VIENNA CONFERENCE ON INSTRUMENTATION

ADVANCES IN CHARGED PARTICLE IDENTIFICATION TECHNIQUES

- **TOF**
- **dE/dx**
- **Cherenkov Light Imaging**

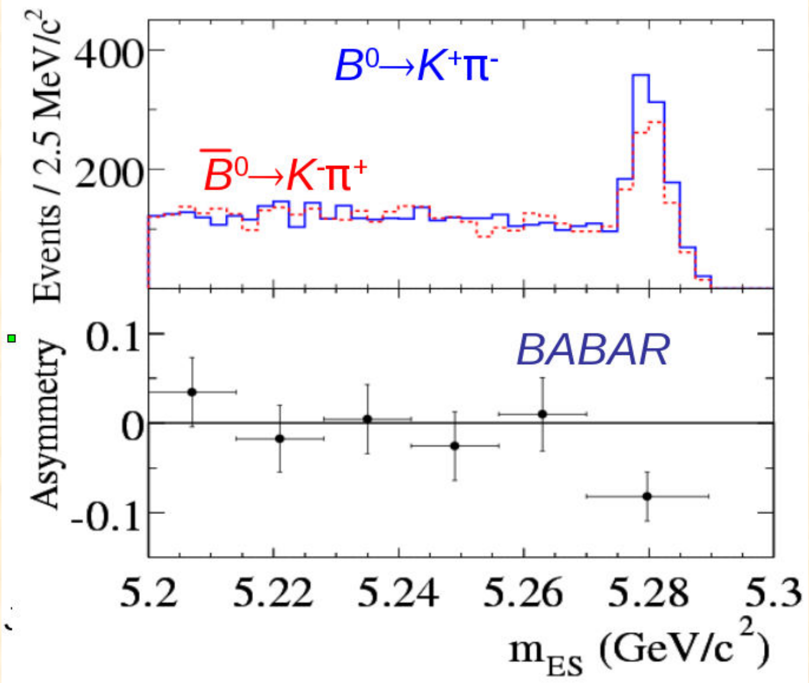
(applications to HEP experiments)

Transition radiation detectors ⇒ see talk by P. Wagner (ATLAS) and posters by M. Petris (CBM) and S. Furletov (TR r/o by a silicon pixel detector)

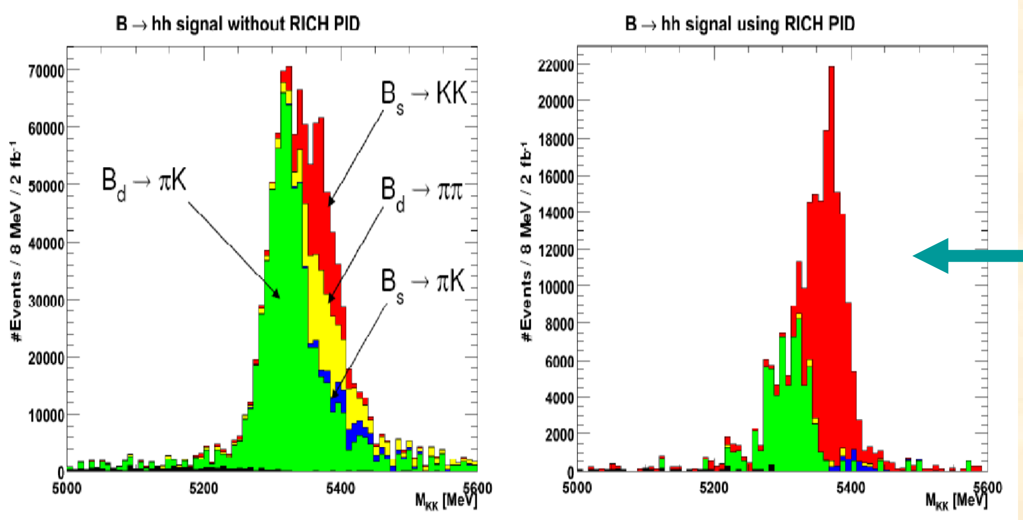
IMPORTANCE OF PID

PID fundamental to many physics studies:

- Hadron physics (COMPASS, PANDA….)
- Flavour physics and CP violation studies (BABAR, BELLE, NA62, LHCb, SuperB…)
- Nucleon structure (HERMES, COMPASS, TJLAB…)
- Heavy ion physics (PHENIX, STAR, ALICE…)



Direct CP Violation in B^0 decays



enhance the signal by a large amount by suppressing the background

PID: limits to performance

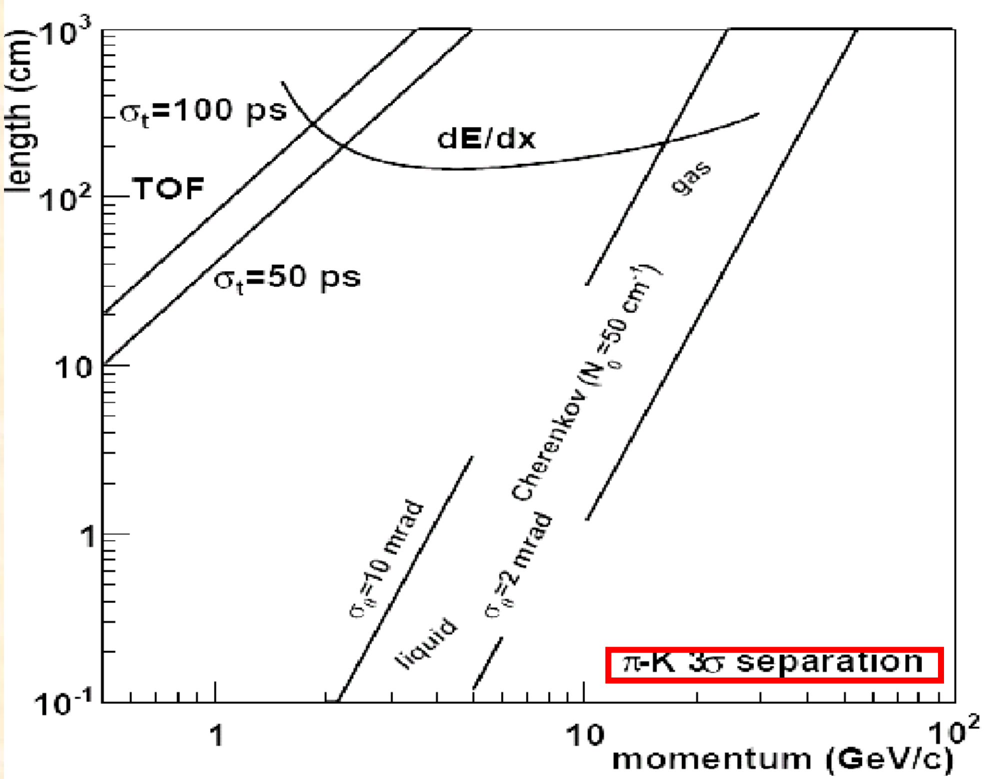
$$TOF \Rightarrow m = p\sqrt{\frac{c^2t^2}{L^2} - 1}$$

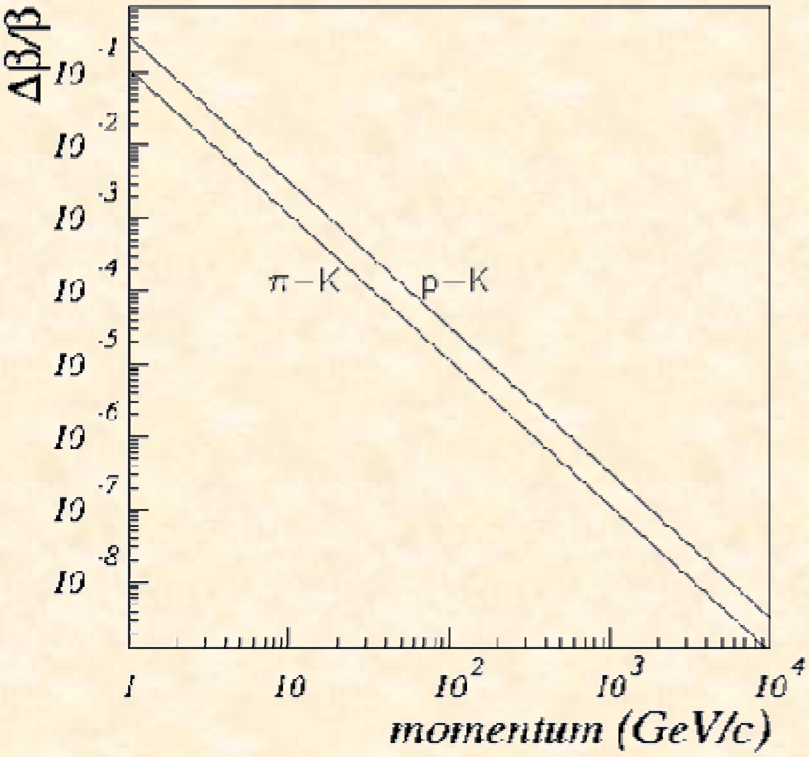
$$\left(\frac{dE}{dx} \propto \frac{1}{\beta^2}\ln\left(\beta^2\gamma^2\right); \mathrm{p}\ \right) \Rightarrow \mathrm{m}$$

$$\mathrm{Cherenkov} \Rightarrow \mathrm{m} = \frac{\mathrm{p}}{\mathrm{c}}\sqrt{\mathrm{n}^2\cos^2\theta_{\mathrm{c}} - 1}$$

$$\left(\frac{\mathrm{dm}}{\mathrm{m}}\right)^2 = \left(\gamma^2\frac{d\beta}{\beta}\right)^2 + \left(\frac{dp}{p}\right)^2$$

$$\frac{\Delta\beta}{\beta} \cong \frac{(m_1^2 - m_2^2)c^2}{2p^2}$$





TOF

Particle separation power

$$n_{\sigma_t,1-2} = \frac{\Delta t_{1-2}}{\sigma_t} = \frac{L}{c\sigma_t}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right) \approx \frac{Lc}{2p^2\sigma_t}\left(m_1^2-m_2^2\right)$$

example:

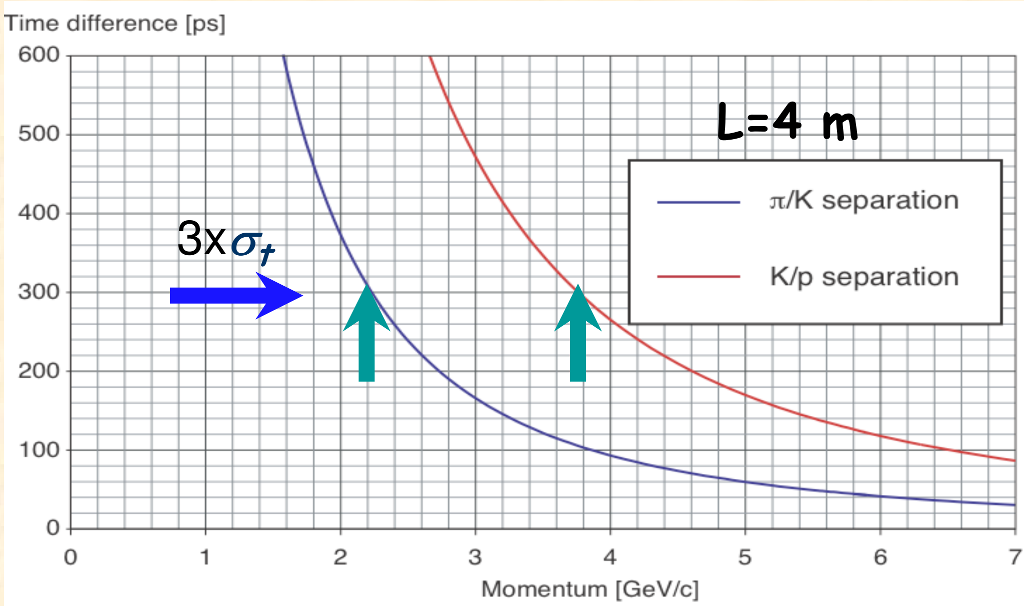
L= 4 m

σ_t= 100 ps

π/K up to 2.2 GeV/c

K/p up to 3.7 GeV/c

For momenta above some GeV/c the particle discrimination is almost lost



Conventional TOF (scintillator + PMTs)

- well proven technology
- good time resolutions -> 50-100 ps (r/o at both ends of the scintillator bar)

- sensitive to B
- expensive

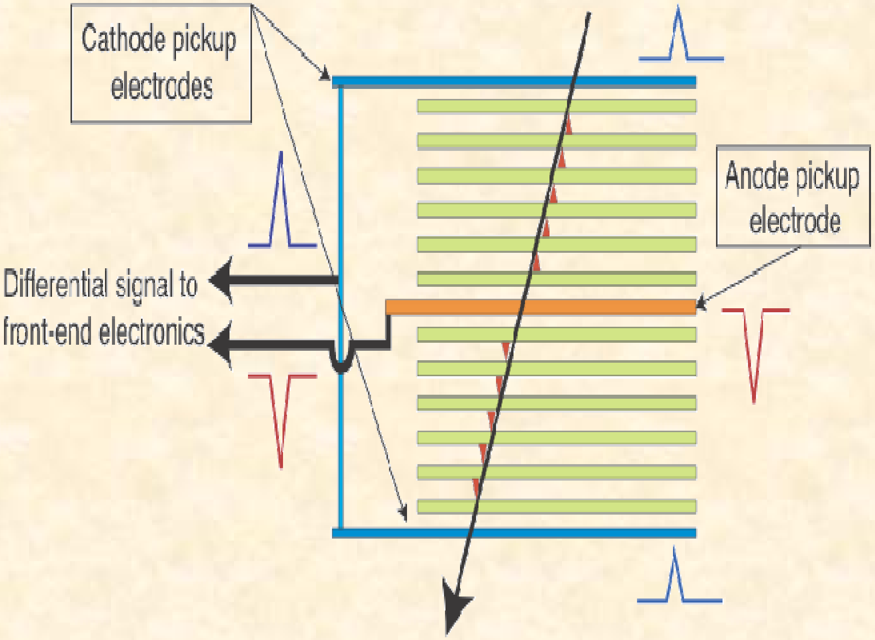
TOF based on fast gaseous counters

- not sensitive to B
- very good time resolutions -> 30-50 ps
- cost effective solution for large surfaces

- capability at high rates

MultiGap Resistive Plate Chambers

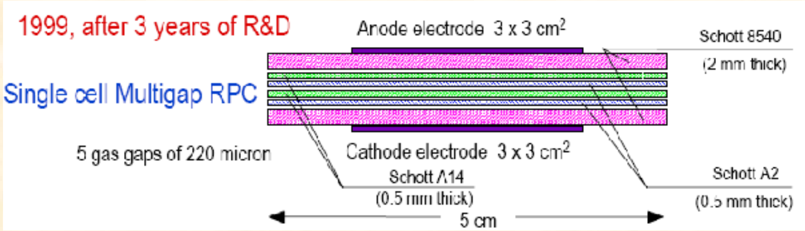
M. C.S. Williams and A. Zichichi,
Nucl. Instrum. Meth. A374, 132 (1996)

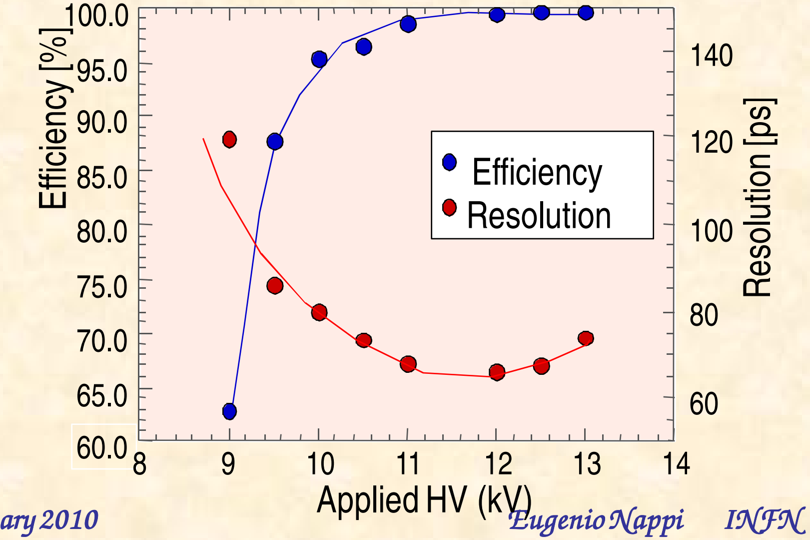


Many narrow (200÷300 μm) gaps made by a stack of equally-spaced resistive glass plates

- inner electrodes electrically floating
- voltages kept by electrostatics and charge flow

Resulting signal is the sum of signals from all gaps (resistive plates are transparent to fast signals)



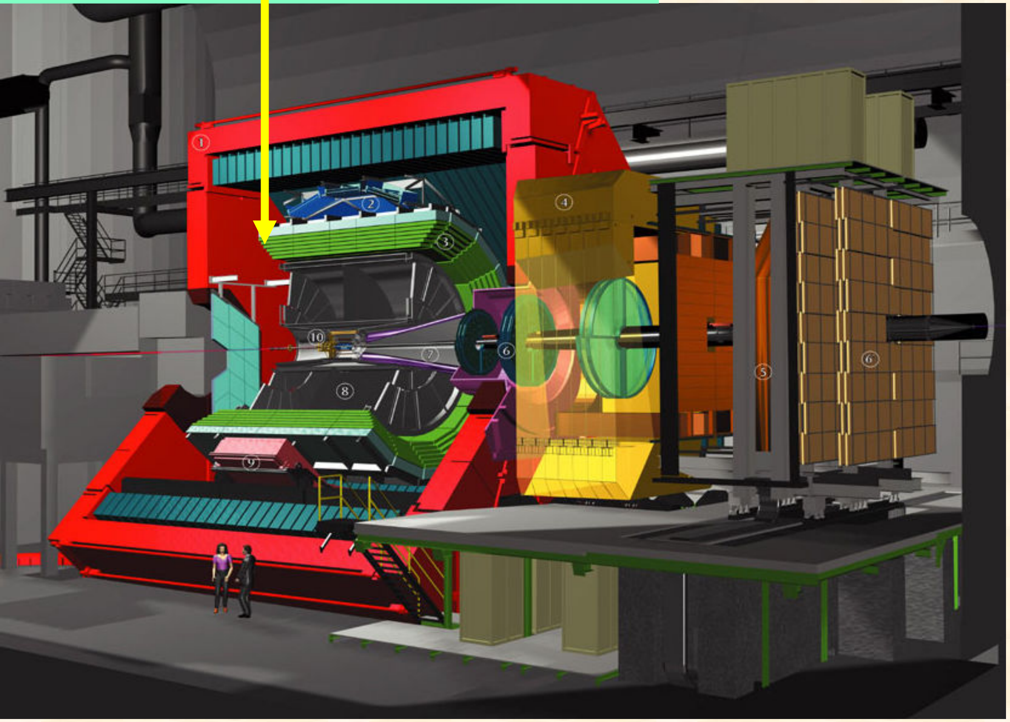


high time resolution due to the reduced jitter

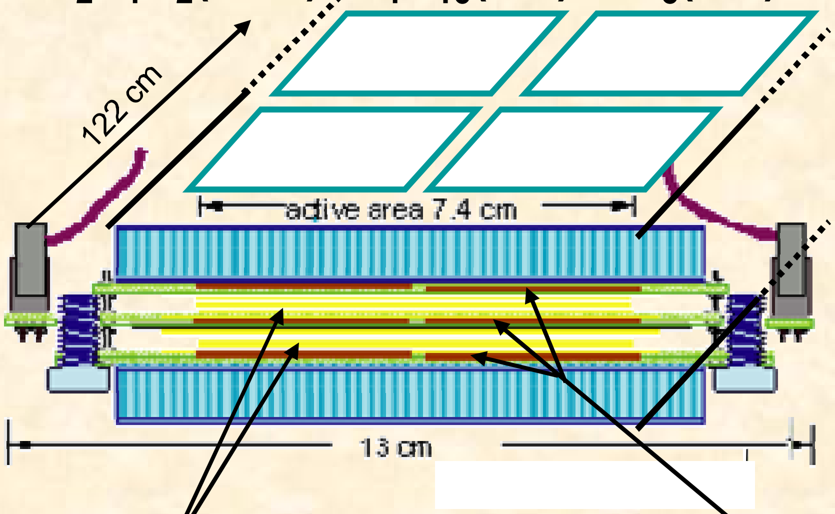
gas avalanche growth dominated by space charge → no formation of streamers/sparks

ALICE MRPC TOF

barrel with radius of 3.7 m
divided into 18 sectors



$C_2F_4H_2(90\%)–C_4H_{10}(5\%)–SF_6(5\%)$



2x5 gas gaps of 250µm

Readout pads 3.5x2.5 cm²

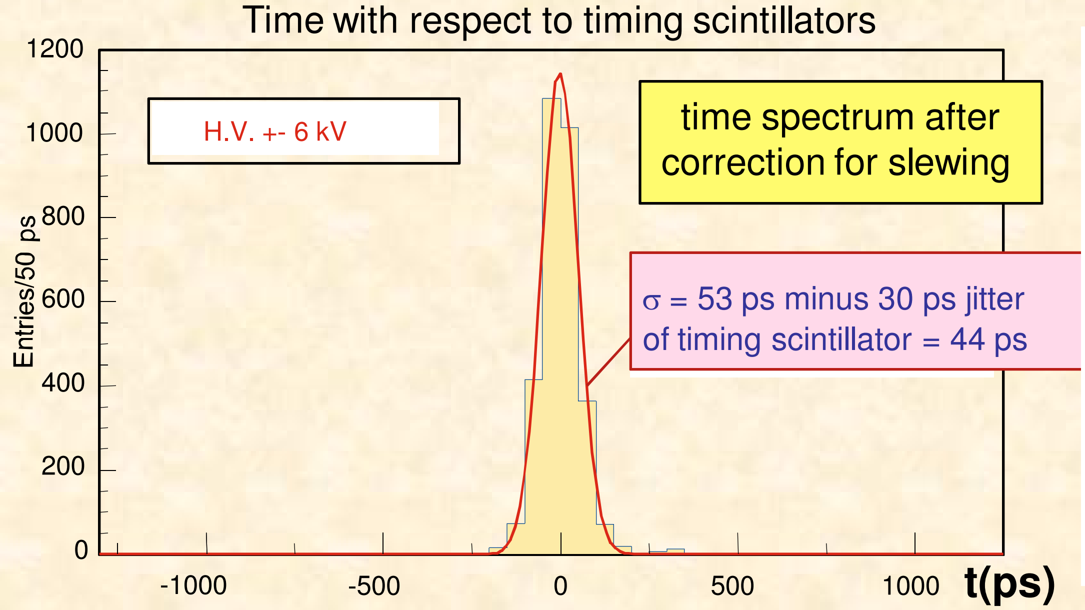
1674 strips in total

160 m² and 160,000 channels

resistive plates made of 'off-the-shelf' soda lime glass (2.4 10^{12} Ω.cm) and fishing-lines as spacers

a standard TOF system built of fast scintillators + photomultipliers would cost >100 MCHF (10 times more)

