LNF Group III Seminar:

Multiplicity and energy dependence of light charged particle production in ALICE at the LHC

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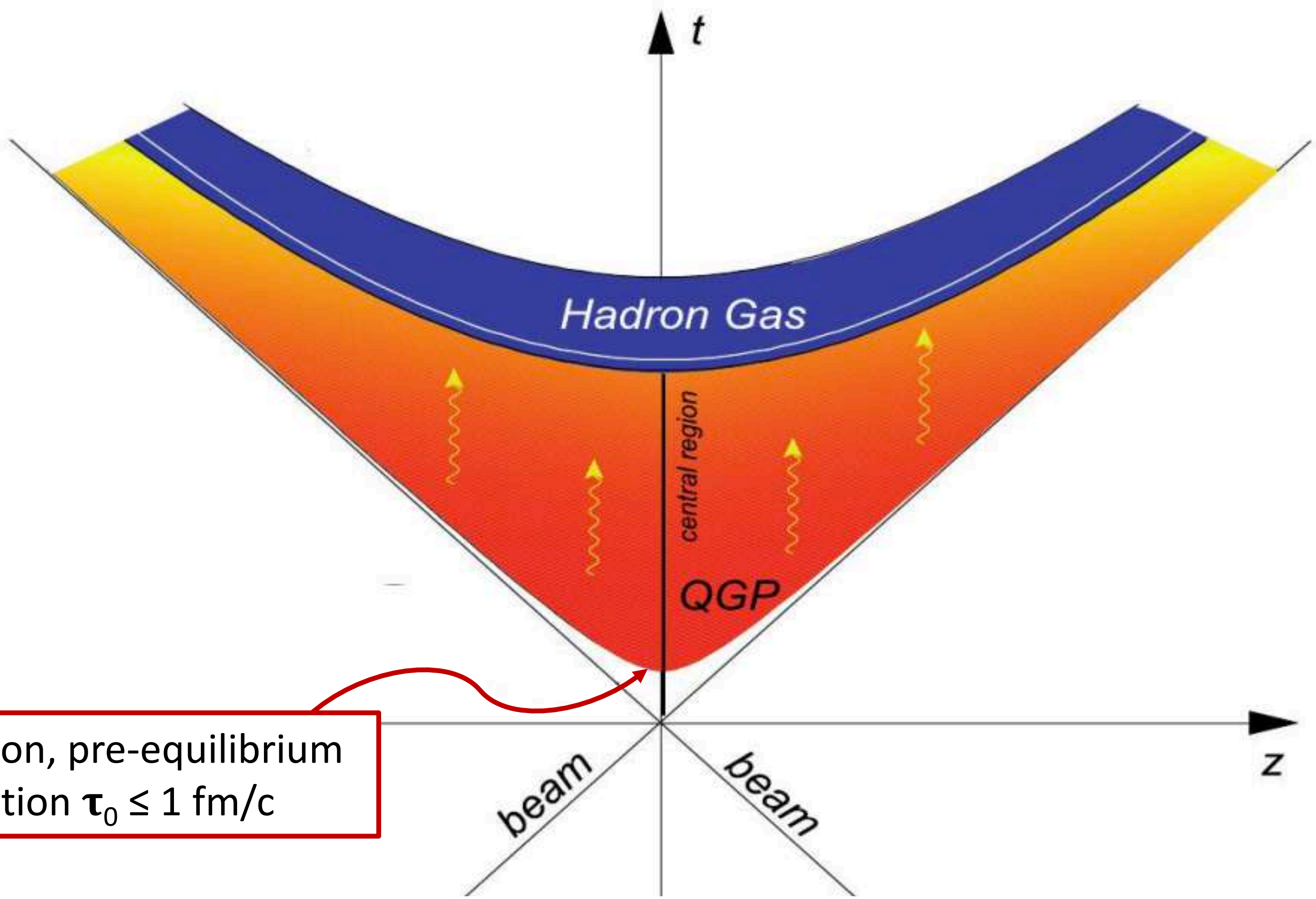
Laboratori Nazionali di Frascati, December 11th 2019

Motivations

Why study light-flavour production in pp, p-A and A-A collisions at different energies at LHC?

- Light-flavour (u, d, s) hadrons produced at low p_T (soft probes) constitute the bulk (more than 99%) of the produced particles at LHC
- Such particles probe the system as a whole, giving the opportunity to study **collective behavior** and **thermodynamic properties** of the medium
- In high-energy particle collisions the **p_T spectra of identified hadrons** carry much information about the system evolution (**Radial flow, Kinetic freeze-out, Chemical freeze-out**, **Energy loss in the medium**)

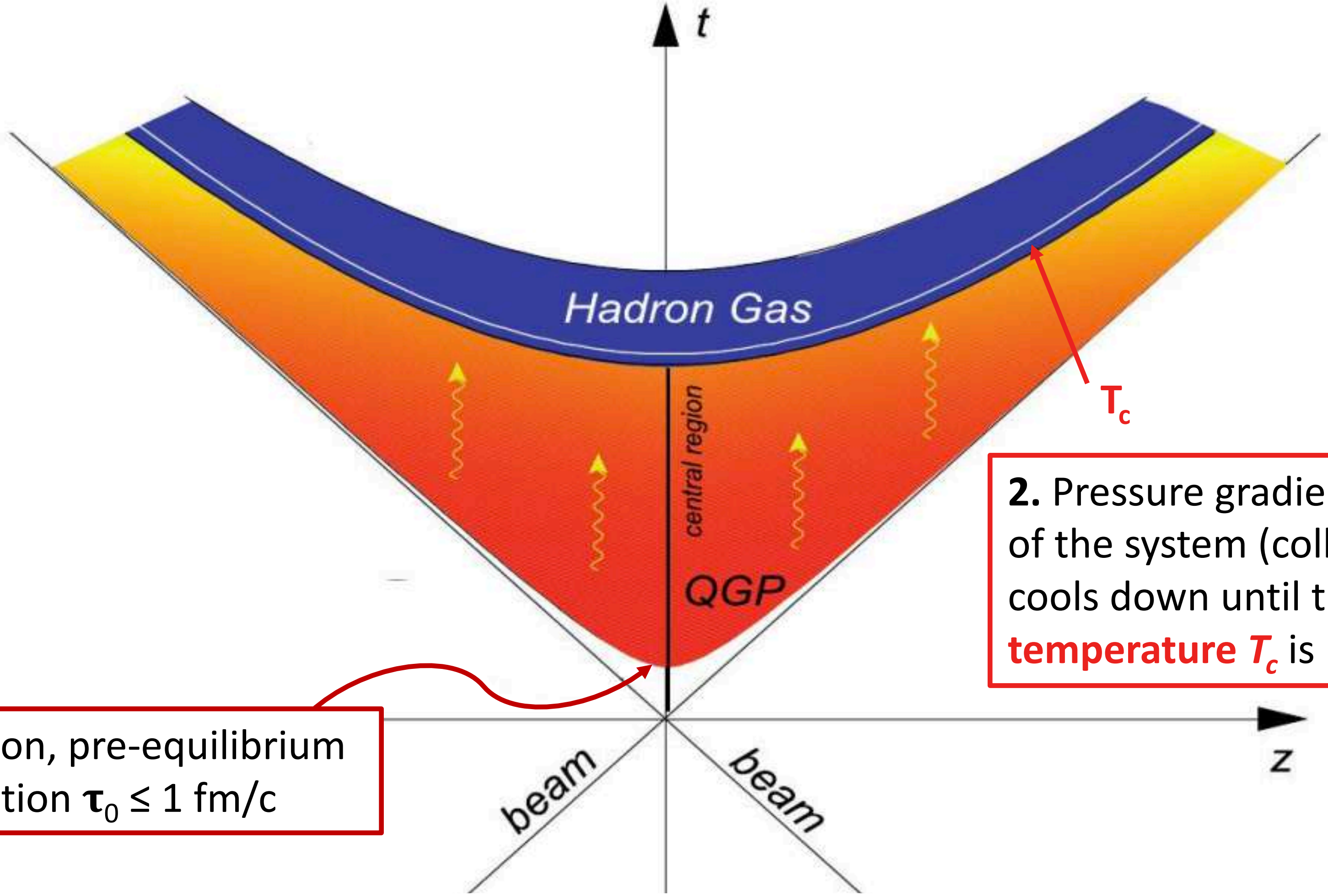
Evolution of a heavy-ion collision



1. QGP formation, pre-equilibrium and thermalization $\tau_0 \leq 1$ fm/c

A Large Ion Collider Experiment

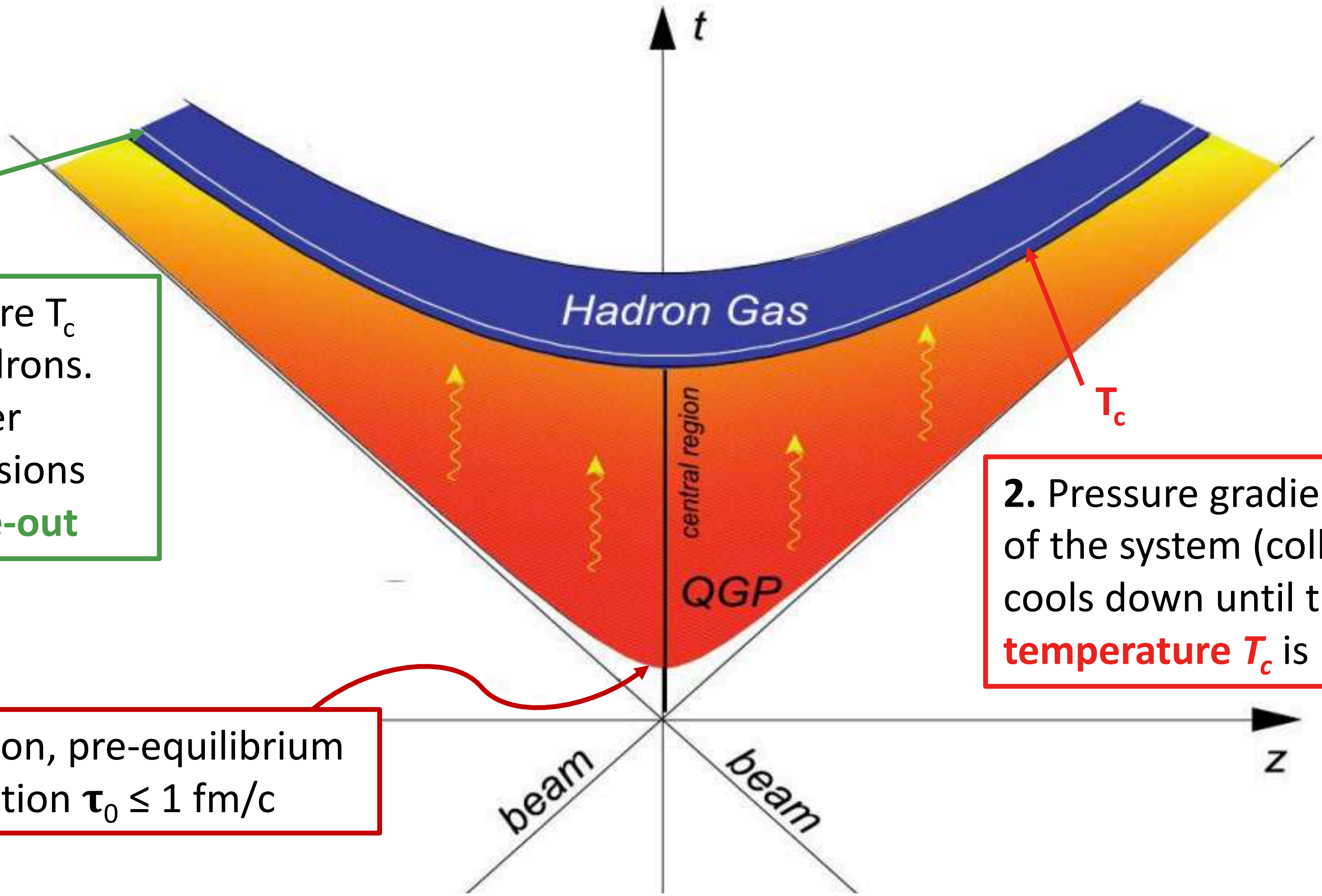
Evolution of a heavy-ion collision



1. QGP formation, pre-equilibrium and thermalization $\tau_0 \leq 1$ fm/c

2. Pressure gradients cause an expansion of the system (collective evolution) that cools down until the **phase-transition temperature T_c** is reached.

Evolution of a heavy-ion collision



3. At the critical temperature T_c partons freeze out into hadrons. The hadron gas then further expands until inelastic collisions stop at the **chemical freeze-out**

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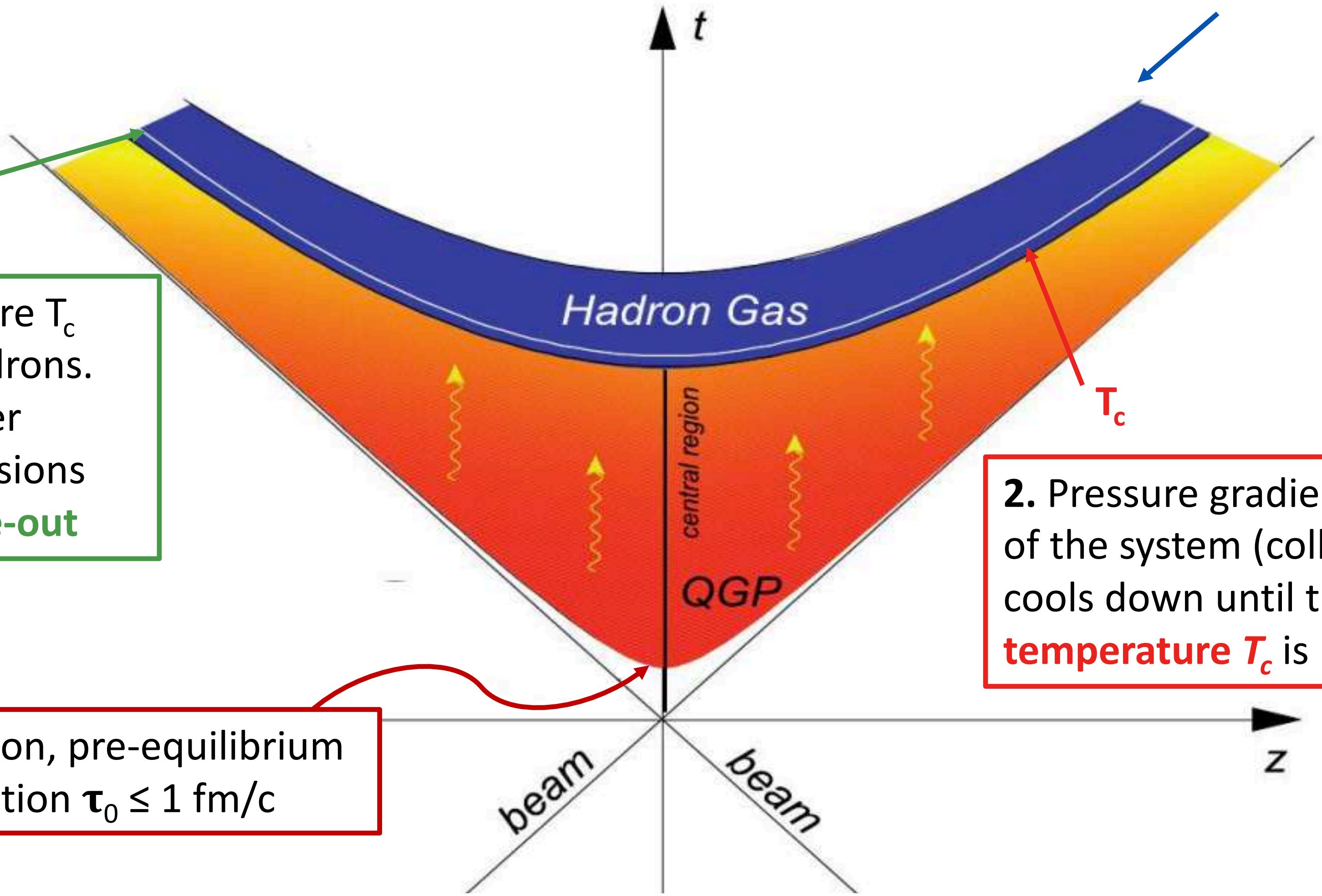

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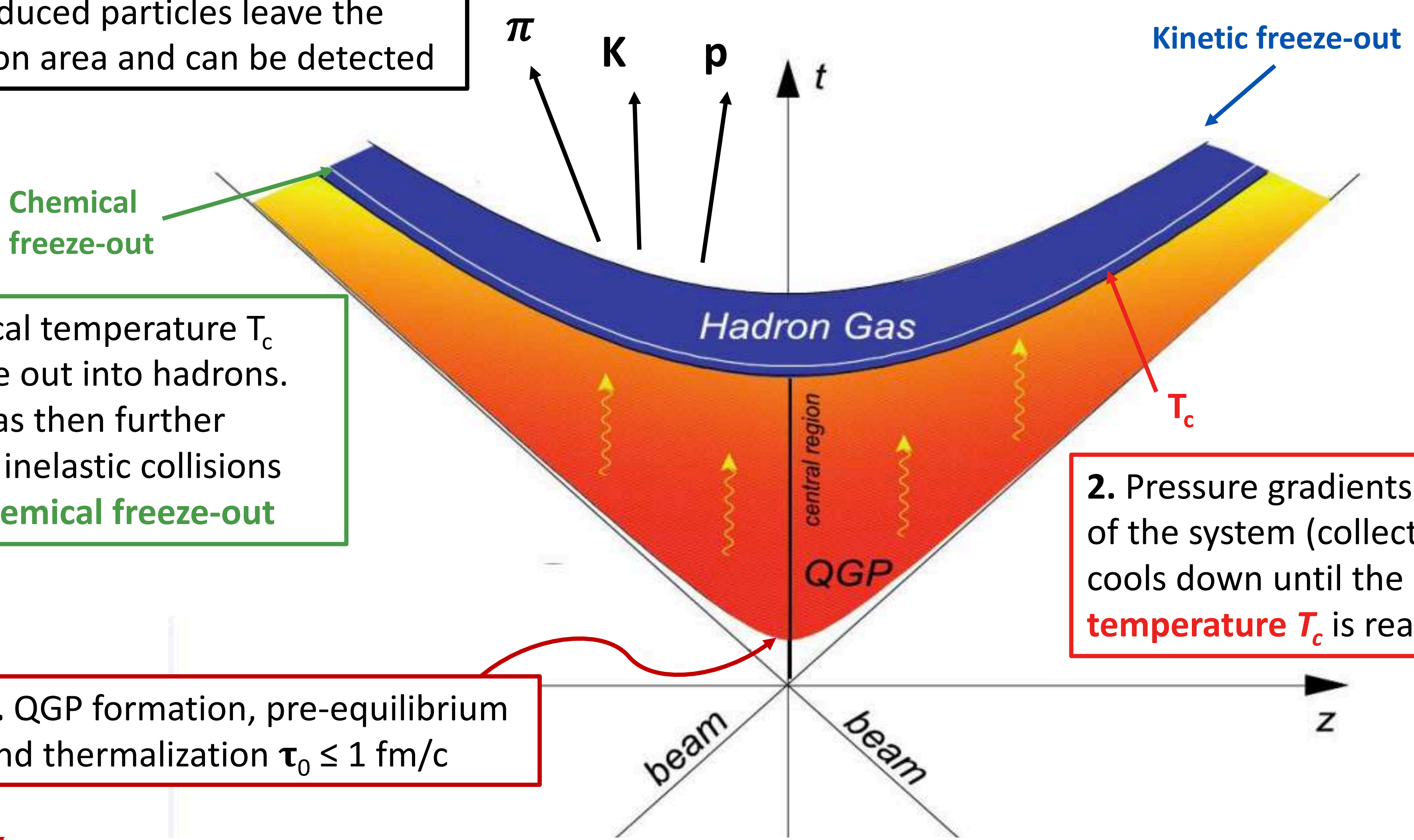
4. The particle yields are frozen. The momentum spectra can still change until elastic collisions stop and the **kinetic freeze-out** is reached.

