Light flavour hadron production in p-Pb collisions in ALICE at the LHC

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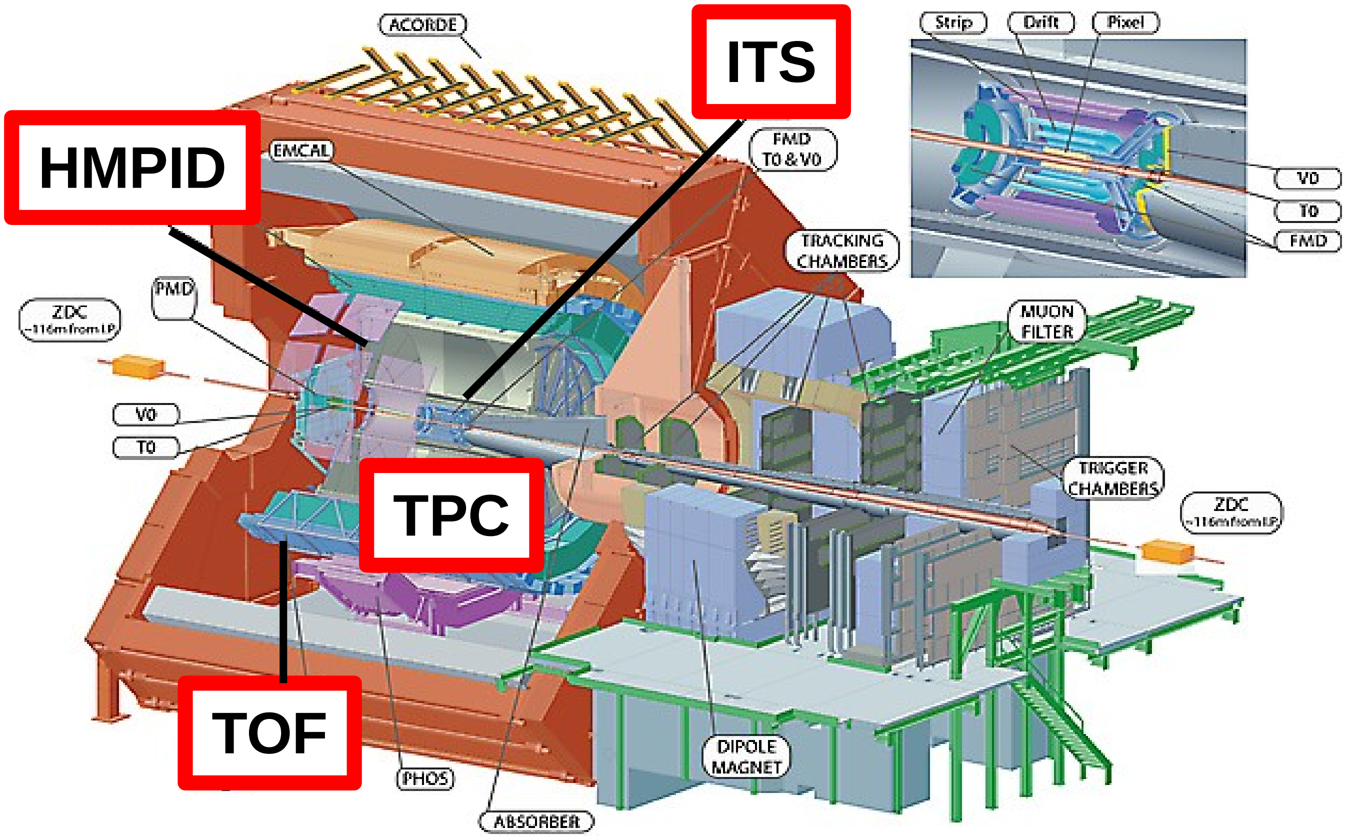
ALICE

INFN Istituto Nazionale di Fisica Nucleare

Outline

- Introduction
  - ALICE detector, PID, pp, p-Pb and Pb-Pb data samples
- Results discussed in this talk:
  - Transverse momentum distributions (π, K, K^0_S, p, Λ)
  - Particle ratios
  - $\langle p_T \rangle$ vs. $dN_{ch}/d\eta$
  - Blast-wave analysis
- Summary and Conclusions

The ALICE detector

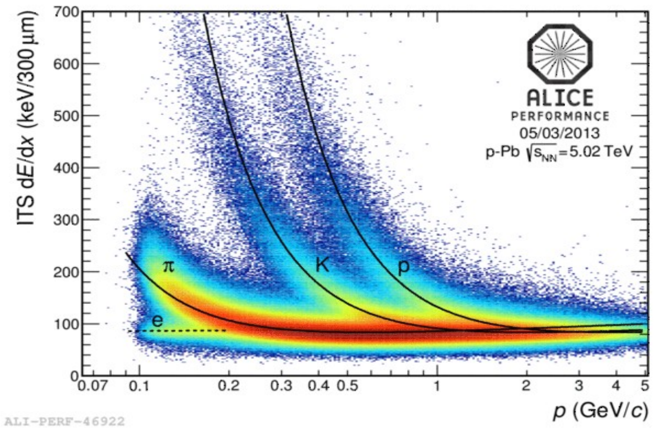


The ALICE detector uses all the known PID techniques

- dE/dx
- Time-of-flight
- Transition radiation
- Cherenkov radiation
- Calorimetry
- Muon filters
- Topological decays

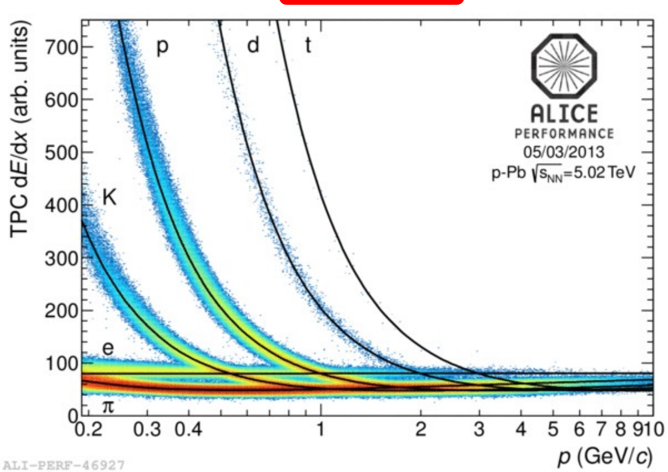
The central barrel detectors are operated in a 0.5 T solenoidal field

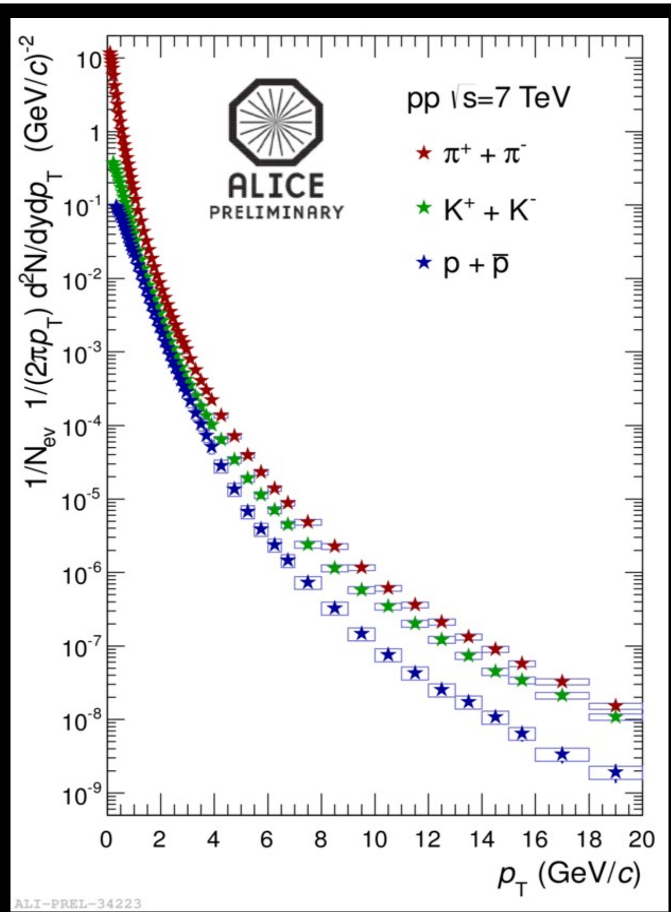
PID Central barrel



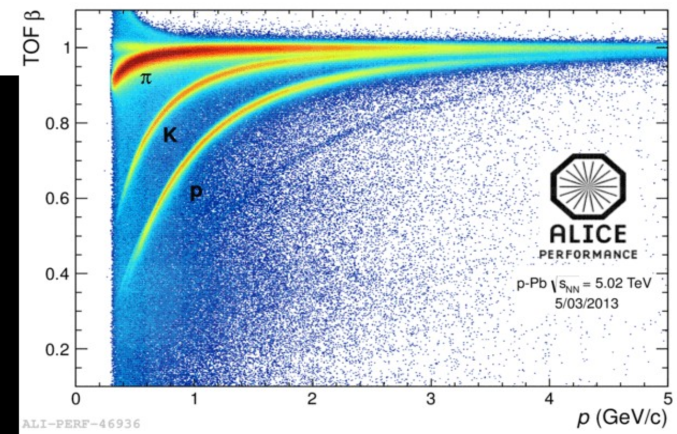
ITS

TPC



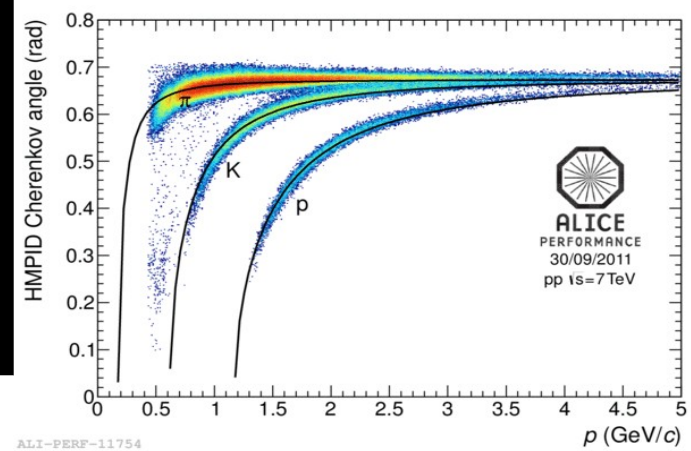


PID from 100 MeV/c to 20 GeV/c



TOF

HMPID

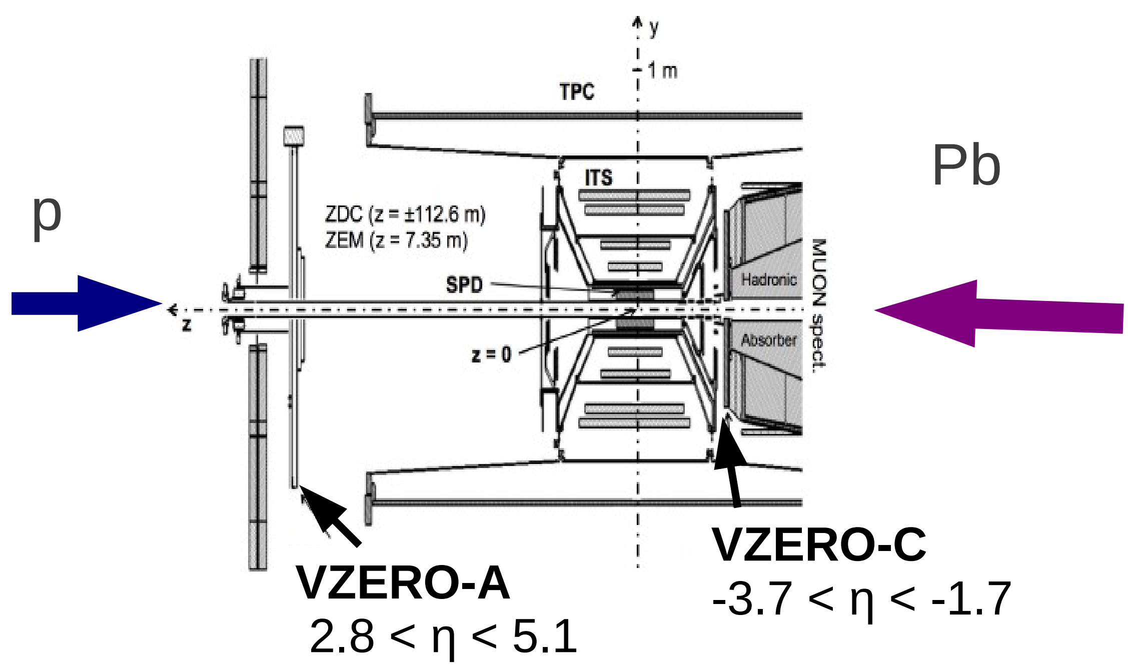


pp, p-Pb and Pb-Pb details

- $\sqrt{s_{pp}}$ = 7. TeV (2010, 2011)
- $\sqrt{s_{Pb\text{-}Pb}}$ = 2.76 TeV (2010, 2011)
- $\sqrt{s_{p\text{-}Pb}}$ = 5.02 TeV (2012, 2013)
  - Asymmetric energy/nucleon in the beams → the nucleon-nucleon center-of-mass system was moving in the laboratory frame with a rapidity of y_{LAB}^{CMS} = -0.465 in the direction of the proton beam

Centrality/Multiplicity selection:

- In pp collisions:
  - tracklets + tracks estimator
- In Pb-Pb collisions:
  - VZEROM (VZERO-A + VZERO-C) (ALICE arXiv:1301.4361)
- In p-Pb collisions:
  - correlation between impact parameter and multiplicity is not as straightforward as in Pb-Pb (VZERO-A chosen)



VZERO (Scintillator hodoscopes)
trigger, beam-BKG rejection

pp, p-Pb and Pb-Pb details

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Centrality/Multiplicity selection:

- In pp collisions:
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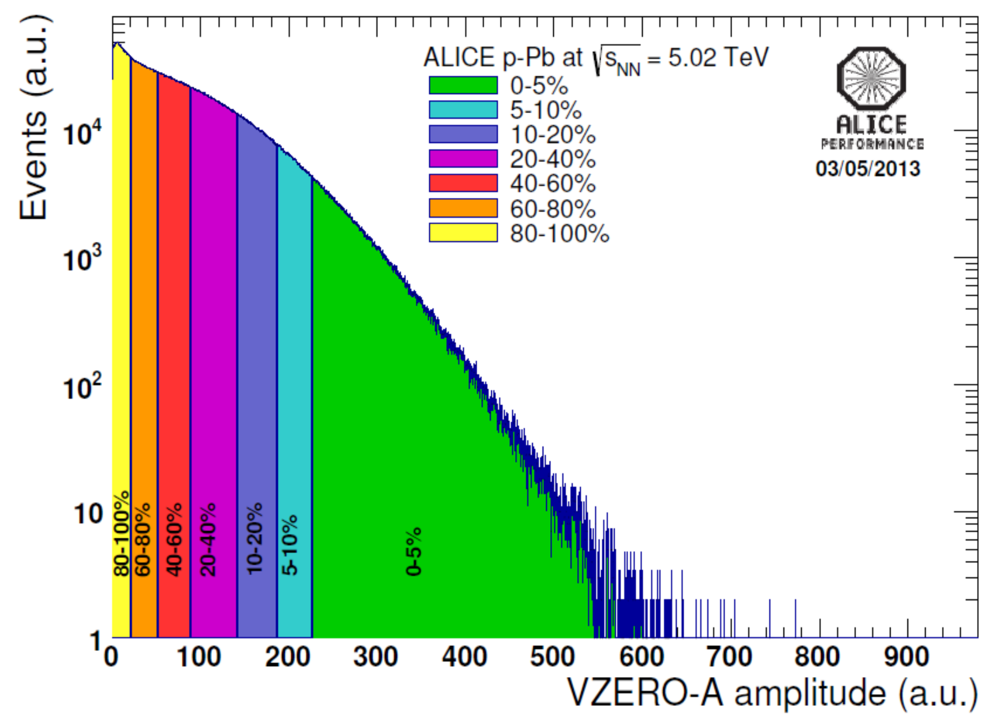
- In Pb-Pb collisions:
  - VZEROM (VZERO-A + VZERO-C) (ALICE arXiv:1301.4361)
- In p-Pb collisions:
  - Seven p-Pb multiplicity event classes based on the amplitude of the signal of the VZERO-A detector (A is the direction of Pb beam)



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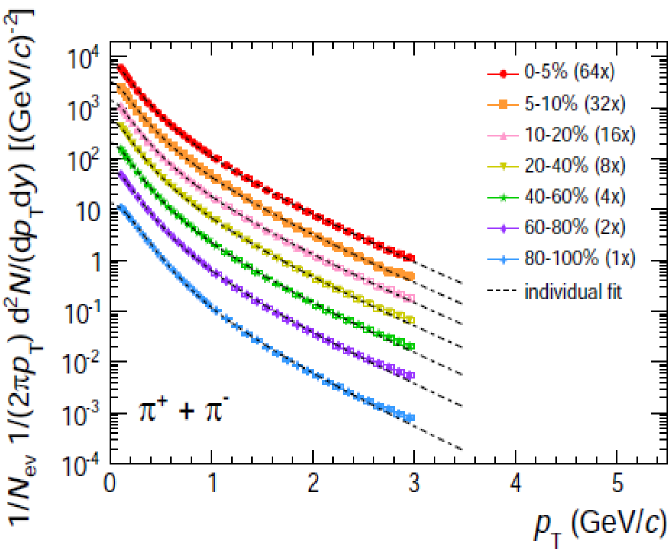
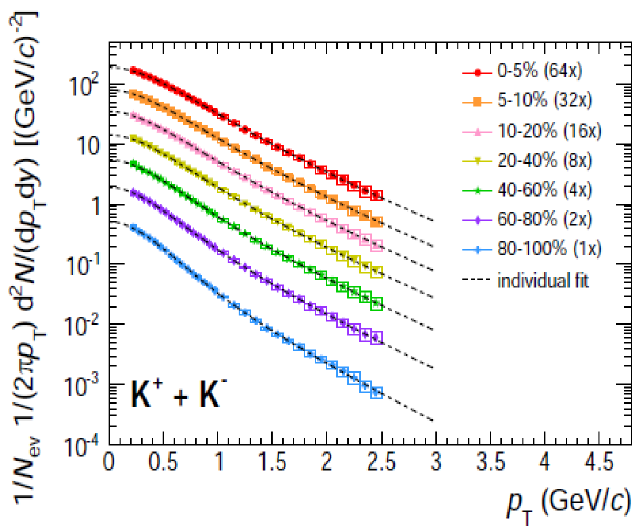
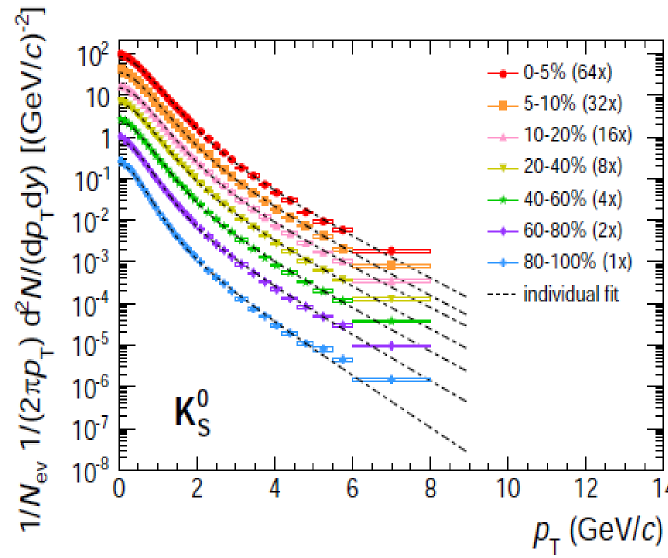
See talk by A. TOIA

