Particle Identification Detectors and Techniques

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October 13, 2011

Foreword – Reference material

- Impossible to cover all the aspects of particle detection!
- This lecture is focused on high energy particle detectors
- Many excellent courses and textbooks are available. These lectures are mainly based on :
- L. Serin (LAL) Lectures given at the TransEuropean HEP School 2008 (thanks Laurent!)
- F. Sauli IEEE NSS/MIC Norfolk 2002
- C. Joram, L Ropelewski Lectures at the CERN Academic Training Program 2004/2005 (many slides borrowed from this series)

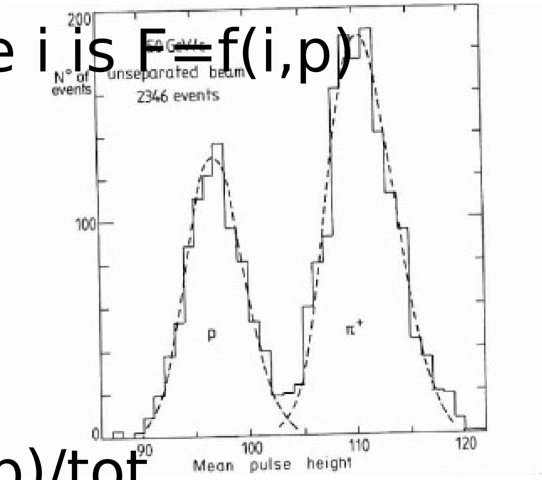
Reference books

- C. Grupen, Particle Detectors, Cambridge University Press, 1996
- K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
- W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
- F. Sauli Principles of operation of multiwire proportional and drift chambers CERN 77-09

Outline

- Introduction and examples
- Time of flight
- Charged particle interaction with matter
- Ionization measurement
- Cherenkov detectors
- Transition radiation

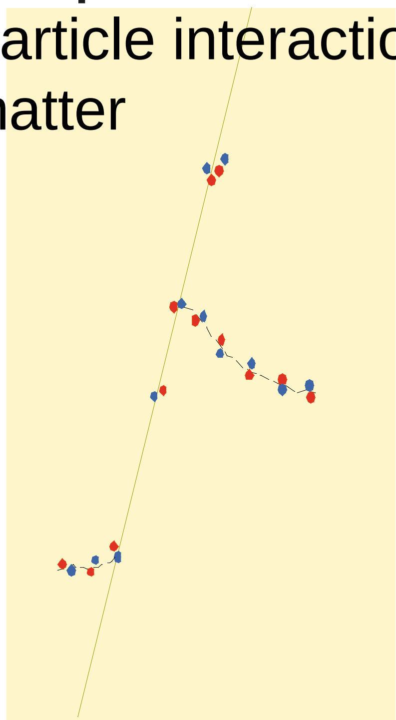
Definitions

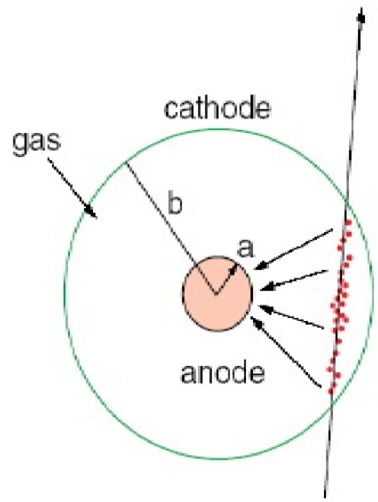


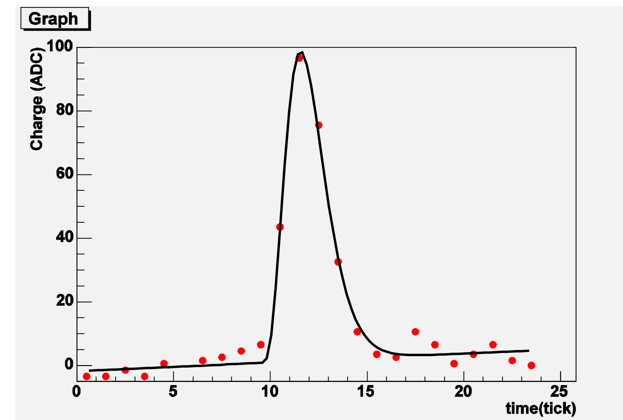
- Suppose the detector response to a particle i is F=f(i,p)
- And it is different from f(j,p)
- i is your signal and j the background
- Then your detector is capable of PID
- You can place a cut on F < Fcut
- Define an efficiency ε(i) = Int (-inf, Fcut)f(i,p)/tot
- A misidentification rate misid(j->i)= Int (-inf, Fcut)f(j,p)/tot
- A rejection factor R=ε(i)/misid(j->i)
- A separation or resolving power S= (<f(i,p)>-<f(j,p)>)/σ

Basis of particle detectors

Particle interaction in matter

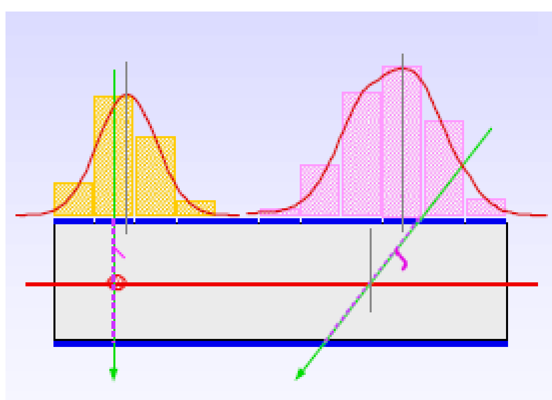






Detector is set up in order to collect the “message” left by the particle ...

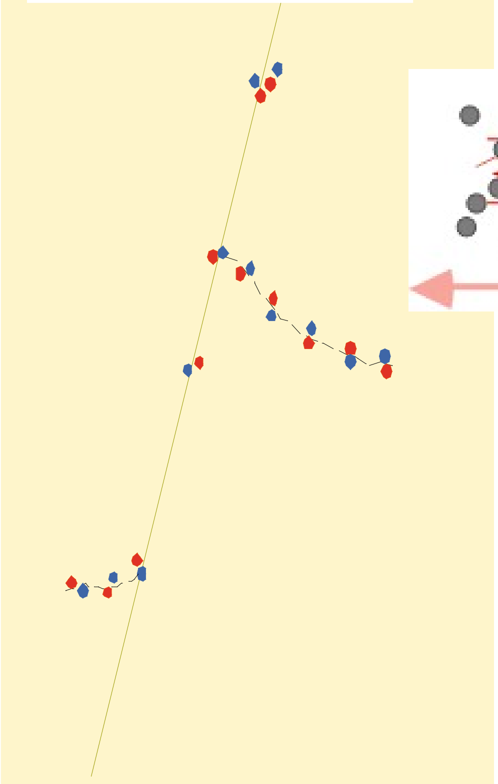
and to produce an electric signal which is recorded



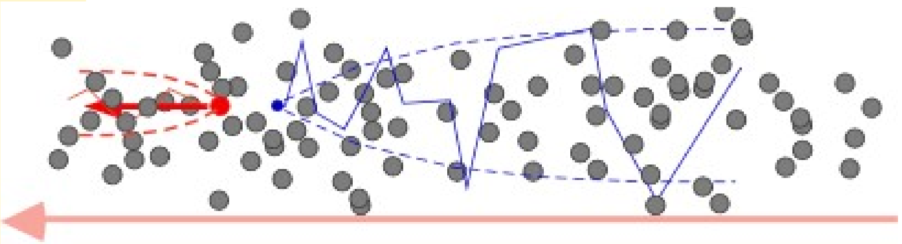
Signal is processed to obtain information about the particle: position, time, momentum, energy, mass ...

Gas detectors: steps

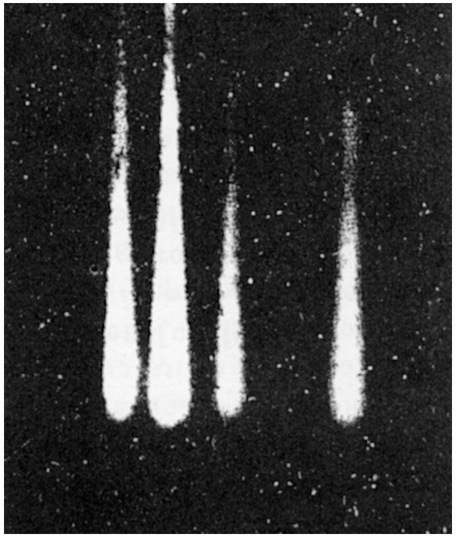
Ionization

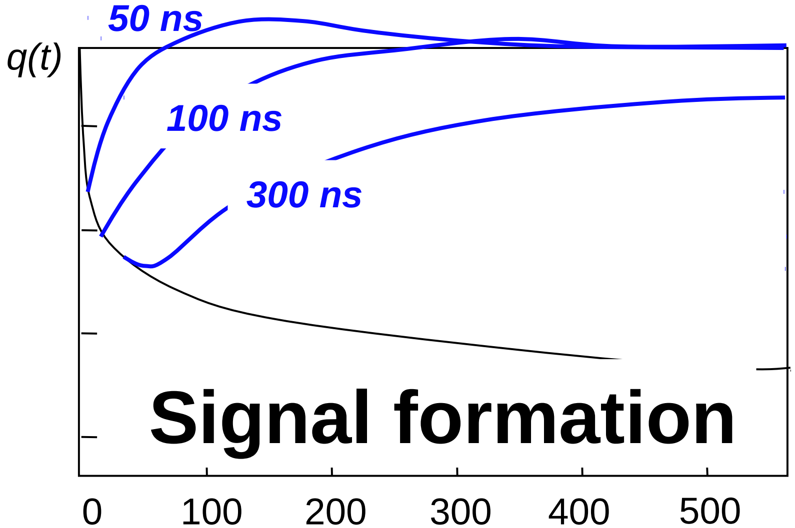


Transport: drift and diffusion



Multiplication





Detection methods and problems

The pristine physics response is altered by thresholds, noise, non-linearity, pile-up, digitization etc

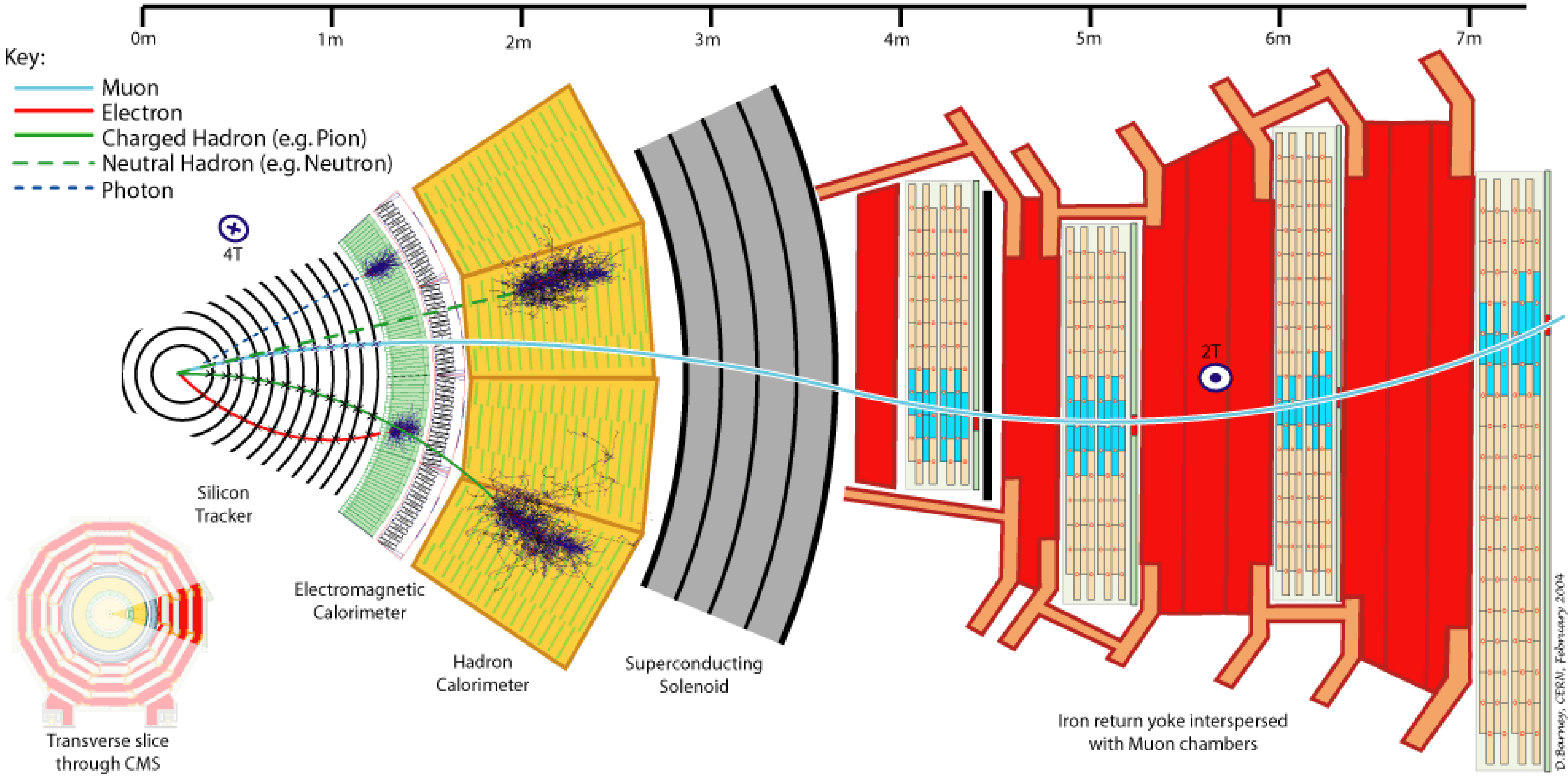
The devil is in the details !

All these interesting effects enter into the efficiencies, misid etc

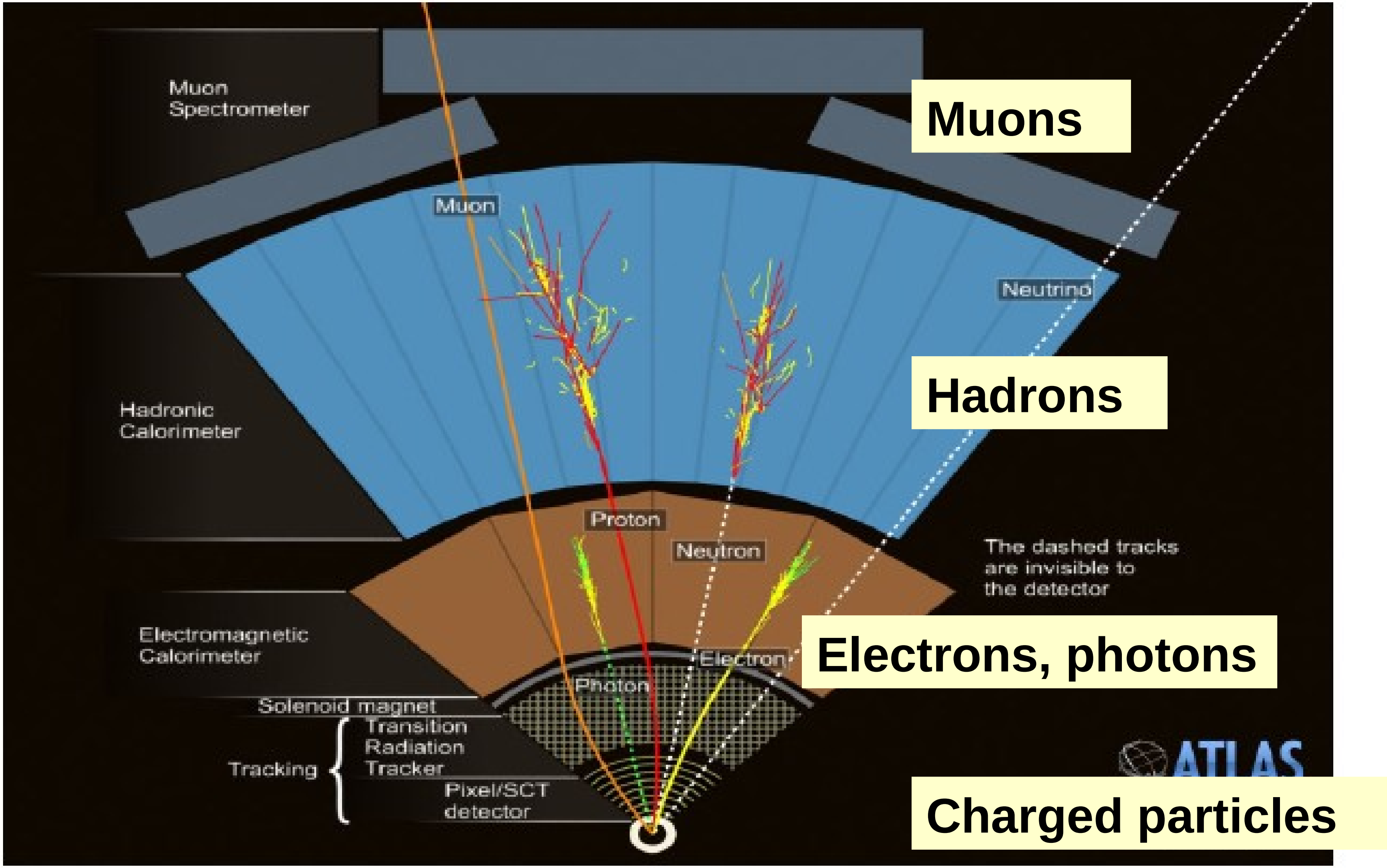
We can take them into account with :

- Detailed MC (understand the physics of your detector!)
- Beam tests
- Control samples

A slice of CMS



Cross section of a modern HEP exp



Typical problems in particle identification

- K-pion : time of flight, ionization, Cherenkov
- electron-pion : E/p, shower shape
- Muon-pion: penetration through dense and thick materials
- It is usual to combine different detectors to achieve a better separation
- This has also the advantage that purity and efficiency can be measured with the data

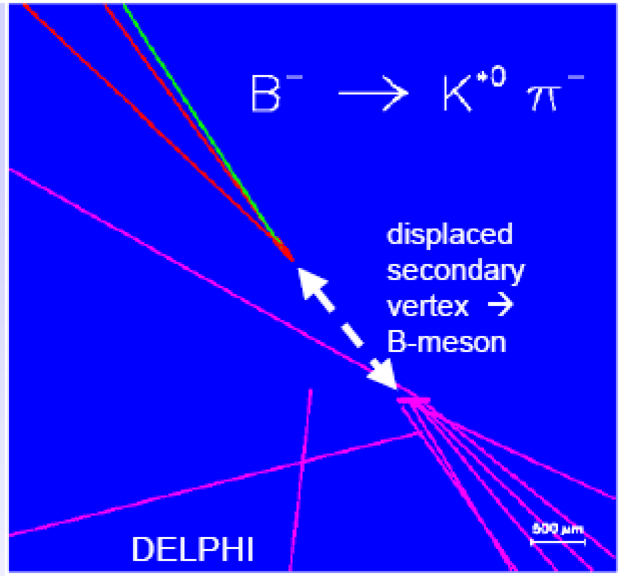
PID example : DELPHI charmless B decay

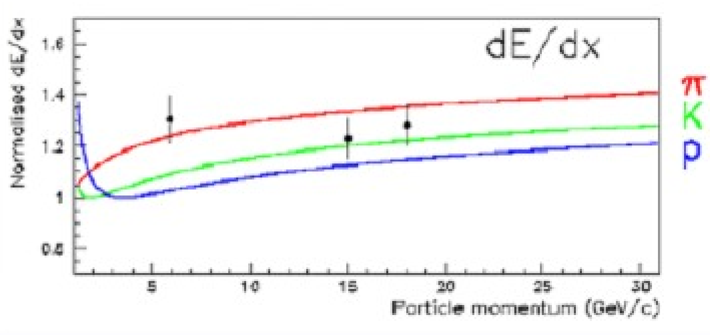
A ‘charmless’ B decay:

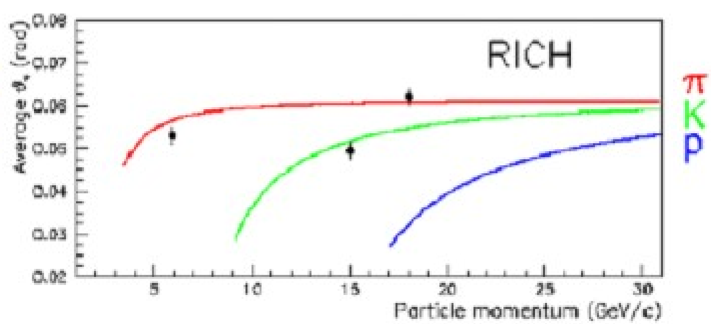
$$B^- \rightarrow K^* \pi^-$$
$$\downarrow$$
$$K\pi$$

1 K + 2 π

in final state



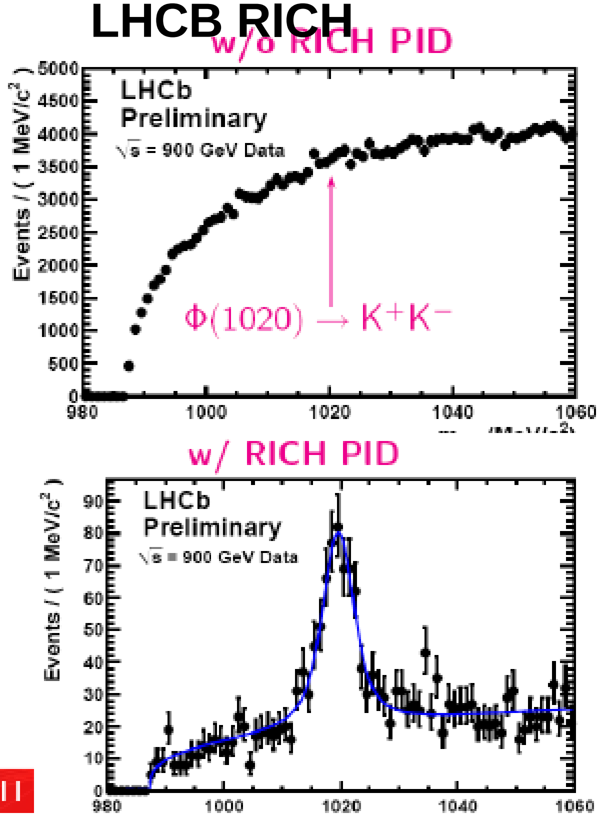




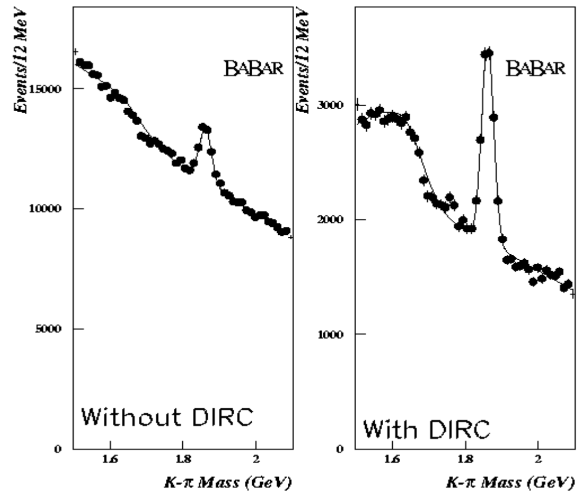
Examples

- Reduction in background using identification

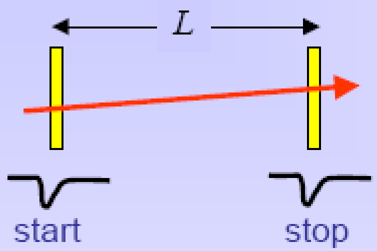
LHCB RICH



BABAR DIRC



Time of flight (ToF)



