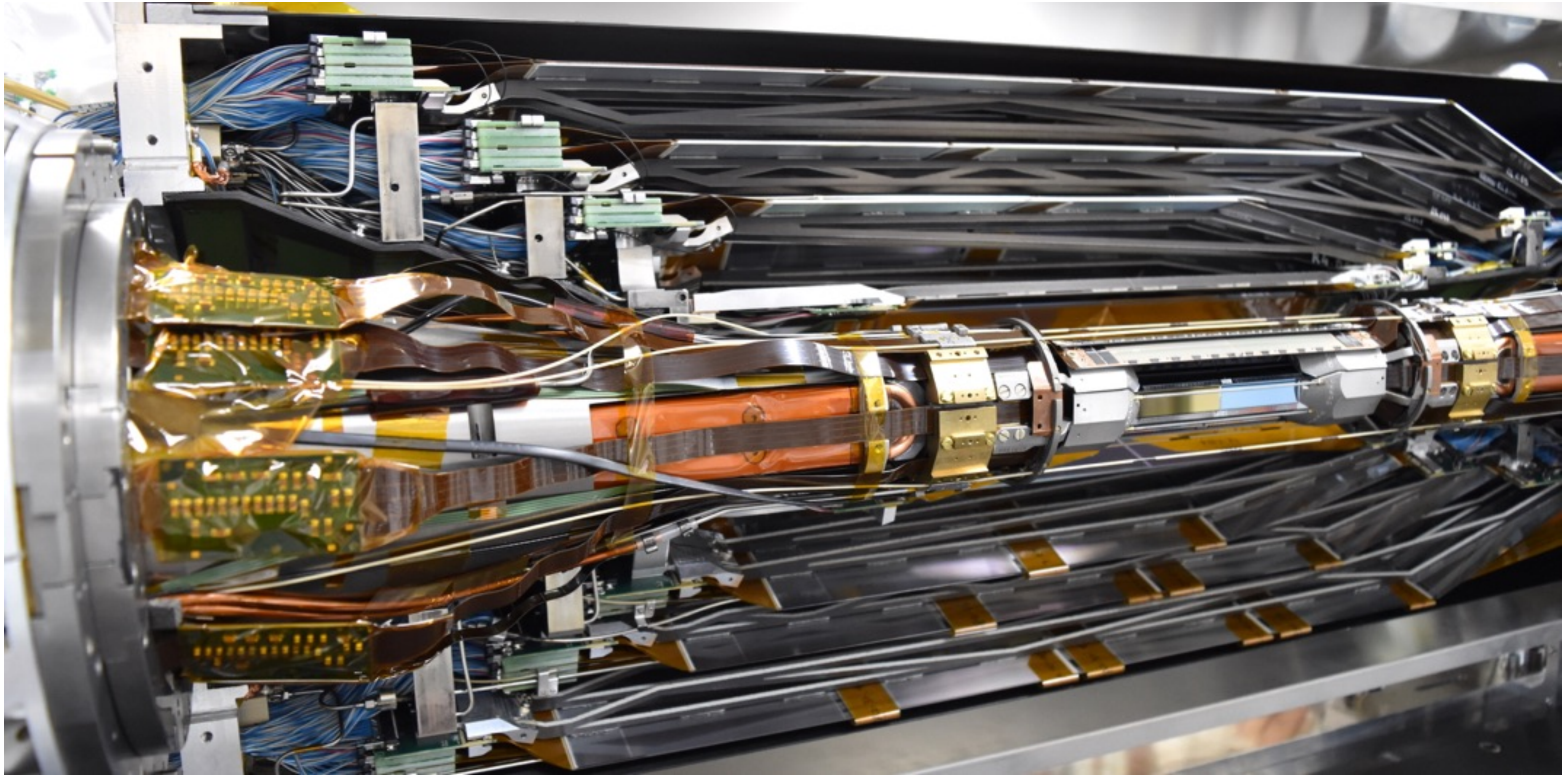


ATLAS
Pixel Detector


CMS Inner Barrel
REXT= 452
EXT

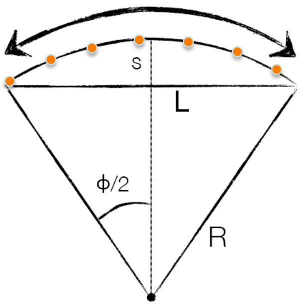

BaBar Vertex Detector

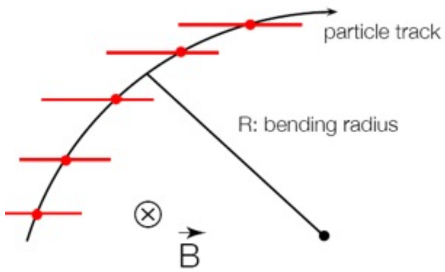
Belle II Vertex Detector



Momentum resolution

- Curvature in magnetic field: measure sagitta of trajectory





Curvature measures transverse momentum p_t

$$p_t = eBR;\ p_t[GeV] = 0.3\ B[T]R[m]$$

- To estimate resolution use sagitta s and path length L
- From geometry $s = \frac{L^2}{8R} = \frac{eBL^2}{8p_t} \rightarrow p_t = \frac{eBL^2}{8s} \rightarrow \frac{\sigma_{p_t}}{p_t} = \frac{\sigma_s}{s} = \frac{8p_t\sigma_s}{eBL^2}$.
- For N equally spaced points $\sigma_s = \frac{\sigma_x}{8}\sqrt{\frac{720}{N+5}}$ is independent of momentum, leading to $\frac{\sigma_{p_t}}{p_t} = const\,\frac{\sigma_x p_t}{BL^2}$
- In addition there is a multiple scattering contribution due to the total amount of material along the particle path

Momentum resolution - 2

- For tracks orthogonal to the magnetic field

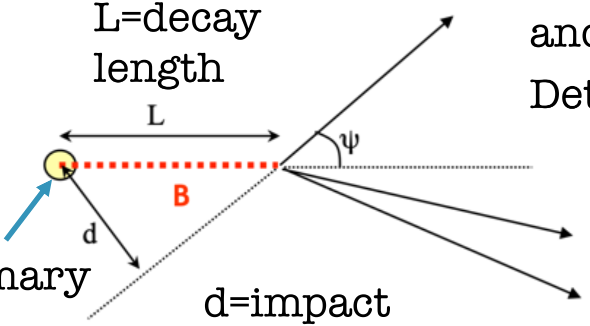
$$\frac{\sigma_{p_t}}{p_t} = C_1 \frac{\sigma_x p_t}{BL^2} \oplus C_2 \frac{1}{B\sqrt{LX_0}}$$

