Soft probes of QGP

An overview of recent results at the LHC

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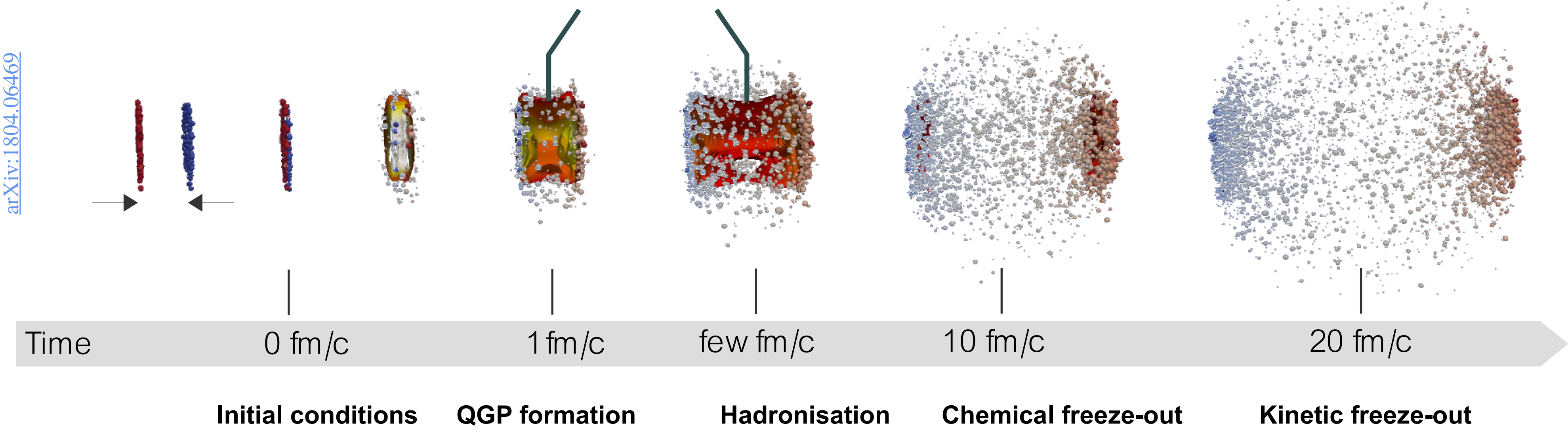
IJCLab Orsay, France

Study of heavy ion collisions at the LHC

Quark-gluon plasma (QGP): A hot and dense medium of deconfined partons

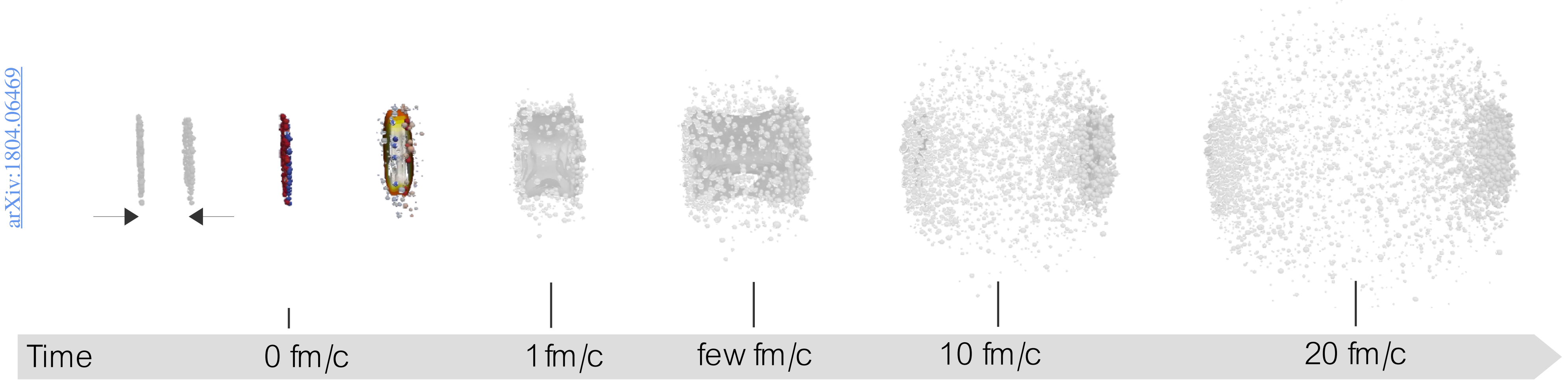


arXiv:1804.06469

More than **99% of the produced particles** have a transverse **momentum lower than 2 GeV/*c***

→ These **soft particles** are of major interest for the characterization of the QGP

Initial conditions



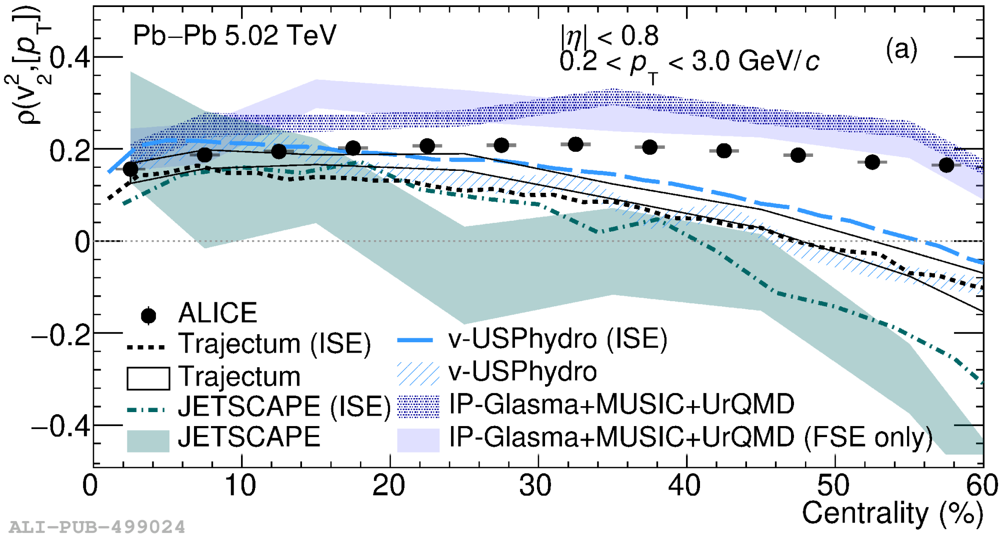
Investigating the initial stages with correlations

Study of the correlation between the initial shape of the fireball (v_2) and its size ($[p_T]$):

$$\rho_2(v_2^2, [p_T]) = \frac{\mathrm{cov}(v_2^2, [p_T])}{\sqrt{\mathrm{var}(v_2^2)}\sqrt{\mathrm{var}([p_T])}}$$

- Positive correlation between the shape and the size of the fireball
- **Better description with** models using **IP-Glasma initial conditions**
- T_RENTo-based models display a strong centrality dependence (Trajectum, JETSCAPE, v-USPhydro)

ALICE, arXiv:2111.06106



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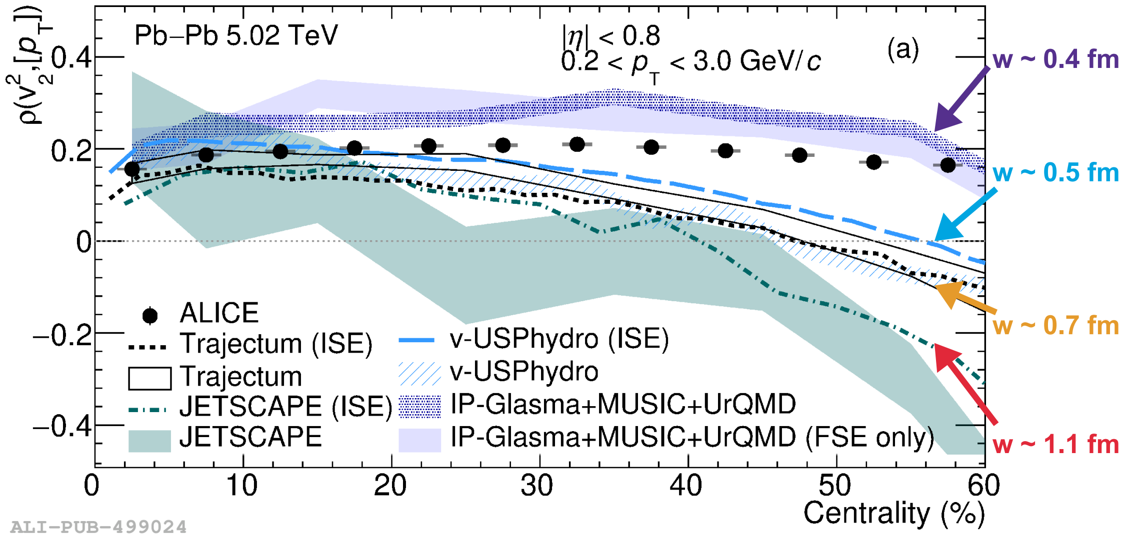

