Charged Particle Identification

1st EIROforum School on Instrumentation,
Joachim Baechler
May, 11th, 2009

Introduction
Physical processes
Requirements for detectors
PID in large scale experiments

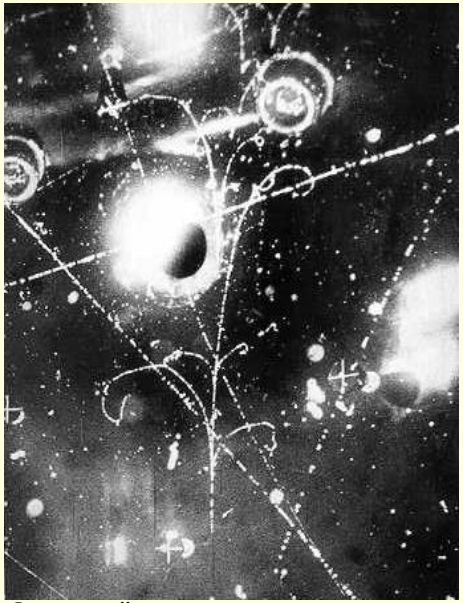
Identification of particles

by measurement of charge & mass with detectors

- High energy physics
- Nuclear physics
- Cosmic ray physics

some years ago …..

(1973)

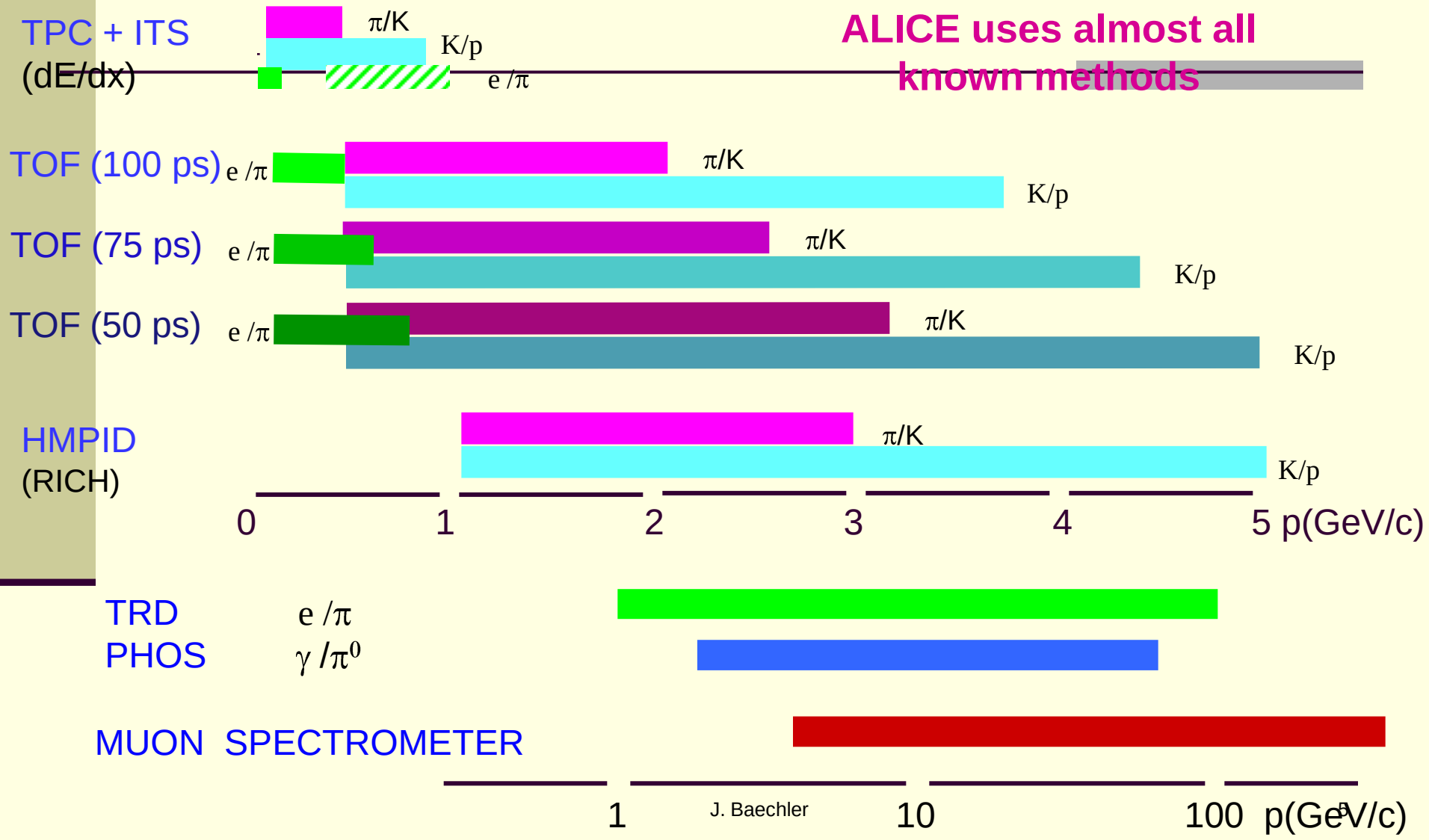


Gargamelle
Bubble Chamber
Courtesy :
IIHE Bruxelles

Scanning of
several million
events …….

MODERN PID detector
ALICE CERN / LHC

Particle Identification in ALICE

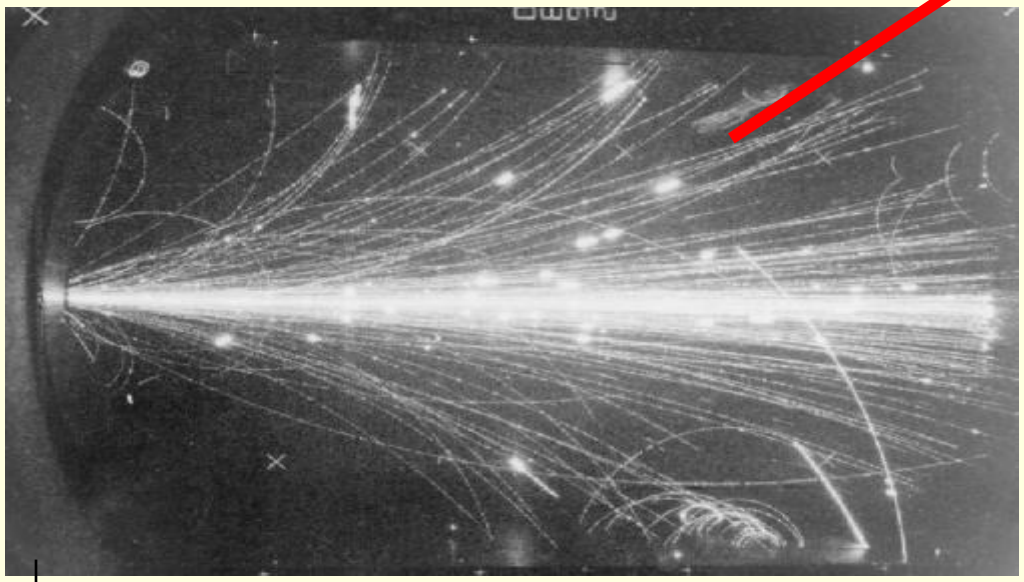


identification of charged particles

NA35 6.4 TeV ^{32}S+ Au (CERN SPS - 1992)

STREAMER CHAMBER :
TRACKING (momentum measurement in magnetic field , but **no particle identification**)

was this a proton or kaon or pion ??
→ need of PID detector !!!!



~ 200 cm

beam ^{32}S

target Au

streamer chamber
B = 1.5 T

J. Baechler

Example :

Particle	Mass (MeV/c^2)	Charge	Strangeness	J^P
p	938.27	+1	0	½
n	939.57	0	0	½
π^+	139.57	+1	0	0⁻
π^0	134.96	0	0	0⁻
e^+	0.511	+1	0	½
μ^+	105.7	+1	0	½
K^+	493.7	+1	+1	0⁻
K^0	497.7	0	+1	0⁻

mass and charge measurement for particle identification

Trigger on central event E_t

particle composition gives information on hot nuclear matter (T, source size etc.)

Principle of charged particle identification

- registration of particle trajectory with tracking detector :

=> momentum measurement :

$p = m \quad v \quad$ | **relativistic :** $p = \gamma\, m_0\, \beta\, c$

Lorentz force : $\underline{F_L} = q\,(\underline{v} \times \underline{B})$, **F-centrifugal :** $\underline{F_c}\ m\ v^2/r$

$F_l = F_c$

→ $p = 0.3\ B\ r$ (p in GeV/c, B in Tesla, r in m)

-> measurement of **β** allows PID of particle
-> PID detector

PID techniques

- Time of Flight
- dE/dx
- Cherenkov radiation
- Transition radiation

combination of different techniques allows to identify charge particles over wide range of momenta

→ diametrically opposed to principle of calorimeter !!

Detector uses :

- Scintillation counter : tracking, fast timing / particle identification, triggering
- Cerenkov counter : particle identification , triggering
- MWPC- TPC : tracking, particle identification
- Transition radiation : high energy particle identification
- Spark counter : high resolution timing

Interaction of charged particle with matter (EM)

- Ionization dE/dx

  If a charge particle moves through a medium, it can transfer an amount of energy that is sufficient to ionize the atoms.

- Cherenkov radiation

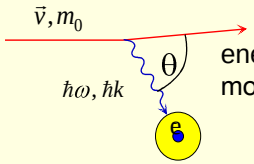
  If a charged particle moves through a medium faster than the phase velocity of light in that medium, it will emit radiation at an angle determined by its velocity and the refractive index of the medium.

- Transition radiation

  When a highly relativistic particle crosses the boundary between two dielectric media, x-ray photons are emitted. The energy of this photons is a function of $\beta\gamma$

Interaction of charged particles with matter (Allison and Cobb (1980))

Interaction of charged particle with the atom of the media via photon exchange

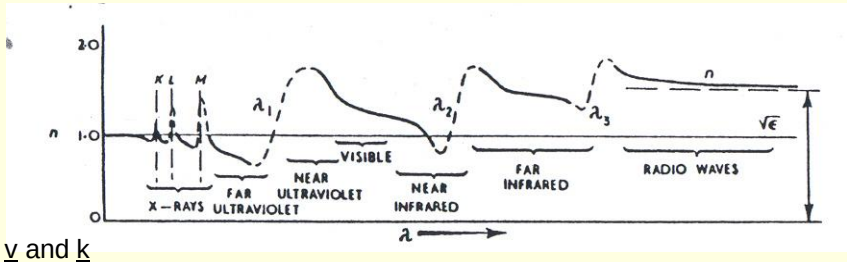


energy: $h\omega$
momentum :h $\underline{k}$

Conservation of energy $\omega =$ $\underline{v}$ $\underline{k}$
and momentum

photon behaviour is described by the dispersion relation :

$$\omega^2 - \frac{k^2 c^2}{\varepsilon} = 0 \quad \longrightarrow \quad \sqrt{\varepsilon}\,\frac{v}{c}\cos\Theta_C = 1$$



Θ_C= angle between $\underline{v}$ and $\underline{k}$

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

❑Optical region
ε is real, >1 Cherenkov radiation is emitted when velocity of particle is above the threshold.

❑Absorption region
ε is complex , range of photons is short. Absorption of virtual photon. ionization of the material

❑X-ray region
sub threshold Cherenkov radiation in presence of discontinuities
In the medium : X-ray transition radiation

Bethe-Bloch (ionization energy loss)

Bethe Bloch formula (*)

Bethe-Bloch equation modified to include the Fermi effect.

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

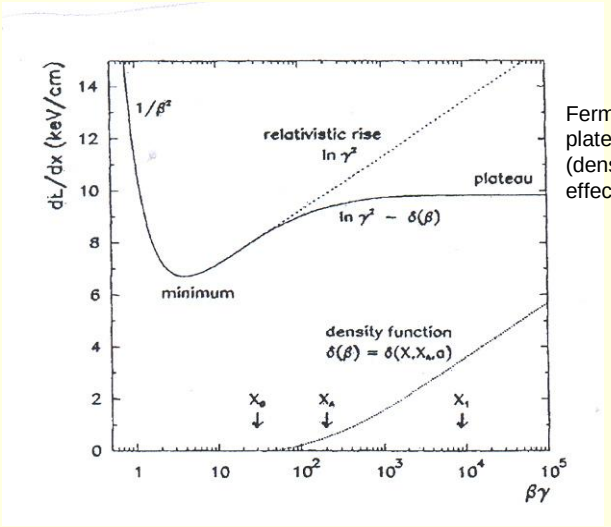
A= Atomic weight of absorbing medium
I = mean excitation potential
Z=Atomic number of absorbing material

ρ= density of absorbing material
z= charge of incident particle

$1/\beta^2$

minimum at $\beta\gamma \sim 4$ -> minimum ionizing particle

Relativistic rise : dE/dx ~ ln γ^2



Fermi plateau (density effect)

de/dX :
-depends quadratically on the charge and velocity of the particle but not on its mass !
-after minimum at $\beta\gamma \sim 3$, the ln γ^2 dominates : relativistic rise
-limitation of rise : dielectric screening (polarization of Medium)- density effect (Fermi); increases with medium density
-constant ionization loss at large γ : Fermi plateau

medium polarization reduces the long range effects

(*)W.R. LEO, Techniques for Nuclear and Particle Physics Experiments Springer-Verlag

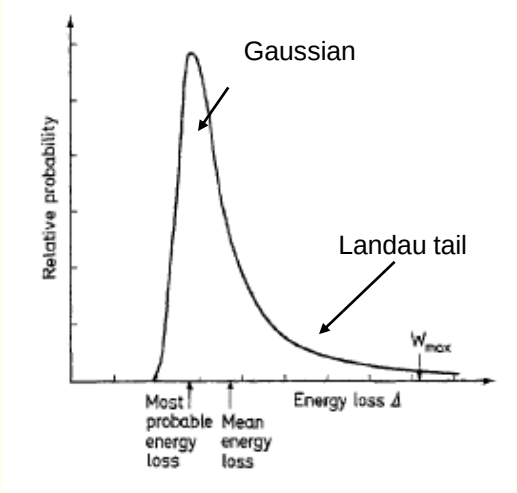
Landau distribution

dE/dx is an average value -> due to statistical nature of interaction with individual atoms in the material.

