Particle Identification

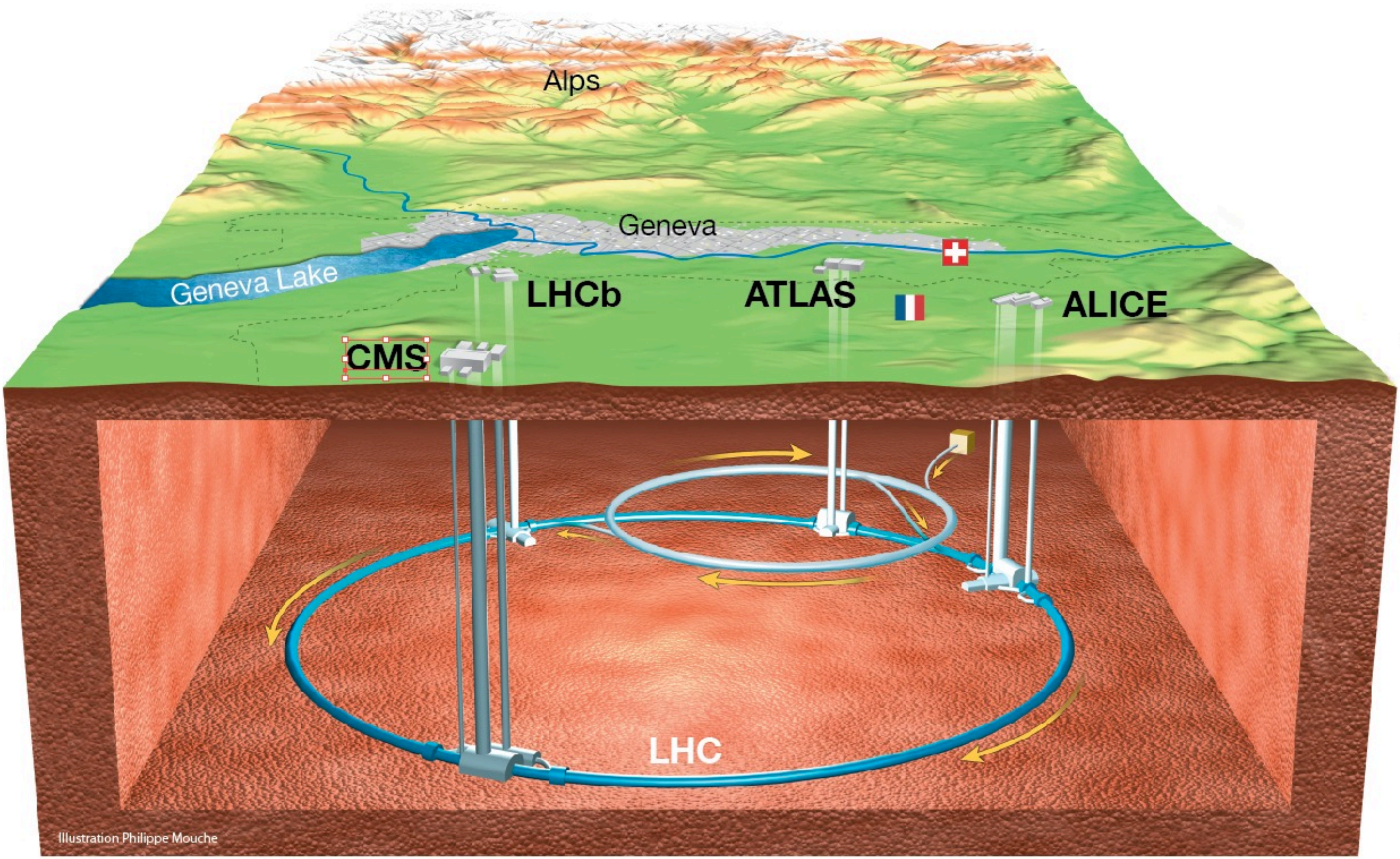
8 July 2014

Christian Lippmann

Introduction (1)

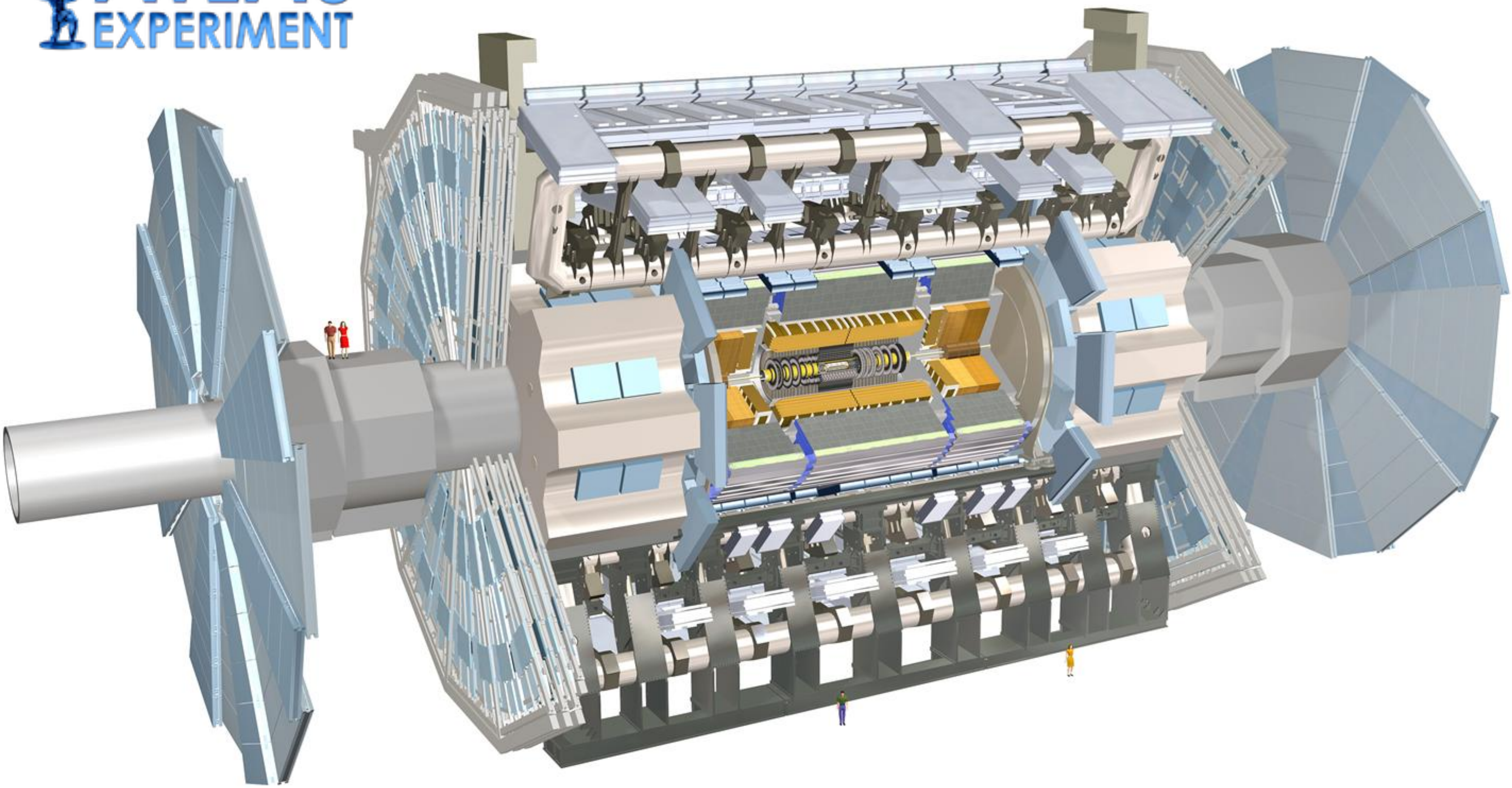
- In addition to tracking and calorimetry, Particle IDentification (PID) is a crucial aspect of most particle and nuclear physics experiments, e.g. at the CERN LHC

LHC and experiments (1)

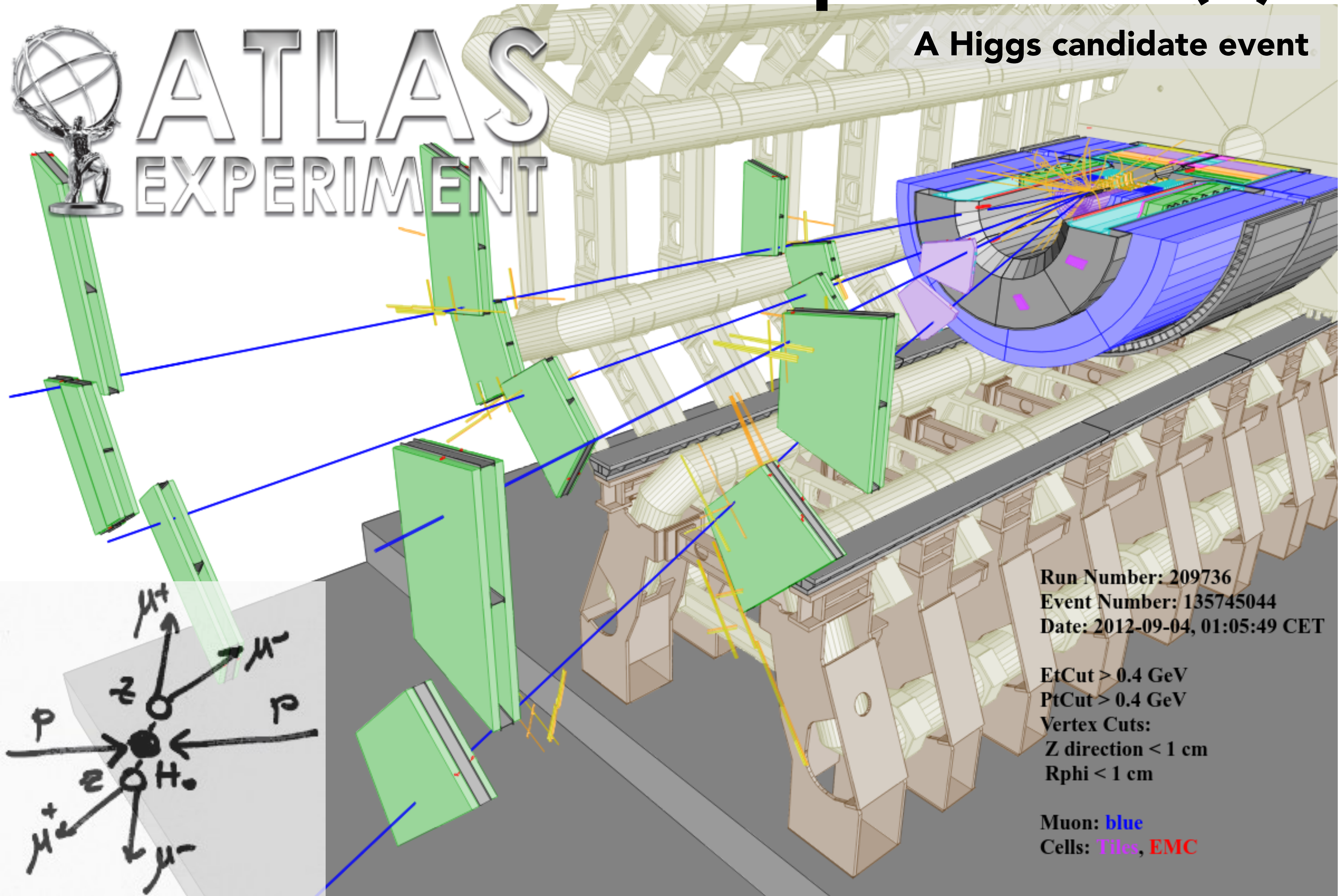


LHC and experiments (2)

ATLAS EXPERIMENT



LHC and experiments (3)



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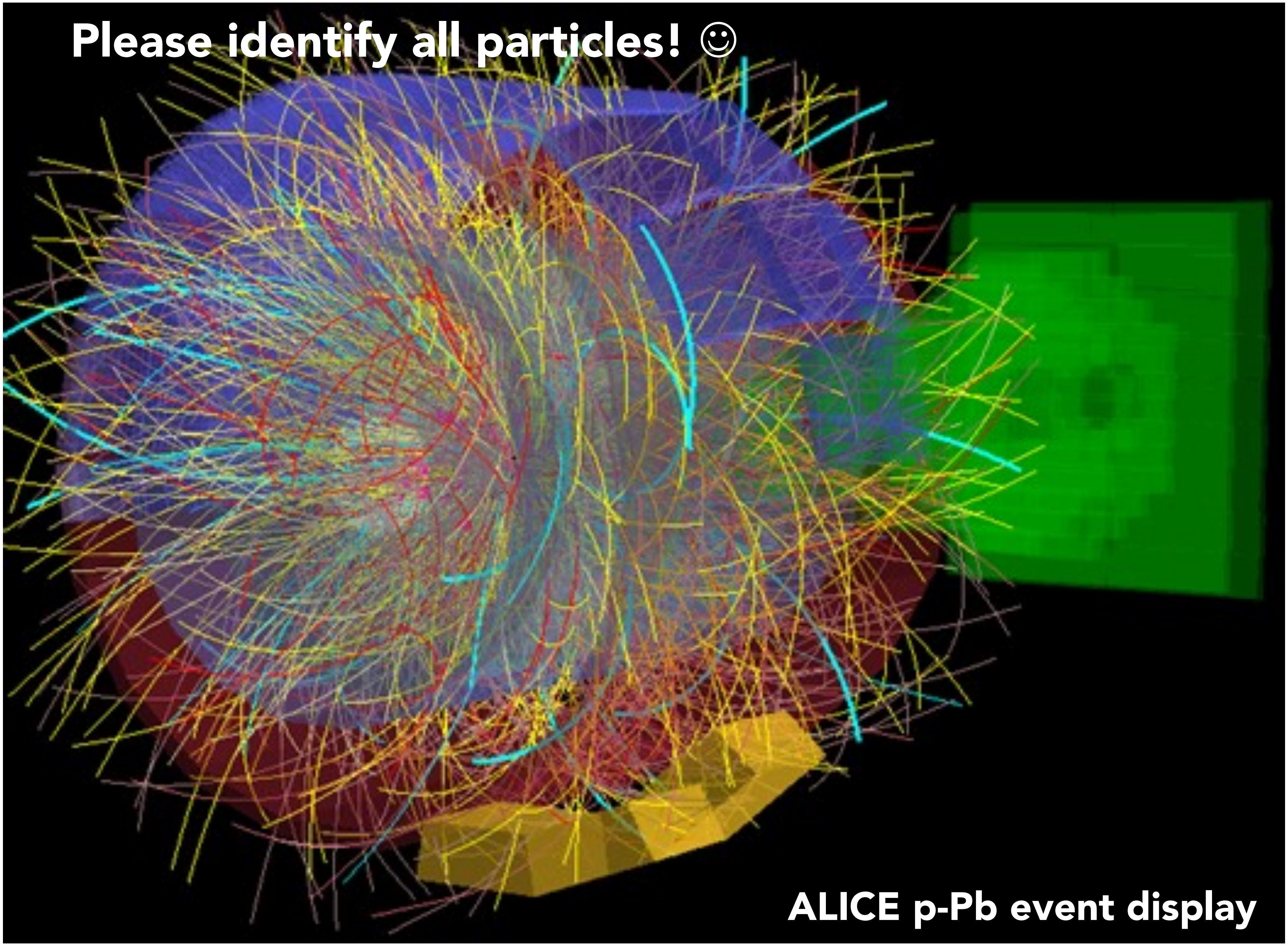
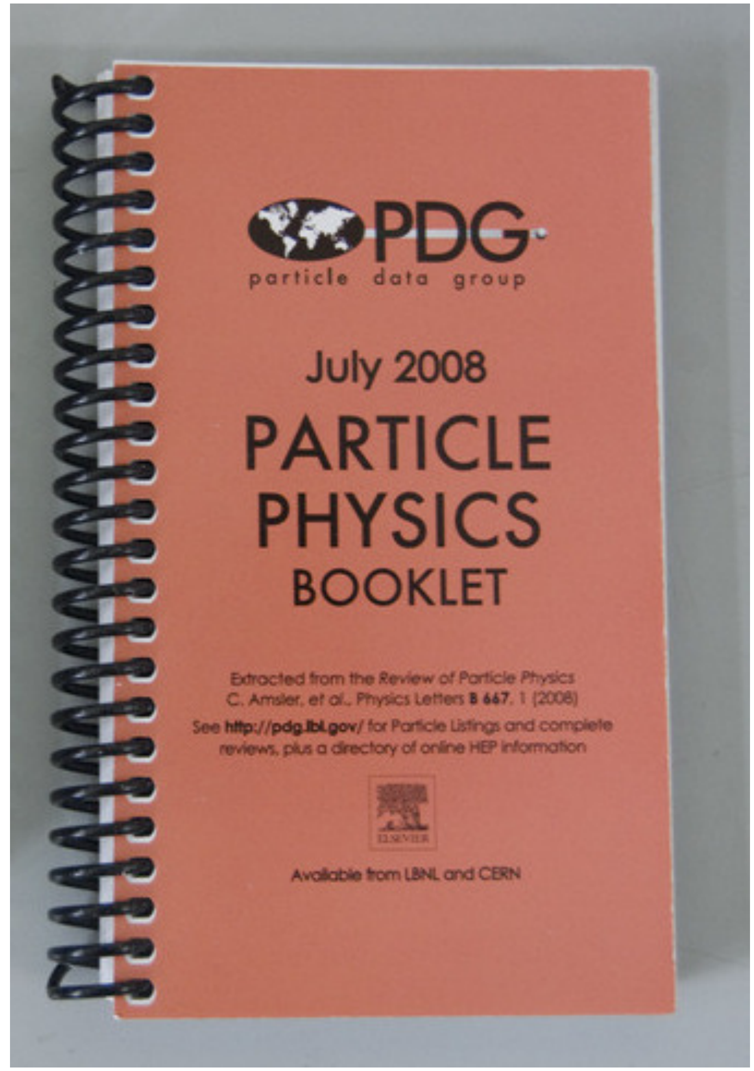


Particles (1)

- There are more than 200 particles described in the particle physics booklet
- Do we have to identify all those in a detector system?



