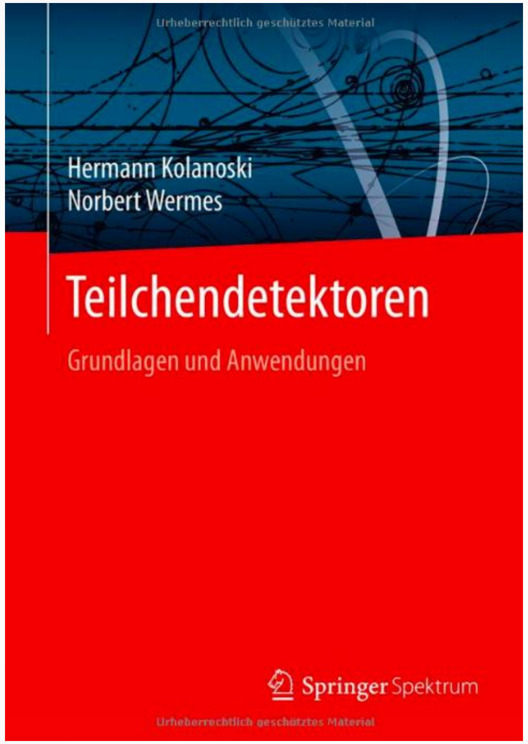
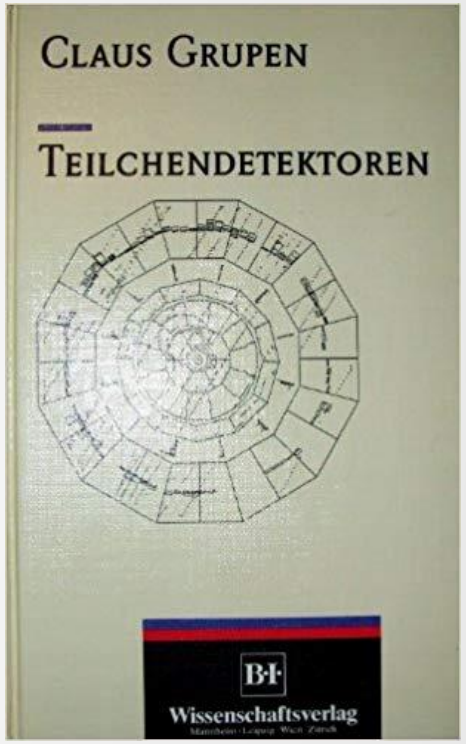
PARTICLE IDENTIFICATION

LECTURE 4 PART 5

REFERENCES

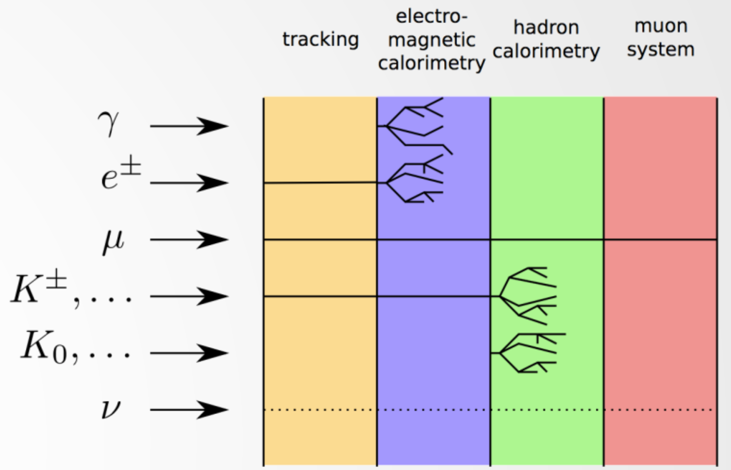
- Vorlesung M. Krammer
  “Teilchendetektoren”
  TU Wien, SS 2015
- Erika Garutti, DESY, Lecture
  “The Physics of
  Particle Detectors”
- Kolanoski, Wermes
  “Teilchendetektoren”, 2015
- K. Kleinknecht,
  “Detektoren für
  Teilchenstrahlung”
- C. Grupen,
  “Teilchendetektoren”, 1993



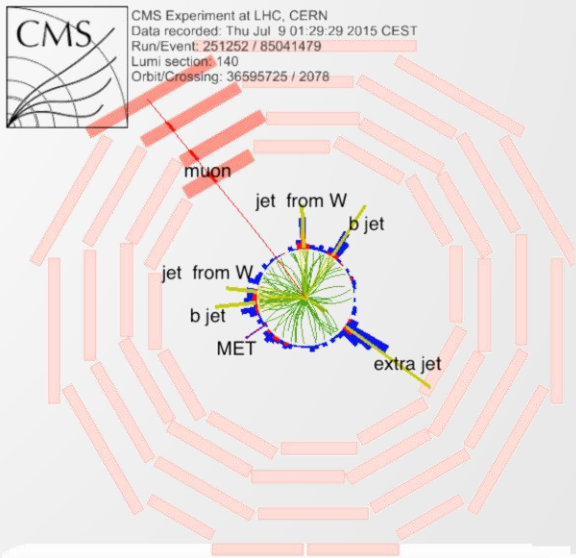


BASICS OF PARTICLE IDENTIFICATION

- We know already several methods to identify particles:
  - Identification of muons as the only charged particles penetrating the hadron calorimeter ⟶ calorimeter
  - Identify weakly interacting particles by "missing momentum" and "missing energy" (e.g. neutrinos) ⟶ hermetic calorimeter/detector systems
  - distinguish e.g. electrons from hadrons by their different calorimetry shower parameters
    - The CMS forward Quartz fibre clorimeter has fibres that start 11cm inwards of the absorber and are typically reached only be hadron showers
  - Identification of long lived particles by the reconstruction of secondary vertices (e.g. particles containing a c or b quark, or a tau lepton) ⟶ precise silicon vertex detectors

