Napredni detektorji delcev in obdelava podatkov (NDDOP) - Uvod

Peter Križan

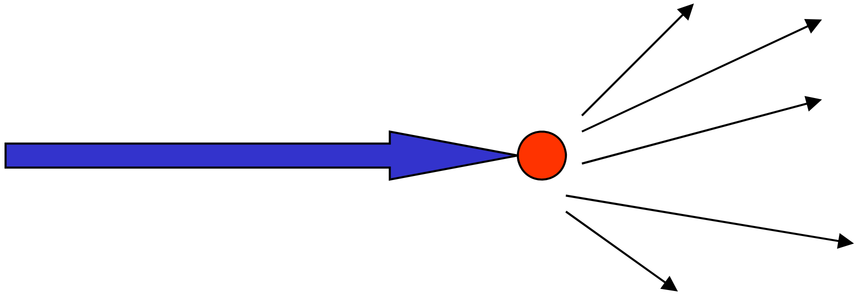
Contents

Particle physics experiments

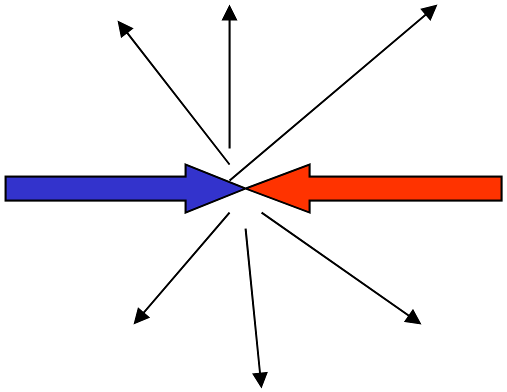
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

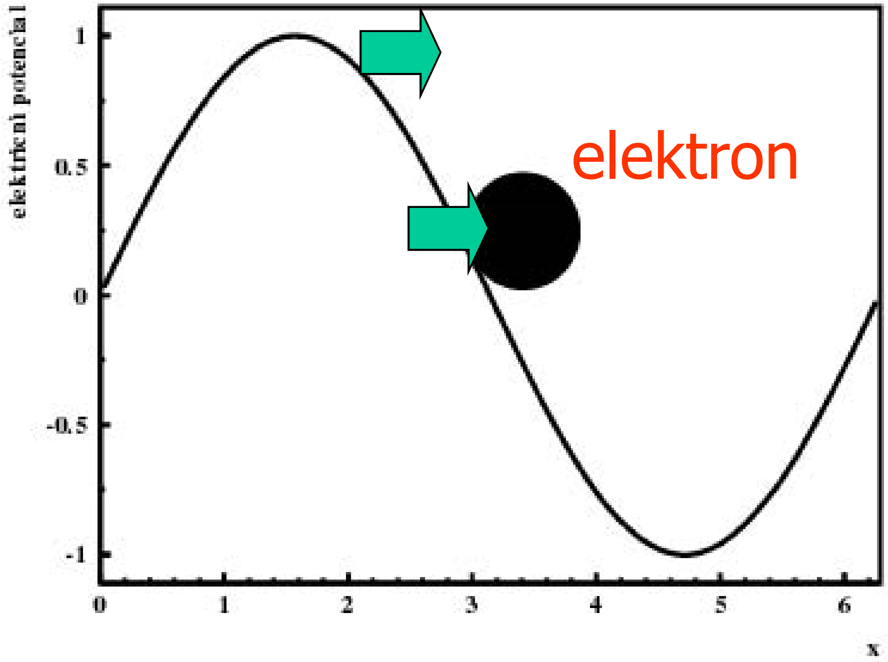


Collider experiments

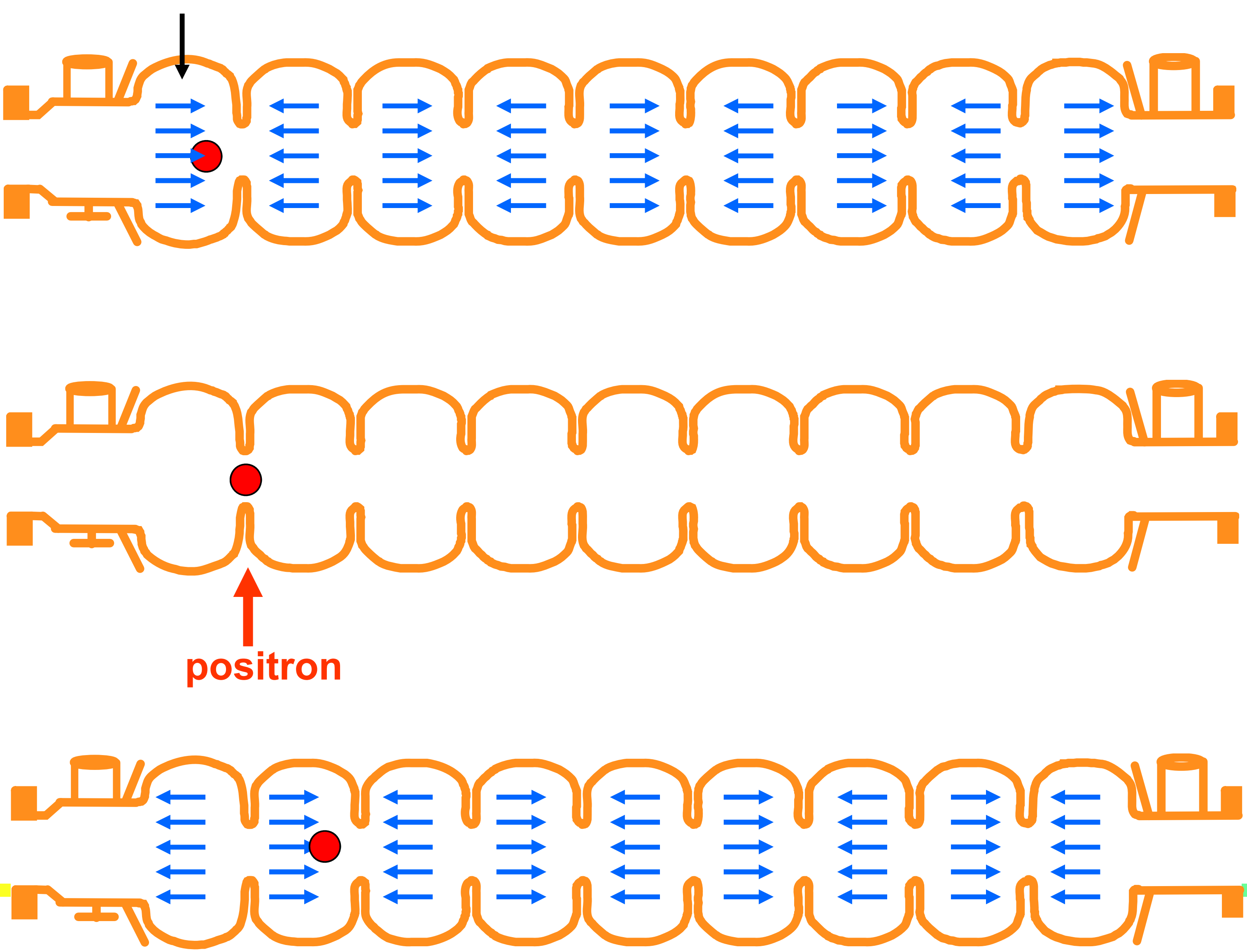


How to accelerate charged particles?

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

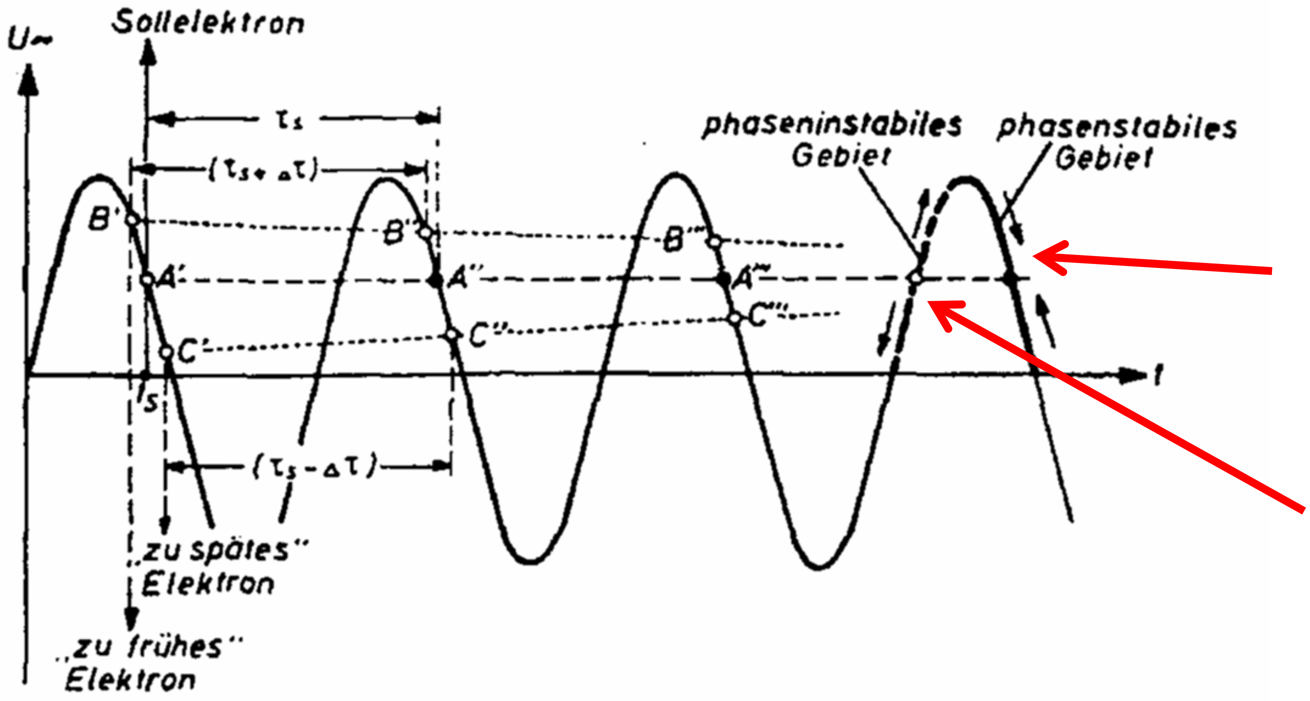


... Similar to surfing the waves


Electric field
positron

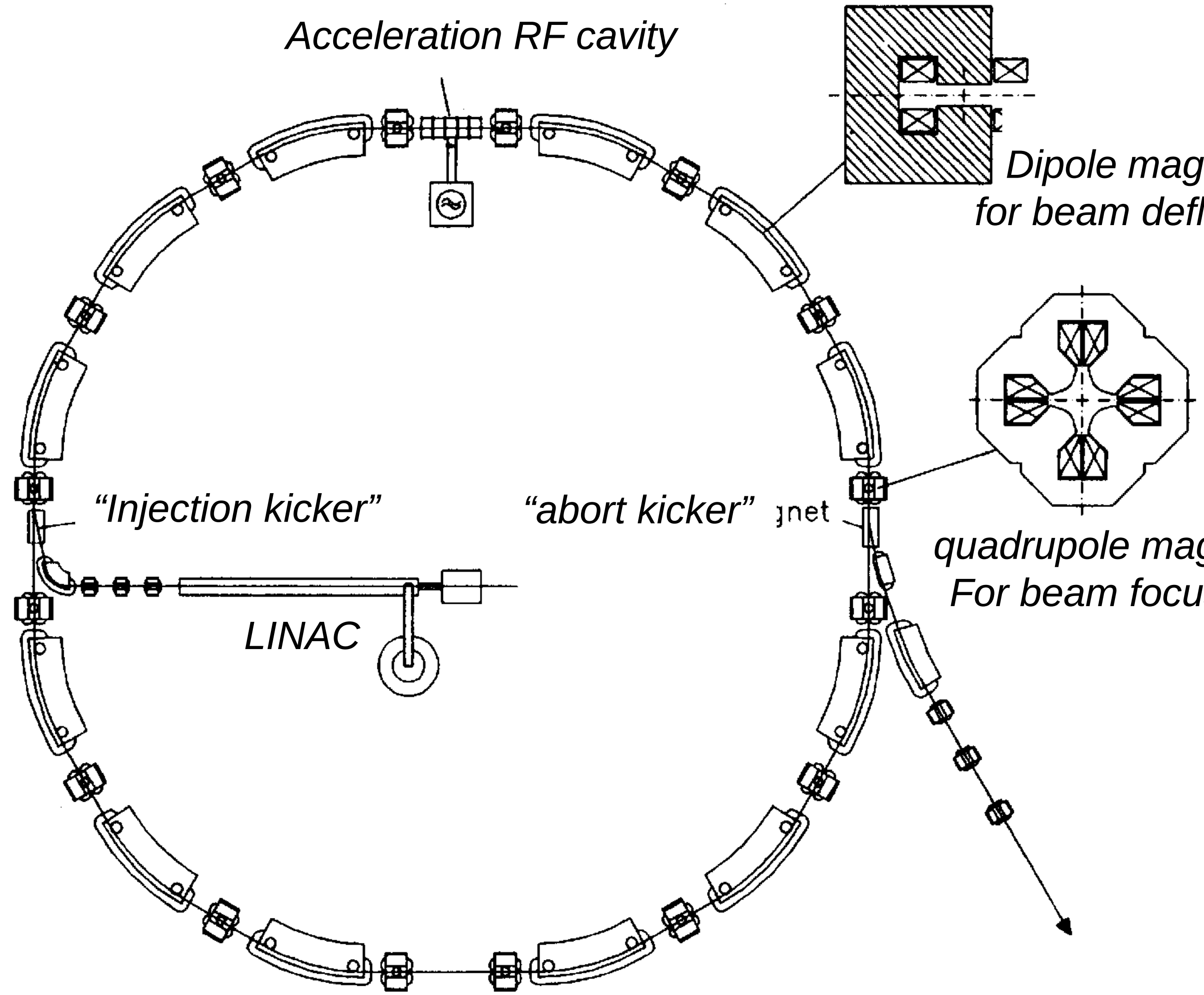
Stability of acceleration

- 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 ~ in phase→ stable orbit
- Not OK if too far away

Synchrotron



Acceleration RF cavity

Dipole magnets for beam deflection

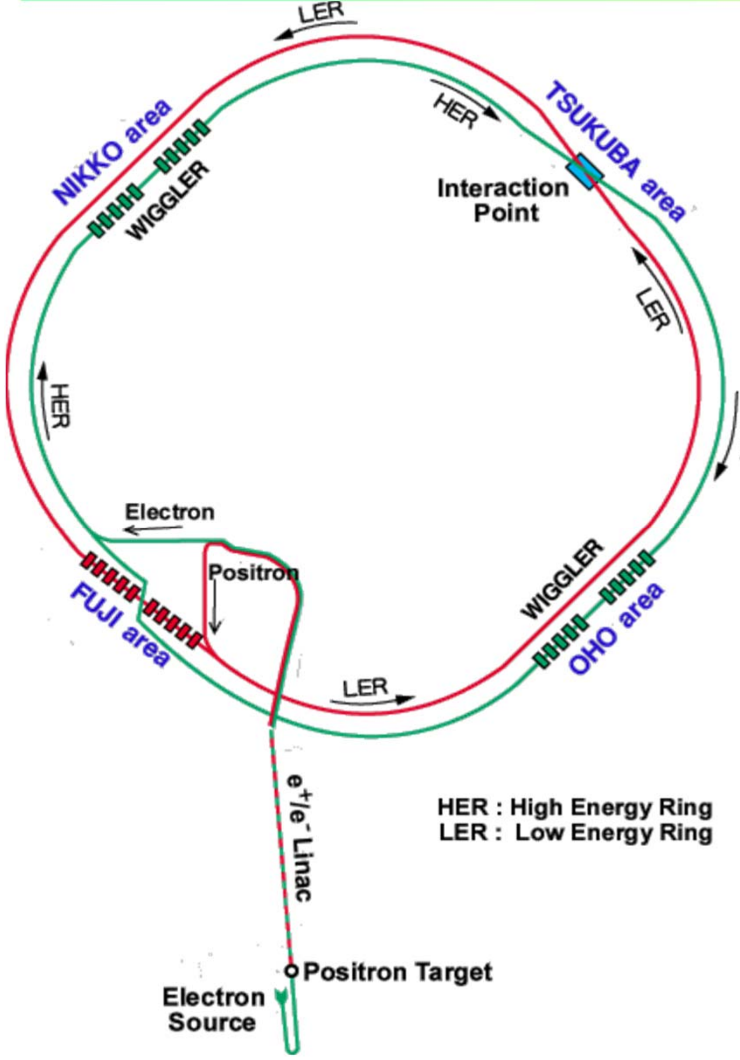
quadrupole magnets For beam focusing

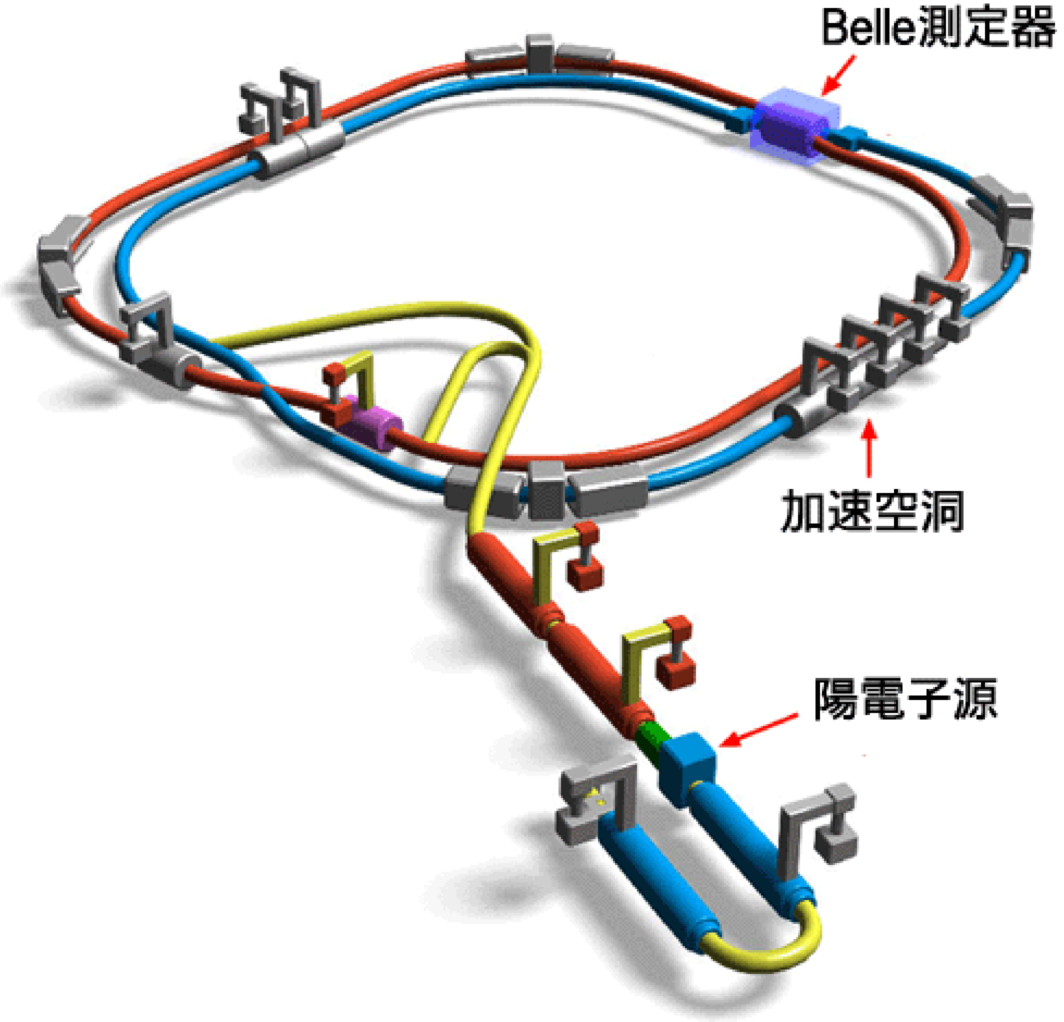
“Injection kicker”

“abort kicker”