Collisions with smaller energy transfer are more likely than those with large transfer.

As consequence the energy loss distribution is asymmetric with tail on the high energy side.

truncated mean calculation :
removing 30-50 % of the signals of the largest size is shifting the mean closer the most probable.

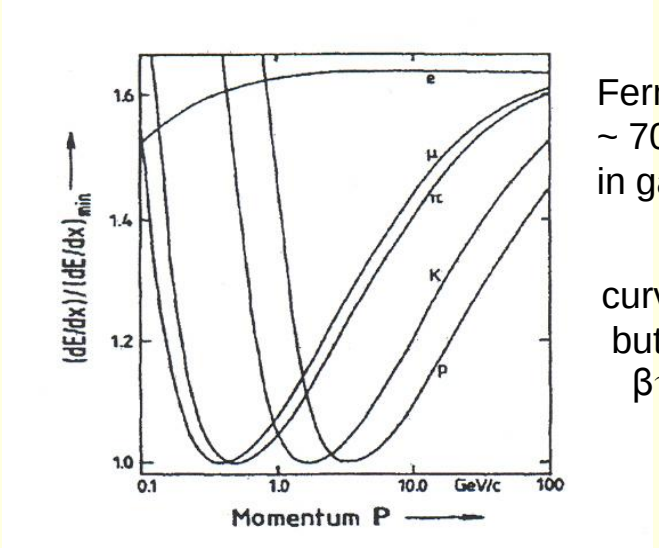


PID via dE/dx

$p = m \beta \gamma$

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

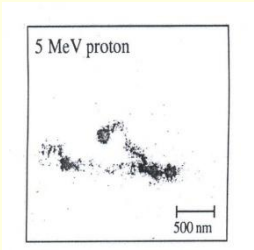
Simultaneous measurement of p and dE/dx



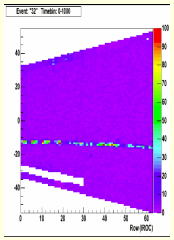
Fermi plateau:
~ 70% higher than minimum in gases at STP !

curves have same shape, but are offset from each other
$\beta\gamma = p/m$ has minimum ~4

Minimum particle momenta is required !



dosimeter **NIM A 416(1998) 85**



1 GeV/c proton in Ne/CO_2

TPC online monitor ALICE TPC – PS CERN

dE/dx resolution

– **dE/dx resolution** (A.H. Walenta et al. Nucl. Instr. and Meth. 161 (1979) 45)

$$\sigma\left(dE/dx\right) \propto n^{-0.43+-0.47}\,(t\cdot p)^{-0.32+-0.36}$$

n: number of sampling layers,
t: thickness of the sampling layer (cm)
p: pressure of the gas (atm)

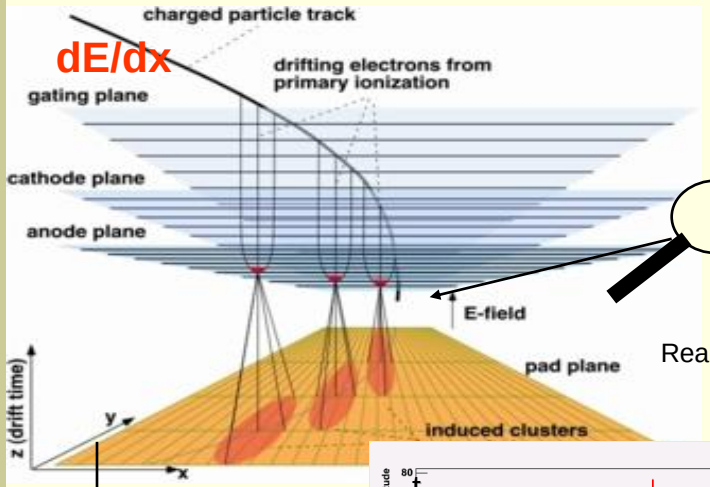
Particle separation D
power of detector to separate the mass of two particles A, B with the same momentum, normalized to σ

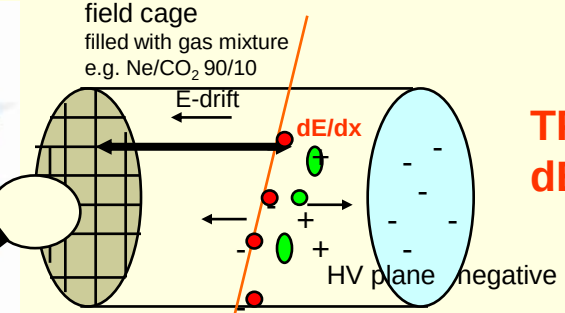
$$D_{A,B} = \frac{(dE/dx)_B - (dE/dx)_A}{\sigma(\mathrm{dE/dx})_B}$$

Principle of TPC

(Time Projection Chamber with MWPC readout)

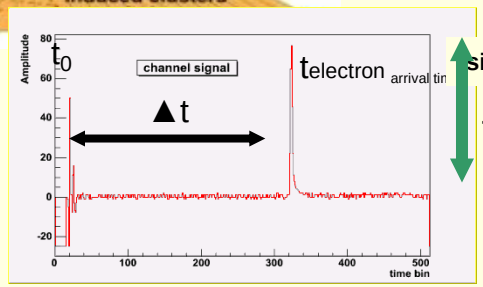
(tracking and dE/dx)





TPC allows tracking and dE/dx measurement

particle at t_0 (measured by external detector)

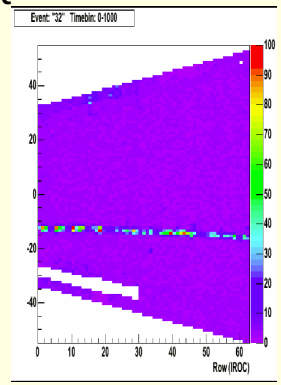


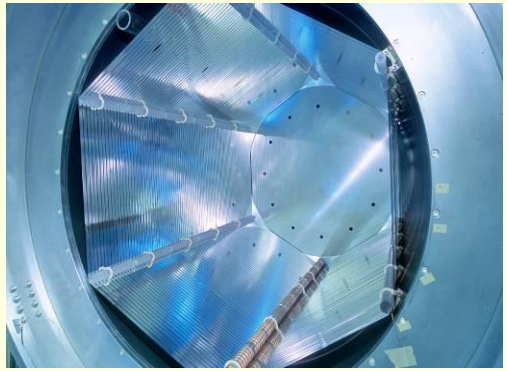
signal on single pad

~ Q

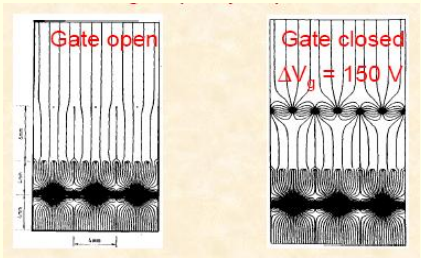
PASA

ADC





(small) field cage



distance = V_{drift} * t

▲t = t_0 - $t_{electron\ arrival\ time}$

Main parameters of a TPC

(example of ALICE TPC)

CERN/LHCC 2000-001
ALICE TDR 7

Parameters of the drift gas

Item	Value
Number of primary electrons for MIP	14.35
First ionization potential	20.77 eV
Effective energy for e–ion pair creation	35.97 eV
Drift velocity at 400 V/cm	2.83 cm/μs
Diffusion constants ($D_T = D_L$)	220 $\mu m/\sqrt{cm}$
Tangent of Lorentz angle ($\omega\tau$)	0.15
Oxygen content	5 ppm

Parameters of the readout chamber

Item	Value
Pad dimensions:	
84.1 cm $< r <$ 132.1 cm	4×7.5 mm^2
134.6 cm $< r <$ 198.6 cm	6×10 mm^2
198.6 cm $< r <$ 246.6 cm	6×15 mm^2
Anode wire spacing	2.5 mm
Anode wire to pad distance:	
84.1 cm $< r <$ 132.1 cm	2 mm
134.6 cm $< r <$ 246.6 cm	3 mm
Gas gain	2×10^4

Parameters of the electronics

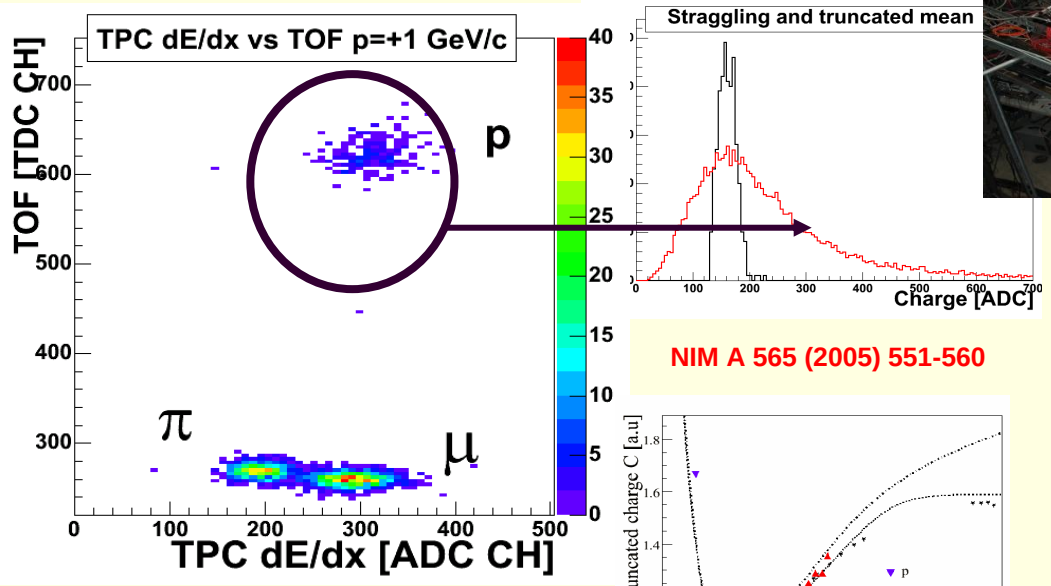
Item	Value
Noise (r.m.s.)	1000 e (in the system)
Dynamic range	2 V, 10 bits
Conversion gain	12 mV/fC
Shaping time	190 ns FWHM
Sampling time	200 ns
Zero suppression	3 ADC counts

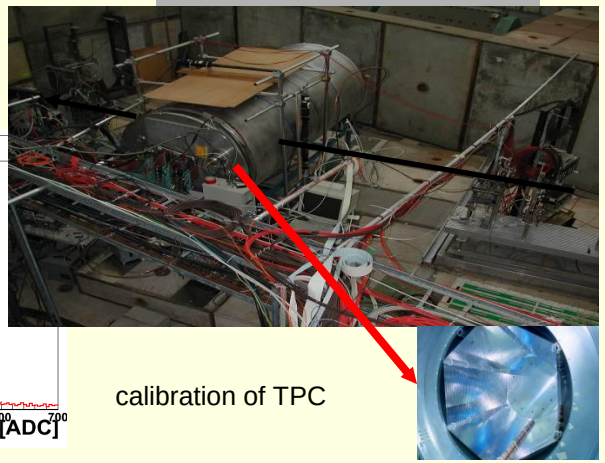
All parameters have to be well matched to achieve the performance requirements

Complex parameter space to optimize !

measurement of dE/dx energy loss curve
(particles with fixed momentum from accelerator - > momentum scan)

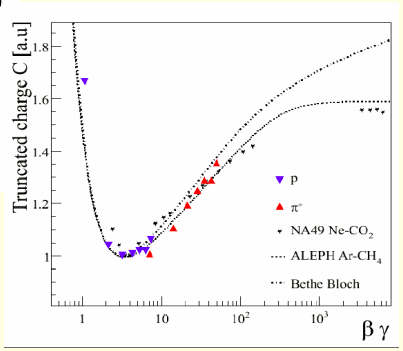
TPC E-loss $_{vs}$ TOF p=+1GeV/c

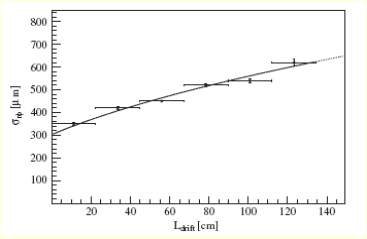




calibration of TPC

NIM A 565 (2005) 551-560





space point resolution in pad direction

dE/dX energy loss curve for new gas mixture

MODERN TPC

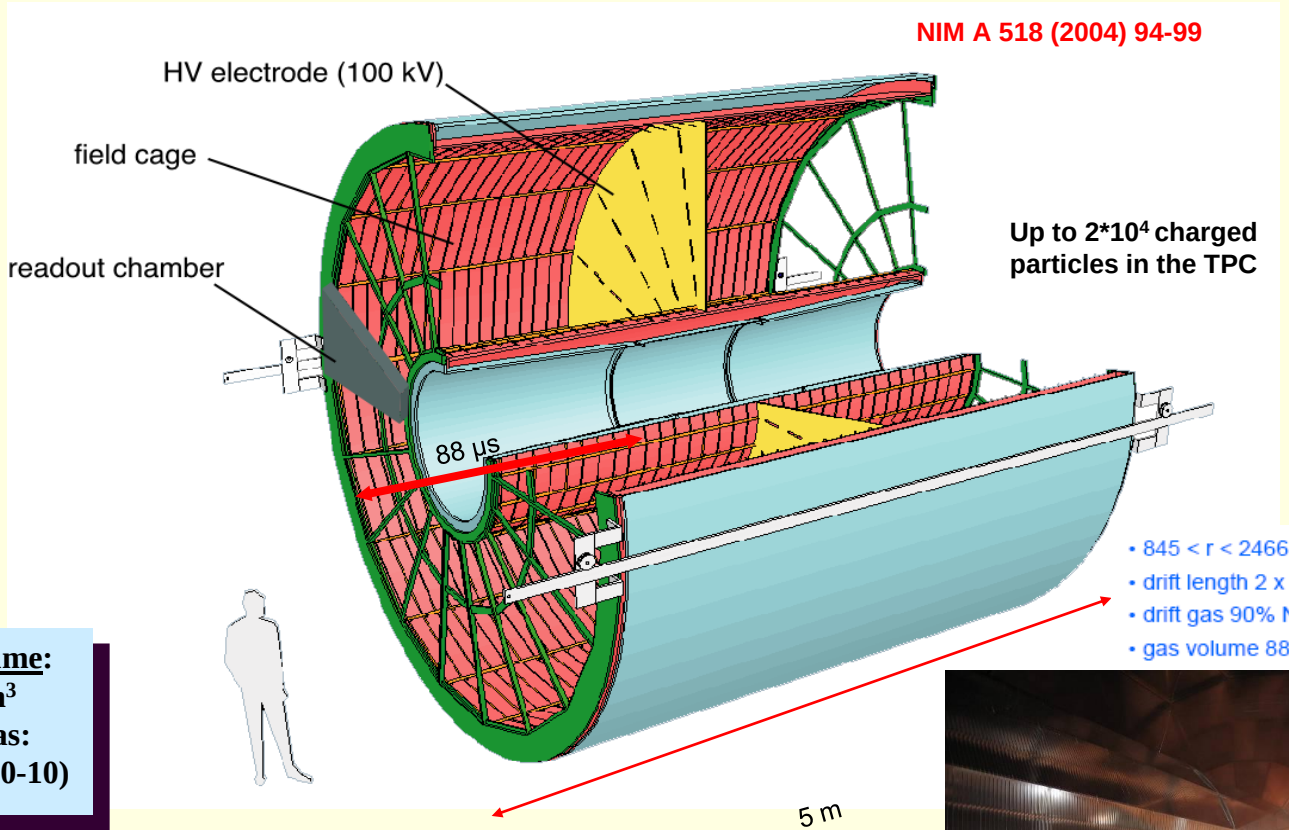
(ALICE TPC)

