Particle Identification in ALICE

Mriganka Mouli Mondal, NISER

Motivation for PID :

Identify all stable particles : **p**, **n**, $\mathbf{K^{\pm}}$, $\mathbf{K^{0}_{L}}$, $\boldsymbol{\pi^{\pm}}$, $\mathbf{e^{\pm}}$, $\boldsymbol{\mu^{\pm}}$, $\boldsymbol{\gamma}$

Neutral particles like the hyperons Λ_0 and $\boldsymbol{\Xi^{0}}$, and short-lived particles (charm, beauty, resonances)

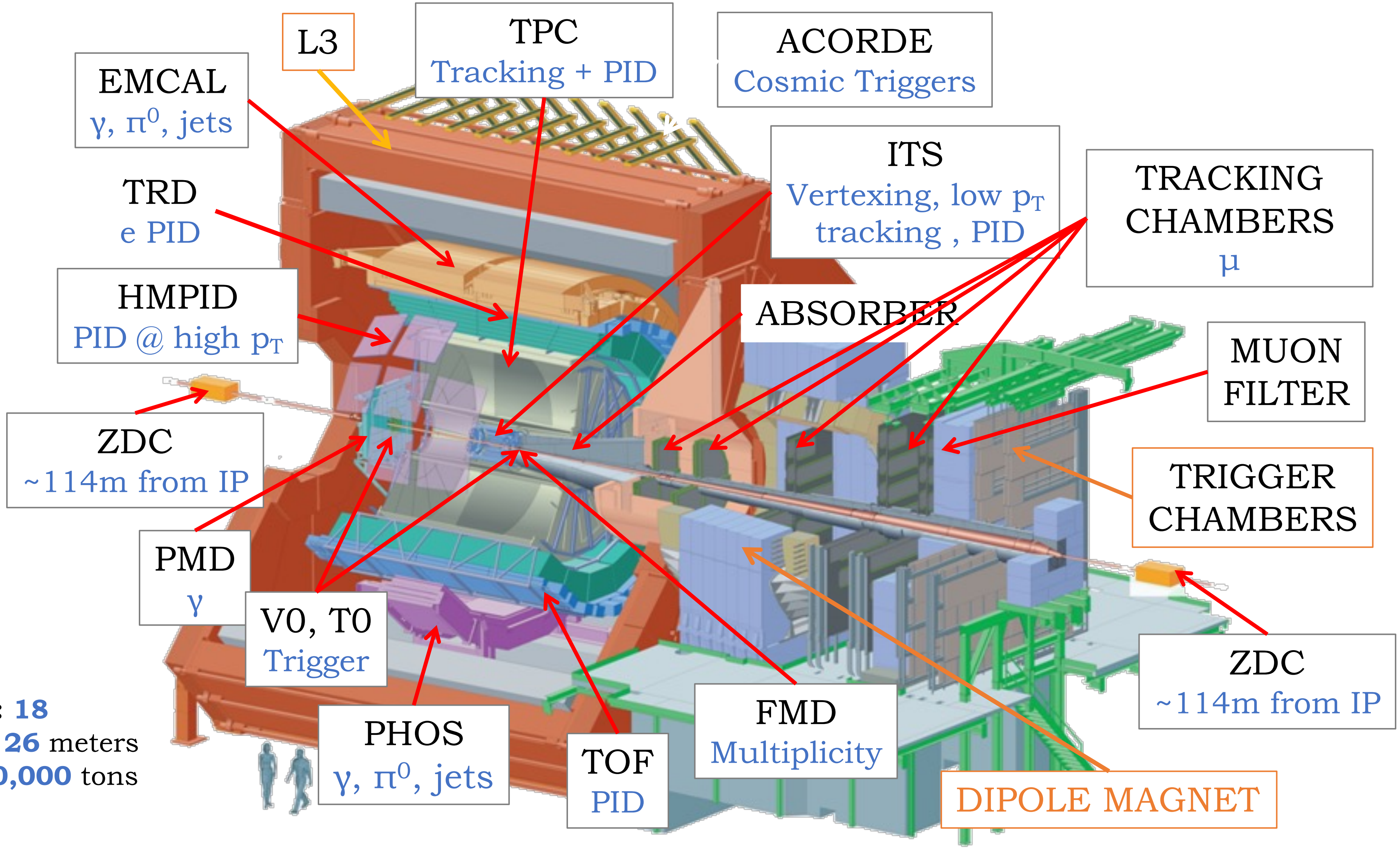
PID is fundamental to many physics studies

- Hadron physics (COMPASS, PANDA….)
- Flavour physics and CP violation studies (BABAR, BELLE, NA62, LHCb, SuperB…)
- Nucleon structure (HERMES, COMPASS, JLAB…)
- Heavy ion physics (PHENIX, **sPHENIX**, STAR, ALICE…)
- SPIN Physics, structure of proton (**future EIC 2032+**)
- Techniques used : (Tracking – determination of the momentum of the particles in magnetic and electric field)

Velocity:	Time-of flight	$\tau \propto 1/\beta$
	Cherenkov angle	$\cos\theta = 1/\beta n$
	Transition radiation	$\gamma \geq 1000$
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2}\ln(a\beta\gamma)$
Total energy:	Calorimeter	$E = \gamma m_0 c^2$

The ALICE Experiment at LHC

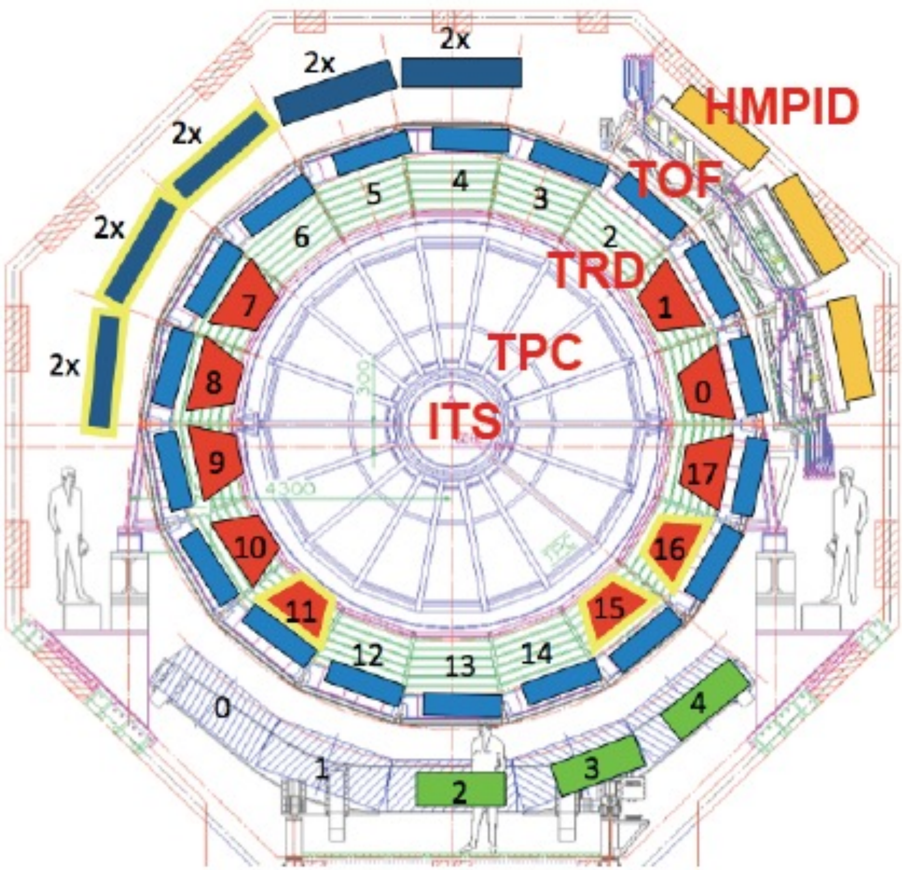
The general-purpose experiment at the CERN LHC designed for heavy-ion physics.



Detectors: **18**
Size: **16 x 26** meters
Weight: **10,000** tons

ALICE PID Detectors

- ❖ **ALICE has a unique capability on the particle identification**

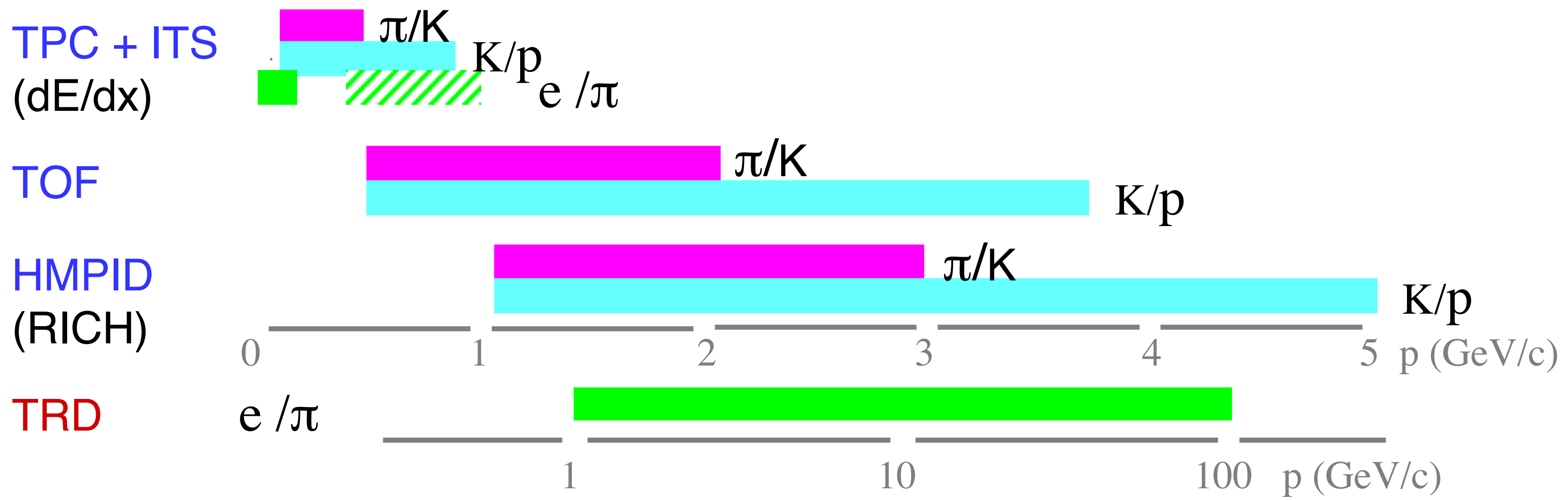


Central PID Detectors:

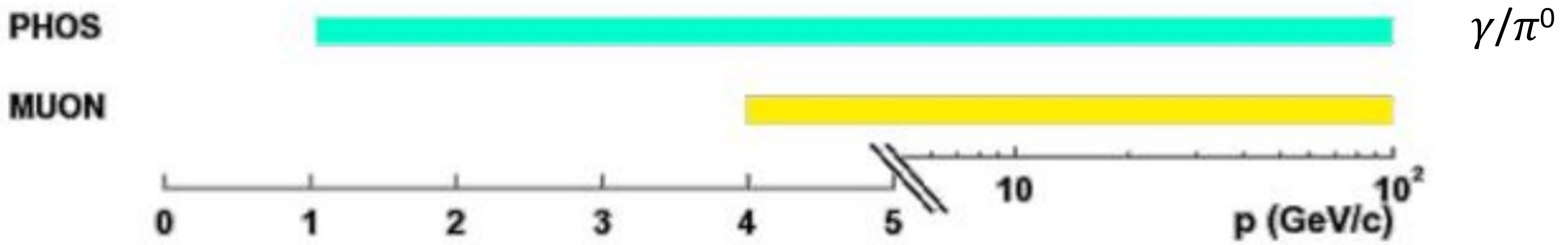
Inner Tracking System
Time Projection Chamber
Transition Radiation Detector
Time-of-Flight
High Momentum PID (RICH)

ALICE PID Overview

Nearly all known PID techniques used in ALICE



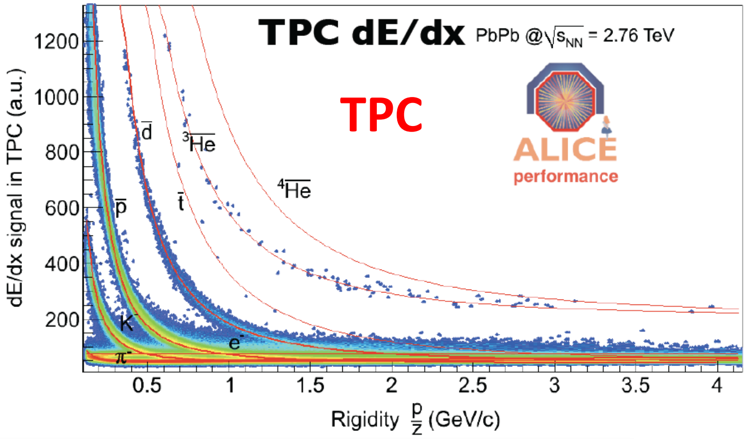
Hadron-ID upto 5 GeV/c with a separation power by 3**σ**
ITS+TPC : PID in soft pt region
TOF : PID at intermediate pt
HMPID: extended beyond Event-by-Event limit (inclusive measurements)

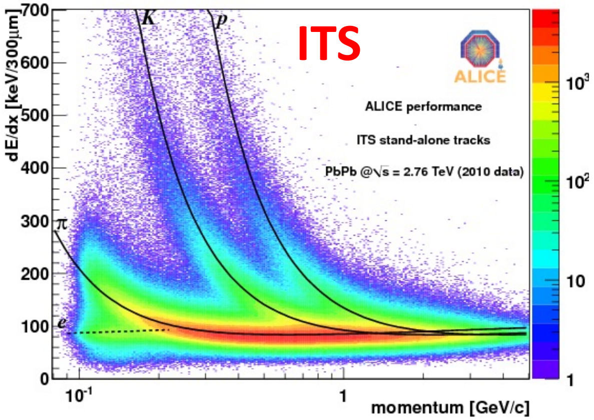


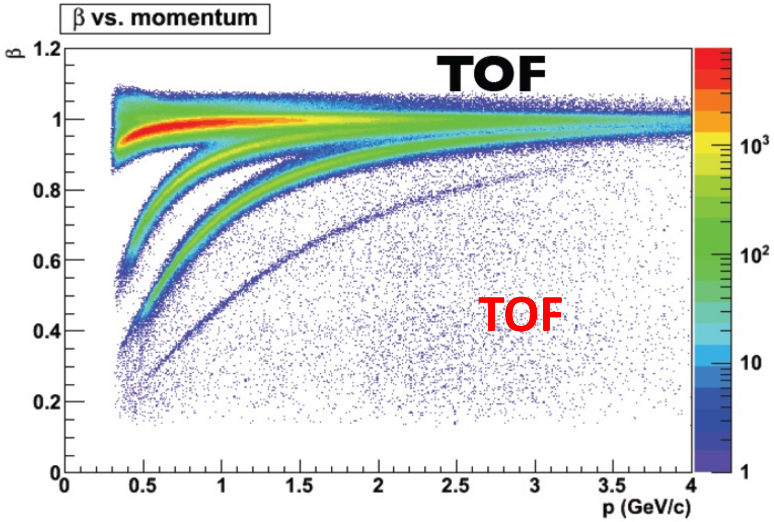
First results with the ALICE experiment at LHC

C. Zampolli for the ALICE Collaboration : 27-29 Aprile, 2011, Perugia

Identified particles





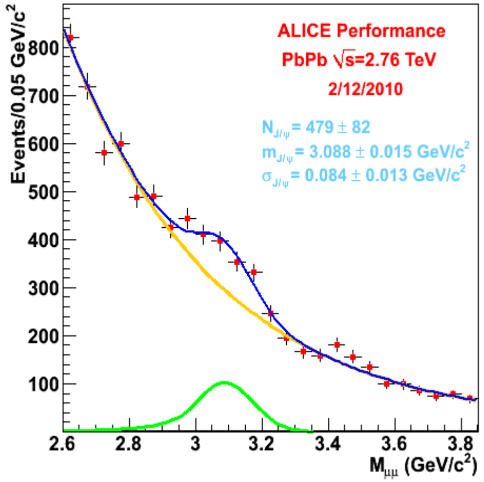


Particles decaying into e, **π**, K, p can be reconstructed from the ITS, TPC and TOF

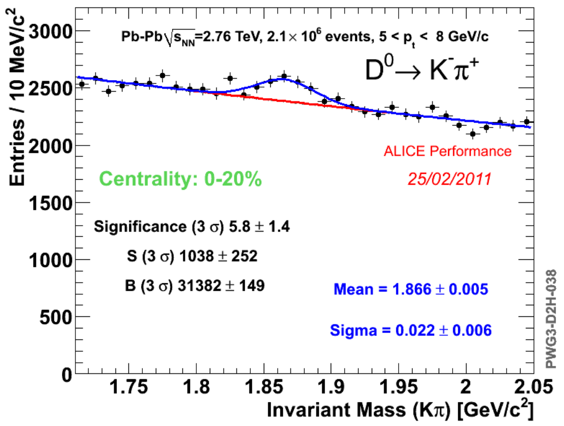
Reconstructed particles :