ALICE TOF PERFORMANCE

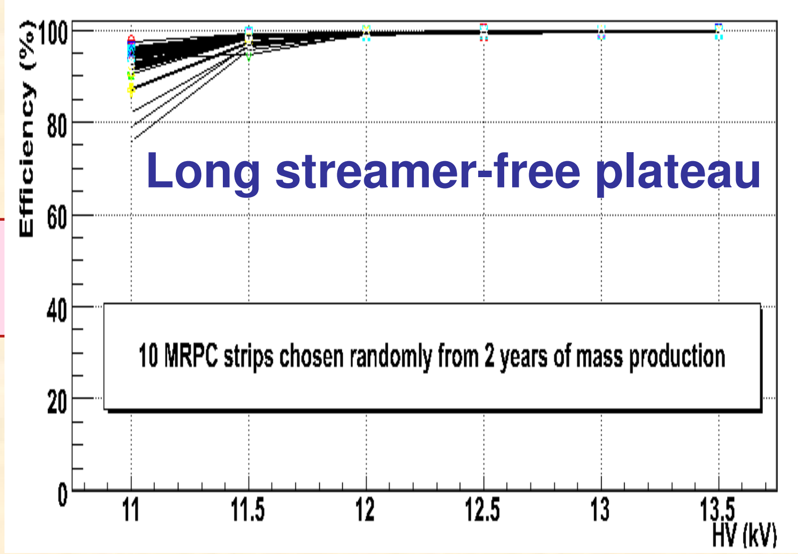


H.V. +- 6 kV

time spectrum after correction for slewing

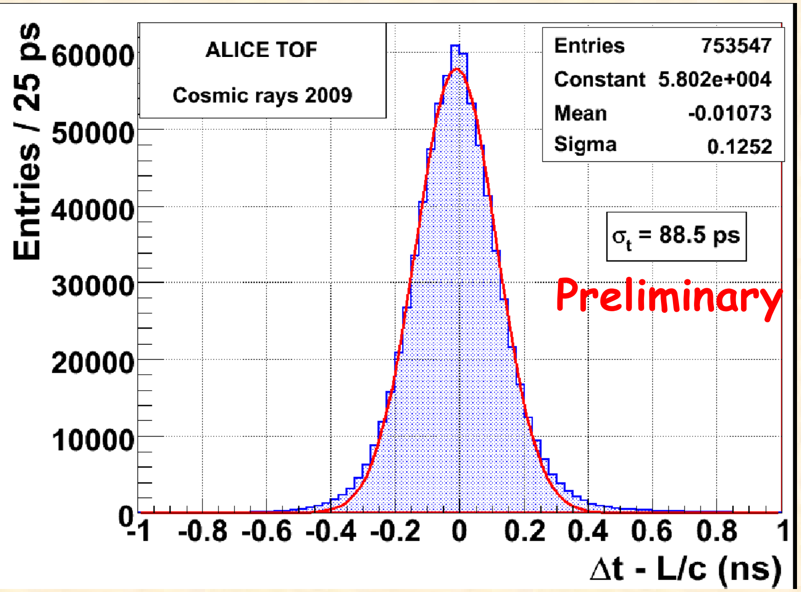
σ = 53 ps minus 30 ps jitter of timing scintillator = 44 ps

2008 JINST 3 S08002



Long streamer-free plateau

10 MRPC strips chosen randomly from 2 years of mass production



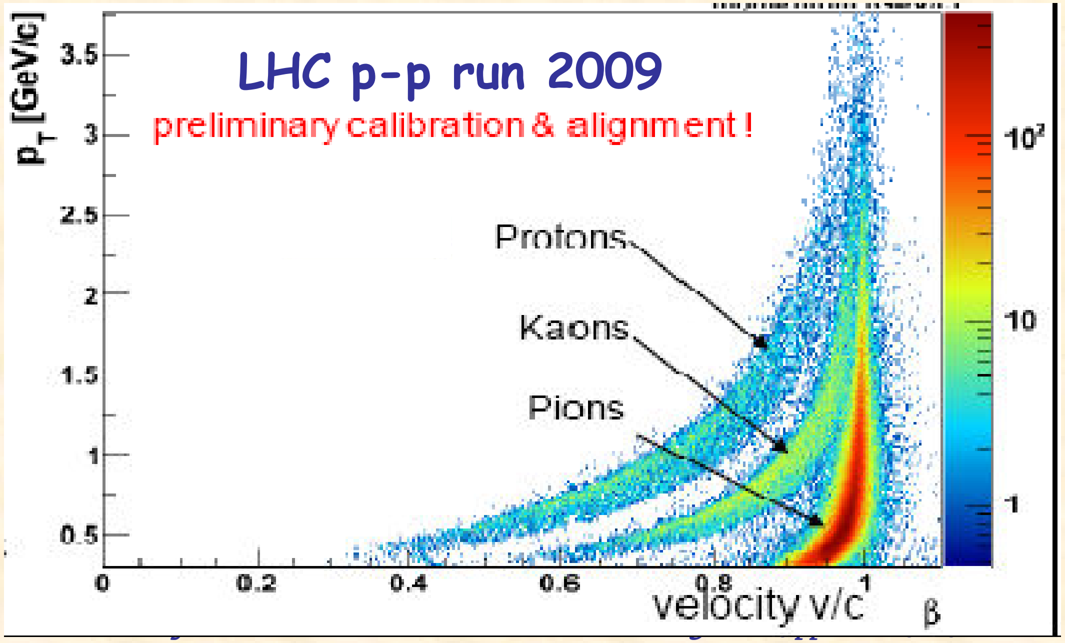
ALICE TOF

Cosmic rays 2009

Entries	753547
Constant	5.802e+004
Mean	-0.01073
Sigma	0.1252

σ_t = 88.5 ps

Preliminary



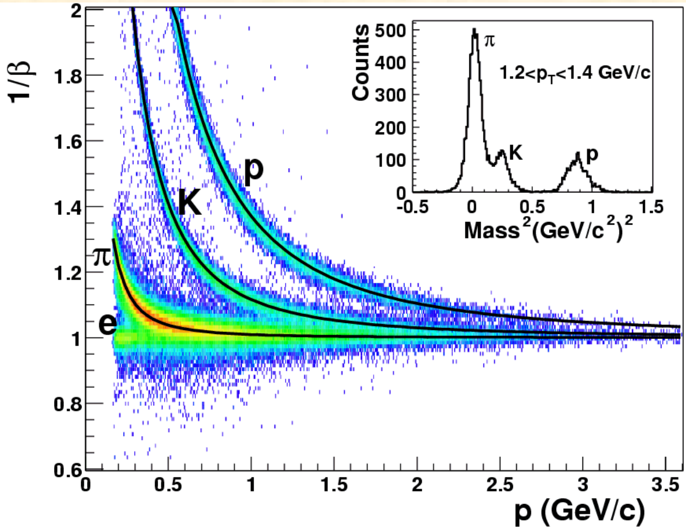
LHC p-p run 2009

preliminary calibration & alignment !

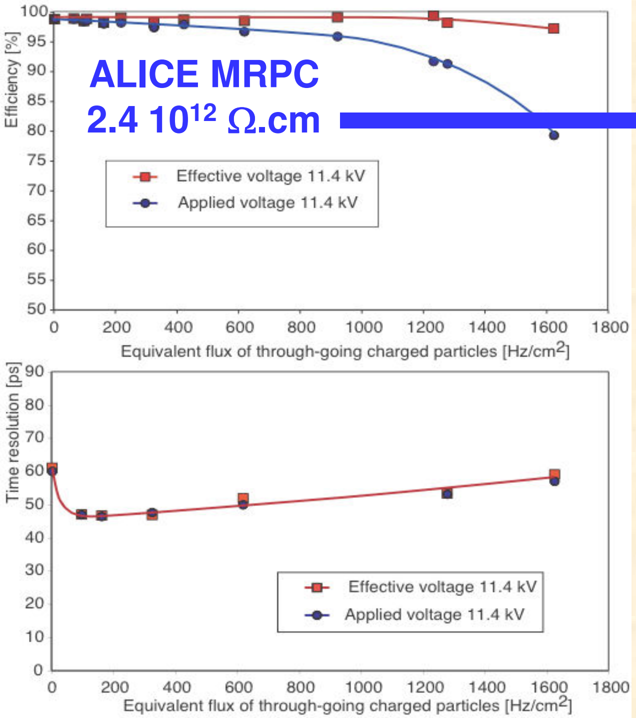
STAR & CBM MRPC TOFs

STAR experiment at RHIC

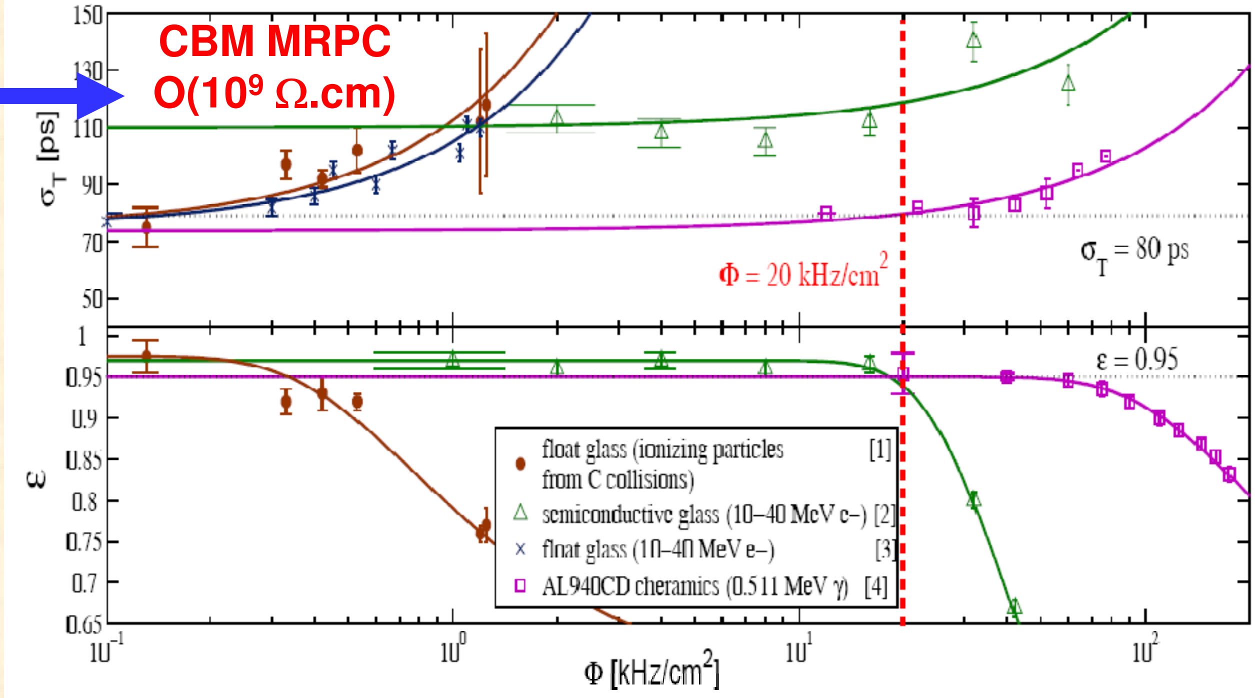
full barrel TOF-MRPCs
total area ~ 64 m^2
4032 modules



CBM experiment at FAIR
area ~ 100 m^2
rate capability: 5 – 20 kHz/cm^2
(L. Naumann and M. Petrovici's posters)



ALICE MRPC
2.4 10^{12} Ω.cm

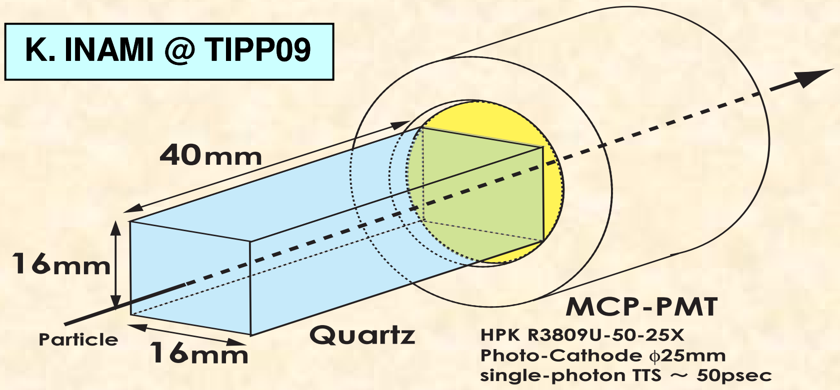


CBM MRPC
O(10^9 Ω.cm)

Prospect: TOF from Cherenkov light

Y.Enari NIM A547 (2005) 490
K.Inami NIM A560 (2006) 303

K. INAMI @ TIPP09

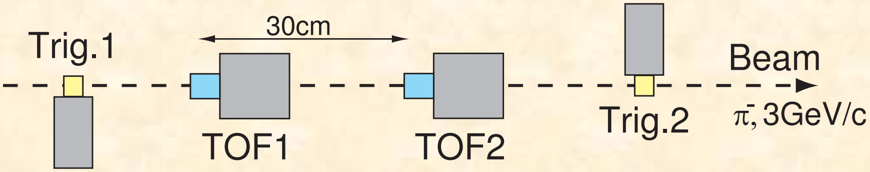


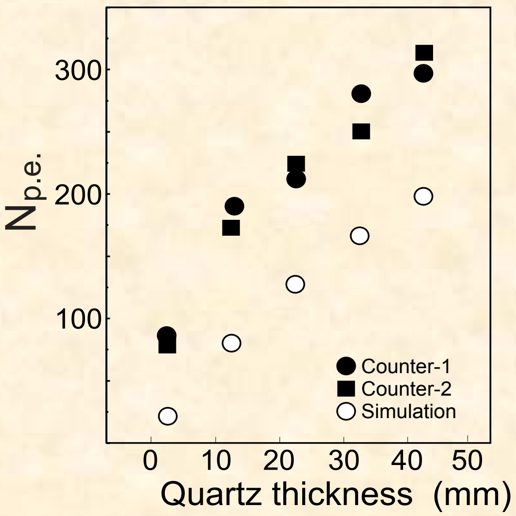
conventional TOF with scintillators

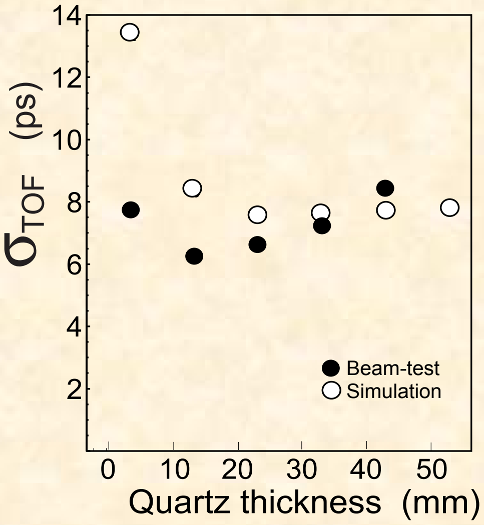
- ☐ long decay time O(ns) in photon emission
- ☐ time jitter due to photon paths

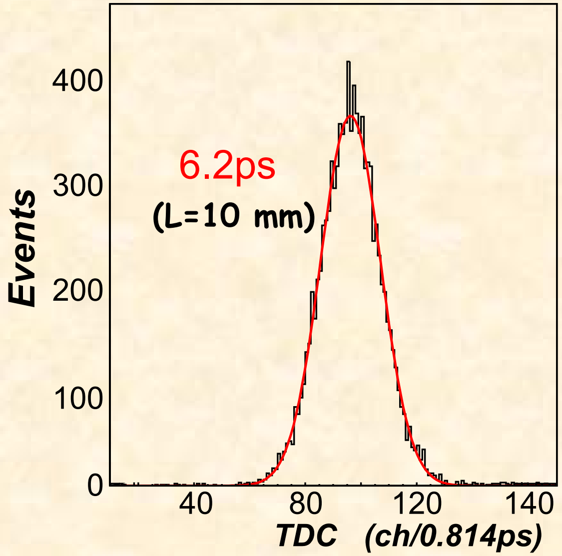
new idea: exploit Cherenkov light

- ■ produced promptly
- ■ almost no time jitter (directionality)





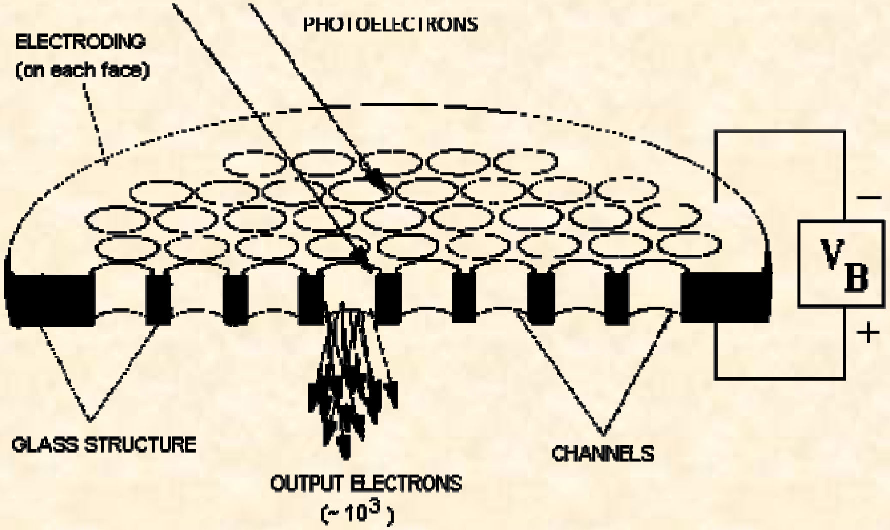


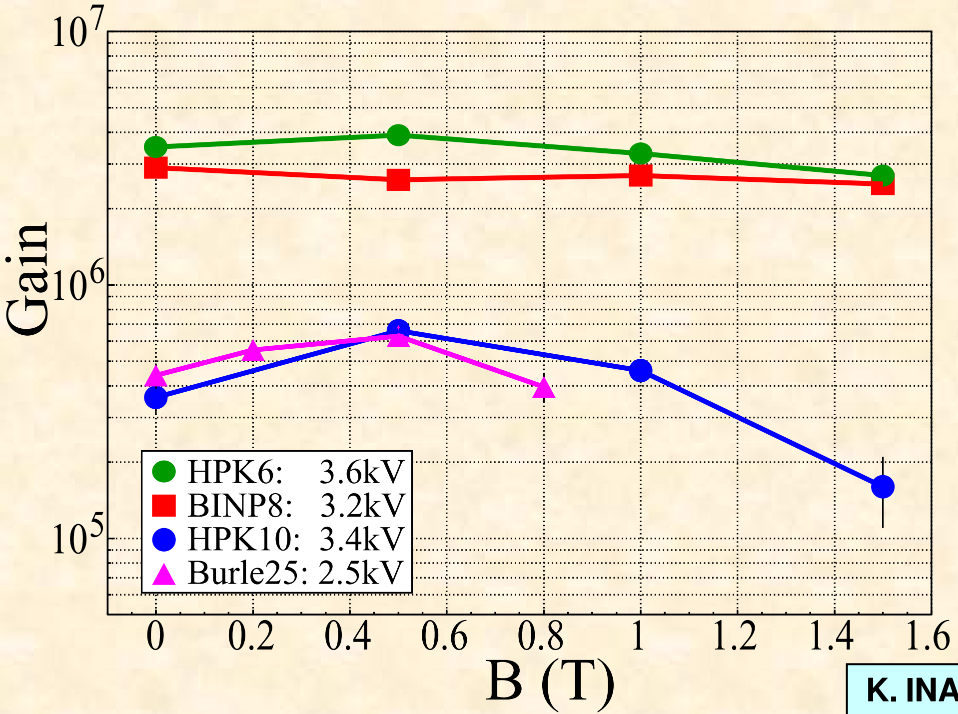


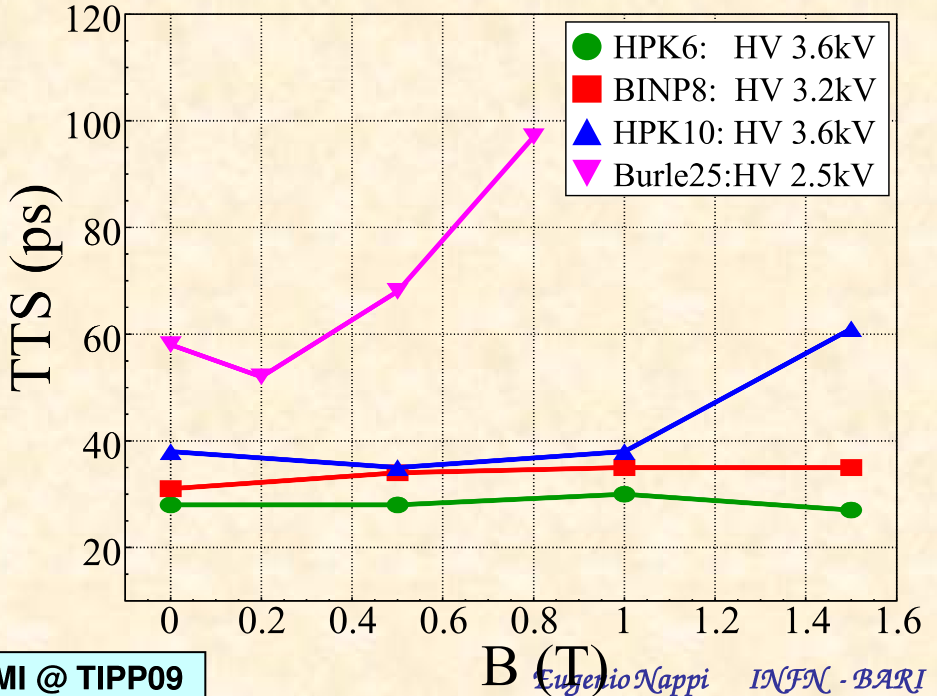
Fast photon detectors: MCP-PMTS

MCP-PMTs (1960s) are based on the concept of continuous dynode electron multiplier (Farnsworth, 1930)

