

Napredni detektorji delcev in obdelava podatkov (NDDOP) - Uvod

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Fizika jedra in osnovnih delcev na FMF



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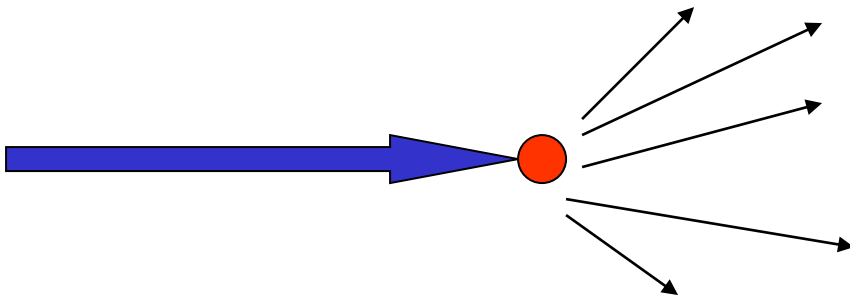
Analysis of data

Particle physics experiments

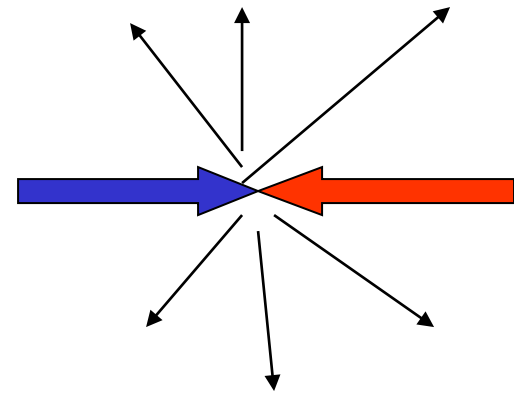
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

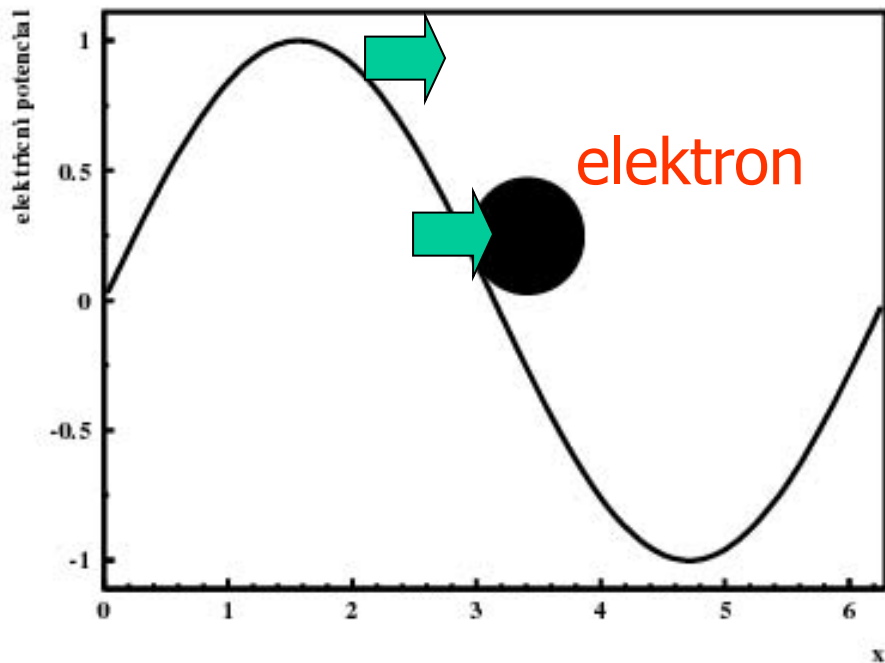


Collider experiments

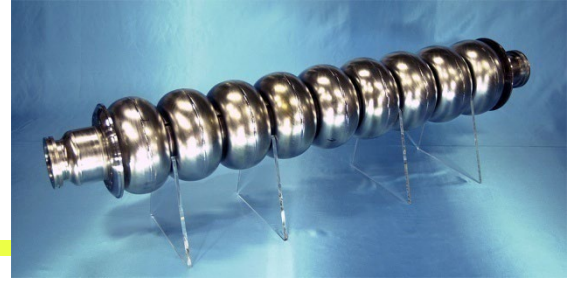


How to accelerate charged particles?

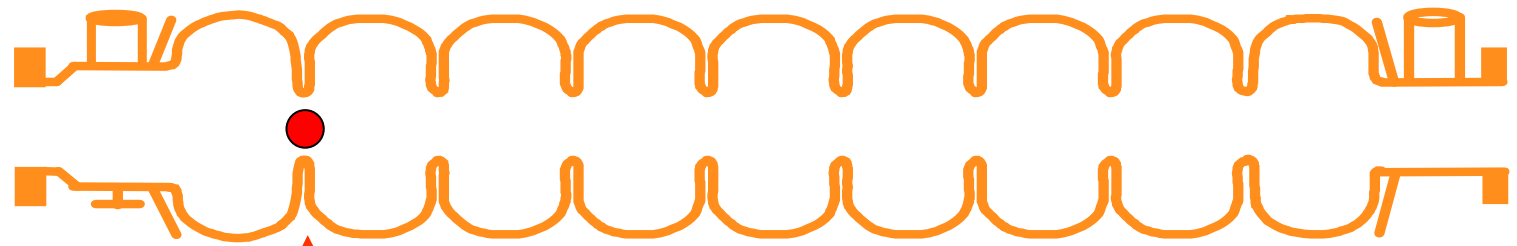
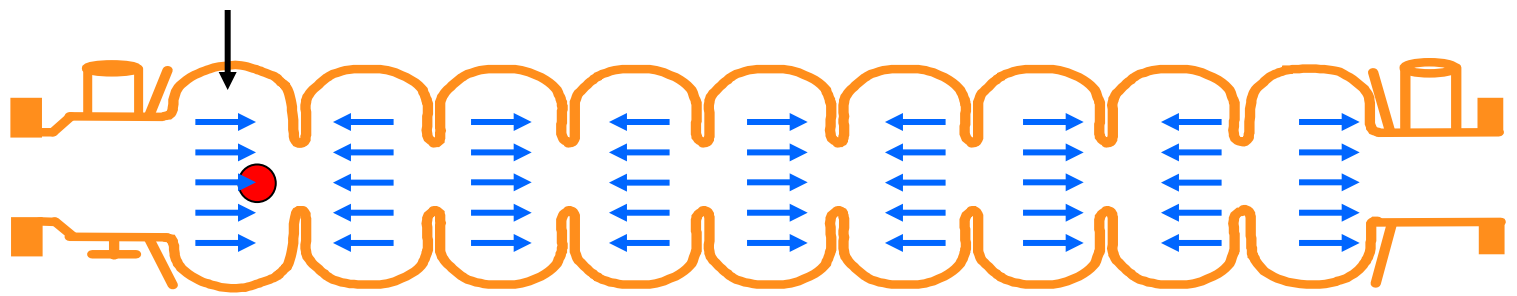
- Acceleration with electromagnetic waves (typical frequency is 500 MHz – mobile phones run at 900, 1800, 1900 MHz)
- Waves in a radiofrequency cavity: $c < c_0$



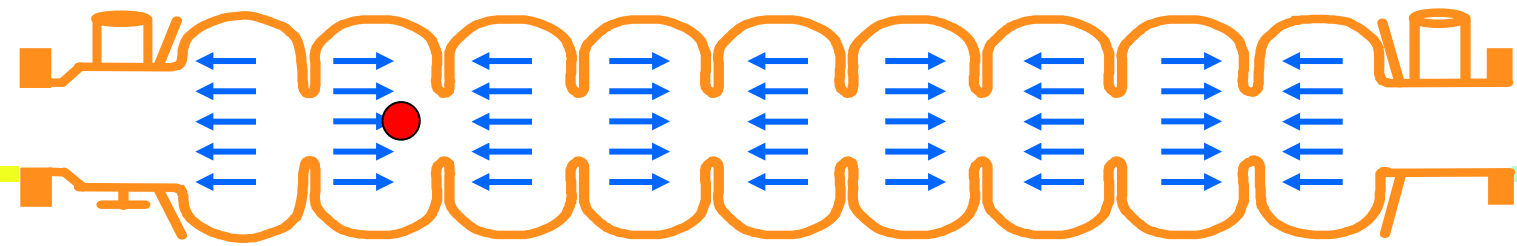
... Similar to surfing the waves



Electric field

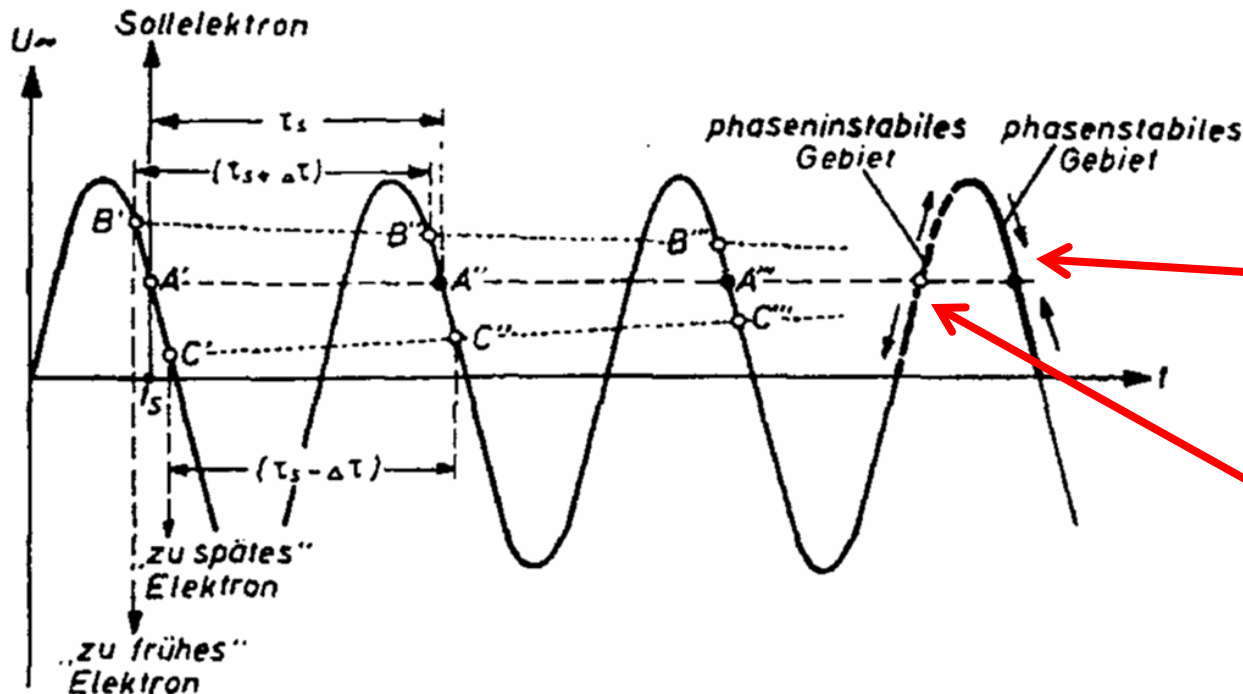


positron



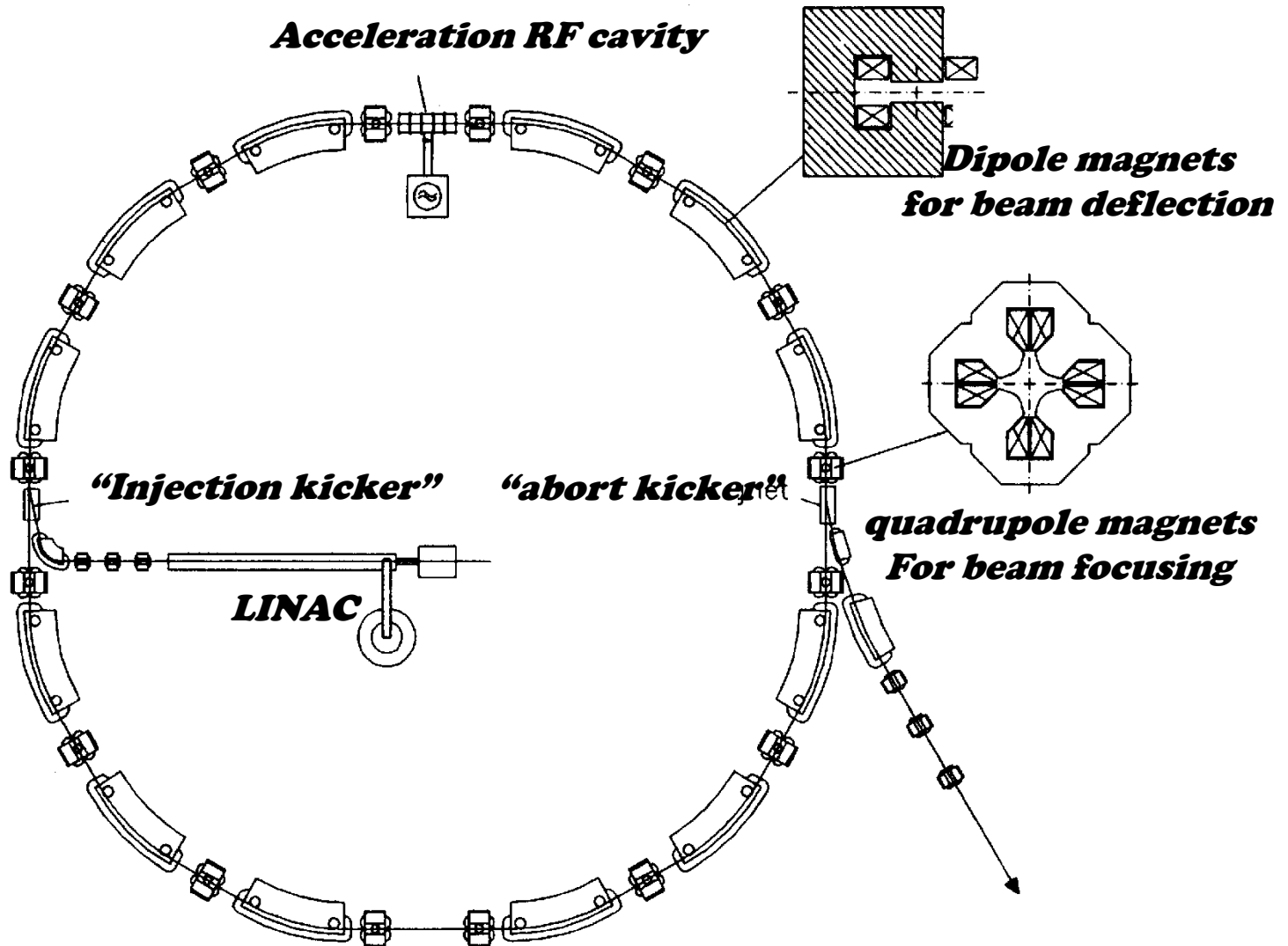
Stability of acceleration

- 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 →

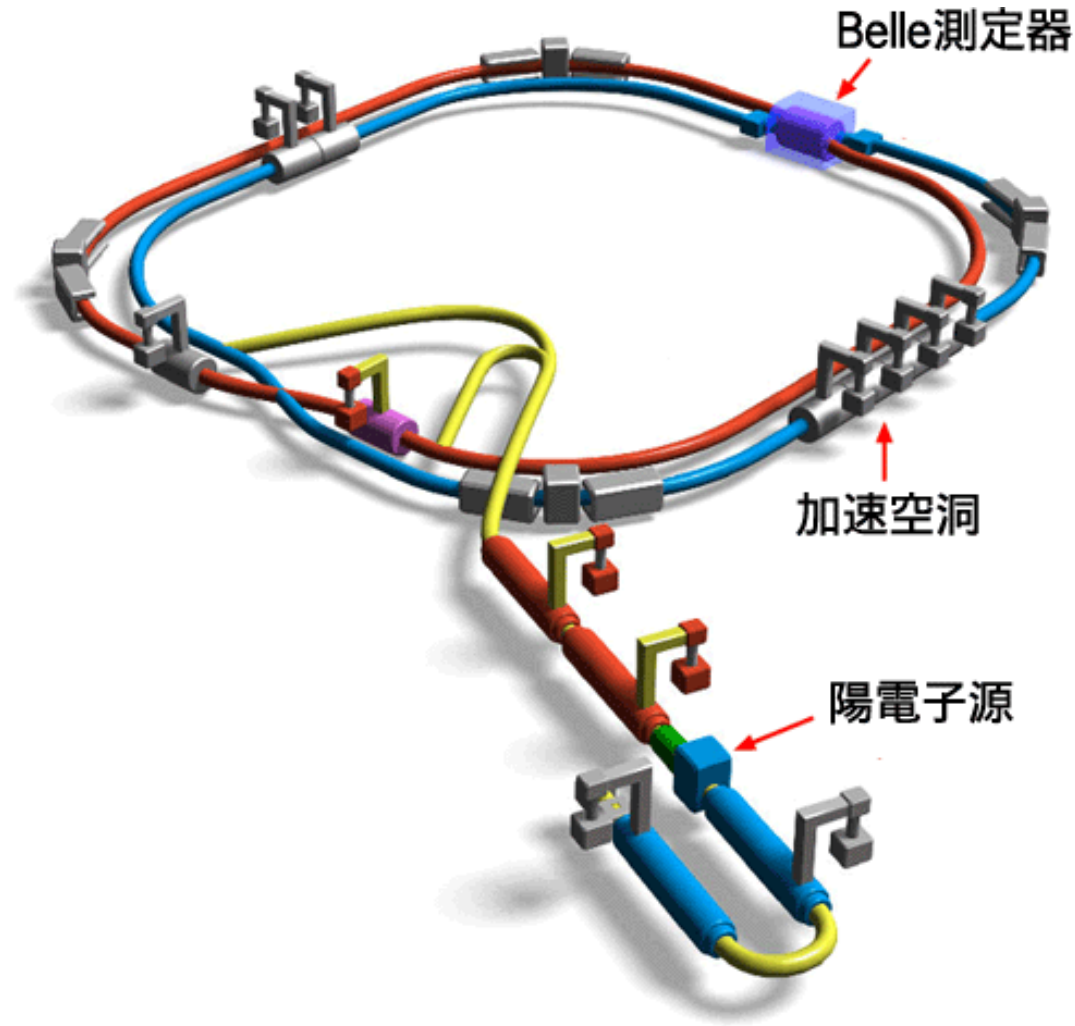
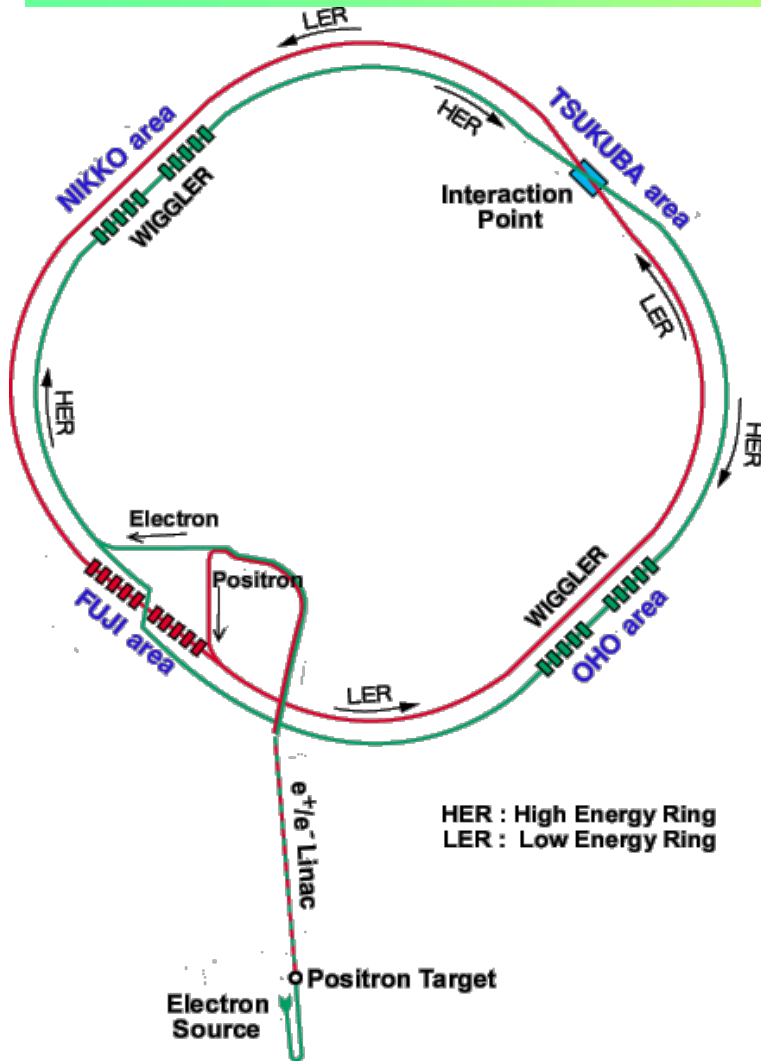


