Detectors in Nuclear and Particle Physics

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Particle identification - parameters

in general, momentum of a particle measured in a spectrometer and another observable are used to identify the species

- velocity
  - time-of-flight $\tau \sim 1/\beta$
  - Cherenkov threshold $\beta > 1/n$
  - transition radiation $\gamma \gtrsim 1000$
  - e/π
- energy loss
  - $-\frac{dE}{dx} \sim \frac{z^2}{\beta^2} \ln a\beta\gamma$
- energy measurement
  - calorimeter (chap. 8)

$$
\begin{aligned}
E &= \gamma m_0 c^2 \\
T &= (\gamma - 1) m_0 c^2 \quad (\text{for } p, n, nuclei) \\
E_{dep} &= \gamma m_0 c^2 + m_0 c^2 \quad (\text{for } \bar{\mathrm{p}}, \bar{\mathrm{n}}, \ldots)
\end{aligned}
$$

Special signatures

photon

- total energy in crystal or electromagnetic sampling calorimeter
  + information on neutrality

neutron

- energy in calorimeter or scintillator with Li, B, or ^{3}He
  + information on neutrality

muon

- only $\mathrm{d}E/\mathrm{d}x$ in thick calorimeter, penetrates thick absorber

K^0, Λ, Ξ, Ω, ...

- reconstruction of m_{inv} of weak decay products

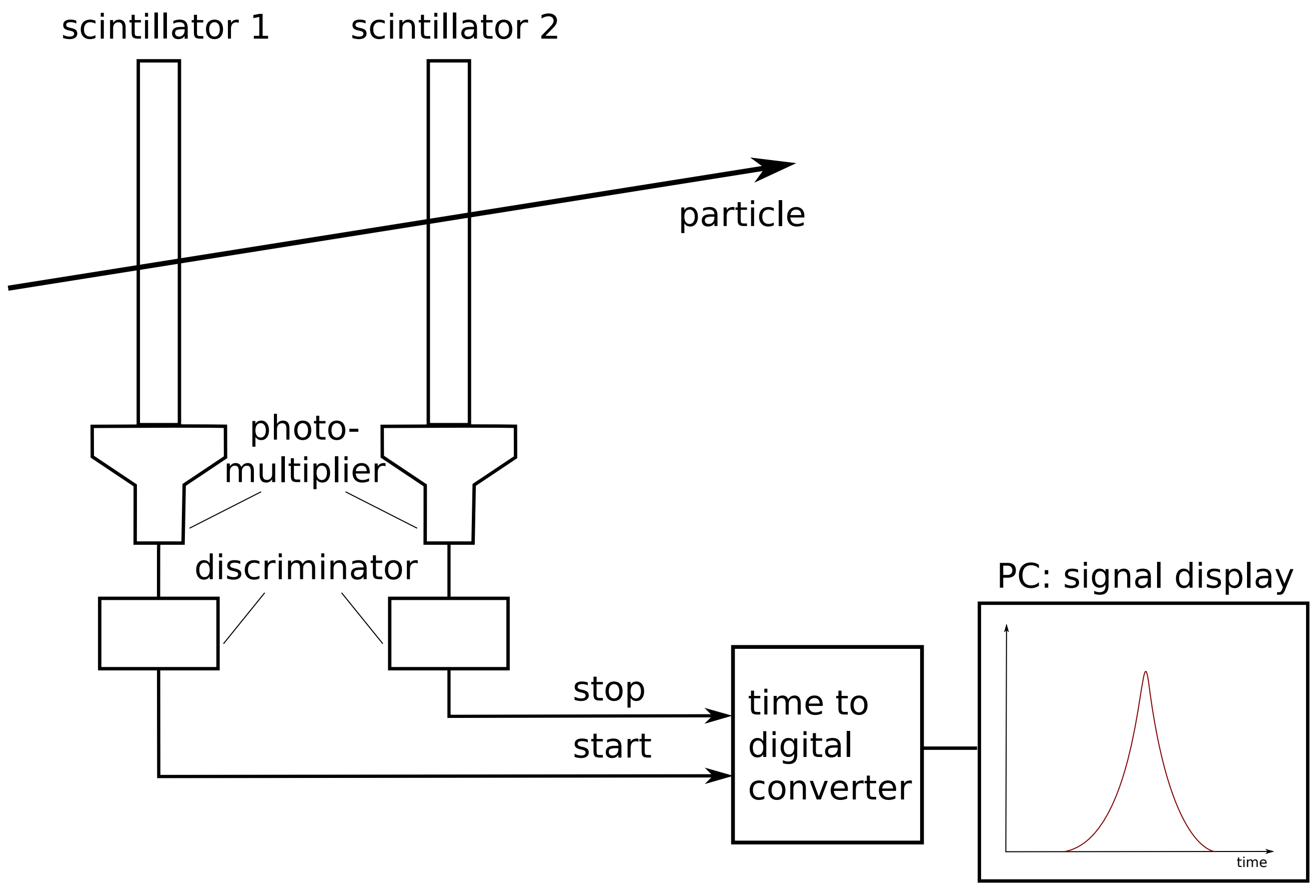
neutrino

- only weak interaction with detector material,
  either as charged or neutral current

7.1 Time of flight τ

time difference between two detectors with good time resolution: ‘start’ and ‘stop’-counter

- typically scintillator or resistive plate chamber, also calorimeter (neutrons)
- coincidence set-up or put all stop-signals into TDC (time-to-digital converter) with common start or stop from ‘beam’ or ‘interaction’



for known distance L between start and stop counter, time-of-flight difference of two particles with masses $m_{1,2}$ and energies and $E_{1,2}$:

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

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

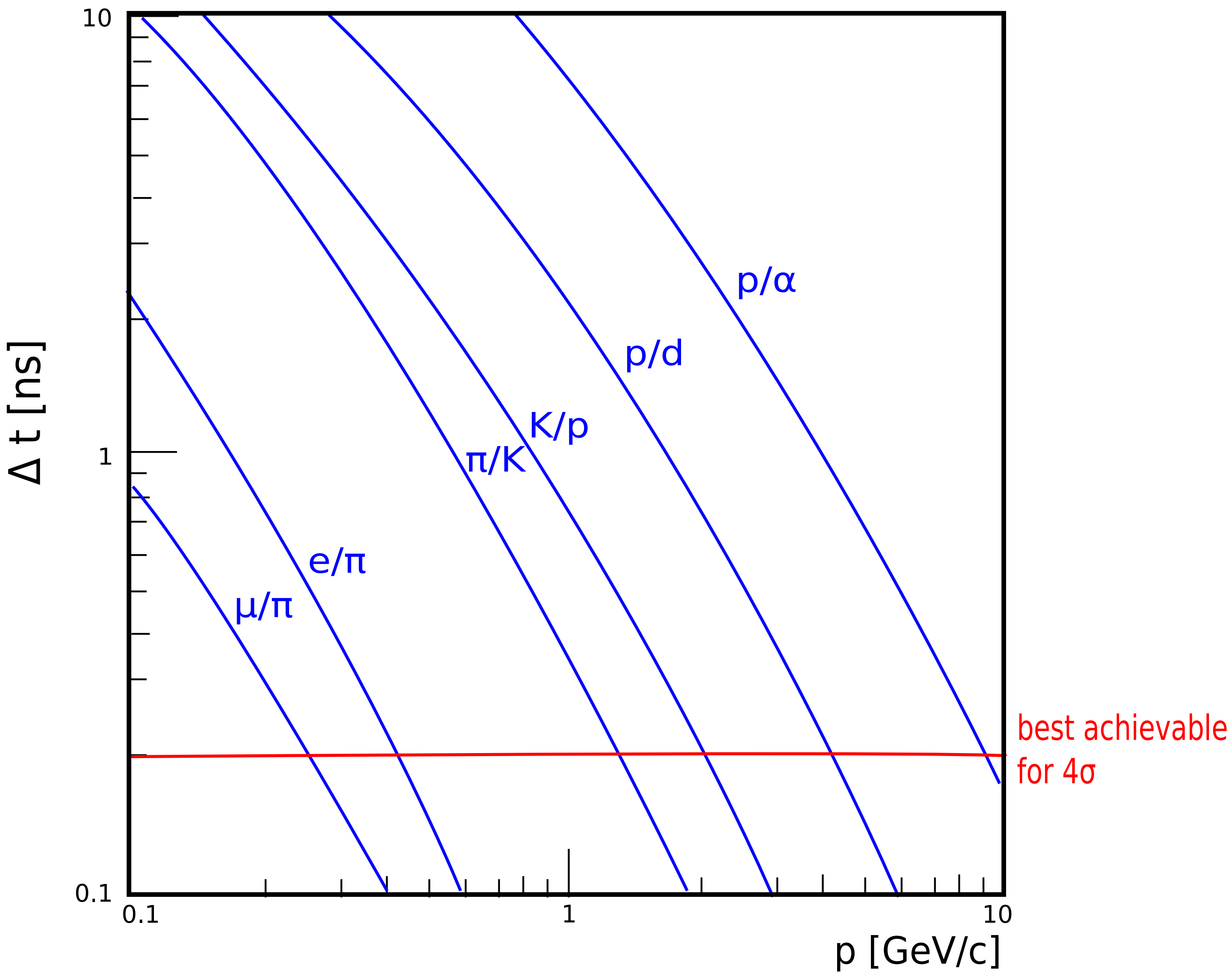
limiting case $\quad E \simeq pc \gg m_0c^2$ $\qquad$ $\boxed{\Delta t = \frac{Lc}{2p^2}(m_1^2 - m_2^2)}$

require e.g. $\Delta t \geq 4\sigma_t$

$\Rightarrow$ separation K/π at $L = 3$ m for $\sigma_t = 300$ ps up to $p = 1$ GeV/c

Cherenkov counter or RPC's $\quad \sigma_t \simeq 40$ ps
scintillator + PM $\quad \sigma_t \simeq 80$ ps

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



but of course distance L can be larger $$ detector area for a given acceptance

particle identification (PID) via time-of-flight at moderate momenta
$\rightarrow$ mass resolution:

$p = \beta\gamma m$ with rest mass m, $\beta = L/\tau$ (here exceptionally $c = 1$ for short notation)

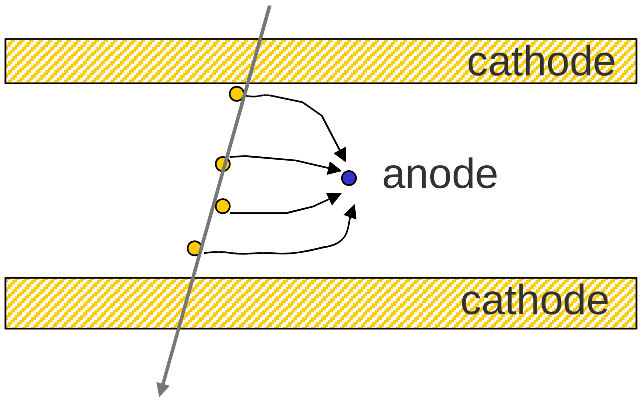
$$
\begin{aligned}
\Rightarrow \quad m^2 &= p^2\left(\frac{\tau^2}{L^2} - 1\right) \\
\delta(m^2) &= 2p\delta p \underbrace{\left(\frac{\tau^2}{L^2} - 1\right)}_{m^2/p^2} + \underbrace{2\tau\delta\tau\frac{p^2}{L^2} - 2\frac{\delta L}{L^3}p^2\tau^2}_{\text{use } \frac{p^2\tau^2}{L^2} = m^2 + p^2 = E^2} \\
&= 2m^2\frac{\delta p}{p} + 2E^2\frac{\delta\tau}{\tau} - 2E^2\frac{\delta L}{L} \\
\sigma(m^2) &= 2\left(m^4\left(\frac{\sigma_p}{p}\right)^2 + E^4\left(\frac{\sigma_\tau}{\tau}\right)^2 + E^4\left(\frac{\sigma_L}{L}\right)^2\right)^{\frac{1}{2}}
\end{aligned}
$$

usually $\dfrac{\sigma_L}{L} \ll \dfrac{\sigma_p}{p} \ll \dfrac{\sigma_\tau}{\tau}$

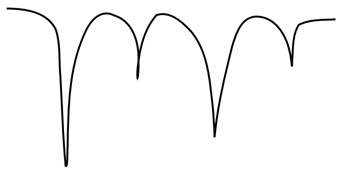
$\Rightarrow$ $\boxed{\sigma(m^2) \simeq 2E^2\frac{\sigma_\tau}{\tau}}$ error in time measurement dominates

7.1.1 Resistive plate chambers: gas detector for precise timing measurement
(material taken from talk by C. Williams on ALICE TOF)

how to get a good timing signal from a gas detector?
where is the problem?

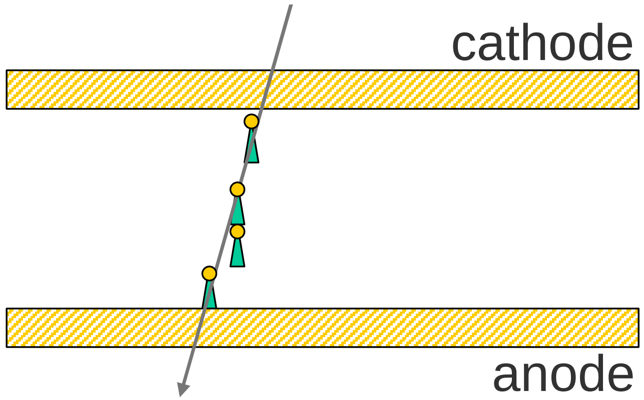


normally signal generated in vicinity of anode wire, timing determined by drift of primary ionization clusters to this wire, signal consists of a series of avalanches
spread over interval of order of 1 μs

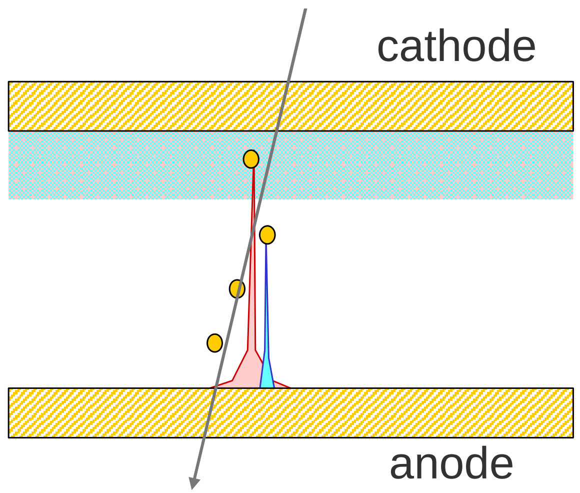


no way to get precision (sub-nanosecond) timing

idea: go to parallel plate chamber
(high electric field everywhere in detector)
clusters start to avalanche immediately
induced signal sum of all simultaneous avalanches



but in practice this is not so . . .



electron avalanche according to Townsend

$$N = N_0 e^{\alpha x}$$

only avalanches that traverse full gas gap will produce detectable signals $\Rightarrow$ only clusters of ionization produced close to cathode important for signal generation.
avalanche only grows large enough close to anode to produce detectable signal on pickup electrodes.

if minimum gas gain at 10^6 (10 fC signal)
and maximum gain at 10^8 (streamers/sparks produced above this limit), then sensitive region first 25% of gap

time jitter $\approx$ time to cross gap $\approx$ gap size/drift velocity

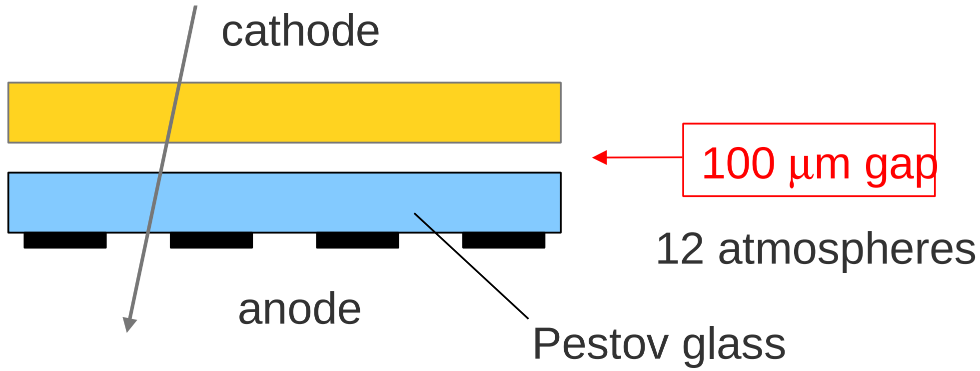
so

a) only a few ionization clusters take part in signal production
b) gap size matters (small is better)

first example: Pestov chamber (about 1970)