- Positive correlation between the shape and the size of the fireball
- **Better description with** models using **IP-Glasma initial conditions**
- T_RENTo-based models display a strong centrality dependence (Trajectum, JETSCAPE, v-USPhydro)

- The **difference between IP-Glasma and T_RENTo models** is mainly **driven by different nucleon size** (w)

→ ALICE measurements favors a **nucleon width parameter of ~0.4 fm** (supported by recent theoretical calculations [1][2])

→ This is **in contradiction with state-of-the-art Bayesian analyses** (from which are extracted QGP's transport coefficients)

[1] arXiv:2111.02908 [2] arXiv:2206.13522

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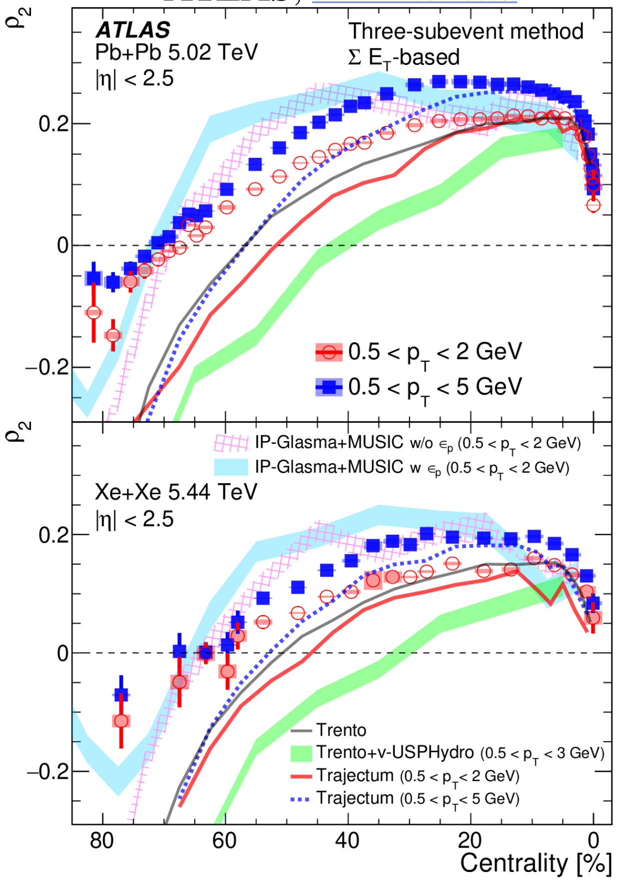
- **Same measurement** was also performed **in ATLAS** in Pb-Pb and Xe-Xe
- Discrepancy between IP-Glasma and T_RENTo was also observed

  → **Better description with models using IP-Glasma initial conditions**

ATLAS, arXiv:2205.00039



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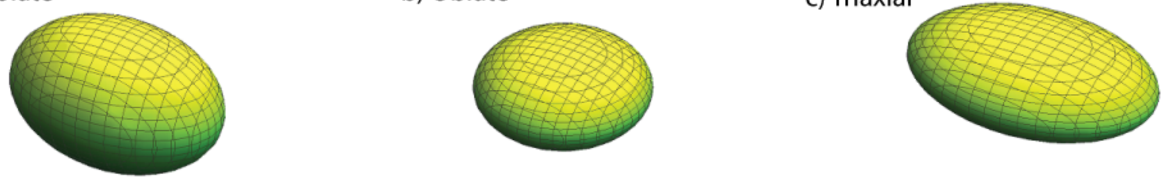
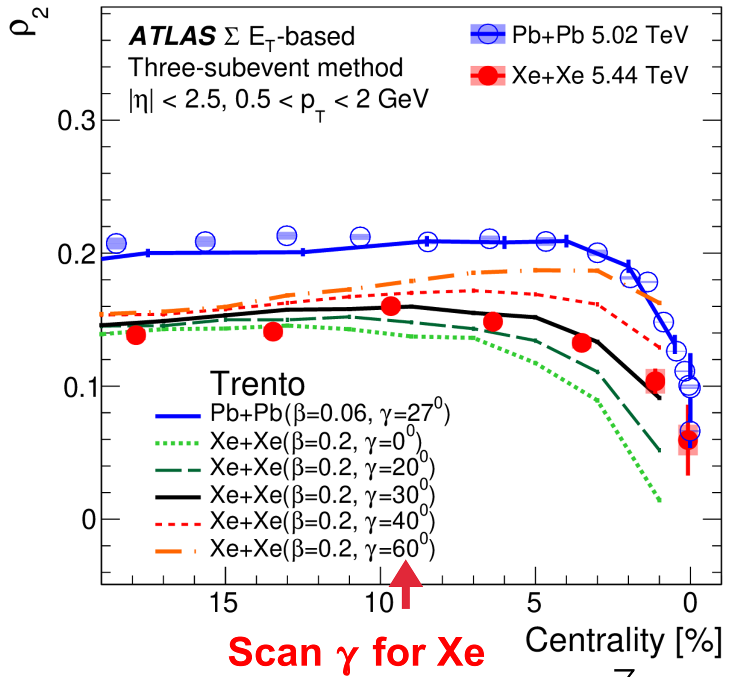
- **Same measurement** was also performed **in ATLAS** in Pb-Pb and Xe-Xe

a) Prolate b) Oblate c) Triaxial



ATLAS, arXiv:2205.00039



- Investigate the sensitivity of $\mathbf{T_RENTo}$ to the nuclear deformation parameter γ_{Xe} (triaxiality) in central collisions
  - **Large sensitivity to γ_{Xe}**
  - ATLAS measurement favors a **triaxial Xe** (γ_{Xe}~30°)

Anisotropic flow fluctuations

Fluctuations in the positions of nucleons in the incident nuclei influence the QGP expansion

→ The elliptic flow fluctuations can provide an insight on the early-stage dynamics of the collision

→ Fluctuation behavior is studied via the multi-particle cumulant values of v_2:

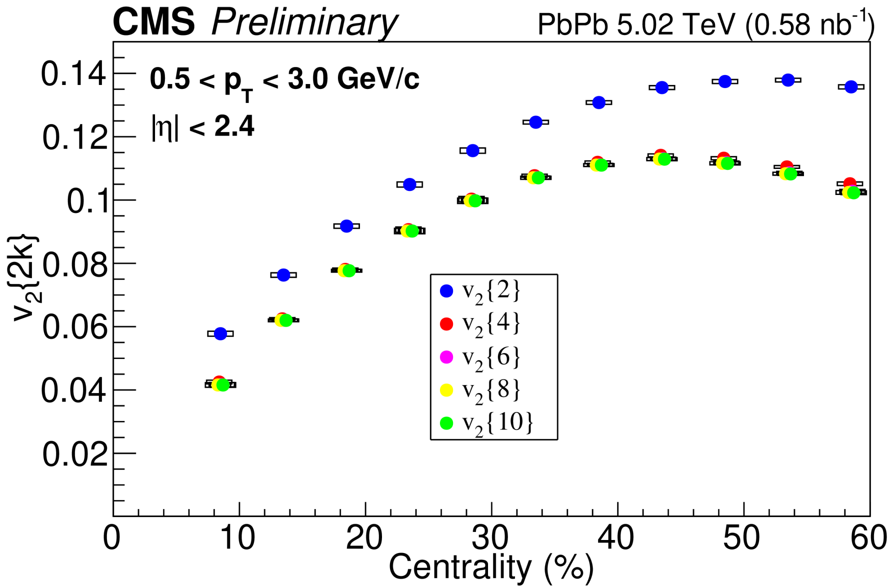
CMS-PAS-HIN-21-010

Measurements of v_2 from 2- to 10-particle cumulant values:

- **First measurement of $v_2\{10\}$**
- Gap between $v_2\{2\}$ and higher order cumulants

→ Consequence of non-Gaussian properties of the flow fluctuations

→ This non-Gaussian behavior can be quantified by the **skewness**, **kurtosis** and **superskewness**



