

ALICE

Studying collective phenomena and very low p_T pion production in pp and A-A collisions with the ALICE experiment

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Politecnico di Torino and I.N.F.N.



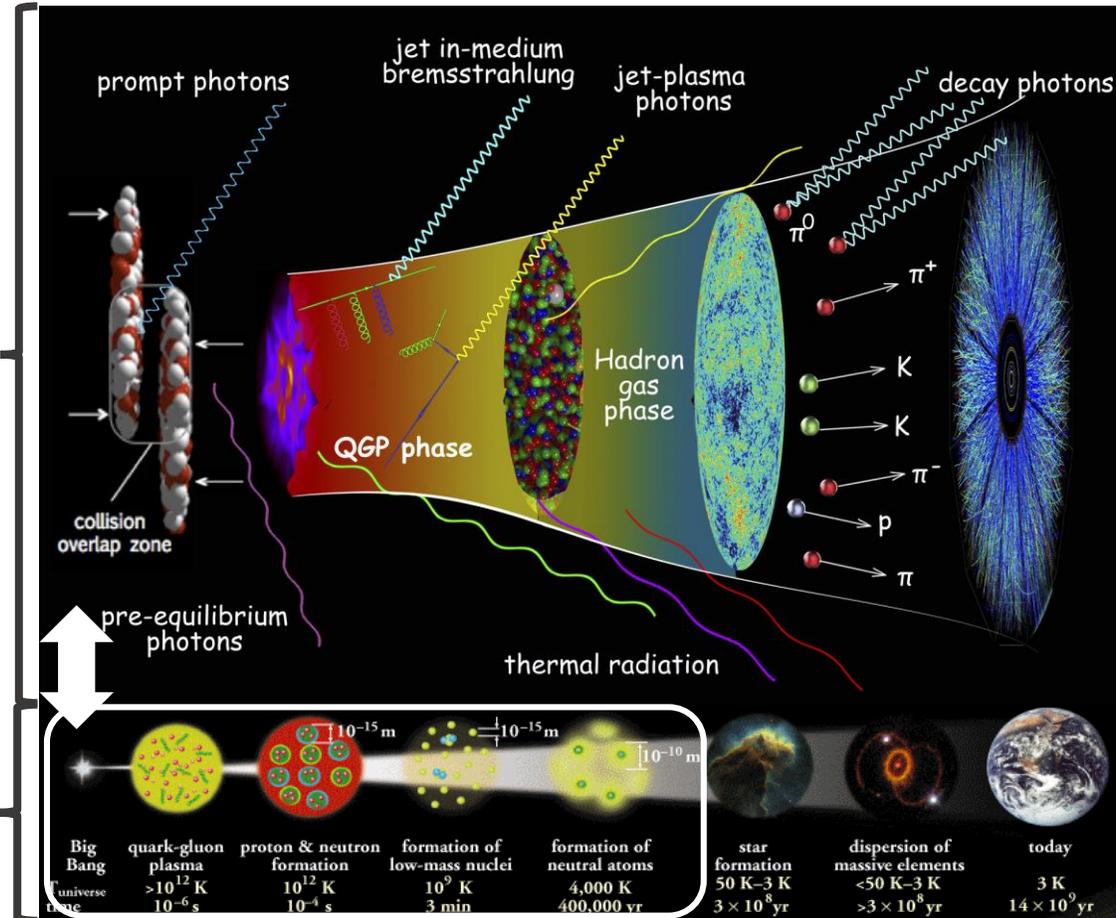
Investigating collectivity

- In heavy ion collisions the p_T distributions of identified hadrons carry information about the collective expansion of the system



A-A collisions

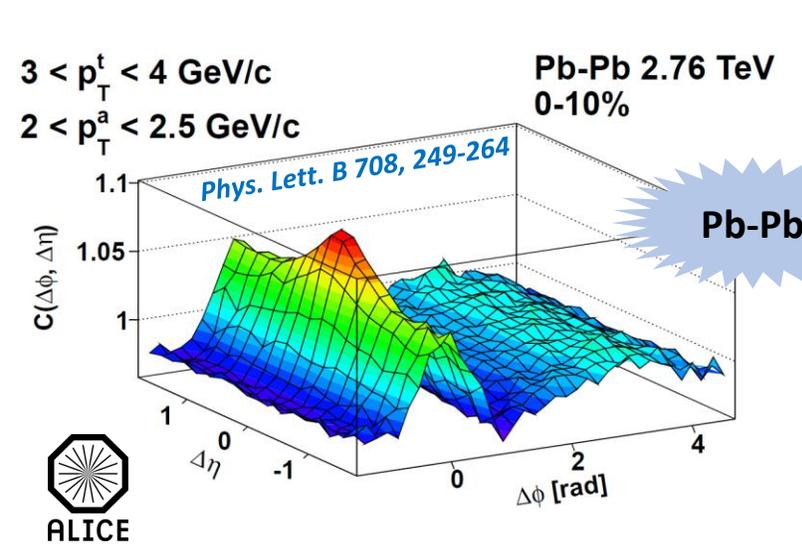
Big Bang



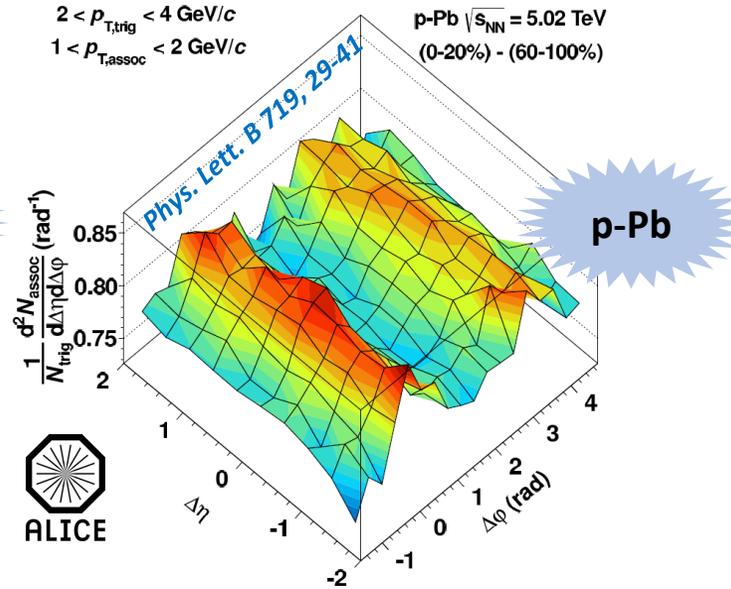
Why study identified particle p_T -spectra in pp and A-A collisions?

- ✓ Comparison between collision systems:
 - ↔ Hints of **collectivity in pp?**
- ✓ Comparison to hydro models
 - ↔ **Kinetic freeze-out temperature?**
 - ↔ Transverse velocity distribution?
- ✓ Particle correlation in longitudinal and azimuthal (η, ϕ) direction
 - ↔ **Anisotropic flow**

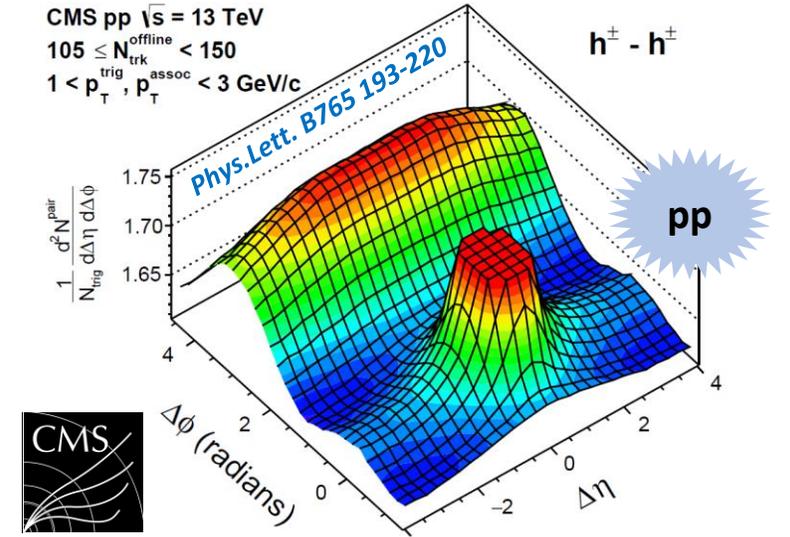
Collectivity & Two-particle angular correlations



Pb-Pb



p-Pb



pp

Pb-Pb collisions

- Bulk-dominated regime, where **hydrodynamic modelling** gives a good description of the data

p-Pb collisions

- **Excess structure** in the correlation forms **two ridges**.
- Consistent with **Colour Glass Condensate** based predictions and **hydro** model calculations

pp collisions (high mult.)

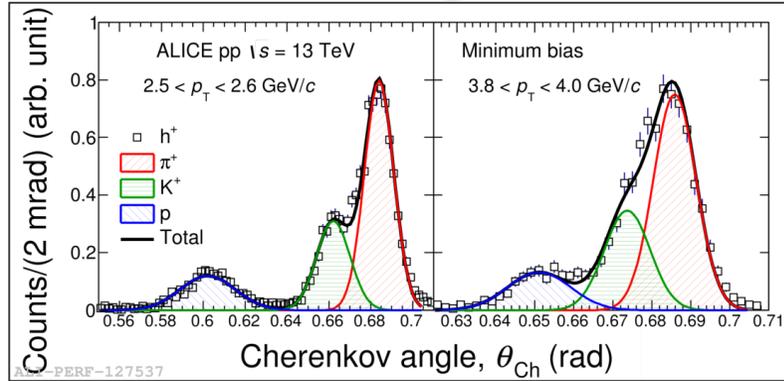
- **Ridge-like structure** visible at $\Delta\phi \approx 0$
- At higher p_T^{trig} (5-6 GeV/c) the ridge almost disappears.
- Qualitatively **similar to what is observed in central Pb-Pb collisions** at LHC energies.
- **Unexpected** in minimum bias pp collisions and **pp MC models**

Outline

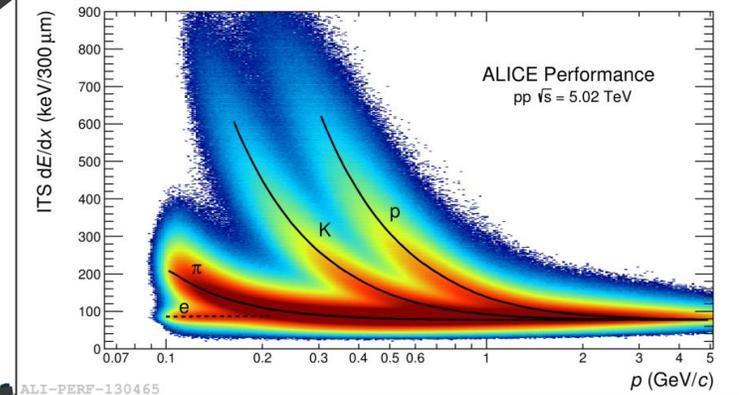
- 1 ALICE experimental apparatus
- 2 Transverse-momentum spectra
- 3 Low- p_T pion production
- 4 Particle ratios
- 5 Blast-wave analysis
- 6 Comparison to models



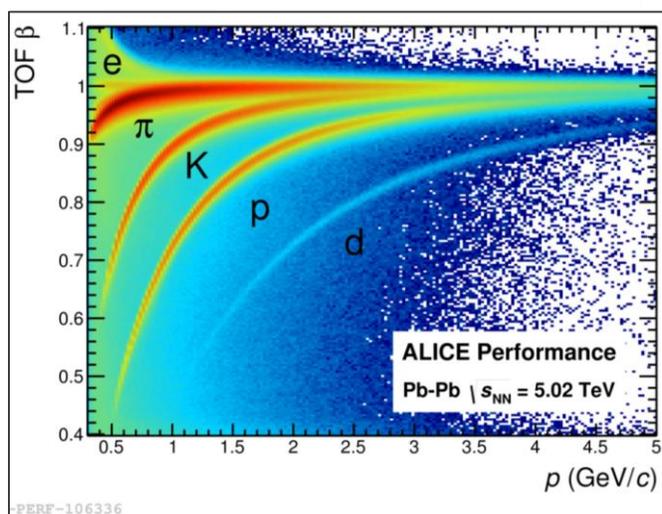
A Large Ion Collider Experiment – Particle ID.



