Particle identification

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- PID by difference in interaction
- PID (Hadron ID) by mass determination
  - Ionization
  - Time-of-flight
  - Cherenkov Ring Imaging

See also: arxiv.org/abs/1101.3276

Introduction

- In addition to tracking and calorimetry, Particle IDentification (PID) is a crucial aspect of most particle and nuclear physics experiments.
- Particle identification techniques are based on the interactions of particles with matter (see Lecture by Bernhard Ketzer).

I. PID by difference in interaction

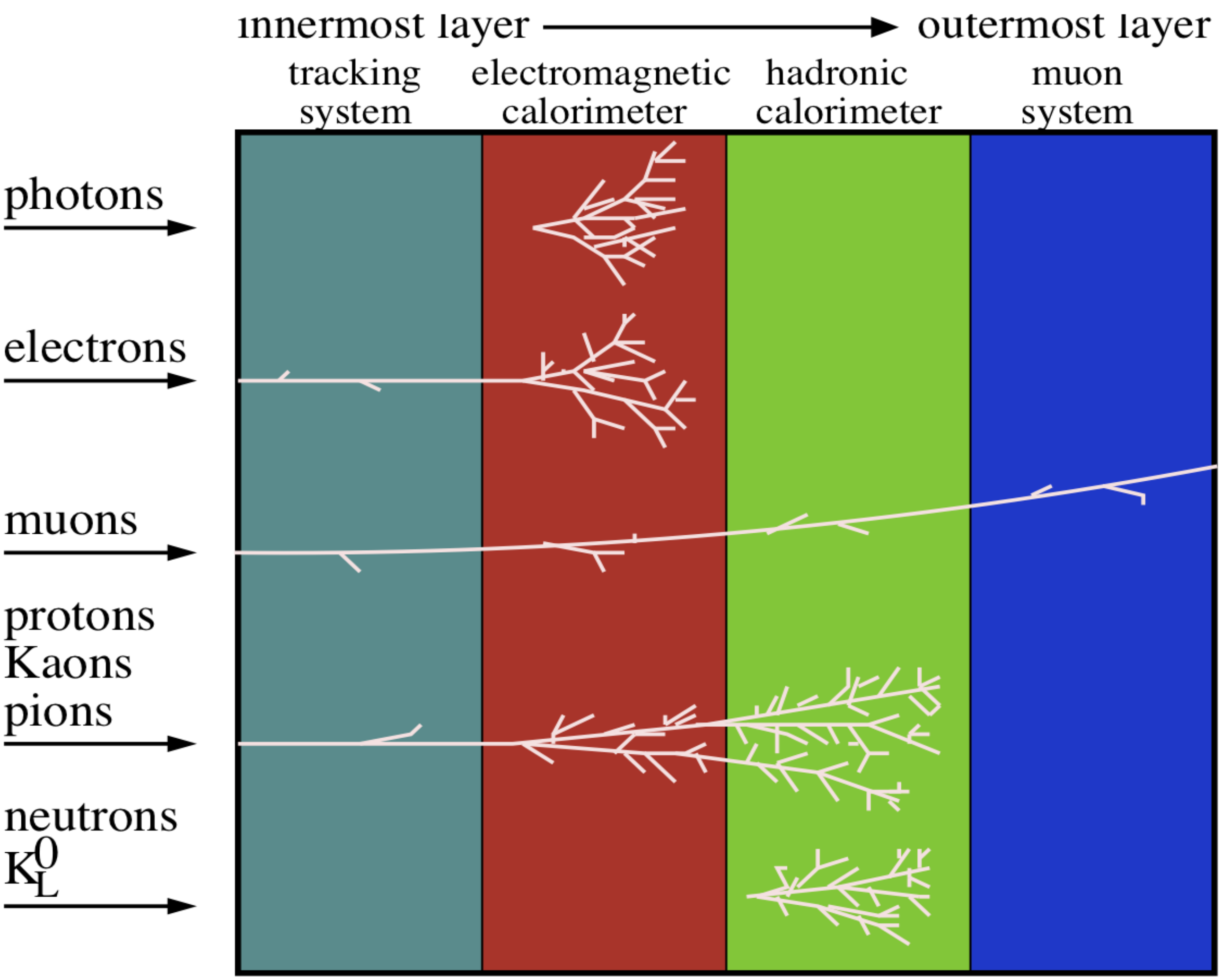
I. PID by difference in interaction

- Experiments are often divided into a few main components, stacked in layers, where each component tests for a specific set of particle properties.

- Particles are identified (e, μ, γ), or at least assigned to families (charged or neutral hadrons), by the characteristic signatures they leave in the detector.

