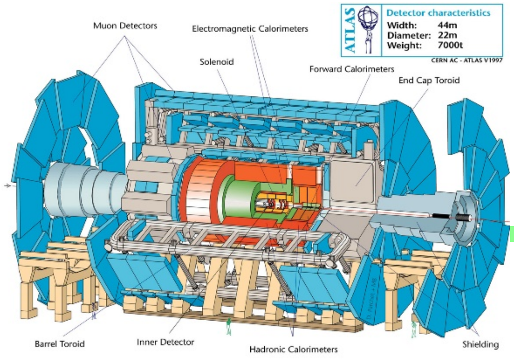
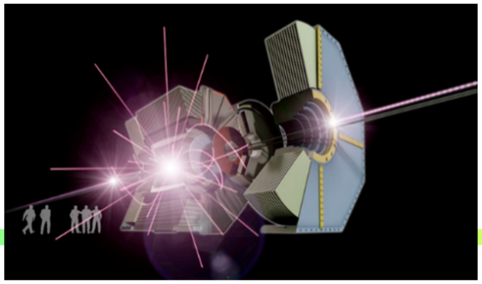
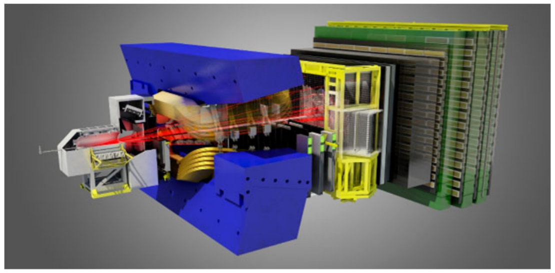
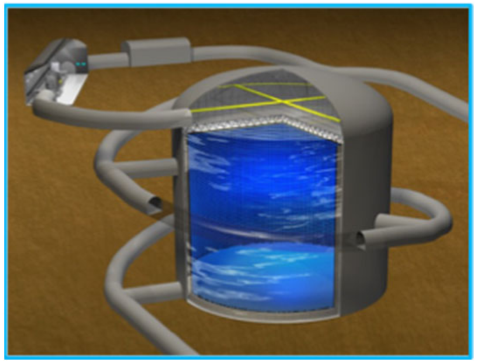








2nd JENNIFER2 SUMMER SCHOOL
ON PARTICLE PHYSICS AND DETECTORS
19 - 27 July 2021 virtual attendance

SCIENTIFIC PROGRAM
Heavy flavour and neutrino physics
Accelerator and detector physics
Statistics and machine learning
Hands-on sessions and virtual tours
Optional follow-up mentorship

Organizing committee

Z. Dolezal (Prague), T. Kobayashi (KEK), T. Matsubara (KEK),
R. Ota (KEK), A. Passeri (INFN), K. Sakashita (KEK),
F. Sanchez (Geneva), A. Soffer (Tel Aviv), S. Uno (KEK)

Students from any country with 3 – 4.5 years of university physics education are invited to apply at https://indico.belle2.org/event/4071/
Application deadline: **31 May 2021**
Contact: **jennifer2-school@ml.post.kek.jp**

JENNIFER²
G.A. 822070

Particle Detectors – part 2

Peter Križan

University of Ljubljana and J. Stefan Institute

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
- Detect neutral hadrons

- Combine final state particles to form intermediate states that decayed too quickly to be directly detected

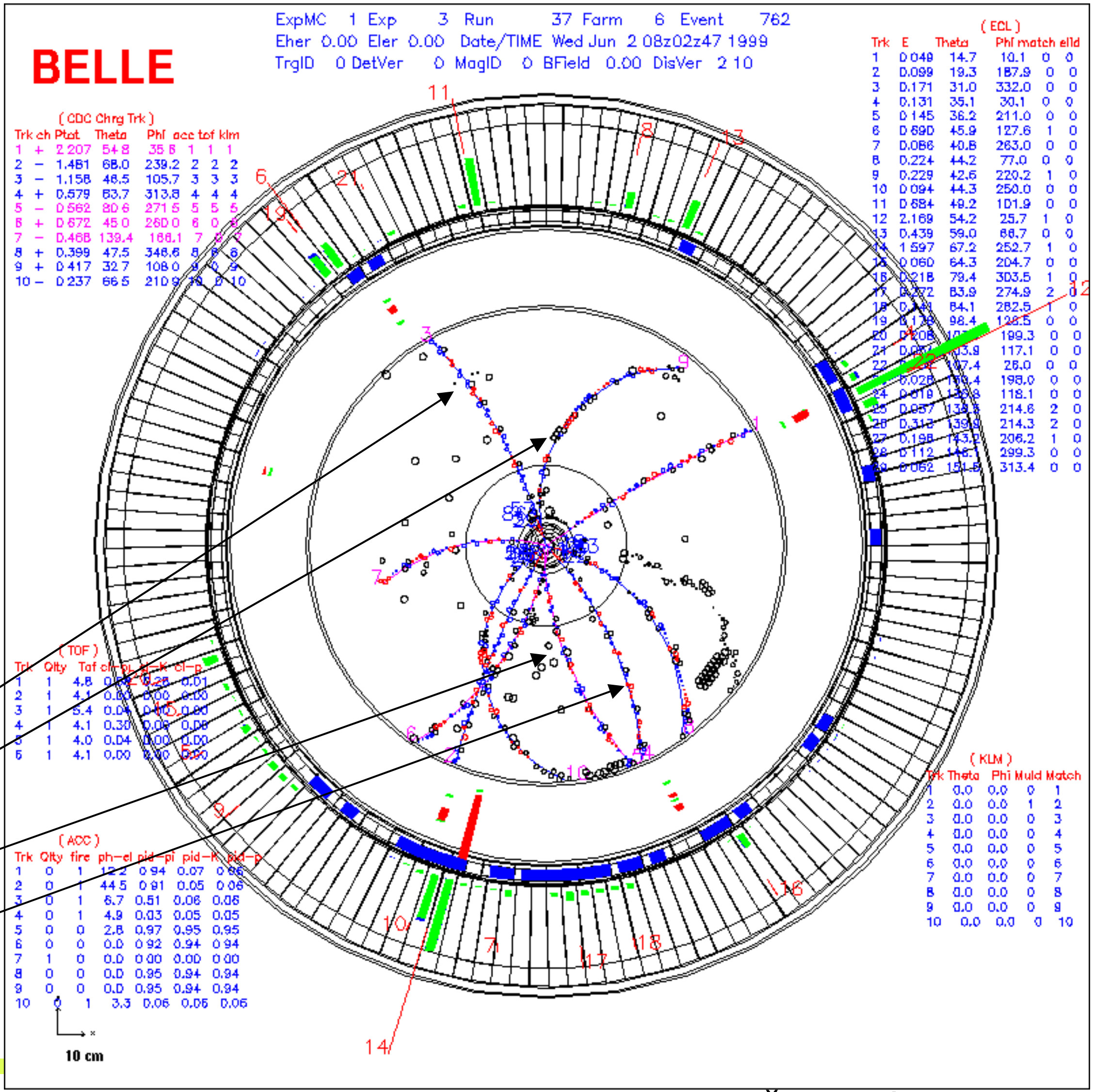
How to understand what happened in a collision?

Illustration on an example:

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

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

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



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	46.5	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	0.066	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	68.7	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	[illegible]	103.9	117.1	0	0
22	[illegible]	107.4	26.0	0	0
[illegible]	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	151.6	313.4	0	0

(TOF)

Trk	Qlty	Tof	cl-pi	cl-K	cl-p
1	1	4.8	0.5?	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	0.00	0.00
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 that decayed close to the production point

How do we reconstruct reaction products that decayed to several stable particles (e.g., 1, 2, 3)?

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

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

The candidates for the X→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?

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

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

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

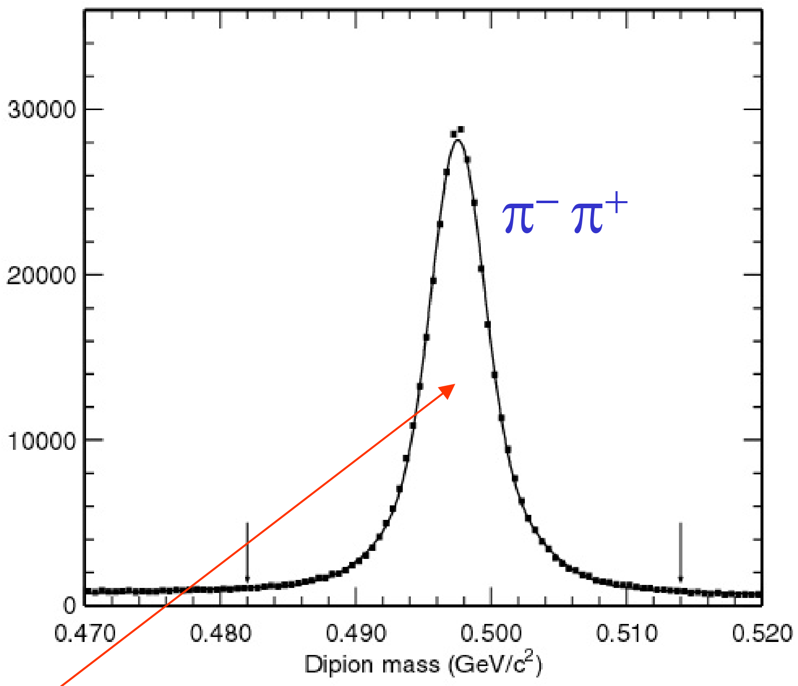
detect ←

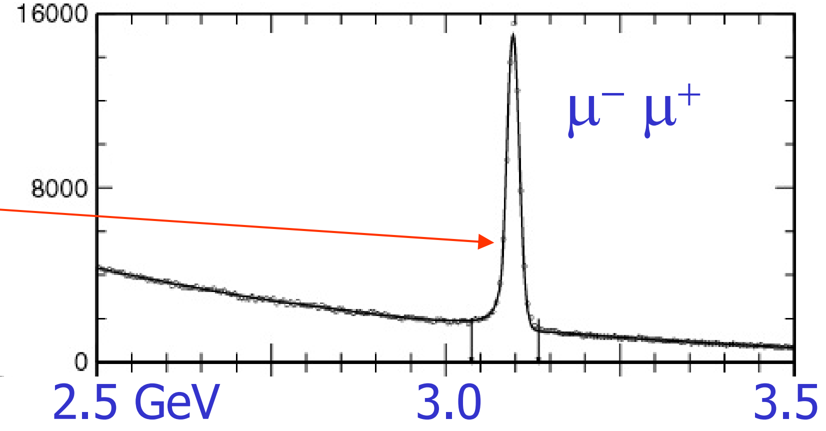
For $\pi^- \pi^+$ in $\mu^- \mu^+$ pairs we calculate the invariant mass:

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

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’)





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).

Components of an experimental apparatus (‘spectrometer’)

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

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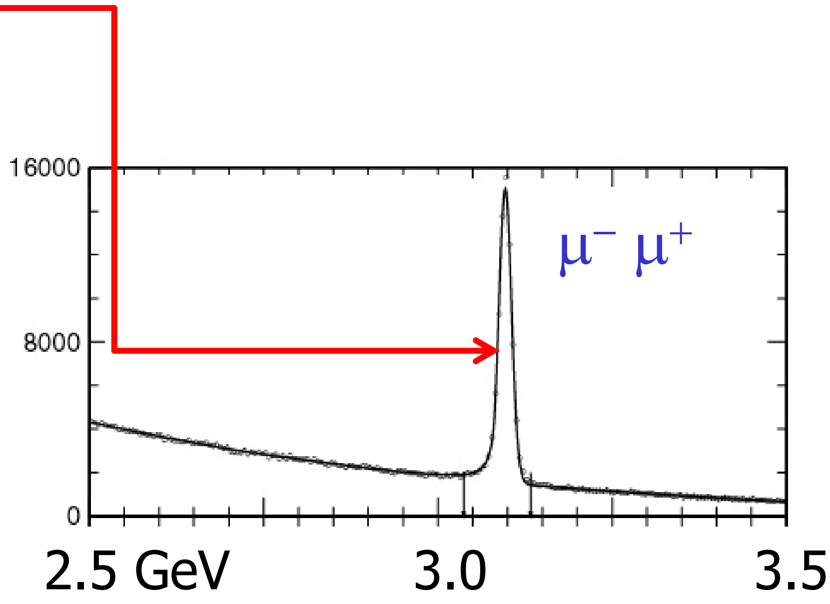
Resolution in invariant mass

$B^0 \rightarrow K^0_S\, J/\psi$, $K^0_S \rightarrow \pi^- \pi^+$, $J/\psi \rightarrow \mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2 \rightarrow M^2c^4 = 2\, p_1 p_2 c^2 (1 - \cos\Theta_{12})$ $(p \gg m_\mu c)$

The J/ψ peak should be narrow to minimize the contribution of random coincidences (‘combinatorial background’) under the peak.

The required resolution in Mc^2: about 10 MeV.



What is the corresponding momentum resolution?

For simplicity assume J/ψ is at rest →
$\Theta_{12}=180^0$, $p_1=p_2=p=1.5$ GeV/c, $Mc^2=2pc$
→ $\sigma(Mc^2) = 2\,\sigma(pc)$ at $p=1.5$ GeV/c

→ $\sigma(p)/p$ = 10 MeV/2/1.5GeV = 0.3%

Momentum resolution

Tracking system uncertainty

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

For N measurements along the track of length L, each with a precision of σ_x , in a magnetic field B

Uncertainty from multiple scattering

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{eB\sqrt{LX_0}}$$

In a detector with an average radiation length X_0

Combined

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{tracking} + \left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{msc}}$$

Momentum resolution - example

For B = 1.5T, L = 1m, N = 50, σ_x = 100 μm, X_0 = 100m

Tracking system uncertainty

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

$$\frac{\sigma_{p_T}}{p_T} = p_T \frac{0.1\times10^{-3}m}{0.3(GeV/m)\times1.5\times1m^2}\sqrt{\frac{720}{54}} = \frac{p_T\times0.0008}{GeV}$$

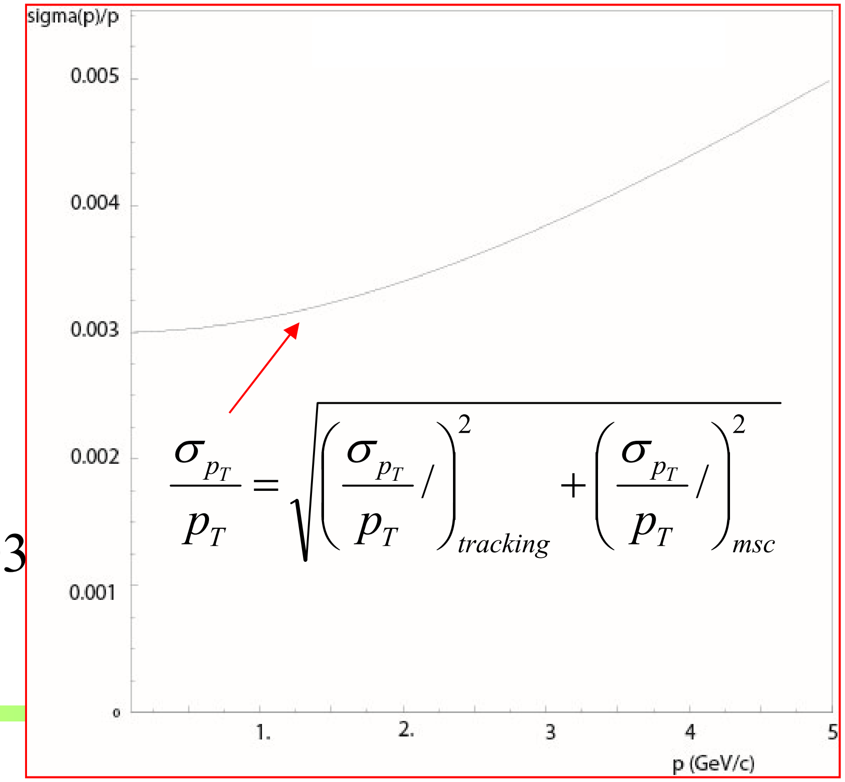
For p_T = 1 GeV: σ_{pT}/p_T = 0.08%

For p_T = 2 GeV: σ_{pT}/p_T = 0.16%

Uncertainty from multiple scattering

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{eB\sqrt{LX_0}}$$

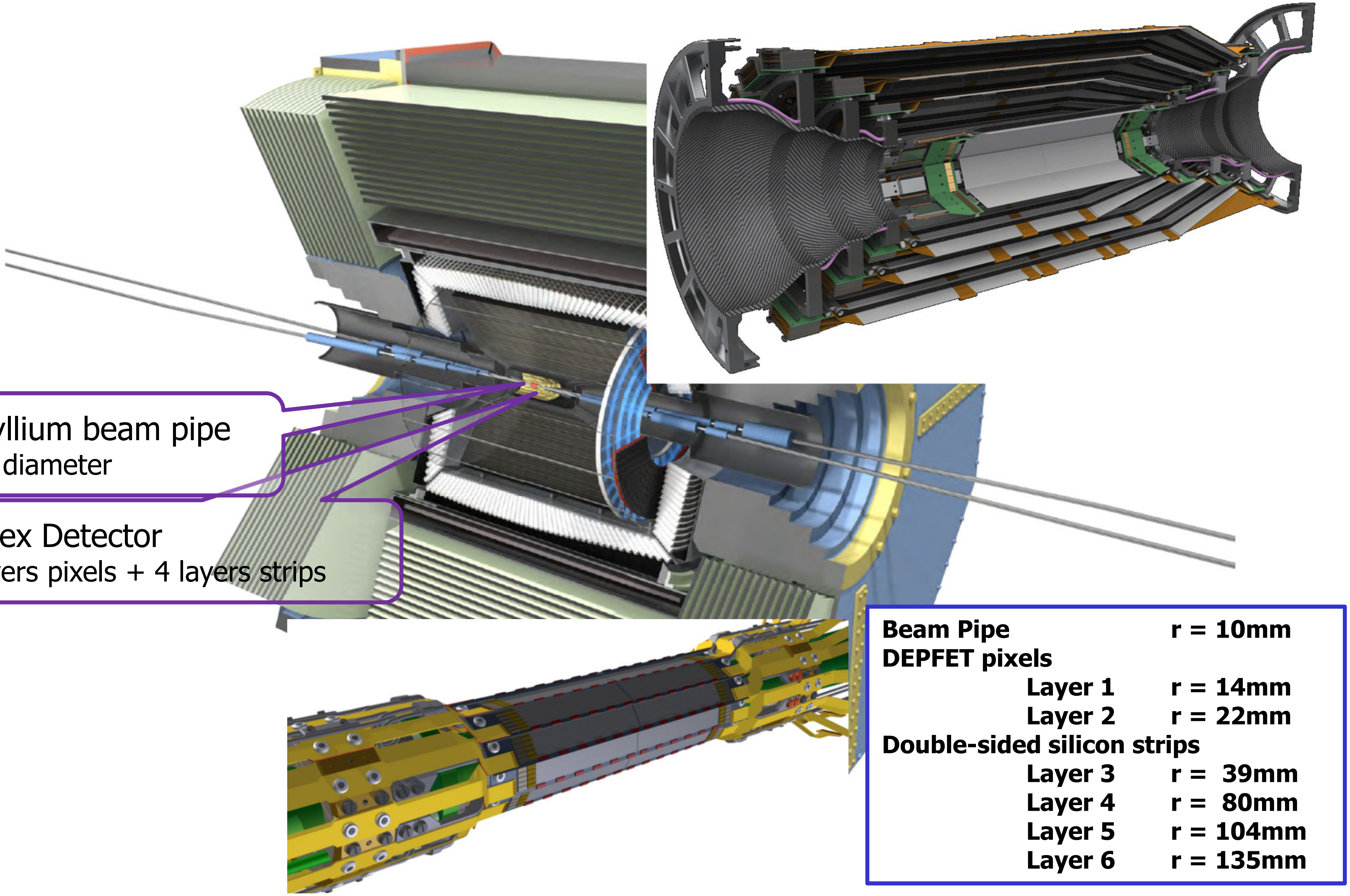
$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{0.3(GeV/m)\times1.5\sqrt{1m\times100m}} = 0.003$$



$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{tracking} + \left(\frac{\sigma_{p_T}}{p_T}/\right)^2_{msc}}$$

N.B. *eB* = 0.3 (B/T) (1/m) GeV/c

Belle II Detector – vertex region



Beryllium beam pipe
2cm diameter

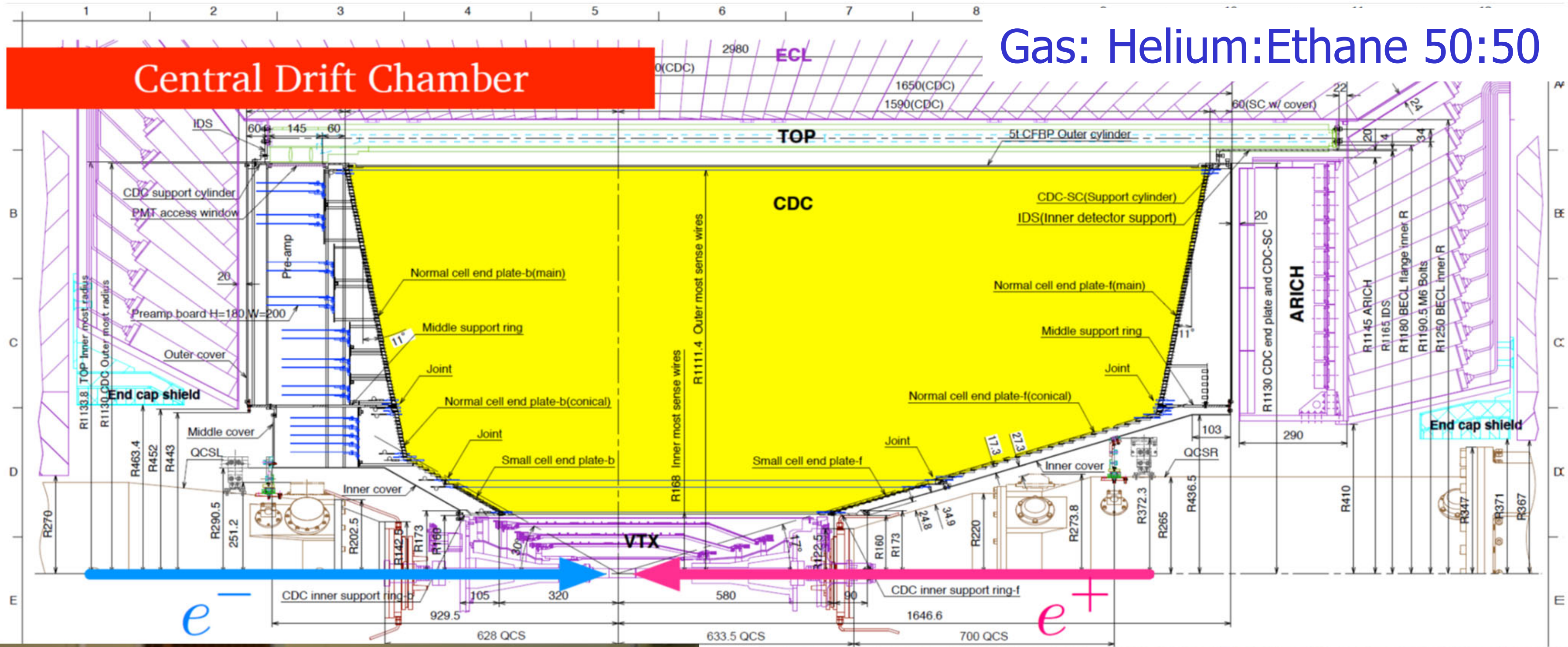
Vertex Detector
2 layers pixels + 4 layers strips

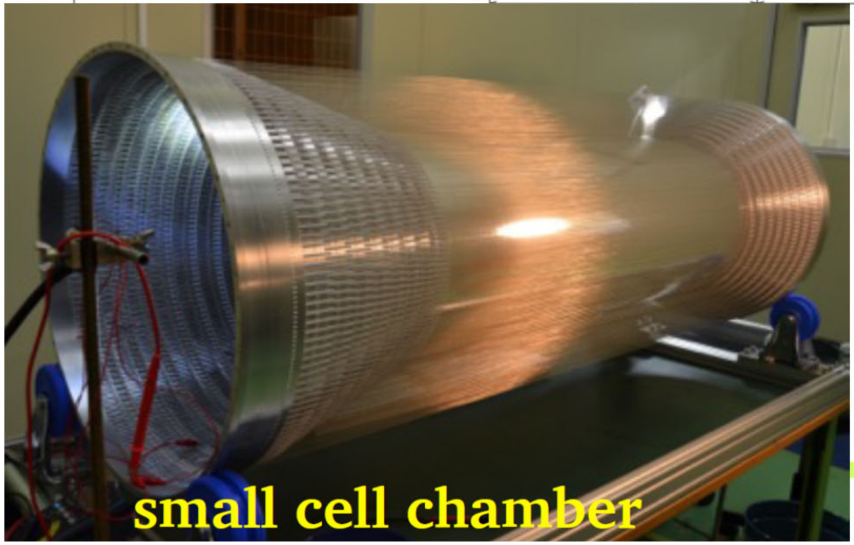
Beam Pipe		**r = 10mm**
DEPFET pixels		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
Double-sided silicon strips		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 104mm**
	Layer 6	**r = 135mm**

Belle II central drift chamber

Central Drift Chamber

Gas: Helium:Ethane 50:50

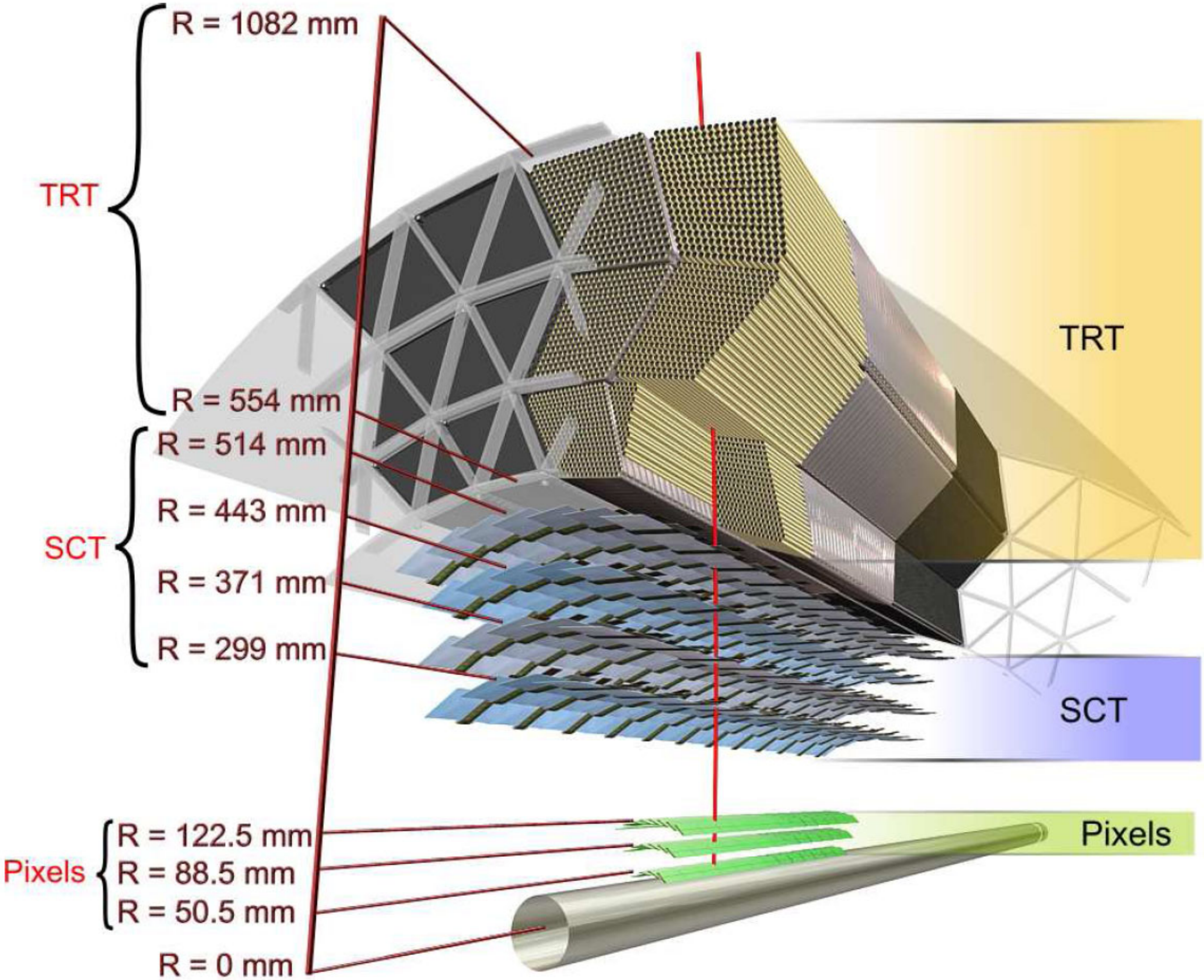




small cell chamber

ATLAS

Tracking system of the inner detector



straw tubes

silicon strip detectors

pixel detectors

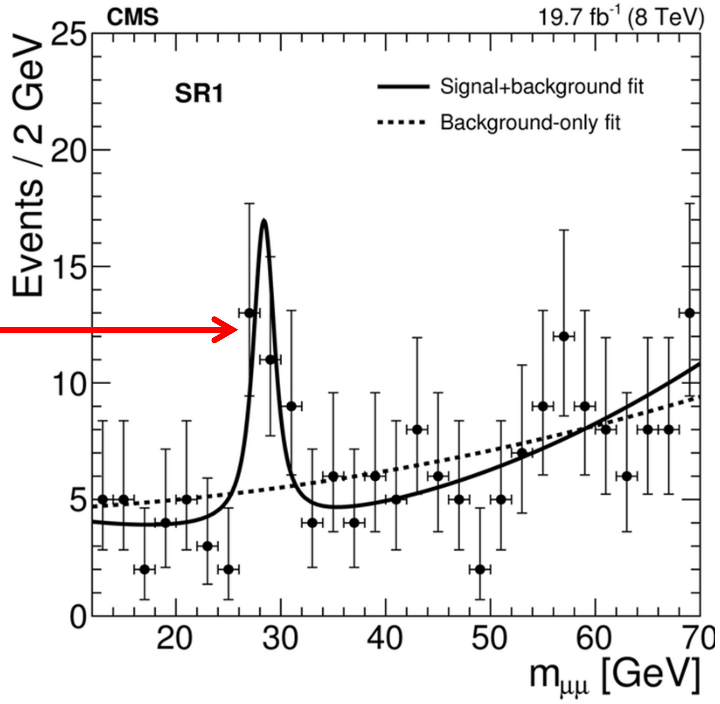
What kind of momentum resolution do we need?

