Universality of scaled particle spectra in ultrarelativistic heavy-ion collisions

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based on 2406.15208

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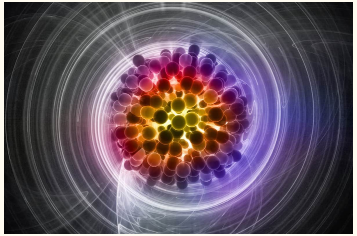
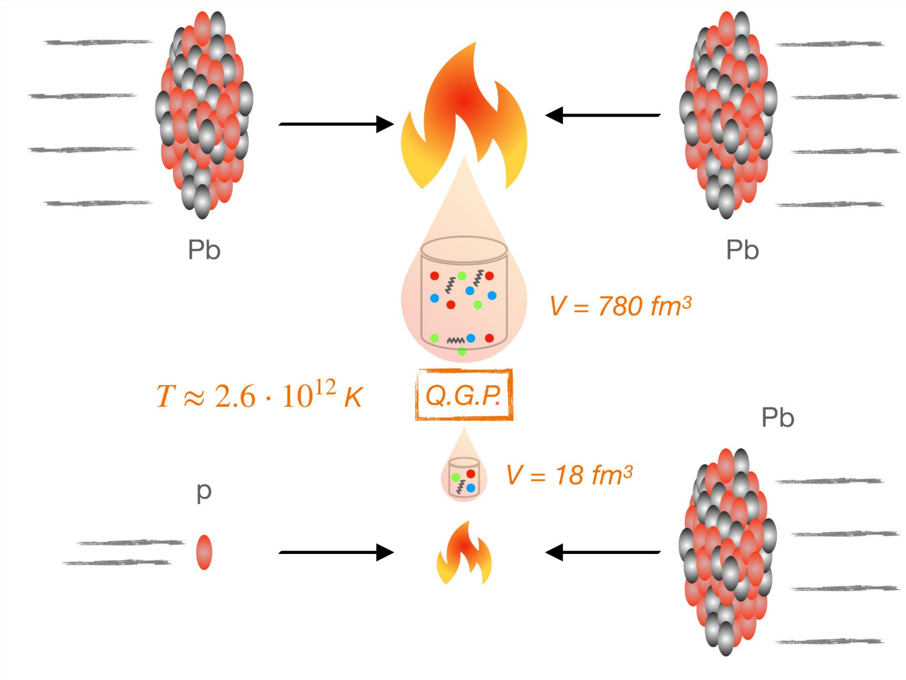
Unifal MG
Universidade Federal de Alfenas

Investigating the Properties of Nuclear Matter Under Extreme Conditions: Quark-Gluon Plasma

QGP: <u>Quarks, anti-quarks and gluons liberated</u>



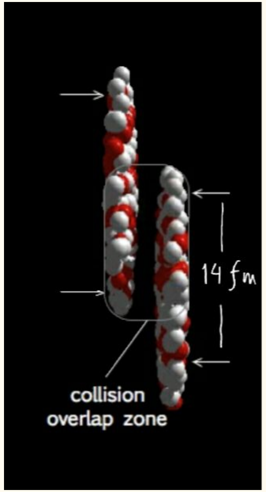


High-energy nuclear collisions provide a unique window into the behavior of nuclear matter under extreme conditions.

Explore fundamental properties of strong interactions.

Particle correlations reveal the dynamics of the generated state.

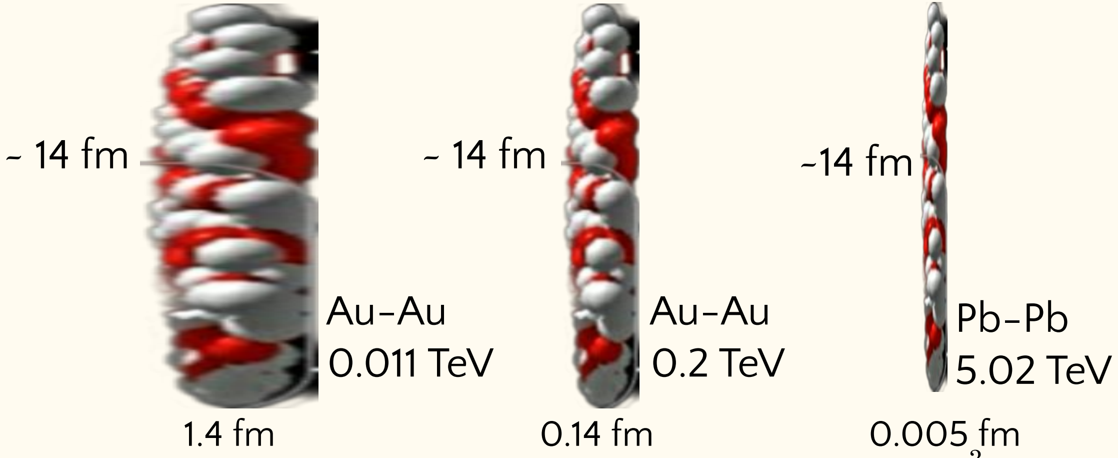
Heavy-Ion Collisions



Relativistic heavy-ion collision: contracted Lorentz disk

$$\frac{14}{\gamma}$$

(1) colliding "pancakes"

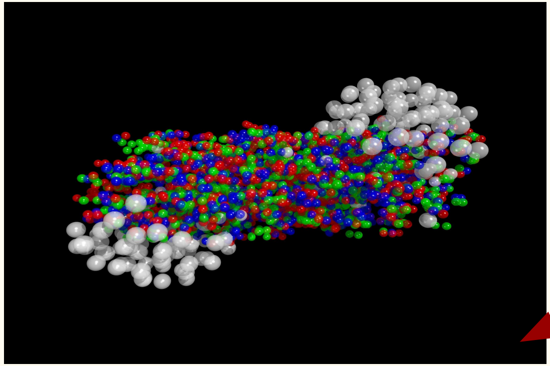


$$\gamma = \begin{cases} 10 & \textbf{NICA} \\ 100 & \textbf{RHIC} \\ 2500 & \textbf{LHC} \end{cases}$$

Heavy-Ion Collisions

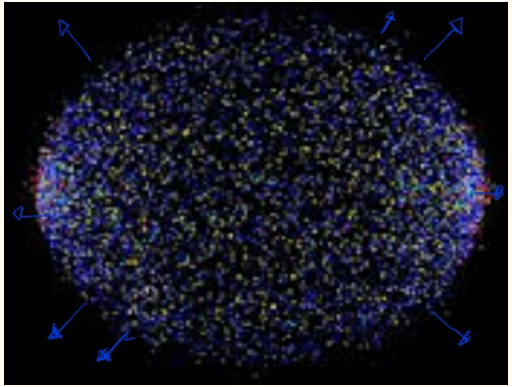
2) Expansion in the Vaccum

$\approx 10^{-22} s$



Matter composed of strongly coupled quarks and gluons

Credit: CERN press



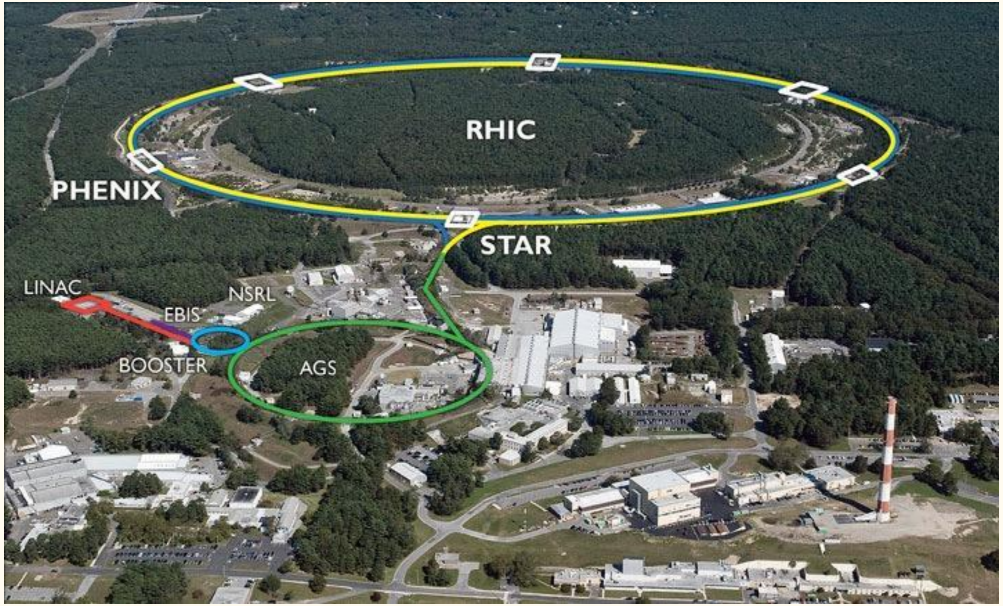
3) density decreases:

thousands of particles produced;
$\sim$ 35000 particles Pb-Pb 5.02 TeV

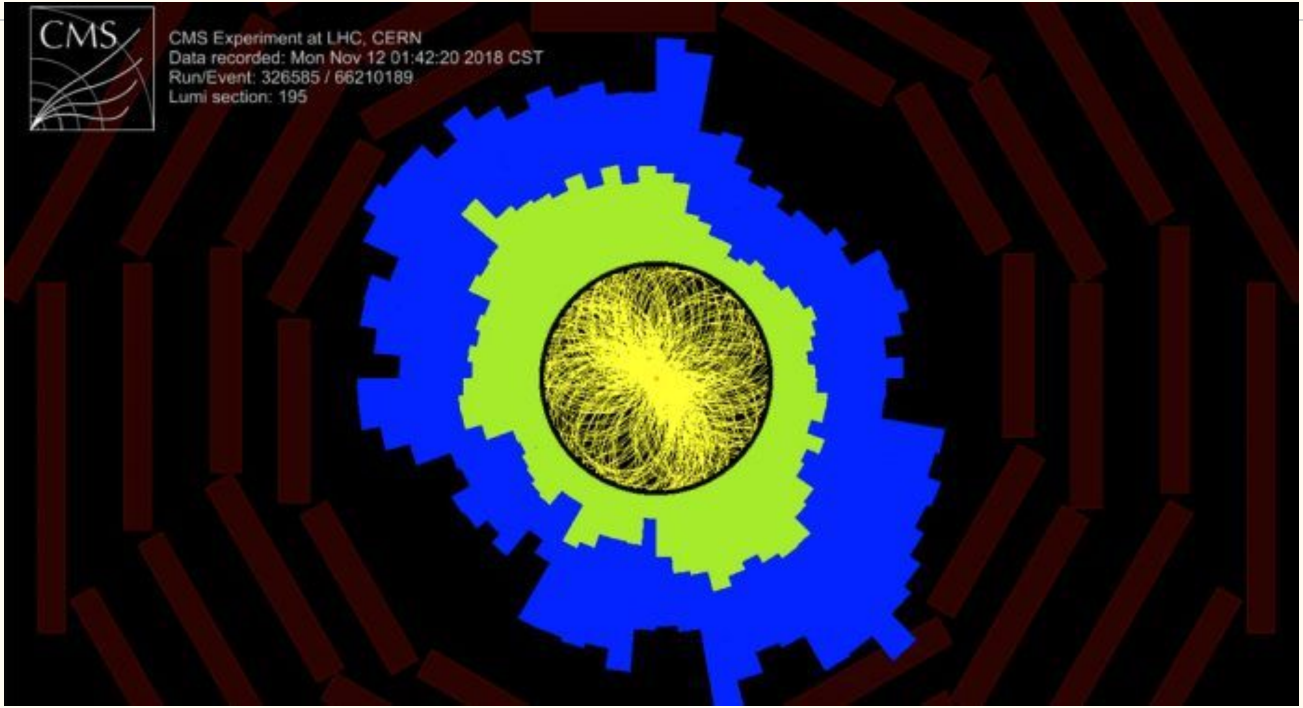
“Discovering” QGP

2005 :

Four experimental groups at the RHIC announced that they have created a **"perfect liquid"** of quarks and gluons through Au-Au collisions at 200 GeV.



How do we know we have a liquid?