J. L. Wiza,
***NIM* 162 (1979), 587 - 601**



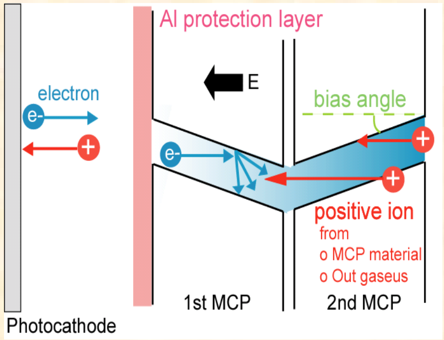




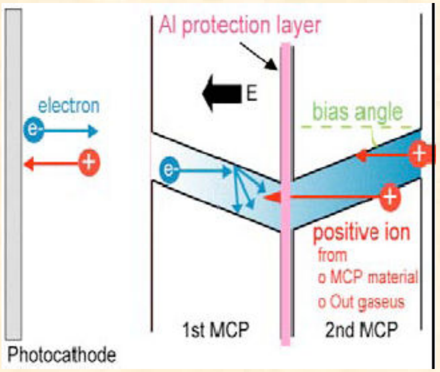
K. INAMI @ TIPP09

MCP_PMT lifetime

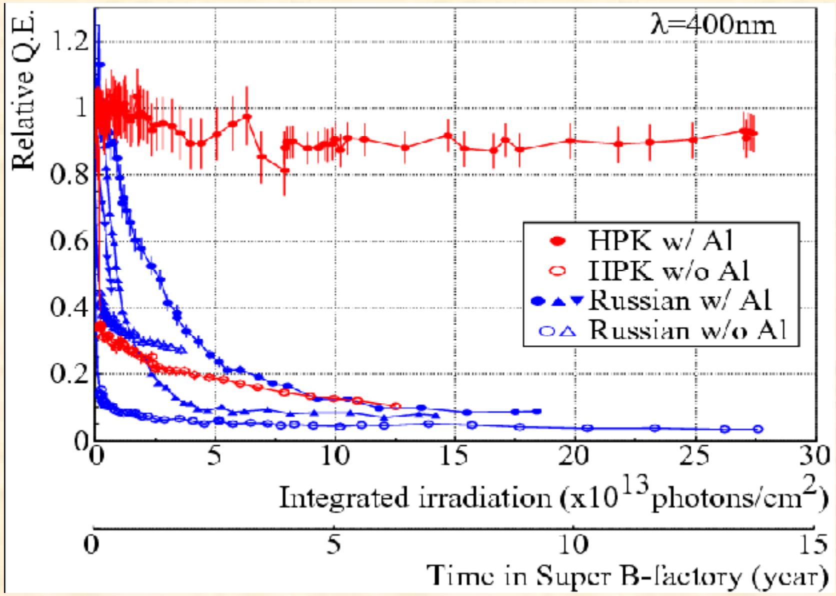
concern: limited photocathode life-time due to ion feedback

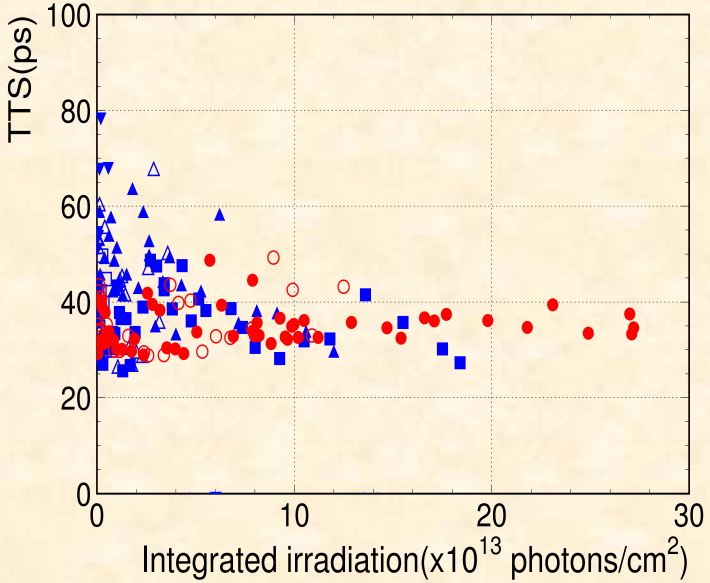


Al foil absorbs almost half of single photoelectrons

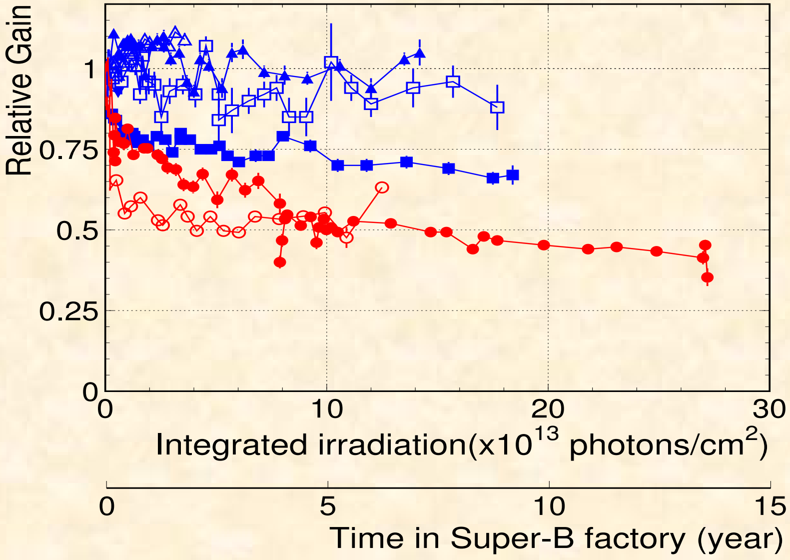


better to place the Al foil in between two MCPs





K. INAMI TIPP09

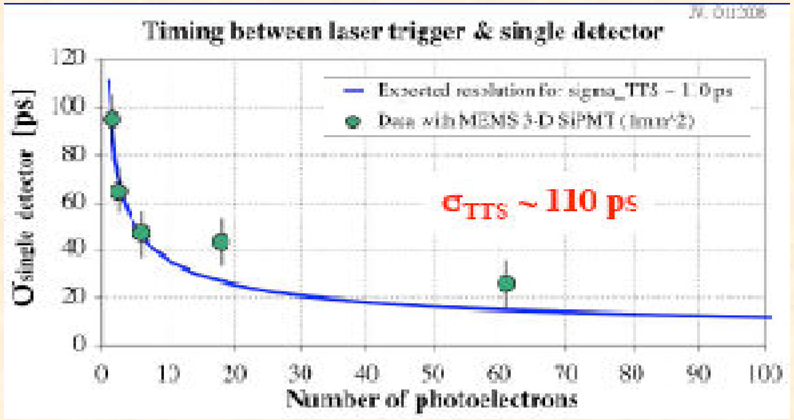


Fast photon detectors: G-APD

- insensitivity to magnetic fields;
- excellent photon counting capability;
- good timing properties;
- strong dependence on voltage and temperature;
- radiation damage (p,n)

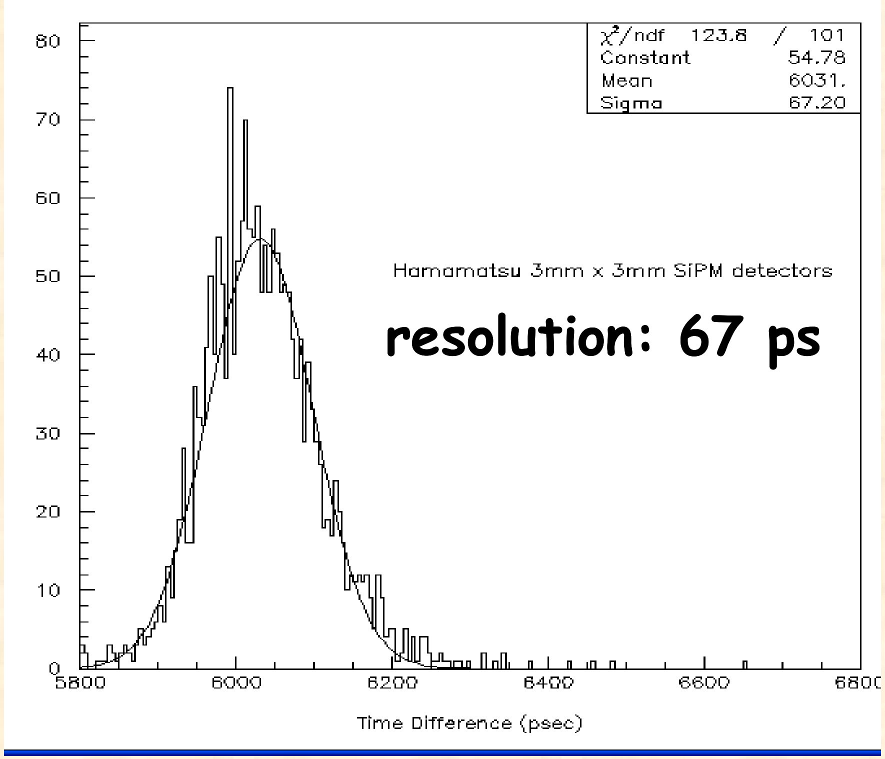
(several talks today + posters)

Colazuol et al, Nucl. Instr & Meth., A581(2007)461

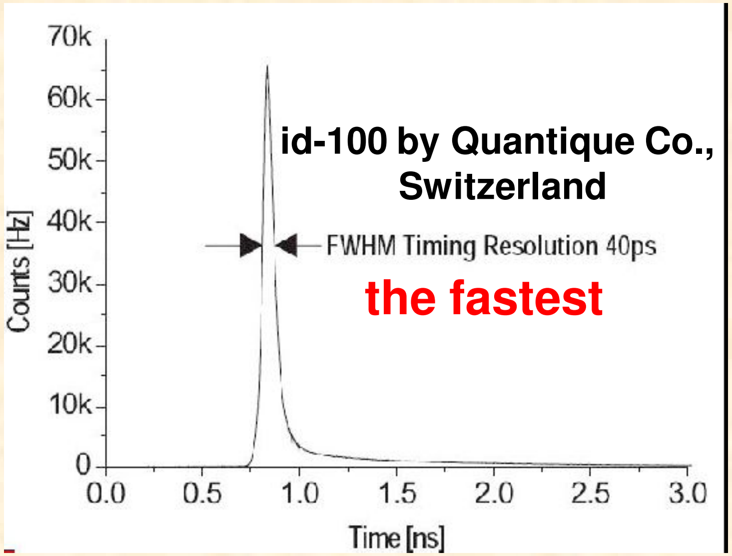


$\sigma_{TTS} \sim 110$ ps

Hamamatsu MPPC 3 x 3 mm^2



resolution: 67 ps



id-100 by Quantique Co., Switzerland

the fastest

PID by dE/dx measurement

Particle dentification particles by simultaneous measurement of tracks and energy losses is a well proven technique since many years

<dE/dx> is practically measured by evaluating ΔE in short intervals δx many times along the track

Main issues:
- large fluctuations (Landau) from sample to sample in the charge deposit
- energetic electrons could move away and are recognized as separate hits

Allison and Cobb, Ann. Rev. Nucl. Part. Sci. 30, 253 (1980) (for gaseous detectors)

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

n: number of samples
t: thickness of the layer (cm)
p: pressure of the gas (atm)

Resolution depends on detector size and pressure (effective track length

- **σ does not follow the $n^{-0.5}$ gaussian dependence owing to the Landau fluctuations;**
- **if the total lever arm (nt) is fixed, it is better to increase n**

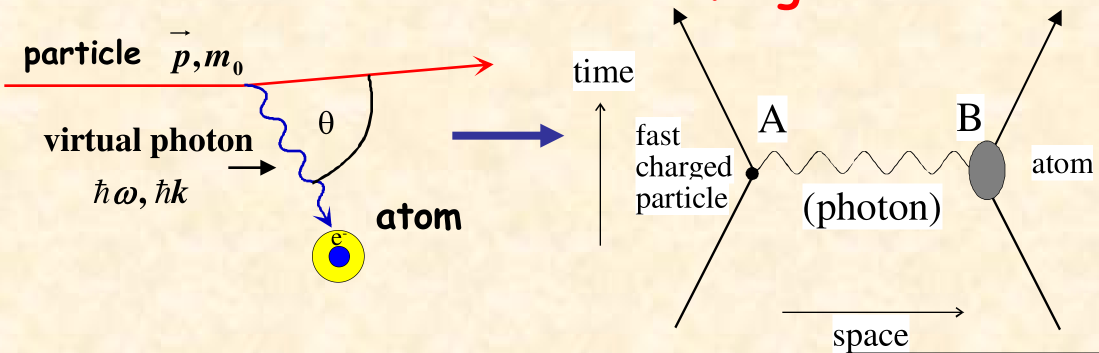
From the theory to the practice

statistical treatment to estimate the “mean” energy loss

- truncated Mean from the lowest 70-80% measured values (most used, robust)
- straggling functions (Landau) (takes into account the full information) (H. Bichsel, Nucl. Instrum. Meth. A562, 154 (2006))

parametrization is fitted to the data or compared to expectation

$\Rightarrow$ various models: level of agreement~3% in the relativistic rise

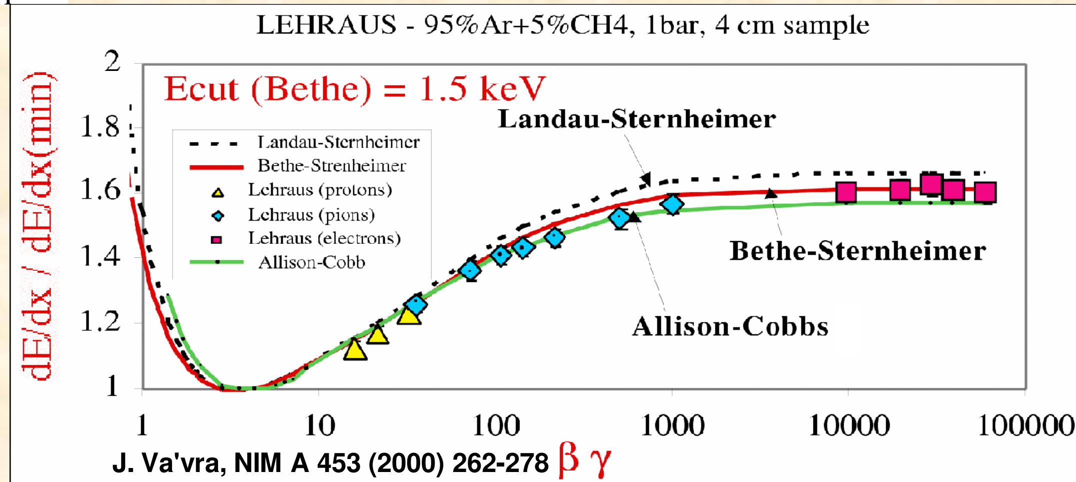


$$\frac{dE}{dx} = -n\int_0^\infty dE \int_{\omega/v}^\infty dp E \frac{d^2\sigma}{dEdp}$$

$$p = \hbar k \qquad E = \hbar\omega$$

density of atoms: $n = \rho N_A / A$

- non relativistic region: dE/dx $\propto 1/\beta^2$
  (more precisely as $\beta^{-5/3}$)
- minimum: at $\beta\gamma = 3 \div 4$ (Minimum Ionizing Particle)
- at high $\beta\gamma$: dE/dx $\propto \ln\gamma^2$ (relativistic rise)



J. Va'vra, NIM A 453 (2000) 262-278

dE/dx resolution

	Type	n	t (cm)	p (bar)	Gas	σ (%)
Belle	Drift ch.	52	1.5	1	He/C_2H_6=50/50	5.5
Babar	Drift ch.	40	1.2	1	He/i-C_4H_{10}=80/20	7.5
CLEO III	Drift ch.	47	1.4	1	He/C_3H_8=60/40	5.0
ALEPH	TPC	338	0.4	1	Ar/CH_4=90/ 10	4.5
PEP	TPC	183	0.4	8.5	Ar/CH_4=80/ 20	3.0
OPAL	Jet ch.	159	1.0	4	Ar/CH_4 /i-C_4H_{10} =88.2/9.8/2	2.8
STAR	TPC	44	1.15-1.95	1	Ar/CH_4=90/ 10	7.5
ALICE	TPC	72	0.75-1	1	Ne/CO_2 /N_2 =85.7/9.5/4.8	5.5
T2K	TPC w/ MM	72	0.97	1	Ar/CF_4 /i-C_4H_{10} =95/3/2	10

- **Higher pressure gives better resolution, however, the relativistic rise saturates at lower βγ ⇒ 4 – 5 bar seems to be the optimal pressure**
- **Helium based detectors (BaBar, BELLE, CLEO-III):**

low ionization statistics compensated by fewer cluster fluctuations

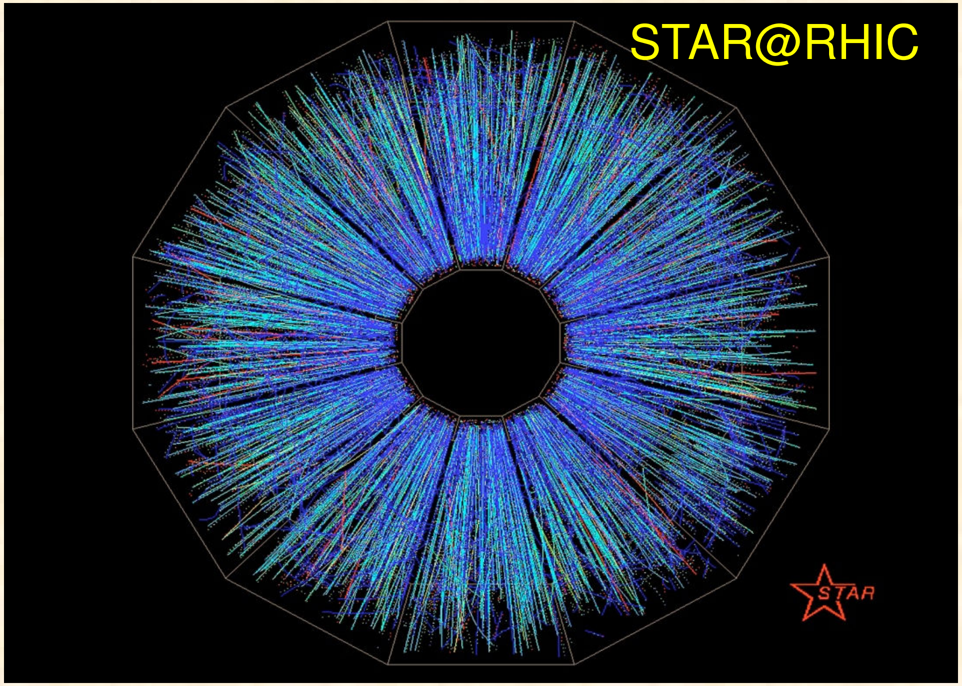
- **Higher content of hydro-carbons gives better resolution (Belle and CLEO III).**

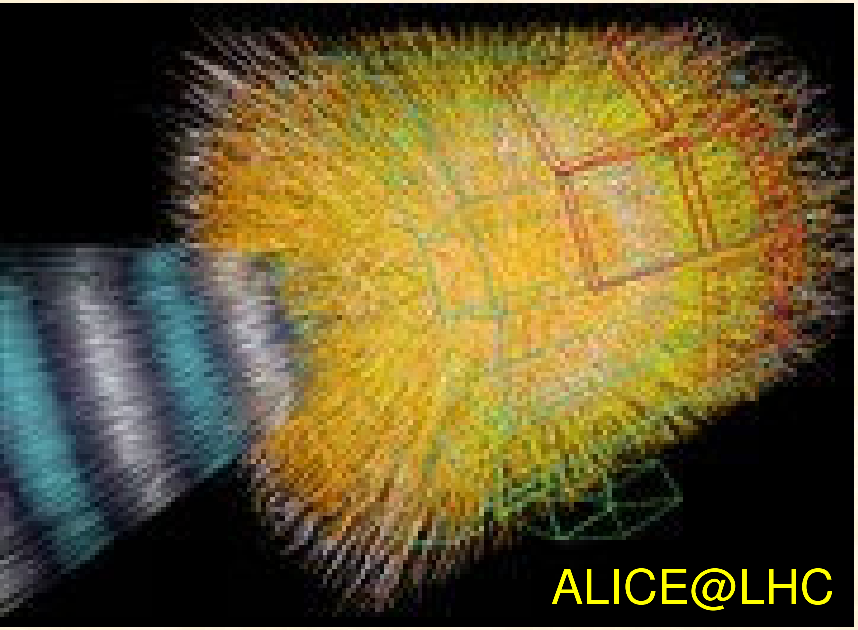
⇒ Landau distribution (FWMH) = 60 % for noble gas, 45% for CH_4, 33% for C_3H_6

Various systematic effects affect performance: calibration, gain, electrical field, noise, ...

