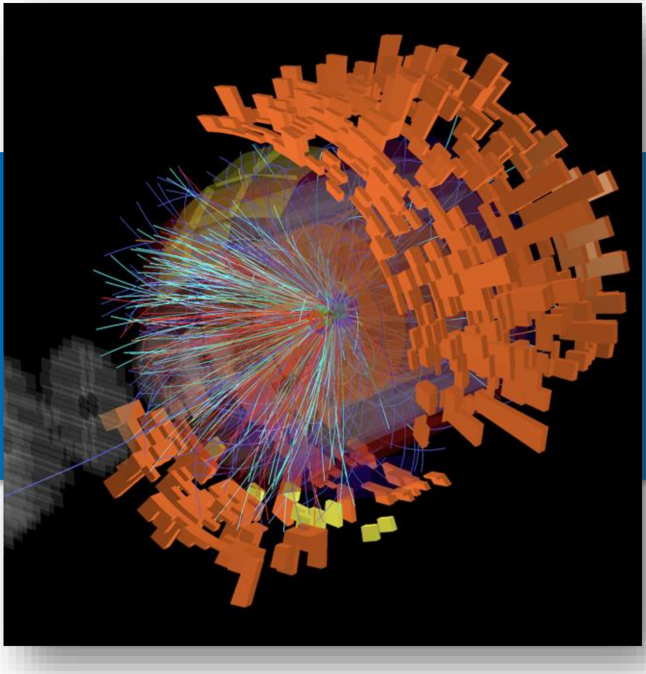


Hadron production in heavy ion collisions

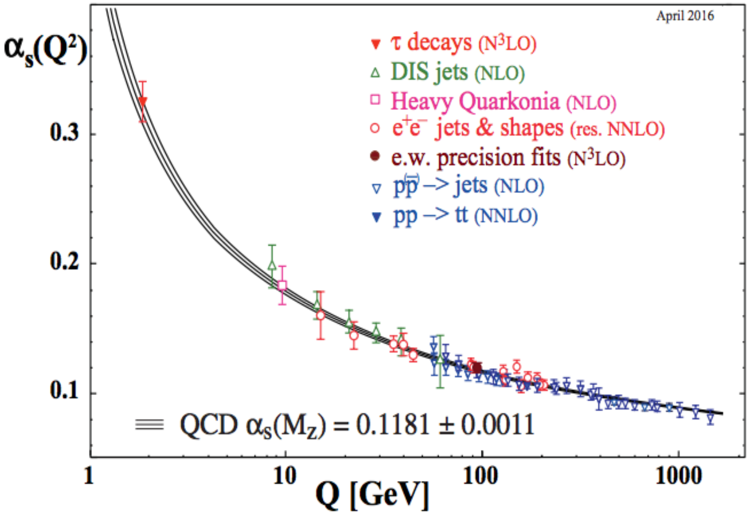
… and down to small systems!

Francesca Bellini, CERN (Switzerland)

Heavy Ion Meeting – Seoul, July 4

QCD and light flavors

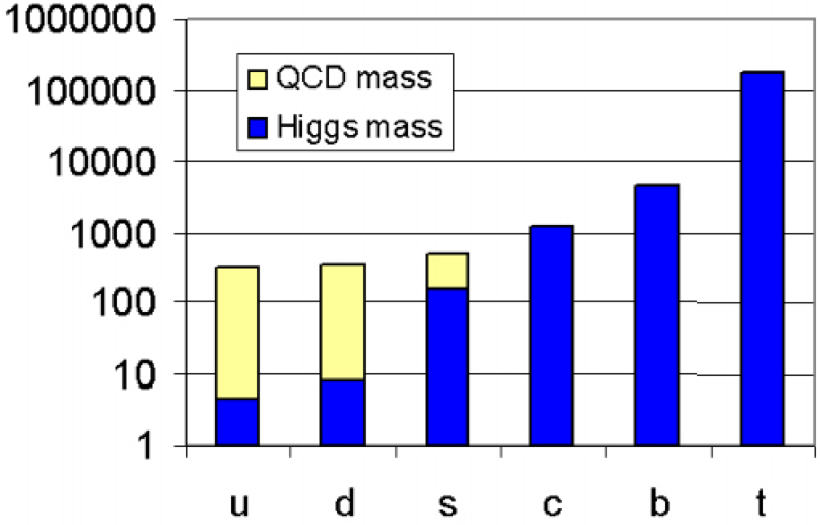
C. Patrignani et al. (PDG), Chin. Phys. C, 40, 100001 (2016)



Confining property of QCD ⇨ colorless hadrons
Asymptotic freedom ⇨ deconfinement, QGP
Confinement and chiral transitions both around the same T_c

Lattice QCD locates the phase transition at
$T_c \sim 145 - 164$ MeV
[A. Bazavov et al., PRD 90 (2014) 094503]

B. Muller, NPA 750 (2005) 84-97



Light flavor (LF) ≡ composed by **u, d** and **s**

$m_u \approx 2.2$ MeV
$m_d \approx 4.7$ MeV
$m_s \approx 96$ MeV

$< \Lambda_{QCD} << m_c \approx 1.3$ GeV

u, d, s can be **thermally produced in QGP**, as $m_{u,d,s} < T_c$

(Some of) The fundamental questions

1. Can we produce **QGP** in AA collisions? And in pp, pA?
   What is the smallest system where we can produce QGP?

2. Can we measure the **chemical freeze-out** temperature T_{ch}?
   Do all (light) flavours freeze-out at the same temperature T_{ch}?

4. How does the **hadronic phase** affect the measured observables?

5. How are **composite ”fragile” objects** such as anti-nuclei formed in AA?

Questions addressed by a comprehensive set of measurements of
identified particle production in all collision systems:
$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, Λ, Ξ, $\wedge$, ρ, K^{*0}, ϕ, $\Sigma^{*\pm}$, Λ^{*}, Ξ^{*0},
(anti)d, (anti)^{3}H, (anti)^{3}He, (anti)^{4}He, (anti)$^3_{\Lambda}$H

It’s all about production mechanisms

Thermal production

Measure p_T-integrated yields and particle ratios

Hydrodynamics (flow)

Fragmentation + recombination

Measure p_T spectra, mean p_T, p_T-differential ratios, flow harmonics, multi-particle correlations

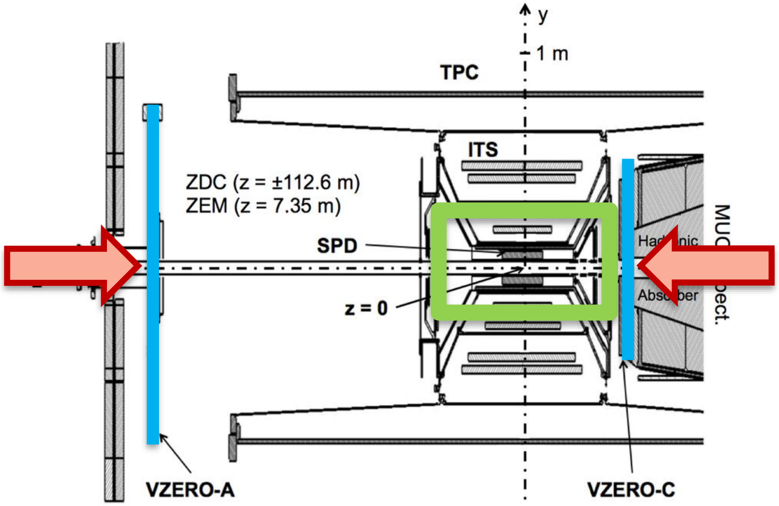
Composite objects
(Anti-)(hyper-)nuclei

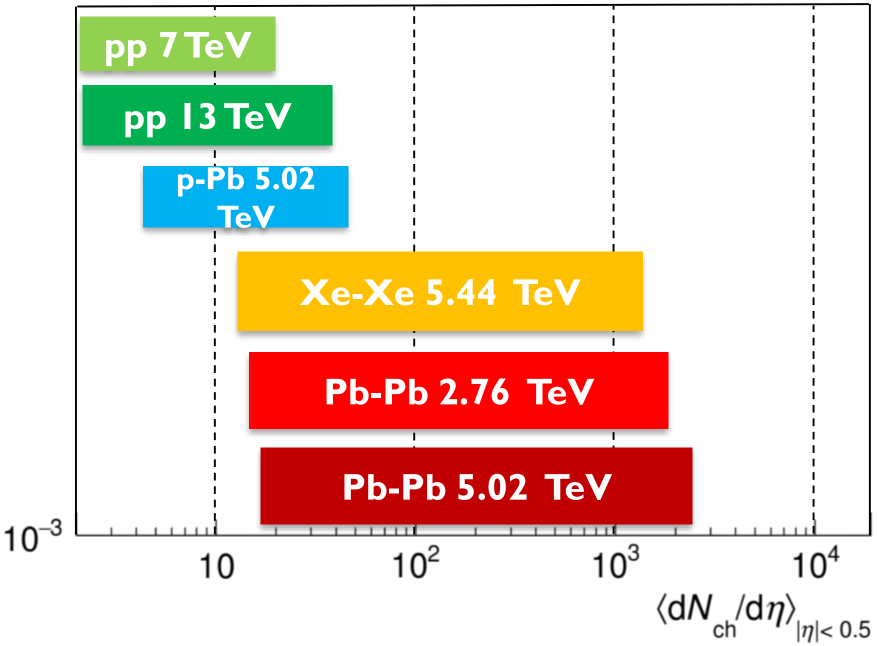
Strangeness

System size ⟺ charged particle multiplicity

Event multiplicity/centrality **classes** defined "slicing" on the signal amplitude measured in **the forward region** / detectors
(In ALICE, in **V0 scintillators**, placed at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C))

$\langle dN_{ch}/d\eta\rangle$, N_{ch} measured in **at mid-rapidity** → avoid "auto-biases" in multiplicity determination, especially in small systems



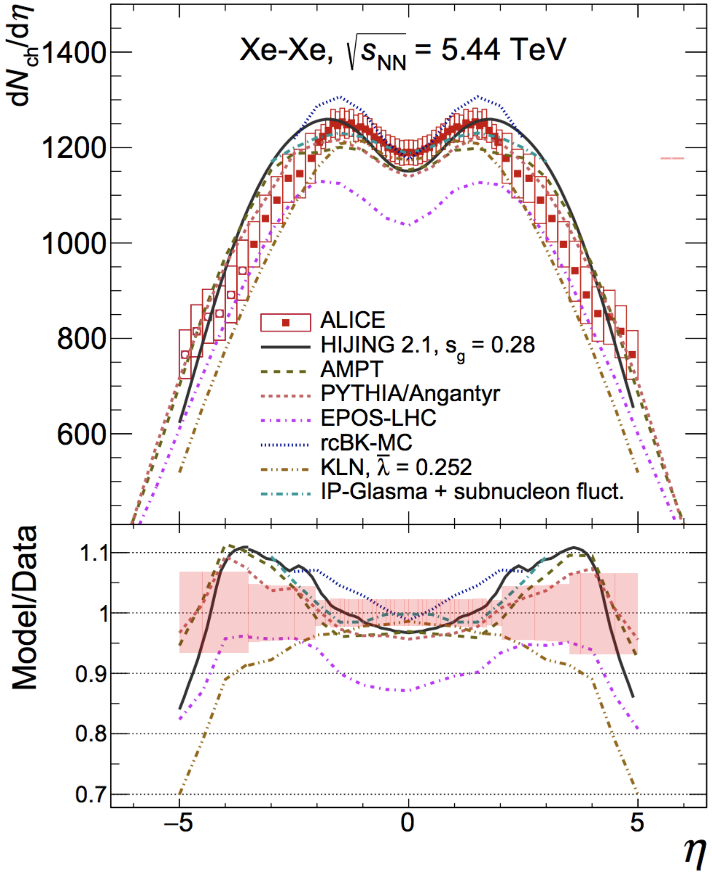


New data in Xe-Xe: test system dependence

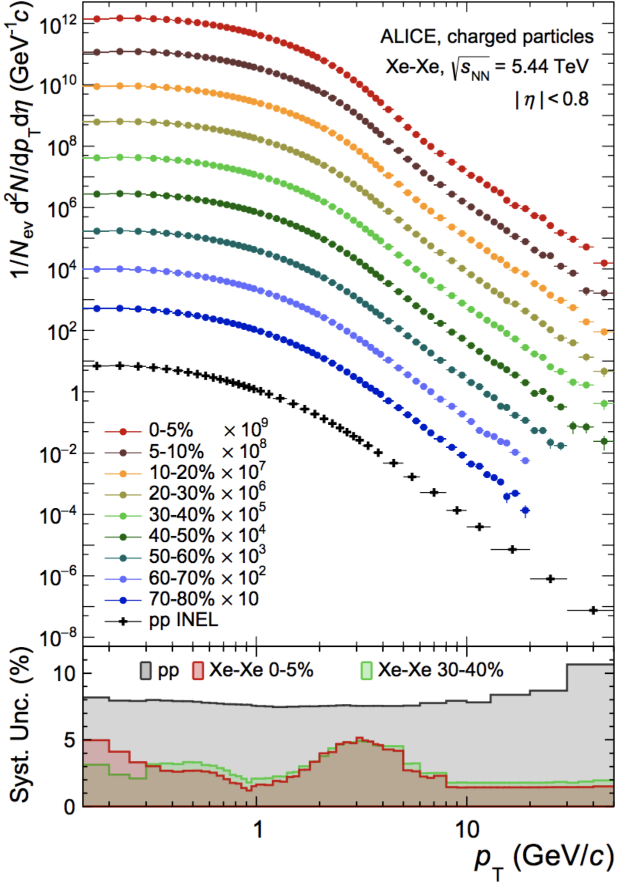
A short (~6h) run with ^{129}Xe at $\sqrt{s_{NN}}$ **= 5.44 TeV** in Nov. 2017

^{129}Xe is smaller nucleus, different geometry wrt ^{208}Pb

ALICE, arXiv:1805.04432

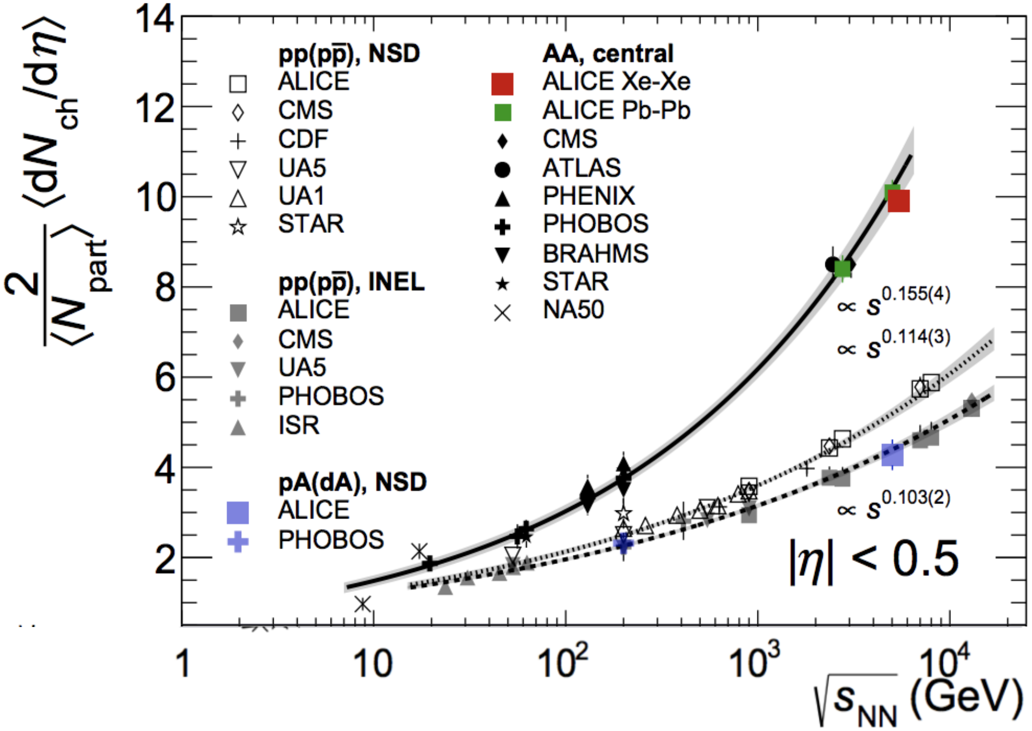


ALICE, arXiv:1805.04399



Charged particle production in AA collisions

ALICE, arXiv:1805. 04432



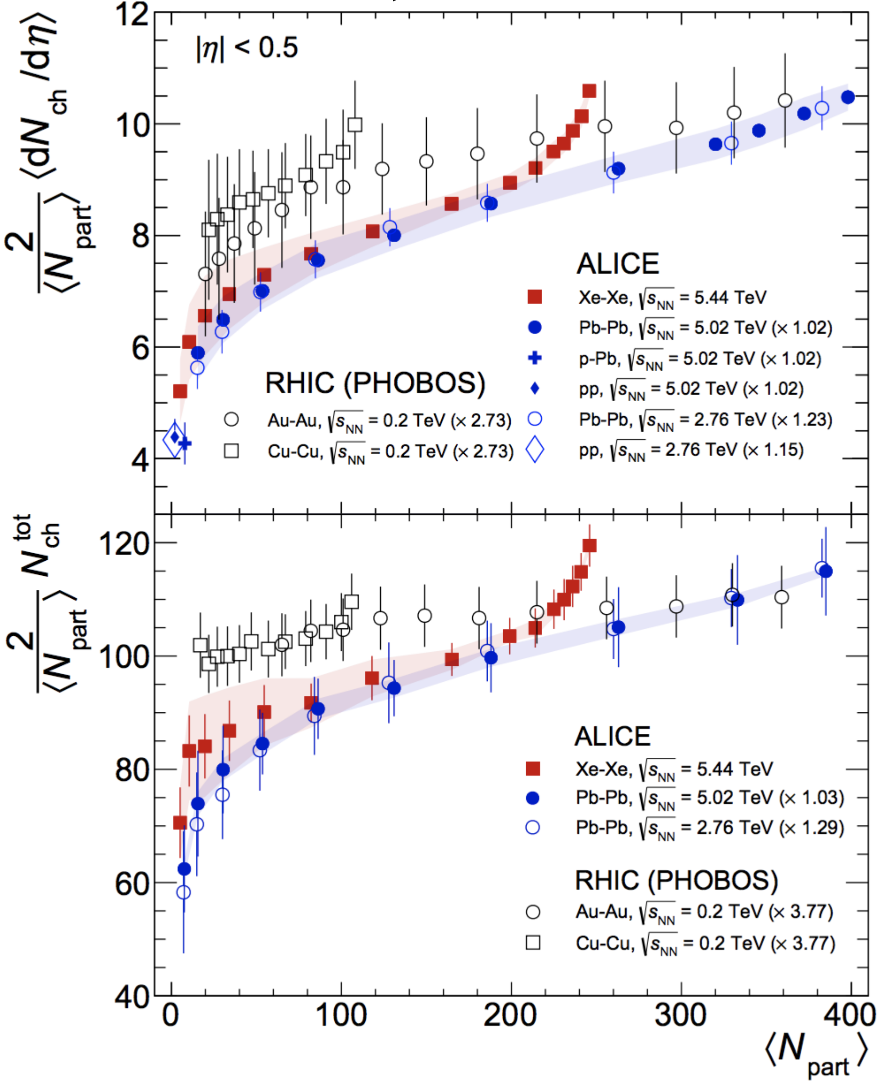
In Pb-Pb $\langle dN_{ch}/d\eta \rangle / \langle N_{part} \rangle$ increases with $\sqrt{s}$ following a steeper power law than pp

About **20% increase from 2.76 TeV to 5.02 TeV** (similar $\langle N_{part} \rangle$)

Similar $\langle dN_{ch}/d\eta \rangle / N_{part}$ in most central **Xe-Xe** and Pb-Pb (little difference in energy)

Xe-Xe vs Pb-Pb

ALICE, arXiv:1805. 04432



Consistency between **Pb-Pb** at different energies

Scaling violations:

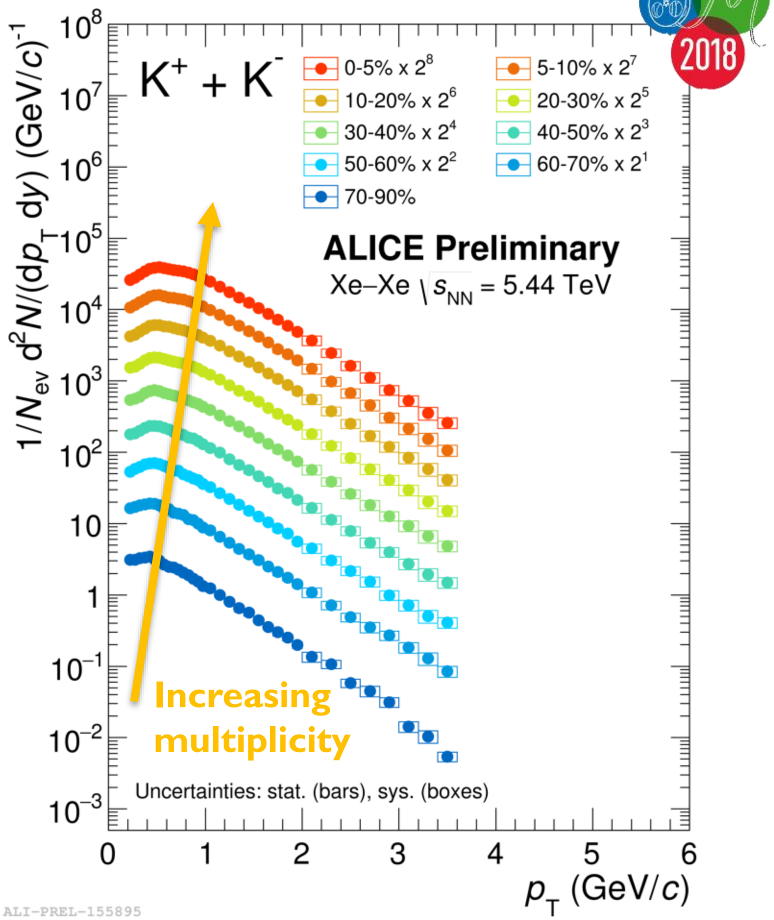
- N_{part} scaling violated
- Central collisions of medium-size nuclei (**Xe**) produce more particles per N_{part} than mid-central collisions of large nuclei (**Pb**) at the same N_{part} **→ to be understood**

π, K, p spectra in AA collisions

πKp constitute the bulk of particle production → **fundamental input!**

- p_T spectra:
    - Compare to hydrodynamic models
    - Quantify radial flow
    - Discuss flow effect vs recombination at intermediate p_T
- p_T-integrated particle ratios
    - Study hadro-chemistry and extract chemical freeze-out temperature
- Nuclear modification factors (R_{AA}, R_{pA})
- Reference for resonance and nuclei production studies

NEW: Xe-Xe 5.44 TeV



Also π, K, p, phi, K* in Xe-Xe (see backup)

"First-order" look at spectral shapes: $\langle p_T \rangle$

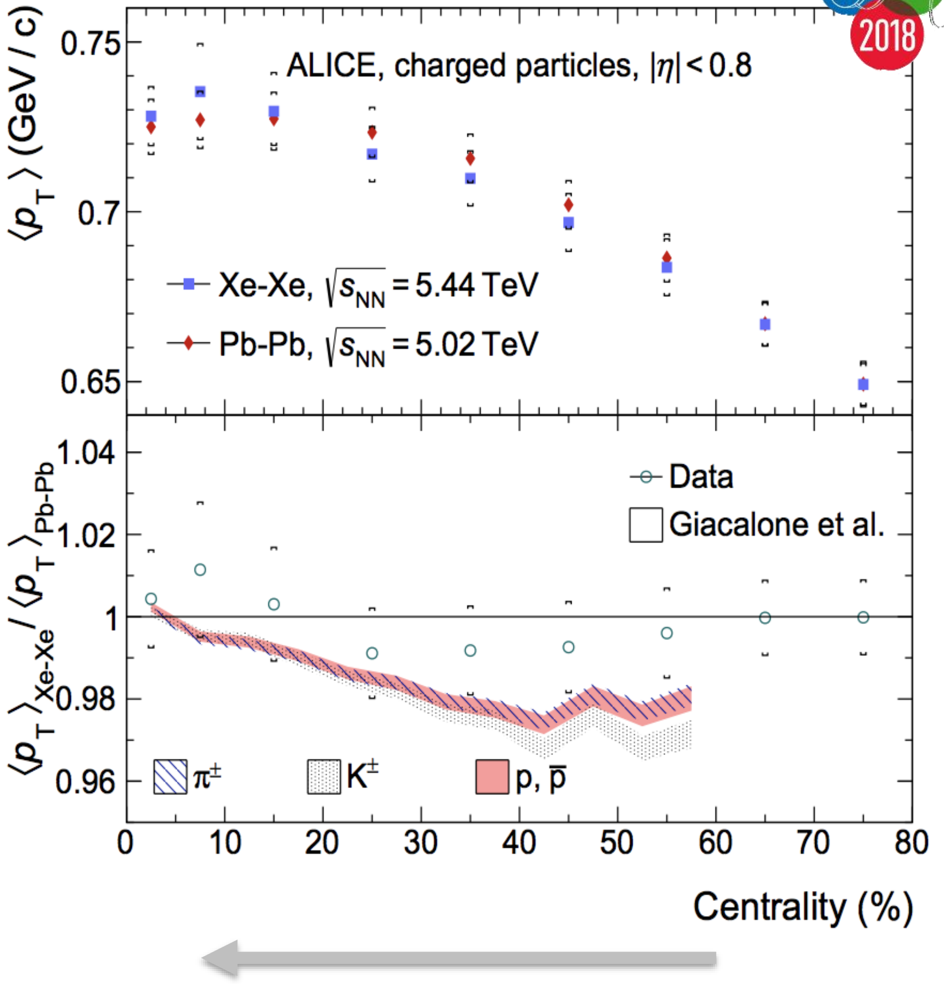
First-moment of the distribution provides first-order characterization of spectral shapes
→ **"day-1" benchmark** for models

Hydrodynamics predicts
[*G. Giacalone et al., PRC 97, 034904 (2018)*]

- weak dependence on centrality in AA collisions
- small difference between Xe-Xe and Pb-Pb, O(3%)
- mass scaling of $\langle p_T \rangle$

→ New data in Xe-Xe for **charged hadrons** show consistency with Pb-Pb and scaling of charged hadron production with charged particle multiplicity

ALICE, arXiv:1805.04399

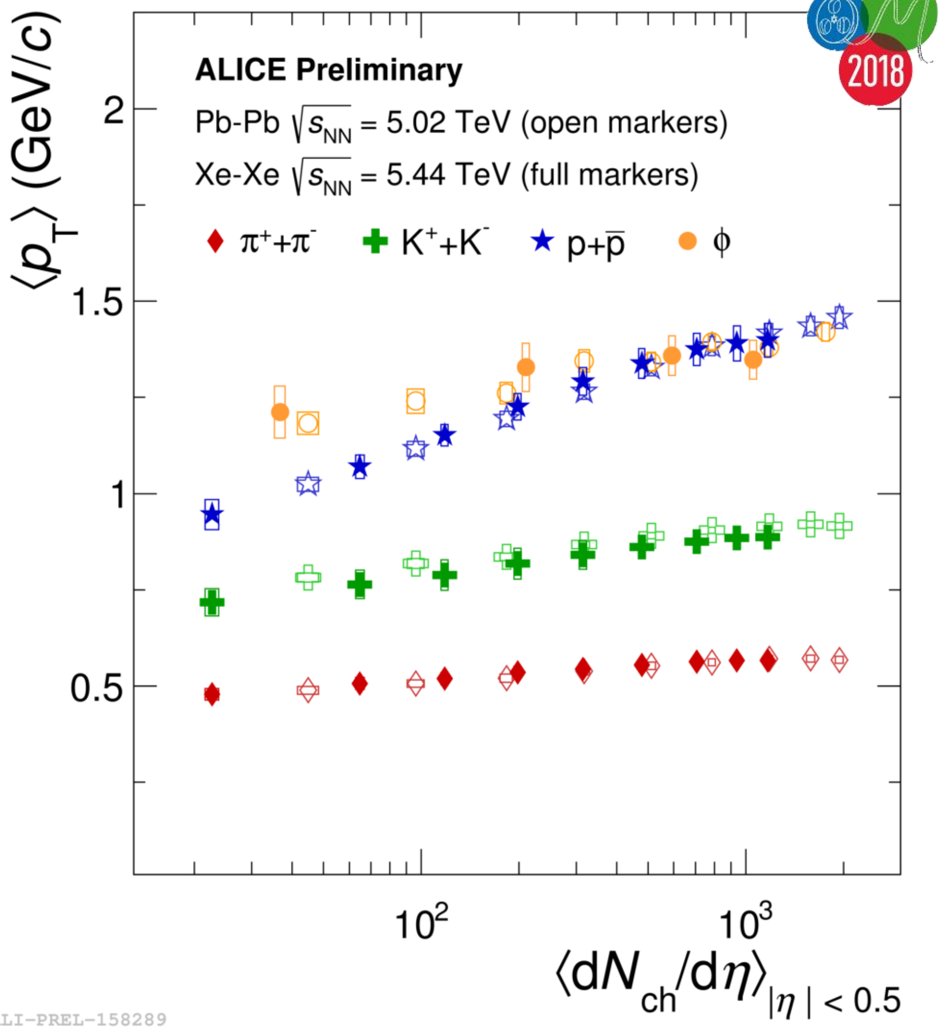


Multiplicity

$\langle p_T \rangle$ of identified hadrons – Pb-Pb, Xe-Xe

$\langle p_T \rangle$ of **identified hadrons** consistent between Xe-Xe and Pb-Pb at similar multiplicities

- Increasing of mean p_T with multiplicity
- Mass ordering observed, as featured by a system experiencing radial flow



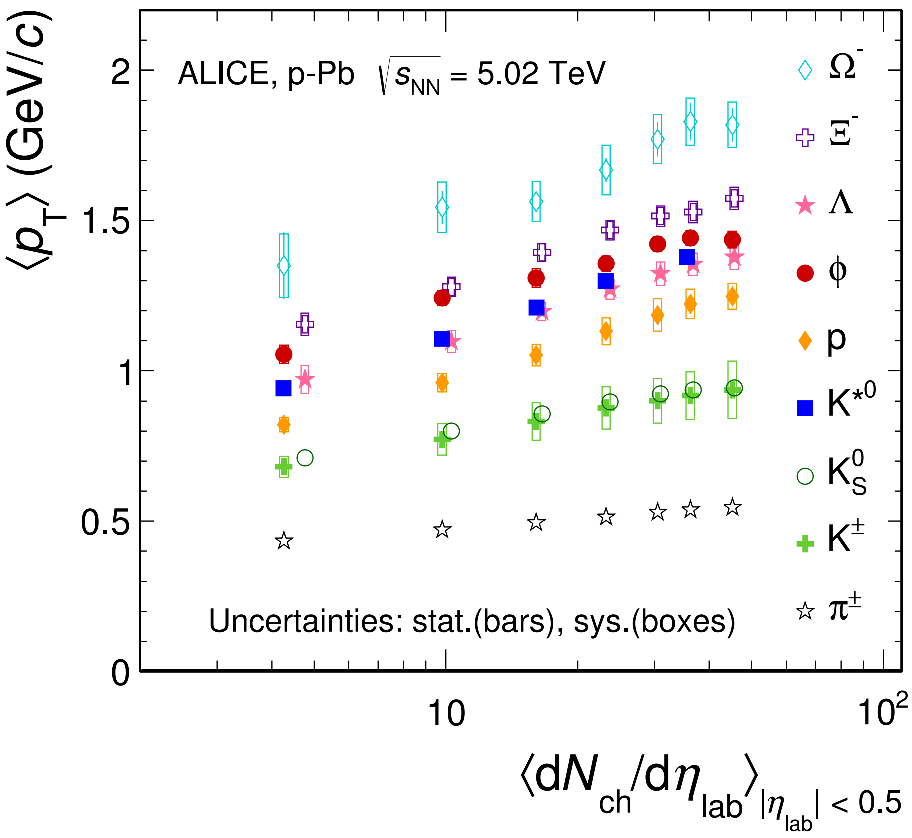
$\langle p_T \rangle$ of identified hadrons - p-Pb

$\langle p_T \rangle$ of **identified hadrons** consistent between Xe-Xe and Pb-Pb at similar multiplicities

- Increasing of mean p_T with multiplicity
- Mass ordering observed, as featured by a system experiencing radial flow

Similar trend with mult. in pp, pA (even steeper!)