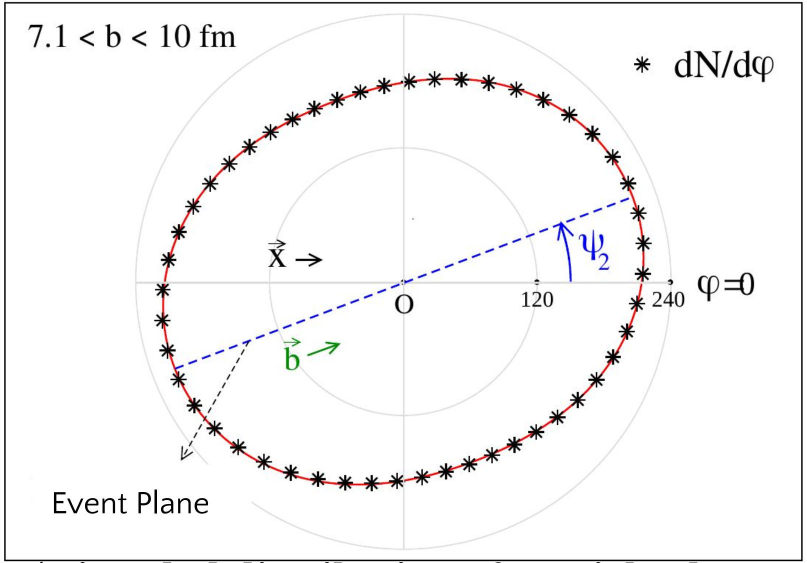


Azimuthal distribution of particles has an ELLIPTIC shape, v_2

i.e. thermalization/collective flow break isotropy

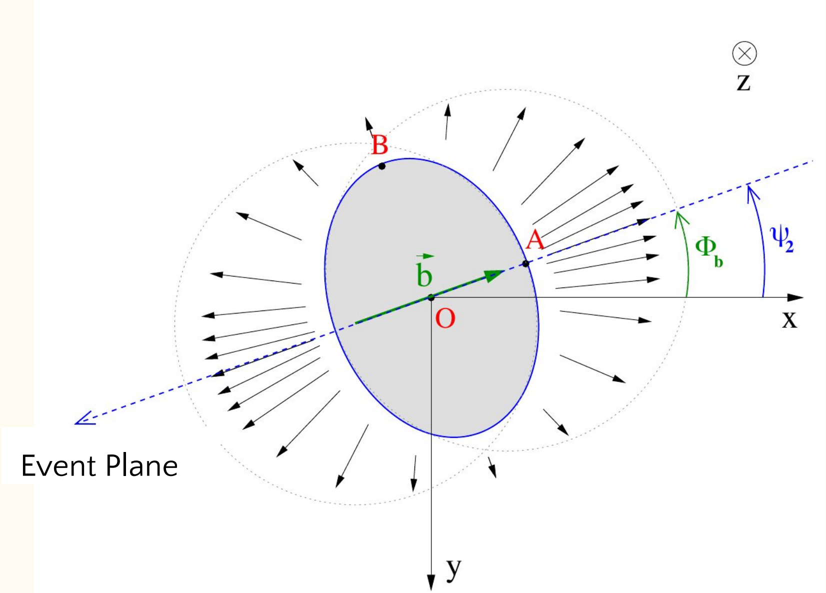
How do we know we have a liquid?

"Experimental Data"



Azimuthal distribution of particles has ELLIPTIC shape, v_2

Initial Condition (QGP)

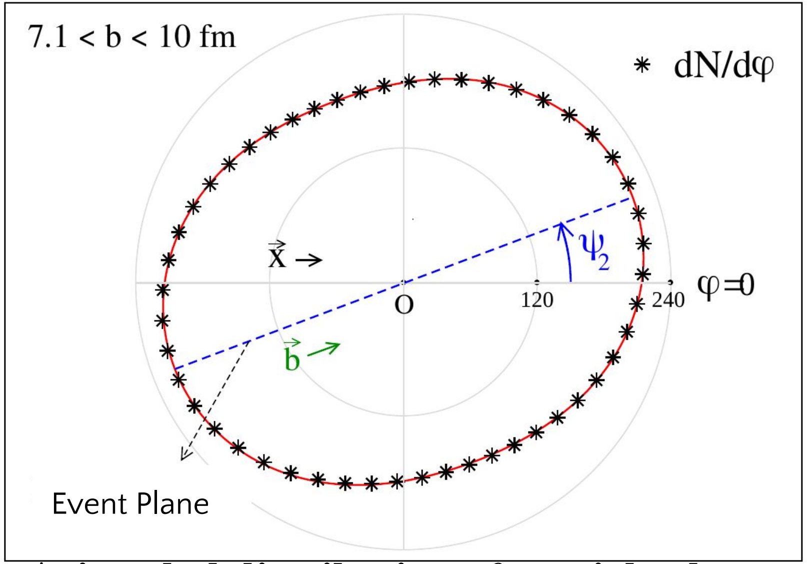


Initial ELLIPTIC shape implies v_2, when QGP behaves as a LIQUID!

How do we know we have a liquid?

"Experimental Data" *Mapping* Initial Condition (QGP)

FG, Grassi, Luzum, Ollitrault 1111.6538



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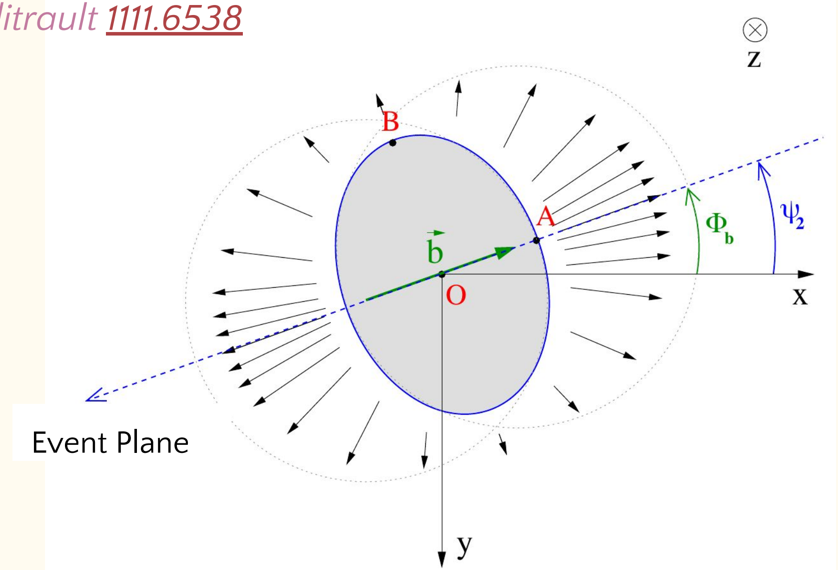
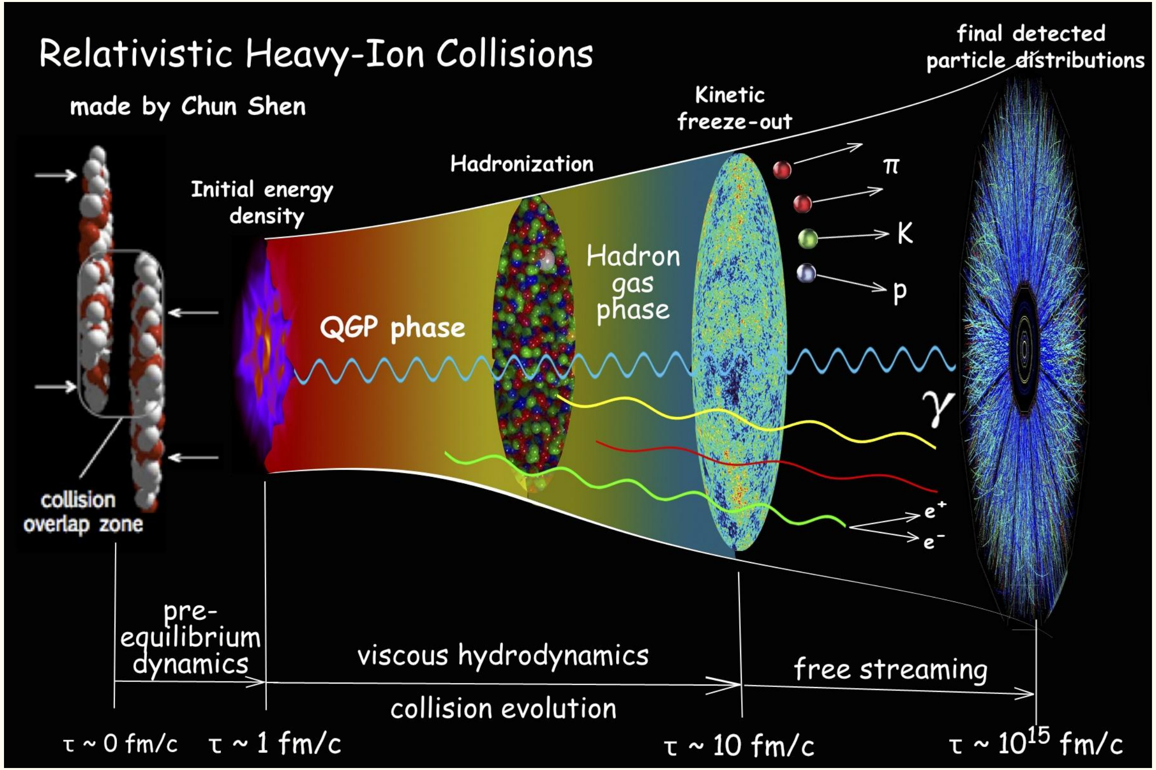
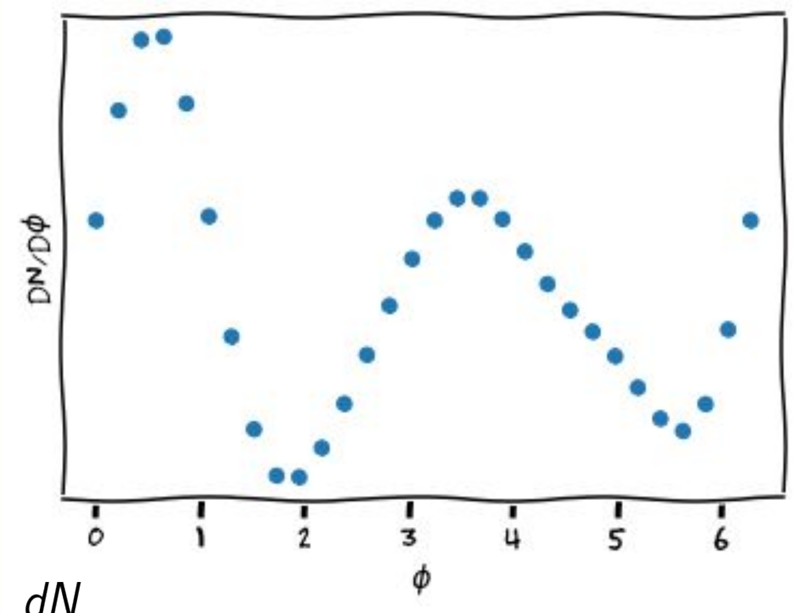


Initial ELLIPTIC shape implies v_2, when QGP behaves as a LIQUID!

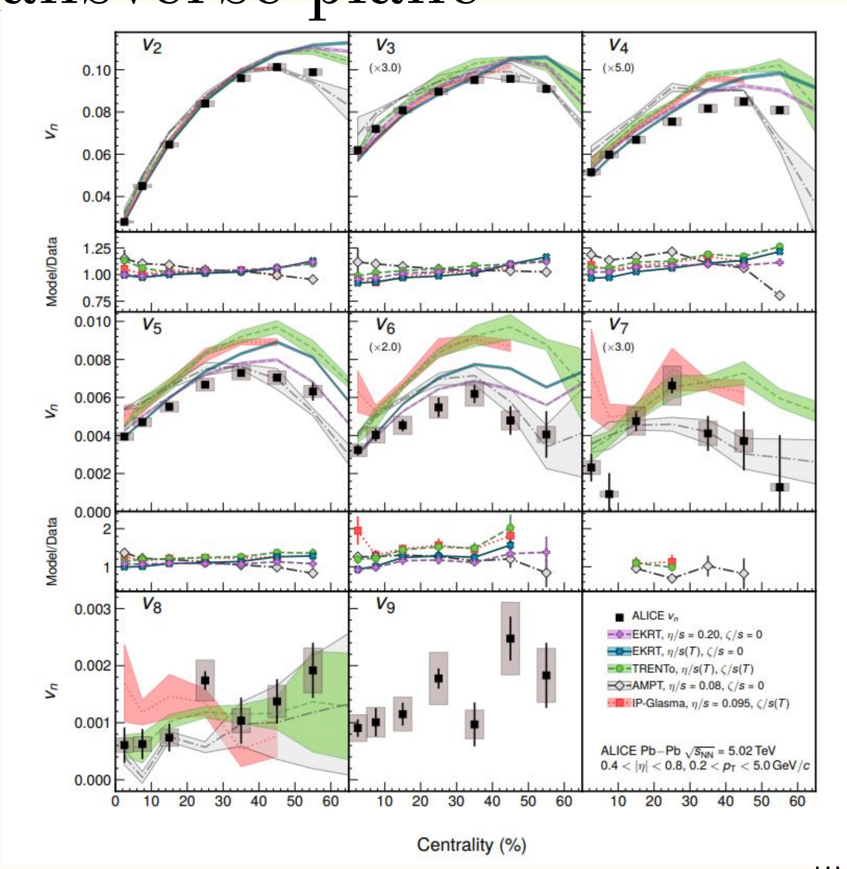
Standard model of relativistic collisions



OBSERVABLES I: Flow
Particle distribution in the transverse plane



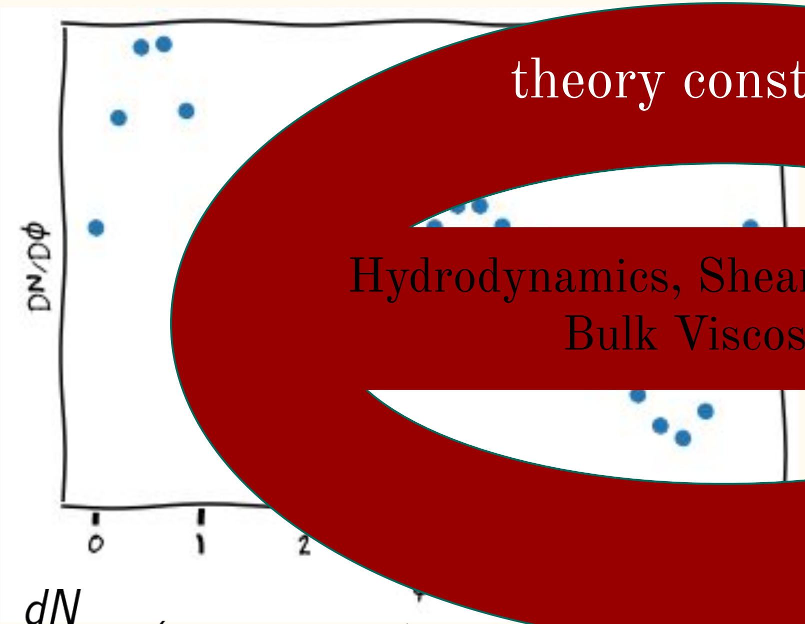
$$\frac{dN}{d\phi} \propto \left(1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \cdots\right)$$