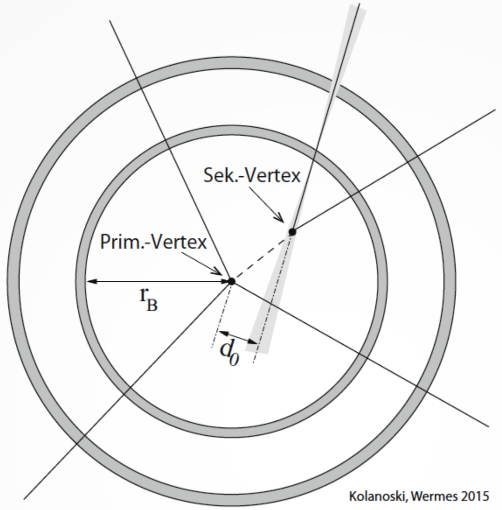


Large missing energy (MET) ⟶ ν candidate



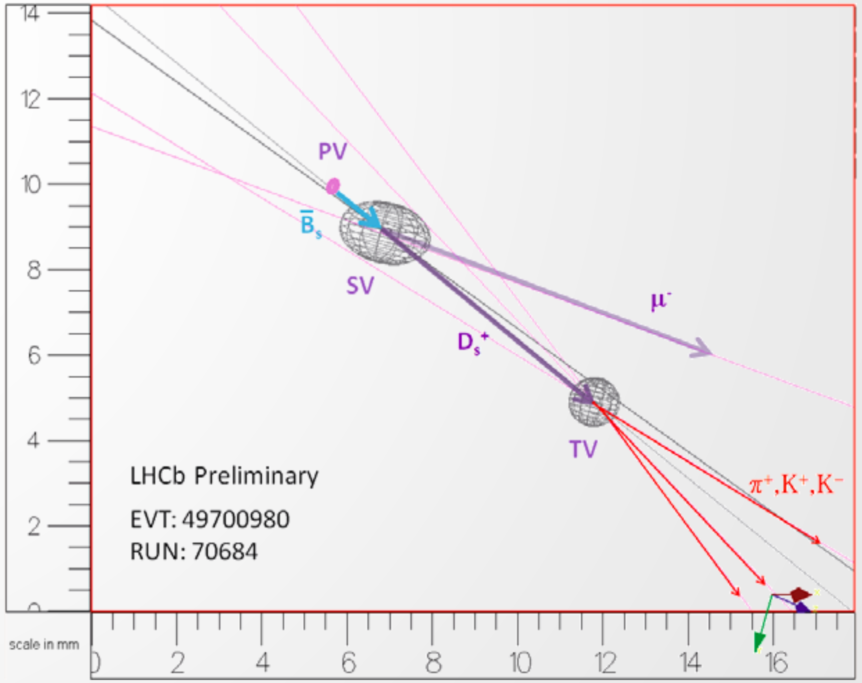
IDENTIFICATION OF LONG LIVED PARTICLES

- The precise extrapolation of the particle tracks toward the interaction point reveals the existence of two secondary vertices
- Most important experimental feature is the impact parameter resolution
- With current precision tracking and at high momenta, limited by multiple scattering in the beam pipe material
  - See 5 GeV pion example in lecture 3!



LHCb example event: At the primary pp vertex (PV), a B^0_s is created that decays at the secondary vertex (SV) to a D_s^+ which subsequently decays at the tertiary vertex (TV)

$$pp \to B_s^0 + X \to D_s^+ \mu^- \bar{\nu}_\mu + X$$
$$\to K^+ K^- \pi^+ + \mu^- \bar{\nu}_\mu + X$$



DISTINGUISHING BETWEEN PARTICLES

- Long-lived (=stable within the detector) particles can be indirectly inentified by their mass

	e	μ	$\pi^{+/-}$	K^+, K^-	p, n
Mass (MeV/c^2)	0,511	106	140	494	938, 940

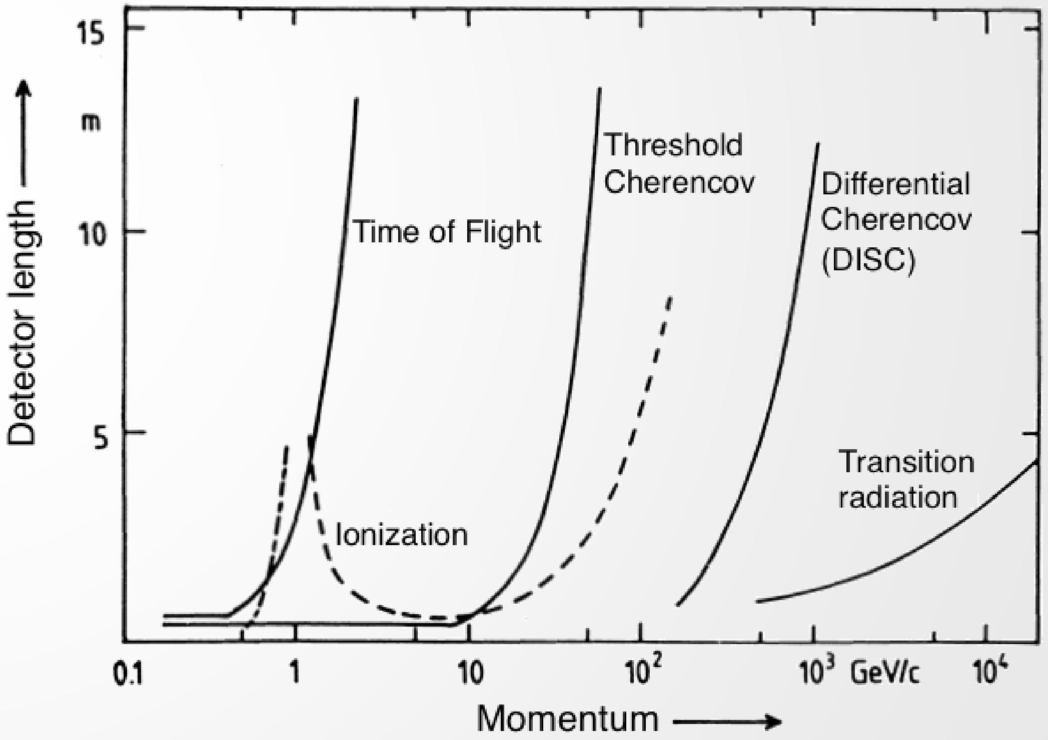
- In high energy experiments one measurement is usually the momentum p. The momentum of charges particles is calculated from the curvature of the particles track in a magnetic field (Spectrometer measurement, see Lecture 4.2)
- The second measurement is a variable depending on the particle velocity (TOF: v, Bethe-Bloch/TPC: β, or Čerenkov/Transition radiation: γ) or energy (calorimetry)
- combine the measurements and calculate mass m from

$$p = mc\beta\gamma,\ E^2 = c^2p^2 + m^2c^4$$

PARTICLE SEPARATION

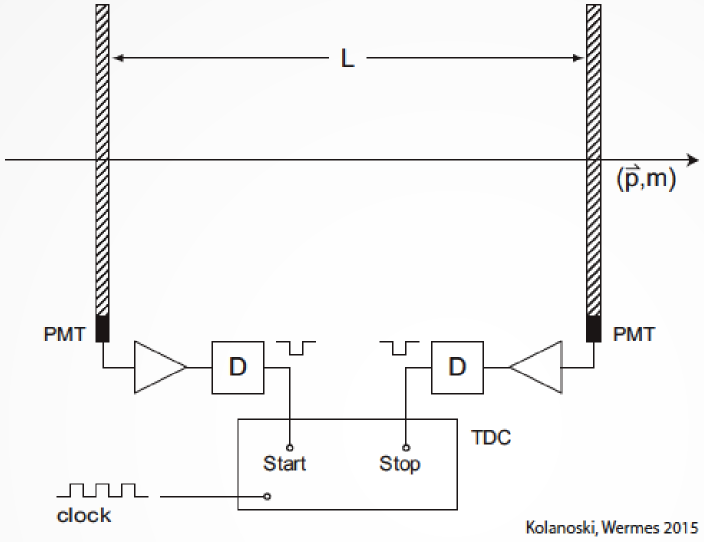
- Methods and instruments discussed in this chapter:
  - Time of flight measurements
  - Multiple ionisation measurements
  - Cherenkov counters
  - Transition radiation detectors
- Different methods are needed for different momenta ranges!