TPC tasks:
- track finding
- momentum measurement
- particle identification

p_t < 10 GeV / c
$|\eta|$ < 0.9

Requirements:
- tracking efficiency: > 90%
- momentum resolution: < 2.5 %
- dE/dx resolution: < 10%

NIM A 518 (2004) 94-99

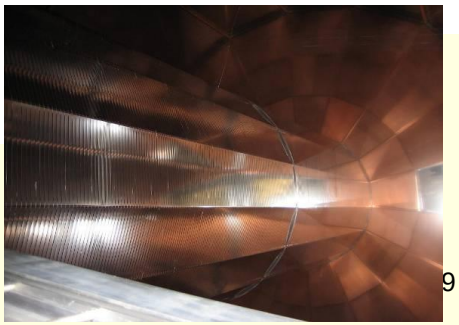


Up to 2*10^4 charged particles in the TPC

- 845 < r < 2466 mm
- drift length 2 x 2500 mm
- drift gas 90% Ne – 10% CO_2
- gas volume 88 m³

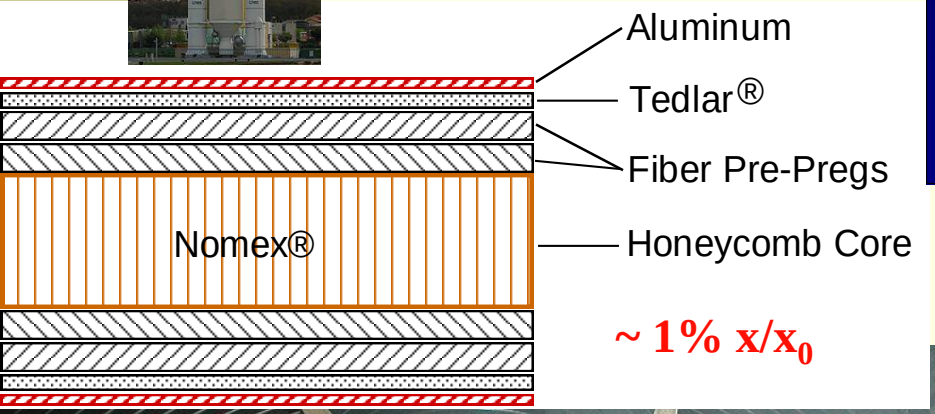
Gas Volume:
~ 88 m^3
Drift gas:
Ne-CO_2 (90-10)

view inside TPC

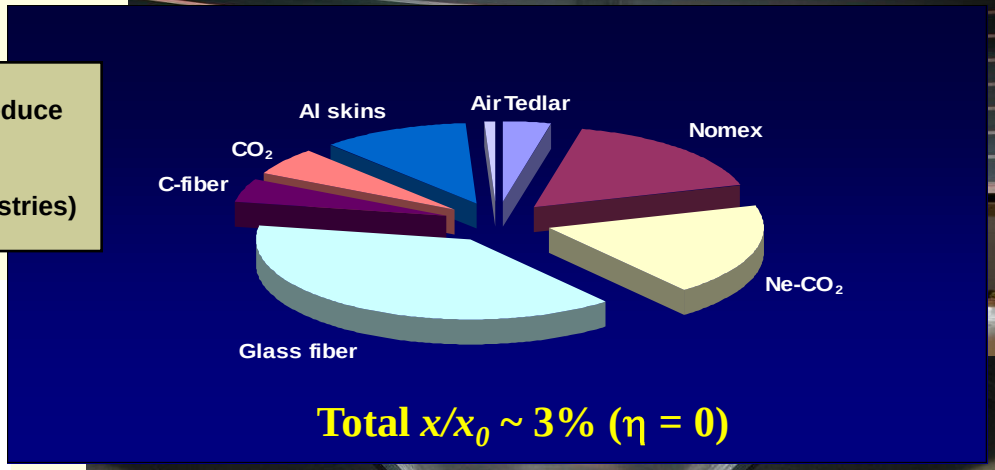


ALICE TPC FIELD CAGE

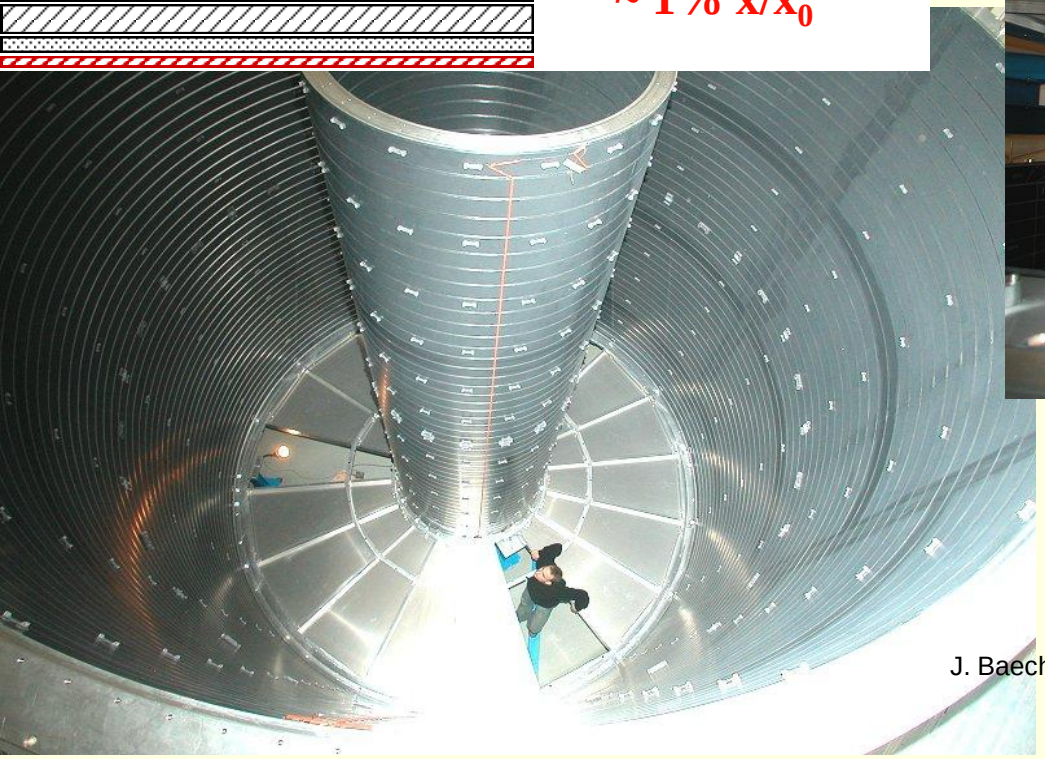
Ultra light materials (composite materials) to reduce multiple scattering and secondary particle production (produced in collaboration with aerospace industries)

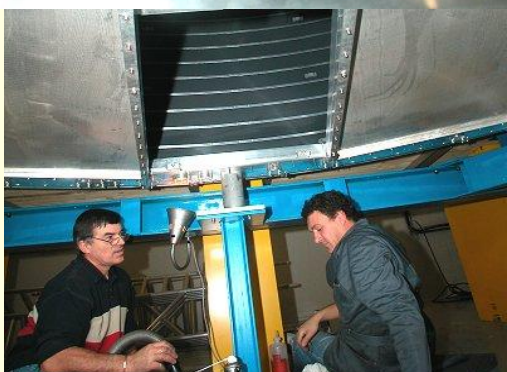


~ 1% x/x_0



Total x/x_0 ~ 3% (η = 0)

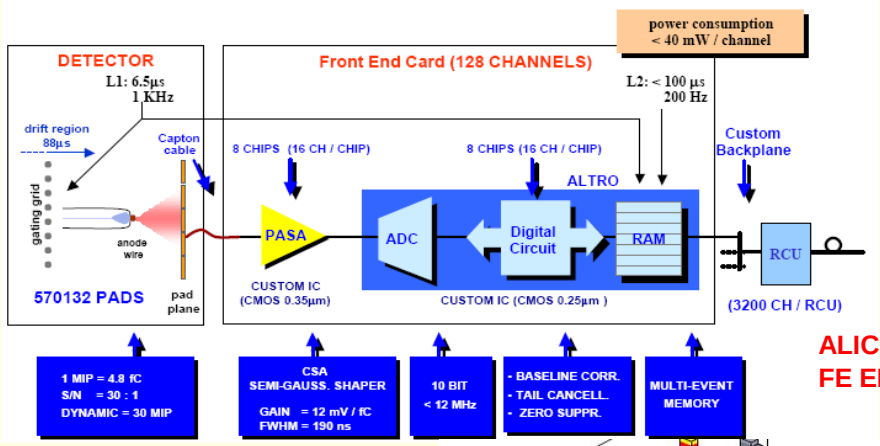




J. Baechler

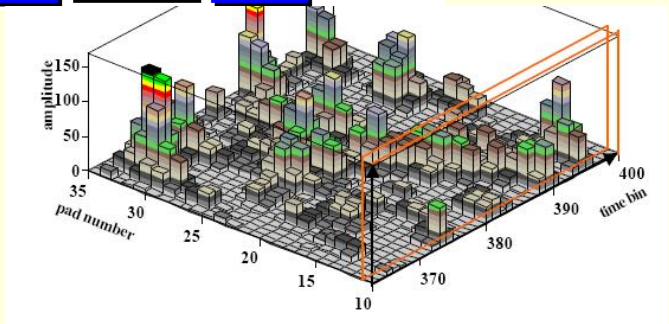
Requirement for dE/dx and tracking: state of the art electronics

Modern PID detectors are a combination of large scale mechanic installations with high-end electronics



ALICE TPC FE ELECTRONIC

Measurement of charge on ~ 500 000 pads every 100 ns !! (over 88 us)



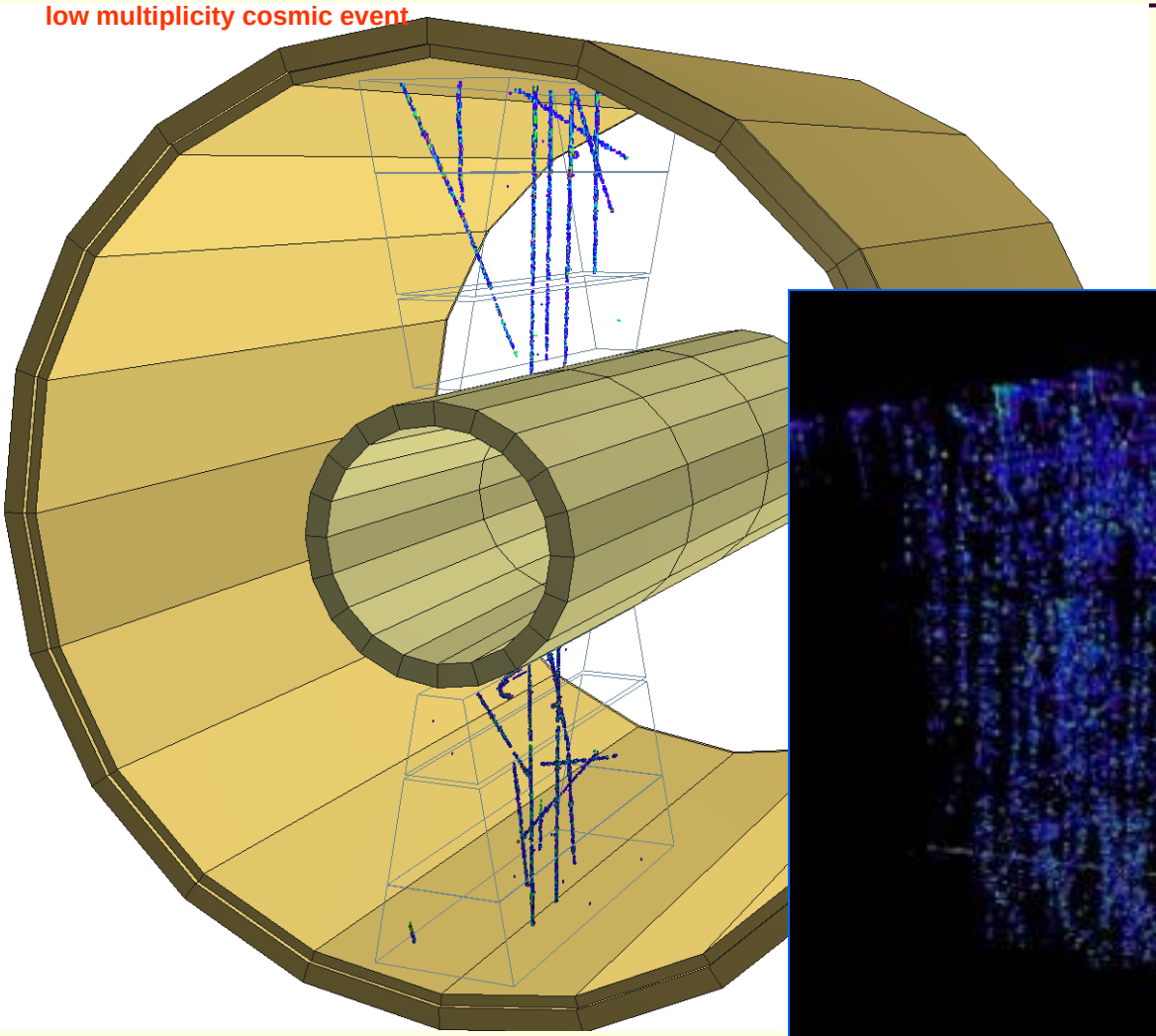
Center of gravity computation from clusters in space (pad) and time allow to determine the space points of the particle track.