40 years ago Y. Pestov realized importance of size
Pestov chambers – gas gap of 100 μm gives time resolution $\approx$ 50 ps, first example of resistive plate chamber

glass electrode and metal electrode

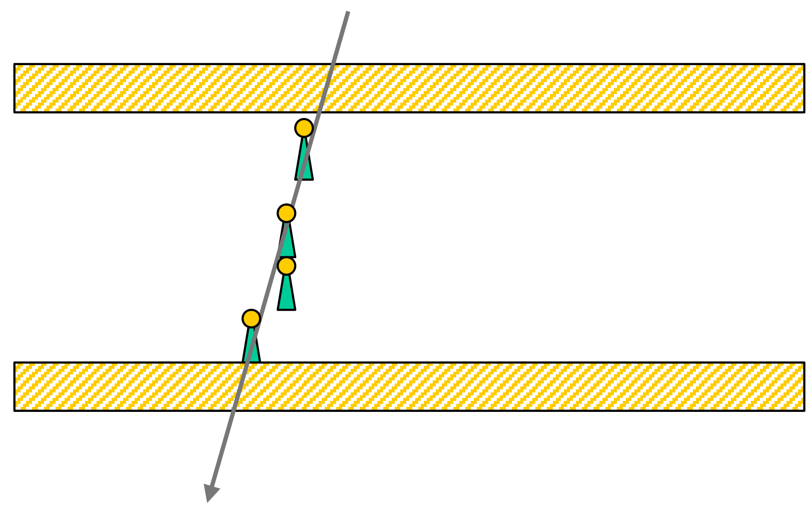


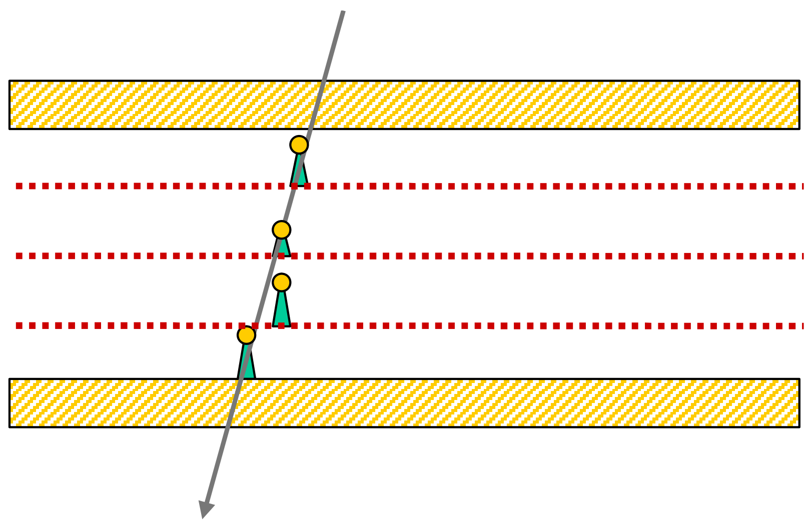
generally, excellent time resolution $\sim$ 50 ps or better!
but long tail of late events
mechanical constraints (due to high pressure)
non-commercial glass
$\rightarrow$ no large-scale detector ever built

how to make real life detector?

a) need very high gas gain (immediate production of signal)

b) need way of stopping growth of avalanches (otherwise streamers/sparks will occur)

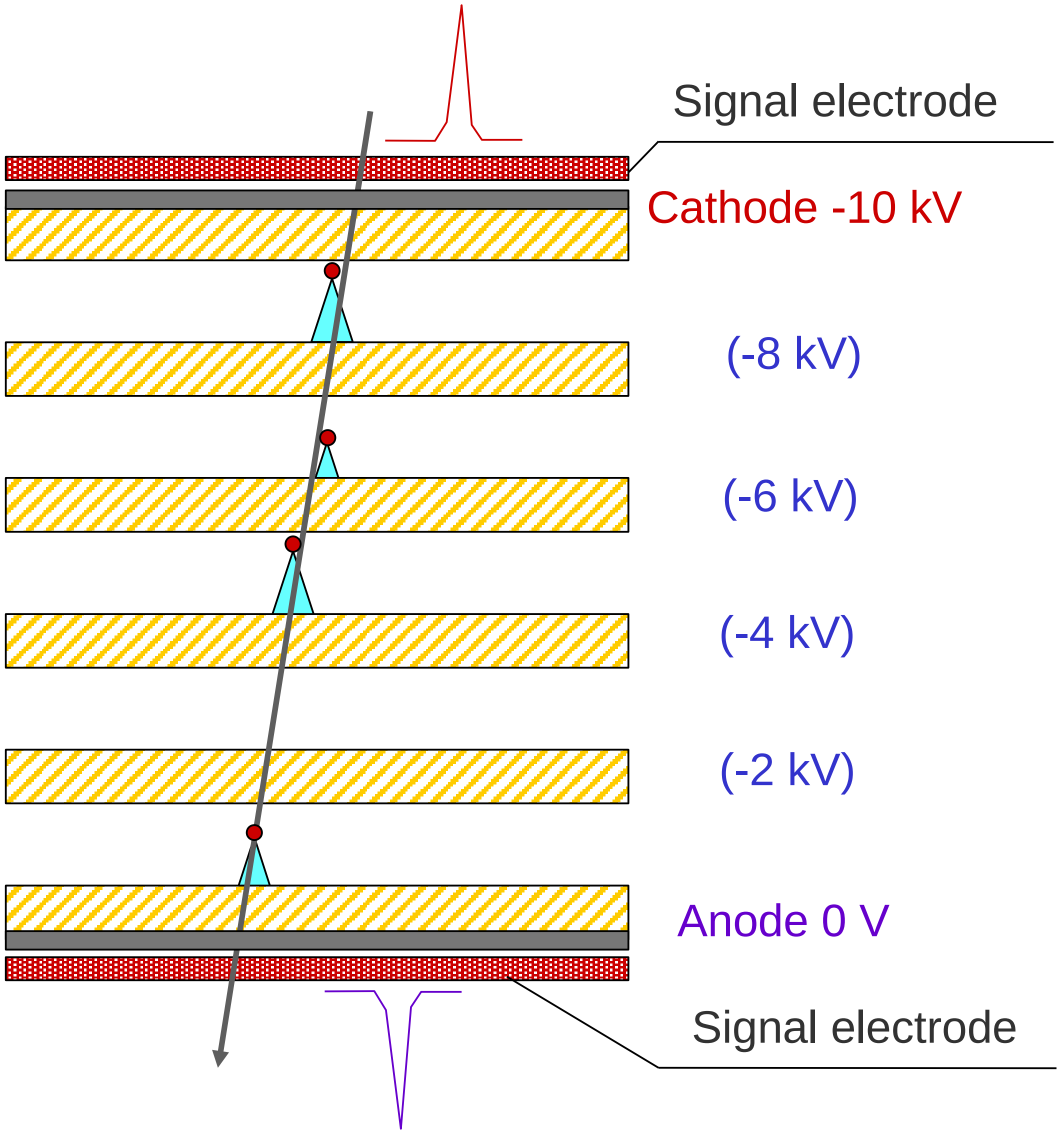




answer: add boundaries that stop avalanche development. These boundaries must be invisible to the fast induced signal - external pickup electrodes sensitive to any of the avalanches

from this idea the Multi-gap Resistive Plate Chamber was born

Multi-gap Resistive-Plate Chamber

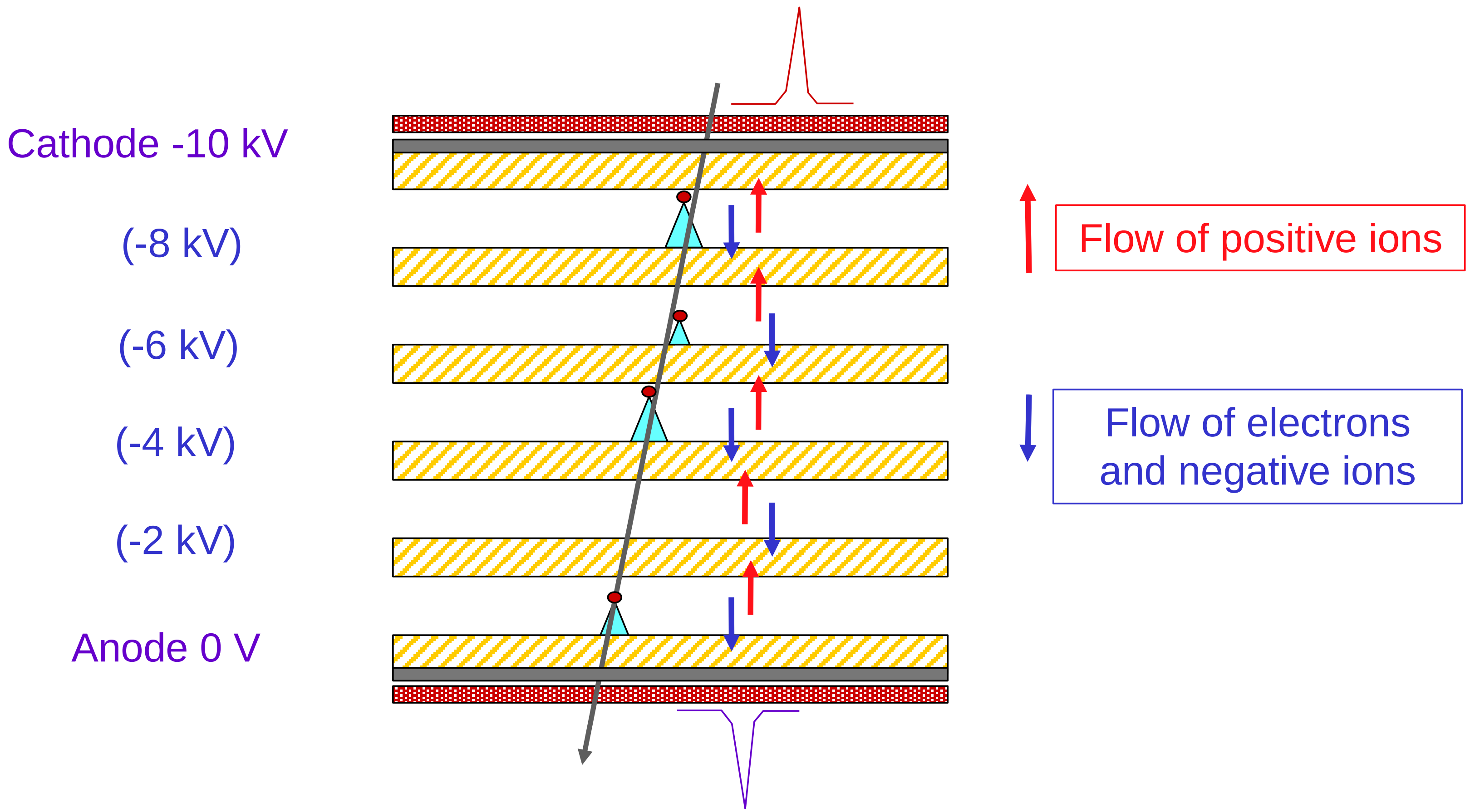


stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

pickup electrodes on external surfaces (resistive plates transparent to fast signal)

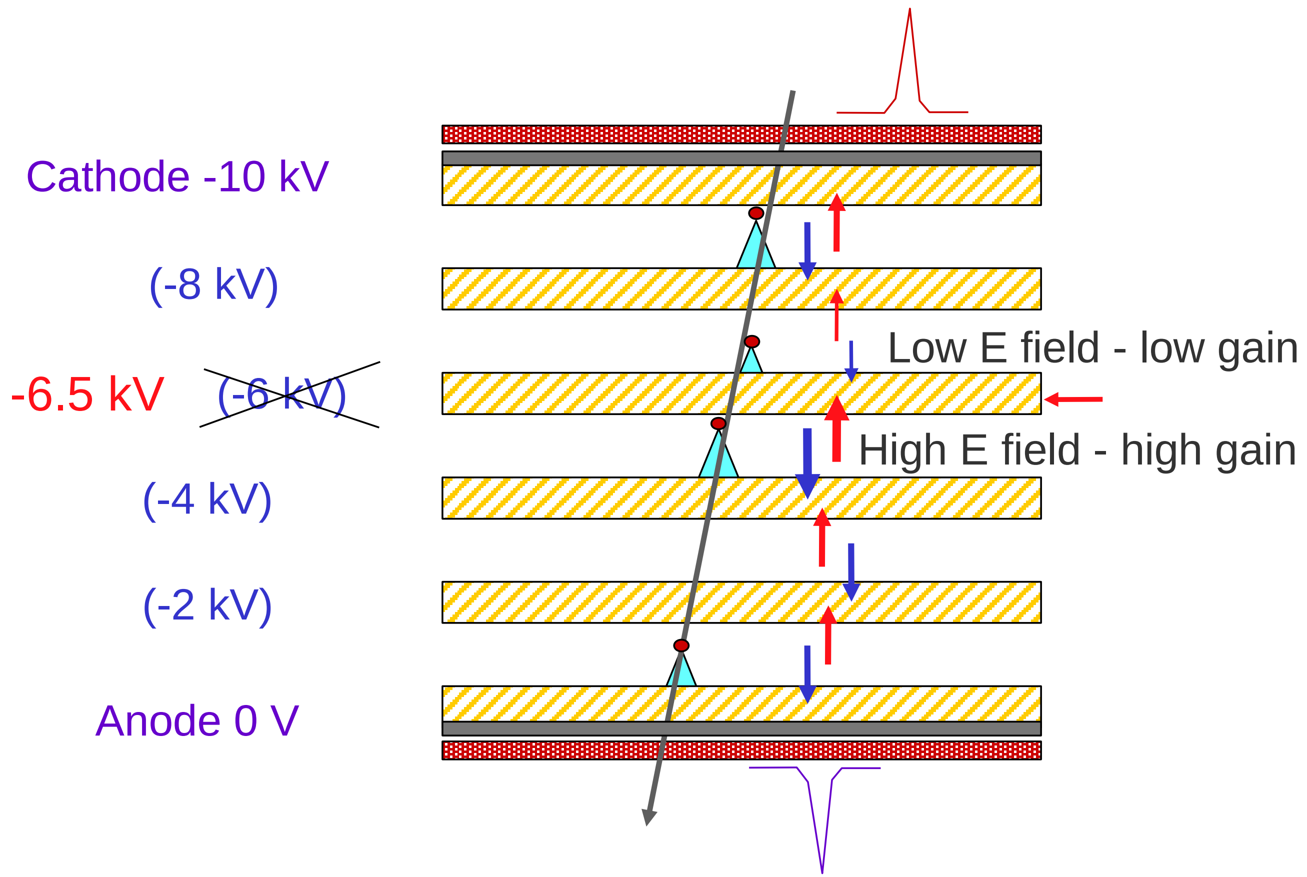
internal plates take correct potential – initially due to electrostatics but kept at correct potential by flow of electrons and positive ions - feedback principle that ensures equal gain in all gas gaps

Internal plates electrically floating!



in this example: 2 kV across each gap (same E field in each gap)
since the gaps are the same size - on average - each plate has same flow of positive ions and electrons (from opposite sides of plate)
thus zero net charge flow into plate. STABLE STATE

What happens if a plate is at a wrong voltage for some reason?

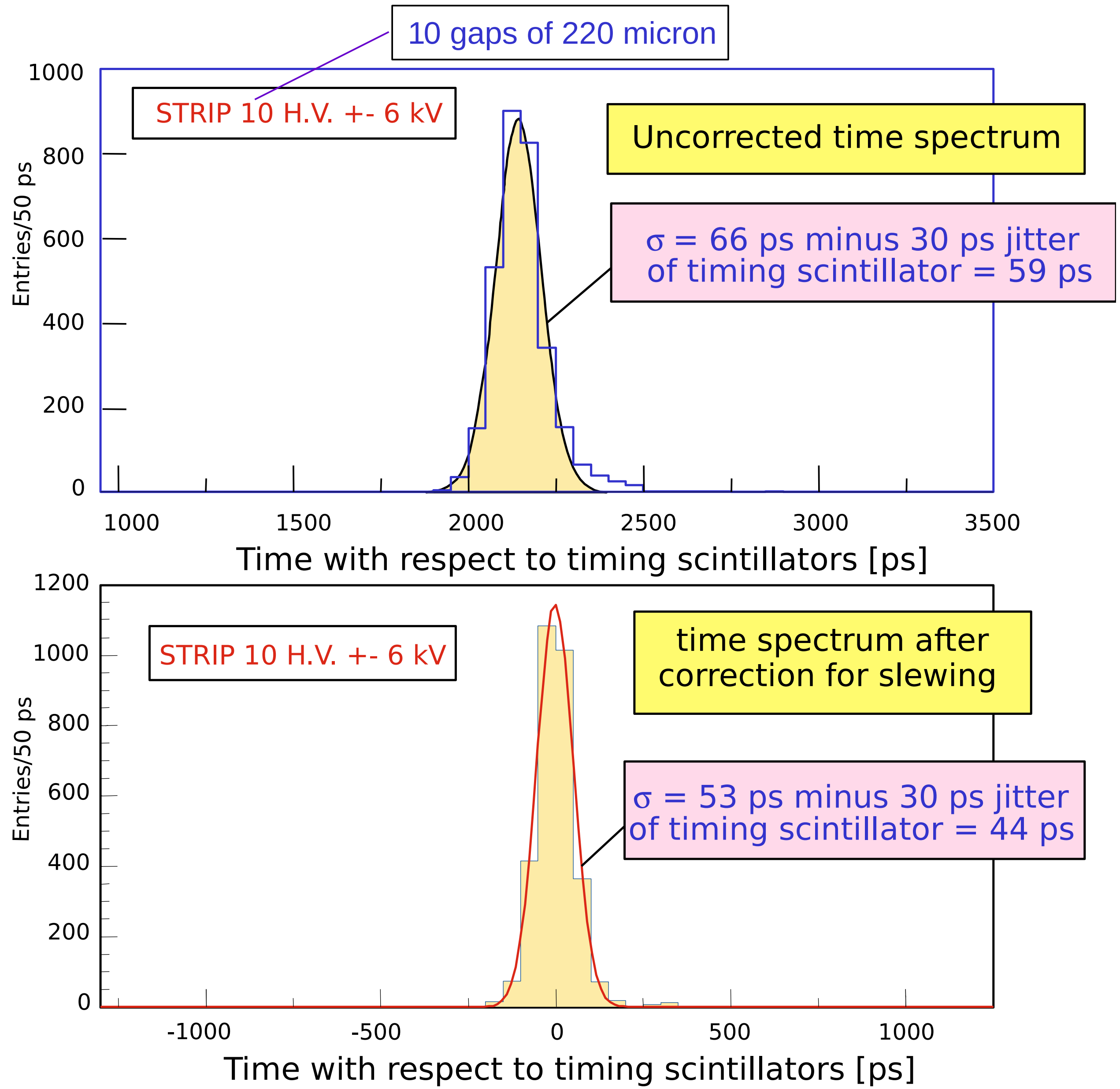


decreased flow of electrons and increased flow of positive ions – net flow of positive charge. This will move the potential on this plate more positive than -6.5 kV (i.e. towards 6 kV)

