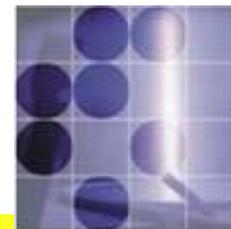




University of Ljubljana

“Jožef Stefan” Institute



High Intensity Frontier in Particle Physics (part 1/2)

Introduction to Experimental Particle Physics

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University of Ljubljana and J. Stefan Institute

Doctoral studies, Specialized Seminar on Experimental Physics

Peter Križan, Ljubljana



Contents of this course

- Lecture 1: Introduction, experimental methods, detectors, data analysis
- Lecture 2: Intensity frontier experiments



Contents

Introduction

Experimental methods

Accelerators

Spectrometers

Particle detectors

Analysis of data

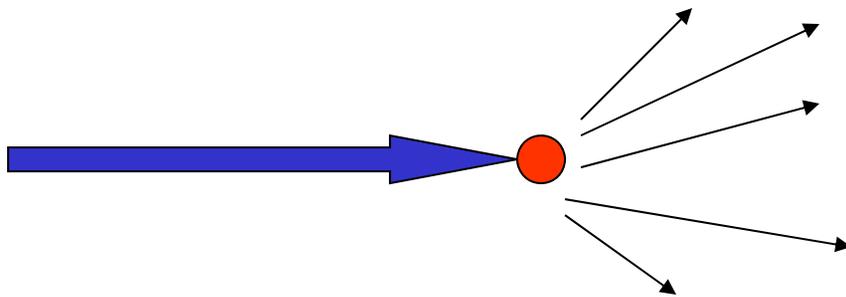


Particle physics experiments

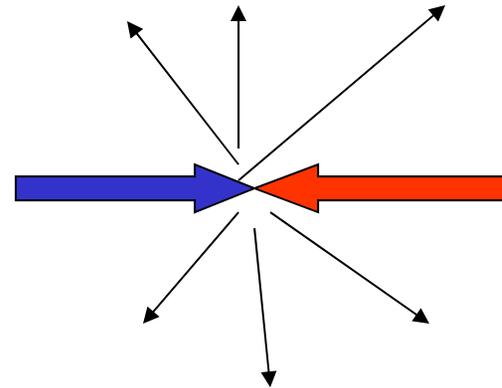
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments



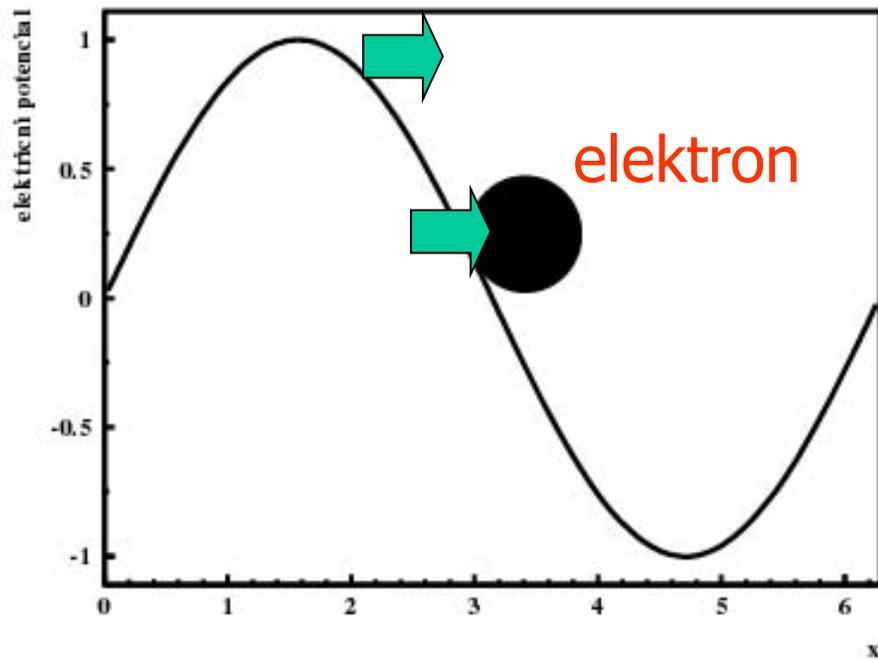
Collider experiments



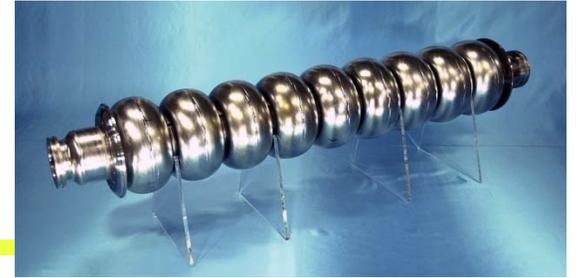


How to accelerate charged particles?

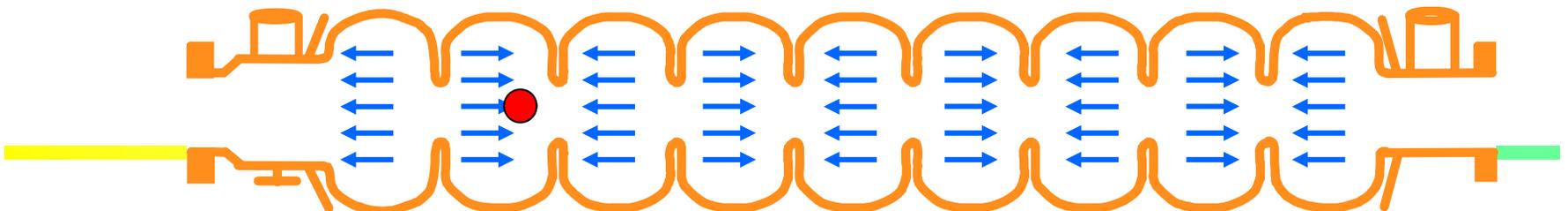
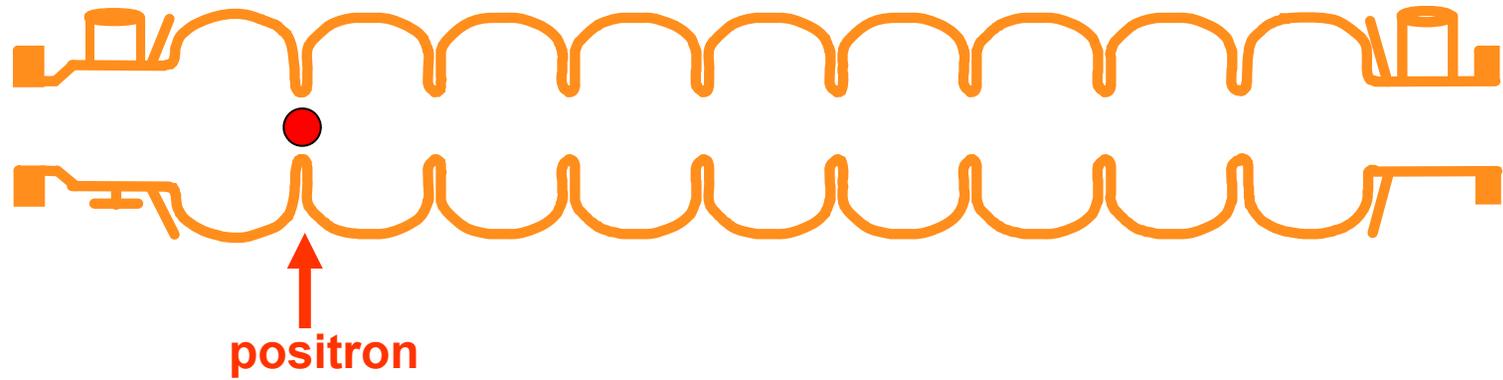
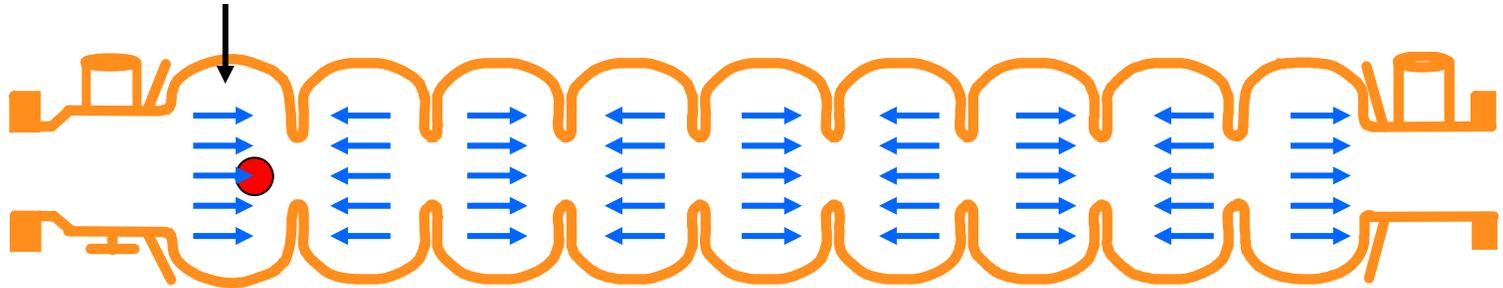
- Acceleration with electromagnetic waves (typical frequency is 500 MHz – mobile phones run at 900, 1800, 1900 MHz)
- Waves in a radiofrequency cavity: $c < c_0$



... Similar to surfing the waves



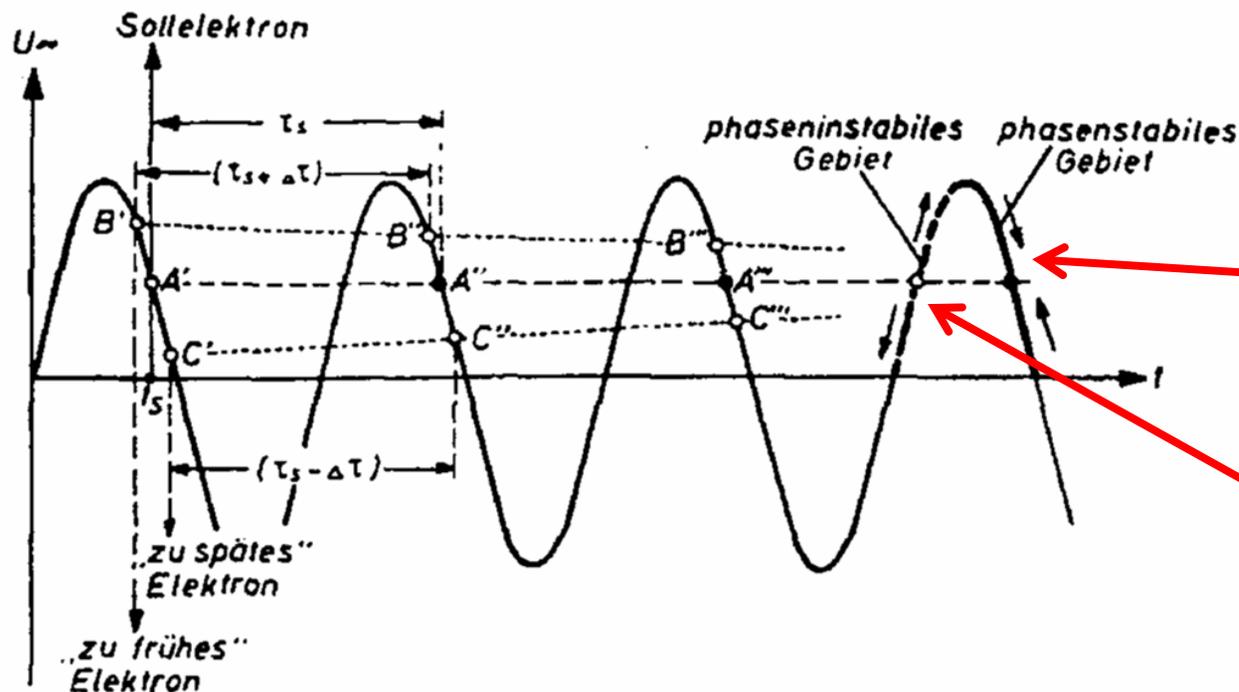
Electric field





Stability of acceleration

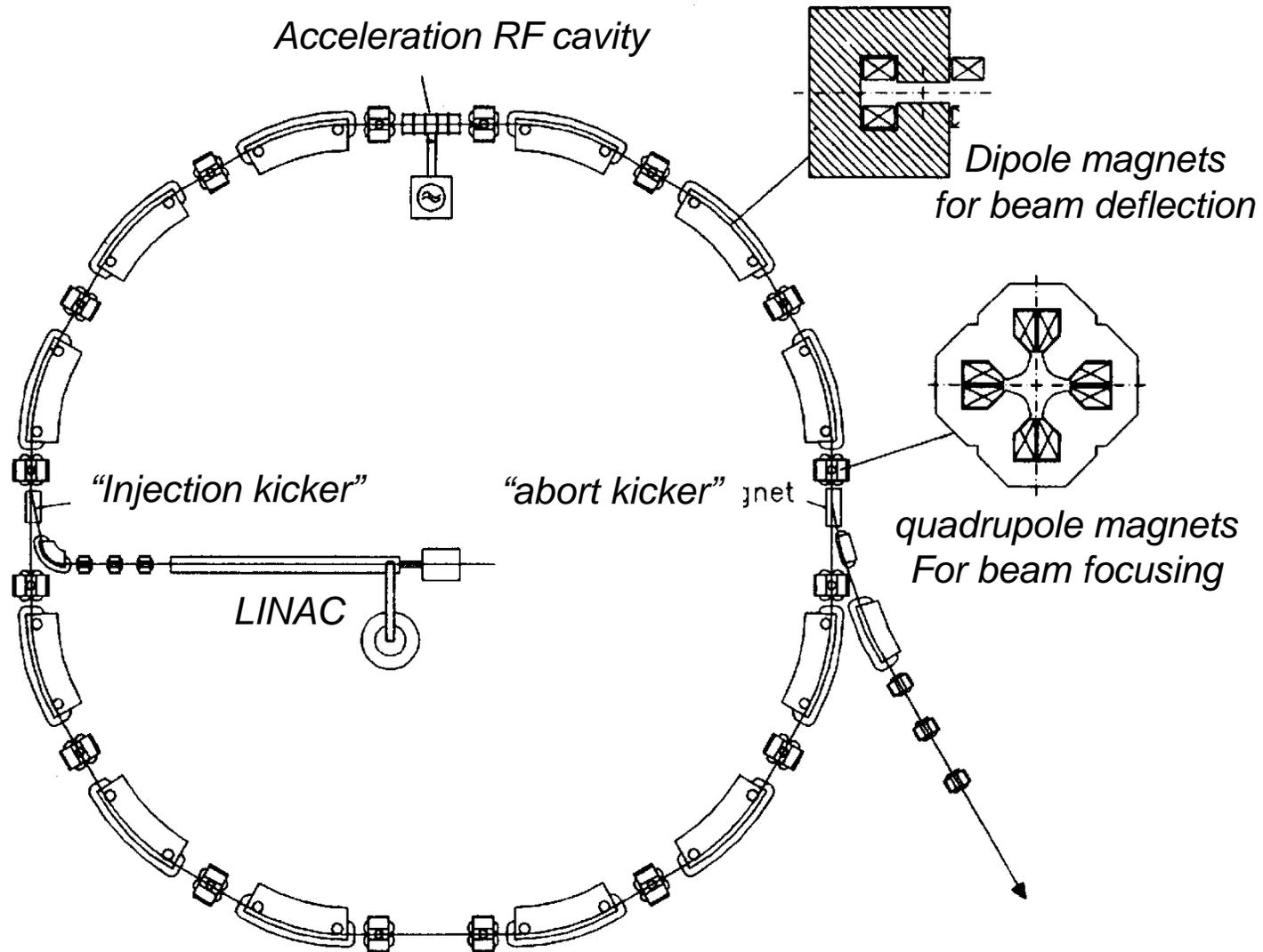
- For a synchronous particles (A): energy loss = energy received from the RF field
- A particle that comes too late (B), gets more energy, the one that is too fast (C), gets less →



- OK if particle \sim in phase → stable orbit
- Not OK if too far away

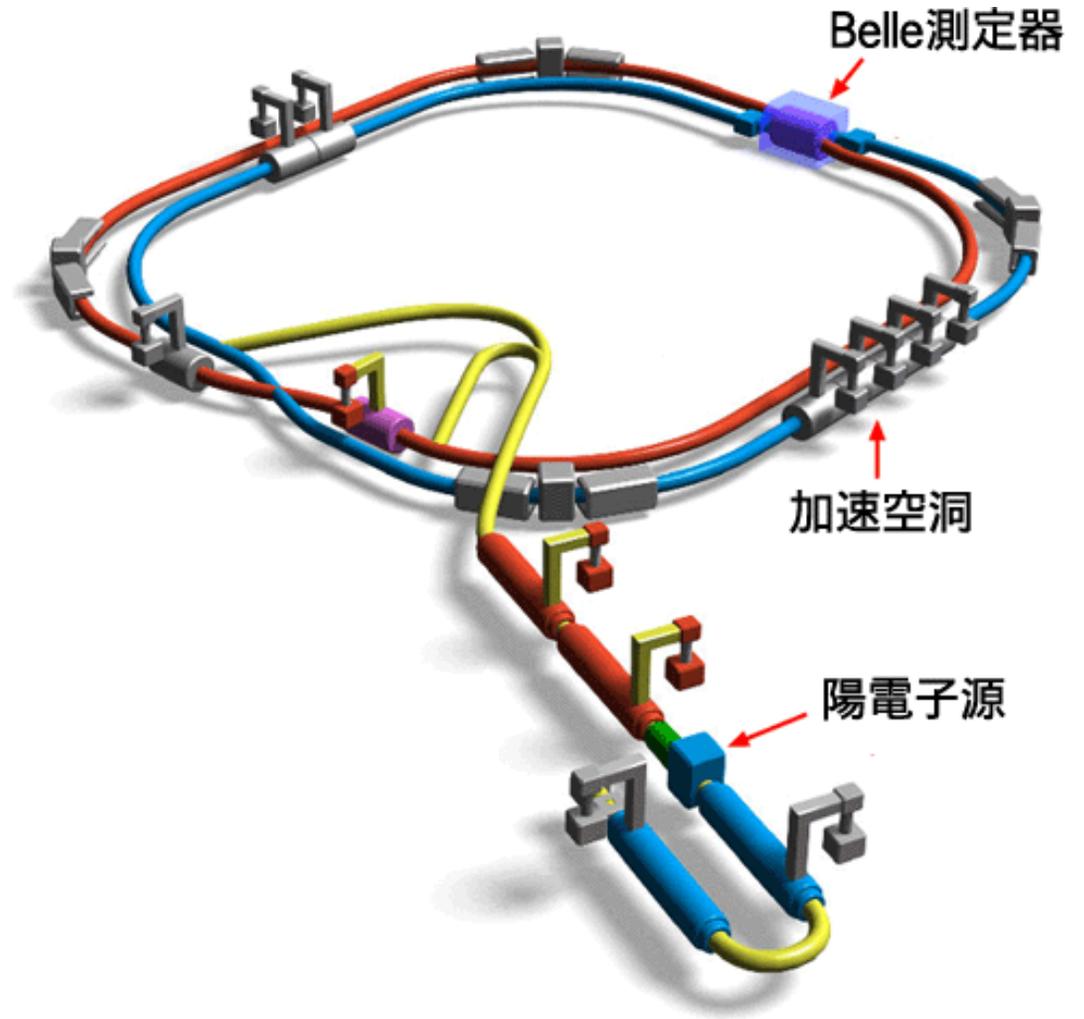
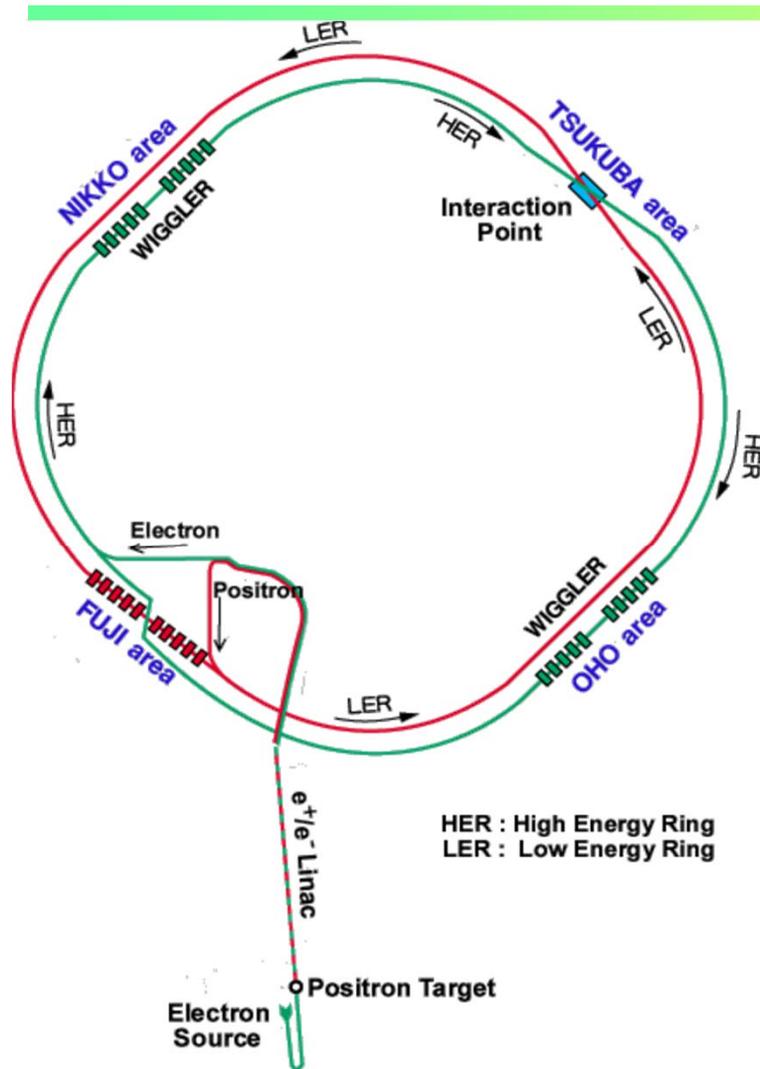


Synchrotron



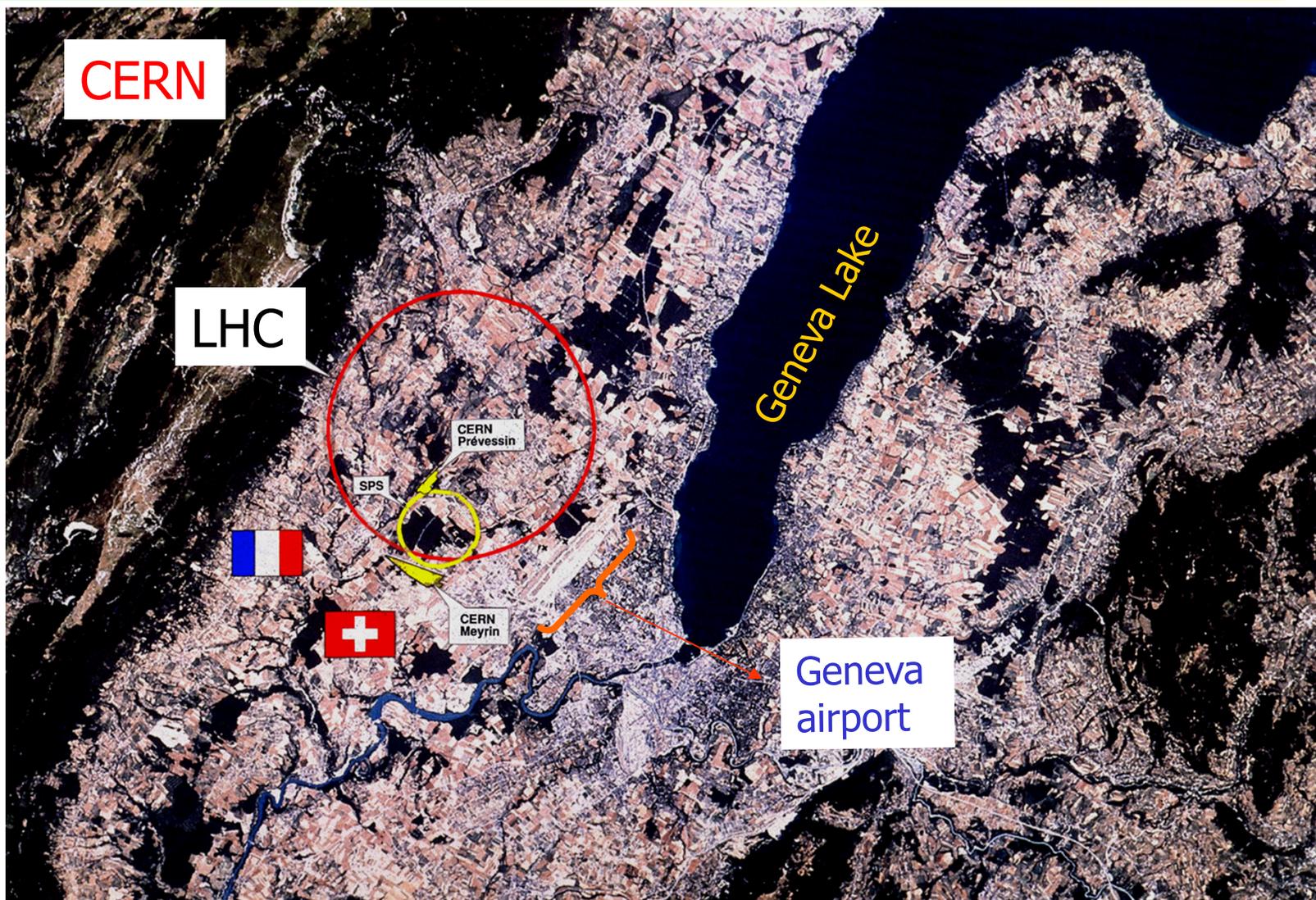


Electron positron collider: KEK-B





Large hadron collider

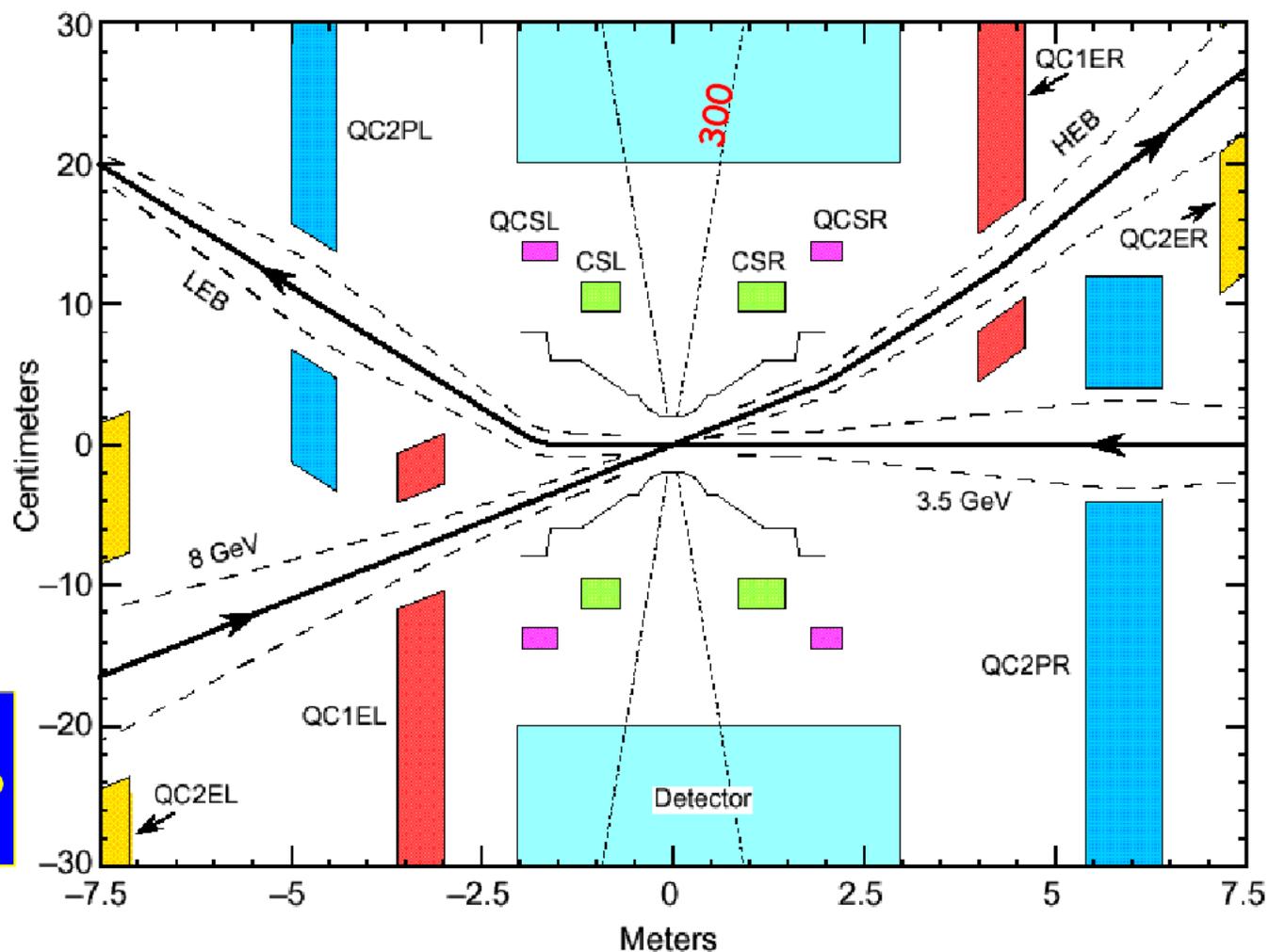




Interaction region: Belle

Collisions at a finite angle $\pm 11\text{mrad}$

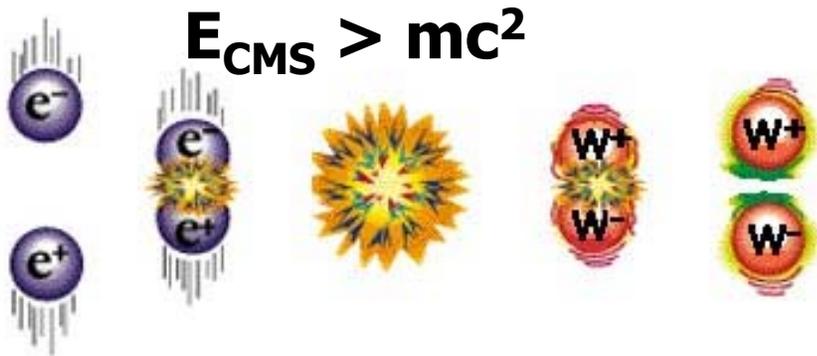
KEKB Interaction Region



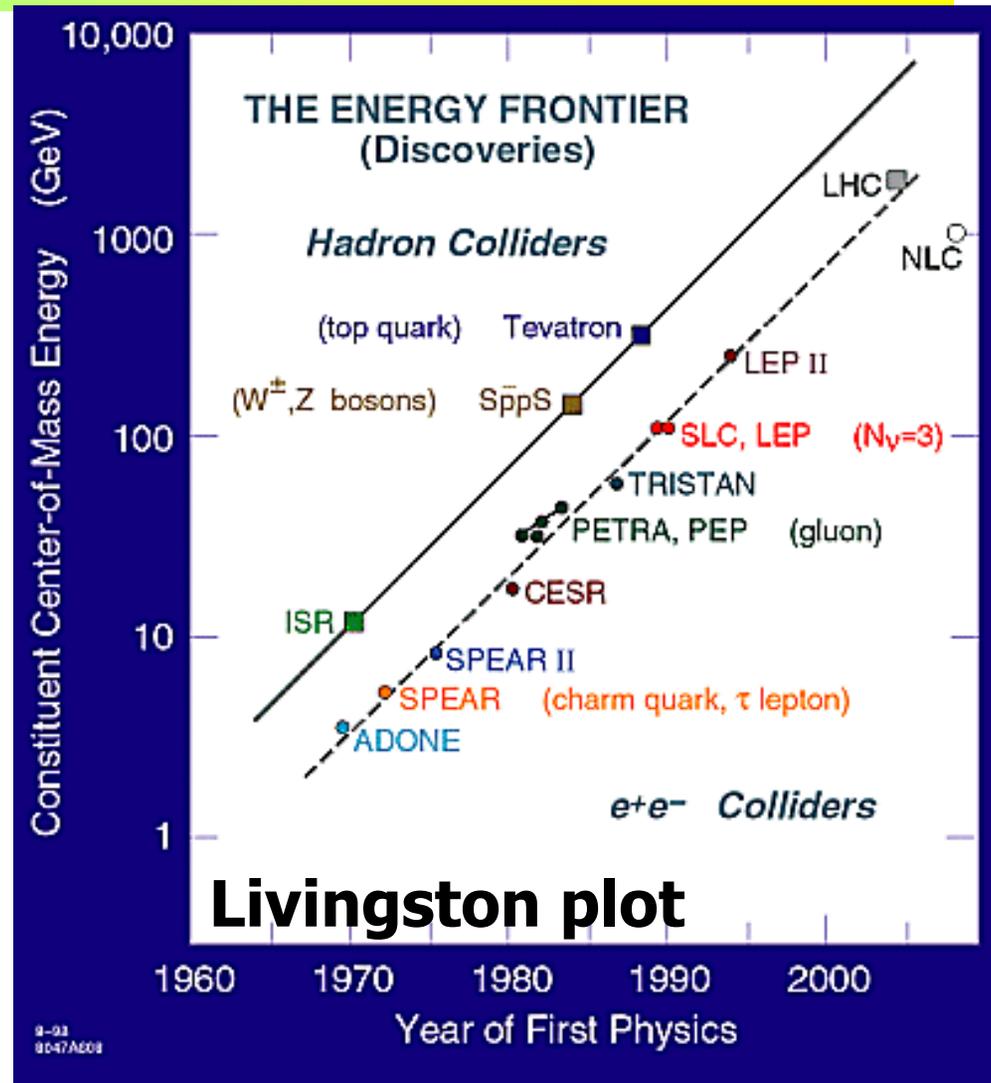


Accelerator figure of merit 1: Center-of-mass energy

If there is enough energy available in the collision, new, heavier particles can be produced.



e.g. LHC, CERN, Tevatron:
search for Higgs bosons,
 $m_{\text{Higgs}} > 100\text{GeV}$





Accelerator figure of merit 2: Luminosity

Observed rate of events = Cross section x Luminosity

$$\frac{dN}{dt} = L\sigma$$

Accelerator figures of merit: **luminosity L**

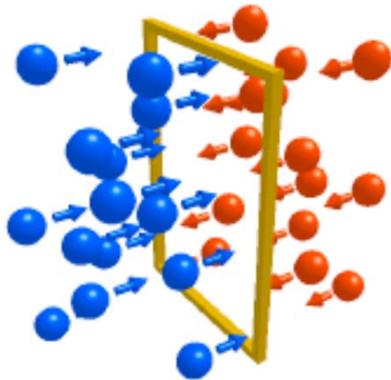
and **integrated luminosity**

$$L_{\text{int}} = \int L(t) dt$$



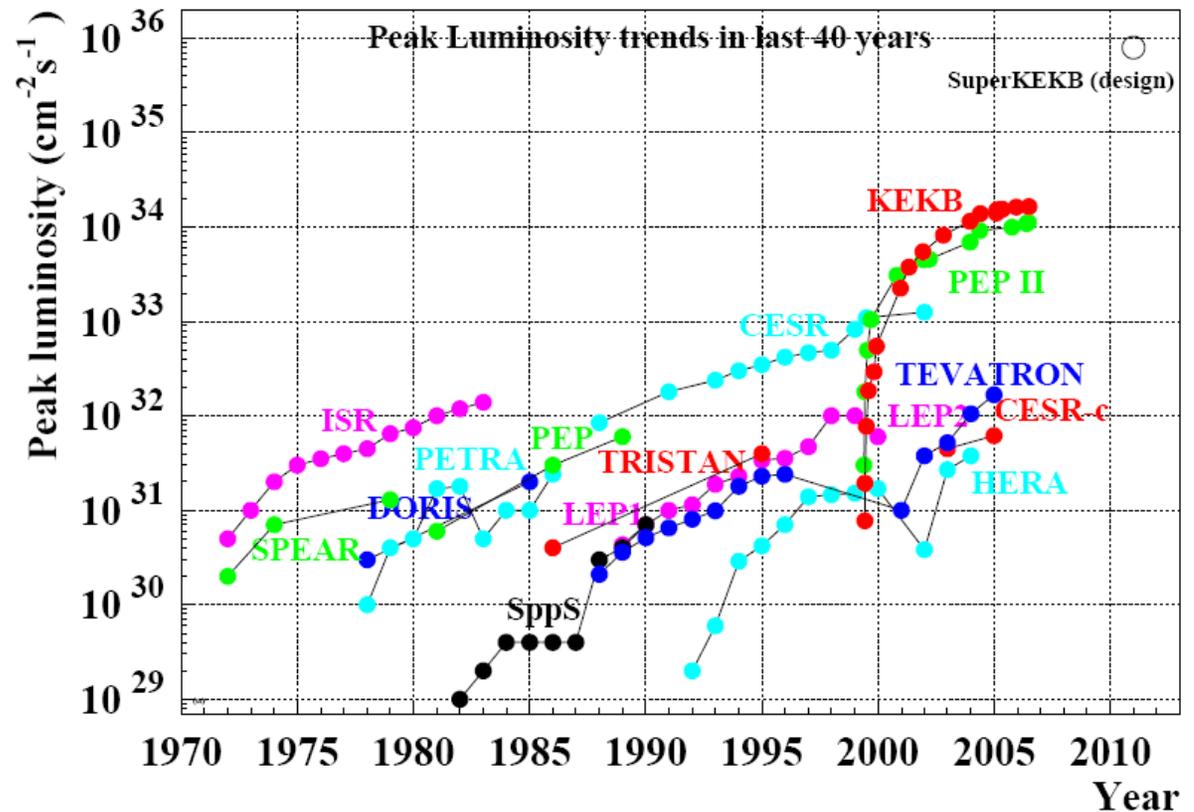
Luminosity vs time

$$R = \mathcal{L}\sigma$$



(number of events/unit time)
= (cross section) X (luminosity)

$$\mathcal{L} = \frac{I_{LER} I_{HER}}{e^2 f_{rev} N_{bunch} A_{eff}}$$



A high luminosity is needed for studies of rare processes.



How to understand what happened in a collision?

- Measure the coordinate of the point ('vertex') where the reaction occurred, and determine the positions and directions of particles that have been produced
- Measure momenta of stable charged particles by measuring their radius of curvature in a strong magnetic field ($\sim 1\text{T}$)
- Determine the identity of stable charged particles (e , μ , π , K , p)
- Measure the energy of high energy photons γ



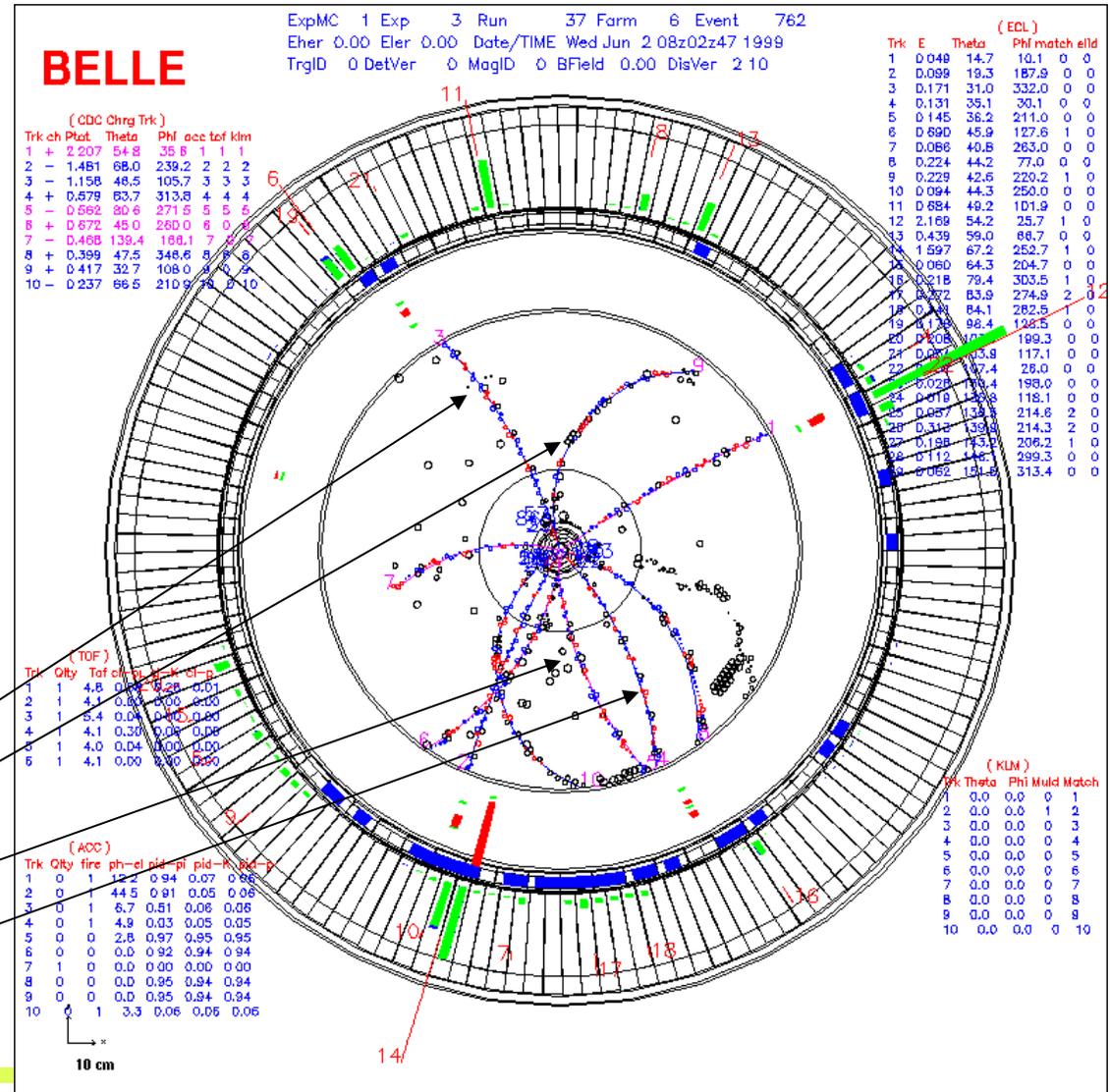
How to understand what happened in a collision?

Illustration on an example:

$$B^0 \rightarrow K^0_S J/\psi$$

$$K^0_S \rightarrow \pi^- \pi^+$$

$$J/\psi \rightarrow \mu^- \mu^+$$





Search for particles which decayed close to the production point

How do we reconstructing final states which decayed to several stable particles (e.g., 1,2,3)?

From the measured tracks calculate the invariant mass of the system ($i= 1,2,3$):

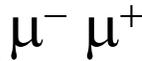
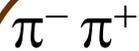
$$M = \sqrt{(\sum E_i)^2 - (\sum \vec{p}_i)^2}$$

The candidates for the $X \rightarrow 123$ decay show up as a peak in the distribution on (mostly combinatorial) background.

The name of the game: have as little background under the peak as possible without losing the events in the peak (=reduce background and have a small peak width).



How do we know it was precisely this reaction?



detect

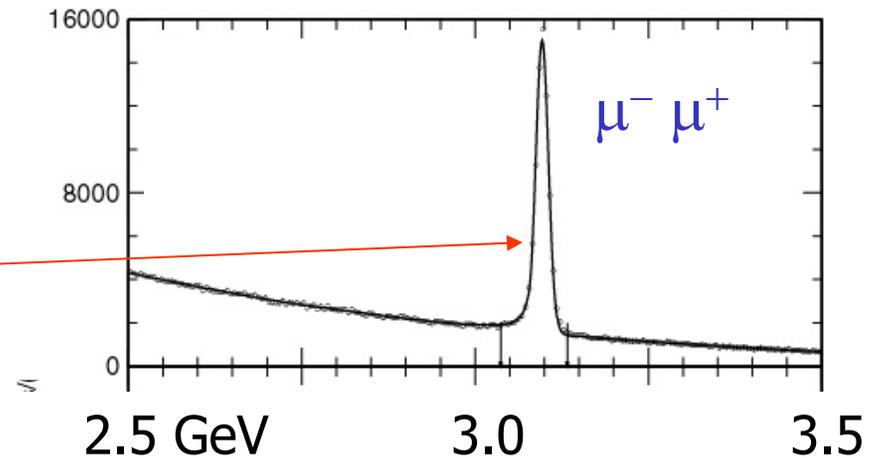
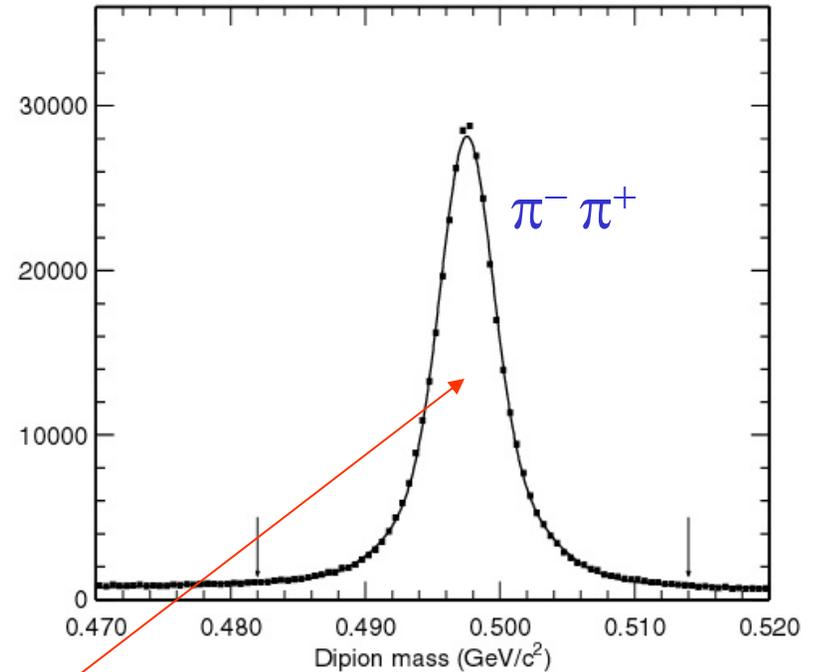
For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

$$M^2 c^4 = (E_1 + E_2)^2 - (p_1 + p_2)^2$$

$M c^2$ must be for K^0_S close to **0.5 GeV**,

for J/ψ close to **3.1 GeV**.