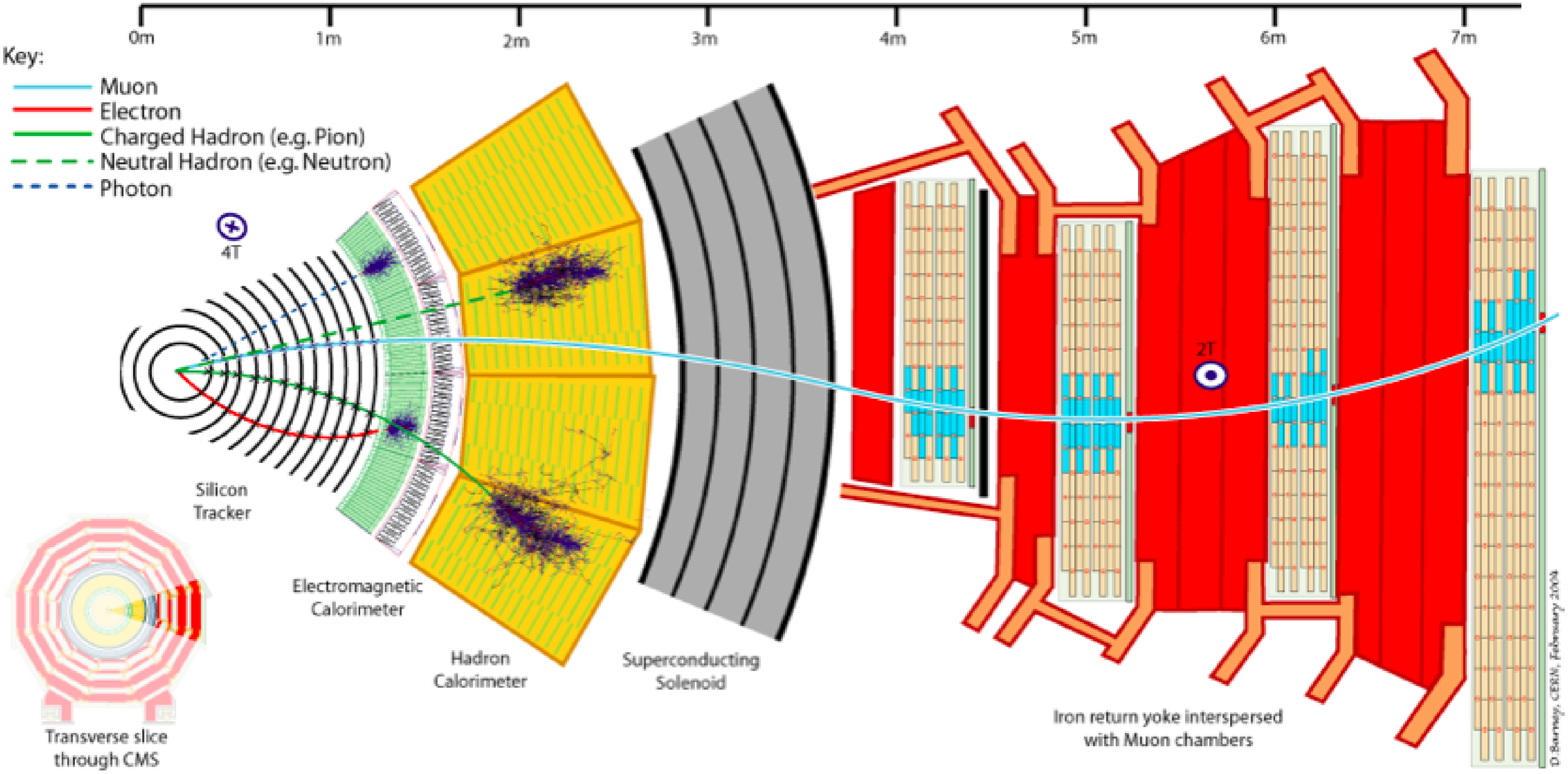
- Examples: ATLAS, CMS

A typical high energy physics experiment



C. Lippmann – 2010

Example: CMS



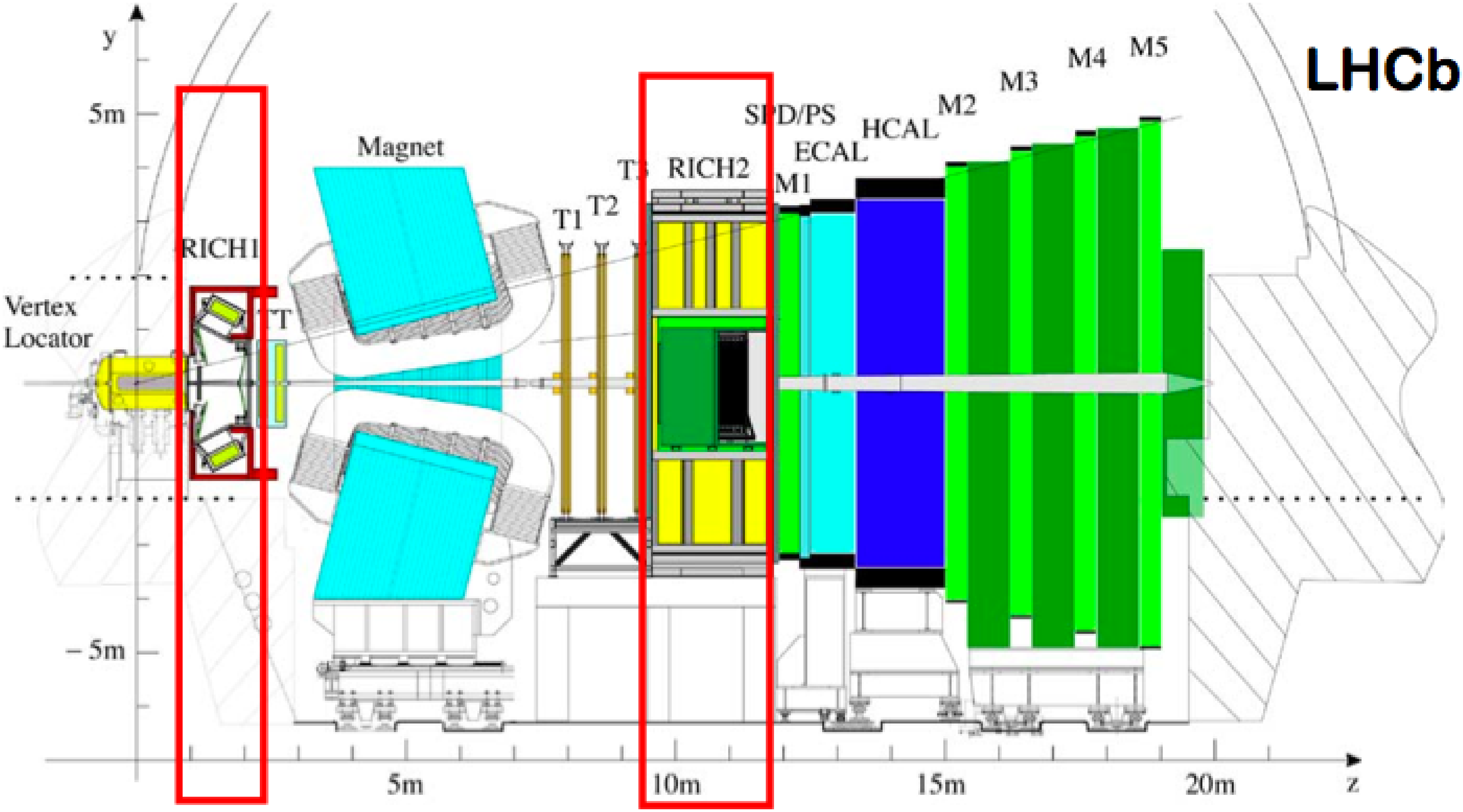
D.Barney, CERN, February 2004

II. PID by mass determination

II. PID by mass determination (1)

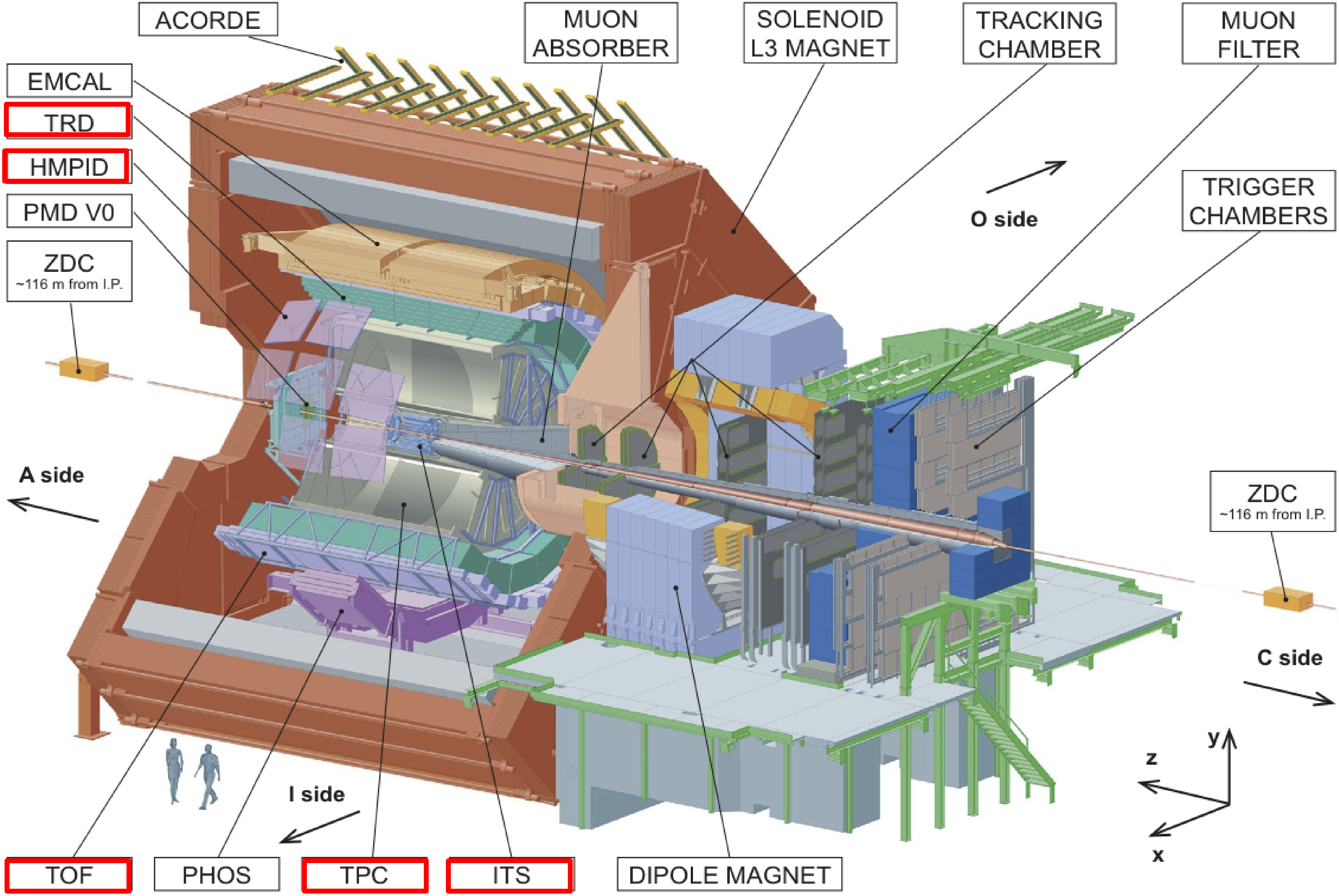
- π, K, p have identical interactions in an experimental setup as the one shown on slide 5 or 8 and are all effectively stable.
- However, their identification can be crucial.
- In order to identify charged hadrons it is necessary to determine their charge and mass.

Example: Hadron ID in LHCb with 2 RICH detectors



Like a slice out of a traditional experiment with the addition of 2 RICH detectors

Example: PID by mass determination in ALICE



II. PID by mass determination (2)

- Since the mass can not be measured directly, it has to be deduced from other variables. These are in general the momentum *p* and the velocity β = *v*/c, where one exploits the basic relationship

$$p = \gamma m v \quad \rightarrow \quad m = \frac{p}{c\beta\gamma}\,.$$

- The resolution in the mass determination is

$$\left(\frac{\mathrm{d}m}{m}\right)^2 = \left(\frac{\mathrm{d}p}{p}\right)^2 + \left(\gamma^2\frac{\mathrm{d}\beta}{\beta}\right)^2.$$

II. PID by mass determination (3)

- The momentum is obtained by measuring the curvature of the track in the magnetic field.

- The particle velocity is obtained by:
  1) measurement of the energy deposit by ionization,
  2) time-of-flight (TOF) measurements,
  3) detection of Cherenkov radiation or
  4) detection of transition radiation (see talk by Tom Dietel).

II. a) Ionization measurements

Restricted average energy loss

- Fast charged particles passing through matter loose energy while they undergo a series of inelastic Coulomb collisions with the atomic electrons of the material (see Bernhard Ketzers lecture).

- The (*restricted*) average energy loss per unit path length (upper limit for energy transfer in single collision E_{cut}):

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \propto \frac{z^2}{\beta^2} \left(\log \frac{\sqrt{2 m_e c^2 E_{cut}}\, \beta\gamma}{I} - \frac{\beta^2}{2} - \frac{\delta}{2} \right) .$$

Charge deposit

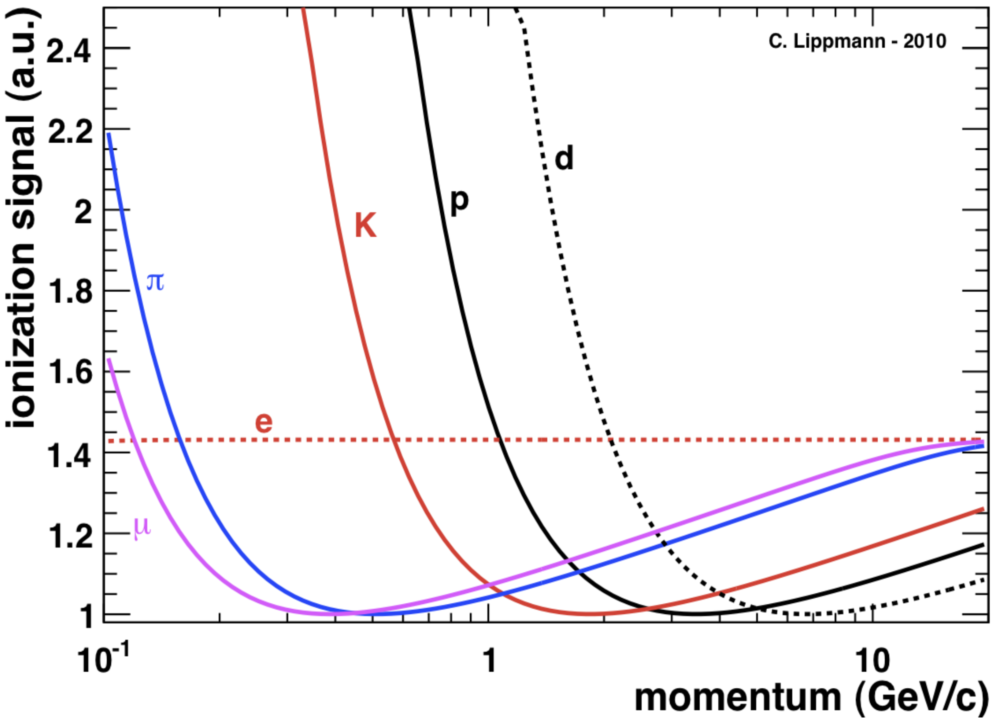
- $\langle \mathrm{d}E/\mathrm{d}x \rangle$ is transformed into the average number of electron/ion pairs (or electron/hole pairs for semiconductors) $\langle N_I \rangle$ along the length x:

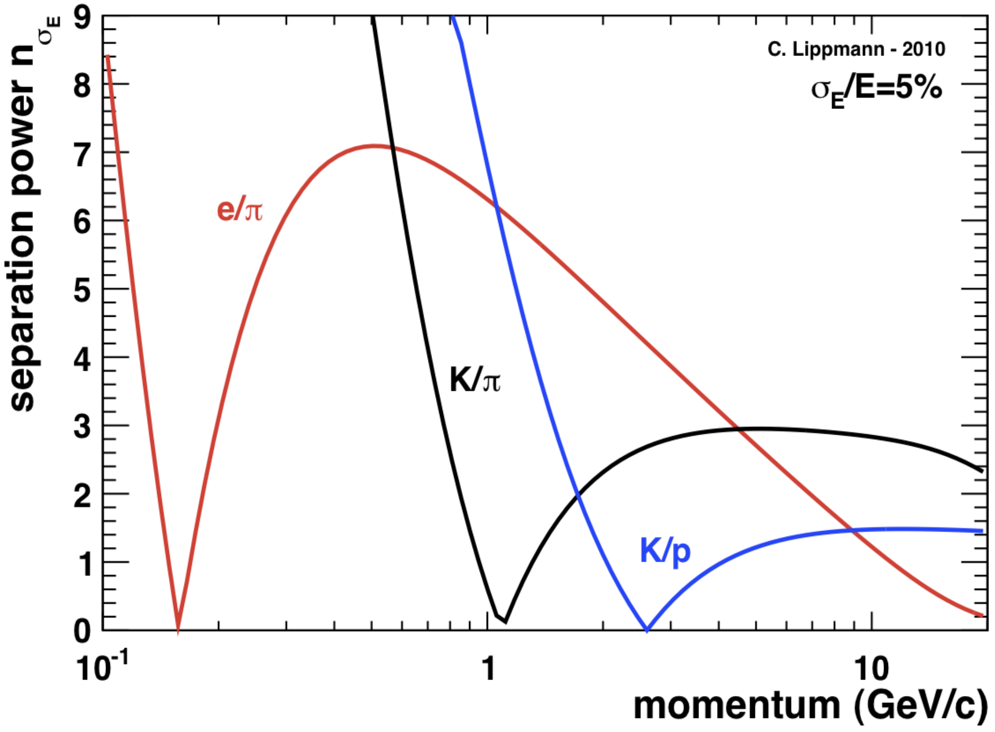
$$x \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \langle N_I \rangle \, W$$

- W is the average energy spent for the creation of one electron/ion (electron/hole) pair.

- Gaseous or solid state counters provide signals with pulse height proportional to the number of electrons $\langle N_I \rangle$.

Ionization: Separation power

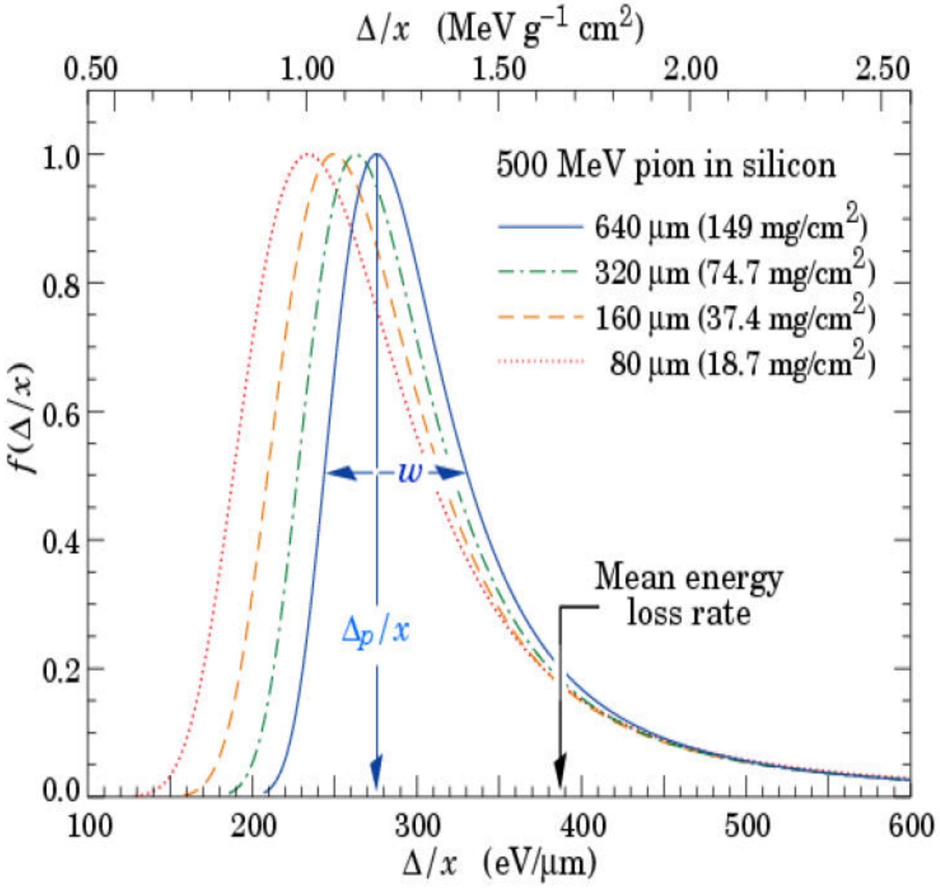




- Ionization signal and particle separation as a function of momentum for a gaseous detector.

