

Impact of Hadronic Transport on Identified Particle Production in Heavy Ion Collisions

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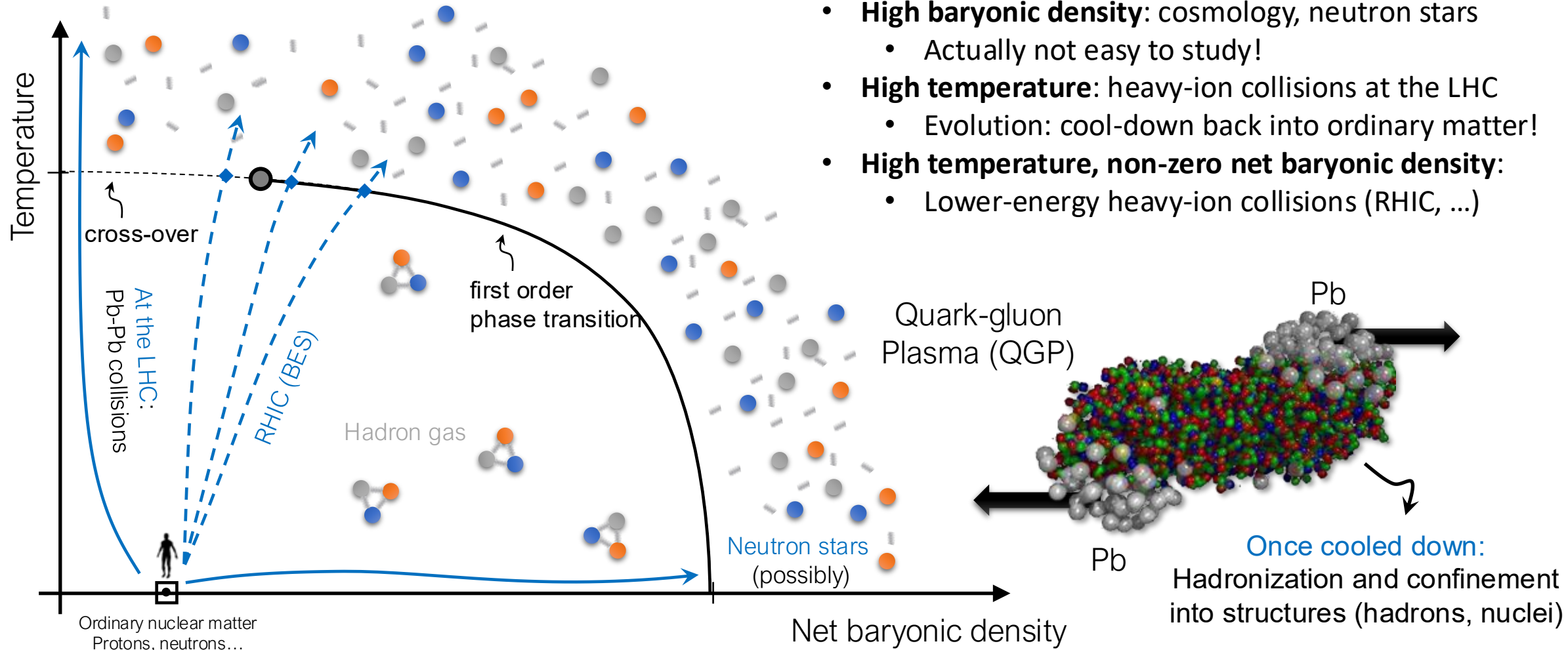
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Outline

- Phase Diagram and QGP
- Motivation and Particle Production
- EPOS4
- Centrality determination
- Results
- Summary

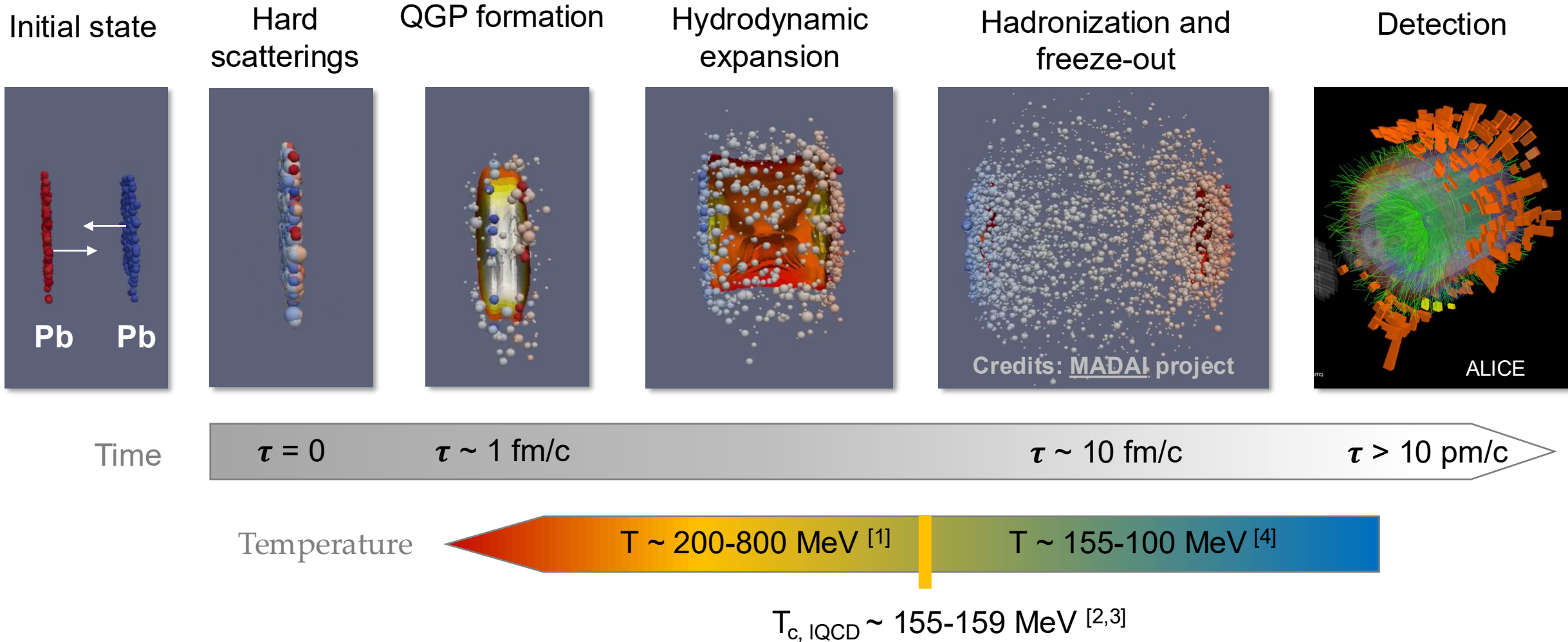
The Phase Diagram Of QCD Matter



How can this be studied?

- **High baryonic density:** cosmology, neutron stars
 - Actually not easy to study!
- **High temperature:** heavy-ion collisions at the LHC
 - Evolution: cool-down back into ordinary matter!
- **High temperature, non-zero net baryonic density:**
 - Lower-energy heavy-ion collisions (RHIC, ...)