ALICE, EPJ C 76 (2016) 245



ALI-PUB-103929

$\langle p_{\mathrm{T}} \rangle$ of identified hadrons - pp

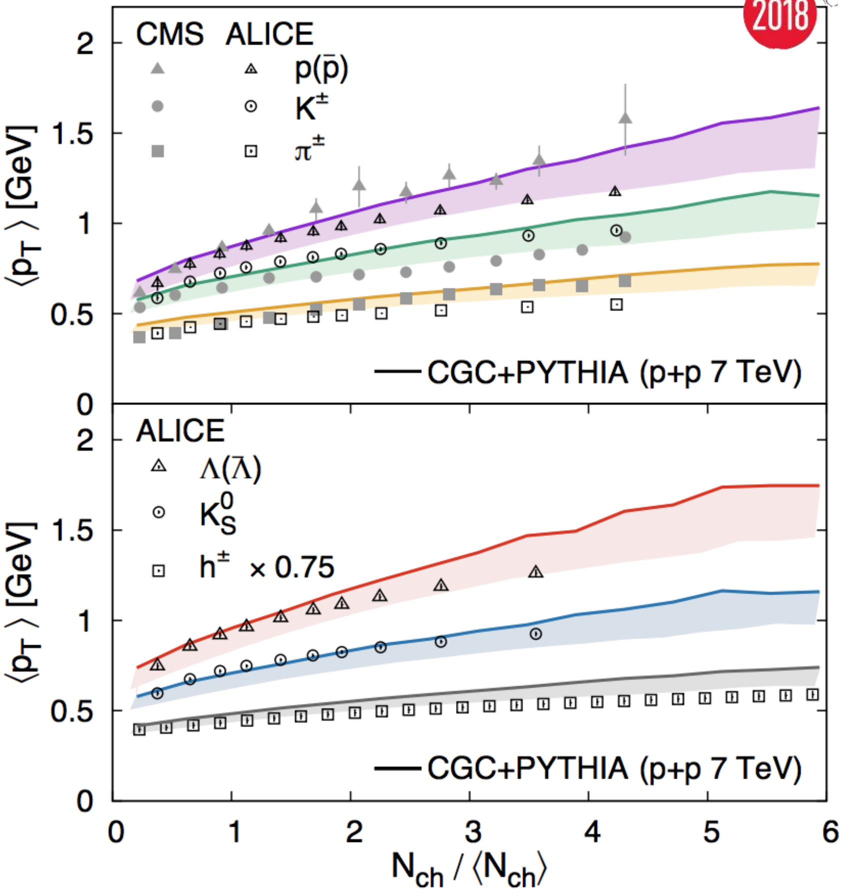
$\langle p_{\mathrm{T}} \rangle$ of **identified hadrons** consistent between Xe-Xe and Pb-Pb at similar multiplicities

- Increasing of mean p_{T} with multiplicity
- Mass ordering observed, as featured by a system experiencing radial flow

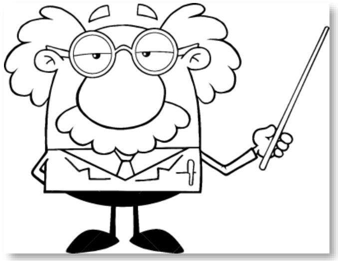
Similar trend with mult. in pp, pA (even steeper!)

BUT also models with initial stage effects (e.g. CGC + PYTHIA) can reproduce the mass ordering (also for v_2!!!)

P. Tribedy, QM 2018



For details on the model, see backup



Mass ordering of $\langle p_T \rangle$ (and v_2) not be an exclusive product of hydrodynamical flow

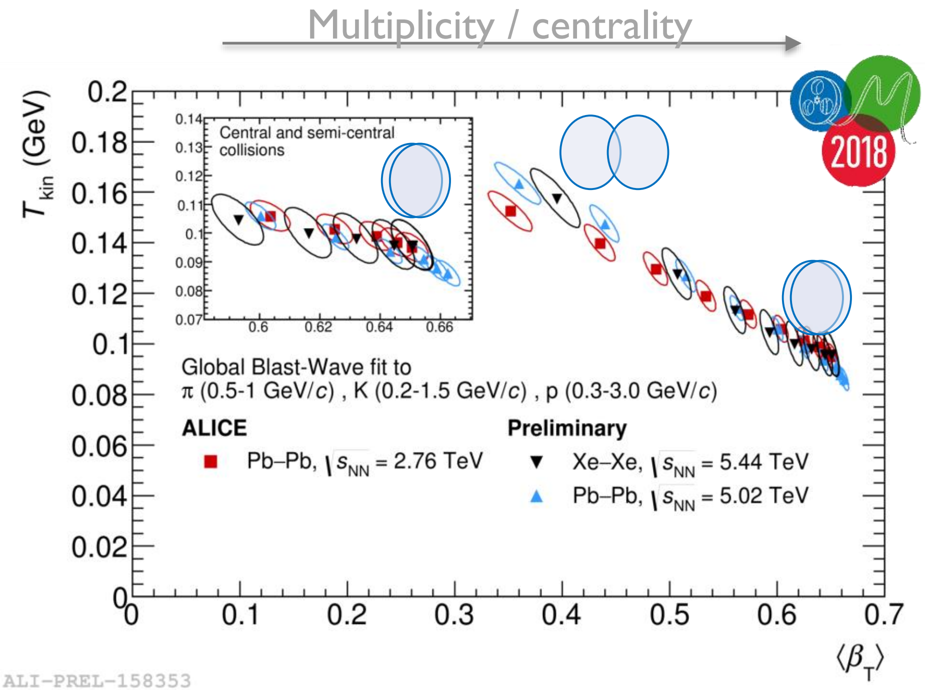
$\langle p_T \rangle$ only provides first-order characterization of spectral shapes, physics is in the full spectrum!

Blast-Wave model fit to spectra

Boltzmann-Gibbs Blast-Wave used to quantify radial flow
[*E. Schnedermann et al., Phys. Rev. C48 (1993) 2462*]

A simplified hydrodynamic model with 3 free fit parameters,
- T_{kin} = kinetic freeze-out temperature
- $\langle \beta_T \rangle$: transverse radial flow velocity
- *n*: velocity profile

to describe particle production from a thermalized source + radial flow boost

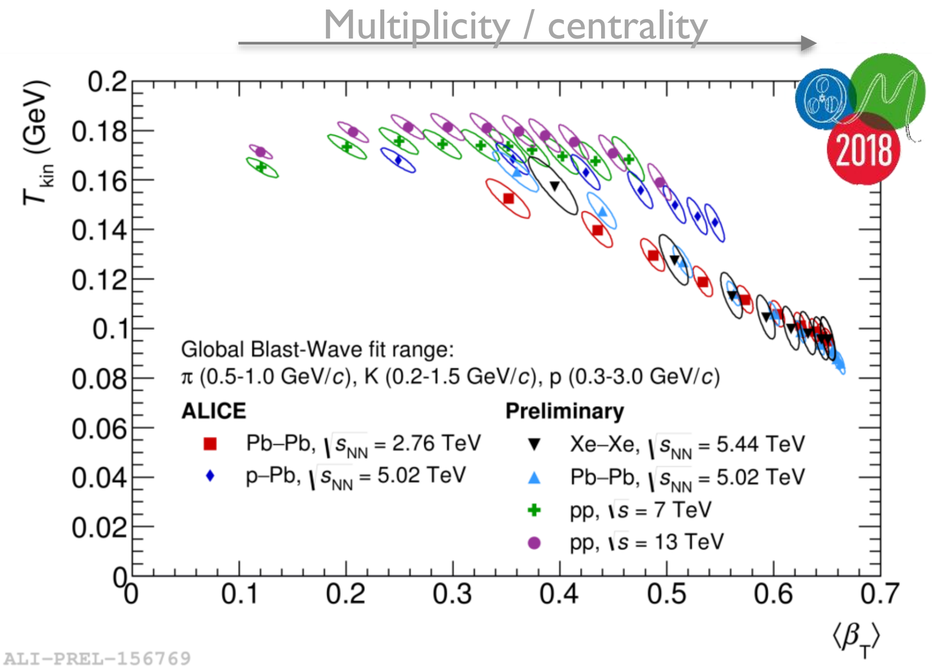


ALI-PREL-158353

Simultaneous fit to π, K, p spectra
- increase of ⟨β_T⟩ with centrality in AA
- Xe-Xe and Pb-Pb consistent

Blast-Wave model fit to spectra

Boltzmann-Gibbs Blast-Wave used to quantify radial flow
[*E. Schnedermann et al., Phys. Rev. C48 (1993) 2462*]



A simplified hydrodynamic model with 3 free fit parameters,

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

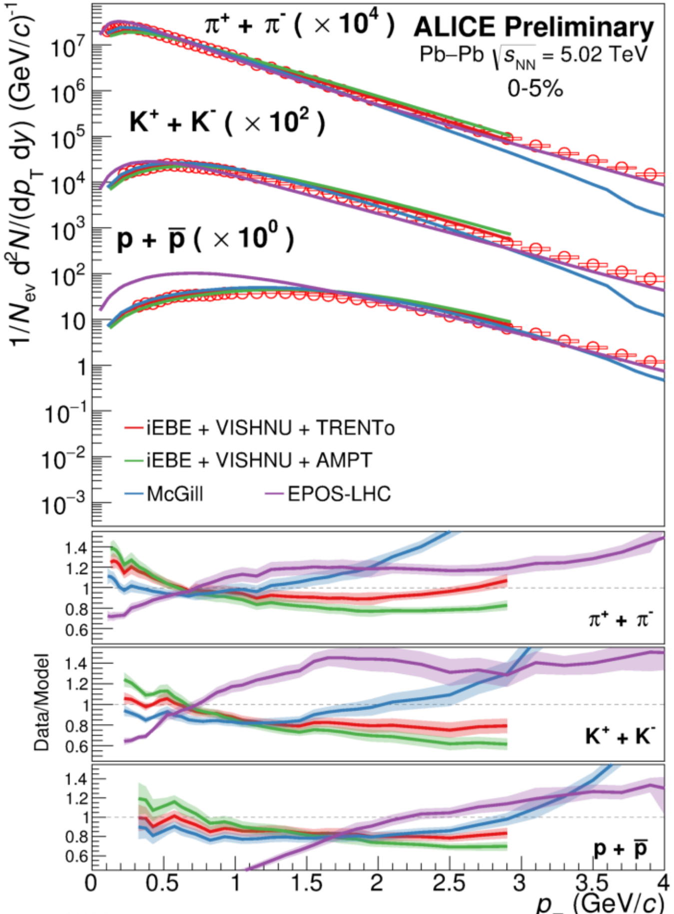
to describe particle production from a thermalized source + radial flow boost

Simultaneous fit to π, K, p spectra

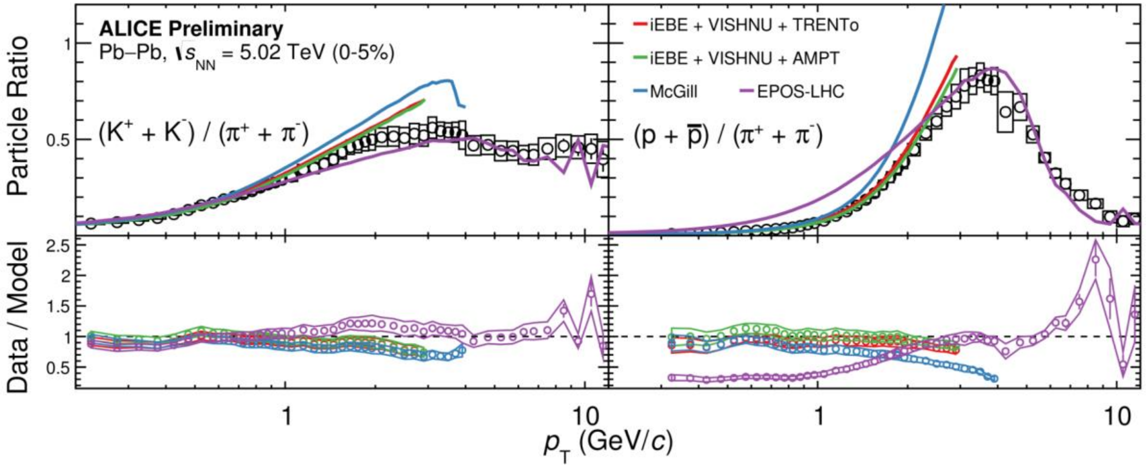
- increase of $\langle\beta_T\rangle$ with centrality in AA
- Xe-Xe and Pb-Pb consistent

- in pp and p-Pb, similar evolution with multiplicity
- at similar multiplicity, $\langle\beta_T\rangle$ is larger for smaller systems

Hydro model comparison – Pb-Pb 0-5%



ALI-DER-136354



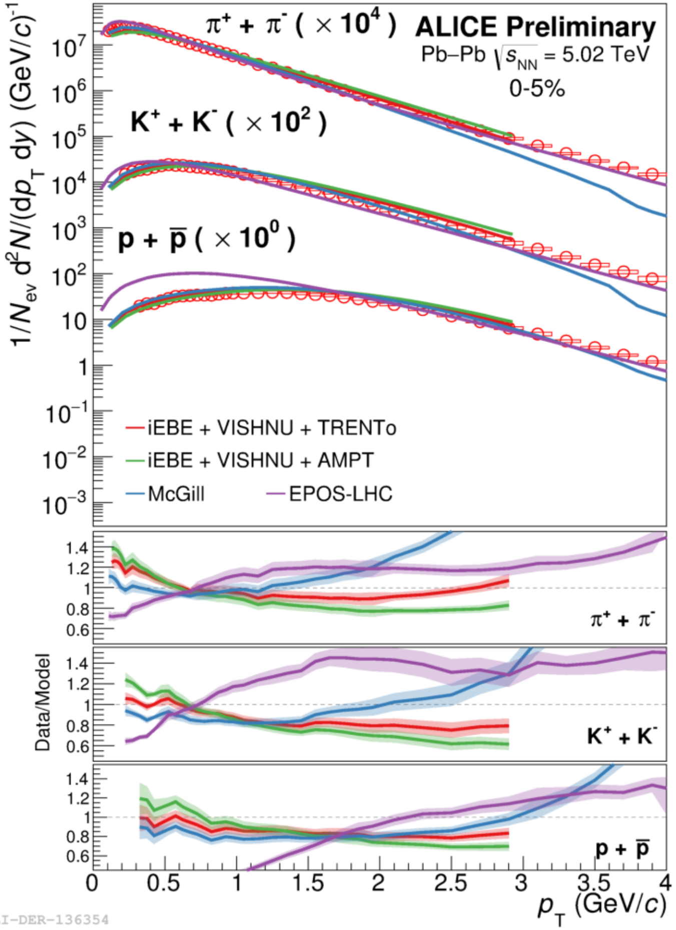
ALI-DER-139092

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

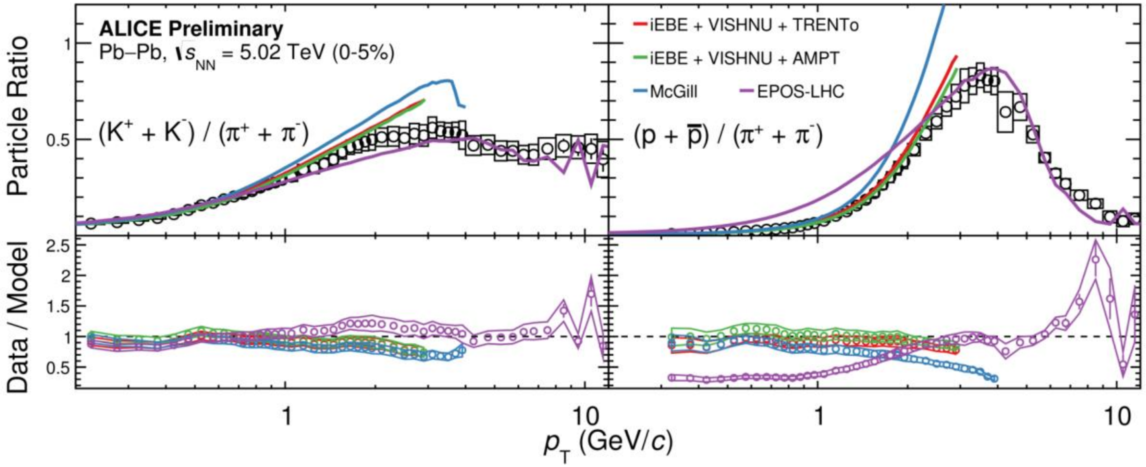
McGill: MUSIC viscous hydro with IP-Glasma initial conditions *[PRC 95 (2017) 064913]*

"**Full-hydro**" models reproduce features of particle spectra and ratios **below 2 GeV/c at 20-30% level**

Hydro model comparison – Pb-Pb 0-5%



ALI-DER-136354



ALI-DER-139092

EPOS-LHC: core (hydro) + corona *[PRC 92 (2015) 034906]* does not reproduce spectra but **qualitatively** captures the spectral **ratios up to higher p_T**

For tested models, agreement **worsens towards peripheral** events / low multiplicity (see backup)

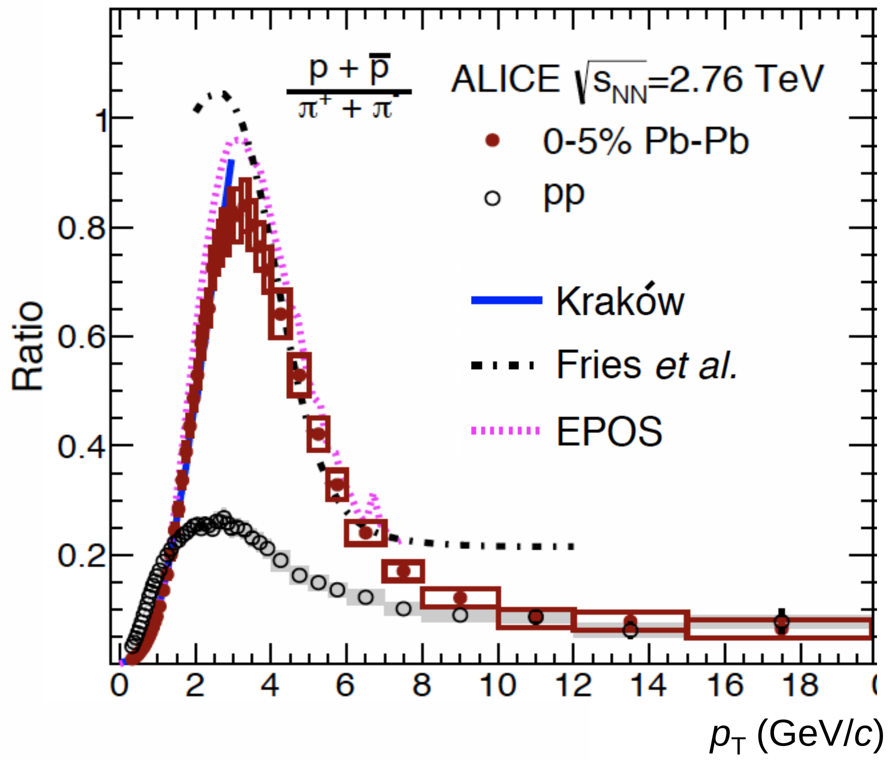
→ **Improvements** are needed to reproduce the evolution with multiplicity, also in view of **extension of hydro description to small systems**

Production mechanisms

Baryon-to-meson ratios are a powerful tool to test production mechanisms and their interplay

- **Low-p_T** rise described by hydro
- Models where **recombination** involves only soft thermal radially **flowing partons** consistent with data
- **High-p_T** p/π is the same in pp and Pb-Pb collisions
  → fragmentation dominates

ALICE, PLB 760 (2016), 196-207

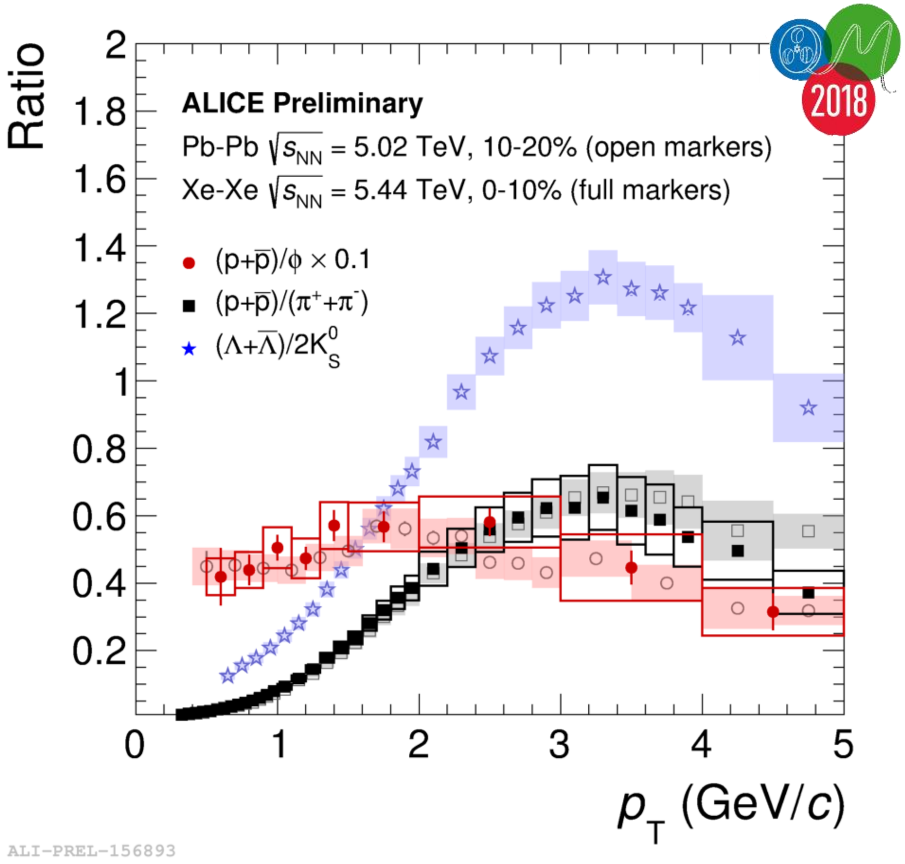


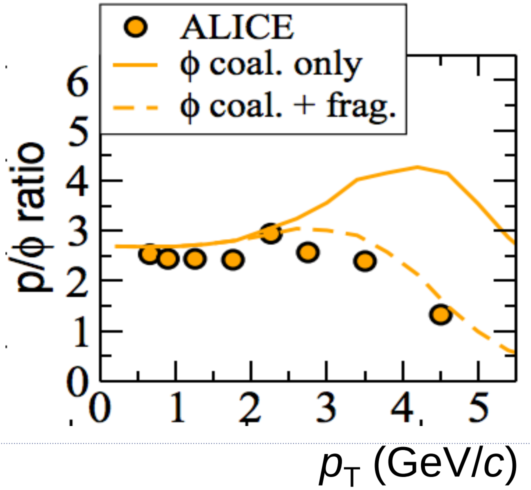
Role of recombination at intermediate p_T

Behaviour in Xe-Xe confirms observations in Pb-Pb at 5.02 TeV (ratios compared at similar multiplicity)

Pivotal role of the **ϕ-meson**, that has similar mass as the proton

- the **flatness of the p/ϕ** ratio is consistent with hydro but can be accommodated by models with recombination

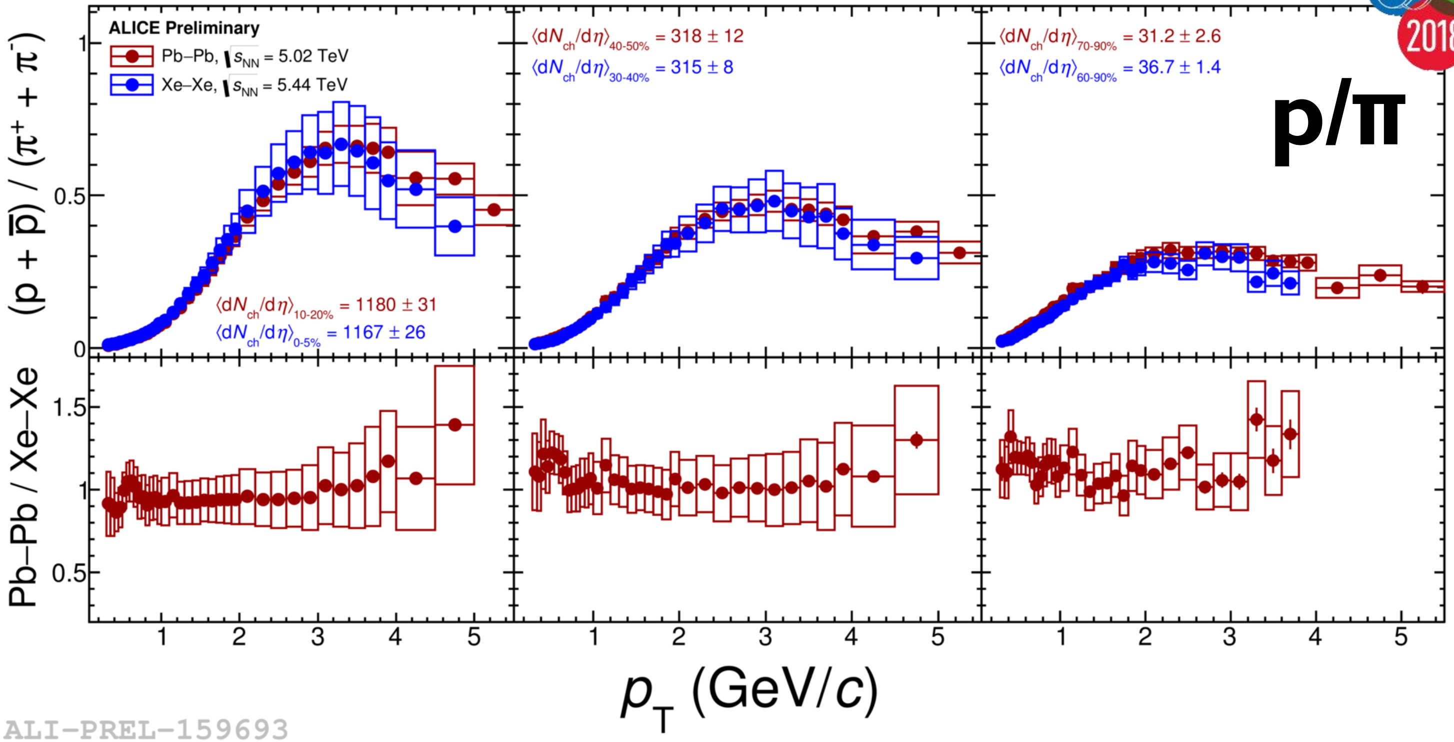




V. Greco at al, PRC 92 (2015) 054904

→ Still an **open point** on whether **recombination or flow** determine the spectral shape **at intermediate p_T**

System size evolution of dynamics



p/π

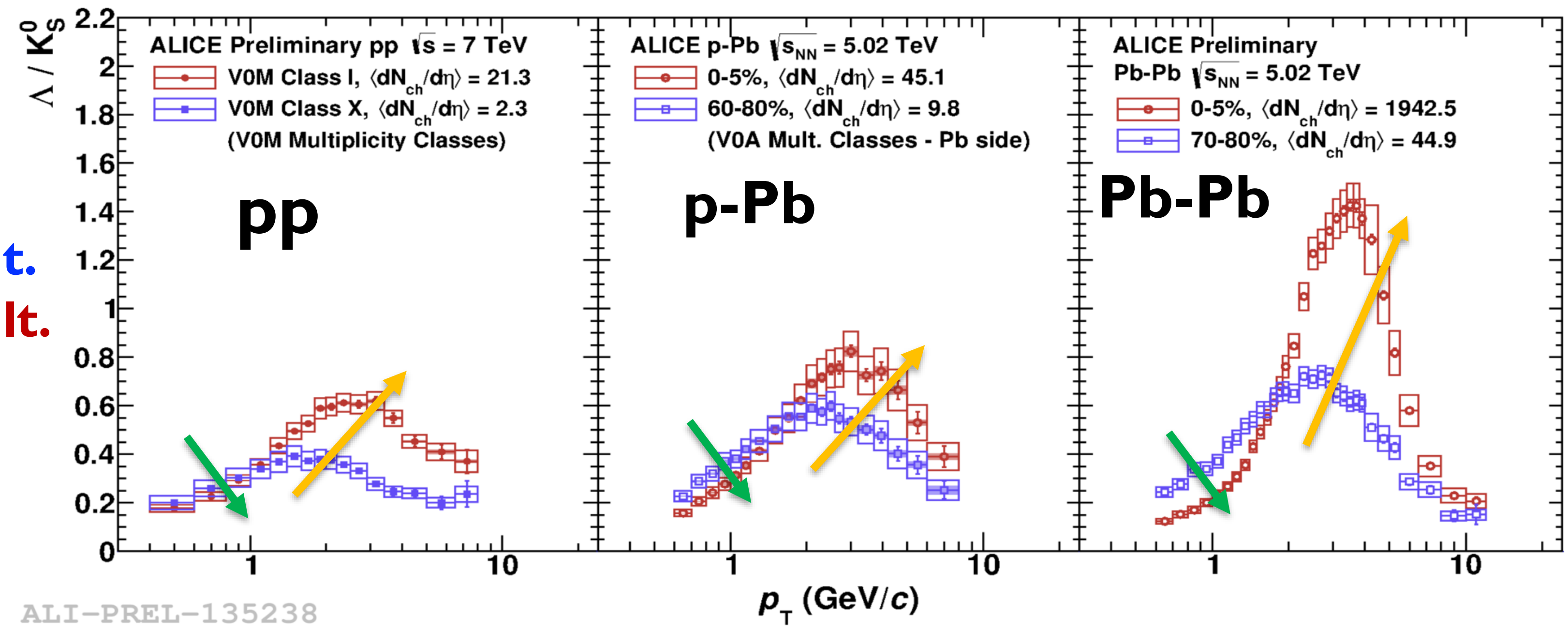
Particle ratios in Pb-Pb at 5.02 TeV and Xe-Xe at 5.44 TeV are **consistent** within uncertainties once **compared at the same multiplicity** (and not just centrality percentile)

Evolution with centrality in AA collisions and the shape of the p/π ratio are consistent with the presence of **radial flow** (mass dependence of spectral shapes)

…down to small systems

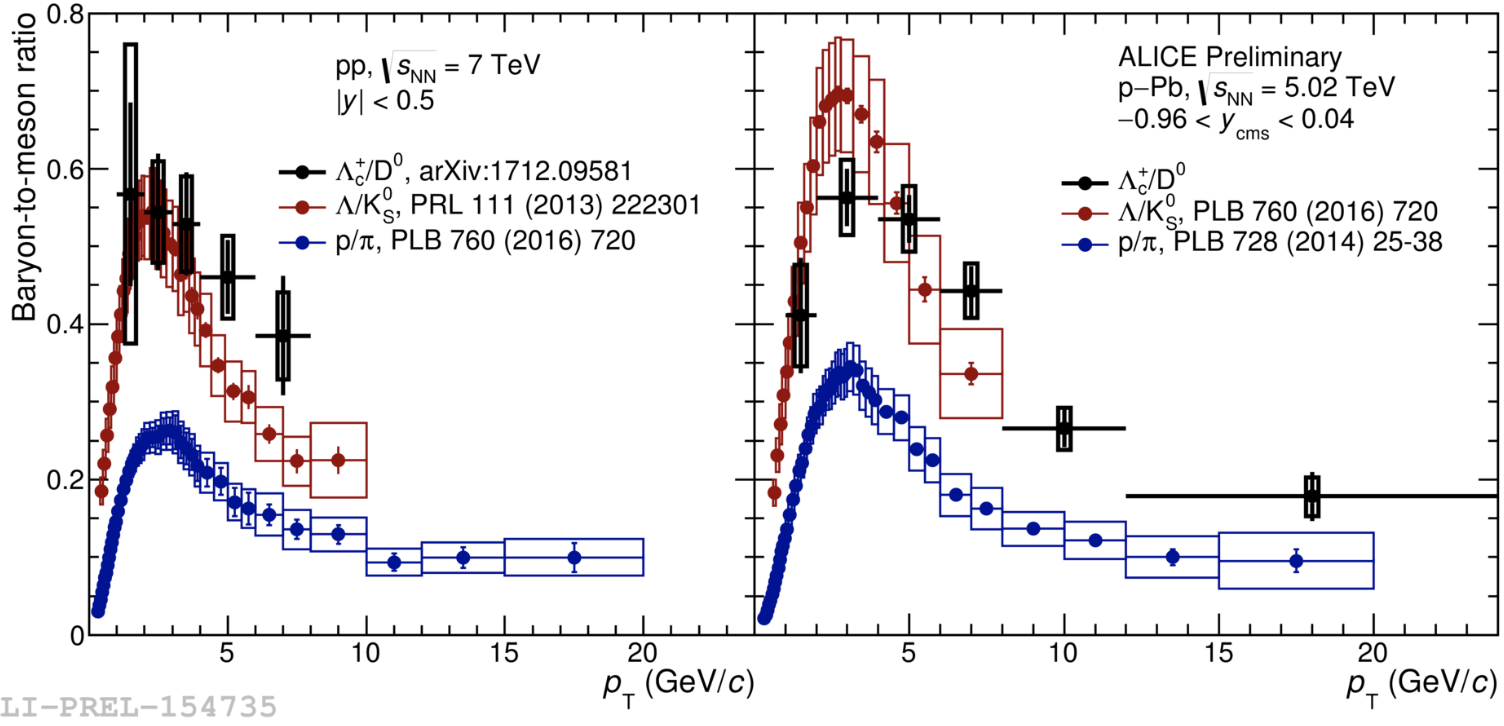
Low mult.