Energy loss fluctuations

- The actual energy loss fluctuates according to a distribution with a long tail (Landau tail).
- The distribution of the charge deposit looks accordingly.
- The mean value is a bad estimator for the ionization signal.



Measurement of the energy deposit

- In general N_R pulse height measurements are performed along the particle track.

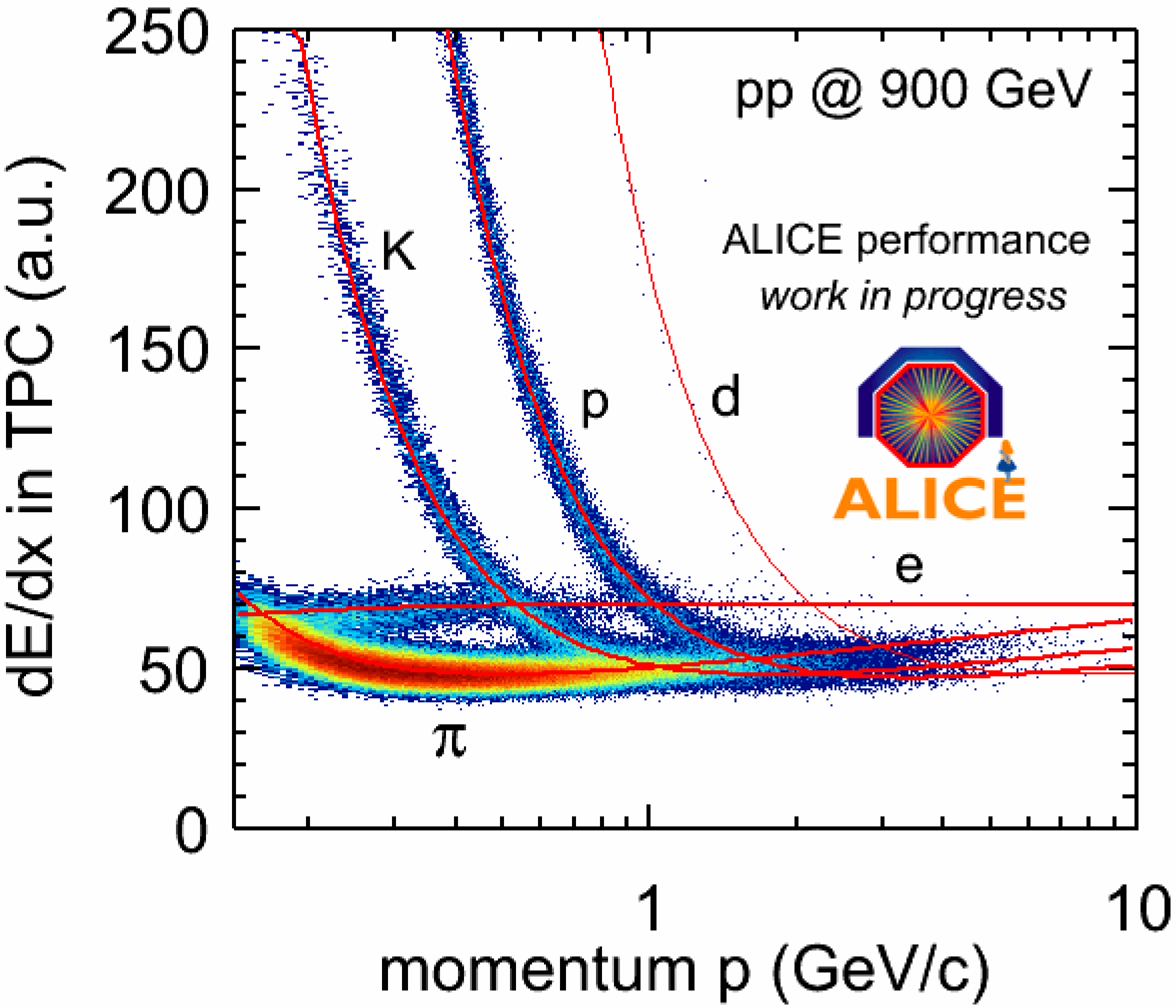
- Usually one uses the truncated mean:

$$\langle R\rangle_a = \frac{1}{M}\sum_{i=1}^{M} R_i \qquad \begin{aligned} &R_i \leq R_{i+1} \text{ for } i = 1, \ldots, n-1 \\ &M = aN_R \end{aligned}$$

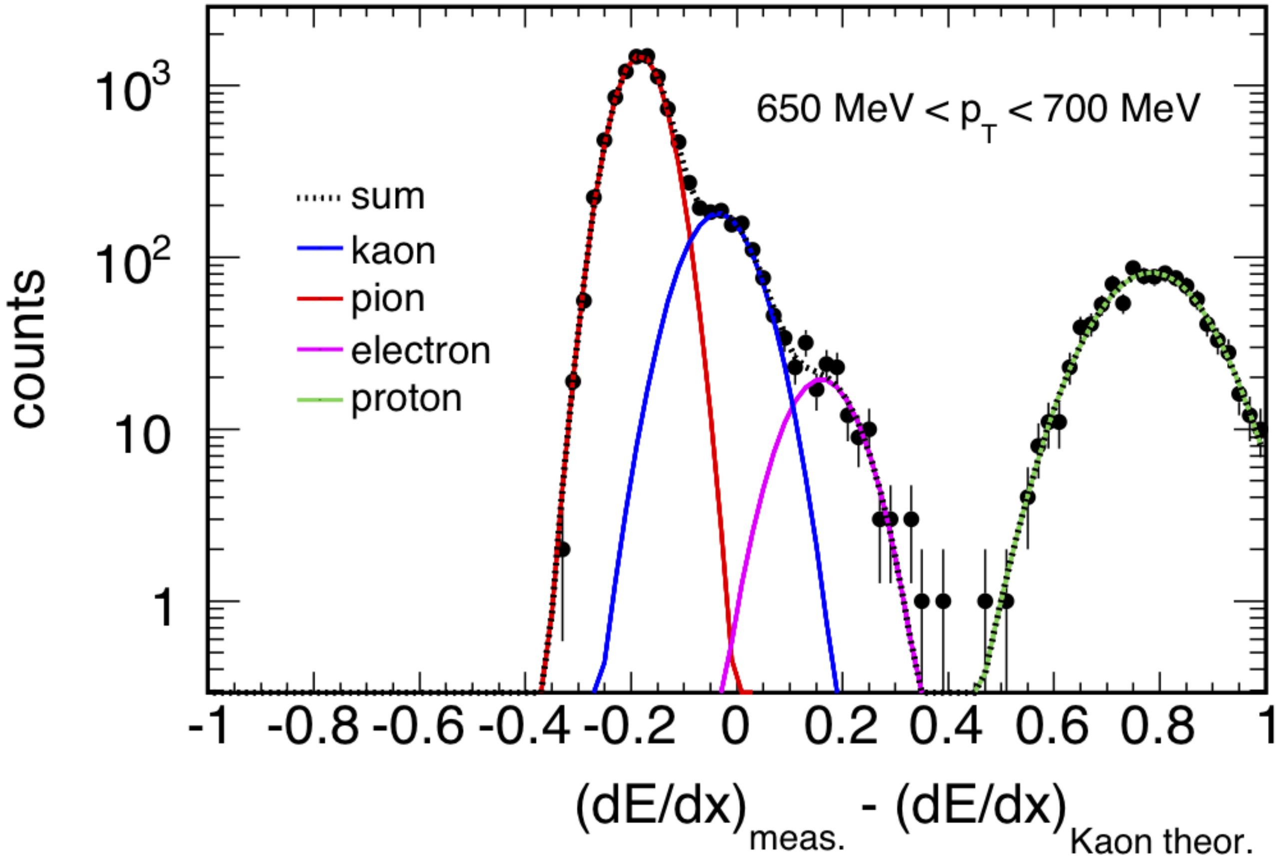
- $\langle R_A \rangle$ approximates well the most probable value of the distribution of the energy deposit. Its distribution is Gaussian.

ALICE TPC: PID at low momenta (1)

- 5% resolution measured in proton collisions.
- In highest multiplicities (Pb collisions) 6% due to overlapping tracks and baseline fluctuations.



ALICE TPC: PID at low momenta (2)



- Momentum window of 50MeV/c width

II. b) Time-of-flight measurements

Method

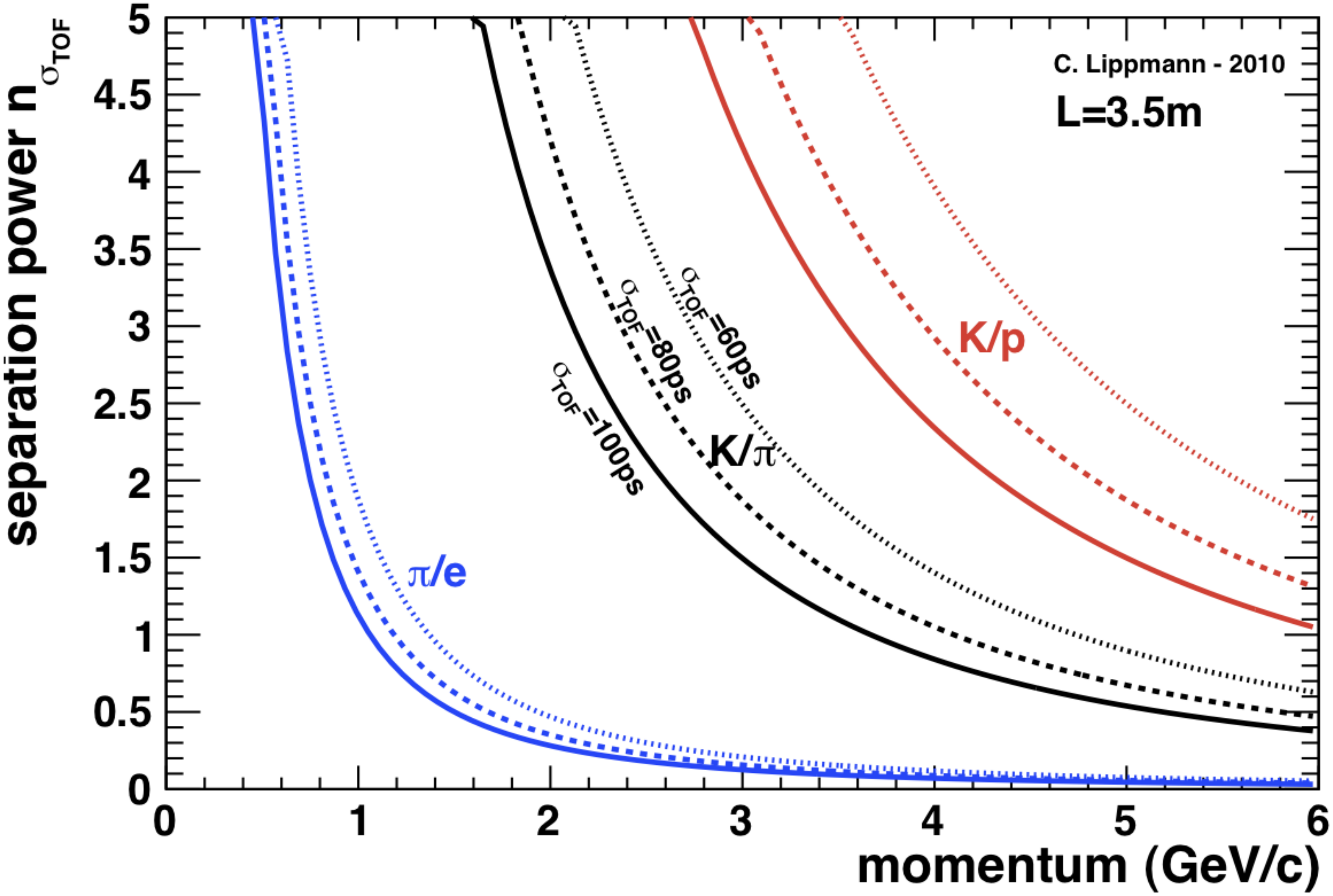
- Time-of-flight (TOF) measurements yield the velocity of a charged particle by measuring the flight time $t = t_1 - t_0$ over a given distance L along the track trajectory.
- One can calculate the mass m from measured values of L, t and p:

$$m = \frac{p}{c}\sqrt{\frac{c^2t^2}{L^2} - 1}\,.$$

- Separation power for two particles A and B:

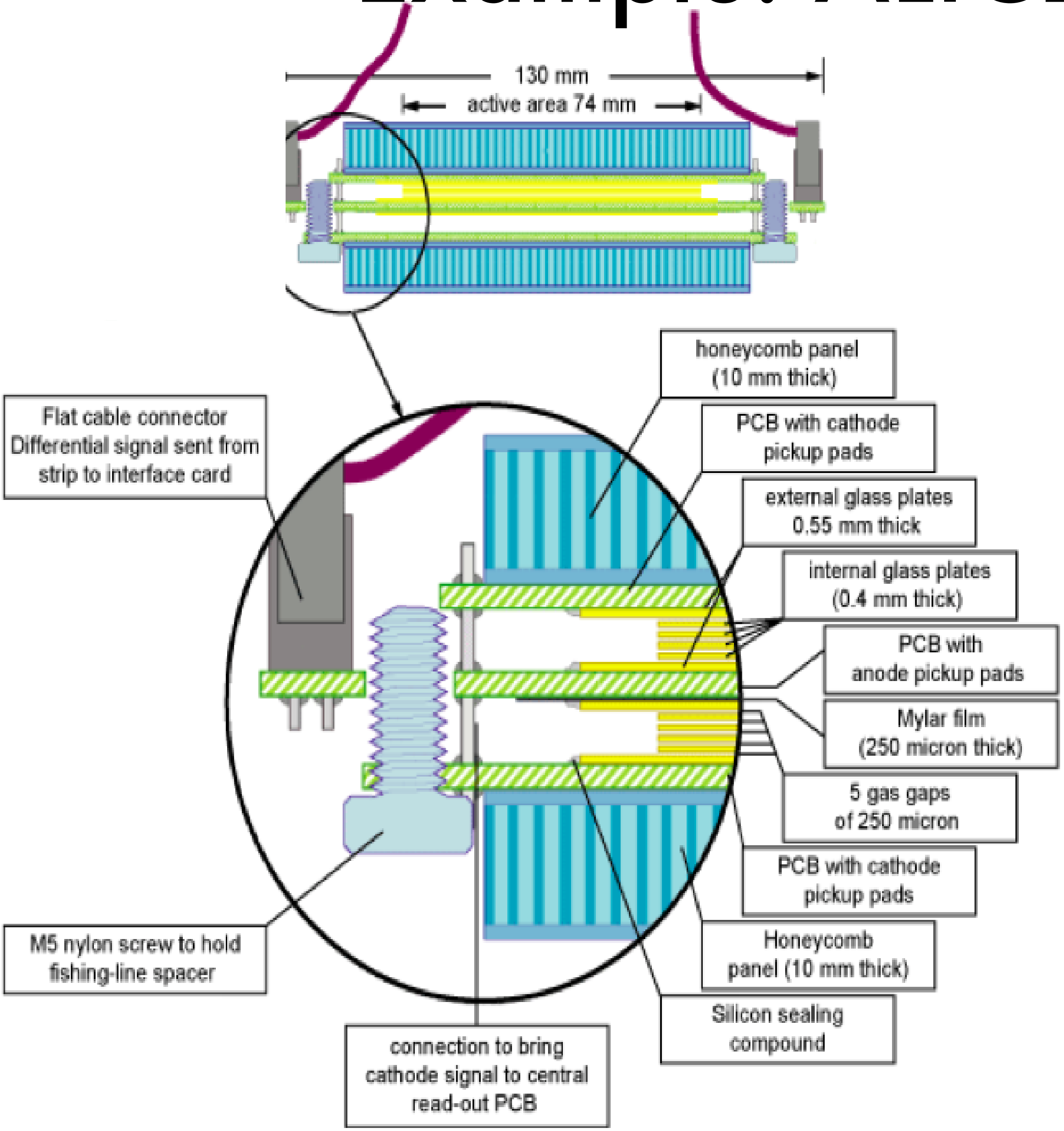
$$n_{\sigma TOF} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2\sigma_{TOF}}|m_A^2 - m_B^2|\,.$$

Separation power



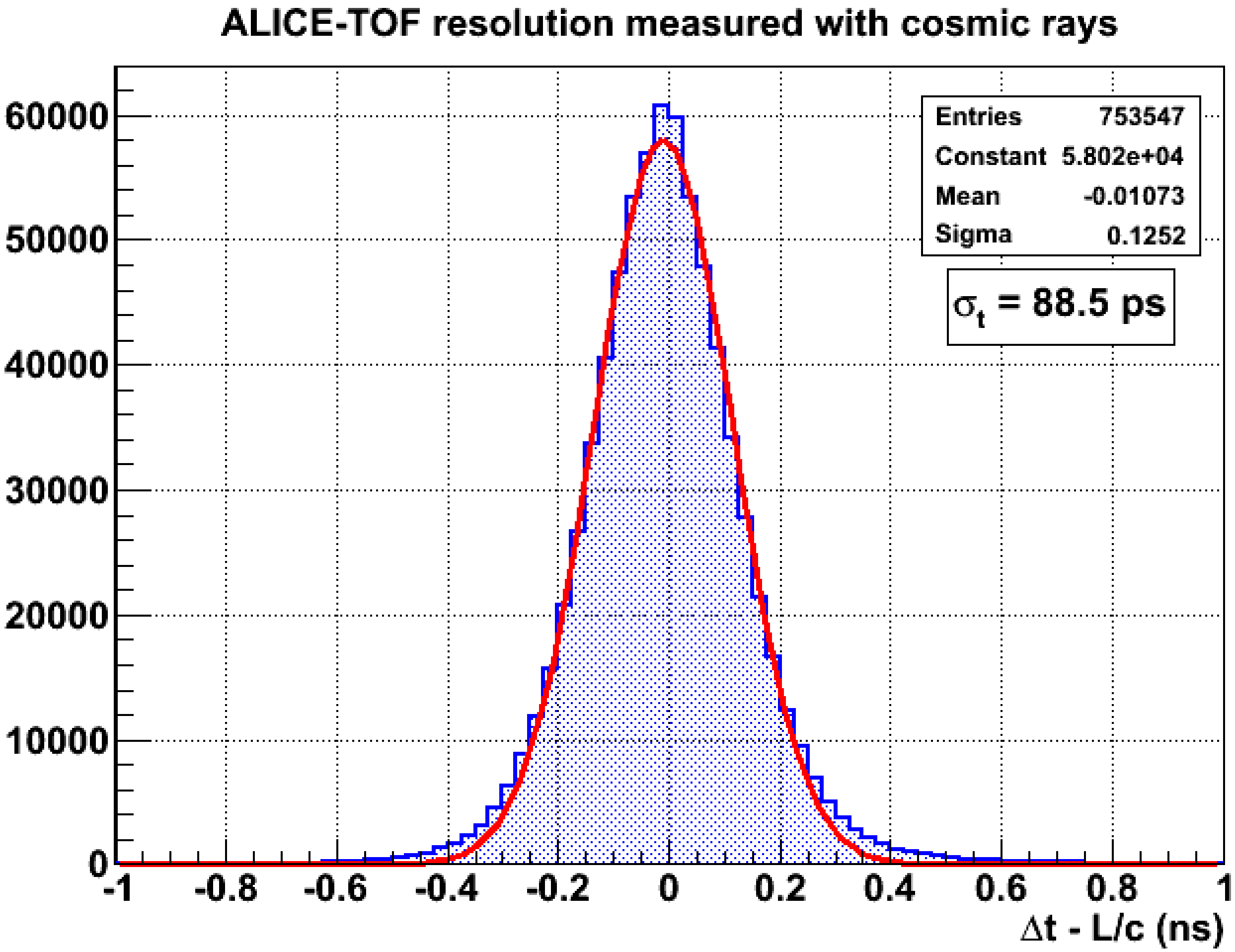
- Important to optimize resolution in the flight time measurement!

Example: ALICE TOF (1)



- Thin gaps with high electric fields for good time resolution.
- Many gaps for good efficiency.
- Resistive plates to guarantee robustness against discharges (or sparks)