Particles (2)

- **Table shows all known particles with mean lifetime sufficiently large to travel more than 10 μm (at GeV energies) before they decay**

particle		constituents	Mass [MeV]	Lifetime τ [s]	$c\tau$
Electron/Positron	$e^{\pm}$		0.511	∞	∞
(Anti)Muon	$\mu^{\pm}$		105.7	2.2×10^{-6}	659 m
(Anti)Tauon	$\tau^{\pm}$		1777	2.9×10^{-13}	87 μm
Electron-Neutrino	ν_e		$< 3 \times 10^{-6}$ *	∞	∞
Muon-Neutrino	ν_μ		<0.19 *	∞	∞
Tau-Neutrino	ν_τ		<18.2 *	∞	∞
Photon	γ		0	∞	∞
Charged Pions	$\pi^{\pm}$	$u\bar{d}, d\bar{u}$	140	2.6×10^{-8}	7.8 m
Charged kaons	$K^{\pm}$	$u\bar{s}, s\bar{u}$	494	1.2×10^{-8}	3.7 m
Neutral kaons	K^0_L, K^0_S	$d\bar{s}, s\bar{d}$	497	5.1×10^{-8}, 8.9×10^{-11}	15.5 m, 2.7 cm
D-Mesons	$D^{\pm}$	$c\bar{d}, d\bar{c}$	1869	1.0×10^{-12}	315 μm
	D^0	$c\bar{u}, u\bar{c}$	1864	4.1×10^{-13}	123 μm
	$D^{\pm}_s$	$c\bar{s}, s\bar{c}$	1969	4.9×10^{-13}	147 μm
B-Mesons	$B^{\pm}$	$u\bar{b}, b\bar{u}$	5279	1.7×10^{-12}	502 μm
	B^0	$b\bar{d}, d\bar{b}$	5279	1.5×10^{-12}	462 μm
	B^0_s	$s\bar{b}, b\bar{s}$	5370	1.5×10^{-12}	438 μm
	$B^{\pm}_c$	$c\bar{b}, b\bar{c}$	~6400	$\sim 5.0 \times 10^{-13}$	~150 μm
Proton	p	uud	938.3	$>10^{25}$ y	∞
Neutron	n	udd	939.6	885.7 s	10^8 km
Lambda	Λ	uds	1116	2.6×10^{-10}	7.9 cm
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- **Also light nuclei (d, t, α) may be produced in heavy ion collisions!**

Introduction (2)

- In addition to tracking and calorimetry, Particle IDentification (PID) is a crucial aspect of most particle and nuclear physics experiments, e.g. at the CERN LHC
- Mainly **8 particles** have to be distinguished inside the detector system: $e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, K^{0}, $p^{\pm}$, n
- Particle identification techniques are **based on the interactions of particles with matter**
  - strong interaction (hadrons) and
  - electromagnetic interactions (if charged particle)
- The **electromagnetic interaction of a charged particle** with a medium can be derived from the treatment of its electromagnetic interaction with that medium, where the interaction is mediated by a corresponding photon
- The processes that occur are ionization, Bremsstrahlung, Cherenkov radiation, and transition radiation

Particle Identification techniques

- I. PID by difference in interaction
- II. PID by mass determination
  - II. a) Ionization measurements
  - II. b) Time-of-flight measurements
  - II. c) Cherenkov ring imaging
  - II. d) Transition radiation imaging
- III. PID in a tracking system

I. PID by difference in interaction

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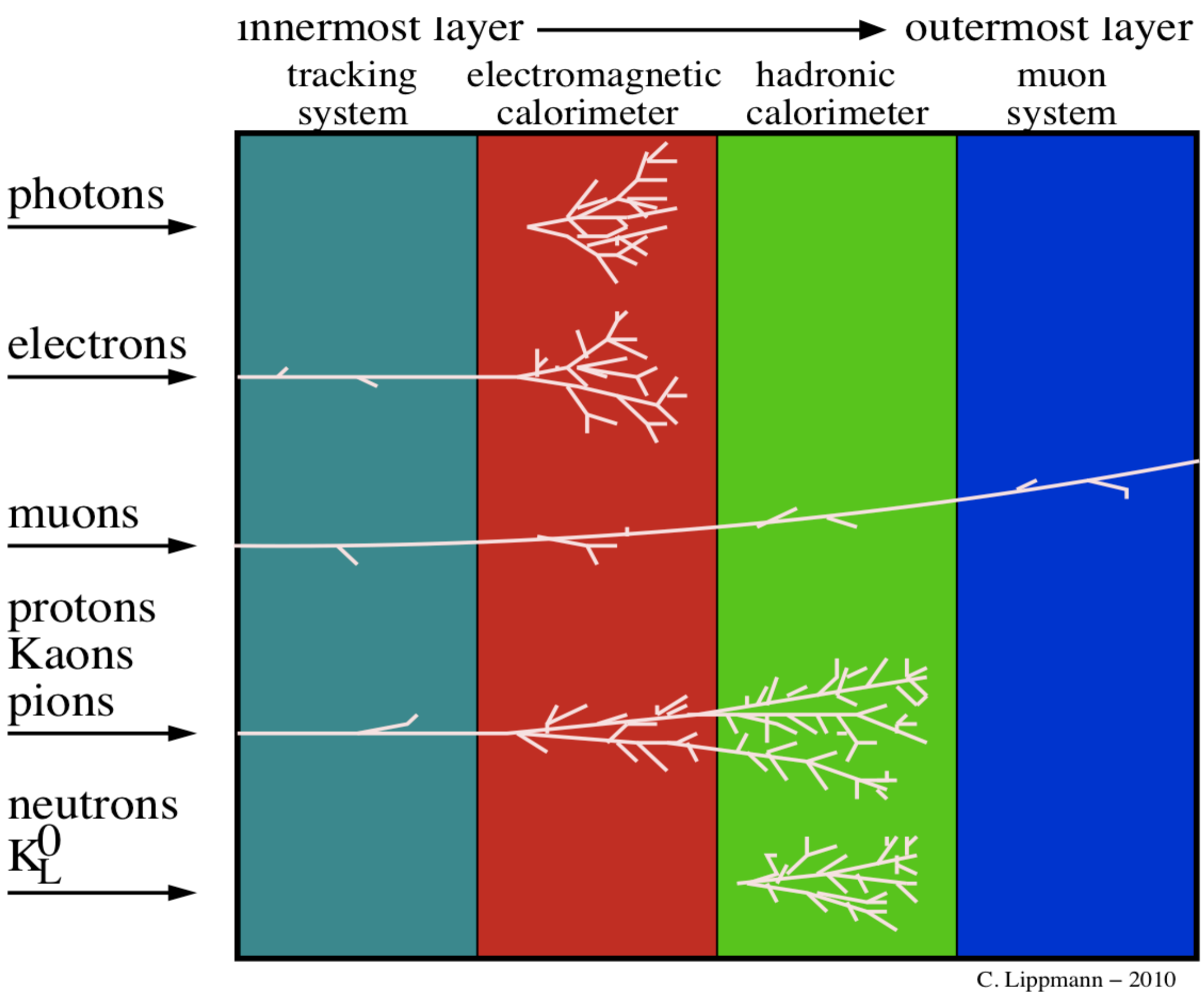
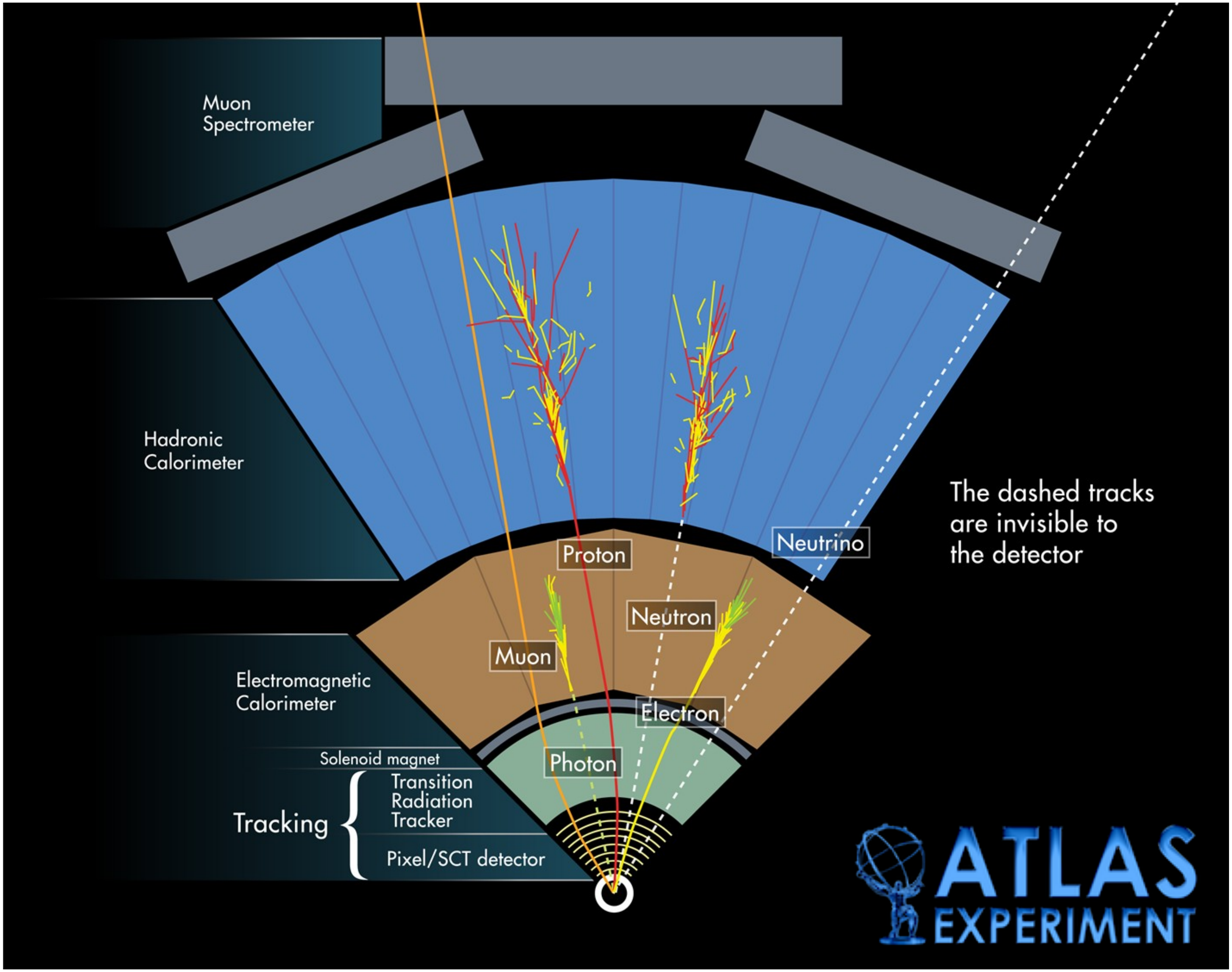
- Experiments are often divided into a few main components, stacked in layers, where each component tests for a specific set of particle properties
- Particles are identified ($e^{\pm}$, $\mu^{\pm}$, γ), or at least assigned to families (charged or neutral hadrons), by the characteristic signatures they leave in the detector
- The individual hadrons can not be distinguished
- Examples: ATLAS, CMS

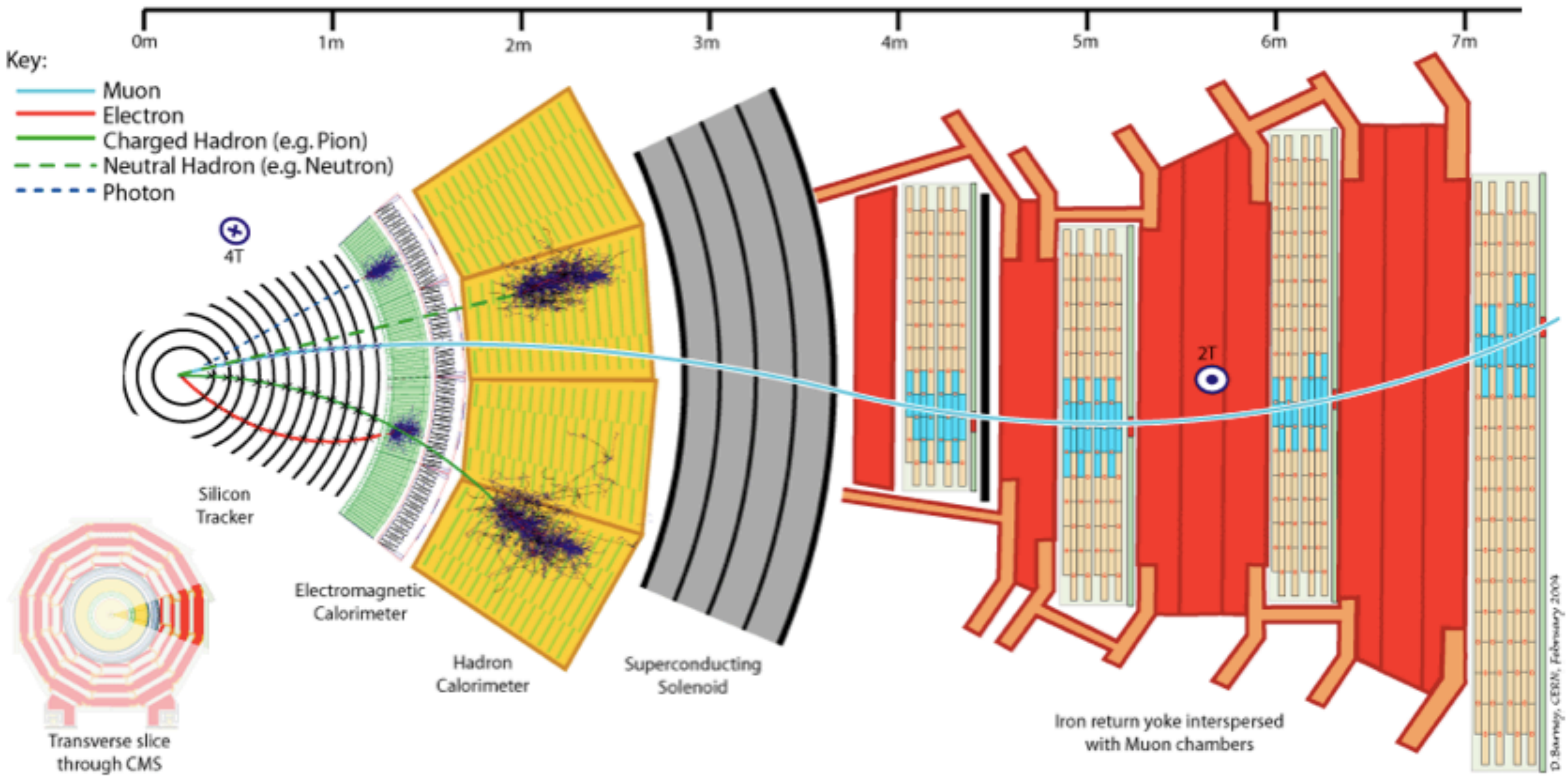
A typical high energy physics experiment