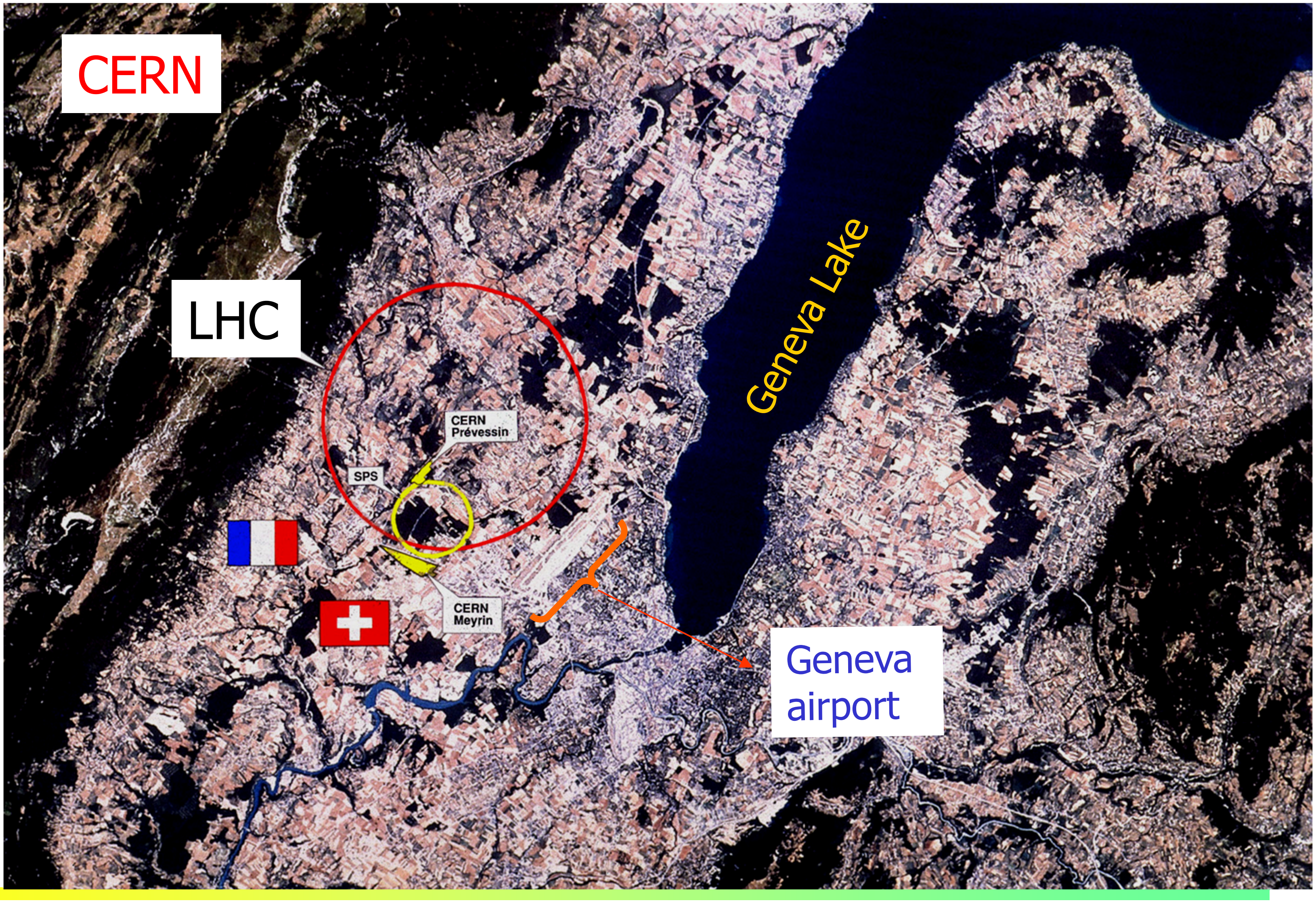
LINAC

Electron positron collider: KEK-B



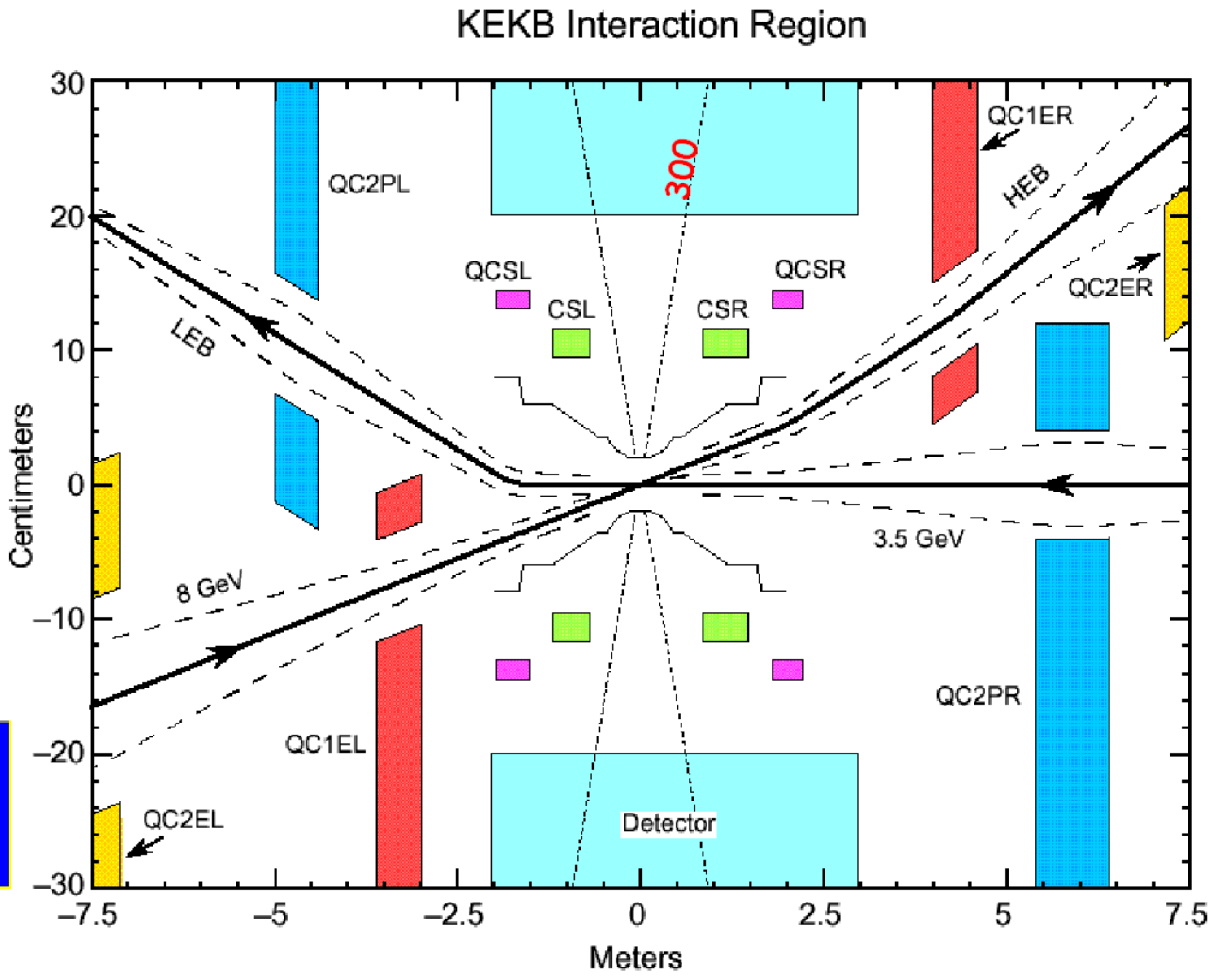


Large hadron collider



Interaction region: Belle

Collisions at a finite angle +-11mrad

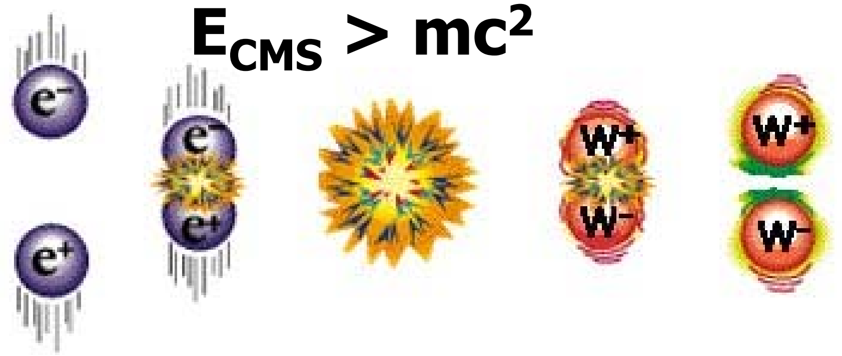


BELLE

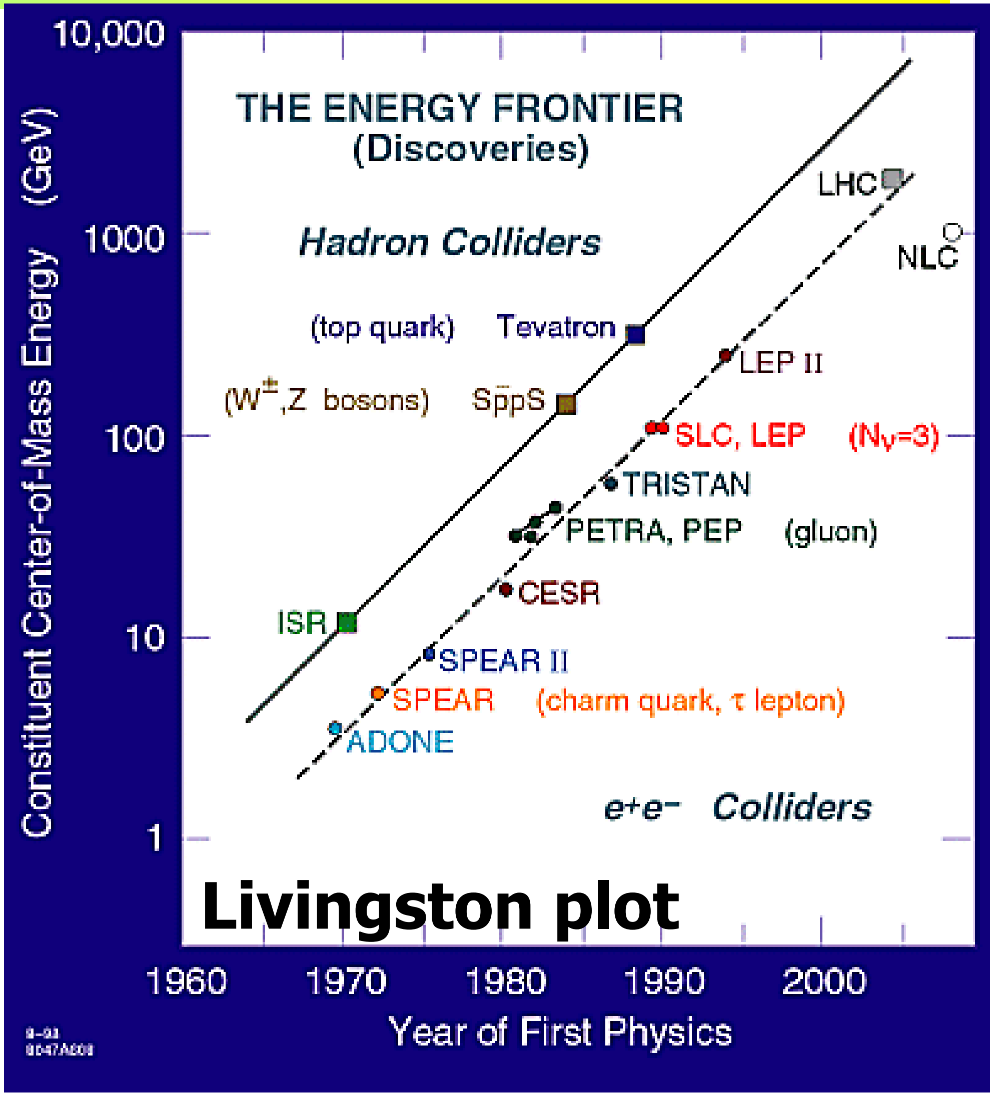
Accelerator figure of merit 1: Center-of-mass energy

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

$E_{CMS} > mc^2$



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



Livingston plot

Accelerator figure of merit 2: Luminosity

Observed rate of events = Cross section x Luminosity

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

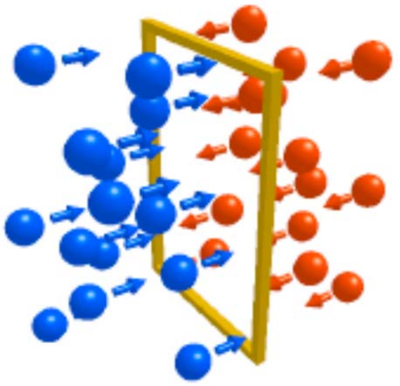
Accelerator figures of merit: luminosity ***L***

and integrated luminosity

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

Luminosity vs time

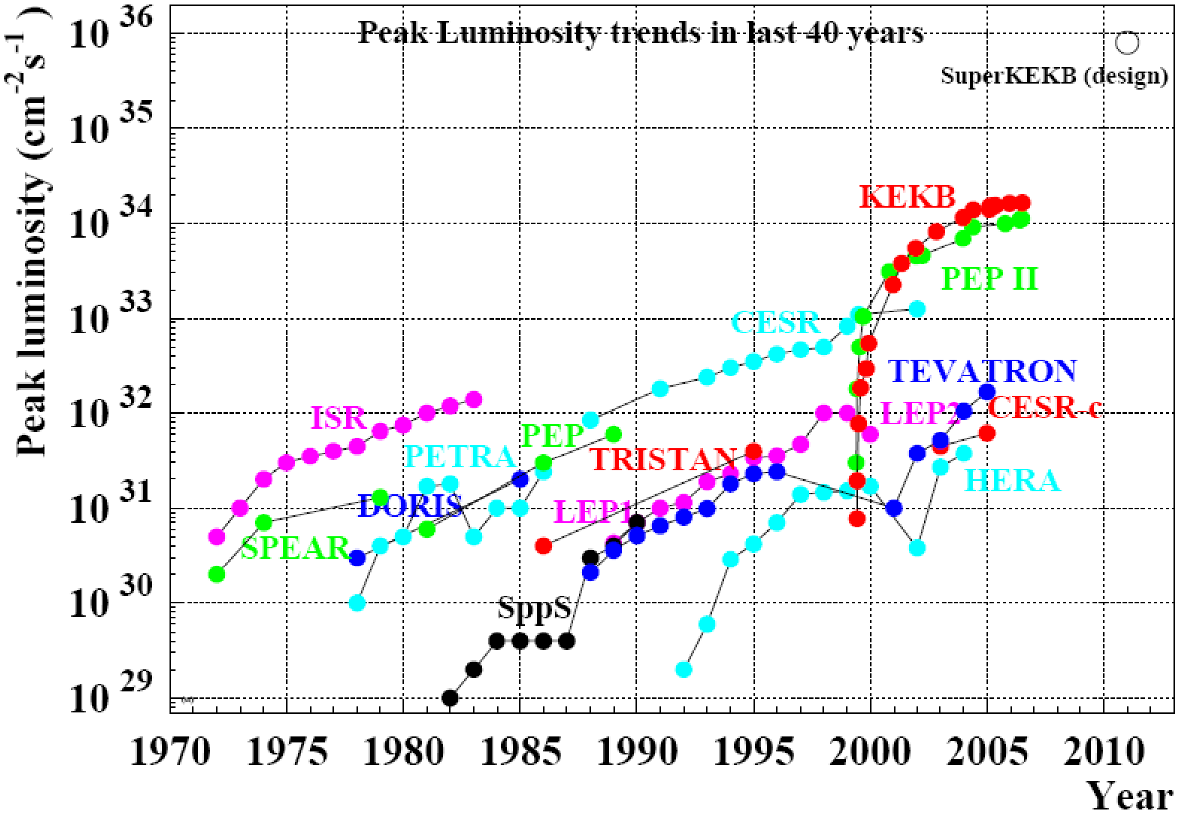
$$R = \mathcal{L}\sigma$$



(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 occured, 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 (~1T)
- Determine the identity of stable charged particles (e, μ, π, K, p)
- Measure the energy of high energy photons γ

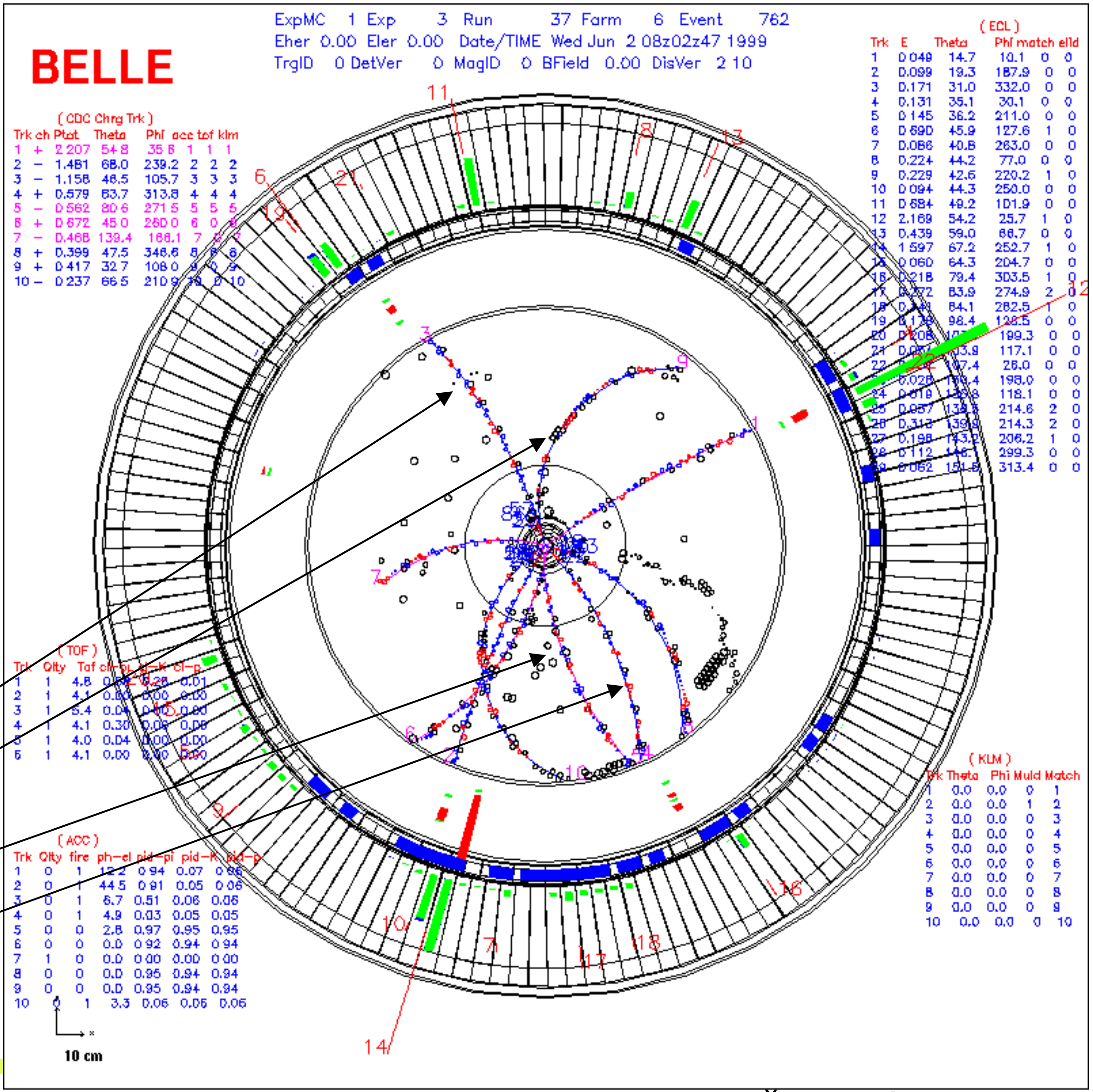
How to understand what happened in a collision?

Illustration on an example:

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

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

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



BELLE

```
ExpMC   1 Exp     3  Run        37 Farm     6  Event     762
Eher  0.00  Eler  0.00  Date/TIME  Wed Jun  2 08z02z47 1999
TrgID   0 DetVer    0  MagID   0  BField  0.00  DisVer  2 10
```

```
        ( CDC Chrg Trk )
Trk ch Ptot    Theta    Phi  acc tof klm
1   +  2 207   54 8     35 6   1   1   1
2   -  1.481   68.0    239.2   2   2   2
3   -  1.158   48.5    105.7   3   3   3
4   +  0.579   63.7    313.8   4   4   4
5   -  0 562   80 6    271 5   5   5   5
6   +  0 672   45 0    260 0   6   0   6
7   -  0.468  139.4    166.1   7   0   7
8   +  0.399   47.5    346.6   8   8   8
9   +  0 417   32 7    108 0   9   0   9
10 -   0 237   66 5    210 9  10   0  10
```

```
                 ( ECL )
Trk   E      Theta      Phi match elId
1    0 049   14.7      10.1   0   0
2    0.099   19.3     187.9   0   0
3    0.171   31.0     332.0   0   0
4    0.131   35.1      30.1   0   0
5    0 145   36.2     211.0   0   0
6    0 690   45.9     127.6   1   0
7    0.086   40.8     263.0   0   0
8    0.224   44.2      77.0   0   0
9    0.229   42.6     220.2   1   0
10   0 094   44.3     250.0   0   0
11   0 684   49.2     101.9   0   0
12   2.169   54.2      25.7   1   0
13   0.439   59.0      88.7   0   0
14   1 597   67.2     252.7   1   0
15   0 060   64.3     204.7   0   0
16   0.218   79.4     303.5   1   0
17   0.272   83.9     274.9   2   0
18   0.141   84.1     282.5   1   0
19   0.178   98.4     128.5   0   0
20   0.208  [illegible] 199.3 0   0
21   0.057  [illegible] 117.1 0   0
22  [illegible] 107.4  26.0   0   0
23   0.028  [illegible] 198.0 0   0
24   0 019  [illegible] 118.1 0   0
25   0.037  [illegible] 214.6 2   0
26   0.313  139.9     214.3   2   0
27   0.198  143.2     206.2   1   0
28   0 112  146.1     299.3   0   0
29   0 062  151.5     313.4   0   0
```

```
        ( TOF )
Trk  Qlty  Tof cl-pi cl-K  cl-p
1    1    4.8  [illegible] 0.26  0.01
2    1    4.1  0.00  0.00  0.00
3    1    5.4  0.04  0.00  0.00
4    1    4.1  0.30  0.08  0.08
5    1    4.0  0.04  0.00  0.00
6    1    4.1  0.00  0.00  0.00
```

```
        ( ACC )
Trk Qlty fire ph-el pid-pi pid-K pid-p
1    0    1   12 2   0 94  0.07  0 06
2    0    1   44 5   0 91  0.05  0 06
3    0    1    6.7   0.51  0.06  0.06
4    0    1    4.9   0.03  0.05  0.05
5    0    0    2.8   0.97  0.95  0.95
6    0    0    0.0   0 92  0.94  0 94
7    1    0    0.0   0 00  0.00  0 00
8    0    0    0.0   0.95  0.94  0.94
9    0    0    0.0   0.95  0.94  0.94
10    0    1    3.3  0.06  0.06  0.06
```

```
       ( KLM )
Trk Theta  Phi Muld Match
1    0.0   0.0   0   1
2    0.0   0.0   1   2
3    0.0   0.0   0   3
4    0.0   0.0   0   4
5    0.0   0.0   0   5
6    0.0   0.0   0   6
7    0.0   0.0   0   7
8    0.0   0.0   0   8
9    0.0   0.0   0   9
10    0.0   0.0   0  10
```

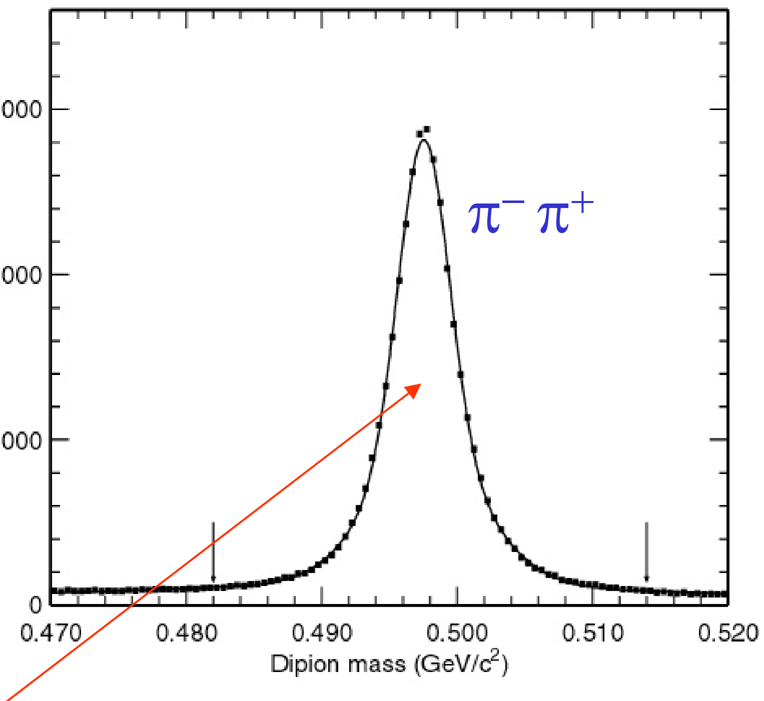
Search for particles which decayed close to the production point

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→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 loosing the events in the peak (=reduce background and have a small peak width).

How do we know it was precisely this reaction?



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

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

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

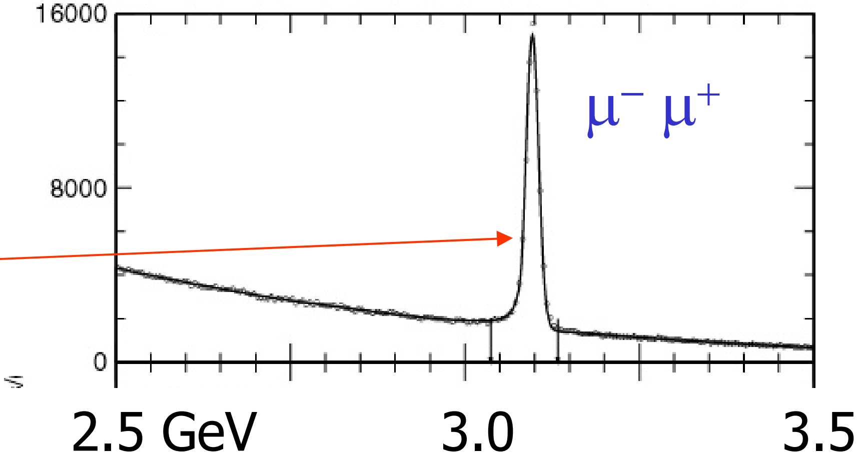
detect

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

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

Mc^2 must be for K^0_S close to 0.5 GeV,

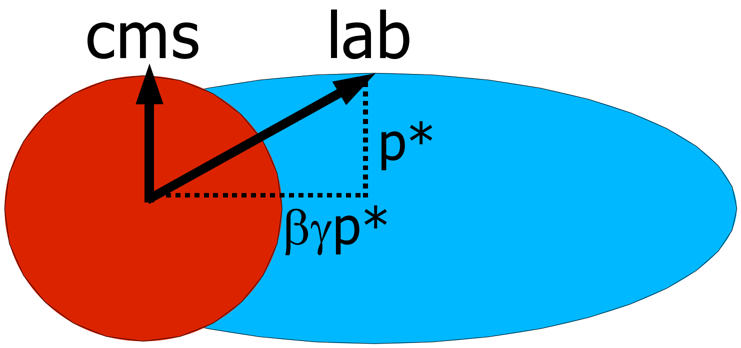
for J/ψ close to 3.1 GeV.