Separation of π and K, showing energy vs. the approximate length of the detector needed:



TIME-OF-FLIGHT (TOF) MEASUREMENTS

- Detectors used are mostly plastic scintillators, typical time resolution of about $\boldsymbol{\sigma}_t \approx 0{,}1 - 0{,}3$ ns
- Advantage:
  - particles traverse a constant length
  - simple operating principle



- time of flight

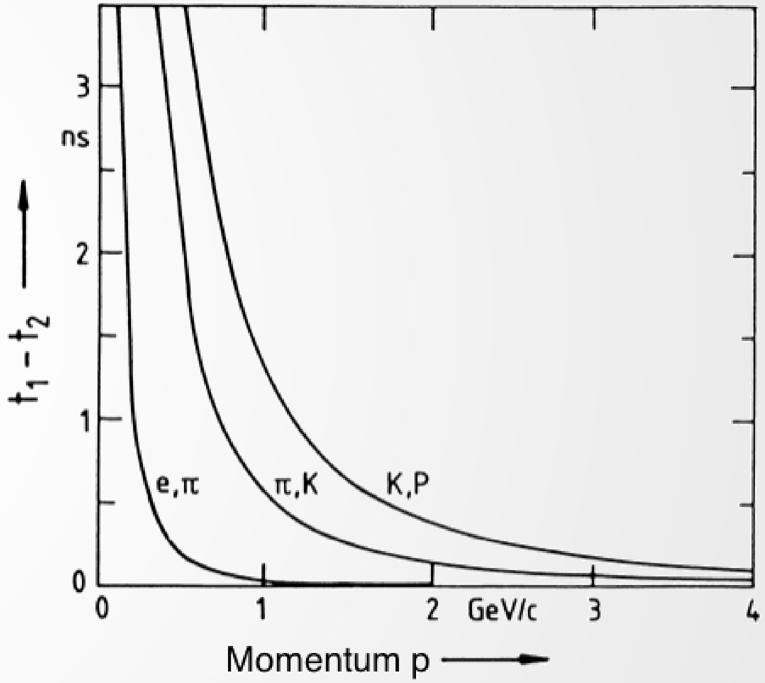
$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left(\sqrt{1+\frac{m_1^2c^2}{p^2}} - \sqrt{1+\frac{m_2^2c^2}{p^2}}\right)$$

ultrarelativistic:

$$\Delta t \approx \frac{\left(m_1^2 - m_2^2\right)Lc}{2p^2}$$

- For the constant time resolution need $L \propto p^2$!

Time of flight difference between particle species for a flight path of 1m:

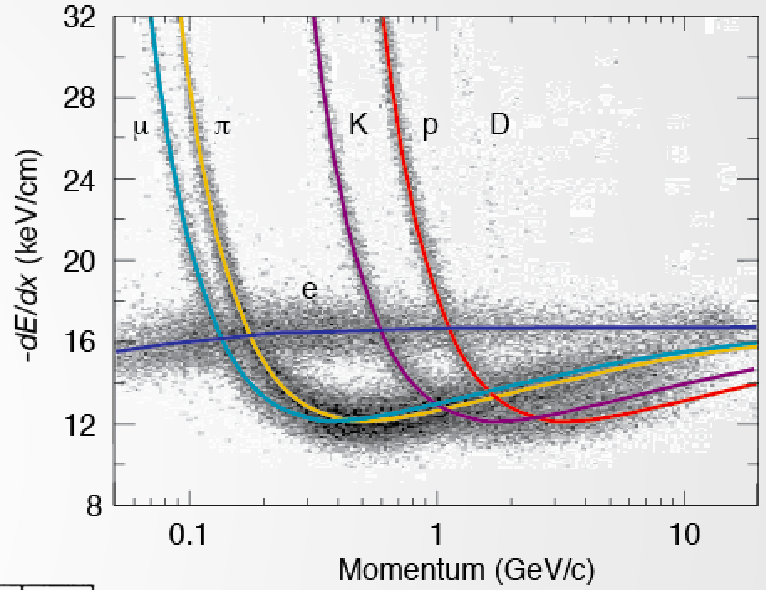


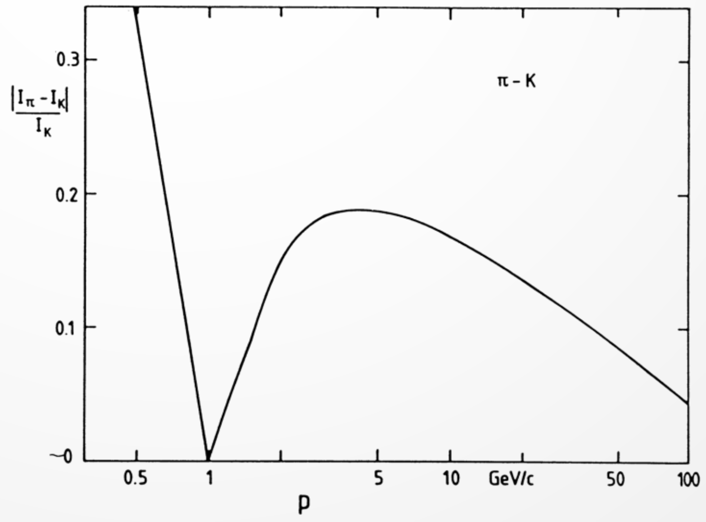
e.g.: Separate π from K with 4 standard deviations, σ_t = 0.3 ns ($\Delta t = 4\,\sigma_t$ = 1.2 ns)
⟶ L ~ 3 m at p = 1 GeV/c but already L ~12 m at p = 2 GeV/c

MULTIPLE IONISATION MEASUREMENTS

- Energy loss of particles (dE/dx) depends on momentum p (Bethe-Bloch formula).
- Multiple ionisation measurements are usually done in gas detectors, e.g. drift chamber, time projection chamber. (Some experiments use also the signals from the silicon sensors)
- The measurement of the ionisation is done at the same time as the measurement of the particle tracks.
- Discrimination is easy at low momentum ($1/\beta^2$ range of Bethe-Bloch formula).
- At high momentum (relativistic rise) the difference is only a few %
  - 5% at 100 GeV

Total energy loss -dE/dx for different particles measured in the PEP4/9 TPC ($Ar–CH_4$ = 80:20 @ 8.5 atm):