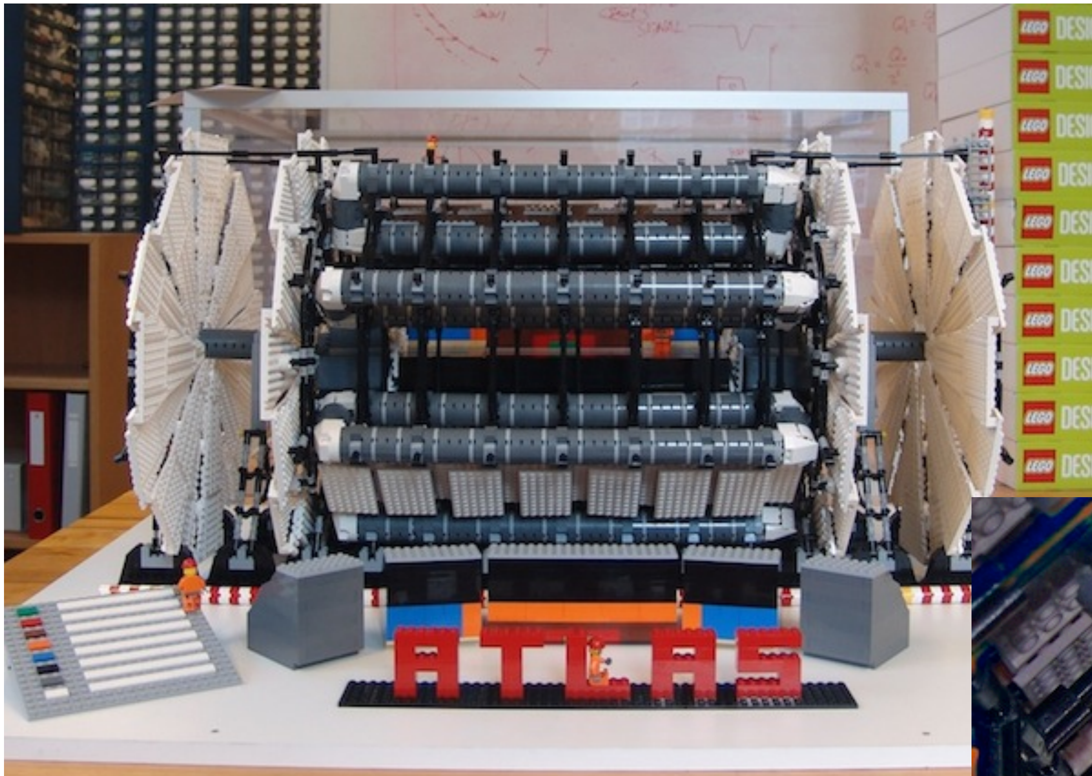
Example 1: ATLAS works like this

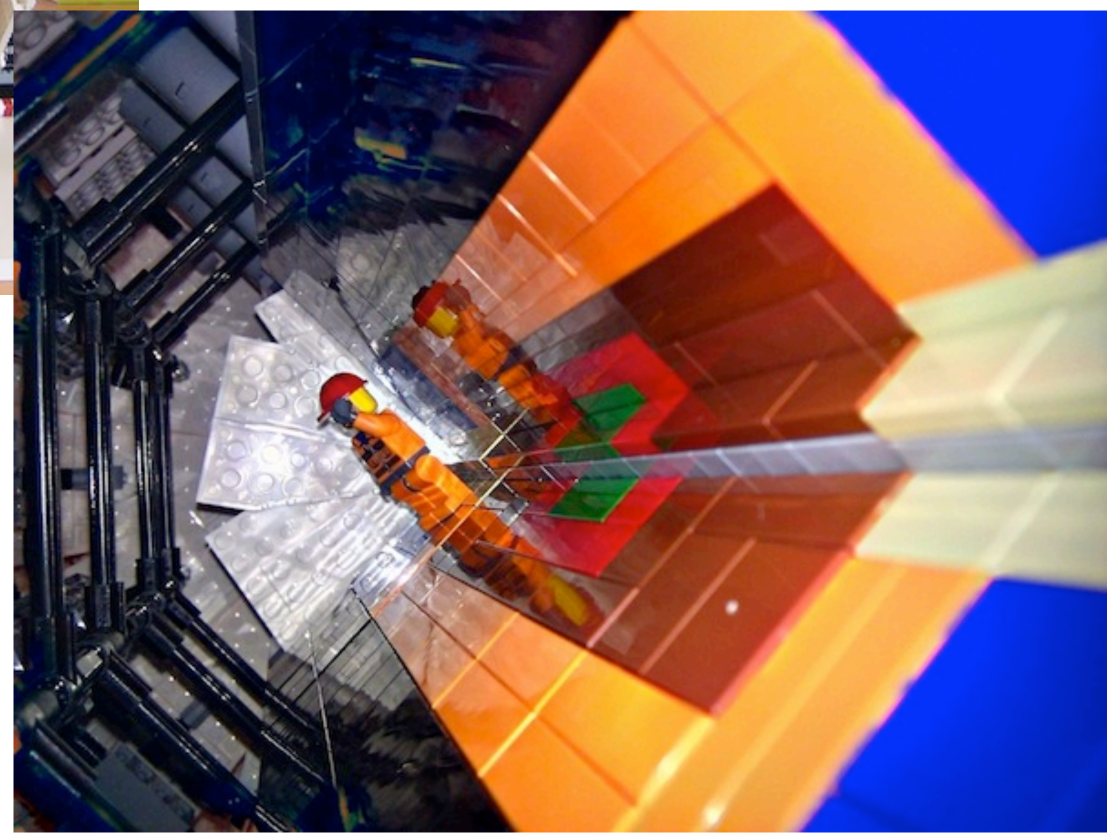


Example 2: CMS as well



Now we know how to build a detector





http://www.atlas.ch/photos/lego.html

ATLAS EXPERIMENT

II. PID by mass determination

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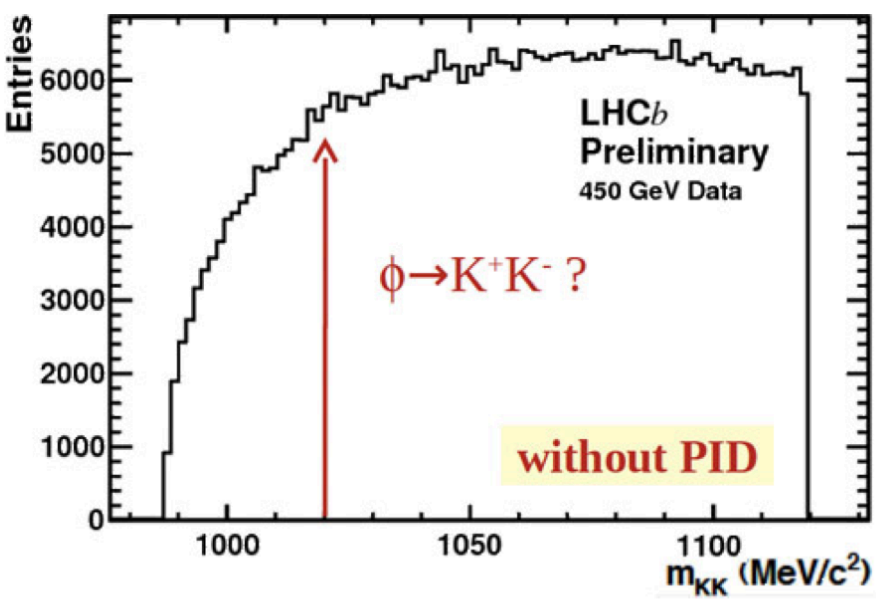
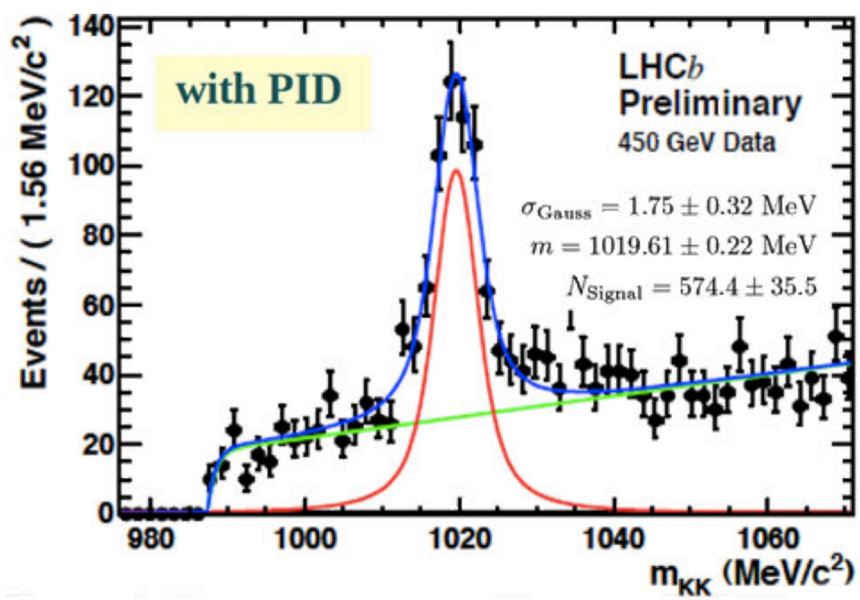
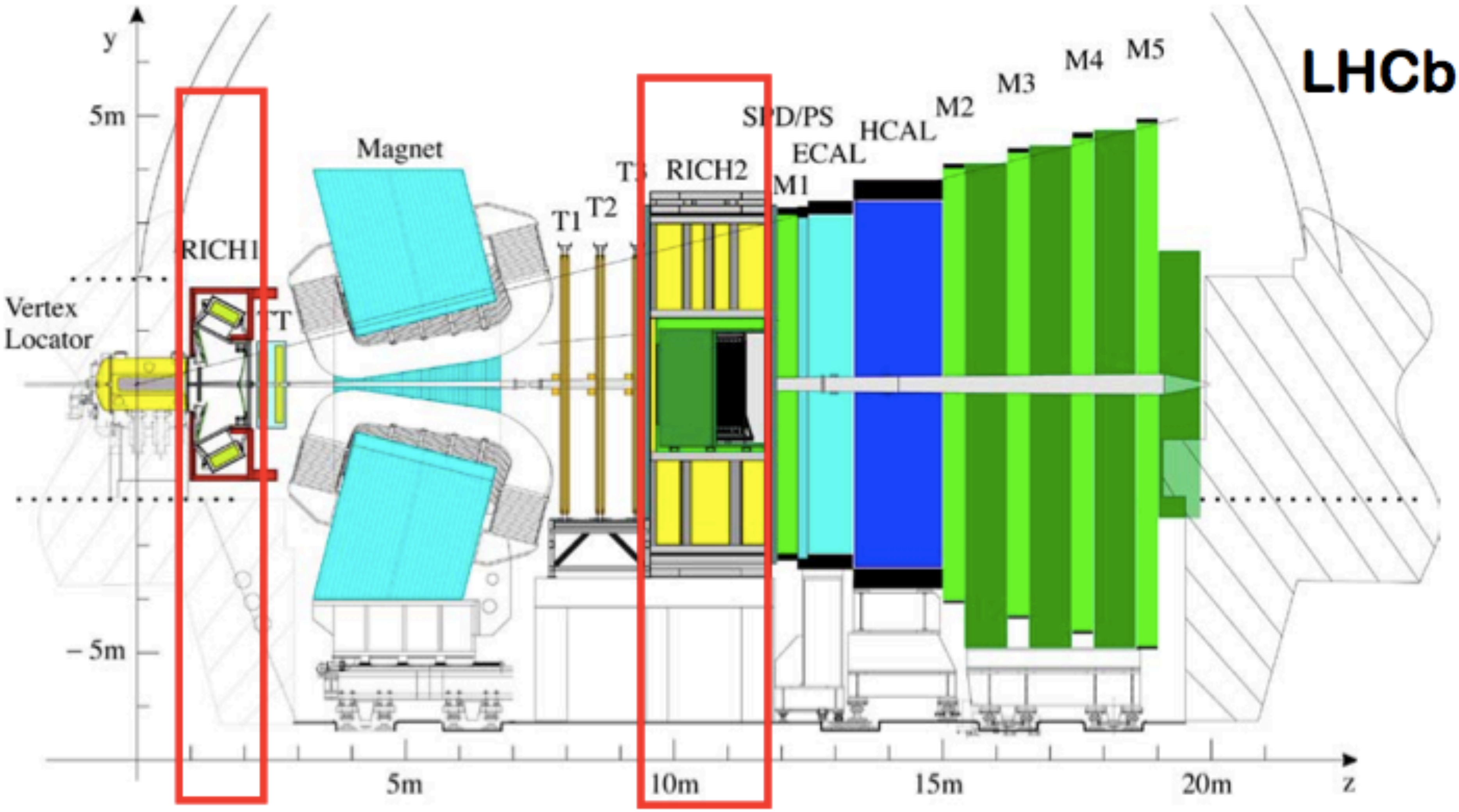
- Charged hadrons (π, K, p) have **identical interactions** with a typical detector (as the one shown before) and are all **effectively stable**
- However, their identification can be crucial
- Example:





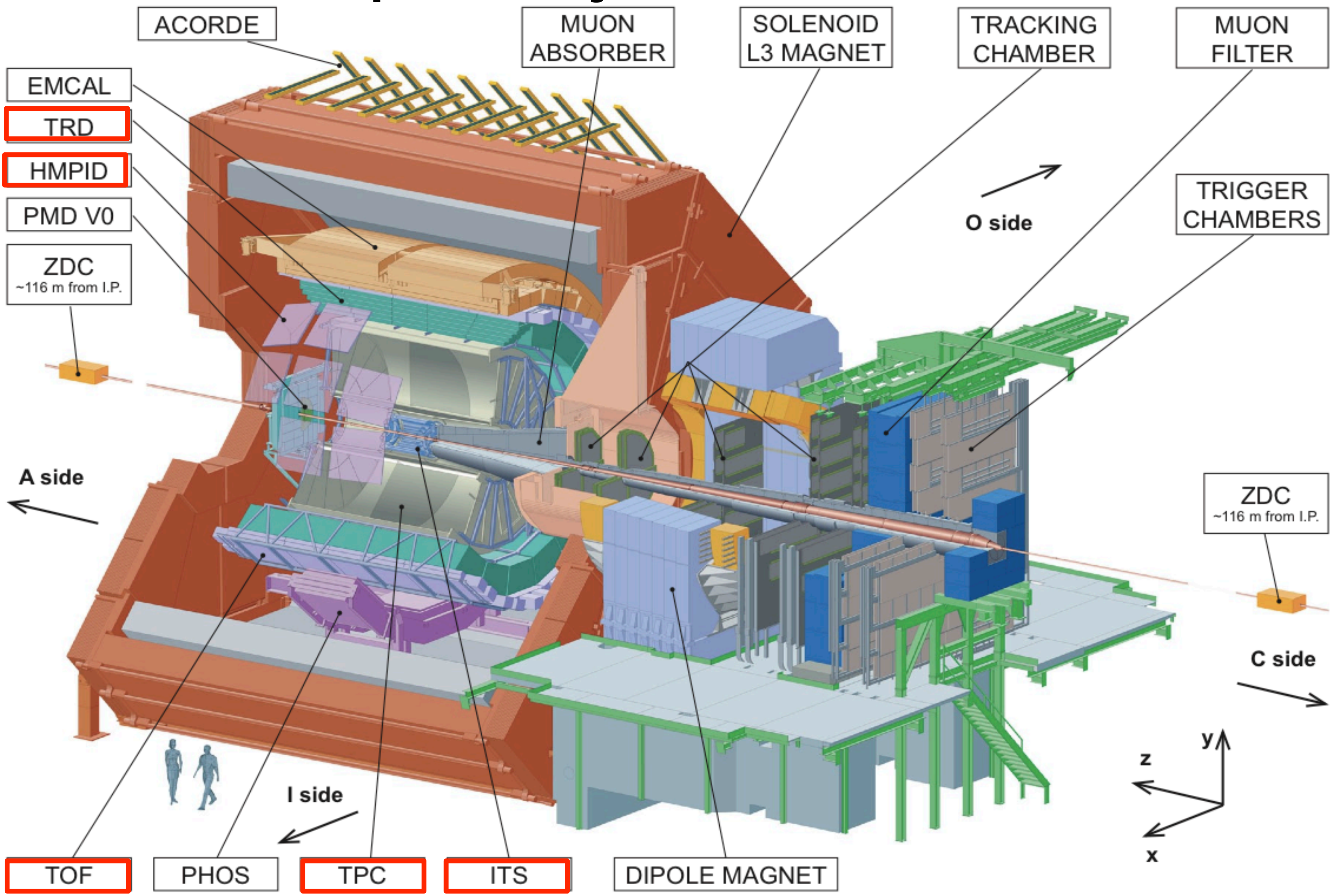
- In order to identify charged hadrons it is necessary to **determine their charge and mass**

Example: Hadron ID in LHCb with 2 RICH detectors



Like a slice out of a ATLAS or CMS, but with the addition of 2 Ring Imaging Cherenkov detectors

Example: PID by mass determination in ALICE



How to measure the mass?

- 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)

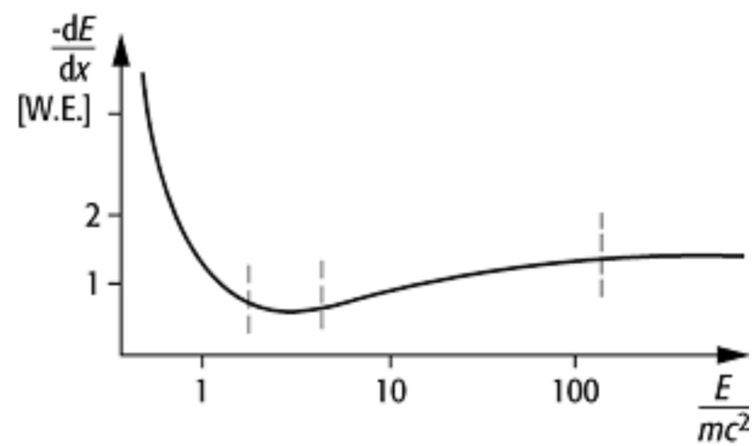
- The momentum is obtained by measuring the curvature of the track in the magnetic field:
  $p \approx 0.3 \cdot B \cdot r$

- The particle velocity β is obtained by:
  a) measurement of the energy deposit by ionization,
  b) time-of-flight (TOF) measurements,
  c) detection of Cherenkov radiation or
  d) detection of transition radiation

II. a) Ionization measurements

II. a) Ionization measurements

- **Fast charged particles passing through matter loose energy while they undergo a series of inelastic Coulomb collisions with the atomic electrons of the material**



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

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

Charge deposit

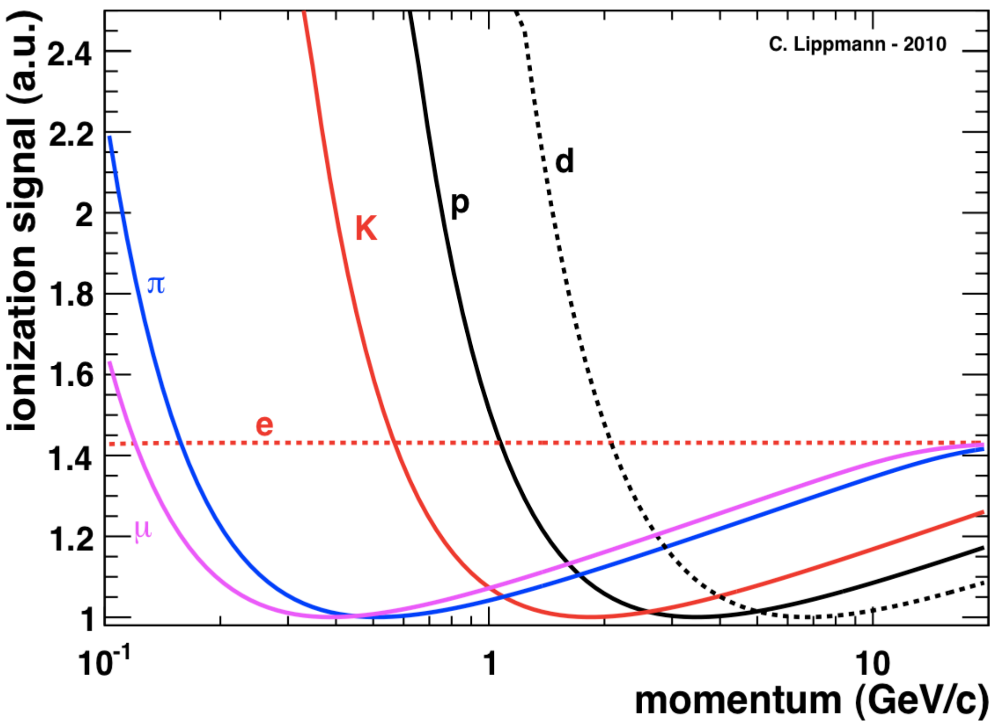
- $\langle dE/dx \rangle$ becomes visible in a detector as the **average number of electron/ion pairs** (or electron/hole pairs for semiconductors) $\langle N_I \rangle$ **along the length x**:

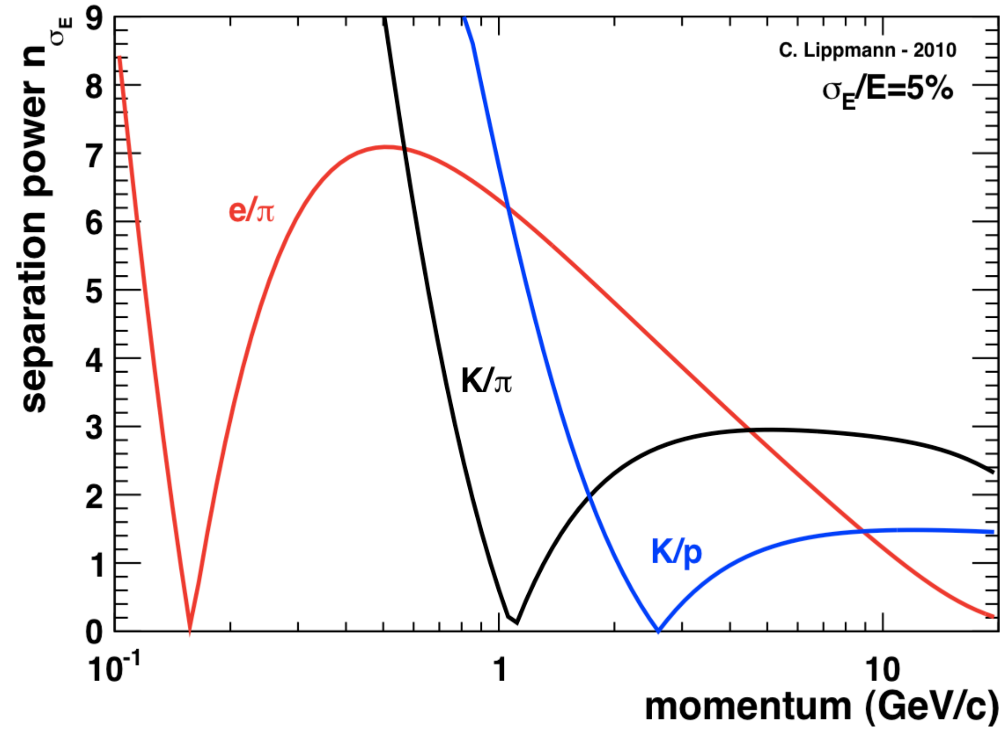
$$x \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \langle N_I \rangle W$$

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

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

Ionization: Separation power





- **Left: Typical ionization signal as a function of momentum in a detector (here a TPC) and particle separation as a function of momentum for a gaseous detector**
- **Right: Separation power:** $n_{\sigma_E} = \dfrac{\Delta_A - \Delta_B}{\langle \sigma_{A,B} \rangle}$.

Energy loss fluctuations

- The actual energy loss fluctuates according to a distribution with a long tail (**Landau tail**) due to δ-electrons
- The distribution of the charge deposit looks accordingly
- The mean value is a bad estimator for the ionization signal
- How can we do better?

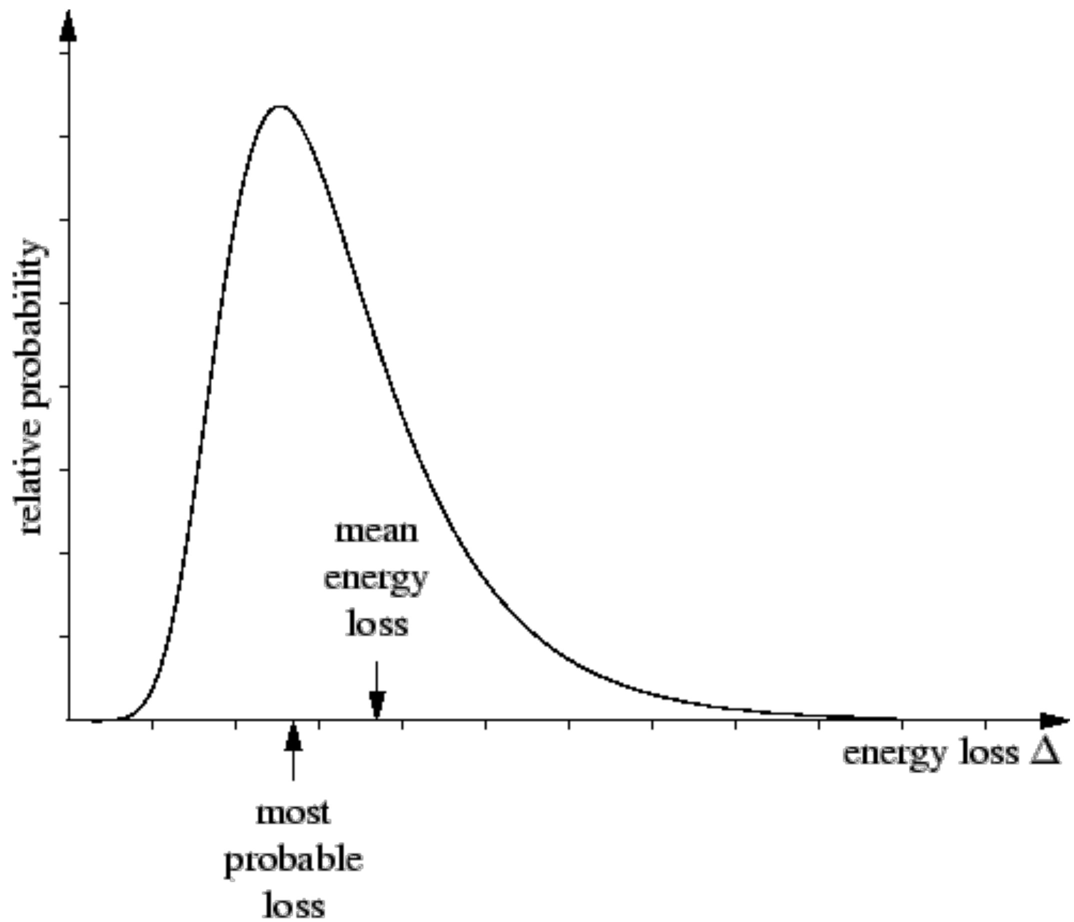


Abb. 3.4: Fluktuationen im Energieverlust: Landau-Verteilung

Measurement of the energy deposit

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

- Usually one uses the **truncated mean**:

$$\langle R \rangle_a = \frac{1}{M} \sum_{i=1}^{M} R_i$$

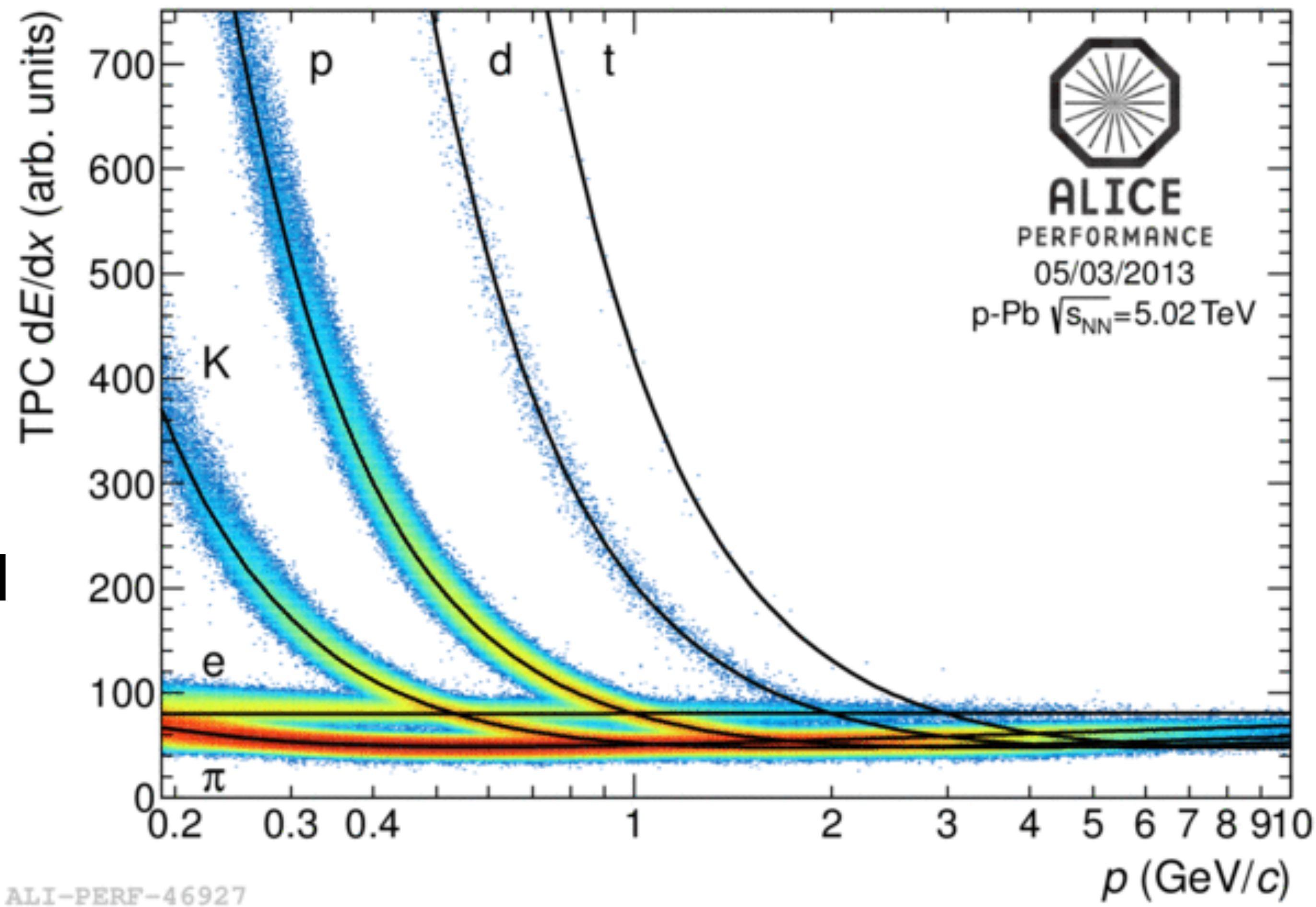
$$R_i \leq R_{i+1} \text{ for } i = 1, \ldots, n-1$$

$$M = aN_R$$

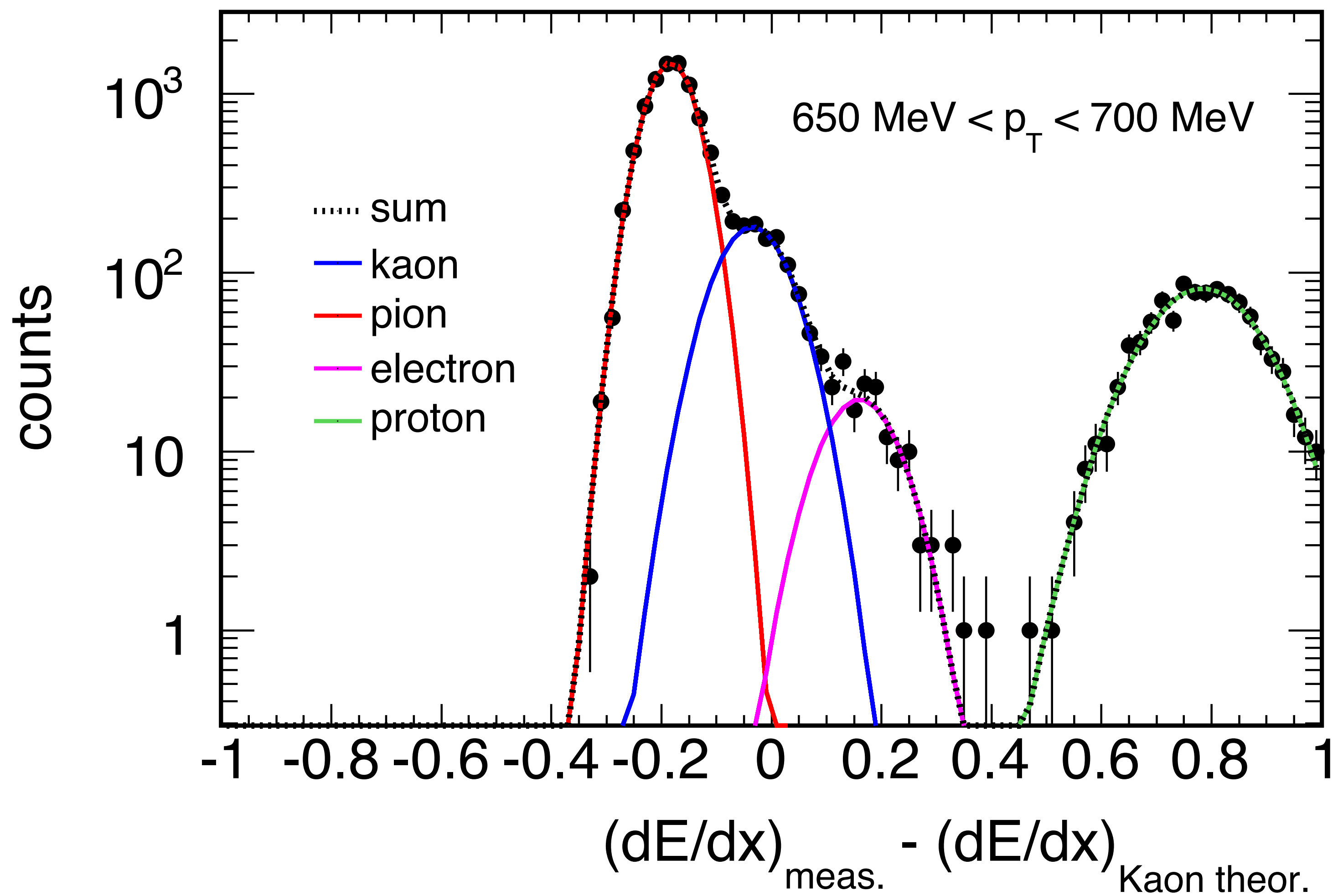
- $\langle R_A \rangle$ **approximates very well the most probable value** of the distribution of the energy deposit. Its distribution is Gaussian

Example: ALICE TPC

- **Excellent PID at low momentum (< 1 GeV/c)**
- **Up to 159 ionisation measurements per track**
- ***a* = 0.6 (truncated mean)**
- **5 % resolution in pp collisions**
- **In highest multiplicity (Pb-Pb collisions) 6% due to overlapping tracks and baseline fluctuations**



ALICE TPC: PID at low momenta



- **Momentum window of 50MeV/c width**

II. b) Time-of-flight measurements

II. b) Time-of-flight measurements

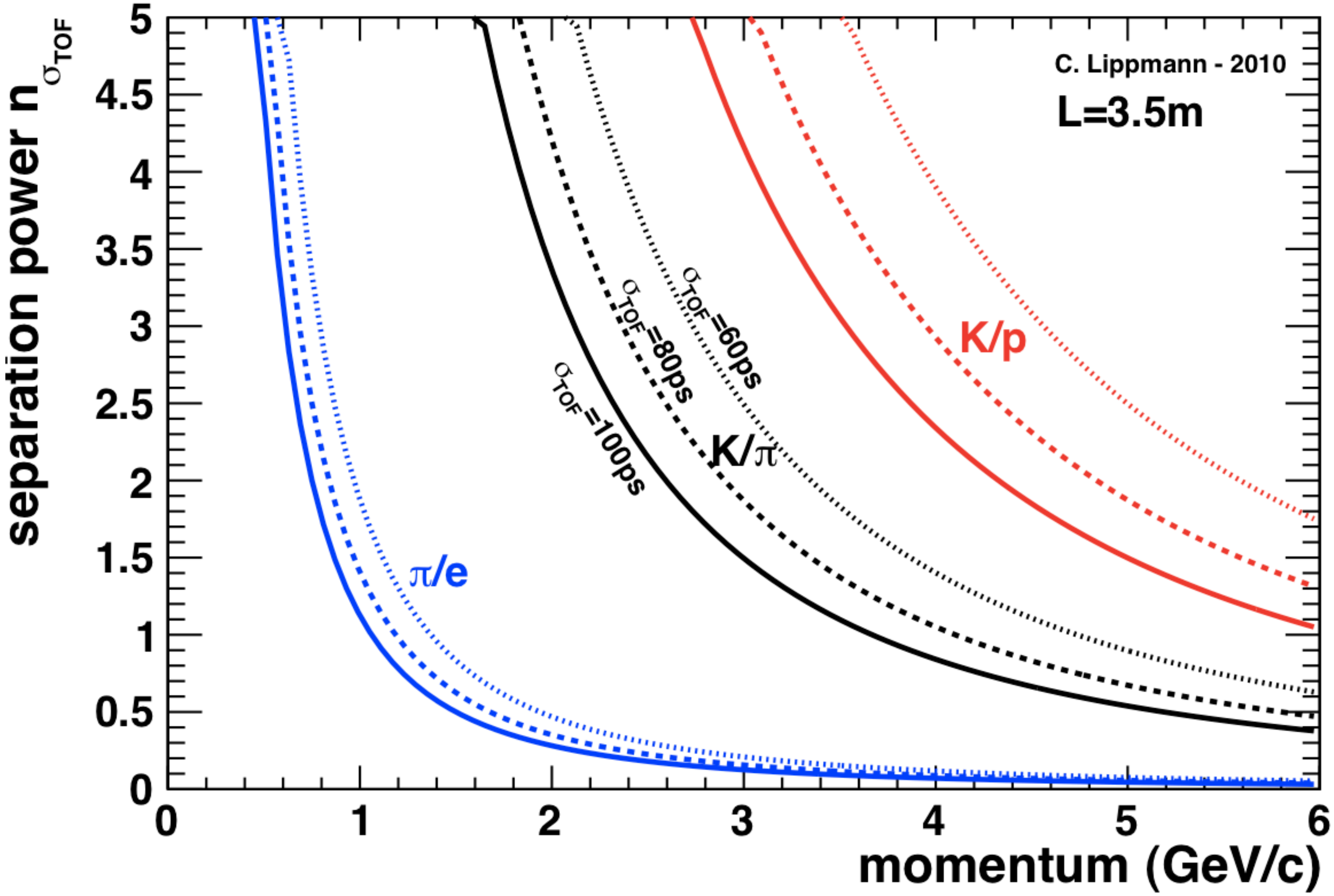
- Time-of-flight (TOF) measurements yield the velocity of a charged particle by measuring the flight time $t = t_1 - t_0$ over a given distance L along the track trajectory
- One can calculate the mass m from measured values of L, t and p:

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

- Separation power for two particles A and B:

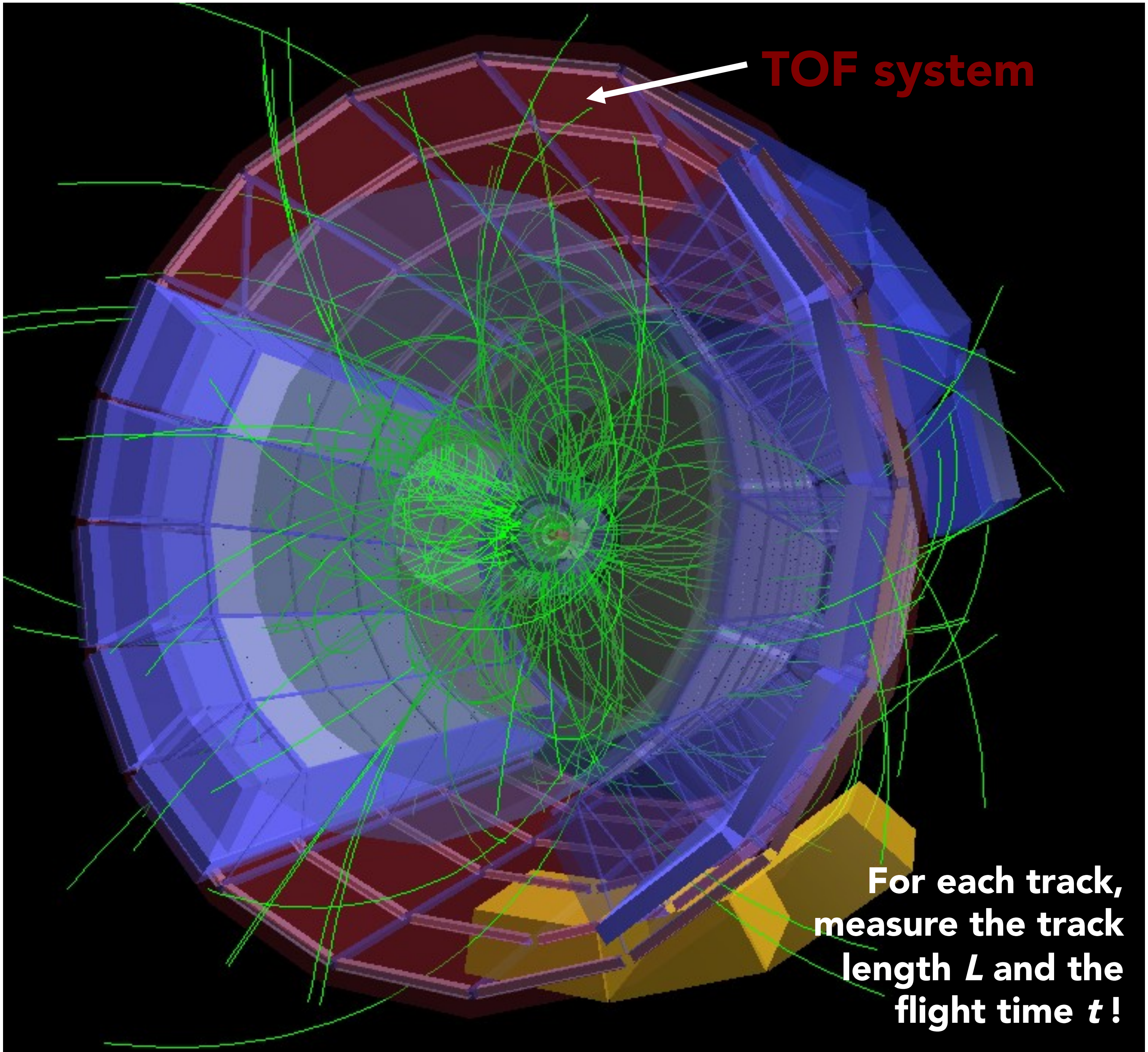
$$n_{\sigma_{TOF}} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2\sigma_{TOF}}|m_A^2 - m_B^2|\ .$$

Separation power

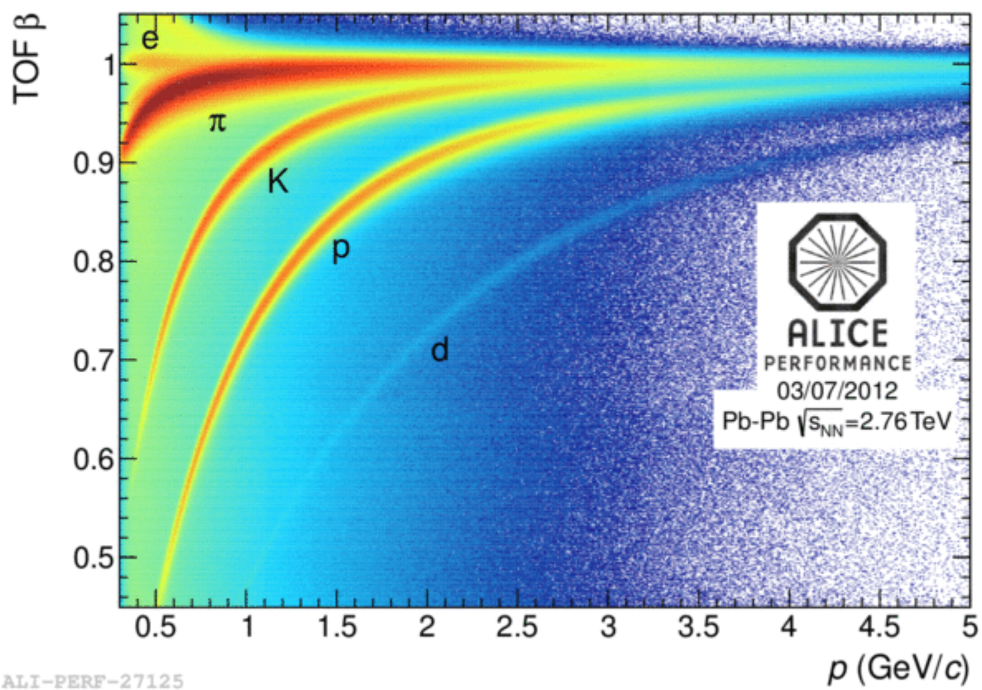


- **Important to optimize resolution in the flight time measurement!**

Example: ALICE TOF

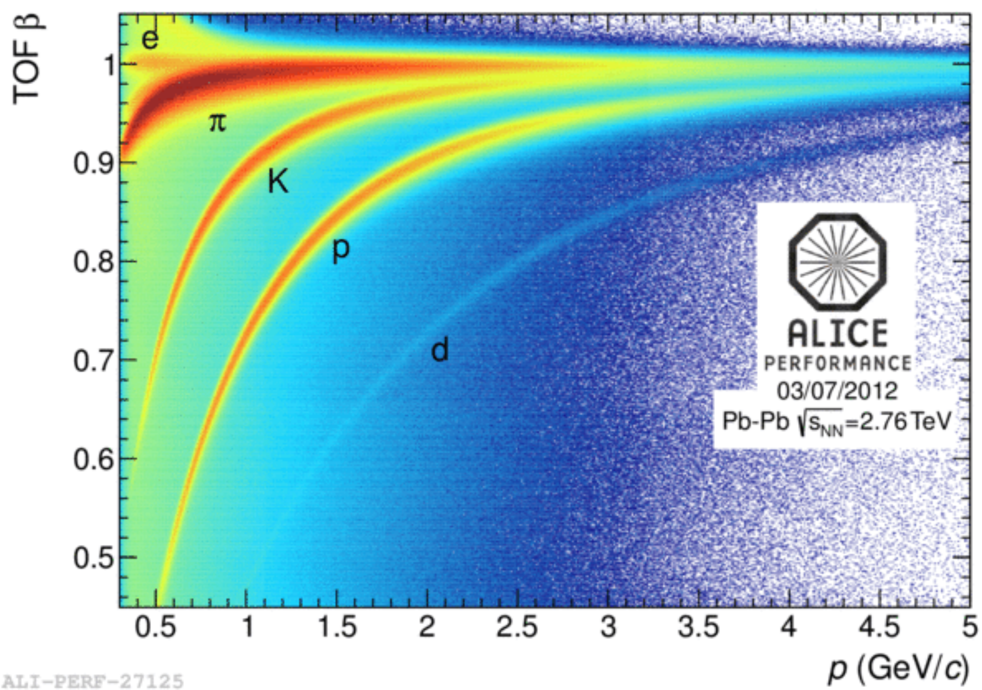


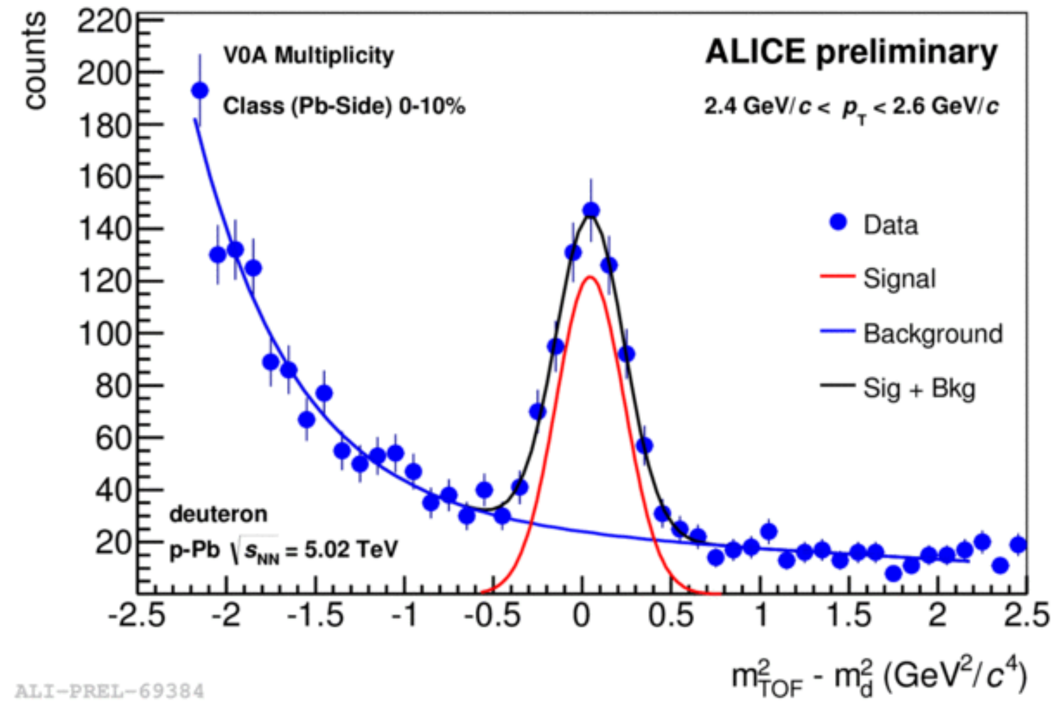
ALICE TOF performance (1)



- **TOF β versus p in data from Pb-Pb collisions**
- **e, pi, K, p and d are clearly visible**
- **Particles outside those bands are tracks wrongly associated with a TOF signal**

ALICE TOF performance (2)

