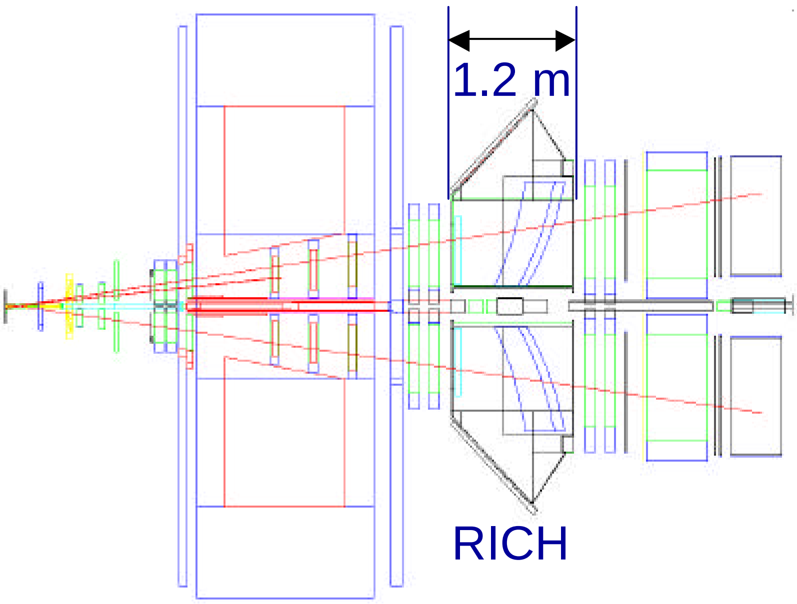
Examples

Application of vacuum based photodetectors in RICH systems

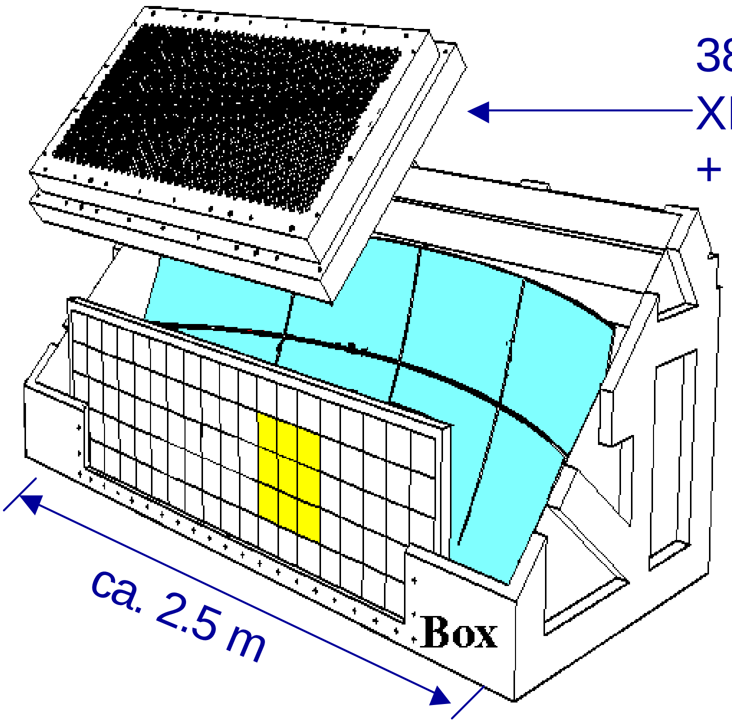
HERMES at DESY



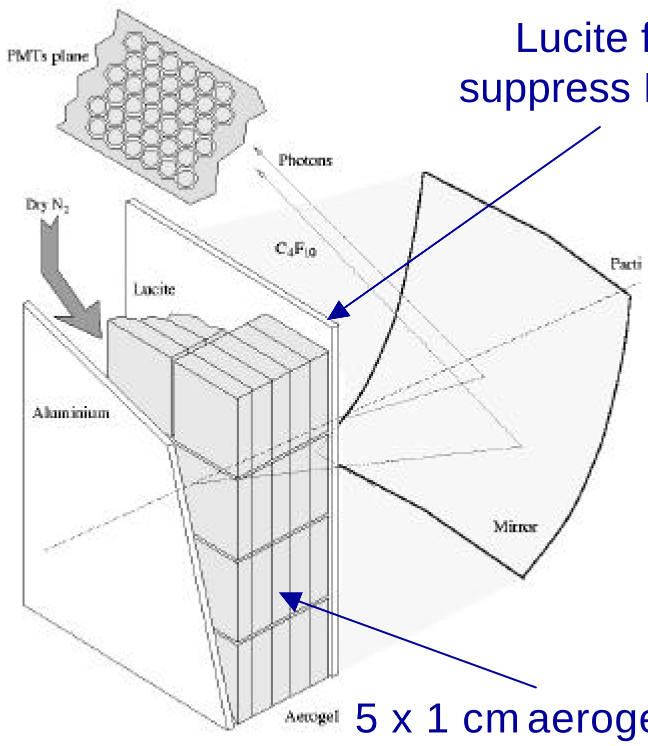
Deep inelastic $\vec{e}\vec{p}$ / $\vec{e}\vec{n}$ scattering
→ nucleon spin structure

Measurement of K asymmetries requires π/K separation from 1 to 20 GeV/c
→ 2 radiators

3D view of one half detector



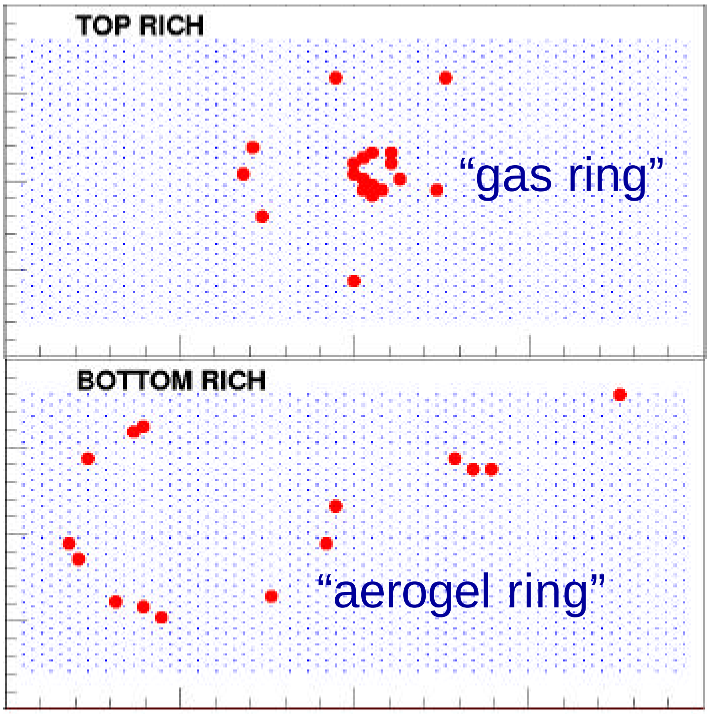
3870 PMTs, Philips XP1911/UV, Ø 3/4" + light funnels



Lucite foil (cut off at 290 nm) to suppress Rayleigh scattered photons

5 x 1 cm aerogel

D. Ryckbosch, NIM A 433 (1999) 98

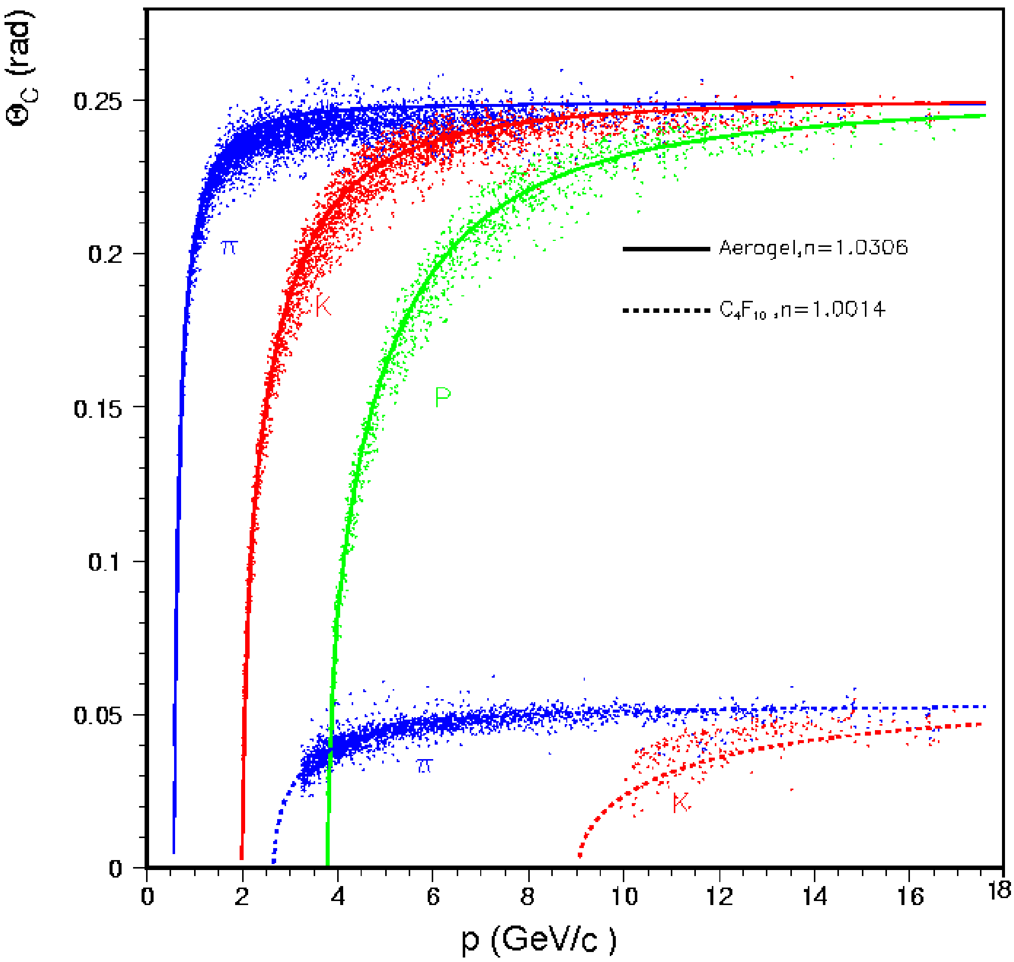


Online Event Display

σ_θ ~ 8 mrad

$N_{p.e.}$ (aerogel) = 8

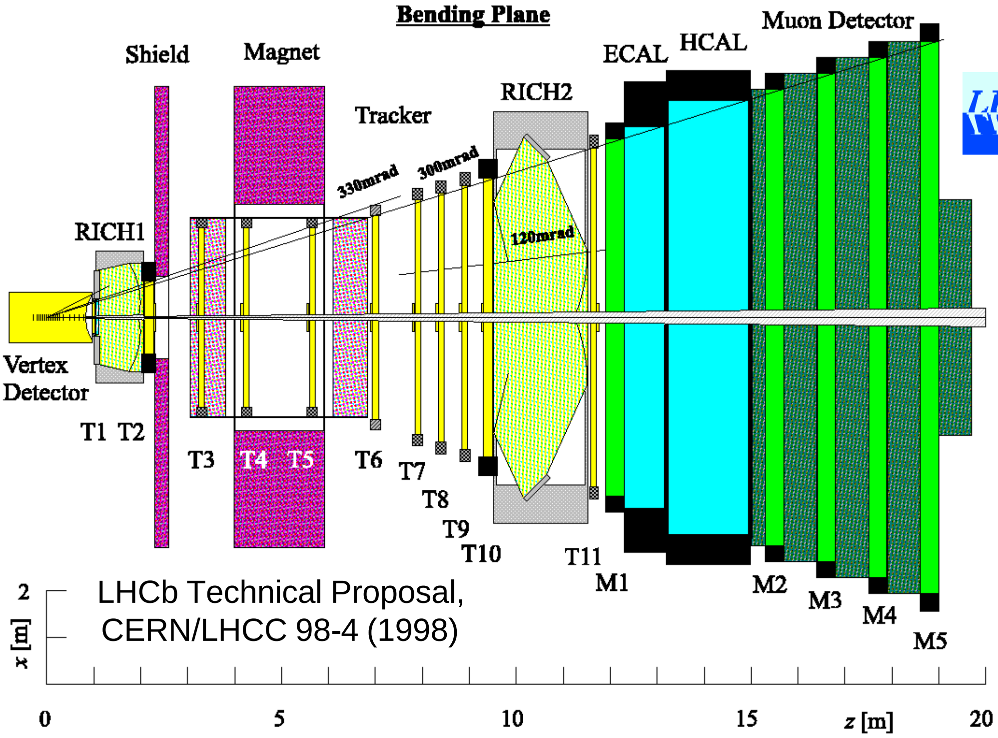
$N_{p.e.}$ (C_4F_{10}) = 12



The LHCb spectrometer

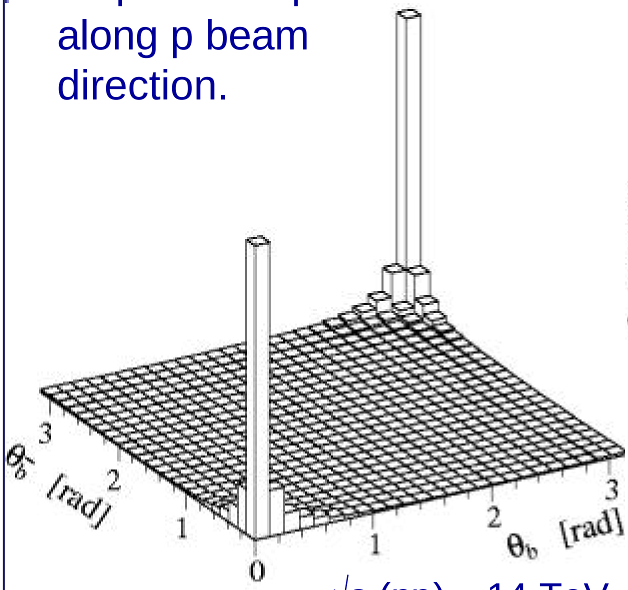
- Study of CP violation
- Study of rare decays

} in the B-meson system

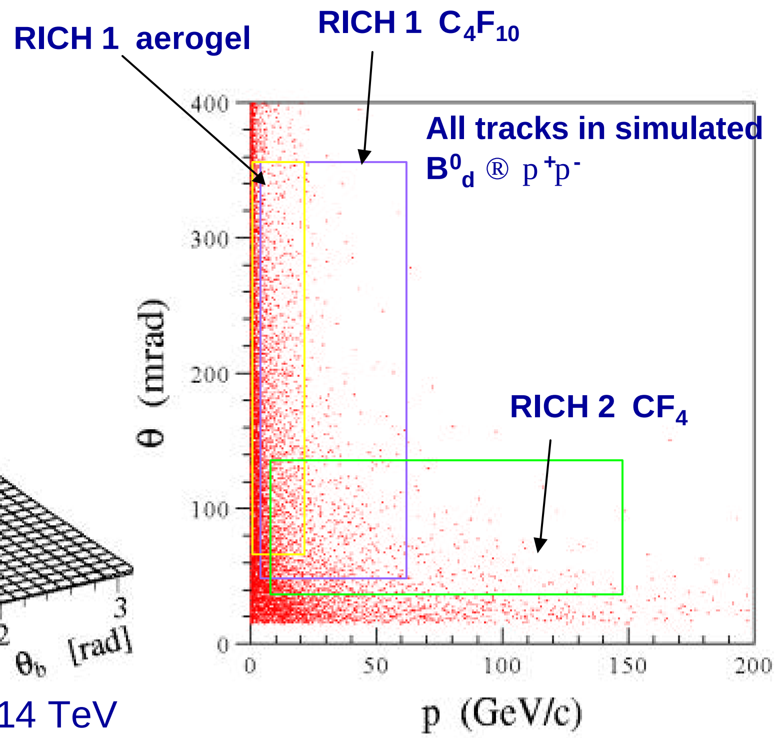


LHCb Technical Proposal, CERN/LHCC 98-4 (1998)

Single arm forward geometry.
$b\bar{b}$ pairs are produced along p beam direction.



$\sqrt{s}$ (pp) = 14 TeV

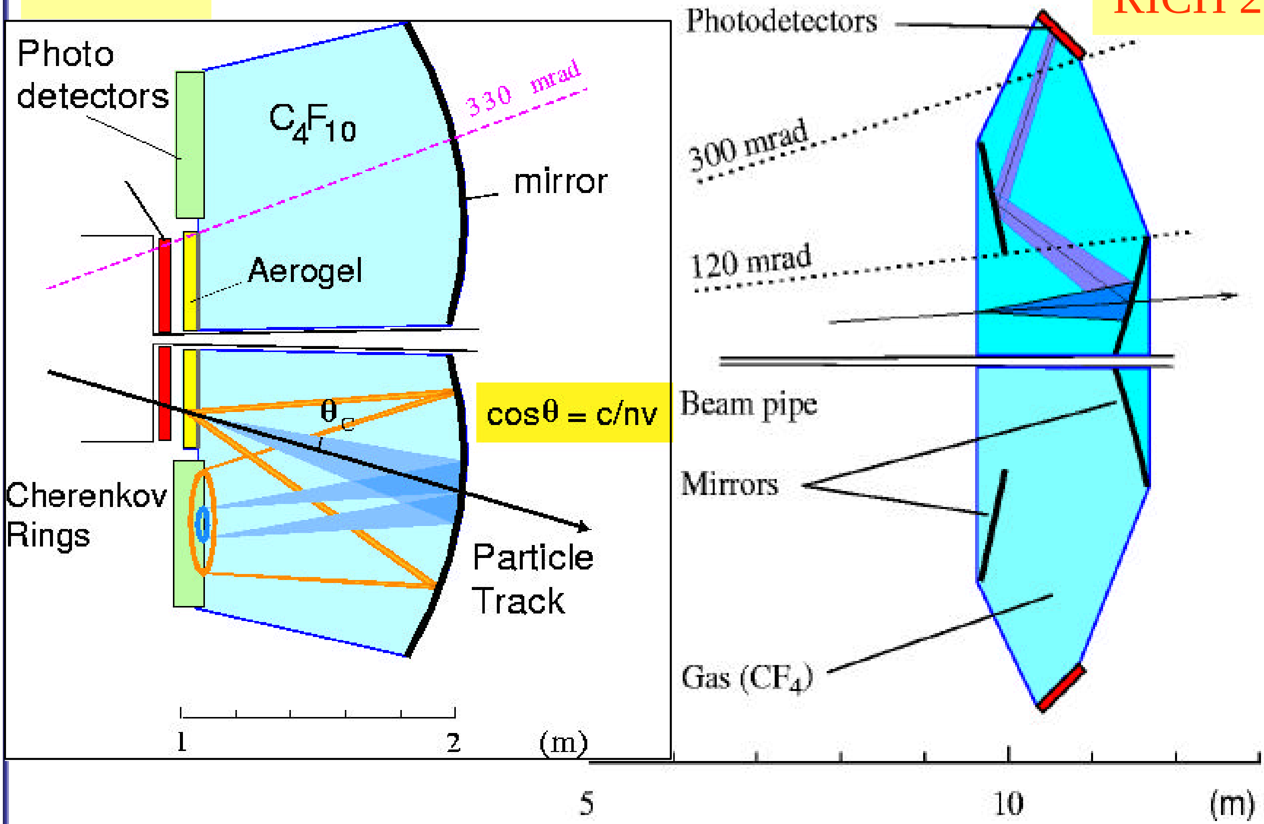


Study of CP violation in various B decay channels requires p/K separation in a large momentum range: $1 \leq p \leq 150$ GeV/c