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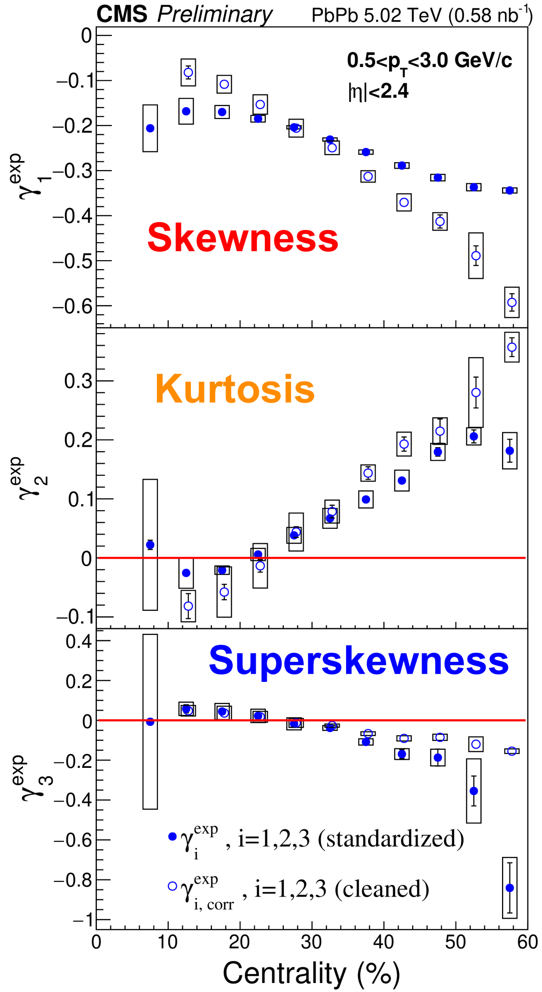
New constrain for hydrodynamic models



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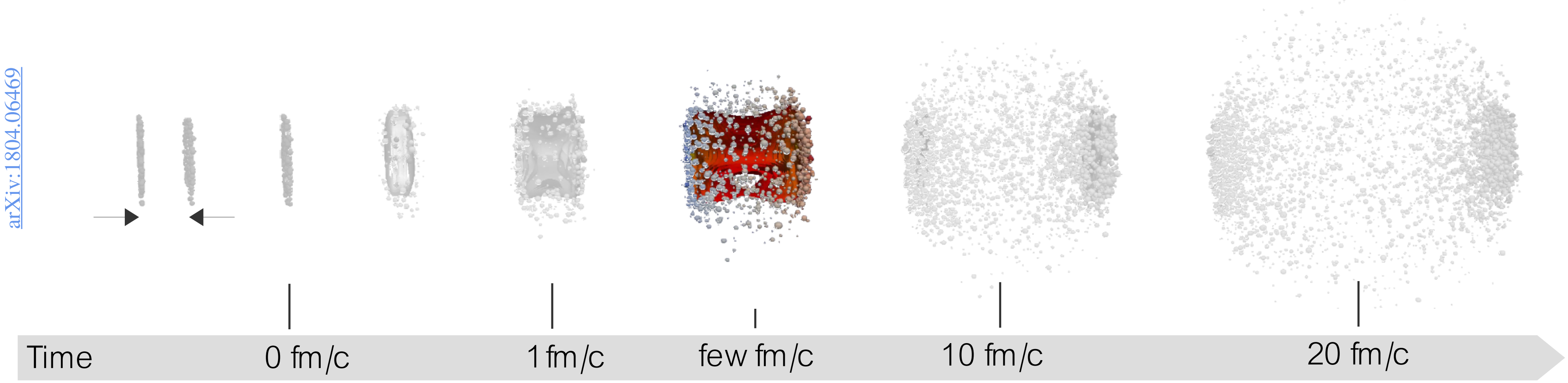
Hadronisation & small systems

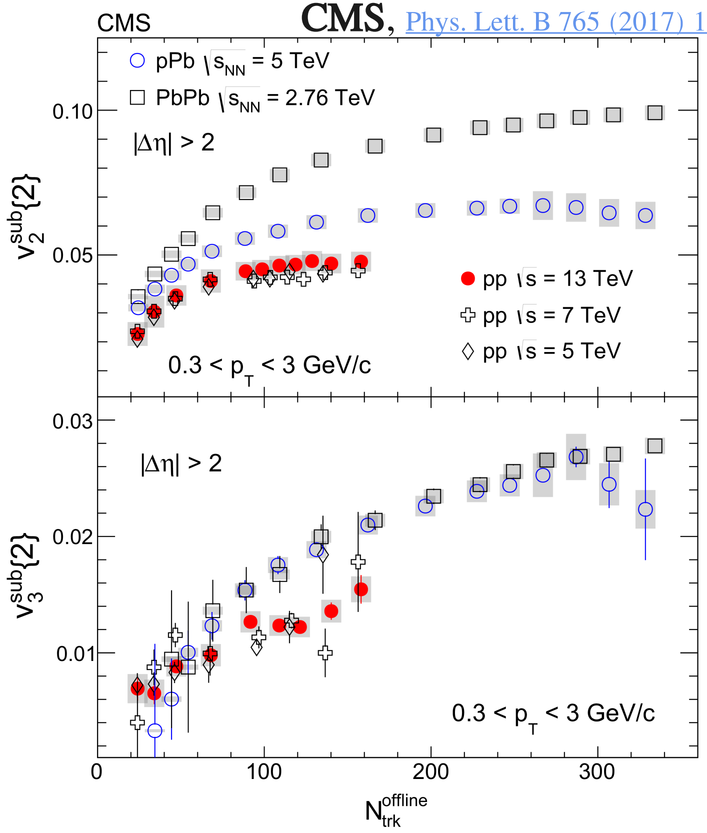


The study of QGP signatures in small systems

There are signs of **QGP-like phenomenon in small systems** (pp and p-Pb)

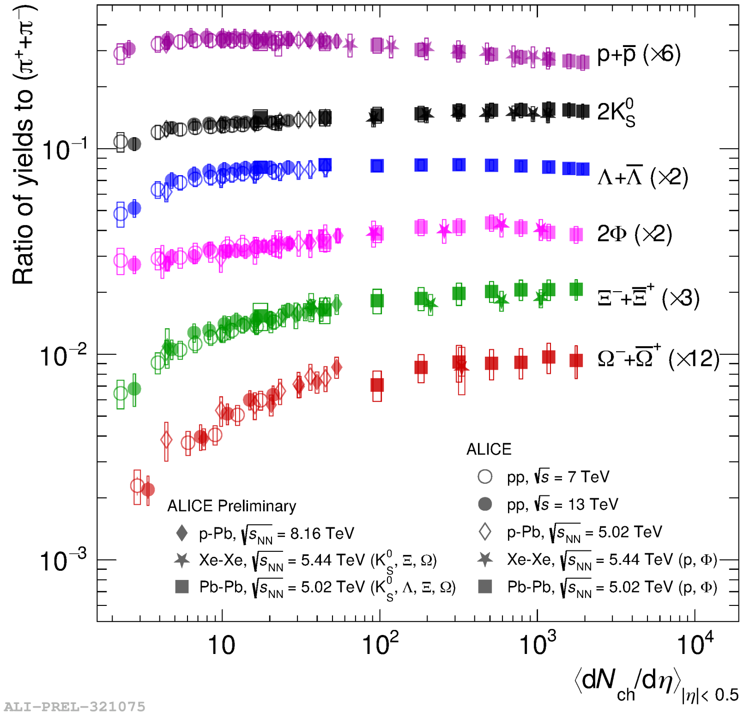
- **Sizeable anisotropic flow**

CMS, Phys. Lett. B 765 (2017) 193



- **Strangeness enhancement**

ALICE, Nature Physics 13, 535-539 (2017)



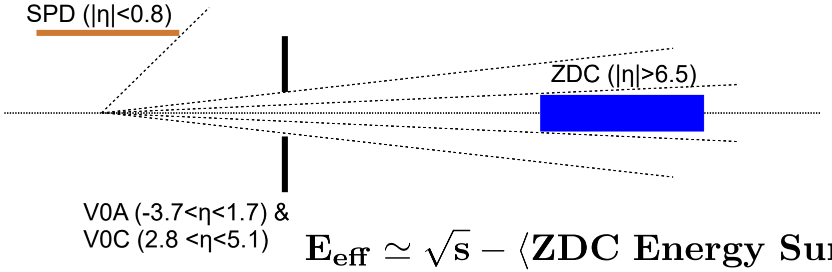
What is the origin of the **observed collectivity in small systems ?**

Initial stage effects on strangeness enhancement

Is strangeness enhancement in **pp collisions** correlated only with final state particle multiplicities or does the initial stage of the collision play a role?