Reminder: example: we are looking for an unknown particle X, X → $\mu^- \mu^+$

$M^2c^4 = (E_1 + E_2)^2 - (p_1 + p_2)^2 \rightarrow M^2c^4 = 2\, p_1\, p_2\, (1 - \cos\Theta_{12})$

The X peak should be narrow to minimize the contribution of random coincidences ('combinatorial background')

The required resolution in Mc^2: about 1 GeV at 30 GeV.



CMS could-be-particle (turned out to be a statistical fluctuation...)

What is the corresponding momentum resolution?

For simplicity assume X is at rest →
$\Theta_{12}=180^0$, $p_1=p_2=p=15$ GeV/c, $Mc^2=2pc$
→$\sigma(Mc^2) = 2\, \sigma(pc)$ at $p=15$ GeV/c

→ $\sigma(p)/p = 1\,\text{GeV}/2/15\text{GeV} = 3\%$

Momentum resolution

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_x p_T}{eBL^2}\sqrt{\frac{720}{N+4}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{13.6MeV}{eB\sqrt{LX_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = p_T \frac{0.1\times 10^{-3} m}{0.3(GeV/m)\times 2\times 1m^2}\sqrt{\frac{720}{54}} = p_T \times 0.0006$$

eB = 0.3 (B/T) (1/m) GeV/c

For B=2T, L = 1m, σ_x = 0.1 mm

For p_T = 1 GeV: σ_{pT}/p_T = 0.06%

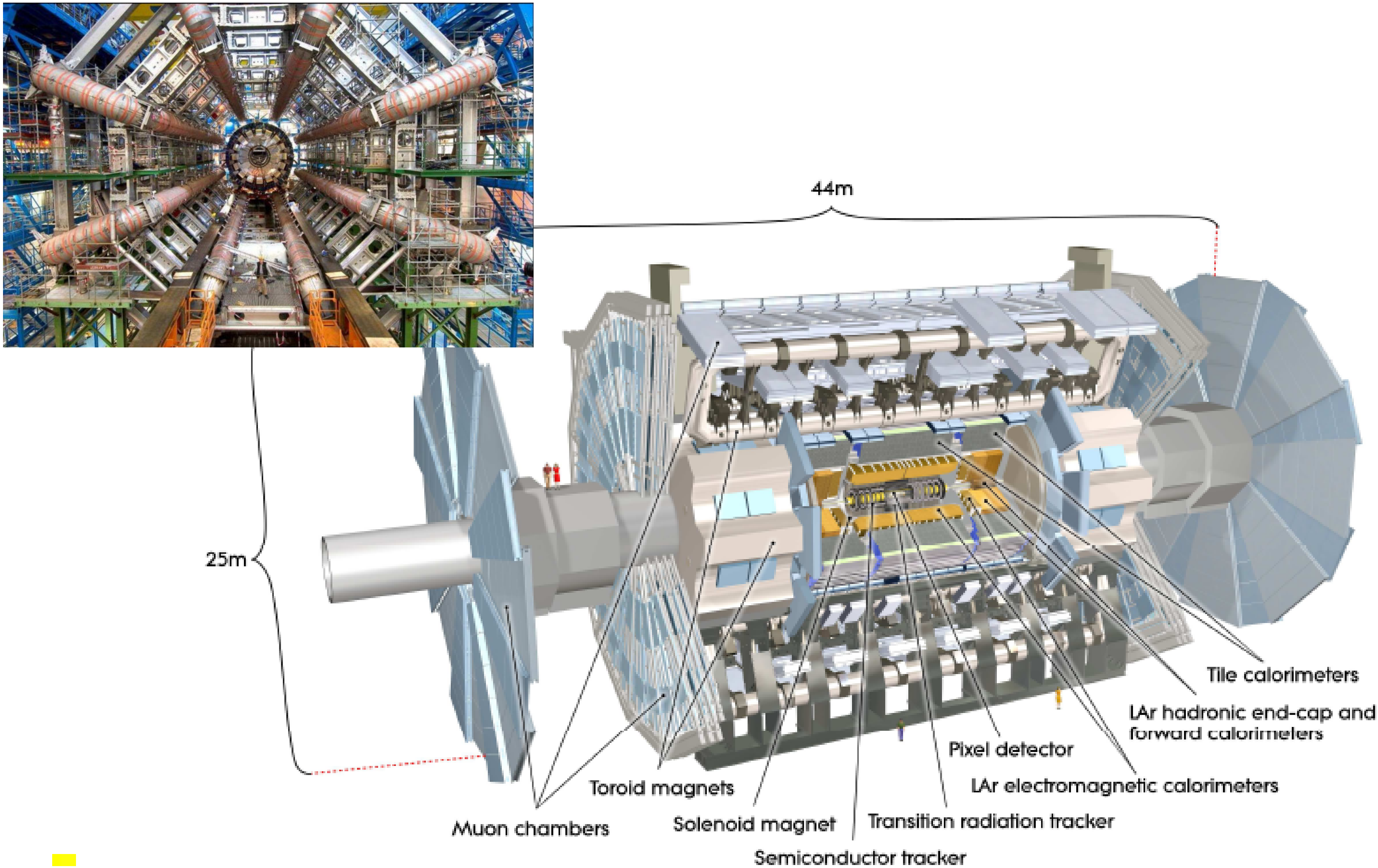
For p_T = 10 GeV: σ_{pT}/p_T = 0.6%

For p_T = 100 GeV: σ_{pT}/p_T = 6%

How to improve high momentum resolution?

- Better resolution: wire chamber → silicon strip detector (full CMS tracker, partly ATLAS)
- Higher field: CMS B=4T
- Longer lever arm for muons: additional tracking in the magnetic muon system (ATLAS)

Momentum measurement for very high energy muons - example ATLAS



Components of an experimental apparatus (‘spectrometer’)

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

Why Particle ID?

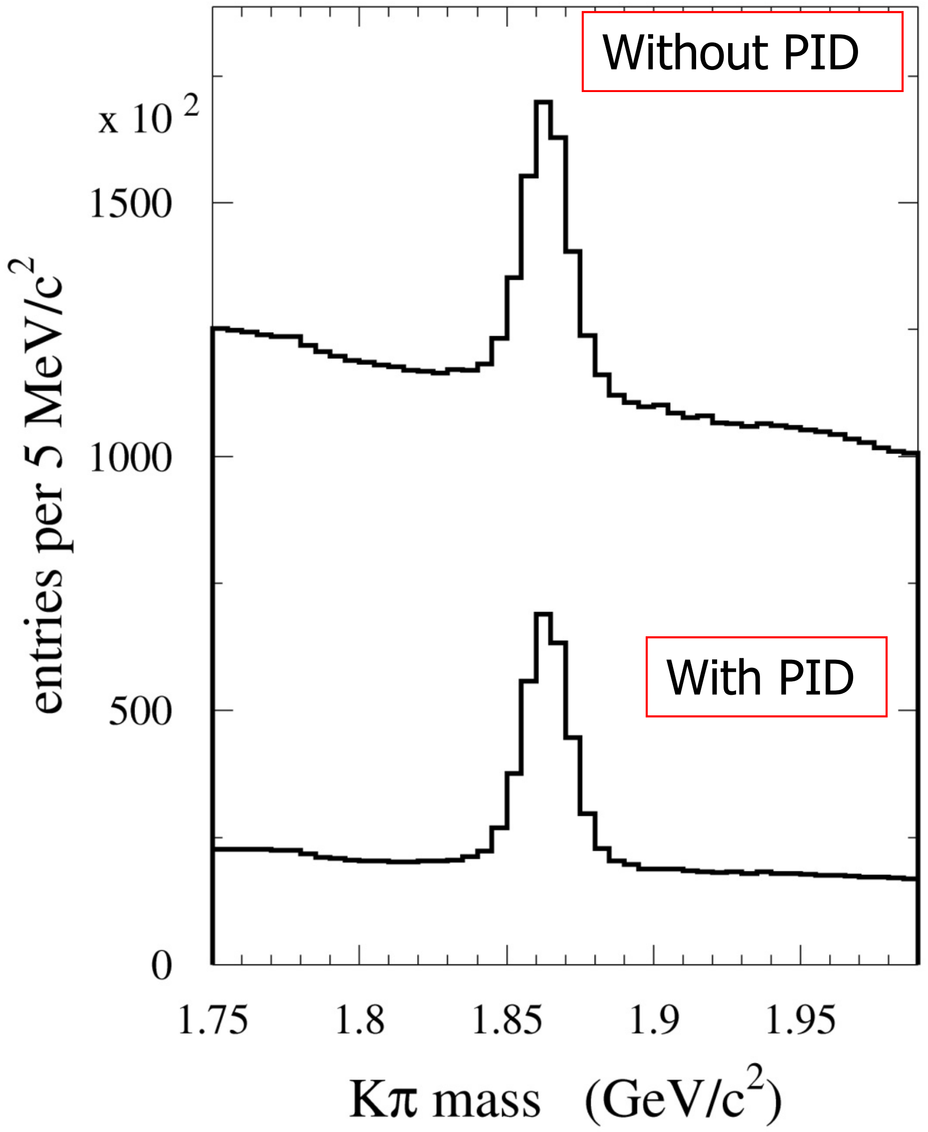
Particle identification is an important aspect of particle, nuclear and astroparticle physics experiments.

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

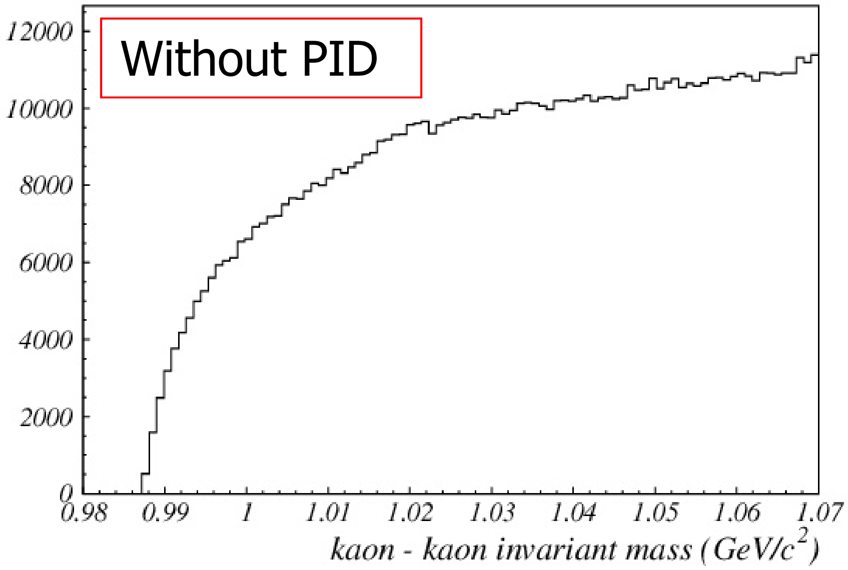
Introduction: Why Particle ID?

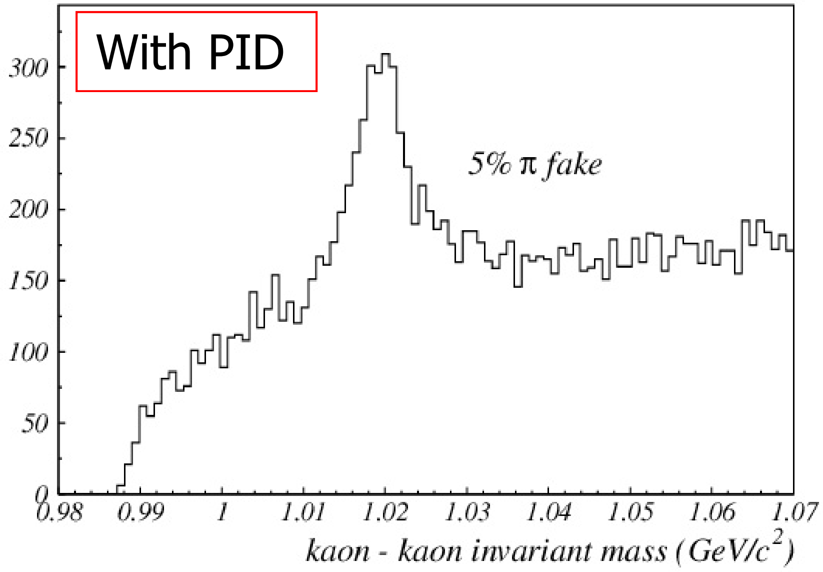


Example 1: B factories

Particle identification reduces combinatorial background by ~3x

Introduction: Why Particle ID?



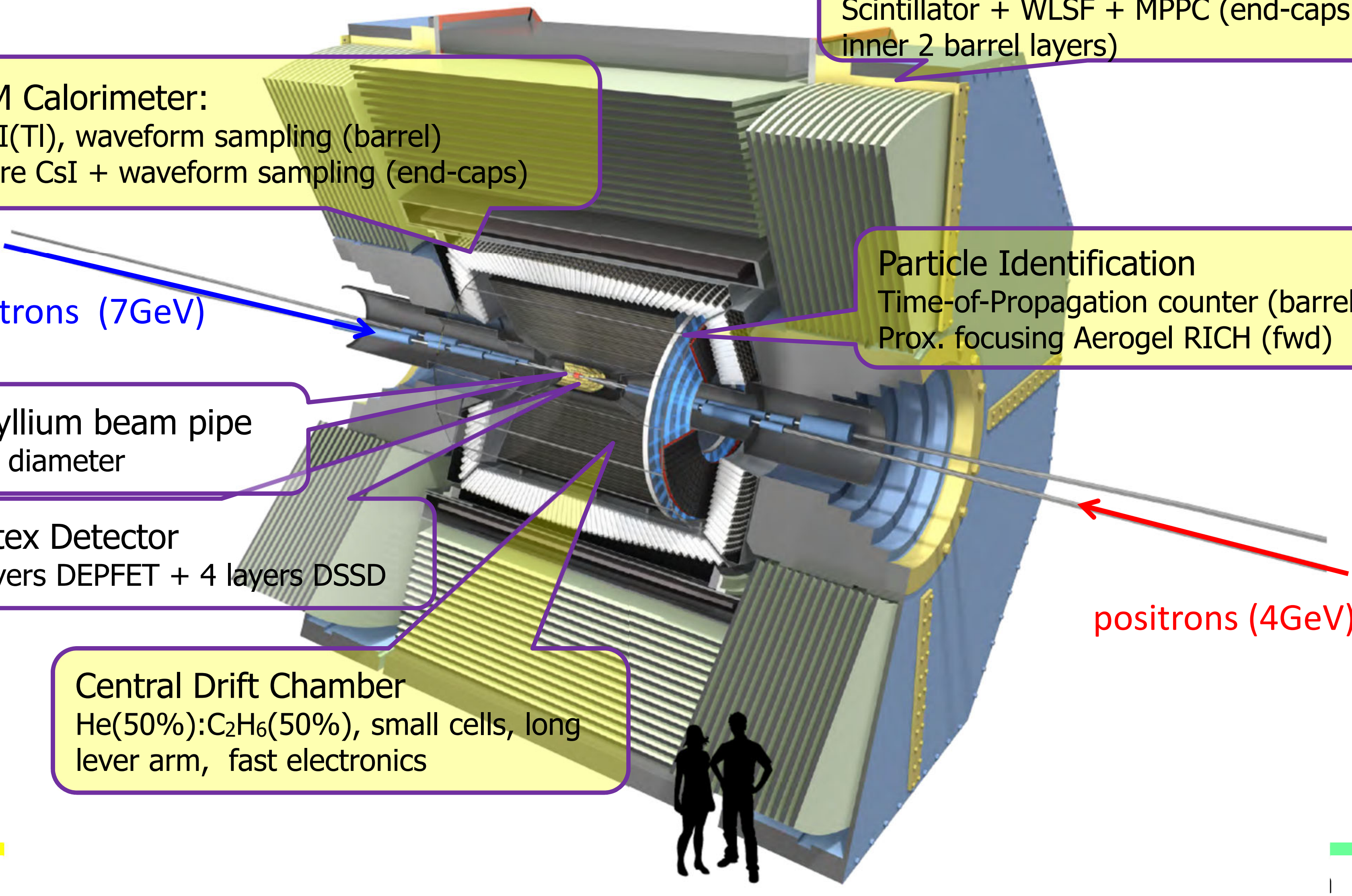


Example 2: HERA-B

K^+K^- invariant mass.

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

Particle identification systems in Belle II



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

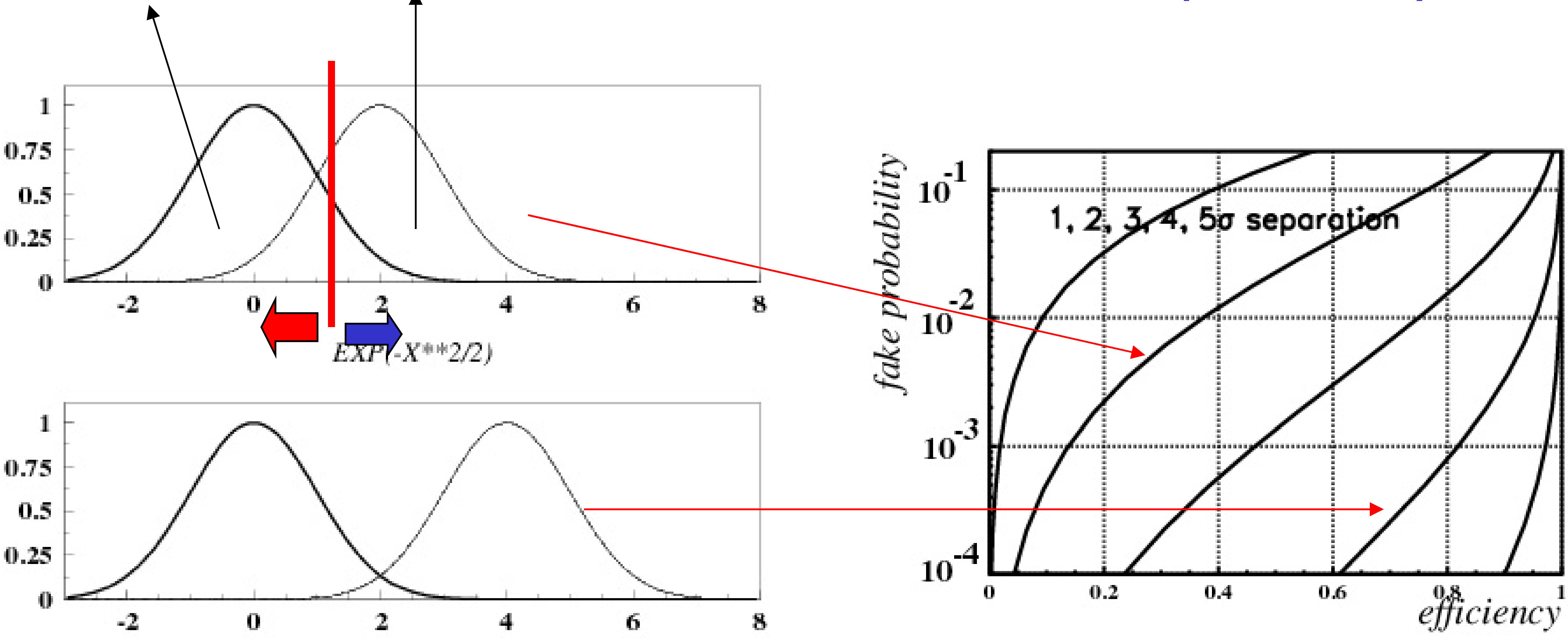
Efficiency and purity in particle identification

Efficiency and purity are tightly coupled!

Two examples:

particle type 1 type 2

eff. vs fake probability



some discriminating variable

Identification of charged particles

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

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

Momentum known (radius of curvature in magnetic field)

→Measure velocity:

- time of flight
- ionisation losses dE/dx
- Cherenkov angle
- transition radiation

Mainly used for the identification of hadrons.

Identification through interaction: electrons and muons

Time-of-flight measurement 2

Required resolution, example:

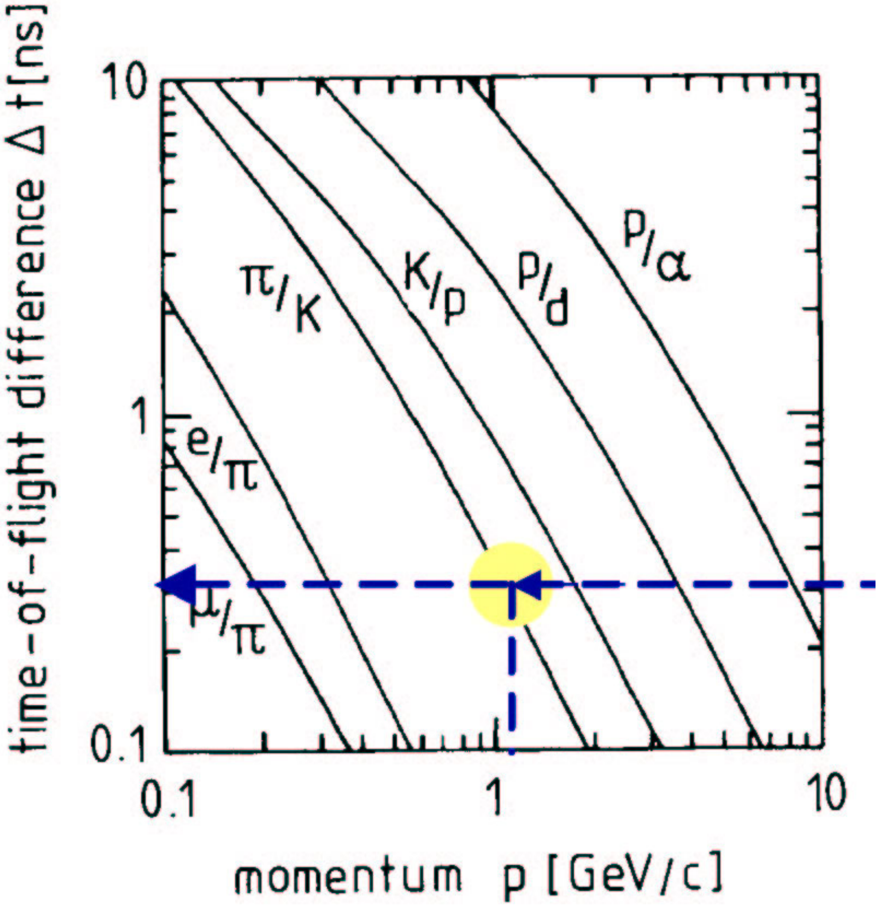
π/K difference at 1GeV/c: 300ps

For a 3σ separation need
σ(TOF)=100ps

Resolution contributions:

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

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

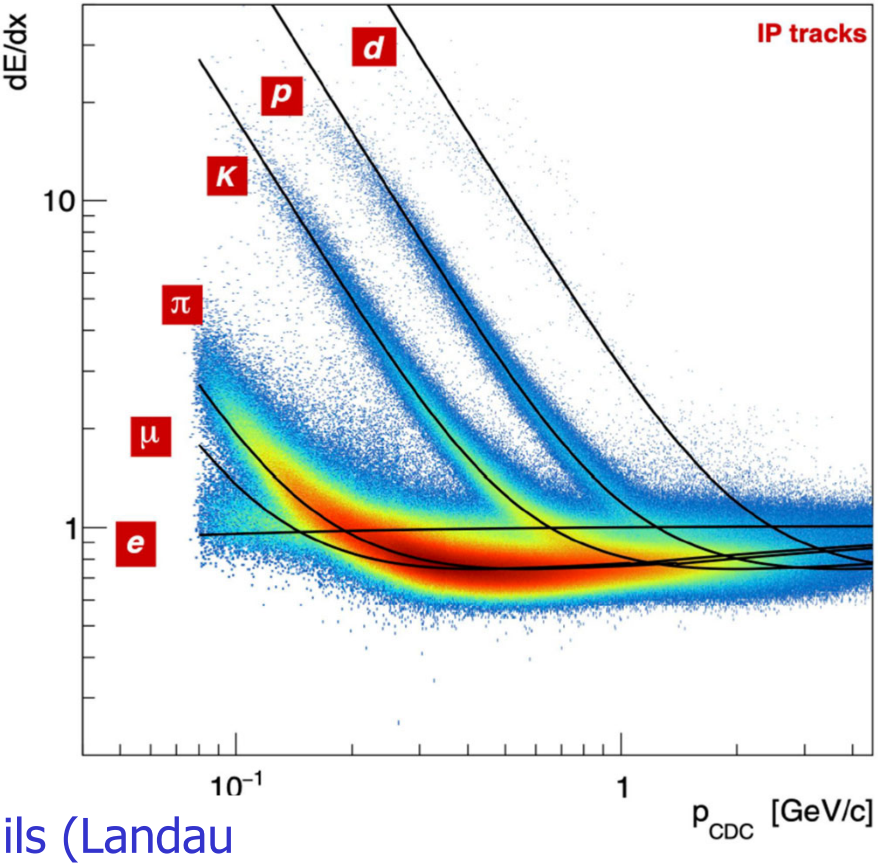


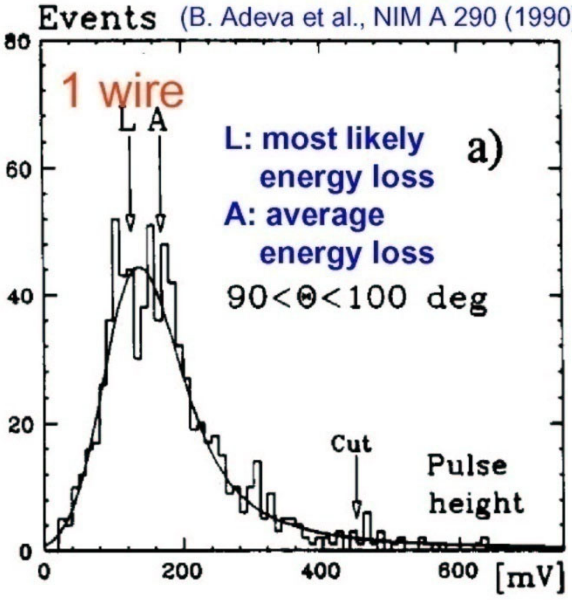
Identification with dE/dx measurement

dE/dx is a function of velocity.

