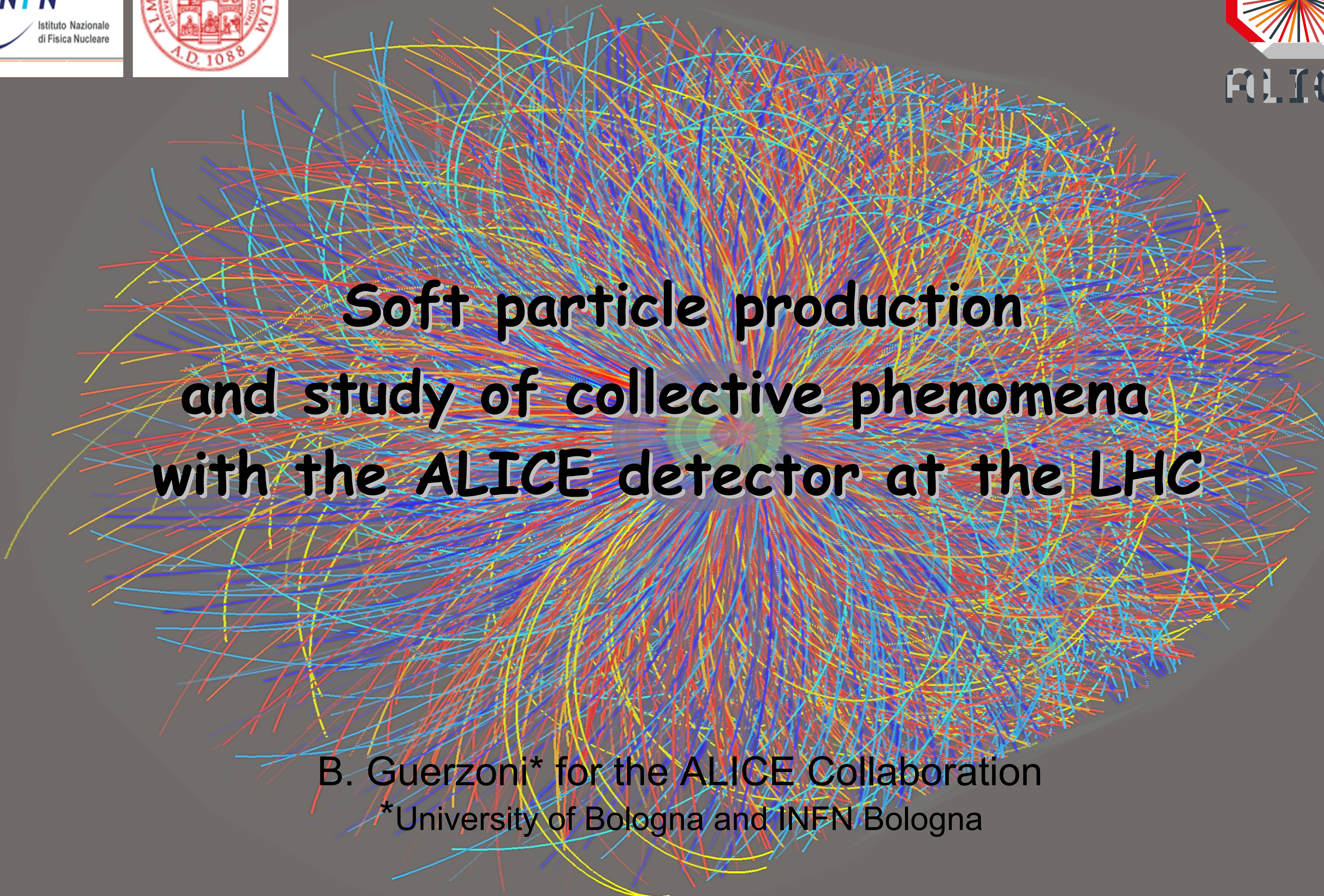
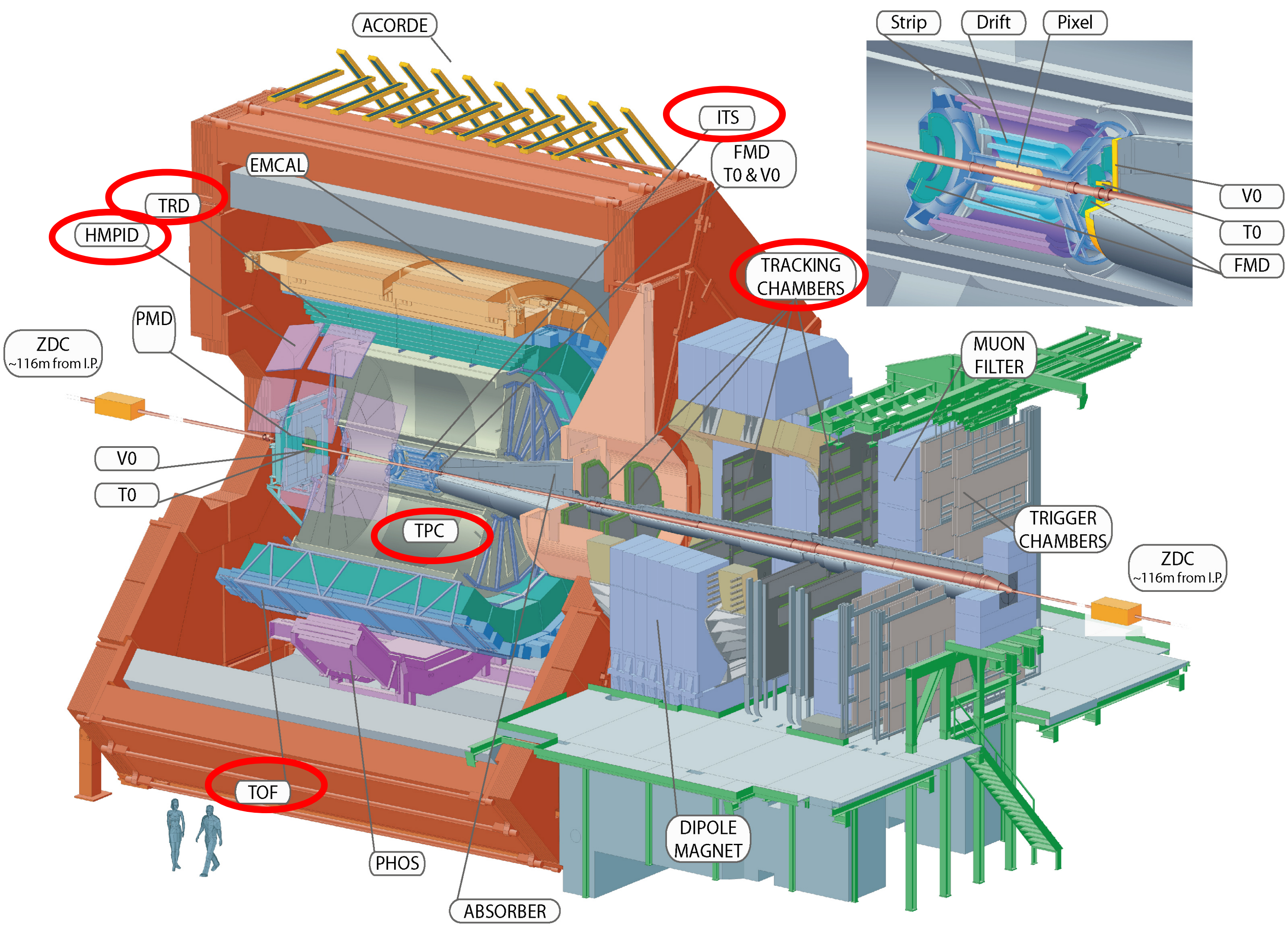


Soft particle production and study of collective phenomena with the ALICE detector at the LHC

B. Guerzoni* for the ALICE Collaboration
*University of Bologna and INFN Bologna

SQM 2015, 06-11 July, Dubna, Russia

The ALICE experiment



- Low material budget
- Optimized for good PID performance

ALICE has several detectors in the central barrel (|η|<0.9) dedicated to PID

- covering complementary p_T ranges
- using different PID techniques:
  - ITS: d*E*/d*x*
  - TPC: d*E*/d*x*
  - TRD: Transition Radiation
  - TOF: Time-of-Flight
  - HMPID: Cherenkov Radiation

ALICE has a forward muon spectrometer (-4.0<η<-2.5) for muon ID

Outline

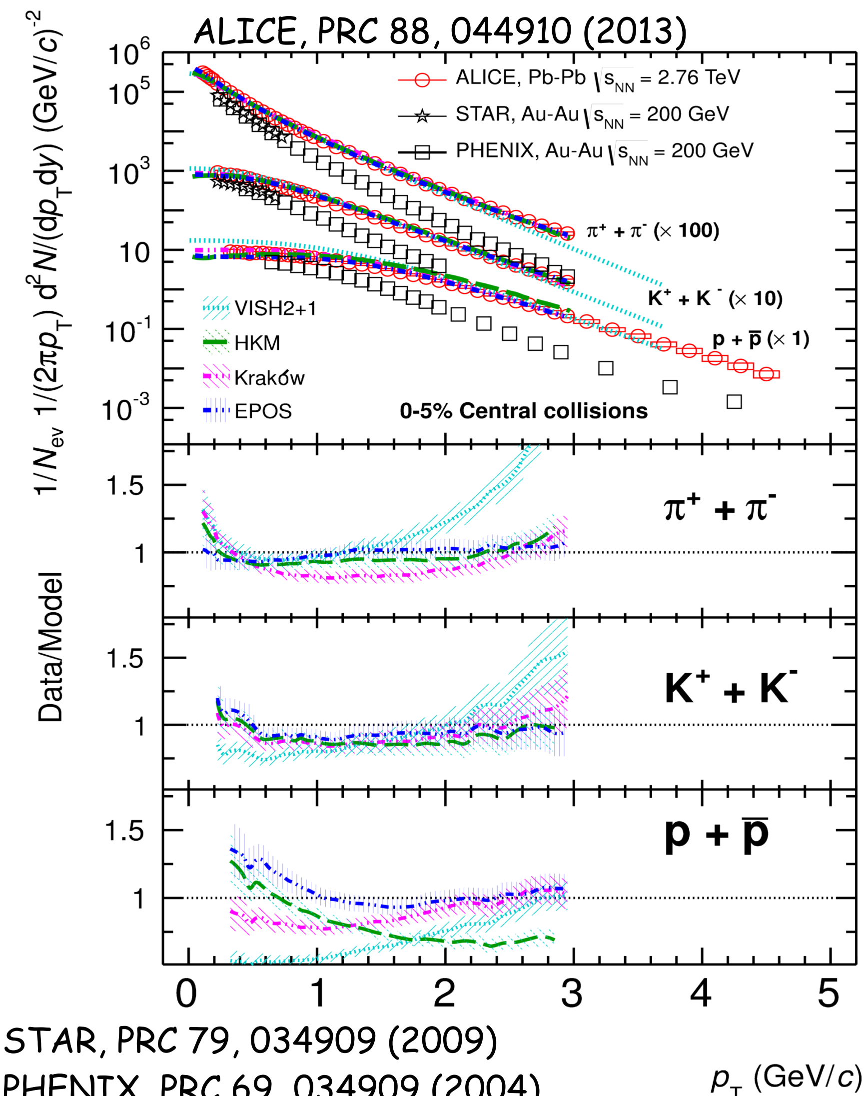
Soft particle production: low p_T spectra