➔ 2 RICH detectors with 3 different radiators

RICH 1

RICH 2



radiator	C_4F_{10}	aerogel
n	1.0014	1.03
p_{thresh} (π)	2.6	0.6 GeV/c
$N_{p.e.}$	55	15
σ_θ	1.1	1.45 mrad
p (3sigma)	70	20 GeV/c

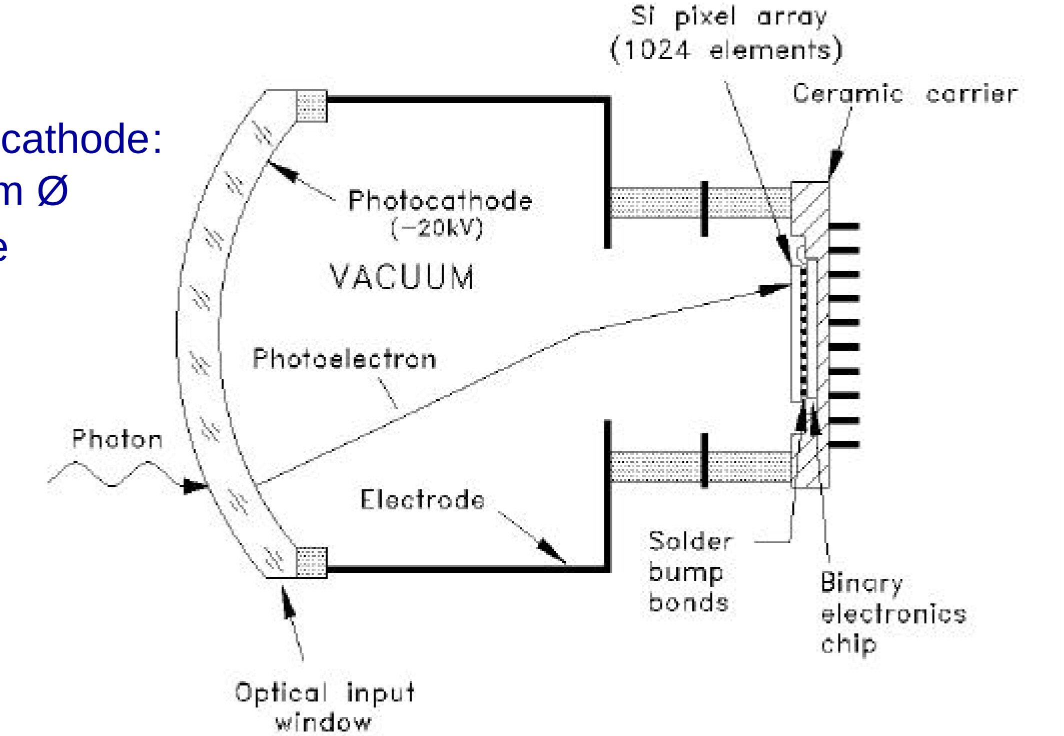
radiator	CF_4
n	1.0005
p_{thresh} (π)	4.4 GeV/c
$N_{p.e.}$	30
σ_θ	0.35 mrad
p (3 sigma)	135 GeV/c

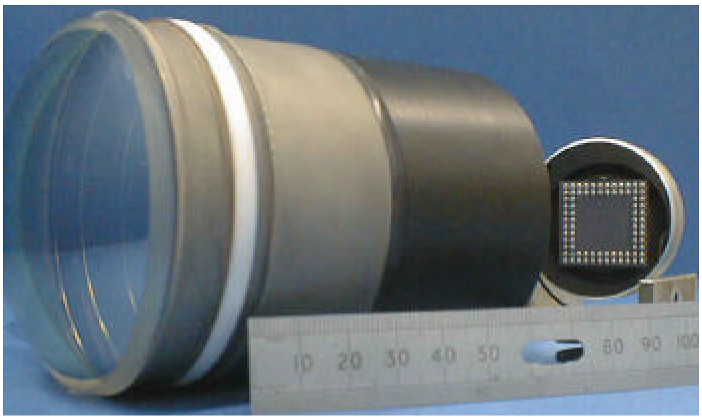
The LHCb RICH photodetector (baseline)

Pixel-HPD, fabricated by LHCb/ DEP(NL)

cross-focused, 80mm Ø, encapsulated readout electronics, 1024 pixels (500 µm x 500 µm), demagnification D ~ 5.

S20 photocathode: 72 mm Ø active





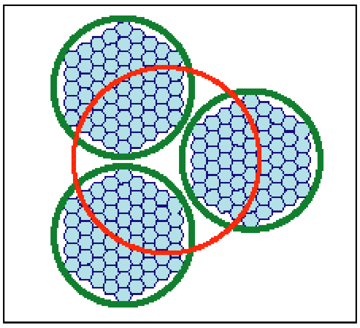
- full-scale prototypes (Phosphor screen or 61 pixel anode) tested .
- e- optics + sensitivity OK
- Final sensor + pixel electronics under development with ALICE tracker.

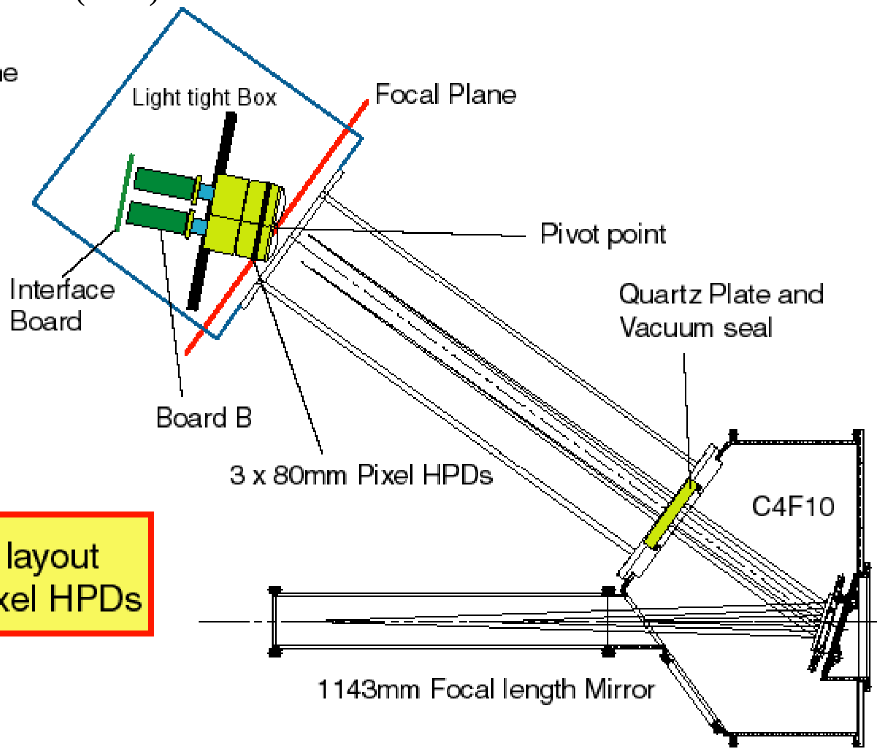
E. Albrecht et al., NIM A 442 (2000) 164-170.

Test beam set-up with Pixel HPD (3 x 61 pixels)

M. Alemi et al., NIMA A 449 (2000) 48-59.

Cherenkov Ring at Focal Plane

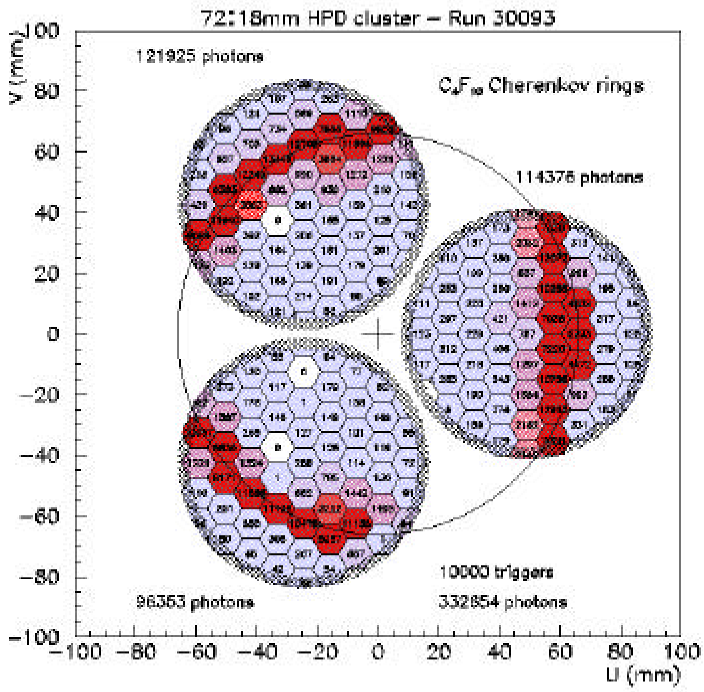




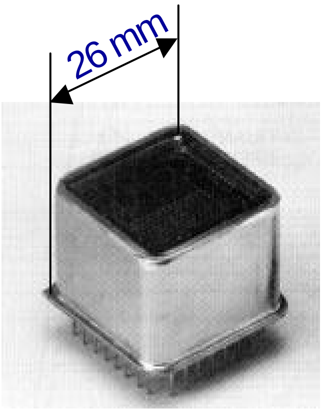
Sketch of prototype layout for cluster test of Pixel HPDs

Cherenkov angle is 53 mrad with C4F10 radiator at 1000mbar

Cherenkov Ring from C_4F_{10}

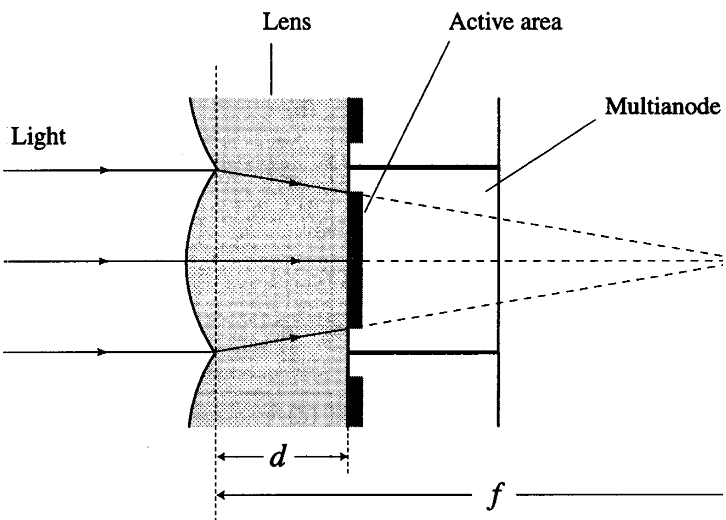


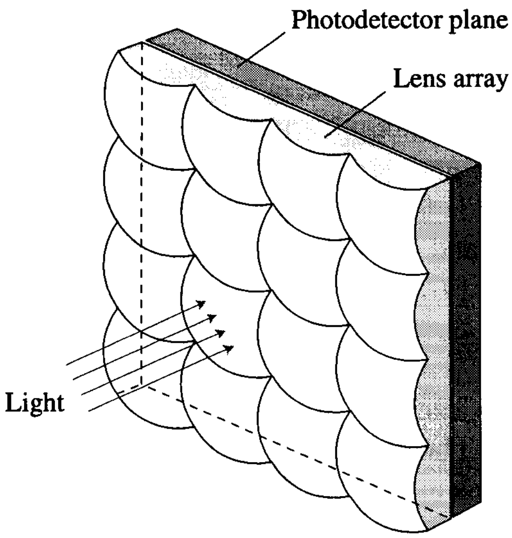
The backup solution



Hamamatsu MaPMT R5900

Poor filling factor (38%) is increased by quartz lenses (ca. x 1.5)

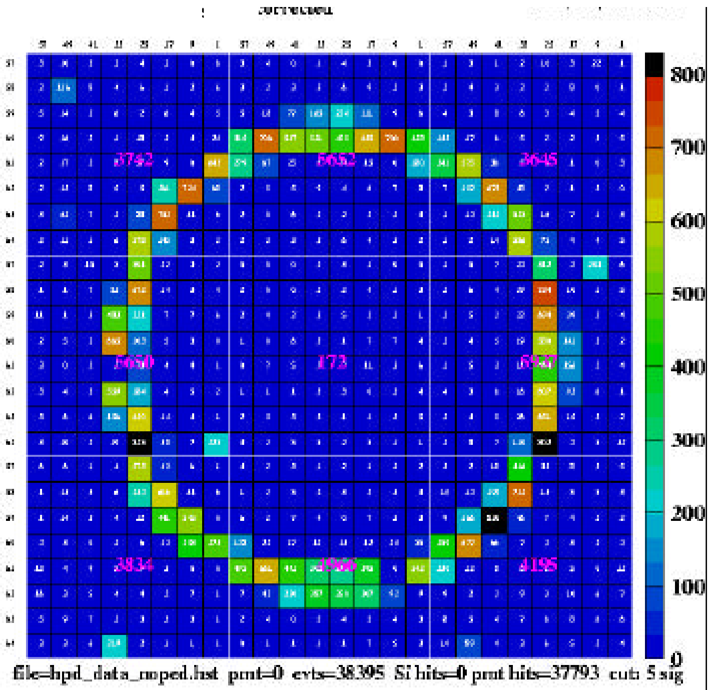




beam tests with a 3 x 3 MaPMT array

Cherenkov Rings from CF_4 at 700mbar

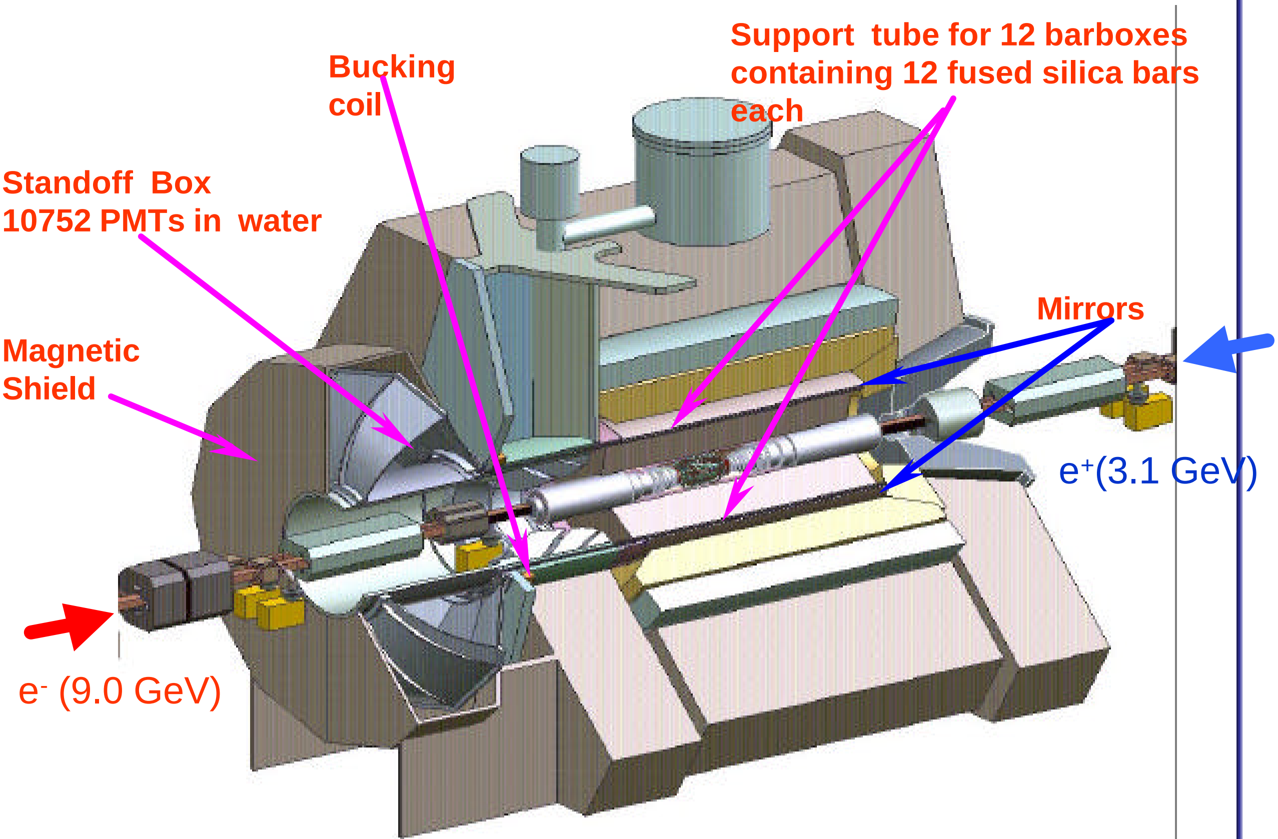
A. Duane at al. LHCb 98-039, RICH



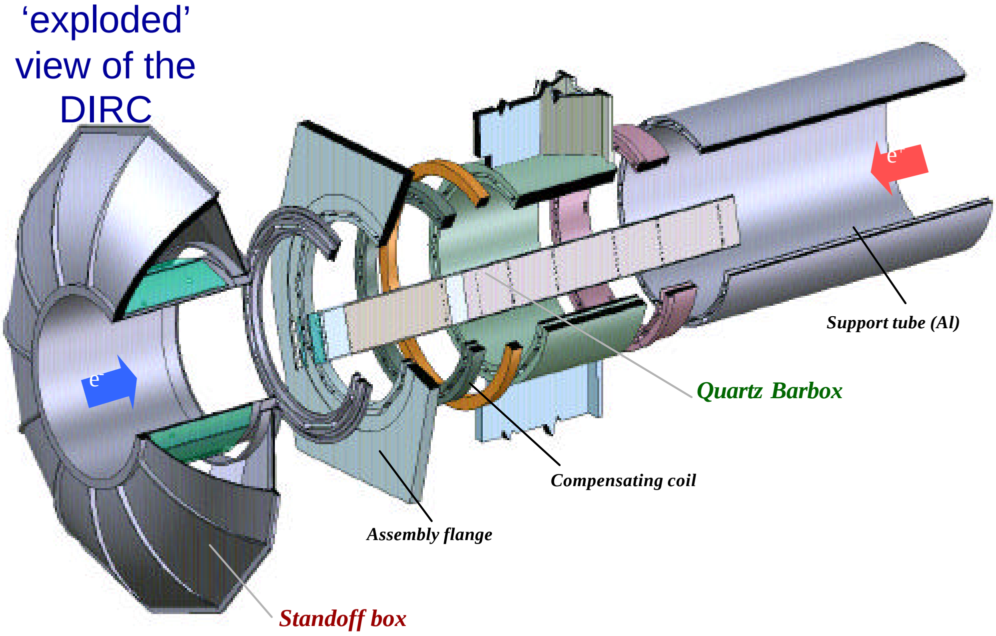
The DIRC of BaBar

(asymmetric B-factory at SLAC)