Quarkonia

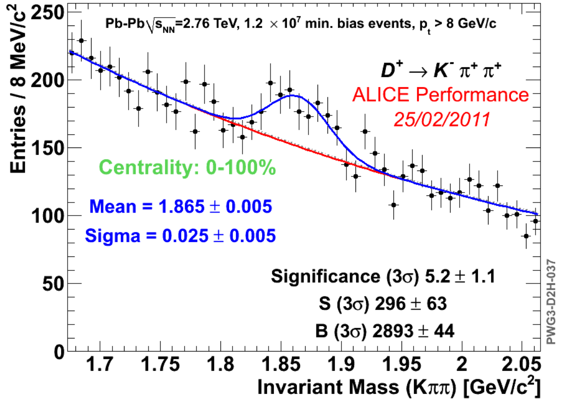
Heavy Flavours



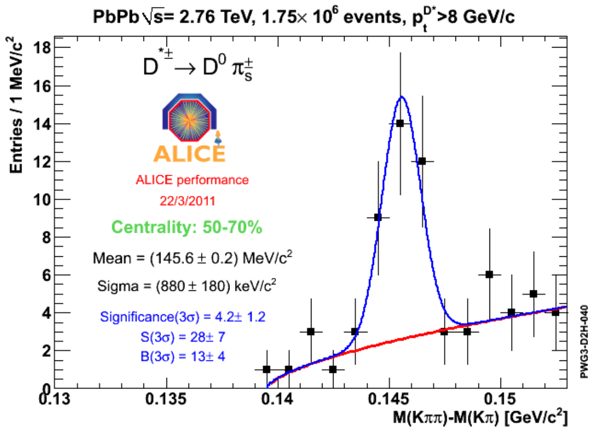
J/ψ → μμ, forward rapidty



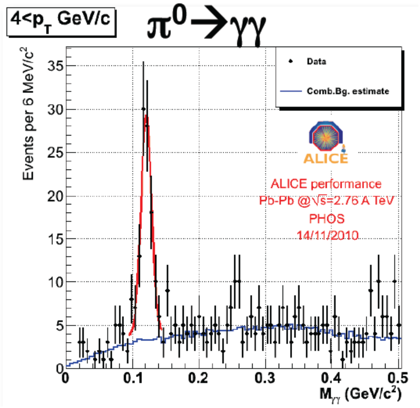
$D^0 \rightarrow K\pi$



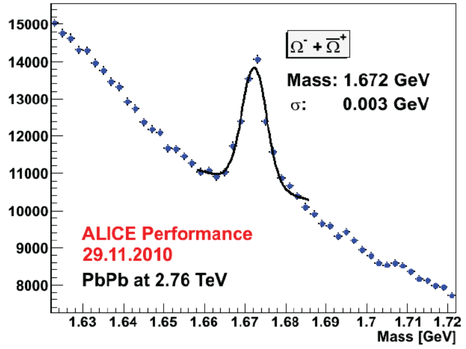
$D^+ \rightarrow K\pi\pi$

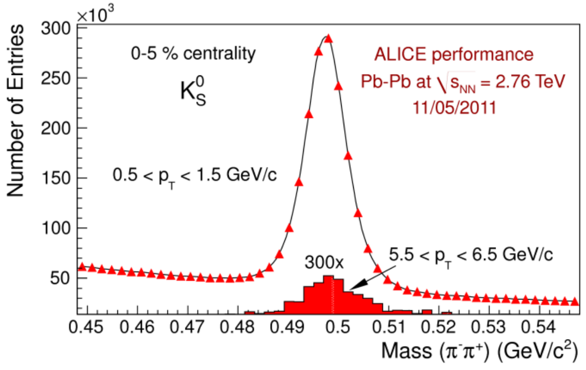


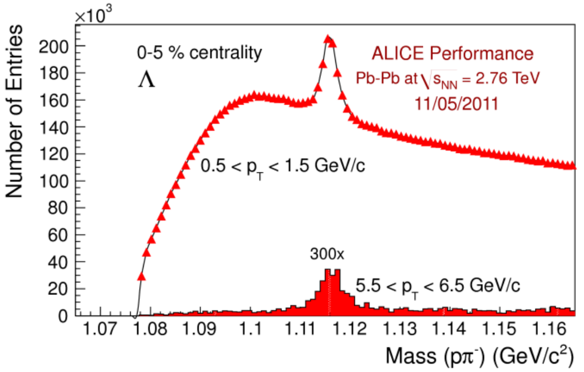
$D^* \rightarrow D^0\pi$



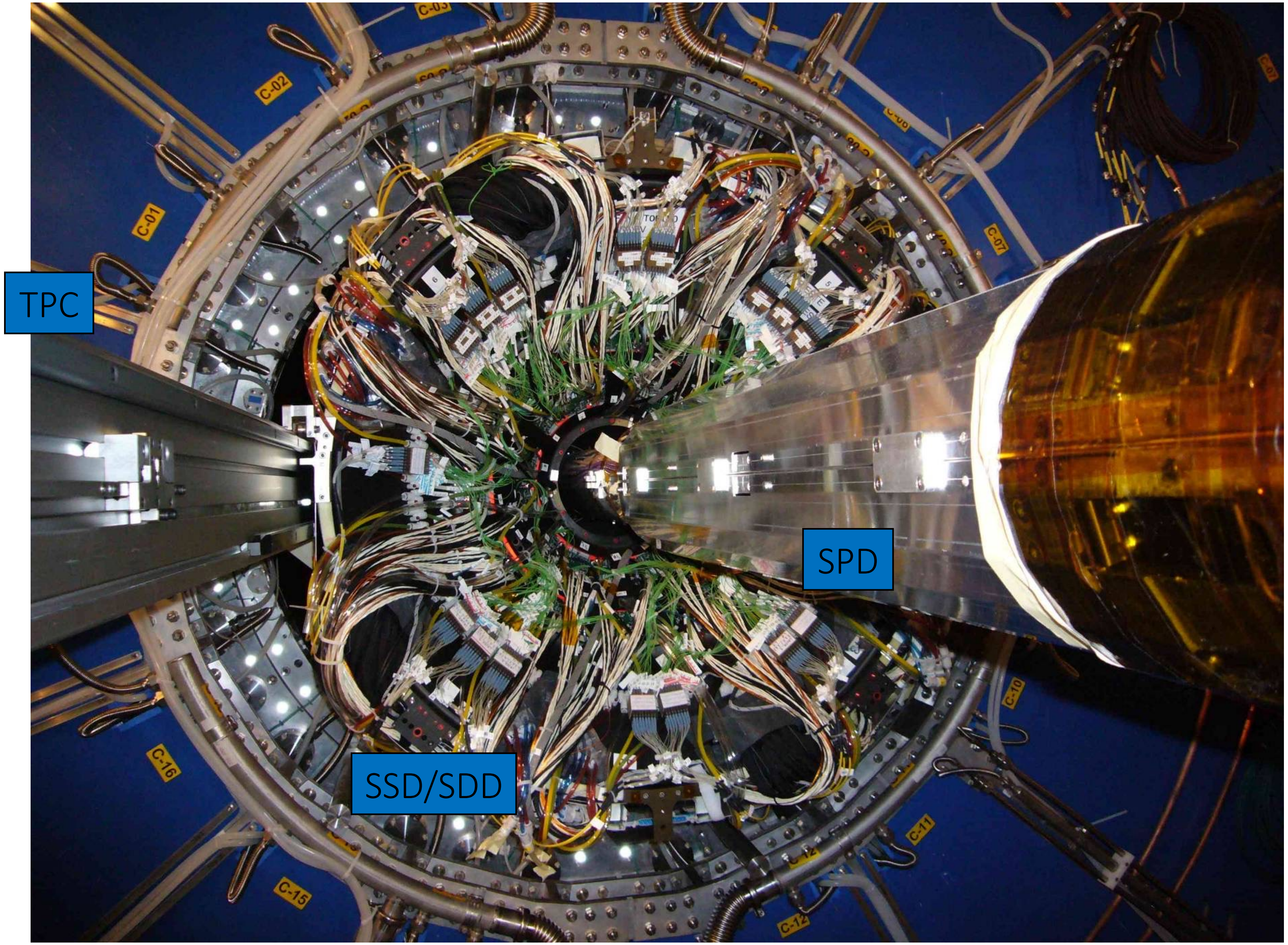
$\Omega^- \rightarrow \Lambda K^-$







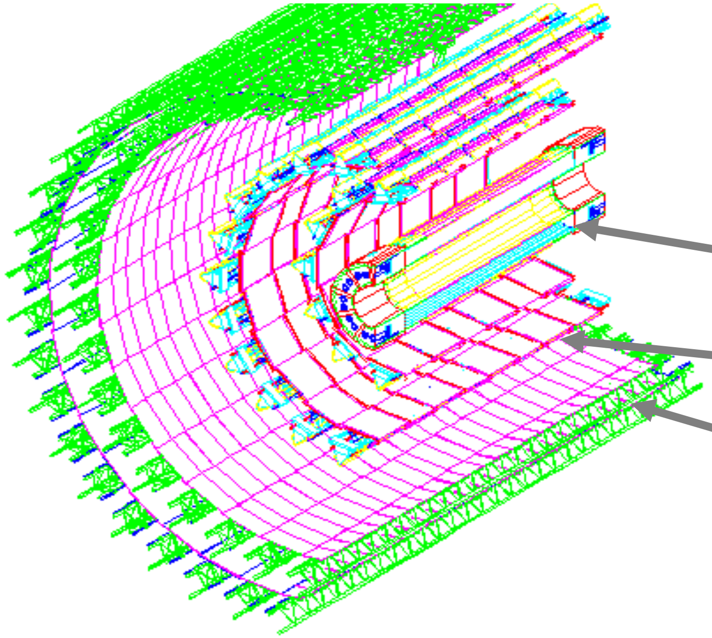
ALICE Inner Tracking System – ITS



ALICE Inner Tracking System – ITS

CERN-LHCC-2013-024 ; ALICE-TDR-017

Six Layers of silicon detectors for precision tracking in $|\eta| < 0.9$
Three technologies to keep occupancy ~2% from R_{min} ~4cm (80 tracks/cm^2) to R_{max}~40cm (1 tracks/cm^2)



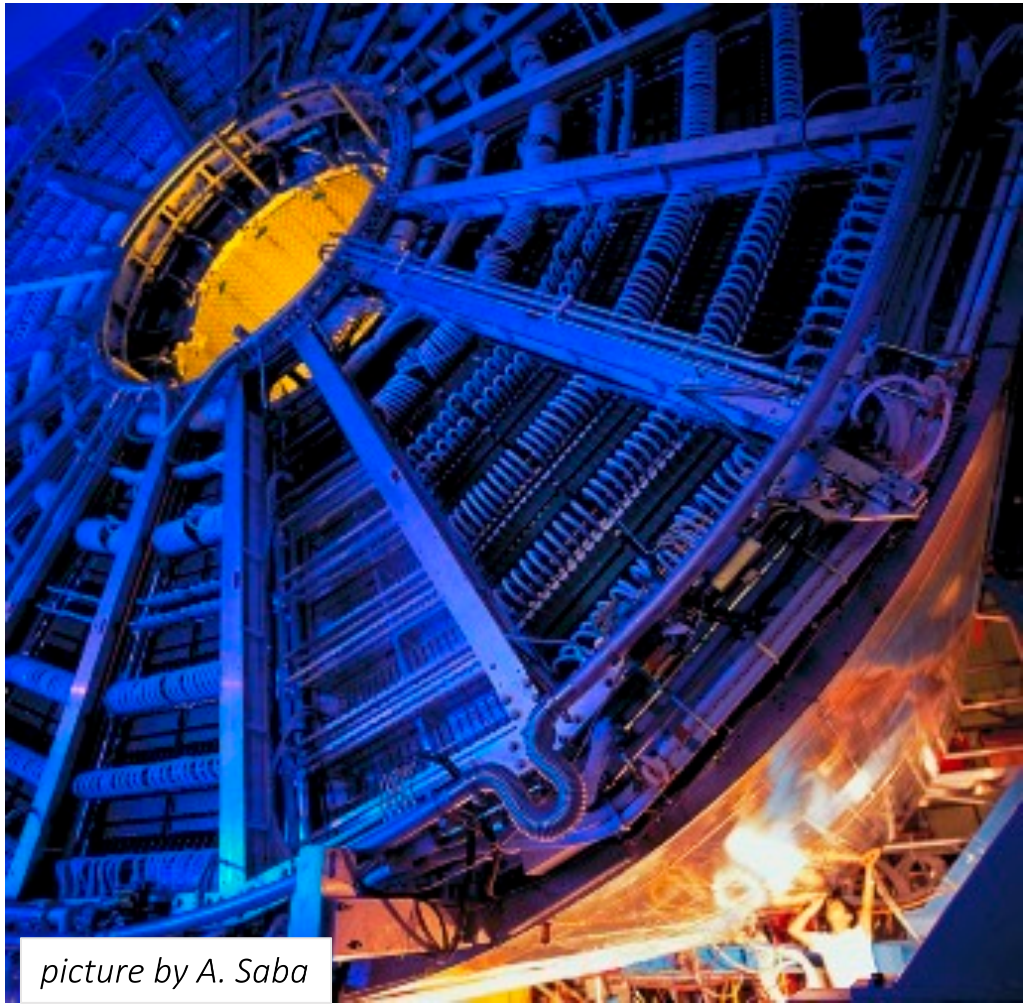
Three technologies:

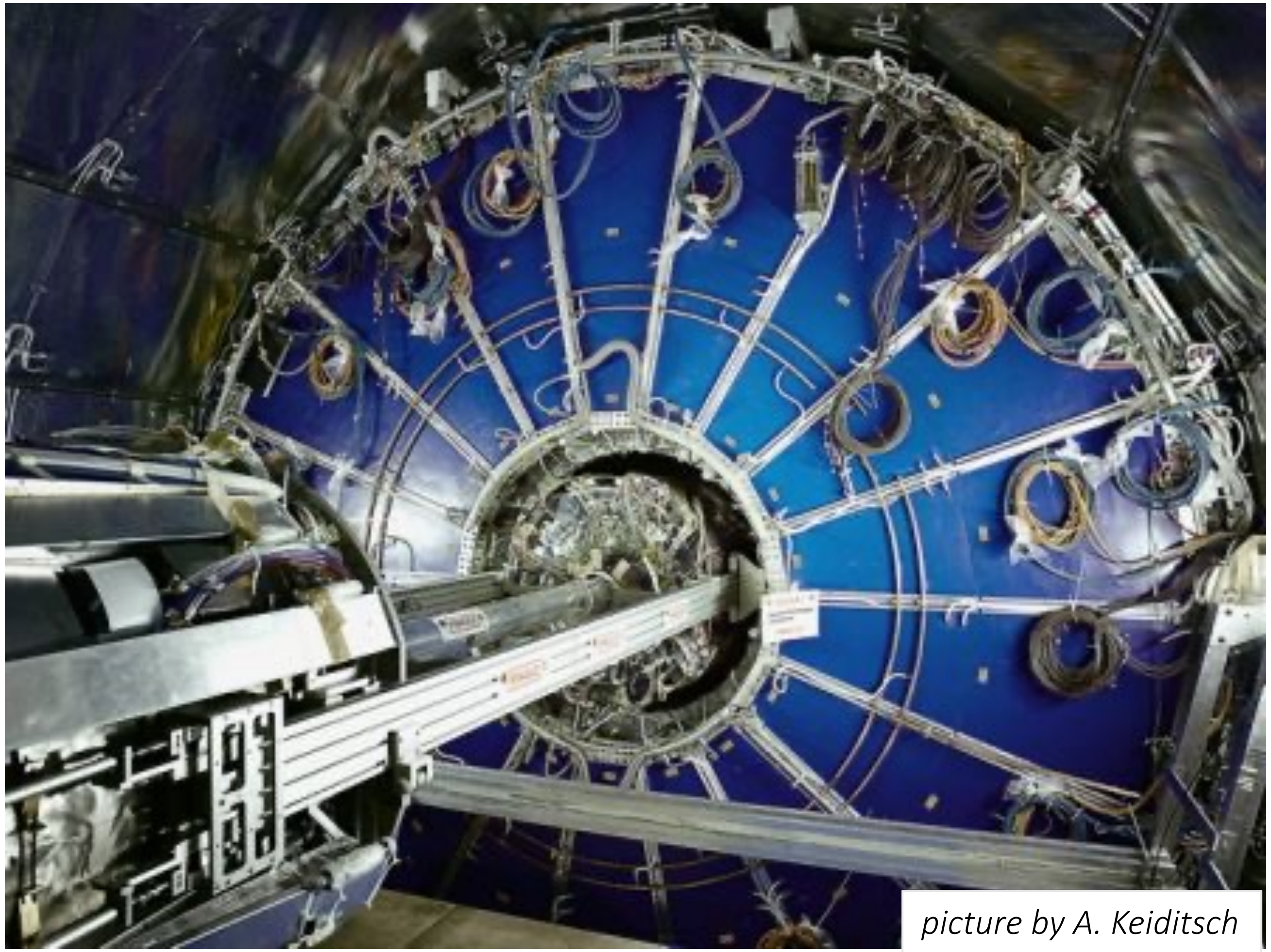
SPD - Silicon Pixel — ~12.5M channels

SDD - Silicon Drift
SSD - Silicon Strip
} Analogue readout for dE/dx

- 3-D reconstruction (<100 μm) for the Primary Vertex
- Secondary vertex Finding (Hyperons, D and B mesons)
- Particle identification vis dE/dx for momenta < 1 GeV
- Standalone reconstruction for very low momentum tracks (< 100 MeV)

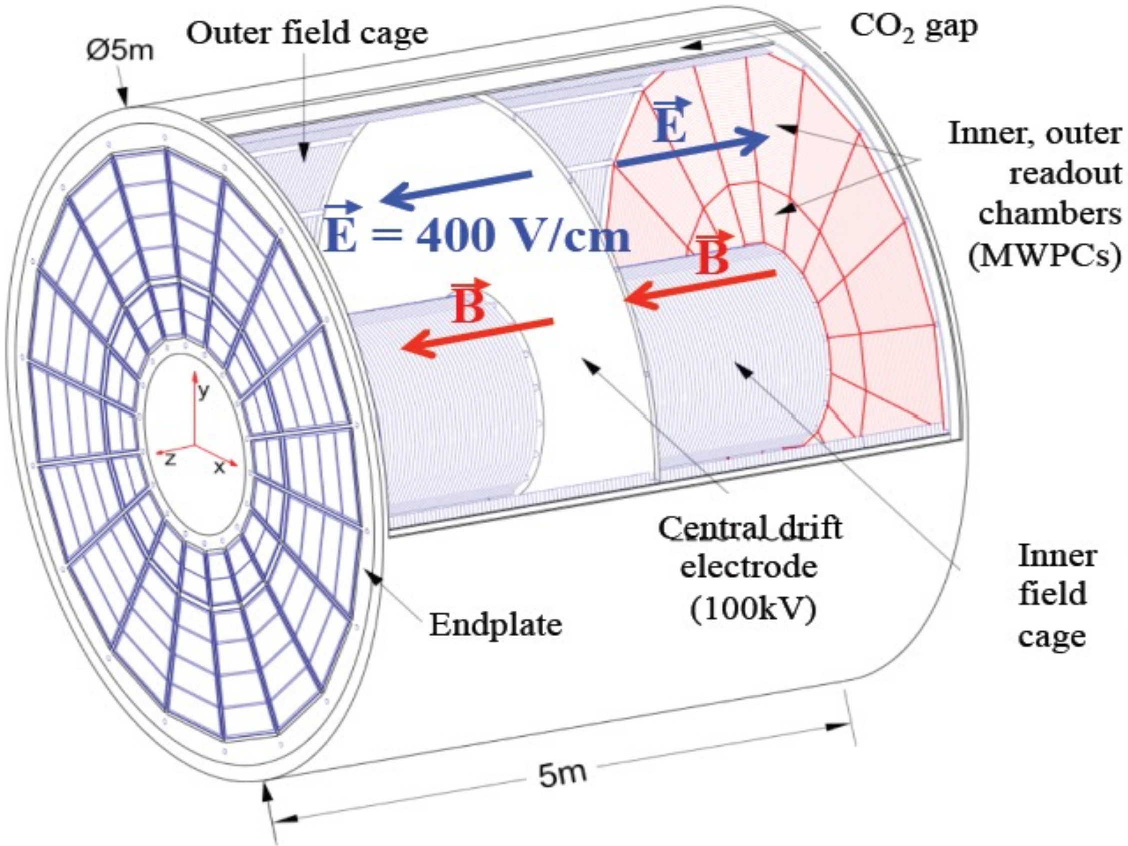
ALICE Time Projection Chamber – TPC


picture by A. Saba


picture by A. Keiditsch

ALICE Time Projection Chamber – TPC

TPC: main tracking device in ALICE



* **Was Ne-CO_2-N_2 before 2011**

** **Requires high level data compression**

TPC main features:

- ~92 m^3 active volume with gas mixture: Ne-CO_2 (90-10)*
- Low drift diffusion
- Maximum drift time 94 ms
- 72 (=18x2x2) MWPCs with pad readout

- Excellent performance on momentum reconstruction and dE/dx
- High readout rate capability:

1 kHz pp collisions

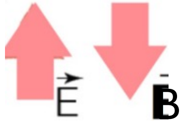
200 Hz central Pb-Pb collisions**

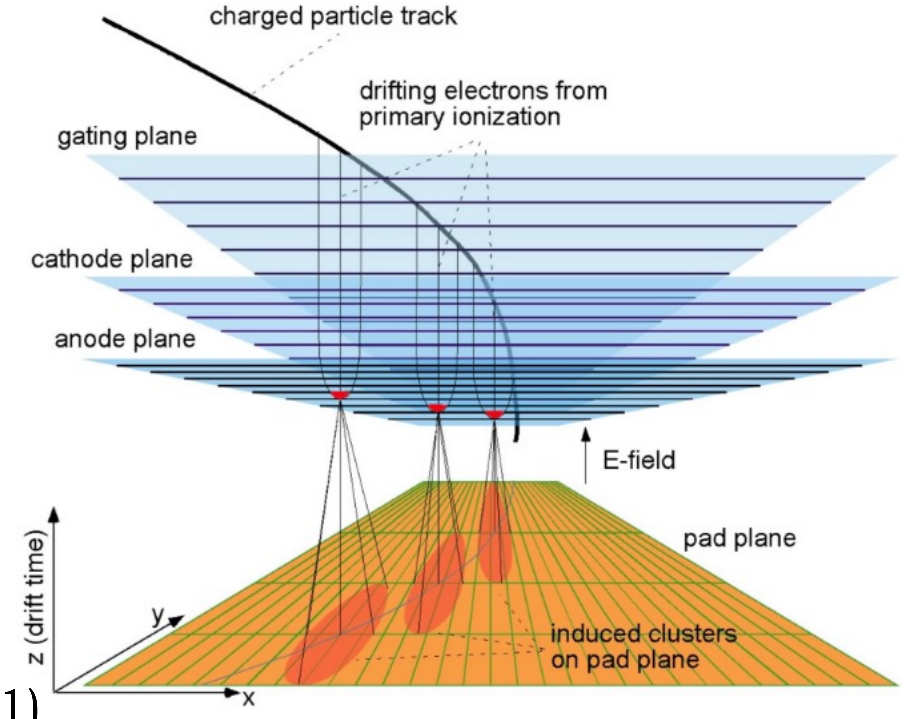
PID at High Multiplicity

TPC PID in the environment of unprecedented densities of charged particles!

Challenges at high track multiplicity

- Cluster pileup
- Distortion due to space charge
- Baseline Fluctuation





Corresponding treatments

- High granularity (small pads) and low diffusion gas mixture
- Drift gas mixture with low primary ionization (low Z)
- ALTRO online ion tail correction (fully commissioned in 2011)

PID at High Multiplicity

Weilin Yu -- Bari TRD Workshop -2022

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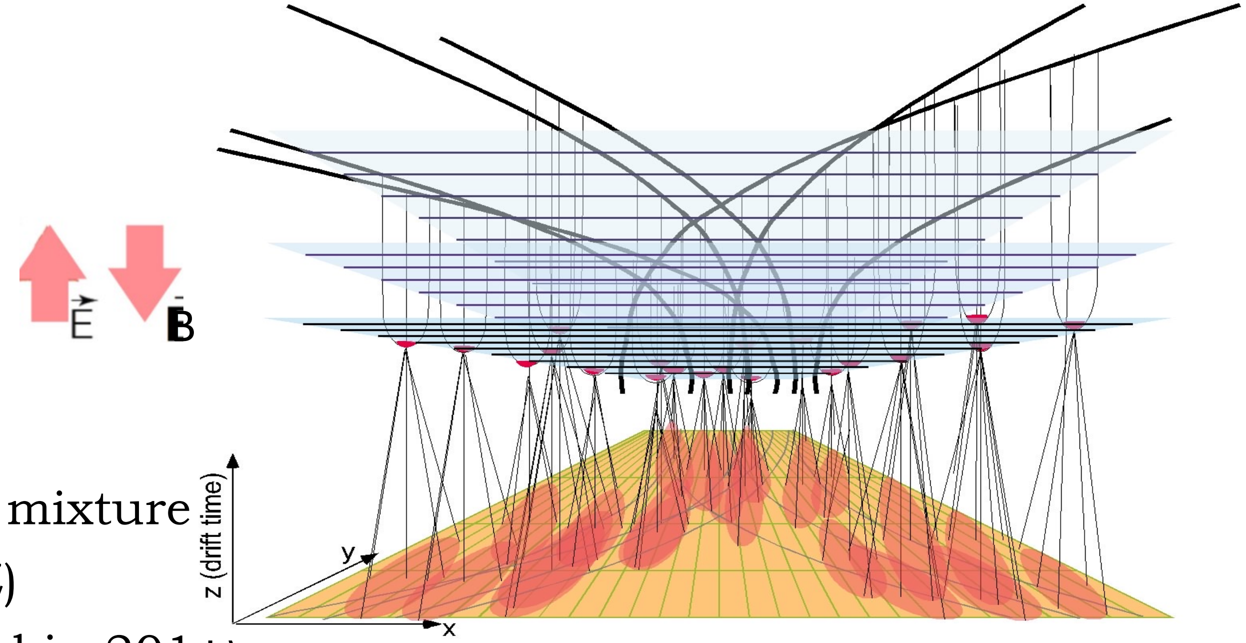

Corresponding treatments

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dE/dx Basics

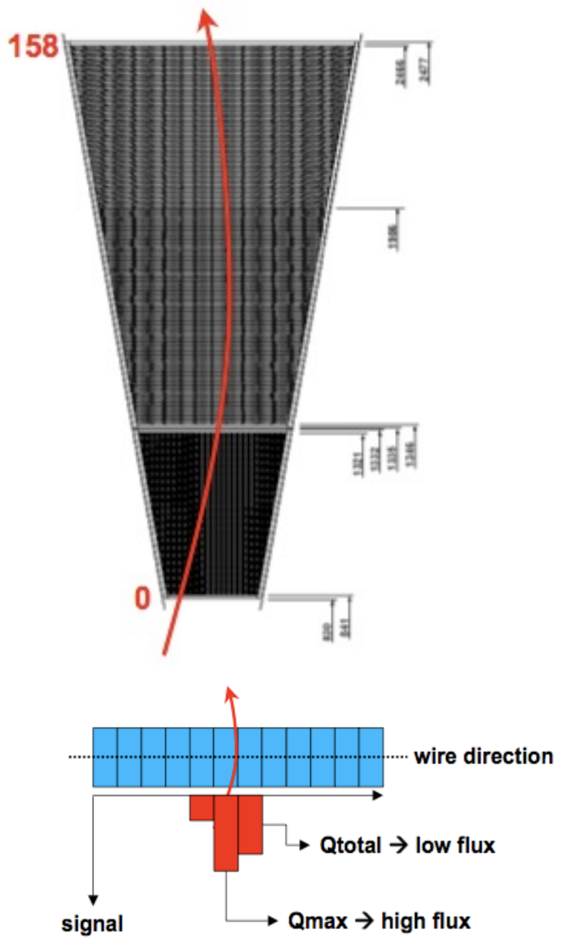
- Energy loss per unit path length is described by the Bethe-Bloch formula

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi N e^4}{mc^2} \frac{z^2}{\beta^2} \left(\frac{1}{2} \ln \frac{2mc^2 E_{max} \beta^2 \gamma^2}{I^2} - \frac{\beta^2}{2} - \frac{\delta(\beta)}{2} \right)$$

  (depends only on charge and rest mass for a fixed momentum)

- Truncated mean (≈70%) is used to remove fluctuations due to the tail towards higher deposits ("Landau-like")
- Small signals of 1-pad clusters are included in the calculation to improve the dE/dx resolution
- Parameterization is fitted to the data (Aleph-Parameterization):

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln\left(P_3 + \frac{1}{(\beta\gamma)^{P_5}}\right) \right)$$

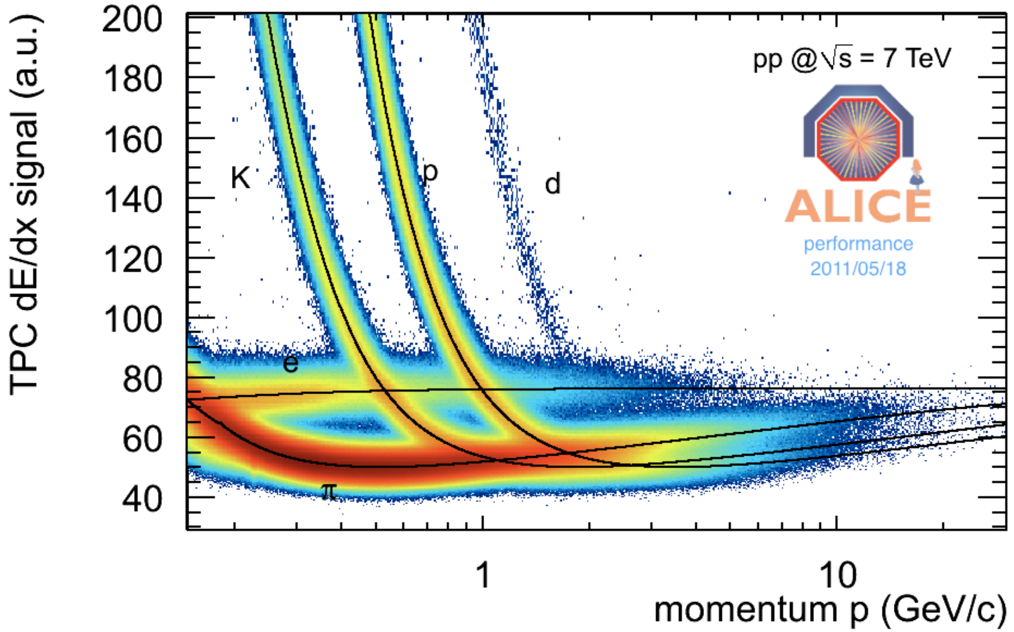


dE/dx measurement in TPC

❖ Up to 159 samples in Ne-CO_2 gas mixture: $\sigma_{dE/dx} \approx 5\%$

❖ Very large dynamic range (up to 26x min. ionizing) allows to identify light nuclei and separate them by their charge

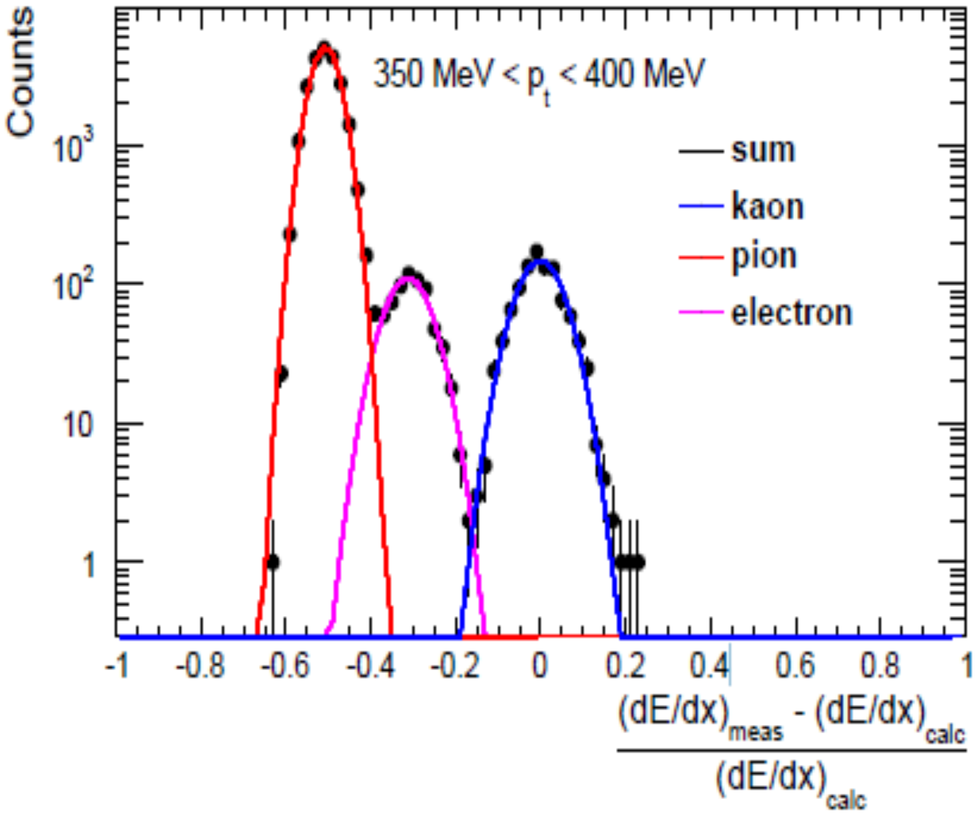
❖ PID can be extended to higher momenta on the relativistic rise using statistical unfolding



Separation of p to K, p becomes constant at large p

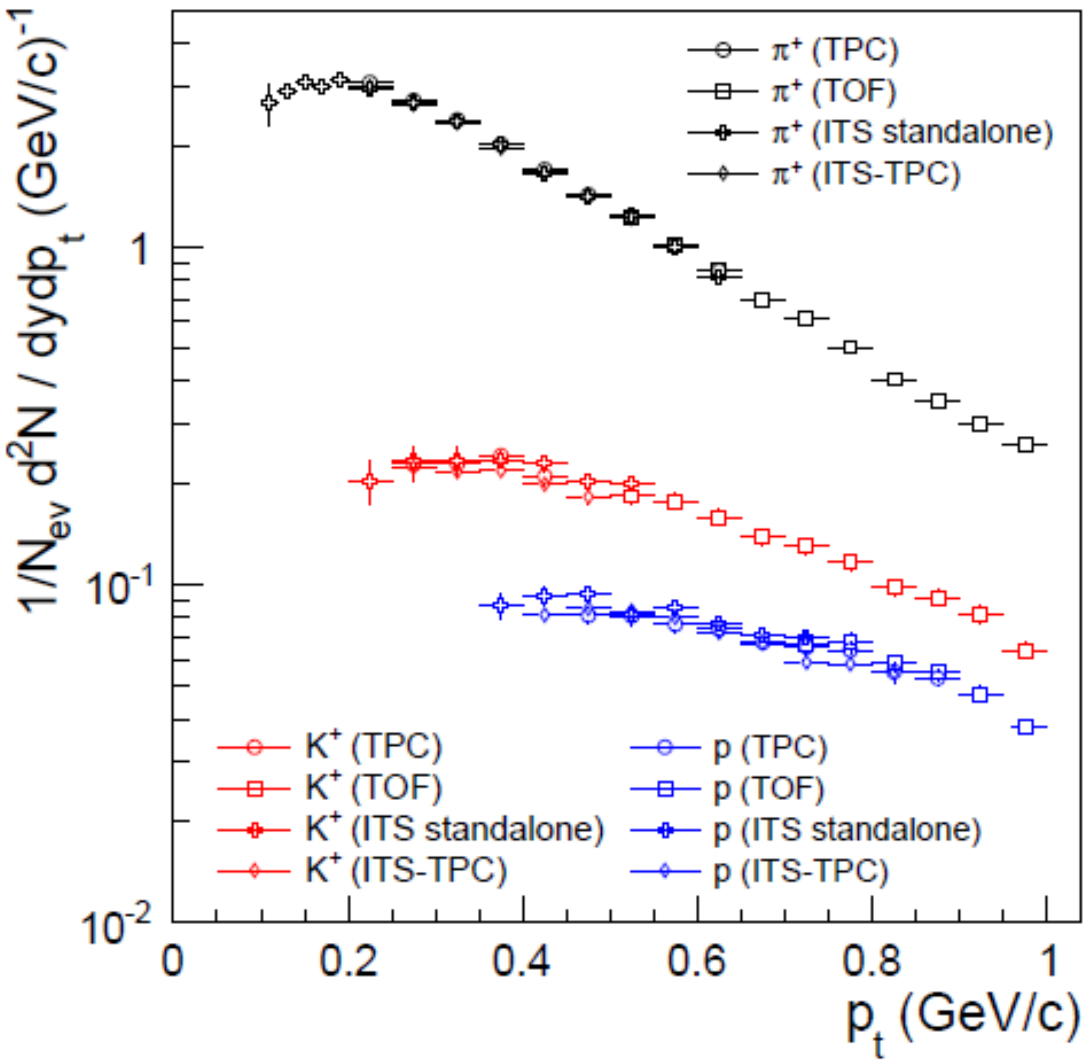
TPC PID at low p_T

❖ In the low p_T region dE/dx is clearly separated, track-by-track PID is even possible, e.g. based on nσ-bands



ALICE Collaboration Eur.Phys.J.C71:1655,2011 (***pp collisions at 900 GeV***)

TPC PID at low p_T



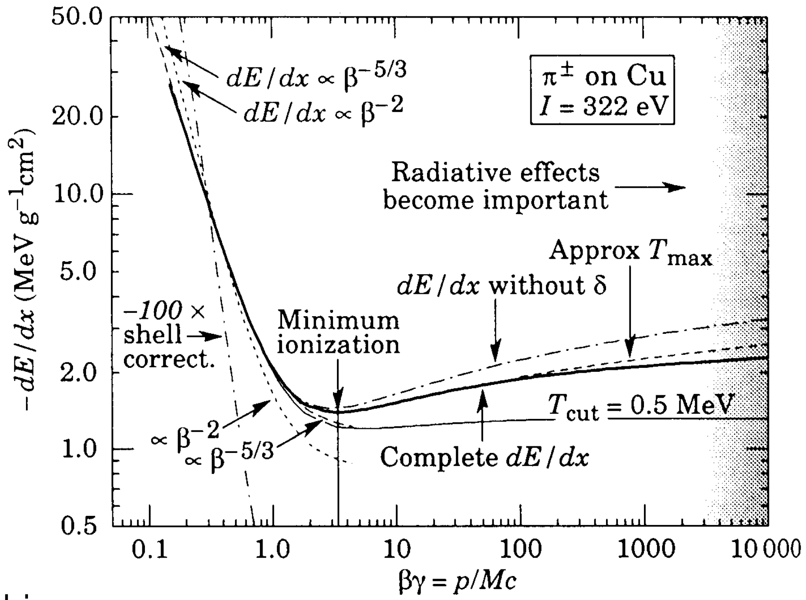
❖ Transverse momentum spectra of positive charged particles from TPC and other sub-detectors of ALICE. ALICE Collaboration Eur.Phys.J.C71:1655,2011

TPC PID on the Relativistic Rise

Macro Delmastro : esipap

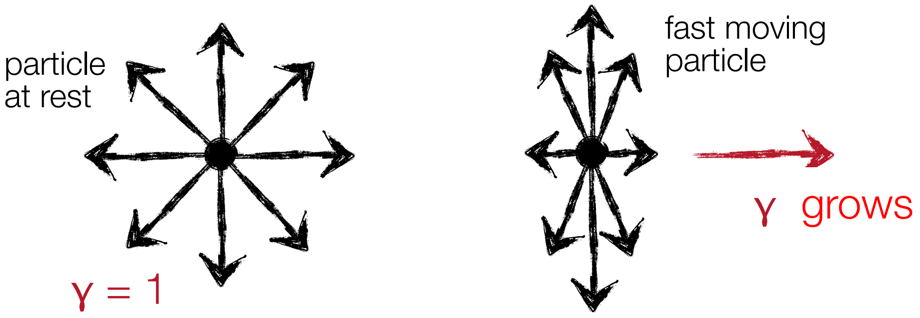
$1/\beta^2$-dependence:

Slower particles fell electric force of atomic electrons for longer time …



Relativistic rise for $\beta\gamma > 4$:

High energy particle: transversal electric field increases due to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...