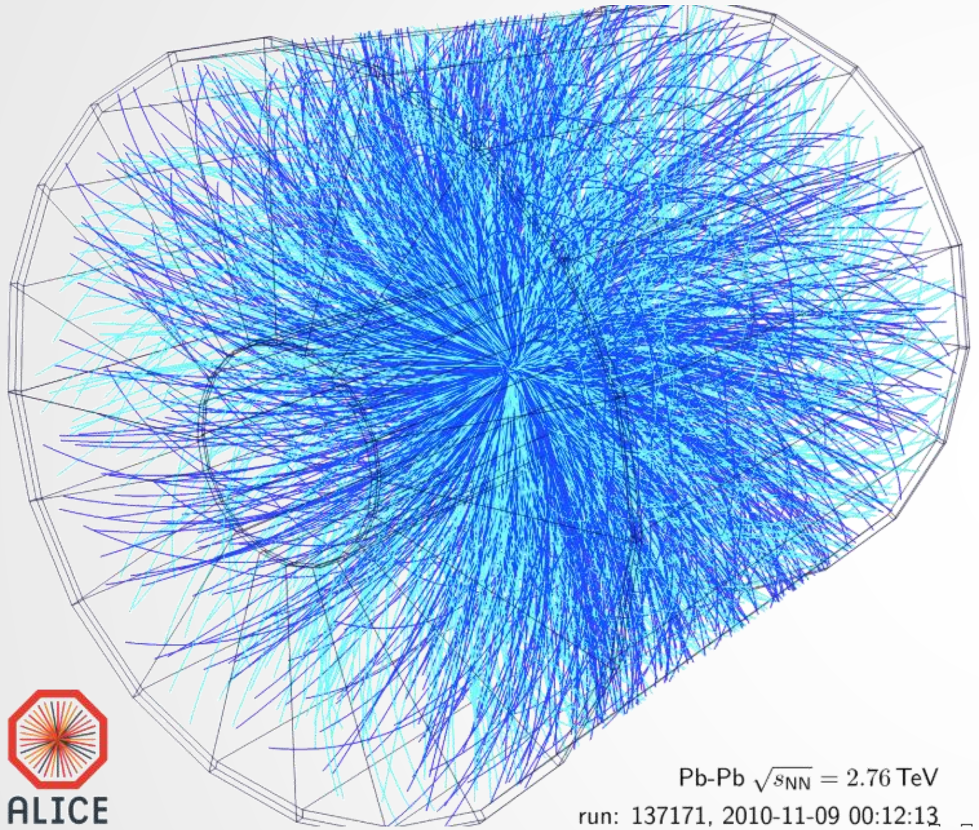


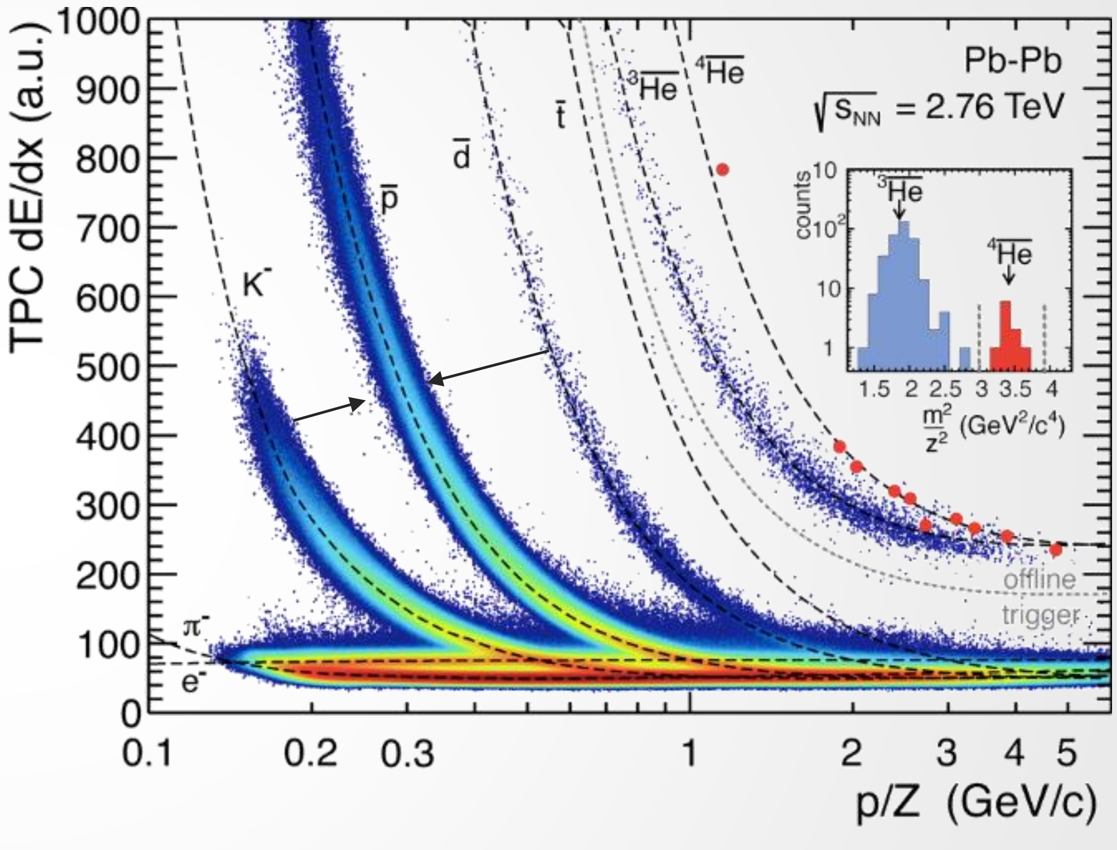


Difference of the mean energy loss for π and K
(K. Kleinknecht, Detektoren für Teilchenstrahlung)

See also Lecture 3 and 4.1!

ALICE TPC





- dE/dx can be used for identifying particles.
- Left: Time Projection Chamber (ALICE detector, Ne/CO_2 gas). Right: dE/dx measurement in Pb/Pb collisions.
- Note: The spread in dE/dx limits particle Identification.