Transverse momentum distributions in p-Pb







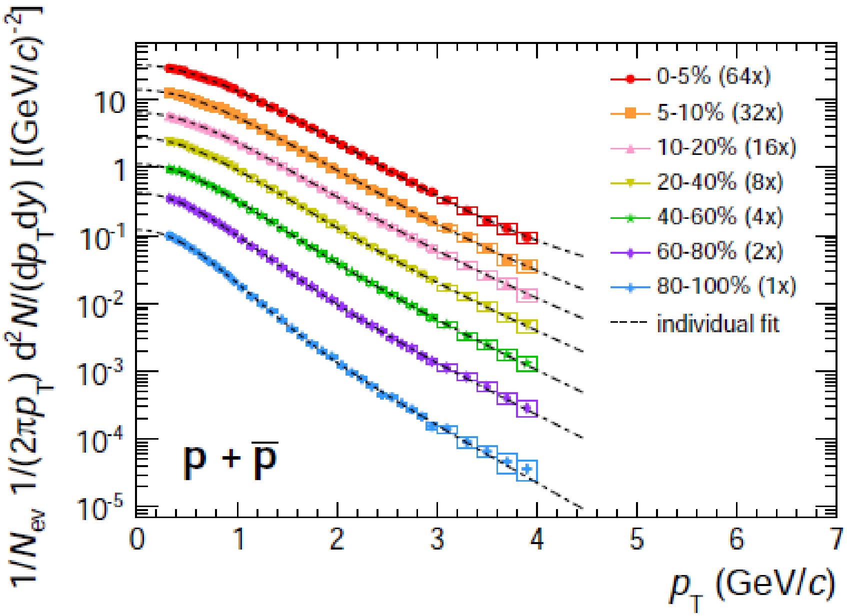
K^0_s were identified exploiting their V^0 weak decay topology in the channel $K^0_s \rightarrow \pi\pi$

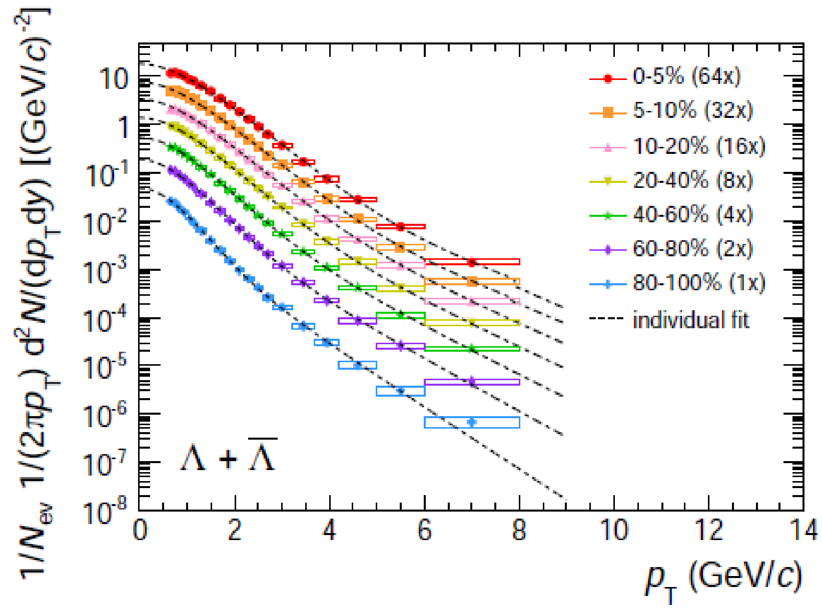
Transverse momentum distribution in several VZERO-A multiplicity classes ($0 < y_{CMS} < 0.5$)

- The dotted lines represent individual Blast-Wave fits for low/high p_T extrapolation

arXiv:1307.6796, CERN-PH-EP-2013-135

Transverse momentum distributions in p-Pb



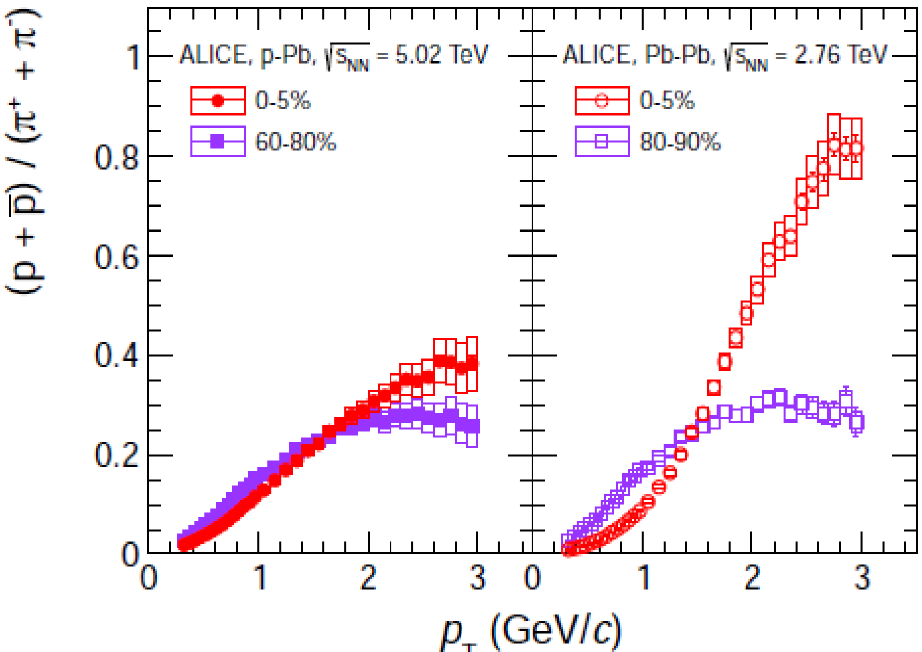


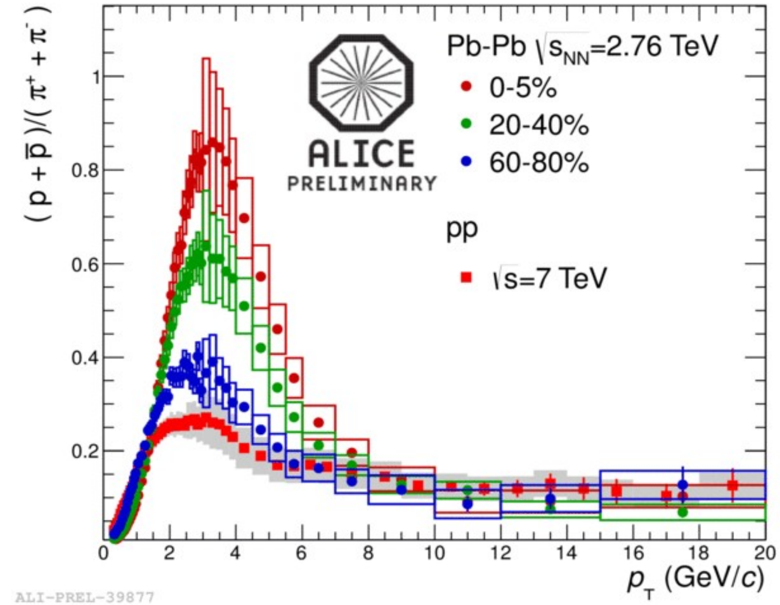
Λ were identified exploiting their V^0 weak decay topology in the channel $\Lambda \rightarrow p\pi$

arXiv:1307.6796, CERN-PH-EP-2013-135

The p_T distribution shows a clear evolution, becoming harder as the multiplicity increases (in particular for p and Λ). Increase of the slope at low p_T (similar in Pb-Pb) This trend is evident looking at the ratios, K/π, p/π, $\Lambda/K^0_S = (\Lambda+\text{bar}(\Lambda))/2K^0_S$ as a function of p_T

Particle ratios vs transverse momentum



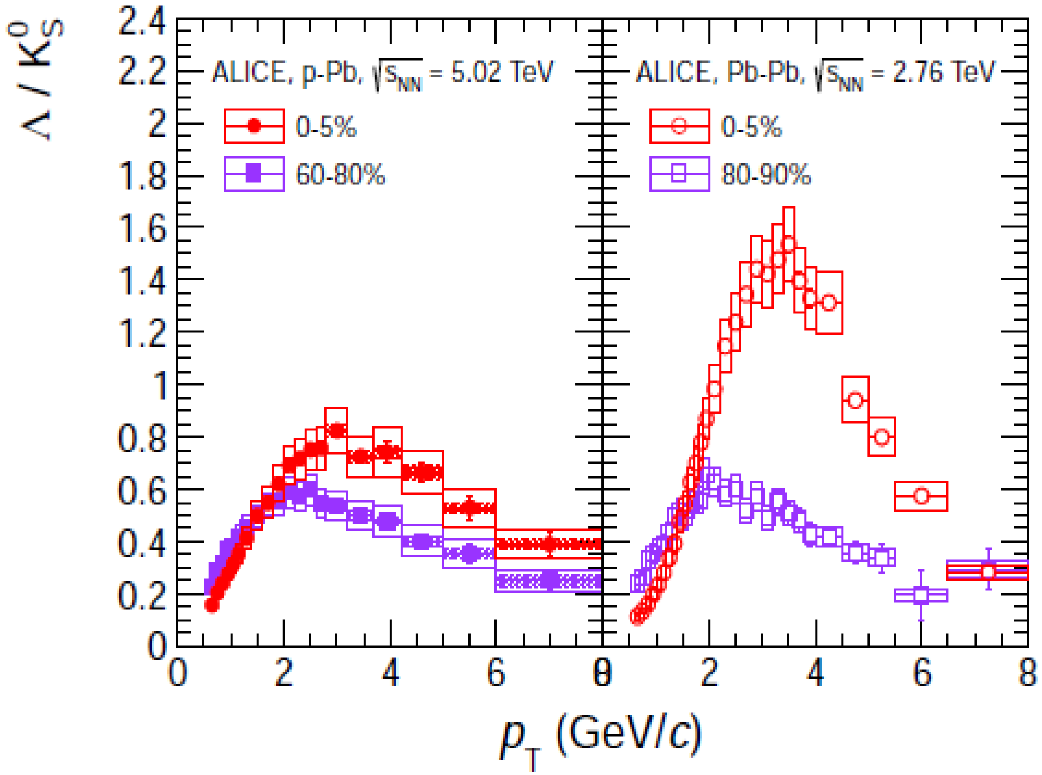


p/π vs p_T

- Similar behaviour as observed in Pb-Pb collisions
  - but much weaker: 0.8 in central Pb-Pb vs 0.4 in highest multiplicity p-Pb
- Significant increase at intermediate p_T with increasing multiplicity → Significant depletion in the low p_T region
- Stronger enhancement in p-Pb at p_T ~ 3 GeV/c than K/π
- pp and Pb-Pb at ~ 8 GeV/*c*: similar values (p-Pb analysis at higher p_T: work in progress)
  - Medium does not affect parton fragmentation (it occours into vacuum)?
- In Pb-Pb: collective flow and/or quark recombination?

arXiv:1307.6796, CERN-PH-EP-2013-135

Particle ratios vs transverse momentum

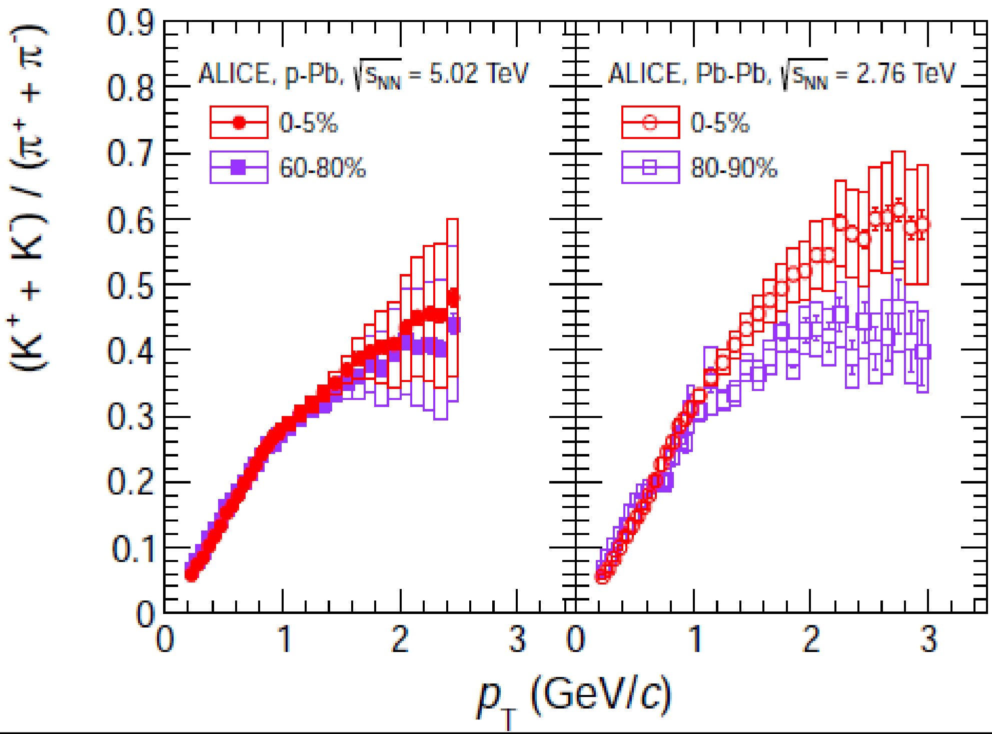


Λ/K^0_S vs p_T

- Similar behaviour as observed in Pb-Pb collisions (but much weaker)
- Significant increase at intermediate p_T with increasing multiplicity → Significant depletion in the low p_T region
- Stronger enhancement at p_T ~ 3 GeV/c than K/π
- In Pb-Pb: collective flow and/or quark recombination?

arXiv:1307.6796, CERN-PH-EP-2013-135

Particle ratios vs transverse momentum



K/π vs p_T

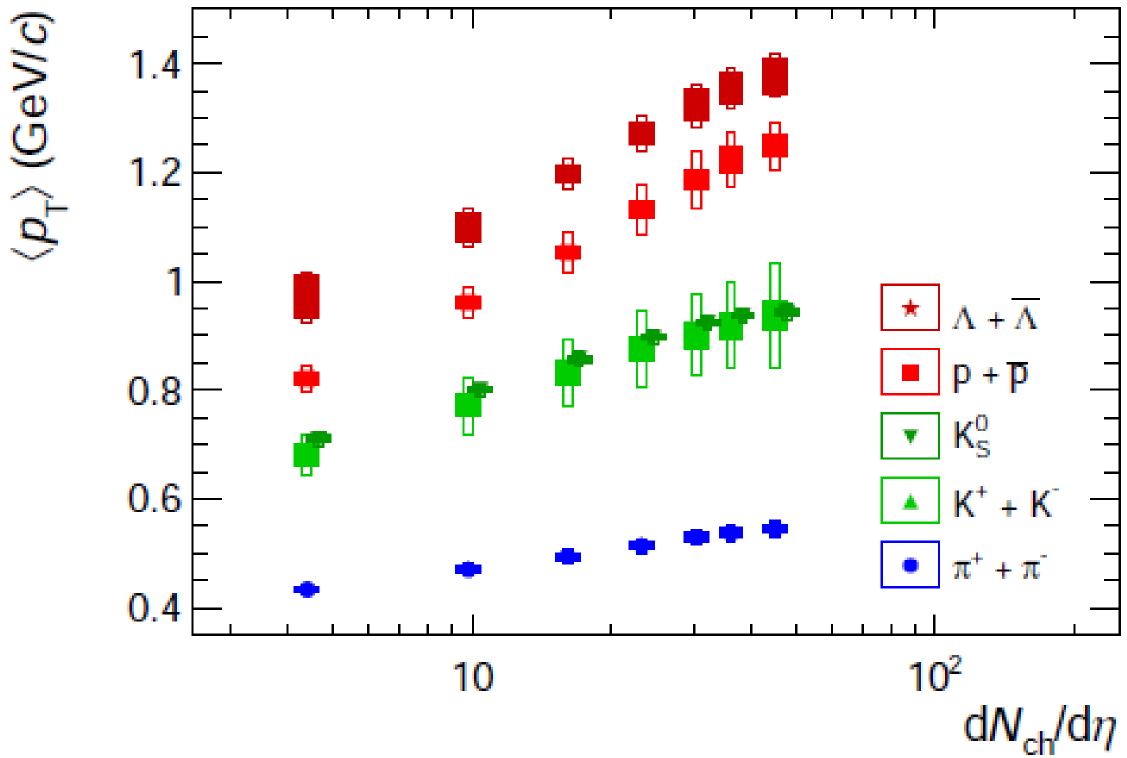
- Weak evolution with multiplicity in p-Pb → small increase at intermediate p_T with increasing VZERO-A multiplicity → corresponding small depletion in the low p_T region
- Similar behaviour as observed in Pb-Pb collisions

arXiv:1307.6796, CERN-PH-EP-2013-135

Note: systematic errors are largely correlated across multiplicity. Multiplicity uncorrelated errors are drawn as a band for p-Pb