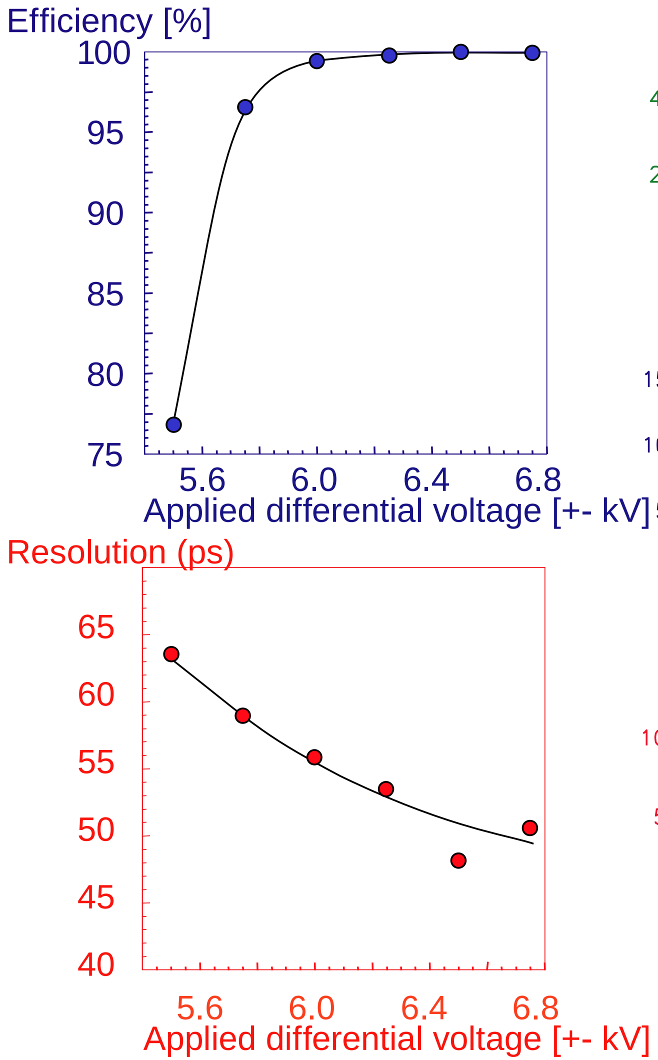
feedback principle that automatically corrects potentials on the resistive plates – stable situation is "equal gains in all gas gaps"

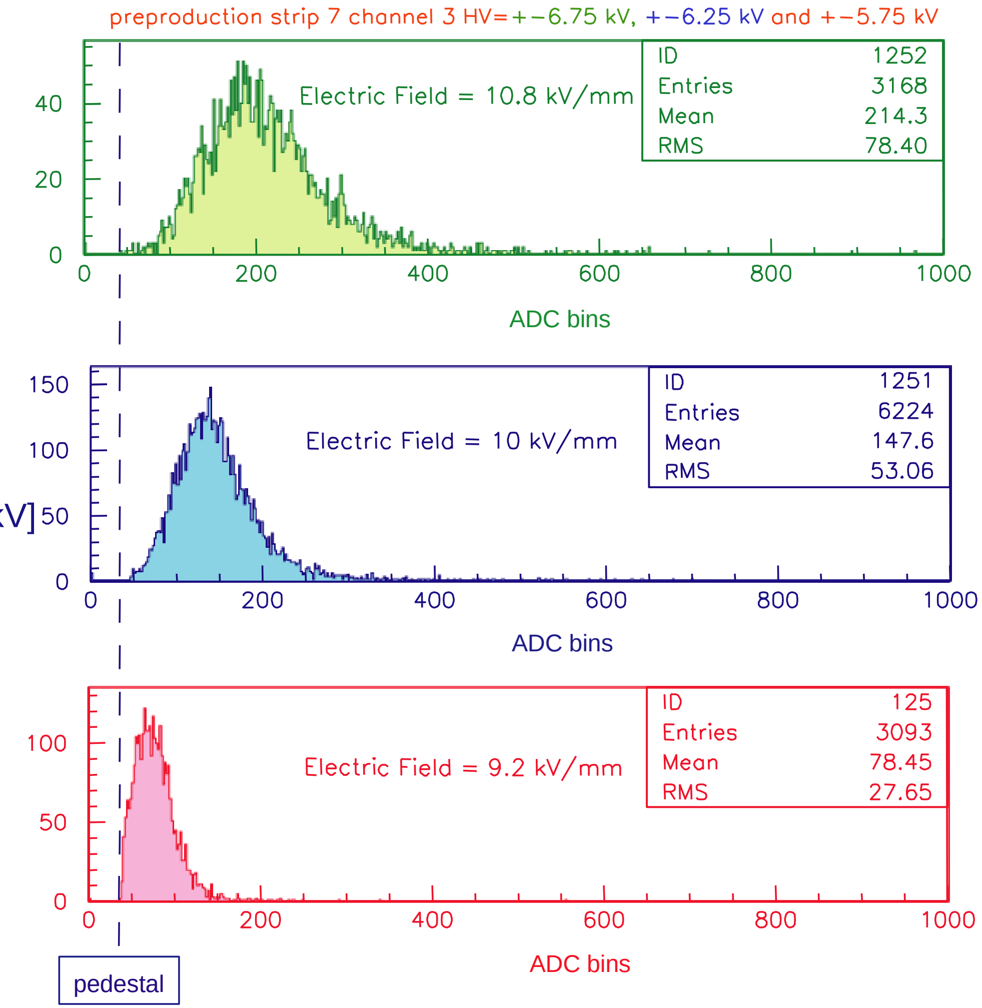
ALICE TOF prototypes

indeed one gets
sub 50 ps
time resolution



test of pre-production strip: 120×7 cm^2
read-out plane segmented into 3.5×3.5 cm^2 pads

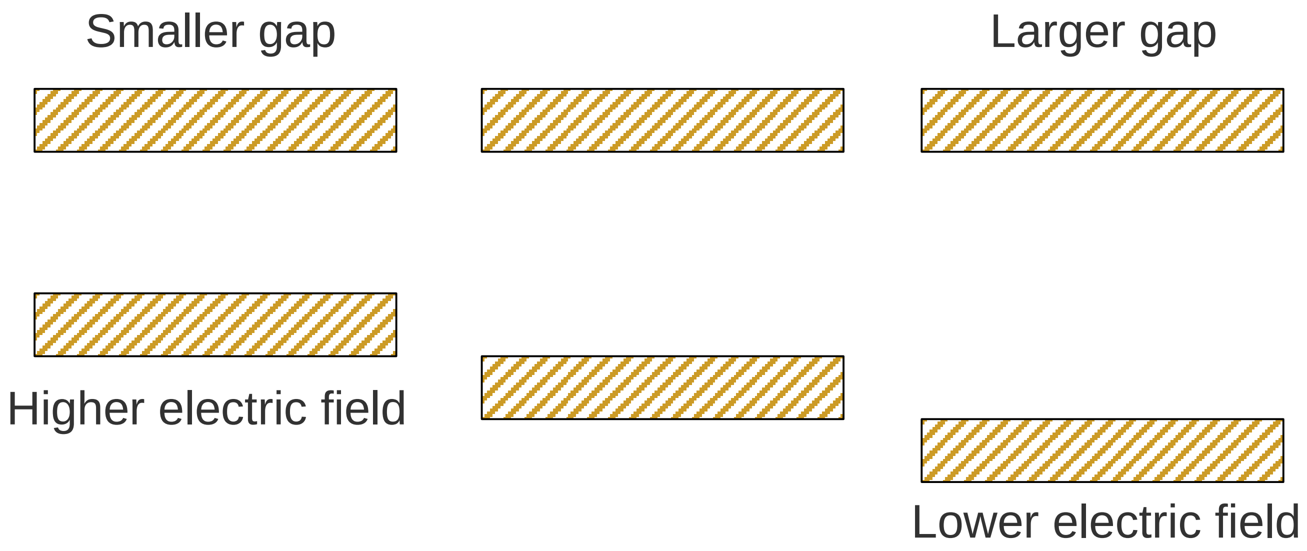




peak of charge spectra well separated from zero
no sign of streamers

but how precise do these gaps of 250 μm have to be?

gain not strongly dependent on gap size - actually loose mechanical tolerance - but why?

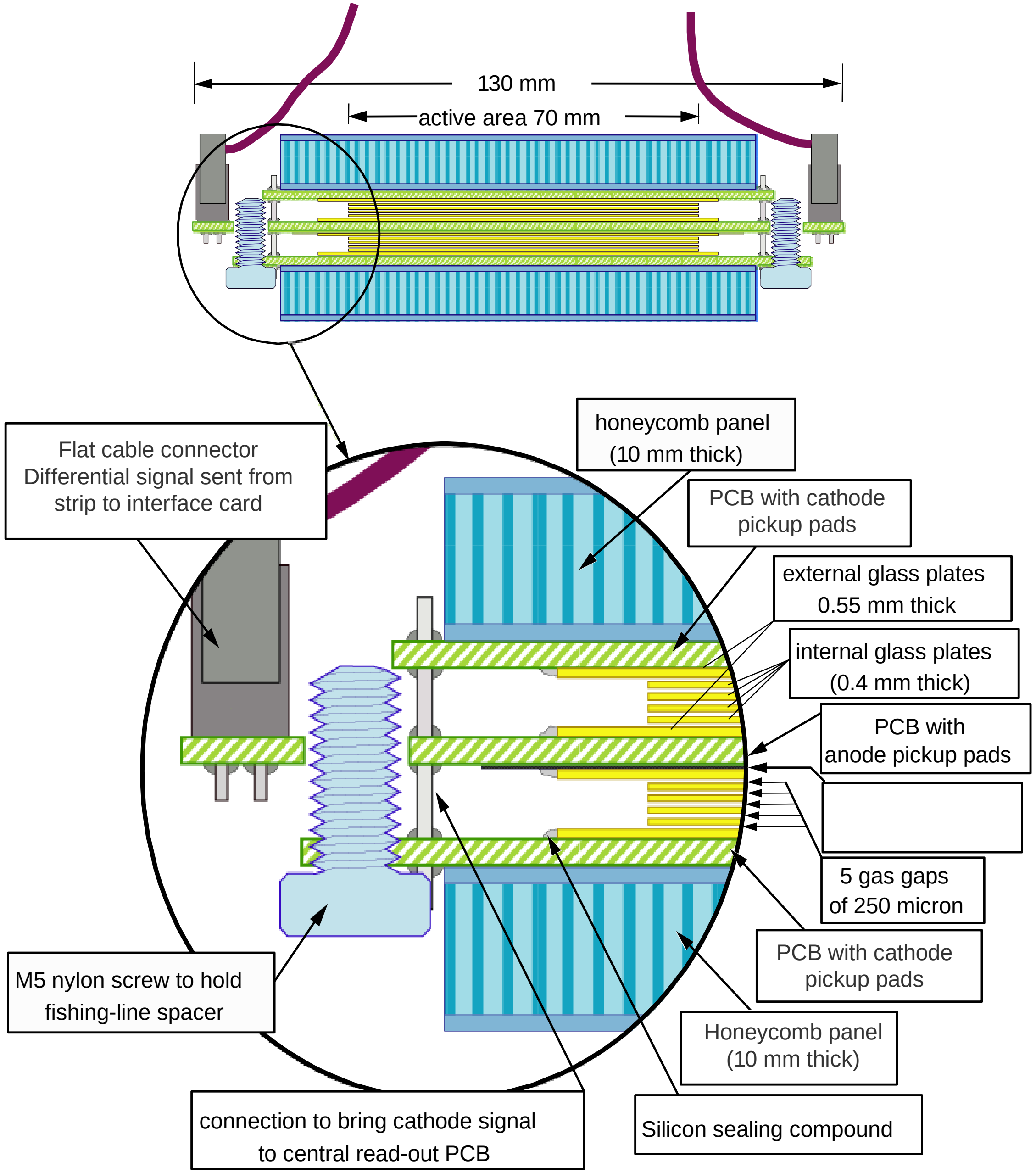


higher Townsend coefficient – higher gas gain but smaller distance for avalanche – lower gas gain

lower Townsend coefficient – lower gas gain but larger distance for avalanche – higher gas gain

with the gas mixture used (90% $C_2F_4H_2$, 5% SF_6, 5% isobutane) and with 250 μm gap size these two effects cancel and gap can vary by ± 30 μm

Cross section of double-stack MRPC – ALICE TOF



double stack
- each stack has 5 gaps (i.e. 10 gaps in total)

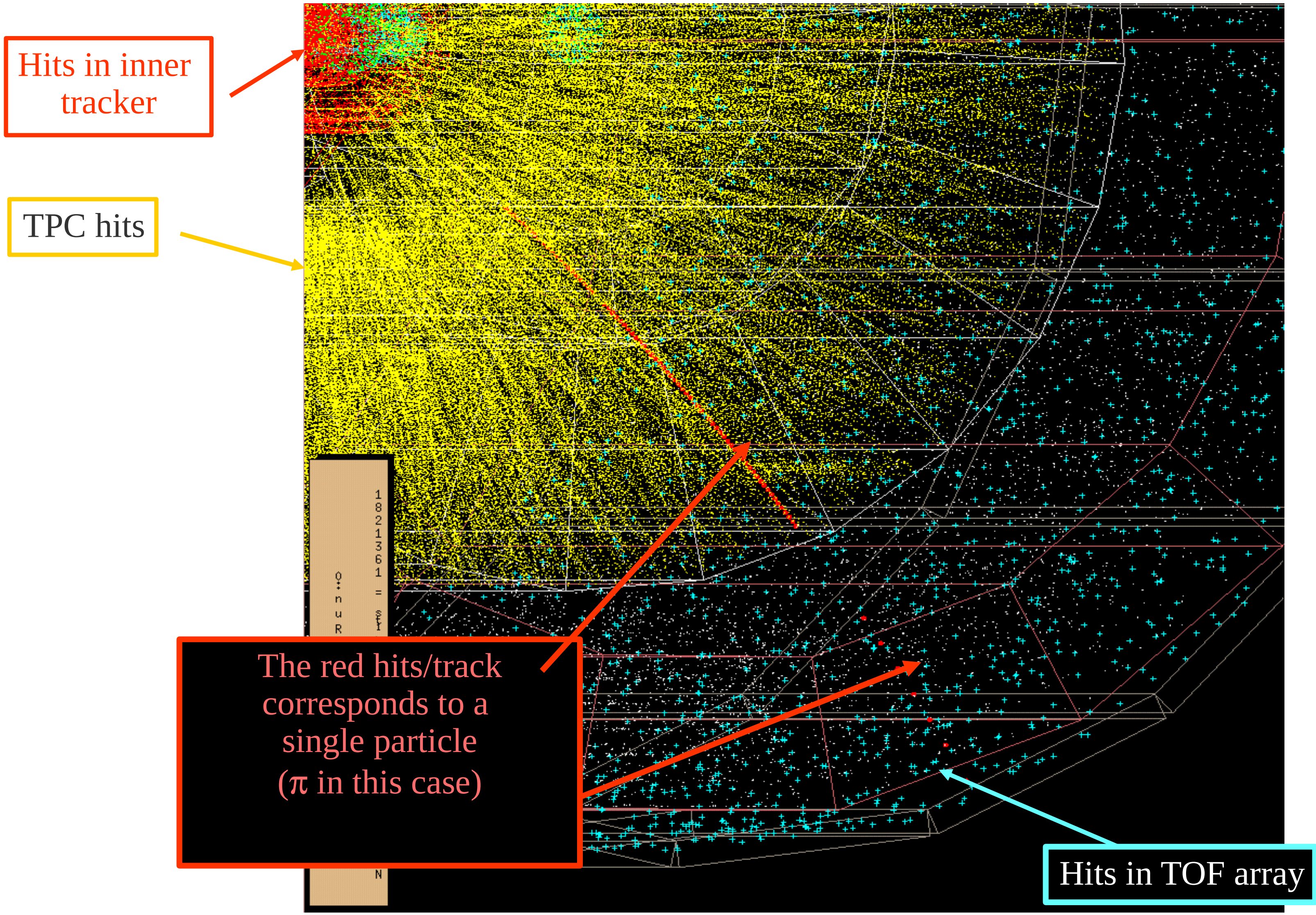
250 μm gap with spacers made from fishing line