Initial stage effects are probed via the effective energy

The **energy effectively available** for particle production in the **initial stages** of the collision



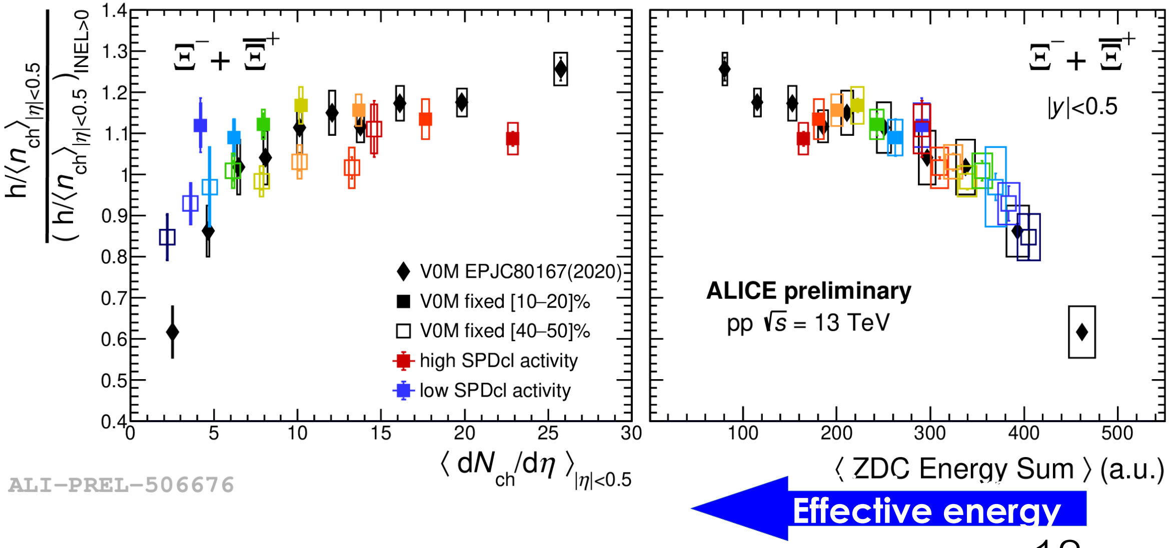
$$E_{eff} \simeq \sqrt{s} - \langle \text{ZDC Energy Sum} \rangle$$

https://alice-figure.web.cern.ch/node/22044

Double differential analysis of the Ξ yield normalised to the charged particle multiplicity:

Large effective energy →

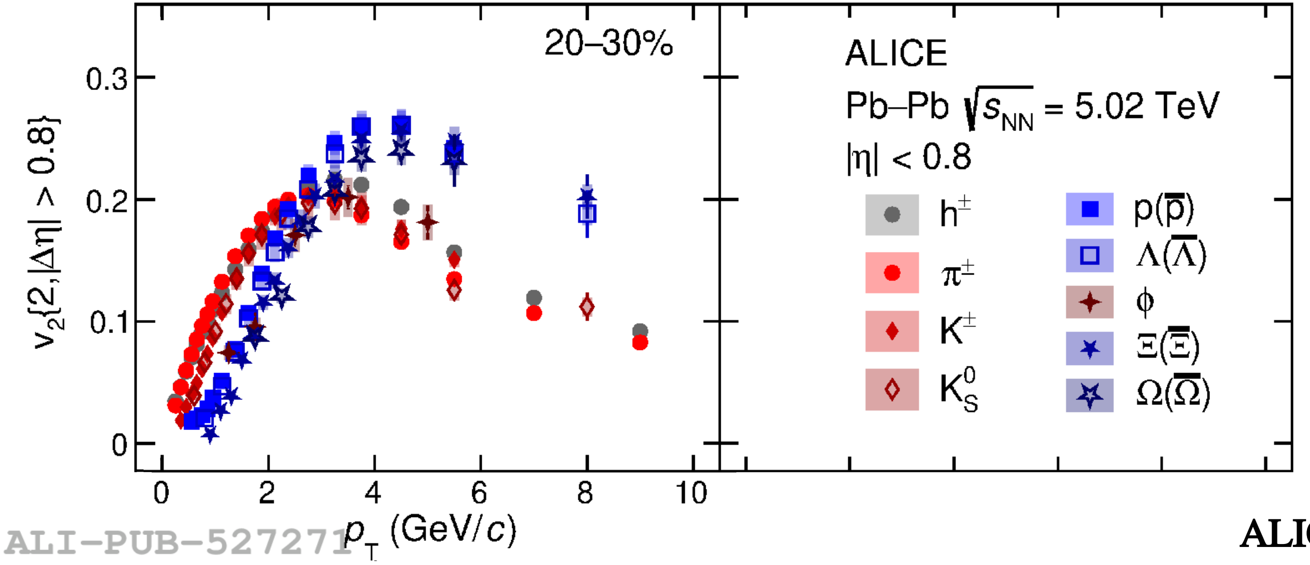
Small effective energy →



Constraining the range of **effective energy strongly affects the strangeness enhancement** with multiplicity

→ **Effective energy plays an important role in the strangeness enhancement**

Flow of identified particles in Pb-Pb collisions



ALICE, arXiv:2206.04587

Two phenomenon are observed in **Pb-Pb collisions**:

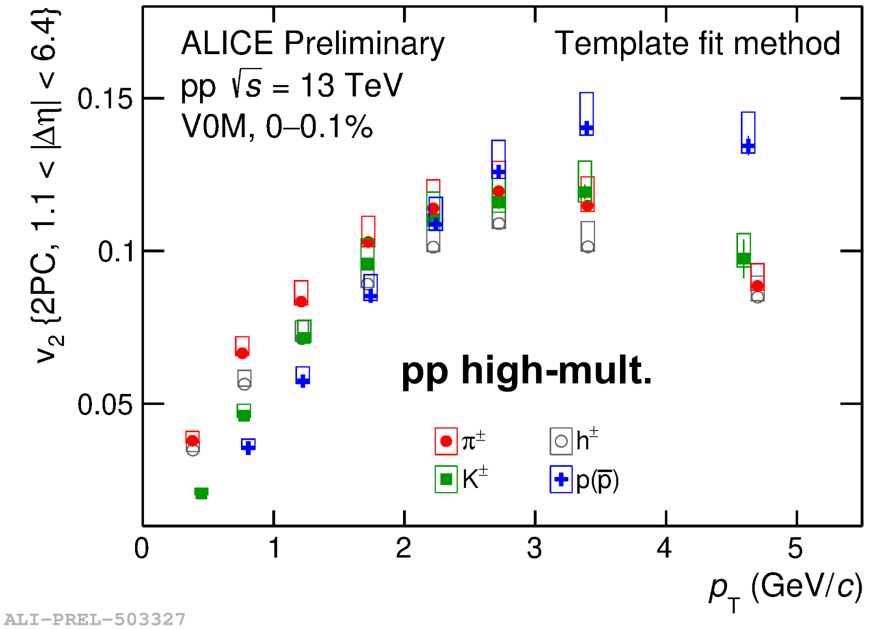
- **Mass ordering at low p_T**

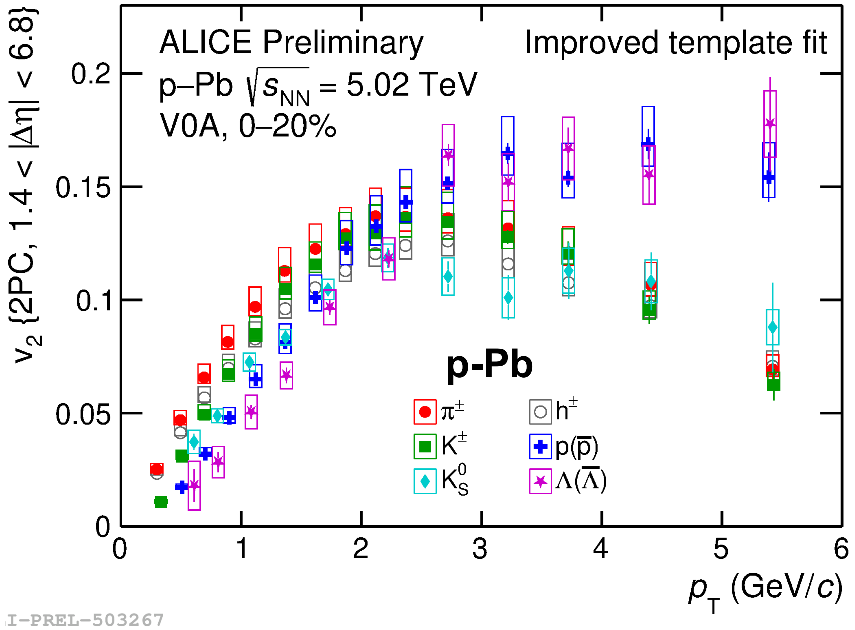
  → Consequence of the radial expansion of the medium (described by hydrodynamics)