- Hydrodynamic interpretation of the spectra in Pb-Pb collisions
- Is there collective behaviour also in pp and p-Pb collisions?
  - Pb-Pb, p-Pb and pp spectra as a function of multiplicity: similarities?
- Particle ratios vs colliding system
- Thermal model interpretation of particle ratios in Pb-Pb

Conclusions

Pb-Pb bulk production: low p_T spectra

ALICE, PRC 88, 044910 (2013)



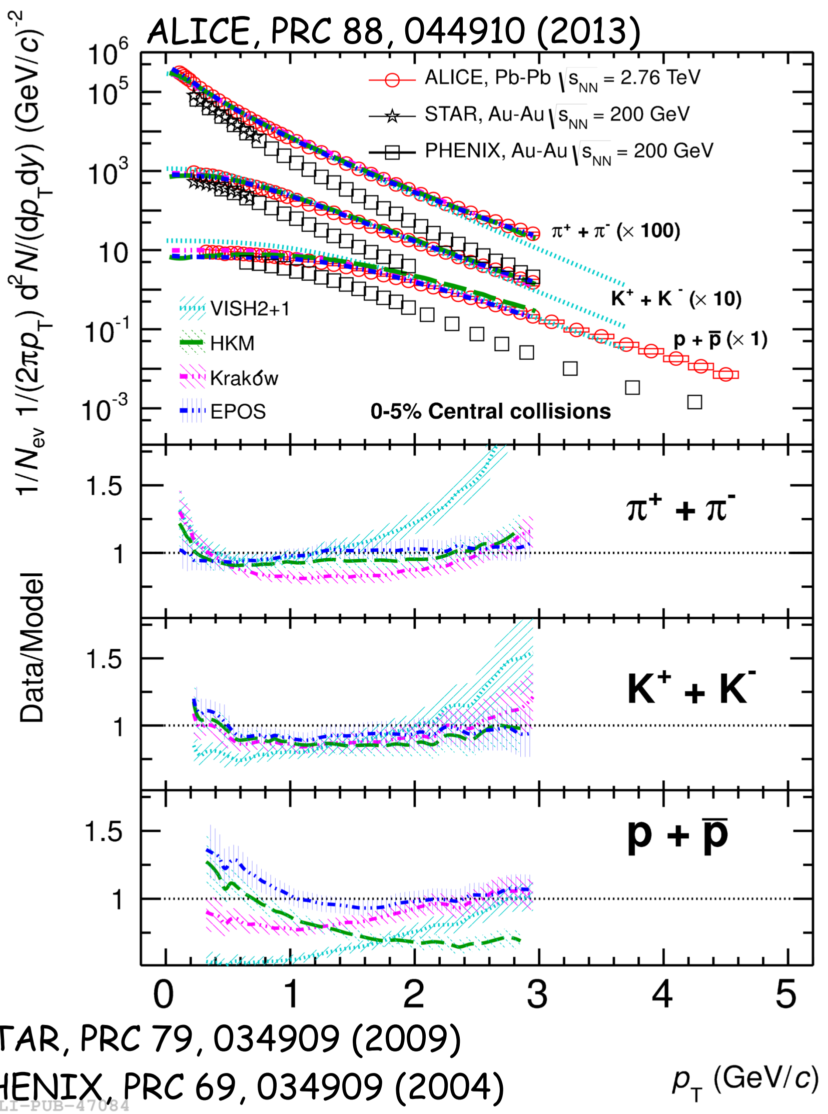
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 034909 (2004)

- Harder spectra compared to RHIC -> stronger radial flow (in hydrodynamic models this is a consequence of increasing particle density)
- Combined blast wave fit* :
  - $\langle\beta_T\rangle$ = 0.65 ± 0.02 -> 10% higher than RHIC consistent with observation of increasing of mean p_T at LHC compared to RHIC for π, K, p
  - Kinetic freeze-out temperature T_{kin}= 95 ± 10 MeV -> comparable with RHIC (sensitive to pion fit range)

*Schnedermann et al., PRC 48, 2462 (1993)

Pb-Pb bulk production: comparison with models

ALICE, PRC 88, 044910 (2013)



STAR, PRC 79, 034909 (2009)

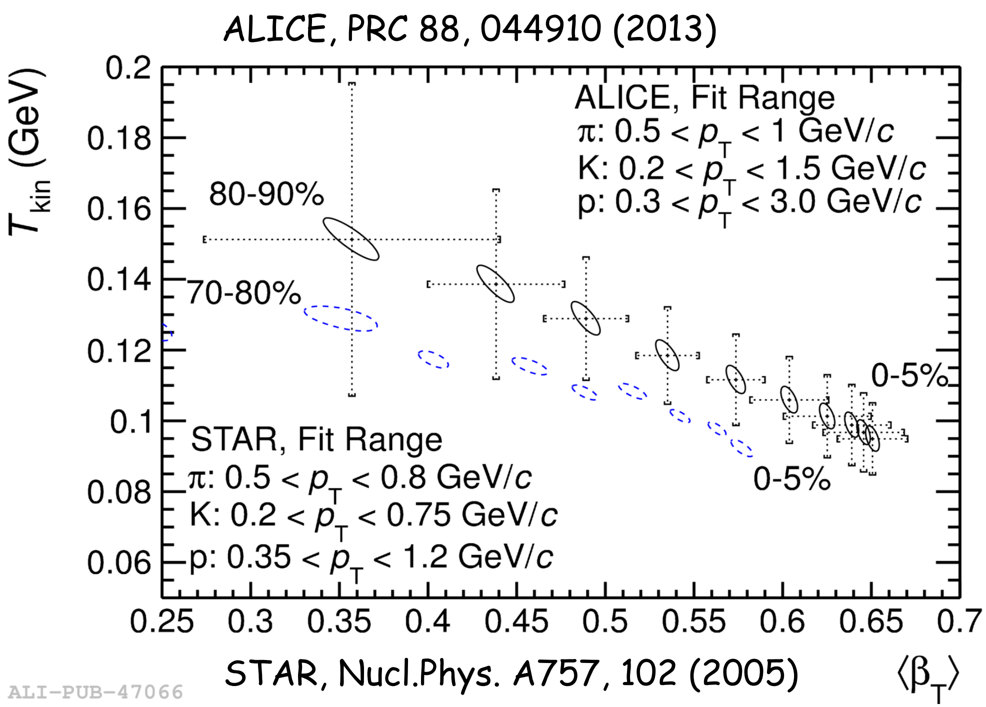
PHENIX, PRC 69, 034909 (2004)

Hydro models:

- VISH2+1: viscous hydrodynamics, no description of hadronic phase
  (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., PRC 87, 024914 (2013))
- Krakow: non equilibrium corrections due to bulk viscosity at the transition from hydro description to particles which change the effective chemical freeze-out temperature Tch
  (Bozek, PRC 85, 064915 (2012))
- EPOS: hydro + UrQMD + jets
  (Werner et al., PRC 85, 064907 (2012))

Pb-Pb bulk production: low p_T spectra

Blast-wave fit parameters for collisions with different centrality at ALICE and RHIC



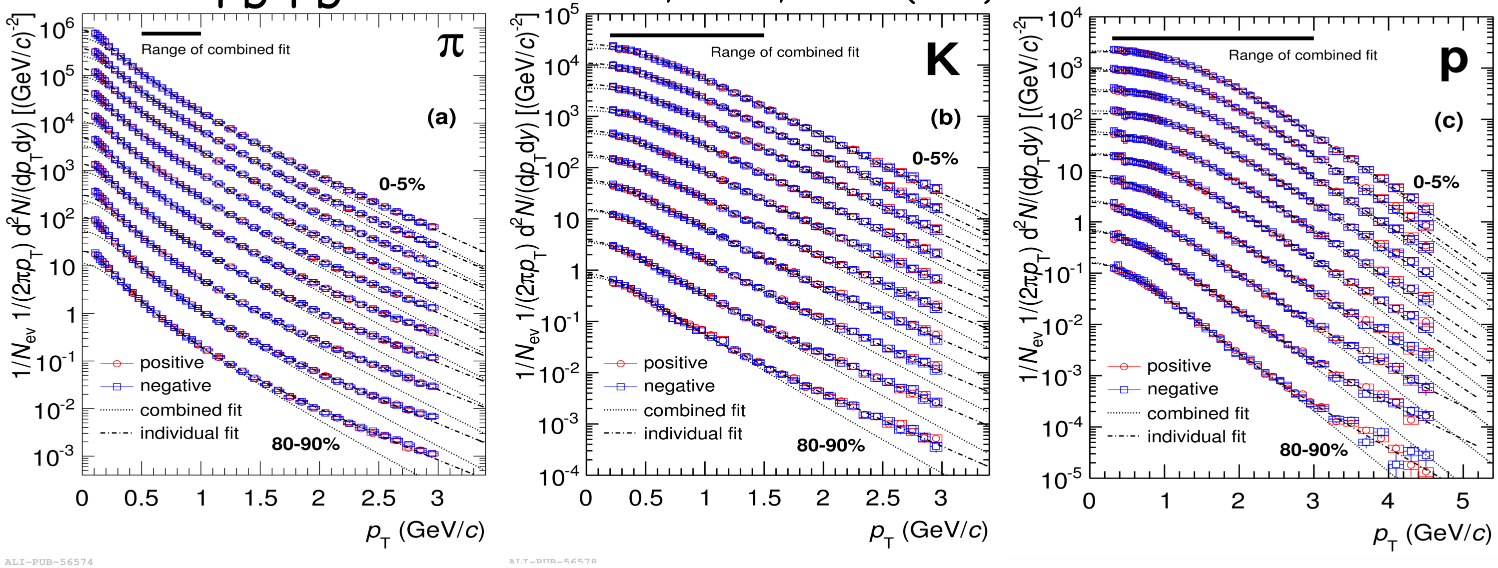
- $\langle\beta_T\rangle$ increases with centrality
- Tkin decreases with centrality

Possible indication of more rapid expansion with increasing centrality

Pb-Pb vs p-Pb spectra: common behavior?