For particles with different masses the Bethe-Bloch curves get displaced → separation is possible if the resolution is good enough – 5%

Belle II CDC: dE/dx vs p





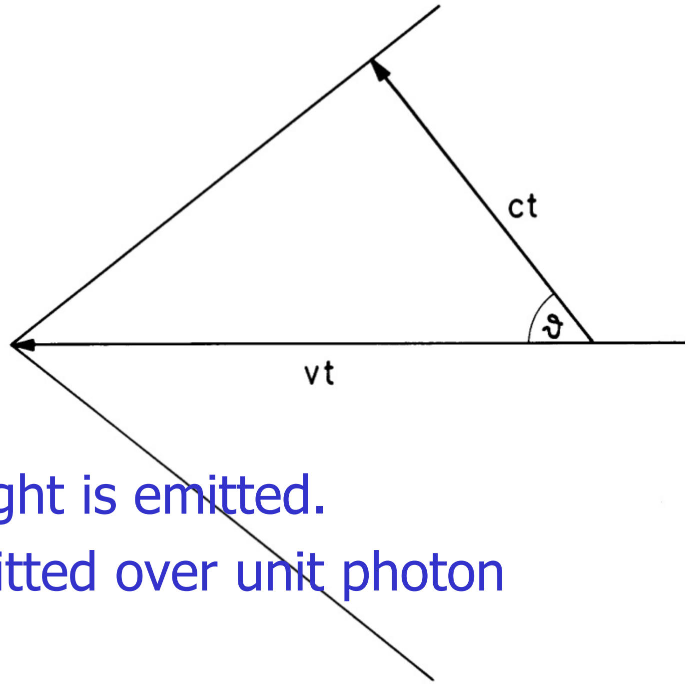
(B. Adeva et al., NIM A 290 (1990))

Problem: long tails (Landau distribution, not Gaussian), use truncated mean, exclude highest values

Cherenkov datectors

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

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



Two cases:

→ $\beta < \beta_t = 1/n$: below threshold no Cherenkov light is emitted.

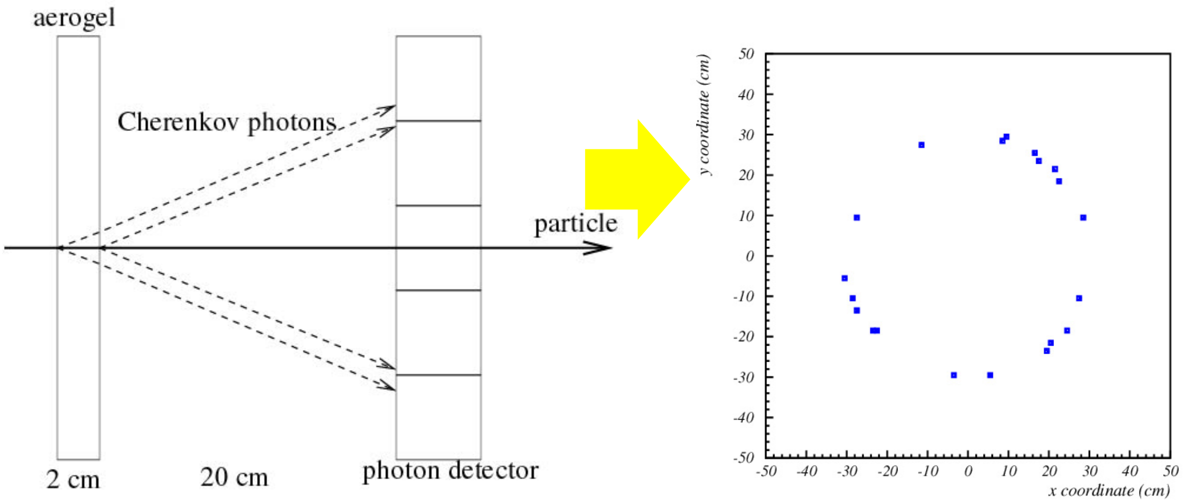
→ $\beta > \beta_t$: the number of Cherenkov photons emitted over unit photon energy E=hν in a radiator of length ***L***:

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

→Few detected photons

Measuring the Cherenkov angle

Particles above threshold: measure θ

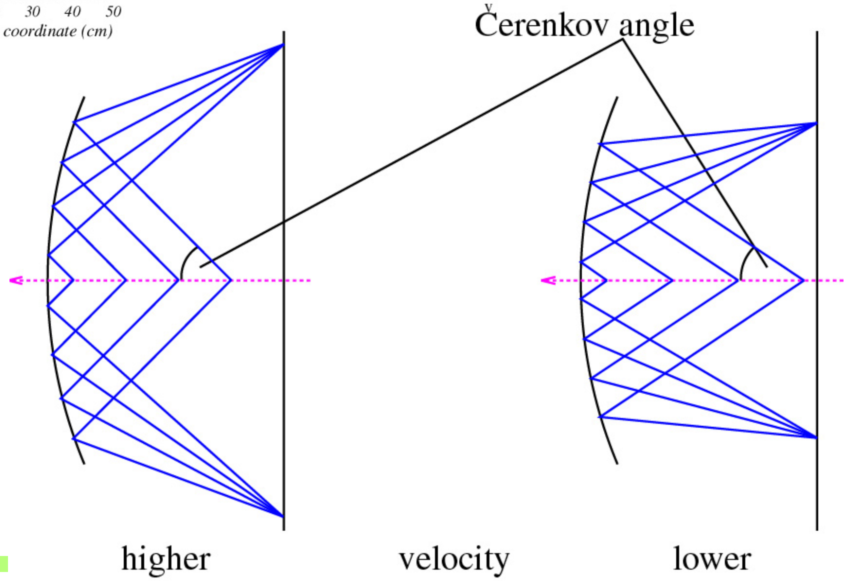


Proximity focusing RICH

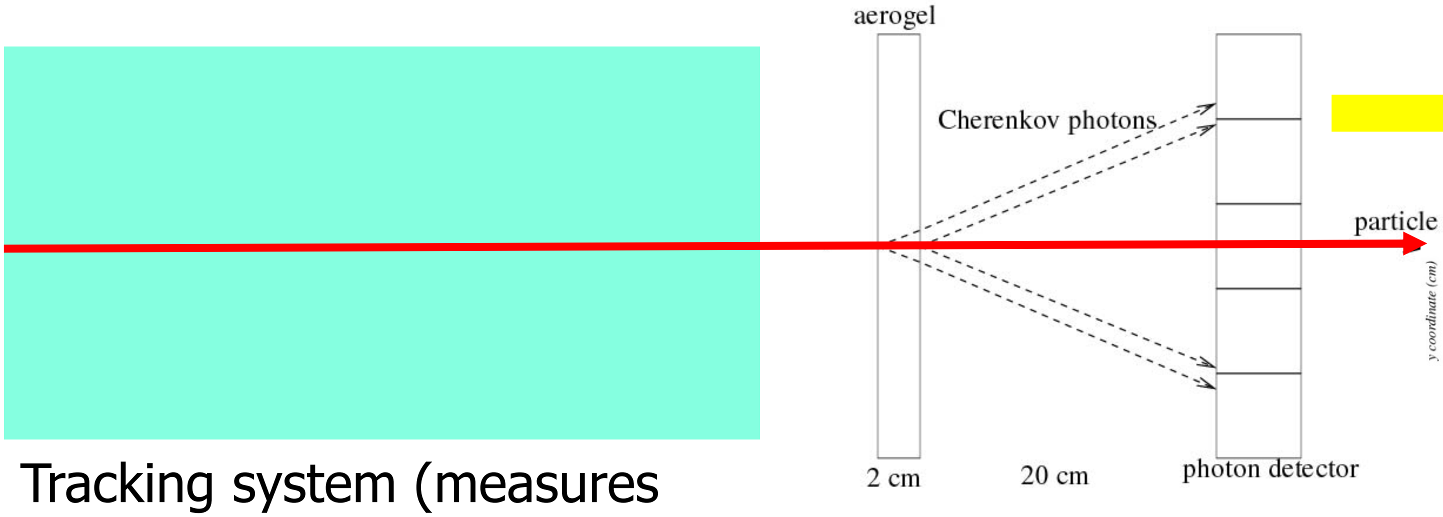
Idea: transform the direction into a coordinate → ring on the detection plane

→ Ring Imaging Cherenkov (RICH) counter

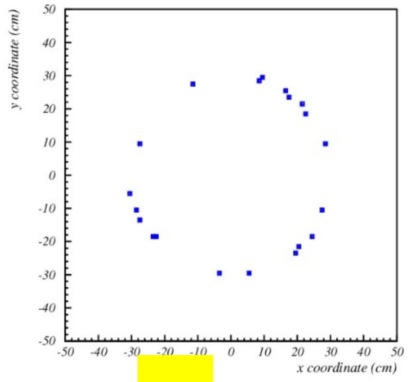
RICH with a focusing mirror

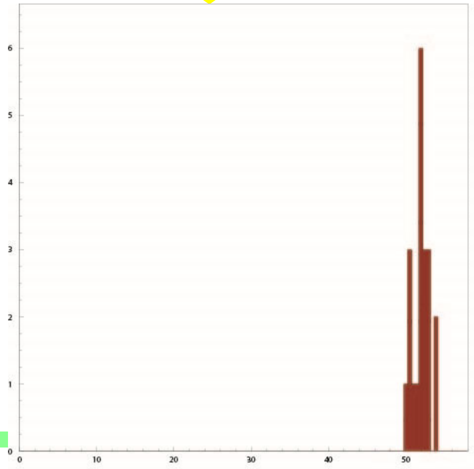


Measuring the Cherenkov angle



Tracking system (measures direction of the particle)

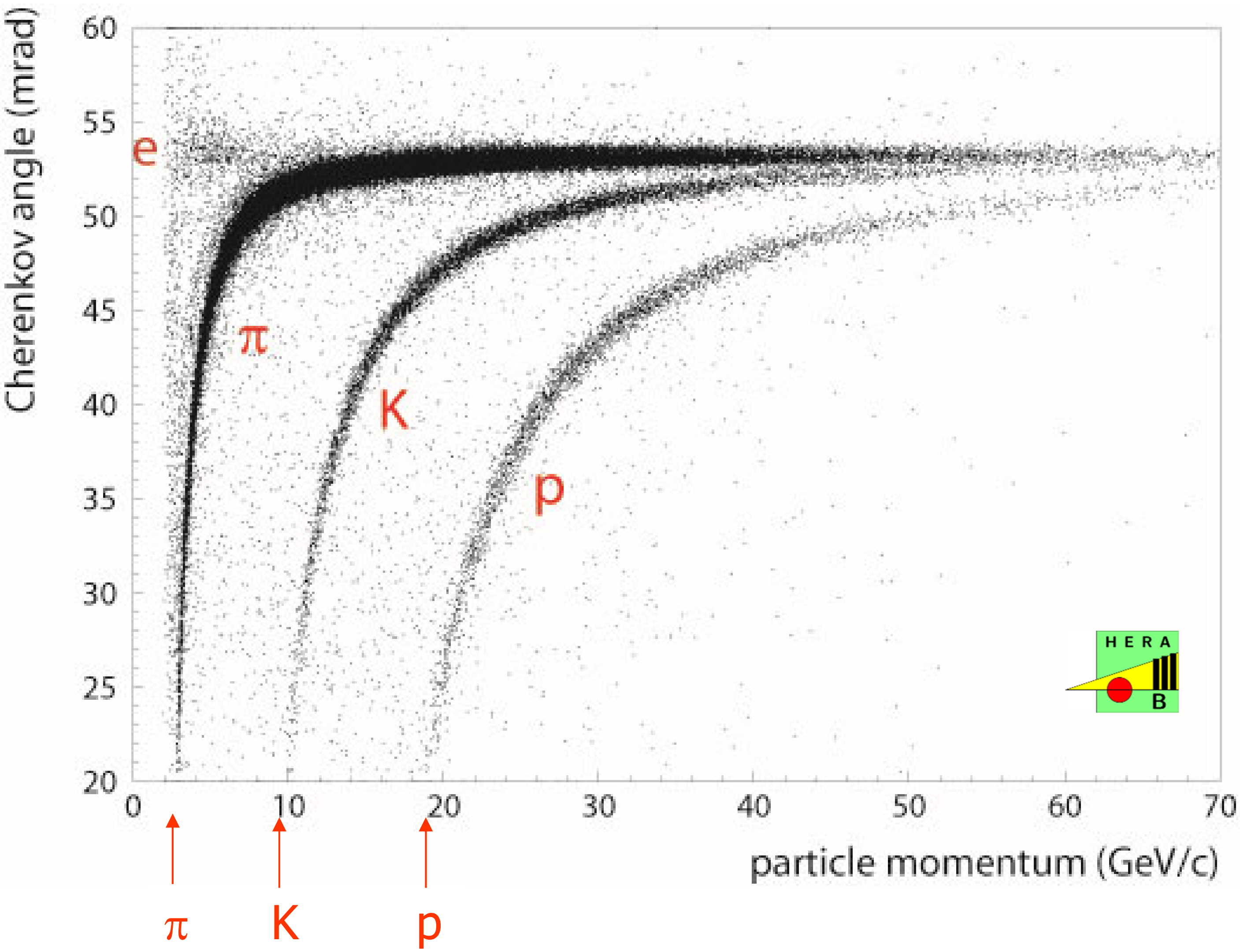



Cherekov angle distribution (mradian)

Tracking system tells us where the particle hit the radiator, and at which angle.

Use this information to calculate the Cherenkov angle for each individual detected photon

Measuring Cherenkov angle



thresholds

Radiator:

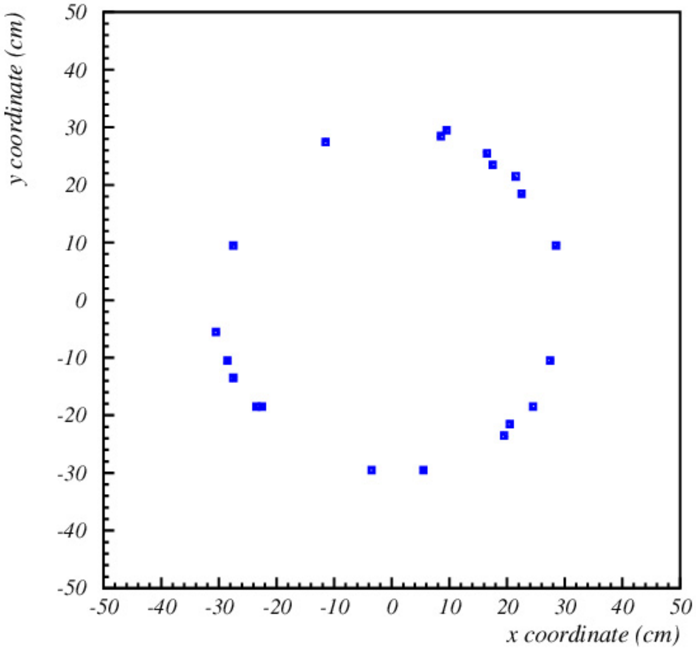
C_4F_{10} gas

Photon detection in RICH counters

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

→ detection of single photons with

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

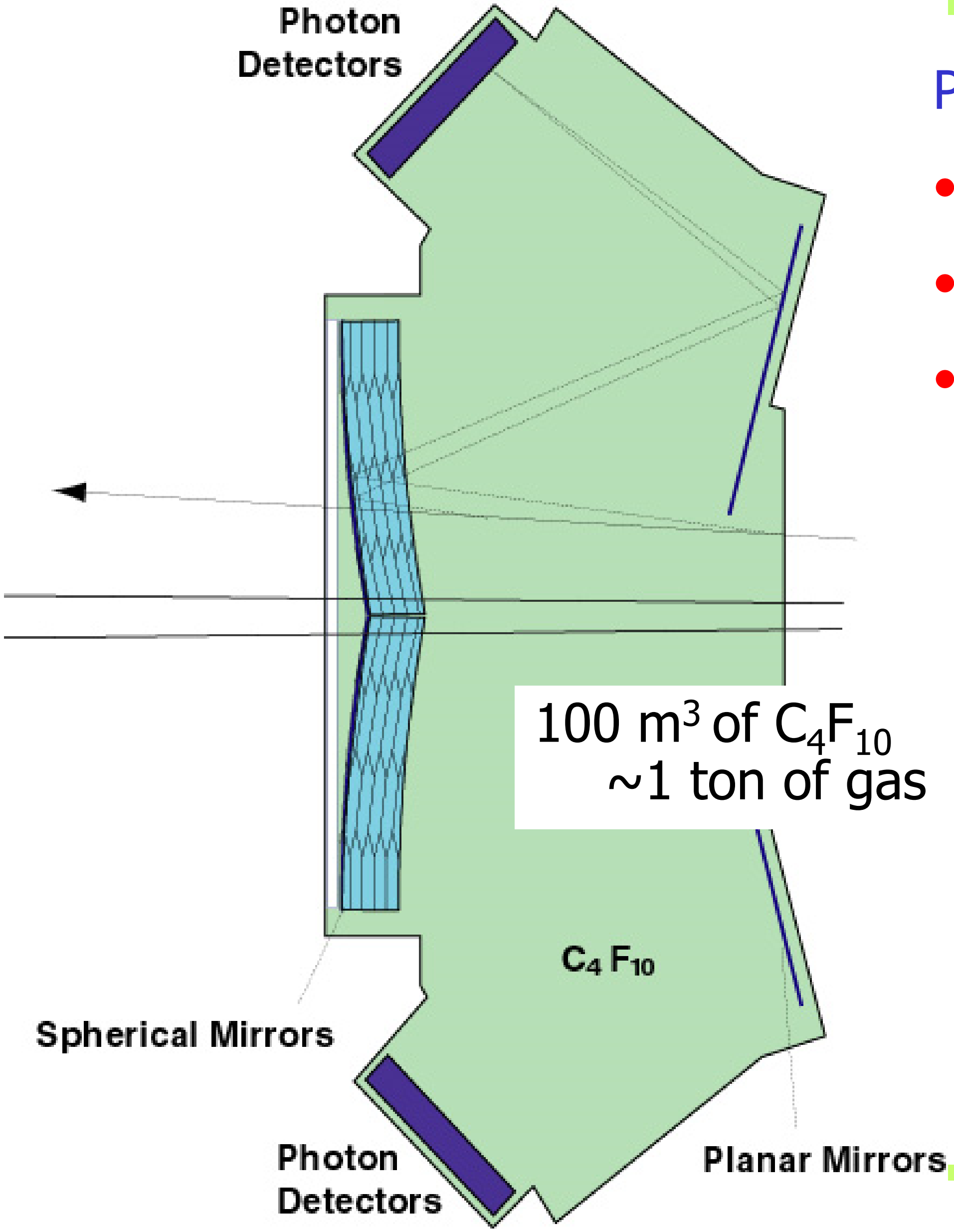


Special requirements:

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

Photon detector is the most crucial element of a RICH counter

HERA-B RICH

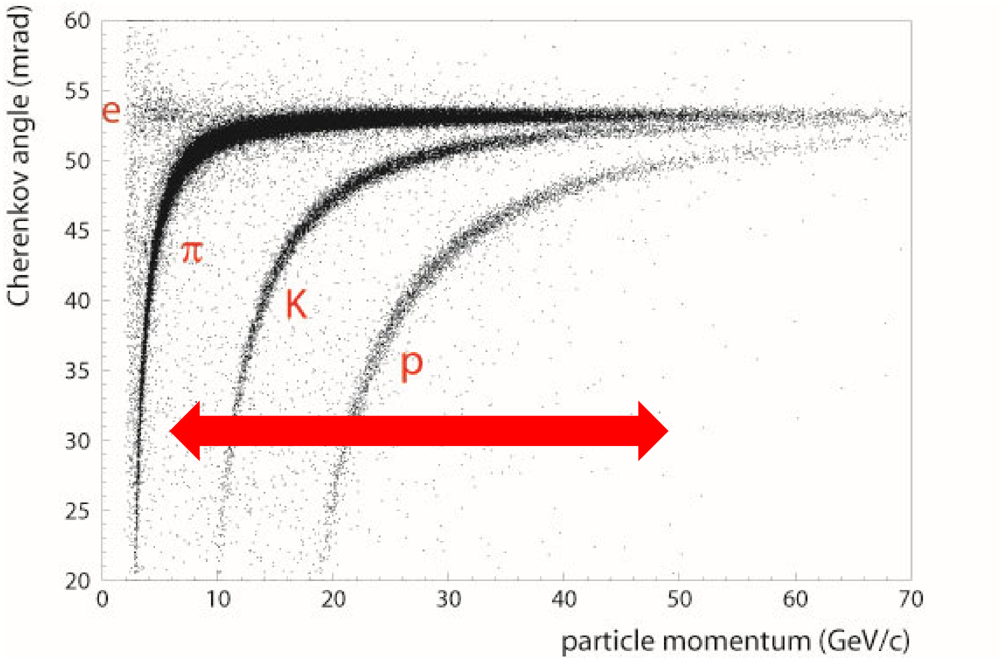


100 m^3 of C_4F_{10}
~1 ton of gas

Photon detector requirements:

- High QE over ~3m^2
- Rates ~1MHz
- Long term stability

Kinematic range of a RICH counter



Example: kinematic range for kaon/pion separation

Kinematic range for separation of two particle types:

•Lower limit p_{min}: sufficiently above lighter particle threshold

•Upper limit p_{max}: given by Cherenkov angle resolution – overlap of the two bands

Rule of thumb: $p_{max} / p_{min} < 10$

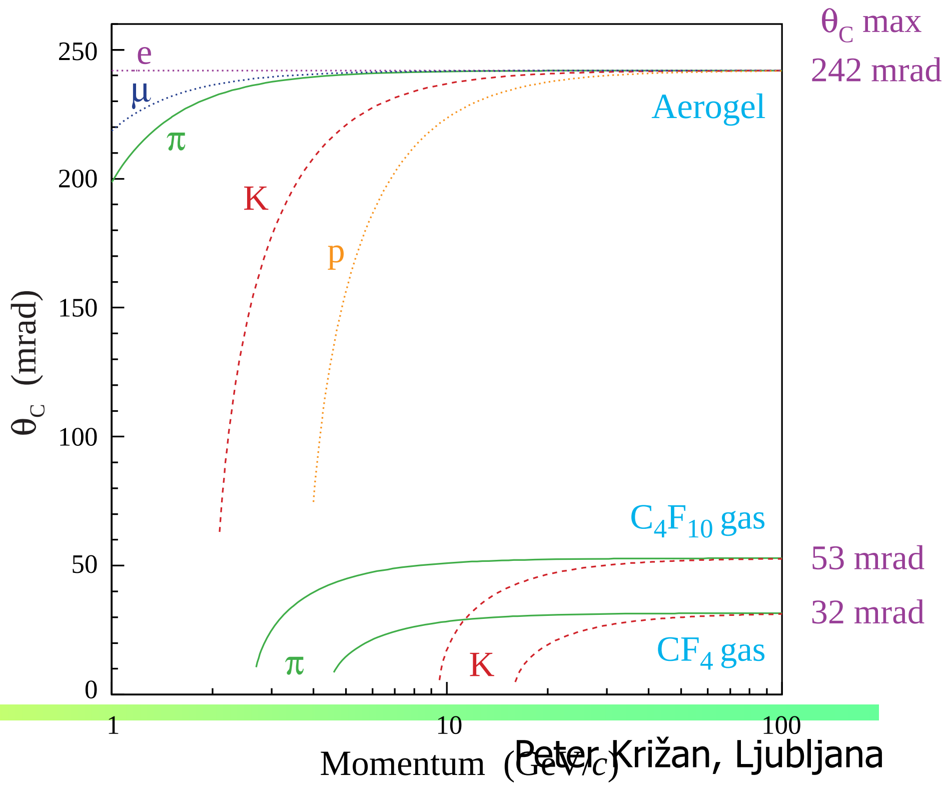
LHCb RIChes

Need:

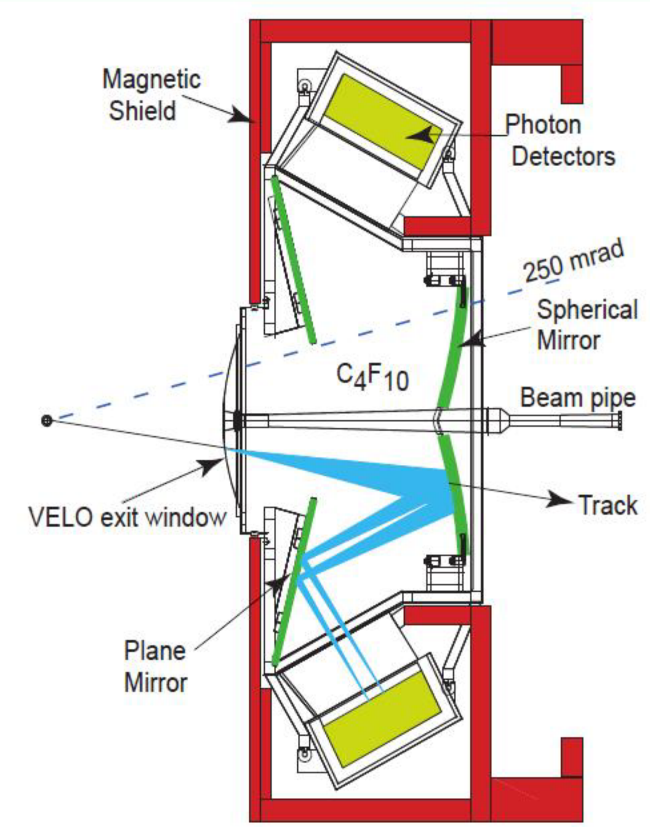
- Particle identification for momentum range ~2-100 GeV/c
- Granularity 2.5x2.5mm^2
- Large area (2.8m^2) with high active area fraction
- Fast compared to the 25ns bunch crossing time
- Have to operate in a small B field