- Improves quadratically with path length L
- Improves linearly with magnetic field
- Degrades linearly with transverse momentum
- Is proportional to point resolution

Secondary vertices

- Heavy flavor particles like D and B decay away from the primary interaction point, generating secondary vertices.
- The distance of closest approach of a particle to the primary vertex is called impact parameter and is connected with the particle decay length

L=decay length



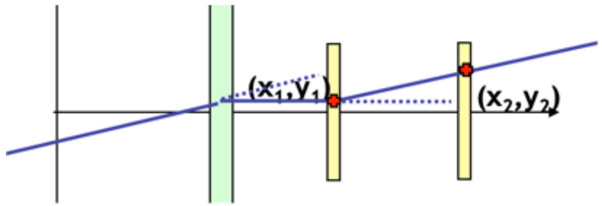
primary

d=impact parameter

For relativistic particles $d = L \sin \psi = O(\gamma\beta c\tau) \cdot O(\gamma^{-1}) = O(c\tau)$

and $\frac{\sigma_L}{L} = \frac{\sigma_d}{c\tau}$ → impact parameter resolution is essential

Determined by: point resolution, distance, multiple scattering



Example: two measurements at distance x_1, x_2 from primary

Some examples

	DELPHI	SLD
detector type	microstrips	CCD
pitch	25 μm (lettura 50 μm)	20 μm x 20 μm
beam pipe	R=5.25 cm, l=0.4% X_0	R=2.35 cm, l=0.5% X_0
first detector layer	R=6.3 cm, l=0.5% X_0	R=2.80 cm, l=0.4% X_0
last detector layer	R=10.7 cm, l=0.5% X_0	R=4.83 cm, l=0.4% X_0
point resolution	8 μm	4.4 μm
$\sigma_{tracking}$	20 μm	11 μm
σ_{ms}	65 μm×GeV	33 μm×GeV

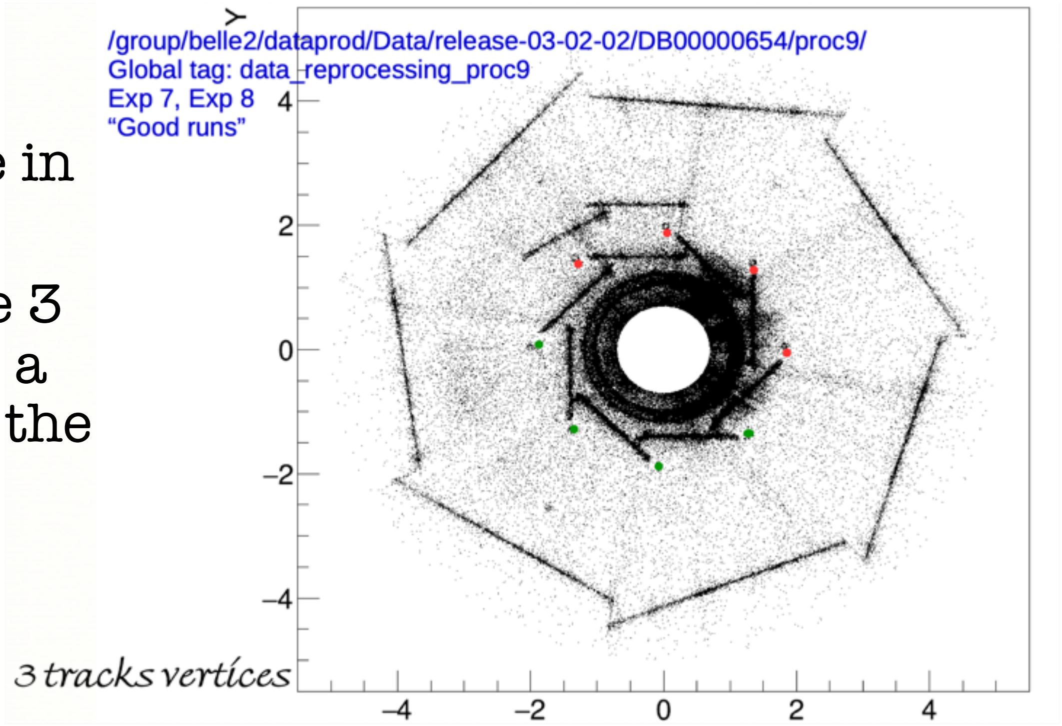
measured values

$$\sigma_d = \frac{\sqrt{x_2^2 + x_1^2}}{x_2 - x_1}\sigma_y \rightarrow \sigma_d = \sigma_{tracking} \oplus \frac{\sigma_{ms}}{p \sin^{3/2}\vartheta} \leftarrow \sigma_d = \sqrt{\sum_i R_i^2 \theta_{0,i}^2}$$

A.Andreazza

Collateral effects: interactions

- Vertices can also arise from undesirable interactions of particle in the detector material
- In this Belle II example 3 track vertices produce a kind of radiography of the detector material.



Particle Identification

Particle Identification

- Two major applications for particle identification:
  - Identification of beam particles (fixed target experiments)
  - Identification of decay products
- Assuming particle momentum is known from magnetic measurements, need second observable to identify particle type:

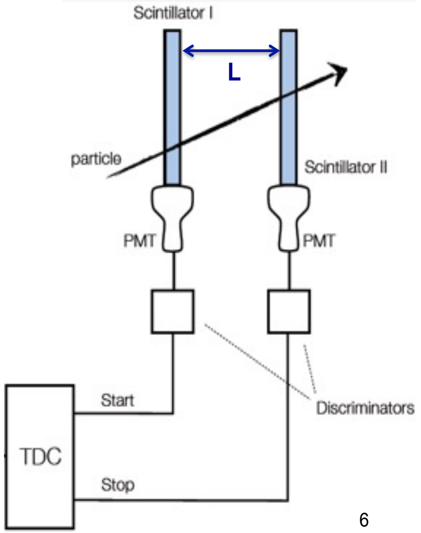
Velocity	Time of flight	$\tau \propto 1/\beta$
	Cherenkov angle or threshold	$\cos\theta = 1/\beta n, \qquad \beta > 1/n$
	Transition radiation	$\gamma > 1000$
	Energy loss (Bethe-Bloch)	$\mathrm{d}E/dx \propto 1/\beta^2$
Total energy	Calorimeter	$E = m\gamma$
Penetration	Instrumented absorber	$\mu^{\pm}$ have no radiation effects and no hadronic interactions