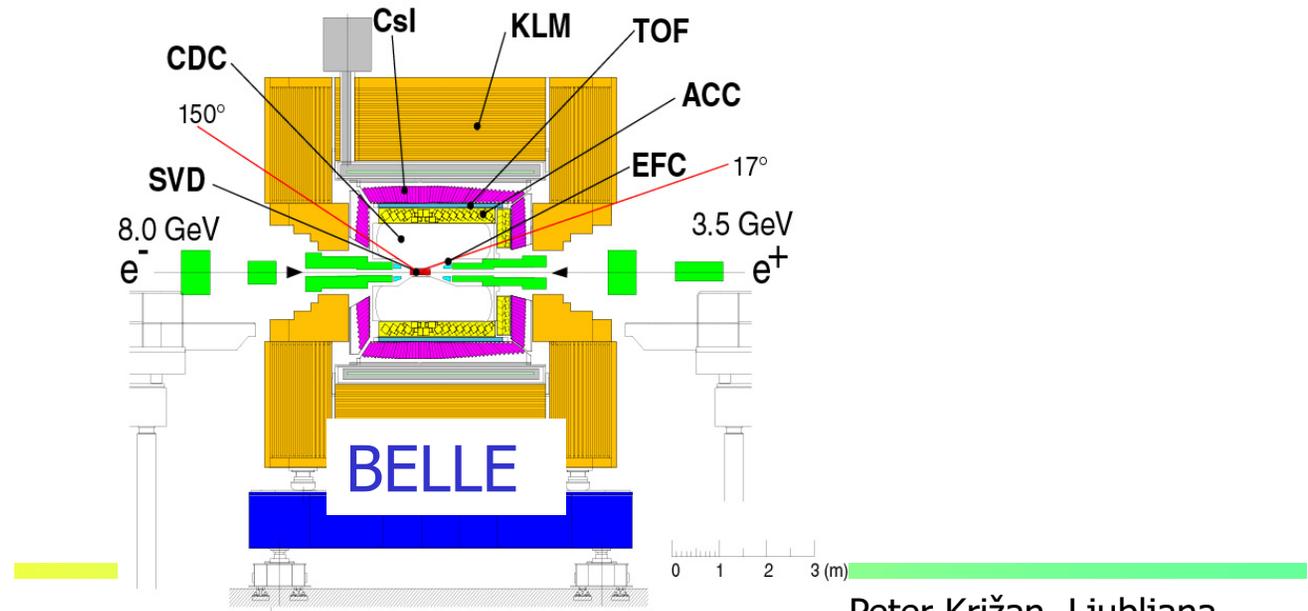
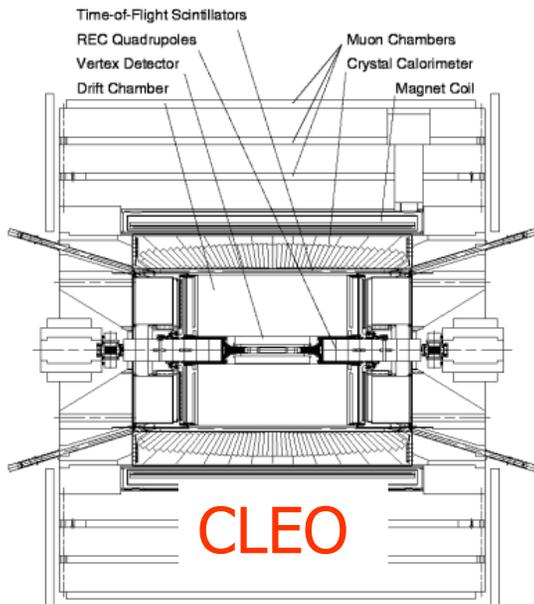
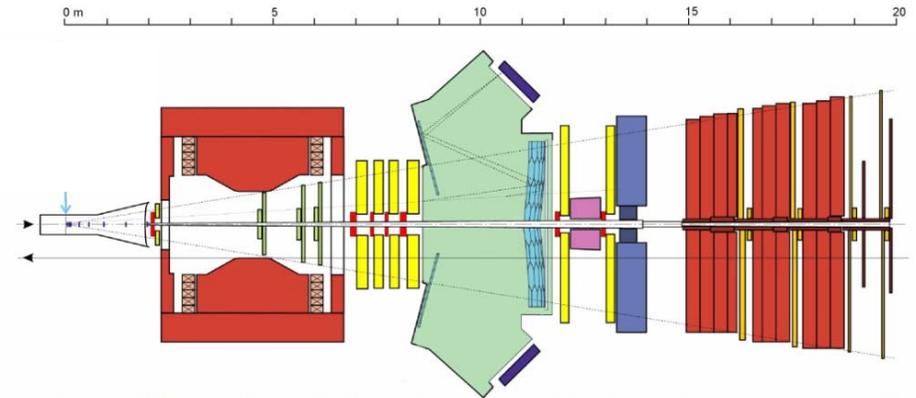
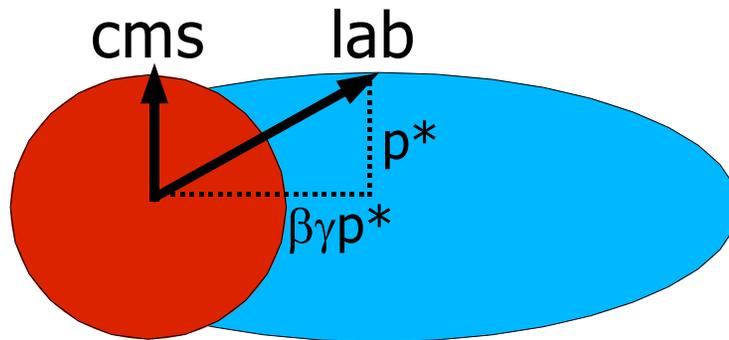
Below the peaks in the histograms:
random coincidences ('combinatorial background')



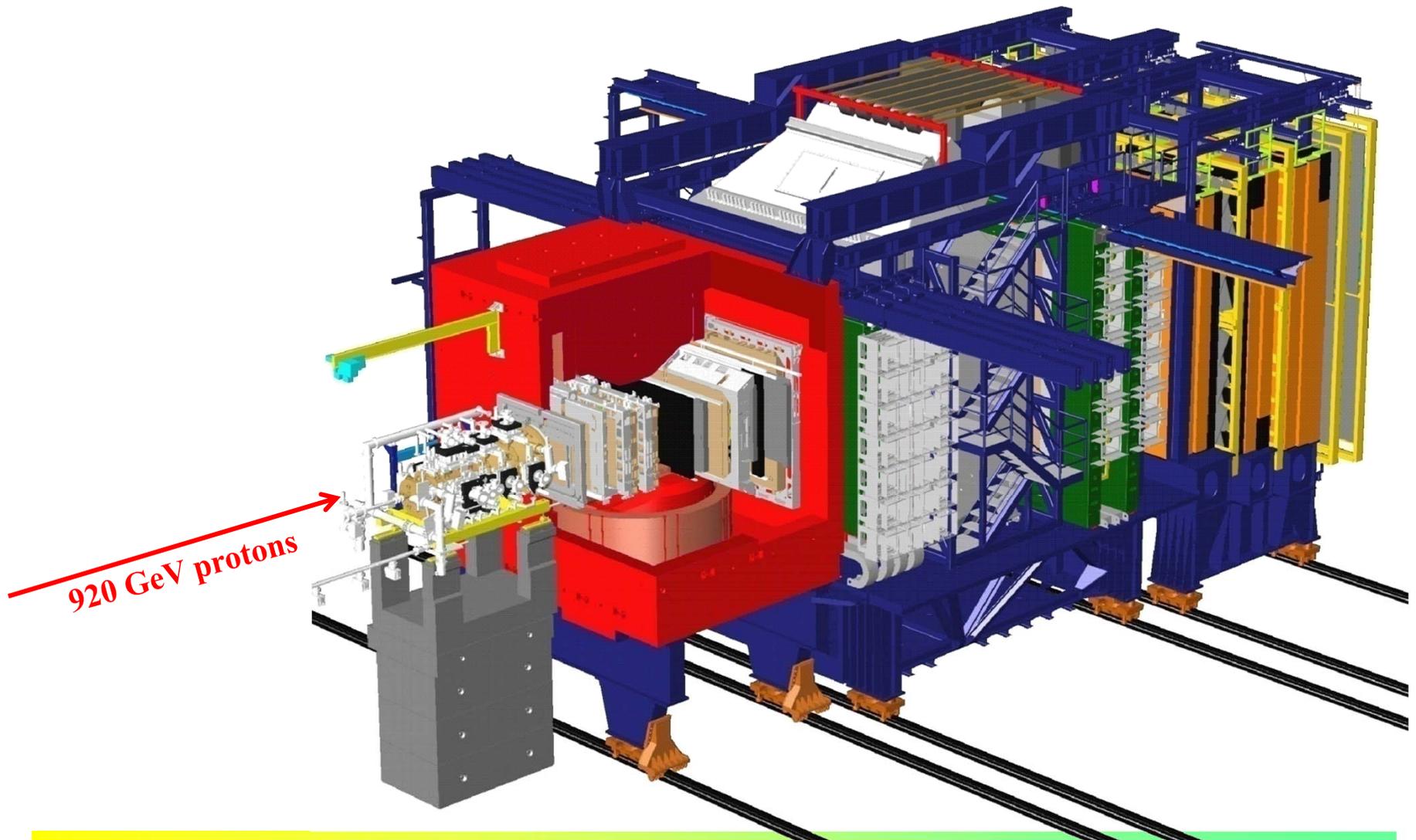
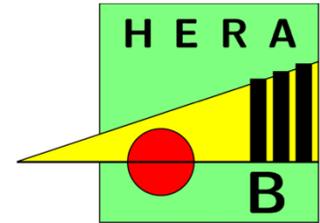


Experimental apparatus

Detector form: **symmetric** for colliders with symmetric energy beams; **extended in the boost direction** for an asymmetric collider; **very forward oriented** in fixed target experiments.

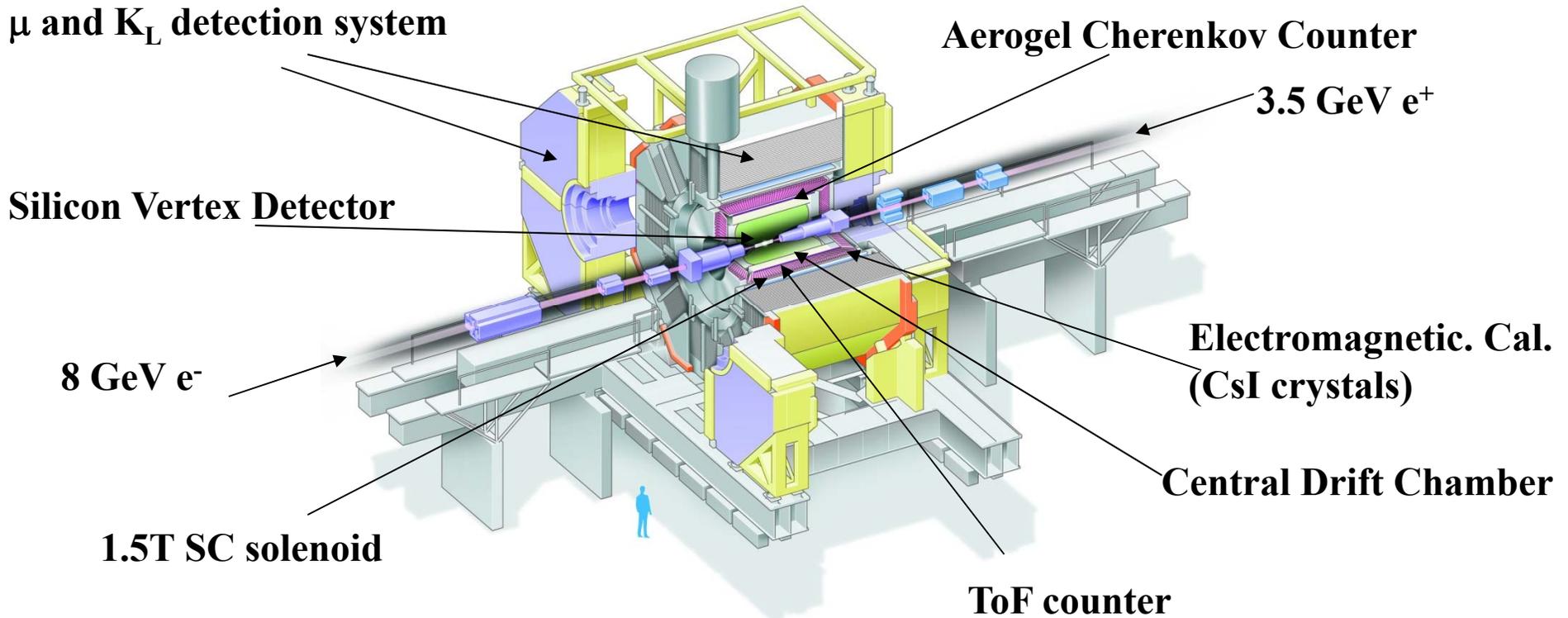


Example of a fixed target experiment: HERA-B





Belle spectrometer at KEK-B

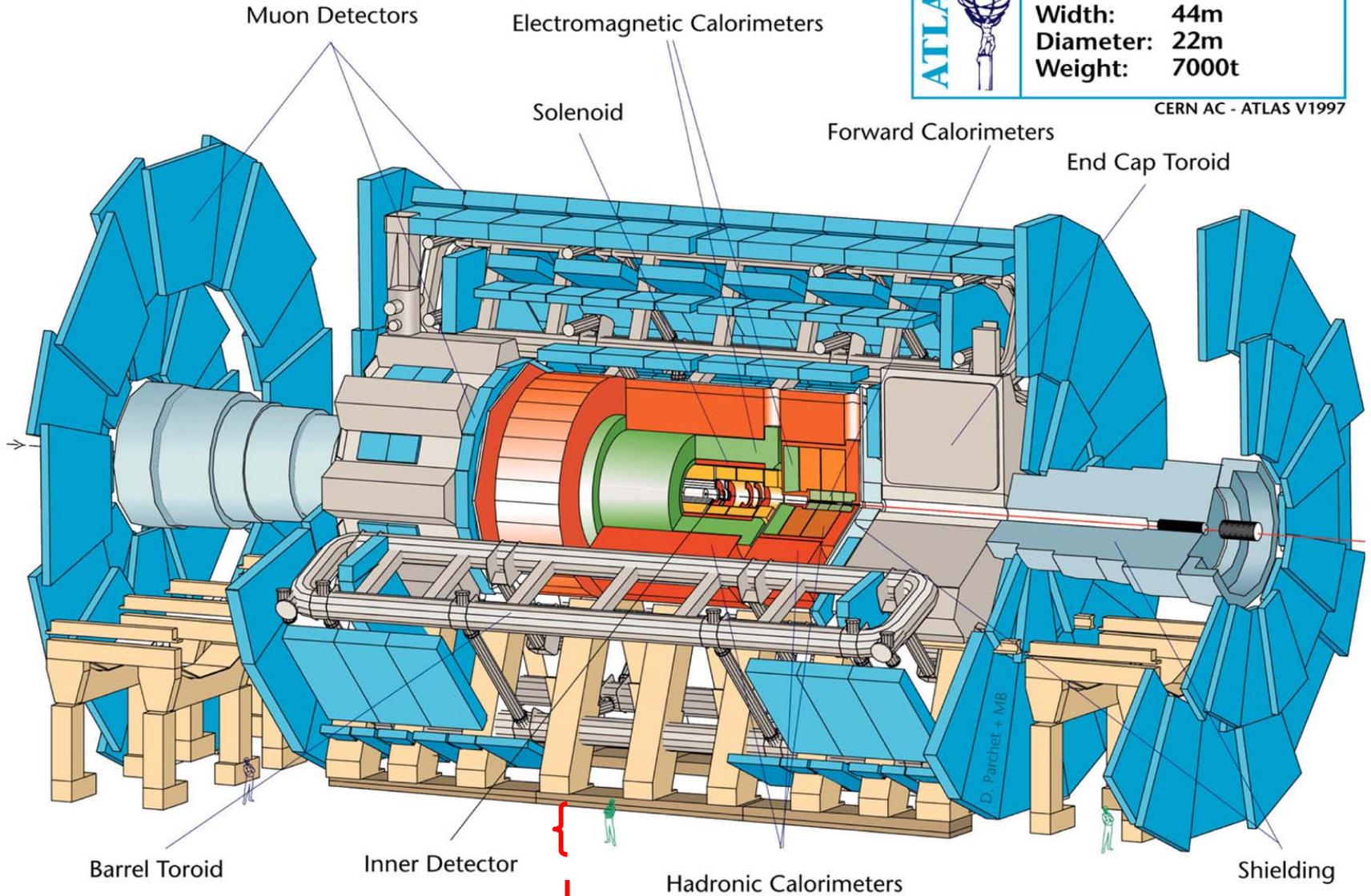




ATLAS at LHC

ATLAS 	Detector characteristics
	Width: 44m
	Diameter: 22m
	Weight: 7000t

CERN AC - ATLAS V1997



A physicist...

Peter Križan, Ljubljana



Components of an experimental apparatus ('spectrometer')

- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

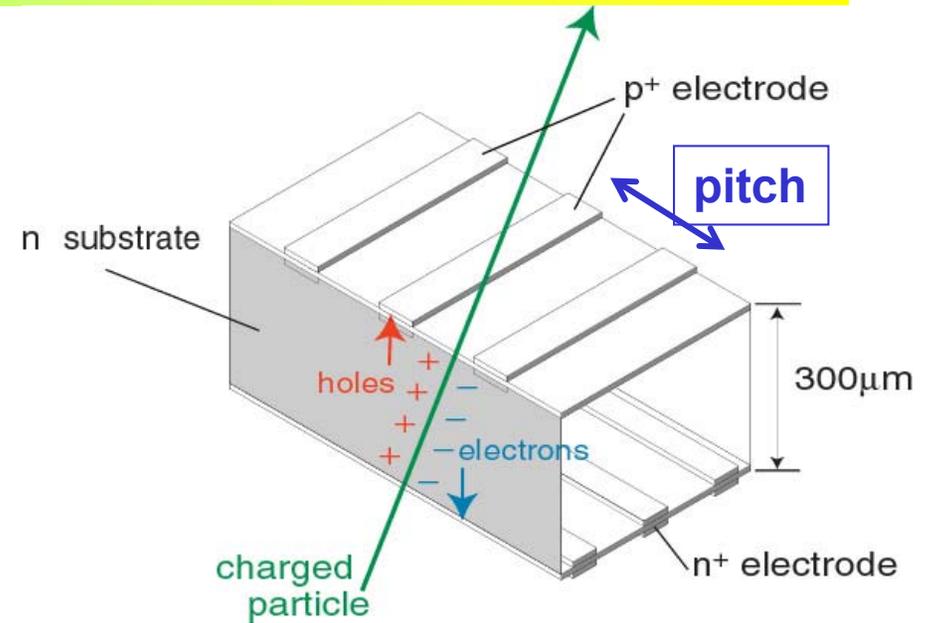
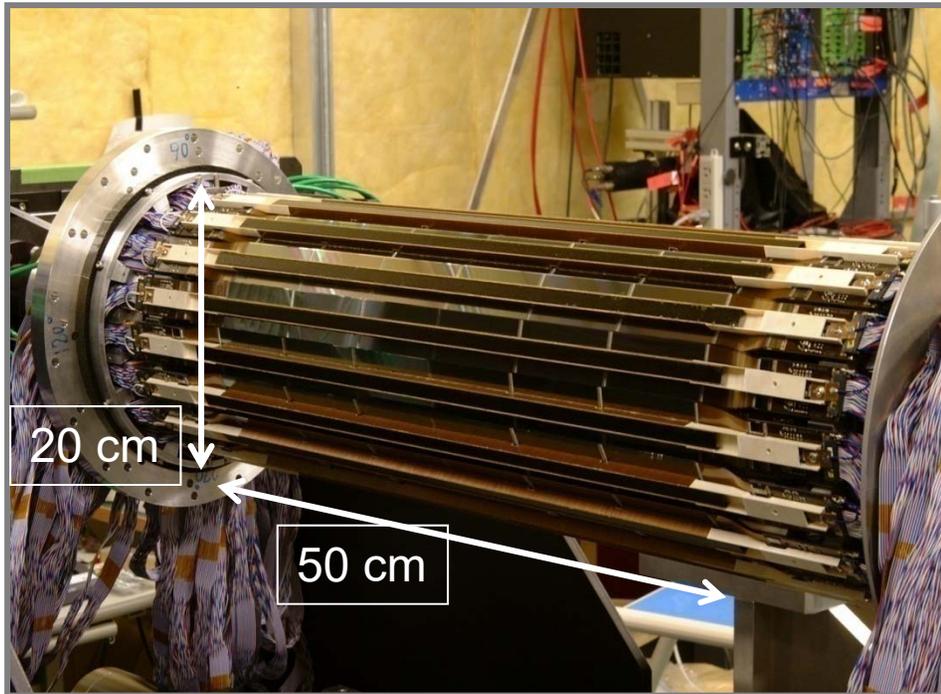


Components of an experimental apparatus ('spectrometer')

- Tracking and vertexing systems
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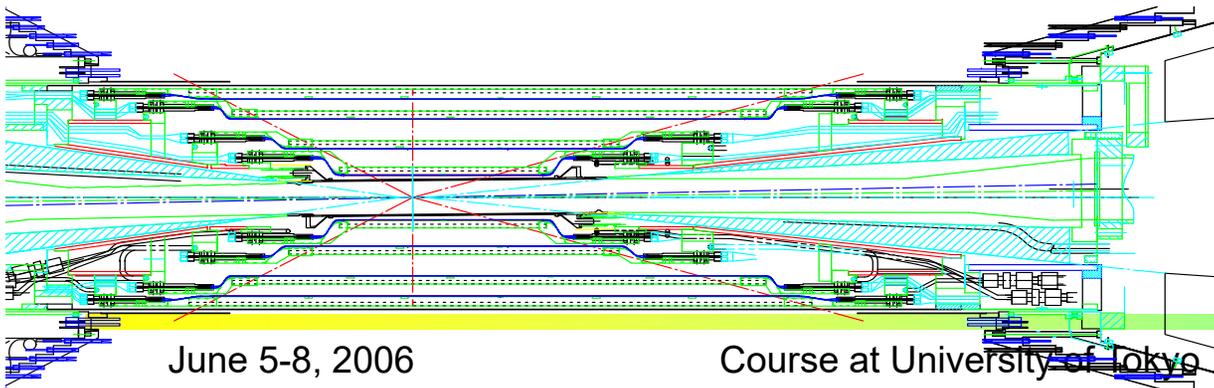


Silicon vertex detector (SVD)



Two coordinates
measured at the same
time

Typical strip pitch $\sim 50 \mu\text{m}$,
resolution about $\sim 15 \mu\text{m}$



June 5-8, 2006

Course at University of Tokyo

Peter Križan, Ljubljana



Interaction of charged particles with matter

Energy loss due to ionisation: depends on $\beta\gamma$, typically about **2 MeV/cm $\rho/(g\text{ cm}^{-3})$** .

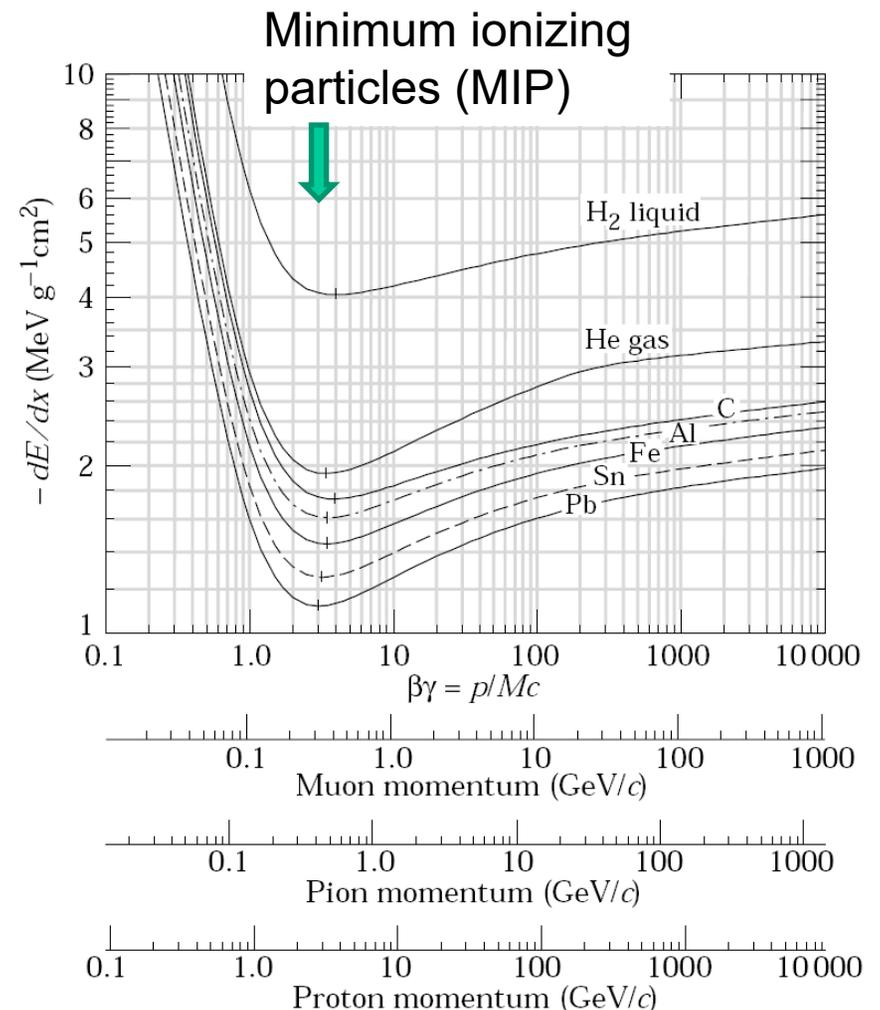
Liquids, solids: few MeV/cm

Gases: **few keV/cm**

Primary ionisation: charged particle kicks electrons from atoms.

In addition: excitation of atoms (no free electron), on average need **W_i** (>ionisation energy) to create e-ion pair.

W_i typically **30eV** \rightarrow per cm of gas about **2000eV/30eV=60** e-ion pairs



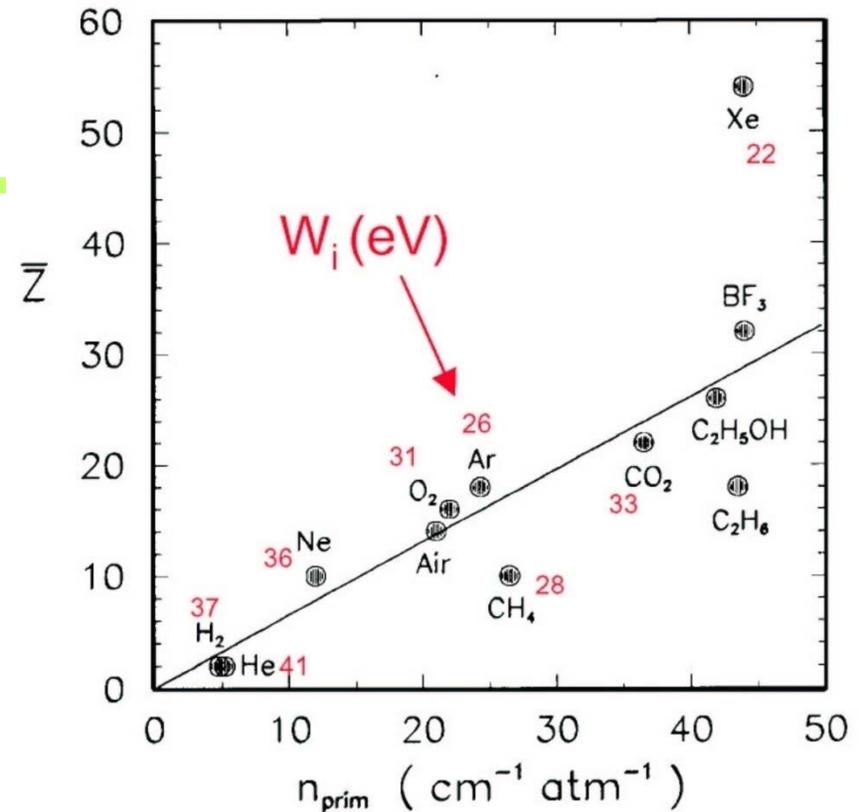


Ionisation

n_{prim} is typically 20-50 /cm
(average value, Poisson like distribution
– used in measurements of n_{prim})

The primary electron ionizes further: secondary e-ion pairs, typically about 2-3x more.

Finally: 60-120 electrons /cm



Can this be detected? 120 e-ion pairs make a pulse of
 $V = ne/C = 2\text{mV}$ (at typical $C = 10\text{pF}$) → NO

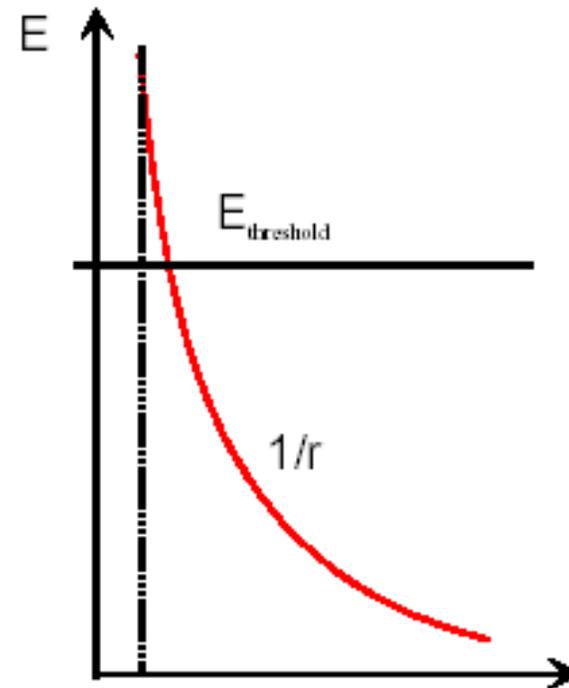
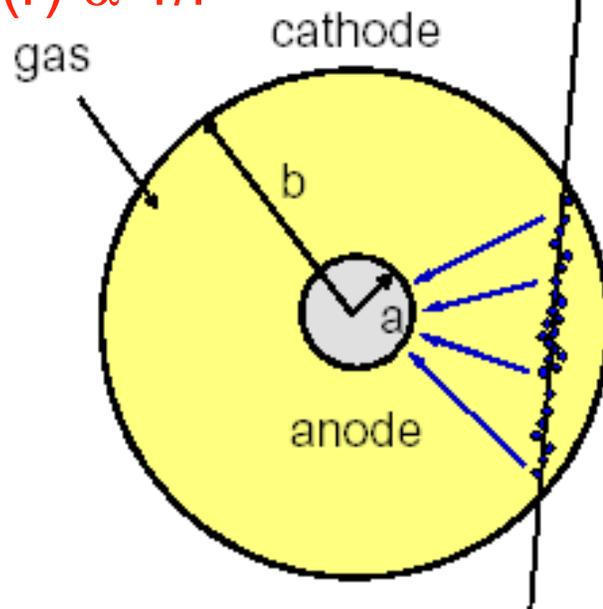
-> Need multiplication



Multiplication in gas

Simplest example: cylindrical counter, radial field, electrons drift to the anode in the center

$$E = E(r) \propto 1/r$$



If the energy eEd gained over several mean free paths (d around 10mm) exceeds the ionisation energy \rightarrow new electron
Electric field needed $\rightarrow E = I/ed = 10\text{V/mm} = 10\text{kV/cm}$



Diffusion and mobility of ions

Diffusion: ions lose their energy in collisions with the gas molecules, thermalize quickly (mean free path around $0.1\mu\text{m}$); Maxwellian energy distribution.

Localized charge distribution diffuses: fraction of charges in dx after time t

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-\frac{x^2}{4Dt}} dx$$

D , diffusion coefficient: typically around $0.05\text{ cm}^2/\text{s}$

The r.m.s. of the distribution for 1D and 3D cases:

$$\sigma_x = \sqrt{2Dt}, \sigma_v = \sqrt{6Dt}$$

Electric field: the Maxwellian distribution changes by very little, ions drift in electric field with an average net (drift) velocity (not instant velocity!) depending linearly on the electric field:

$$\mathbf{v}_D^+ = \mu^+ (\mathbf{E}/p)$$

μ^+ : mobility, related to D , $D^+/\mu^+ = kT/e = 0.026\text{V}$

Typical values for μ^+ : $1\text{-}2\text{ cm}^2\text{ atm/Vs}$; at 1 kV/cm : 1 cm/ms



Drift velocity of electrons

No simple relation to E field,
typical value $5\text{cm}/\mu\text{s}$

Few examples:

Argon changes drastically
with additives

Methane, ethane, CO_2

Methylal, Ethylene

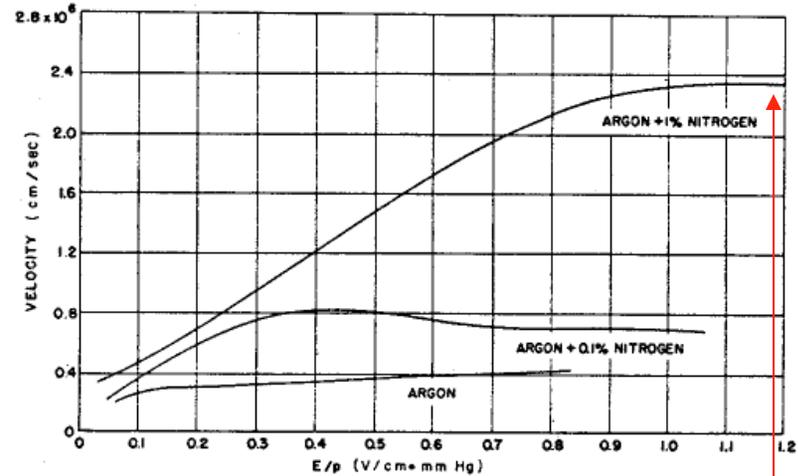


Fig. 25 Drift velocity of electrons in pure argon, and in argon with small added quantities of nitrogen. The very large effect on the velocity for small additions is apparent²².

Very useful: in some gas mixtures v_D gets saturated

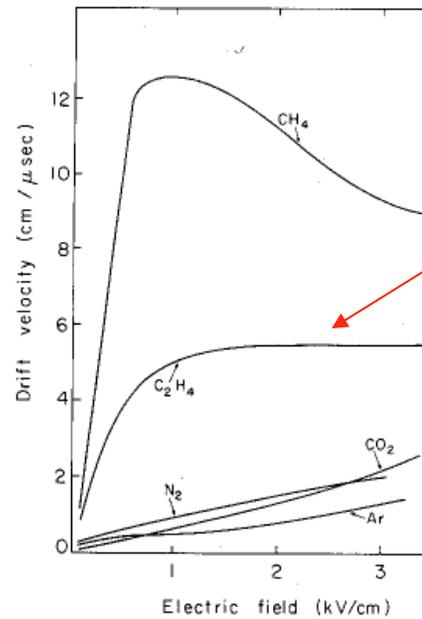


Fig. 26 Drift velocity of electrons in several gases at normal conditions^{12,22,23}

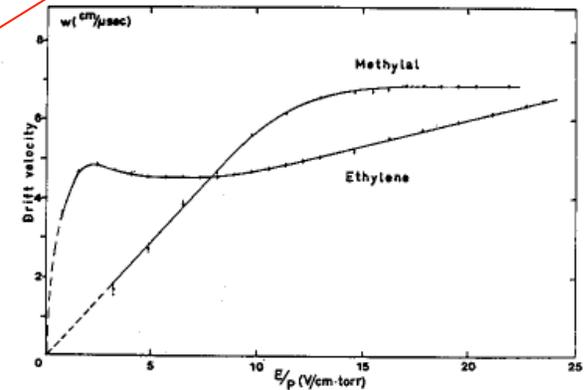
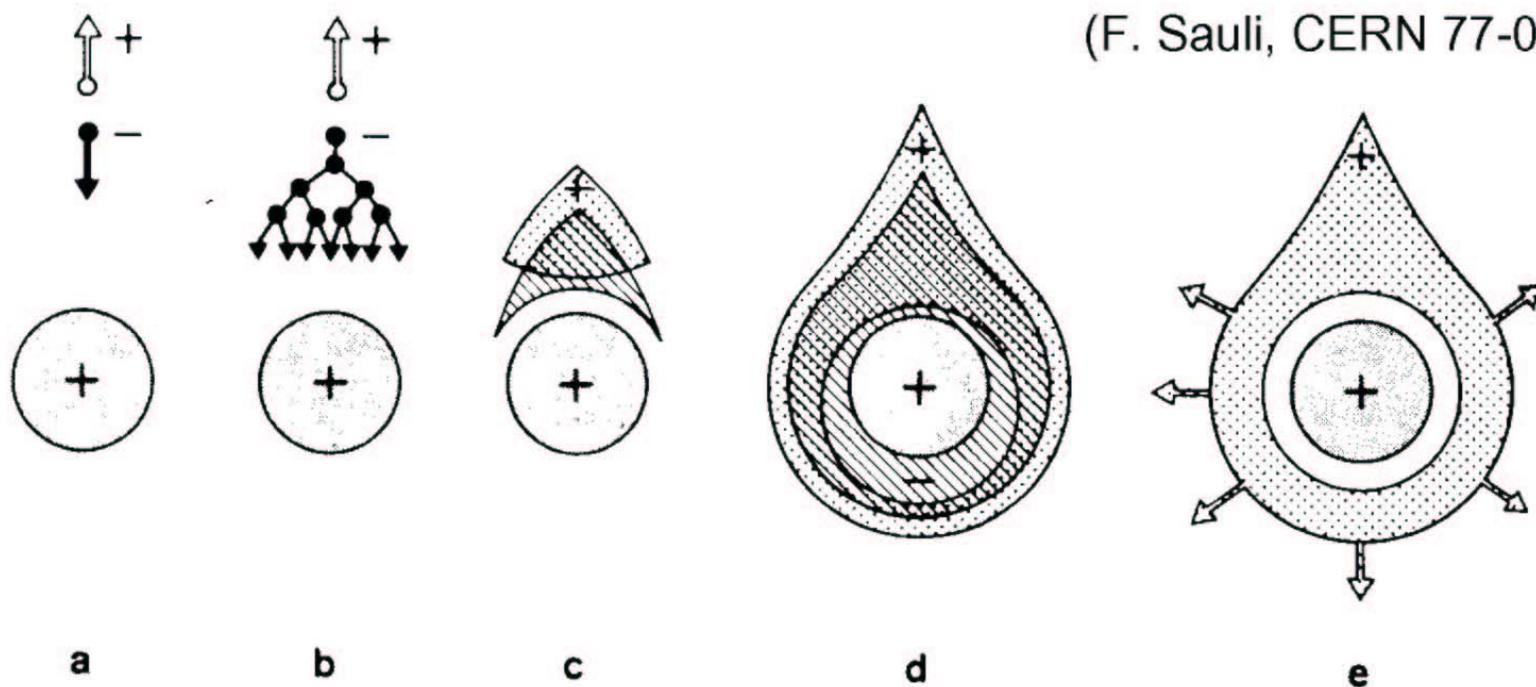


Fig. 27 Drift velocity of electrons in methylal $[(\text{OCH}_3)_2\text{CH}_2]$ and in ethylene (C_2H_4)²⁴



Multiplication in gas

Electron travels (drifts) towards the anode (wire); close to the wire the electric field becomes high enough (several kV/cm), the electron gains sufficient energy between two subsequent collisions with the gas molecules to ionize -> **start of an avalanche**.



Signal development 2

$$QE dr = -U_0 C l du \quad \longleftarrow$$

$$E = \frac{U_0 C}{2\pi\epsilon_0} \frac{1}{r}$$

$$Q = n M e_0$$

$$u(t) = \int_0^t du = -\frac{Q}{2\pi\epsilon_0 l} \ln \frac{r(t)}{a}$$

$$\frac{dr}{dt} = v = \mu^+ \frac{E}{p} = \frac{\mu^+ U_0 C}{p} \frac{1}{2\pi\epsilon_0 r}$$

$$\int_a^r r dr = \frac{\mu^+ U_0 C}{p} \frac{1}{2\pi\epsilon_0} \int_0^t dt$$

$$r(t) = \sqrt{a^2 + \frac{\mu^+ U_0 C}{p} \frac{t}{\pi\epsilon_0}} = a \sqrt{1 + \frac{t}{t_0}}$$

$$t_0 = \frac{\pi\epsilon_0 p}{\mu^+ U_0 C} (b^2 - a^2) \approx 500 \mu s$$

The work of the electric force on the ions drifting in the electric field, $QE dr$, is supplied by the generator: charge $C l du$ flows through the HV source with high voltage U_0 ($C = \text{cap. per unit length}$).

$$u(t) = -\frac{Q}{4\pi\epsilon_0 l} \ln\left(1 + \frac{t}{t_0}\right)$$

Note: Electrons are produced very close to the anode, drift over a small potential difference -> contribute very little to the signal (1%)



Signal development 3

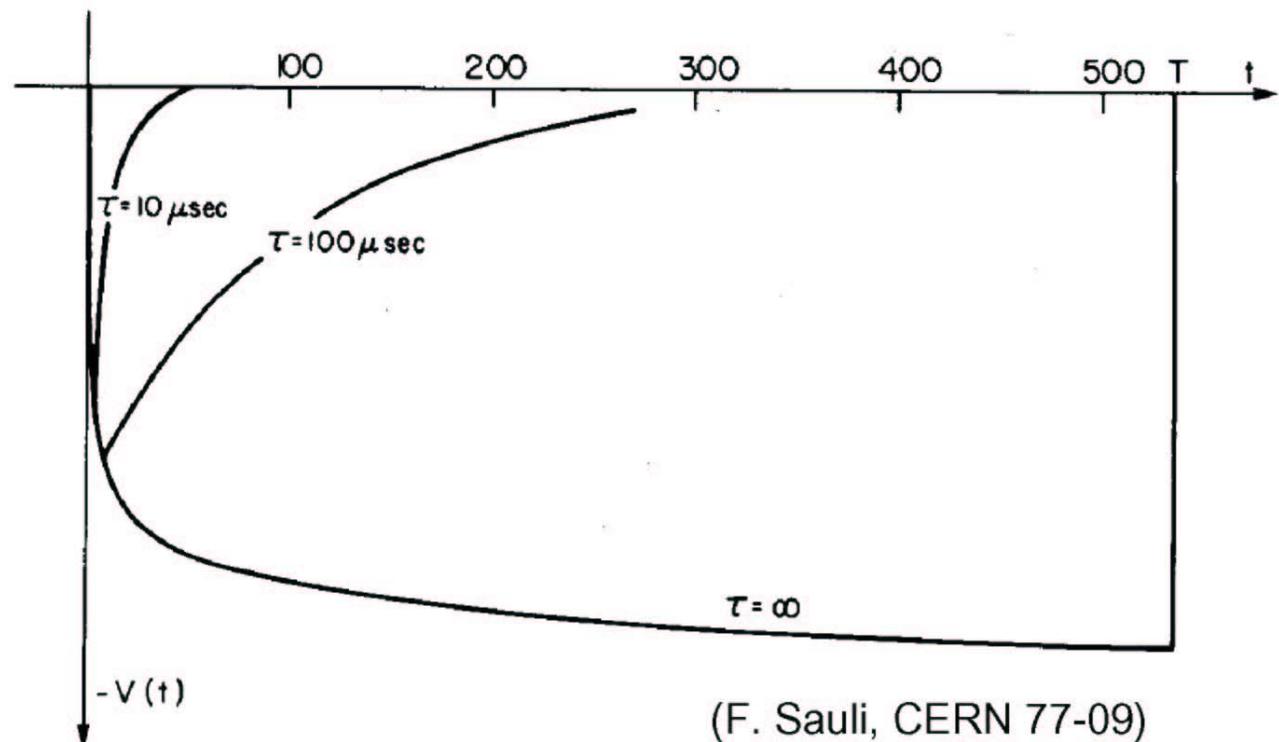
Time evolution of the signal

$$u(t) = -\frac{Q}{4\pi\epsilon_0 l} \ln\left(1 + \frac{t}{t_0}\right)$$

with no RC filtering ($\tau = \text{inf.}$) and with time constants $10\mu\text{s}$ and $100\mu\text{s}$.

If faster signals are needed \rightarrow smaller time constants \rightarrow smaller signals

e.g. $\tau = 40\text{ns}$: max $u(t)$ is about $\frac{1}{4}$ of the $\tau = \text{inf.}$ case

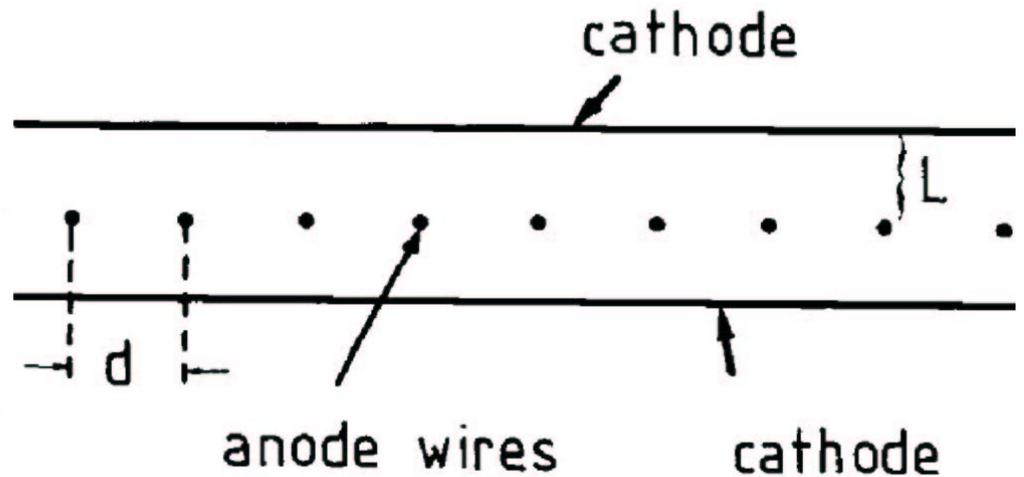
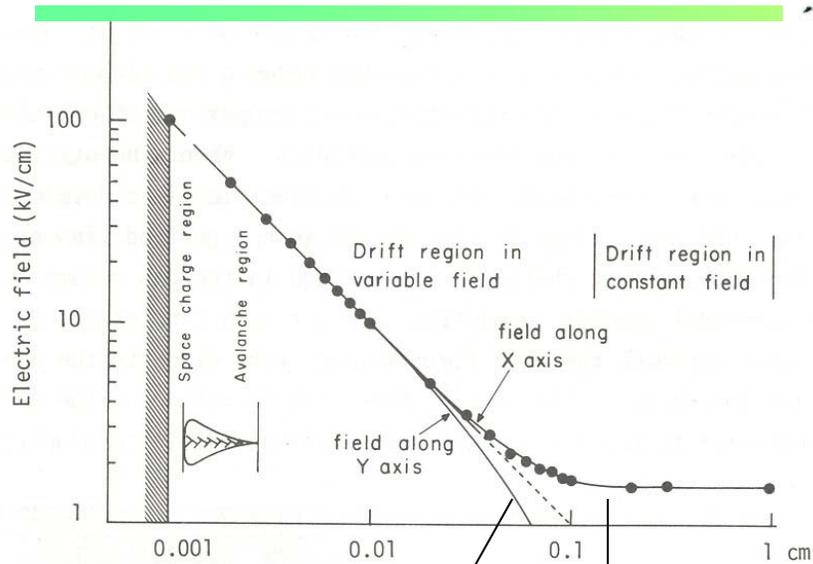


(F. Sauli, CERN 77-09)

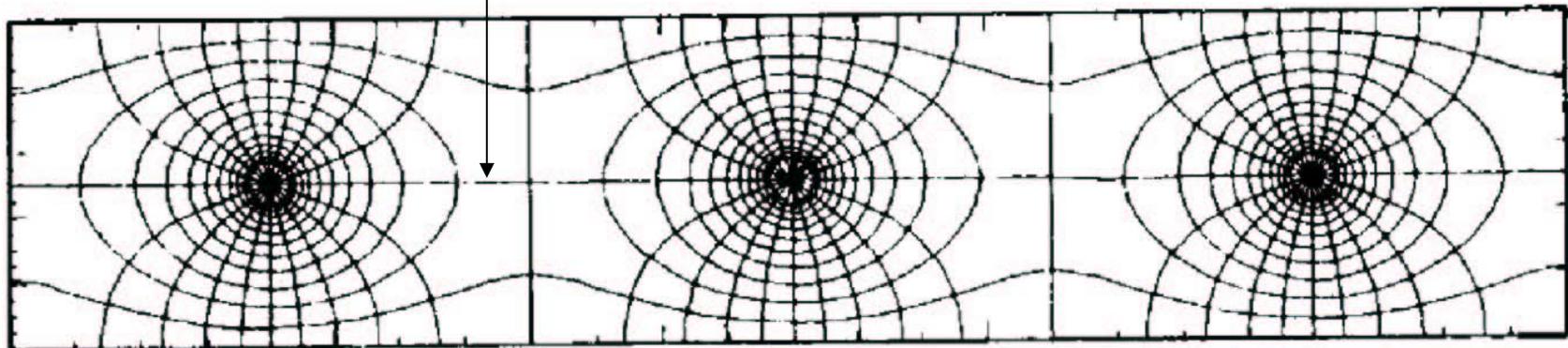
Peter Križan, Ljubljana



Multiwire proportional chamber (MWPC)



Typical parameters:
 $L=5\text{mm}$, $d=1\text{-}2\text{mm}$,
wire radius = 20 μm





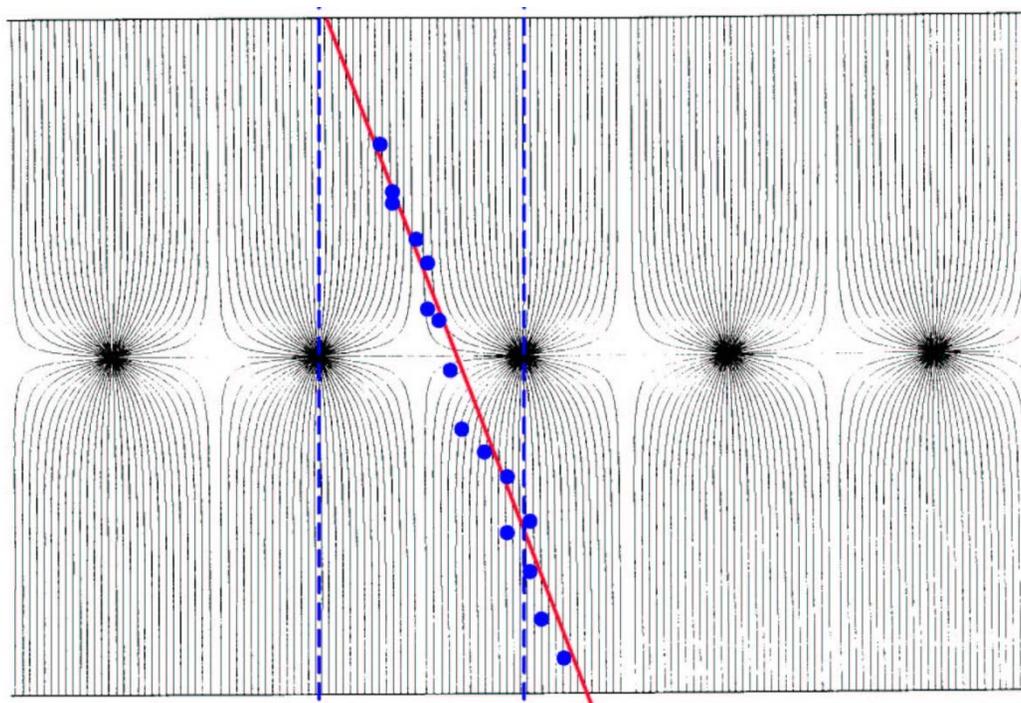
Multiwire proportional chamber (MWPC)

The address of the fired wire gives only 1-dimensional information.