“Little Bang in the Laboratory”: Evolution of Ultra Relativistic Heavy Ion Collisions

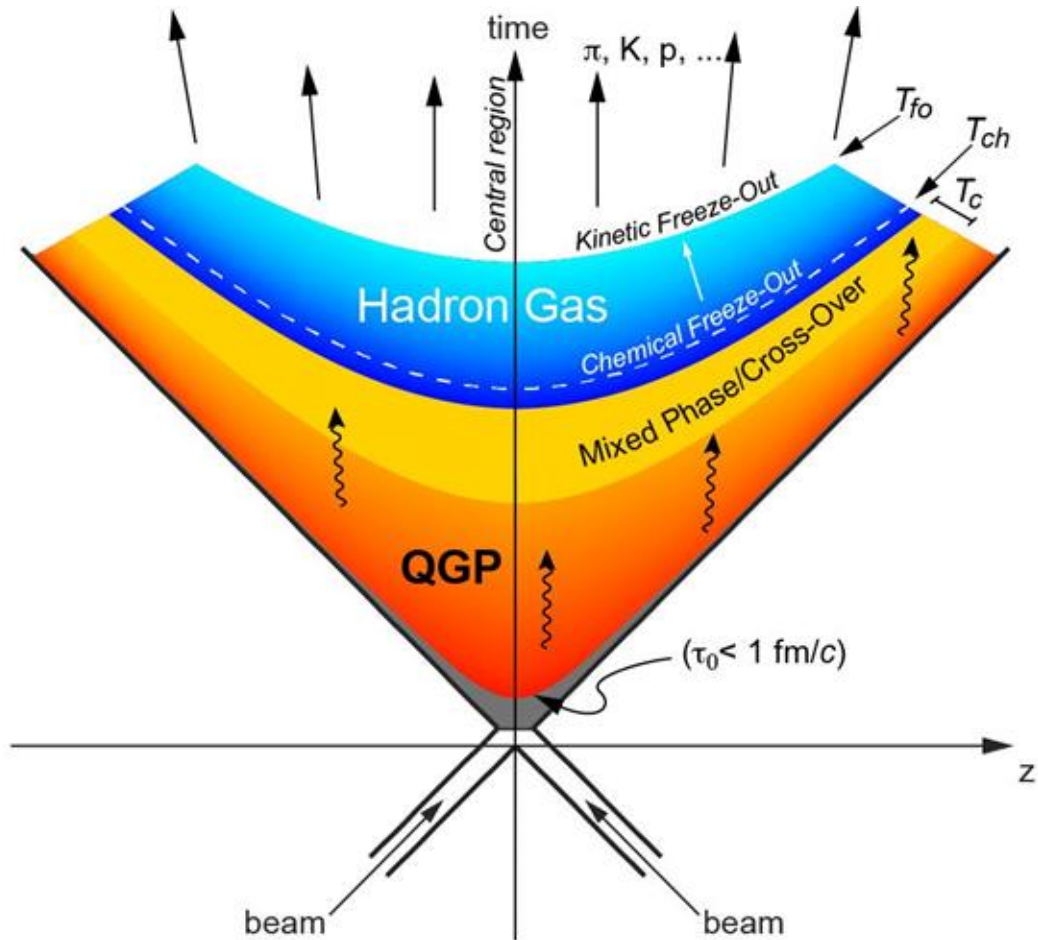


No direct observation of the QGP is possible
→ rely on emerging particles as “probes”

- [1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
- [2] A. Bazavov et al., Phys. Lett. B 795 (2019)
- [3] Borsaniy et al. PRL 125 (2020) 5, 052001
- [4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

$$T_{c, \text{IQCD}} \sim 155\text{-}159 \text{ MeV} \text{ [2,3]}$$

Get Insight into QGP Properties



How to investigate the QGP which stays “beyond the horizon” of the freeze-out?

→ Three classes of observables
(multi-messengers from the QGP):

Low P_T → Soft particles: Hadrons with small momentum, decoupling from the equilibrated system at the kinetic freeze-out

→ Exhibit Collective dynamics and thermal production

High P_T → Hard probes: Energetic and/or massive particles / jets produced in hard-scattering processes in the early stages of collision and traversing the QGP

→ Are Sensitive to parton Energy Loss

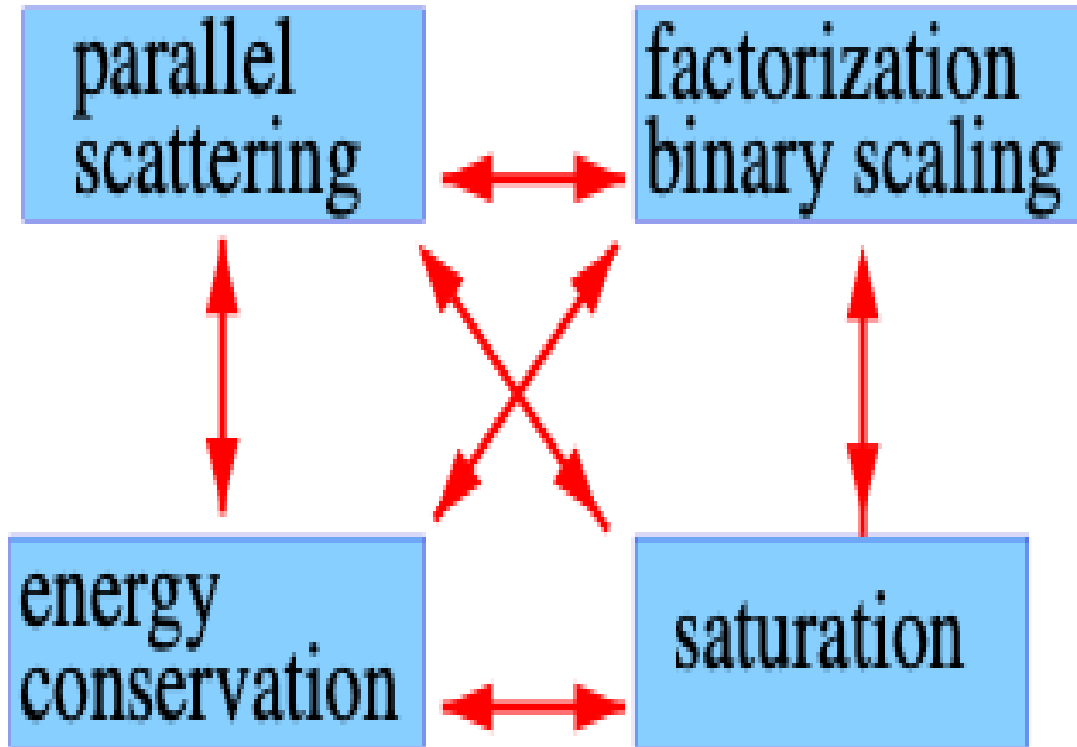
Electromagnetic probes: Photons and dileptons produced in the hot phase and not influenced by later stages

General case : not only AA valid for pp if enough particles are produced !

Motivation: Particle Production In Heavy Ion Collisions

- These final-state hadrons retain the evolution of the collision, carrying signatures of the early interactions, the development of initial-state fluctuations, the subsequent collective hydrodynamic expansion and the complex dynamics of hadronization.
- The combination of a number of complementary observables enables the characterization of QGP dynamics.
- Identified-hadron measurements ($\pi^\pm, K^\pm, p(\bar{p})$) (probe the medium's thermodynamics, collective expansion, and hadronization, offering mass-flavor, and baryon-number dependent sensitivity).
- p/π reveal baryon-to-meson enhancement at intermediate p_T and constrain mechanisms like radial flow and recombination.
- K/π and K^\pm spectral shapes are sensitive to strangeness enhancement and the medium's equilibration of strange quarks.