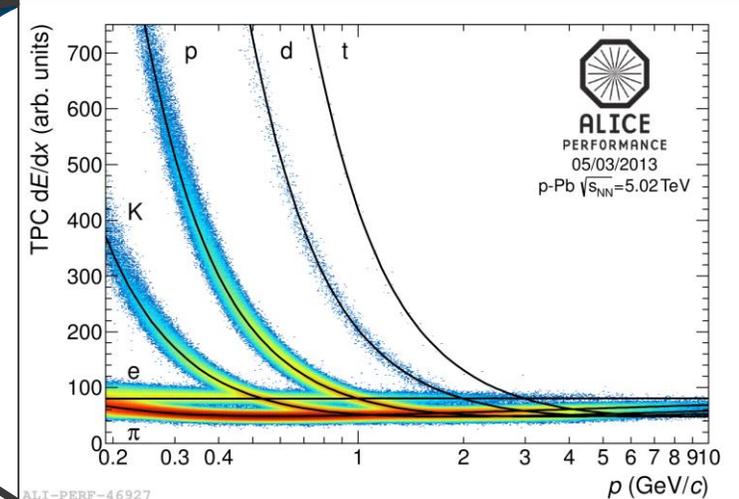
HMPID



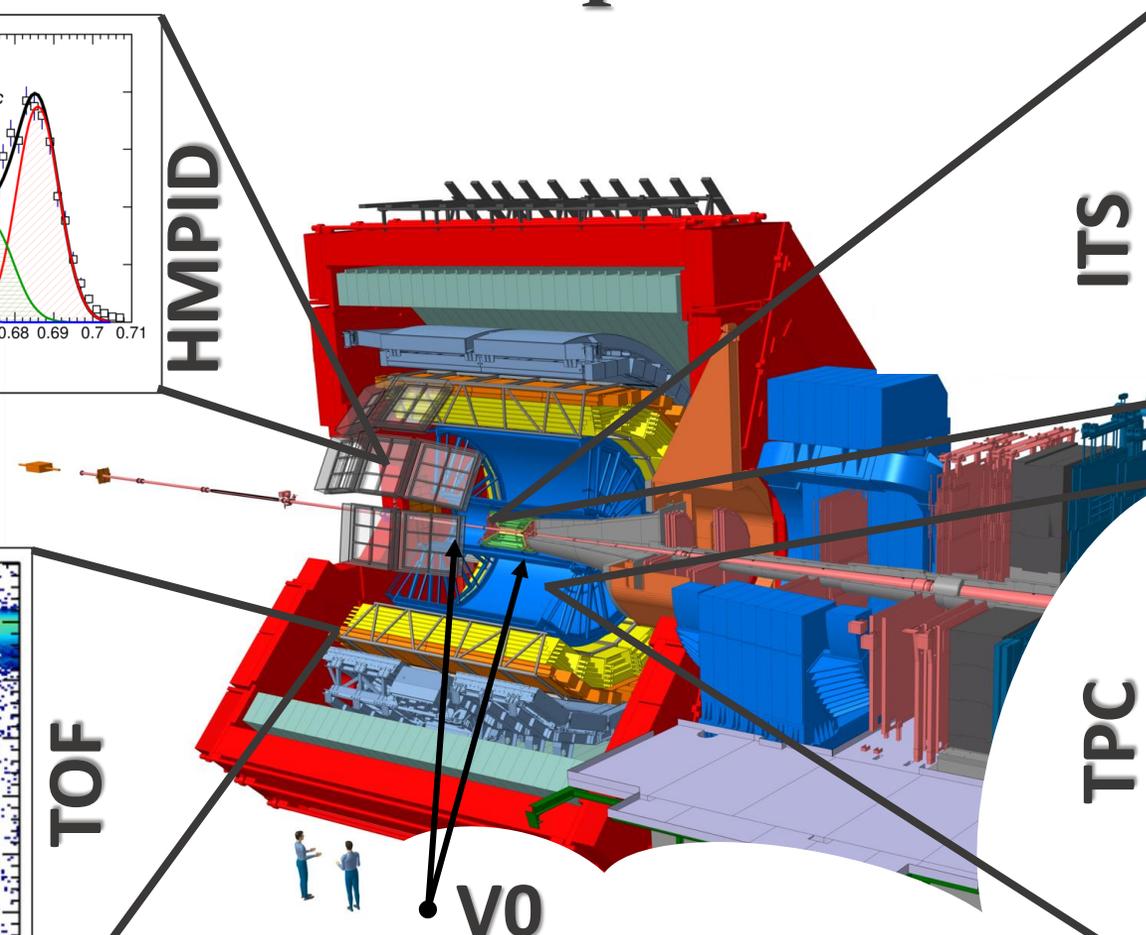
ITS



TOF

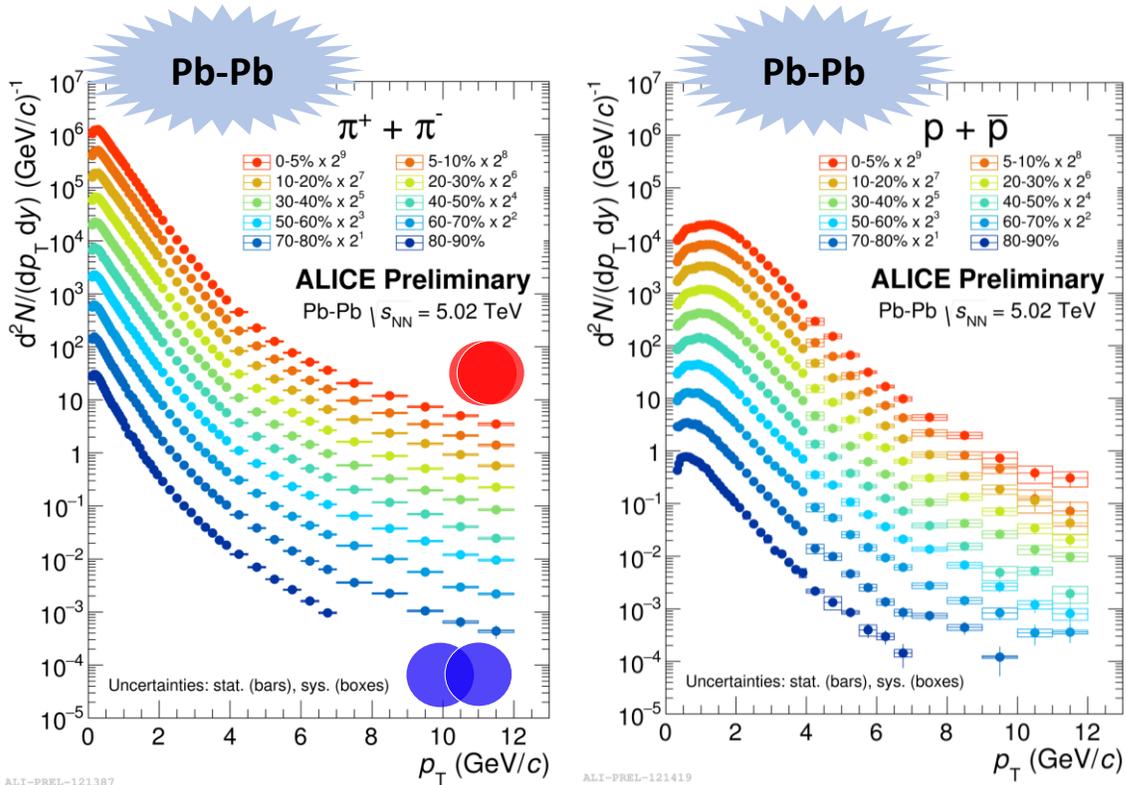


TPC



▶ Trigger + centrality determination by slicing the measured signal amplitude distribution.

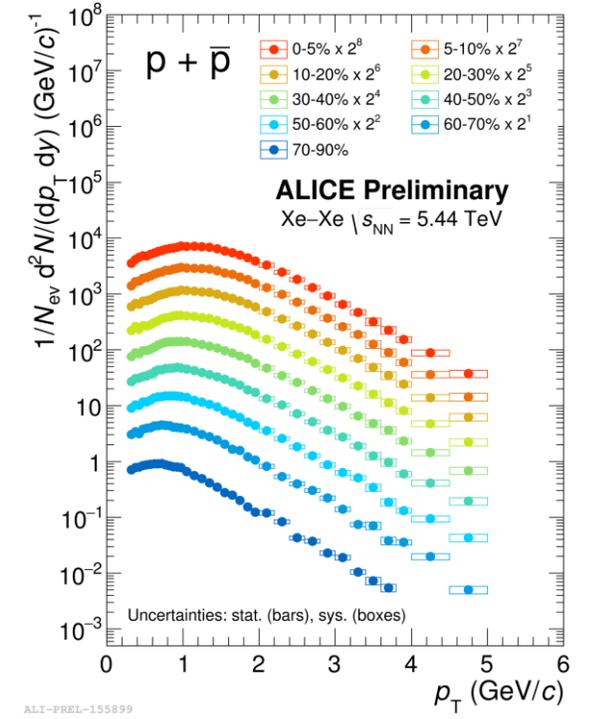
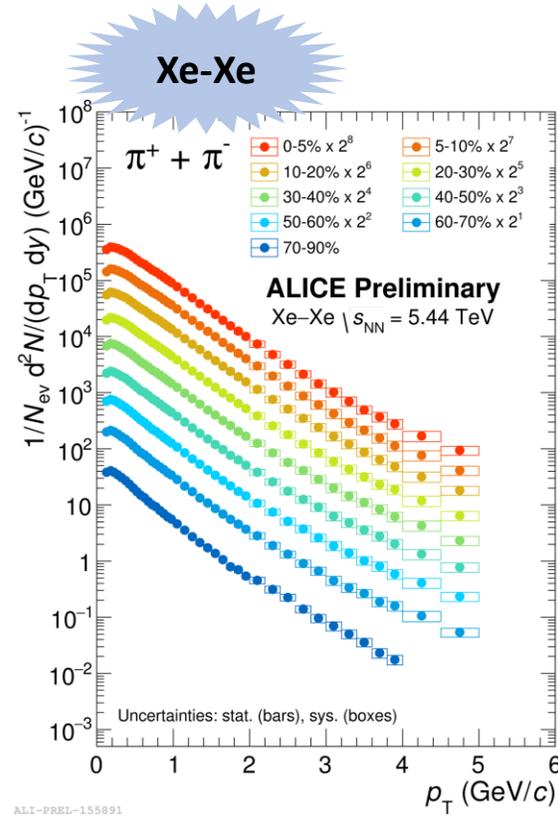
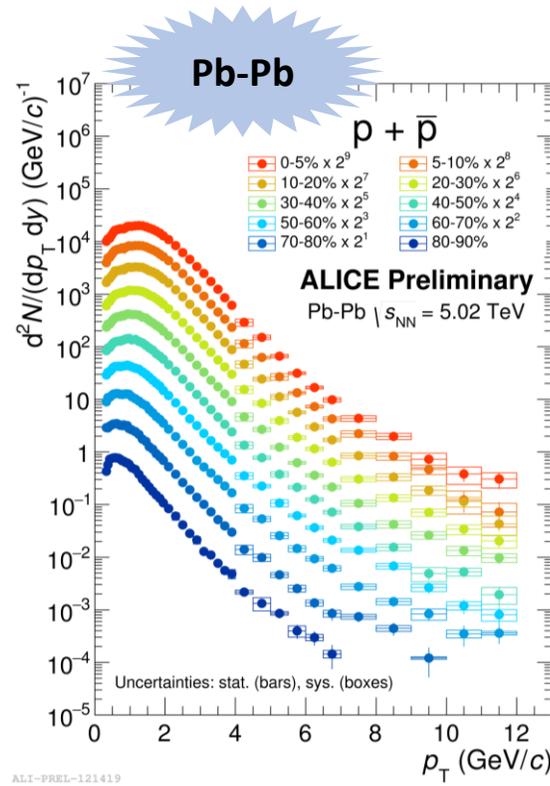
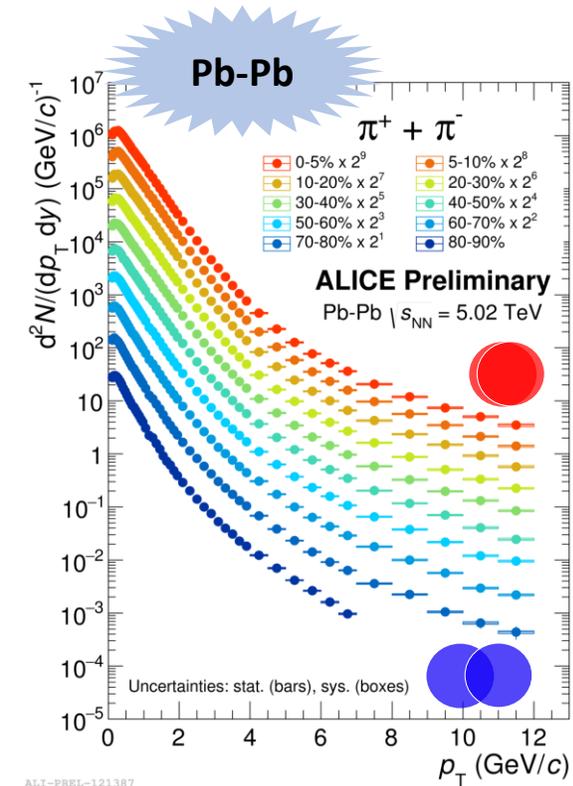
Transverse momentum spectra



- Spectra in Pb-Pb: the spectra become harder as the multiplicity increases and the change is most pronounced for heavier particles → Effect of **radial flow**



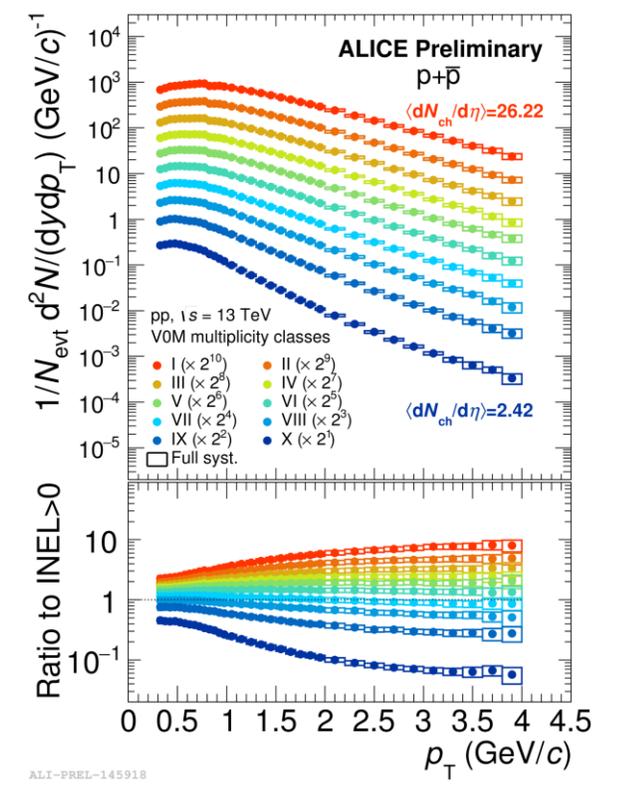
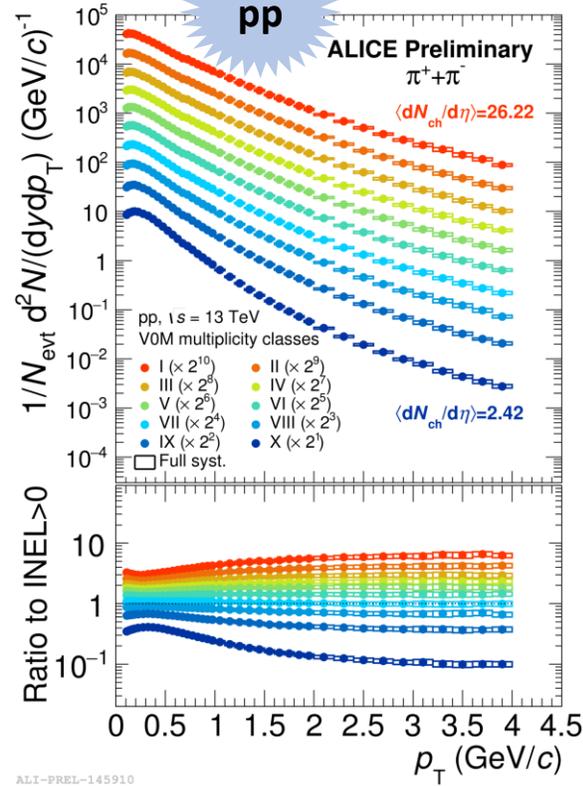
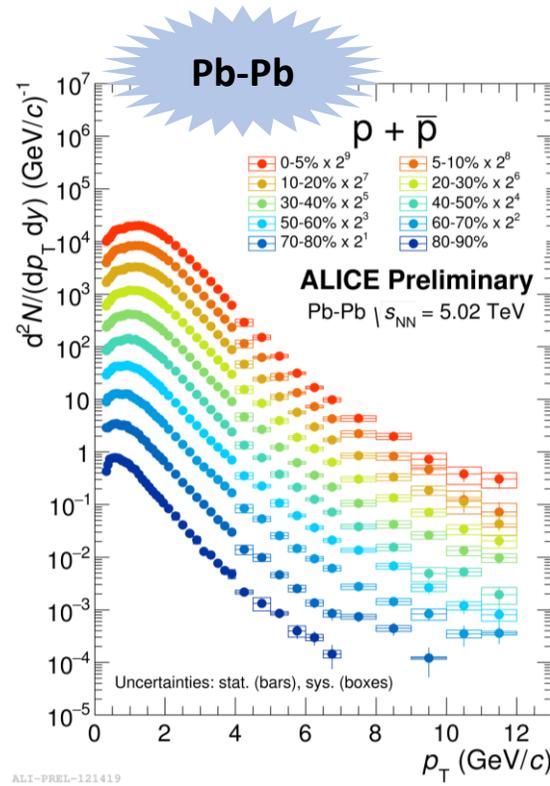
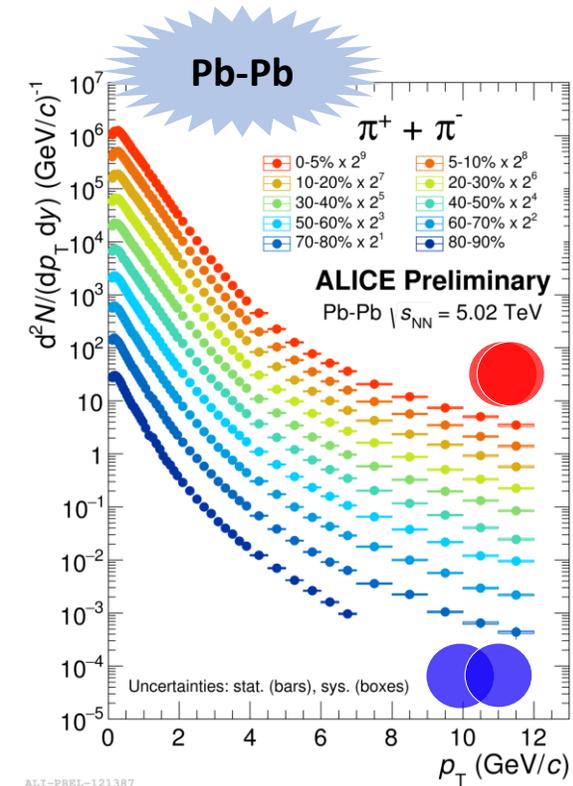
Transverse momentum spectra



- Spectra in Pb-Pb: the spectra become harder as the multiplicity increases and the change is most pronounced for heavier particles → Effect of **radial flow**
- Spectra in Xe-Xe: lower p_T reach but, at low p_T , similar behaviour as in Pb-Pb