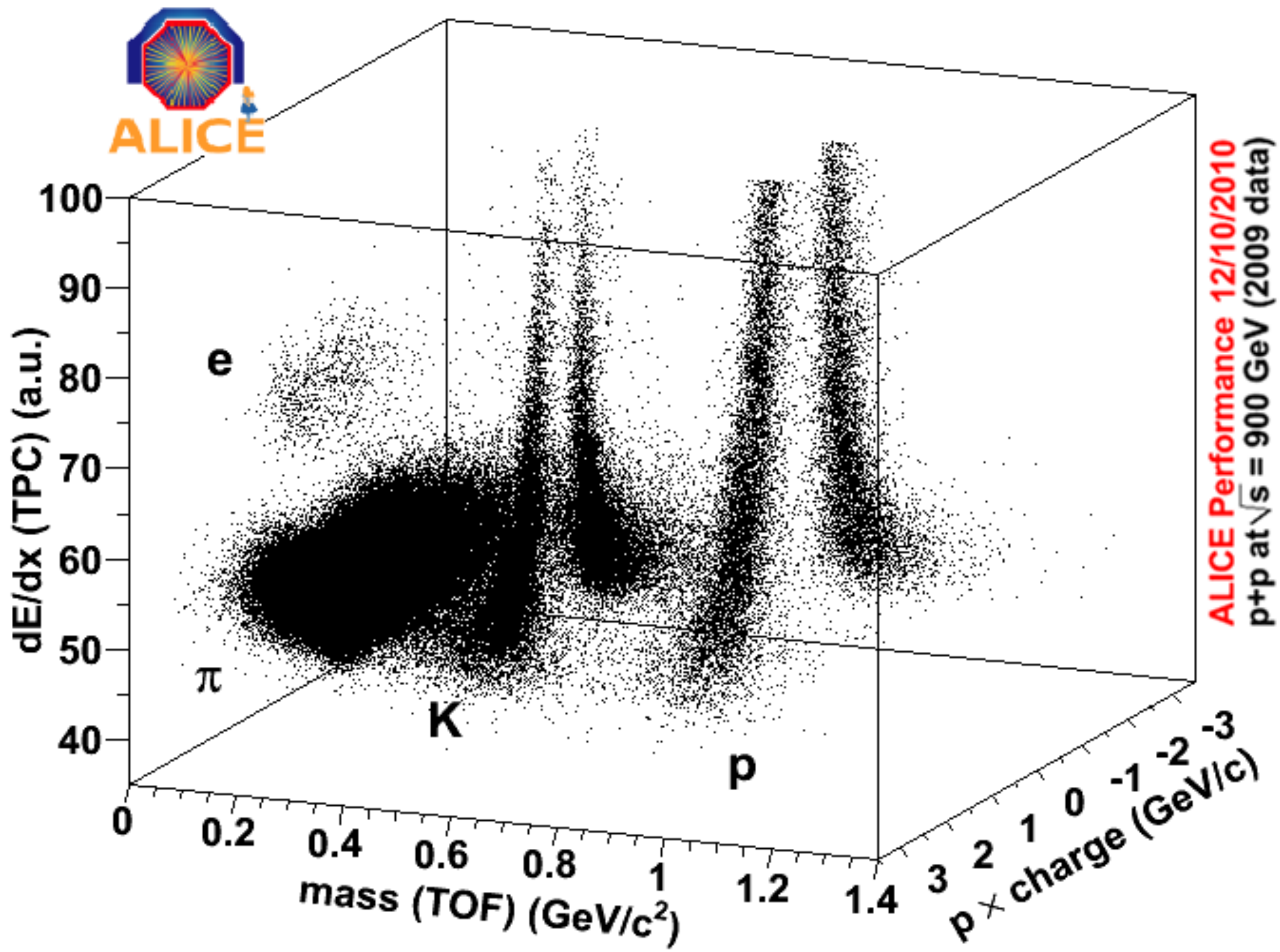




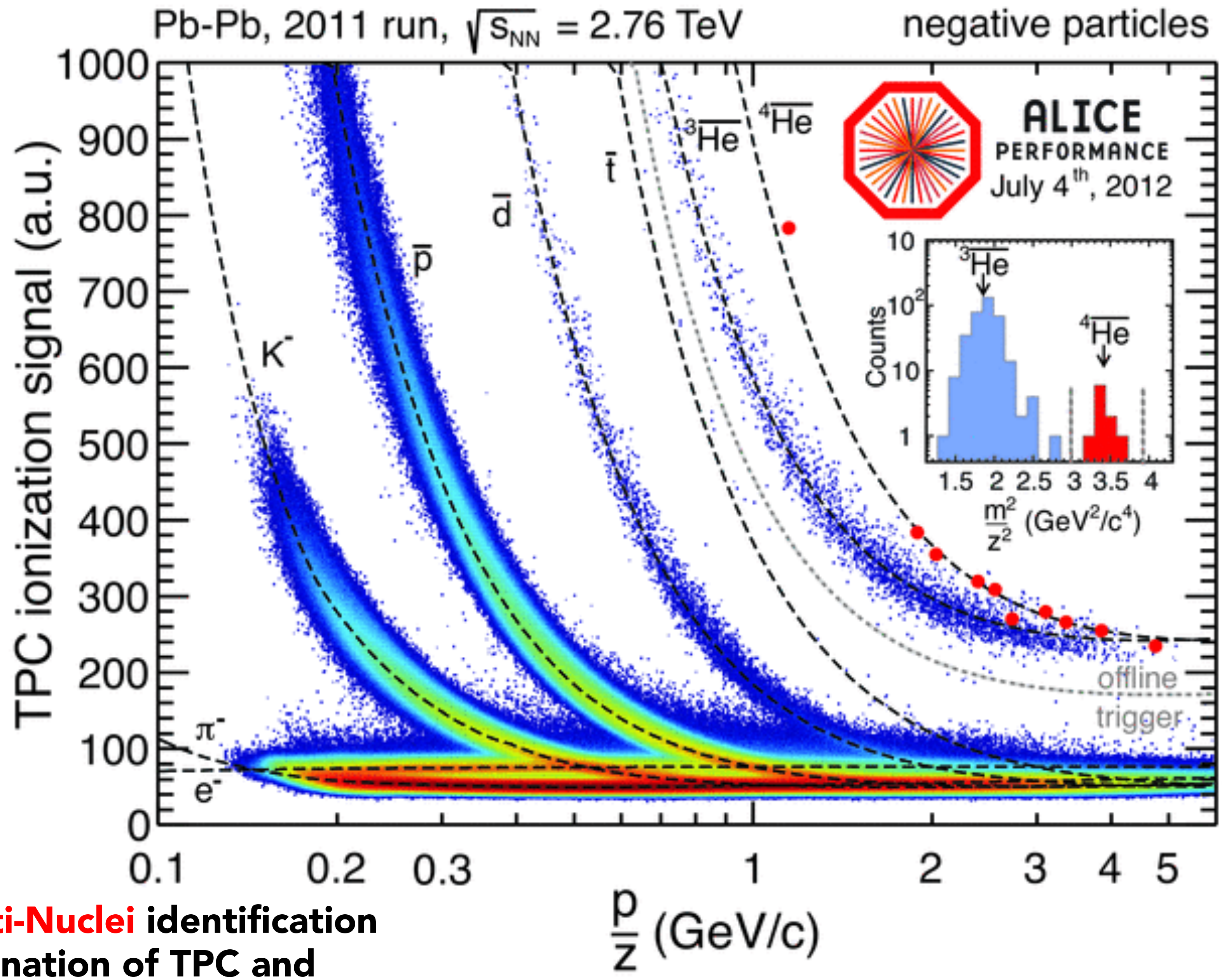
- **TOF β-p performance in Pb-Pb run 2011**
- **e, pi, K, p and d are clearly visible**
- **Particles outside those bands are tracks wrongly associated with a TOF signal.**

- **Example of TOF mass fit for particle identification**
- **In this case we use it to study deuteron production in Pb-Pb collisions at the LHC**

Combining TPC and TOF PID (1)



Combining TPC and TOF PID (2)



Light **Anti-Nuclei** **identification by combination of TPC and TOF PID**

II. c) Cherenkov ring imaging

II. c) Cherenkov ring imaging

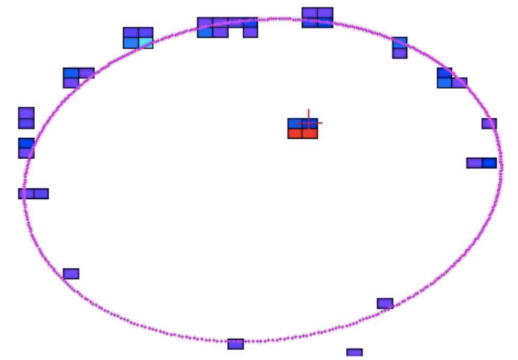
- Cherenkov radiation is a shock wave resulting from a charged particle moving through a material **faster than the velocity of light in the material**
- Cherenkov radiation propagates with a **characteristic angle** with respect to the particle track Θ_C, that depends on the particle velocity:

$$\cos(\Theta_C) = \frac{1}{\beta n}$$

- 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 and allow measurement of the Cherenkov angle Θ_C

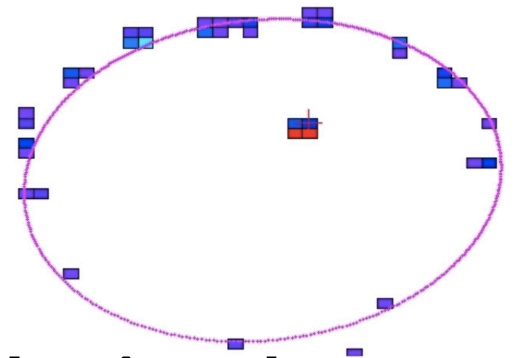


- The particle mass can be determined as

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

- All Cherenkov detectors at the LHC are RICH devices

Separation power (1)



- The Cherenkov angle is determined by $N_{p.e.}$ measurements of the angles of emission of the single Cherenkov photons
- 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 an additional factor of $1/\sqrt{n^2-1}$, which allows to adjust the detector configuration in order to achieve the desired momentum coverage

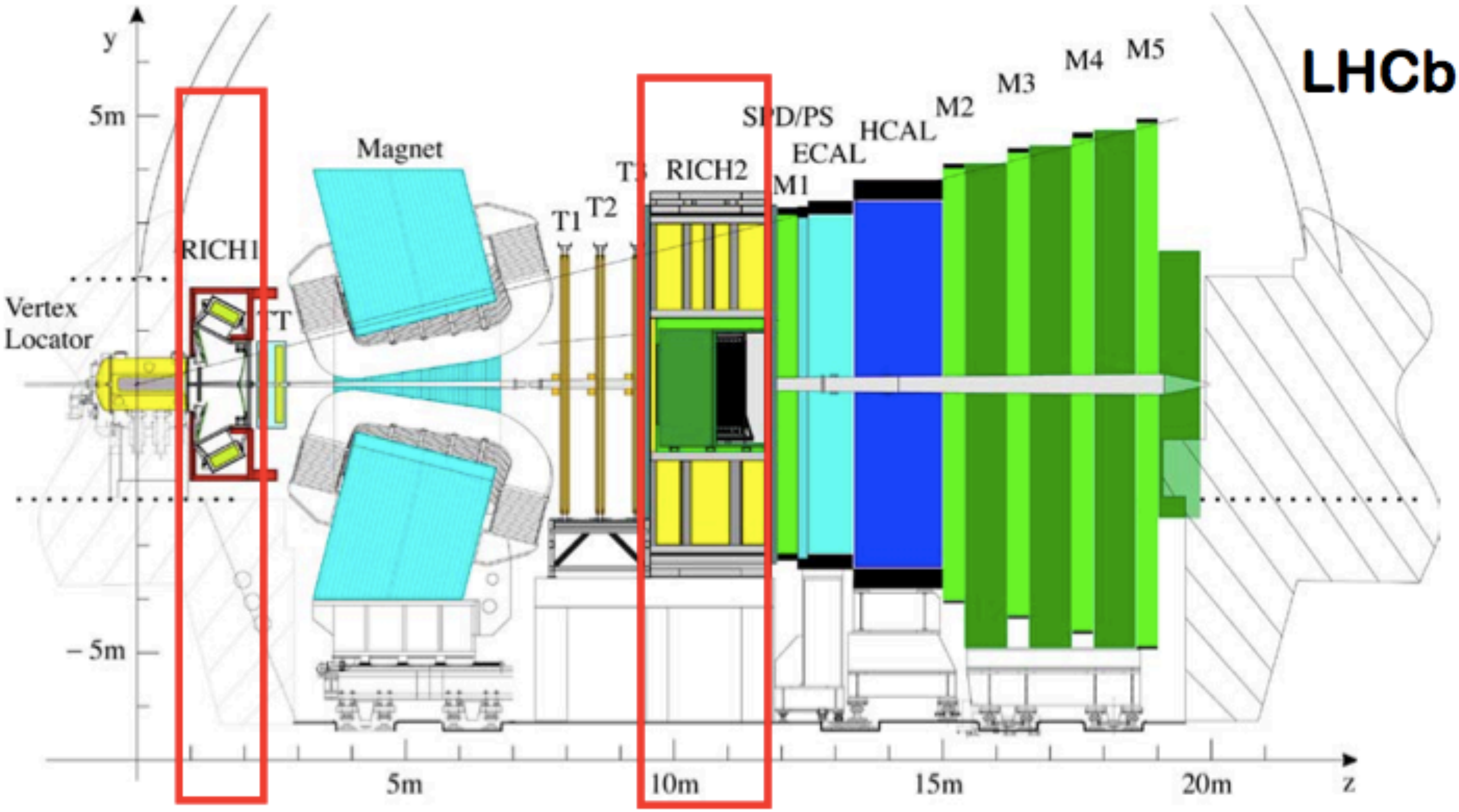
Cherenkov detectors

- 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

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

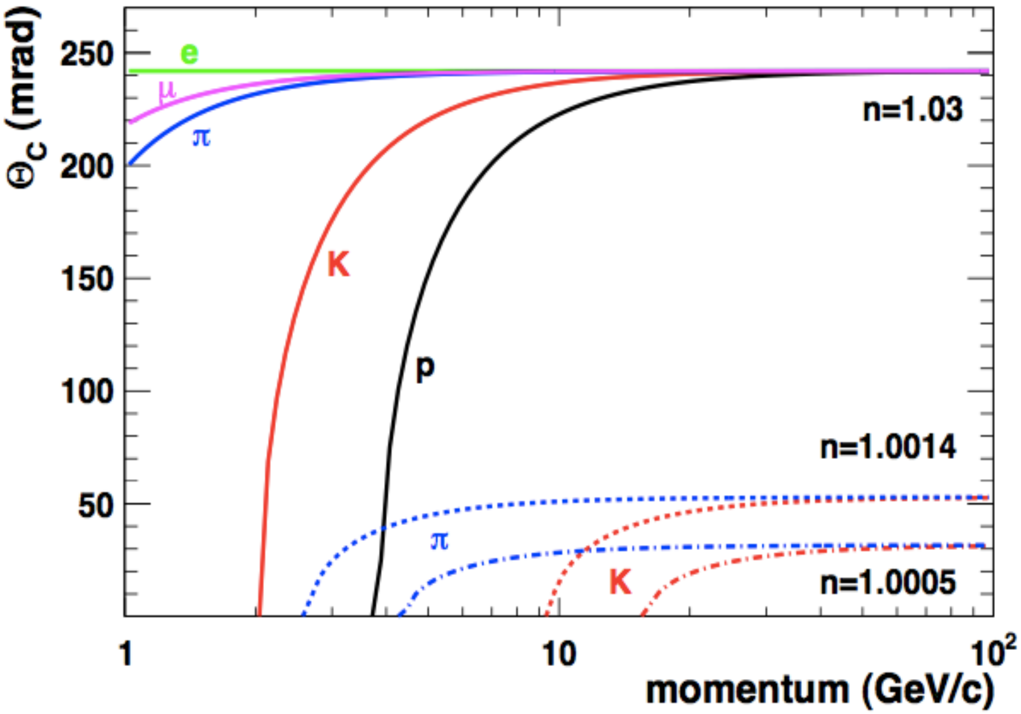
- with L= path length of particle through radiator and N_0 the **quality factor** or **figure of merit** containing the light transmission, collection and detection efficiencies

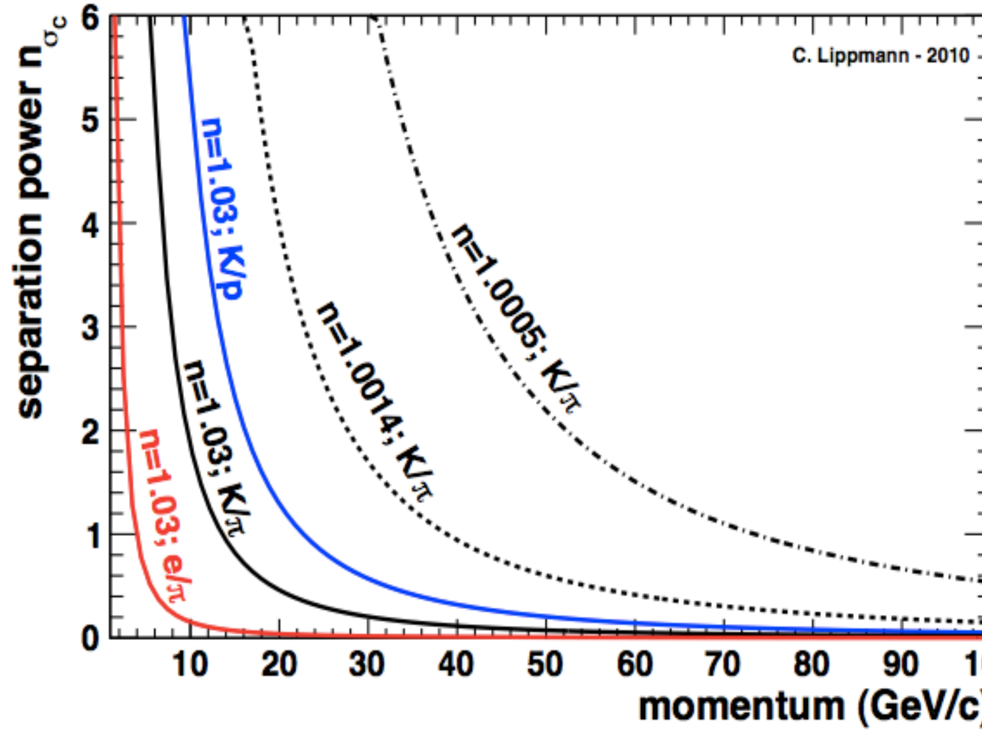
Example: LHCb RICH (1)



Like a slice out of a ATLAS or CMS, but with the addition of 2 Ring Imaging Cherenkov detectors with 3 different radiators

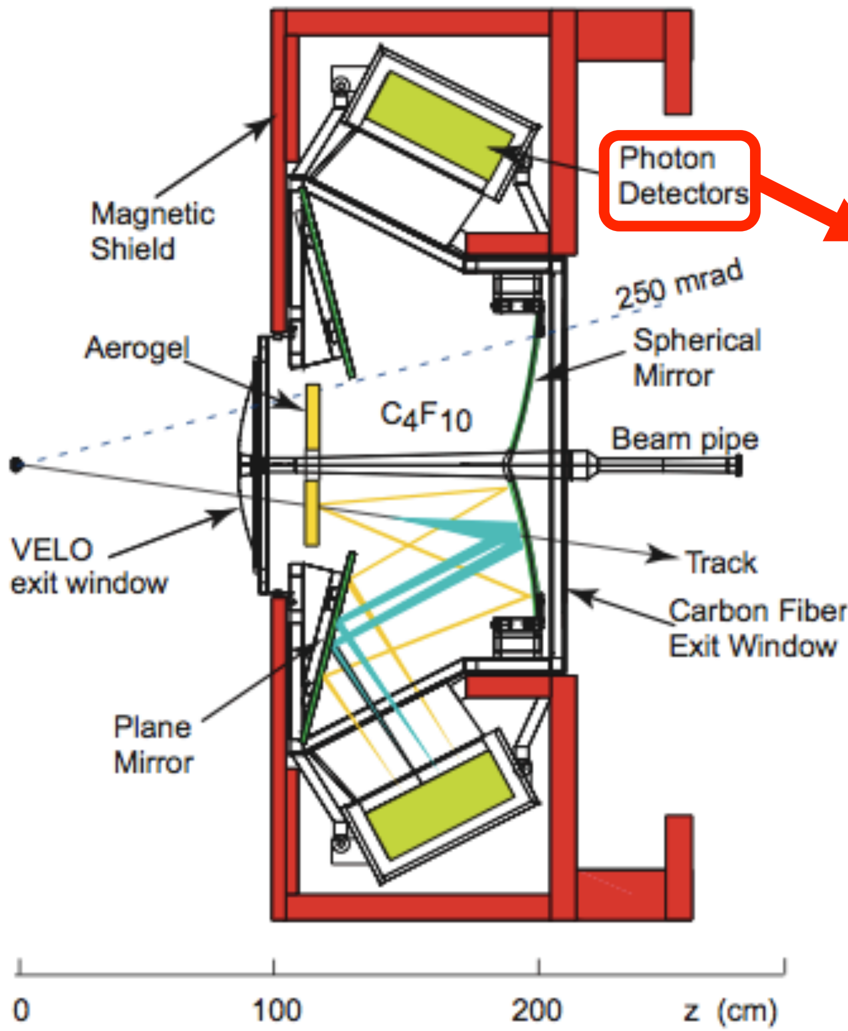
Example: LHCb RICH (2)