EPOS4 Event Generator

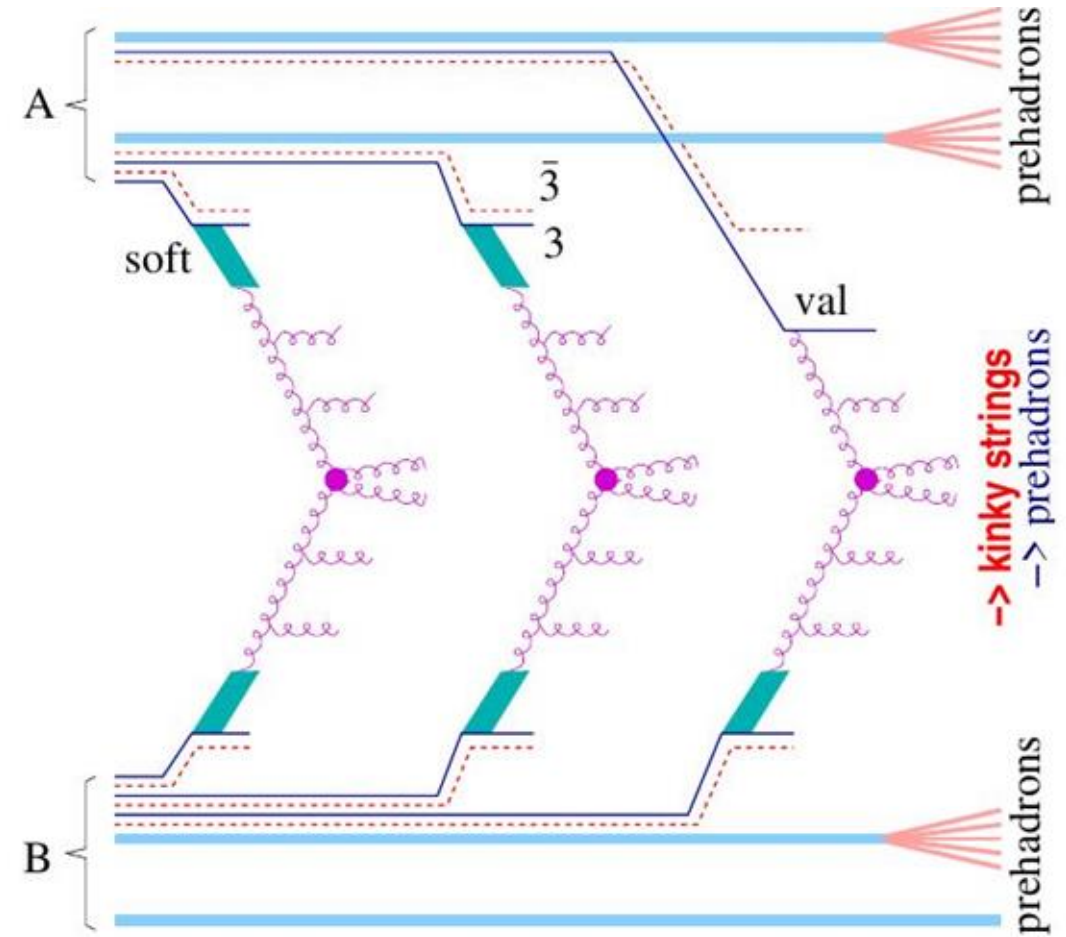


- A “complete” event generator
 - to do normal pp physics (total cross section, light flavor spectra, jets, charm,...)
 - which **in addition** accounts for collective effects in small systems
 - which **in addition** can handle nuclear scatterings from LHC to RHIC
- To check if we get a consistent overall picture

EPOS4 is designed as a general purpose approach (SPS, RHIC, LHC for pp or Heavy Ion), **with conceptual problems of earlier EPOS versions being solved.**

From Pomerons to Prehadrons

- Very compact summary (details: arXiv:2306.02396) :
- Each parton-parton interaction is represented with a "Pomeron" (a parton ladder)
- From multiple Pomeron configurations, after making the link with pQCD, we get partonic configurations
 - color flow diagrams
 - parton chains
 - kinky strings
 - Prehadrons
- also: remnants
 - Prehadrons
- At the end: **many prehadrons**



Core-Corona

The core holds a much higher energy density as the peripheral corona and can be treated as a fluid that evolves and possibly decays into hadrons that can collide with each other

- We consider all prehadrons (at given τ). For each one, we estimate its energy loss if it would move out of this system

- ➔ If the energy loss is bigger than the energy of the prehadron, it is considered to be a “core prehadron”
- ➔ If the energy loss is smaller than the energy, the prehadron escapes, It is called “corona prehadron”

- The core prehadrons constitute “bulk matter”

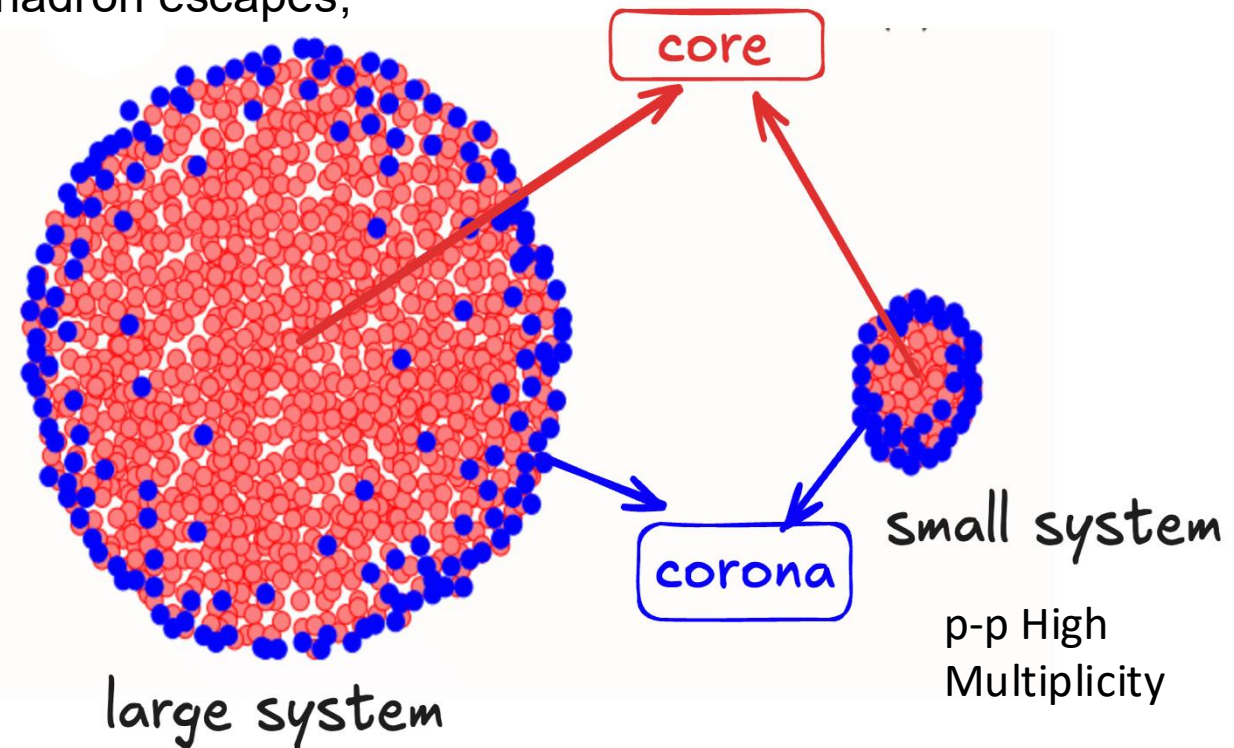
- ➔ which will be treated via hydrodynamics and decays eventually microcanonically (NEW)

- The corona prehadrons become simply hadrons

- ➔ propagate with reduced energy

- Details: Phys. Rev. Lett., 98:152301, 2007. 15

Phys. Rev. C, 89:064903, 2014. 15



Key Observables

System Studied:

- Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe Collisions at $\sqrt{s_{NN}} = 5.44$ TeV

Key Observables:

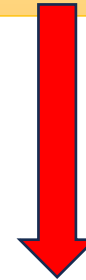
- Charged particle multiplicity
- Transverse momentum spectra
- pT fluctuations
- Flow harmonics (v_2, v_3)

Reference for EPOS4 and ALICE data



ALICE Data

EPOS4 (0.5 M Events)
(with and Without UrQMD afterburner)