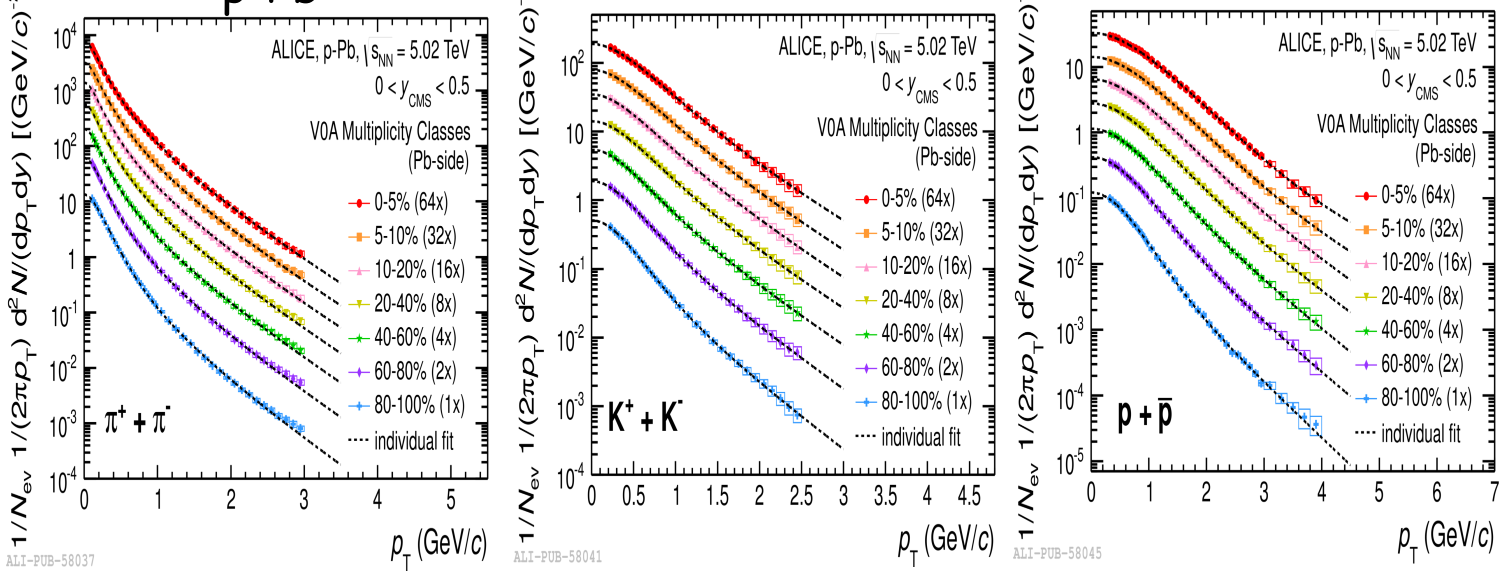
Pb-Pb

ALICE, PRC 88, 044910 (2013)



p-Pb

ALICE, Phys. Lett. B 728 (2014)



Pb-Pb and p-Pb:

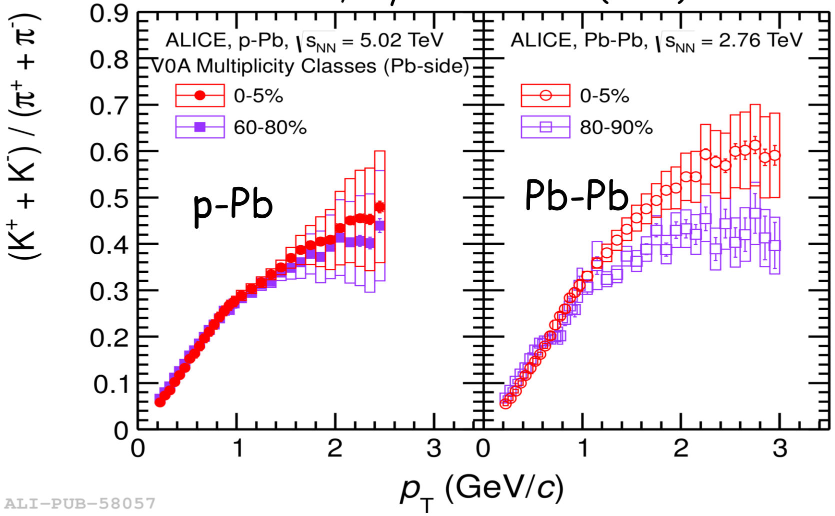
- spectra evolution with centrality/multiplicity
- spectra become harder as the multiplicity increases especially for heavier particles

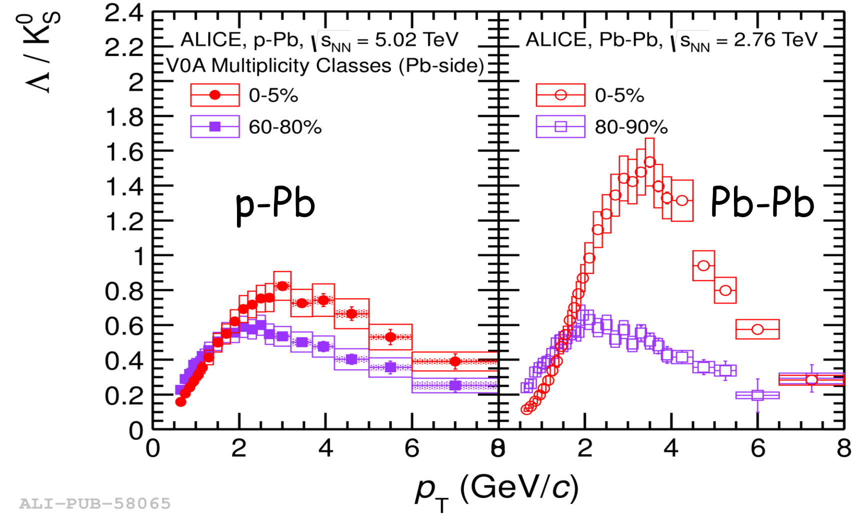
↓

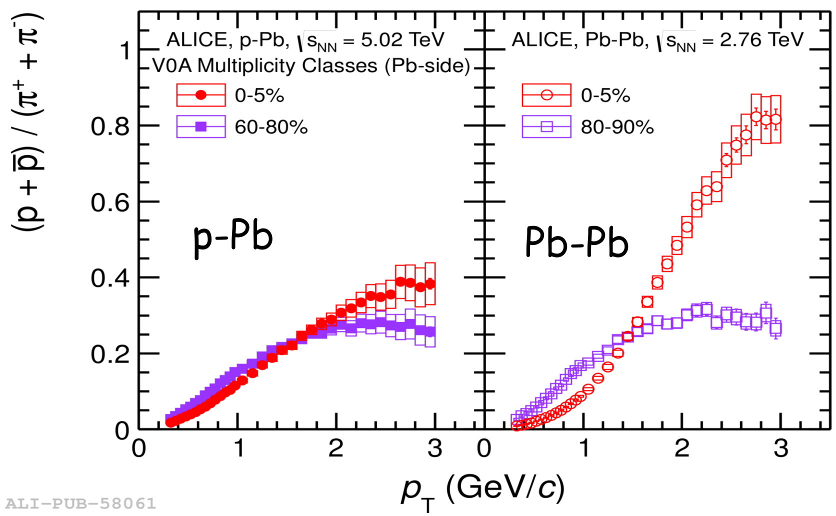
Indication of collective radial expansion also in p-Pb collisions?

Pb-Pb vs p-Pb ratios of spectra: common behavior?

ALICE, Phys. Lett. B 728 (2014)







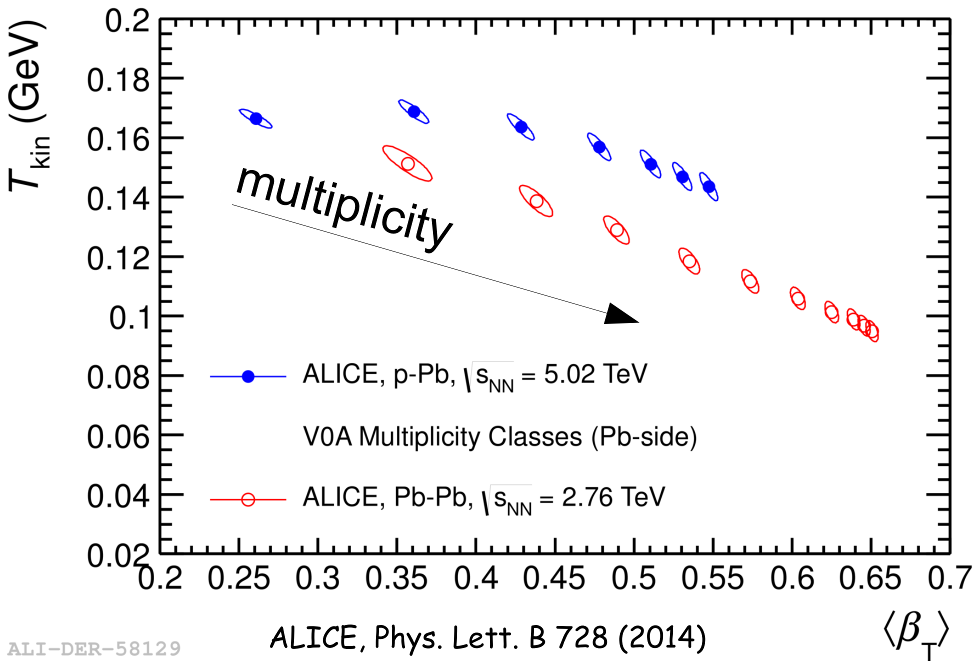
- Spectra become harder as the multiplicity increases
- Mass dependence of spectral shape evolution with multiplicity

p-Pb shows a similar behavior as Pb-Pb, where it is explained in terms of collective radial expansion or coalescence -> final state effects needed to describe p-Pb data ?

p-Pb: testing the collective radial expansion of the system

How to compare spectral shapes and evolution in different collision systems?

-> simultaneous fit of spectra with Blast wave function (Schnedermann et al., PRC 48, 2462 (1993))



ALICE, Phys. Lett. B 728 (2014)

1-Similar trend for p-Pb and Pb-Pb -> consistent with radial flow in p-Pb

At similar $dN_{ch}/d\eta$:

- T_{kin} comparable for the two systems
- $\langle\beta_T\rangle$ higher in p-Pb collisions

 stronger collective flow for smaller system size? Shuryak, arXiv:1301.4470 [hep-ph]

 in p-Pb high multiplicity selection biases the sample towards harder collisions ->this could lead to the larger $\langle\beta_T\rangle$

