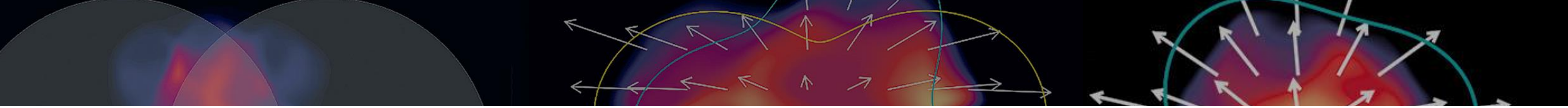


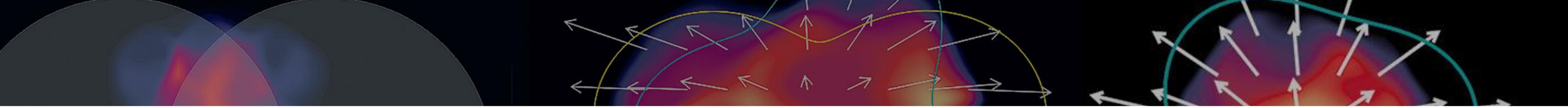
Soft probes of collectivity, from hadrons to nuclei

Nicolò Valle, INFN, Sezione di Pavia

EuNPC

CAEN, September 22th 2025

INFN
Istituto Nazionale di Fisica Nucleare



Soft probes of collectivity, from hadrons to nuclei

- Collectivity in heavy-ion physics
- Importance of varying system size

Eu N P C

CAEN, September 22th 2025

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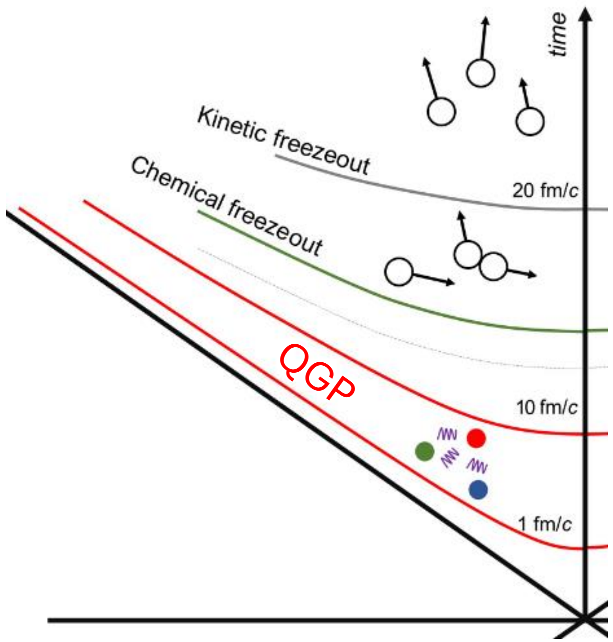
Soft probes, in large and small colliding systems

Soft probes in heavy-ion collisions:

- Study of collective phenomena
- Test statistical limits of particle production
- Disentangle hadronic phase effects



Hadrochemisty

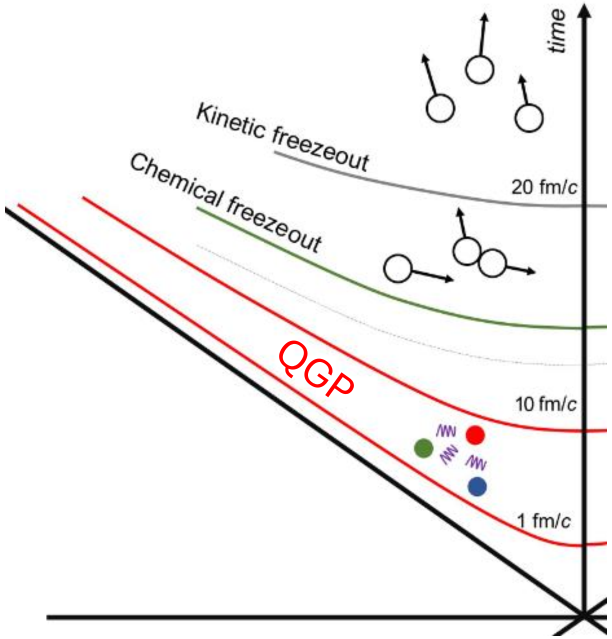
Rescattering
Coalescence

Particle flow

Soft probes, in large and small colliding systems

Soft probes in heavy-ion collisions:

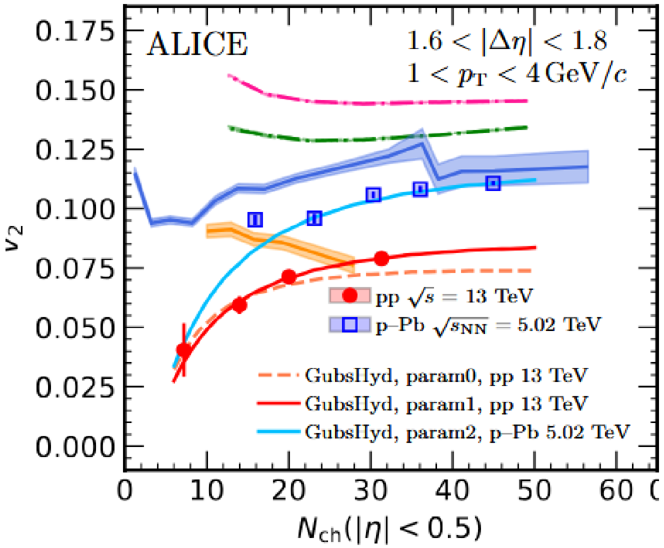
- Study of collective phenomena
- Test statistical limits of particle production
- Disentangle hadronic phase effects



Small systems

- Multi-parton interactions needed to explain multiplicity
- Cross talk needed to explain p_T spectra at the LHC
- Parton density fluctuations in the initial stages

2308.16591



→ Exploit small colliding systems for a deeper understanding of AA collisions

Collective flow

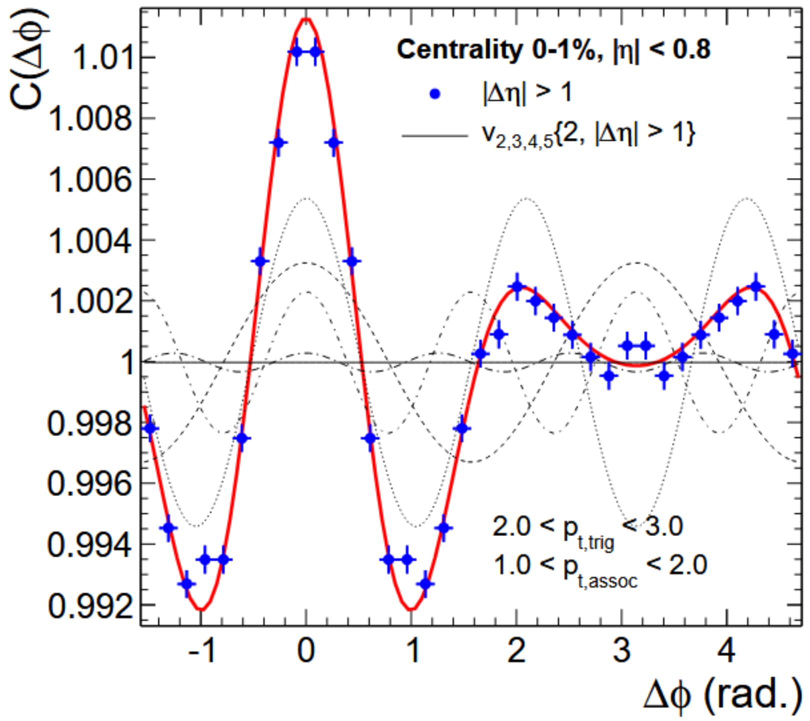
$$\frac{dN}{d\vec{p}} \propto \left[1 + 2\sum_n v_n(\vec{p})\cos(n(\phi - \psi_n))\right]$$

Anisotropic flow

Interacting matter → the initial spatial anisotropy reflects on anisotropy of final momenta

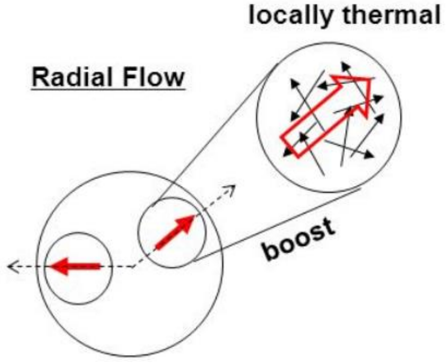
Sensitive to shear viscosity, entropy, …