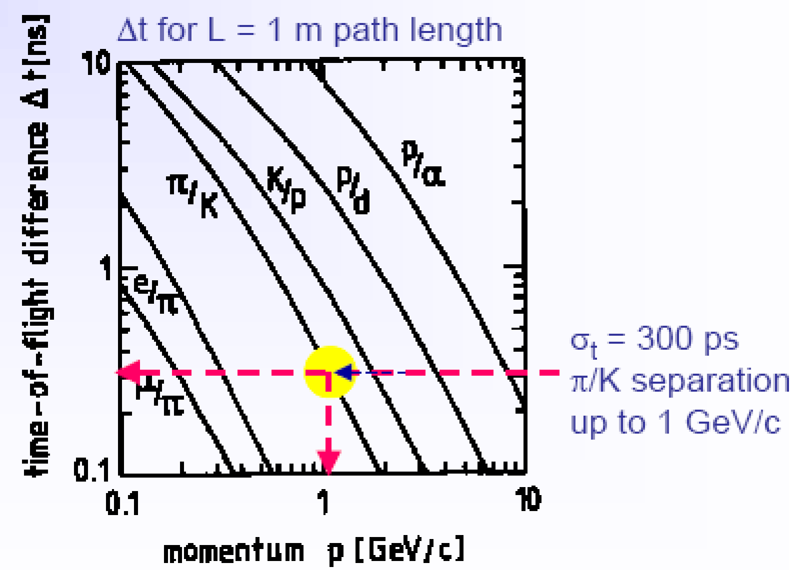
$$t = \frac{L}{\beta c} \longrightarrow \beta = \frac{L}{tc}$$

Combine TOF with momentum measurement

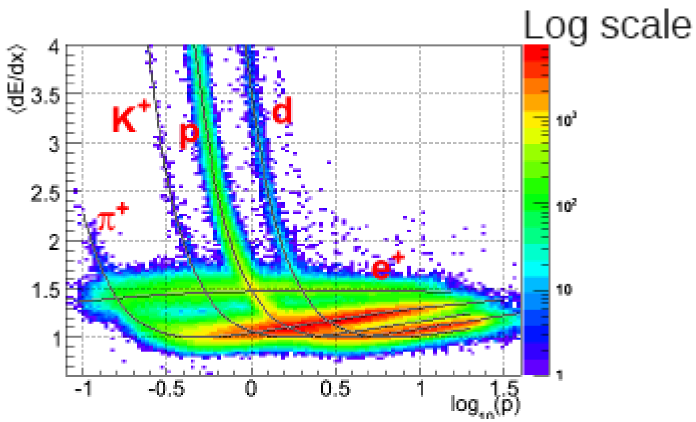
$$p = m_0 \beta\gamma \longrightarrow m_0 = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

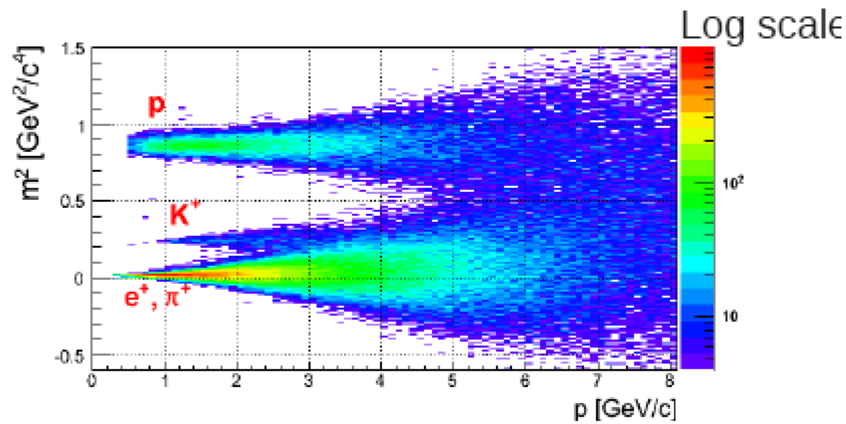
$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + \frac{m_1^2 c^2}{p^2}} - \sqrt{1 + \frac{m_2^2 c^2}{p^2}}\right) = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

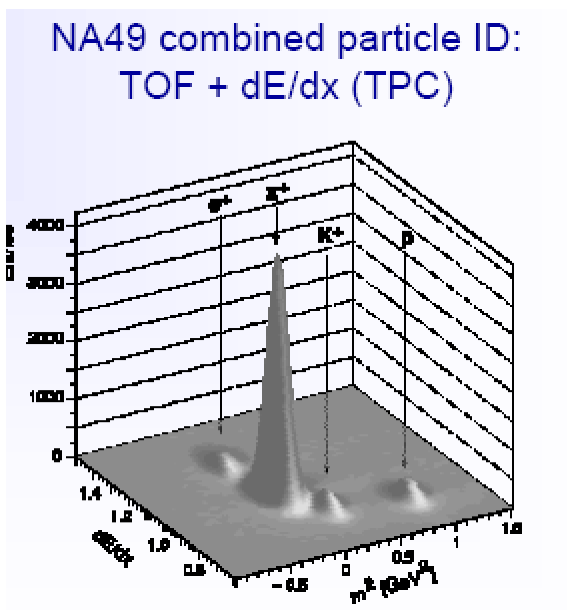
Typical resolution o(100) ps
Advantage of ToF: simple, optimum at very low momenta
Complementary to other techniques



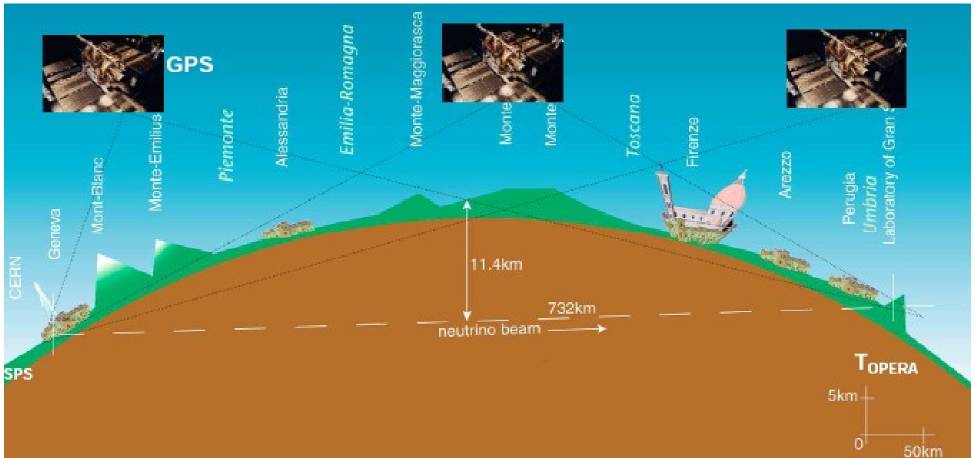
Example ToF and Ionization: NA61





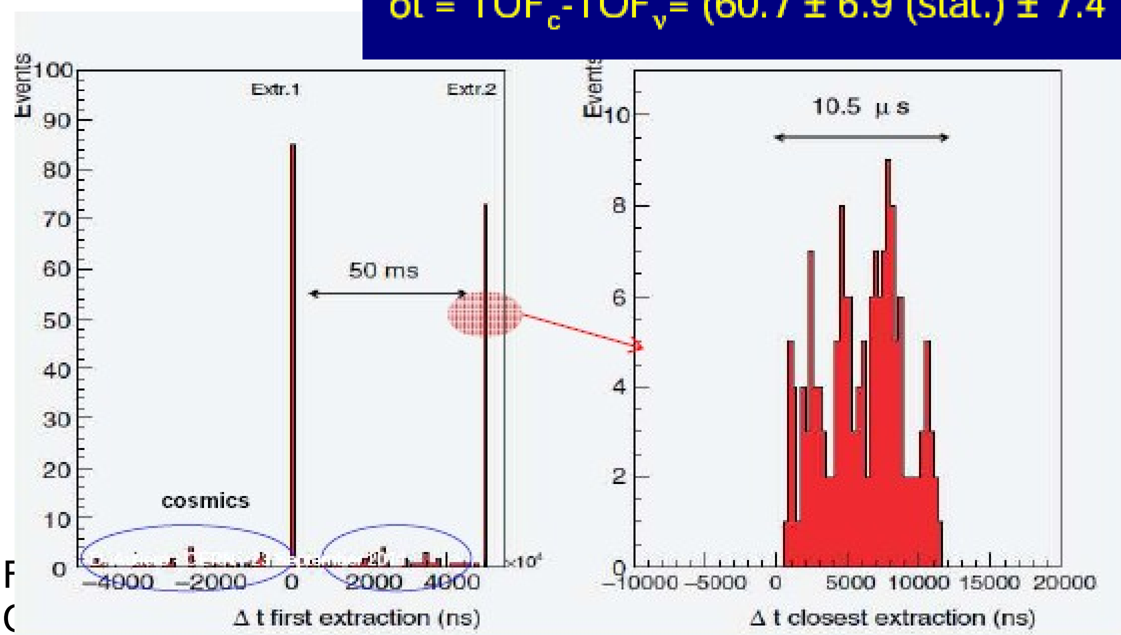


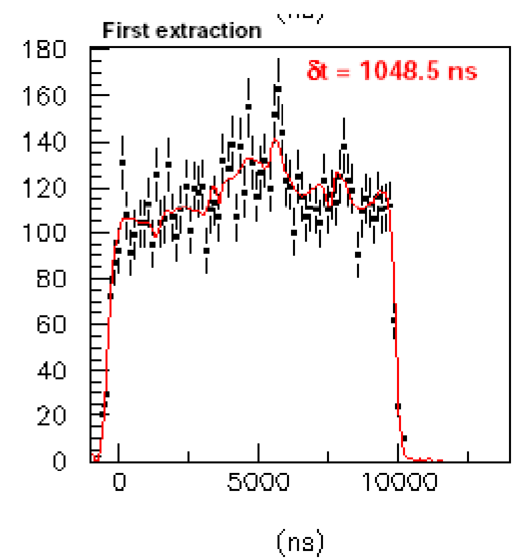
An intriguing ToF measurement



OPERA on CNGS neutrino beam
Baseline 730 km (CERN to Gran Sasso
~ 2 ms total flight time

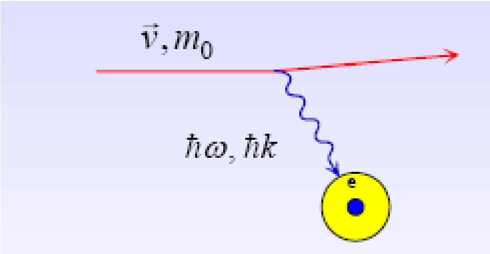
$\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (stat.) \pm 7.4\ (sys.))$ ns





Interaction of charged particles

- For a charged particle traversing a layer of material, three processes can occur
  - Ionization of atoms
  - Cherenkov radiation
  - Transition radiation



Consider a particle of mass m_0, velocity v emitting a photon (ω,k) in a material of refractive index n and dielectric constant

$$\epsilon = \epsilon_1 + i\epsilon_2$$

$$n = \Re\sqrt{\epsilon_1}$$

$$\omega = v k \cos\theta_c \quad h\omega \ll \gamma m_0 c^2$$

Energy momentum conservation

$$\omega^2 = \frac{k^2 c^2}{\epsilon}$$

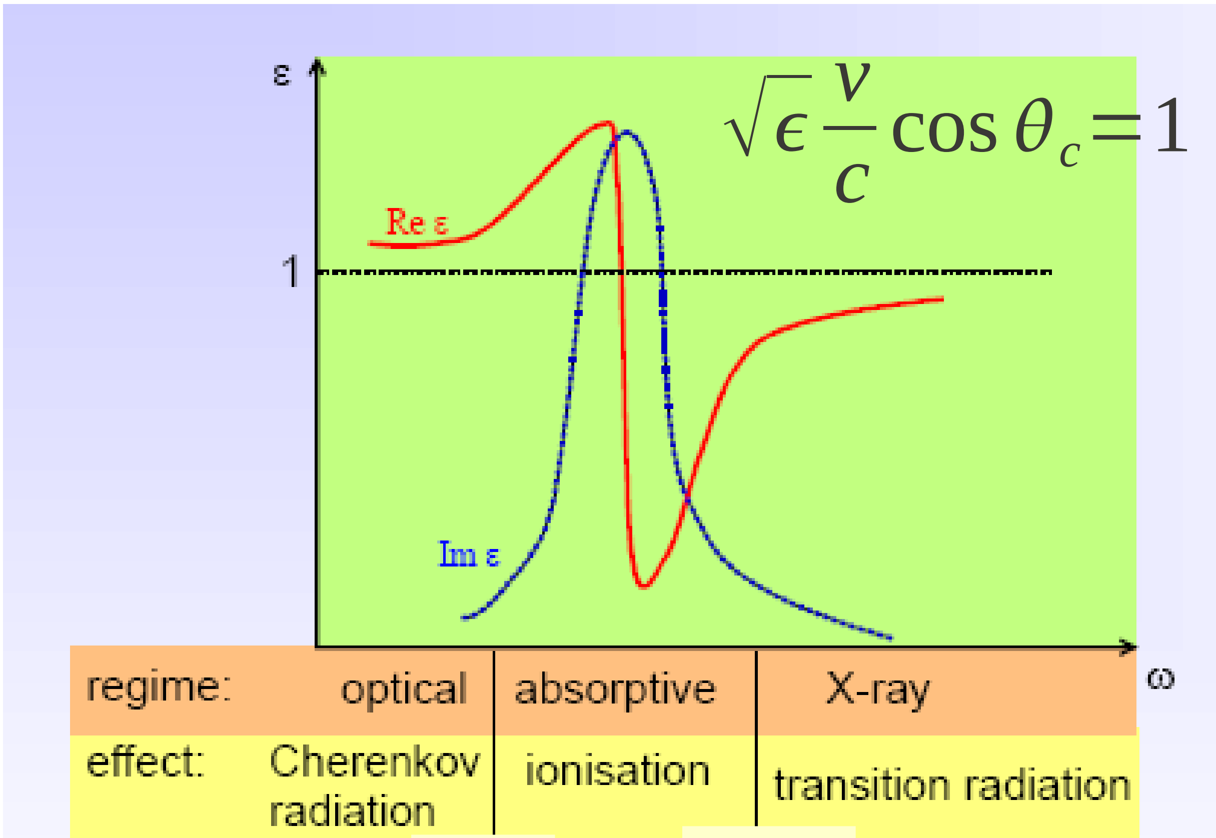
Dispersion relation

$$\sqrt{\epsilon}\frac{v}{c}\cos\theta_c = 1$$

Θ angle between the photon and the incoming particle

Allison, Wright 1983

Interaction of charged particles



~eV

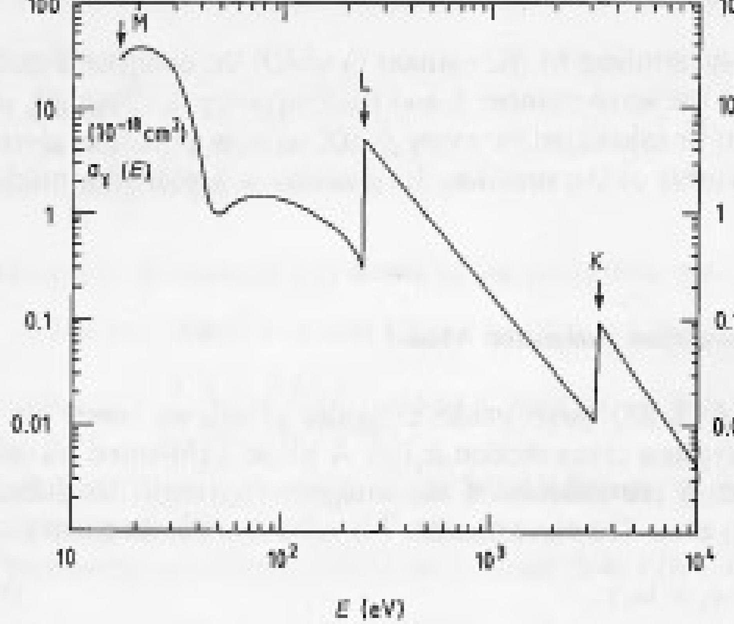
~keV

Below the excitation energies of the material ε is real and > 1. Real Cherenkov photons for

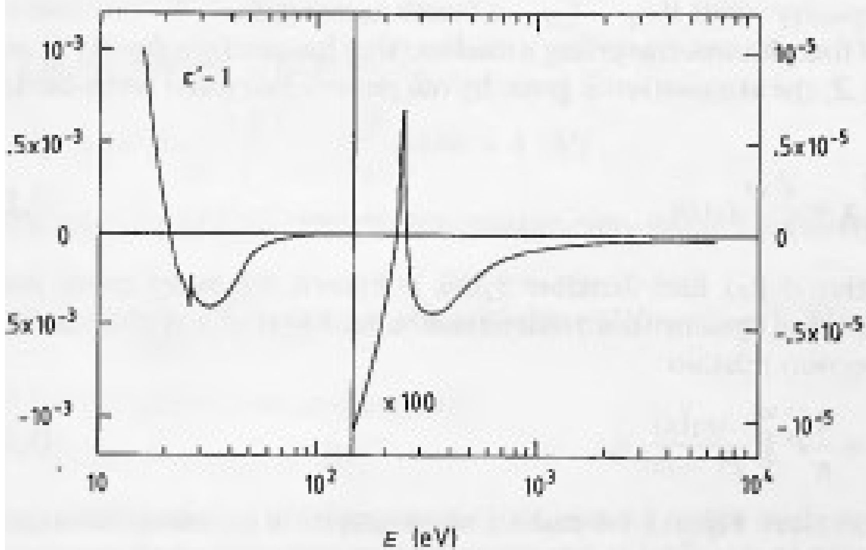
$$v > \frac{c}{\sqrt{\epsilon}}$$

Above 5 keV, real photons are emitted if there are discontinuities in the material => transition radiation

From 2 eV to 5 keV, ε is a complex number, virtual photons are exchanged, ionization and excitation



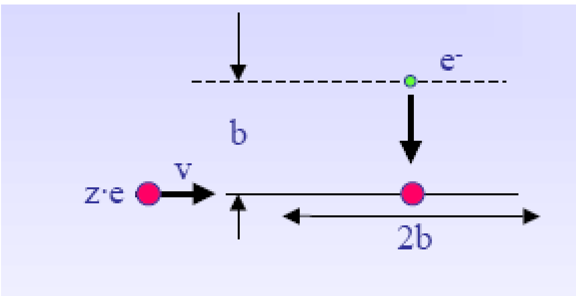
ig. 1.4. Total photo-ionization cross-section of Ar as a function of the photon energy, as compiled y Marr and West [MAR 76]. The imaginary part of the dielectric constant is calculated from this urve using (1.23)



ig. 1.5. The real part of ε as a function of E, calculated from Fig. 1.4 using (1.24) [LAP 80]

Understanding Bethe Bloch

- Consider a single collision with one electron



$$F_c = \frac{z e^2}{b^2} \qquad \Delta t = 2\frac{b}{v} \qquad \Delta p_e = F_c \Delta t$$

$$\Delta E_e = \frac{(\Delta p_e)^2}{2 m_e} = \frac{2 z^2 e^4}{b^2 v^2 m_e} = \frac{2 r_e^2 m_e c^2 z^2}{b^2} \frac{1}{\beta^2}$$

$$r_e = \frac{e^2}{m_e^2 c^2} = 2.8\, fm$$

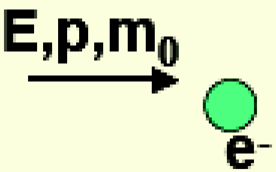
The number of collisions is given by the electron density in the medium

$$N_e \propto \frac{Z}{A} N_A \rho$$

To get the total energy loss we need to integrate this expression for all impact parameter b, or equivalently for all energy loss from the ionization potential to the maximum kinetic energy transfer to the electron E_max

Maximal energy transfer

$$E_{kin}^{max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e / m_0 + (m_e / m_0)^2} = \frac{2m_e p^2}{m_0^2 + m_e^2 + 2m_e E / c^2}$$



A few remarks :

1) If m_0 large enough and low energy → $2m_e c^2\beta^2\gamma^2$,
   for a 1 GeV muon, E^{max}=100 MeV

2) For heavy relativistic particles, → $E^2/(E+(m_0c)^2/2m_e)$, can transfer the total energy only in extreme relativistic case.

3) Special case of electron, can not make approximation: $E^{Max} = E - m_e c^2$

H. Bethe Ann. D Phys. 5 (1930) 325

Energy loss for heavy particles : Bethe-Bloch

Average energy loss for a particle of charge z in a material of atomic number A/Z

$$\frac{dE}{dx} = -4\pi \rho N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I^2} E_{max}^{kin} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}]$$

N_A Avogadro number

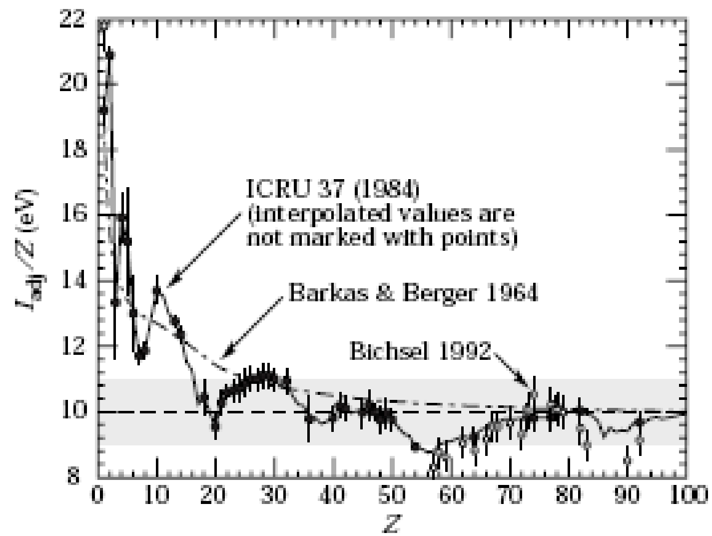
r_e classical electron radius

I mean excitation potential

δ density effect correction

C/Z shell correction

Precise at the % level



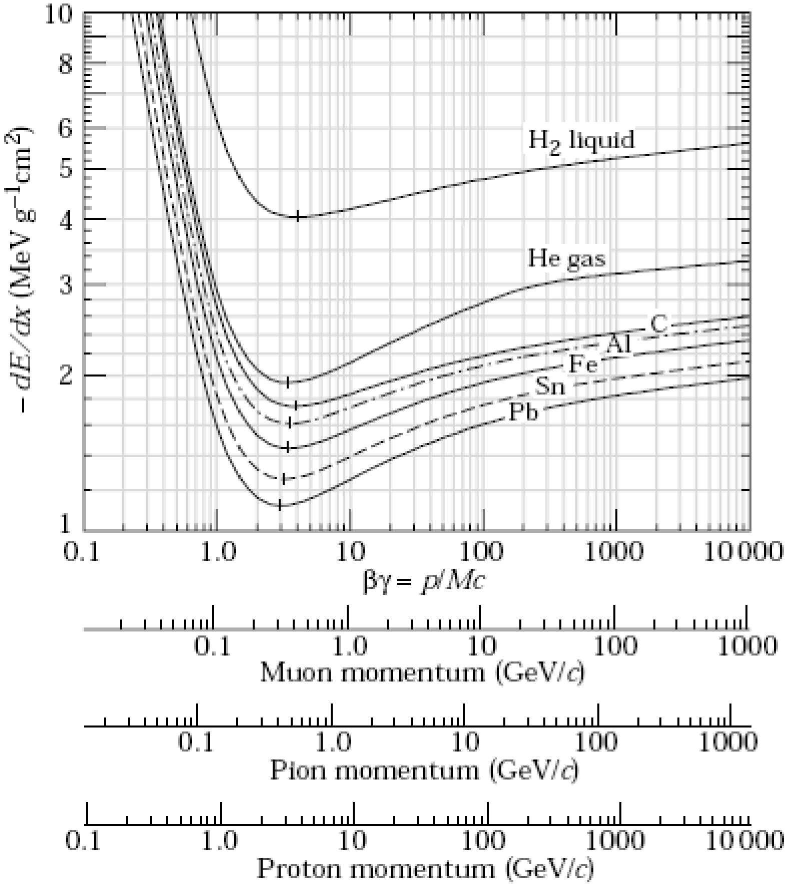
Energy loss for heavy particle: Bethe-Bloch