PID by dE/dx in a harsch environment

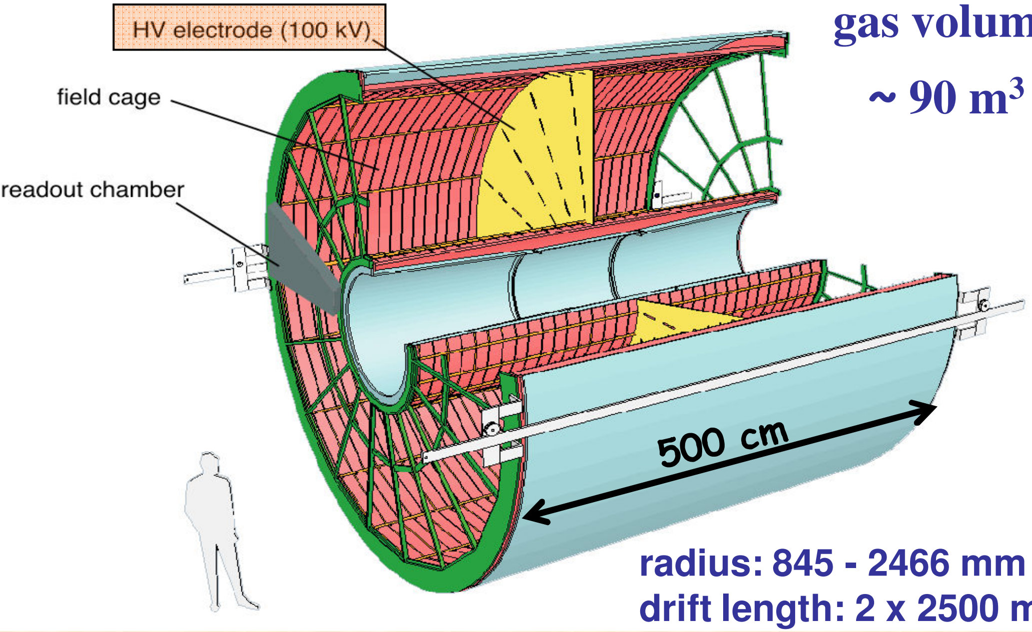
High density track environment:
- ion space charge build-up in drift volume by large backgrounds;
- ion space charge around sense wire (gas amplification region);
- reduced number of samples along each track due to the limited double track resolution (worse separation power)





ALICE TPC:
- chosen the time/pad area which yields still reasonable signal (S/N > 20);
- optimized aspect ratio;
- minimized diffusion: "cold gas", high drift field 400 V/m, central electrode at 100 kV.

ALICE TPC



gas volume

~ 90 m^3

radius: 845 - 2466 mm
drift length: 2 x 2500 mm

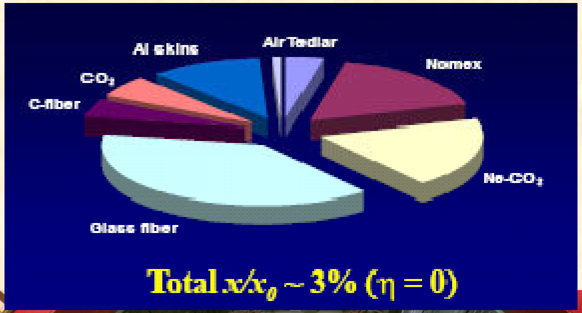
88 μs drift time ($E=400$ V/cm, $B=0.5$ T)

~ 600 k readout pads (32 m^2)

1000 samples in time direction

→ 6x10^8 pixels in space

high structural integrity with low-mass and low-Z material



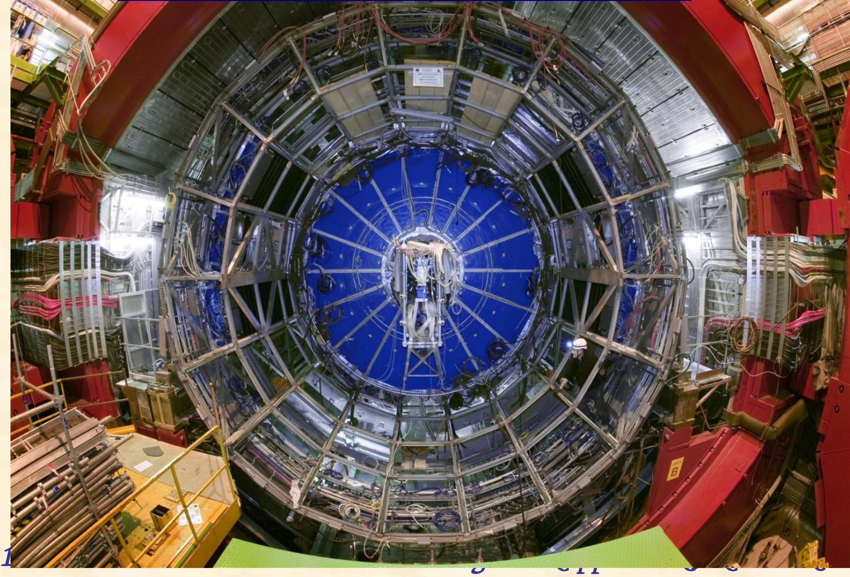
Total $x/x_0 \sim 3\%$ ($\eta = 0$)

gas: 85.7 % Ne – 9.5 % CO_2 – 4.8 % N_2

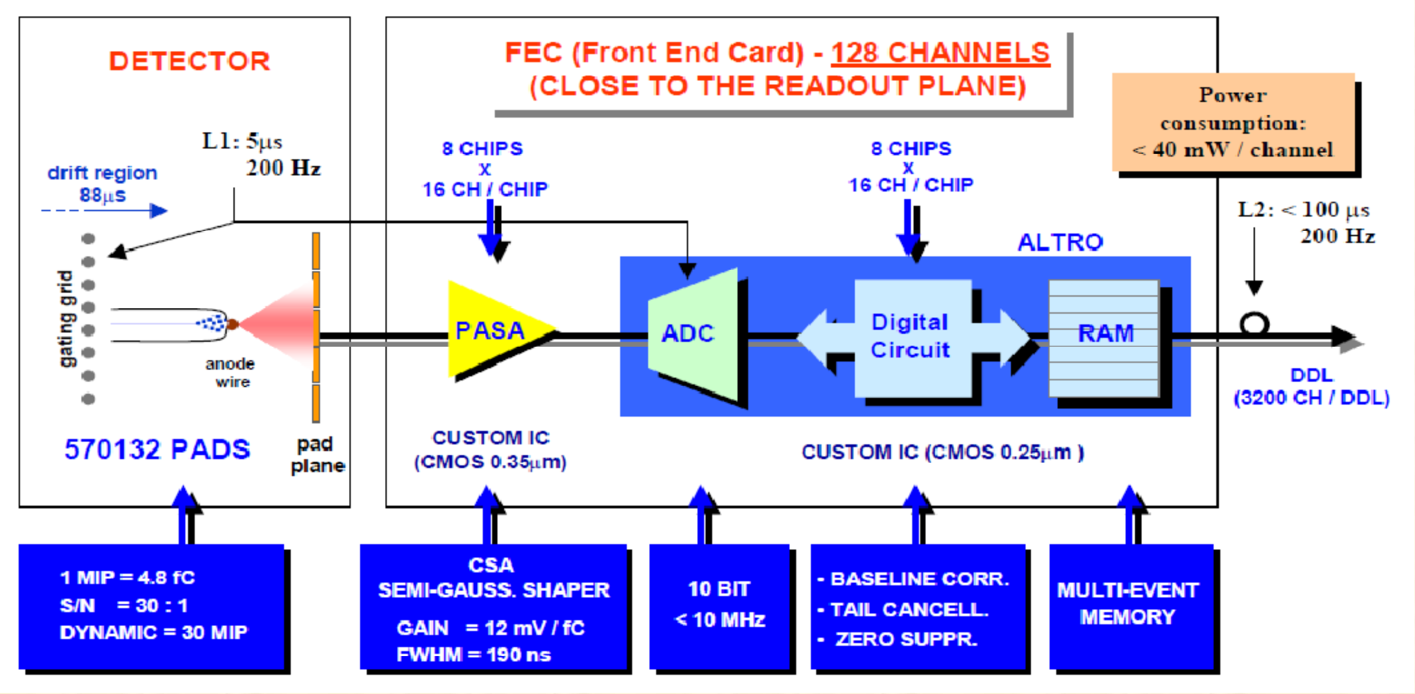
drift velocity non saturated

➢ **temp. stability of 0.1 K required**

- ❑ about 60 adjustable cooling circuits;
- ❑ FEE enveloped in copper plates (≈27kW);
- ❑ TPC cage protected by thermal screens (CO_2)



ALICE TPC R/O electronics



DETECTOR

drift region 88μs

L1: 5μs 200 Hz

gating grid

anode wire

pad plane

570132 PADS

FEC (Front End Card) - 128 CHANNELS (CLOSE TO THE READOUT PLANE)

8 CHIPS x 16 CH / CHIP

8 CHIPS x 16 CH / CHIP

PASA

ALTRO

ADC

Digital Circuit

RAM

Power consumption: < 40 mW / channel

L2: < 100 μs 200 Hz

DDL (3200 CH / DDL)

CUSTOM IC (CMOS 0.35μm)

CUSTOM IC (CMOS 0.25μm)

1 MIP = 4.8 fC
S/N = 30 : 1
DYNAMIC = 30 MIP

CSA
SEMI-GAUSS. SHAPER
GAIN = 12 mV / fC
FWHM = 190 ns

10 BIT
< 10 MHz

- BASELINE CORR.
- TAIL CANCELL.
- ZERO SUPPR.

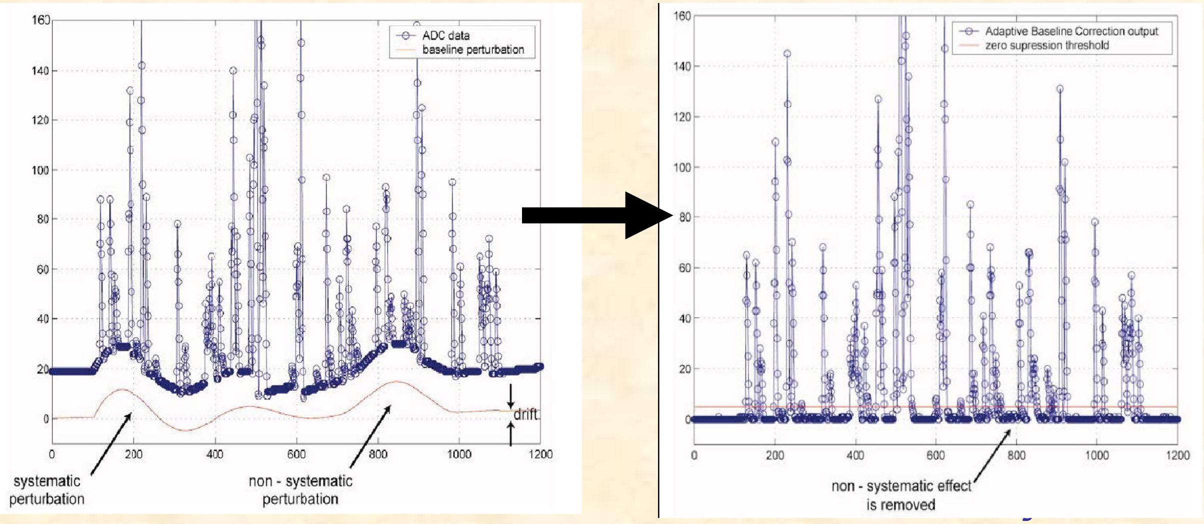
MULTI-EVENT MEMORY

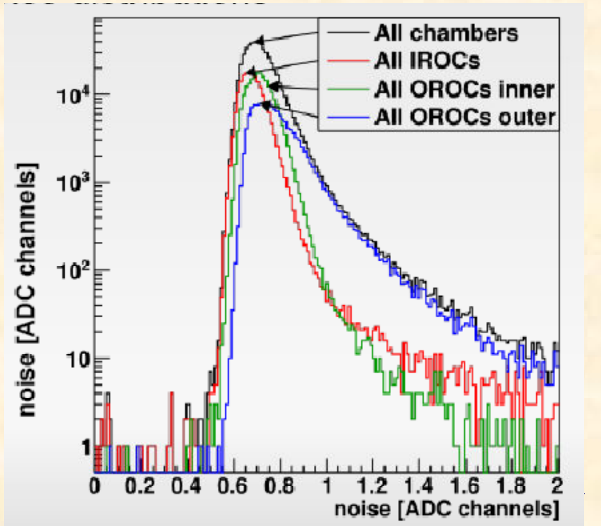
PROGRAMMABLE DIGITAL FILTER

- ion tail cancellation;
- baseline restoration;
- common mode subtraction

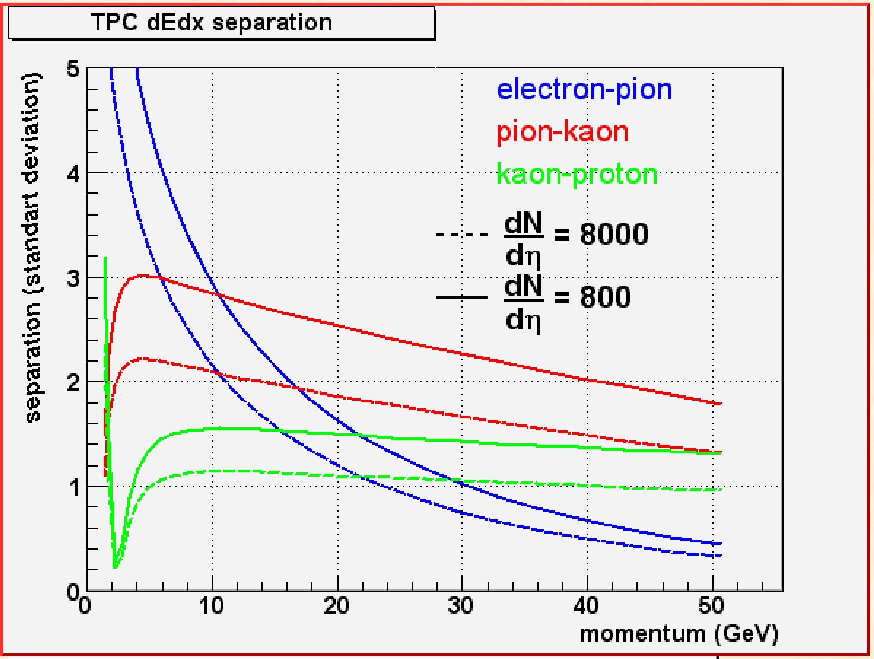
mean noise level 0.7 ADC count (700 e^-) (design: 1 ADC count)

B. Mota et al, Nucl. Instr. and Meth. A535(2004)500



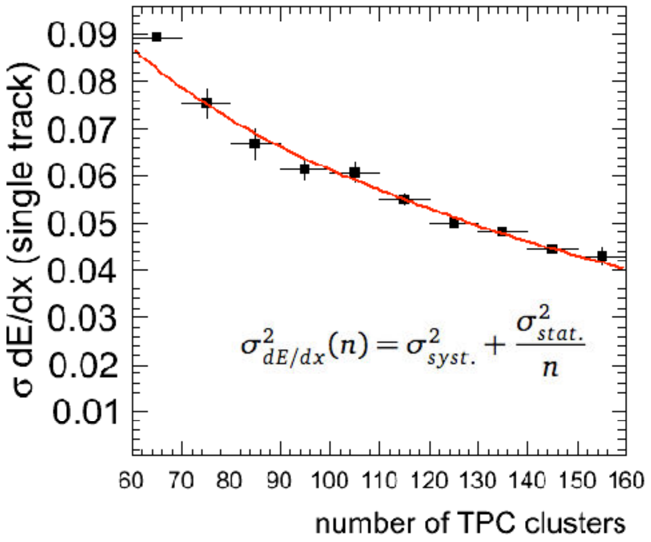


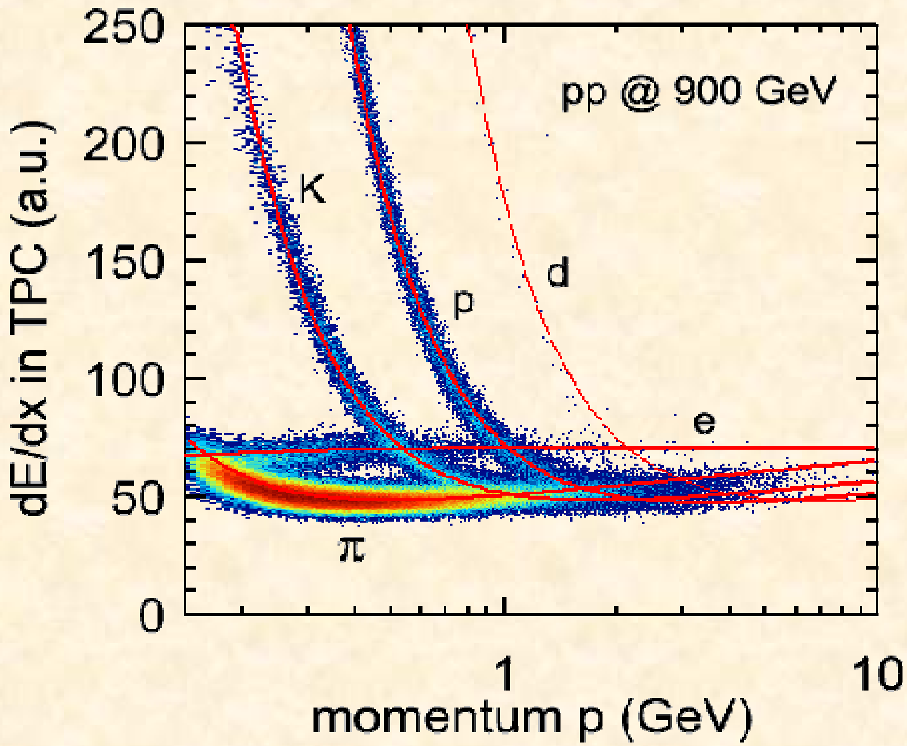
ALICE TPC PERFORMANCE



$\sigma_{dE/dx}$ = 6.8%
at dN/dy=8000
(5.5% for isolated tracks)

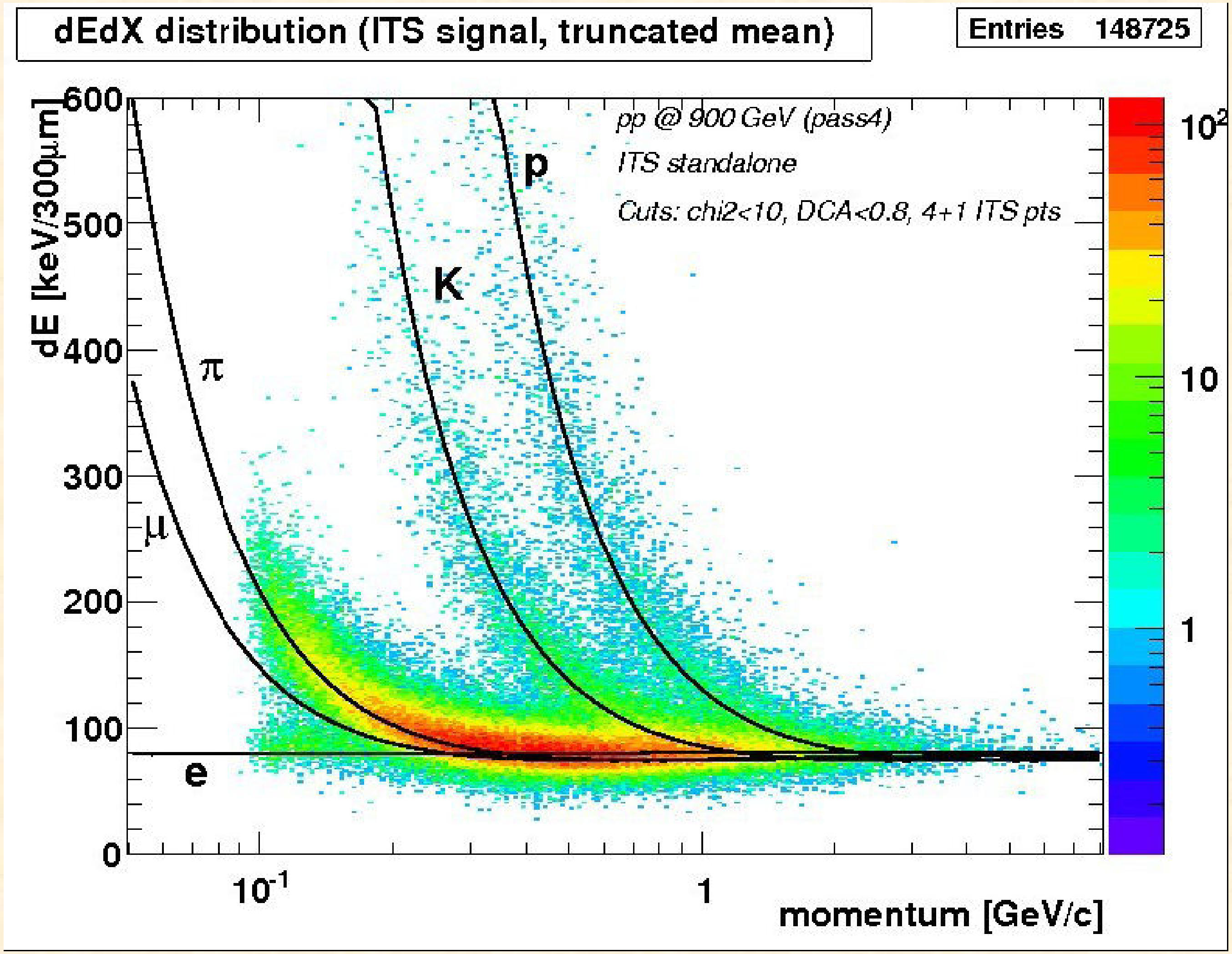
(2008 JINST 3 S08002)





dE/dx spectrum from ~10 million real events

ALICE: dE/dx measurement by Si trackers



Talk by M. Sitta

TPCs readout by MPGD

MPGD's advantages:

- no ExB effect (bi-dimensional symmetry);
- intrinsic ion feedback suppression (< 1-2%);
- more flexibility in readout structures;
- robust construction

T2K (first application of bulk MM)