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

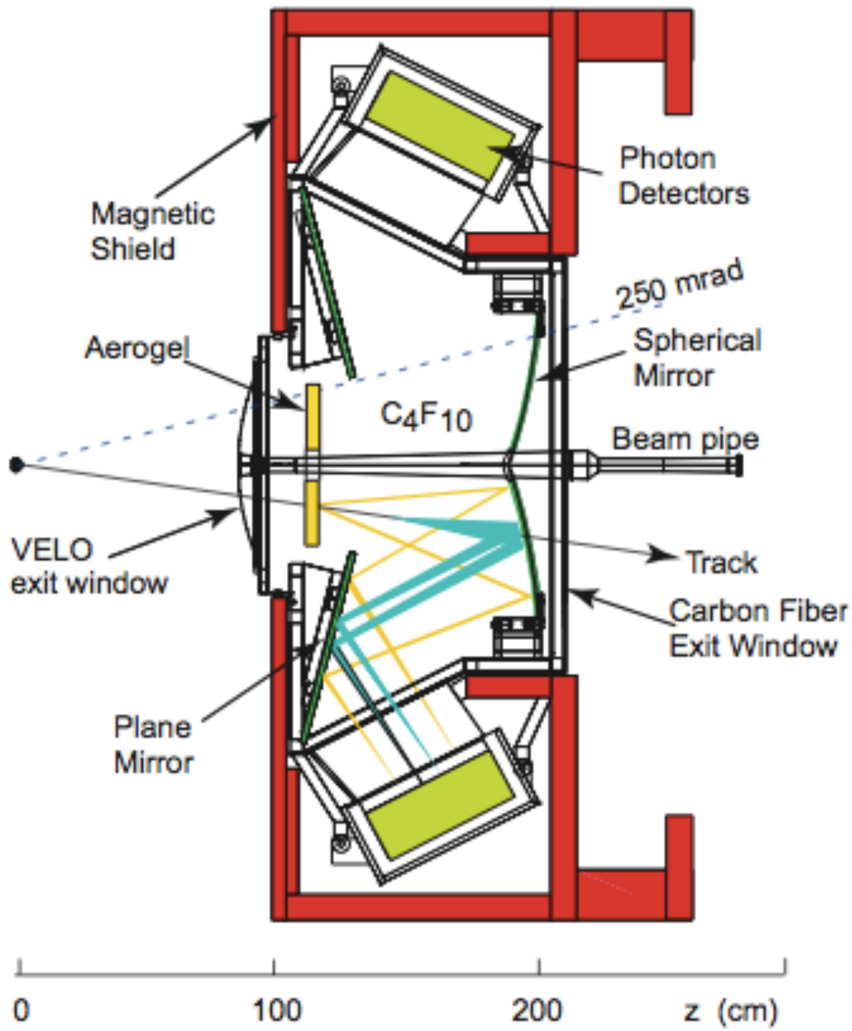
Example: LHCb RICH (3)



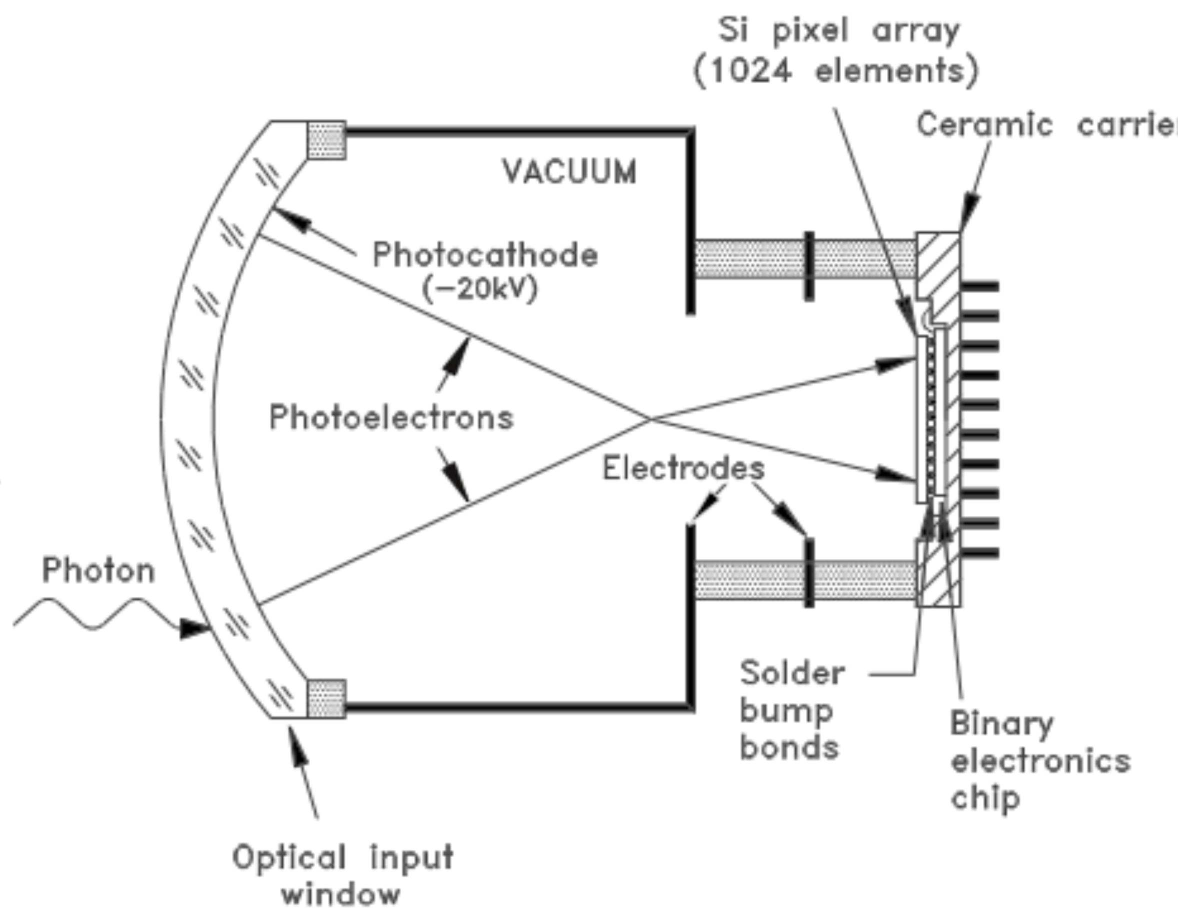
LHCb RICH1

LHCb HPD photon detectors

Example: LHCb RICH (4)

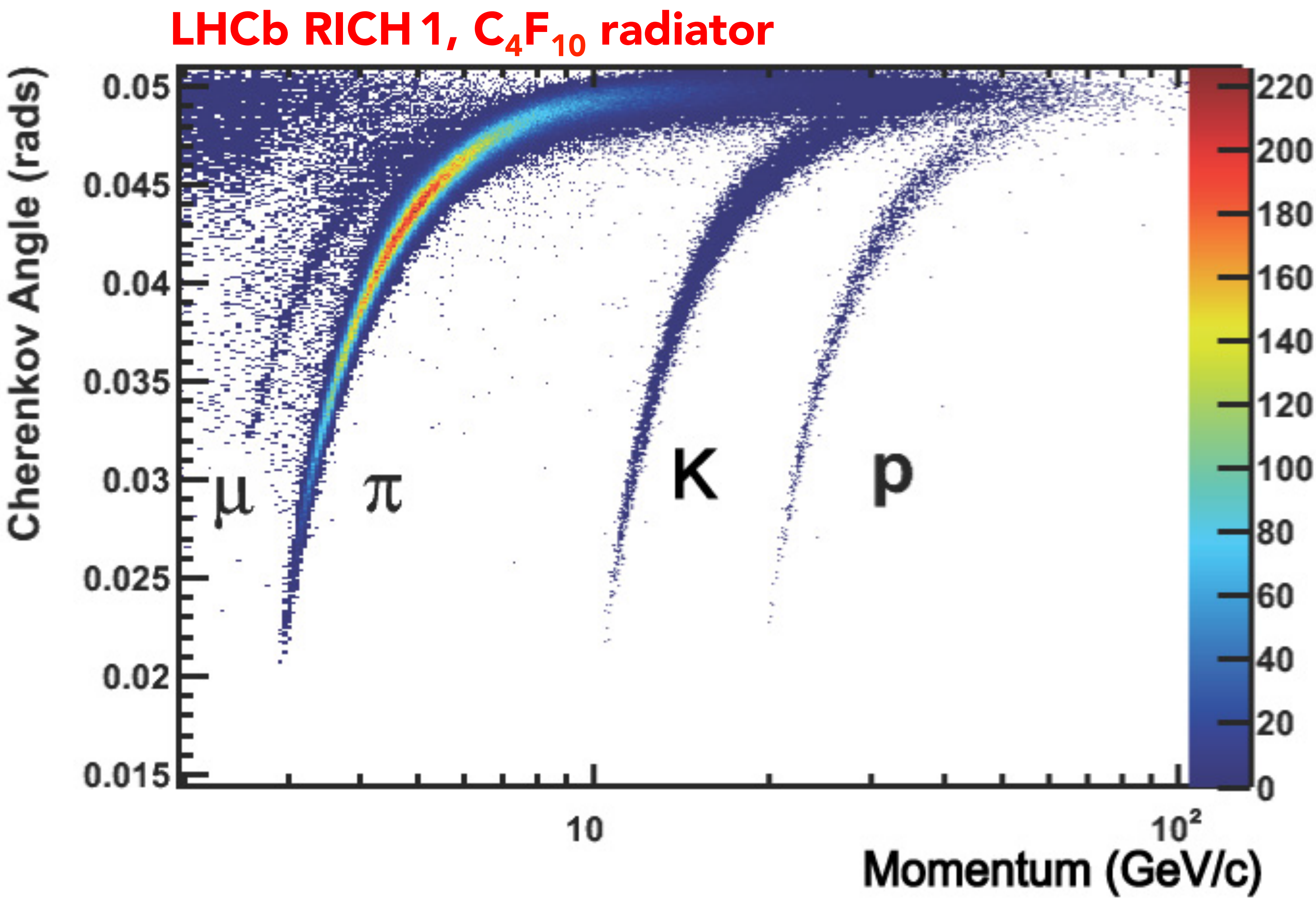


LHCb RICH1



LHCb HPD photon detectors

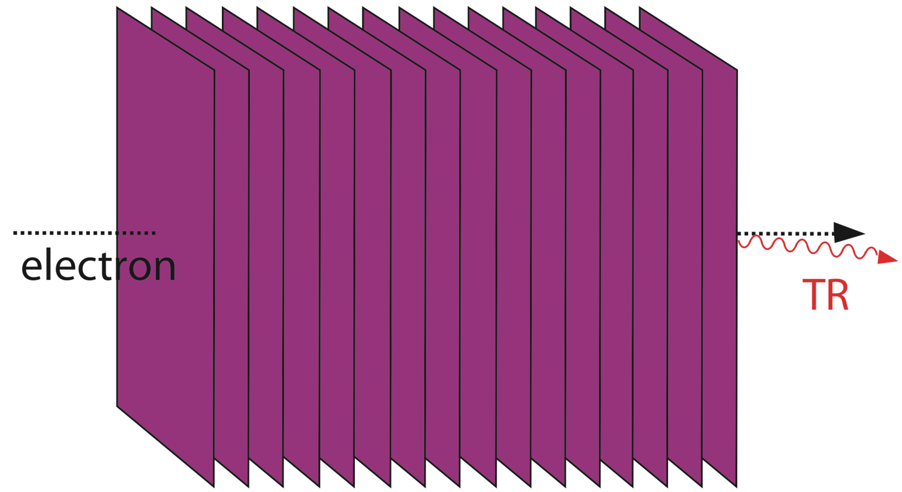
Example: LHCb RICH (5)



II. d) Transition radiation imaging

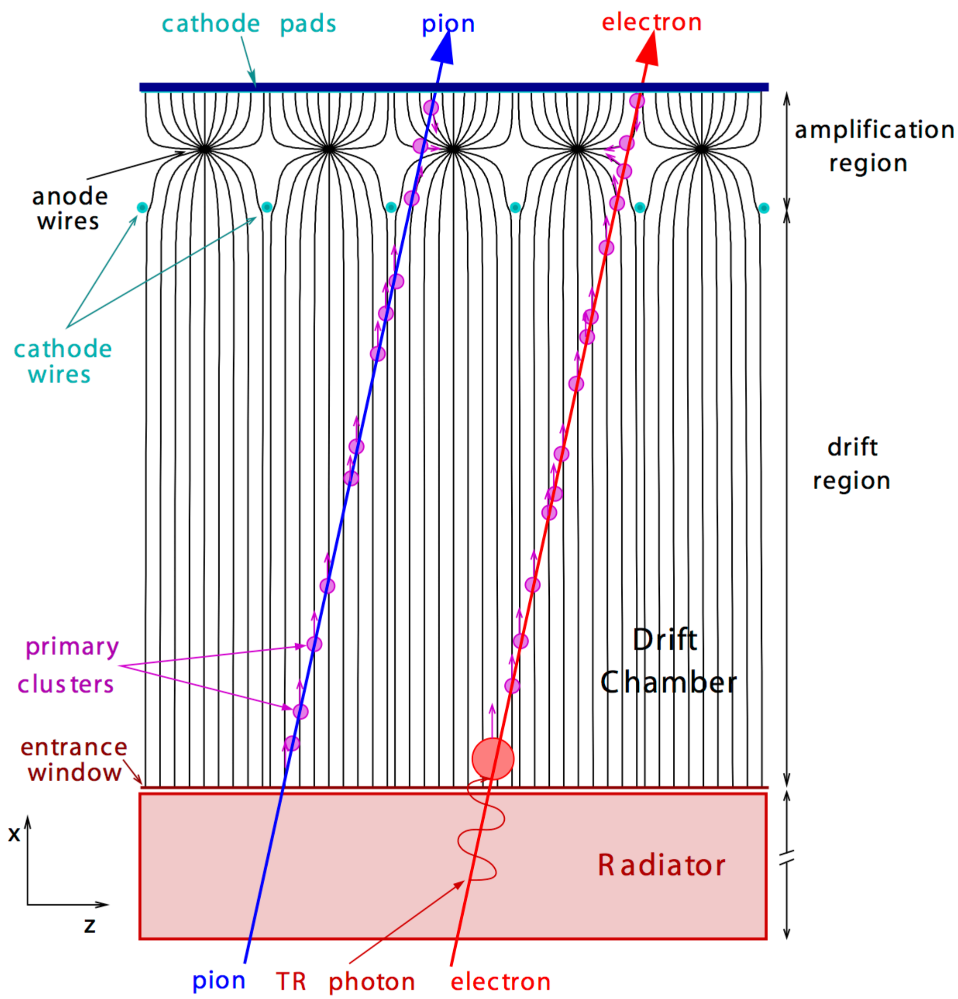
II. d) Transition radiation imaging

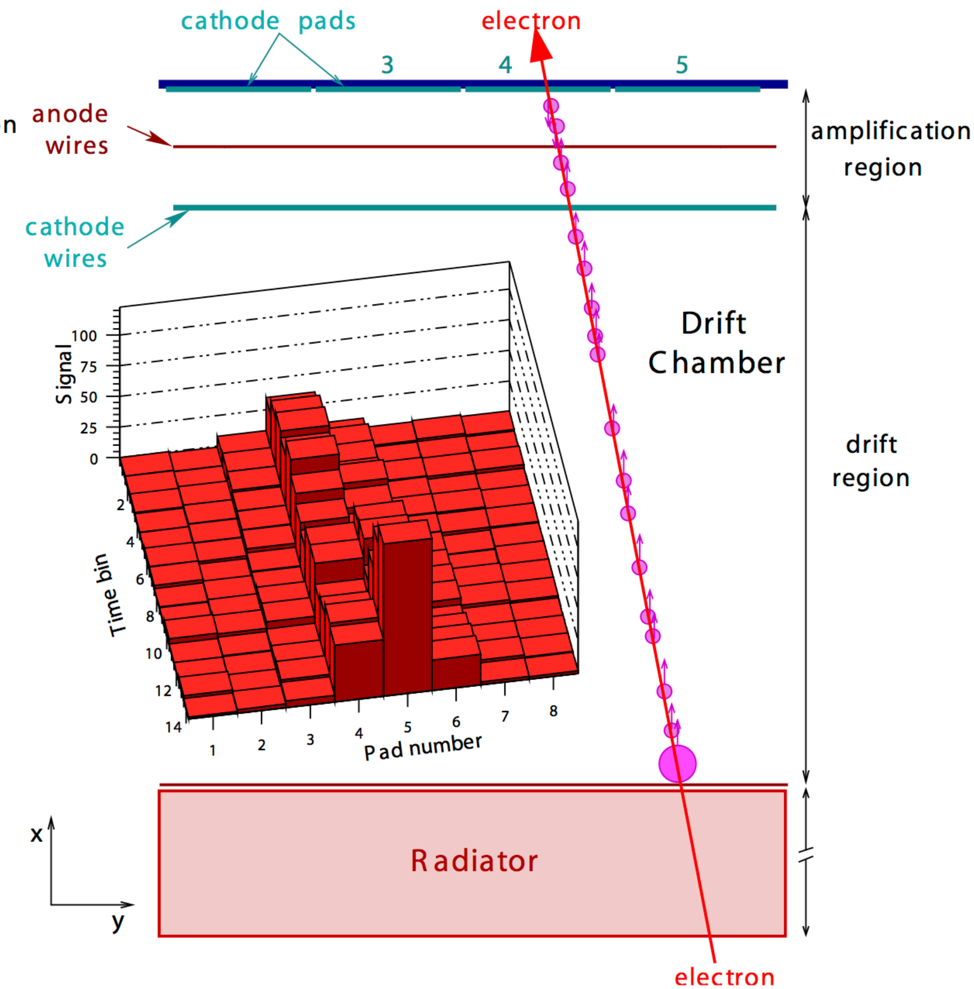
- Transition radiation (TR) can be produced when a fast charged particle crosses an inhomogeneous medium
- For highly-relativistic charged particles ($\gamma > 1000$), the spectrum of the emitted radiation extends into the X-ray domain



- TR production probability is only about $\alpha = 1/137$ per boundary. Thus many boundaries are added: e.g. about 100 foils to produce ≈ 1 photon
  - Can also use irregular radiator structures (foam, fibers)
- Conversion leads to large energy deposit compared to the average energy deposit via ionization
- In momentum range $1 < p < 10$ GeV/c only electrons produce TR → electron identification!

