University of Ljubljana

Eksperimentalna fizika jedra in osnovnih delcev (EFJOD) - Uvod

Experimental particle and nuclear physics – Introduction

Peter Križan

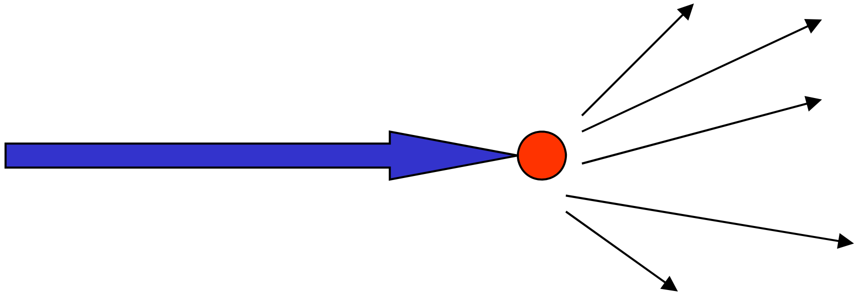
Contents

Particle physics experiments

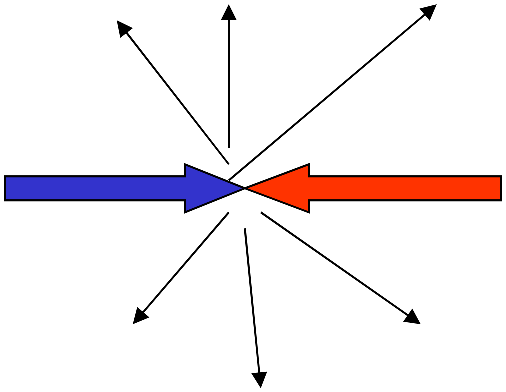
Accelerate elementary particles, let them collide → energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

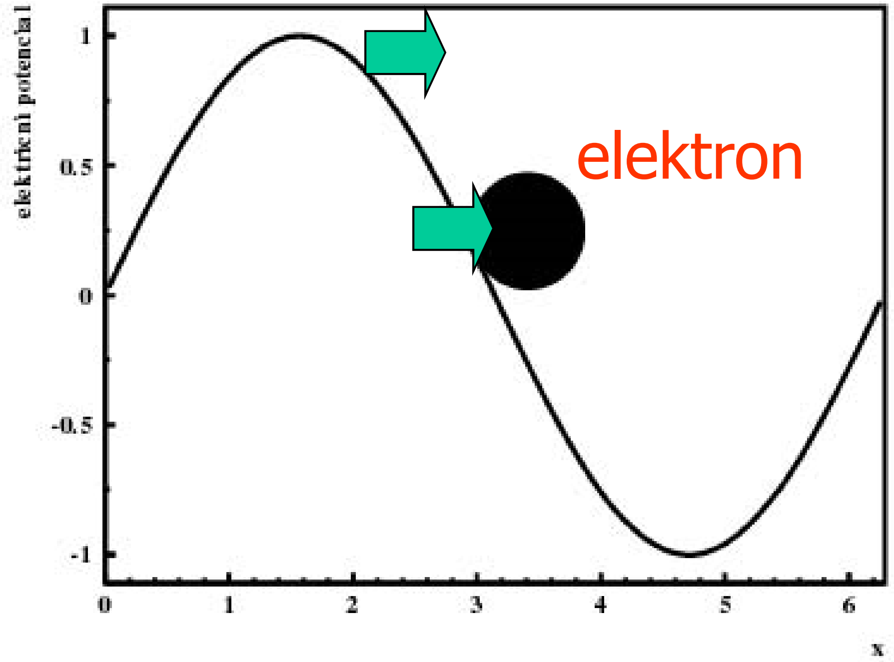


Collider experiments

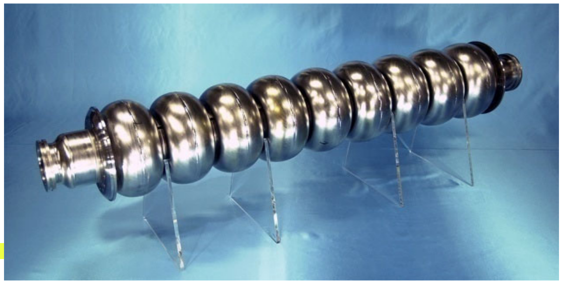


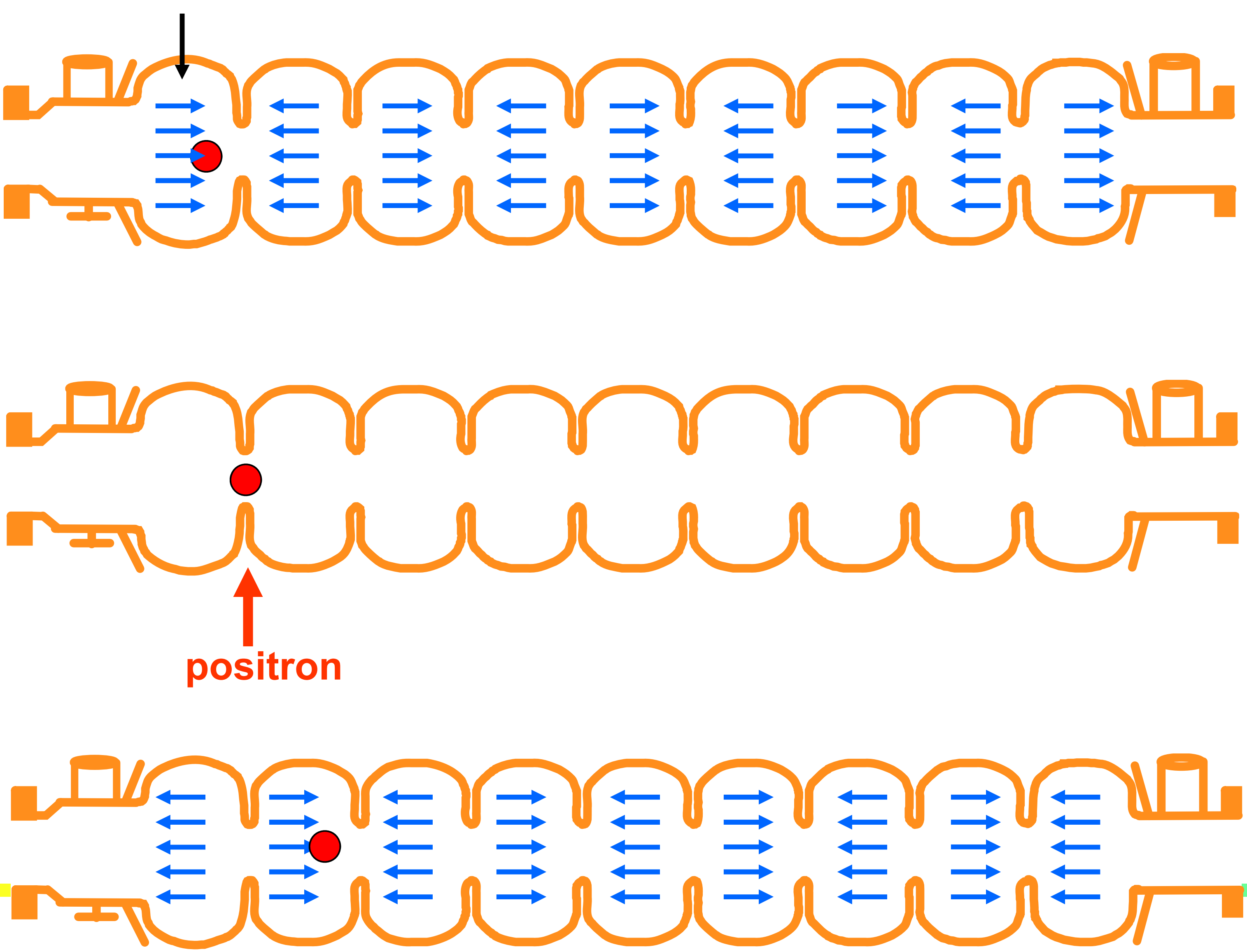
How to accelerate charged particles?

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



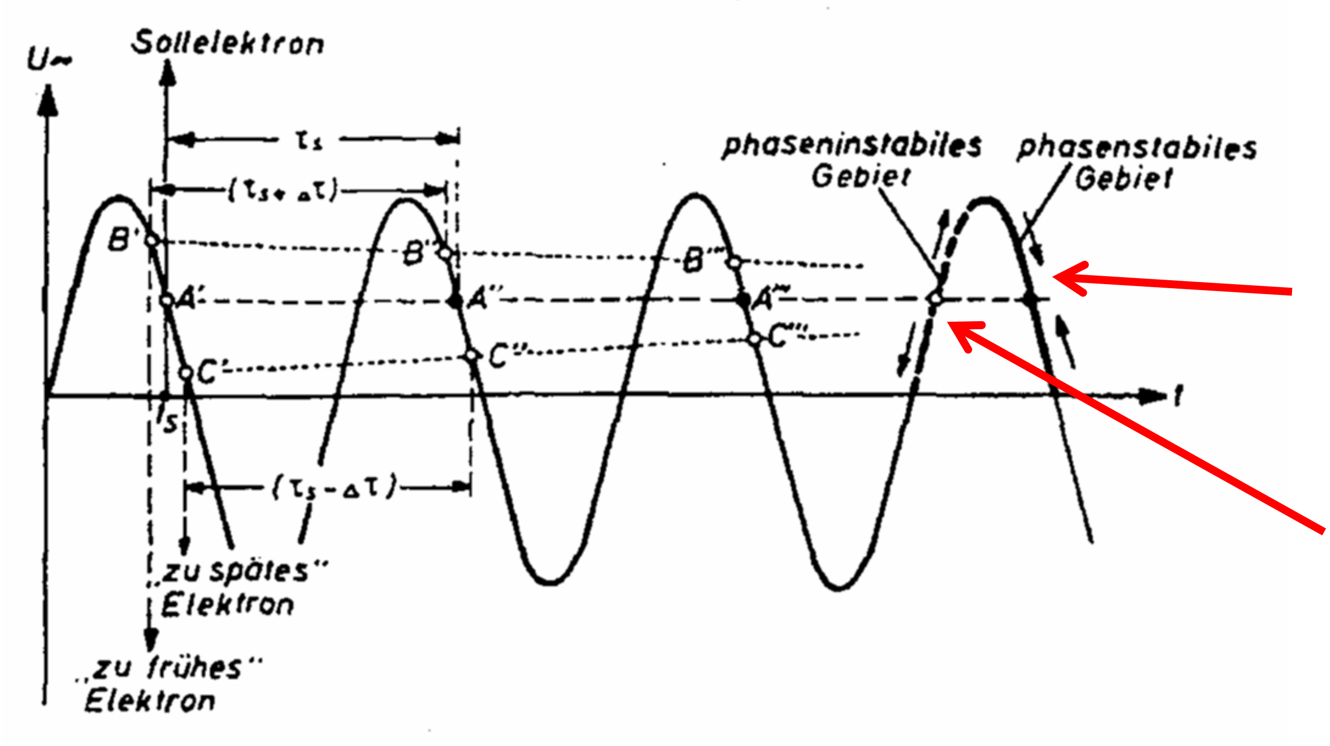
... Similar to surfing the waves




Electric field
positron

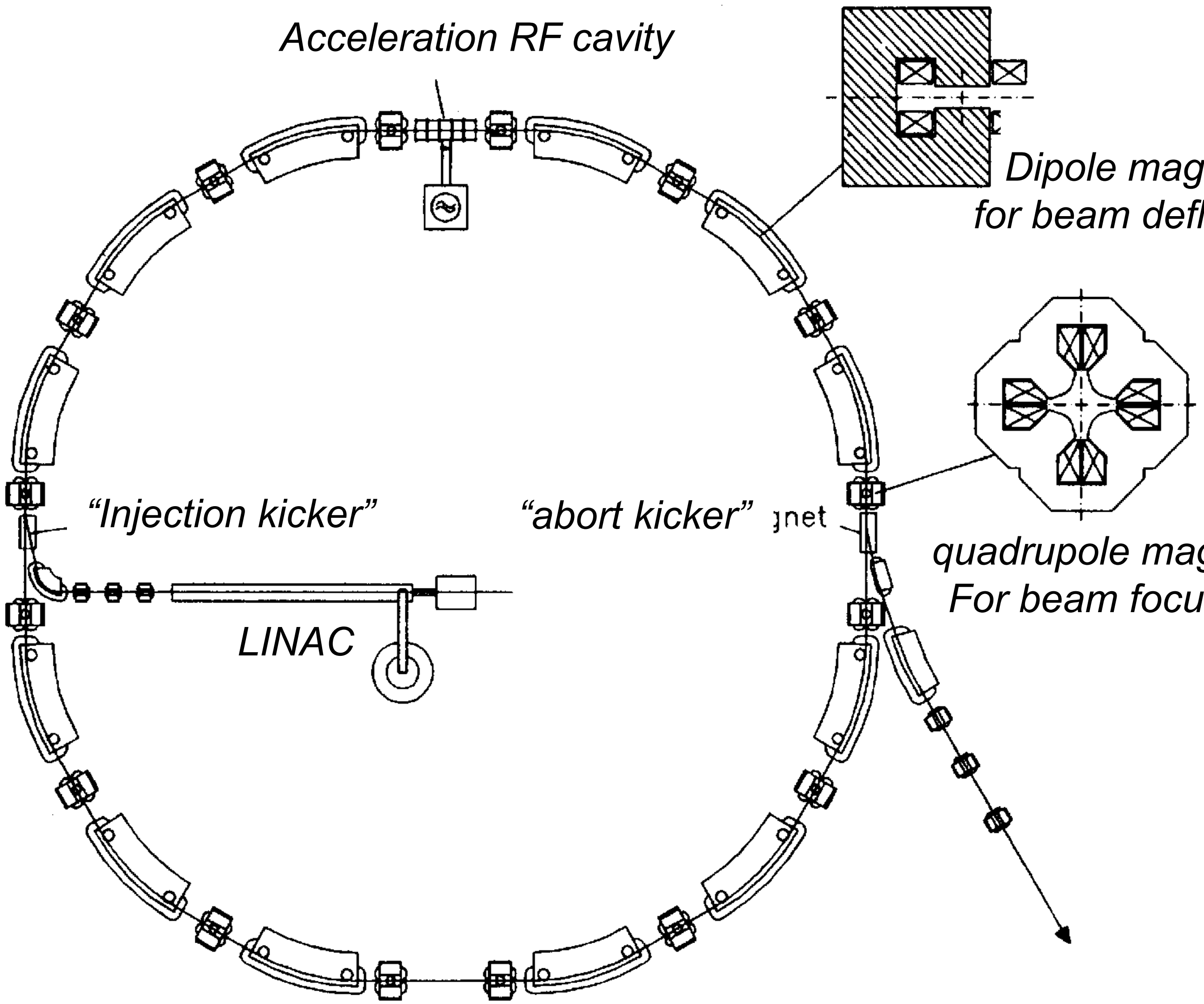
Stability of acceleration

- 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

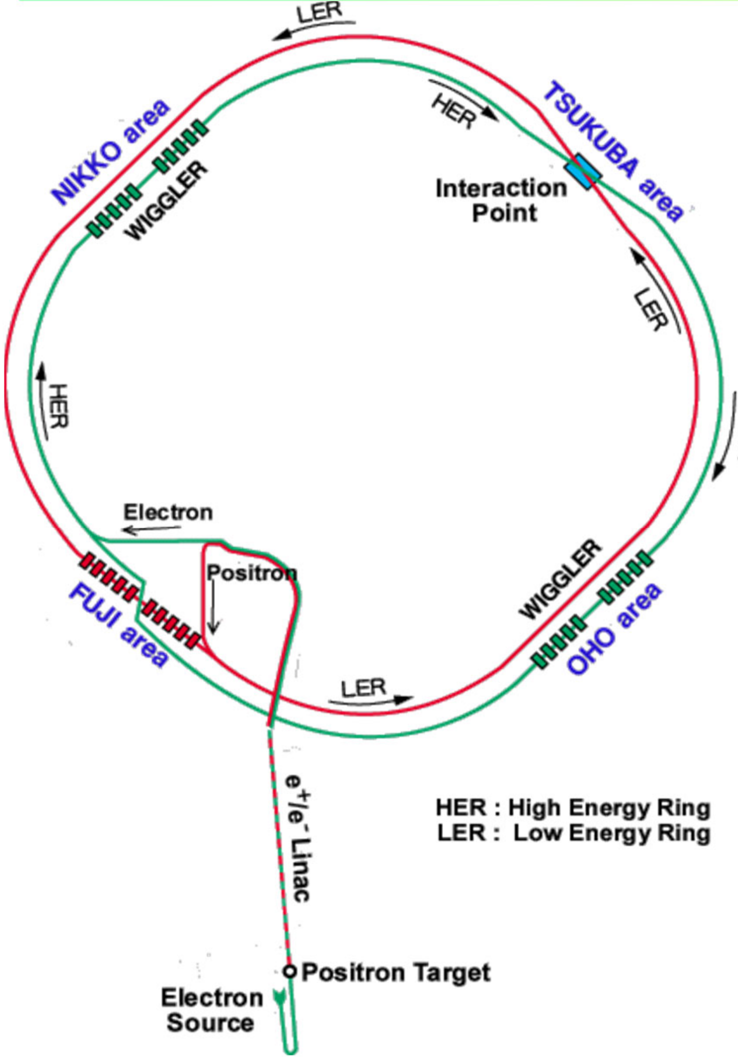
"Injection kicker"

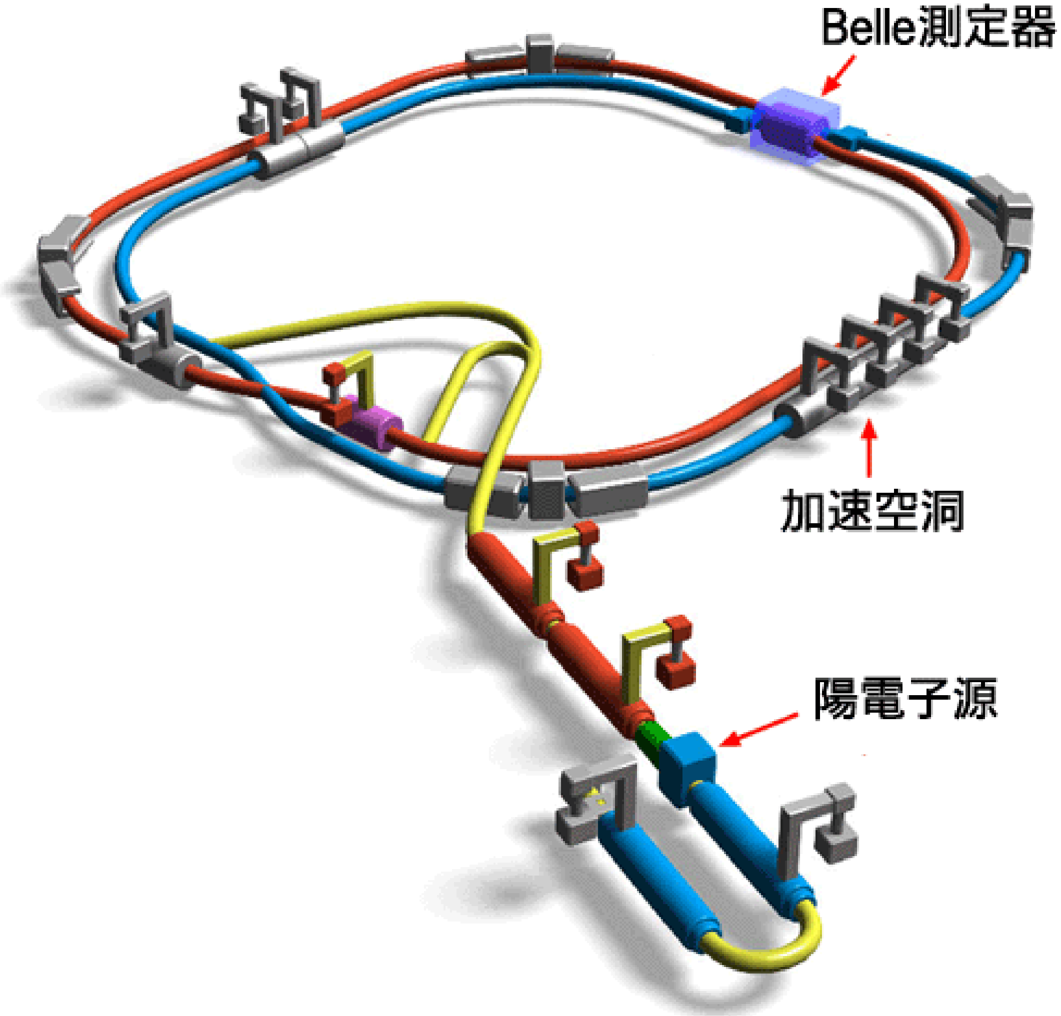
"abort kicker"