High mult.



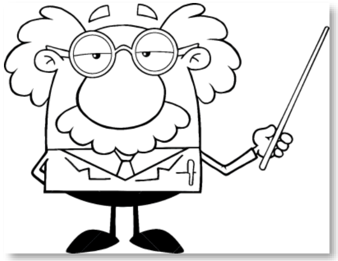
Across the three systems the baryon-to-meson ratios **evolve with multiplicity** in a qualitatively similar way

Baryon-to-meson – heavy-flavor sector



Heavy flavor baryon-to-meson ratio in small systems similar to light-flavors (Λ/K^0_S)

- Not reproduced by models (PYTHIA, etc… see backup)



We observe a continuous evolution of spectral shapes and ratios with multiplicity across different systems

In HI hydrodynamics works at low $p_{T,}$ interplay with recombination at intermediate p_T is still an open point

In small systems, origin of collectivity is still to be understood

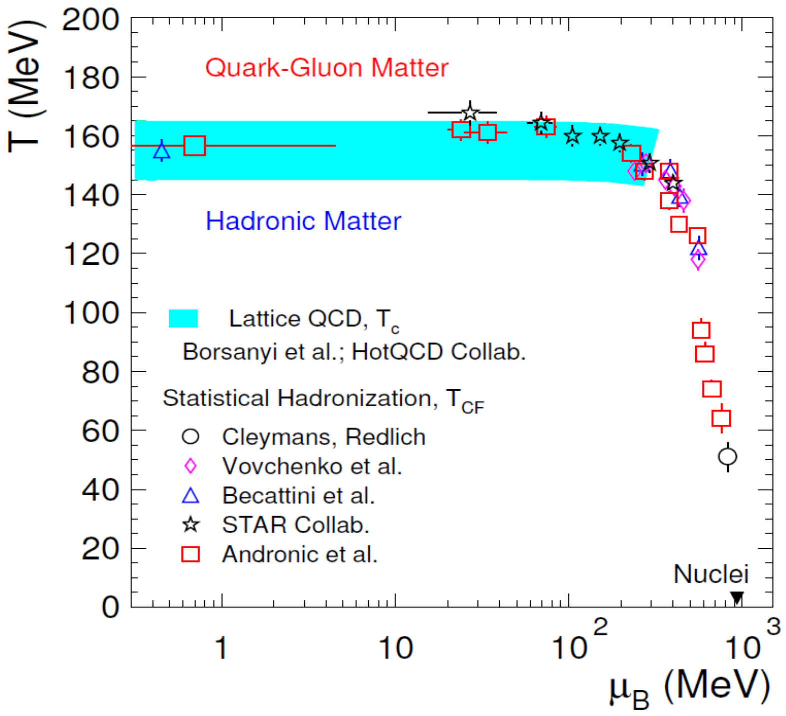
Statistical hadronisation model in a nutshell

Thermal fits map heavy-ion collisions to the QCD phase diagram and allow for comparison with lattice-QCD results.

Conventional picture: (ideal) hadron-resonance gas model in chemical equilibrium (based on Grand Canonical ensemble)

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

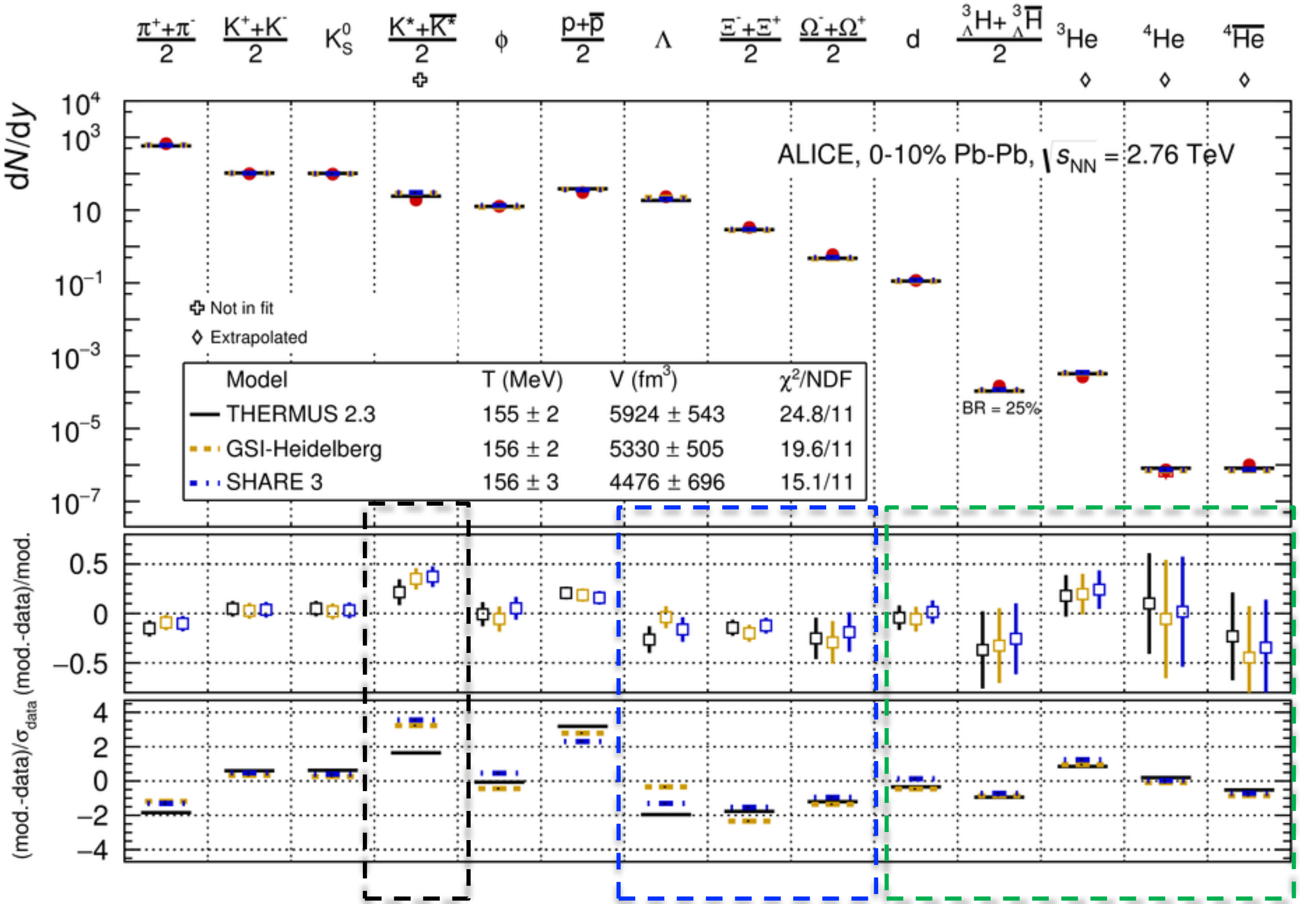
- Fit to yields: parameters μ_B, T_{ch}, V
- Thermal model fit to yields: V cancels out
- Fits based on minimization of χ^2
- Deviations from (GC) equilibrium through empirical under(over)-saturation parameters for strange, charm or light quarks (γ_s, γ_c, γ_q)



A. Andronic et al., *arXiv:1710.09425*

V. Vovchenko, LIGHT UP workshop

Thermal model fit to Pb-Pb 2.76 TeV (0-10%)



Production of (most) light-flavour hadrons described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature,

T_{ch} ≈ 156 MeV

Deviation for short-lived K^{*0} resonance

Tensions between protons and multi-strange

Nuclei included

Figure from *ALICE, Nucl. Phys. A 971 (2018) 1-20*
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 (2011) 142
SHARE: Petran et al, arXiv:1310.5108

Thermal model fit to Pb-Pb 5.02 TeV (0-10%)

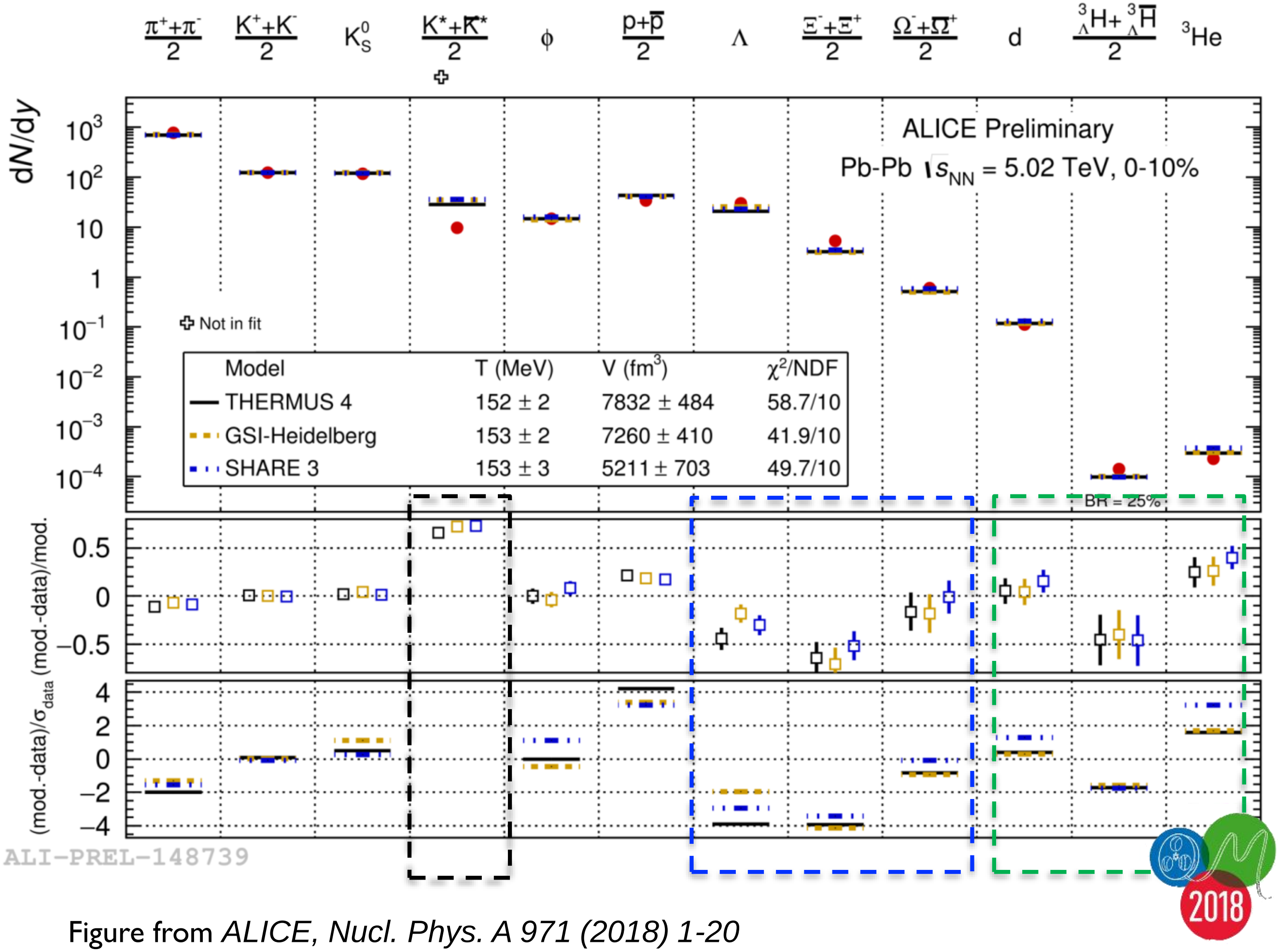


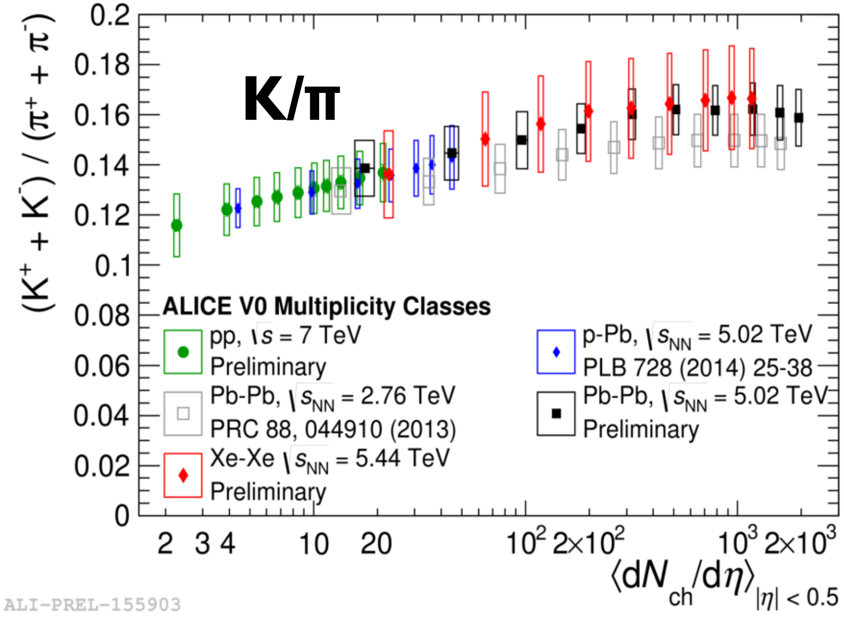
Figure from *ALICE, Nucl. Phys. A 971 (2018) 1-20*
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 (2011) 142
SHARE: Petran et al, arXiv:1310.5108

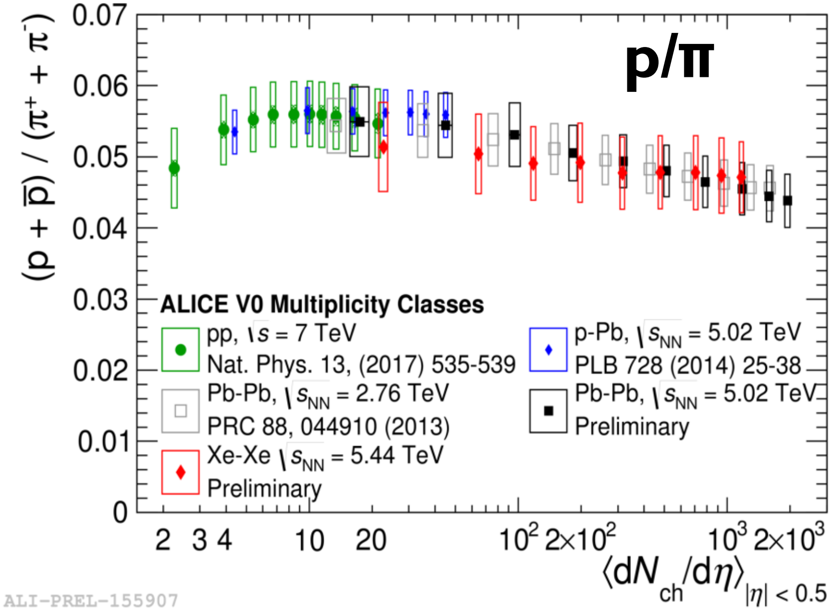
New preliminary ALICE data in **0-10% Pb-Pb at 5.02 TeV** can be fitted with a slightly lower temperature, **T ≈ 153 MeV** and higher χ^2/ndf ~ 4-6

Tensions between protons and multi-strange are **confirmed** at the new energy

- Strange particles prefer a higher temperature.

System size evolution of hadrochemistry





Chemistry is driven by **charged particle multiplicity**, i.e. the size of the system (regardless of its type and $\sqrt{s}$)

→ A further test for thermal model will be the fit to the Xe-Xe data, to check dependence on system size of Tch

Resonance suppression in central AA

Short-lived resonance ratios to long-lived particles are **suppressed as centrality increases** in AA collisions

✓ **ρ(770)/π** (ρ lifetime = 1.3 fm/c)

✓ **K(892)^0/K** (K* lifetime = 4.5 fm/c)

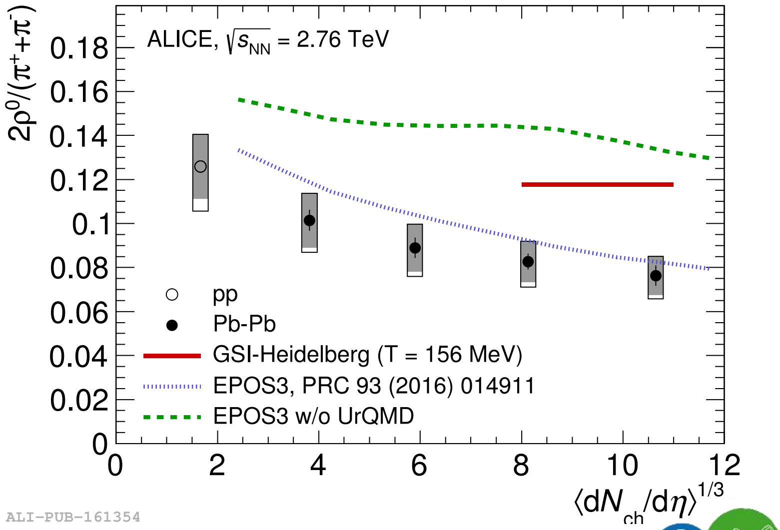
✓ **Λ(1520)/Λ** (Λ* lifetime = 12.5 fm/c)

✓ **Ξ(1530)/Ξ** (Ξ* lifetime = 22.5 fm/c)

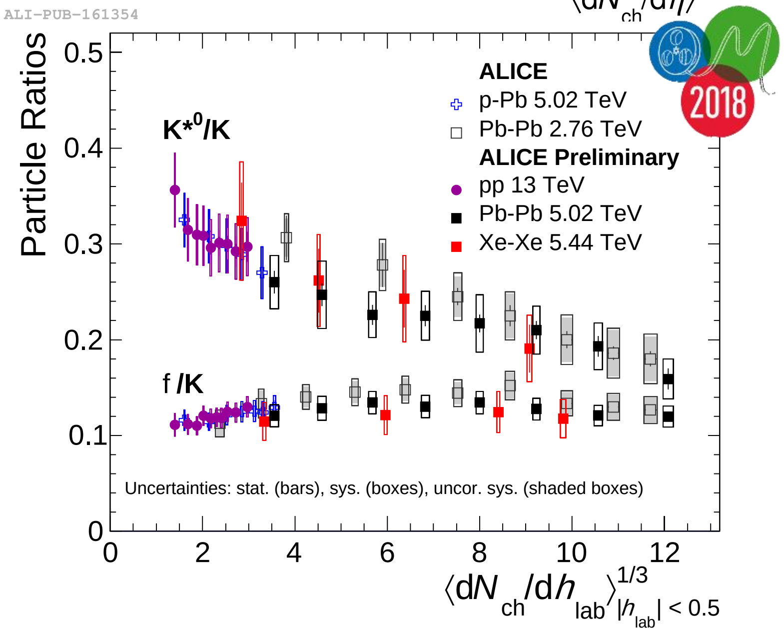
✗ **ϕ(1020)/K** (ϕ lifetime = 45 fm/c)

- Re-scattering effects expected to be stronger in central collisions, as the medium is denser and lasts longer
- Depending on the species, regeneration effects might be dominant → measure Sigma*!

arXiv:1805.04365



ALI-PUB-161354



Resonance suppression in central AA

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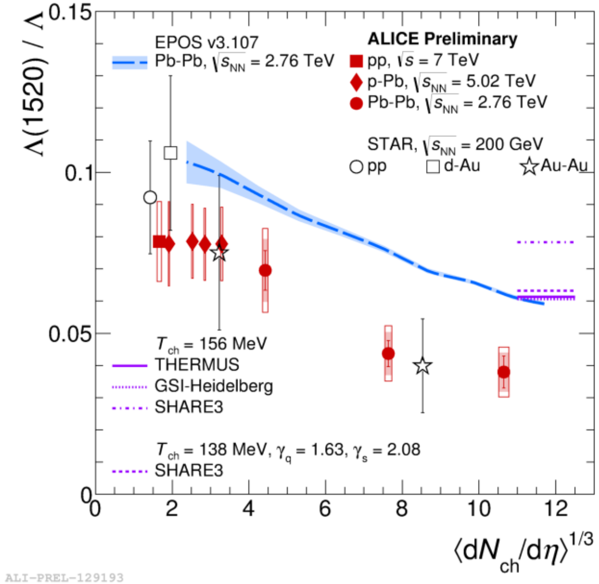
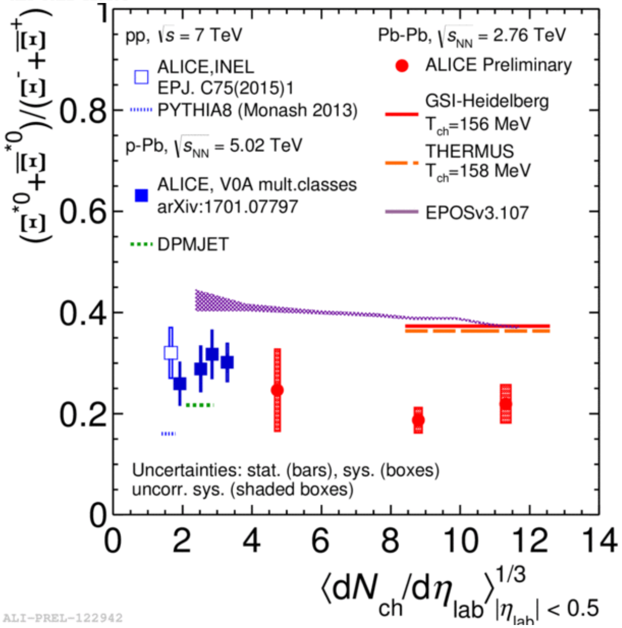
- ✓ **Λ(1520)/Λ** (Λ* lifetime = 12.5 fm/c)
- ✓ **Ξ(1530)/Ξ** (Ξ* lifetime = 22.5 fm/c)
- ✗ **ϕ(1020)/K** (ϕ lifetime = 45 fm/c)

- Re-scattering effects expected to be stronger in central collisions, as the medium is denser and lasts longer

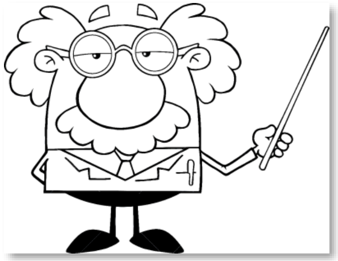
- Depending on the species, regeneration effects might be dominant → measure Sigma*!

arXiv:1805.04361





In thermal fits, differences between protons and strangeness sector observed at 2.76 TeV are confirmed at 5.02 TeV



Entering an era of precision tests for thermal model(s)

Important role of the hadronic phase for resonances. Is there more to the story (baryon annihilation for p)?

(Anti-)nuclei production

2 main models give predictions consistent in order of magnitude but based on different parameters:

Thermal production at chemical freeze-out/phase boundary

- Key parameters are mass and chemical freeze-out temperature:

$$\mathrm{d}N/\mathrm{d}y \sim \exp\left(-m/T_{\mathrm{ch}}\right)$$

- Model provides yields but no p_T spectra (no dynamics)

Coalescence of nucleons at kinetic freeze-out

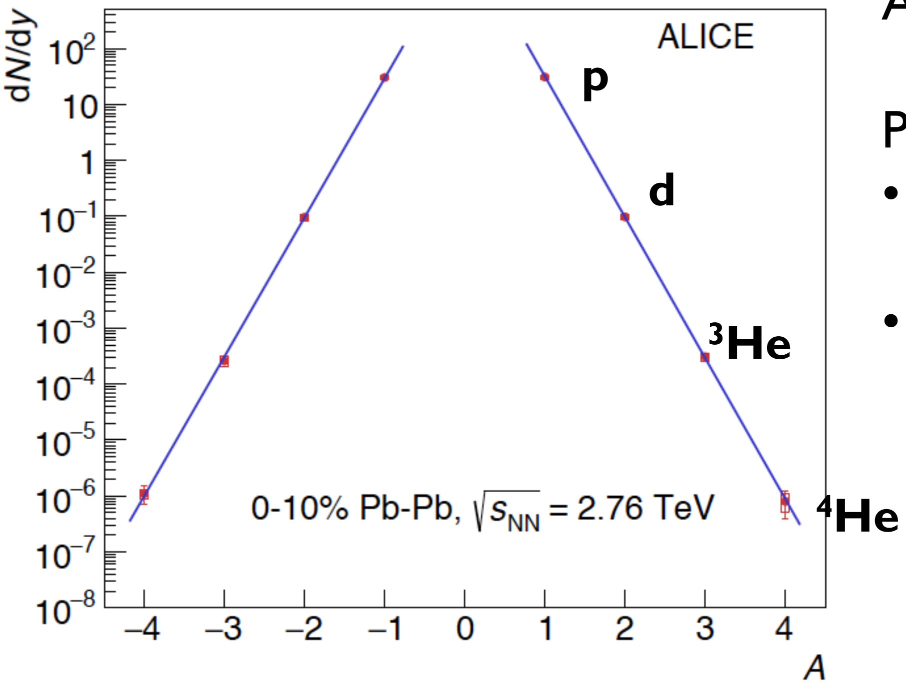
- Key parameters are nuclear wave functions, size of the (hyper)nucleus
- Production probability quantified by **coalescence parameter B_A**
- "Simple" coalescence model limited -- **source size to be included** in modeling
- Model provides spectra

$$\boxed{E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A}$$

Key measurements: multiplicity-dependence of nuclei with different sizes relative to the system size *[F. Bellini, A. Kalweit, in preparation]*

Nuclei are rare objects

ALICE Coll.. arXiv:1710.07531



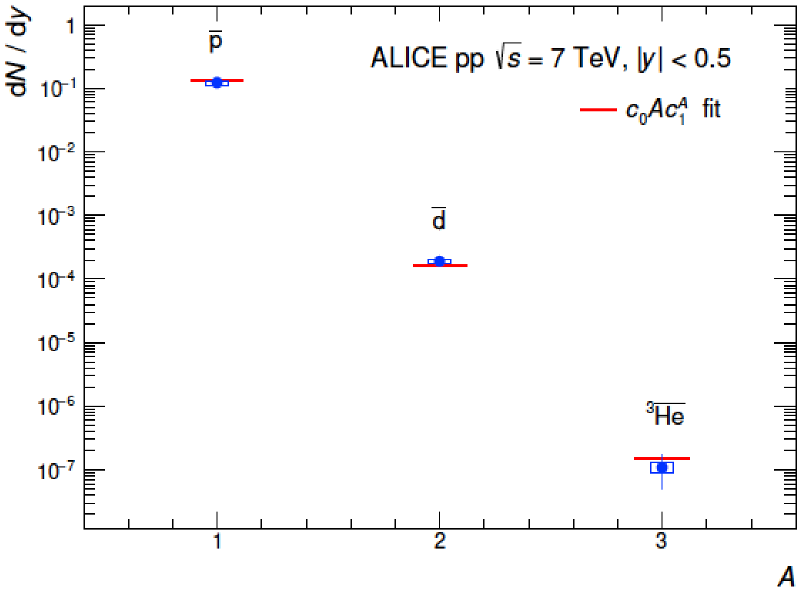
Anti-matter / matter ~ 1 at the LHC

Pb-Pb collisions:

- "penalty factor" for adding one nucleon ~ 300
- Consistency with thermal model expectations

pp/p-Pb collisions:

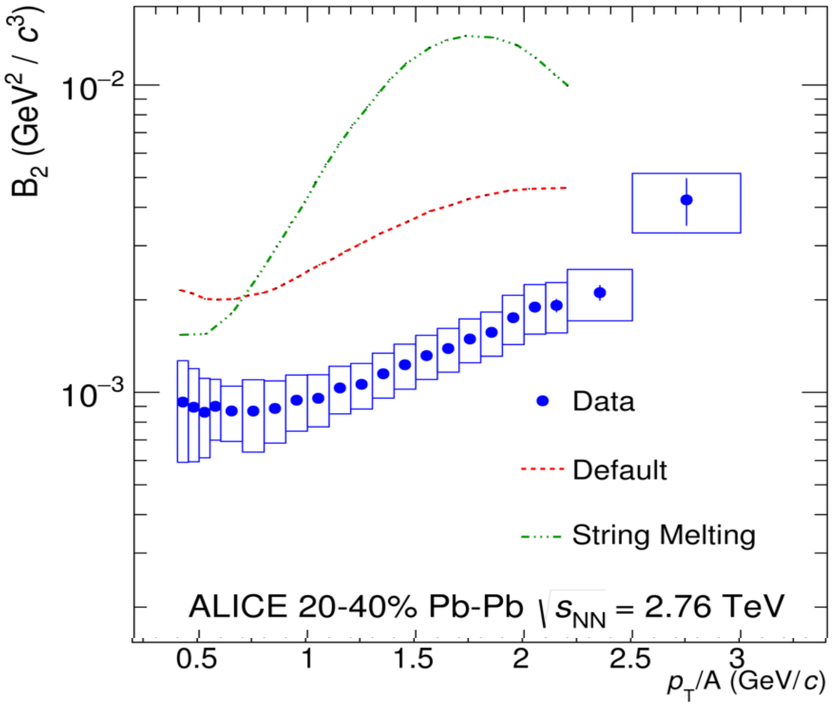
- "penalty factor" for adding one nucleon ~600-10^3



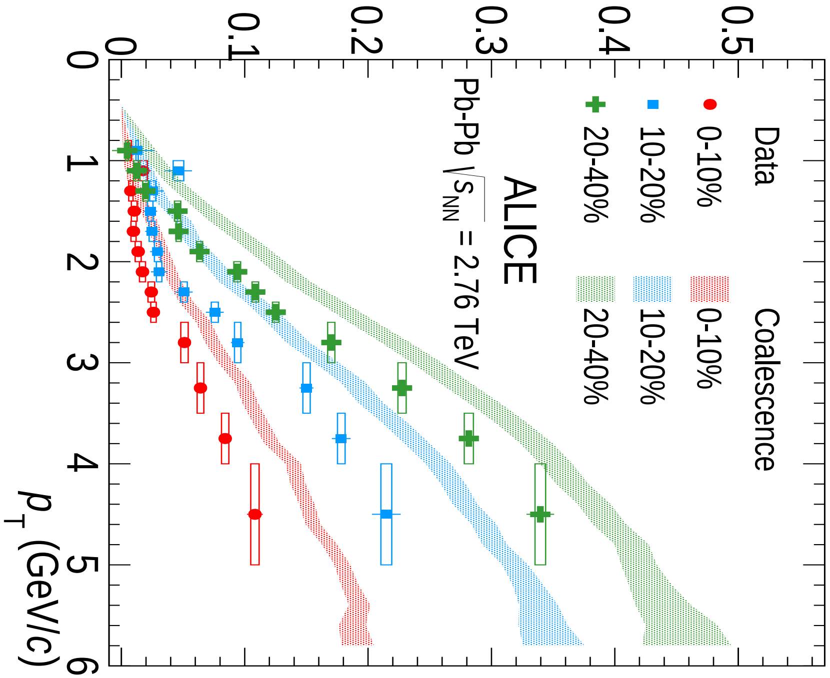
Deuteron flows in AA

Deuterons develop v_2, surviving in the fireball despite their low binding energy (B_E ~ 2.2 MeV)
→ Proposed deuteron as "6-quarks bag" formed thermally *(A. Andronic et al.)*