Mean p_T vs. charged multiplicity in p-Pb

ALICE

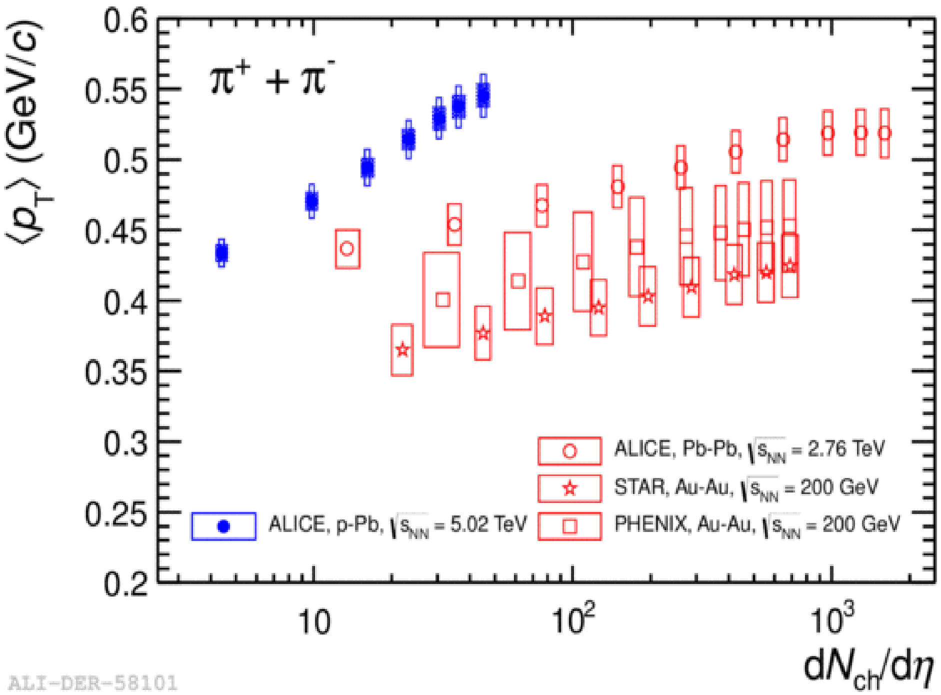


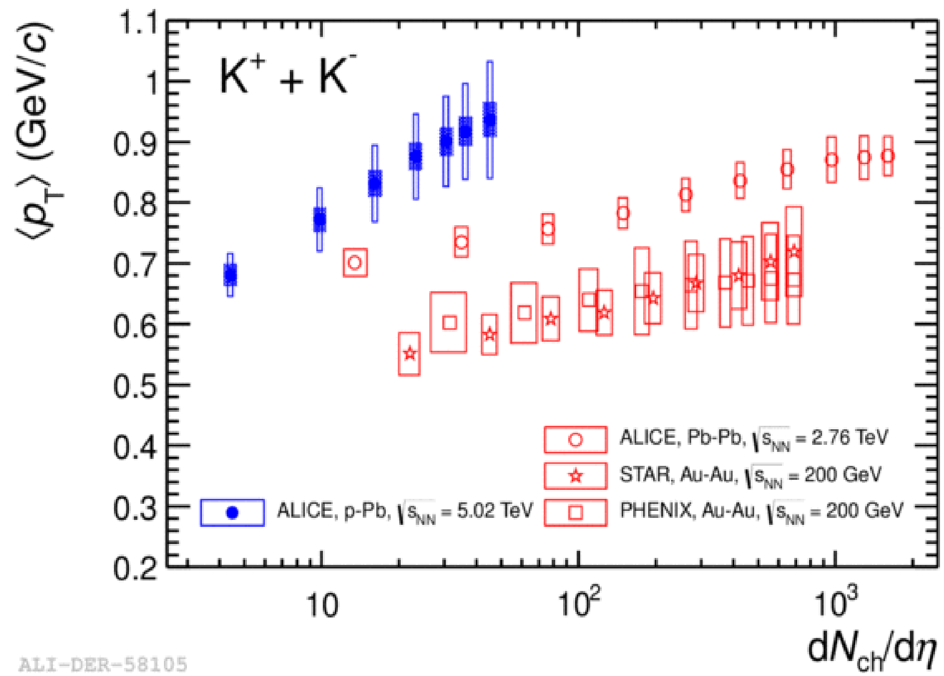
$<p_T>$ vs. $dN_{ch}/d\eta$

- Extrapolation: 0 - 10 GeV/c
- $<p_T>$ increases with multiplicity (stronger for heavier particles)
- Mass ordering: larger mass → larger $<p_T>$
- Trend already observed in Pb-Pb collisions as a function of the multiplicity

arXiv:1307.6796, CERN-PH-EP-2013-135

Mean p_T vs. charged multiplicity





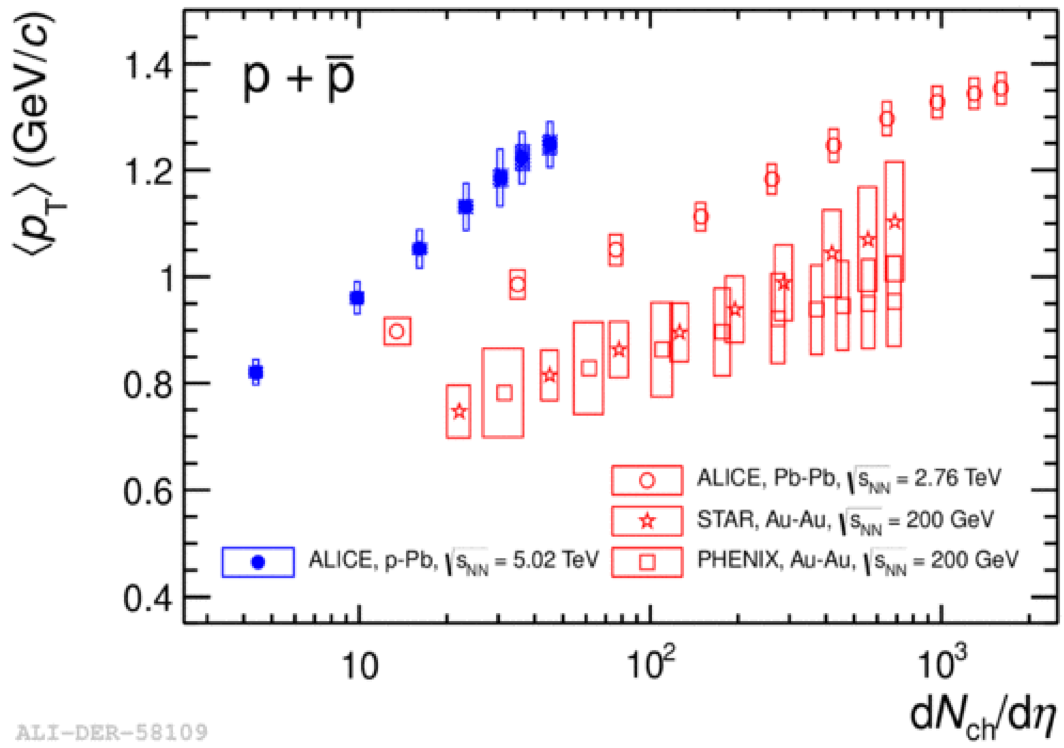
$\langle p_T \rangle$ vs. $dN_{ch}/d\eta$ (pions and kaons)

- Similar behaviour as in Pb-Pb → $\langle p_T \rangle$ increases with multiplicity
- p-Pb values higher than Pb-Pb for similar multiplicity → harder spectra
- relative increase (low/high multiplicity) similar to Pb-Pb

ALICE, arXiv:1303.0737 [hep-ex]
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)

arXiv:1307.6796, CERN-PH-EP-2013-135

Mean p_T vs. charged multiplicity



$\langle p_T \rangle$ vs. $dN_{ch}/d\eta$

- Protons show similar behaviour as pions and kaons
  - → $\langle p_T \rangle$ increases with multiplicity
  - → $\langle p_T \rangle$ higher than Pb-Pb for similar multiplicity

arXiv:1307.6796, CERN-PH-EP-2013-135

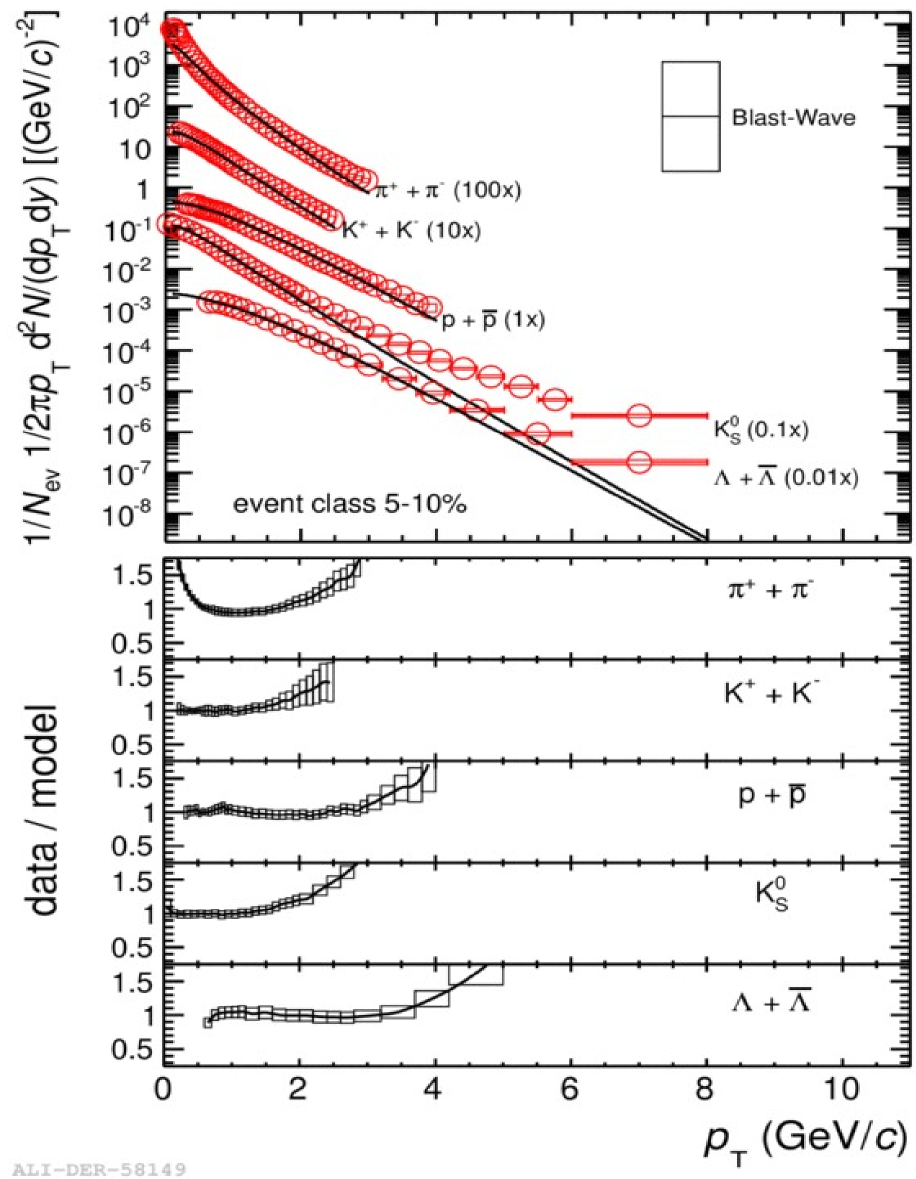
Blast-wave analysis

- Hydro-motivated Blast-wave model
  (assumption: locally thermalized medium, expanding collectively with a common velocity field and undergoing an instantaneous common freeze-out)
  Schnedermann, PRC 48, 2462 (1993)

- Simultaneous fits to all particles with 3 common parameters:
  - $\langle\beta_T\rangle$ radial flow
  - T_{fo} freezeout temperature
  - n velocity profile

- Global fit performed in the transverse momentum ranges:

- π → 0.5 – 1.0 GeV/*c*
- K → 0.2 – 1.5 GeV/*c*
- p → 0.3 – 3.0 GeV/*c*
- K^0_S → 0.0 – 1.5 GeV/*c*
- Λ → 0.6 – 3.0 GeV/*c*

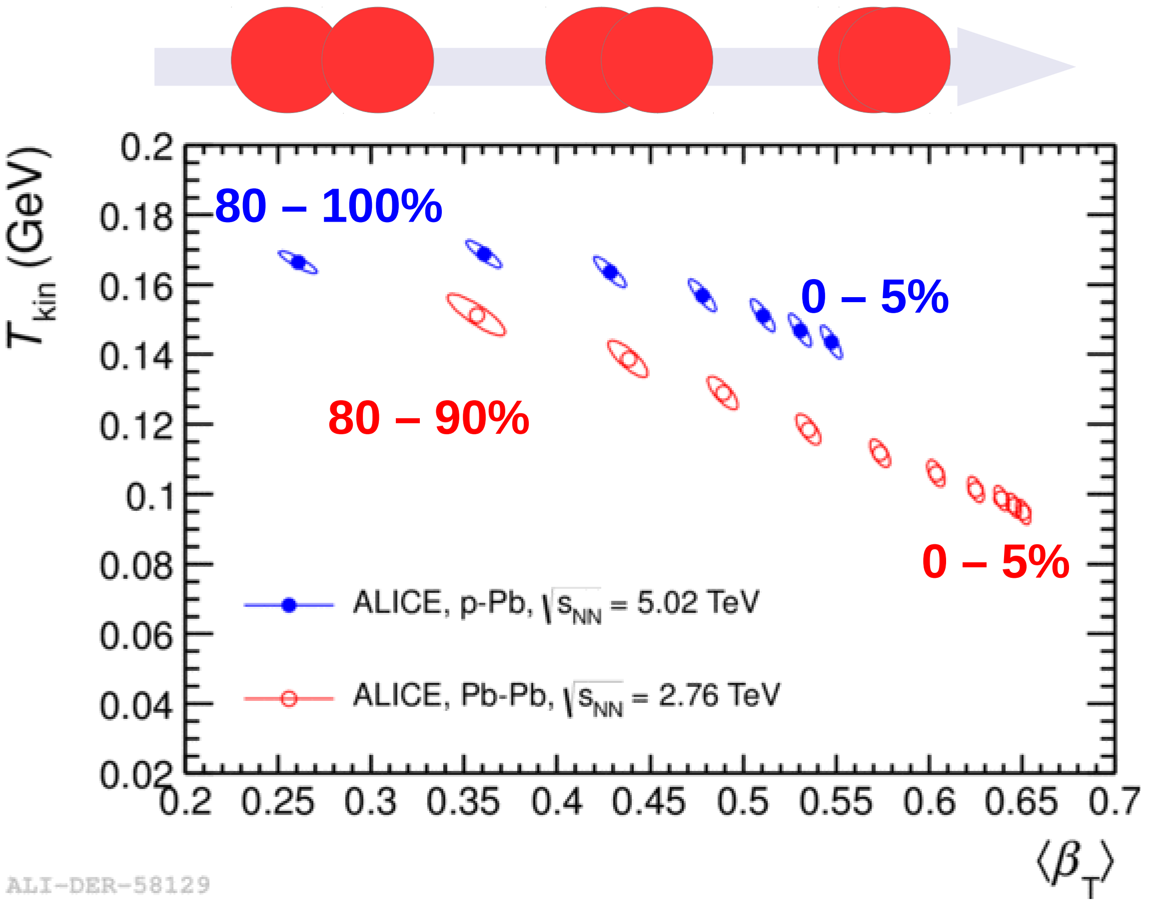


arXiv:1307.6796, CERN-PH-EP-2013-135

Blast-wave Parameters

Fit π / K / p / K^0_S / Λ

- No significant change excluding K^0_S, Λ
- T_{fo} is similar in p-Pb and Pb-Pb
- $\langle\beta_T\rangle$ larger for p-Pb for same multiplicity
- Pb-Pb: possible indication of more rapid expansion with increasing centrality
- p-Pb: Indicative of stronger collective flow for smaller system size?
  Shuryak, arXiv:1301.4470 [hep-ph]



arXiv:1307.6796, CERN-PH-EP-2013-135

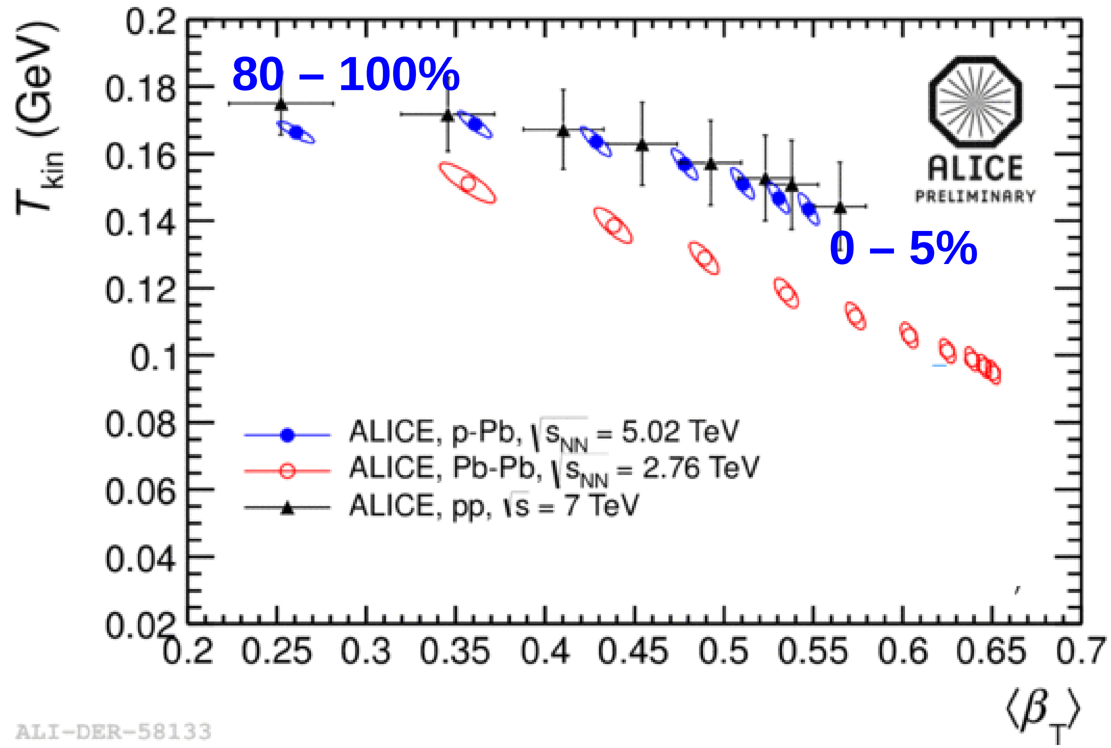
Caveat BW: the actual values of the fit parameters depend substantially on the fit range

Blast-wave Parameters

π/K/p Blast-wave analysis

- Applied to spectra from pp collisions selected in charged multiplicity measured in |η| < 0.8
- Slightly different global fit ranges used:
  - π → 0-5 – 1.0 GeV/*c*
  - K → 0.3 – 1.5 GeV/*c*
  - p → 0.5 – 2.5 GeV/*c*
- Behaviour similar in p-Pb and Pb-Pb

arXiv:1307.6796, CERN-PH-EP-2013-135



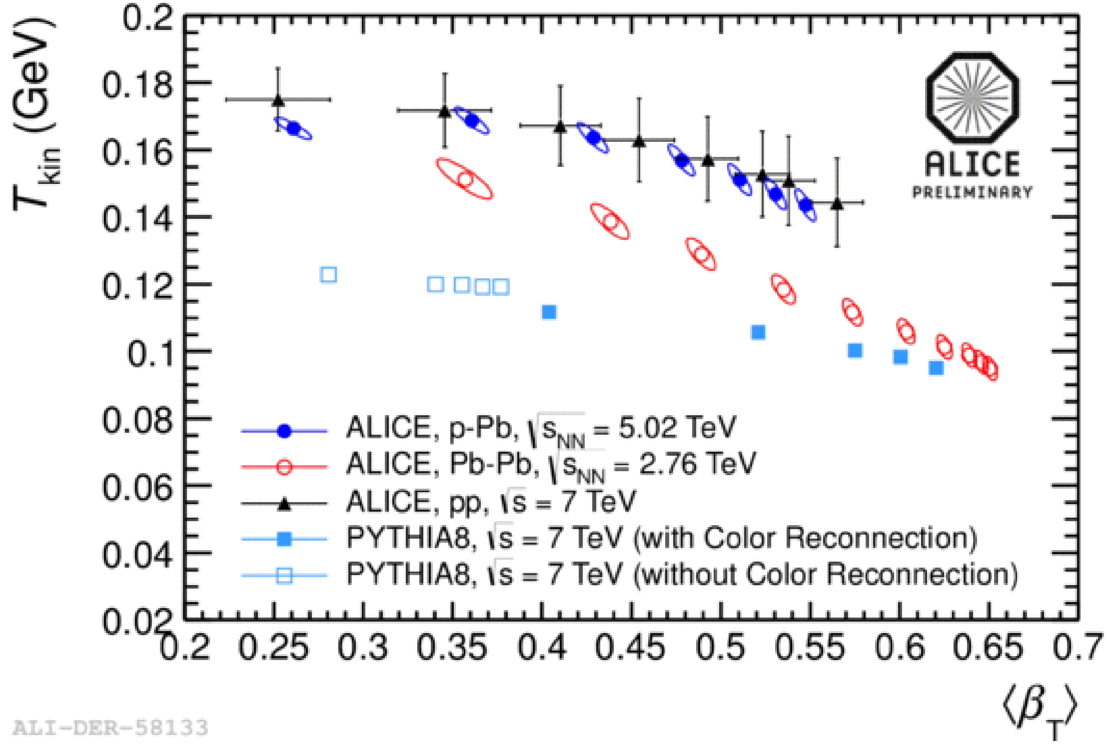
Caveat pp: multiplicity selection at mid rapidity (selection bias)

Blast-wave Parameters

π/K/p Blast-wave analysis

- Applied to output from the PYTHIA8 event generator with and without color reconnection (CR) (arXiv:1303.6326)
- This mechanism is necessary in PYTHIA tunes to describe the evolution of mean p_T with multiplicity in pp collisions.
- If CR enabled: shows the same qualitative behaviour.
  - <u>This model has no collective flow</u>

→ Other final state mechanisms (CR) can mimic the effect of radial flow.