ALICE TOF: Time resolution

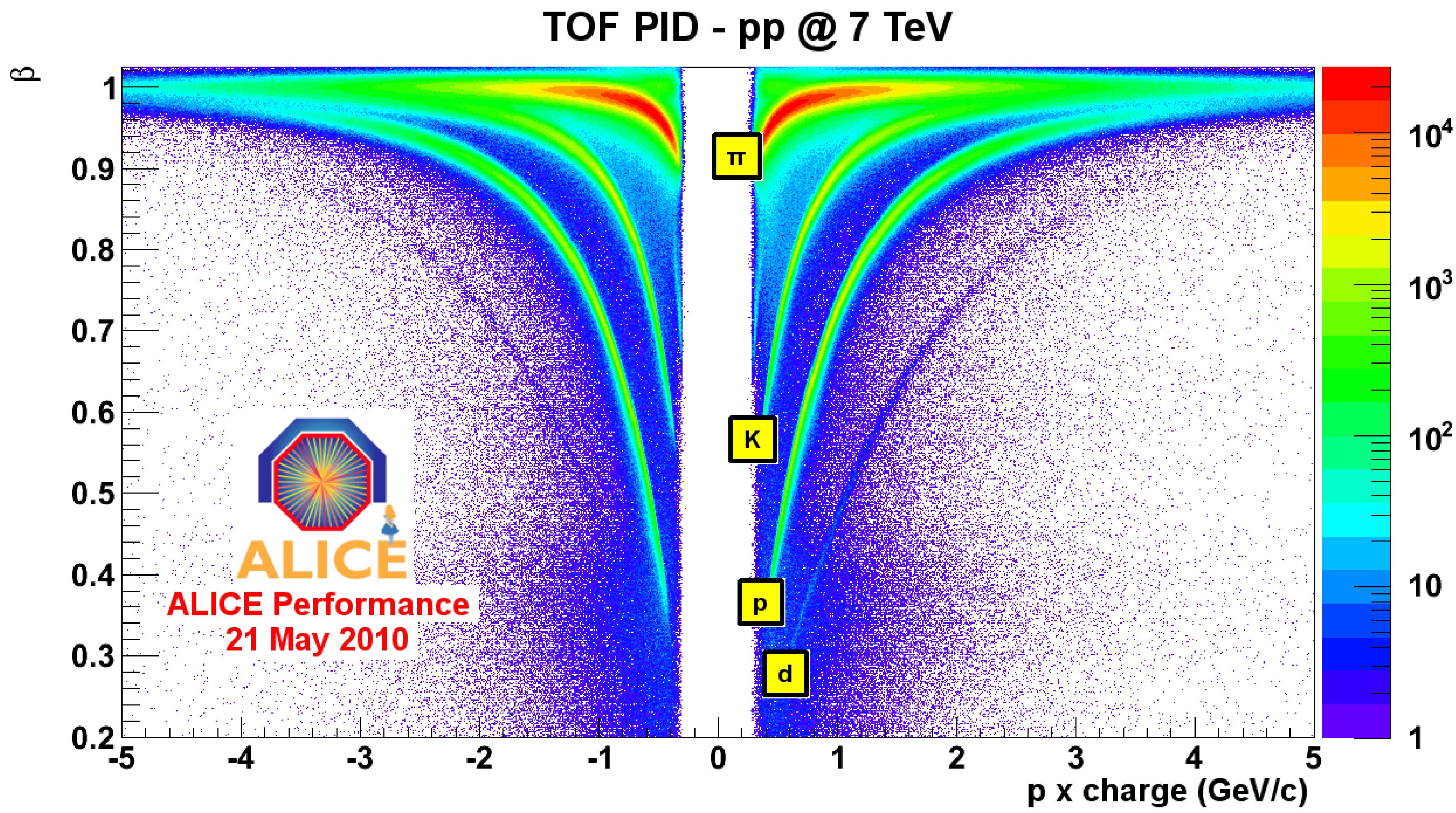


$$\sigma^2_{TOF} = \sigma^2_{t_0} + \sigma^2_{t_1}$$

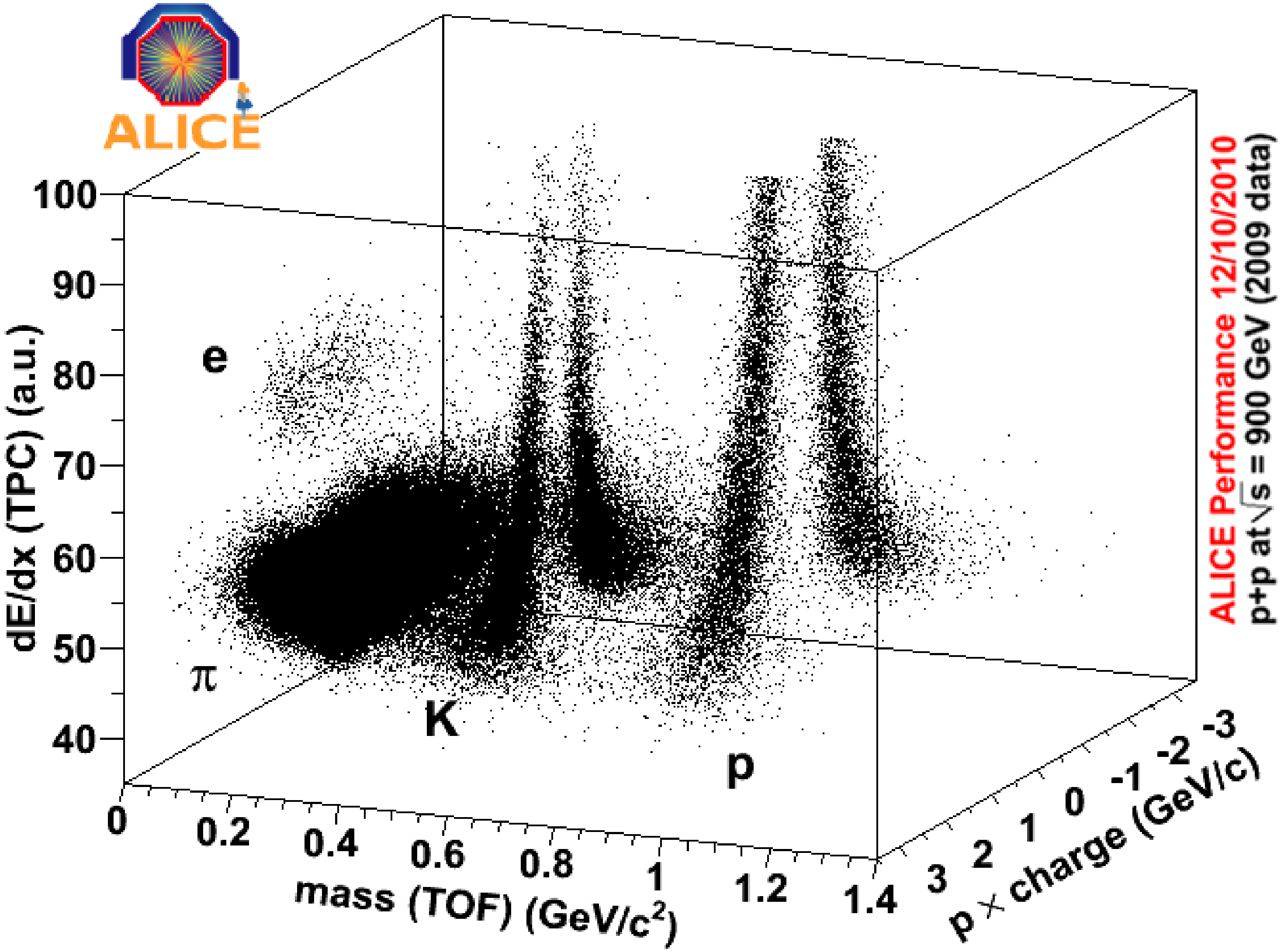
- Preliminary resolution with intermediate calibration from 2009 with cosmic tracks: σ_{t_1} =88.5ps

- Goal: σ_{t_1} =65ps

ALICE TOF: Velocity distribution for different particle types



Combining different PID techniques in ALICE



II. c) Cherenkov ring imaging

Theory

- Cherenkov radiation is a shock wave resulting from a charged particle moving through a material faster than the velocity of light in the material.
- Cherenkov radiation propagates with a characteristic angle with respect to the particle track Θ_C, that depends on the particle velocity: $$\cos(\Theta_C) = \frac{1}{\beta n}$$
- *n* = refractive index of material
- Cherenkov radiation is only emitted above a threshold velocity $\beta_t = 1/n$

RICH technique

- RICH detectors resolve the ring shaped image of the focused Cherenkov radiation.
- Through the measurements of the Cherenkov angle and the momentum the particle mass can be determined:

$$m = \frac{p}{c}\sqrt{n^2 \cos^2(\Theta_C) - 1}\,.$$

- All Cherenkov detectors at the LHC are RICH devices.

Separation power (1)

- The separation power is approximately given by

$$n_{\sigma\Theta_C} \approx \frac{c^2}{2p^2\langle\sigma_{\Theta_C}\rangle\sqrt{n^2-1}}|m_B^2 - m_A^2|$$

- with the angular resolution

$$\sigma_{\Theta_C}^2 = \left(\frac{\sigma_{\Theta_i}}{\sqrt{N_{p.e.}}}\right)^2 + \sigma_{Glob}^2 \, .$$

- In typical counters σ_{Θ_C} varies between 0.1 and 5 mrad.

Separation power (2)

- Note the similarity of the formula for the separation power:

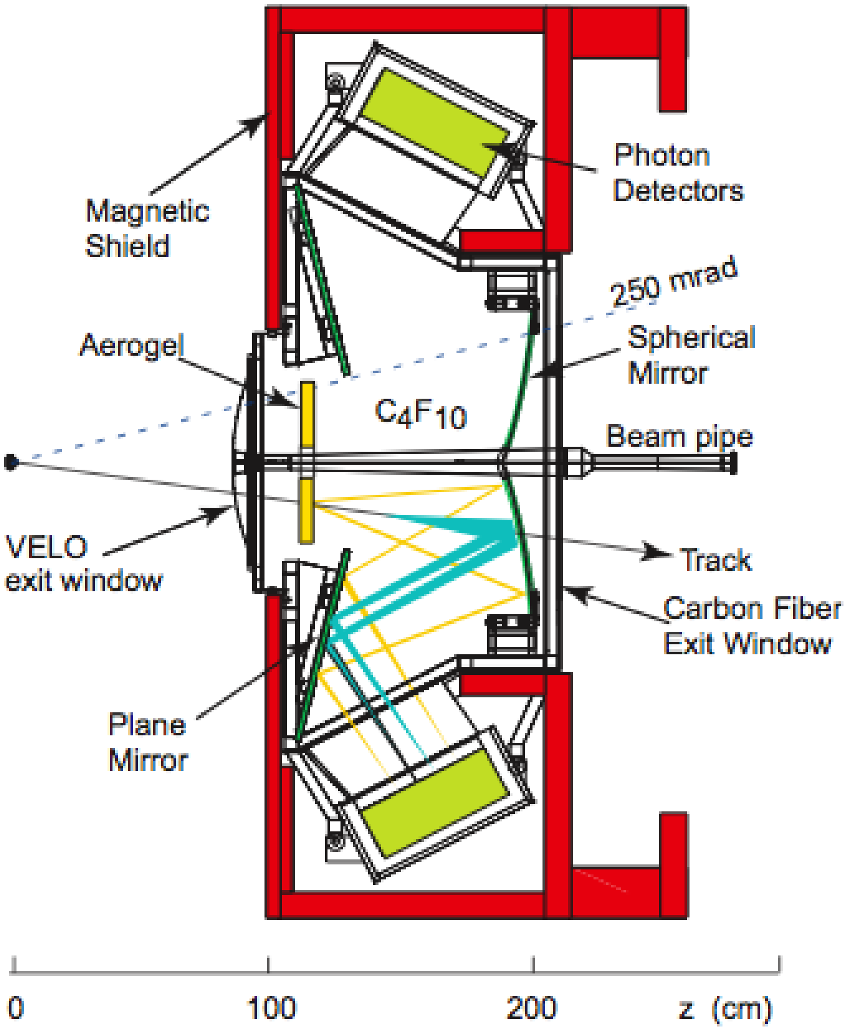
$$n_{\sigma_{\Theta_C}} \approx \frac{c^2}{2p^2 \langle \sigma_{\Theta_C} \rangle \sqrt{n^2 - 1}} |m_B^2 - m_A^2|$$

with the one for time-of-flight measurements:

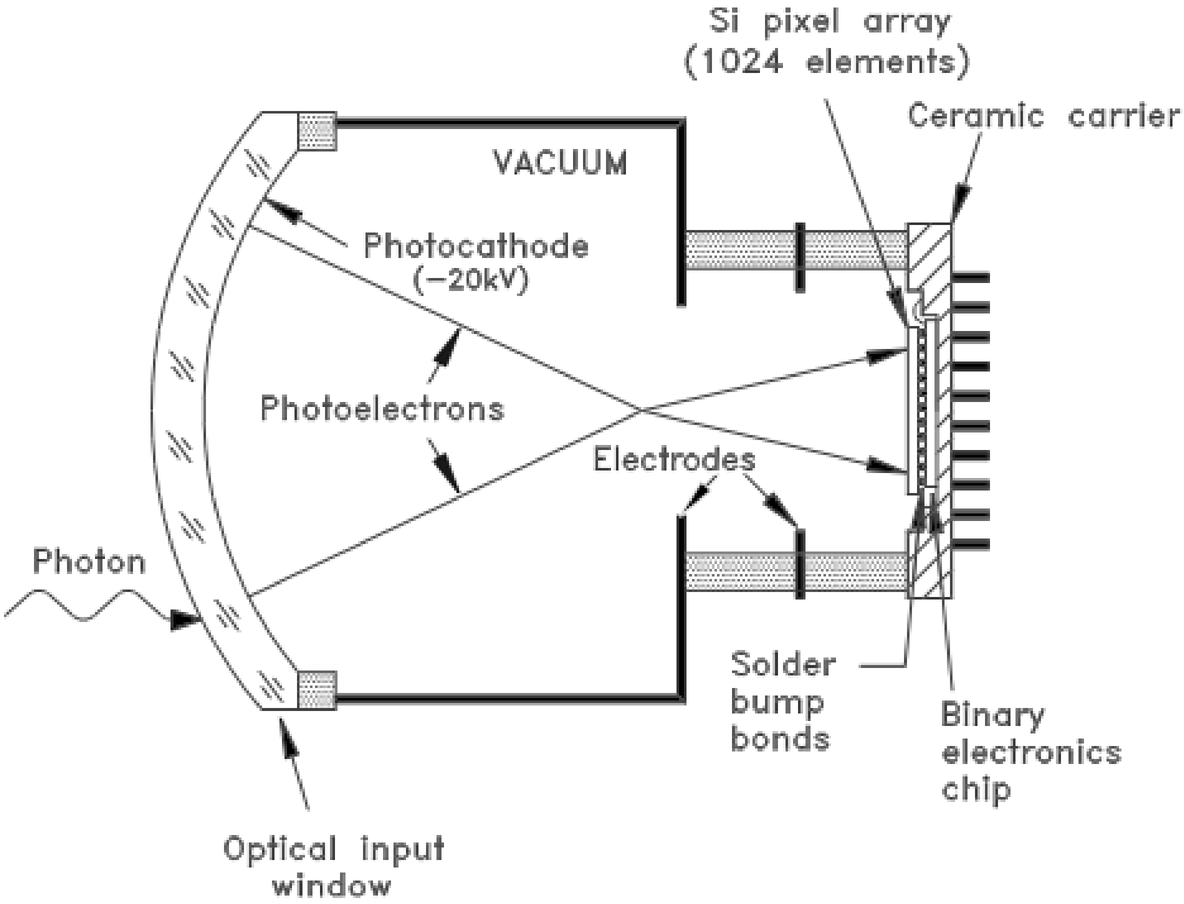
$$\frac{Lc}{2p^2 \sigma_{TOF}} |m_A^2 - m_B^2| \; .$$

- In the case of a RICH there is however an additional factor of $1/\sqrt{n^2-1}$, which allows to adjust the detector configuration in order to achieve the desired momentum coverage.