- **Baryon-meson splitting of v_2 at intermediate p_T** (p_T > 3 GeV/*c*)

  → Presence of partonic collectivity

Observation of collective effects in small system



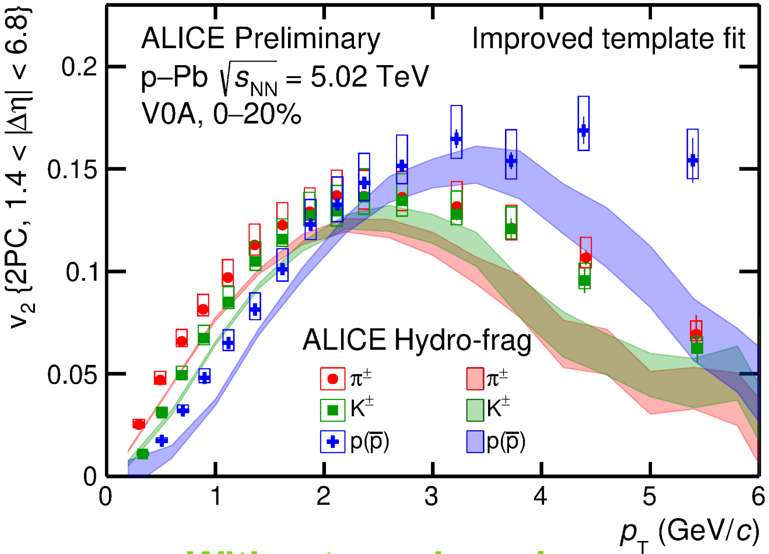


Study of the elliptic flow of identified particles using hadron-hadron correlations **in pp and p-Pb collisions:**

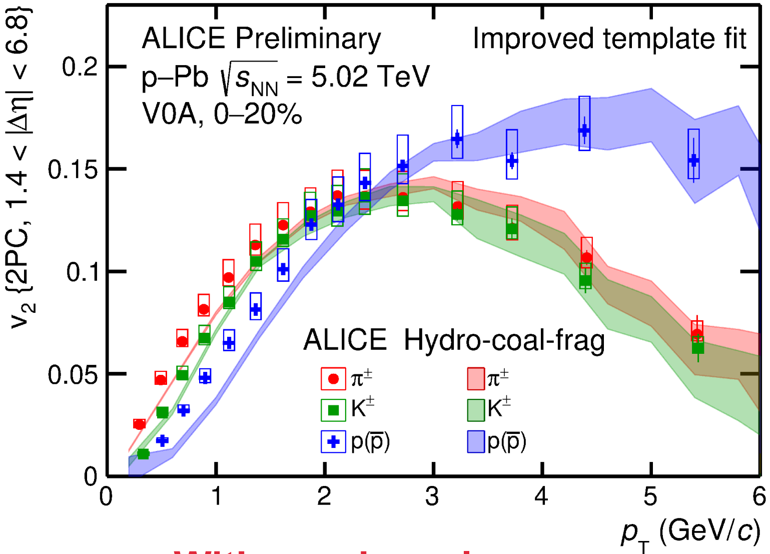
- **Mass ordering at low p_T**
- **Baryon-meson splitting of v_2 at intermediate p_T** (p_T > 3 GeV/c)

→ Same observations as in Pb-Pb collisions

Observation of collective effects in small system



Without quark coalescence



With quark coalescence

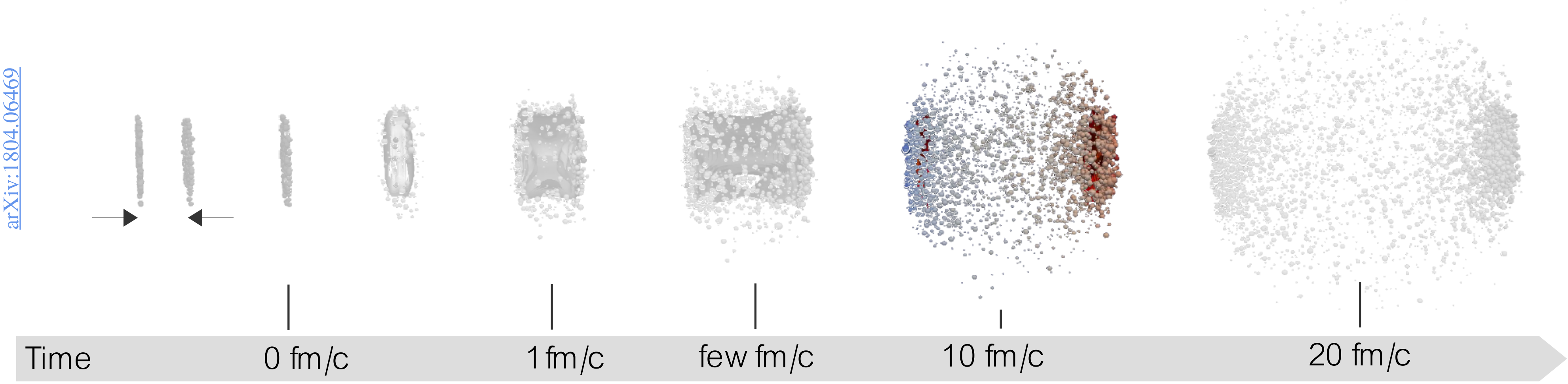
Study of the elliptic flow of identified particles using hadron-hadron correlations **in p-Pb collisions**:

- **Model with hydrodynamics, quark coalescence and jet fragmentation** reproduces the data
- **Model without quark coalescence** can not describe the trend at intermediate p_T

→ **Partonic collectivity in small systems**

Freeze-out & rescattering

arXiv:1804.06469



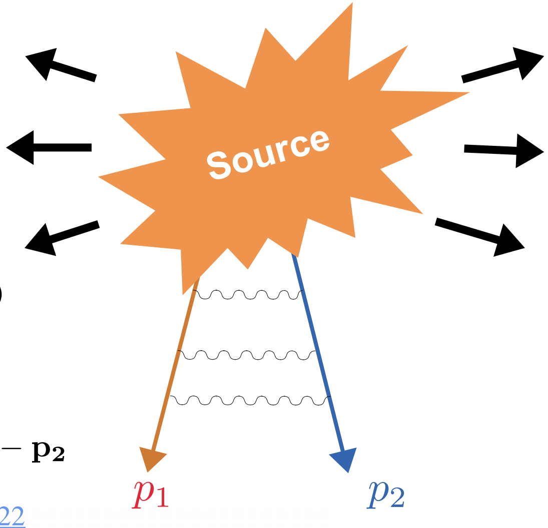
Shape of the particle emitting source

Femtoscopy measurement: particle correlation $\mathrm{C(q)}$ at low q

- Related to the source S(q): $C(q) \approx 1+ \mid S(q) \mid^2$
- In the past, **mostly Gaussian or Cauchy shapes** were assumed for $\mathrm{C(q)}$
- **A more general source distribution is a Lévy distribution** (with core-halo model)

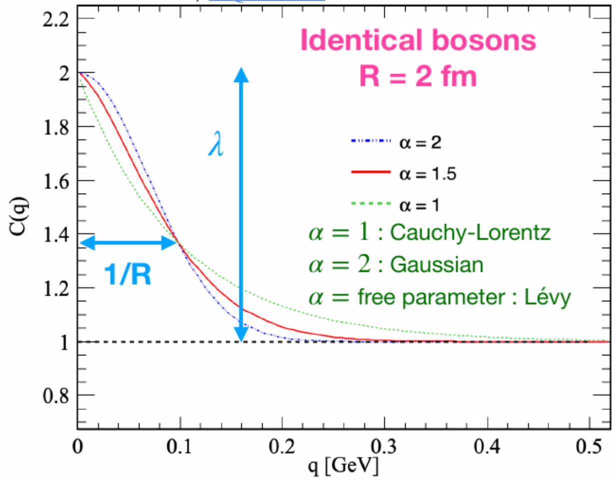
$$C(q) \approx 1 \pm \lambda e^{-|qR|^{\alpha}}$$

  - α: Lévy stability index → **Source shape**
  - R: scale parameter of the medium → Spatial scale
  - λ: correlation strength→ core-halo ratio