1105.3865



Radial flow

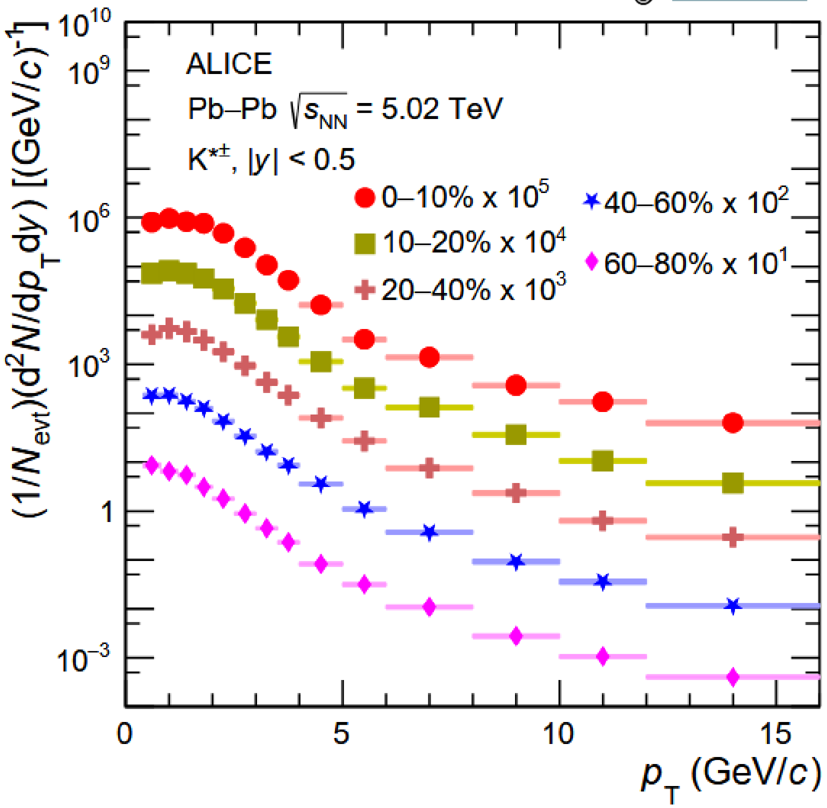
- Common expansion velocity of particles
- Translates into modification of p_T spectra

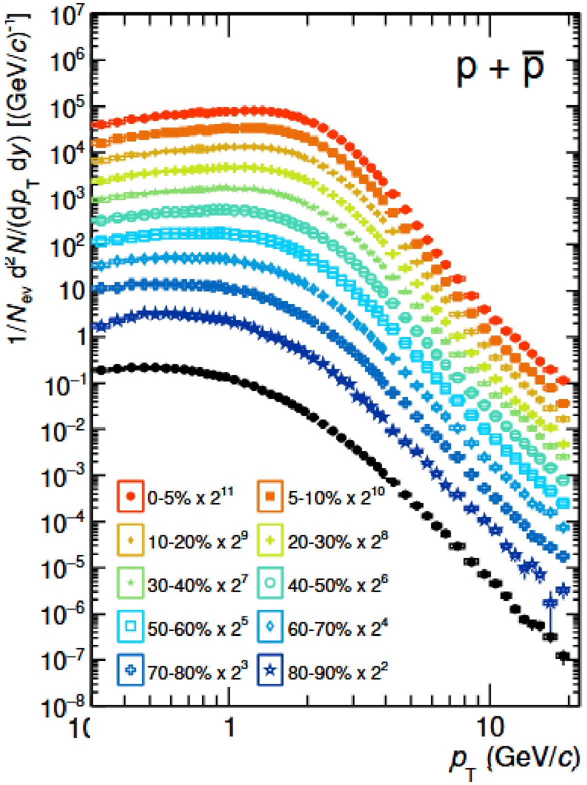


→ low bulk and shear viscosity lead to large radial and anisotropic flows

- Spectra get harder going from peripheral to central A-A collisions
- Higher effect for heavier particle species
- Well reproduced by hydro calculations (at least at low p_T)

2308.16119





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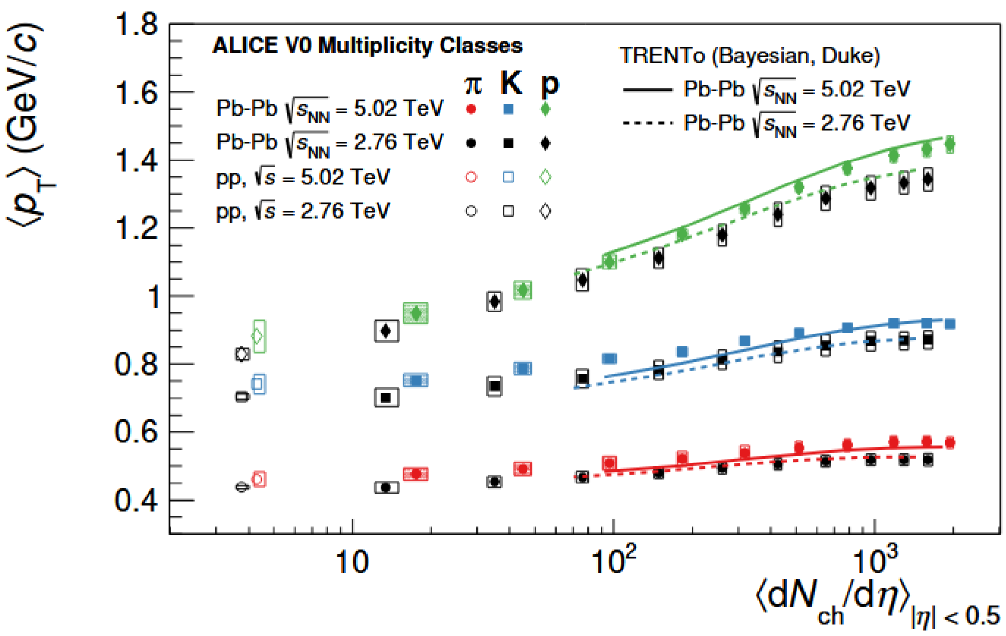
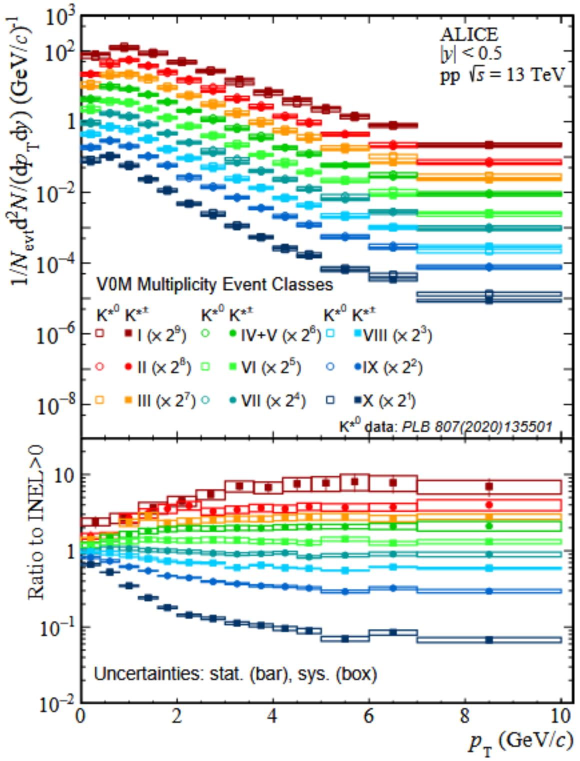


Radial flow, small systems

- ❑ Hardening of p_T spectra well established also in pp and p-Pb
- ❑ Different measurements consistent with the presence of a short hadronic phase in small systems .. ?