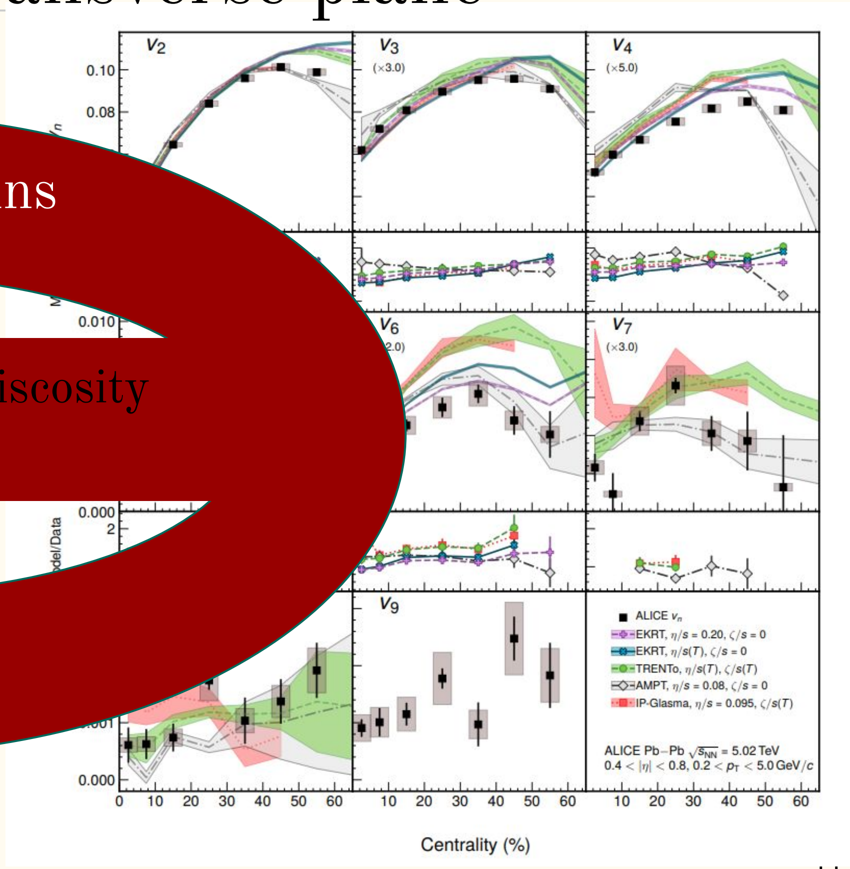
OBSERVABLES I: Flow
Particle distribution in the transverse plane

theory constrains

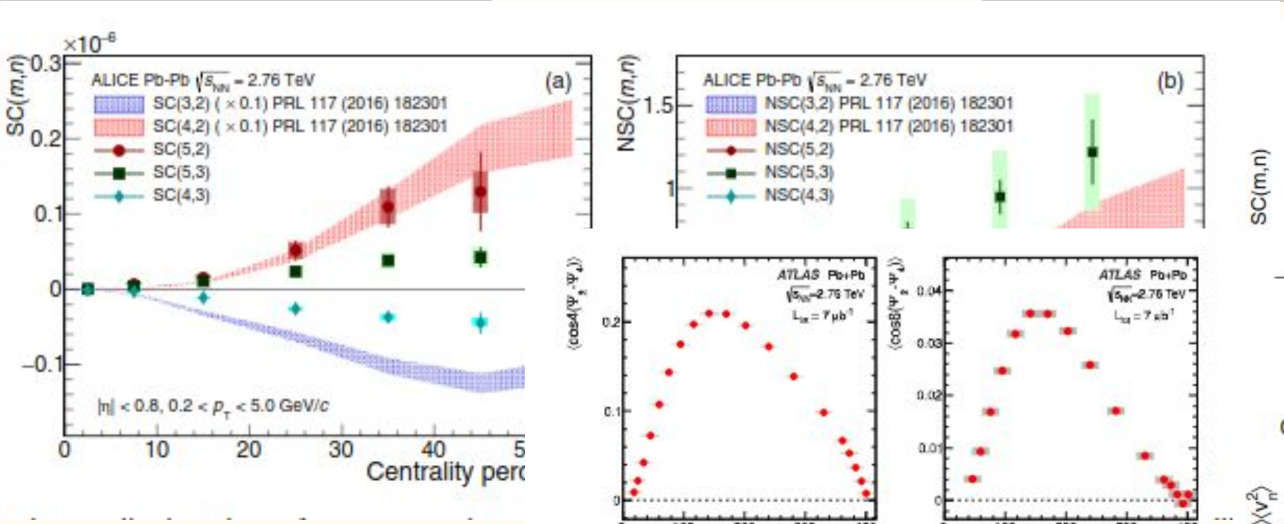
Hydrodynamics, Shear Viscosity
Bulk Viscosity

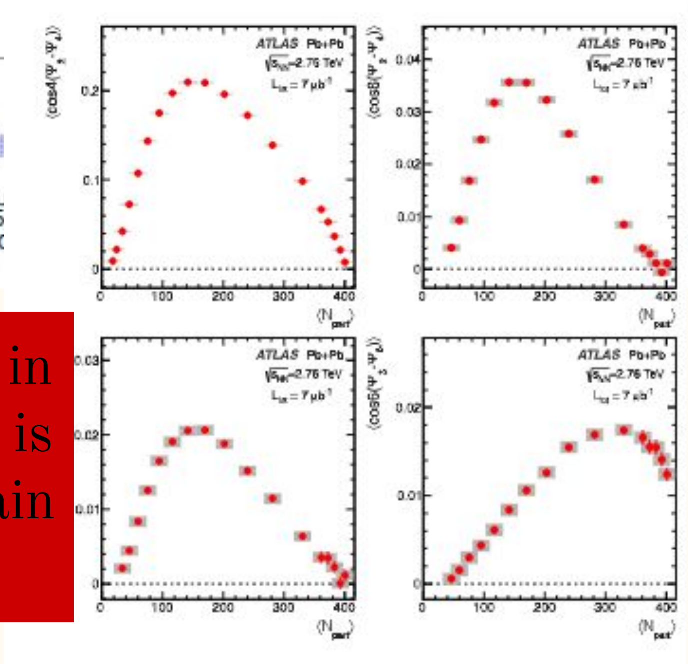


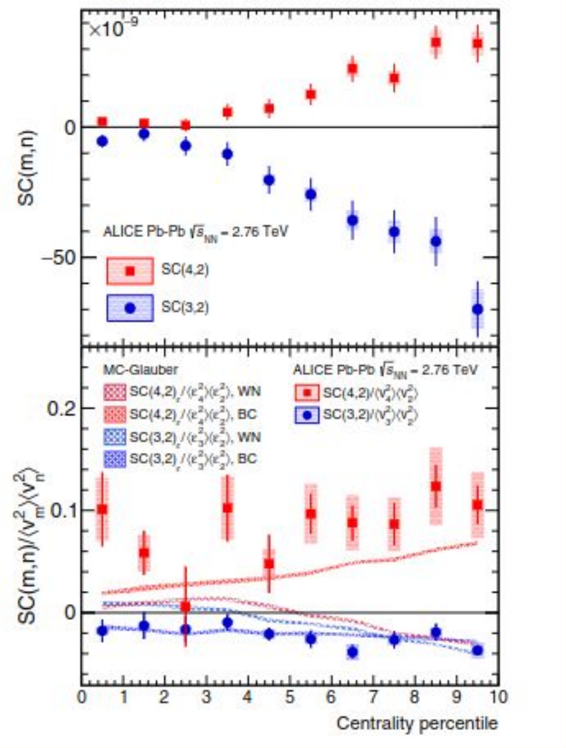
$$\frac{dN}{d\phi} \propto (1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \cdots)$$



OBSERVABLES I: Flow & Correlations





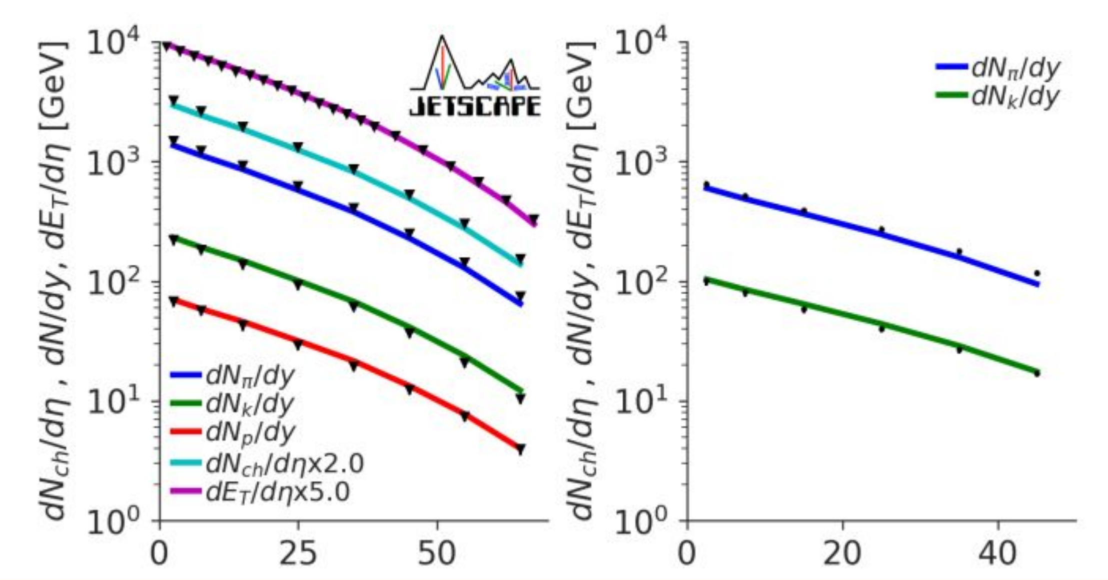


Particle distribution in the transverse plane is one of the main observables in HIC

OBSERVABLES II:
Multiplicity: Charged Particle Number

Global analysis (Bayesian)

Pb-Pb 5.02 TeV **Au-Au 200 GeV**



centrality (%) **centrality (%)**

JETSCAPE 2011.01430

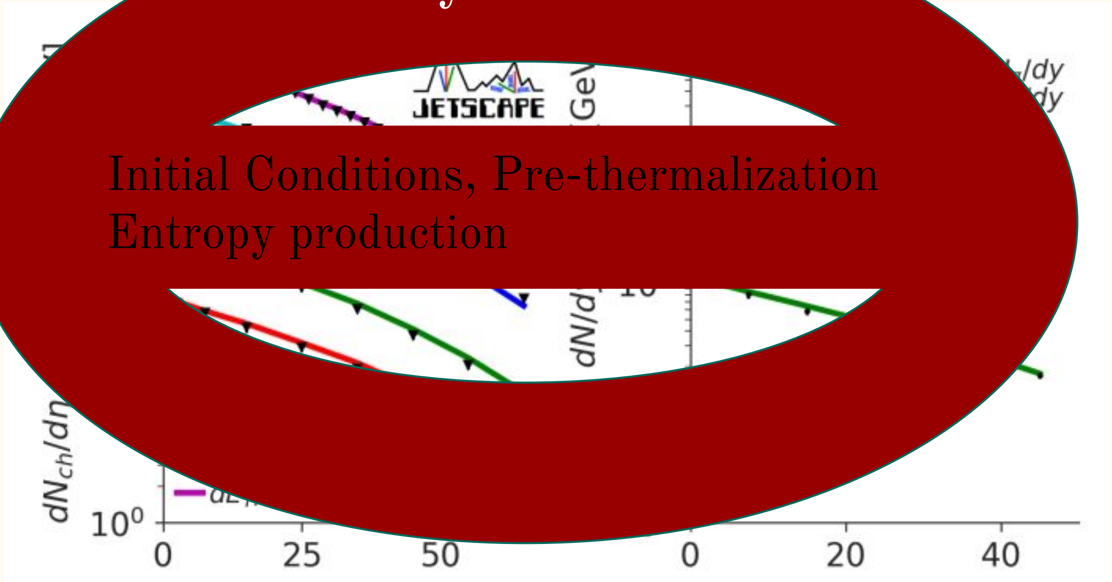
OBSERVABLES II:
Multiplicity: Charged Particle Number

Global analysis (Bayesian)