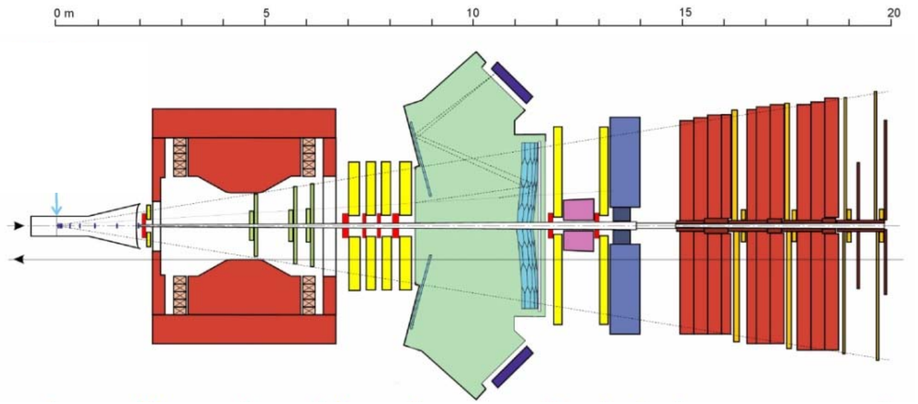


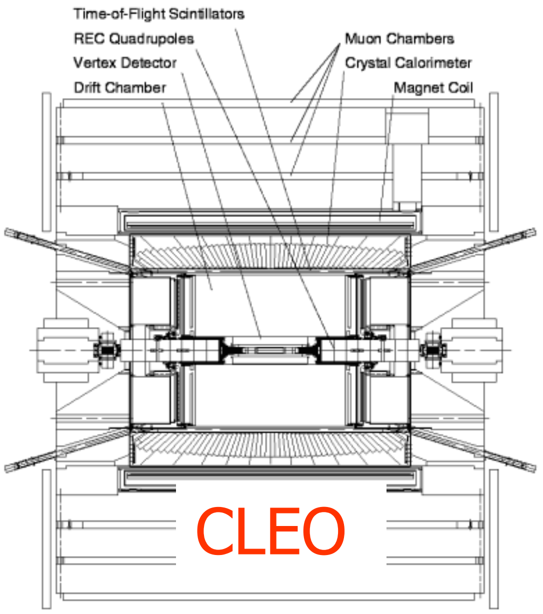
Rest in the histrogram: random coincidences ('combinatorial background')

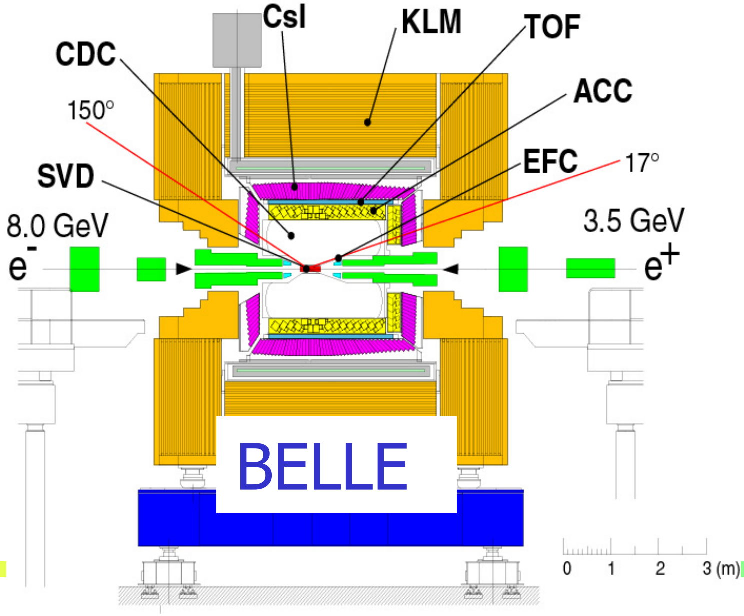
Experimental aparatus

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.

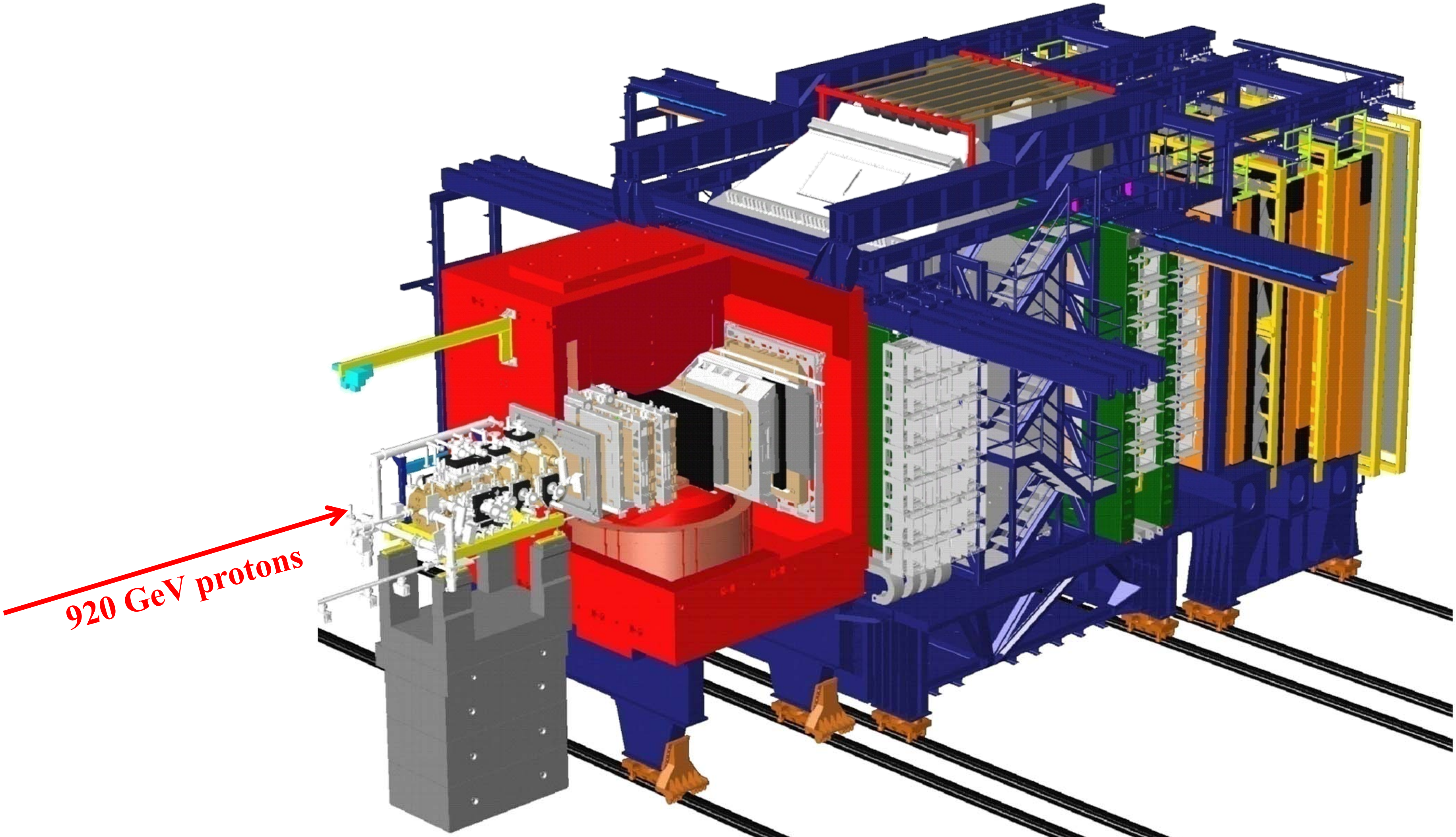




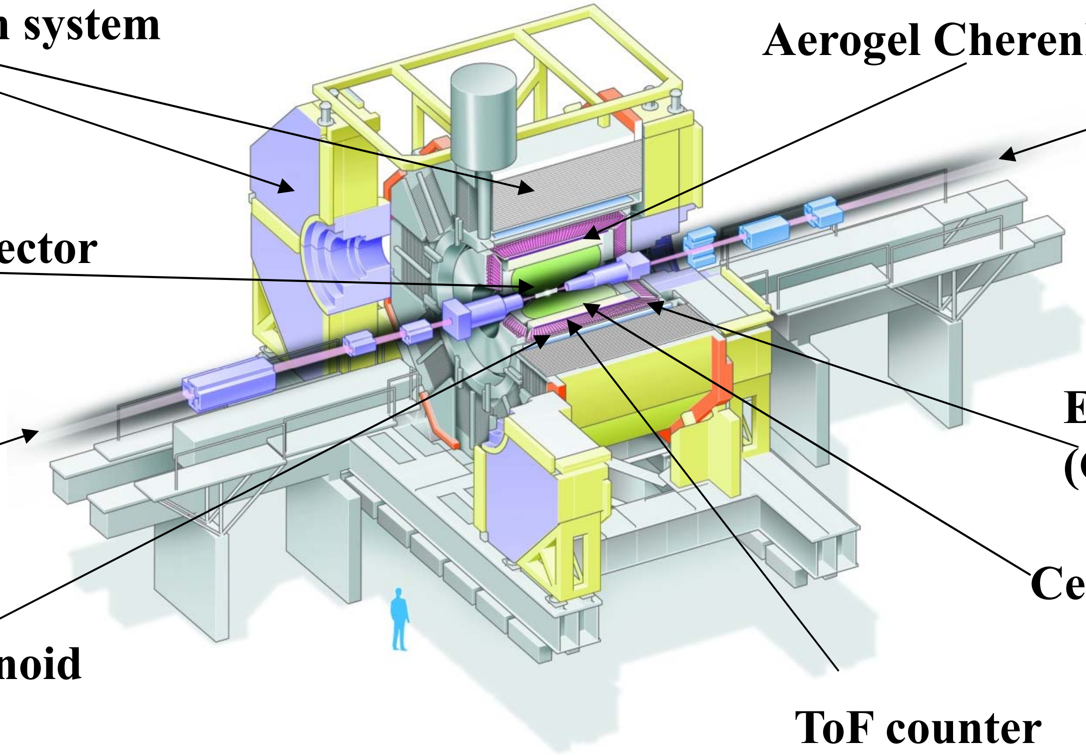




Example of a fixed target experiment: HERA-B



Belle spectrometer at KEK-B



μ and K_L detection system

Aerogel Cherenkov Counter

3.5 GeV e^+

Silicon Vertex Detector

Electromagnetic. Cal. (CsI crystals)

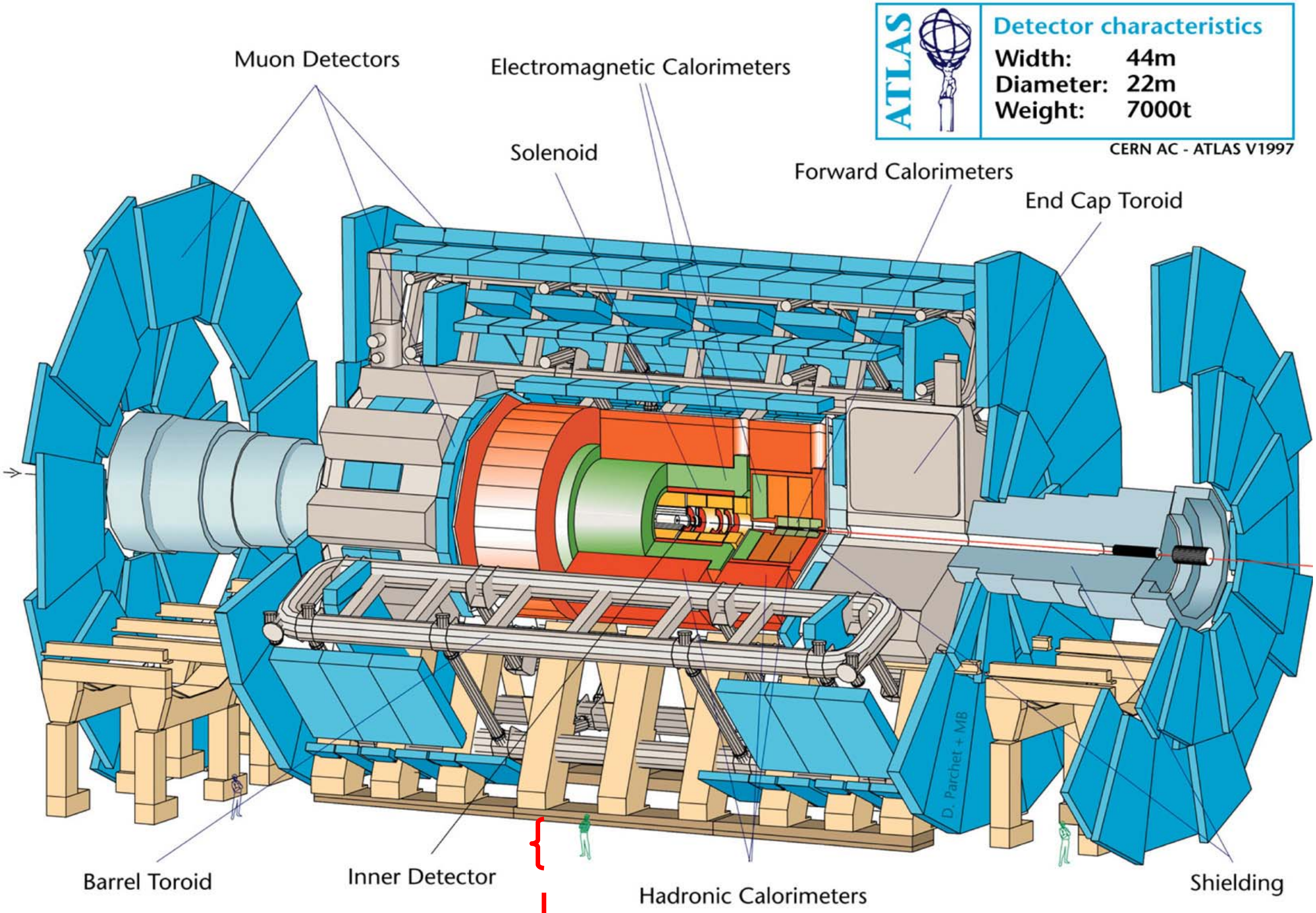
8 GeV e^-

Central Drift Chamber

1.5T SC solenoid

ToF counter

ATLAS at LHC



A physicist...

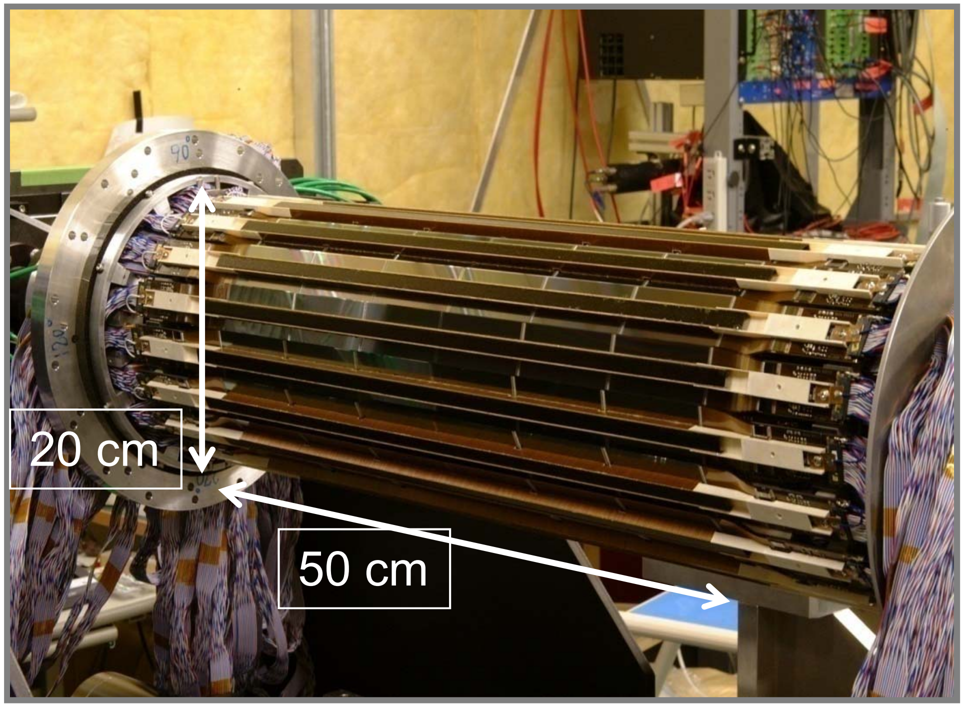
Components of an experimental apparatus (‘spectrometer’)

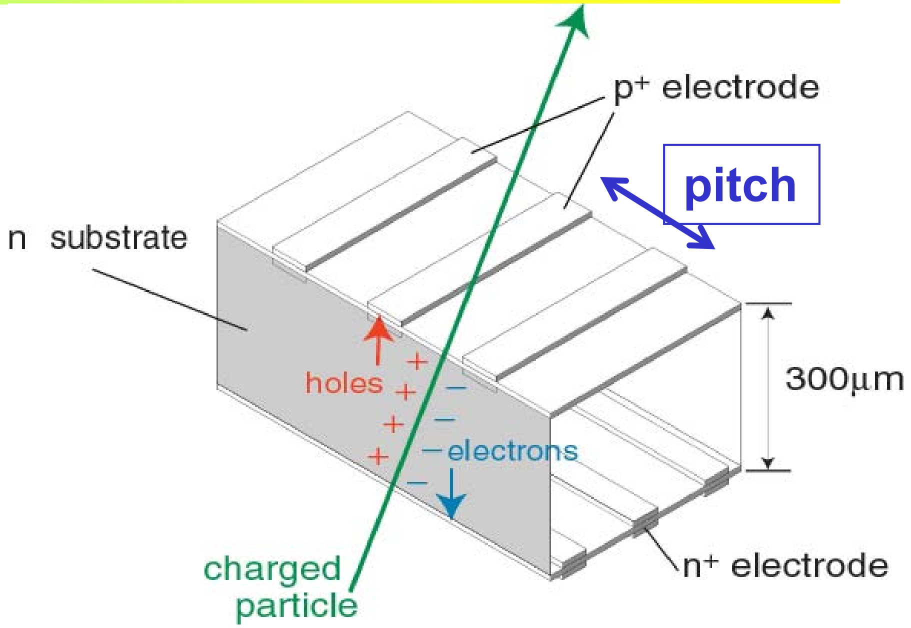
- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

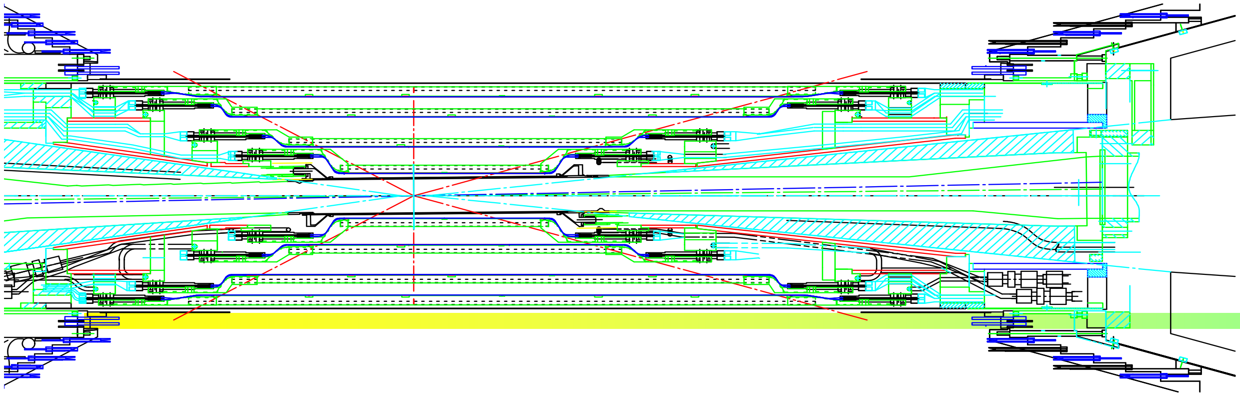
Components of an experimental apparatus (‘spectrometer’)

- 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 ~50μm, resolution about ~15 μm

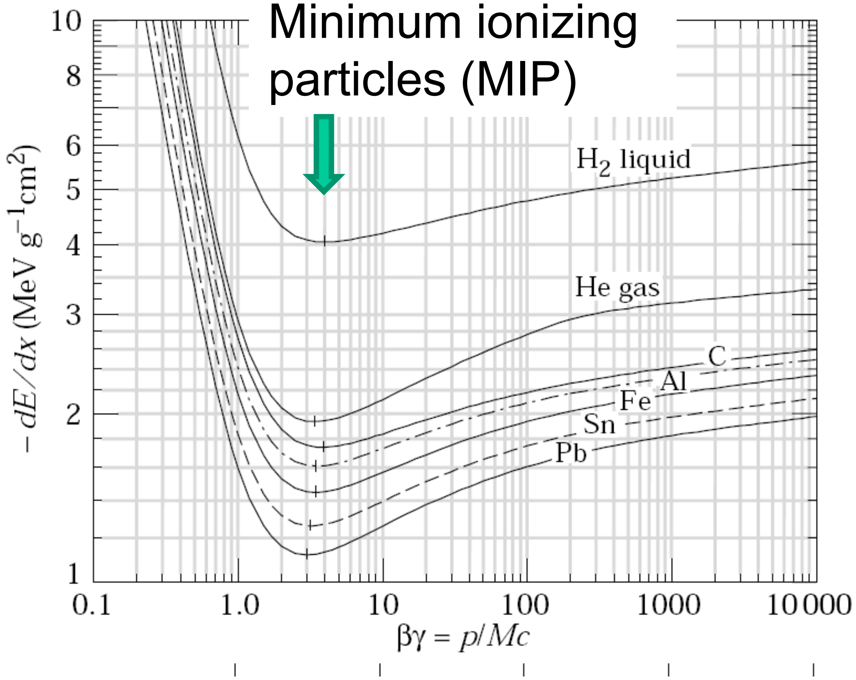
Interaction of charged particles with matter

Energy loss due to ionisation:

depends on βγ, in the minimum about 2 MeV/cm ρ/(g cm^{-3}).

Liquids, solids: few MeV/cm

Gases: few keV/cm


Minimum ionizing particles (MIP)

Bethe-Bloch equation

Straggling functions: energy loss distribution

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

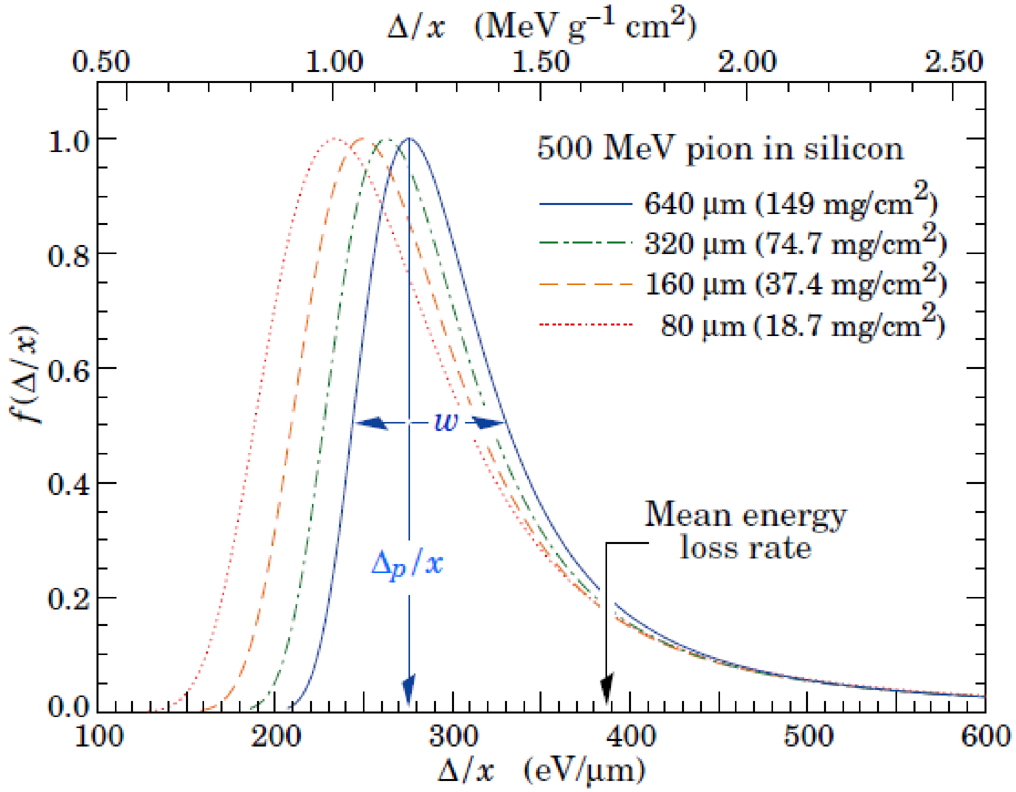
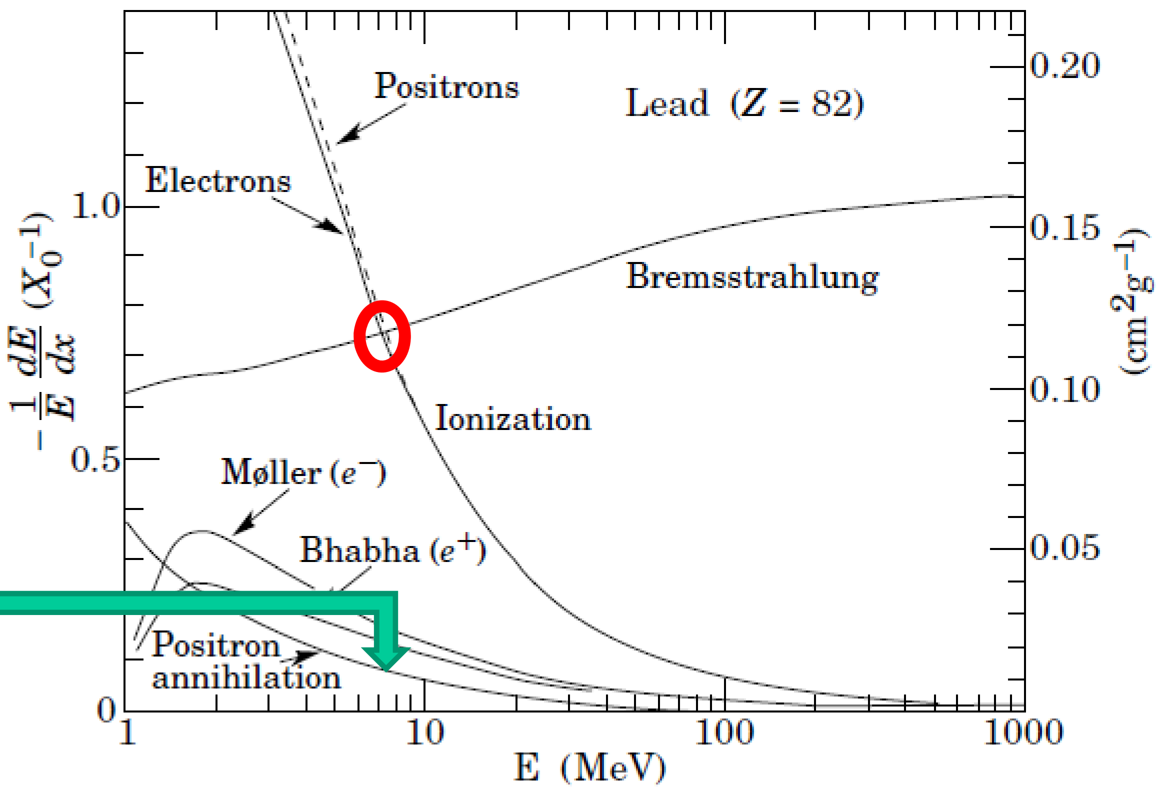


Figure 27.7: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value δ_p/x. The width w is the full width at half maximum. See full-color version on color pages at end of book.