The total charge deposit of a particle (dE/dx) is associated with sum of clusters associated with that track

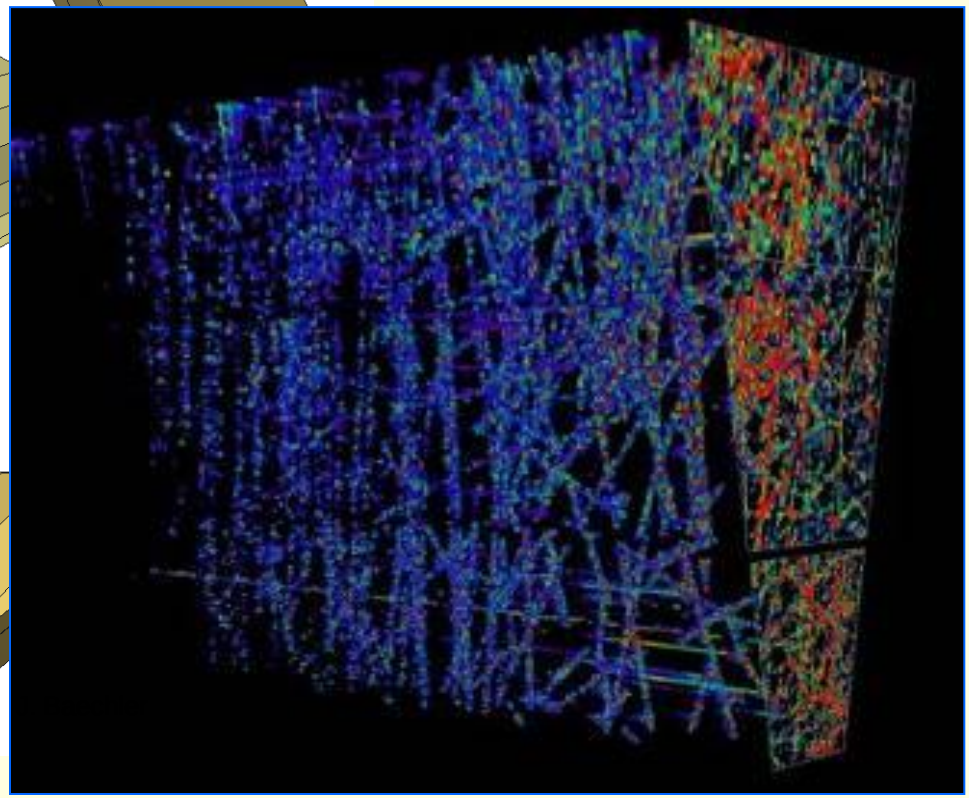
The precision of the charge measurement strongly depends on the baseline stability of the electronics.
(change of signal level provoked by consecutive charges arriving on a pad within read out time

Cosmic rays in ALICE TPC

low multiplicity cosmic event



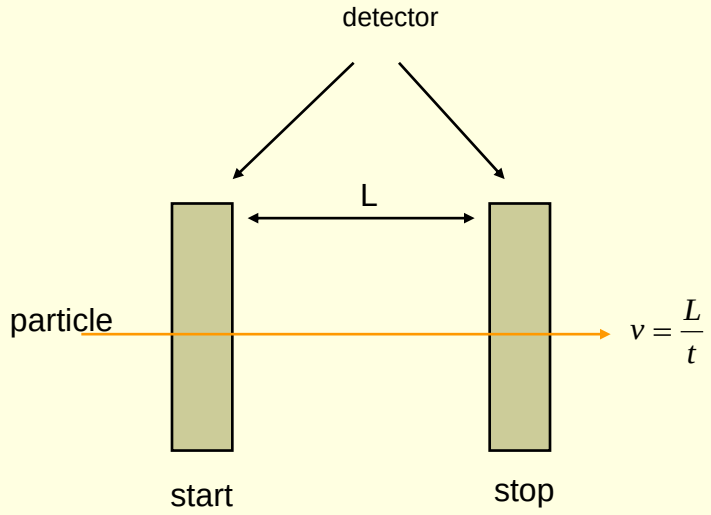
high multiplicity cosmic event



Time Of Flight - TOF

- principle

Time of flight measurements yield the velocity of the particles over a given distance



$$t = \frac{L}{c}\sqrt{1 + \frac{(m_0 c^2)^2}{(pc)^2}}$$

L = 1.5 m -> L/c = 5.0 ns

Time of flight

- particle separation

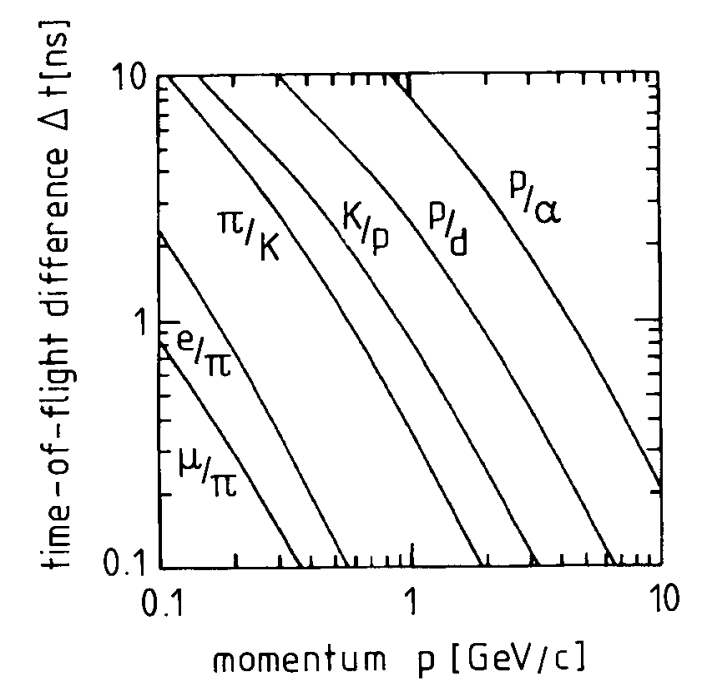
Time difference t for two particles with mass m_1 and m_2 and momentum p:

$$\Delta t = \frac{L}{c}\left[\sqrt{1+\frac{(m_1 c^2)^2}{(pc)^2}} - \sqrt{1+\frac{(m_2 c^2)^2}{(pc)^2}}\right]$$

E >> $m_1 c^2,\ m_2 c^2$

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

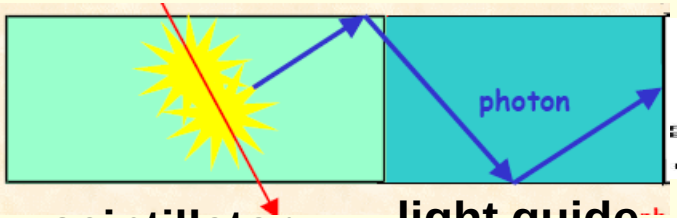
Flight of time difference ▲t for different particle pairs with L = 1m

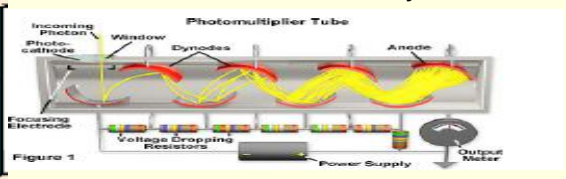


TOF

-DETECTOR (SCINTILLATOR)

~ 10^6 secondary electrons





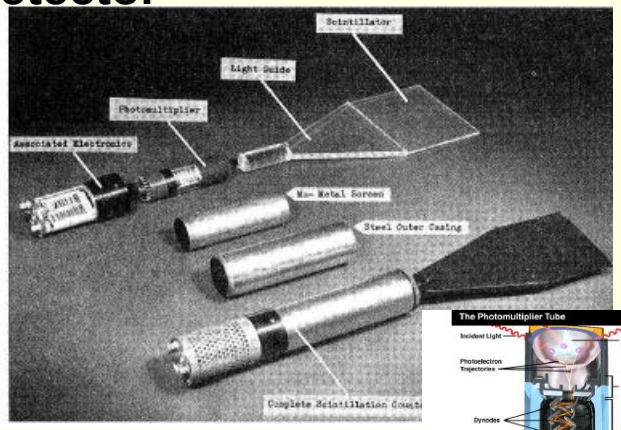
scintillator

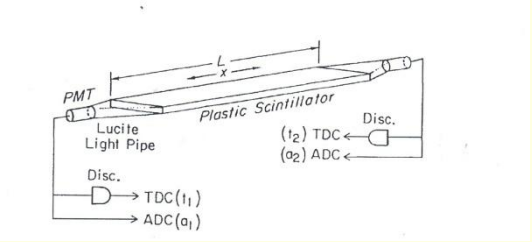
production of scintillation light (luminescence)

light guide

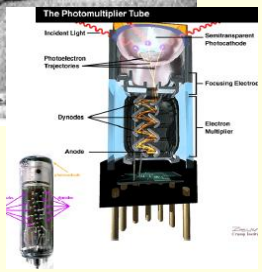
To match scintillator with PMT

Photon detector





- start and stop counters :
  - plastic scintillators
  - gaseous detectors
- Signal processing (time and charge measurement)
- Calibration : correction for cable length, delay times ..
- Permanent stability monitoring



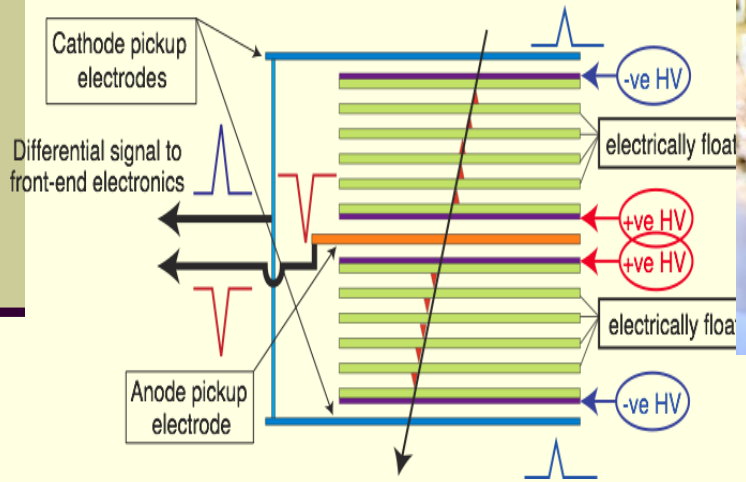
TOF

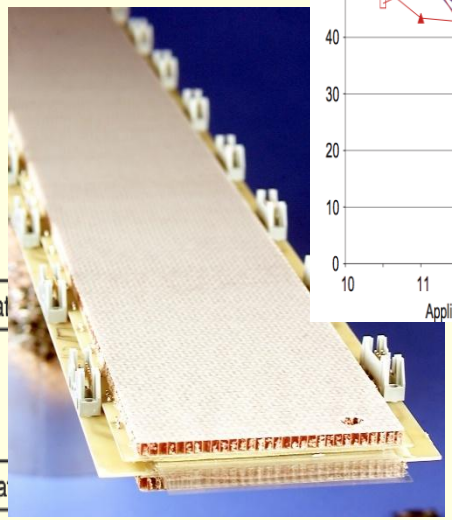
-DETECTOR (RPC Resistive Plate Chamber)
(multi gap resistive plate chamber – M.C.S. Williams)

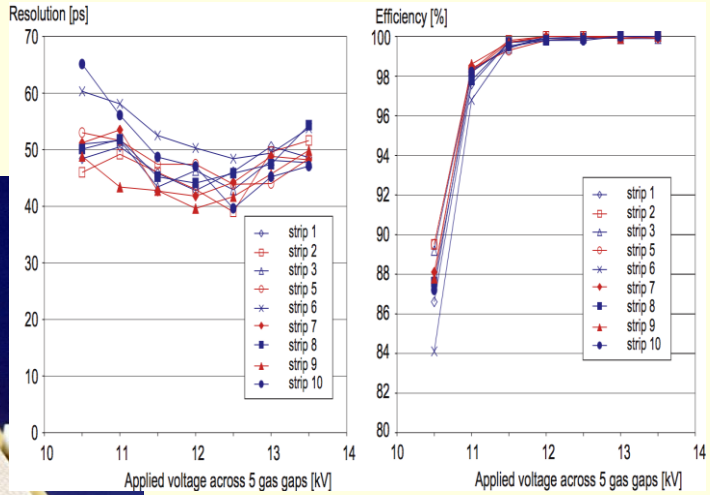
Principle :