Evolution of a heavy-ion collision

5. Produced particles leave the collision area and can be detected

4. The particle yields are frozen. The momentum spectra can still change until elastic collisions stop and the **kinetic freeze-out** is reached.



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1. QGP formation, pre-equilibrium and thermalization $\tau_0 \leq 1$ fm/c

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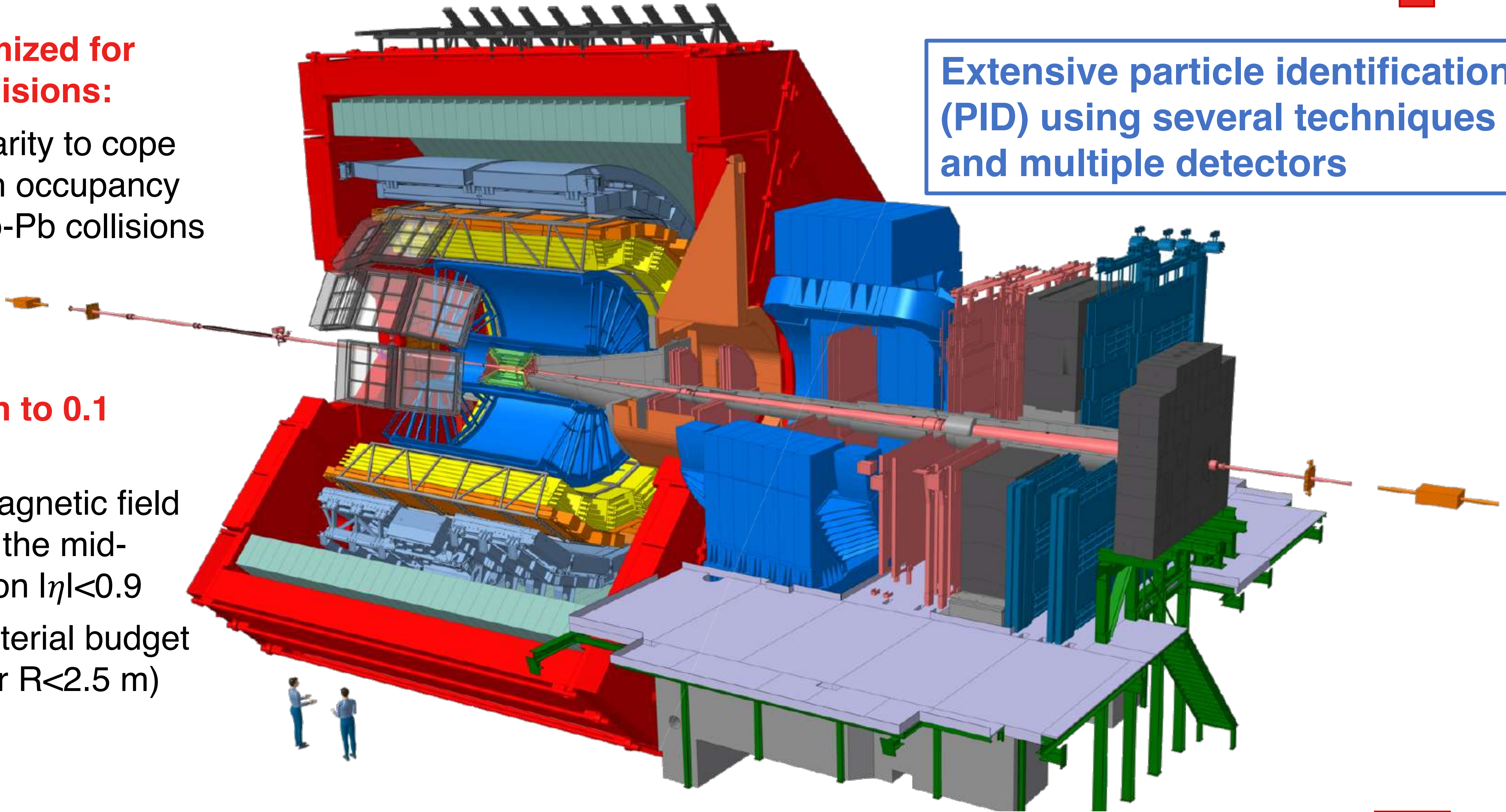
ALICE detector

Detector optimized for Heavy Ion collisions:

- High granularity to cope with the high occupancy events in Pb-Pb collisions

Tracking down to 0.1 GeV/c:

- Moderate magnetic field (B=0.5 T) in the mid-rapidity region |η|<0.9
- Very low material budget (<10% X_0 for R<2.5 m)



Extensive particle identification (PID) using several techniques and multiple detectors

ALICE detector

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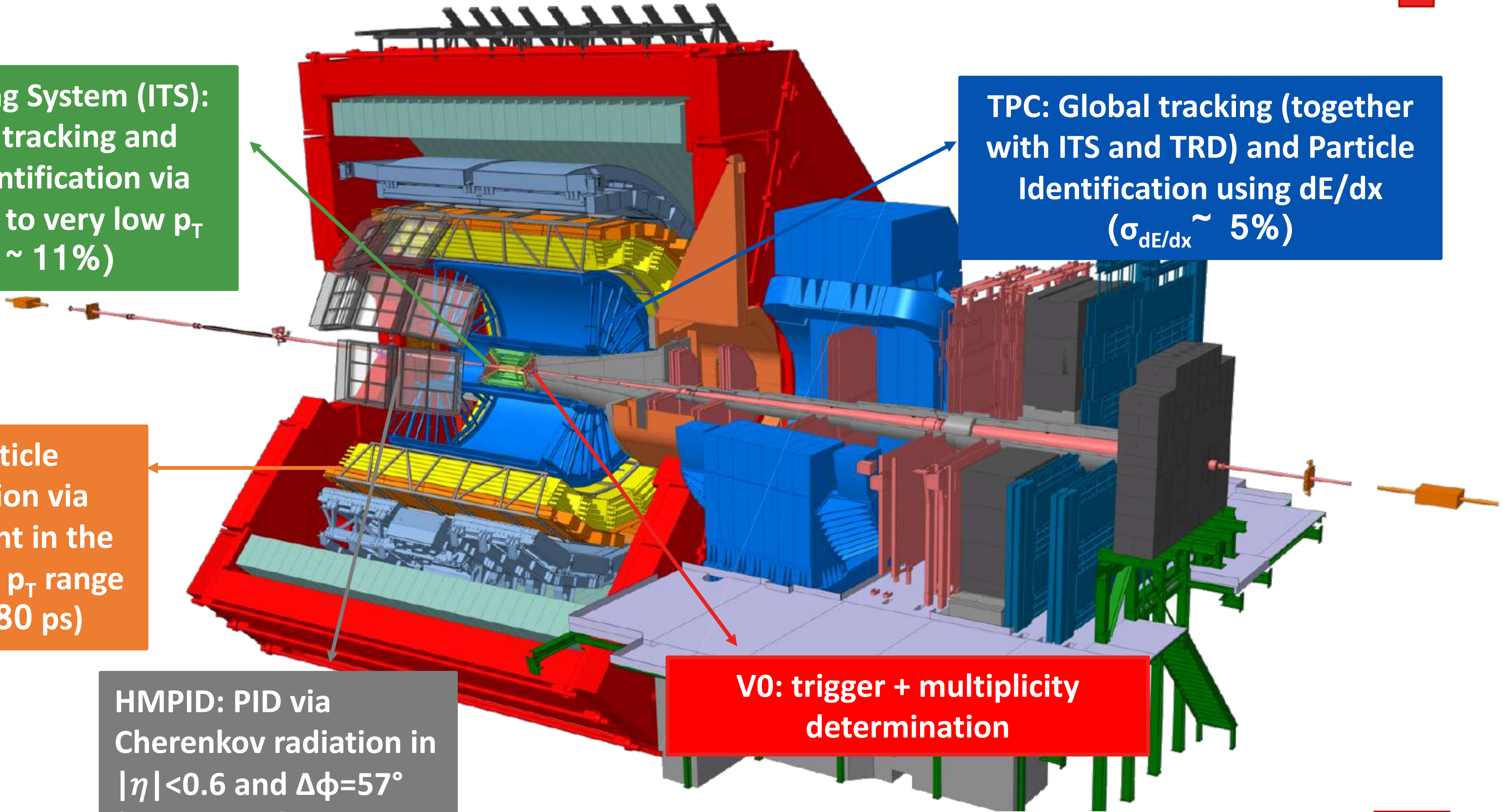

Inner Tracking System (ITS): Vertexing, tracking and Particle identification via dE/dx down to very low p_T ($\sigma_{dE/dx}$ ~ 11%)

TPC: Global tracking (together with ITS and TRD) and Particle Identification using dE/dx ($\sigma_{dE/dx}$~ 5%)

TOF: Particle Identification via Time-of-Flight in the intermediate p_T range (σ_{TOF}~60-80 ps)

HMPID: PID via Cherenkov radiation in $|\eta|<0.6$ and $\Delta\phi=57°$ (σ ~ 3 mrad)

V0: trigger + multiplicity determination

A Large Ion Collider Experiment

ALICE detector

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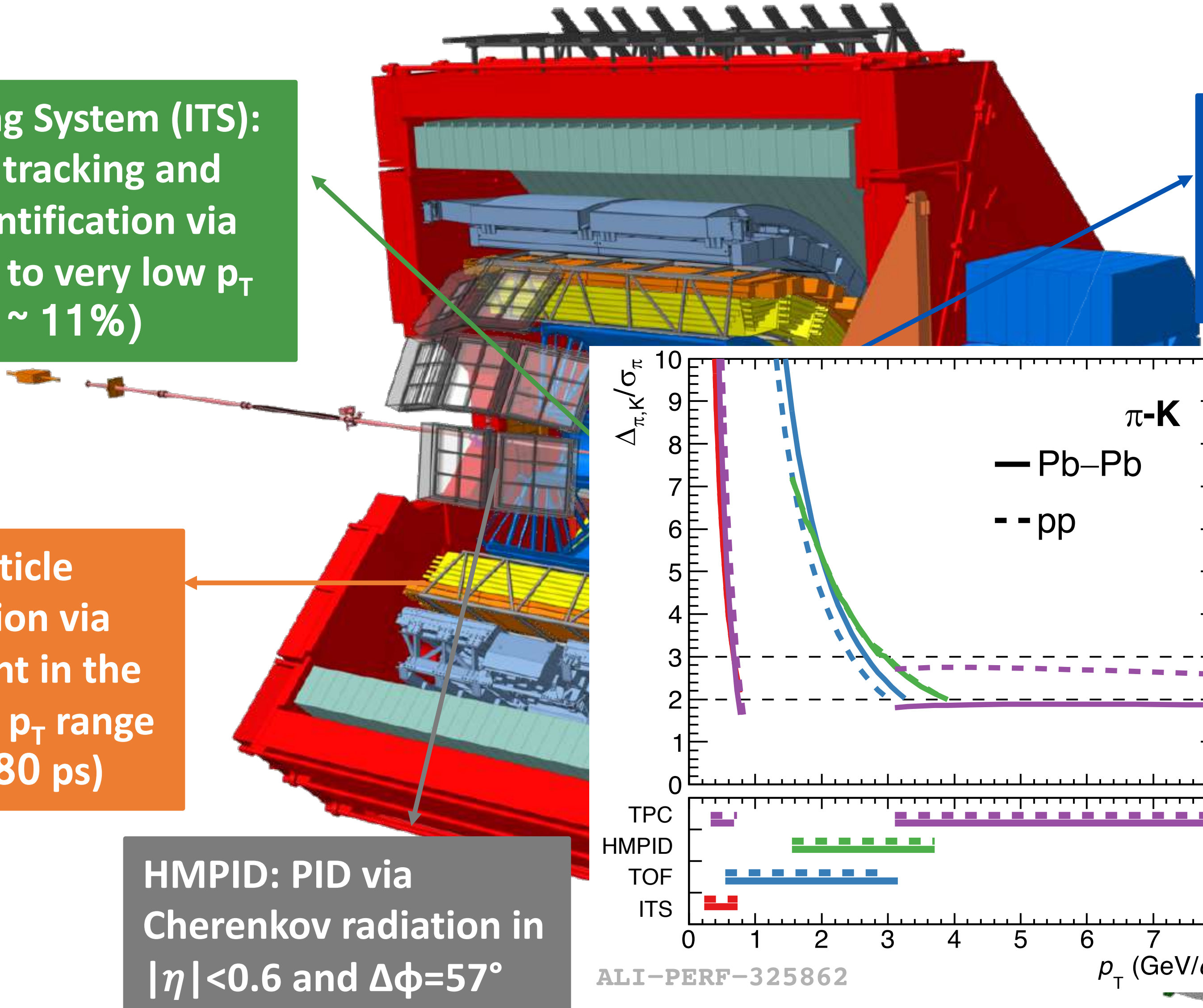