Normally digital readout:
spatial resolution limited to

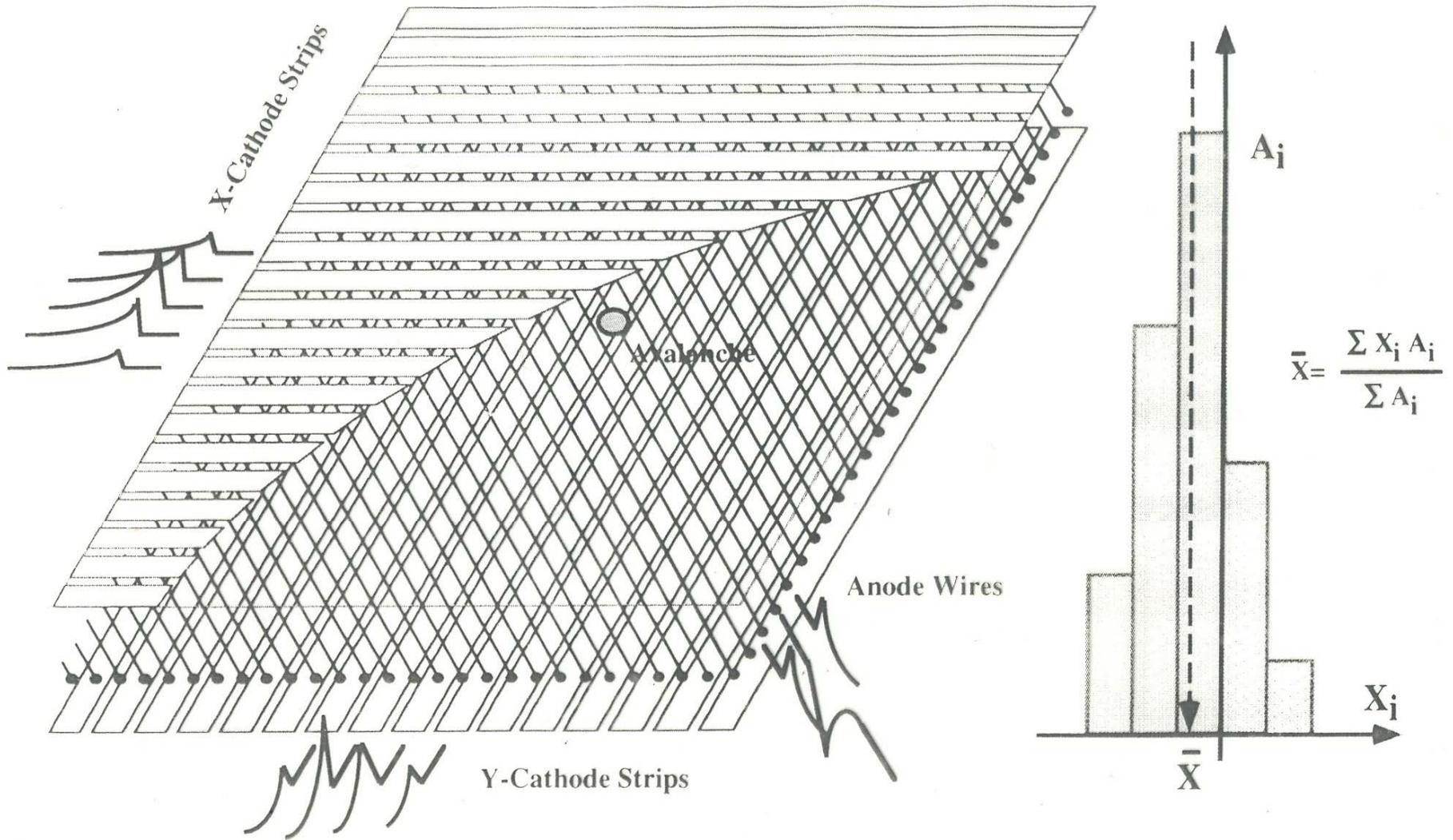
$$\sigma = d/\sqrt{12}$$

for $d=1\text{mm} \rightarrow \sigma = 300 \text{ }\mu\text{m}$



Revolutionized particle physics experiments
→ Nobel prize for G. Charpak

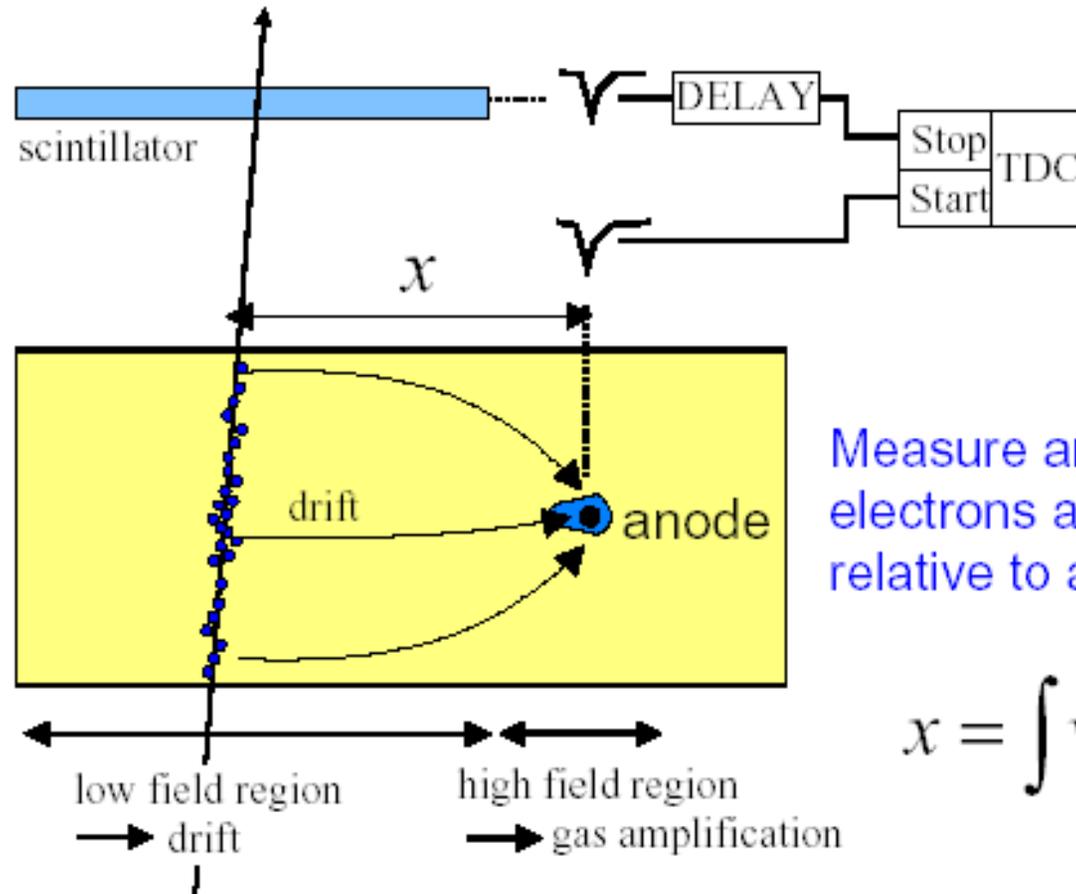
1
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Drift chamber

Improve resolution by measuring the drift time of electrons



Measure arrival time of electrons at sense wire relative to a time t_0 .

$$x = \int v_D(t) dt$$



Drift chamber: resolution

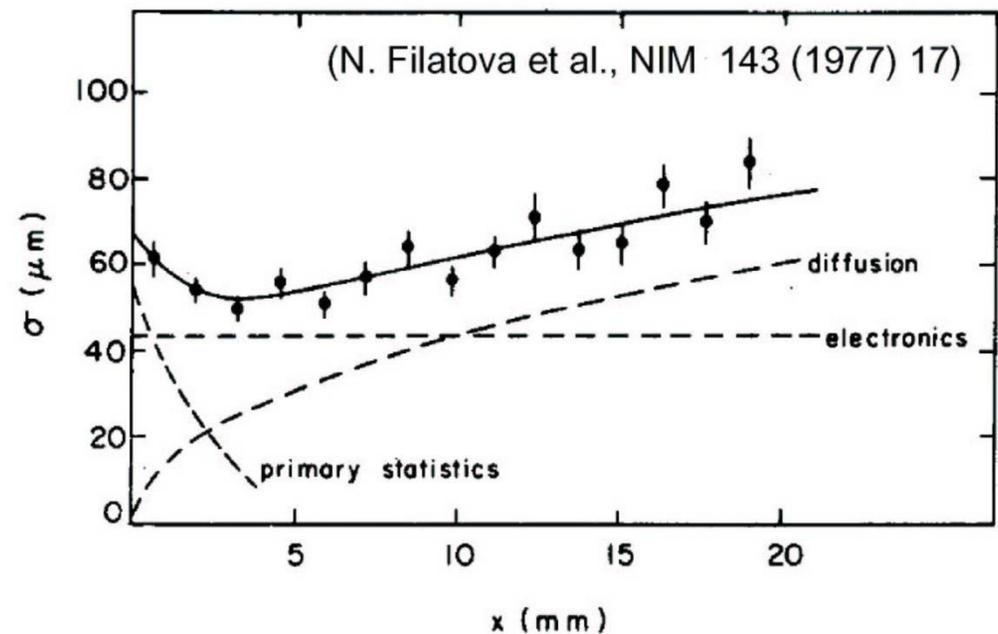
Resolution determined by

- diffusion,
- primary ionisation statistics,
- electronics,
- path fluctuations.

Diffusion: $\sigma_x \propto \sqrt{Dt} \propto \sqrt{x}$

Primary ionisation statistics: if e-ion pairs are produced over distance L, the probability that the first one is produced at x from the wire is $e^{-nx/L}$

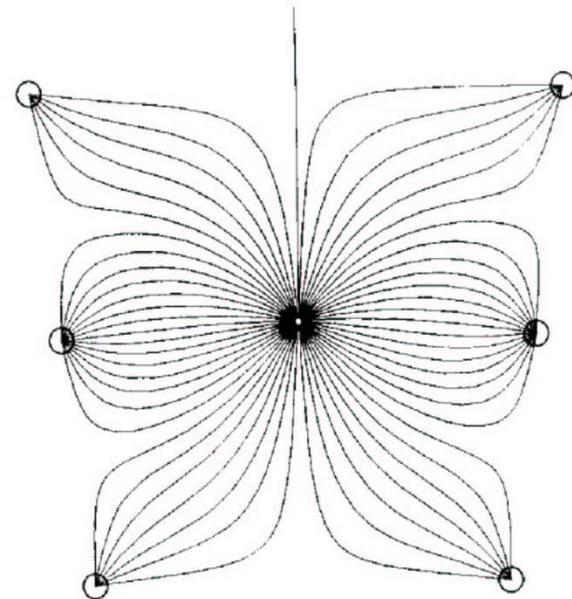
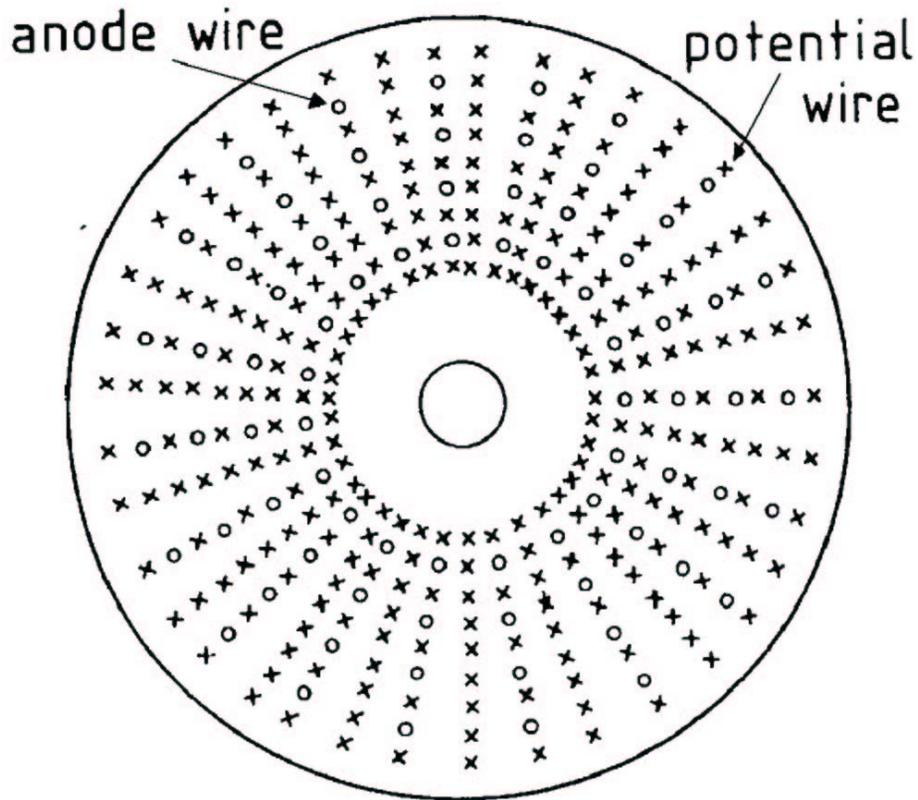
Resolution as a function of drift distance





Drift chamber with small cells

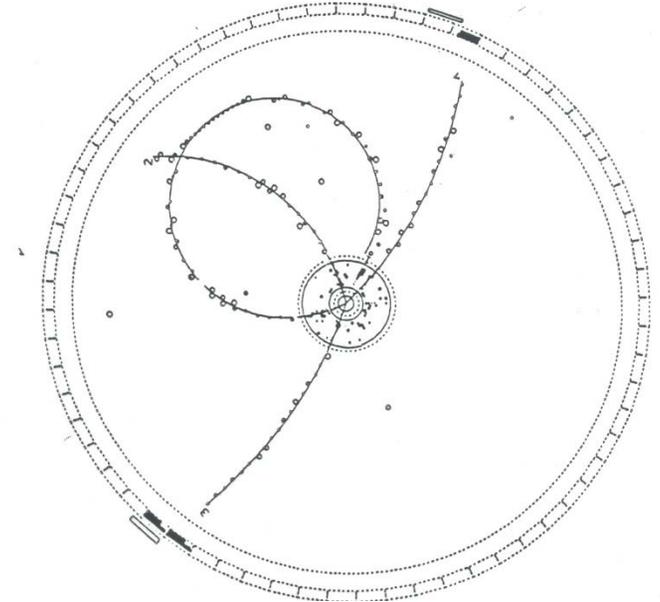
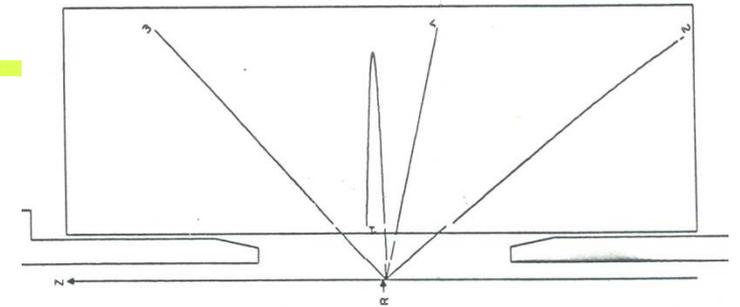
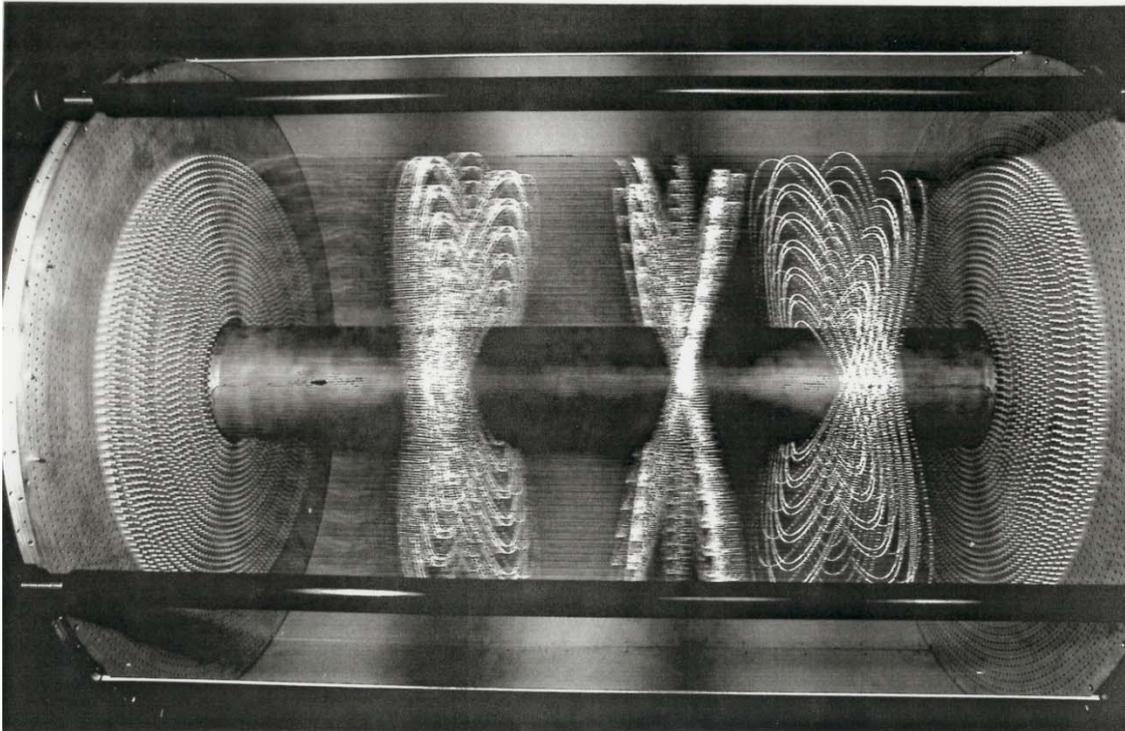
One big gas volume, small cells defined by the anode wire and field shaping (potential) wires





Drift chamber with small cells

Example: ARGUS drift chamber with axial and 'stereo' wires (at an angle to give the hit position along the main axis)

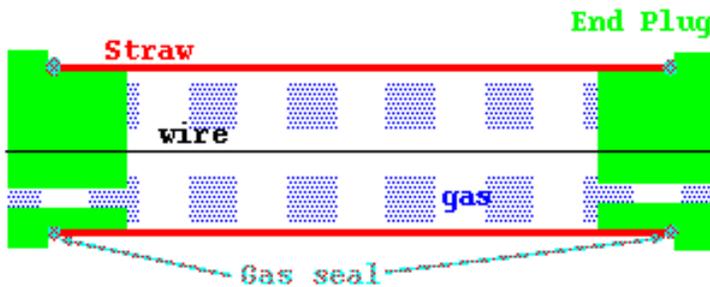


Typical event in two projections

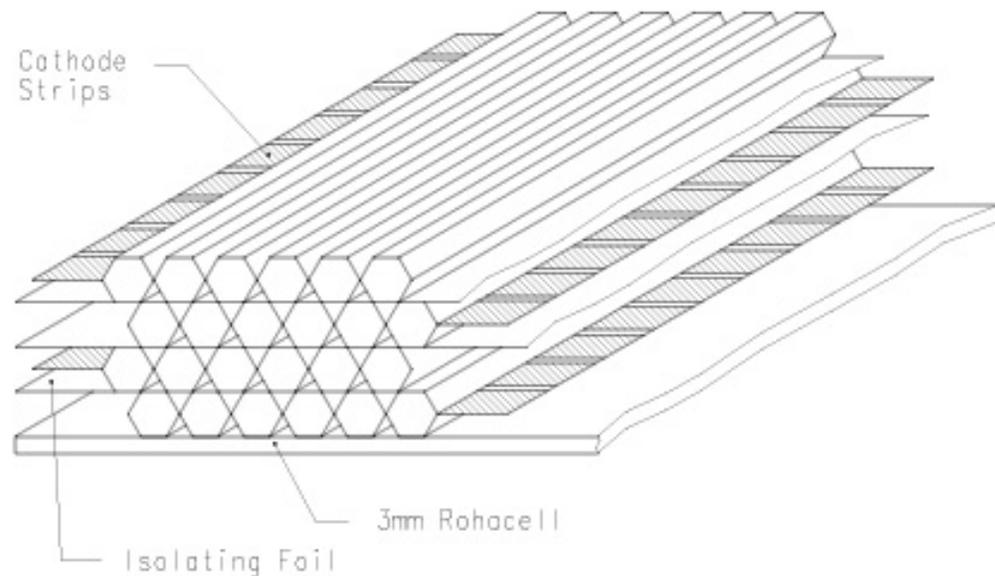


Single cell drift chamber

Simplify manufacturing: put each wire in a tube (straw or hexagonal); useful for large areas.



Cells can be several meters long!





Diffusion and mobility of electrons in magnetic field

E perpendicular to B

Lorentz force perpendicular to B \rightarrow net drift at an angle α to E

$$\tan \alpha = \omega \tau$$

α : Lorentz angle

ω : cyclotron frequency, $\omega = eB/m$

τ : mean time between collisions

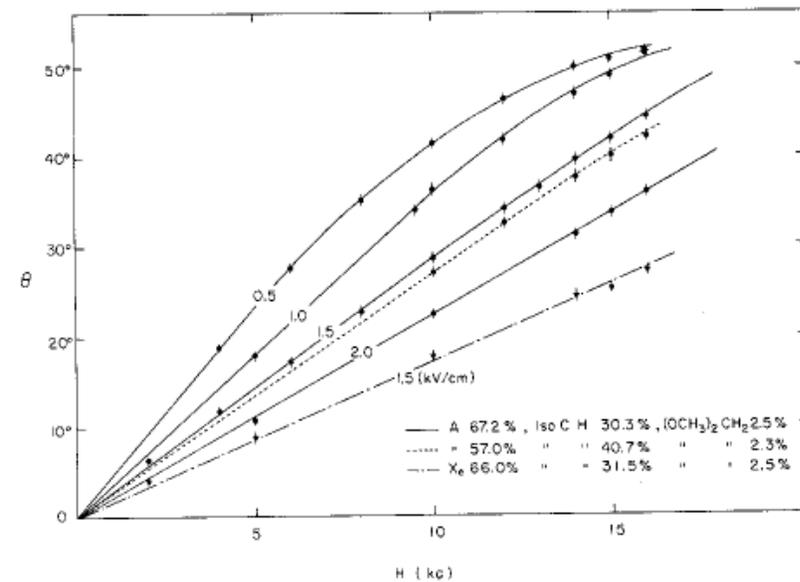
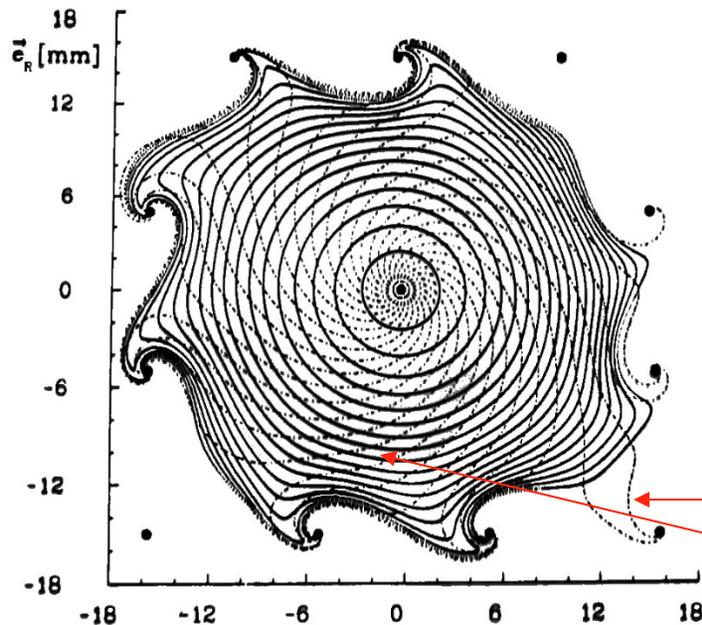


Fig. 38 Measured drift angle (angle between the electric field and the drift directions) as a function of electric and magnetic field strength⁹.

Drift lines in a radial E field (dash-dotted)

Isochrones (full lines)



Diffusion and mobility of electrons in magnetic field 2

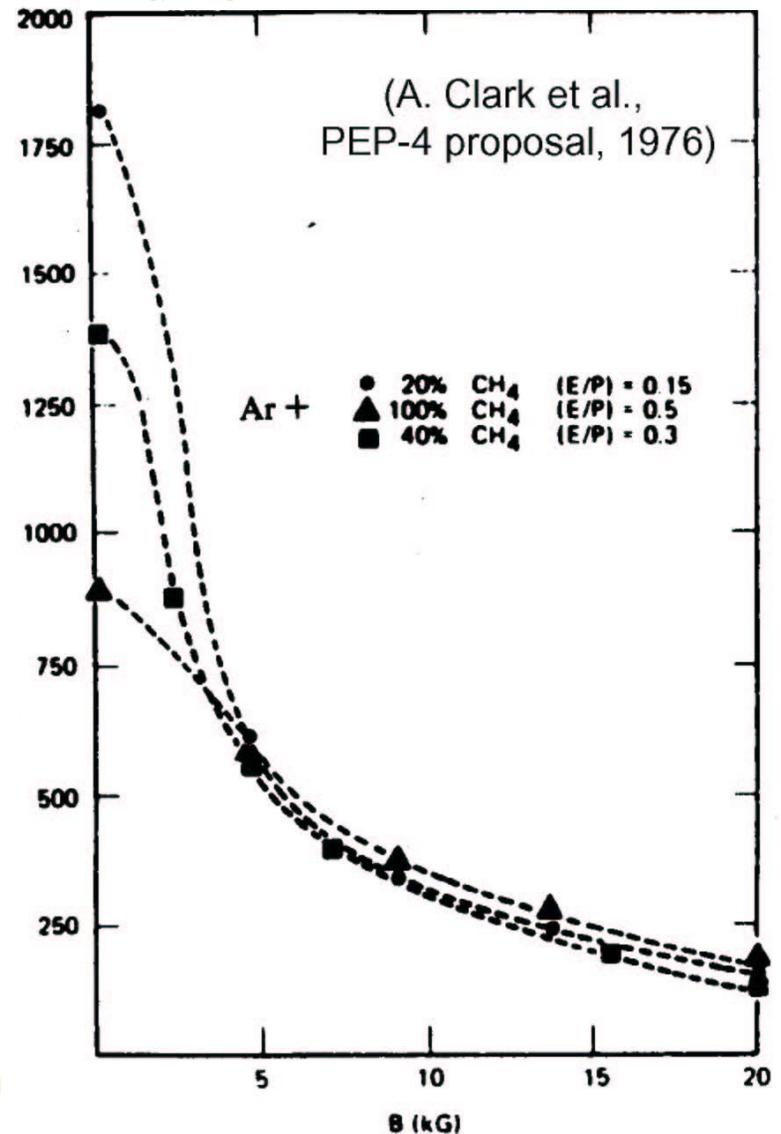
E and B parallel:

drift along E, diffusion in the transverse direction reduced! – departing electrons get curled back:

$$D_T(B) = D_0 / (1 + \omega^2 \tau^2)$$

→ Less diffusion in the transversal direction!

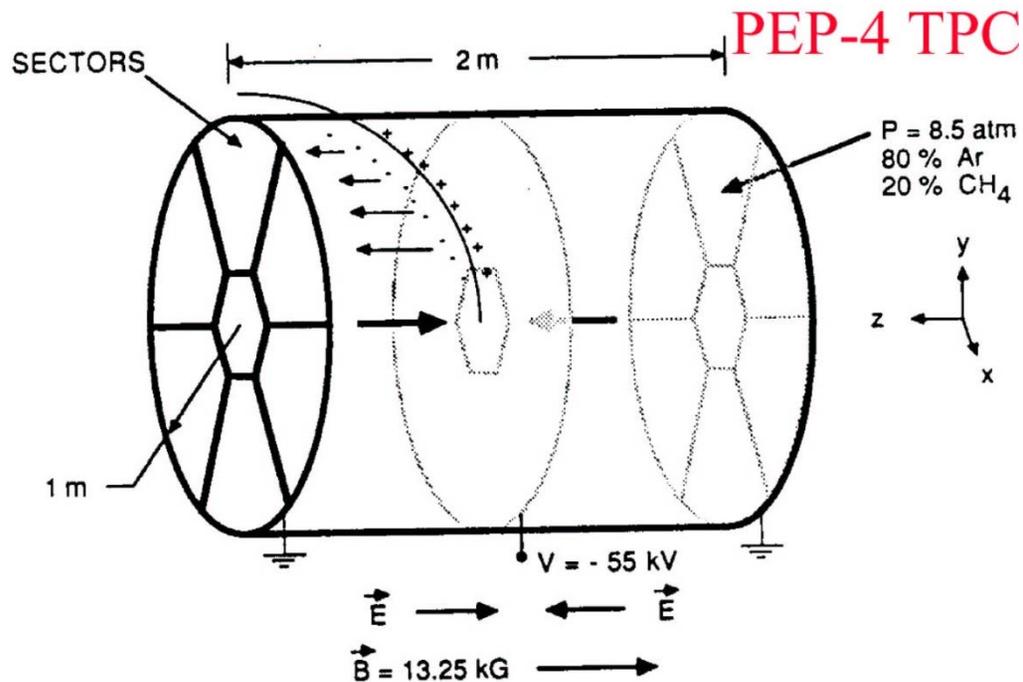
σ (μm) for 15cm drift distance





Drift chamber: TPC – time projection chamber

3-dimensional information: drift over a large distance,
2 dim. read-out at one side



Diffusion: no problem for the transverse coordinate
in spite of the very long drift distance because B
parallel to E (drift direction).



Drift chamber: TPC – time projection chamber

z coordinate (along the E, B field): from drift time

2 dim. read-out at one side:

- Anode wires and cathode pads
- Anode wires and cathode strips (perpendicular)

Resolutions for the ALEPH TPC ($d=3.6\text{m}$, $L=4.4\text{m}$):

in x,y: **173 mm**, in z: **740 mm**.

Potential problems:

- need an excellent drift velocity monitoring (long drift distance)
 - high quality gas (long drift distance)
 - space charge: ions drifting back to the cathode
-



Components of an experimental apparatus ('spectrometer')

- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)



Why Particle ID?

Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

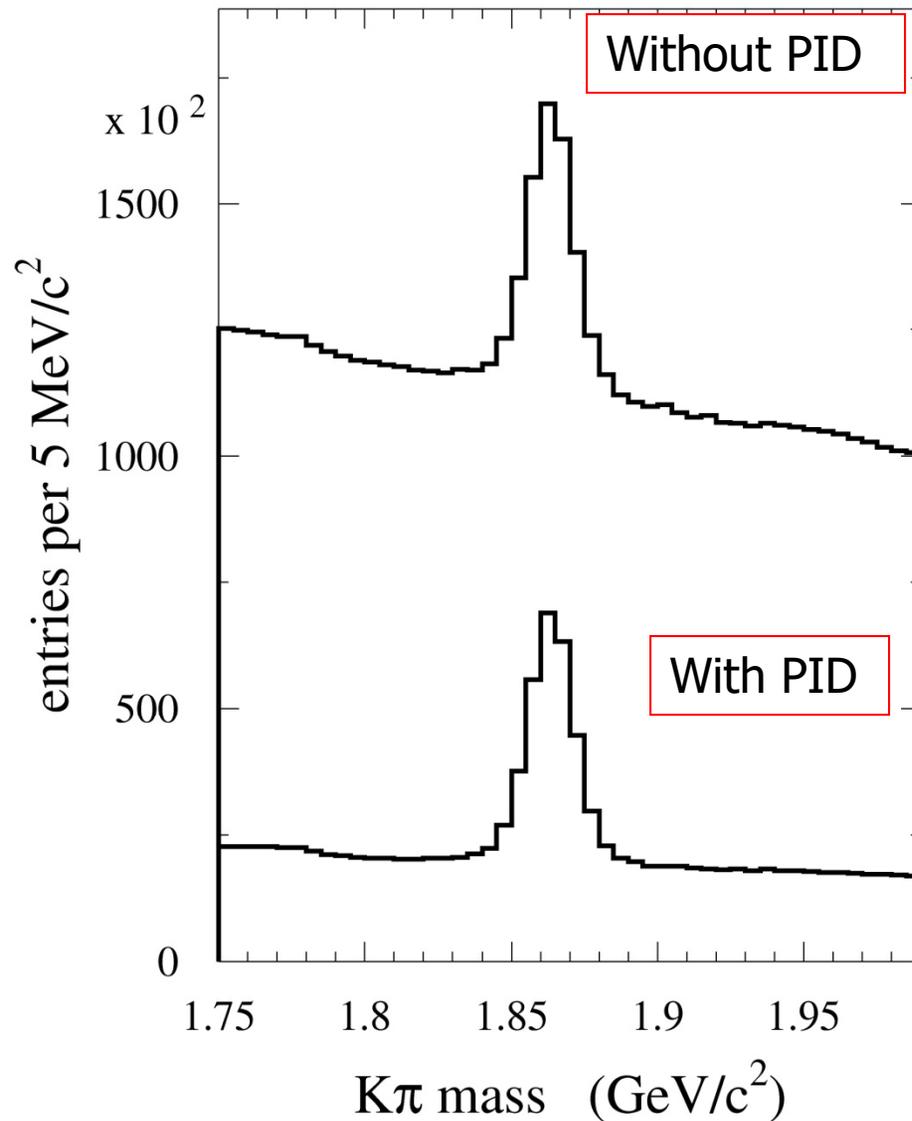
Some physical quantities in particle physics are only accessible with sophisticated particle identification (B-physics, CP violation, rare decays, search for exotic hadronic states).

Nuclear physics: final state identification in quark-gluon plasma searches, separation between isotopes

Astrophysics/astroparticle physics: identification of cosmic rays – separation between nuclei (isotopes), charged particles vs high energy photons



Introduction: Why Particle ID?

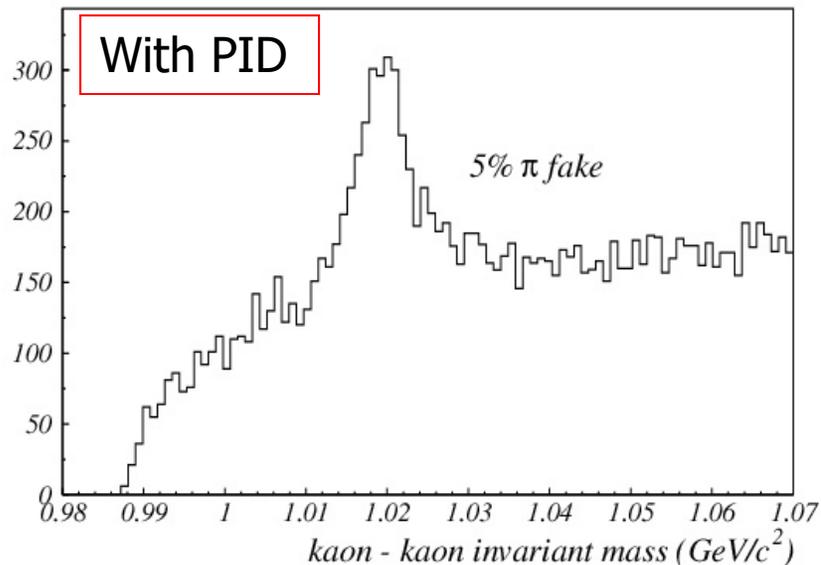
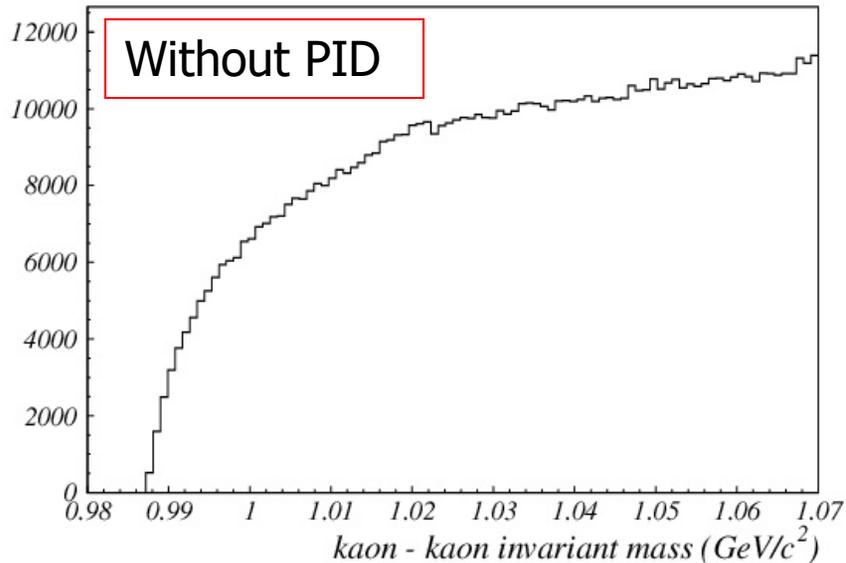


Example 1: B factories

Particle identification
reduces combinatorial
background by $\sim 3x$



Introduction: Why Particle ID?



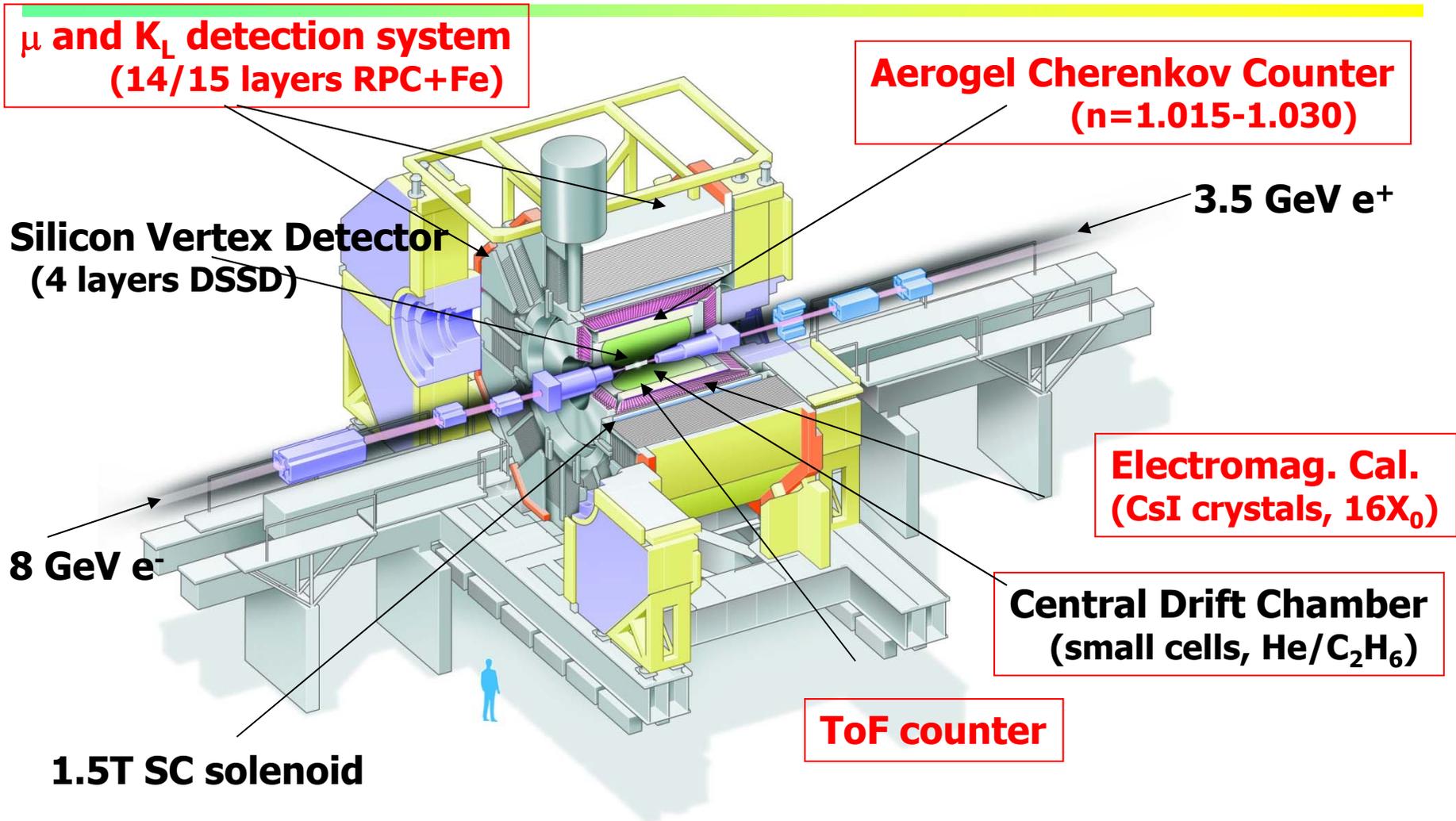
Example 2: HERA-B

K^+K^- invariant mass.

The $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.



Particle identification systems in Belle

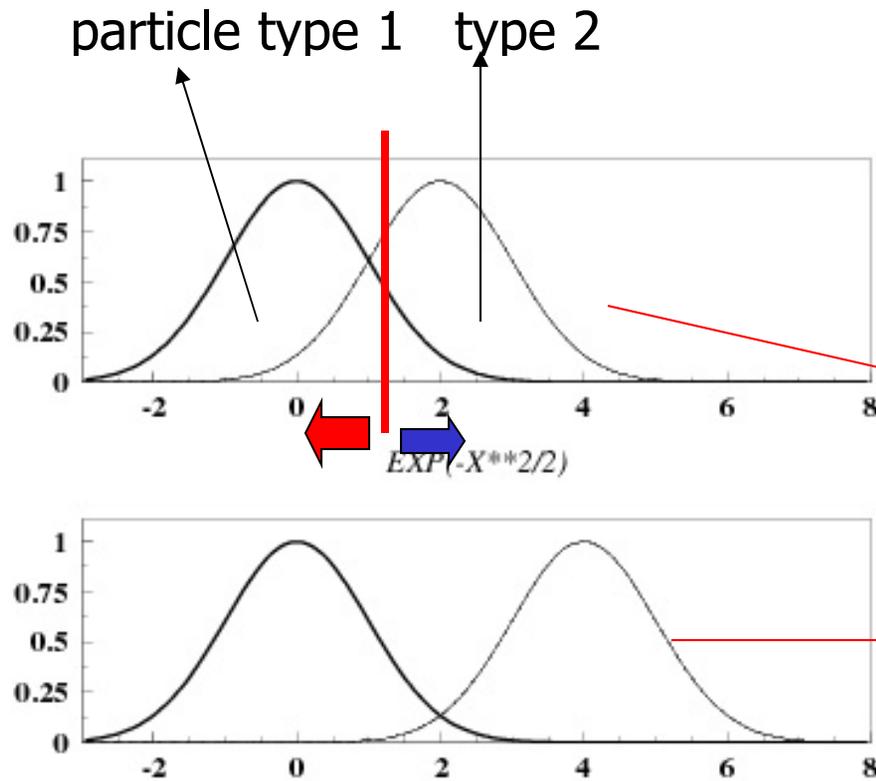




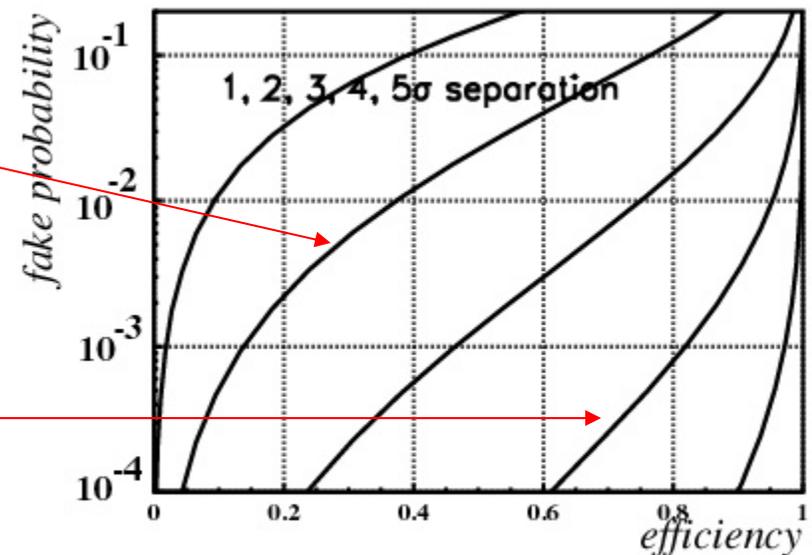
Efficiency and purity in particle identification

Efficiency and purity are tightly coupled!

Two examples:



eff. vs fake probability



some discriminating variable



Identification of charged particles

Particles are identified by their **mass** or by the **way they interact**.

Determination of mass: from the relation between momentum and velocity, $p = \gamma mv$.