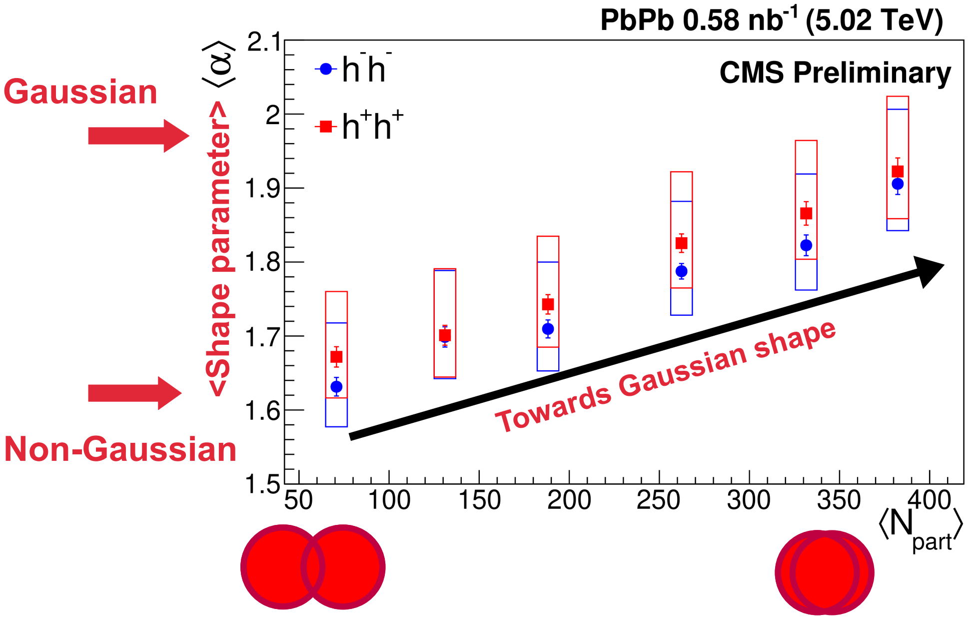
$\mathbf{q} = \mathbf{p_1} - \mathbf{p_2}$

R. Pradhan, SQM2022



→ Use femtoscopy measurement to study the shape of the particle emitting source

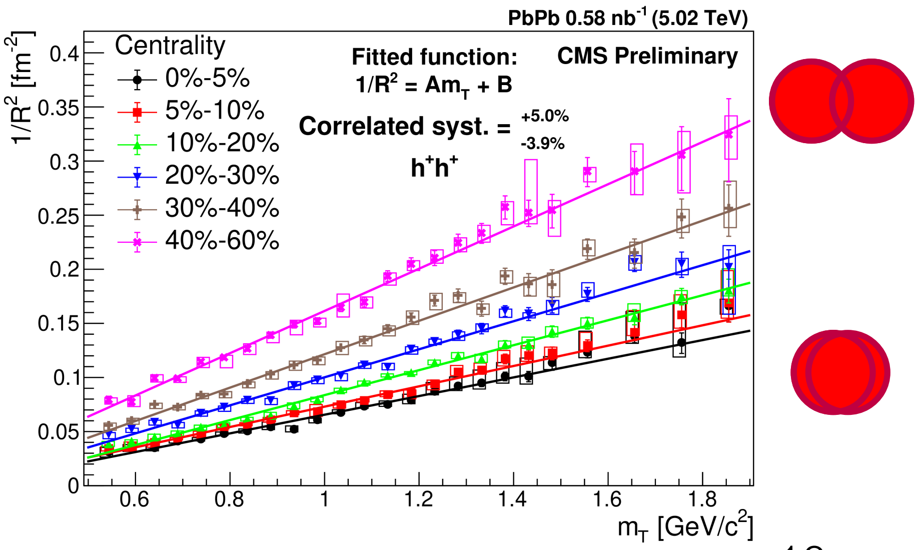
Shape of the particle emitting source



The **average shape parameter** is between 1.6 and 2

- **The source is described by a Lévy distribution**
- The shape is centrality dependent
- Gaussian shape is only approached in the most central events

CMS-PAS-HIN-21-011



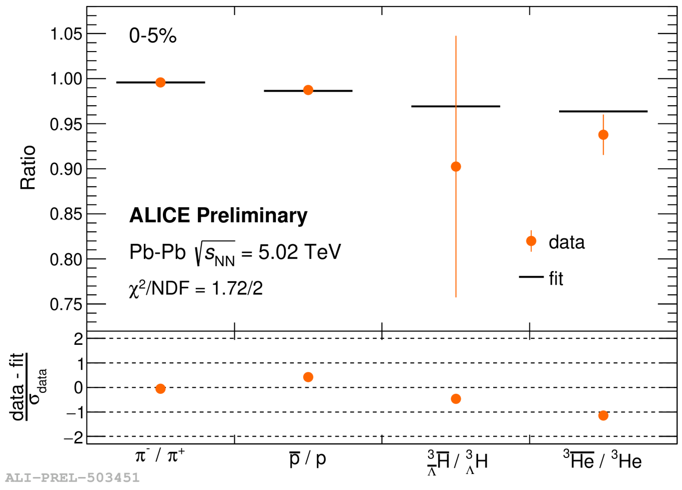
Linear scaling $1/R^2 = Am_T + B$

- **Predicted by hydrodynamics** for a Gaussian source
- **Same linear behavior for a Lévy source**
- Larger slope in peripheral events

→ related with expansion velocity and freeze-out temperature

Precision measurement μ_B via $\overline{\text{Baryon}}$/Baryon ratio

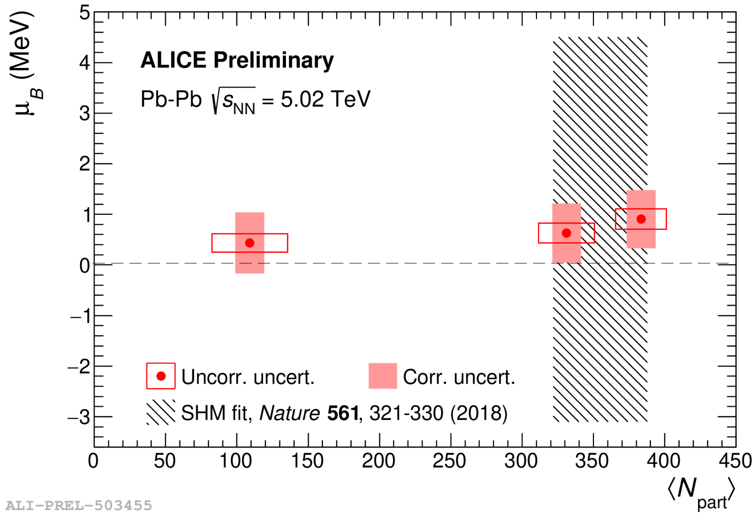
https://alice-figure.web.cern.ch/node/21620



μ_B and μ_{I3} are extracted from the fit with SHM equation

$$\bar{h}/h \approx \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

with $T = 156.2 \pm 1.5$ MeV



New measurement of the antimatter/matter imbalance

- [B = 0 ; S = 0] → π — Imbalance < 0.5%
- [B = 1 ; S = 0] → p — Imbalance ~1%
- [B = 3 ; S = 0] → ^{3}He — Imbalance ~6%
- [B = 3 ; S = 1] → $^3_\Lambda$H — Imbalance ~10%

Baryon number = B ; Strangeness number = S

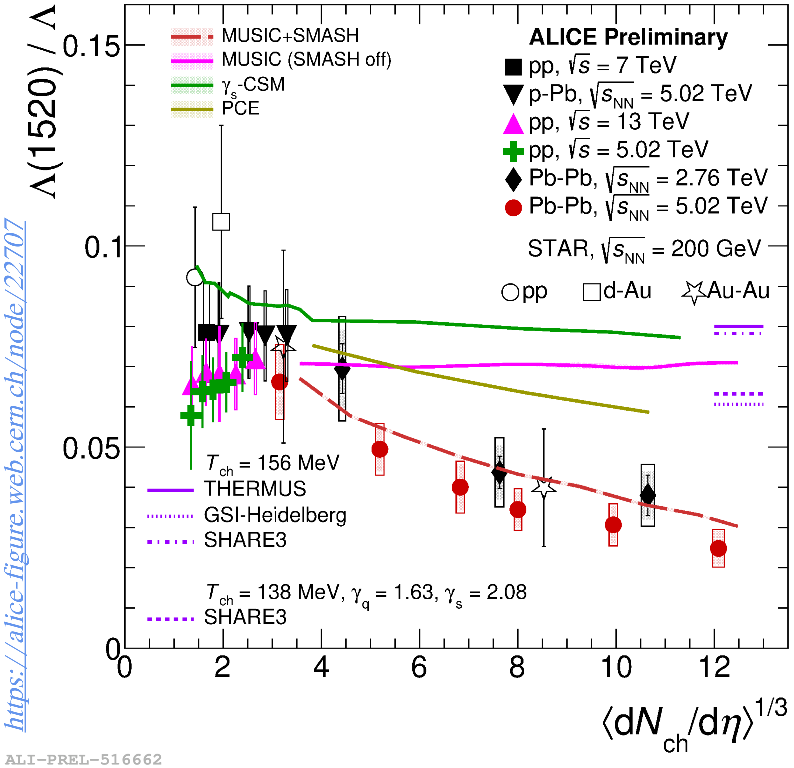
- **Precision** on the baryochemical potential value has been **improved by a factor 10**
- **μ_B is close to 0** at the LHC