Summary of PID methods

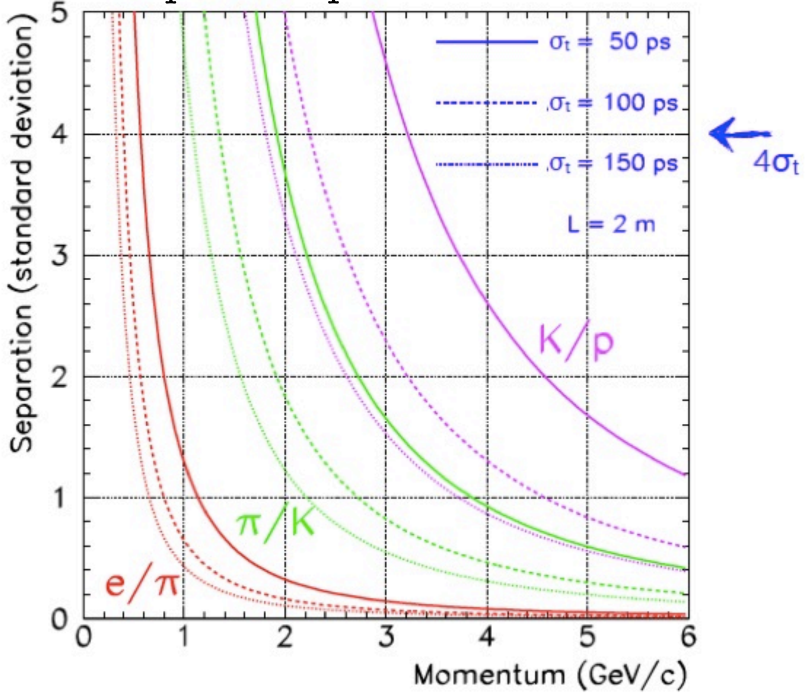
- Different methods for different particles and different momenta.
  - Need to combine different information into a likelihood estimator.
  - Indicate the separation of two mass hypotheses as "number of σ"
- Main discrimination tools:
  - e/π: match momentum to total energy electromagnetic calorimeter. $E/p = 1$ for fully absorbed electrons.
  - π/μ: penetration in instrumented absorber, μ penetrates much more
  - $\pi/K, K/p$ Cherenkov angle measurement.
  - K_L/n: penetration and shape of shower in hadronic calorimeter/instrumented absorber
  - TOF and dE/dx useful in the low β regime

Time of flight

- Measure signal time difference between two detectors with good time resolution (<100ps). $\beta = L/c\Delta t$
- For example
  - Scintillators + PMT/SiPM
  - Resistive plate chambers (RPCs)

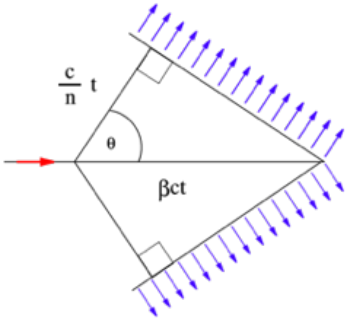


Separation power for L=2m



Cherenkov angle

- Need a radiator in which $\beta > 1/n$
- Different technologies:
  - Threshold Cherenkov Counters (Many experiments)
  - RICH: Ring Imaging CHerenkov counter (Many experiments)
  - DIRC: Detector of Internally Reflected
  - Cherenkov radiation (Babar)
  - TOP: Time of Propagation Counter (Belle II)
- Photon detection is a crucial part of the system: tiny signal
  - PMT / MCP-PMT/ SiPM
  - Hybrid Photon Detectors
  - ....



$$v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$$

$$\cos\theta_c = \frac{1}{n\beta}$$

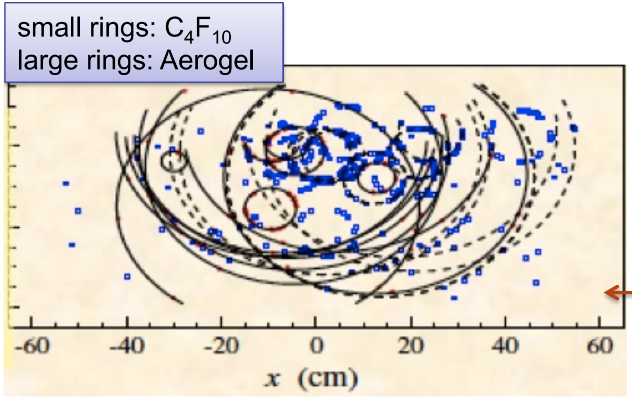
LHCb RICH system

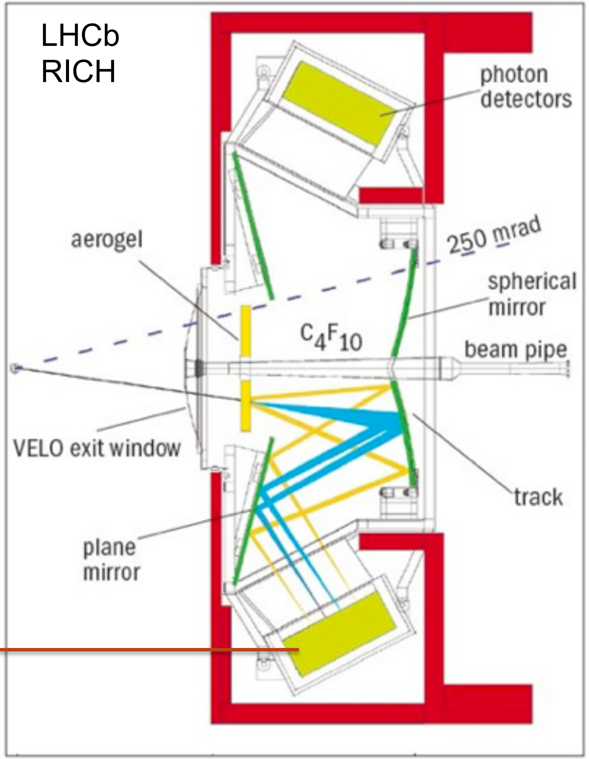
Determination of β from ring radius:

$$\beta = \frac{1}{n\cos(2r/R_s)}$$

R_s : radius of spherical mirror

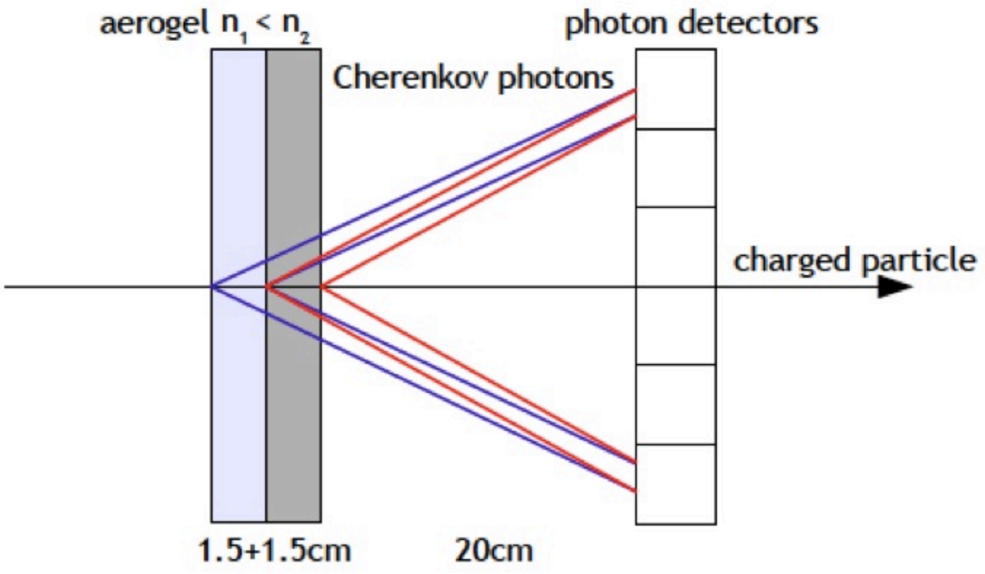
Different radiators
Complex mirror sustem to focus light on photon detectors

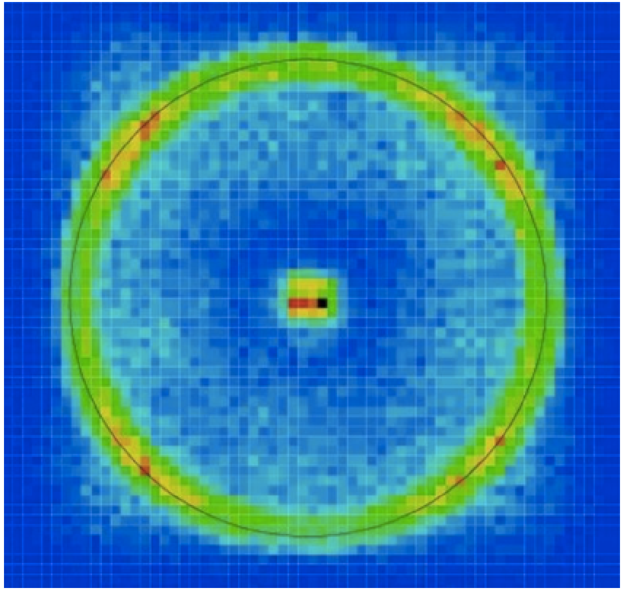




Belle II Focusing Aerogel System

- Use slightly different n_1, n_2 to get more photons without blurring the image





DIRC / TOP

- PMTs sensitive to magnetic field → in collider detectors one must bring the light outside of the magnetic region preserving the angle information
- Use very well polished super-flat quartz bars and use internal reflection

DIRC @ BABAR : Detector of Internally Reflected Cherenkov radiation

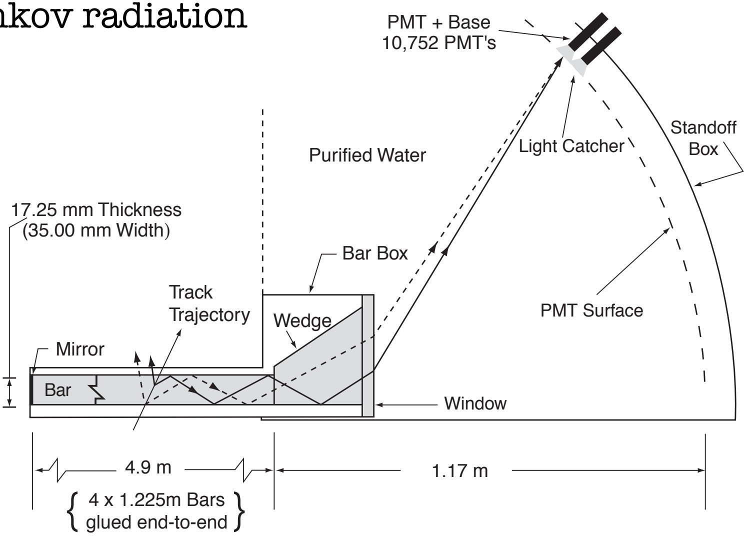
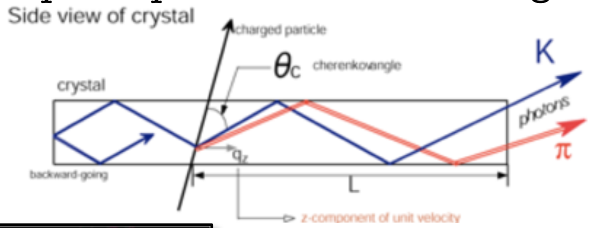
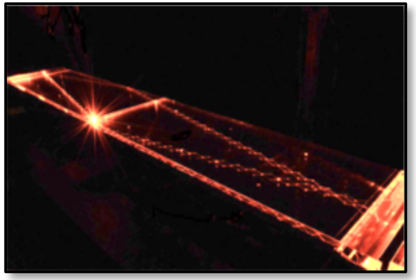
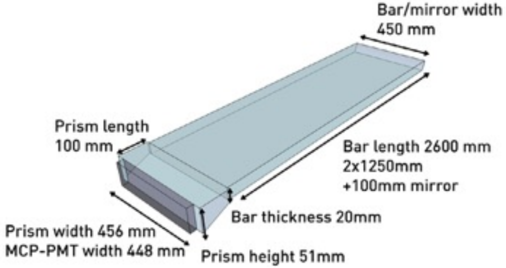


Fig. 3. Schematic of the DIRC fused silica radiator bar and imaging region.