Momentum known (radius of curvature in magnetic field)

→ Measure velocity:

time of flight

ionisation losses dE/dx

Cherenkov angle

transition radiation

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons



Time-of-flight measurement (TOF)

Measure time difference over a known distance, determine velocity

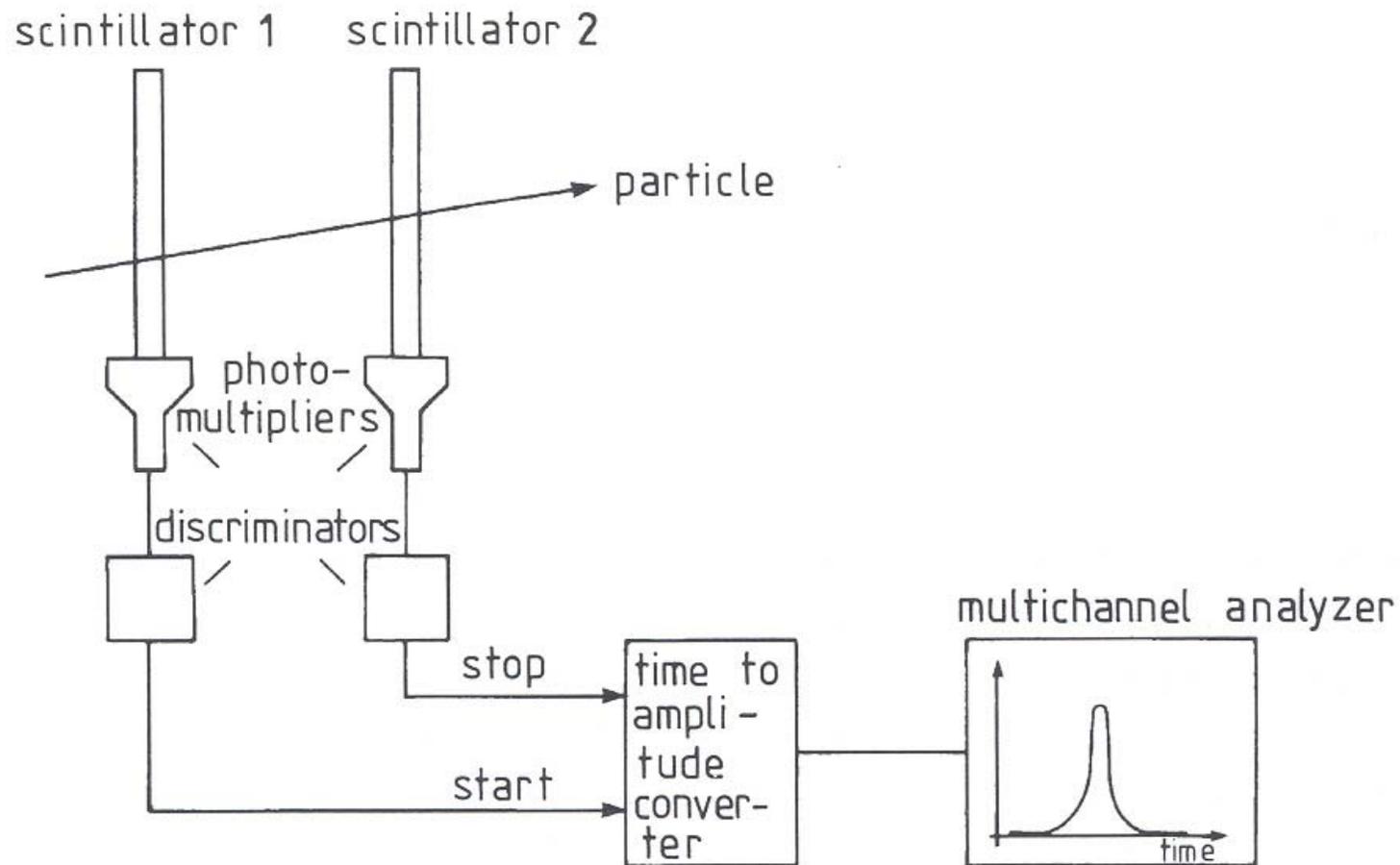


Fig. 6.5. Working principle of time-of-flight measurement.



Time-of-flight measurement 2

Required resolution, example:

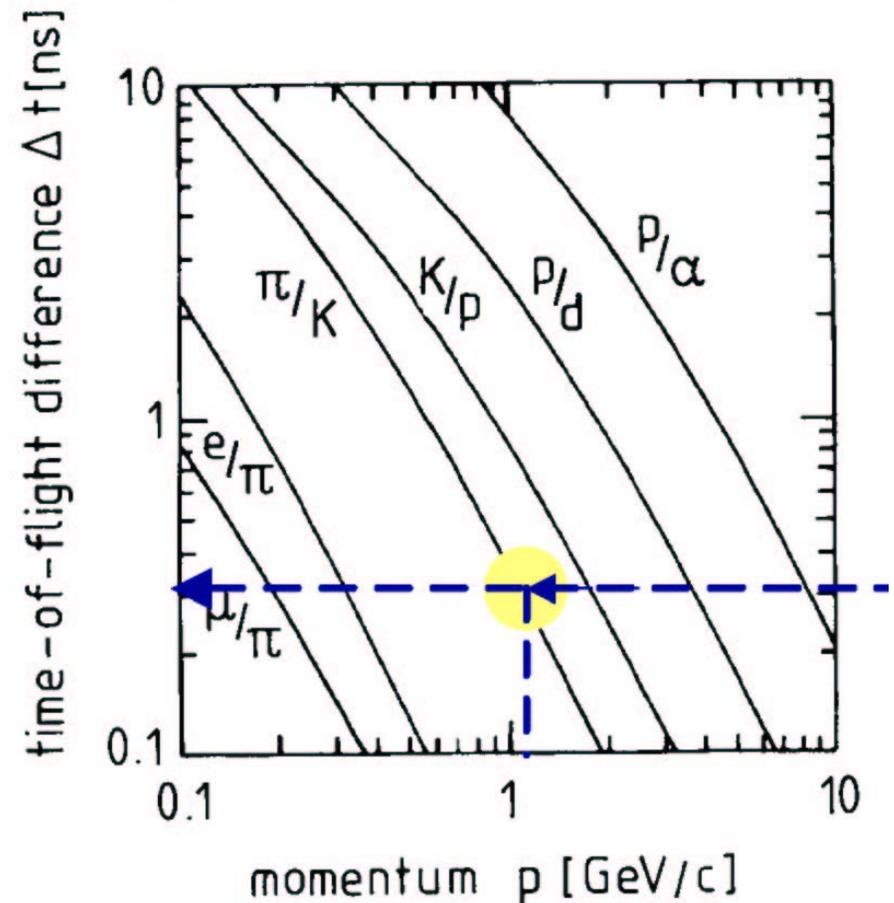
π/K difference at 1 GeV/c: 300ps

For a 3σ separation need
 $\sigma(\text{TOF})=100\text{ps}$

Resolution contributions:

- PMT: transient time spread (TTS)
- Path length variation
- Momentum uncertainty

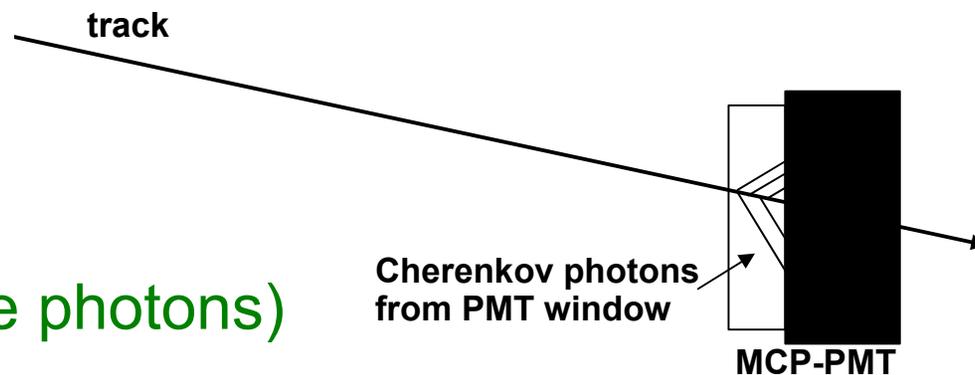
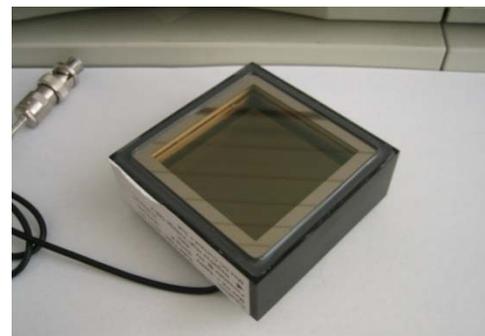
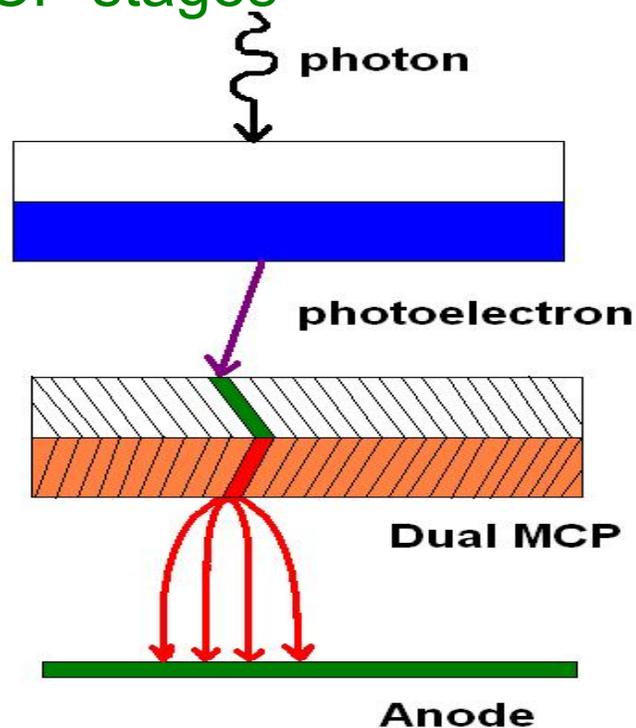
Time difference between two particle species for path length=1m





Very fast: MCP-PMT

Microchannel plate (MCP) PMT: multi-anode PMT with two MCP stages

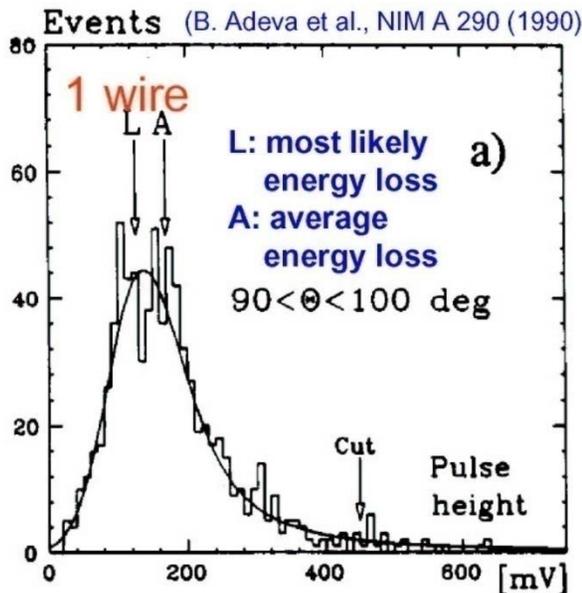


→ very fast ($\sigma \sim 40\text{ps}$ for single photons)

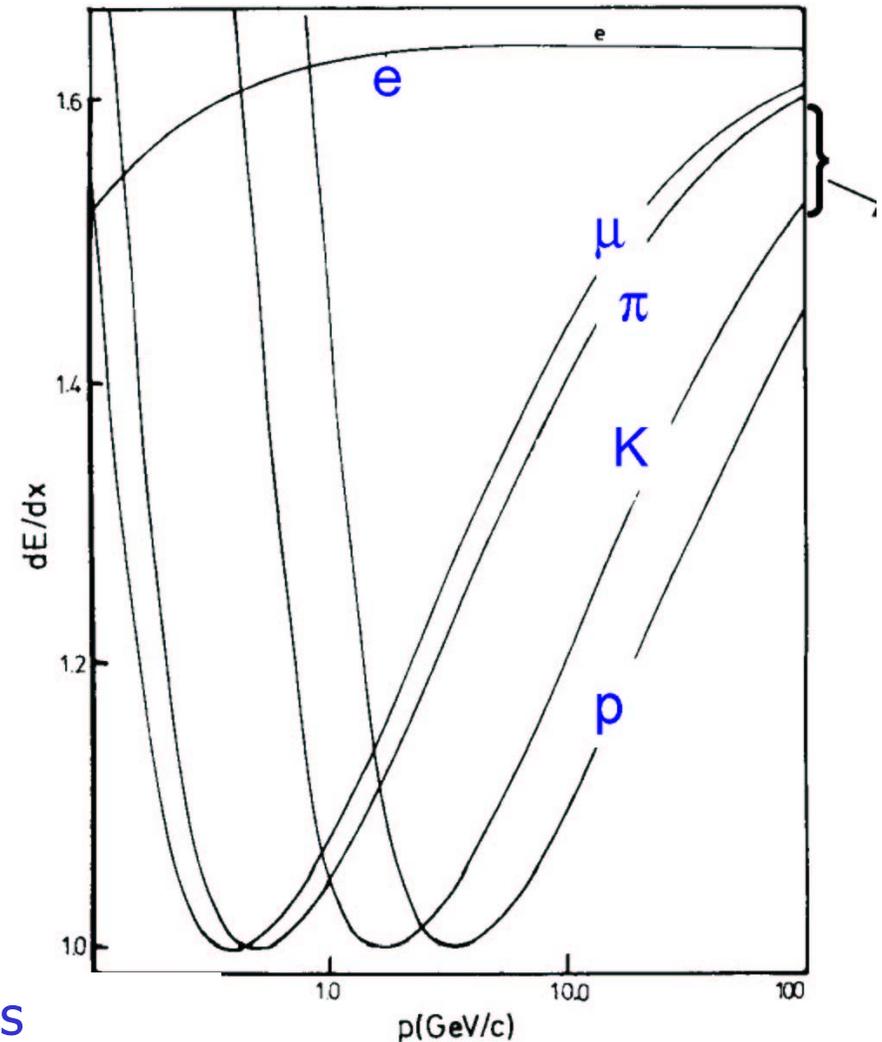


Identification with dE/dx measurement

dE/dx is a function of velocity.
For particles with different mass the Bethe-Bloch curve gets displaced \rightarrow separation is possible if the resolution is good enough



Problem: long tails
(Landau distribution,
not Gaussian)

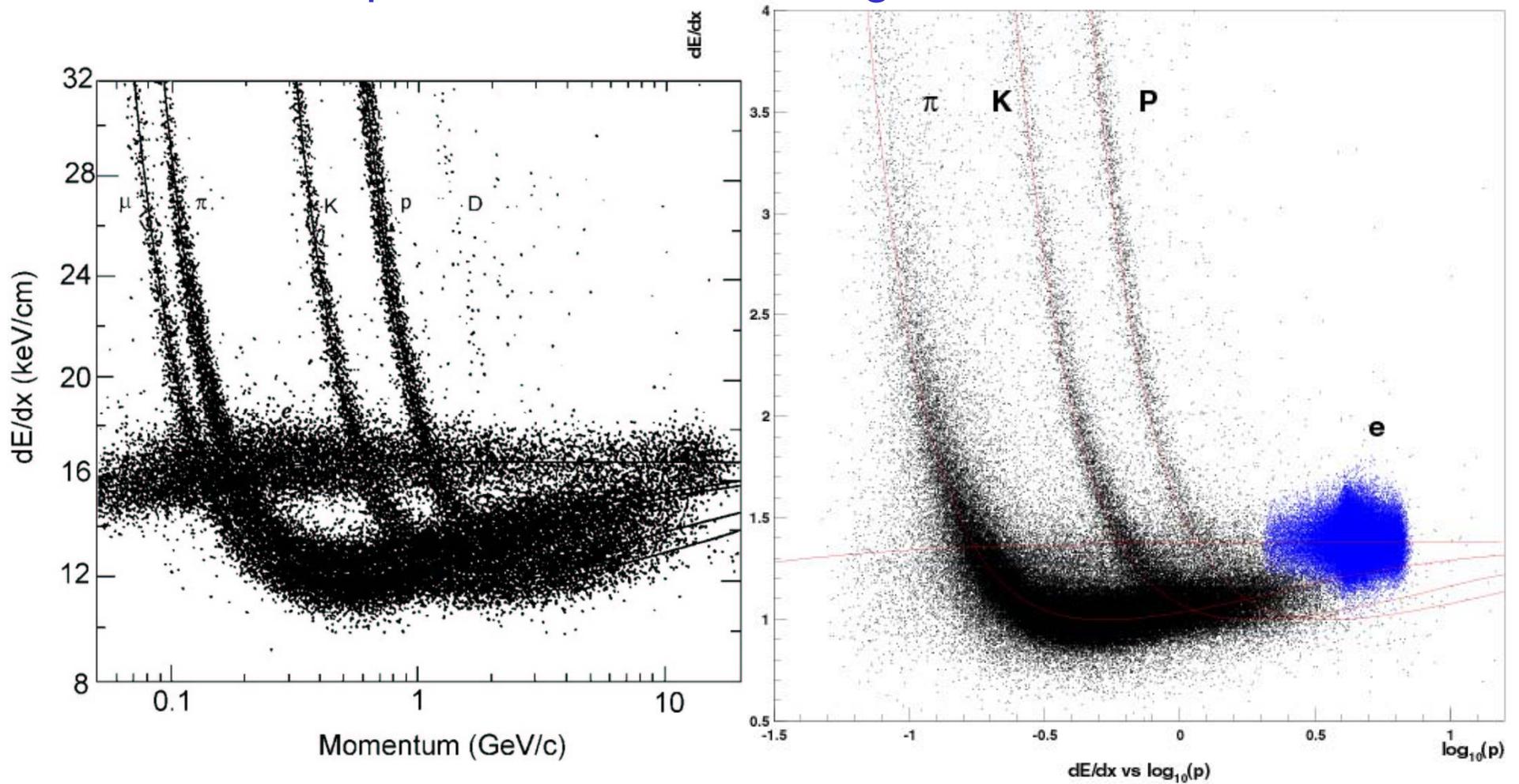


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Identification with dE/dx measurement

dE/dx performance in two large drift chambers.

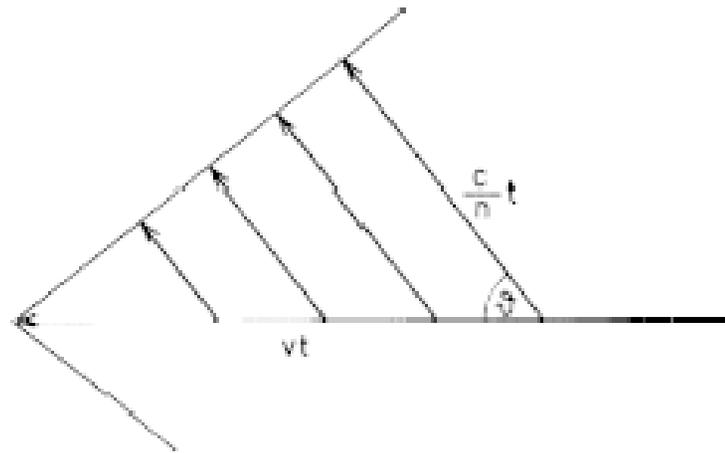




Čerenkov radiation

A charged track with velocity $v = \beta c$ above the speed of light c/n in a medium with index of refraction $n = \sqrt{\epsilon}$ emits **polarized light** at a characteristic (Čerenkov) angle,

$$\cos\theta = c/nv = 1/\beta n$$



Two cases:

- 1) $\beta < \beta_t = 1/n$: below threshold no Čerenkov light is emitted.
- 2) $\beta > \beta_t$: the number of Čerenkov photons emitted over unit photon energy $E = h\nu$ in a radiator of length L amounts to

$$\frac{dN}{dE} = \frac{\alpha}{\eta c} L \sin^2 \theta = 370(\text{cm})^{-1} (\text{eV})^{-1} L \sin^2 \theta$$



Number of detected photons

Example: in 1m of air ($n=1.00027$) a track with $\beta=1$ emits **$N=41$ photons** in the spectral range of visible light ($\Delta E \sim 2$ eV).

If Čerenkov photons were detected with an average detection efficiency of $\varepsilon=0.1$ over this interval, **$N=4$ photons** would be measured.

In general: number of detected photons can be parametrized as
 $N = N_0 L \sin^2\theta$

where N_0 is the figure of merit,
$$N_0 = \frac{\alpha}{\eta c} \int Q(E)T(E)R(E)dE$$

and **$Q T R$** is the product of photon detection efficiency, transmission of the radiator and windows and reflectivity of mirrors employed.

Typically: $N_0 = 50 - 100/\text{cm}$



Cherenkov counters

Threshold counters --> count photons to separate particles below and above threshold; for $\beta < \beta_t = 1/n$ (below threshold) no Čerenkov light is emitted

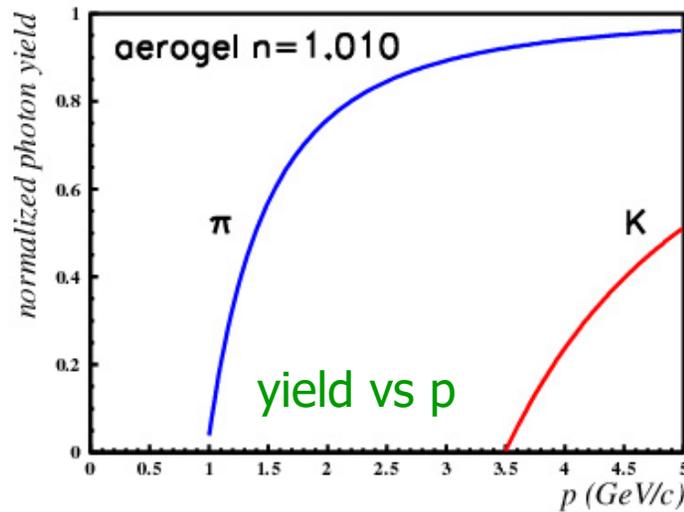
Ring Imaging (RICH) --> measure Čerenkov angle and count photons



Belle ACC (aerogel Cherenkov counter): threshold Čerenkov counter

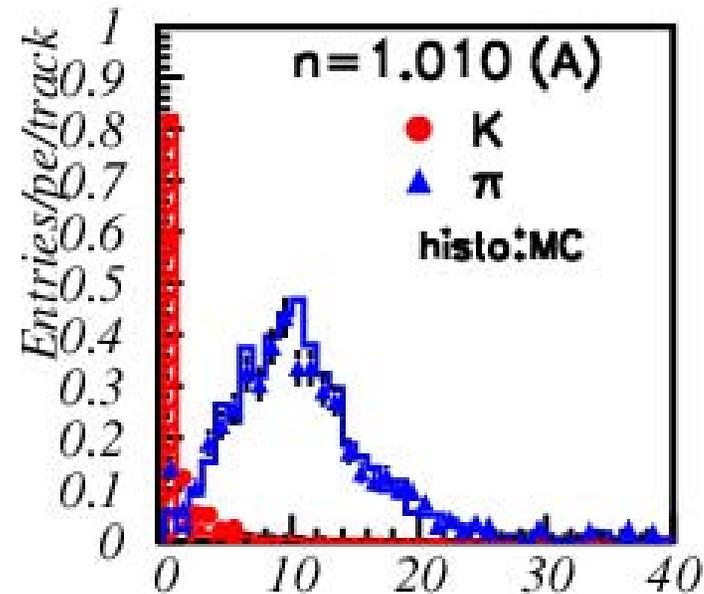
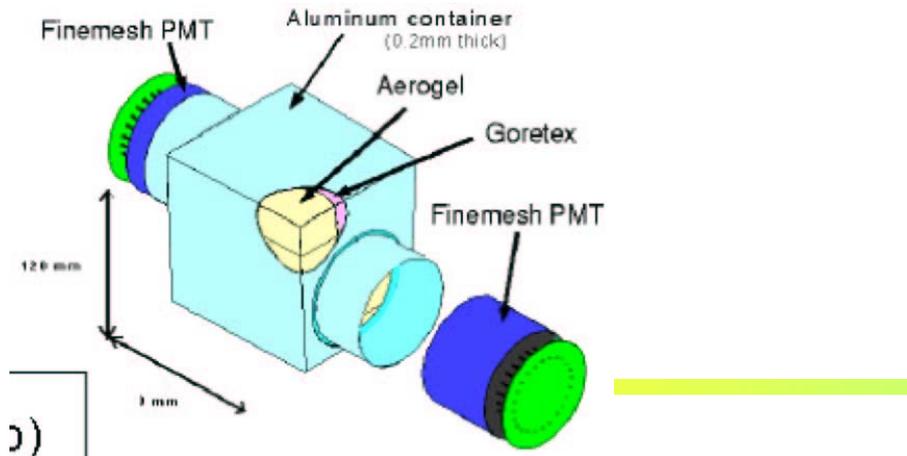


K (below thr.) vs. π (above thr.): adjust n



measured for $2 \text{ GeV} < p < 3.5 \text{ GeV}$
expected, measured ph. yield

Detector unit: a block of aerogel
and two fine-mesh PMTs

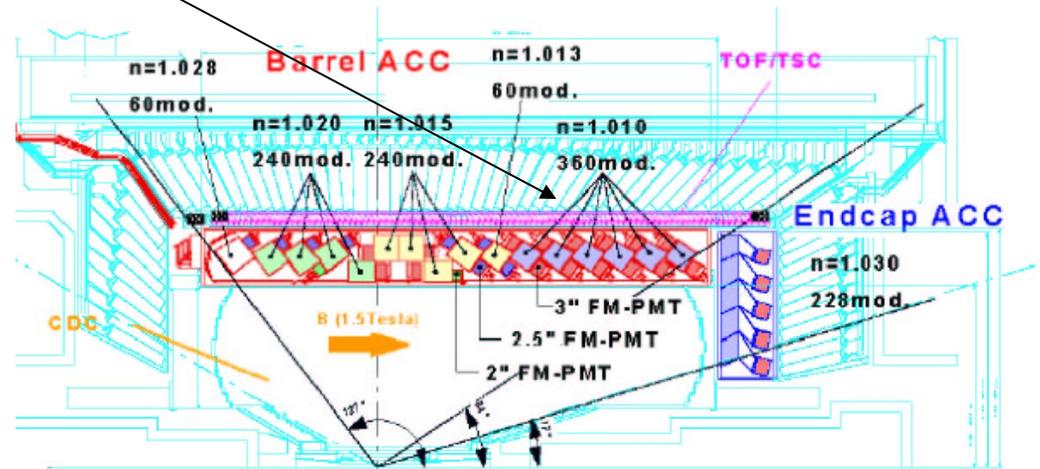
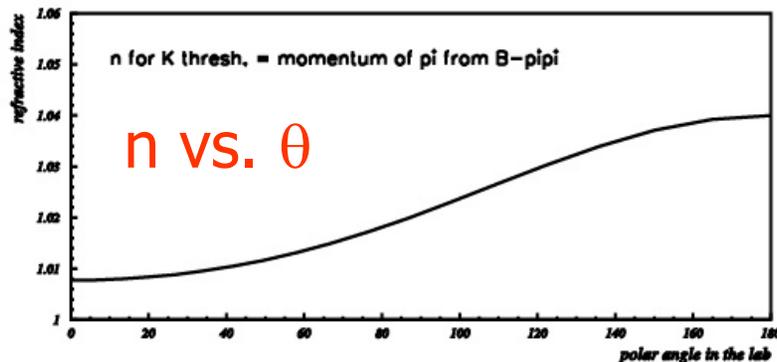
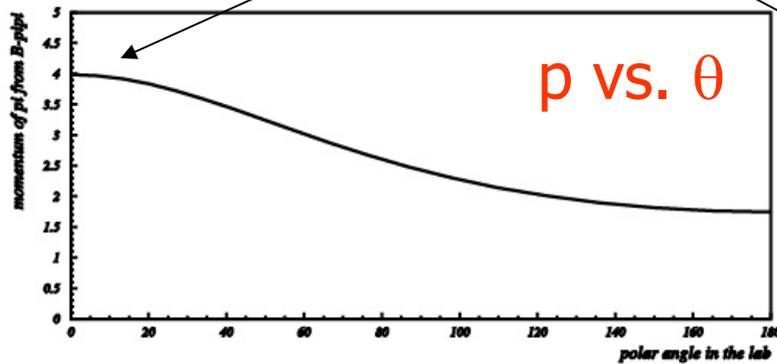




Belle ACC (aerogel Cherenkov counter): threshold Cherenkov counter

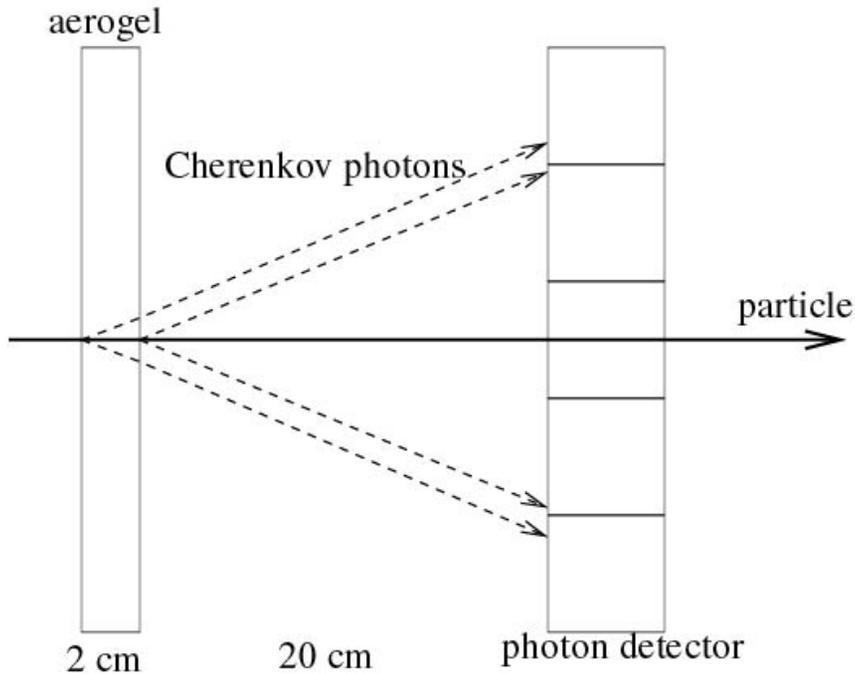


K (below thr.) vs. π (above thr.): adjust n for a given angle kinematic region (more energetic particles fly in the 'forward region')



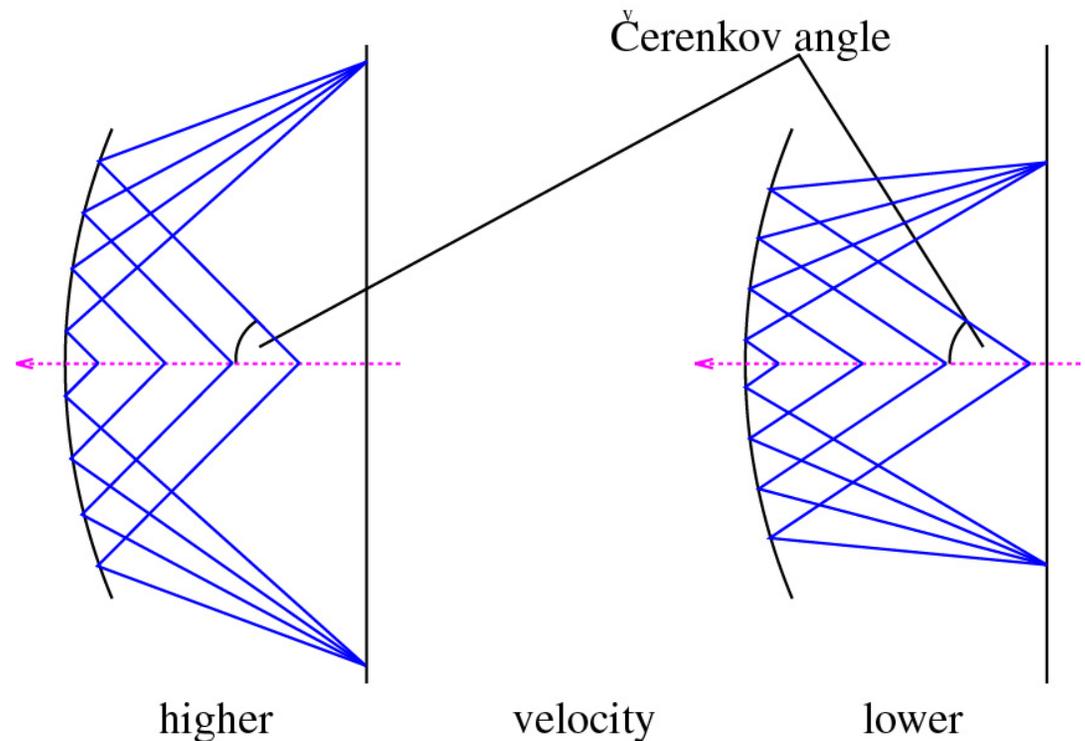


Measuring Cherenkov angle



Proximity focusing RICH

Idea: transform the **direction** into a **coordinate** →
ring on the detection plane
→ **Ring Imaging CHerenkov**

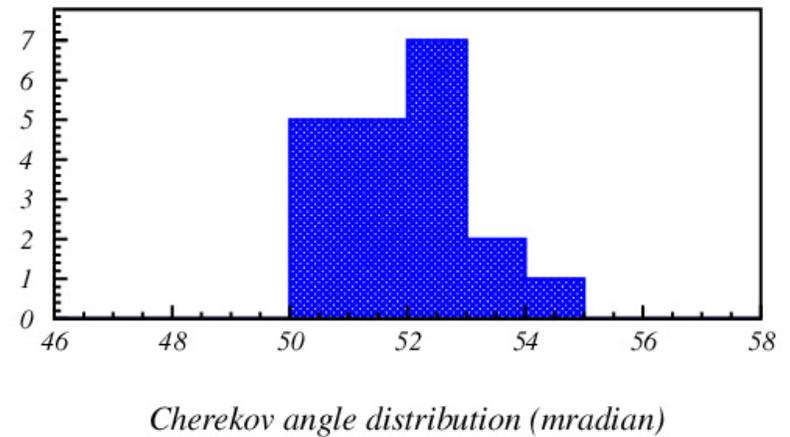
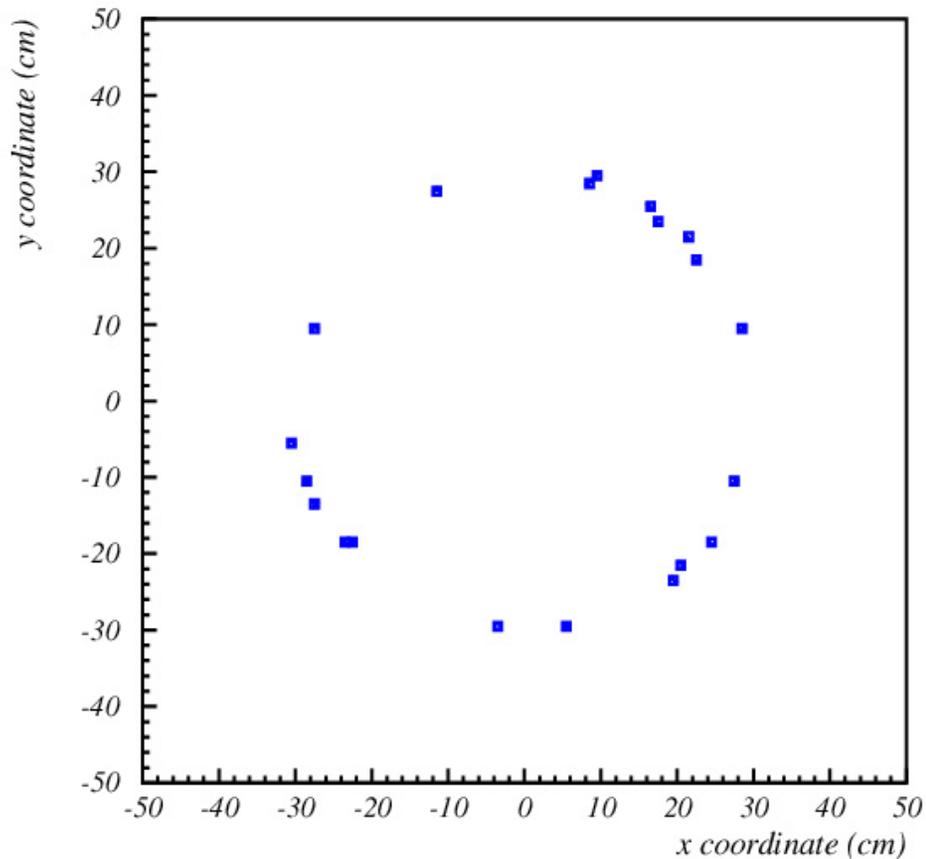


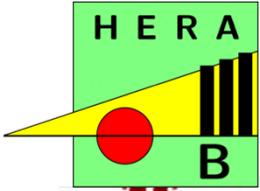
RICH with a focusing mirror



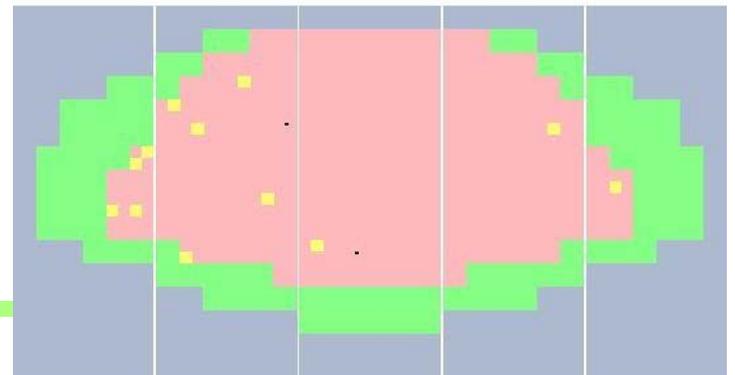
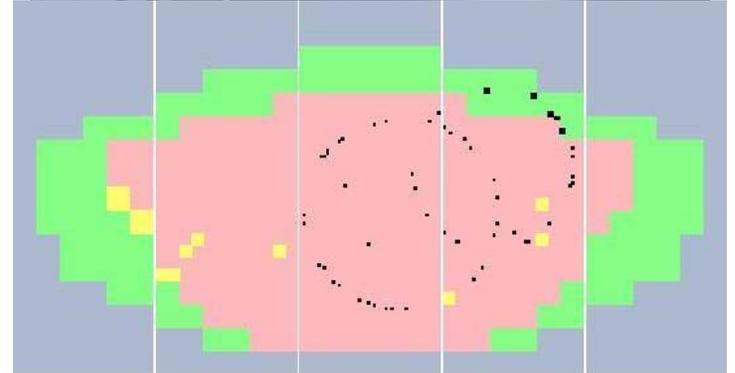
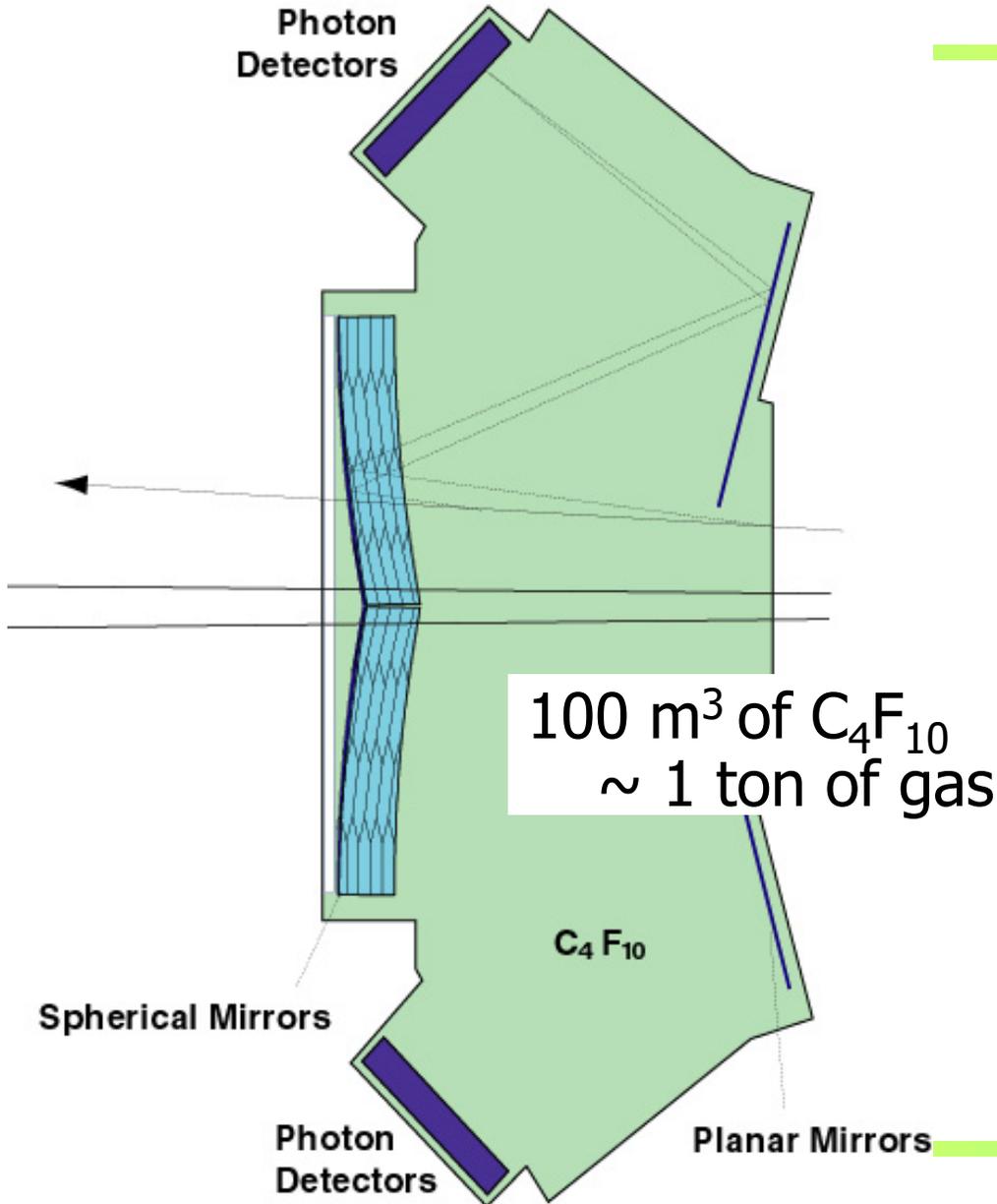
RICH counter 2

From the image on the photon detector, the Čerenkov angle of the track can be reconstructed, i.e. from the known track direction (ring center) and hit coordinate the angle is calculated and plotted for each individual photon





HERA-B RICH



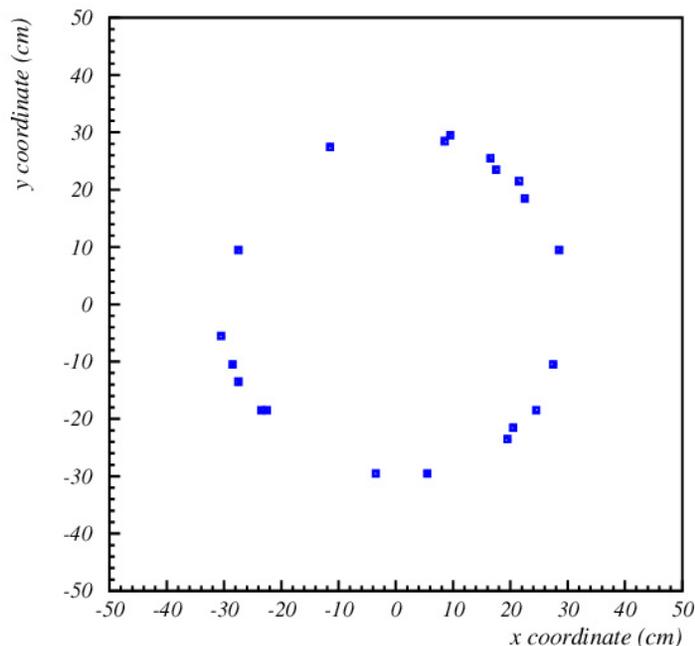


Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

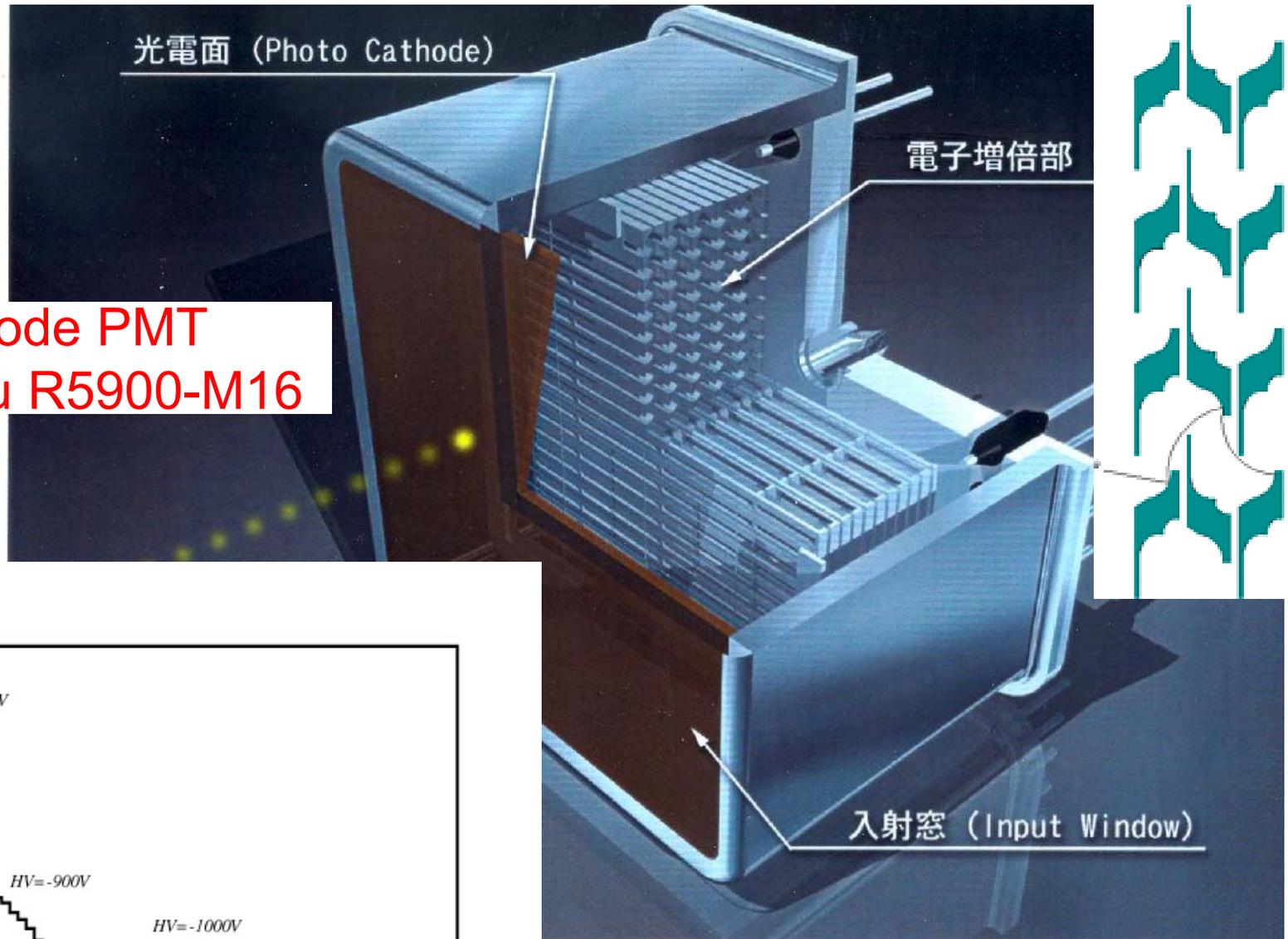
→ detection of **single** photons with

- sufficient **spatial resolution**
- **high efficiency** and **good signal-to-noise** ratio
- over a **large area** (square meters)