- OK if particle \sim in phase → stable orbit
- Not OK if too far away

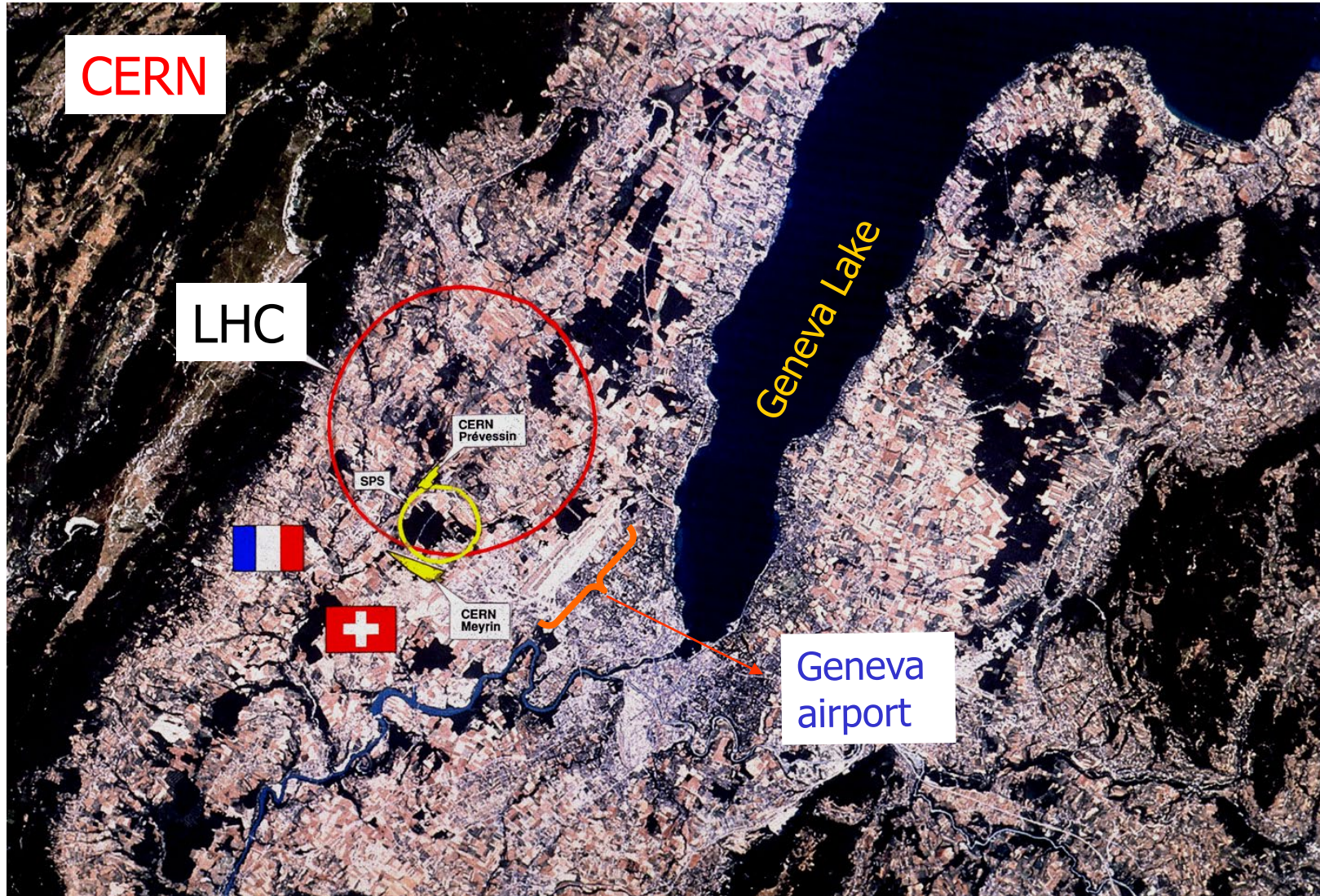
Synchrotron



Electron positron collider: KEK-B



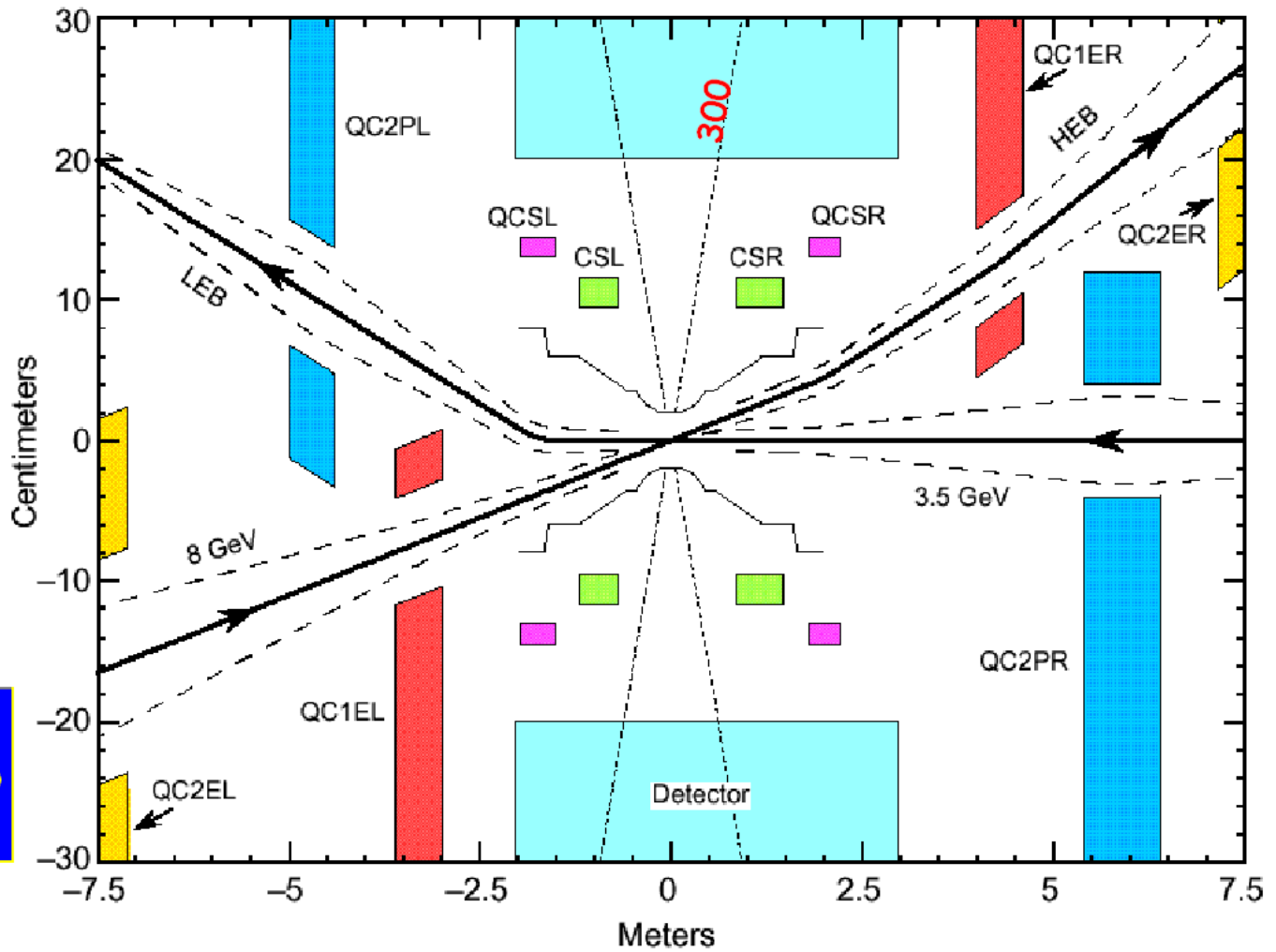
Large hadron collider



Interaction region: Belle

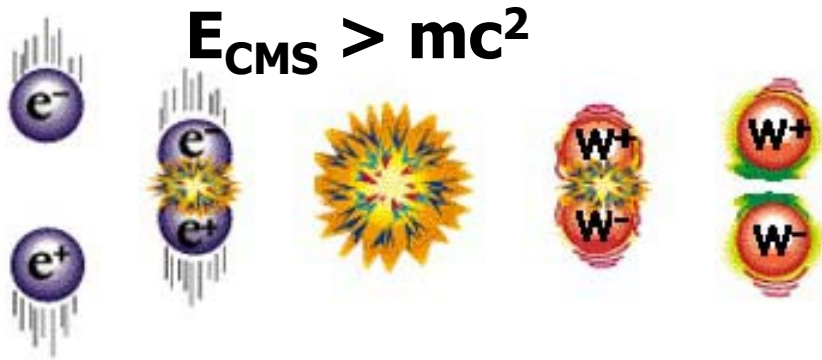
Collisions at a finite angle $\pm 11\text{mrad}$

KEKB Interaction Region

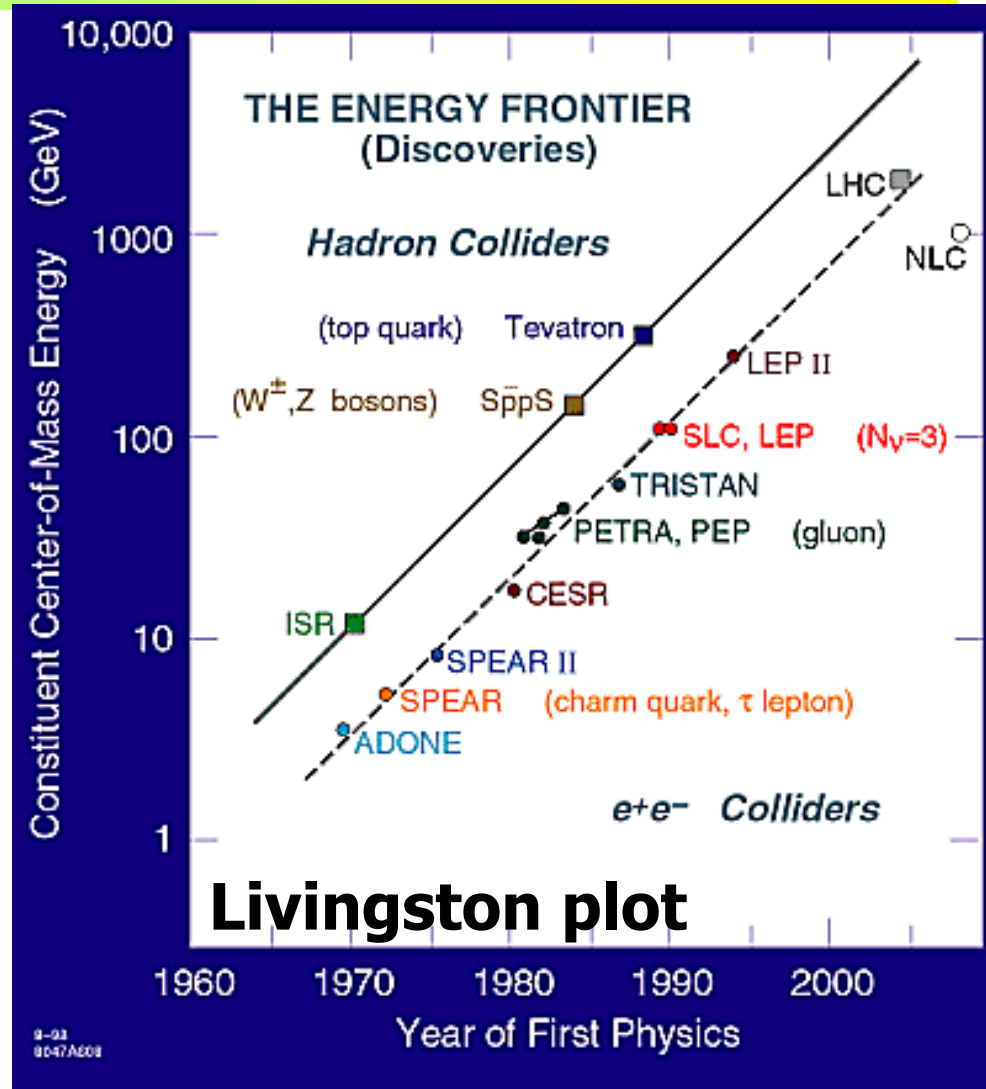


Accelerator figure of merit 1: Center-of-mass energy

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

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

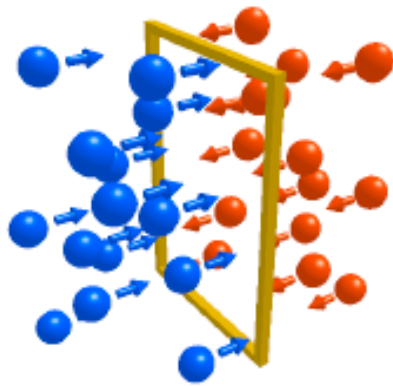
Accelerator figures of merit: **luminosity L**

and **integrated luminosity**

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

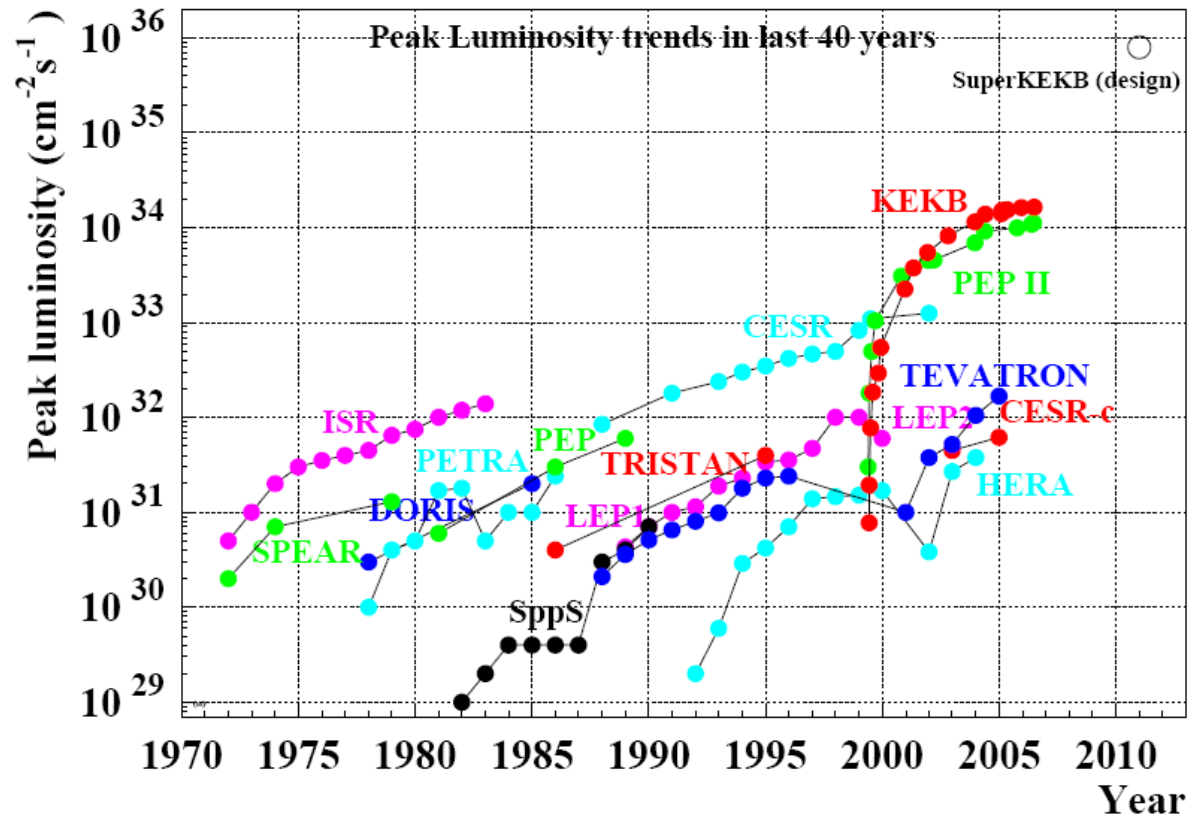
Luminosity vs time

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



(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

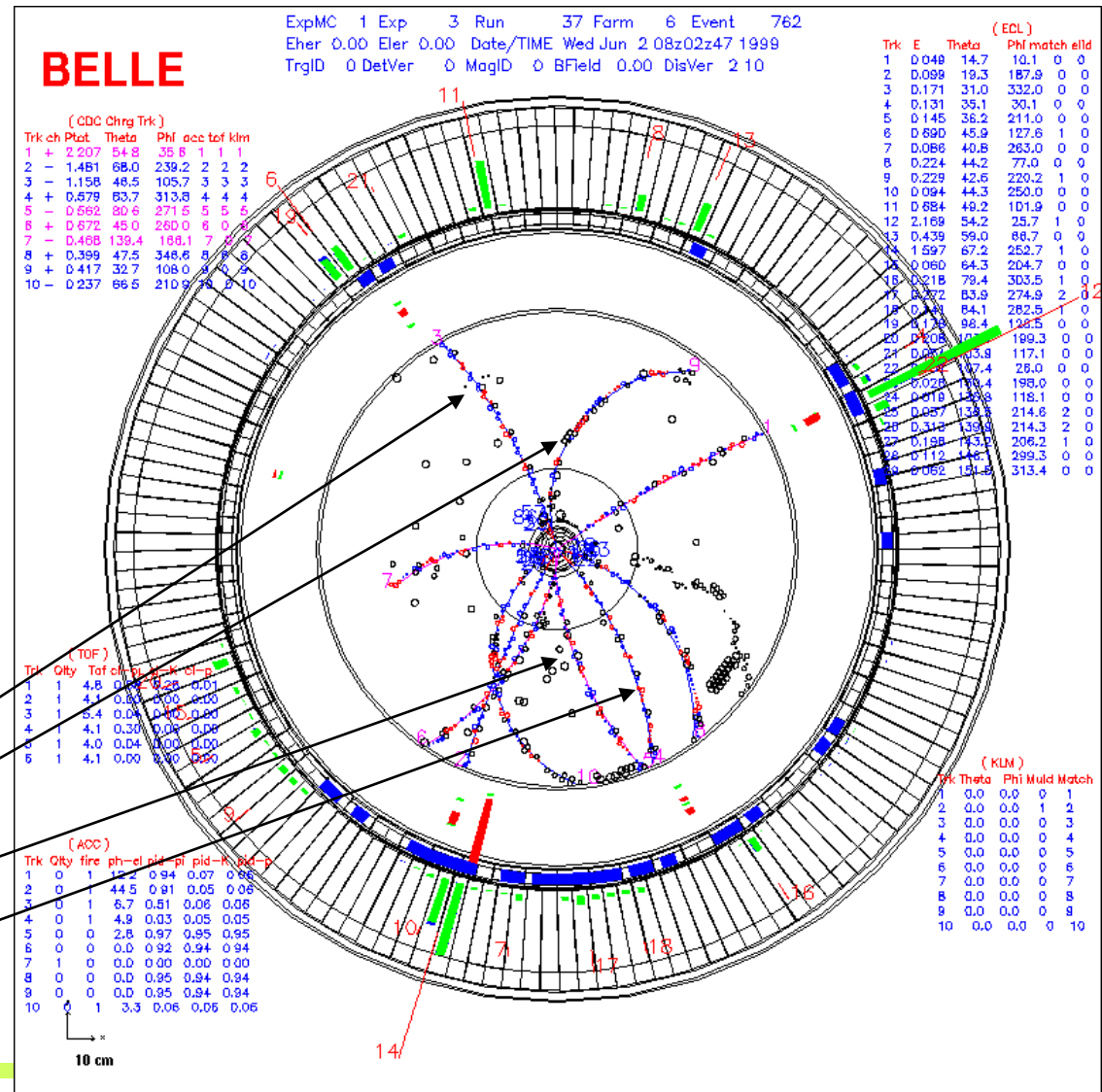
How to understand what happened in a collision?

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 reconstruct final states which decayed to several stable particles (e.g., 1,2,3)?

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

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

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?

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

$$K^0_S \rightarrow$$

$$\pi^- \pi^+$$

$$J/\psi \rightarrow$$

$$\mu^- \mu^+$$

detect

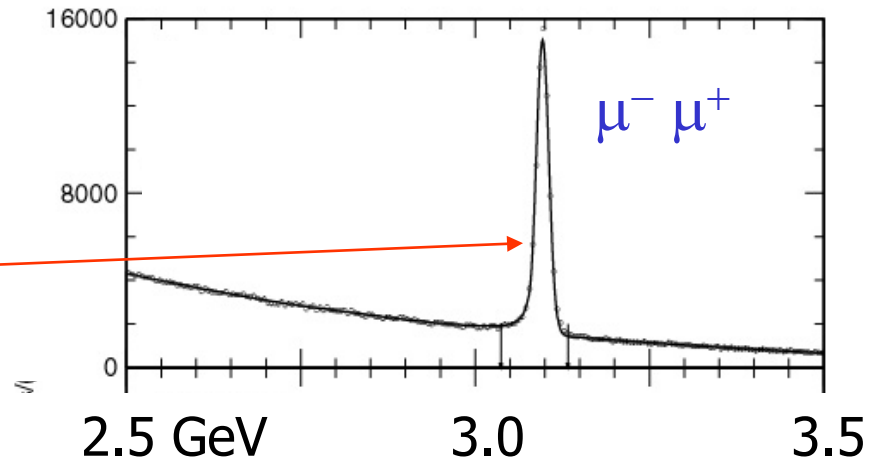
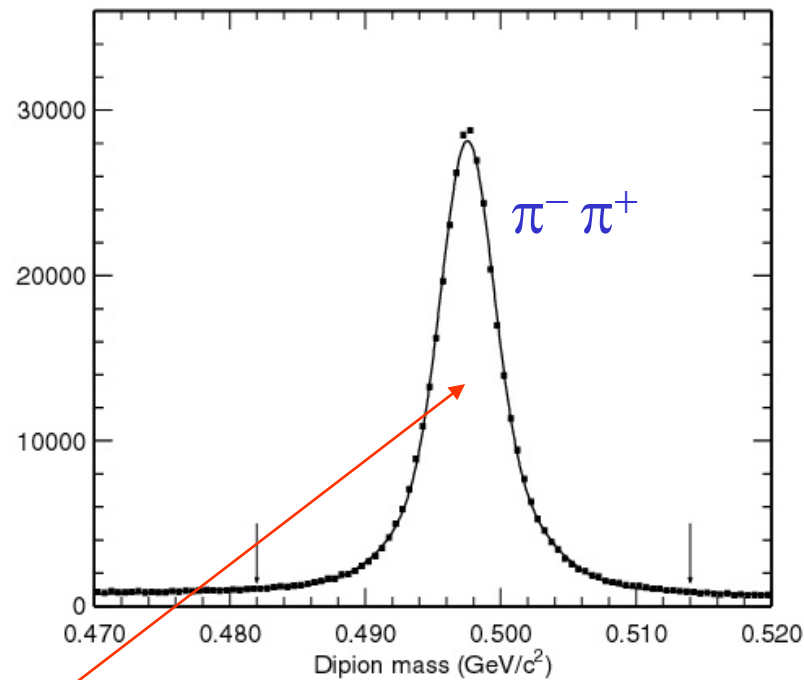
For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

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

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

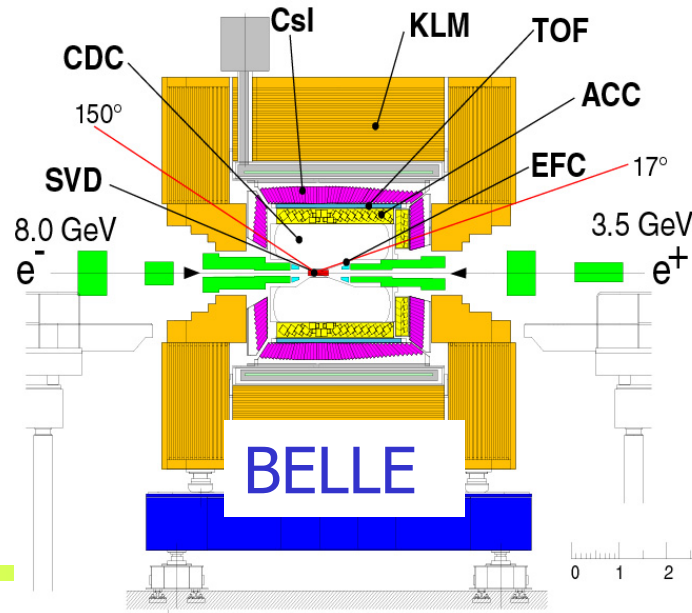
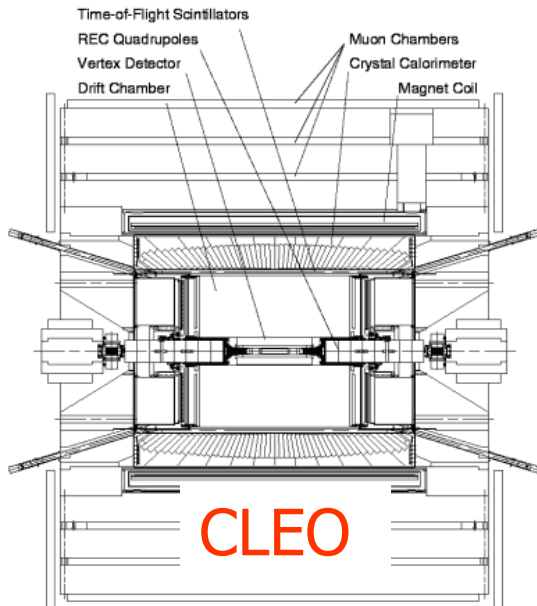
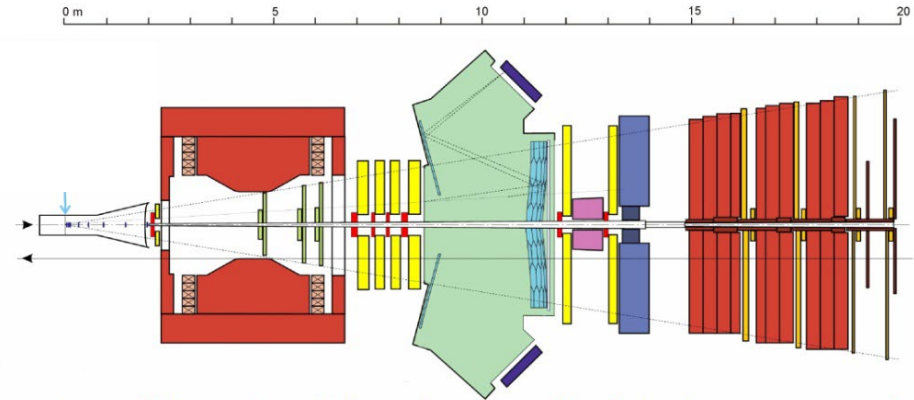
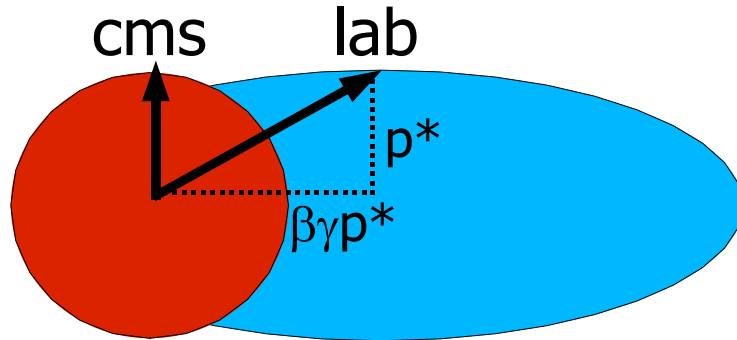
for J/ψ close to **3.1 GeV**.