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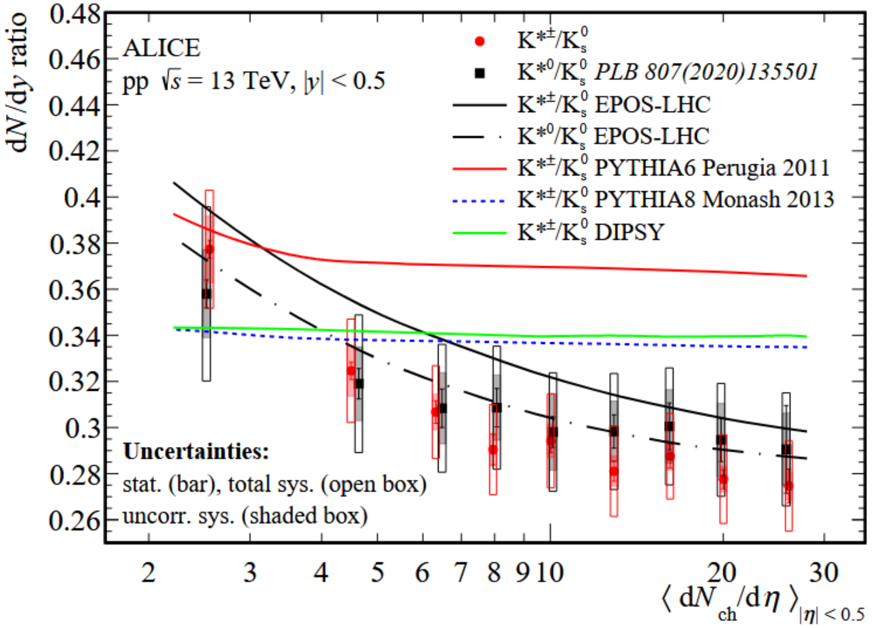
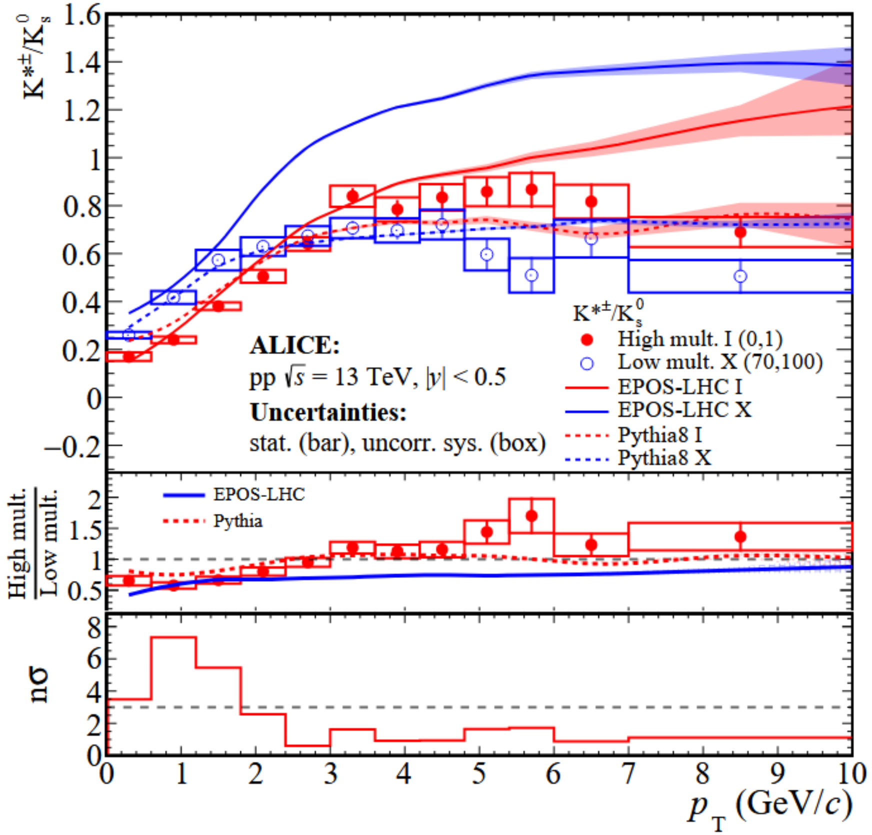
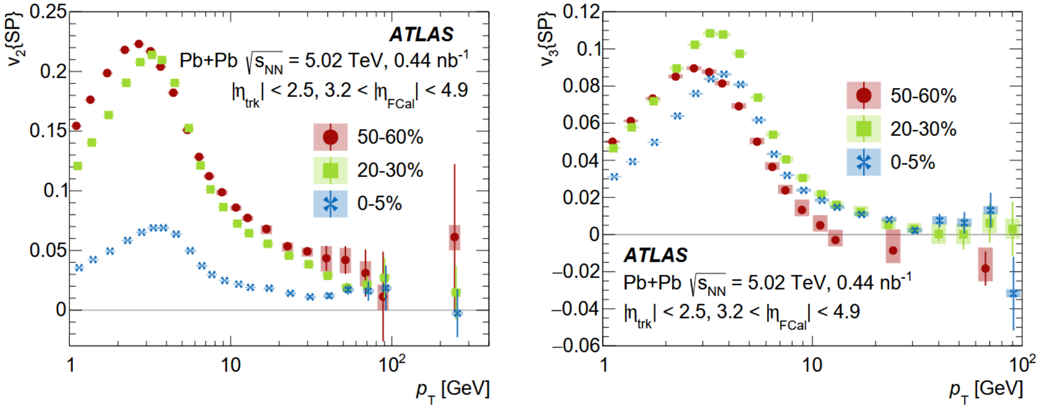




Anisotropic flow

- A well established observation
- Higher coefficients for semi-peripheral collisions (higer eccentricity)
- Reproduced by hydronicamic calculation with almost perfect fluid
- Recent results showing $v_n \neq 0$ up to very high p_T

2412.15658



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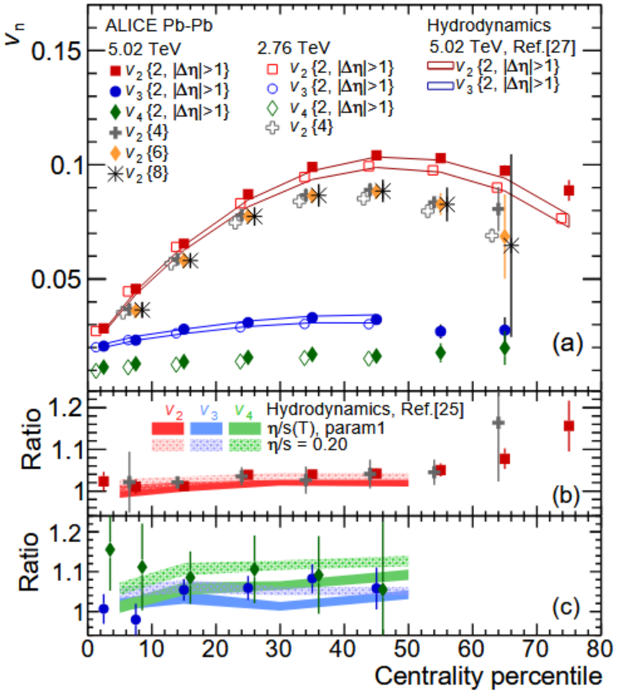
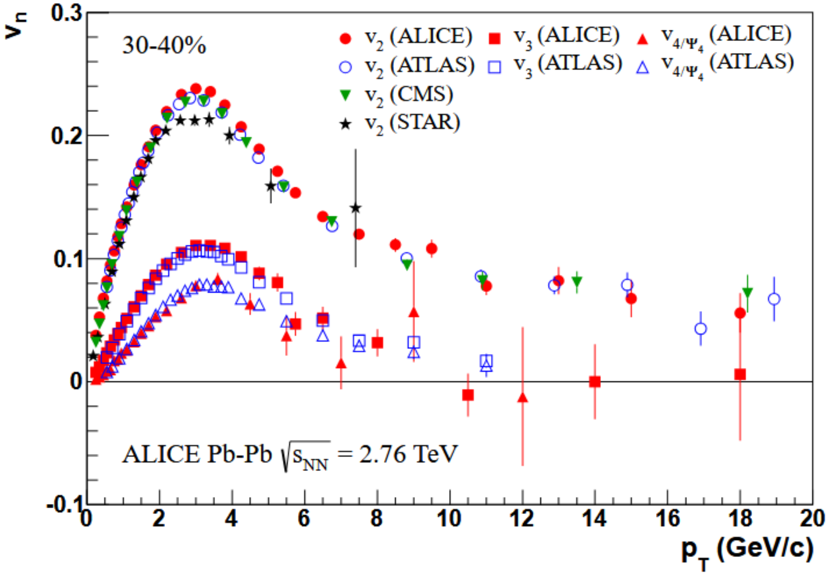
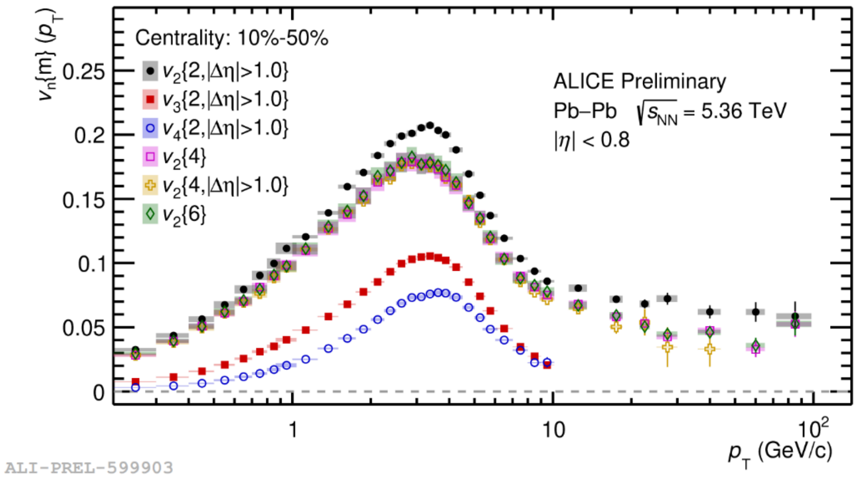


1205.5761



ALICE prelim, QM2025

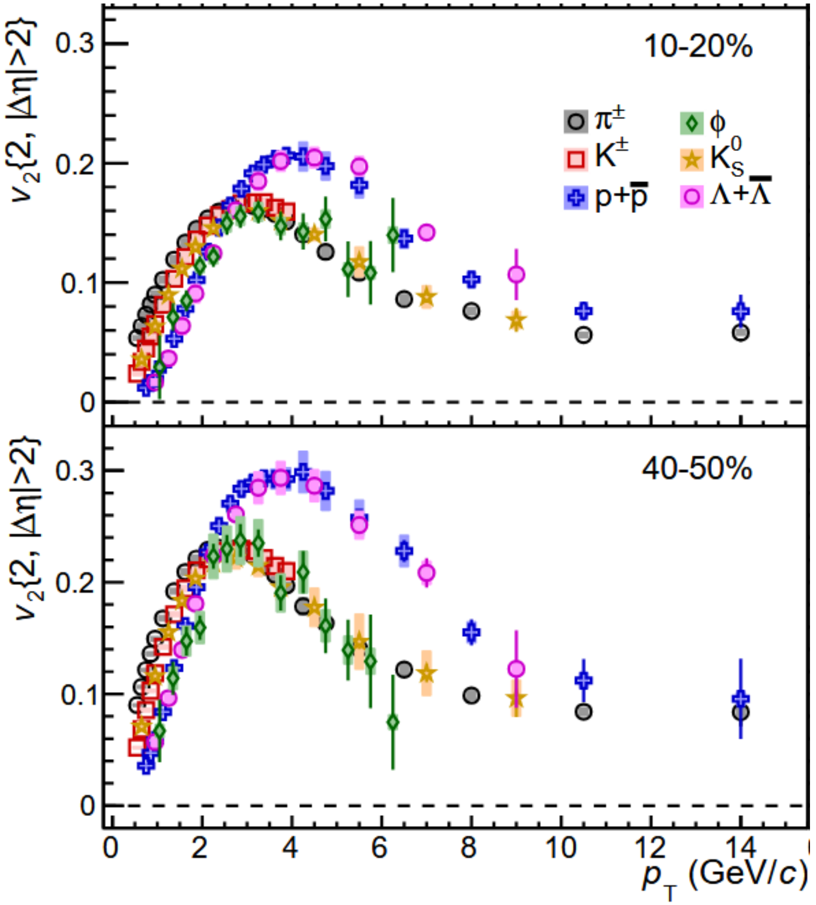


Anisotropic flow

- ❑ Mass ordering at low p_T
- ❑ Baryon/meson grouping at higher p_T ← quarks recombine