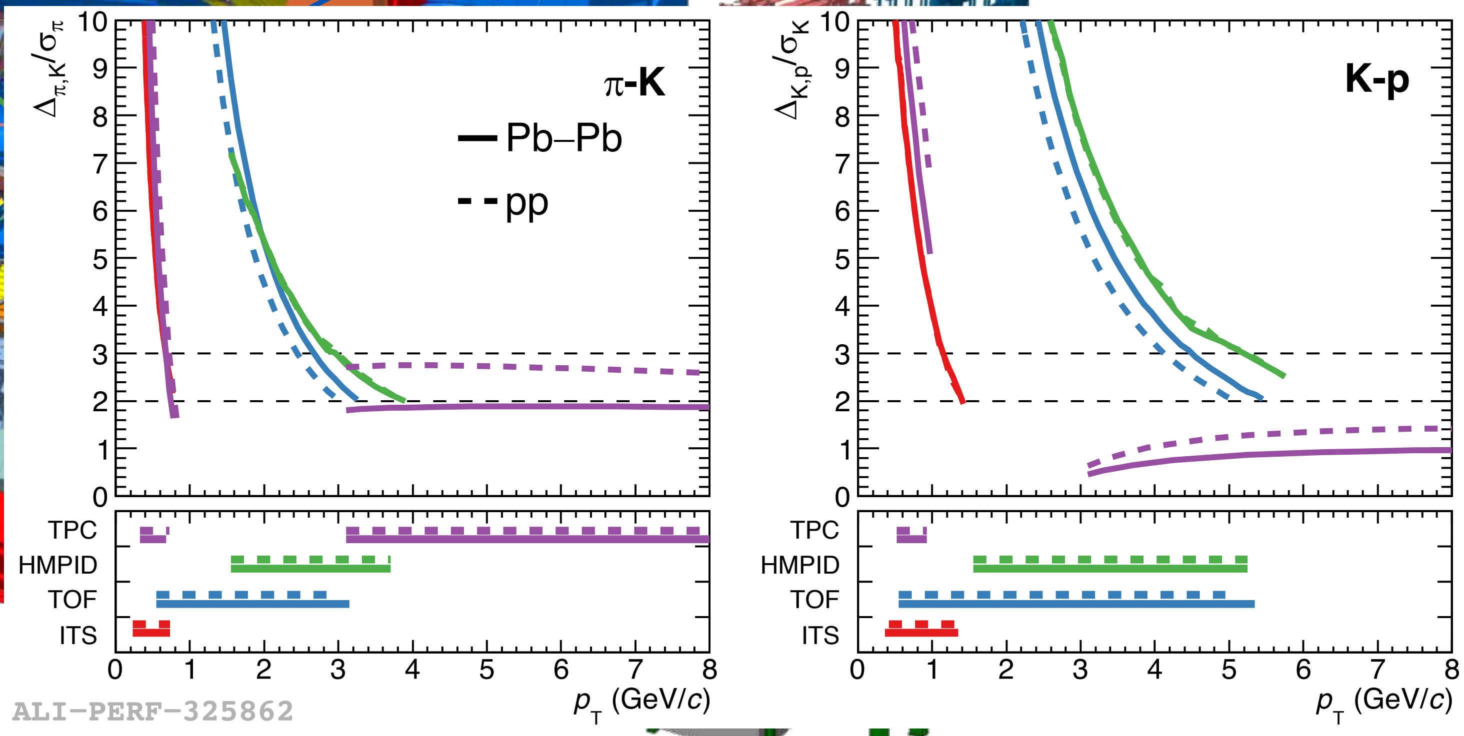

Particle identification

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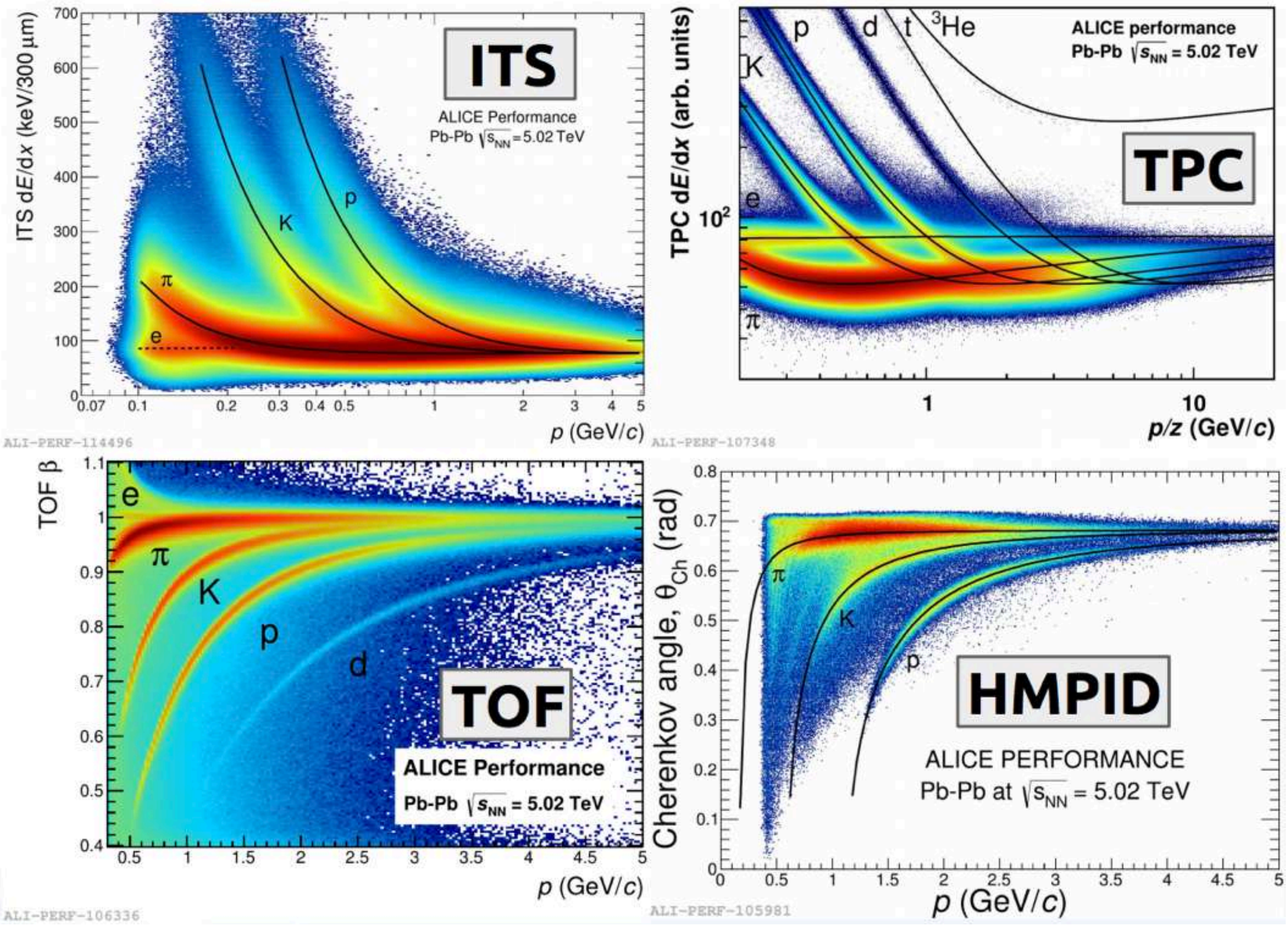
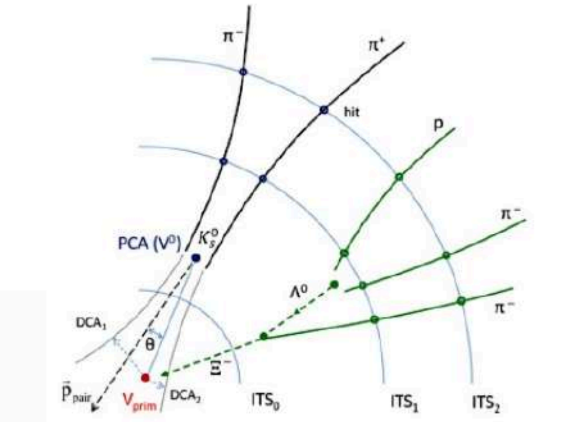
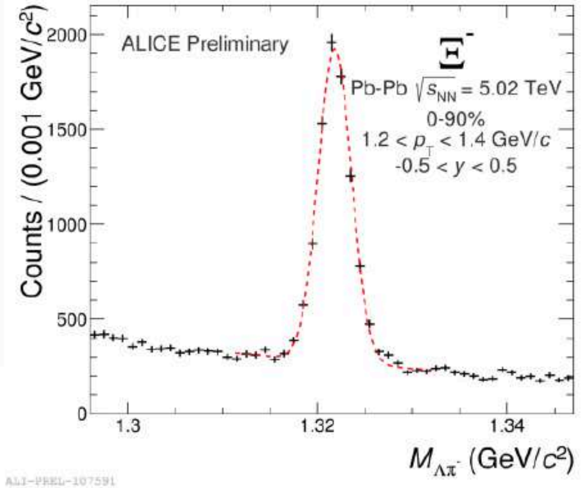


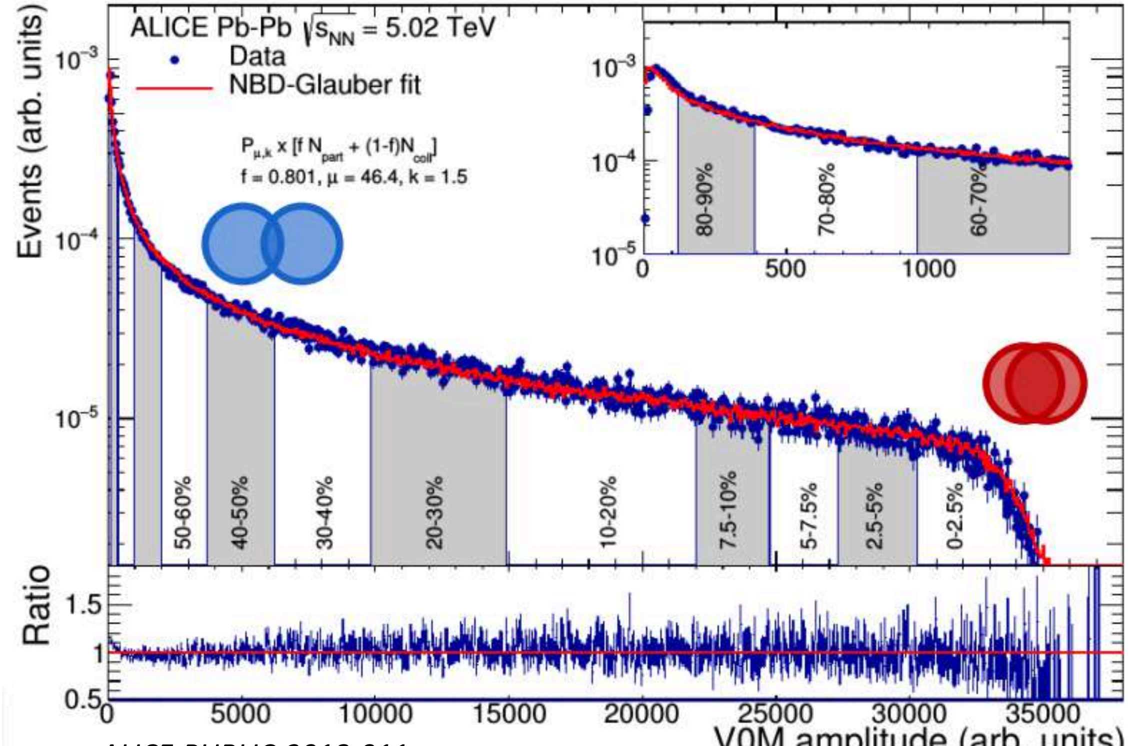
Decay topology
secondary vertex reconstruction +
invariant mass analysis



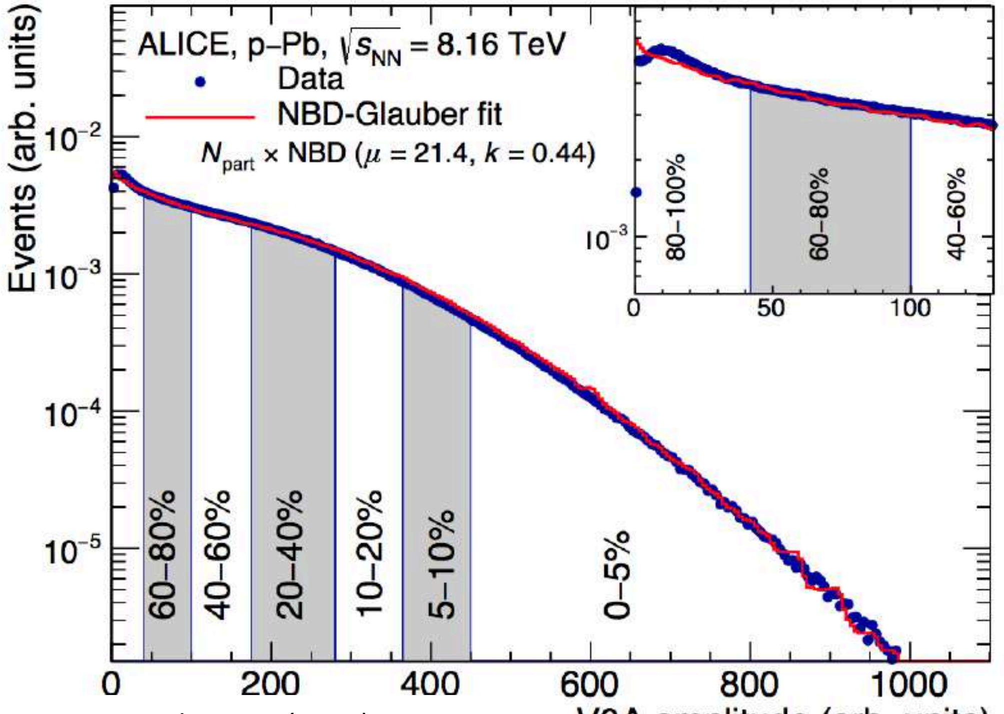


Event multiplicity and centrality

- Multiplicity is defined as the number of charged particles per event
- Linked through the impact parameter to the collision centrality in Pb–Pb
- ALICE measures the event activity at forward rapidity with the V0 detector
- Wide range of measured multiplicities from ≈ 2 in pp to ≈ 2000 in central Pb–Pb



ALICE-PUBLIC-2018-011



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p_T-spectra of π, K and p [Pb-Pb 5.02 TeV]

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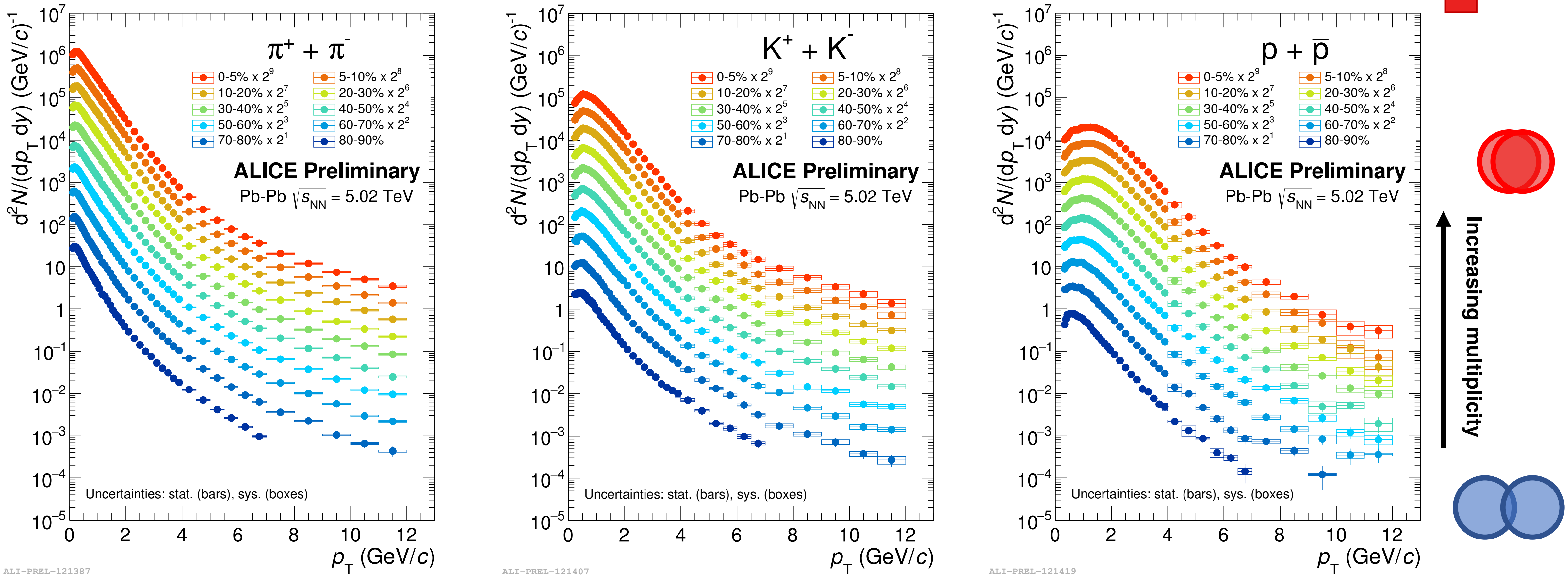

- Spectra become **harder as the multiplicity increases** (flattening visible at low p_T)
- **Mass-dependent hardening** of the soft part with increasing centrality as expected from collective hydrodynamic expansion (**radial flow**): the change is most pronounced for heavier particles

p_T-spectra of π, K and p [p-Pb 8.16 TeV]