quadrupole magnets
For beam focusing

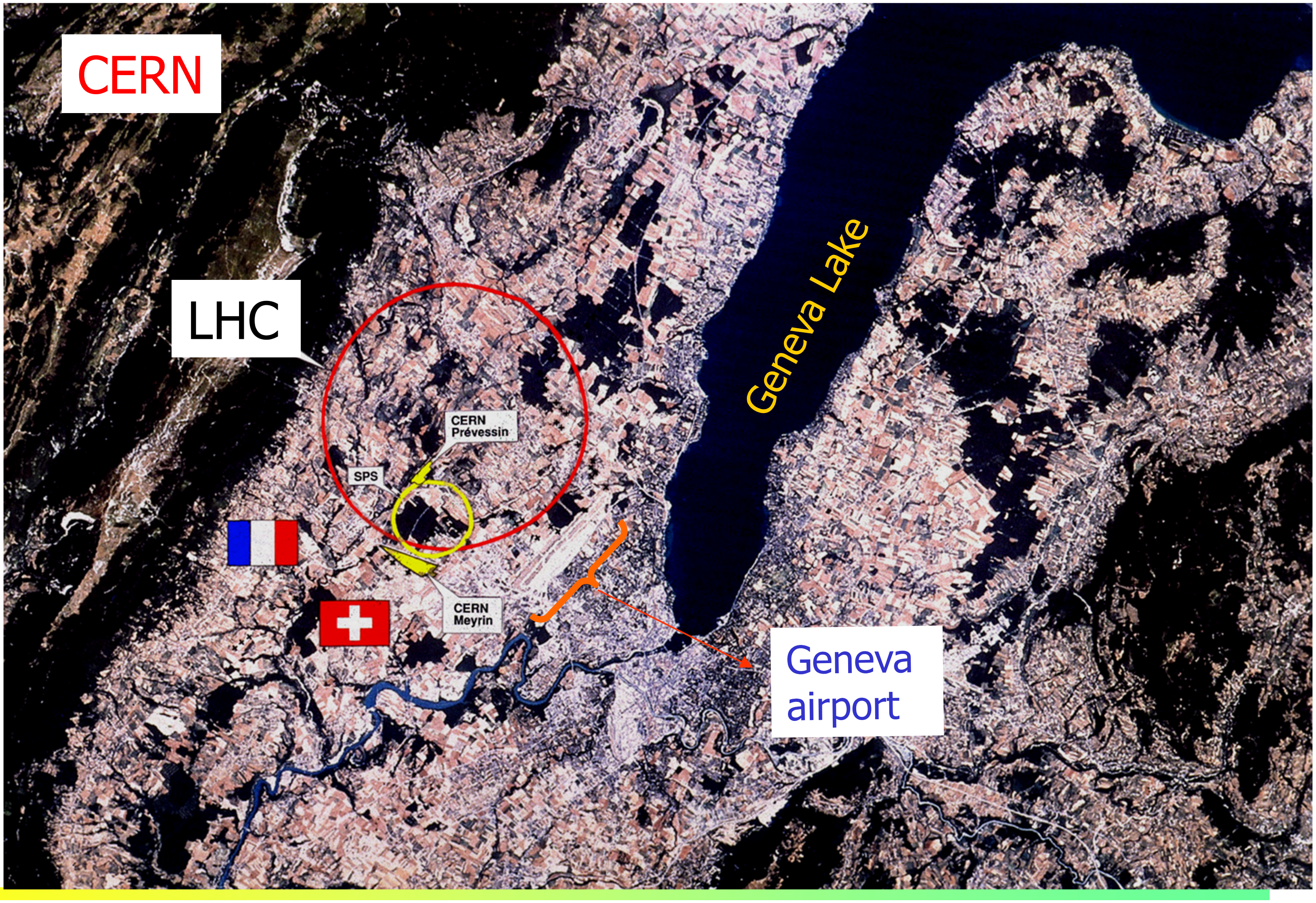
LINAC

Electron position collider: KEK-B



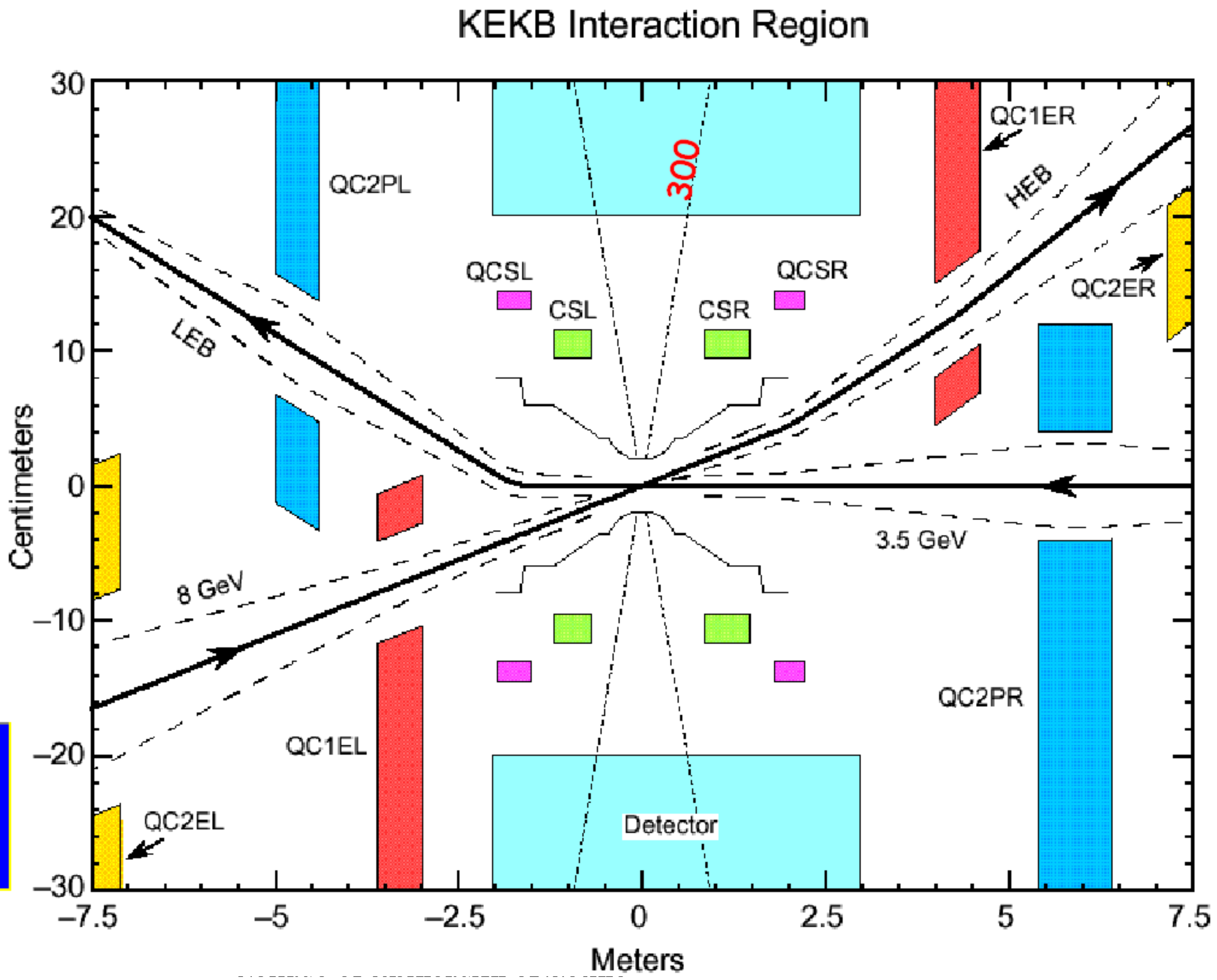


Large hadron collider



Interaction region: Belle

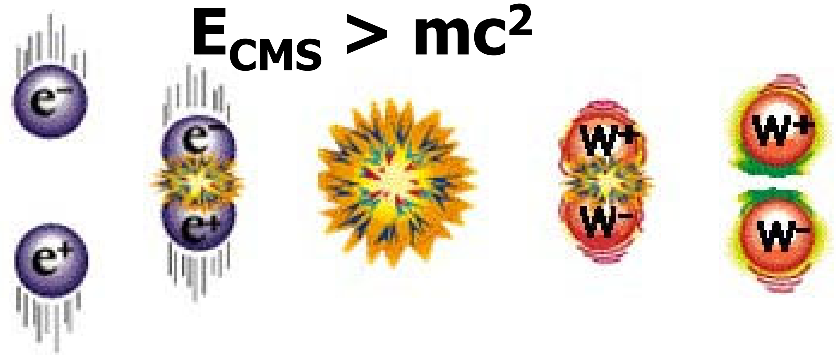
Collisions at a finite angle +-11mrad



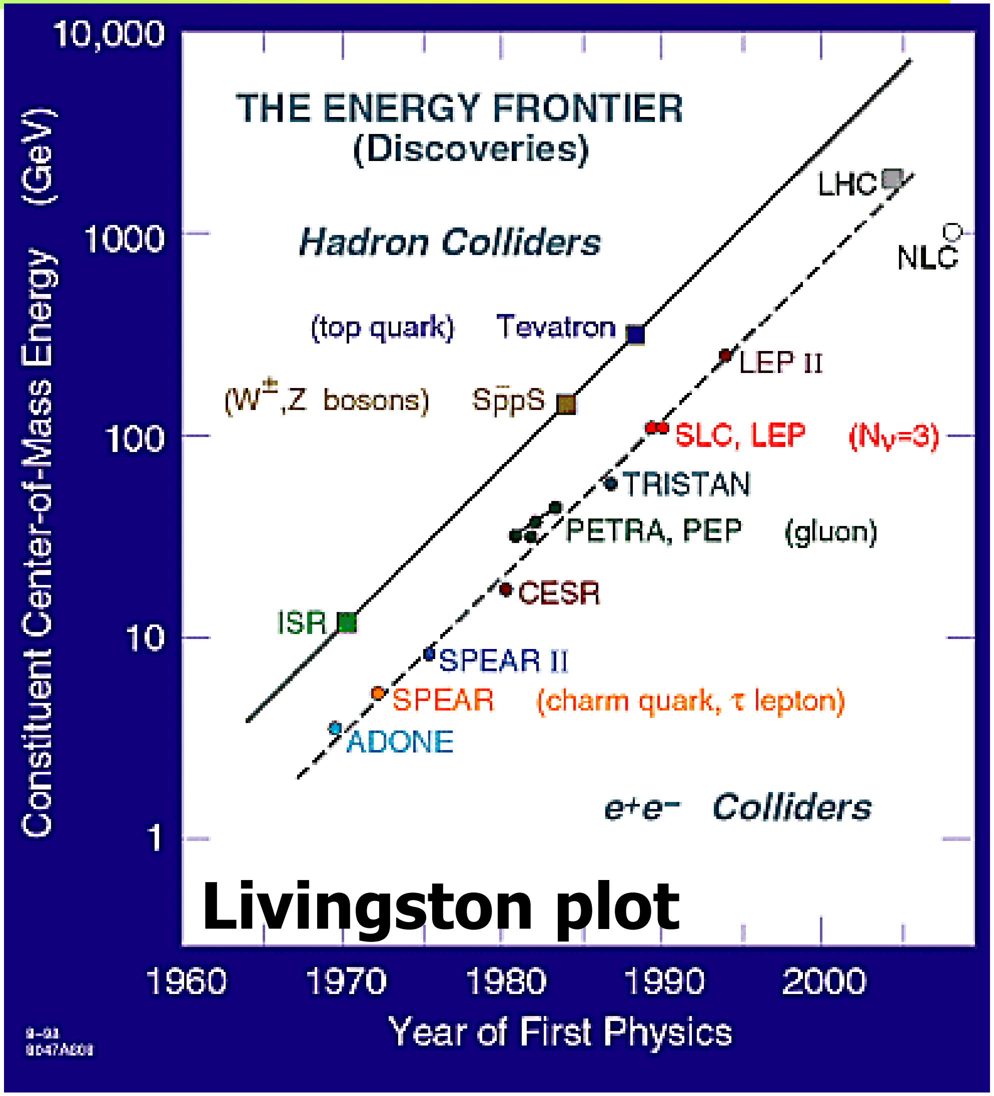
Accelerator figure of merit 1: Center-of-mass energy

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, $m_{Higgs} > 100\text{GeV}$



Livingston plot

Accelerator figure of merit 2: Luminosity

Observed rate of events = Cross section x Luminosity

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

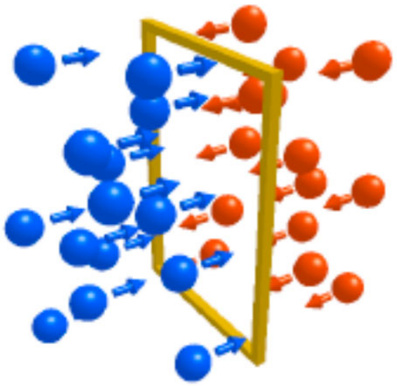
Accelerator figures of merit: luminosity ***L***

and integrated luminosity

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

Luminosity vs time

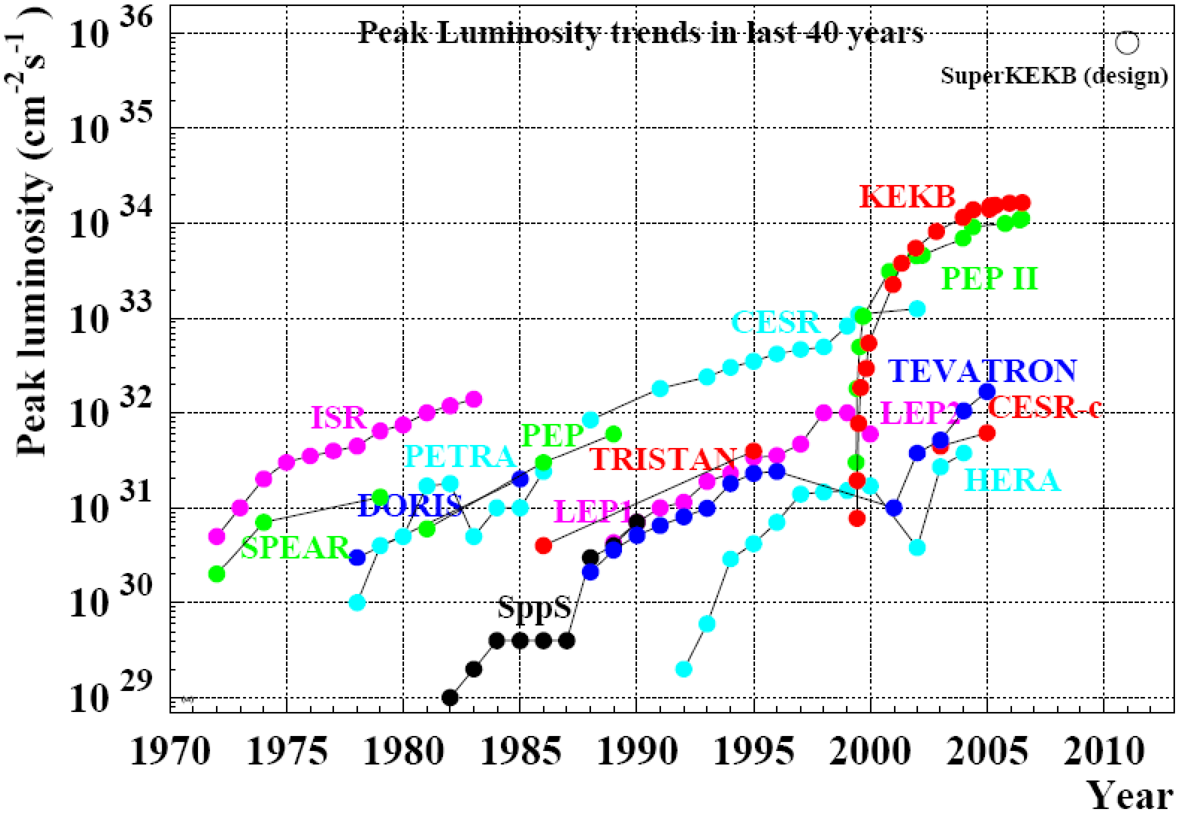
$$R = \mathcal{L}\sigma$$



(number of events/unit time)

= (cross section) X (luminosity)

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



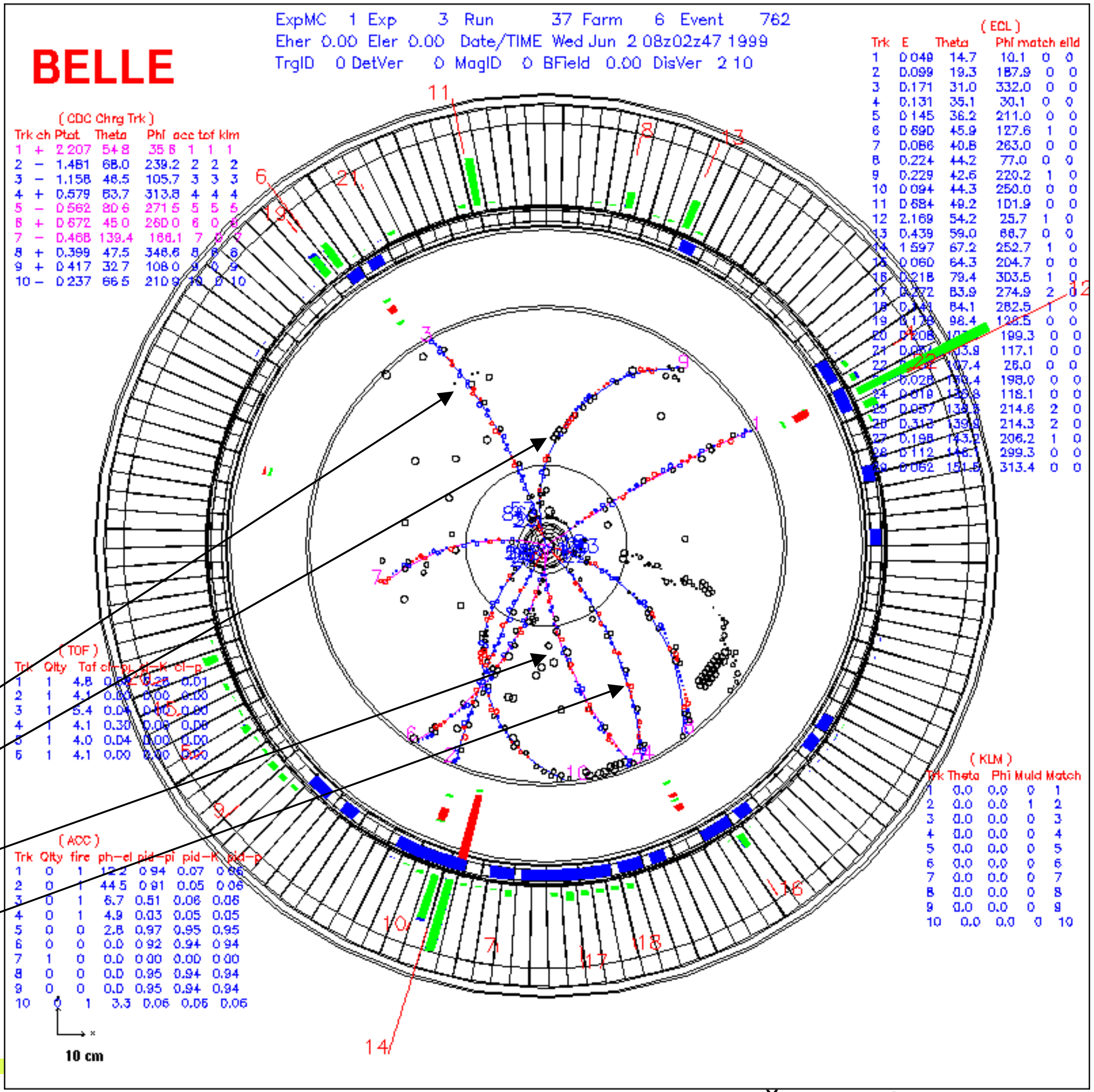
A high luminosity is needed for studies of rare processes.

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:



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

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

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

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

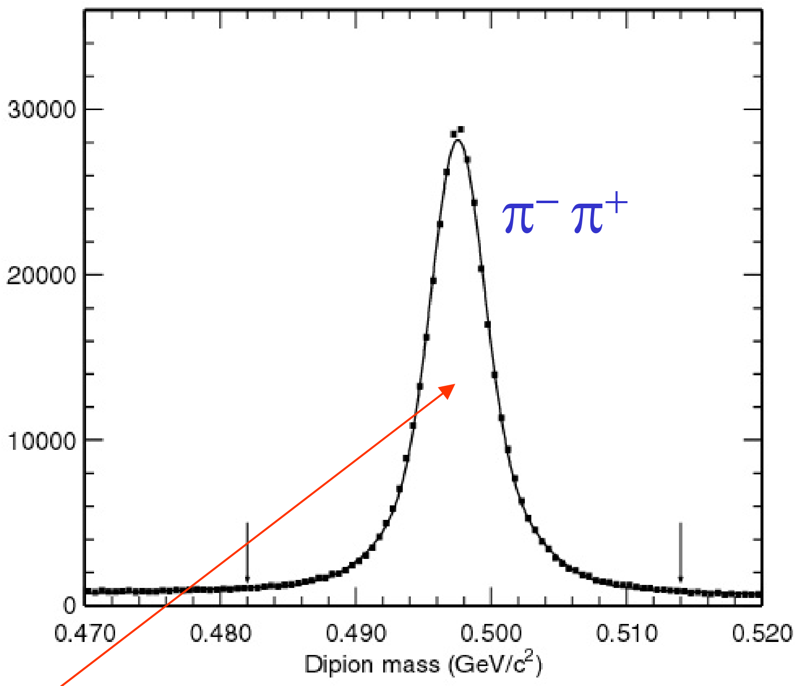
For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

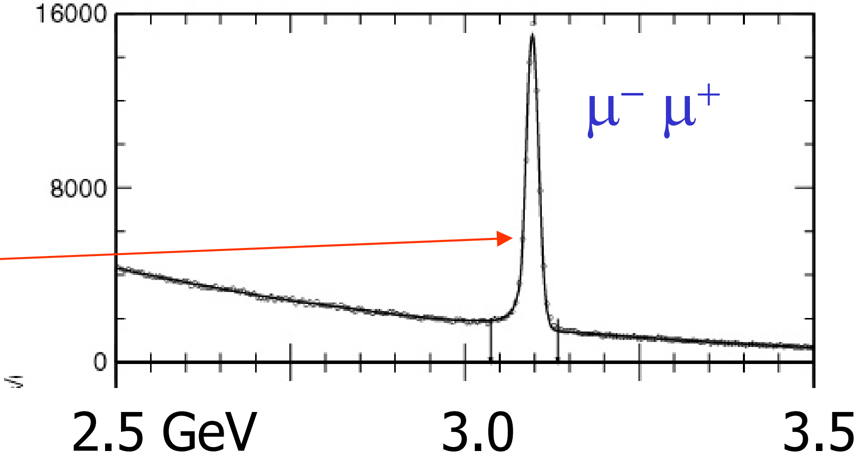
$M^2c^4=(E_1+ E_2)^2- (p_1+ p_2)^2$

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

for J/ψ close to 3.1 GeV.

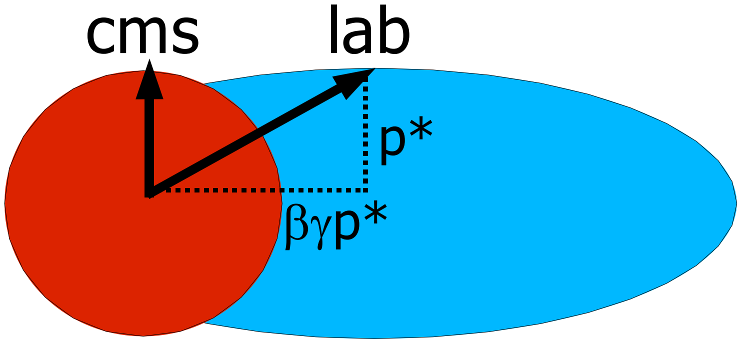
Rest in the histrogram: random coincidences (‘combinatorial background’)

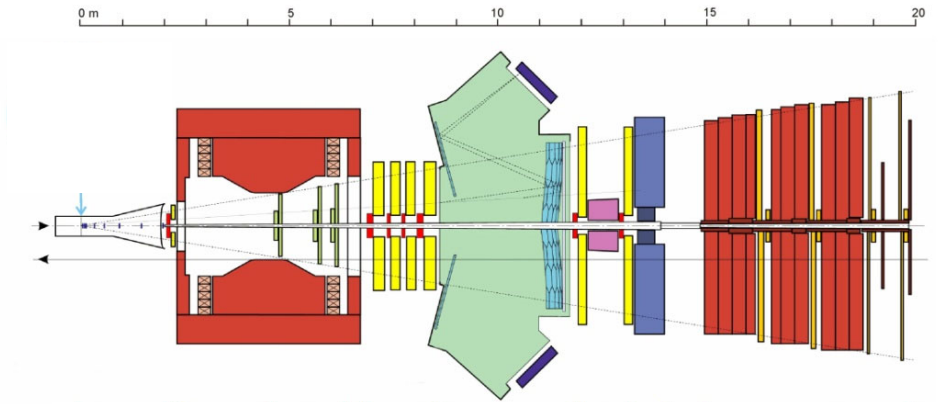


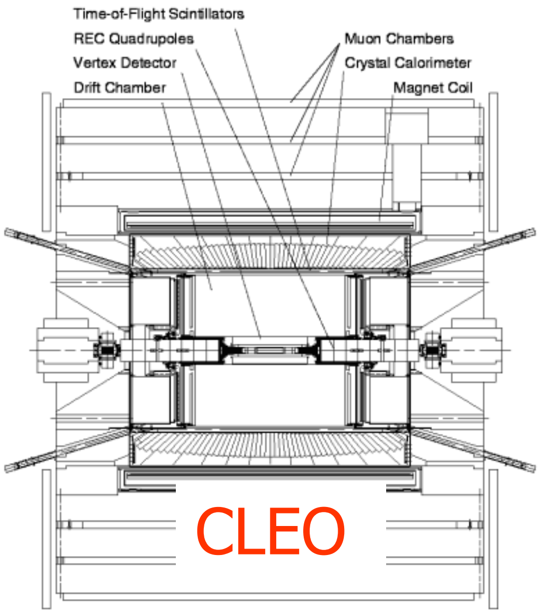


Experimental aparatus

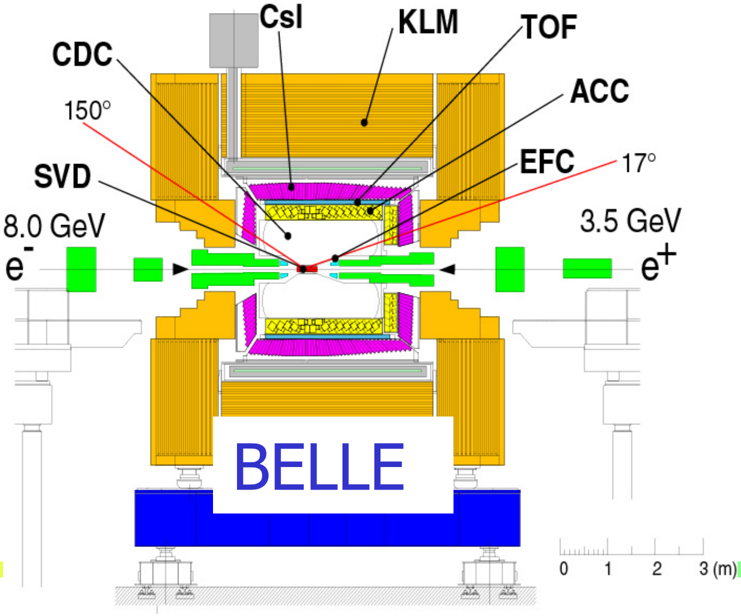
Detector form: symmetric for colliders with symmetric energy beams; extended in the boost direction for an asymmetric collider; very forward oriented in fixed target experiments.