Rest in the histogram: random coincidences ('combinatorial background')

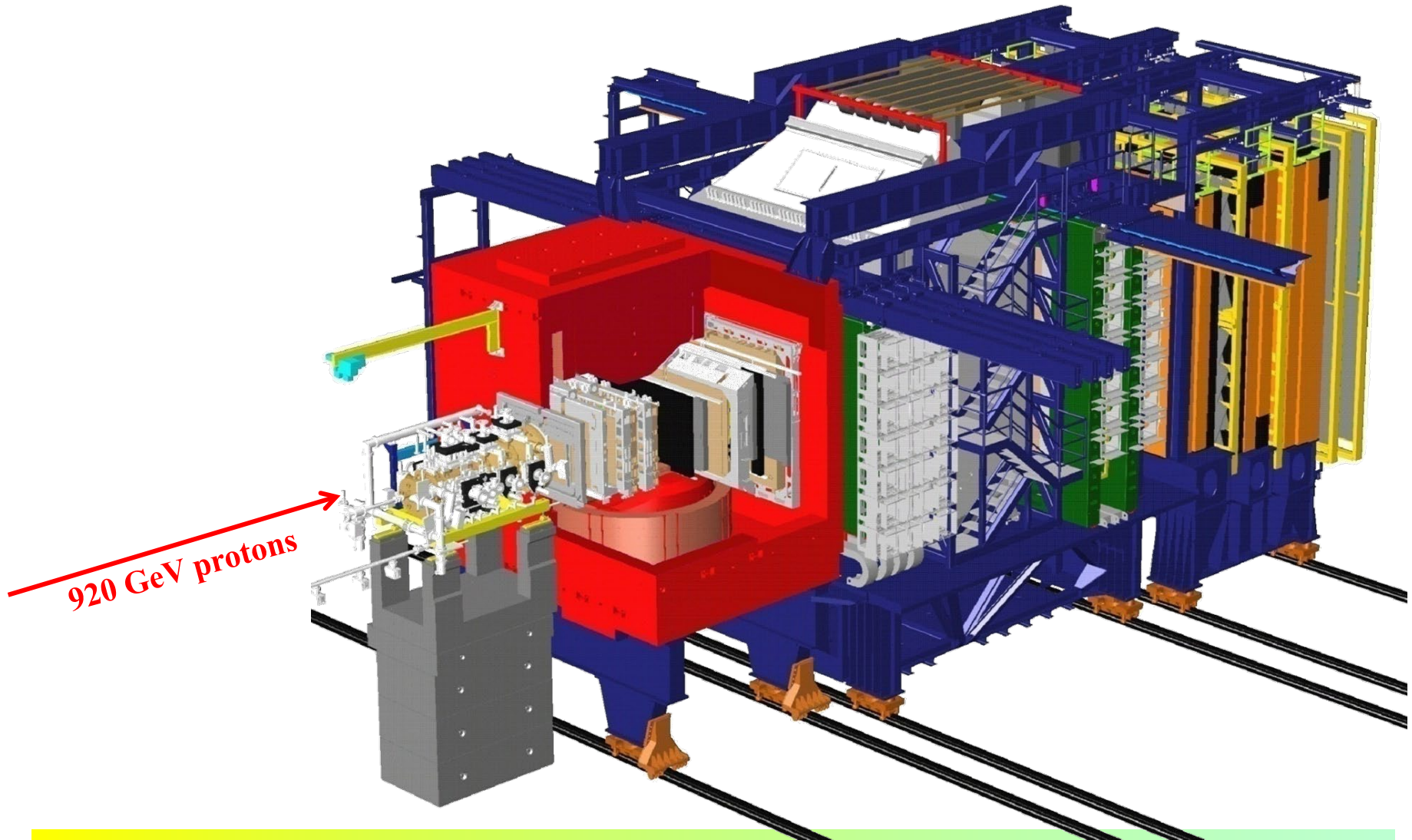
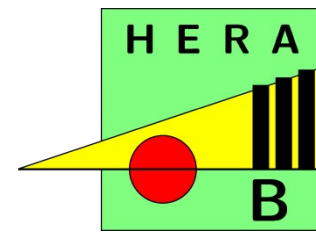


Experimental apparatus

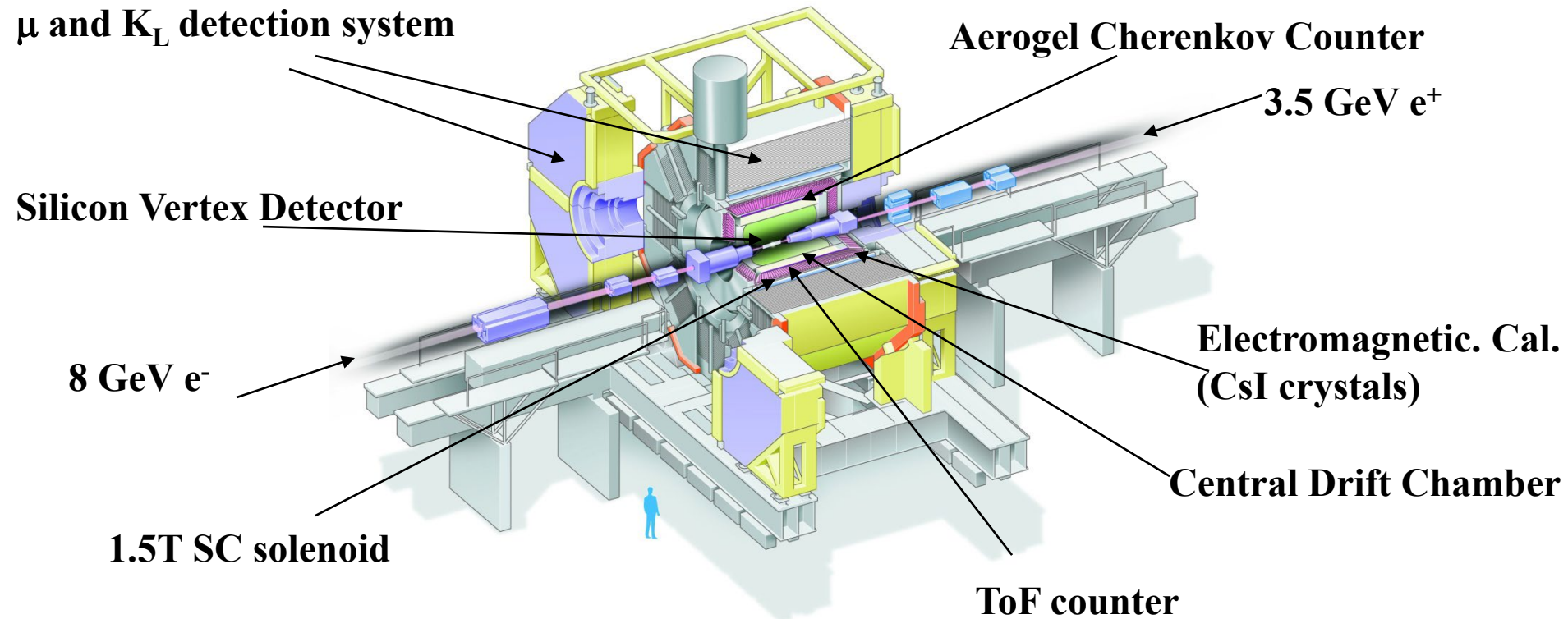
Detector form: **symmetric** for colliders with symmetric energy beams; **extended in the boost direction** for an asymmetric collider; **very forward oriented** in fixed target experiments.




Example of a fixed target experiment: HERA-B



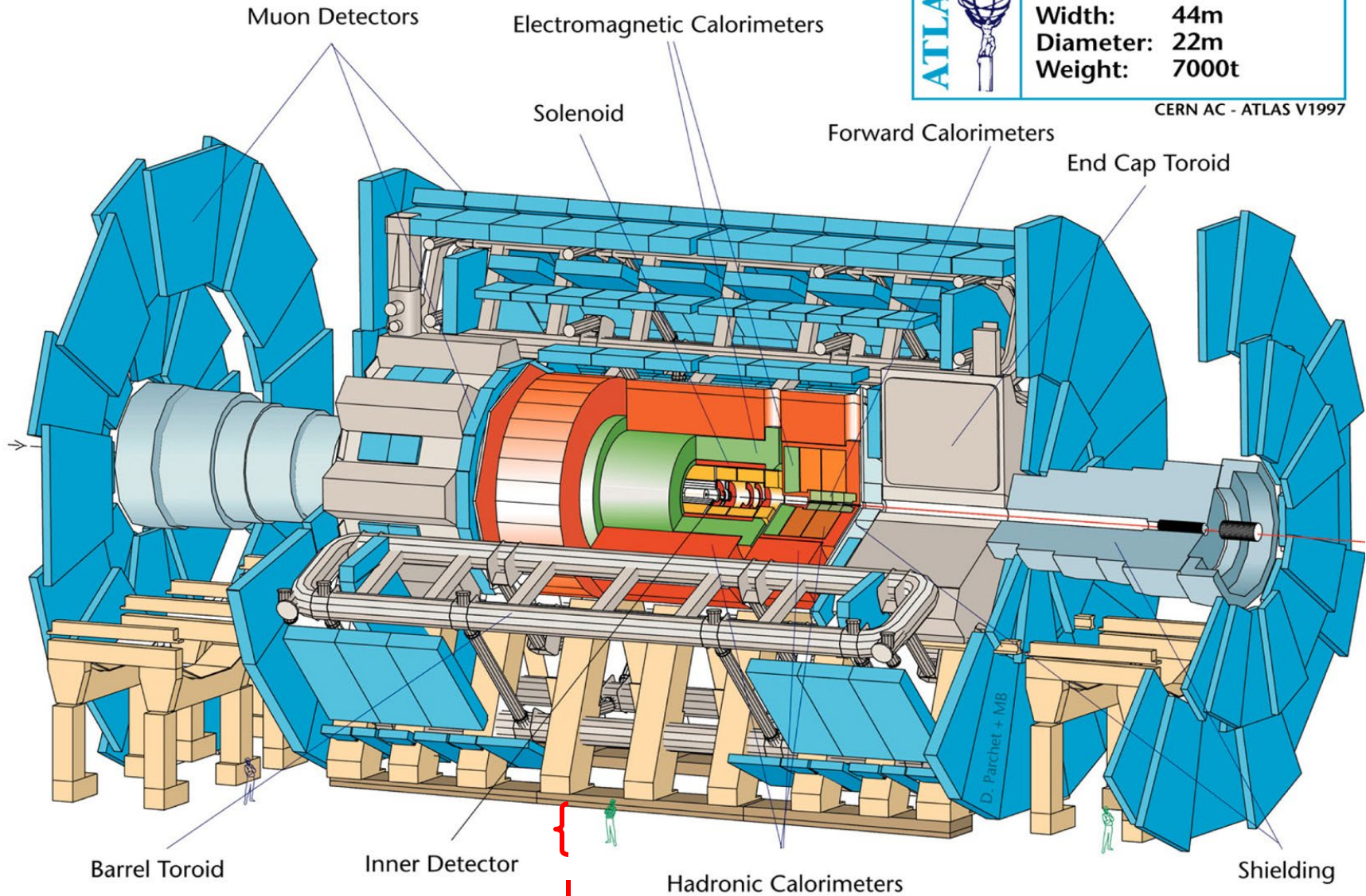
Belle spectrometer at KEK-B



ATLAS at LHC

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

CERN AC - ATLAS V1997



A physicist...

Peter Križan, Ljubljana

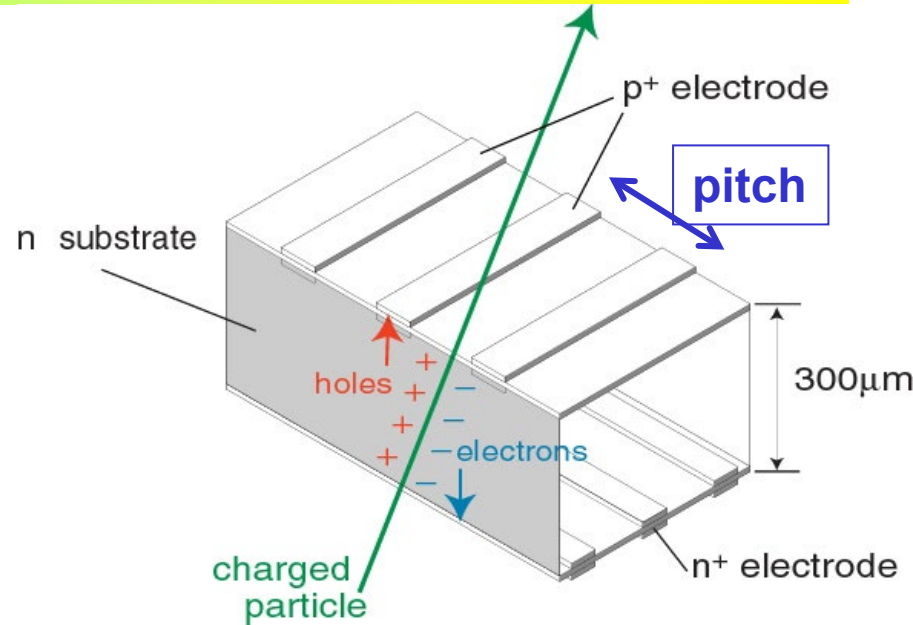
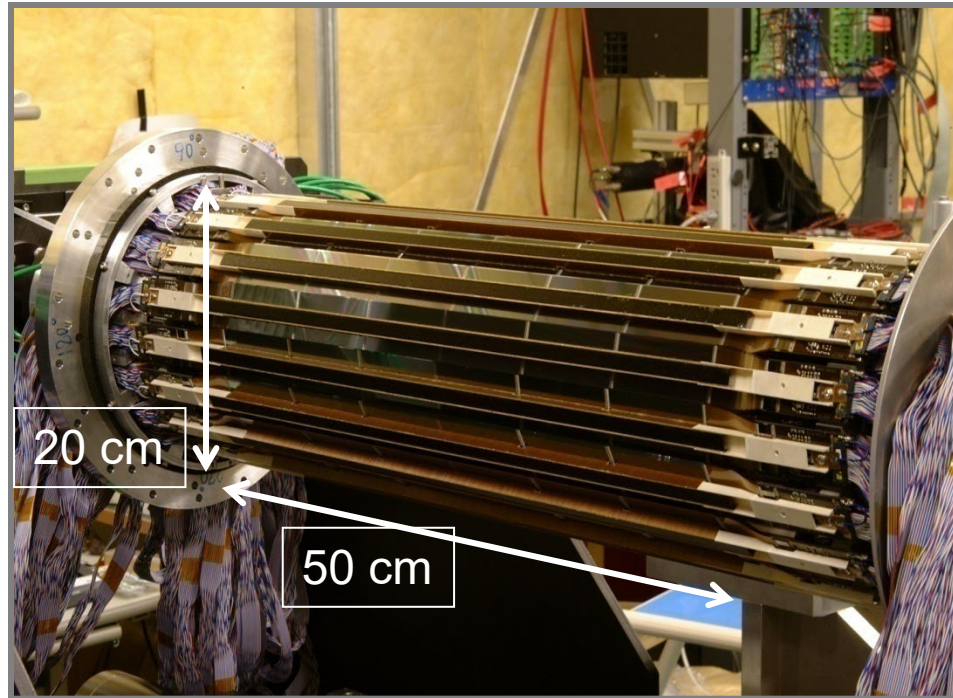
Components of an experimental apparatus ('spectrometer')

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

Components of an experimental apparatus ('spectrometer')

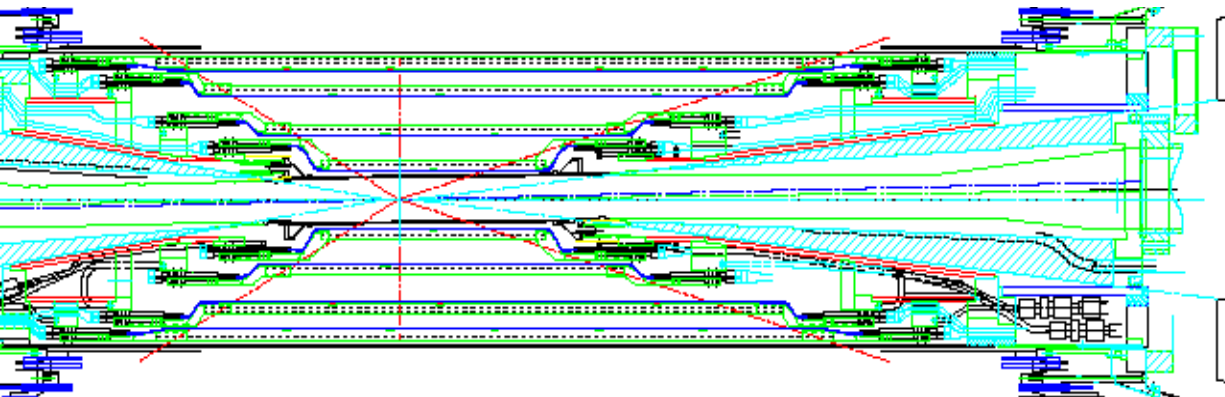
- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

Silicon vertex detector (SVD)



Two coordinates
measured at the same
time

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

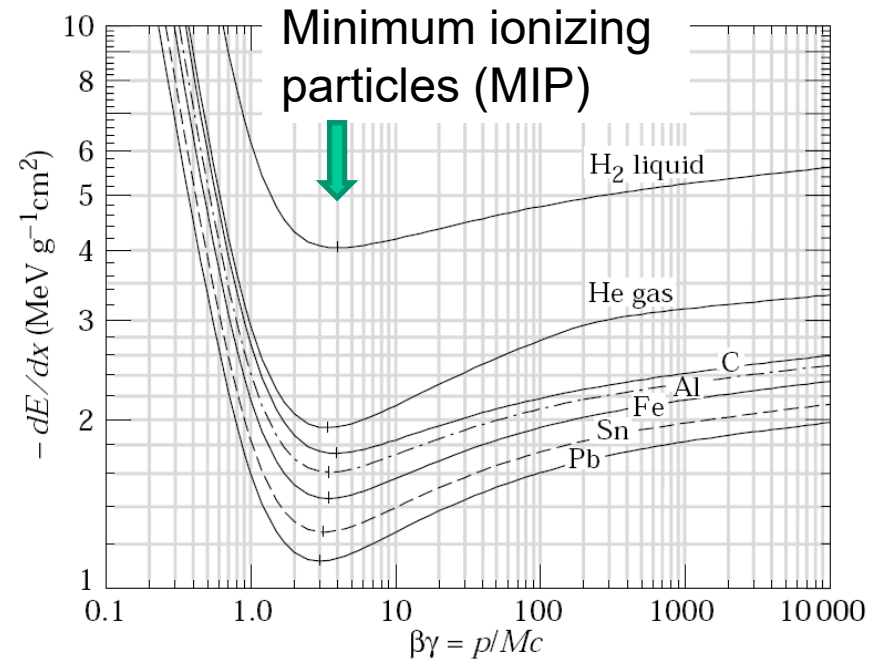


Interaction of charged particles with matter

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

Liquids, solids: few MeV/cm

Gases: **few keV/cm**



Bethe-Bloch equation

Straggling functions: energy loss distribution

Bethe-Bloch equation only give the average (mean) energy loss

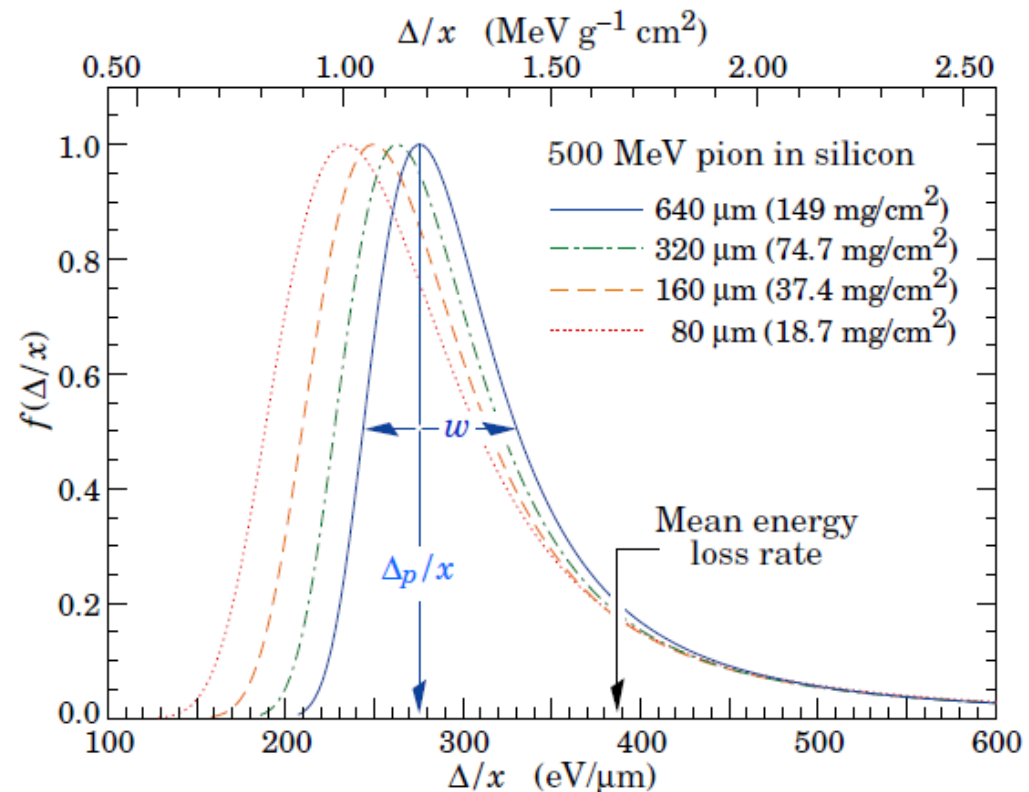


Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x . The width w is the full width at half maximum. See full-color version on color pages at end of book.