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



Critical energy E_c

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

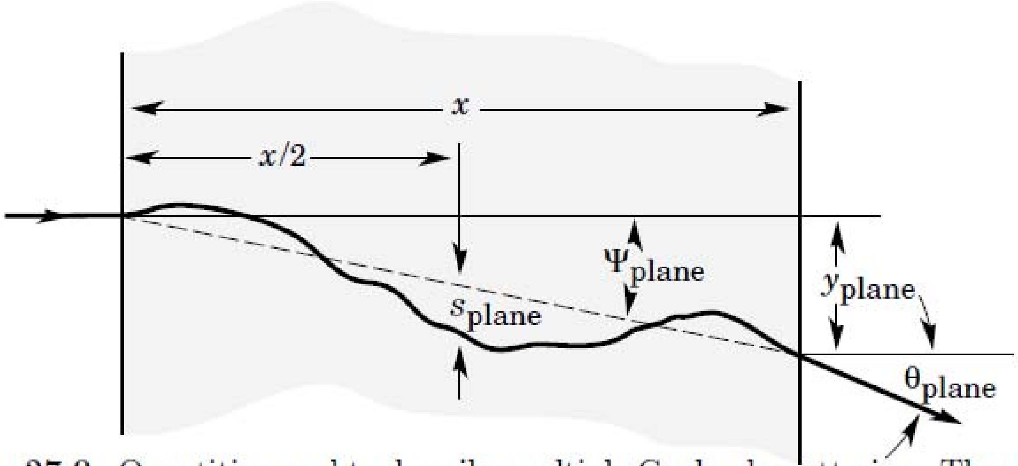


Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Interaction of charged particles with matter

Energy loss due to ionisation: depends on βγ, typically about 2 MeV/cm ρ/(g cm^{-3}).

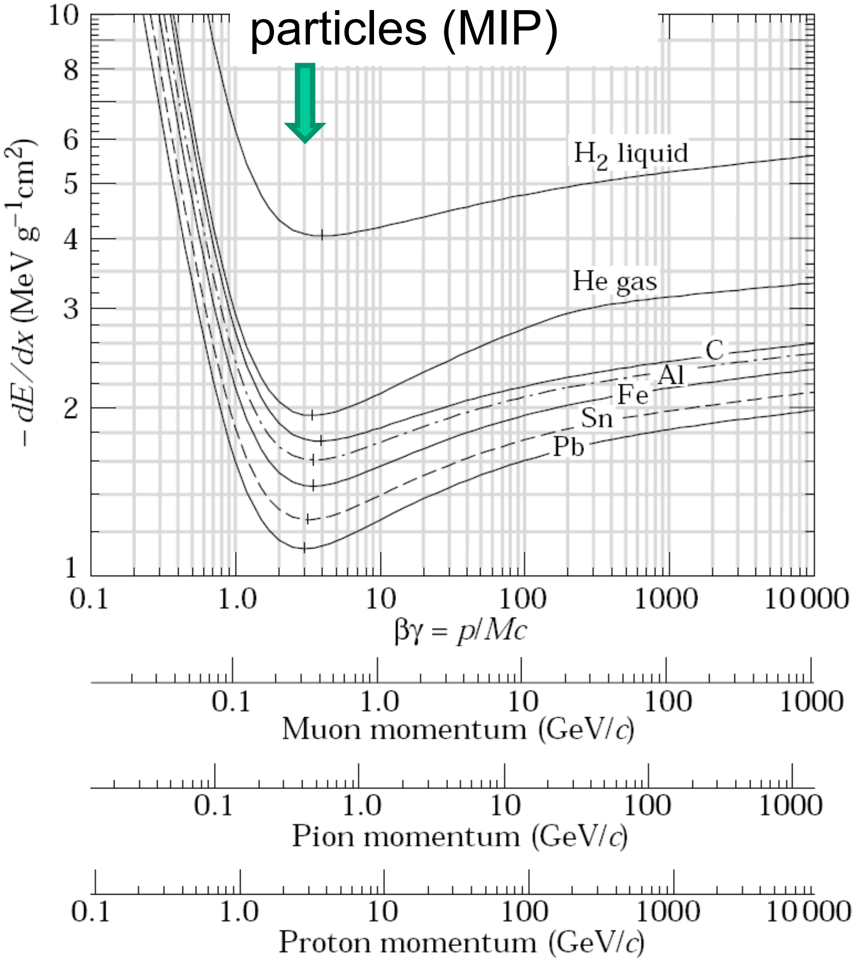
Liquids, solids: few MeV/cm

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 → per cm of gas about 2000eV/30eV=60 e-ion pairs



Minimum ionizing particles (MIP)

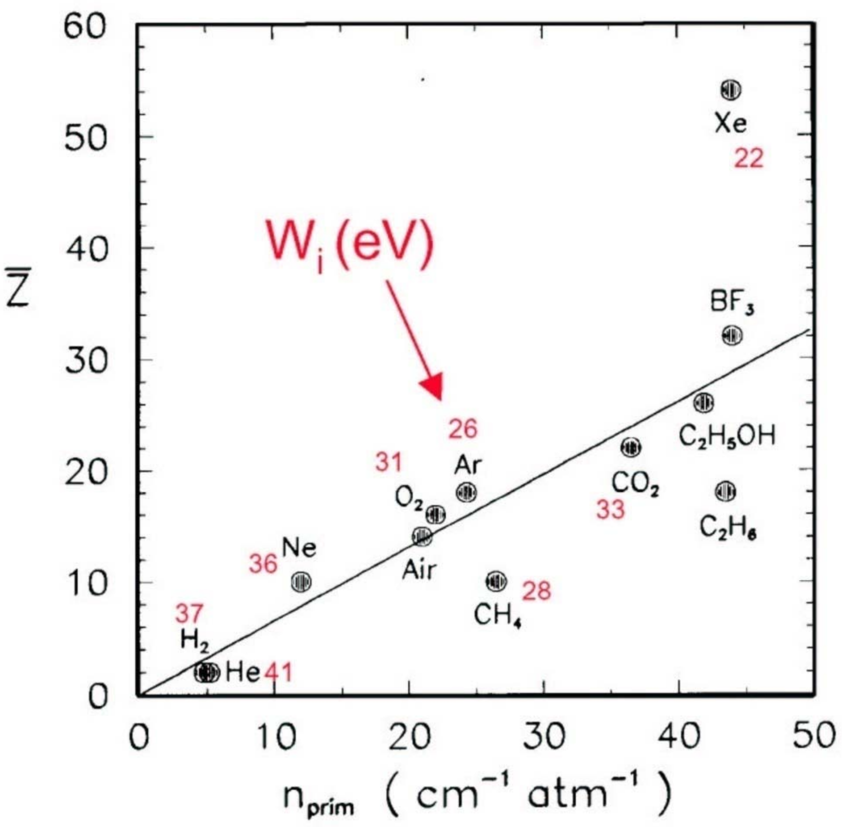
Ionisation

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



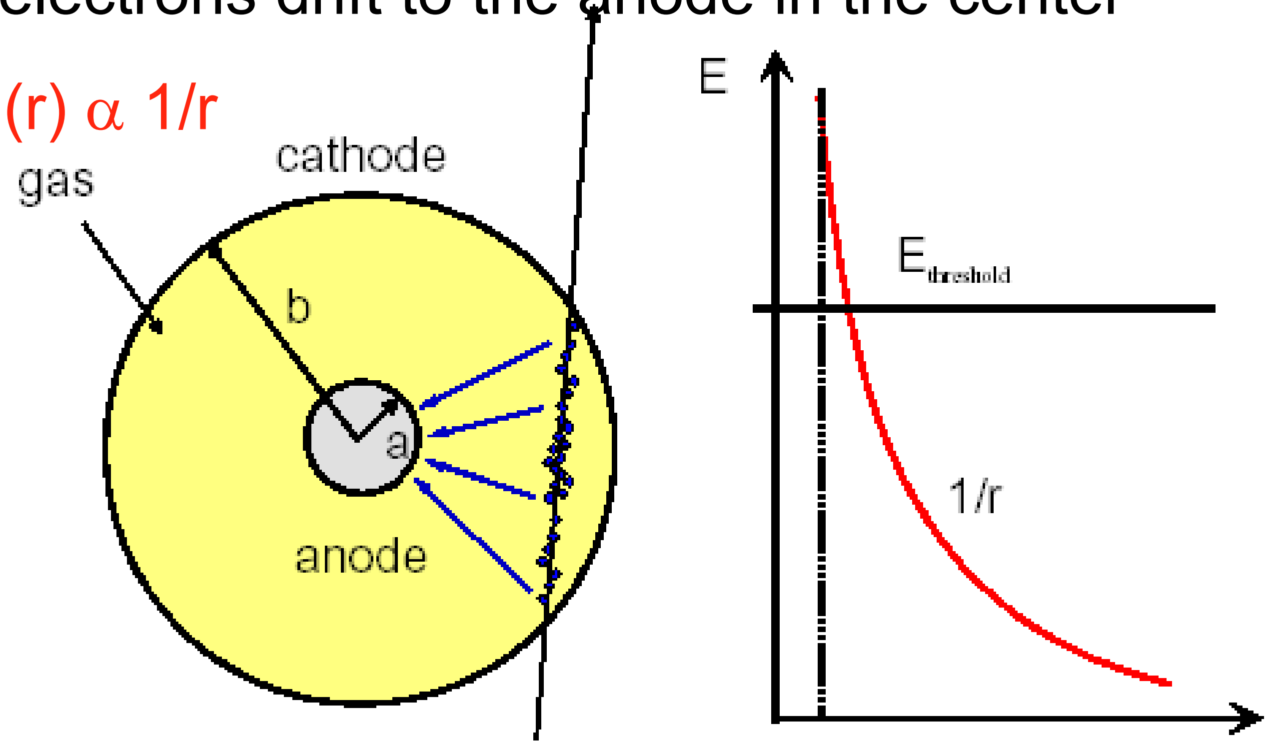
Can this be detected? 120 e-ion pairs make a pulse of $V=ne/C=2mV$ (at typical C=10pF) → NO

-> Need multiplication

Multiplication in gas

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

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

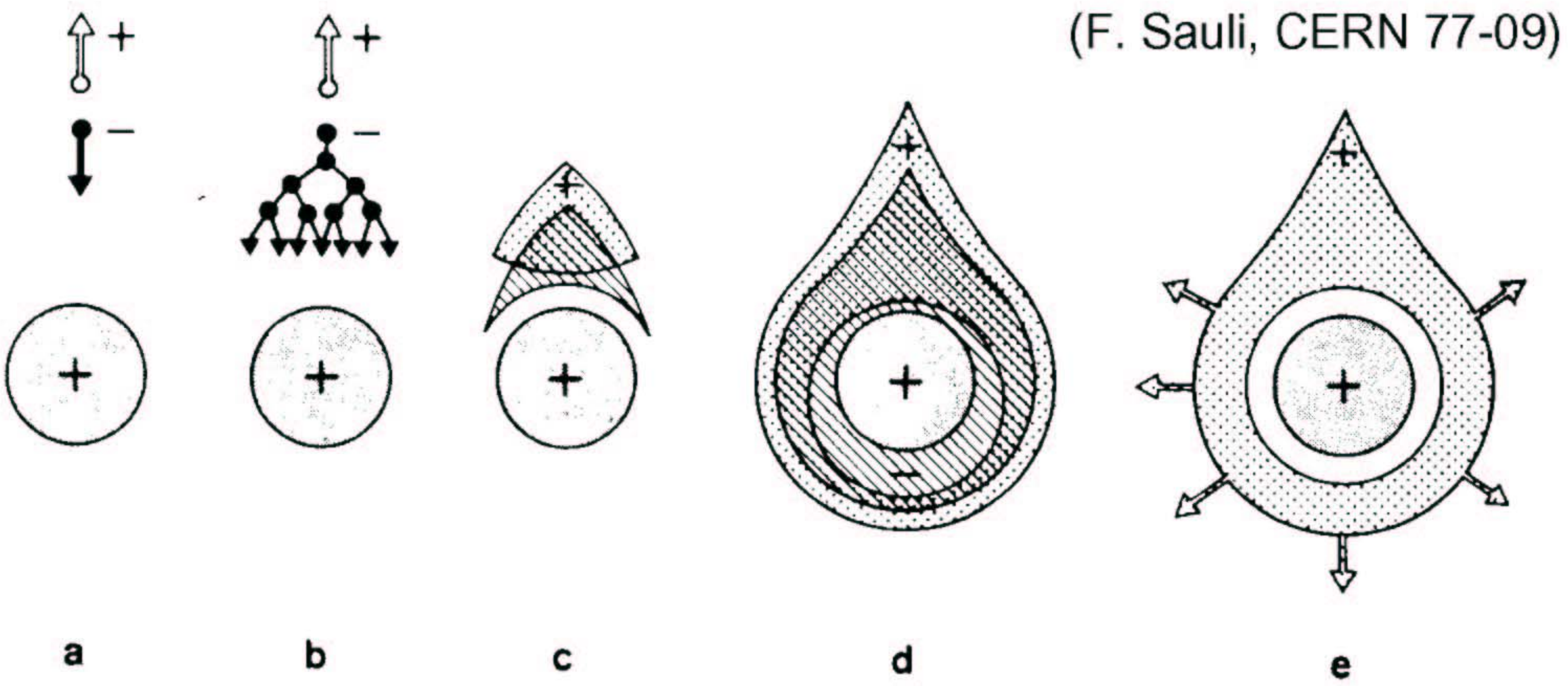


If the energy eEd gained over several mean free paths (d around 10mm) exceeds the ionisation energy → new electron

Electric field needed → $E = I/ed = 10V/\mu m$ = 100kV/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.



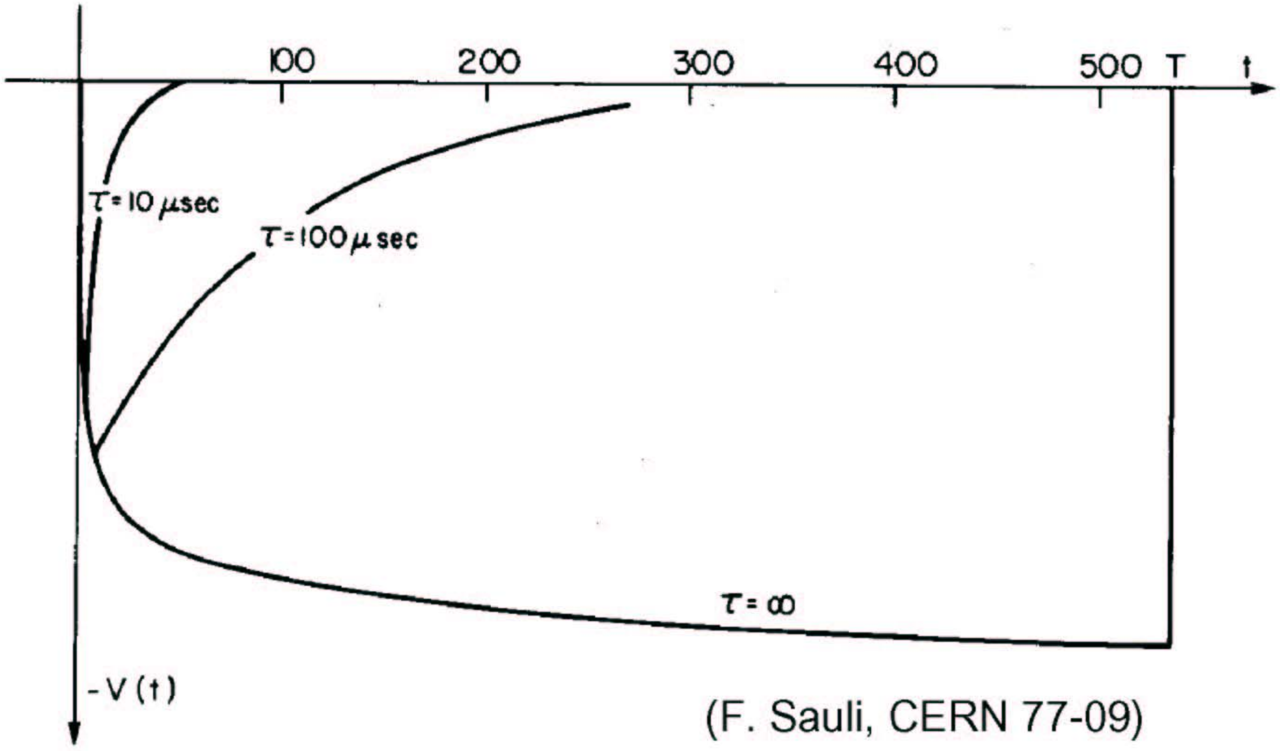
(F. Sauli, CERN 77-09)

Signal development

Time evolution of the signal

$$u(t) = -\frac{Q}{4\pi\varepsilon_0 l}\ln(1+\frac{t}{t_0})$$

with no RC filtering (τ = inf.) and with time constants 10μs and 100μs.

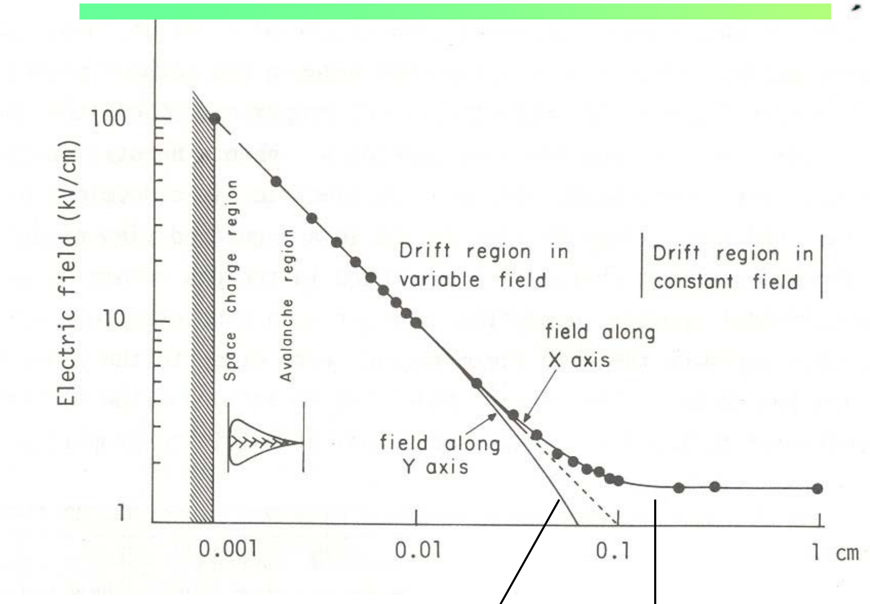


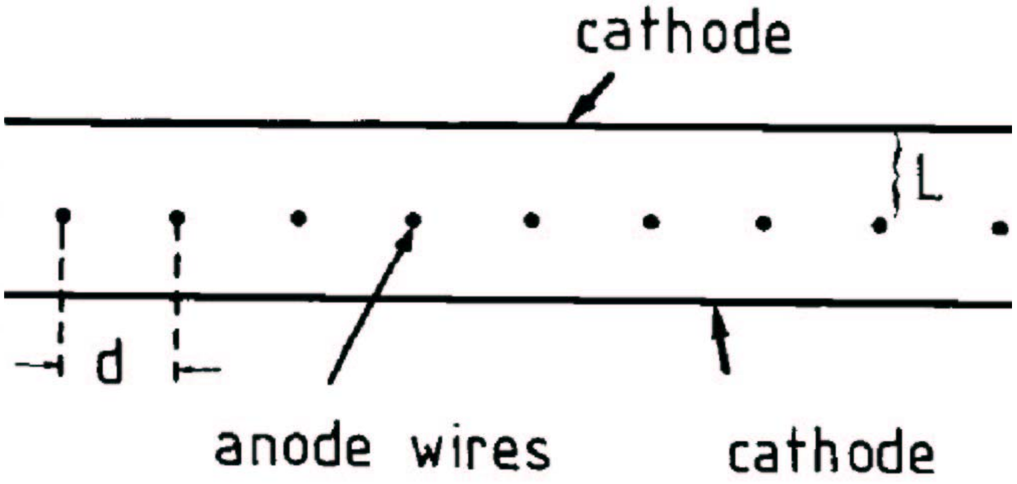
(F. Sauli, CERN 77-09)

If faster signals are needed → smaller time constants→ smaller signals

e.g. τ =40ns: max u(t) is about ¼ of the τ = inf. case

Multiwire proportional chamber (MWPC)

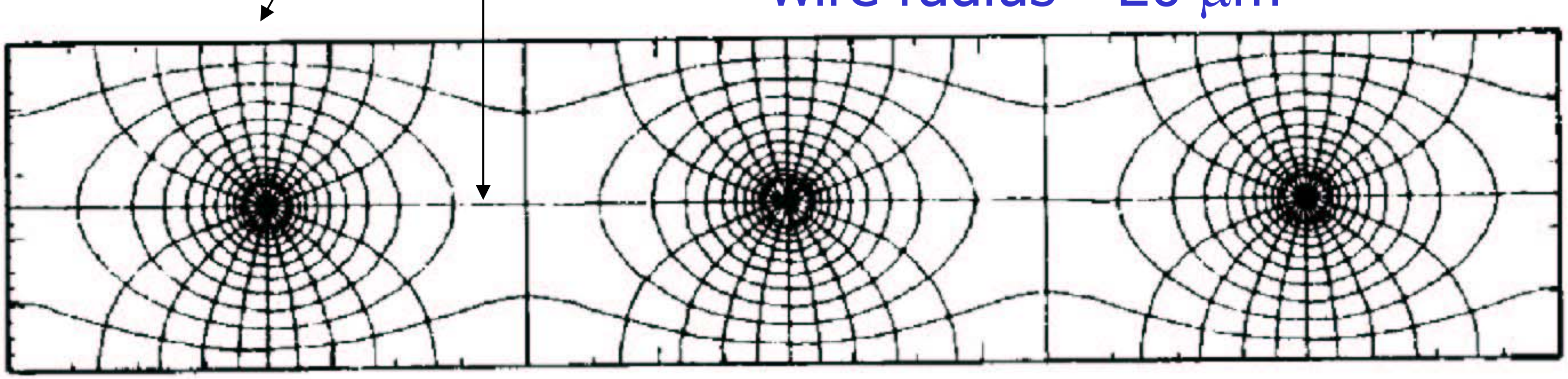




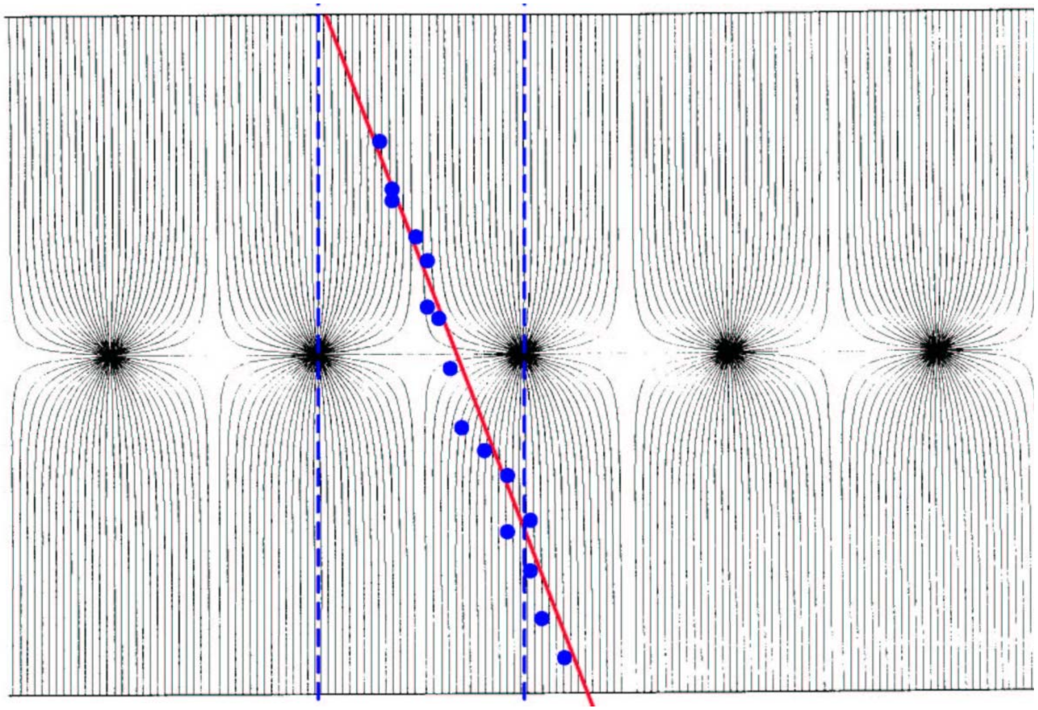
Typical parameters:

L=5mm, d=1-2mm,

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

$\sigma = d/\mathrm{sqrt}(12)$

for d=1mm → σ =300 μm

Revolutionized particle physics experiments
→ 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?