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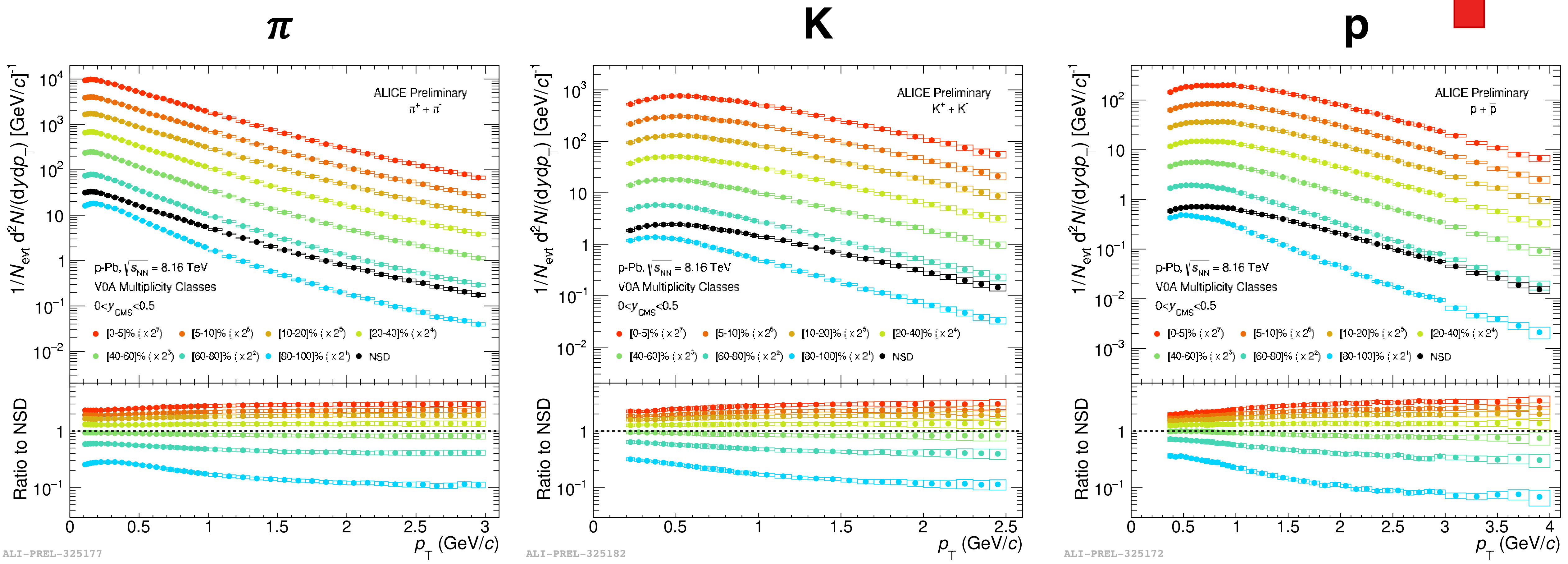
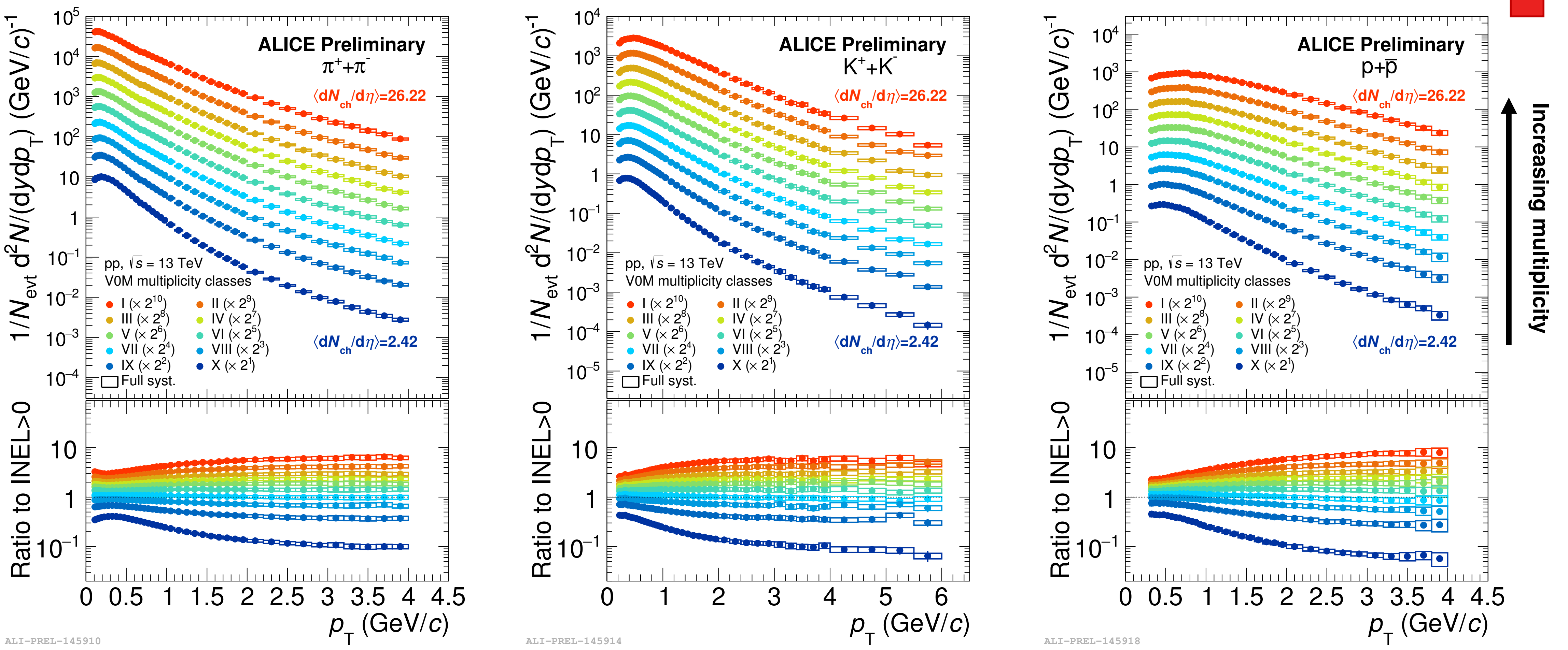


- **Mass-dependent hardening** of the soft part with increasing centrality
- Hints of radial flow in p-Pb collisions?

p_T-spectra of π, K and p [pp 13 TeV]



- **Mass-dependent hardening** of the soft part with increasing centrality
- Hints of radial flow in high multiplicity pp collisions?

Mean transverse momenta $<p_T>$

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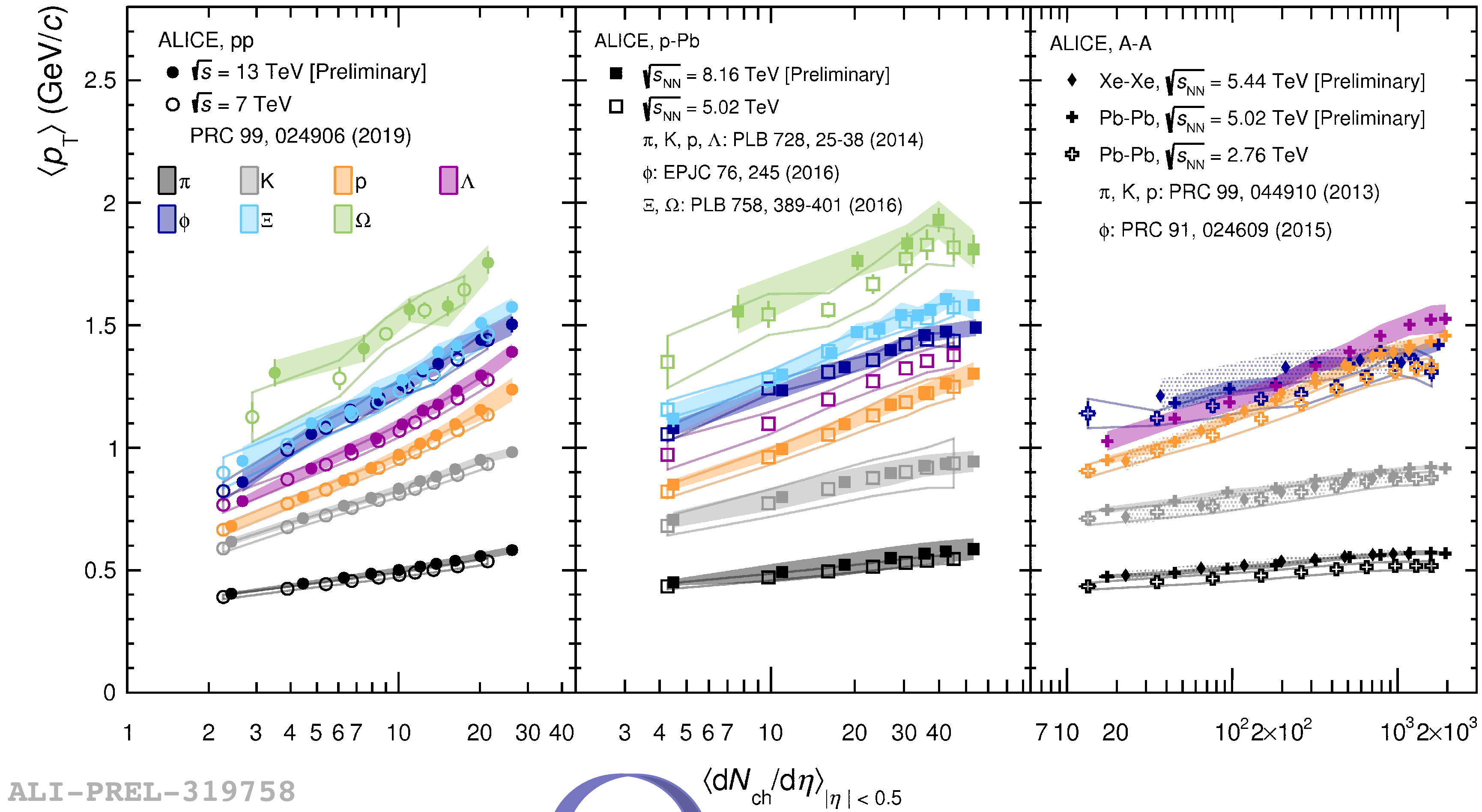

- **Spectra get harder with increasing multiplicity**
- Central A-A : particles with similar masses have similar $<p_T>$ (expected from hydrodynamics)
- Mass ordering violated by ϕ in pp, p-Pb and peripheral A-A
- Small hardening of the spectra with increasing √s
- At similar multiplicity $<p_T>$ is larger for smaller systems

$M_\Omega(1672) > M_\Xi(1322) > M_\Lambda(1116) > M_\Phi(1020) > M_p(938) > M_K(494) > M_\pi(140)$ (Approximated masses in MeV)

Particle ratios: evolution with the system size

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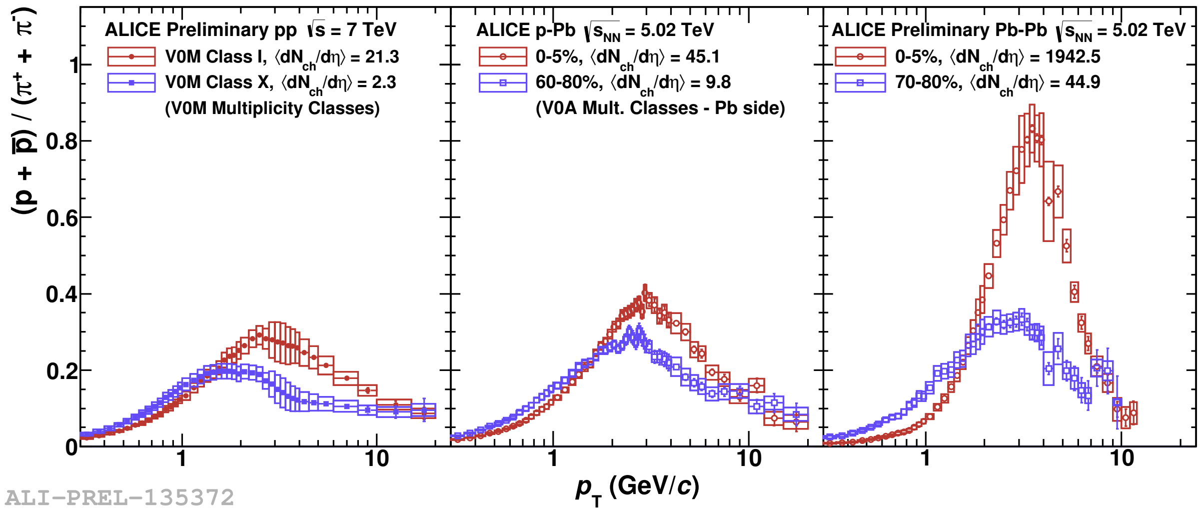

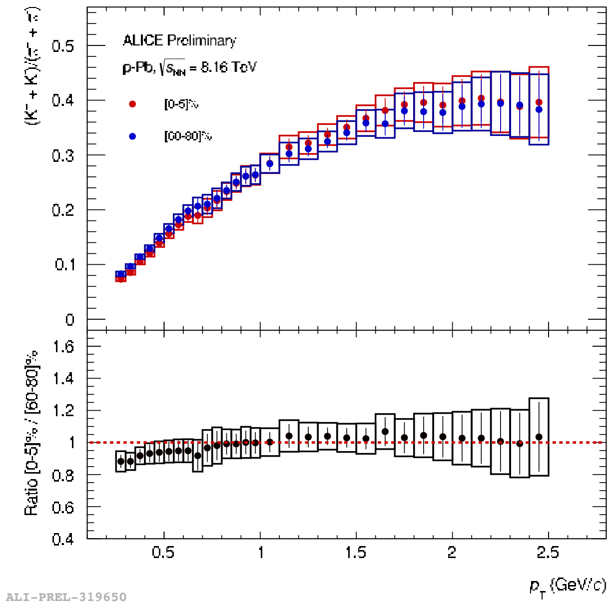

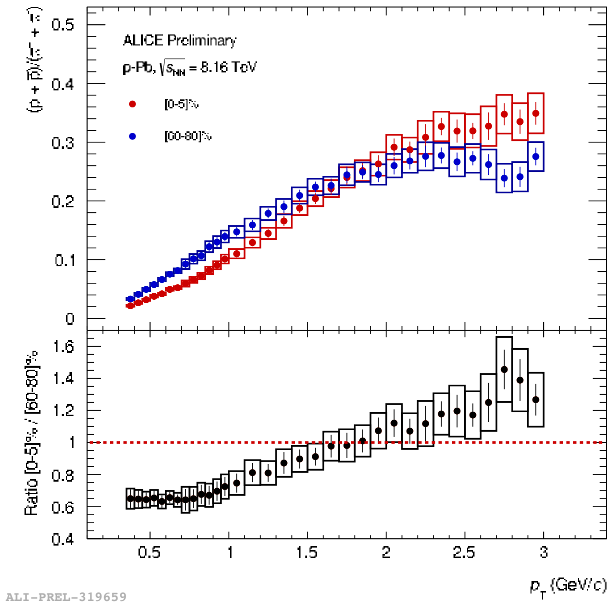

- Ratios indicate that mass and multiplicity are the main parameters driving particle spectra (as foreseen by hydro)
- p/π: **significant evolution with the size of the collision system from low to high multiplicity** (similar flow-like features for pp, p-Pb and Pb-Pb systems)
  - Peripheral Pb-Pb collision are similar to pp and p-Pb collisions (low multiplicity)
  - depletion at low p_T, enhancement at intermediate p_T
- **K/π:** very small enhancement with multiplicity

Baryon-to-meson ratios are sensitive to particle production mechanisms [radial flow at low p_T, radial flow/recombination at mid-p_T (?)]

Particle ratios: evolution with the system size

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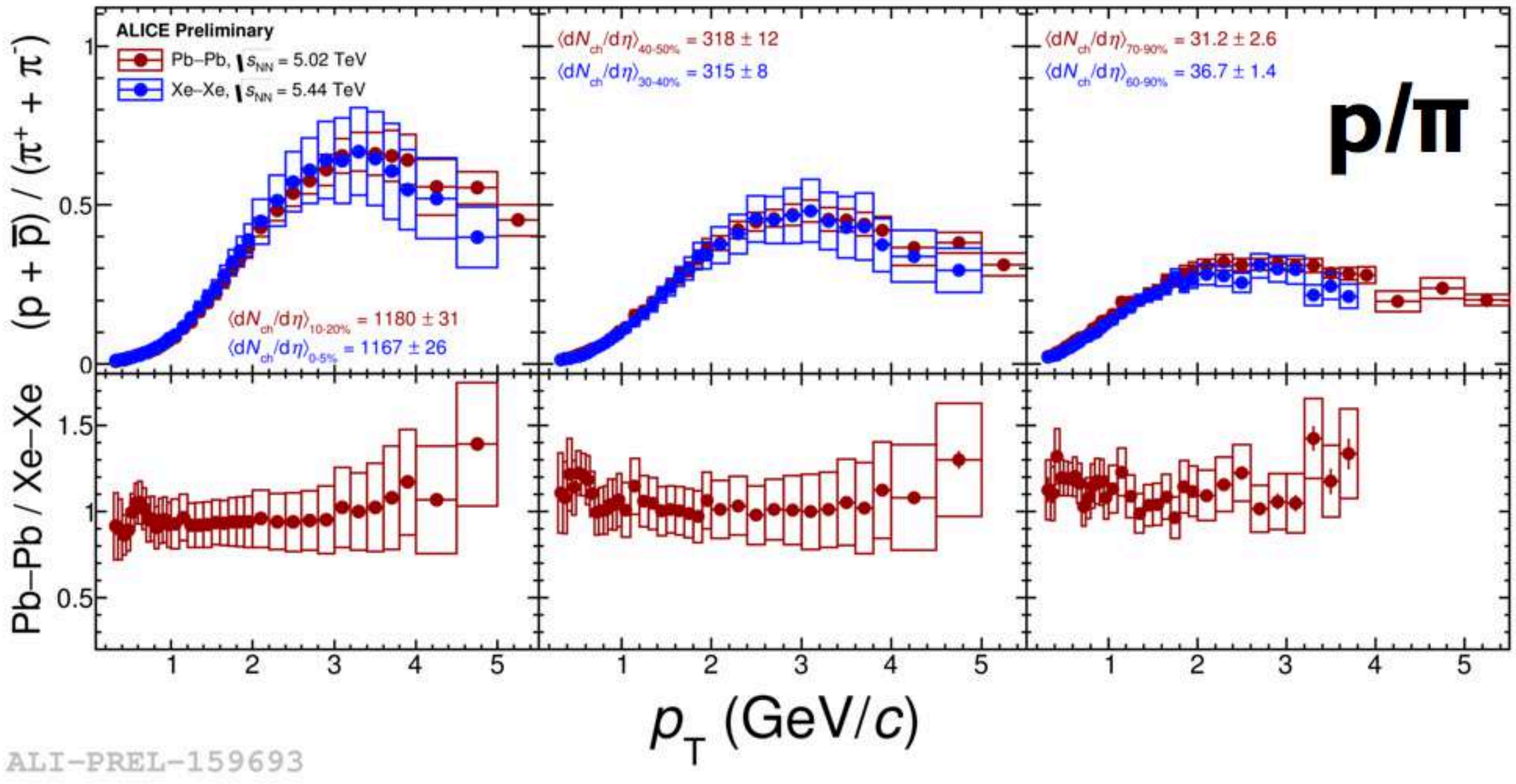
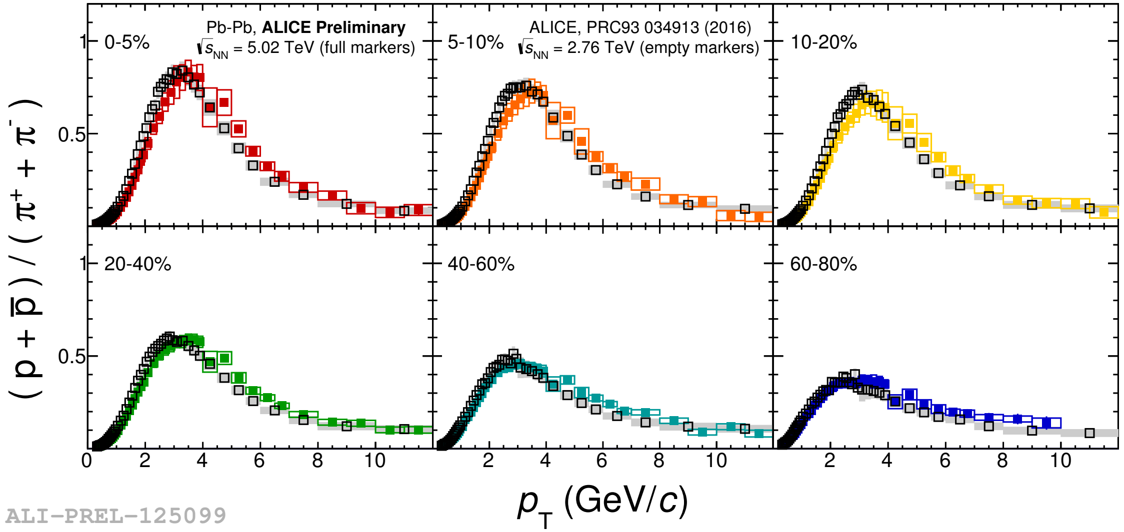
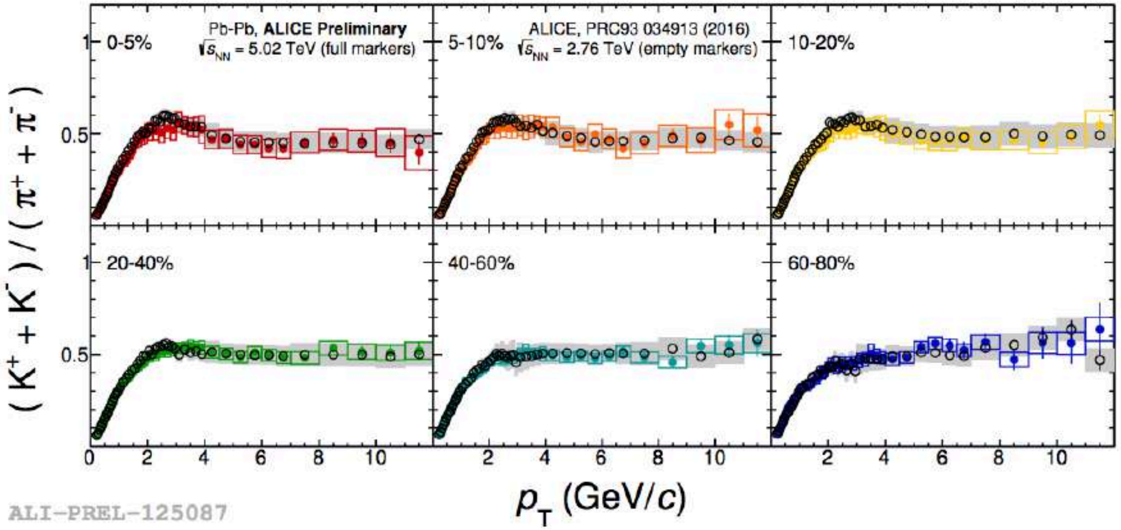