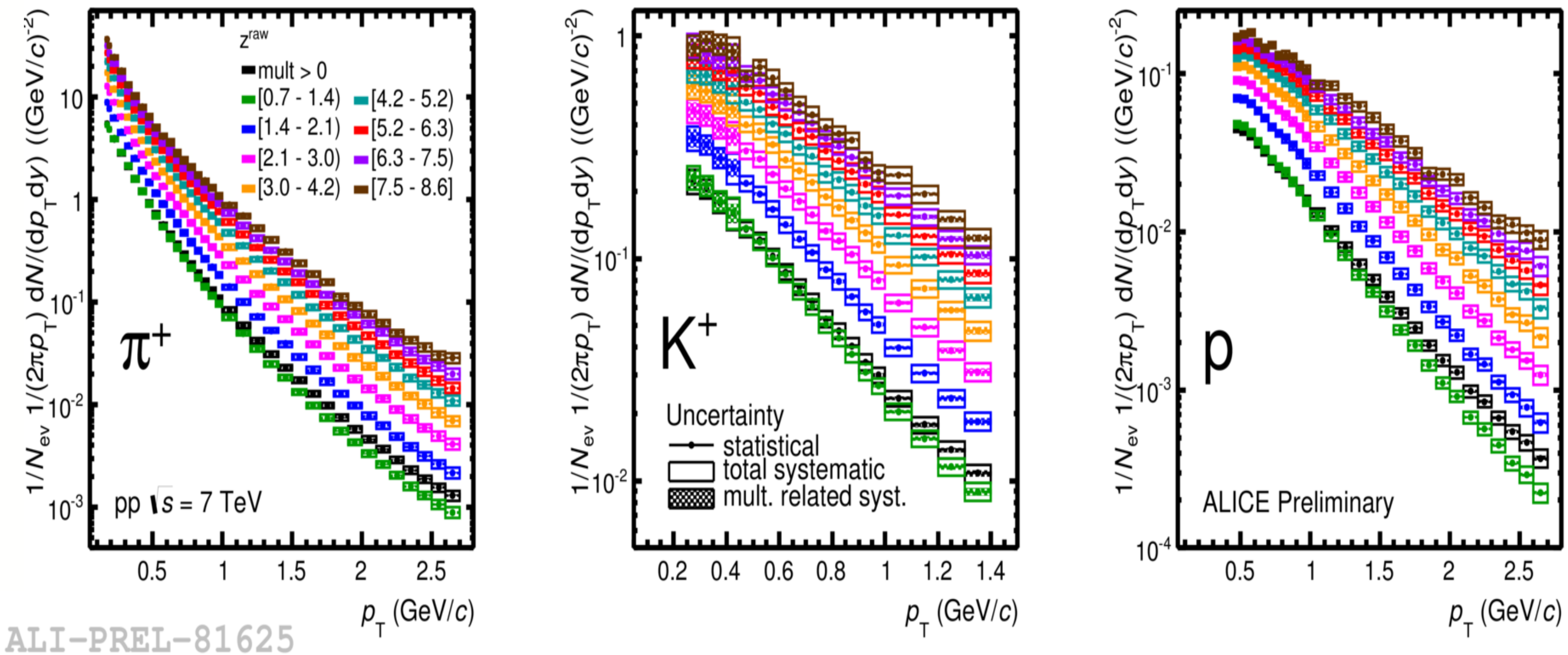
And in pp collisions?

The multiplicity in pp can be quantified by the ratio:

$$z^{raw} = \frac{(N_{ch}^{raw})_{limit}}{\langle N_{ch}^{raw} \rangle_{mult>0}}$$

$$\langle N_{ch}^{raw} \rangle = 9.6, \ |\eta| < 0.8$$

N_{ch}^{raw}	z^{raw}
7-12	0.7-1.3
13-19	1.4-2.0
20-28	2.1-2.9
29-39	3.0-4.1
40-49	4.2-5.1
50-59	5.2-6.2
60-71	6.3-7.4
72-82	7.5-8.6

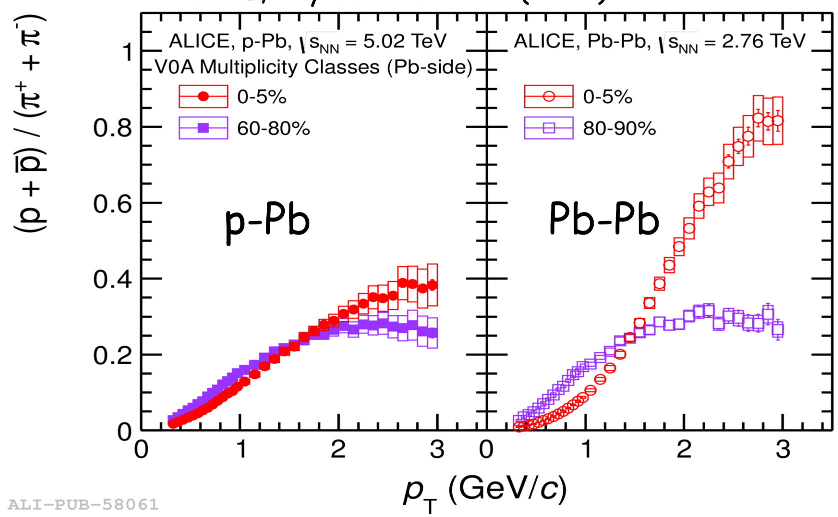


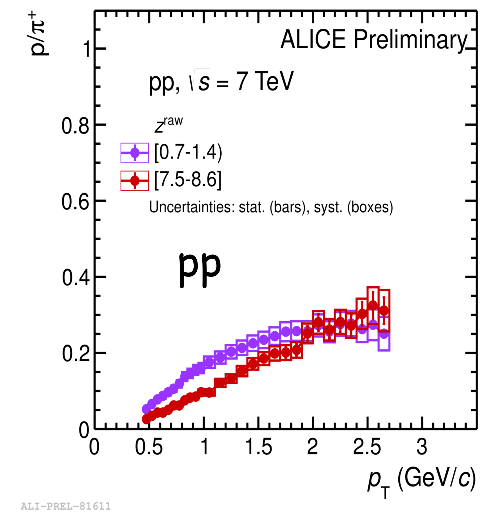
- Multiplicity dependence of the spectral shape
- Spectra become harder as a function of multiplicity and particle mass

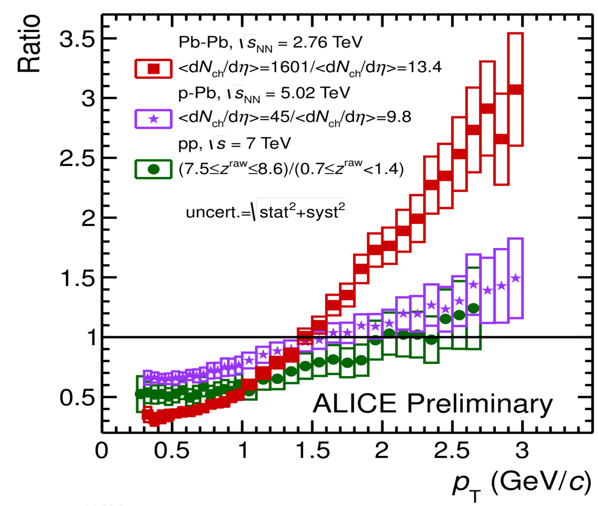
  -> mass ordering as expected from hydrodynamics?

And in pp collisions?

ALICE, Phys. Lett. B 728 (2014)





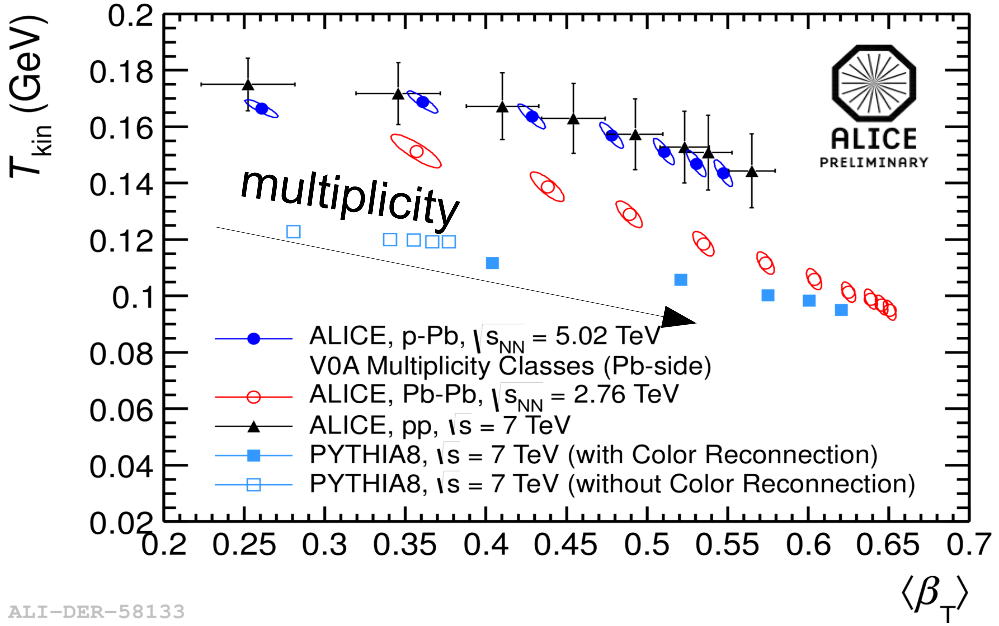


- Heavier particles have larger p_T for all the colliding systems
- Similar trend for pp and p-Pb
- Stronger increase in Pb-Pb

Testing the collective radial expansion

How to compare spectral shapes and evolution in different collision systems?

-> simultaneous fit of spectra with Blast wave function (Schnedermann et al., PRC 48, 2462 (1993))



1-Similar trend for p-Pb and Pb-Pb -> consistent with radial flow in p-Pb

At similar $dN_{ch}/d\eta$:

- T_{kin} comparable for the two systems
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 stronger collective flow for smaller system size? Shuryak, arXiv:1301.4470 [hep-ph]

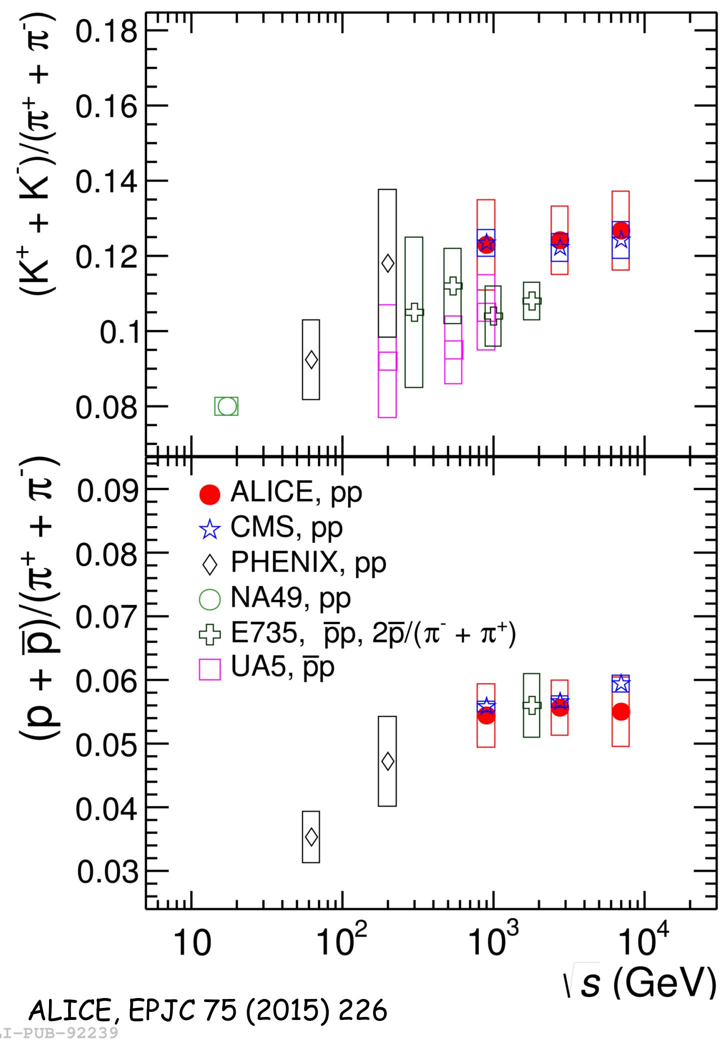
2-PYTHIA (no hydro-like collectivity implemented) shows similar features -> color reconnection (CR) produces flow-like patterns in pp A.Ortiz et al. Phys. Rev. Lett. 111 (2013),042001