resistive plates ‘off-the-shelf’
- soda lime glass

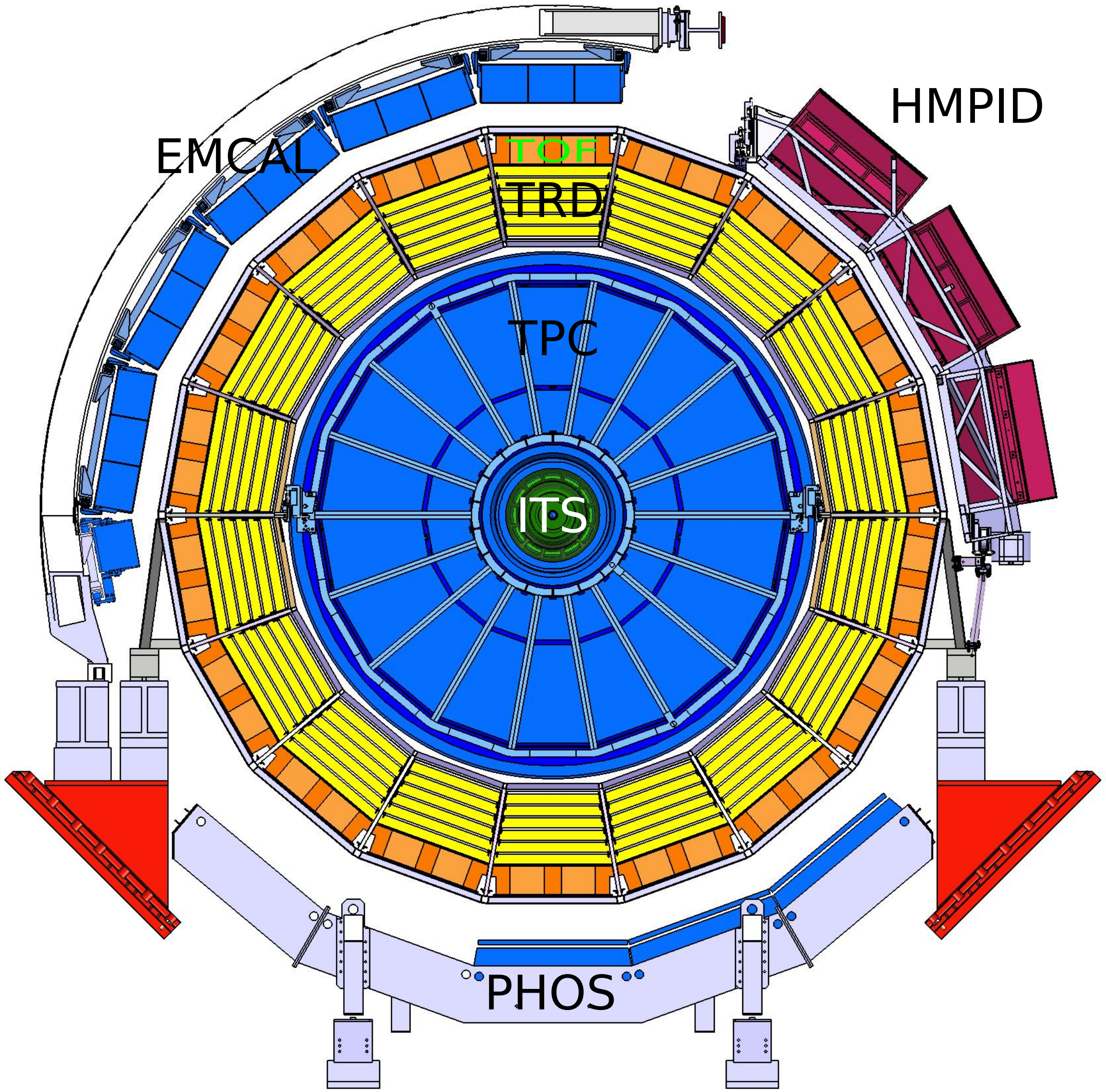
400 μm internal glass
550 μm external glass

resistive coating 5 MΩ/*square*

TOF with very high granularity needed!

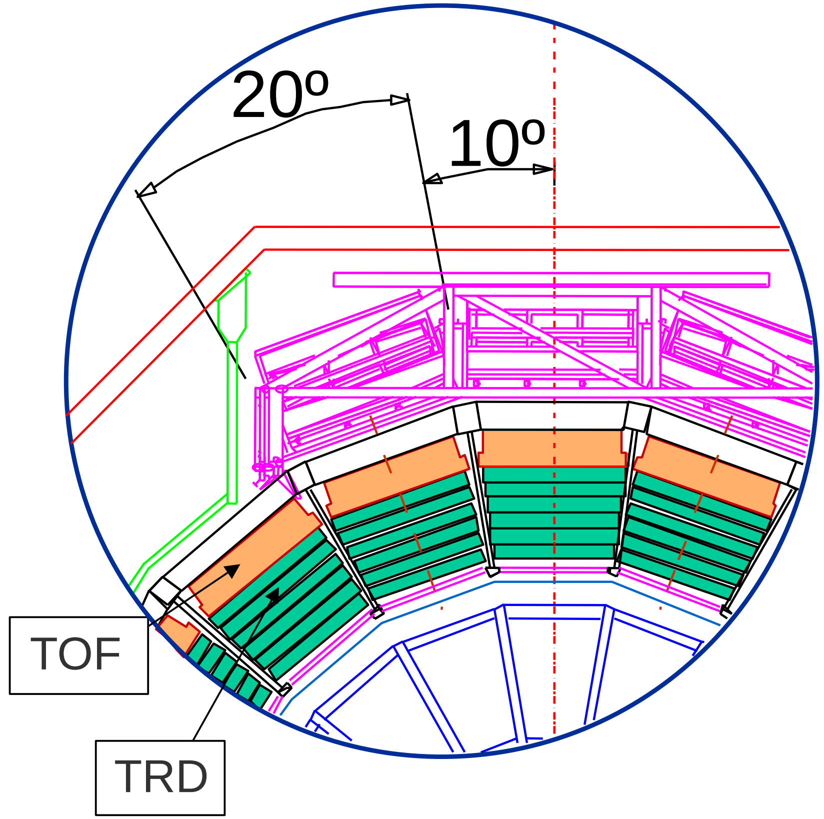


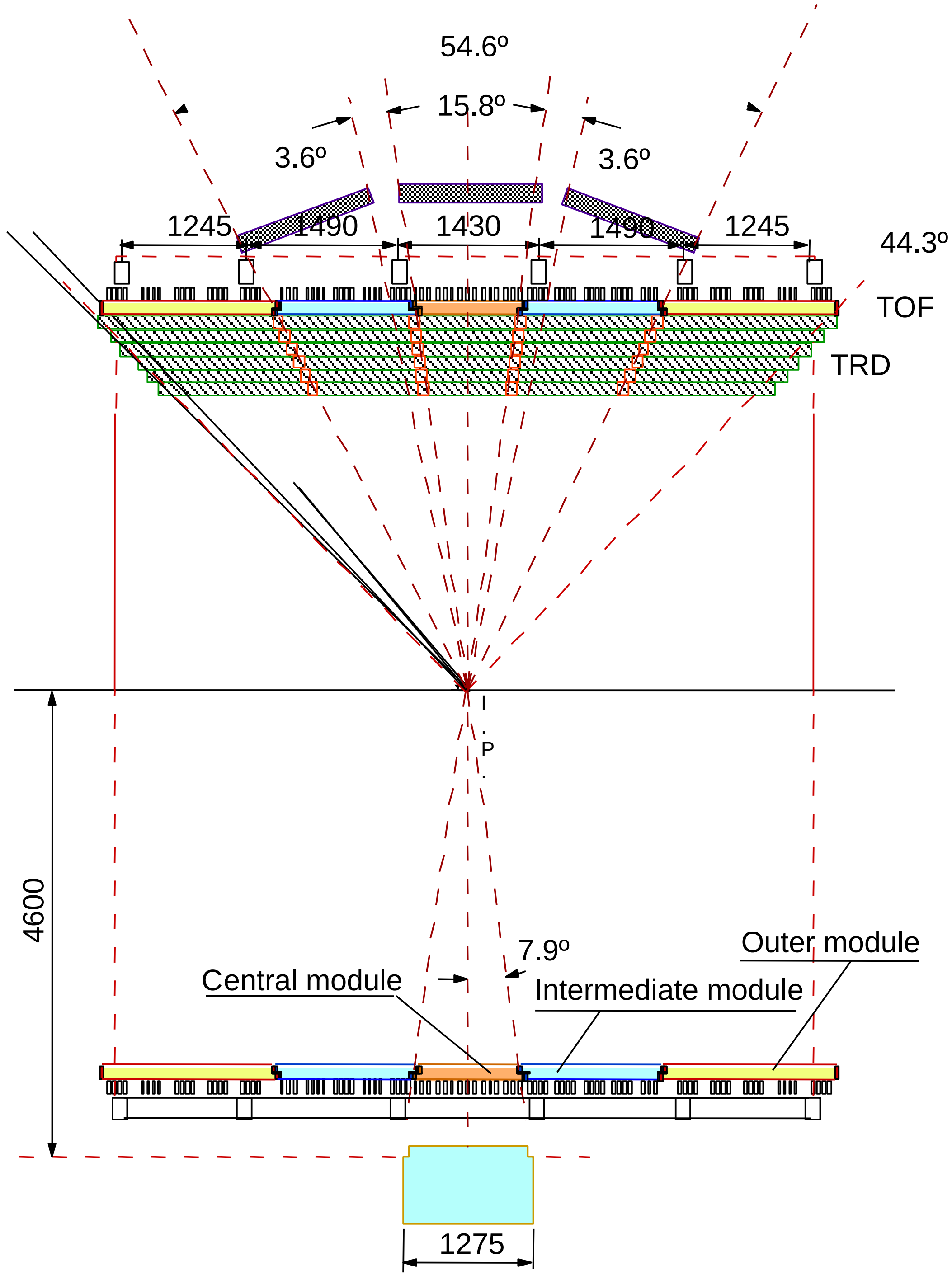
array to cover whole ALICE barrel - 160 m^2 and 100 ps time resolution
highly segmented - 160,000 channels of size 2.5×3.5 cm^2 gas detector is only choice!



cross section of ALICE detector

TOF array arranged as a barrel with radius of 3.7 m, divided into 18 sectors

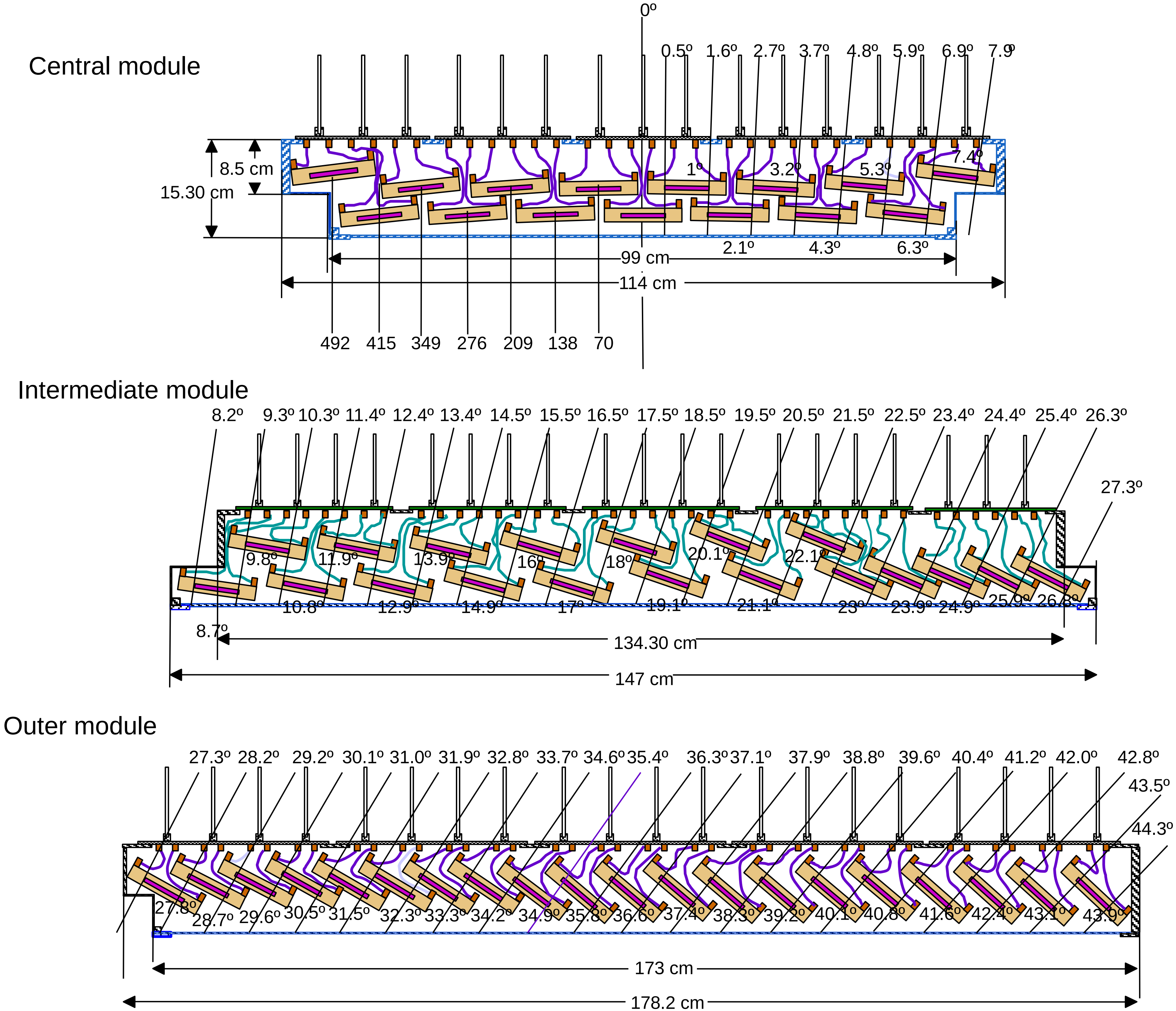




along beam direction
each sector divided into 5 modules

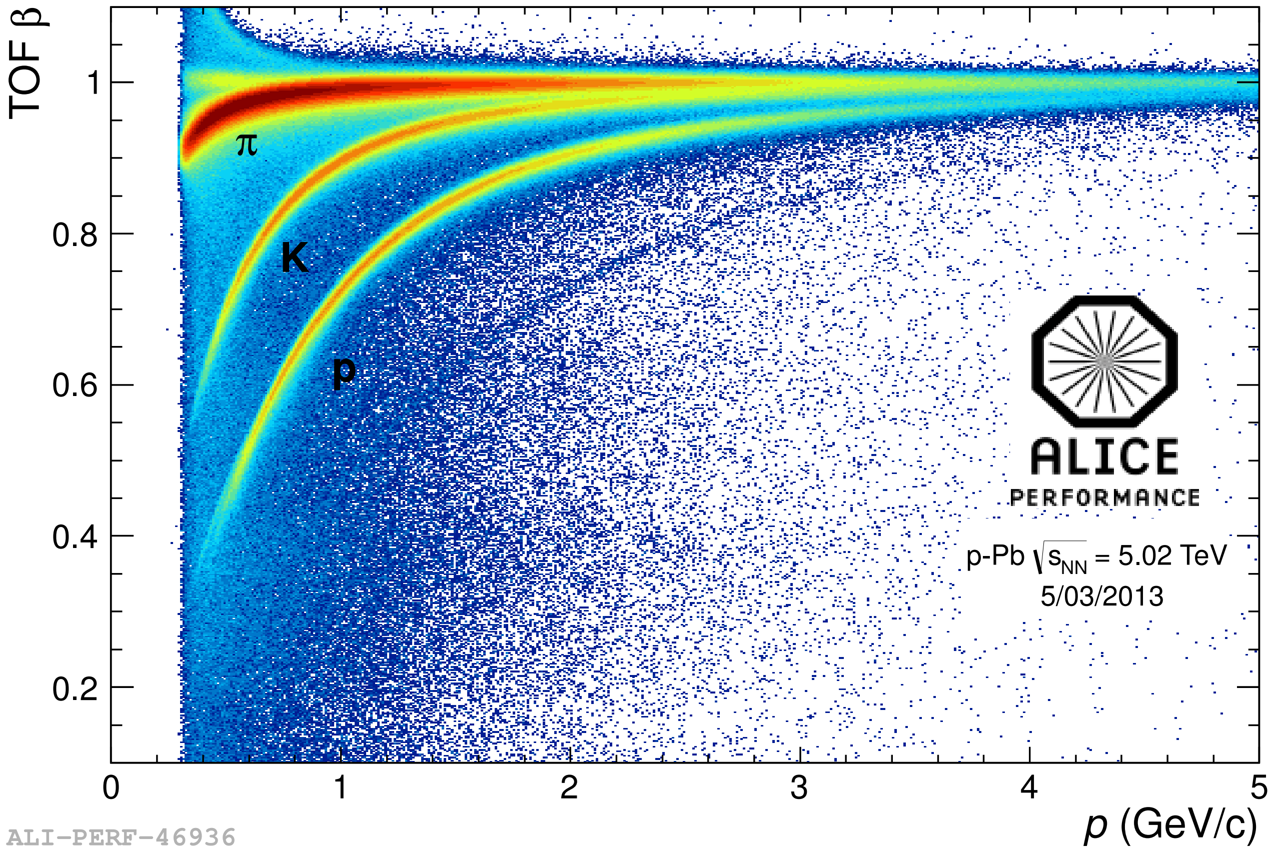
i.e. $5 \times 18 = 90$ modules in total