See talk by P. CHRISTIANSEN

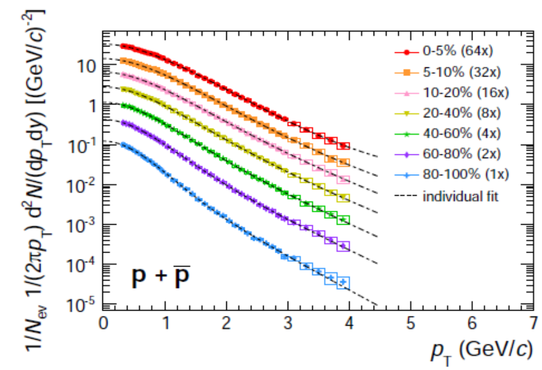
arXiv:1307.6796, CERN-PH-EP-2013-135

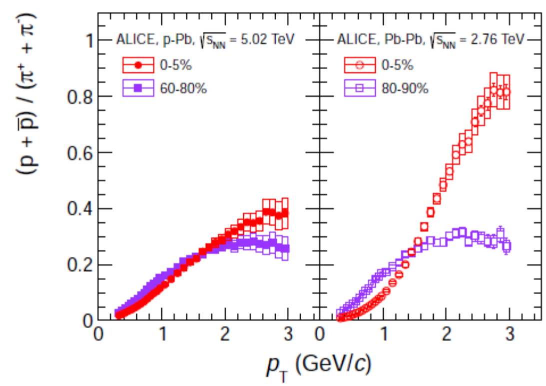
Summary and conclusions

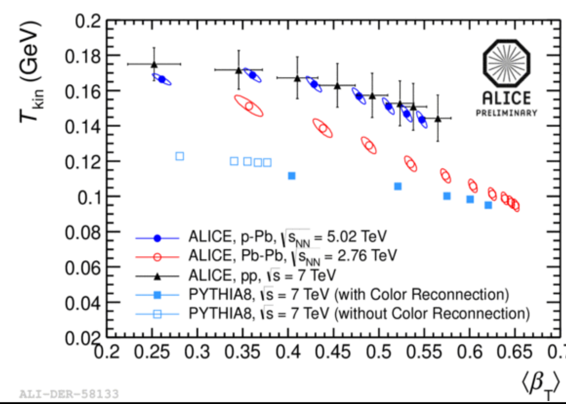
- ALICE has measured the transverse momentum distribution (π, K, K^0_S, p, Λ) in pp, p-Pb and in Pb-Pb collisions

- Hadron production vs multiplicity
  - Evolution of p/π and Λ/K^0_S vs p_T with $dN_{ch}/d\eta$ in p-Pb collisions
  - $\langle p_T \rangle$ increases with multiplicity, (p-Pb higher than Pb-Pb for same $dN_{ch}/d\eta$)

- Blast-wave model fits to pion, kaon and proton:
  - Similarities with Pb-Pb, pp (PYTHIA and data) shows the same trend.
  - Current results do not exclude hydro-like collective flow in p-Pb collisions
  - Other final state mechanisms (CR) can mimic the effect of radial flow

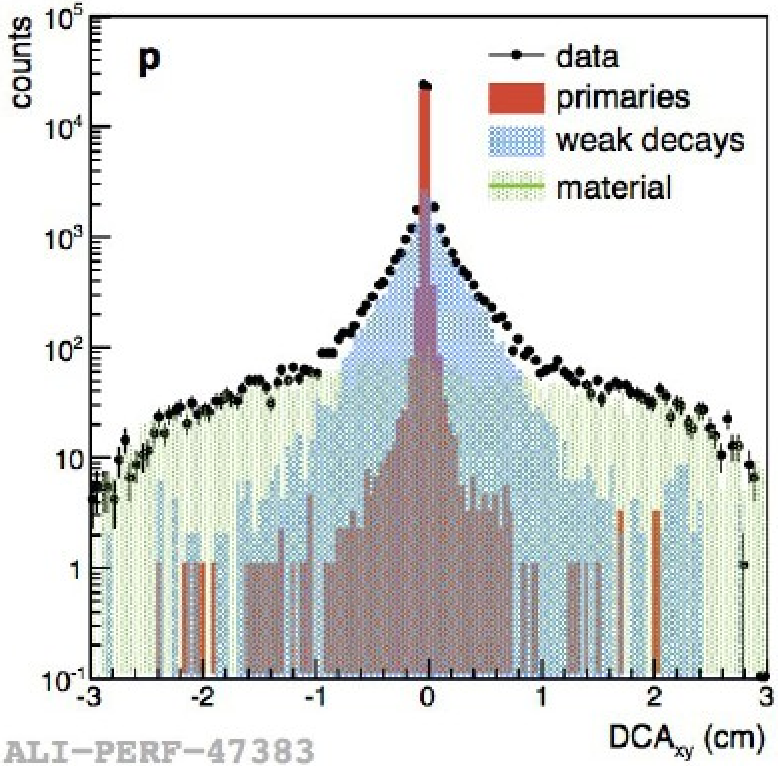


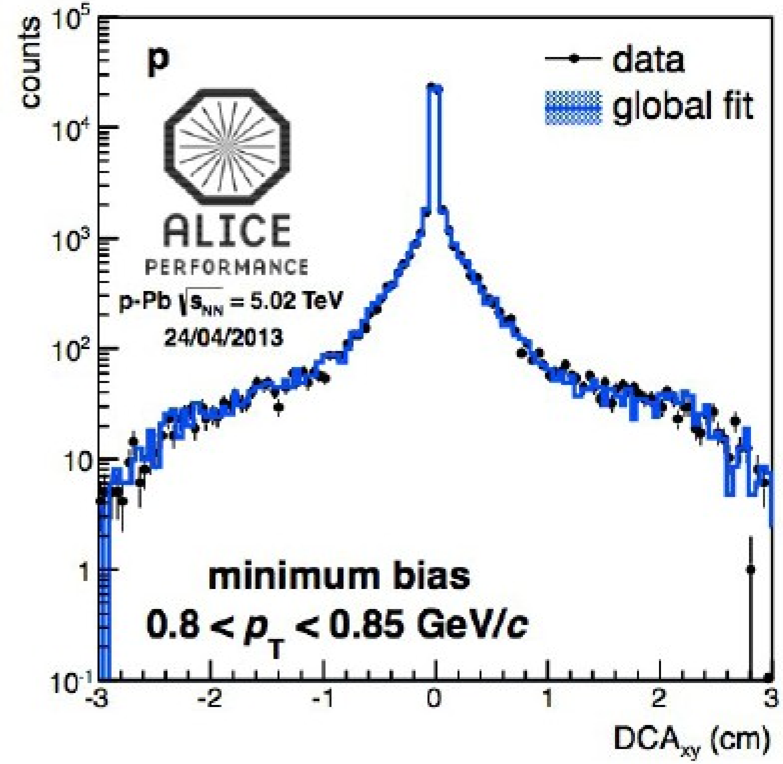




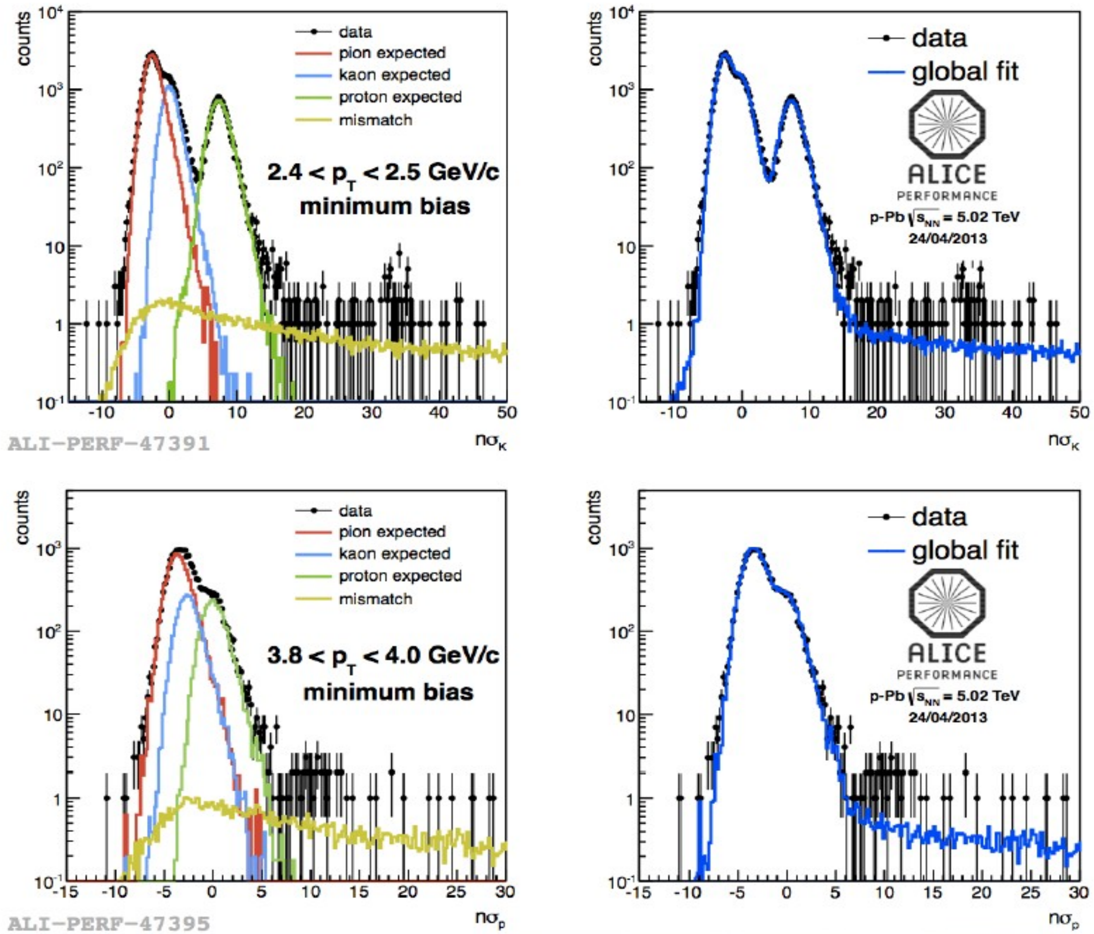
Subtraction of secondary protons

Remove protons from weak decays ($\Lambda \rightarrow p\pi^-$, $\Sigma^+ \rightarrow p\pi^0$)
Remove protons knocked out from the material
Use measured DCA distribution and fit it with MC templates



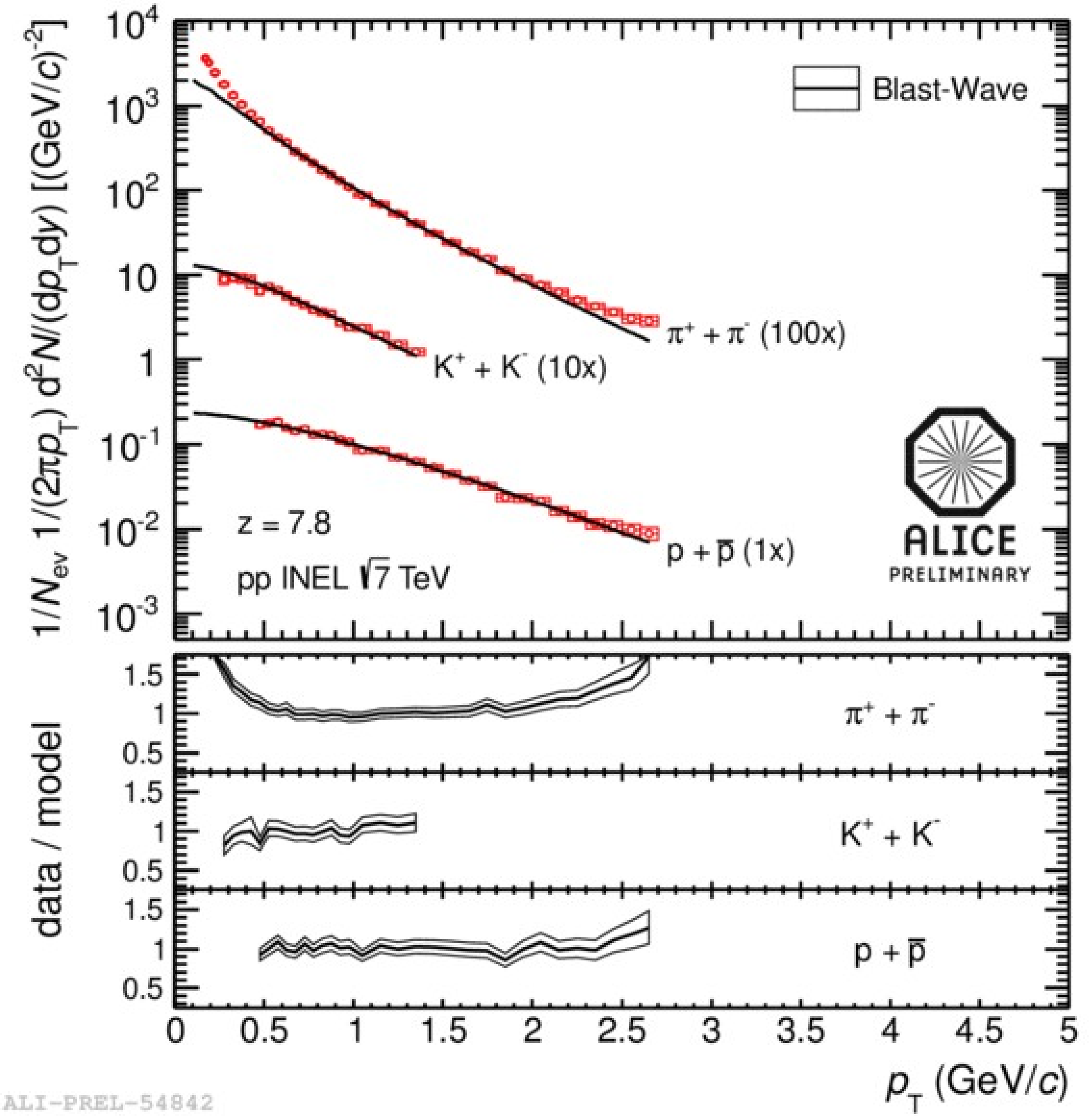


TOF raw yield extraction



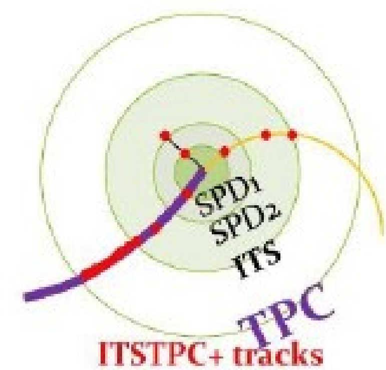
Since p-Pb center of mass system moved in laboratory frame with a rapidity of y_NN = -0.465, the nominal acceptance of the central barrel of ALICE detector was asymmetric with respect to y_CMS =0;
In order to ensure good detector acceptance and optimal particle identification performance, tracks were selected in the rapidity interval 0<y_CMS<0.5 in the nucleon-nucleon center of mass system.

pp (7 TeV)

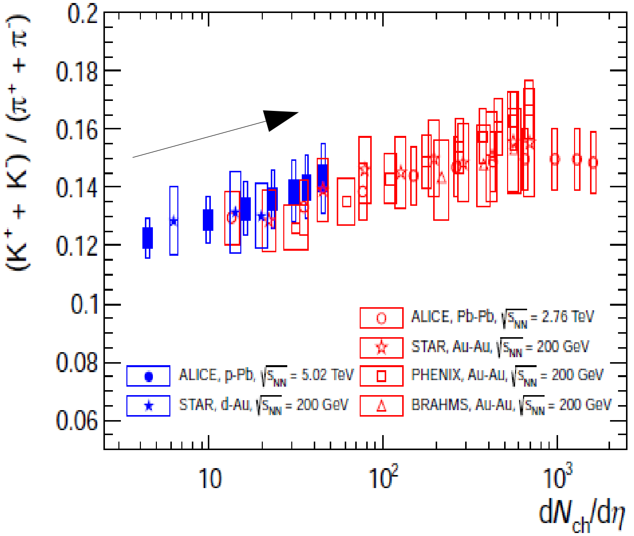


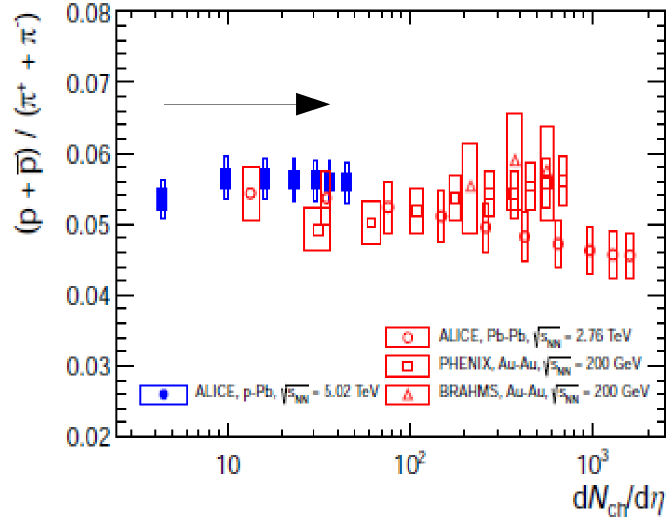
Multiplicity: number of charged particles in |eta|<0.8;

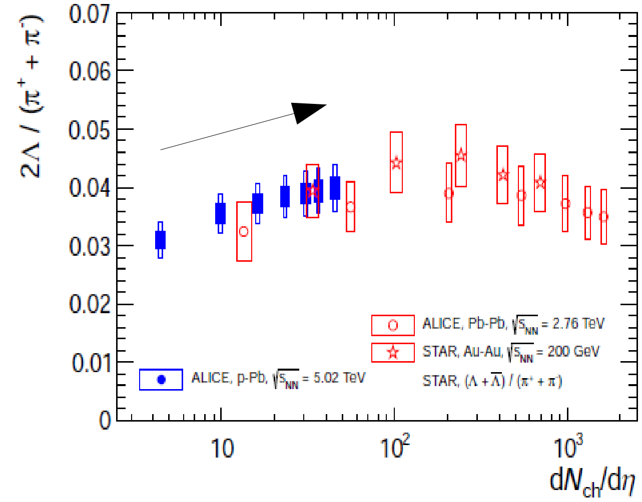
Blast-wave fit to high multiplicity pp events;



Particle ratios vs. charged multiplicity







K/π vs $dN_{ch}/d\eta$

- Small increase with multiplicity also in p-Pb collisions
- In line with the trend estabilished by Pb-Pb and lower energy RHIC results

p/π vs $dN_{ch}/d\eta$

- No significant evolution with multiplicity in p-Pb collisions
- In line with the values of Pb-Pb and lower energy in p-Pb collisions