3-pp data show similar features

-> Blast-Wave spectral-shape analysis not yet conclusive

Flow, correlations, .. can provide further information

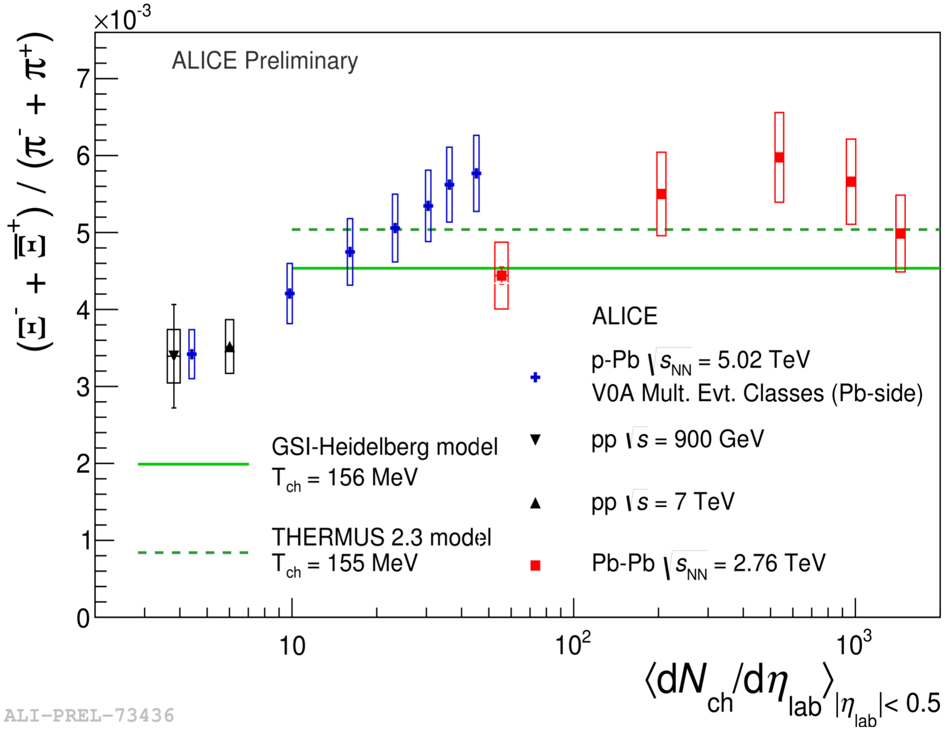
pp particle ratios vs √s

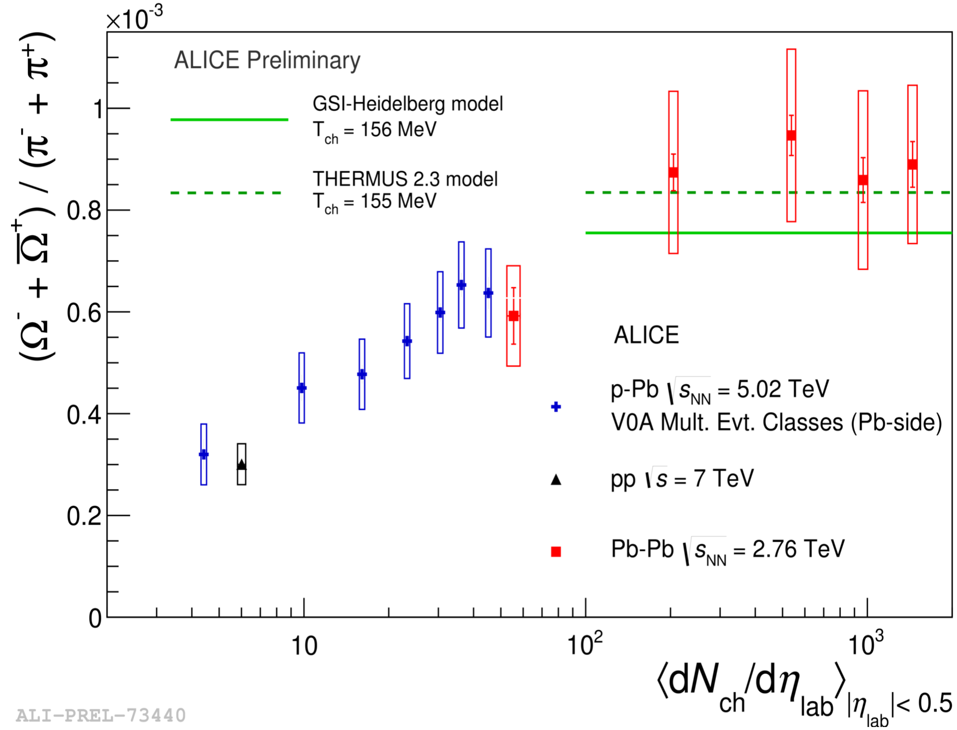


ALICE, EPJC 75 (2015) 226

p_T integrated particle ratios measured in pp collisions show no significant energy dependence at the LHC

Particle ratios vs colliding systems: strangeness enhancement





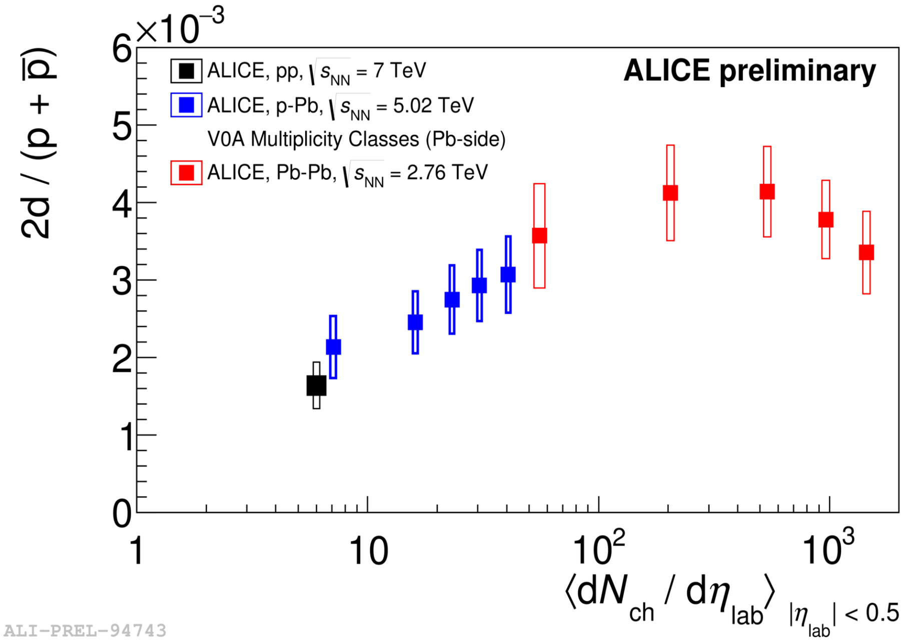
See M. Nicassio talk

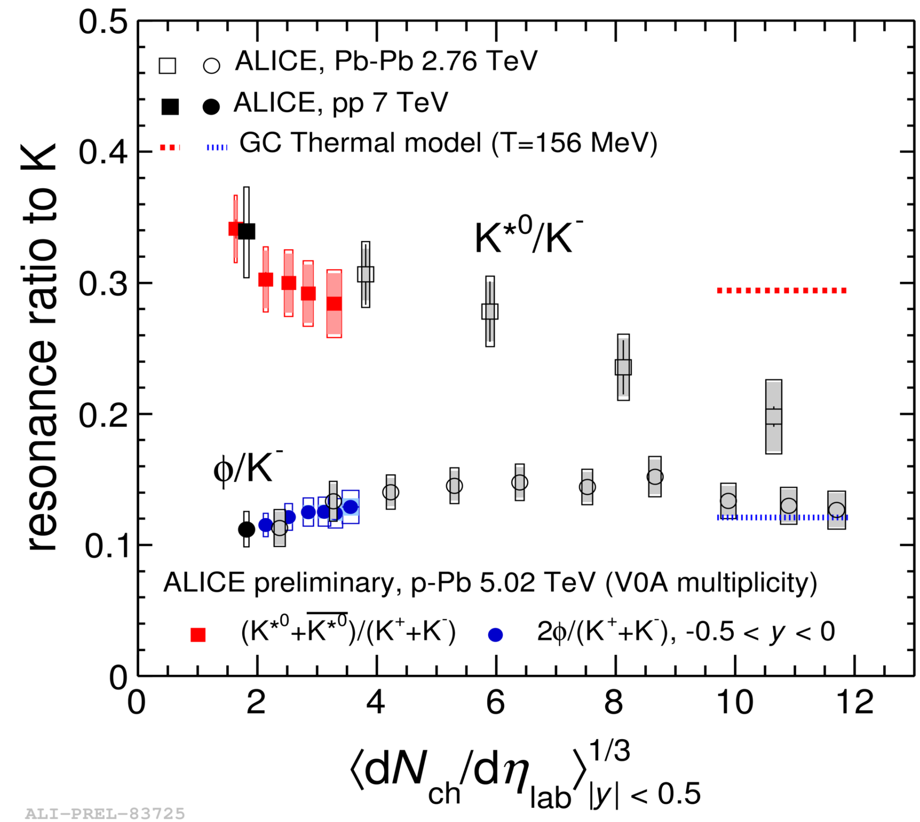
Ξ/π and Ω/π : strangeness enhancement as a function of multiplicity in p-Pb collisions

Low-multiplicity: consistent with pp

High-multiplicity: compatible with central (Ξ) or peripheral (Ω) Pb-Pb

Particle ratios vs colliding systems: deuteron enhancement and K* suppression





d/p: increasing trend with multiplicity in p-Pb
pp collisions is a factor 2.2 lower than in Pb-Pb collisions