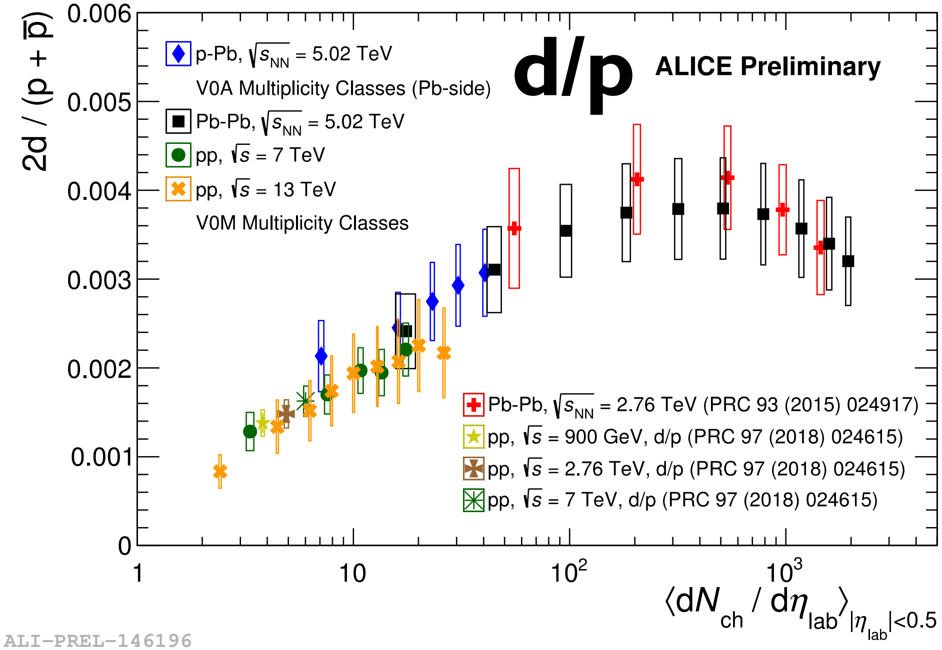
Simple coalescence fails in reproducing the deuteron B_2 and v_2



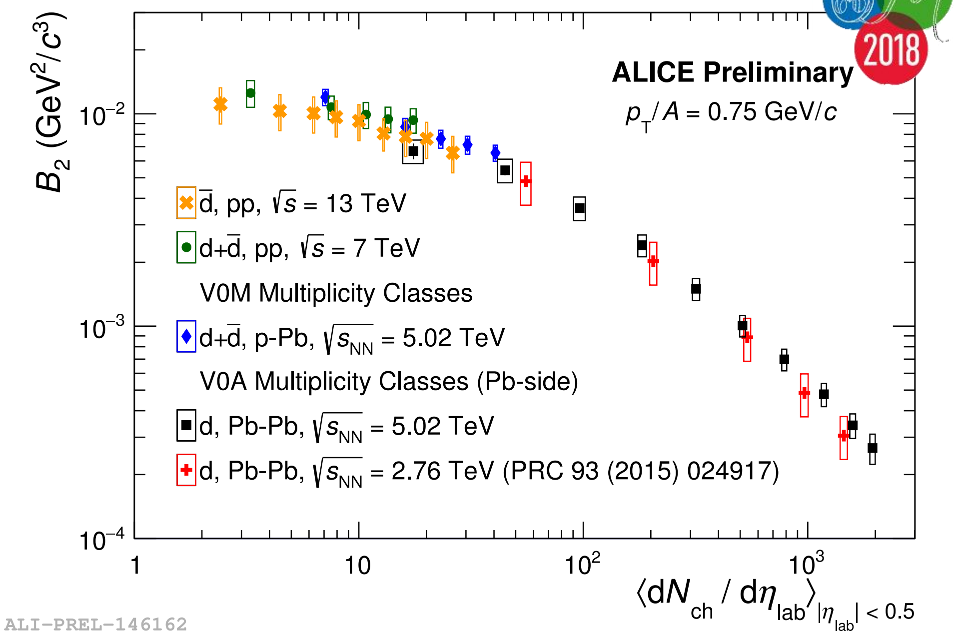
ALICE Coll., arXiv:1707.07304



Nuclei production across collision systems



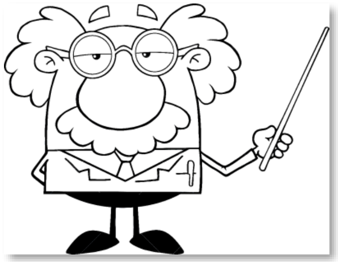
ALI-PREL-146196



ALI-PREL-146162

Smooth evolution of d/p ratio across systems and no significant $\sqrt{s_{NN}}$ dependence at $\mu_B = 0$

B_2 decrease with centrality in Pb-Pb is explained as an increase in the source volume (in “full” coalescence models, e.g. Scheibl-Heinz, Sato-Yazaki, Nagle, …)



Many new results in the nuclei sector at the LHC contribute to the systematic study of production mechanisms

Key measurements: multiplicity-dependence of nuclei with different sizes relative to the system size to probe coalescence vs thermal production

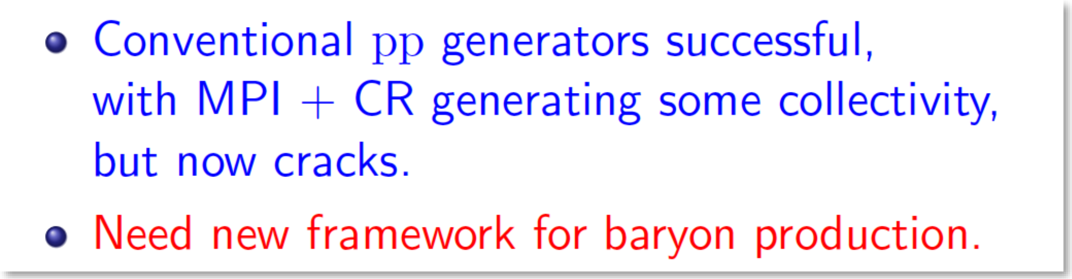
Strangeness production

Enhancement of strangeness from low to high multiplicity pp, p-Pb collisions, until saturation in Pb-Pb [ALICE, *Nat. Phys. 13, 535–539 (2017)*]

→ confirmed with new data from LHC Run II

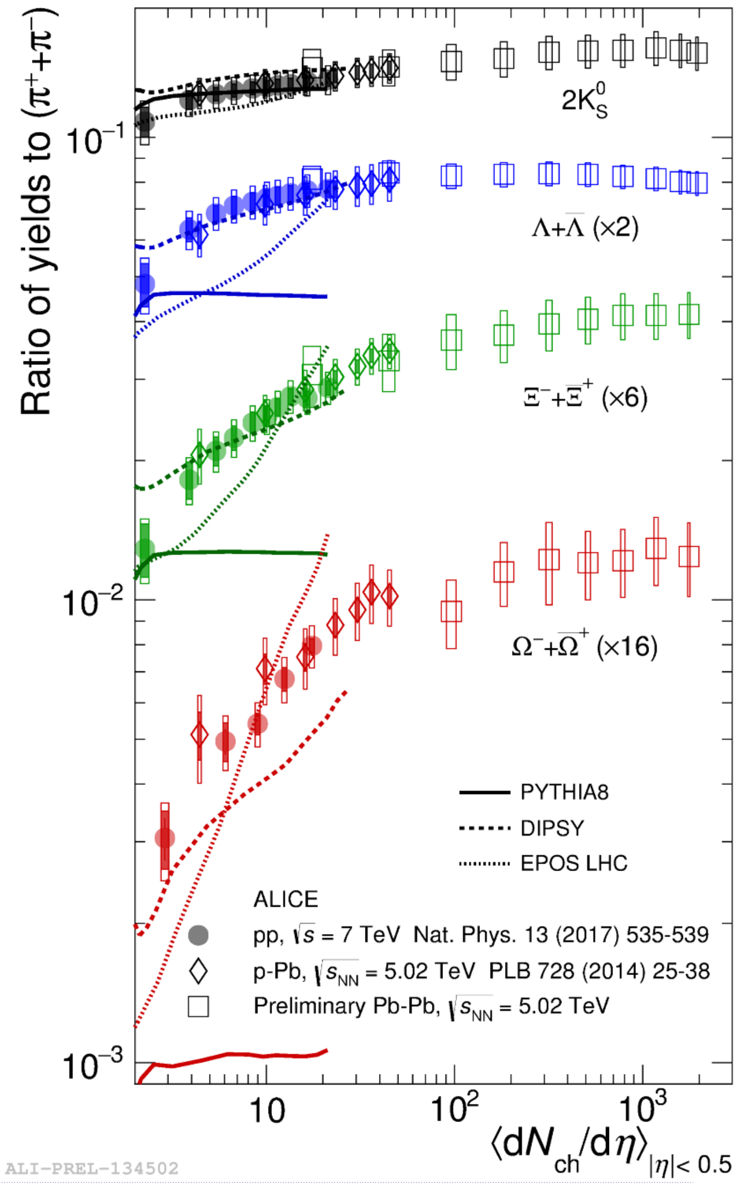
Ongoing efforts to explain behavior with models

- Lund string, color ropes (PYTHIA, DIPSY)
- core-corona (EPOS-LHC)
- thermal-statistical (canonical suppression)
  [V. Vislavicius, A. Kalweit, aXiv:1610.03001]



- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.

T. Sjostrand, Quark Matter 2018



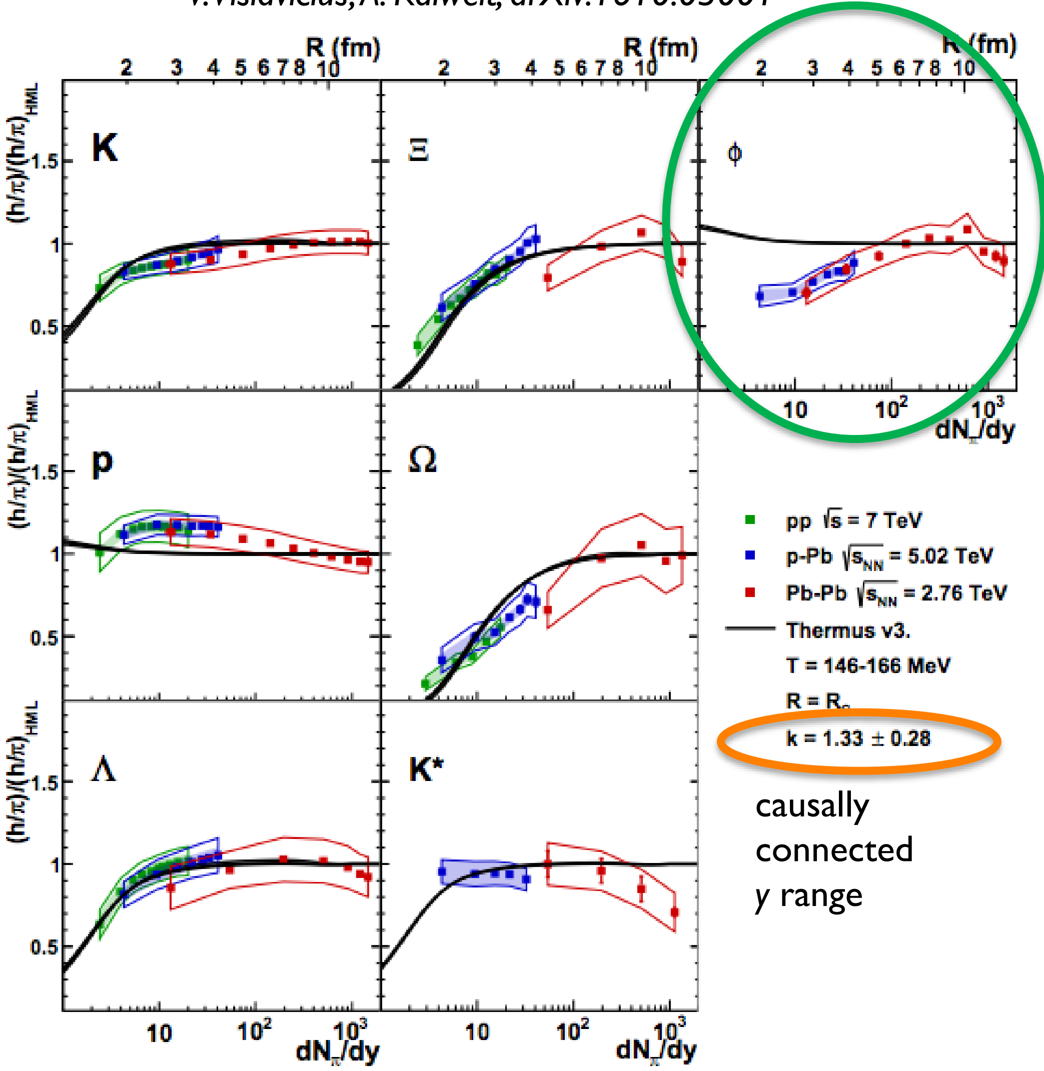
Strangeness canonical suppression

In equilibrium SHM models strangeness enhancement is a result of the **canonical suppression** of strangeness production **in small systems** due to the explicit **conservation** of the **strangeness** quantum number in a finite system

First comparisons to model calculations based on THERMUS code

→ agreement with data within uncertainties, **except for ϕ** meson (also "immune" to canonical suppression)

V. Vislavicius, A. Kalweit, arXiv:1610.03001



causally connected *y* range

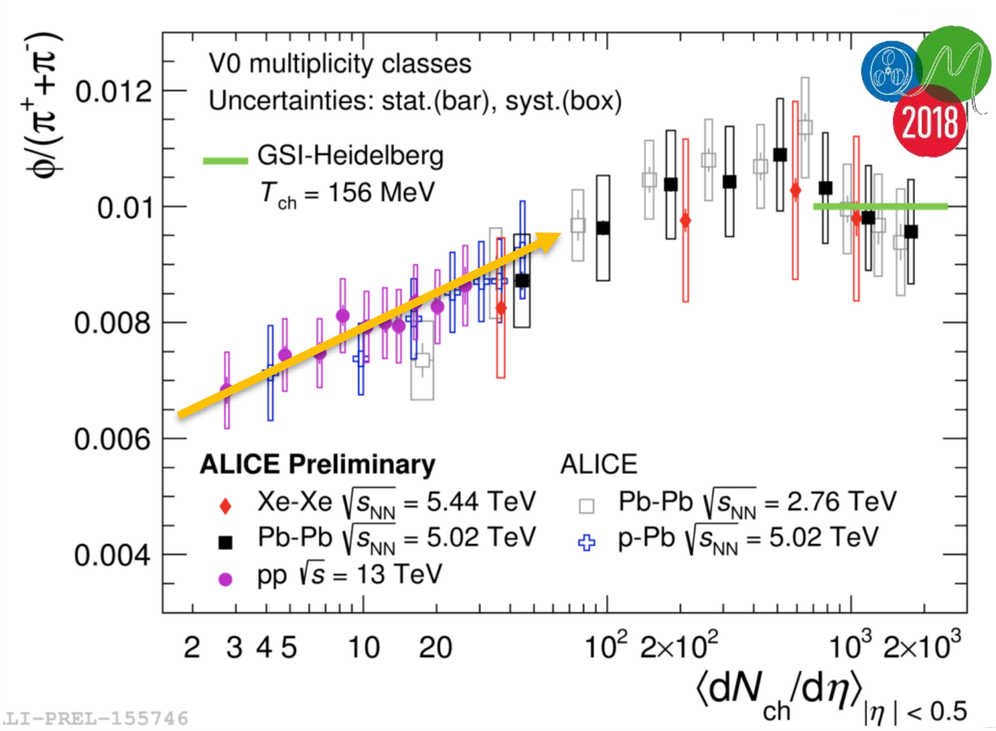
The special role of φ meson

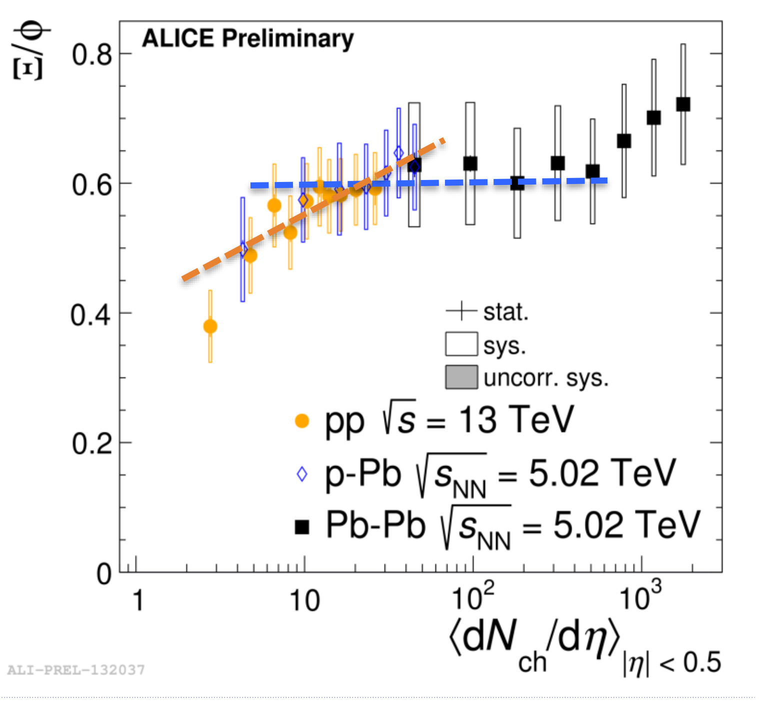
As a s-sbar pair (S=0) with the same mass as the proton, the ϕ meson is “special”

→ Does ϕ behave like a S=0 or S=2 particle?

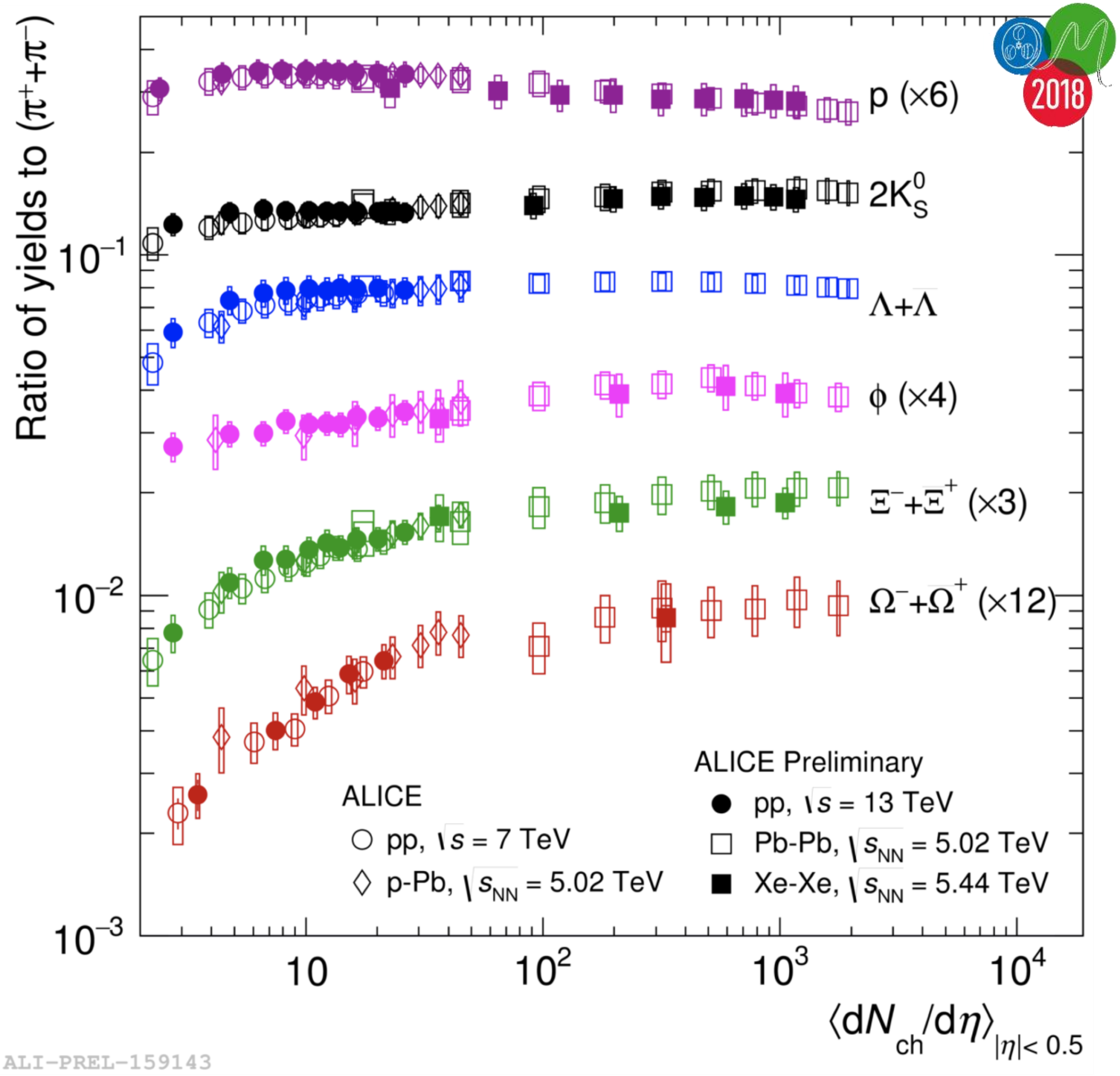
- Indications of increase of ϕ/π ratio with multiplicity in small systems
- Flat Ξ/ϕ for multiplicities between ~6 and ~700? Or slightly increasing in pp, p-Pb vs multiplicity?

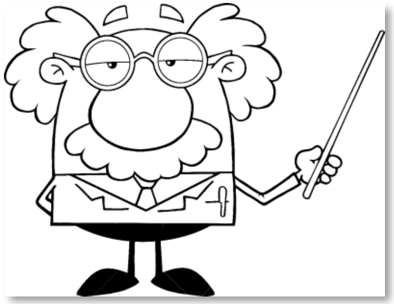
→ Need more precision from experiment!





System size evolution of hadrochemistry





Particle composition evolves smoothly across collision systems, depending on charged particle multiplicity.

Common origin in all systems?

For MC generators, work is still needed to reproduce evolution with system size in view of a unified description of all collision systems

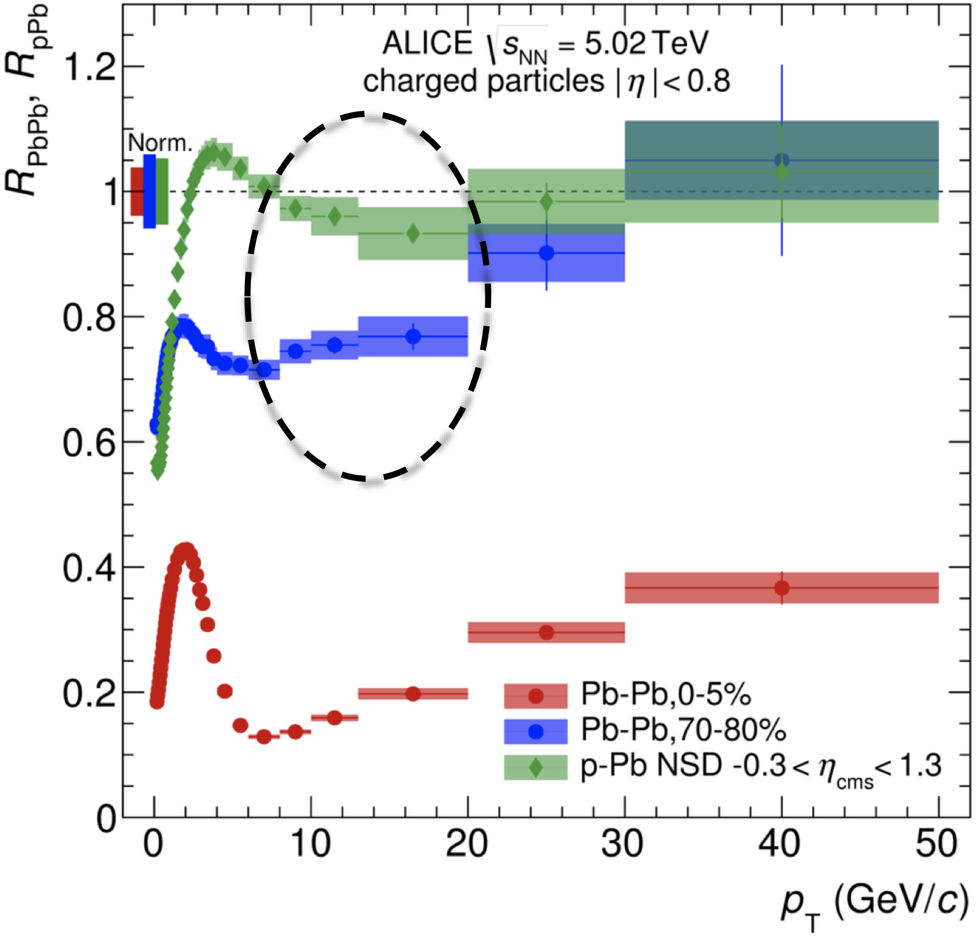
Collectivity but no jet quenching?

Similarities are observed for flow observables between **peripheral Pb-Pb and high multiplicity p-Pb** collisions.

New and more precise measurements from ALL experiments on nuclear modification factors.

In (minimum bias) **p-Pb**, no suppression at high-p_T is observed, contrary to **peripheral Pb-Pb.**

→ Do we understand this?



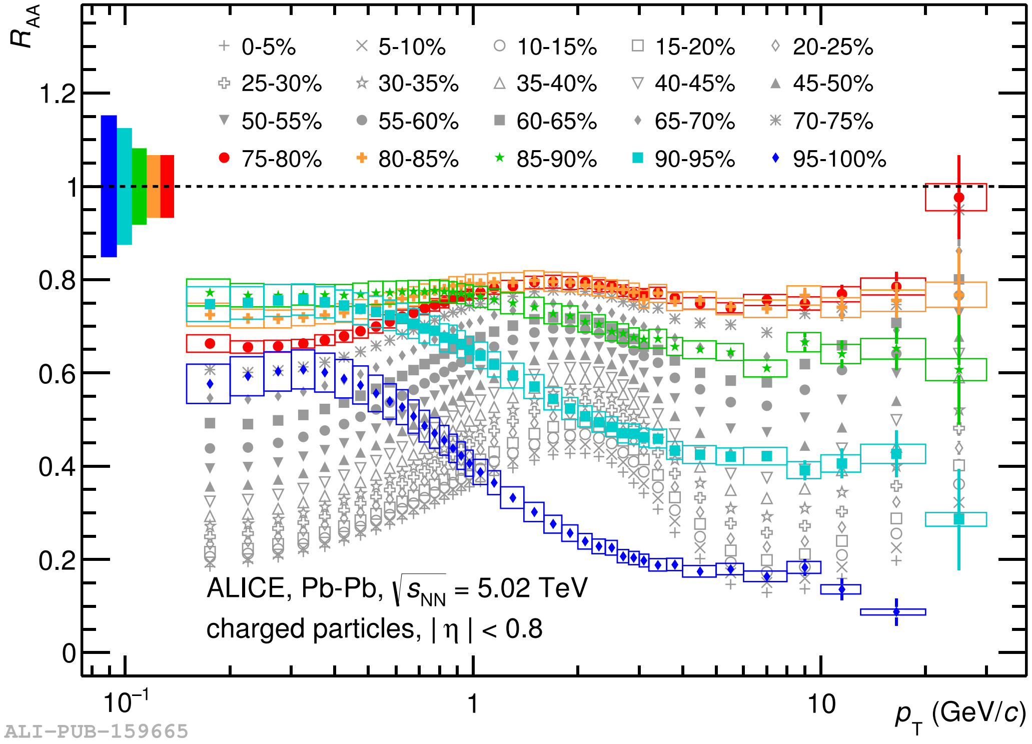
ALICE, arXiv:1802.09145

Nuclear modification in very peripheral collisions

New measurement in very fine centrality bins!

Strong change of behaviour of R_{AA} beyond 80% centrality

ALICE, arXiv:1805.05212



Nuclear modification in very peripheral collisions

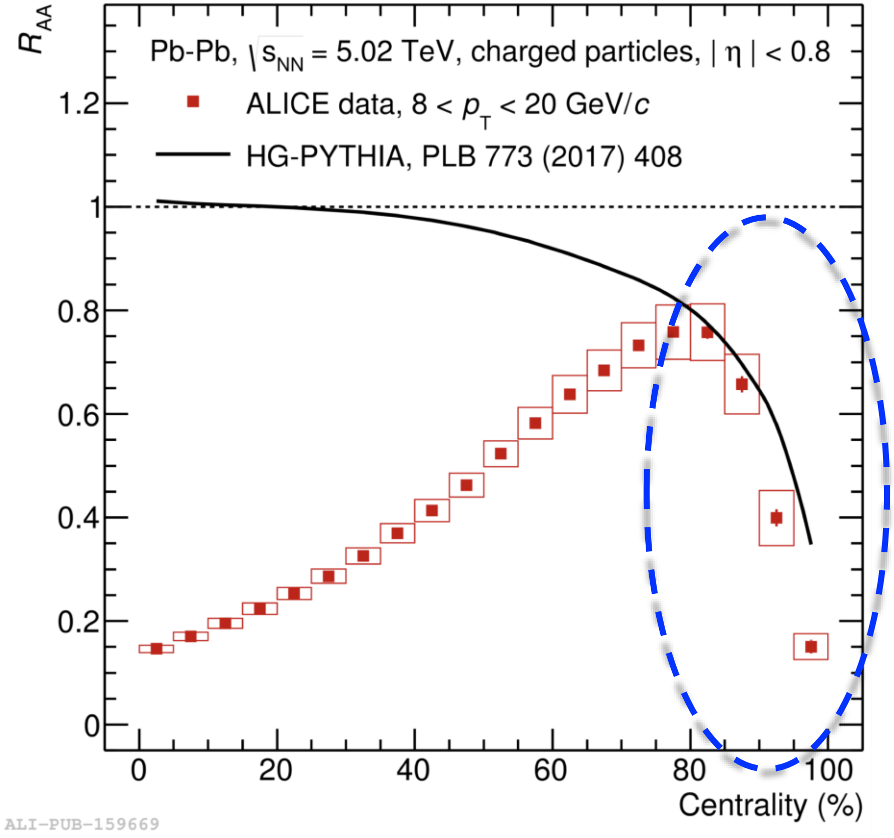
New measurement in very fine centrality bins!

Strong change of behaviour of R_{AA} beyond 80% centrality

→ reproduced by HG-PYTHIA with **biases** in event selection and collision geometry, and no nuclear modification.

Considering this, the jet quenching signal is smaller than typical systematics above ~80% centrality → **consistent with R_{pPb}**

ALICE, arXiv:1805.05212



Conclusions and outlook

Continuity in chemistry and dynamics across collision systems (dependence on charged particle **multiplicity**) is observed.

pp, p-nucleus collisions are much more than a "reference" for heavy-ion collisions

MC generators can generate collective-like behaviour but **fail in the details** of hadron (baryon) production as a function of multiplicity.

Absence of jet-quenching in small systems remains as the main **challenge to the final-state effect interpretation**.

Origin of collectivity in small systems is still **to be understood**.