- Particle ratios in Pb-Pb at 5.02 TeV and Xe-Xe at 5.44 TeV are consistent within uncertainties once compared at the same multiplicity (and not just centrality percentile)
- Evolution with centrality in A-A collisions and the shape of the p/π ratio are consistent with the presence of radial flow (mass dependence of spectral shapes)

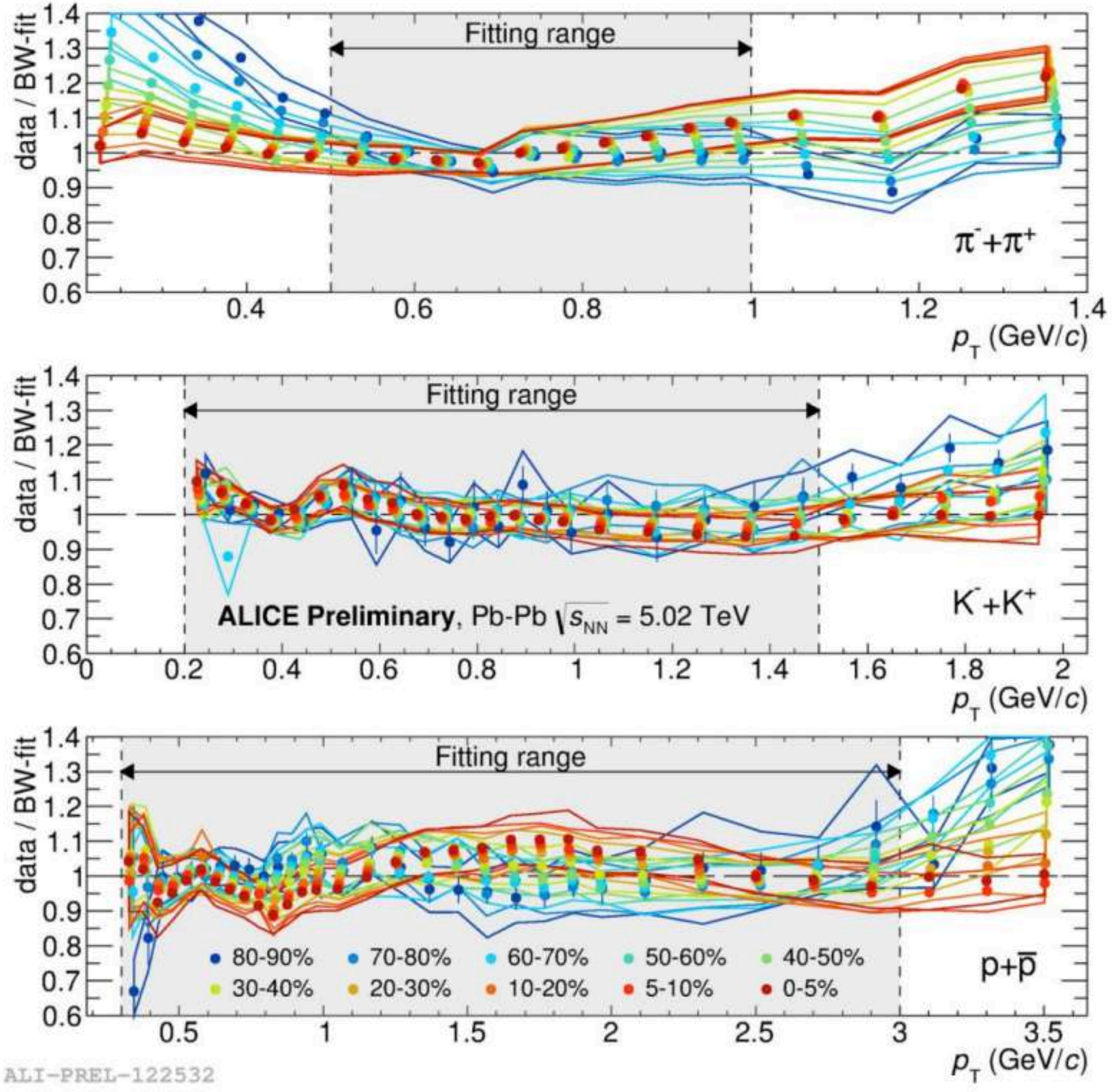
Particle ratios: evolution with the energy





- Indication of a slightly larger radial flow in central collisions compared to lower energies:
  - p/π: small blueshift of the maxima —> (slightly) larger radial flow at 5.02 TeV
  - K/π: no significant difference between 2.76 and 5.02 TeV
  - The effect is more evident in p/π than in K/π, due to the larger mass difference

Radial flow and Blaste-Wave model

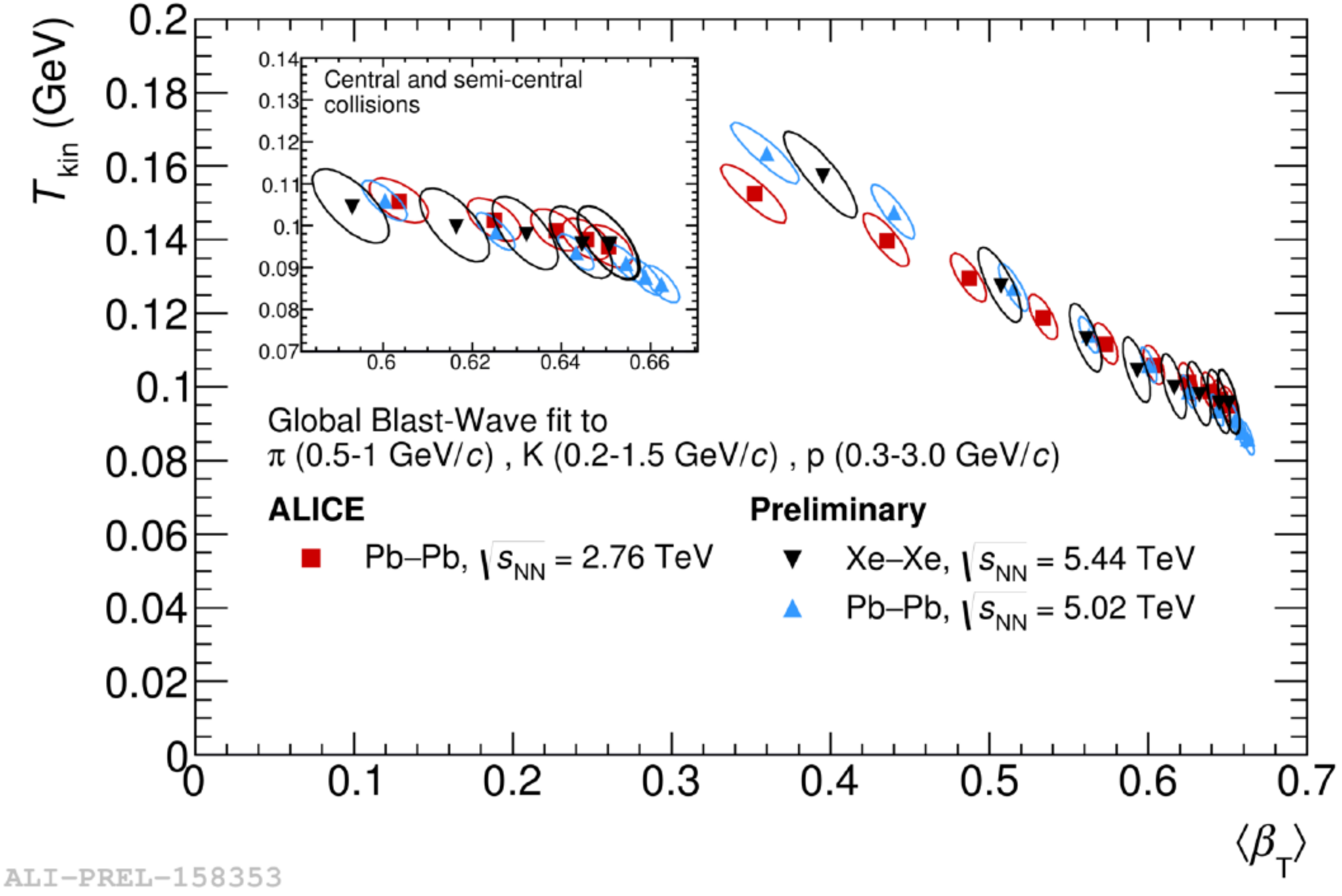


Simplified hydrodynamical model used to quantify radial flow [*E. Schnedermann et al., Phys. Rev. C48 (1993) 2462*] with 3 free fit parameters,

- T_{kin} = kinetic freeze-out temperature
- $\langle\beta_T\rangle$ = transverse radial flow velocity
- n = velocity profile

- **Baste-Wave model**: Locally thermalized medium, collective expansion with common expansion velocity β_T and freeze-out temperature T_{kin}
- Describes the particle distribution at kinetic freeze-out as a result of the expansion of a thermalized source
- Boltzmann-Gibbs statistics is used as an initial thermal distribution
- Free parameters are obtained with a simultaneous fit to the measured π/K/p distributions

Blaste-Wave results



Large systems (AA collisions):

- Largest $<\beta_T>$ and lowest T_{kin} for central AA collisions
- The expansion velocity slightly increases with the collision energy
- Xe-Xe and Pb-Pb consistent

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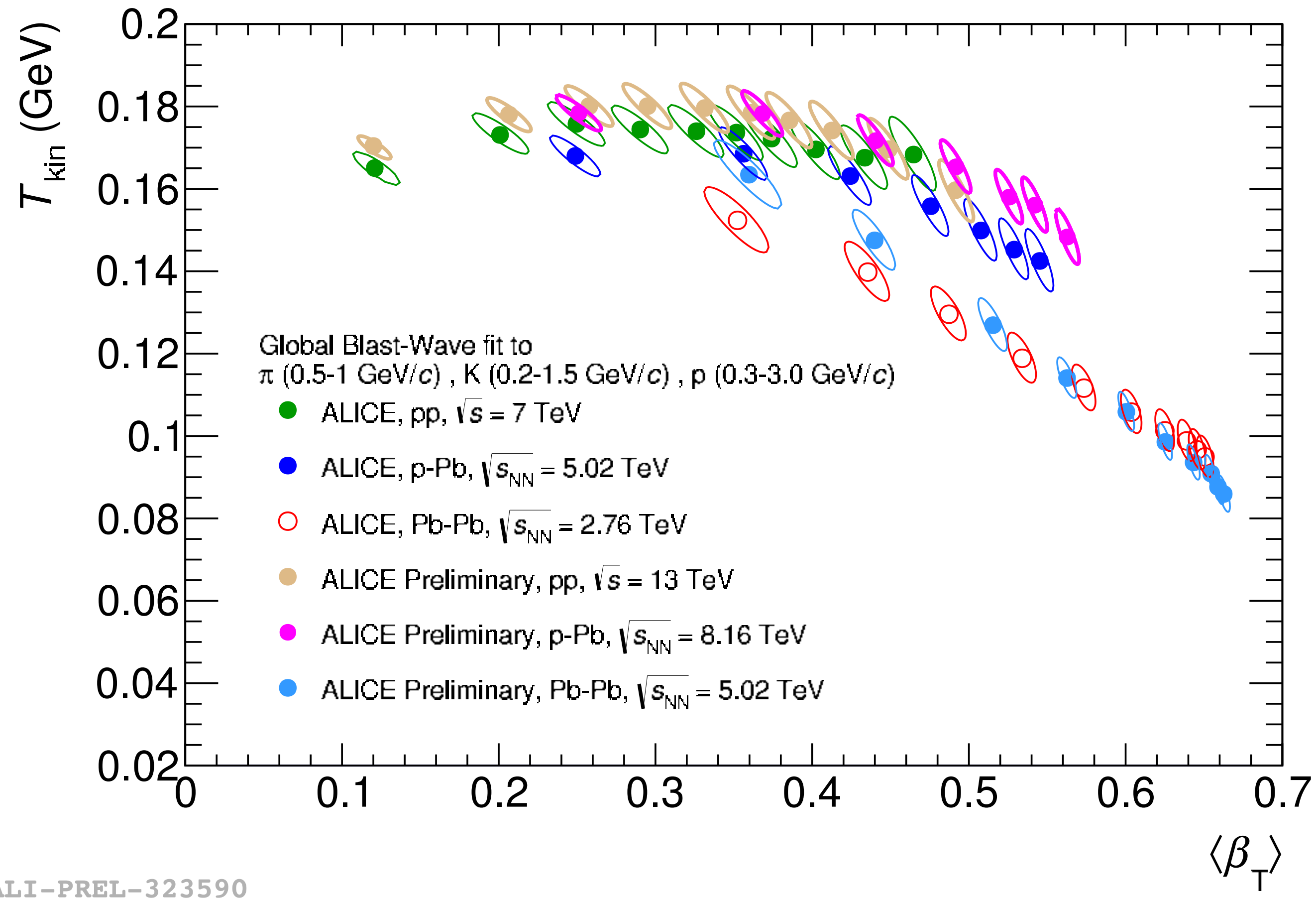
Blaste-Wave results



Large systems (AA collisions):

- Largest $<\beta_T>$ (strongest radial flow) and lowest T_{kin} for central AA collisions
- The expansion velocity slightly increases with the collision energy
- Xe-Xe and Pb-Pb consistent

Small systems (pp and p-Pb)

- Weaker correlation between T_{kin} and $<\beta_T>$
- pp and p-Pb show a similar trend and values are comparable: higher T_{kin} in p-Pb 8.16 TeV wrt 5.02 TeV
- Larger decoupling temperature with respect to heavy-ion collisions
- Only for high multiplicity p-Pb show a similar trend to Pb-Pb (radial flow in p-Pb?)