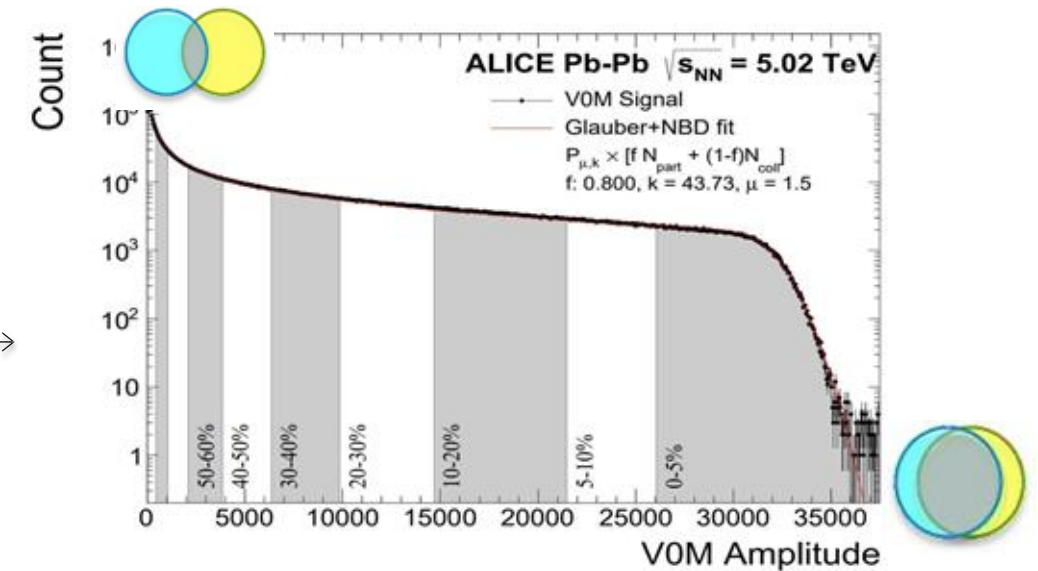
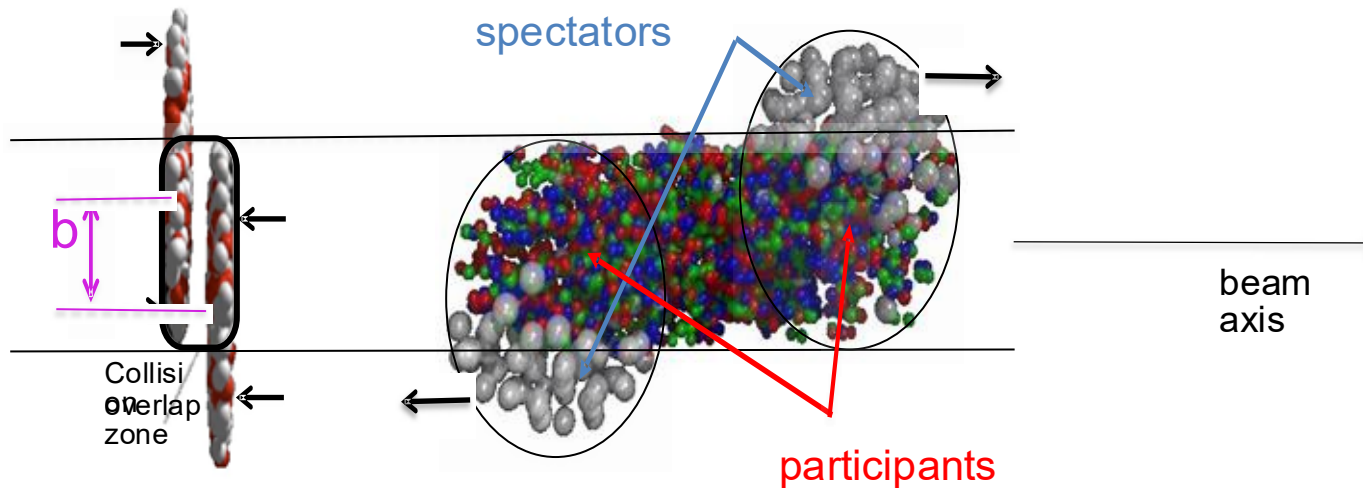


This comparison **enables the isolation of hadronic rescattering effects and helps understand how late-stage interactions influence** bulk particle production, transverse-momentum correlations, and anisotropic flow across different collision systems.

How To Characterize The Heavy Ion Collision

We can control a posteriori the geometry of the collision by selecting in **centrality**.

Centrality = fraction of the total hadronic cross section of a nucleus-nucleus collision, typically expressed in percentile, and related to the impact parameter (b)

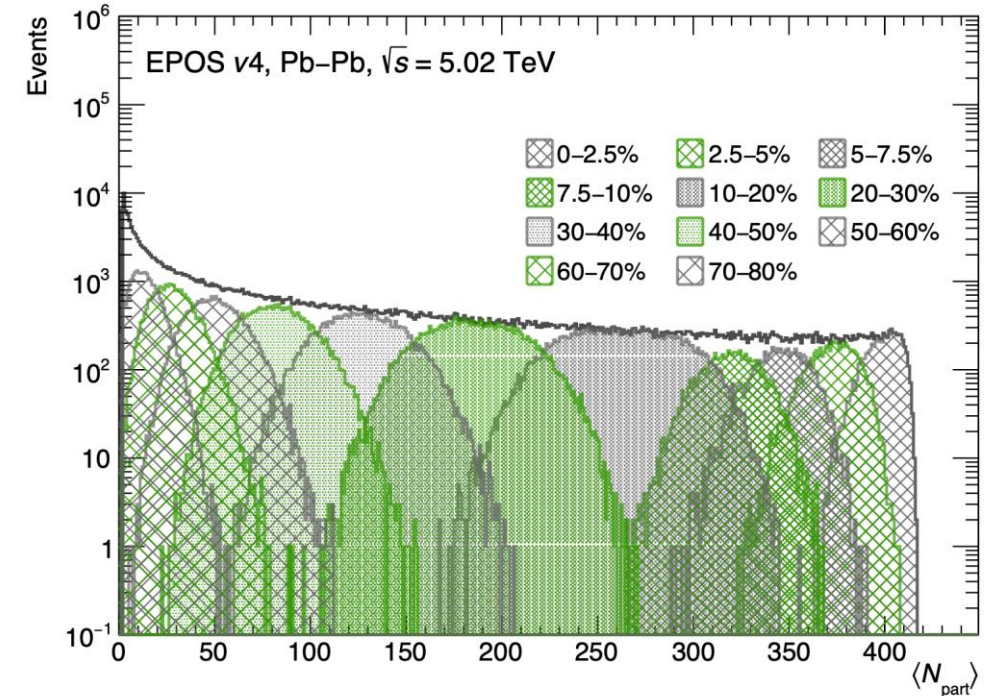
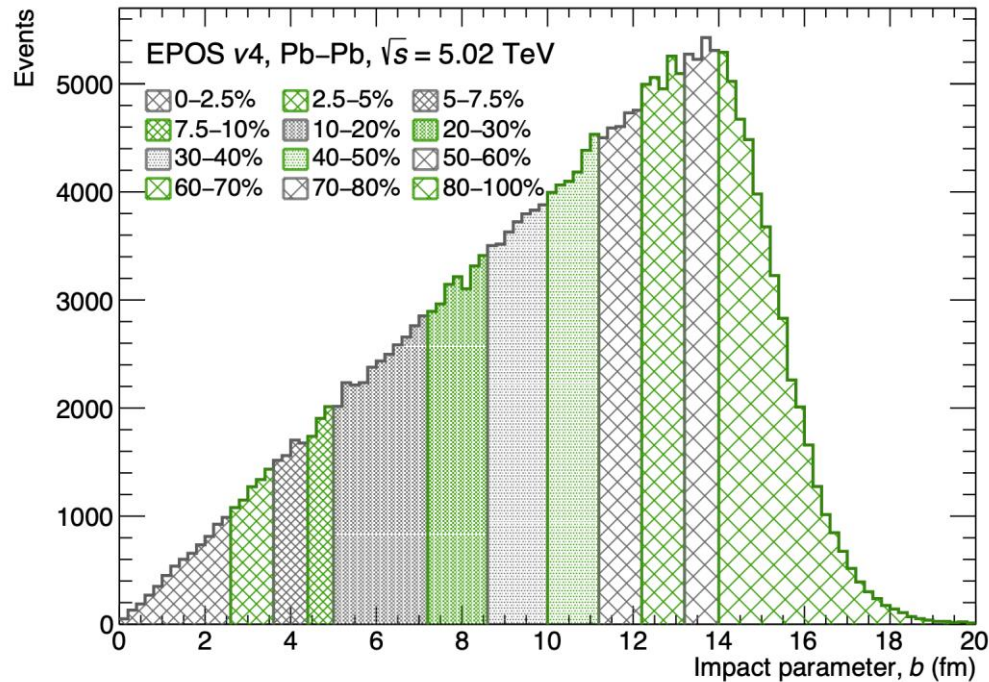


Other variables related to centrality:

- N_{coll} , number of binary nucleon-nucleon collisions
- N_{part} number of participating nucleons

Centrality is determined by *counting the number of particles* (multiplicity) or *measuring the energy deposition* in a **region of phase space independent from the measurement**, to avoid biases/autocorrelations in the results.

Centrality Determination EPOS4



- The **impact parameter distribution** defines centrality classes (central \rightarrow small, peripheral \rightarrow large b)
- The number of participating nucleons $\langle N_{part} \rangle$ decreases with increasing centrality percentile
- A clear correlation between b and $\langle N_{part} \rangle$ ensures a consistent mapping of **geometry to final-state observables**.
- Centralities are calculated using the impact parameter].