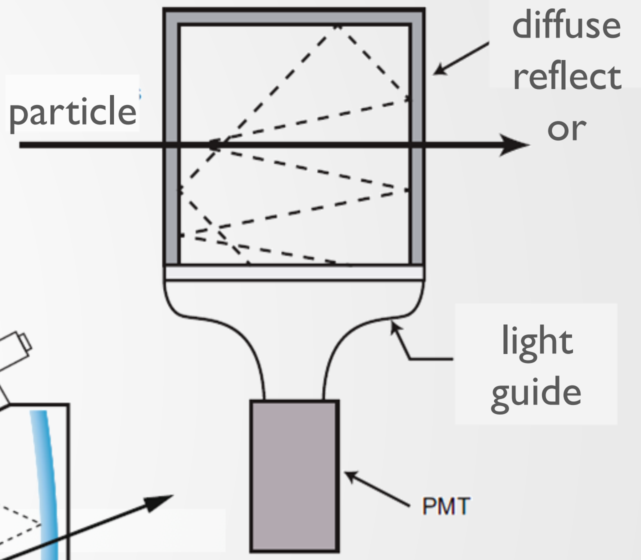
ČERENKOV COUNTERS

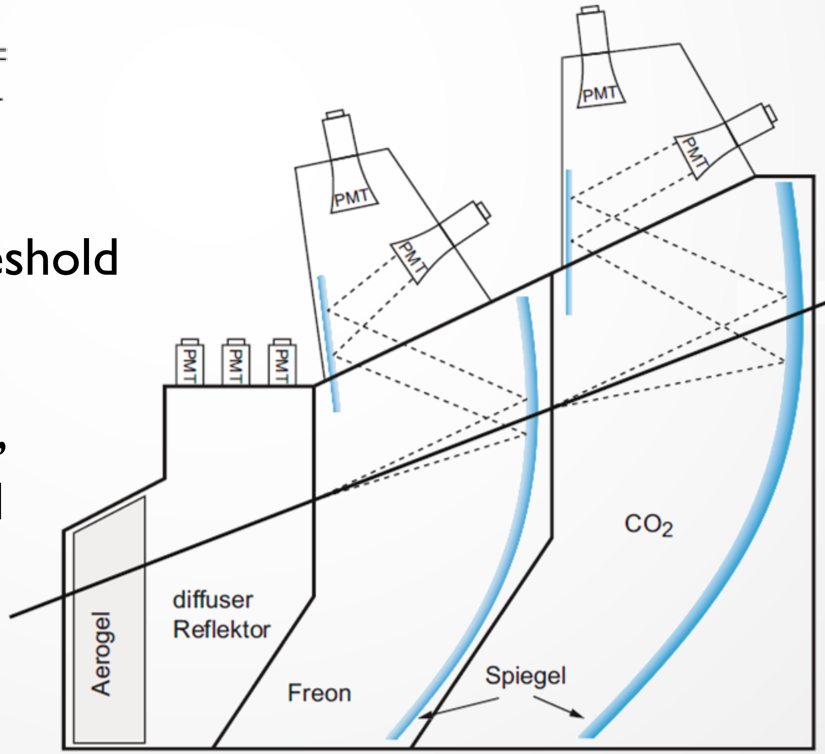
- A charged particle travelling in matter (refraction index of n) with a velocity larger than the velocity of light in this material emits Cherenkov light. Čerenkov light is a weak source: ≈0.1-1% of Ionization.
- Recap from Lecture 3: $\cos\theta_c = (\beta n)^{-1}, \; \theta_{\max} = \cos^{-1} n^{-1}$

$$\frac{\theta_c}{\theta_{max}} = \frac{R_c}{R_{max}} \approx \sqrt{1 - \frac{\gamma_{th}^2}{\gamma^2}}, \quad \gamma_{\text{th}} = \frac{n}{\sqrt{n^2-1}}$$

- Radiation is emitted in narrow rings
- High refractive index needed for low threshold
  - Values with n≈1 for discrimination
- Čerenkov counters detect these photons, (focusing mirrors), disregarding the spatial and spectral structure
- The TASSO Čerenkov counter achieves p/π separation by using three materials

principle of a Čerenkov counter:





Čerenkov detector in the TASSO experiment (PETRA/DESY) with three different gases/thresholds

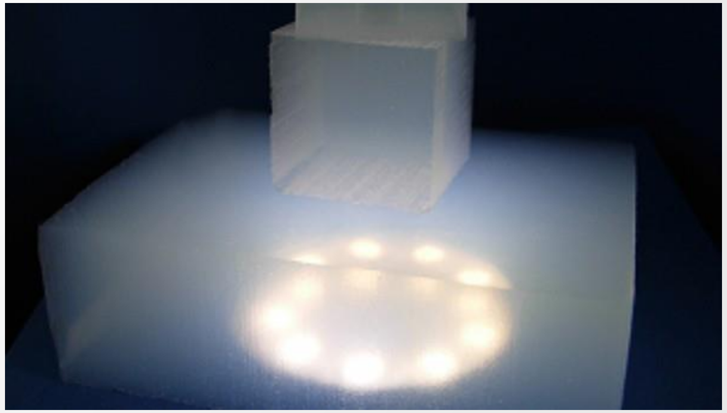
MATERIALS

Medium	Brechungs-index	γ_{th}	p_{th}^{p} (GeV/c)	p_{th}^{K} (GeV/c)	p_{th}^{π} (GeV/c)	p_{th}^{e} (GeV/c)
Festkörper / Flüssigkeiten						
Eis	1.310	1.55	1.1	0.58	0.16	$6.0 \cdot 10^{-4}$
NaF	1.325	1.52	1.1	0.57	0.16	$5.9 \cdot 10^{-4}$
Quarzglas	1.458	1.37	0.9	0.47	0.13	$4.8 \cdot 10^{-4}$
Borosilikatglas	1.474	1.36	0.8	0.46	0.13	$4.7 \cdot 10^{-4}$
Plexiglas	1.492	1.35	0.8	0.45	0.13	$4.6 \cdot 10^{-4}$
Plast.-Szint.	1.580	1.29	0.8	0.40	0.11	$4.2 \cdot 10^{-4}$
Bleiglas	1.670	1.25	0.7	0.37	0.10	$3.8 \cdot 10^{-4}$
NaI	1.775	1.21	0.6	0.34	0.10	$3.5 \cdot 10^{-4}$
CsI	1.787	1.21	0.6	0.33	0.09	$3.5 \cdot 10^{-4}$
C_6F_{14} (180 nm)	1.283	1.60	1.2	0.61	0.17	$6.4 \cdot 10^{-4}$
Wasser	1.333	1.51	1.1	0.56	0.16	$5.8 \cdot 10^{-4}$
Alkohol	1.361	1.47	1.0	0.53	0.15	$5.5 \cdot 10^{-4}$
Paraffinöl	1.444	0.69	1.39	0.9	0.47	$4.9 \cdot 10^{-4}$
Aerogel	1.24 –1.007	1.69 –8.50	1.3 –7.9	0.7 –4.2	0.19 –1.18	0.7–4.3 $\times 10^{-3}$

Medium	Brechungs-index	γ_{th}	p_{th}^{p} (GeV/c)	p_{th}^{K} (GeV/c)	p_{th}^{π} (GeV/c)	p_{th}^{e} (GeV/c)
Gase (1 bar, 0°C, C_5F_{12} bei 40°C)						
He	1.000035	119.7	112.3	59.1	16.7	0.061
Ne	1.000066	87.0	81.6	43.0	12.1	0.044
H_2	1.000132	61.6	57.7	30.4	8.6	0.031
Ar	1.000282	42.1	39.5	20.8	5.9	0.022
Luft	1.000292	41.4	38.8	20.4	5.8	0.021
Luft (STP)	1.000289	42.5	39.8	21.0	5.9	0.022
CH_4	1.000444	33.6	31.5	16.6	4.7	0.017
CO_2	1.000449	33.4	31.3	16.5	4.7	0.017
CF_4 (180 nm)	1.00053	30.7	28.8	15.2	4.3	0.016
Freon 114	1.00140	18.9	17.7	9.3	2.6	0.010
C_4F_{10} (180 nm)	1.00150	18.3	17.1	9.0	2.5	0.009
C_5F_{12} (180 nm)	1.00172	16.2	15.1	8.0	2.3	0.008