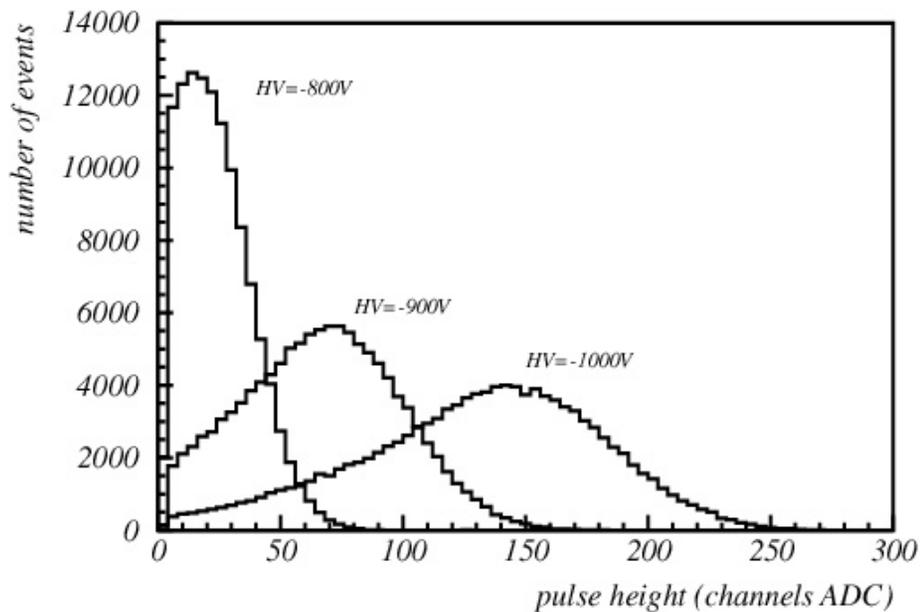


Special requirements:

- **Operation in magnetic field**
- **High rate capability**
- **Very high spatial resolution**
- **Excellent timing (time-of-arrival information)**



**Multianode PMT
Hamamatsu R5900-M16**



- Excellent single photon pulse height spectrum
- Low noise

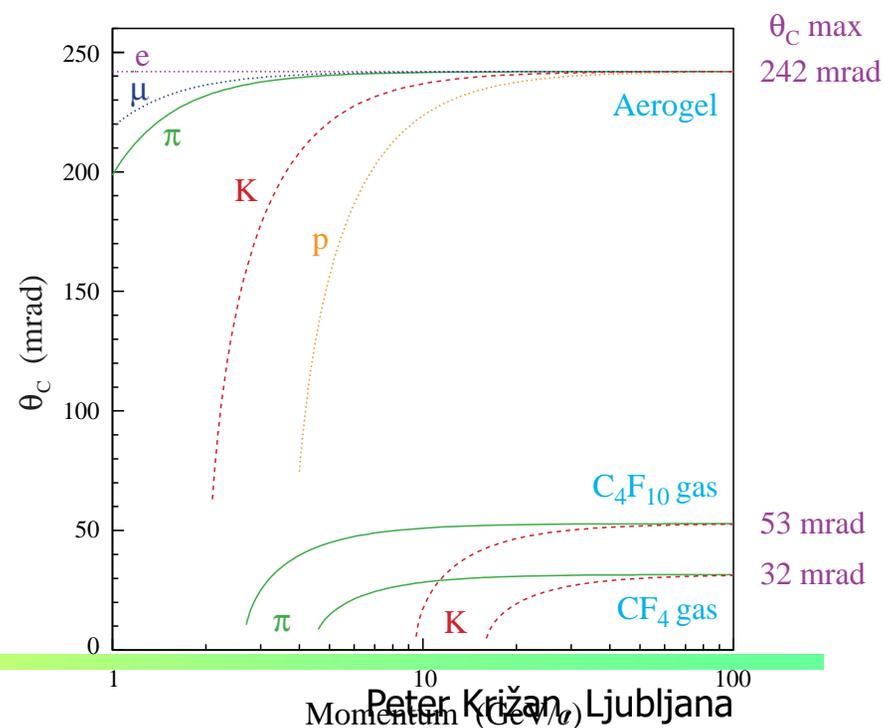


Multiple radiators: LHCb RICHes

Need:

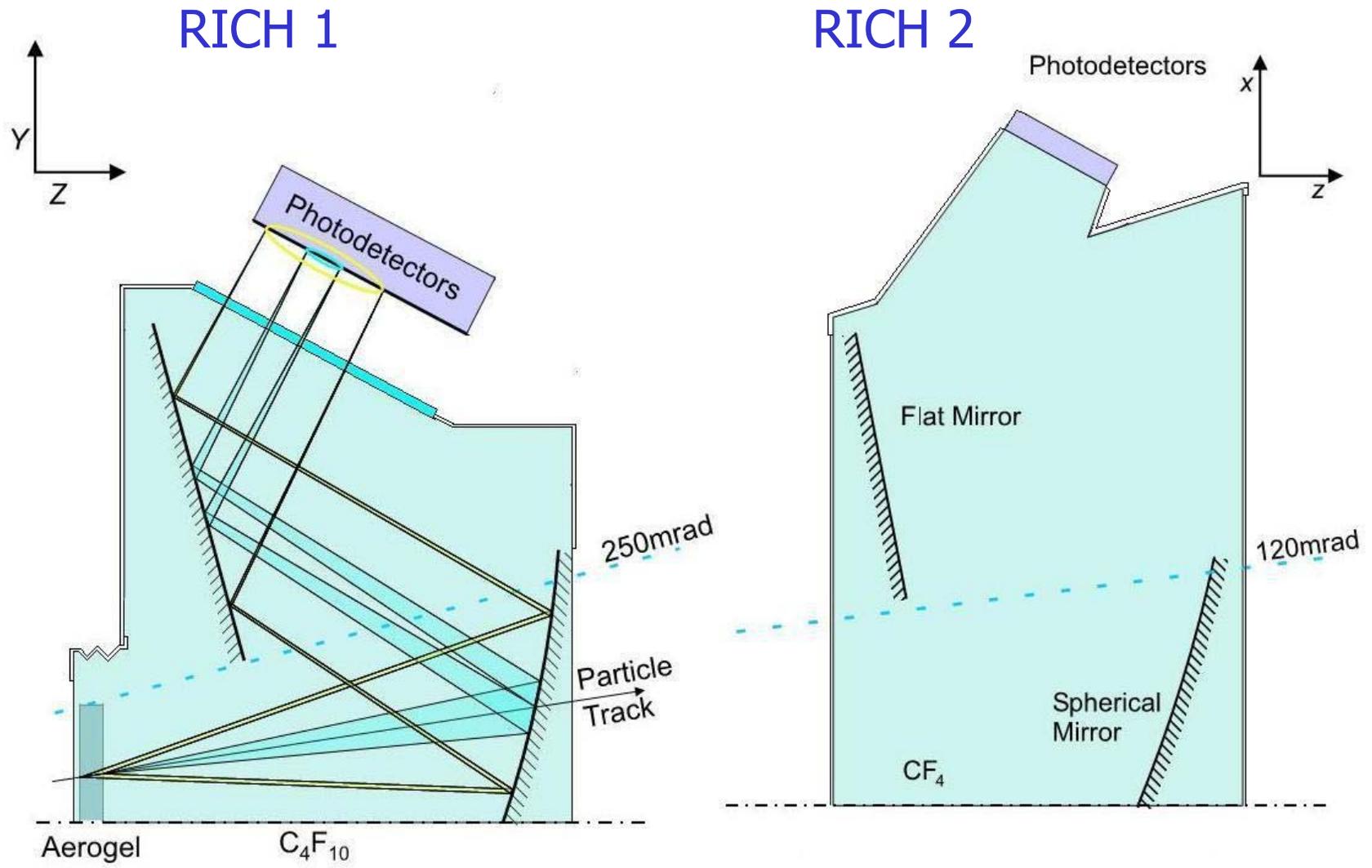
- Particle identification for momentum range $\sim 2-100$ GeV/c
- Cannot cover such a kinematic range with a single RICH

→ 3 radiators
(aerogel, CF_4 , C_4F_{10})



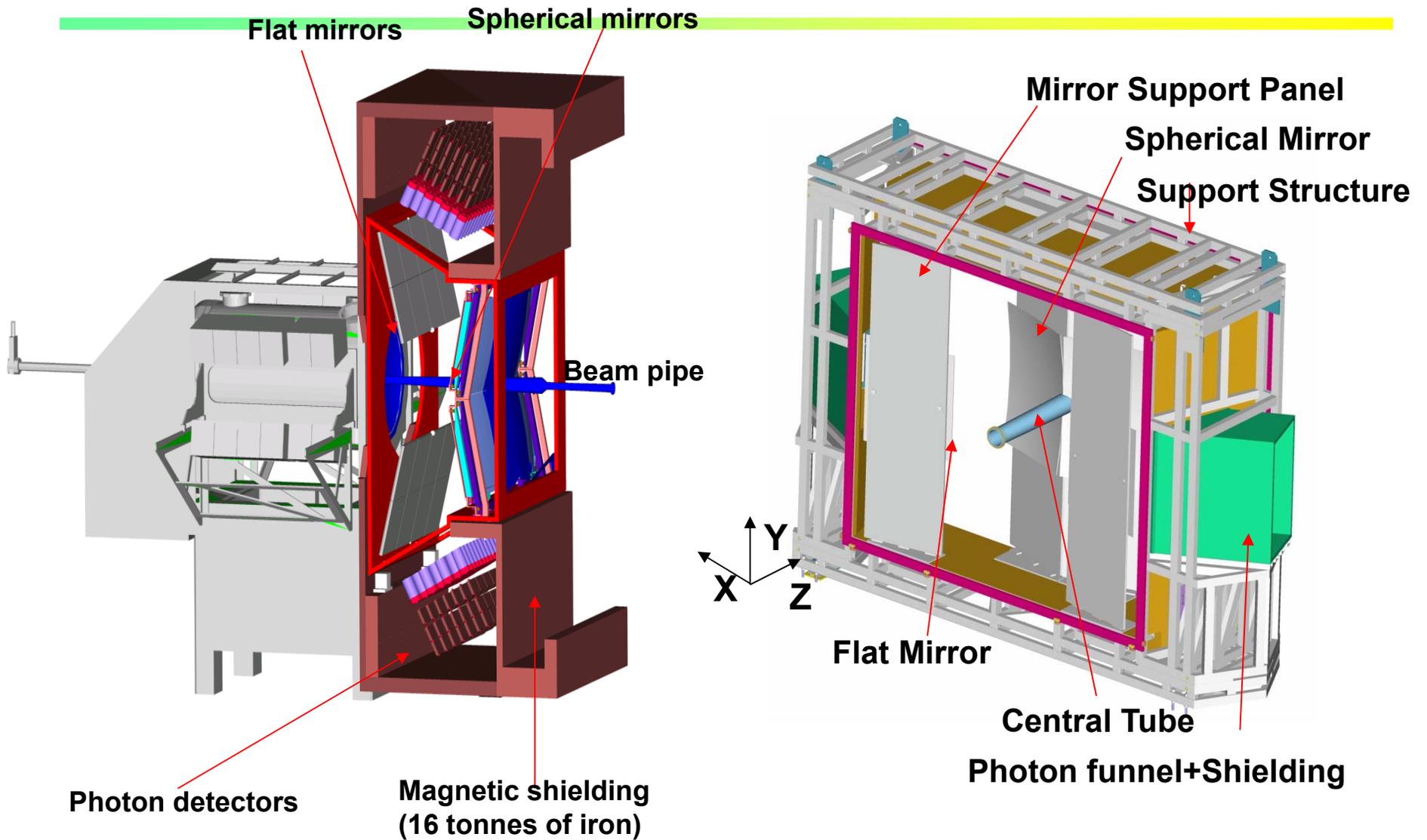


LHCb RICHes





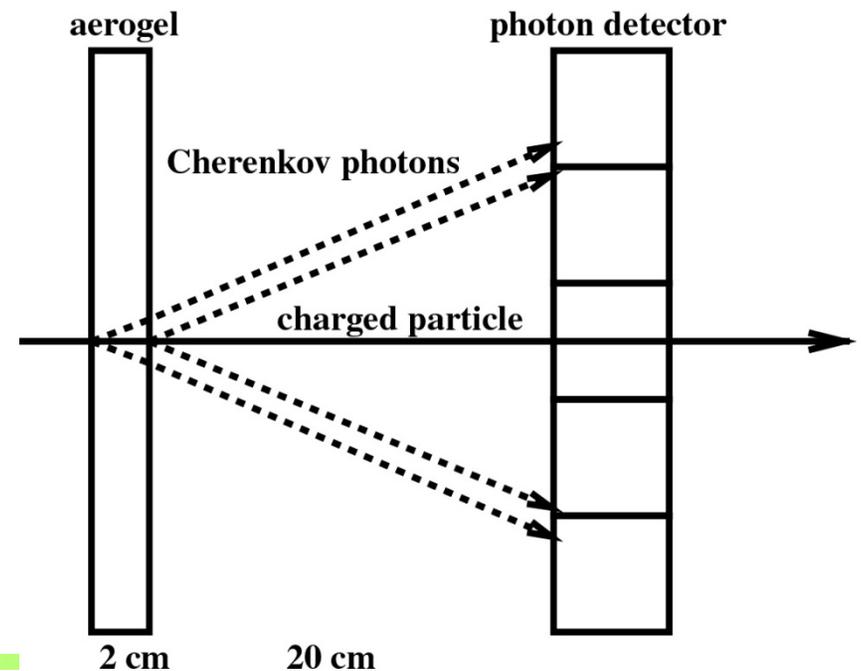
LHCb RICHes





Resolution of a RICH counter

- Photon impact point resolution (photon detector resolution)
- Emission point uncertainty
- Dispersion: $n=n(\lambda)$ in $\cos\theta = 1/\beta n$
- Track parameters
- Errors of the optical system



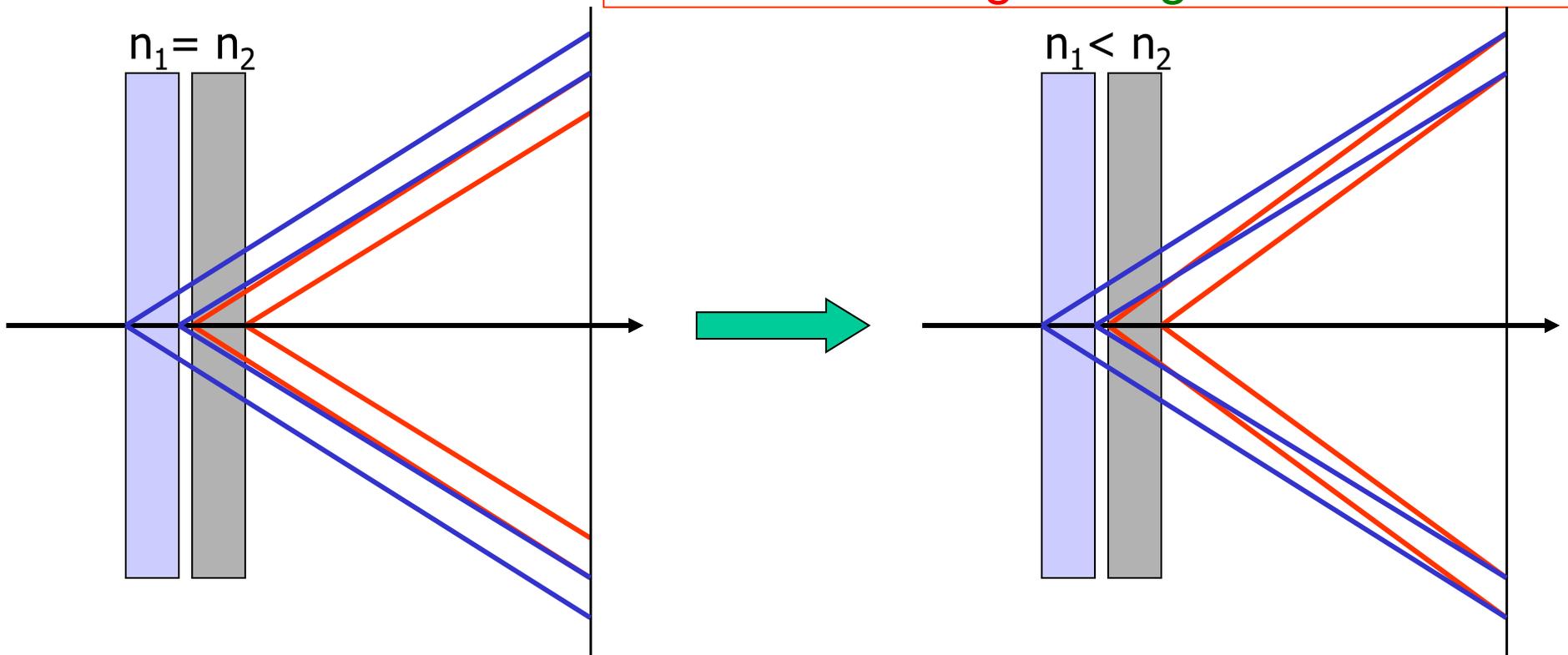
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Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal



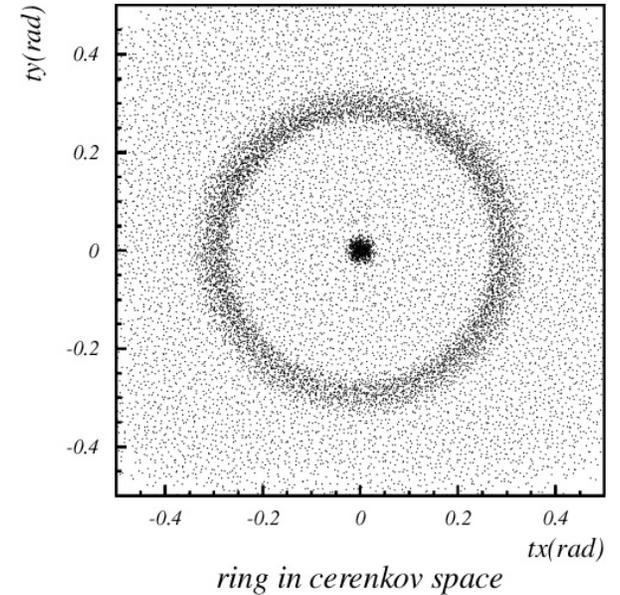
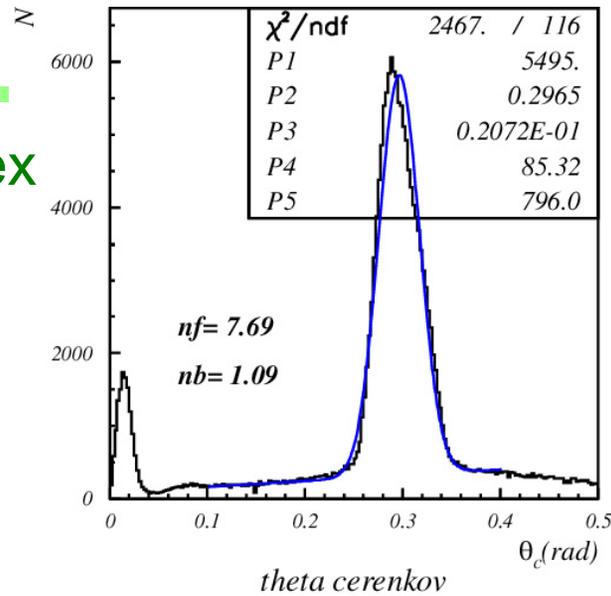
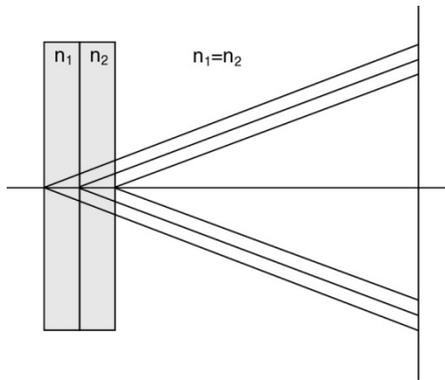
→ stack two tiles with different refractive indices: “focusing” configuration

→ focusing radiator

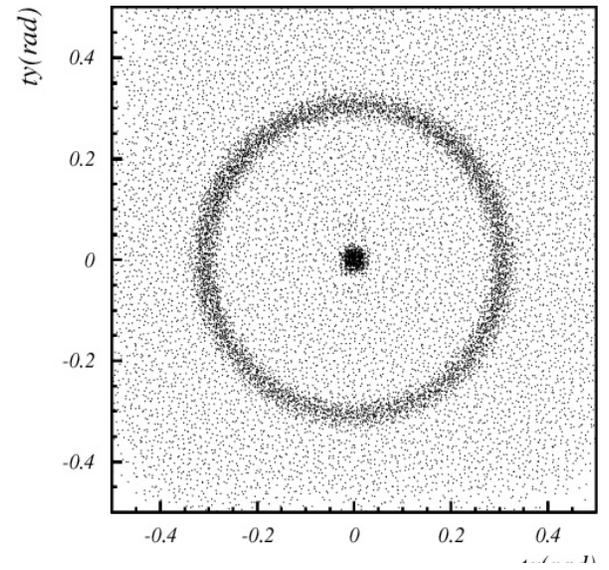
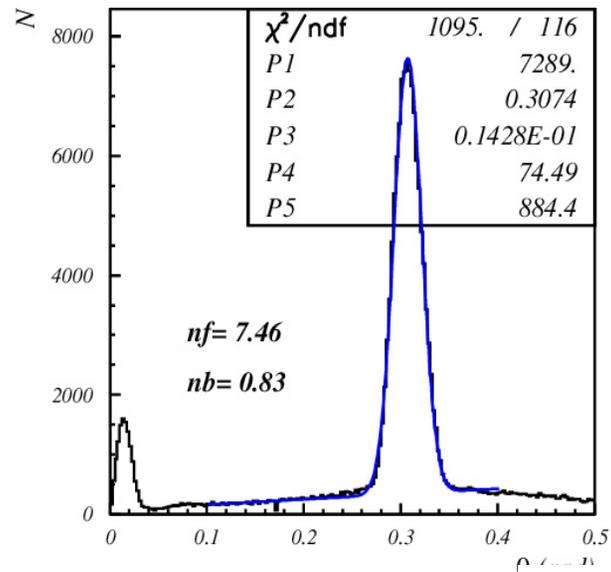
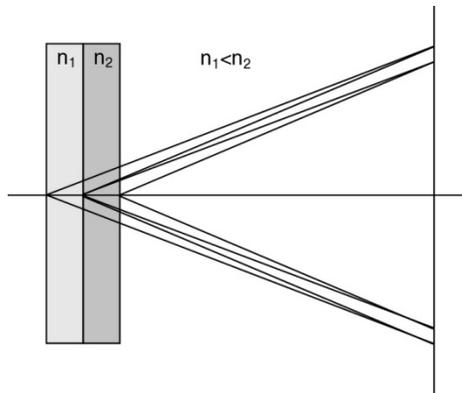


Focusing configuration – data

4cm aerogel single index



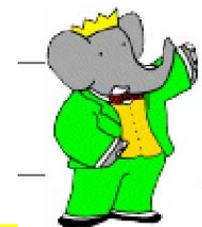
2+2cm aerogel



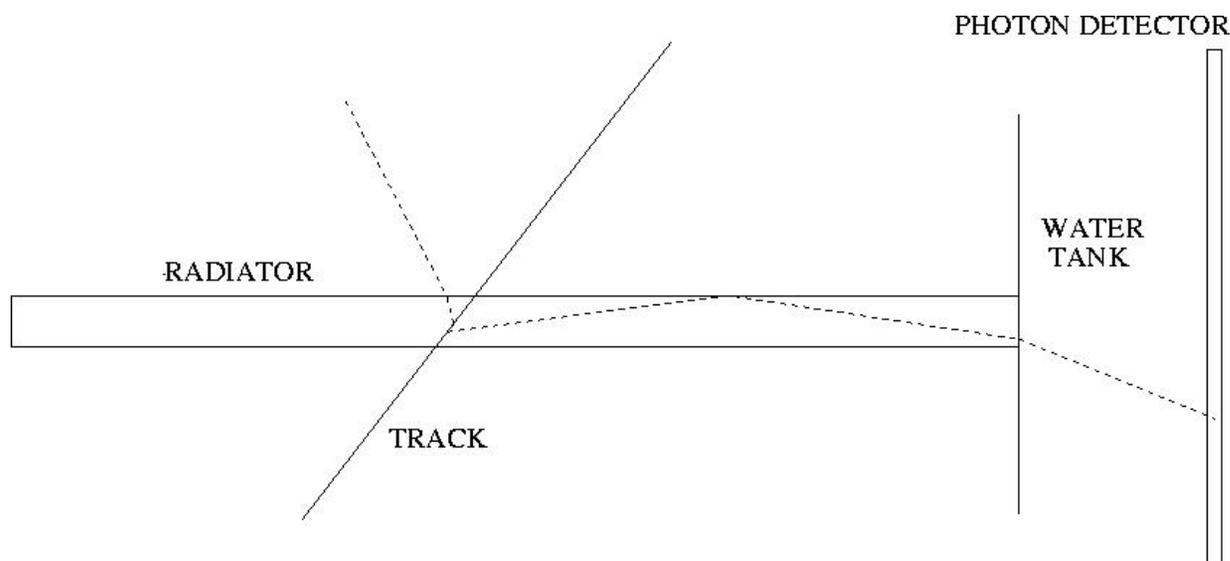
→ NIM A548 (2005) 383



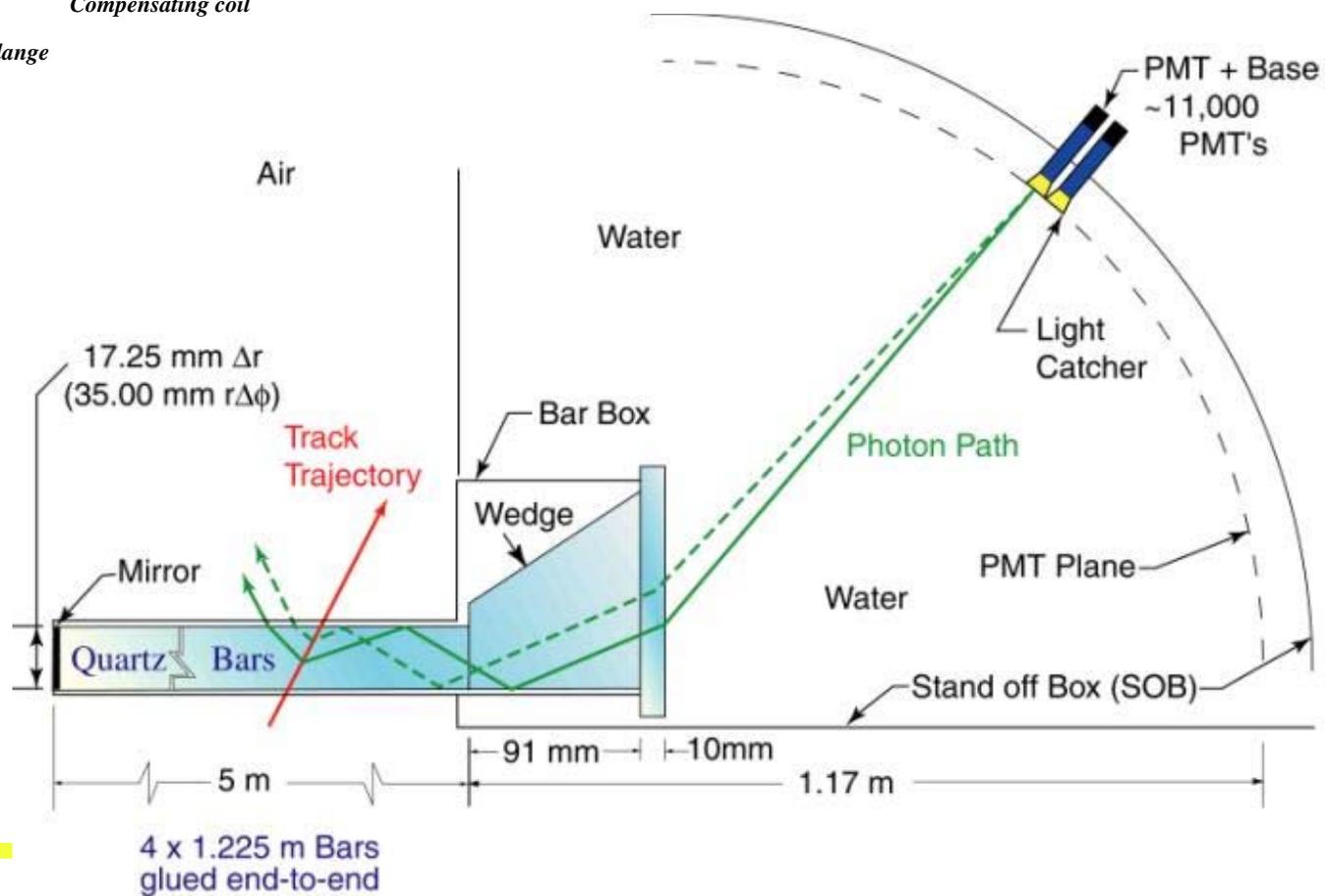
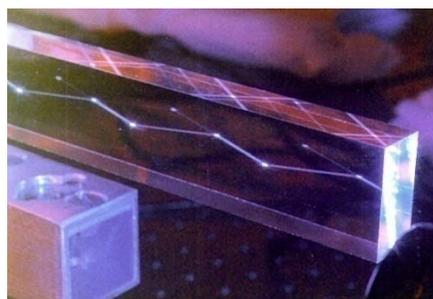
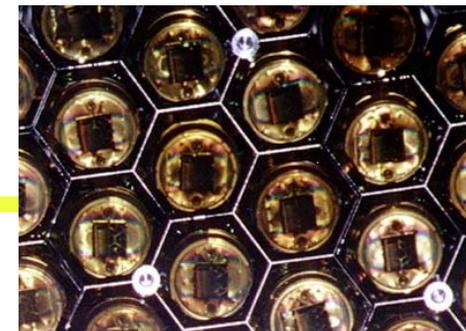
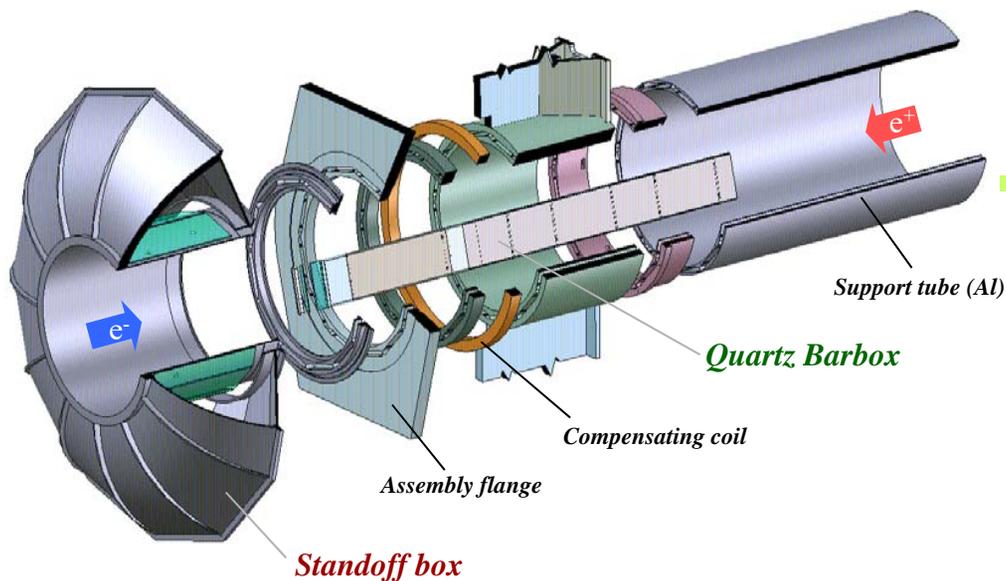
DIRC: Detector of Internally Reflected Cherenkov photons



DIRC: a special kind of RICH (Ring Imaging Cherenkov counter) where Čerenkov photons trapped in a solid radiator (e.g. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.



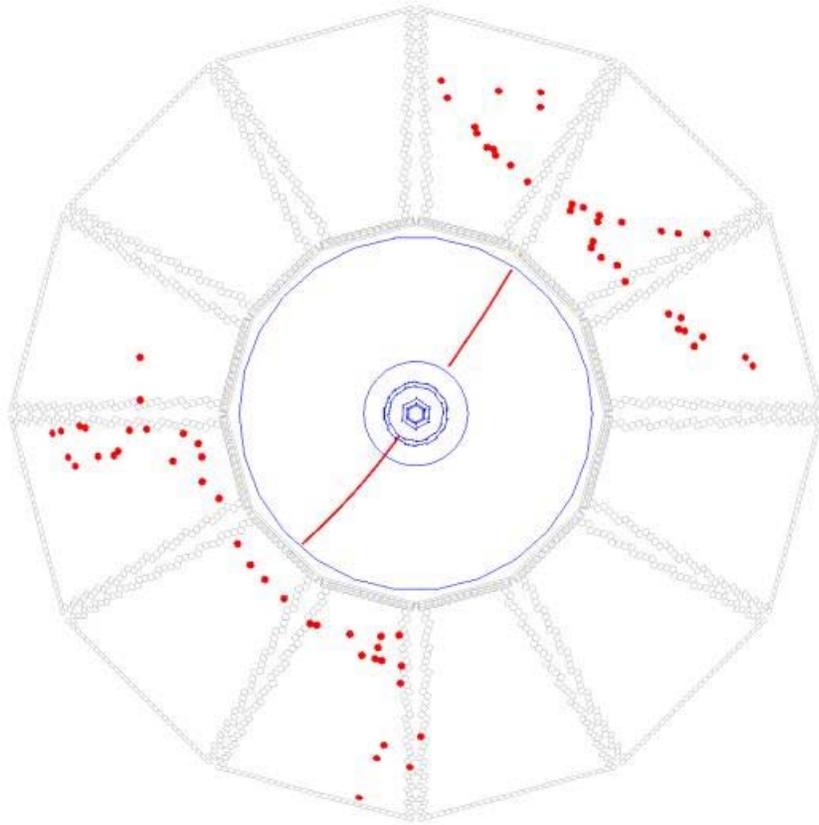
DIRC



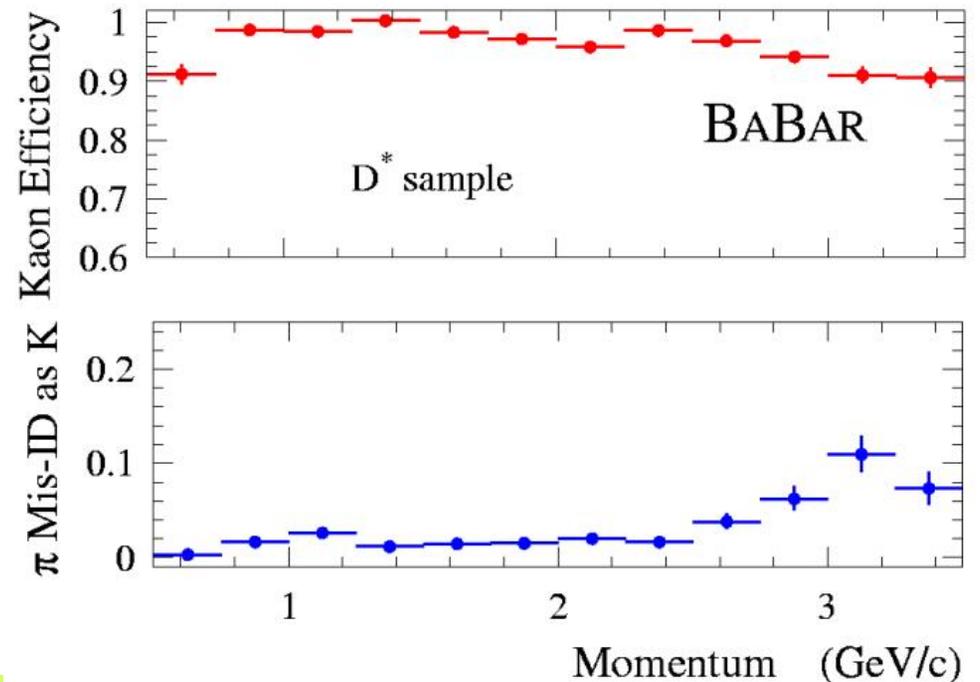


DIRC performance

Babar DIRC: a Bhabha event $e^+ e^- \rightarrow e^+ e^-$

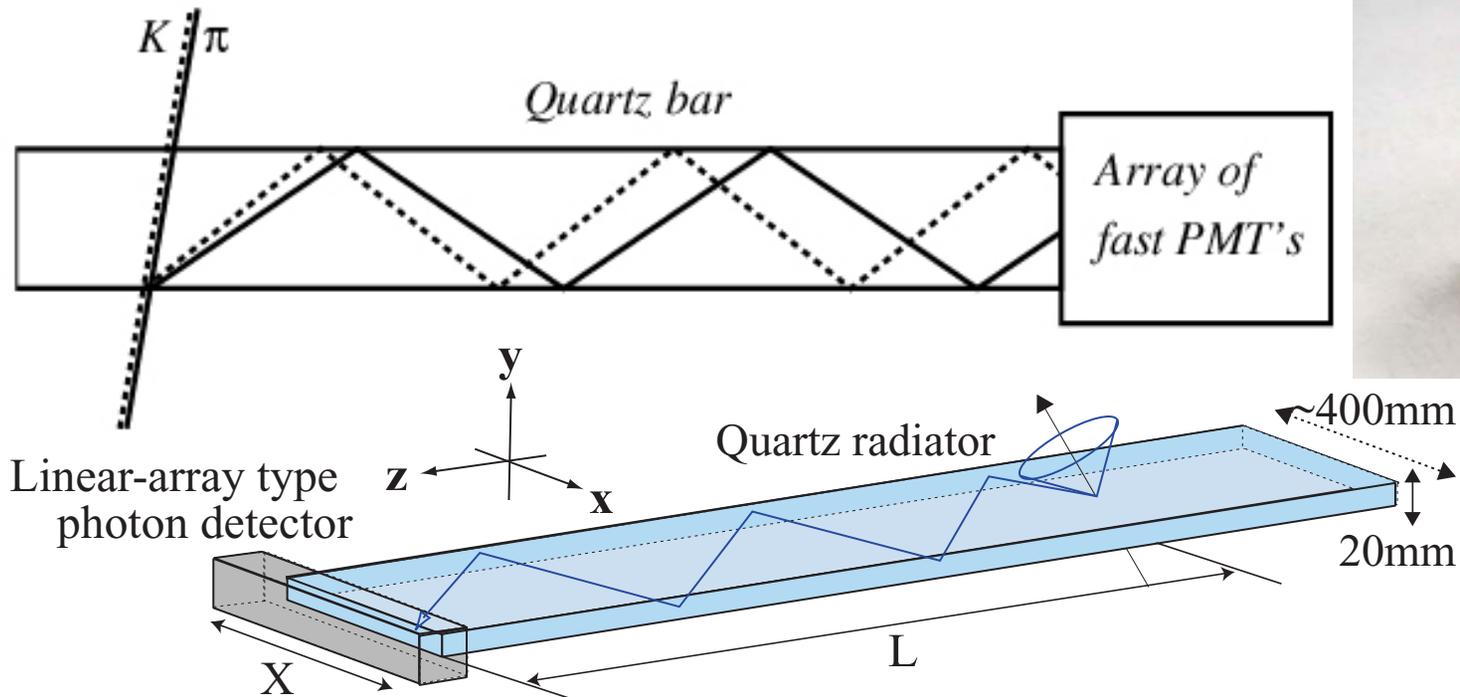


To check the performance, use kinematically selected decays: $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+$





Time-Of-Propagation (TOP) counter



Similar to DIRC, but instead of two coordinates measure:

- One (or two coordinates) with a few mm precision

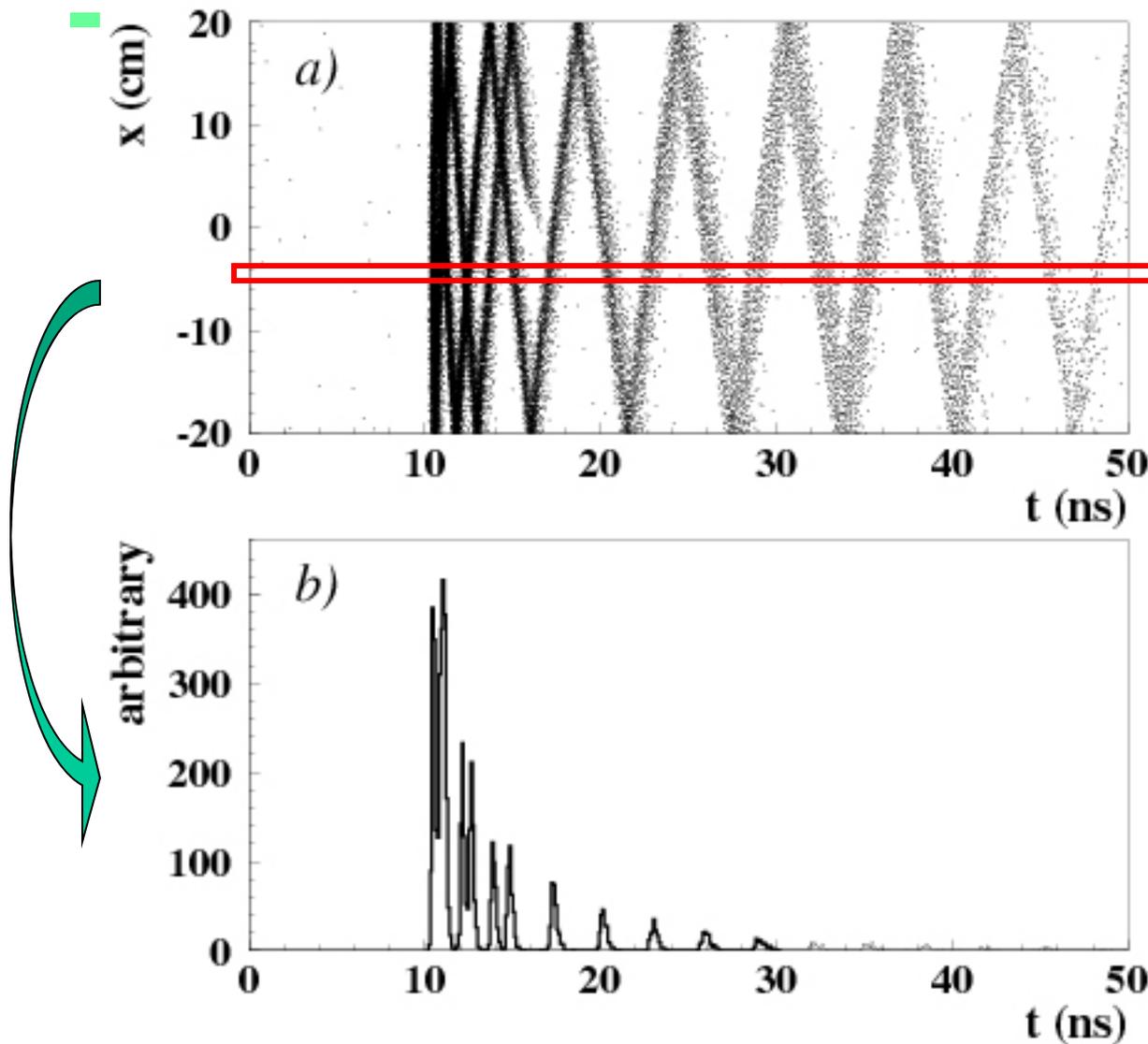
- **Time-of-arrival**

- Excellent time resolution $< \sim 40\text{ps}$

- required for single photons in 1.5T B field



TOP image



Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~ 80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K



Transition radiation detectors

X rays emitted at the boundary of two media with different refractive indices, emission angle $\sim 1/\gamma$

Emission rate depends on γ (Lorentz factor): becomes important at $\gamma \sim 1000$

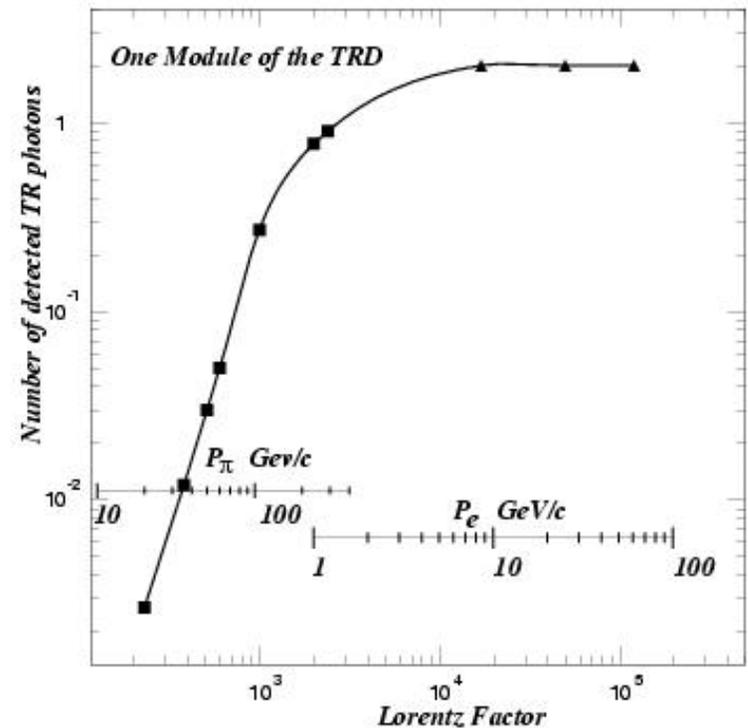
- Electrons at 0.5 GeV
- Pions, muons above 100 GeV

In between: discrimination e vs pions, mions

Detection of X rays: high Z gas – Xe

Few photons per boundary can be detected
Need many boundaries

- Stacks of thin foils or
- Porous materials – foam with many boundaries of individual 'bubbles'



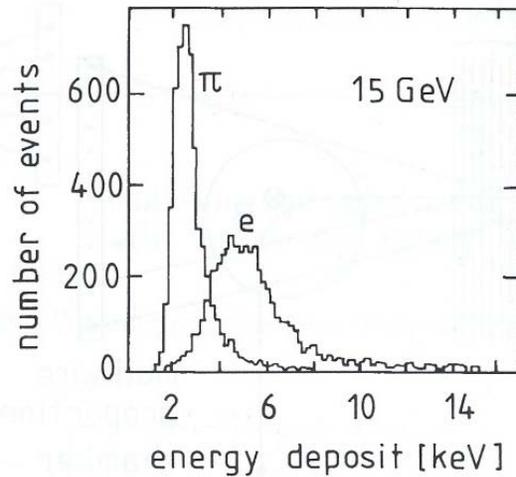


Fig. 6.25. Energy-loss distribution of 15 GeV electrons and pions in a transition radiation detector [467].

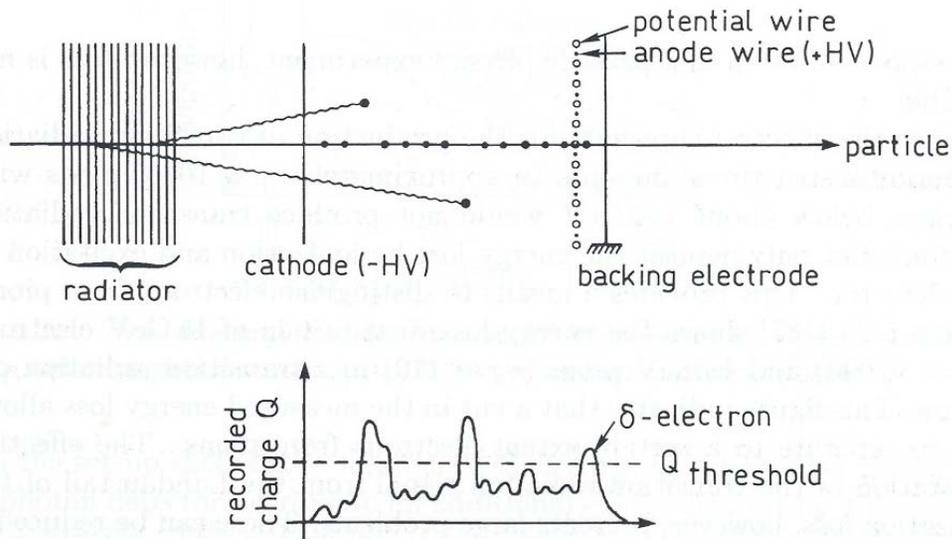
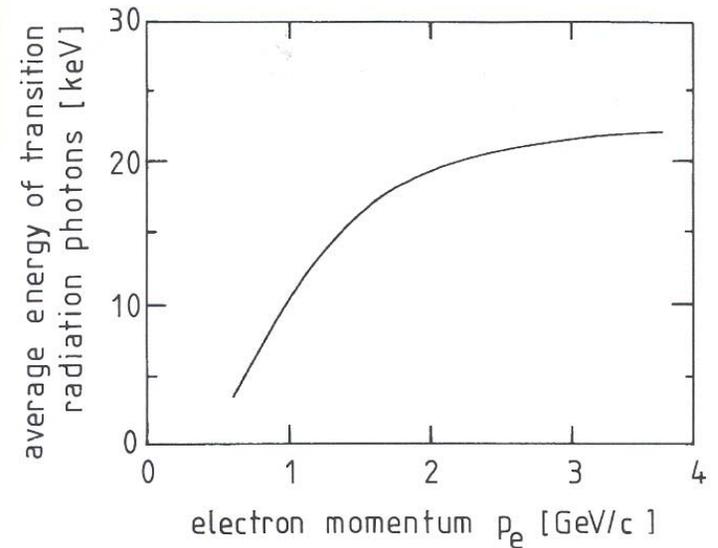


Fig. 6.26. Principle of separating ionization energy loss from the energy loss from emission of transition radiation photons.