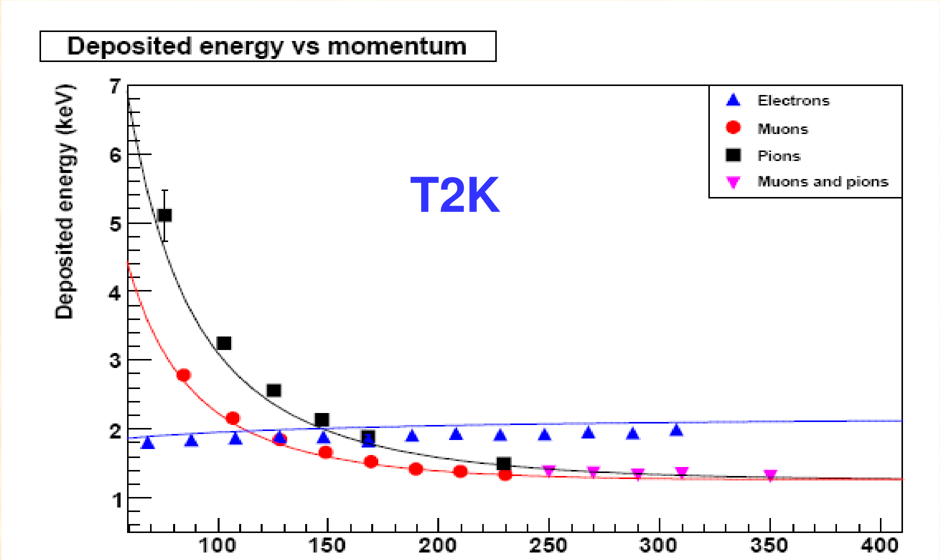
Long Baseline Neutrino oscillation experiment

3 large TPCs

~120 k channels

drift distance: 90 cm

total active area ~9m^2



σ(dE/dx)<10%

to perform e/μ separation

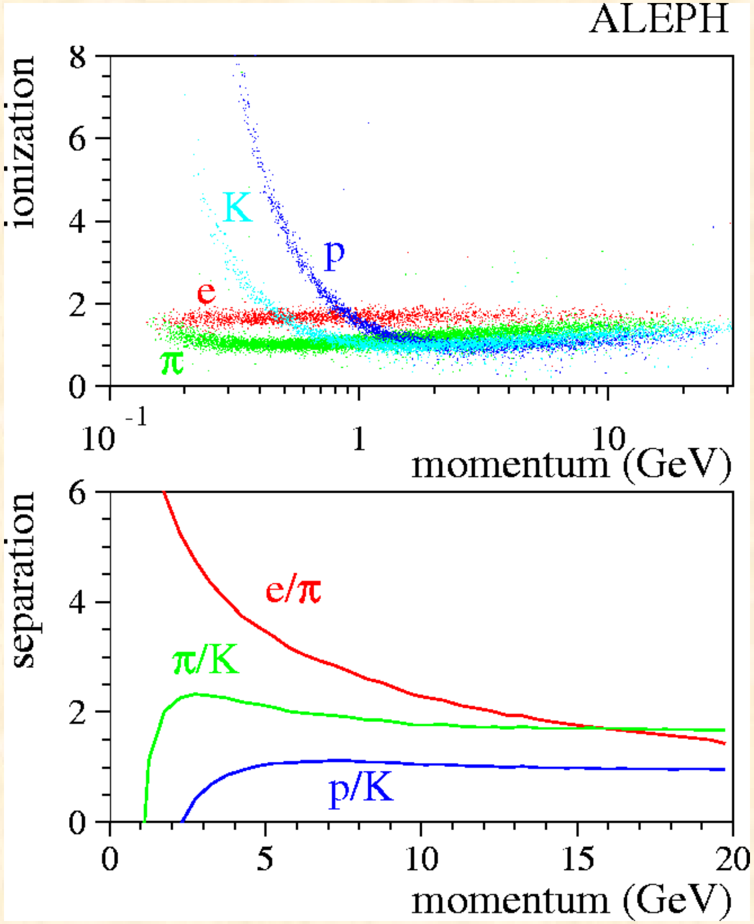
TPC R&D:

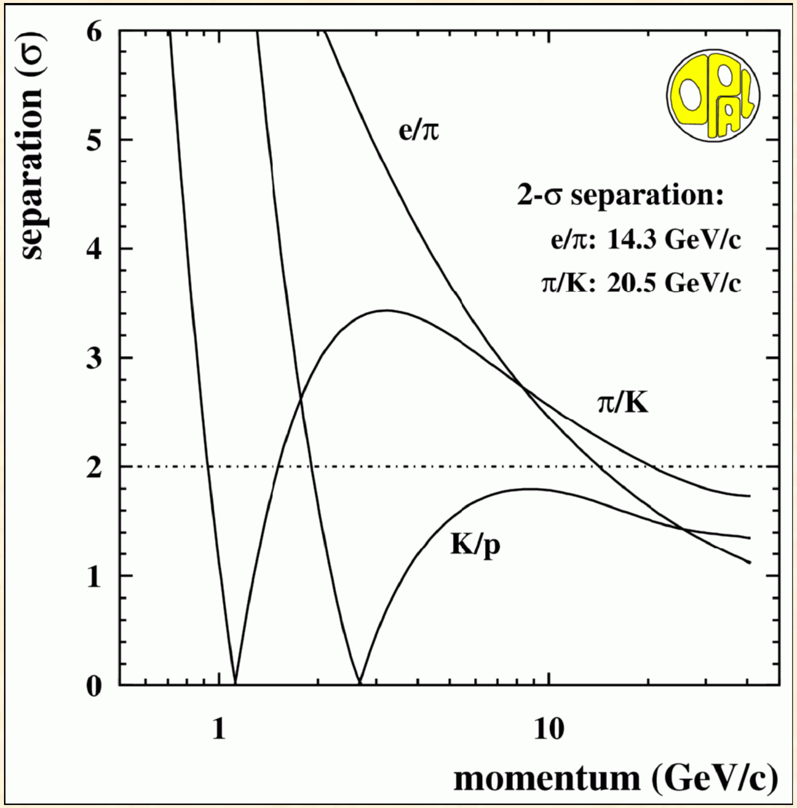
- ILC (talk by P. Schade)

- PANDA at FAIR (Poster by L. Fabbietti)

Separation Power

$$N_{S.D.}(A;B) = \frac{dE/dx(A) - dE/dx(B)}{\sigma(dE/dx)}$$





2-σ separation:
e/π: 14.3 GeV/c
π/K: 20.5 GeV/c

PID by dE/dx never reaches a good particle separation

dE/dx : prospect

CLUSTER COUNTING OF PRIMARY IONIZATION

- exploit poissonian statistics of primary clusters
- first ideas by A. Davidenko (1969) and by A. H. Walenta (1979); more studies by G. Malamud, A. Breskin, B. Chechik early 90's.
- expected an improvement up to a factor 2 over charge integration method

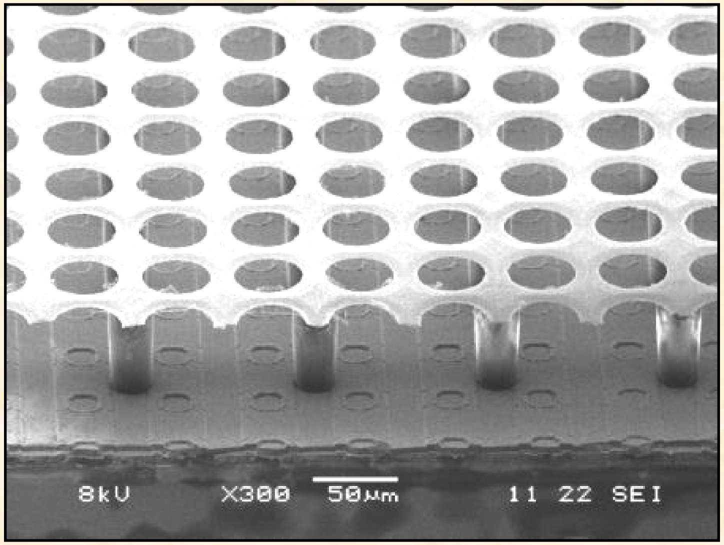
So far nobody has succeeded to apply this method in experiments

Main issues:

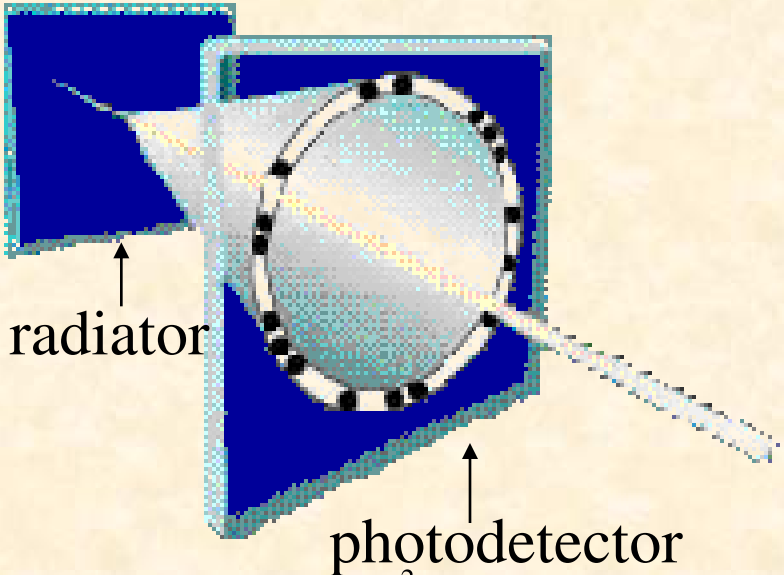
- clusters are 300-400 μm apart → few ns separation;
- diffusion merges clusters

Hope:
new fast digitizers combined with wafer post-processing techniques integrating MPGDs to pixelized sensors (talk by H. Van Der Graaf)

seen single electrons; if associable with primary clusters, then the dE/dX measurement can be based on cluster counting



Cherenkov light imaging



Unique tool to identify charged particles with a high separation power over a range of momenta from few hundred MeV/c up to several hundred GeV/c

$$\cos\theta = \frac{1}{n\beta} \Rightarrow \left(\frac{\sigma_\beta}{\beta}\right)^2 = \left(\tan\theta\,\sigma_\theta\right)^2 + \left(\frac{\Delta n}{n}\right)^2$$

$$m = \frac{p}{\beta\gamma} = p\sqrt{n^2\cos^2\theta_c - 1}$$

Separation power :

$$\theta_2 - \theta_1 = n\sigma_{\theta_c} \qquad \sigma_\theta^2 = \sum_i \Delta\theta_i^2 \Rightarrow \sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

$\Downarrow$ PARTICLE MASS m_1 $\quad$ $\Downarrow$ PARTICLE MASS m_2

minimize σ_θ

maximize $N_{p.e}$

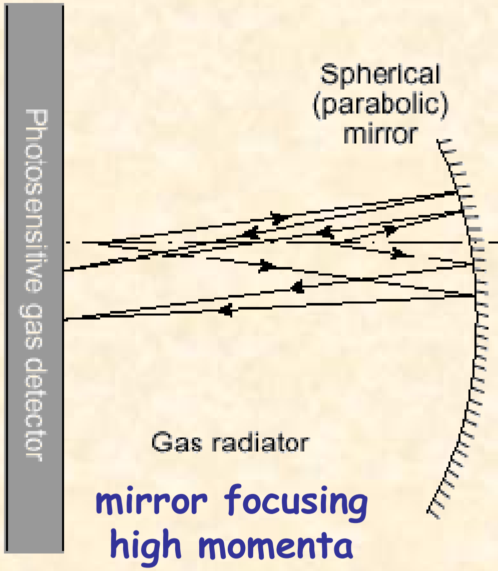
low chromaticity

high granularity

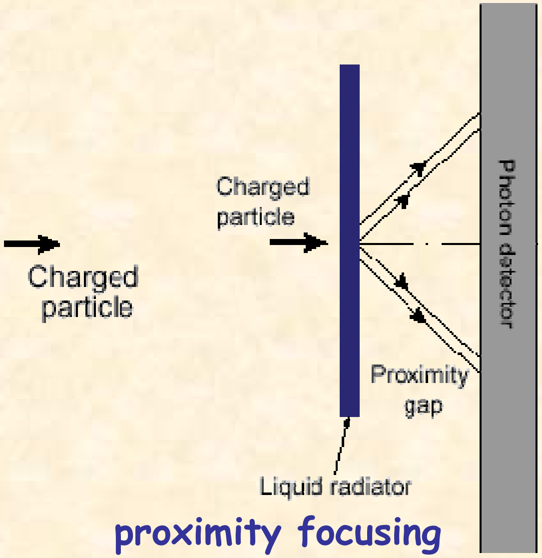
high packing density

goal:
detect the maximum number of photons with the best angular resolution

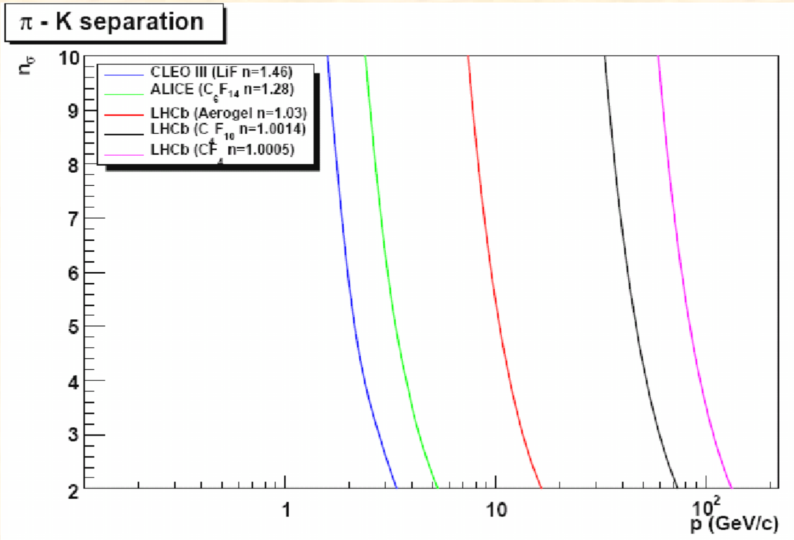
RICH counters



mirror focusing
high momenta



proximity focusing
low momenta



Experiment	Type	Radiator (n)/L	Photodetector
ALICE	Proximity focusing	C_6F_{14} (1.029)/1.5 cm	MWPC (CsI+CH_4)
COMPASS	Mirror focusing	C_4F_{10} (1.0014)/3 m	CsI MWPC + MAPMT
LHCb	Mirror focusing	Aerogel (1.03)/ 5 cm C_4F_{10} (1.0014)/ 80 cm CF_4 (1.0005) / 200 cm	HPD
NA62*	Mirror focusing	Ne (1.000063) / 18 m	PMT
CLEO-III	Proximity focusing	LiF (1.46) / 1 cm	MWPC (TEA+CH_4)

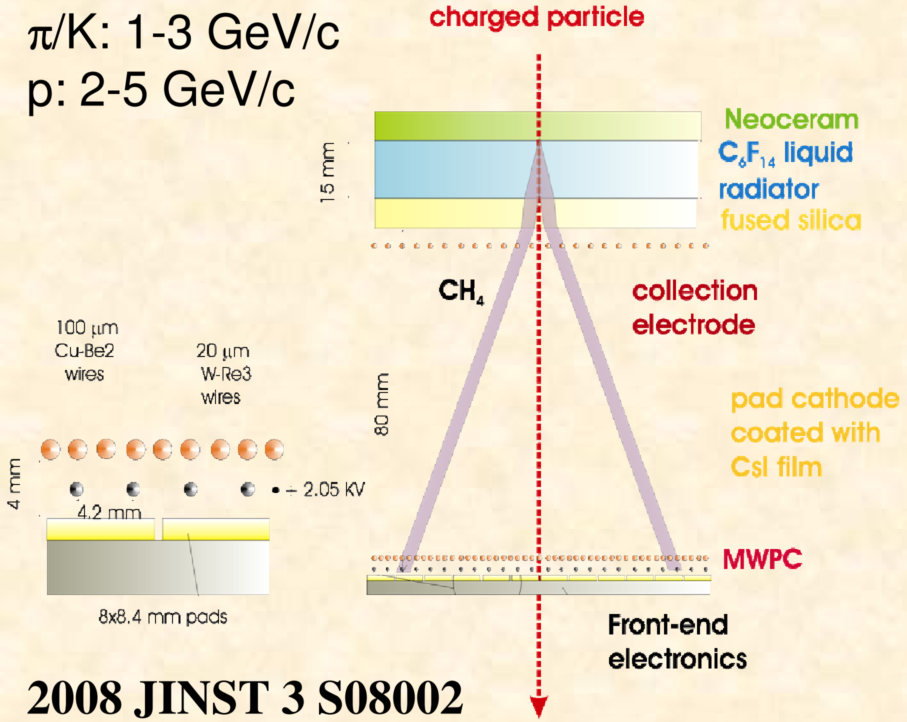
* Talk by G. ANZIVINO *(Univ.of Perugia and INFN)*

ALICE-HMPID

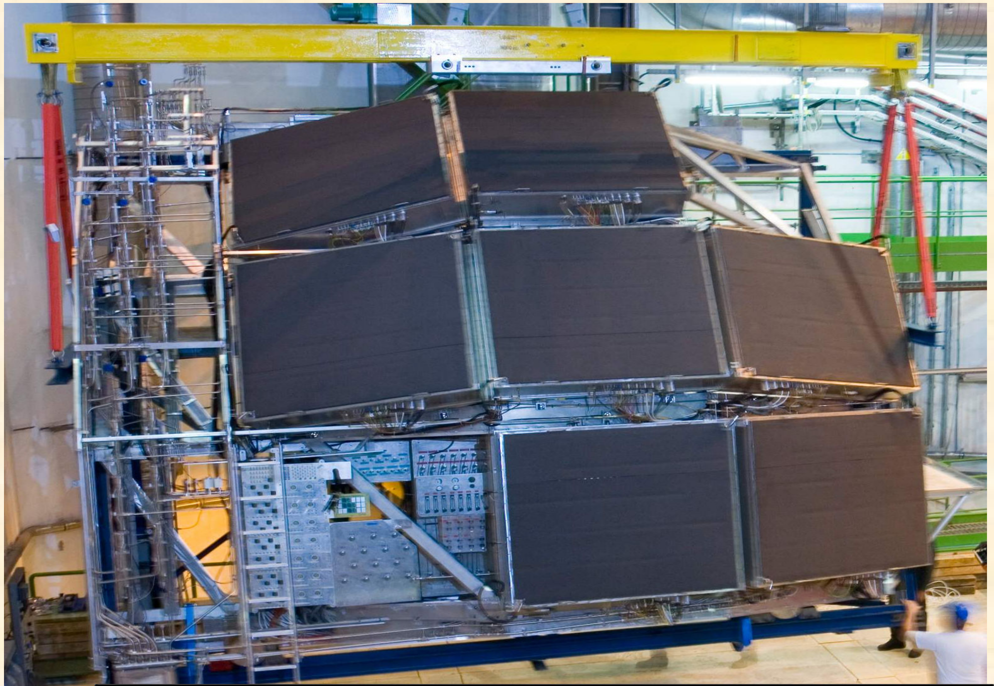
High Momentum Particle Identification Detector

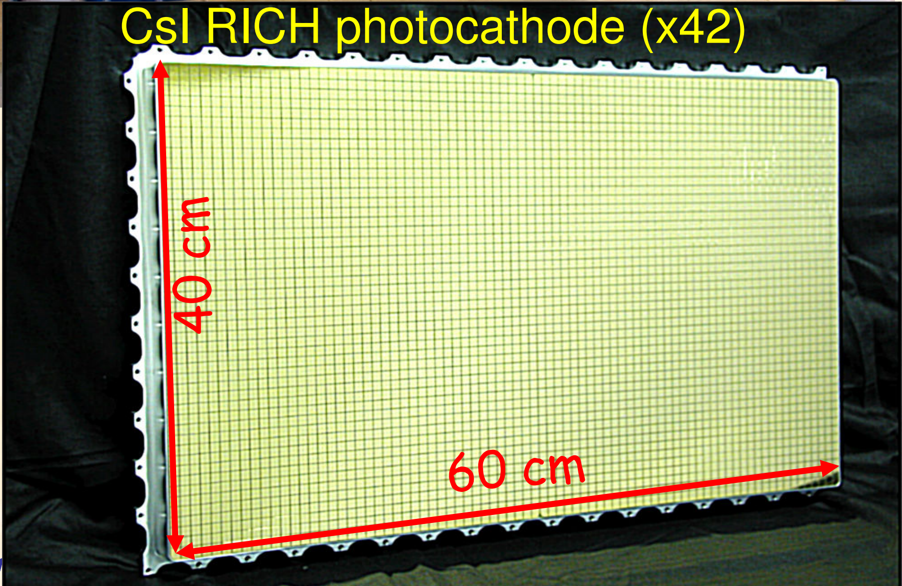
π/K: 1-3 GeV/c

p: 2-5 GeV/c



2008 JINST 3 S08002

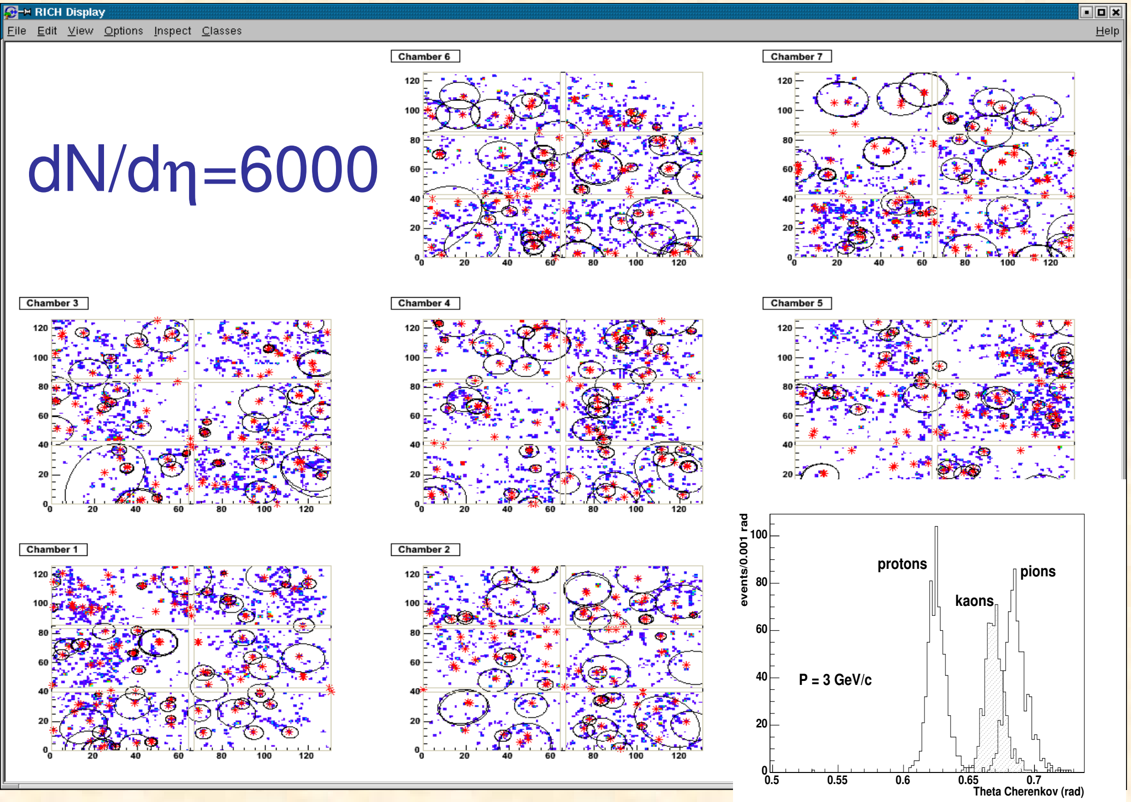



CsI RICH photocathode (x42)

analogue pad readout (~160 k channels)
the largest scale (11 m^2) application of CsI photocathodes