Transverse momentum spectra

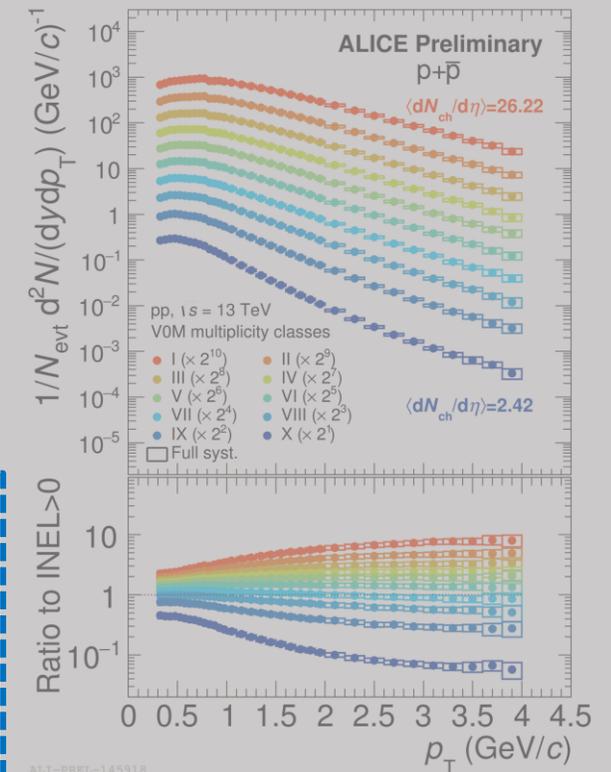
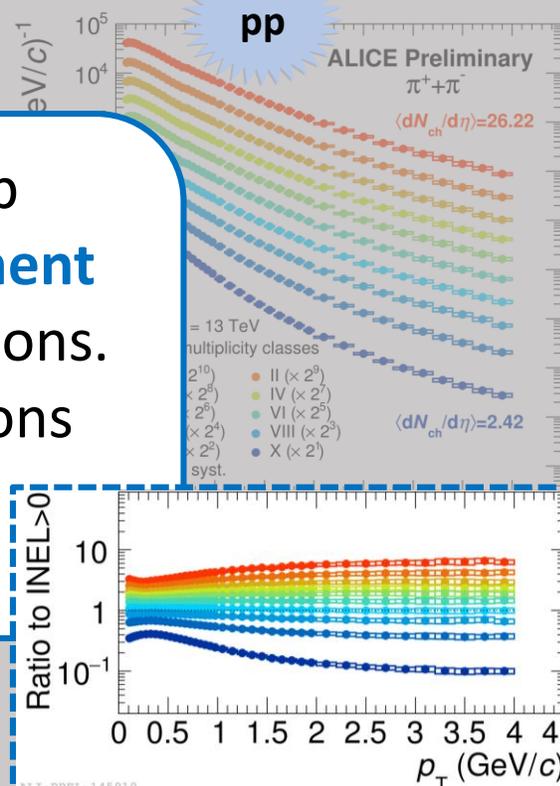
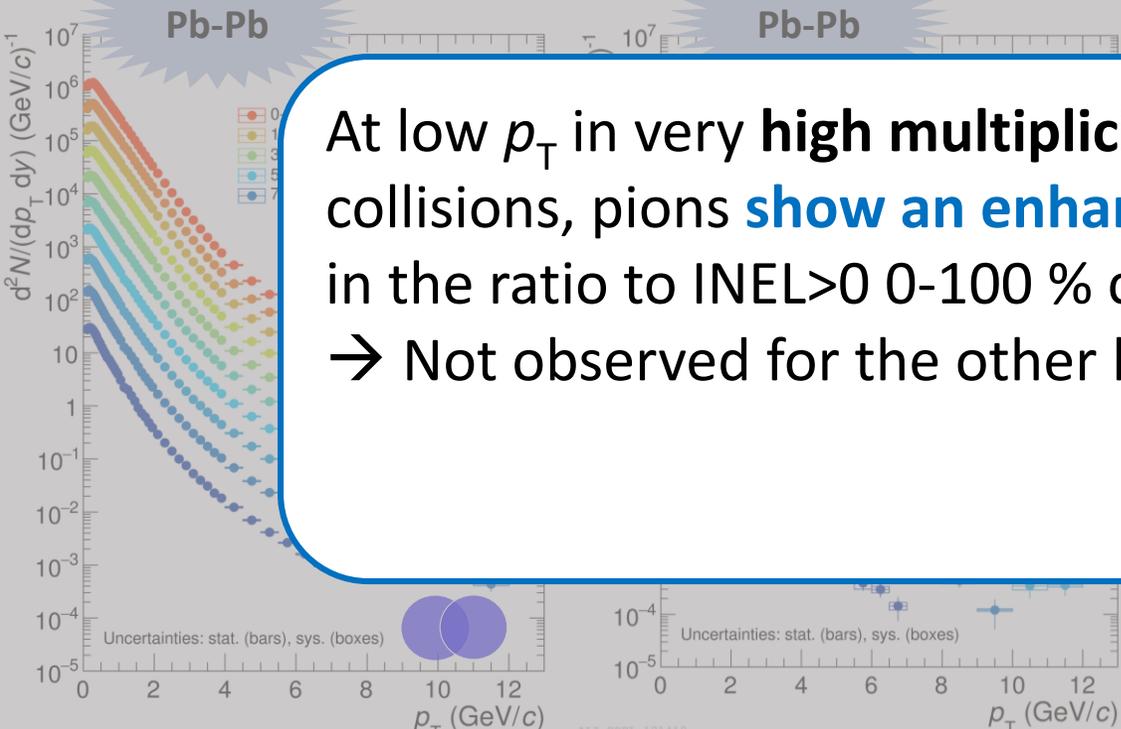


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- Spectra in pp: softer compared to Pb-Pb. A shape dependence across multiplicities is observed.



Transverse momentum spectra

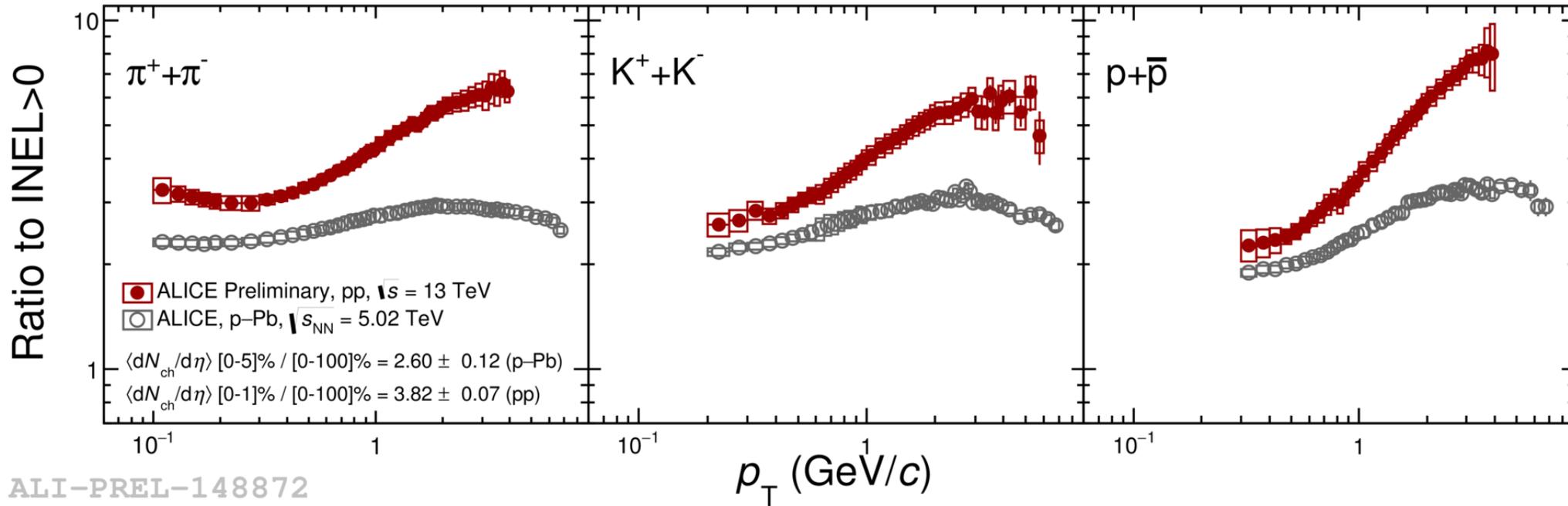
At low p_T in very high multiplicity pp collisions, pions show an enhancement in the ratio to INEL>0 0-100 % collisions.
 → Not observed for the other hadrons



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Low p_T pions in pp and p-Pb collisions

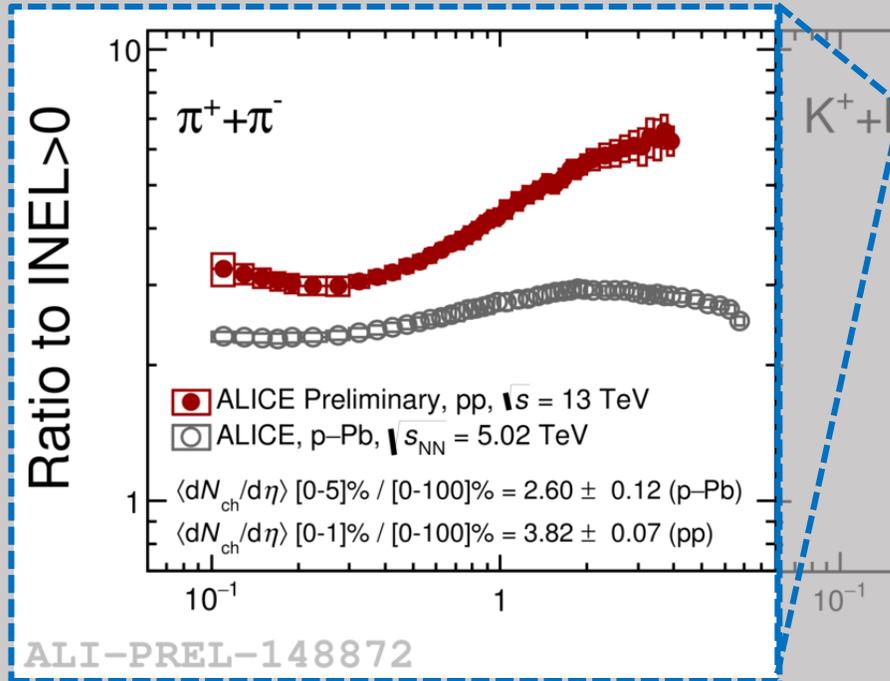


HIGH MULTIPLICITY

- Low p_T pion production shows an enhancement in pp collisions at high multiplicity
 - not observed for kaons and protons
 - **not observed in p-Pb** at similar charged-particle multiplicities



Low p_T pions in pp and p-Pb collisions

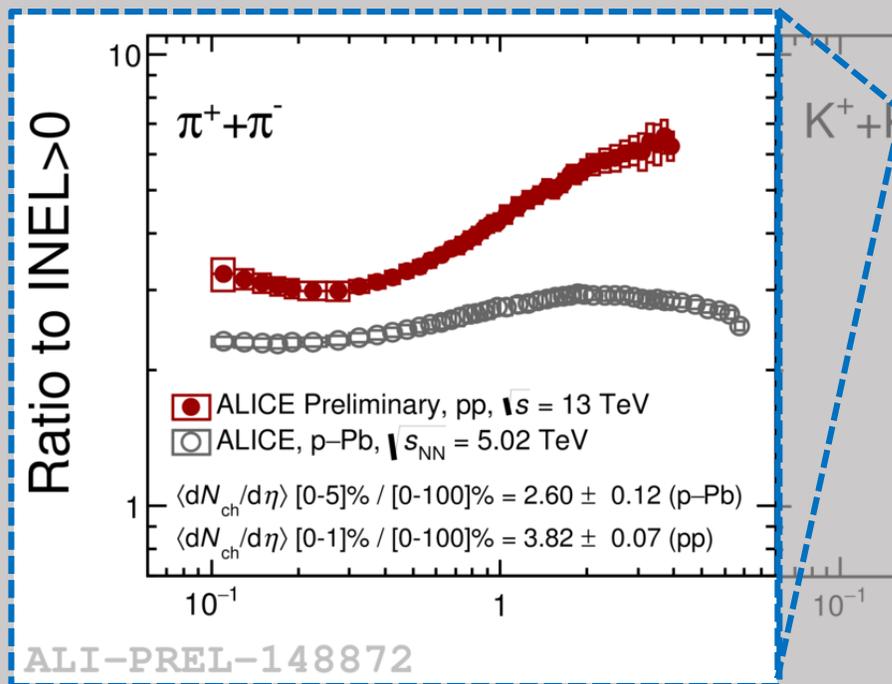


- **Possible explanation:** the matter produced at LHC energies is formed out of chemical equilibrium
 - Chemical non-equilibrium model predicts that the pion abundances are characterized by a **non-zero value of the chemical potential (μ)** that is close to the **critical value for the Bose-Einstein Condensation (BEC)**
 - $\sim 5\%$ of the pions are expected to be in the condensate

- Low p_T pion production shows a
 - Phys. Rev. C 91, 054909 (2015)*
 - Rev. Mod. Phys. 89, 35001 (2017)* and proto
 - not observed in p-Pb at similar ch



Low p_T pions in pp and p-Pb collisions

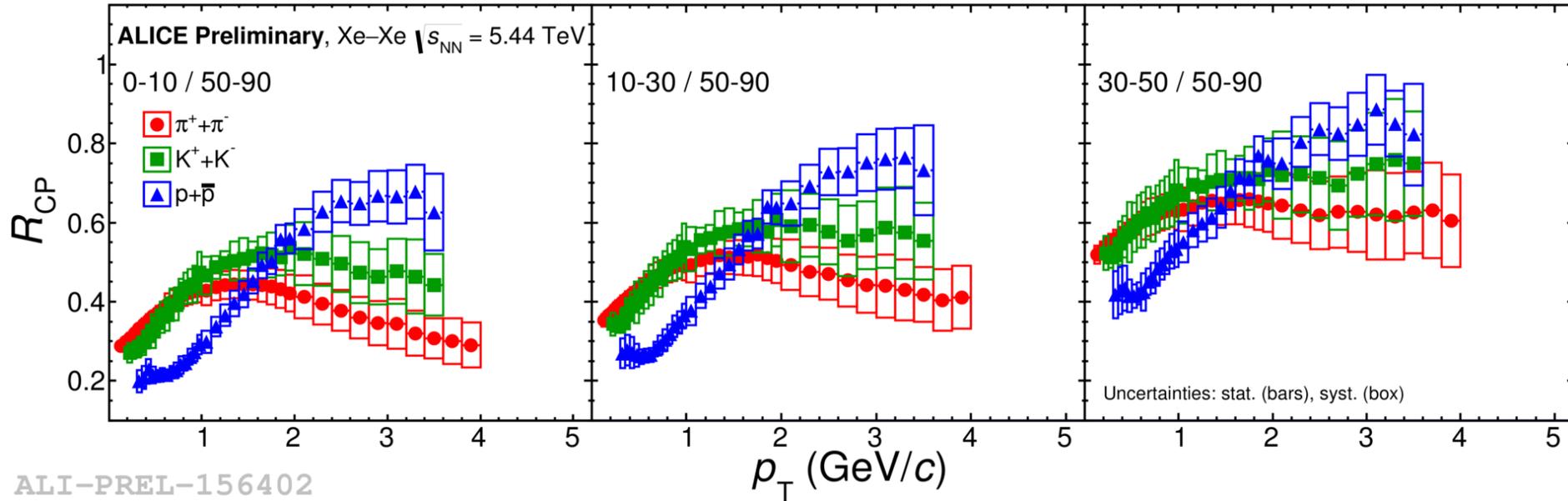


- **Possible explanation:** the matter produced at LHC energies is formed out of chemical equilibrium
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 - $\sim 5\%$ of the pions are expected to be in the condensate
- At **LHC energies**, models **without** chemical equilibrium and with $\mu_\pi \neq 0$ describes better the low- p_T pion spectra
 - The fit gives $\mu_\pi \approx m_\pi \rightarrow$ **BEC reached?**
- From 2-3-pion correlations in ALICE, the fraction of coherent pions is as large as **$23\% \pm 8\%$**

- Low p_T pion production shows a...
 - Phys. Rev. C 91, 054909 (2015)*
 - Rev. Mod. Phys. 89, 35001 (2017)*
 - Phys. Rev. C 89 (2014) 024911*



Low p_T pions in Xe-Xe collisions



ALI-PREL-156402

Ratio
central-to-
peripheral

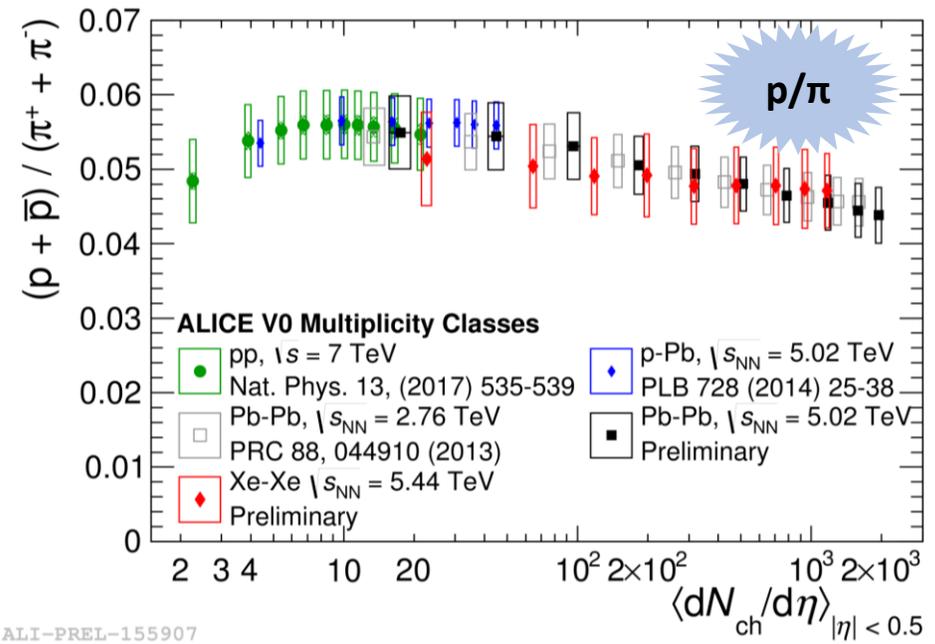
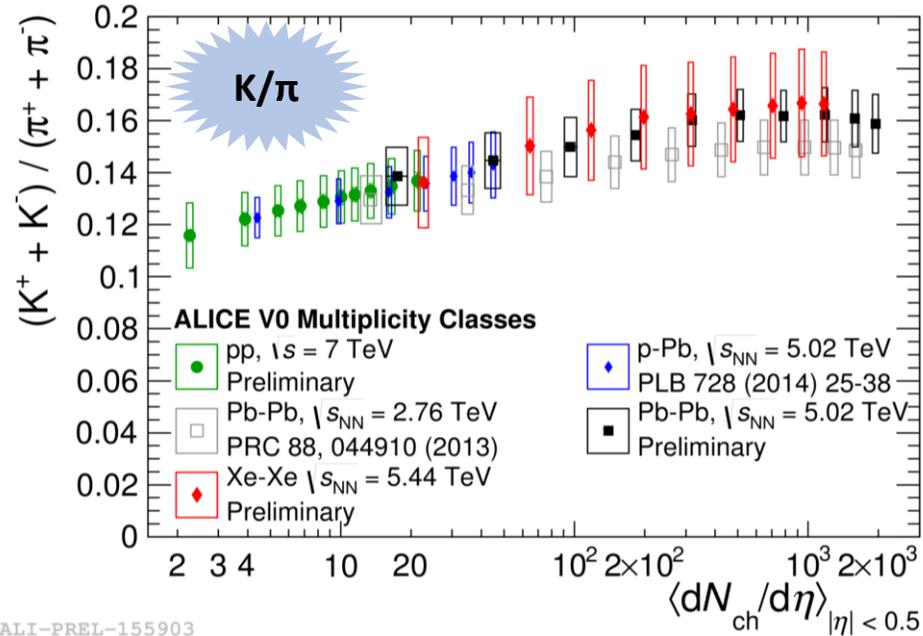
- **Pions are less suppressed** at low p_T with respect to K, p
 - Radial flow only or condensation effects?
- At $p_T \gtrsim 2$ GeV/c a clear **mass ordering** is observed

$$R_{CP} = \frac{1/\langle T_{AA}^{cent} \rangle \cdot (d^2 N^{cent} / (dp_T dy))}{1/\langle T_{AA}^{periph} \rangle \cdot (d^2 N^{periph} / (dp_T dy))}$$