Properties of hadronic phase with resonances

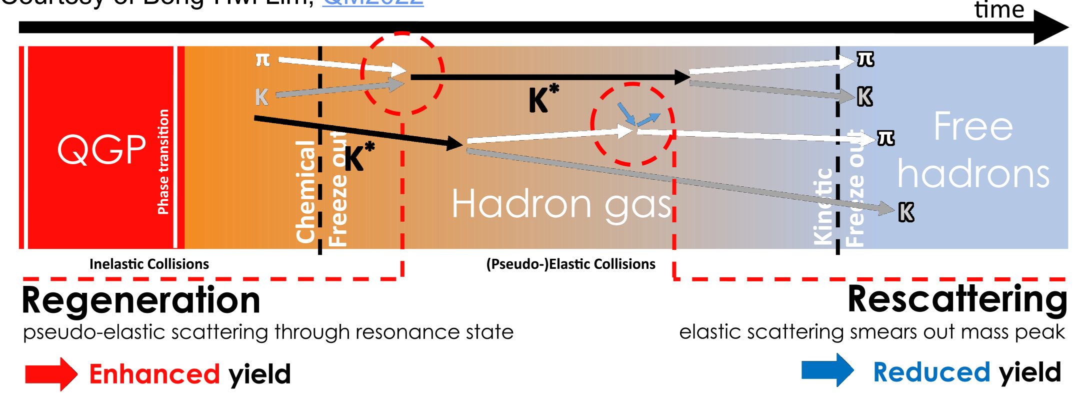
Resonance lifetime (fm/c):

$\rho^0(1.3) < K^{*0}(4.0) < \Sigma^{*\pm}(5.5) < \mathbf{\Lambda^*(12.6)} < \Xi^*(21.7) < \phi(46.3)$

Suppressed | Not suppressed



Courtesy of Bong-Hwi Lim, QM2022



Suppression of the Λ(1520)/Λ yields in Pb-Pb events:

- Decreasing trend with **~7σ significance** in central Pb-Pb events wrt peripherals
- **Trend with centrality reproduced by hydrodynamic (MUSIC) with hadronic afterburner (SMASH)**
- No suppression observed in pp and p-Pb collisions

→ **Yet another confirmation of existence of a hadronic phase lasting enough to cause a significant reduction of the yield of short lived resonances**

Conclusion

Initial conditions:

- Correlation between the size and the shape of the fireball better described by models using IP-Glasma
- T_RENTo model shows large sensitivity to the triaxiality of deformed nuclei in the most central collisions
- New hydrodynamic observables via high-order cumulants of the elliptic flow

Hadronisation:

- Strangeness enhancement in pp collisions is correlated with the initial stage of the collision
- Observation of partonic collectivity in small systems

Freeze-out and rescattering:

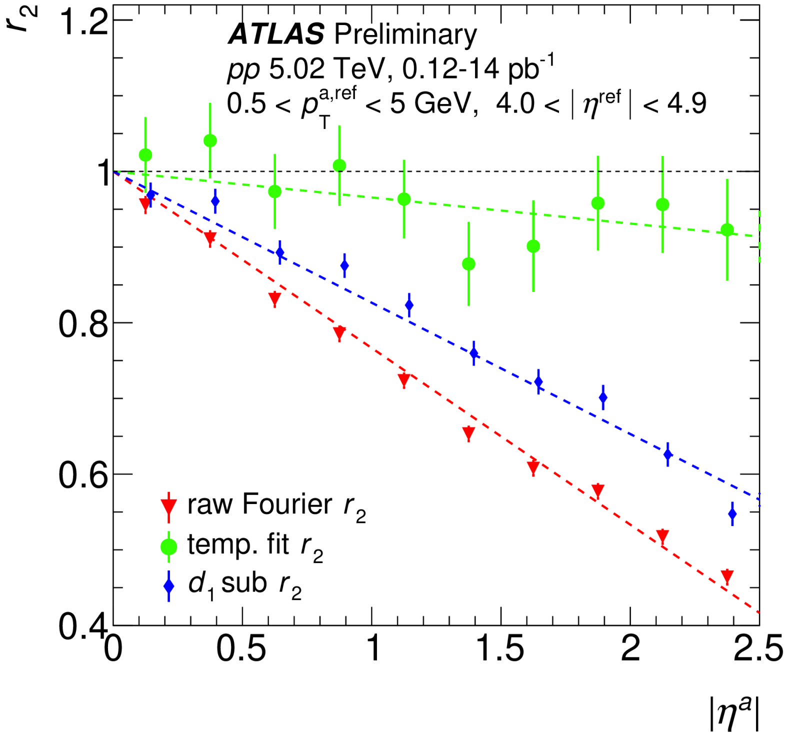
- The particle-emitting source shape is described by a Lévy distribution
- New measurement of μ_B with a precision increased by a factor 10
- The suppression of the $\Lambda(1520)$ yield is well reproduced by MUSIC with SMASH afterburner

With the start of LHC Run 3, more measurements are to come!

Backup slides

Longitudinal structure of the initial state

ATLAS-CONF-2022-020



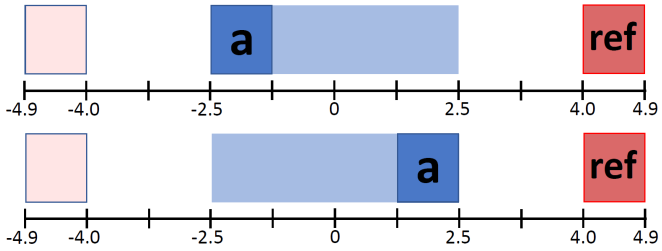
Study of the longitudinal dependence of flow in **pp and Xe-Xe**

- Also called **longitudinal flow decorrelation**
- Provide constraints on the initial longitudinal dynamics

Measurement of the **flow decorrelation**

$$r_2(|\eta_a|) = \frac{v_{2,2}(-|\eta_a|)}{v_{2,2}(|\eta_a|)} = 1 - 2F_2|\eta_a|$$

Longitudinal flow decorrelation (→ F_2)