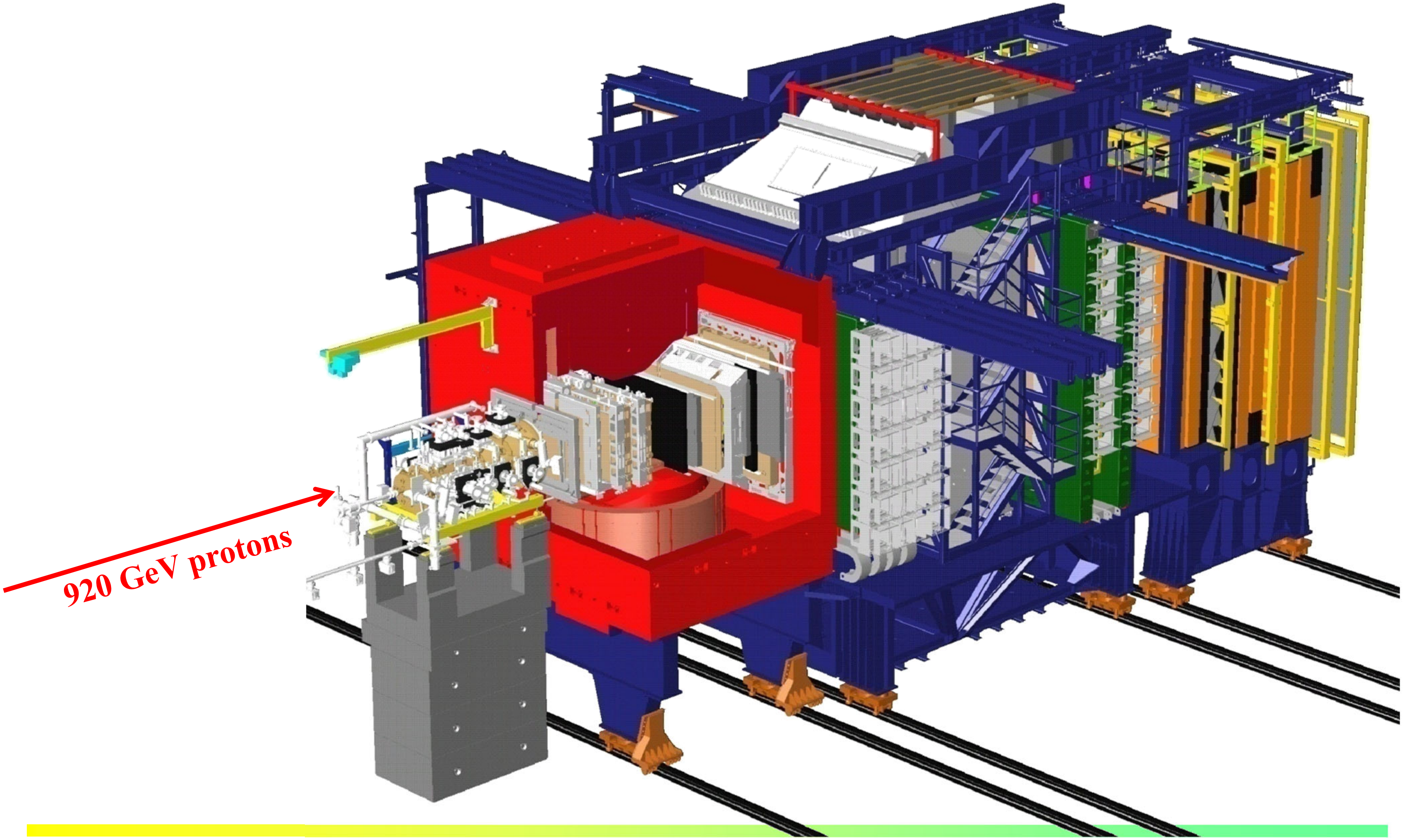


CLEO

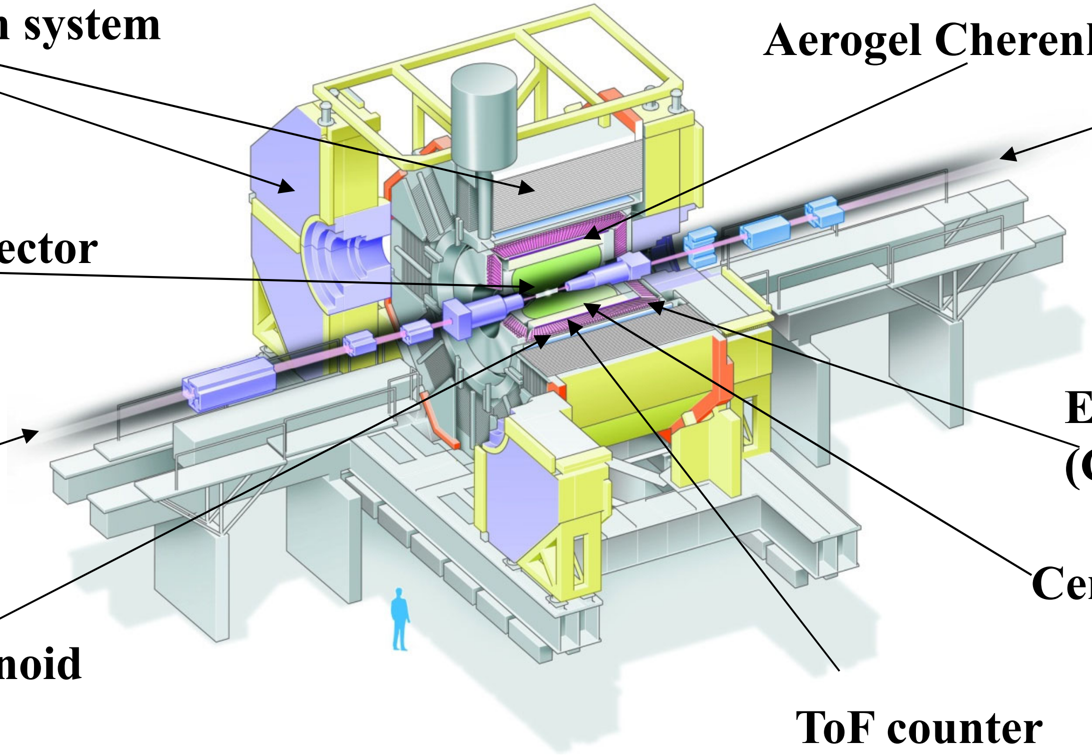


BELLE

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

8 GeV e^-

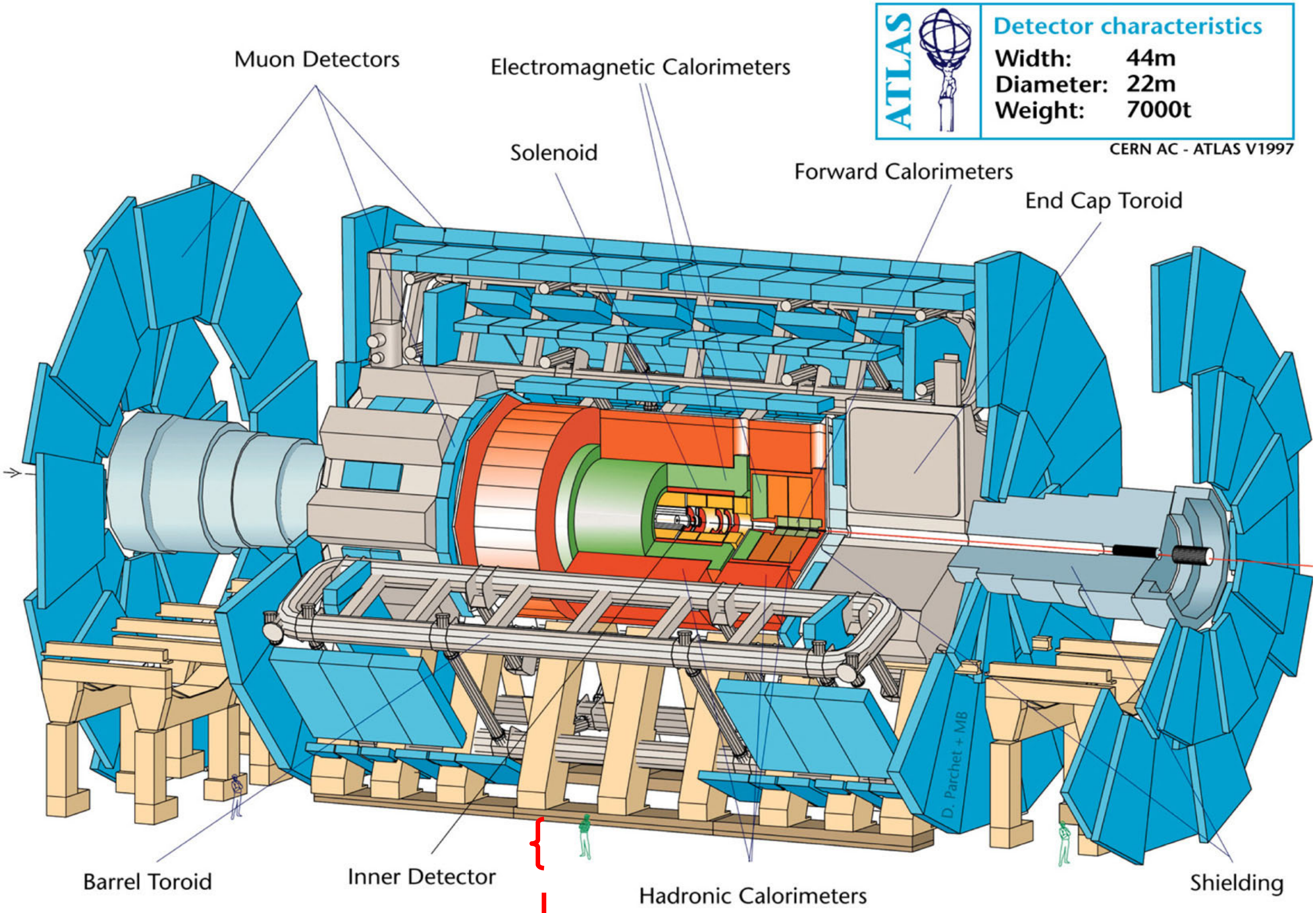
Electromagnetic. Cal. (CsI crystals)

Central Drift Chamber

1.5T SC solenoid

ToF counter

ATLAS at LHC



A physicist...

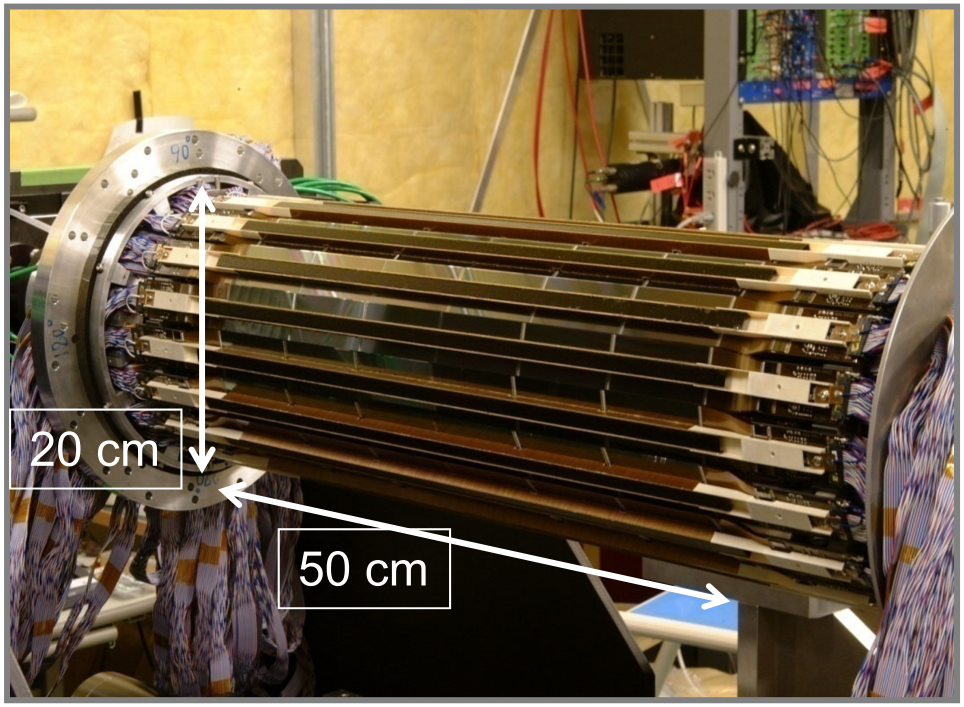
Components of an experimental apparatus (‘spectrometer’)

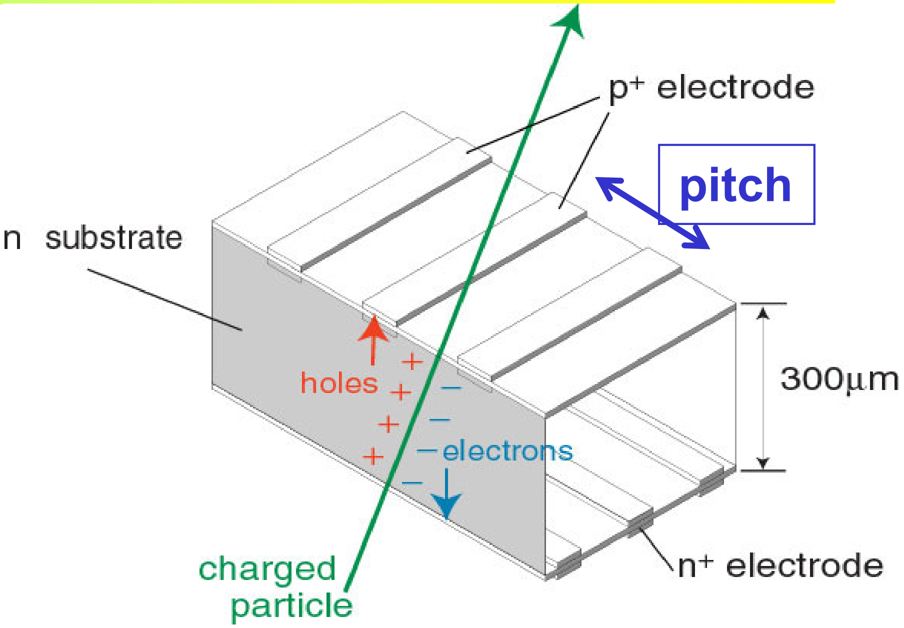
- Tracking and vertexing systems
- Particle identification devices
- Calorimeters (measurement of energy)

Components of an experimental apparatus (‘spectrometer’)

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

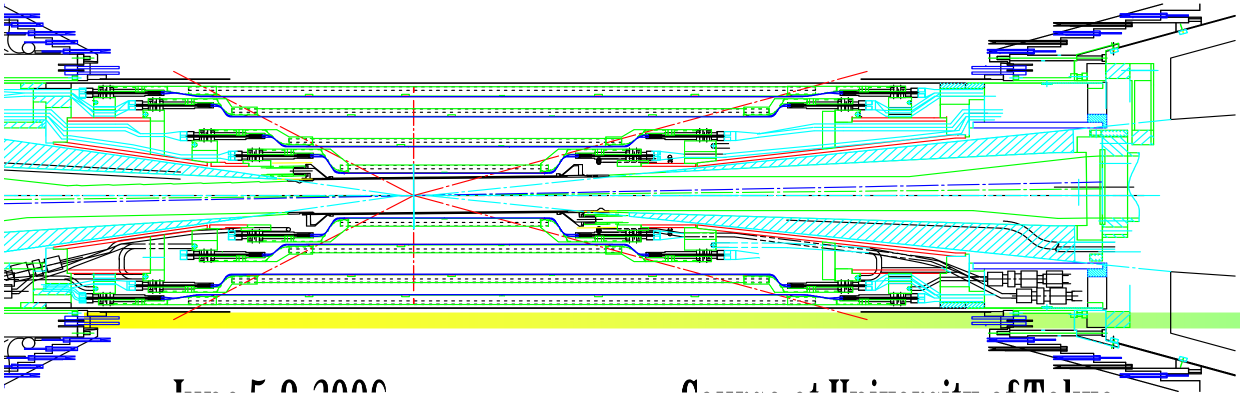
Silicon vertex detector (SVD)





Two coordinates measured at the same time

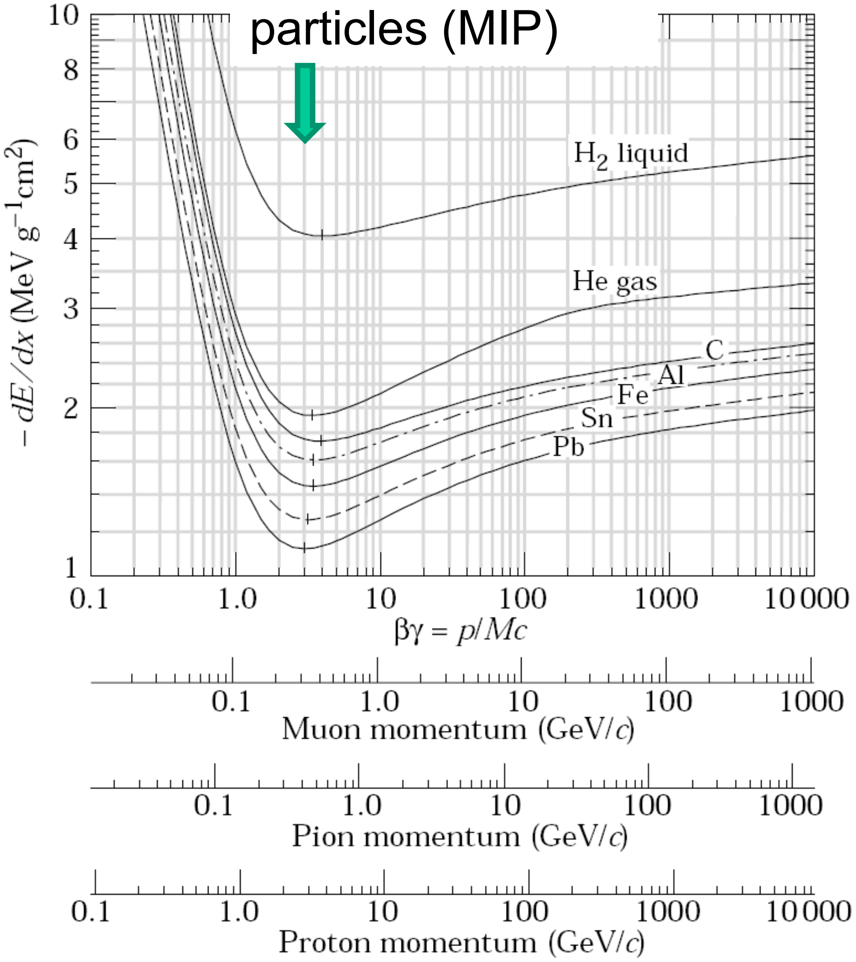
Typical strip pitch ~50μm, resolution about ~15 μm



Interaction of charged particles with matter

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

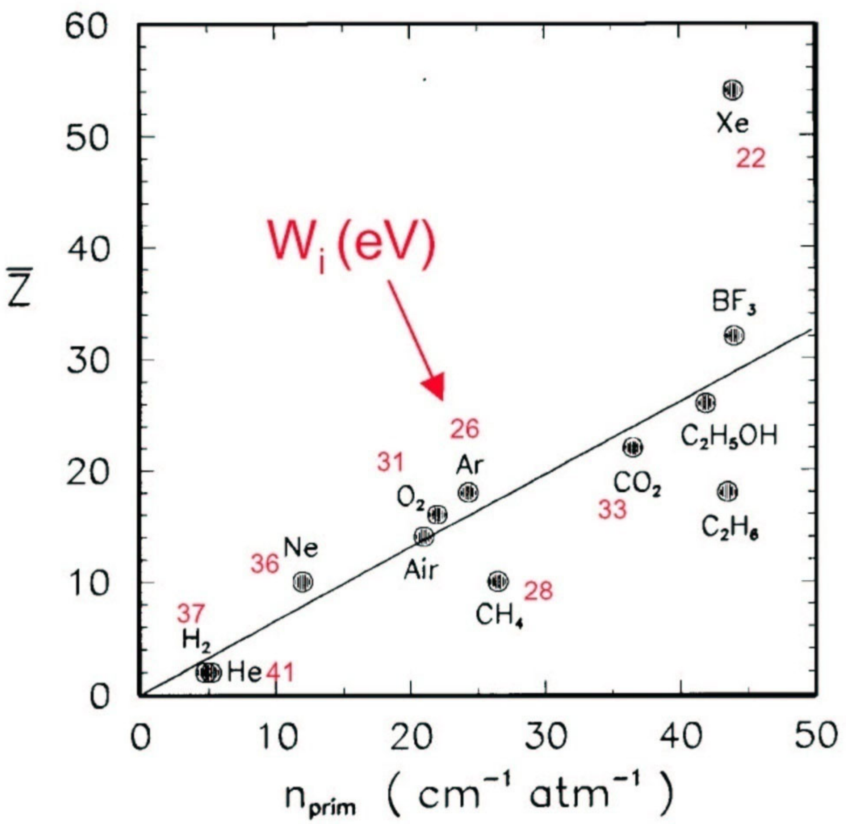
Ionisation

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



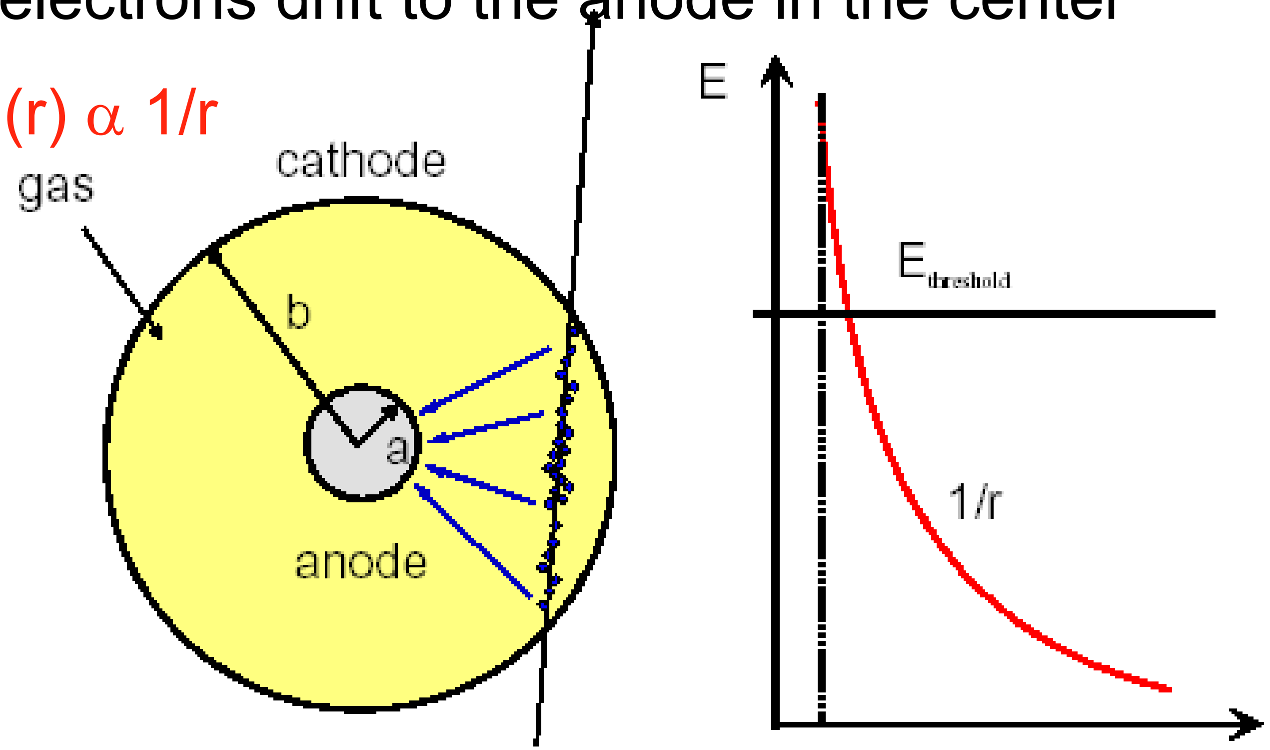
Can this be detected? 120 e-ion pairs make a pulse of $V=ne/C=2mV$ (at typical C=10pF) → NO