TOP @ BELLE II: Time Of Propagation counter
Use also the time difference due to photons different optical paths for different angles

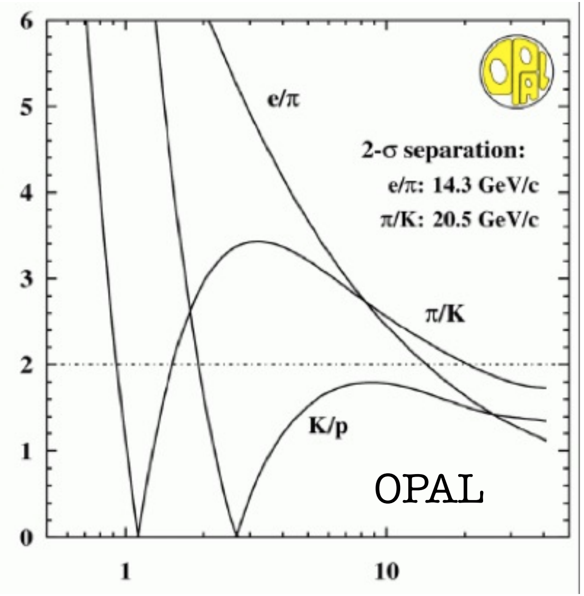


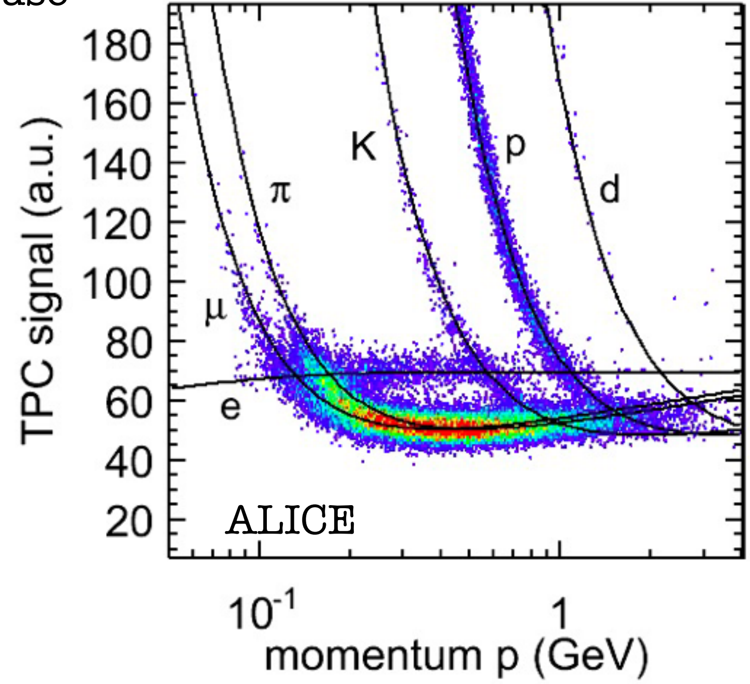




dE/dx method

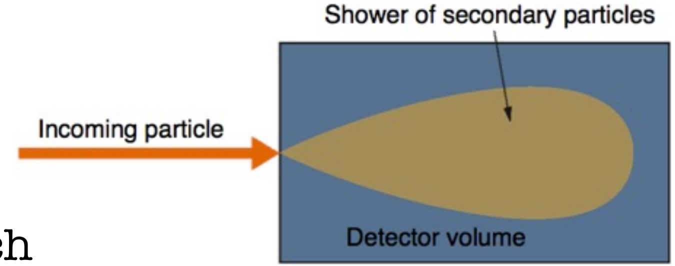
- Use the low momentum part of the Bethe-Bloch curve where $\frac{dE}{dx} \propto \frac{z^2}{\beta^2}\ln(a\beta^2\gamma^2)$
- Fluctuations make the method difficult to use
- Can complements other methods



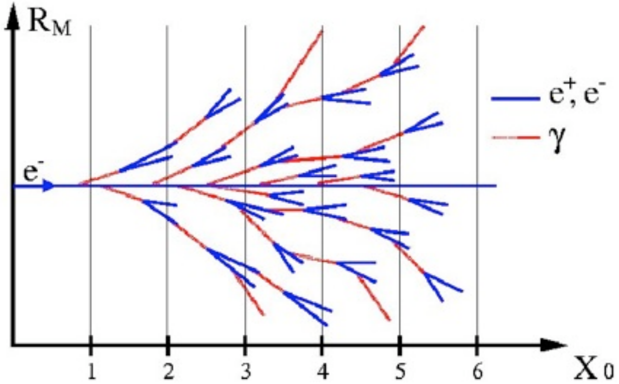


Calorimetry

- Total absorption of a particle: destructive measurement of total energy
  - Eventually converted in heat →calorimeter
- The medium is dense so the first particle interacts, producing secondary particles which undergo further interactions, producing a shower