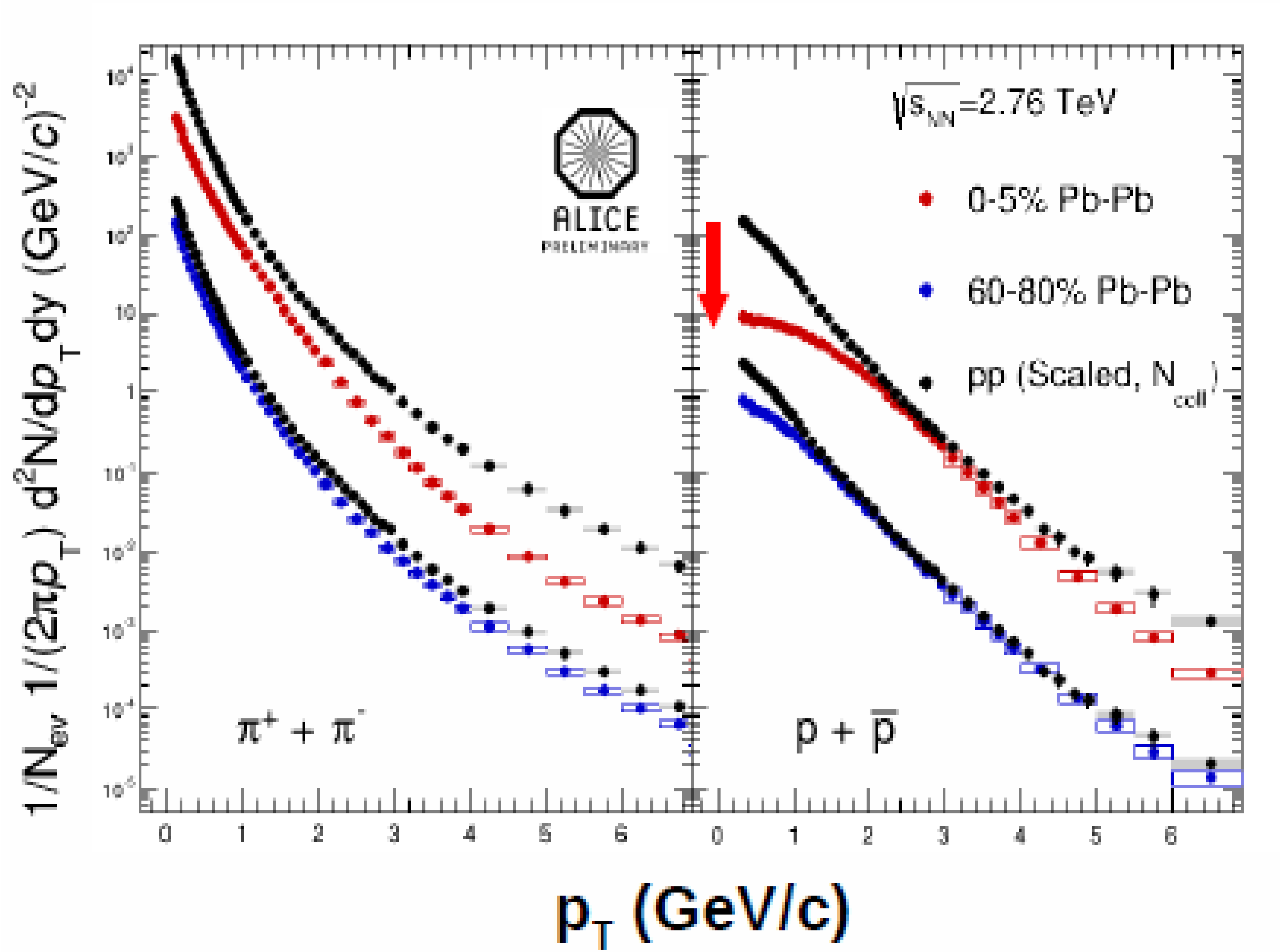
Λ/π vs $dN_{ch}/d\eta$

- Hints at a small increase at low multiplicity in p-Pb
- In line with the values of Pb-Pb and lower energy in p-Pb collisions

Pb-Pb: this is typically attributed to a reduced canonical suppression of strangeness production in larger freeze-out volumes or to an enhanced strangeness production in a quark-gluon plasma

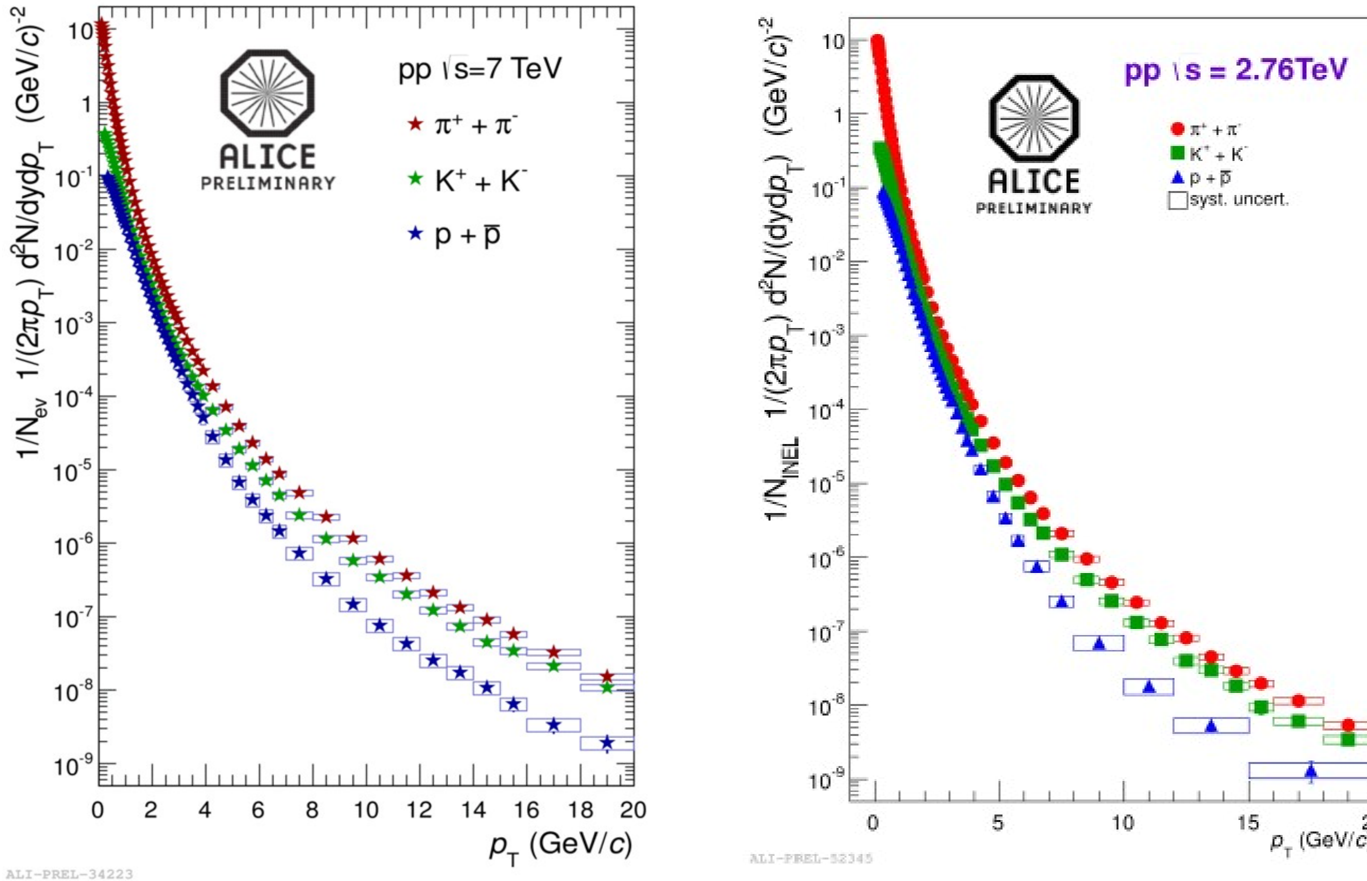
ALICE, arXiv:1303.0737 [hep-ex]
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)

Radial Flow



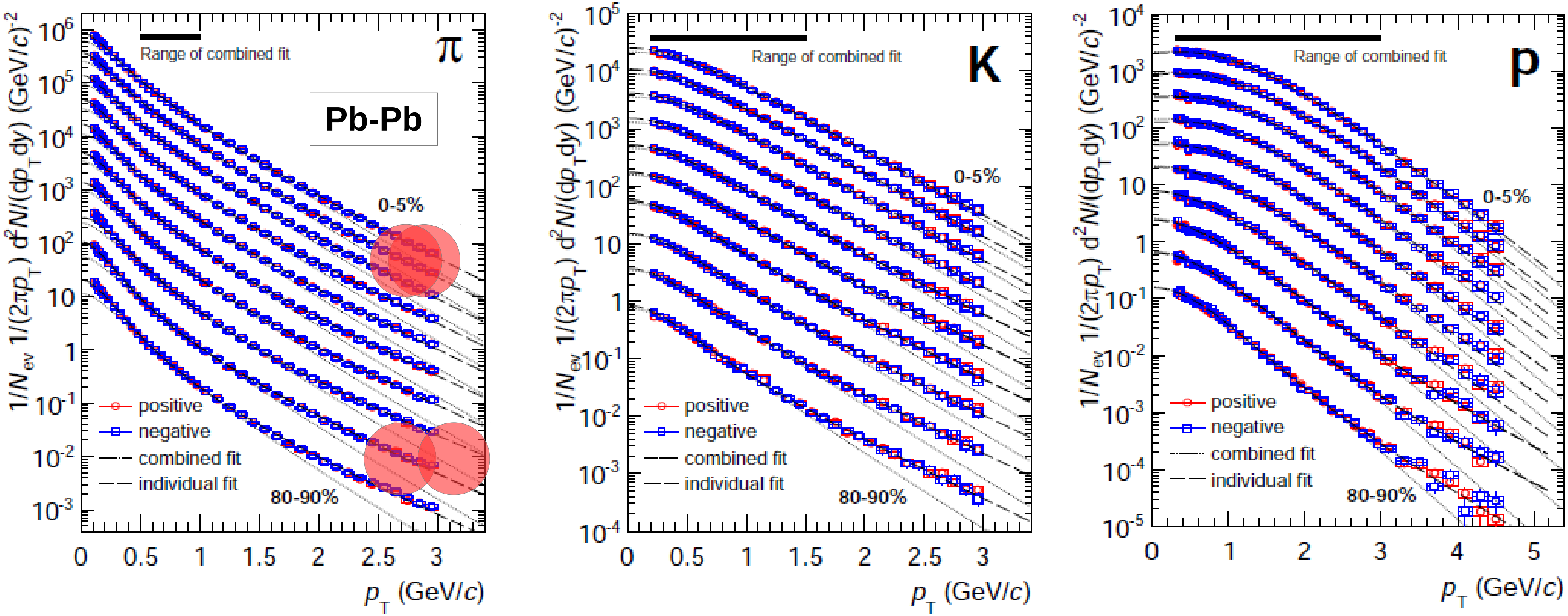
$\sqrt{s_{NN}}$=2.76 TeV
0-5% Pb-Pb
60-80% Pb-Pb
pp (Scaled, N_{coll})
ALICE
PRELIMINARY
$\pi^+ + \pi^-$
$p + \bar{p}$
$1/N_{ev}\ 1/(2\pi p_T)\ d^2N/dp_T dy\ (GeV/c)^{-2}$
p_T (GeV/c)

Transverse momentum distributions in pp



- PID from 100 MeV/c to 20 GeV/c
- ALICE subdetectors relevant for pp analysis (pp @ 2.76 and 7 TeV):
  - ITS, TPC, TOF and HMPID;

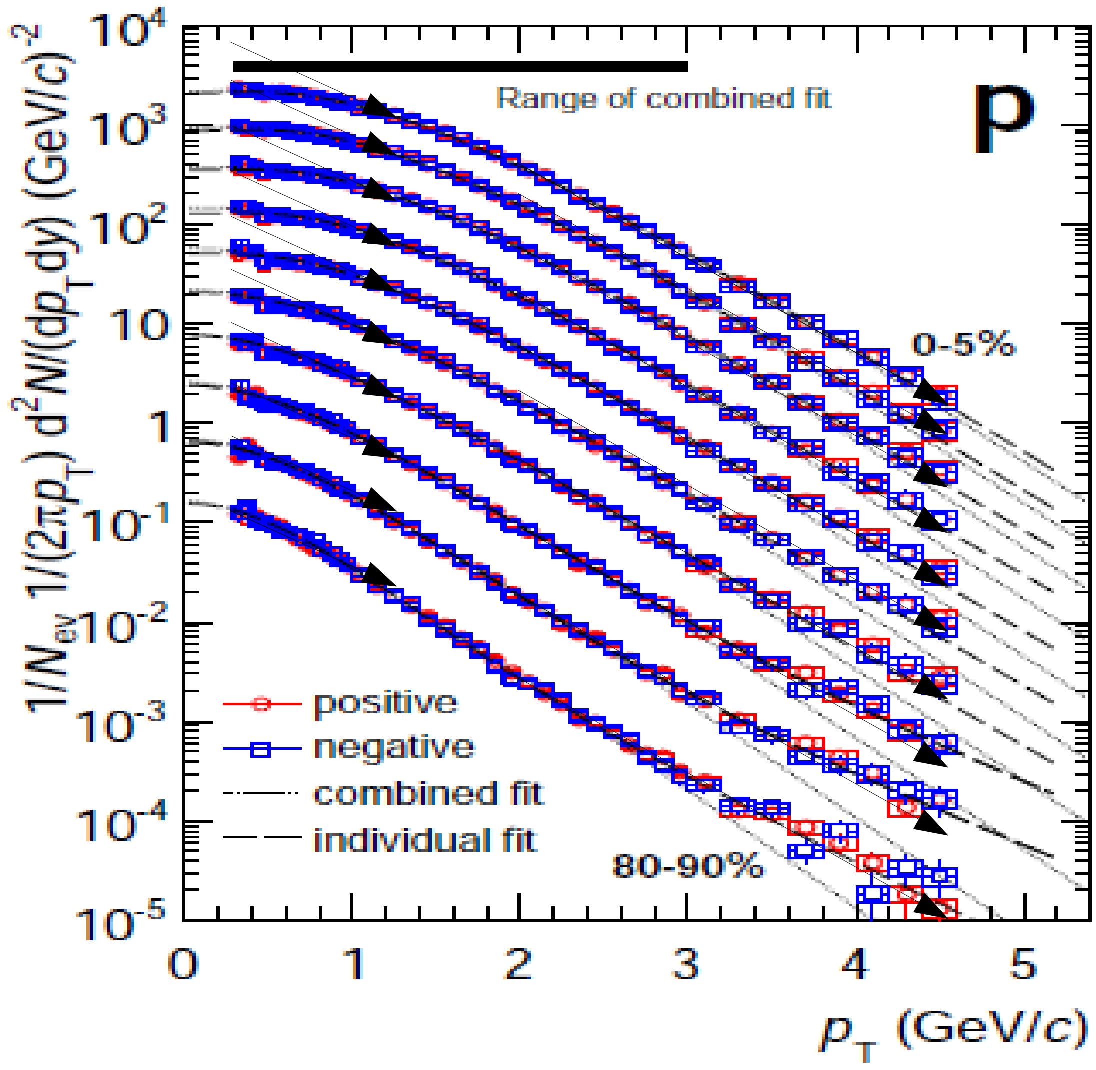
Transverse momentum distributions in Pb-Pb



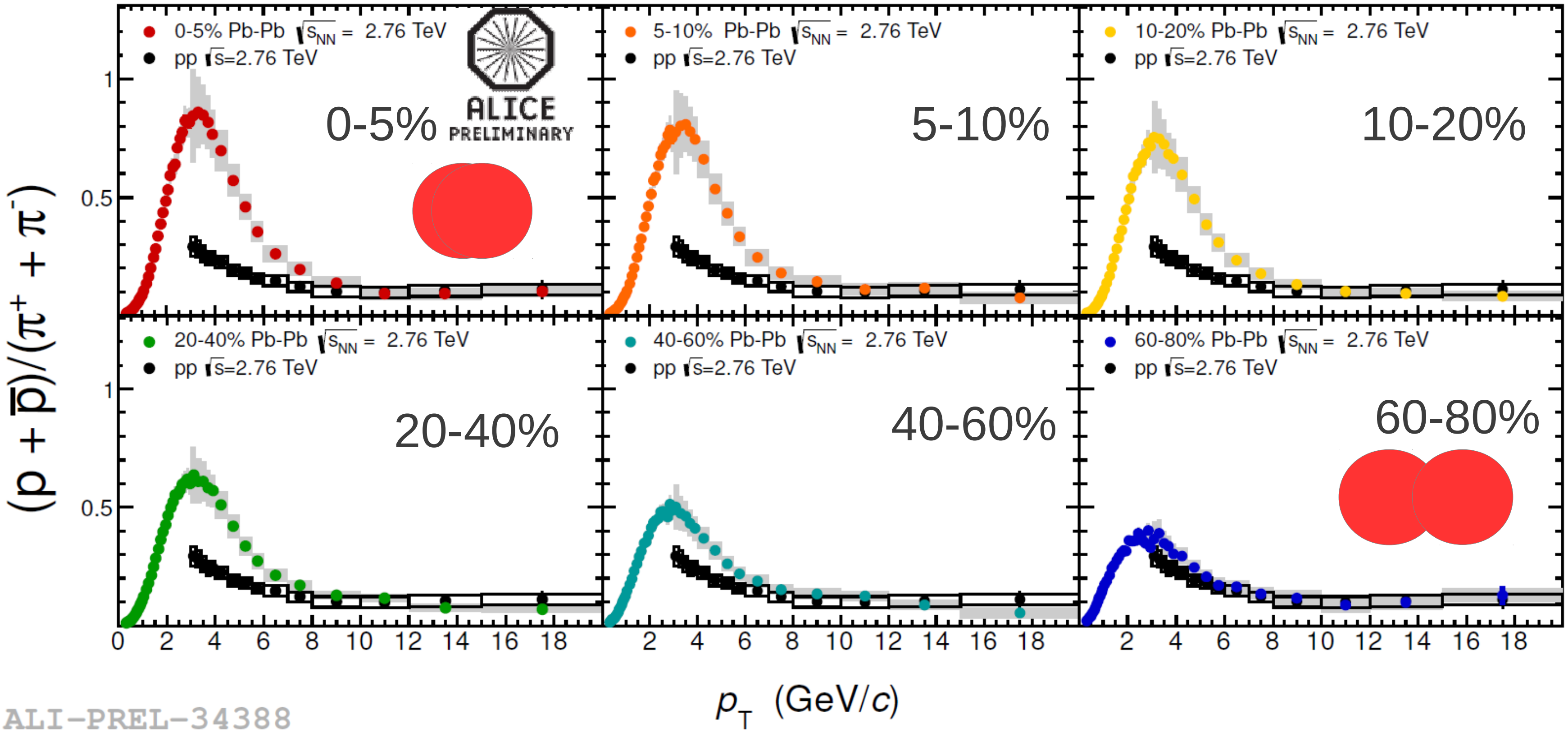
- Spectra at low p_T as a function of centrality.
- PID techniques used:
  - ITS, TPC and TOF;
- The spectra get harder with increasing centrality → in hydrodynamic models, it is a consequence of the collective expansion → stronger radial flow with increasing centrality;

arXiv:1303.0737v1

Transverse momentum distributions in Pb-Pb



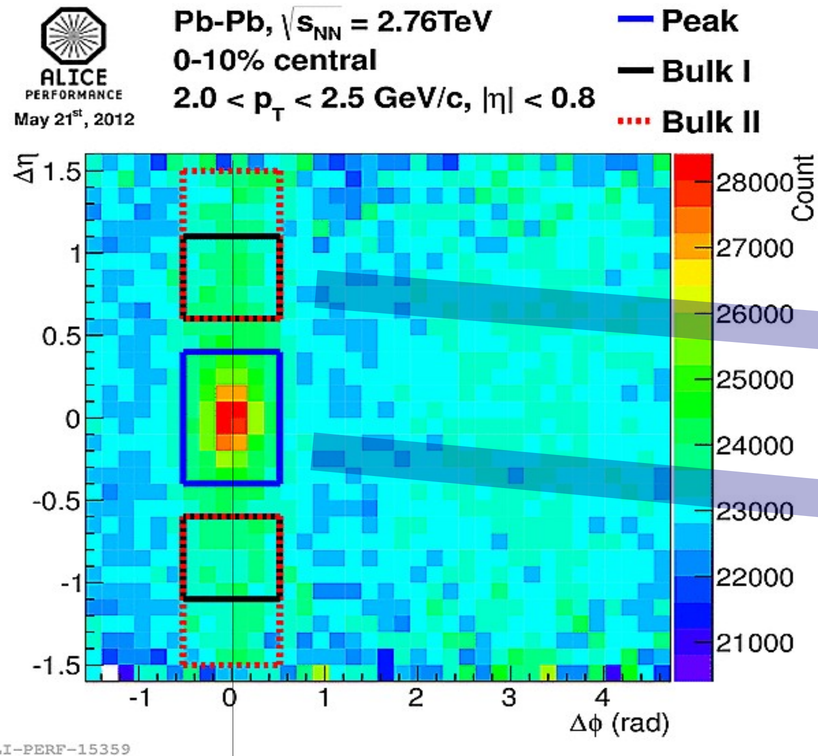
Baryon-to-meson ratio at intermediate p_T