Charge particle Production

Particle Production

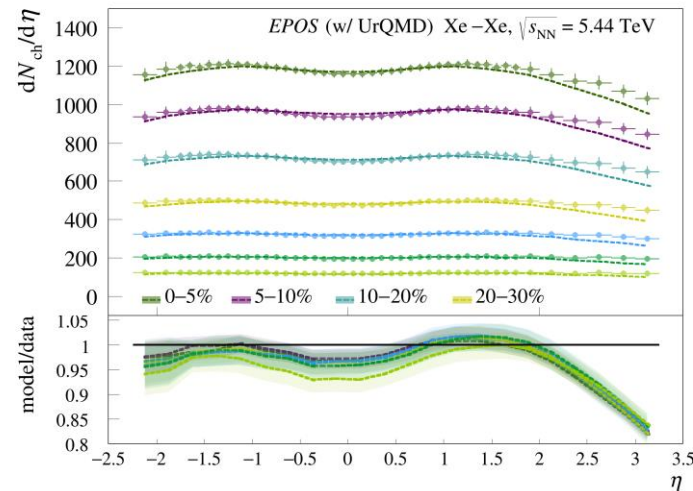
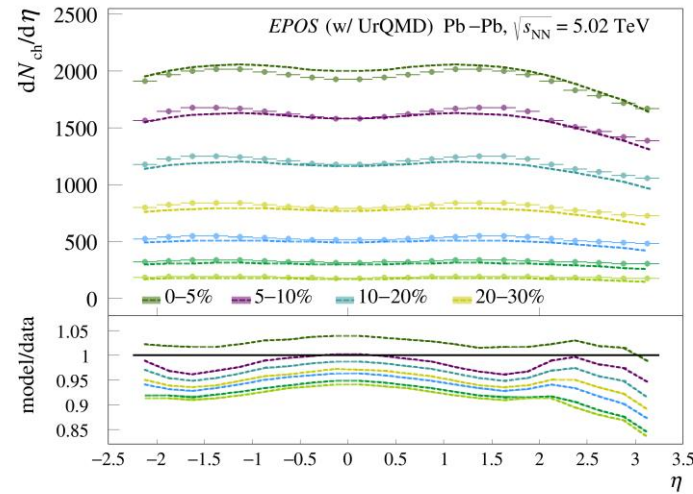
- constitutes the most fundamental observable in relativistic nuclear collisions
- Connected to initial energy density, subsequent expansion dynamics and freeze-out conditions of the system.
- serves as a proxy for entropy production and provide a natural measure of collision activity,

Centrality dependence \rightarrow geometry (N_{part}, N_{coll})

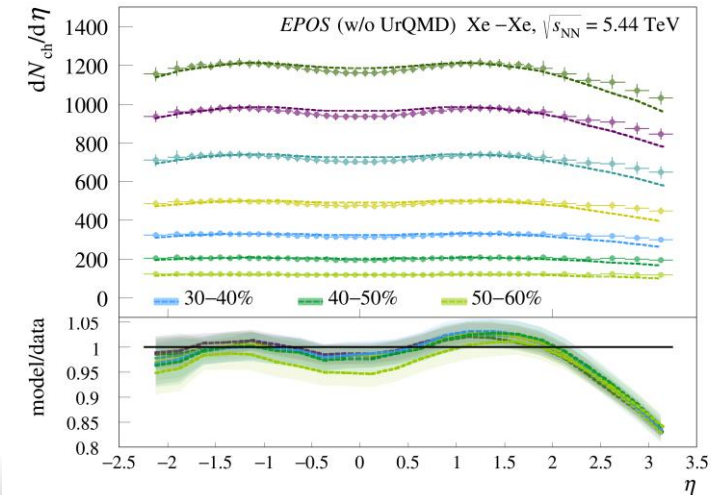
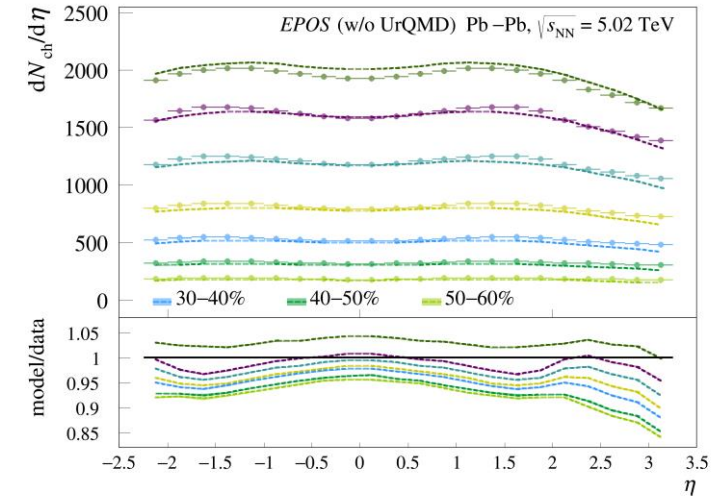
- Constrains initial-state models:
 - Glauber, CGC (initial state)
 - Hydrodynamics + transport
- Provides constraints on particle production mechanisms
- Mid-rapidity dip is observed with Broad distribution
- A distinct minimum at mid-rapidity (around $\eta \approx 0$) reflects enhanced radial flow

Ratio below Unity \rightarrow indicating reduced multiplicity from hadronic rescattering.