Pb-Pb 5.0 **200 GeV**

theory constrains

Initial Conditions, Pre-thermalization
Entropy production



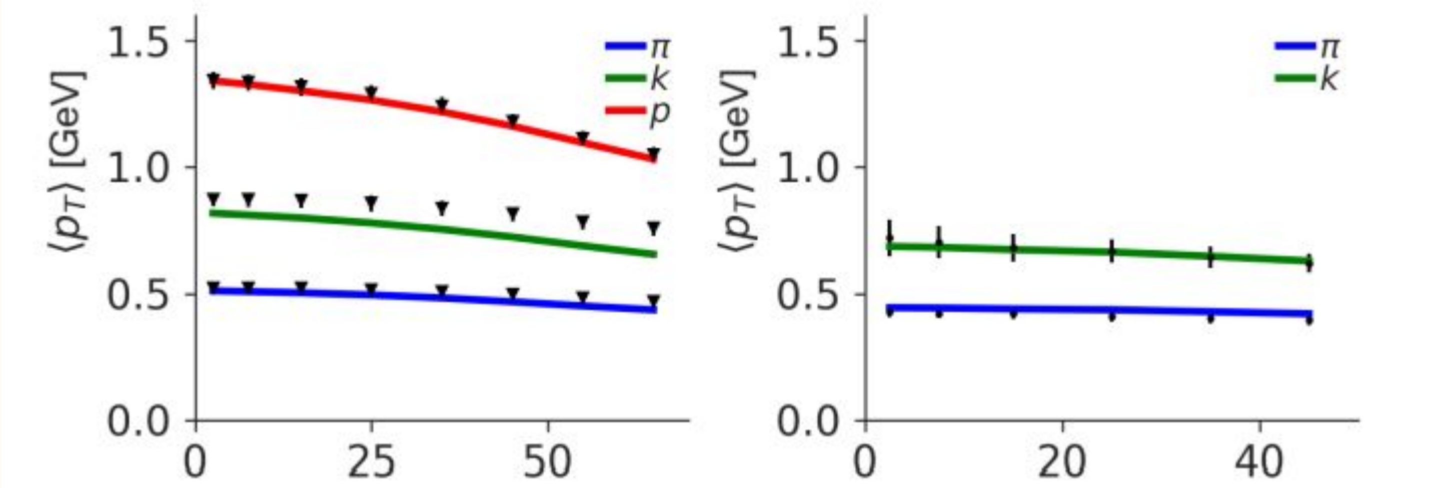
centrality (%) **centrality (%)**

JETSCAPE 2011.01430

OBSERVABLES III:
Mean transverse momentum

Global analysis (Bayesian)

Pb-Pb 5.02 TeV **Au-Au 200 GeV**



centrality (%) **centrality (%)**

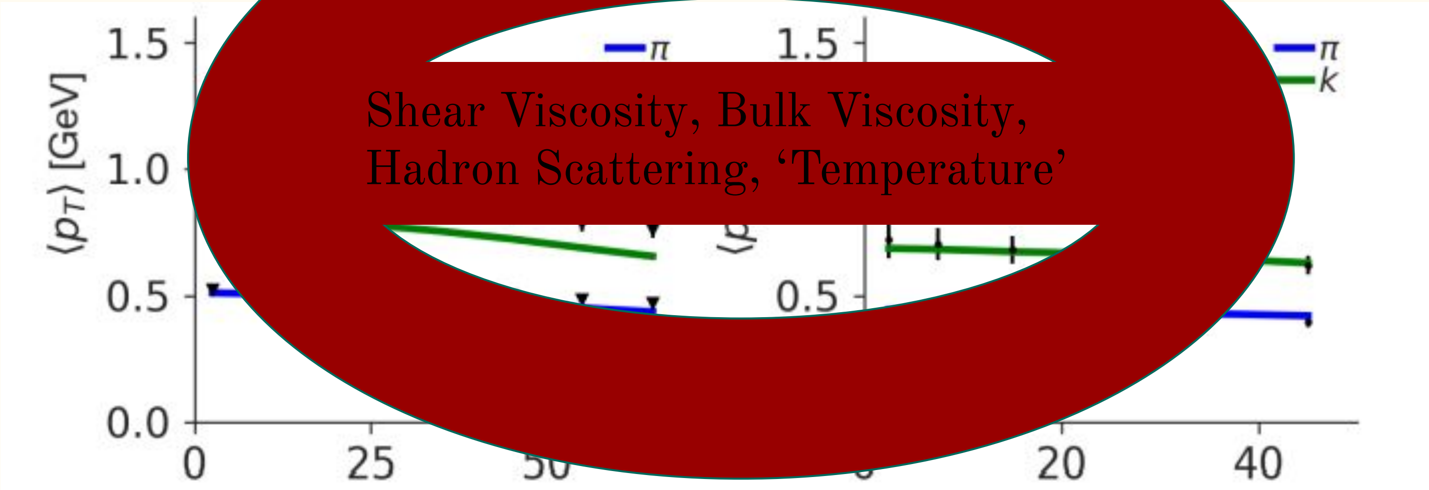
JETSCAPE 2011.01430

OBSERVABLES III:
Mean transverse momentum

Global analysis (Bayesian)

theory constrains

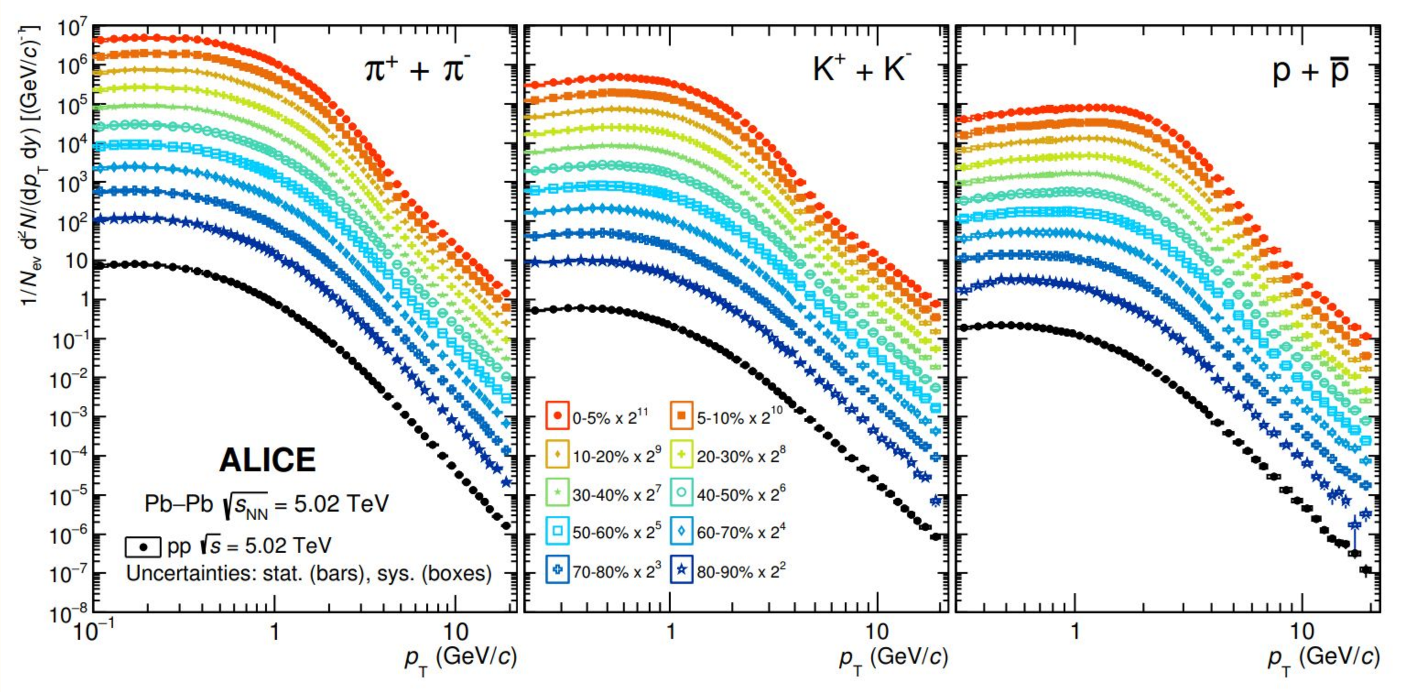
Shear Viscosity, Bulk Viscosity,
Hadron Scattering, ‘Temperature’



centrality (%) **centrality (%)**

JETSCAPE 2011.01430

OBSERVABLES III: Transverse momentum spectra

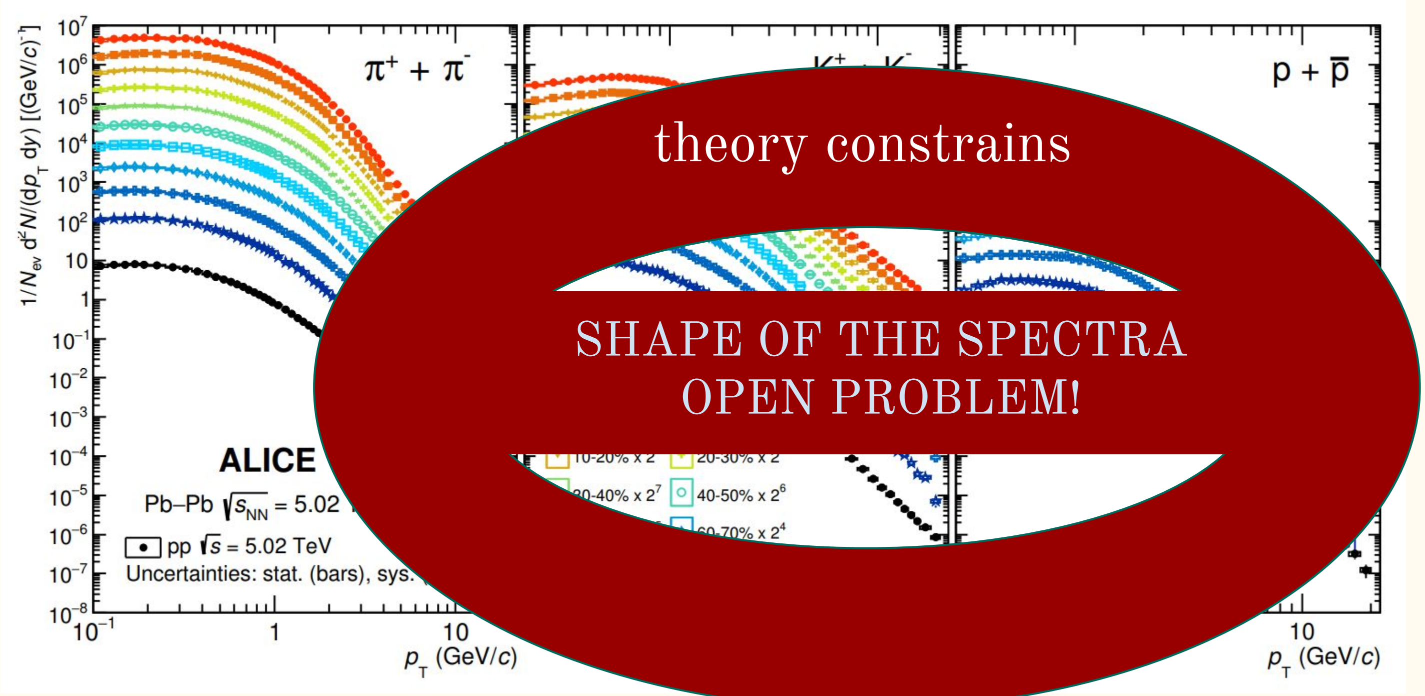


Pion	Kaon	Proton
80%	10%	5%

relative proportions of particles produced

ALICE 1910.07678

OBSERVABLES III: Transverse momentum spectra



theory constrains

SHAPE OF THE SPECTRA
OPEN PROBLEM!

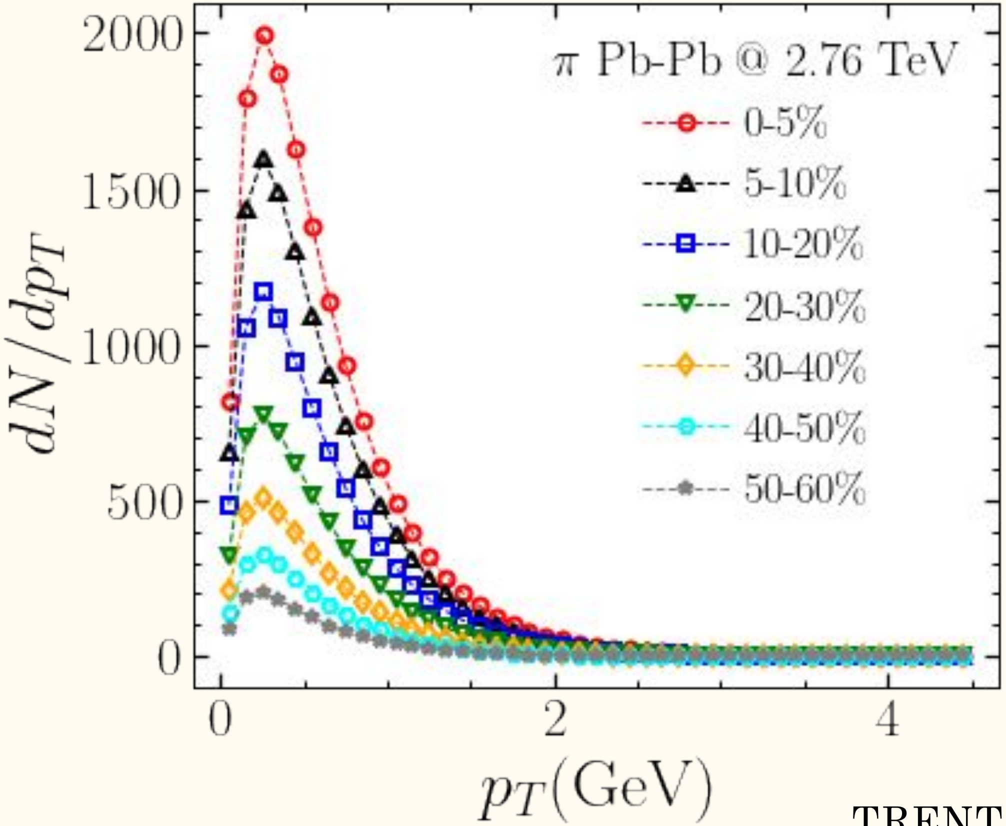
Pion	Kaon	Proton
80%	10%	5%

relative proportions of particles produced

ALICE 1910.07678

What can we learn from the p_T-spectra?