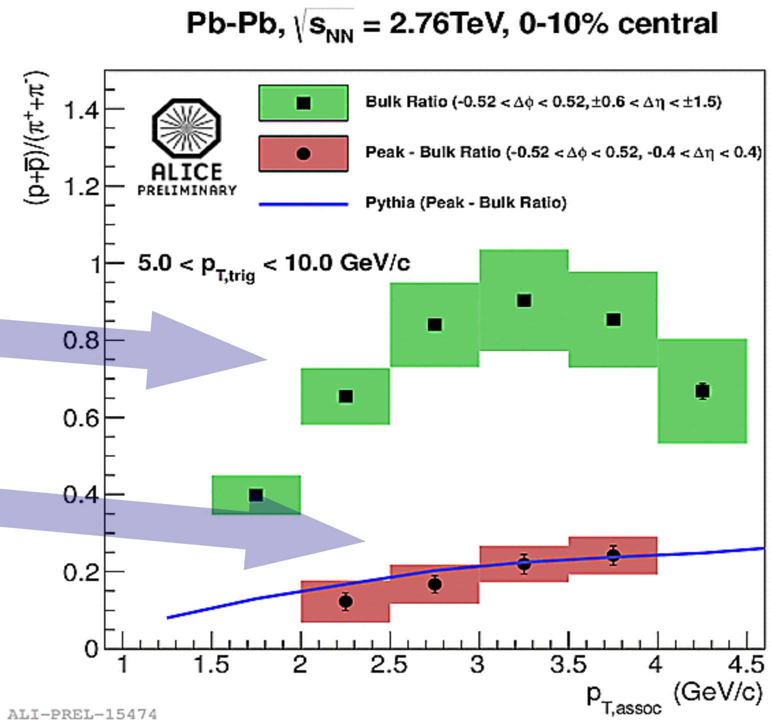


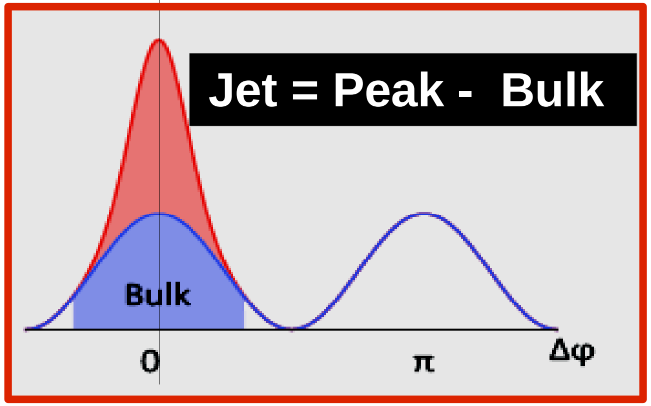
- For p_T > 10 GeV/*c* pp and Pb-Pb value are similar.
  - Parton fragmentation independent of particle species

- Enhancement of the baryon-to-meson ratio at intermediate transverse momentum (3-7 GeV/*c*) (at ~ 3 GeV/*c* up to 3x higher than in pp);

Baryon-to-meson ratio at intermediate p_T

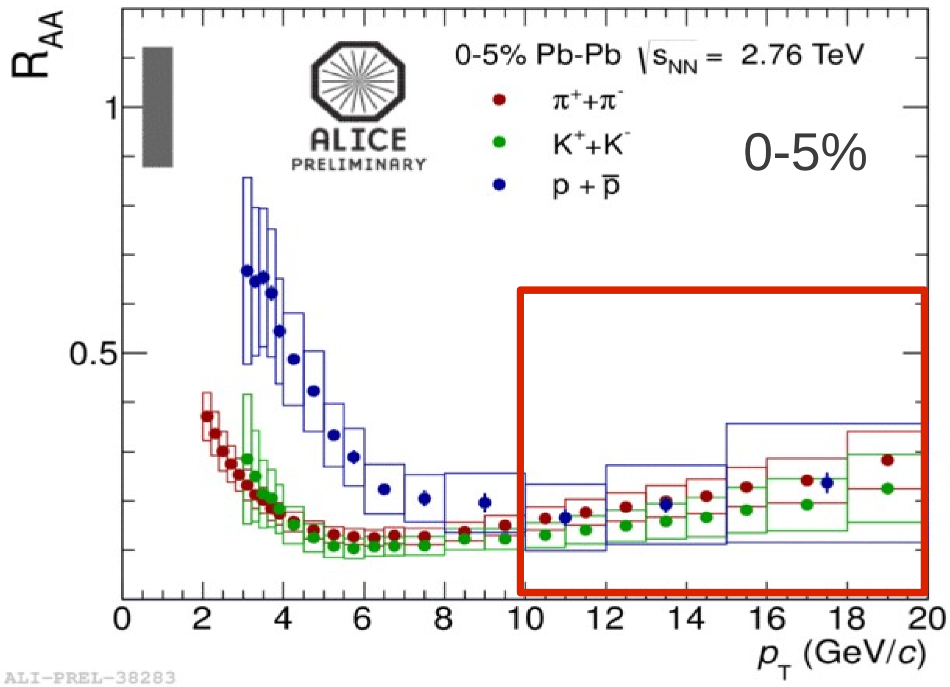


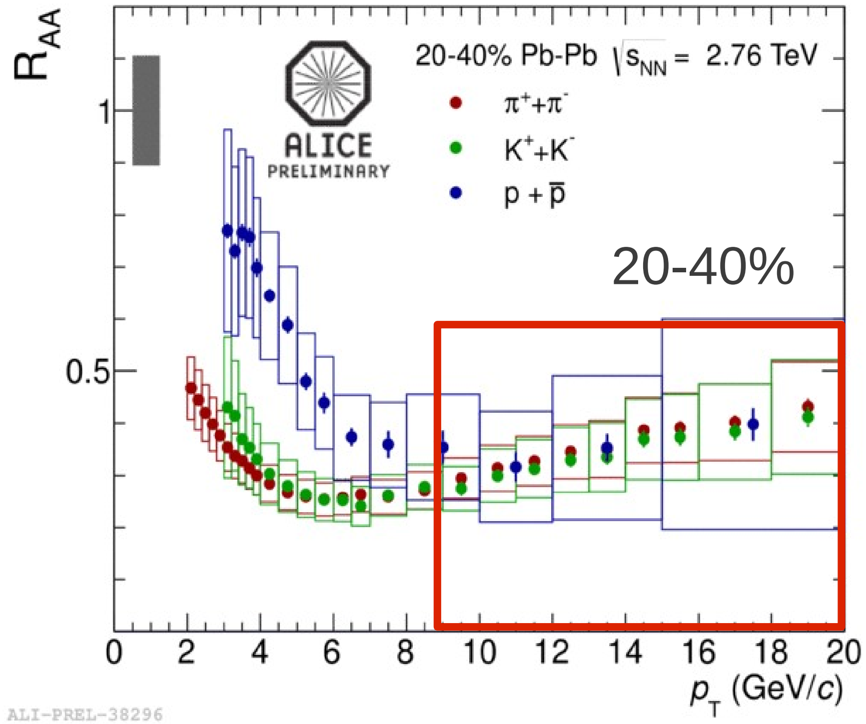




- Two particle correlation: p/π in the bulk and in the jet;
- Enhancement of the baryon-to-meson ratio:
  → The Baryon anomaly is an effect restricted to the bulk, absent in the jet!

Identified hadron R_{AA}



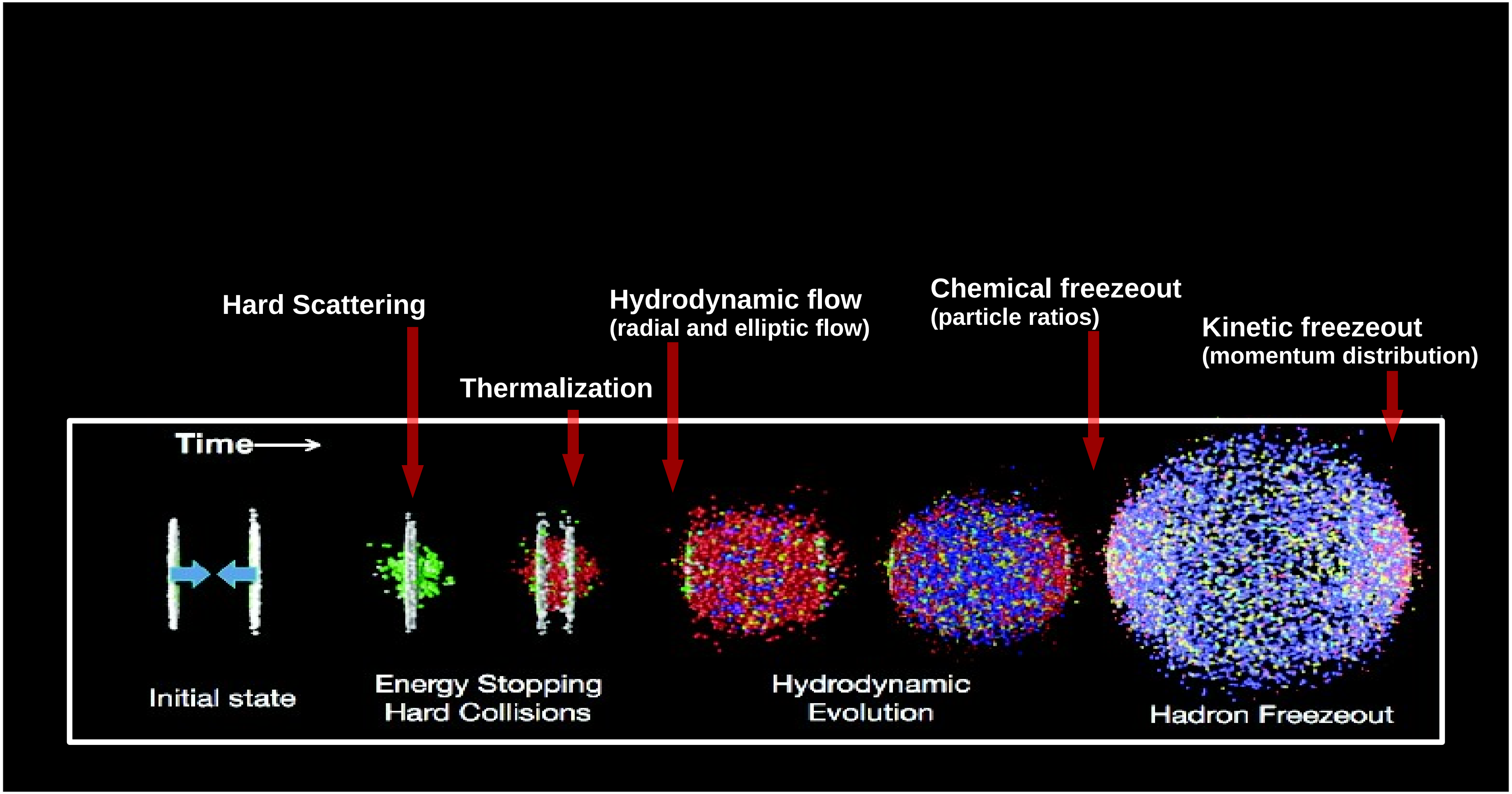


$$R_{AA} = \frac{AA}{\text{rescaled pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$

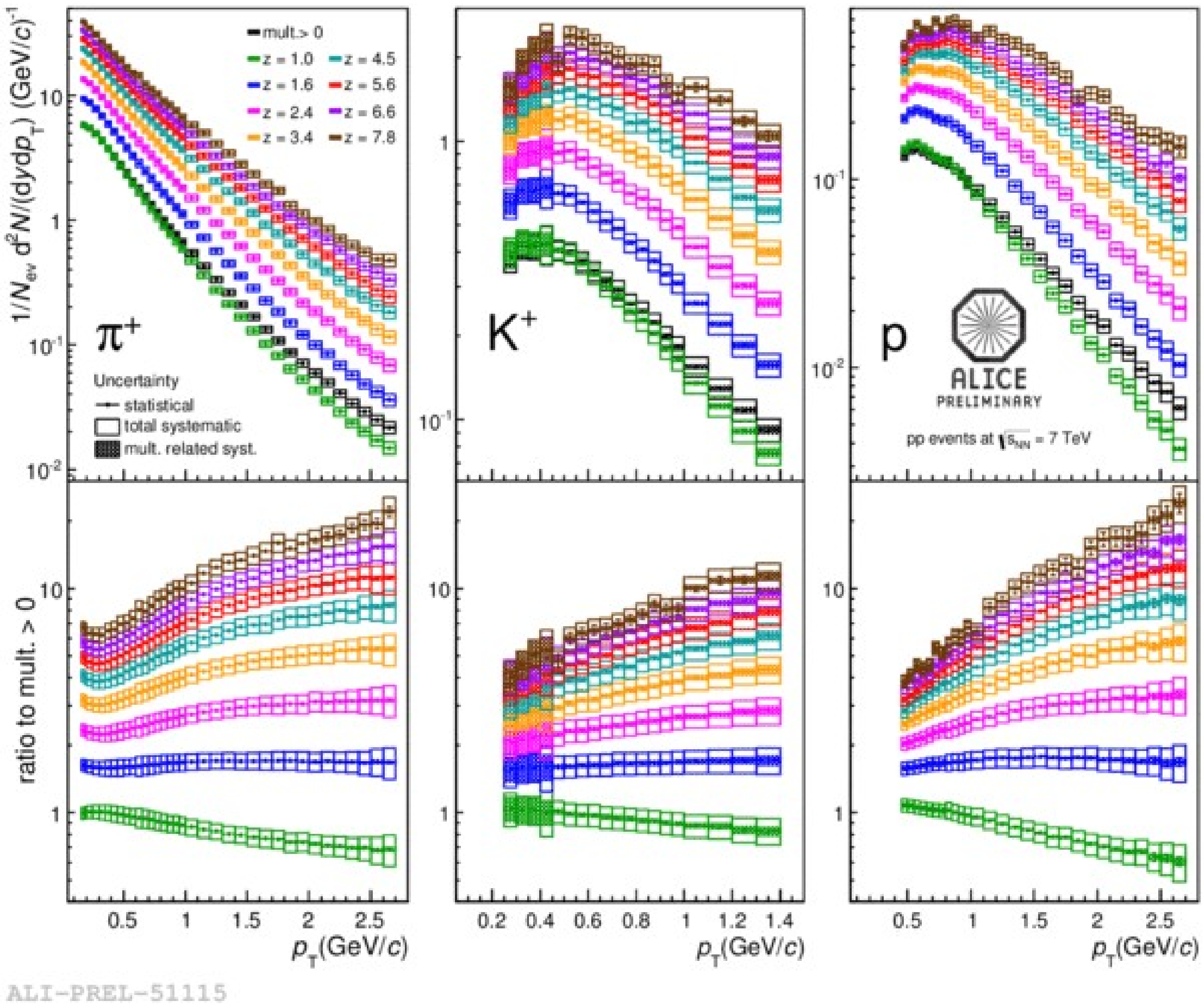
- R_{AA} (p) > R_{AA}(K) ~ R_{AA}(π)
- R_{AA} compatible for the three species at high p_T (p_T > 8- 10 GeV/c) within the uncertainties

→ no significant species dependence at high p_T

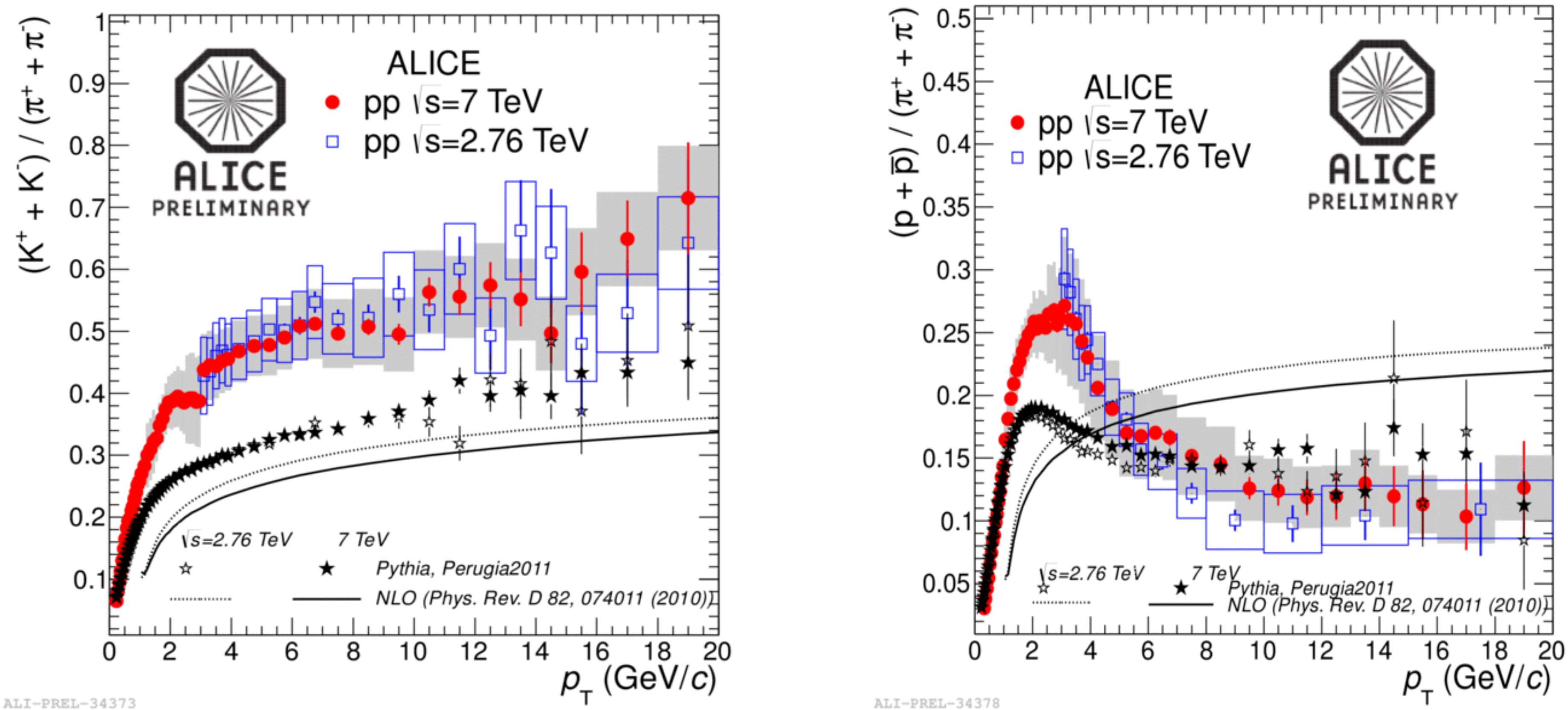
Heavy Ion collisions dynamical evolution