STRANGENESS

Strangeness from the HI perspective

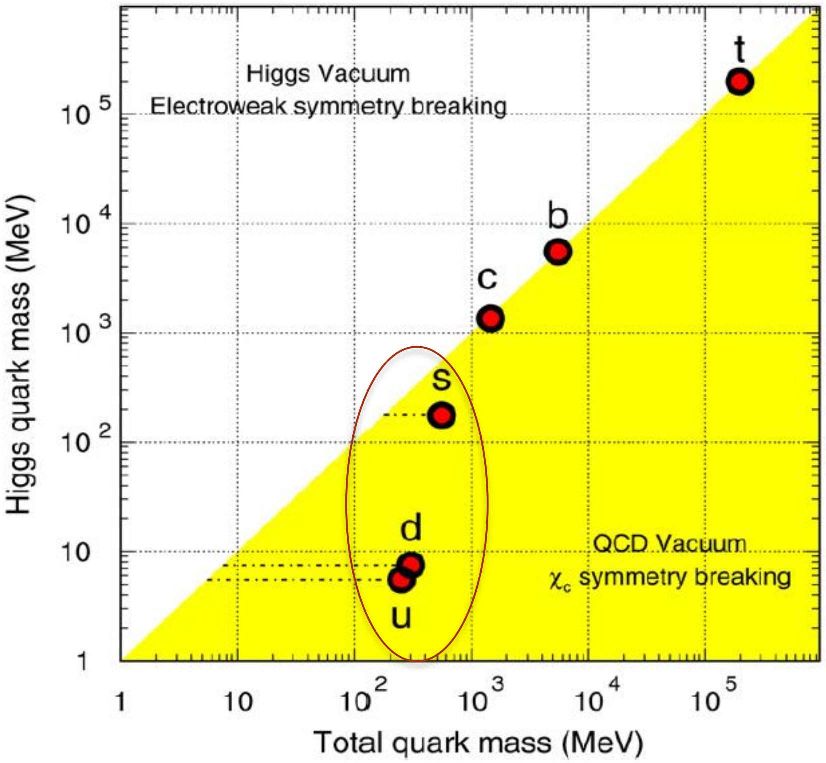
- ~300 MeV are enough to create an $s\bar{s}$ pair[1] (even less if $m_s^{QCD} \rightarrow m_s^{Higgs}$ by restoration of chiral symmetry in the QGP phase)

- Strange quarks are dominantly produced by (thermalised[2]) gluon fusion in QGP

- Strangeness enhacement wrt pp collisions historically proposed as signature for a deconfined QGP[3]

- pp collisions as reference

arXiv:nucl-ex/0610043



[1] PDG group, Chin. Phys. C38 (2014) 090001
[2] E. Shuryak, Phys. Rev. Lett. 68 (1992) 3270
[3] J. Rafelski and B. Muller, PRL 48 (1982) 1066

$\boldsymbol{m_u} \approx 2.3$ MeV
$\boldsymbol{m_d} \approx 4.8$ MeV
$\boldsymbol{m_s} \approx$ **96 MeV**

$< \Lambda_{QCD}$
$<< \boldsymbol{m_c} \approx 1.3$ GeV

Strangeness from the pp perspective

- Producing strangeness is "expensive"
  → threshold problem

  E.g. in the Lund String model

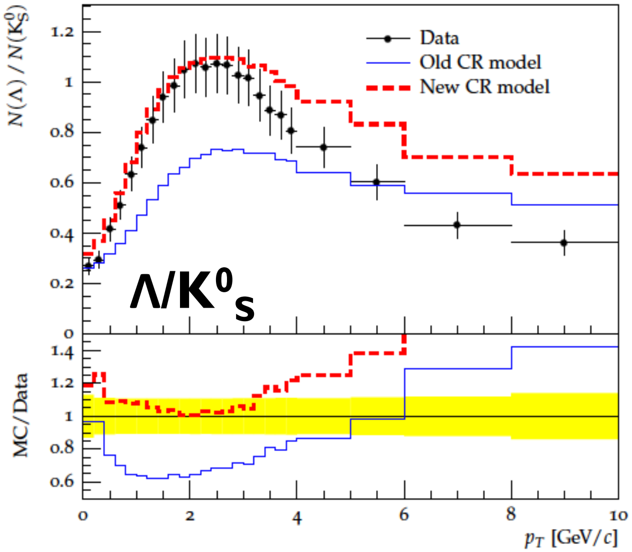
  $$\mathrm{Prob}(m_q^2, p_{\perp q}^2) \propto \exp\boxed{\left(\frac{-\pi m_q^2}{\kappa}\right)} \exp\left(\frac{-\pi p_{\perp q}^2}{\kappa}\right)$$

  E.g. in a hadron gas
  π + π → π + π + Λ + Λ-bar, $E_{th} \sim 2200$ MeV

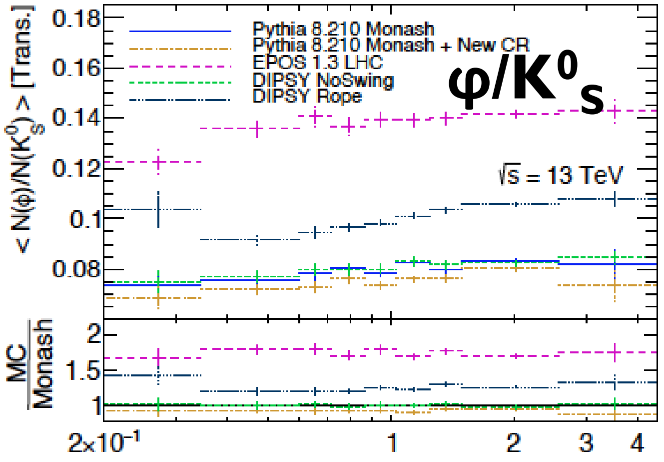
- Measurements of strange hadron production used as input for tuning Monte Carlo generators

- Contribute to the understanding of the rich structure of the underlying event arising from MPI in pp, p-Pb collisions

J.R. Christiansen, P. Skands, JHEP 08 (2015) 003



P. Skands et al. arXiv:1603.05298



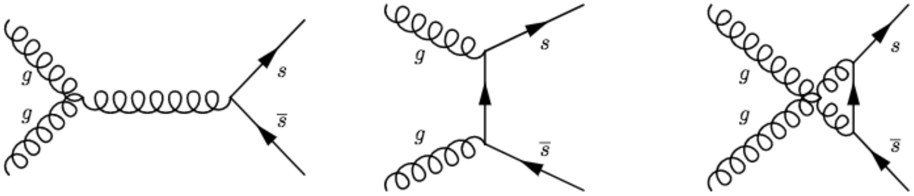
Relative transverse activity, R_T

Strangeness production in QGP

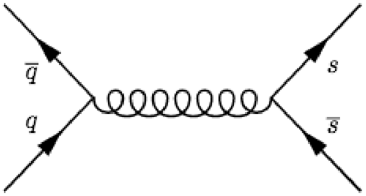
- ~300 MeV are enough to create an s-sbar pair (even less if $m_s^{QCD} \rightarrow m_s^{Higgs}$ by restoration of chiral symmetry)
- gluon fusion (a) is the dominant mechanism for strangeness production over quark annihilation (b)
  - Gluons quickly thermalise in t < 1 fm/c

  [E. Shuryak, Phys. Rev. Lett. 68 (1992) 3270]
- The backward reaction of (b) depends on the s quark density, thus on the QGP lifetime → saturation of strangeness abundance
- After hadronisation, the abundance of (multi)strange hadrons reflects that of strangeness in the partonic phase
  - If the hadronic phase is short enough to avoid re-diffusion
  - For small hadronic cross sections

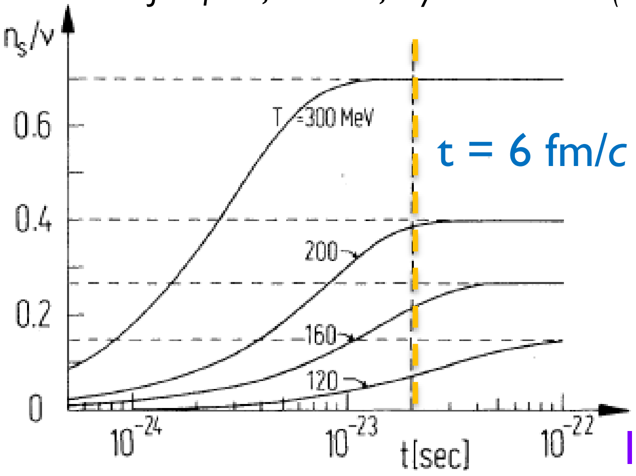
(a) $gg \rightarrow s\bar{s}$



(b) $q\bar{q} \rightarrow s\bar{s}$



J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066

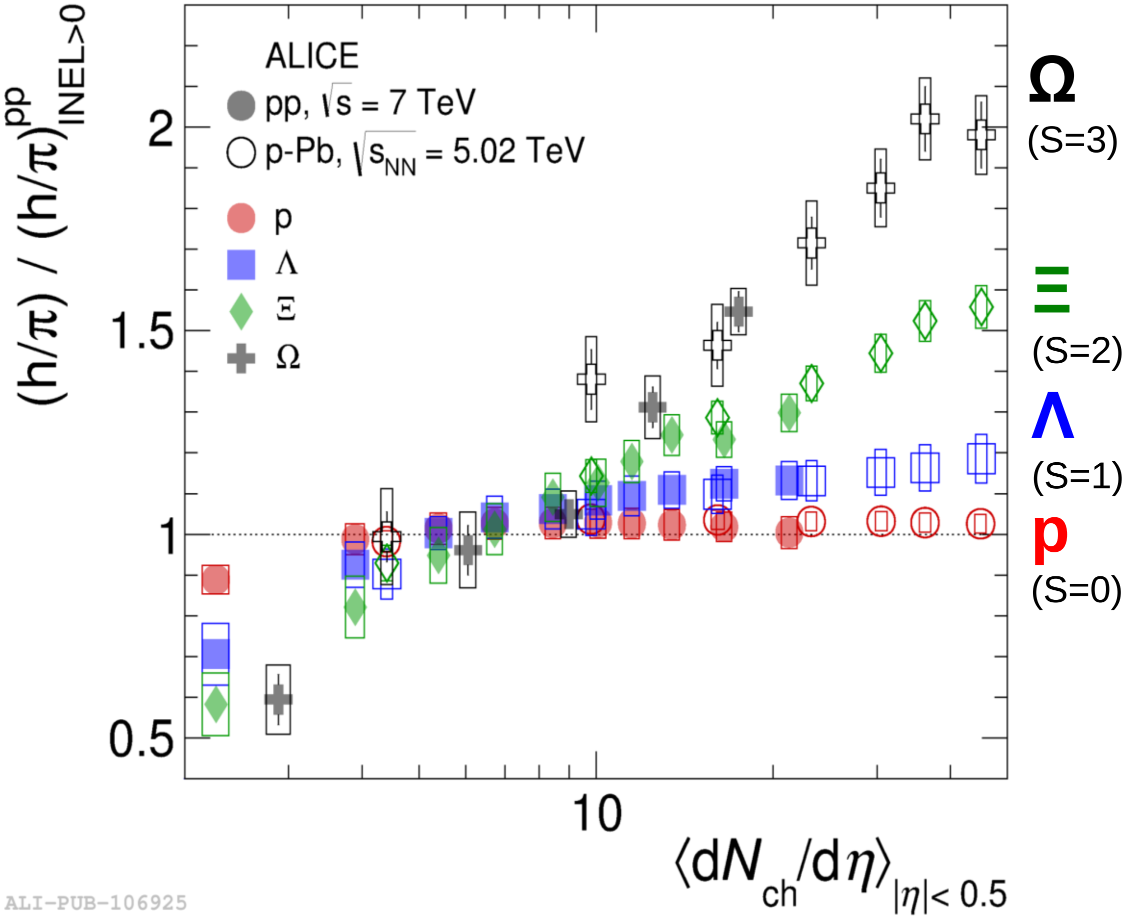


t = 6 fm/c

lifetime

FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various

Strangeness enhancement in pp



No increase for p/π is observed

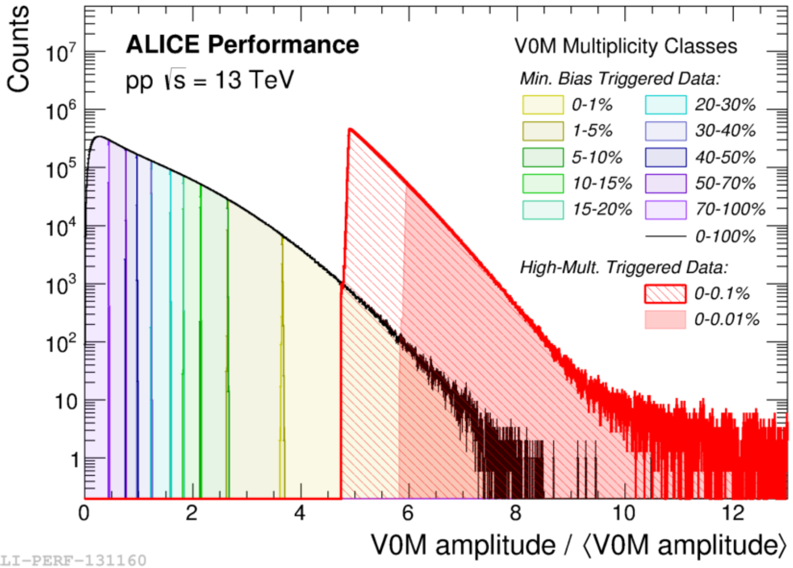
Hierarchy of the increase associated **with the strangeness content**

What's next?

① *Does strangeness keep increasing with multiplicity or saturate?*

High multiplicity-triggered data sample in pp 13 TeV (2016, 2017) being analysed

Measure in p-Pb at 8.16 TeV, Xe-Xe at 5.44 TeV, more differential in peripheral Pb-Pb collisions (2018)



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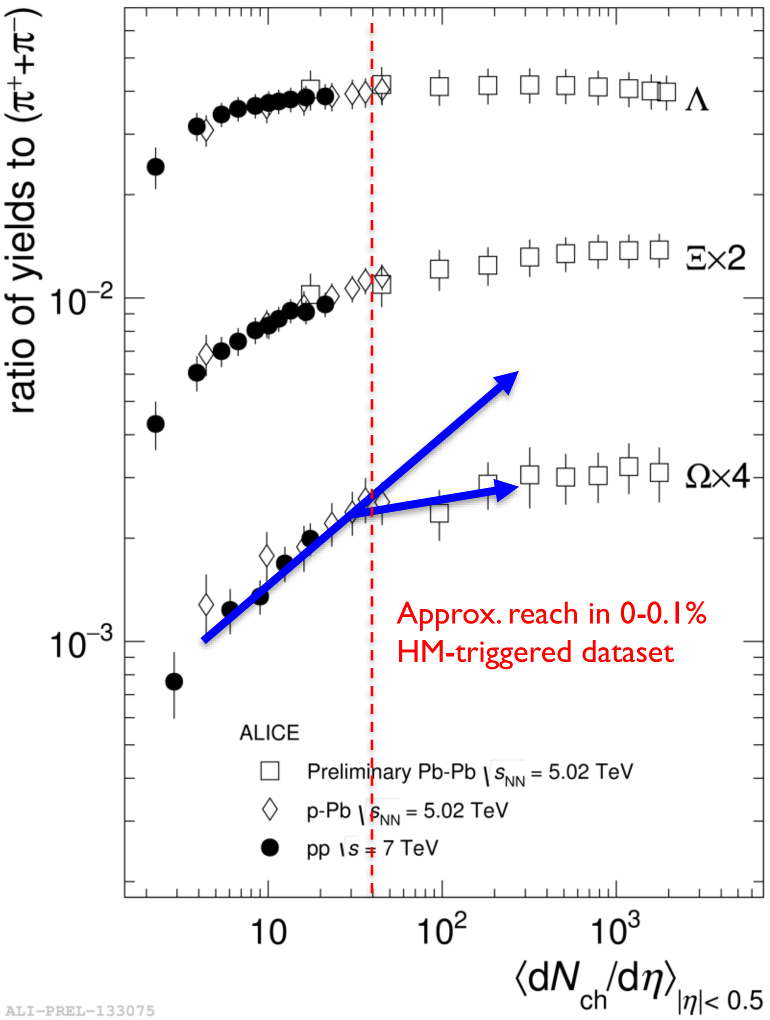


Approx. reach in 0-0.1% HM-triggered dataset

ALI-PREL-133075

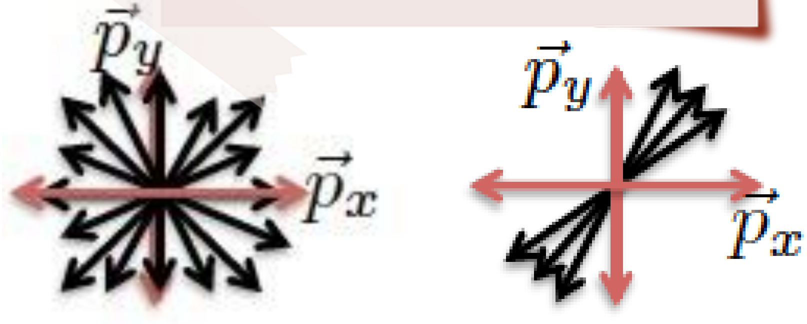
What’s next?

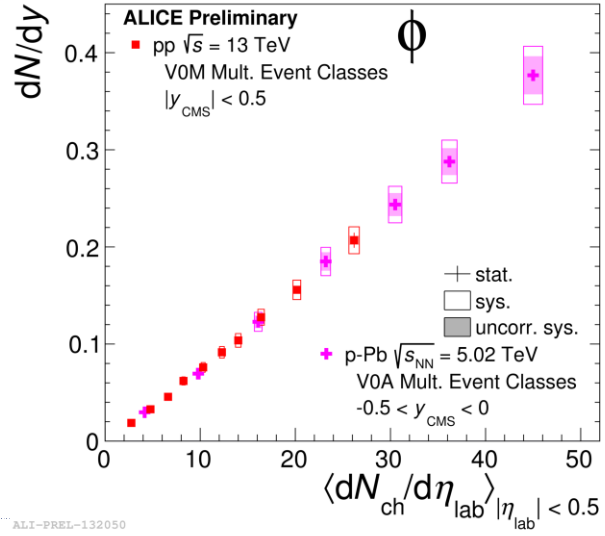
② *Can we relate high multiplicity with soft- or hard-QCD dominated processes?*
Use event shapes as tools to select jetty/isotropic events in high multiplicity pp

② *Can the ϕ meson provide further insights on strangeness production vs multiplicity?*
Measure more differential (event shapes?), extract φ/π, improve precision

③ *New observables…*

Ongoing studies on inclusive charged and identified particle production vs transverse spherocity and multiplicity





COLLECTIVITY IN SMALL SYSTEMS

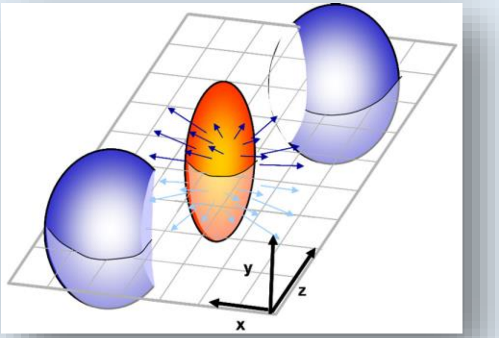
Collectivity (in short)

"Loose" definition: correlations of (more than 2) particles across rapidity due to a common source

Origin of collectivity:

- **Initial state** correlations → among hadrons in the final state arise from momentum correlations at partonic level [gluon saturation, CGC]
- **Final state** correlations → anisotropies and correlations in space converted into anisotropies in momentum space, e.g. via hydrodynamic flow [established in Pb-Pb collisions]

Flow in heavy-ion collisions



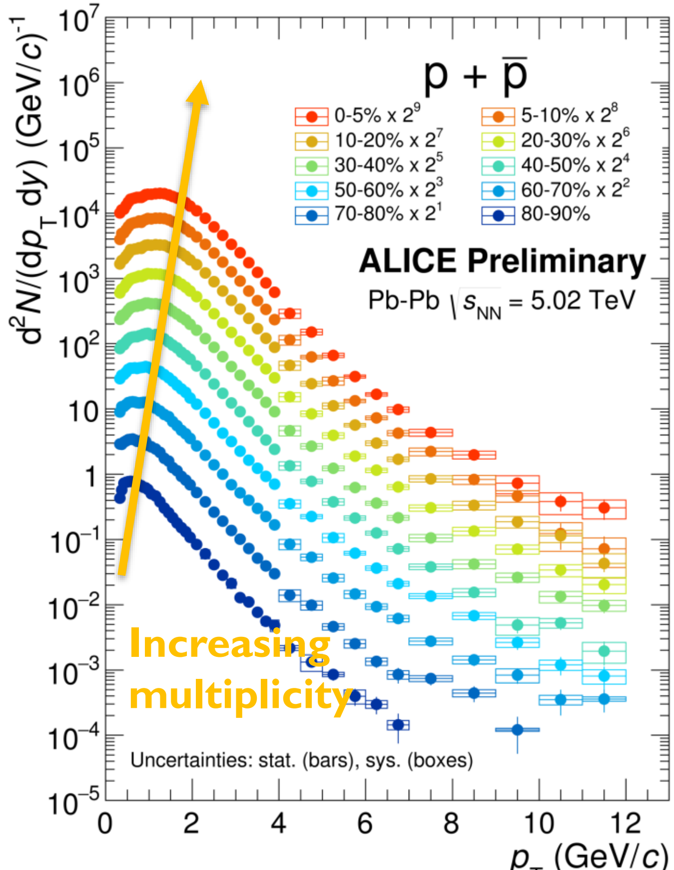
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} \boxed{v_n} \cos[n(\varphi - \Psi_n)]\right),$$

Characteristic features:

- Multiplicity dependence
- Higher harmonics azimuthal flow
- Mass scaling of v_2
- Correlations between harmonics

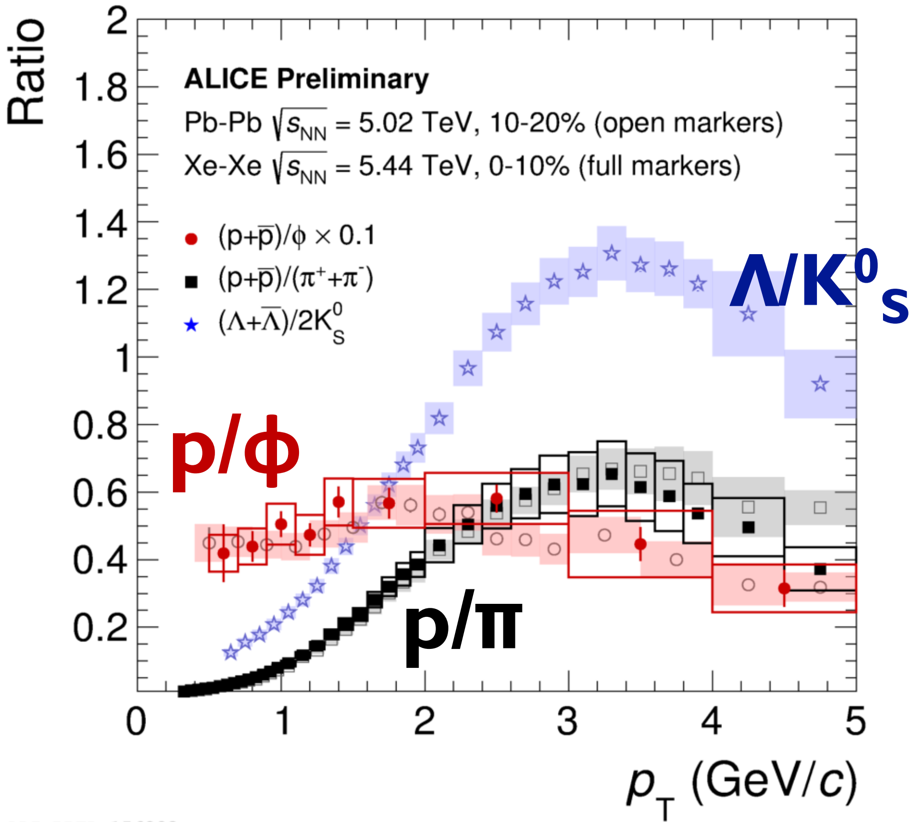
The hallmarks of flow in AA collisions

Increase in mean p_T with increasing centrality → Push from radial flow affects low p_T part of spectra



ALI-PREL-121419

Baryon-to-meson ratios (with Δm) → sensitive to particle production mechanisms (radial flow at low p_T, recombination at mid-p_T)

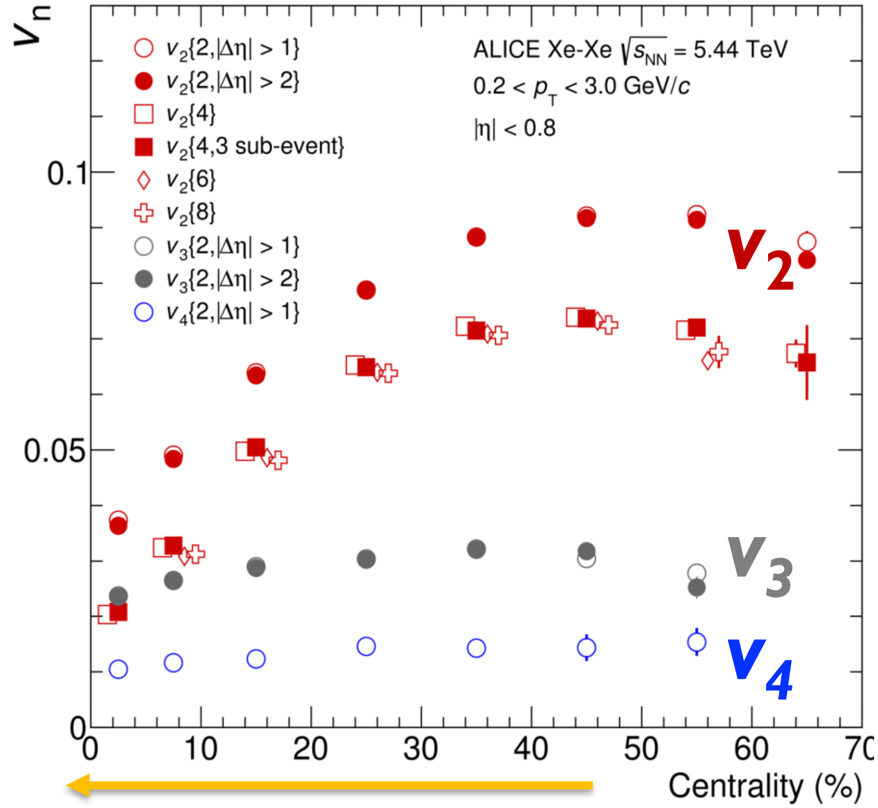


ALI-PREL-156893

The hallmarks of flow in AA collisions

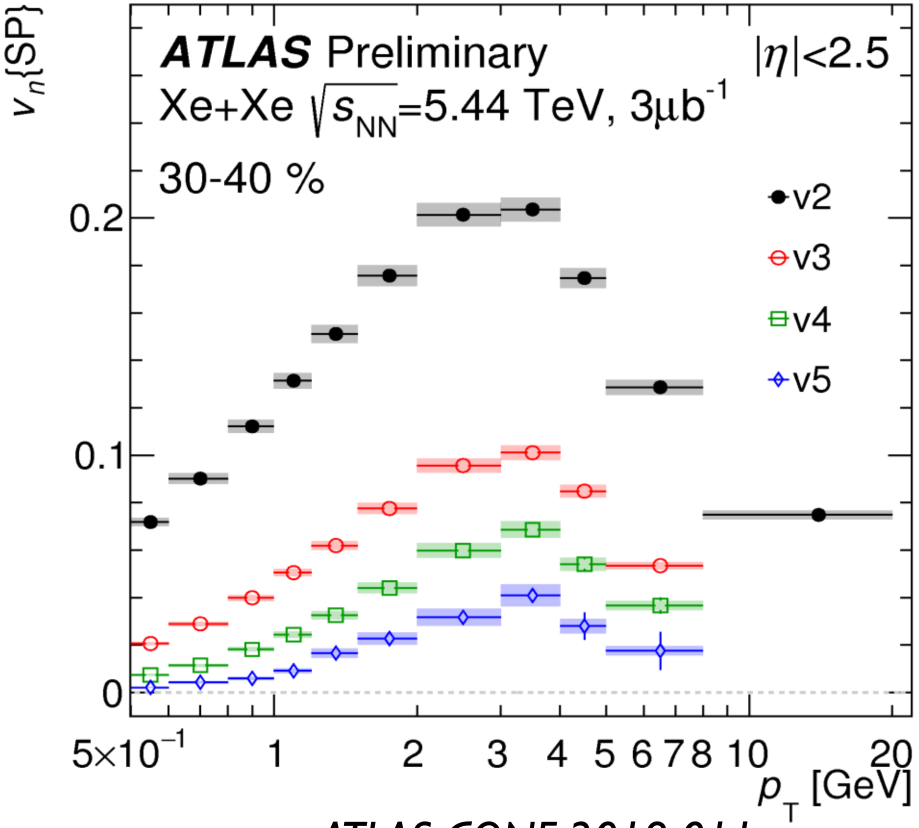
Centrality / multiplicity dependence
→ reflects the degree of "anisotropy"
in the initial geometry of the collision

Non-zero higher-order flow coefficients
("harmonics") → sensitivity to
fluctuations of initial geometry



Increasing multiplicity

ALICE, arXiv:1805.01832

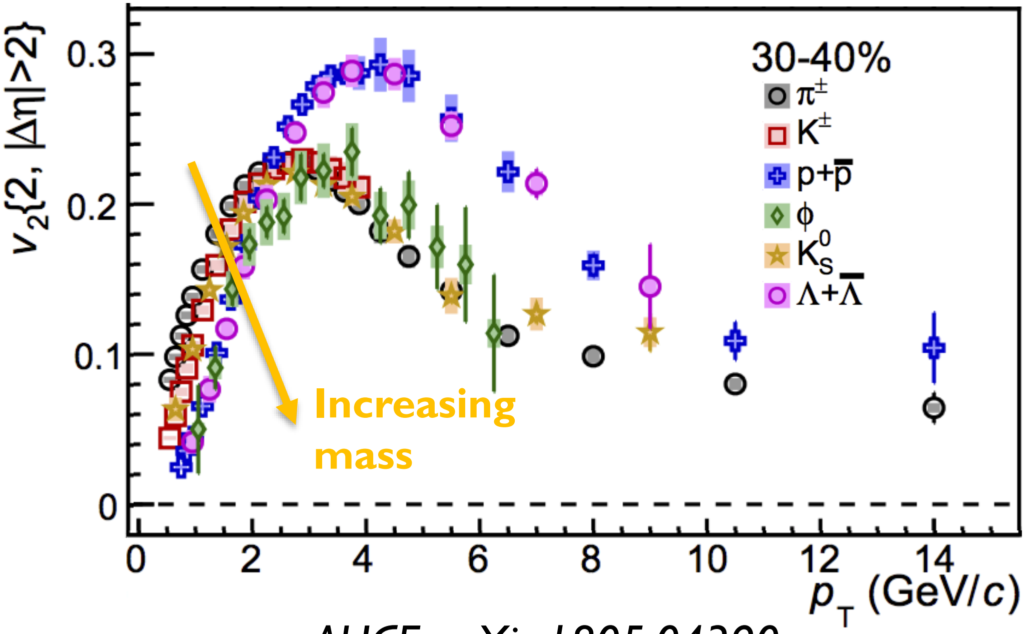


ATLAS-CONF-2018-011

The hallmarks of flow in AA collisions

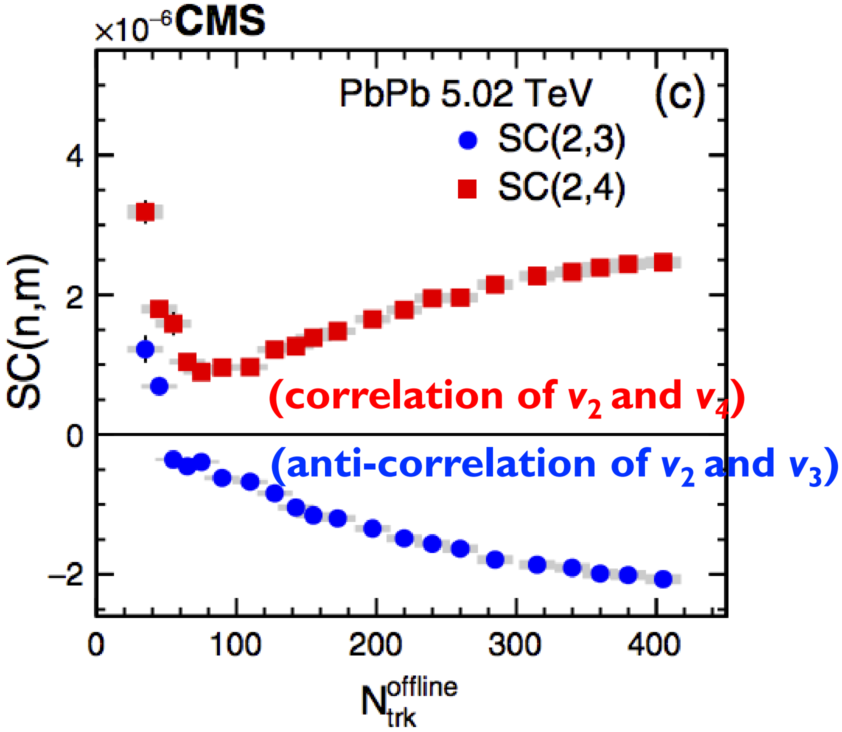
Mass scaling of flow coefficients
→ Expansion under a common velocity field