Example: ALICE TRD



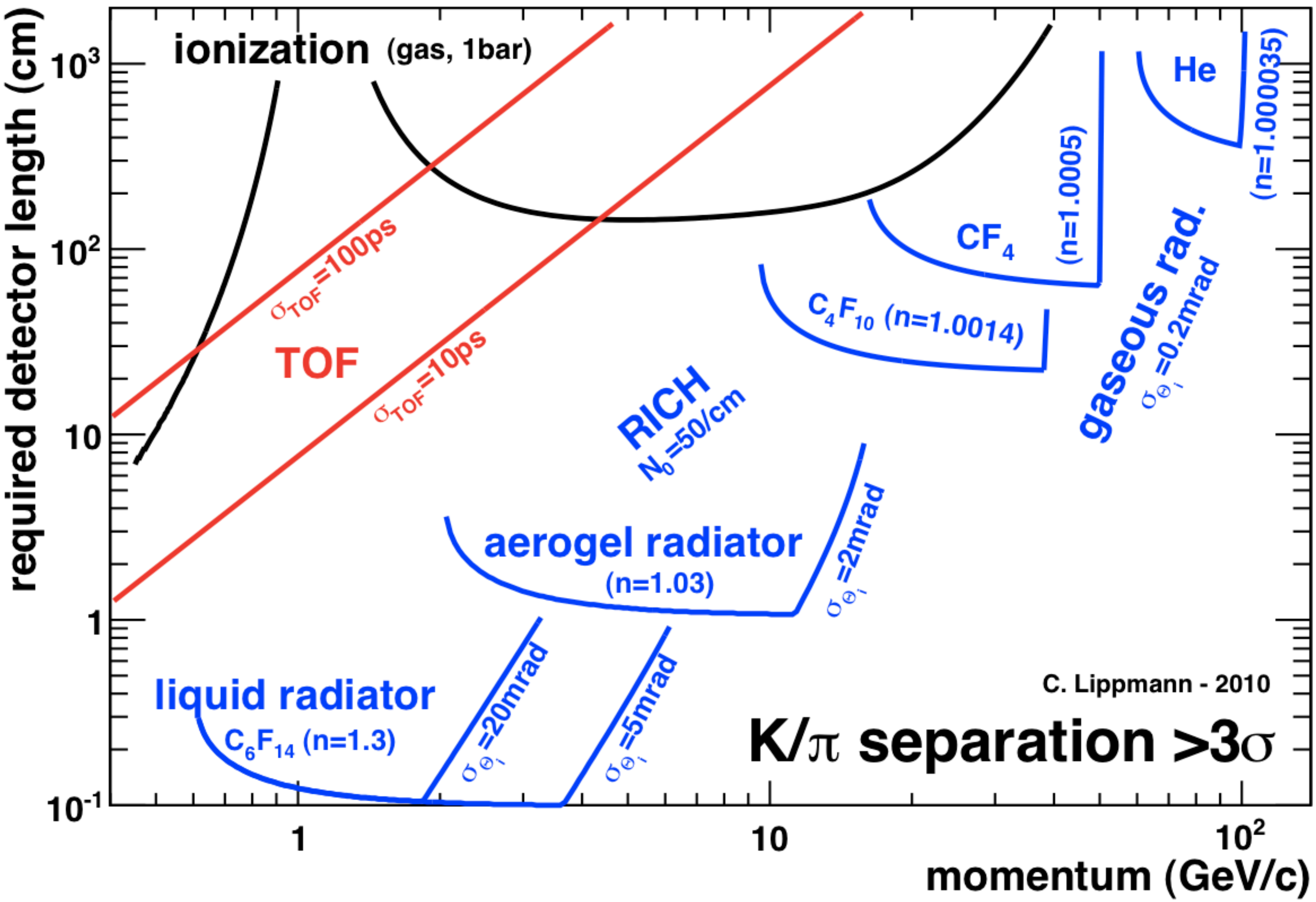


1. **Electrons crossing radiator produce TR photons**
2. **Xe gas mixture: efficient TR photon absorption**
3. **TR signal plus ionization creates larger pulses for e than for e.g. π**

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)



required detector length (cm)
10^3
10^2
10
1
10^{-1}
1
10
10^2
momentum (GeV/c)
ionization (gas, 1bar)
σ_{TOF}=100ps
σ_{TOF}=10ps
TOF
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
C. Lippmann - 2010
K/π separation >3σ

Summary (3)

- See also http://arxiv.org/abs/1101.3276

III. PID in a tracking system

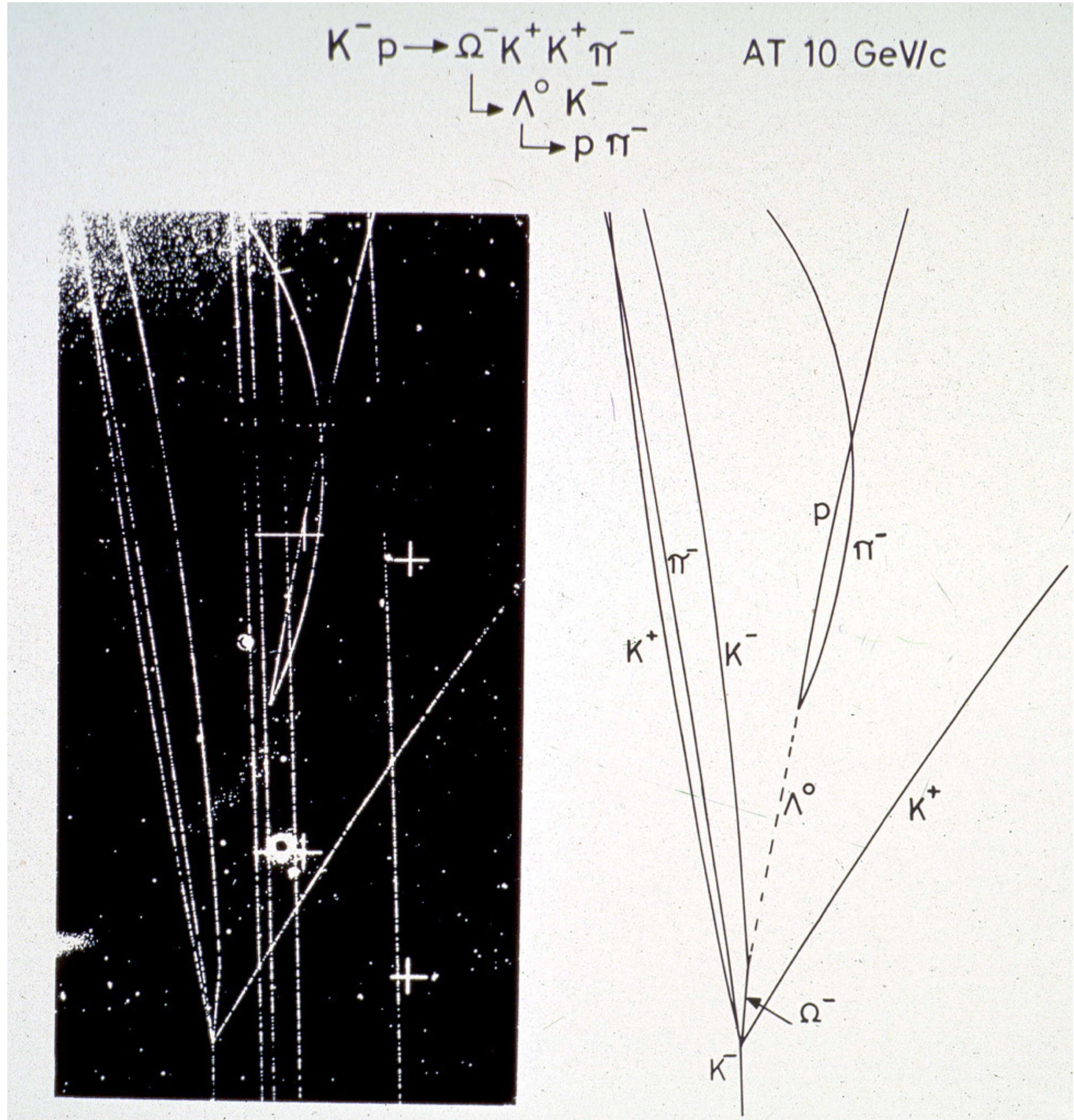
V_0's (1)

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

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

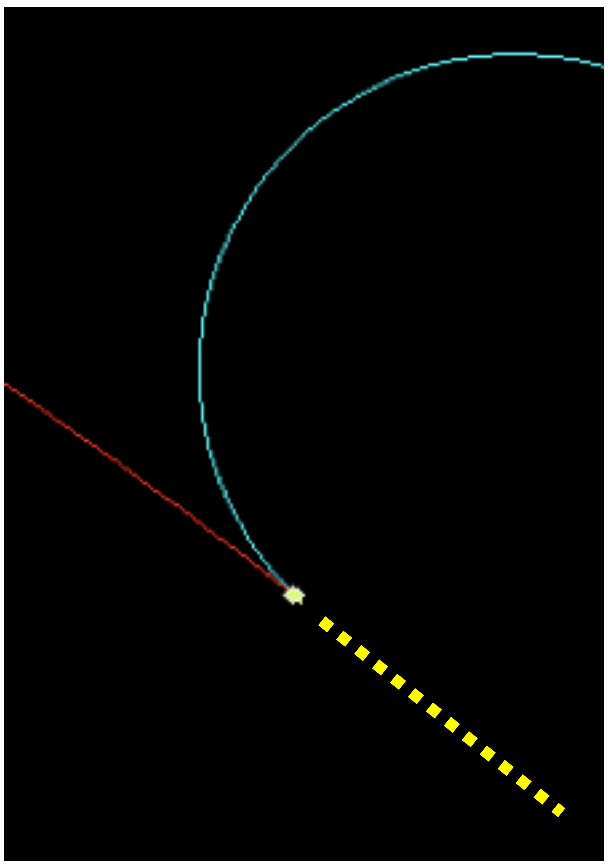
$$\Lambda \rightarrow p^+ \pi^-$$

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

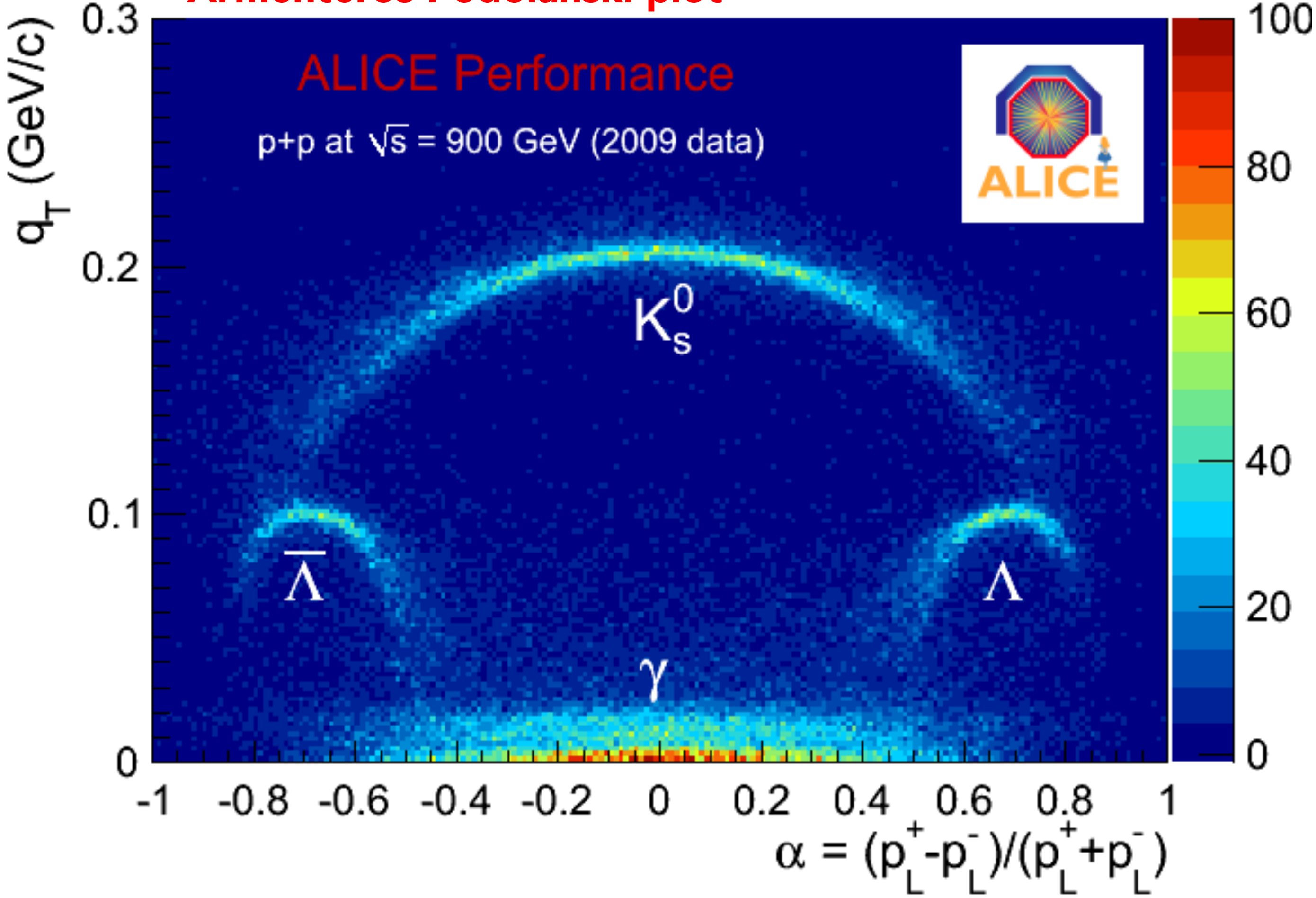


V_0's (2)

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



"Armenteros Podolanski plot"



Kaon ID through kink topology

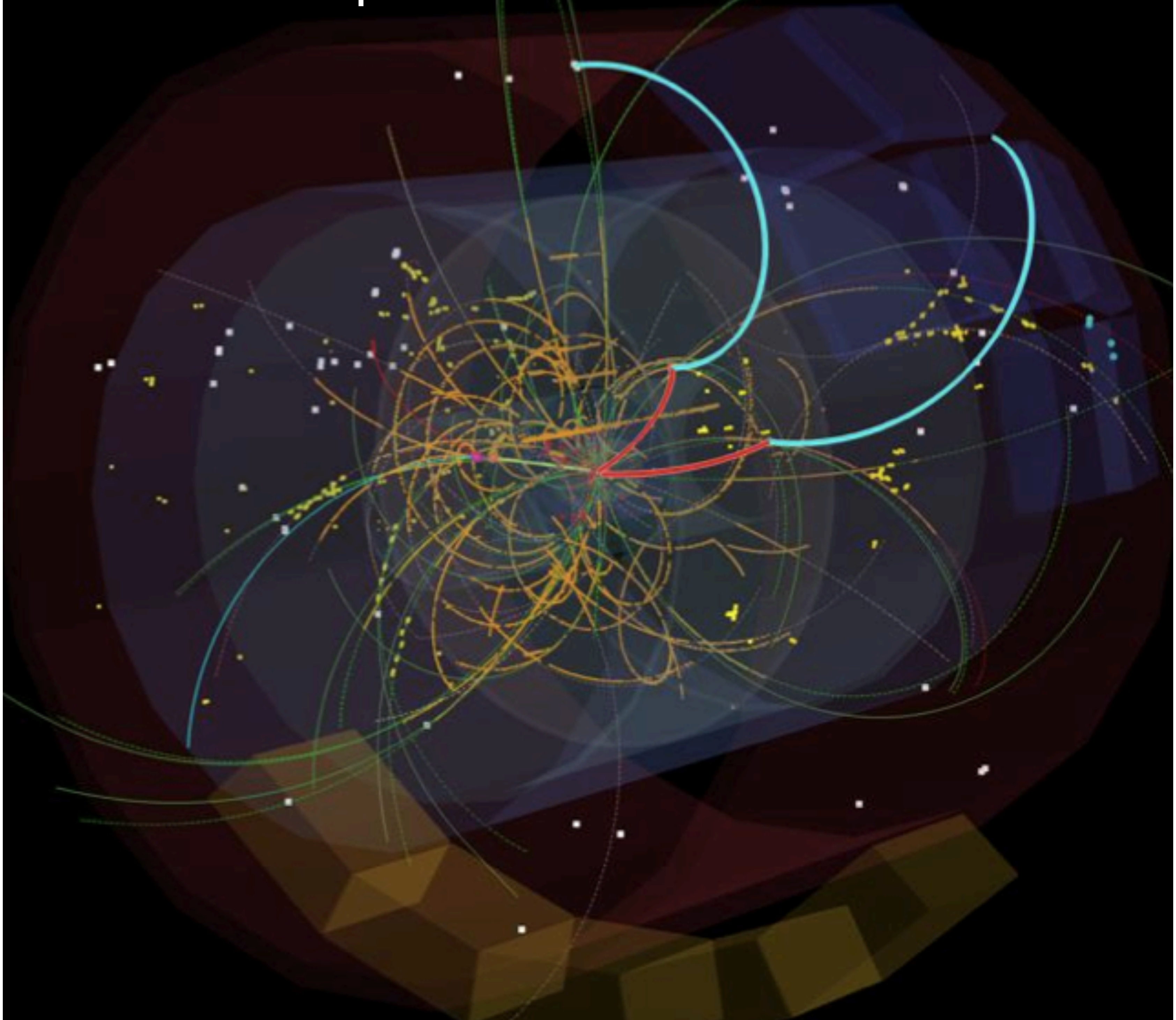
- Charged Kaons may decay in a high- resolution tracking system:

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

- 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



Tau Identification

- Tau Leptons have a lifetime of 0.29ps
- They decay into many final states
- Decay products are seen in detector
- Accurate vertex detectors detect that they come from secondary vertex (about 0.5mm