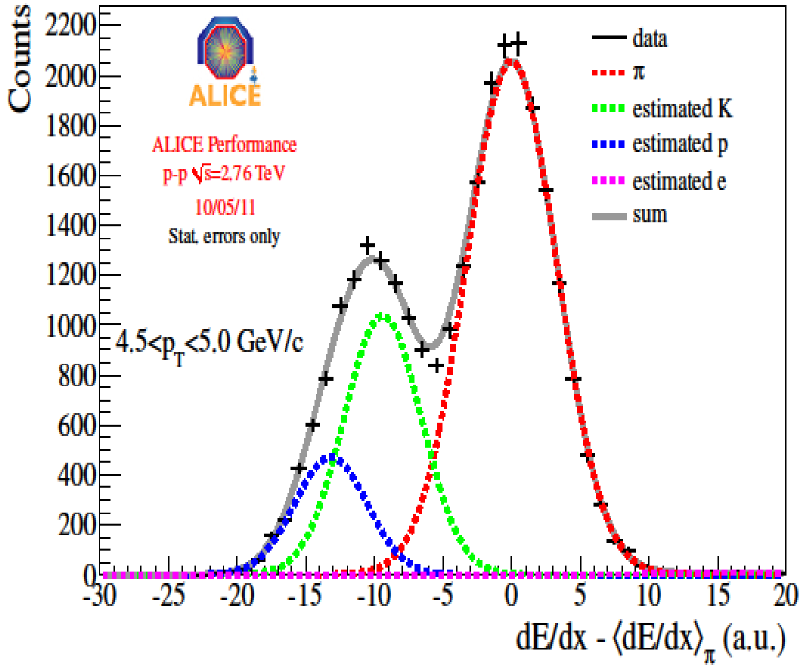
Corrections:

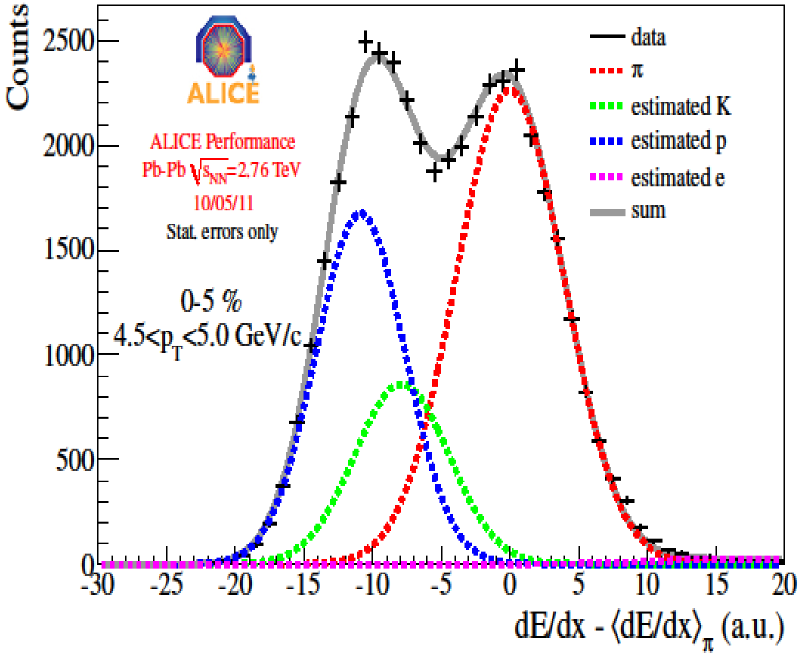
low energy : shell corrections

high energy : density corrections

TPC PID on the Relativistic Rise

- dE/dx - <dE/dx>$_p$ for different p_T slices
- Fitted with 4 Gaussians (p, K, p, e)
- Statistical unfolding, means and widths constrained from Bethe-Bloch and MIP respectively





ALICE Transition Radiation Detector – TRD

6 layer TRD, covering the whole azimuthal central region

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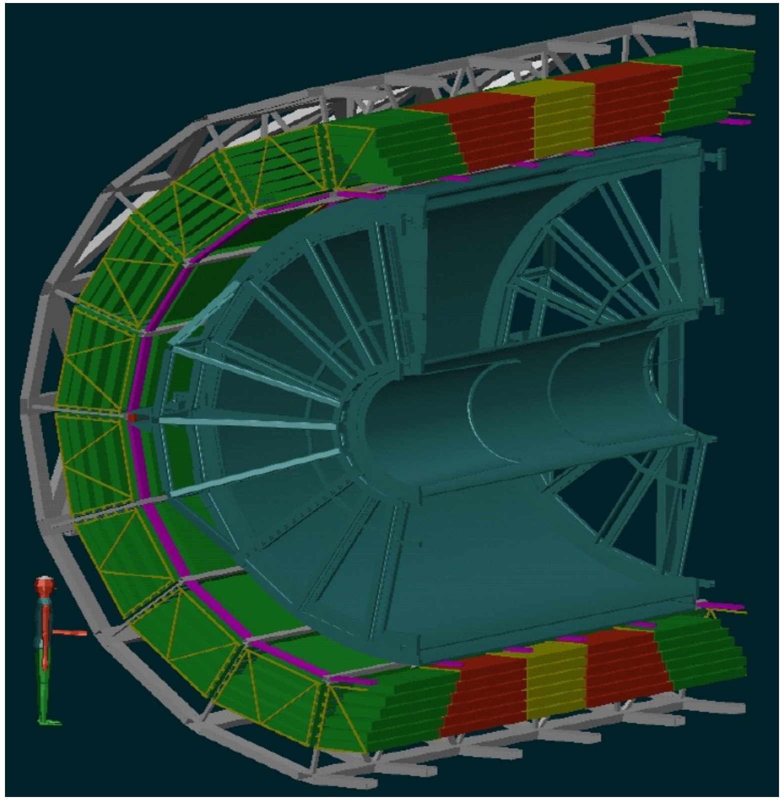
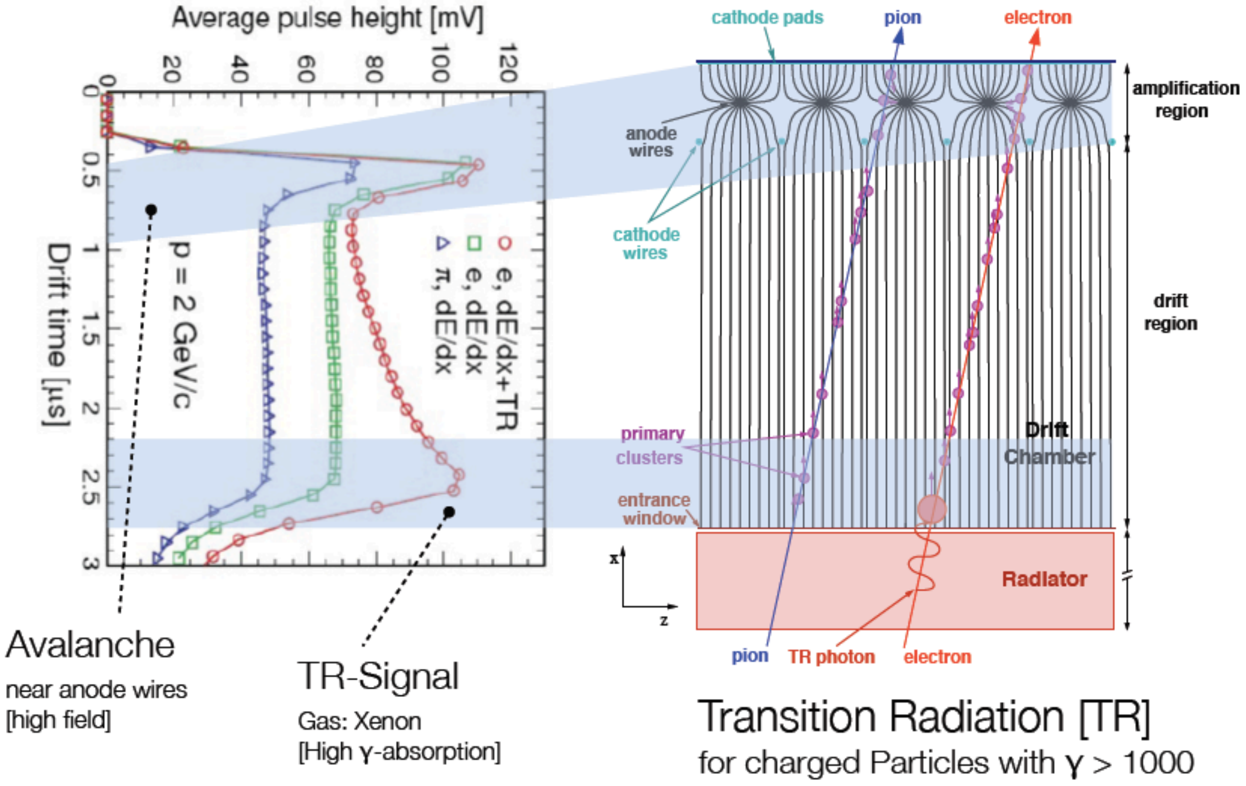


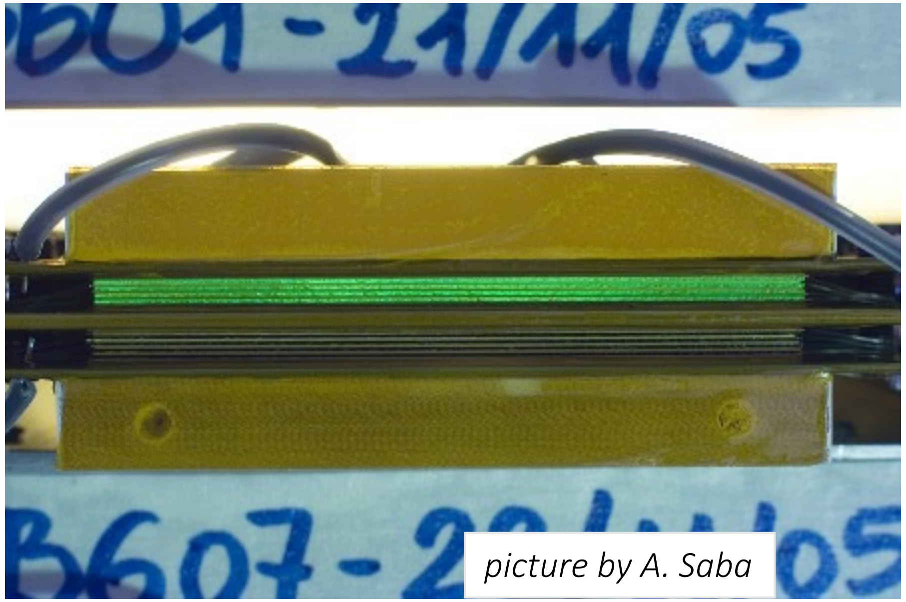
Transition radiation detectors - ALICE



- **Electron ID** in the momentum range p > 1 GeV/c
- Fast **trigger** for high-p_T particles
- Hadron **PID**

ALICE Time Of Flight – TOF

Large array at R ~ 3.7 m, covering $|\eta| < 0.9$ and full ϕ with 18 sectors (supermodules), with a total active area of ~160 m^2

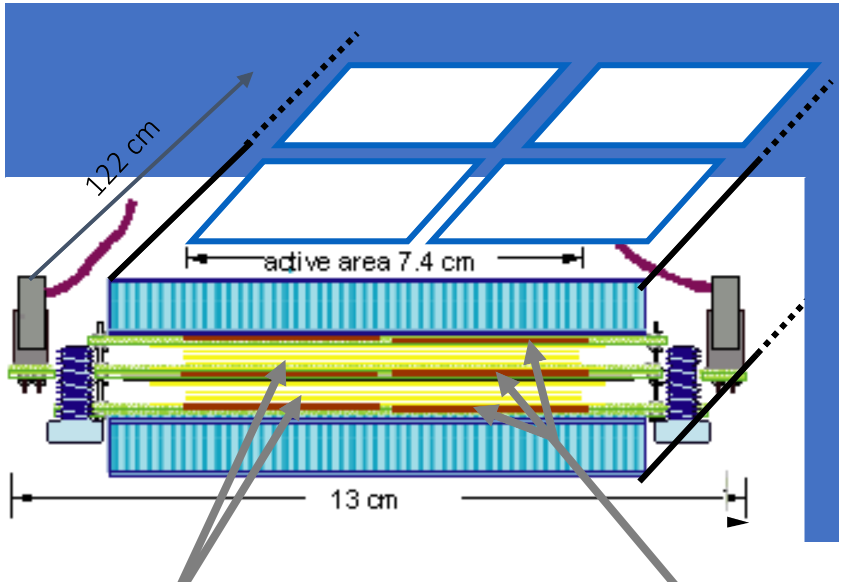


picture by A. Saba

TOF Supermodule

ALICE Time Of Flight – TOF

Large array at R ~ 3.7 m, covering |η| < 0.9 and full ϕ with 18 sectors (supermodules), with a total active area of ~160 m^2



2x5 gas gaps of **250µm**

Readout pads **3.5x2.5 cm^2**

- TOF basic element: double-stack **Multigap RPC** strip
- Occupancy < 15% (O(10^5) readout channels)
- Separation **π/K, K/p @** low/intermediate p, better than 3σ from ~0.5 GeV/c up to a few GeV/c

- Intrinsic Resolution **~ 40 ps**
- Efficiency **> 99%**

Measurement of particle velocity

- Time of flight

Measure signal time difference between two detectors with good time resolution [start and stop counter]

- Typical detectors:

  Scintillation counter + photodetector

  time resolutions ~50-100 ps (r/o at both ends of the scintillator bar)

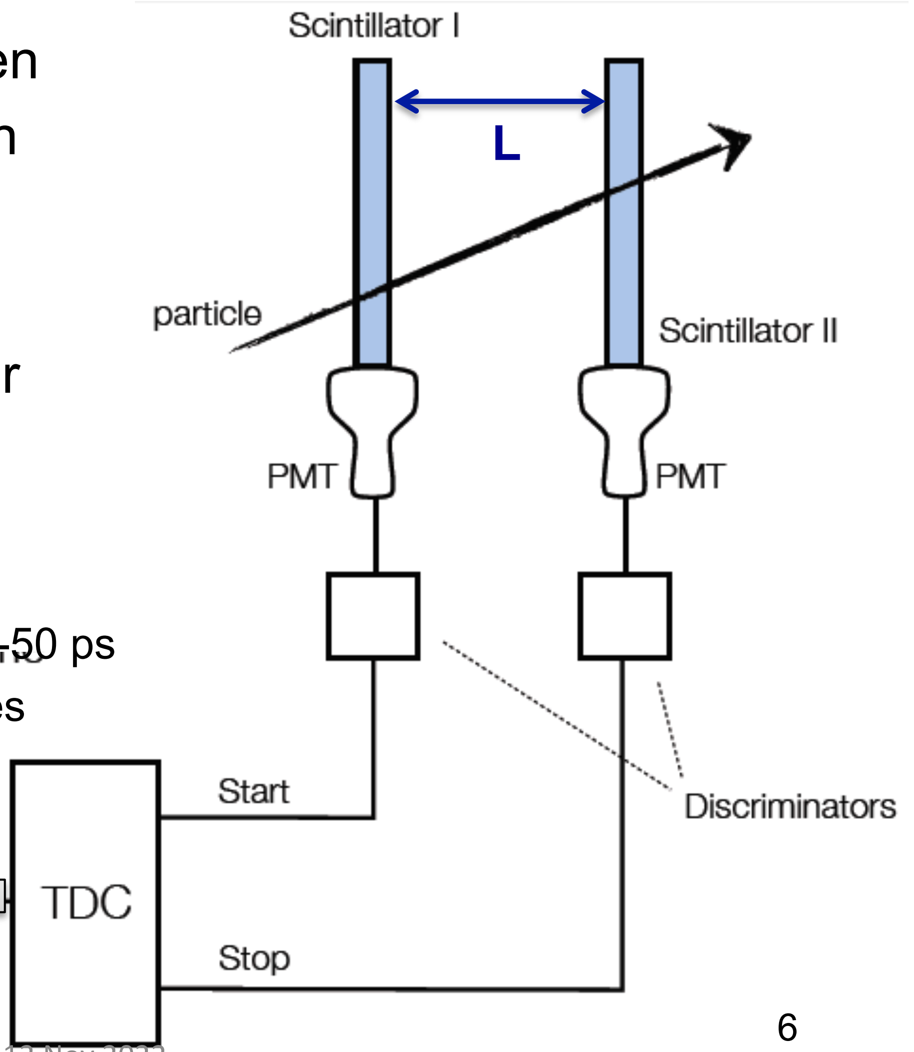
  Resistive Plate Chamber (RPC)

  not sensitive to B, time resolutions ~30-50 ps

  cost effective solution for large surfaces

$$\Delta t = t_2 - t_1 = \frac{L}{c\beta}$$

Multi-channel analyzer t_1 , t_2



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Time-of-Flight method

Distinguishing particles with ToF:
[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2

Distance L : distance between ToF counters

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[\left(pc + \frac{m_1^2c^4}{2pc}\right) - \left(pc + \frac{m_2^2c^4}{2pc}\right)\right]$$

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

For L = 2 m:

Requiring $\Delta t \gtrsim 4\sigma_t$ K/π separation possible up to p = 1 GeV if $\sigma_t \approx 200$ ps ...

Cherenkov counter, RPC : $\sigma_t \approx 40$ ps ...
Scintillator counter : $\sigma_t \approx 80$ ps ...