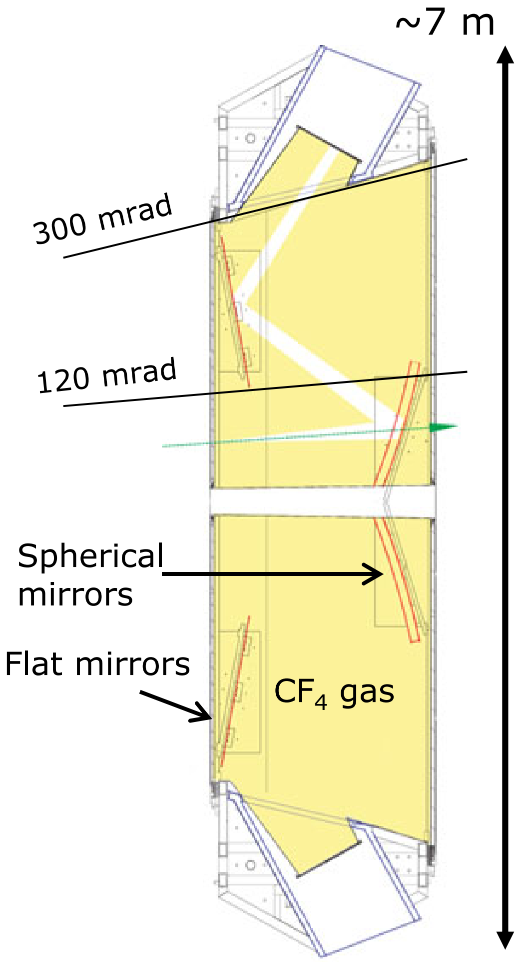
→3 radiators

- Aerogel
- C_4F_{10} gas
- CF_4 gas



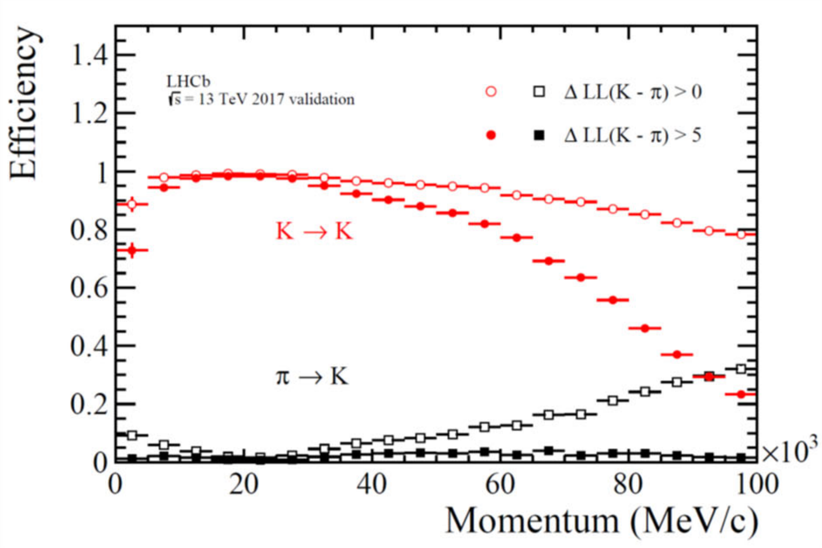
LHCb RICHes

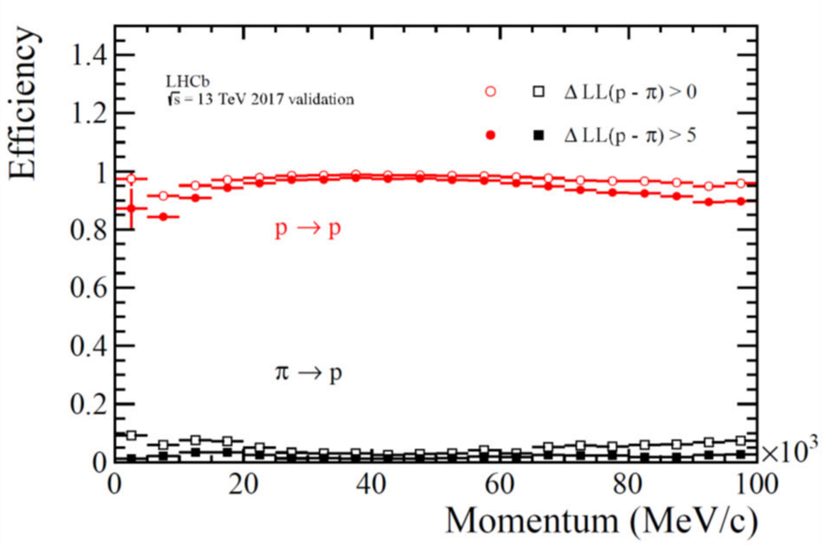


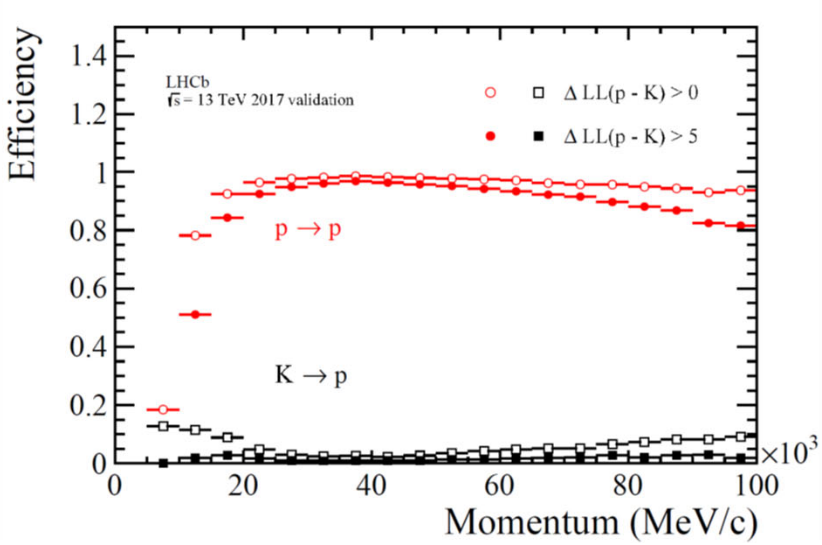


RICH 1 + 2

LHCb RICHes: performance

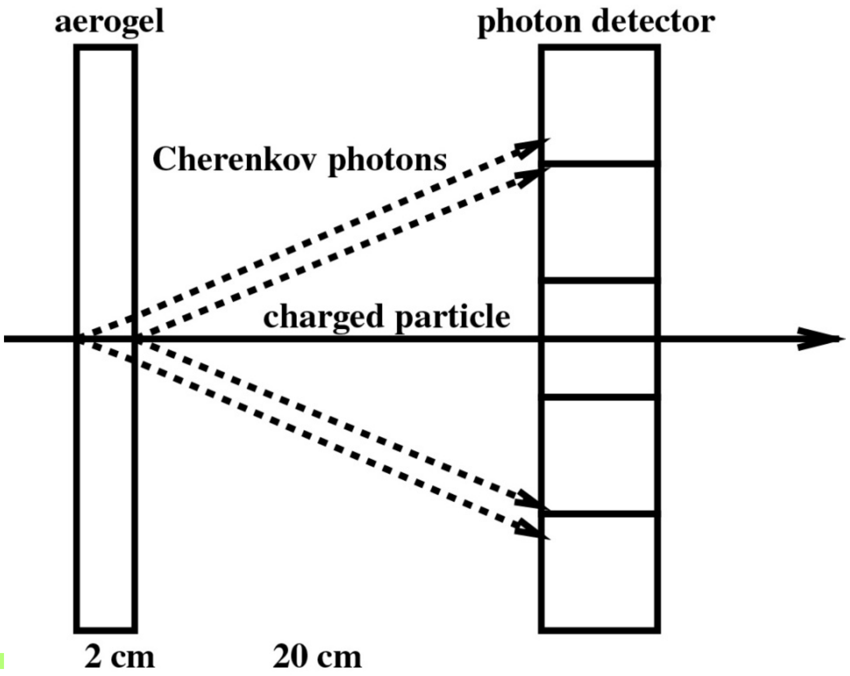






Resolution of a RICH counter

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

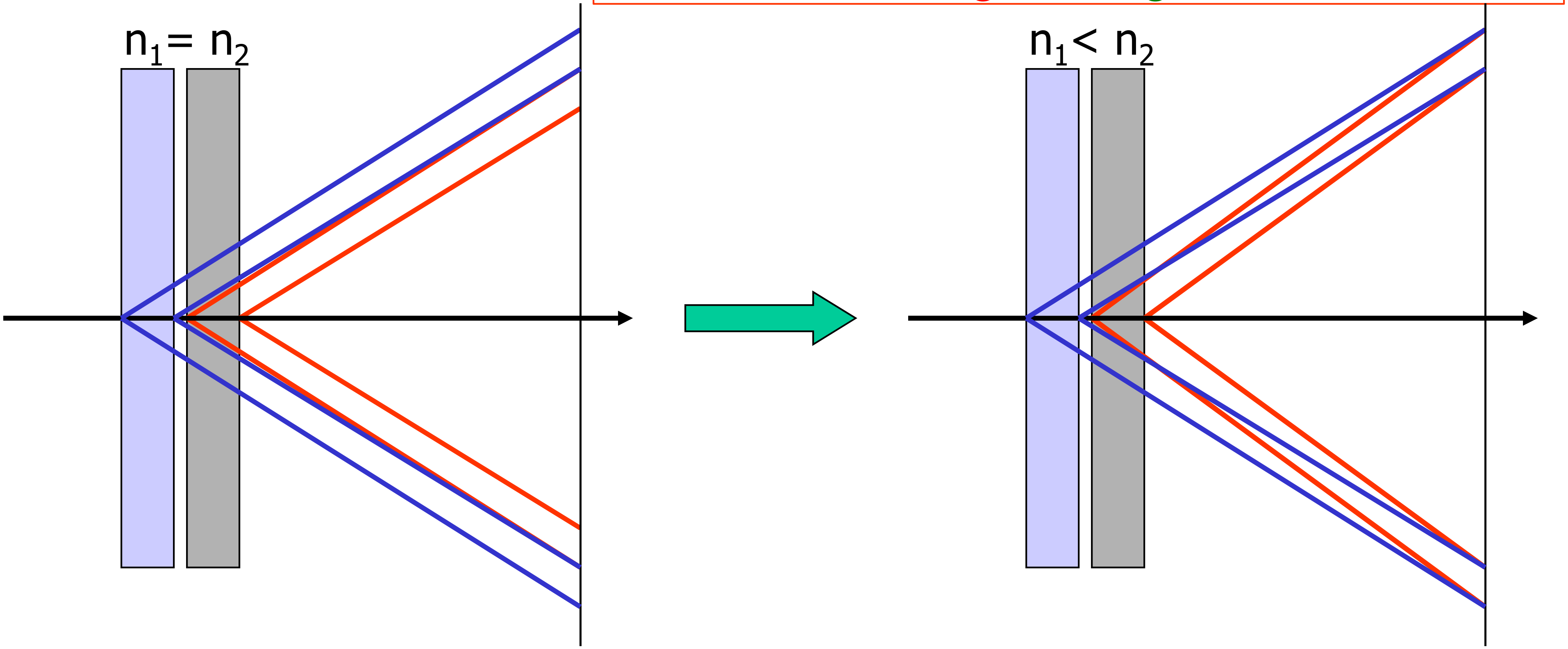


Radiator with multiple refractive indices

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

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

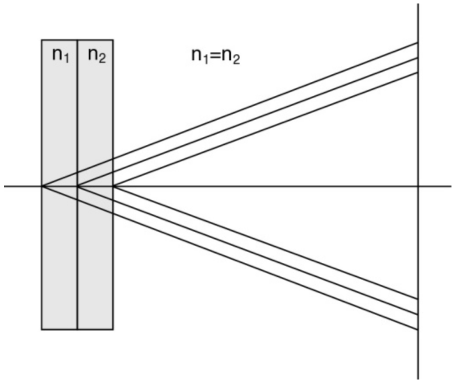
normal

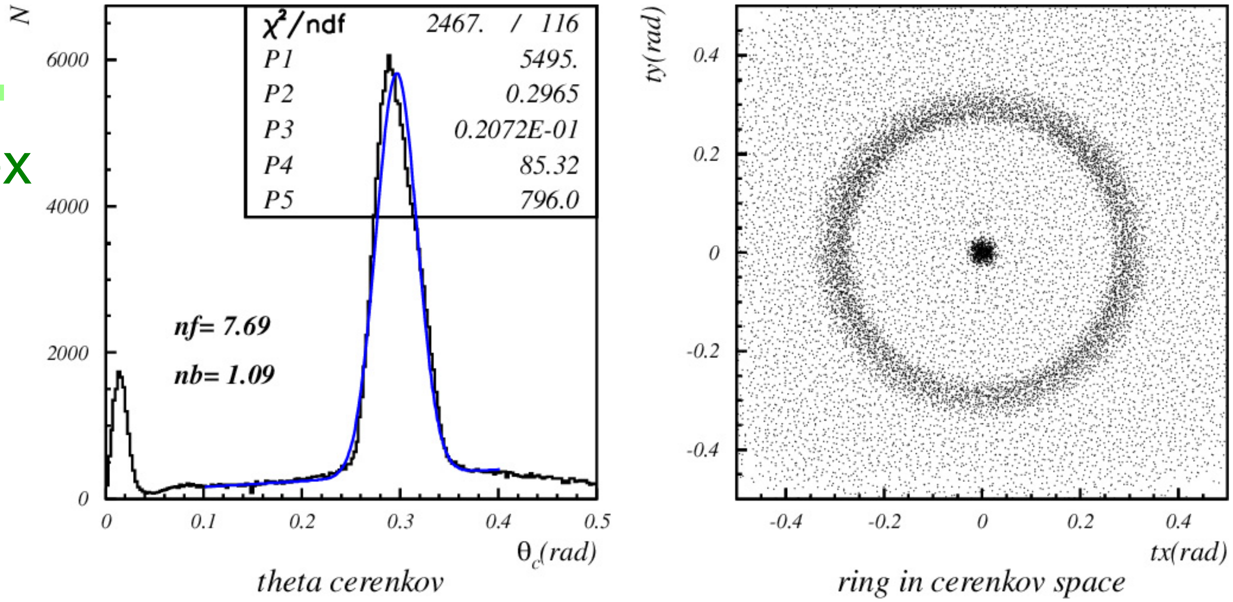


→ focusing radiator

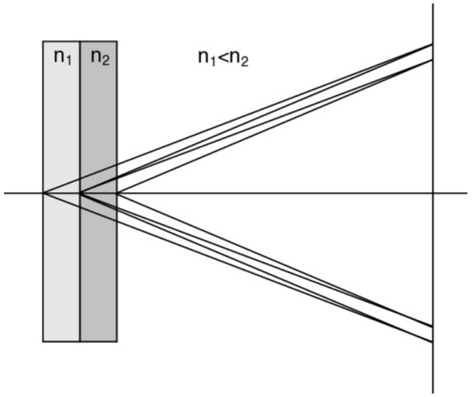
Focusing configuration – data

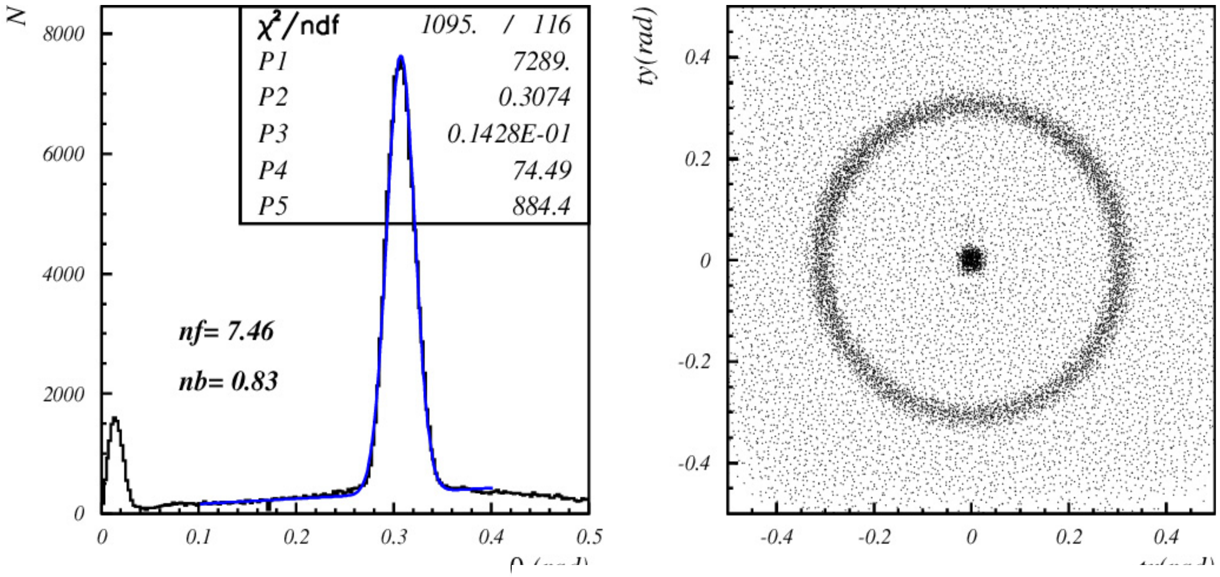
4cm aerogel single index





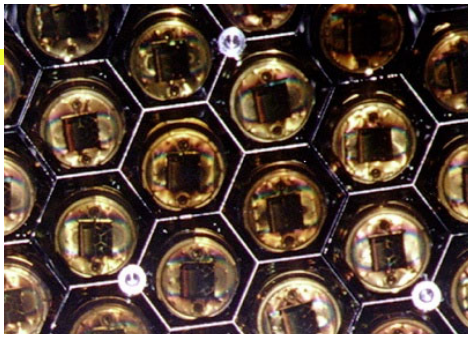
2+2cm aerogel

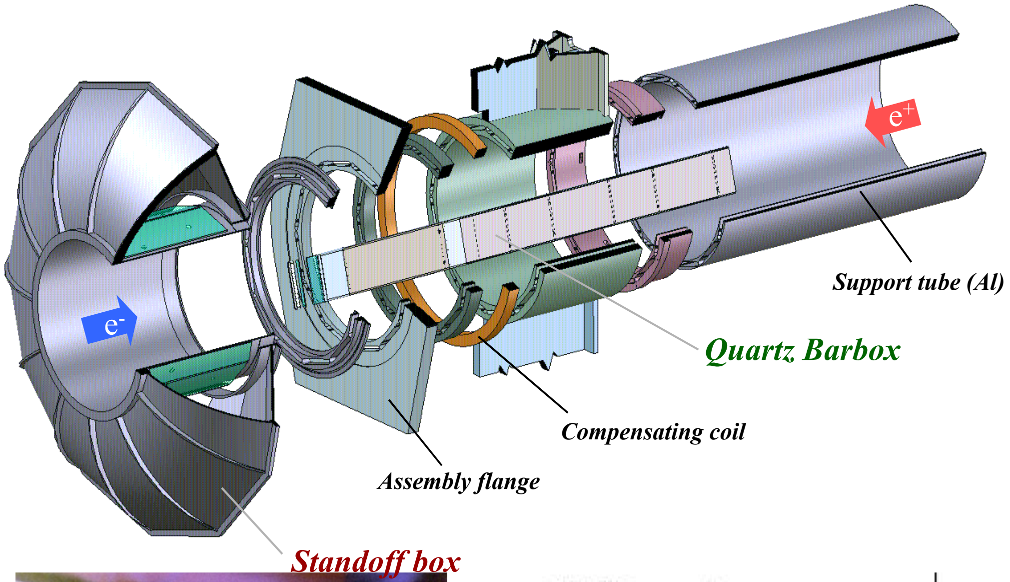


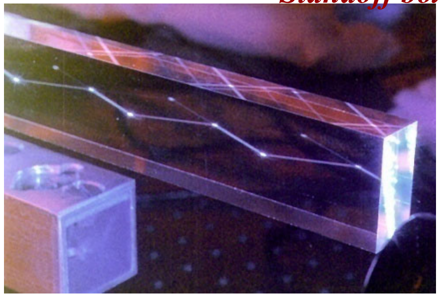


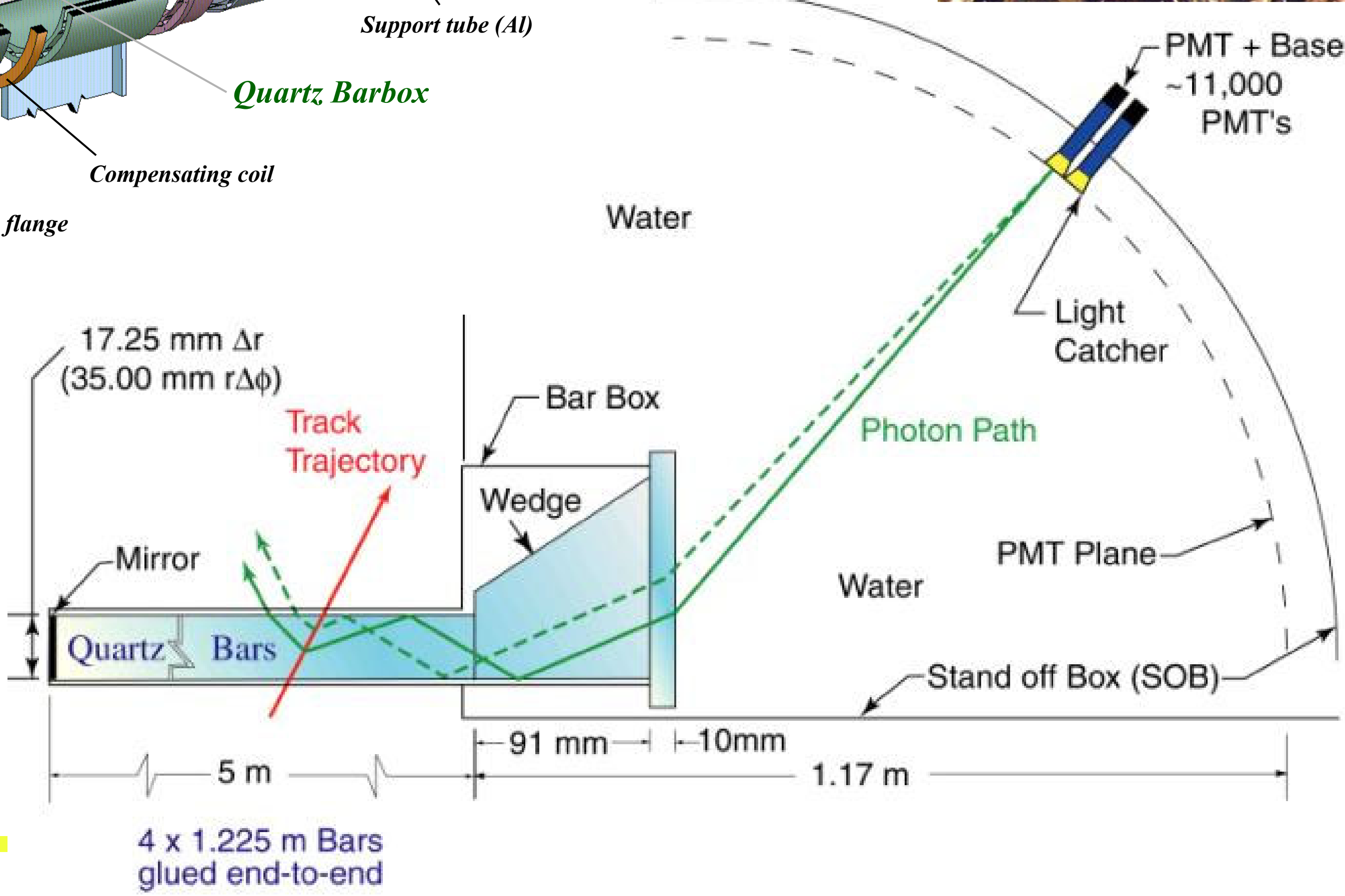
→NIM A548 (2005) 383

DIRC - Detector of Internally Reflected Cherekov photons - a special kind of RICH where Cherenkov photons trapped in a solid radiator (e.q. quartz) are propagated along the radiator bar to the side, and detected as they exit and traverse a gap.

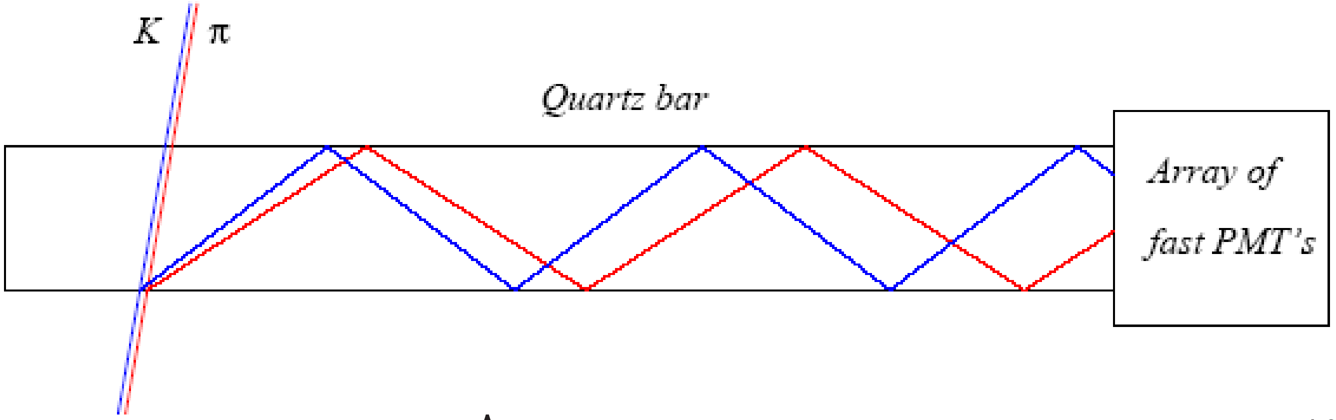


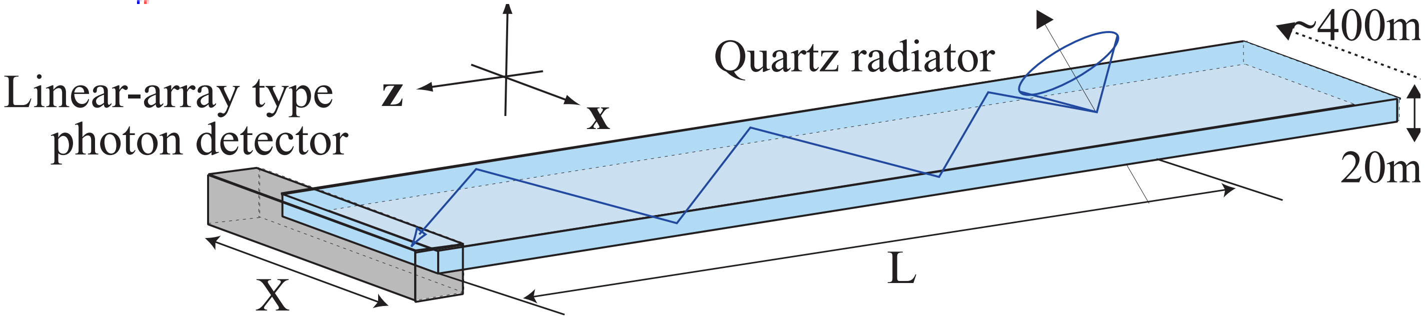


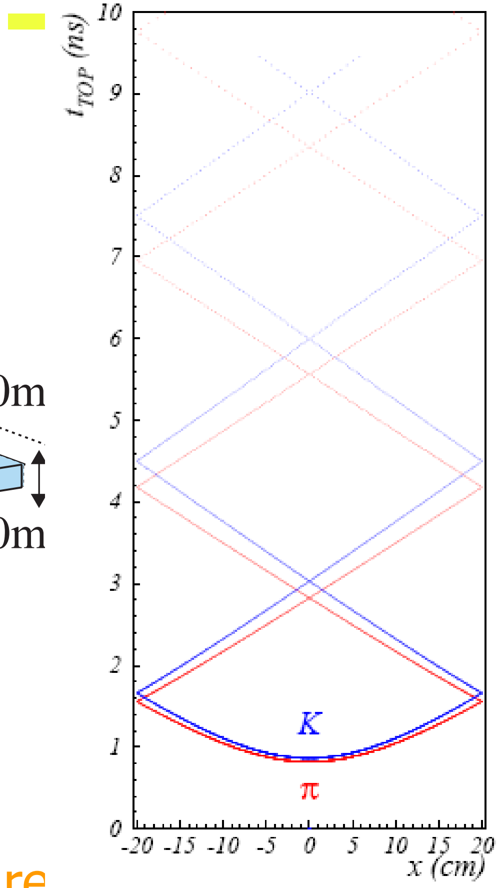




Time-Of-Propagation (TOP) counter



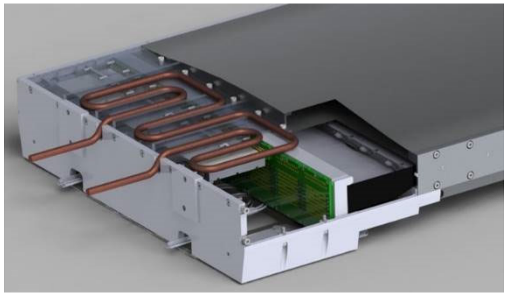


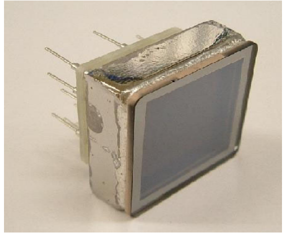


Similar to DIRC, but instead of two coordinates measure

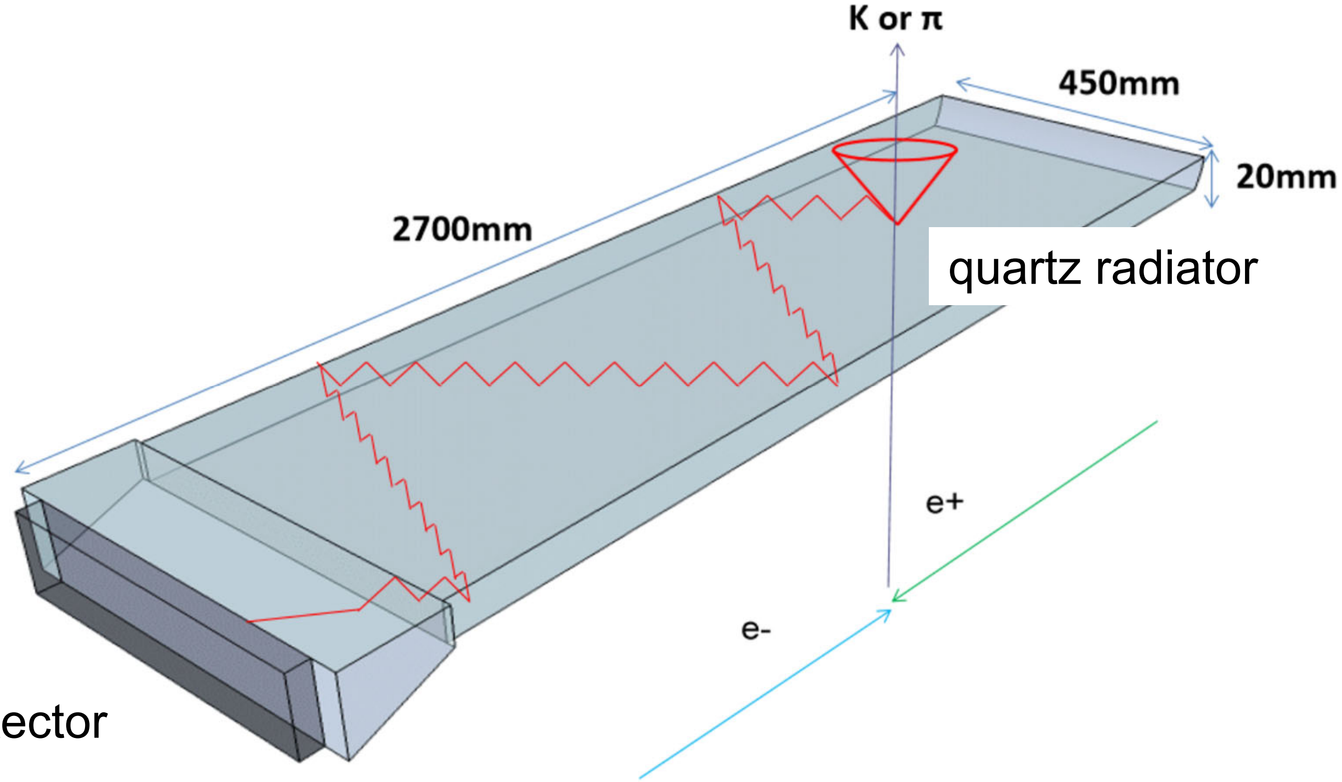
- One (or two coordinates) with a few mm precision
- Time-of-arrival