T_{AA} : nuclear overlap function

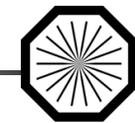


p_T -integrated yield ratios vs multiplicity

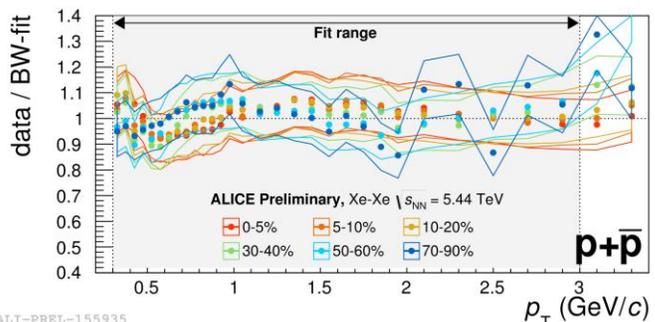
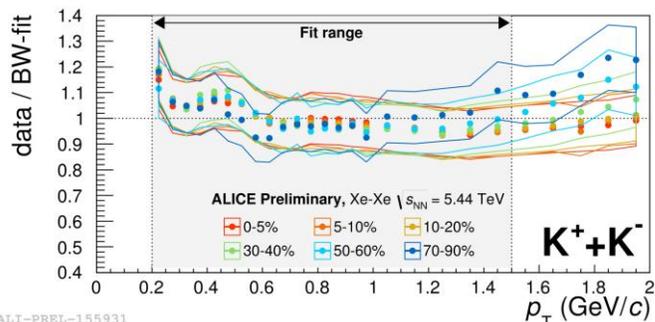
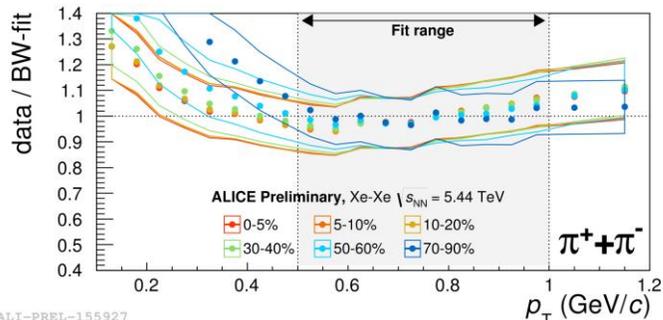


- Hints of an increasing trend of the K/π ratio \rightarrow **Strangeness enhancement?**
- Hints of a decreasing trend of the p/π ratio at high multiplicity \rightarrow **Baryon-antibaryon annihilation?**
- No significant evolution with the collision energy

The chemical composition is **independent of collision system at same $\langle dN_{ch}/d\eta \rangle$**



Blast-wave fit to spectra



Xe-Xe

Boltzmann-Gibbs blastwave model: a three parameters simplified hydrodynamical model*

* *Phys. Rev. C 48 (1993) 2462*

$$E \frac{d^3 N}{dp^3} \propto \int_0^R m_T I_0 \left(\frac{p_T \sinh(\rho)}{T_{kin}} \right) K_1 \left(\frac{m_T \cosh(\rho)}{\beta_T} \right) r dr$$

$$\rightarrow m_T = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1}(\beta_T) \quad \beta_T(r) = \beta_s \left(\frac{r}{R} \right)^n$$

The resulting spectrum is a superposition of individual thermal sources, each boosted with the boost angle ρ

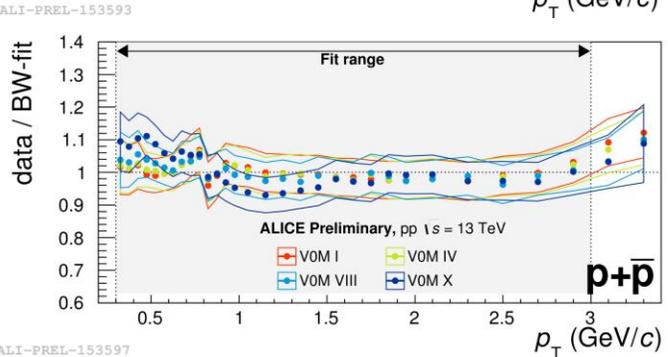
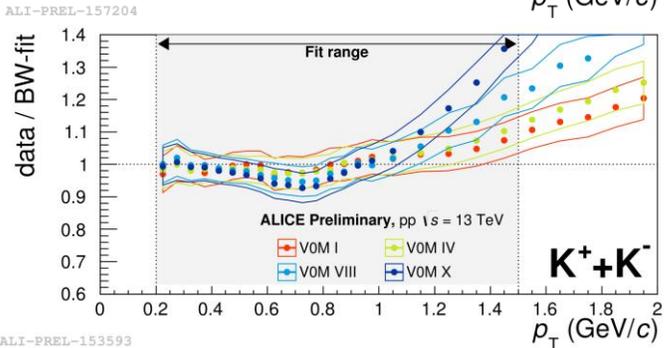
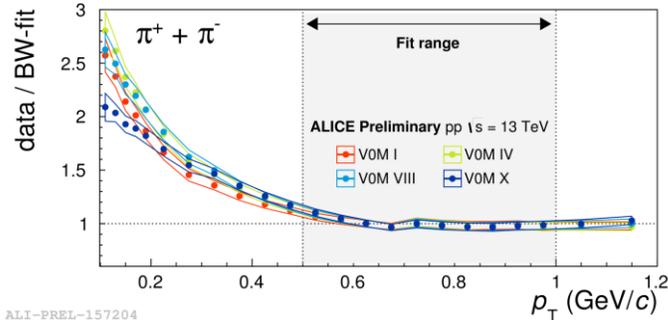
n : exp. of velocity profile \leftrightarrow profile
 T_{kin} : kinetic freeze-out temperature
 $\beta_T(r)$: transverse velocity distribution
 β_s : surface velocity
 ρ : boost angle

- Simultaneous Boltzmann-Gibbs fit to π , K and p using Pb-Pb 2.76 TeV fit ranges

\rightarrow Good description of data \rightarrow Clear manifestation of **strong radial flow** in central collisions



Blast-wave fit to spectra



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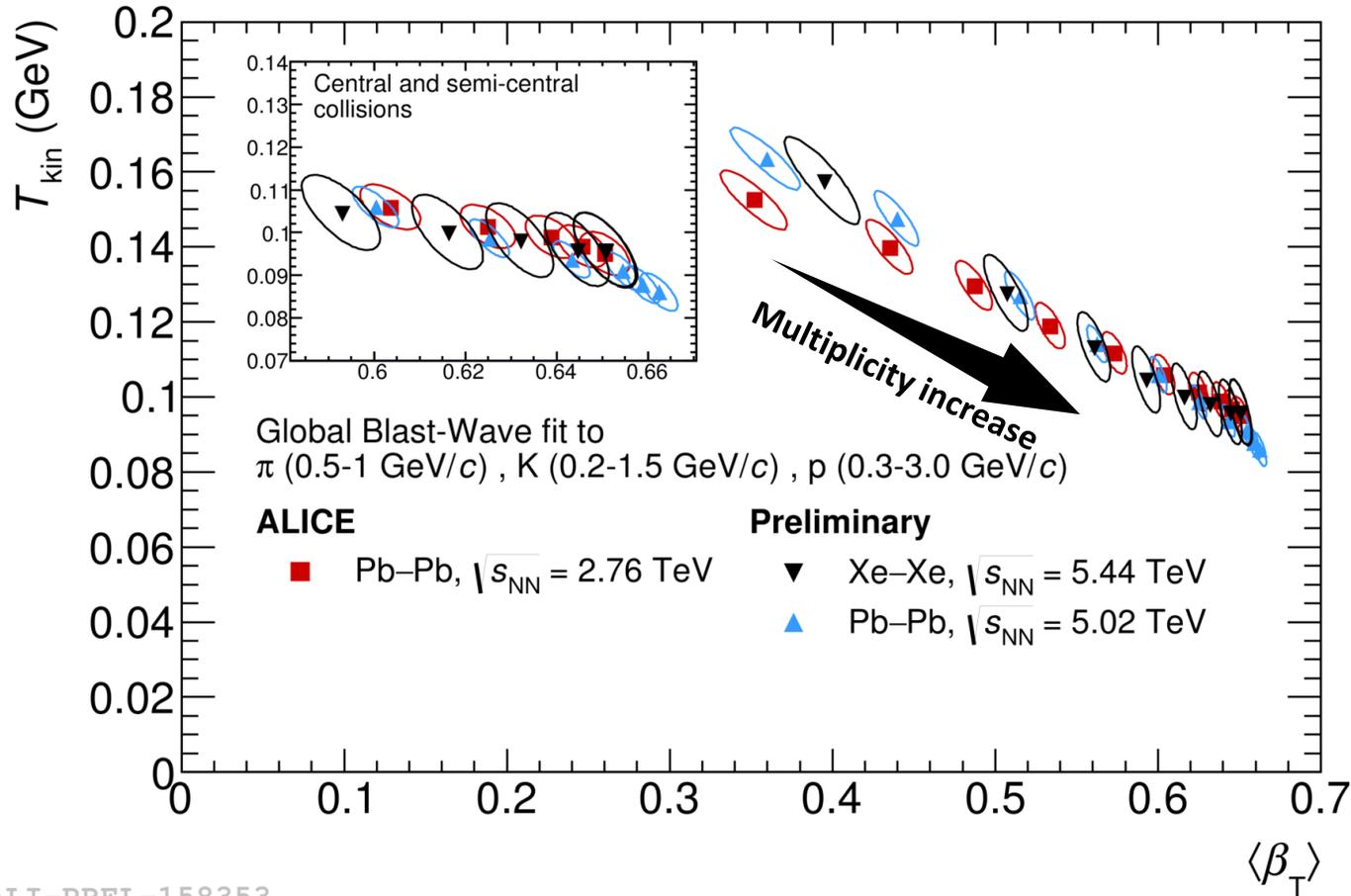
- Simultaneous Boltzmann-Gibbs fit to π , K and p using Pb-Pb 2.76 TeV fit ranges

\rightarrow Good description of data in the fit range

pp



Blast-wave fit to spectra in pp, p-A, A-A

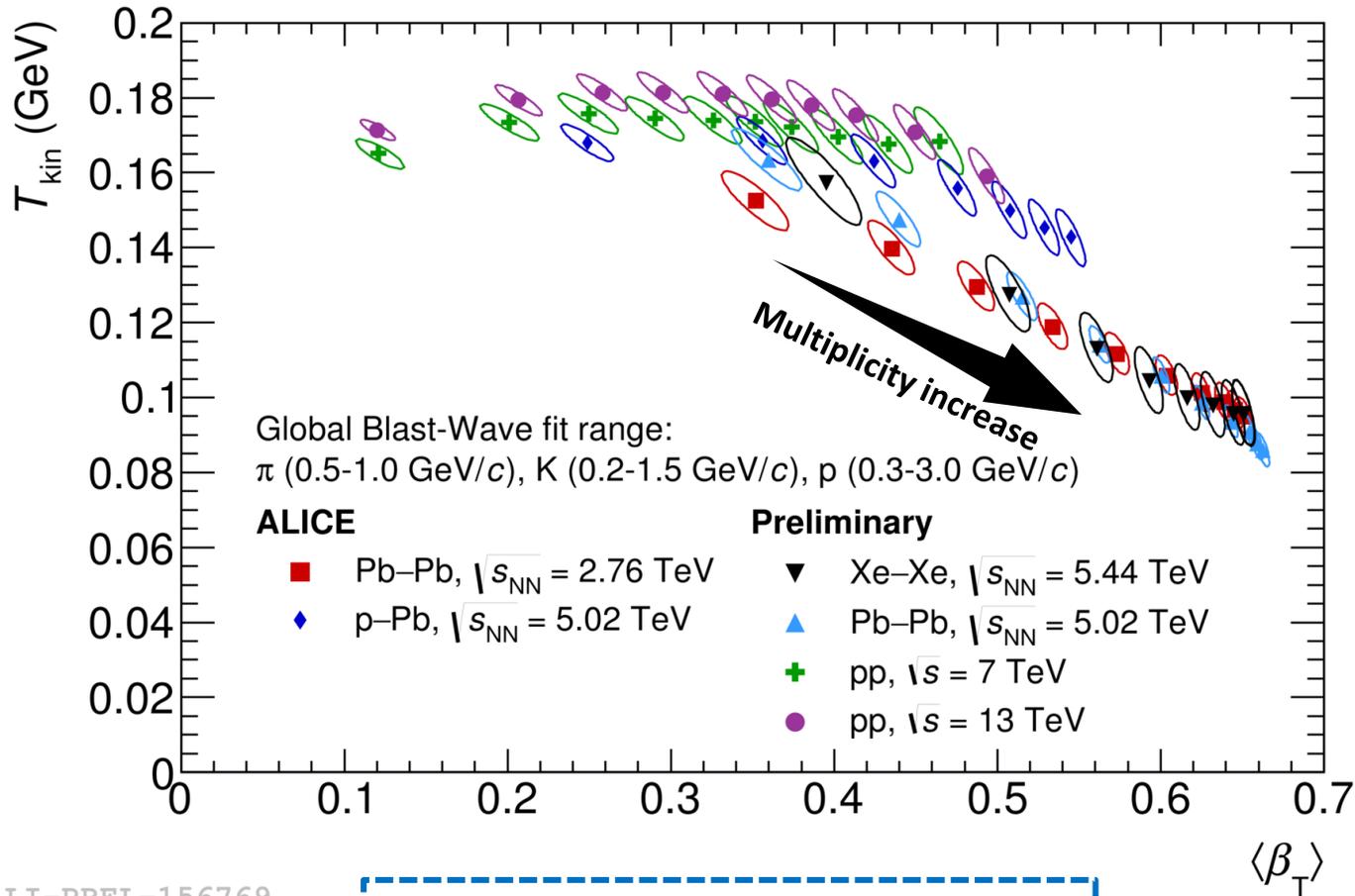


Large systems

- Larger $\langle \beta_T \rangle$ for central Pb-Pb collisions
- Comparable T_{kin} and $\langle \beta_T \rangle$ in Pb-Pb and Xe-Xe collisions at a similar $\langle dN_{ch}/d\eta \rangle$