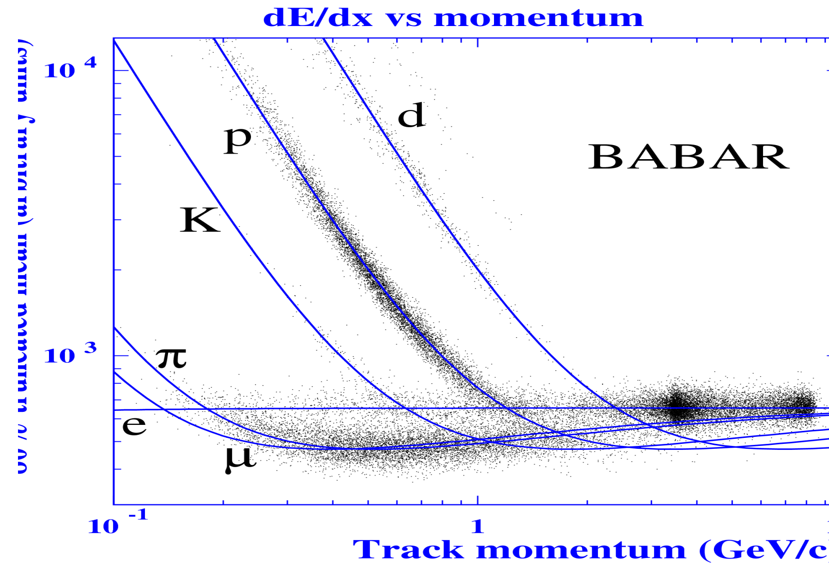
Average energy loss per unit length dx of a particle of charge z in a material of atomic number A/Z, in low energy approximation

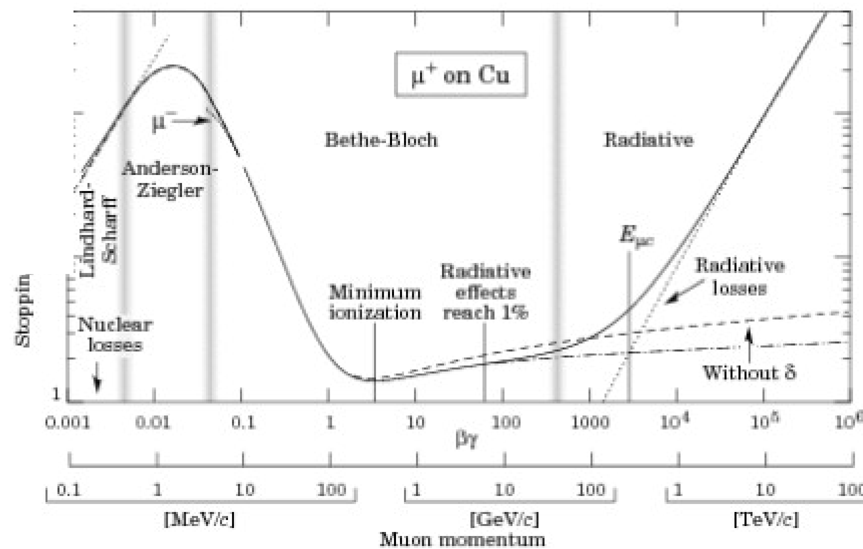
$$-\frac{1}{\rho}\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2} - 2\frac{C}{Z}\right)$$

- Independent of incoming particle mass
- proportional to Z/A of the absorber material and z^2
- in low energy domain, decreases as $1/\beta^2$ ($\beta^{-5/3}$) “slower particle loose more energy “
- reach a minimum around $\gamma\beta = 3\text{-}4$, called Minimum Ionizing Particles or mips quite similar for all elements ~2 MeV/(g/cm^2)
- Above minimum, relativistic rise as $2\ln(\gamma)$
- δ term important at high energy : comes from polarization of the atoms along incoming particle →screening effect of the field, decreases loss at high energy
- C term important at low energy to take into account effects which appear when β of the particle ~ β of bound electrons.

Energy loss: examples







A few illustrative numbers

Energy loss of a 10 GeV muon in 1cm of plastic scintillator (ρ =1) or a gas chamber (ρ =0.001) ?

Muons can be considered as a mip with 2 MeV/(g/cm^2)
→2 MeV in 1 cm scintillator
→2 keV in 1 cm of gas
To stop a 450 GeV muon beam, will need 900 m of concrete (density 2.5) !

How many meters of air to stop an α particle of 2 MeV ?

Particle with very low β (below the minimum ionization)
dE/dx around 700 MeV /(g/cm^2) and ρ =1g/l → 0.7 MeV/cm
Can stop a α in 2-3 cm of air

MIP: Minimum Ionizing Particle
Length unit: dx = ρ (g/cm**3) ds (cm) in g/cm**2 because energy loss per area density is almost independent of the material

Energy loss

Bethe Bloch describes the average energy loss. For a thin absorber the energy loss has a very asymmetric (long tail) shape, described by a Straggling function

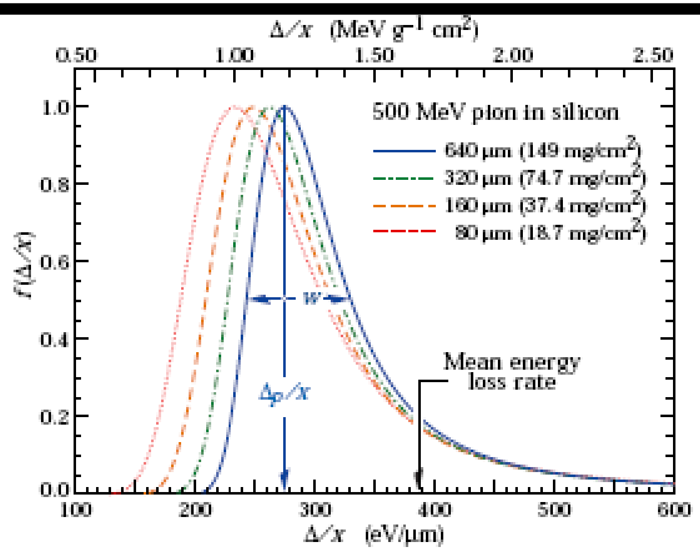
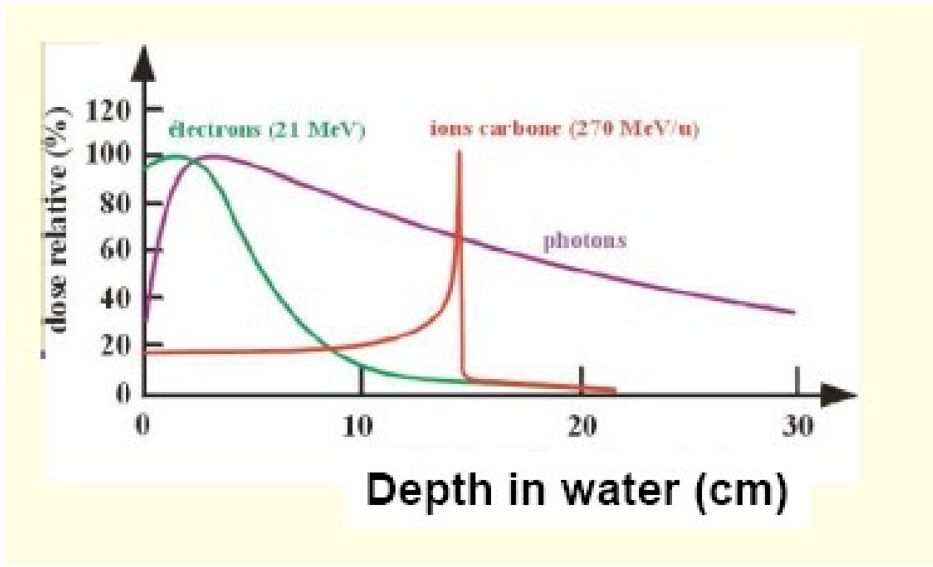


Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum.

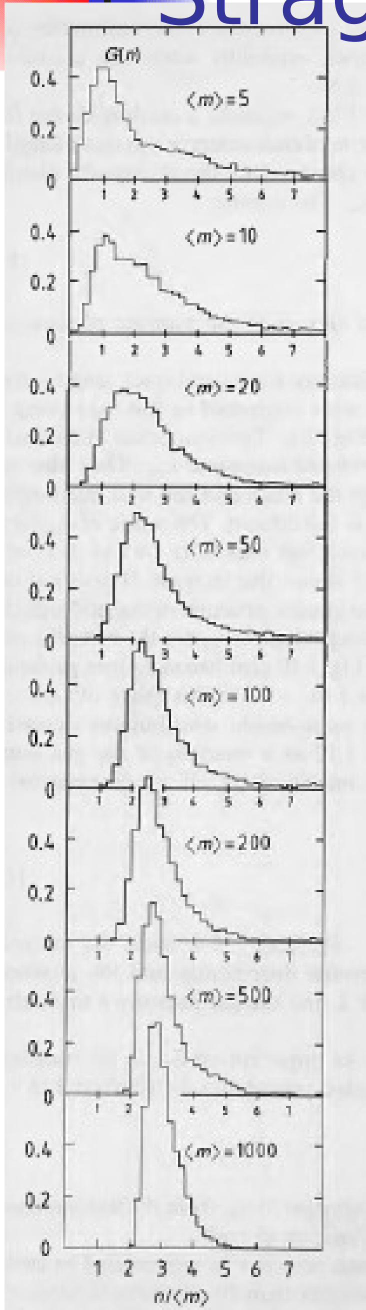
NB: the mean value is not so useful to characterize this distribution in this case

The energy loss is larger at small β (energy), i.e end of the path in matter
Bragg peak
Not used in High Energy physics but basis of medical application, hadrontherapy



Straggling functions in thin absorbers

Allison Cobb 1980



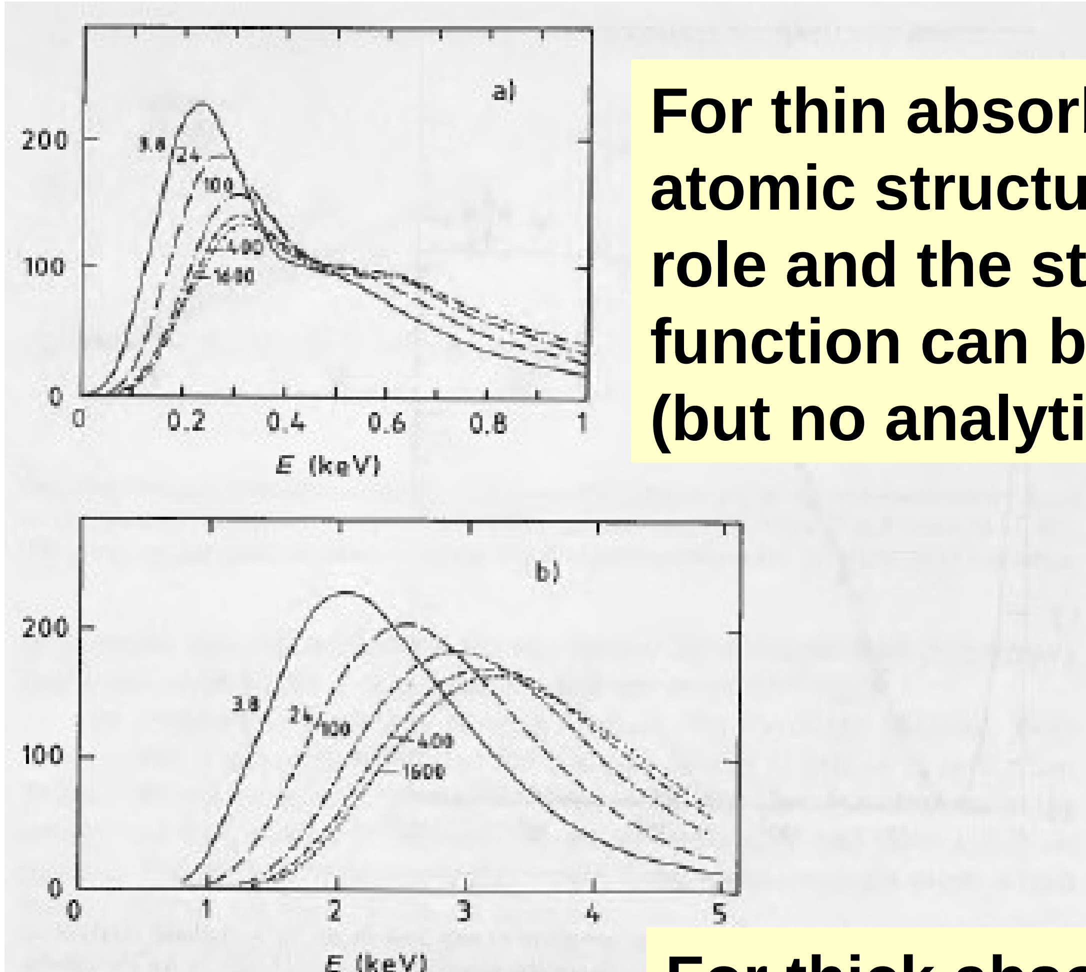


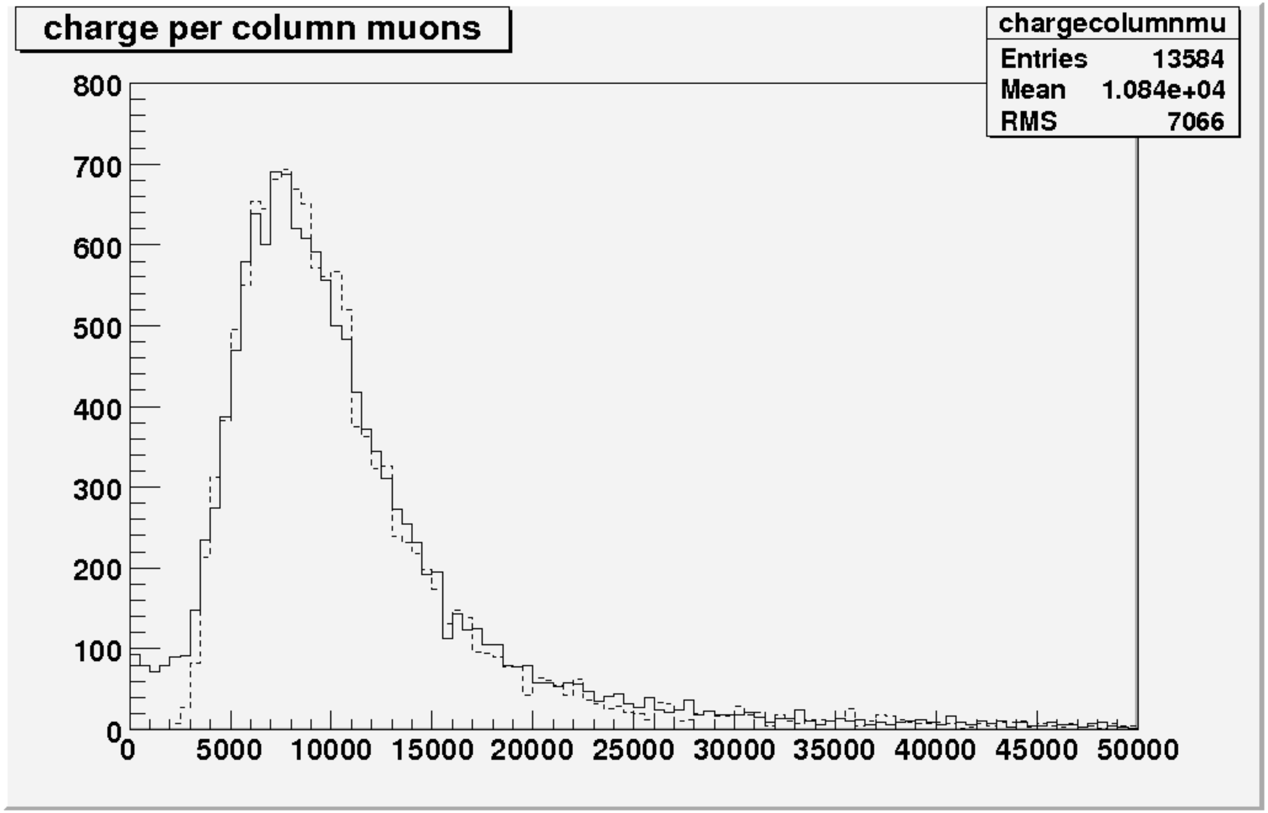
Fig. 1.21a, b. dE/dx-distributions calculated with the PAI ... values of γ (a) sample length 0.3 cm; (b) 1.5 cm, both at nor...

For thin absorbers, the atomic structure plays a role and the struggling function can be computed (but no analytical form)

For thick absorbers, due to the central limit theorem, the straggling function approaches a Gaussian

Ionization loss muons 150 MeV

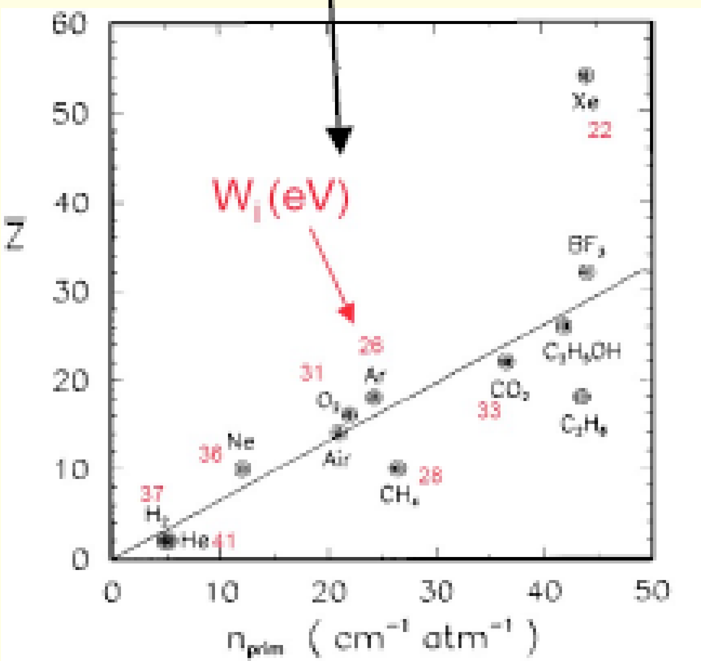
- 0.97 cm Argon T2K TPC, dashed PAI model



Gaseous detector

Number of electron/ion pair produced in a gas by ionization of charged particle :

N_T = N(primary) + N(secondary). Generally N(Secondary) ~2 or 3 N(primary)



Example : dE/dx in Ar = 1.519 MeV/(g.cm^2)
density : 1.396g/l

$N_T = \Delta E/w = 1.519\ 10^6 * 1.396\ 10^{-3} / 26$
= 80 pairs /cm

About 10 times smaller than electronics noise in charge preamp ! → Needs amplification of signal

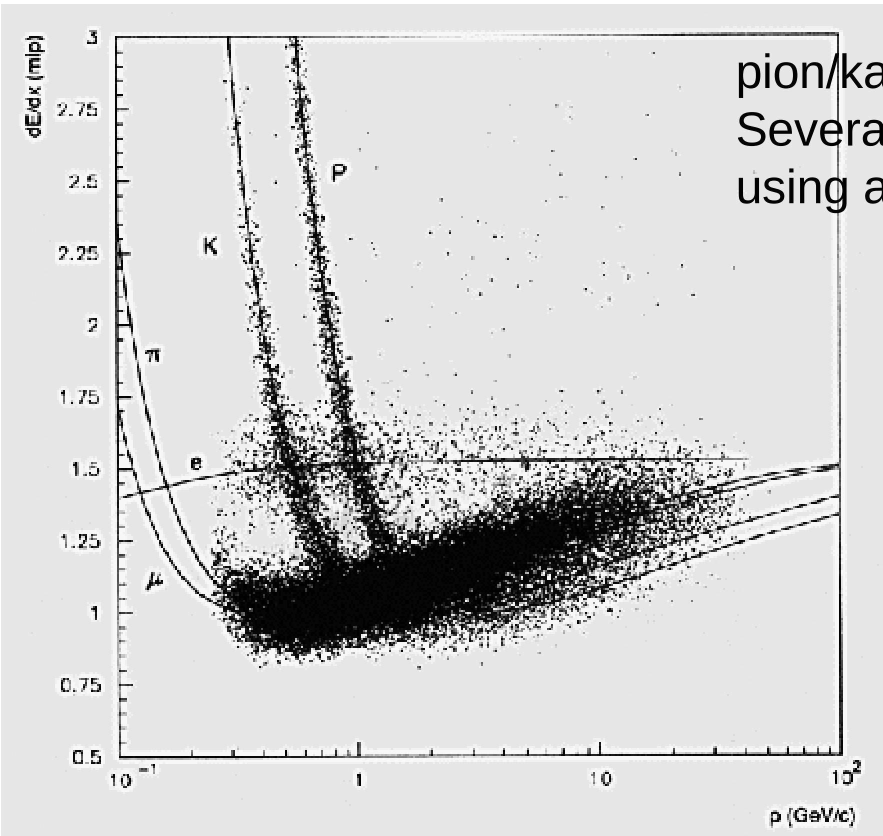
w > ionization potential I (15.6 eV for Argon) because include inner shell mechanism + fraction of energy dissipated by excitation and secondary ionization…

PID with ionization measurements

$$p = m_0 \beta \gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

Simultaneous measurement of p and dE/dx defines mass m_0, hence the particle identity



pion/kaon separation requires resolution 5%
Several overlap : ambiguity need to be resolved using another detector

PID with ionization measurements

- Ionization measurements are available in most HEP experiments because they are related to tracking detectors
- Many samples along a track, usually 10-100 range
- However each measurement is sampled from a broad distribution with large tails
- How can we turn many low-quality measurements into a precision identification ?