Transition radiation - 1

Separation of X ray detection –
high energy deposit on one
place – against ionisation
losses

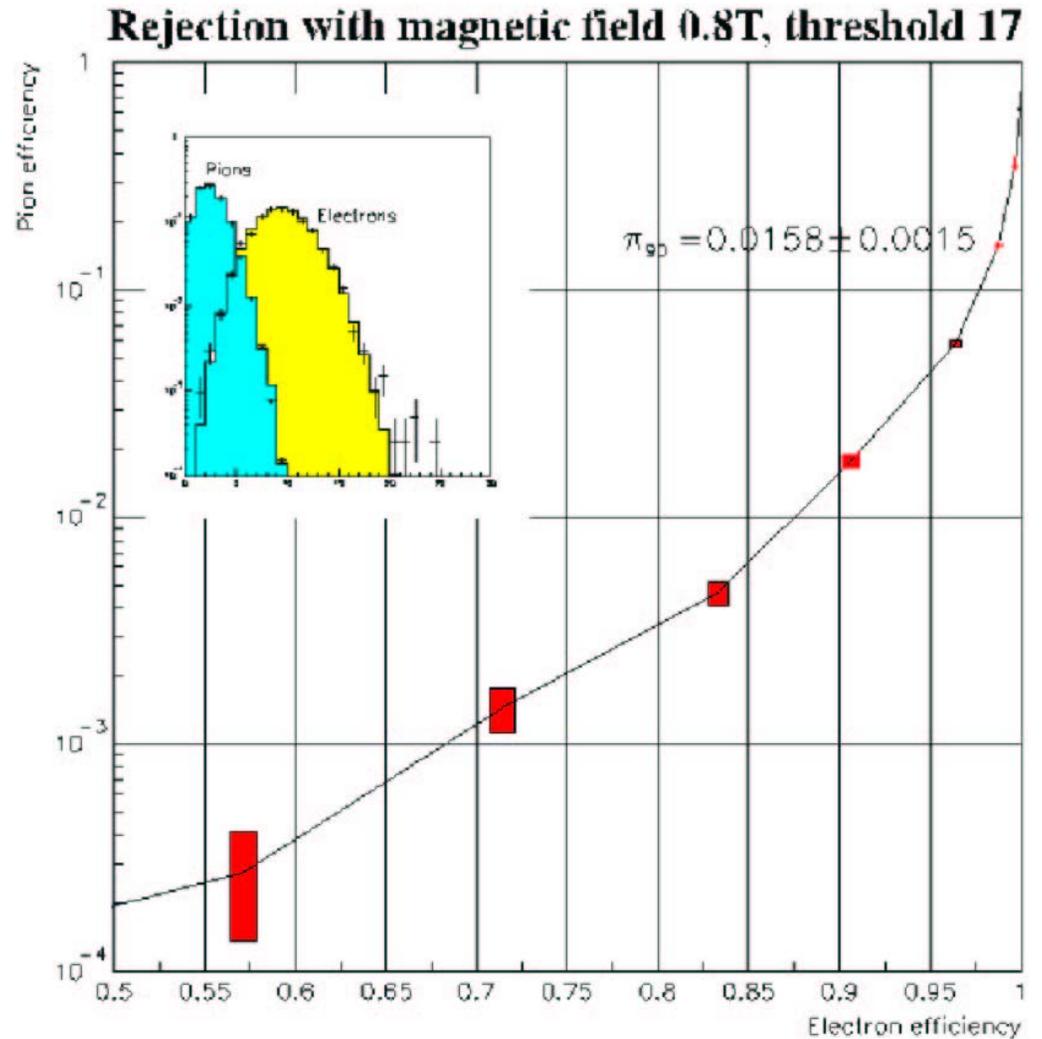
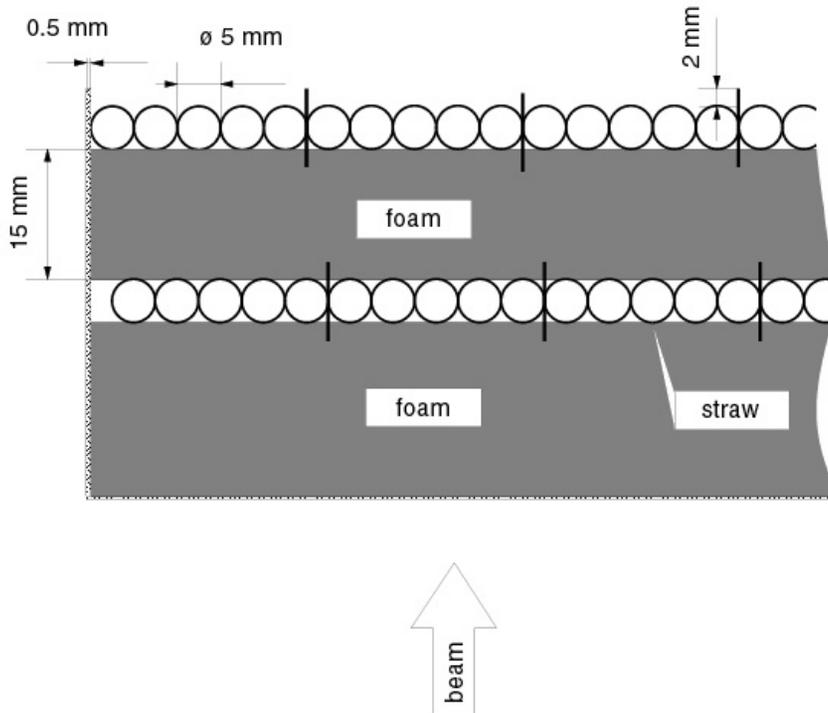




Transition radiation - 3

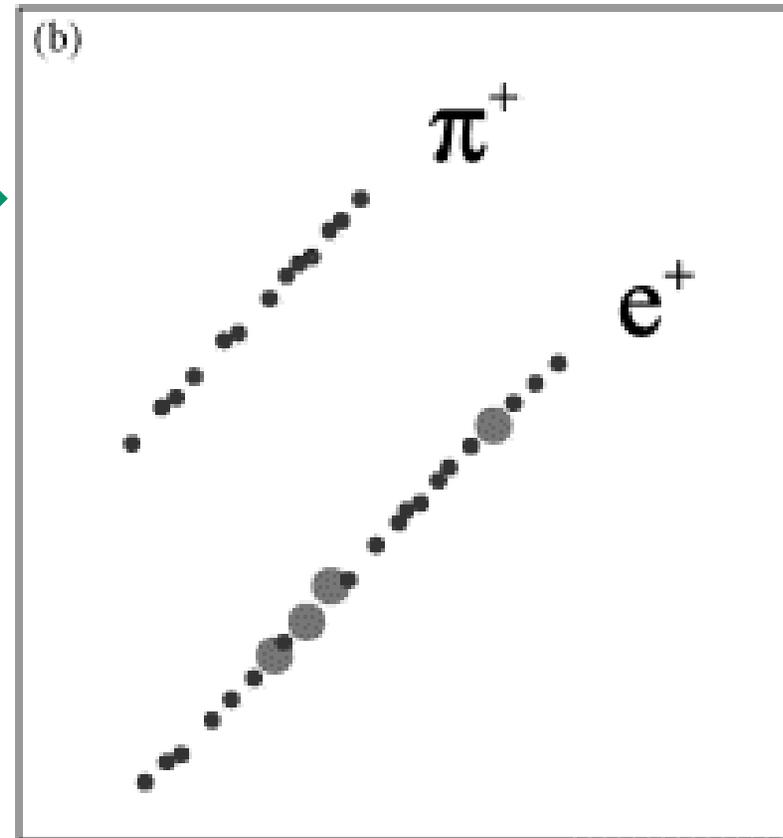
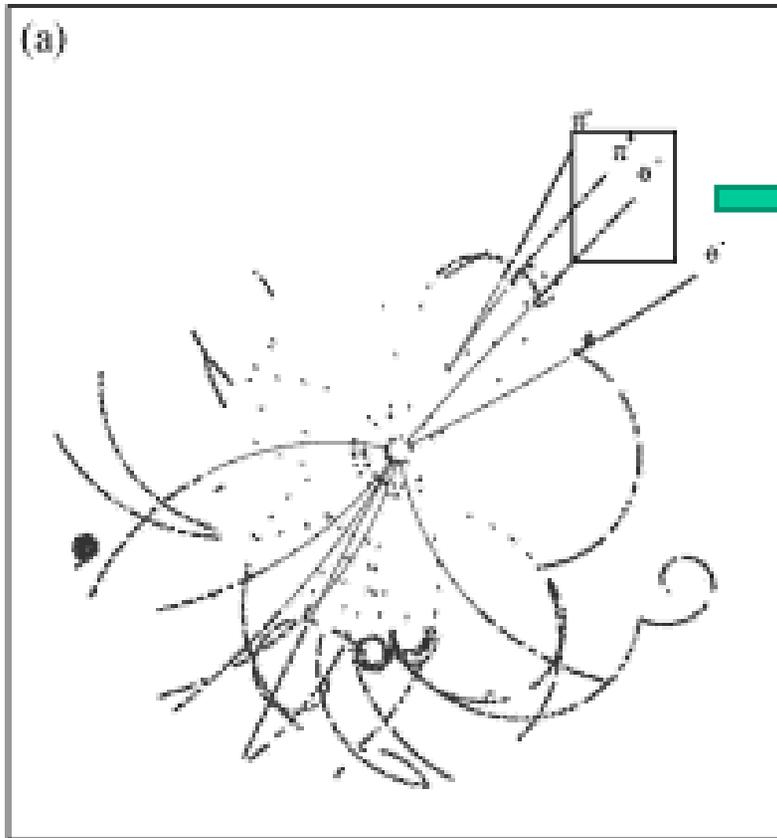
Example of performance 2

Radiator: organic foam
between the detector tubes
(straws made of capton foil)





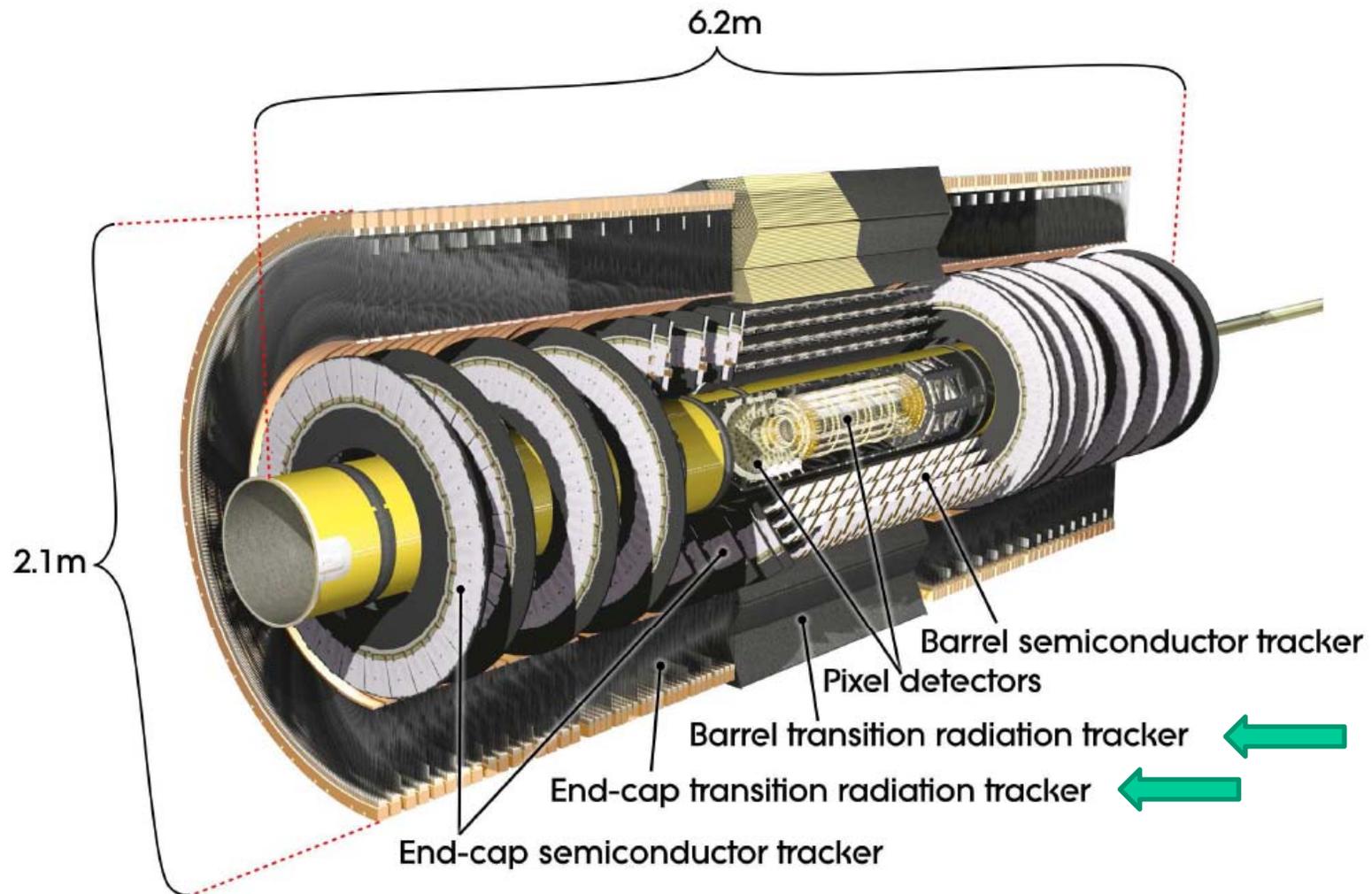
TRT: pion-electron separation

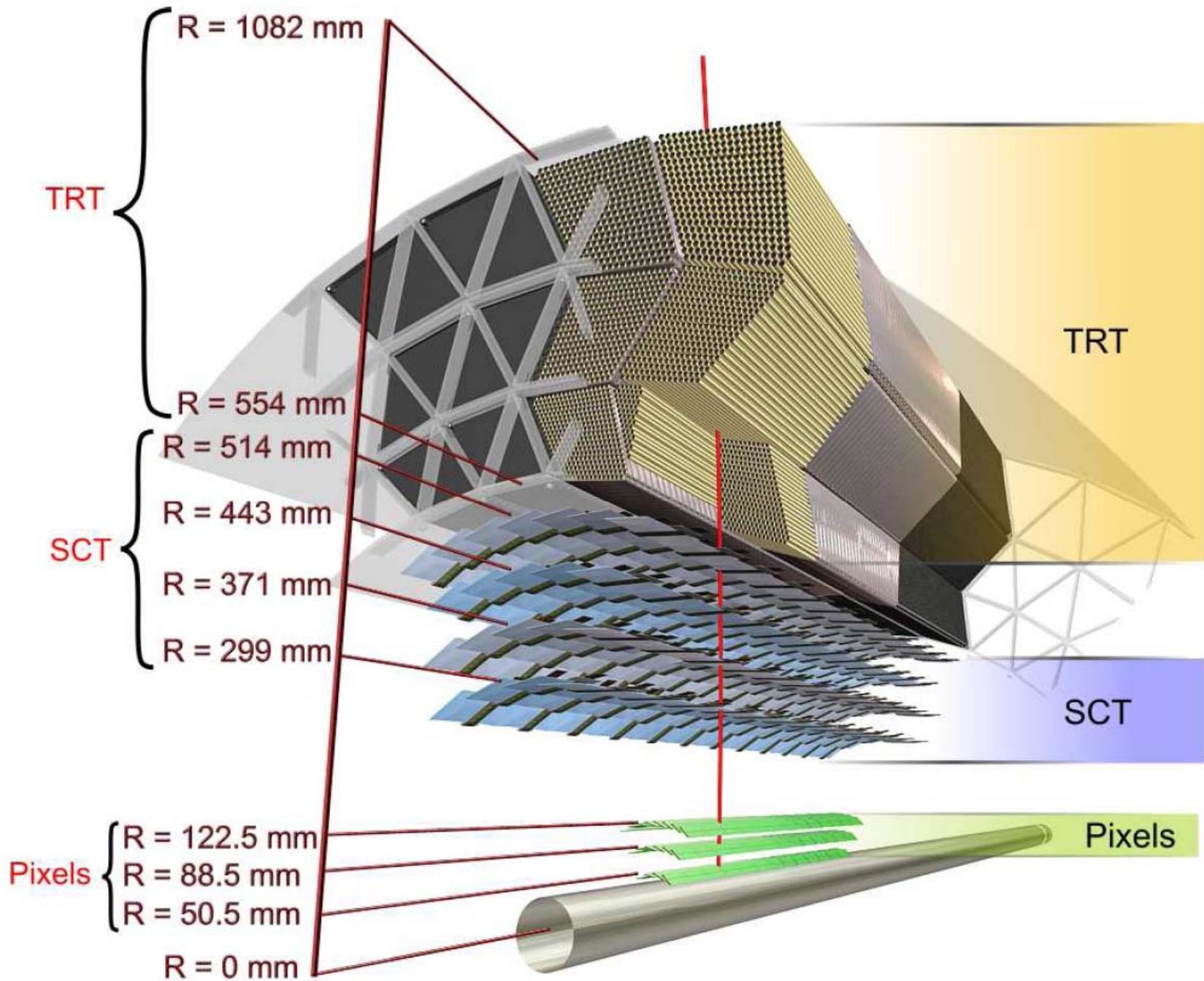


Small circles: low threshold (ionisation), big circles: high threshold (X ray detection)



Transition radiation detector in ATLAS: combination of a tracker and a transition radiation detector



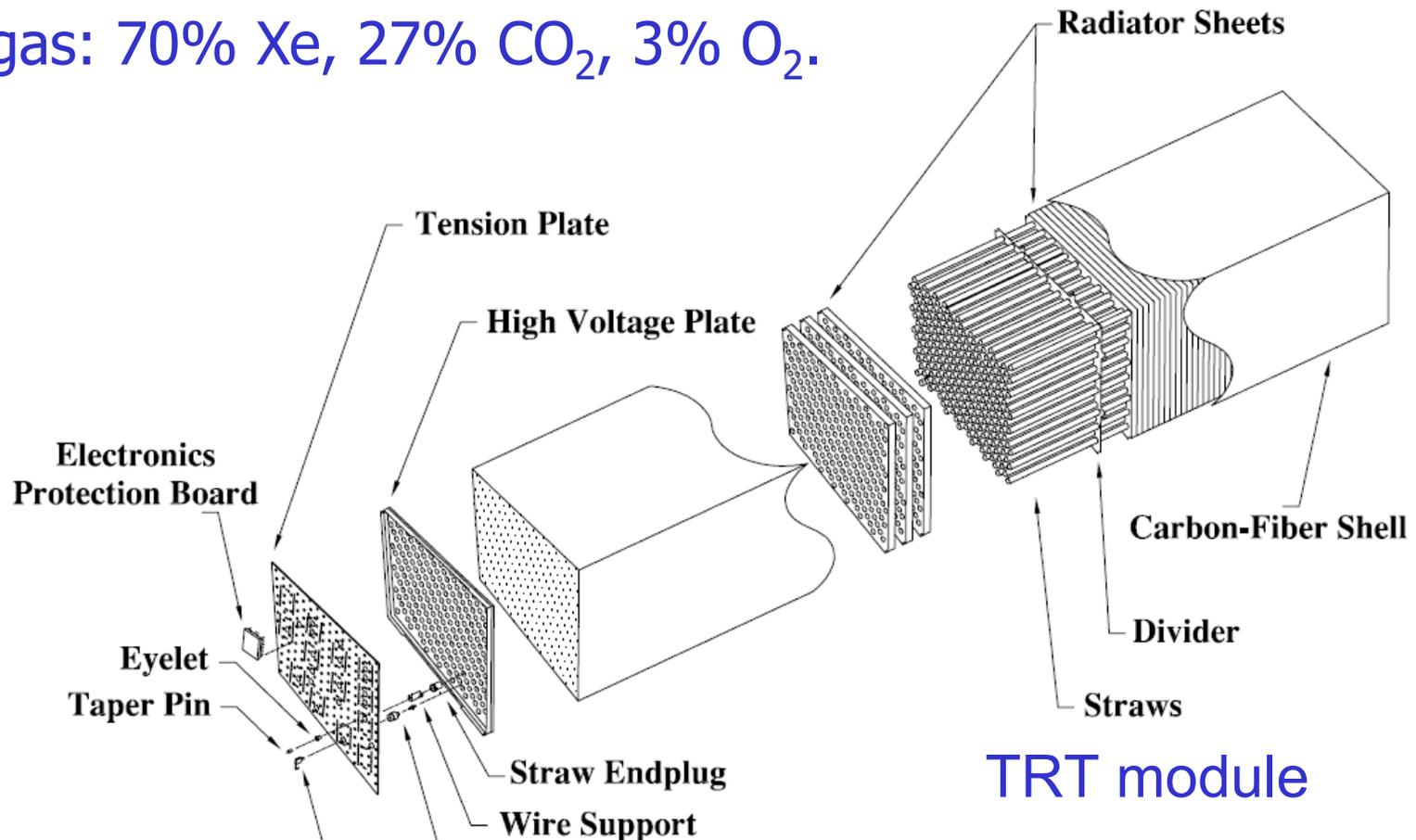




ATLAS TRT: combination of Transition Radiation detector and a Tracker

Radiator: 3mm thick layers made of polypropylene-polyethylene fibers with ~ 19 micron diameter, density: 0.06 g/cm^3

Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO₂, 3% O₂.



Particle identification: Comparison of methods

- Time-of-flight
- dE/dx measurement
- Čerenkov counters
- Transition radiation counters

Compare by calculating the length of detector needed for a given separation (3σ)

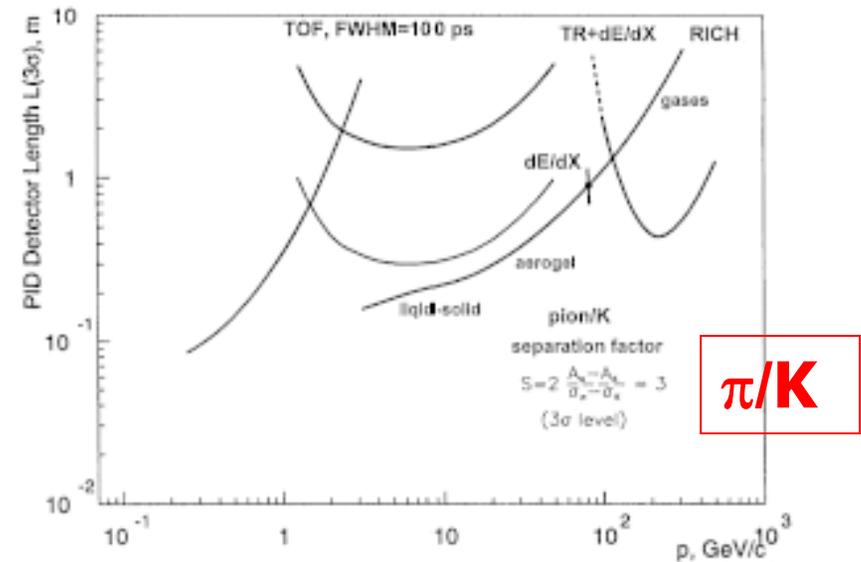


Fig. 14. Pion-kaon separation by different PID methods: the length of the detectors needed for 3 sigma separation.

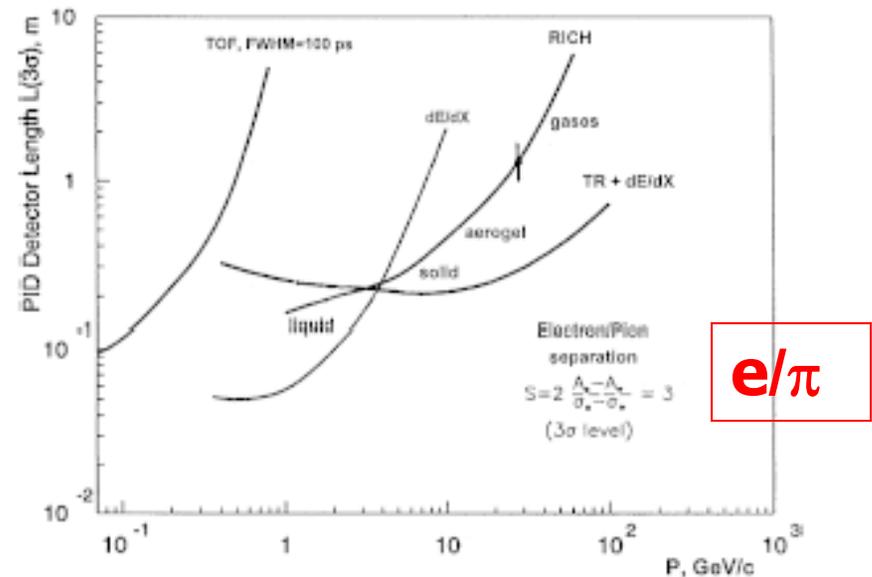
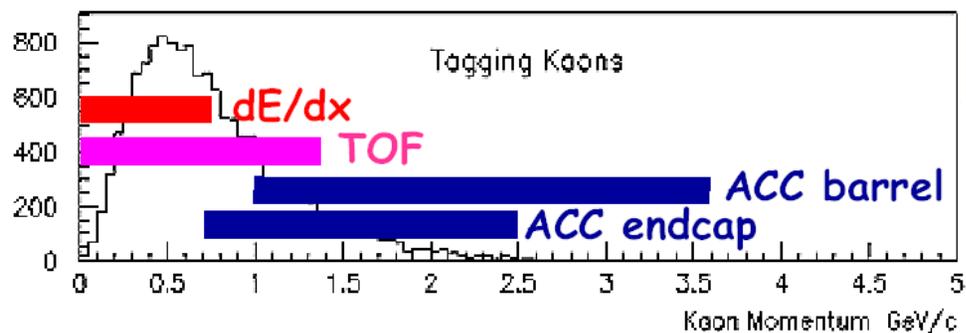


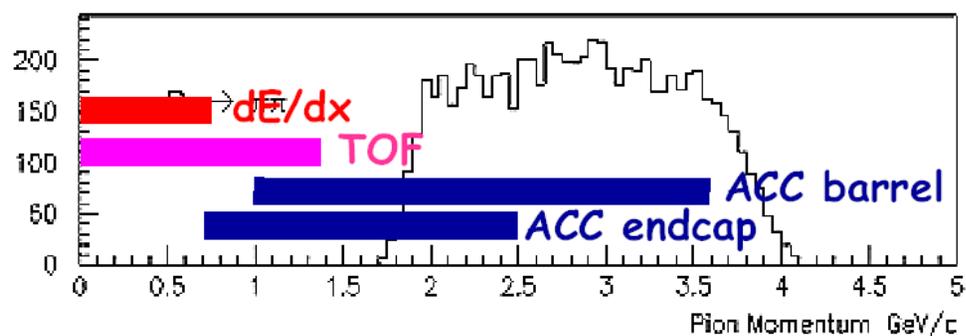
Fig. 15. The same as Fig. 14 for electron-pion separation.



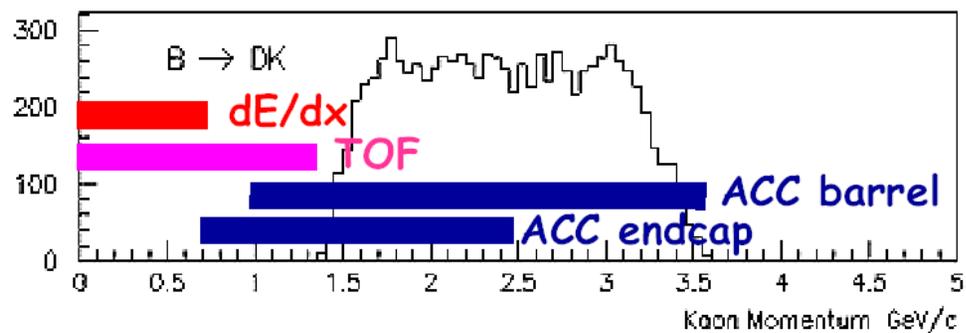
PID coverage of kaon/pion spectra



Tagging Kaons



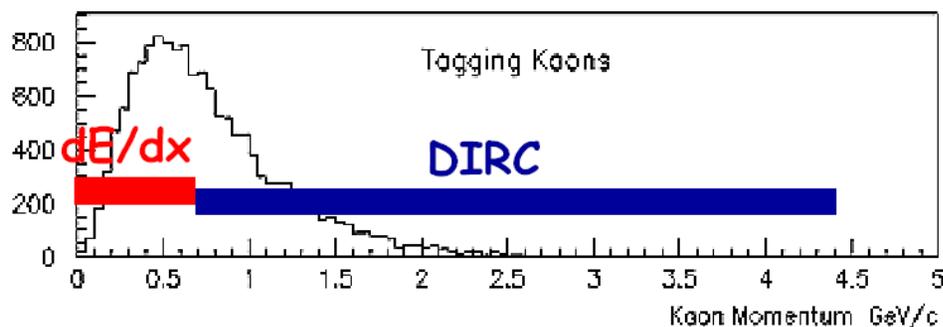
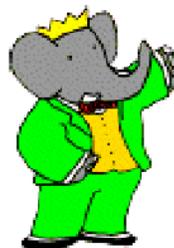
$B \rightarrow \pi\pi$



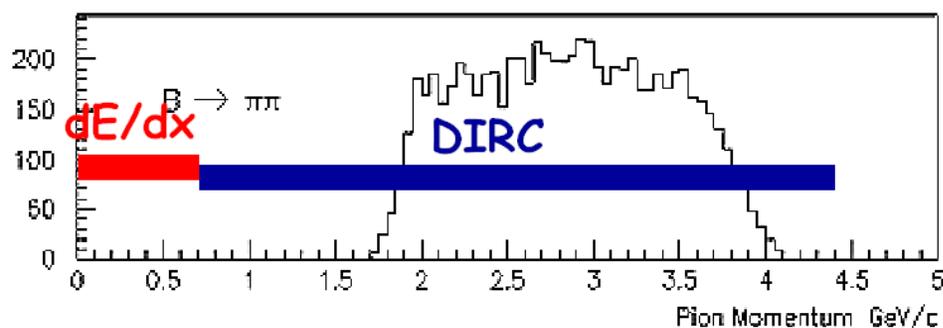
$B \rightarrow DK$



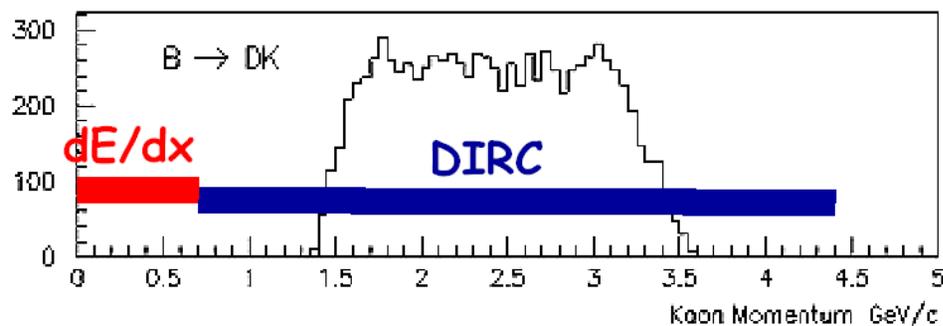
PID coverage of kaon/pion spectra



Tagging Kaons



$B \rightarrow \pi\pi$



$B \rightarrow DK$



Muon and K_L detector at B factories

Separate muons from hadrons (pions and kaons): exploit the fact that muons interact only electromag., while hadrons interact strongly \rightarrow need a few interaction lengths to stop hadrons (interaction lengths = about 10x radiation length in iron, 20x in CsI). A particle is identified as muon if it penetrates the material.



Detect K_L interaction (cluster): again need a few interaction lengths.

Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

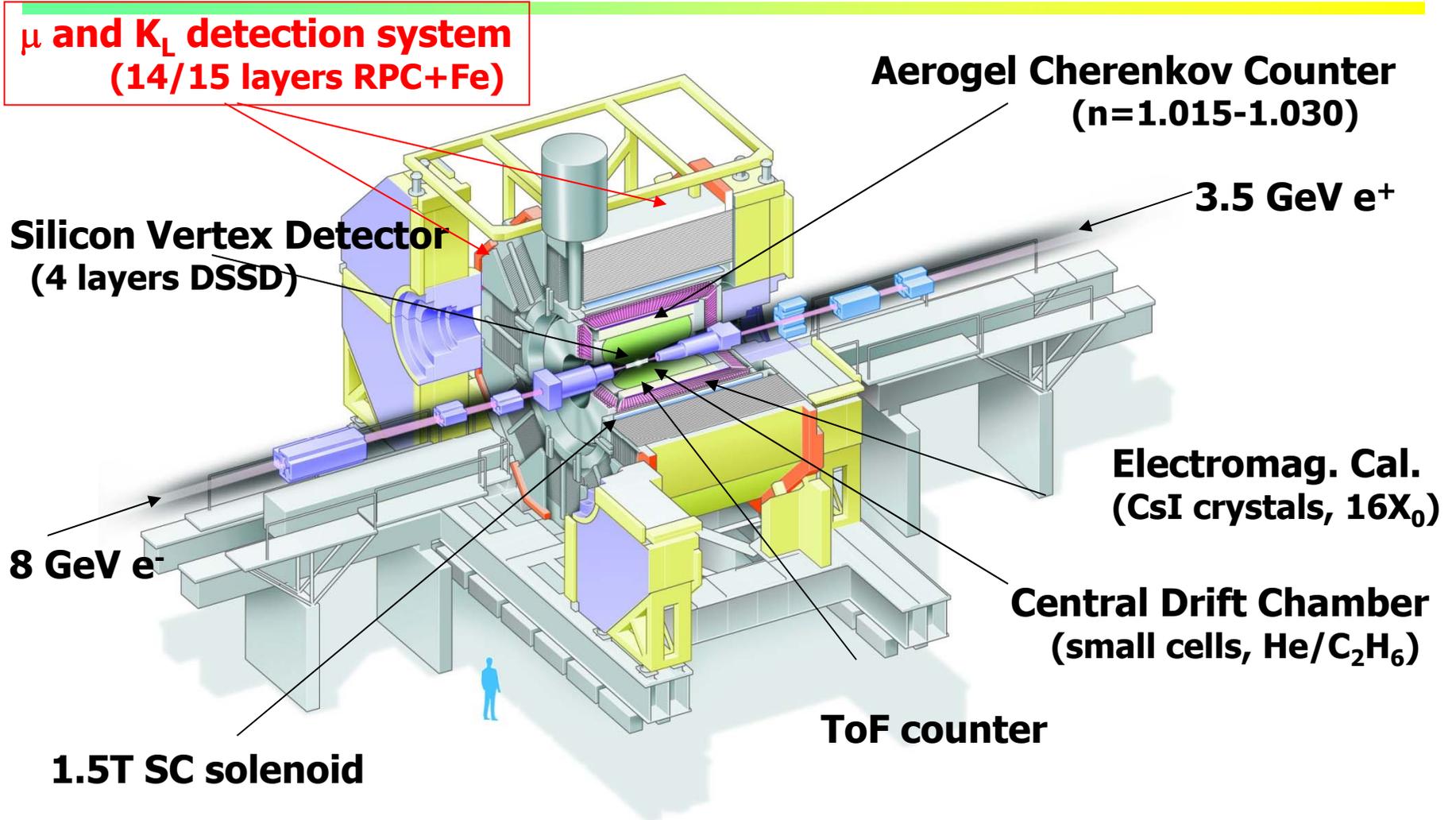
Interaction length: iron 132 g/cm², CsI 167 g/cm²

$(dE/dx)_{\min}$: iron 1.45 MeV/(g/cm²), CsI 1.24 MeV/(g/cm²)

$\rightarrow \Delta E_{\min} = (0.36+0.11) \text{ GeV} = 0.47 \text{ GeV} \rightarrow$ reliable identification of muons possible above $\sim 600 \text{ MeV}$



Example: Muon and K_L detection at Belle





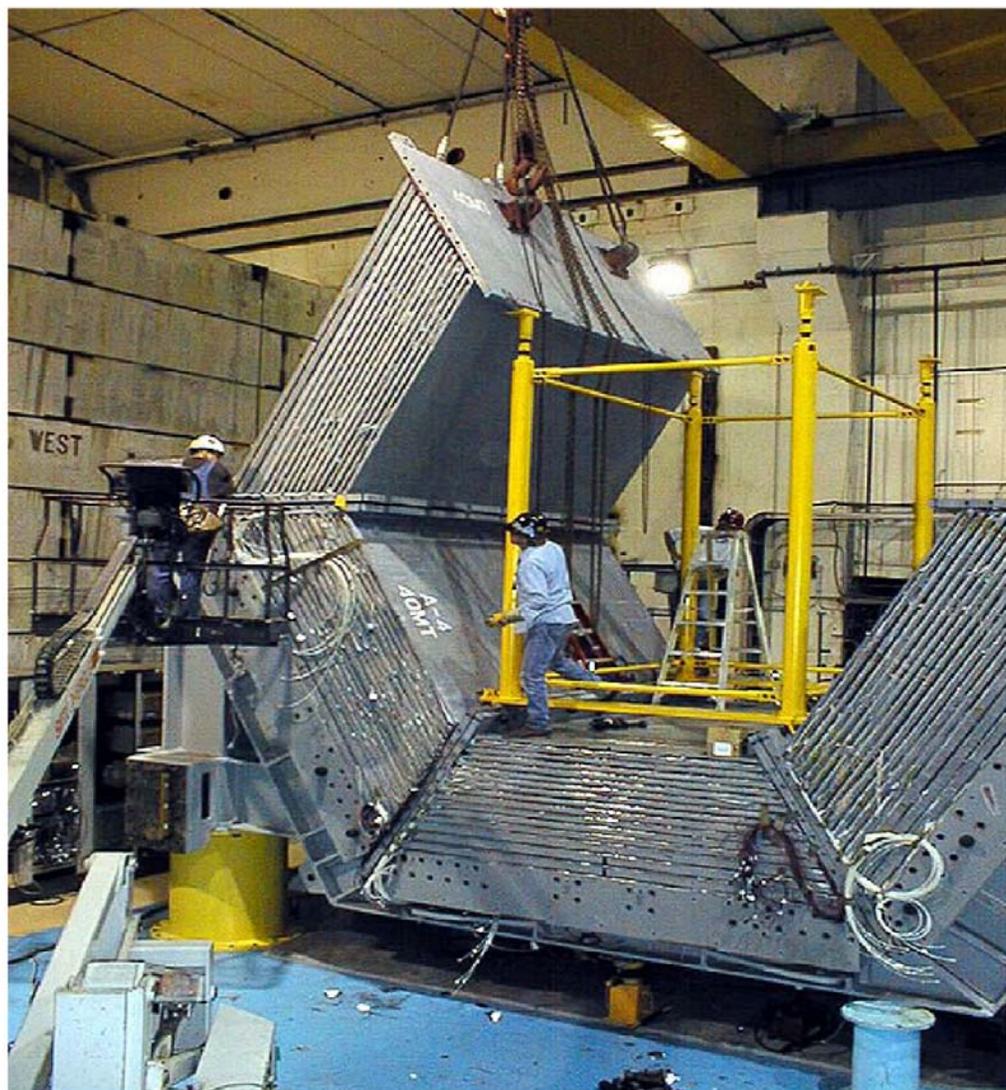
Muon and K_L detector

Up to 21 layers of resistive-plate chambers (RPCs) between iron plates of flux return

Bakelite RPCs at BABAR

Glass RPCs at Belle

(better choice)





Muon and K_L detector

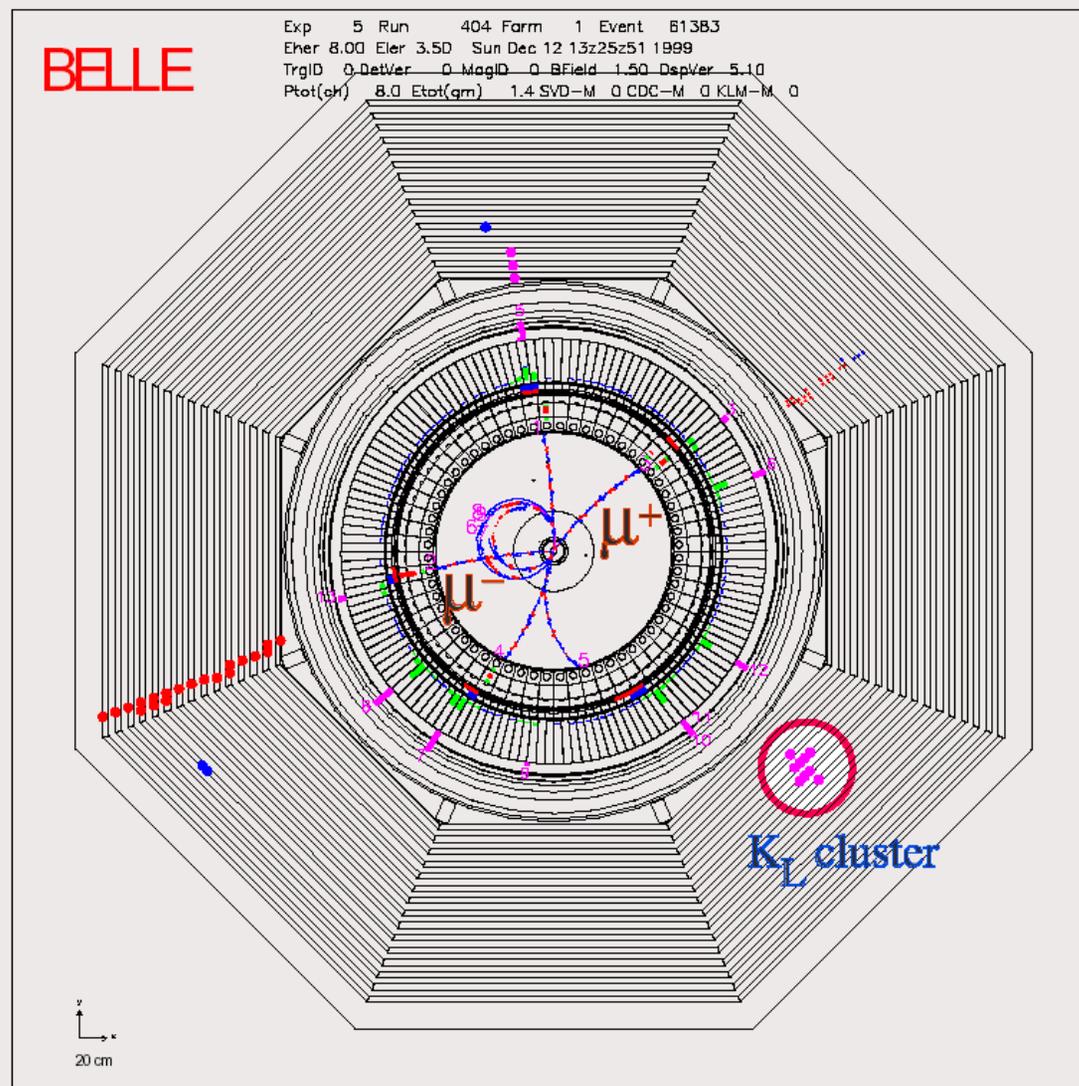
Example:

event with

- two muons and a

- K_L

**and a pion that
partly penetrated**





Muon and K_L detector performance

Muon identification: efficient for $p > 800$ MeV/c

efficiency

fake probability

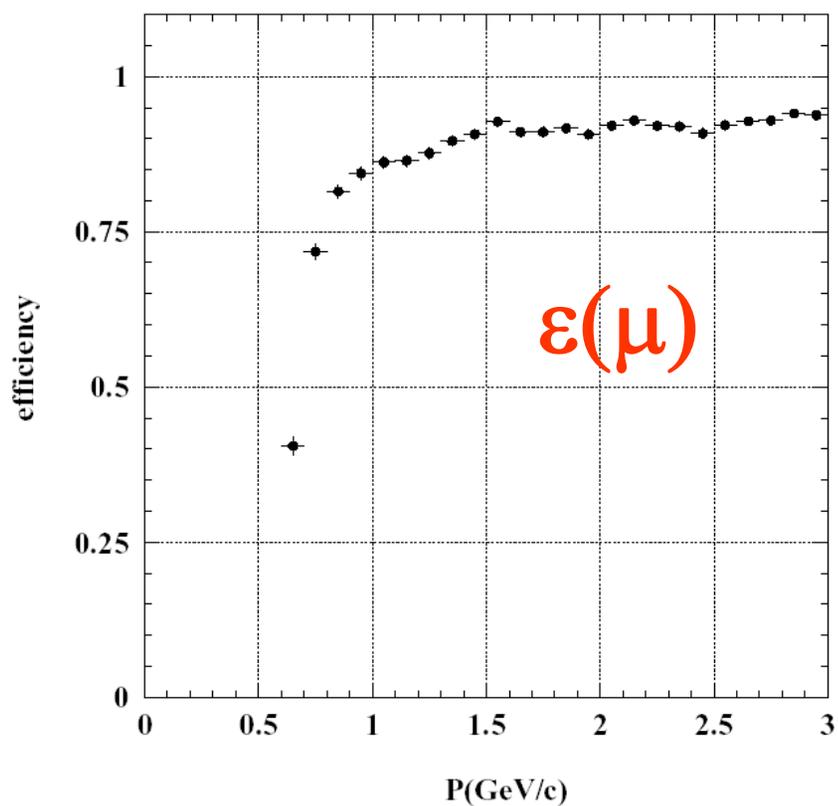


Fig. 109. Muon detection efficiency vs. momentum in KLM.

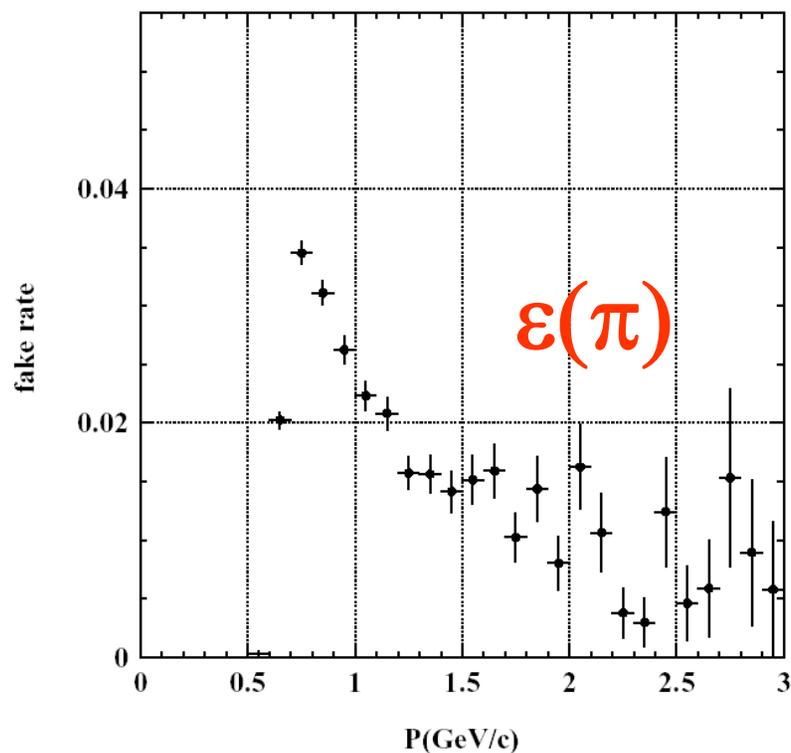


Fig. 110. Fake rate vs. momentum in KLM.