Electrons: fractional energy loss, $1/E \, dE/dx$

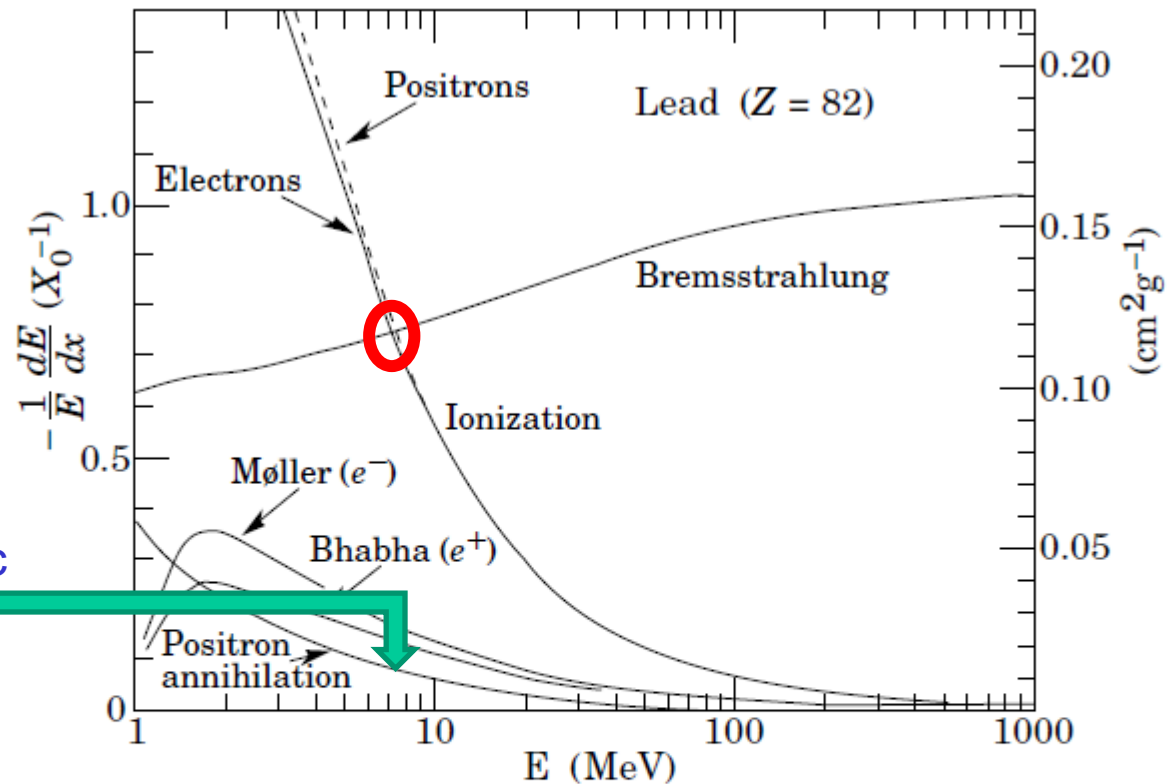


Figure 27.10: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\text{Pb}) = 5.82 \text{ g/cm}^2$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\text{Pb}) = 6.37 \text{ g/cm}^2$).

Multiple Coulomb scattering

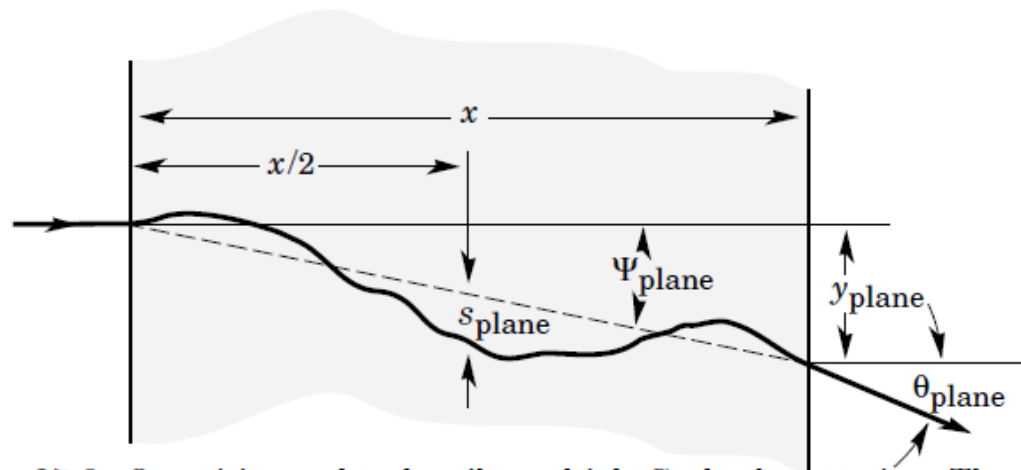


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Interaction of charged particles with matter

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

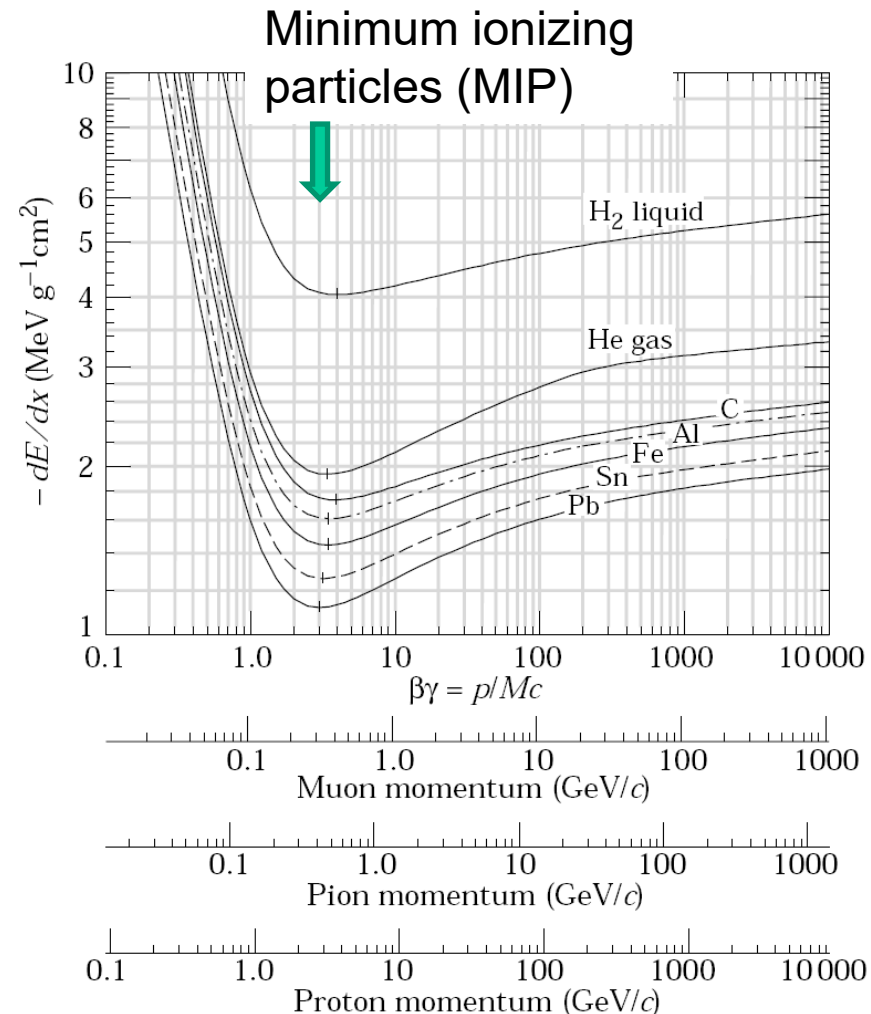
Liquids, solids: few MeV/cm

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



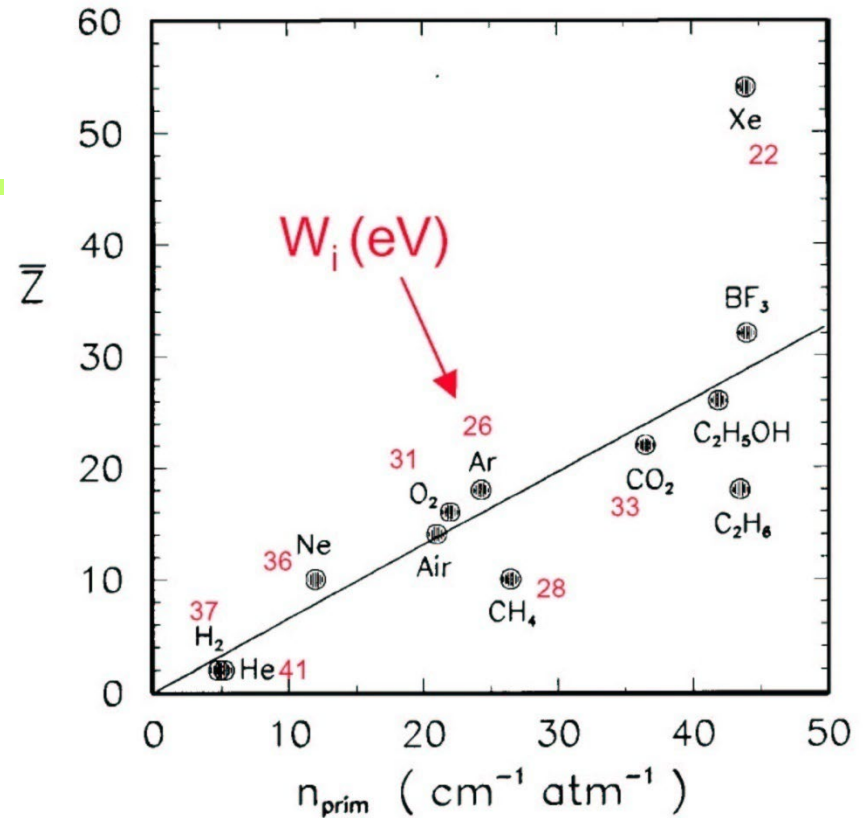
Ionisation

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



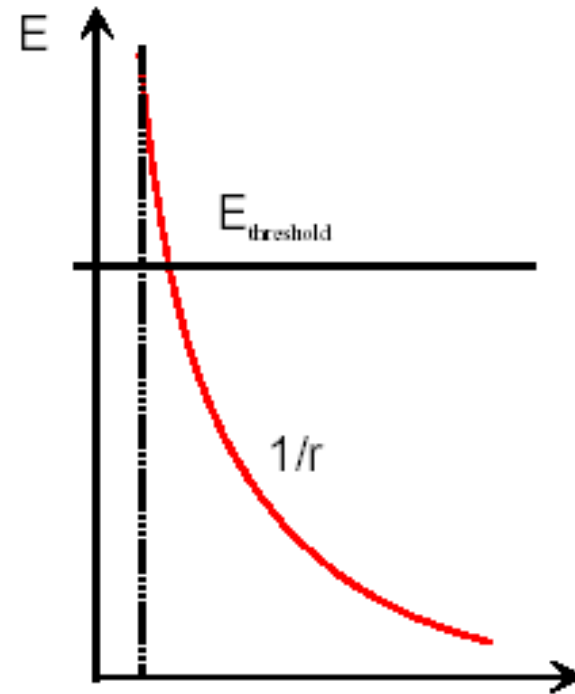
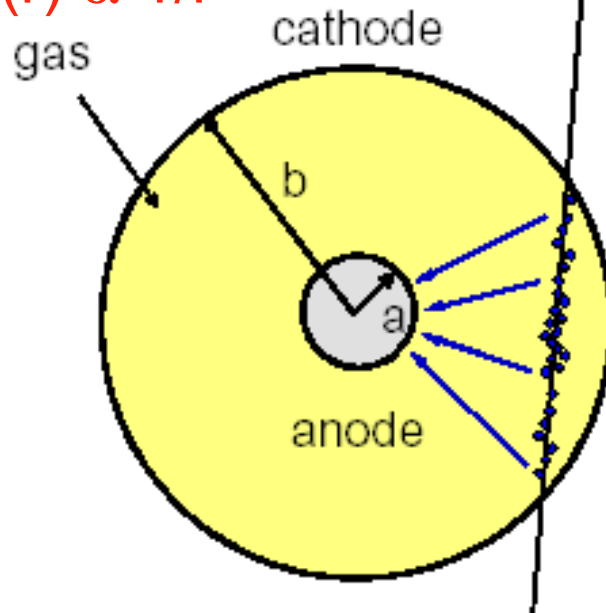
Can this be detected? 120 e-ion pairs make a pulse of
 $V=ne/C=2\text{mV}$ (at typical $C=10\text{pF}$) → NO

-> Need multiplication

Multiplication in gas

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

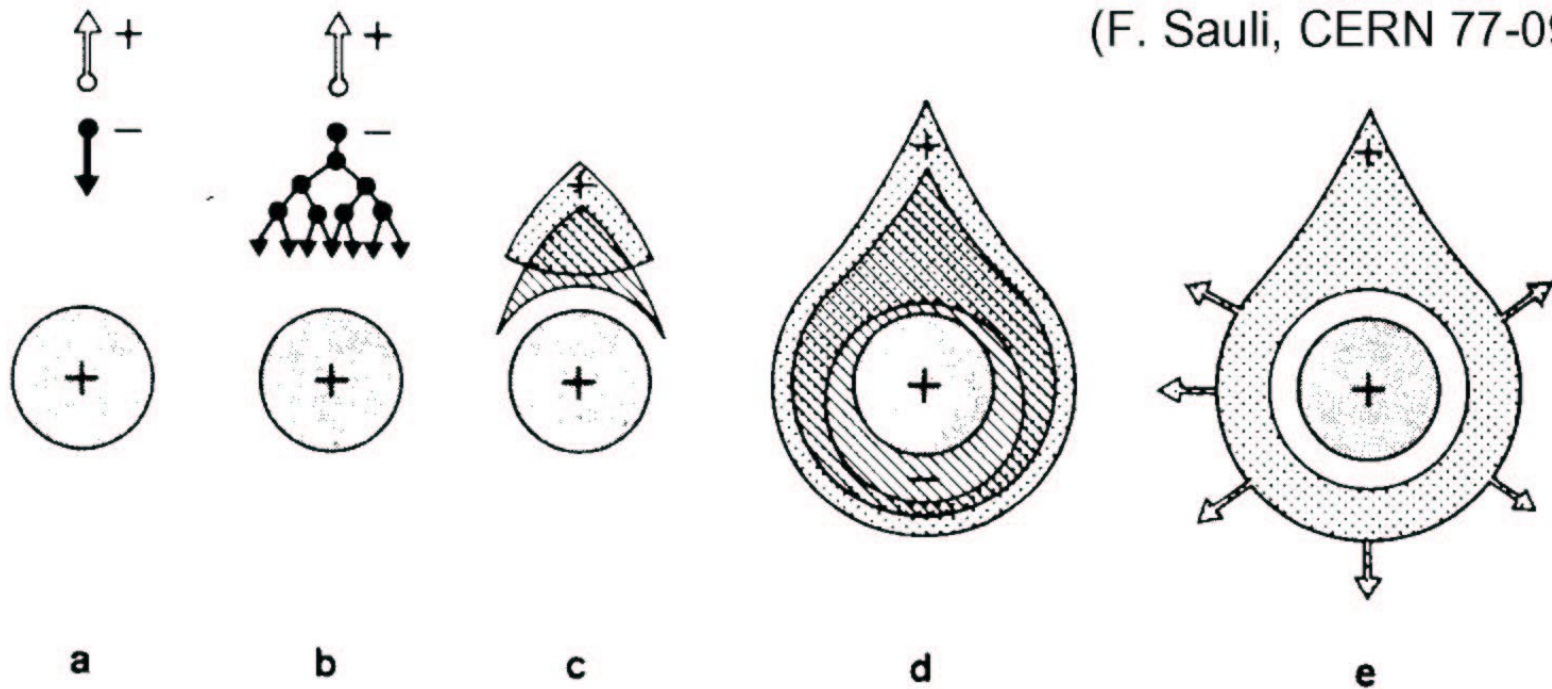
$$E = E(r) \propto 1/r$$



If the energy eEd gained over several mean free paths (d around 10mm) exceeds the ionisation energy \rightarrow new electron
Electric field needed $\rightarrow E = I/ed = 10\text{V}/\mu\text{m} = 100\text{kV}/\text{cm}$

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

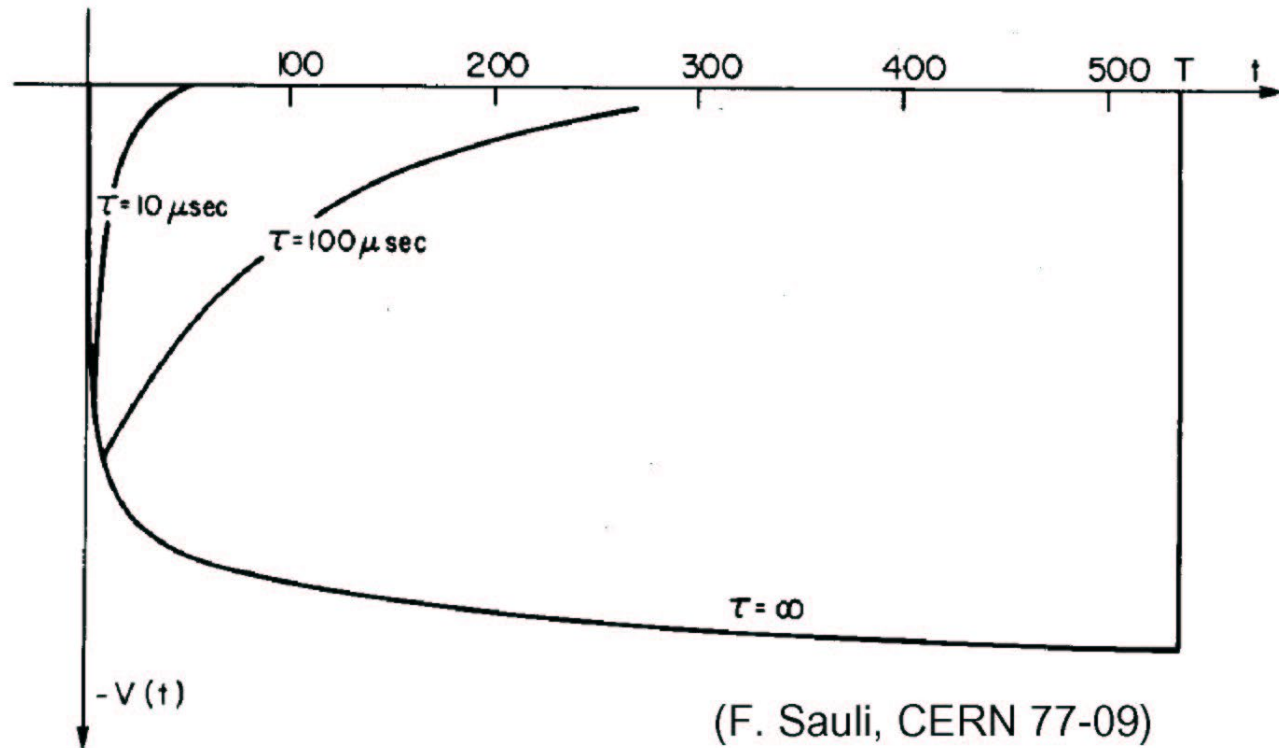
Time evolution of the signal

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

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

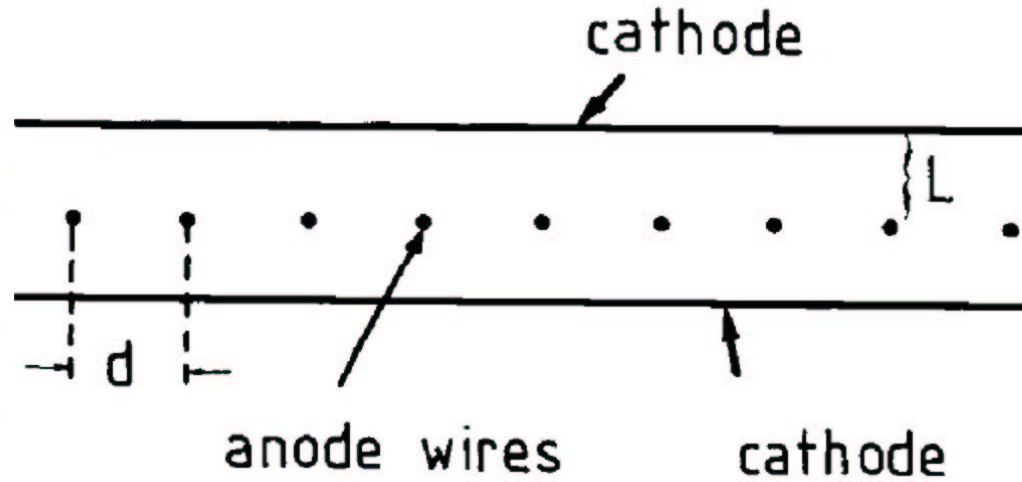
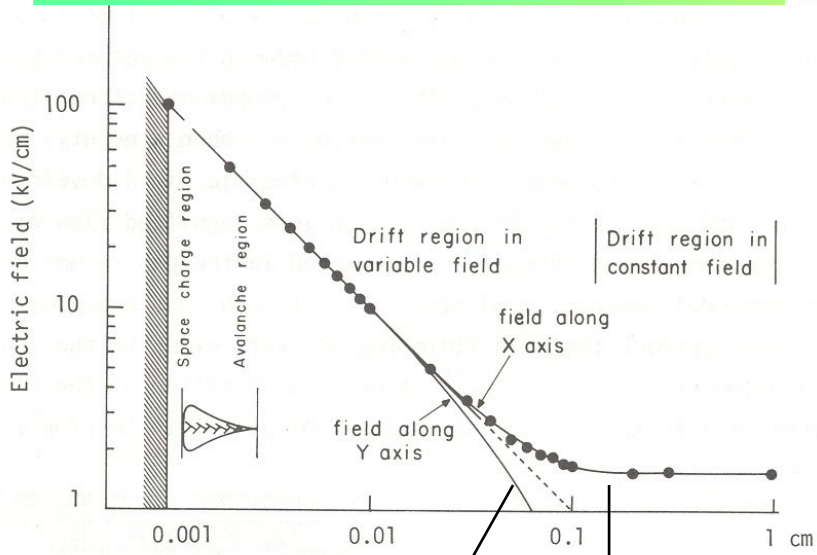
e.g. $\tau = 40\text{ns}$: max $u(t)$ is about $\frac{1}{4}$ of the $\tau = \text{inf.}$ case



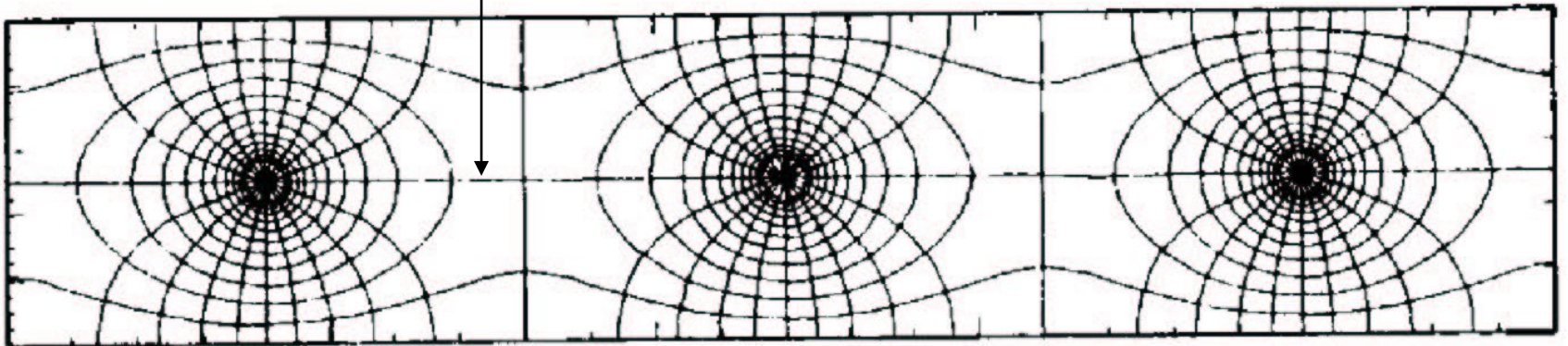
(F. Sauli, CERN 77-09)

Peter Križan, Ljubljana

Multiwire proportional chamber (MWPC)



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



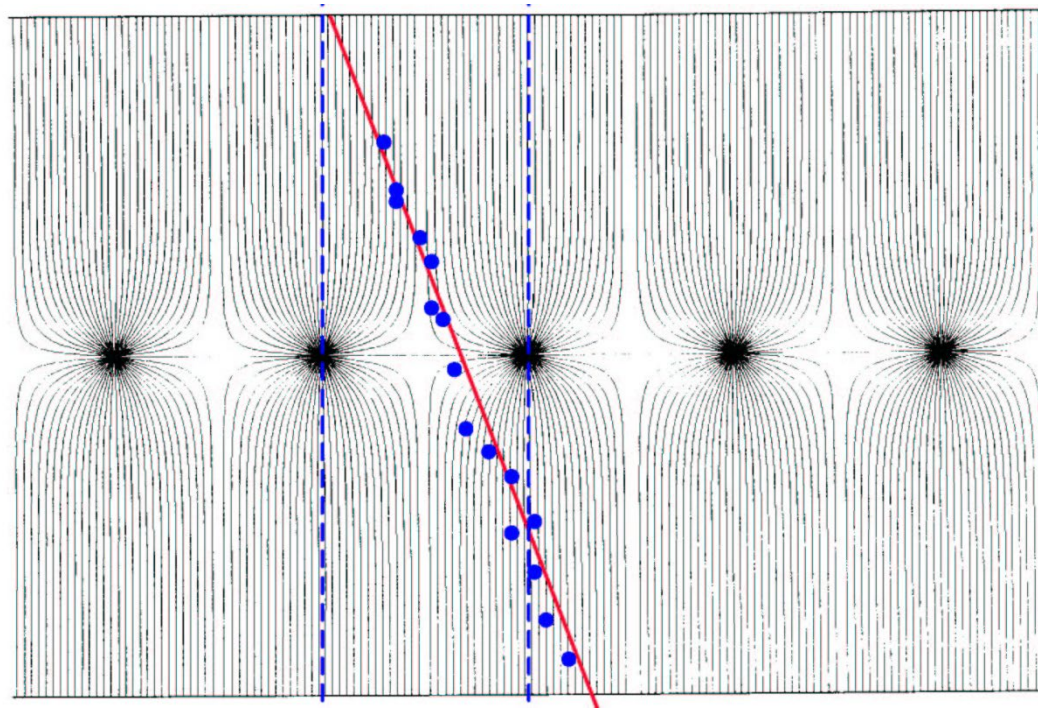
Multiwire proportional chamber (MWPC)

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

Normally digital readout:
spatial resolution limited to

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

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



Revolutionized particle physics experiments
 \rightarrow Nobel prize for G. Charpak

Components of an experimental apparatus ('spectrometer')

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

Why Particle ID?