Example:

Pion/Kaon separation ...
[$m_K \approx 500$ MeV, $m_\pi \approx 140$ MeV]

Assume:
p = 1 GeV, L = 2 m ...

$$\rightarrow \Delta t \approx \frac{2\ \mathrm{m}\cdot c}{2\ (1000)^2\ \mathrm{MeV}^2/c^2}\left(500^2 - 140^2\right)\ \mathrm{MeV}^2/c^4$$

$$\approx 800\ \mathrm{ps}$$

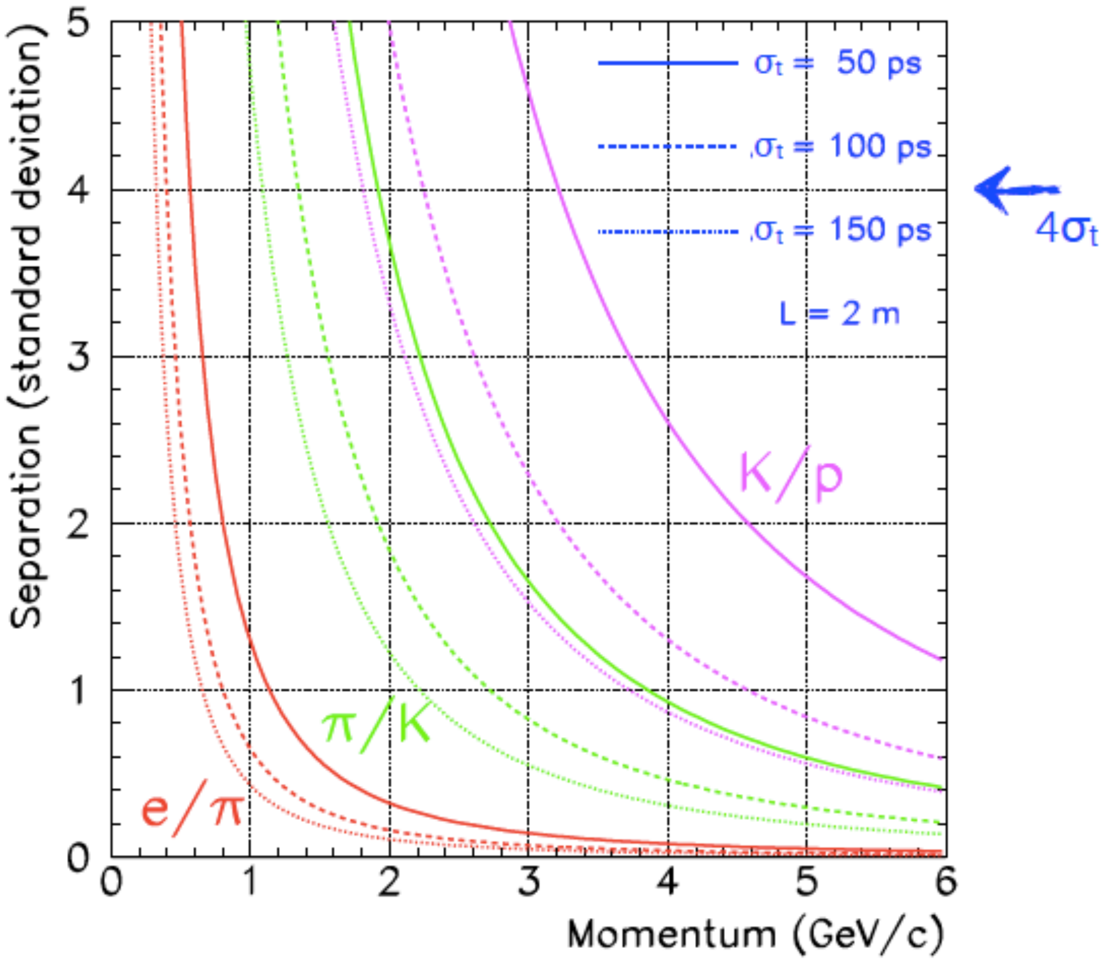
7

https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L12_PID.pdf

Time of flight performance

Difference in time-of-flight in σ_t

[L = 2 m]

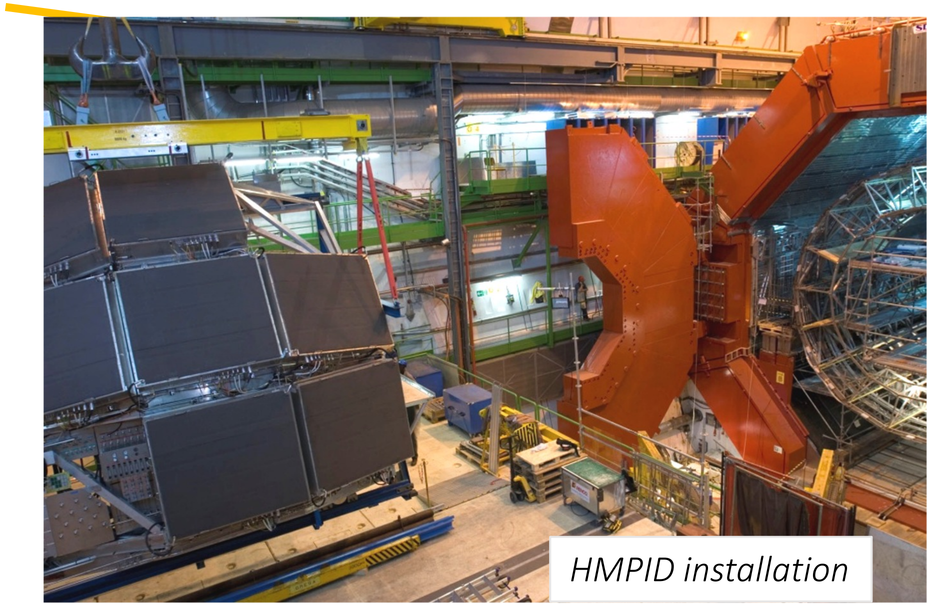


Can you write a program to make this plot?

ALICE High Momentum Particle ID Detector – HMPID

SINGLE-ARM proximity-focus RICH, at 4.7 m, with 7 modules for an active area of ~11 m^2

picture by A. Saba

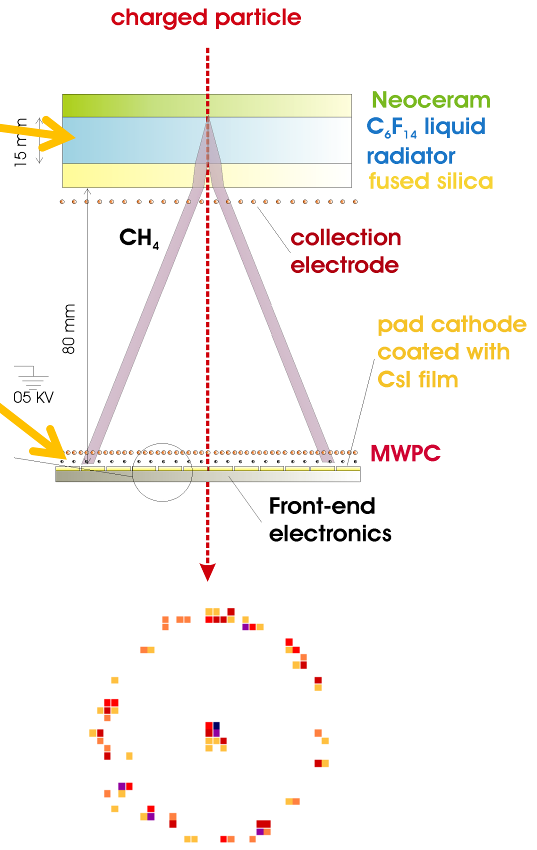


HMPID installation

ALICE High Momentum Particle ID Detector – HMPID

SINGLE-ARM proximity-focus RICH, at 4.7 m, with 7 modules for an active area of ~11 m^2

- 15 mm layer of C_6F_{14} liquid radiator (n = 1.2989 @ λ = 175 nm, p_{th} = 1.21 m (GeV/c)
- **CsI** thin films deposited onto a cathode plane of MWPC (**O**(10^5) readout channels), the largest scale application
- **Hadron ID @ high momenta**, $1 < p_T < 3$ GeV/c for π and K, $1 < p_T < 5$ GeV/c for p

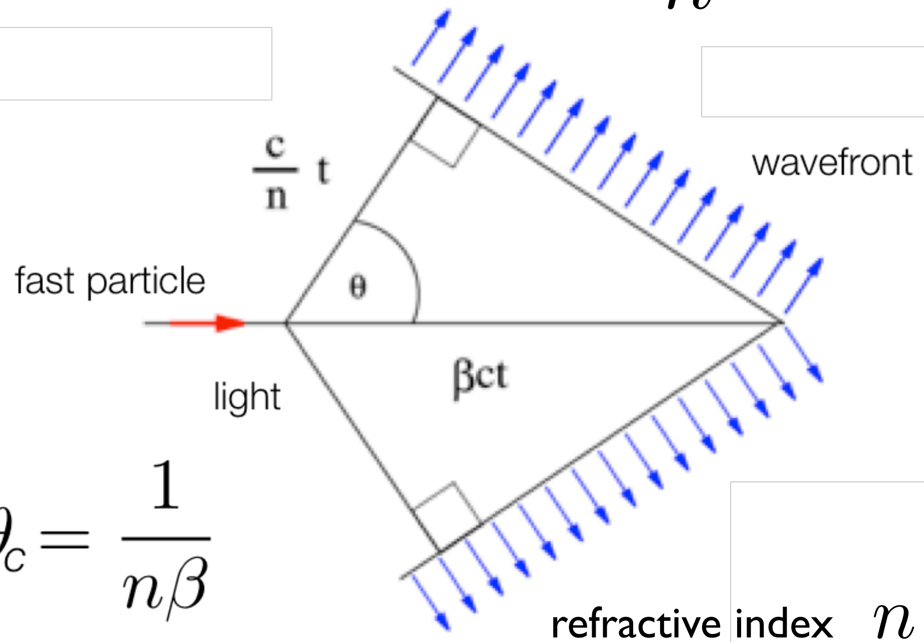


Cherenkov radiation

Particles moving in a medium with speed larger than speed of light in that medium will loose energy by emitting electromagnetic radiation

- ✓ Charged particle polarize medium generating an electrical dipole varying in time
- ✓ Every point in trajectory emits a spherical EM wave, waves constructively interfere…

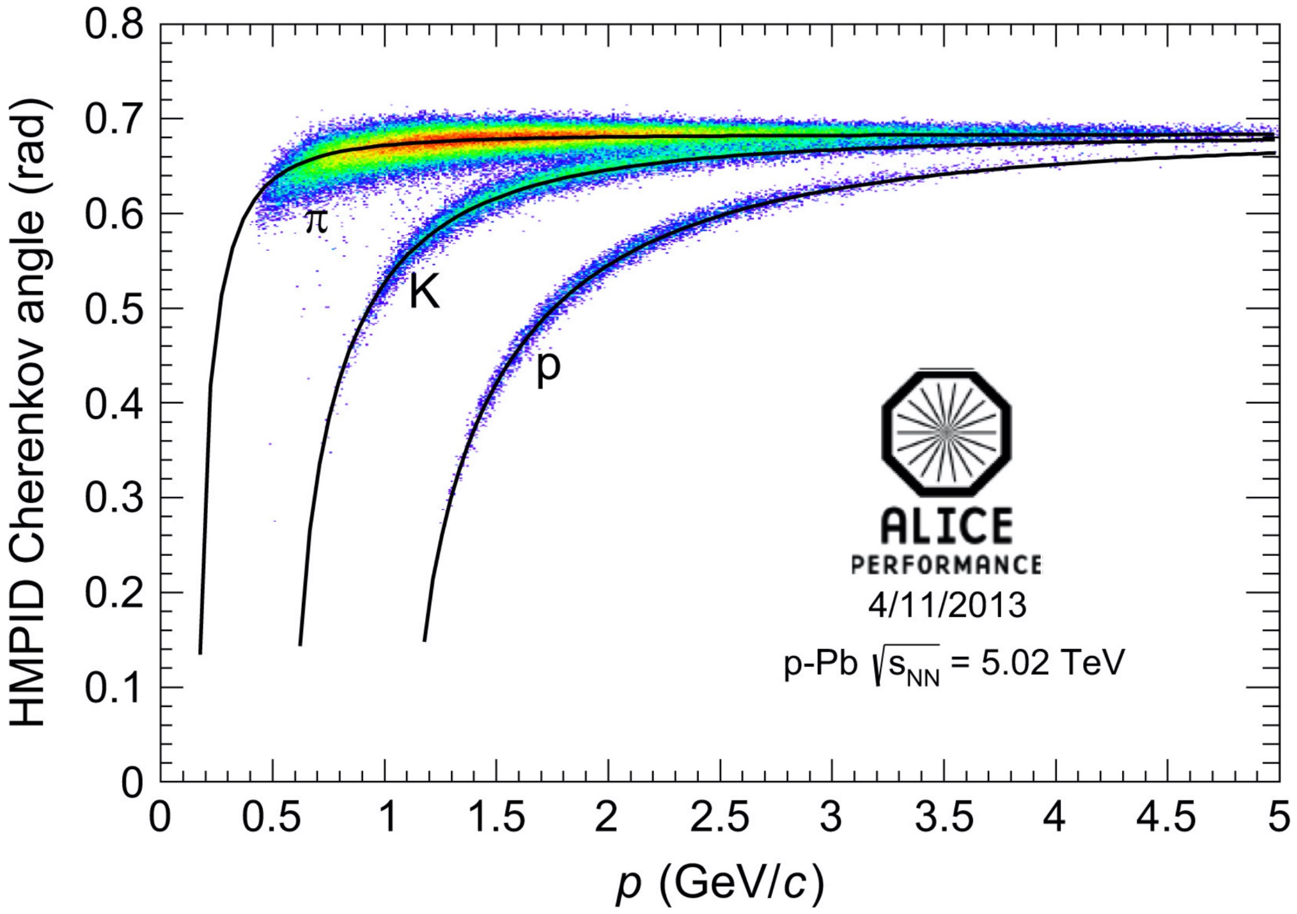
$$\beta > \frac{1}{n}$$



$$\cos\theta_c = \frac{1}{n\beta}$$

refractive index $n = \sqrt{\varepsilon}$ dielectric constant

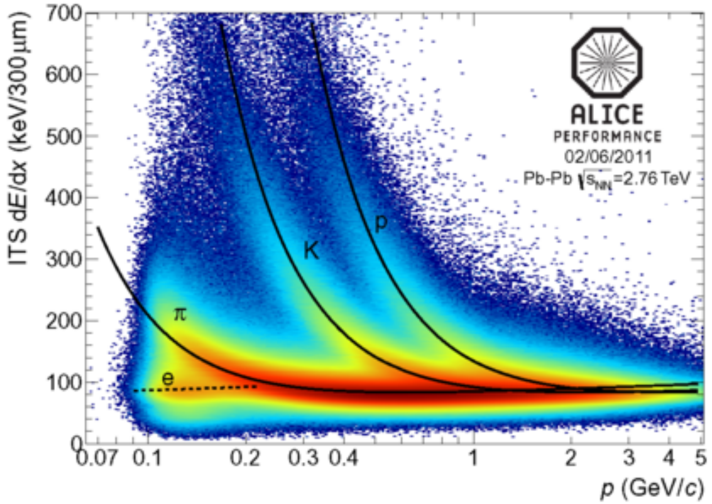
Cherenkov angle from HMPID : pPb

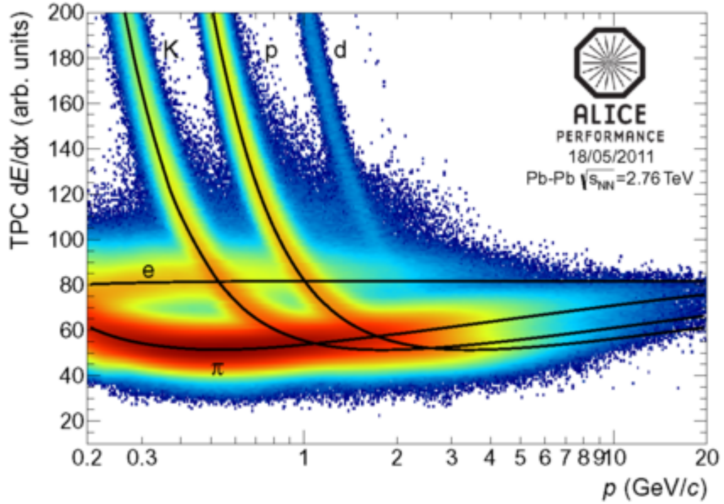


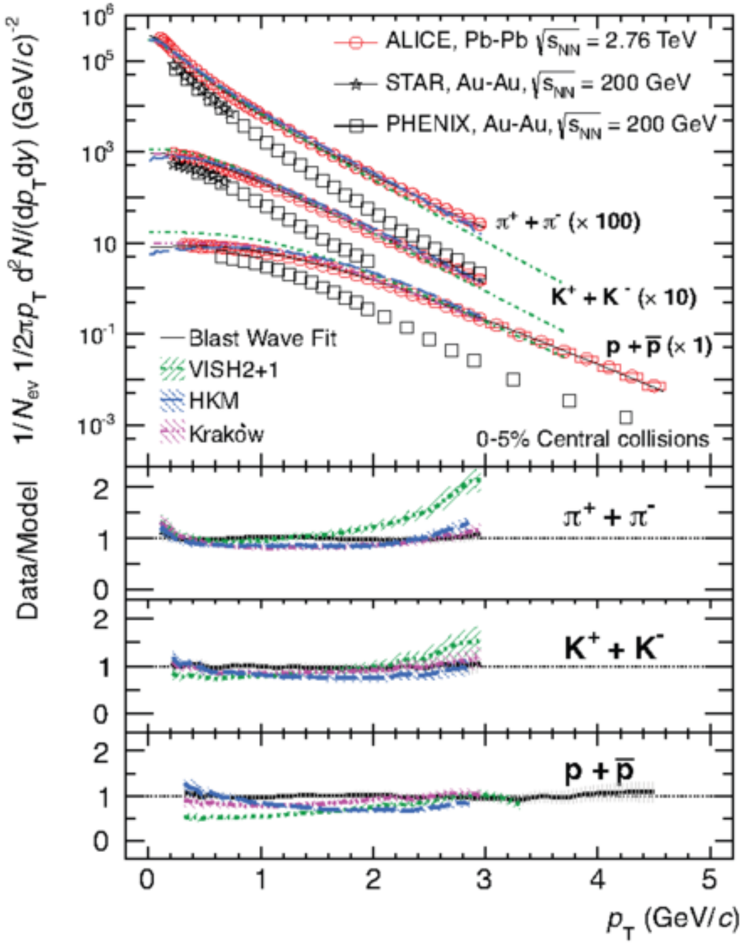
j.nima.2014.05.031

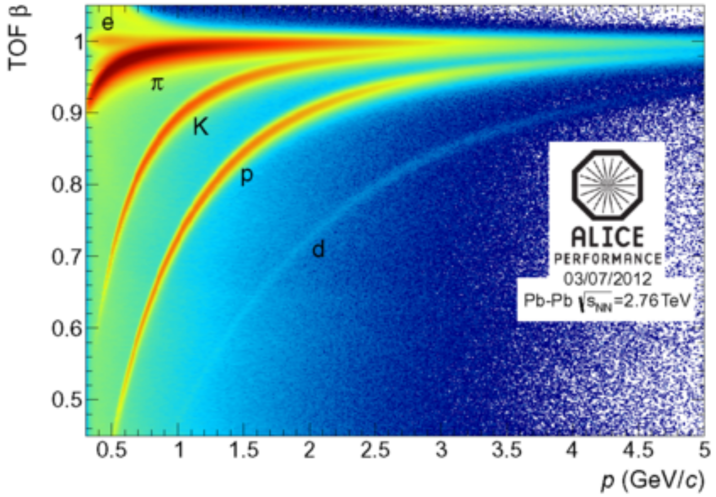
Combined PID : ITS+TPC+TOF+HMPID

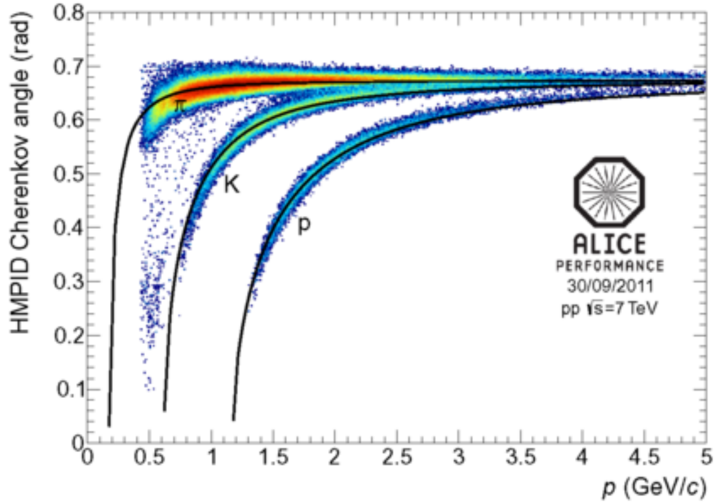
Nuclear Physics A 904–905 (2013) 162c–169c