Heavy Ion collisions dynamical evolution

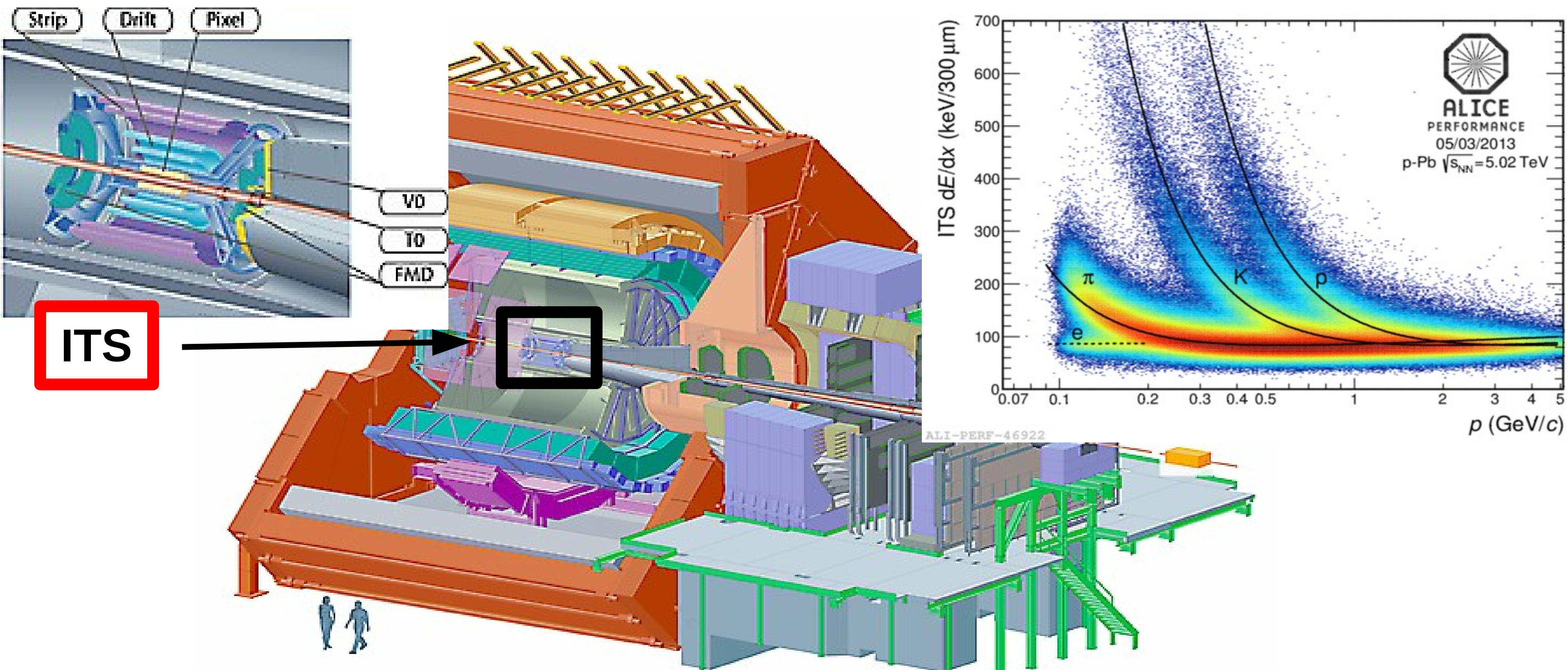

1/N_ev d²N/(dydp_T) (GeV/c)^-1
mult.> 0
z = 1.0
z = 1.6
z = 2.4
z = 3.4
z = 4.5
z = 5.6
z = 6.6
z = 7.8
π+
Uncertainty
statistical
total systematic
mult. related syst.
K+
p
ALICE
PRELIMINARY
pp events at √s_NN = 7 TeV
ratio to mult. > 0
p_T(GeV/c)
ALI-PREL-51115

Particle ratios vs p_T in pp (2.76 and 7 TeV)



- Ratios are similar at 7 TeV and 2.76 TeV and they are not reproduced by theory
- Color reconnection improves a description of ratio by PYTHIA [arXiv:1303.6326]

The ALICE detector

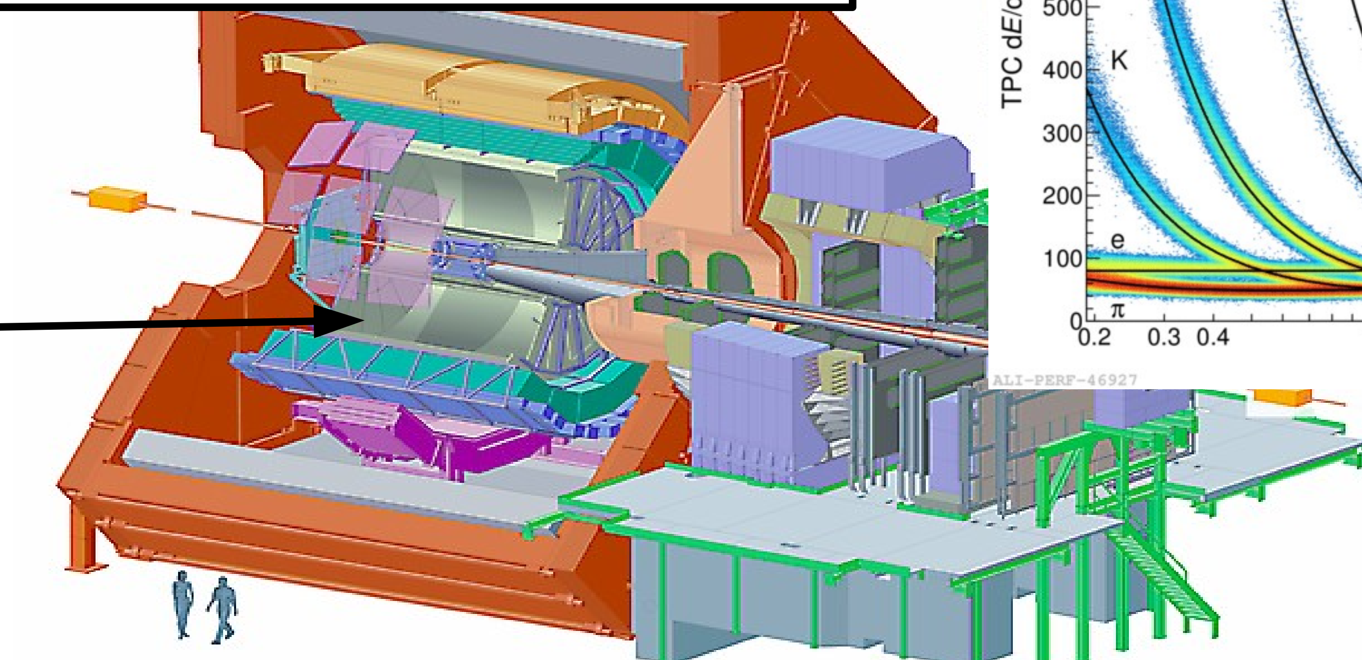


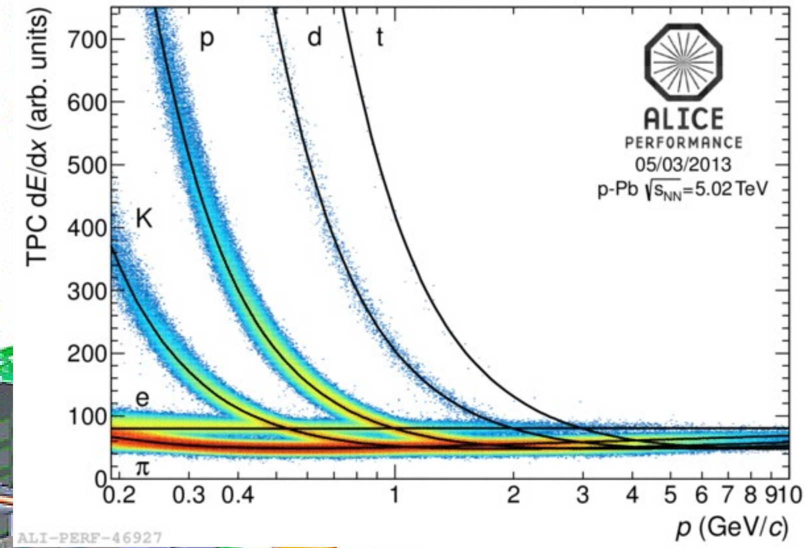
ALICE subdetectors relevant for p-Pb analysis:

- ITS tracking + vertexing
  - 6 layers of silicon detectors: SPD, SDD & SSD (PID)
    - PID - low p_T: 0.1 (pion), 0.2 (Kaon), 0.3 (proton) GeV/*c*)

The ALICE detector

TPC: the main tracking detector
PID via dE/dx in gas – Ne/Co^3 (90:10)
Gas volume: 88 m^3





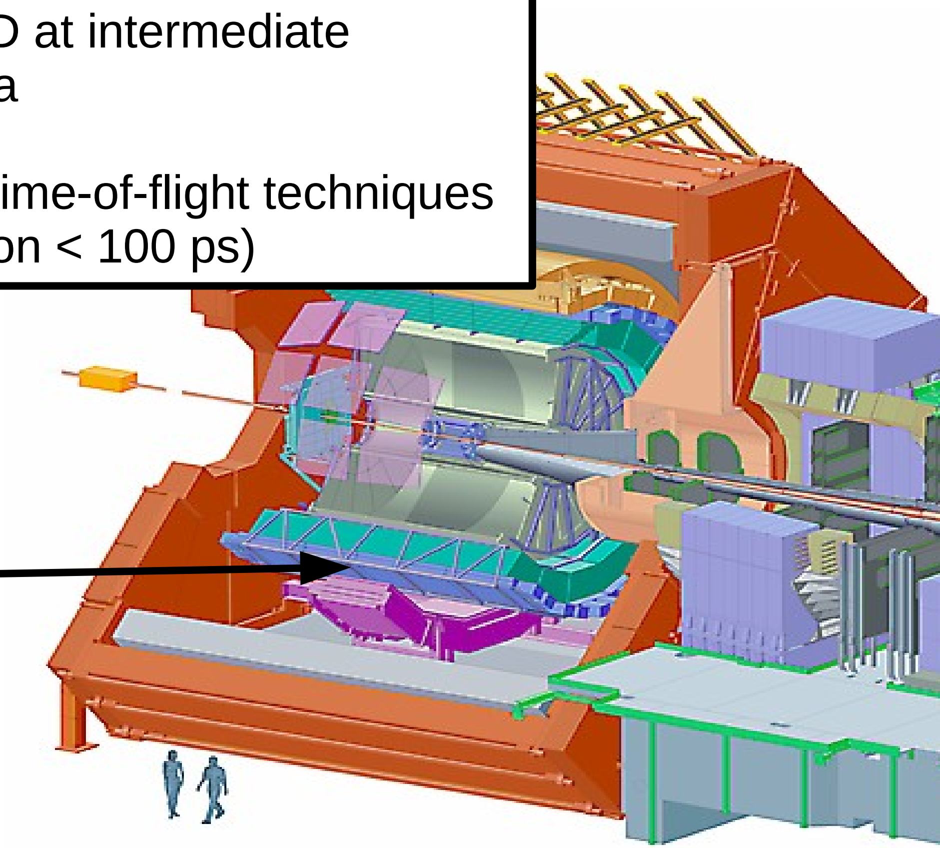
ALICE subdetectors relevant for p-Pb analysis:

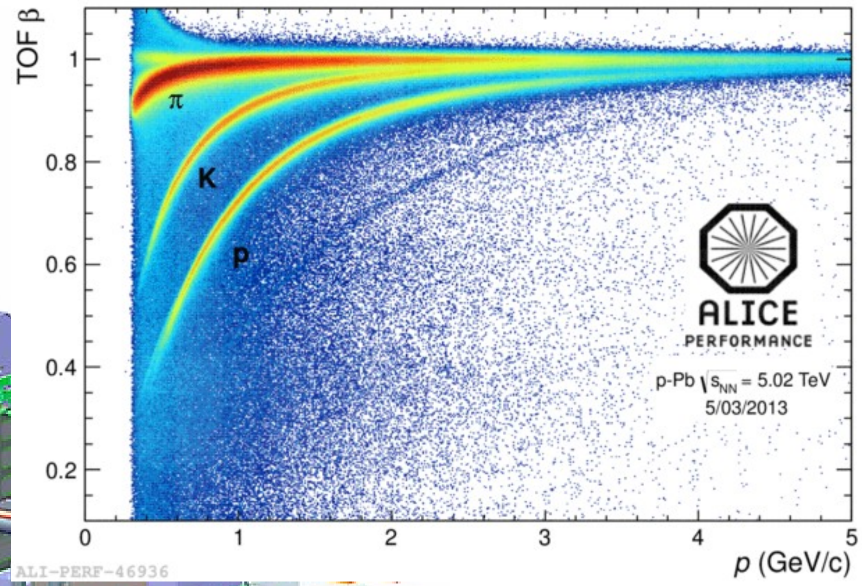
- VZERO — trigger, beam-BKG rejection
- ITS — tracking + vertexing
- TPC — tracking + vertexing + PID (dE/dx)
- TOF (+T0) — PID

The ALICE detector

TOF: PID at intermediate momenta

PID via time-of-flight techniques (resolution < 100 ps)





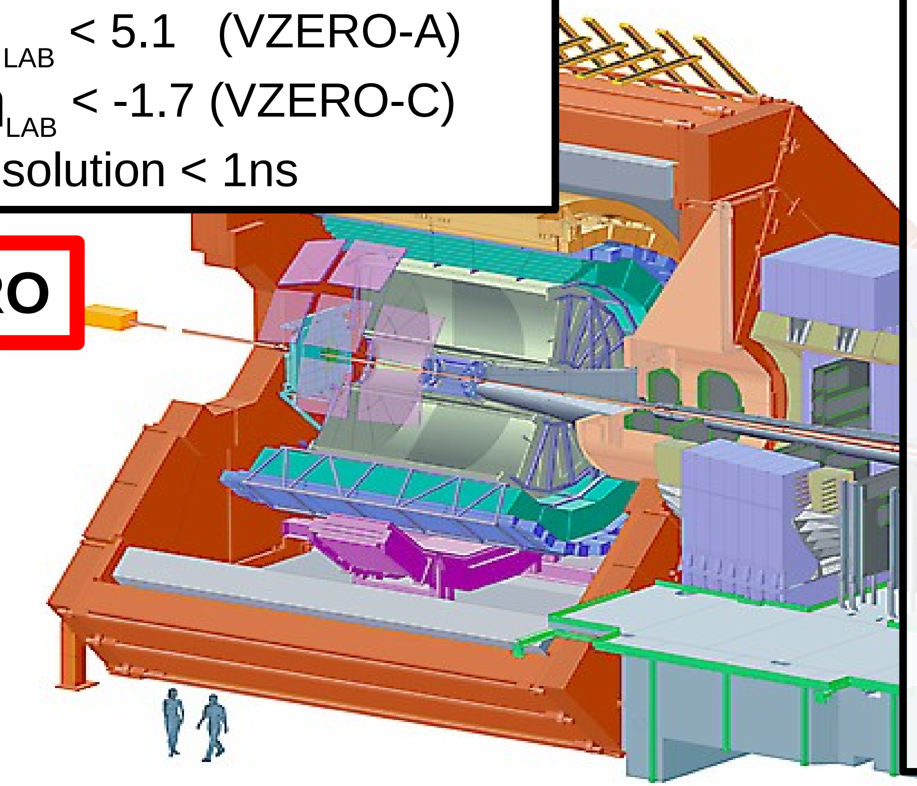
ALICE subdetectors relevant for p-Pb analysis:

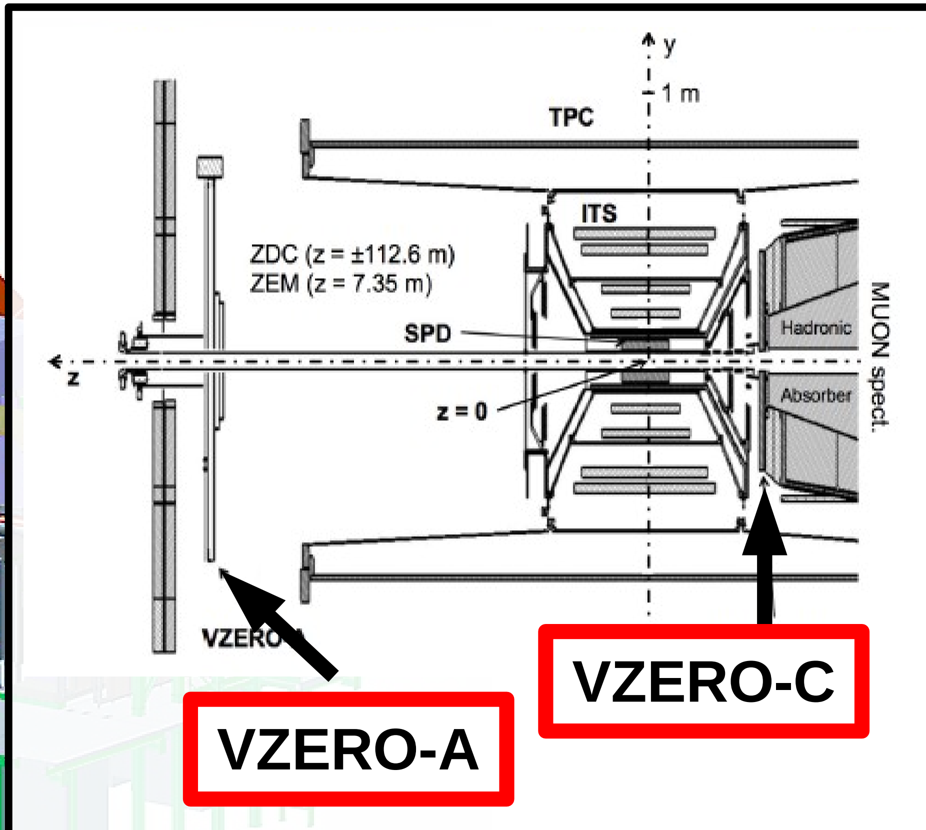
- VZERO trigger, beam-BKG rejection
- ITS tracking + vertexing
- TPC tracking + vertexing + PID (dE/dx)
- TOF (+T0) PID