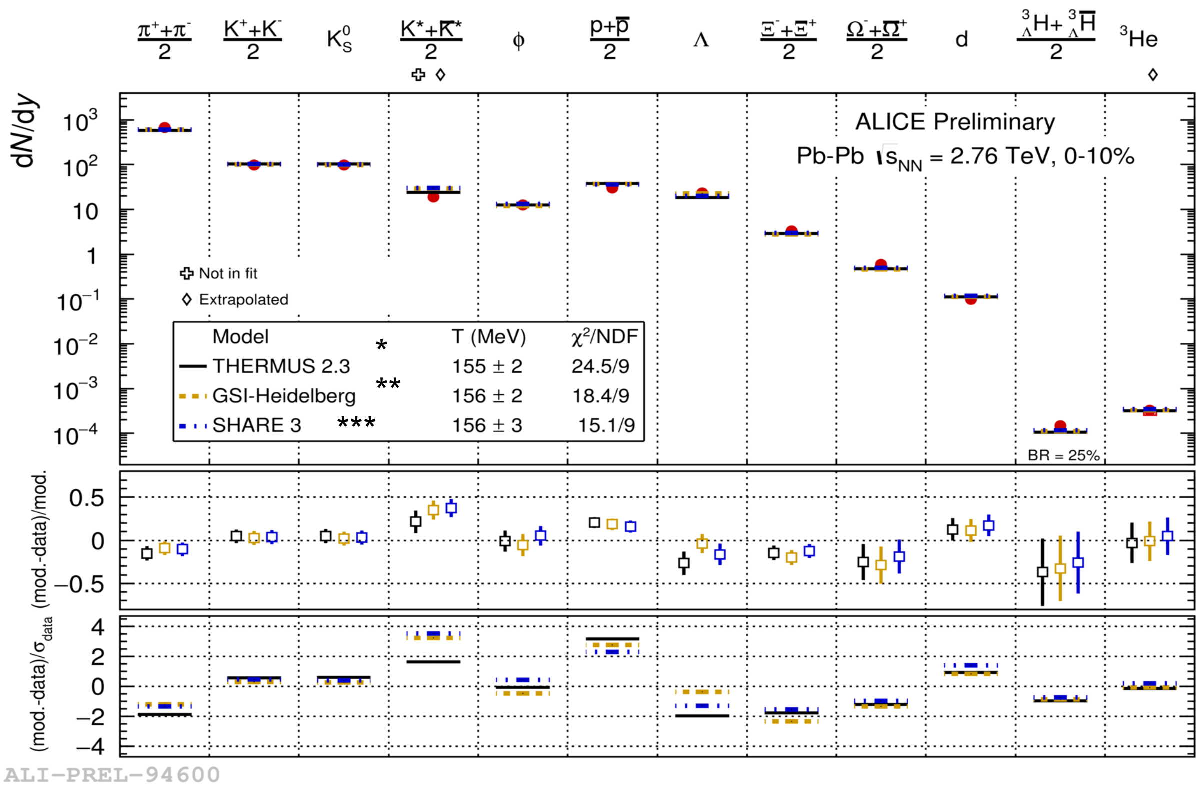
See F. Barile talk

Φ/K: no strong centrality dependence, consistent for pp, p-Pb and Pb-Pb

K*/K: significant suppression from pp and peripheral Pb-Pb to central Pb-Pb

See V.Riabov talk

Thermal models in Pb-Pb



dN/dy interpreted in terms of thermal models -> properties of the system at the chemical freeze-out:

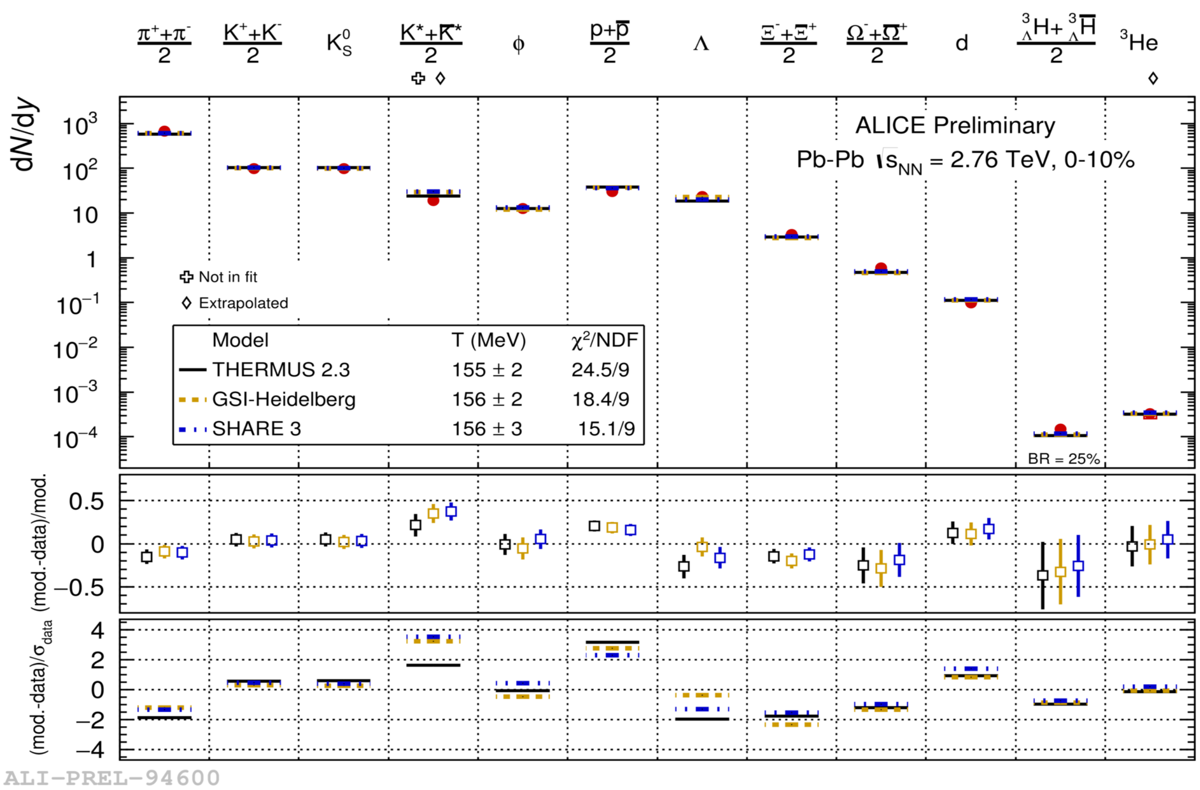
- chemical freeze-out temperature (T_{ch})
- baryochemical potential (μ_B=0 at LHC)
- Volume (V)
- Non equilibrium parameters ($\gamma_{s,q}$ in SHARE model)

3 equilibrium thermal models: THERMUS 2.3*, GSI** and SHARE ($\gamma_s=\gamma_q=1$)***

- Different implementations of equilibrium thermal models yield the same T_{ch} (≈ 156 MeV)
- It is lower than T_{ch} from lower energy extrapolation (≈ 164 MeV)

*S. Wheaton *et al.*, Comp. Phys. Commun. 180 (2009) 84; **A. Andronic et al., PLB 673 (2009) 142; ***M. Petran *et al.*, arXiv:1310.5108v2

Thermal models in Pb-Pb



- Anomaly of the p with respect to equilibrium model expectations
- Agreement restored if p (and K*) are excluded from the fits (X^2/ndf goes from 2 to 1)

Deviation from thermal ratio:

- final state interactions in hadronic phase
- non equilibrium thermal model ($\gamma_{q,s}$>1)
- flavor dependent freeze-out temperature

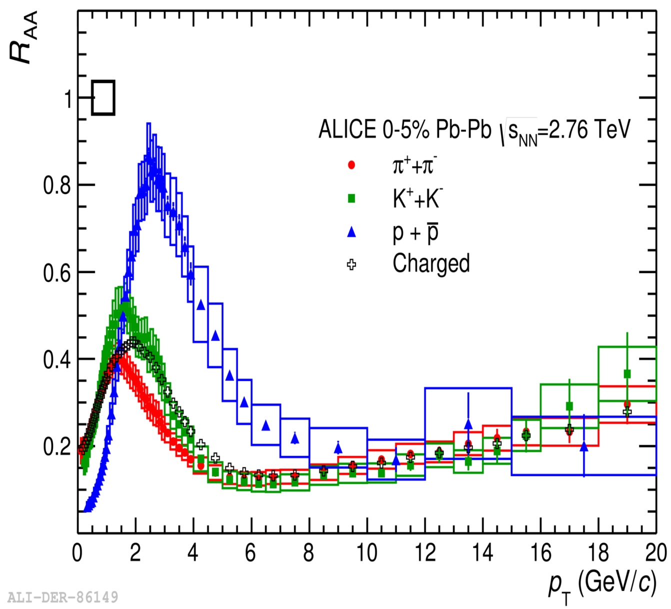
Conclusions

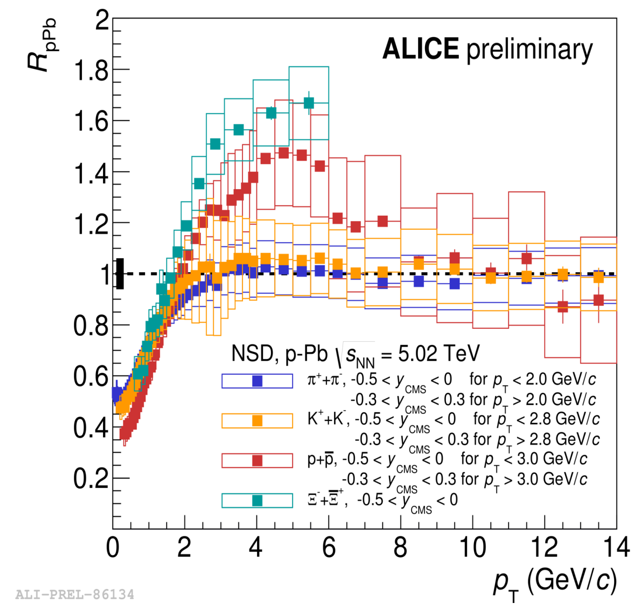
Soft particle production allows one to:

- test hydro models to describe low p_T Pb-Pb spectra
- look for possible collective behavior (radial flow expansion) in pp and p-Pb:
  - particle spectra show similar evolution as a function of centrality/multiplicity in pp, p-Pb, Pb-Pb -> flow-like patterns in high multiplicity p-Pb and pp
- study how the particle ratios change in different colliding systems
  - strangeness and deuteron enhancement + K* and baryon suppression moving from pp to p-Pb to Pb-Pb collisions
- get information of the system at chemical freezeout thanks to thermal models

Backup

R_{AA} vs R_{pPb}



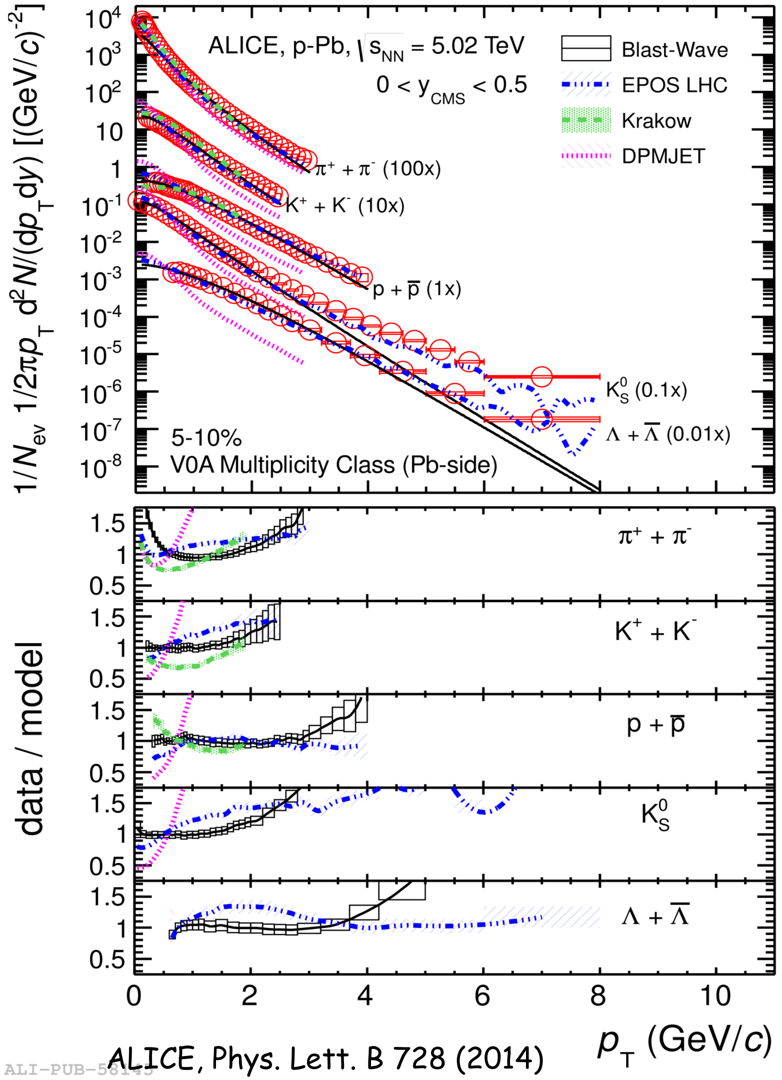


- p_T < 8 GeV/c: p less suppressed than π and K
- p_T > 10 GeV/c same suppression for π, K, p