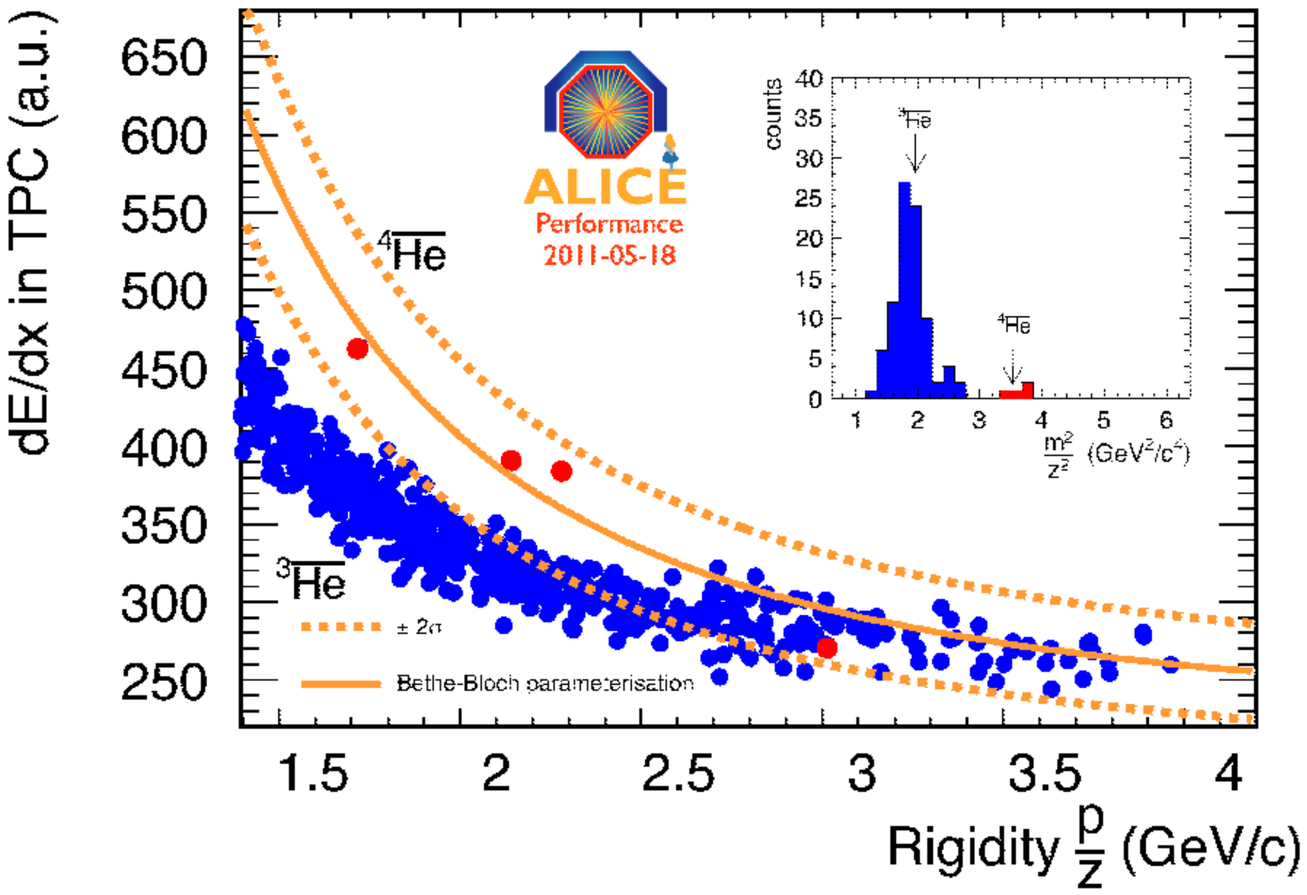




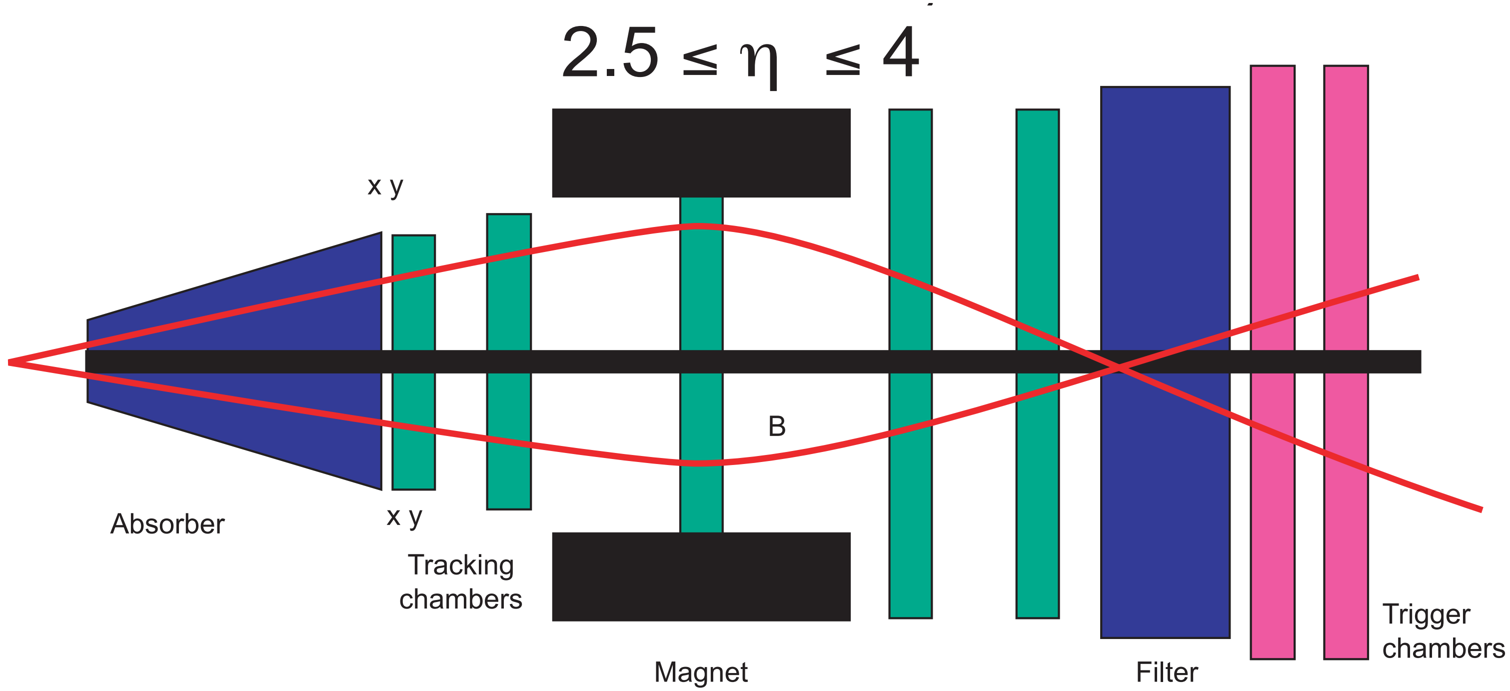
Anti Alpha Observation

❖ 4 candidates for anti-alpha (PID using TPC and TOF)

Nuclear Physics A
Volumes 904–905, 2 May 2013, Pages 547c-550c

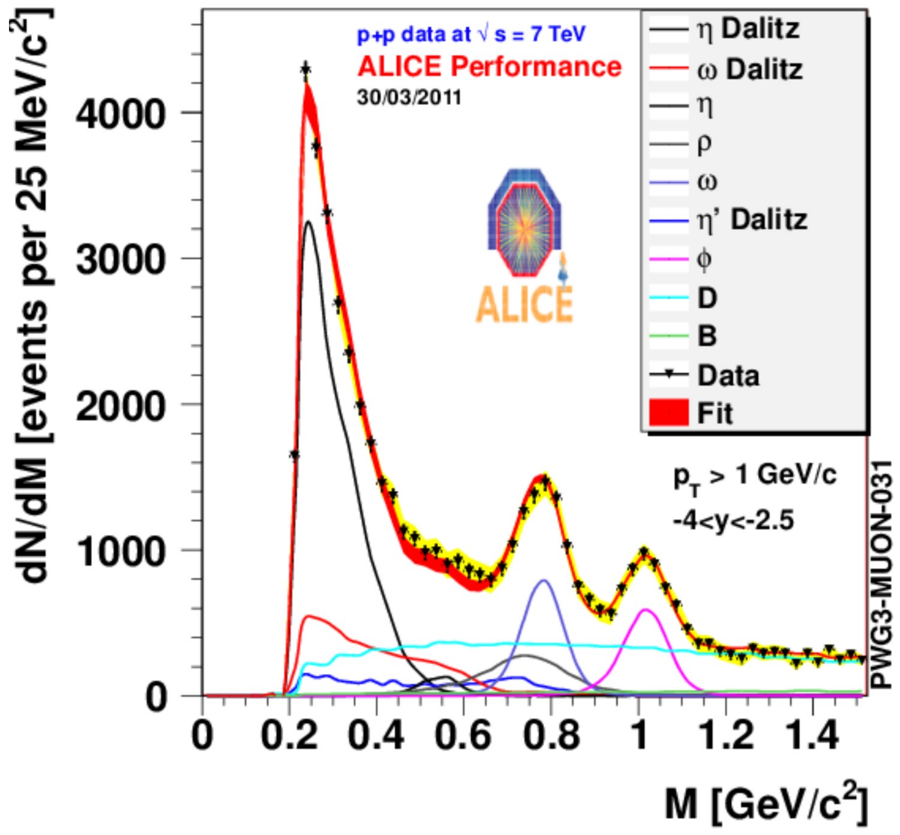


Muon PID

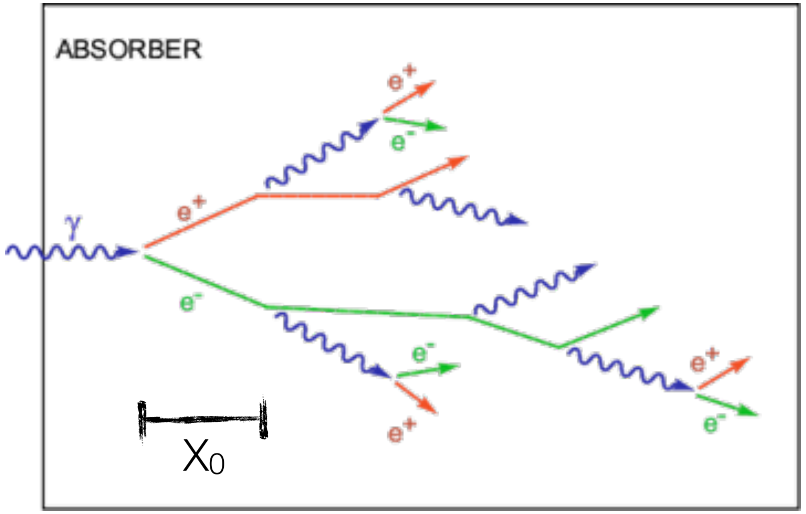


Basic principle of the Dimuon spectrometer: an absorber to filter the background, a set of tracking chambers before, inside and after the magnet and a set of trigger chambers.

Nuclear Physics A 00 (2021)

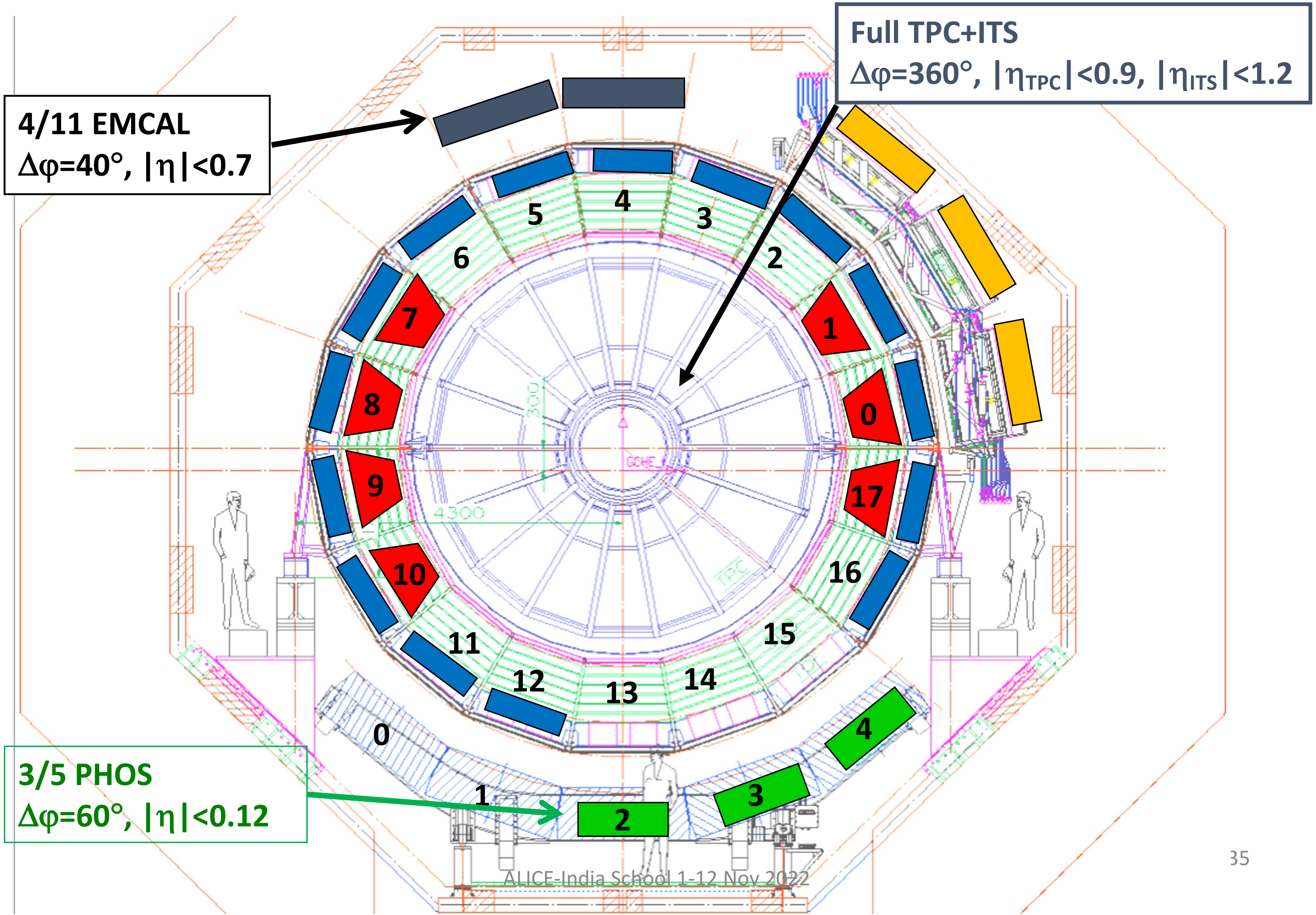


γ-π^0 Detection



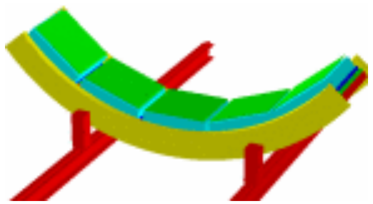
Electromagnetic shower in PHOS and EMCAL for photons and electrons