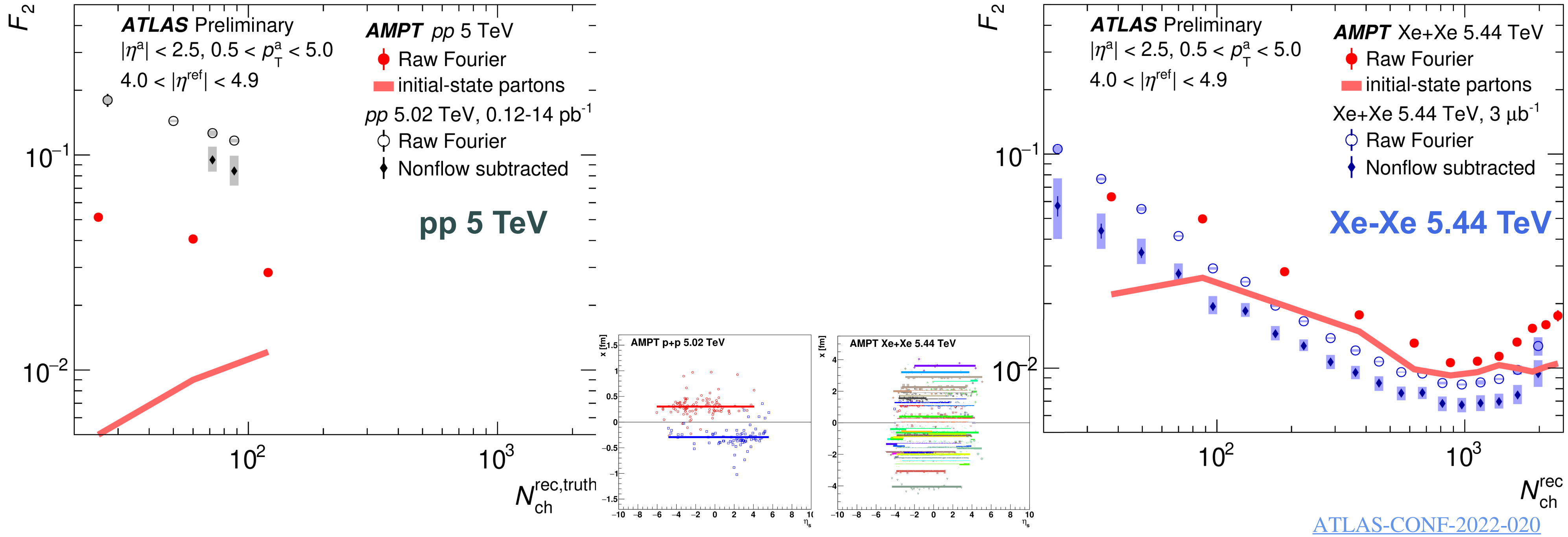


raw Fourier: combination of flow and non-flow

temp. fit: subtract ~85% of non-flow contribution

d_1 sub: subtract ~25% of non-flow contribution

Longitudinal structure of the initial state



ATLAS-CONF-2022-020

Study of the longitudinal dependence of flow in **pp and Xe-Xe:**

- **Larger decorrelation in pp** than in Xe-Xe at similar multiplicities
- **Good qualitative agreement** between AMPT and the **Xe-Xe** data, and **poor agreement in pp**
- **Disfavors AMPT pp initial-state model with a small number of strings**

Investigating the initial stages with correlations

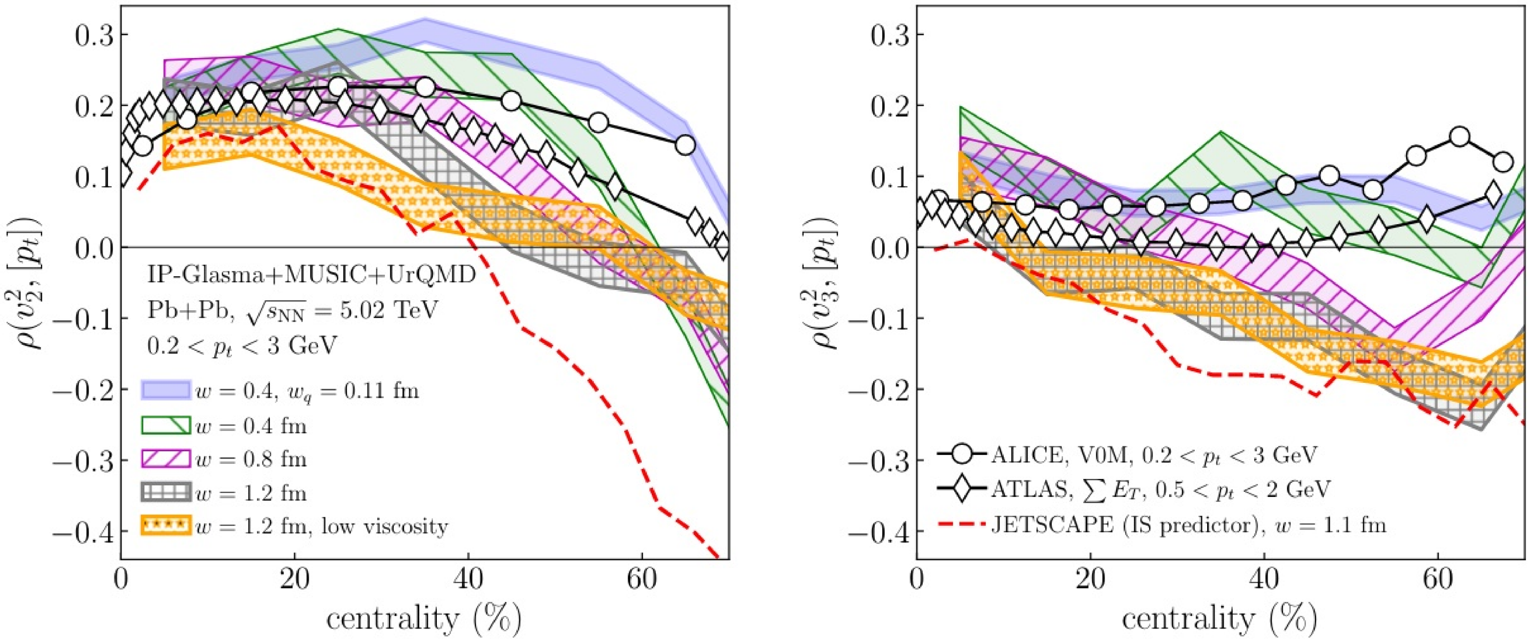


FIG. 2. Results of the IP-Glasma+MUSIC+UrQMD framework for $\rho(v_2^2, [p_t])$ (left) and $\rho(v_3^2, [p_t])$ (right). Different types of shaded bands correspond to different values of the nucleon width. The orange band with starry hatches corresponds instead to a calculation with reduced viscosities. The dashed lines are estimators using JETSCAPE initial conditions. Symbols are preliminary ATLAS data [23] (diamonds) for charged particles with $0.5 < p_t < 2$ GeV, $|\eta| < 2.5$ and the centrality defined via $\sum E_T$, and preliminary ALICE data [22] (circles) for charged particles with $0.2 < p_t < 3$ GeV, $|\eta| < 0.8$, and the centrality defined via V0M amplitude. We note that the larger upper p_t cut implemented in the ALICE analysis explains in part the larger magnitude of their ρ_n compared to ATLAS data for non-central collisions.

arXiv:2111.02908

Initial stage effects on strangeness enhancement

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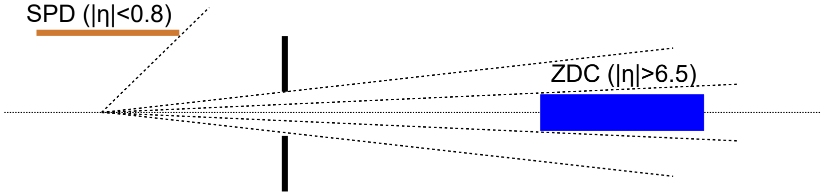


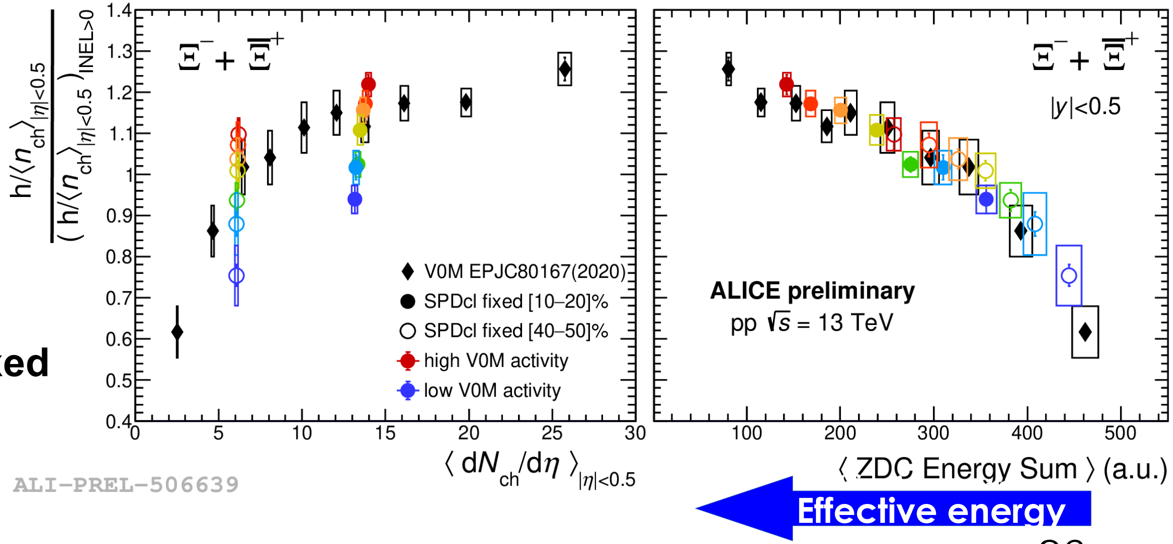
$$\mathbf{E_{eff}} \simeq \sqrt{\mathbf{s}} - \langle \mathbf{ZDC\ Energy\ Sum} \rangle$$

https://alice-figure.web.cern.ch/node/22044

Double differential analysis of the Ξ yield normalised to the charged particle multiplicity:

High multiplicity at midrapidity

Low multiplicity at midrapidity



There is a **strangeness enhancement with effective energy**, when the **multiplicity is fixed**

→ **Effective energy plays an important role in the strangeness enhancement**