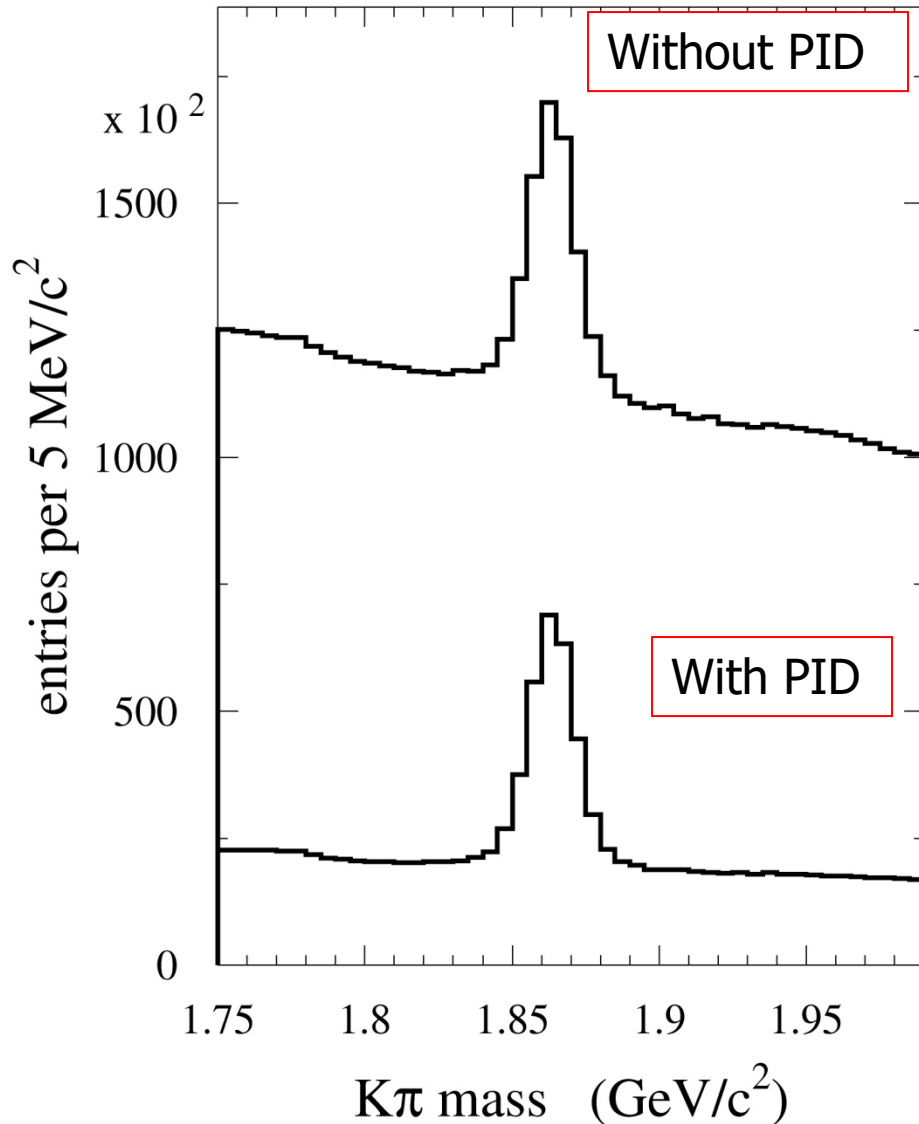
Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

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

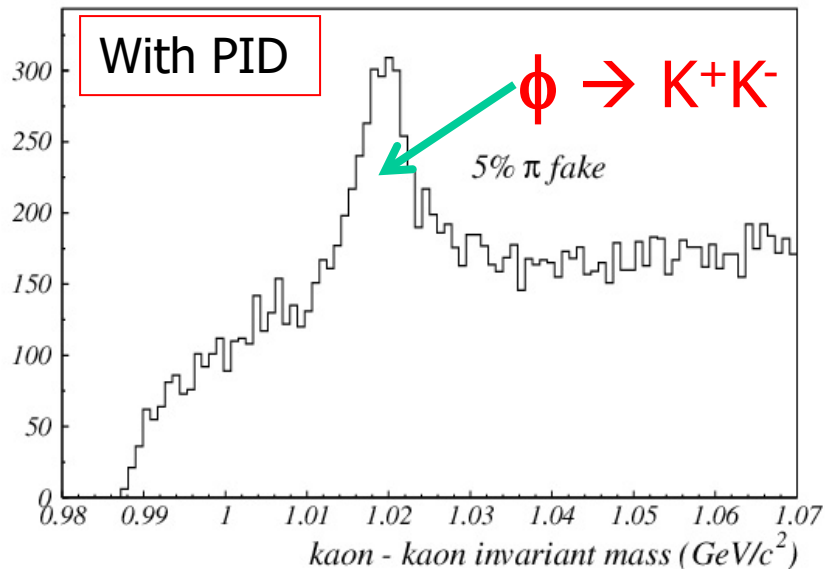
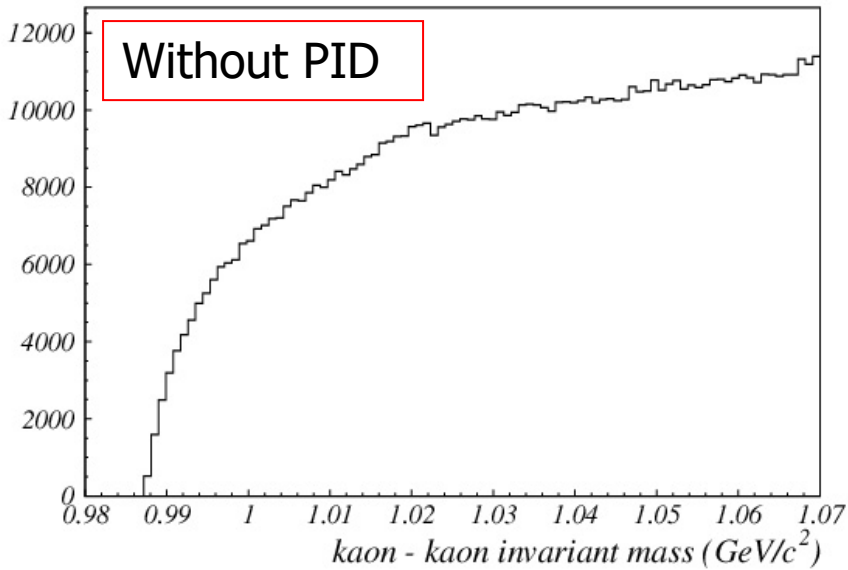
Introduction: Why Particle ID?



Example 1: B factories

Particle identification
reduces combinatorial
background by $\sim 5x$

Introduction: Why Particle ID?

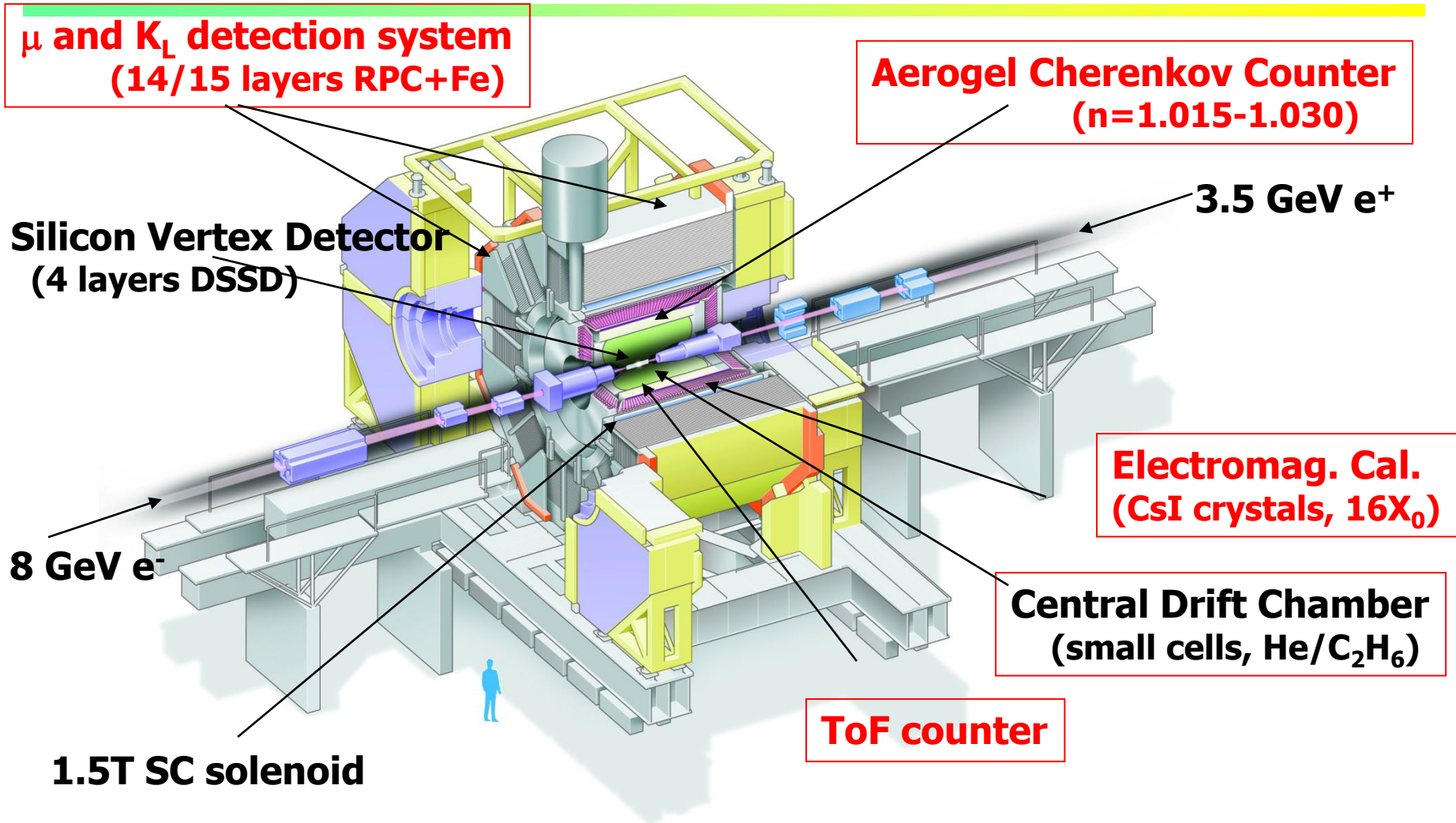


Example 2: HERA-B

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



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, $p = \gamma m v$.

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

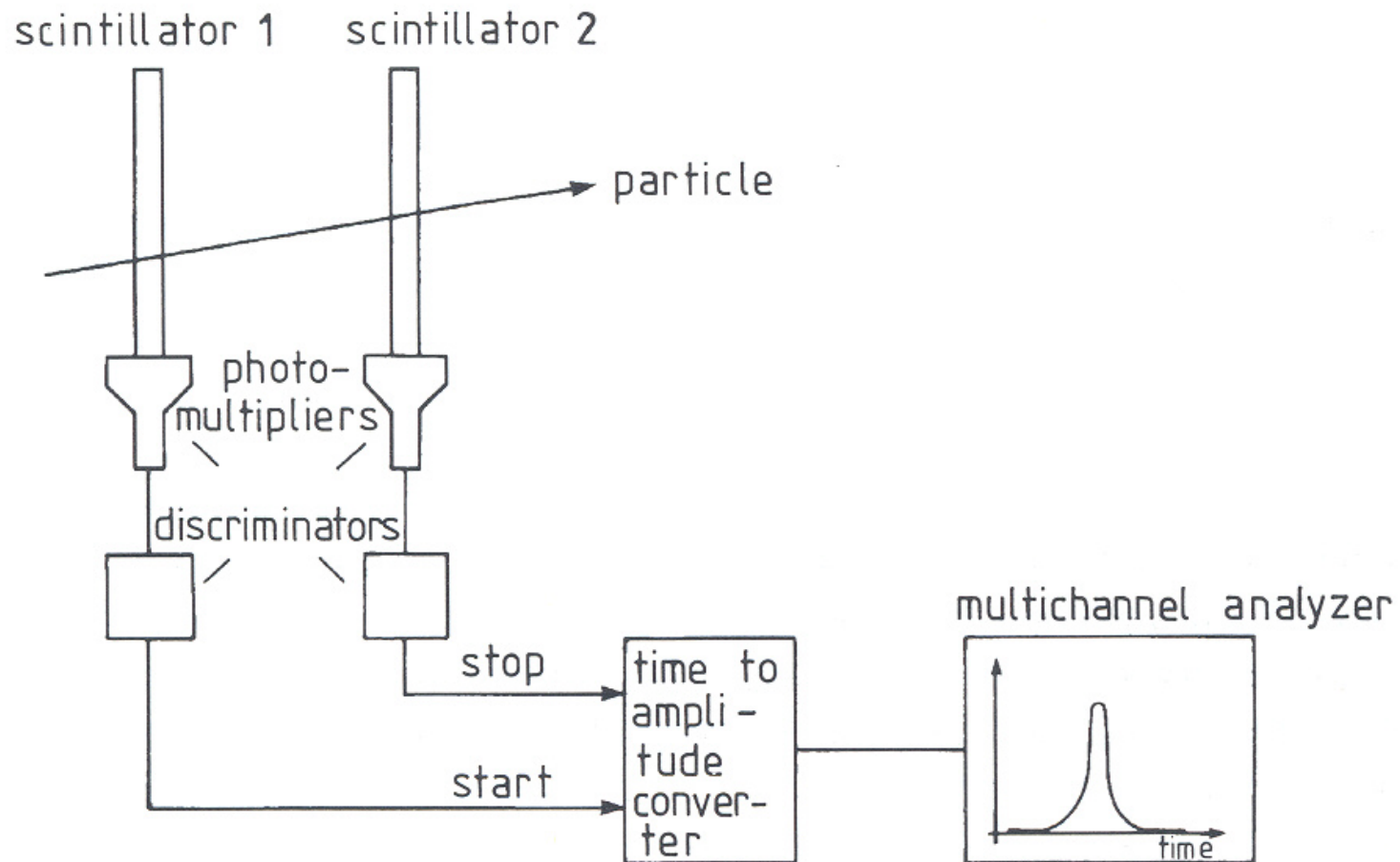
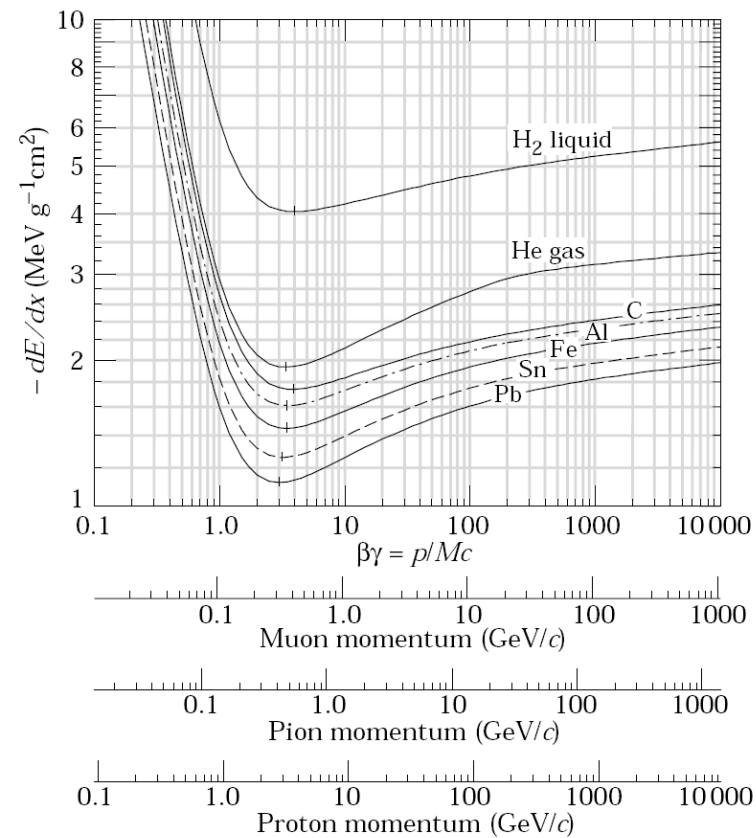
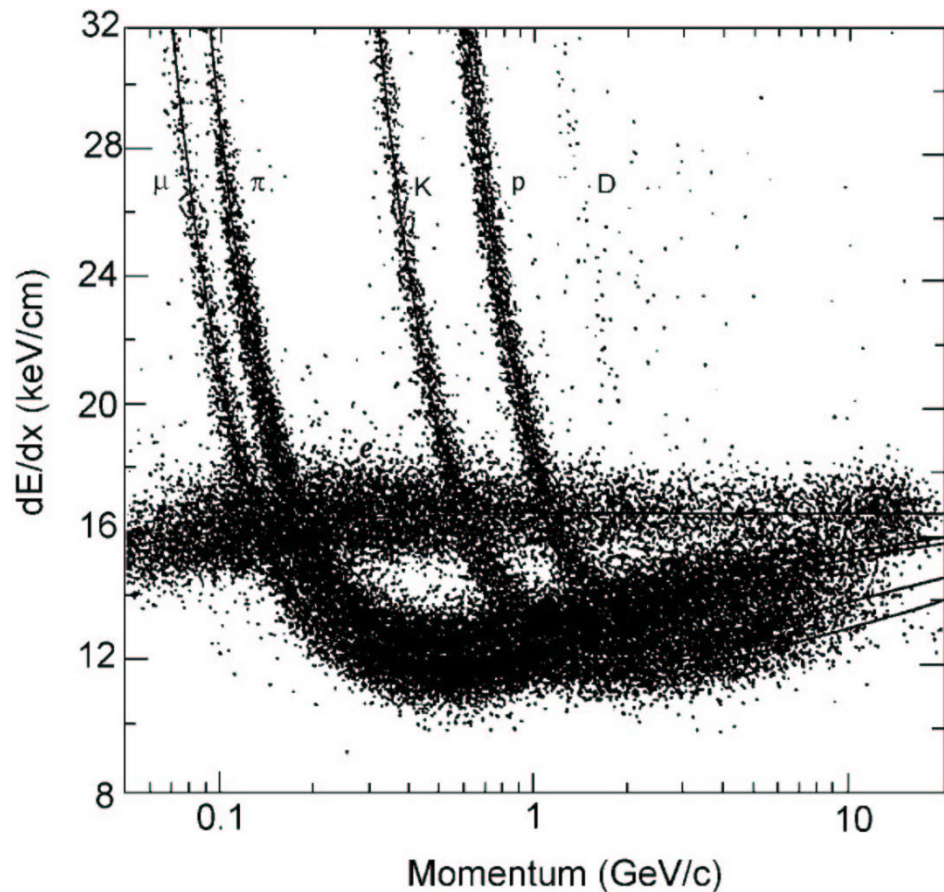


Fig. 6.5. Working principle of time-of-flight measurement.

Identification with dE/dx measurement

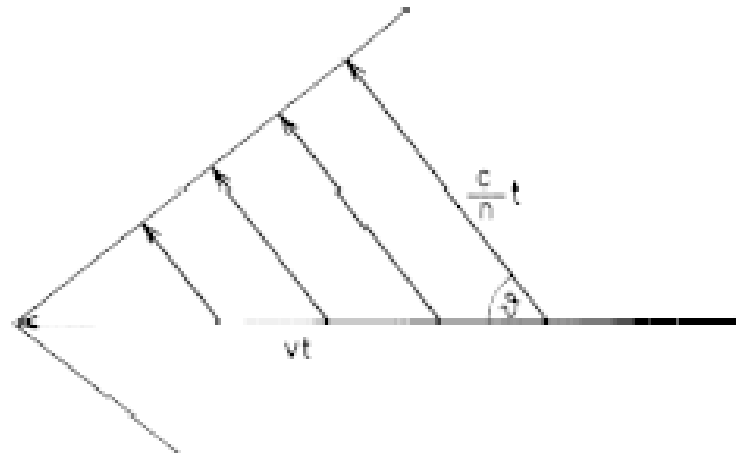
dE/dx performance in a large drift chamber.