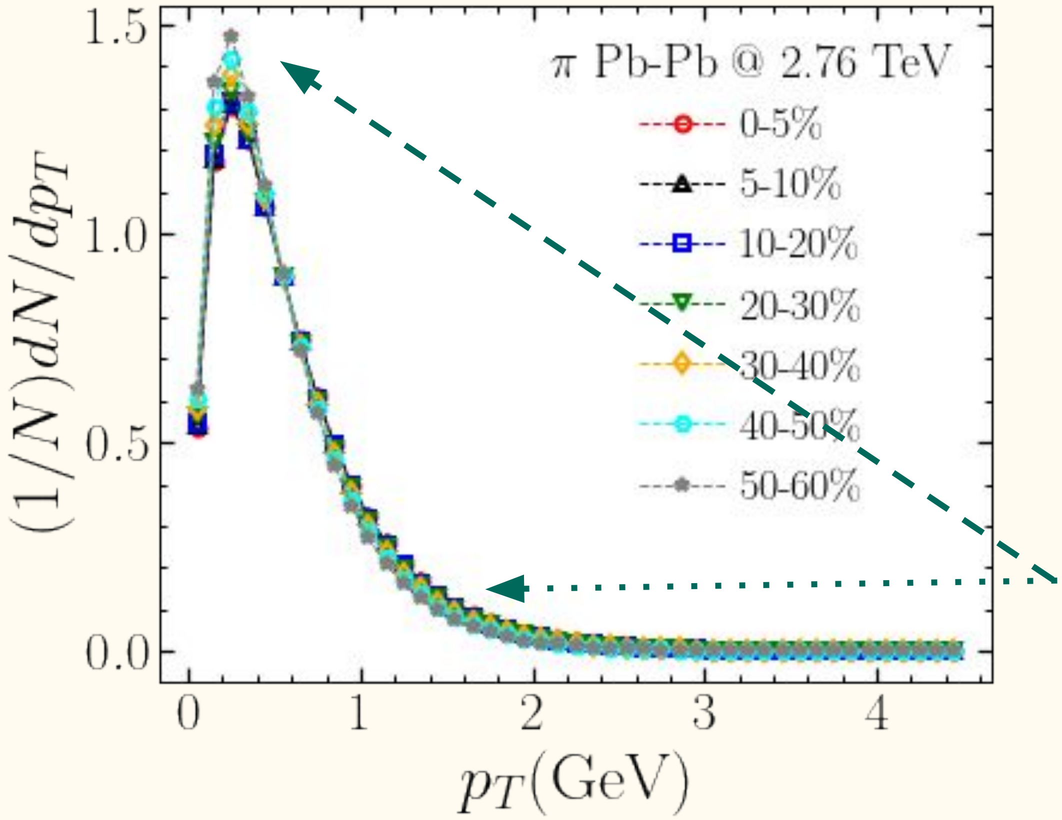
p_T-spectra in hybrid simulation



- Focus on the most abundant particle: pion.
- p_T-spectra is dependent of the *centrality*.
- From p_T-spectra we obtain the multiplicity N and the mean momentum, used in the Bayesian analysis.

TRENTO+KOMPOST+MUSIC+URQMD

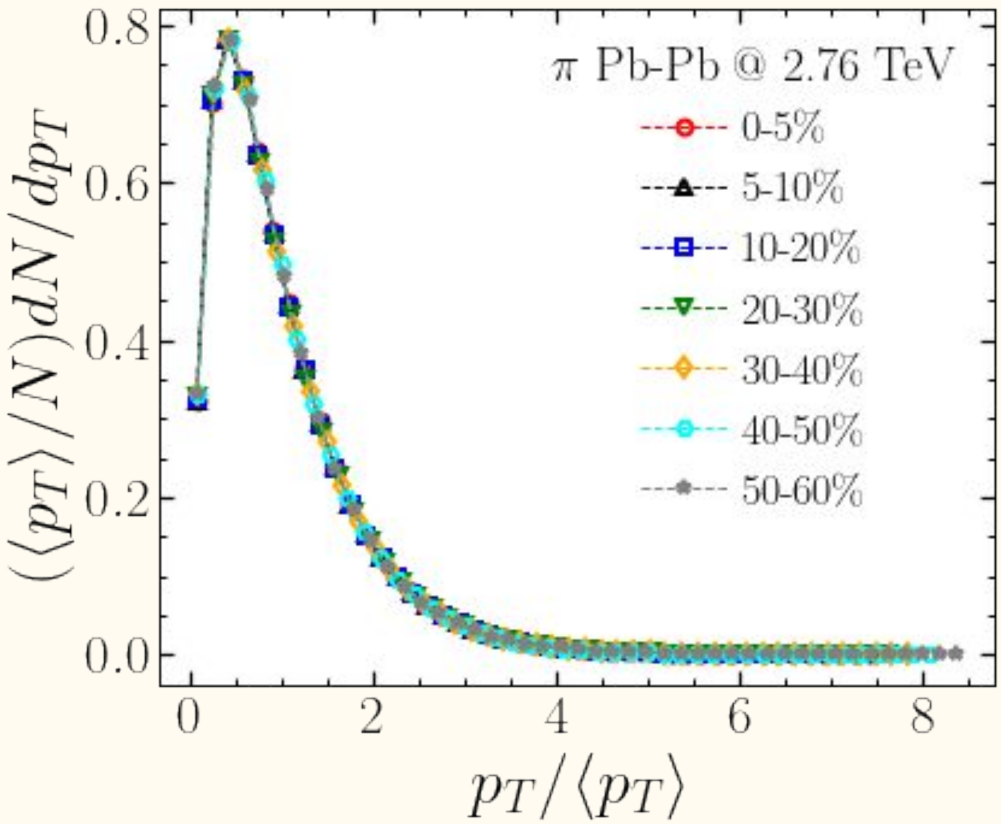
p_T-spectra in hybrid simulation



- Remove global scale: N
- The p_T-spectra's $\frac{1}{N}\frac{dN}{dp_T}$,

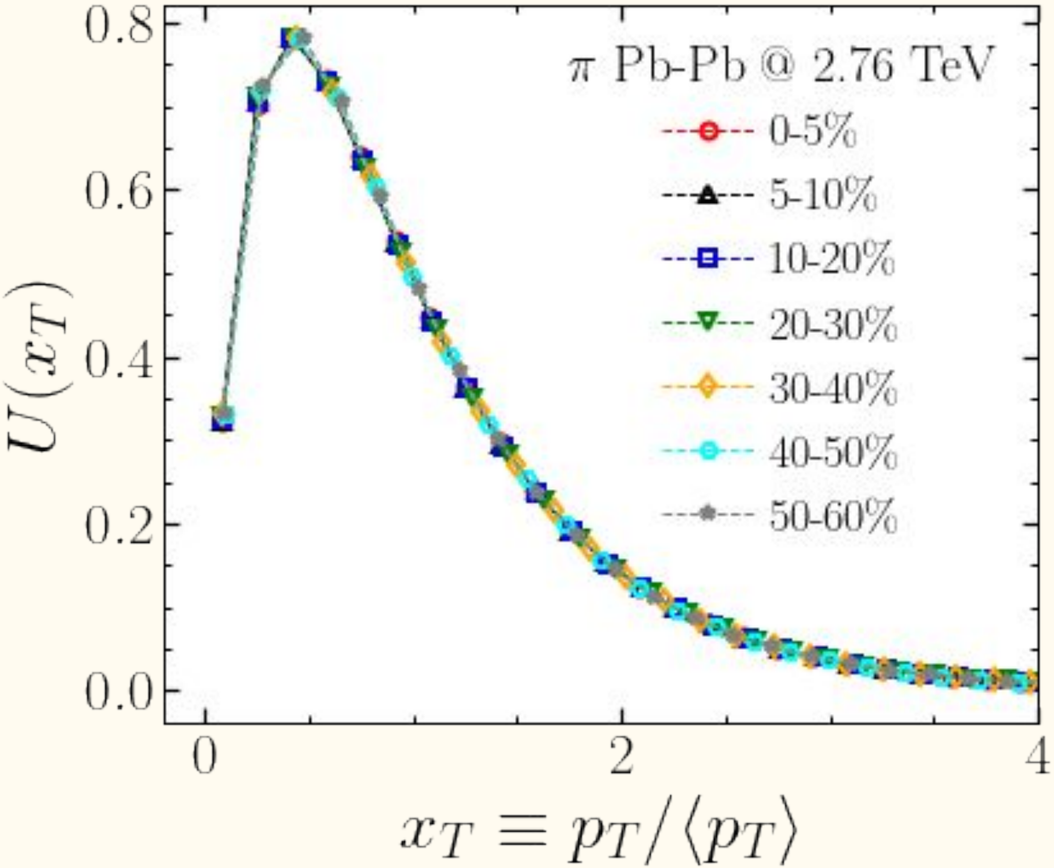
  have similar scale (roughly independent of centrality).
- Normalized spectras.
- It shrinks when it goes towards peripheral collisions.

Scaled p_T-spectra in hybrid simulation



- Remove global scale: N, $\langle p_T \rangle$
- Scaled p_T-spectra have 'same' scale. $\frac{\langle p_T \rangle}{N} \frac{dN}{dp_T}$
- Scaled spectra seem to be independent of *centrality*, when it is described by relativistic hydrodynamics!

Scaled p_T-spectra in hybrid simulation



- A ‘new’ differential spectra:

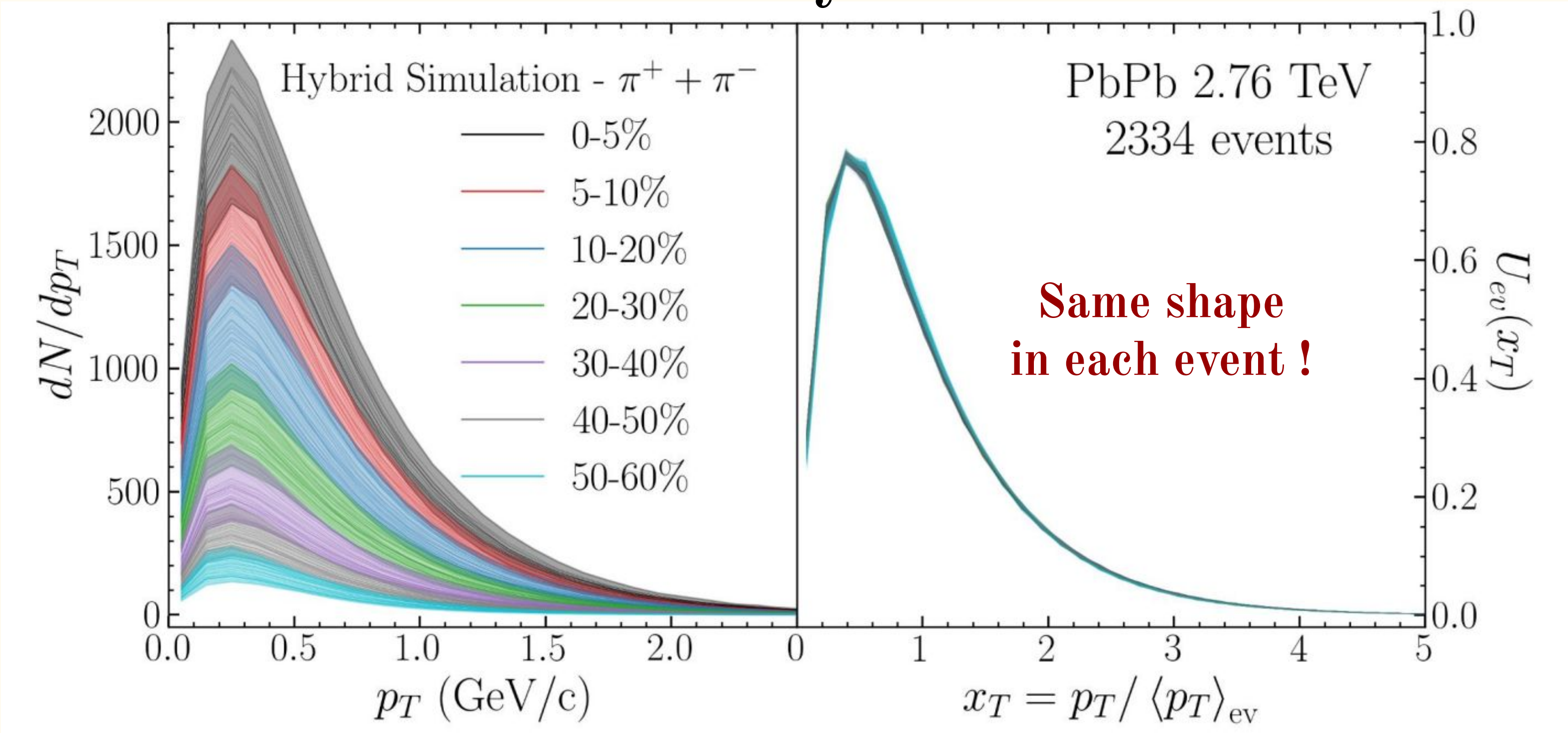
$$U(x_T) \equiv \frac{\langle p_T \rangle}{N}\frac{dN}{dp_T} = \frac{1}{N}\frac{dN}{dx_T}$$

- Universality appears in simulation for the average spectra.