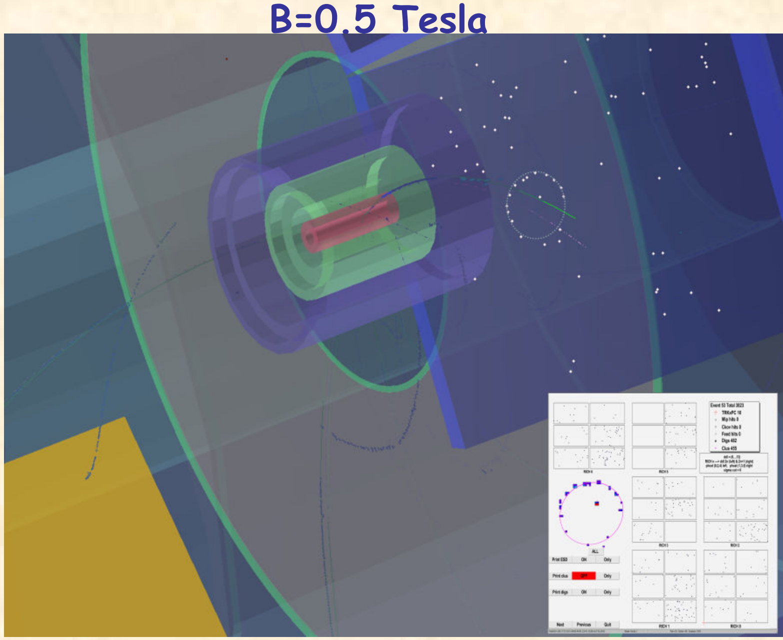
<u>CsI-RICHs:</u>
COMPASS, HADES, Hall-A at TJLAB

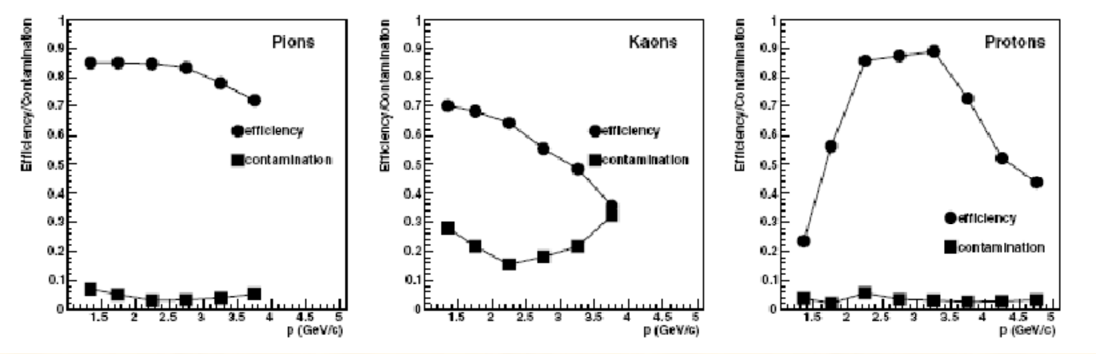
HMPID PERFORMANCE

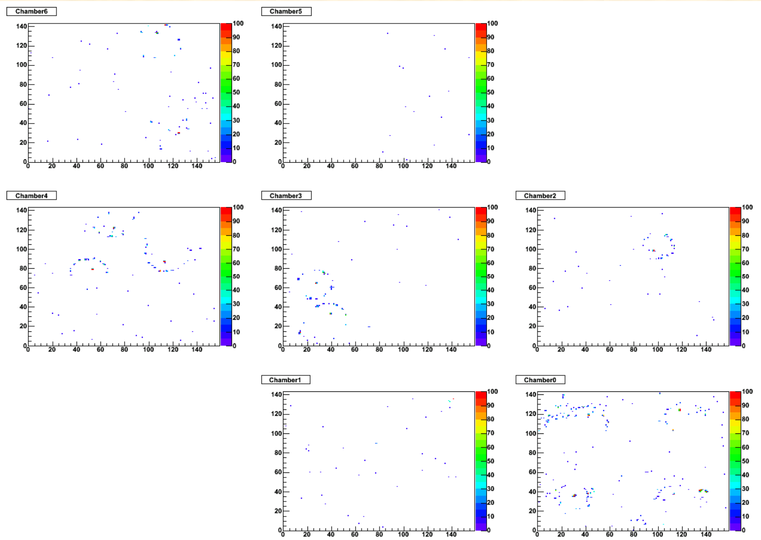


dN/dη=6000

LHC run 2009: pp 450 + 450 GeV/c, B=0.5 Tesla

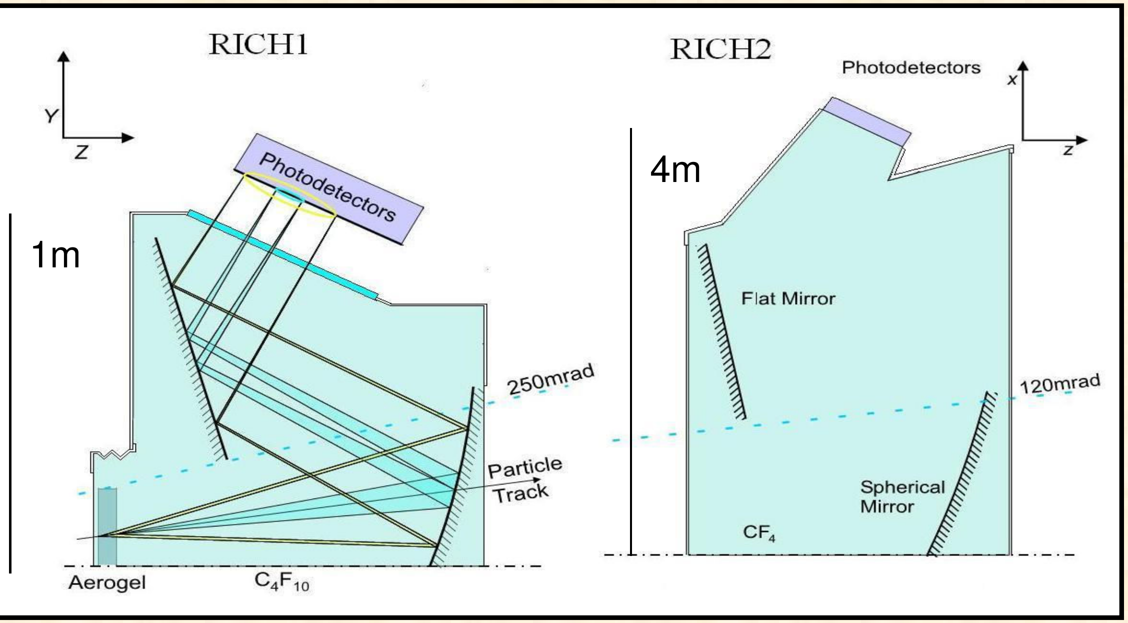


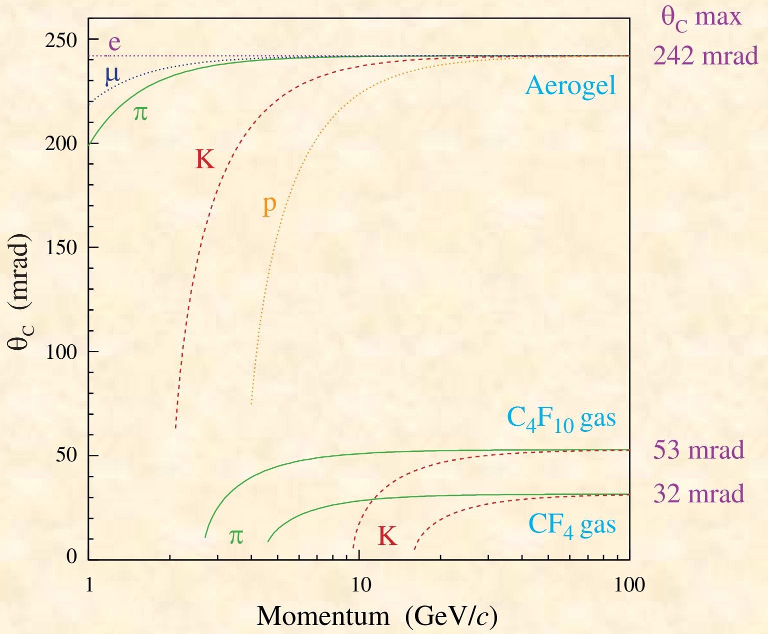


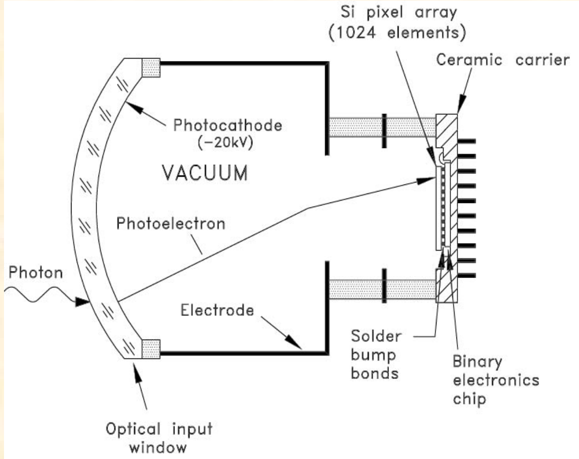


15-20 February 2010

LHCb RICHs



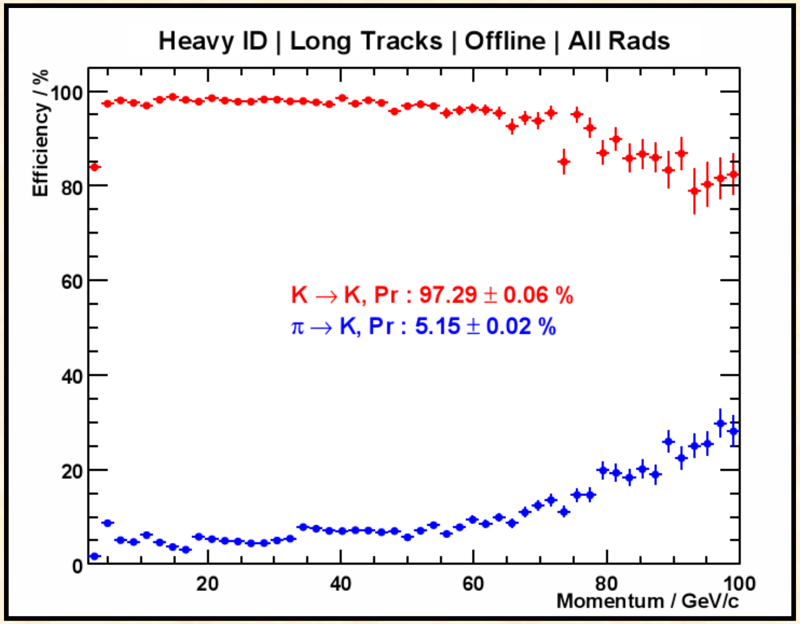




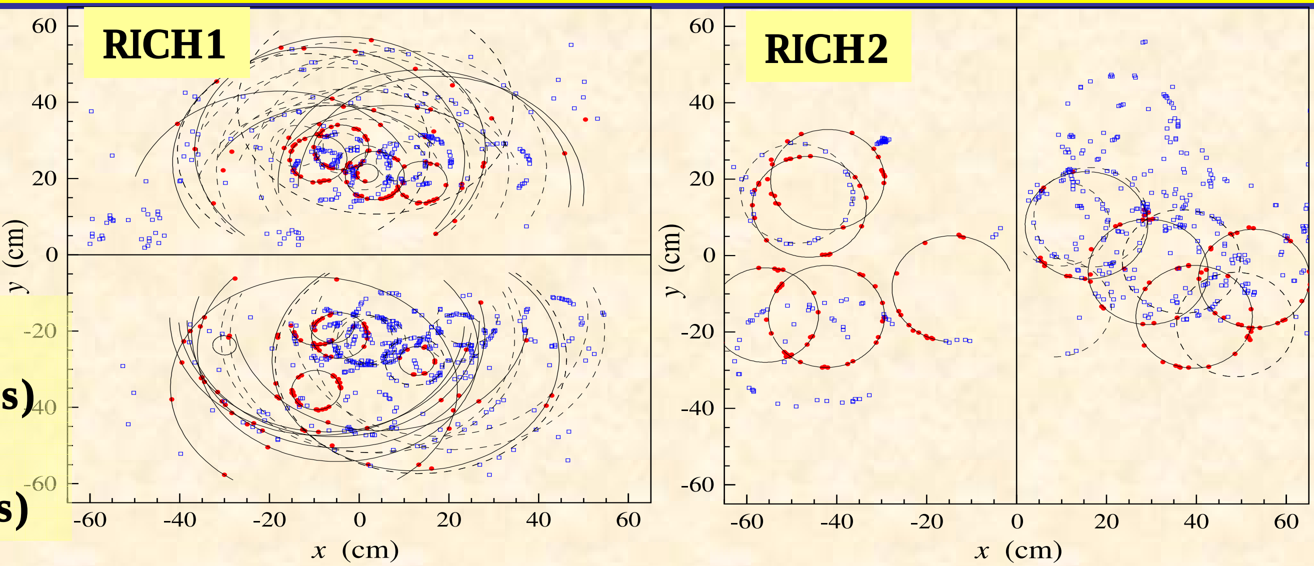
484 HPDs
active area = 3.3 m²

HPDs developed in collaboration with industry (Photonis-DEP)

- **quartz window with S20 photocathode;**
- **cross-focusing optics;**
- **space resolution 2.5 x 2.5 mm²;**
- **low noise (dark count rate < 5 kHz/cm²);**
- **0.5 Mchannels**

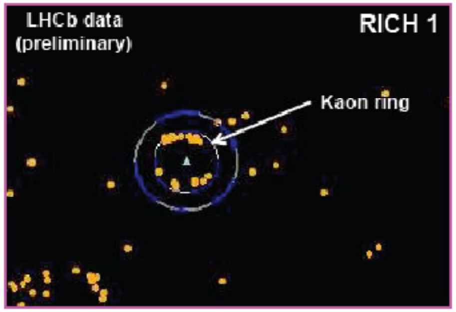


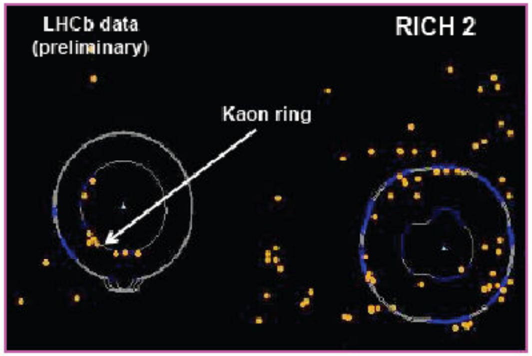
LHCb pp events

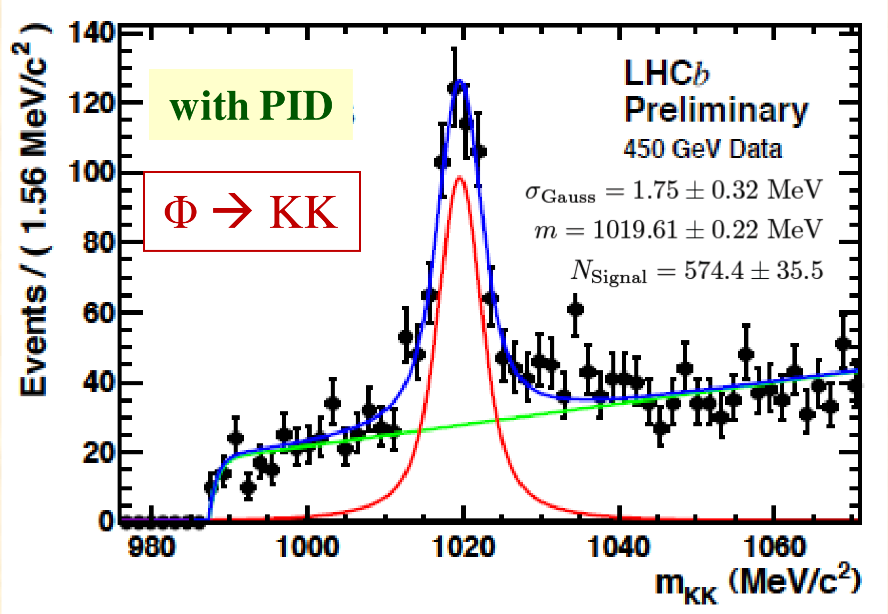


C_4F_{10}
(small rings)
Aerogel
(large rings)

CF_4





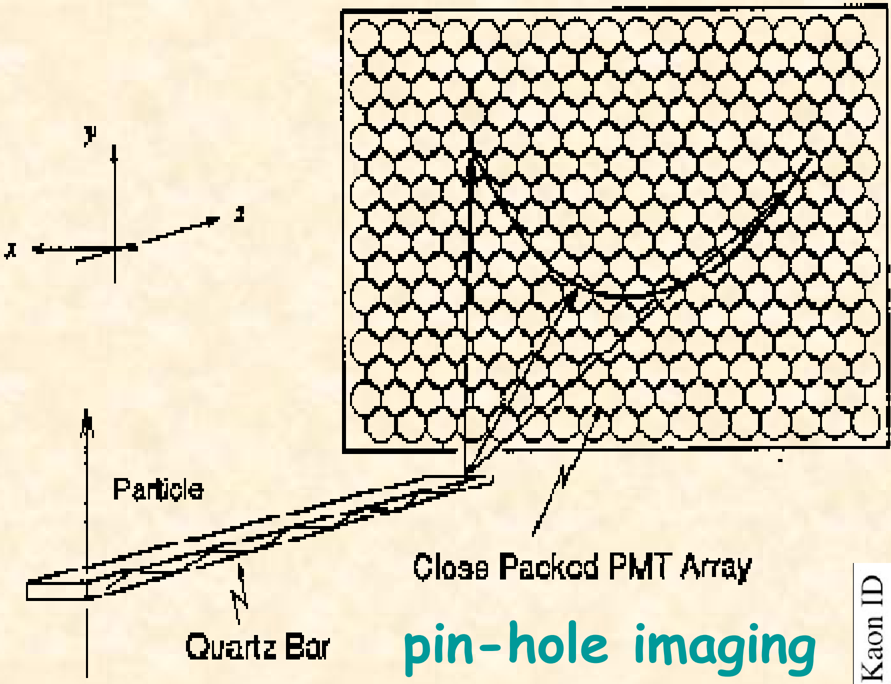


with PID

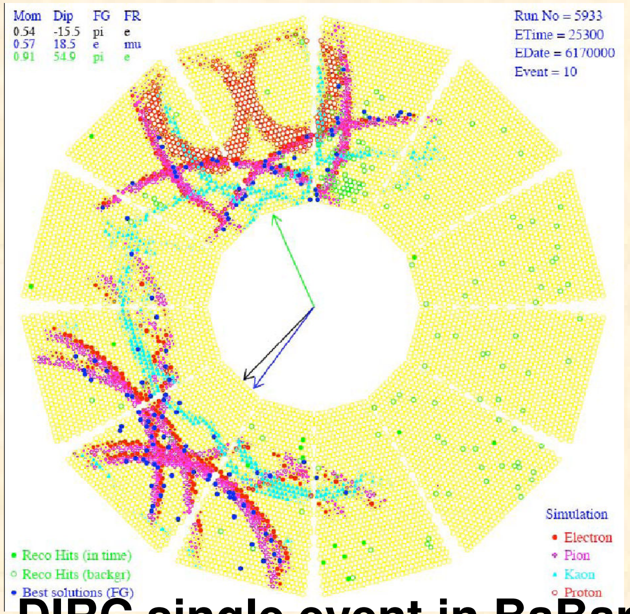
$\Phi \rightarrow KK$

DIRC

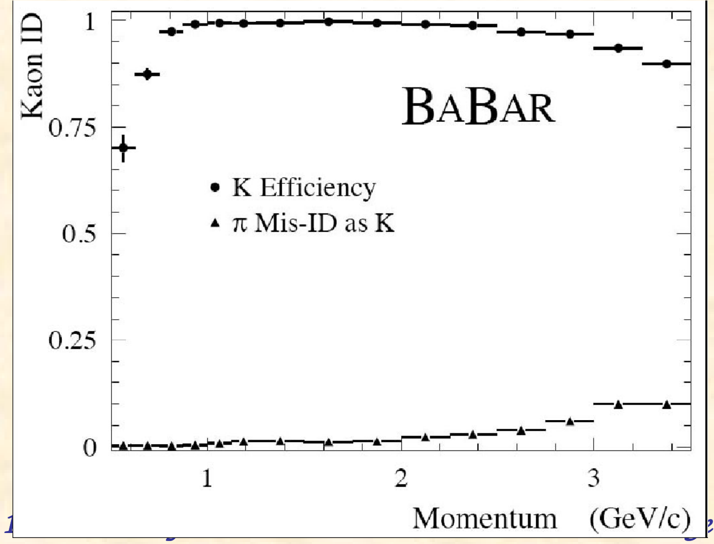
Detection of Internally Reflected Cherenkov light in accurately polished quartz bar (B. Ratcliff, NIM A479(2002)1)