160 m^2 and 160,000 channels


Central module
0°
0.5° 1.6° 2.7° 3.7° 4.8° 5.9° 6.9° 7.9°
1° 3.2° 5.3° 7.4°
2.1° 4.3° 6.3°
8.5 cm
15.30 cm
99 cm
114 cm
492 415 349 276 209 138 70
Intermediate module
8.2° 9.3° 10.3° 11.4° 12.4° 13.4° 14.5° 15.5° 16.5° 17.5° 18.5° 19.5° 20.5° 21.5° 22.5° 23.4° 24.4° 25.4° 26.3°
27.3°
9.8° 11.9° 13.9° 16° 18° 20.1° 22.1°
10.8° 12.9° 14.9° 17° 19.1° 21.1° 23° 23.9° 24.9° 25.9° 26.8°
8.7°
134.30 cm
147 cm
Outer module
27.3° 28.2° 29.2° 30.1° 31.0° 31.9° 32.8° 33.7° 34.6° 35.4° 36.3° 37.1° 37.9° 38.8° 39.6° 40.4° 41.2° 42.0° 42.8°
43.5°
44.3°
27.8° 28.7° 29.6° 30.5° 31.5° 32.3° 33.3° 34.2° 34.9° 35.8° 36.6° 37.4° 38.3° 39.2° 40.1° 40.8° 41.6° 42.4° 43.1° 43.9°
173 cm
178.2 cm

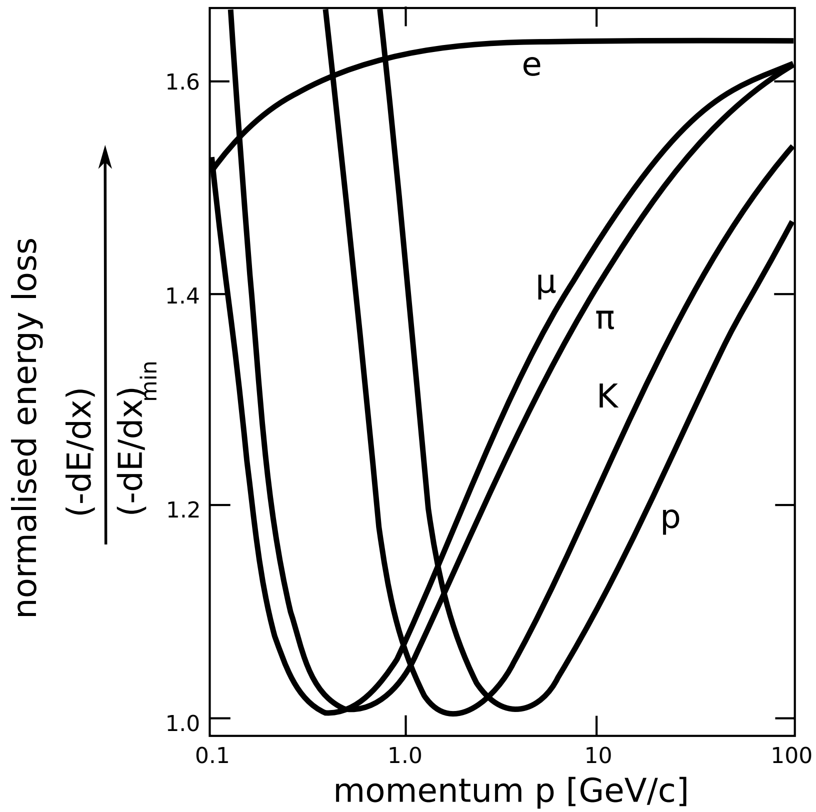
ALICE TOF time resolution

for full system one gets 80 ps resolution

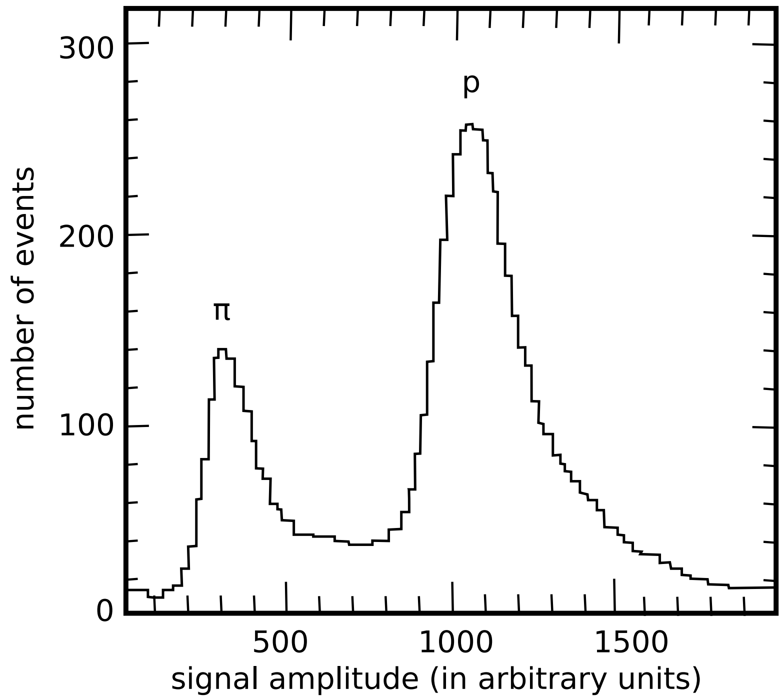


7.2 Specific energy loss

use relativistic rise of dE/dx - but is that possible with Landau fluctuations?
effective way to suppress fluctuations: make many measurements of dE/dx and truncate large energy-loss measurements

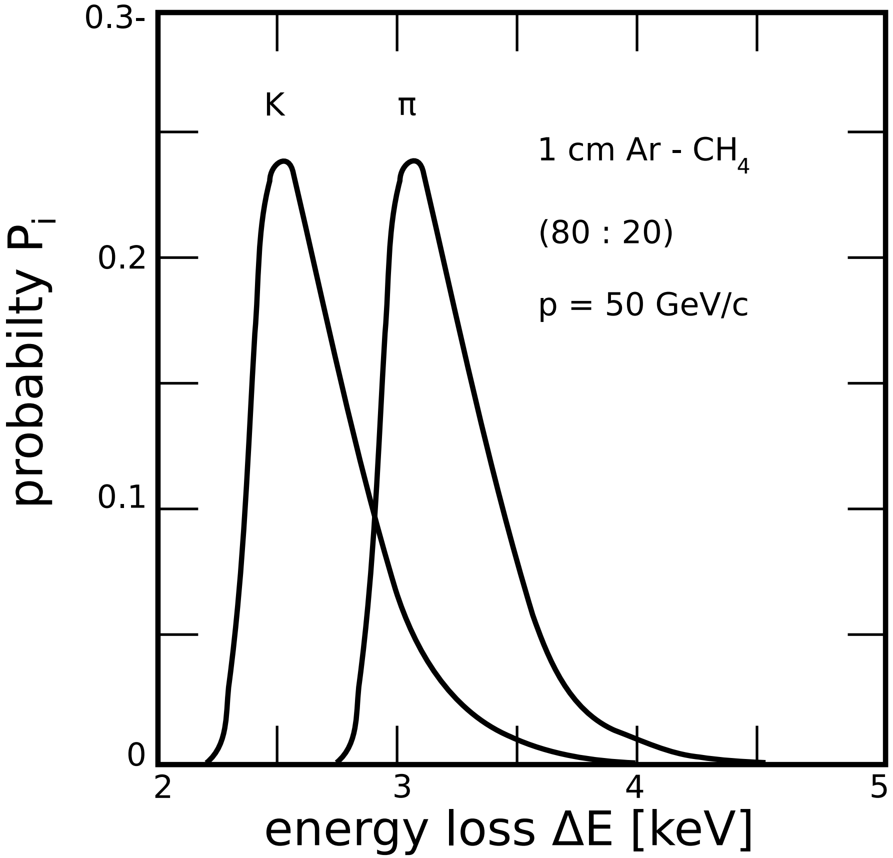


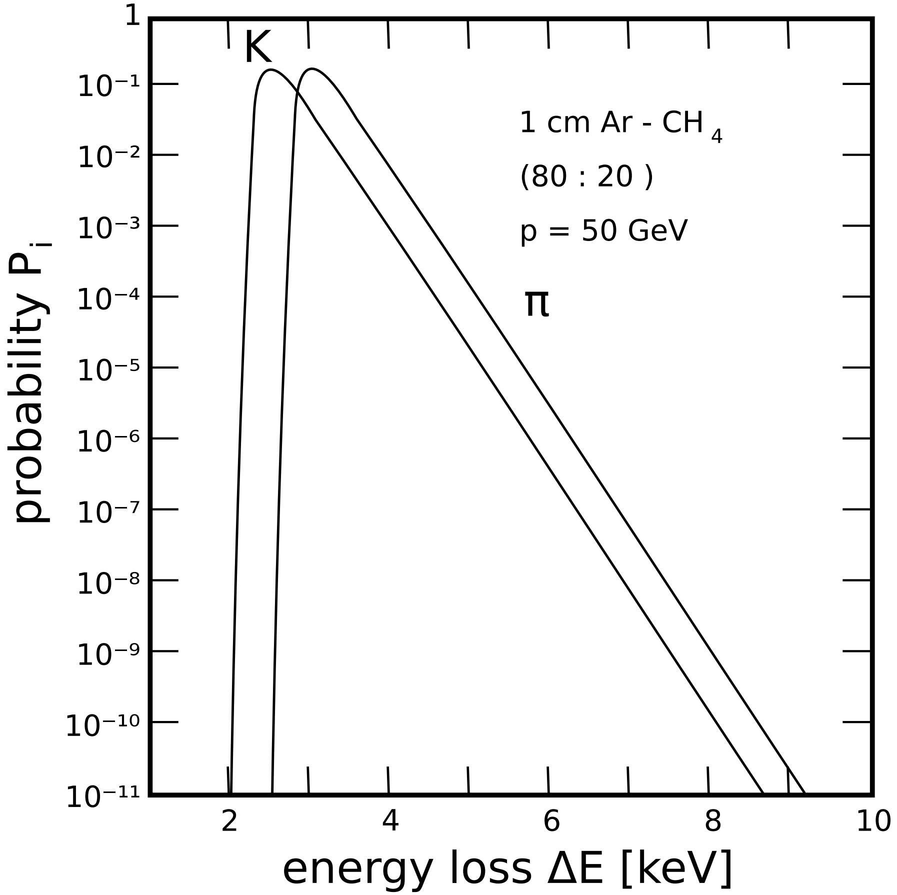
mean energy loss relative to minimum ionization, normally only μ/π separation excluded



energy loss distribution for 600 MeV/c π and p in Si (3mm)
$p > p_{min.ion}$ for protons

normally, due to Landau tail, very large overlap of, e.g., pion and kaon





truncated mean method:
many measurements and truncation to the $30 - 50\%$ highest $\mathrm{d}E/\mathrm{d}x$ values for each track

Alternative: 'likelihood'-method for several $\frac{dE}{dx}$-measurements

probability that pion produces a signal x: $p^i_\pi(x)$
for each particle measurements $x_1 \ldots x_5$
probability for pion:

$$P_1 = \prod_{i=1}^{5} p^i_\pi(x_i)$$

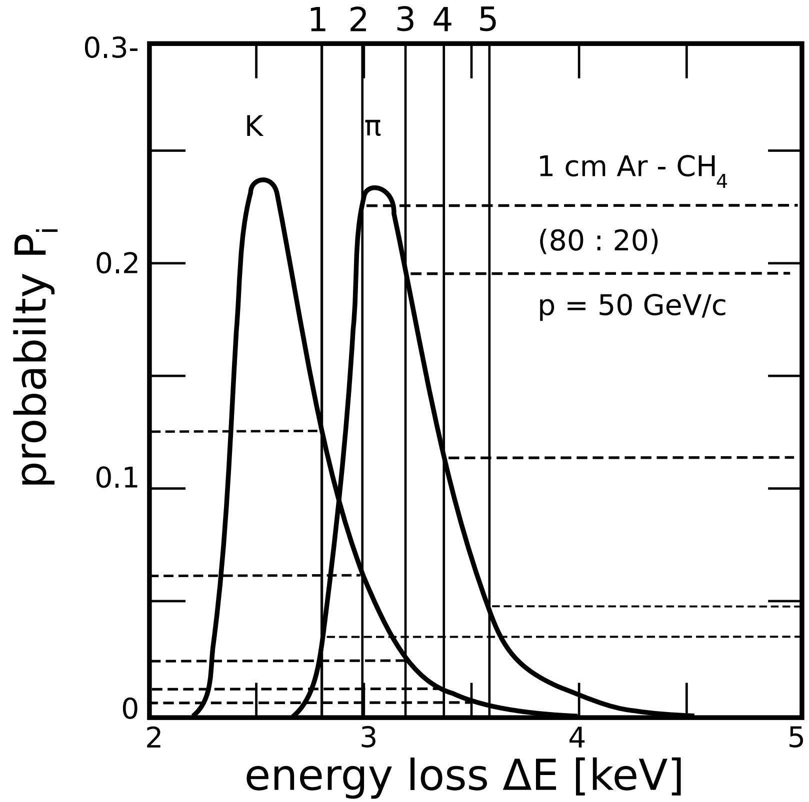
probability for kaon:

$$P_2 = \prod_{i=1}^{5} p^i_K(x_i)$$

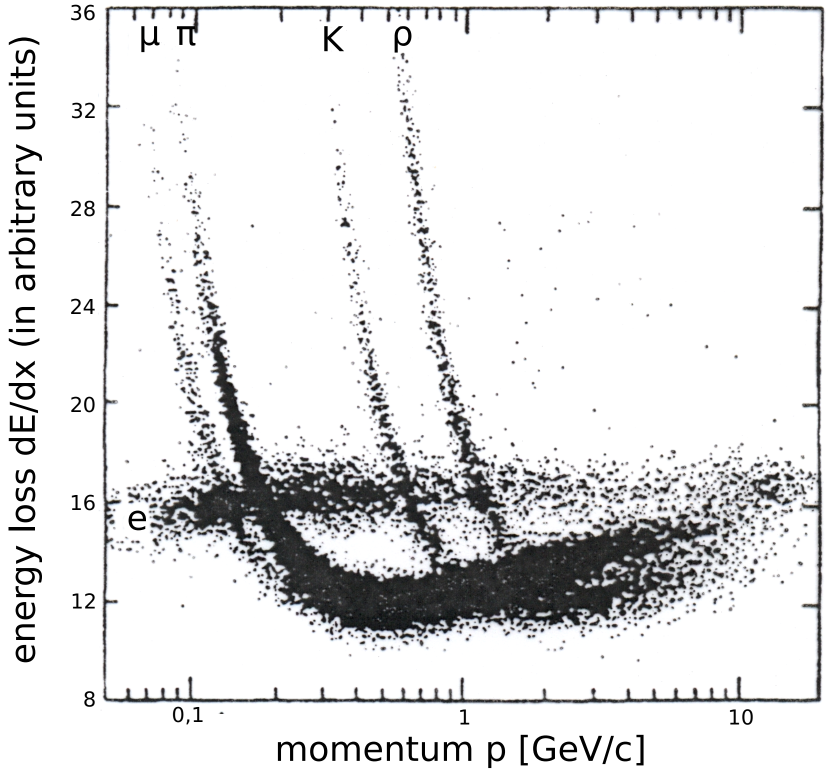
$$P_\pi = \frac{P_1}{P_1 + P_2}$$

$$\left.\begin{array}{l} P_1 = 7.1 \cdot 10^{-6} \\ P_2 = 1.5 \cdot 10^{-8} \end{array}\right\} \qquad P_\pi = 99.8\%$$

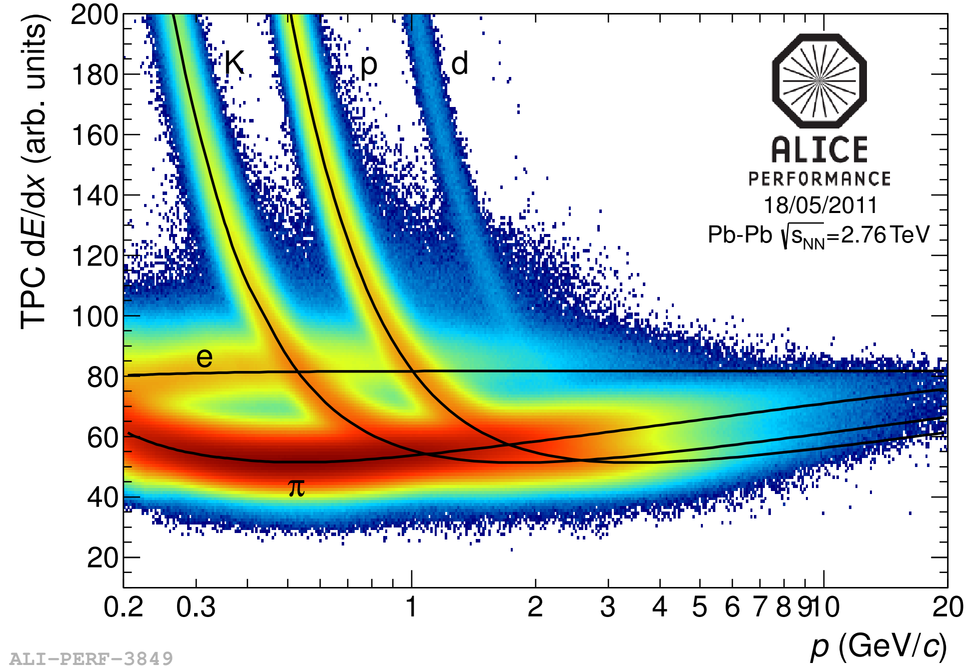
(see example on the right)



	1	2	3	4	5
p^i_K	0.123	0.061	0.025	0.013	0.006
p^i_π	0.031	0.236	0.192	0.108	0.047



multiple energy loss measurement in TPC (TPC/Two-Gamma collaboration, LBNL 1988)