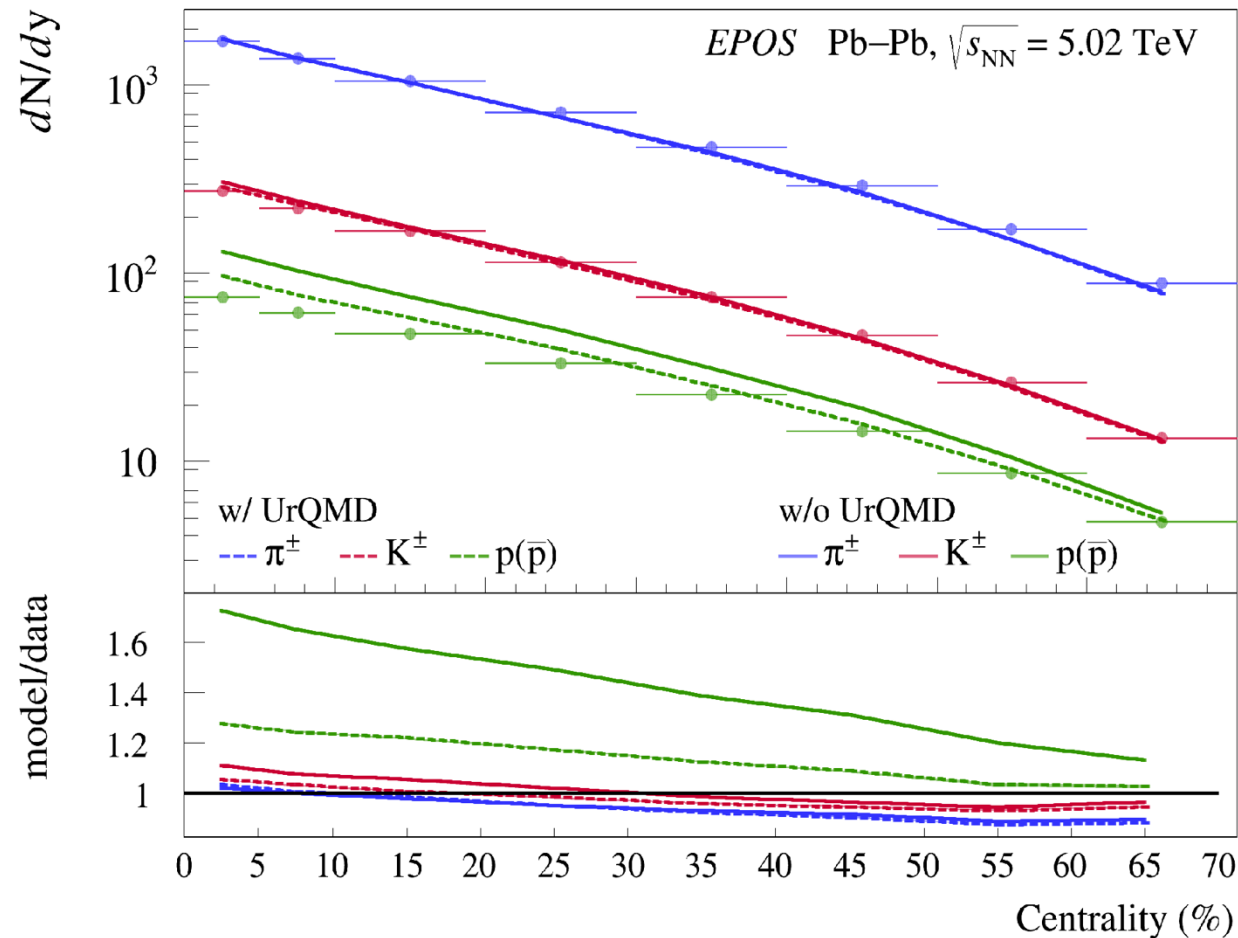
with UrQMD



Without UrQMD

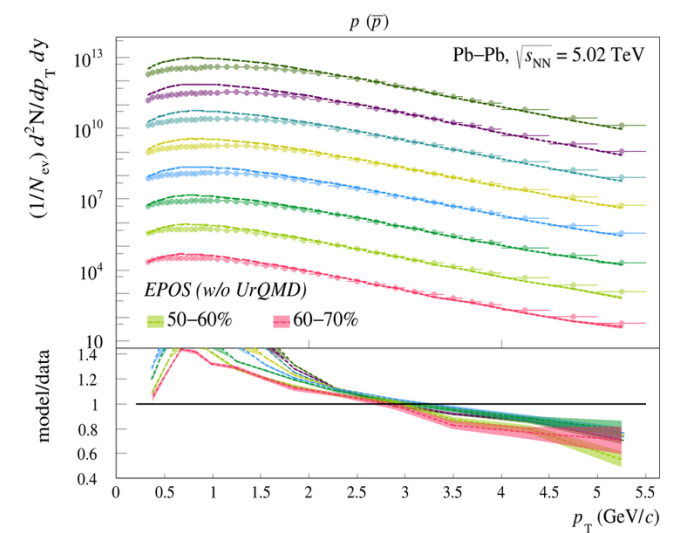
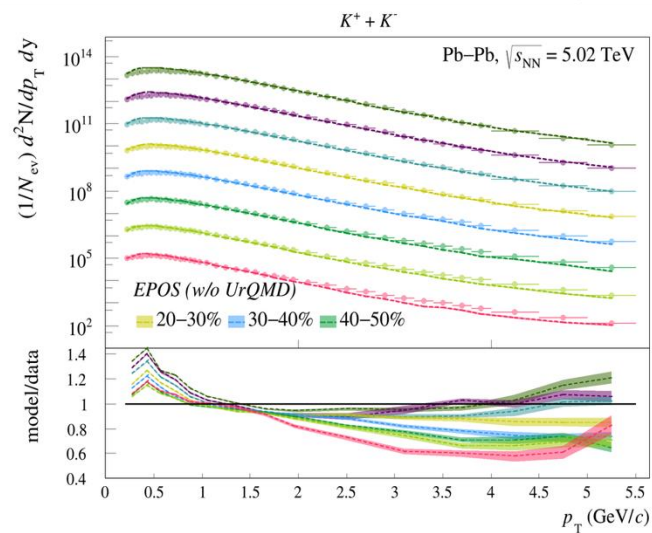
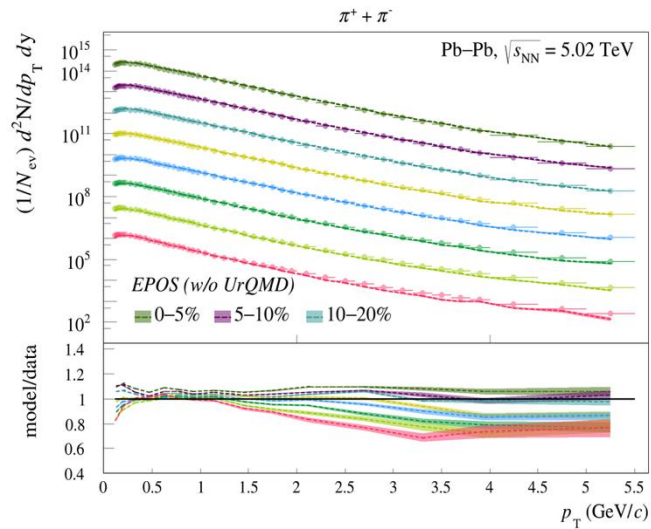
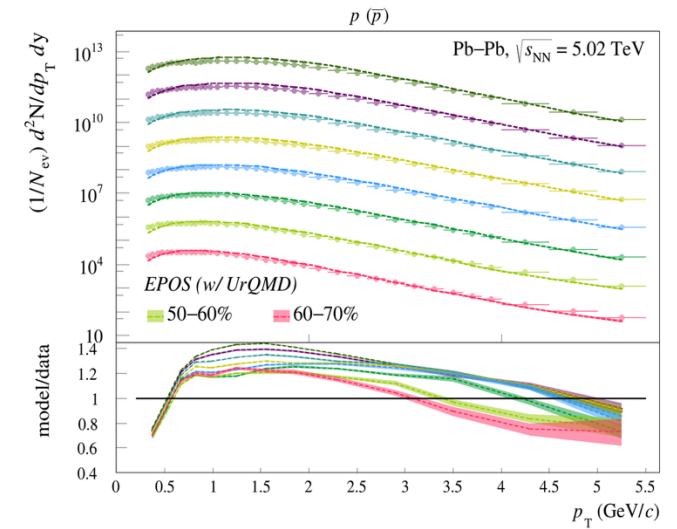
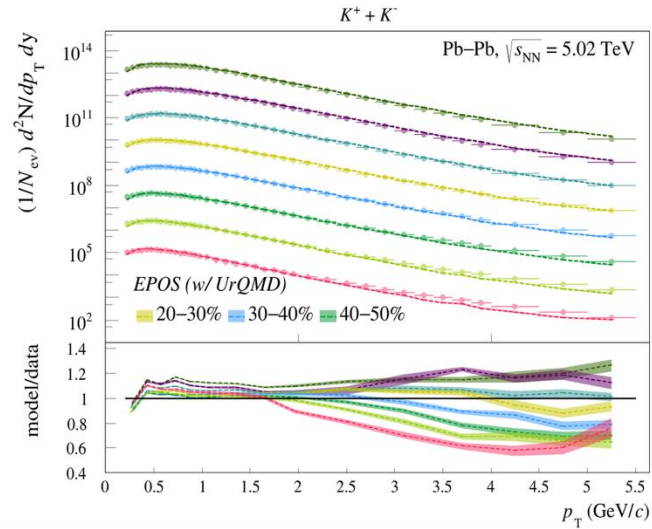
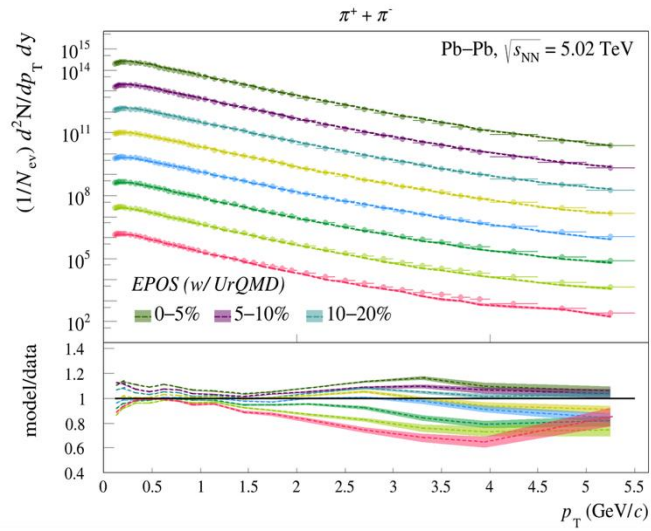