- ○ Mass ordering verified alsof for light nuclei

1805.04390



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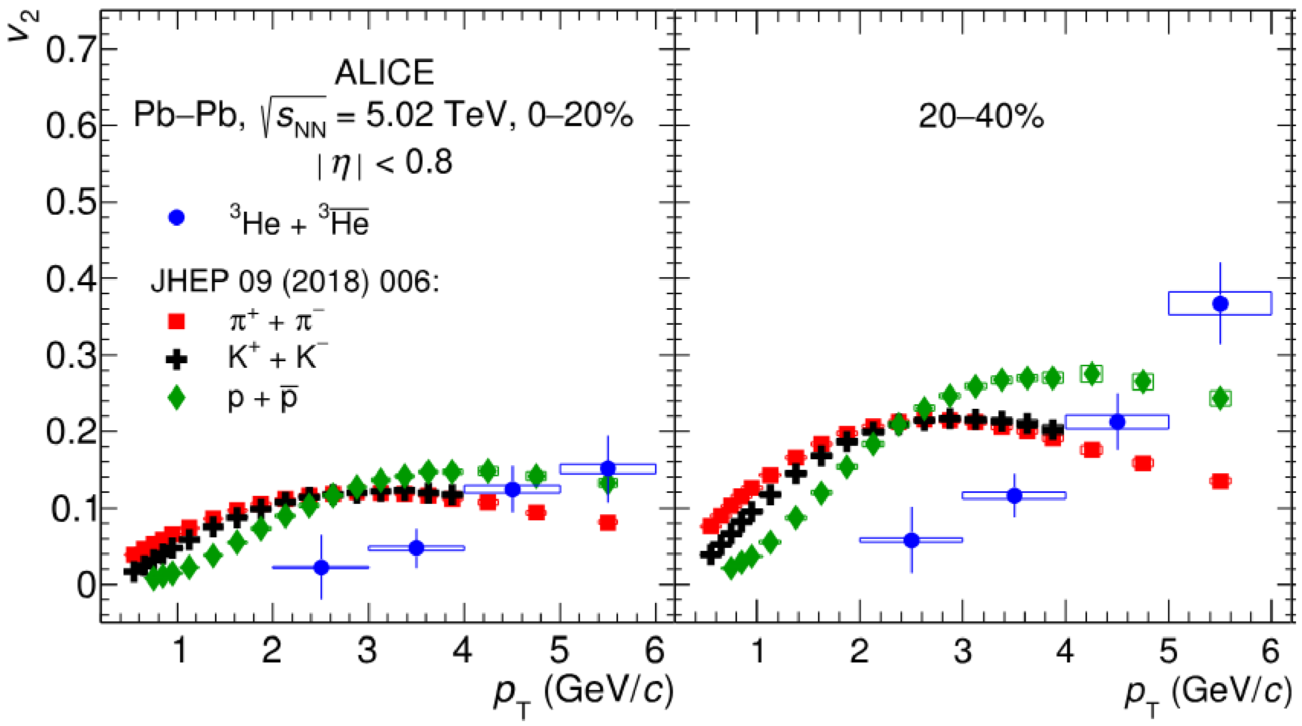
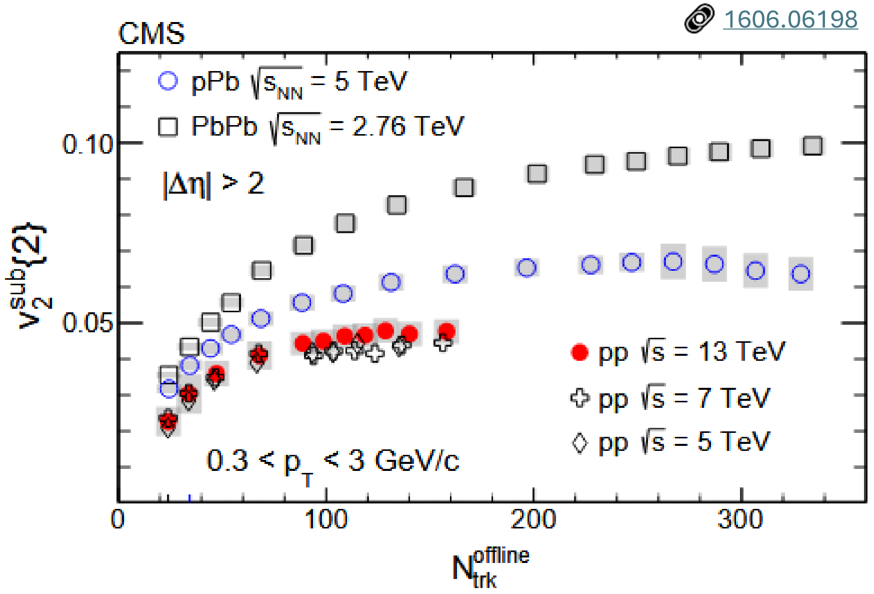


Anisotropic flow, small systems

- $v_2 > v_3 > v_4 \neq 0$ in all colliding systems
- Mass ordering as evidence of radial flow

1606.06198



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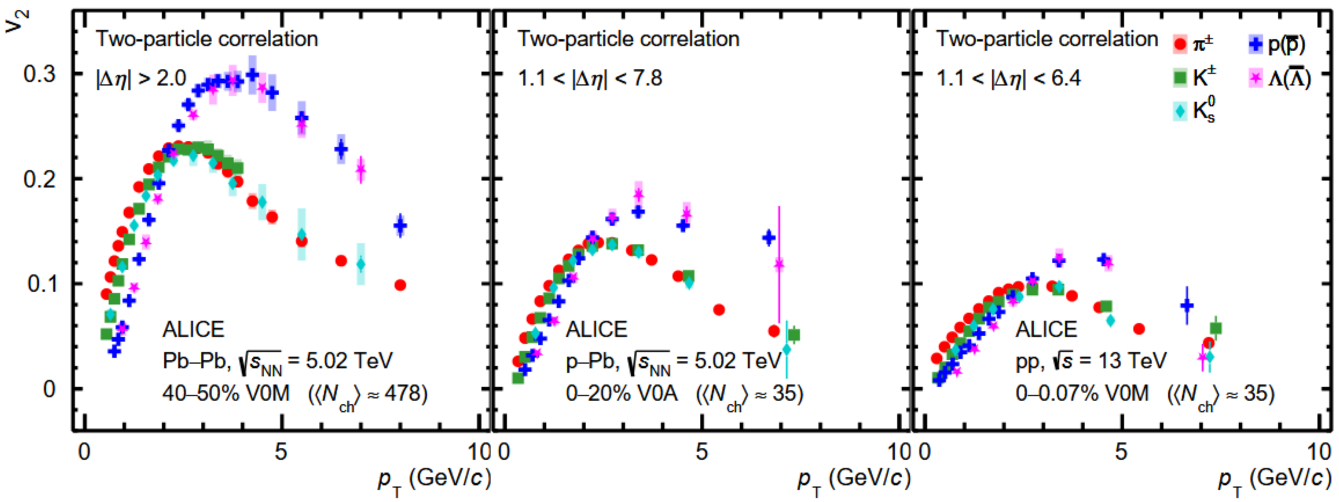

Anisotropic flow, small systems

- $v_2 > v_3 > v_4 \neq 0$ in all colliding systems
- Mass ordering as evidence of radial flow
- v_3, ... sensitive to parton density anisotropy and similar across systems