Blast-wave fit to spectra in pp, p-A, A-A



p-Pb → Stronger radial gradients

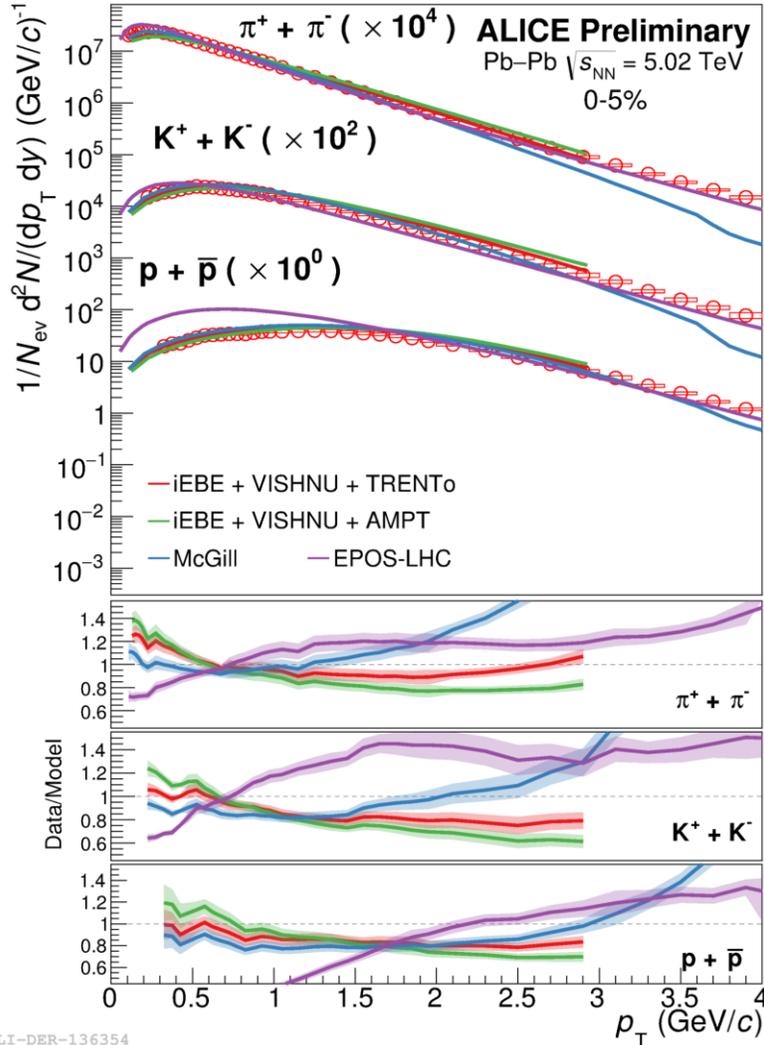
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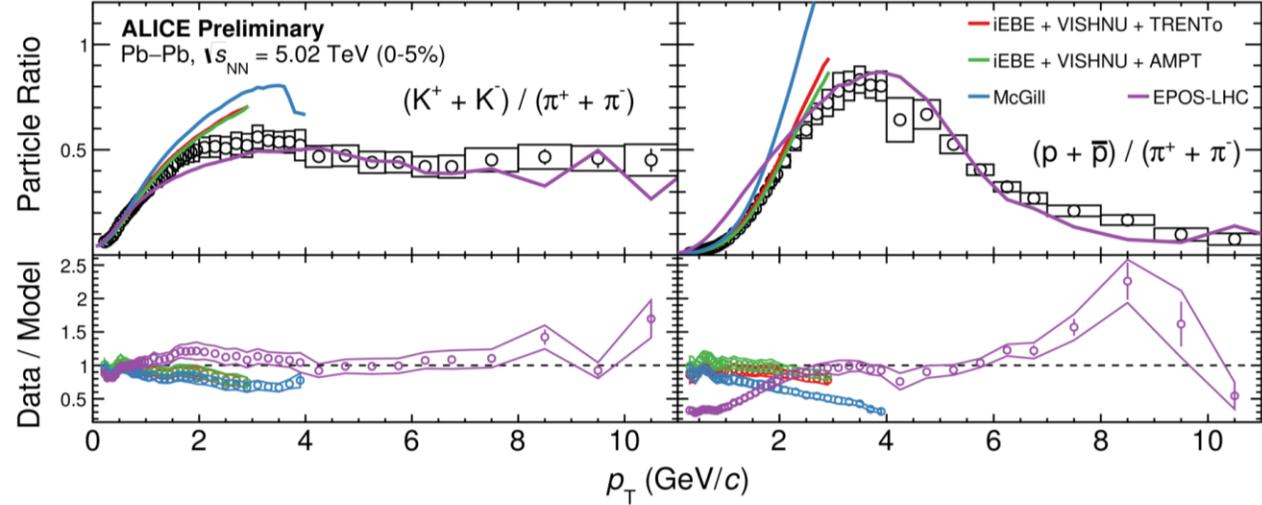
Small systems

- p-Pb & pp vs A-A
 - p-Pb and Pb-Pb show a similar trend consistent with the presence of radial flow in p-Pb collisions.
 - At similar $\langle dN_{ch}/d\eta \rangle$,
 - comparable T_{kin} for p-Pb and Pb-Pb, whereas $\langle\beta_T\rangle$ is significantly higher in p-Pb (color reconnection effects under study)
 - pp and p-Pb shows a similar trend and values are comparable

[Pb-Pb 0-5 %] Spectra compared to models



ALI-DER-136354

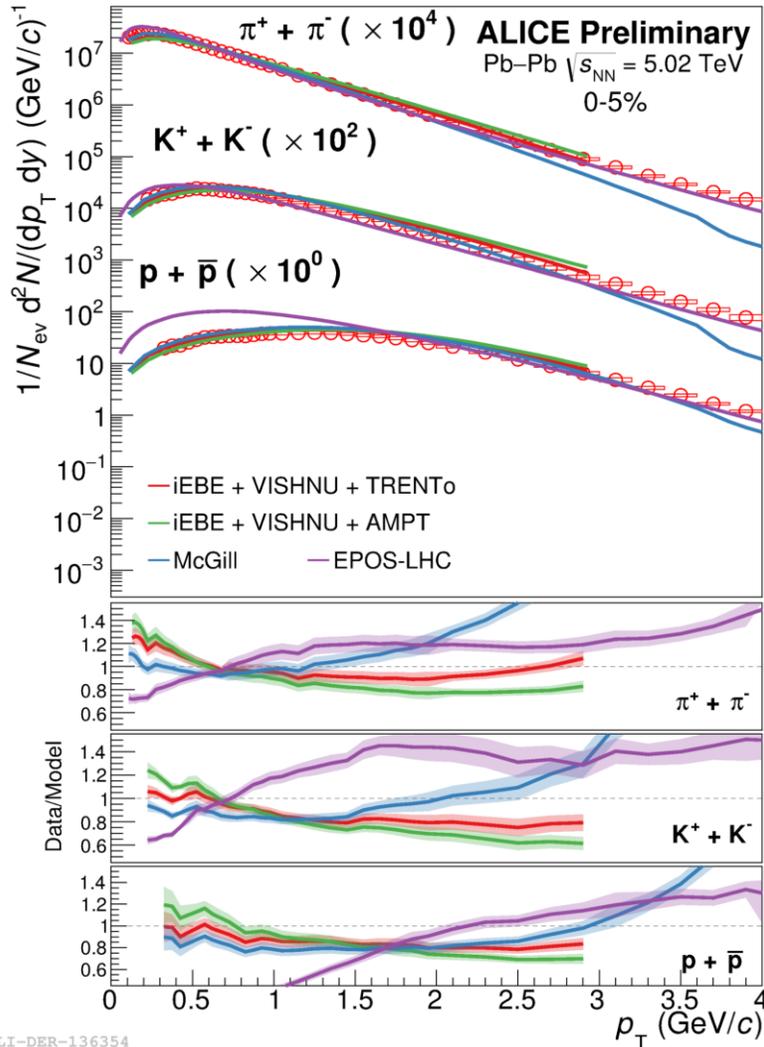


ALI-DER-136346

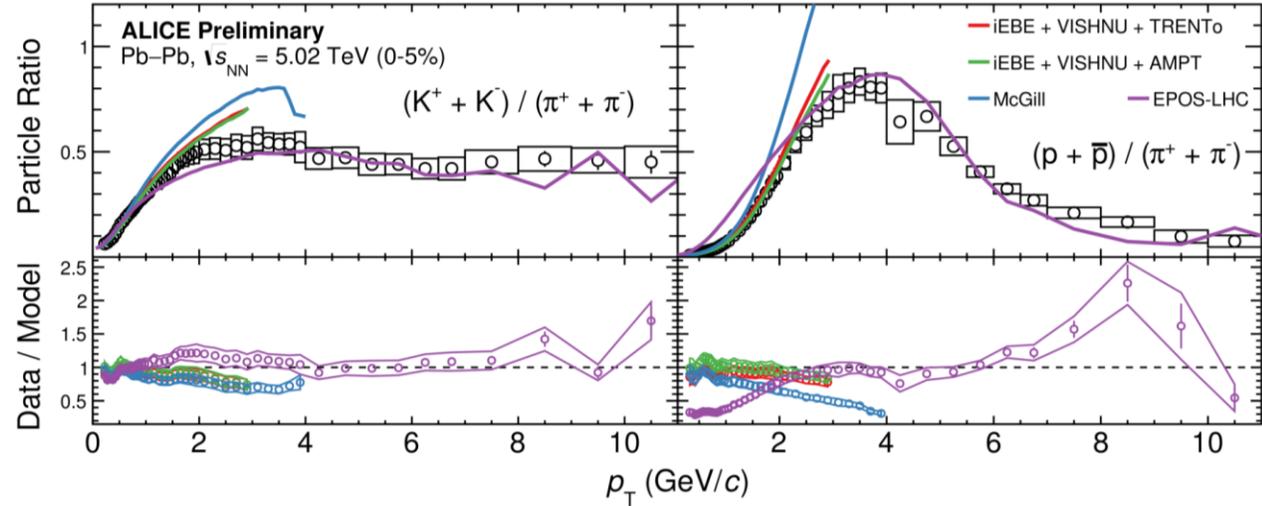
iEBE-VISHNU (*arXiv:1703.10792v1; Phys.Rev. C92, 014903 (2015) & 011901(R) (2015)*)

- Viscous hydrodynamics (QGP expansion) + Hadron cascade model (UrQMD) to simulate the evolution of the hadron resonance gas
- **Trento initial conditions**: effective model where entropy is deposited proportional to the generalized mean of nuclear overlap density
- **AMPT initial conditions**: initial state includes fluctuations at the nucleonic and subnucleonic levels and considers pre-equilibrium dynamics of partonic matter.
- **Good agreement at low p_T**

[Pb-Pb 0-5 %] Spectra compared to models



ALI-DER-136354



ALI-DER-136346

EPOS-LHC (Phys.Rev. C 92, 034906 (2015))

- Non uniform fireball divided into the **core** (high density) and **corona** (lower density).

→ **Describes better particle ratios** in central Pb-Pb collisions

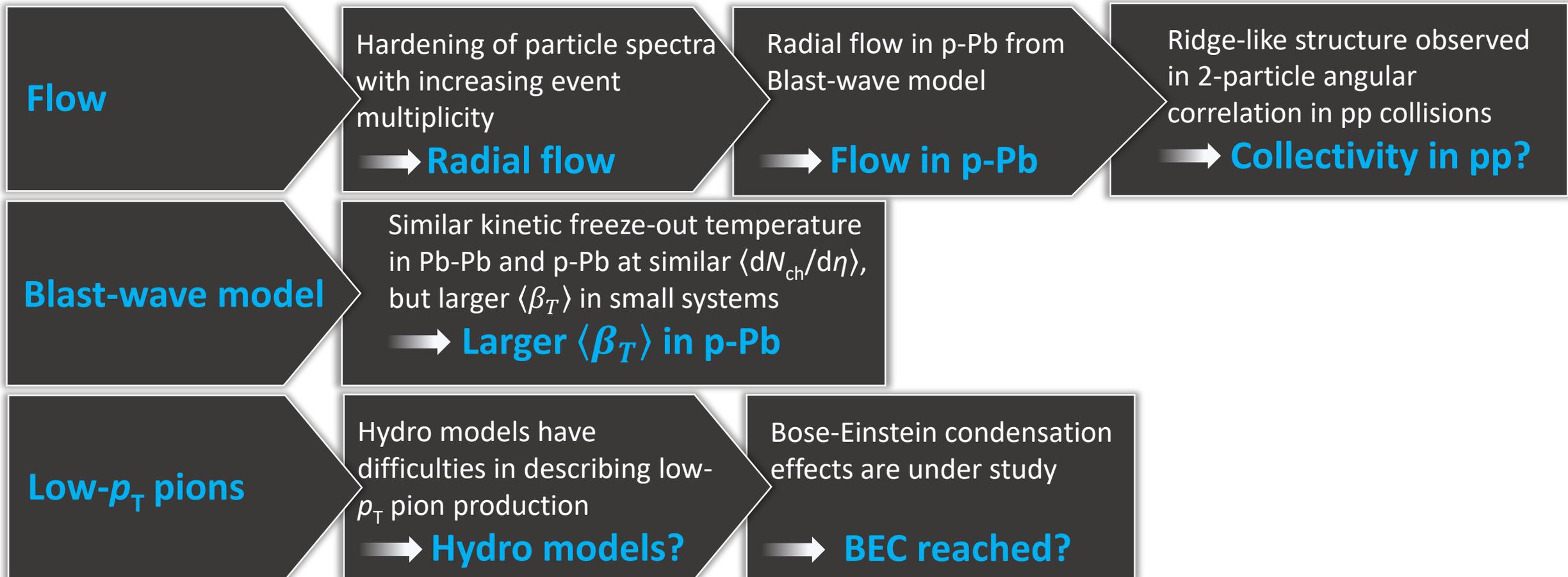
McGill (Phys. Rev. C 95, 064913 (2017))

- IP-Glasma initial condition matched to hydrodynamic variables and evolved using viscous hydrodynamic model (MUSIC).

→ **Good agreement at low p_T**

Conclusion

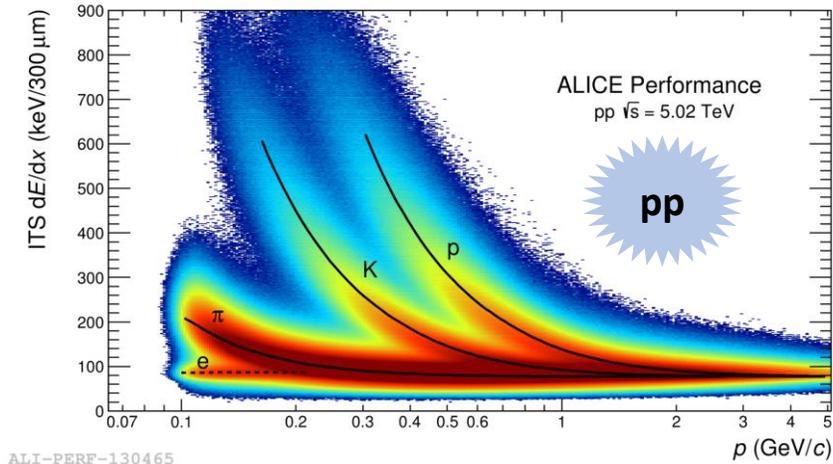
- Particle transverse-momentum spectra and angular correlations have been measured by ALICE in pp, p-Pb, Pb-Pb and Xe-Xe at different collision energies