Correlations between harmonics
→ Sensitivity to fluctuations in initial geometry (v_2, v_3) and medium-transport properties (v_2, v_4)



Increasing mass

ALICE, arXiv:1805.04390

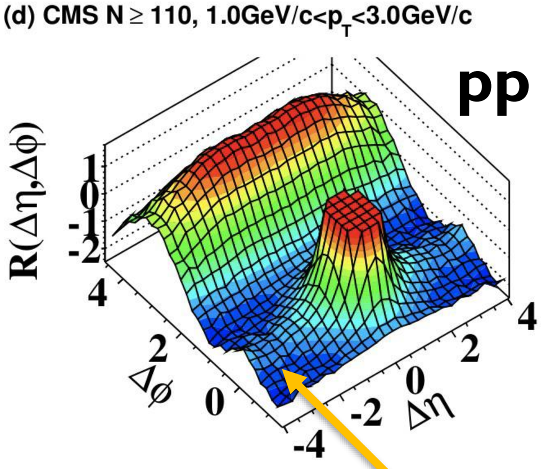


(correlation of v_2 and v_4)

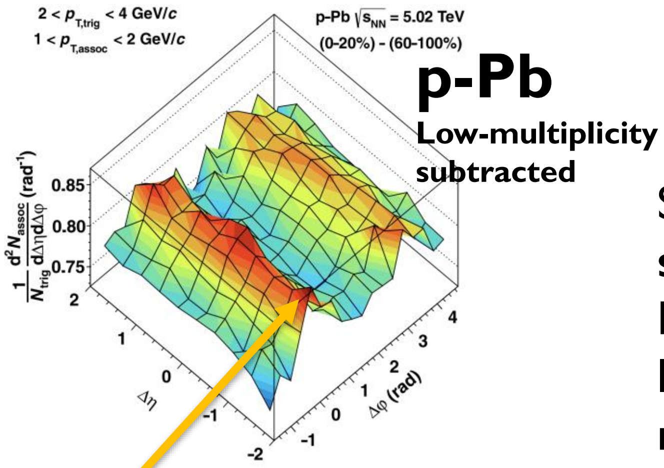
(anti-correlation of v_2 and v_3)

CMS, PRL 120, 092301 (2018)

Signs of collectivity in small systems

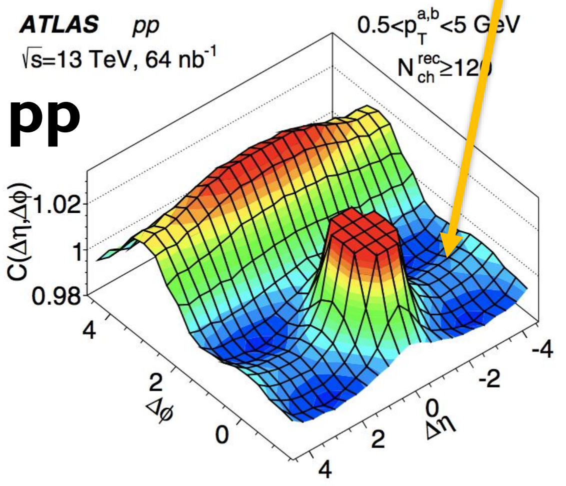


CMS, JHEP 09 (2010) 091

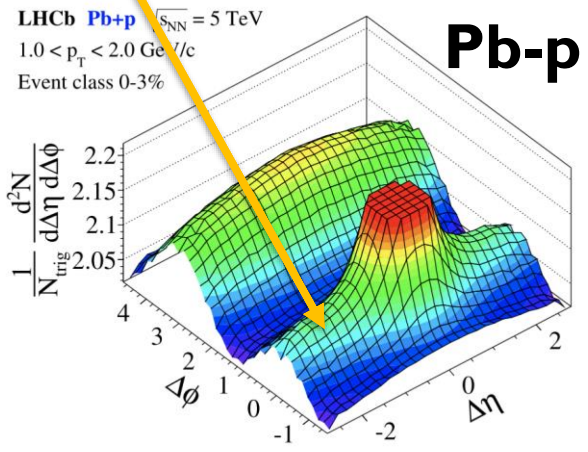


ALICE, PLB 719 (2013) 29

Near side ridge



ATLAS, PRC 96, (2017) 024908



LHCb, PLB 762 (2016) 473–483

Signs of collectivity in **small systems** "discovered" at the LHC in terms of long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\phi = 0$) "ridge" in 2-particle correlations, visible in **high multiplicity** pp, p-Pb, Pb-p collisions

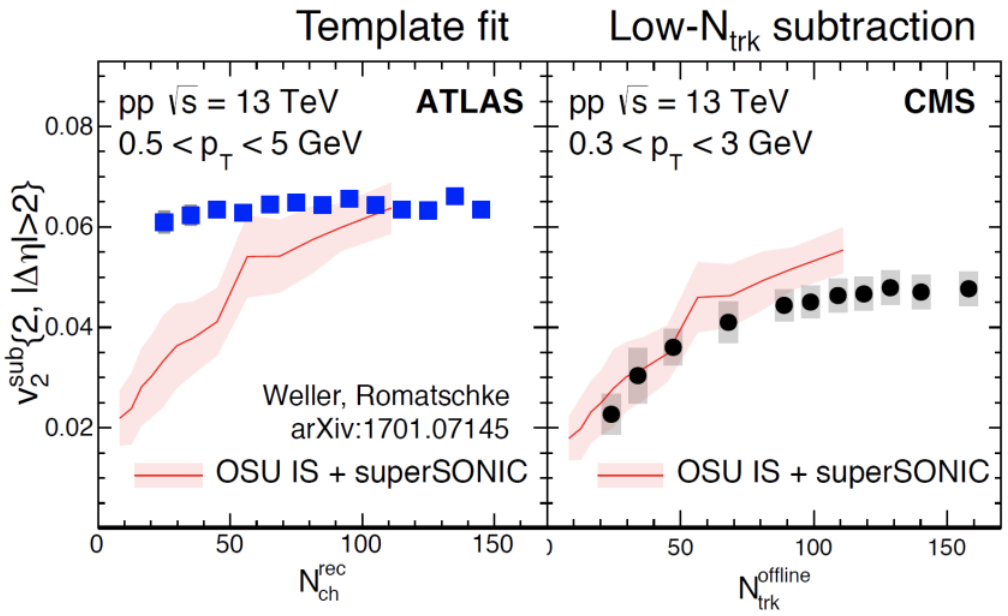
Are these long-range correlations coming from (hydrodynamic) flow?

→ Investigated with new measurements with run 2 data, new analysis techniques

The challenge of removing “non-flow”

In **small systems** the contribution of **non-flow** cannot be neglected:

- Different contribution from jets
- Larger fluctuations in the number of particle sources



A word of **caution**:

- Sensitivity to the event class definitions used in analysis *[ATLAS, EPJ C (2017) 77-428]*
- Sensitivity to strategy for non-flow background subtraction

Non-flow subtraction / suppression is a delicate business in pp, p-Pb!
Big effort ongoing in defining “smart” observables / new techniques

If collectivity, it involves more than 2 particles

Measure elliptic flow v_2 using correlations among *k* particles in a single event, subtracting correlations from smaller number of particles

[A. Bilanzic et al., PRC 83 (2011) 044913]

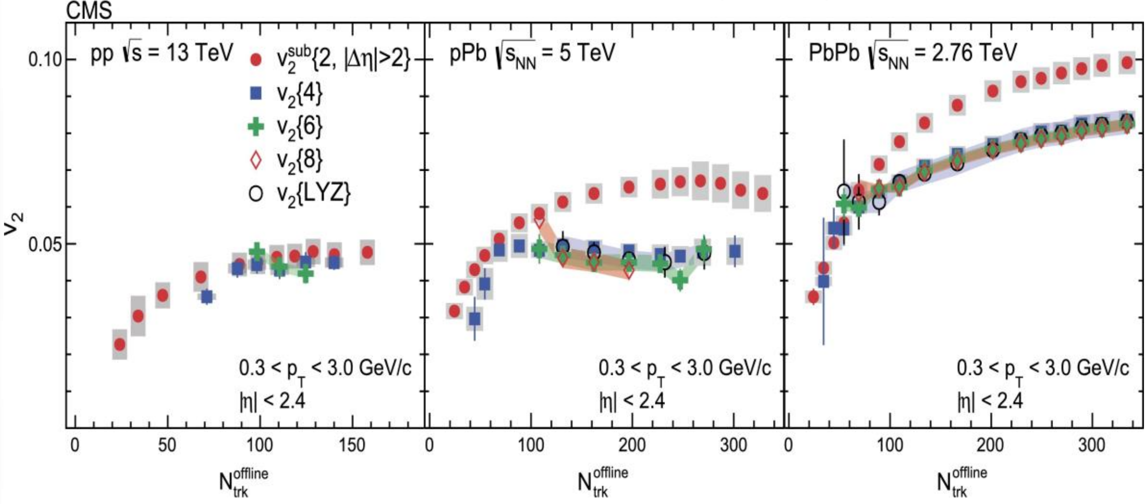
Multi-particle cumulants, $c_n\{k\}$

$$c_n\{2\} = \langle\langle 2\rangle\rangle = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$

Related to the flow harmonics, $v_n\{k\}$

$$v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}},$$
$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4}.$$

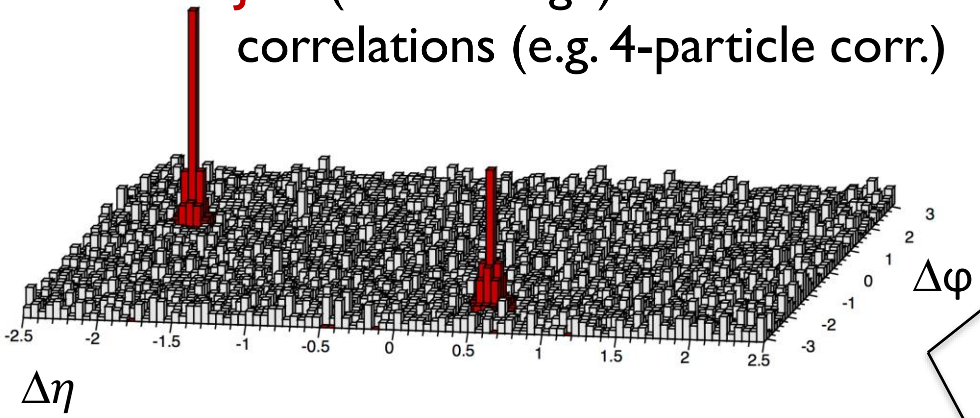
CMS, PLB 765 (2017) 193



If long-range, correlations stay across sub-events

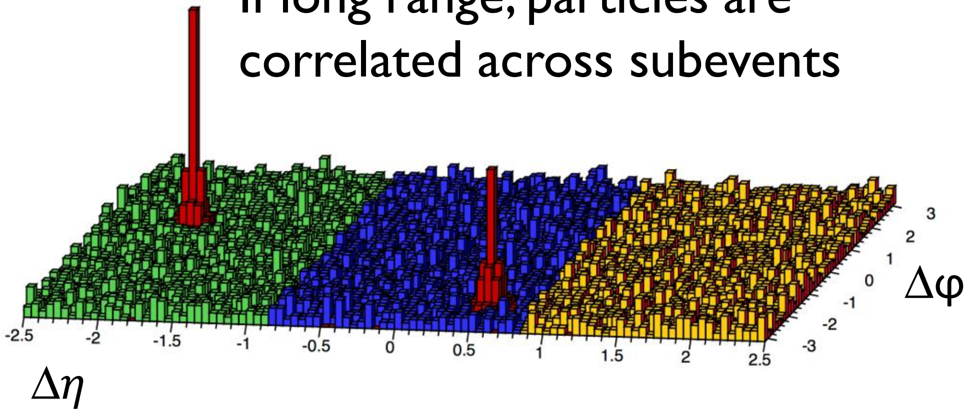
Whole event

Jets (short-range) contribute to correlations (e.g. 4-particle corr.)



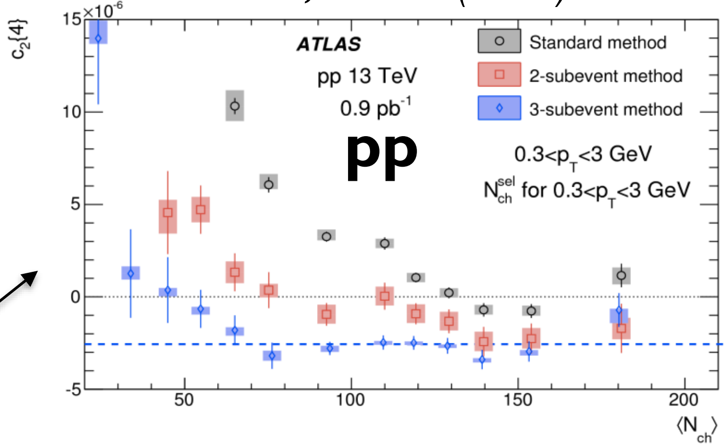
≥ 2 Sub-events

If long range, particles are correlated across subevents

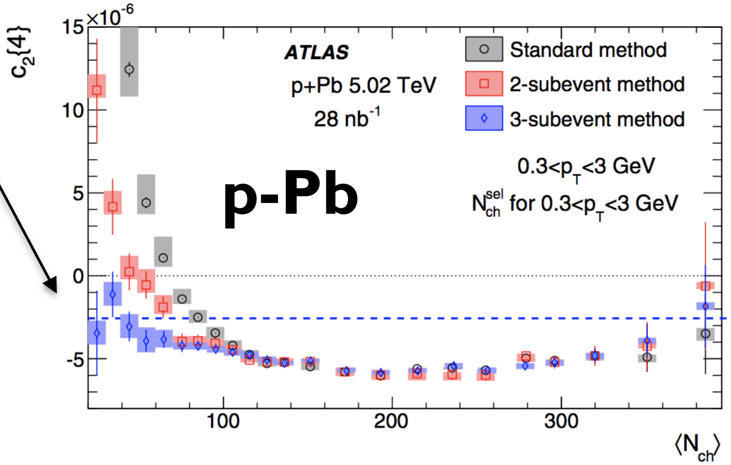


Figures from M. Zhou, QM 2017
J. Jia et al., PRC 96, 034906 (2017)

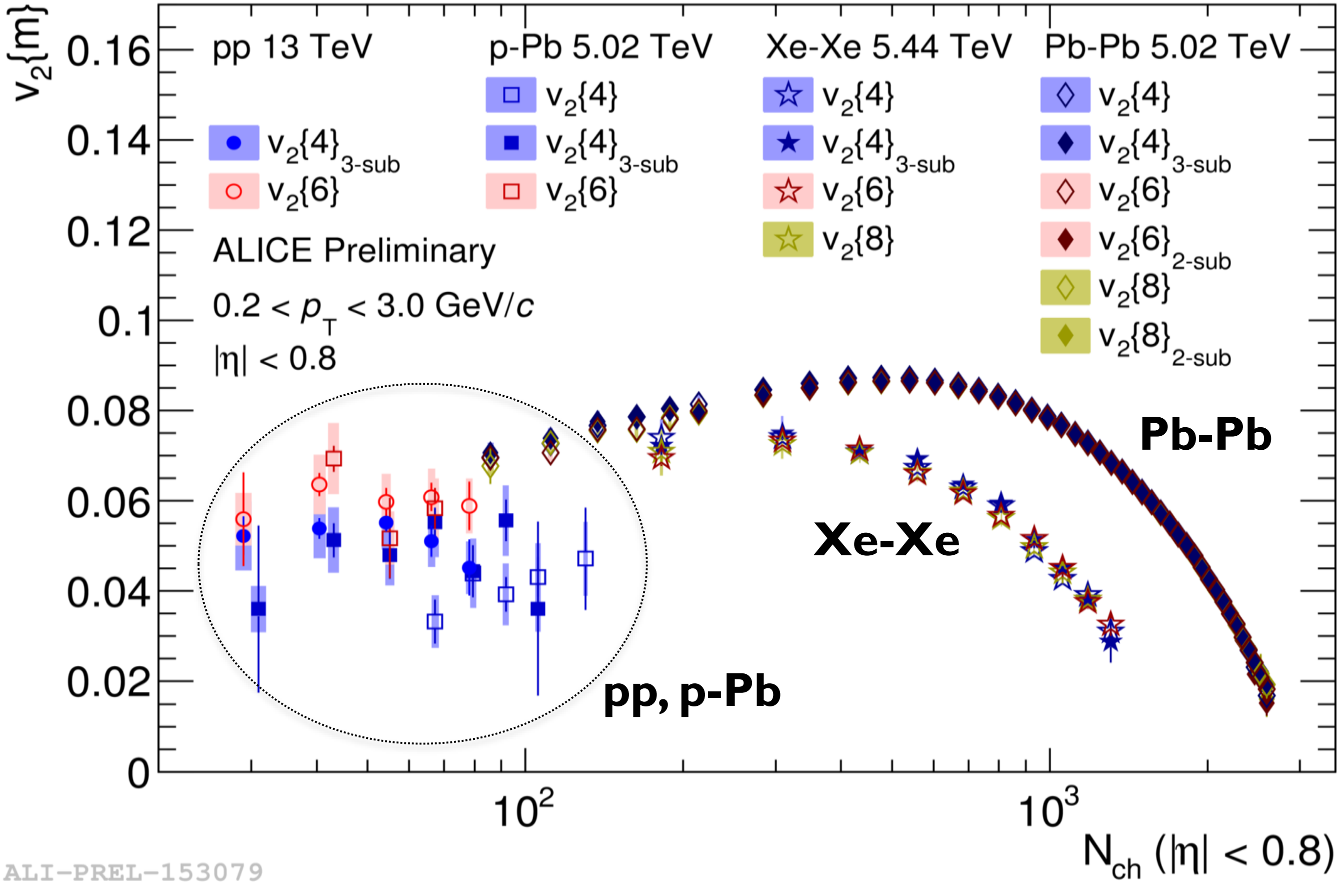
ATLAS, PRC 97 (2018) 024904

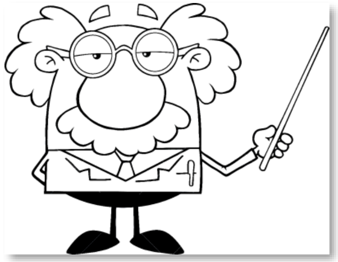


x10^{-6}



True collectivity in small systems!

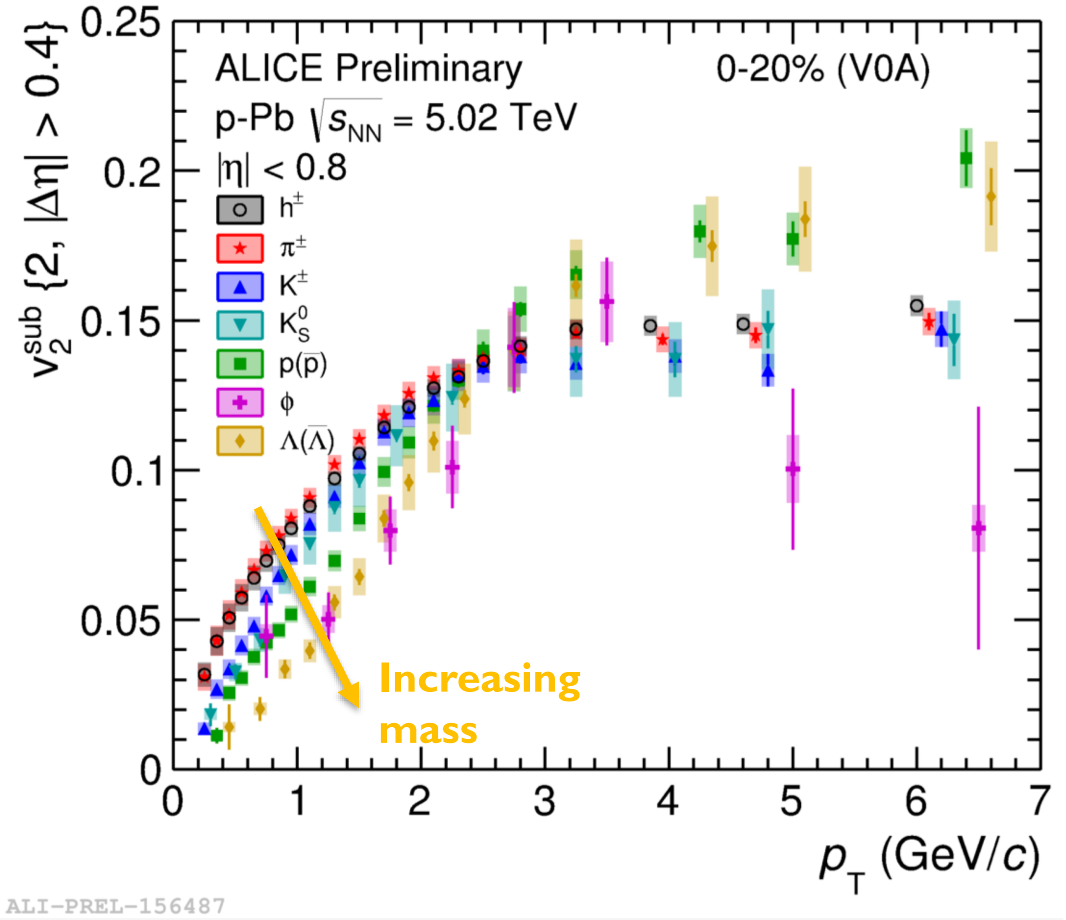




$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ → true collectivity (even) in smallest systems

$v_2\{2\}$ larger → residual "non-flow"

Light-flavor particle v_2



Clear **mass ordering** at **low p_T** in p-Pb from new results on v_2^{sub} for identified hadrons

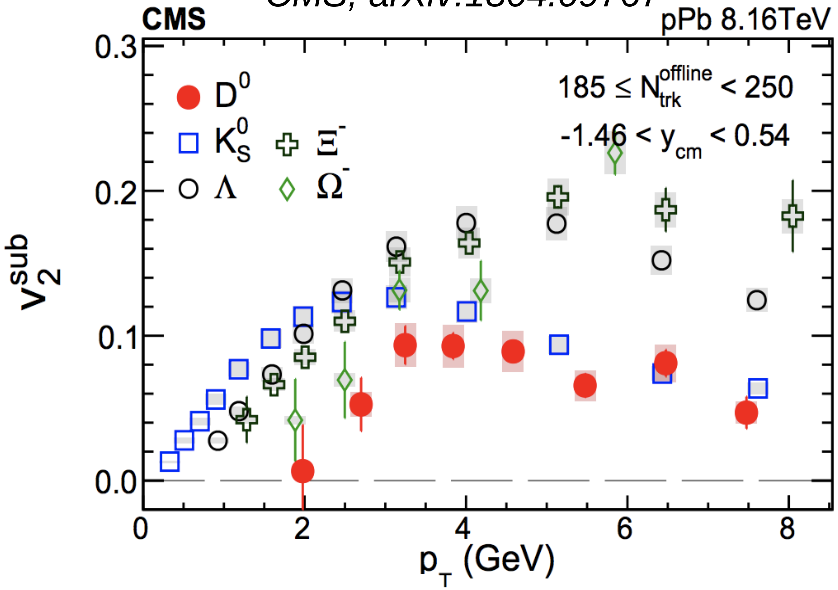
Consistent with hydrodynamics (and AA)

BUT also reproducible with other model with initial state effects!!!

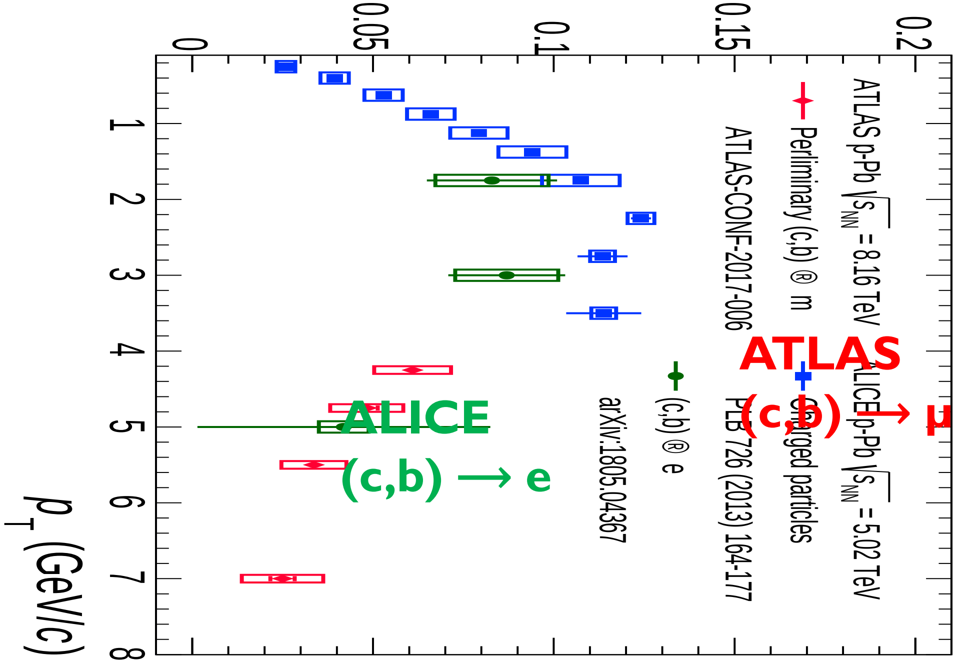
P. Tribedy, QM2018

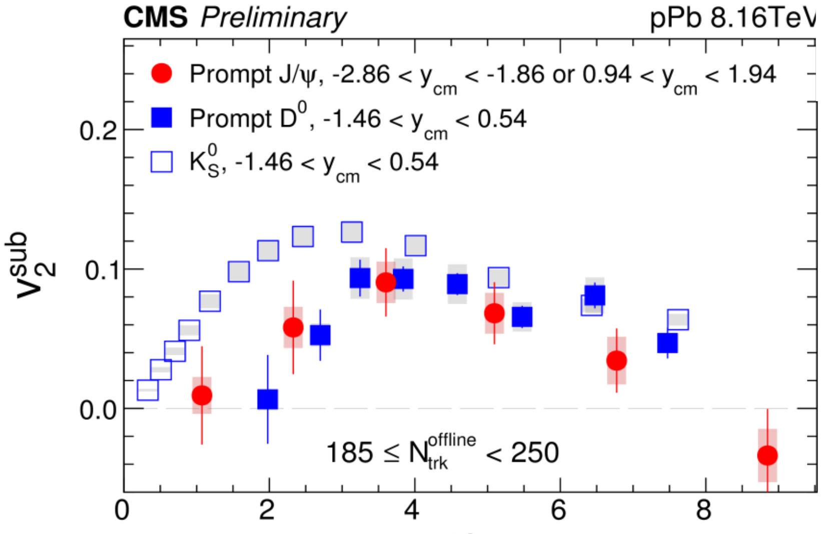
Heavy-flavor particle v_2 in p-Pb

CMS, arXiv:1804.09767



ALICE, arXiv:1805.04367, ATLAS-CONF-2017-006



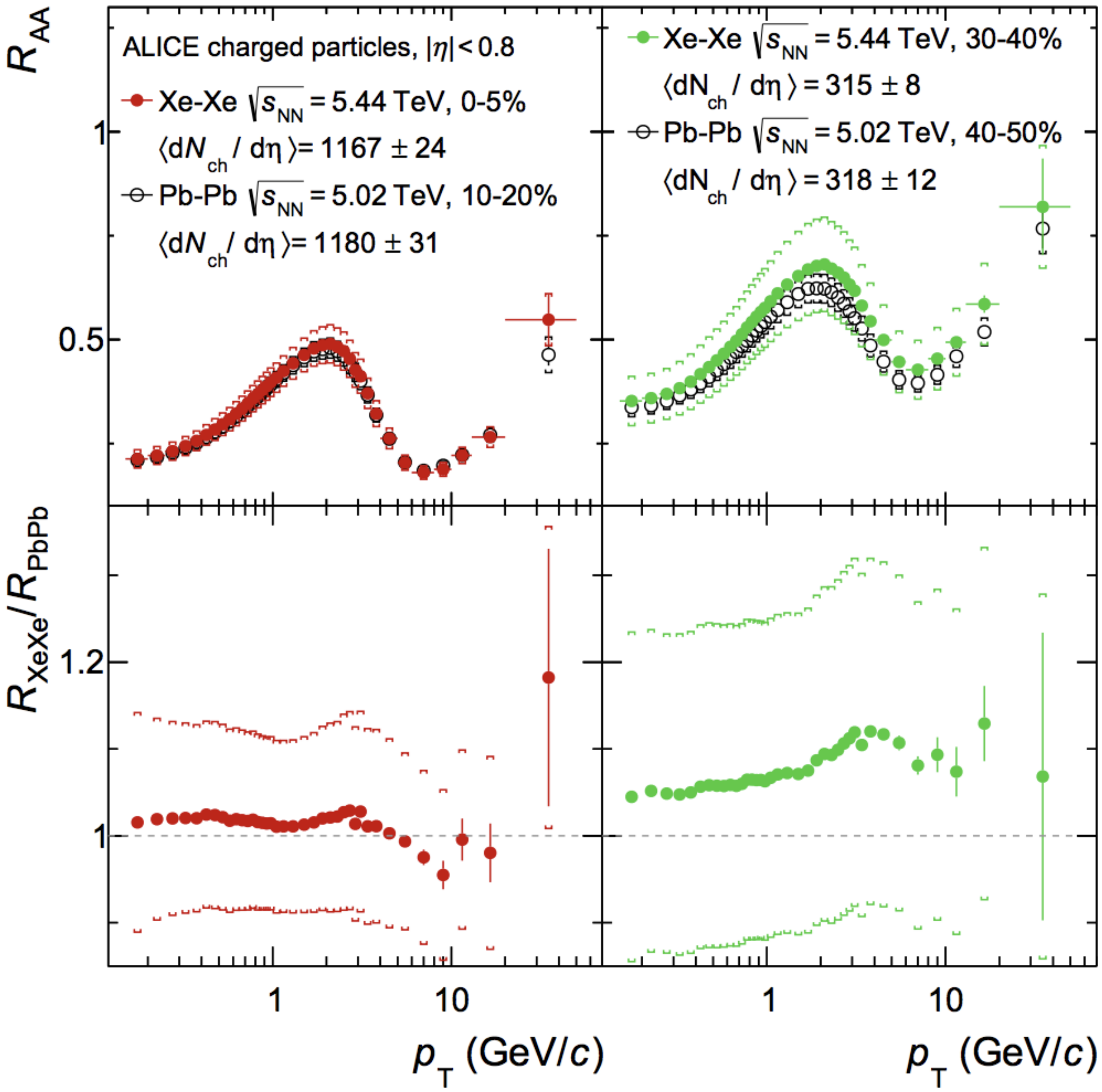


CMS-PAS-HIN-18-010

Both light- and heavy-flavour hadrons show large azimuthal anisotropy in p-Pb collisions, up to 7-8 GeV/c