Blaste-Wave results vs multiplicity

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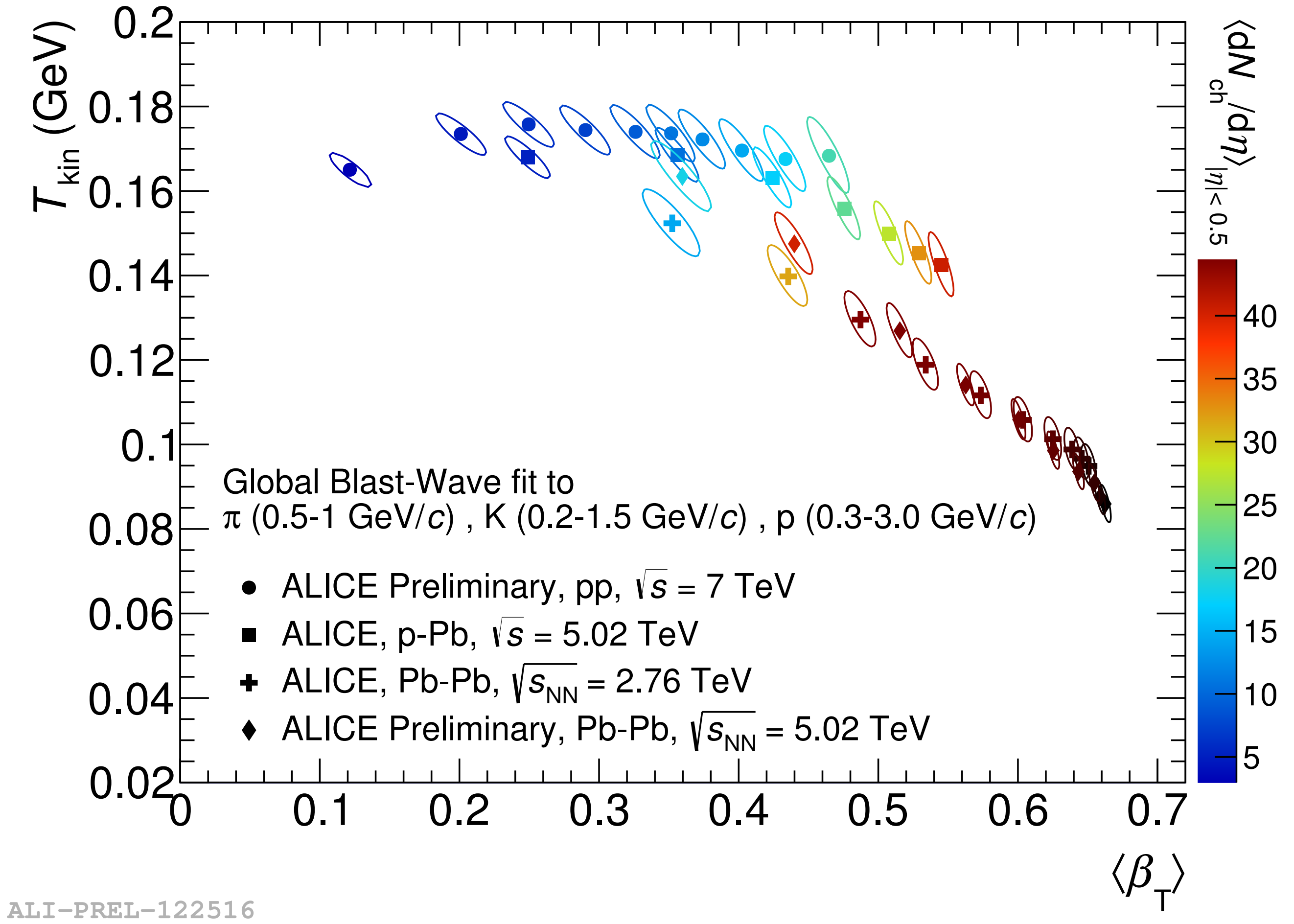

- For AA collisions <β_T> increases with the centrality, while T_{kin} decreases
- Continuous evolution as a function of the event multiplicity is found in small systems (pp, p-Pb)
- **At similar multiplicity <β_T> is larger for smaller systems. The same is true for <p_T>**

It is not possible to conclude with BW analysis that the observed trend in the different systems is driven by the same type of collectivity (radial flow)

QCD effects such as color reconnection (CR), where no hydro expansion is assumed, can mimic the effects of radial flow:

- e.g. p/π vs multiplicity in pp collisions is described better by Pythia8 with CR than w/o CR

Comparison to Hydro models - central

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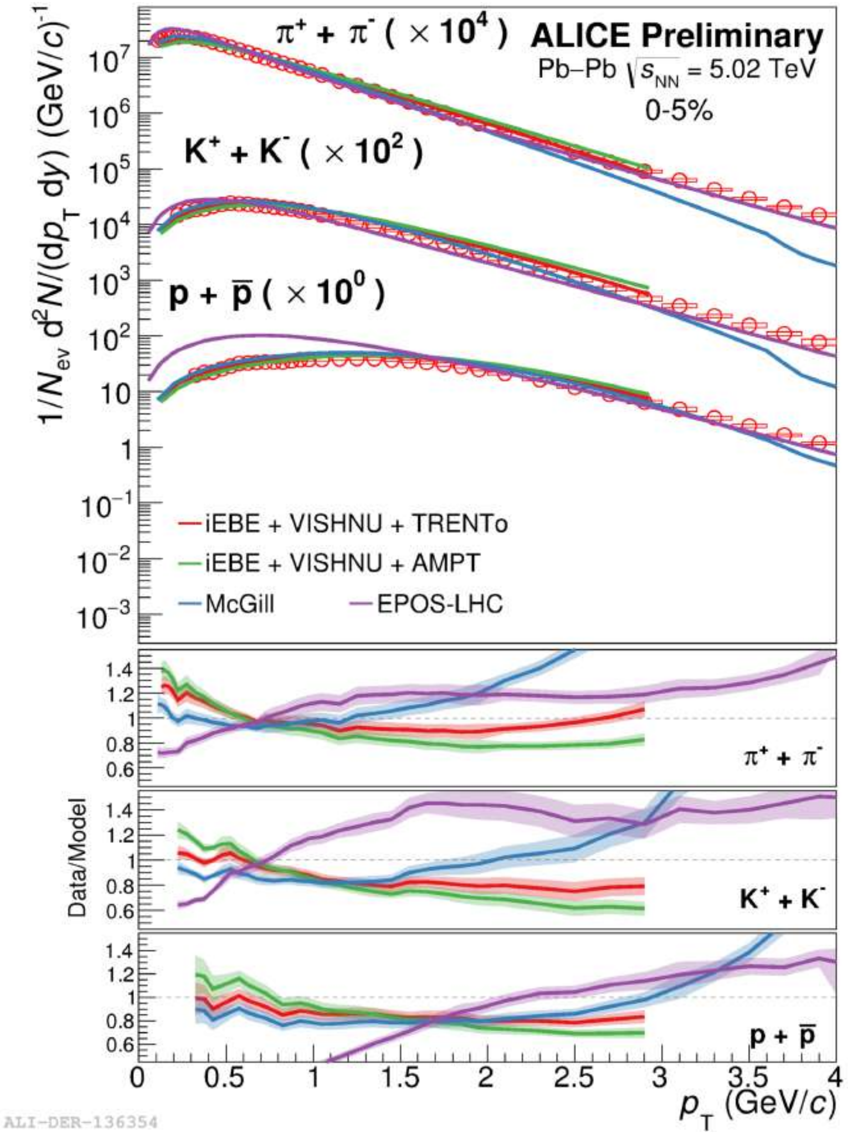

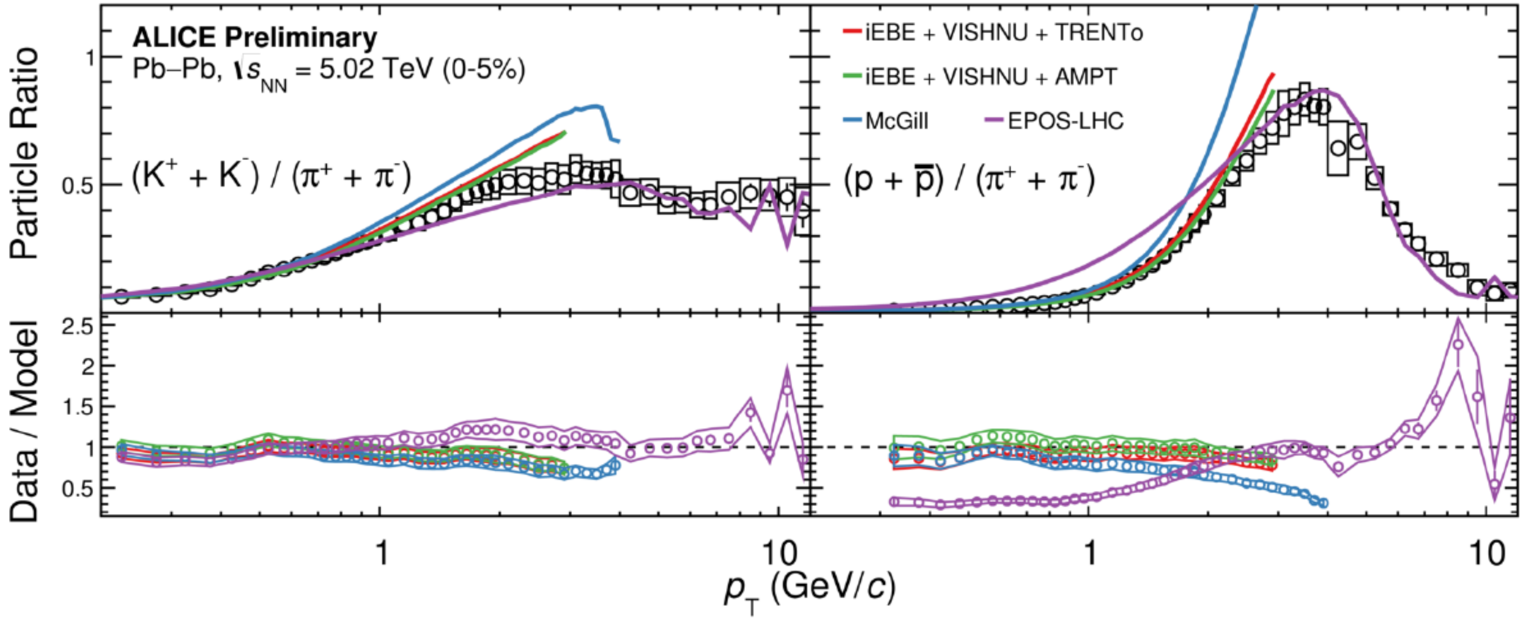

ALI-DER-139092

iEbyE + VISHNU + Trento / AMPT: viscous hydro with different initial conditions *[arXiv:1703.10792v1, PRC 92, (2015) 014903, PRC 92 (2015) 011901(R)]*

McGill: MUSIC viscous hydro with IP-Glasma initial conditions *[PRC 95 (2017) 064913]*

EPOS-LHC: core (hydro) + corona *[PRC 92 (2015) 034906]* **qualitatively** captures the spectral **ratios up to higher p_T**

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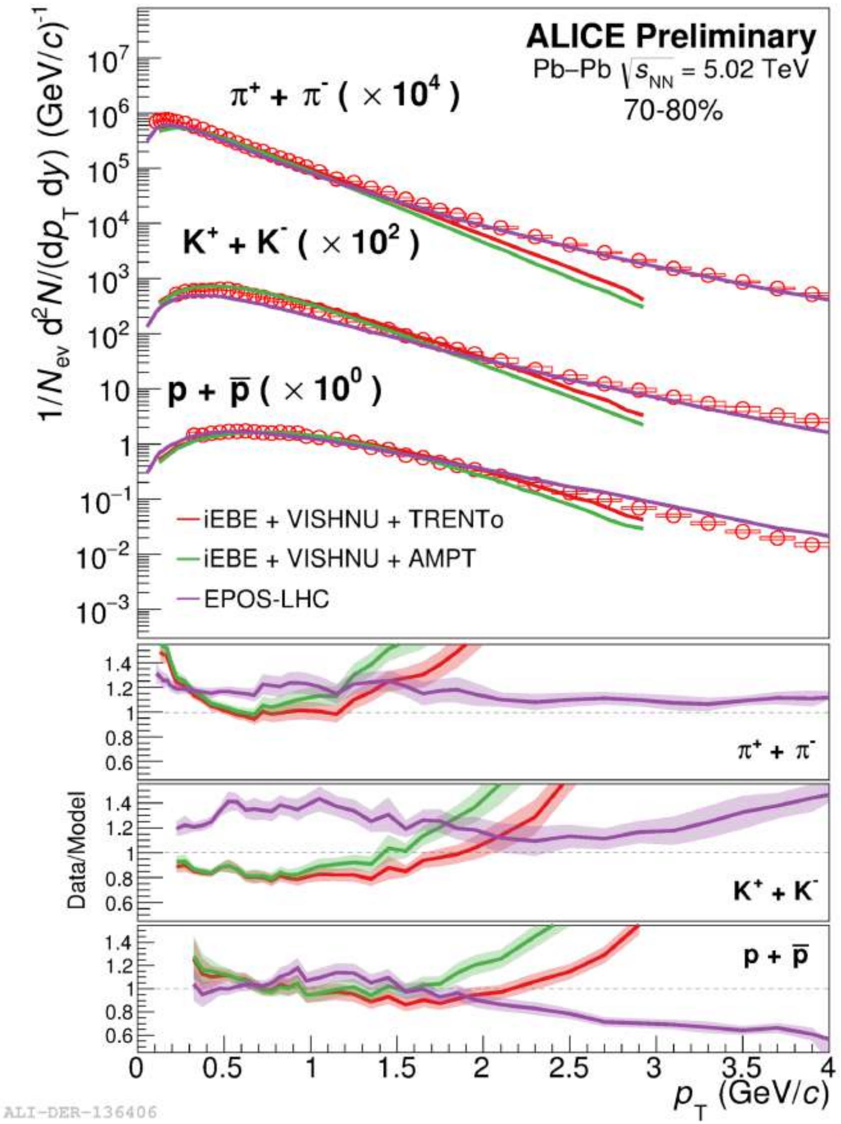
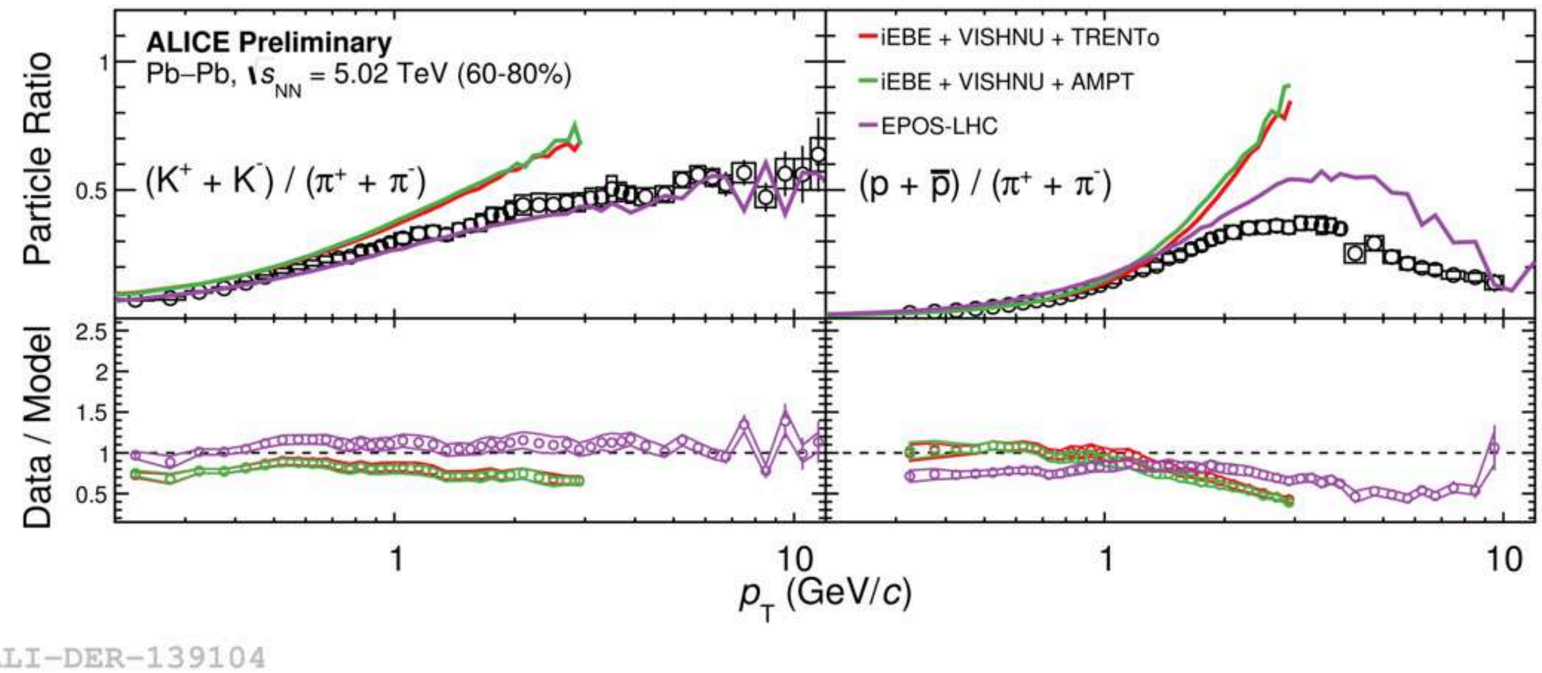
Comparison to Hydro models - peripheral





"Full-hydro" models reproduce features of particle spectra and particle ratios for $p_T < 2$ GeV/c at 20-30% level for central collisions

Agreement **worsens towards peripheral / low multiplicity events** → Improvements are needed to reproduce the evolution with multiplicity, also in view of extension of hydro description to small systems