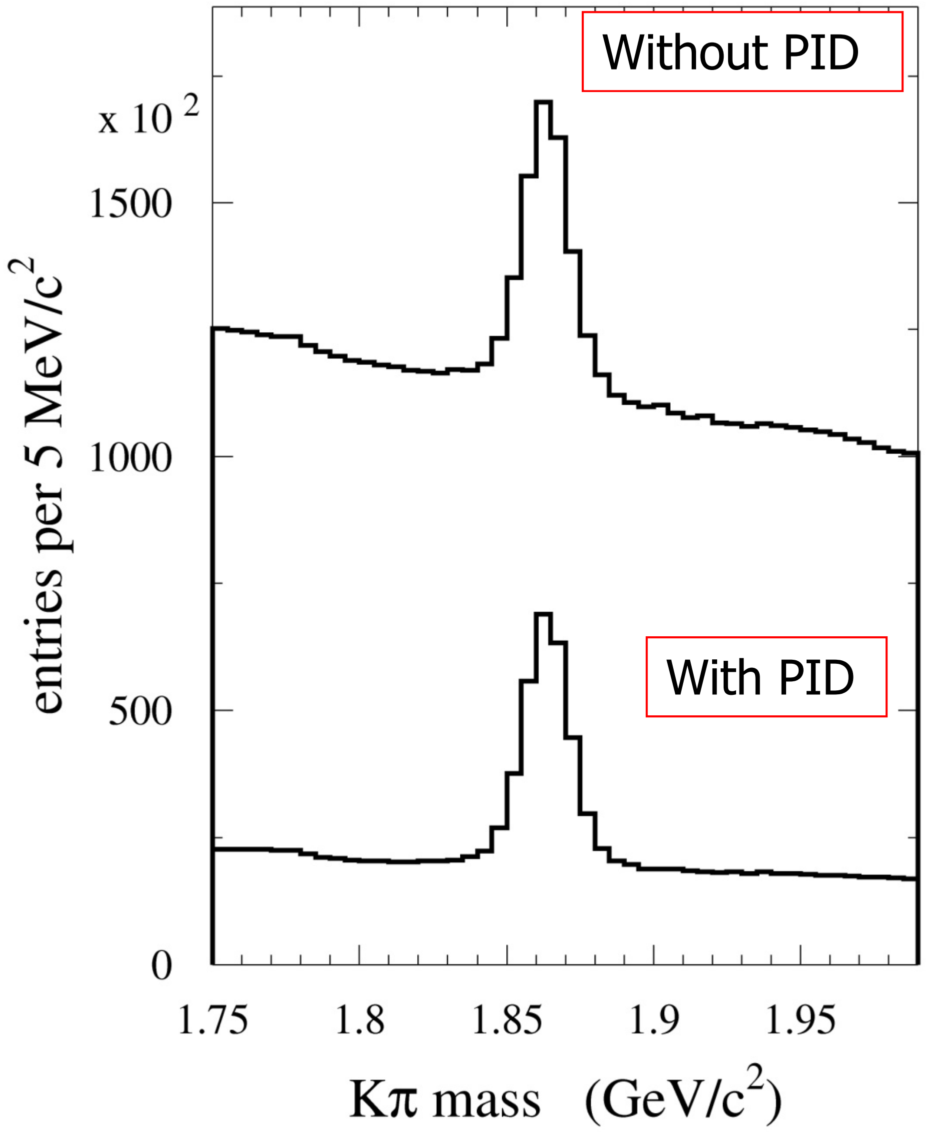
Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

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

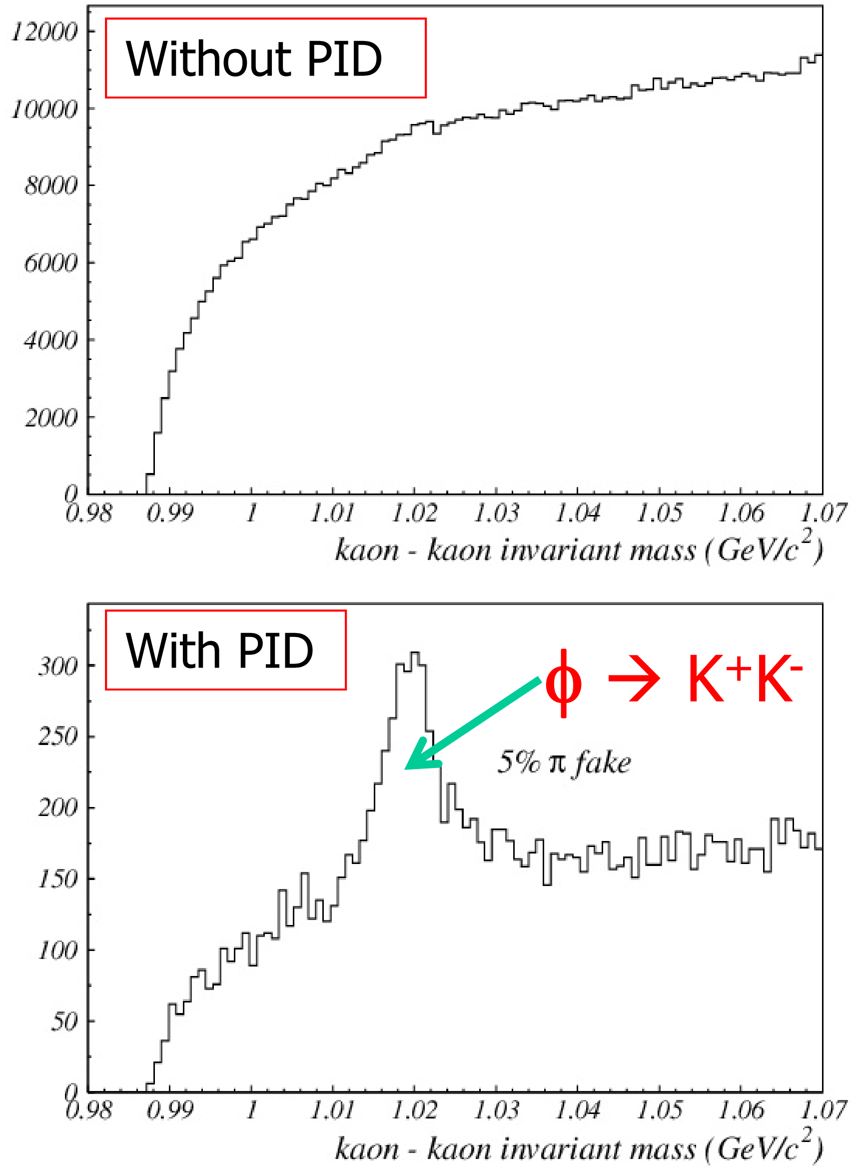
Introduction: Why Particle ID?



Example 1: B factories

Particle identification reduces combinatorial background by ~5x

Introduction: Why Particle ID?

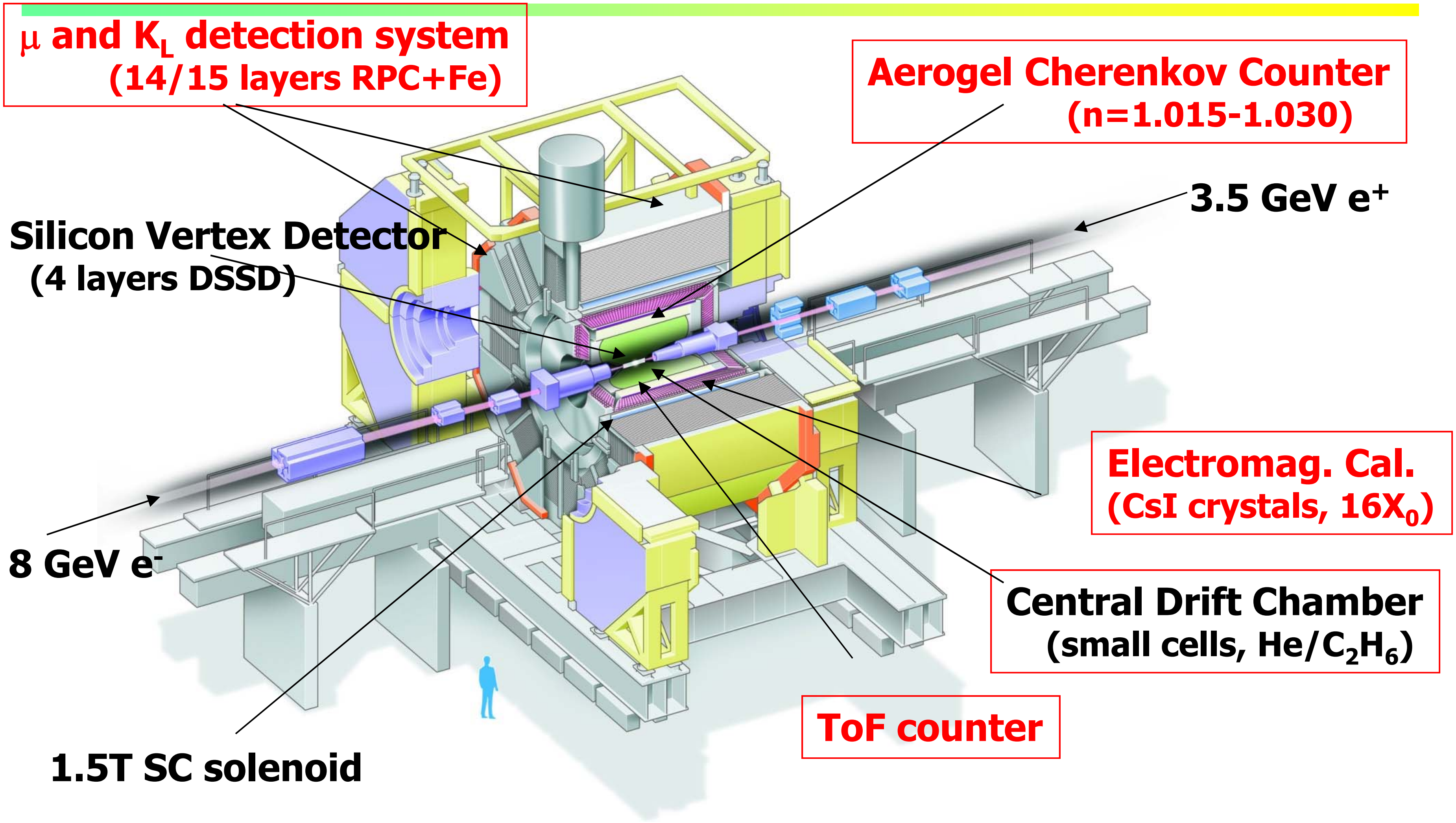


Example 2: HERA-B

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



μ and K_L detection system (14/15 layers RPC+Fe)

Aerogel Cherenkov Counter (n=1.015-1.030)

3.5 GeV e^+

Silicon Vertex Detector (4 layers DSSD)

Electromag. Cal. (CsI crystals, $16X_0$)

8 GeV e^-

Central Drift Chamber (small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

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

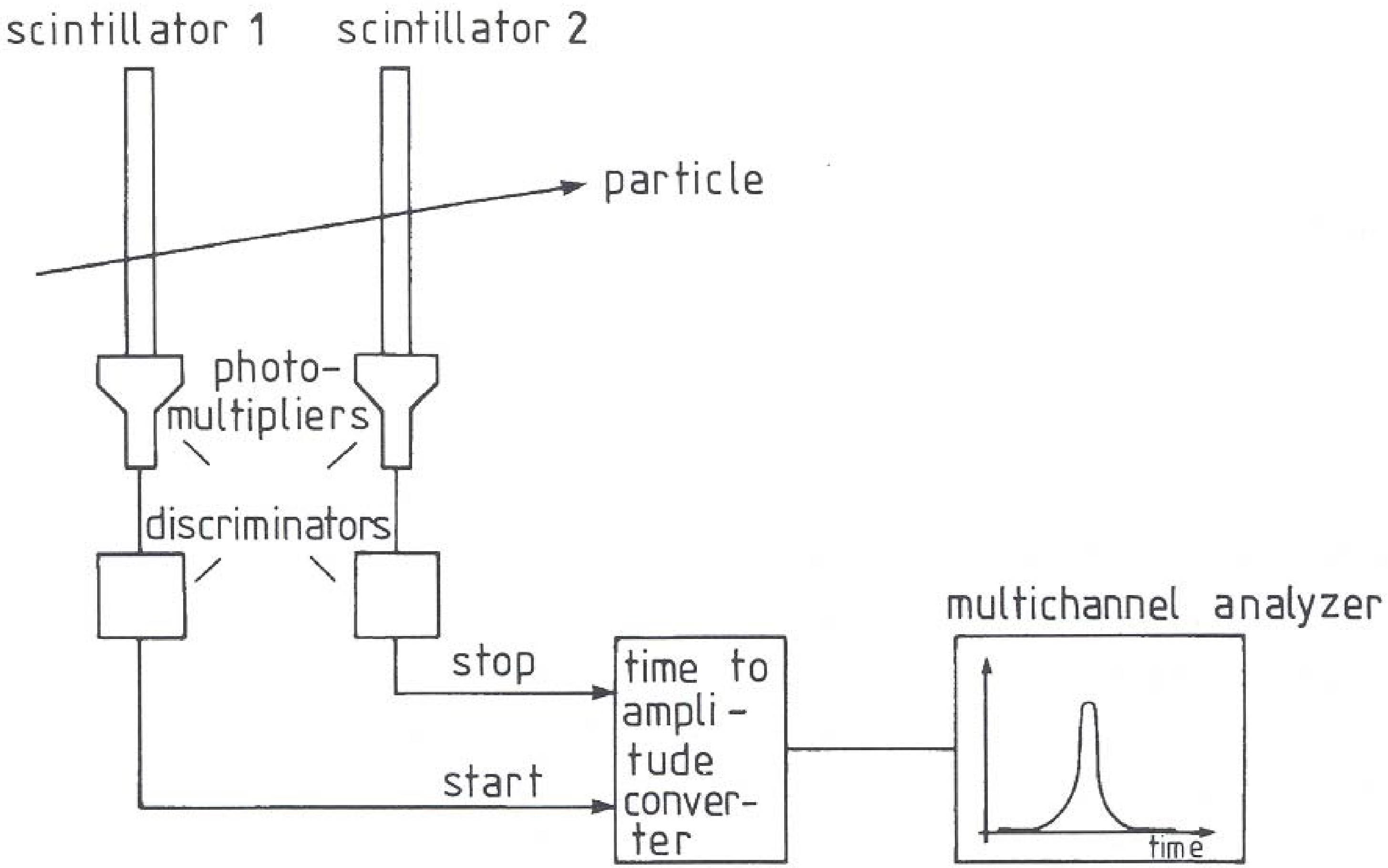
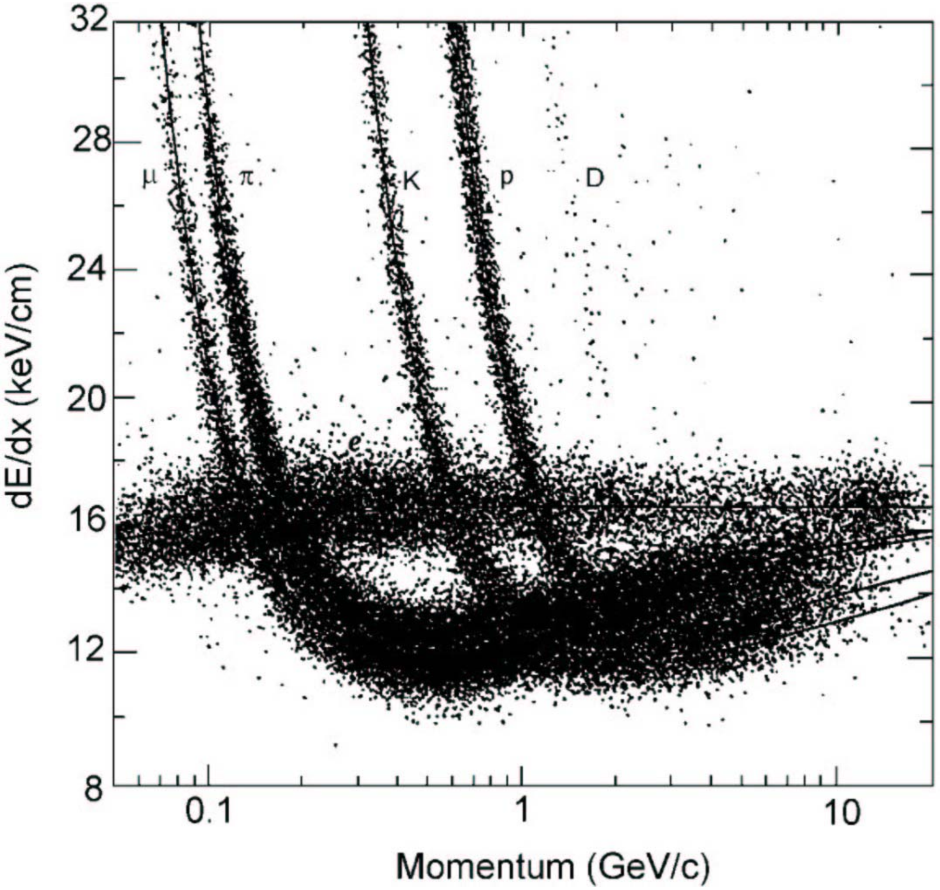
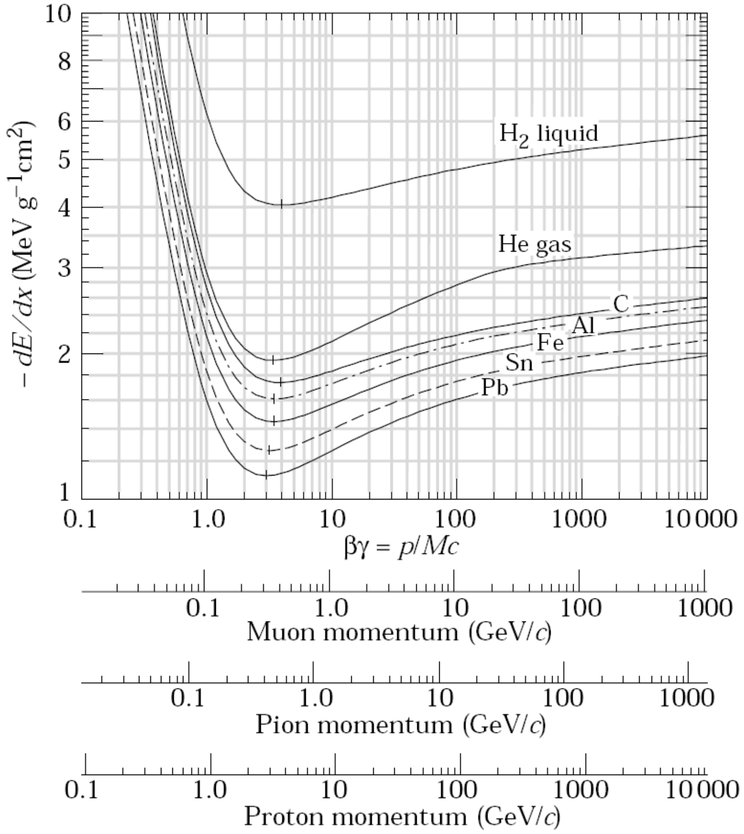


Fig. 6.5. Working principle of time-of-flight measurement.

Identification with dE/dx measurement

dE/dx performance in a large drift chamber.

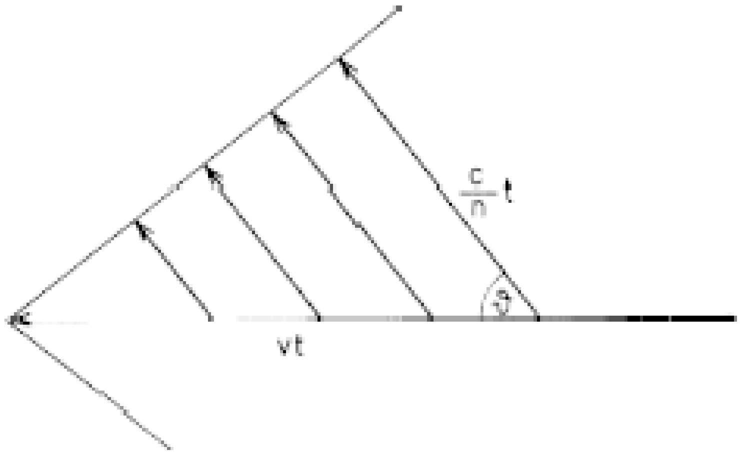




Čerenkov radiation

A charged track with velocity v=βc above the speed of light c/n in a medium with index of refraction n= sqrt(ε) 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.