NIM A 374 (1996) 132

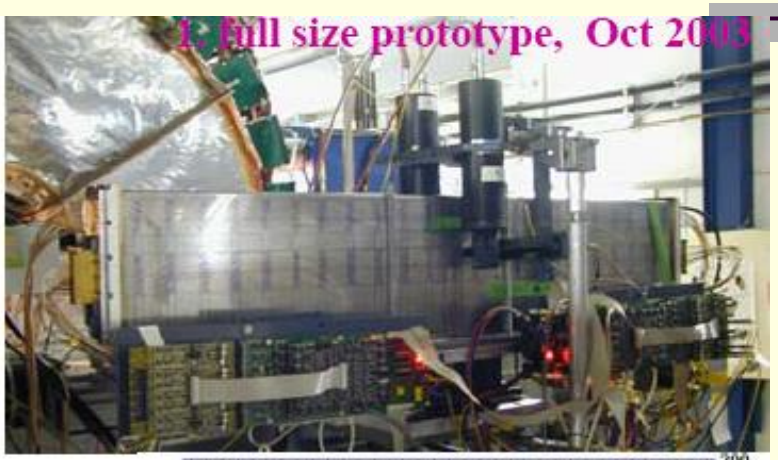
Stack of equally-spaced resistive plates
Voltage applied to the external surfaces
Pickup electrode on external surface
(resistive plate transparent to fast signal

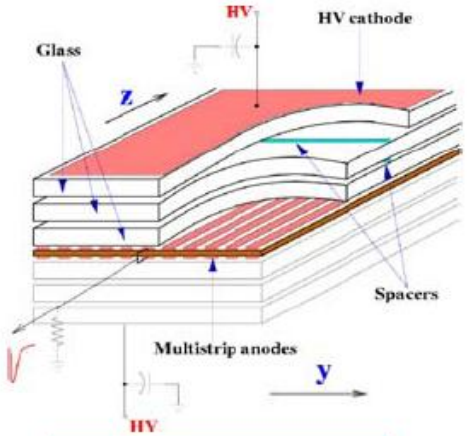






FOPI – RPC (GSI)



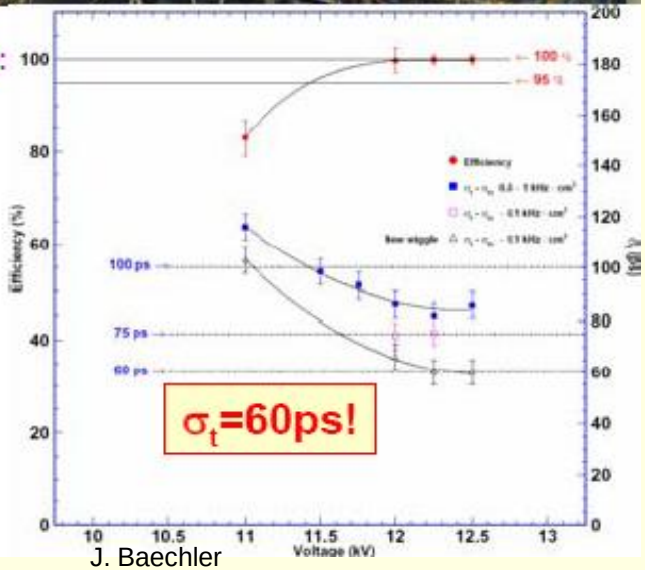


Multi-Gap-Strip-RPC

Gap-size:	250-300 μm
Hochspannung:	~3kV/gap

N.Herrmann, Uni Heidelberg

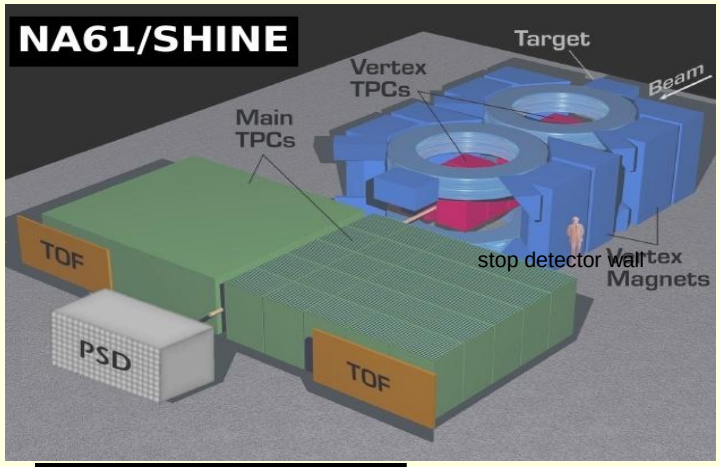
Performance:



TOF particle identification NA49

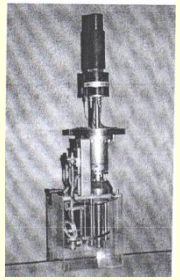
NA49/N61 Experiment (scintillator based TOF)

- Scintillator based TOF

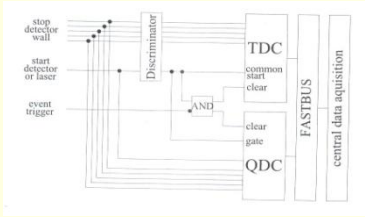


$\sigma = 25$ ps

start detector



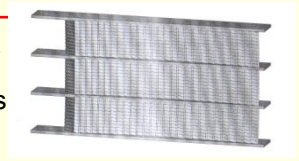
Flight path ~ 15 m

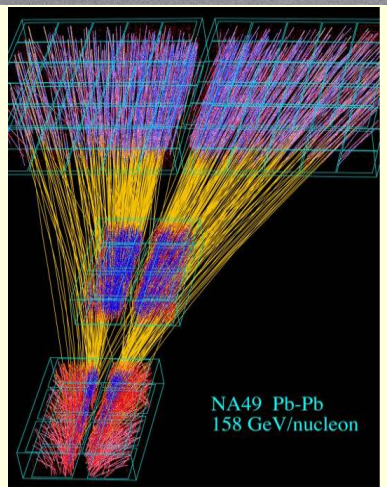


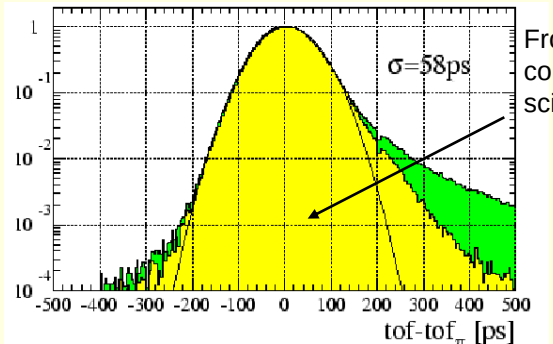
Signal processing

stop detector

$\sigma = 60$ ps







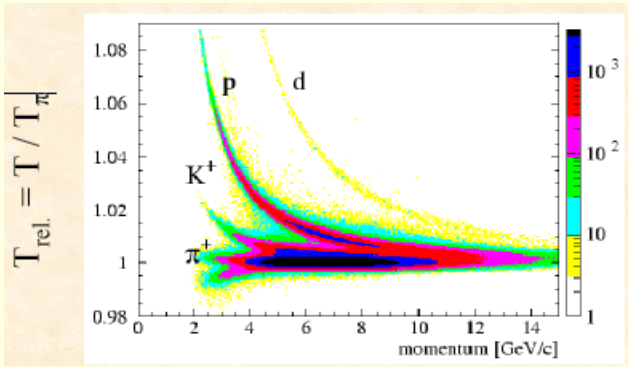
From gamma conversion in scintillator

J. Baechler

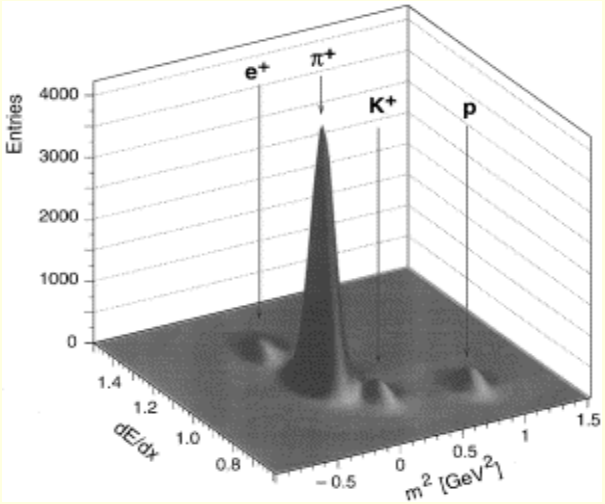
TOF NA49

- experimental results

TOF (alone)

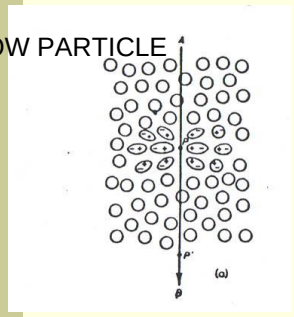


TOF with TPC



Cerenkov radiation

SLOW PARTICLE



Slow particle:

no net polarization

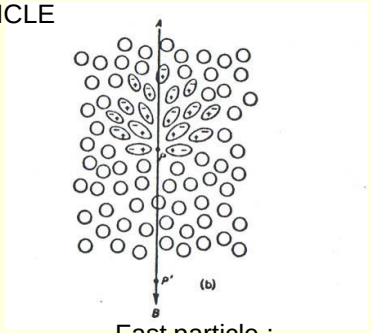
Charged particle moving with velocity v in transparent medium with index of refraction n

v > c/n

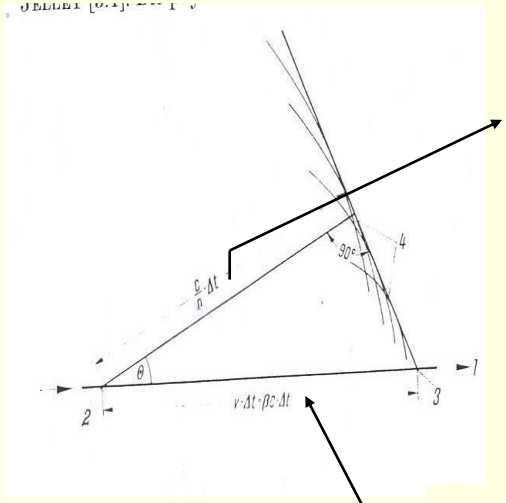
generates EM radiation with continuous spectrum. The radiation has angle (in respect to particle trajectory)

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

FAST PARTICLE



Fast particle :
dipole in particle direction



Construction of wave front (Hygen)
Created by a particle moving with a
Velocity v > c/n

$$\cos\theta = \frac{\frac{c}{n}\Delta t}{\beta c \Delta t} = \frac{1}{\beta n}$$

The Cerenkov light is 100 % linear polarized.

The polarization vector is perpendicular to the Cherenkov cone, pointing away form the particle path.

Transmission of C- light through optical components require the use of Fresnel formulas :

For PID the number of C photons arriving in the photon detector is essential

For a medium of given refractive index n , There is threshold velocity β_{min} ,below which no radiation takes place

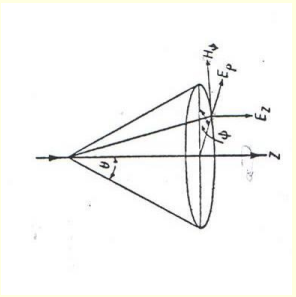
Cerenkov radiation number of photons

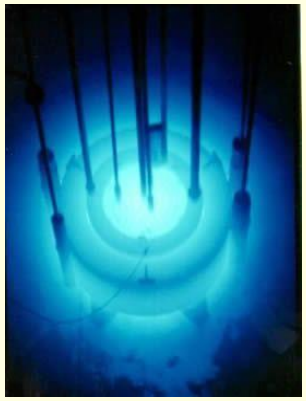
$\cos(\Theta) = 1/\beta n$

Radiated energy

$$W = 4\pi^2 \frac{e^2}{c^2} l \int_{\beta n>1} \left(1 - \frac{1}{\beta^2 n^2}\right) \nu \, d\nu =$$

$$= 4\pi^2 e^2 l \int_{\beta n>1} \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^3} .$$





Nuclear installation

Number of photons :

$$N(\lambda_1, \lambda_2) = 4\pi^2 \frac{e^2}{h c} l \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^2} .$$

$$N(\lambda_1, \lambda_2, n = const.) \approx \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) * \sin^2\theta$$

supersonic aircraft v>speed of sound (mechanic)