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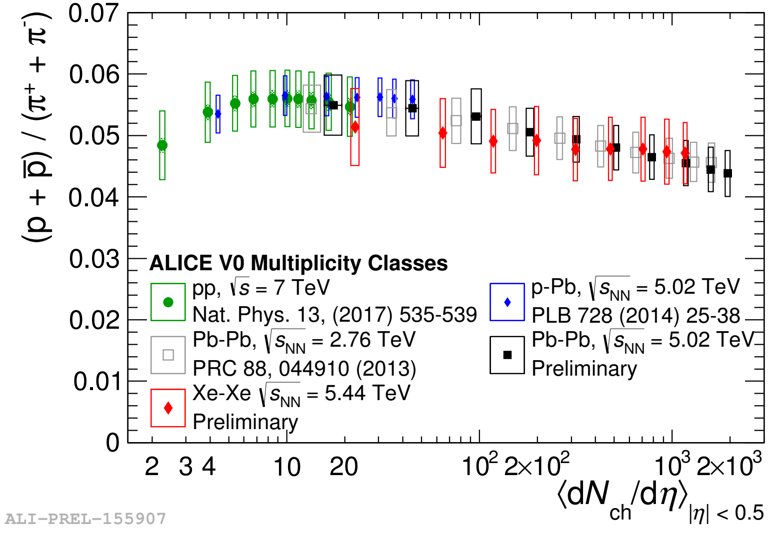
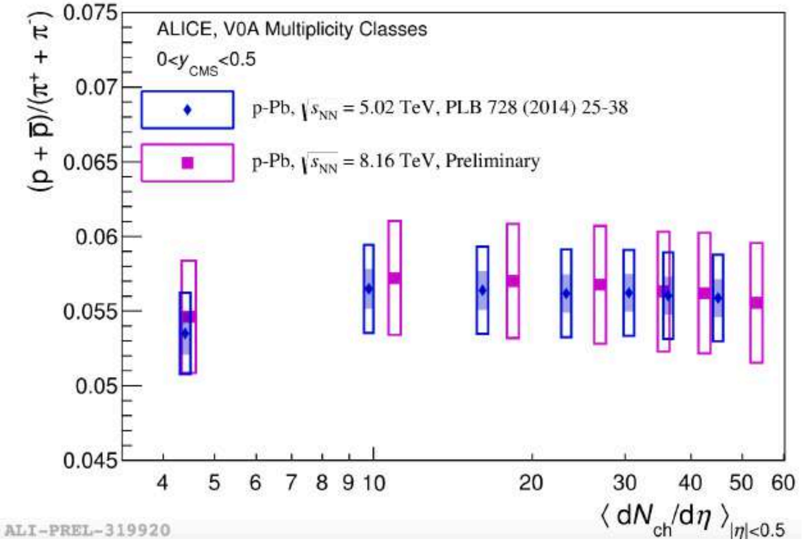
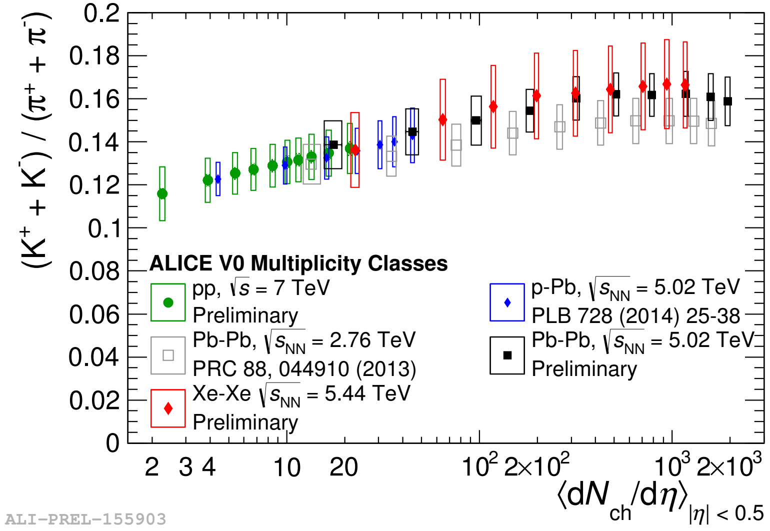
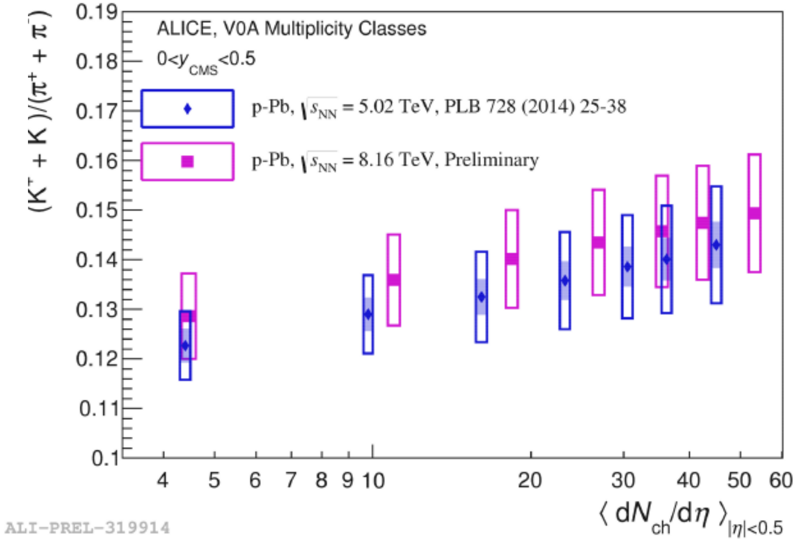
Integrated particle yields









- The integrated particle yields exhibit a **continuous evolution with the charged particle multiplicity** independent of the collision system
- At large multiplicities, ratios in small systems reach the values observed in heavy-ions

Chemical composition independent of collision system at the same $\langle dN_{ch}/d\eta \rangle$

Thermal model fit [Pb-Pb at 2.76 TeV]

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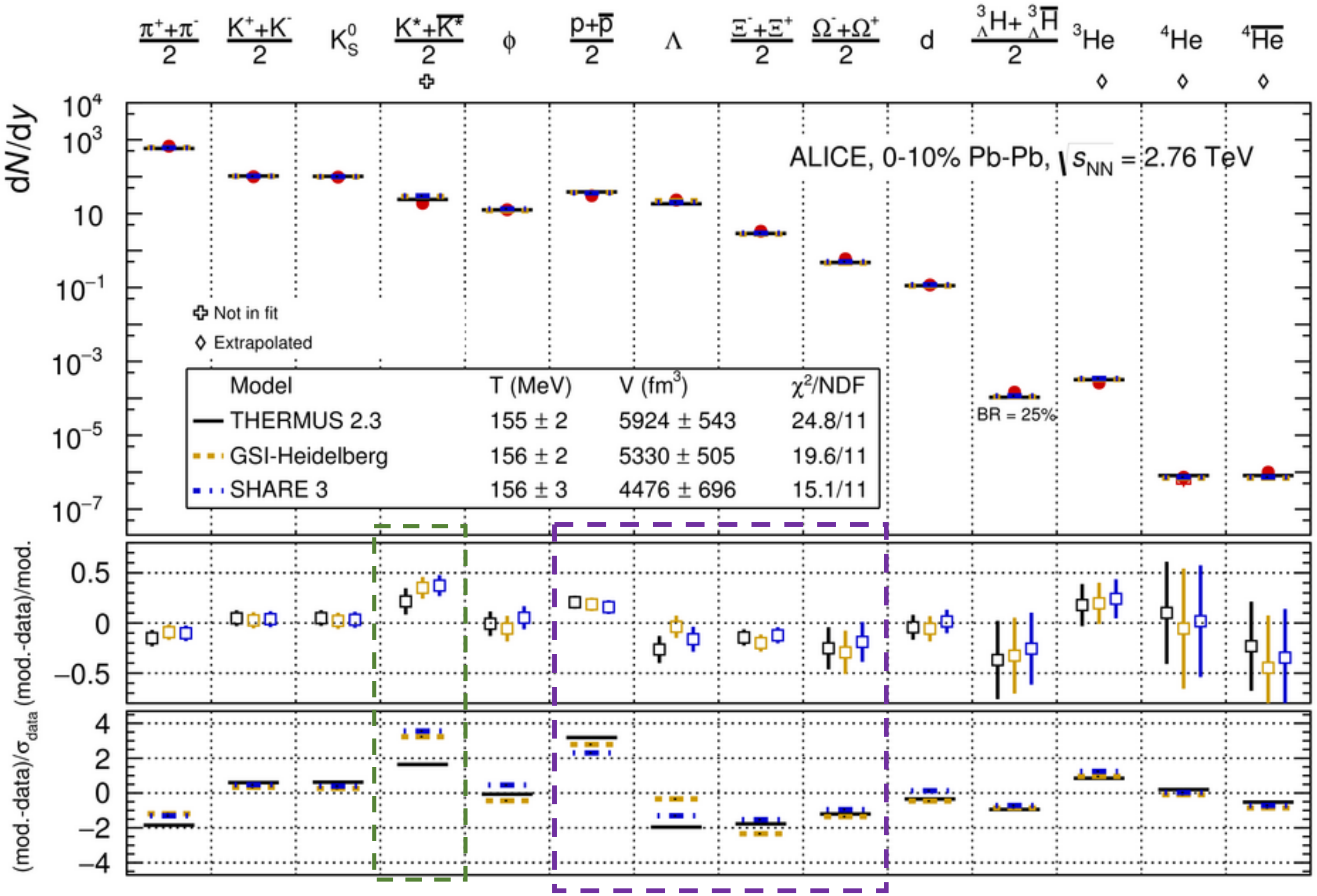

Model	T (MeV)	V (fm³)	χ²/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

ALICE, Nucl. Phys. A 971 (2018) 1-20

- **Describe hadron yields as produced in a system in thermal and chemical equilibrium** from the system's partition function
- same conclusions and parameters from 3 different model implementations (*)

Particle abundancies in Pb-Pb [0-10%] at 2.76 (5.02) TeV are well described [χ^2/ndf ~ 2 (4-5)] with a **chemical freeze-out temperature T_{ch} =156 (153) MeV**

Deviation for short-lived **K^{*0} resonance** that suffers from **re-scattering** in the late hadronic phase

(*) *THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84*
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

Thermal model fit [Pb-Pb at 5.02 TeV]

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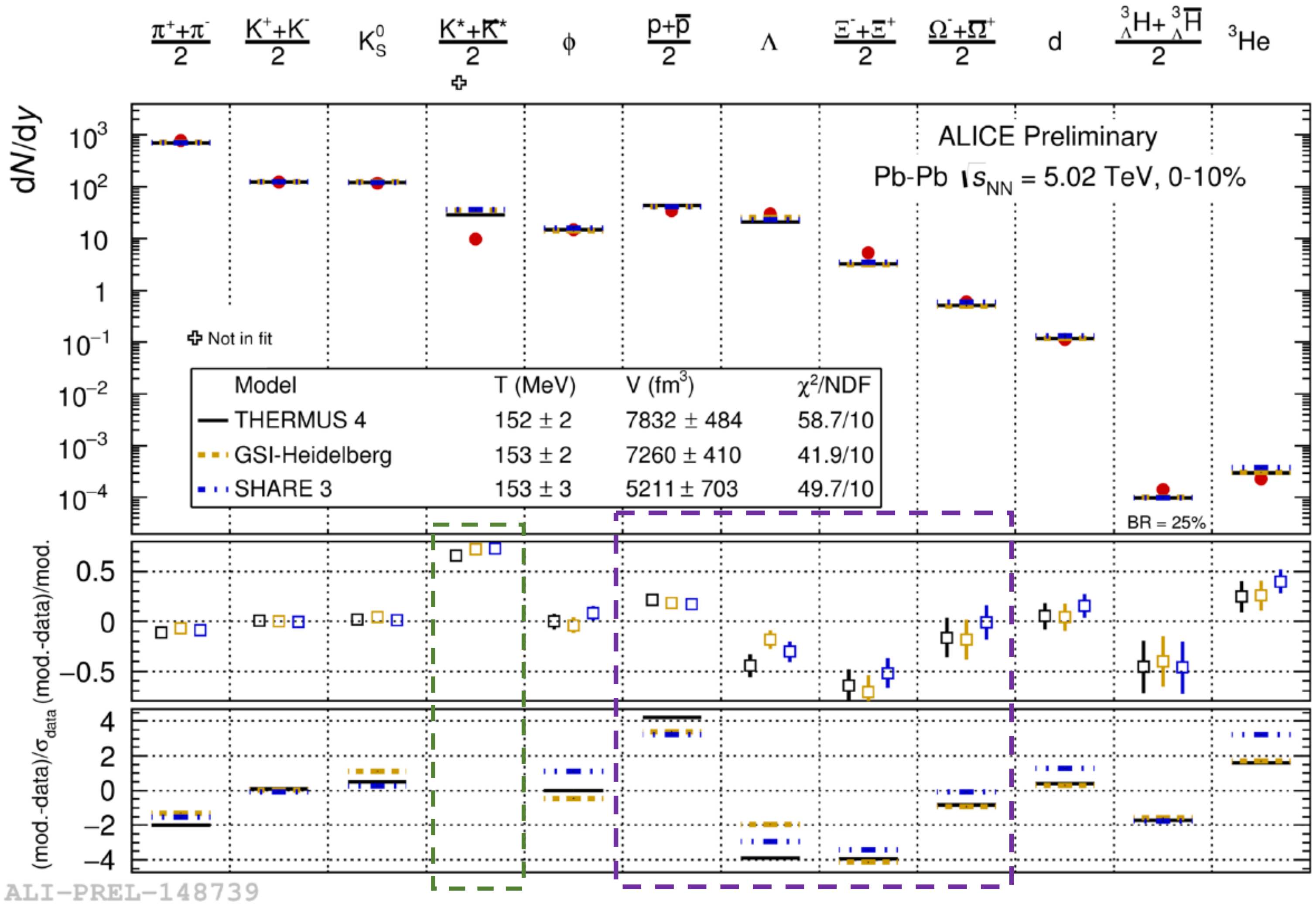

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Tensions between protons and multi-strange: incomplete hadron spectrum (?), baryon annihilation in hadronic phase (?), interacting hadron gas (?),…

(*) *THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84*
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

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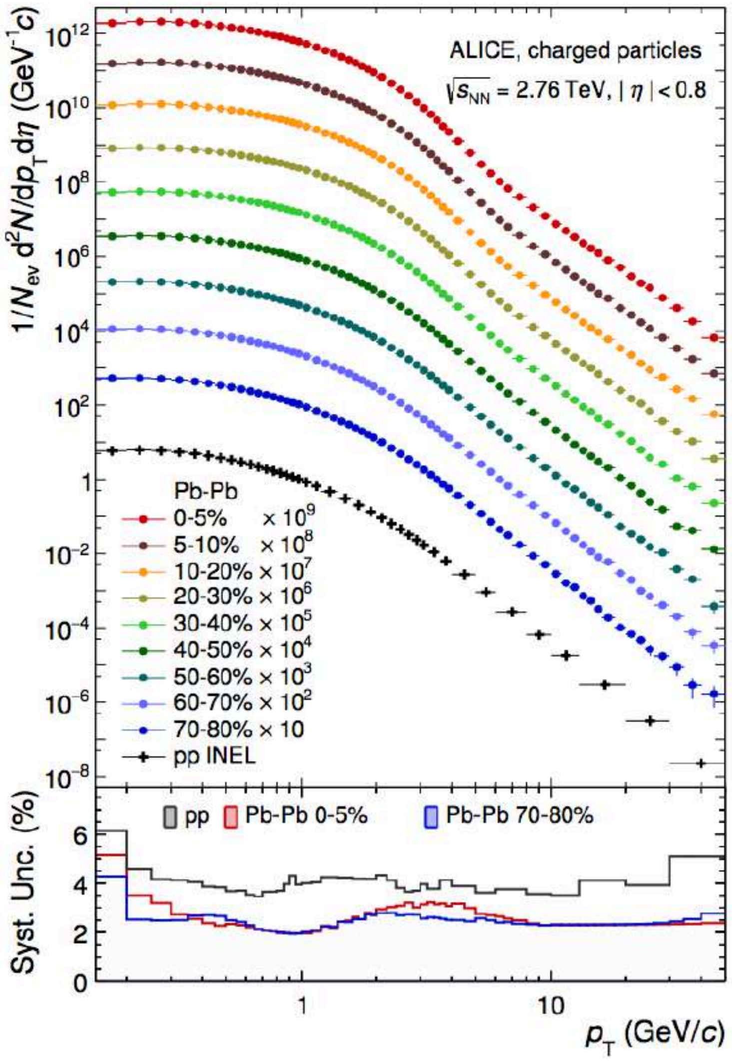
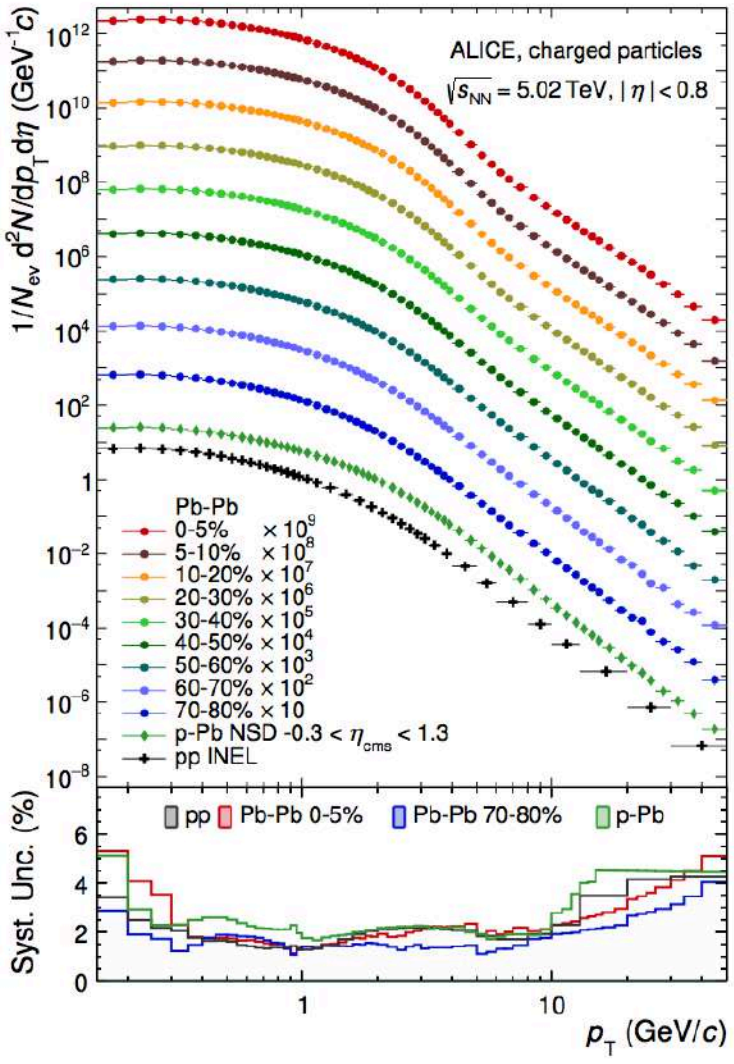
Spectra: what happens at high p_T ?