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,

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

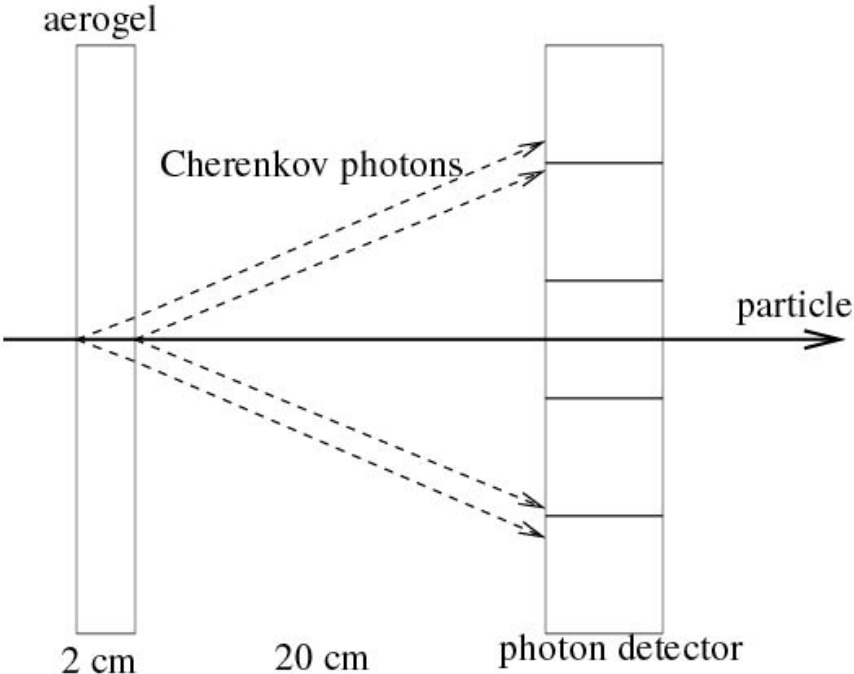


Two cases:

- 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

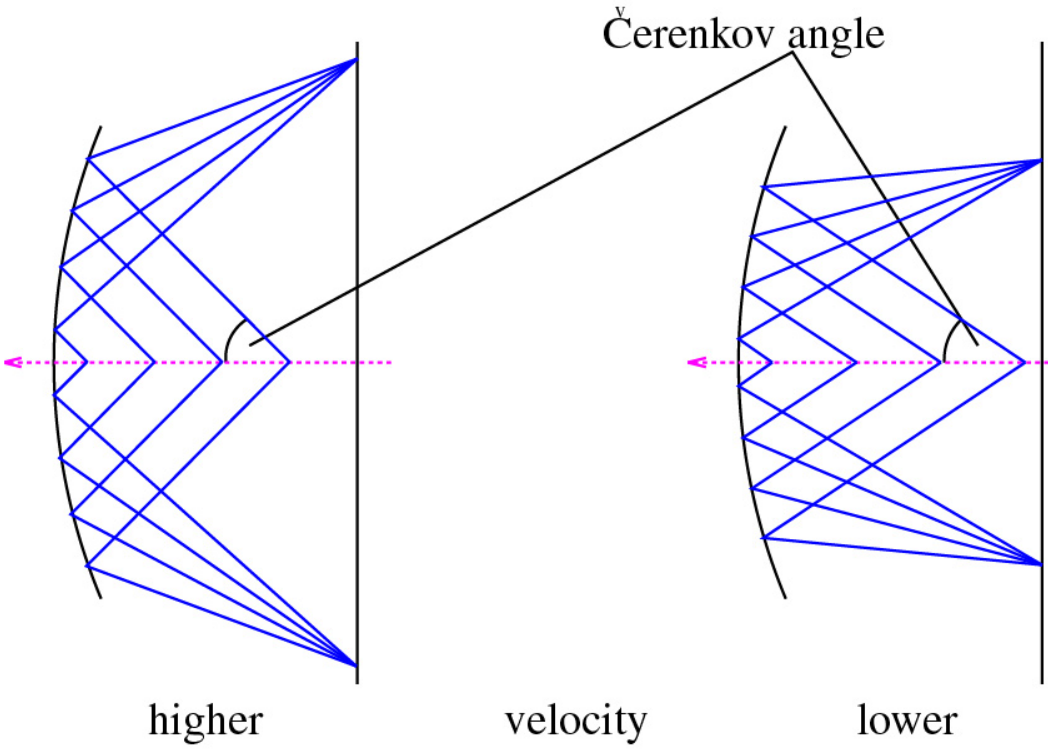
$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2 \theta = 370(\text{cm})^{-1} (\text{eV})^{-1} L \sin^2 \theta$$

Measuring Cherenkov angle



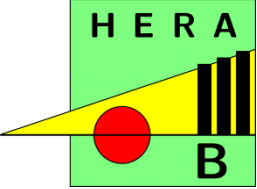
Proximity focusing RICH

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



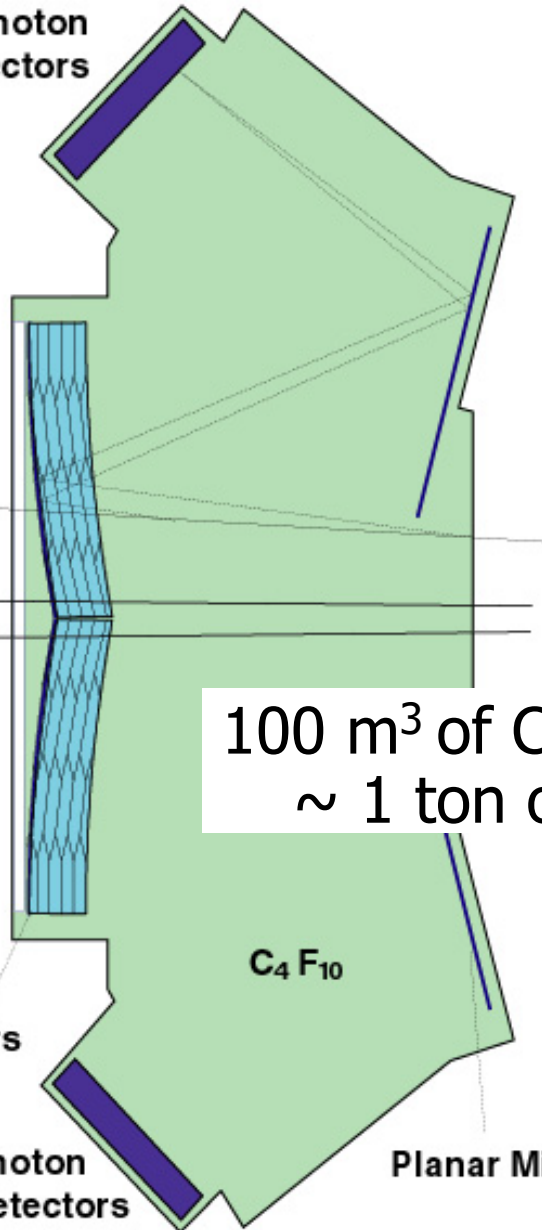
RICH with a focusing mirror





HERA-B RICH

Photon
Detectors

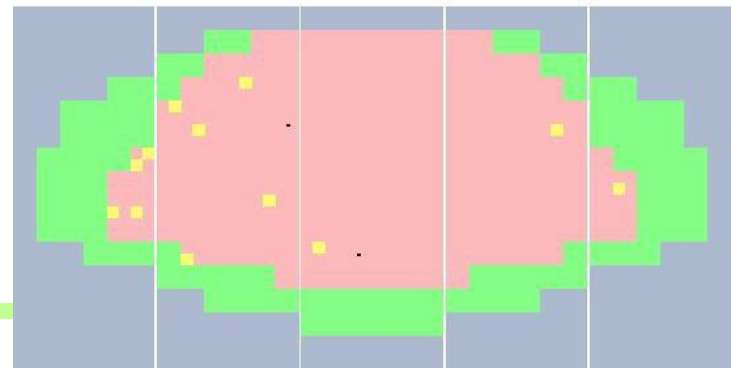
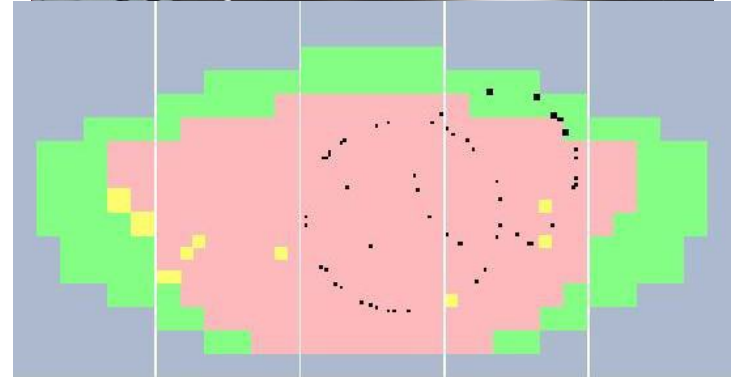


100 m³ of C₄F₁₀
~ 1 ton of gas

Spherical Mirrors

Photon
Detectors

Planar Mirrors



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 $\gamma \sim 1000$

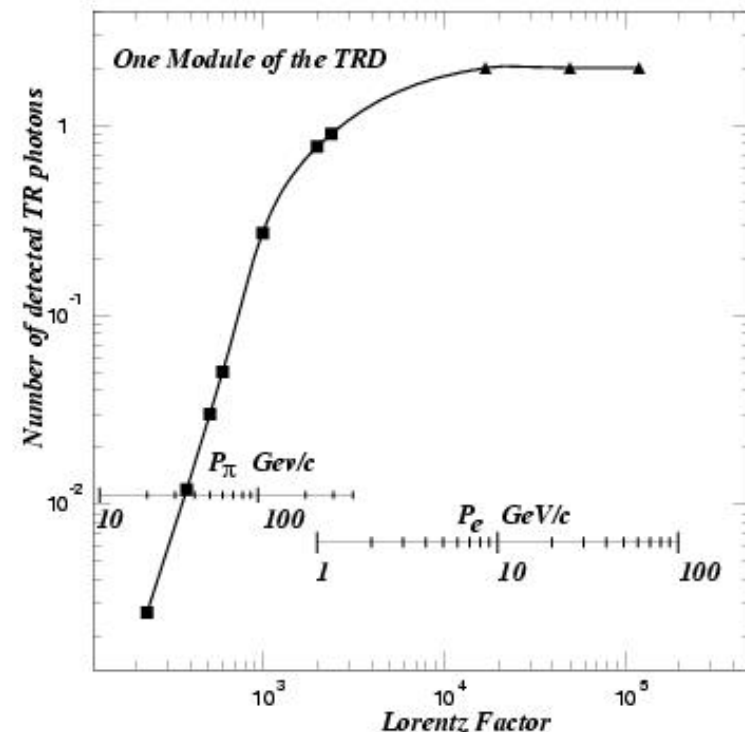
- Electrons at 0.5 GeV
- Pions, muons above 100 GeV

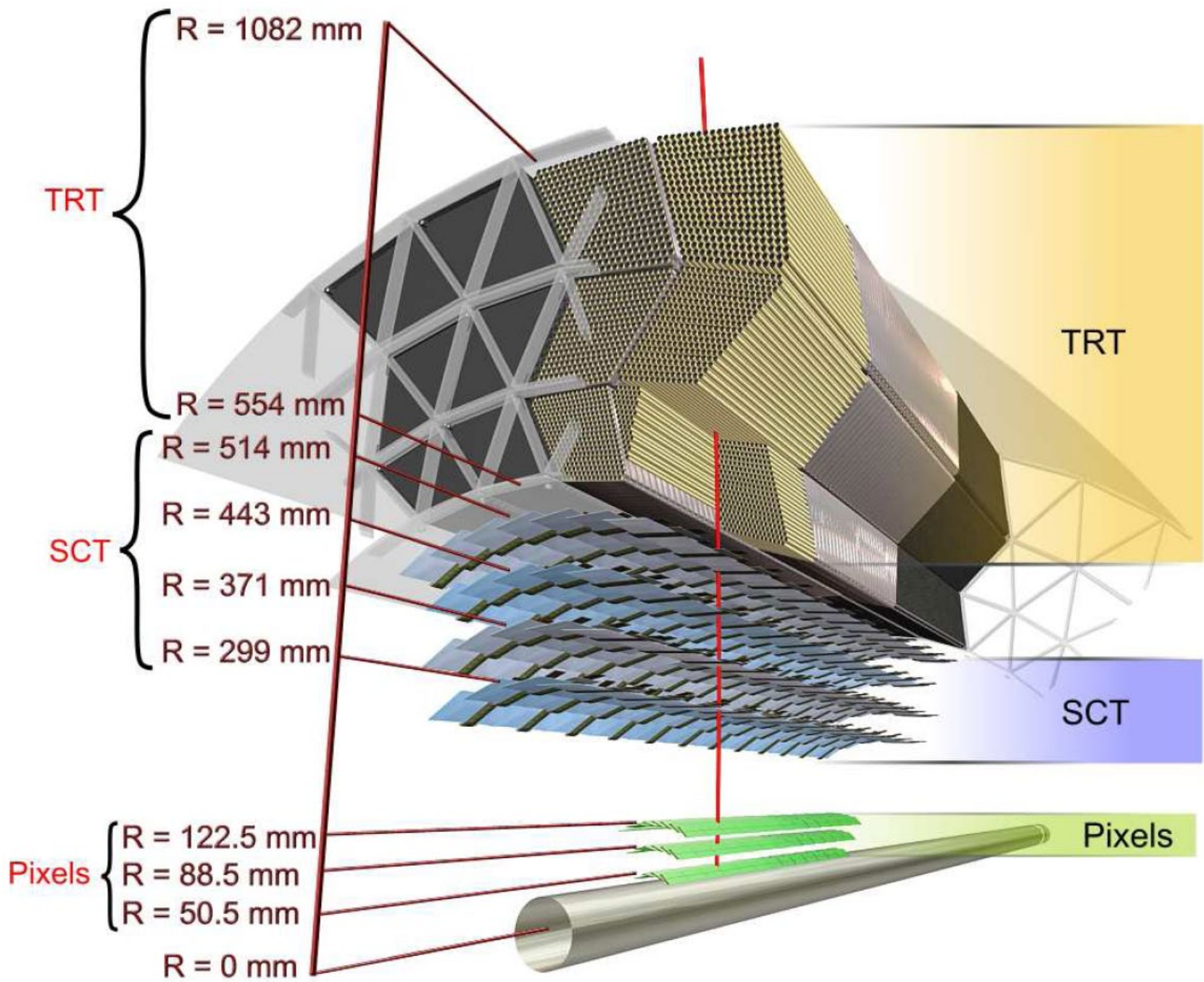
In between: discrimination e vs pions, mions

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'





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.

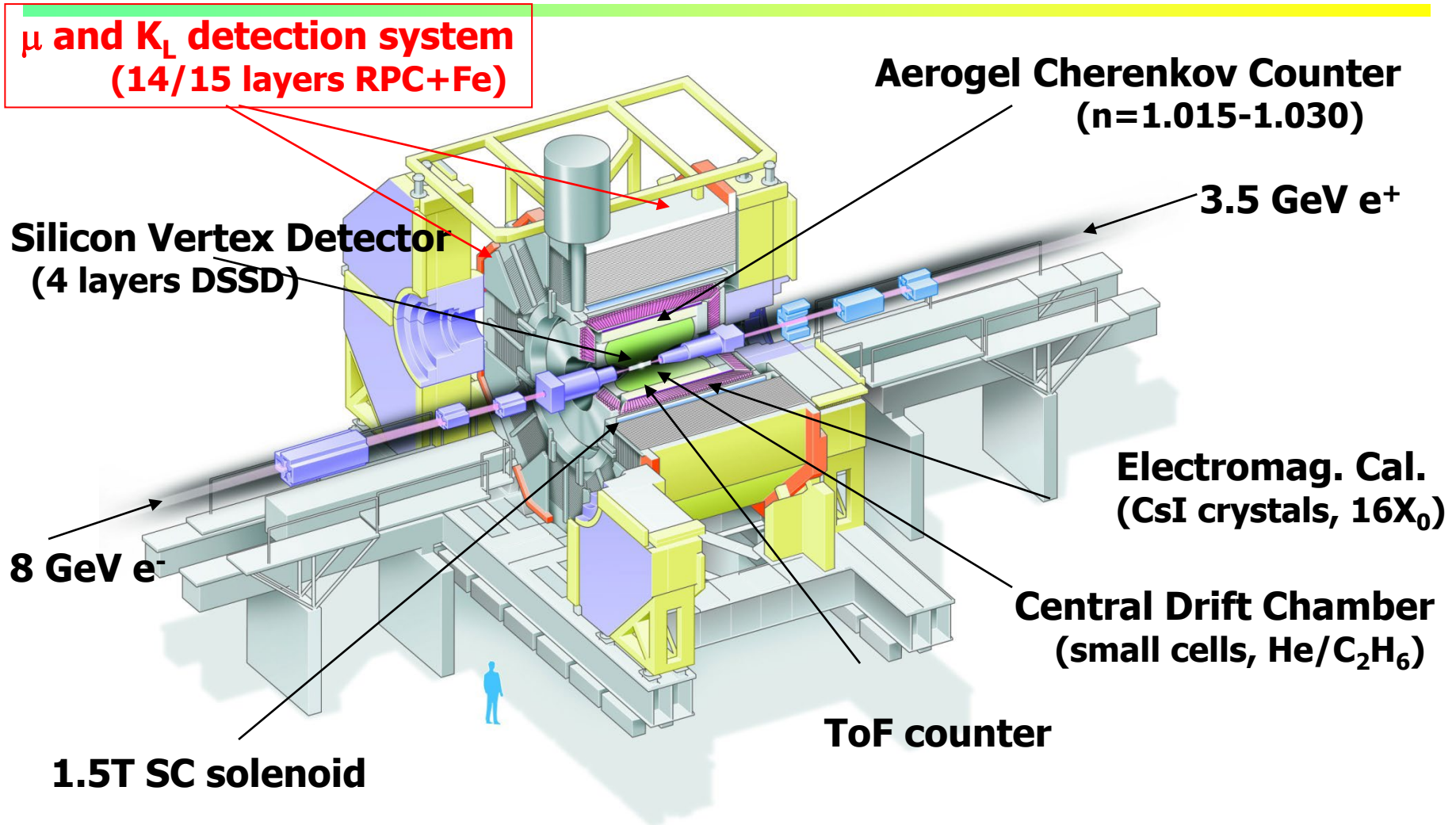
Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

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)

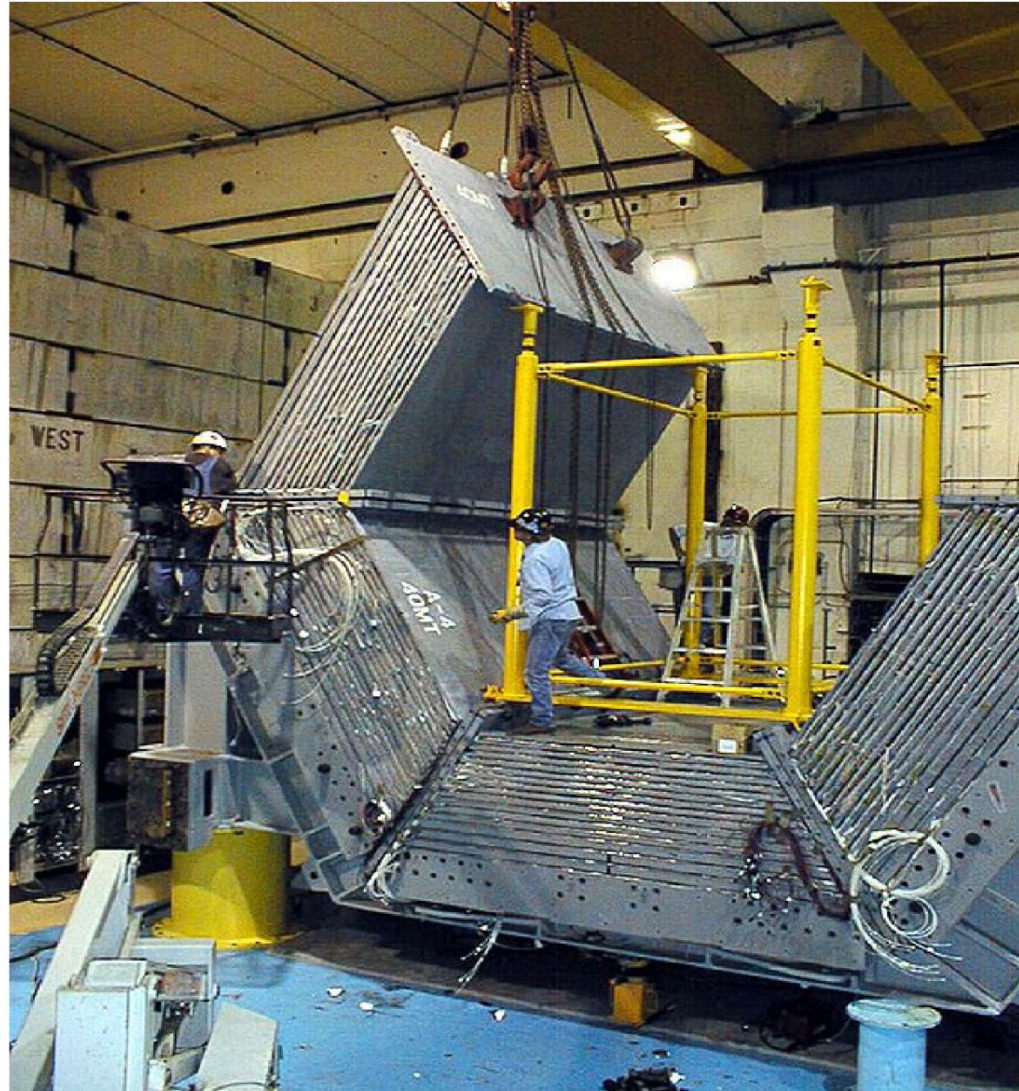
$\rightarrow \Delta E_{\min} = (0.36+0.11) \text{ GeV} = 0.47 \text{ GeV} \rightarrow$ reliable identification of muons possible above $\sim 600 \text{ MeV}$