- Is this an ‘average’ effect?

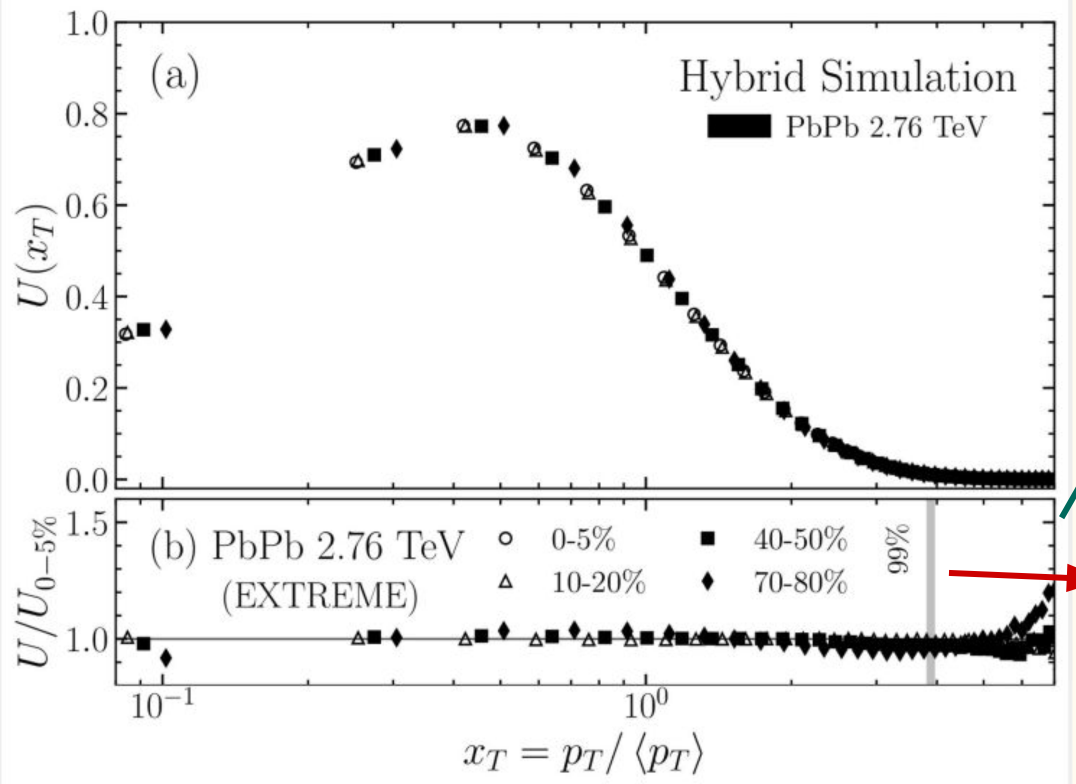
EXTREME 2406.15208

Scaled p_T-spectra in hybrid simulation: Event-by-event



Universality of scaled p_T-spectra can be a signature of a hydrodynamic phase?

Scaled p_T-spectra in hybrid simulation: Different Systems and Energy

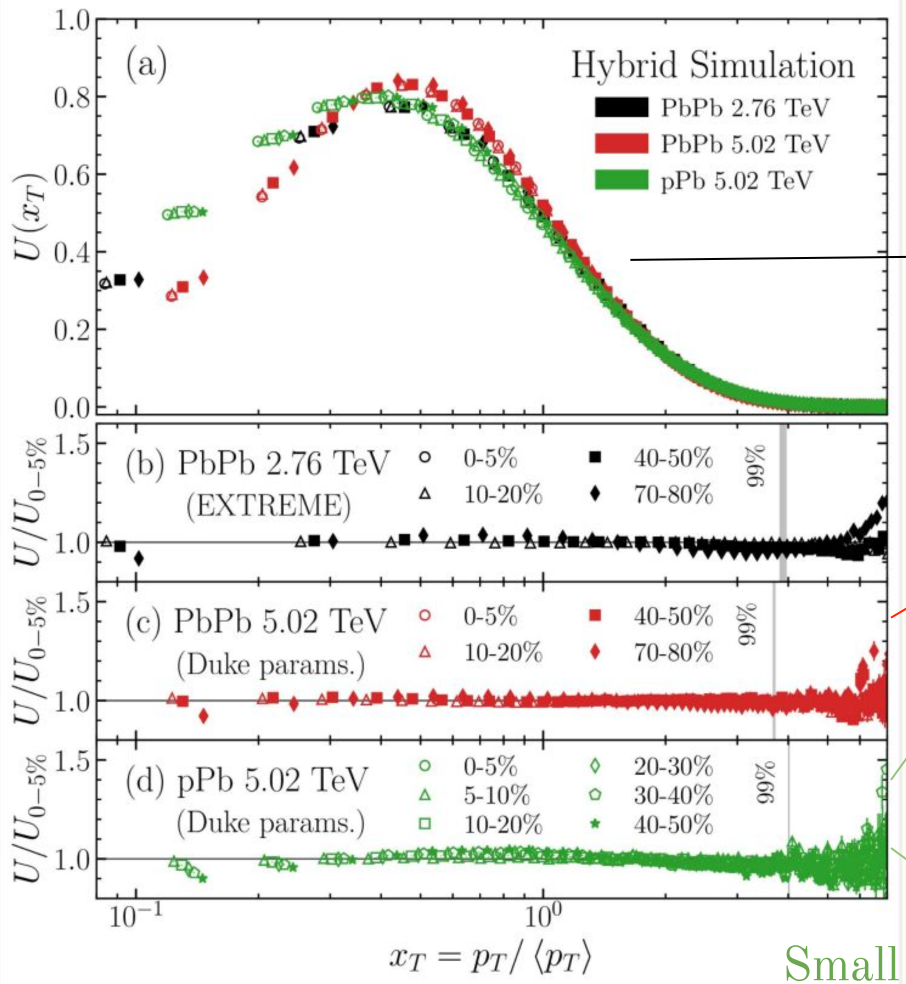


Details about the shape of the spectra

- N and $\langle p_T \rangle$ have to be computed for the whole spectra.
- Difference between $U(x_T)$ from most central collision and other centralities.
- Same shape for 99% of pions produced.

EXTREME 2406.15208

Different Systems and Energy

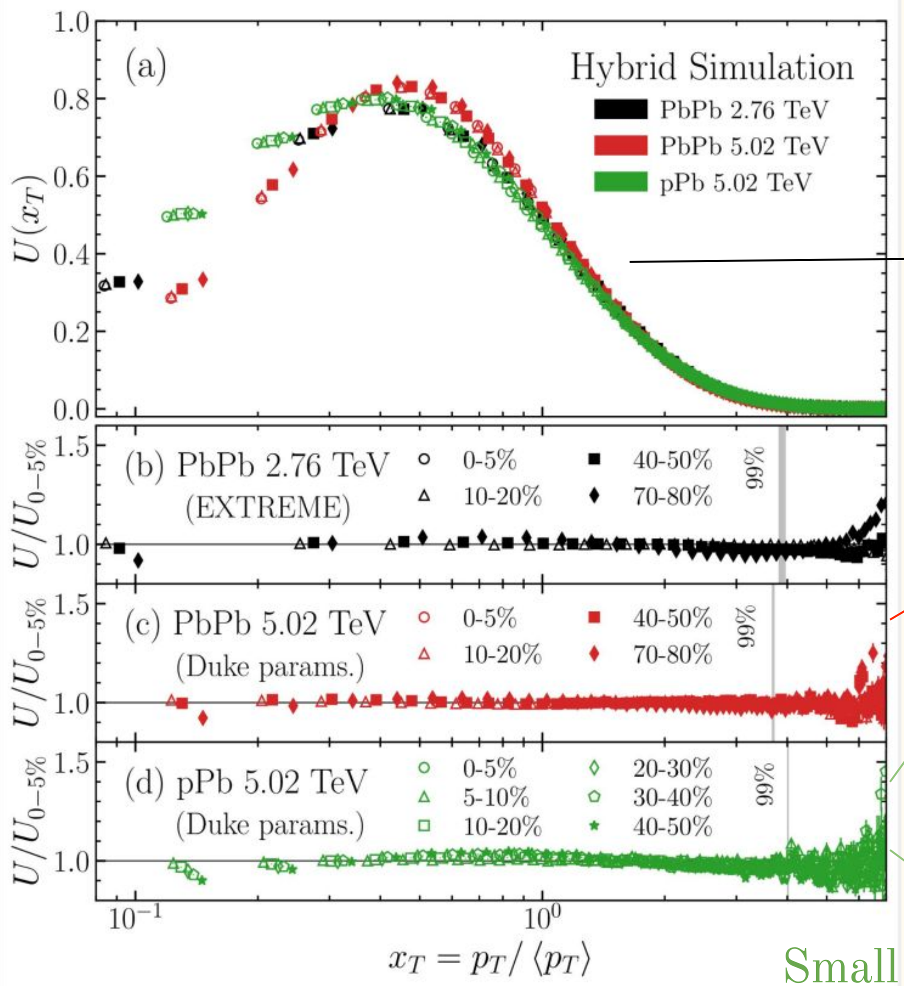


- Different shapes for different systems and energy.
- Universality within the same system at fixed energy; Centrality independent.

Small System (pPb)

EXTREME 2406.15208

Different Systems and Energy



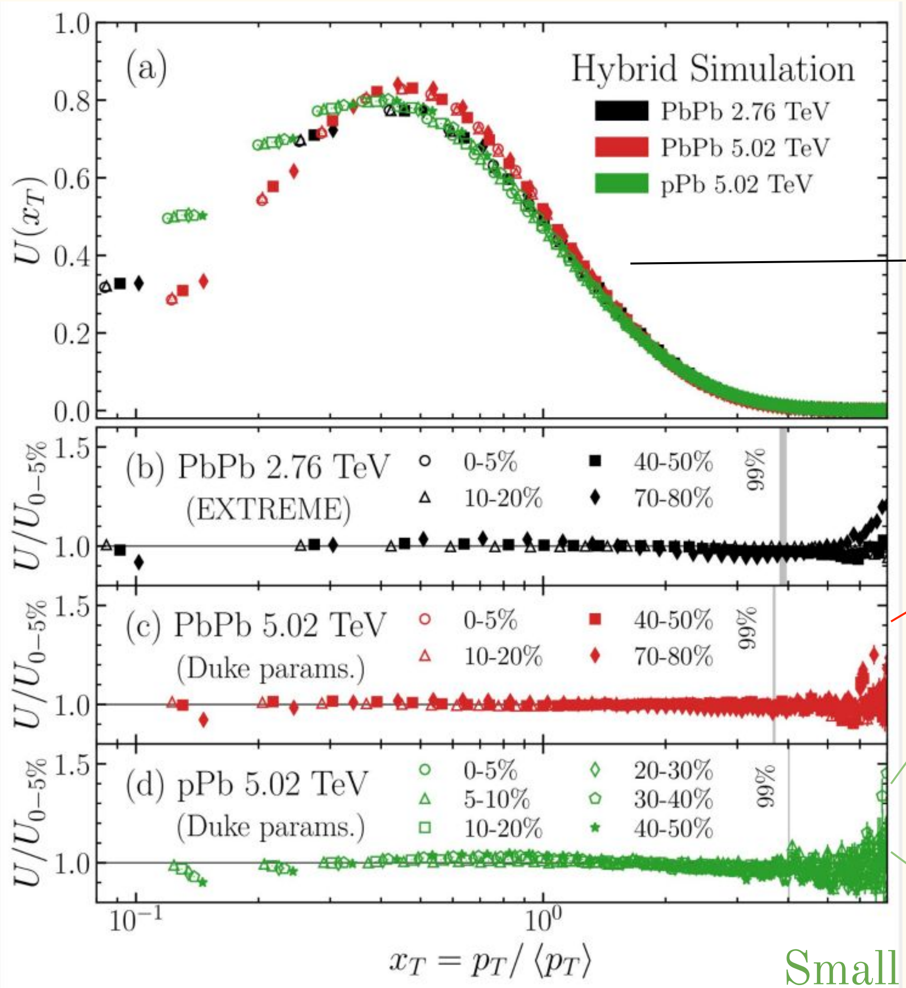
- Different shapes for different systems and energy.
- Universality within the same system at fixed energy; Centrality independent.

Universal scaling in fluid dynamics
(even with non-hydrodynamic effects, as hadronic decays and collisions)

Small System (pPb)

EXTREME [2406.15208]

Different Systems and Energy



- Different shapes for different systems and energy.
- …ver…ty within the same s… …gy;

Un… …mics

(even with … …ic decay…

Is there u*niversality* in the experimental data?