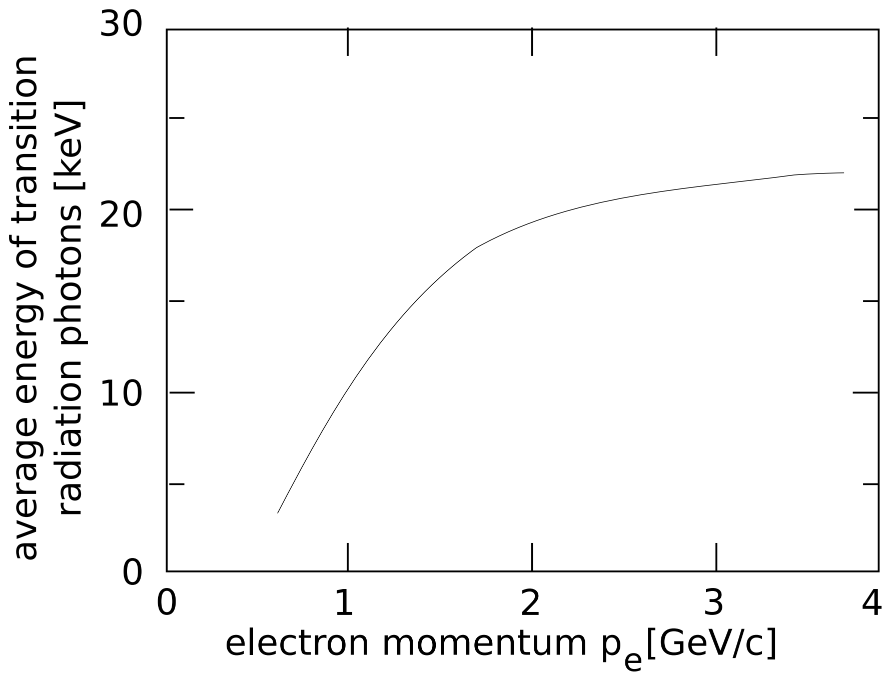


ALICE TPC $\sigma(dE/dx)/dE/dx = 6\%$ ($Ne/C0_2/N_2$)

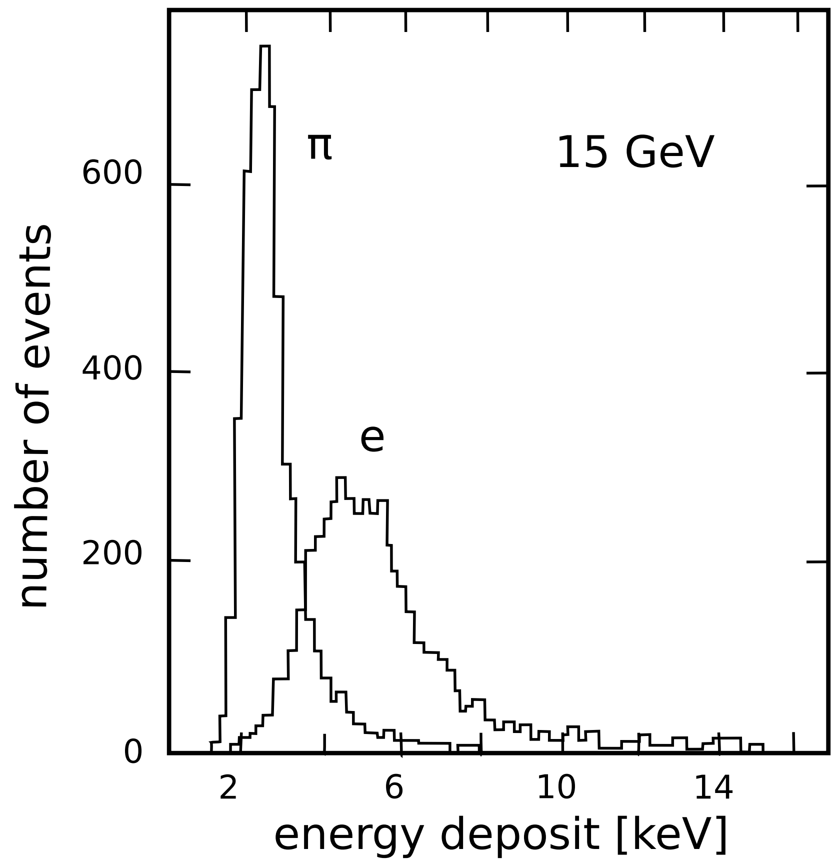
record: 3% have been reached (NA49 at SPS with Ar/CH_4, larger cells)

7.3 Transition Radiation

effect: see chapter 2, particles with Lorentz factor $\gamma \gtrsim 1000$ emit X-ray photon when crossing from medium with one dielectric constant into another, probability of order α per boundary crossing

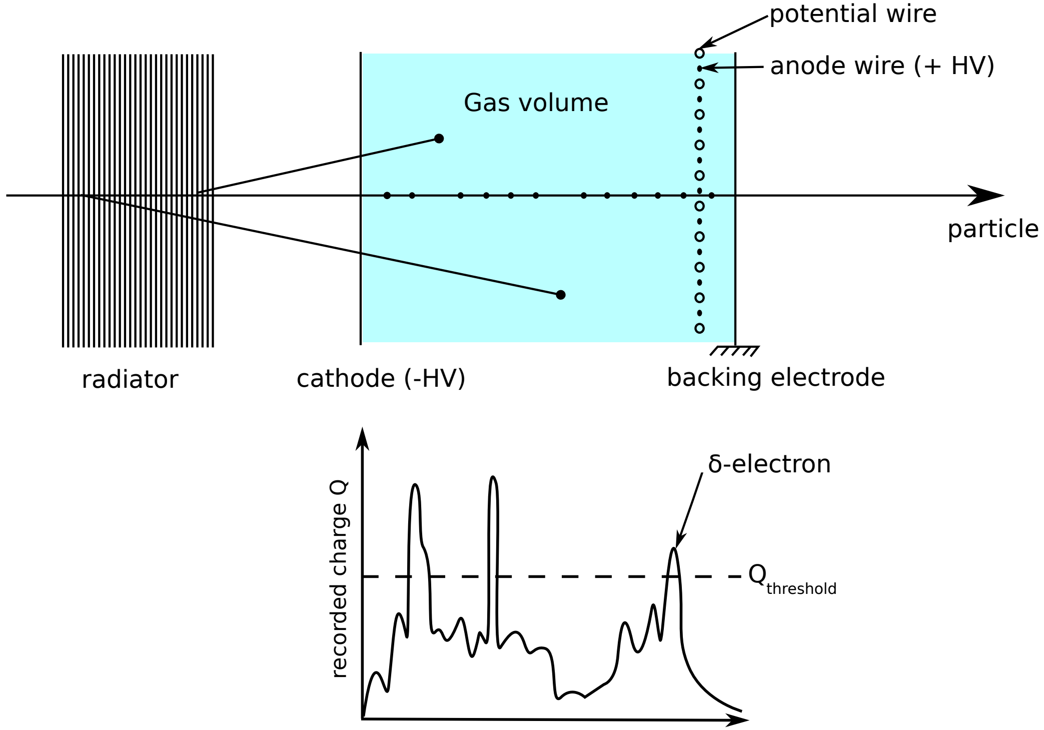


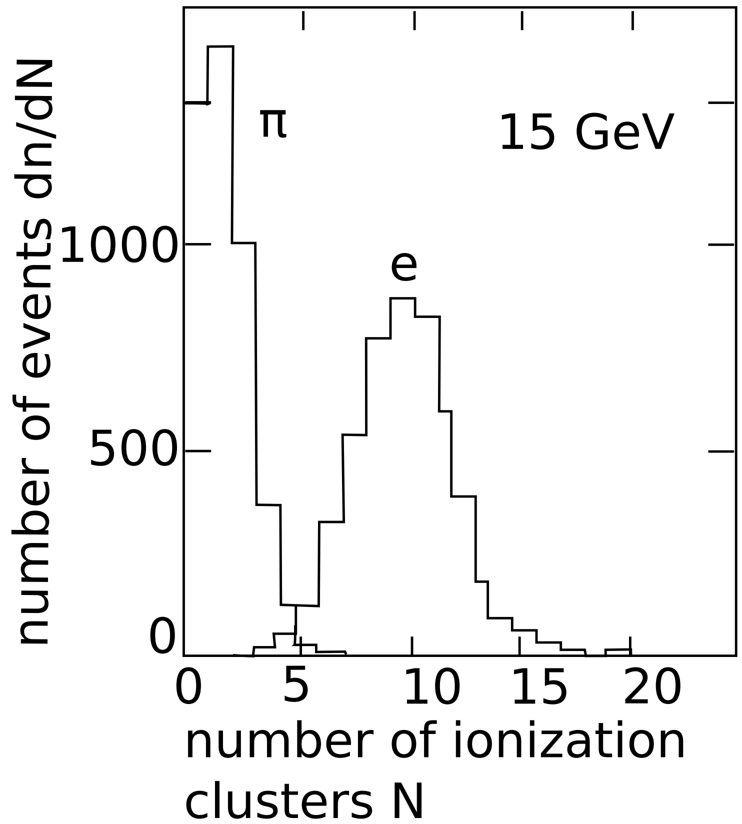
mean energy of transition radiation photon as function of electron momentum.



energy loss distribution for 15 GeV e, π in transition radiation detector

Transition radiation detector – TRD (schematic)





principle of separating ionization energy loss from the energy loss from emission of transition radiation photons

energy loss (excitation, ionization) plus transition radiation

distribution of number of clusters above some threshold for 15 GeV e, π

e/π separation in a transition radiation detector

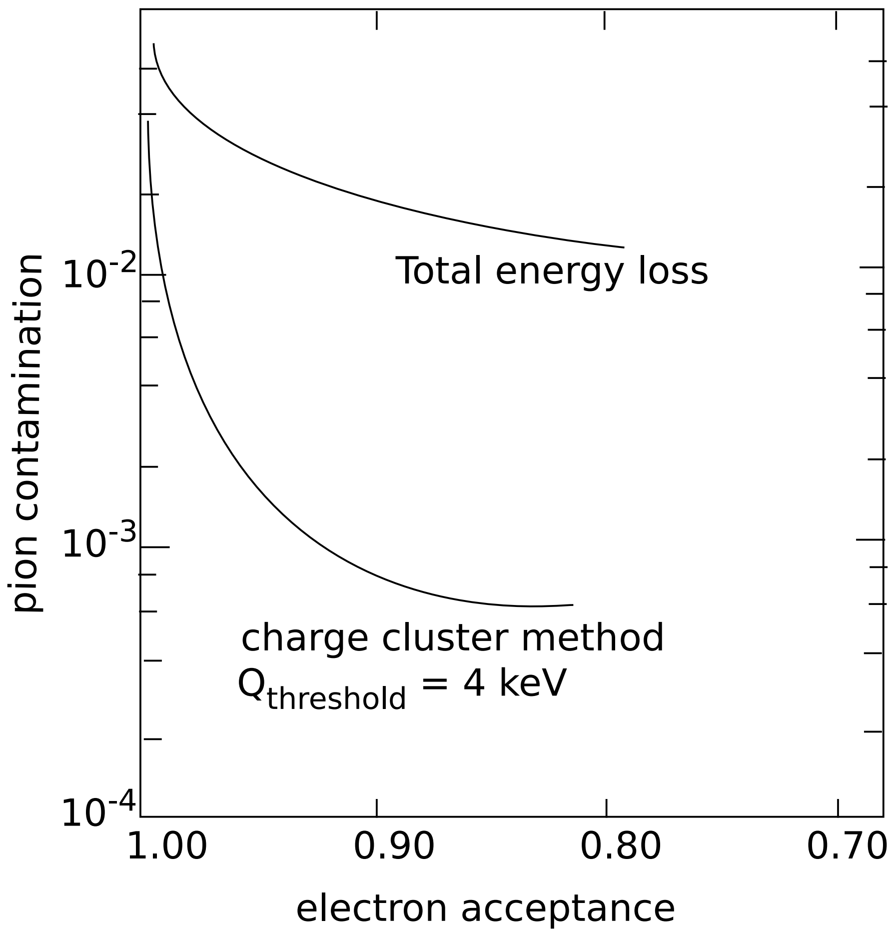
traditionally, two methods for electron discrimination

- total energy loss
- cluster counting method

novel type: ALICE TRD

- makes use of spatial information of TR absorption

last hour if time



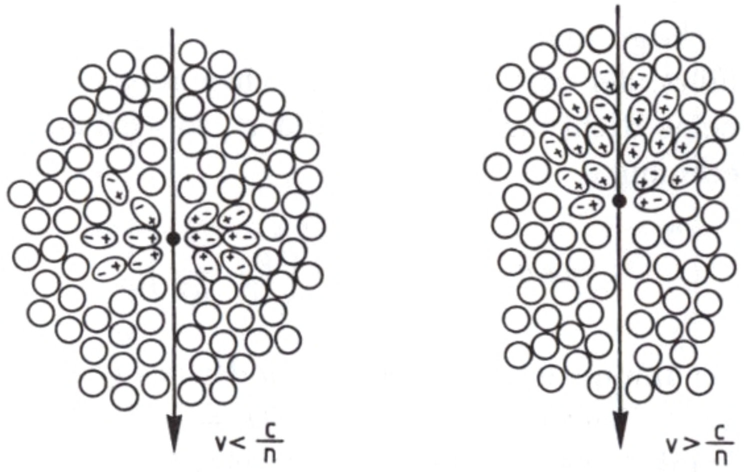
e/π separation at 15 GeV in a Li-foil radiator.

7.4. Cherenkov radiation

real photons emitted when $v > c/n$

$v < c/n$

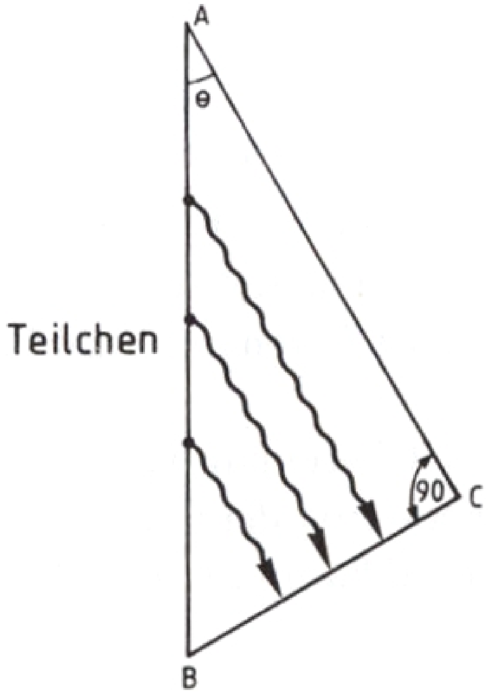
induced dipoles symmetric, no net dipole moment



$v > c/n$

induced dipoles not symmetric $\rightarrow$ non-vanishing dipole moment

illustration of the Cherenkov effect



$$AB = \Delta t \beta c$$

$$AC = \Delta t \frac{c}{n}$$

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

simple geometric determination of the Cherenkov angle θ_c

threshold effect: radiation for $\beta > 1/n$, asymptotic angle $\theta_c = arc \cos \frac{1}{\beta n}$

number of Cherenkov photons per unit path length in interval $\lambda_1 - \lambda_2$ (see Chapter 2)

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2} \qquad (z = \text{charge in e})$$

in case of no dispersion (n const. in interval)

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = 2\pi\alpha z^2 \sin^2\theta_c \frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}$$

application of Cherenkov radiation for separation of particles with masses $m_1,\ m_2$ at constant momentum (say $m_1 < m_2$)

to distinguish: particle 1 above threshold $\beta_1 > 1/n$
particle 2 at most at threshold $\beta_2 = 1/n$ or $n^2 = \frac{\gamma_2^2}{\gamma_2^2 - 1}$

in $\lambda = 400 - 700$ nm range, lighter particle with $\gamma_1^2 \gg 1$ radiates

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = 490 \sin^2\theta_c$$

$$= 490 \frac{(m_2c^2)^2 - (m_1c^2)^2}{p^2c^2} \text{photons per cm}$$

use $\sin^2\theta_c = 1 - \cos^2\theta_c = 1 - \frac{\gamma_2^2 - 1}{\beta_1^2\gamma_2^2} \approx \frac{1}{\gamma_2^2} - \frac{1}{\gamma_1^2}$