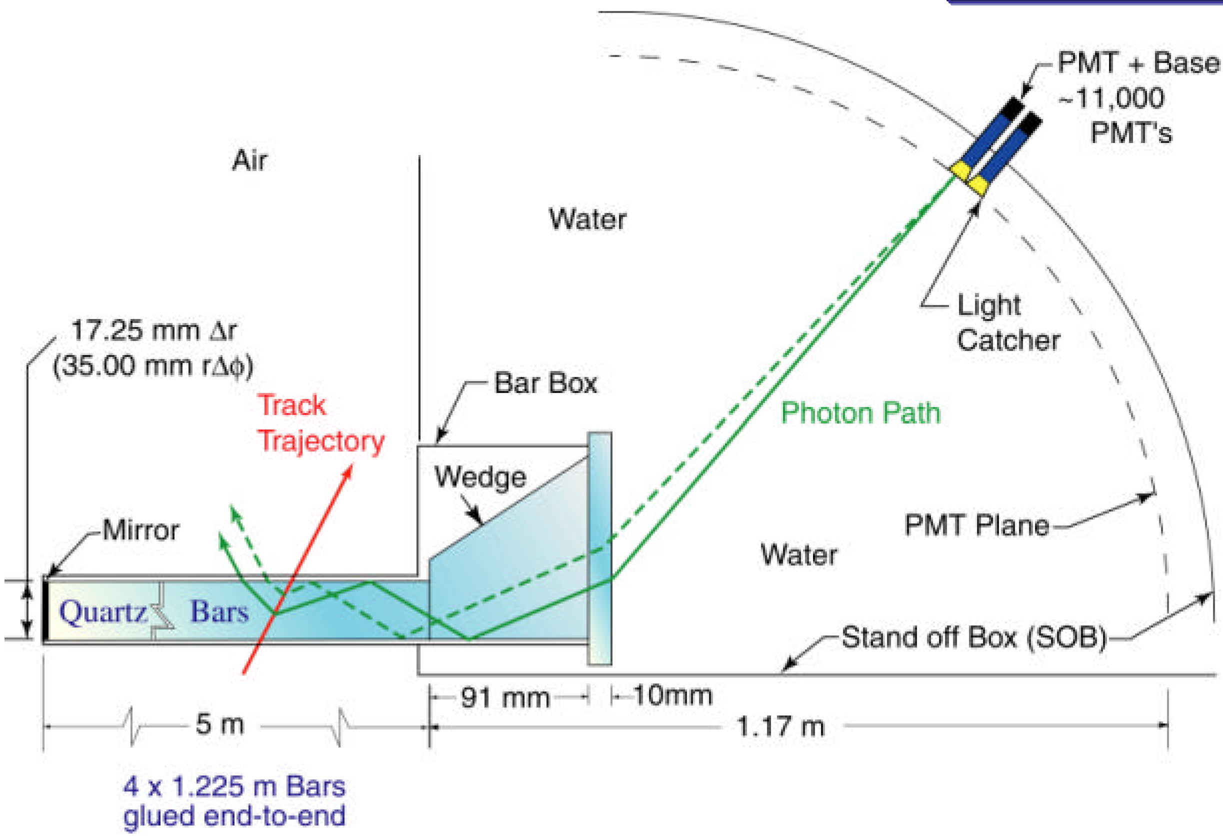
P. Cole et al, NIM A 343 (1999) 456
I. Adam et al., SLAC-PUB-8345



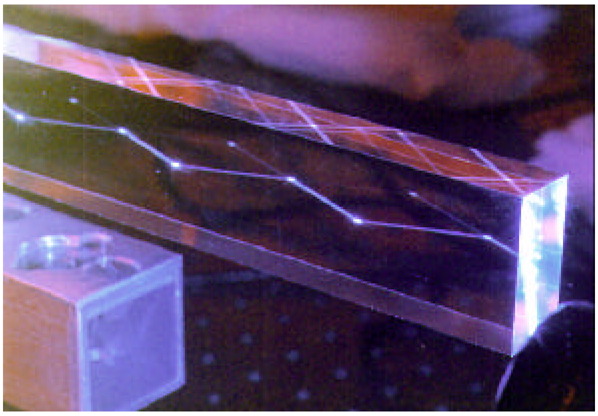
'exploded' view of the DIRC



Basic principle of the DIRC
Detection of Internally Reflected Cherenkov light



Transport of C-light by internal reflection in quartz bar. Detection by PMT array. Stand off tank filled with water for ref. index matching.



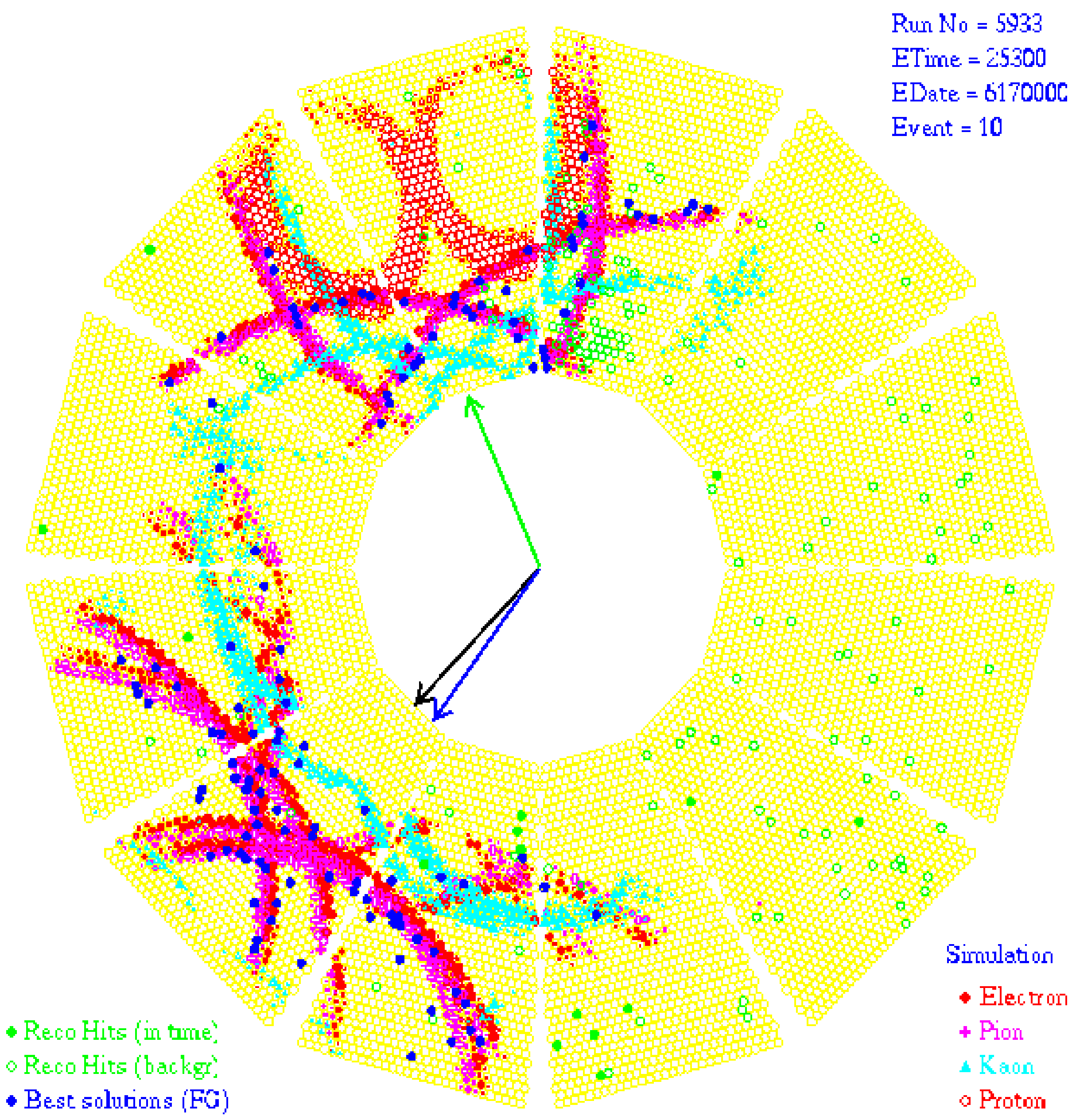
- $N_{quartz} = 1.47$,
- $\theta_{crit.} = 43^o$, $\theta_c^{max} = 47^o$
- T = 99.9 % / m
- R = 99.96 %
- ~200-400 bounces
- loss ~10-20% = $f(\theta_{dip})$

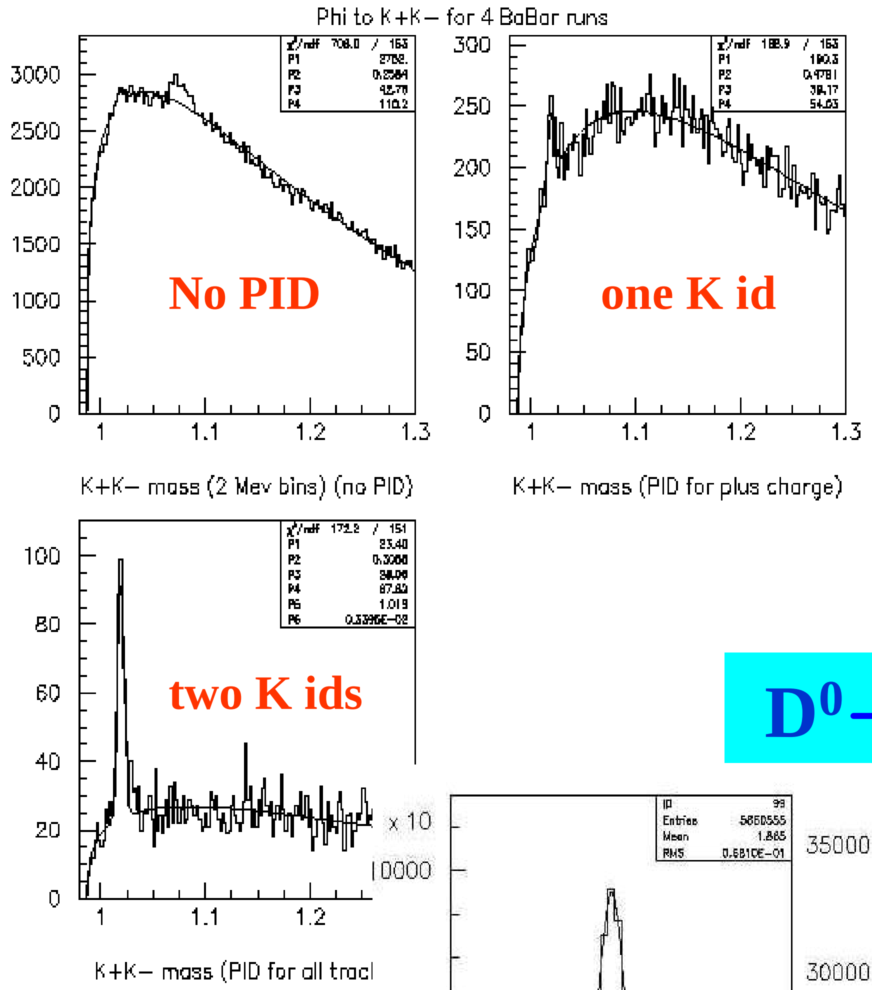
- σ_θ = 9.8 mrad, (7.0 mrad from $Ø_{PMT}$=28 mm, 5.4 mrad from dn/dE).
- $N_{p.e.} \sim 30$
- π/K separation of 3.1 σ at p = 3 GeV/c

Event reconstruction:

Cherenkov “ring” is decomposed into disjointed segments.

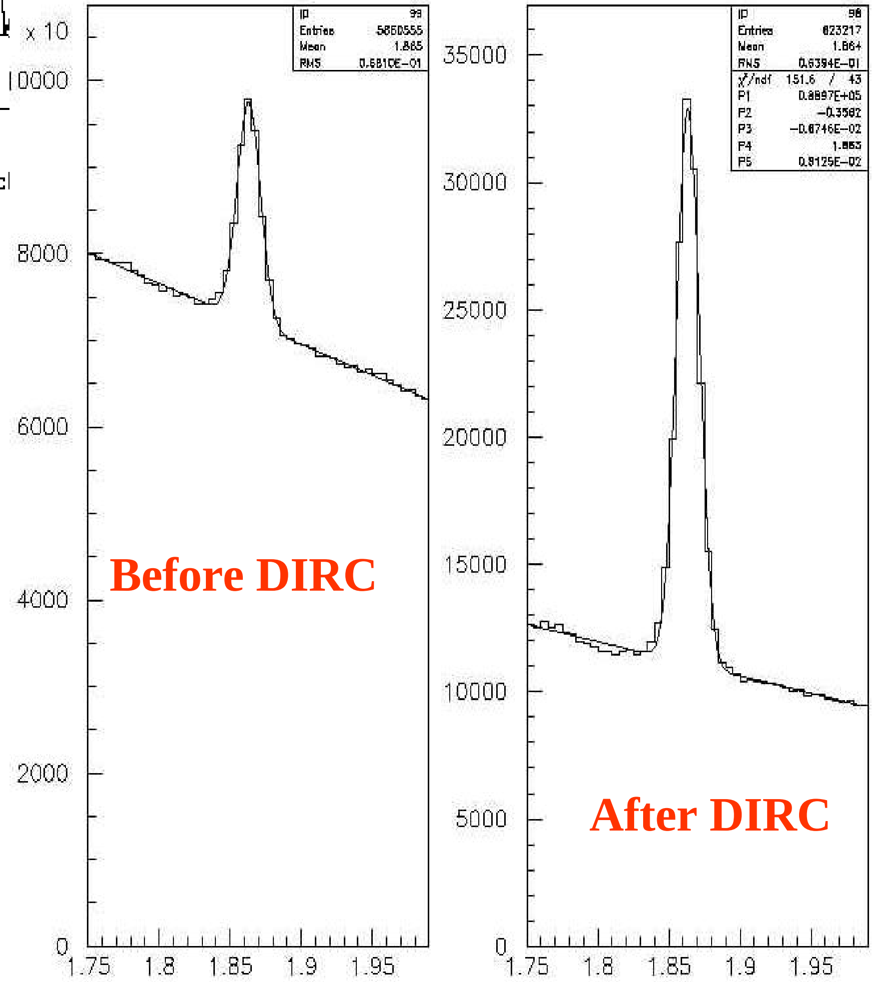
- Calculate likelihood for pattern to be generated by signal or background using e,μ,π,K,p hypotheses.
- Arrival time of photons t = f(θ) can be used as consistency check for bckgd suppression.

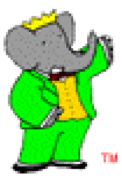




$f \rightarrow K^+K^-$

$D^0 \rightarrow K^+p^-$





Auxiliary systems for RICH detectors

Goal: Operate RICH at optimum physics performance in a safe and stable way.

This requires usually a number of auxiliary systems like...

- Circulation systems for radiator fluids (gas or liquid)
- Circulation systems for detector gases (with TEA / TMAE)
- Measurement of radiator transparency
- Measurement of radiator refractivity
- Cleaning of fluids

not covered in this lectures, but very important…

Slow Control (monitoring, control, alarm management)

Circulation Systems for radiator fluids

Some basic considerations

An ideal radiator vessel

- is perfectly leak tight
- is mechanically stable, i.e. it stands any $\Delta p = p_{rad} - p_{atm}$
- has massless front and rear walls (in terms of X_0)

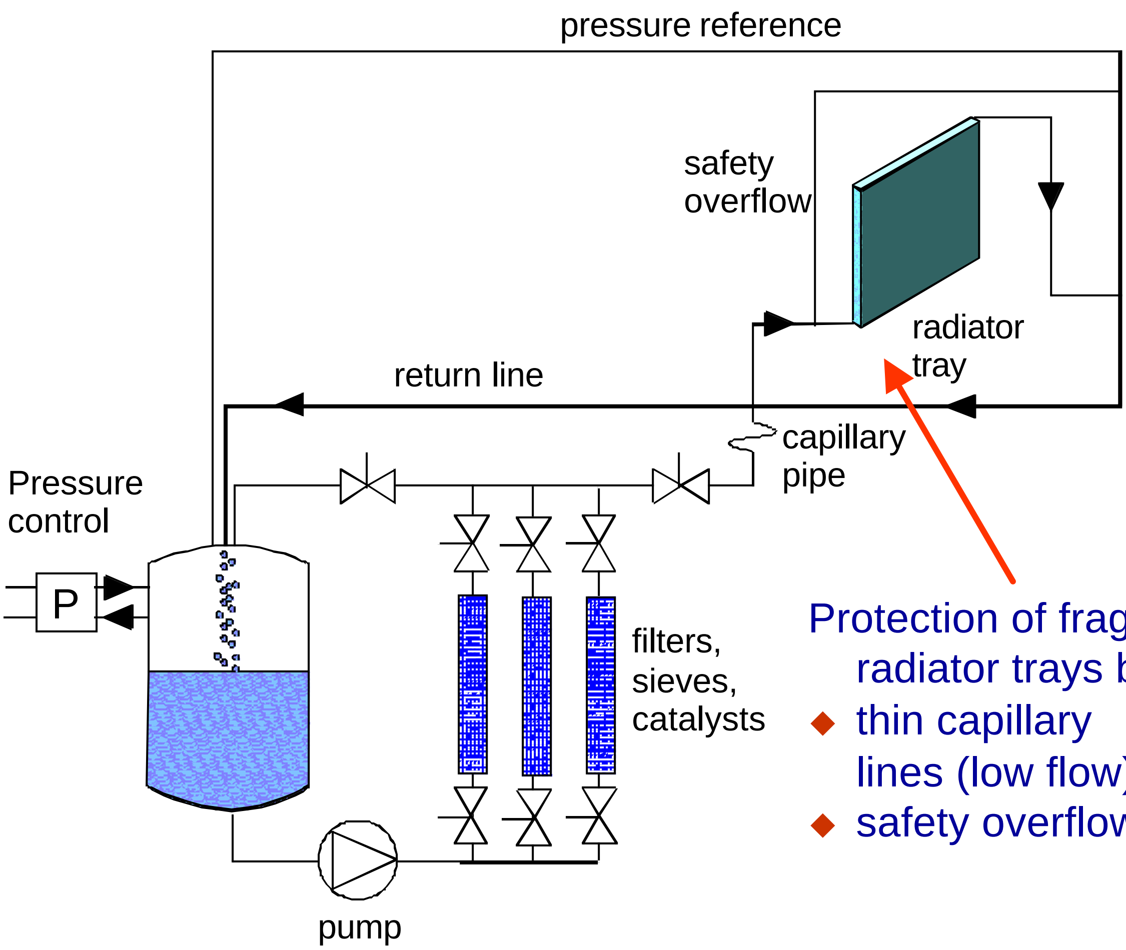
A real radiator vessel

- has a certain leak rate
- stands only very small Δp (some mbar)
- represents always too much material

➔ Circulation and online cleaning of radiator fluid (liquid or gas) indispensible.

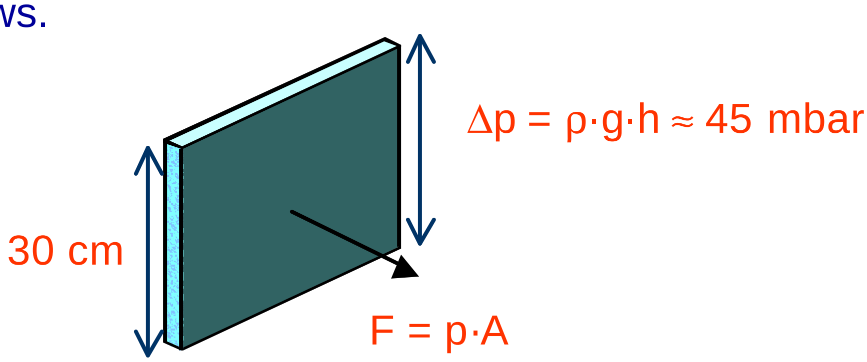
➔ Circulation system required: cope with atmospheric pressure variations, allow filling and emptying of the fluids.