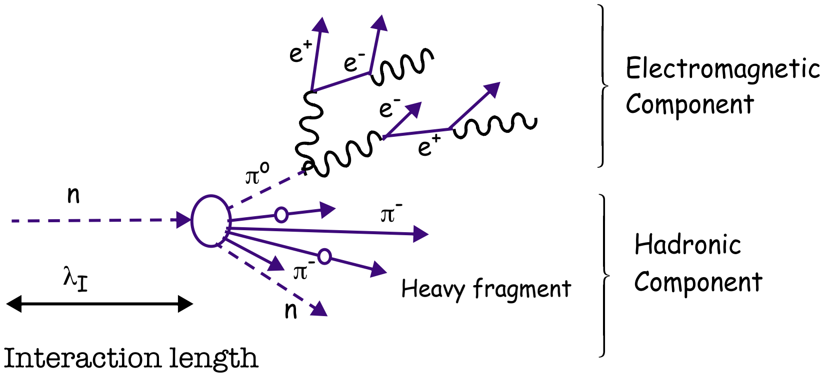


Electromagnetic shower



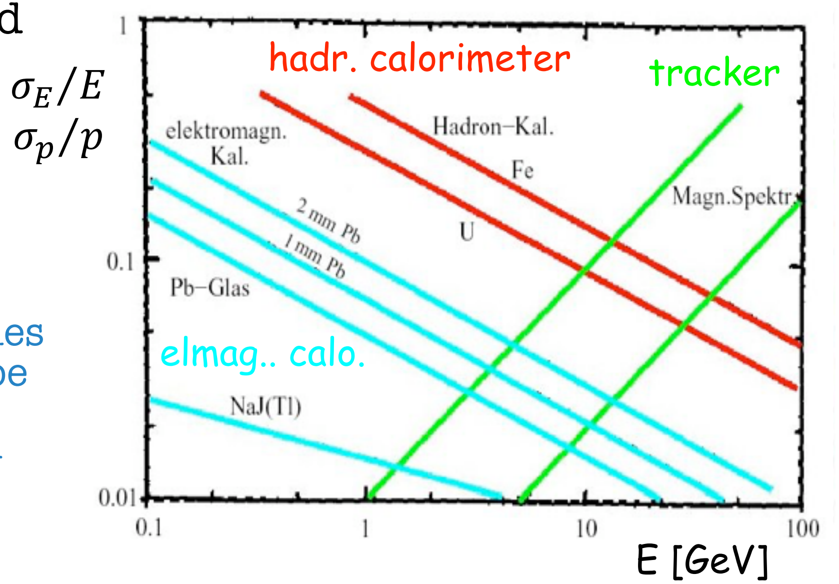
Rad lengths

Hadronic shower



Use of calorimetry

- Calorimetry is a widespread technique in particle physics:
  - Instrumented targets (e.g. neutrino experiments)
  - 4π detectors for collider experiments
  - Measure both charged and neutral particles
- Various detection mechanisms are used
  - Scintillation
  - Cherenkov radiation
  - Ionization
  - Phonons/thermal effects
- Energy resolution
  - Stochastic process, number of secondaries is proportional to E, so $\sigma_E/E \propto 1/\sqrt{E}$, to be compared with $\sigma_p/p \propto p$
  - At high energy calorimetry is necessary



Electromagnetic shower

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

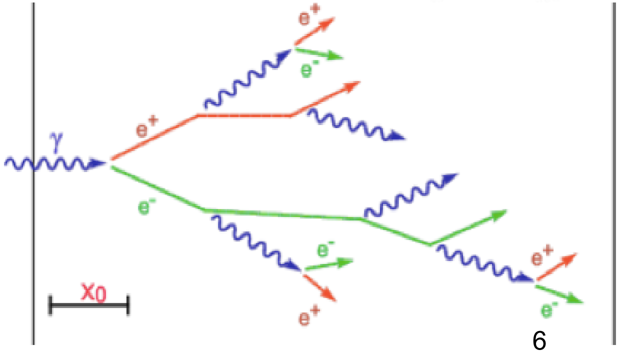
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

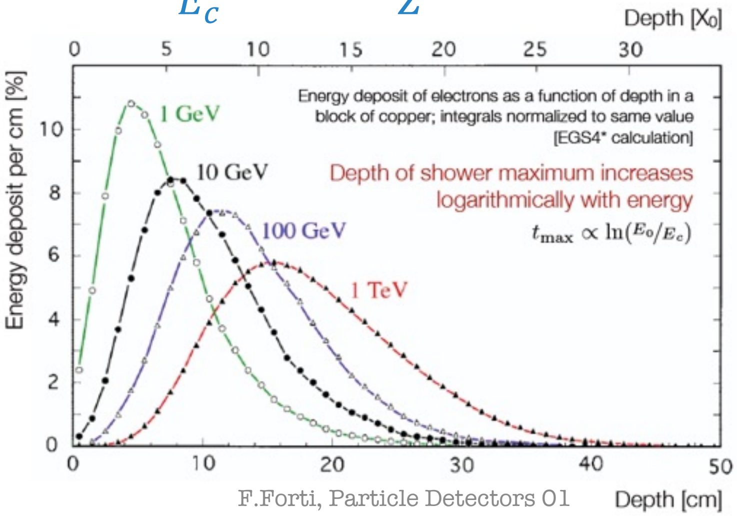
$$\rightarrow E = E_0 e^{-x/X_0}$$

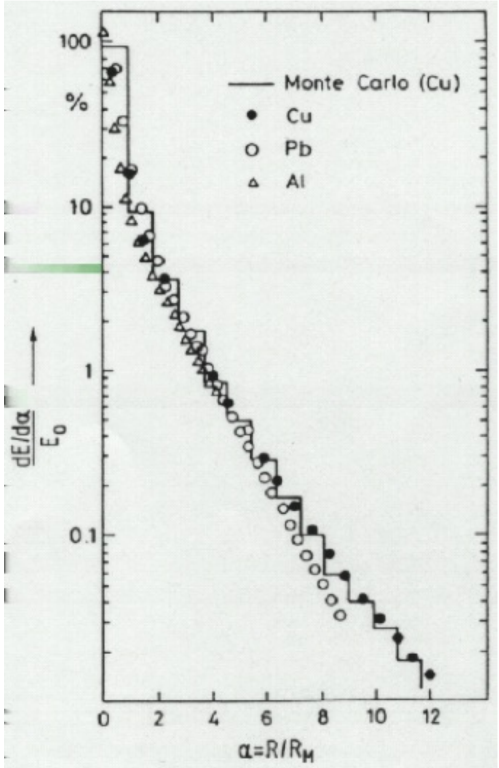
After passage of one X_0 electron has only $(1/e)^{\text{th}}$ of its primary energy ...
[i.e. 37%]



Development of EM shower

- Transverse
  - Main contribution from low energy electrons at
    $$E \approx E_c: <\theta> \approx 21MeV/E_c$$
  - With an approximate range X_0 the lateral spread (Molière radius) is
    $$R_M \approx \frac{21MeV}{E_c} X_0 \approx \frac{7A}{Z}$$
- Longitudinal





Useful numbers for back of the envelope calculations

Radiation length: $$X_0 = \frac{180A}{Z^2} \frac{\mathrm{g}}{\mathrm{cm}^2}$$

Critical energy:
[Attention: Definition of Rossi used]
$$E_c = \frac{550\ \mathrm{MeV}}{Z}$$

Shower maximum:
$$t_{\max} = \ln \frac{E}{E_c} - \begin{cases} 1.0 & e^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

Longitudinal energy containment:
$$L(95\%) = t_{\max} + 0.08Z + 9.6\ [X_0]$$

Transverse Energy containment:
$$R(90\%) = R_M$$
$$R(95\%) = 2R_M$$

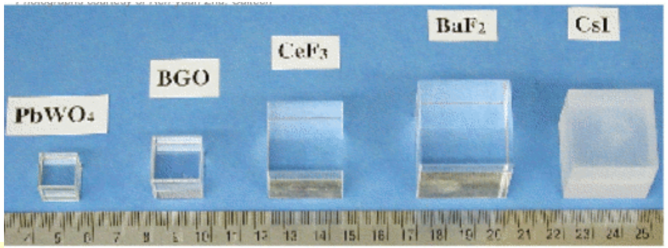
Problem:
Calculate how much Pb, Fe or Cu is needed to stop a 10 GeV electron.