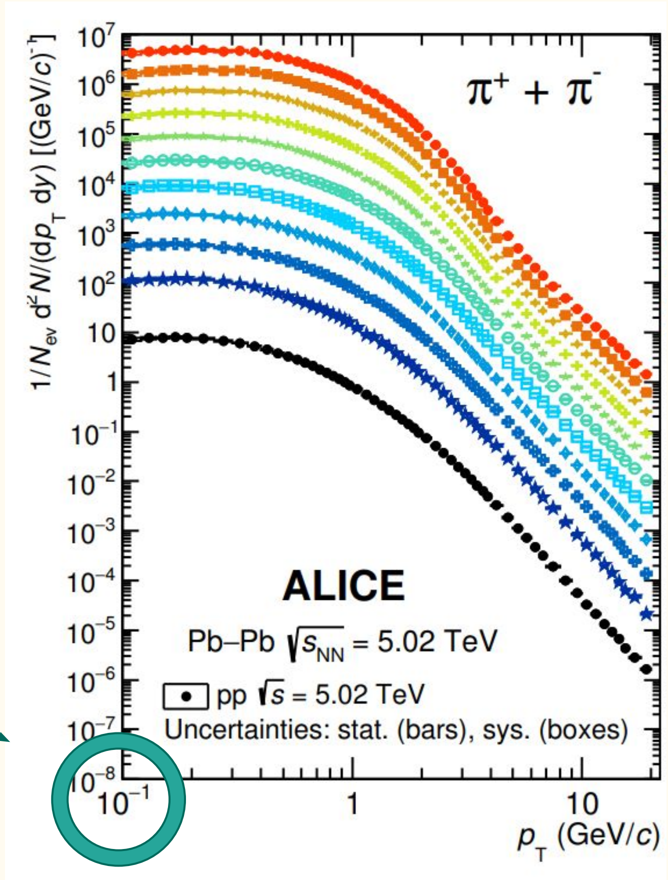
Small System (pPb)

EXTREME [2406.15208]

$U(x_T)$ in experimental data

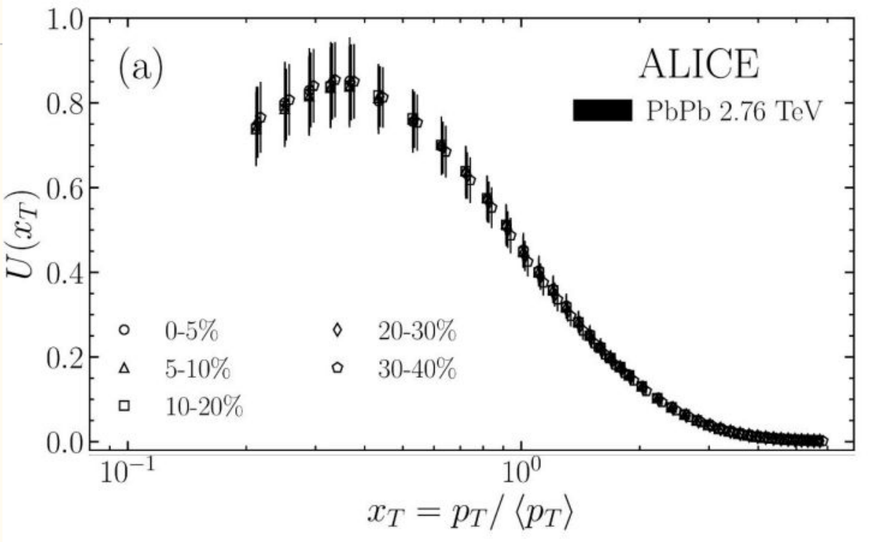
Particles are not measured at ‘low momentum’.

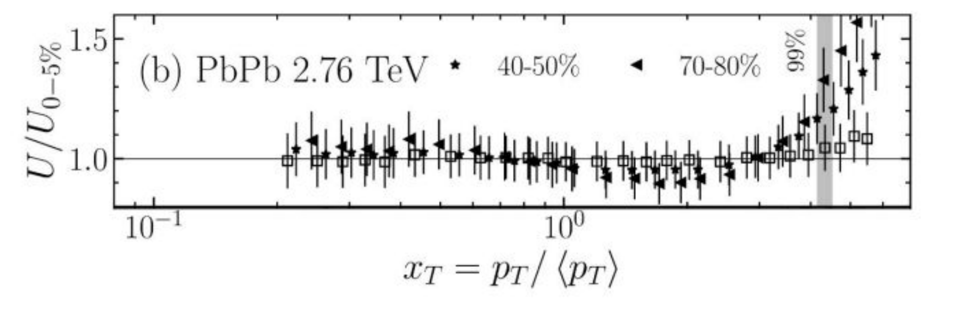
It is necessary to extrapolate the spectra for $p_T = 0$ in order to obtain the global scales.



Log Scale:
Large error bars.

$U(x_T)$ in experimental data

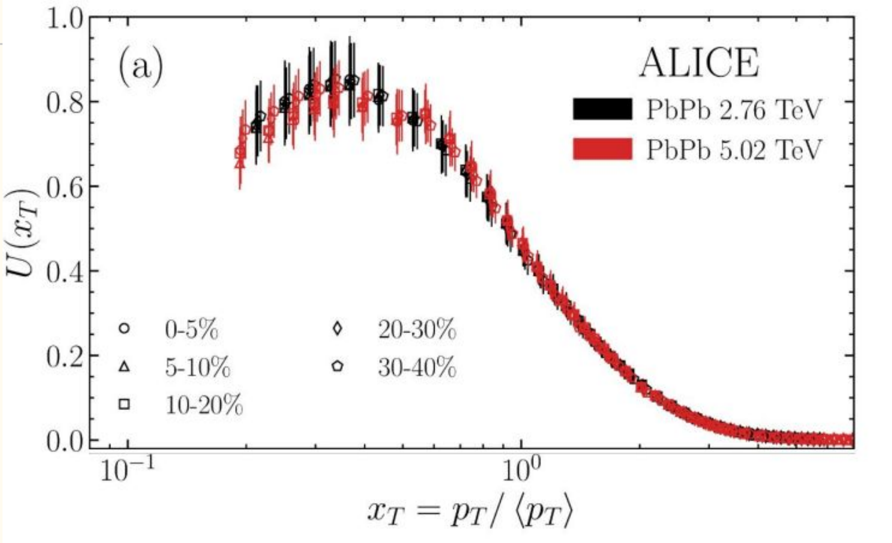


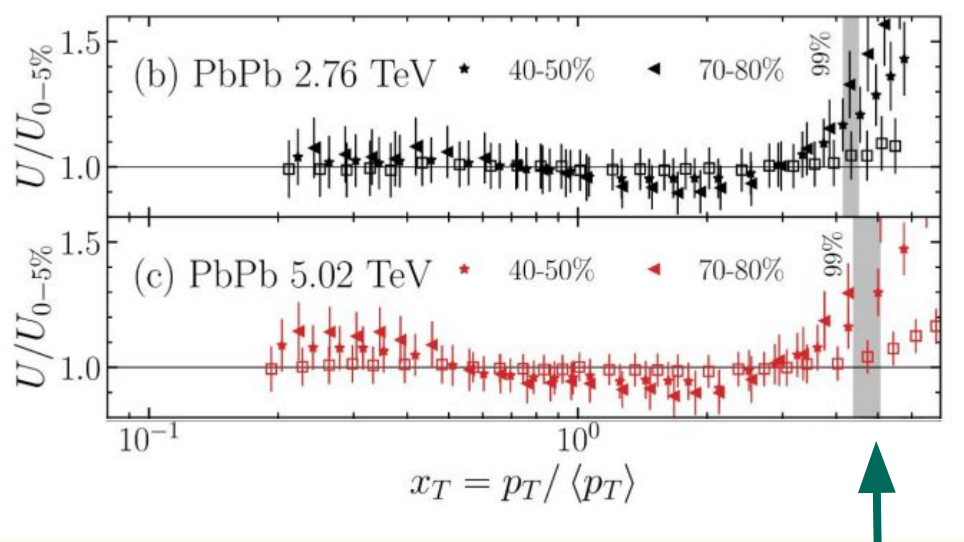


$\langle p_T \rangle$ and N extrapolated by ALICE

universal shape up to $x_T = 3$.
(within the error bars)

$U(x_T)$ in experimental data

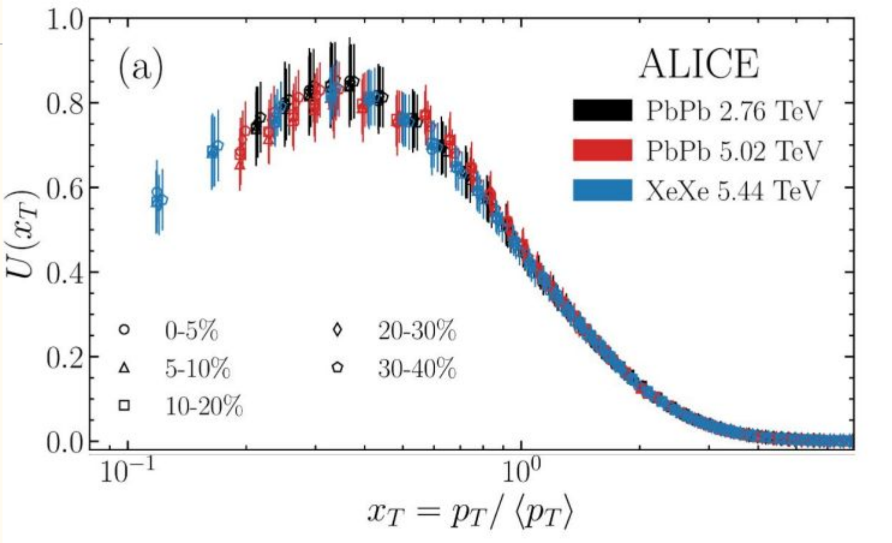


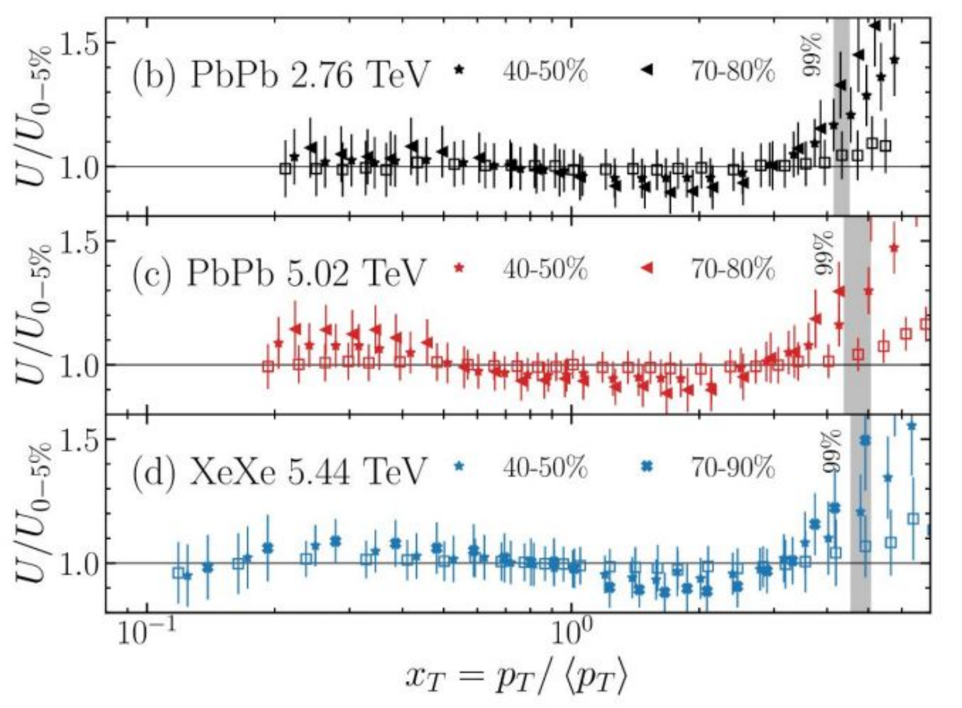


- universal shape up to $x_T = 3$. *(within the error bars)*
- PbPb at different energies, the same universal shape. *(within the error bars)*

- Peripheral collisions at large x_T don't match.
- Different physics? Jets? ...