Schematic of a radiator liquid circulation system for C_6F_{14} (DELPHI)



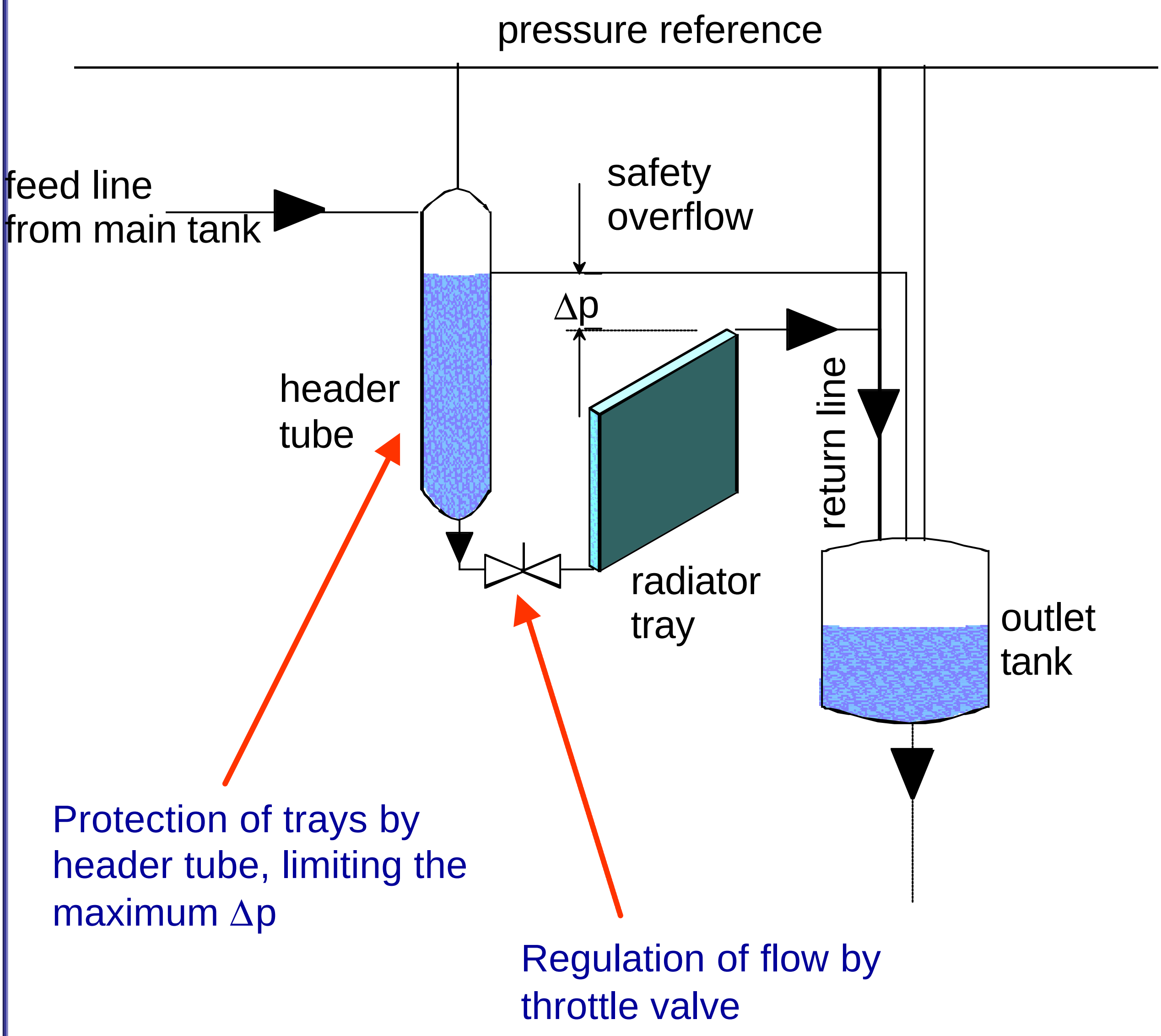
Protection of fragile radiator trays by
- thin capillary lines (low flow)
- safety overflow

The high density of C_xF_{2x+2} liquids ($\rho \approx 1.6$ g/cm^3) results in considerable hydrostatic pressures and forces on the windows.

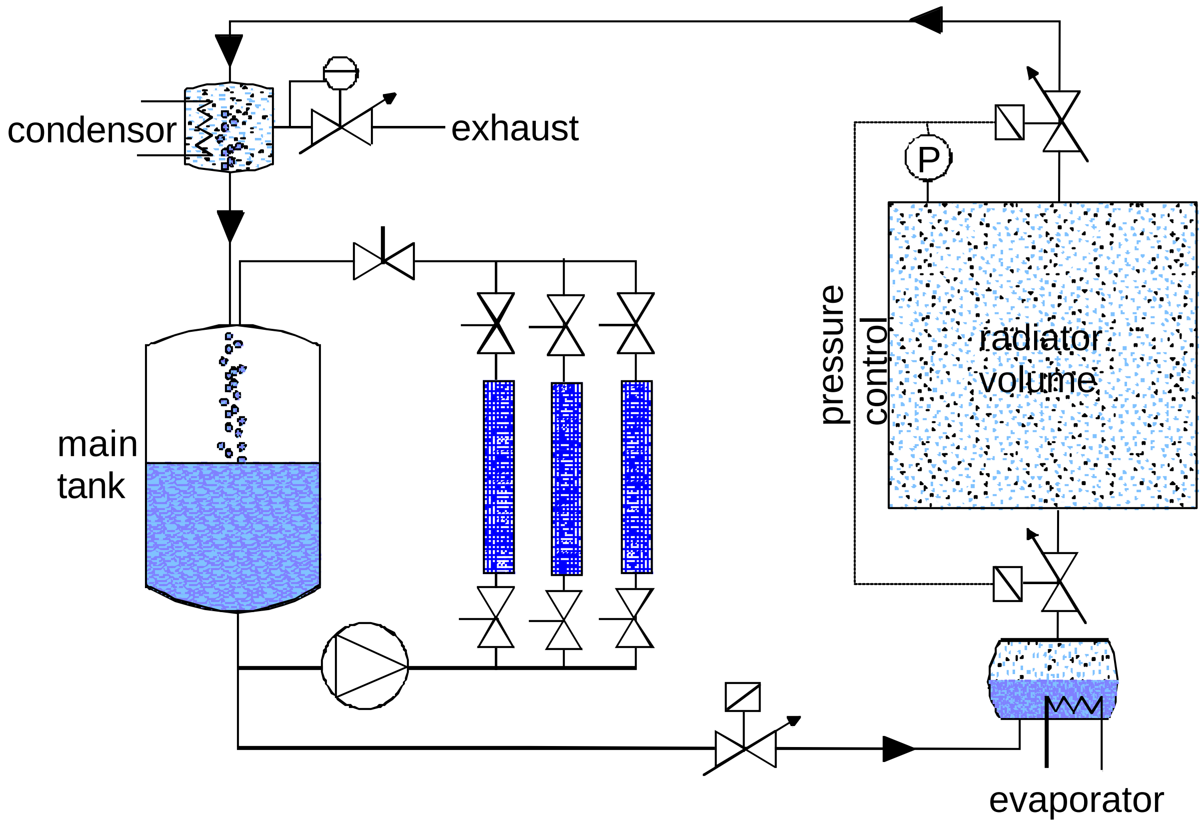


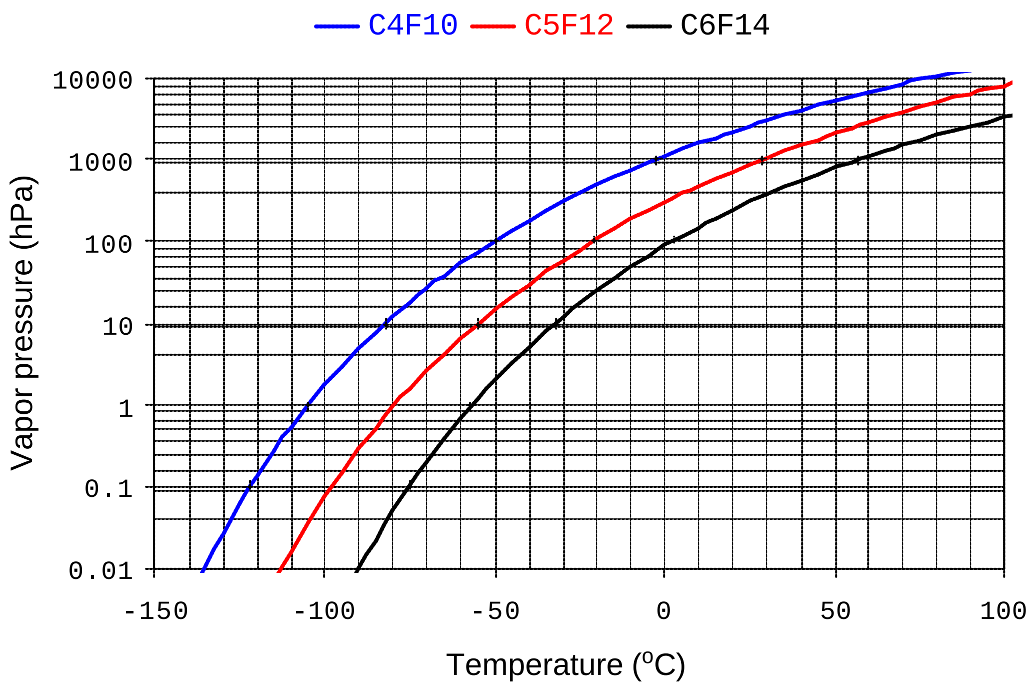
$\rightarrow$ DELPHI operates radiators at -45 mbar underpressure.

Detail of a proposed gravity flow system for C_6F_{14} (ALICE)



Schematic of a radiator gas circulation system for C_5F_{12} (DELPHI)





Circulation systems for detector gases

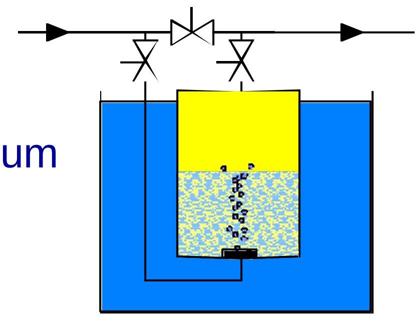
Provide detector gas of high purity, correct pressure, flow (and temperature).

Purity: no electronegative impurities ! Keep O_2 and H_2O below 1 ppm. Use filters (oxysorb) plus high quality components (no rubber, no plastic, stainless steel whenever possible).

2 variants:

1) TMAE / TEA based systems.

Gas is photosensitive + amplification medium in a MWPC or TPC detector. TMAE / TEA admixture by bubblers.
$T_{system} > T_{bath}$!



Temperature controlled water bath

2) CsI based systems.

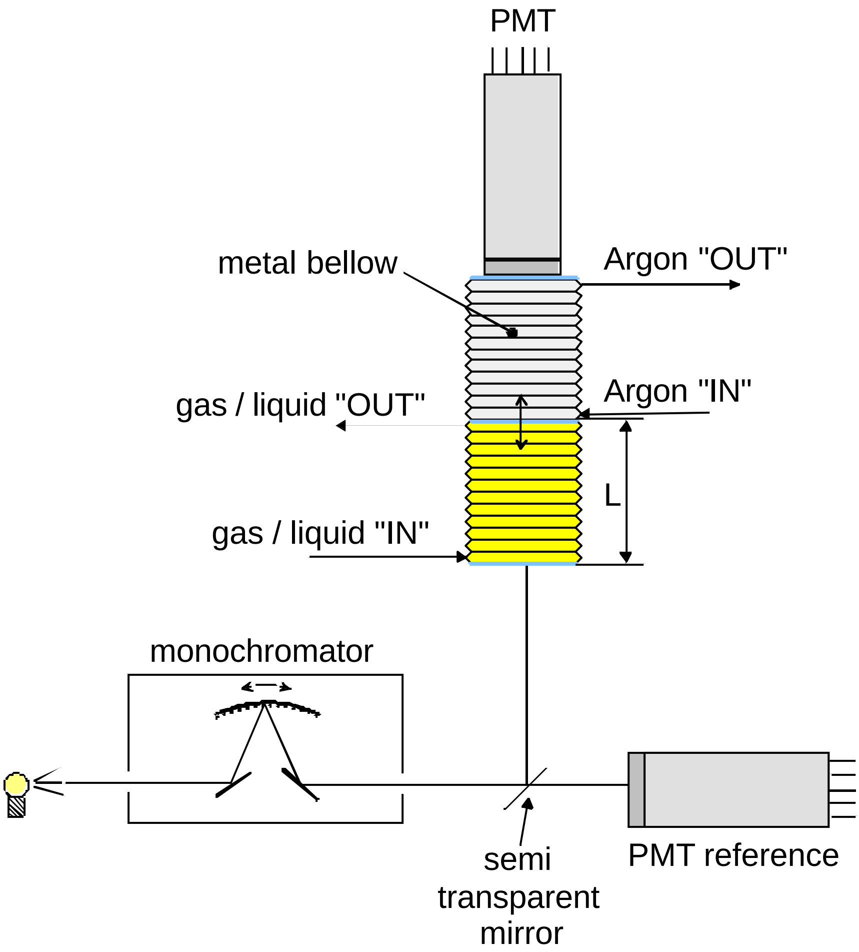
Gas is only amplification medium. Problem: CsI must not come in touch with air for more than a few minutes !

Transparency measurement

Transparency of the radiator medium crucial for yield, particularly for RICHes in the UV (TMAE, TEA, CsI).

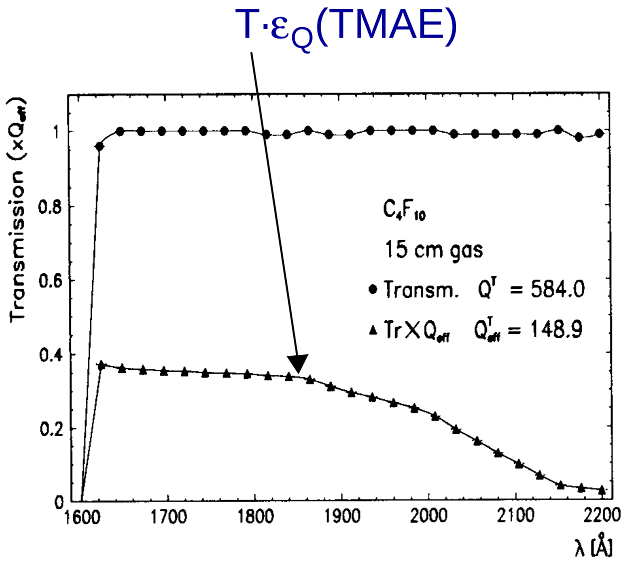
Regular monitoring required.

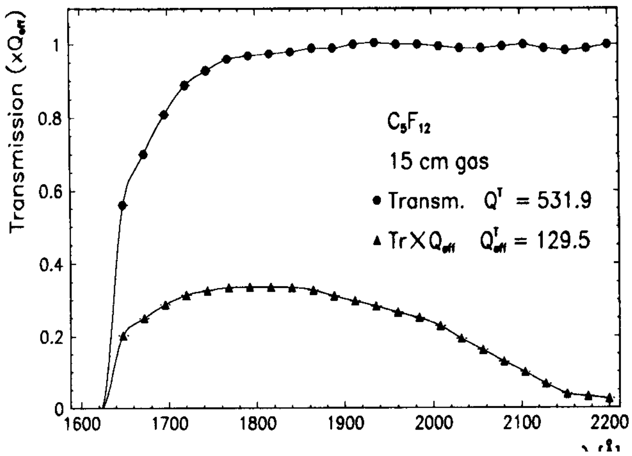
Wavelength dependent monitoring ➔ monochromator set-up