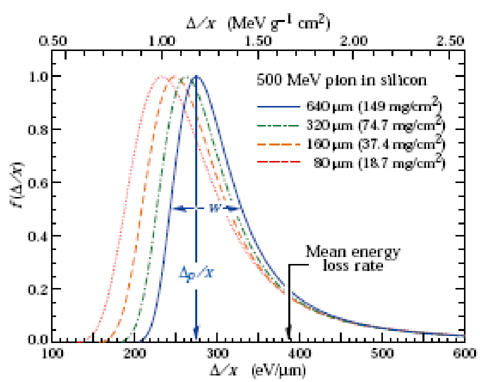
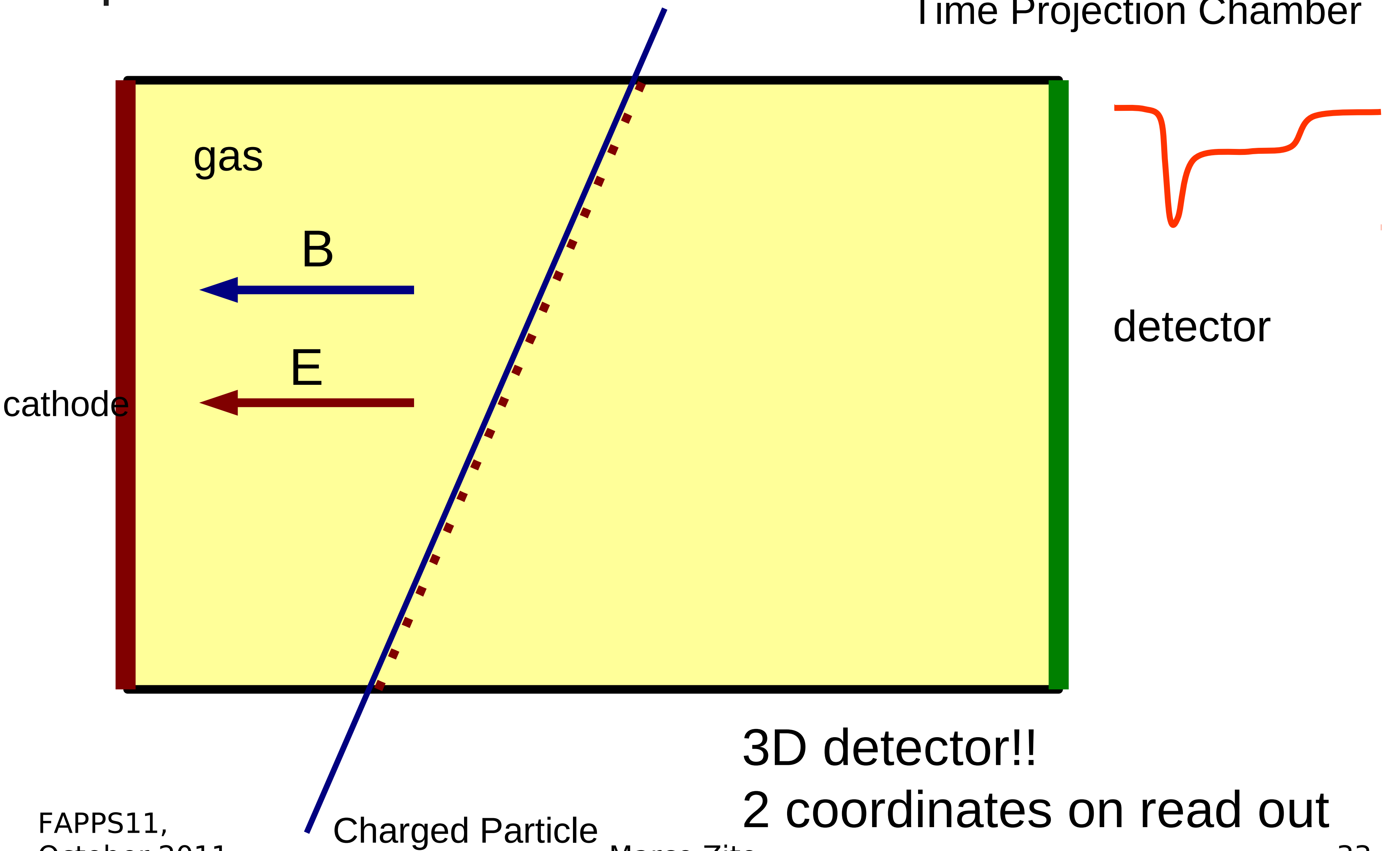


Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum.

An example: PID with the T2K TPC

Principle of the TPC

Time Projection Chamber

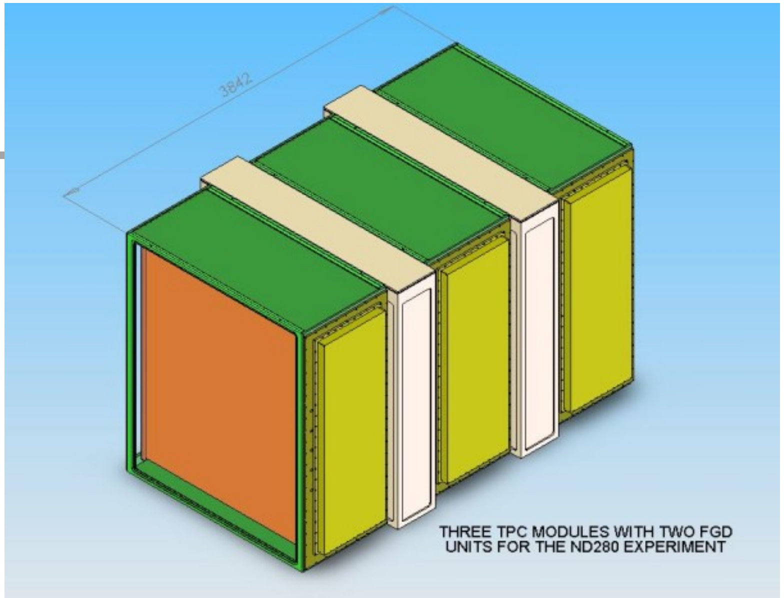


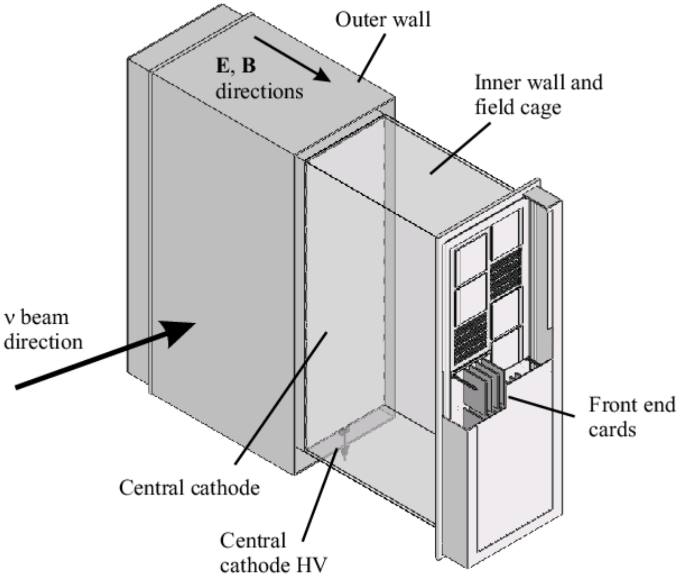
3D detector!!

2 coordinates on read out plane+drift time

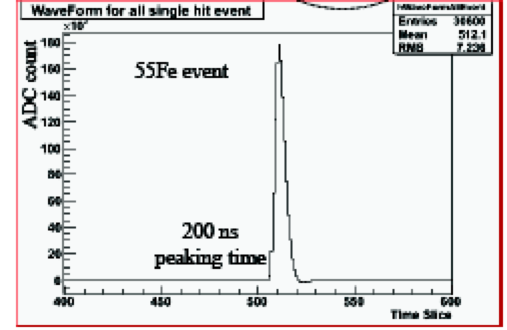
TPC Parameters

- Drift: 90 cm
- E drift 200 V/cm → cathode ~ 20 kV
- B 0.2 T
- Gas: Ar-CF_4(3%)-isobutane(2%)
- Drift velocity ~7cm/µs
- Transverse diffusion 240 µm/sqrt(cm)
- MM gain ~ 1000
- Pad size 9.7x6.7 mm
- N channels 120 k
- Required resolutions
- σ(p)/p < 10 % at 1 GeV/c
- σ(dE/dx) <~ 10%



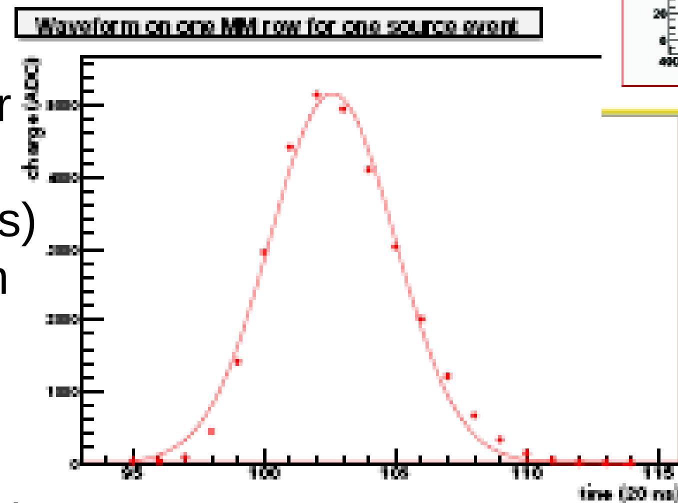


TPC signals



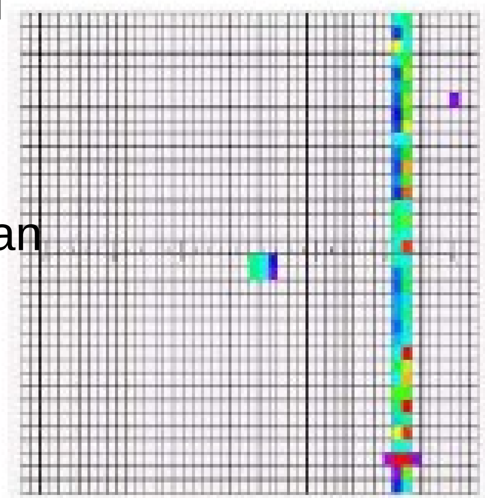
1 time bin = 50 ns (20 MHz sampling freq.)

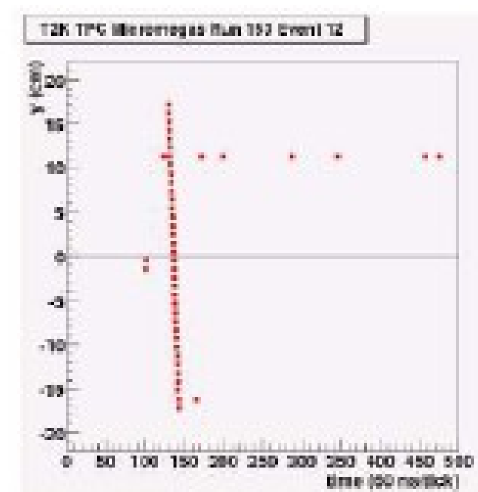
On each pad: sample the signal for the whole drift time. In our case every 30 ns for 15 µs (511 samples)
Determine the drift coordinate from the signal peak



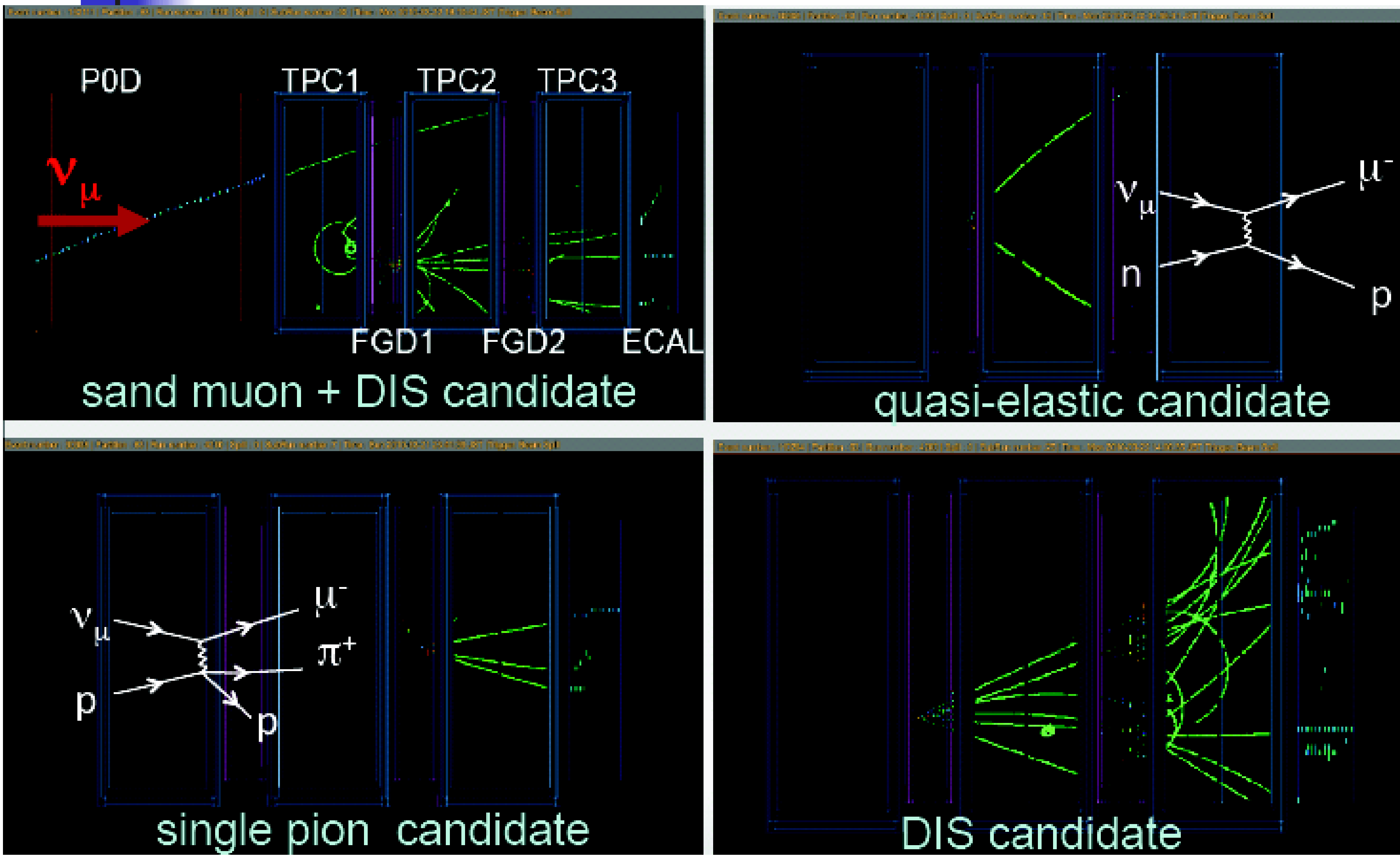
On the readout plane: determine the position of the track from the height of the signals on two adjacent pads

Simple minded: do barycenter
More sophisticated: find fitting gaussian





Neutrino interaction with the TPC



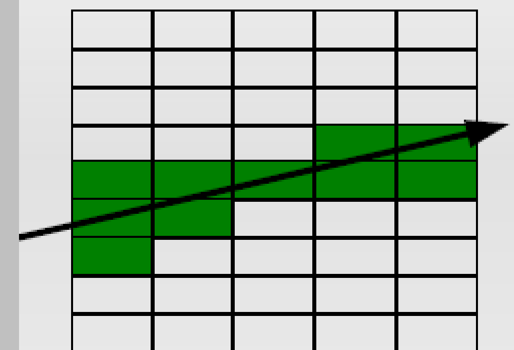
Truncated mean method

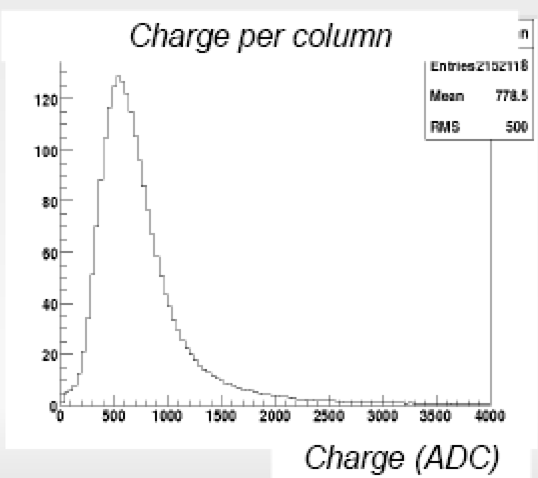
For each track we have 72 ionization samples

Classify them in increasing order

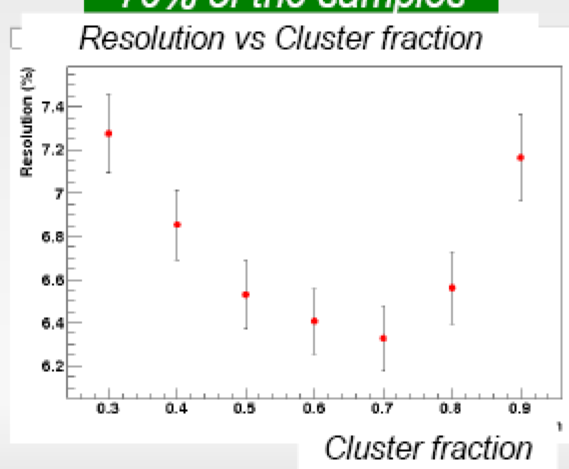
Keep only the lower 70%

Compute the mean C_T of the remaining samples

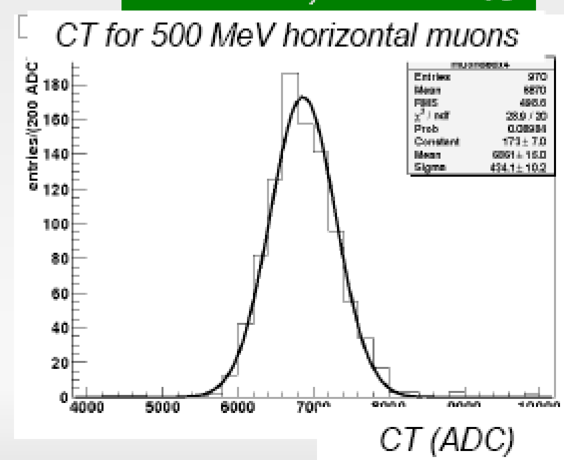




70% of the samples



Mean 70% clusters Gaussian, Res=6.4%



Truncated mean distribution

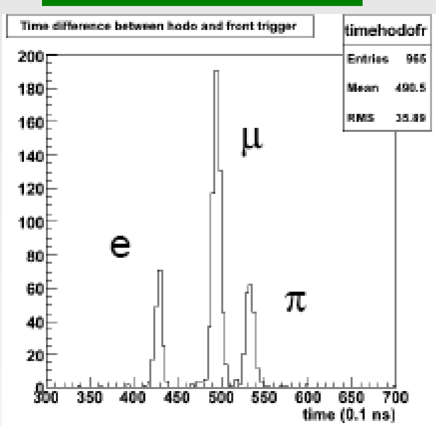
- P = 150 MeV/c, 3 different particles (e, μ, π) selected using the Time Of Fligth

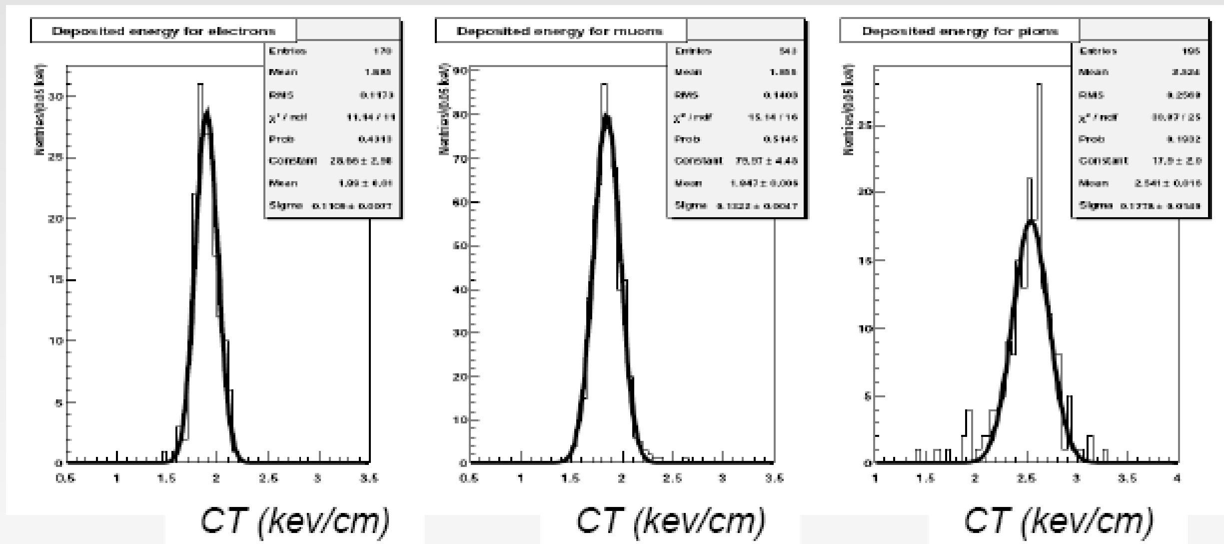
CT for electrons resolution=5.6%

CT for muons resolution=6.7%

CT for pions resolution=6.9%

TOF

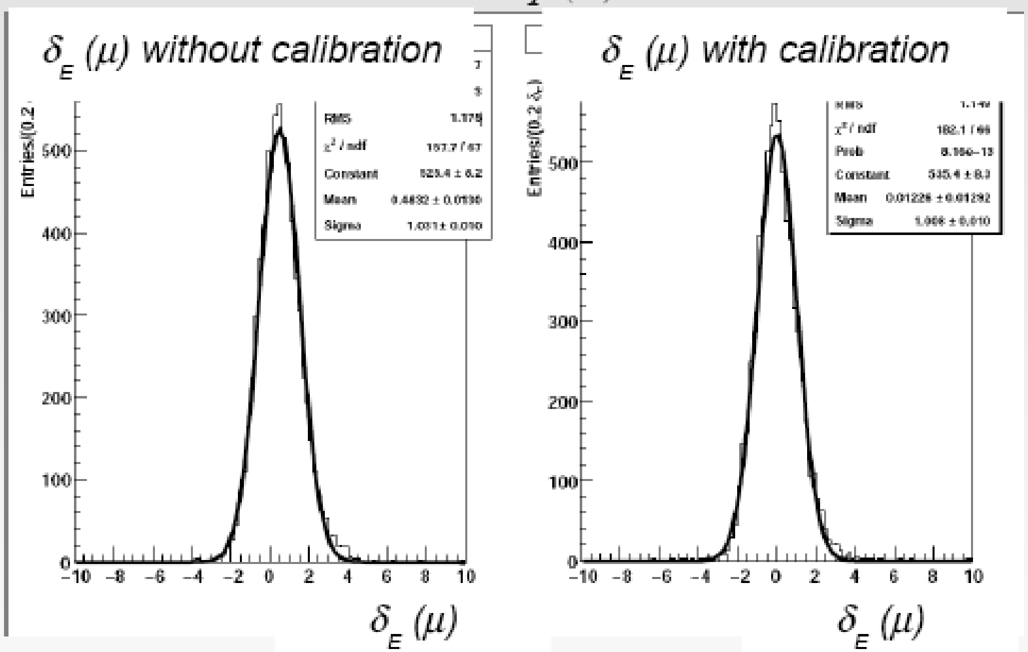




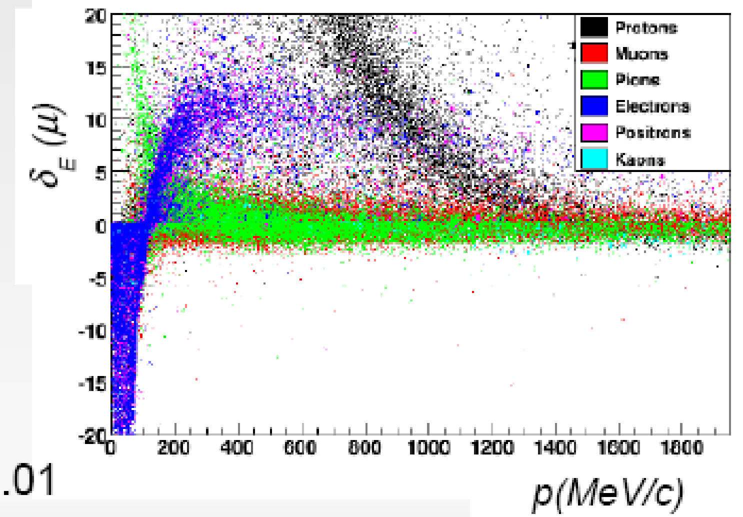
PID Pulls

- Taking all the calibration factors into account we define a pull variable in the different particle hypothesis to perform the PID

$$\delta_E(i) = \frac{C_T - C_E(i)}{\sigma_T(i)} \quad (i = e, \mu, \pi, p, K)$$



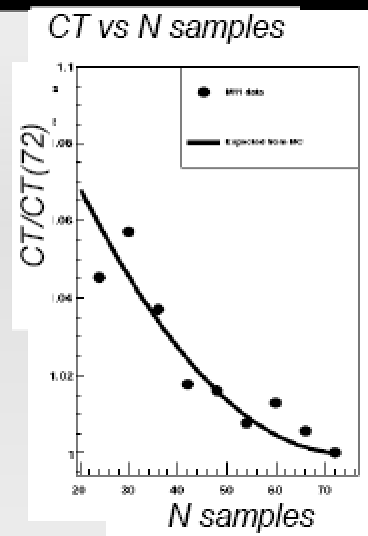
Pull muon hypothesis
For different particles coming from
Simulated ν interactions in the FGD