-> Need multiplication

Multiplication in gas

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

E = E(r) α 1/r

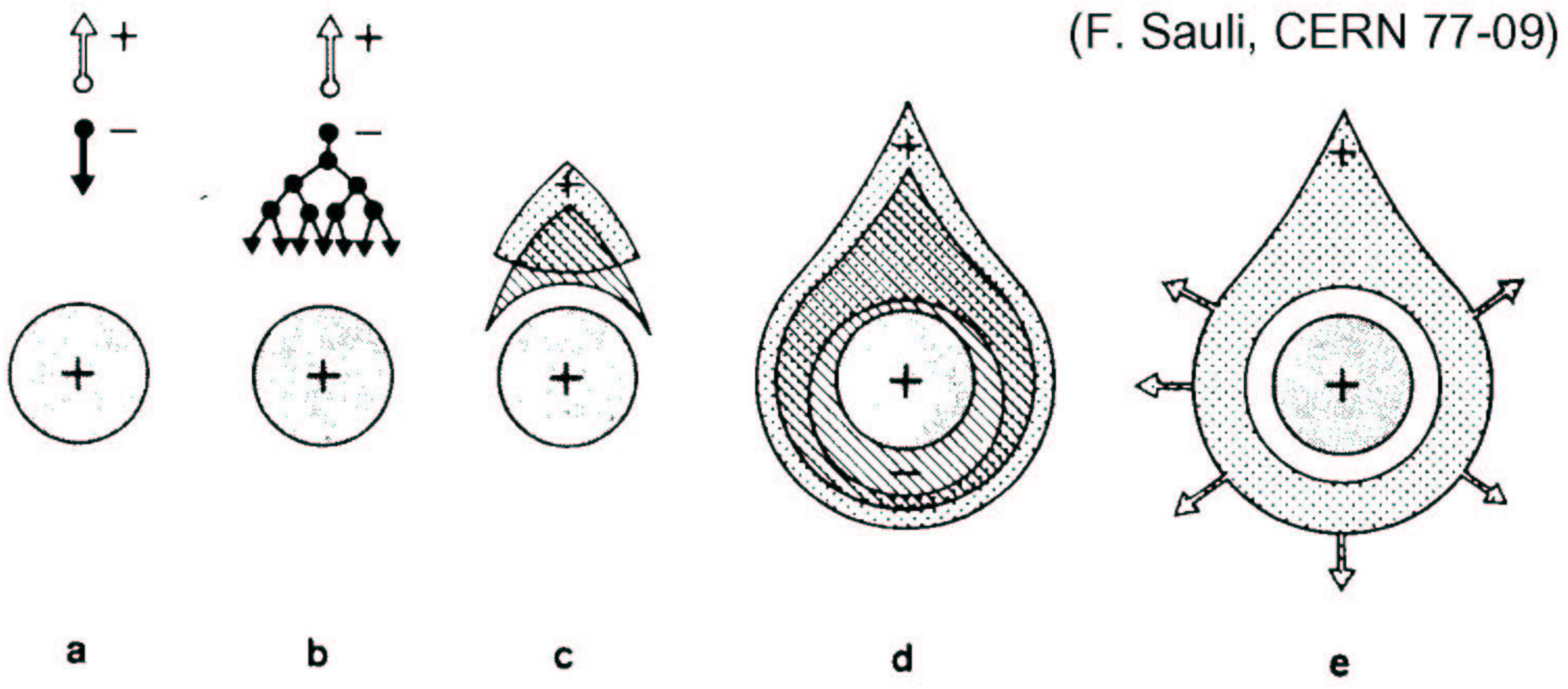


If the energy eEd gained over several mean free paths (d around 10mm) exceeds the ionisation energy → new electron

Electric field needed → E = I/ed = 10V/mm = 10kV/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.



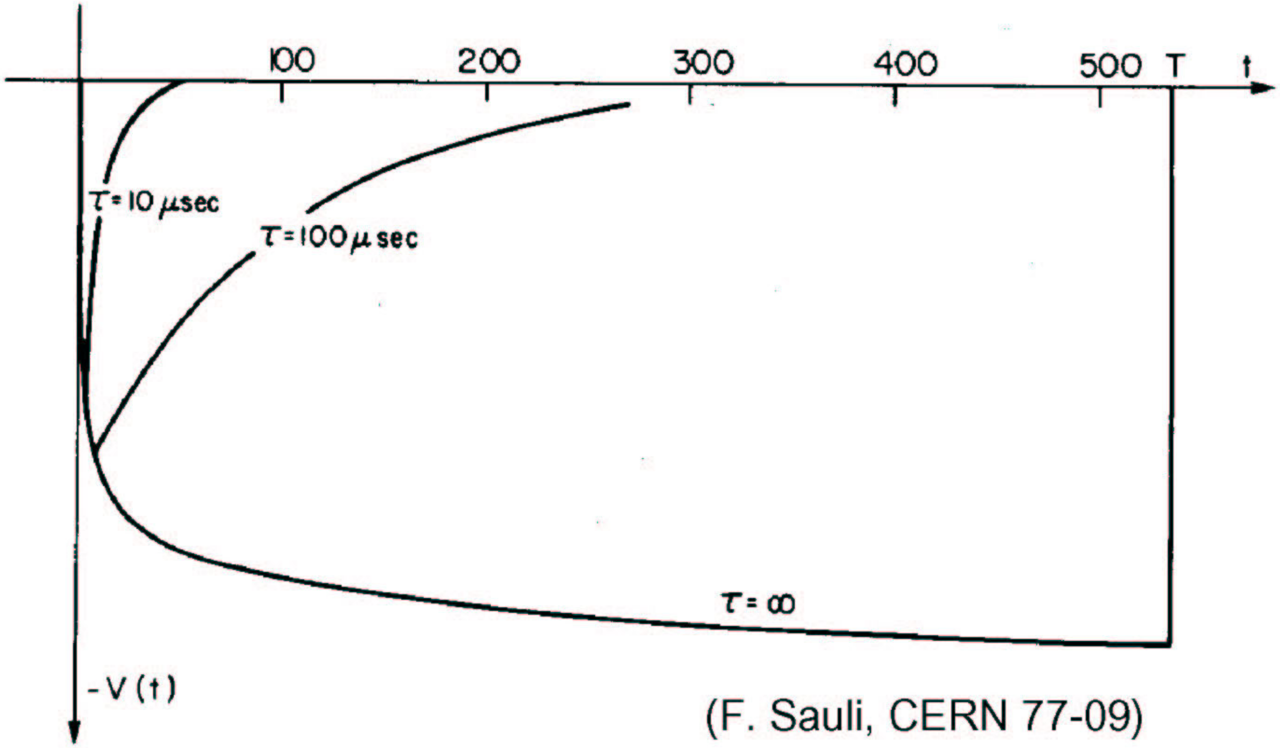
(F. Sauli, CERN 77-09)

Signal development 3

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.



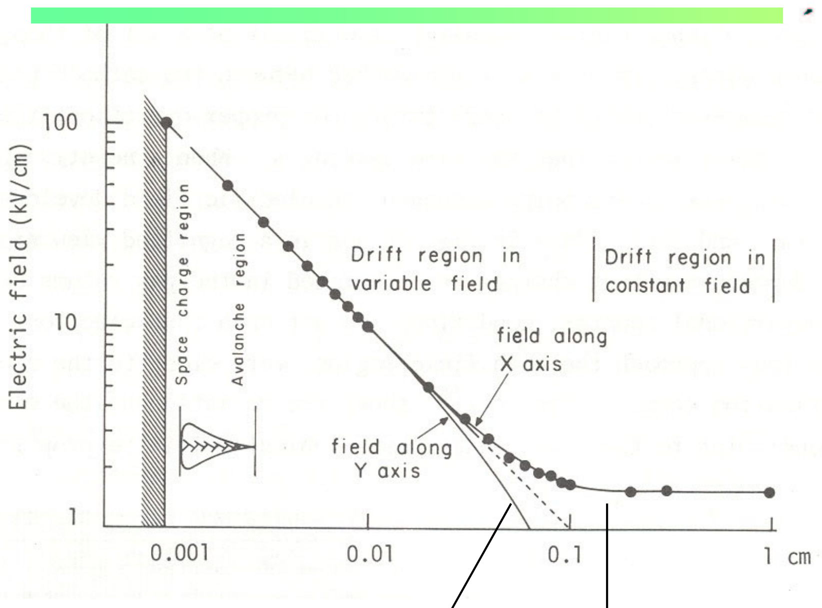
(F. Sauli, CERN 77-09)

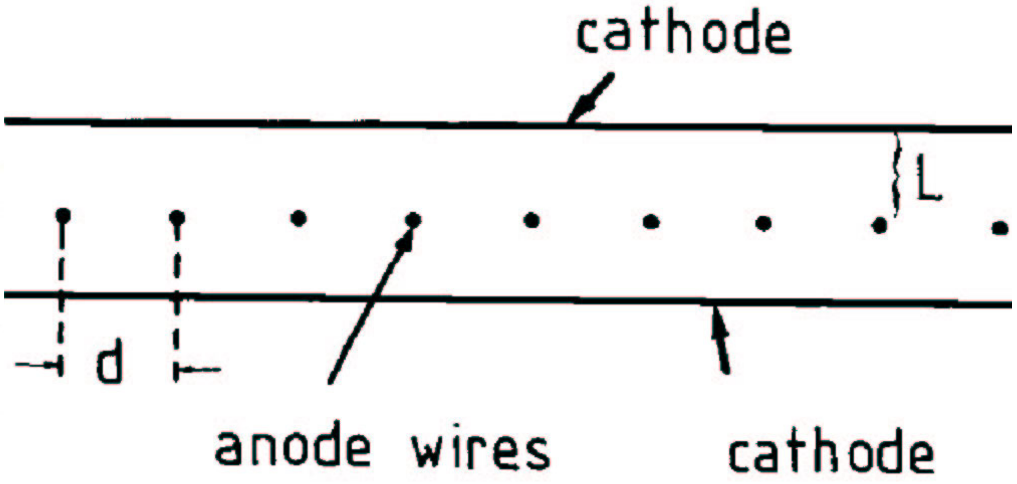
If faster signals are needed → smaller time constants→ smaller signals

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

Peter Križan, Ljubljana

Multiwire proportional chamber (MWPC)

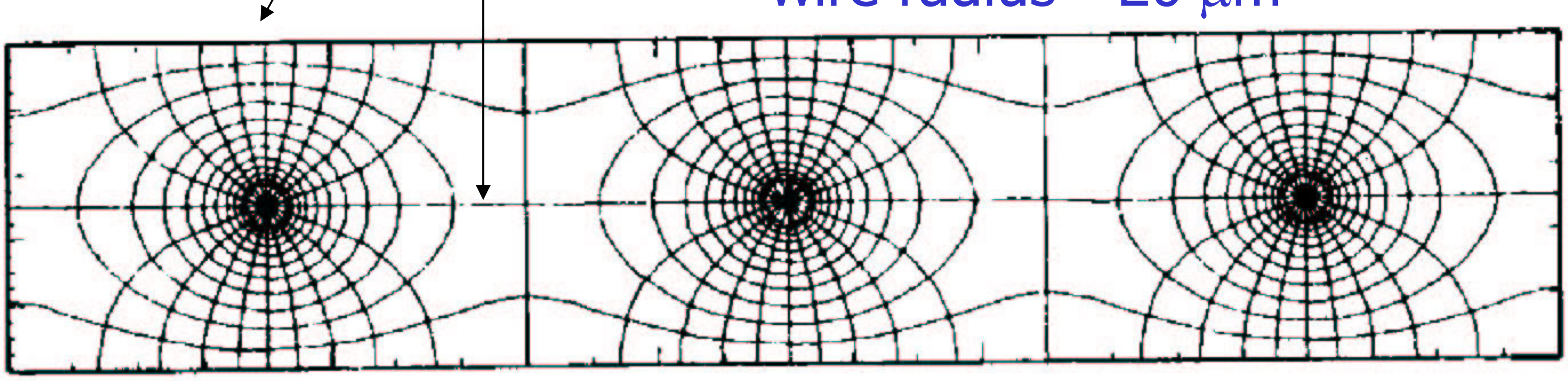




Typical parameters:

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

wire radius =20 μm



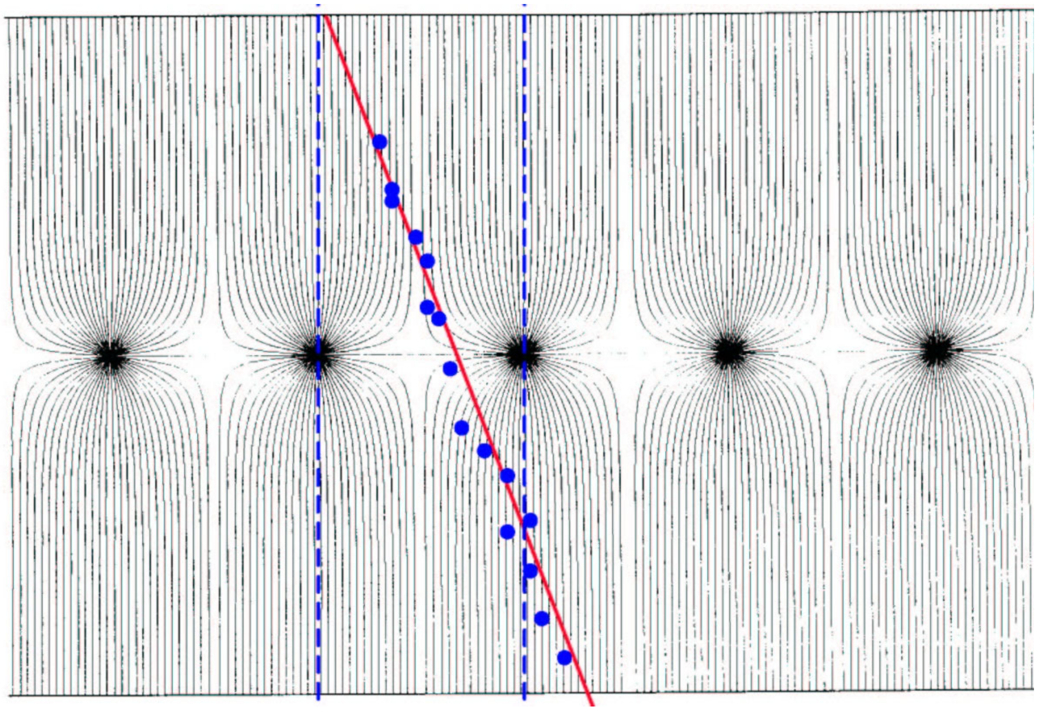
Multiwire proportional chamber (MWPC)

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

Normally digital readout: spatial resolution limited to

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

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



Revolutionized particle physics experiments
→ Nobel prize for G. Charpak

Components of an experimental apparatus (‘spectrometer’)

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

Why Particle ID?

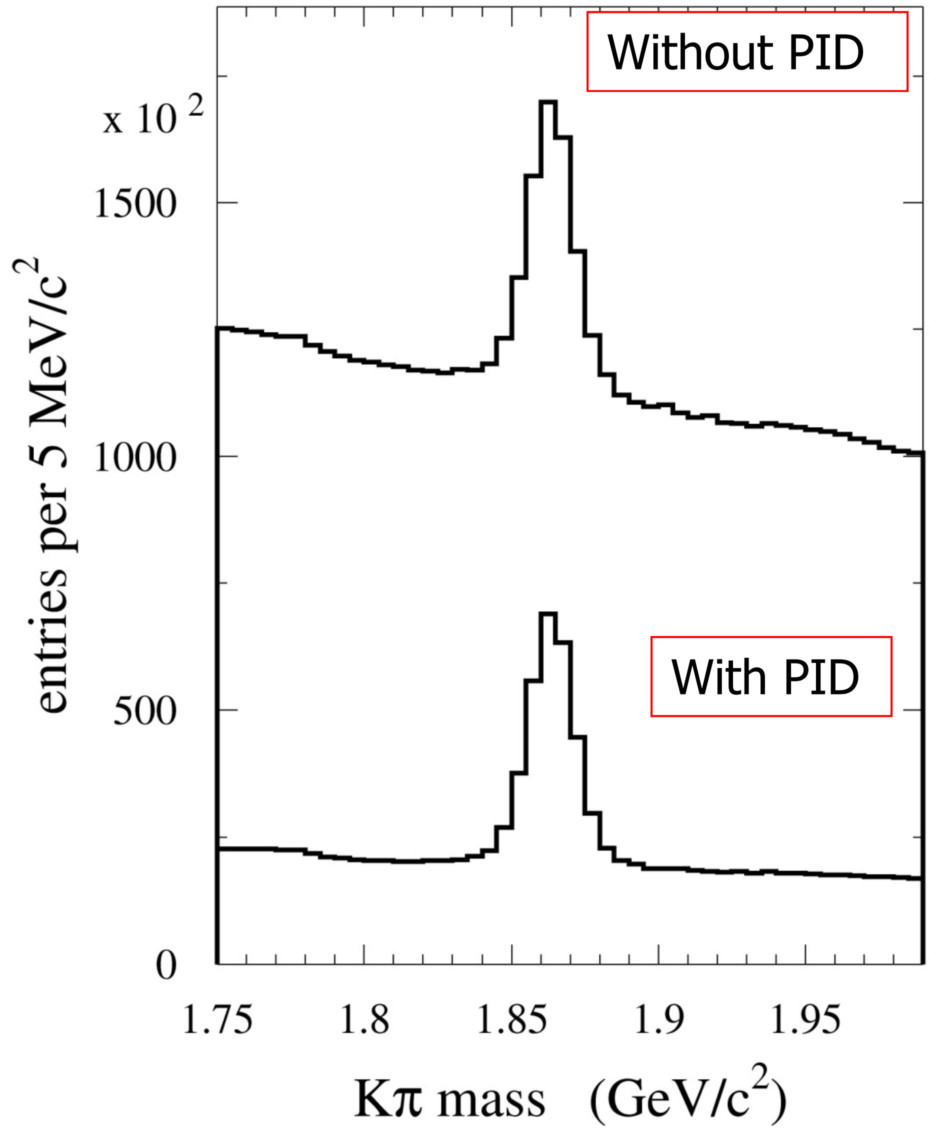
Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

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

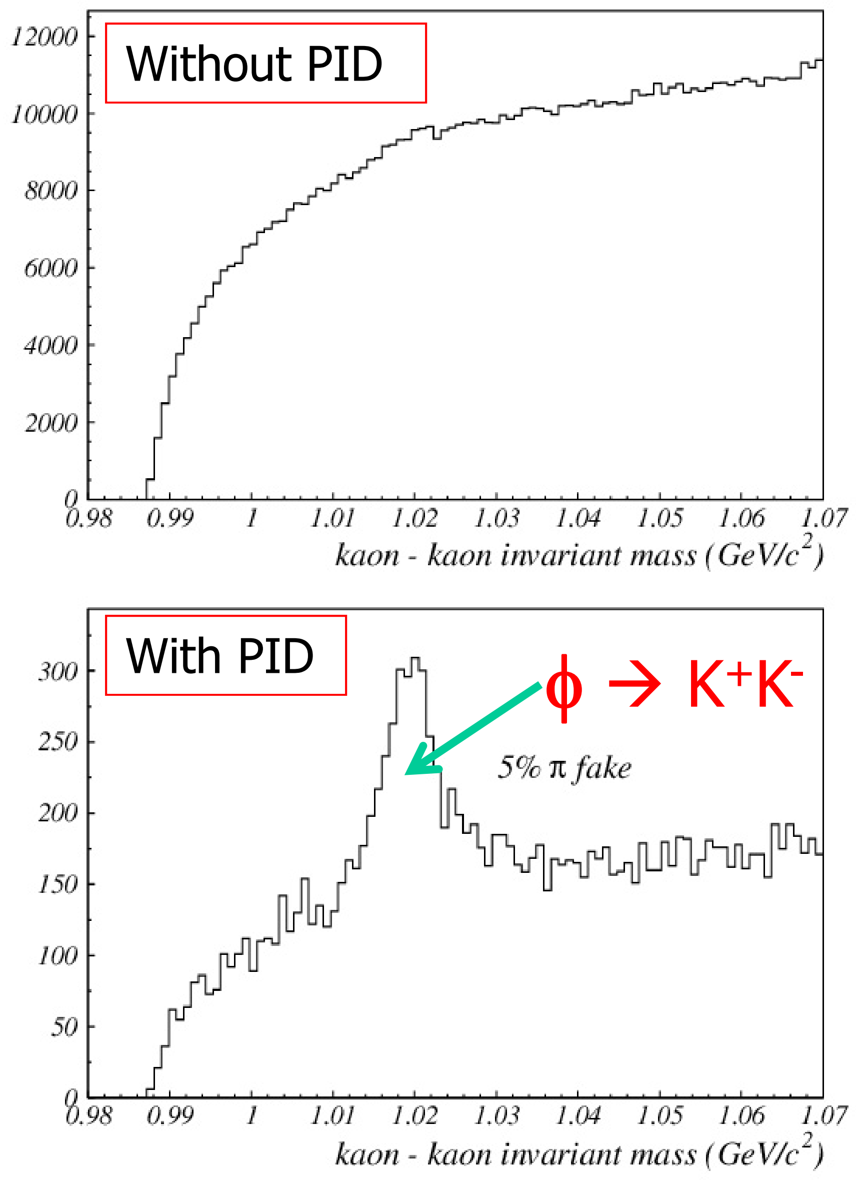
Introduction: Why Particle ID?