Muon and K_L detector performance

K_L detection: resolution in direction →

K_L detection: also with possible with electromagnetic calorimeter (0.8 interaction lengths)

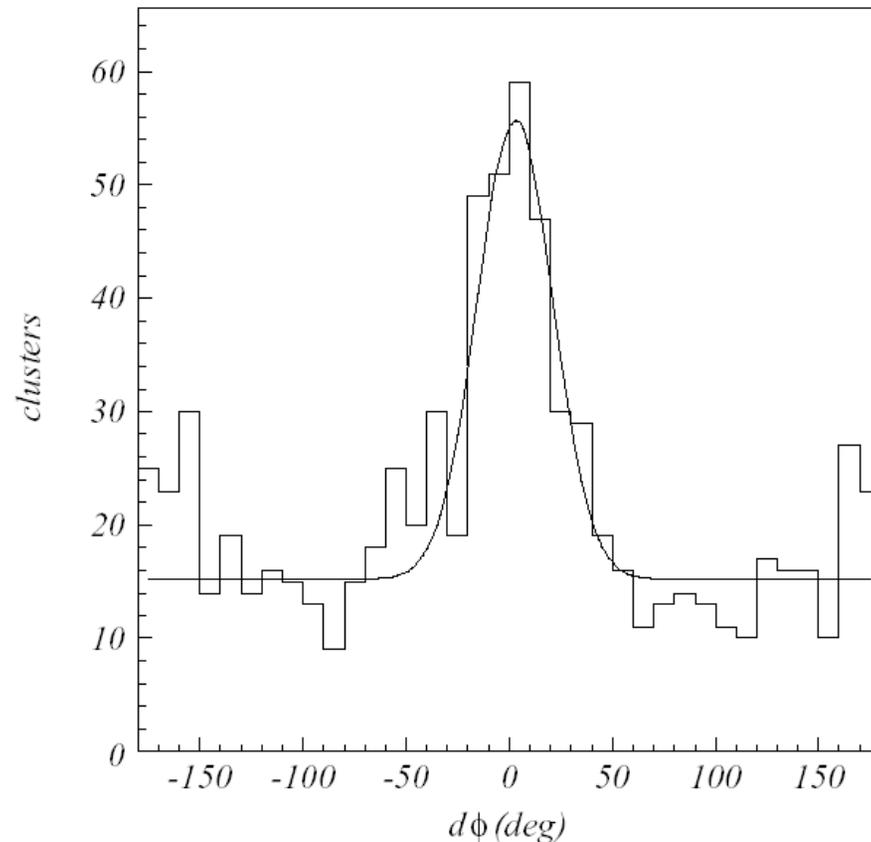
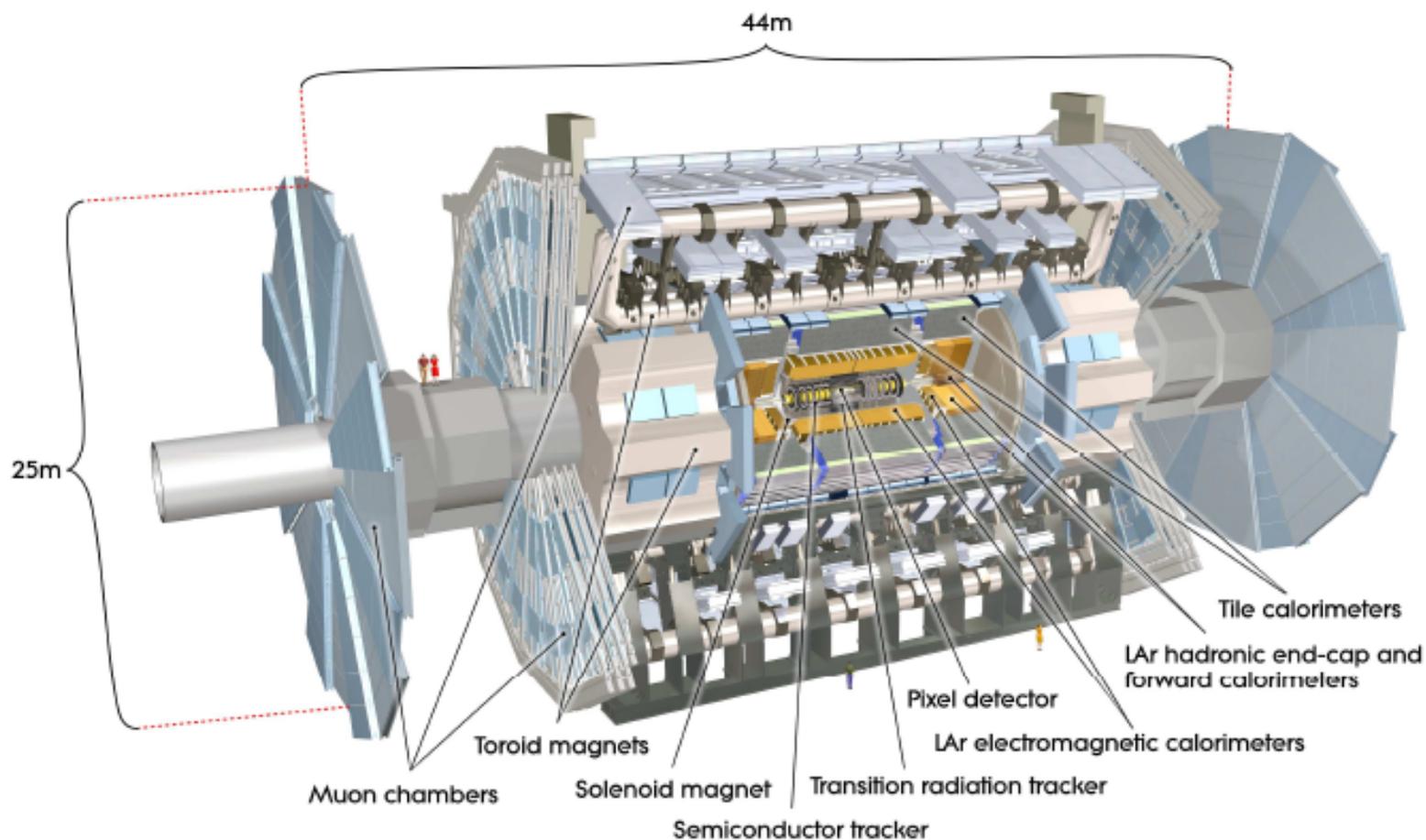


Fig.107. Difference between the neutral cluster and the direction of missing momentum in KLM.

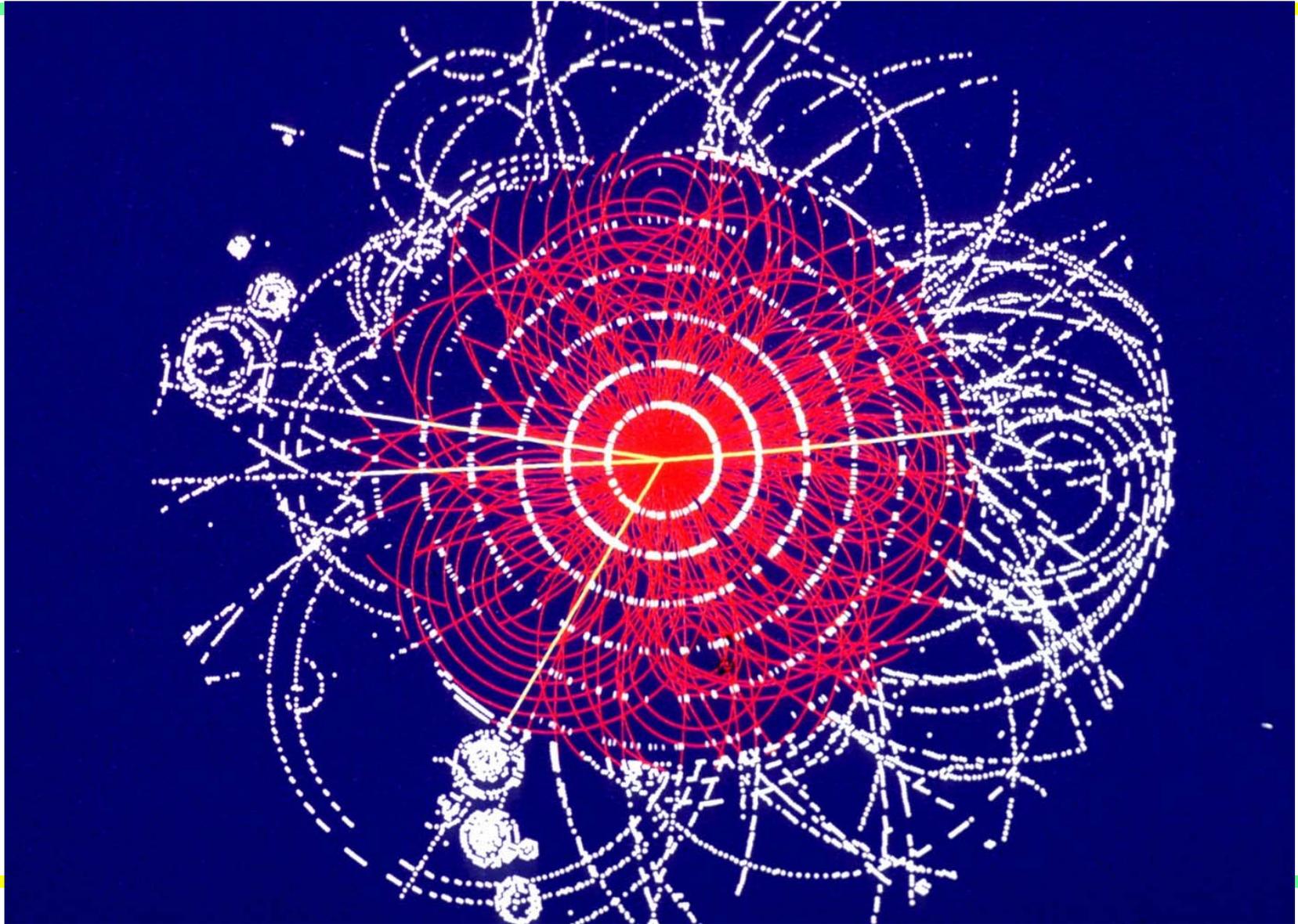


Identification of muons at LHC - example ATLAS



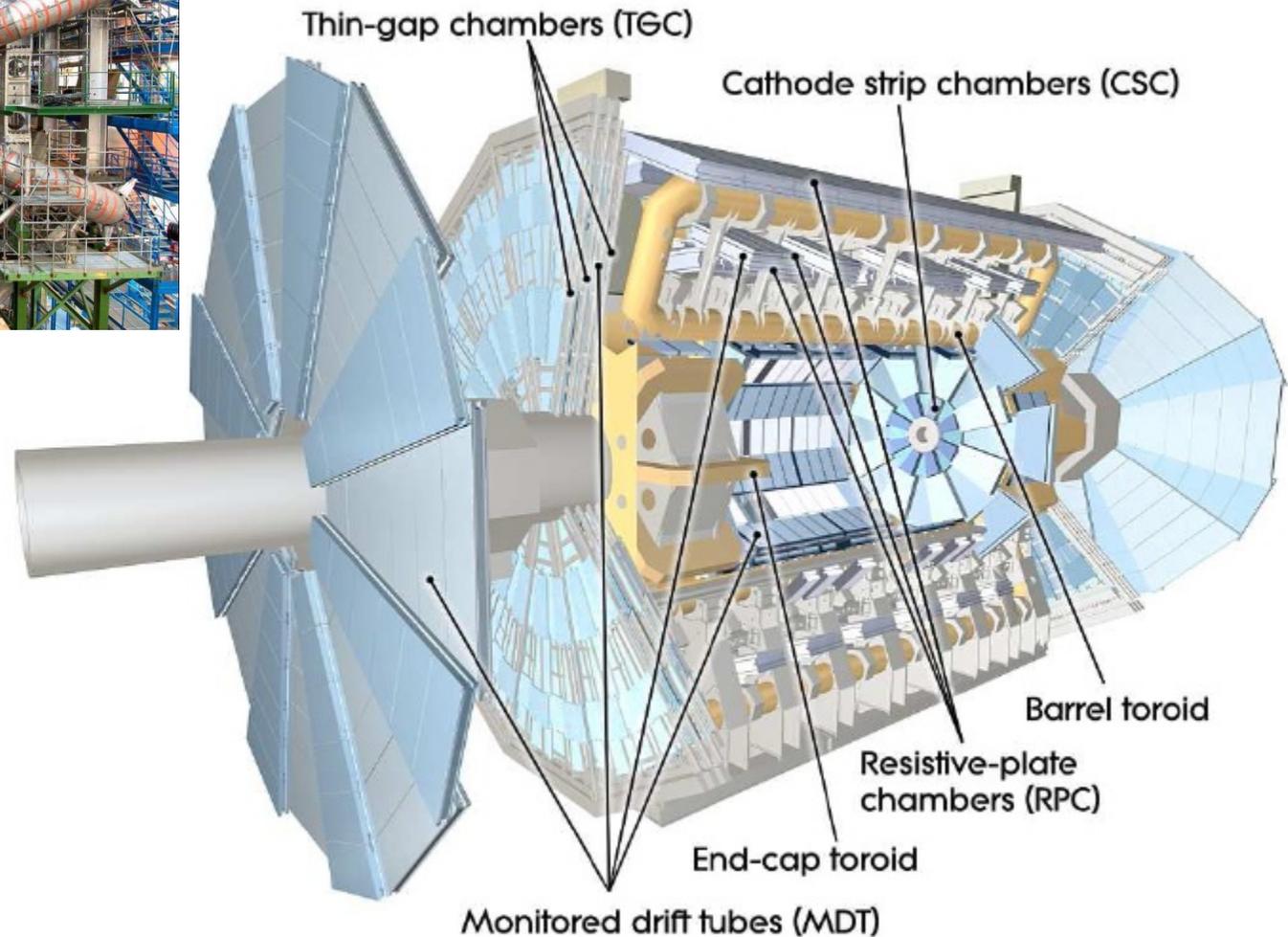
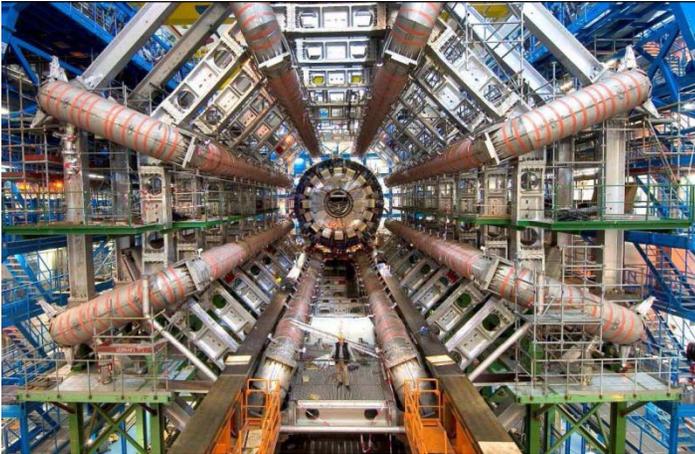


MC simulation: $H \rightarrow 4 \mu$ (ATLAS)





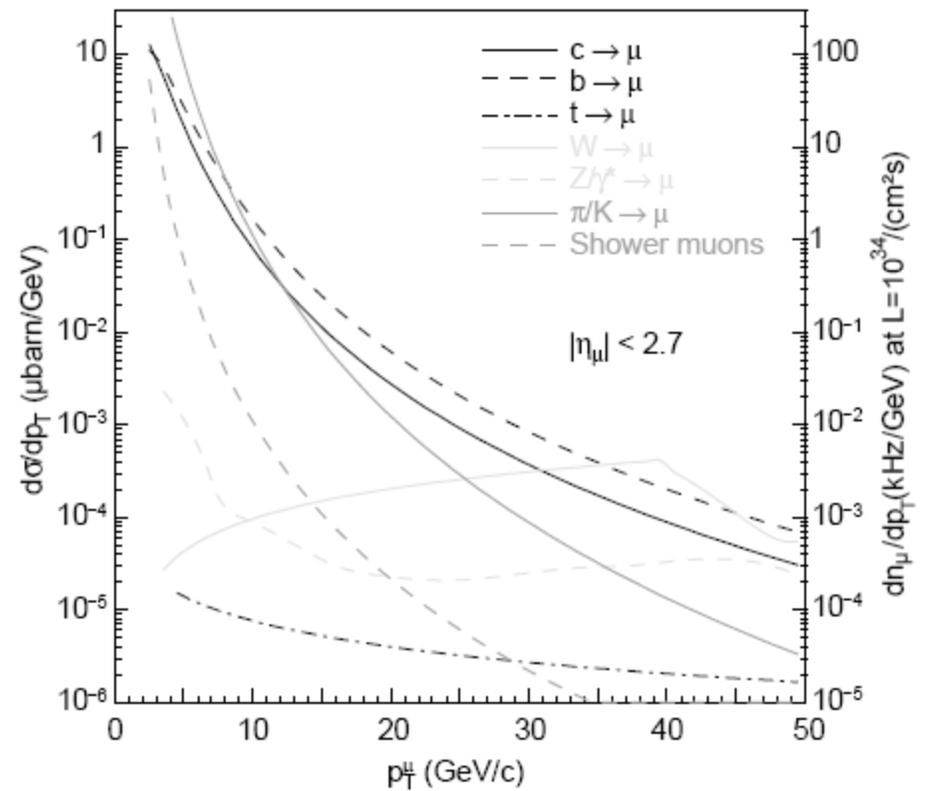
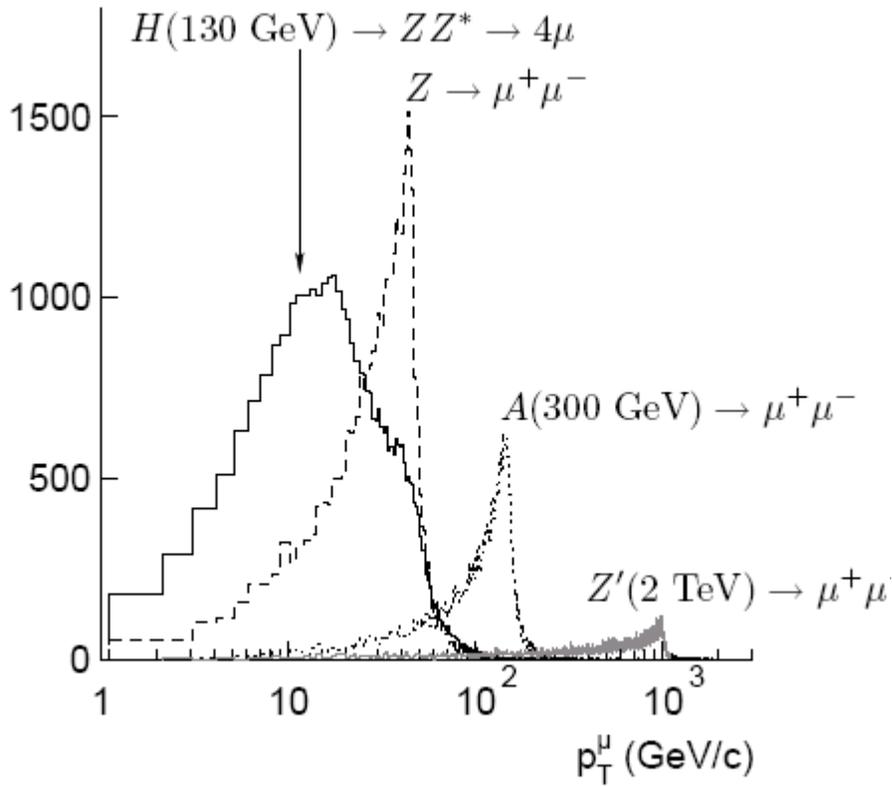
Identification of muons in ATLAS



- Identify muons
- Measure their momentum



Muon spectrum





Muon identification in ATLAS

Material in front of the muon system

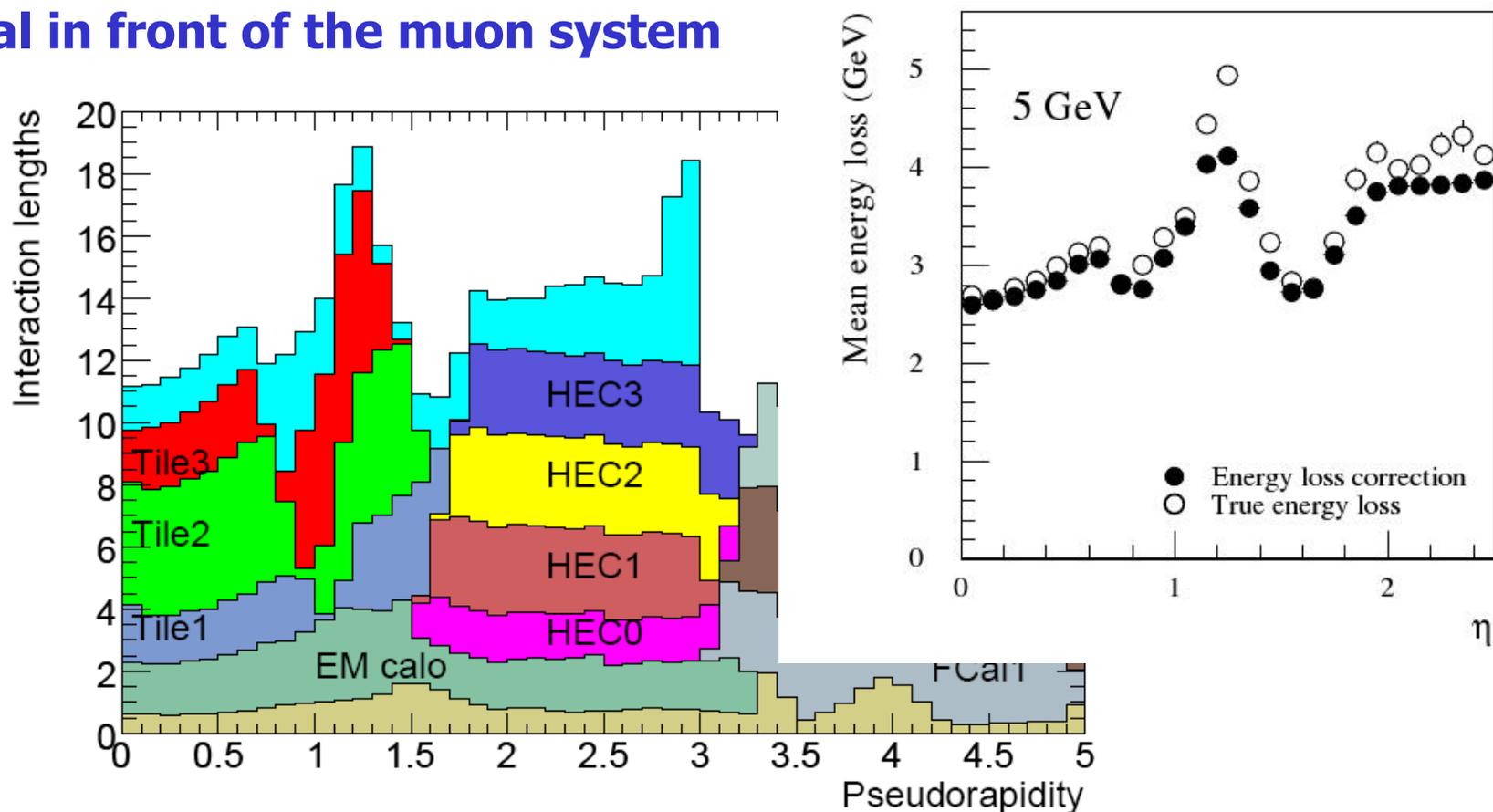


Figure 5.2: Cumulative amount of material, in units of interaction length, as a function of $|\eta|$, in front of the electromagnetic calorimeters, in the electromagnetic calorimeters themselves, in each hadronic layer, and the total amount at the end of the active calorimetry. Also shown for completeness is the total amount of material in front of the first active layer of the muon spectrometer (up to $|\eta| < 3.0$).



Muon identification efficiency

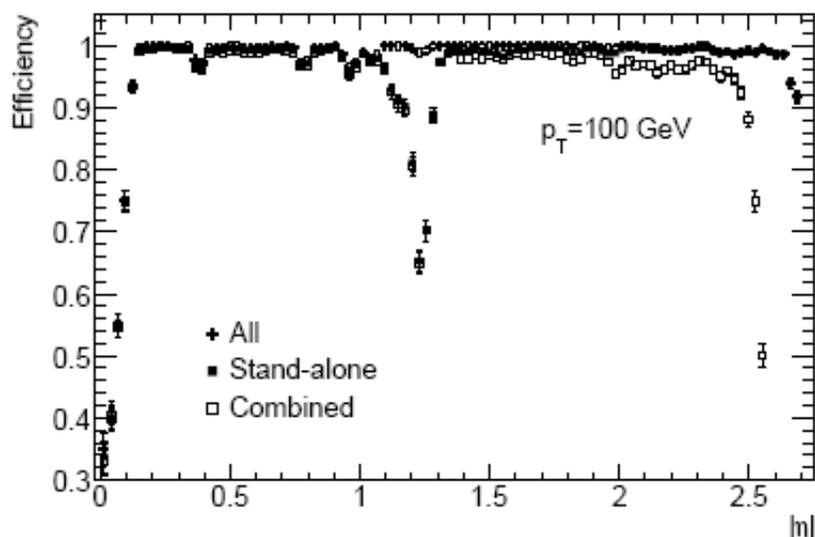


Figure 10.37: Efficiency for reconstructing muons with $p_T = 100$ GeV as a function of $|\eta|$. The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.

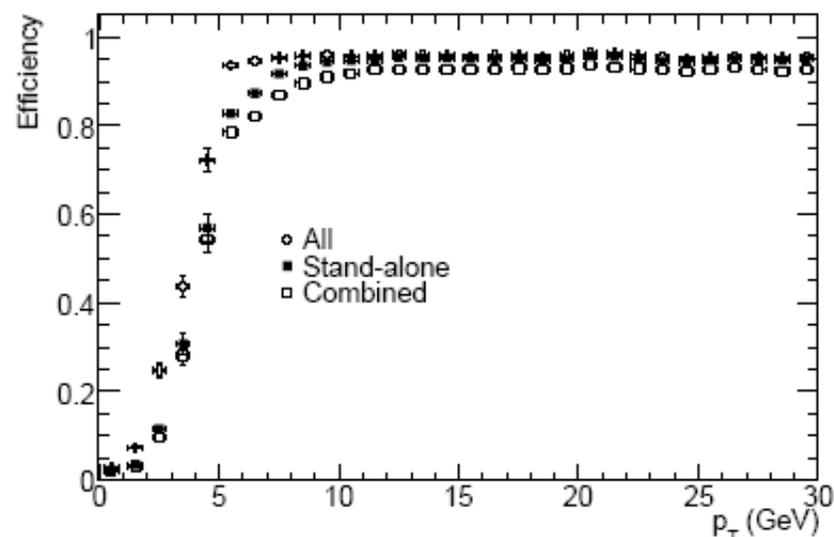


Figure 10.38: Efficiency for reconstructing muons as a function of p_T . The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.



Neutrino detection

Use inverse beta decay



However: cross section is very small!

$6.4 \cdot 10^{-44} \text{ cm}^2$ at 1MeV

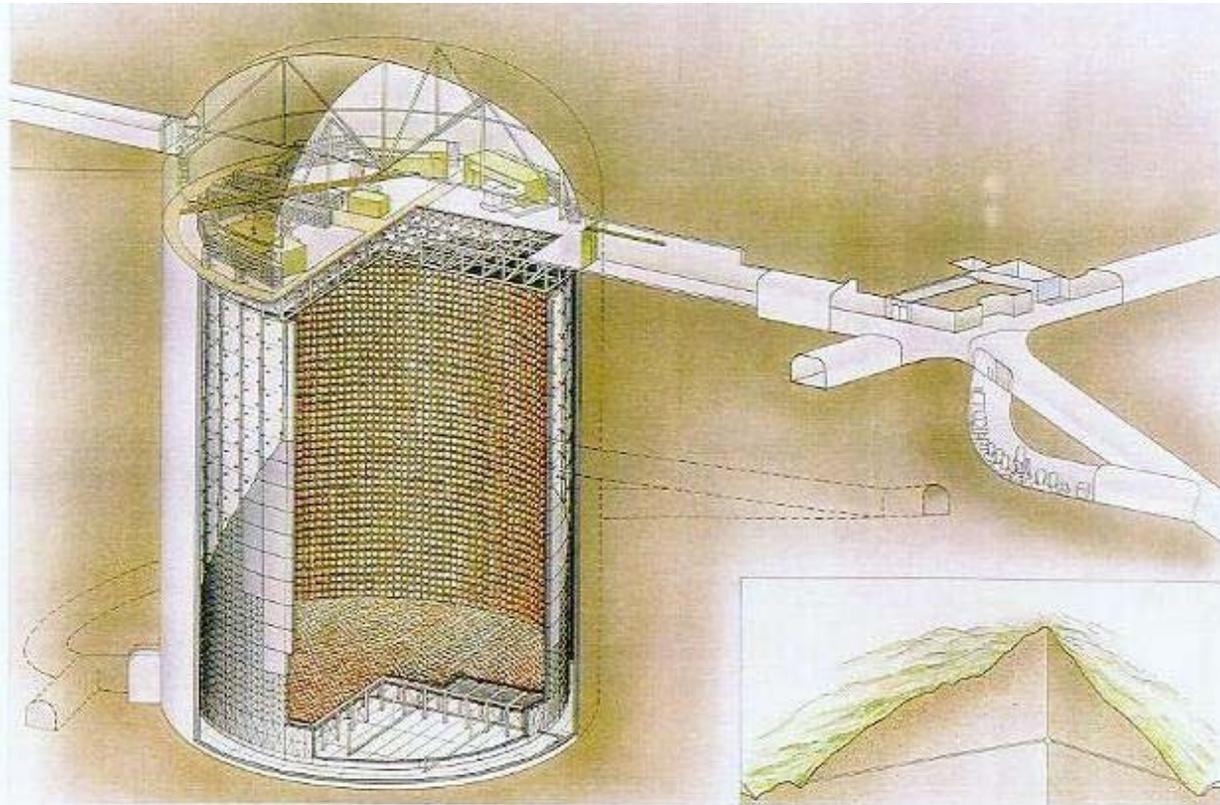
Probability for interaction in 100m of water = $4 \cdot 10^{-16}$

Not much better at high energies:
 $0.67 \cdot 10^{-38} \text{ E}/1\text{GeV cm}^2$ per nucleon

At 100 GeV, still 11 orders below the proton-proton cross section

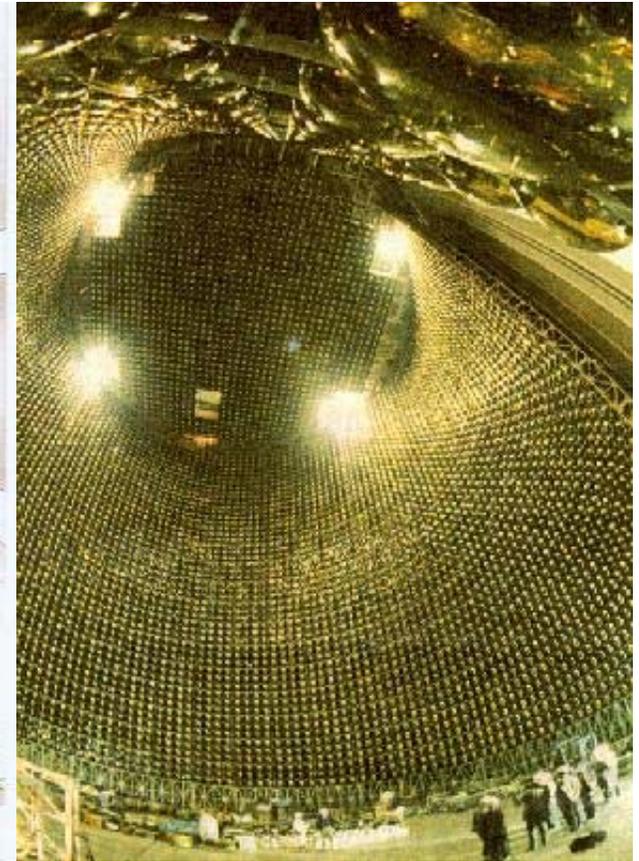


Superkamiokande: an example of a neutrino detector



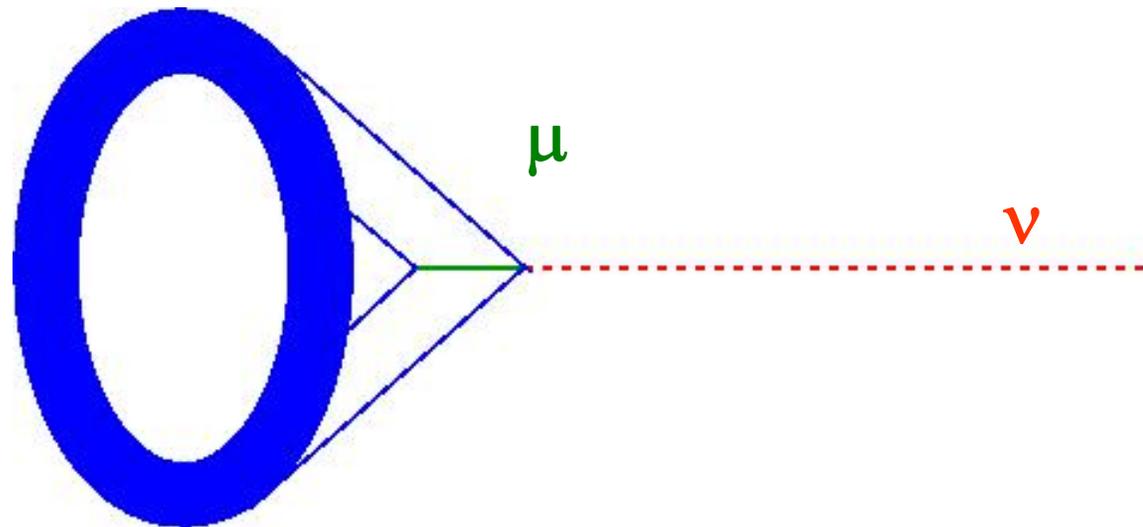
SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKI





Superkamiokande: detection of electrons and muons



The muon or electron emits Cerenkov light
→ ring at the detector walls

- Muon ring: sharp edges
- Electron ring: smeared



Superkamiokande: detection of neutrinos by measuring Cherenkov photons



Light detectors: HUGE
photomultiplier tubes

M. Koshiba



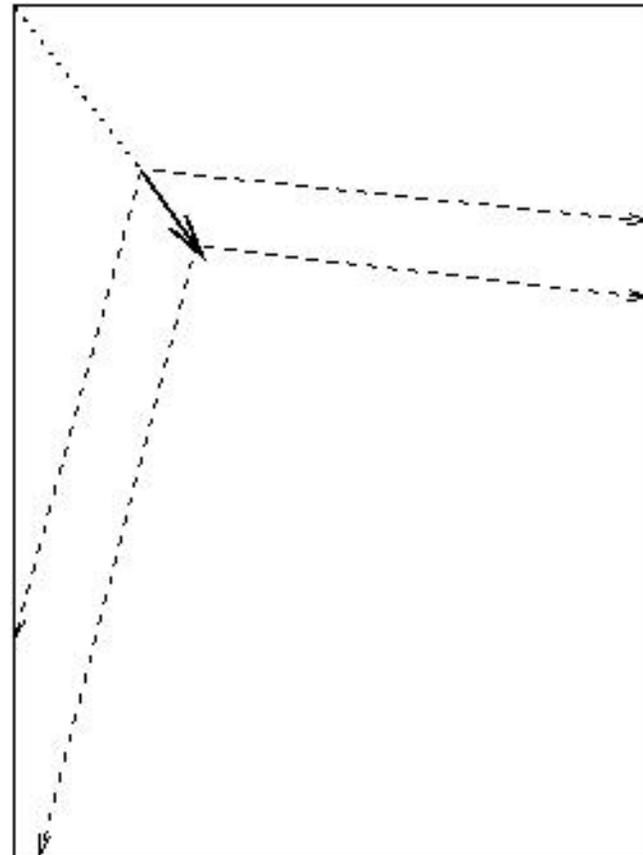
Muon vs electron

Cherenkov photons from
a muon track:

Example: 1 GeV muon
neutrino

Track length of the
resulting muon:
 $L = E / (dE/dx) =$
 $= 1 \text{ GeV} / (2 \text{ MeV/cm}) = 5 \text{ m}$

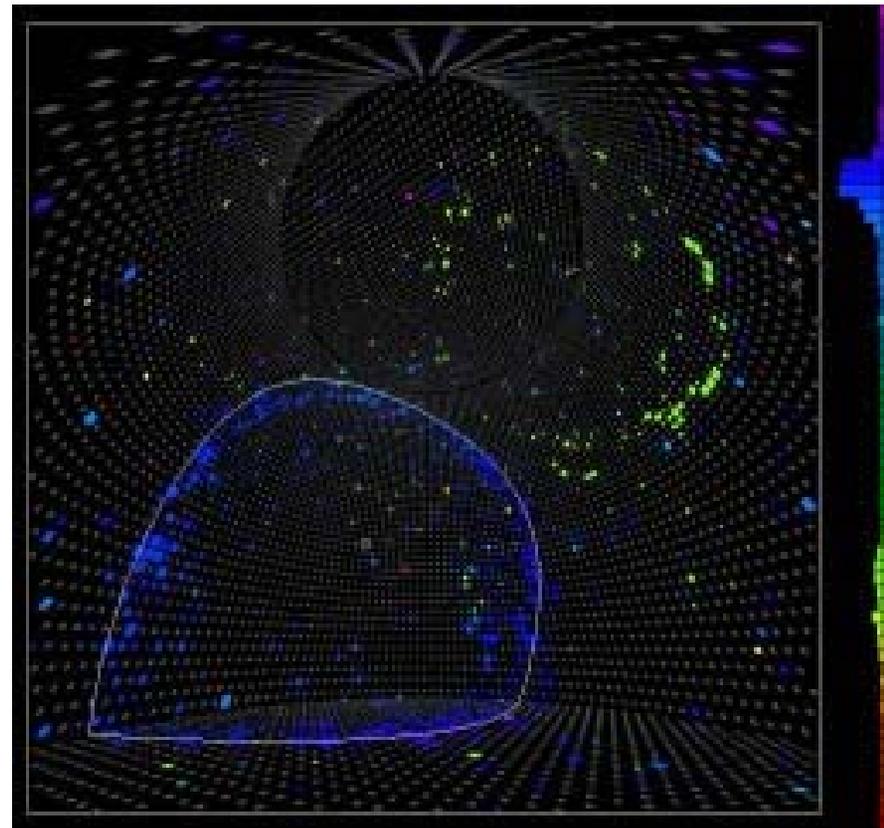
→ a well defined “ring” on
the walls





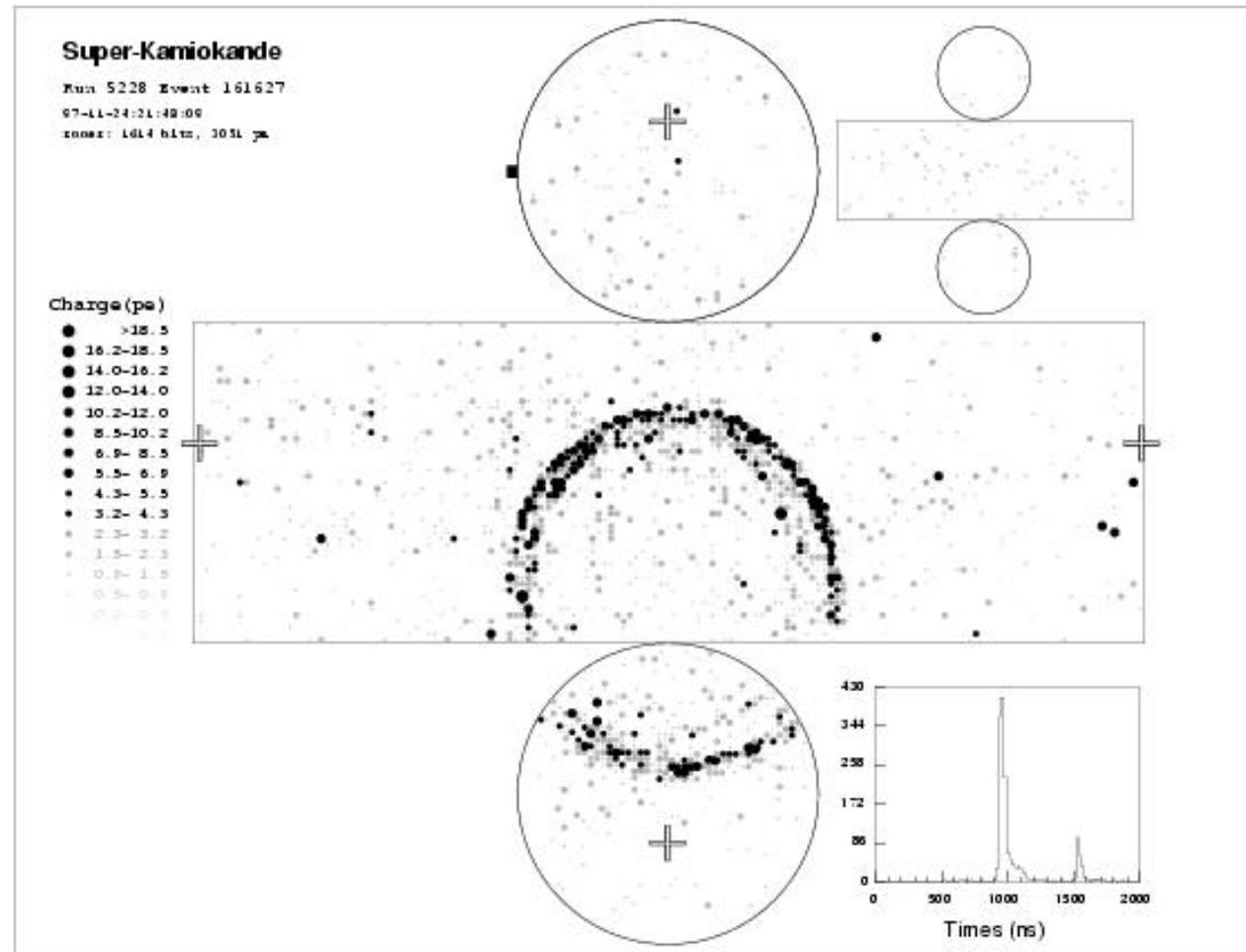
Superkamiokande: muon event

Muon 'ring' as seen by
the photon detectors





Muon event: photon detector cylinder walls

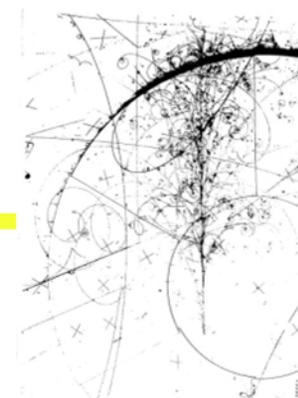


neutrino detection

Peter Križan, Ljubljana



Cherenkov photons from an electron track



Electron starts a shower!