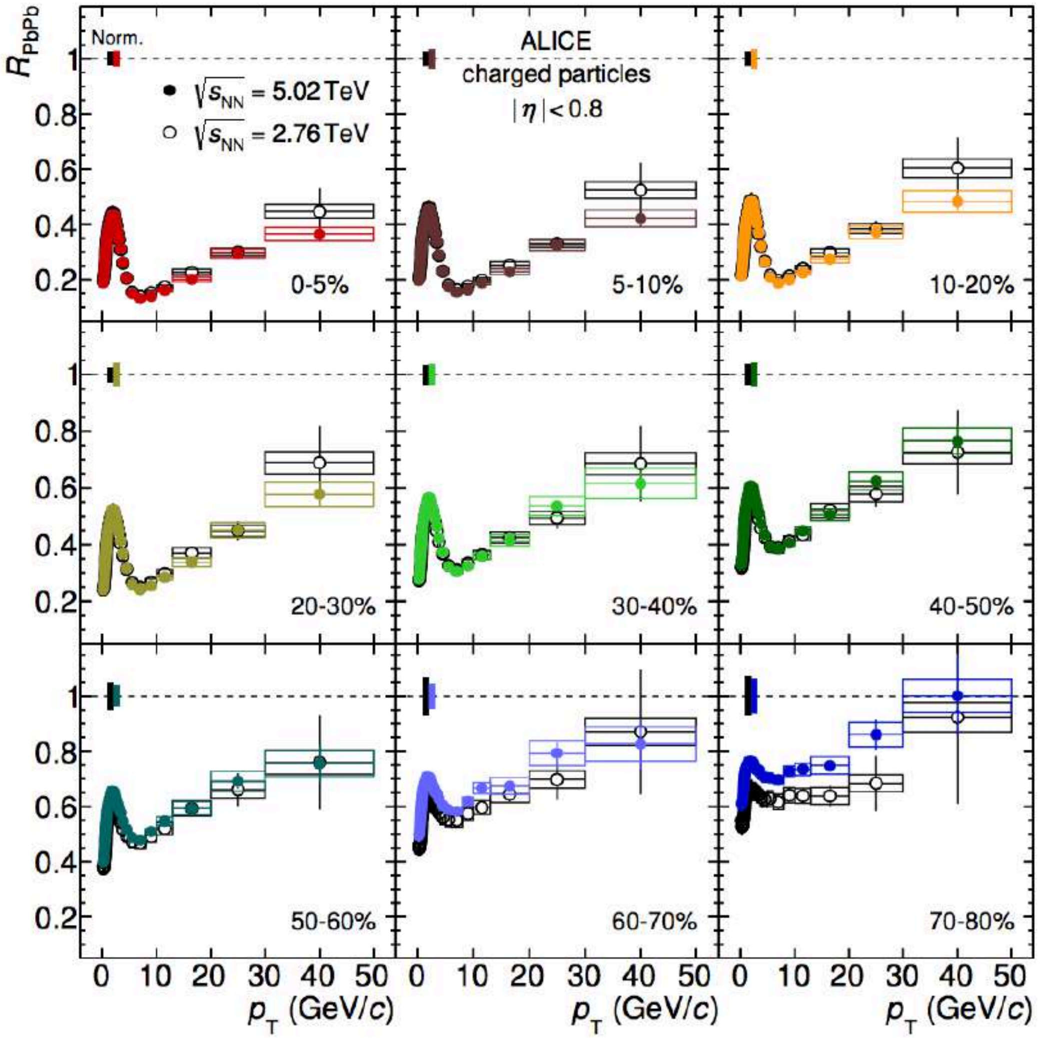


- Inclusive charged particle spectra for different collision system at 2.76 and 5.02 TeV measured up to p_T=50 GeV/c
- With increasing collision centrality, a marked depletion of the Pb-Pb spectra develops for p_T > 5 GeV/c

- Suppression of high p_T particles due to hard partons energy loss in the medium (jet-quenching)
- Such medium effects are quantified with the nuclear modification factor R_{AA}:

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{ch}^{AA}/dp_T}{dN_{ch}^{pp}/dp_T}$$

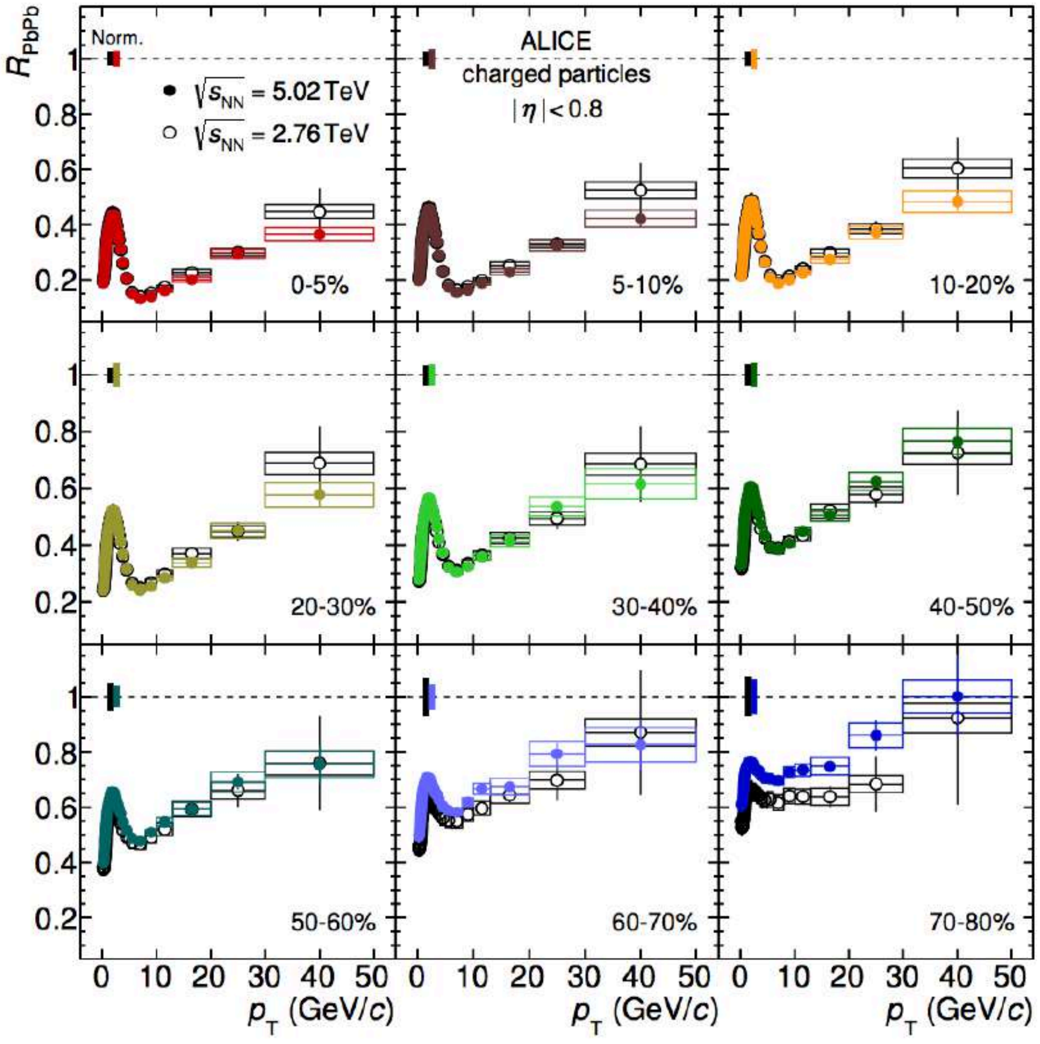
Nuclear modification factors



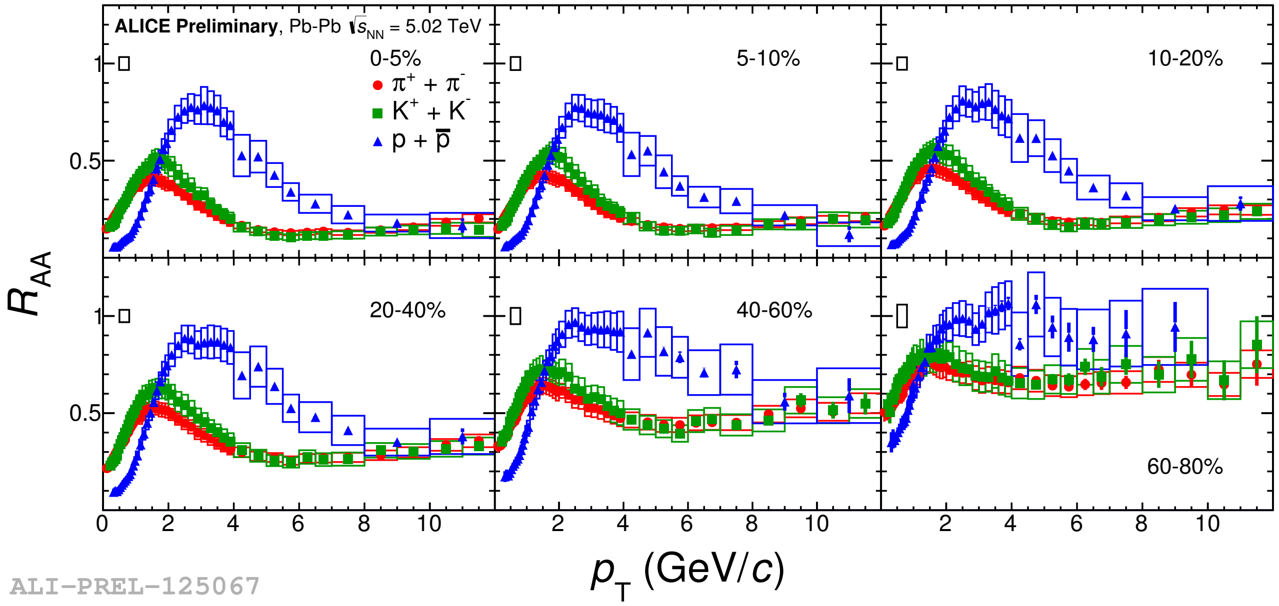
- R_{AA} has a strong centrality dependence
- Very similar in magnitude for the two collision energies
  - ➢ In central collisions [0–5%] : suppression factor of ~8 ($R_{AA} \approx 0.13$) at p_T = 6–7 GeV/c. Rise for p_T > 7 GeV/c, up to ~0.4
  - ➢ In peripheral collisions [70–80%]: suppression of ~30% for intermediate p_T and rise up to unity for the highest p_T bin.

A Large Ion Collider Experiment

Nuclear modification factors



- R_{AA} has a strong centrality dependence
- Very similar in magnitude for the two collision energies
  - ➢ In central collisions [0–5%] : suppression factor of ~8 ($R_{AA} \approx 0.13$) at p_T = 6–7 GeV/c. Rise for p_T > 7 GeV/c, up to ~0.4
  - ➢ In peripheral collisions [70–80%]: suppression of ~30% for intermediate p_T and rise up to unity for the highest p_T bin.



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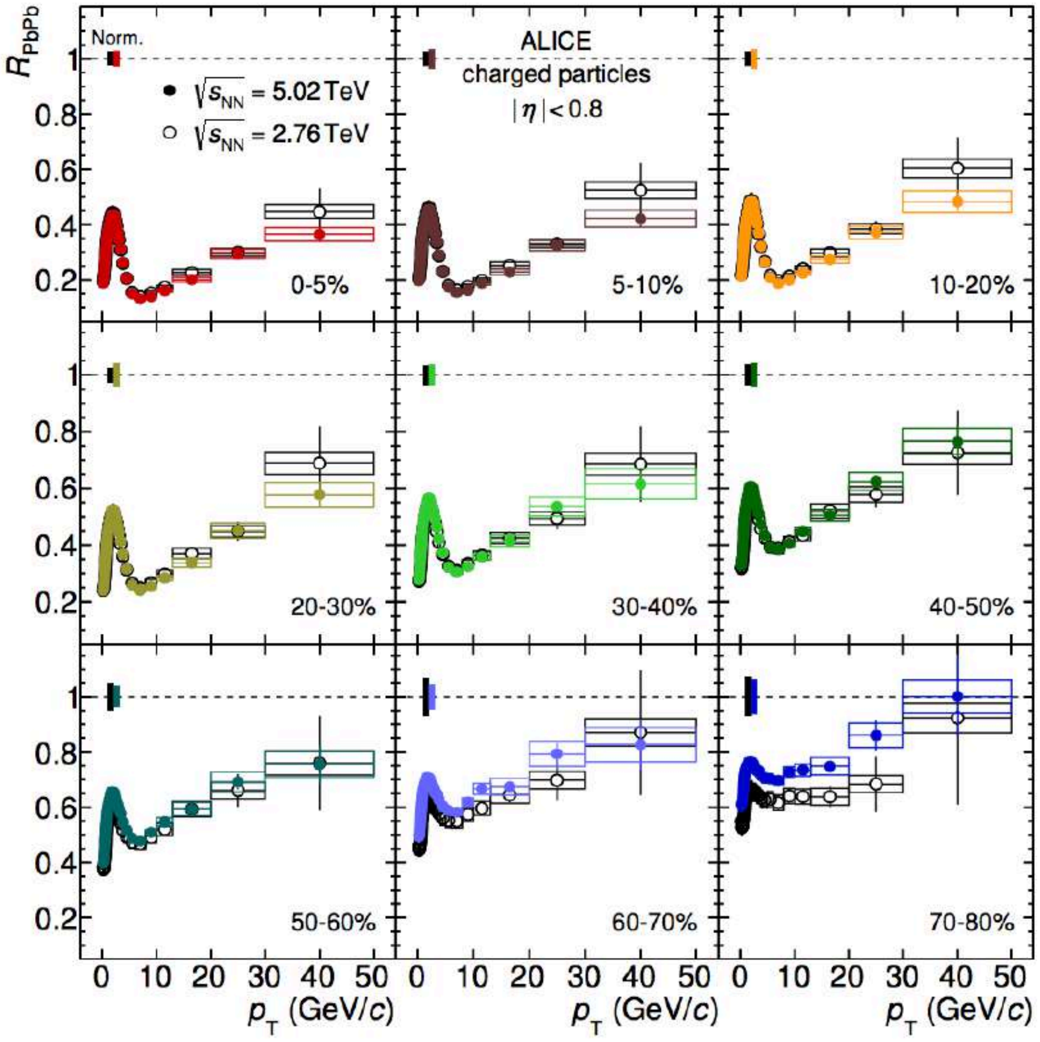

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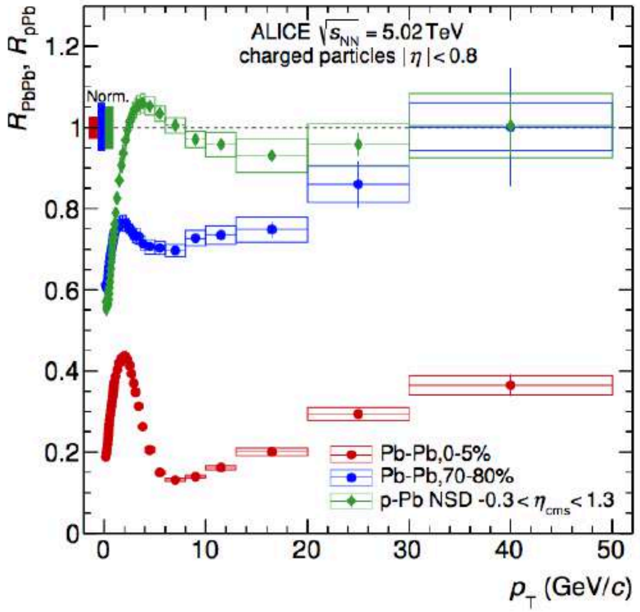

- No suppression at high-p_T in p-Pb
- Peripheral Pb-Pb collisions show similarities with high-multiplicity p-Pb in other observables (e.g. particle ratios, flow) but $R_{AA} < 1$
- A long-standing puzzle: **Collectivity but no jet quenching?**

Summary

- Identified particle spectra (π/K/p/...) have been measured by ALICE in all collision systems provided by the LHC, allowing systematic studies to be performed as a function of the collision energy and of the collision system
- Several similarities between pp, p-Pb, and Pb-Pb collisions have been reported – collectivity, thermodynamic parameters, particle ratios…
- Some conclusions:
  - Radial flow effects are measurable in the hadron distributions (hardening)→Hints of radial flow in small systems
  - Hadron chemistry driven by multiplicity and not by collision energy nor system
  - For Pb-Pb at 2.76 (5.02) MeV: thermal fit with a single chemical freeze-out temperature of T_{ch} = 153 (156) MeV, while Blaste-Wave fit model shows a strong radial flow and significantly lower T_{kin}
  - Similar kinetic freeze-out temperature in Pb-Pb and p-Pb at similar $dN_{ch}/d\eta$, but larger β_T in small systems
  - QCD effects such as color reconnection (CR) can mimic the effects of radial flow
  - Suppression of high p_T particles due to hard partons energy loss in the medium in Pb-Pb→ In p-Pb collectivity, but not high-p_T particles suppression?

Thank you!

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ALICE

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