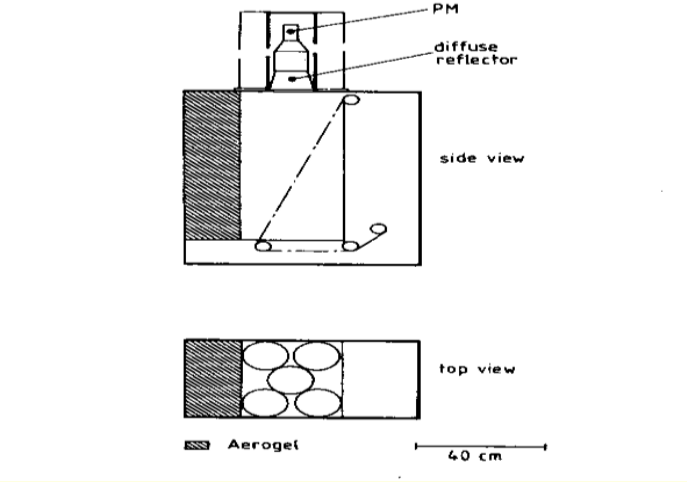
Threshold Cerenkov counter

separate two particle with

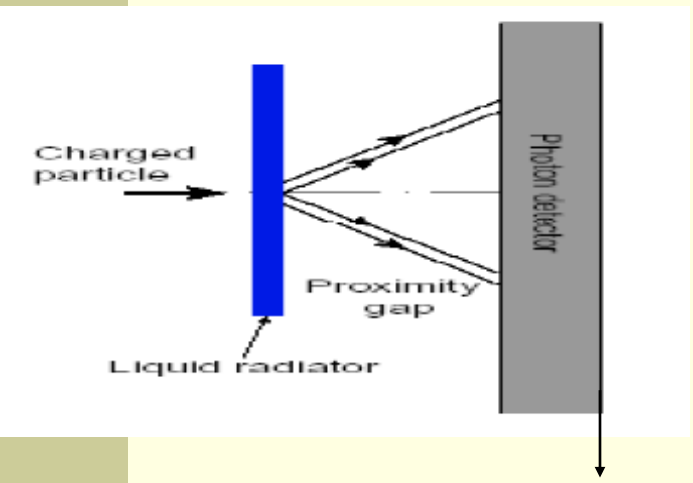
mass m_1 and m_2 , $m_2 > m_1$

for m_2 just below threshold $\beta_2^2 \approx \frac{1}{n^2}$

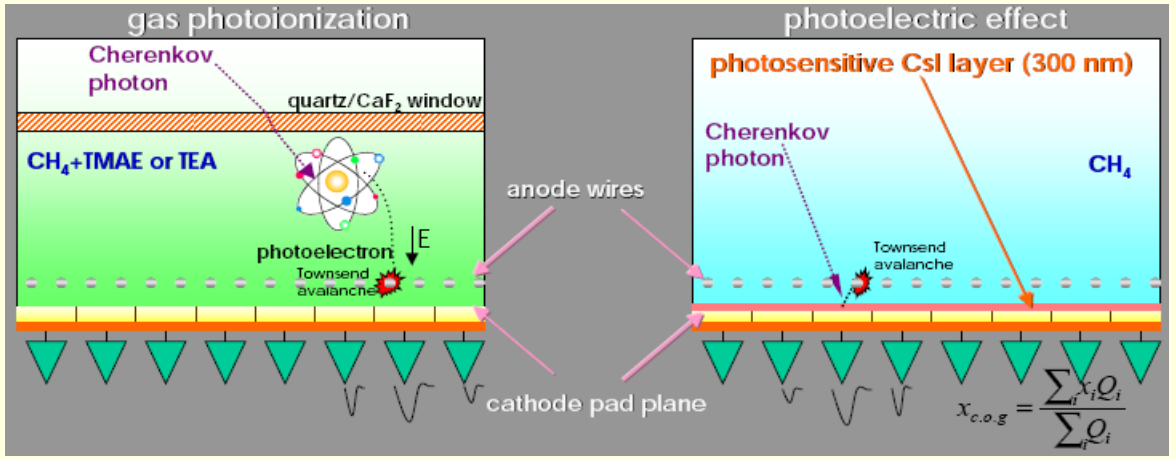
N_{phot} for m_1: $\sim \sin^2 \theta_c$



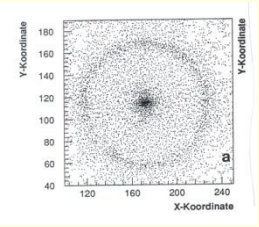
Ring Imaging Cerenkov Counter (RICH)



Conversion of Cerenkov photons with detector



Optical readout with CCD camera is as well possible – MWPC is than replaced with optical transparent window



Cerenkov photons registered with CCD camera
(overlay of ~ 2000 events)
NA35/CERN

dispersion $\Delta\theta = \frac{\Delta n}{\beta \mathrm{tg}\,\theta}$

Modern photo detector for ALICE HMPID

NIM A 433 (1999) 190-200

RADIATOR

15 mm liquid C_6F_{14},
n ~ 1.2989 @ 175nm

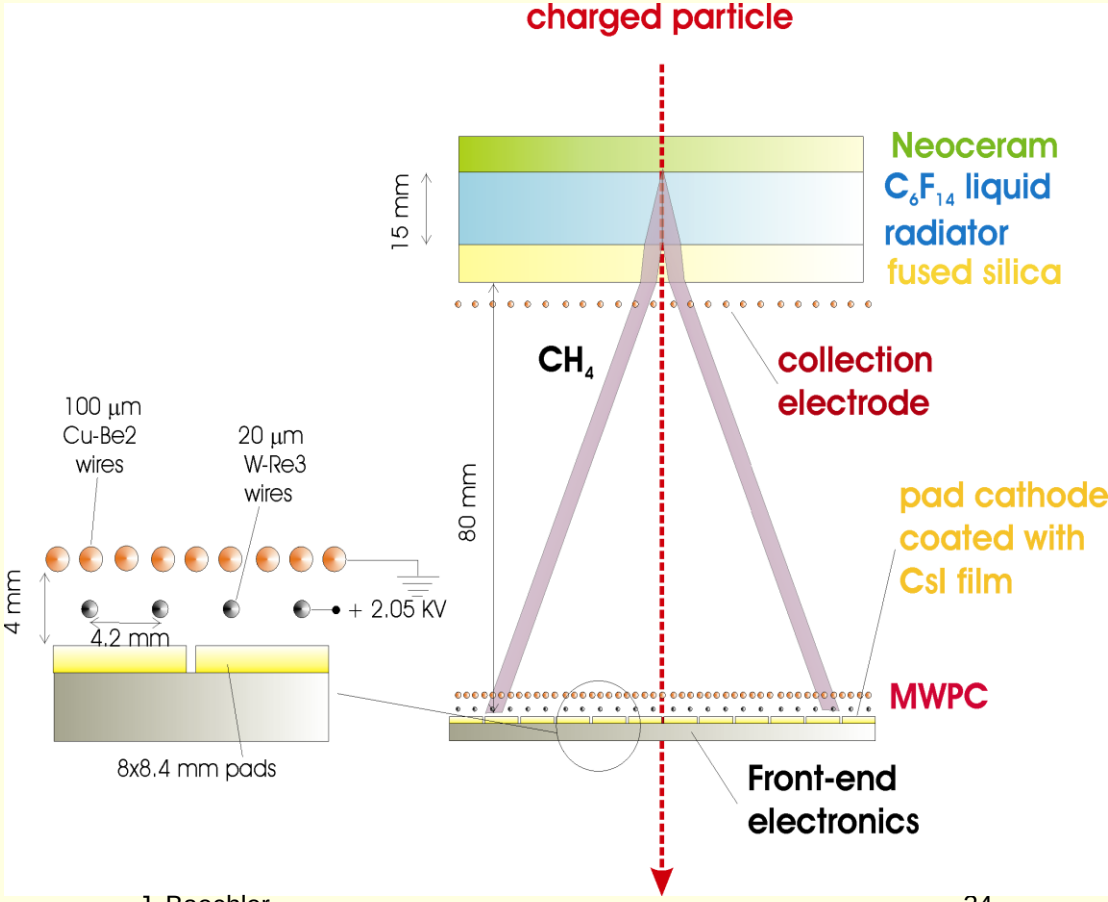
PHOTON CONVERTER

Reflective layer of CsI
QE ~ 25% @ 175 nm.

PHOTOELECTRON DETECTOR

- MWPC with CH_4 at atmospheric pressure (4 mm gap) HV = 2050 V.

- Analogue pad readout



Particle Identification

C-counter - RICH

Particle identification. particle mass m: $m = p\sqrt{n^2 \cos^2\theta - 1}$

Cerenkov angle resolution

photon ring

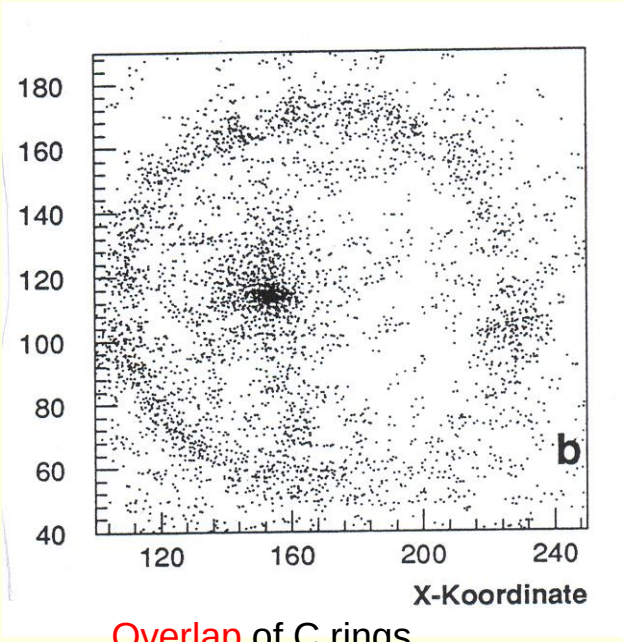
$$\sigma_\theta^2 = \sum_i \Delta\theta_i^2 \Rightarrow \sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N_{ph}}}$$

i=Δn,dl,..

minimize maximize

β resolution

$$\frac{\sigma_\beta}{\beta} = \tan\theta_c \sigma_{\theta_c}$$

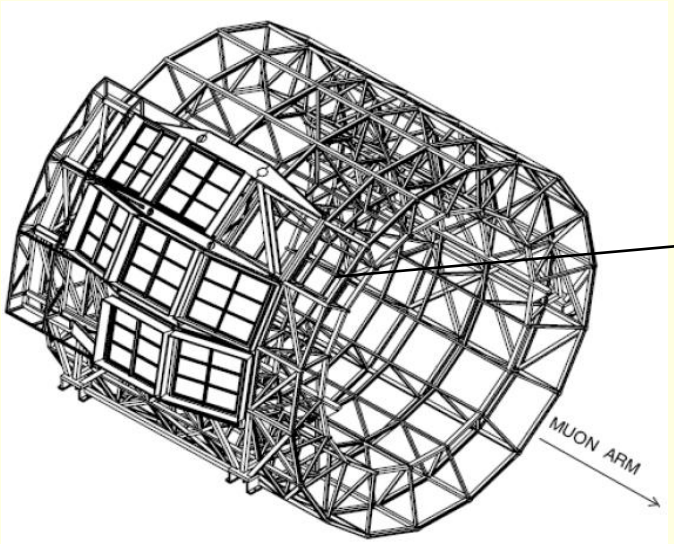


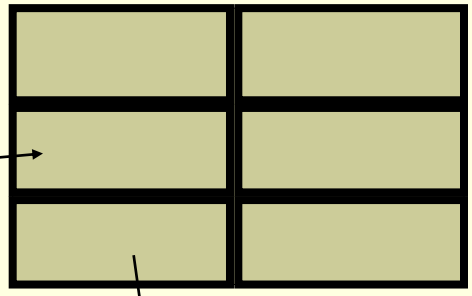
Overlap of C rings
60 GeV/c pions (SPS)
Inclination of detector : 5^0

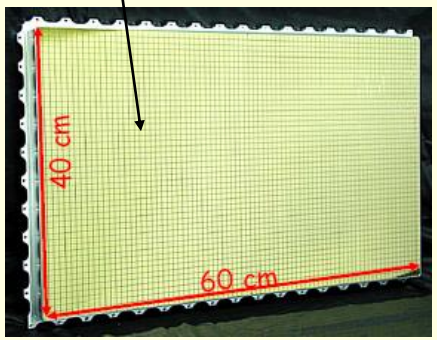
RICH with optical readout
NA35/CERN

Large scale RICH

(HMPID ALICE)



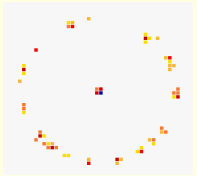




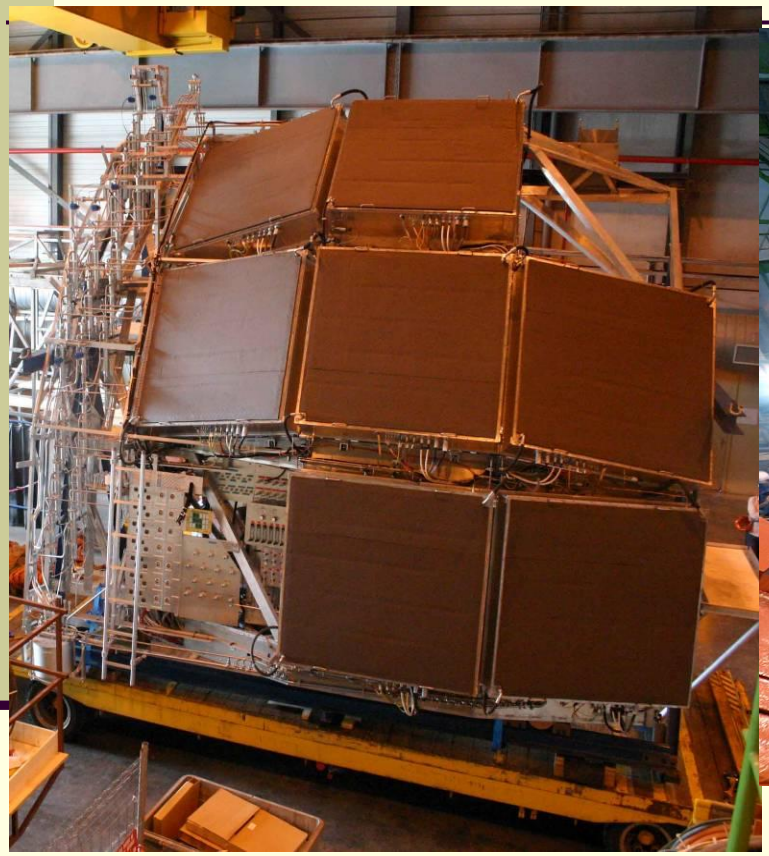
CsI photo-cathode is segmented in 0.8x0.84 cm pads