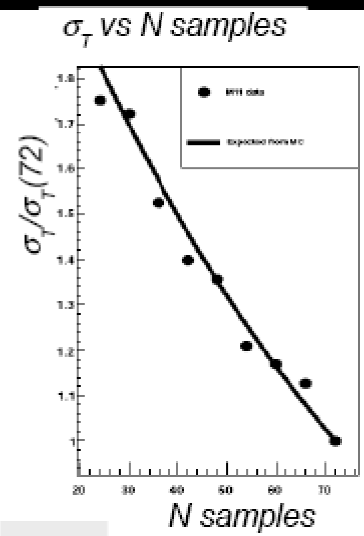


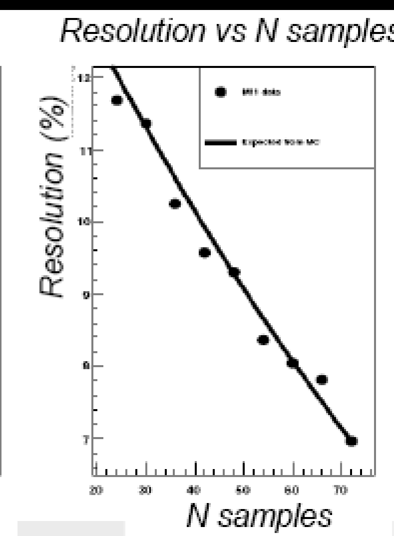
- Before calibration: Mean=0.48±0.01 Sigma=1.03±0.01
- After calibration: Mean= 0.01±0.01 Sigma=1.01±0.01

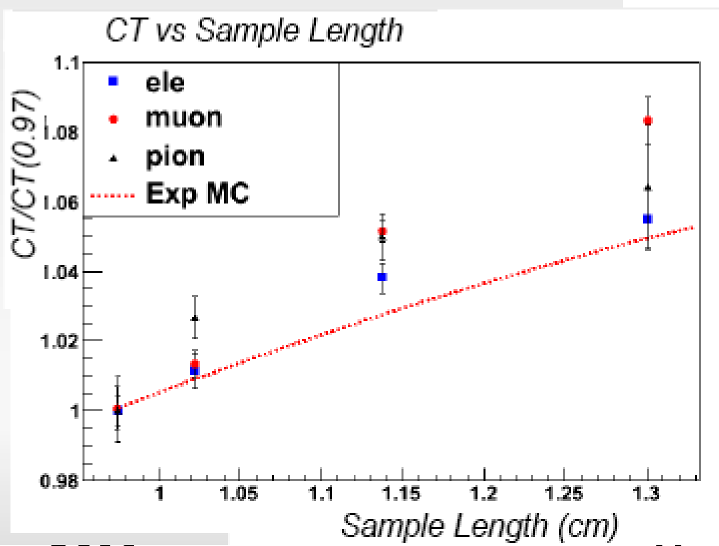
Dependences on the number of samples and on the sample length

- Dependence of CT and σ on the number of samples
  - Resolution from 7% (72 samples) to 12% (24 samples)





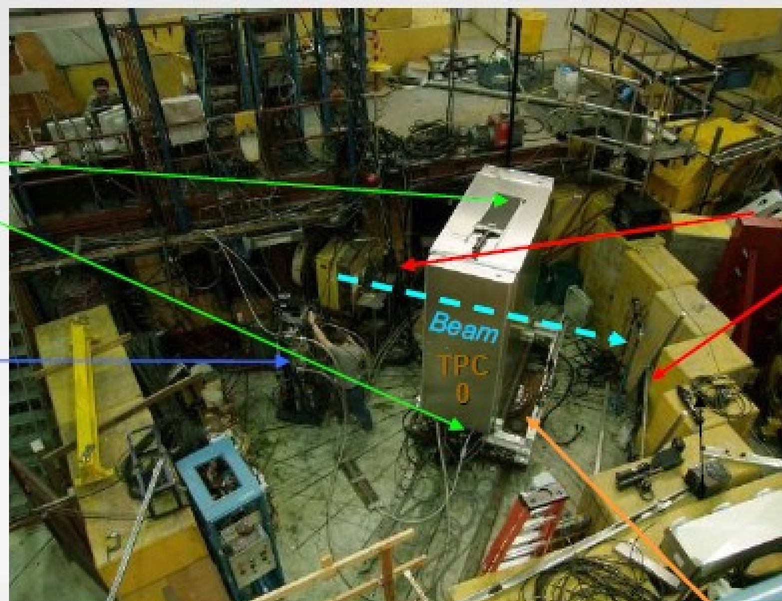


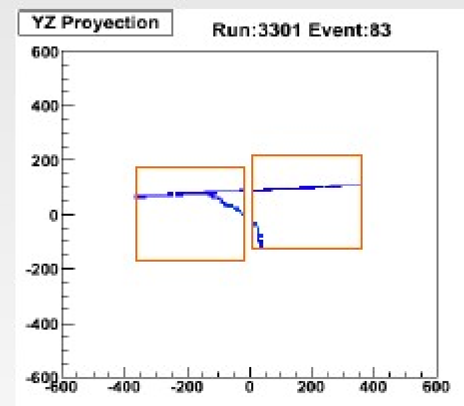


- Dependence studied taking data with TPC at different angles with respect to the beam
  - CT 6% larger if SL changed from 0.97 cm → 1.3 cm

TPC beam tests

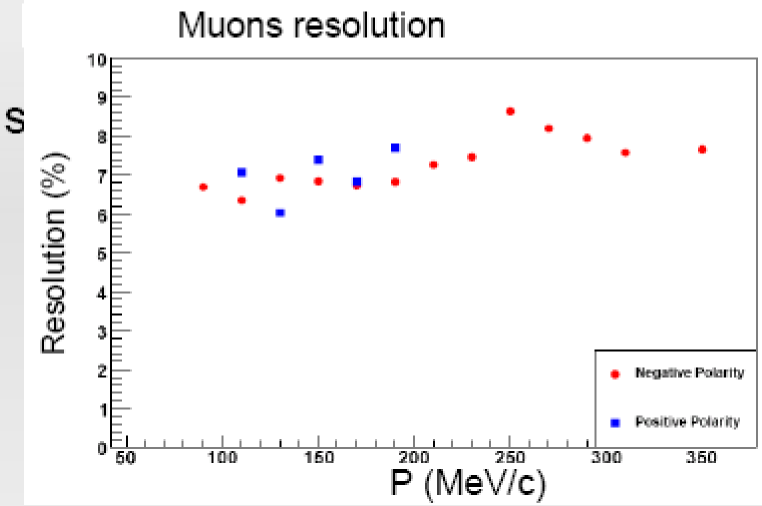
- After the construction all the TPCs underwent beam tests in the M11 area at TRIUMF
- The beam provided μ, e, π with momenta up to 400 MeV/c
- A Time Of Flight system provided the PID independentely from the TPC
- We used these data to test and validate the PID methods

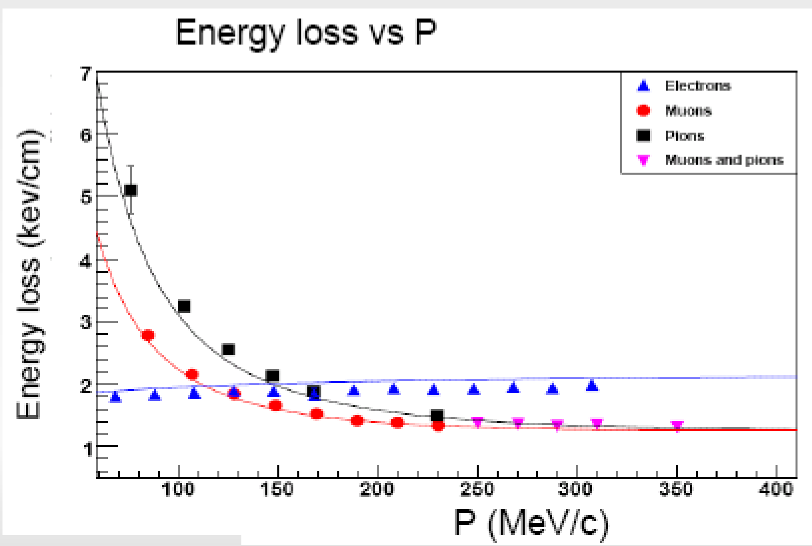


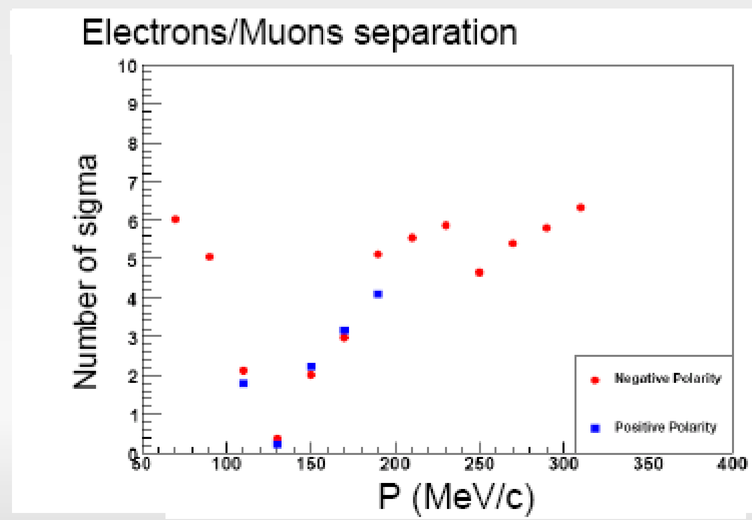


Beam tests: PID results

- Good agreement data/MC
  - MC slightly overestimate the electrons energy lost → we took this effect into account in our PID parameterization
- μ resolution better than 8% for all p
- e/μ separation larger than 5σ if p>200 MeV/c

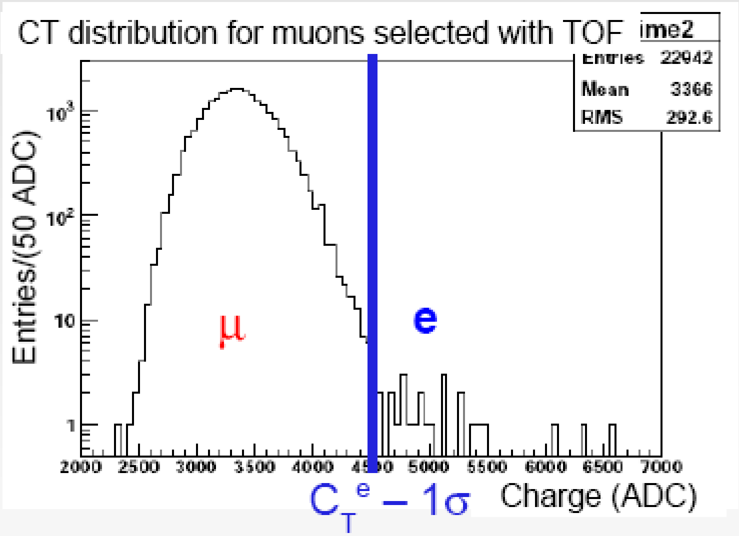






Misidentification rate

- We used TPC beam test to measure the misidentification probability
  - Monochromatic beam of μ, e and π
- Possibility of selecting a clean sample of muons using TOF



Very low misidentification probability:

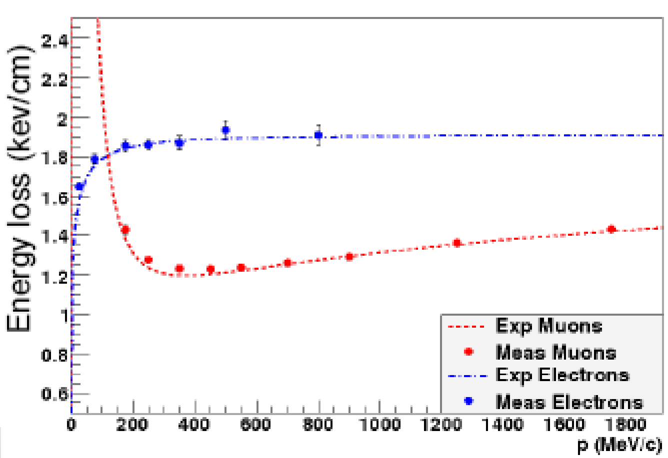
- $(0.1\pm0.02)\%$ for $-1<\delta_E(e)<2$
- $(0.4\pm0.04)\%$ for $-2<\delta_E(e)<2$

- But beam was up to 370 MeV $\rightarrow$ we need to study the misidentification probability at larger momenta

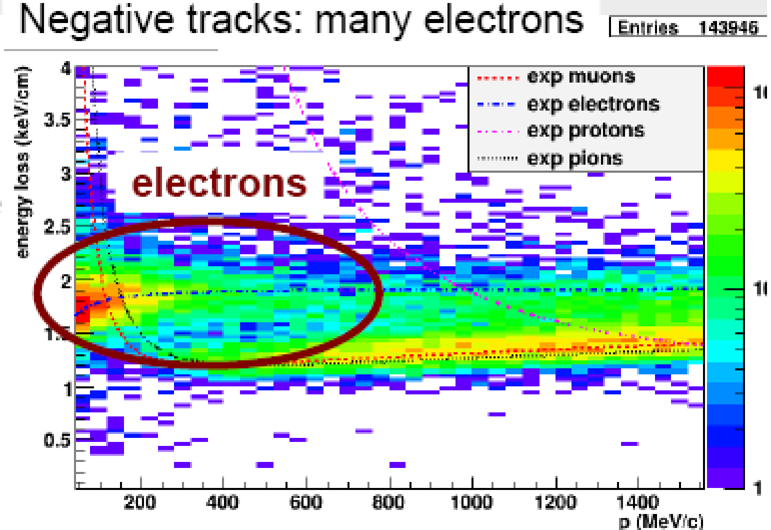
PID tests with cosmics

- Contemporary measurement of momentum and energy loss in cosmics
- We developed a method to equalize the gain of the 72 MicroMegas improving the deposited energy resolution
- Important to check our parameterization for muons and electrons (up to 1 GeV)
- This parameterization is fundamental to measure the ν_e component in the beam

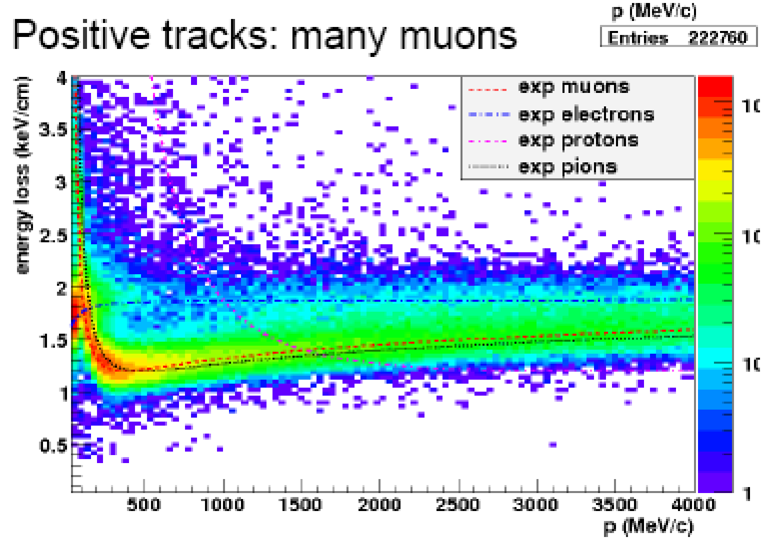
CT vs P



Negative tracks: many electrons

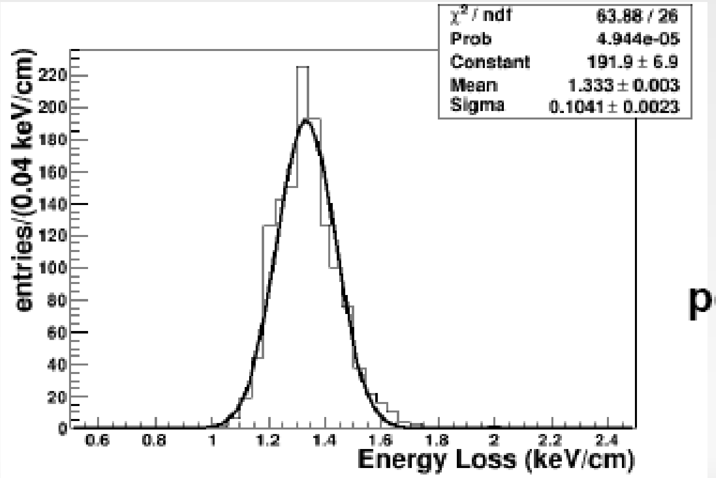


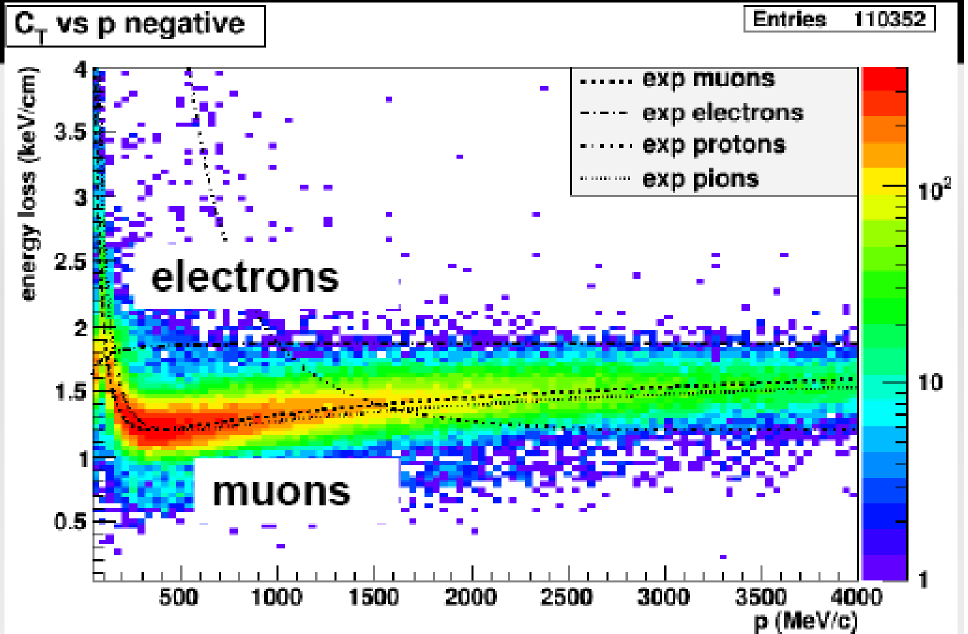
Positive tracks: many muons

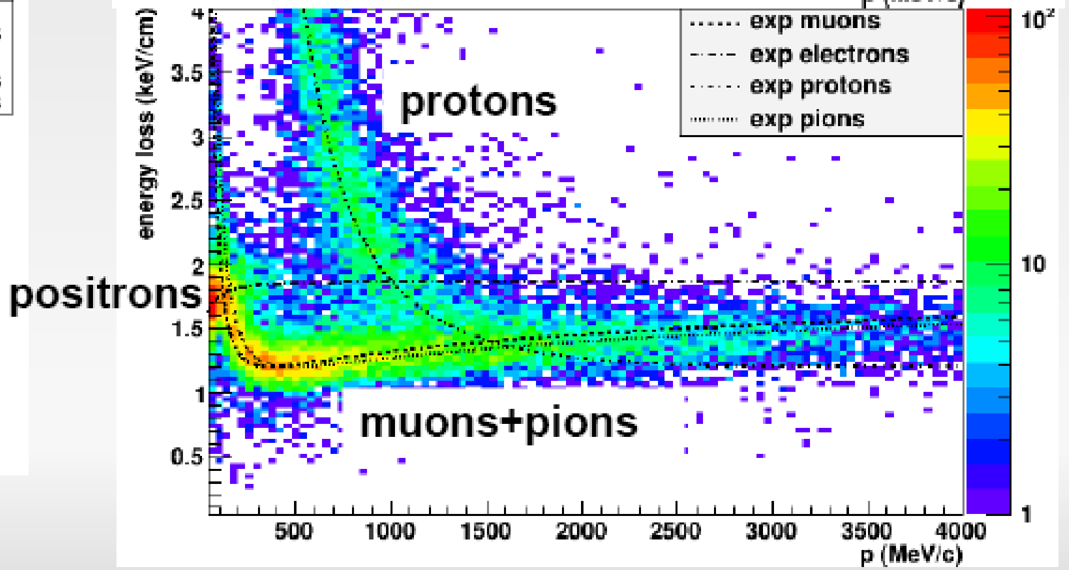


PID tests with beam related events

- Negative tracks: mainly muons, few electrons
- Positive tracks: protons, pions, some positrons
- 7.8% deposited energy resolution for MIPs → reached the required performances

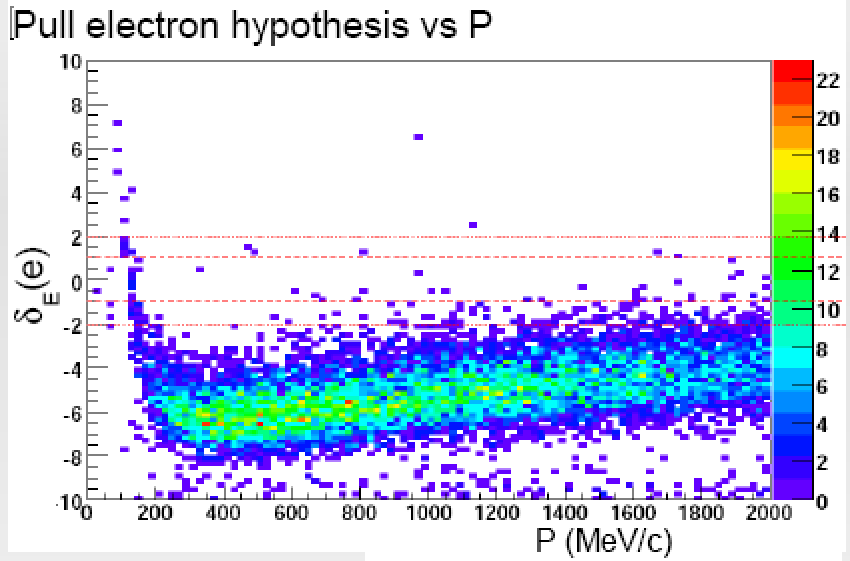






Muon misidentification probability

- To go to higher energy we can use through going muons at ND280
- Select them by requiring:
  - Only one track per TPC
  - Negative charge
  - Compatible with a μ in TPC3



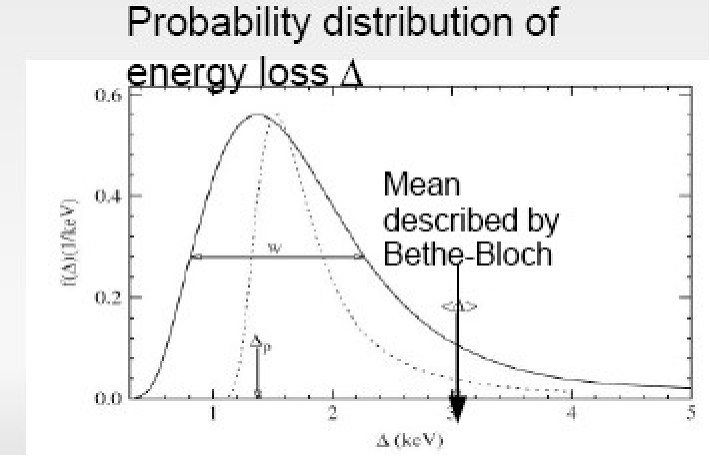
Momenta (MeV/c)	N ev $-1 < \delta_E(e) < 2$	N ev $\lvert\delta_E(e)\rvert < 2$	N tot	Mis prob (%) $-1 < \delta_E(e) < 2$	Mis prob (%) $\lvert\delta_E(e)\rvert < 2$
$200 < p < 500$	3	7	1966	0.15 ± 0.09	0.36 ± 0.13
$500 < p < 1000$	9	25	3767	0.24 ± 0.08	0.66 ± 0.13
$1000 < p < 1500$	11	64	3238	0.34 ± 0.10	1.98 ± 0.25
$1500 < p < 2000$	27	128	2413	1.12 ± 0.22	5.30 ± 0.47
$2000 < p < 3500$	99	423	3352	2.95 ± 0.30	12.62 ± 0.61
$3500 < p < 5000$	68	220	955	7.12 ± 0.86	23.04 ± 1.55