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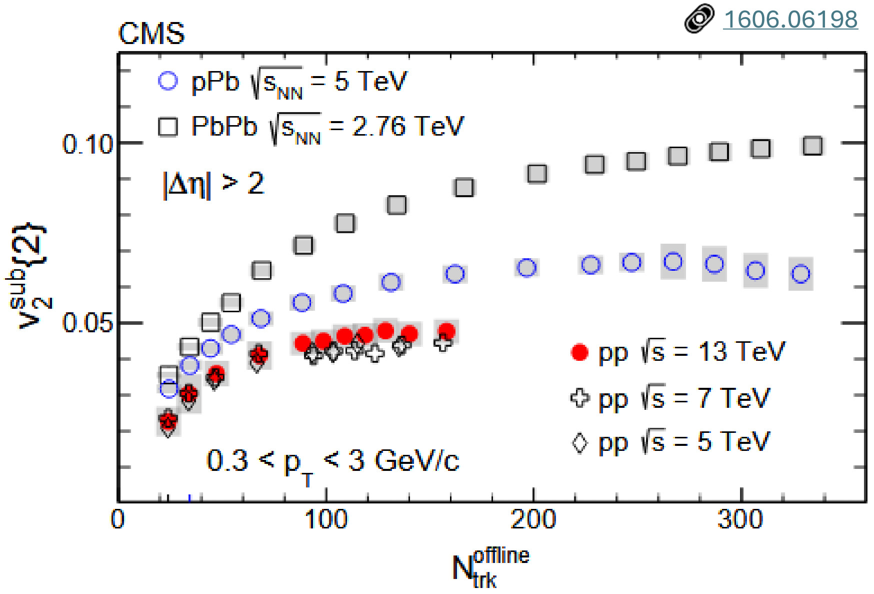

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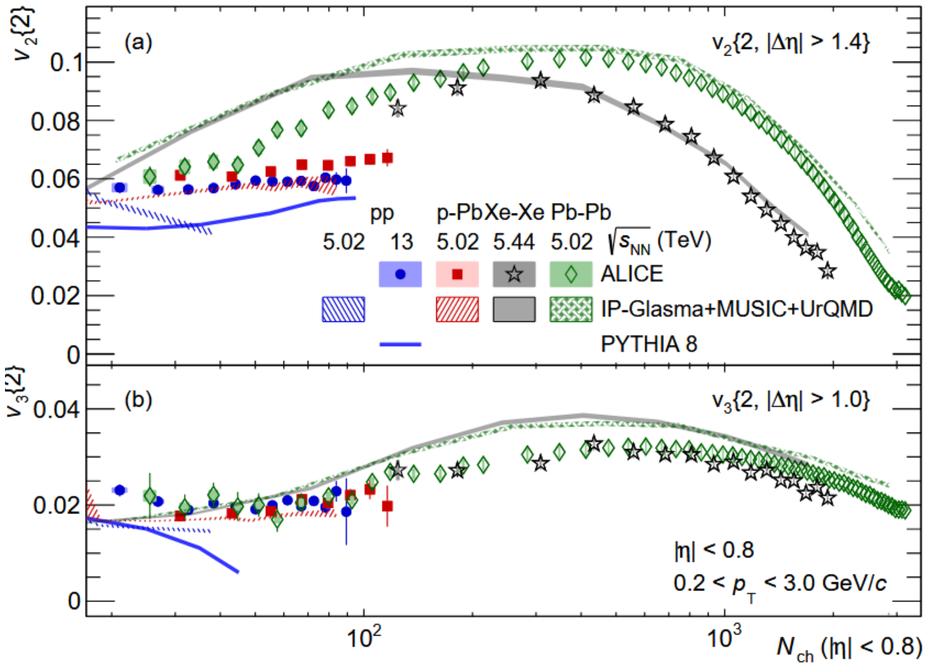

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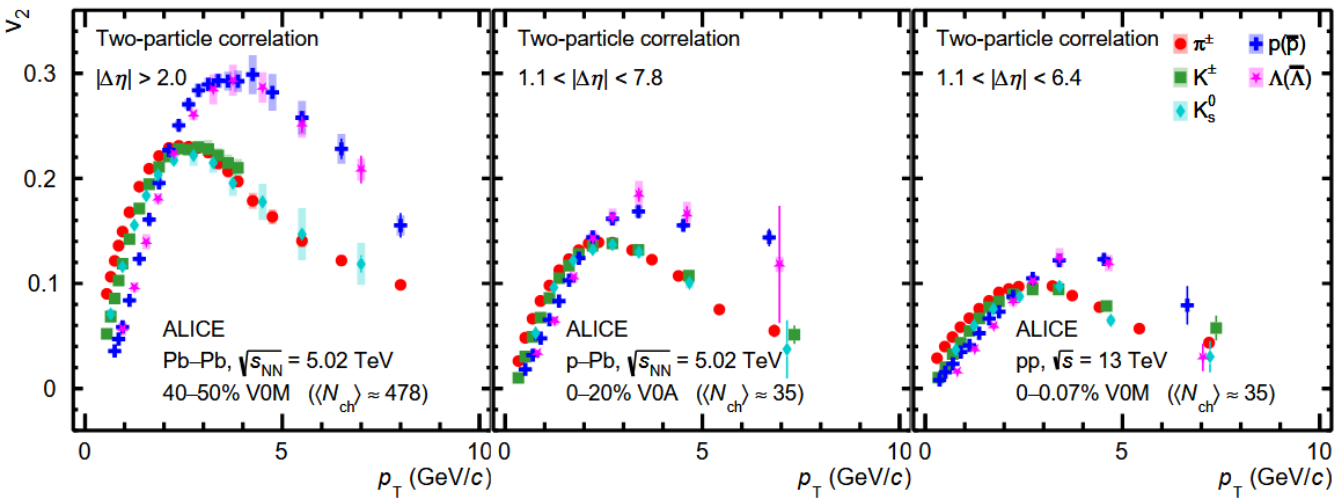
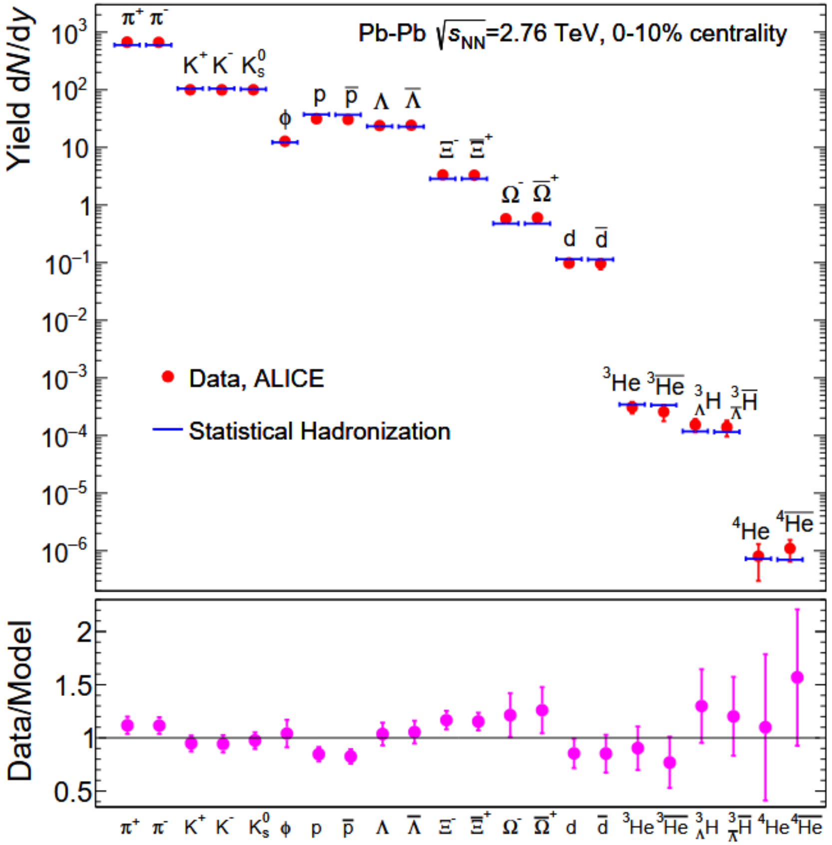
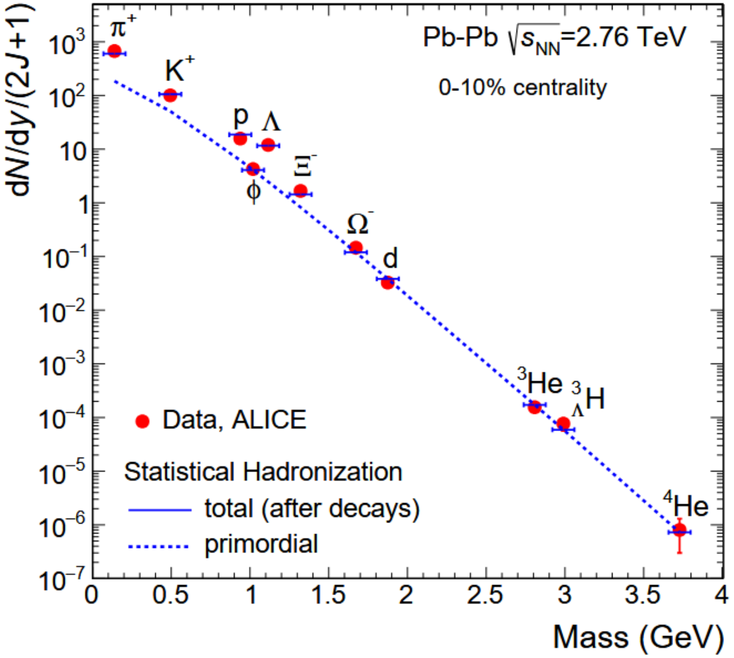


Hadrochemistry

- Statistical thermal models predicts light-flavor hadron abundances over orders of magnitude
- Hot hadron-resonance gas in thermal equilibrium
- At LHC: $\mu_B \simeq 0,\ T_{cf} \simeq 155\ MeV$