pin-hole imaging



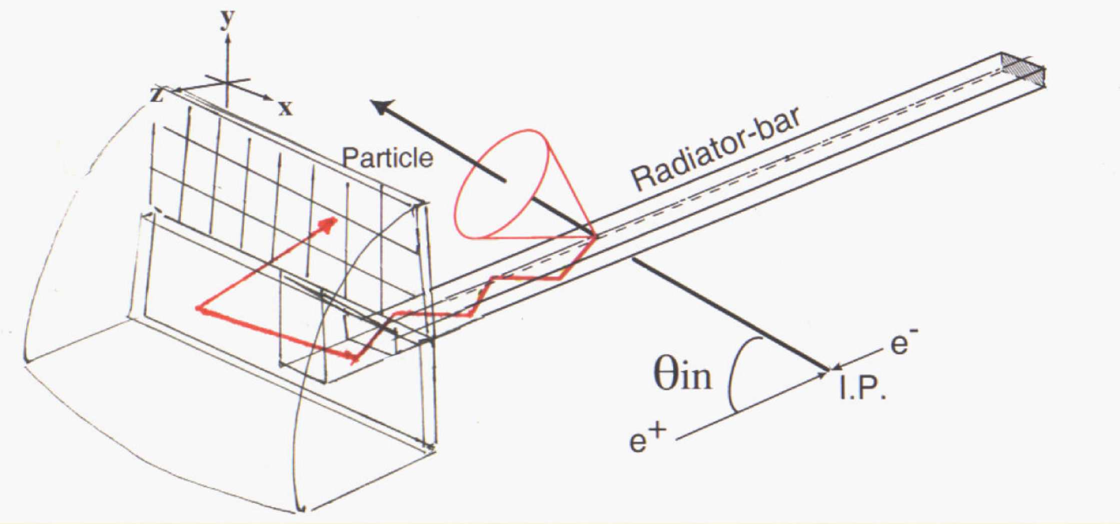
DIRC single event in BaBar



I. Adam et al.,
Nucl.Inst.&Meth., A 538 (2005) 281-357

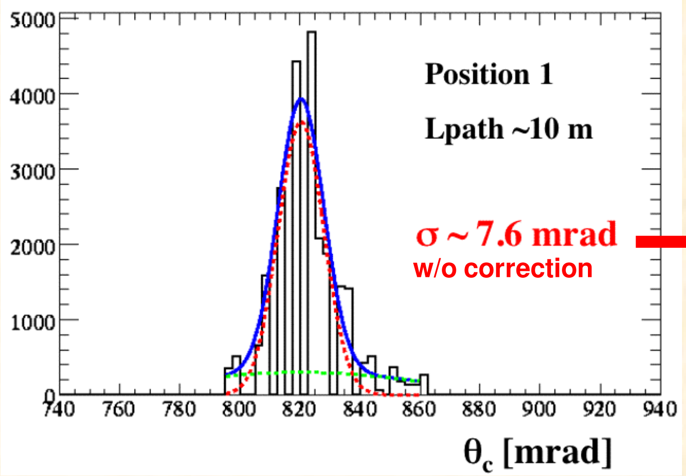
Focusing DIRC

measurement of position and time to correct chromaticity

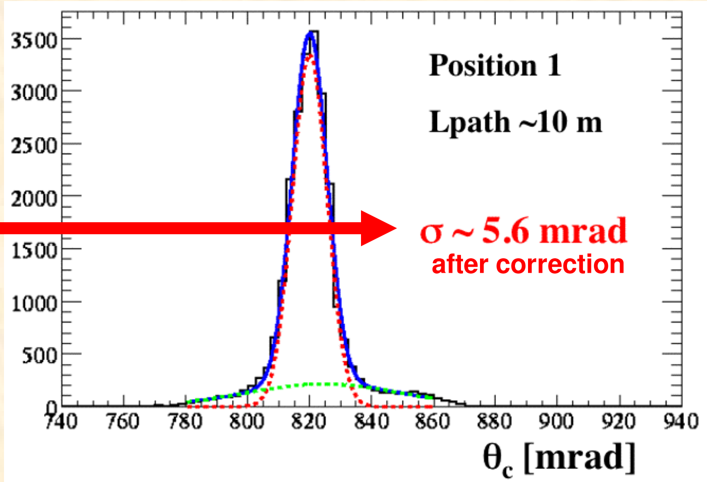


- focusing (to remove the bar thickness dependence);
- smaller pixels reduce the expansion volume by a factor of 7-10;
- fast photodetectors to remove chromatic dependence

correction of chromatic dispersion proved thanks to the fast timing properties of MCP-PMTs



$\sigma \sim 7.6$ mrad
w/o correction

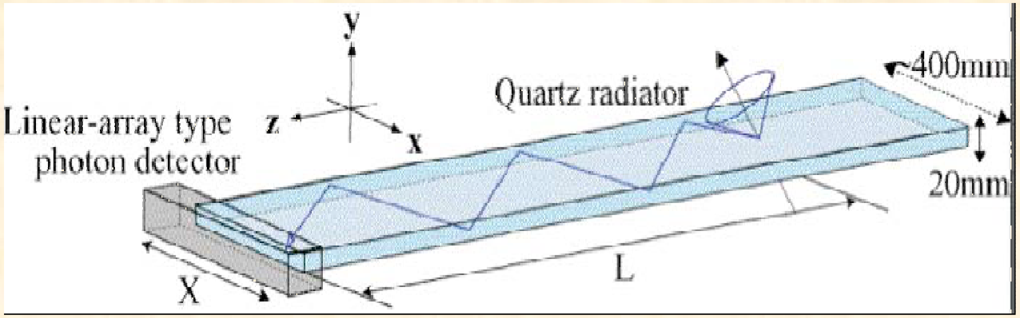


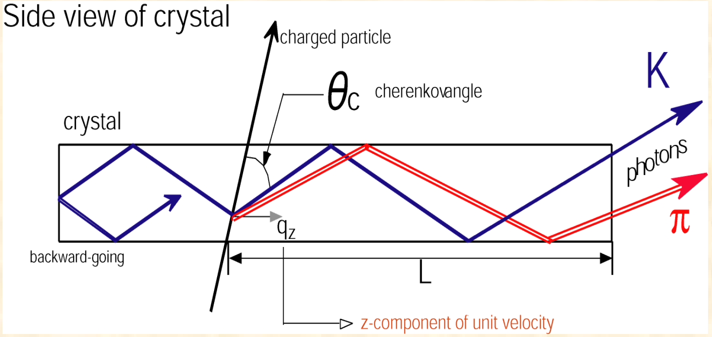
$\sigma \sim 5.6$ mrad
after correction

Burle/Photonis MCP-PMT 85012-501
(64 pixels, **10 μm pore diameter**)

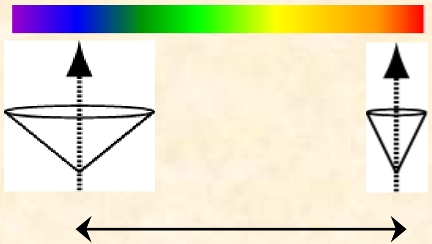
TOP

Time Of Propagation (TOP) detector (NIM A453(2000)331)





$$n_g(\lambda) = n_p(\lambda) - \lambda \cdot dn_p(\lambda)/d\lambda$$



$\Delta\theta_c$~1.2mrad

Chromatic time dispersion: ~ 100 ps

$$TOP = \frac{L \cdot n_g(\lambda)}{c \cdot q_z}$$

$t_K - t_\pi$(3 GeV/c)=75 ps for 1 m flight path

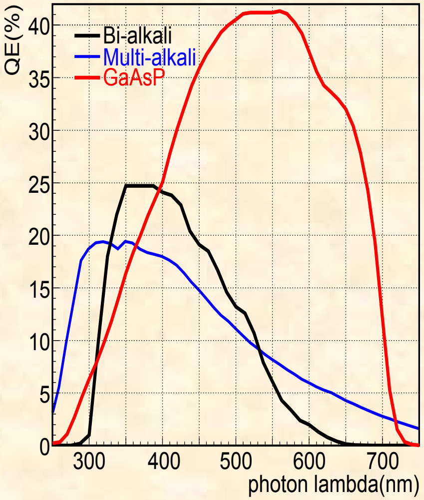
Yellow: bialkali photocathode
Red: GaAsP photocathode

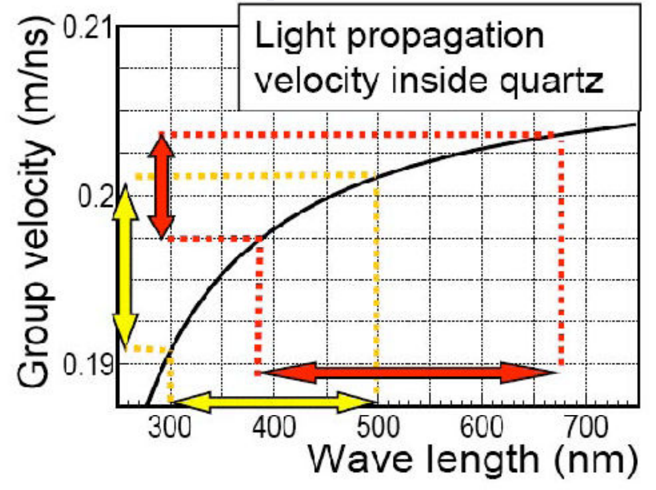
GaAsP MCP-PMT

- higher QE than bialkali;
- at longer wavelengths,

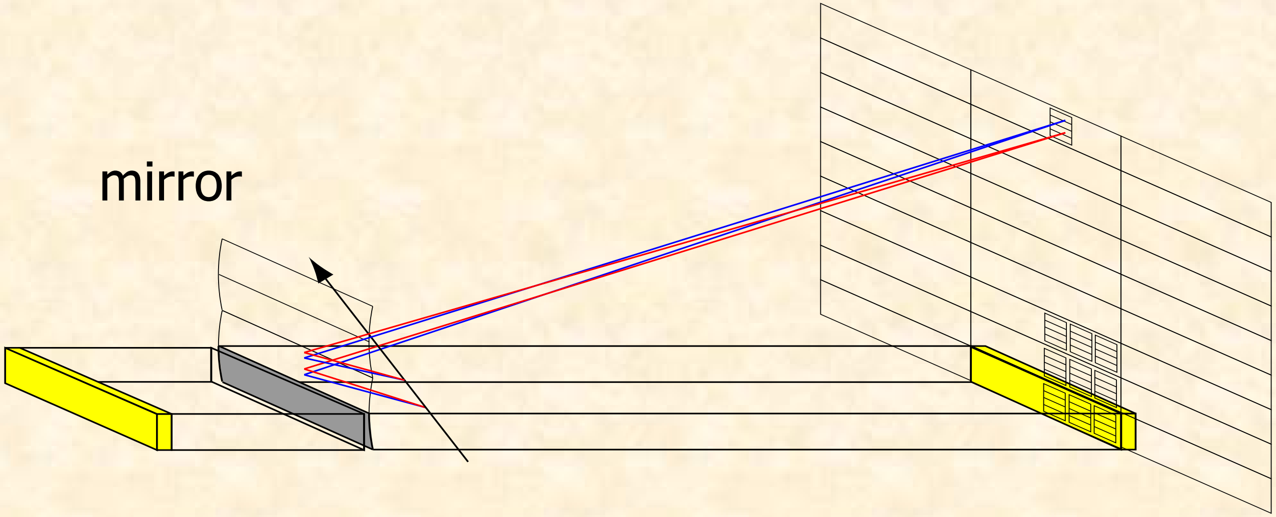
the group velocity spread is smaller

- time resolution= 35 ps for single p.e. (gain=0.6 x10^6)

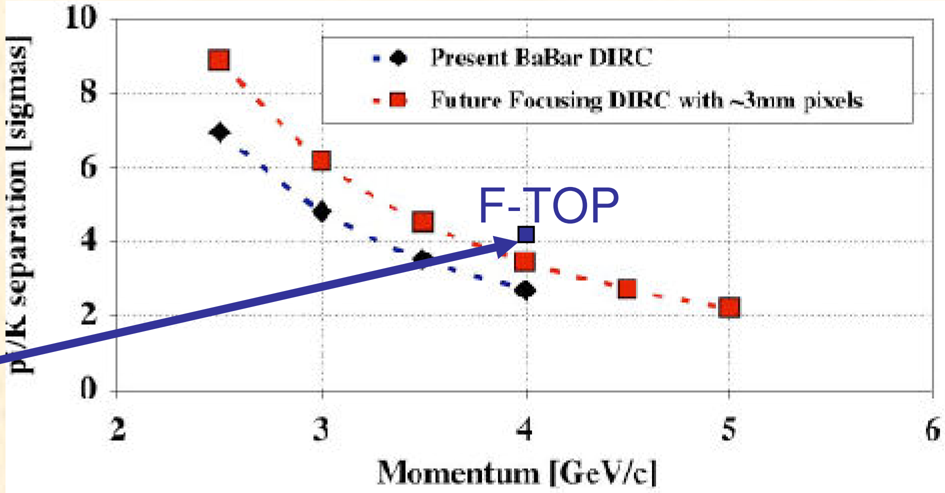




Focusing- TOP



option	π/K separation at 4 GeV/c
TOP + GaAsP	3.5 sigma
Focusing + GaAsP	4.2 sigma



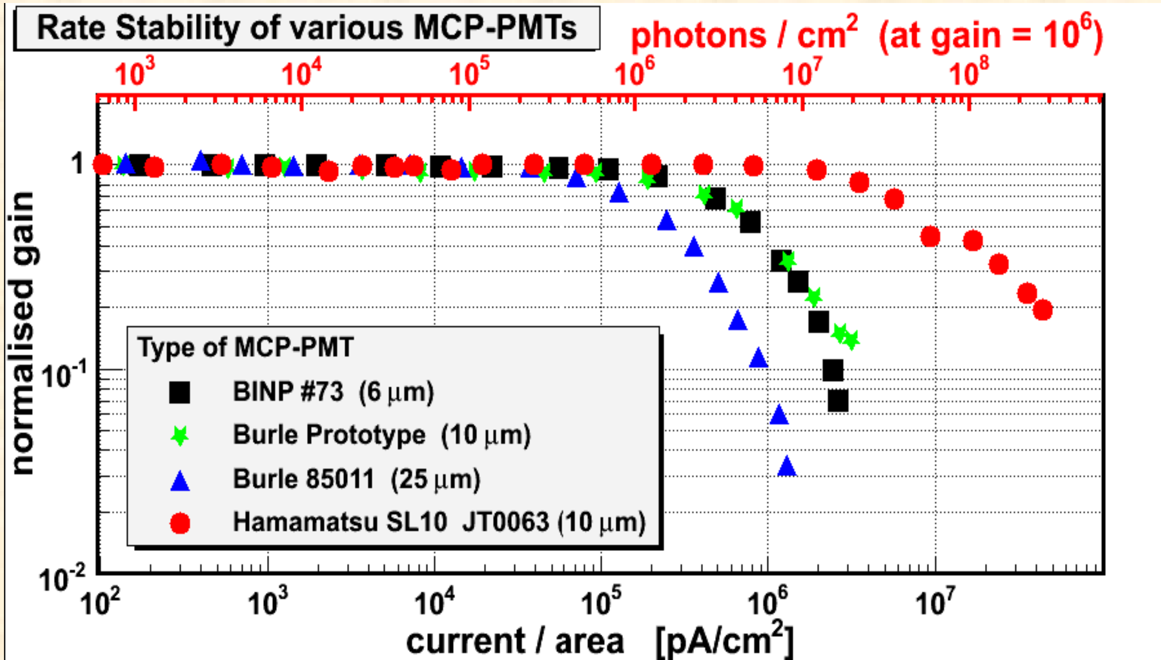
Applications of DIRC-like counters

Future experiments at Super-B factories (x 100 KEK B-Factory luminosity)

PANDA* and CBM experiments at FAIR (interaction rates up to 20 MHz)

- harsch radiation environment (up to 10 Mrad)
- high photon rates (up to 1 MHz/channel)
- immunity to magnetic field of 1-2 Tesla

***Talk by SEITZ, Björn**



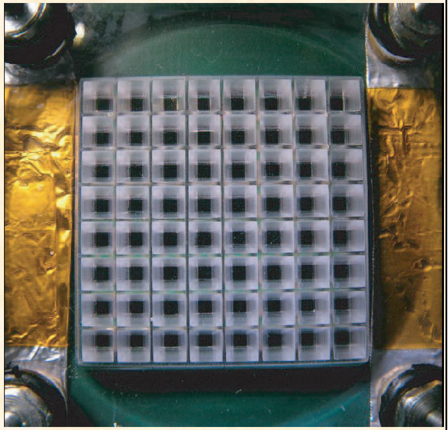
A. Lehmann et al., Jinst 4 P11024, 2009

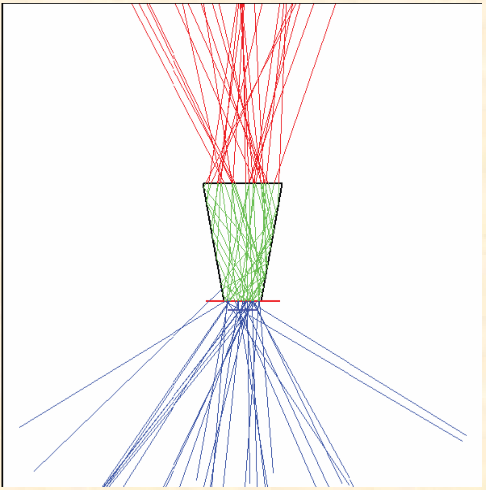
G-APD for RICH applications

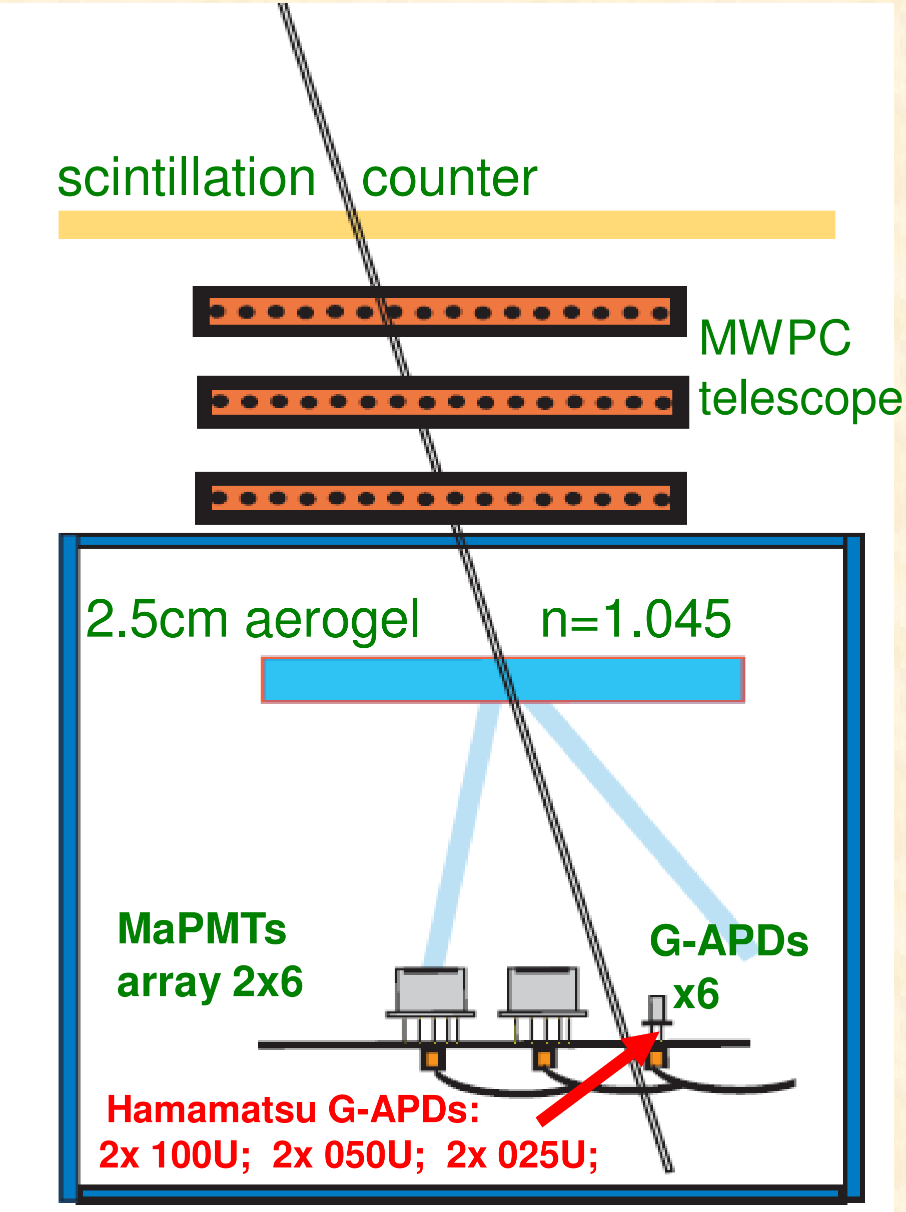
G-APD has many interesting properties for Cherenkov Imaging applications

first Cherenkov photons observed by the Ljubliana team (P. Krizan et al.)
G-APDs provided 4 x more photons than MAPMTs per photon detector area – in agreement with expectations

further studies with light guides to increase PDE (P. Krizan, 2009 JINST 4 P11017 and talk by R. Dolenec)