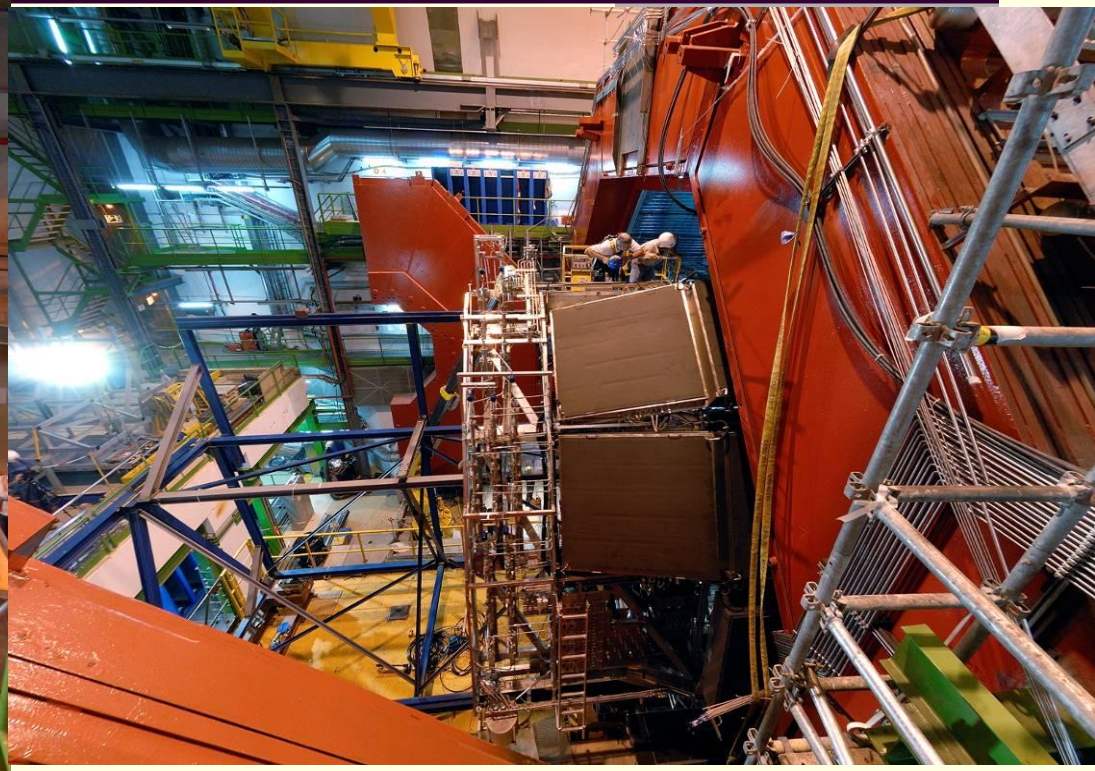
Total number of pads per chamber = 161280

High number of photons in C ring



ALICE HMPID – RICH





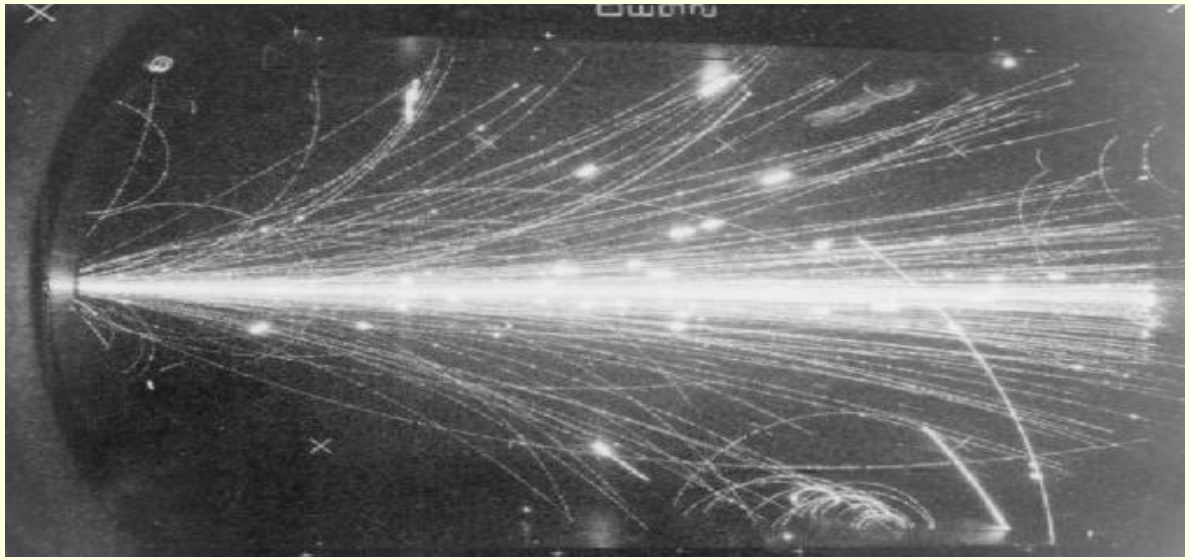
- **7 modules, each ~1.5x1.5 m2**
- **3 radiator trays, 6 photo-cathodes, 23’040 pads**
- **Total CsI area ~ 11 m2**

Example of PID with RICH in NA35 Experiment

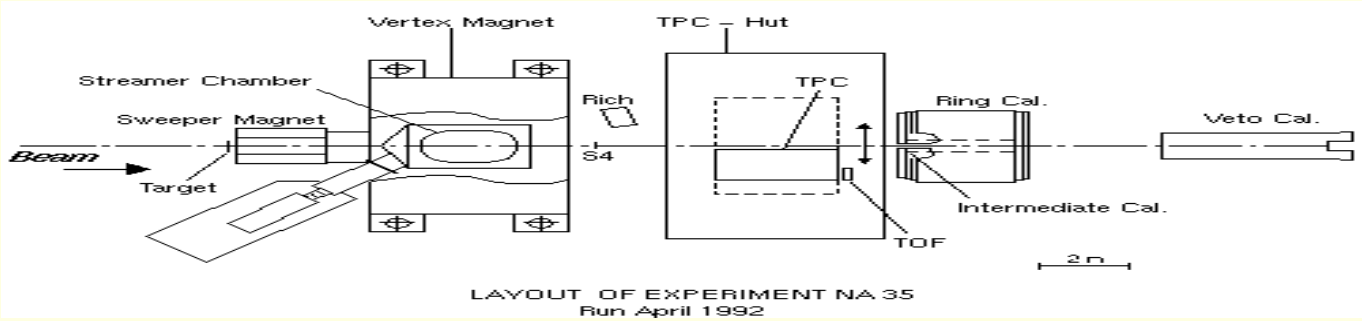
Streamer chamber (tracker) and RICH (particle identification)

Streamer chamber

NIM A 343 (1994) 213-217



RICH

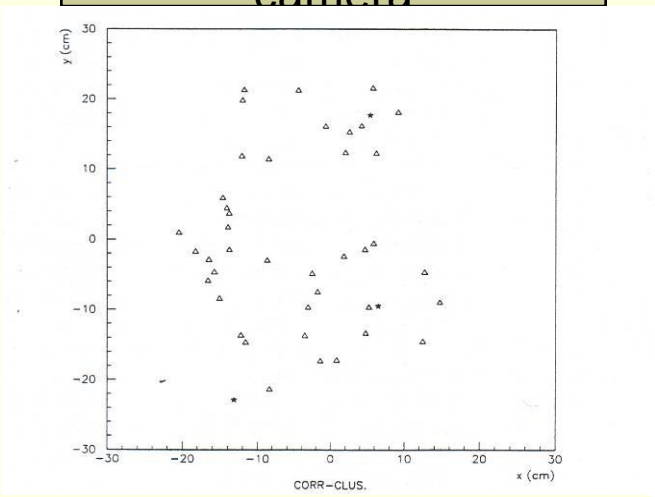


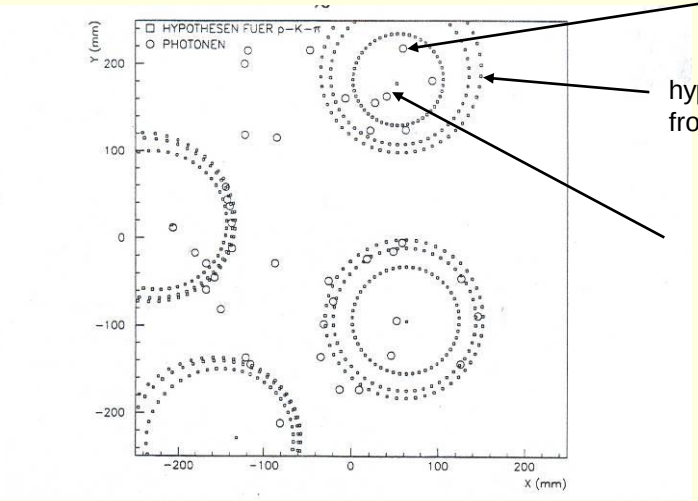
LAYOUT OF EXPERIMENT NA 35
Run April 1992

Cerenkov ring detection
proximity RICH detector (50*50 cm^2) with optical readout

C-photons (COG) recorded with CCD camera

C-photons + hypothesis p,K,pi





COG of recorded C-photon

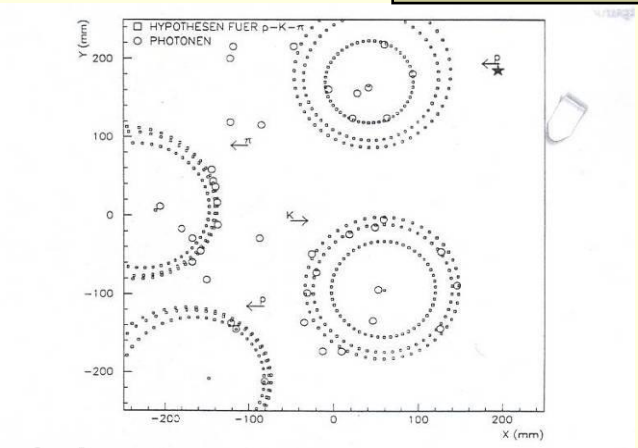
hypothesis from tracker

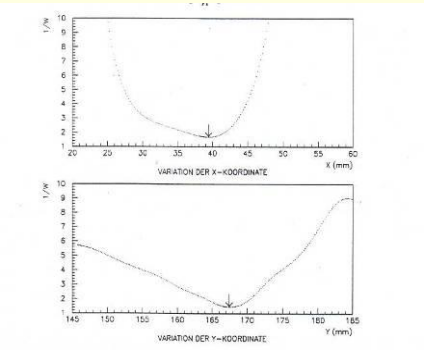
multiple scattering

Imprecise particle hitpoint predicted by tracker

Example of identified Proton and Kaon (NA35 S+Au)

Moving of hypothesis searching for max probability





Side minima can lead to wrong identity of particle

Information from RICH

$$W^{Proton} = \sum_{Photon} \frac{1}{\sigma_{Prot}\sqrt{2\pi}} \exp -\left(\frac{A_{Photon} - A^{Proton}_{Mean}}{\sqrt{2}\,\sigma_{Proton}}\right)^2$$

$$W^{Kaon} = \sum_{Photon} \frac{1}{\sigma_{Kaon}\sqrt{2\pi}} \exp -\left(\frac{A_{Photon} - A^{Kaon}_{Mean}}{\sqrt{2}\,\sigma_{Kaon}}\right)^2$$

$$W^{Pion} = \sum_{Photon} \frac{1}{\sigma_{Pion}\sqrt{2\pi}} \exp -\left(\frac{A_{Photon} - A^{Pion}_{Mean}}{\sqrt{2}\,\sigma_{Pion}}\right)^2$$

$$PID = Max\,(W^{Pion}, W^{Kaon}, W^{Proton})$$

Computed for given particle momentum

Probability that photons belong to a hypothesis →

NIM A 343 (1994)273-275

Analysis of data requires the detailed detector simulation

J. Baechler

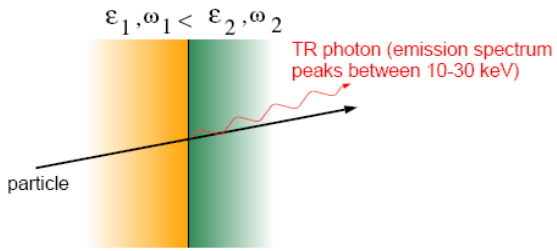
Summary of the different steps
(example of particle identification with a RICH - Cerenkov counter in NA35)

- trigger on an event of interest
- record with tracking detector and the RICH detector synchronously the event
- follow particle tracks from tracker detector through magnetic field to the RICH
- determine momentum (p_x,p_y,p_z) and hit point coordinates of particles in the RICH
- simulate the photon distribution in the RICH detector for each particle recorded
  → Hypothesis p – K - pi
- compare the recorded Cerenkov photons with the hypothesis

=> **PID**

Transition radiation

Transition radiation is produced when a relativistic particle traverses an inhomogeneous medium, in particular the boundary between materials of different electrical properties.



intensity: $I \propto m\gamma = m/\sqrt{(1-\beta^2)}$ ⇒ **particle identification**

1919 J. E. Lilienfeld discovers, that metal surfaces emit light when hit by electrons (Lilienfeld–Strahlung):

"...es ist Dunkeladaption des Auges notwendig, um um einen Leuchtfleck, erzeugt von einem Elektronenstrahl mit 5 keV Energie und 20 μA Strahlstrom, wahrzunehmen." (Physikalische Zeitschrift 1919 **20**, 280)

1946 W. Ginzburg and G. Frank publish their theory of Transition Radiation.

>1960 experiments prove, that "Lilienfeld–Strahlung" is Transition Radiation

>1970 the phenomenon of Transition Radiation is used for particle identification at HEP experiments (e.g. R 806 at CERN)

