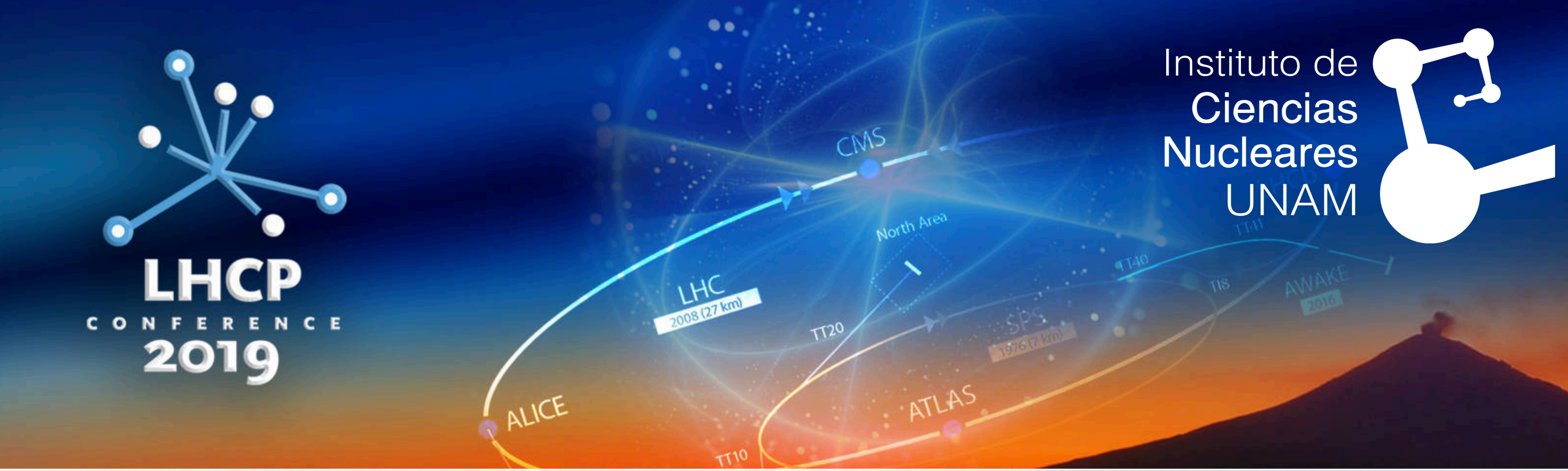


Particle production and flow-like effects in small systems

Antonio Ortiz, on behalf of the ALICE, ATLAS, CMS and LHCb Collaborations

May 22, 2019
Puebla, Mexico

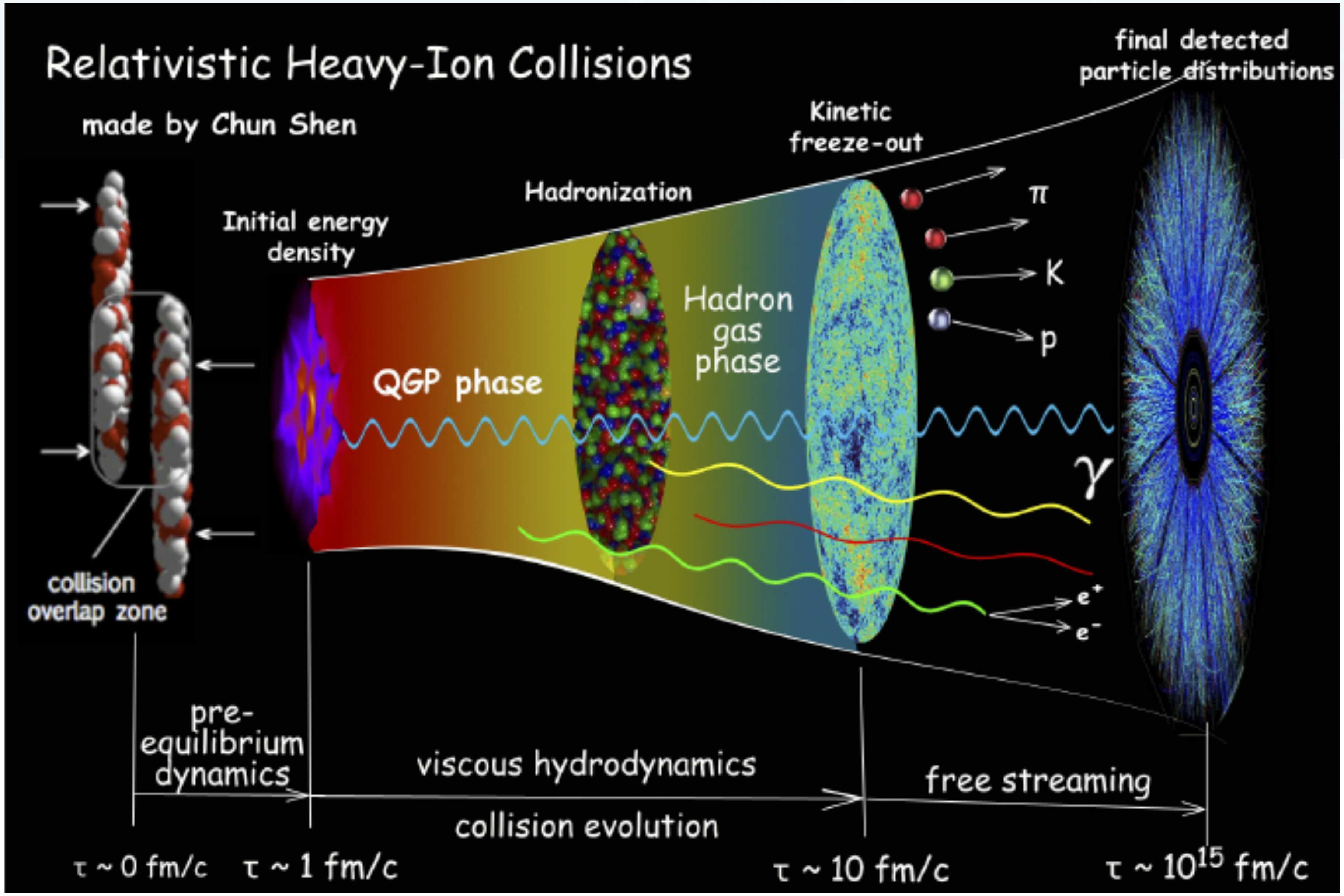
Outline

- Introduction
- Recent results
  - Correlation between global multiplicity and hard physics
  - Anisotropic flow in small systems