Identified particles Yield dn/dy

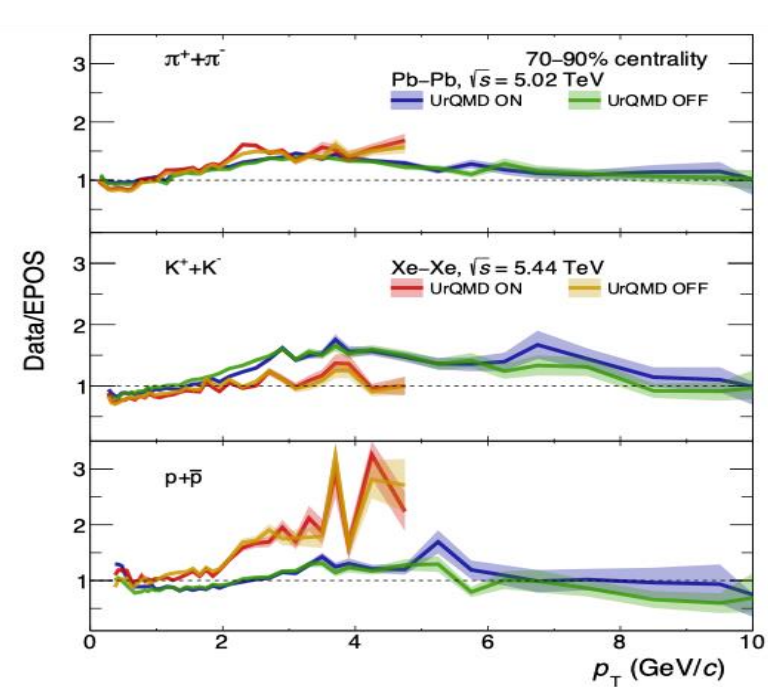
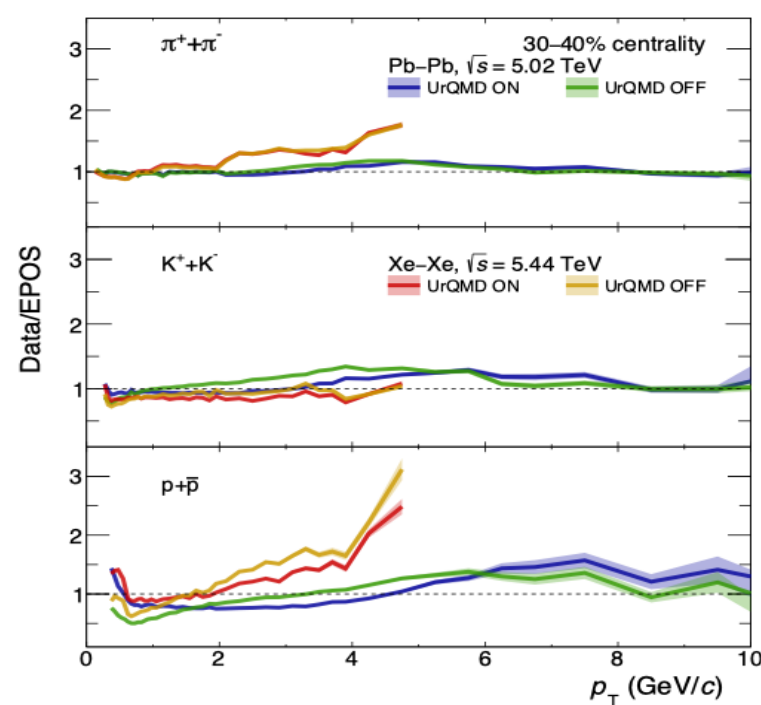
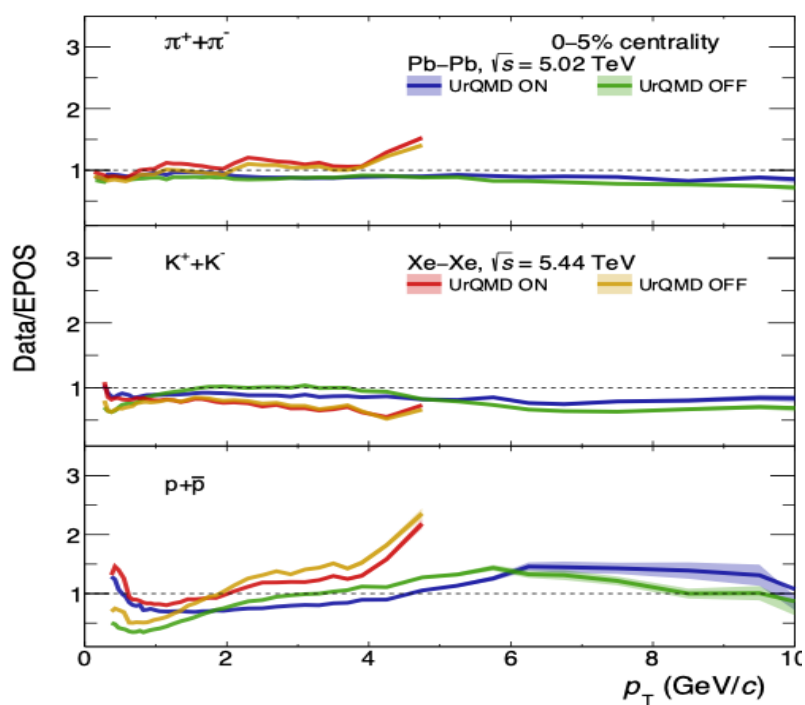


- The ratio of calculations with UrQMD to those without falls below unity for protons, particularly in central collisions.
- This suppression arises from baryon-antibaryon annihilation processes within the dense hadronic phase simulated by UrQMD.
- These rescattering effects are necessary to bring the proton yields into better agreement with the experimental data, indicating the late hadronic stage plays an important role in shaping the baryon production.

Transverse Momentum Spectra



The model provides a consistent description of the experimental data for both Pb-Pb and Xe-Xe across the measured centrality classes.



Protons → two compelling effects of hadronic phase

At low p_T (≤ 2 GeV/c), the inclusion of UrQMD

- noticeable suppression of the yield, also visible in kaons
- Due to baryon-antibaryon annihilation processes in the dense hadronic phase.

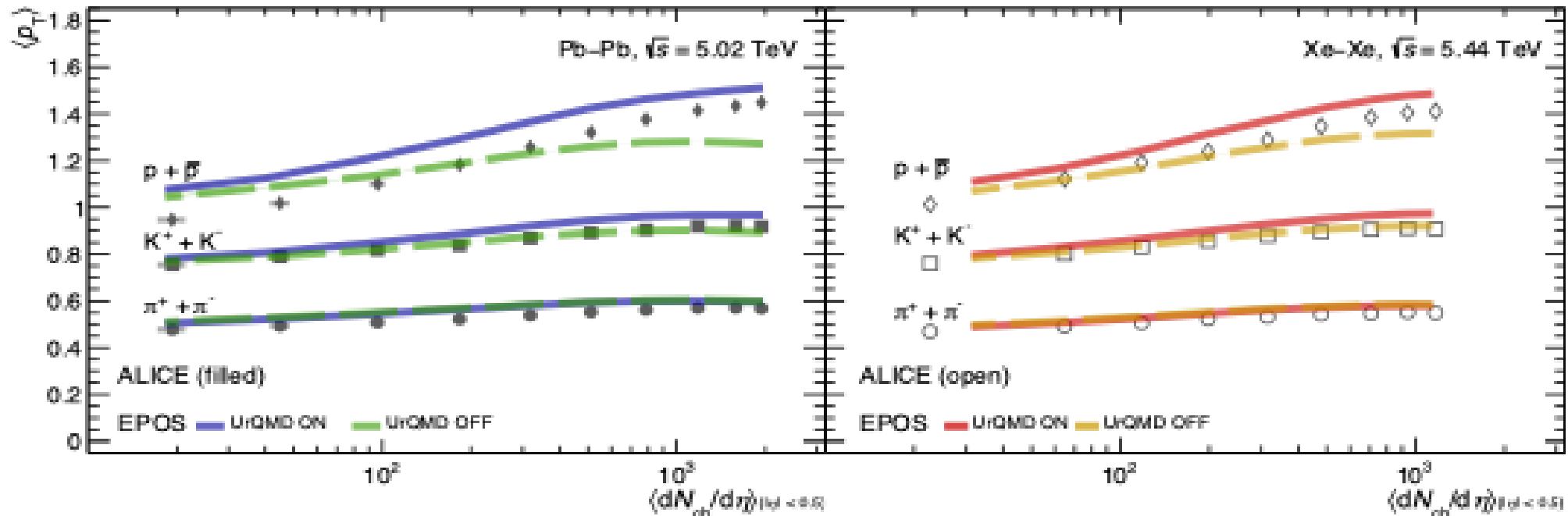
At intermediate p_T , hadronic Rescattering generates additional radial flow, shifting protons to higher transverse momenta and hardening the spectra.