- TR angular distribution for relativistic particle:

  sharp maximum at $\theta = 1/\gamma$

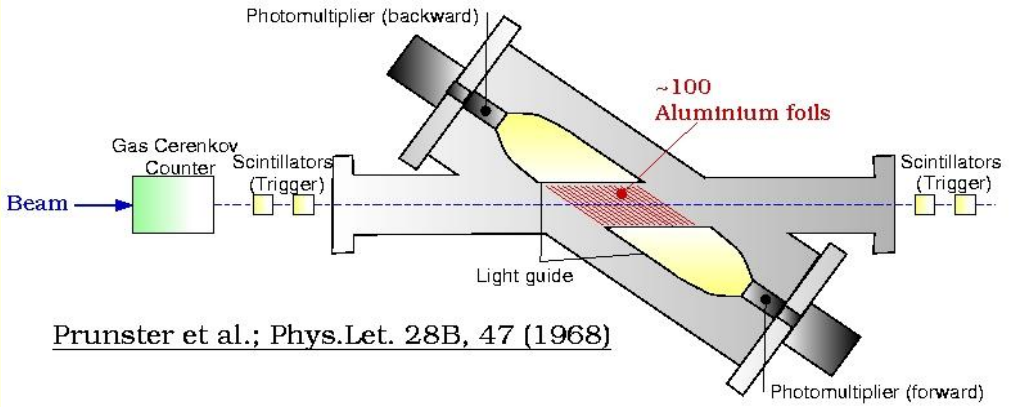
  ⟹ *detector has to be sensitive to photons (10-30 keV) along a particle track.*

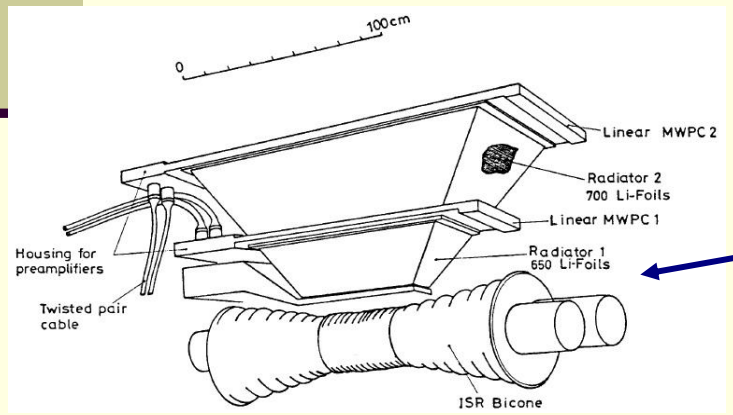
- total energy radiated at single boundary:

  $E \propto (1/3)\,\alpha\,\gamma\,\hbar\,\omega_{plasma} \qquad (\omega_{plasma} = \frac{(\omega_2-\omega_1)^2}{(\omega_2+\omega_1)})$

  ⟹ *choice of materials, $\omega_i \gg \omega_j$, but materials should not absorb TR photons!*

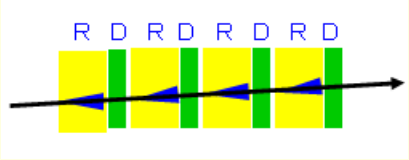
Some History of transition radiation



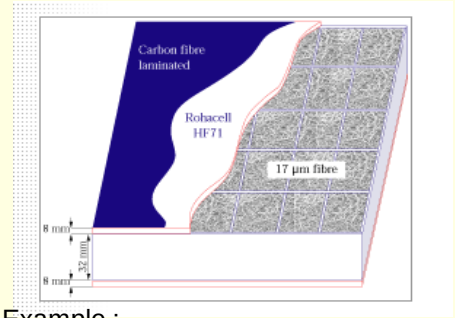


- 1975: First TRD for electron ID in balloon flight
- 1976: First TRD in HEP experiment for electron ID R806 @ ISR (CERN)

Principle of TRD detector



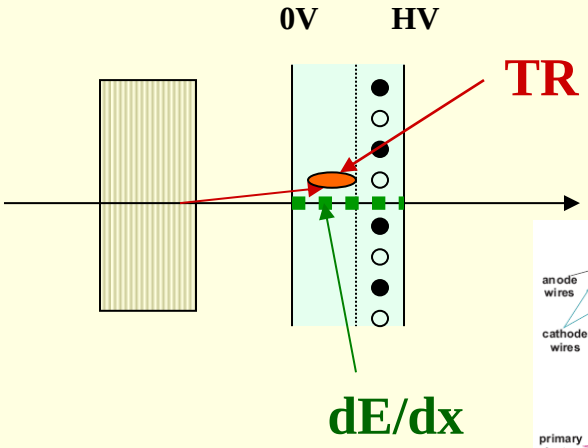
Stack of radiator – detector

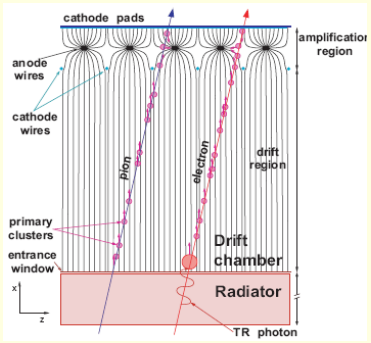


Example :
ALICE TRD radiator :

Polypropylene fibre mats

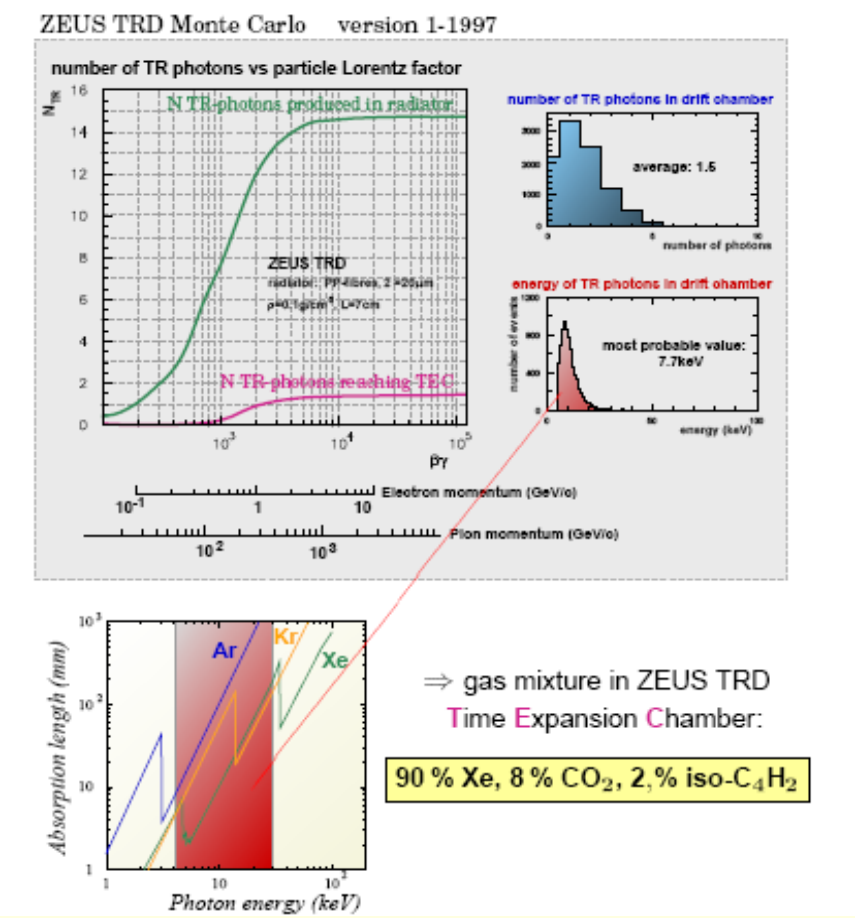
of 3.2 cm thickness between two Rohacell foam sheets of 0.8 cm thickness each



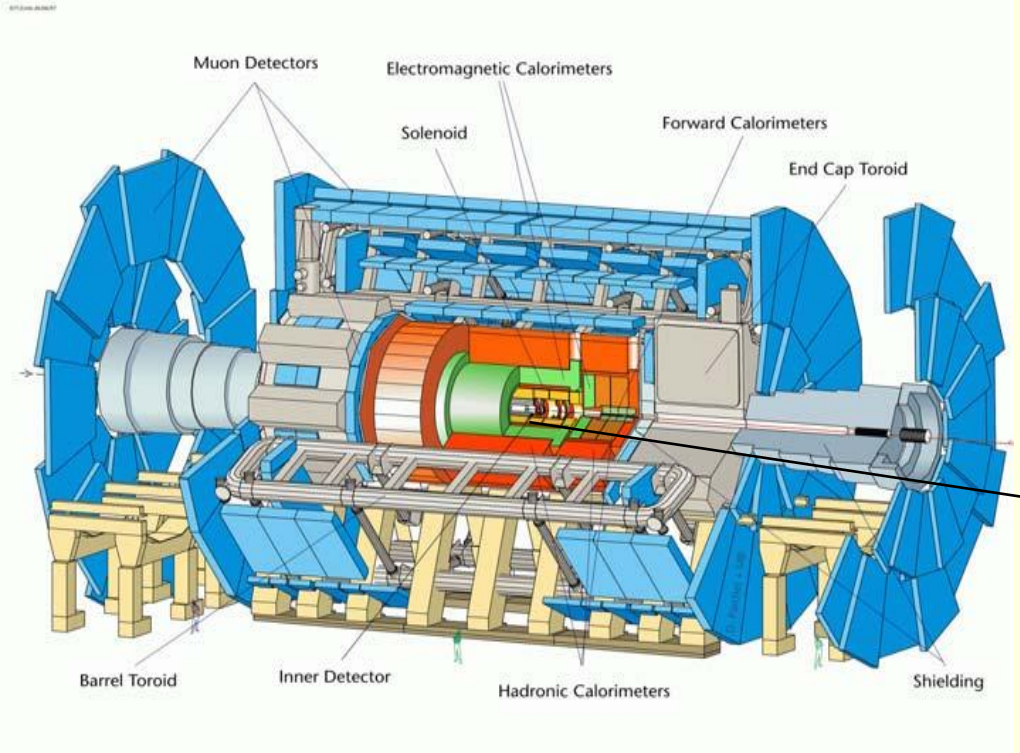


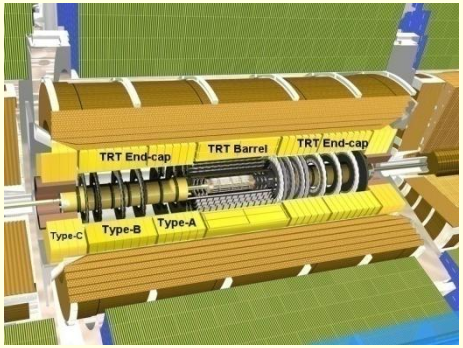
Xe gas mixture for detector

(ZEUS TRD)



ATLAS TRD

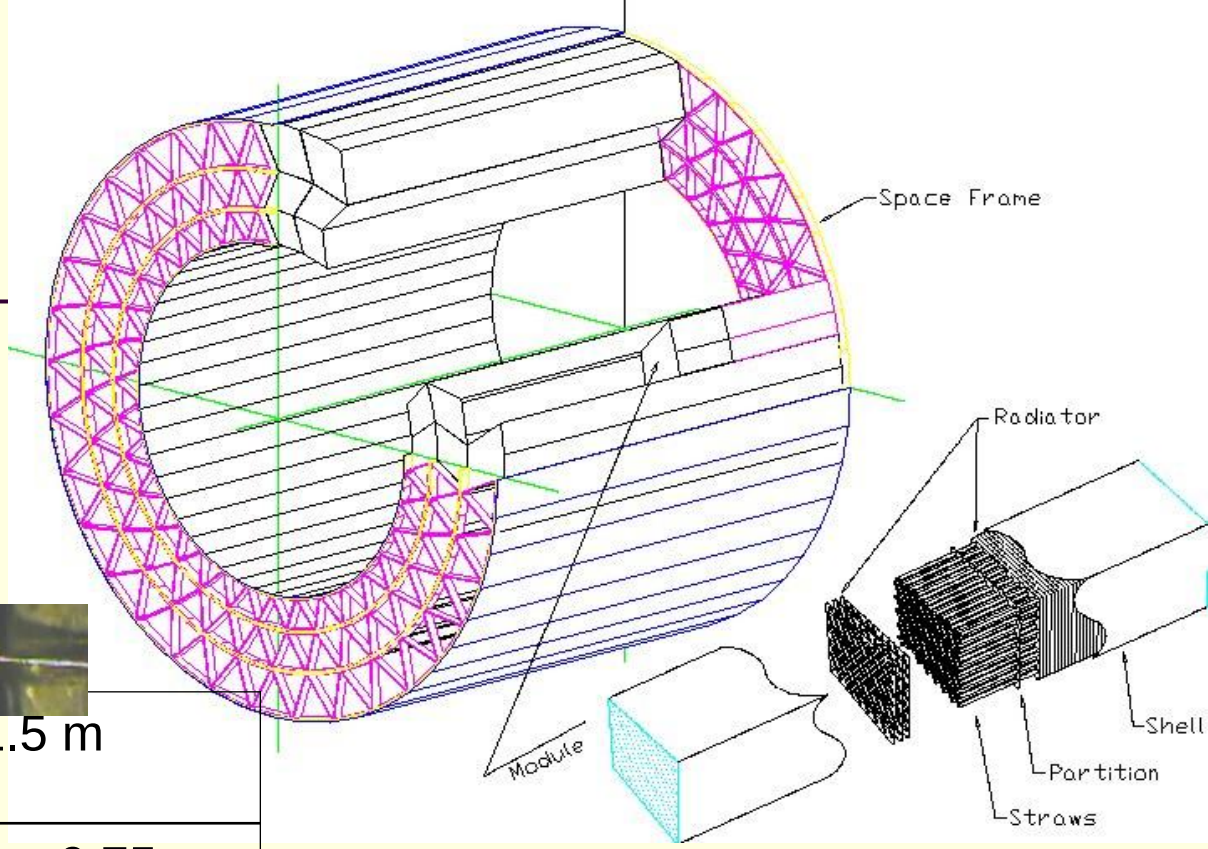

Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


TRT End-cap
TRT Barrel
TRT End-cap
Type-C
Type-B
Type-A

TRT Barrel

- 3 module types, forming 3 rings of 32 identical modules
- 52544 straws total
- glass wire-joint provides independent

Module Length	1.5 m
Sense Wire Length	2 x 0.75 m
Straw Diameter	4 mm
Wire Diameter	30 μm
Distance between straws	6.8 mm
High Voltage Grouping	8 straws



Basic Module Design

Straws are embedded in foam radiators and supported by dividers and endplates, which are connected along the module by a carbon-fiber shell