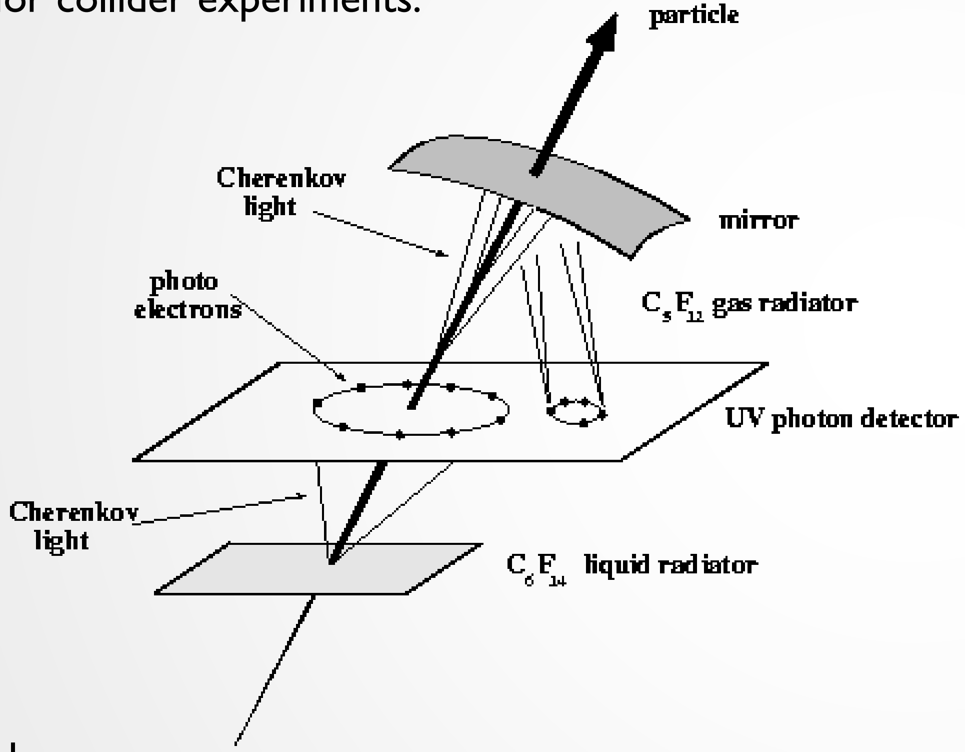
- Aerogel is a very light nano-porous material from SiO_2 and water with a density dependent refractive index.
  - It can be manufactured in densities such that n closes the gap between gases and liquids.

Aerogels with various densities:



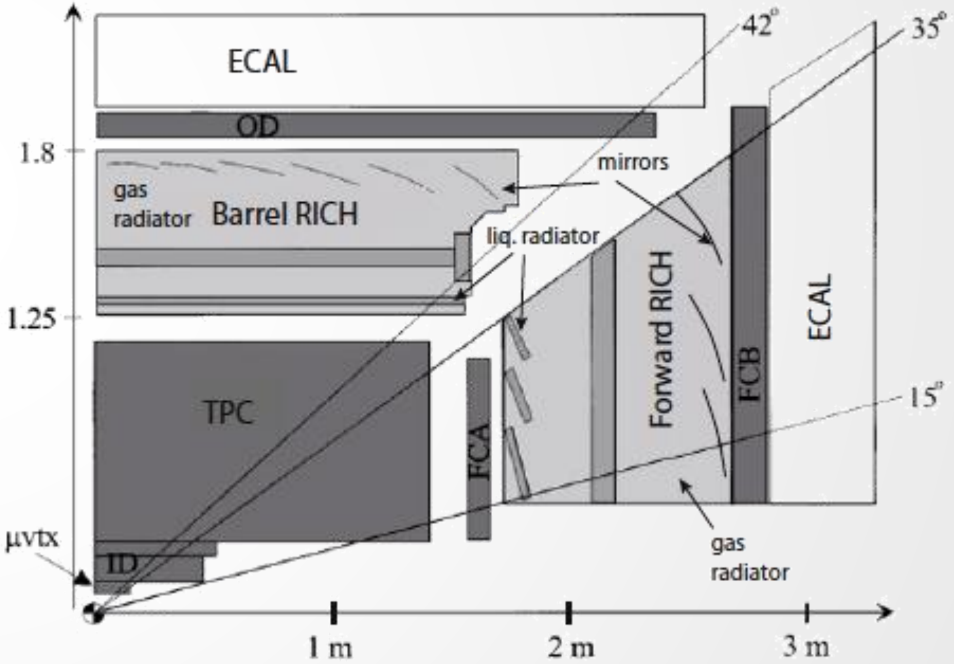
RING IMAGING ČERENKOV DETECTORS

- Ring Imaging Cherenkov Counters (RICH) use also the information of the angle of photon emission. Geometry developed for collider experiments.



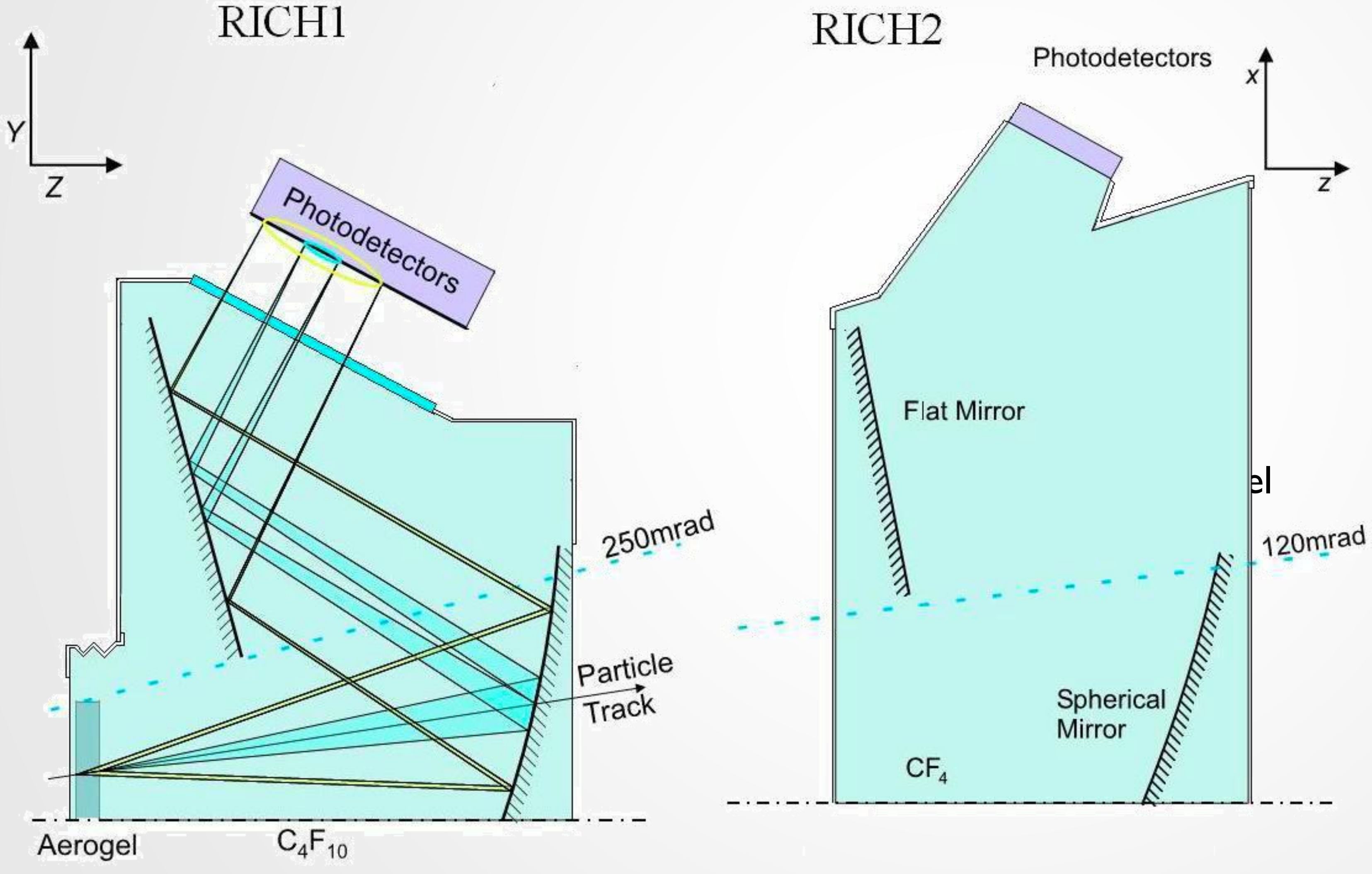
- Two principles:
  1. (top) Photons generated in a gas-radiator are reflected by a mirror that focuses the Cherenkov light and a photo detector is placed in the focal plane ⟶ ring of photons is mapped onto the photo detector. Used for e.g. e/π discrimination