Pions

- the effect of the hadronic phase is small,
- low mass makes them less sensitive to additional radial flow and their yields remain largely unchanged

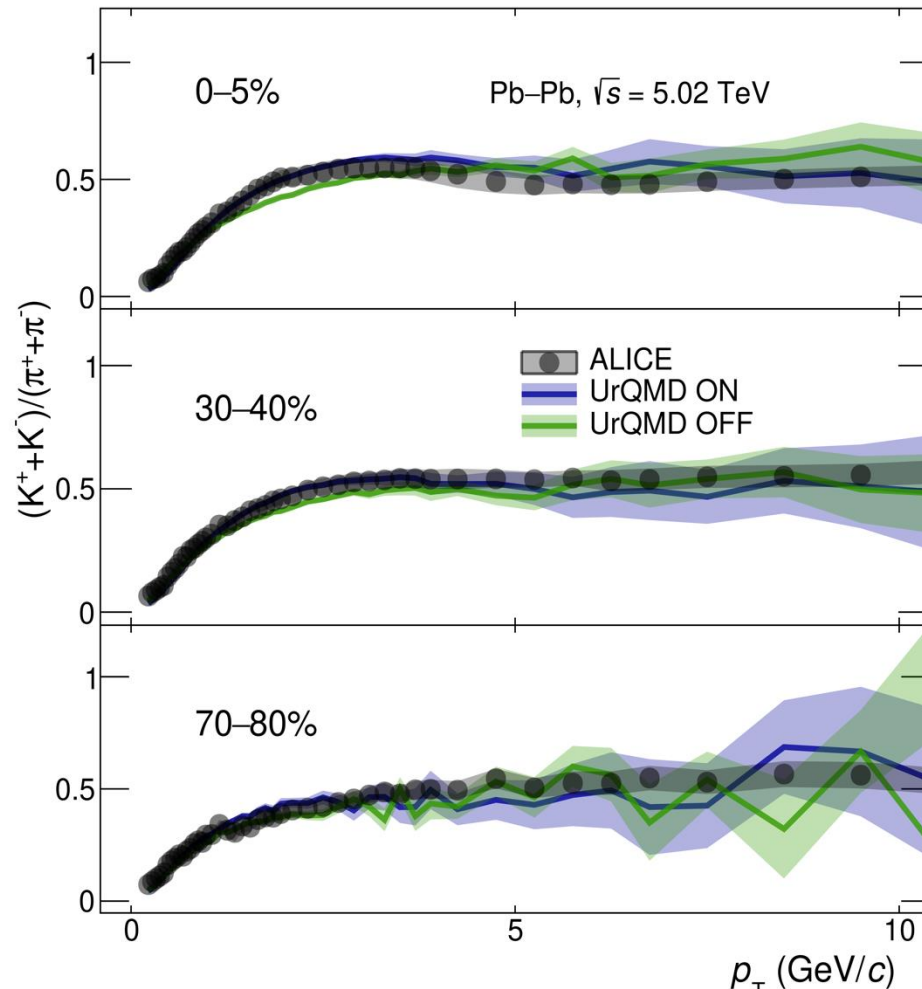
plays an important role in reproducing the shape of the proton spectra observed in the data.

Identified particles Mean P_T



- Mass ordering observed \rightarrow signature of radial flow generated when the core is going through hydrodynamic expansion [K. Werner, Phys. Rev. C 109, 014910 (2024)].
- The UrQMD afterburner further modifies the spectra
 - \rightarrow for heavier particles it leads to a moderate hardening, reflecting additional radial flow generated during the hadronic cascade and the depletion of low- p_T protons through annihilation processes.

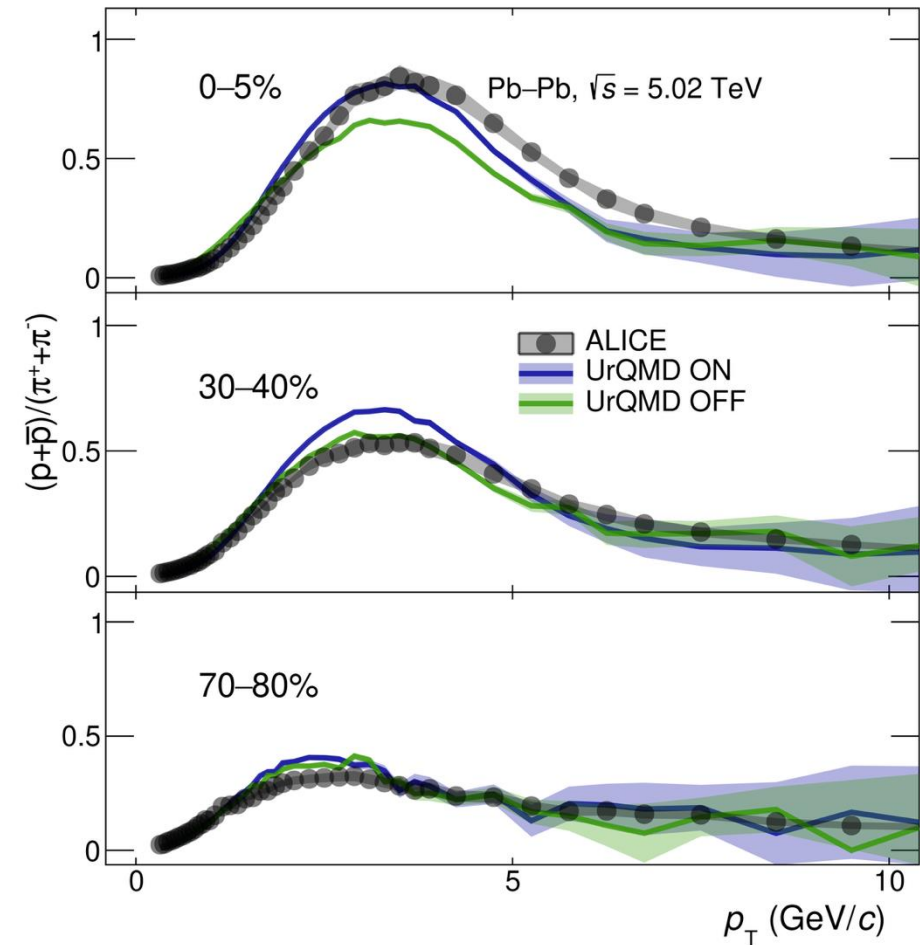
Ratio's vs P_T (Kaon/Pion)



- Ratio is flat and almost p_T - independent.
- Centrality changes the overall level more than the p_T - shape; more-central events show a higher plateau.
- Meson production and radial flow effects largely cancel between kaons and pions.
- EPOS4 (UrQMD ON/OFF) reproduces the weak p_T dependence and centrality trend of ALICE data.

Ratio's vs p_T (Proton/Pion)

- Ratio rises at low–intermediate (p_T 3–1) GeV/c), then decreases toward higher p_T ;peak grows with centrality.
- Protons receive stronger radial-flow boost (mass-ordering); coalescence/recombination enhances baryons at intermediate p_T .
- UrQMD reduces low- p_T p and \bar{p} via annihilation, slightly softening the peak.
- EPOS4 captures the bump and centrality dependence.



Summary and Outlook

EPOS4 results of Pb–Pb and Xe-Xe Collisions are shown with UrQMD ON and OFF, isolating late hadronic effects across centrality; comparing identified-hadron p_T spectra, and K^\pm/π^\pm and $p(\bar{p})/\pi^\pm$ ratios with ALICE data.

- π , K, p spectra harden with centrality, showing stronger radial flow for heavier hadrons; UrQMD mainly reshapes low- p_T baryons via baryon–antibaryon annihilation and resonance feed-down, while mesons are modestly affected.
- K/π (shape + centrality): Rises at low–intermediate p_T then flattens; higher normalization with centrality consistent with strangeness enhancement; EPOS4 (ON/OFF) matches ALICE trends.
- p/π (baryon enhancement): Peaks at intermediate p_T from radial flow/coalescence; UrQMD suppresses low- p_T protons and broadens the peak, clarifying core–corona centrality effects.
- EPOS4 with UrQMD achieves good overall agreement with ALICE.
- Studies on Flow variables are done and more results to come from light ions (O-O Collisions , etc)

Thank you!

Backup Slides