First bin in agreement with TPC beam test

- Thanks to the TPC PID we can keep the muon misidentification probability below 1%

Usual jargon to be avoided

- dE/dx → ionization measurement : we are not measuring average energy loss but the most probable value
- Bethe-Bloch : this refers to the average energy loss, the most probable value vs p follows a different functional law (usually no a priori analytic form)
- Landau distribution, Landau tails → straggling function. The Landau distribution is not a good parameterization for the most common straggling functions in gas detectors



Identification with ionization measurements

- Peculiar detector response
- But many measurements
- Can be combined for a powerful PID
- With features to be well understood

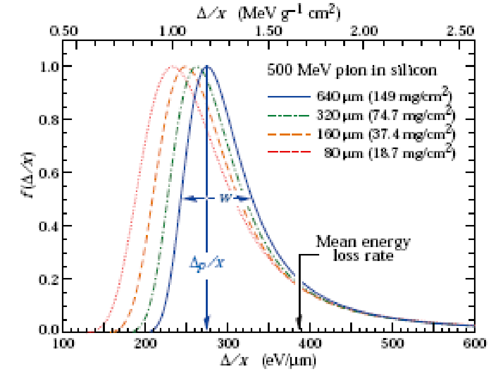
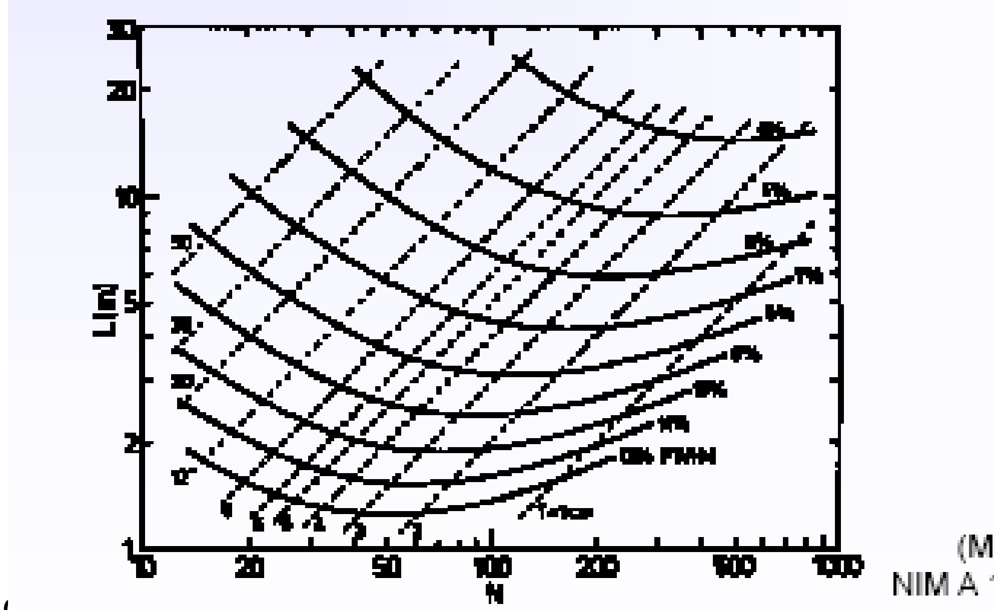


Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum.



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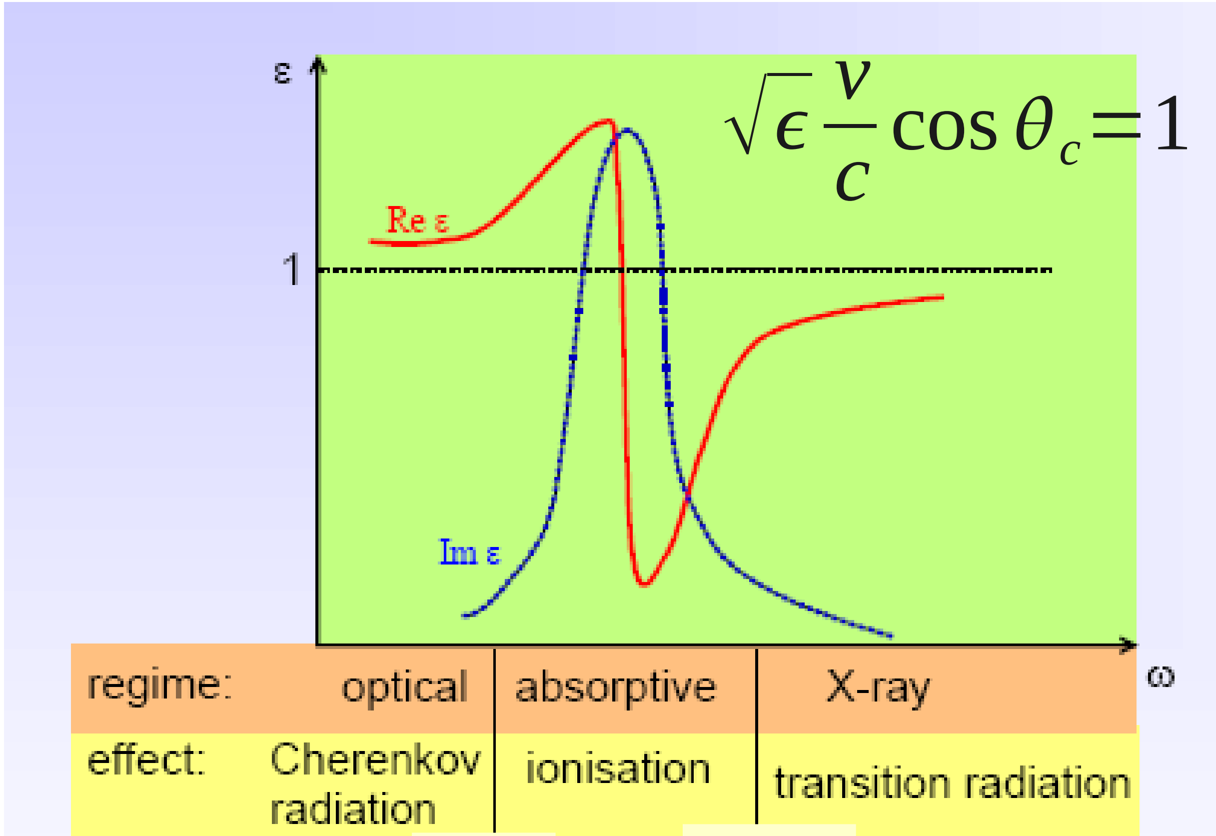
Cherenkov radiation

Allison, Wright 1983

Interaction of charged particles



~eV

~keV

Below the excitation energies of the material ε is real and > 1.
Real Cherenkov photons for

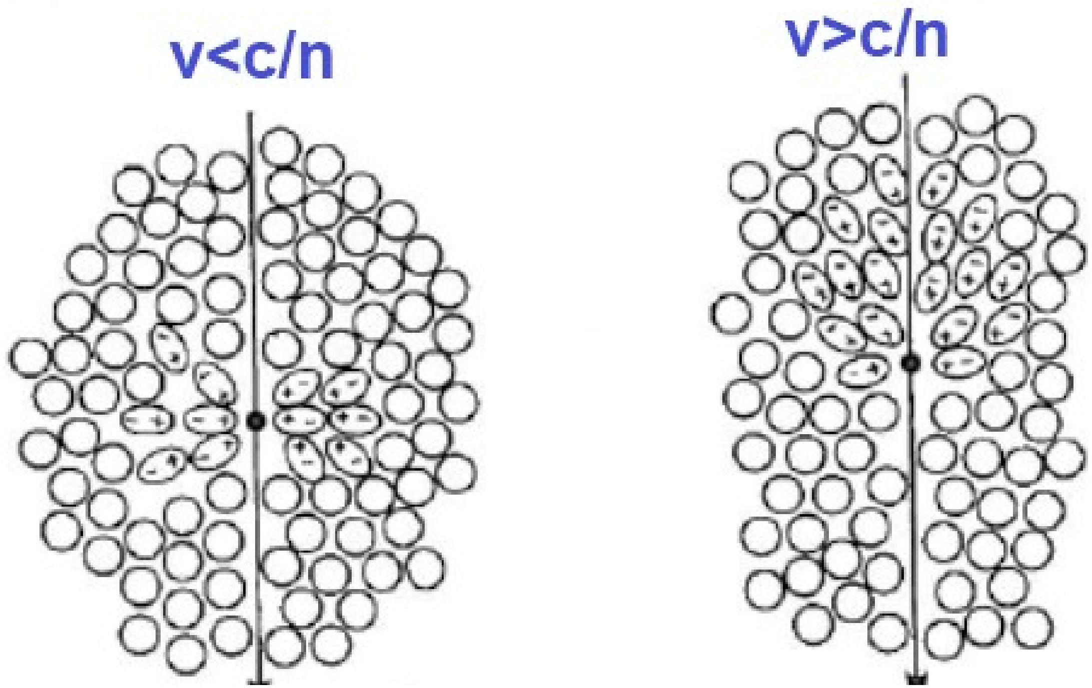
$$v > \frac{c}{\sqrt{\epsilon}}$$

Above 5 keV, real photons are emitted if there are discontinuities in the material => transition radiation

From 2 eV to 5 keV, ε is a complex number, virtual photons are exchanged, ionization and excitation

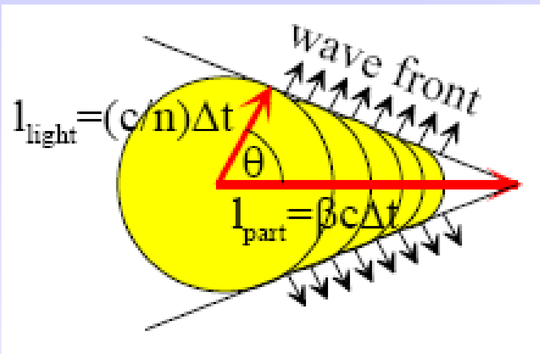
Cherenkov radiation

Cerenkov radiation is emitted when a charged particle passes through a dielectric medium with a velocity > threshold speed (speed of light in the medium)

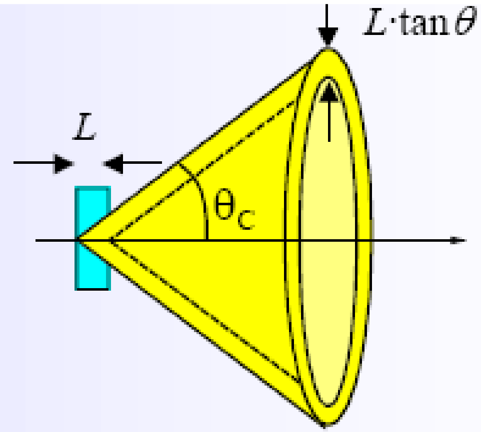


Cherenkov radiation

Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity β>1/n



$$\cos\theta_C = \frac{1}{n\beta}$$
with $n = n(\lambda) \geq 1$

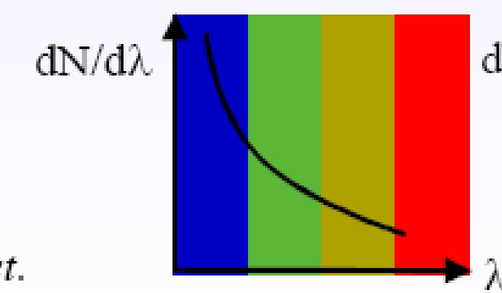


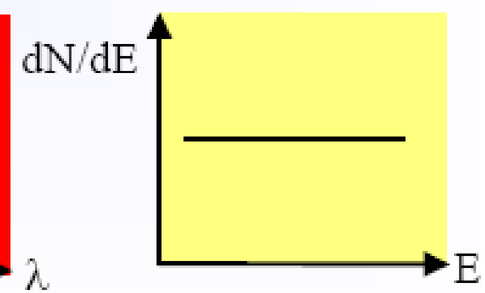
- $\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$ Cherenkov threshold
- $\theta_{max} = \arccos\frac{1}{n}$ 'saturated' angle (β=1)

Number of emitted photons per unit length and unit wavelength interval

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dxdE} = const.$$





Cherenkov radiation

medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

*NTP

- Energy loss by Cherenkov radiation small compared to ionization (≈0.1%)
- Cherenkov effect is a very weak light source

→ need highly sensitive photodetectors

Number of detected photo electrons $N_{p.e.} = L \sin^2\theta \underbrace{\frac{\alpha}{\hbar c} \int_{E_1}^{E_2} \varepsilon_Q(E) \prod_i \varepsilon_i(E) dE}_{N_0 = 370 \cdot eV^{-1} \cdot cm^{-1} \langle \varepsilon_{total} \rangle \Delta E}$

$\Delta E = E_2 - E_1$ is the width of the sensitive range of the photodetector (photomultiplier, photosensitive gas detector...)

N_0 is also called figure of merit (~ performance of the photodetector)

Example: for a detector with $\langle \varepsilon_{total} \rangle \cdot \Delta E = 0.2 \cdot 1\, eV$ $L = 1\, cm$

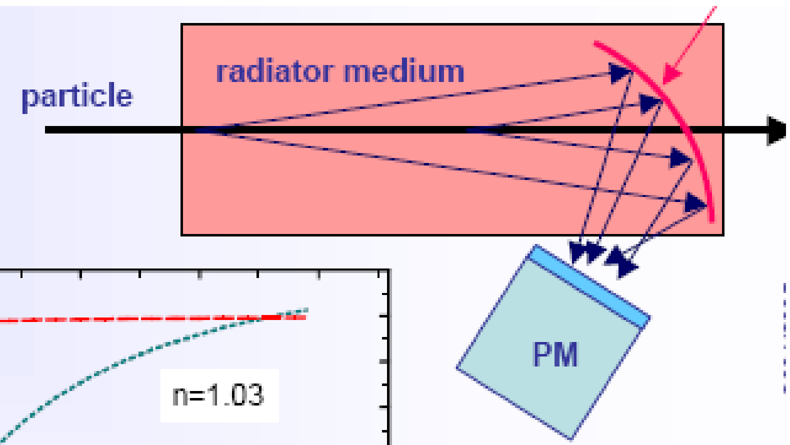
and a Cherenkov angle of $\theta_C = 30^\circ$

one expects $N_{p.e.} = 18$ photo electrons

Threshold Cherenkov detectors

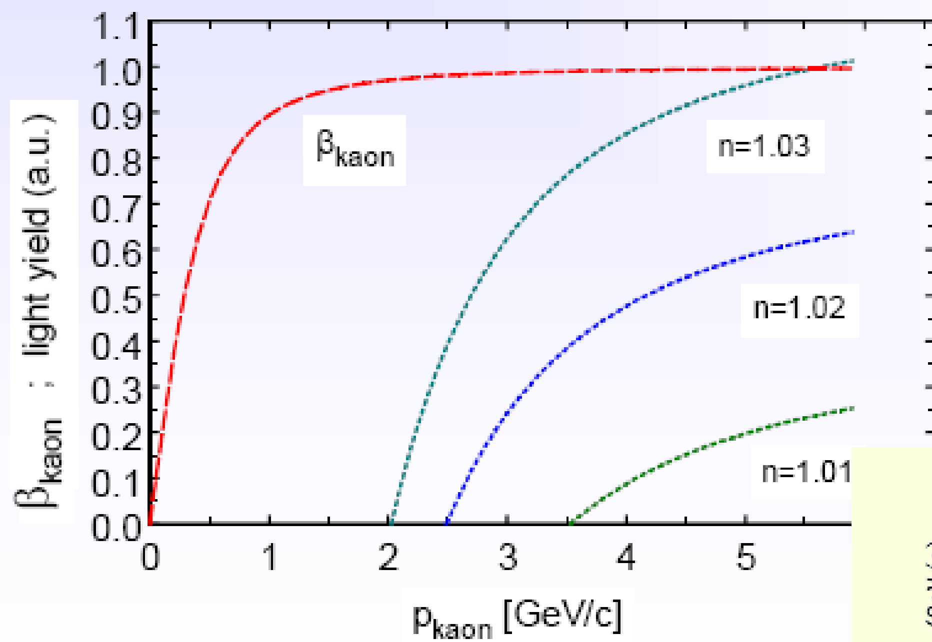
Threshold Cherenkov detectors

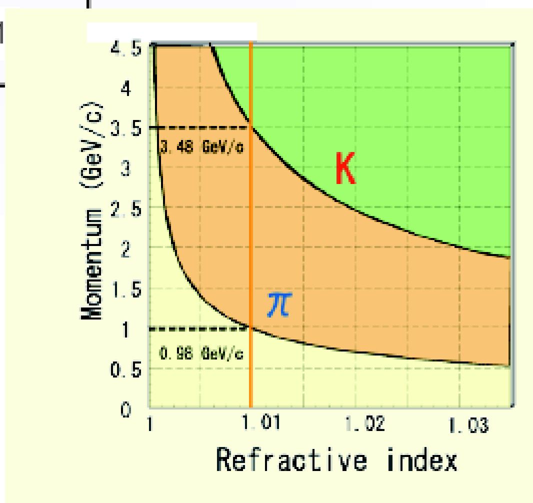
$$N_{ph} \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\cdot\left(1 + m^2/p^2\right)$$



Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

Goal: π/K separation





Commonly used also on beam line instrumentation

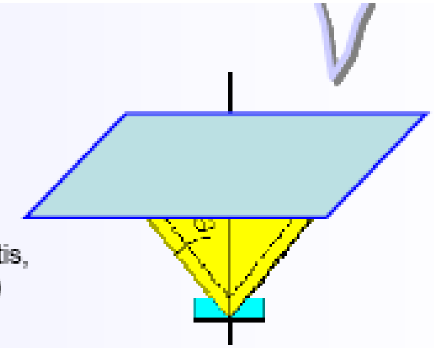
Ring Imaging Cherenkov detectors (RICH)

RICH detectors determine θ_C by intersecting the Cherenkov cone with a photosensitive plane

→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

(J. Seguinot, T. Ypsilantis, NIM 142 (1977) 377)



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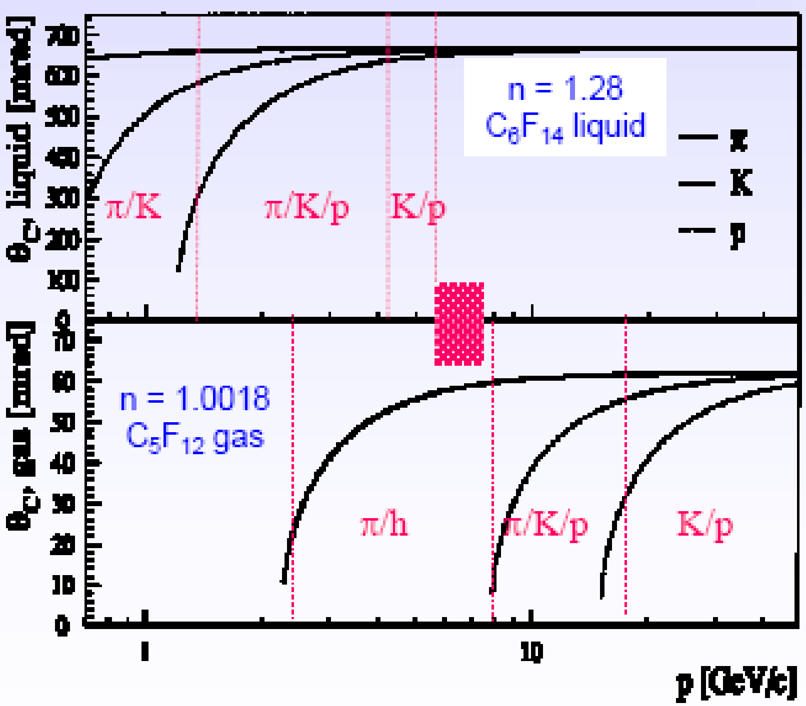


$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right)$$
$$= \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$

$$\cos\theta_C = \frac{1}{n\beta} \quad \rightarrow \quad \frac{\sigma_\beta}{\beta} = \tan\theta\cdot\sigma_\theta$$

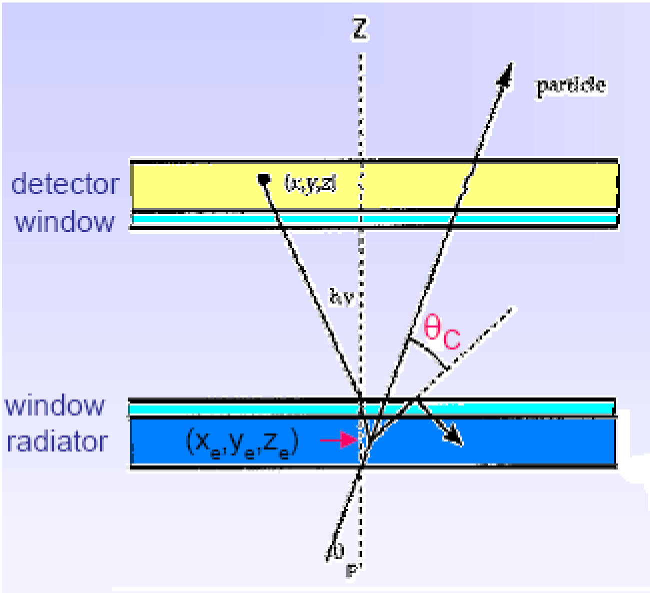
Detect $N_{p.e.}$ photons (photoelectrons) →

$$\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$$

→ minimize $\sigma_\theta^{p.e.}$

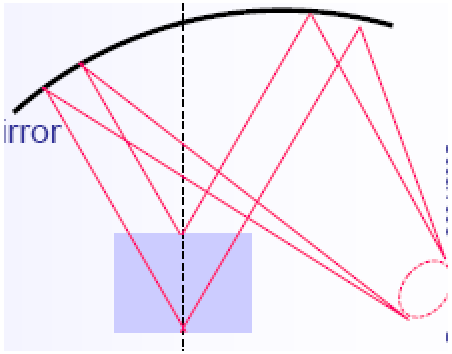
→ maximize $N_{p.e.}$

RICH performance

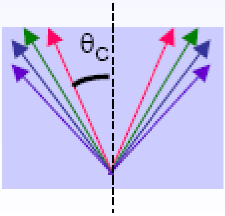


Determination of θ_c requires :

- Good resolution on the detected photon
- Thin radiator (or focusing system)
- Accuracy on track direction and momentum