The ALICE detector

2 arrays of 32 scintillator each
$2.8 < \eta_{LAB} < 5.1$ (VZERO-A)
$-3.7 < \eta_{LAB} < -1.7$ (VZERO-C)
Time resolution < 1ns

VZERO



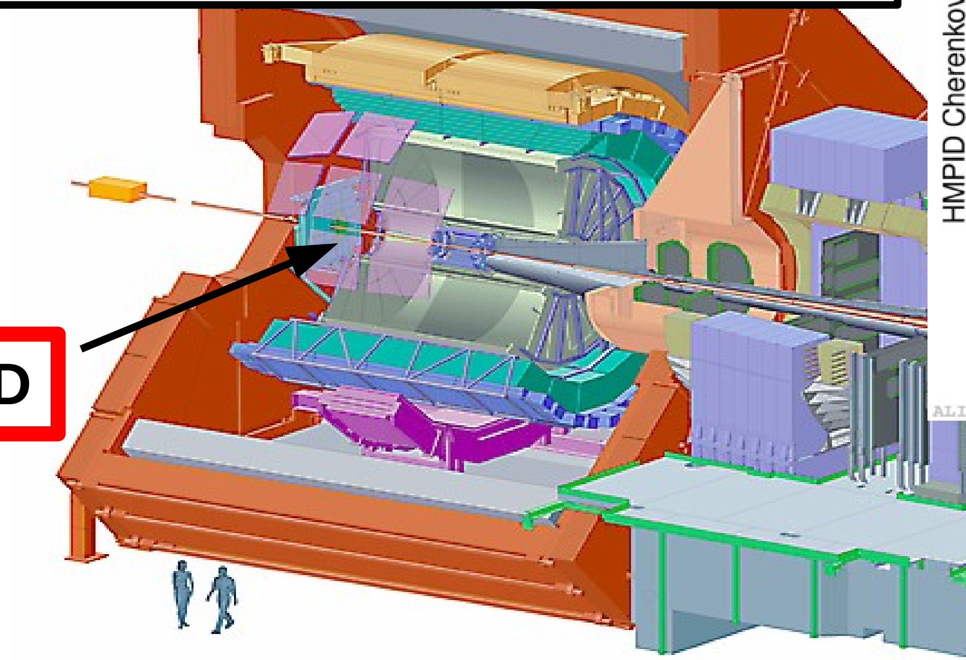


ALICE subdetectors relevant for p-Pb analysis:

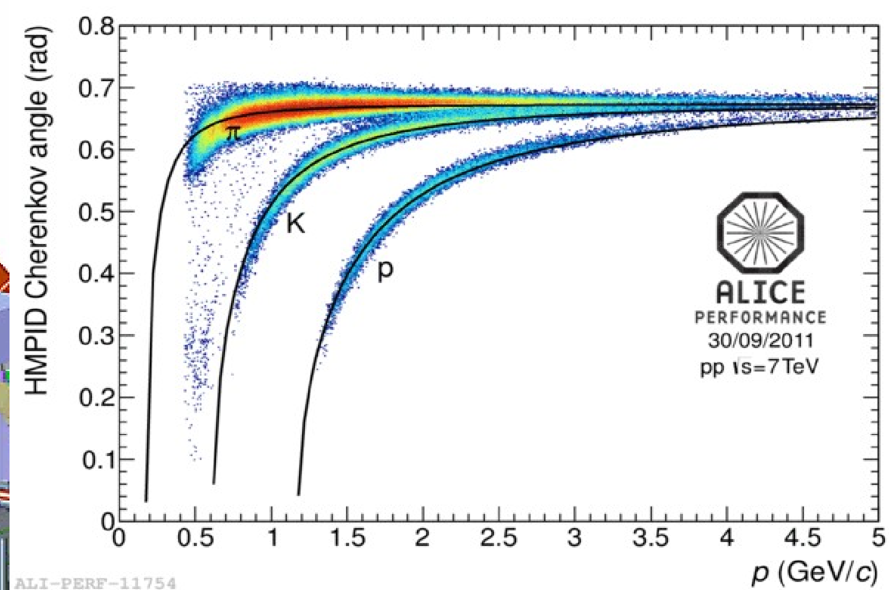
- VZERO trigger, beam-BKG rejection
- ITS tracking + vertexing
- TPC tracking + vertexing + PID (dE/dx)
- TOF (+T0) PID

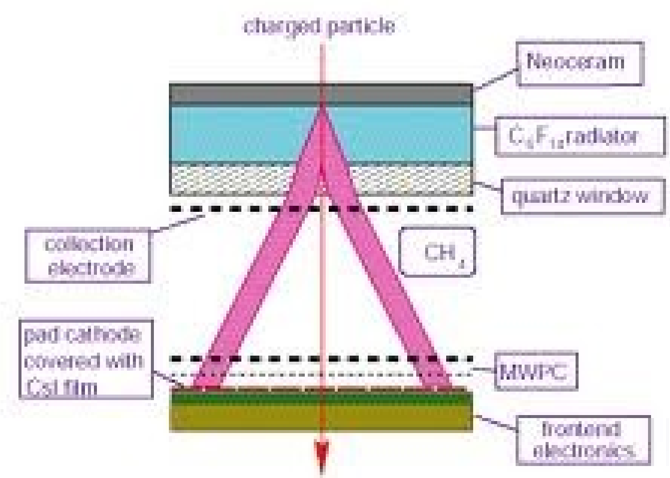
The ALICE detector

HMPID: PID at intermediate momenta
PID via Cherenkov angle measurement
Radiator: liquid C_6F_{14} (perfluorohexane)



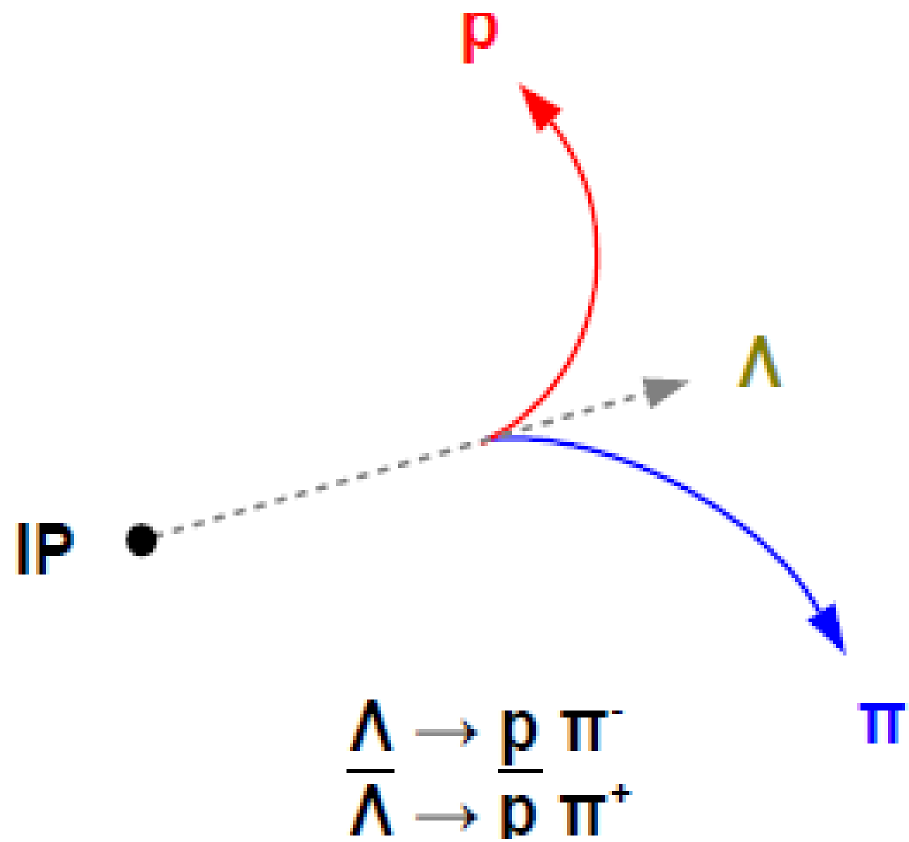
HMPID



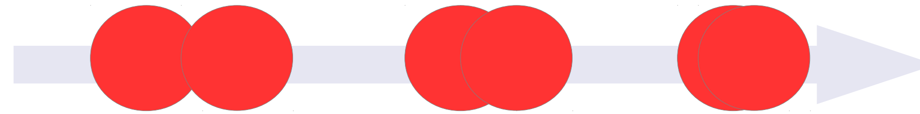


For pp analysis, also used:

- HMPID PID
  - π, K $1.5 < p_T < 3$ GeV/c
  - p $1.5 < p_T < 6$ GeV/c


p
Λ
IP
π
$\Lambda \rightarrow p\,\pi^-$
$\bar{\Lambda} \rightarrow \bar{p}\,\pi^+$

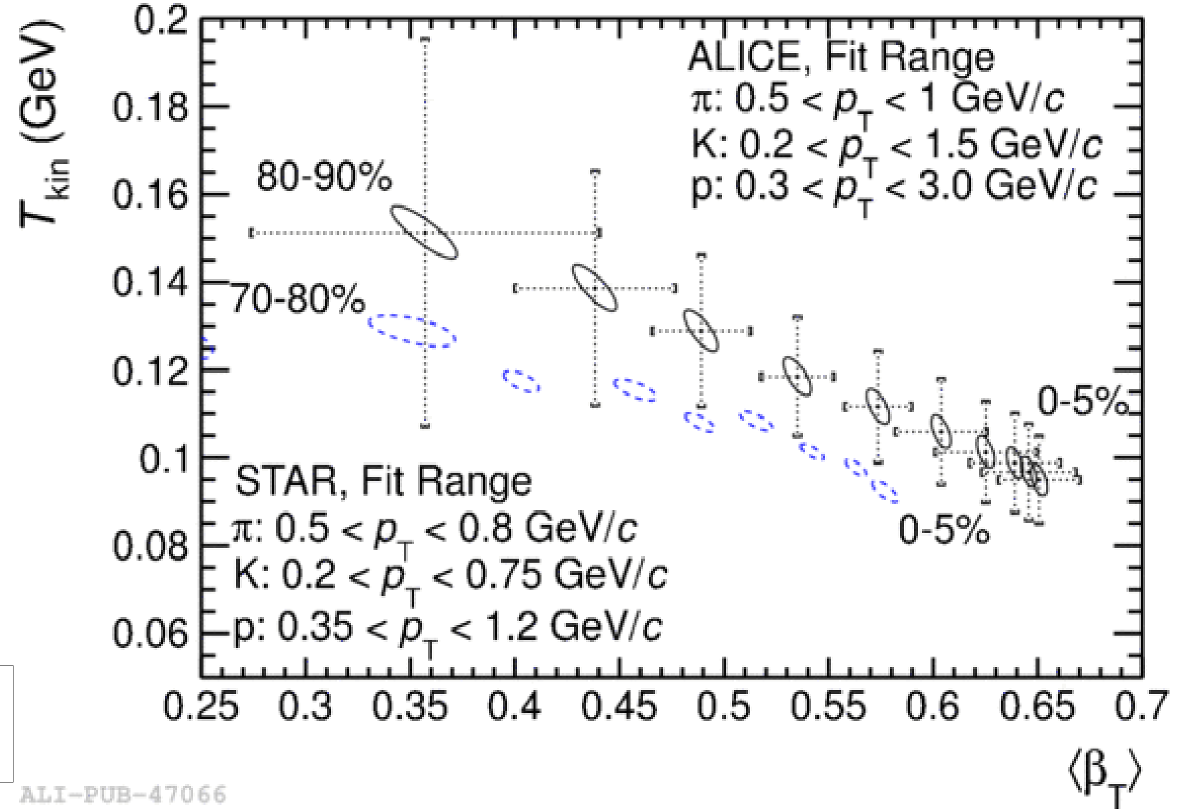
Kinetic freezeout (Pb-Pb @ 2.76 TeV)



$\langle \beta_T \rangle$ increases with centrality

T_{kin} decreases with centrality

n ~ 0.7 in central collisions - increase towards peripheral collisions (spectrum not being thermal).



arXiv:1303.0737v1
(STAR Collaboration), Phys. Rev. C 79, 034909 (2009).
(PHENIX Collaboration),Phys. Rev. C69, 034909 (2004).

Possible indication of more rapid expansion with increasing centrality.
In peripheral collisions it is consistent with the expectation of a **shorter lived fireball with stronger radial gradients*.**

***U. W. Heinz, 165 (2004), aiXiv:0407360**

Pb-Pb:Transverse momentum distributions at low p_T

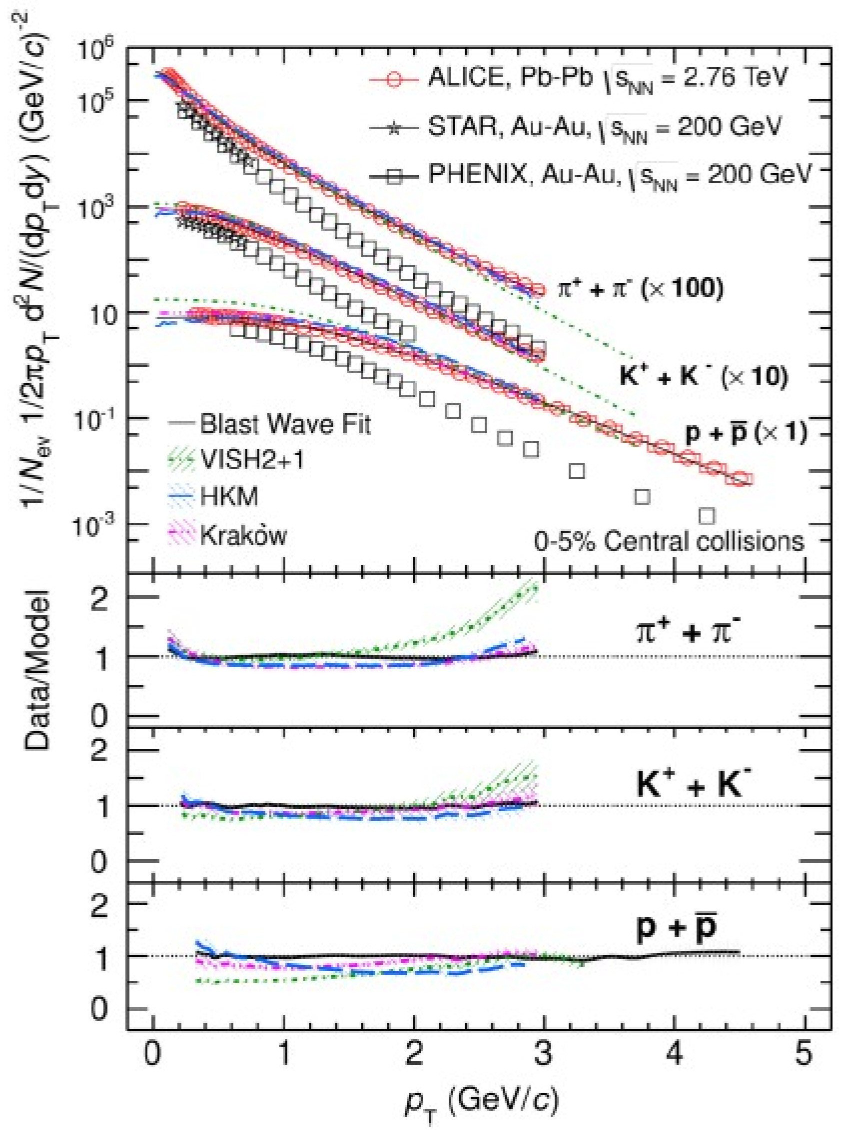
Hydro models:

VISH2+1: viscous hydrodynamics,
Difference: no description of hadronic phase in the model. Yield are taken to be thermal at Tch = 165 MeV
(Shen et al., PRC 84, 044903 (2011))

HKM: hydro+UrQMD*, hadronic phase builds additional radial flow, mostly due to elastic interactions, and affects particle ratios due to inelastic interactions
(Karpenko et al., arXiv:1204.5351)

Krakow: introduces non equilibrium corrections due to viscosity at the transition from the hydrodynamic description to particles which change the effective Tch
(Bozek, PRC 85, 034901 (2012))

The last two models reproduce well the data supporting a hydrodynamic interpretation of the trasnsverse momentum spectra at the LHC.



*Hadronic cascade model

Event class	VZERO-A range (arb. unit)	$\langle dN_{ch}/d\eta \rangle$ $\lvert\eta_{lab}\rvert < 0.5$
0–5%	> 227	45 ± 1
5–10%	187–227	36.2 ± 0.8
10–20%	142–187	30.5 ± 0.7
20–40%	89–142	23.2 ± 0.5
40–60%	52–89	16.1 ± 0.4
60–80%	22–52	9.8 ± 0.2
80–100%	< 22	4.4 ± 0.1

Table 1: Definition of the event classes as fractions of the analyzed event sample and their corresponding $\langle dN_{ch}/d\eta \rangle$ within $\lvert\eta_{lab}\rvert < 0.5$ (systematic uncertainties only, statistical uncertainties are negligible).

Table 3: Charged particle multiplicity density [26] (total uncertainties) and mid-rapidity particle yields $\frac{dN_i}{dy}\Big|_{|y|<0.5}$ (statistical uncertainties and systematic uncertainties including extrapolation uncertainty). The last column indicates the additional normalization uncertainty coming from the centrality definition.

Centrality	$dN_{ch}/d\eta$	π^+	π^-	K^+	K^-	p	$\overline{p}$	Norm. Uncertainty
0–5%	1601 ± 60	733 ± 54	732 ± 52	109 ± 9	109 ± 9	34 ± 3	33 ± 3	0.5%
5–10%	1294 ± 49	606 ± 42	604 ± 42	91 ± 7	90 ± 8	28 ± 2	28 ± 2	0.5%
10–20%	966 ± 37	455 ± 31	453 ± 31	68 ± 5	68 ± 6	21.0 ± 1.7	21.1 ± 1.8	0.7%
20–30%	649 ± 23	307 ± 20	306 ± 20	46 ± 4	46 ± 4	14.4 ± 1.2	14.5 ± 1.2	1%
30–40%	426 ± 15	201 ± 13	200 ± 13	30 ± 2	30 ± 2	9.6 ± 0.8	9.7 ± 0.8	2%
40–50%	261 ± 9	124 ± 8	123 ± 8	18.3 ± 1.4	18.1 ± 1.5	6.1 ± 0.5	6.2 ± 0.5	2.4%
50–60%	149 ± 6	71 ± 5	71 ± 4	10.2 ± 0.8	10.2 ± 0.8	3.6 ± 0.3	3.7 ± 0.3	3.5%
60–70%	76 ± 4	37 ± 2	37 ± 2	5.1 ± 0.4	5.1 ± 0.4	1.9 ± 0.2	2.0 ± 0.2	5%
70–80%	35 ± 2	17.1 ± 1.1	17.0 ± 1.1	2.3 ± 0.2	2.3 ± 0.2	0.90 ± 0.08	0.93 ± 0.09	6.7%
80–90%	13.4 +1.6 -1.2	6.6 ± 0.4	6.6 ± 0.4	0.85 ± 0.08	0.86 ± 0.09	0.36 ± 0.04	0.36 ± 0.04	+12% -8.5%

* factor ~ 1.7