- R_{pPb} of π, K, p consistent with unity at large p_T
- mass ordering at intermediate p_T
- Cronin peak in charged R_{pPb} from protons

In Pb-Pb collisions the mass ordering is attributed to radial flow -> collective behavior (flow-like effect) in p-Pb collisions?

p-Pb: testing the collective radial expansion of the system

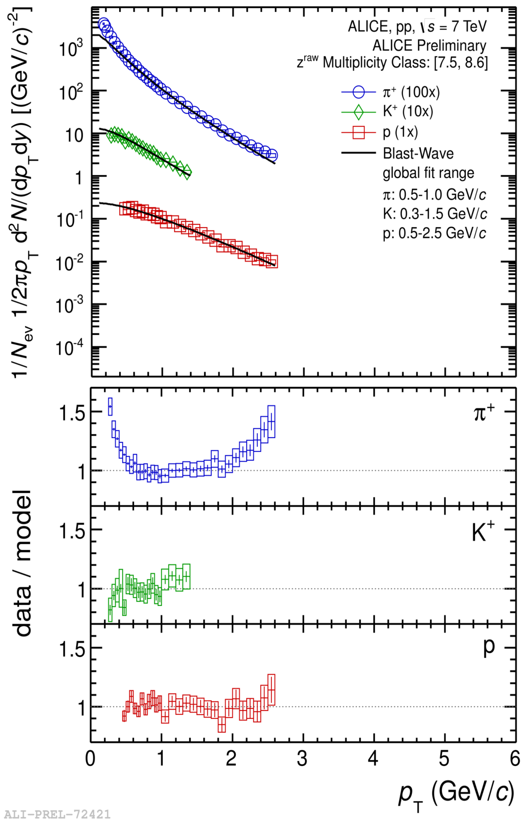


ALICE, Phys. Lett. B 728 (2014)

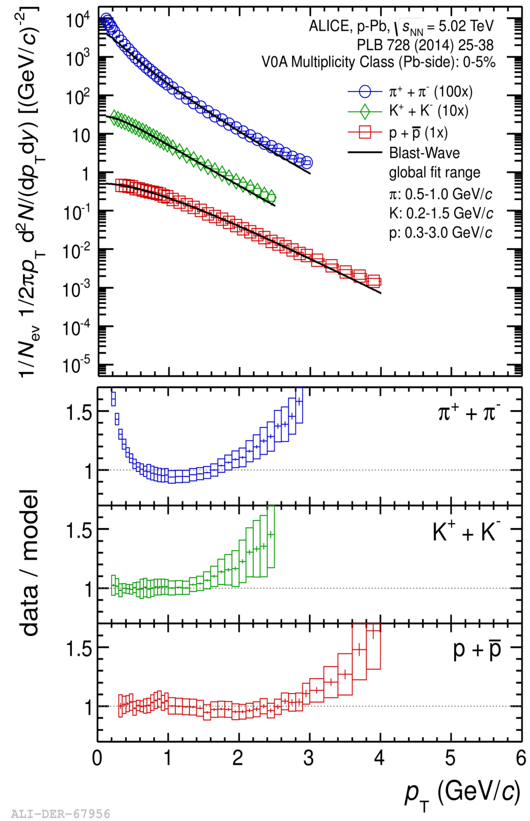
- **DPMJET** QCD inspired generator:. Can not reproduce p_T distributions and <p_T> of charged particles.
- **Krakow** (Bozek, PRC85, 014911 (2012)), viscous hydro model. Reproduces π and K for p_T < 1 GeV/c where hydro effects dominate. At higher p_T the observed deviations for pions and kaons are possibly due to non-thermal component. Good description of p.
- **EPOS LHC** (Pierog et al., arXiv:1306.0121 [hep-ph]), initial hard scattering creates "flux tubes" which either escape the medium and hadronize as jets, or contribute to the bulk matter, described in terms of hydrodynamics. It can reproduce π and p within 20% over the full measured range; larger deviations for kaons and lambdas.

Models including hydrodynamics better describe the data

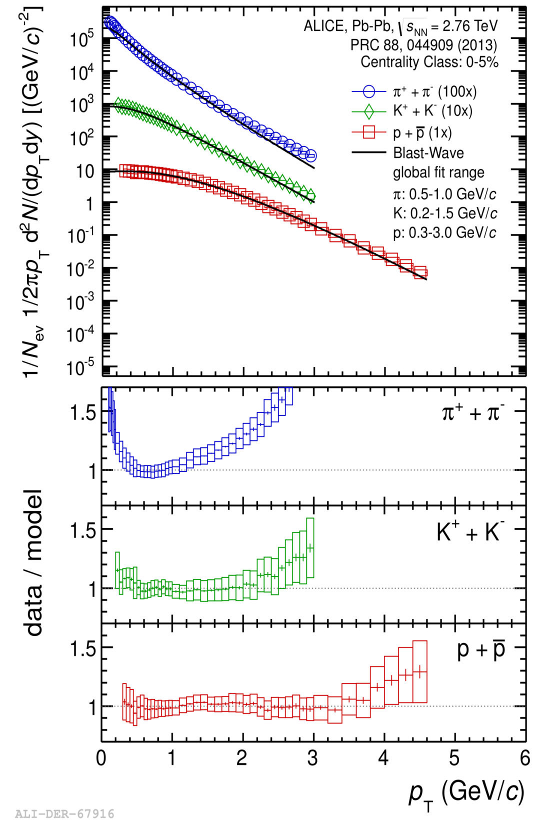
Blast wave fit in pp, p-Pb, Pb-Pb



ALICE, Phys. Lett. B 728 (2014)

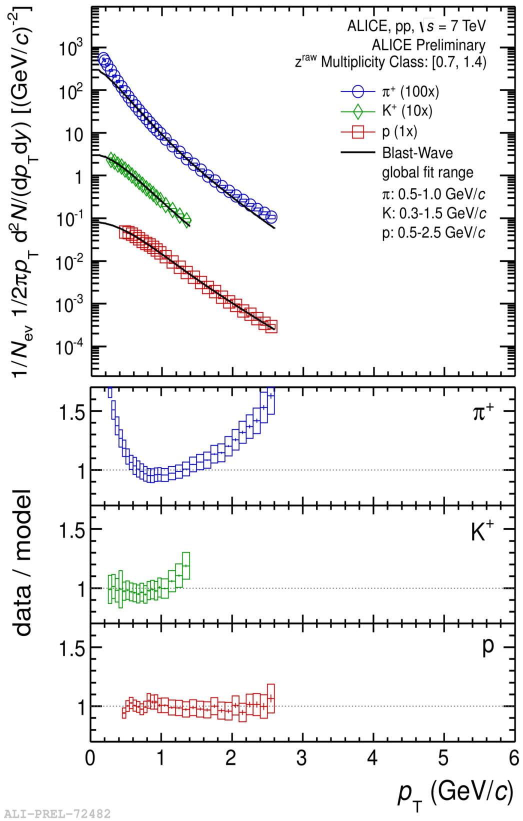


ALICE, PRC 88, 044910 (2013)

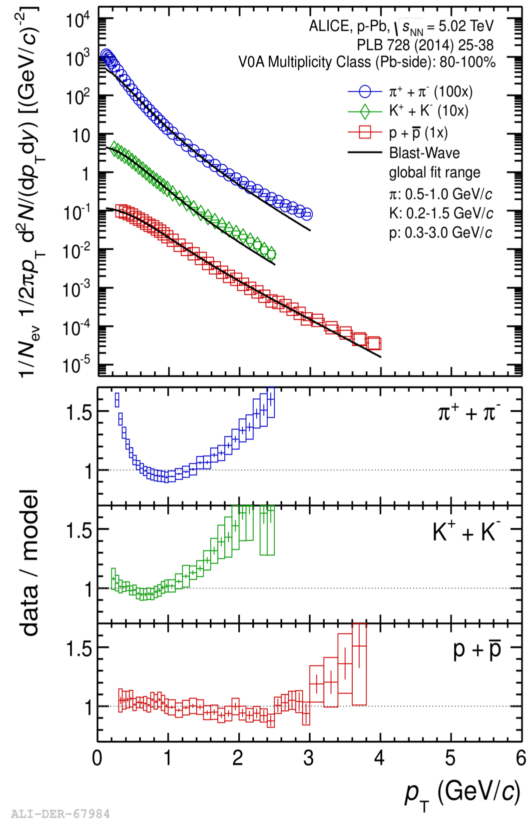


- The quality of the fits is similar for all three systems
- The p_T range on which the spectra follows the hydro shape increases going towards higher multiplicity/centrality

Blast wave fit in pp, p-Pb, Pb-Pb



ALICE, Phys. Lett. B 728 (2014)



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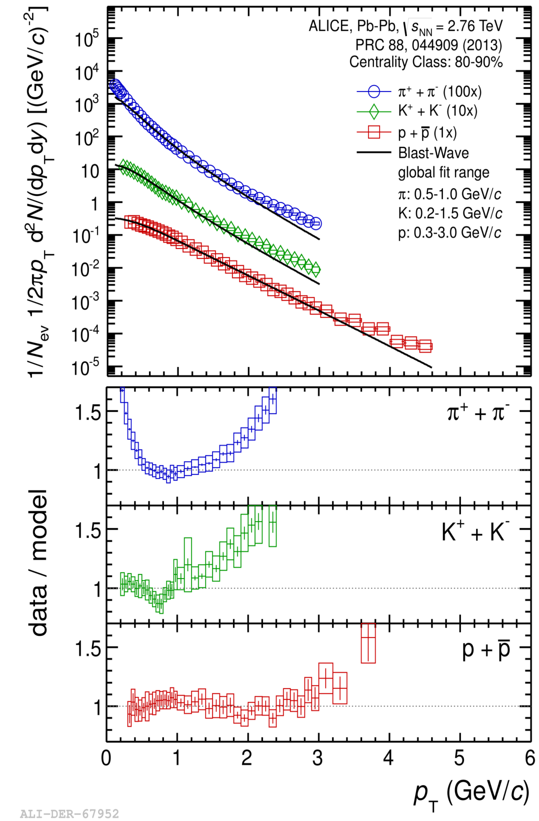