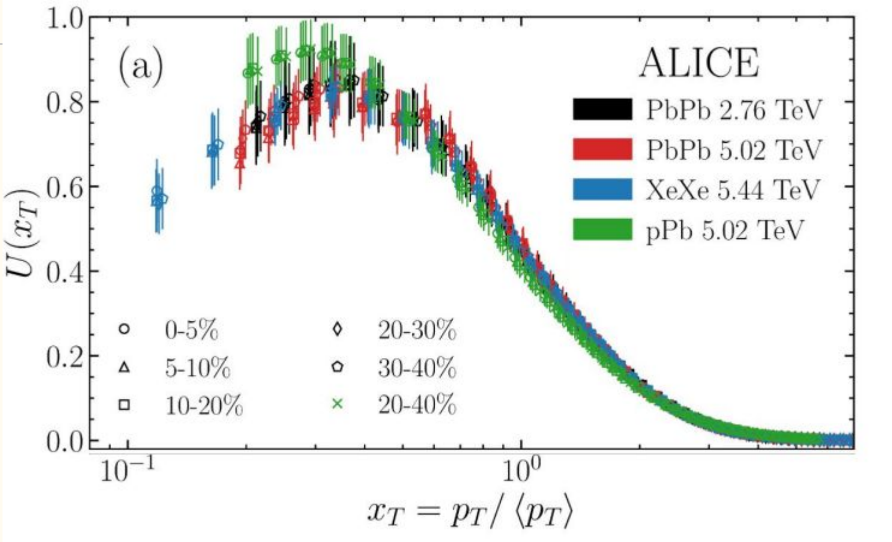
$U(x_T)$ in experimental data

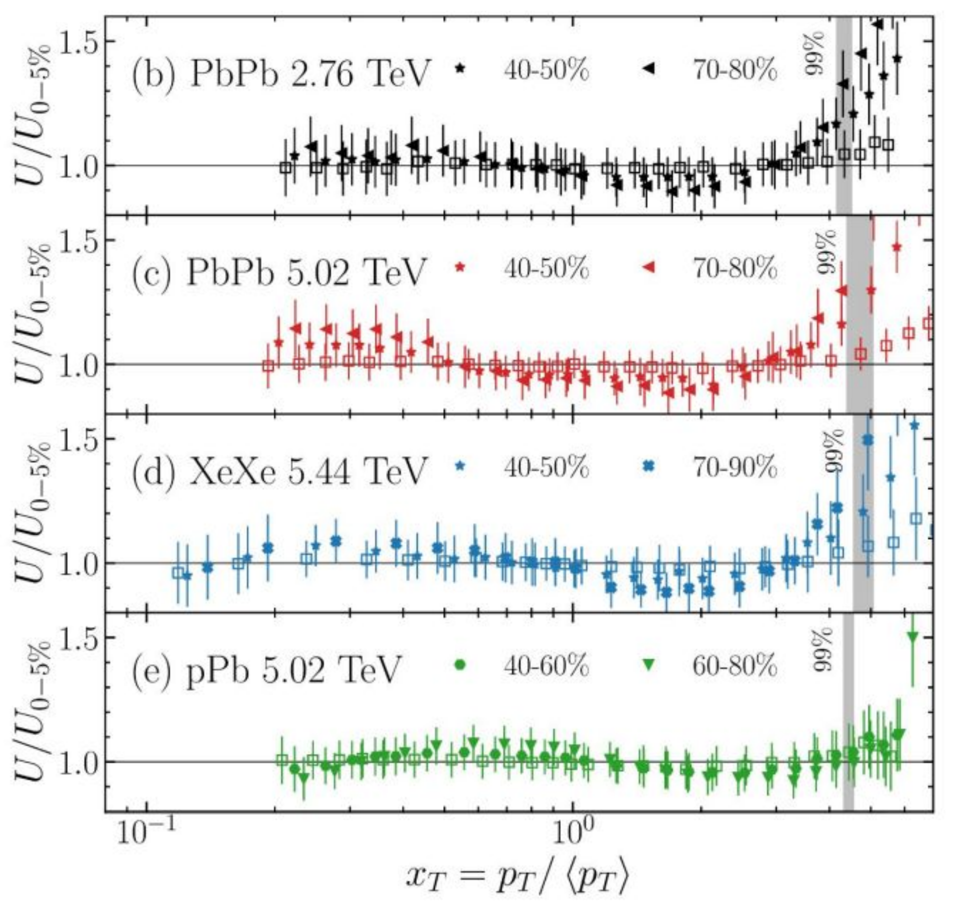




- universal shape up to $x_T = 3$. *(within the error bars)*
- Large systems: the same universal shape. *(within the error bars)*

$U(x_T)$ in experimental data

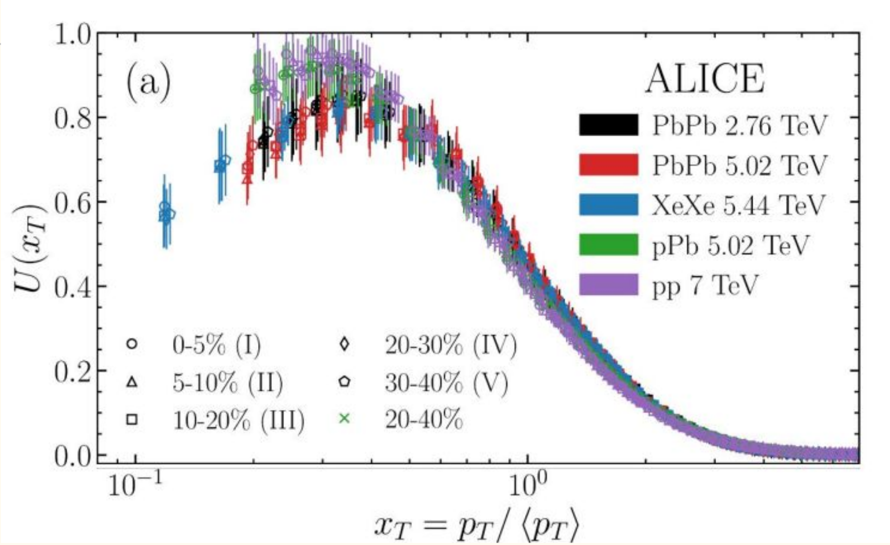




small systems

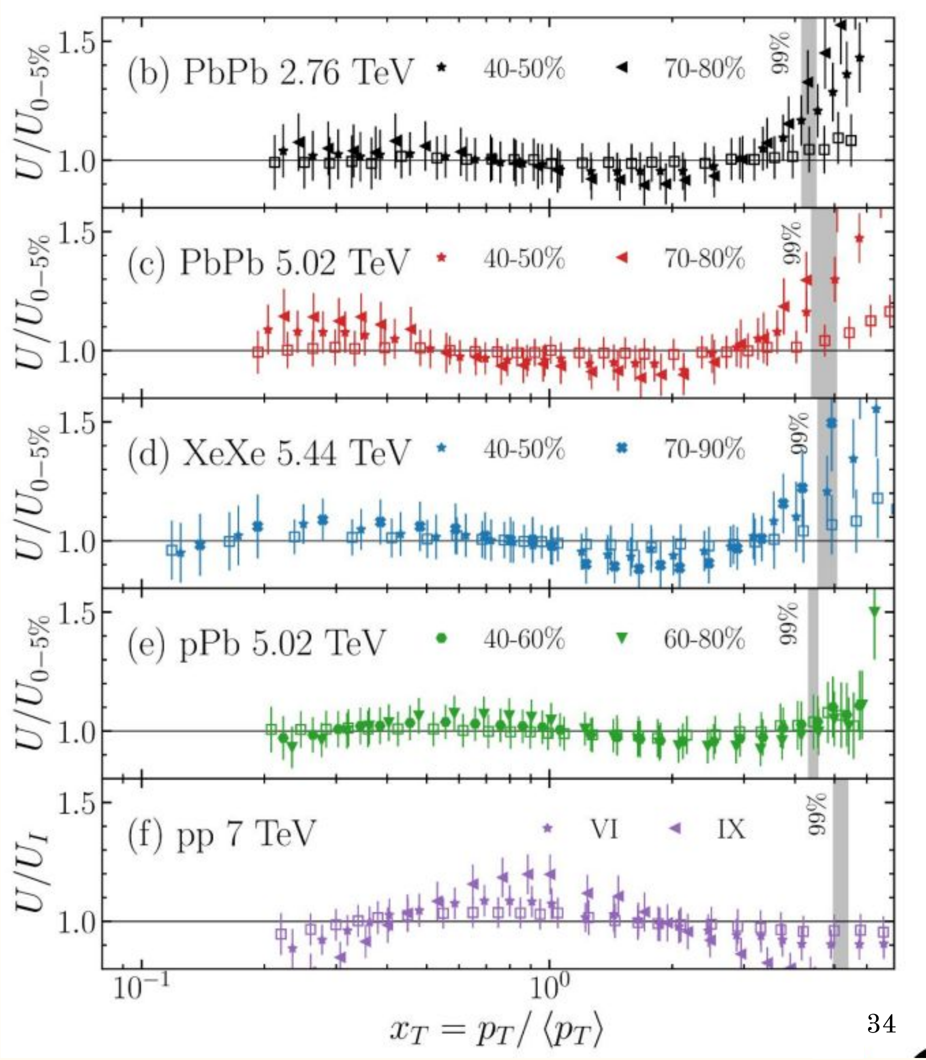
- pPb: universal shape up to $x_T = 5$. *(within the error bars)*
- pPb has the same universal shape as the large systems, HOWEVER, *within the LARGE error bars.*

$U(x_T)$ in experimental data



small systems

- pp: no universal shape.
- Different physics? No collectivity?



Summary

- A universal scaling $U(x_T)$ was identified, and validated through both experiments and hydrodynamic simulations.

- ALICE data show universality in Pb-Pb, Xe-Xe, and p-Pb collisions, but not in p-p collisions. The universal behavior breaks at high pT, suggesting a transition out of the hydrodynamic regime.

- These findings support the formation of a QGP in p-Pb collisions and potentially in high-multiplicity p-p events, however further experimental precision is needed. (smaller error bars).

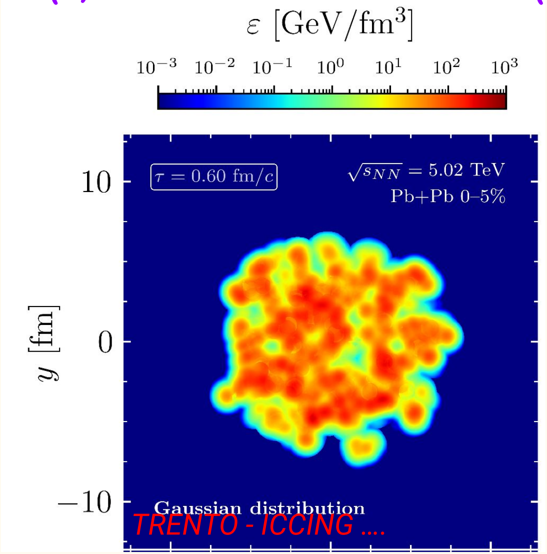
- $U(x_T)$ opens avenues for studying QCD matter in extreme conditions, exploring lower-energy collisions, the QCD critical point, and collective effects in other systems.

THANK YOU FOR YOUR ATTENTION!

Backup Slides

Standard model of relativistic collisions

(1) Initial Conditions (QGP)



pre-equilibrium phase

(2) Hydro Evolution

$$\partial_\mu T^{\mu\nu} = 0 \quad T^{\mu\nu} = T_0^{\mu\nu} - \Pi^{\mu\nu}$$

Ideal → $$T_0^{\mu\nu} = (e + P)u^\mu u^\nu - g^{\mu\nu} P$$

Viscous → $$\Pi^{\mu\nu} = \eta\sigma^{\mu\nu} + \zeta\Delta^{\mu\nu}\nabla_\lambda u^\lambda + \mathcal{O}(\partial^2)$$

shear *bulk*

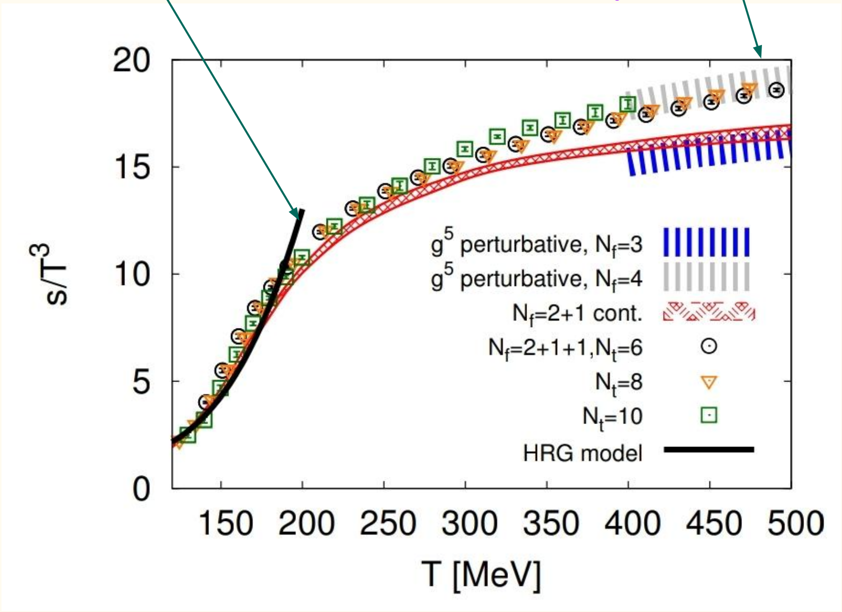
(3) Hadronization:

When expanding, temperature and densities decrease, until the moment of emitting particles: Cooper-Frey, URQMD, AfterBurner …...
then we have a spectrum of emitted particles

Lattice QCD

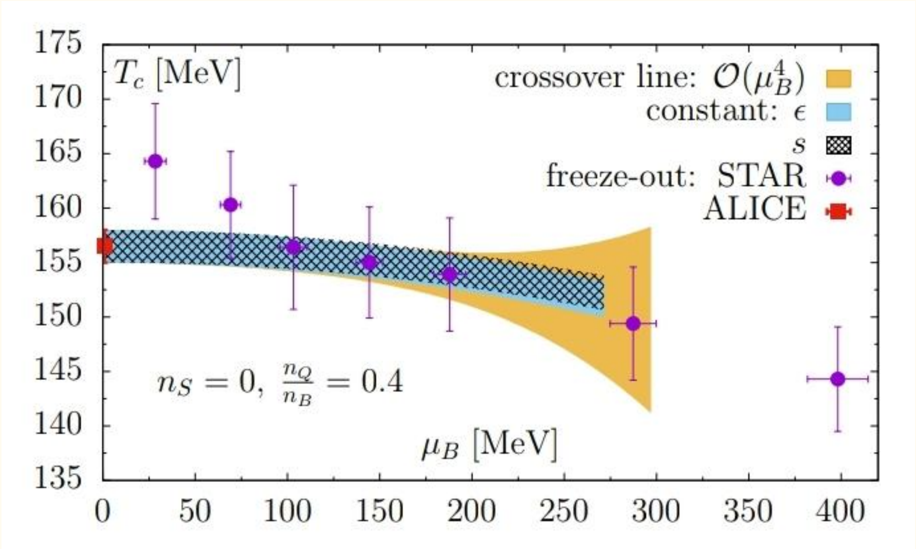
HRG

Perturbative QCD



S Borsányi, Nucl. Phys. A, 904 (2013), 270

HotQCD Collaboration, PLB 795, 15 (2019)



Bayesian and Spectra