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



Muon and K_L detector

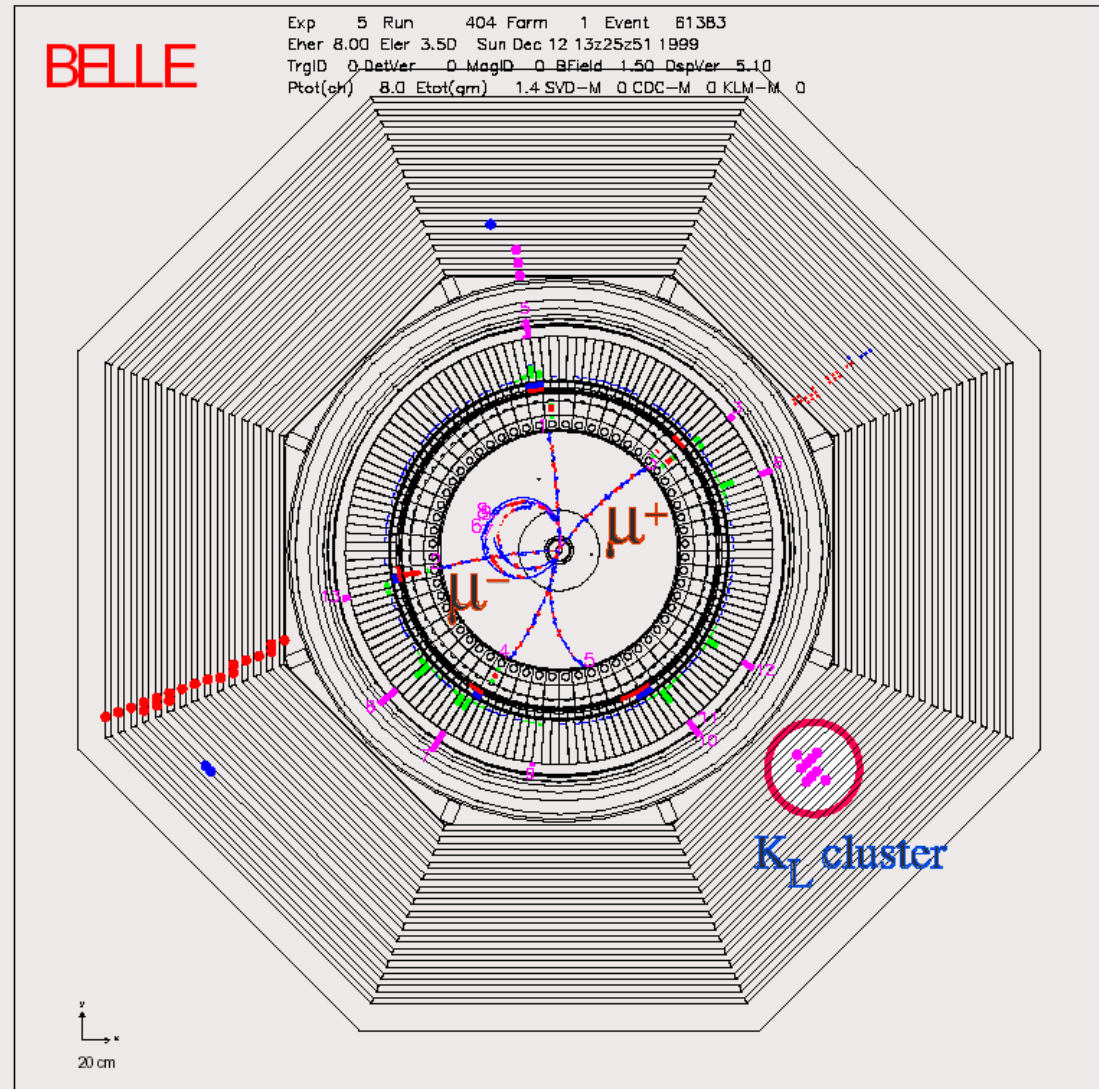
Example:

event with

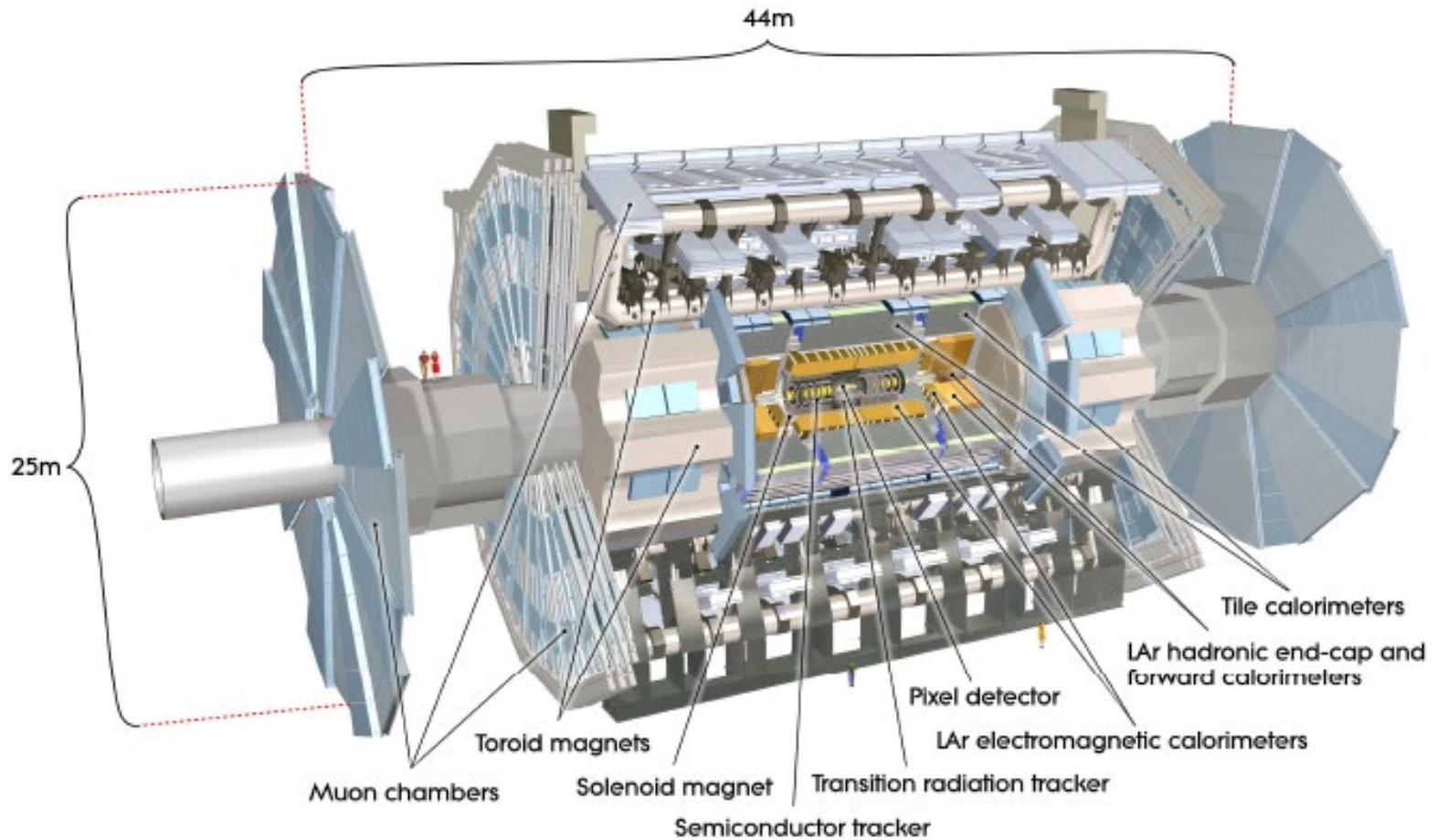
- two muons and a

- K_L

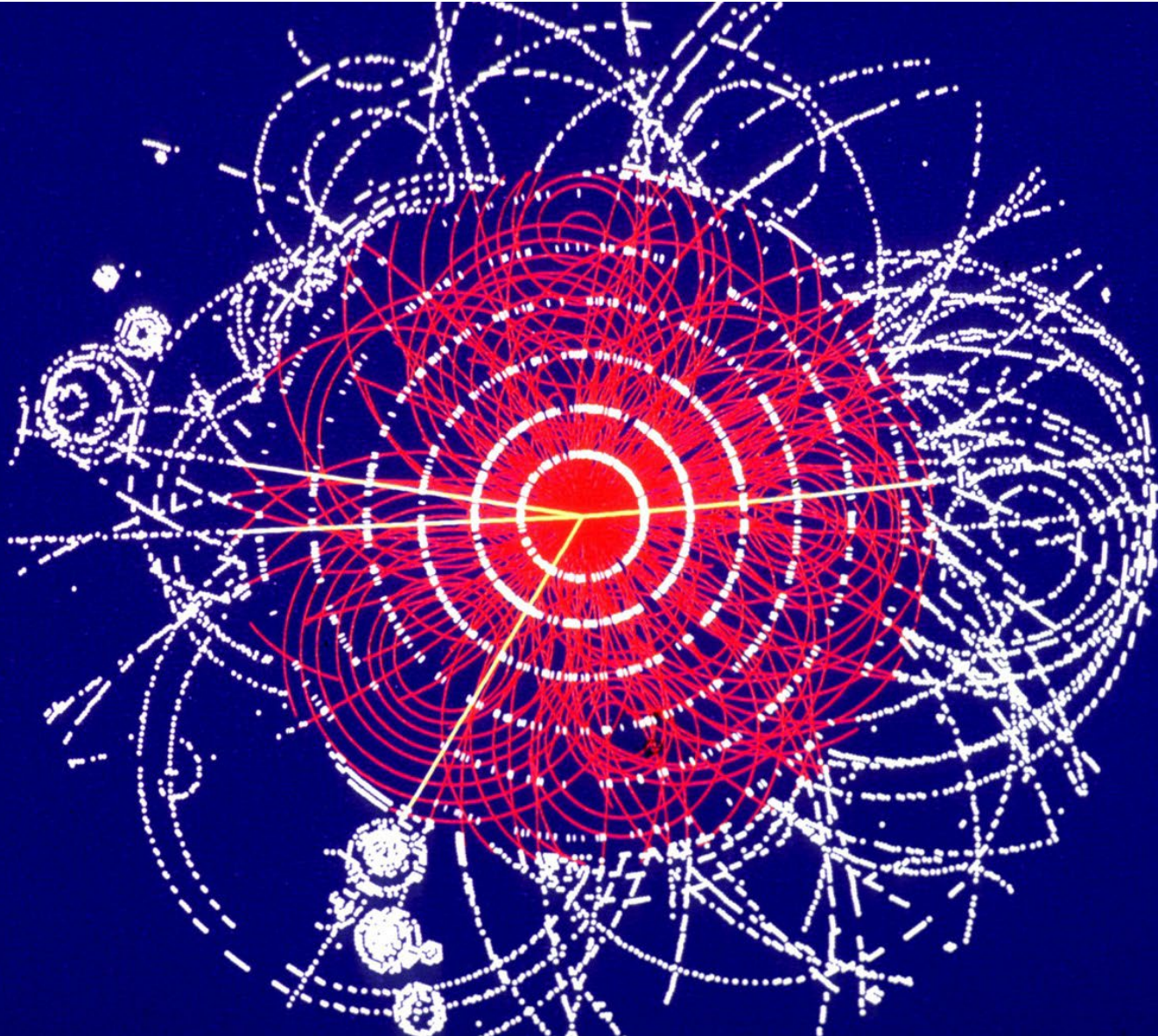
and a pion that
partly penetrated



Identification of muons at LHC - example ATLAS



$H \rightarrow 4 \mu$ (ATLAS)



Neutrino detection

Use inverse beta decay



However: cross section is very small!

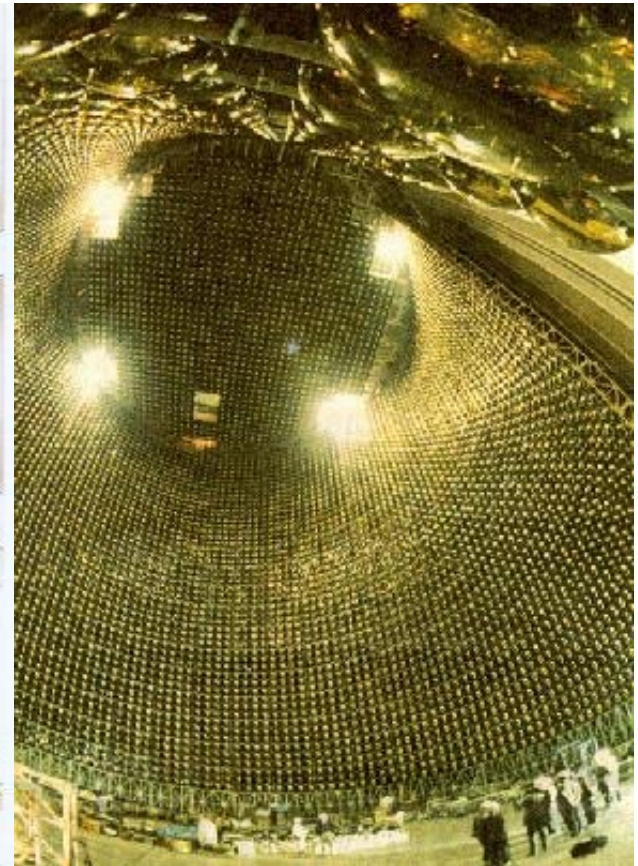
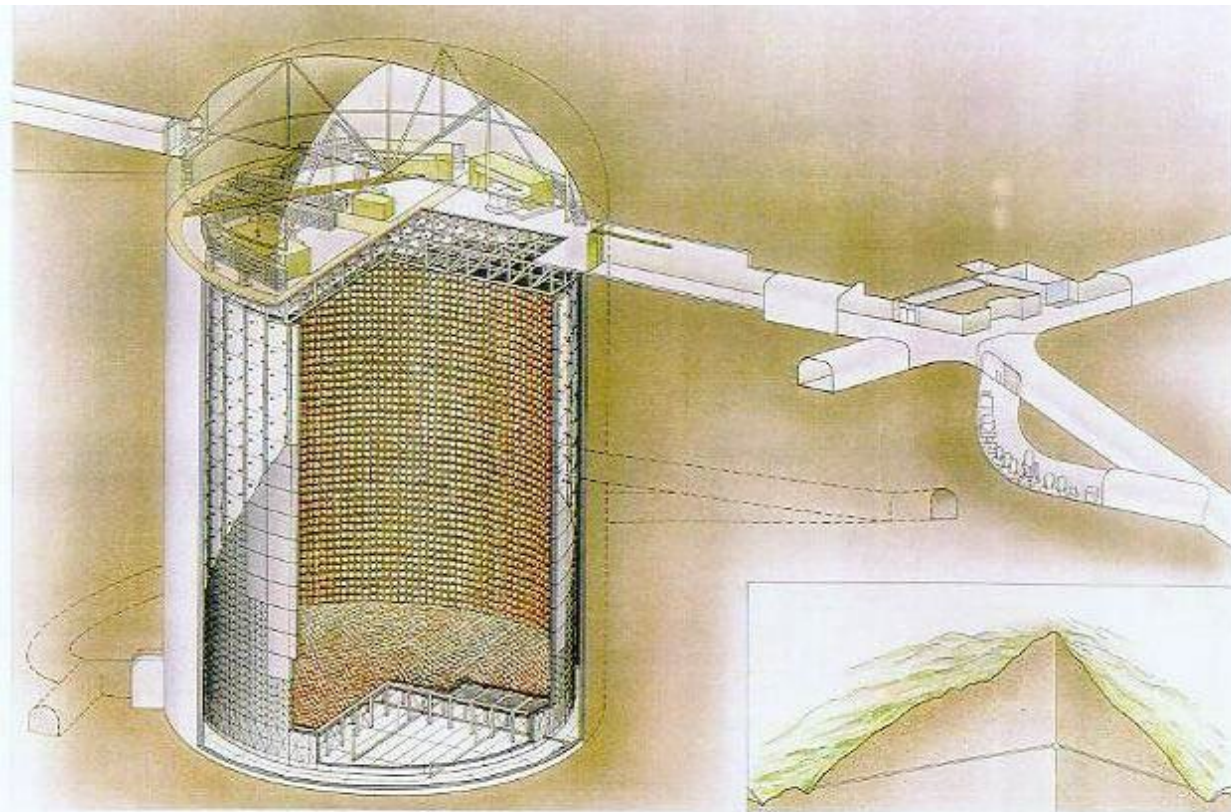
$6.4 \cdot 10^{-44} \text{ cm}^2$ at 1MeV

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

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

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

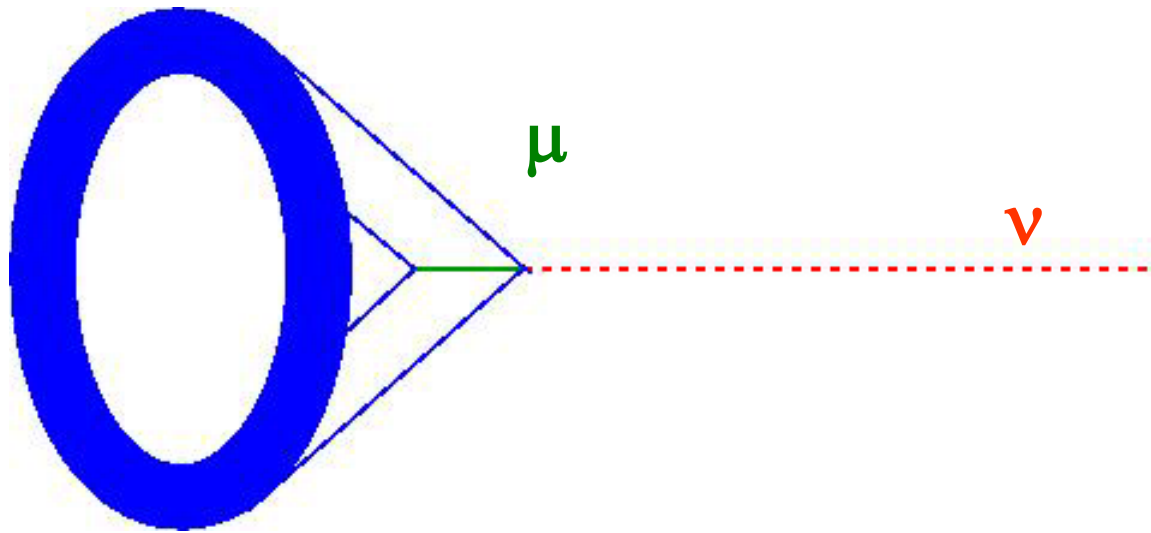
Superkamiokande: an example of a neutrino detector



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

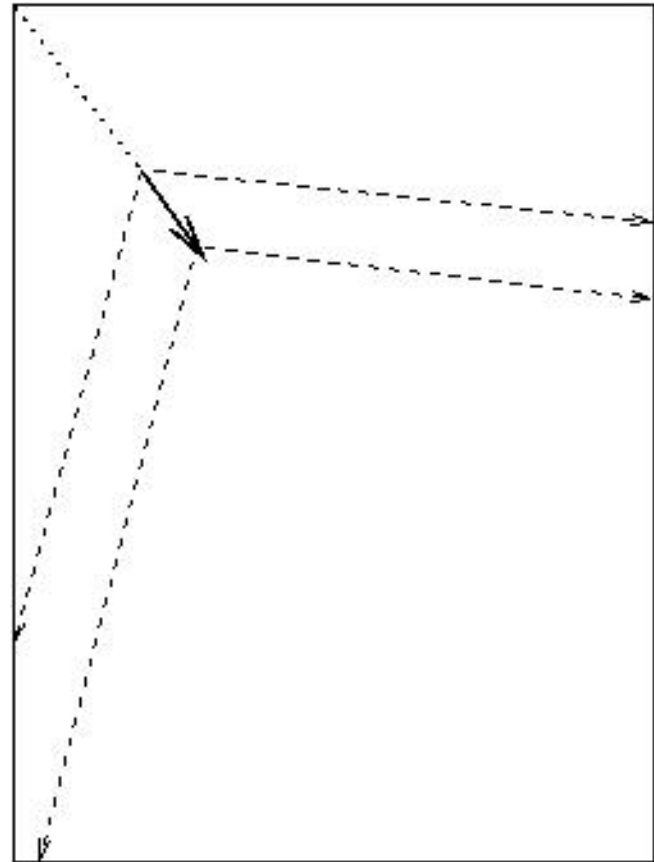
Muon vs electron

Cherenkov photons from
a muon track:

Example: 1 GeV muon
neutrino

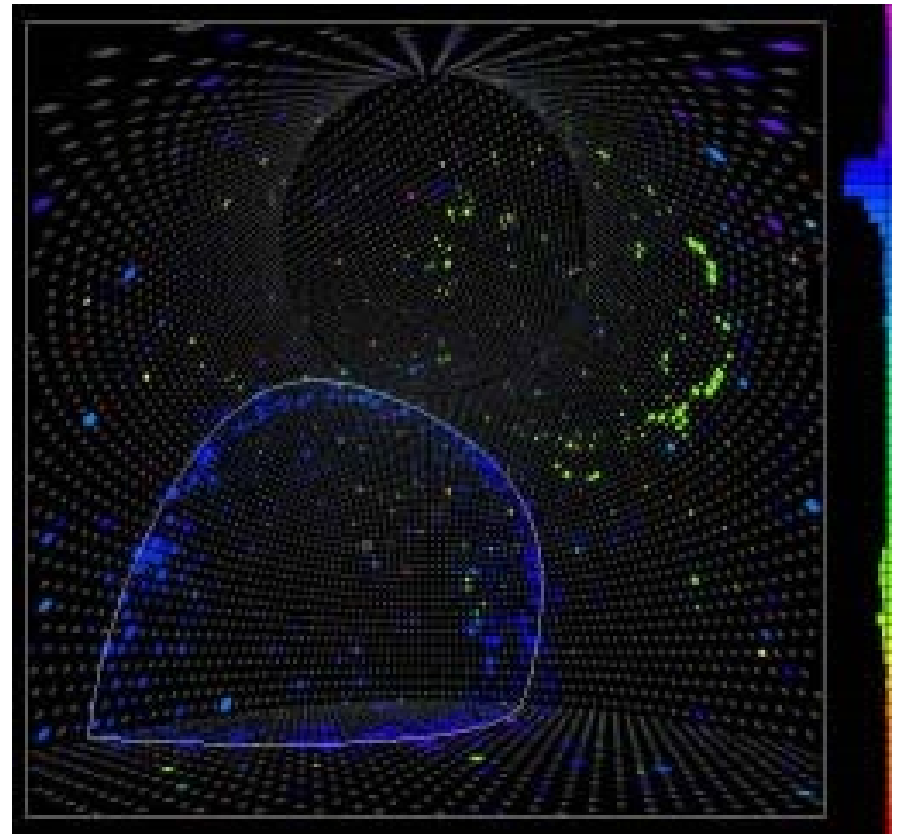
Track length of the
resulting muon:
 $L = E / (dE/dx) =$
 $= 1 \text{ GeV} / (2 \text{ MeV/cm}) = 5 \text{ m}$

→ a well defined “ring” on
the walls

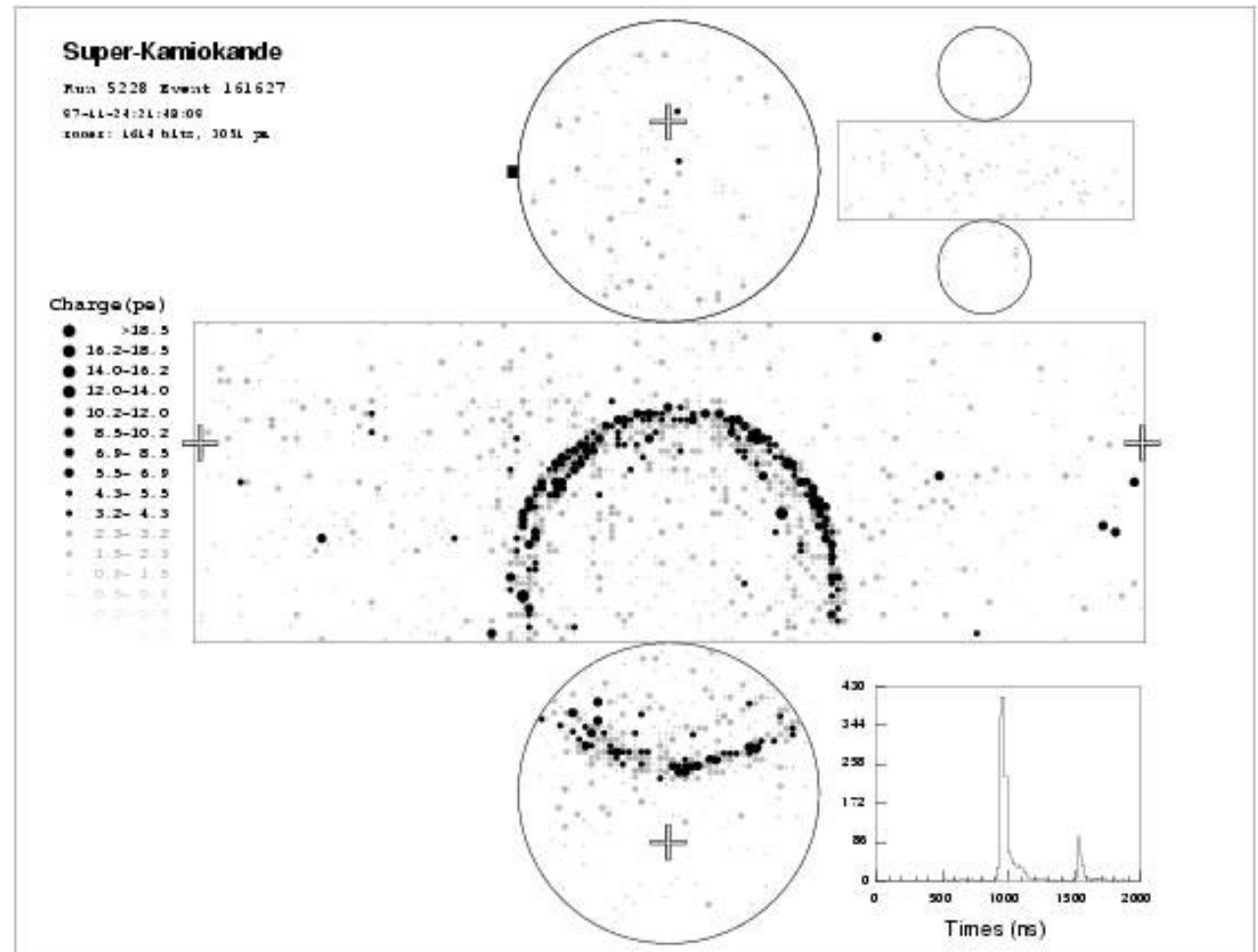


Superkamiokande: muon event

Muon 'ring' as seen by
the photon detectors



Muon event: photon detector cylinder walls



Detection of very high energy neutrinos (from galactic sources)

The expected fluxes are very low:

Need really huge volumes of detector medium!