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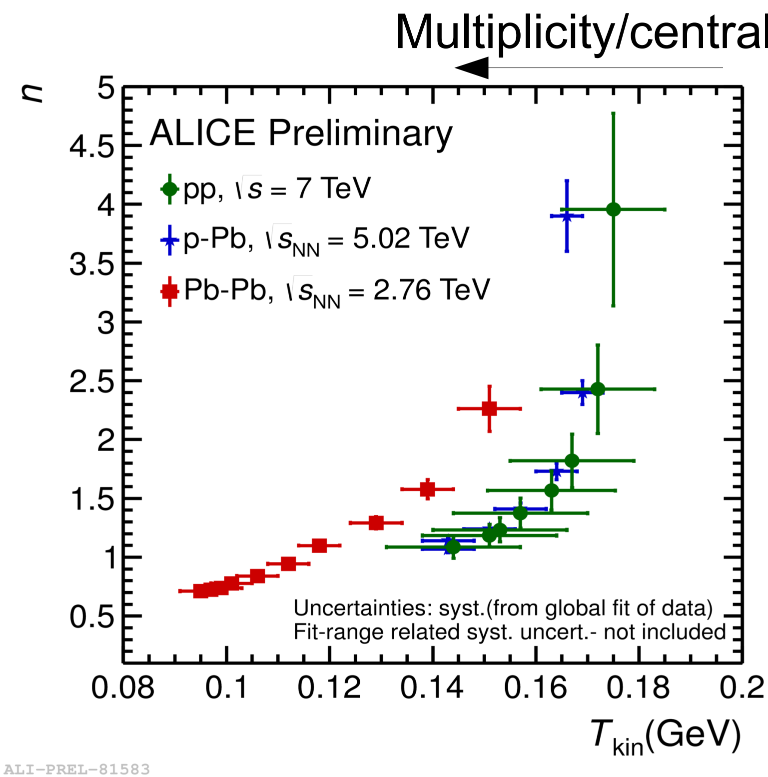
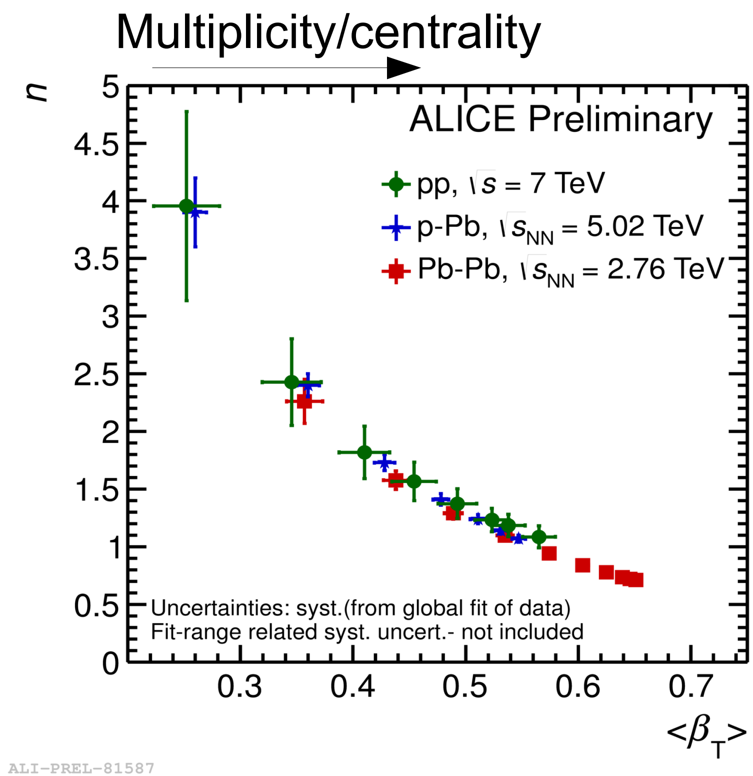


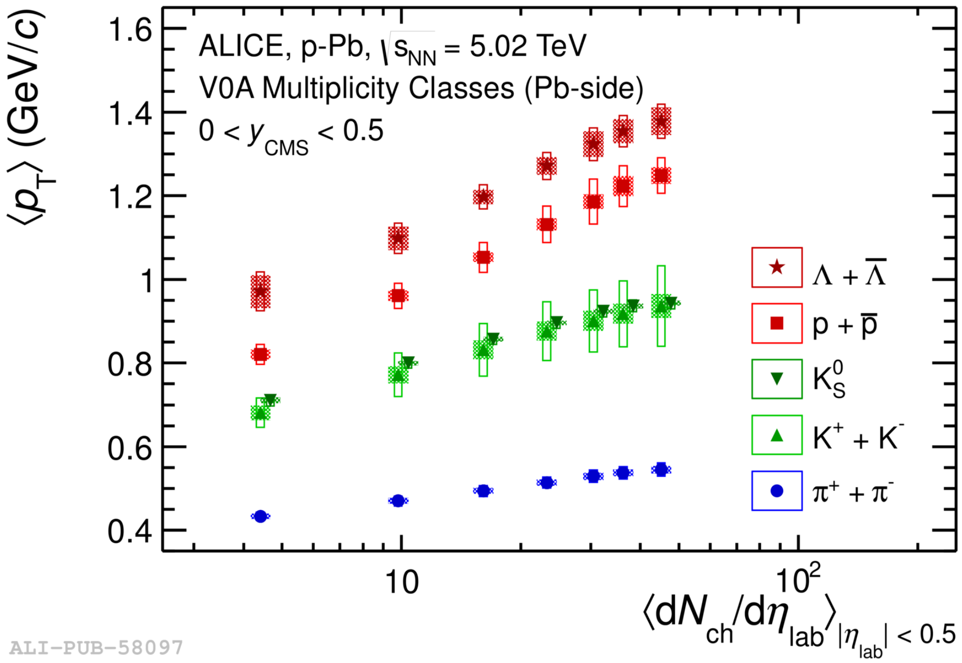


$n - T_{kin}$ correlations:

similar for pp and p-Pb; Pb-Pb has lower T_{kin} values

$\langle\beta_T\rangle$ approaches a linear dependence as a function of position in the fireball for pp, p-Pb and Pb-Pb

p-Pb: mean p_T



$\langle p_T \rangle$ increases with multiplicity, at a rate which is stronger for heavier particles. A similar mass ordering is also observed in Pb-Pb collisions as a function of multiplicity.

Blast-wave function

Assumption: locally thermalized medium, expanding collectively with a common velocity field and undergoing an instantaneous common freeze-out.

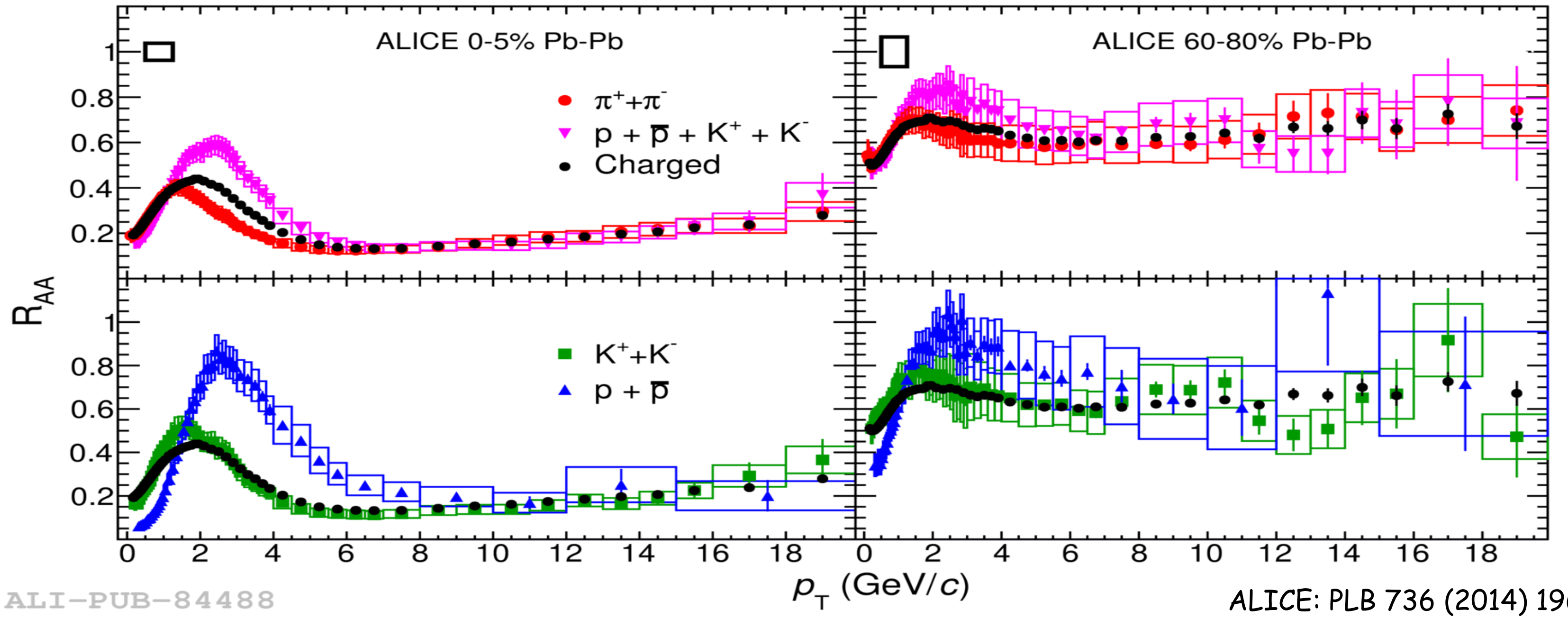
$$\frac{1}{p_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} \propto \int_0^R r\mathrm{d}r\, m_{\mathrm{T}}\, I_0\left(\frac{p_{\mathrm{T}}\sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_{\mathrm{T}}\cosh\rho}{T_{kin}}\right), \qquad (1)$$

where the velocity profile ρ is described by

$$\rho = \tanh^{-1}\beta_{\mathrm{T}} = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_s\right). \qquad (2)$$

Here, $m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$ is the transverse mass, I_0 and K_1 are the modified Bessel functions, r is the radial distance from the center of the fireball in the transverse plane, R is the radius of the fireball, $\beta_{\mathrm{T}}(r)$ is the transverse expansion velocity, β_s is the transverse expansion velocity at the surface, n is the exponent of the velocity profile and T_{kin} is the kinetic freeze-out temperature. The free parameters in the fit are T_{kin}, β_s, n and a normalization parameter.

π, K, p: R_{AA}



ALICE: PLB 736 (2014) 196-207

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

- p_T < 8 GeV/c: p less suppressed than π and K
- p_T > 10 GeV/c same suppression for π, K, p -> particle composition and ratios at high p_T are the same in medium and in vacuum (disfavors models where large energy loss is associated with mass ordering or large fragmentation differences between baryons and mesons)