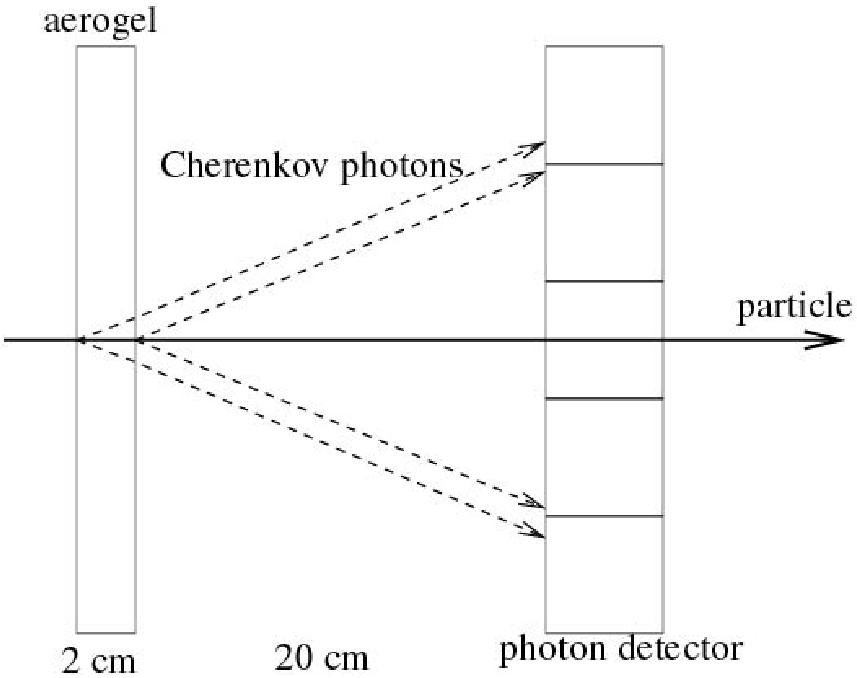
2) $\beta > \beta_t$: the number of Čerenkov photons emitted over unit photon energy E=hν in a radiator of length L amounts to

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

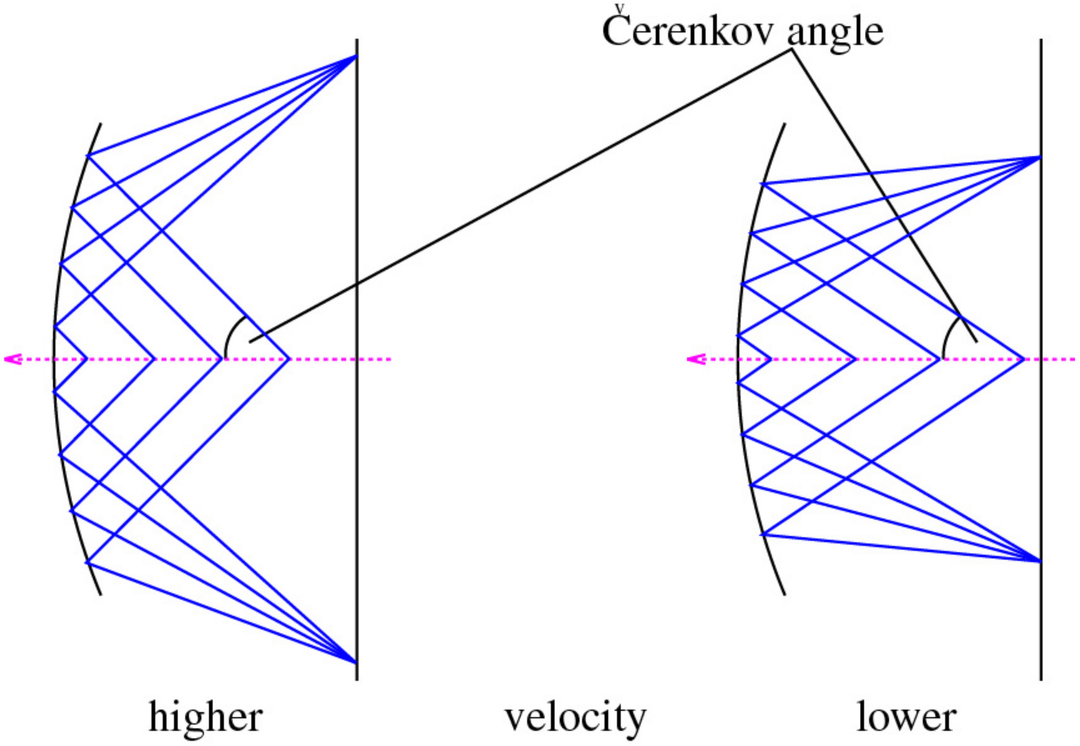
Measuring Cherenkov angle

Idea: transform the direction into a coordinate → ring on the detection plane

→ Ring Imaging CHerenkov

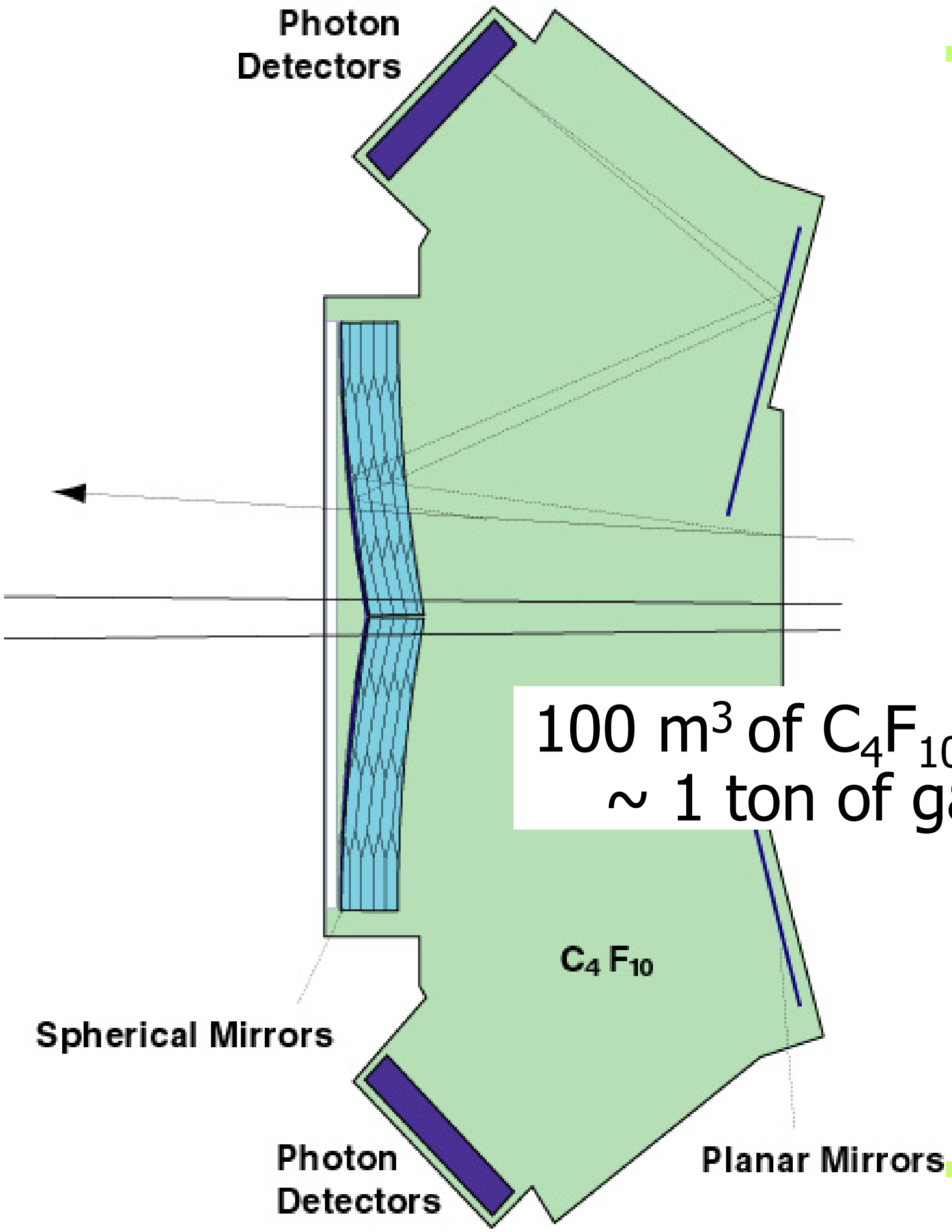


Proximity focusing RICH

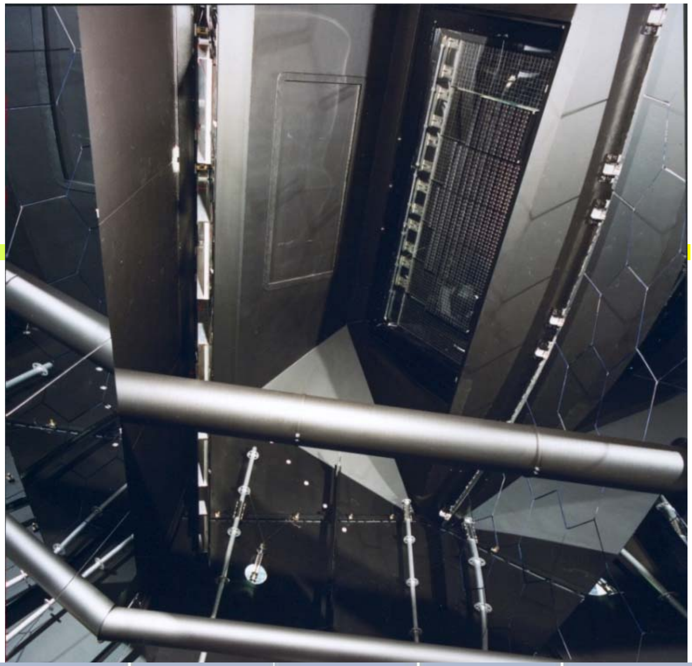


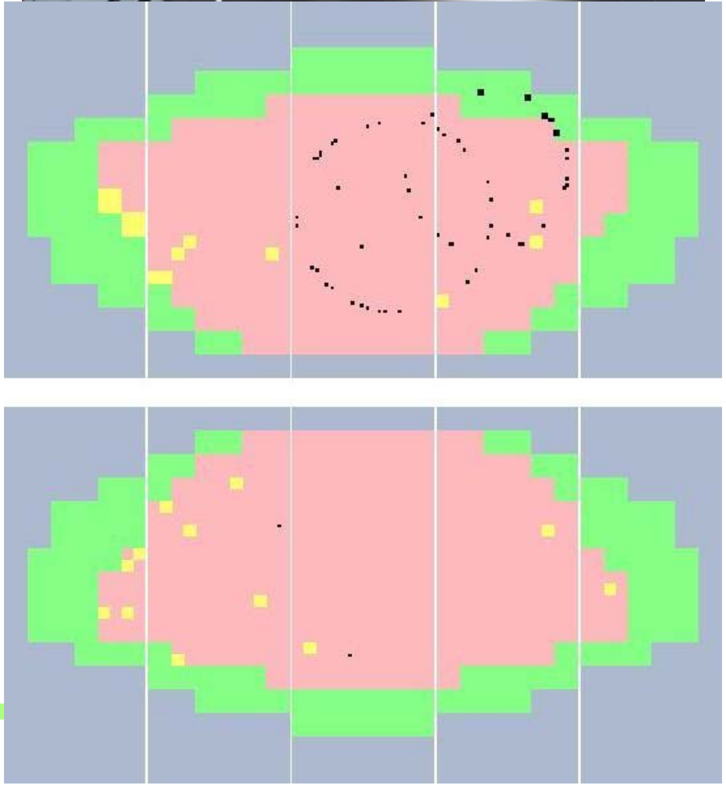
RICH with a focusing mirror

HERA-B RICH



100 m^3 of C_4F_{10}
~ 1 ton of gas





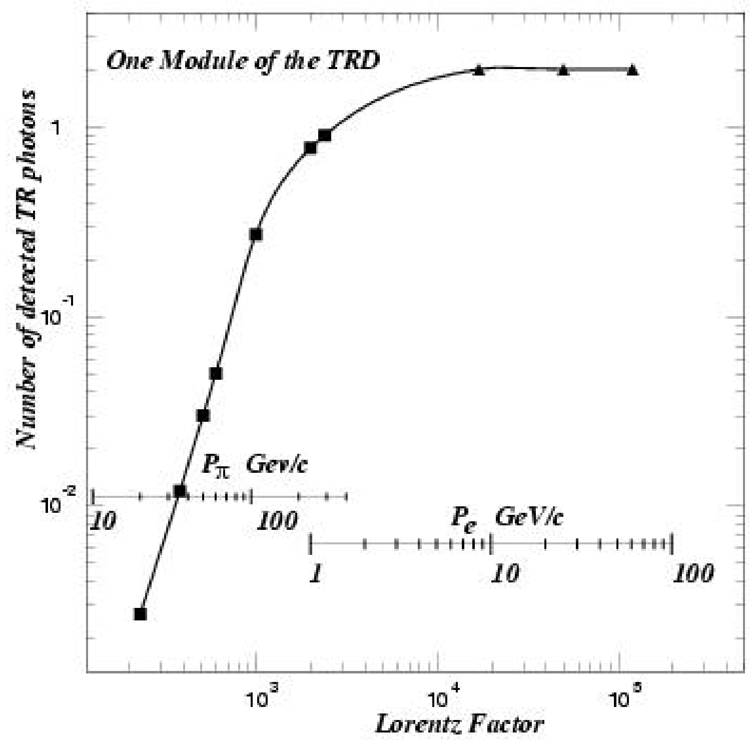
Transition radiation detectors

X rays emitted at the boundary of two media with different refractive indices, emission angle ~1/γ

Emission rate depends on γ (Lorentz factor): becomes important at γ~1000

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

In between: discrimination e vs pions, mions

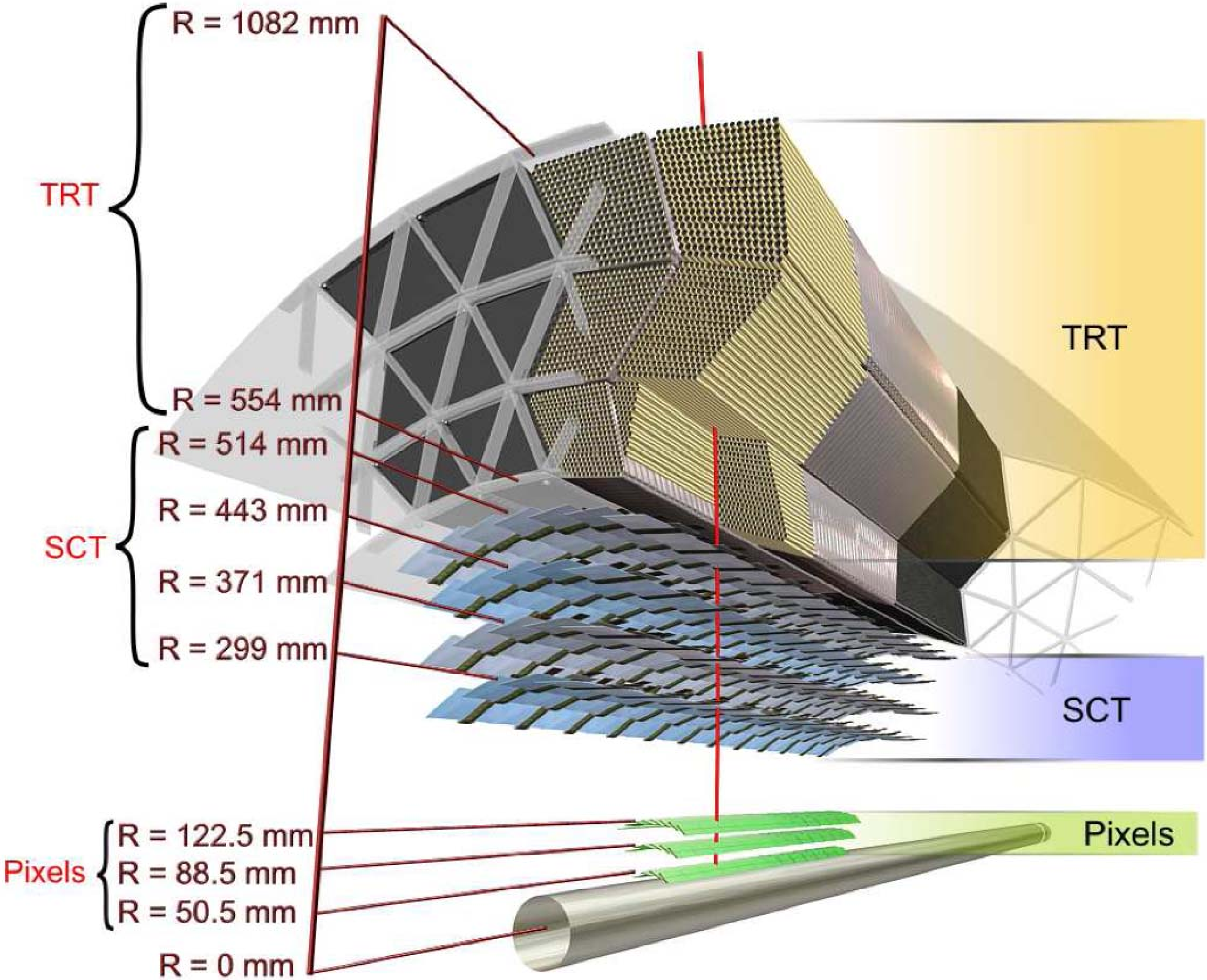


Detection of X rays: high Z gas – Xe

Few photons per boundary can be detected

Need many boundaries

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


R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels

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 → 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.

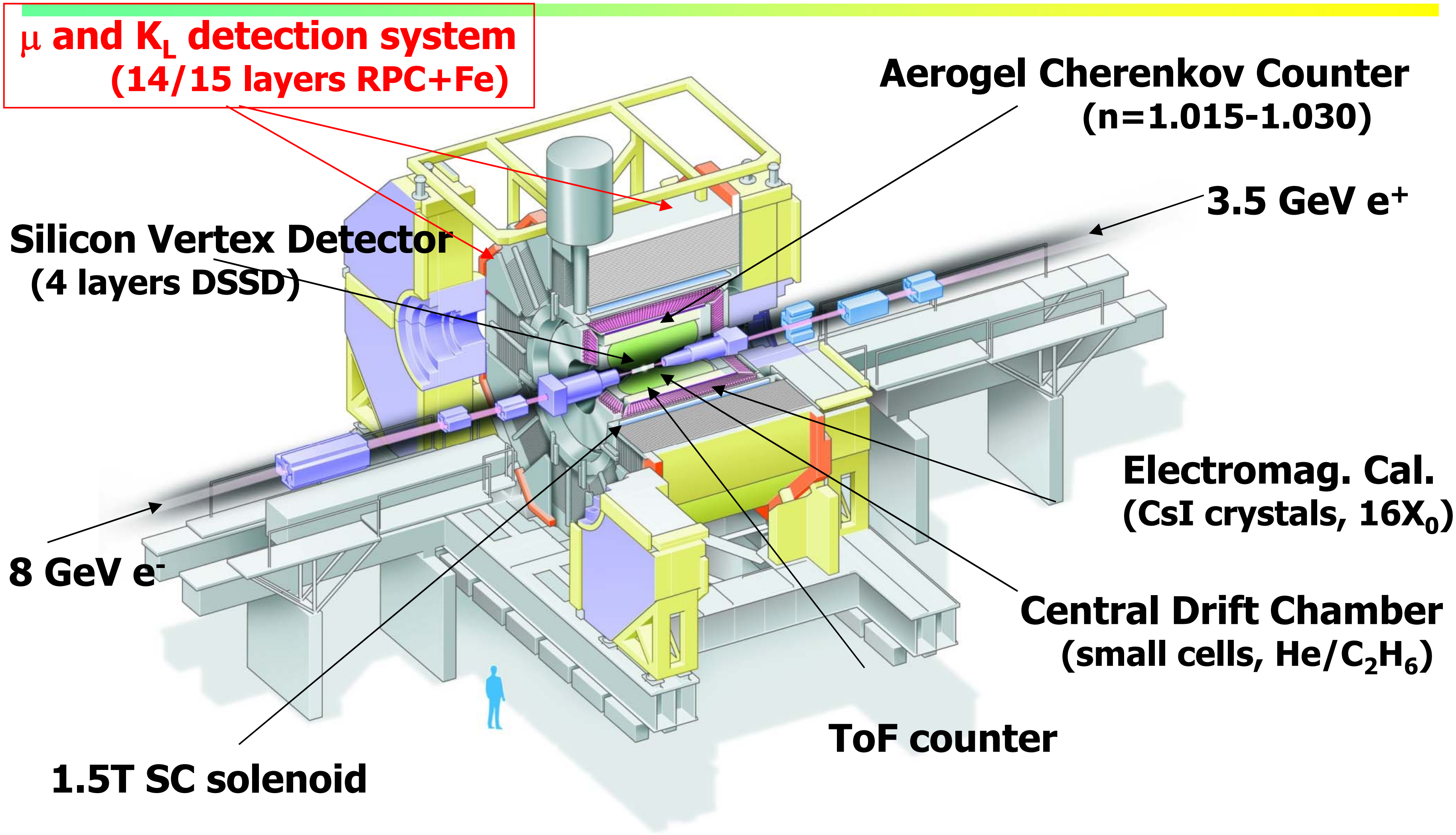
Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

Interaction length: iron 132 g/cm^2, CsI 167 g/cm^2

$(dE/dx)_{min}$: iron 1.45 MeV/(g/cm^2), CsI 1.24 MeV/(g/cm^2)

→ ΔE_{min} = (0.36+0.11) GeV = 0.47 GeV → reliable identification of muons possible above ~600 MeV

Example: Muon and K_L detection at Belle



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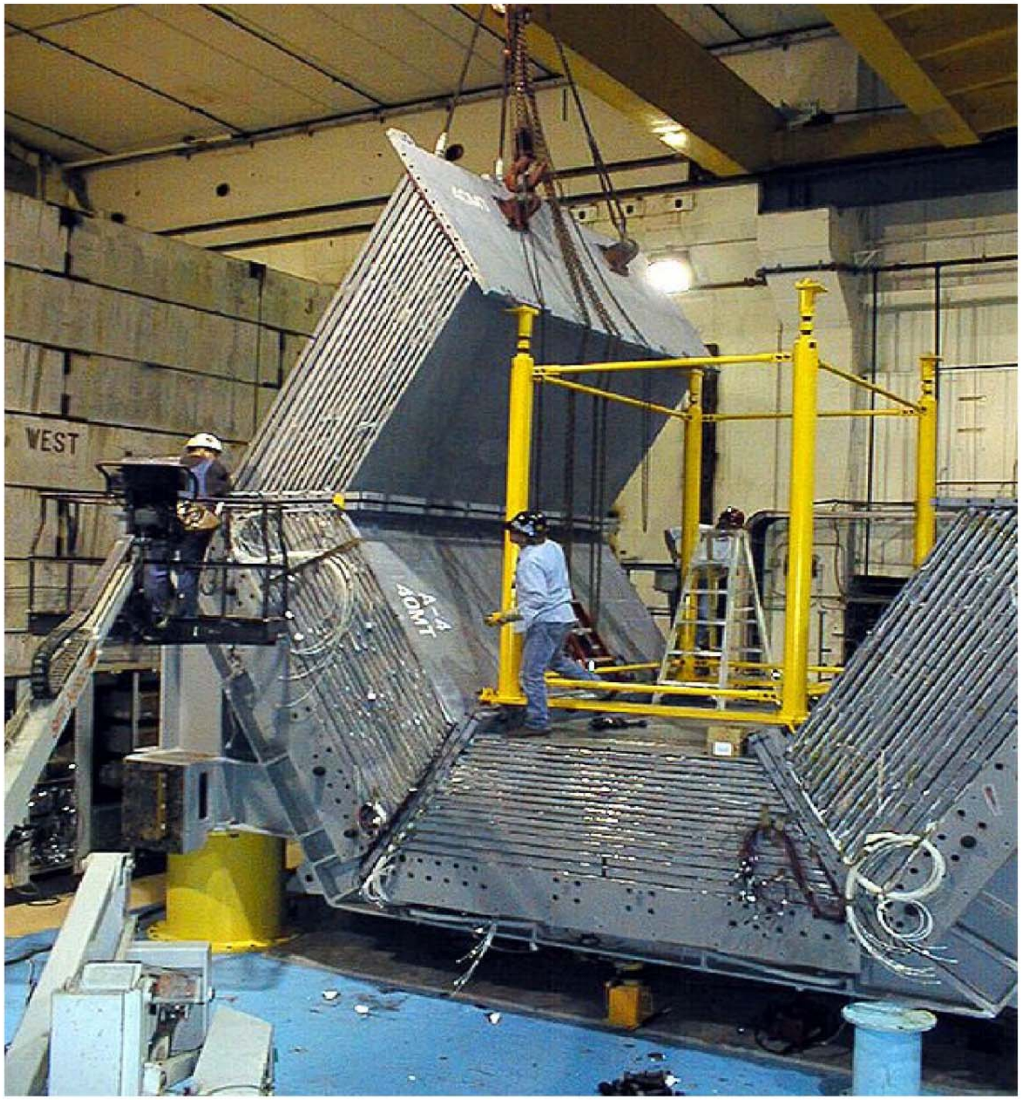
ToF counter

1.5T SC solenoid

Muon and K_L detector

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



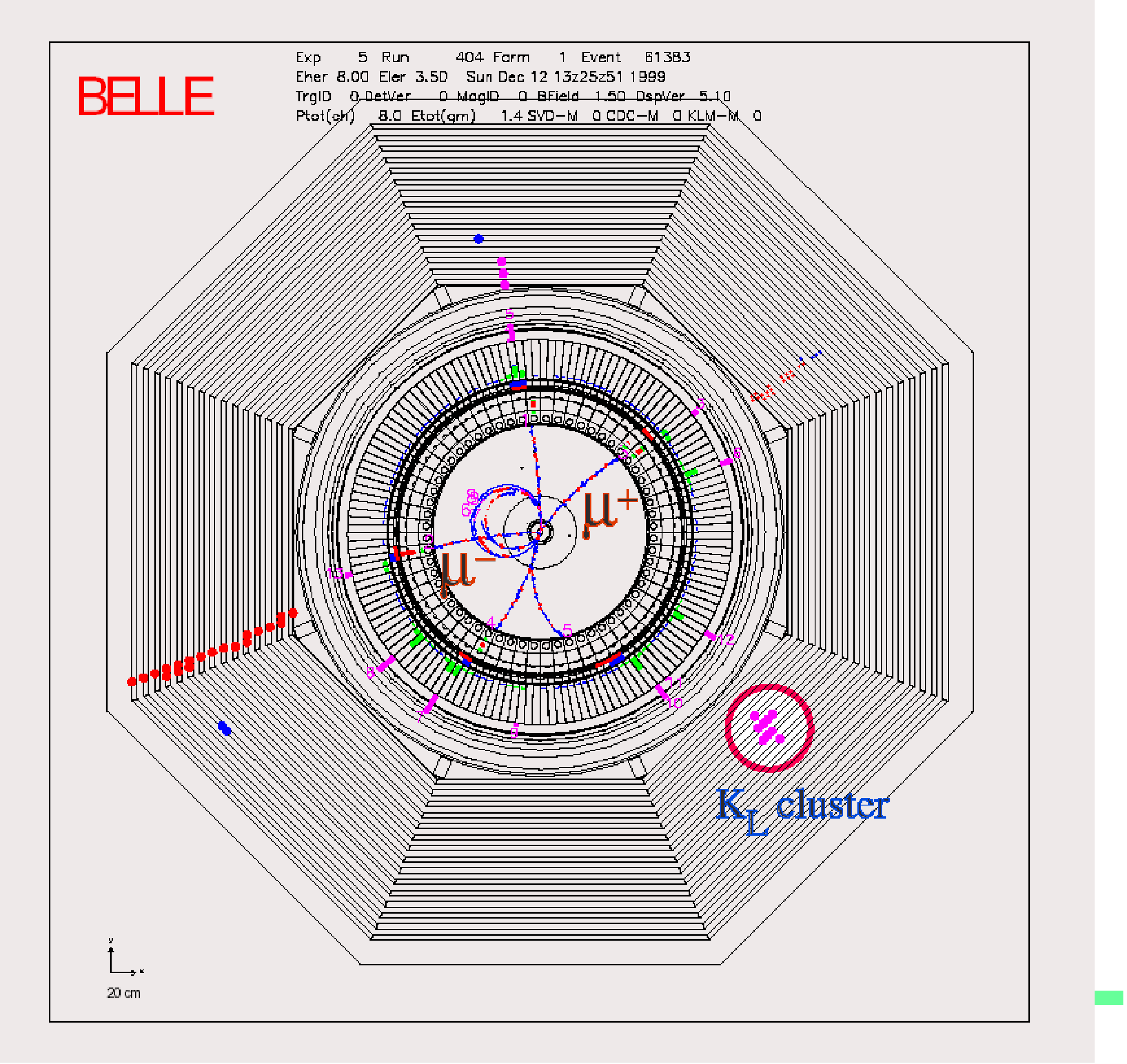
Muon and K_L detector

Example:

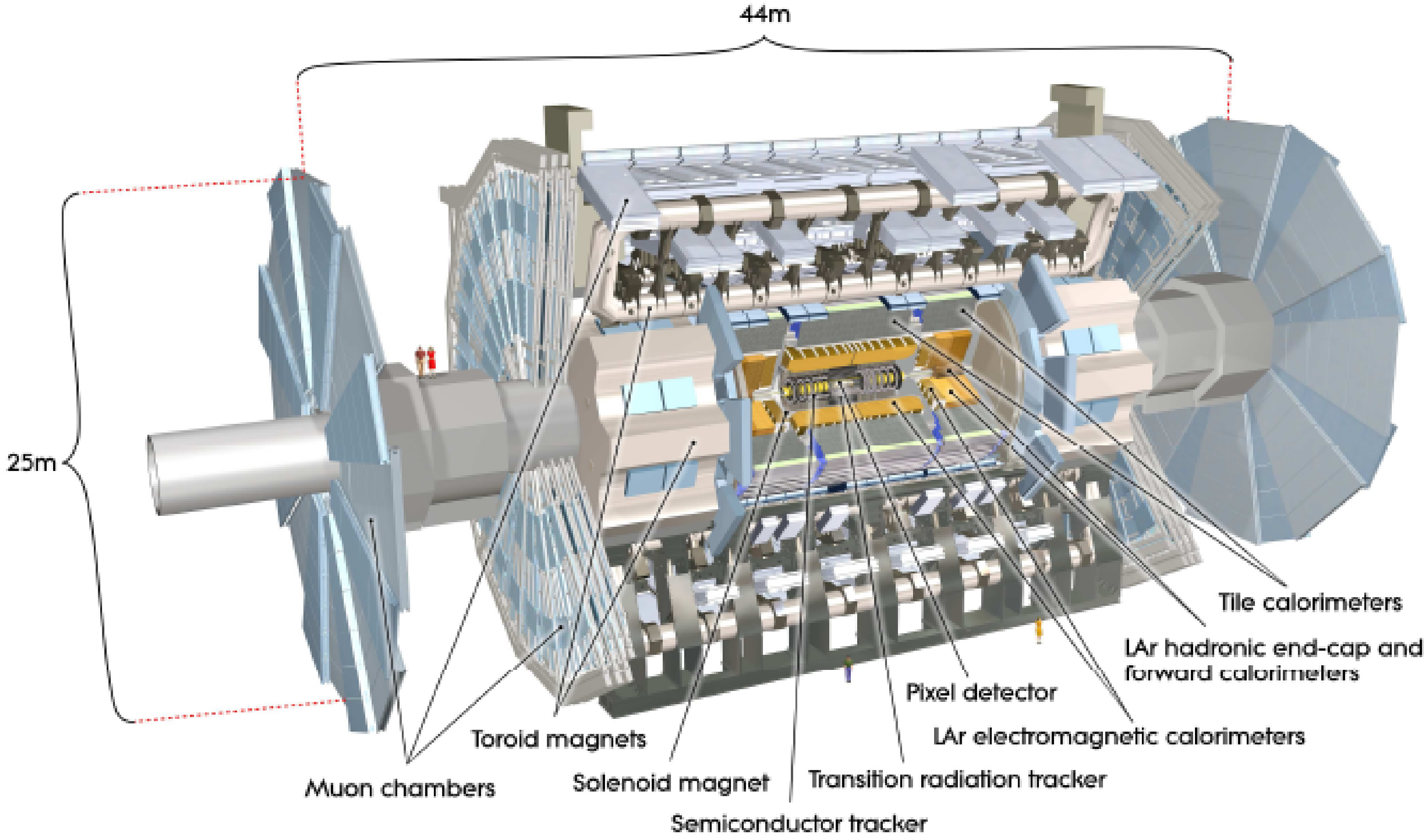
event with

- **two muons and a**
- **K_L**

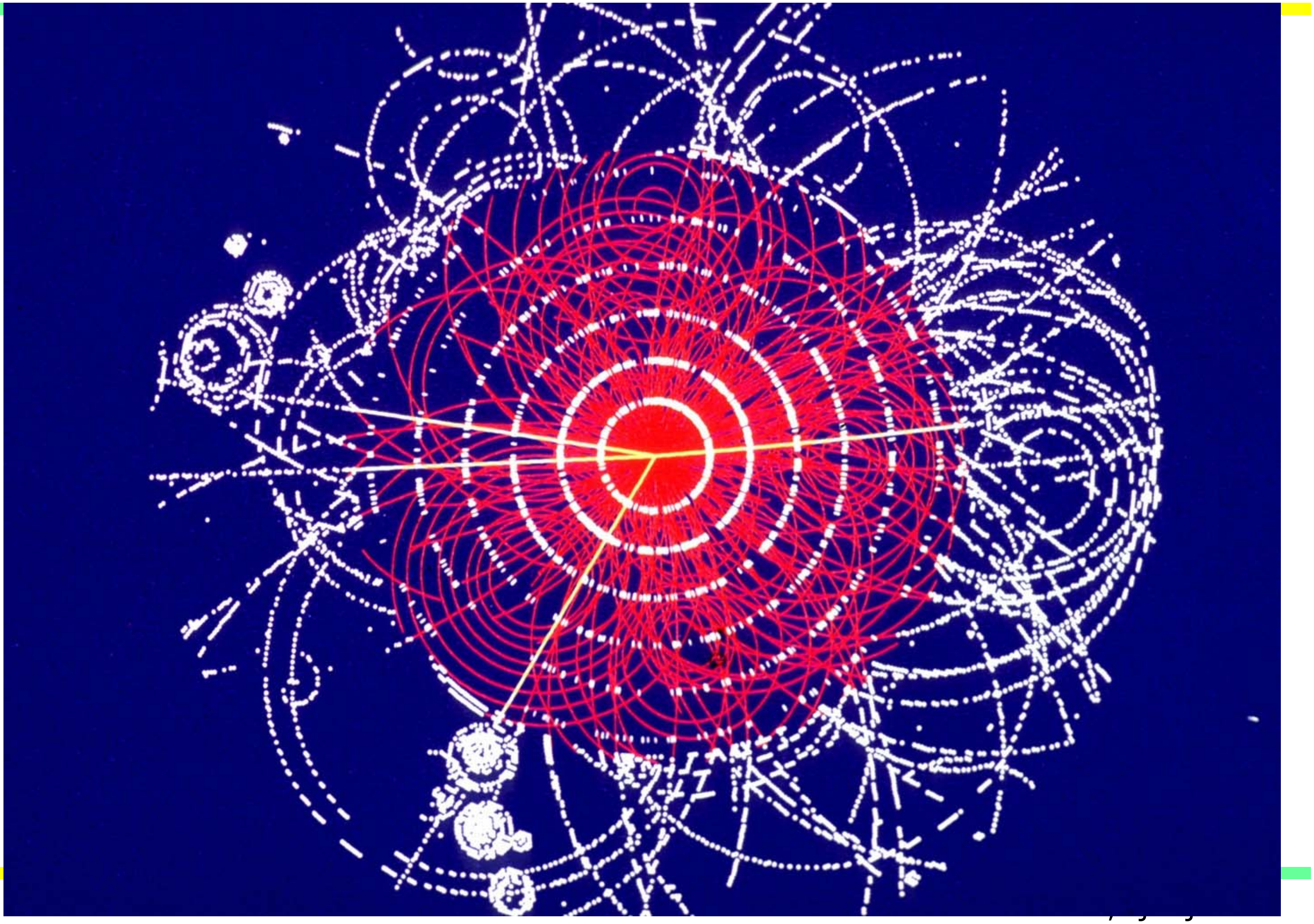
and a pion that partly penetrated



Identification of muons at LHC - example ATLAS



H → 4 μ (ATLAS)



Neutrino detection

Use inverse beta decay

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

$\nu_\mu + n \rightarrow p + \mu^-$

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$

$\nu_\tau + n \rightarrow p + \tau^-$

$\bar{\nu}_\tau + p \rightarrow n + \tau^+$

However: cross section is very small!

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

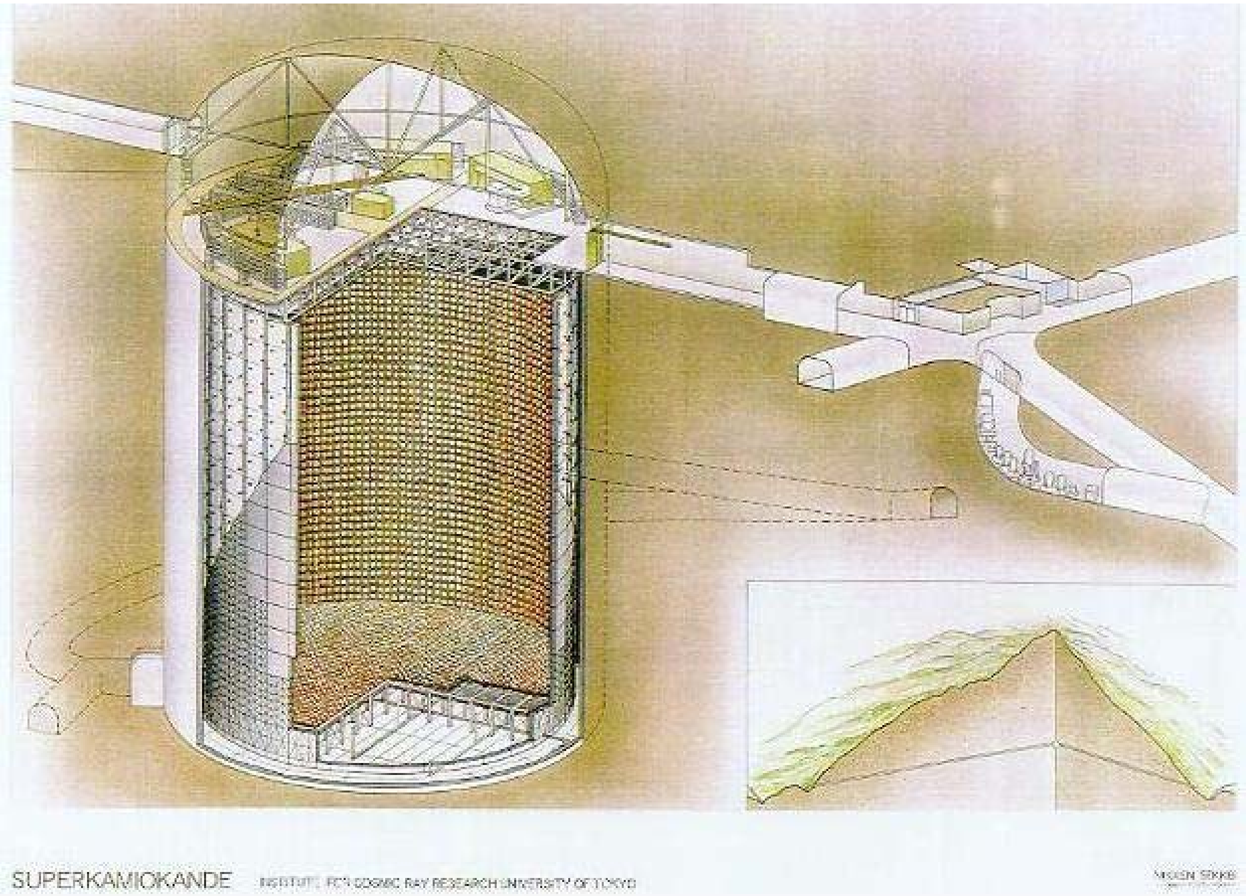
Probability for interaction in 100m of water = $4\ 10^{-16}$

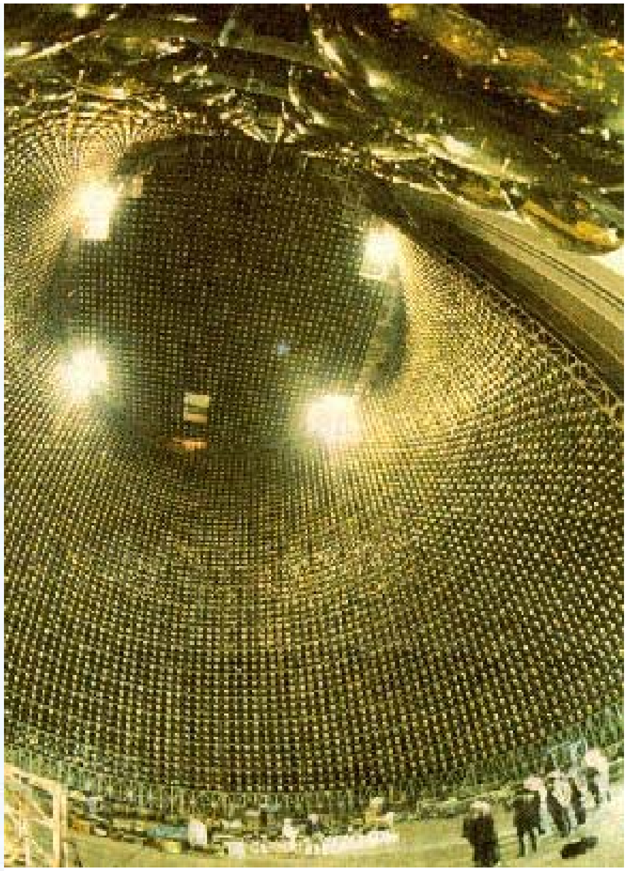
Not much better at high energies:

$0.67\ 10^{-38}$ E/1GeV cm^2 per nucleon

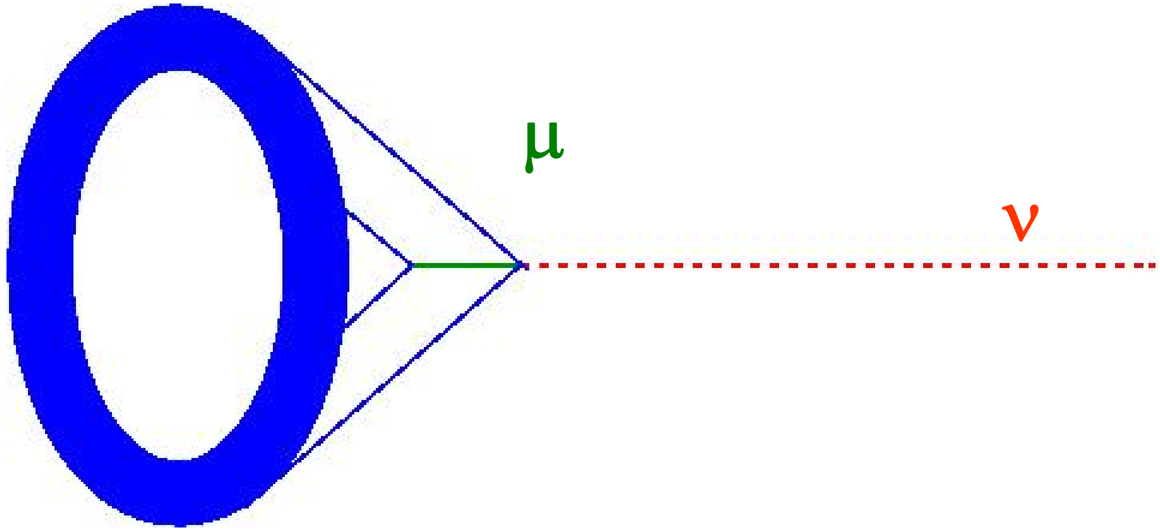
At 100 GeV, still 11 orders below the proton-proton cross section

Superkamiokande: an example of a neutrino detector





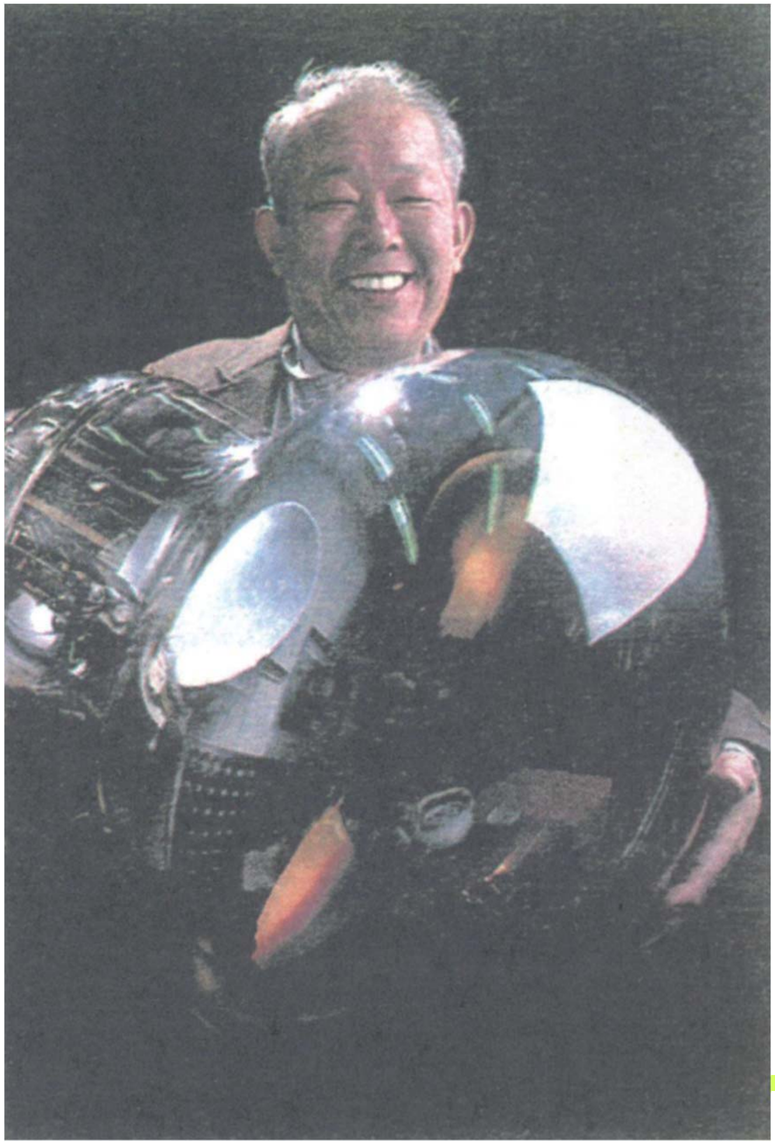
Superkamiokande: detection of electrons and muons



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

- Muon ring: sharp edges
- Electron ring: smeared

Superkamiokande: detection of neutrinos by measureing Cherenkov photons



Light detectors: HUGE photomultiplier tubes

M. Koshiba

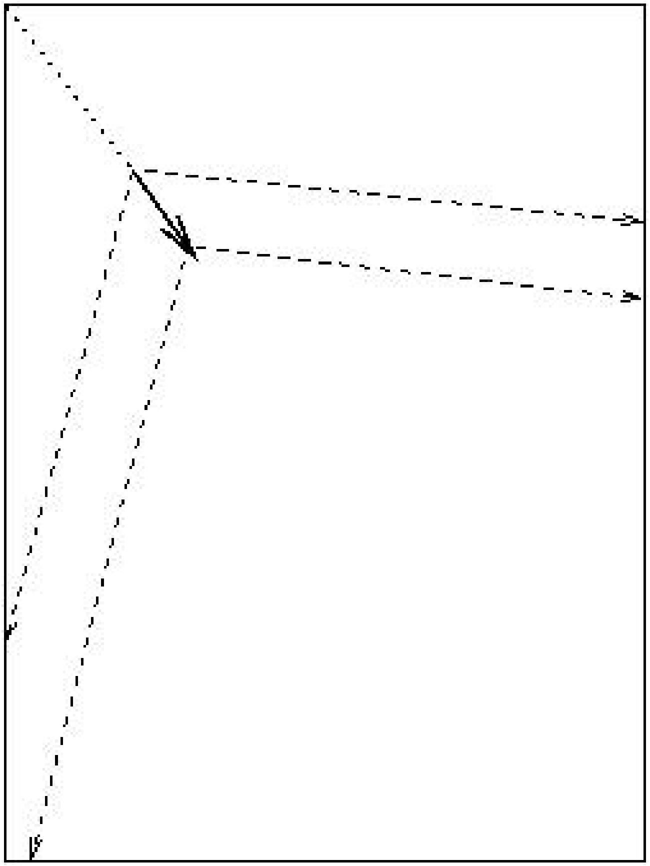
Muon vs electron

Cherenkov photons from a muon track:

Example: 1GeV muon neutrino

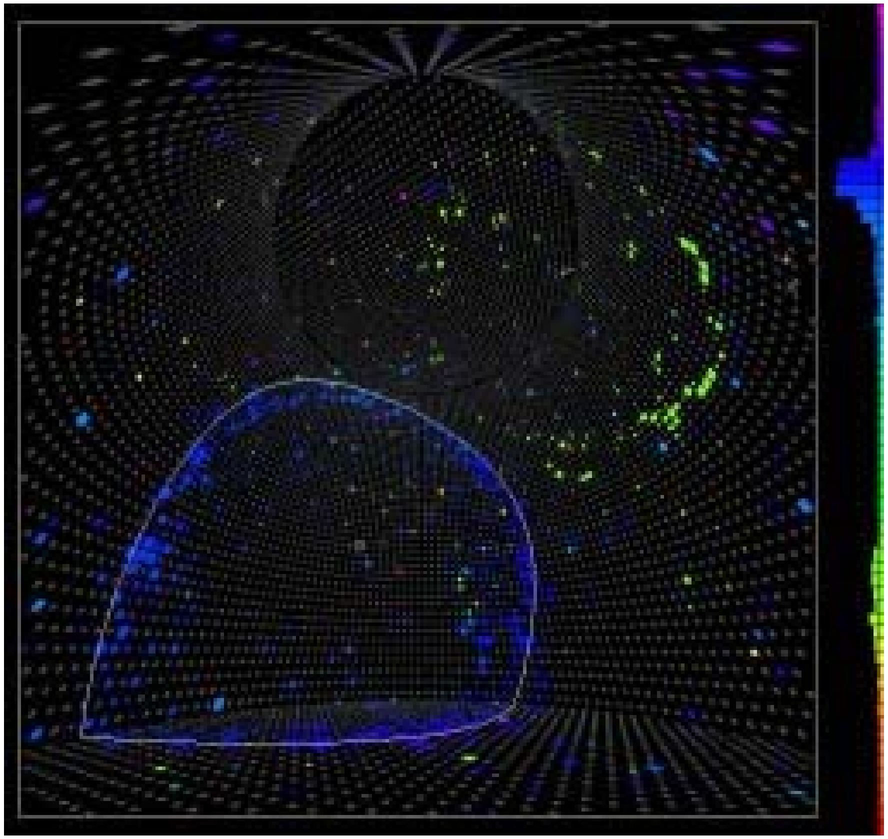
Track length of the resulting muon:
L=E/(dE/dx)=
=1GeV/(2MeV/cm)=5m

→ a well defined “ring” on the walls

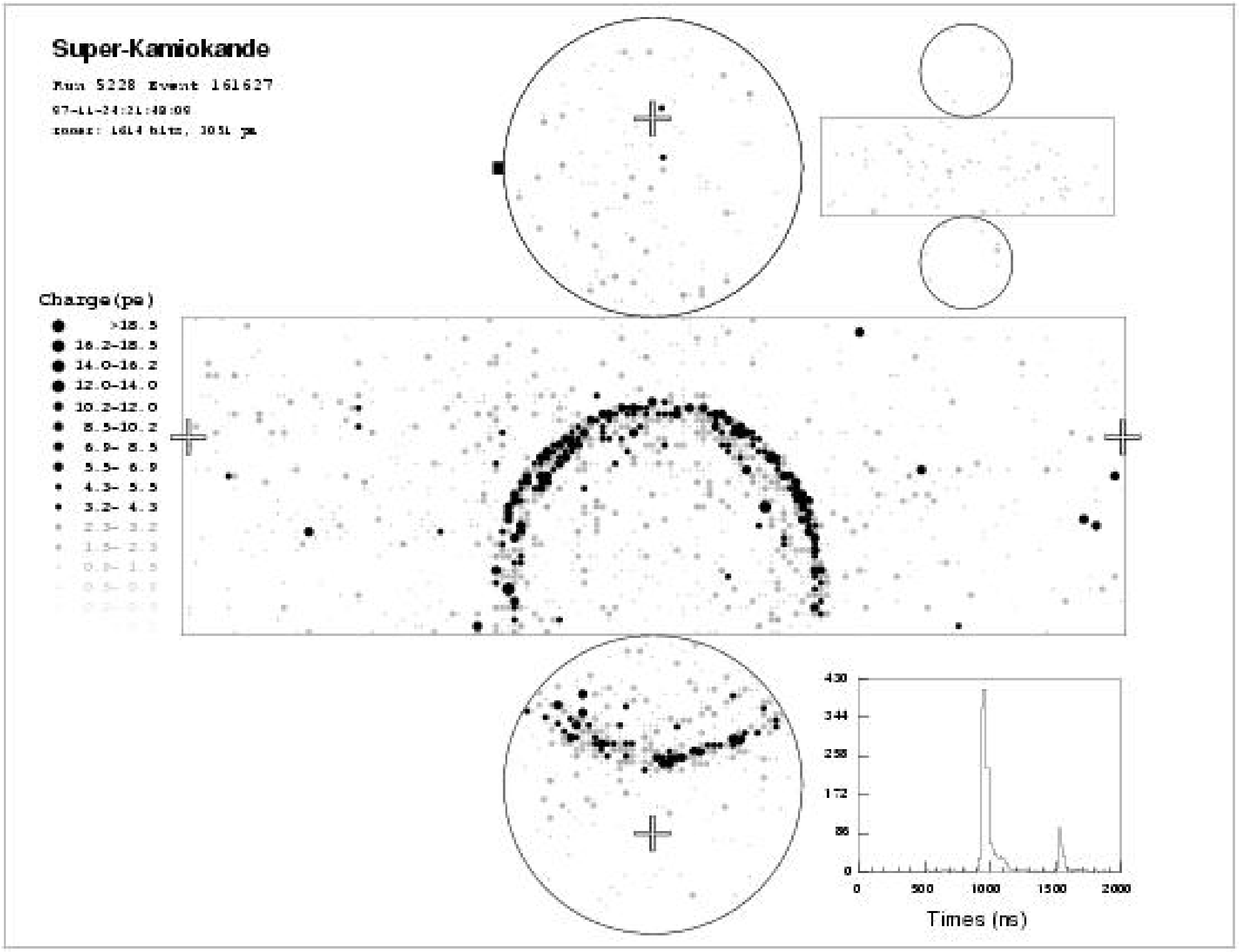


Superkamiokande: muon event

Muon 'ring' as seen by the photon detectors



Muon event: photon detector cillinder walls



Detection of very high energy neutrinos (from galactic sources)

The expected fluxes are very low:

Need really huge volumes of detector medium!