- the chromatic error - an 'irreducible' error

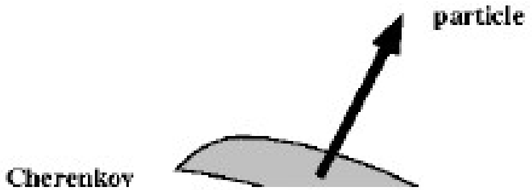


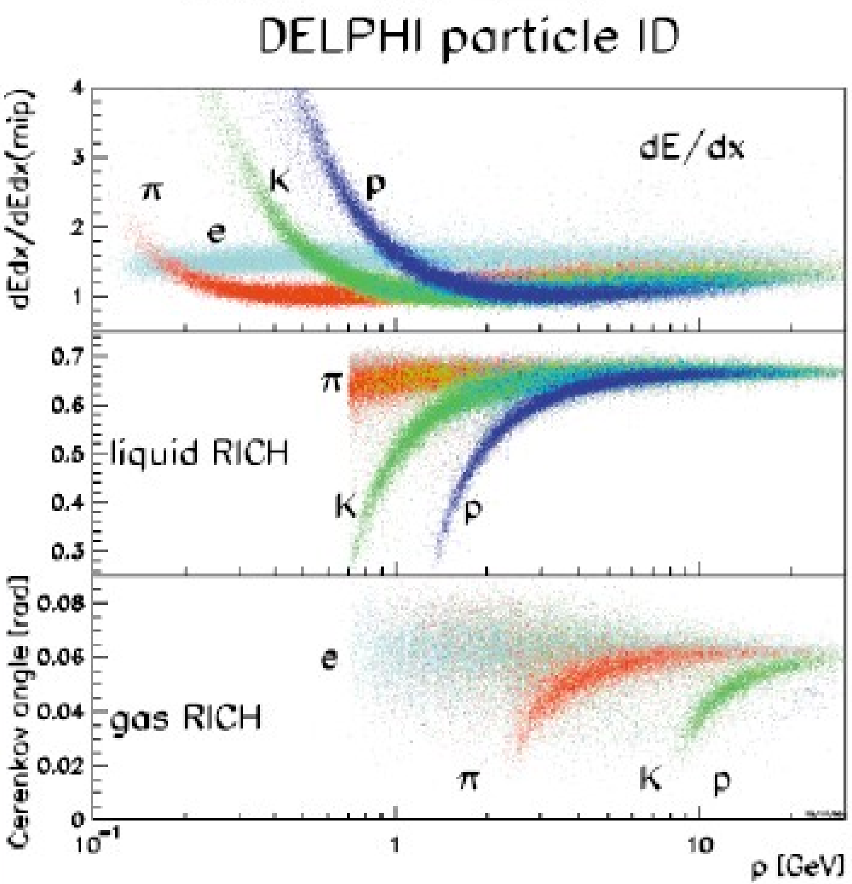
$$n_{rad} = n(E)$$

$$\sigma_\theta^c = \frac{1}{n \tan\theta}\sigma_n = \frac{1}{n\tan\theta}\frac{dn}{dE}\sigma_E$$

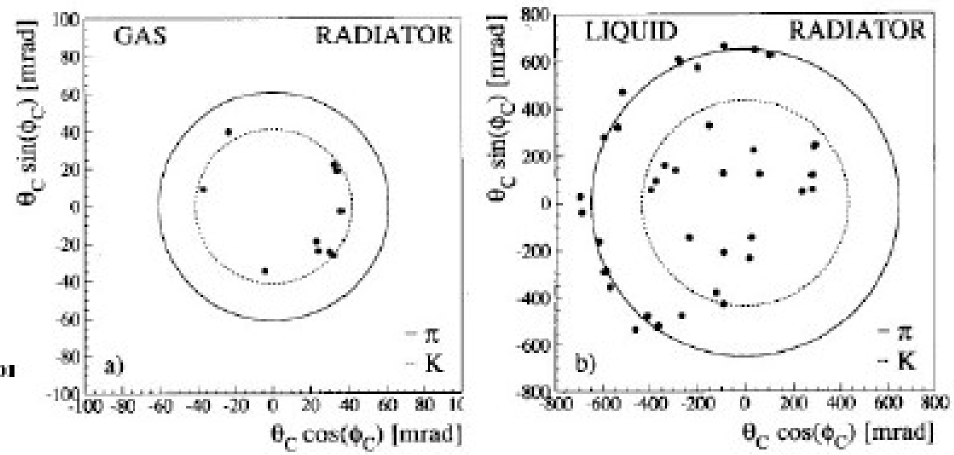
RICH detector : Delphi at LEP

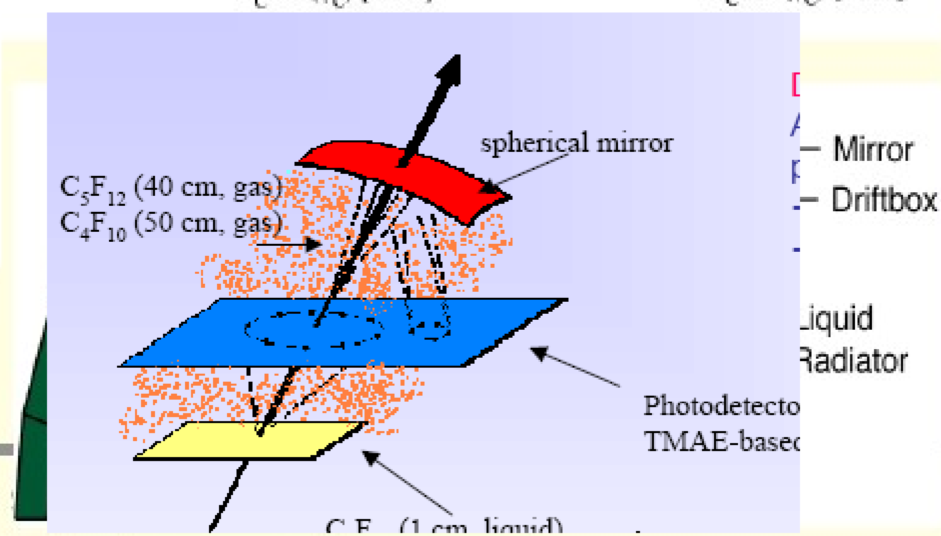
2 radiators but one photon detector for
π/K/p identification 0.7-45 GeV



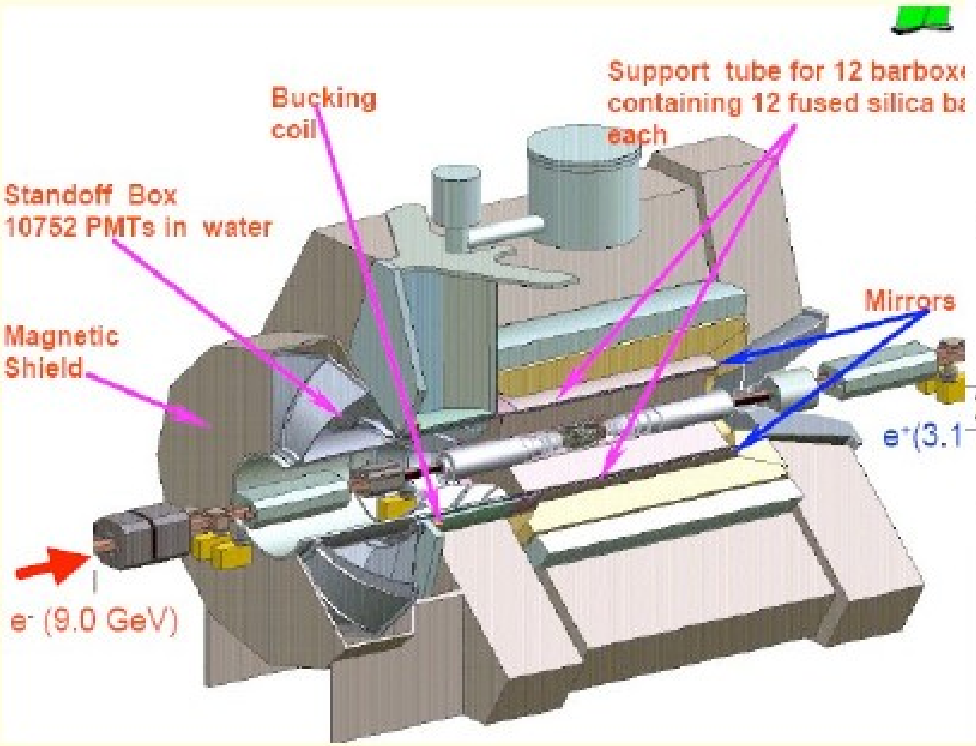


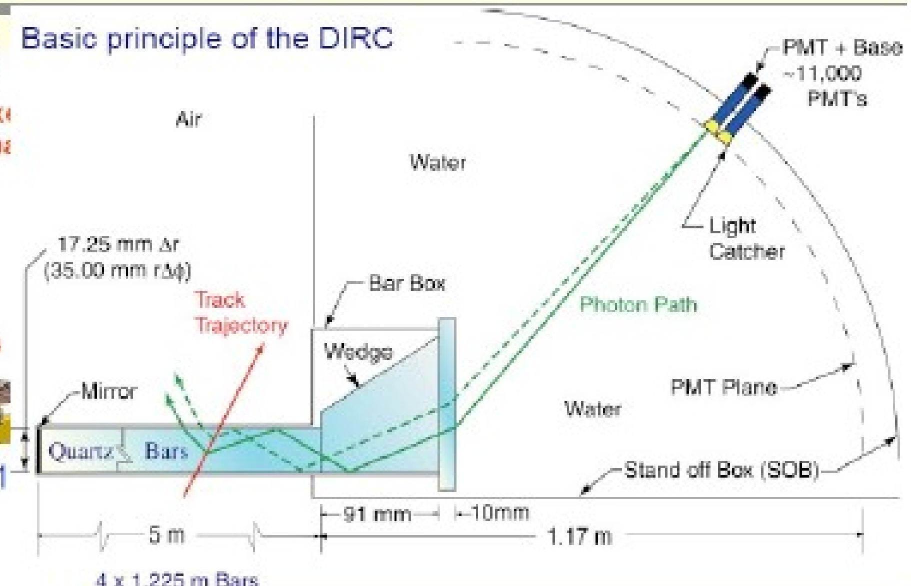
Photon detector based on TMAE (220nm) added to drift gas of a MWPC
Drift over 1.5 m →slow response



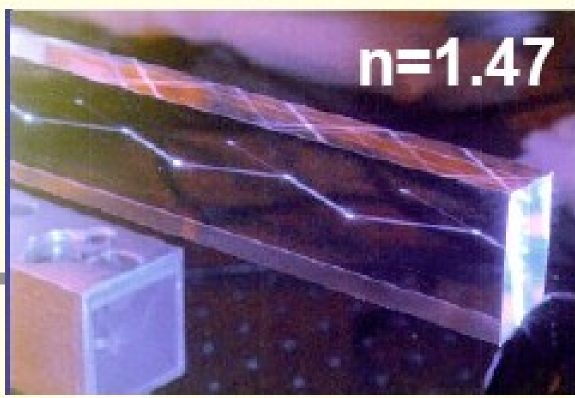


Babar: Detector for Internally Reflection Cerenkov



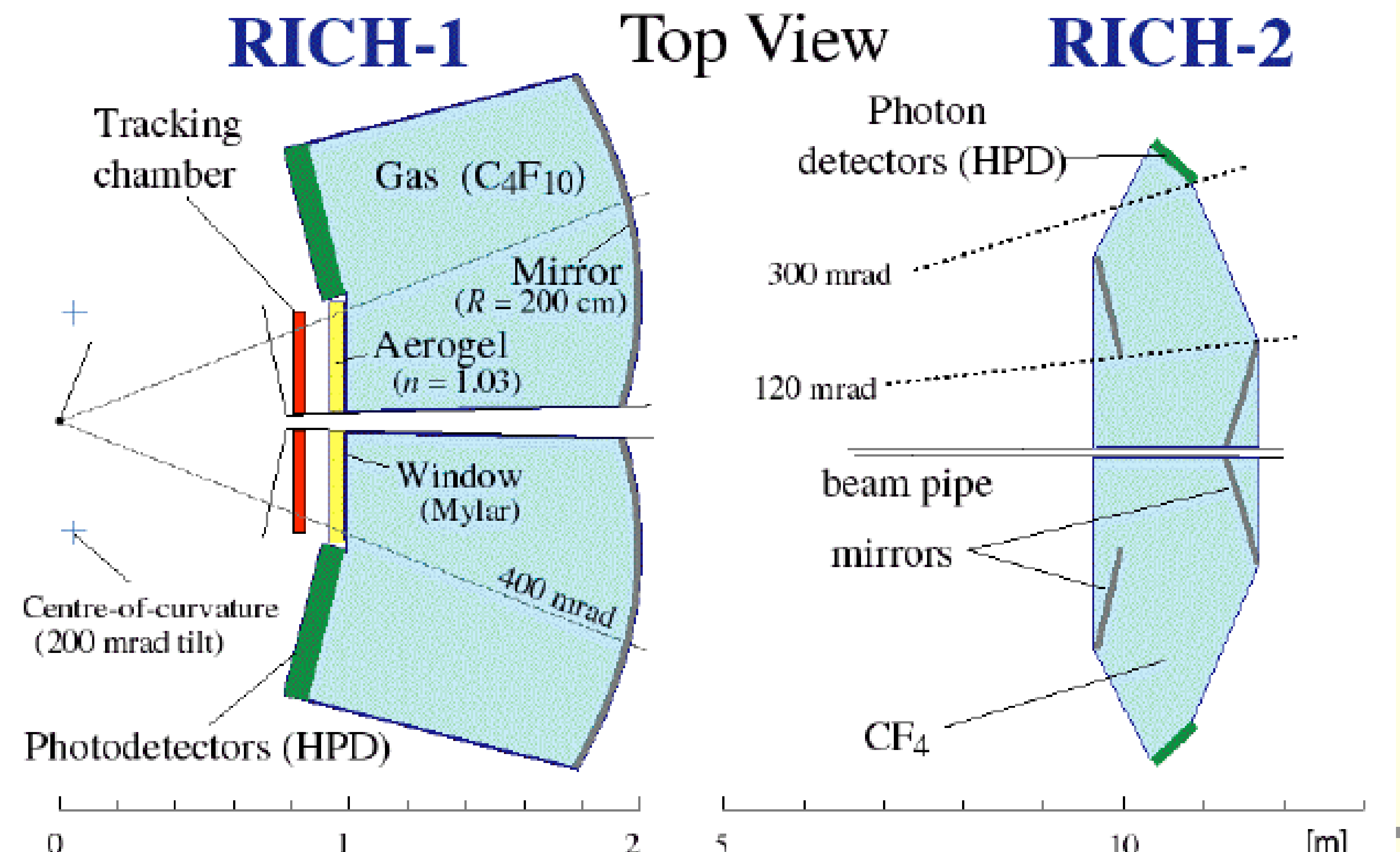


Quartz use to produce cerenkov light and transport light up to PMT



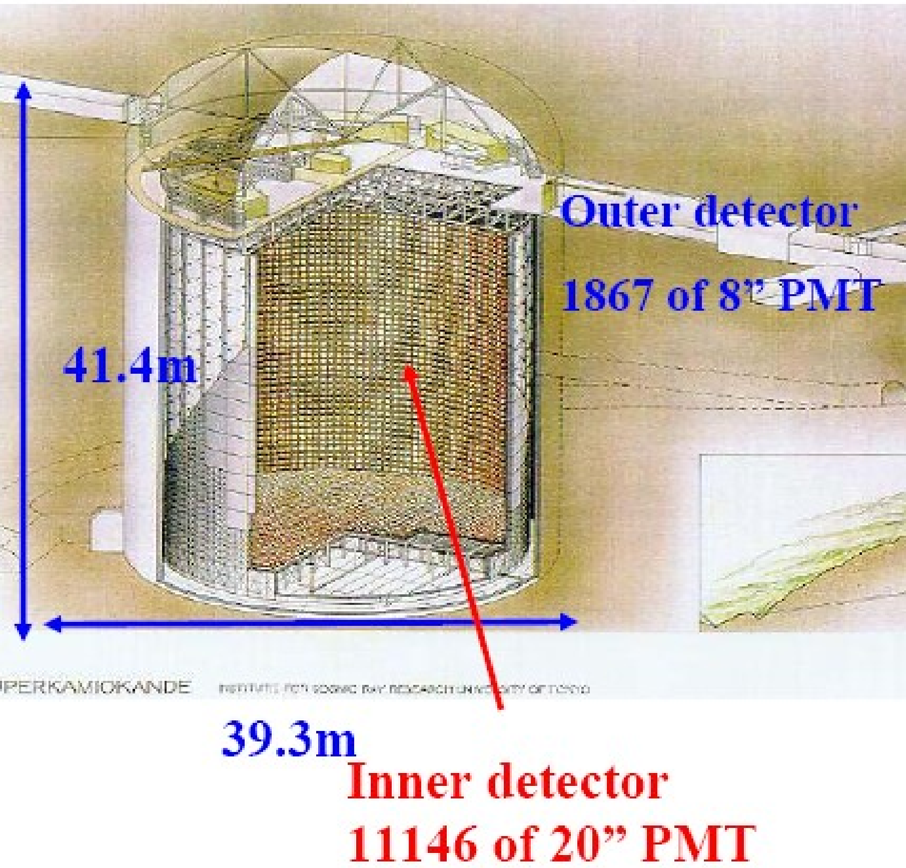
LHCb

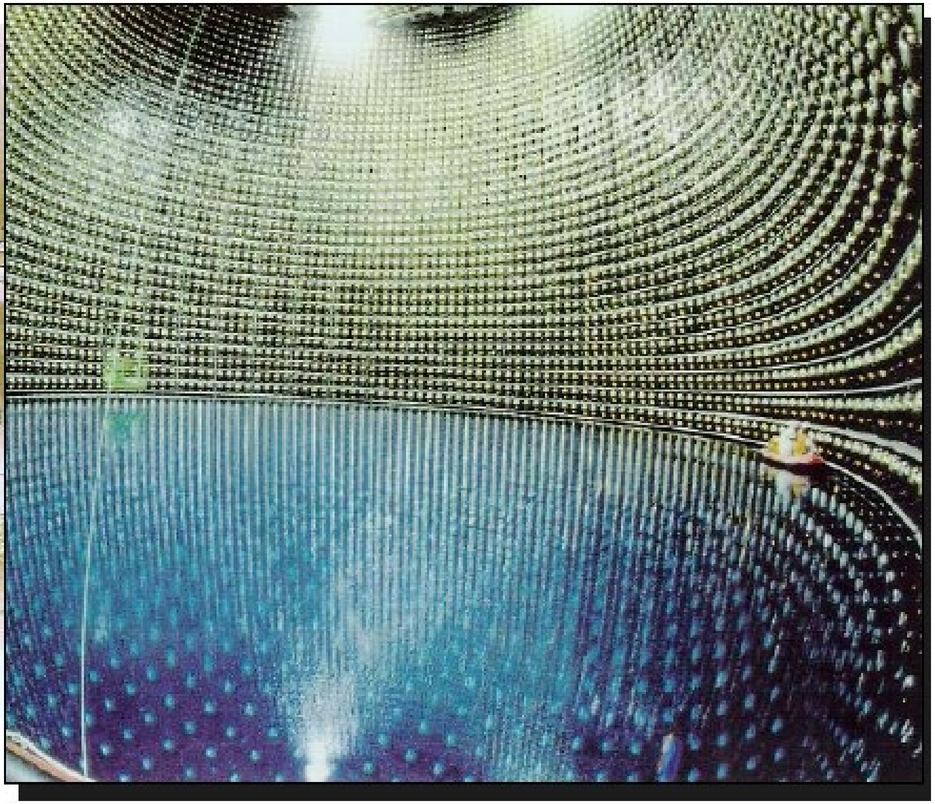
Two detectors (HPD) and three radiators :
aerogel (2-10 GeV), C_4F_{10} (10-60), CF_4 (16-100)



Super Kamiokande

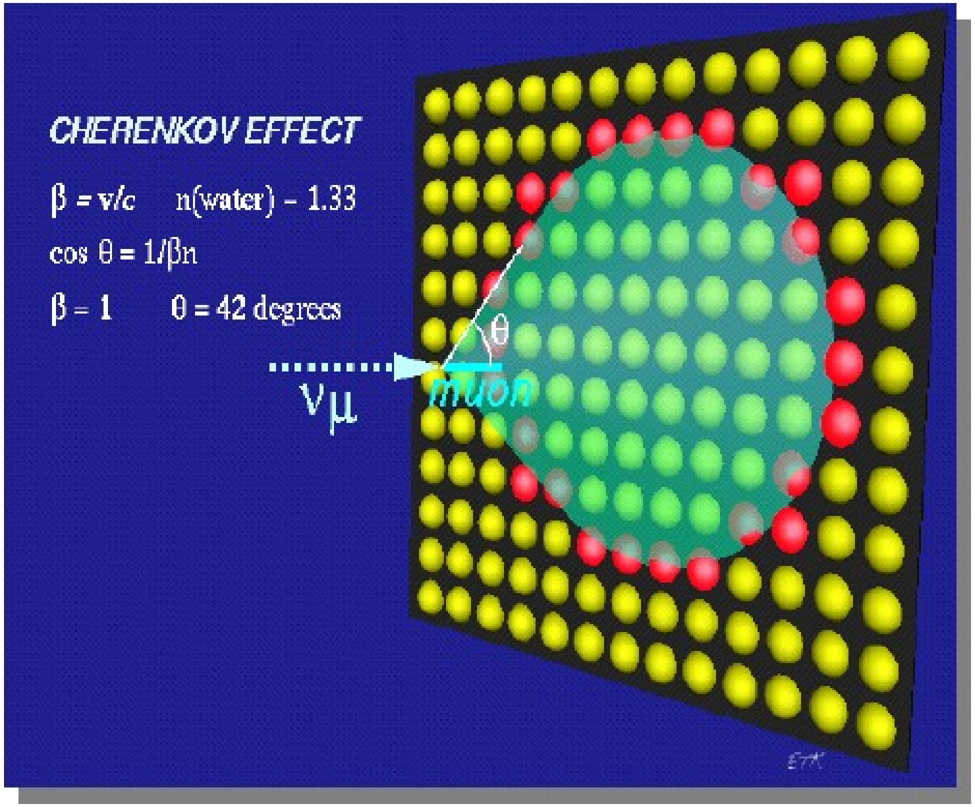
50 kton



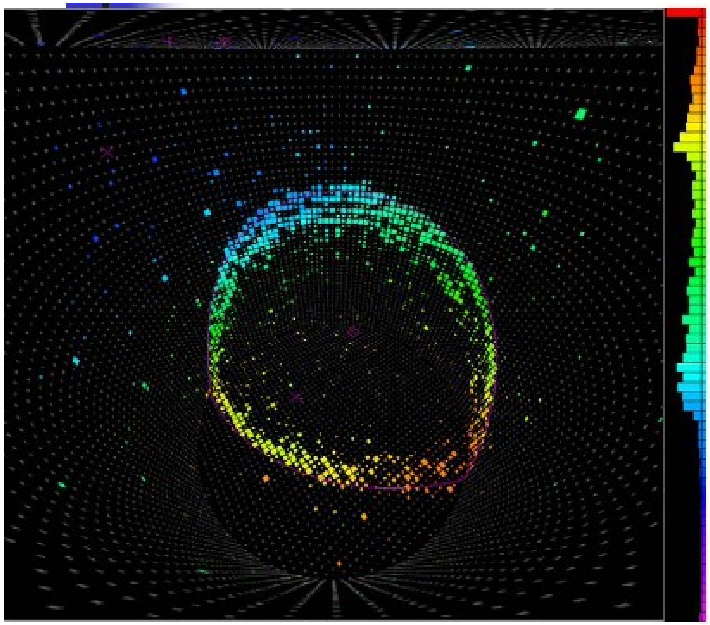


Principle of identification

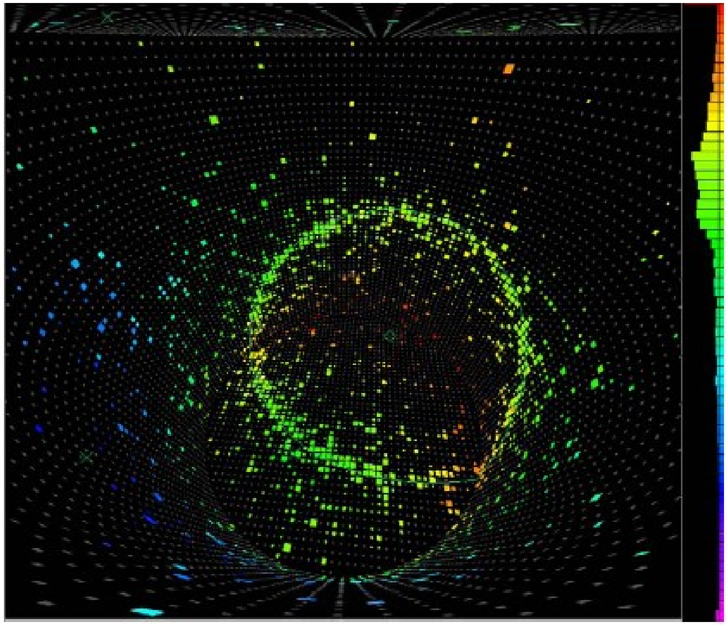
- Interaction vertex from timing
- Particle direction from ring shape
- Energy from measured pulse in the PMTs
- Particle identification from pattern