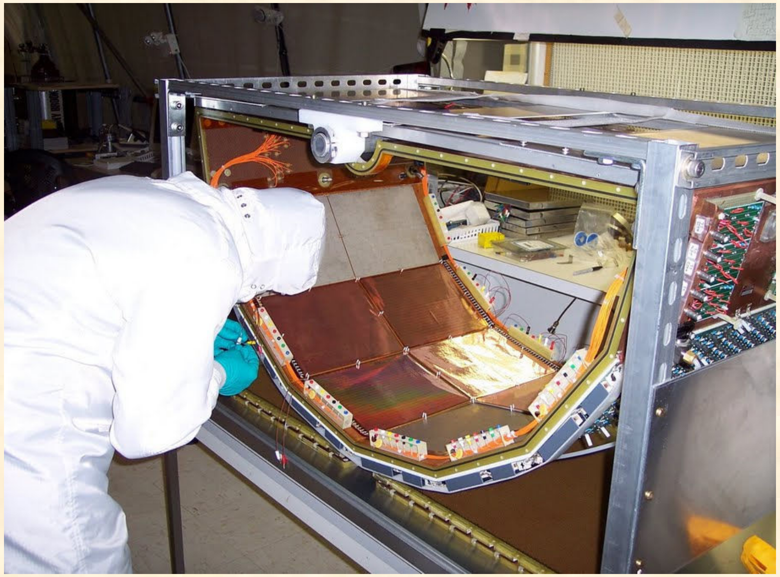






GEM as Cherenkov photodetectors

HBD in PHENIX at RHIC



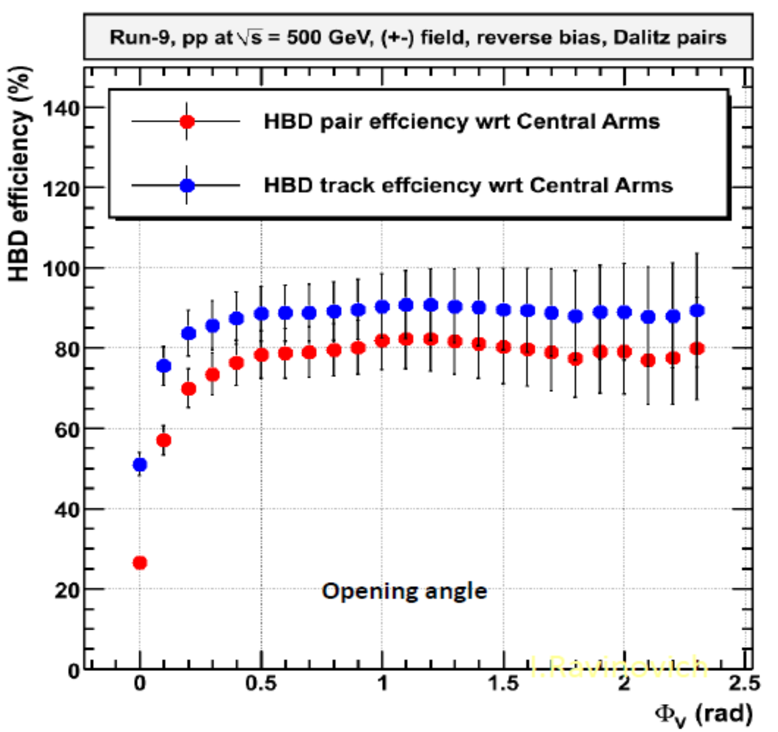
- single electron efficiency > 90%;
- noise=0.2 pe at a gain of 5000;
- 90 % rejection of photon conversions and Dalitz decays

the entire HBD (~1m^2) is fully operational for data taking (Au-Au collisions) of Run 10 started in Dec 2009

conceived by Weizmann team

- operation in CF$_4$ (only electrons above Cherenkov threshold)
- windowless CsI photodetector:

→ bandwidth down to 120 nm (10 eV)



p.e. yield per e-track ~ 22

HBD for the J-PARC E16 experiment: K. AOZI's poster

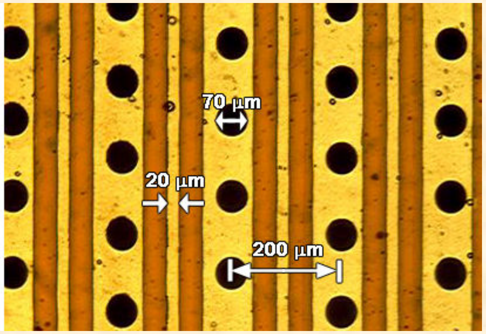
Innovative ion-blocking geometries

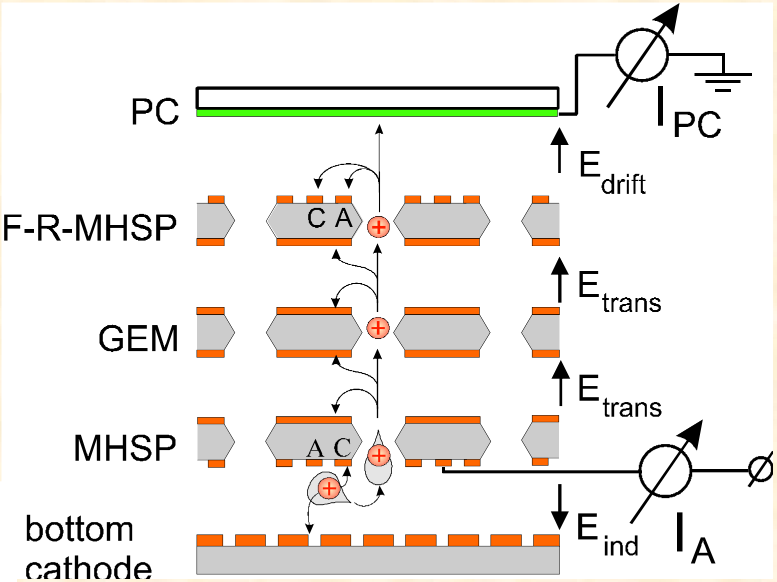
Micro-hole + Flipped reverse-bias strip plates (to deviate avalanche ions)

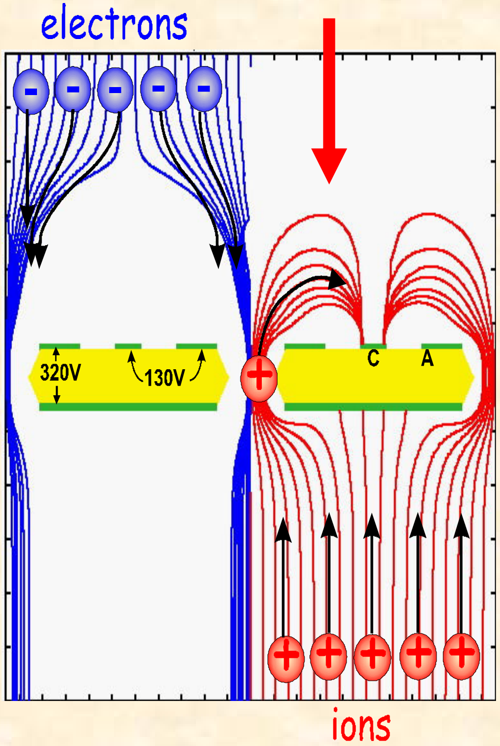
R. Chechik and A. Breskin,
Nucl. Instrum. Meth. A 595 (2008) 116
[arXiv:0807.2086]

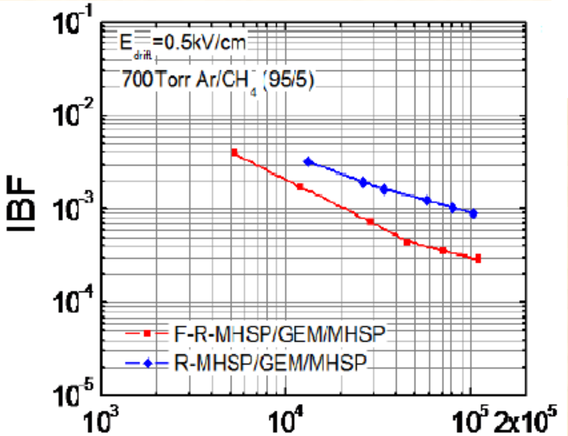
ions are trapped by negatively biased cathode strips

MHSP









A. Lyashenko
NDIP08 Workshop

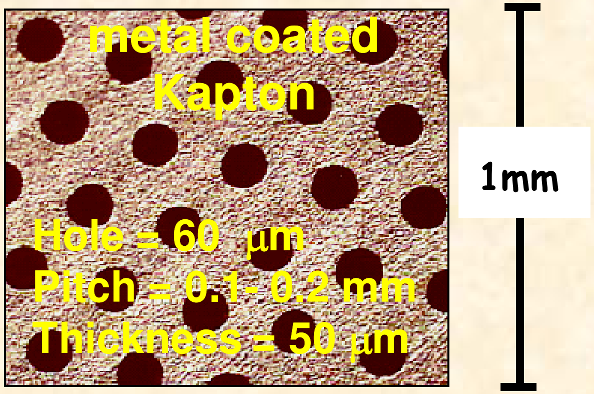
- **short multiplication times -> fast signals [width 10 ns, time resolution below 2 ns]**
- **high gain [>10^5]**
- **high rate capability (> 10^6 particles/mm^2)**

TGEM & RETGEM

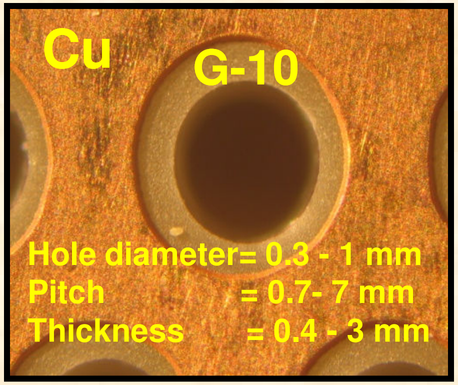
L. Periale et al., NIM A478,2002,377, Chechik et al. NIM A535 (2004) 303

10^3-10^4 gain in single GEM

10^5 gain in single-TGEM

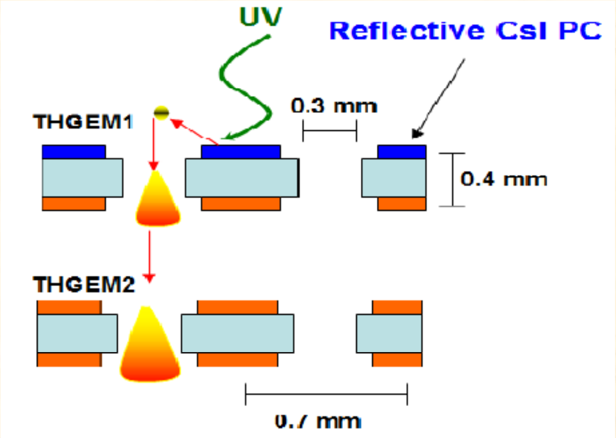


Hole = 60 µm
Pitch = 0.1- 0.2 mm
Thickness = 50 µm

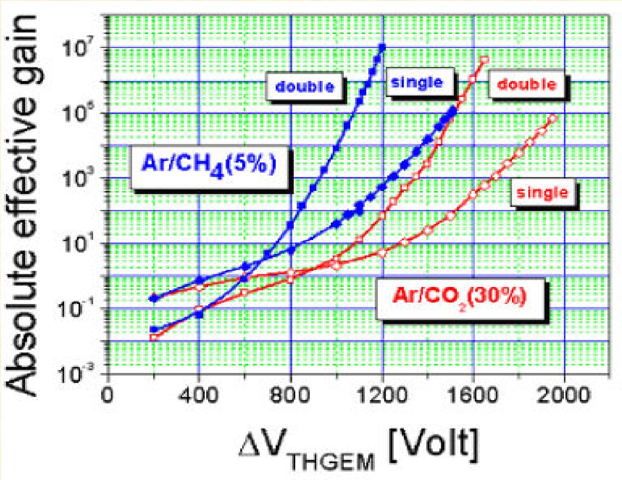


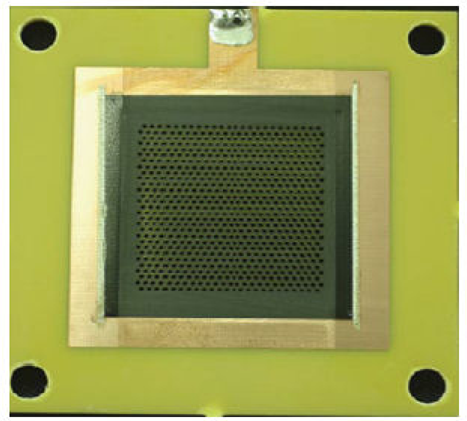
Hole diameter= 0.3 - 1 mm
Pitch = 0.7- 7 mm
Thickness = 0.4 - 3 mm

- standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching of the hole's rims (prevents discharges)
- very robust, mechanically self-supporting



IBF <10%
time resolution of 8 ns RMS



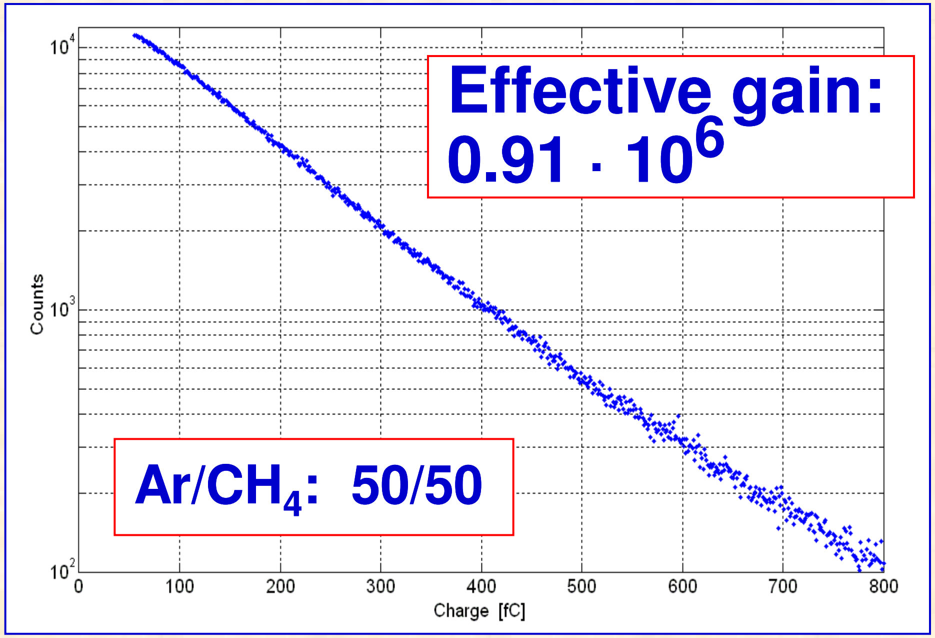


RETGEM (V. Peskov)
- resistive kapton using screen printing technology
- sizes up to 50x50 cm^2

Thick GEM and spark-protected RETGEM are robust and cost effective solution for large area RICH applications (COMPASS and ALICE RICH upgrades)

ALICE & COMPASS R&Ds on MPGDs

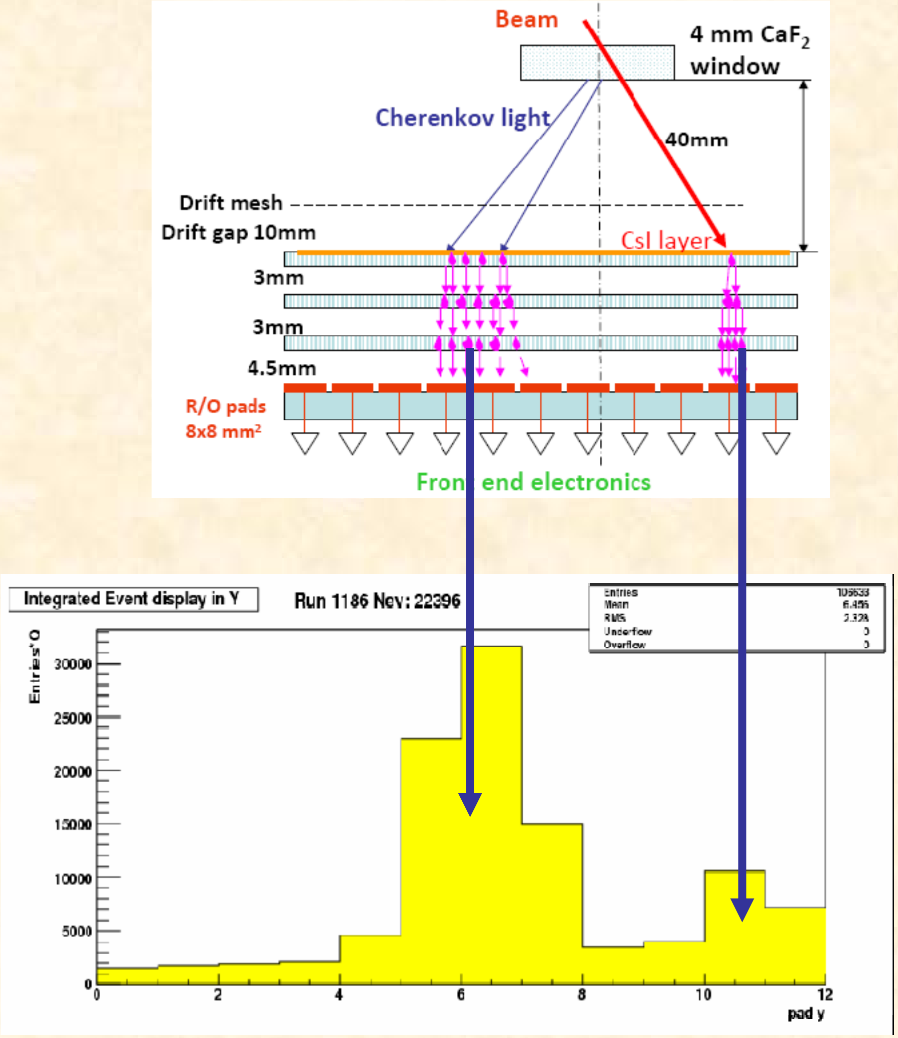
STABLE UP TO 10^6 :
GAIN-VALUES IN PMT RANGE !



Effective gain: $0.91 \cdot 10^6$

Ar/CH_4: 50/50

S. Dalla Torre (COMPASS), ICATTP2009



ALICE: TGEM test @PS (Nov. 2009)

Summary

TOF:

- MRPCs: example of an outstanding detector ($\sigma_t < 50$ ps) made by window glasses and fishing lines;
- very fast and B-tolerant photodetectors (MCP-PMTs, G-APDs) opened new directions by exploiting Cherenkov light vs. scintillator light

(plot)

Ionization energy loss:

- PID feasibility in very high multiplicity events by STAR & ALICE;
- TPCs readout by MPGDs could make possible cluster counting

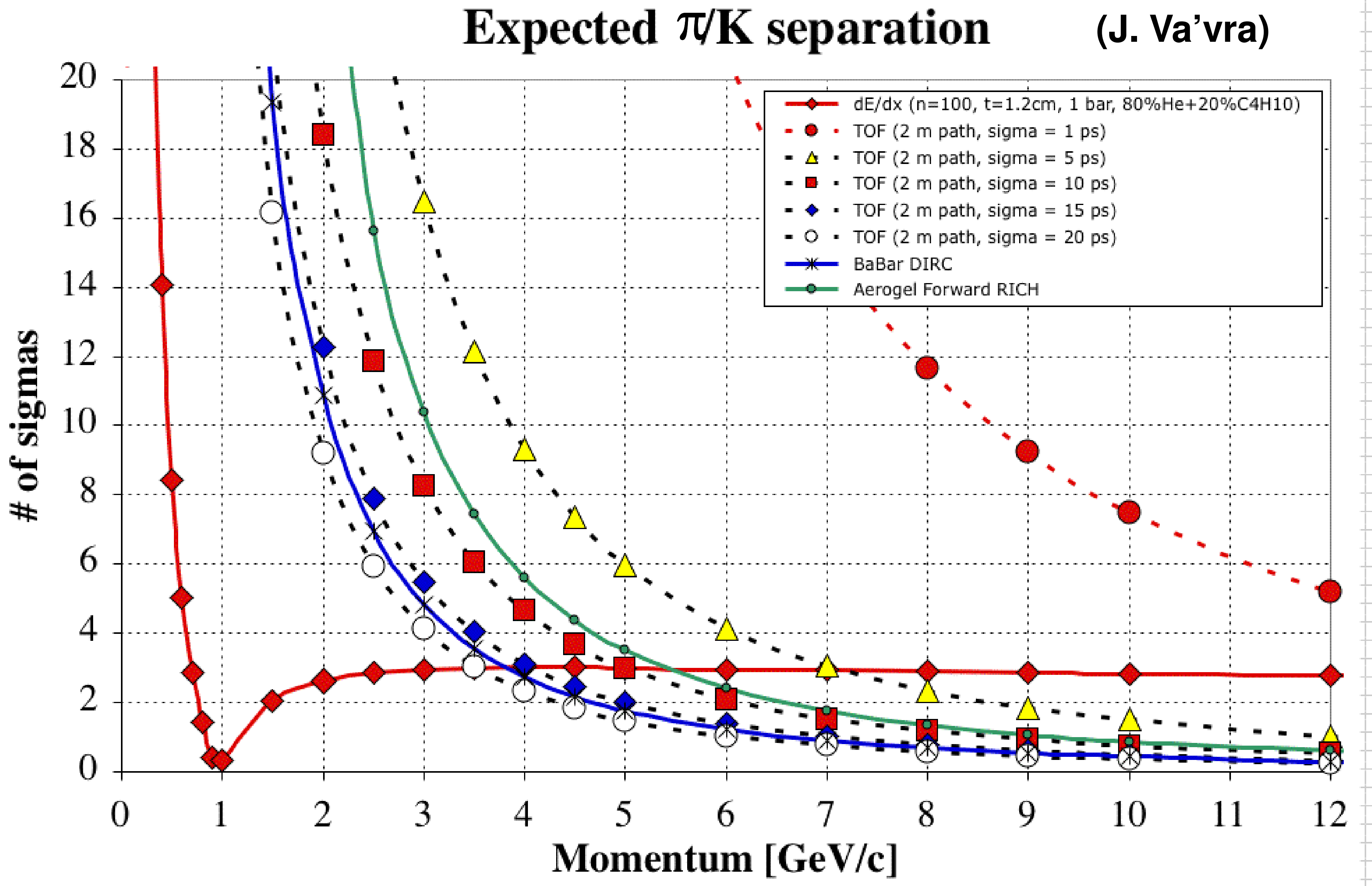
Cherenkov light imaging: new exciting advances!

- timing to correct chromaticity;
- MPGD & G-APD seem mature to be used as photodetectors

To learn more:

7th International Workshop on Ring Imaging Cherenkov Detectors (RICH 2010) - Cassis, Provence, France, 3-7 May 2010

Projected ps-TOF PID performance


Expected π/K separation (J. Va'vra)