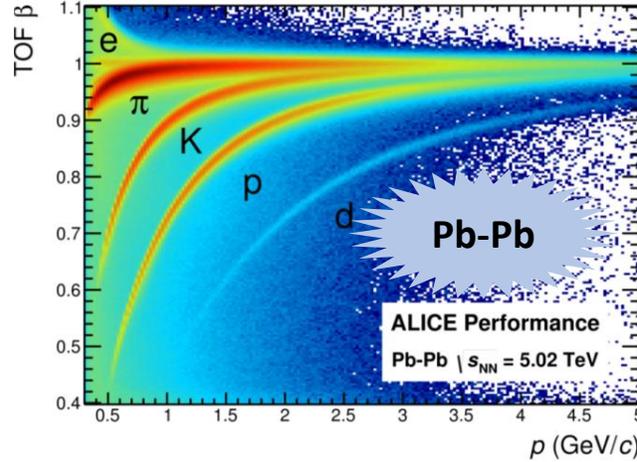


Backup slides

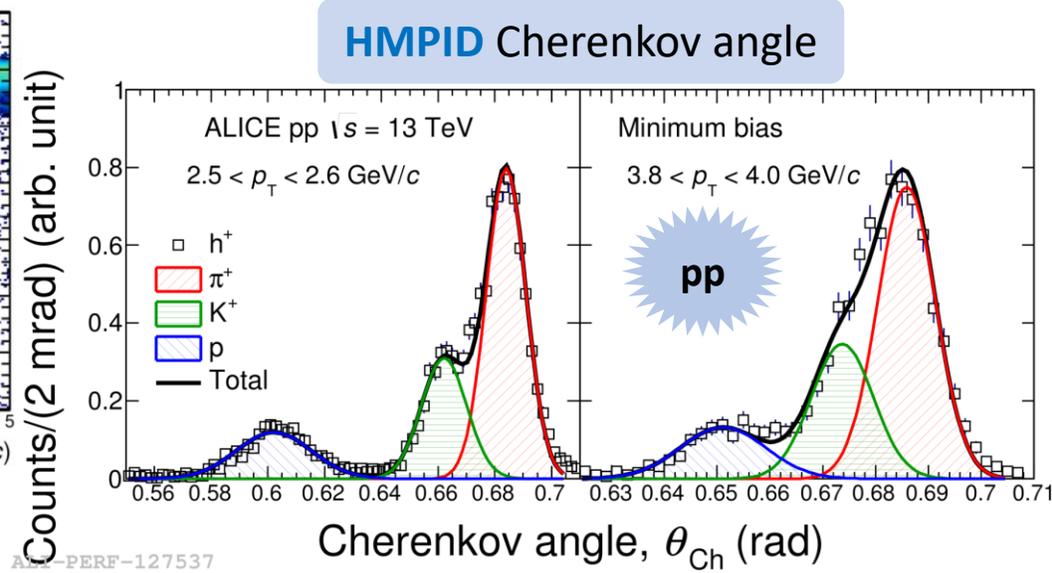
Particle Identification in ALICE



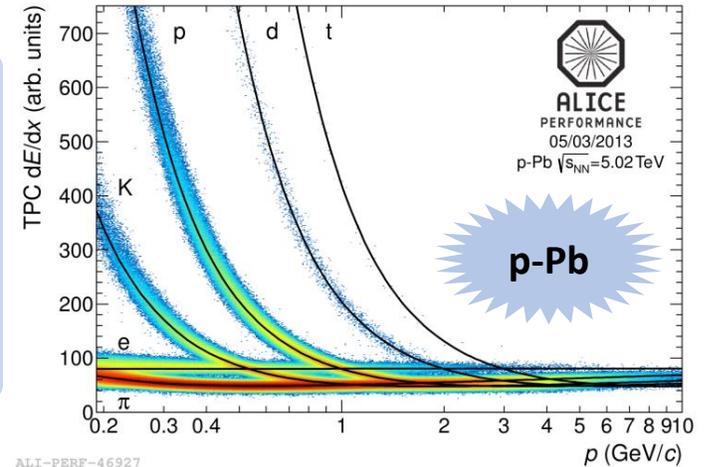
ITS dE/dx vs p



TOF β vs p



TPC dE/dx vs p

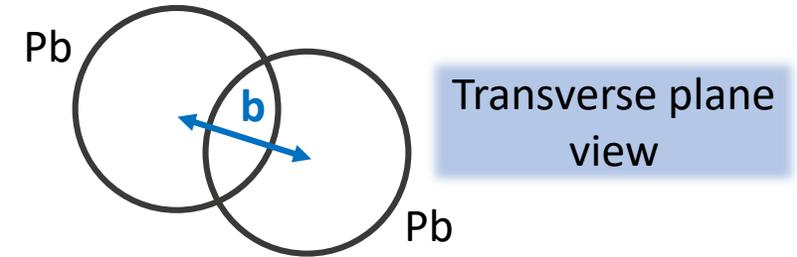


- **ITS**: average energy loss in the four outermost layers
- **TOF**: time-of-flight measurement ($\sigma_{TOF} \sim 80$ ps)
- **HMPID**: Cherenkov angle measurement
- **TPC**: average energy loss in TPC gas (Ar-CO₂)

Event centrality & multiplicity in ALICE

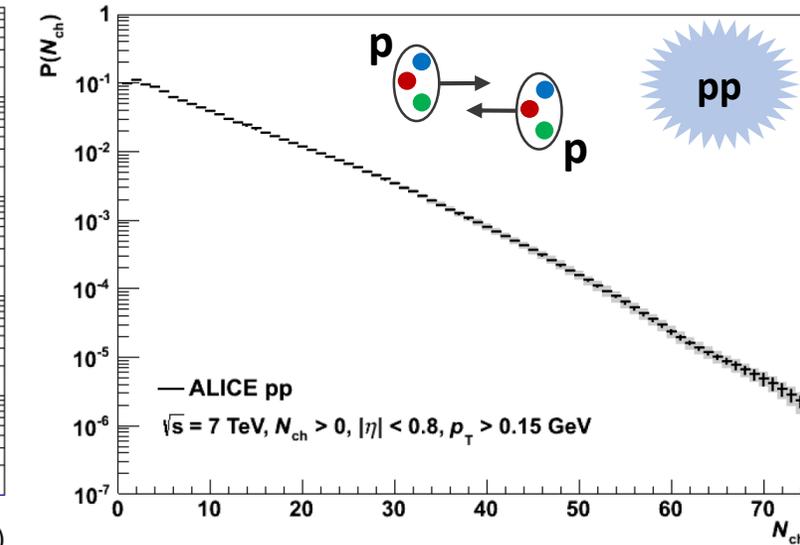
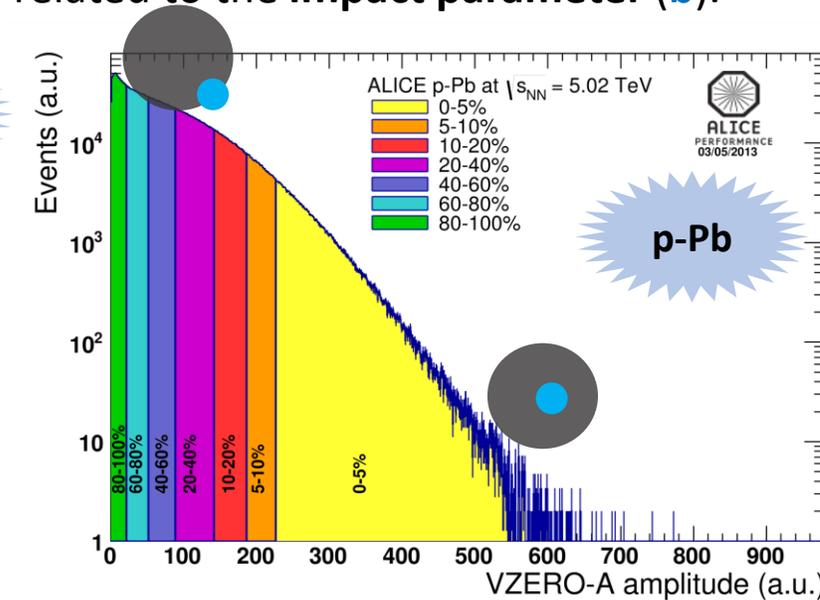
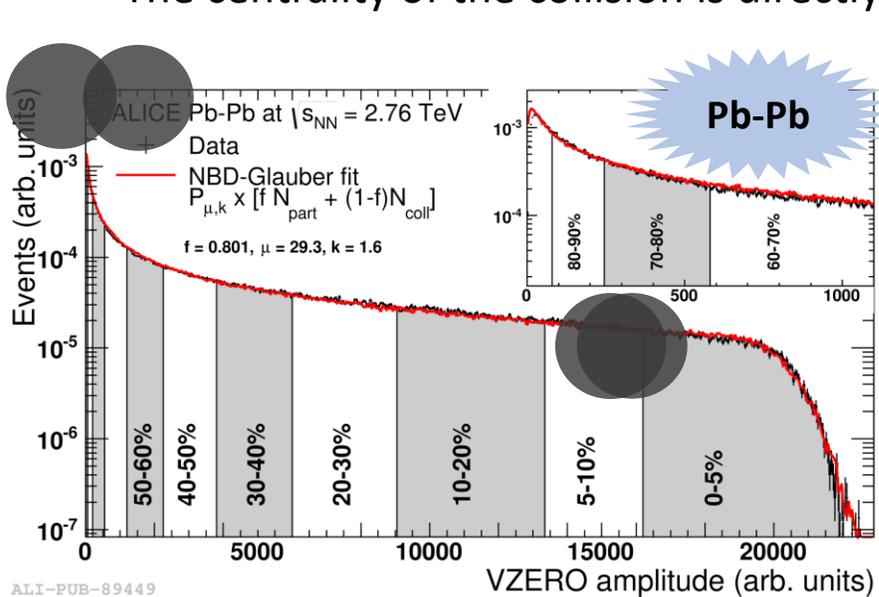
pp, p-Pb, Pb-Pb

- Centrality/multiplicity defined as the **percentile** of the hadronic cross section corresponding to a particle multiplicity above a given threshold.
- Event multiplicity classes defined from the amplitude of the signal in the **VZERO** detectors.



Pb-Pb

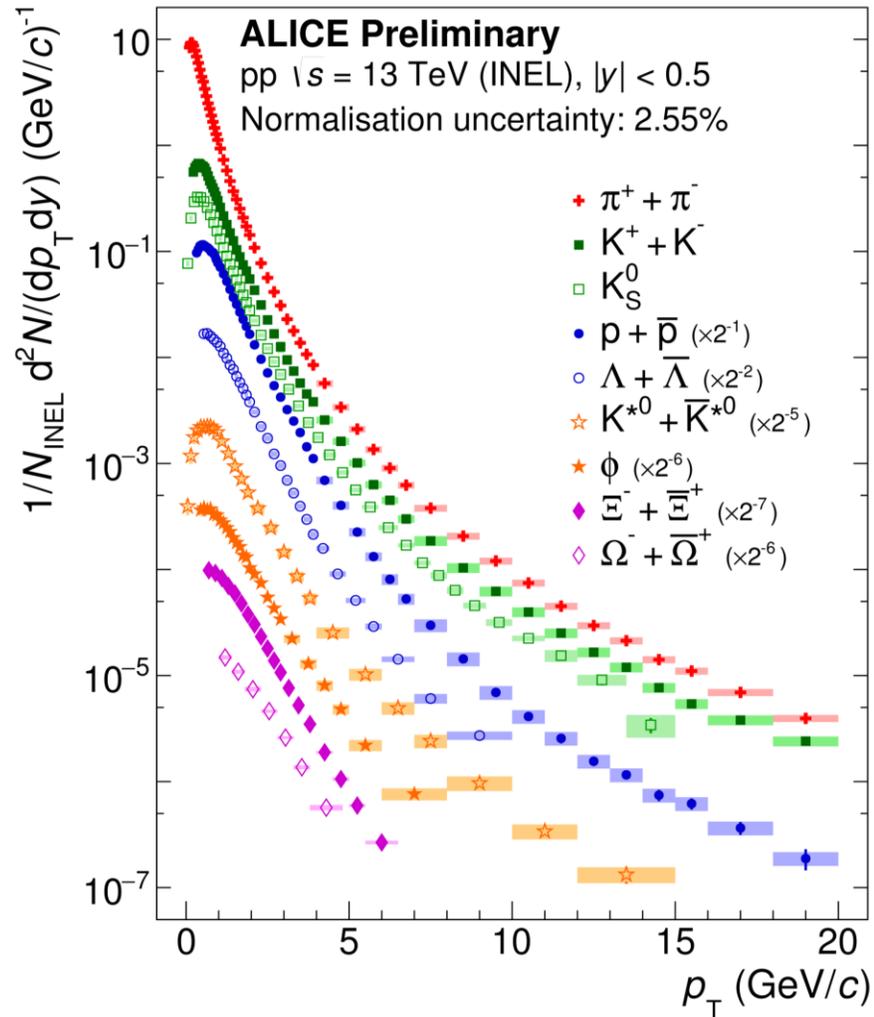
- The centrality of the collision is directly related to the **impact parameter (b)**.



ALI-PUB-89449

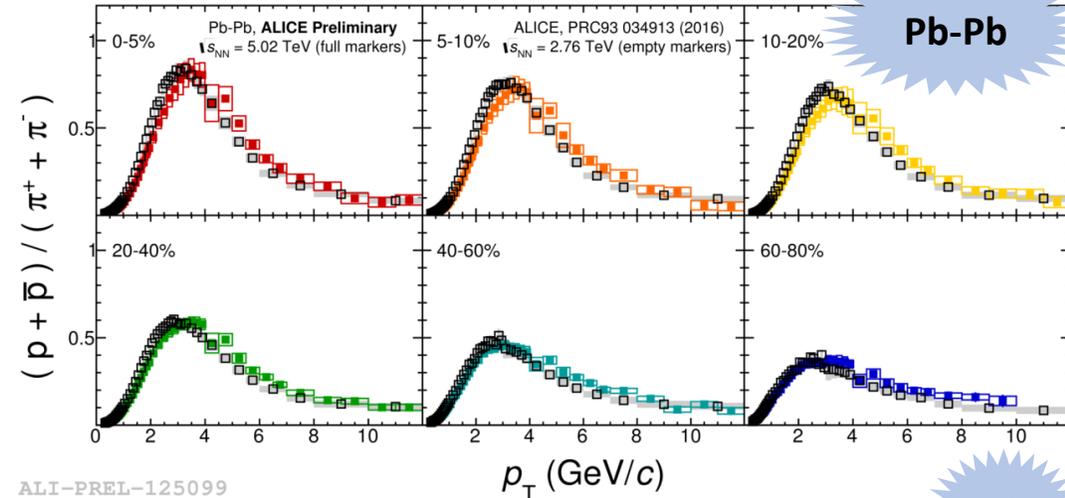
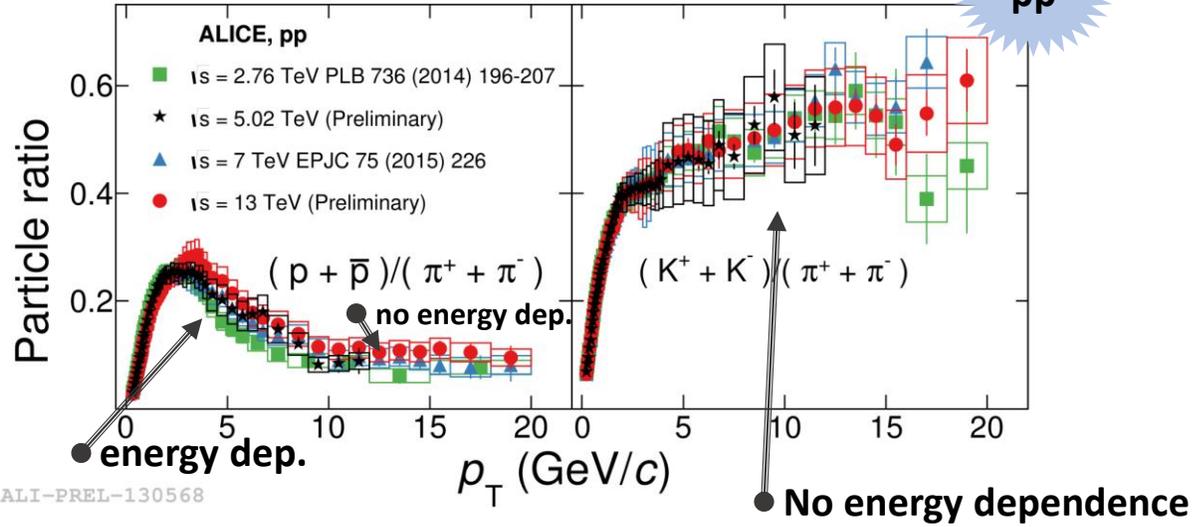
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Particle spectra in pp at 13 TeV

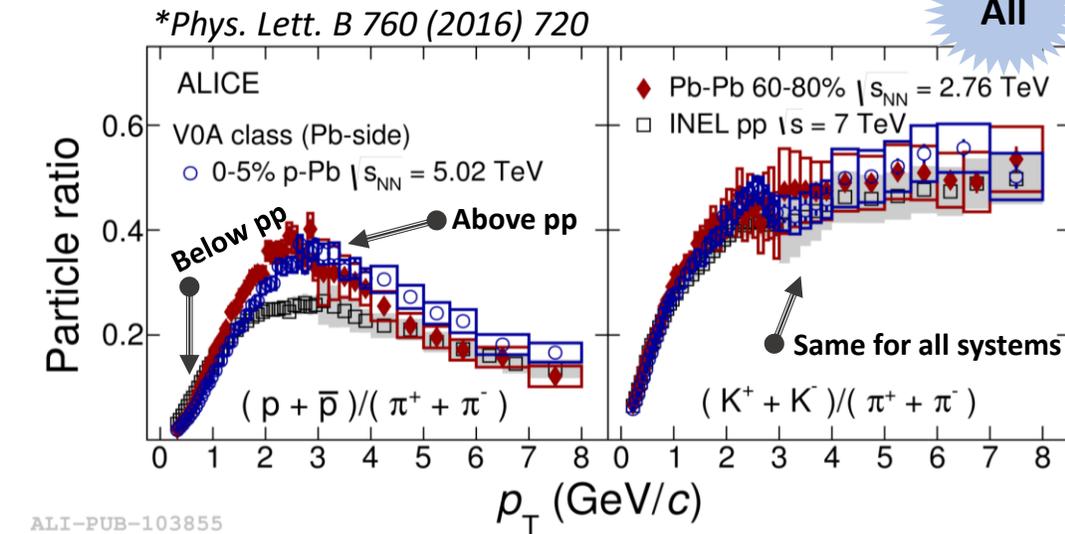


- Mass ordering of identified particle spectra is clearly visible in pp collisions