Belle II Barrel PID: Time of propagation (TOP) counter





Photon detector



- Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity at 1.5 T

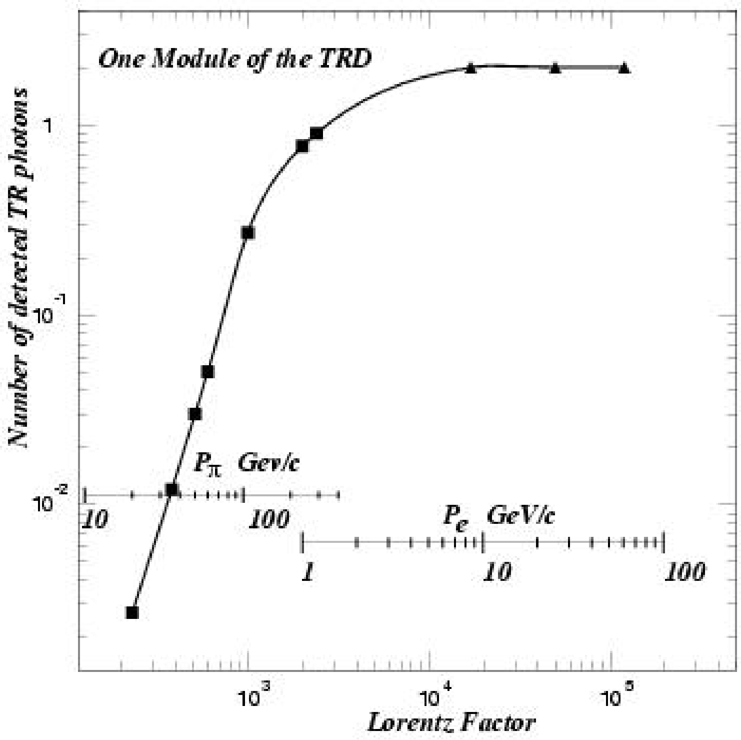
Transition radiation detectors

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

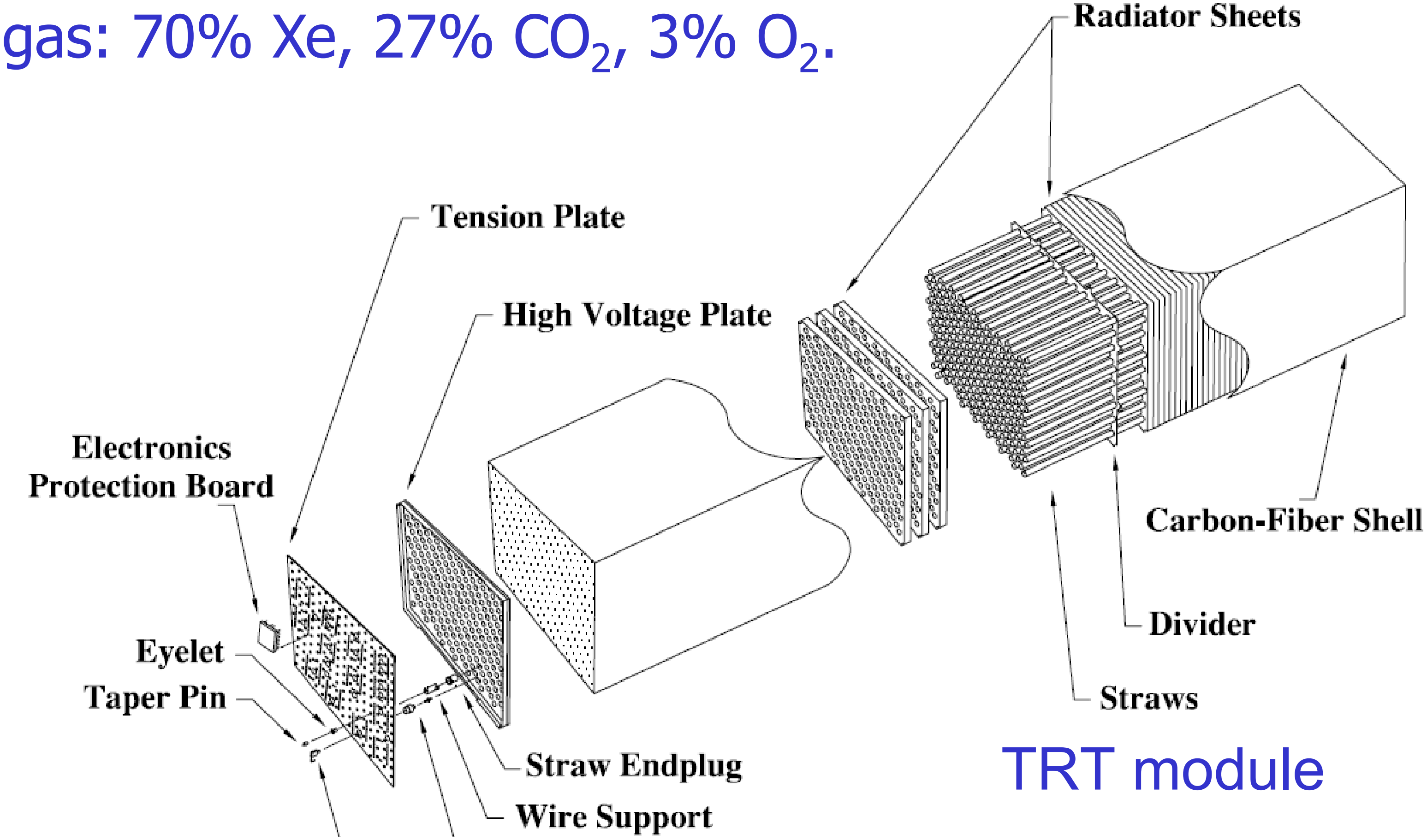
Need many boundaries

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

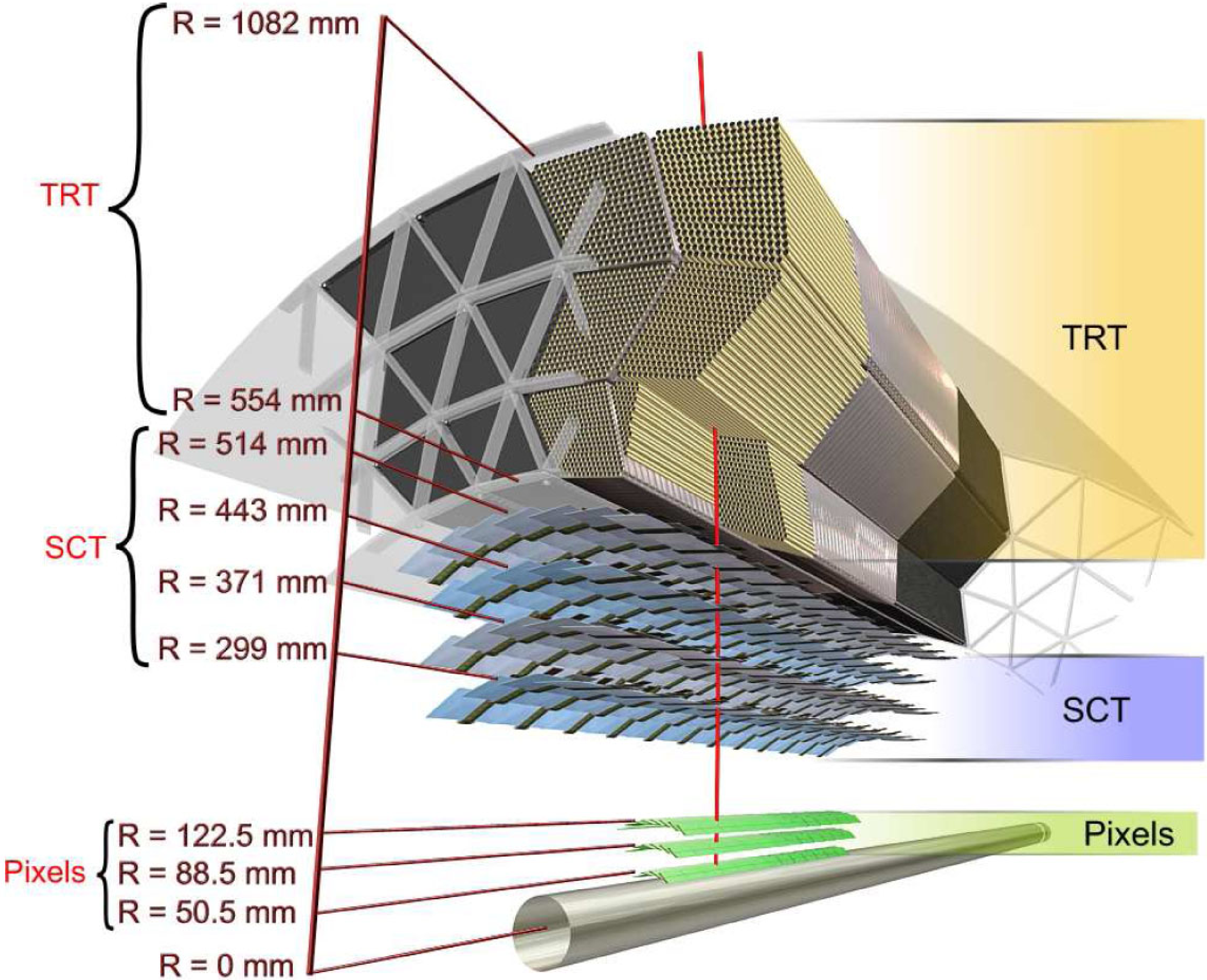
ATLAS TRT: combination of Transition Radiation detector and a Tracker

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

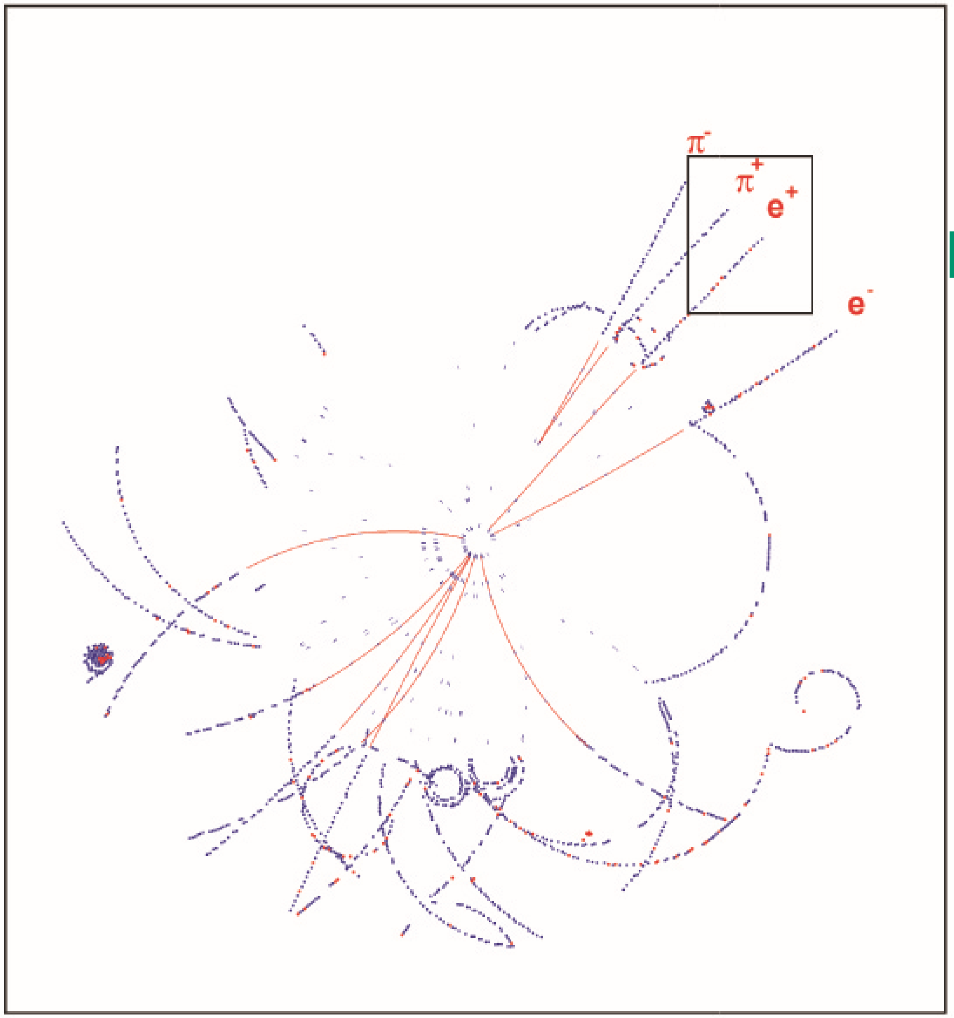
Straw tubes: 4mm diameter with 31 micron diameter anode wires, gas: 70% Xe, 27% CO_2, 3% O_2.

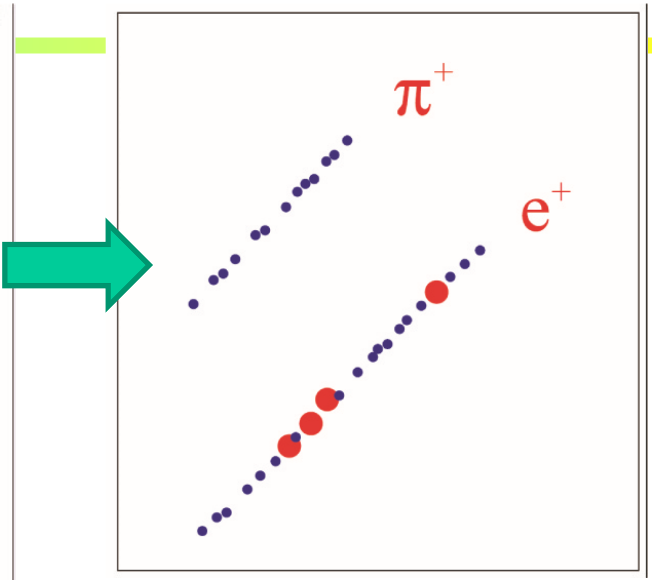


TRT module

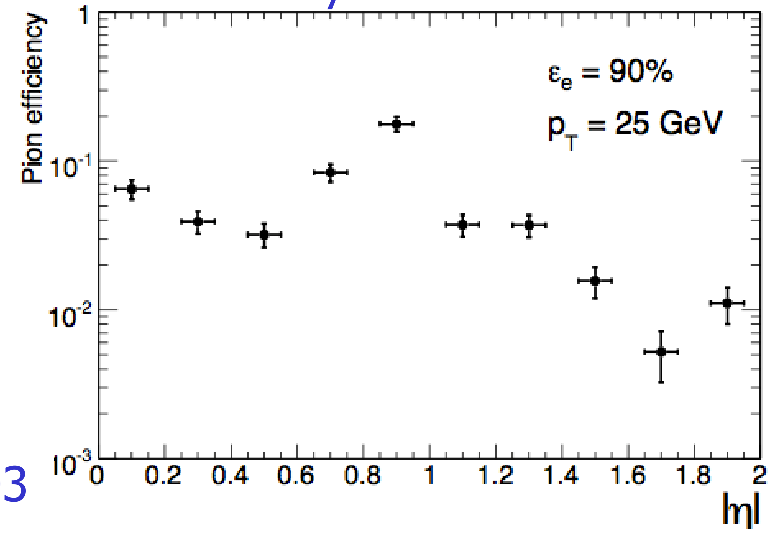

R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels

TRT: pion-electron separation





π fake probability at 90% e efficiency



→ JINST 3 (2008) S08003

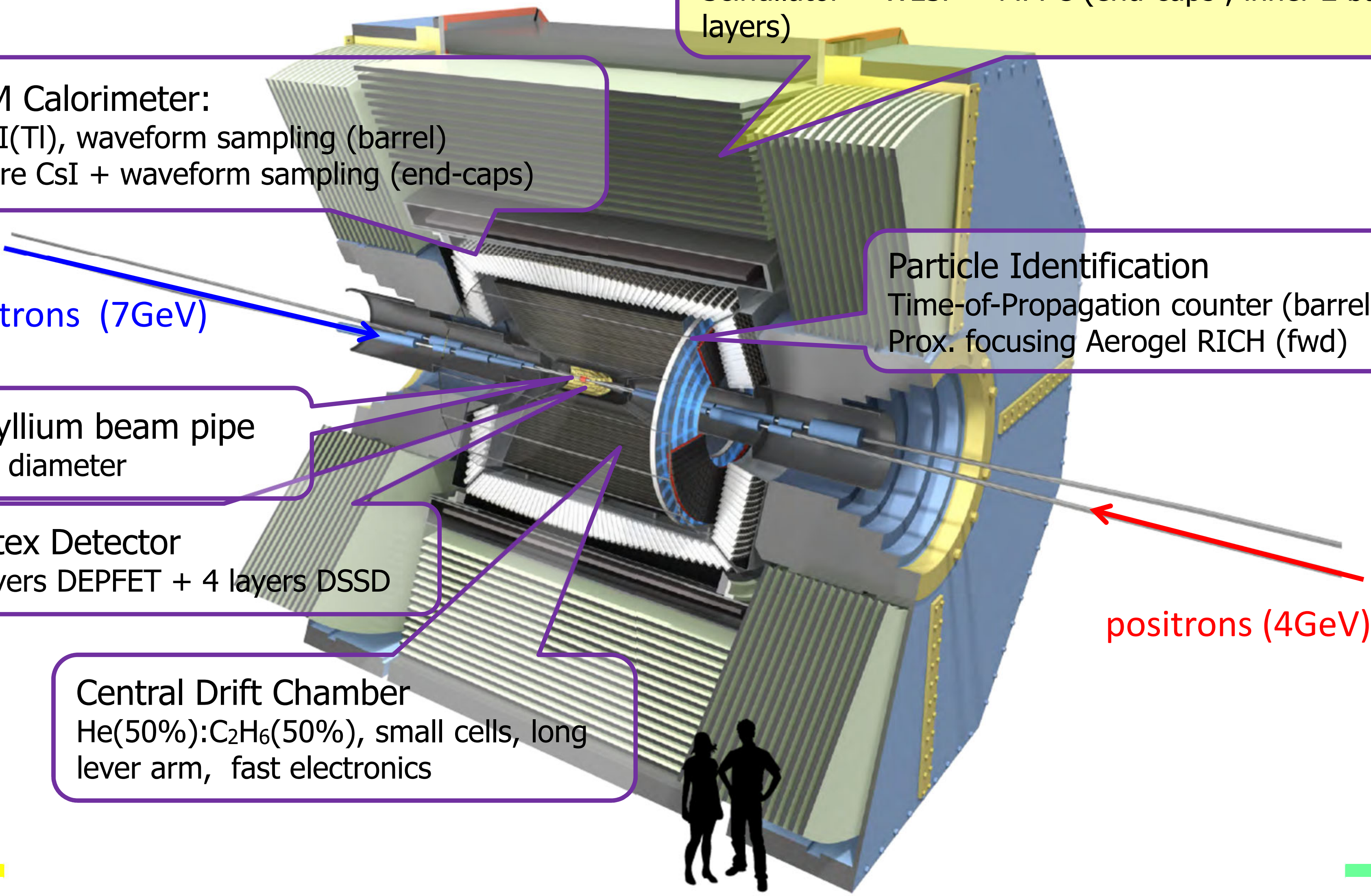
Muon and K_L detector at B factories

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 – stong interaction analog to radiation length = 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.

Example: Muon and K_L detection at Belle II



KL and muon detector:14/15 layers RPC+Fe
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electrons (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

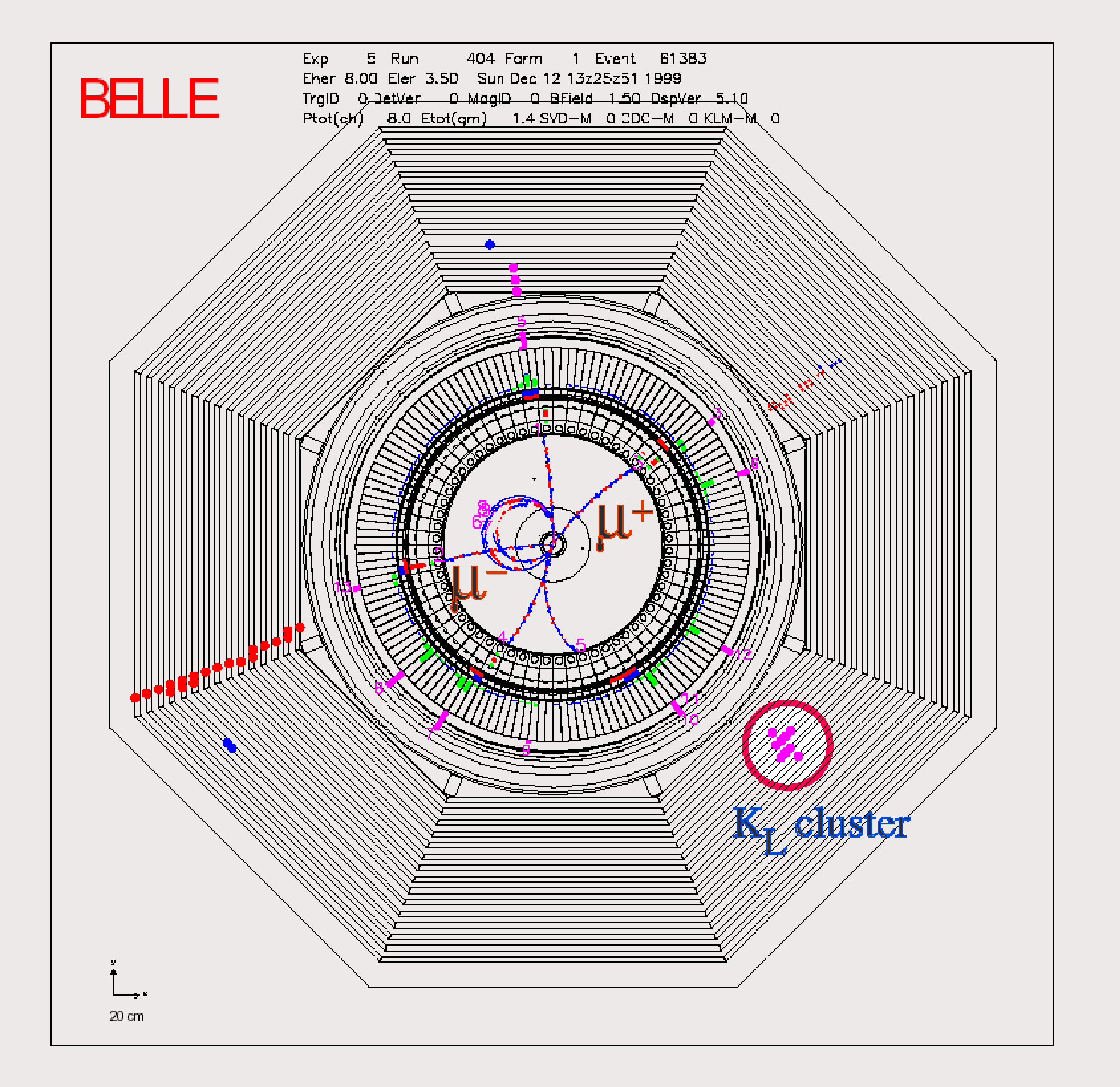
Muon and K_L detector

Example:

event with

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

and a pion that partly penetrated



Muon and K_L detector performance

Muon identification: efficient for p>800 MeV/c

efficiency

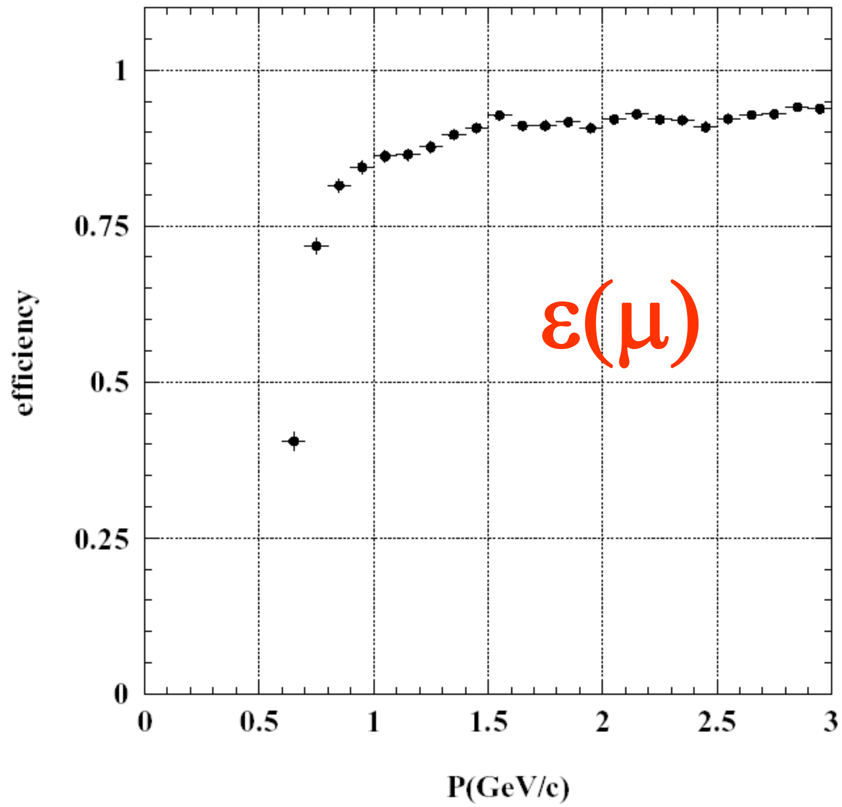


Fig. 109. Muon detection efficiency vs. momentum in KLM.