Example 1: B factories

Particle identification reduces combinatorial background by ~5x

Introduction: Why Particle ID?

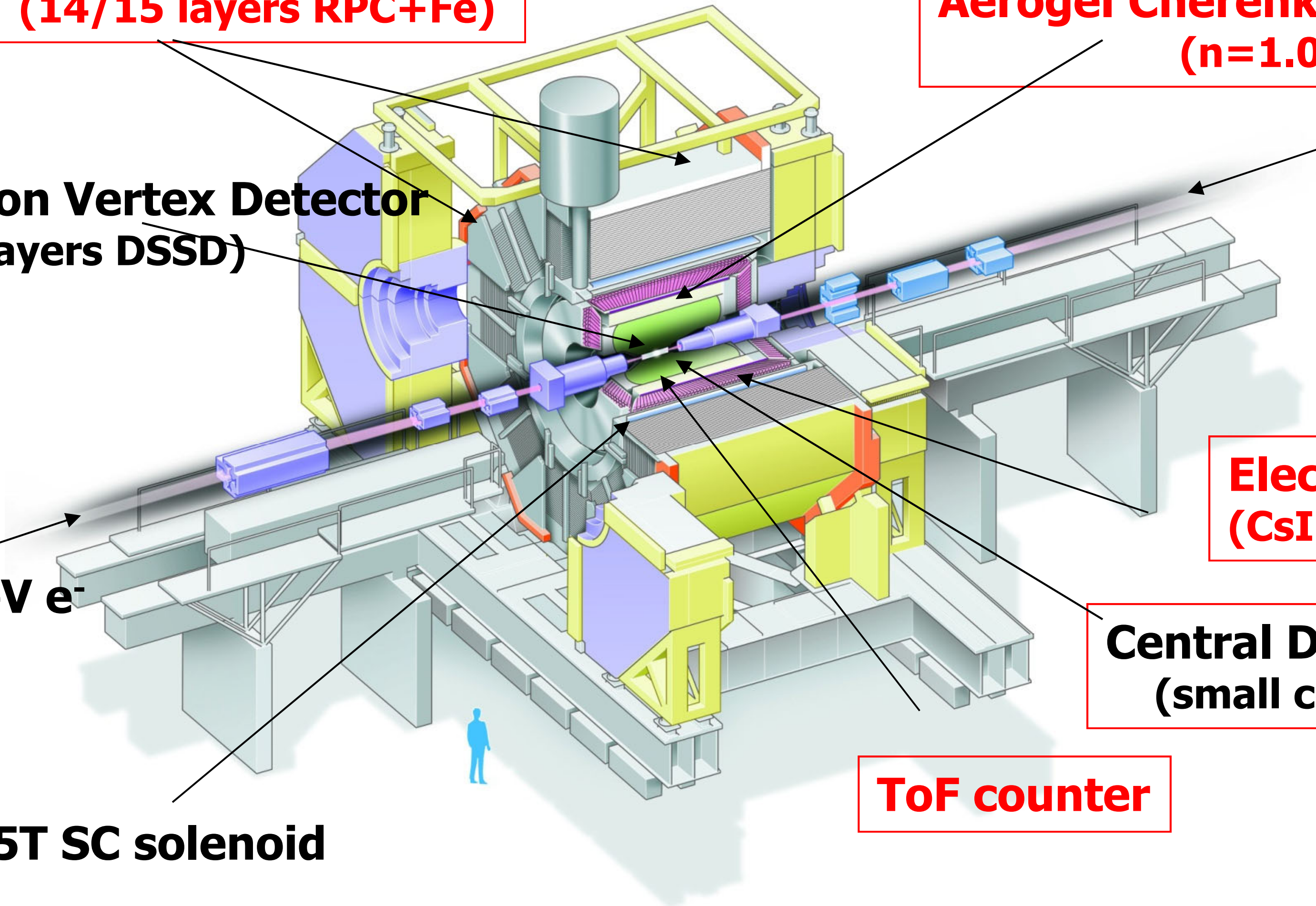


Example 2: HERA-B

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

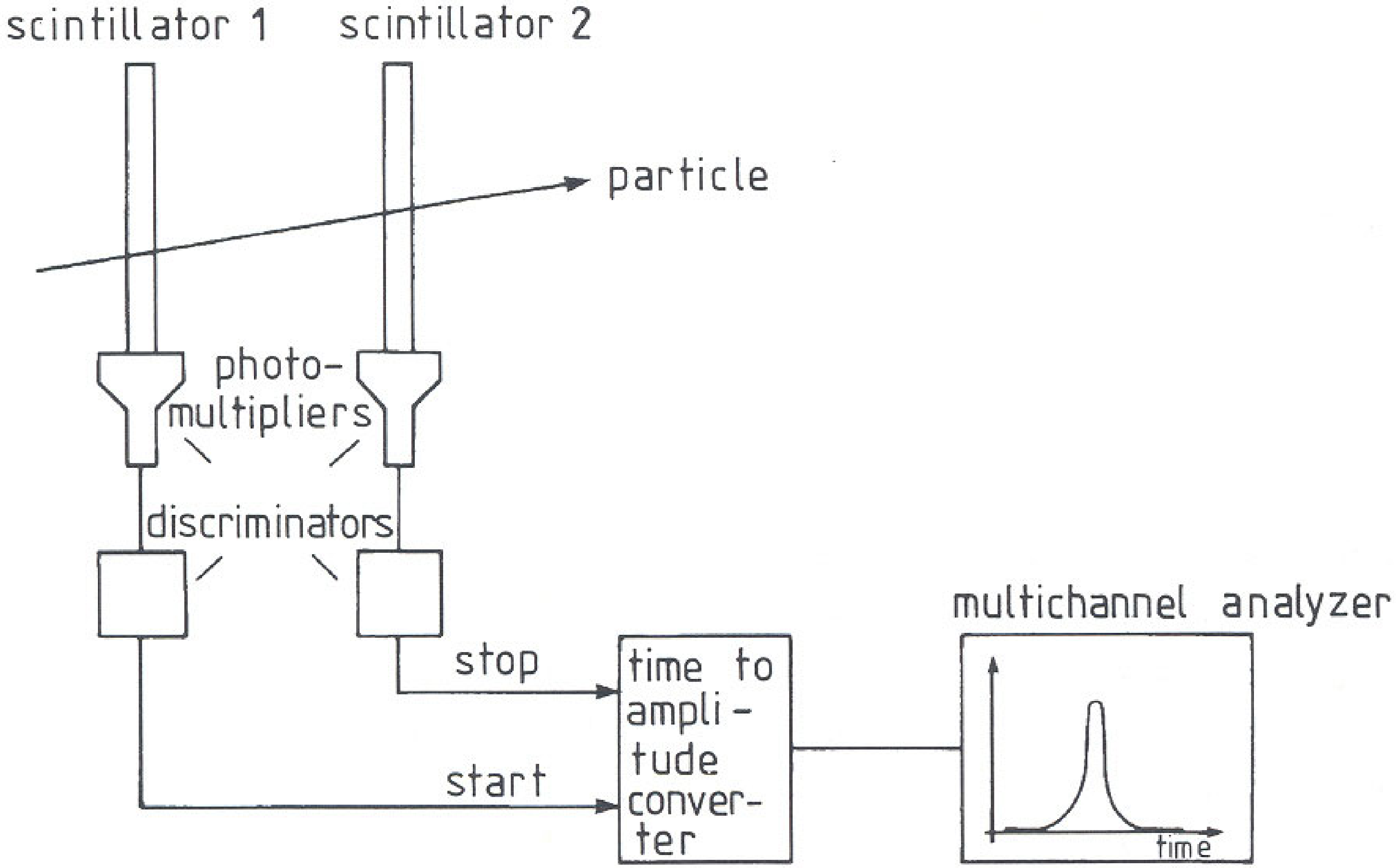
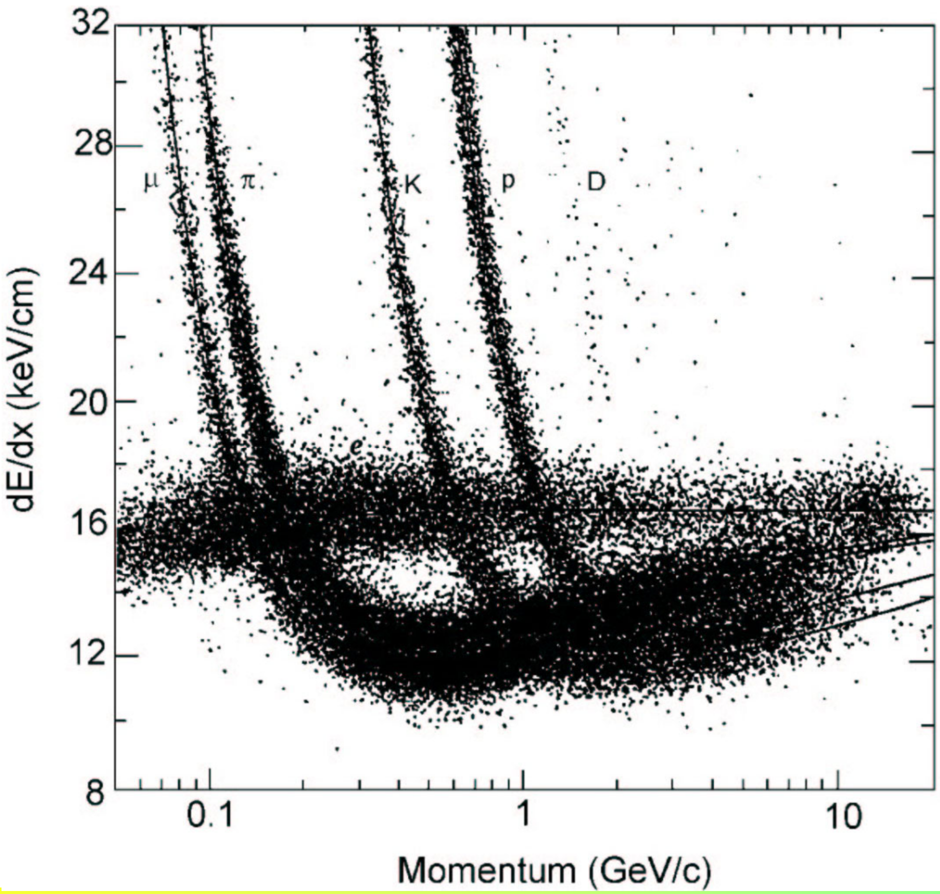


Fig. 6.5. Working principle of time-of-flight measurement.

Identification with dE/dx measurement

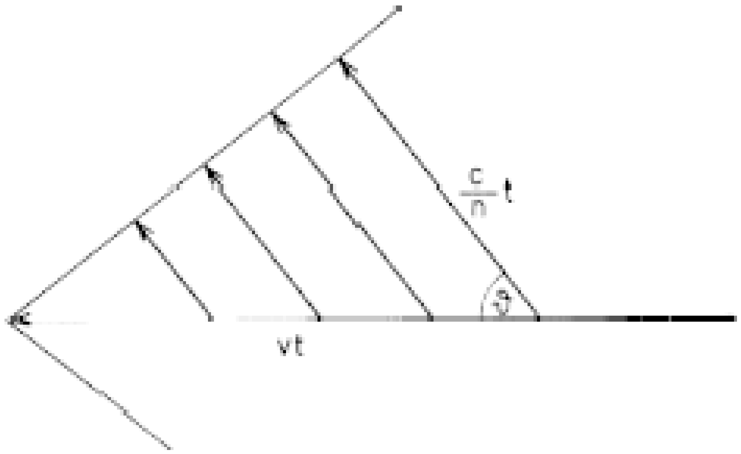
dE/dx performance in a large drift chamber.



Čerenkov radiation

A charged track with velocity v=βc above the speed of light c/n in a medium with index of refraction n= ⌧ε emits polarized light at a characteristic (Čerenkov) angle,

cosθ = c/nv = 1/βn



Two cases:

1) β **<** β$_t$ = 1/n: below threshold no Čerenkov light is emitted.

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

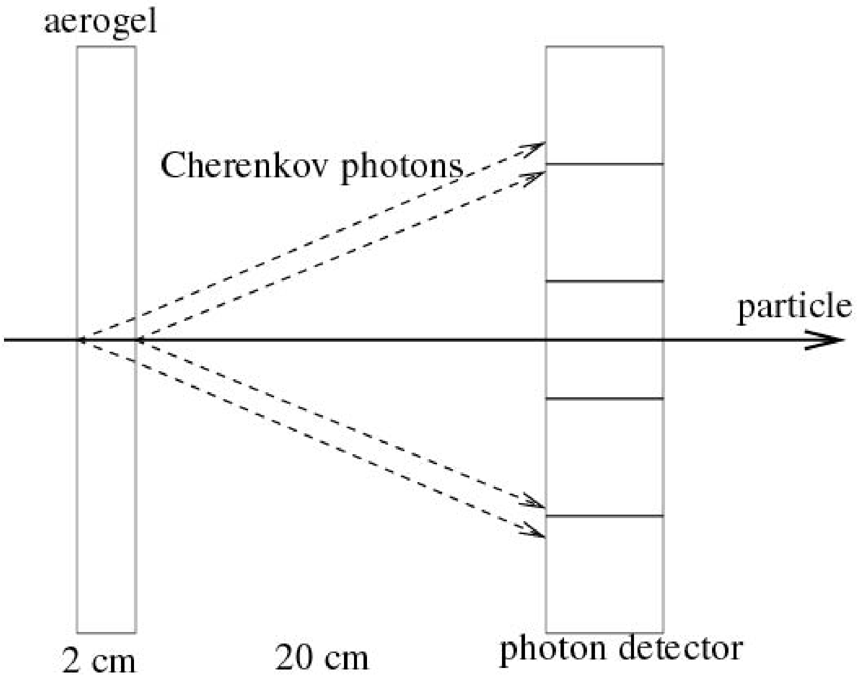
$$\boxed{\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370(cm)^{-1}(eV)^{-1} L \sin^2\theta}$$

Measuring Cherenkov angle

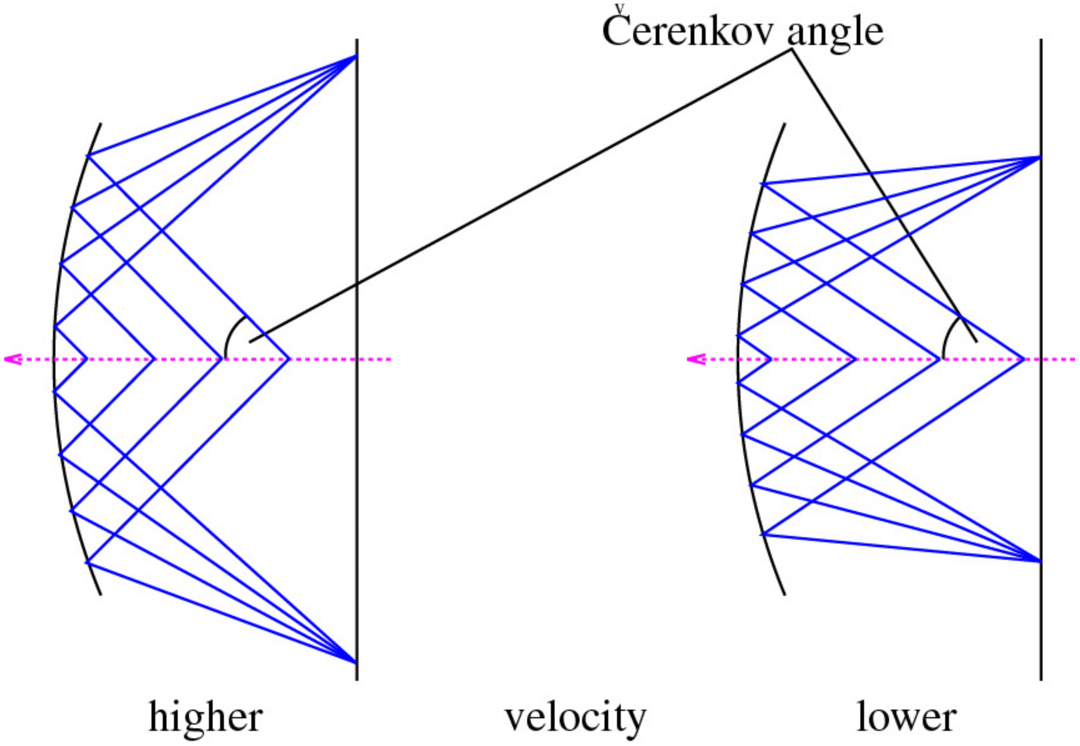
Idea: transform the direction into a coordinate →