Pb : Z=82 , A=207, ρ=11.34 g/cm^3
Fe : Z=26 , A=56, ρ=7.87 g/cm^3
Cu : Z=29 , A=63, ρ=8.92 g/cm^3

Classes of calorimeters

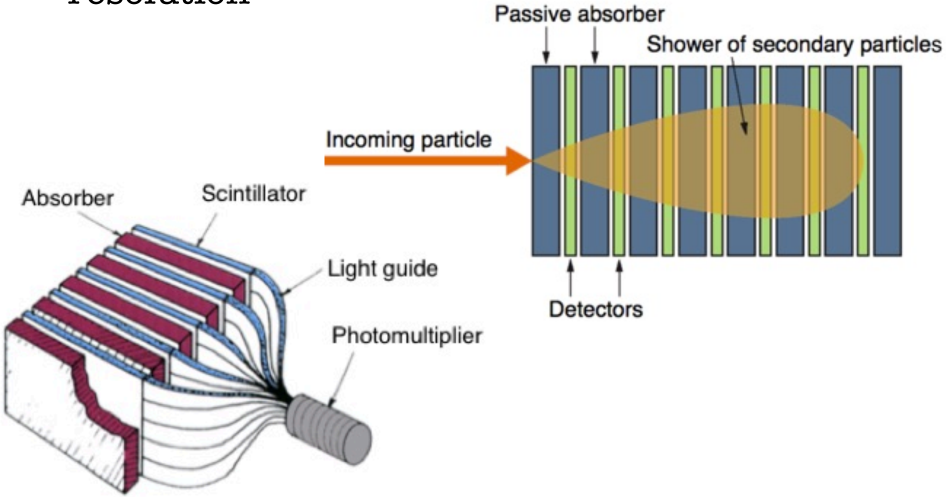
Homogeneous calorimeters

- A single medium serves as both absorber and detector:
  - scintillating crystals (CsI, BGO, $PbWO_4$, LYSO, …), lead glass, or Liquid Xe, LKr.
- Collect all energy if deep enough: good resolution
- Volume and depth limited by cost and fabrication issues



Sampling calorimeters

- Layers of passive absorber (Pb, Cu) alternate with active detector layers (Scintillator, LAr, Silicon)
- Scalable: can be made very thick; relatively cheap
- Collect only fraction of energy limits resolution



Energy resolution

- Energy is proportional to number of particles.
  If all are counted: $E \propto N, \sigma \propto \sqrt{N} \propto \sqrt{E} \rightarrow \sigma/E \propto 1/\sqrt{E}$
- In practice there are more terms in resolution:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- a : Stochastic term
  - Statistical shower fluctuations
  - Sampling fluctuation
  - Signal quantum fluctuations (eg photoelectron statistics)
- b : Constant term
  - Inhomogeneities and imperfections (hardware, calibration, dimensional variations
  - Non-linearity of readout electronics
  - Longitudinal containment fluctuations (leakage can be $\propto E^{-1/4}$)
  - Dead material in front or within the calorimeter
- c : Noise term
  - Readout electronics noise
  - Radio-activity, pile-up (energy coming from other events)

Homogeneous calorimeters energy resolution

- Assume W is the mean energy needed to produce a ‘signal quantum’, for instance an electron-ion pair or a photon
- The number of ‘quanta’ $\langle N \rangle = E/W$ will be Poisson distributed with $\sigma_N = 1/\sqrt{\langle N \rangle}$ leading to $\frac{\sigma_E}{E} = \frac{1}{\sqrt{N}} = \sqrt{\frac{W}{E}}$ → the smaller W, the better the energy resolution
- If there is correlation in the production of signal quanta, the fluctuations are reduced
  - This is called the “Fano factor” $F < 1$ leading to $\frac{\sigma_E}{E} = \sqrt{\frac{FW}{E}}$
  - For instance for gamma spectroscopy Ge(Li) detectors have F=0.1 leading to a stochastic term

$$\frac{\sigma_E}{E} = 1.7\%/\sqrt{E(keV)}$$

Material	W (eV)
Ge	2.9
Si	3.6
Gas	30
Plastic Scintillator	100

Sampling calorimeter resolution

- Main contribution: sampling fluctuations, from fluctuations in the number of charged particles n_{ch} crossing active layers.
- n_{ch} increases linearly with energy and the inverse of the thickness t of the absorbing layer: $n_{ch} \propto E/t$
- For uncorrelated samples the stochastic term is

$$\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{n_{ch}}} \propto \frac{\sqrt{t}}{\sqrt{E}}$$

- Finer sampling results in better resolution. In practice reaching the same resolution of homogenous calorimeters for low energy is impractical, but sampling calorimeters dominate at high energy.

Some example EM calorimeters

Homogeneous calorimeters:

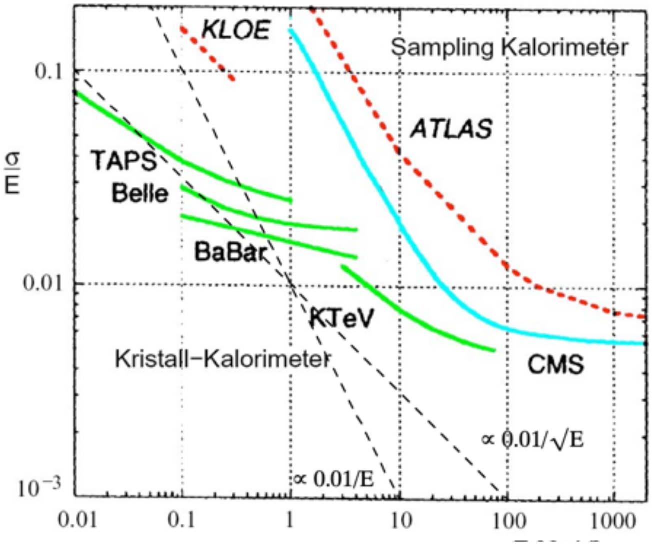
Experiment	Material	Energy resolution (E in GeV)
NA48	Liquid Kr	4.8%/√E ⊕ 0.22%
BELLE	CsI(Tl)	0.8%/√E ⊕ 1.3%
CMS	$PbWO_4$	2.7%/√E ⊕ 0.55%*