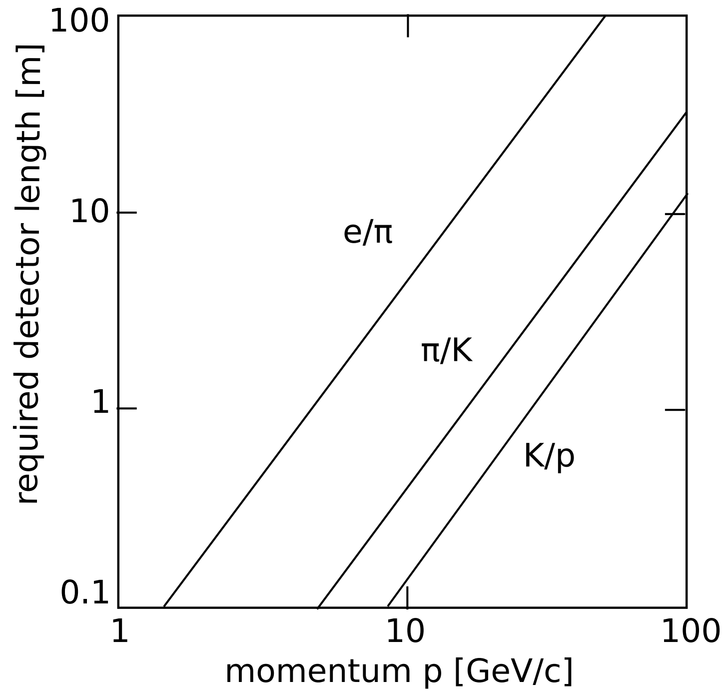
for radiator of length L in cm and quantum efficiency q of photocathode

$$N = 490 \frac{(m_2c^2)^2 - (m_1c^2)^2}{p^2c^2} \cdot L \cdot q$$

and for threshold at N_0 photoelectrons

$$L = \frac{N_0 p^2 c^2}{490[(m_2c^2)^2 - (m_1c^2)^2] \cdot q} \text{ (cm)}$$

defines the necessary length of the radiator



required detector length for $N_0 = 10$ and $q = 0.25$

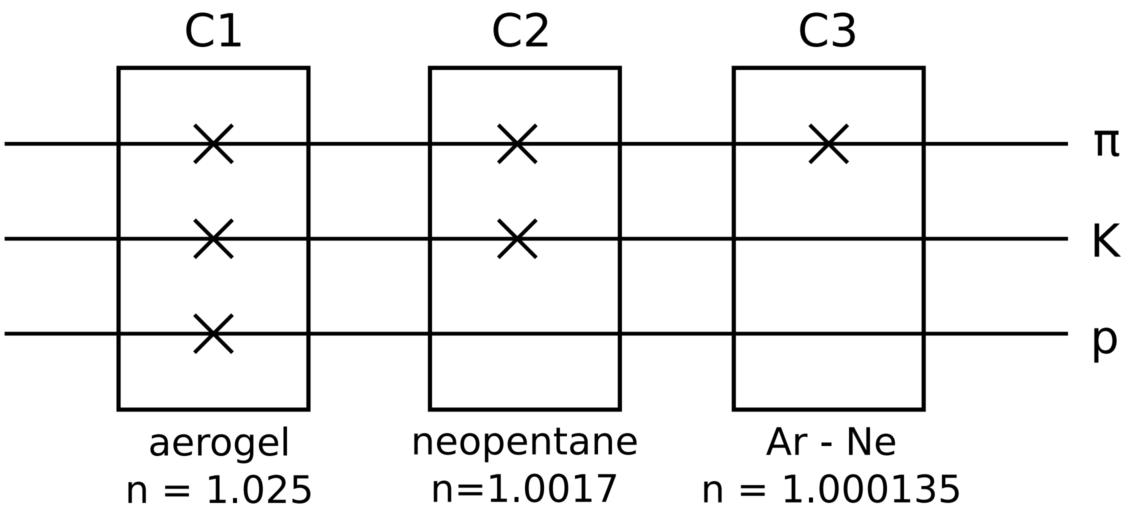
π/K/p separation with Cherenkov detector: use several threshold detectors

p [GeV/c]	Particle	γ	$1/\beta$
10	π	71.9	1.0001
	K	20.3	1.0012
	p	10.6	1.0044

condition for no radiation:

$$\beta < \frac{1}{n} \quad \text{or}$$

$$\frac{1}{\beta} > n$$



principle of particle identification by threshold Cherenkov counters (x represents production of Cherenkov photons)

$$\begin{aligned} \pi &: C1 \cdot C2 \cdot C3 \text{ pion trigger} \\ K &: C1 \cdot C2 \cdot \overline{C3} \text{ kaon trigger} \\ p &: C1 \cdot \overline{C2} \cdot \overline{C3} \text{ proton trigger} \end{aligned}$$

Differential Cherenkov detectors

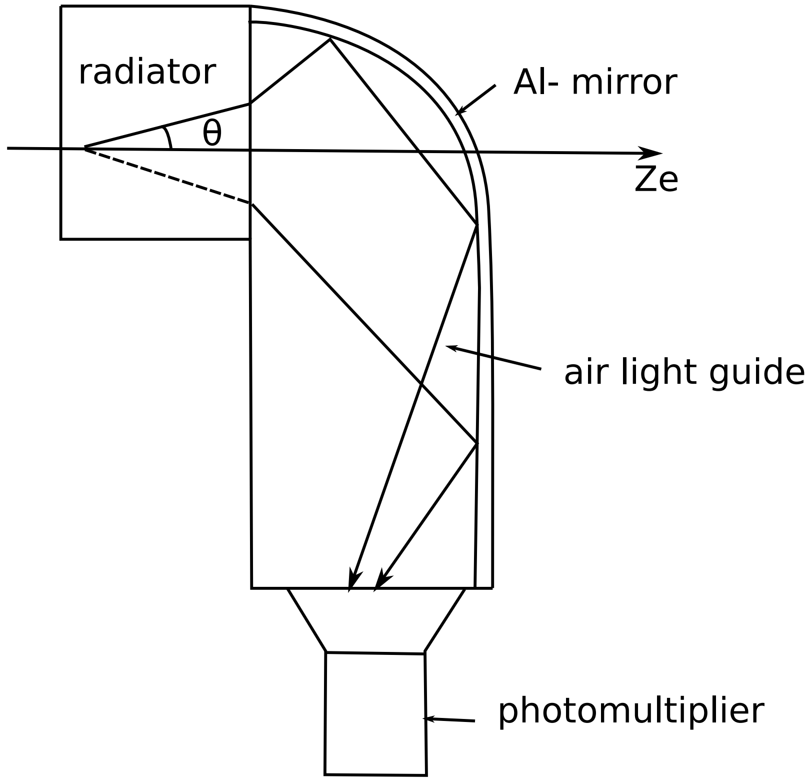
selection of velocity interval in which then actually velocity is measured
accept particles above threshold velocity $\beta_{min} = 1/n$
detect light for particles between β_{min} and a value β_t where by total reflection light does not propagate into (air) light guide

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

the critical angle for total reflection:

$$\sin\theta_t = \frac{1}{n} \quad \rightarrow \quad \cos\theta_t = \sqrt{1 - \frac{1}{n^2}}$$

$$\Rightarrow \beta\text{-range} \qquad \frac{1}{n} < \beta < \frac{1}{\sqrt{n^2 - 1}}$$



working principle of a differential Cherenkov counter

example: diamond $n = 2.42 \quad \Rightarrow \quad 0.41 < \beta < 0.454$, i.e. $\Delta\beta = 0.04$ window selected if optics of read-out such that chromatic aberrations corrected $\Rightarrow$ velocity resolution $\Delta\beta/\beta = 10^{-7}$ can be reached

principle of **DISC** (Discriminating Cherenkov counter)

Ring Imaging Cherenkov counter (RICH) I

optics such that photons emitted under certain angle θ form ring of radius r at image plane where photons are detected.
spherical mirror of radius R_S projects light onto spherical detector of radius R_D.

focal length of spherical mirror: $f = \frac{R_S}{2}$

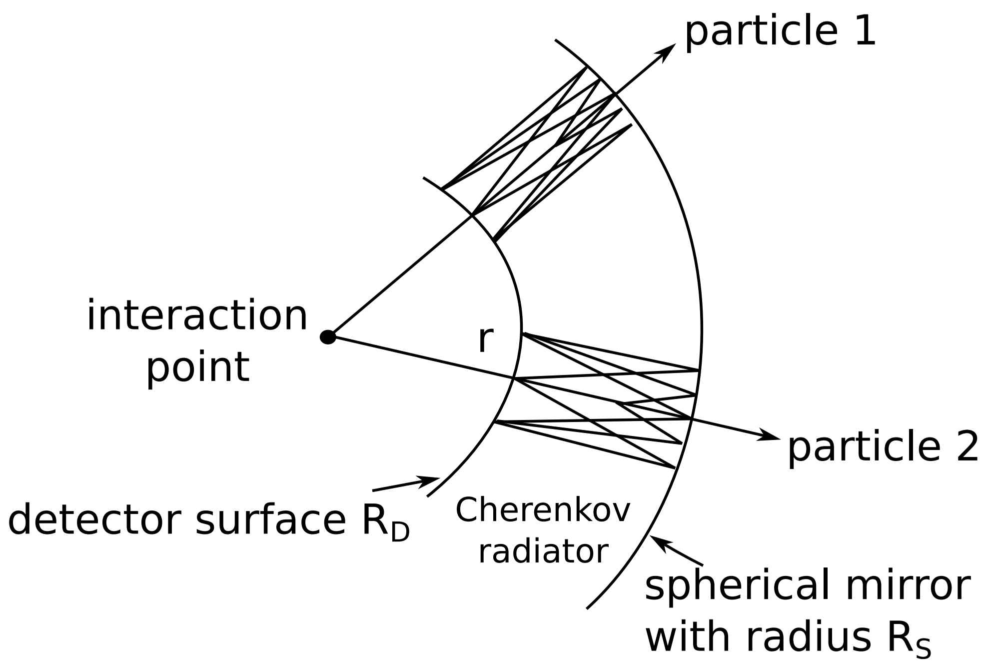
place photon detector in focus: $R_D = R_S/2$

Cherenkov light emitted under angle θ_c

radius of Cherenkov ring at detector:

$$r = f \cdot \theta_c = \frac{R_s}{2\theta_c}$$

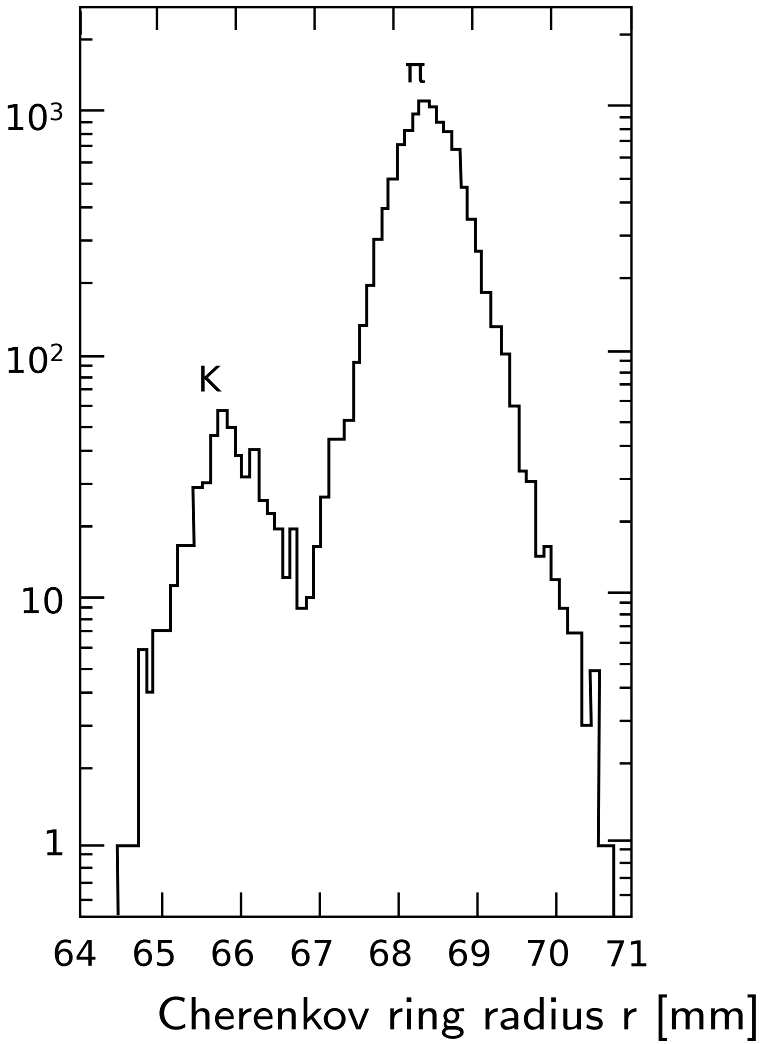
$$\Rightarrow \beta = \frac{1}{n\cos(2r/R_S)}$$



working principle of a RICH counter

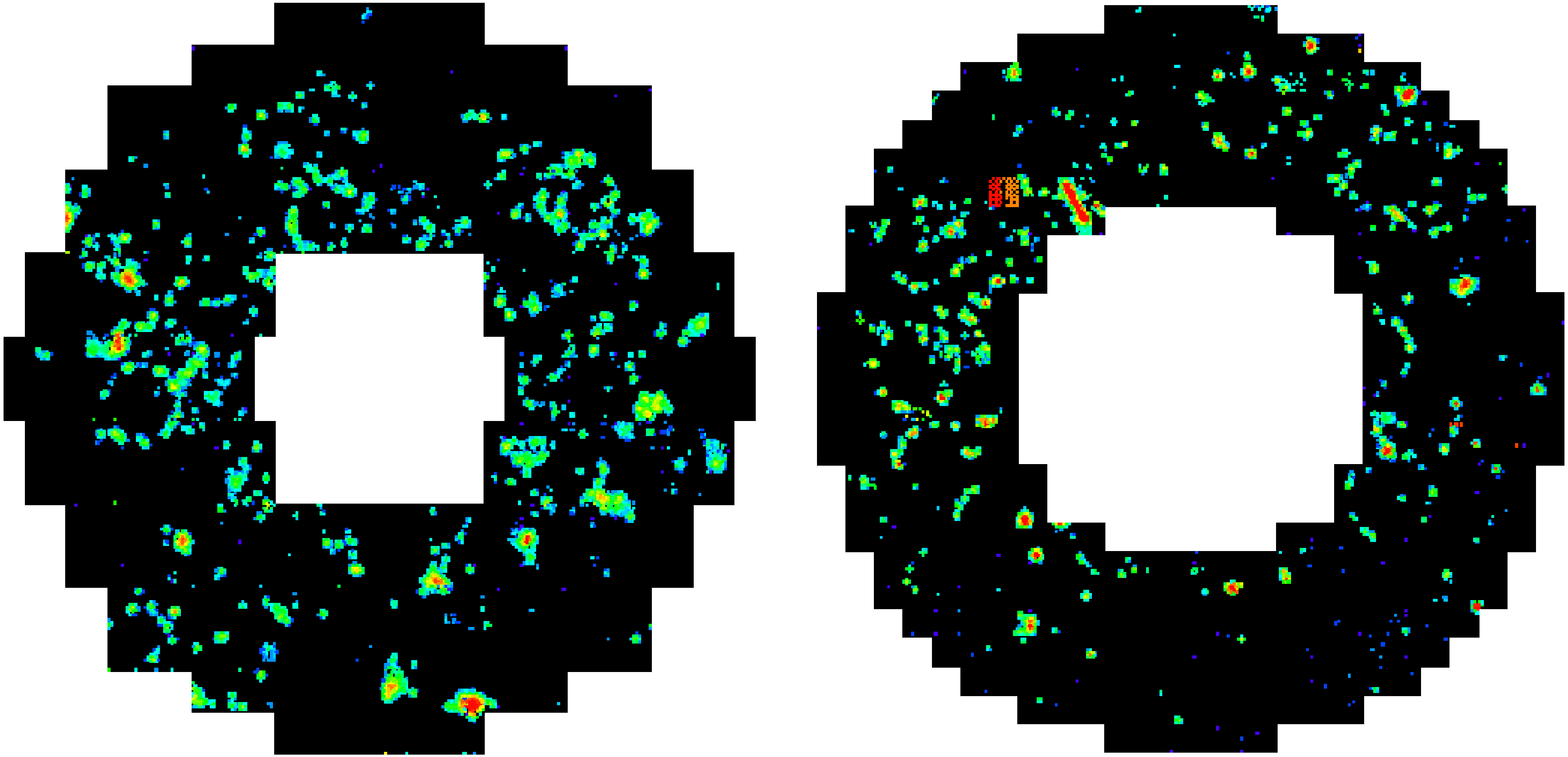
photon detection: - photomultiplier
- multi-wire proportional chamber or parallel-plate avalanche counter filled with gas that is photosensitive, i.e. transforms photons into electrons.
e.g. addition of TMAE vapor $(CH_3)_2N)_2C = C_5H_{12}N_2 \quad E_{ion} = 5.4$ eV)
- or CsI coated cathode of MWPC (ALICE HMPID or hadron blind detector HBD in PHENIX)

example: K/π separation at $p = 200$ GeV/c



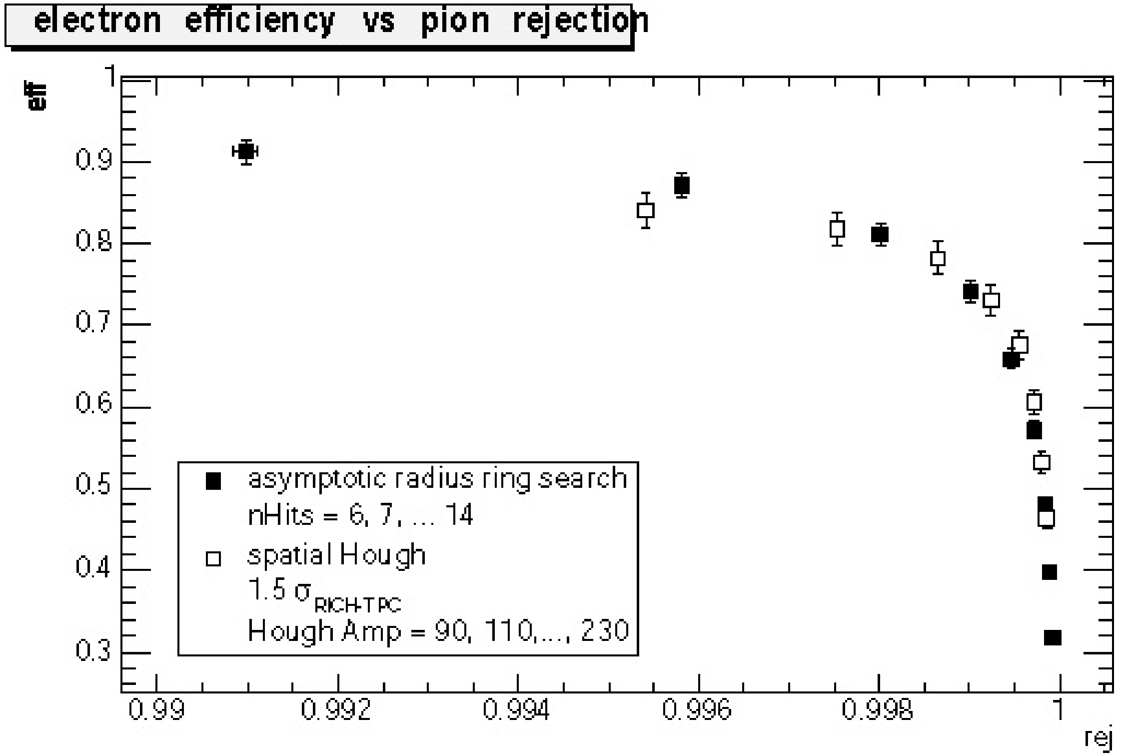
photons detected in MWPC filled with He(14%), TEA (triethyl-amine, 3%), CaF_2 entrance window (UV transparent)