Cherenkov photons from an electron generated shower

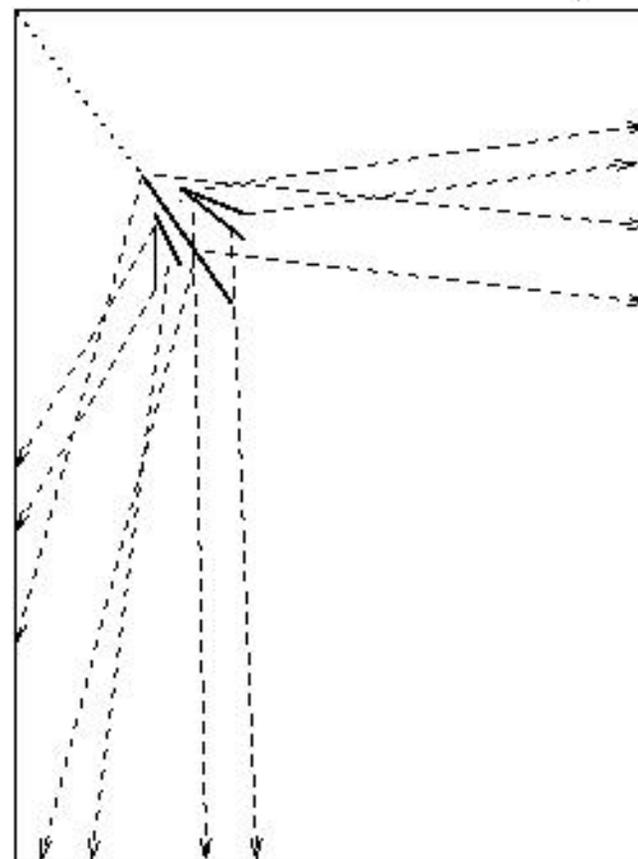
Example: 1 GeV el. neutrino

Shower length:

$$L = X_0 \cdot \log_2(E/E_{\text{crit}}) = \\ 36\text{cm} \cdot \log_2(1\text{GeV}/10\text{MeV}) \\ = 2.5\text{m}$$

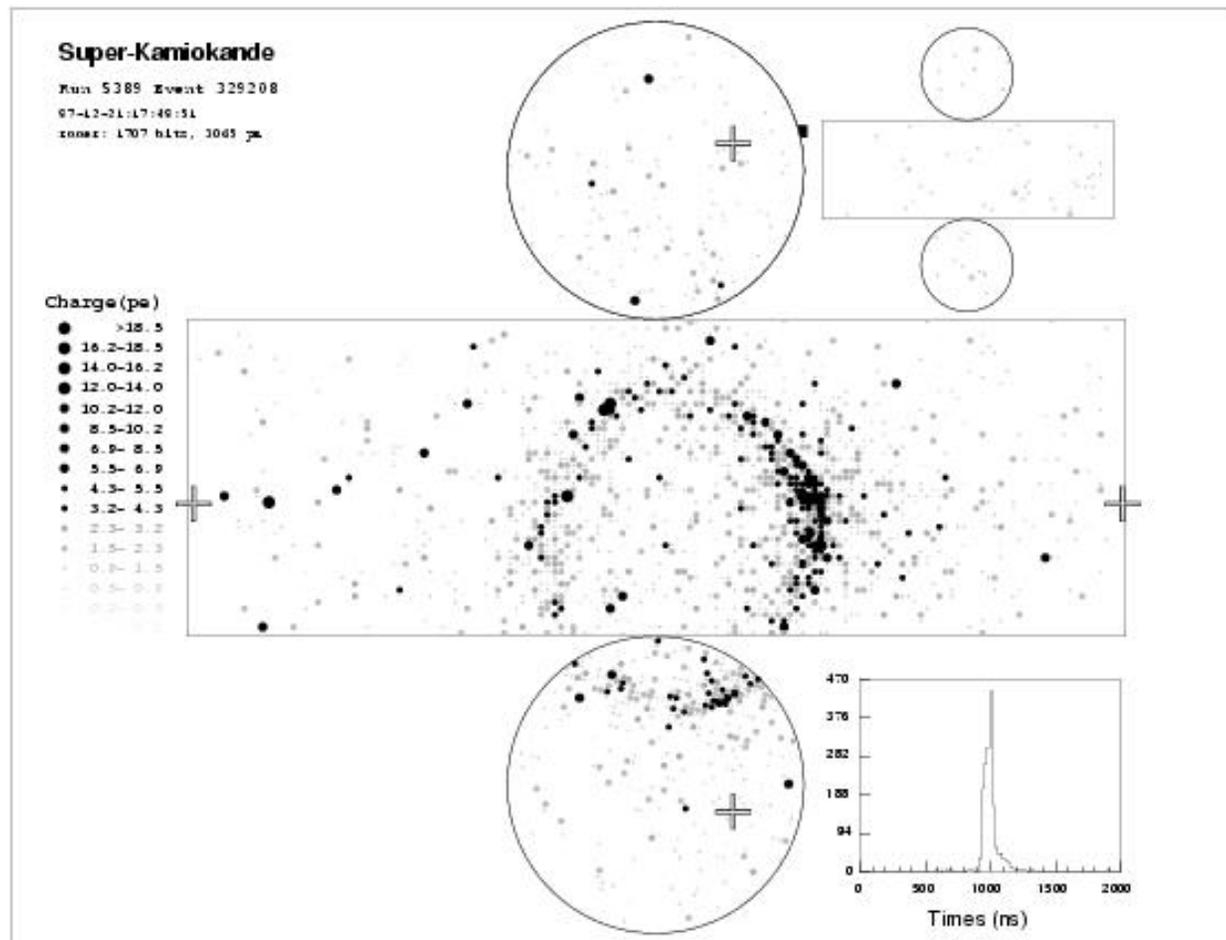
Shower particles are not parallel to each other

-> a blurred, less well defined "ring" on the walls





Electron event: blurred ring

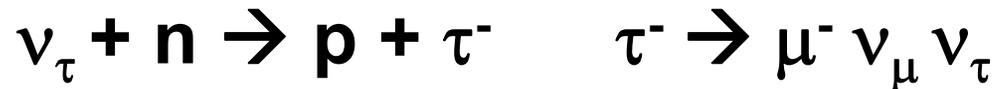


neutrino detection

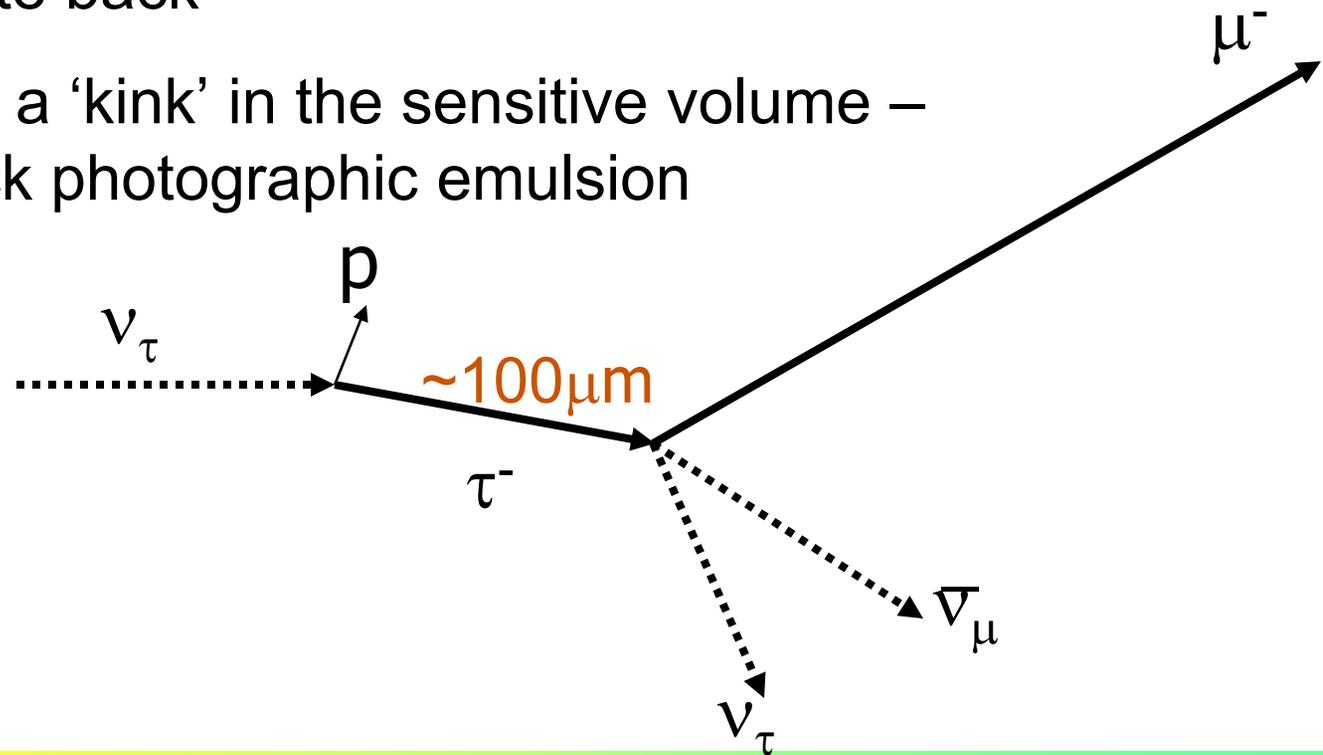
Peter Krizan, Ljubljana



Detection of τ neutrinos

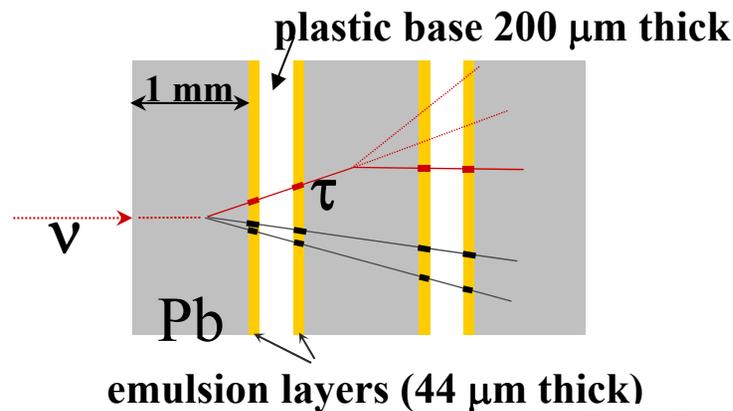
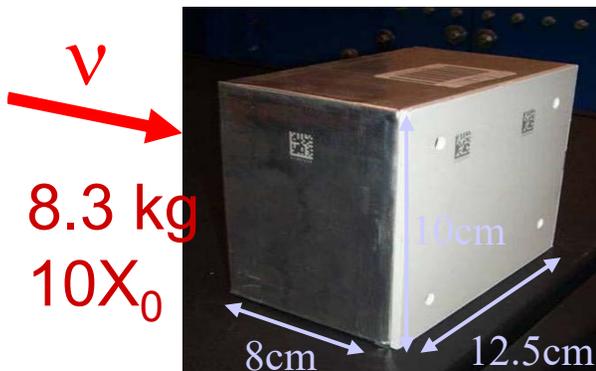
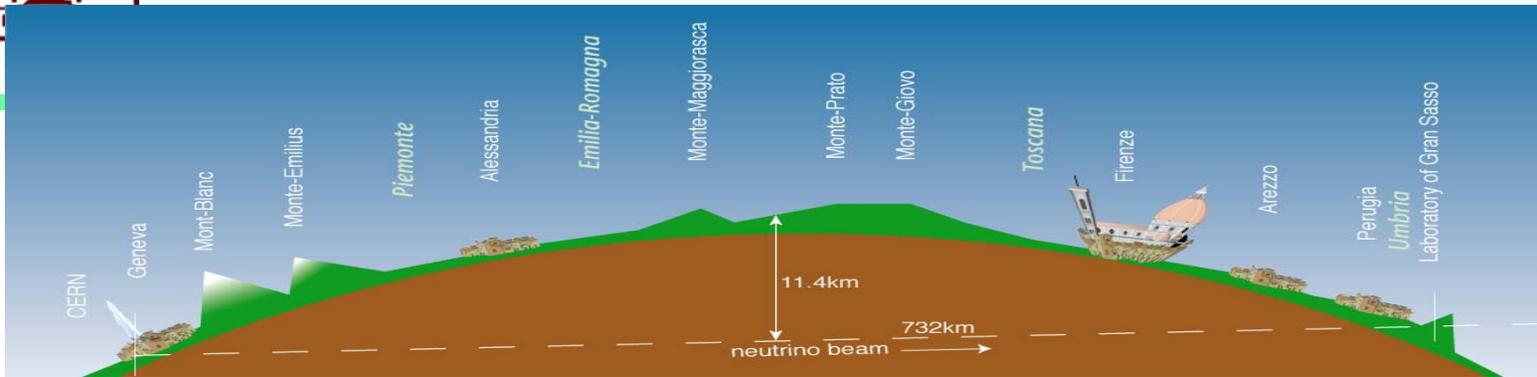


- ◆ Detect and identify muon
- ◆ Extrapolate back
- ◆ Check for a 'kink' in the sensitive volume – e.g. a thick photographic emulsion

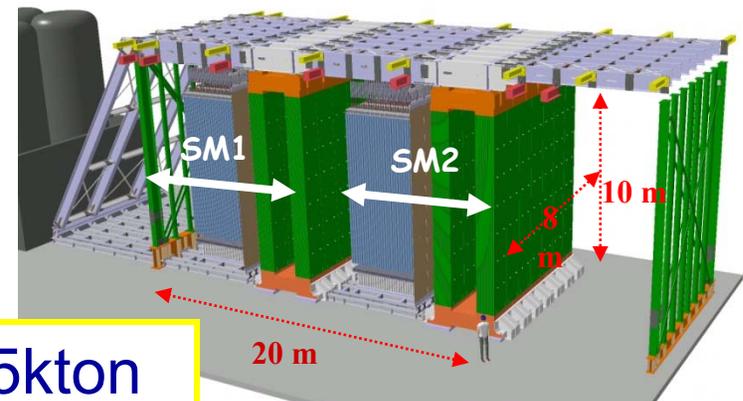




Detection of τ neutrinos: OPERA



Detection unit: a brick with 56 Pb sheets (1mm) + 57 emulsion films



155000 bricks, detector tot. mass = 1.35kton



Detection of very high energy neutrinos (from galactic sources)

The expected fluxes are very low:

Need really huge volumes of detector medium!

What is huge? From $(100\text{m})^3$ to $(1\text{km})^3$

Also needed: directional information.

Again use: $\nu_{\mu} + n \rightarrow p + \mu^{-}$; μ direction coincides with the direction of the high energy neutrino.

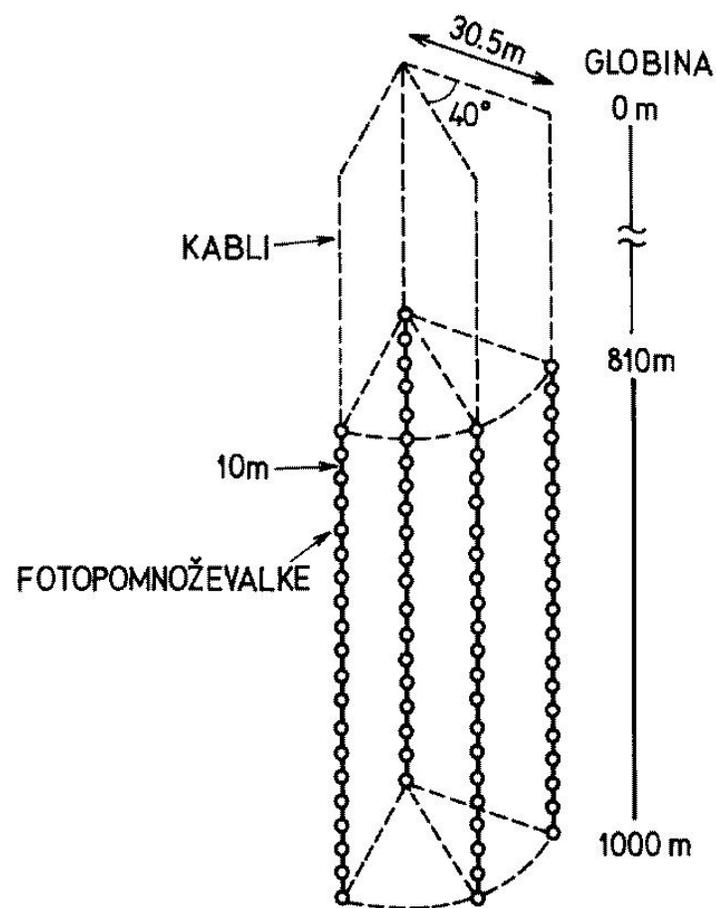


AMANDA: use the Antarctic ice instead of water

Normal ice is not transparent due to Rayleigh scattering on inhomogeneities (air bubbles)

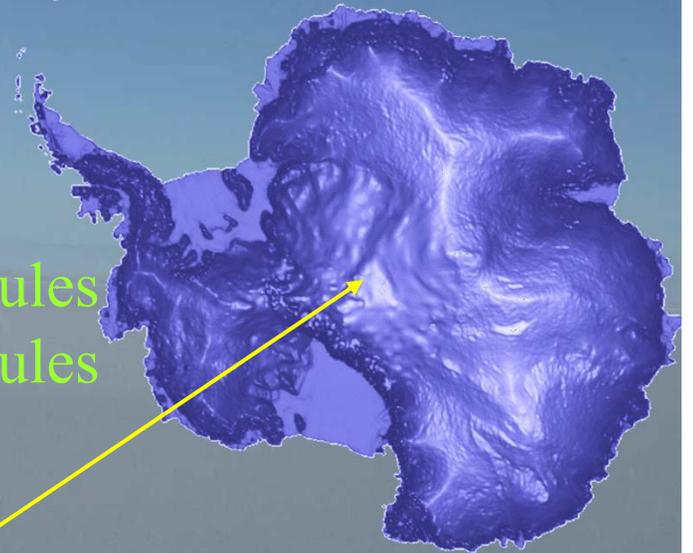
At high pressures (large depth) there is a phase transition, bubbles get partly filled with water -> transparent!

Originally assumed: below 800m OK; turned out to be much deeper.



AMANDA

- 1993 First strings AMANDA A
- 1998 AMANDA B10 ~ 300 Optical Modules
- 2000 AMANDA II ~ 700 Optical Modules
- 2010 ICECUBE 4800 Optical Modules



South Pole

Dome

Summer camp

road to work

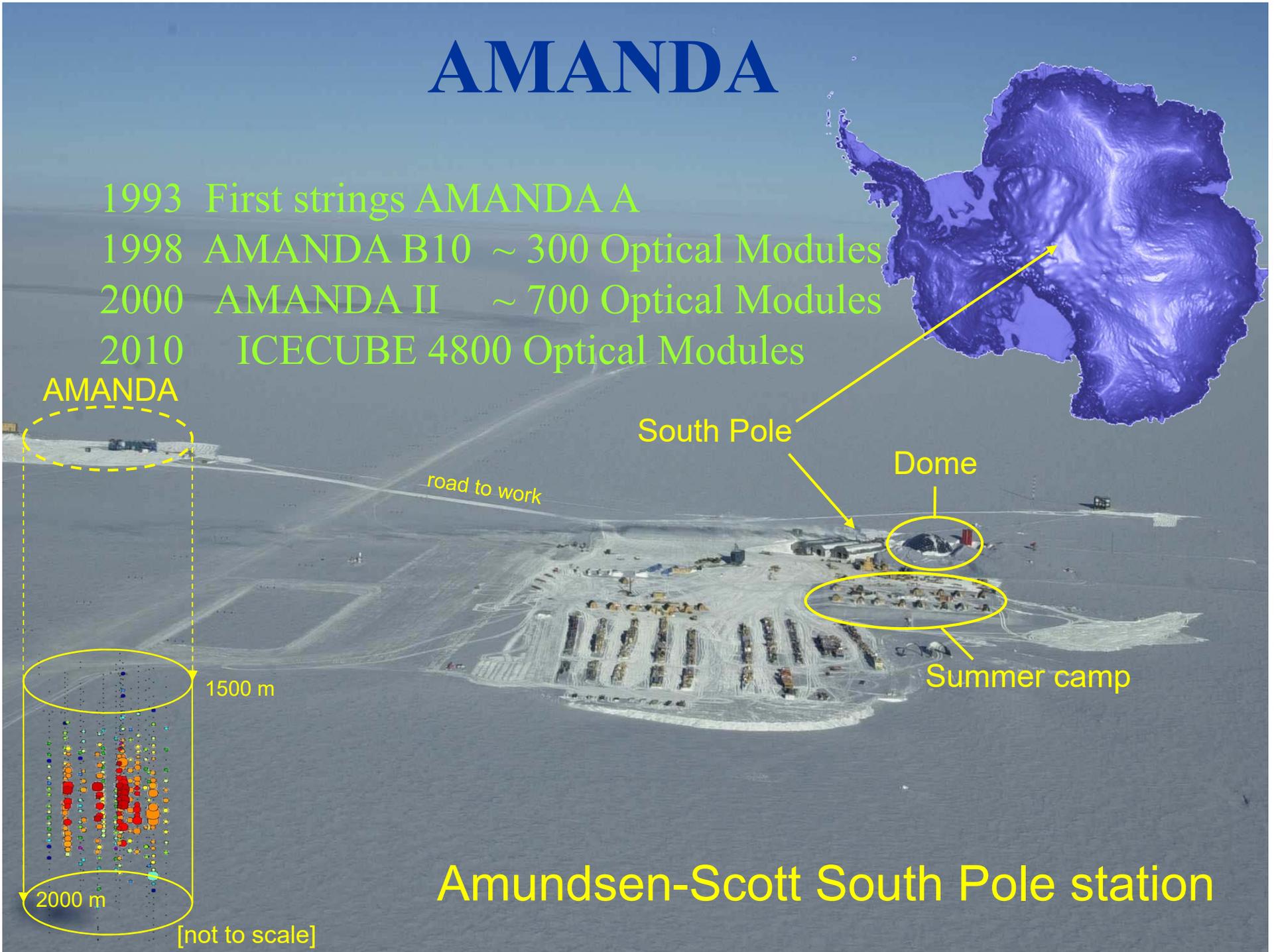
AMANDA

1500 m

2000 m

[not to scale]

Amundsen-Scott South Pole station





Reconstruction of direction and energy of incident high energy muon neutrino

For each event:

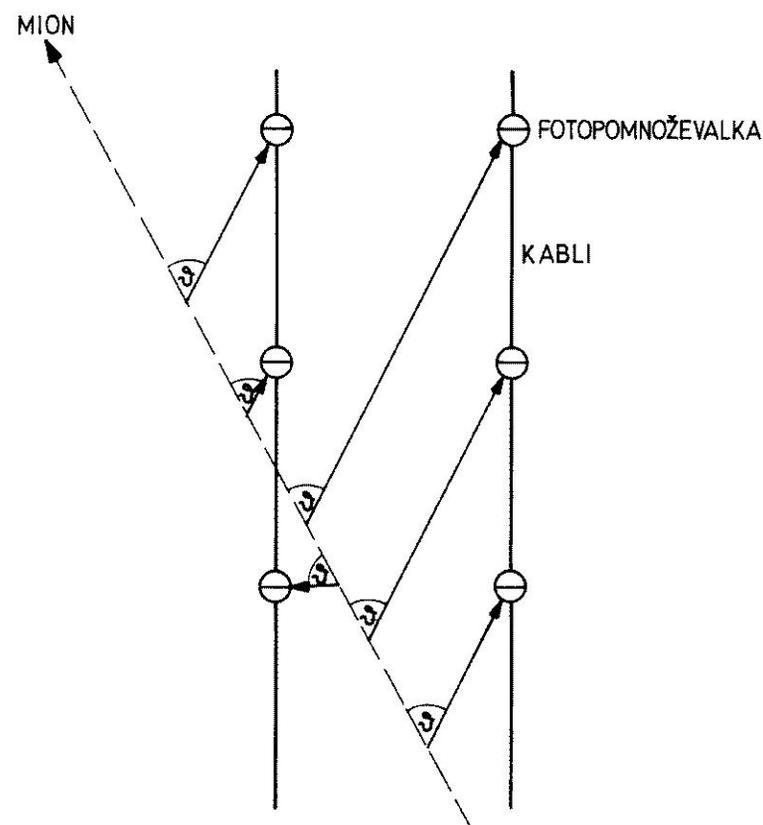
Measure time of arrival on each of the tubes

Cherenkov angle is known:
 $\cos\theta = 1/n$

Reconstruct muon track

Track direction \rightarrow neutrino direction

Track length \rightarrow neutrino energy



AMANDA

Example of a detected event, a muon entering the PMT array from below



Analysis of data

If we have N independent (unbiased) measurements x_i of some unknown quantity μ with a common, but unknown, variance σ^2 , then

$$\hat{\mu} = \frac{1}{N} \sum_{i=1}^N x_i$$

$$\hat{\sigma}^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \hat{\mu})^2$$

are unbiased estimates of μ and σ^2 . The errors of the estimates are

- for μ : σ/\sqrt{N}
- for σ : $\sigma/\sqrt{2N}$ (for Gaussian distributed x_i and large N)



Analysis of data 2: unbinned likelihood fit

Assume now that we have N independent (unbiased) measurements x_i that come from a probability density function (p.d.f.) $f(x; \theta)$, where $\theta = (\theta_1, \dots, \theta_m)$ is a set of m parameters whose values are unknown. The method of maximum likelihood takes the estimators θ **to be those values of θ that maximize the likelihood function,**

$$L(\boldsymbol{\theta}) = \prod_{i=1}^N f(x_i; \boldsymbol{\theta}) .$$

It is easier to minimize $-\ln L$ (same minimum) \rightarrow a set of m equations

$$\frac{\partial \ln L}{\partial \theta_i} = 0 , \quad i = 1, \dots, m .$$



Analysis of data 3

The errors and correlations between parameters $\theta = (\theta_1, \dots, \theta_m)$ can be found from the inverse of the covariance matrix

$$(\hat{V}^{-1})_{ij} = - \left. \frac{\partial^2 \ln L}{\partial \theta_i \partial \theta_j} \right|_{\hat{\theta}}$$

The variance σ^2 on the parameter θ_i is V_{ii}



Analysis of data 4: binned likelihood fit

If the sample is large (high n), data can be grouped in a histogram. The content of each bin, n_i , is distributed according to the Poisson distribution with mean $\nu_i(\theta)$,

$$f(\nu_i(\theta), n_i) = \nu_i(\theta)^{n_i} \exp(-\nu_i(\theta)) / n_i!$$

The parameters θ are determined by maximizing a properly normalized likelihood function

$$-2 \ln \lambda(\boldsymbol{\theta}) = 2 \sum_{i=1}^N \left[\nu_i(\boldsymbol{\theta}) - n_i + n_i \ln \frac{n_i}{\nu_i(\boldsymbol{\theta})} \right]$$

In the limit of zero bin width, maximizing this expression is equivalent to maximizing the unbinned likelihood function.



Analysis of data 5: least squares method

If we have N independent measurements of variable y_i at points x_i , and if y_i are Gaussian distributed around a mean $F(x_i, \theta)$ with variance σ_i^2 , the log likelihood function yields

$$\chi^2(\boldsymbol{\theta}) = -2 \ln L(\boldsymbol{\theta}) + \text{constant} = \sum_{i=1}^N \frac{(y_i - F(x_i; \boldsymbol{\theta}))^2}{\sigma_i^2}$$

and the parameters θ are determined by minimizing this expression.

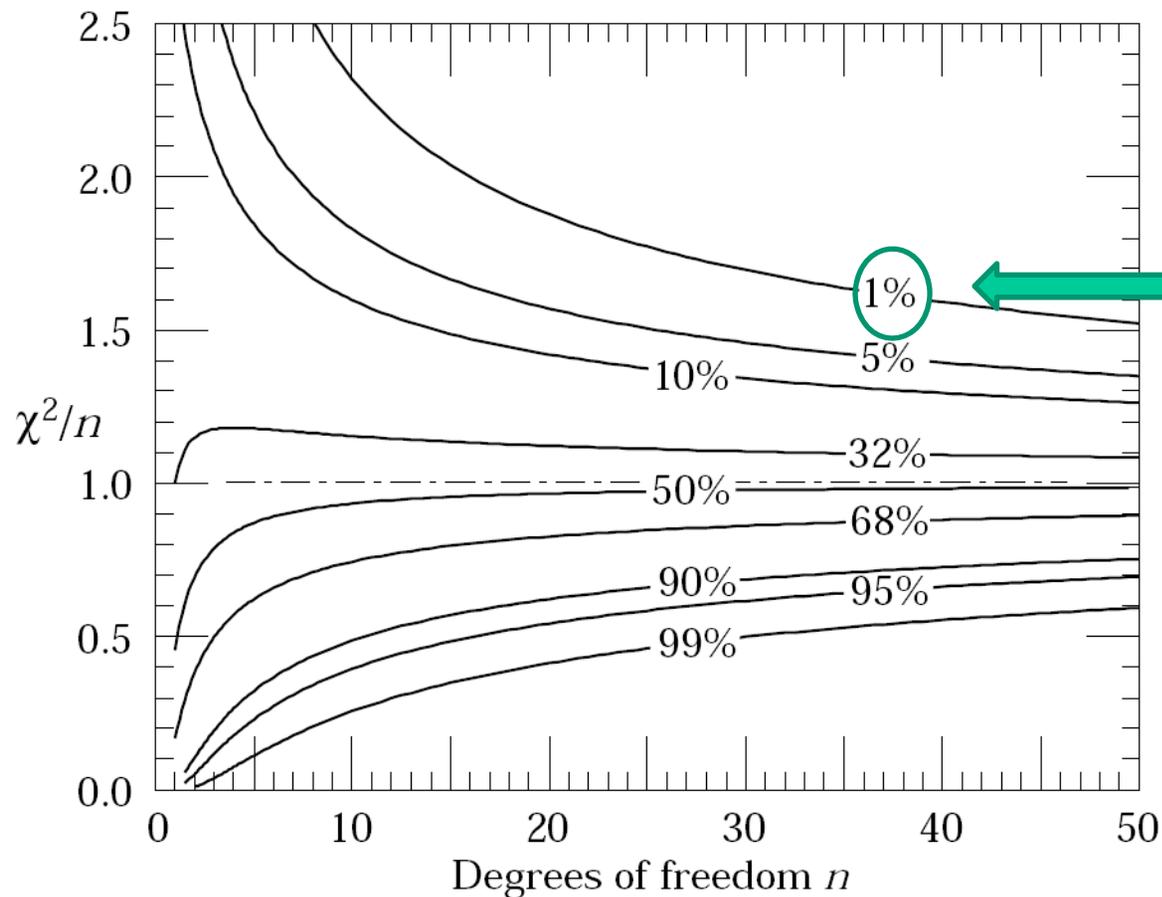
This weighted sum of squares can be used in a general case of a non-Gaussian distribution \rightarrow **Least squares method**



Analysis of data 6: least squares method

The value of χ^2 at the minimum is an indication of the goodness of fit. The mean of χ^2 should be equal to the number of degrees of freedom, $n = N - m$, where m is the number of parameters.

Popular: quote χ^2/n



Probability that the fit would give χ^2/n bigger than the observed value



Contents of this course

- Lecture 1: Introduction, experimental methods, detectors, data analysis
- Lecture 2: Intensity frontier experiments - tomorrow



Backup slides



Gas mixtures for drift chambers and MWPCs

Main component: a gas with a **low** average ionisation energy W_i - **nobel gases** have less degrees of freedom.

Add to this:

- A component which **absorbs photons** ('quencher') produced in the avalanche (deexcitation of atoms and ions) – an organic molecule with a lot of degrees of freedom: isobutane, methane, CO_2 , ethane
- A component which **prevents** that ionized organic molecules would travel to the cathode, stop there, and **polymerize** to form poorly conductive layers: a gas which has a low ionisation energy - methylal
- A small concentration of an **electronegative gas** (freon, ethylbromide) which prevents the electrons travel too far (to prevent that electrons which escaped from the cathode start **new avalanches**) allows to work at high gains (10^7)

'Magic mixture': 72% Ar, 23.5% isobutane, 4% methylal, 0.5% freon



Time-of-flight measurement 3

Resolution of a PMT: transient time spread (TTS), time variation for single photons

Tubes for TOF have to be optimized for small TTS.

Main contribution after the optimisation: photoelectron time spread before it hits the first dynode.

Estimate: take two cases, one with $T=1\text{eV}$ and the other with $T=0$ after the photoelectron leaves the photocathode; take $U=200\text{V}$ and $d=10\text{mm}$

$T=1\text{eV}$: $v_0 = \sqrt{2T/m} = 0.002 c$, $a=F/m=200\text{eV}/(10\text{mm} \cdot 0.5 \cdot 10^6\text{eV}/c^2)$

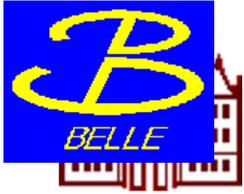
$d = v_0 t + at^2/2 \rightarrow t = \sqrt{(2d/a + (v_0/a)^2)} - v_0/a$

$T=0\text{eV}$: $v_0 = 0 \rightarrow t = \sqrt{2d/a} = 2.3\text{ns}$

Time difference: 170ps is a typical value.

Good tubes: $\sigma(\text{TTS})=100\text{ps}$

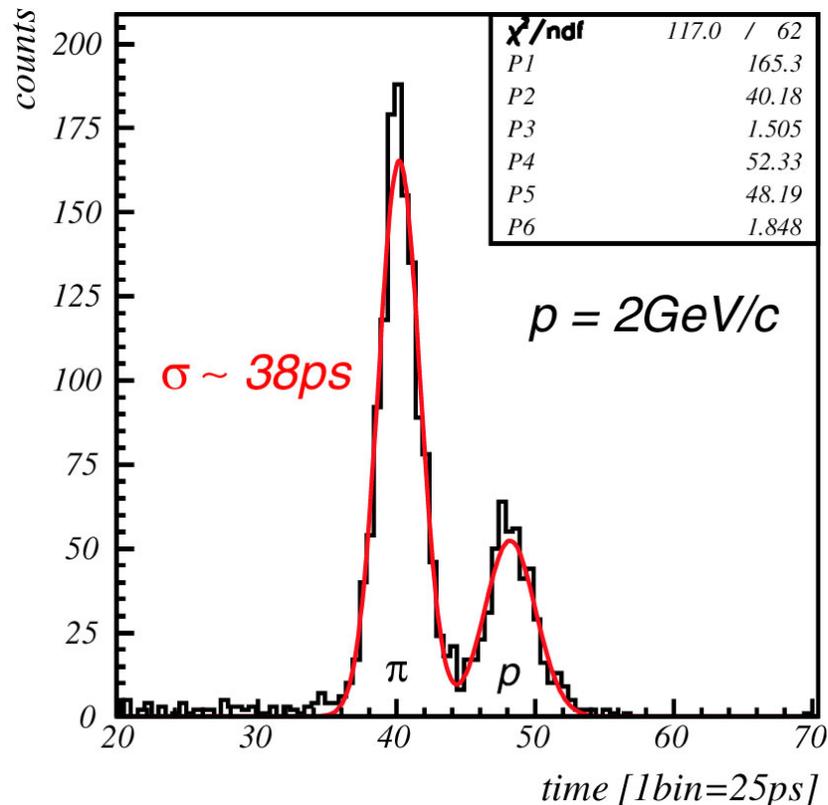
For N photons: $\sigma \sim \sigma(\text{TTS}) / \sqrt{N}$



TOF capability: window photons

Expected number of detected Cherenkov photons emitted in the PMT window (2mm) is **~15**

→ Expected resolution **~35 ps**



TOF test with pions and protons at $2 \text{ GeV}/c$.

Distance between start counter and MCP-PMT is 65cm

→ In the real detector $\sim 2\text{m}$

→ 3x better separation



Components of an experimental apparatus ('spectrometer')

- Tracking and vertexing systems
- Particle identification devices
- **Calorimeters (measurement of energy)**



Calorimetry Design: B factories

Requirements

- Best possible energy and position resolution: 11 photons per $Y(4S)$ event; 50% below 200 MeV in energy
- Acceptance down to lowest possible energies and over large solid angle
- Electron identification down to low momentum

Constraints

- Cost of raw materials and growth of crystals
- Operation inside magnetic field
- Background sensitivity

Implementation

Thallium-doped Cesium-Iodide crystals with 2 photodiodes per crystal

Thin structural cage to minimize material between and in front of crystals

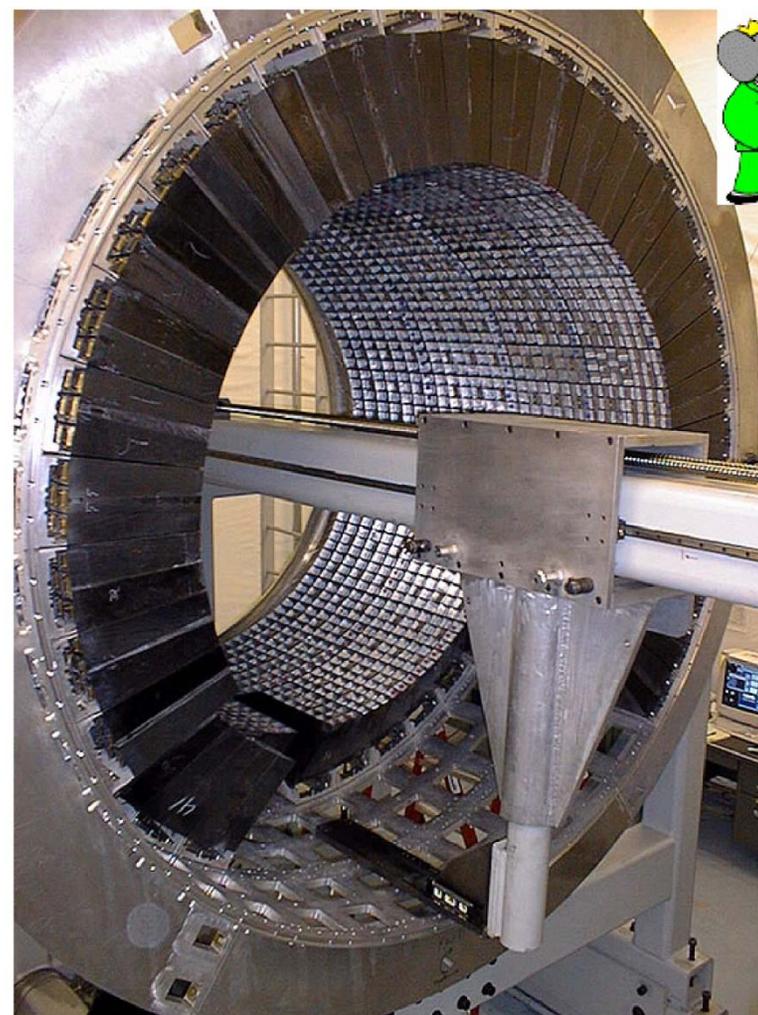
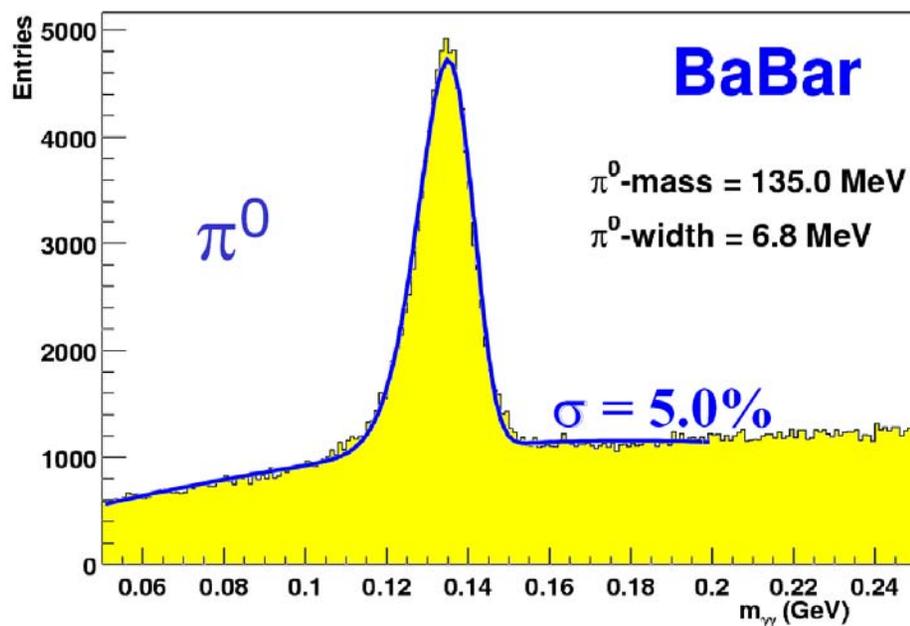


Calorimetry: BaBar

6580 CsI(Tl) crystals with
photodiode readout

About $18 X_0$, inside solenoid

$$\frac{\sigma(E)}{E} = \frac{(2.32 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E}} \oplus (1.85 \pm 0.07 \pm 0.1)\%$$

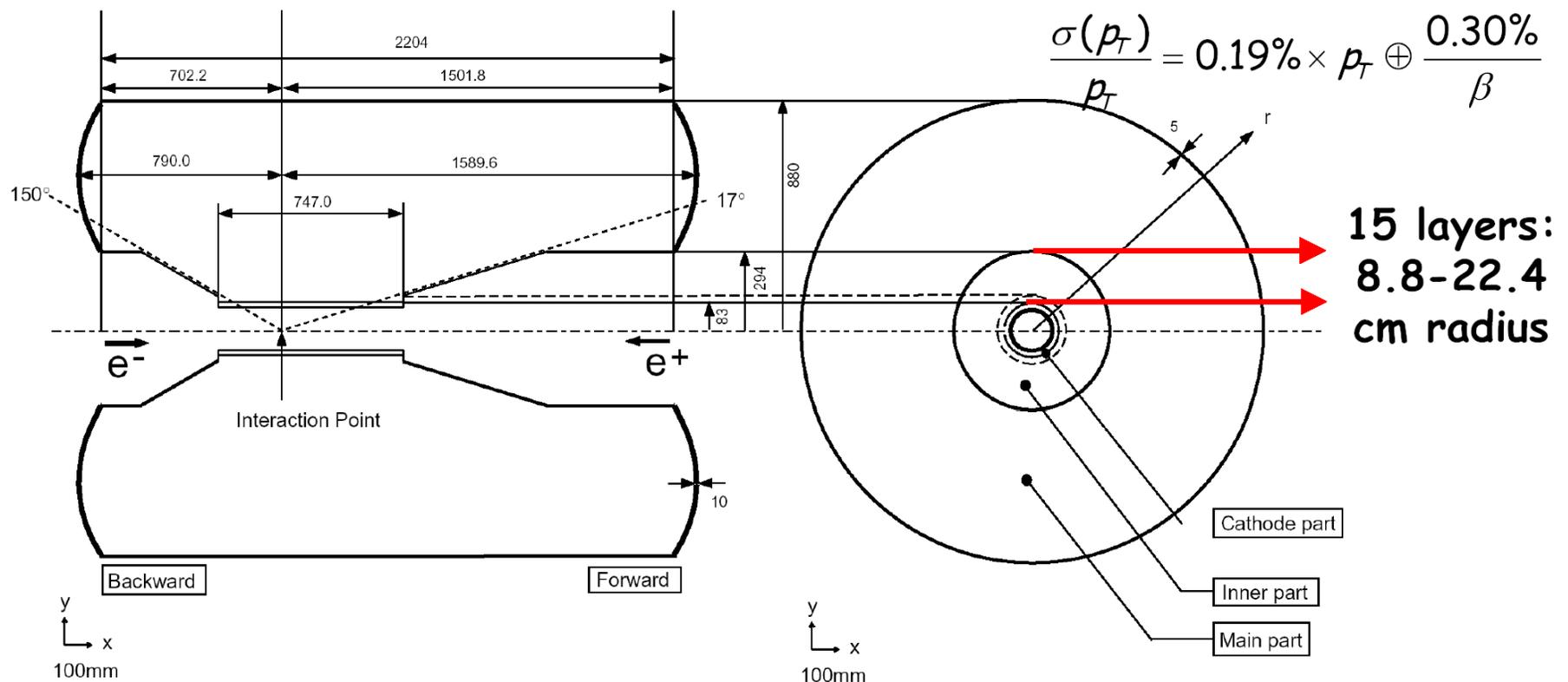




Belle central drift chamber



- 50 layers of wires (8400 cells) in 1.5 Tesla magnetic field
- Helium:Ethane 50:50 gas, Al field wires, CF inner wall with cathodes, and preamp only on endplates
- Particle identification from ionization loss (5.6-7% resolution)





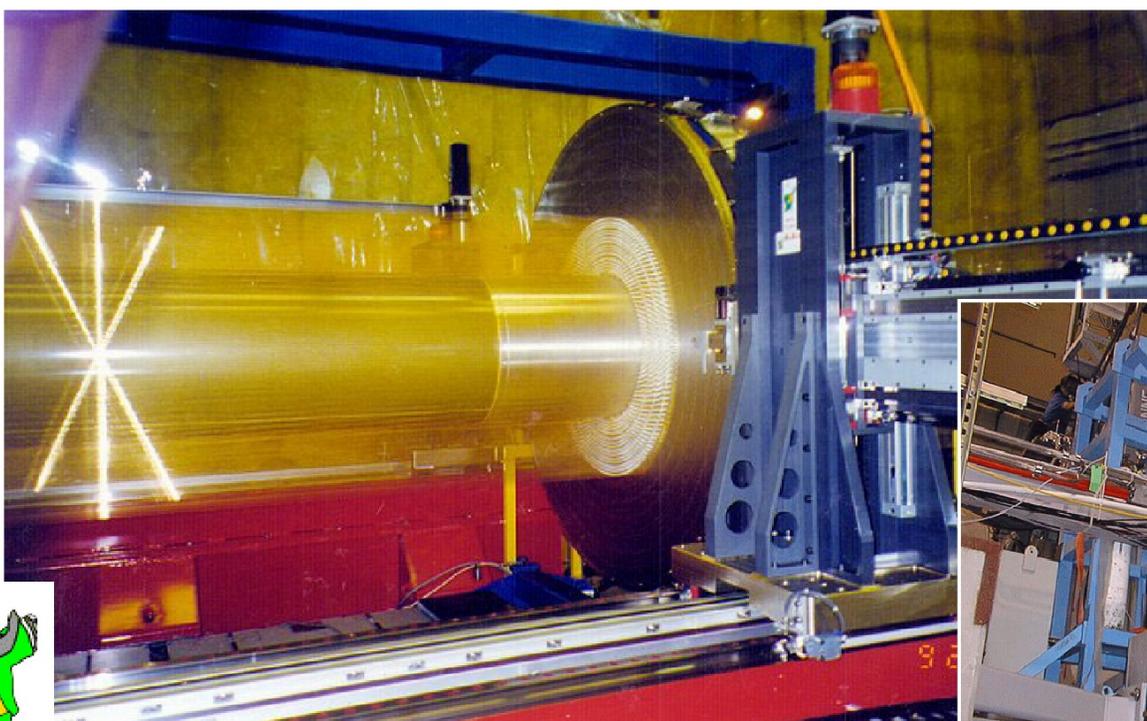
Tracking: BaBar drift chamber



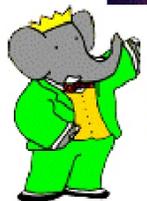
40 layers of wires (7104 cells) in 1.5 Tesla magnetic field

Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate

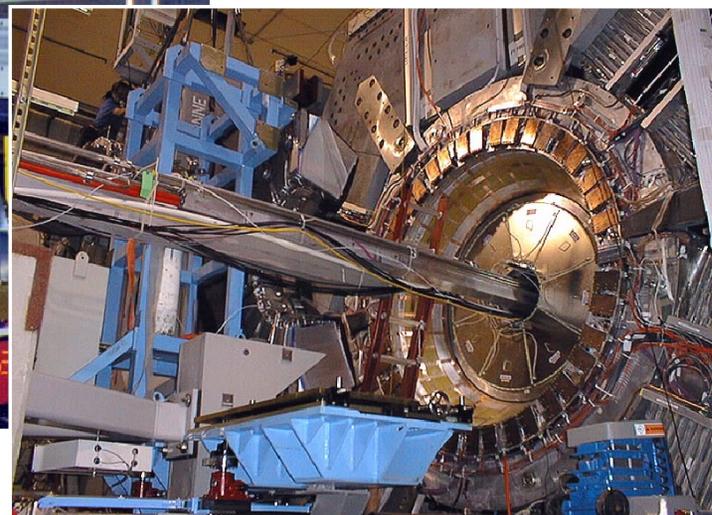
Particle identification from ionization loss (7% resolution)



$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$



16 axial, 24 stereo layers





TRT performance

at 90% electron efficiency

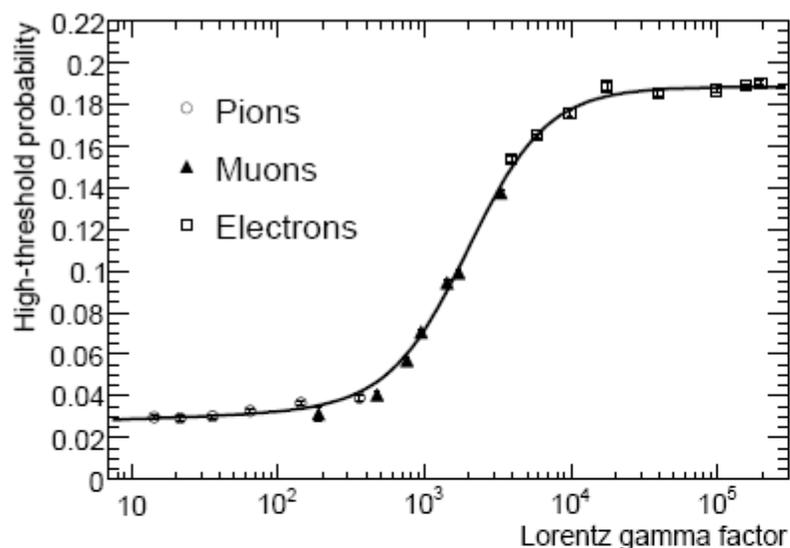


Figure 10.25: Average probability of a high-threshold hit in the barrel TRT as a function of the Lorentz γ -factor for electrons (open squares), muons (full triangles) and pions (open circles) in the energy range 2–350 GeV, as measured in the combined test-beam.

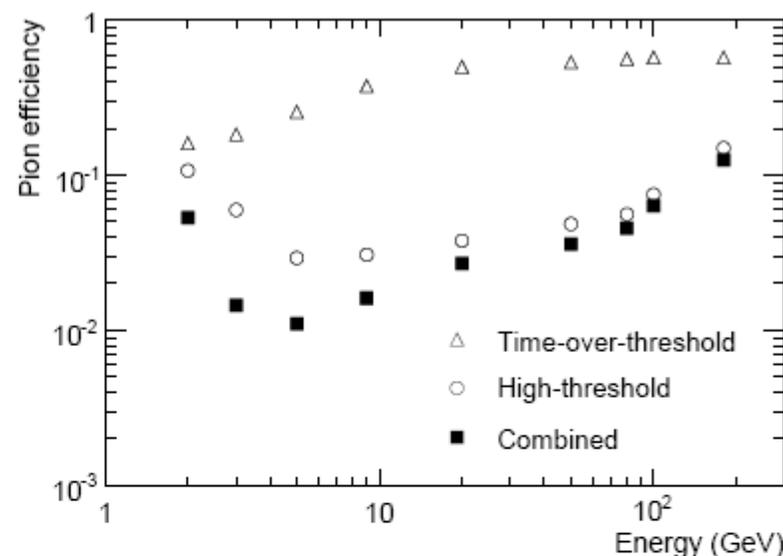


Figure 10.26: Pion efficiency shown as a function of the pion energy for 90% electron efficiency, using high-threshold hits (open circles), time-over-threshold (open triangles) and their combination (full squares), as measured in the combined test-beam.



ATLAS: muon fake probability

Sources of fakes:

- Hadrons: punch through negligible, >10 interaction lengths of material in front of the muon system (remain: muons from pion and kaon decays)
- Electromagnetic showers triggered by energetic muons traversing the calorimeters and support structures lead to low-momentum electron and positron tracks, an irreducible source of fake stand-alone muons. Most of them can be rejected by a cut on their transverse momentum ($p_T > 5$ GeV reduces the fake rate to a few percent per triggered event); can be almost entirely rejected by requiring a match of the muon-spectrometer track with an inner-detector track.
- Fake stand-alone muons from the background of thermal neutrons and low energy γ -rays in the muon spectrometer ("cavern background"). Again: $p_T > 5$ GeV reduces this below 2% per triggered event at 10^{33} cm^{-2} s^{-1} . Can be reduced by almost an order of magnitude by requiring a match of the muon-spectrometer track with an inner-detector track.



Luminosity: improvement in time

Luminosity of KEKB
Oct. 1999 - Dec. 2006