ALICE setup for 2010



Calorimeters: PHOS and EMCAL

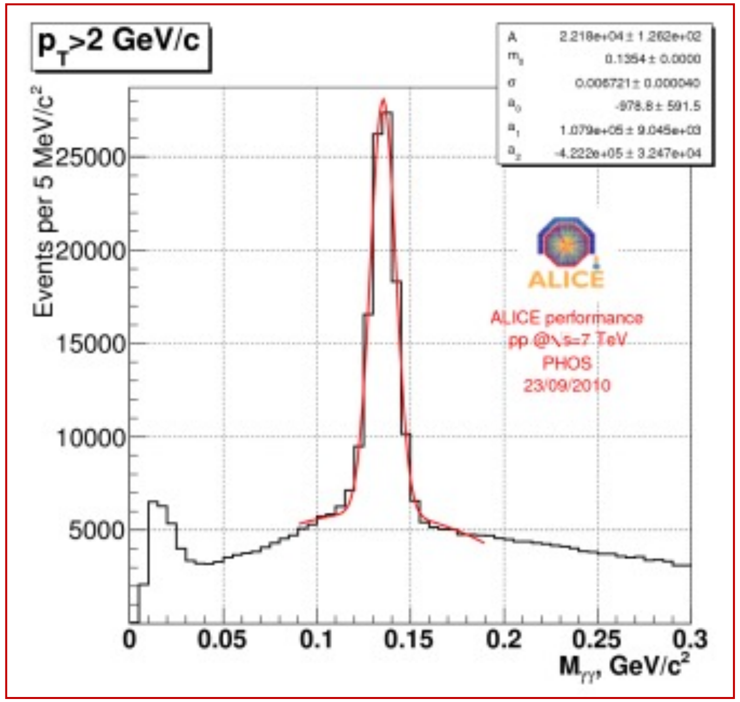
PHOS



σ_E/E (%) $\sqrt{\left(\frac{1.3}{E}\right)^2 + \frac{3.3^2}{E} + 1.12^2}$

σ_x (mm) $\sqrt{\frac{3.26^2}{E} + 0.44^2}$

R_{ip} (cm) 460

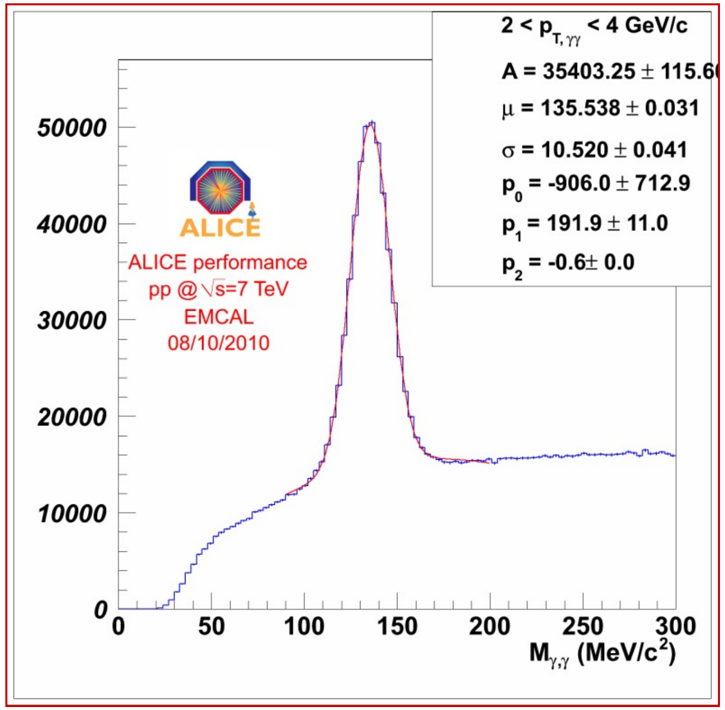


EMCAL

σ_E/E (%) $\sqrt{\left(\frac{1.7}{E}\right)^2 + \frac{11.3^2}{E} + 4.8^2}$

σ_x (mm) $1.5 + \frac{5.3}{\sqrt{E}}$

R_{ip} (cm) 428



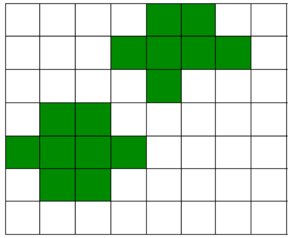
γ-π^0 discrimination

Three regions of analysis

increasing p_T

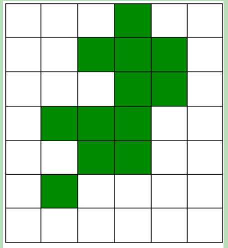
well separated clusters
➔ invariant mass analysis

< 15 GeV/c in EMCal
< 30 GeV/c in PHOS



merged clusters
not spherical
➔ shower shape analysis

5 - 40 GeV/c in EMCal
30 - 100 GeV/c in PHOS

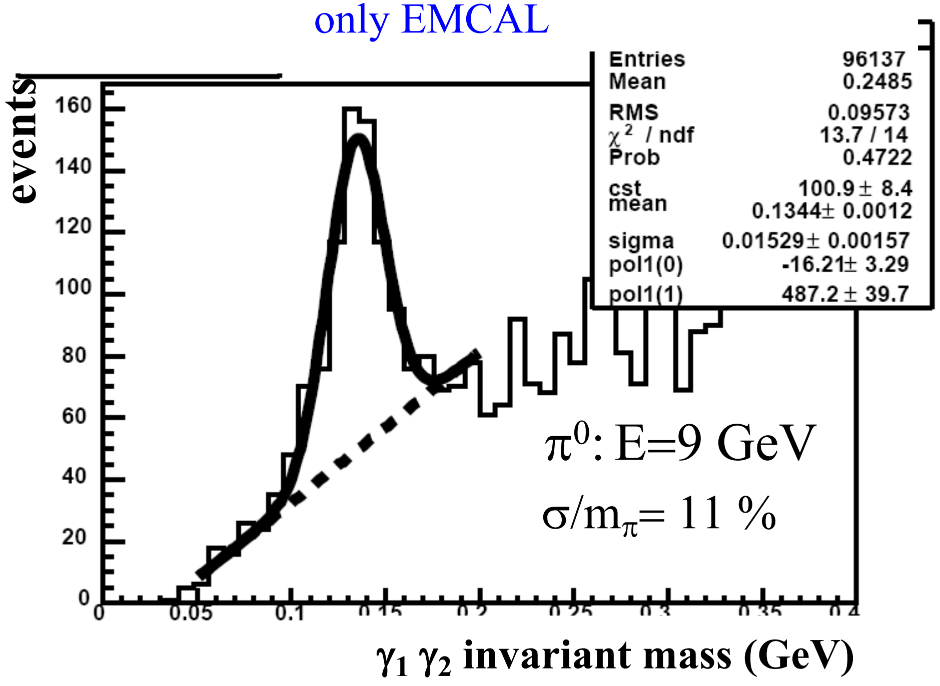


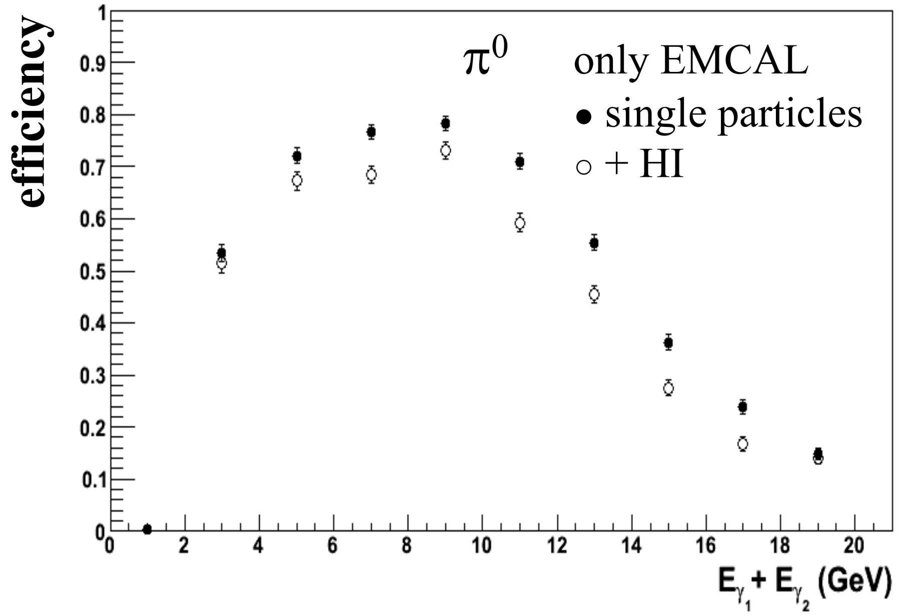
Opening angle << 1 cell
all π^0's at this energy are in jets
➔ isolation cut

> 40 GeV/c only method in EMCal

π^0 reconstruction via invariant mass

simulation: single particles+HI
only EMCAL

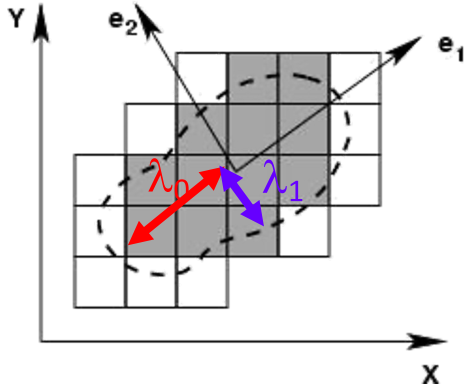




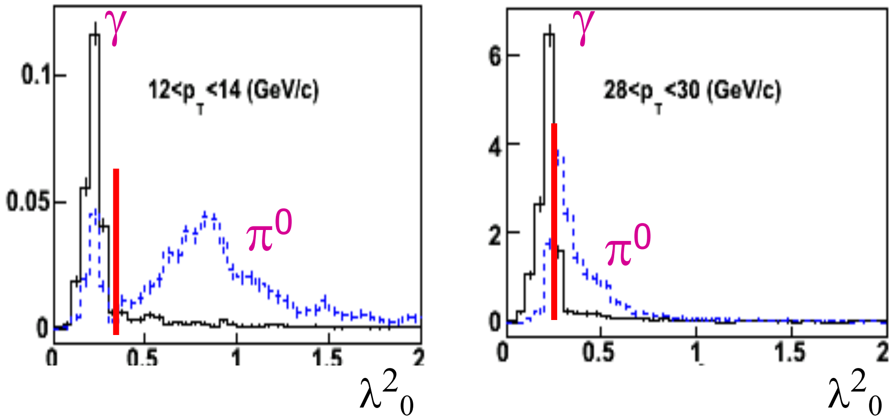
→ effect of the HI environment: efficiency decreases (<10%)
→ measurement with more than 10% efficiency up to 15 GeV/c

Particle identification with the calorimeters

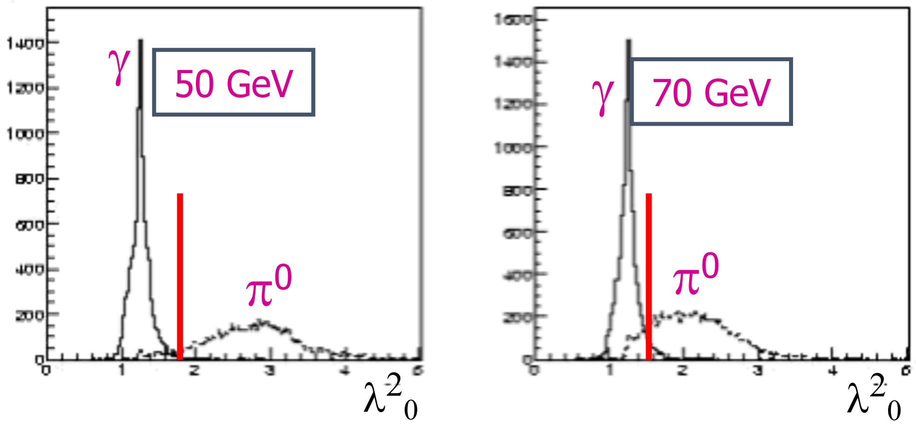
- Different particles produce showers of different shapes.
- One of the most sentitive parameter is the main axis of the shower ellipse λ_0
- **Identification probability of photons in pp collisions close to 90%, in PbPb around 60-70%**
- **Overlap of π^0 decay photons can be rejected in PHOS for 30<E<100 GeV and in EMCal for 5<E<40 GeV.**



EMCal

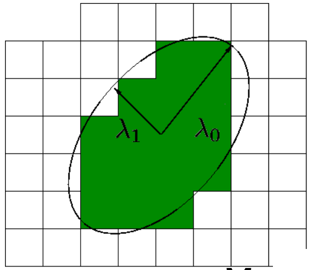


PHOS



ALICE-INT-2005-016, ALICE PPR vol II

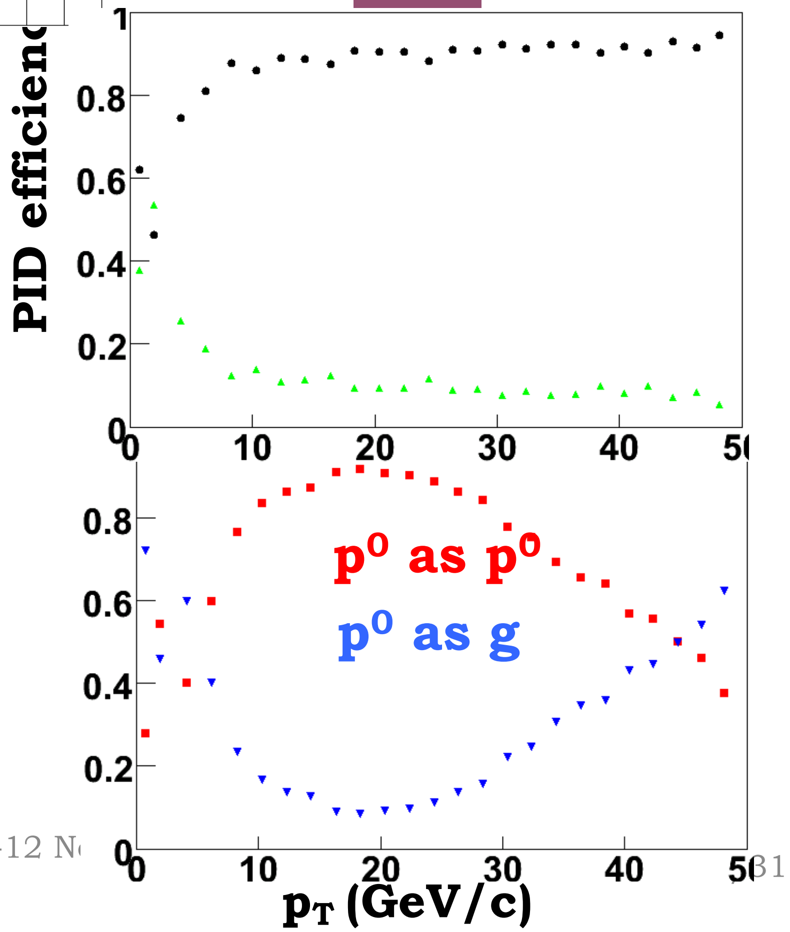
γ-π^0 discrimination in EMCal: Shower Shape Analysis