fake probability

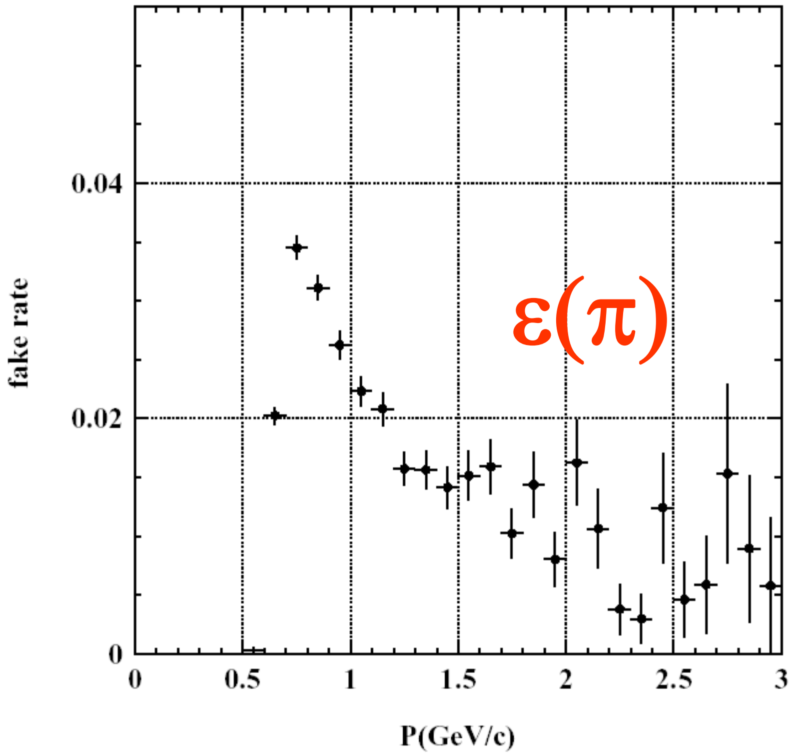
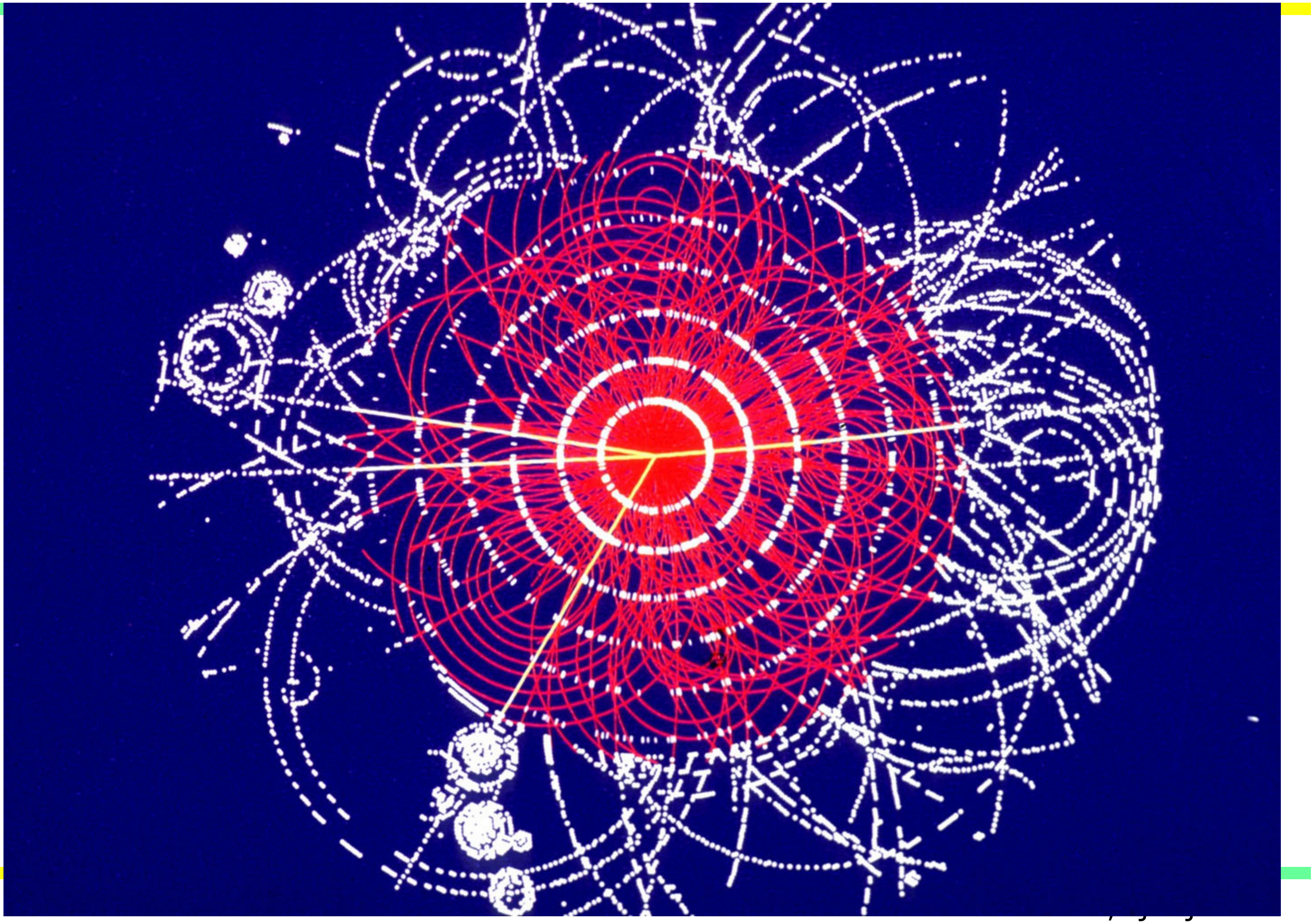
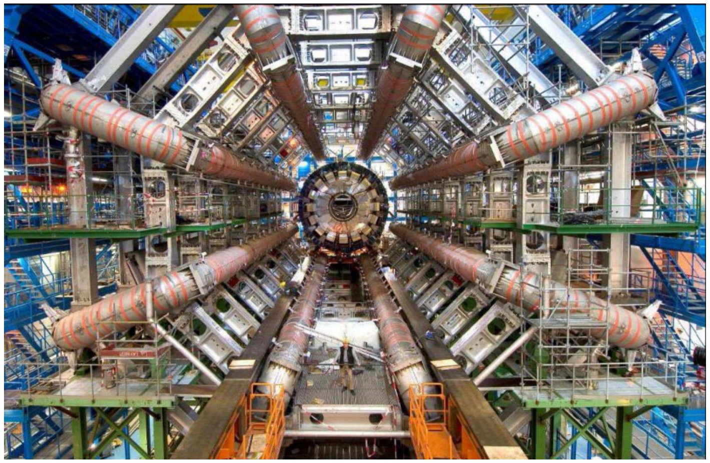


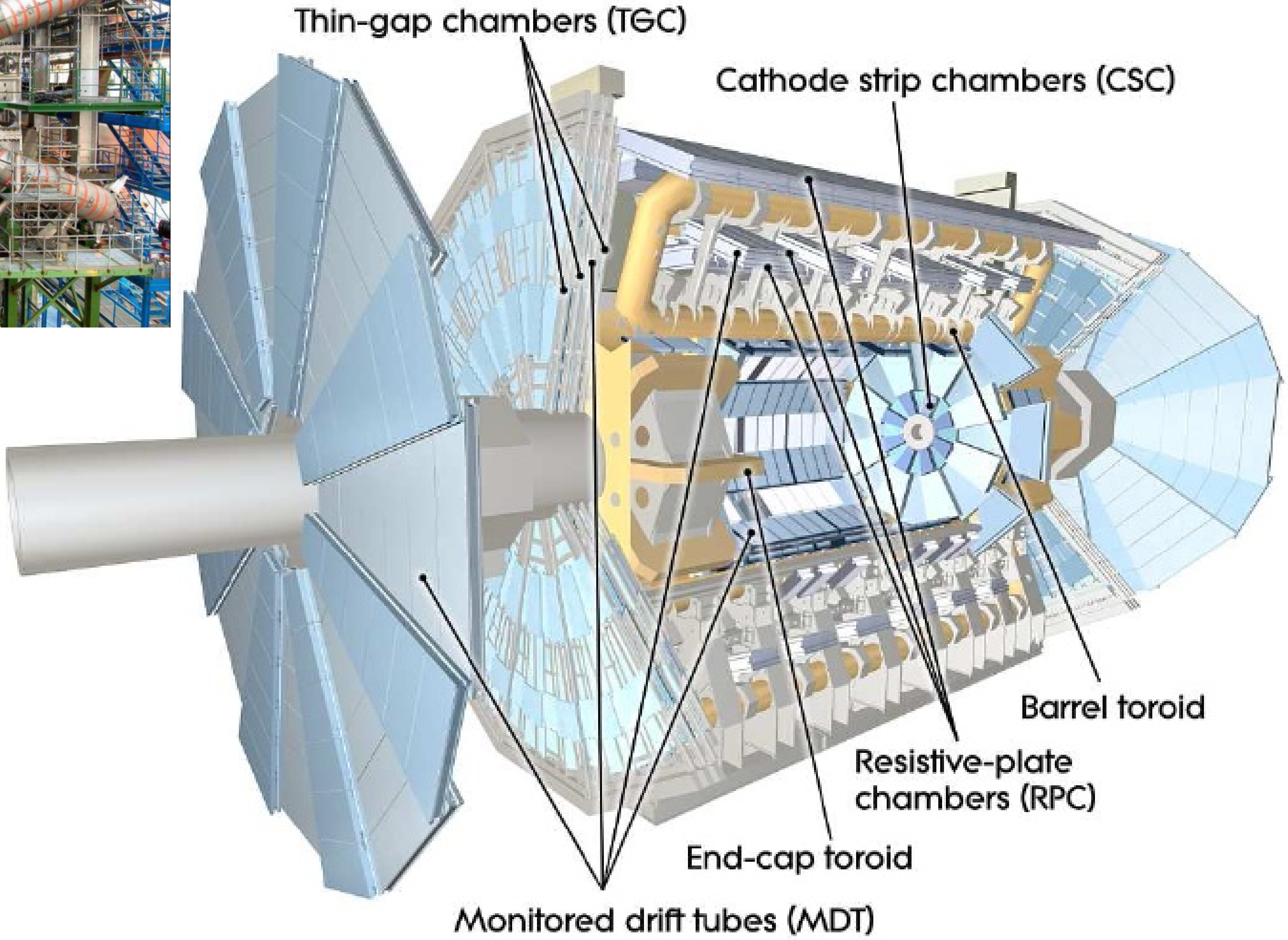
Fig. 110. Fake rate vs. momentum in KLM.

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



Identification of muons in ATLAS





- Identify muons
- Measure their momentum

Components of an experimental apparatus (‘spectrometer’)

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

Calorimeters (measurement of energy)

Calorimetry:

Energy measurement by total absorption, combined with spatial reconstruction.

Calorimetry is a “destructive” method

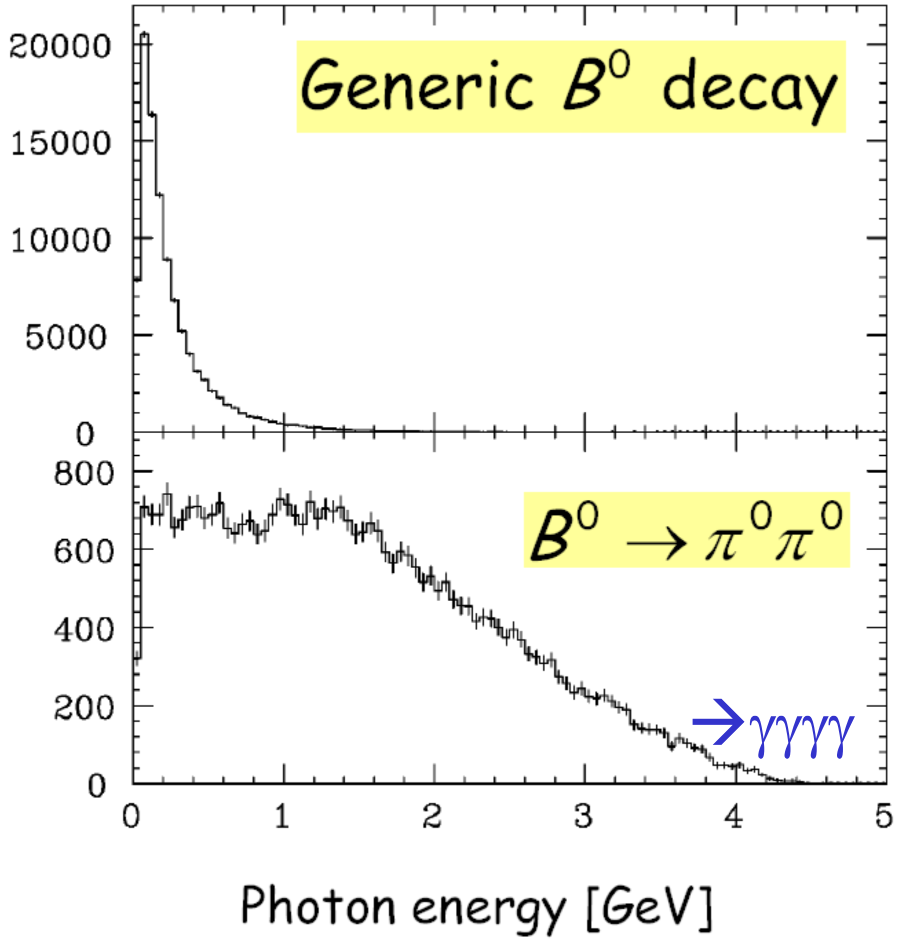
Detector response α E

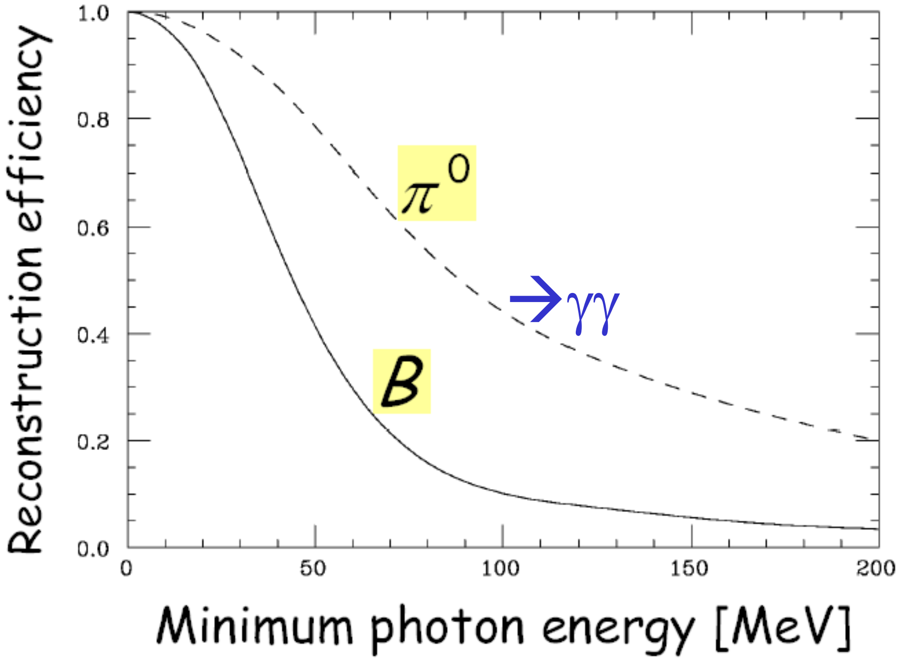
Calorimetry works both for
- charged (e± and hadrons) and
- neutral particles (n,γ)

Basic mechanism: formation of electromagnetic or hadronic showers.

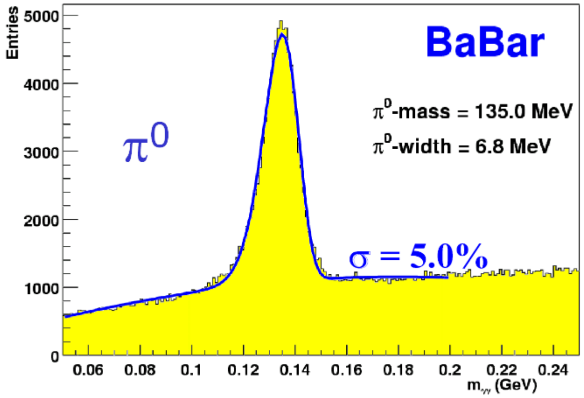
Finally, the energy is converted into ionization or excitation of the matter.

Requirements at a B factory: Photons





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



Calorimetry Design: B factories

Requirements

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

Constraints

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

Implementation

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

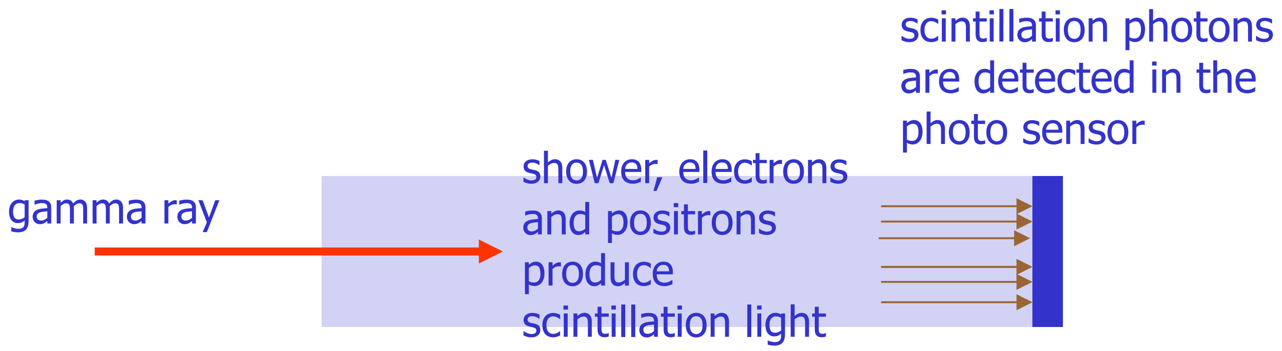
Thin structural cage to minimize material between and in front of crystals

Requirements: Photons

$\pi^0 \rightarrow \gamma\gamma$ Need to reconstruct neutral pions from gamma pairs

- Should also work for low energy gammas (photons)
- Excellent energy resolution

Detection of photons: scintillator crystal + photosensor



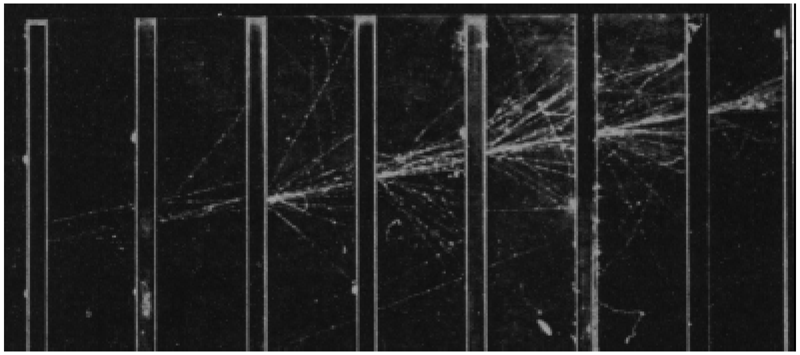
scintillation photons
are detected in the
photo sensor

gamma ray

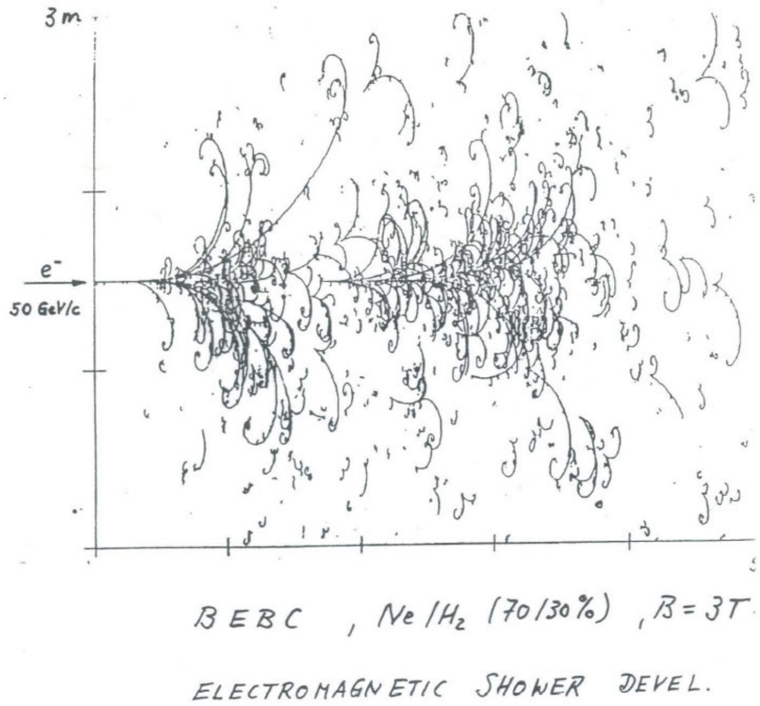
shower, electrons
and positrons
produce
scintillation light

How does a shower develop? Gamma → e+e- pair production → bremstrahlung gammas → e+e- pair production → ….

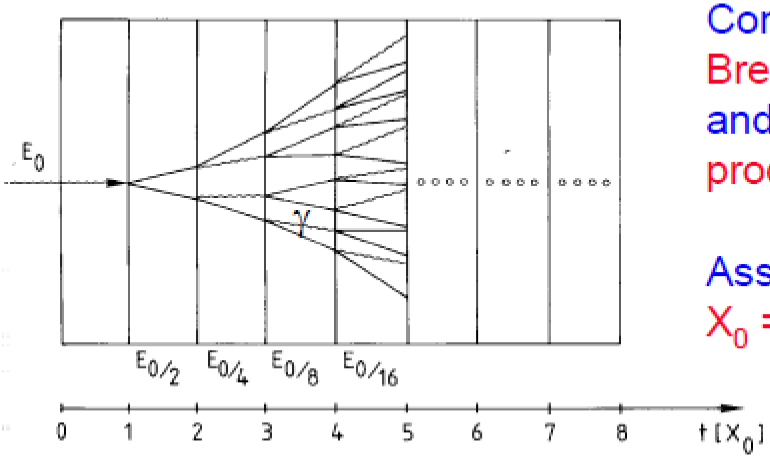
Electromagnetic Cascades (showers)



Electron shower in a cloud chamber with lead absorbers



Simple qualitative model



Consider only Bremsstrahlung and pair production.

Assume:
$X_0 = \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

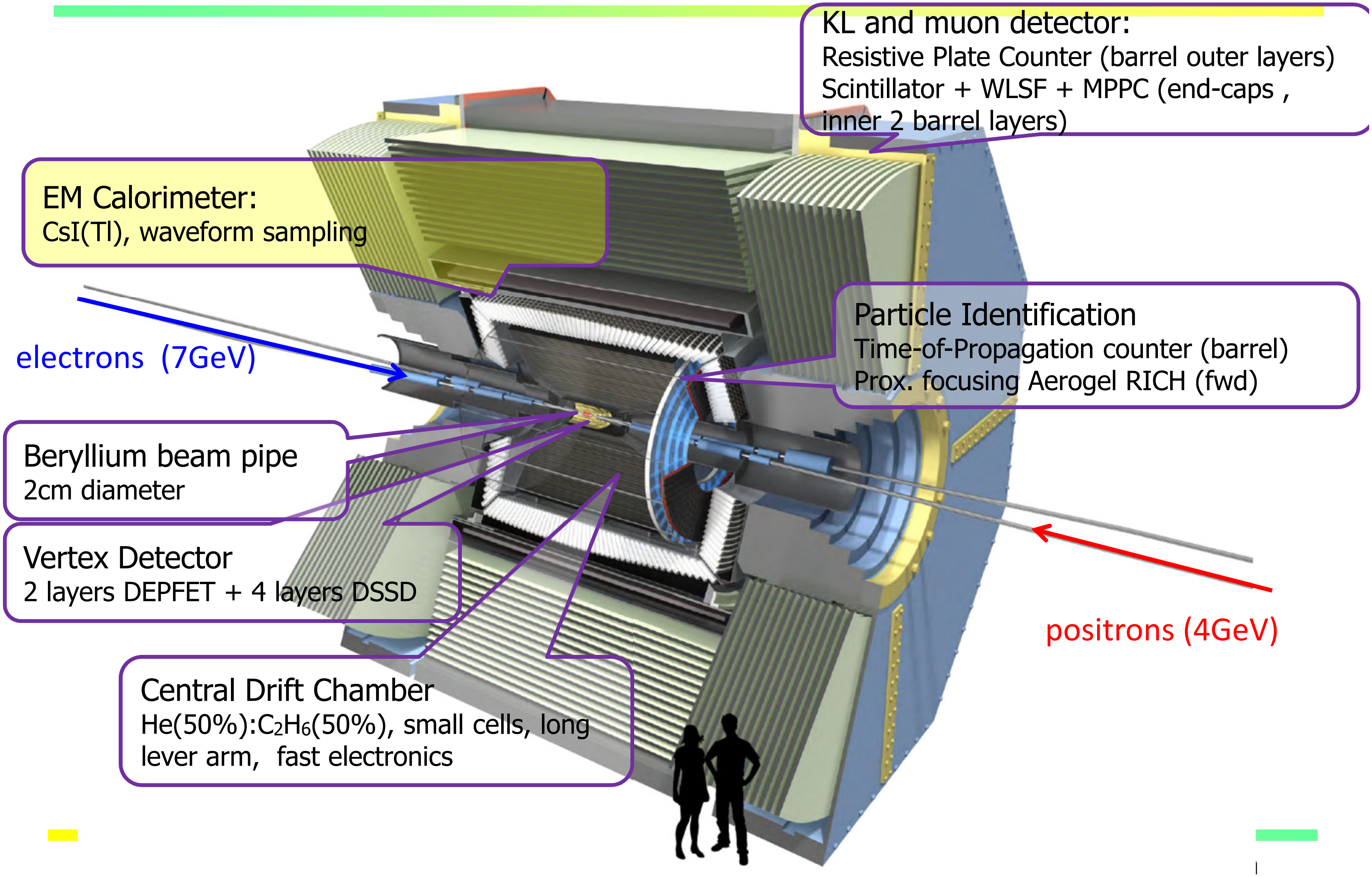
Process continues until $E(t)<E_c$

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \qquad N^{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption.

→ Calorimeter size depends only logarithmically on E_0

Calorimetry in Belle II



KL and muon detector:
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Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

◆ Energy resolution of a calorimeter (intrinsic limit)

$$N^{total} \propto \frac{E_0}{E_c}$$ total number of track segments

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N)}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E_0}}$$ holds also for hadron calorimeters

Also spatial and angular resolution scale like $1/\sqrt{E}$

Relative energy resolution of a calorimeter improves with E_0

More general:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term

Constant term

Inhomogenities
Bad cell inter-calibration
Non-linearities

Quality factor !