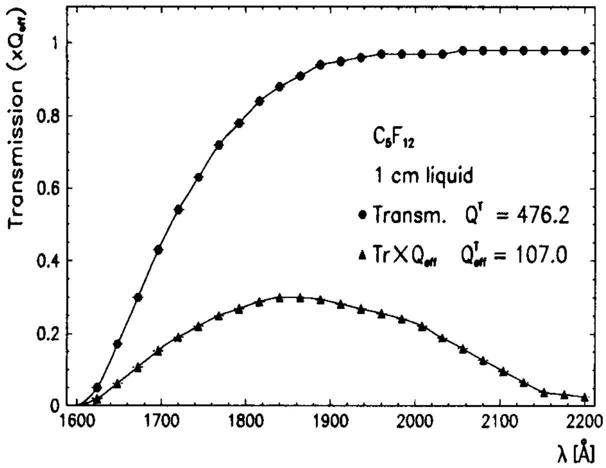


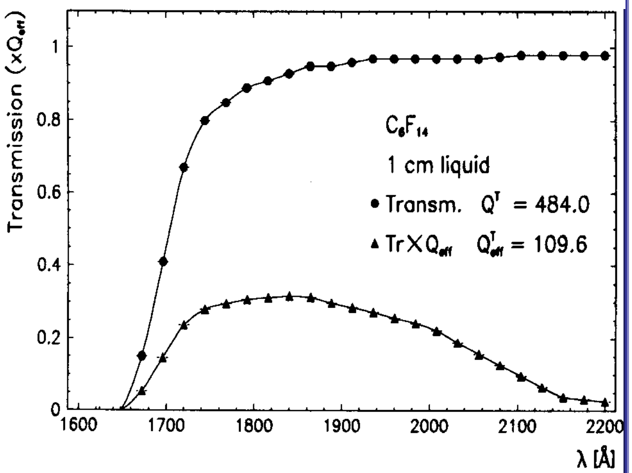
G. Lenzen et al., NIM A 343 (1994) 268

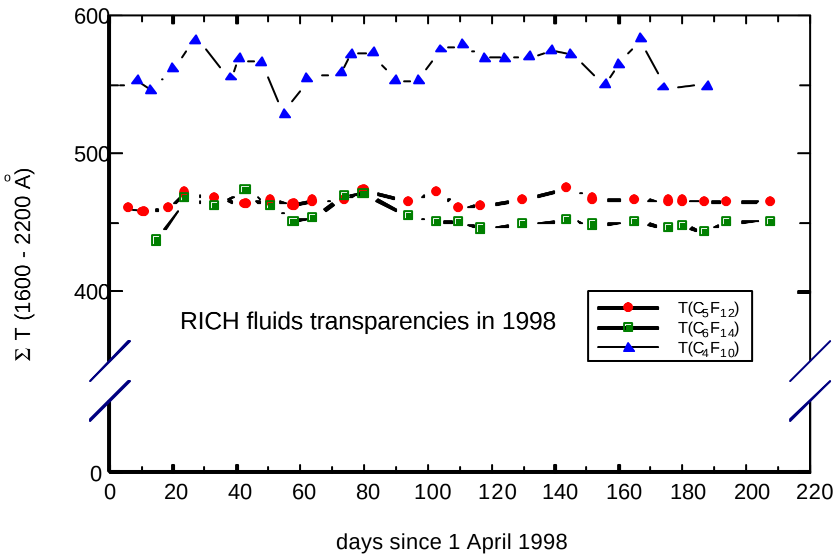
T-measurements in DELPHI





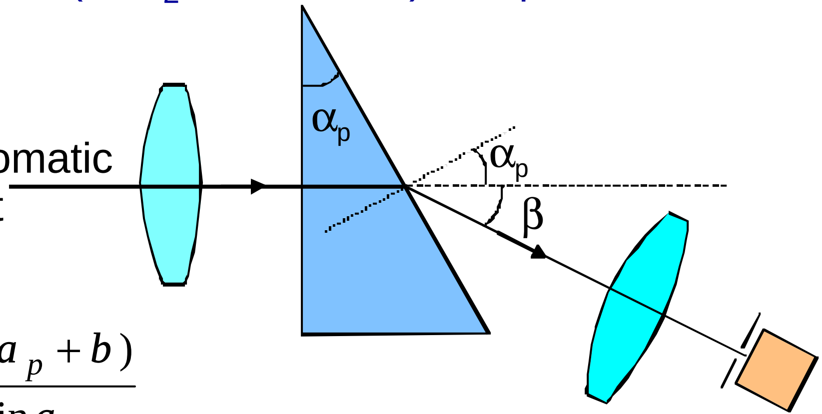






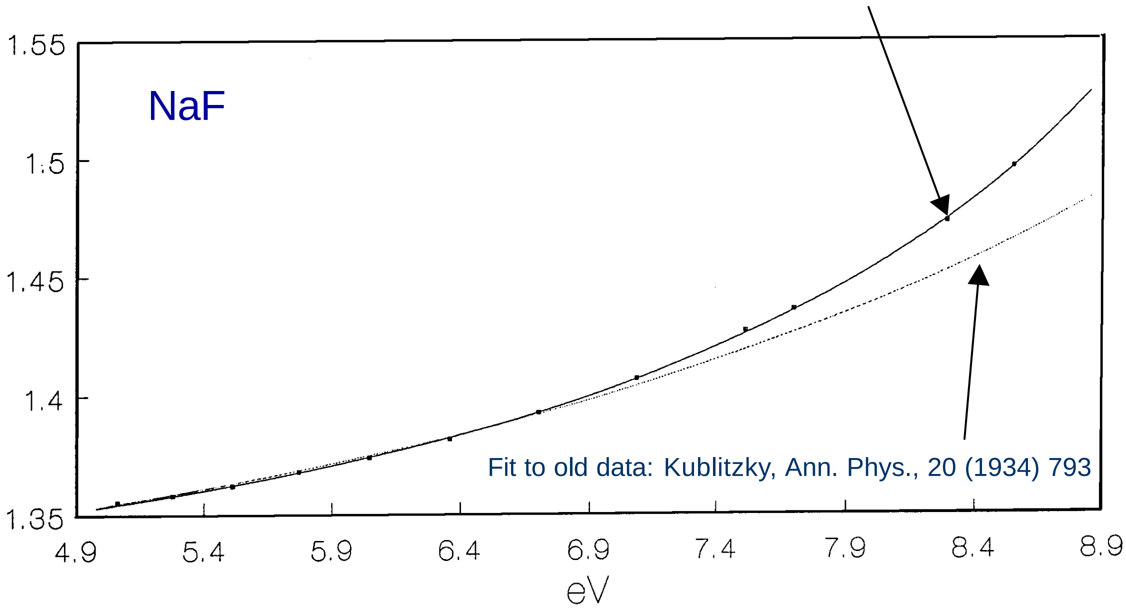
Measurement of refractive indices

- For solids (CaF_2, NaF, LiF…) use prism method



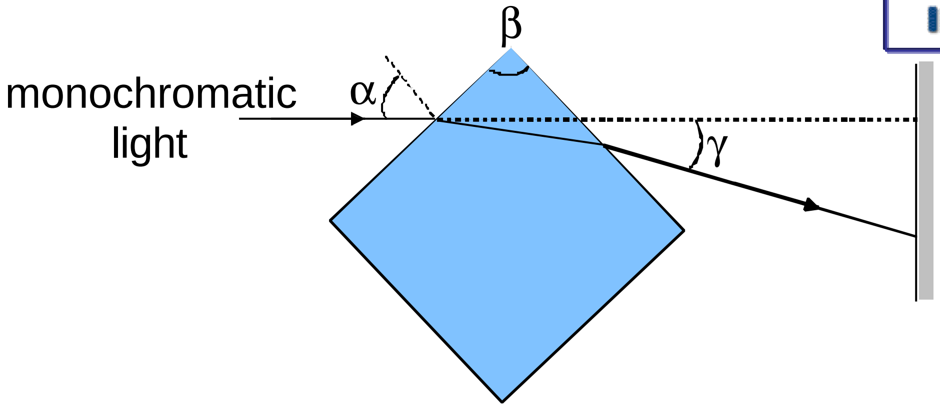
$$n_p = \frac{\sin(\alpha_p + \beta)}{\sin \alpha_p}$$

(M. Hempstead et al. NIM A 306,(1991) 207)



- For liquids (e.g. C_6F_{14}) a hollow quartz prism can be used.

- A method for measuring to aerogel tiles

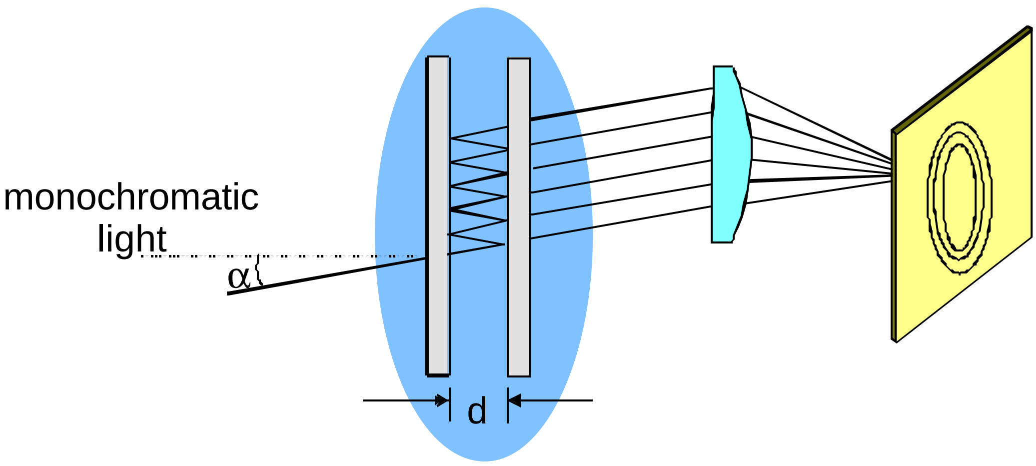


$$\gamma = \alpha - \beta + \arcsin\left(n \cdot \sin\left(\beta - \arcsin\left(\frac{\sin\alpha}{n}\right)\right)\right)$$

β and n can be determined from two measurments with different α.

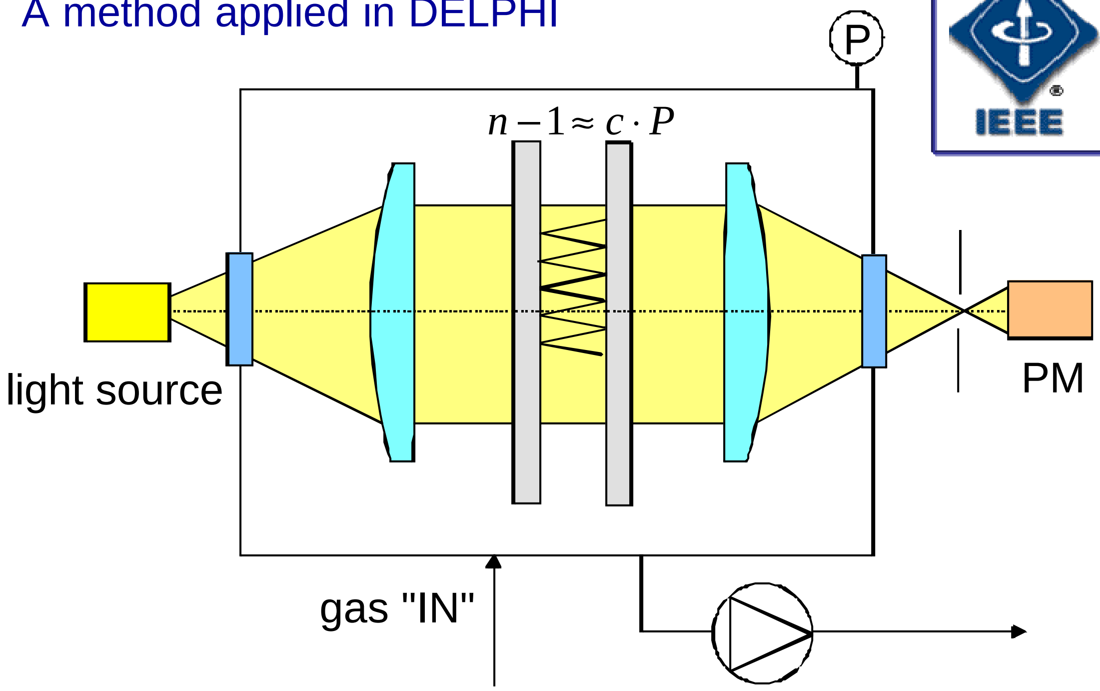
(A.R. Buzykaev et al. NIM A 433,(1999) 396)

- For gases a Fabry-Perot spectrometer may be used



Constructive interference: $2d \cdot n \cdot \cos\alpha = m\lambda$

A method applied in DELPHI

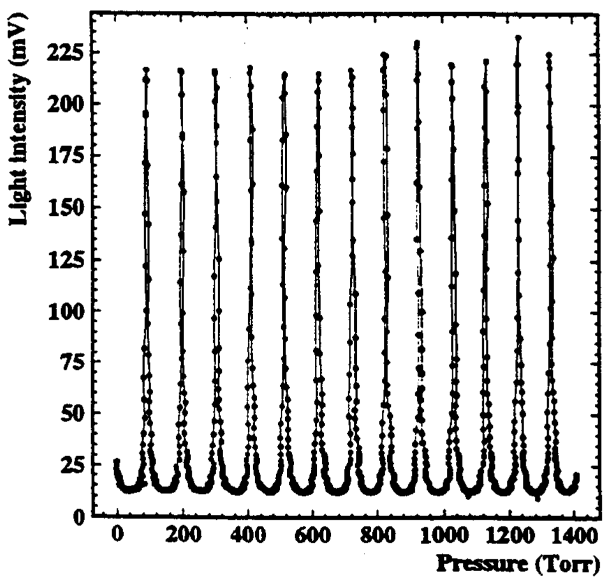


Vary gas pressure from 0 to p and observe modulation of central fringe.

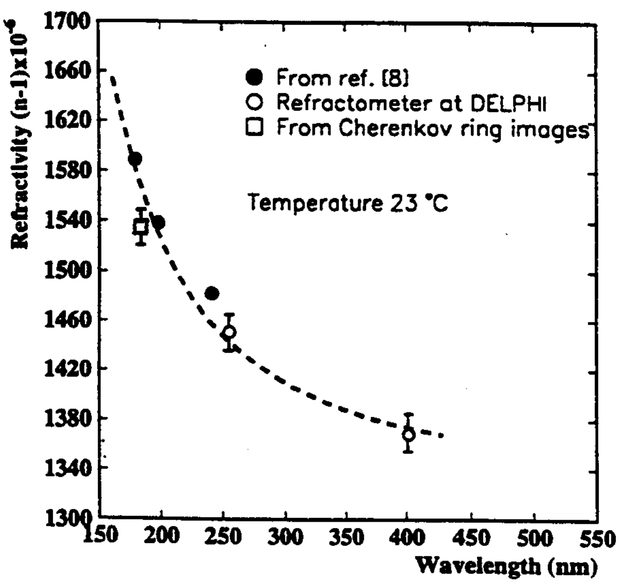
For $n-1 \ll 1$ $\quad n-1 \approx c \cdot P = \dfrac{l}{2d} N_f(P)$

E. Fokitis et al., Nucl. Phys. B (Proc. Suppl.), 1995, 246

C_4F_{10} gas, λ = 253.7 nm



C_4F_{10} gas, T=23ºC, p=760 Torr



Cleaning of Cherenkov fluids

- Gases and liquids used as Cherenkov radiators are usually procduced by industry for conventional applications which do not require high purity.
- Example Fluorocarbons: fire extinguishing agent, coolant.

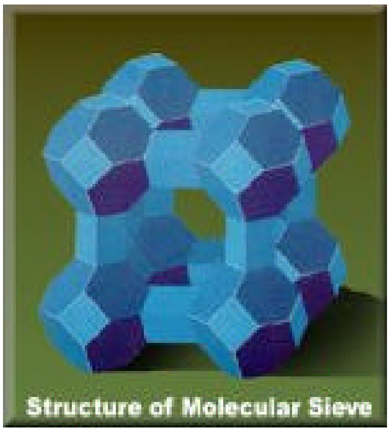
➔ Use as Cherenkov radiators requires removal of dissolved water, oxygen and other impurities, which are not transparent below $\lambda \leq 200$ nm.

Cleaning applied to liquid or gas phase

Molecular sieves

microporous aluminosilicate crystal

Available with cavity sizes 3 - 13 Å.
It traps molecules smaller than the cavity and repels others.



$Na_{12}\,[(AlO2)_{12} \bullet (SiO_2)_{12}] \bullet XH_2O$

Used as beads of 2-3 mm ø

Main application: removal of water.
Capacity for : ca. 200 mg H_2O / g

Regeneration by baking at T>200ºC under dry air (N_2) flow

Oxygen removal

Use of chromium based (CrO_3 "OXISORB") or copper based reducing agents.

Remove O_2 (< 5ppb) but also H_2O (<20 ppb)

Oxisorb cartridges are fairly expensive (ca. 1000 Euro for a cartridge with 9 l O_2 capacity) if large material quantities with high contamination levels are to be cleaned.

Activated carbon

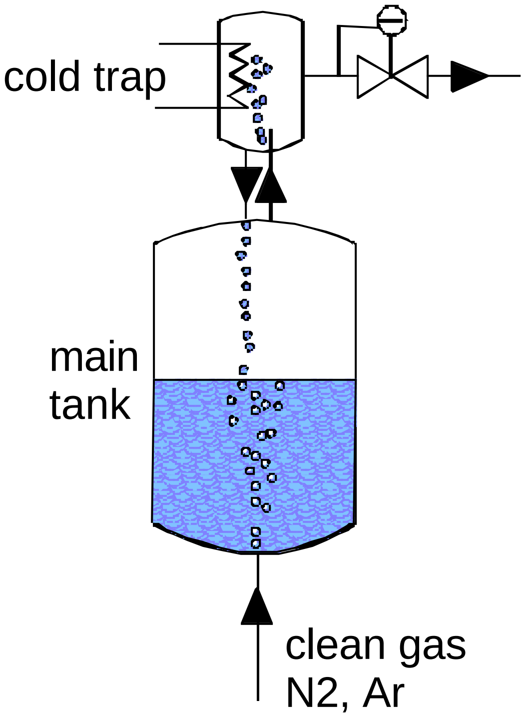
Carbonisation → at 1000ºC

Sponge-like material with molecular pore dimensions and huge specific surface (800-1600 m²/g

Mainly organic contaminants are trapped inside pores. Saturated material can be thermally regenerated or replaced (because it is cheap).

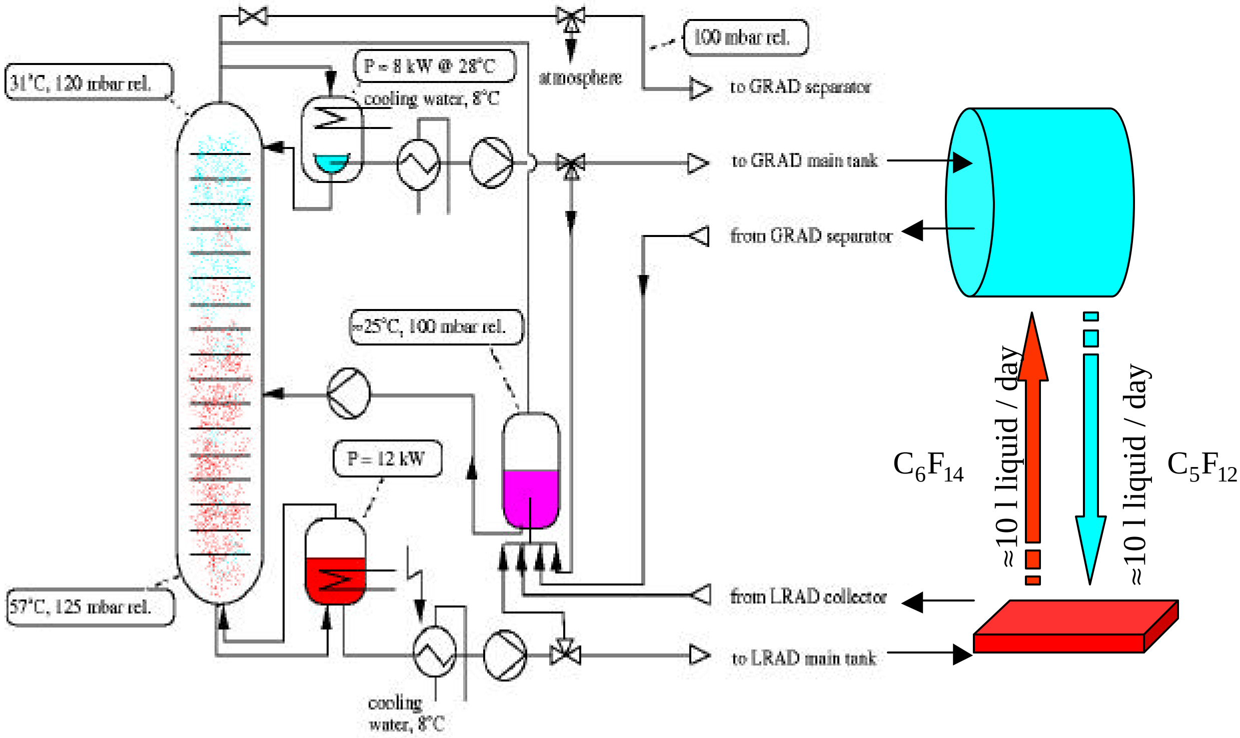
Important: activated carbon cartridges have should be combined with fine pore filters!