Example: LHCb RICH

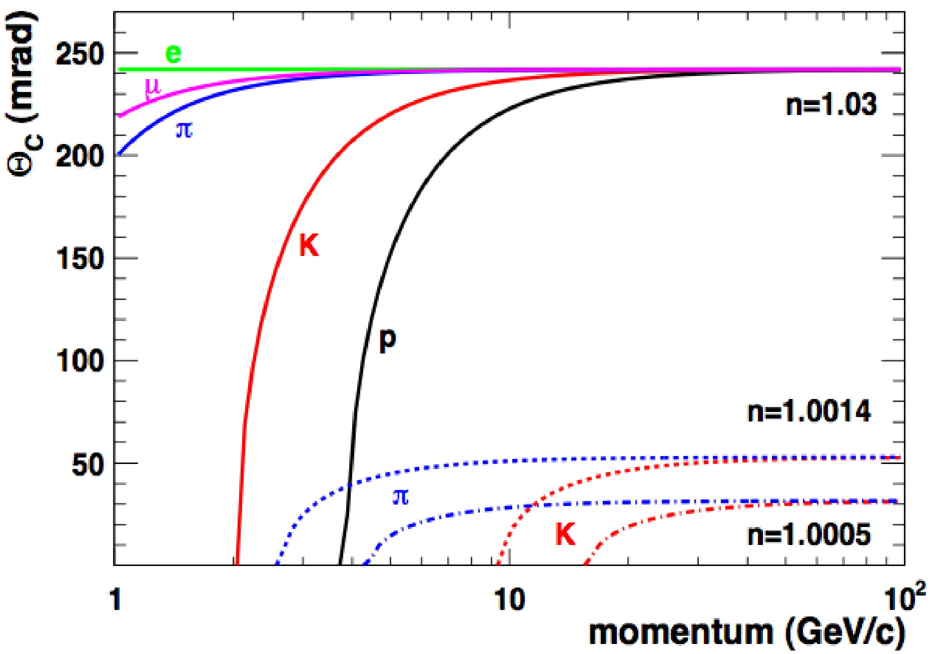


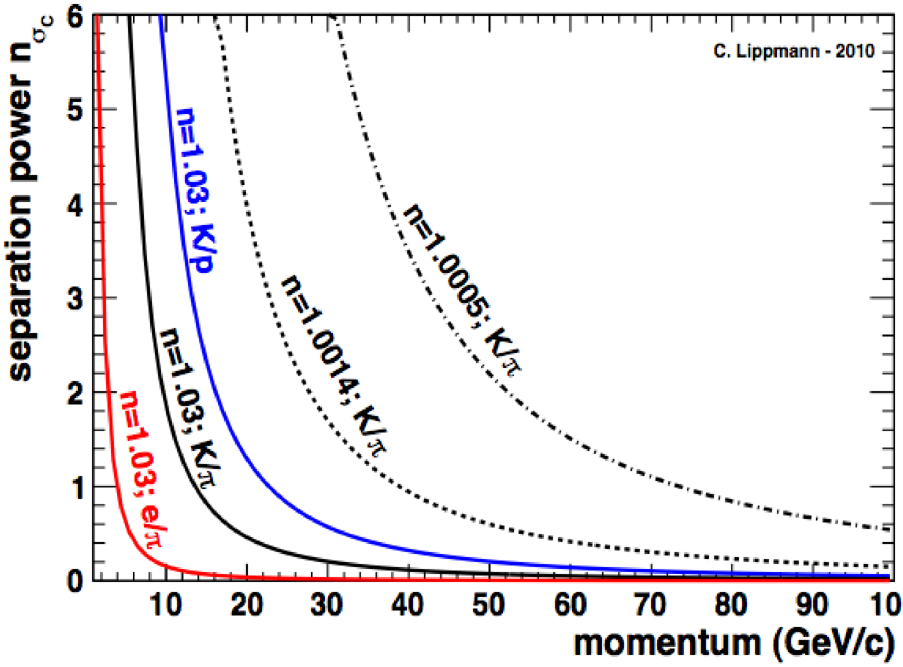
LHCb RICH1



LHCb HPD photon detector

LHCb RICH: 3 different radiators



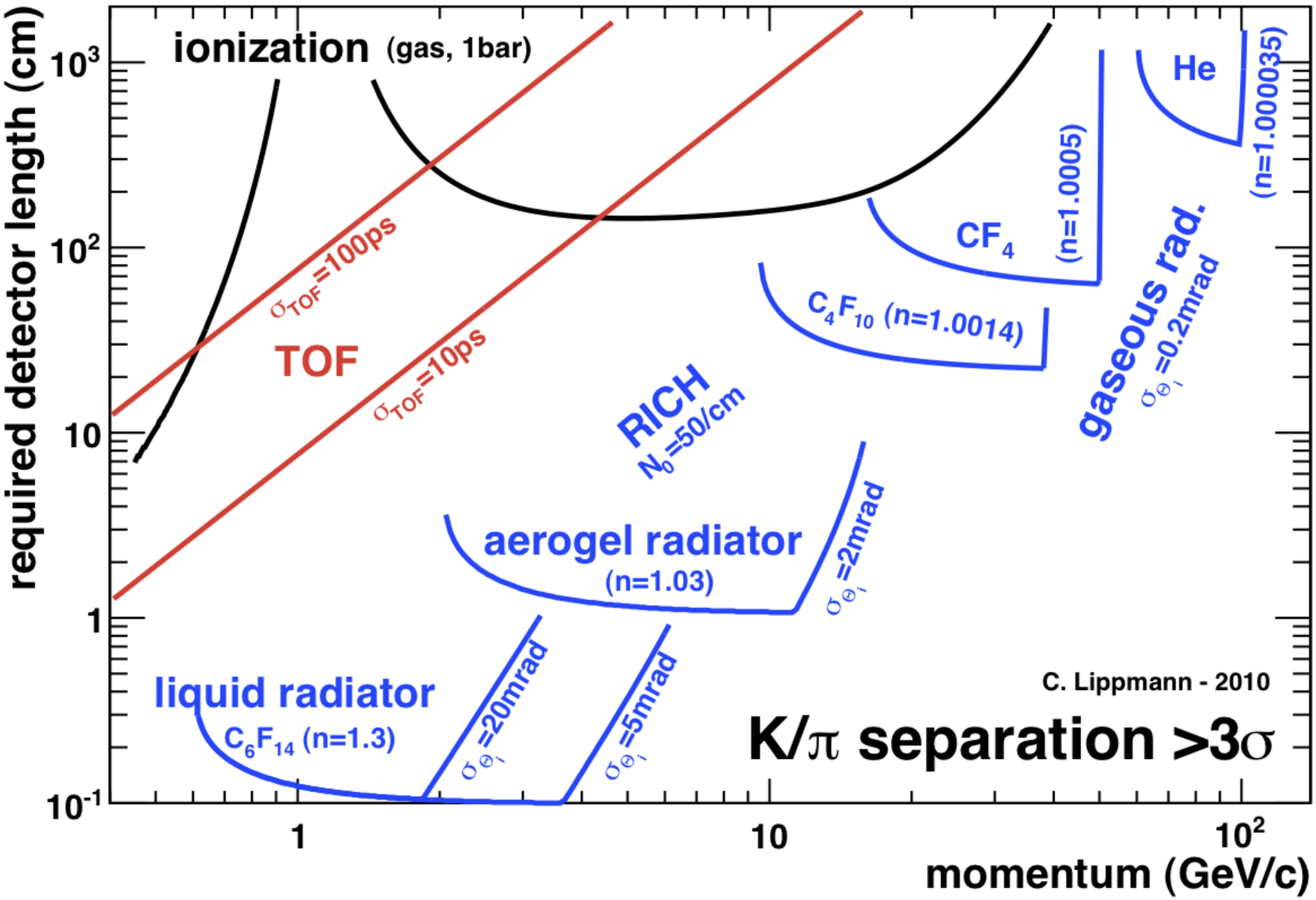


- Cherenkov angles and achievable separation as a function of momentum with the 3 different materials used in the LHCb RICH system.

Summary (1)

- Leptons and photons may be identified by the way they interact.
- In order to identify charged hadrons (π, K, p), their mass has to be determined.
- This is done by measuring momentum and velocity. The velocity can be determined by 4 different means, each applicable in a certain momentum region.
- The Cherenkov imaging is the most flexible method, as it allows to tune the response of the detector by varying the refractive index (and the length of the radiator), and makes accessible also very high momenta (>100 GeV/c).

Summary (2)



ionization (gas, 1bar)
σ_{TOF}=100ps
TOF
σ_{TOF}=10ps
RICH
N_0=50/cm
aerogel radiator
(n=1.03)
σ_{Θ_i}=2mrad
liquid radiator
C_6F_{14} (n=1.3)
σ_{Θ_i}=20mrad
σ_{Θ_i}=5mrad
C_4F_{10} (n=1.0014)
CF_4
(n=1.0005)
He
(n=1.000035)
gaseous rad.
σ_{Θ_i}=0.2mrad
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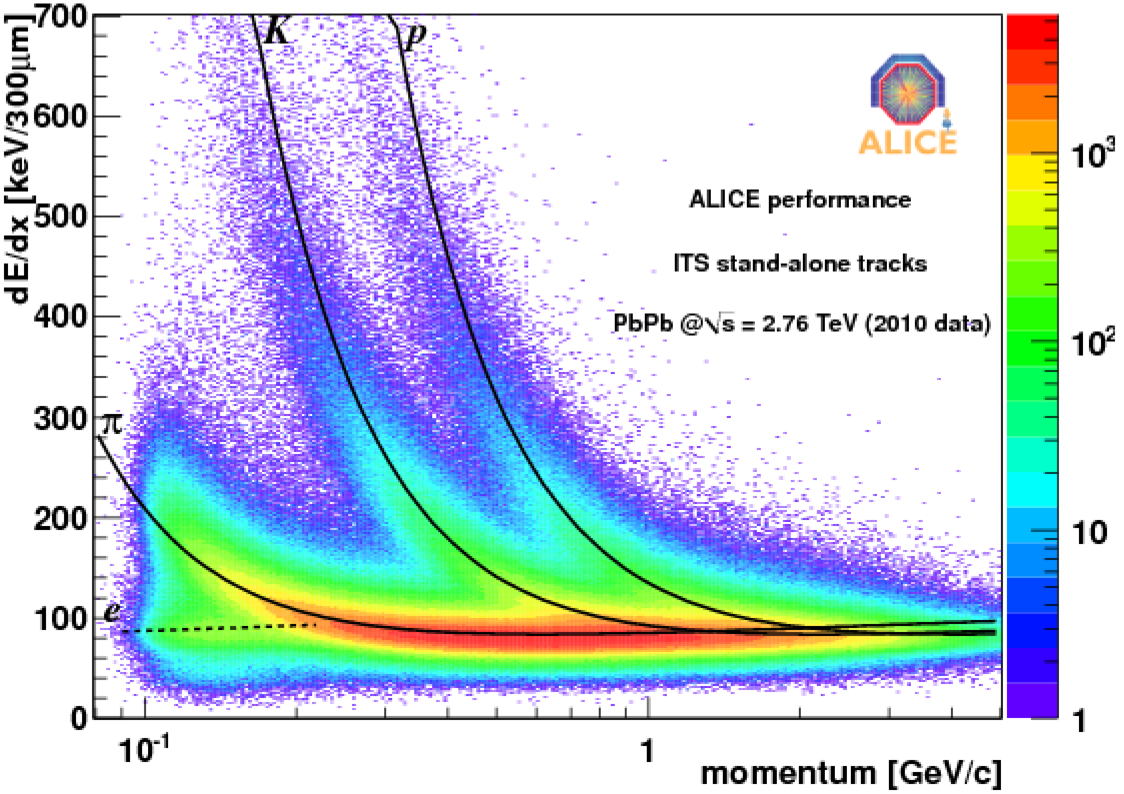
K/π separation >3σ
required detector length (cm)
10^{-1}
1
10
10^2
10^3
momentum (GeV/c)
1
10
10^2