event displays - CERES RICH

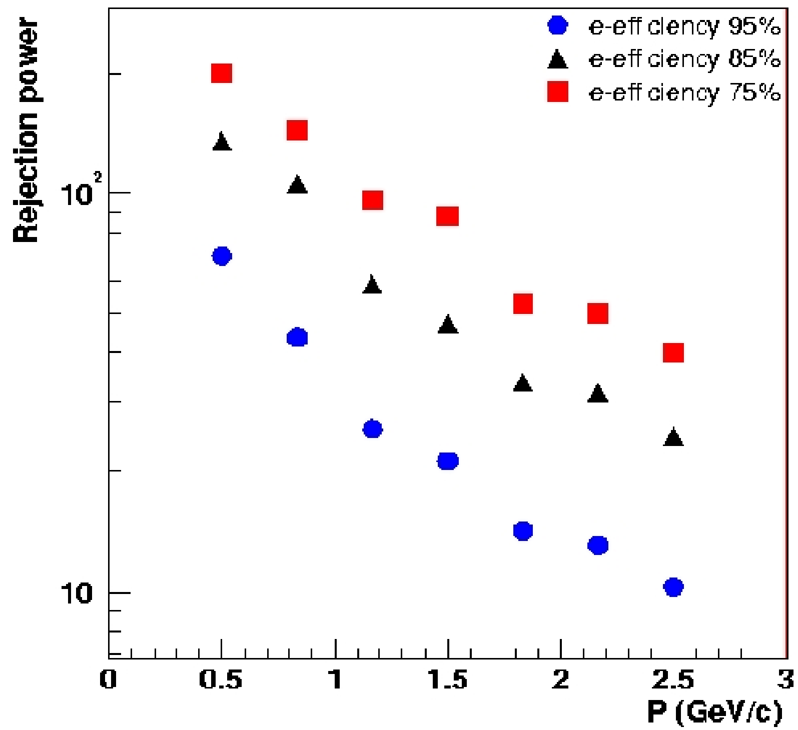


1 electron produces about 10 photons

CERES Electron Identification with TPC and RICH



RICH π rejection vs. efficiency



π rejection via TPC dE/dx

combined rejection - e.g. at 1.5 GeV/c at 67% e-efficiency $\rightarrow 4 \cdot 10^4$ π rejection

DIRC – Detection of Internally Reflected Cherenkov Light

collection and imaging of light from total internal reflection (rather than transmitted light)
optical material of radiator used in 2 ways simultaneously:
- Cherenkov radiator
- light guide for Cherenkov light trapped in radiator by total int. reflection

advantage: photons of ring image can be transported to a detector away from path of radiating particle
intrinsically 3d, position of hit $\rightarrow \theta_c, \phi_c$ and time $\rightarrow$ long. position

example: BABAR at SLAC

- rectangular radiator from fused silica
n=1.473
radiation hard, long attenuation length, low chromatic dispersion, excellent optical finish possible
- surrounded by nitrogen n≈1.00
- stand-off box filled with water n=1.346 (close to radiator)

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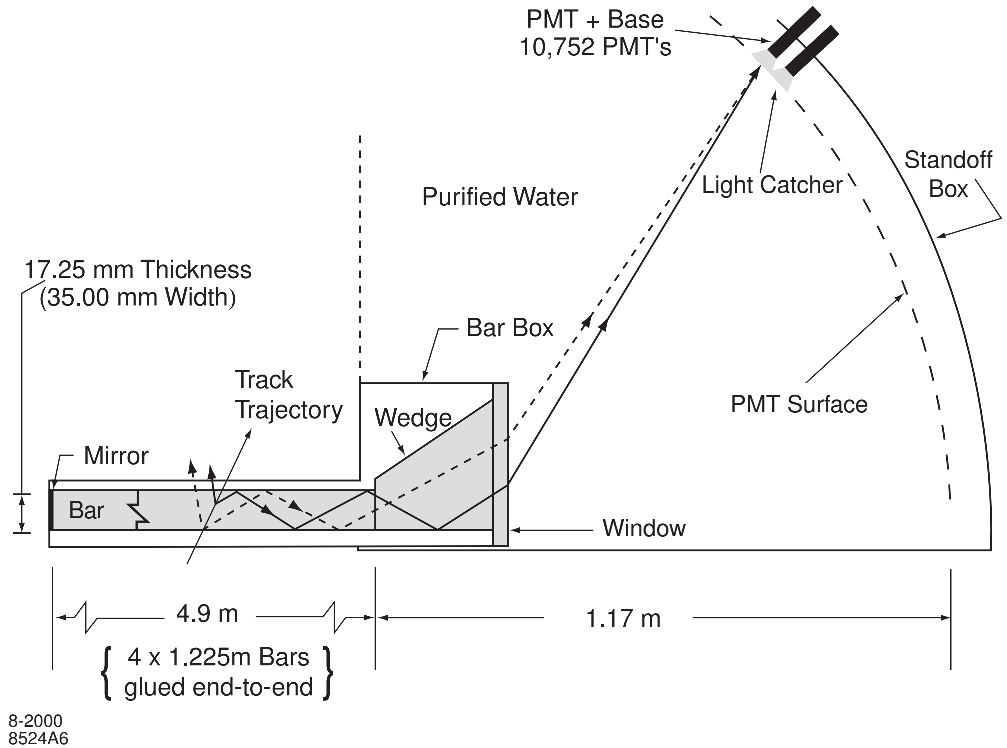
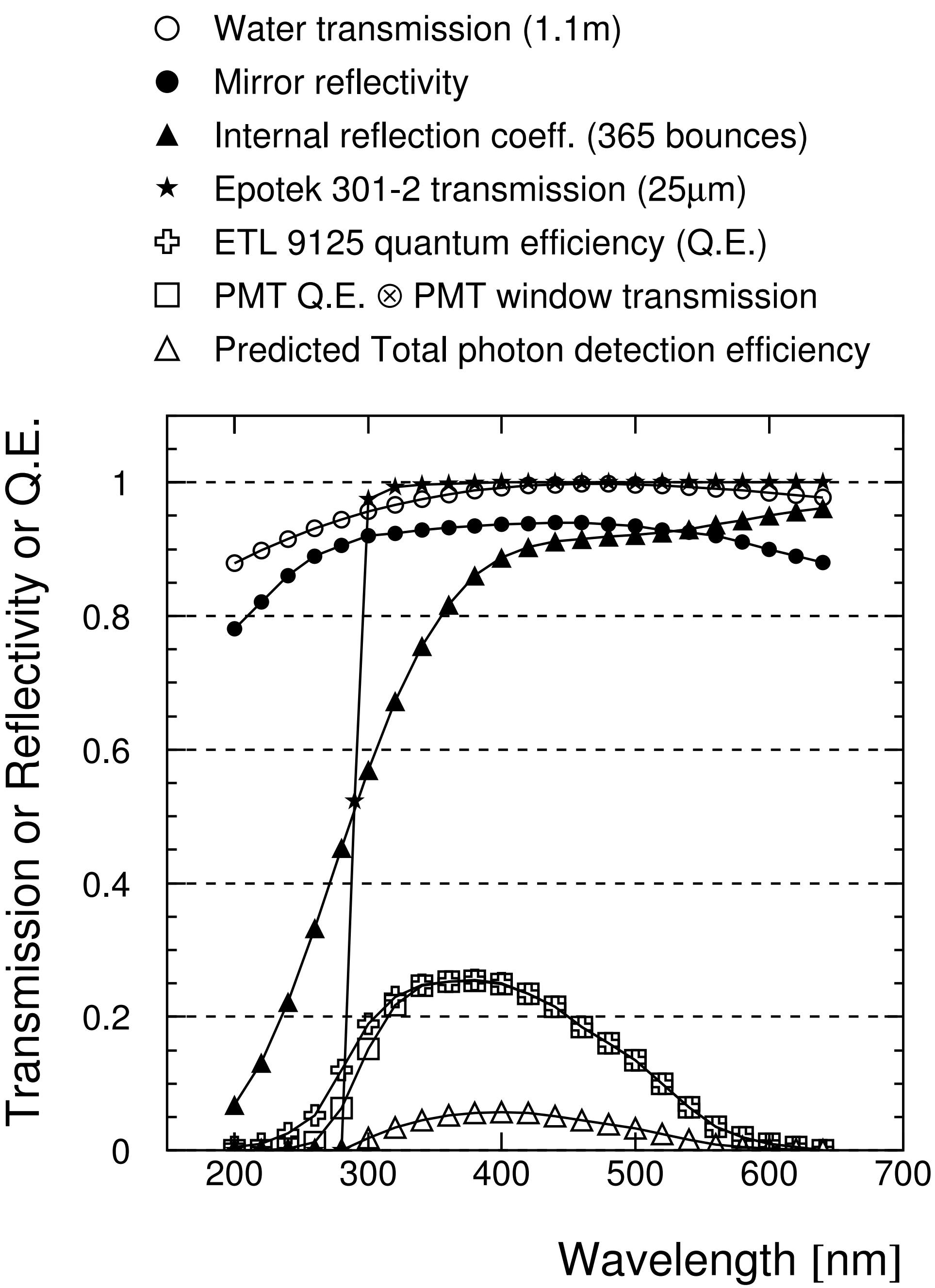
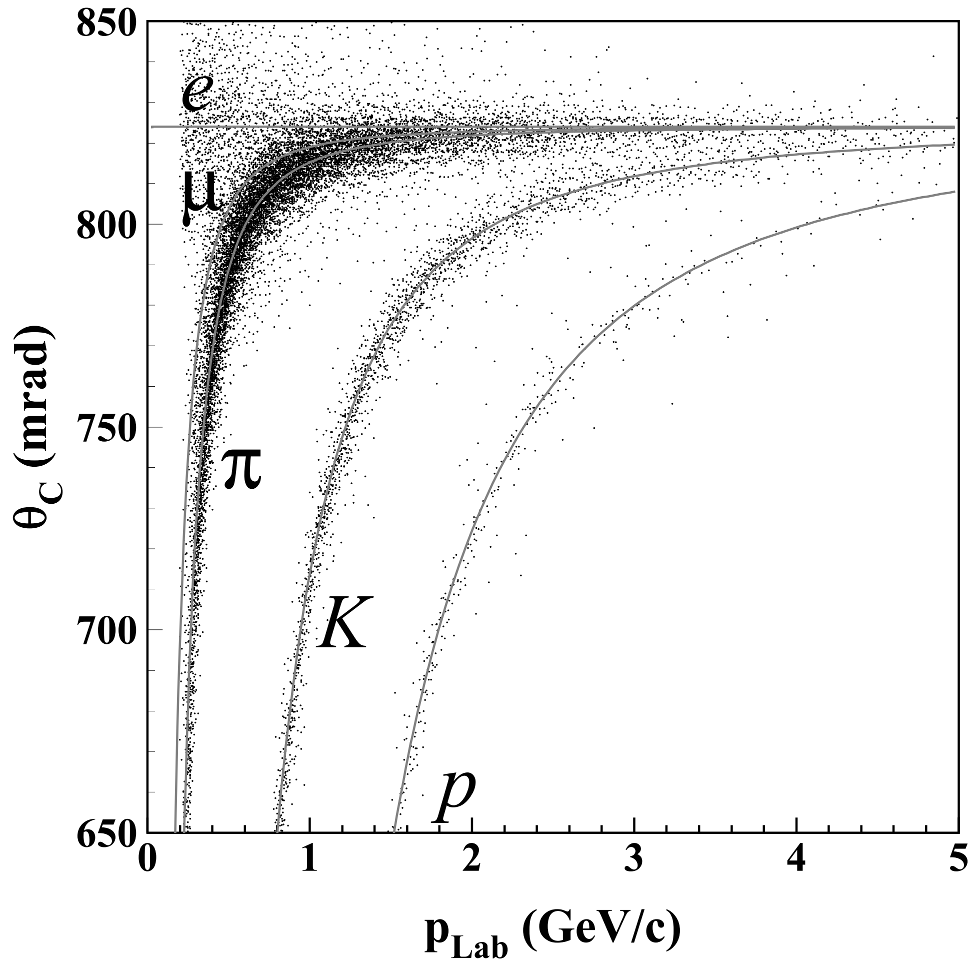






kaons can be separated up to 4 GeV/c

BABAR physics: decays of B^0 to study CP violation

b-tagging (78 % of $B^0 \rightarrow K^+ + X$)

golden channel for CP: $B^0 \rightarrow J/\psi + \phi$

and $\phi \rightarrow K^+ + K^-$

Comparision different PID methods for K/π separation

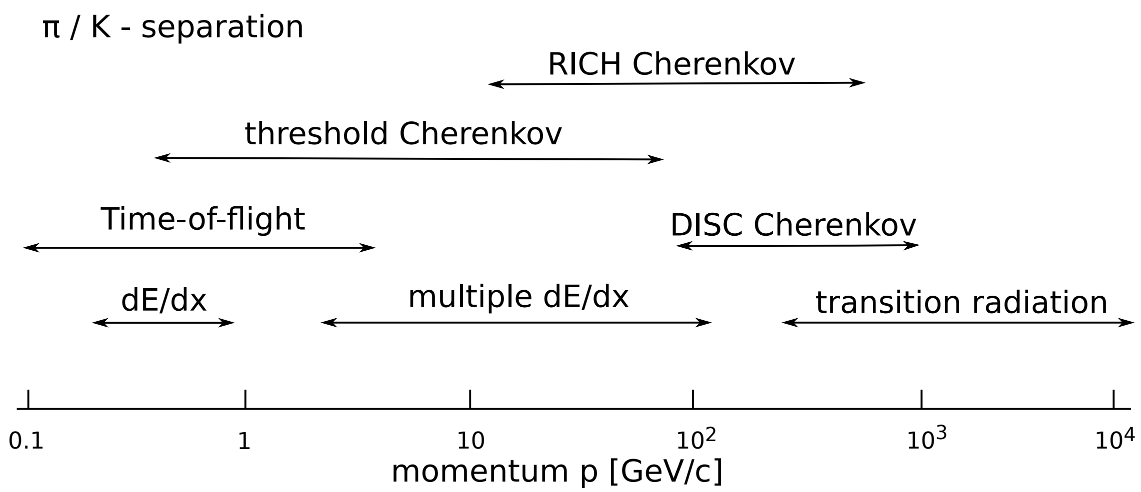
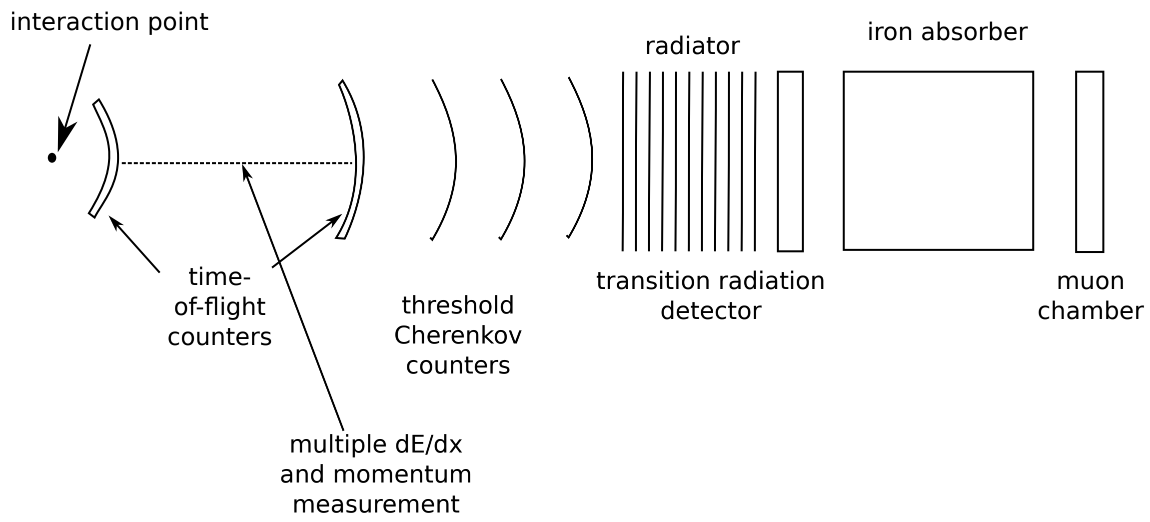


illustration of various particle identification methods for K/π separation along with characteristic momentum ranges.



a detector system for PID combines usually several methods