1710.09425 / Nature





Hadrochemistry

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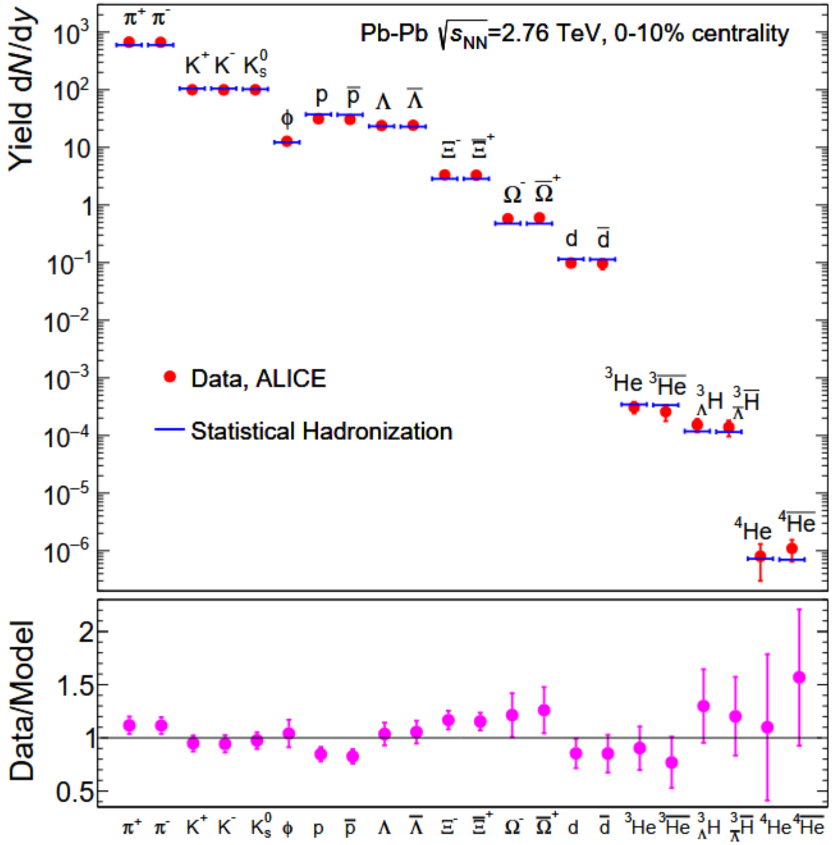
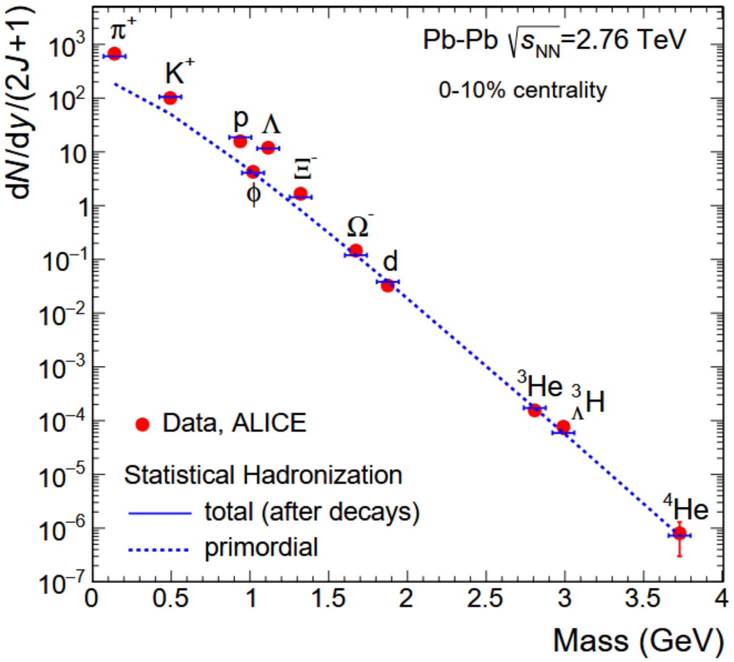
1710.09425 / Nature

The yields depend on M and T

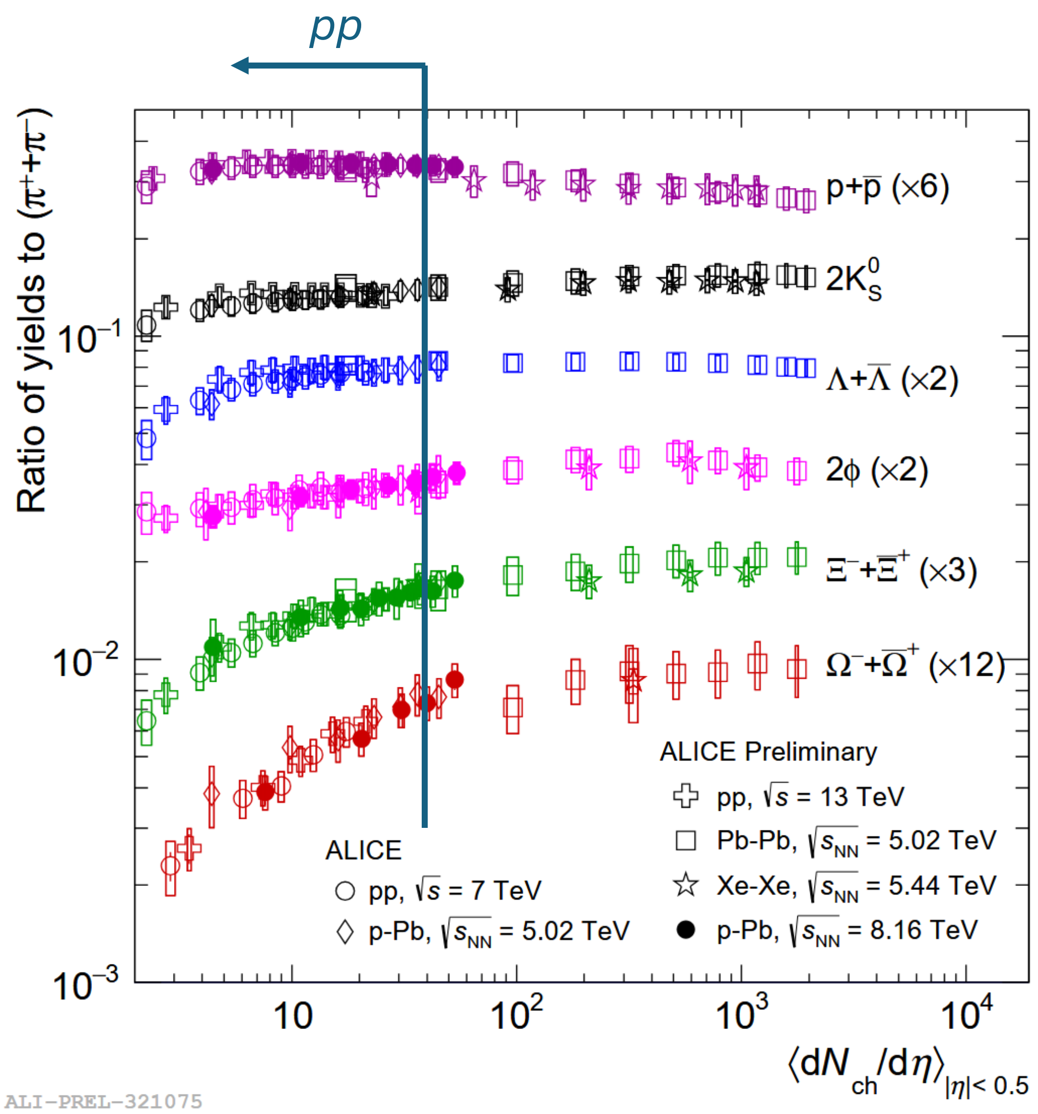
Loosely bound nuclei production compatible with thermal production





Particle production

- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content
- Smooth evolution of particle production with charged-particle multiplicity across *pp*, *p*-Pb, Xe-Xe, and Pb-Pb collisions
  - Hadron chemistry is driven by the multiplicity (system size)