DELPHI (LEP) dual RICH system
UV sensitive Drift Chamber
(75% CH_4 + 25% C_2H_6 +TMAE)
TMAE: photosensitive additive

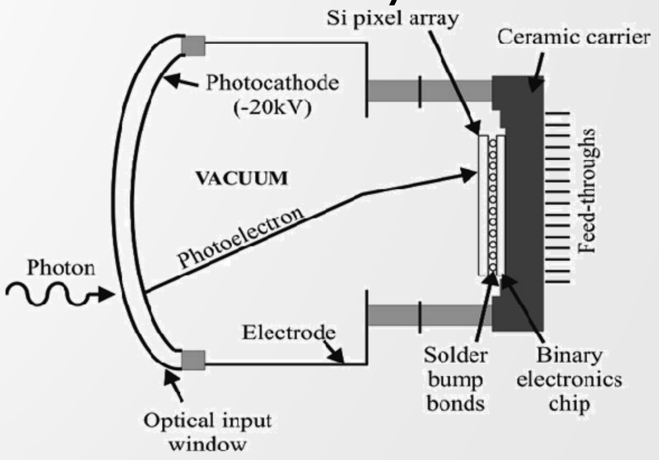


2. (bottom) a liquid or solid thin radiator produces a ring originating from a single vertex (no focusing mirror needed), e.g. π/K/p discrimination

LHCB RICH SYSTEMS



- The LHCb RICH-1/2 systems use 3 radiators:
  - aerogel & C_4F_{10} gas in RICH-1 optimized for low energetic particles (closer to the interaction vertex)
- CF_4 in RICH-2
- Photodetector: Hybrid PMT

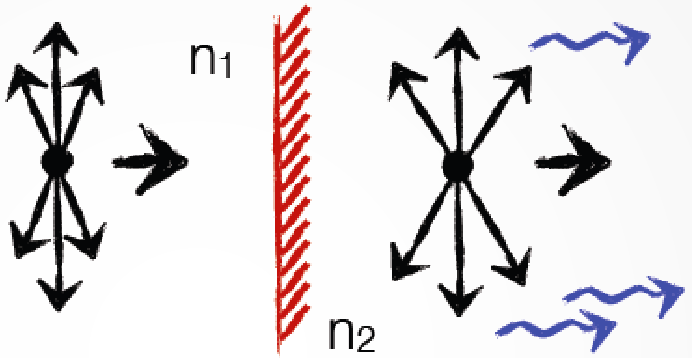


TRANSITION RADIATION

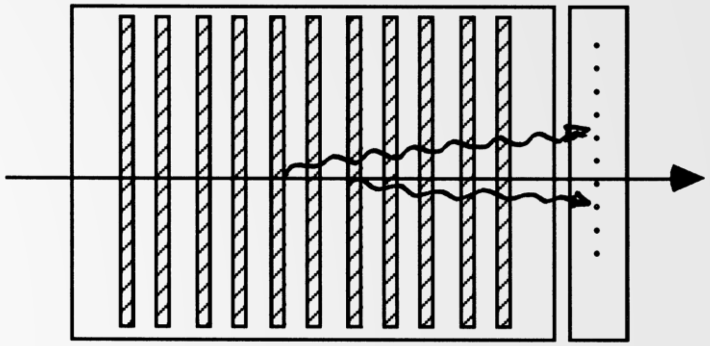
- A charged particle traversing the boundary of materials with different refraction index $n_1 \neq n_2$ emits transition radiation.
- The total emitted energy E_{tot} is proportional to γ
  - only fast electrons and positrons (γ>1000) emit transition radiation
  - used for the identification of electrons and positrons when their momentum is known
- The numbers of photons emitted per transition is very small

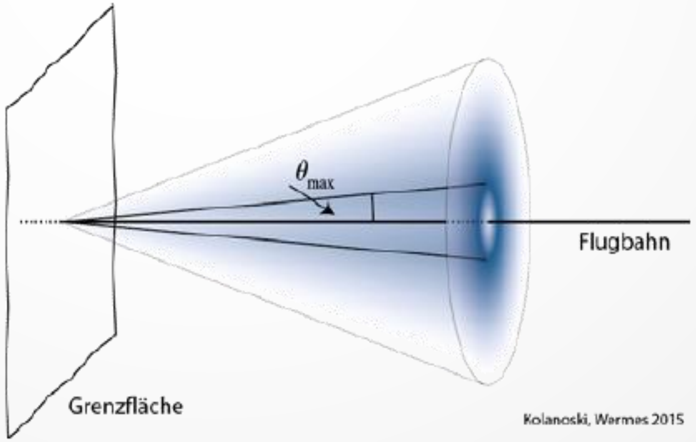
  many transitions (boundaries) are needed
- The angle of emission is small $\boldsymbol{\theta}_{mpv} \sim \boldsymbol{\gamma}^{-1}$,
  - photons from the transition radiation are very close to the particle track

principle:

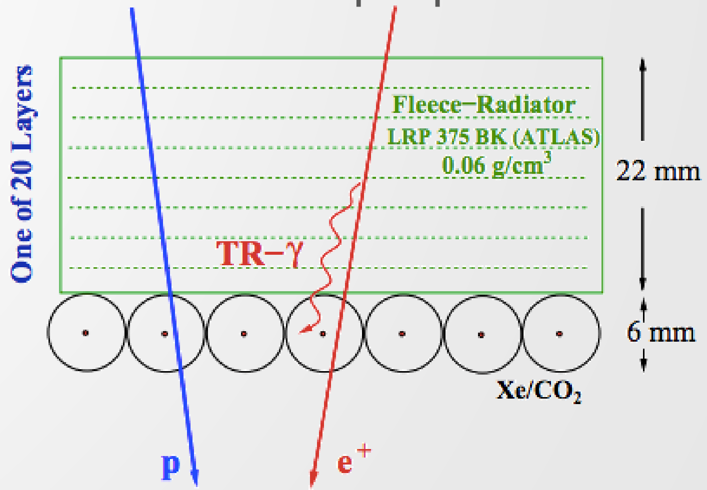


frequently used geometry: assembly of foils:

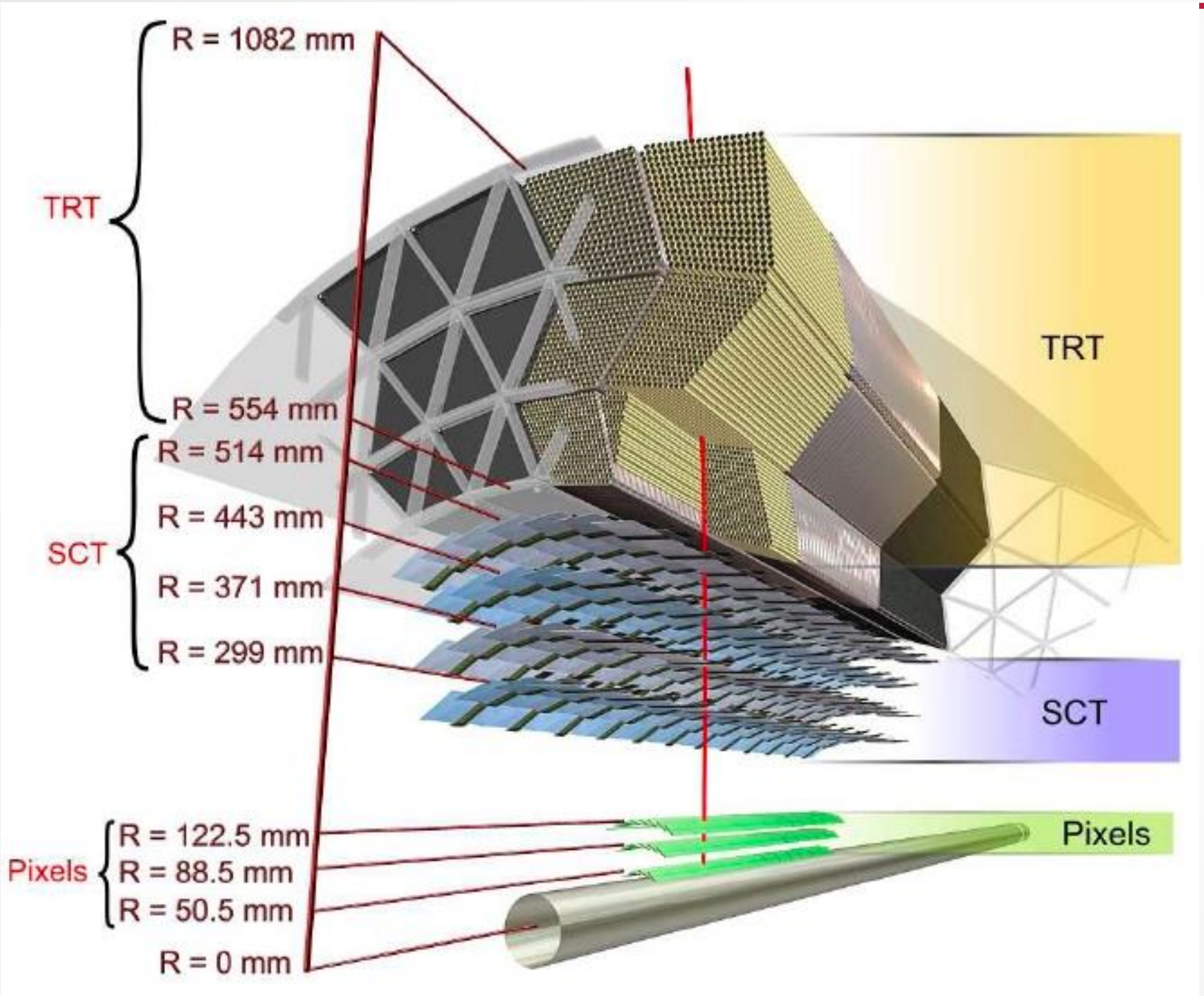




AMS TRD for e^+/p separation:

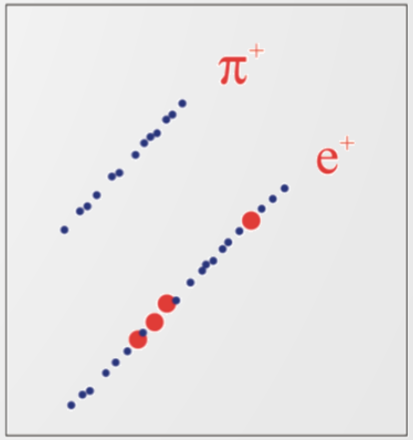


ATLAS TRANSITION RADIATION TRACKER



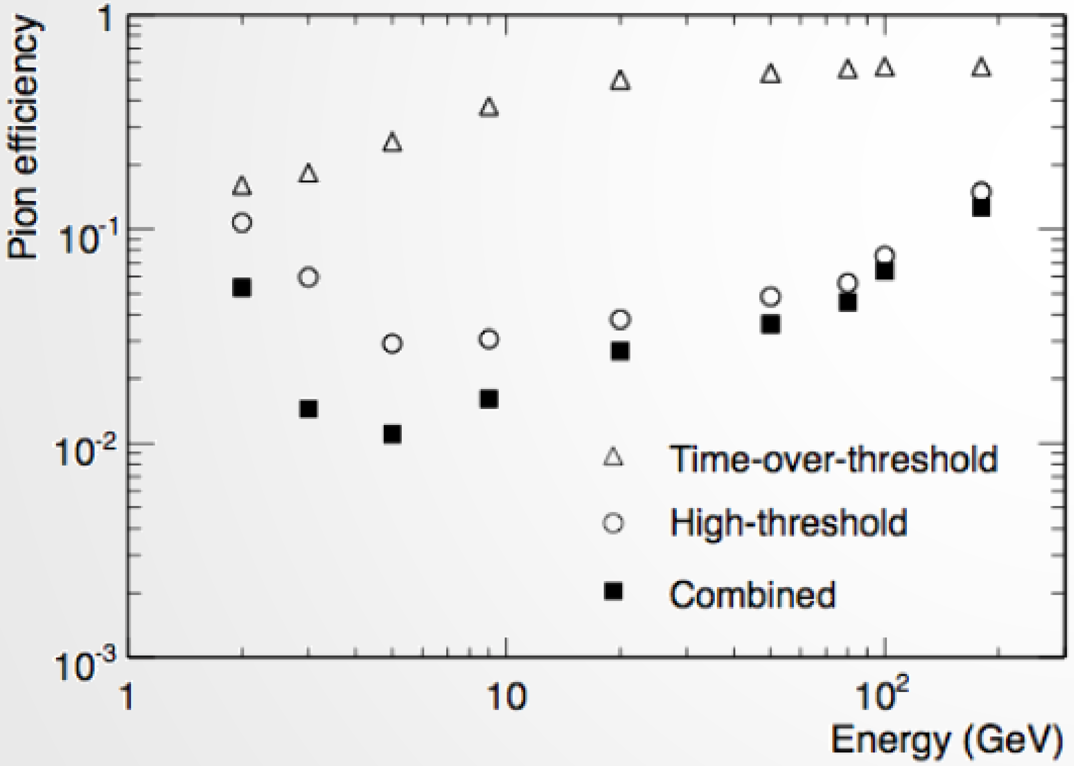
- straw tubes with xenon-based gas mixture: $Xe/CO_2/O_2$ 70%/27%/3%
- 4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire
- Radiator: polypropylene-polyethylene fibres (19 μm) between the straws
- Detector: „Straw tubes“ embedded in radiator

Two tracks
with high (TR, red)
and low (ionization)
signal



ATLAS TRANSITION RADIATION TRACKER

- Discrimination power of electrons against π in the ATLAS TRT
- Plot shows wrong π assignment at 90% electron efficiency



The ATLAS Collaboration, 2008, JINST 3 S08003

… simulated performance.

THE END!