  - Radial flow (identified charged particle production vs multiplicity and transverse spherocity)
  - Hadrochemistry
- Summary

Introduction

Heavy-ion collisions

Compressing a large amount of energy in a small volume produces a "fireball" of hot matter (~T of universe at ~10 μs after Big-Bang)



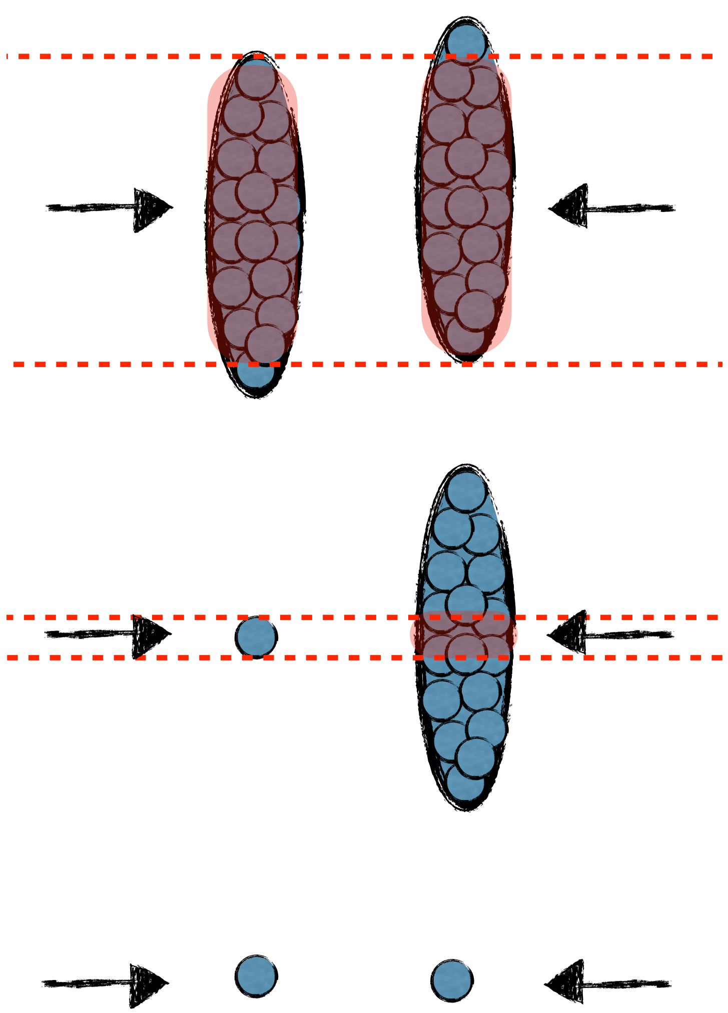
RHIC and LHC: compelling evidence of the formation of a "strongly interacting" Quark Gluon Plasma