ADDITIONAL SLIDES

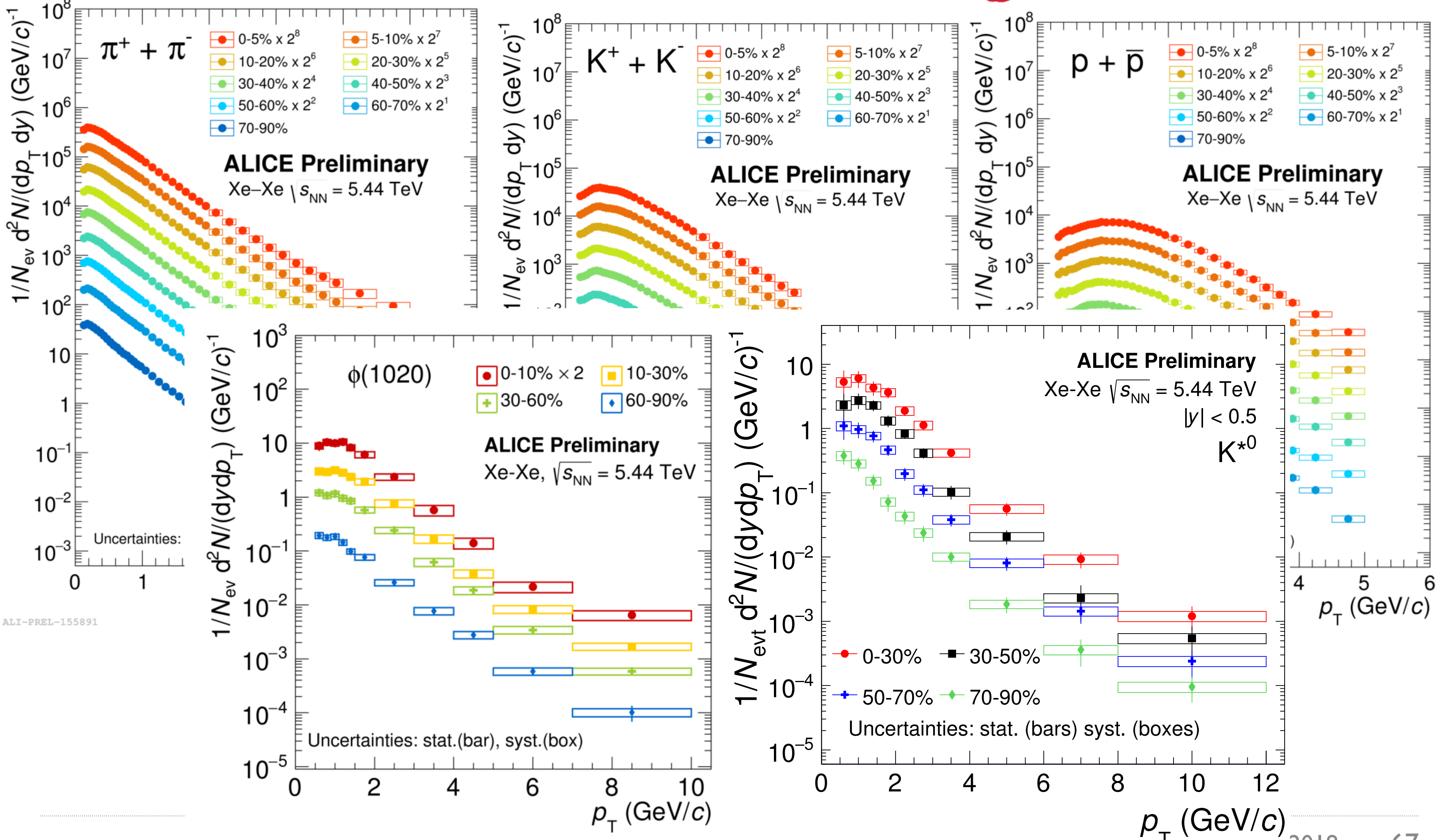
R_{AA} in Pb-Pb and Xe-Xe



R_{AA} in Xe-Xe and Pb-Pb consistent if compared at similar charged particle multiplicity

Identified particle production in |y|<0.5

NEW: Xe-Xe 5.44 TeV



ALI-PREL-155891

ALI-PREL-148421

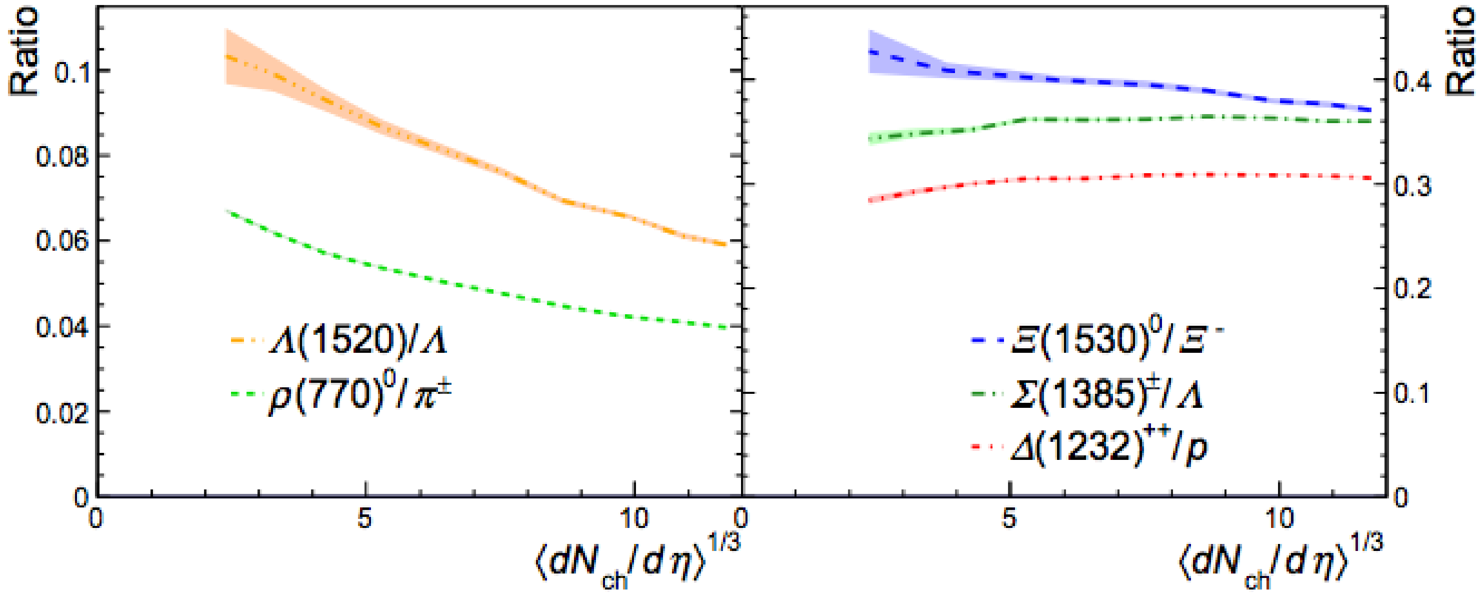
ALI-PREL-148564

Probing the hadronic phase with resonances

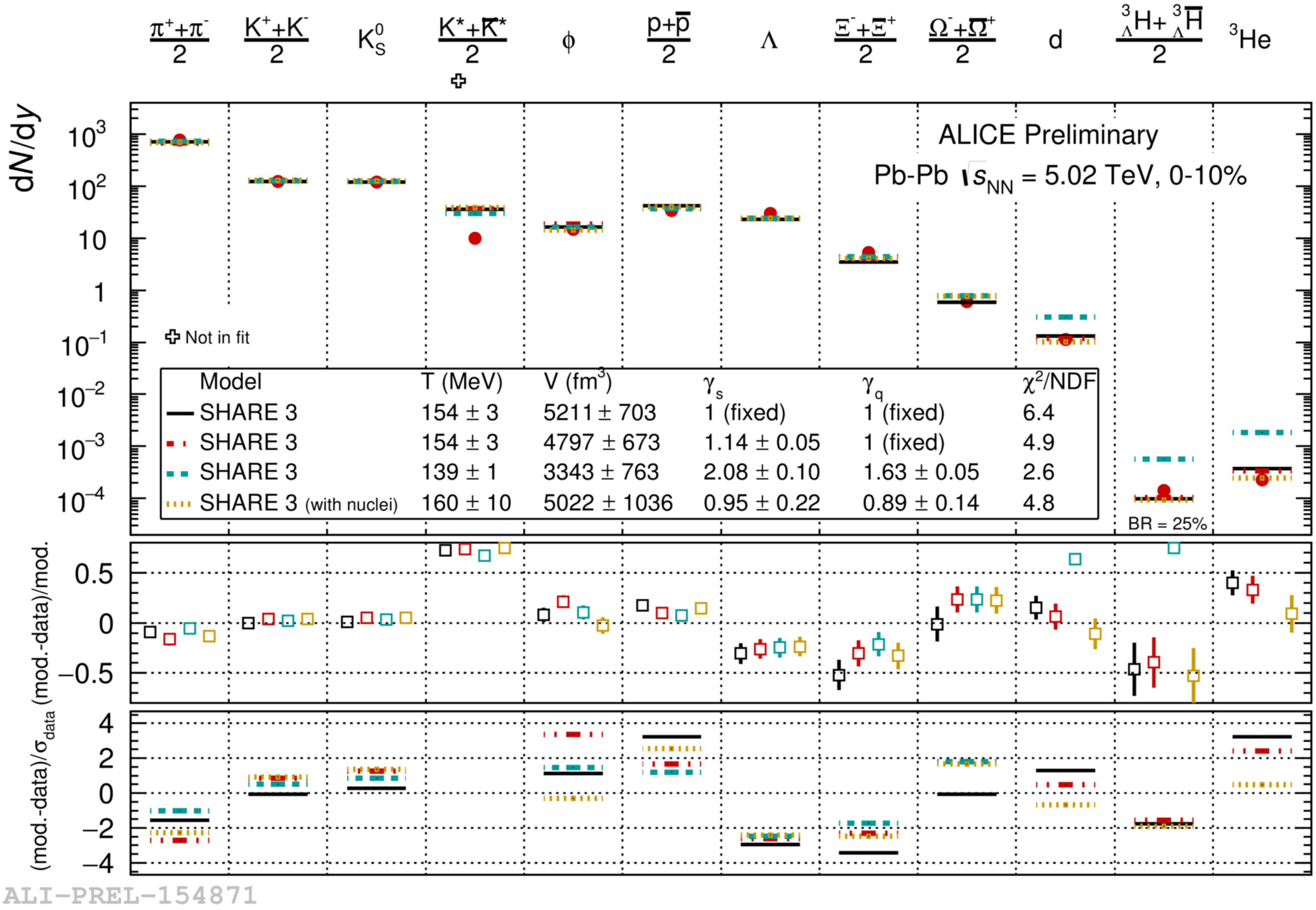
Key measurements:

- Resonance yields and **ratios to long-lived particles vs. centrality**
  - Re-scattering effects expected to be stronger in central collisions, as the medium is denser and lasts longer
  - Depending on the species, regeneration effects might be dominant (e.g. Σ*)
- Spectra **down to low p_T**
  - Improve precision on the yields by minimising the extrapolated fraction
  - UrQMD predicts the largest effects for $p_T < 2$ GeV/c

A. Knospe et al. Phys. Rev. C 93 (2016) 014911



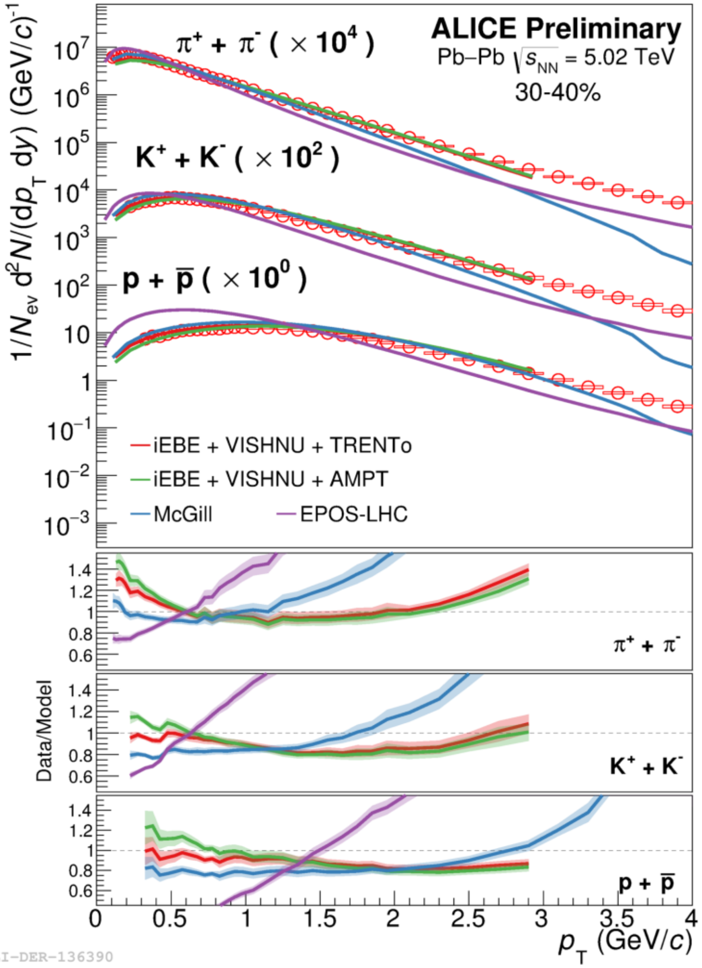
SHARE fit – Pb-Pb 5.02 TeV (0-10%)



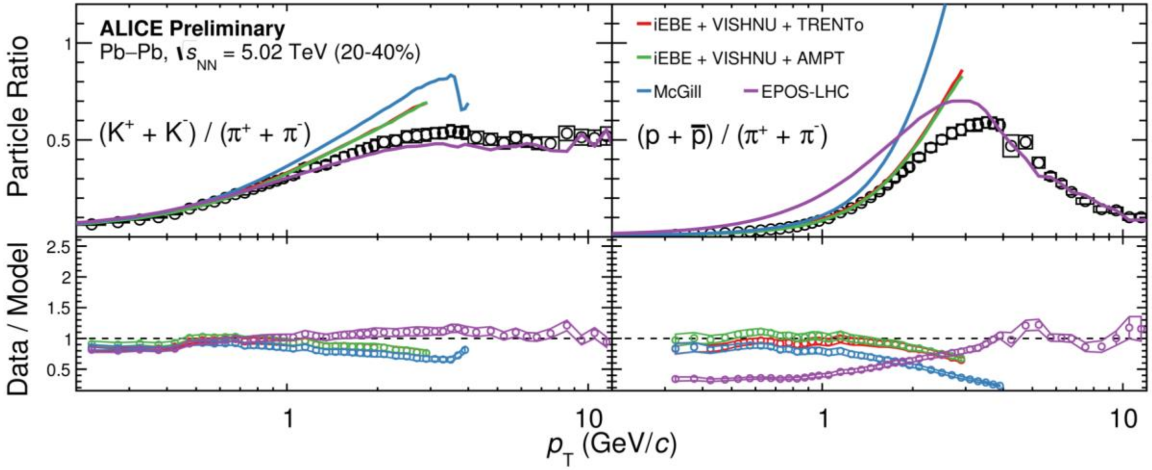
Model	T (MeV)	V (fm^3)	γ_s	γ_q	χ^2/NDF
— SHARE 3	154 ± 3	5211 ± 703	1 (fixed)	1 (fixed)	6.4
- - SHARE 3	154 ± 3	4797 ± 673	1.14 ± 0.05	1 (fixed)	4.9
▪ ▪ SHARE 3	139 ± 1	3343 ± 763	2.08 ± 0.10	1.63 ± 0.05	2.6
⋯ SHARE 3 (with nuclei)	160 ± 10	5022 ± 1036	0.95 ± 0.22	0.89 ± 0.14	4.8

SHARE: M. Petran et al.. PRC88 (2013) 3, 034907

Hydro model comparison – semi-central Pb-Pb

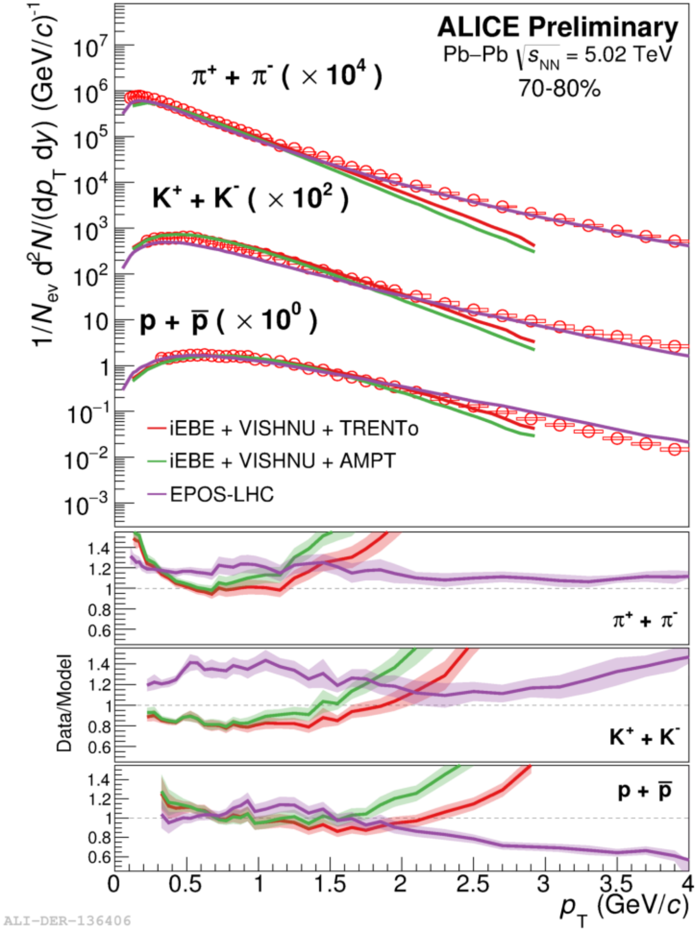


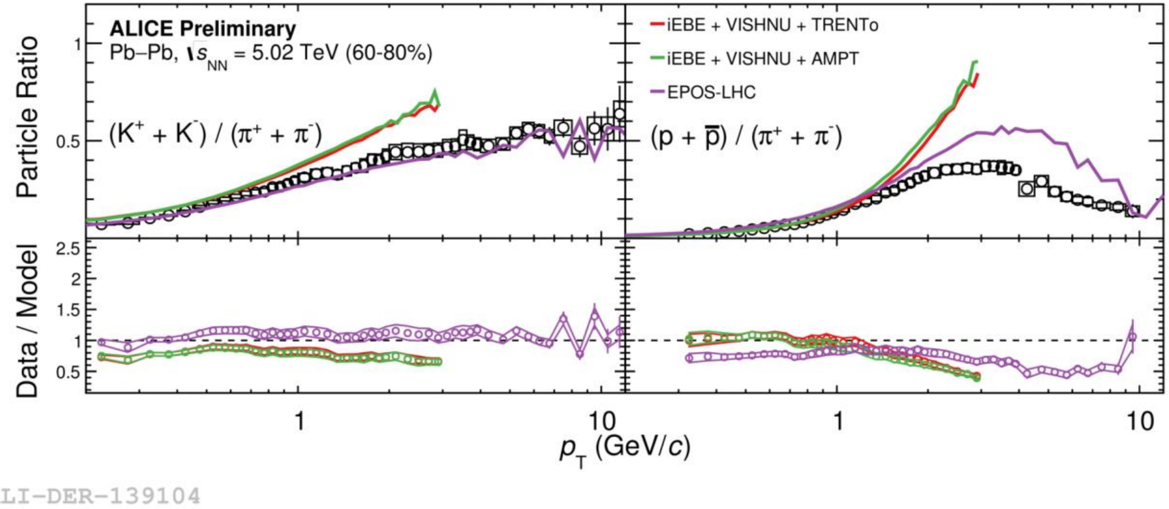
ALI-DER-136390



I-DER-139126

Hydro model comparison - peripheral Pb-Pb



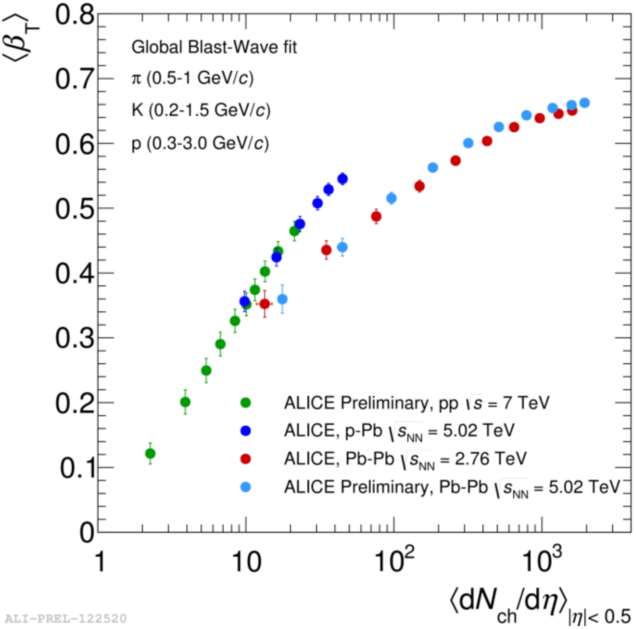


Blast-Wave fits to particle spectra

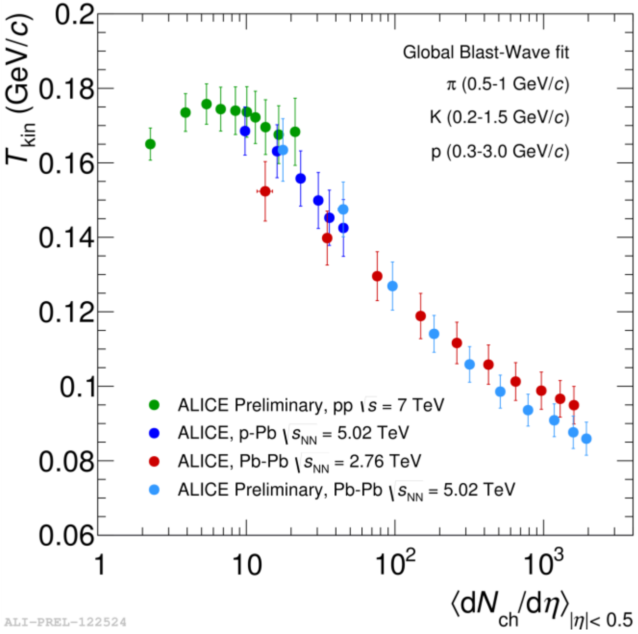
Boltzmann-Gibbs Blast-Wave model [E. Schnedermann et al., Phys. Rev. C48 (1993) 2462]

A simplified hydrodynamic model with 3 free fit parameters:

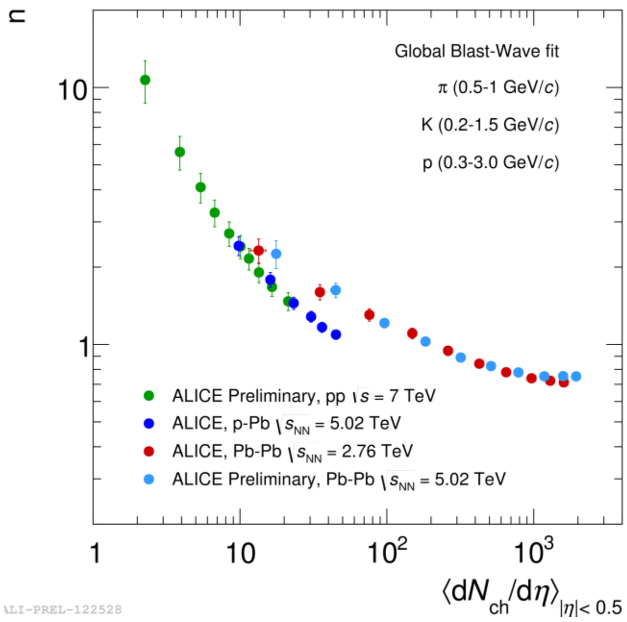
- β_T: transverse radial flow velocity
- T_{kin} = kinetic freeze-out temperature
- n: velocity profile



ALI-PREL-122520



ALI-PREL-122524



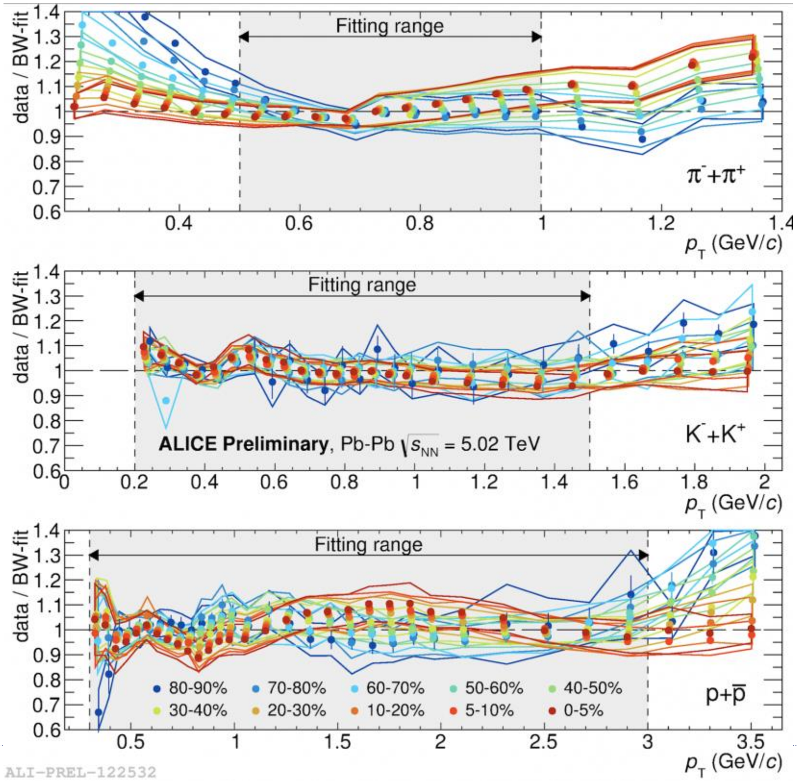
ALI-PREL-122528

Blast-Wave fits - Pb-Pb

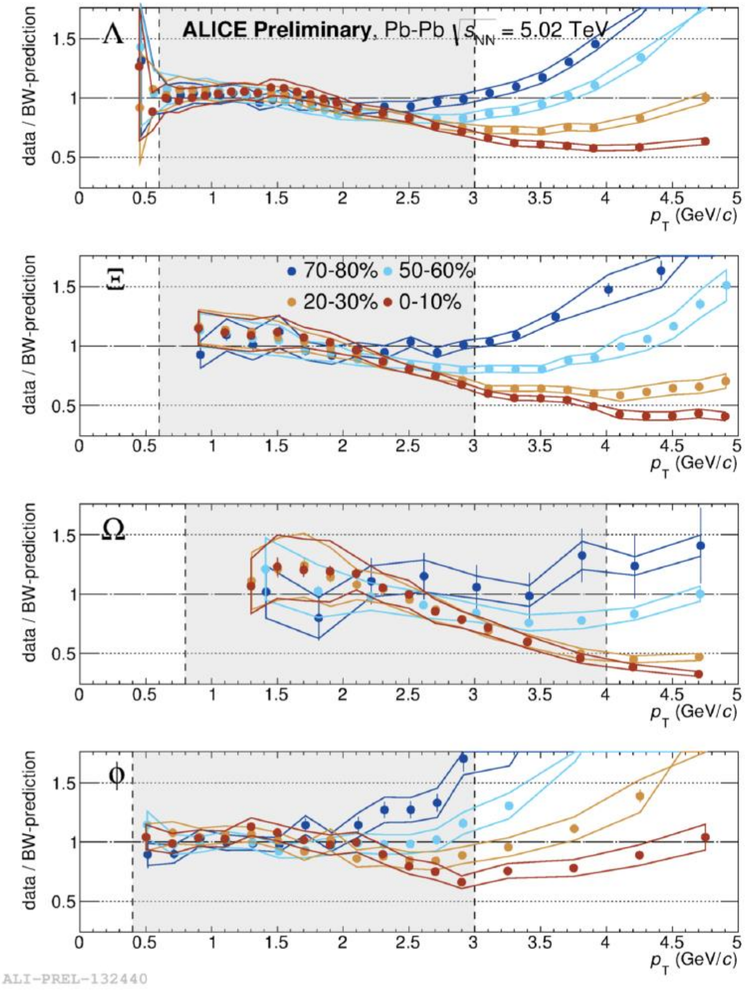
Caveats:

- Sensitivity to fit range: low p_T particle spectra affected by resonance decay in the hadronic phase
- Sensitivity to the set of particles included in the fi

π,K,p fitted
(gray bands indicate used fitting range)



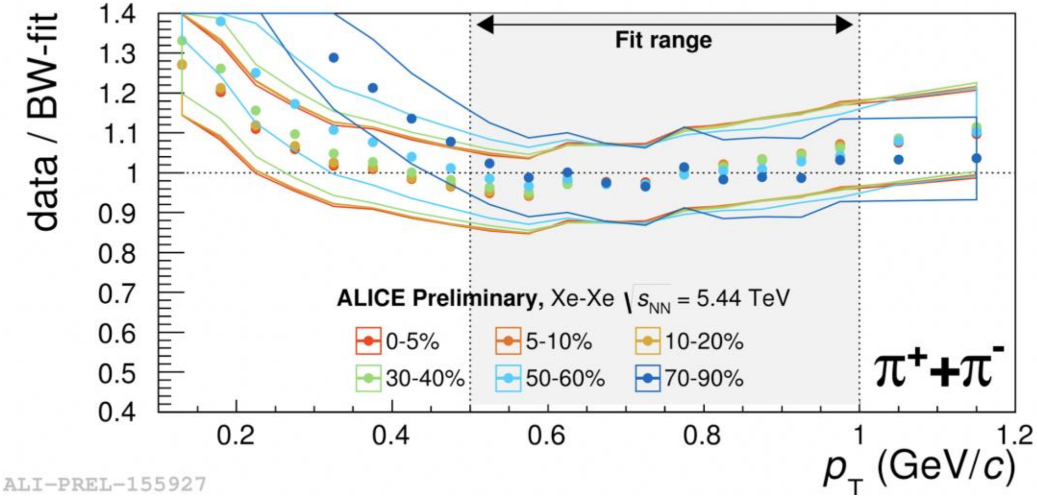
ALI-PREL-122532



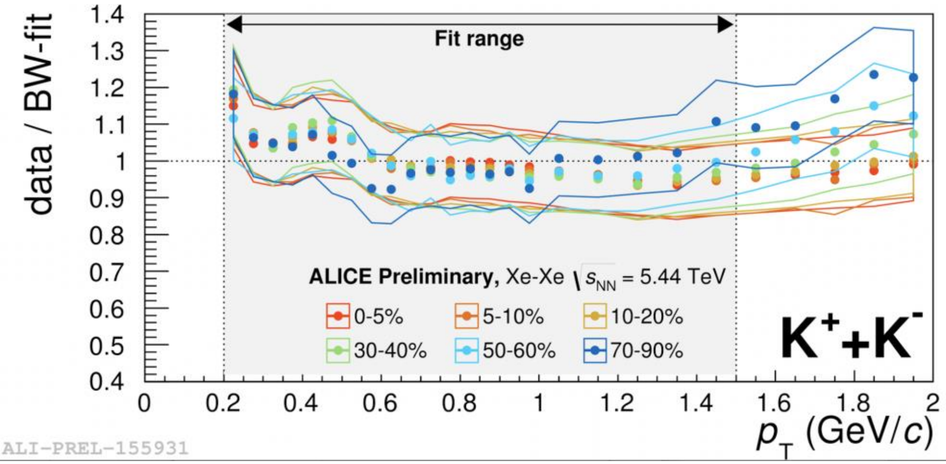
ALI-PREL-132440

Λ, Ξ, Ω, ϕ compared to prediction obtained from fit parameters resulting from π,K,p (gray bands indicate range in which fit works ok in Pb-Pb 2.76 TeV)