Neutrino events in SK



Atmospheric muon (FC)



Atmospheric electron

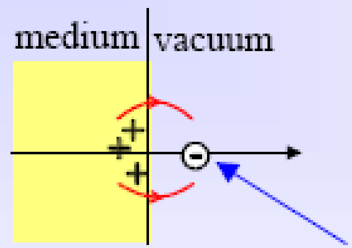
Transition radiation

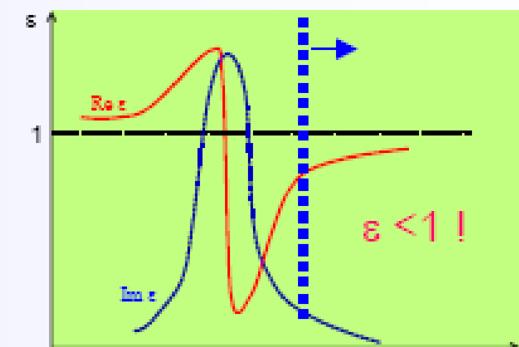
Transition Radiation was predicted by Ginzburg and Franck in 1946

TR is electromagnetic radiation emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

TR is also called sub-threshold Cherenkov radiation

A (too) simple picture





regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

A correct relativistic treatment shows that…

(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

- Radiated energy per medium/vacuum boundary

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \boxed{W \propto \gamma} \longrightarrow$$

only high energetic e± emit TR of detectable intensity.
→ particle ID

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \left(\begin{array}{c}\text{plasma}\\ \text{frequency}\end{array}\right) \quad \hbar\omega_p \approx 20\text{eV} \ \ (\text{plastic radiators})$$

Transition radiation

- Number of emitted photons / boundary is small $\quad N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$

  → Need many transitions → build a stack of many thin foils with gas gaps

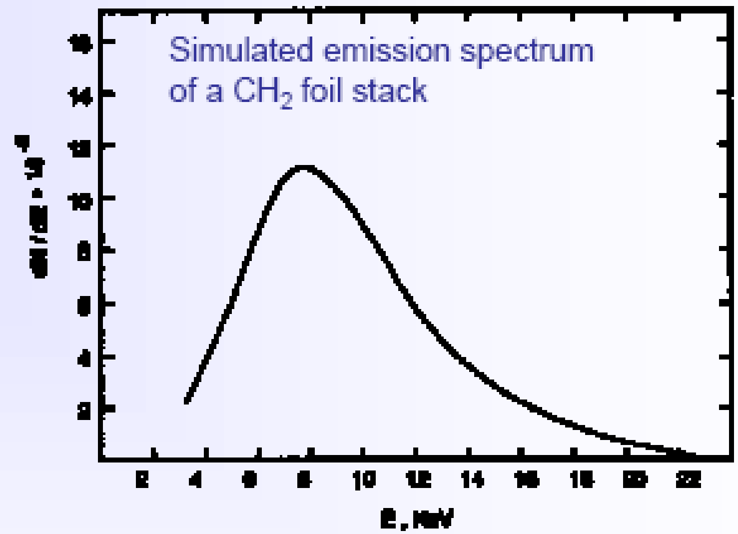
- Emission spectrum of TR = f(material, γ)

  Typical energy: $\quad \hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

  → photons in the keV range

- X-rays are emitted with a sharp maximum at small angles $\quad \theta \propto 1/\gamma$

  → TR stay close to track



- Particle must traverse a minimum distance, the so-called formation zone Z_f, in order to efficiently emit TR.

$$Z_f = \frac{2c}{\omega(\gamma^{-2} + \theta^2 + \xi^2)}, \quad \xi = \omega_p / \omega$$

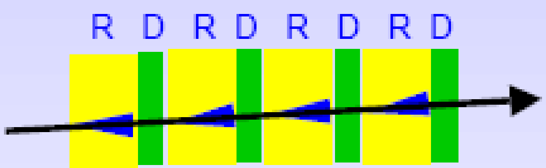
Z_f depends on the material (ω_p), TR frequency (ω) and on γ.

$Z_f(air)$ ~ mm, $Z_f(CH_2)$ ~ 20 µm → important consequences for design of TR radiator.

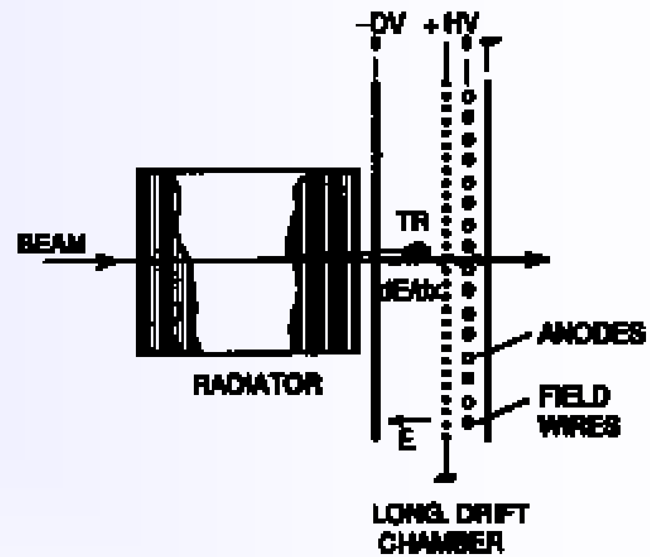
Transition radiation

- TR Radiators:
  - stacks of thin foils made out of CH_2 (polyethylene), $C_5H_4O_2$ (Mylar)
  - hydrocarbon foam and fiber materials

  Low Z material preferred to keep re-absorption small ($\propto Z^5$)

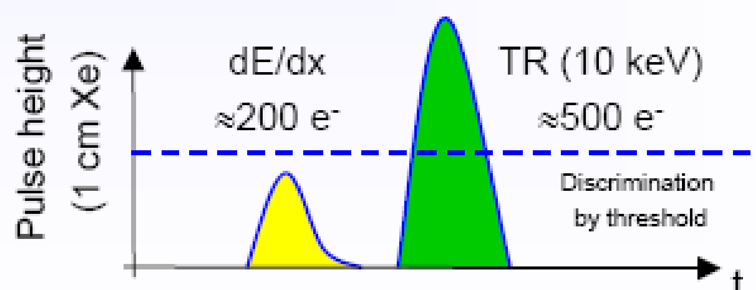


alternating arrangement of radiators stacks and detectors
→ minimizes reabsorption



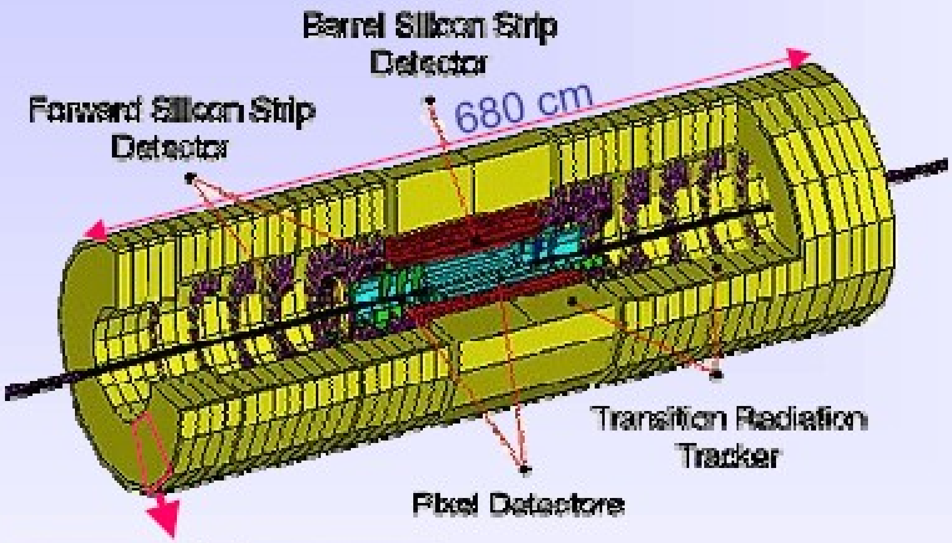
- TR X-ray detectors:
  - Detector should be sensitive for $3 \leq E_\gamma \leq 30$ keV.
  - Mainly used: Gas detectors: MWPC, drift chamber, straw tubes…
  - Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

    → gas with high Z required, e.g. Xenon (Z=54)
  - Intrinsic problem: detector "sees" TR and dE/dx

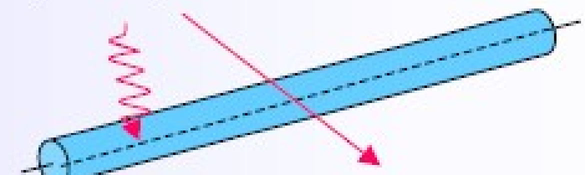


ATLAS TRT

The ATLAS Transition Radiation Tracker (TRT)



Straw tubes (d = 4mm) based tracking chamber with TR capability for electron identification.



Active gas is $Xe/CO_2/O_2$ (70/27/3) operated at ~2×10^4 gas gain; drift time ~ 40ns (fast!)

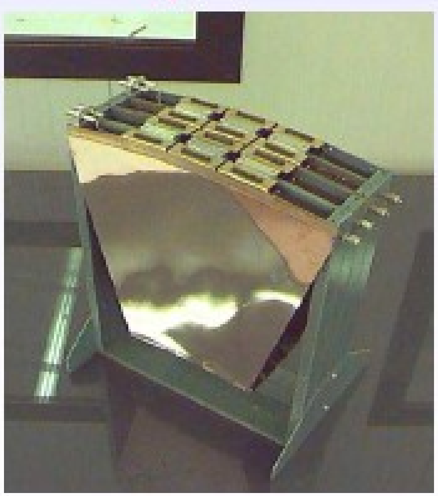


photo of an endcap TRT sector.

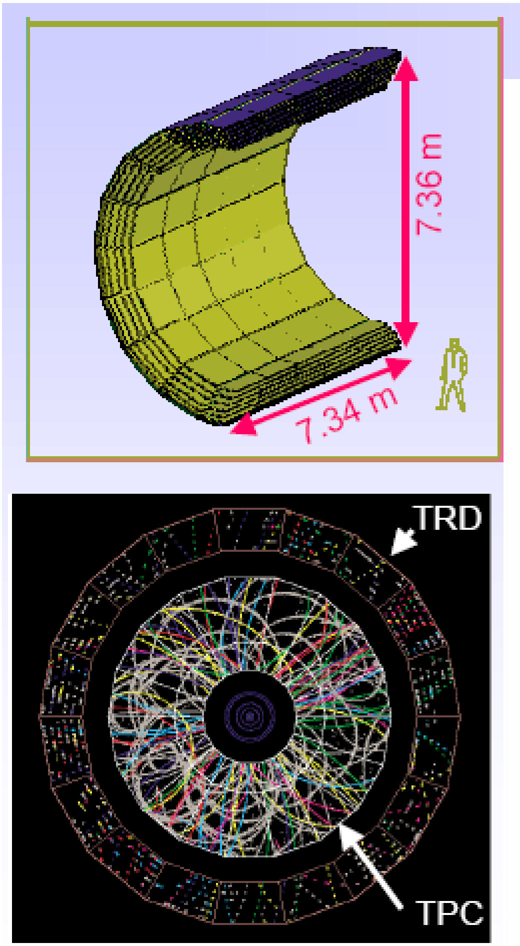
Radiators

- Barrel: Propylen fibers
- Endcap: Propylen foils

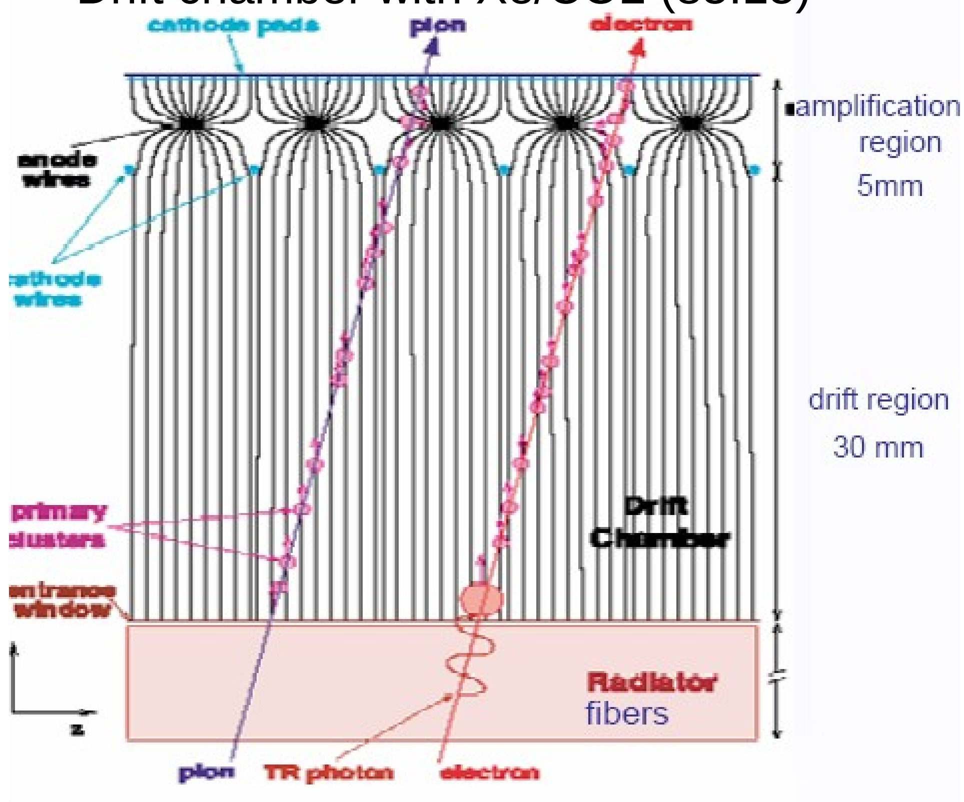
  d=15 µm with 200 µm spacing.

Counting rate ~ 6-18 MHz at LHC design luminosity 10^{34} $cm^{-2}s^{-1}$

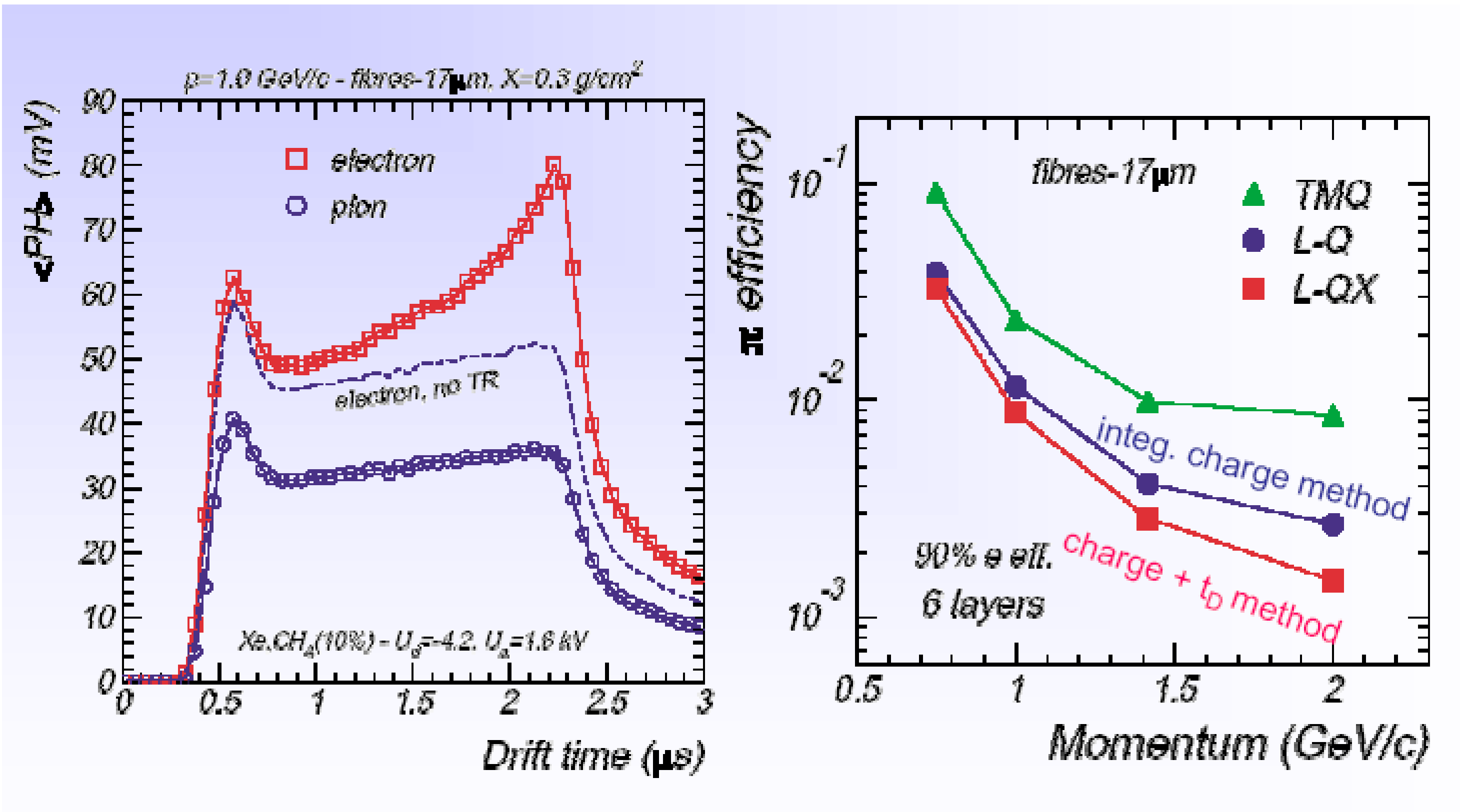
ALICE TRD



Drift chamber with Xe/CO2 (85:15)

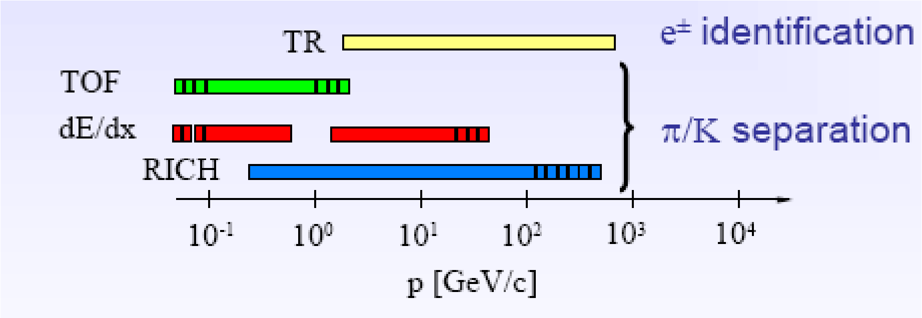


ALICE TRD performance

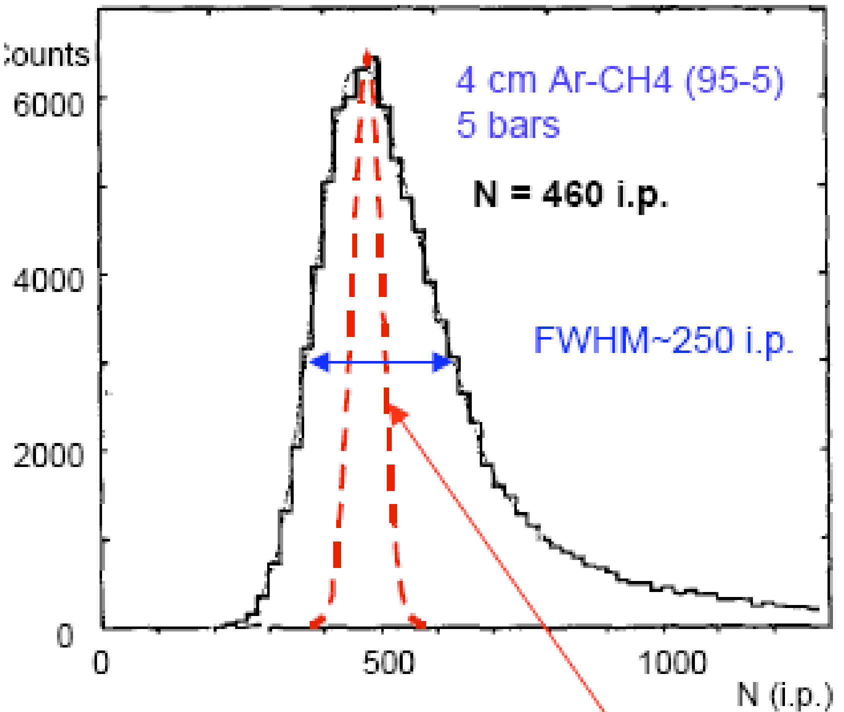


PID summary

- Muons: low energy deposition in calorimeter. High penetration
- Electrons: Shower in calorimeter. E/p
- e/μ/π/K/p Ionization, ToF, Cherenkov, Transition Radiation

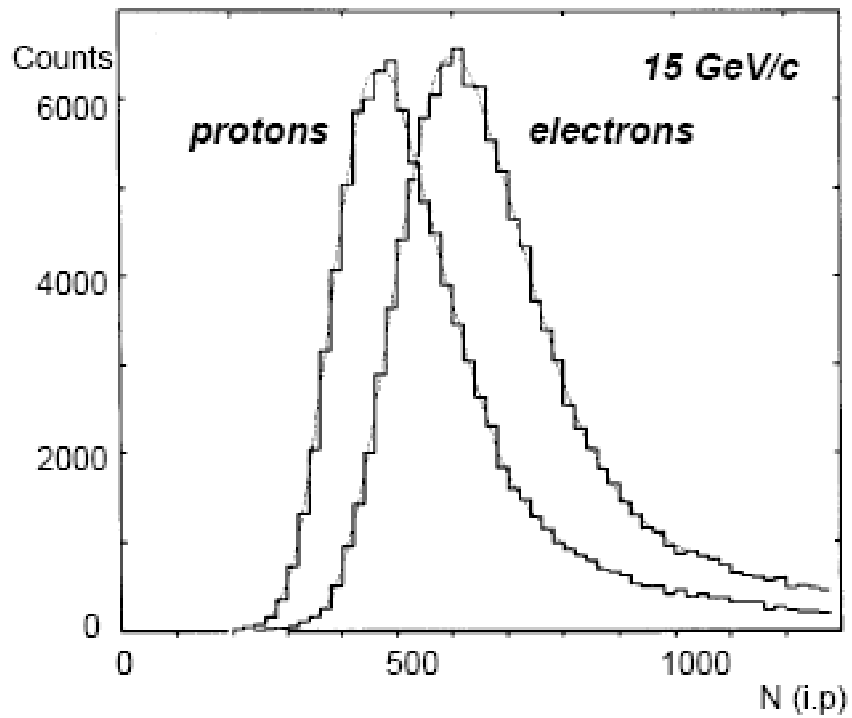


Energy loss: straggling functions



For a Gaussian distribution: $\sigma_N \sim 21$ **i.p.**
FWHM ~ 50 i.p.

PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples



I. Lehraus et al, Phys. Scripta 23(1981)727