More slides

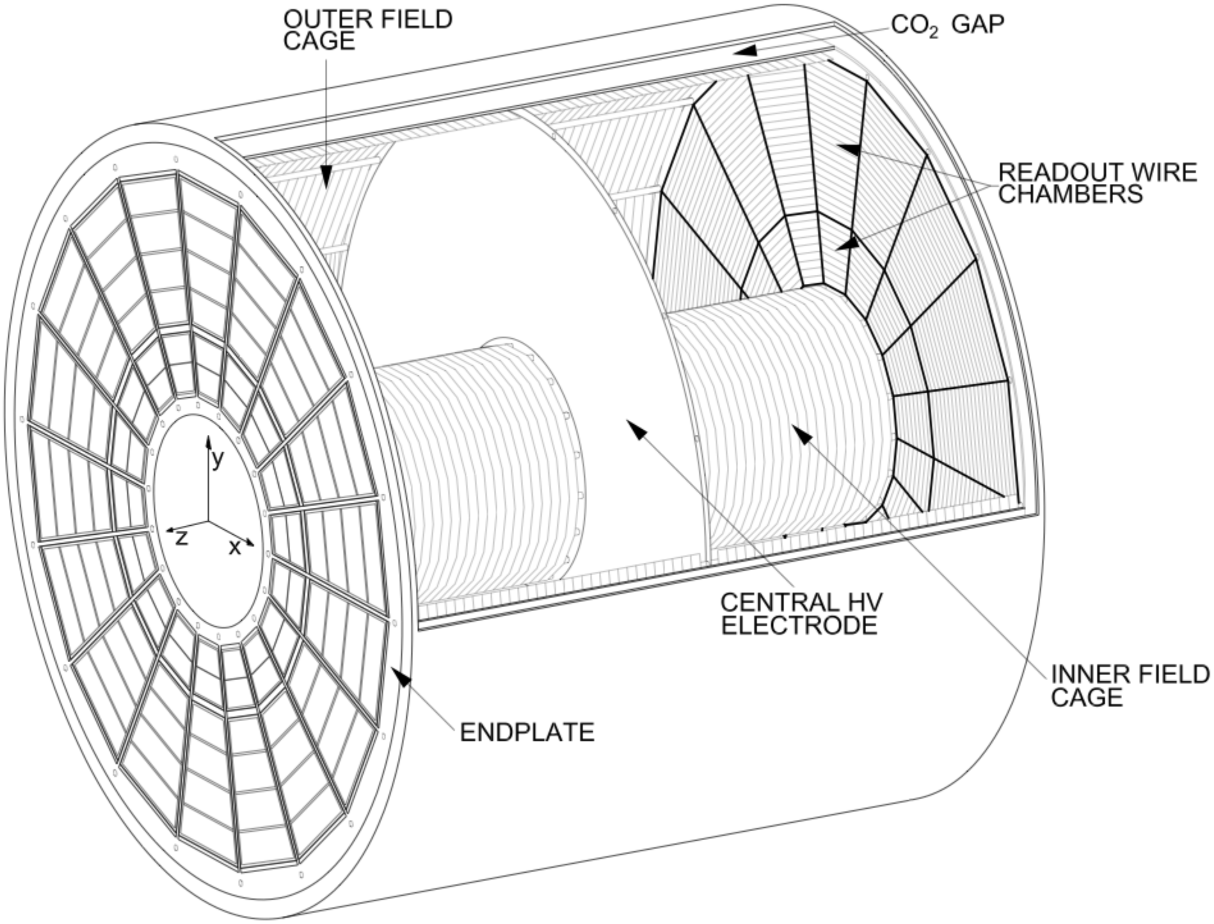
Example: ALICE ITS

- ALICE plot for the ITS detector (silicon). The momentum is measured by the TPC and ITS working together.

- Good PID for low momenta.

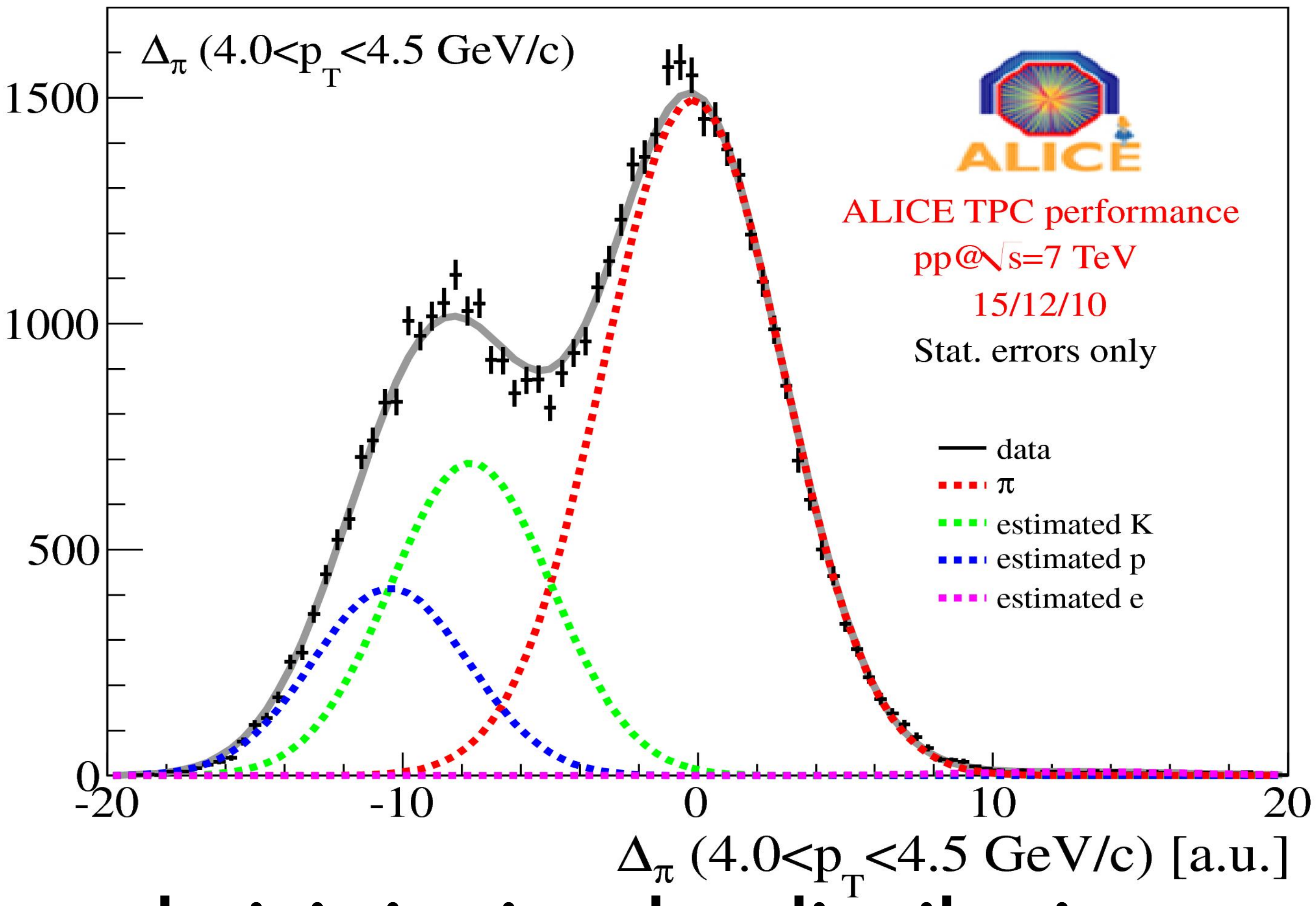


Example: ALICE TPC (1)



- Largest gaseous TPC
- Ne, CO$_2$ gas mixture (90-10)
- Readout based on wire chambers
- 557.568 readout channels
- Sophisticated digital electronics (baseline correction, signal tail cancellation, multi event buffering)

ALICE TPC: PID in the relativistic rise



ALICE work in progress

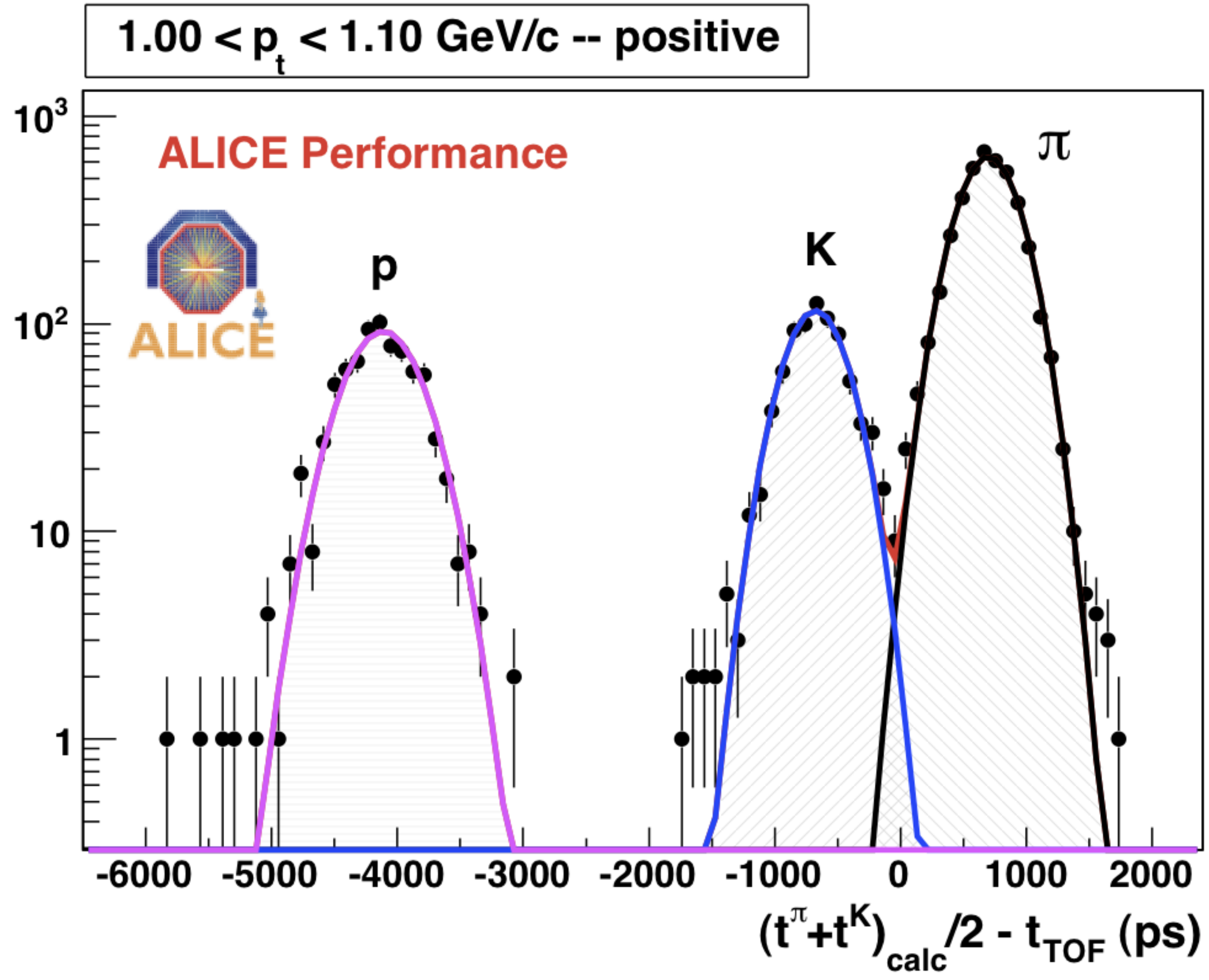
- In the relativistic rise the distributions overlap and PID becomes more challenging.
- Momentum window of 500MeV/c

Current detectors for TOF measurements

- Scintillators are often used but for large area detectors their readout becomes too expensive.

- In large heavy-ion experiments like STAR and ALICE Resistive Plate Chambers are used, as they offer a cheaper alternative based on gaseous detectors using parallel plate technology.

ALICE TOF: Particle separation



- Particle separation using TOF in ALICE in a 100MeV/c momentum bin

Cherenkov detectors

- In general, Cherenkov detectors contain a radiator through which charged particles pass (a transparent dielectric medium) and a photon detector.
- The number of photoelectrons ($N_{p.e.}$) detected can be approximated as

$$N_{p.e.} \approx N_0 z^2 L \sin^2(\Theta_C)$$

- with L= path length of particle through radiator and N_0 the quality factor or figure of merit containing the light transmission, collection and detection efficiencies.