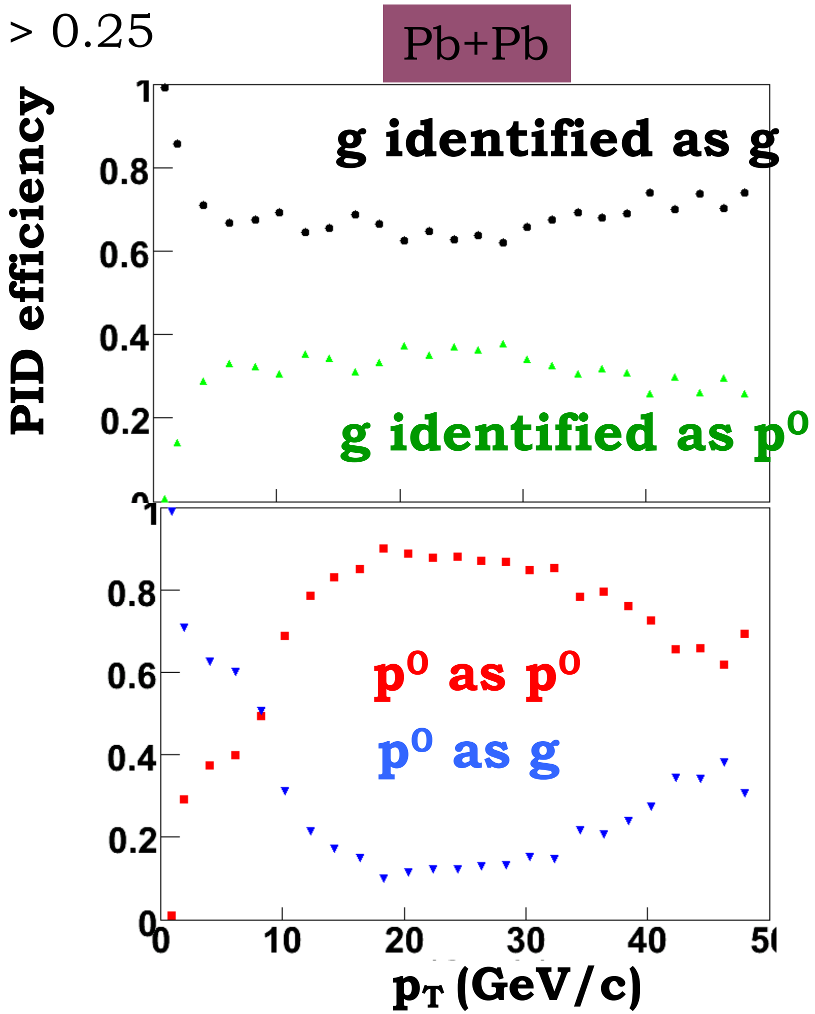


Uniform g and p^0 distributions, weighted to match
INCNLO predictions

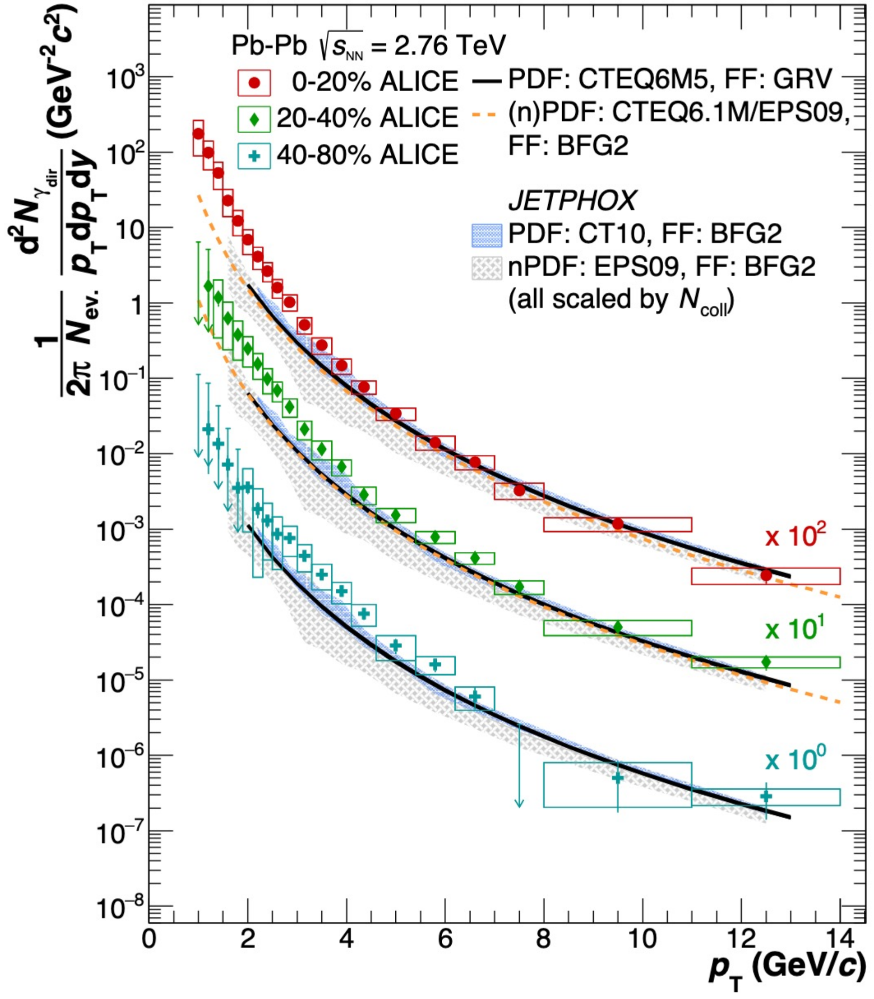
identified g: $l_0^2 < 0.25$

identified p^0: $l_0^2 > 0.25$



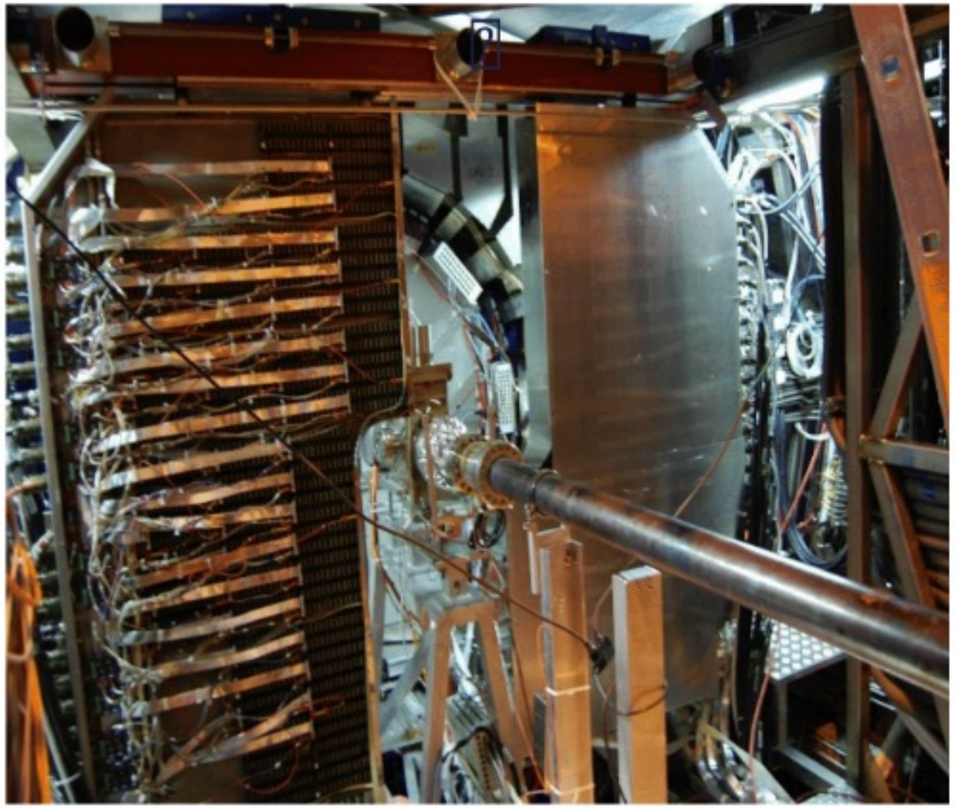


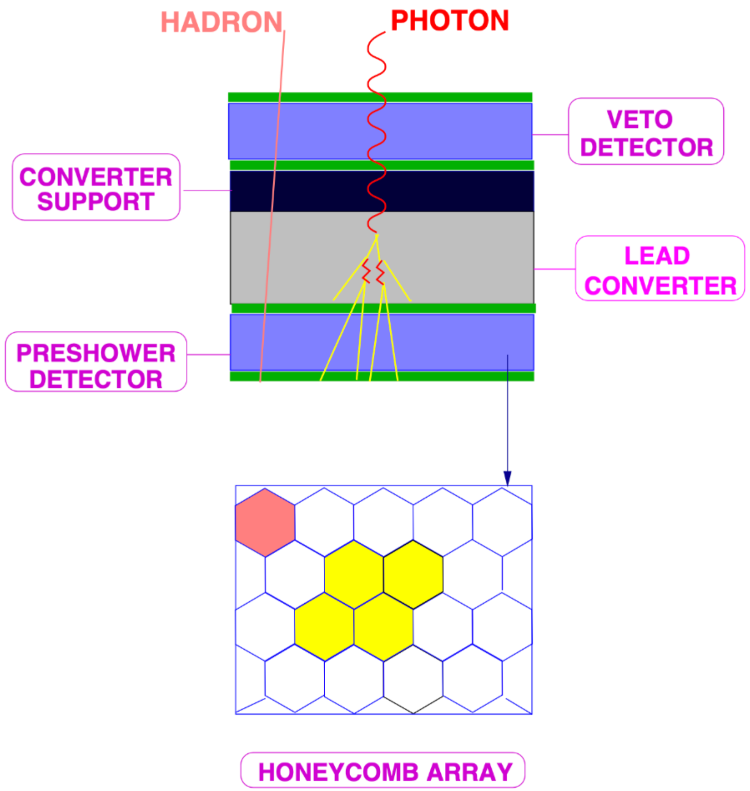
Direct photon x-section in Pb-Pb using PHOS



Phys. Lett. B 754 (2016) 235-248

Photon Multiplicity detector (PMD)





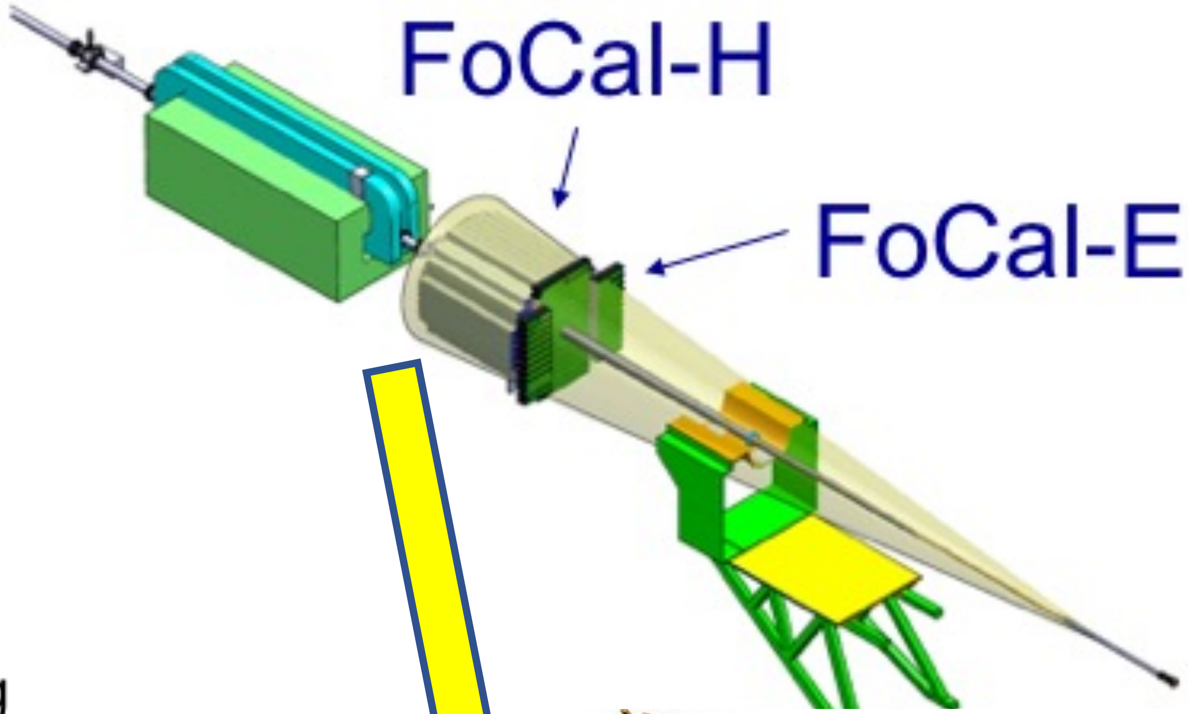
CERN-LHCC-99-32, CERN-OPEN-2000-184

FOCAL detector to be installed in the similar acceptance to that of the PMD

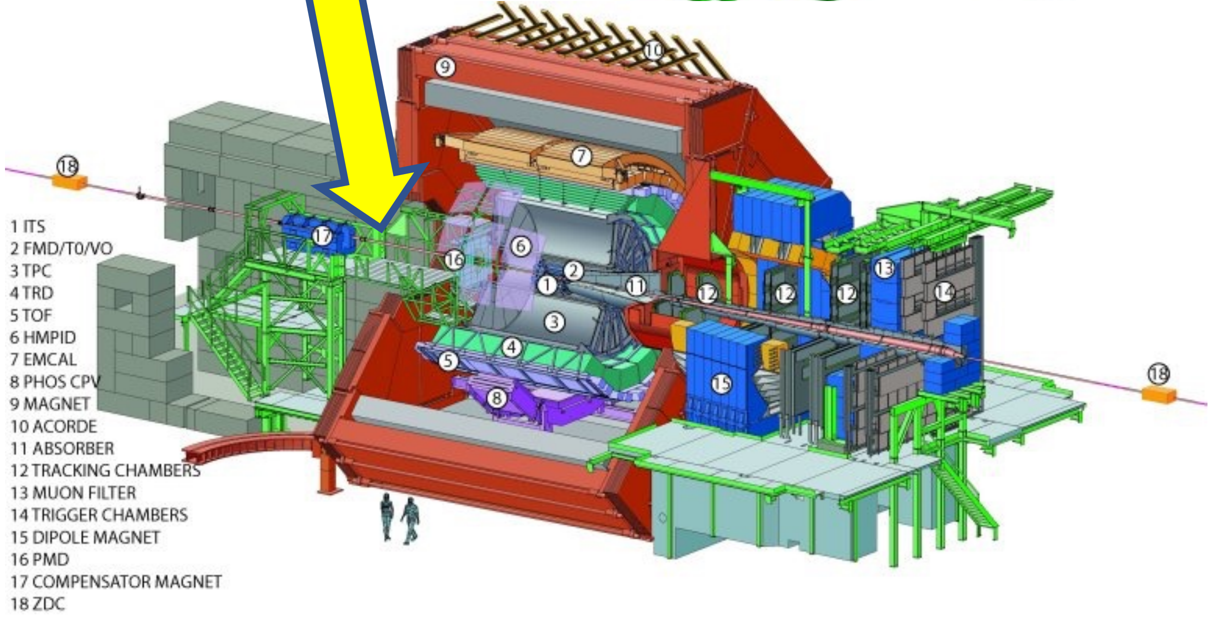
FoCal (ALICE FOrward CALorimeter)

3.5< η <5.5
7.0m from IP

small-x physics



FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0
FoCal-H: conventional Cu-Sc sampling calorimeter for photon isolation and jets



FOCAL Lecture : Ganesh Tambave

Summary

- An overview of PID techniques used in ALICE is given
- PID for charged tracks :
- PID for neutral particles :

ALICE analysis and PID lecture : Prottay Das

ALICE references :

For details : TDR of the respective detector contain complete picture of the detector principle and proposed capabilities

Many contents and slides taken from :

C. Zampolli : Incontri di Fisica delle Alte Energie – IFAE 27-29 Aprile, 2011, Perugia

Italo-Hellenic School of Physics 2006

The Physics of LHC: theoretical tools and experimental challenges

Olav Ullaland
PH Department, CERN

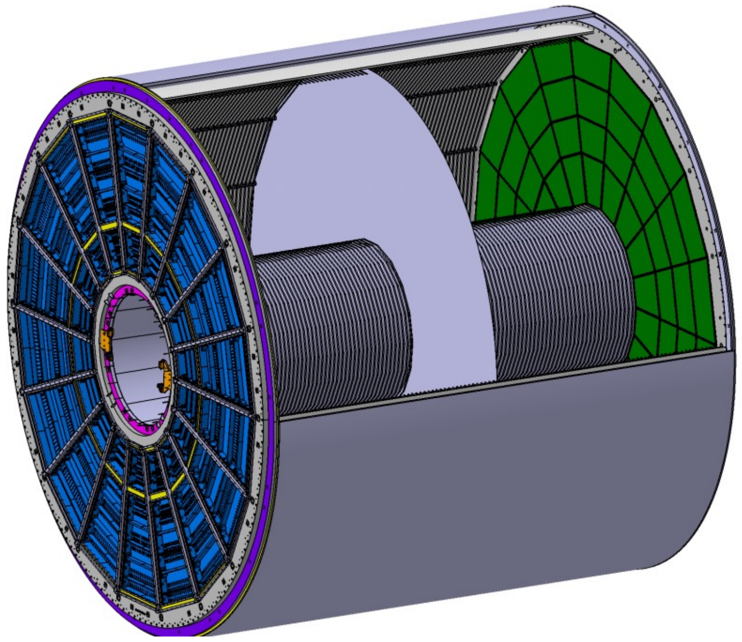
esipap
European School of Instrumentation in Particle & Astroparticle Physics

Marco Delmastro

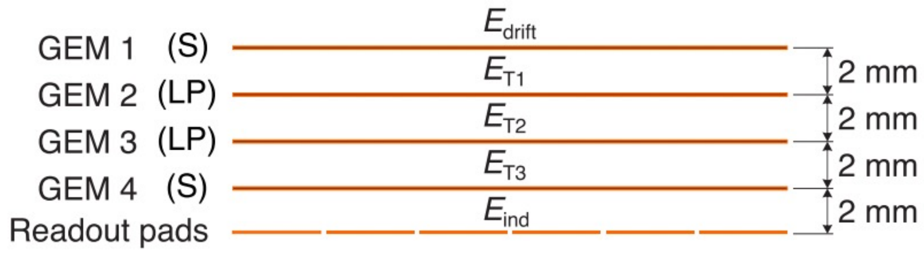
Particle ID in ALICE   Silvia Arcelli

Particle Identification in STAR : Chitrasen Jena

ALICE TPC Upgrade



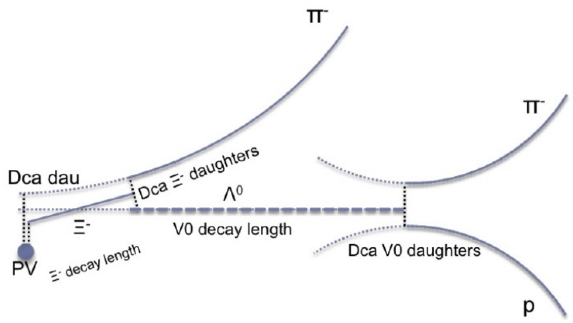
- ALICE upgrade is to exploit the increased Pb–Pb luminosity delivered by the LHC
  A minimum-bias interaction rate of up to 50 kHz
- Replacement of the MWPC-based readout chambers by Gas Electron Multipliers (GEMs)
- GEM detectors arranged in stacks containing four GEMs each, and continuous readout electronics based on the SAMPA chip
- The selected gas, Ne-CO_2-N_2 (90-10-5) provides robustness against primary discharges.
- Upgrade of the ALICE TPC was completed in 2020.



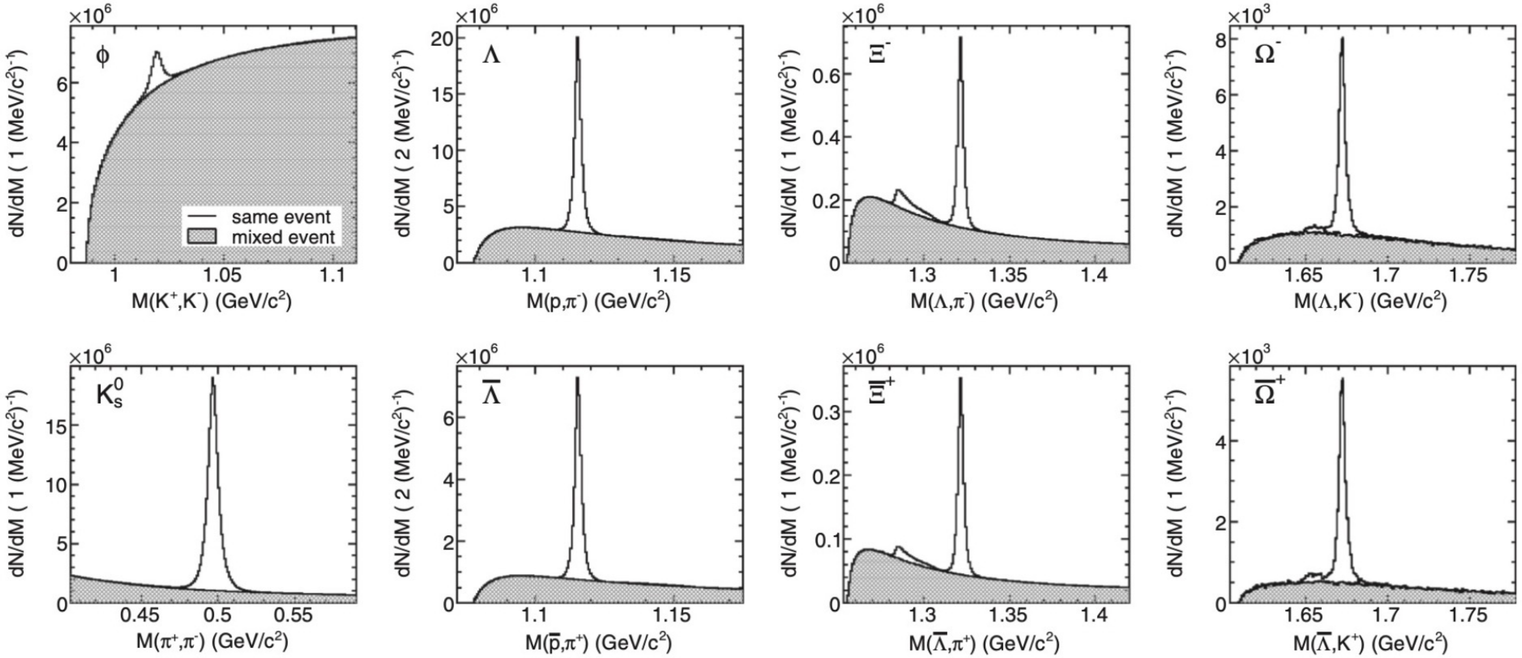
arXiv:2012.09518v2

Reconstruction of (multi-)strange hadrons

- $K_s^0 \to \pi^+ + \pi^-$ (69.2%)
- $\phi \to K^+ + K^-$ (49.2%)
- $\Lambda(\bar{\Lambda}) \to p + \pi^-(\bar{p} + \pi^+)$ (63.9%)
- $\Xi^-(\bar{\Xi}^+) \to \Lambda + \pi^-(\bar{\Lambda} + \pi^+)$ (99.887%)
- $\Omega^-(\bar{\Omega}^+) \to \Lambda + K^-(\bar{\Lambda} + K^+)$ (67.8%)



$$m_{inv} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}$$



Phys. Rev. C 88, 014902 (2013)

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