Sampling calorimeters:

Experiment	Detector	Detector thickness [mm]	Absorber material	Absorber thickness [mm]	Energy resolution (E in GeV)
UA1	Scintillator	1.5	Pb	1.2	15%/√E
SLD	liquid Ar	2.75	Pb	2.0	8%/√E
DELPHI	Ar + 20% CH_4	8	Pb	3.2	16%/√E
ALEPH	Si	0.2	W	7.0	25%/√E
ATLAS	liquid Ar		Pb		10%/√E ⊕ 0.7%*
LHCb	Scintillator		Fe		10%/√E ⊕ 1.5%*

M. Krammer

* Design values

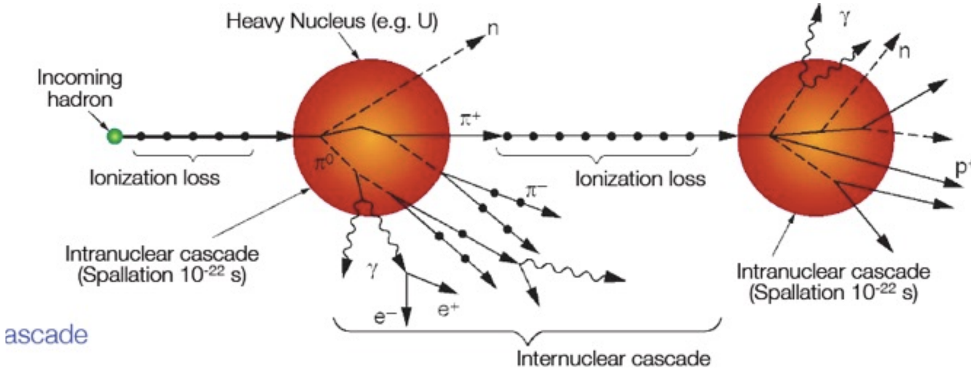


C.Niebuhr E(GeV)

Hadronic calorimeters

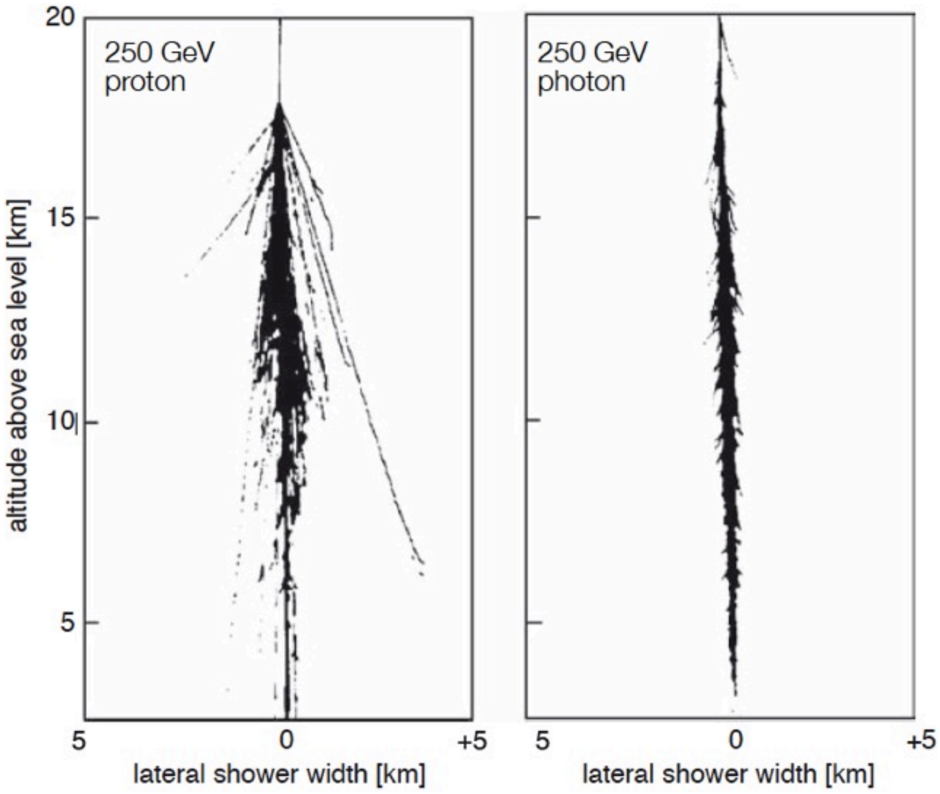
- Hadrons also produce showers, with a similar mechanism, but also differences:
  - 1. Hard interaction of hadron with nucleus - λ_{int}
  - 2. Spallation: intra-nuclear cascade with possibility of nuclear excitation
  - 3. Secondary interactions
  - Electromagnetic and hadronic components give different responses
  - Some energy can be lost in nuclear excitations

	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8



Hadronic vs. electromagnetic

- Comparison of simulated showers in atmosphere for protons and photons
- Hadronic showers much more difficult to model and understand
- Great effort in getting the same response from the em and hadronic components (compensation).



Simulated air showers

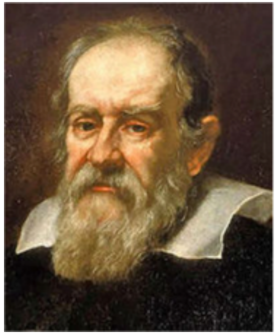
Take away message

- Modern detectors measure as much as possible

- Tracking for momentum and position, reconstruct vertices
  - Gas or silicon detectors
- Particle identification essential to properly reconstruct the decay chain
  - TOF, Cherenkov light, dE/dx as a complement
- Calorimetry measures total energy
  - The only way of measuring neutrals

Conclusion

Detectors are our eyes. We need to use all the possible technologies and tools to perform the best measurement we can.



Galileo Galilei

- Measure what can be measured, and make measurable what cannot be measured.

Freeman Dyson

- The effect of a concept-driven revolution is to explain old things in new ways.
- The effect of a tool-driven revolution is to discover new things that have to be explained.