Particle ratios



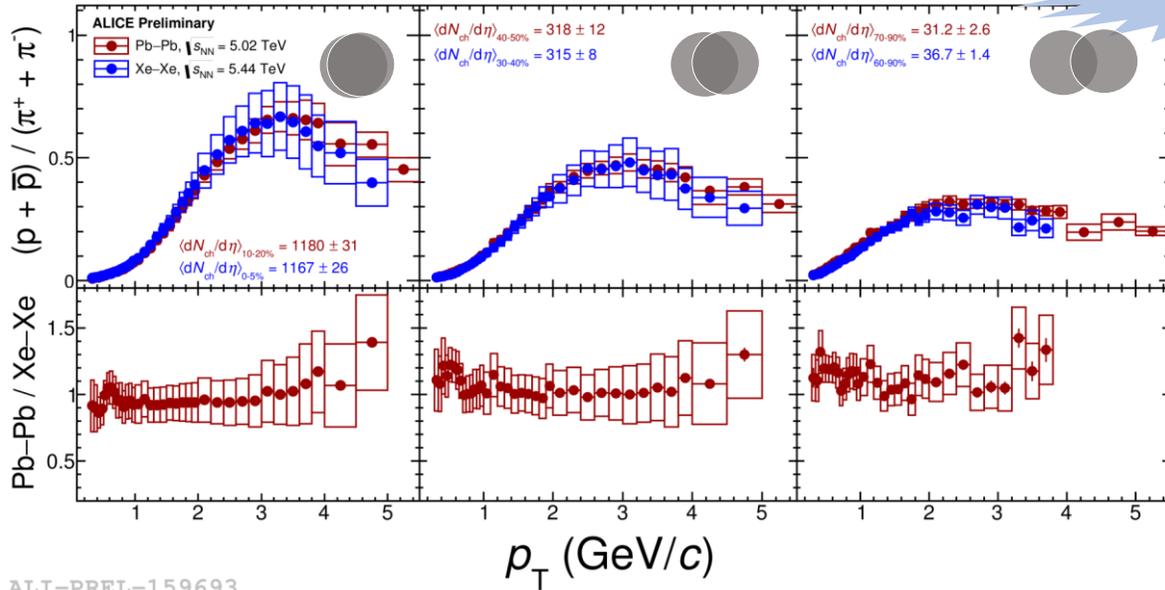
- pp at 2.76, 5.02, 7 and 13 TeV
 - K/π : no significant change with \sqrt{s}
 - ρ/π : shift of the maximum towards higher p_T with increasing \sqrt{s} in the intermediate p_T region.
- Pb-Pb at 2.76 vs. 5.02 TeV
 - Indication of a slightly higher **radial flow** in central collisions compared to lower energies.
- pp (approx. baseline), p-Pb and Pb-Pb*
 - K/π : same within sys and stat uncertainties.
 - ρ/π : **similar flow-like features for p-Pb and Pb-Pb systems.**





Proton-to-pion ratios

Pb-Pb, Xe-Xe



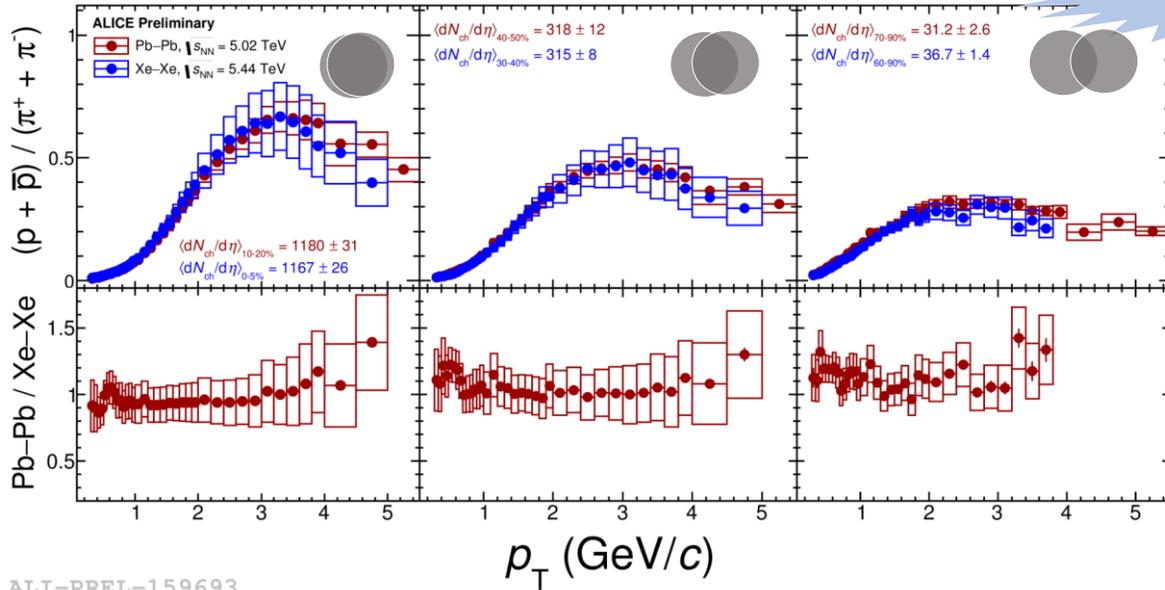
ALI-PREL-159693

- Pb-Pb 5.02 TeV vs Xe-Xe 5.44 TeV
 - Typical flow bump at around $p_T = 3$ GeV/c, more evident in central collisions
 - **Compatible** structure in the two colliding systems



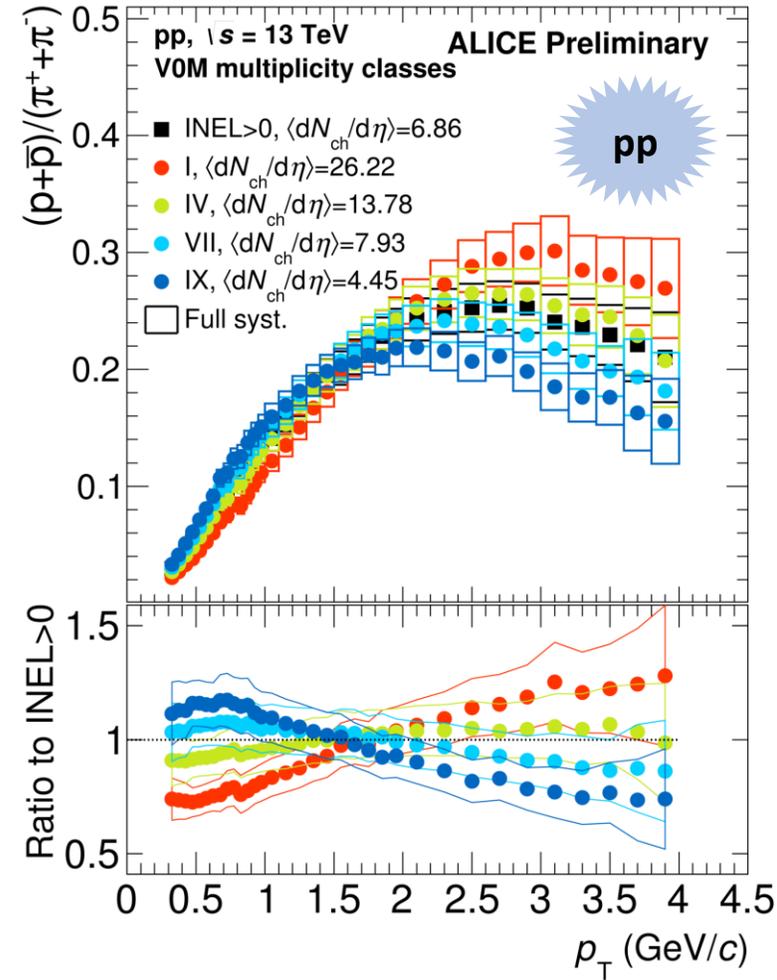
Proton-to-pion ratios

Pb-Pb, Xe-Xe



ALI-PREL-159693

- **Pb-Pb 5.02 TeV vs Xe-Xe 5.44 TeV**
 - Typical flow bump at around $p_T = 3$ GeV/c, **more evident in central collisions**
 - **Compatible** structure in the two colliding systems
- **pp 13 TeV**
 - Similar flow-like feature, the peak is more suppressed compared to A-A
 - **Multiplicity dependence** is observed as in A-A



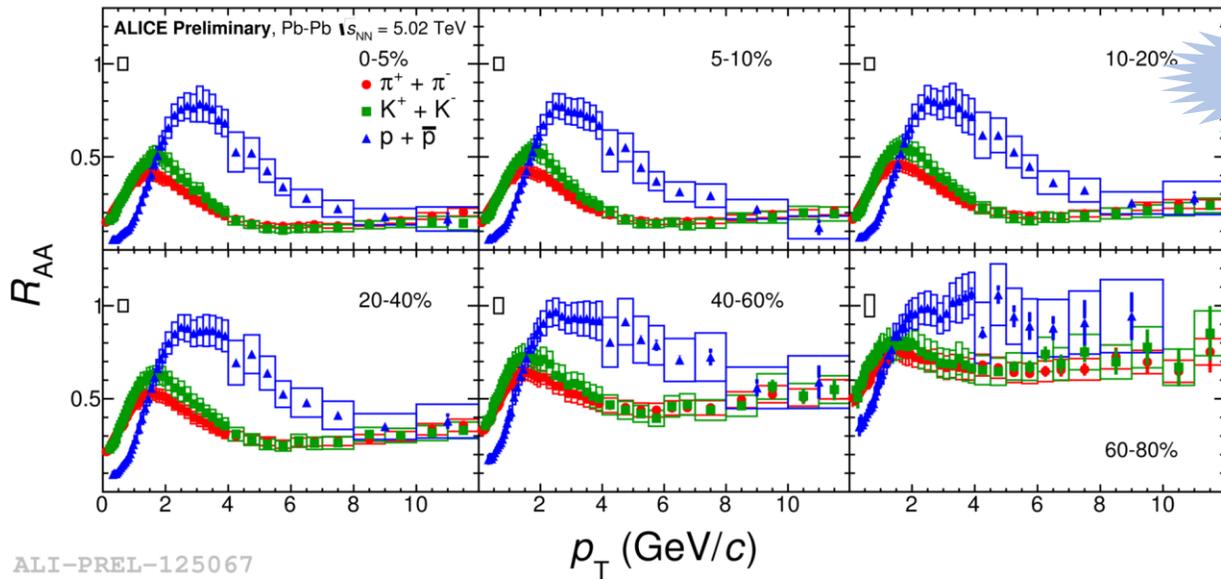
ALI-PREL-145926

Nuclear modification factor

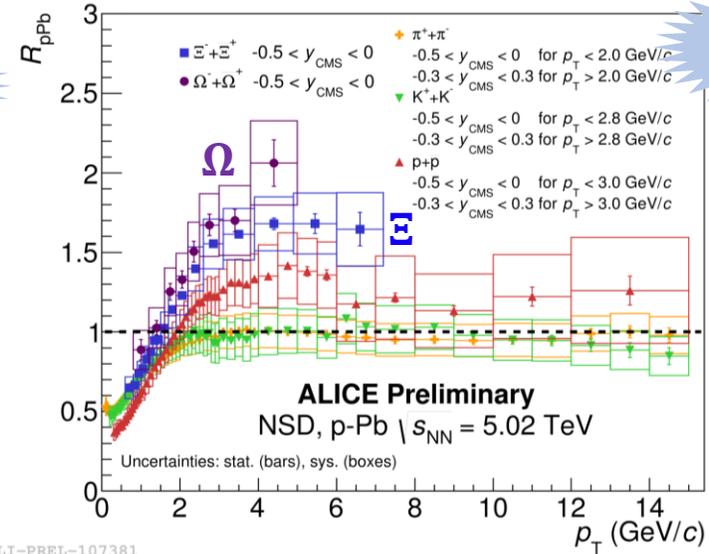
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dydp_T}{d^2 N_{pp}/dydp_T} \begin{cases} > 1 & \text{(enhancement)} \\ = 1 & \text{(no medium effects)} \\ < 1 & \text{(suppression)} \end{cases}$$

$\langle N_{coll} \rangle$ = number of collisions

Test if AA or pA can be described by incoherent superposition of N_{coll} binary collisions



Pb-Pb



p-Pb

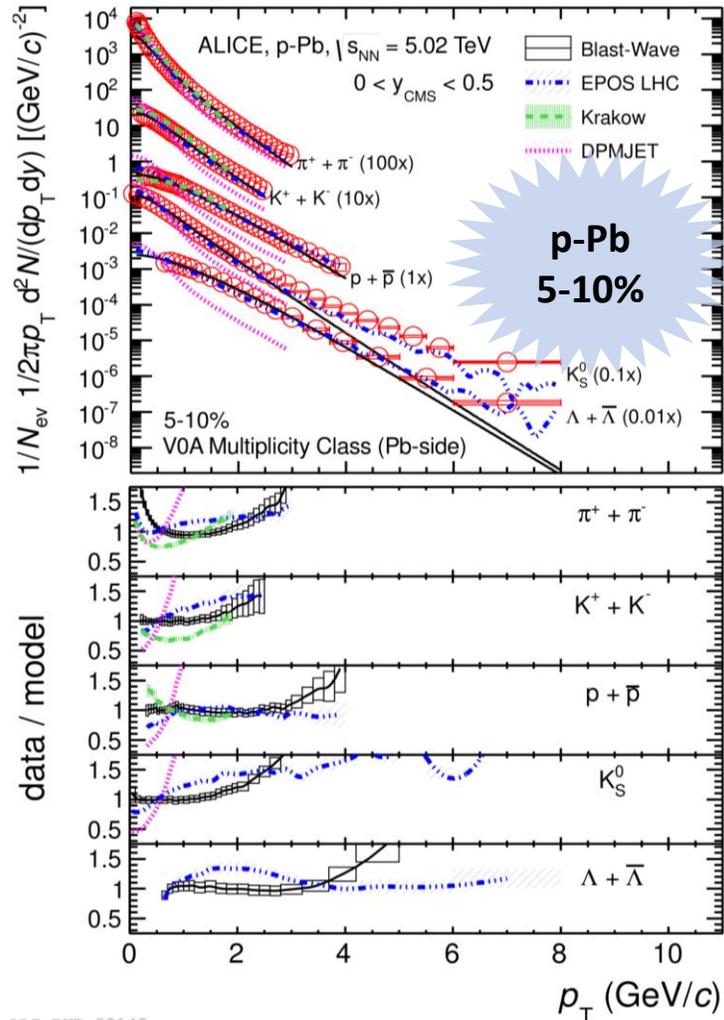
Collectivity in p-Pb?

- π, K, p equally suppressed for all centralities at high p_T (> 8 GeV/c)

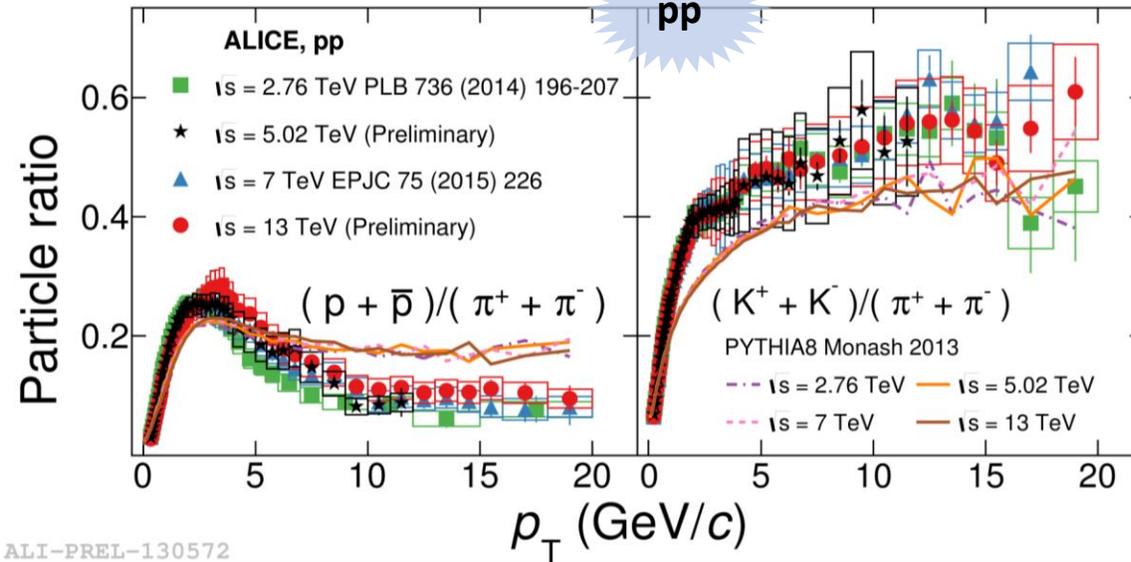
- R_{pPb} compatible with 1 at high p_T for all particle species
- Mass ordering at intermediate p_T (Cronin region)
 - Strong enhancement for p, Ξ and Ω
 - Similar enhancement observed in Pb-Pb and at RHIC.