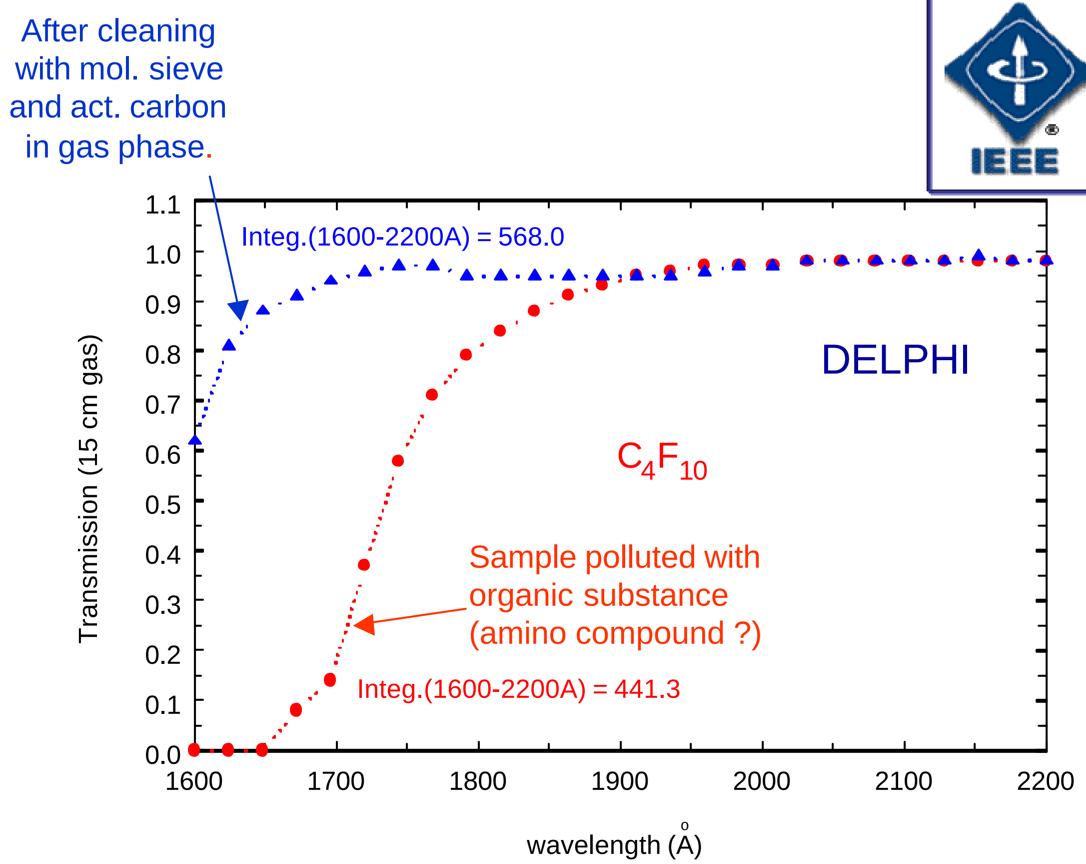
"Washing" of liquids

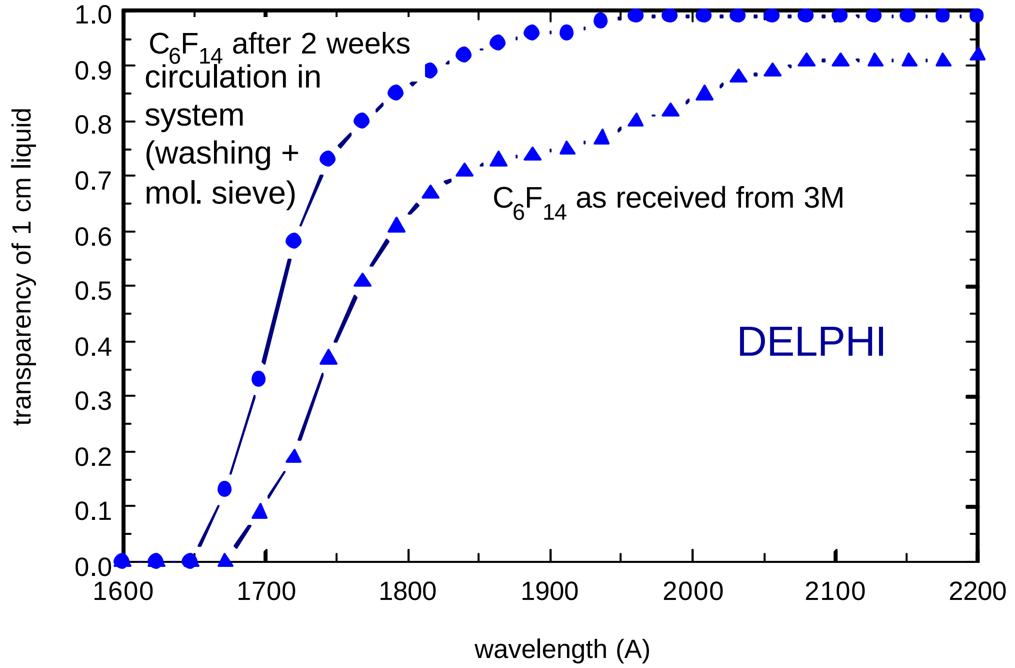


"Extreme" case: Distillation (DELPHI)

C. Joram, DELPHI note 98-53 RICH 94




After cleaning with mol. sieve and act. carbon in gas phase.
Integ.(1600-2200A) = 568.0
DELPHI
C4F10
Sample polluted with organic substance (amino compound ?)
Integ.(1600-2200A) = 441.3
Transmission (15 cm gas)
wavelength (Å)


C6F14 after 2 weeks circulation in system (washing + mol. sieve)
C6F14 as received from 3M
DELPHI
transparency of 1 cm liquid
wavelength (A)

Some alternative methods for Particle Identification

The <u>avarage</u> specific energy loss:
Bethe-Bloch formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4pN_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{b^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 g^2 b^2}{I^2} T^{max} - b^2 - \frac{d}{2} \right]$$

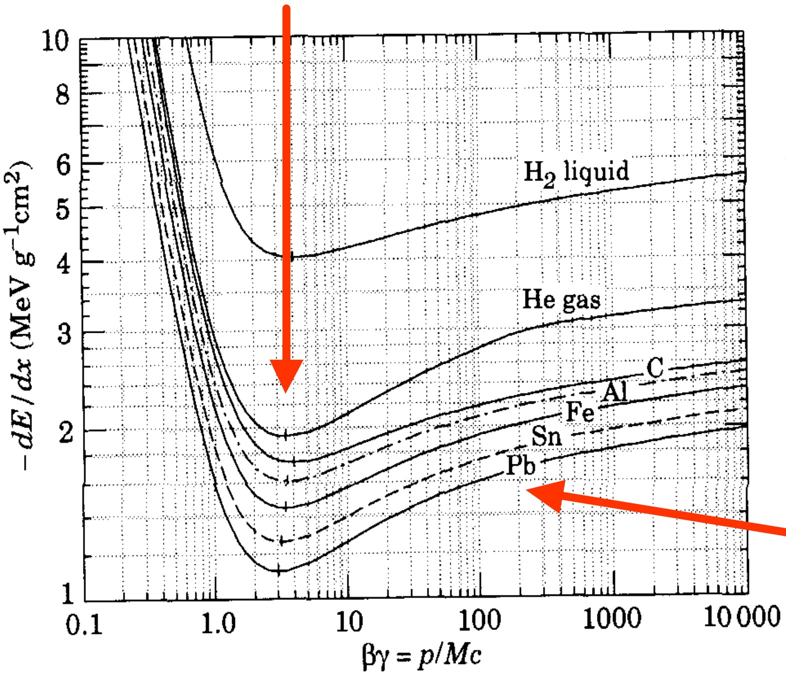
- dE/dx in [MeV g^{-1} cm^2]
- dE/dx depends only on β, independent of m
- Formula takes into account energy transfers

  $I \leq dE \leq T^{max}$ I : mean excitation potential

  $I \approx I_0 Z$ with $I_0 = 10$ eV (rough approximation, I fitted for each element)
- Bethe-Bloch formula only valid for “heavy” particles ($m \geq m_\mu$).

  Electrons and positrons need special treatment ($m_{proj}=m_{target}$), in addition Bremsstrahlung!

Region of minimum ionization $\frac{dE}{dx} \approx 1..2\ MeV\,g^{-1} cm^2$



Z/A does not differ much for the various elements, except for Hydrogen!

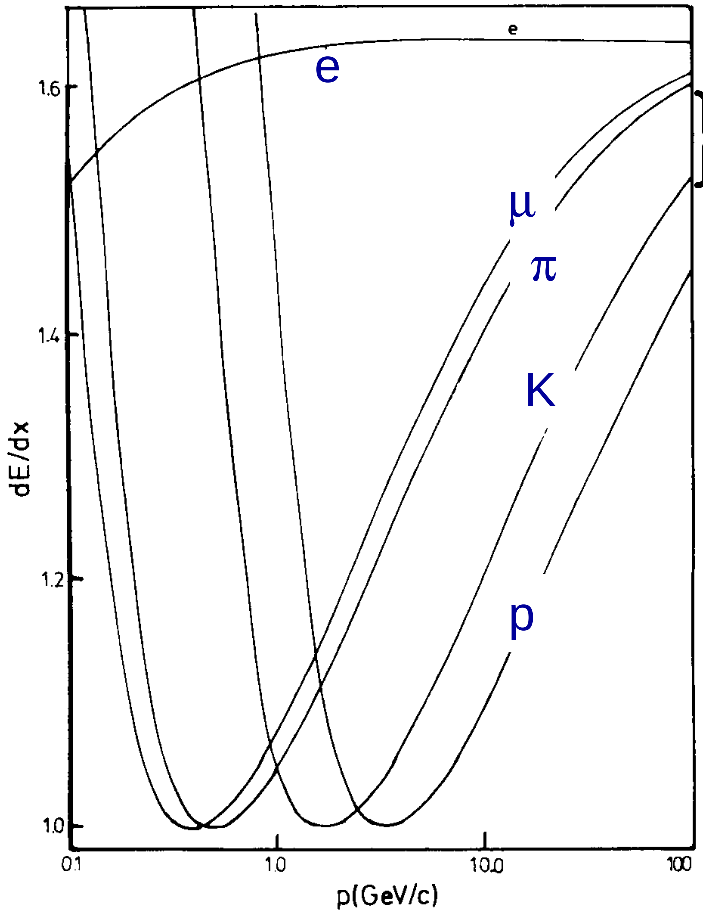
Relativistic rise

Particle ID using the specific energy loss dE/dx

$$p = m\beta\gamma$$

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

Simultaneous measurement of p and dE/dx defines m, i.e. particle identity



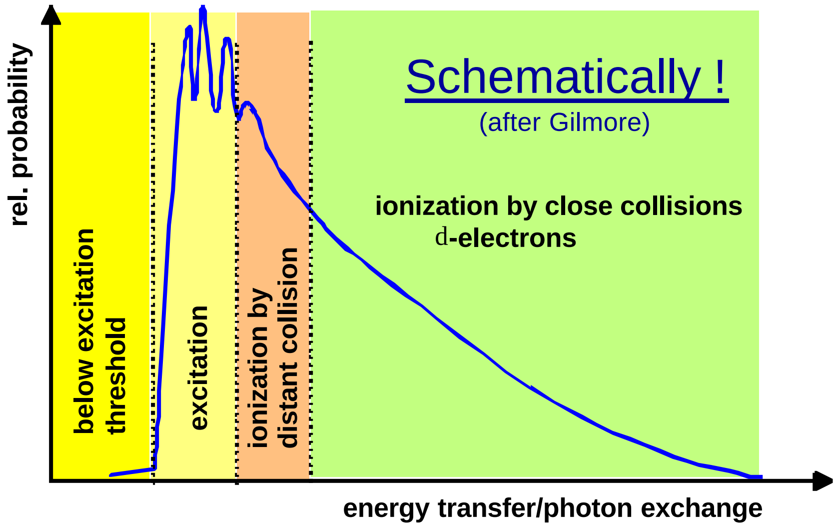
Average energy loss for e,μ,π,K,p in 80/20 Ar/CH_4 (NTP)
(J.N. Marx, Physics today, Oct.78)

π/K separation (2σ) requires a dE/dx resolution of < 2.5%

But: Large fluctuations + Landau tails !

Real detectors (limited granularity) do not measure <dE/dx>, but the energy ΔE deposited in a layer of finite thickness δx.

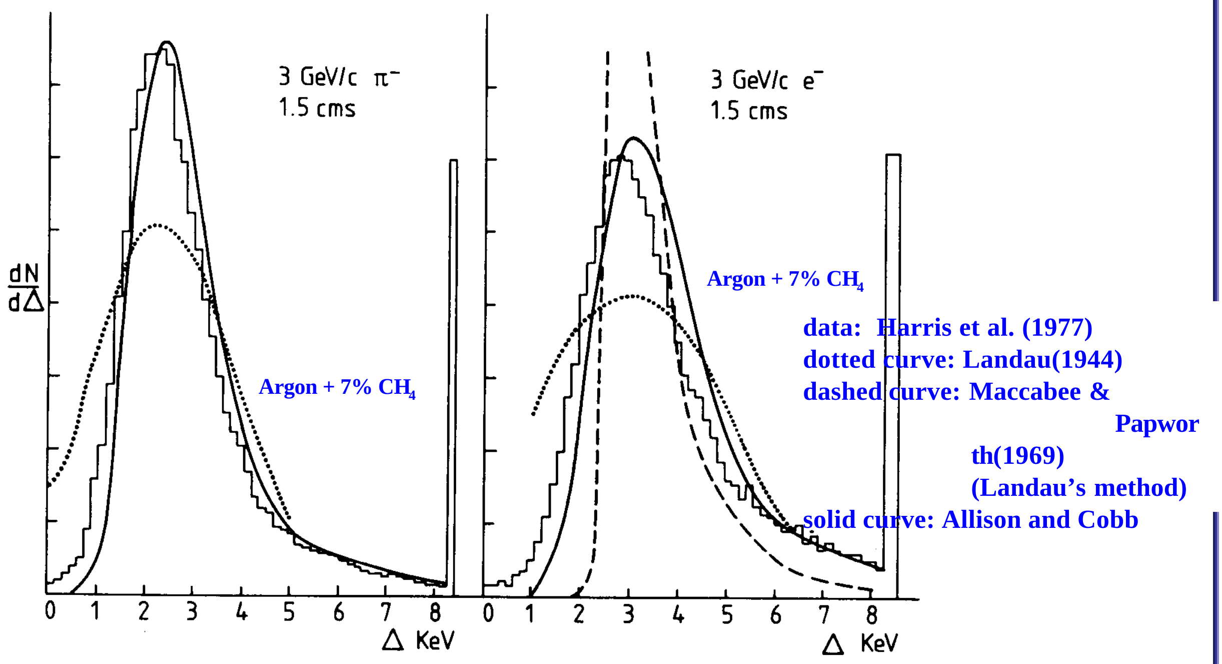
ΔE is the result of n collisions with energy transfers E_i and cross-section $d\sigma/dE_i$



For thin layers (and low density materials):

$\rightarrow$ Few collisions, some with high energy transfer.

$\rightarrow$ large fluctuations + "Landau tails"



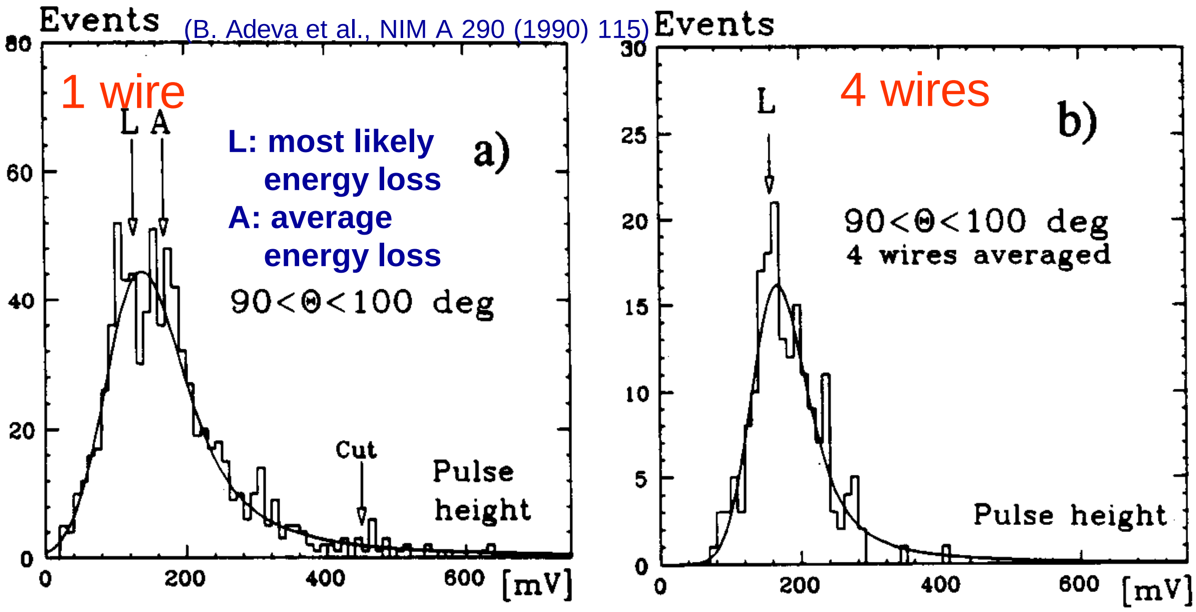
For thick layers and high density materials:

$\rightarrow$ Many collisions $\rightarrow$ Central Limit Theorem $\rightarrow$ Gaussian shape distributions.

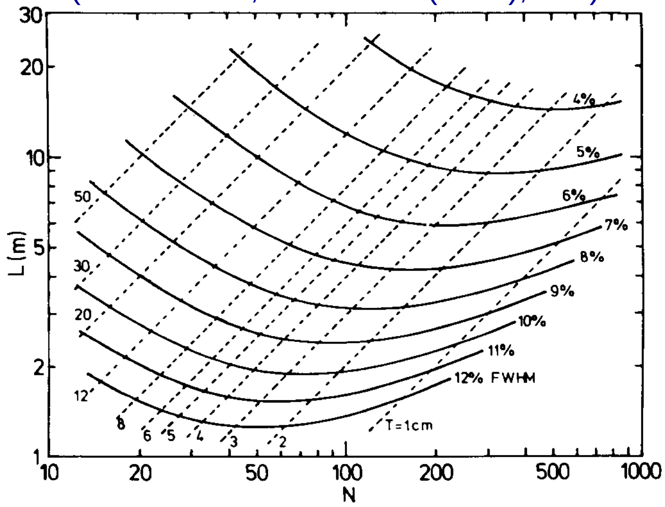
Improve dE/dx resolution and fight Landau tails

- Chose gas with high specific ionization
- Devide detector length L in N gaps of thickness T.
- Sample dE/dx N times

(B. Adeva et al., NIM A 290 (1990) 115)



(M. Aderholz, NIM A 118 (1974), 419)



Don't cut the track into too many slices !
There is an optimum for each total detector length L.

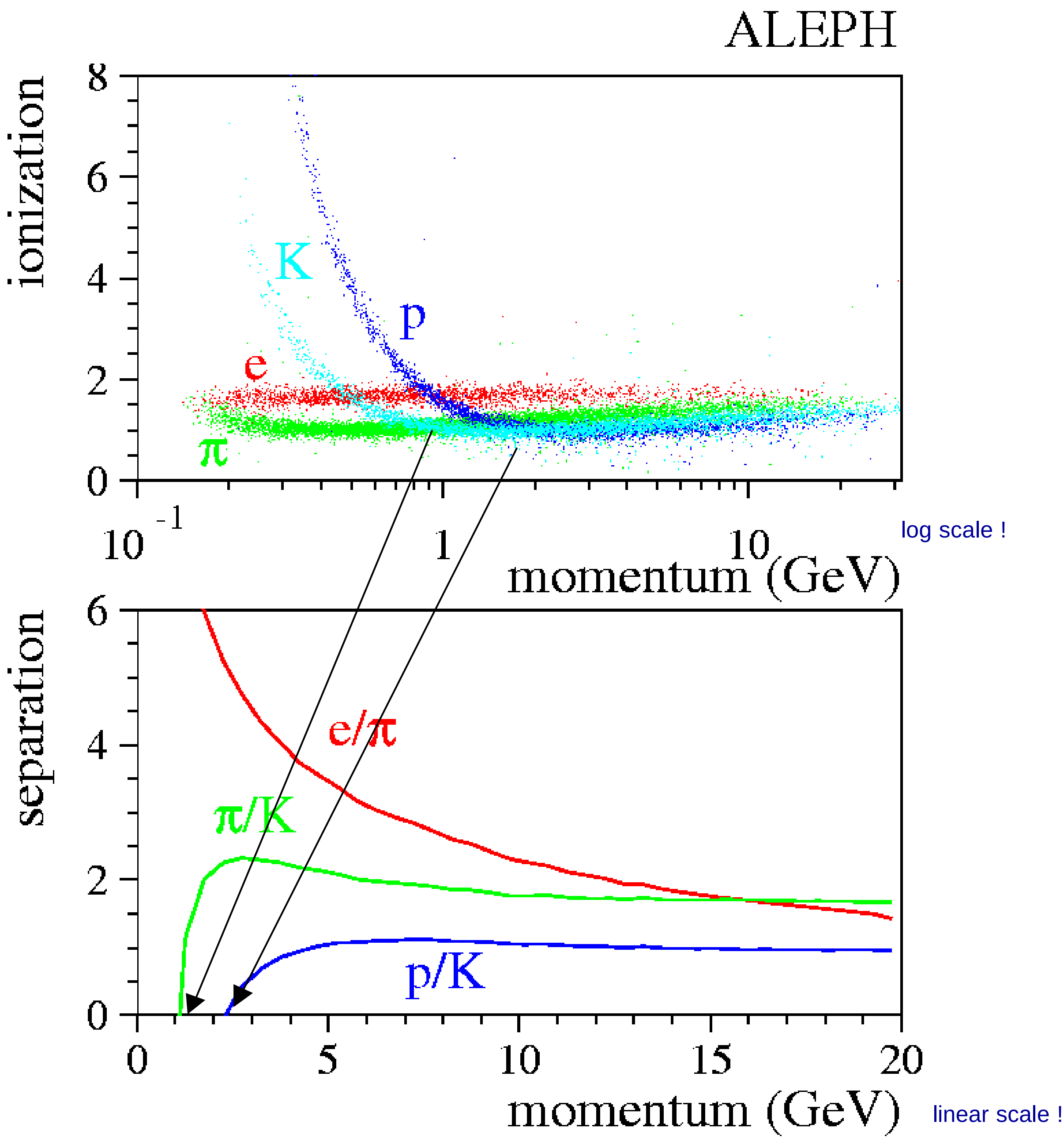
- calculate truncated mean, i.e. ignore samples with (e.g. 40%) highest values
- Also pressure increase can improve resolution, but reduced rel. rise due to density effect !