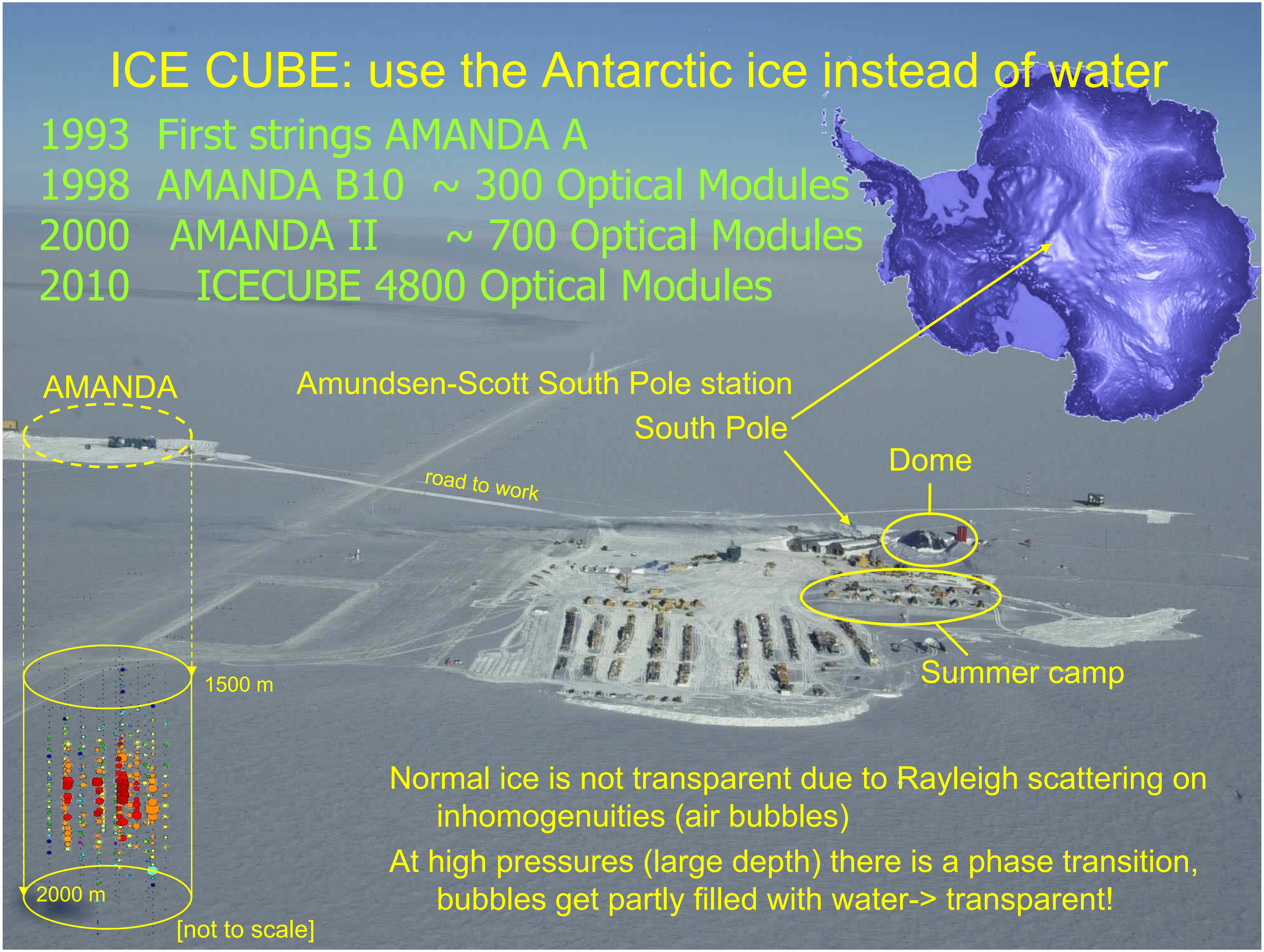
What is huge? From $(100\mathrm{m})^3$ to $(1\mathrm{km})^3$

Also needed: directional information.

Again use: $\nu_\mu + n \to p + \mu^-$; 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



Normal ice is not transparent due to Rayleigh scattering on inhomogenuities (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 netrino

For each event:

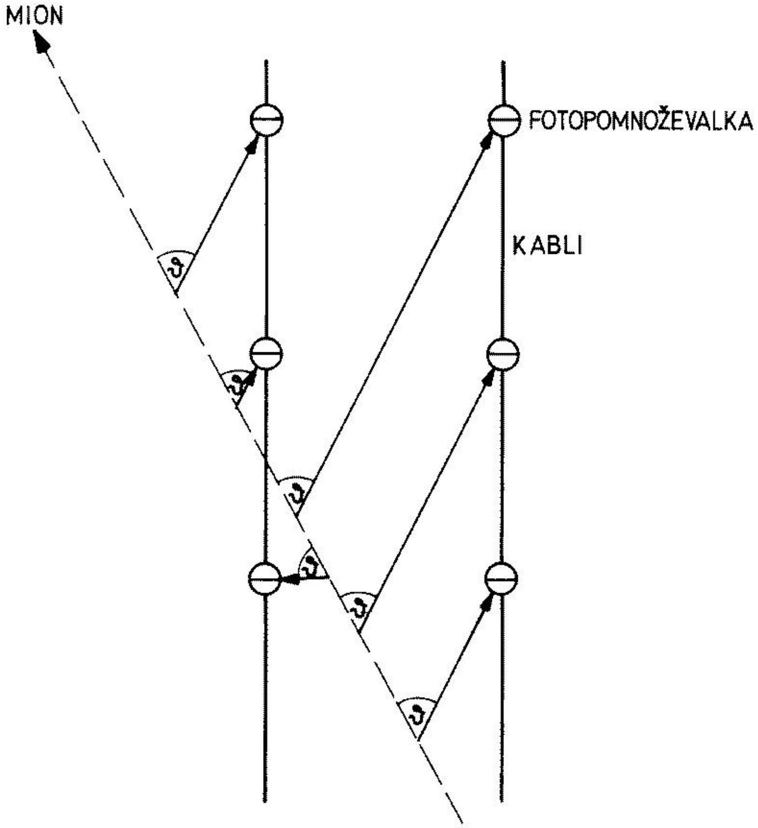
Measure time of arrival on each of the tubes

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

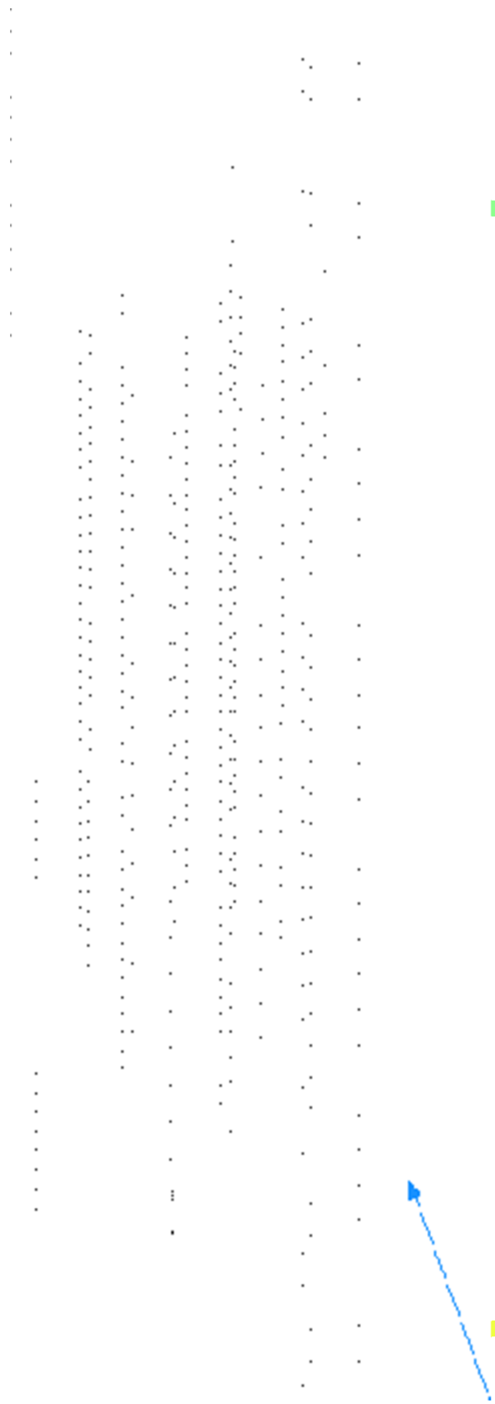
Reconstruct muon track

Track direction -> neutrino direction

Track length -> neutrino energy



ICE CUBE



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

Detekcija kozmičnih delcev na balonu

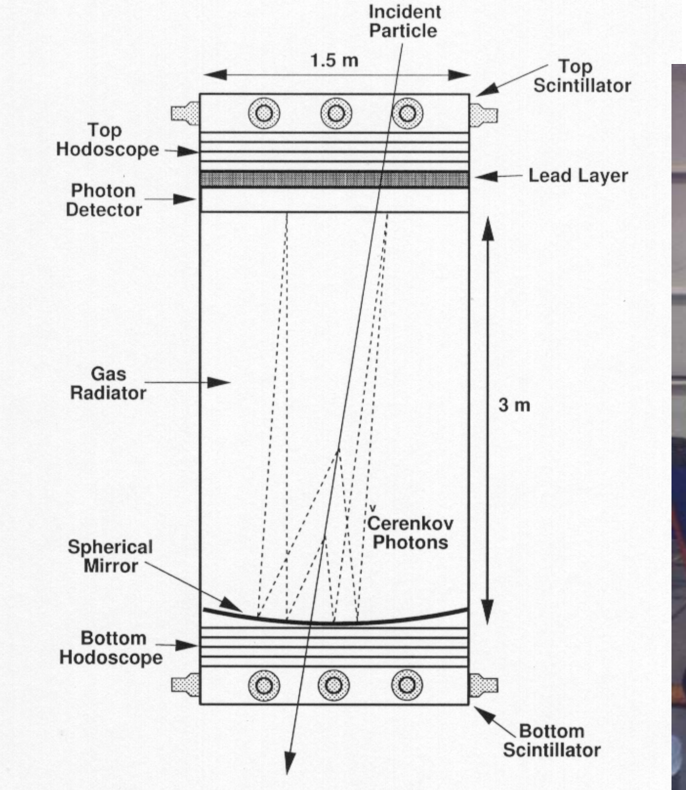
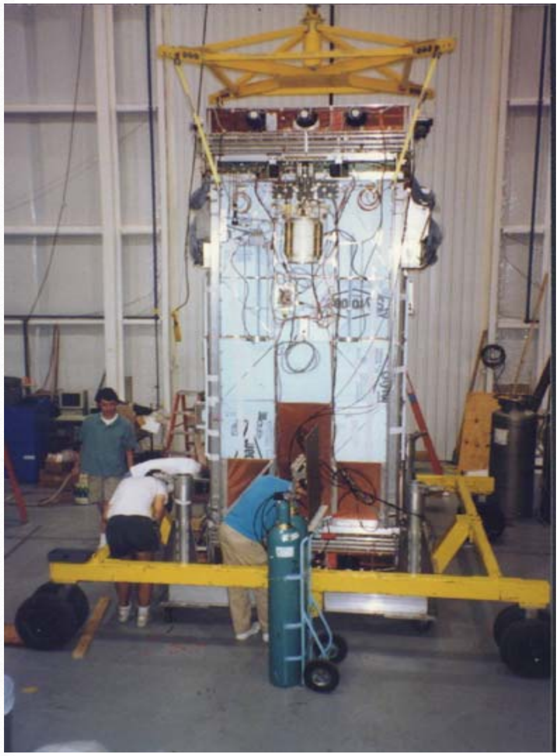
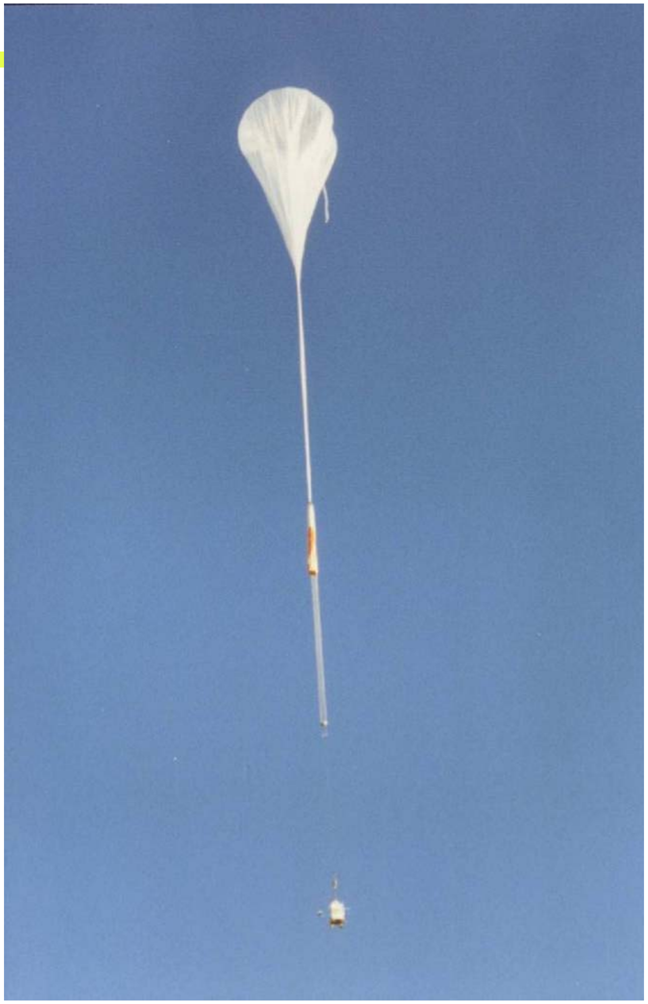
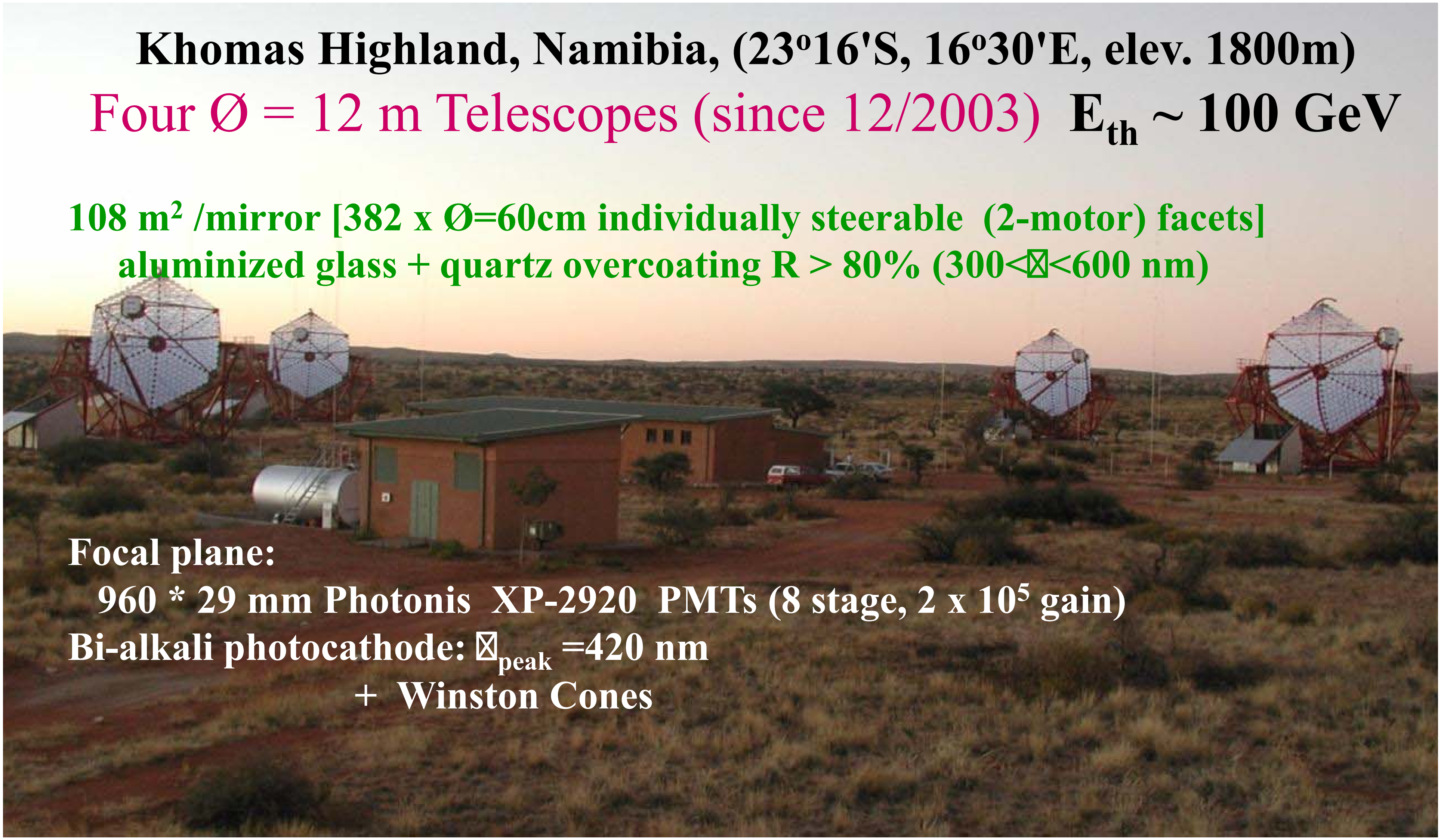


Fig. 1. Schematic cross-section of the instrument





HESS 1 UHE Gamma Ray Telescope
Stereoscopic Quartet

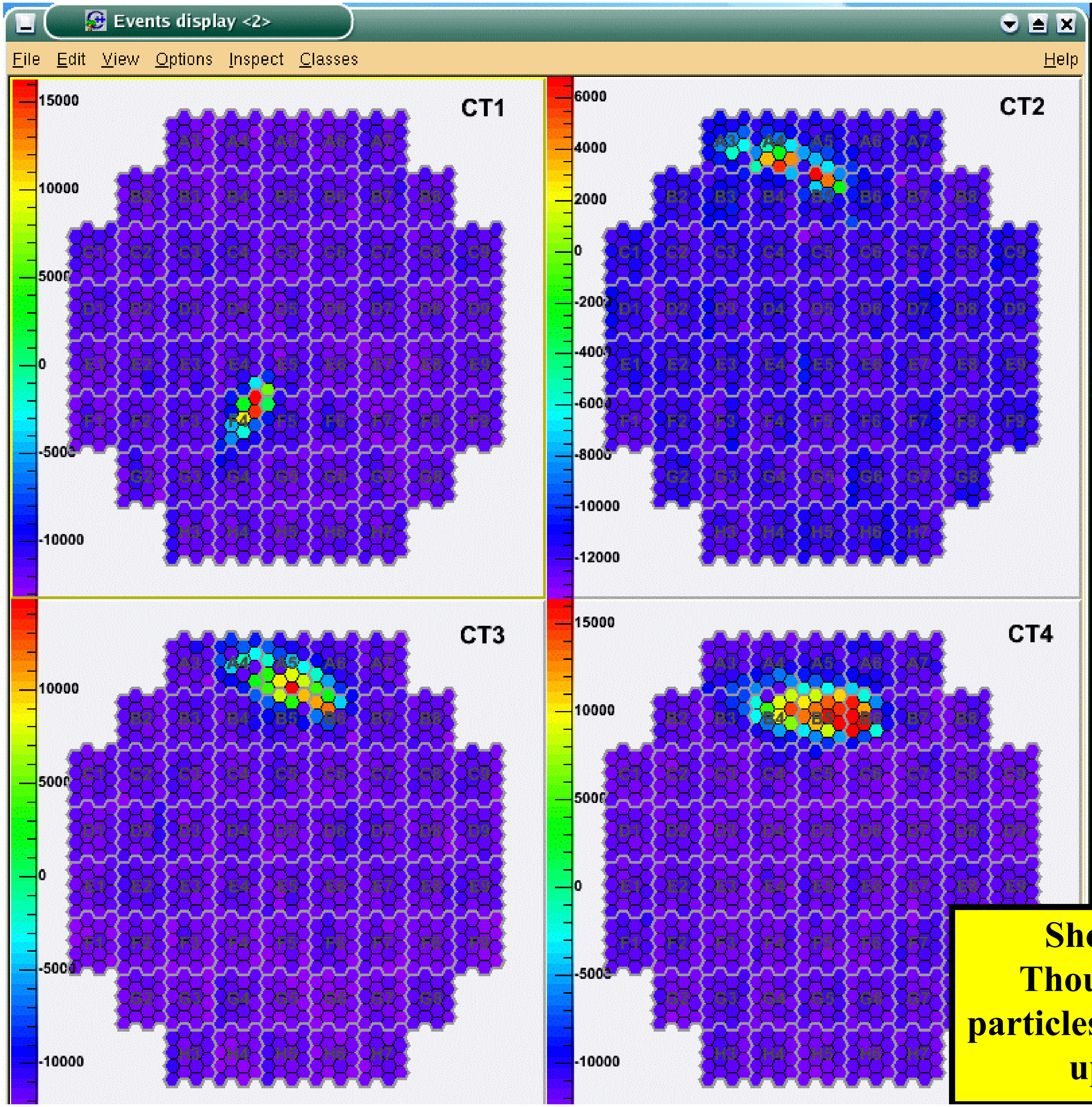


Khomas Highland, Namibia, ($23^o16'$S, $16^o30'$E, elev. 1800m)

Four Ø = 12 m Telescopes (since 12/2003) **E_{th} ~ 100 GeV**

108 m^2 /mirror [382 x Ø=60cm individually steerable (2-motor) facets]
aluminized glass + quartz overcoating R > 80% (300<⊠<600 nm)

Focal plane:
960 * 29 mm Photonis XP-2920 PMTs (8 stage, 2 x 10^5 gain)
Bi-alkali photocathode: ⊠$_{peak}$ =420 nm
+ Winston Cones



Detection of high-energy gamma rays

using Cherenkov telescopes

The HESS
Concept

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

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 experiments: HERA-B
- 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 2021/2022):

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
- G. Knoll, Radiation Detection and Measurement**,** 3rd Edition, 2000
- 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

- 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 prefererably taken already

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