Comparison with models



ALI-PUB-58145



ALI-PREL-130572

p-Pb collisions (*Phys. Lett. B* 728 (2014) 25-38)

- **Krakow**¹: event-by-event (3+1)-D perfect fluid hydrodynamic
 - Reproduces particle spectra reasonably well
- **DPMJET**²: QCD-inspired model based on Glauber-Gribov formalism
 - Fails to reproduce particle spectra
- **EPOS-LHC**: pi, K and p reasonably well reproduced especially at low p_T

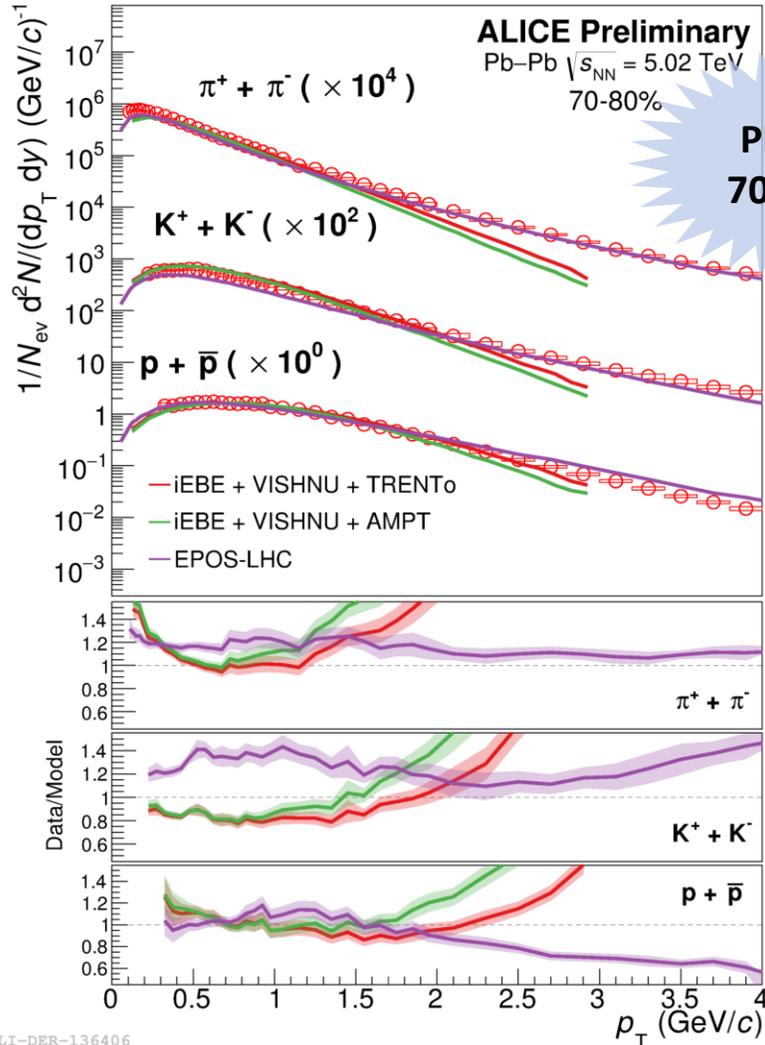
pp collisions

- Pythia 8³ generator overestimates p/pi and underestimates K/pi

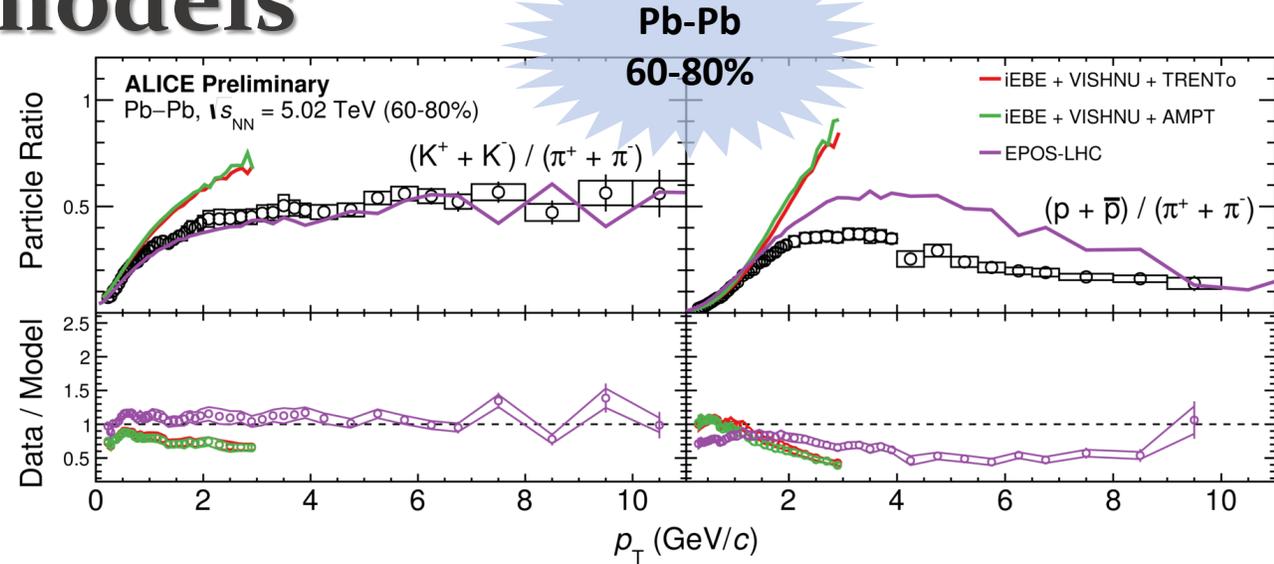
¹Bozek, PRC 85, 014911 (2012)
²Roesler et al., arXiv:hep-ph/0012252
³arXiv:1404.5630v1



Comparison with models



ALI-DER-136406



ALI-DER-136350

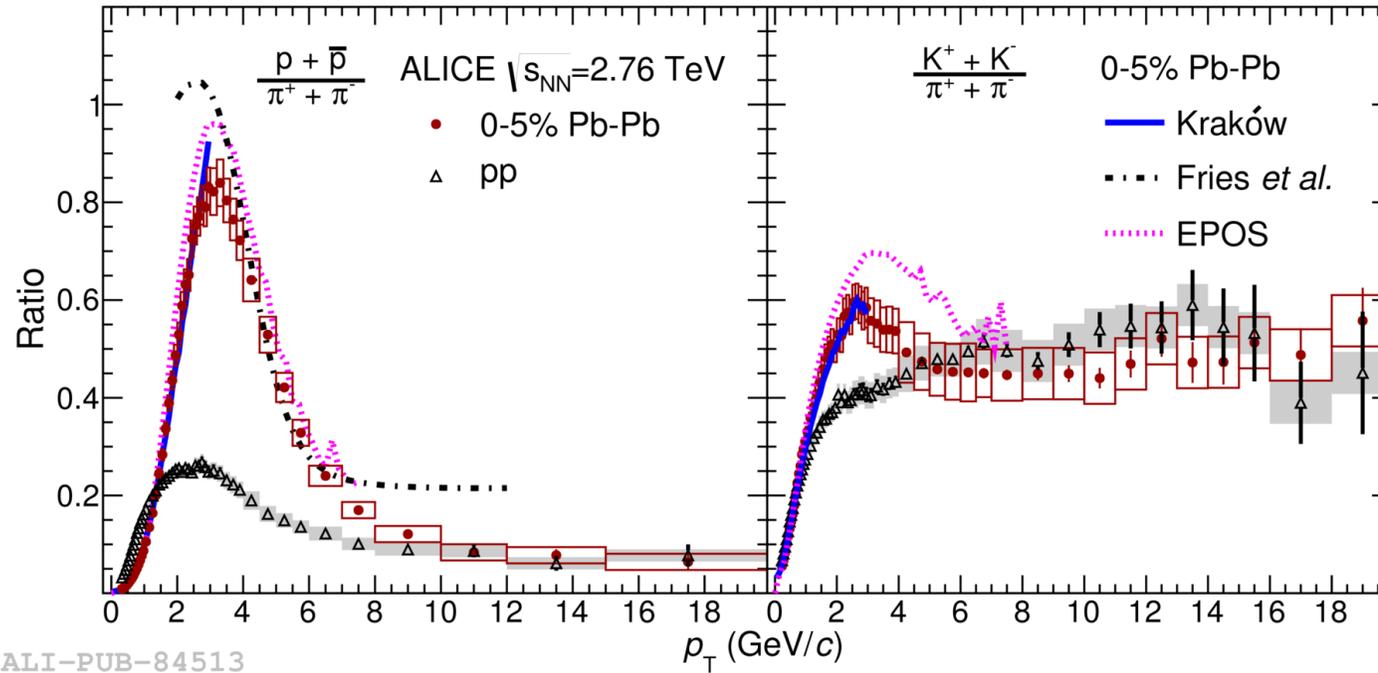
EPOS-LHC (Phys.Rev. C 92, 034906 (2015))

- Non uniform fireball divided in the **core** (high density) and **corona** (lower density).
- Describes better π , K, K/ π in peripheral Pb-Pb collisions

iEBE-VISHNU with TRENTo and AMPT initial conditions

→ Good agreement at low p_T

[Pb-Pb 2.76 TeV] Particle ratios vs models

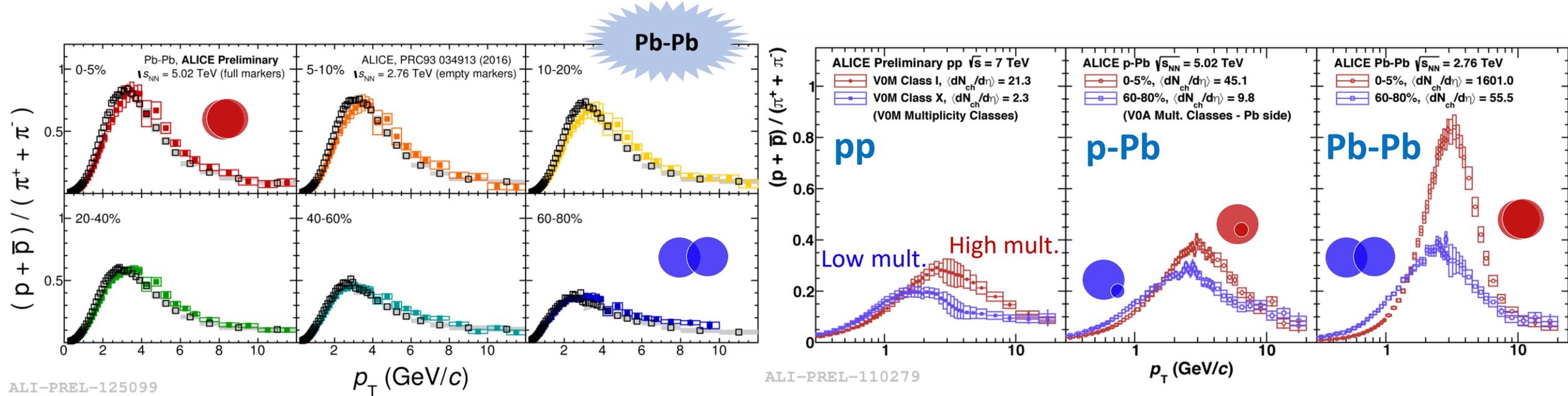


arXiv:1401.1250v4 [nucl-ex]

- **Kraków**: good description of particle ratios
- **Fries *et al.*¹** includes recombination processes and pQCD at high p_T
 → Good description of p/π between 4 and 7 GeV/c
- **EPOS**: describes better p/π . For K/π , good agreement only at low p_T
 → Tends to overestimate the peaks

¹Phys. Rev. C 68, 044902 (2003)

Particle ratios



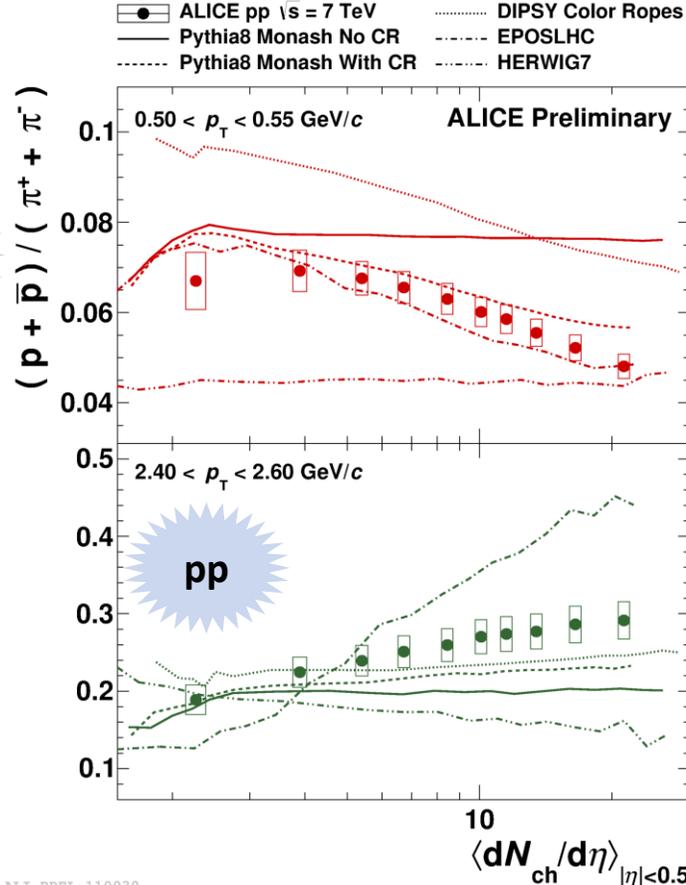
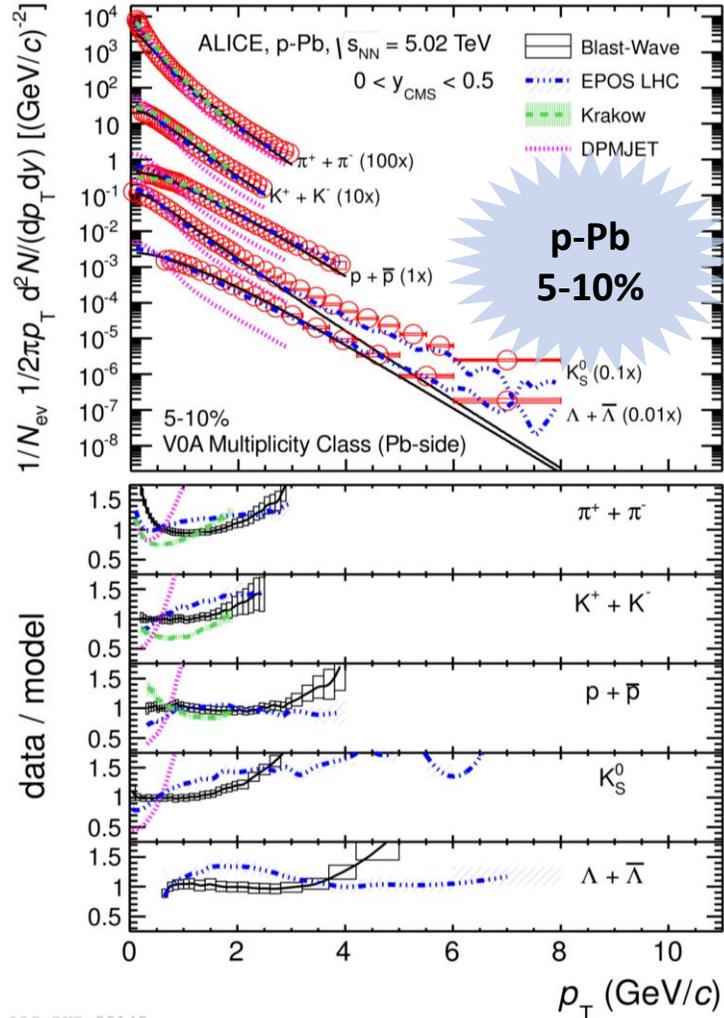
- Pb-Pb at 2.76 vs 5.02 TeV

- Indication of a slightly higher **radial flow** in central collisions compared to lower energies.

- pp, p-Pb and Pb-Pb

- p/π : similar flow-like features for pp, p-Pb and Pb-Pb systems

[p-Pb 5-10 % and pp] Comparison to models



p-Pb collisions (*Phys. Lett. B* 728 (2014) 25-38)

- **Kraków**¹: event-by-event (3+1)-D perfect fluid hydrodynamic
→ Reproduces particle spectra **reasonably well**
- **DPMJET**²: QCD-inspired model based on Glauber-Gribov formalism
→ **Fails** to reproduce particle spectra
- **EPOS-LHC**: pi, K and p reasonably well reproduced especially at low p_T

pp collisions

- **PYTHIA 8**³ (with CR) describes better integrated particle ratios.
- **EPOS-LHC** agrees better in low p_T ranges
- **DIPSY**⁴ with color ropes correctly reproduces the p/π shape at low p_T → better agreement at higher p_T and low $\langle dN_{ch} / d\eta \rangle$
- **HERWIG**⁵ is an event generator that performs simulations at next-to-leading order in QCD
→ **Fails** to describe data

ALI-PREL-110939

¹Bozek, *PRC* 85, 014911 (2012)
²Roesler et al., *arXiv:hep-ph/0012252*
³*arXiv:1404.5630v1*
⁴*arXiv:1412.6259v3*; ⁵*arXiv:1512.01178v1*

ALI-PUB-58145