Example ALPEPH TPC

Gas: Ar/CH_4 90/10

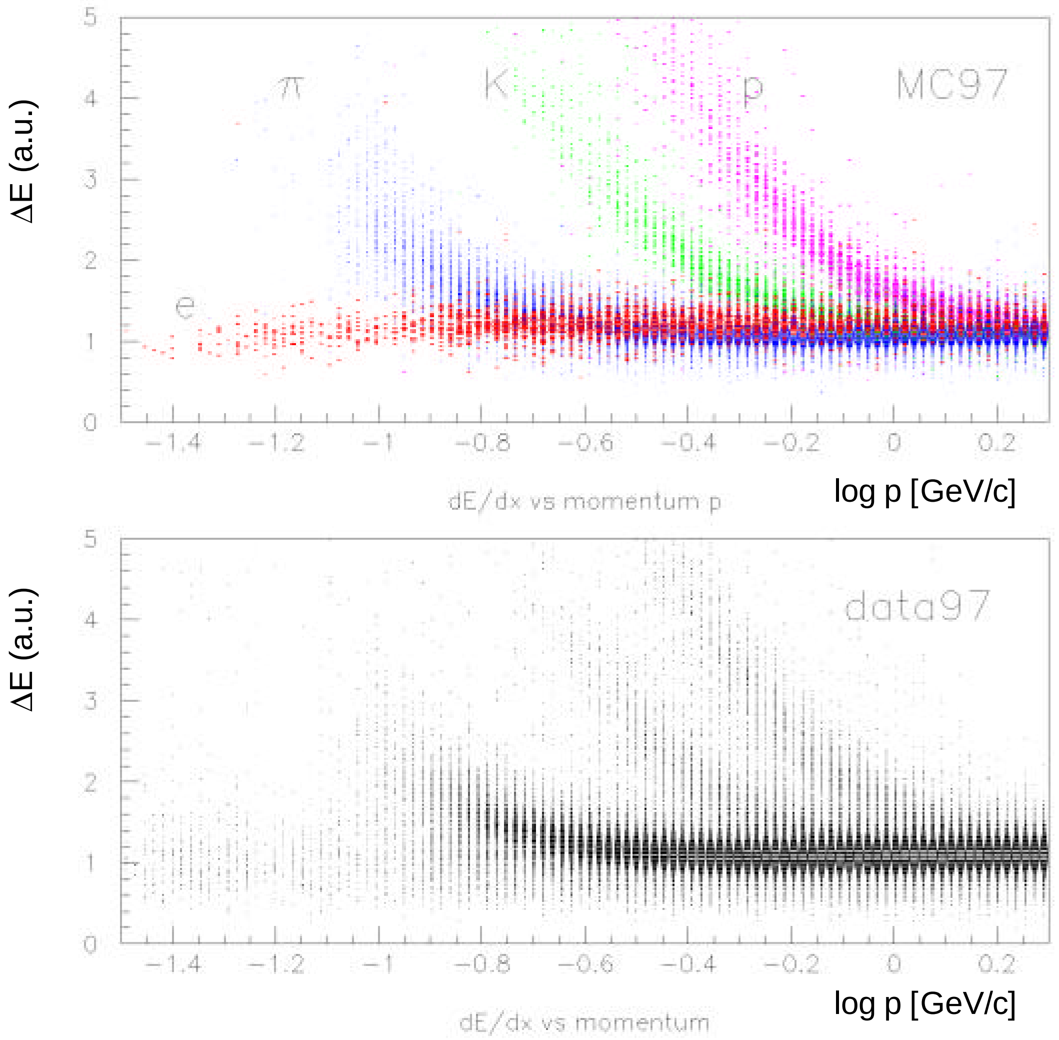
$N_{samples}$ = 338, wire spacing 4 mm

dE/dx resolution: 4.5% for Bhabhas, 5% for m.i.p.'s



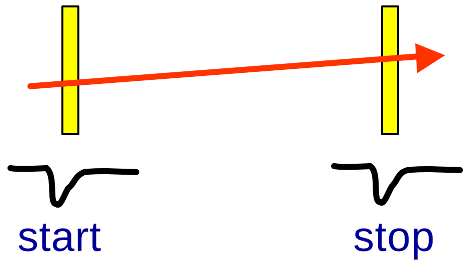
dE/dx can also be used in Silicon detectors

Example DELPHI microvertex detector (3 x 300 μm Silicon)



Time of flight

$$t = \frac{L}{bc}$$



Combine TOF with momentum measurement

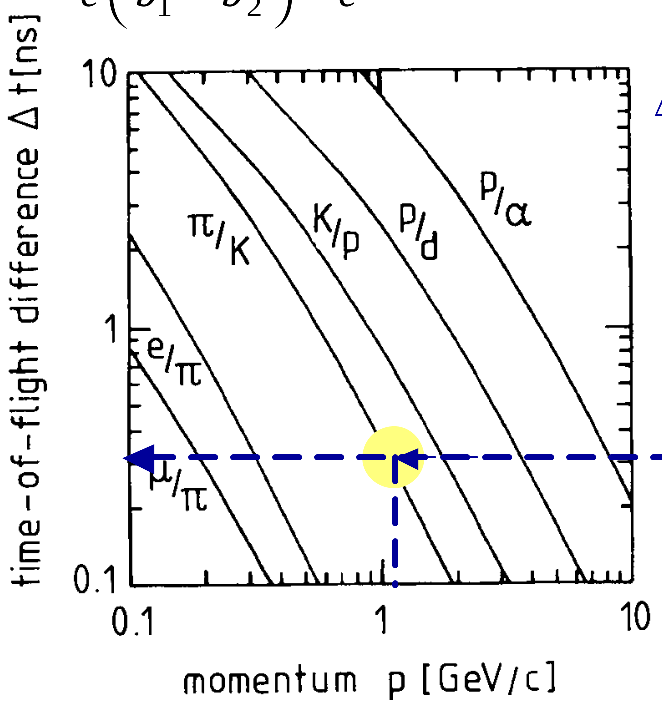
$$m = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

Mass resolution

$$\frac{dm}{m} = \frac{dp}{p} + g^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

TOF difference of 2 particles at a given momentum

$$\Delta t = \frac{L}{c}\left(\frac{1}{b_1} - \frac{1}{b_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$



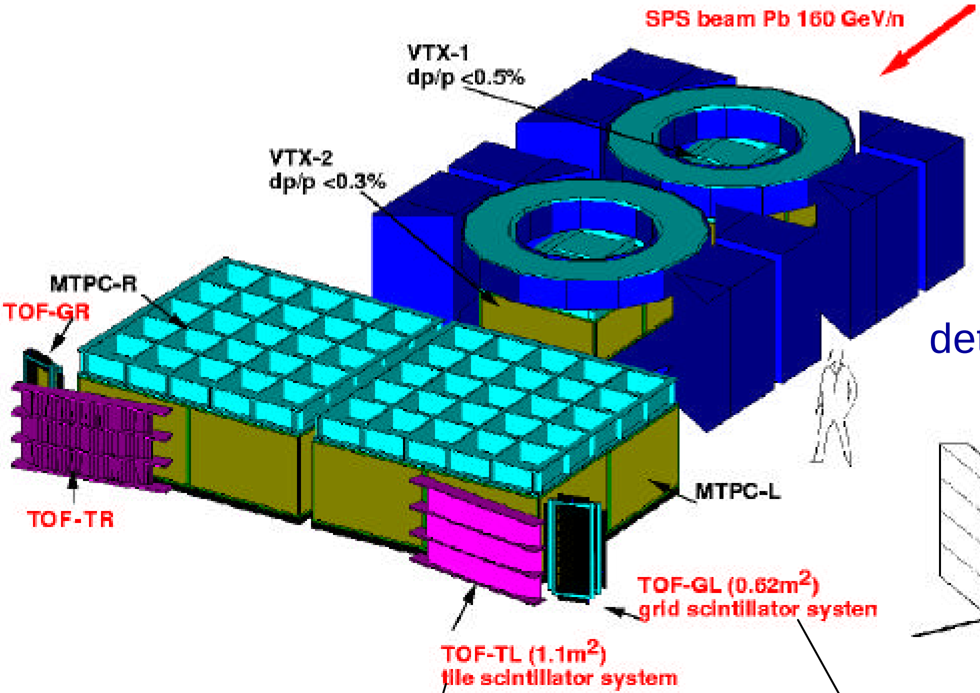
Δt for L = 1 m path length

σ_t = 300 ps
π/K separation up to 1 GeV/c

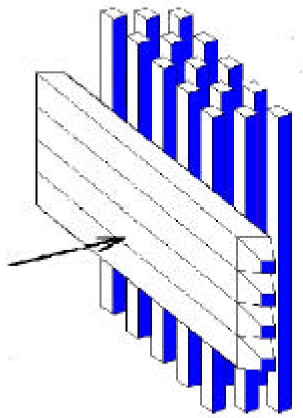
TOF requires fast detectors (plastic scintillator, gaseous detectors), approporiate signal processing (constant fraction discrimination, corrections + continuous stability monitoring.

Example: CERN NA49 Heavy Ion experiment

Na 49 experimental setup (part)



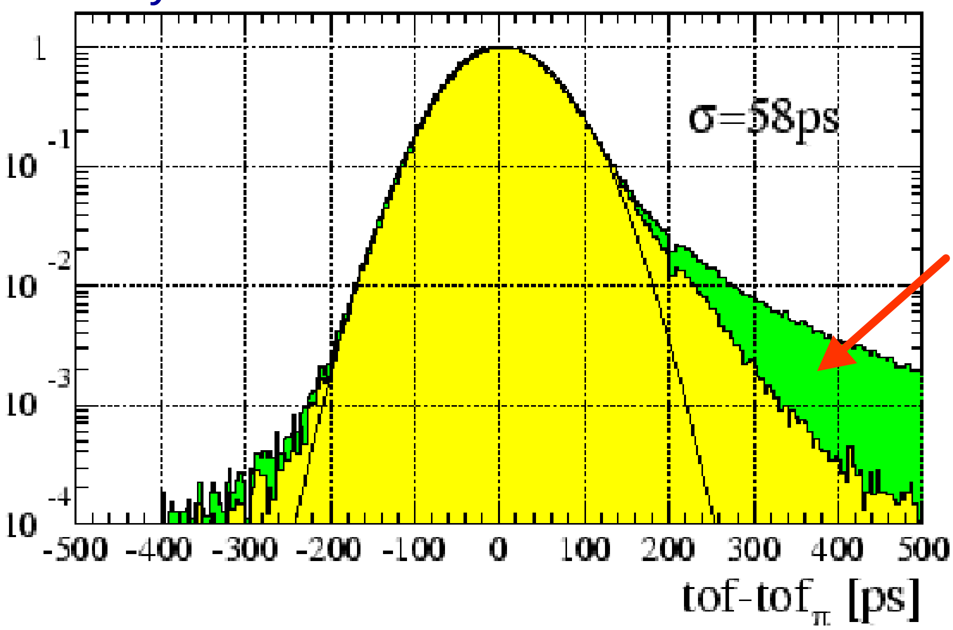
detail of the grid



Small, but thick scint.
8 x 3.3 x 2.3 cm

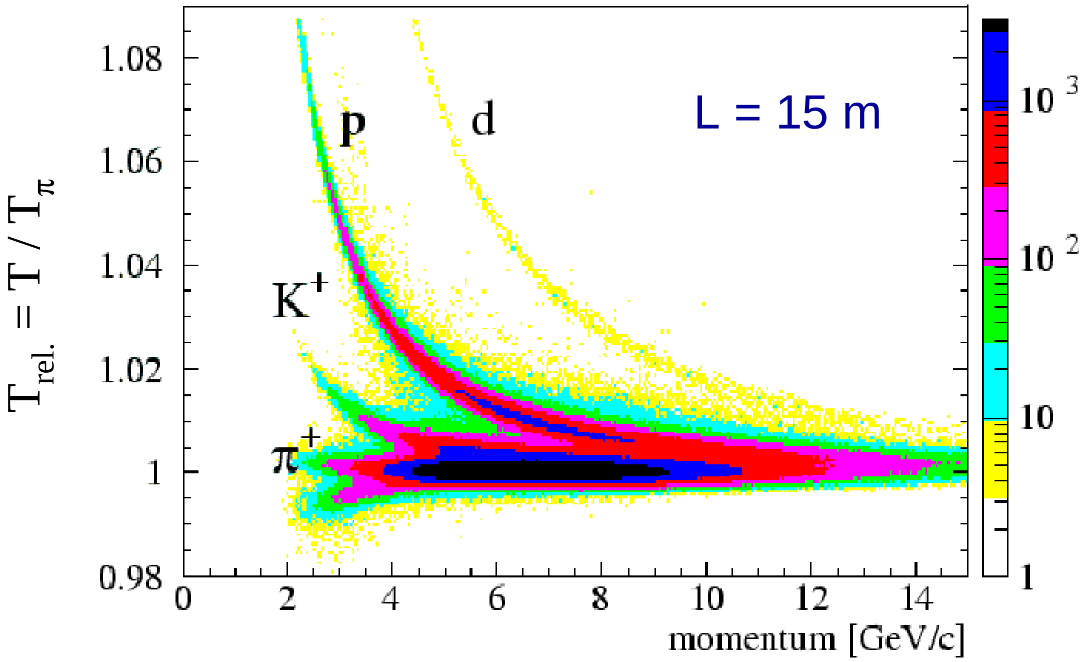
Long scint. (48 or 130 cm),
read out on both sides

System resolution of the tile stack

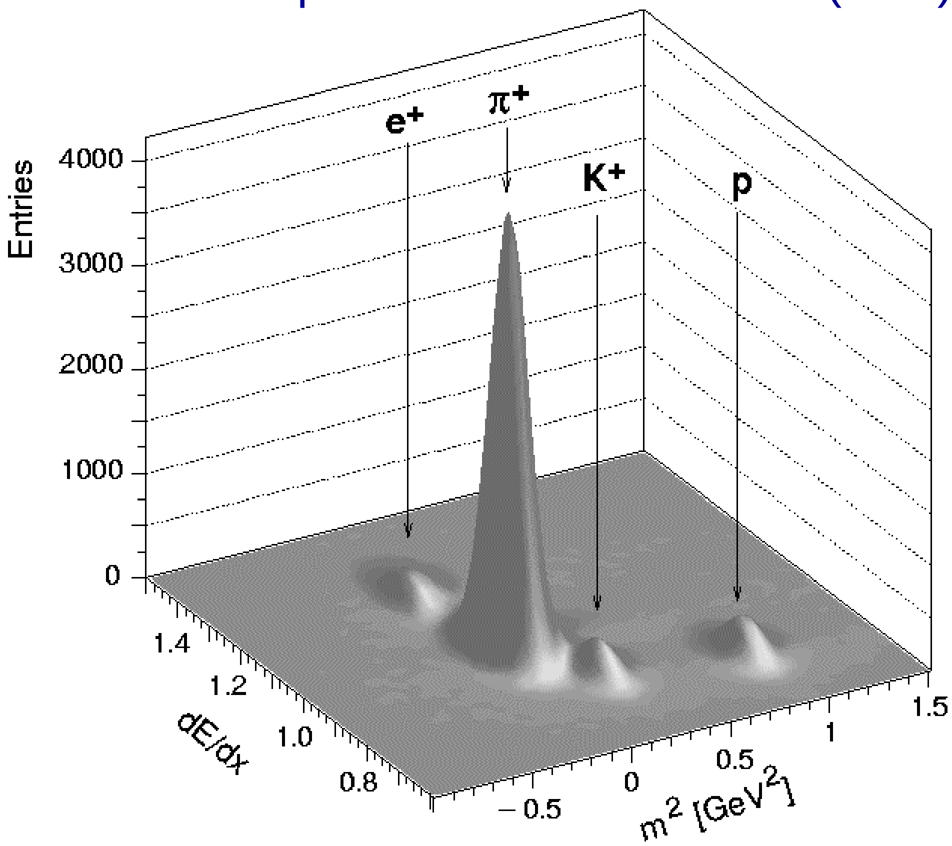


From γ conversion in scintillators

NA49 particle ID with TOF only



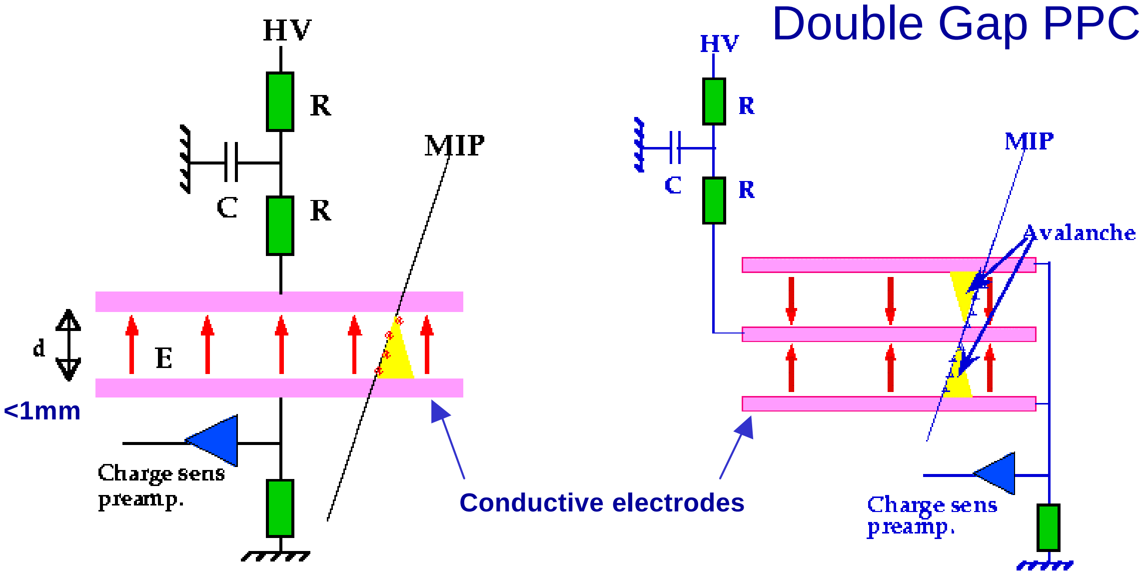
NA49 combined particle ID: TOF + dE/dx (TPC)



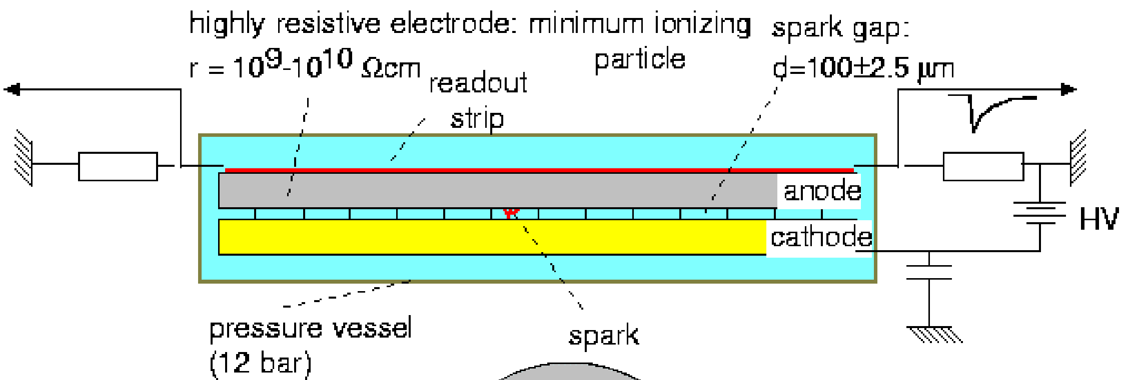
TOF with fast gaseous detectors

Parallel Plate Chambers (PPC)

Double Gap PPC



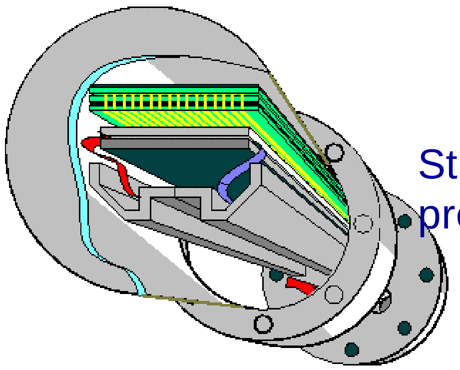
$\sigma_t \approx 200$ ps (ALICE test beam)



LICE technical proposal)

ALICE test beam:

$\sigma_t \approx 40$ ps !