ring on the detection plane

→ Ring Imaging CHerenkov

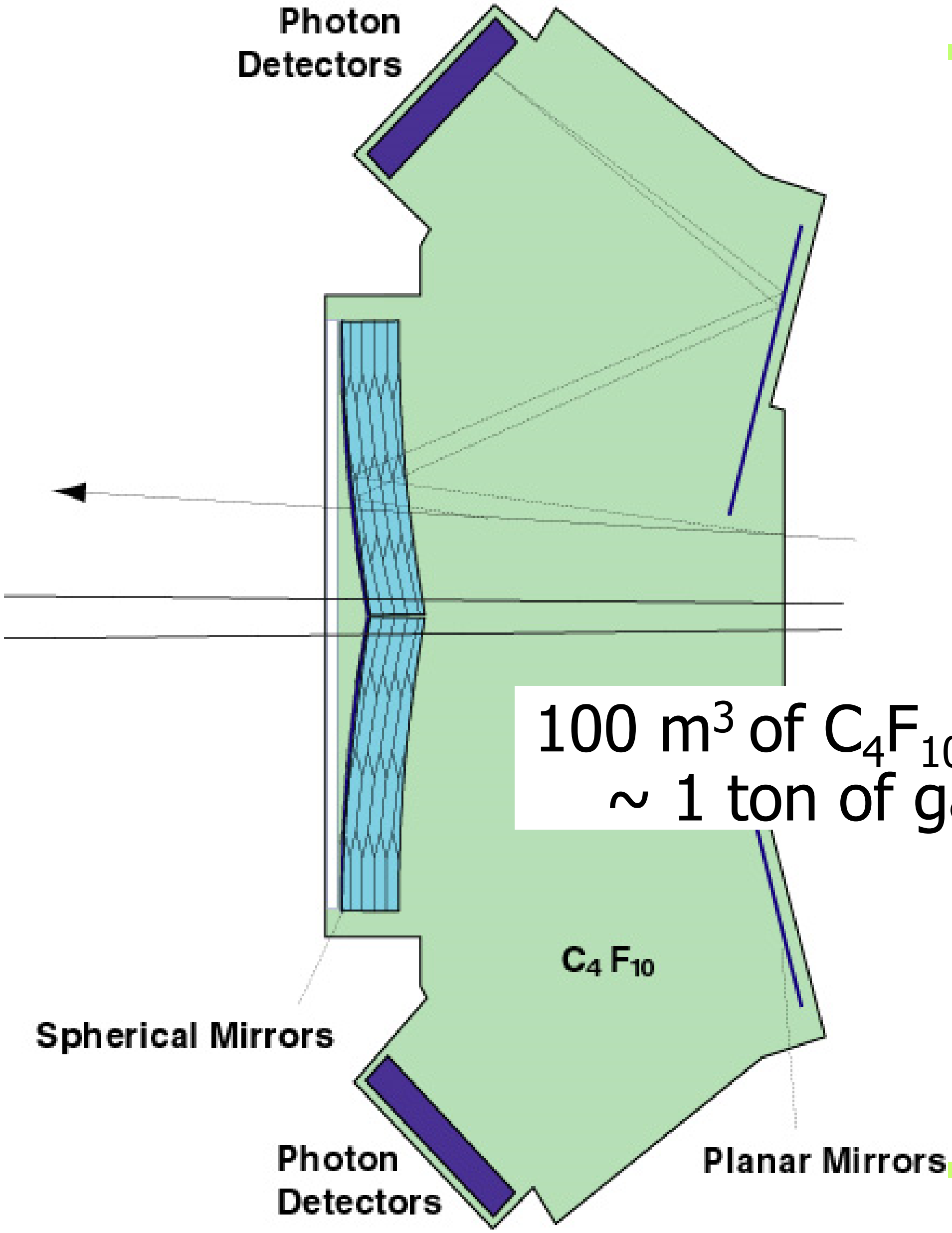


Proximity focusing RICH

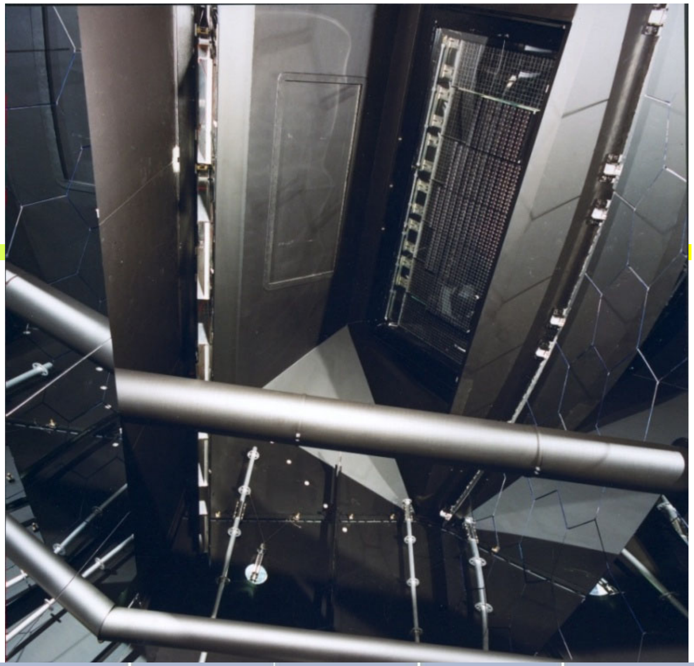


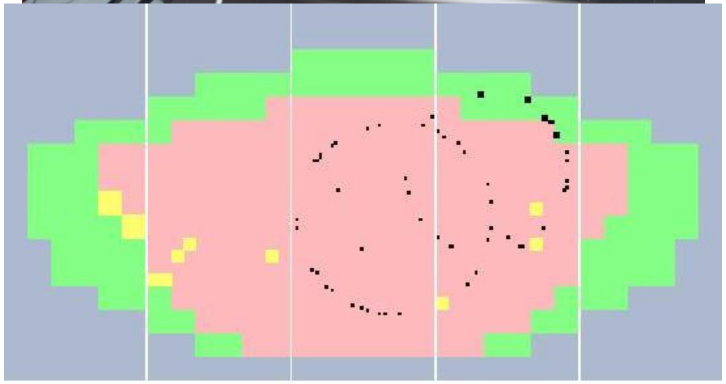
RICH with a focusing mirror

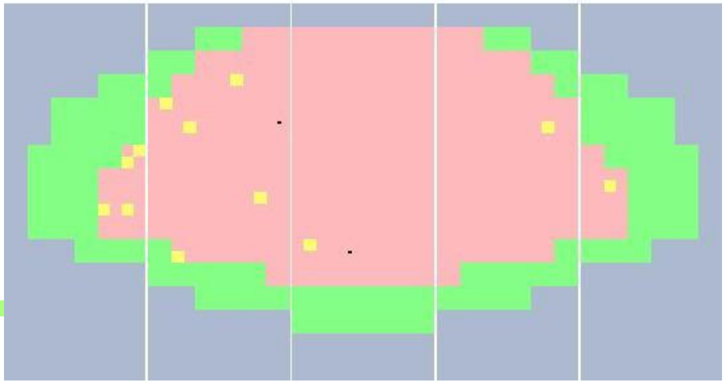
HERA-B RICH



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







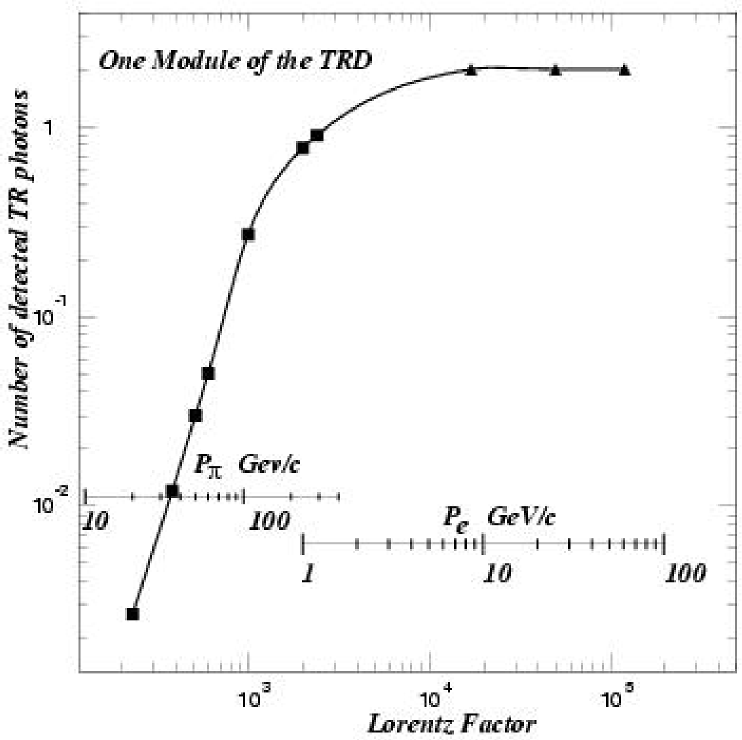
Transition radiation detectors

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

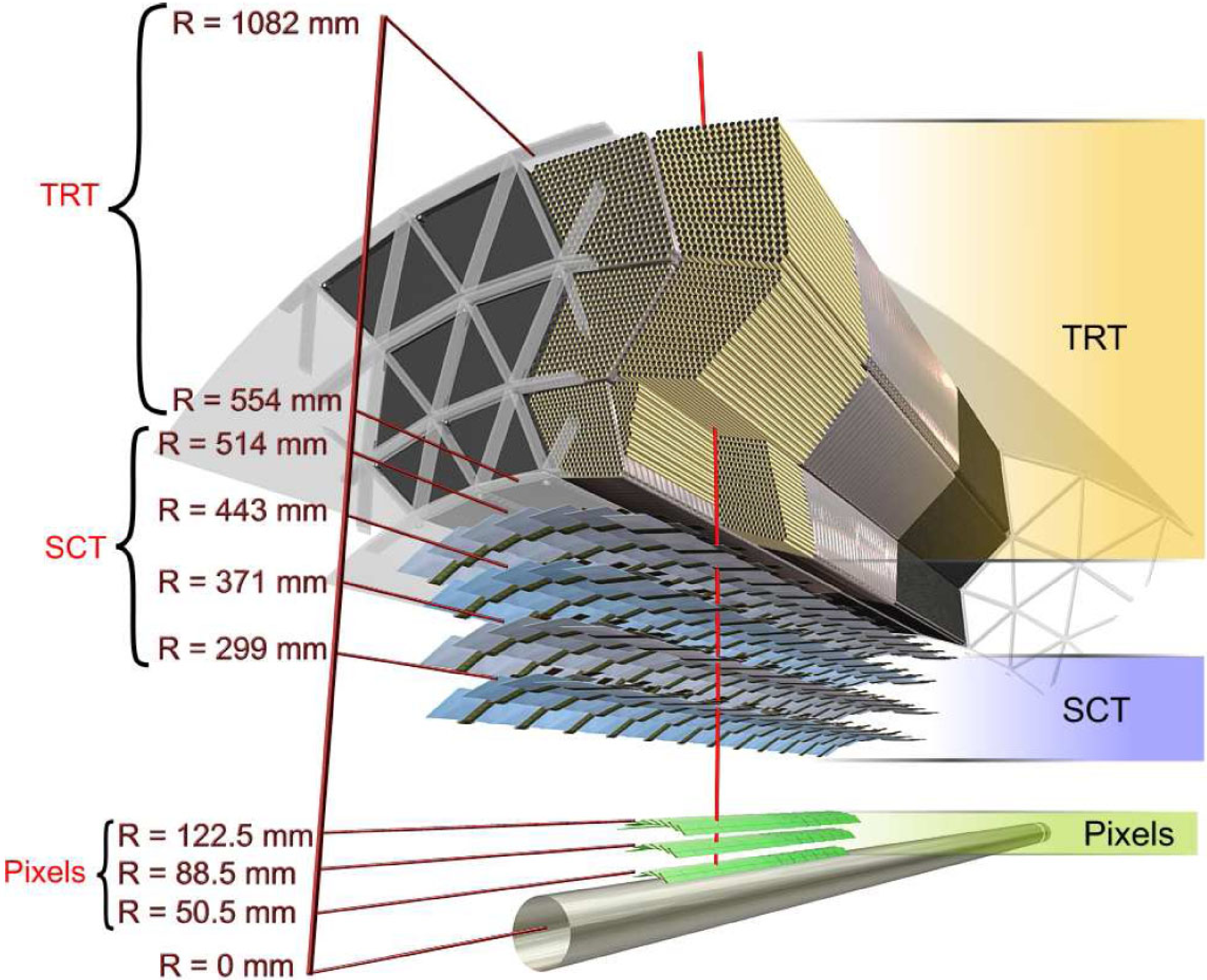


Detection of X rays: high Z gas – Xe

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.

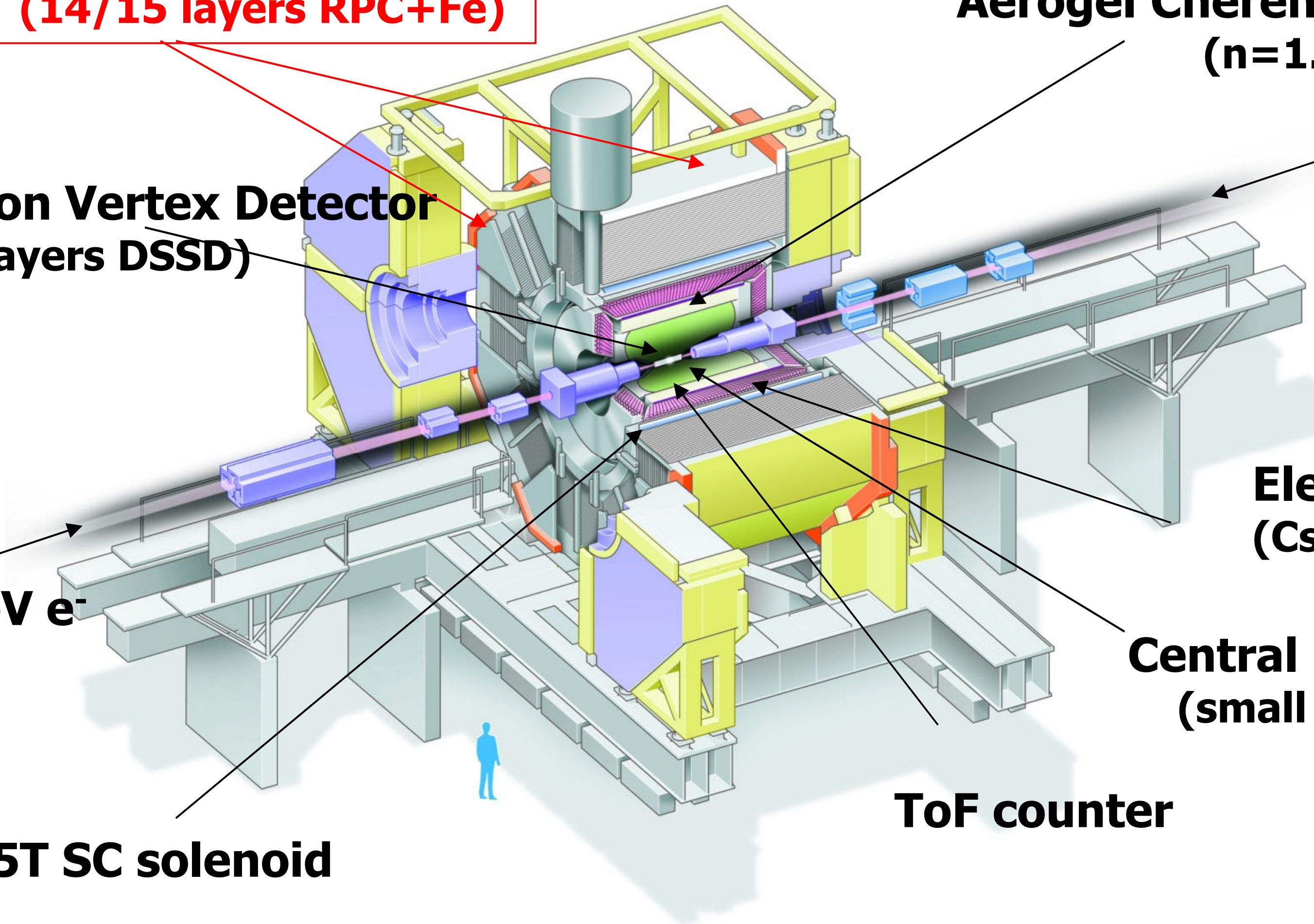
Some numbers: 0.8 interaction length (CsI) + 3.9 interaction lengths (iron)

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



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^-

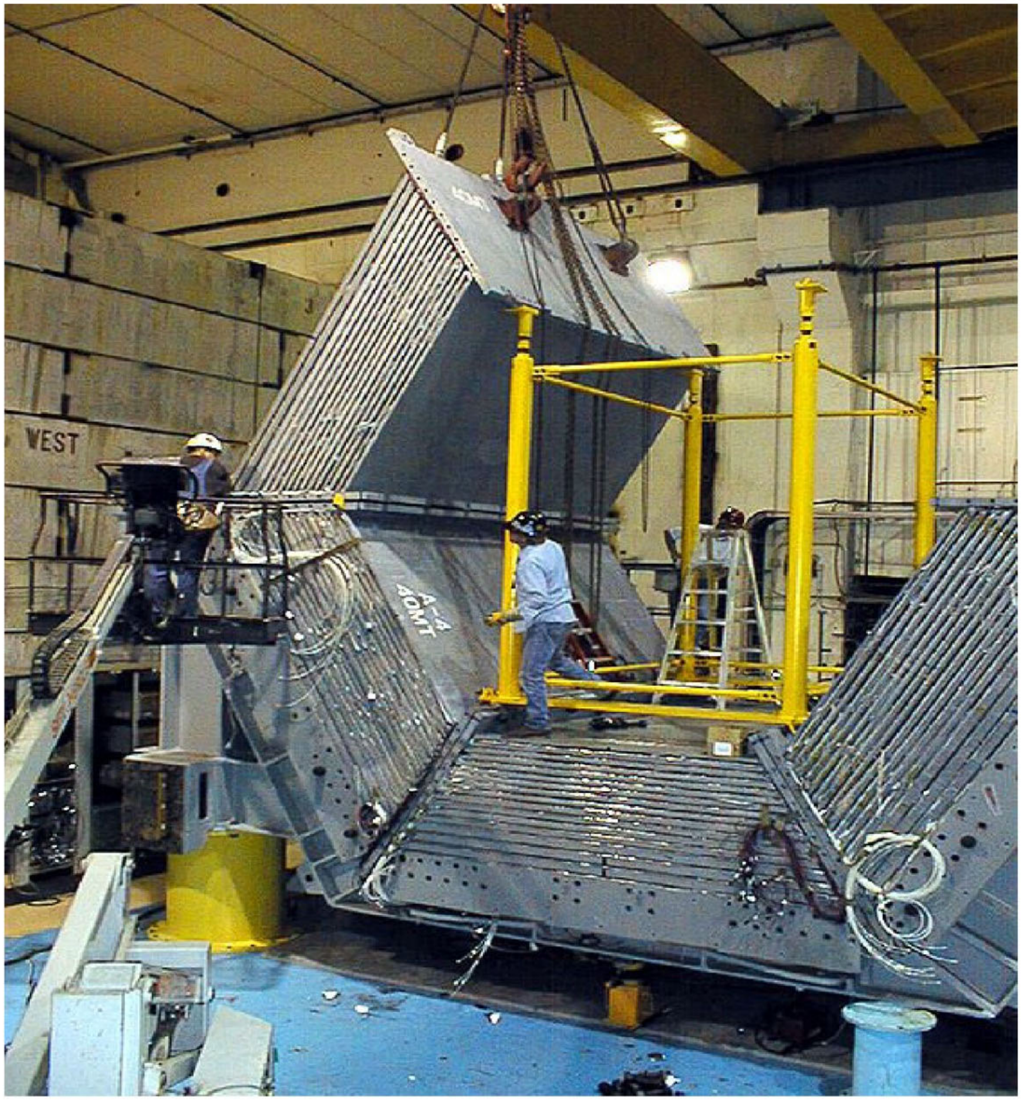
Central Drift Chamber
(small cells, He/C_2H_6)

ToF counter

1.5T SC solenoid

Muon and K_L detector

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



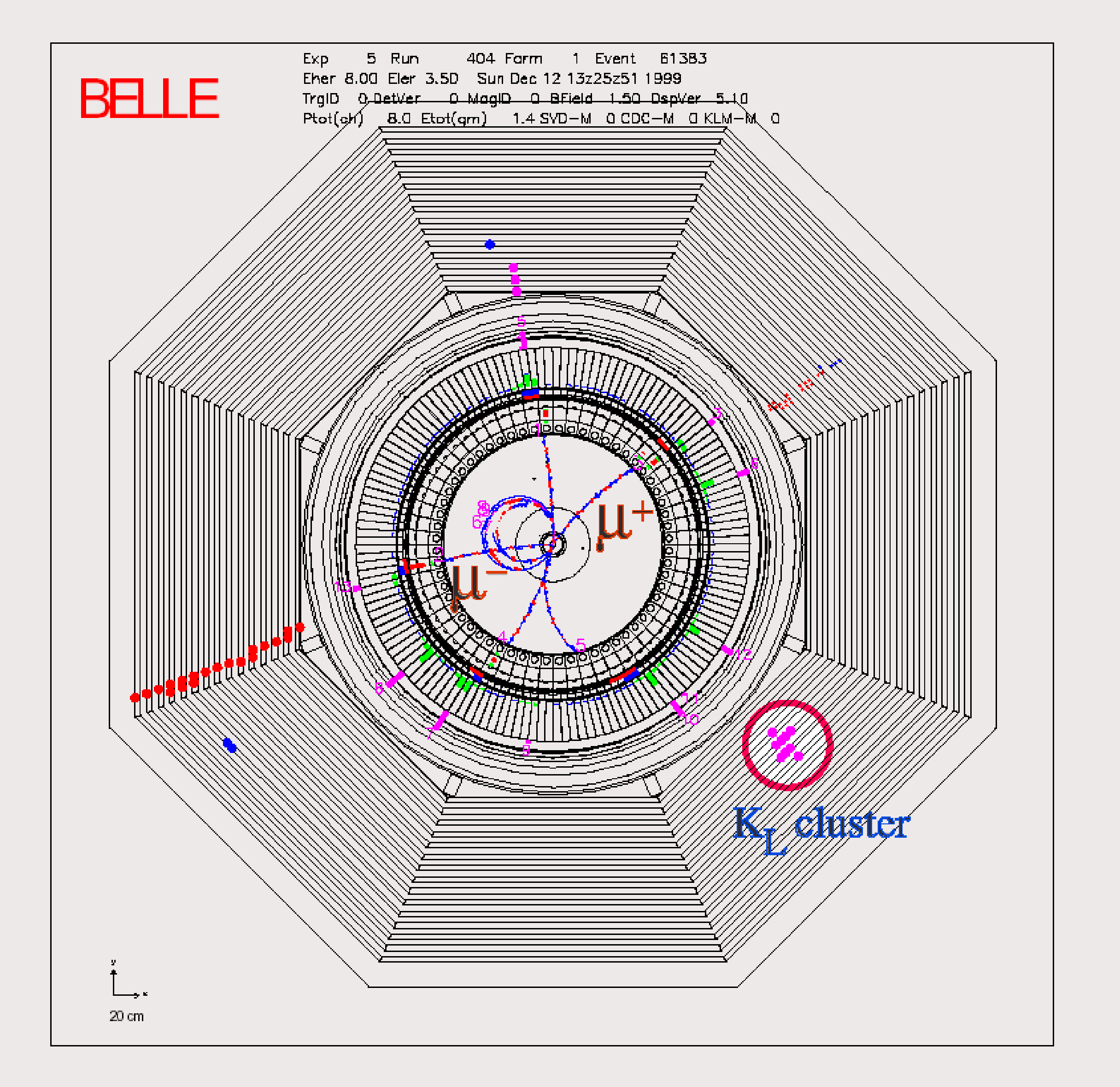
Muon and K_L detector

Example:

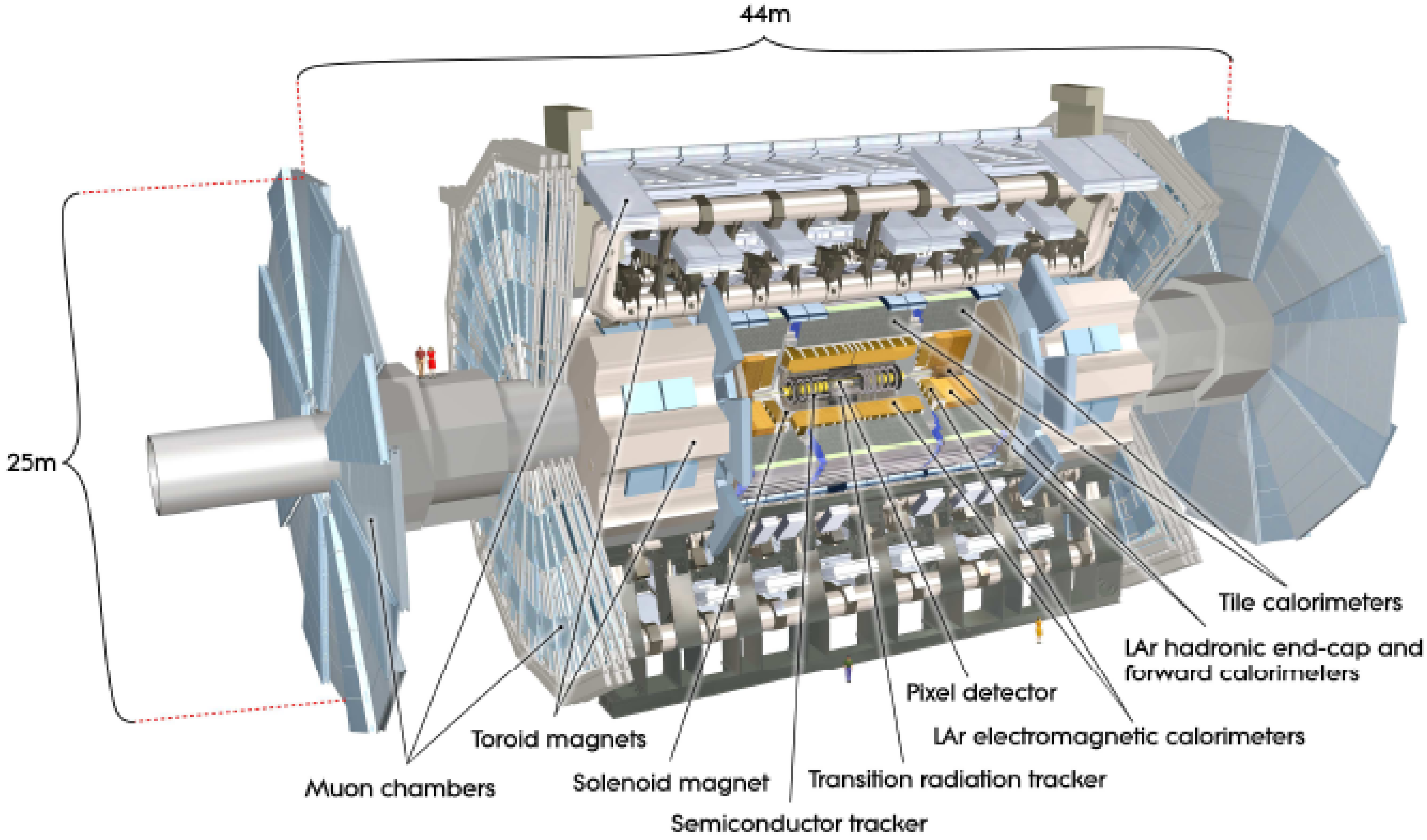
event with

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

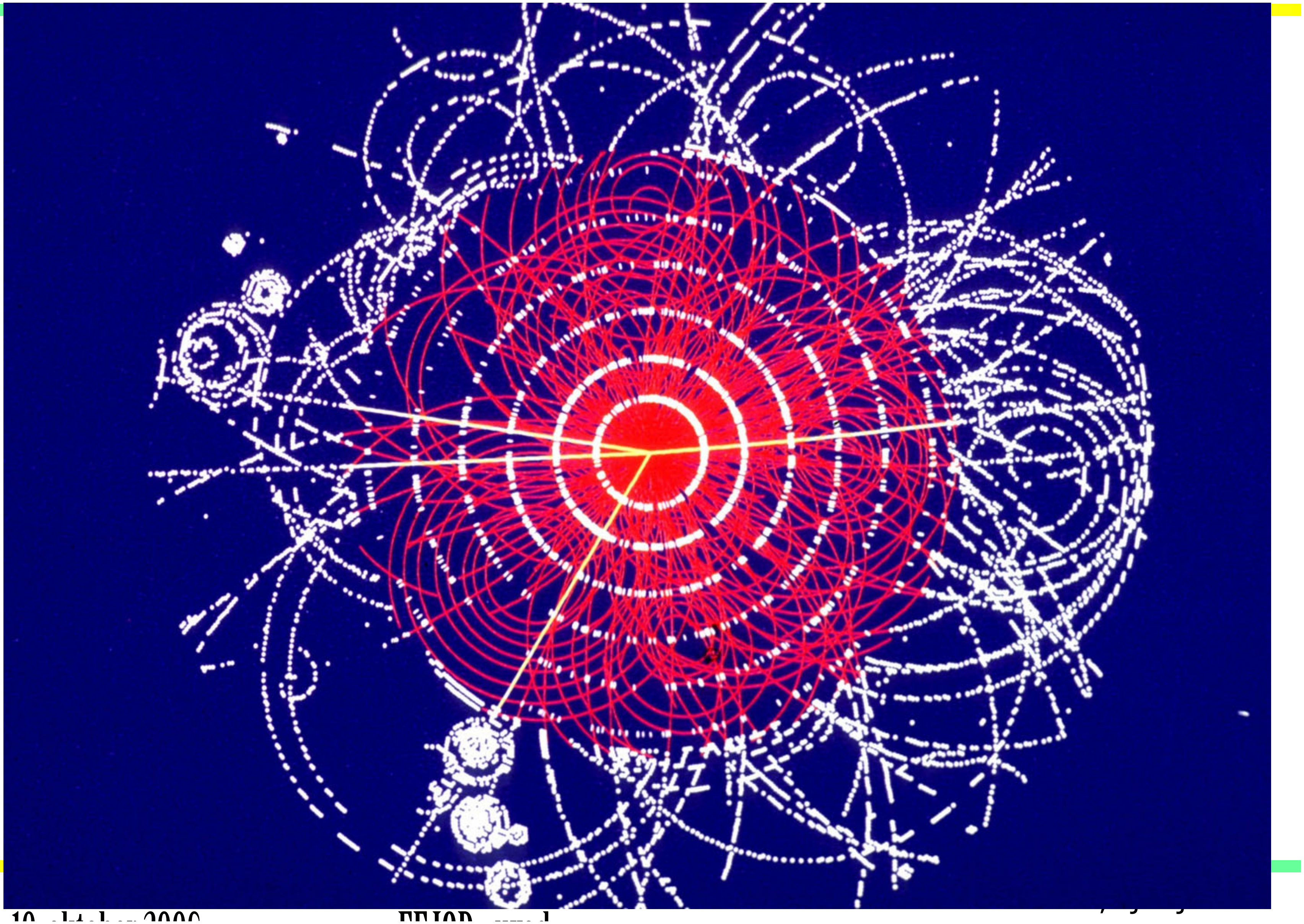
and a pion that partly penetrated



Identification of muons at LHC - example ATLAS



MC simulation: 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

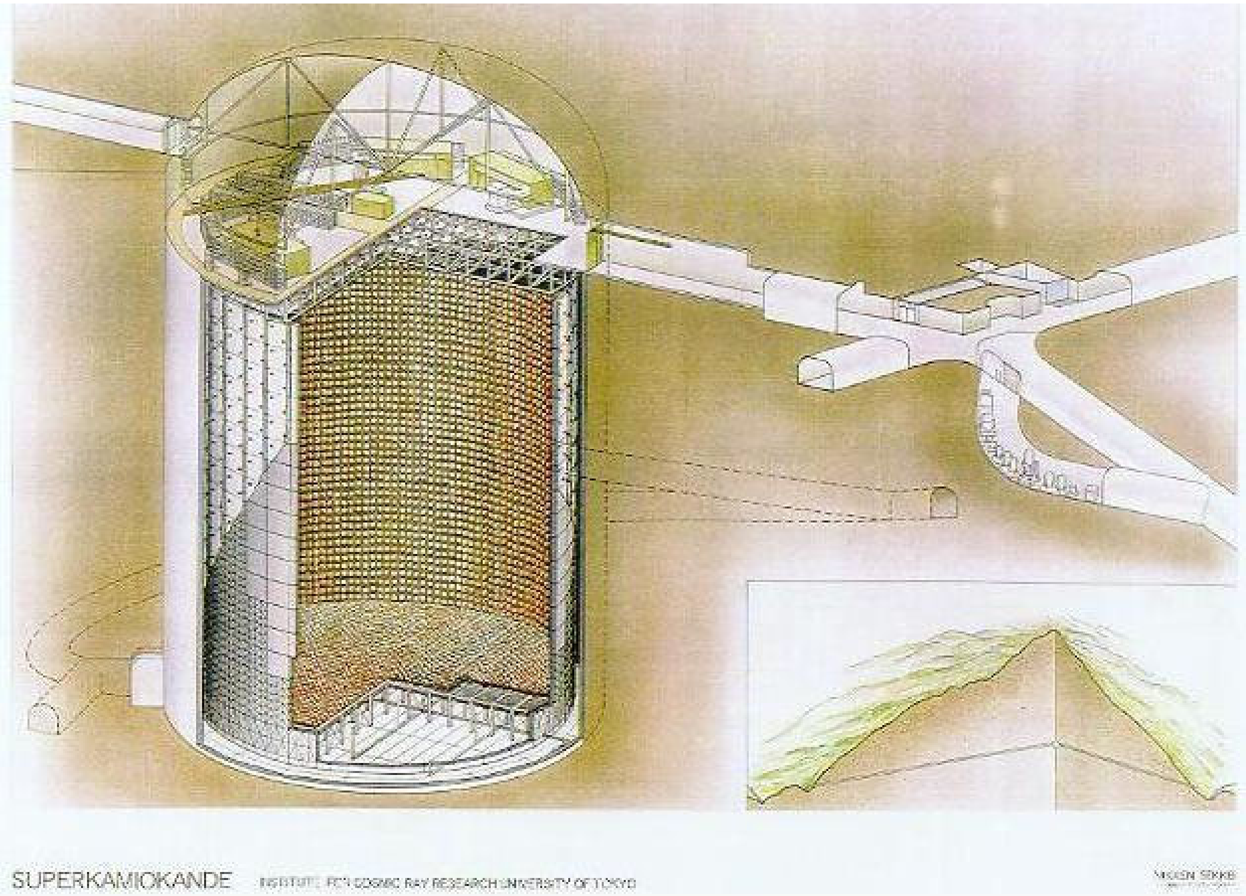
Probability for interaction in 100m of water = 4 10^{-16}

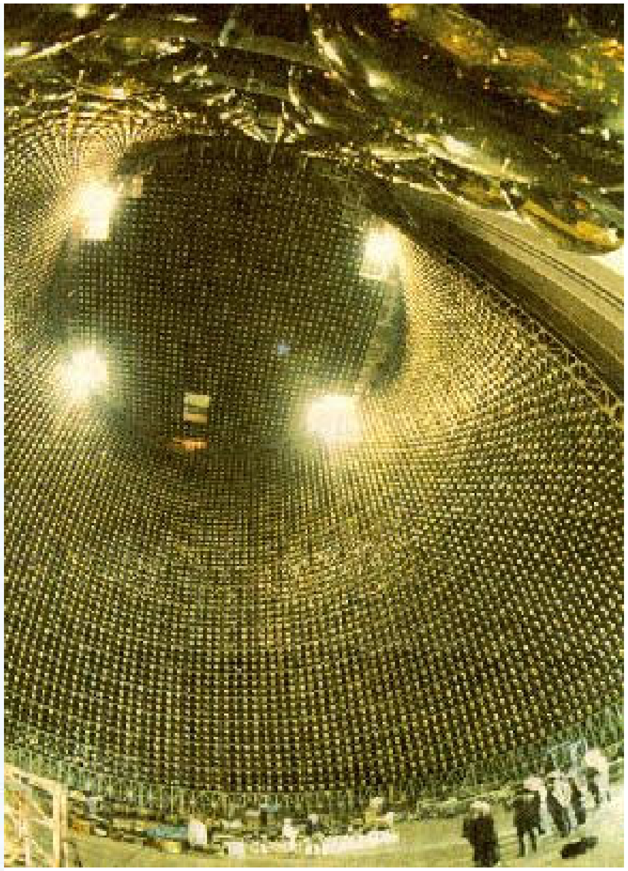
Not much better at high energies:

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

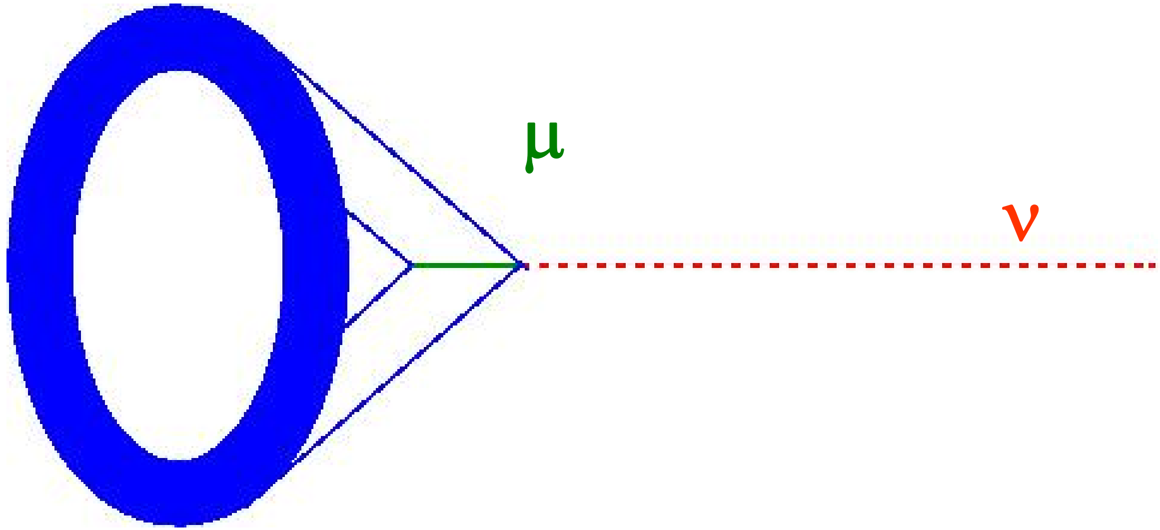
At 100 GeV, still 11 orders below the proton-proton cross section

Superkamiokande: an example of a neutrino detector





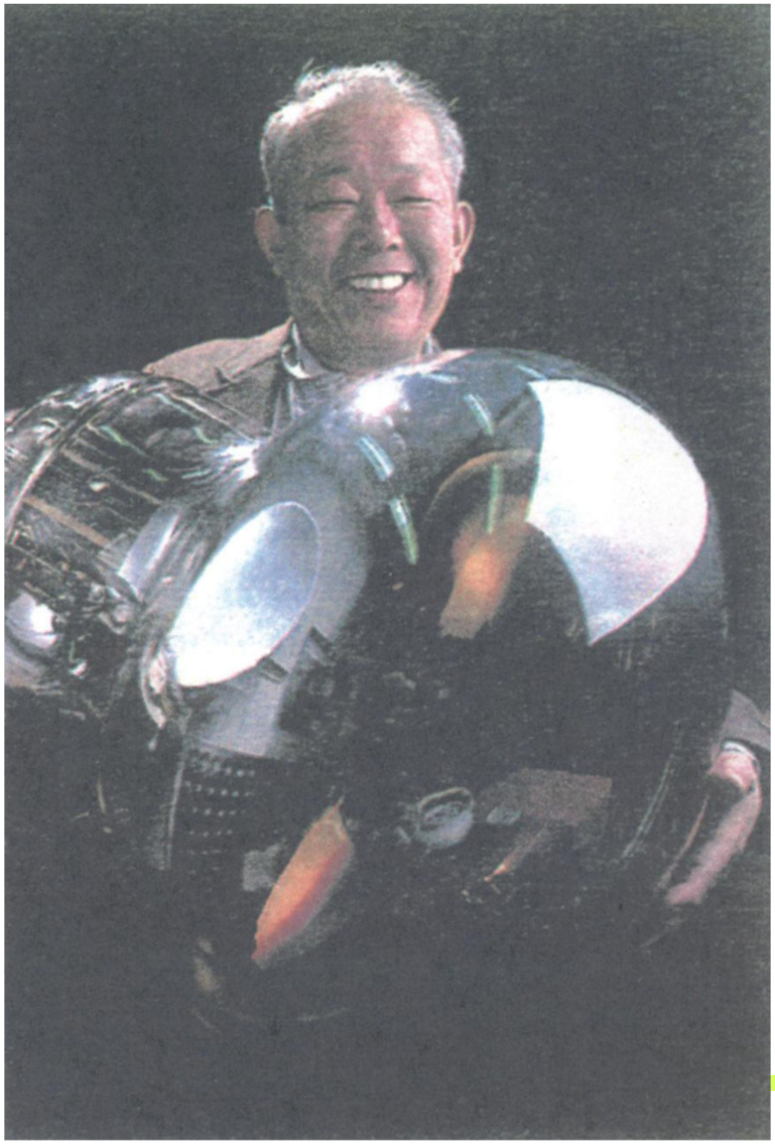
Superkamiokande: detection of electrons and muons



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

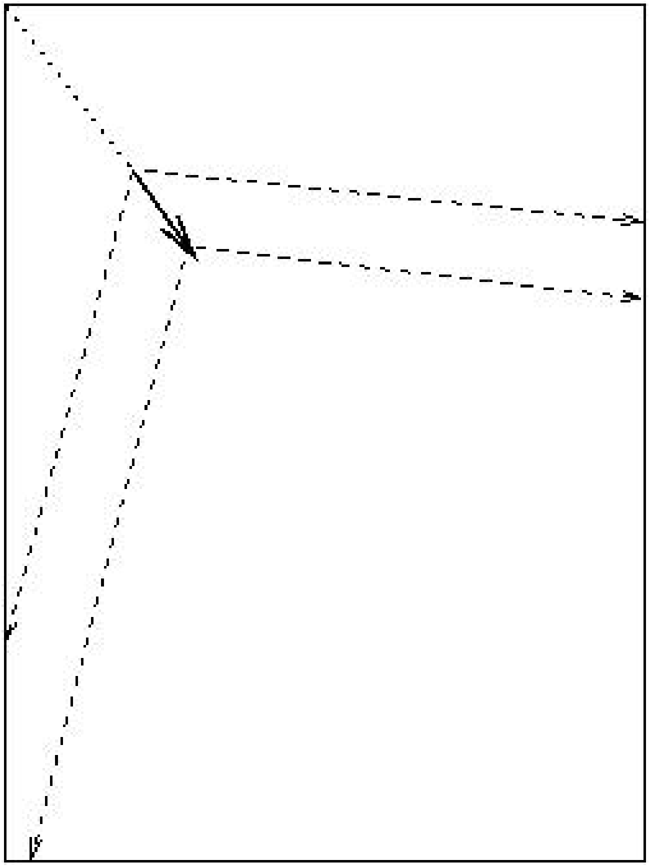
Muon vs electron

Cherenkov photons from a muon track:

Example: 1GeV muon neutrino

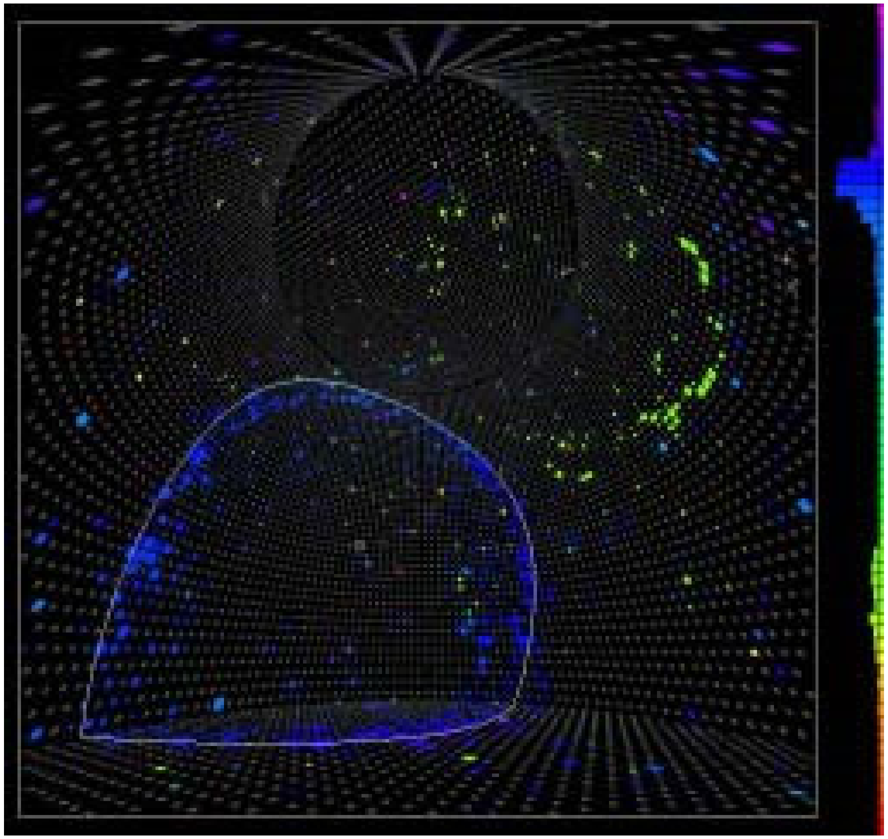
Track length of the resulting muon: L=E/(dE/dx)= =1GeV/(2MeV/cm)=5m

→ a well defined “ring” on the walls

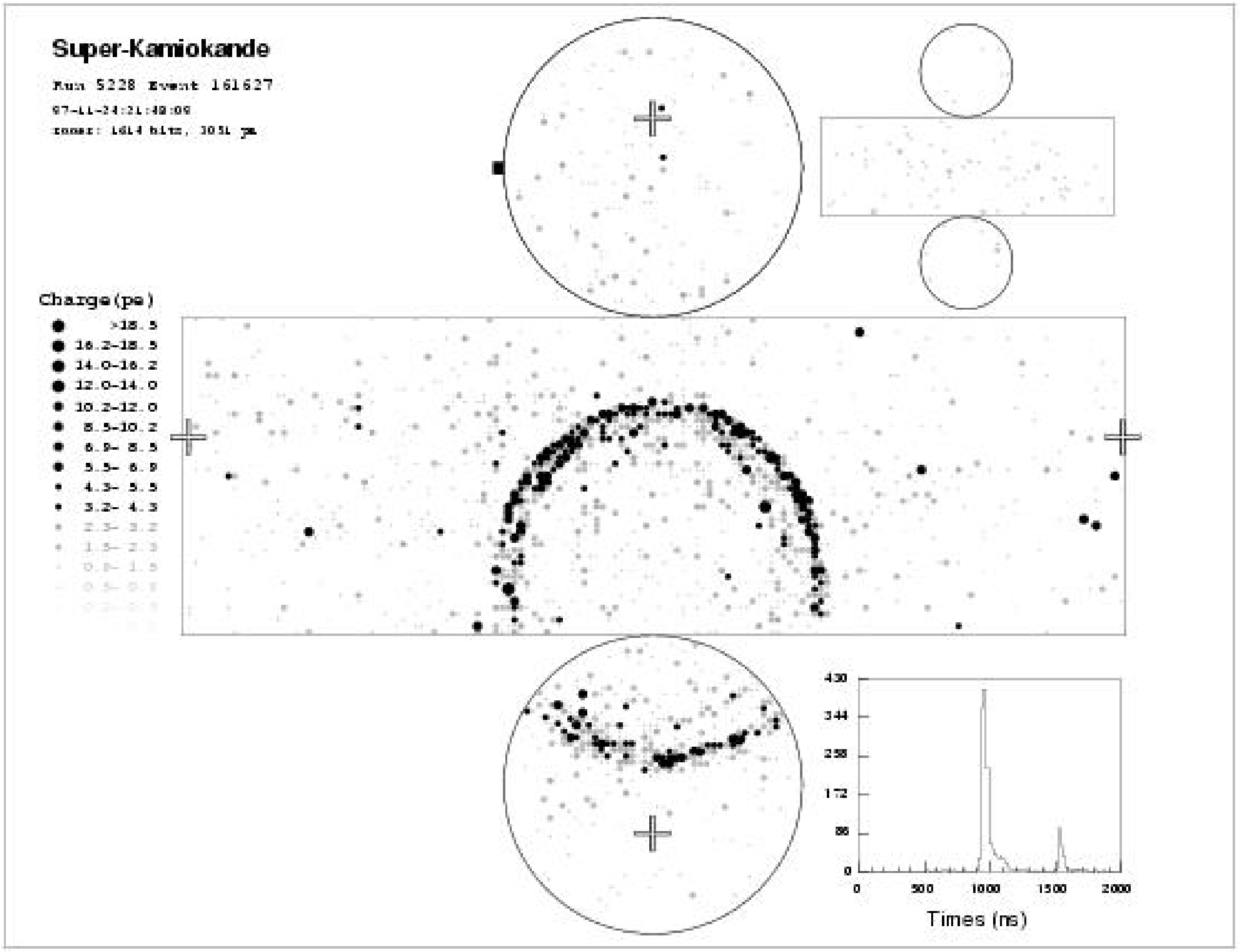


Superkamiokande: muon event

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 $(100\text{m})^3$ 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.

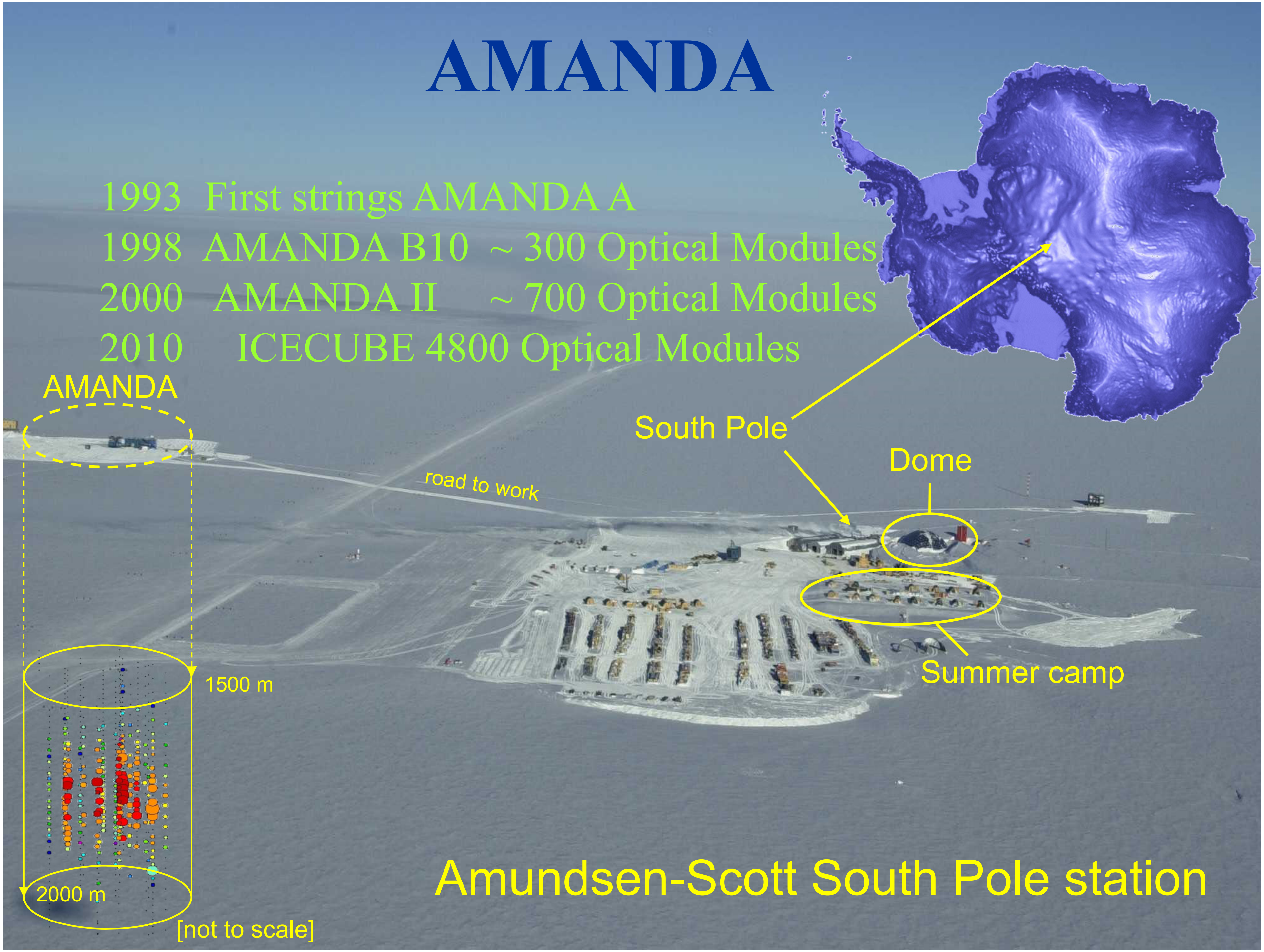
AMANDA

1993 First strings AMANDA A

1998 AMANDA B10 ~ 300 Optical Modules

2000 AMANDA II ~ 700 Optical Modules

2010 ICECUBE 4800 Optical Modules



Reconstruction of direction and energy of incident high energy muon netrino

For each event:

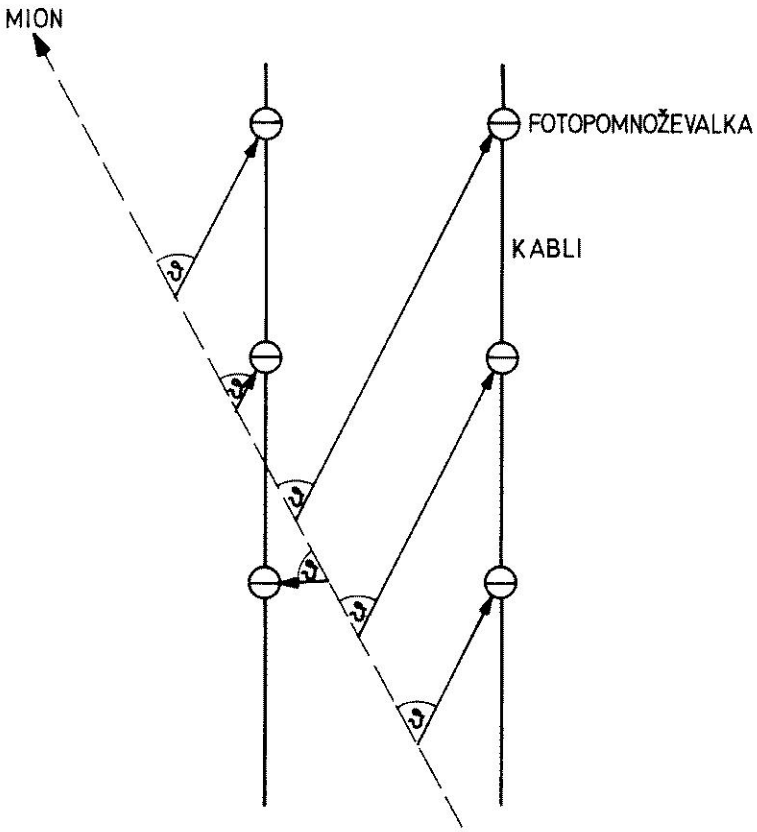
Measure time of arrival on each of the tubes

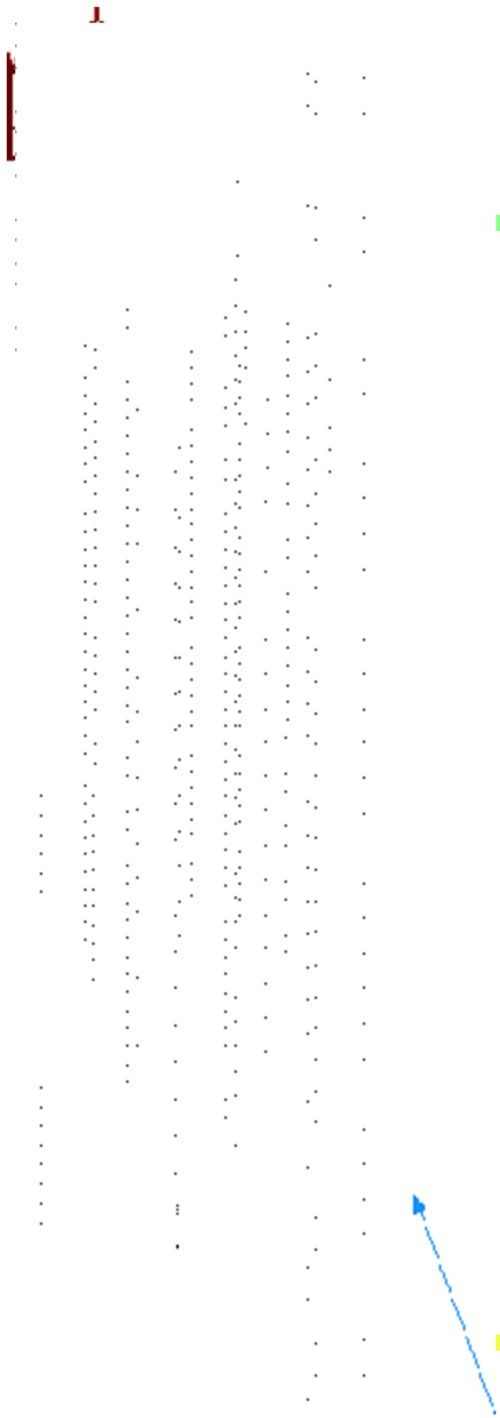
Cherenkov angle is known: $\cos\theta = 1/n$

Reconstruct muon track

Track direction -> neutrino direction

Track length -> neutrino energy





AMANDA

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

Detekcija kozmičnih delcev na balonu

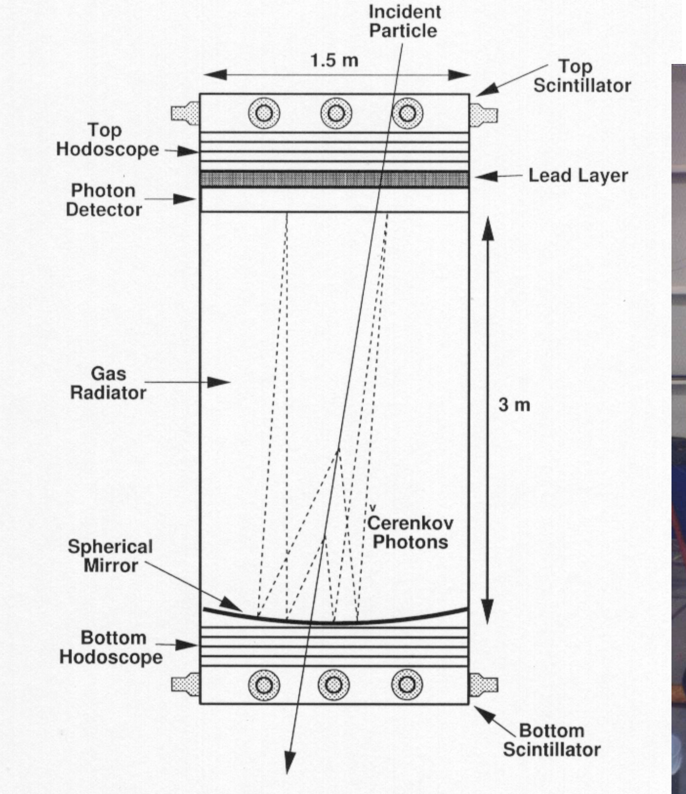
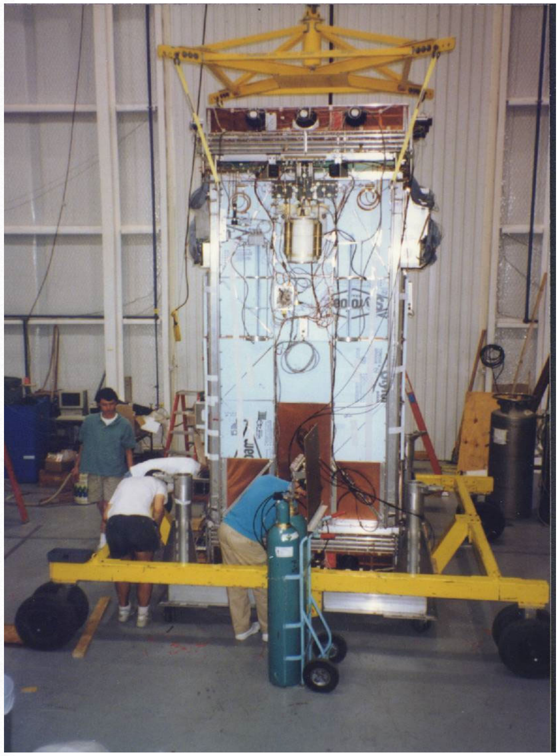
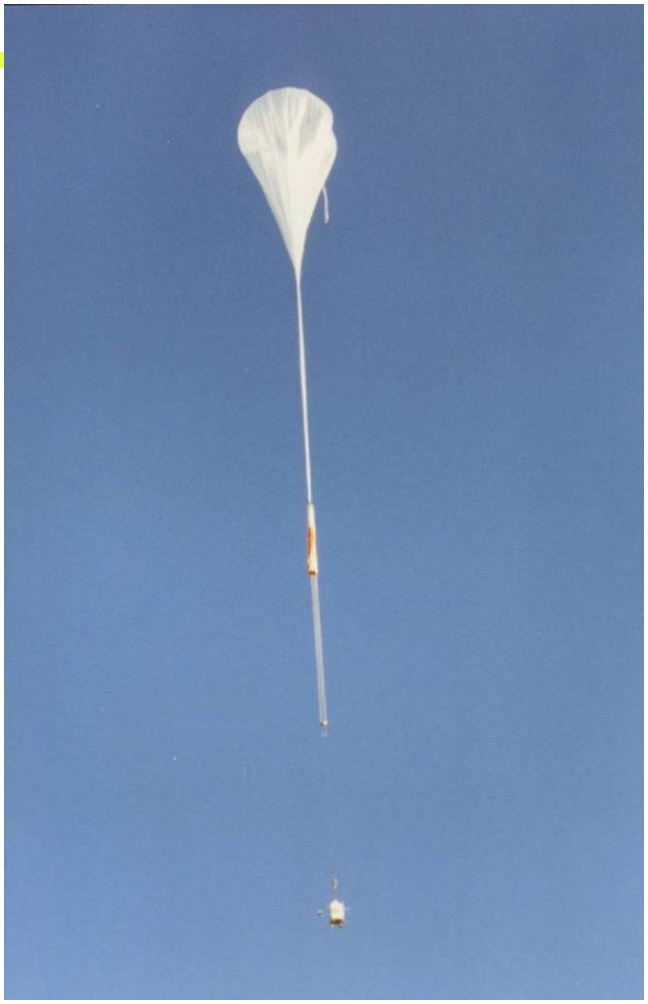
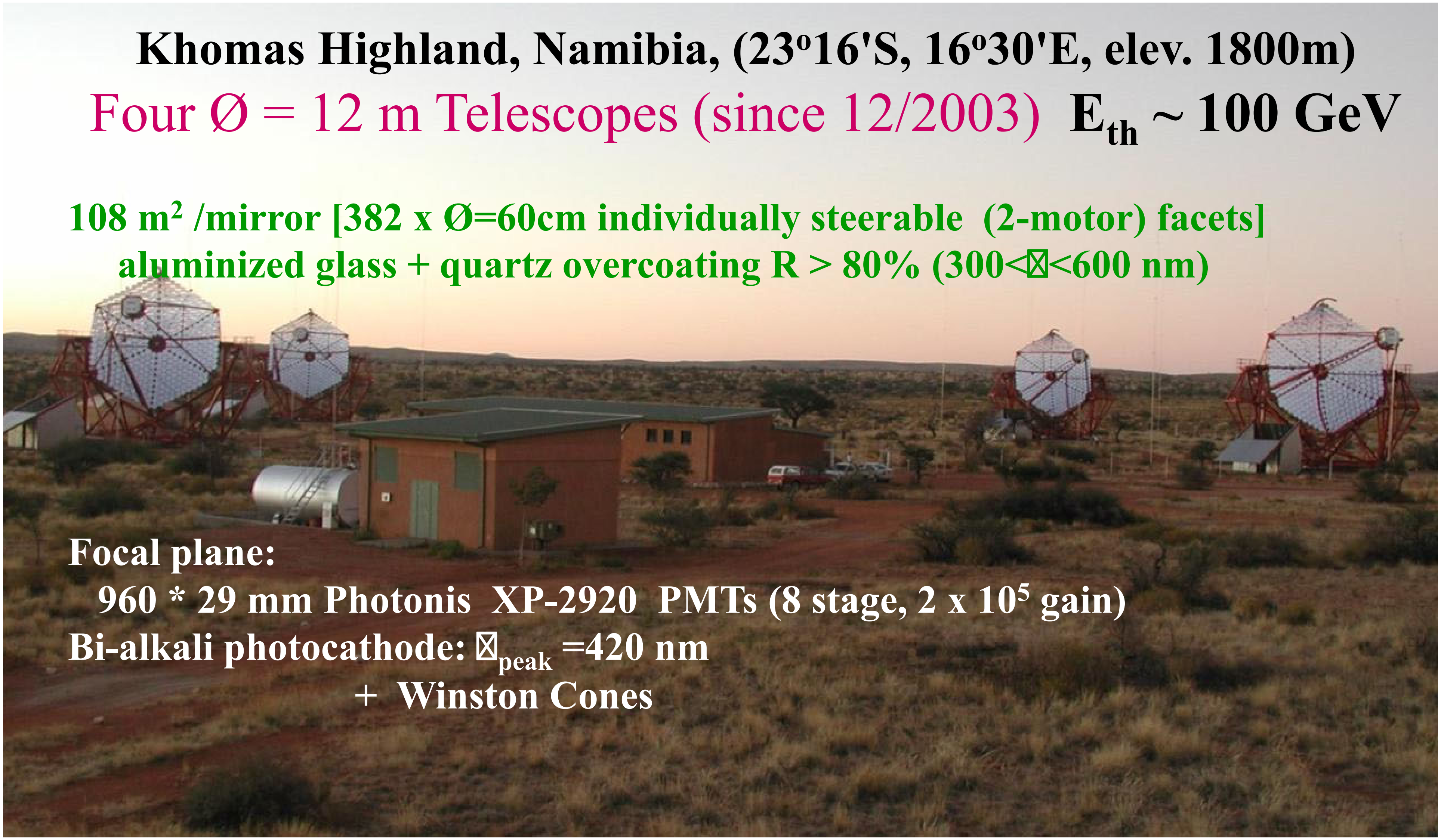


Fig. 1. Schematic cross-section of the instrument





HESS 1 UHE Gamma Ray Telescope Stereoscopic Quartet



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

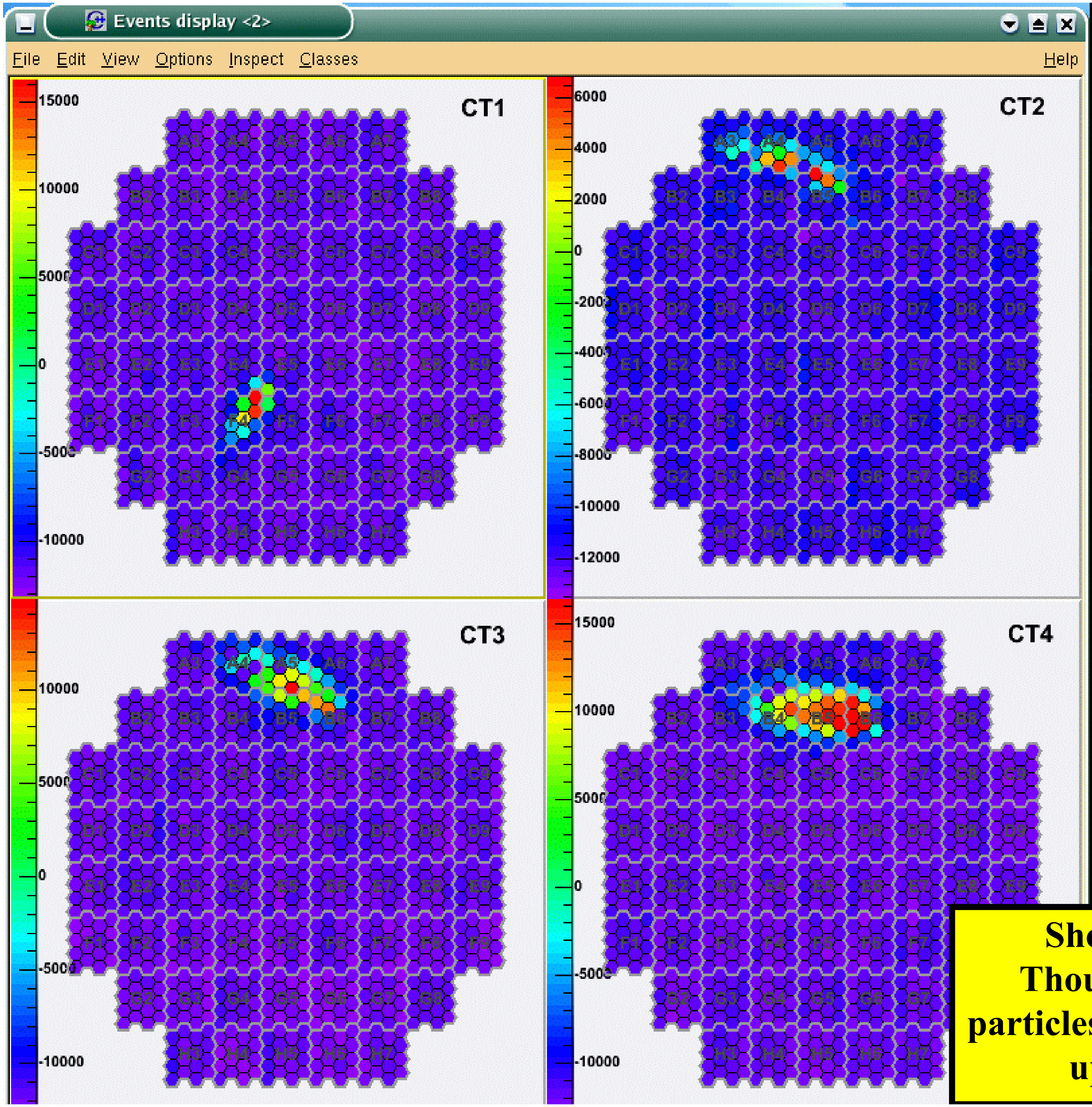
Four Ø = 12 m Telescopes (since 12/2003) **E_{th} ~ 100 GeV**

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

Focal plane:
960 * 29 mm Photonis XP-2920 PMTs (8 stage, 2 x 10^5 gain)
Bi-alkali photocathode: λ_{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**

Course overview

- Introduction
- Interactions of charged particles and photons with matter
- Ionisation detectors
- Scintillation detectors
- Semiconductor detectors
- Detection of neutrinos, neutrons and low energy γ rays
- Electronics
- DAQ
- Particle identification
- Measuring energy

Literatura

Web page of this course:

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

Slides can be found at

http://www-f9.ijs.si/~krizan/sola/efjod/slides

Vsebina predmeta

Interakcija nabitih delcev in fotonov s snovjo: interakcija težkih nabitih delcev, formula Betheja in Blocha, doseg, energijsko stresanje. Interakcija elektronov s snovjo, ustavljanje elektronov, zavorno sevanje. Večkratno sipanje. Interakcija visokoenergijskih fotonov s snovjo, fotoefekt, Comptonovo sipanje, tvorba parov. Razvoj elektromagnetnih pljuskov.

Ionizacijski detektorji v fiziki osn. delcev: večžične proporcionalne komore (načini odčitavanja signala, izkoristek, izbira plinske mešanice, delovanje pri velikih pogostostih štetja, staranje). Potovalne komore, komora s časovno projekcijo (TPC). Detekcija UV svetlobe, žarkov X in gama. Tekočinski ionizacijski detektorji.

Uporaba polvodniških detektorjev v fiziki osn. delcev, jedrski fiziki in astrofiziki: Pozicijsko-občutljivi silicijevi detektorji (konstrukcija in uporaba). Pixel detektorji, CCD senzorji. Detekcija žarkov X in gama. Sevalne poškodbe.

Scintilacijski detektorji: Kratka ponovitev osnovnih značilnosti (organski scintilatorji - kristali, tekočine, plastiki; anorganski kristali; plini in stekla). Izkoristek za različne vrste sevanja. Linearnost.

Detektorji svetlobe: Fotopomnoževalke, transport fotoelektronov, sekundarni elektroni. Mikrokanalne plošče, razvoj signala, delovanje v močnih magnetnih poljih. Polvodniški detektorji svetlobe (fotodiode, plazovne fotodiode, silicijeve fotopomnoževalke).

Vsebina predmeta 2. del

Elektronska obdelava signalov: Formiranje signala v različnih vrstah detektorjev. Pretvorba v napetostni signal. Šum. Nabojno občutljivi predojačevalec. Oblikovanje sunkov. Izražanje signalov z elementarnimi funkcijami, razsežnost signala. Kategorizacija signalov.

Identifikacija delcev v eksperimentalni fiziki jedra in fiziki osnovnih delcev: Meritev časa preleta. Meritev dE/dx pri nizkih energijah. Večkratno merjenje specifične ionizacije. Števci Čerenkova: pragovni detektor, detektor obročev Čerenkova (RICH). Prehodno sevanje. Detekcija nevtronov in nevtrinov.

Merjenje energij: Elektromagnetni kalorimetri. Hadronski kalorimetri. Umerjanje in kontrola kalorimetrov.

Temeljna literatura

1. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer Verlag, Berlin 1994.
2. H. Kolanoski, N. Wermes, Particle Detectors, Oxford 2021.
3. Handbook of Particle Detection and Imaging, edited by Claus Grupen, Irène Buvat, Springer Verlag, Berlin/Heidelberg 2012
4. G.F. Knoll, Radiation Detection and Measurement, J. Wiley, New York 1979.
5. F. Sauli (editor), Instrumentation in High Energy Physics, World Scientic 1992.
6. K. Kleinknecht, Detectors for Particle Radiation, Cambridge University Press 1987.
7. P. Horowitz, W. Hill, The Art of Electronics, Cambridge University Press 1996.

Pogoji

Obisk predavanj in vaj, pisni izpit, ustni izpit.

Literatura po poglavjih

http://www-f9.ijs.si/~krizan/sola/efjod/literatura.txt

Prehod nabitih delcev in fotonov skozi snov

1. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Berlin; poglavje: Passage of Radiation Through Matter

Ionizacijski detektorji

1. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Berlin; poglavje: Ionization Detectors

Scintilacijski detektorji

1. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Berlin; tri poglavja: Scintillation Detectors, Photomultipliers, Scintillation Detector Mounting and Operation

Polprevodniški detektorji

1. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Berlin; poglavje: Semiconductor Detectors

Literatura po poglavjih

http://www-f9.ijs.si/~krizan/sola/efjod/literatura.txt

Detekcija nevtronov, nevtrinov in žarkov gama

1. K. Kleinknecht, Detectors for Particle Radiation, Cambridge University Press; podpoglavje Neutron Counters v poglavju Particle identification.
2. W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag, Berlin; razstreseno po poglavjih Passage of Radiation Through Matter, Ionization Detectors, Scintillation Detectors

Identifikacija nabitih delcev

1. K. Kleinknecht, Detectors for Particle Radiation, Cambridge University Press; poglavje Particle identification v kombinaciji s prosojnicami.

Merjenje energije

1. K. Kleinknecht, Detectors for Particle Radiation, Cambridge University Press; poglavje Measurement of Energy

Vsa poglavja (in še več) pokriva H. Kolanoski, N. Wermes, Particle Detectors

Literatura po poglavjih

http://www-f9.ijs.si/~krizan/sola/efjod/literatura.txt

Dodatno čtivo:

1. C. Grupen, B. Shwartz, Particle Detectors, Cambridge University Press, 2008. (zamenjava za Kleinknechta)
2. Handbook of Particle Detection and Imaging, Volume 1 and 2,

edited by Claus Grupen, Irène Buvat. Poglavja so prispevali vrhunski strokovnjaki s posameznih področij.

3. T. Ferbel (editor), Experimental Techniques in High-Energy Nuclear and Particle Physics, 2nd Edition, World Scientic 1991.
4. F. Sauli (editor), Instrumentation in High Energy Physics,

World Scientic 1992.

5. G.F. Knoll, Radiation Detection and Measurement, J. Wiley, New York 1979.
6. P. Horowitz, W. Hill, The Art of Electronics, Cambridge University Press 1996.
7. H. Wiedermann, Particle Accelerator Physics, Springer-Verlag 1993.
8. K.G. Stephen, High Energy Beam Optics, Interscience Publishers 1996.

7\. G. Cowan, Statistical Data Analysis, Oxford University Press, 1998.

Literatura, širši seznam

Books

- H. Kolanoski, N. Wermes, Particle Detectors, Oxford 2021.
- 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 (2020, 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)

Pogoji

- Pisni izpit
- Ustni izpit