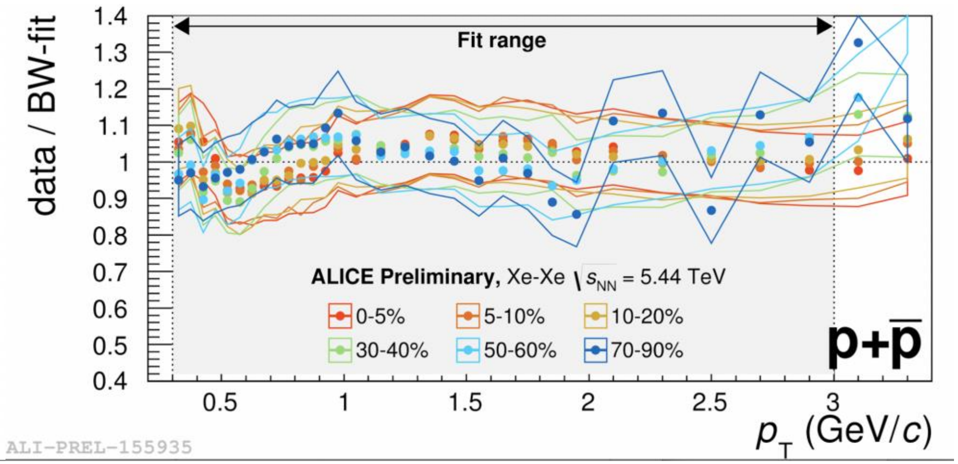
Blast-Wave fits - Xe-Xe



ALI-PREL-155927



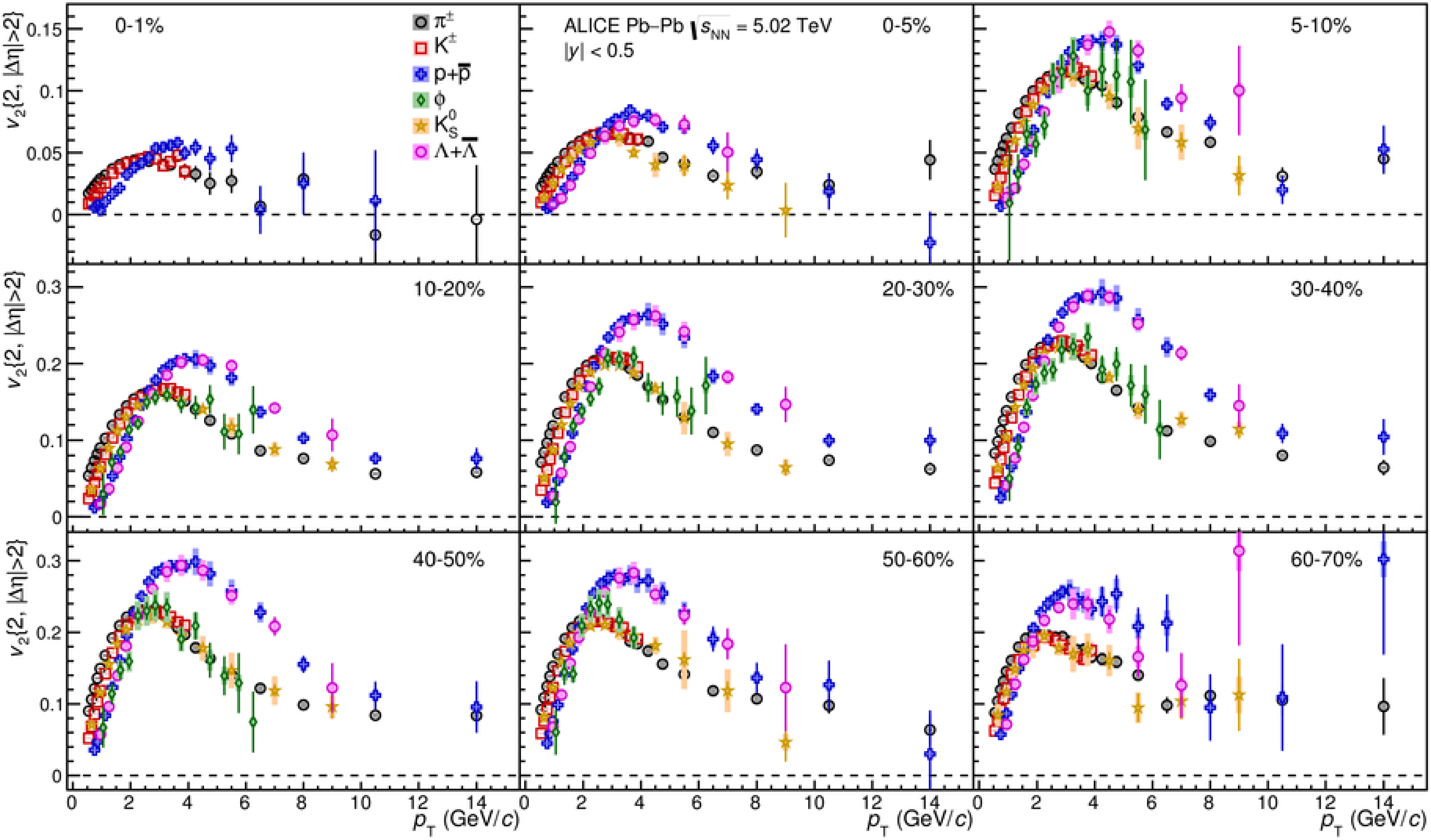
ALI-PREL-155931



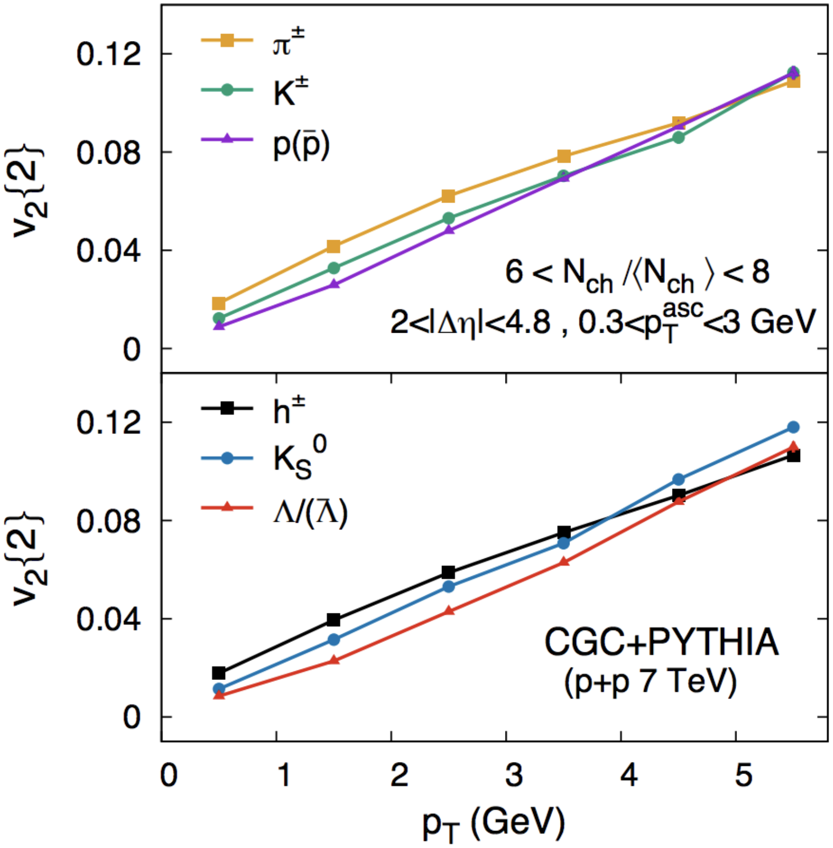
ALI-PREL-155935

v_2 of identified hadrons in Pb-Pb 5.02 TeV

arXiv:1805.04390



Light-flavor particle v_2



P. Tribedy, Quark Matter 2018

Clear **mass ordering** at **low p_T** in p-Pb from new results on v_2^{sub} for identified hadrons

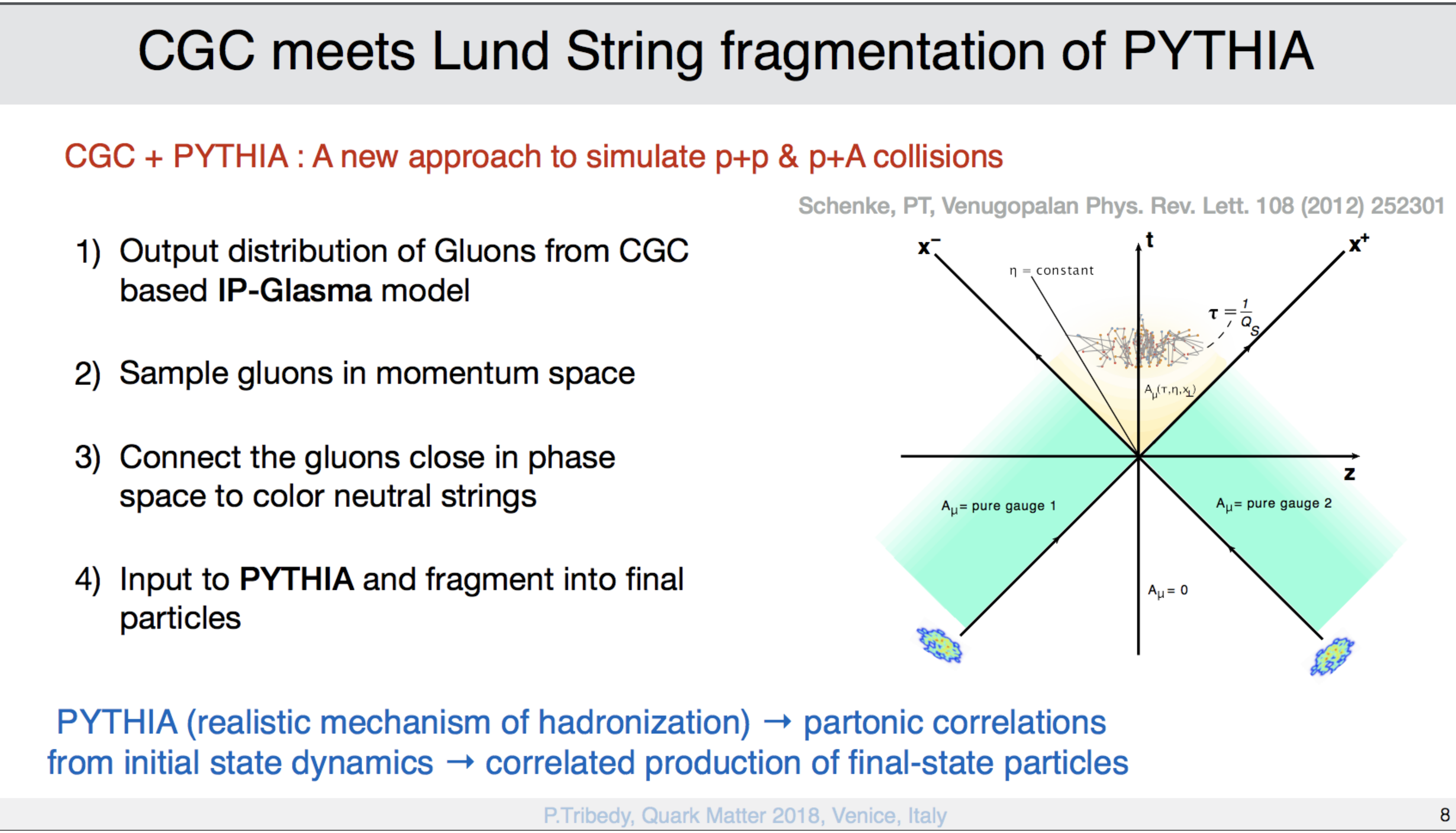
→ Consistent with hydrodynamics (and AA)

BUT it could also be due to other effects

- Initial stage effects (CGC + PYTHIA)
- Parton escape (AMPT)
- Hadronic rescattering (UrQMD)

Is mass ordering no longer an exclusive product of hydrodynamic flow?

CGC + Pythia



CGC meets Lund String fragmentation of PYTHIA

CGC + PYTHIA : A new approach to simulate p+p & p+A collisions

1) Output distribution of Gluons from CGC based **IP-Glasma** model
2) Sample gluons in momentum space
3) Connect the gluons close in phase space to color neutral strings
4) Input to **PYTHIA** and fragment into final particles

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

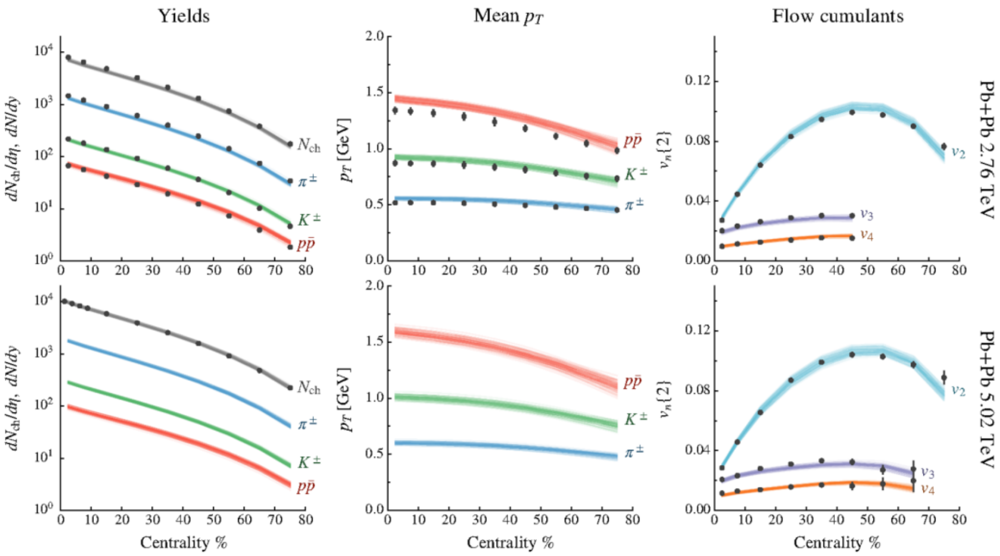
PYTHIA (realistic mechanism of hadronization) → partonic correlations from initial state dynamics → correlated production of final-state particles

P.Tribedy, Quark Matter 2018, Venice, Italy

8

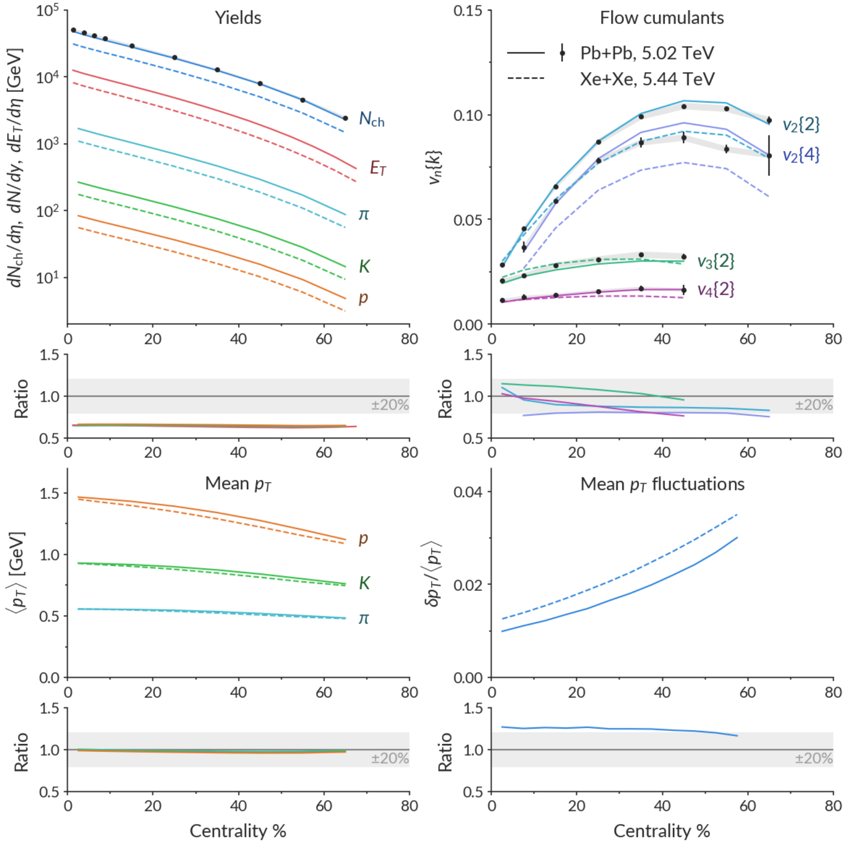
Bayesian analysis, Pb-Pb and Xe-Xe

QM 2017

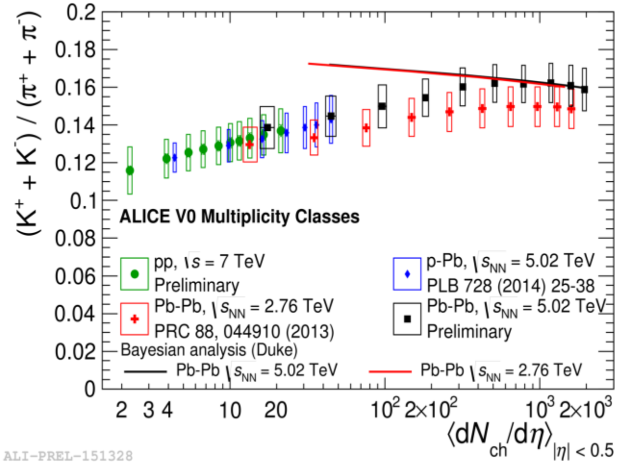


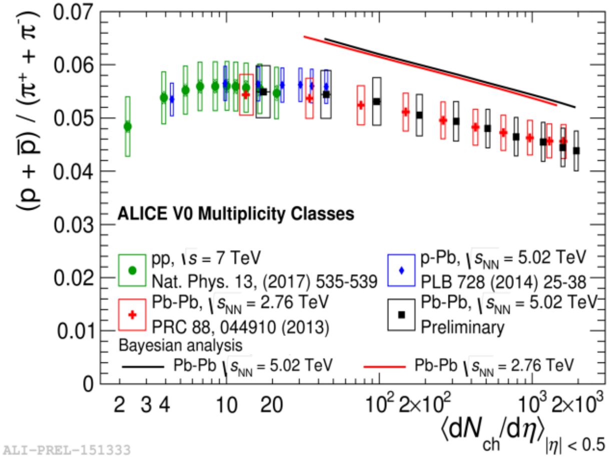
G. Bernhardt et al., NPA 967 (2017) 293–296 (top)
J.S. Moreland et al., priv. comm. (right)

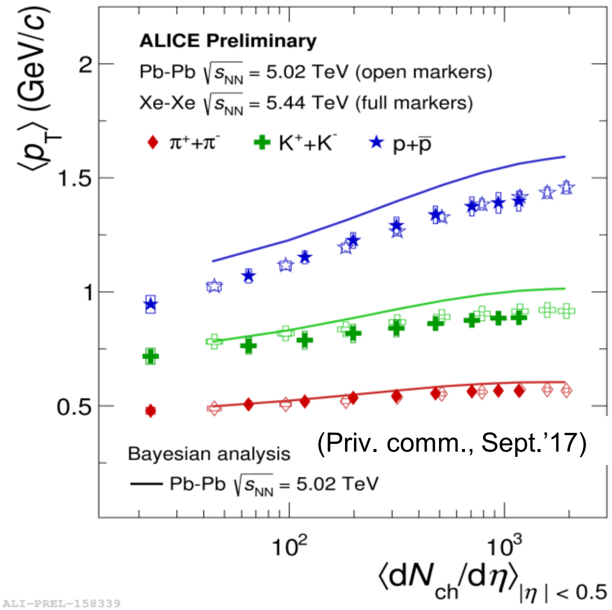
2018, new



Comparison to Bayesian analysis







(Priv. comm., Sept.'17)

Mean p_T and integrated yields in Pb-Pb at 2.76 TeV are used as input to a multi-parameter **Bayesian analysis** to extract predictions for 5.02 TeV

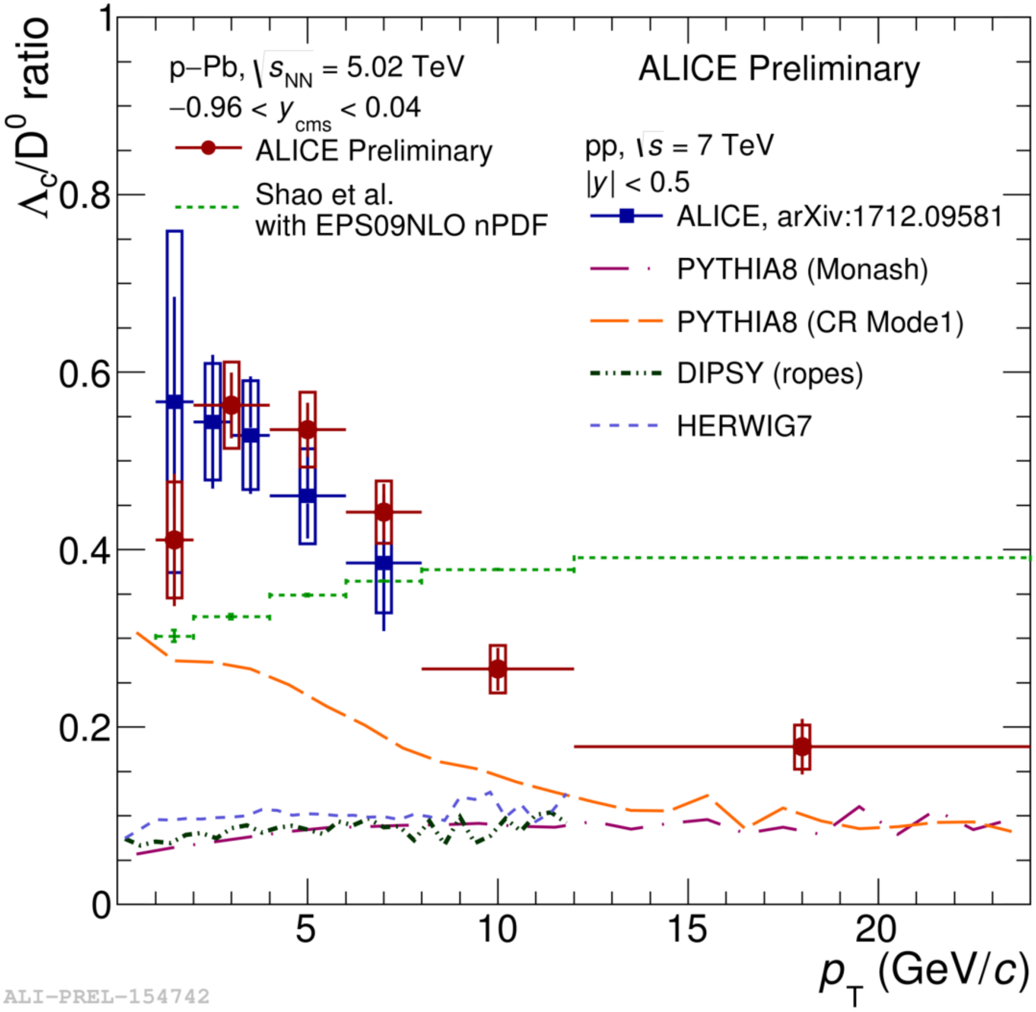
[G. Bernhardt et al., NPA 967 (2017) 293–296]

Comparison with ALICE results at 5 TeV indicate that

- the K/π ratio is reproduced in most central collisions, but description fails in peripheral
- p/π and mean transverse momenta overestimated, trend with multiplicity described qualitatively → model improvements since 2017

Lc/D ratio in small systems vs MC

ALICE, arXiv:1712.09581

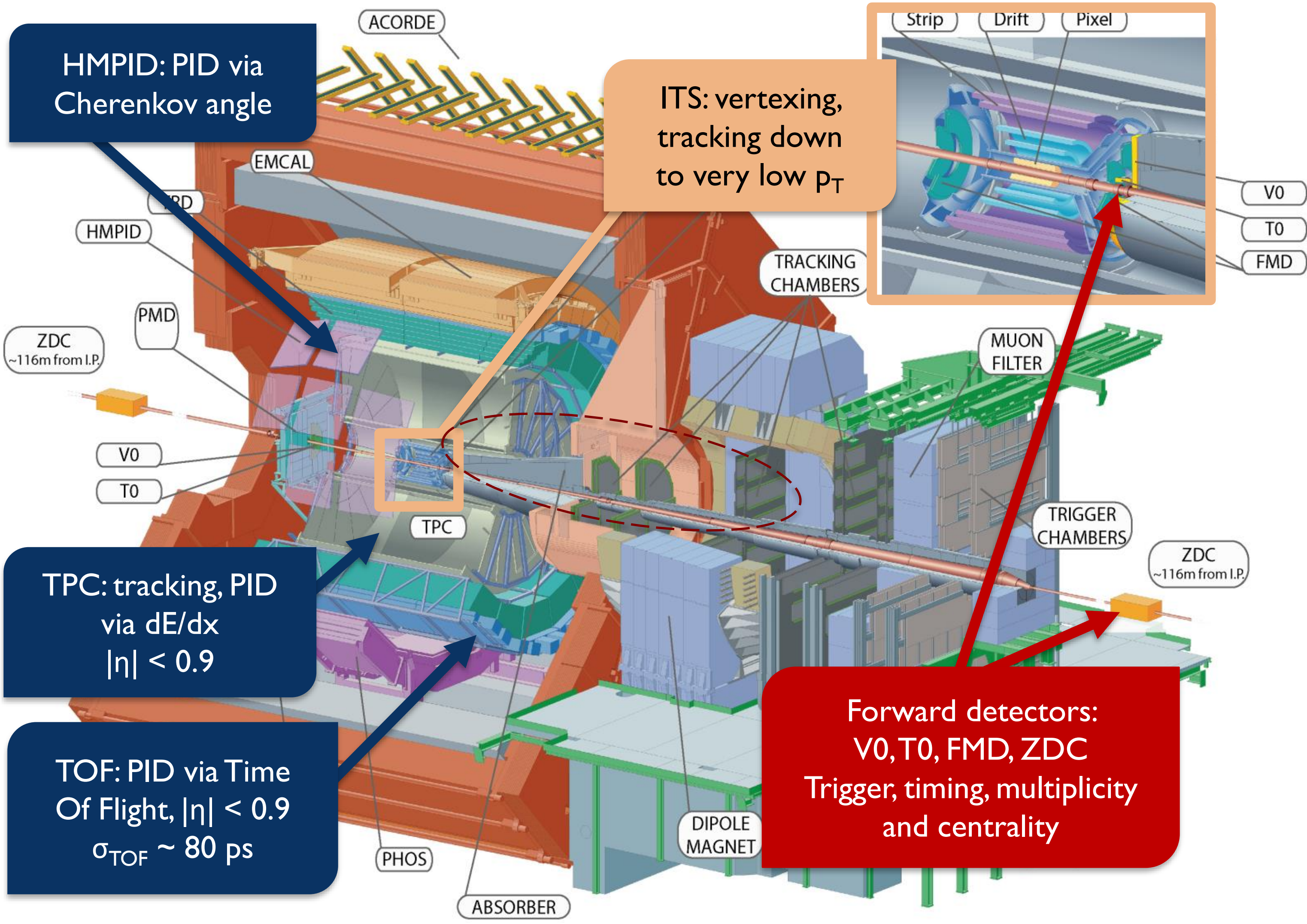


The ALICE detector at the LHC

ALICE
- Low p_T
- PID

ATLAS/CMS
- Wide η
- High p_T

LHCb
- Forward η
- Fixed target



HMPID: PID via Cherenkov angle

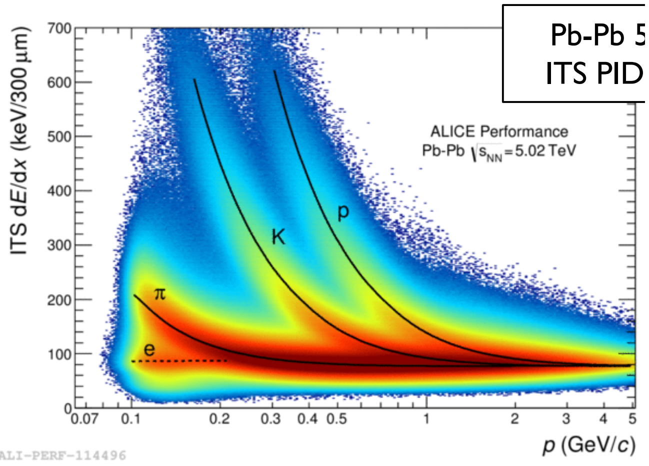
ITS: vertexing, tracking down to very low p_T

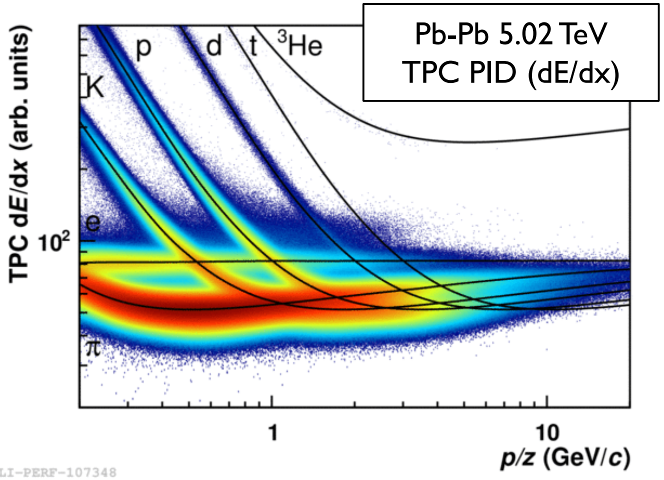
TPC: tracking, PID via dE/dx $|\eta| < 0.9$

TOF: PID via Time Of Flight, $|\eta| < 0.9$ $\sigma_{TOF} \sim 80$ ps

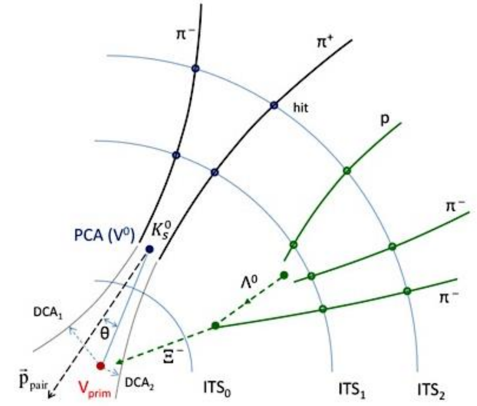
Forward detectors: V0, T0, FMD, ZDC Trigger, timing, multiplicity and centrality

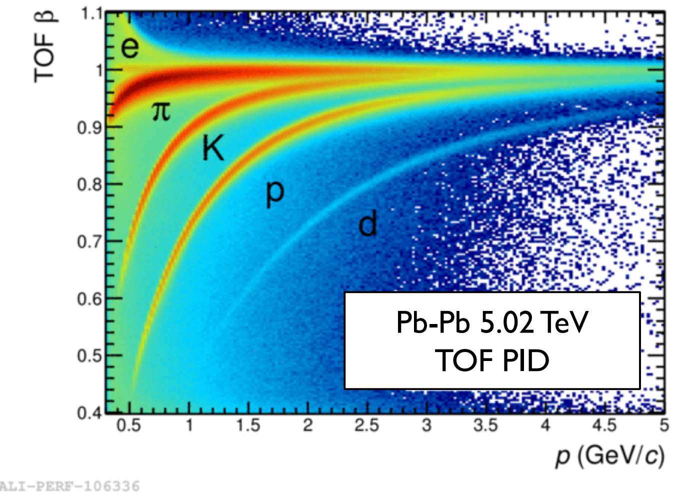
Particle identification in ALICE

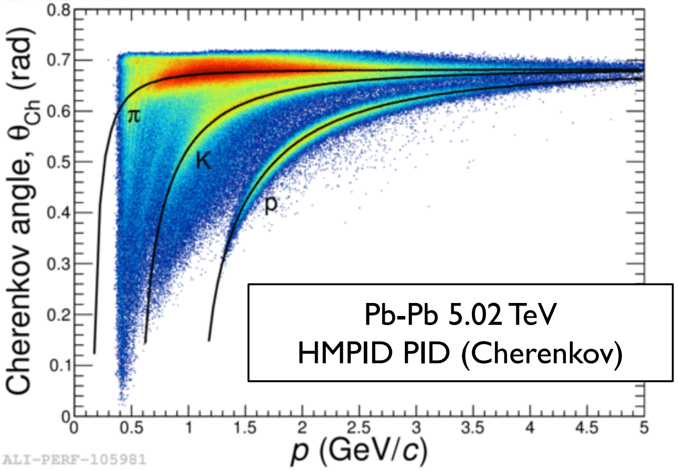

Pb-Pb 5
ITS PID

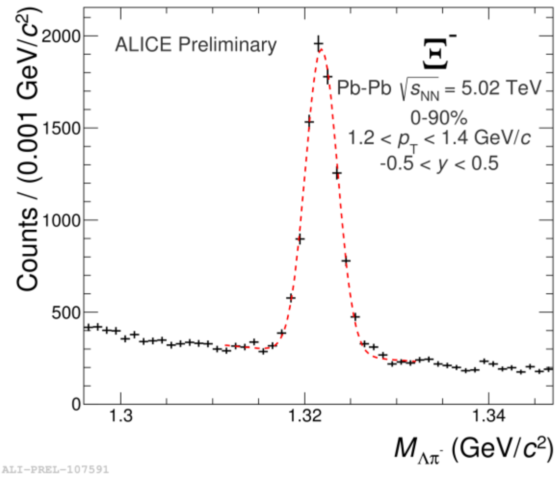

Pb-Pb 5.02 TeV
TPC PID (dE/dx)

Decay topology
secondary vertex reconstruction +
invariant mass analysis




Pb-Pb 5.02 TeV
TOF PID


Pb-Pb 5.02 TeV
HMPID PID (Cherenkov)



Identification of light flavour hadrons and light (anti-)nuclei via practically all known PID techniques in 0.1 GeV/c < p_T < 30 GeV/c