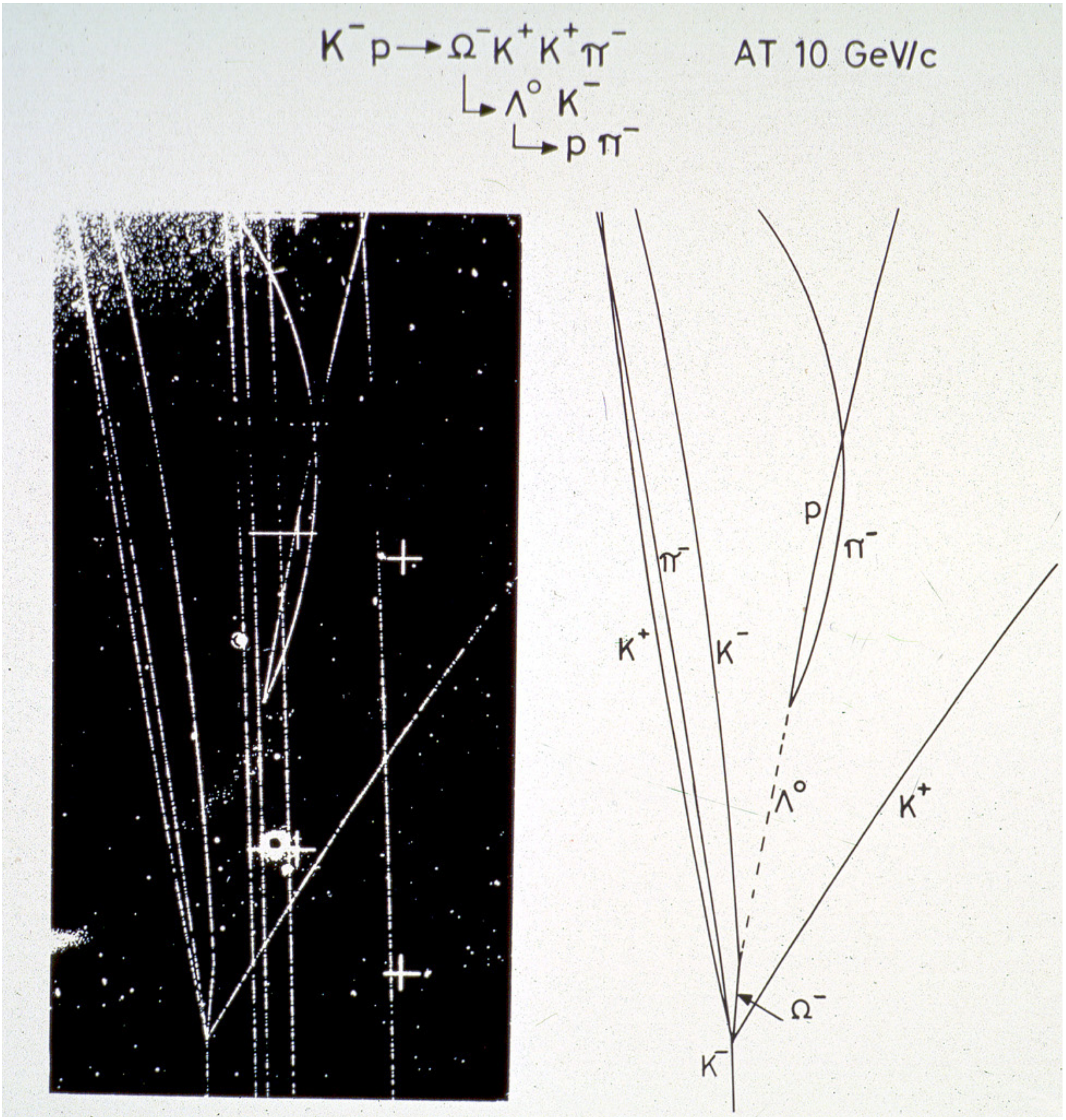
PID in a tracking system: V_0's (1)

$$K_s^0 \rightarrow \pi^+\pi^-$$

$$\gamma \rightarrow e^+e^-$$

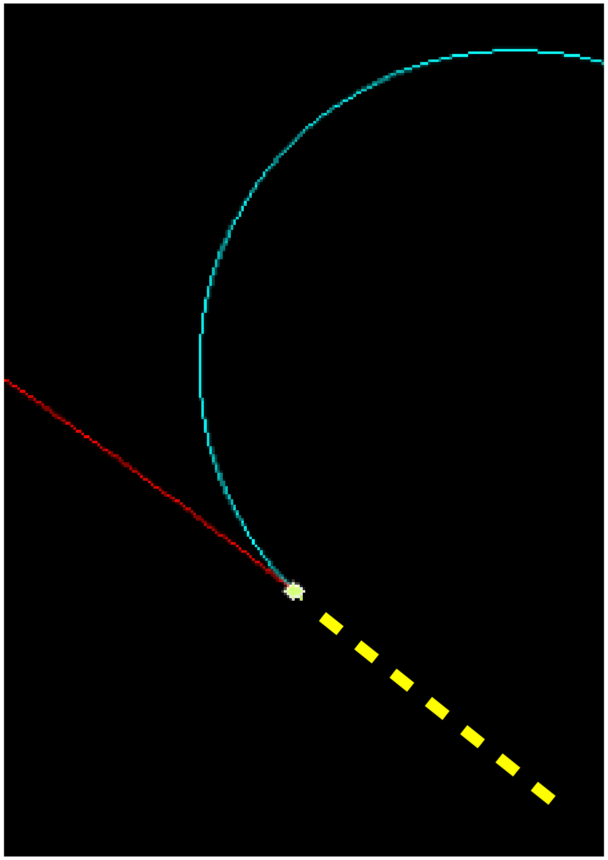
$$\Lambda \rightarrow p^+\pi^-$$

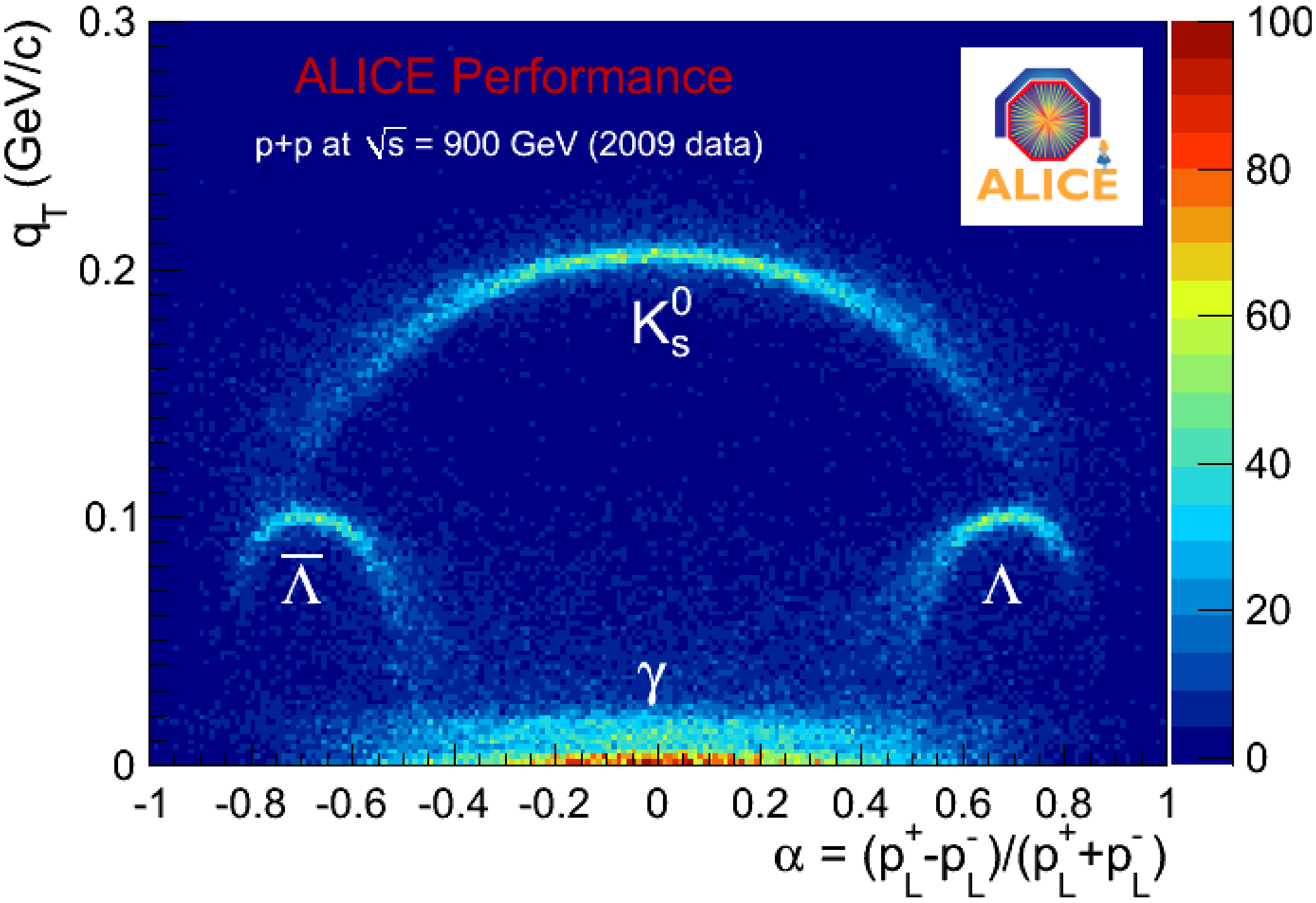
$$\overline{\Lambda} \rightarrow p^-\pi^+$$



PID in a tracking system: V_0's (2)

- V_0's can be reconstructed from the kinematics of their decay products, without needing to identify the π or p.





PID in a tracking system: Kaon kinks

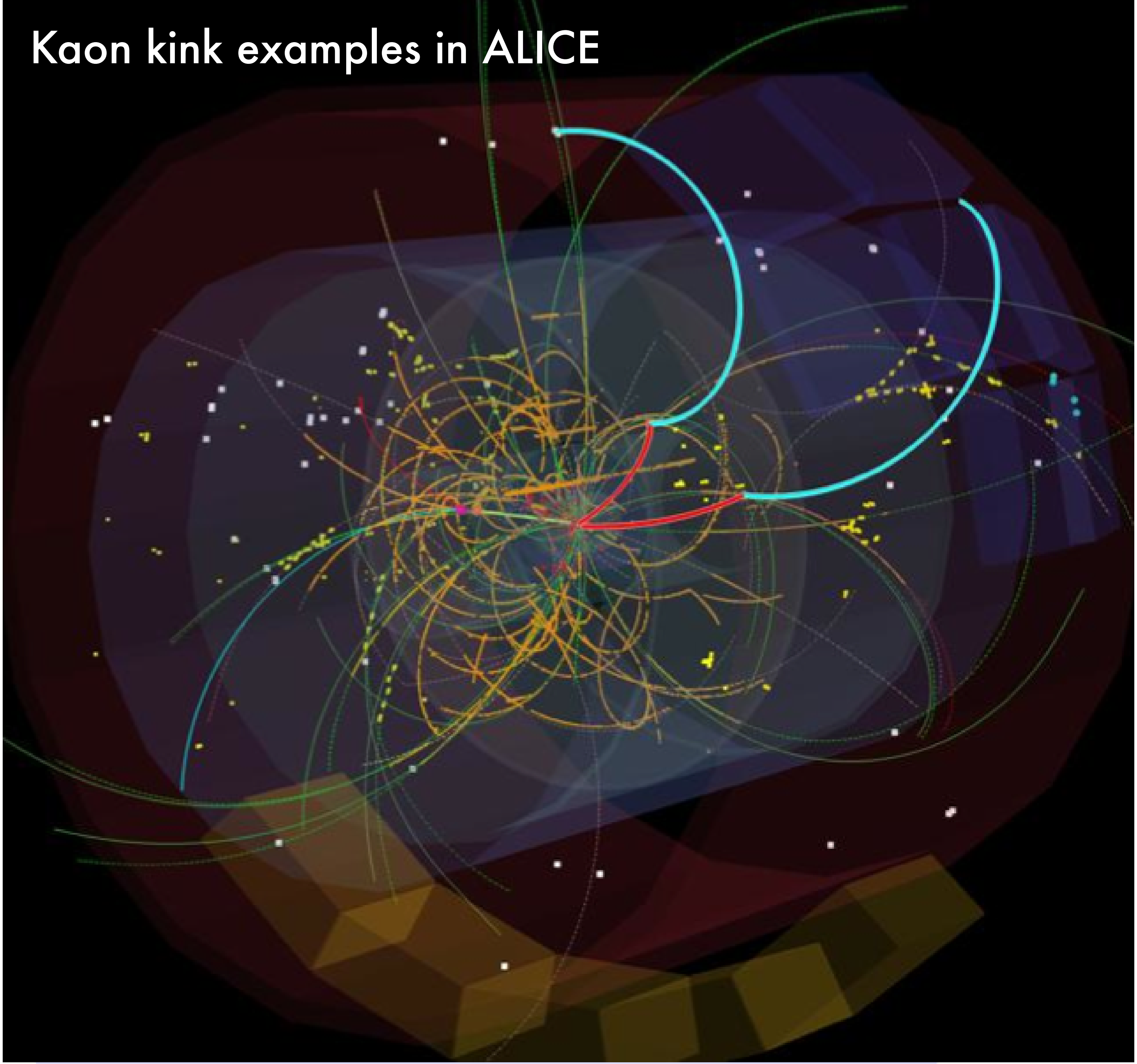
- Charged Kaons may decay in a high-resolution tracking system:

$$K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}\ (64\%) \text{ and } K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\ (21\%)$$

- In that case they can be identified through the characteristic "kink" topology (see next slide).

- The Kaon identification process is then reduced to the finding of kinks in the tracking system.

Kaon kink examples in ALICE



More particles: Tau and neutrino

- Tau Leptons:
  - Lifetime 0.29ps; decay into many final states
  - Decay products are seen in detector
  - Accurate vertex detectors detect that they come from secondary vertex (about 0.5mm)

- Neutrinos:
  - Usually detected indirectly in HEP (collider) experiments through missing energy

More particles: Quarks

- Quarks:
  - Not seen in the detector, due to confinement
  - At large energy production of jets
  - Different flavours can be separated (at least statistically) by looking for displaced tracks from b- and c-hadron decays.