Noise term

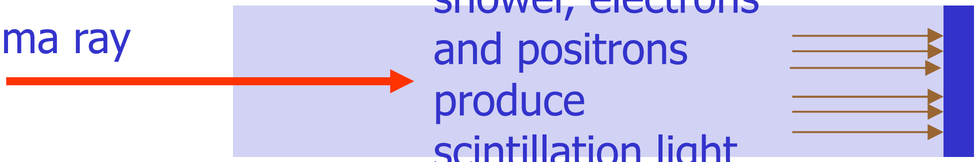
Electronic noise
radioactivity
pile up

Requirements: Photons

$\pi^0 \rightarrow \gamma\gamma$ Need to reconstruct neutral pions from gamma pairs

- Also gammas (photons) with low energy
- Excellent energy resolution

Detection of photons: scintillator crystal + photosensor



scintillation photons are detected in the photo sensor

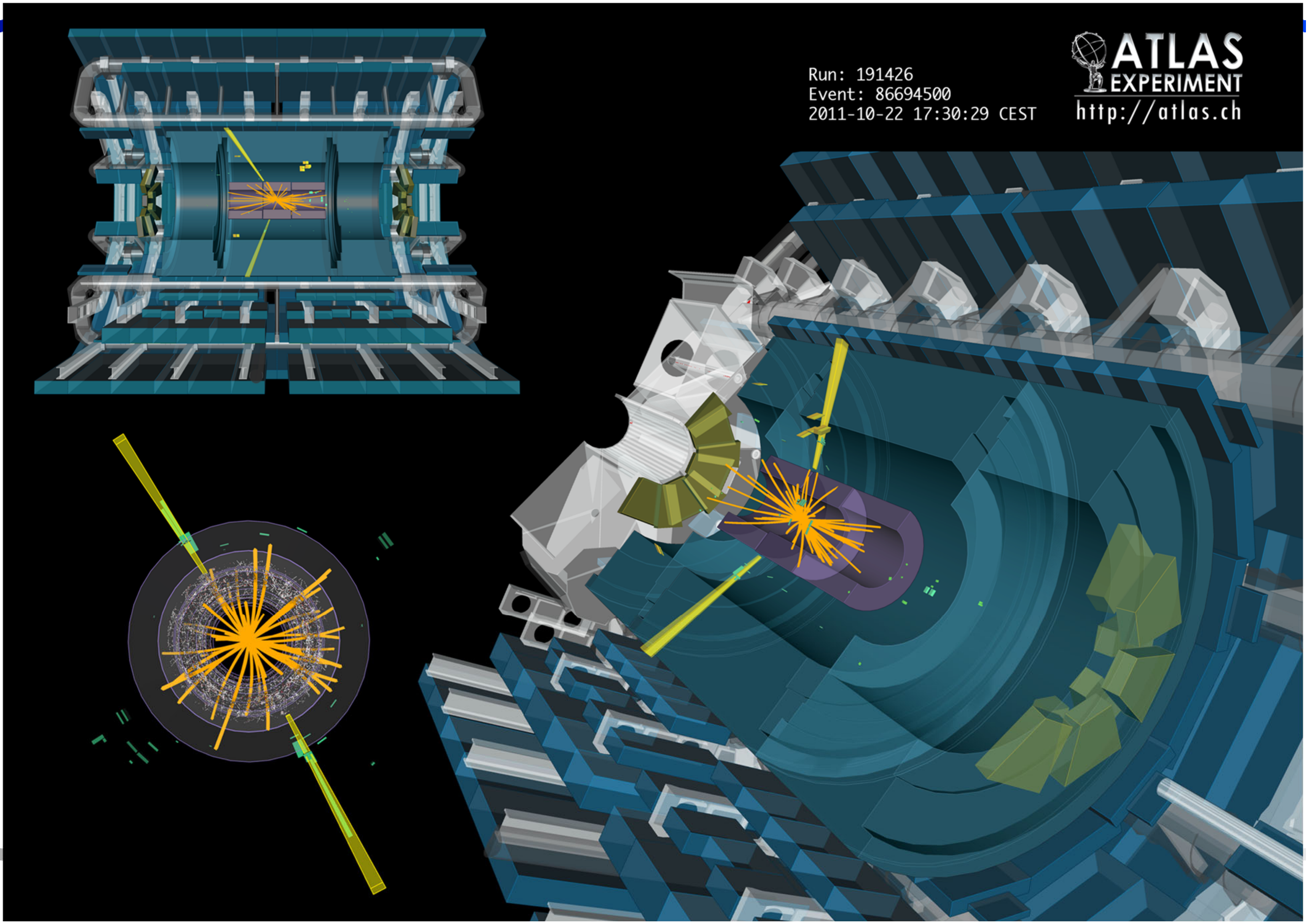
gamma ray

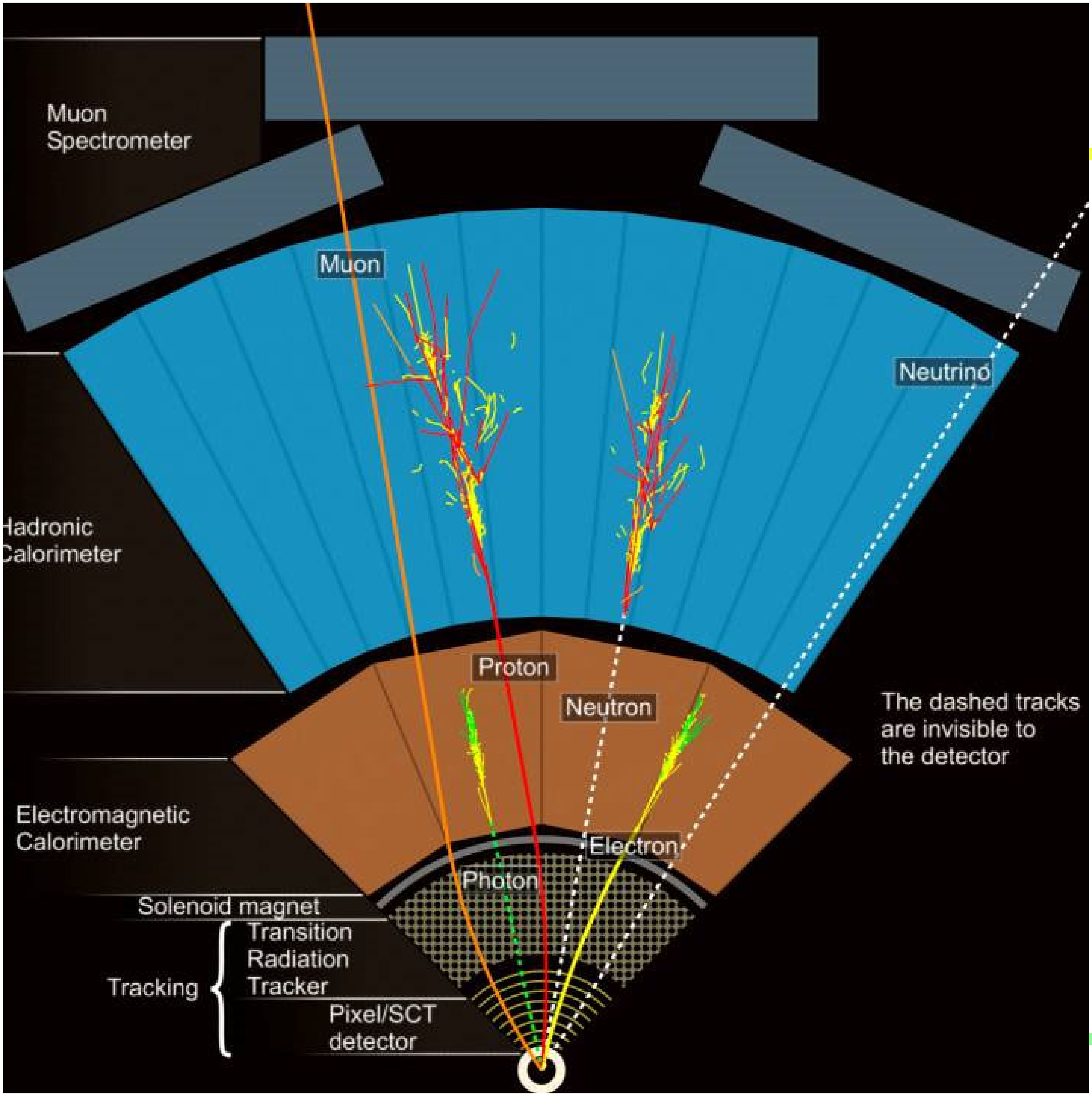
shower, electrons and positrons produce scintillation light

Need:

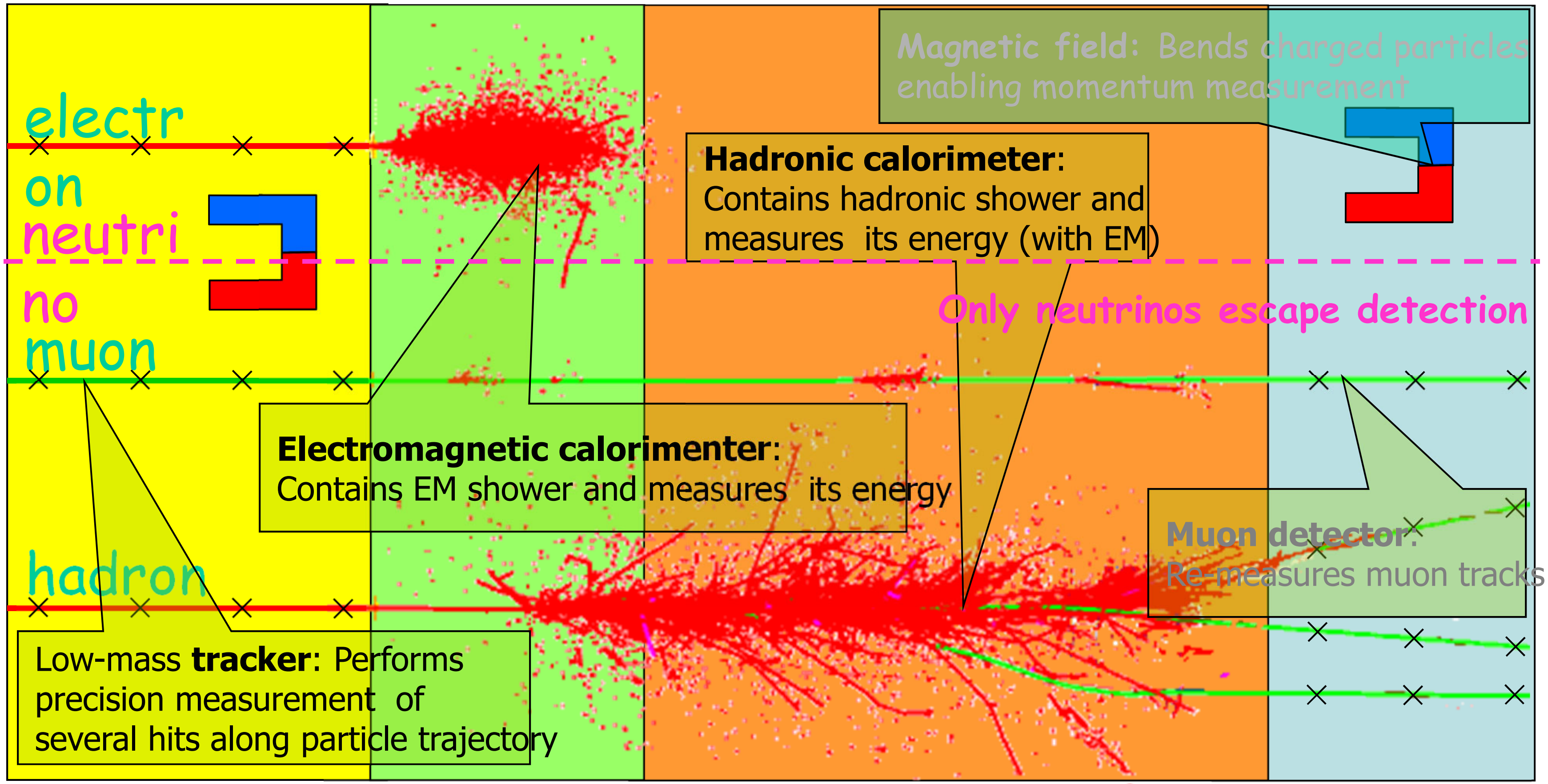
- High light yield (many scintillation photons) ← $\sigma(E)/E \ \alpha \ N^{-1/2}$
- photo-sensor with low noise (noise spoils resolution)

Higgs boson decay to two high-energy gammas, H → $\gamma\gamma$, as seen by the ATLAS detector




Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector

Generic LHC Detector for all Particles



Magnetic field: Bends charged particles enabling momentum measurement

Hadronic calorimeter: Contains hadronic shower and measures its energy (with EM)

Only neutrinos escape detection

Electromagnetic calorimenter: Contains EM shower and measures its energy

Muon detector: Re-measures muon tracks

Low-mass **tracker**: Performs precision measurement of several hits along particle trajectory

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

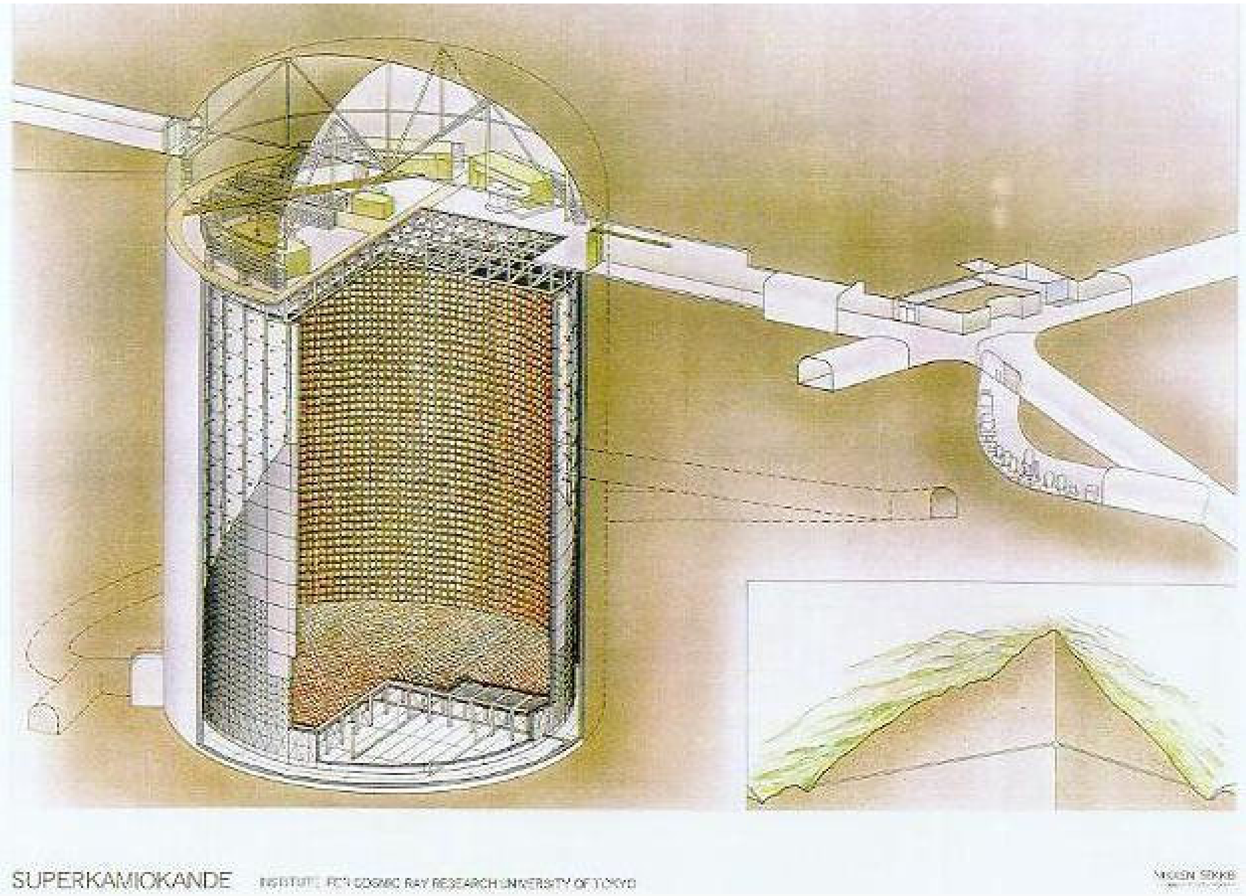
Probability for interaction in 100m of water = 4 10^{-16}

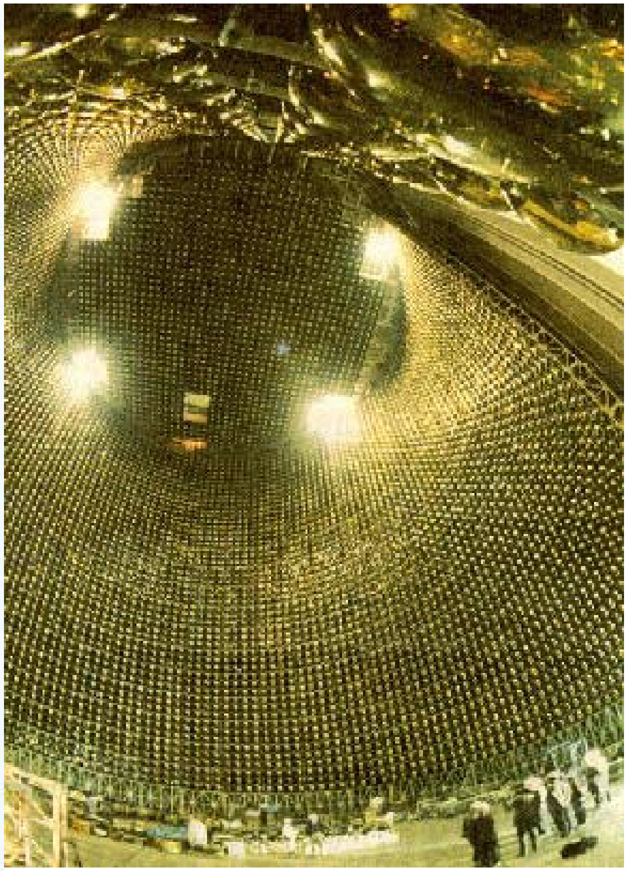
Not much better at high energies:

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

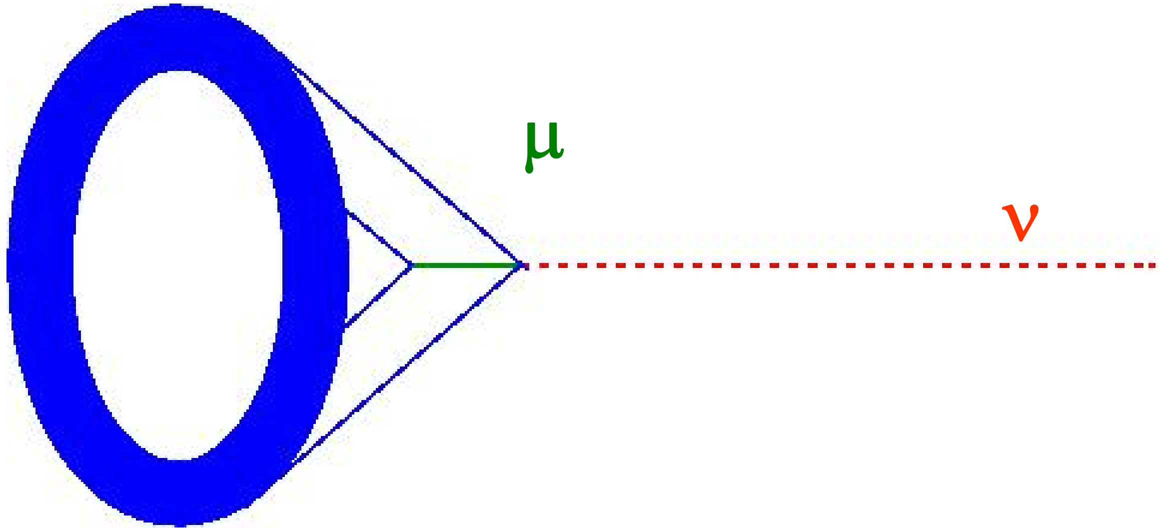
At 100 GeV, still 11 orders below the proton-proton cross section

Superkamiokande: an example of a neutrino detector





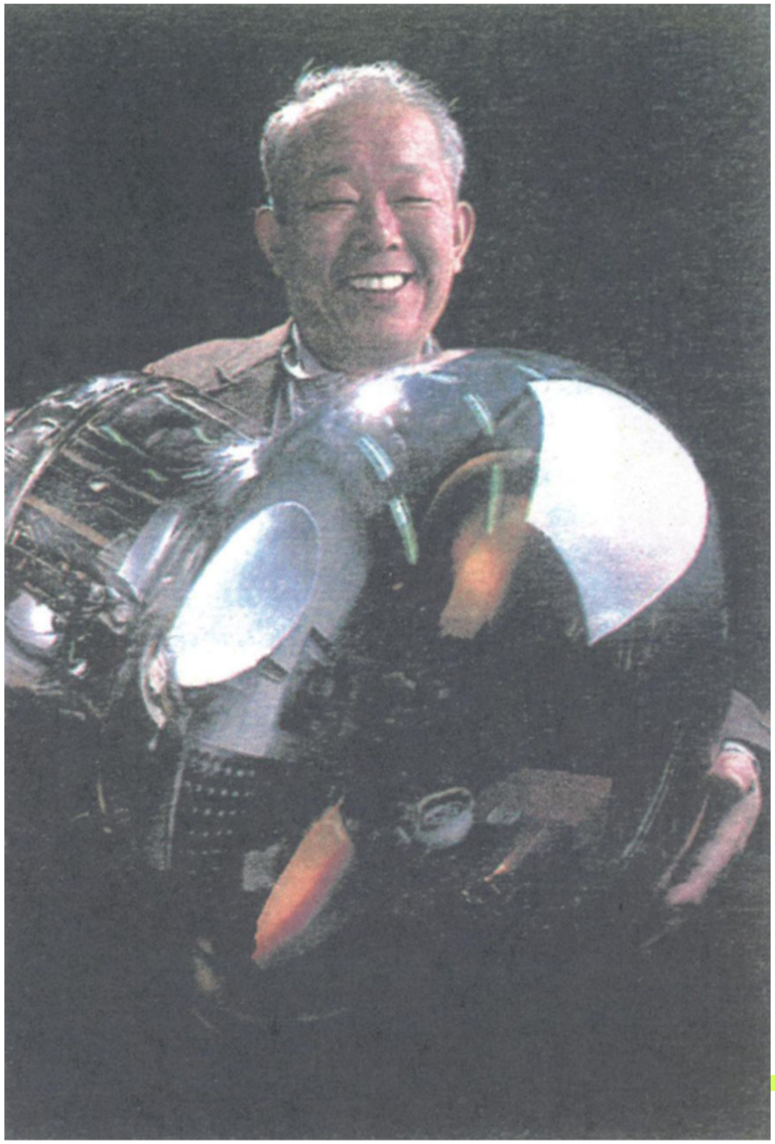
Superkamiokande: detection of electrons and muons



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

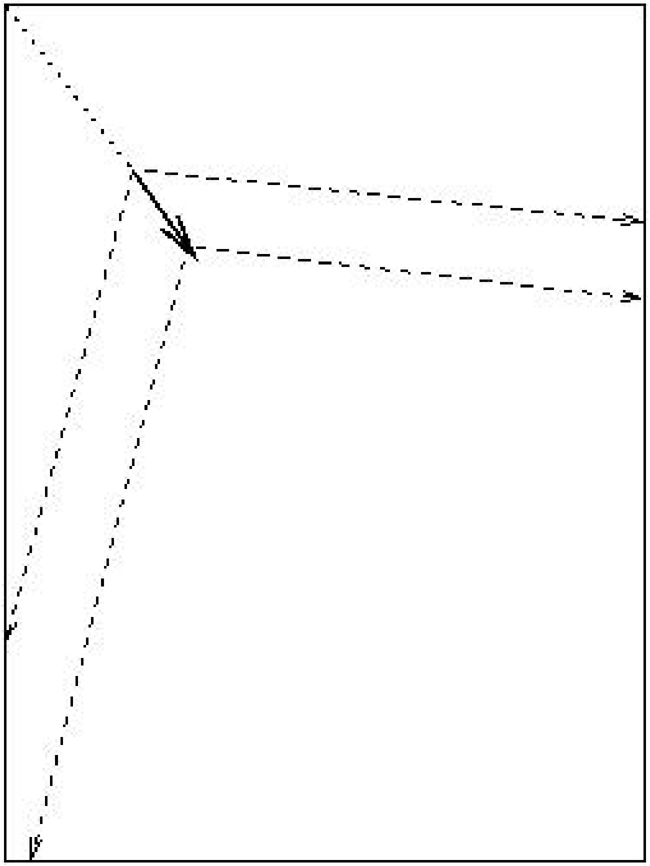
Muon vs electron

Cherenkov photons from a muon track:

Example: 1GeV muon neutrino

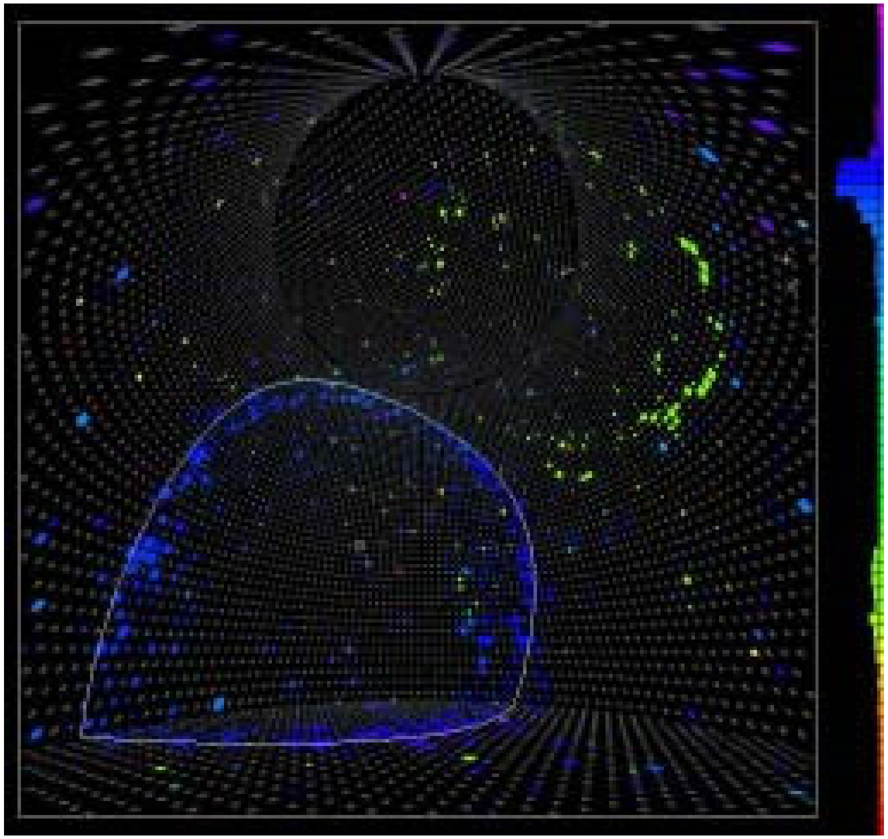
Track length of the resulting muon: L=E/(dE/dx)= =1GeV/(2MeV/cm)=5m

→ a well defined "ring" on the walls

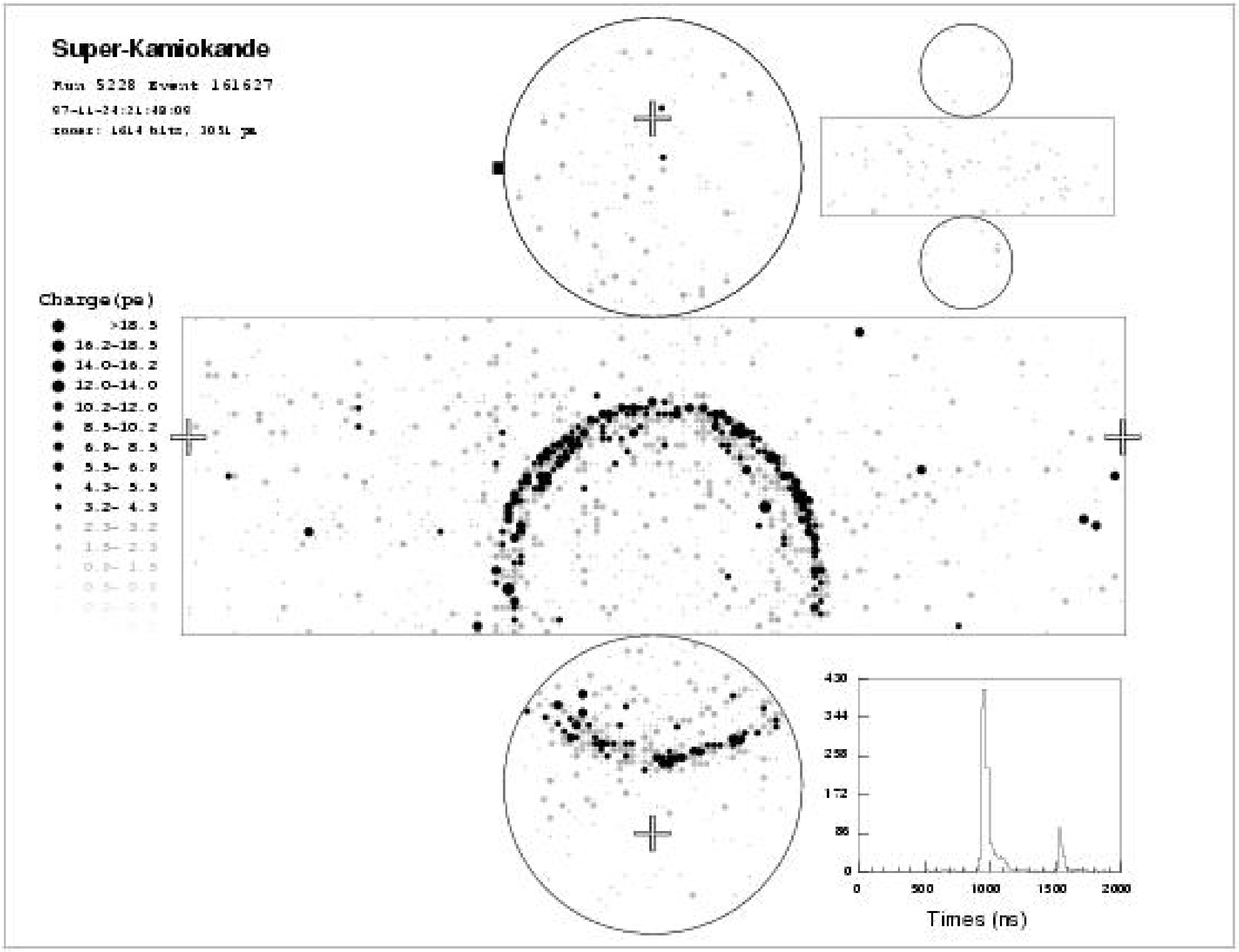


Superkamiokande: muon event

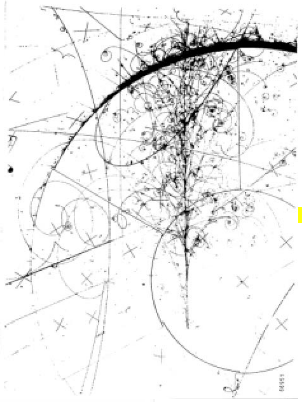
Muon ‘ring’ as seen by the photon detectors



Muon event: photon detector cillinder walls



Cherenkov photons from an electron track



Electron starts a shower!