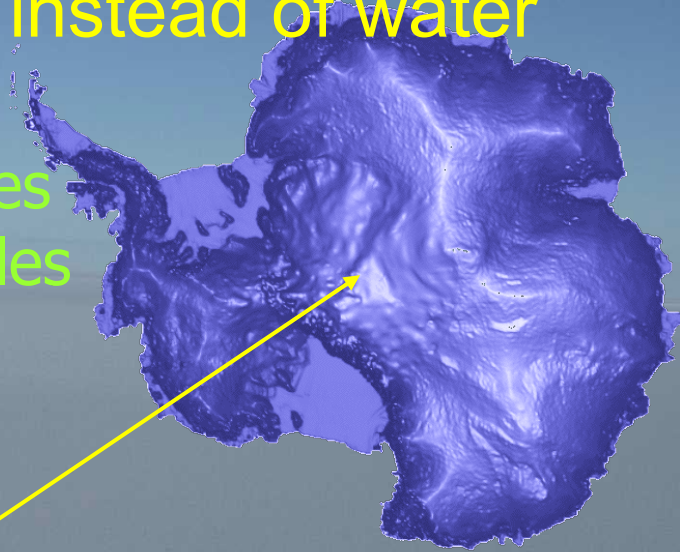
What is huge? From $(100\text{m})^3$ to $(1\text{km})^3$

Also needed: directional information.

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

ICE CUBE: use the Antarctic ice instead of water

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



AMANDA

Amundsen-Scott South Pole station
South Pole

road to work

Dome

Summer camp

1500 m

2000 m

[not to scale]

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!

Reconstruction of direction and energy of incident high energy muon neutrino

For each event:

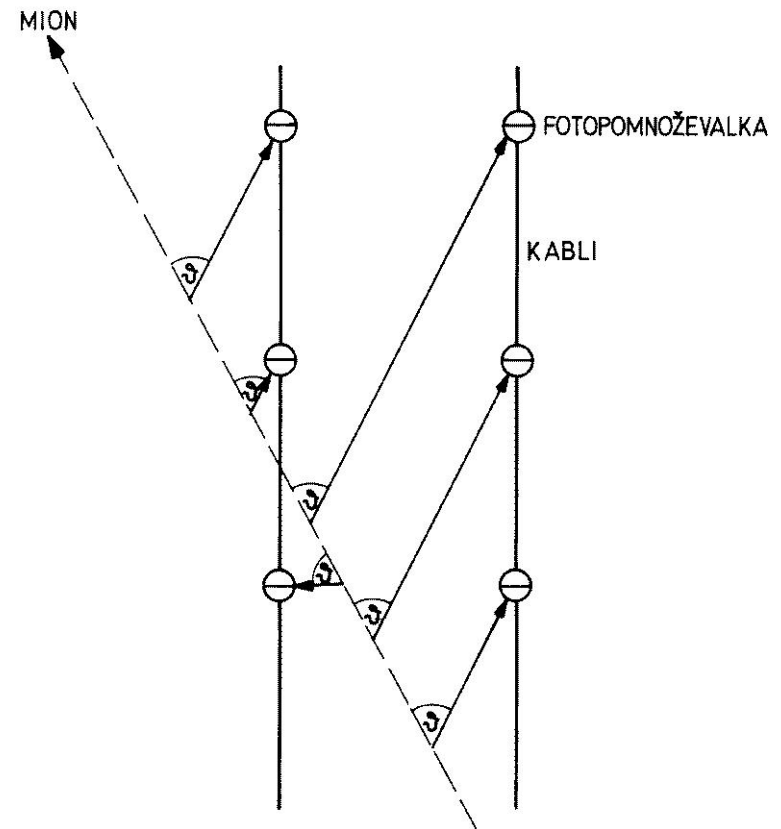
Measure time of arrival on each of the tubes

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

Reconstruct muon track

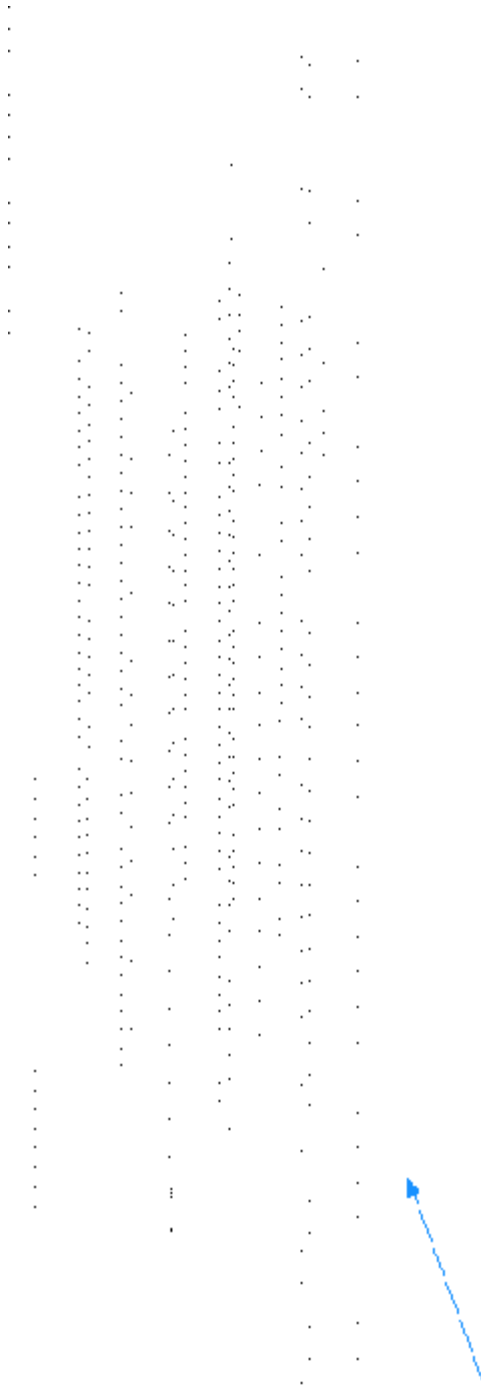
Track direction \rightarrow neutrino direction

Track length \rightarrow neutrino energy



ICE CUBE

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



Detekcija kozmičnih delcev na balonu

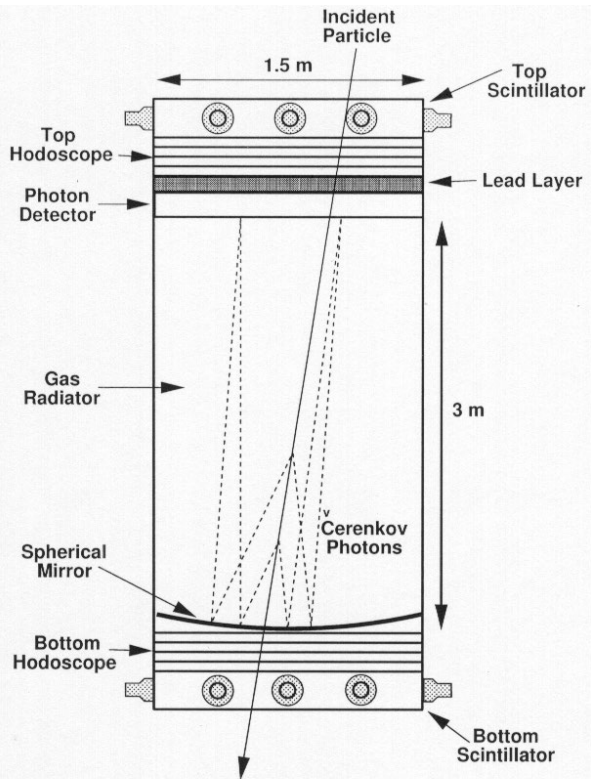
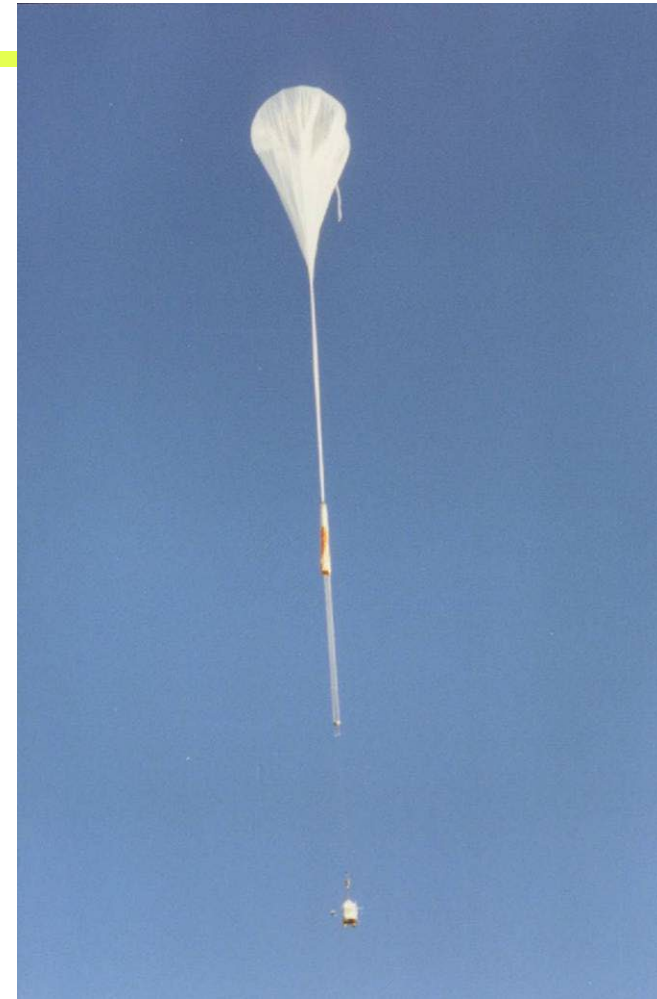
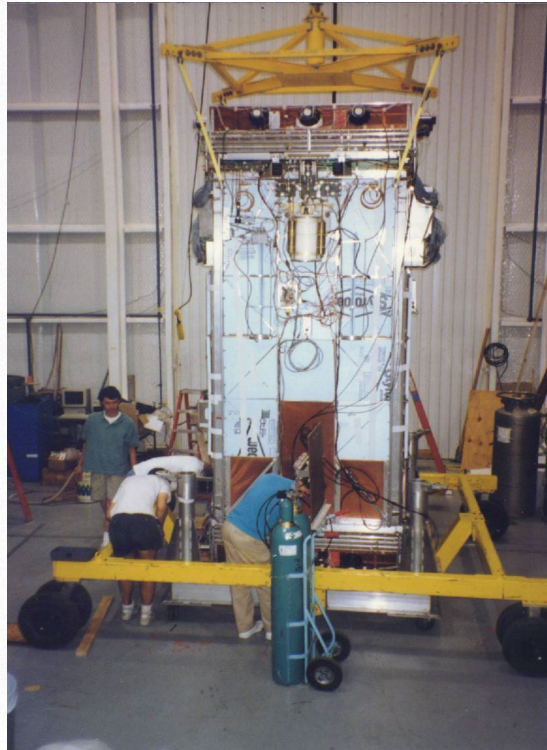


Fig. 1. Schematic cross-section of the instrument

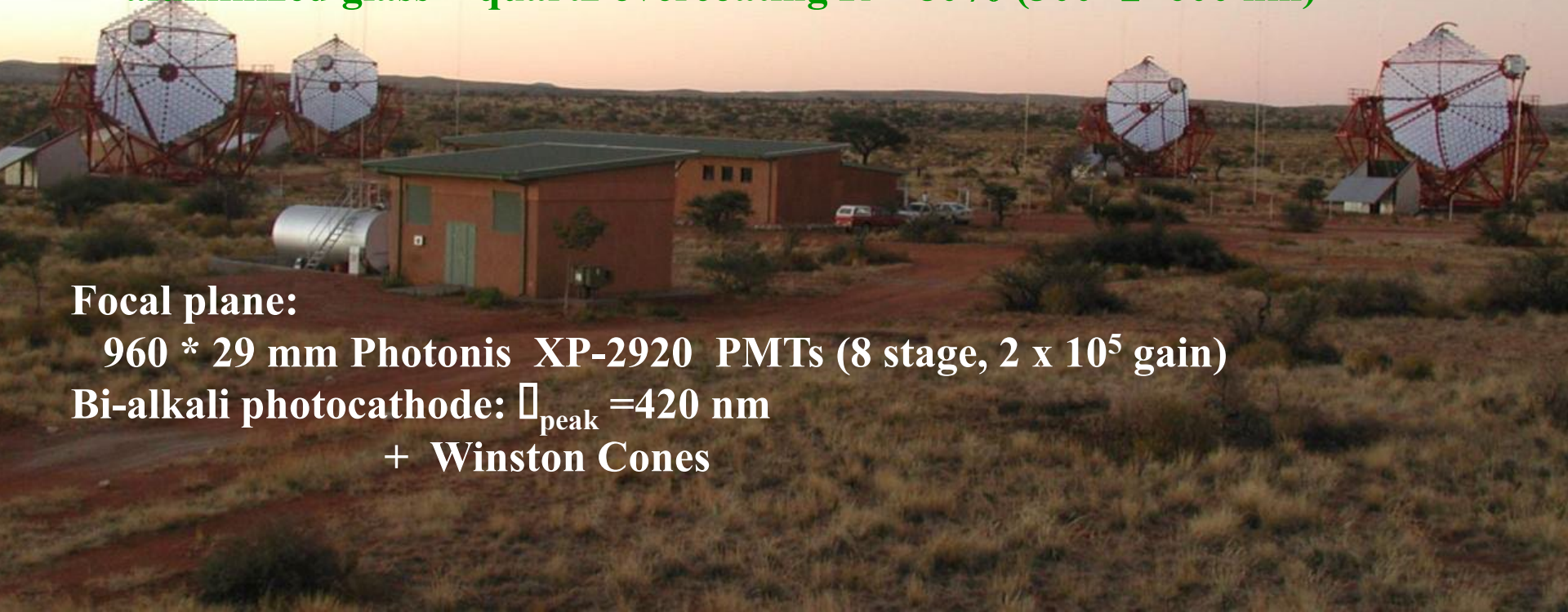


HESS 1 UHE Gamma Ray Telescope Stereoscopic Quartet

Khomas Highland, Namibia, (23°16'S, 16°30'E, elev. 1800m)

Four $\varnothing = 12$ m Telescopes (since 12/2003) $E_{th} \sim 100$ GeV

**108 m² /mirror [382 x $\varnothing=60$ cm individually steerable (2-motor) facets]
aluminized glass + quartz overcoating $R > 80\%$ ($300 < \lambda < 600$ nm)**

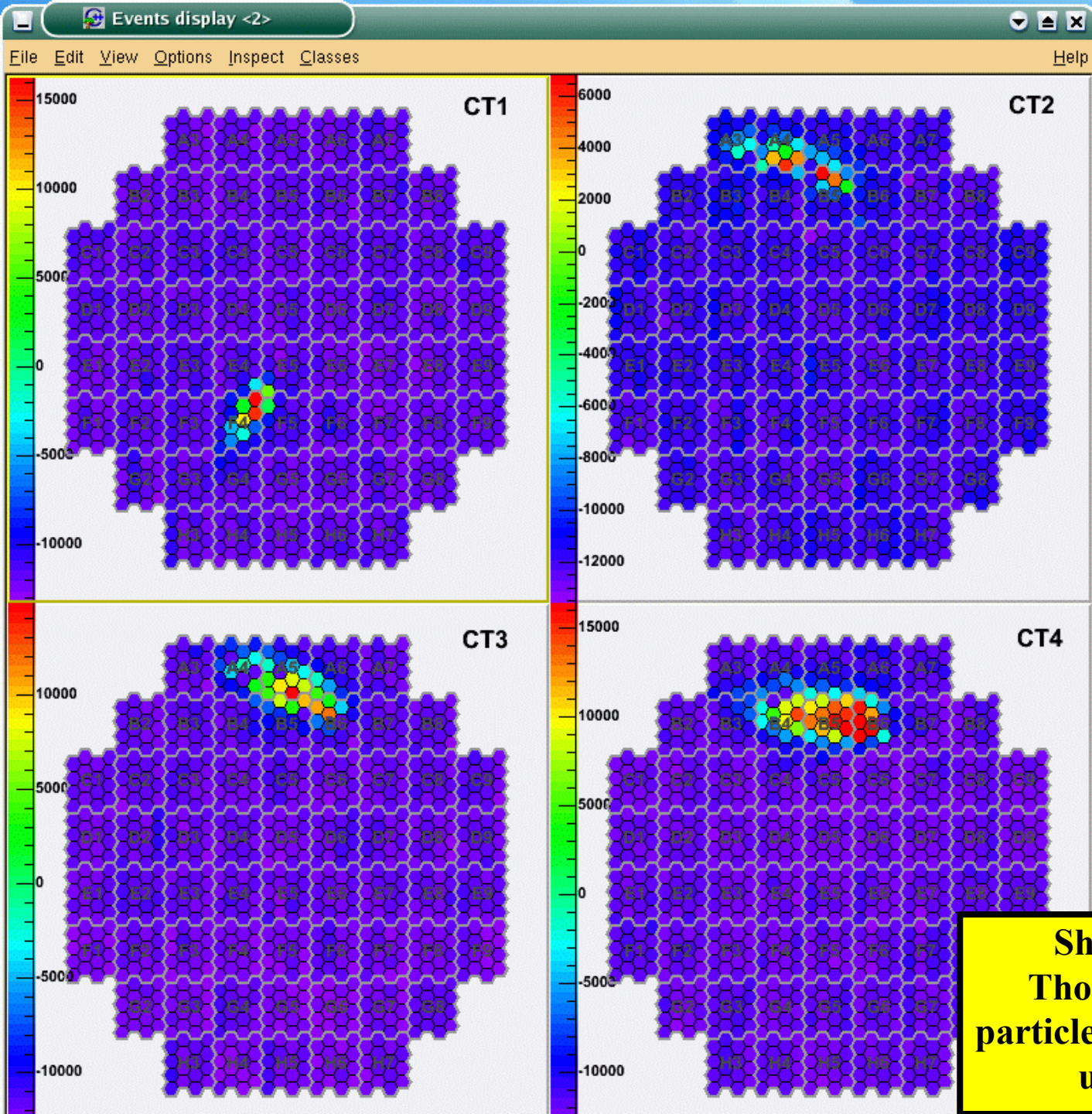


Focal plane:

960 * 29 mm Photonis XP-2920 PMTs (8 stage, 2×10^5 gain)

Bi-alkali photocathode: $\lambda_{peak} = 420$ nm

+ Winston Cones



Detection of high-energy gamma rays

using Cherenkov telescopes

The HESS 1 Concept

Shower mainly E-M.
Thousands of relativistic particles give Čerenkov light in upper atmosphere

Data analysis

Last but not least, the data from detectors have to be **analyzed** and **interpreted**.

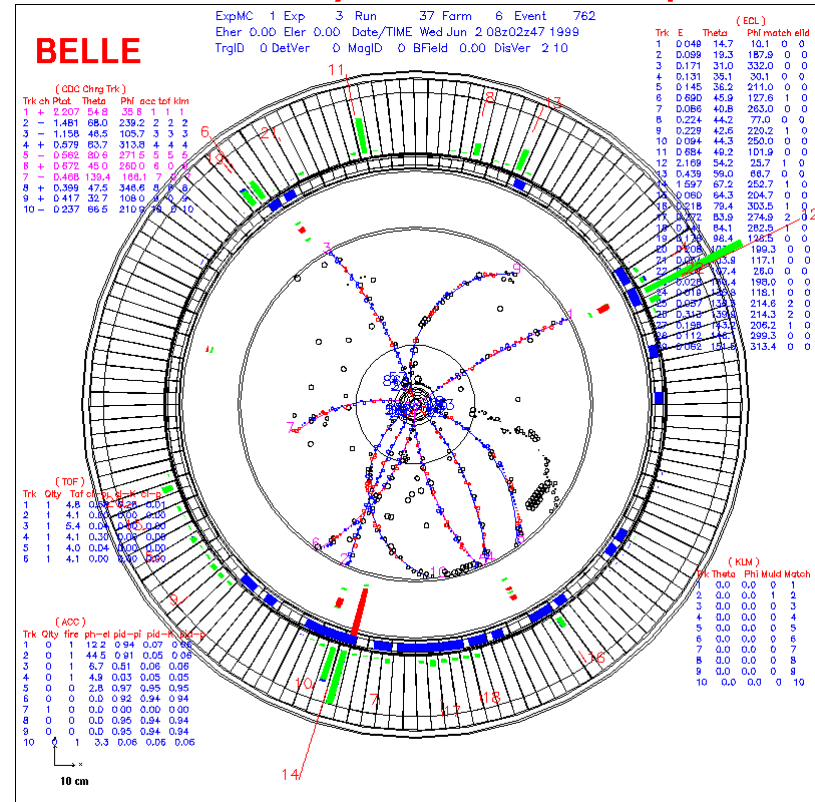
From signals on detectors,

- We reconstruct tracks, estimate the momentum and vertex position
- Determine the identity of particles
- Estimate the energy deposited in the calorimeter

Sophisticated methods are used to calibrate the detector components.

Monte Carlo simulation is used to determine the expected response of the detector.

Advanced analysis methods, including ML and AI, are used to select the reaction under study from the test (=background)



Overview

Introduction, review of detectors

Interaction of particles and photons with matter

Selected experiments in elementary particle physics

- $e^+ e^-$ collider: Belle and Belle II
- LHC: ATLAS and CMS
- Fixed target and forward region experiments: HERA-B and LHCb
- Underground experiments (neutrinos and dark matter)
- Astroparticle physics experiments

Data analysis and processing.

Literature

Web page of this course:

<http://www-f9.ijs.si/~krizan/sola/nddod/nddod.html>

Slides can be found at

<http://www-f9.ijs.si/~krizan/sola/nddod/slides>

Complementary course (run in odd years, e.g 2023/2024):

Experimental particle and nuclear physics

<http://www-f9.ijs.si/~krizan/sola/efjod/program.html>

Literature

Selected experiments

- Cahn, Goldhaber: The Experimental Foundations of Particle Physics

Books

- C. Grupen, Particle Detectors, Cambridge University Press, 1996
- W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer, 1994
- K. Kleinknecht, Detektoren für Teilchenstrahlung, 3rd edition, Teubner, 1992; Detectors for Particle Radiation, Cambridge University Press 1987.
- H. Wiedermann, Particle Accelerator Physics, Springer-Verlag 1993.
- P. Horowitz, W. Hill, The Art of Electronics, Cambridge University Press 1996.
- G. Cowan, Statistical Data Analysis, Oxford University Press, 1998.

Overview papers

- Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
- Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.

Other sources

- Particle Data Book (2008, older version useful as well)
- R. Bock, A. Vasilescu, Particle Data Briefbook
<http://www.cern.ch/Physics/ParticleDetector/BriefBook/>
- Proceedings of detector conferences (Vienna VCI, Elba, IEEE)

Requirements

Advanced particle detectors and data handling -
Napredni detektorji delcev in obdelava podatkov

- Written exam – problem solving
- Oral exam

Additional literature

- More slides from my courses in Barcelona, Tokyo and Nagoya - together with more pointers to relevant literature

<http://www-f9.ijs.si/~krizan/sola/barcelona/barcelona.html>

<http://www-f9.ijs.si/~krizan/sola/tokyo/tokyo.html>

<http://www-f9.ijs.si/~krizan/sola/nagoya-ise/nagoya-ise.html>

Prerequisites

If you take this course, you should have preferably already taken:

- Moderna fizika 2/Modern physics 2 (introduction to nuclei and particles)
- Merjenje ionizirajočega sevanja (or Eksp. fiz. jedra in delcev/Exp. Particle and nuclear physics)
- Fizika jedra in osnovnih delcev/Physics of nuclei and particles