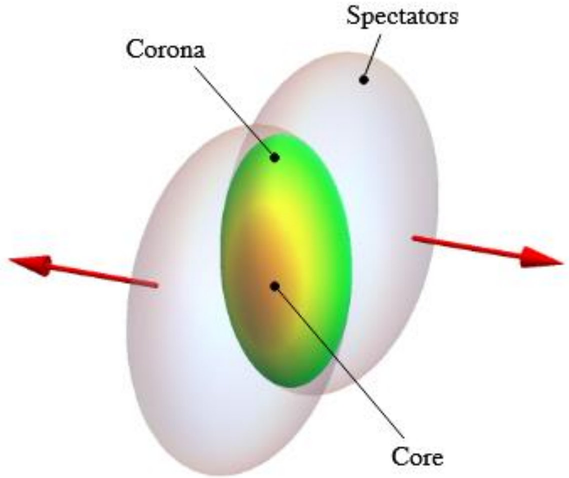


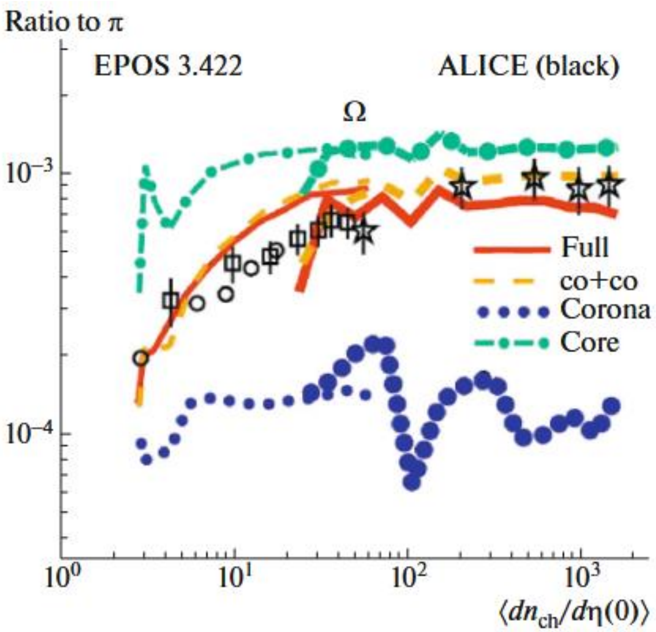
Particle production

Core: high density, QGP, thermal hadronization

Corona: scatterings, string fragmentation, lower density, hadronization in vacuum

2003.13757





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Particle production

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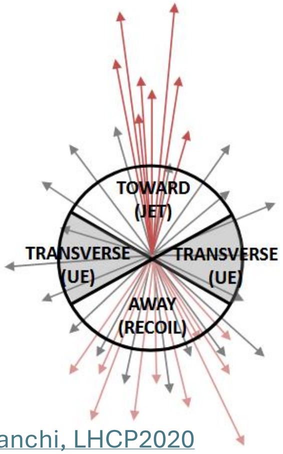
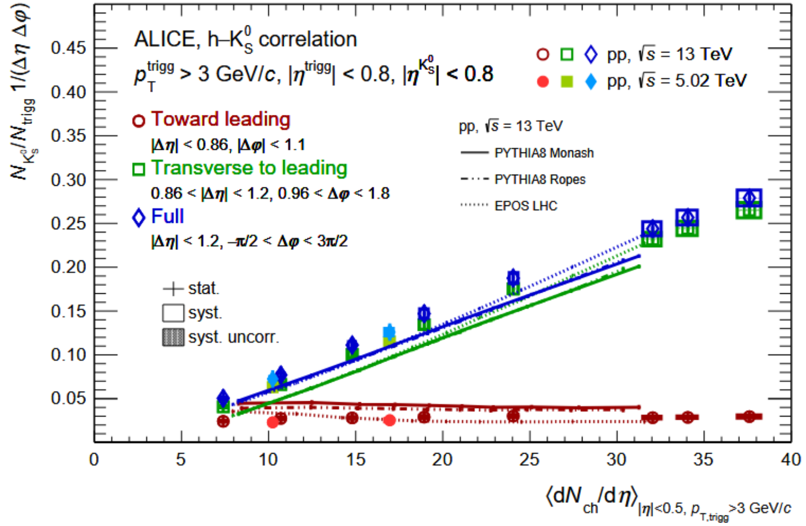


L.Bianchi, LHCP2020



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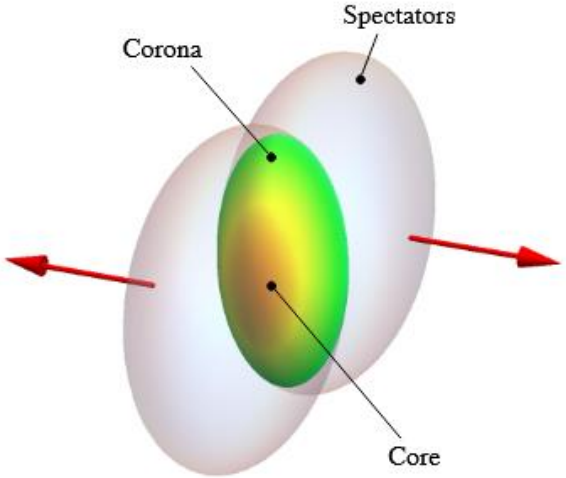

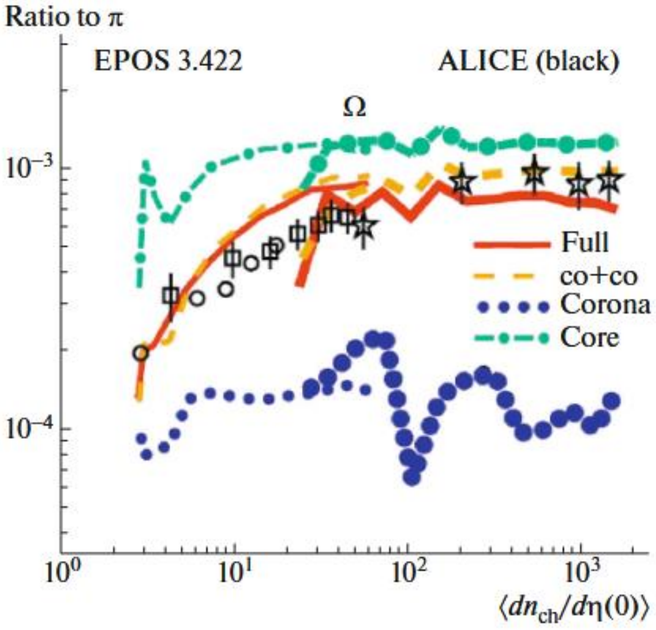

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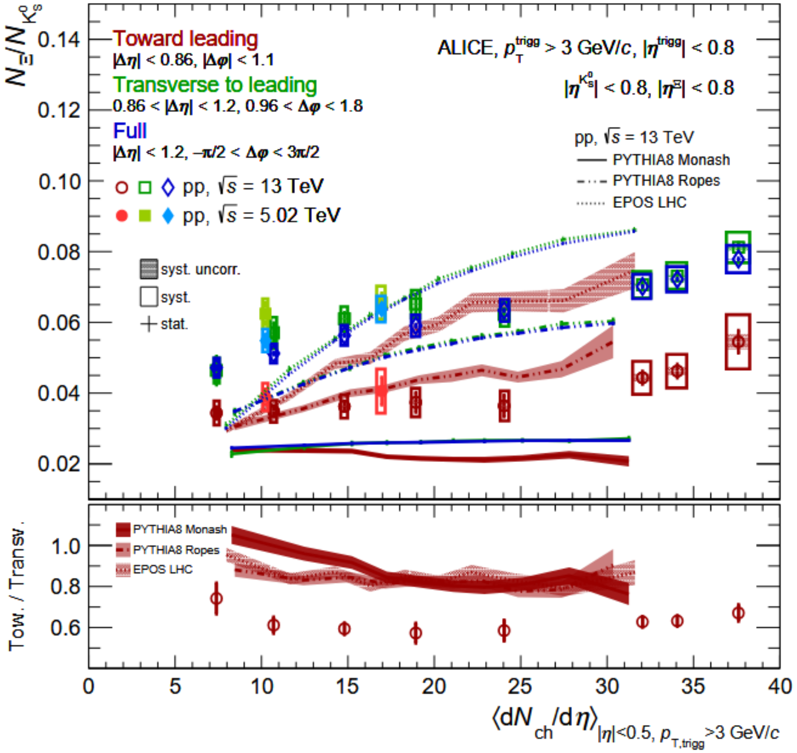
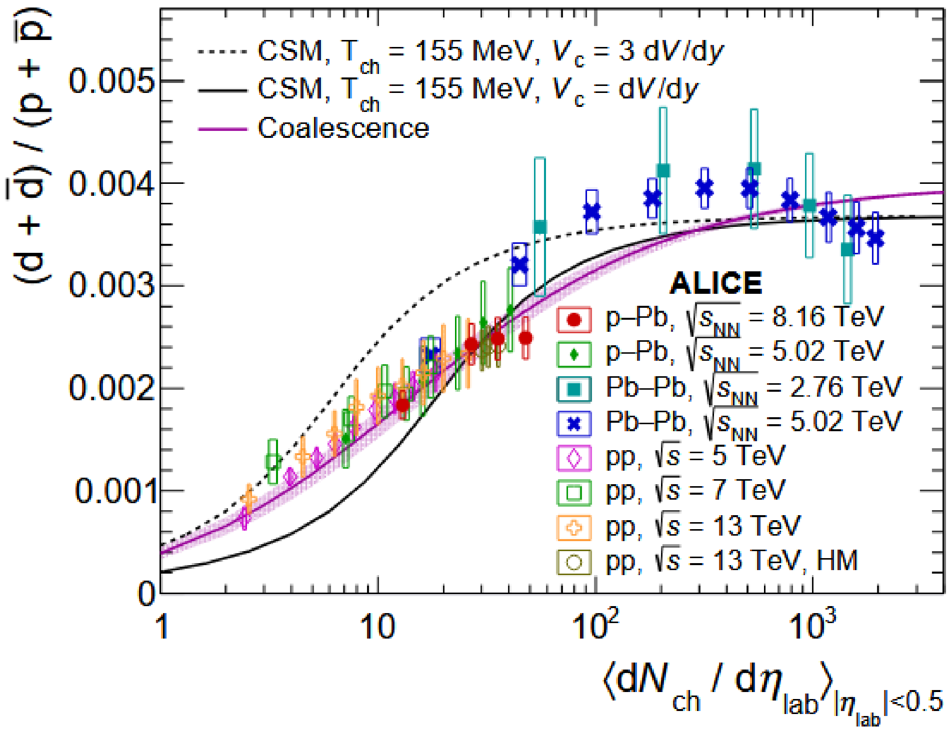
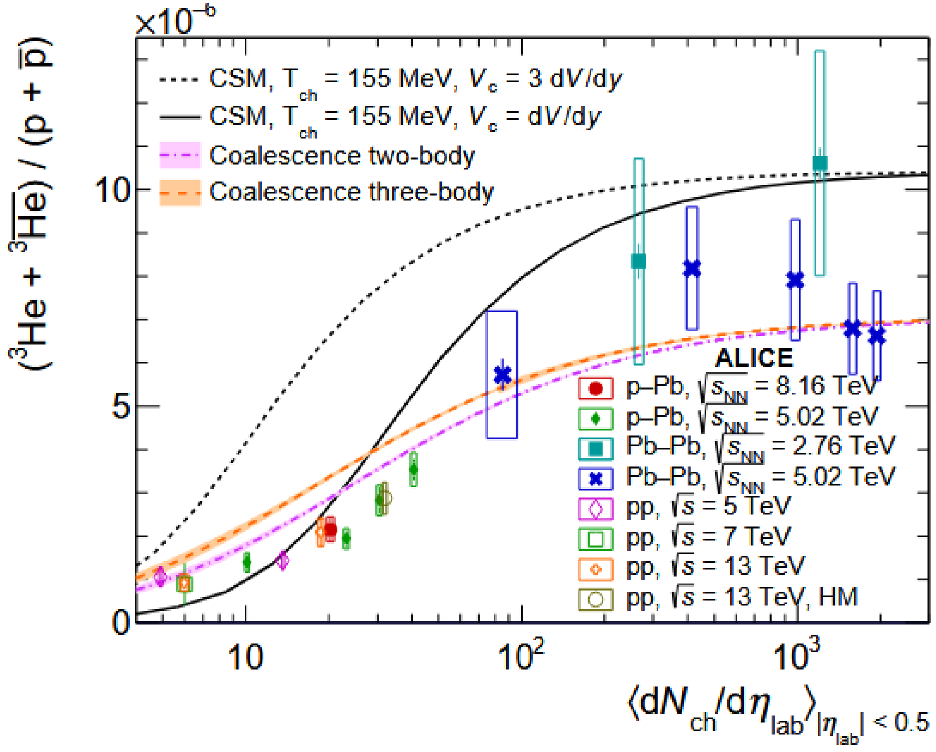