Cherenkov photons from an electron generated shower

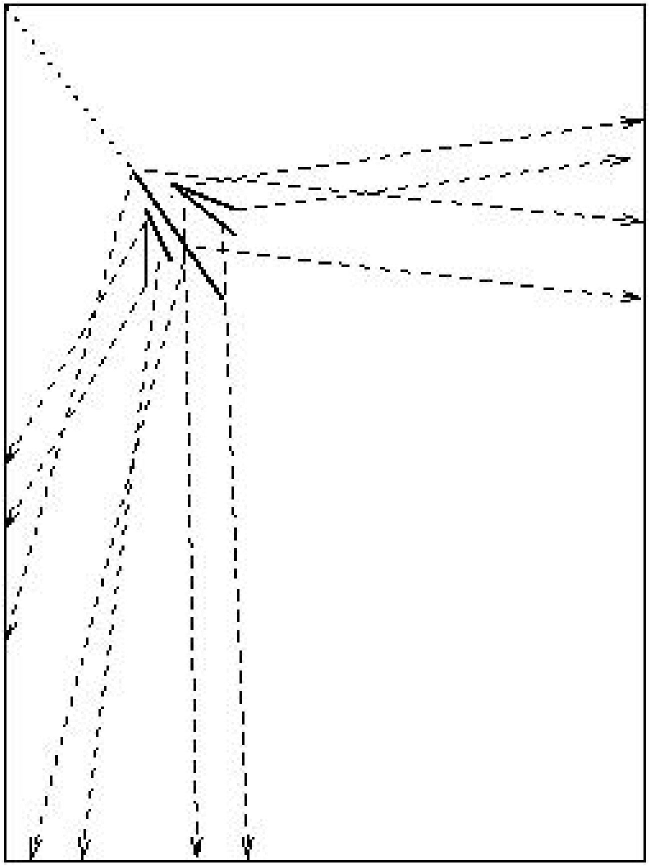
Example: 1GeV el. neutrino

Shower length:

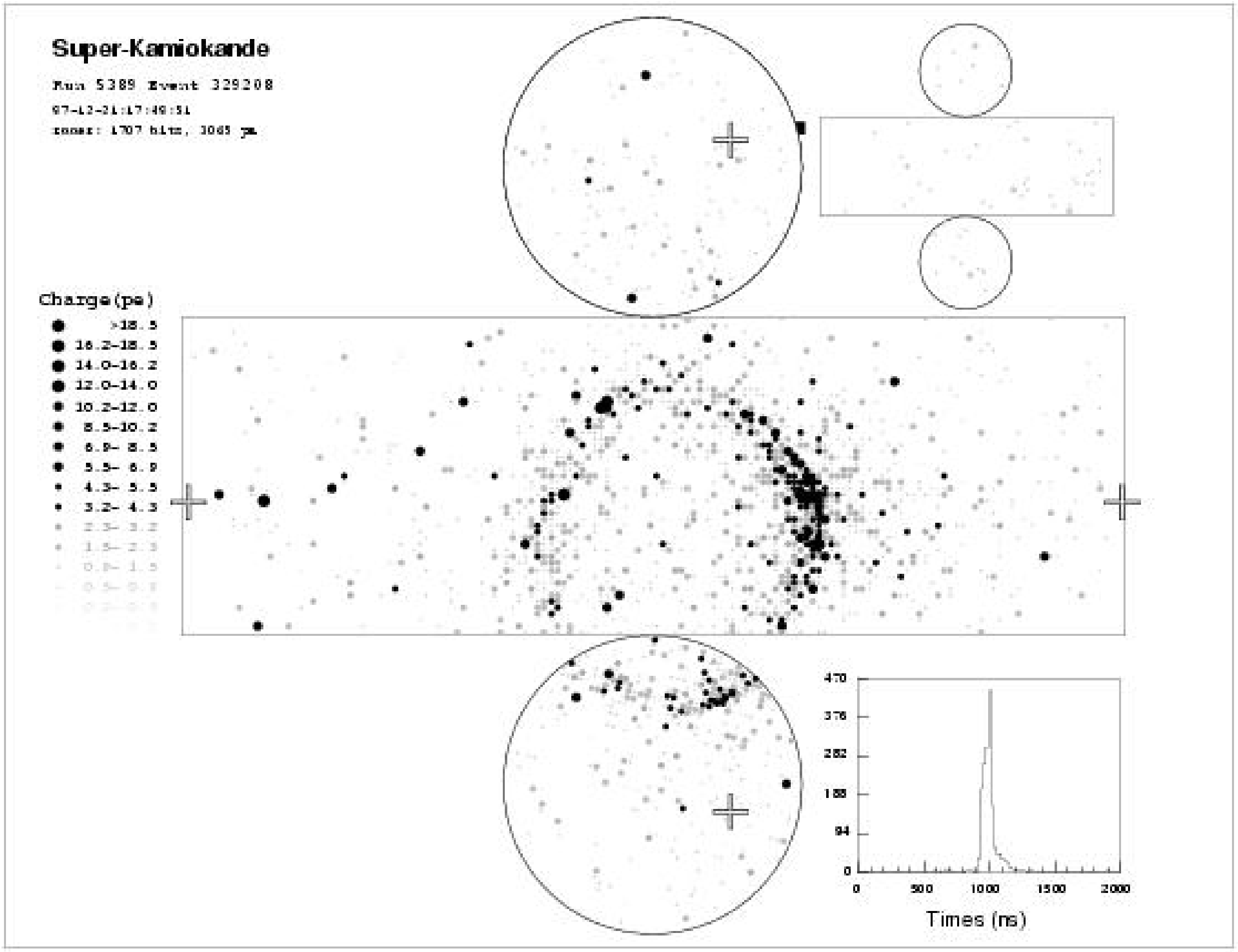
$L=X_0*\log_2(E/E_{crit})= 36cm*\log_2(1GeV/10MeV) =2.5m$

Shower particles are not parallel to each other

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



Electron event: blurred ring

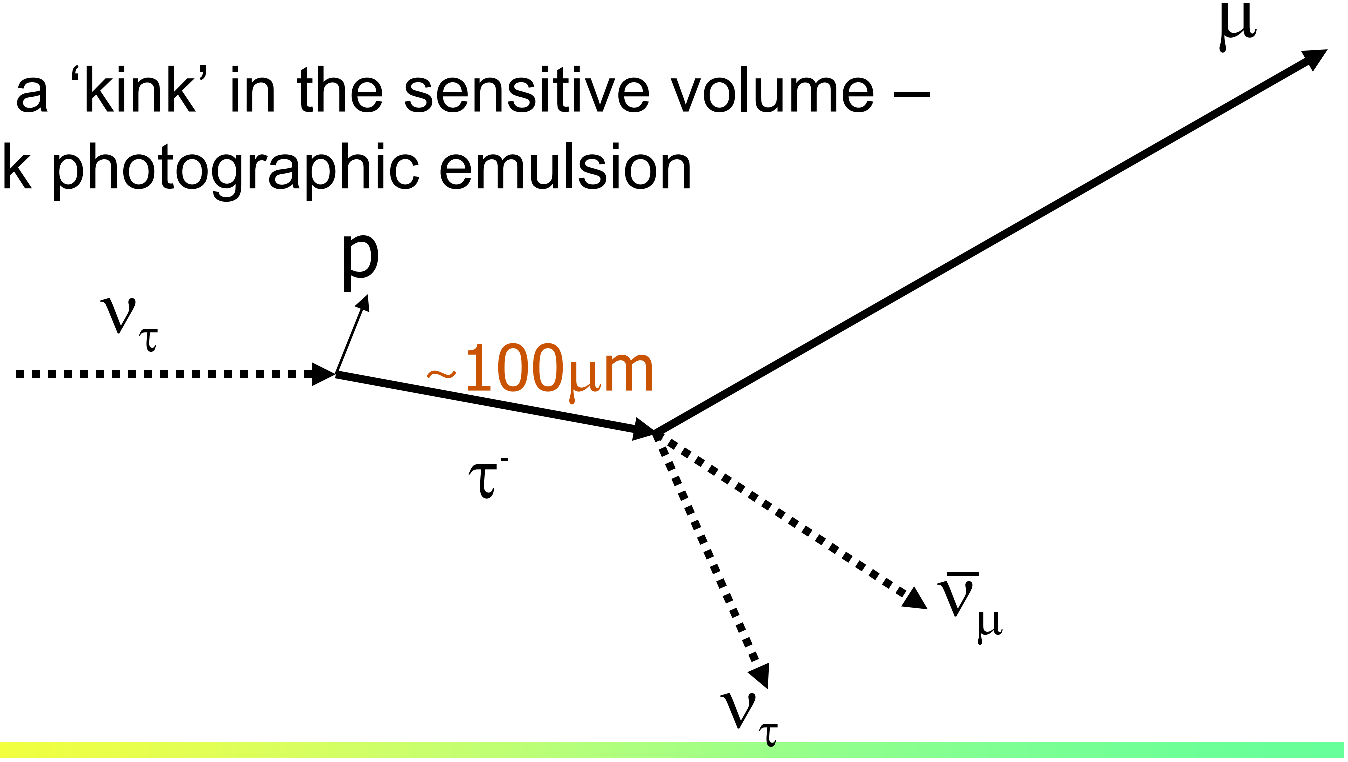


Backup slides

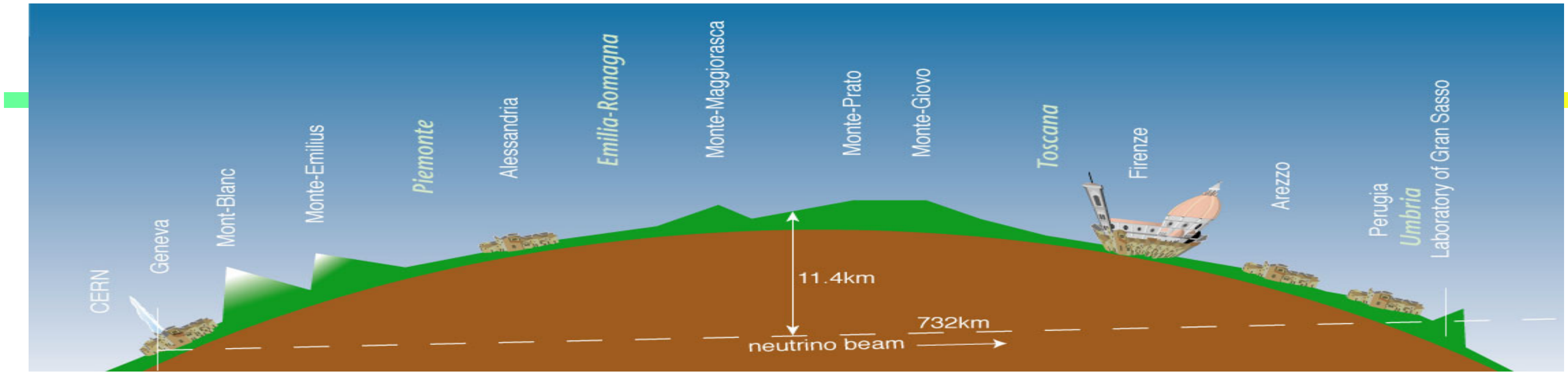
Detection of τ neutrinos

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

- Detect and identifiy mion
- Extrapolate back
- Check for a ‘kink’ in the sensitive volume – e.g. a thick photographic emulsion

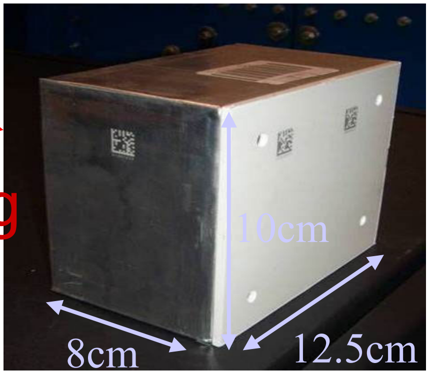


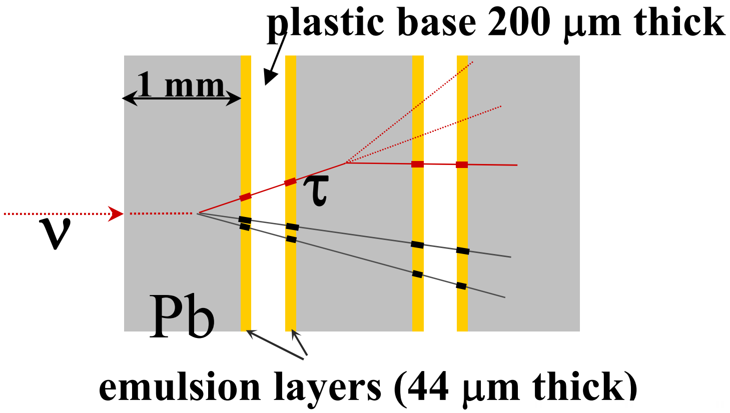
Detection of τ neutrinos: OPERA



ν

8.3 kg
$10X_0$





plastic base 200 μm thick

1 mm

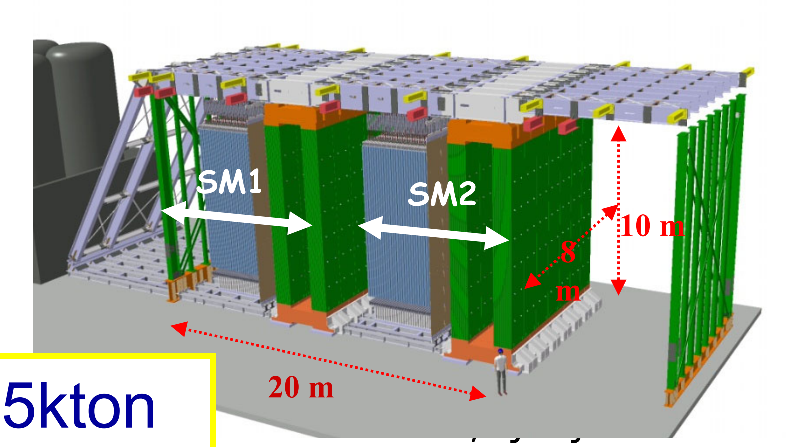
τ

ν

Pb

emulsion layers (44 μm thick)

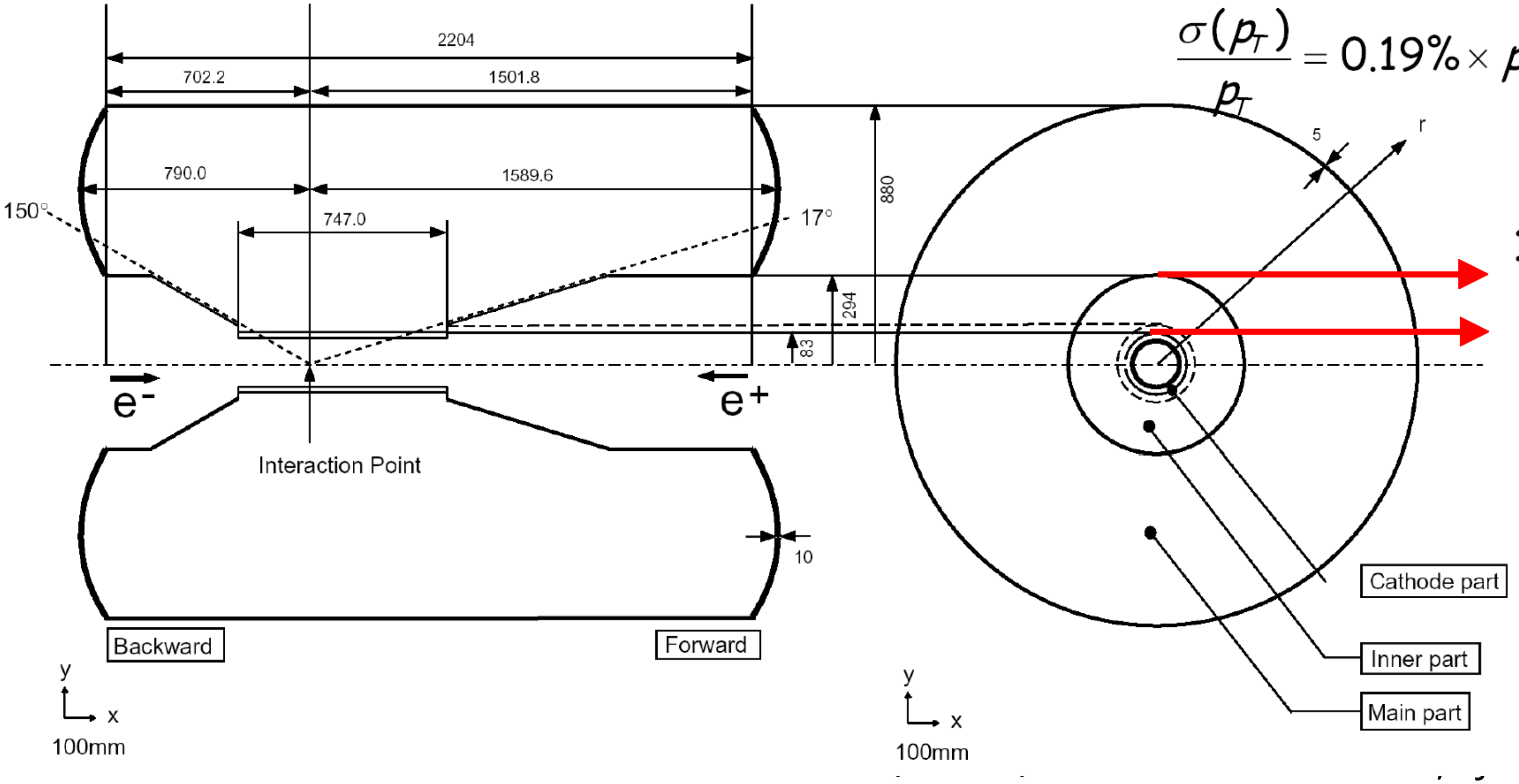
Detection unit: a brick with 56 Pb sheets (1mm) + 57 emulsion films



155000 bricks, detector tot. mass = 1.35kton

Belle central drift chamber

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



$$\frac{\sigma(p_T)}{p_T} = 0.19\% \times p_T \oplus \frac{0.30\%}{\beta}$$

15 layers:
8.8-22.4
cm radius

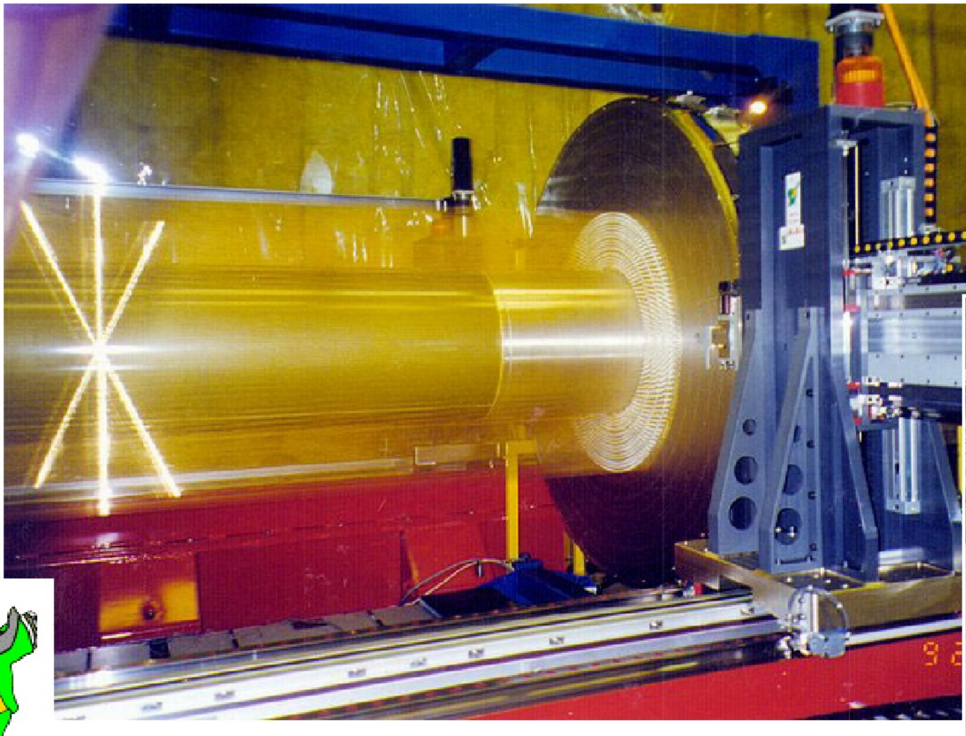
Tracking: BaBar drift chamber

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

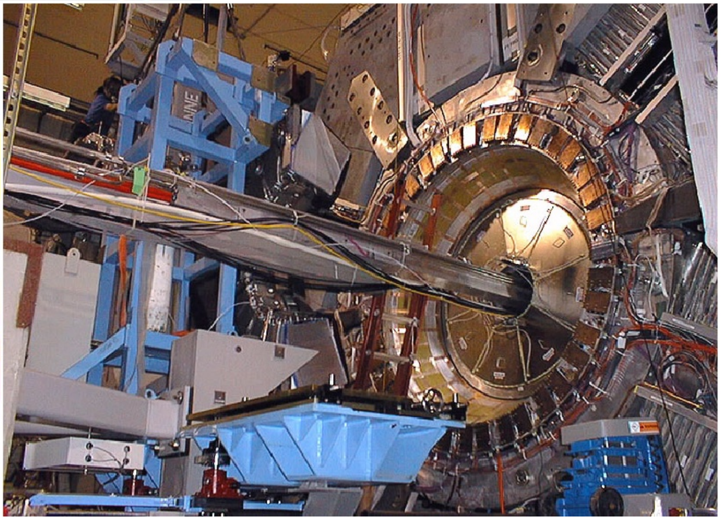
Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate

Particle identification from ionization loss (7% resolution)

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



16 axial, 24 stereo layers



6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A\rangle$	Nucl.coll. length λ_T $\{\text{g cm}^{-2}\}$	Nucl.inter. length λ_I $\{\text{g cm}^{-2}\}$	Rad.len. X_0 $\{\text{g cm}^{-2}\}$	$dE/dx\|_{\text{min}}$ $\{\text{MeV g}^{-1}\text{cm}^2\}$	Density $\{\text{g cm}^{-3}\}$ $(\{\text{g}\ell^{-1}\})$	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	
Air (dry, 1 atm)			0.49919	61.3	90.1	36.62	(1.815)	(1.205)		78.80	
Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			

W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
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Shielding concrete			0.50274	65.1	97.5	26.57	1.711	2.300			
Borosilicate glass (Pyrex)			0.49707	64.6	96.5	28.17	1.696	2.230			
Lead glass			0.42101	95.9	158.0	7.87	1.255	6.220			
Standard rock			0.50000	66.8	101.3	26.54	1.688	2.650			
Methane (CH_4)			0.62334	54.0	73.8	46.47	(2.417)	(0.667)	90.68	111.7	[444.]
Ethane (C_2H_6)			0.59861	55.0	75.9	45.66	(2.304)	(1.263)	90.36	184.5	
Propane (C_3H_8)			0.58962	55.3	76.7	45.37	(2.262)	0.493(1.868)	85.52	231.0	
Butane (C_4H_{10})			0.59497	55.5	77.1	45.23	(2.278)	(2.489)	134.9	272.6	
Octane (C_8H_{18})			0.57778	55.8	77.8	45.00	2.123	0.703	214.4	398.8	
Paraffin ($CH_3(CH_2)_{n\approx23}CH_3$)			0.57275	56.0	78.3	44.85	2.088	0.930			
Nylon (type 6, 6/6)			0.54790	57.5	81.6	41.92	1.973	1.18			
Polycarbonate (Lexan)			0.52697	58.3	83.6	41.50	1.886	1.20			
Polyethylene ($[CH_2CH_2]_n$)			0.57034	56.1	78.5	44.77	2.079	0.89			
Polyethylene terephthalate (Mylar)			0.52037	58.9	84.9	39.95	1.848	1.40			
Polyimide film (Kapton)			0.51264	59.2	85.5	40.58	1.820	1.42			
Polymethylmethacrylate (acrylic)			0.53937	58.1	82.8	40.55	1.929	1.19			1.49
Polypropylene			0.55998	56.1	78.5	44.77	2.041	0.90			
Polystyrene ($[C_6H_5CHCH_2]_n$)			0.53768	57.5	81.7	43.79	1.936	1.06			1.59
Polytetrafluoroethylene (Teflon)			0.47992	63.5	94.4	34.84	1.671	2.20			
Polyvinyltoluene			0.54141	57.3	81.3	43.90	1.956	1.03			1.58
Aluminum oxide (sapphire)			0.49038	65.5	98.4	27.94	1.647	3.970	2327.	3273.	1.77
Barium flouride (BaF_2)			0.42207	90.8	149.0	9.91	1.303	4.893	1641.	2533.	1.47
Bismuth germanate (BGO)			0.42065	96.2	159.1	7.97	1.251	7.130	1317.		2.15
Carbon dioxide gas (CO_2)			0.49989	60.7	88.9	36.20	1.819	(1.842)			[449.]
Solid carbon dioxide (dry ice)			0.49989	60.7	88.9	36.20	1.787	1.563	Sublimes at 194.7 K		
Cesium iodide (CsI)			0.41569	100.6	171.5	8.39	1.243	4.510	894.2	1553.	1.79
Lithium fluoride (LiF)			0.46262	61.0	88.7	39.26	1.614	2.635	1121.	1946.	1.39
Lithium hydride (LiH)			0.50321	50.8	68.1	79.62	1.897	0.820	965.		
Lead tungstate ($PbWO_4$)			0.41315	100.6	168.3	7.39	1.229	8.300	1403.		2.20
Silicon dioxide (SiO_2, fused quartz)			0.49930	65.2	97.8	27.05	1.699	2.200	1986.	3223.	1.46
Sodium chloride (NaCl)			0.55509	71.2	110.1	21.91	1.847	2.170	1075.	1738.	1.54
Sodium iodide (NaI)			0.42697	93.1	154.6	9.49	1.305	3.667	933.2	1577.	1.77
Water (H_2O)			0.55509	58.5	83.3	36.08	1.992	1.000(0.756)	273.1	373.1	1.33
Silica aerogel			0.50093	65.0	97.3	27.25	1.740	0.200	(0.03 H_2O, 0.97 SiO_2)		