Study of the pressure vessel

Particle ID with the impact parameter method

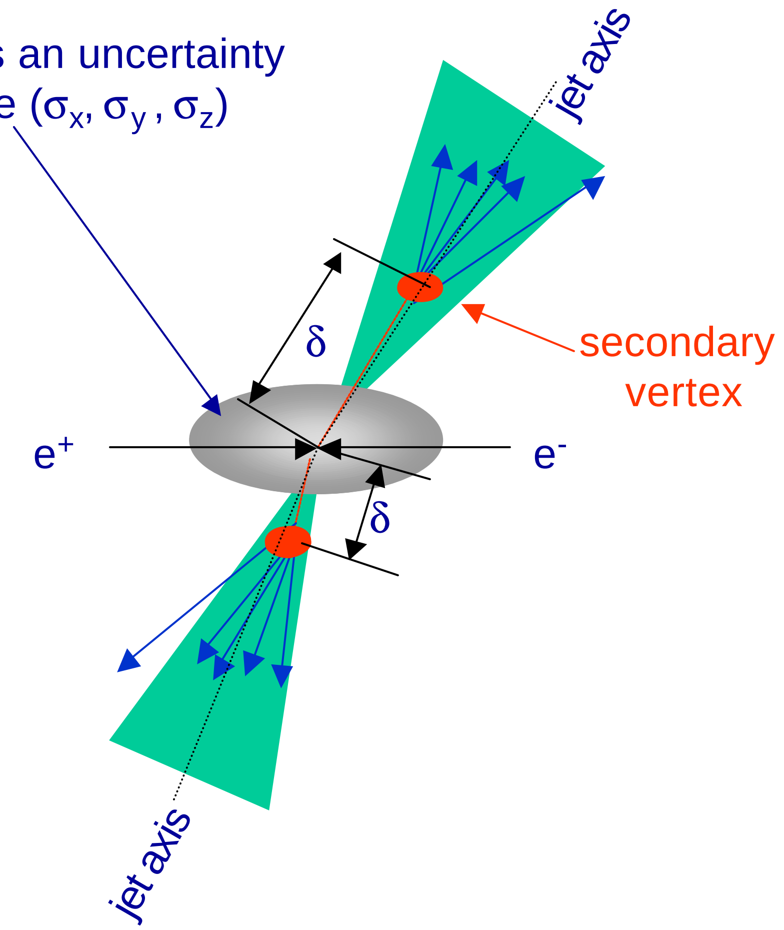
= heavy flavour tagging

Idea: identify particles containing b (and c) quarks by means of their lifetime

$\tau_b \approx 1.6 \cdot 10^{-12}$ s   average flight distance $d = \beta c \gamma \tau \approx \gamma \cdot 0.5$ mm

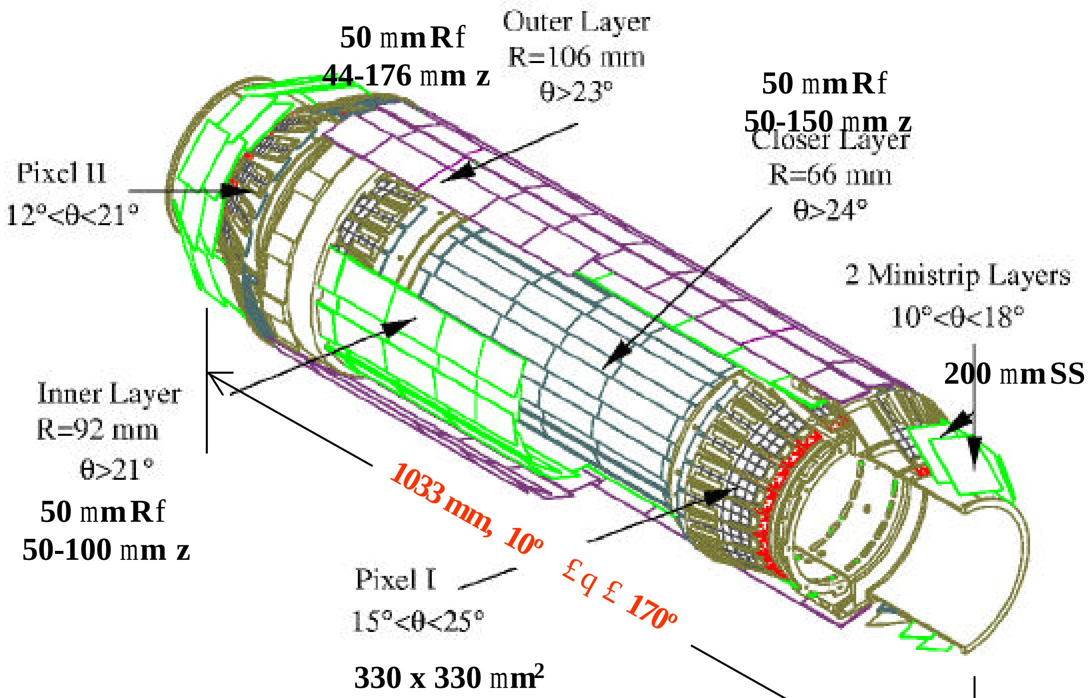
$$e^+e^- \to Z^0 \to b\bar{b} \to 2 \text{ jets including B-hadrons}$$

The primary vertex has an uncertainty due to the beam size ($\sigma_x, \sigma_y, \sigma_z$)



The impact parameter δ measures the displacement of the secondary vertex in the direction of the jet axis.

DELPHI micro vertex detector



readout channels

ca. 174 k strips, 1.2 M pixels

total readout time: 1.6 ms

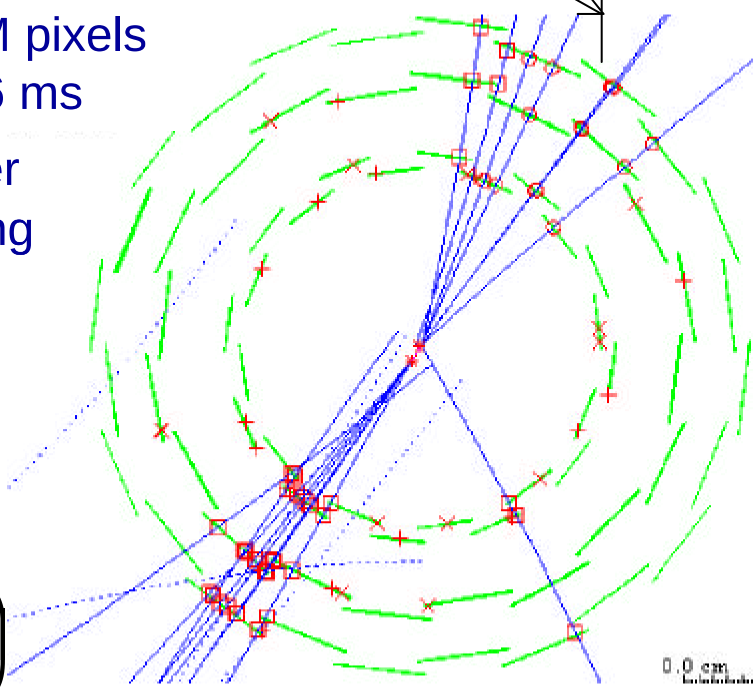
Total dissipated power

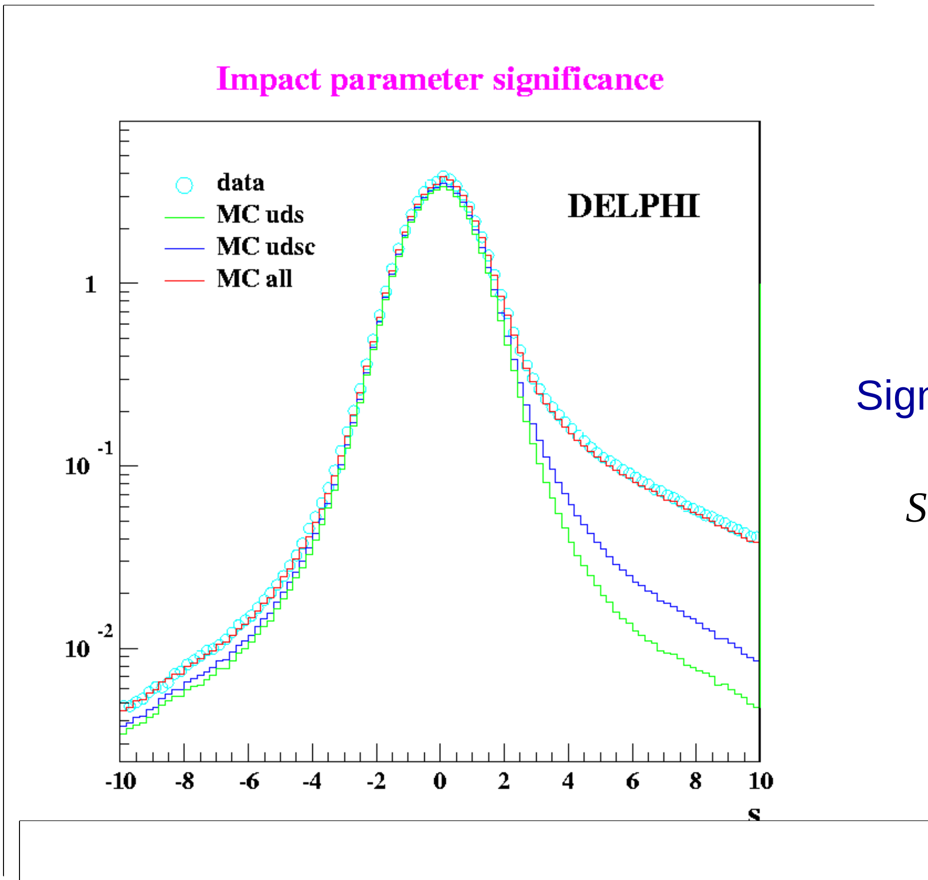
400 W → water cooling system

Hit resolution in barrel part ≈ 10 μm

Impact parameter resolution (rϕ)

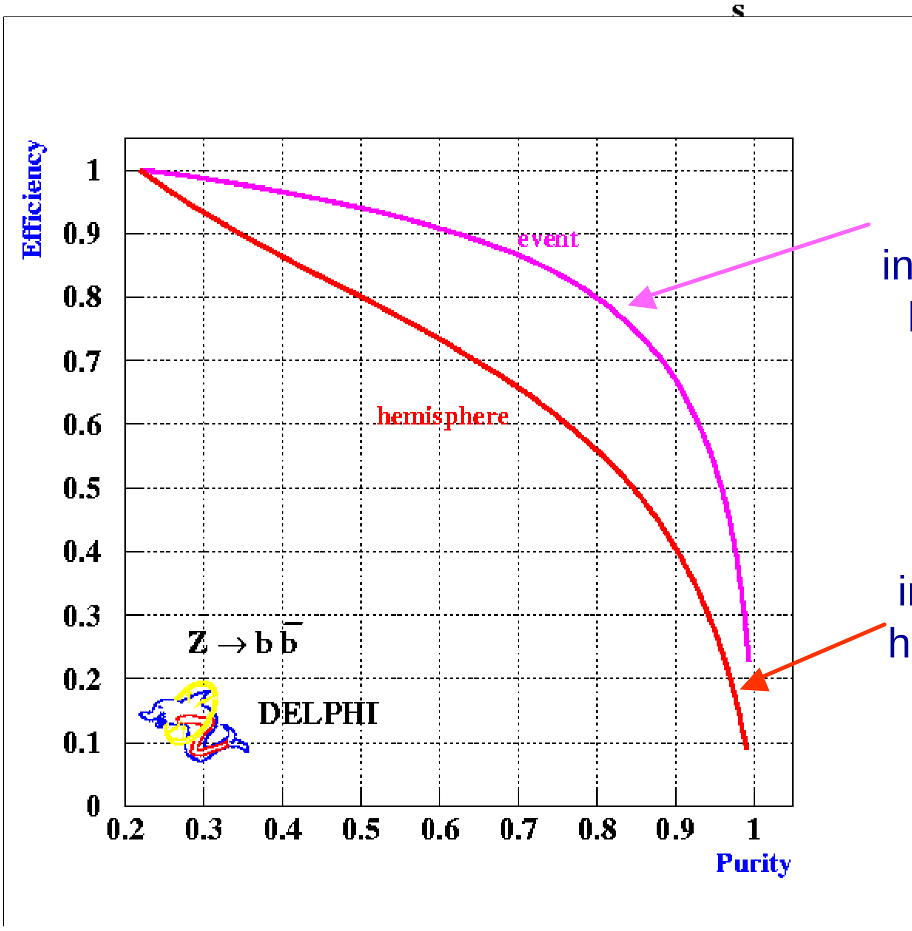
$$28mm \oplus 71/\left(p\sin^{\frac{3}{2}} q\right)$$





Significance

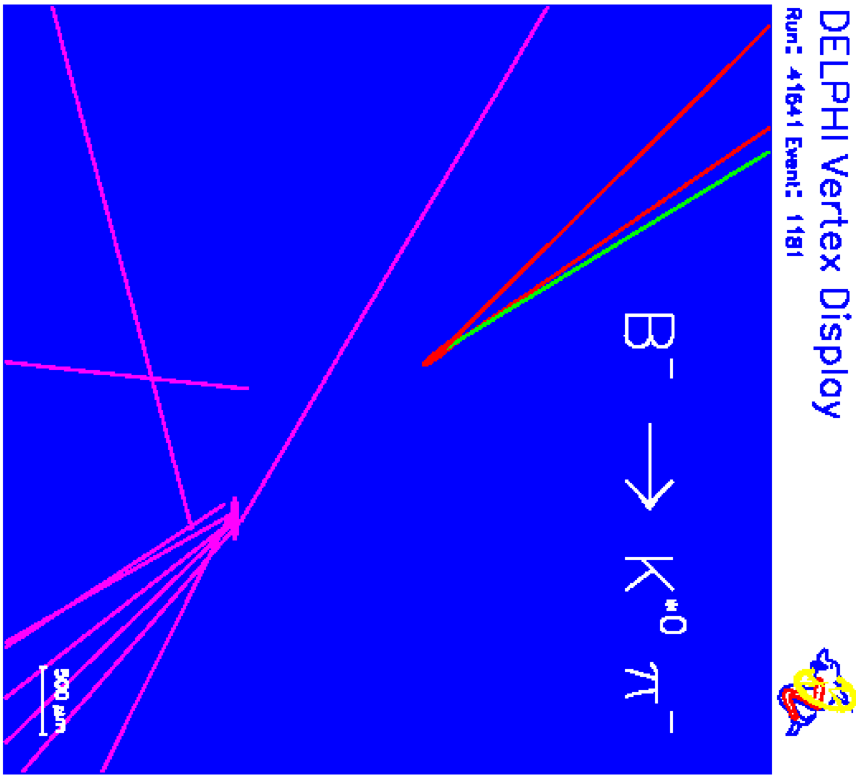
$$S = \frac{d}{s_d}$$



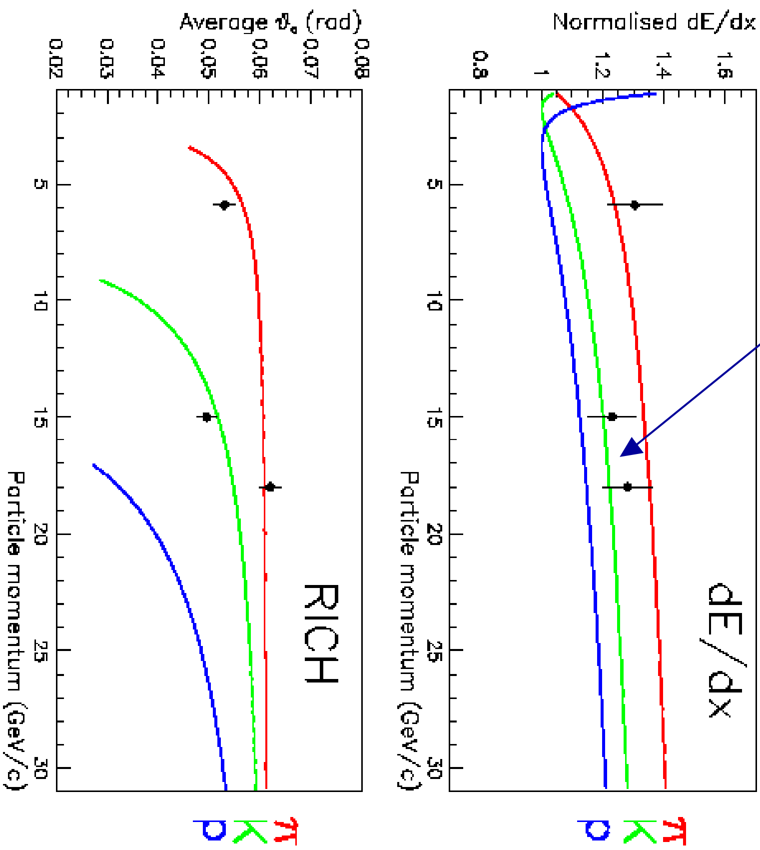
Combined information of 2 hemispheres

information of 1 hemisphere only

A ”charmless” B decay



$$B^- \rightarrow K^{0*}\,\pi^-$$
$$\downarrow$$
$$K\pi$$



ambiguous identification in dE/dx