Particle production, nuclei

- d, ^{3}He and ^{3}H significantly enhanced at higher multiplicity
  - Canonical suppression ?
  - Coalescence probability at kinetic freeze-out ?

2212.04777



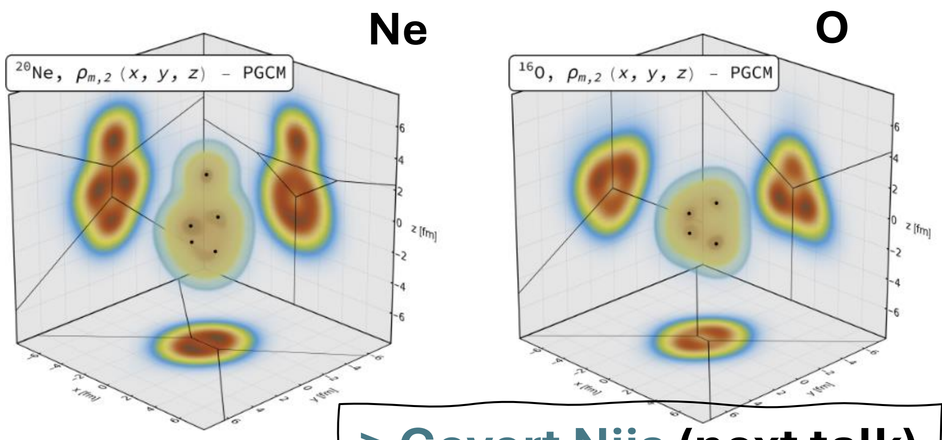


OO, NeNe

Hydrodynamic calculations employ QGP equation of state to predict v_n

v_2 sensitive to deformed shape of the nucleus

Common initial pictures from experiments, look like a QGP

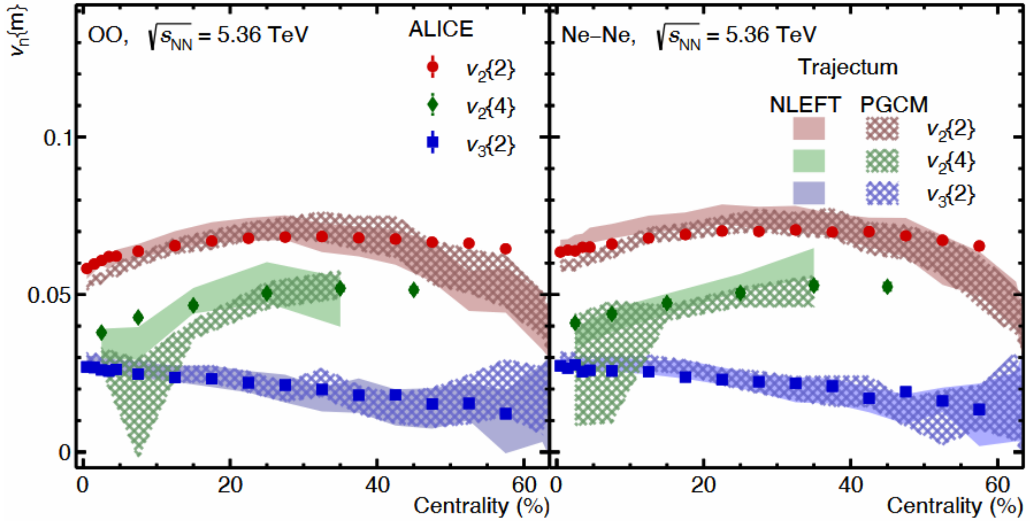


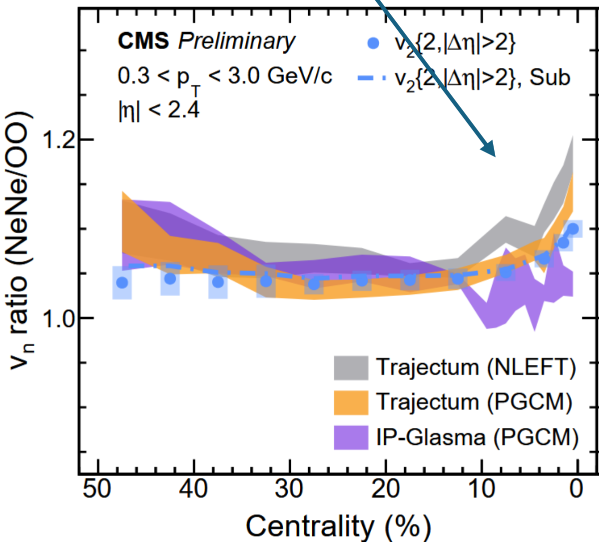
> Govert Nijs (next talk)

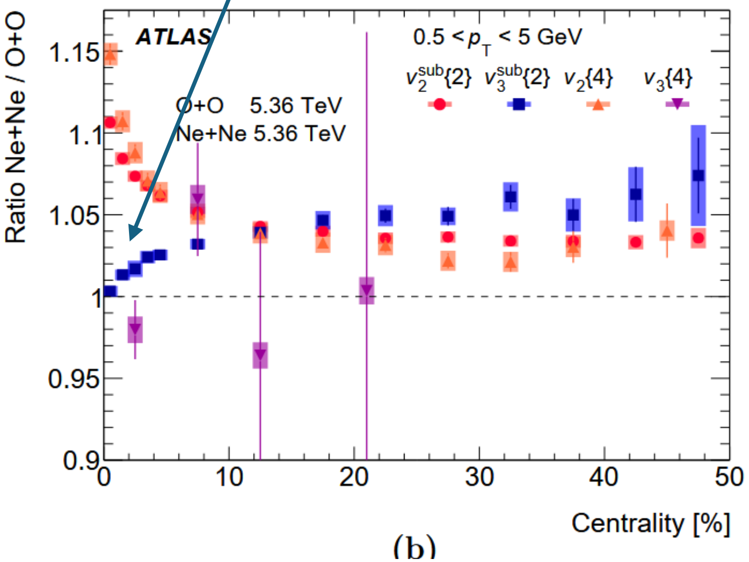
Results
- ALICE
- CMS
- ATLAS

Ne, O similar in size... ratio driven by different shape?

Similar triangular flow between the two systems







Conclusions

- Studying soft probes in heavy-ions:
  - A color-deconfined thermalized medium is produced in heavy-ion collisions at the LHC
  - It's an almost perfect fluid expanding hydrodynamically
  - It undergoes chemical freezeout at $\sim 150 - 160$ MeV
  - Nucleosynthesis is consistent with thermal production
  - In small systems....
    - Hadrochemistry and collectivity at high-multiplicity match what is observed in A-A
    - Challenging scenario for any theoretical model

Follow the HI session for more

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Thank you

backup