- Collectivity
- Hadrochemistry
- Parton energy loss
- Quarkonium suppression

Ann. Rev. Nucl. Part. Sci. 68 (2018) 339-376

Traditional approach

pp and p-A (even peripheral A-A) collisions traditionally studied as "control experiments" to extract the genuine properties of QGP in central A-A collisions



QGP

Initial state effects

Reference data

Change of perspective

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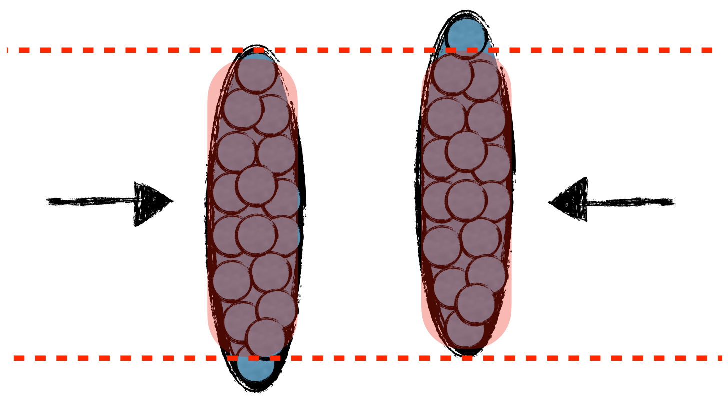
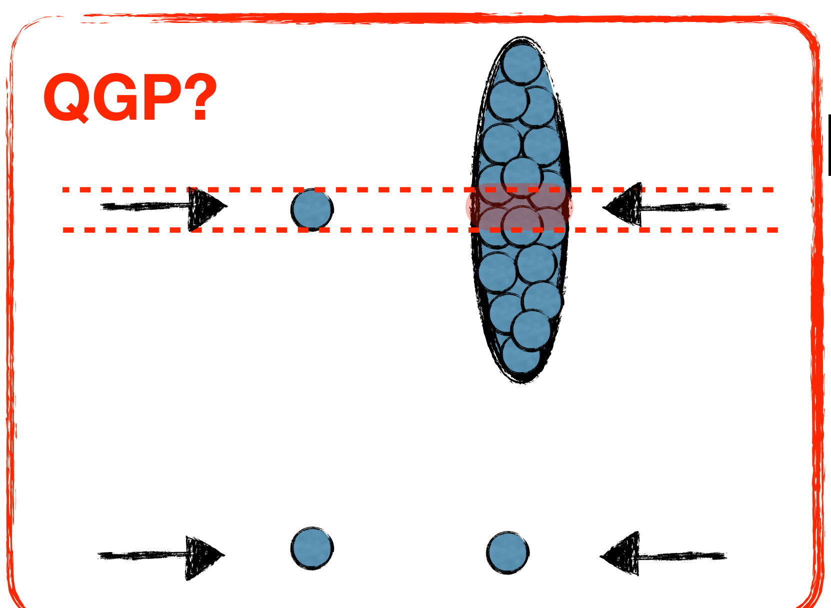


QGP



Initial state effects

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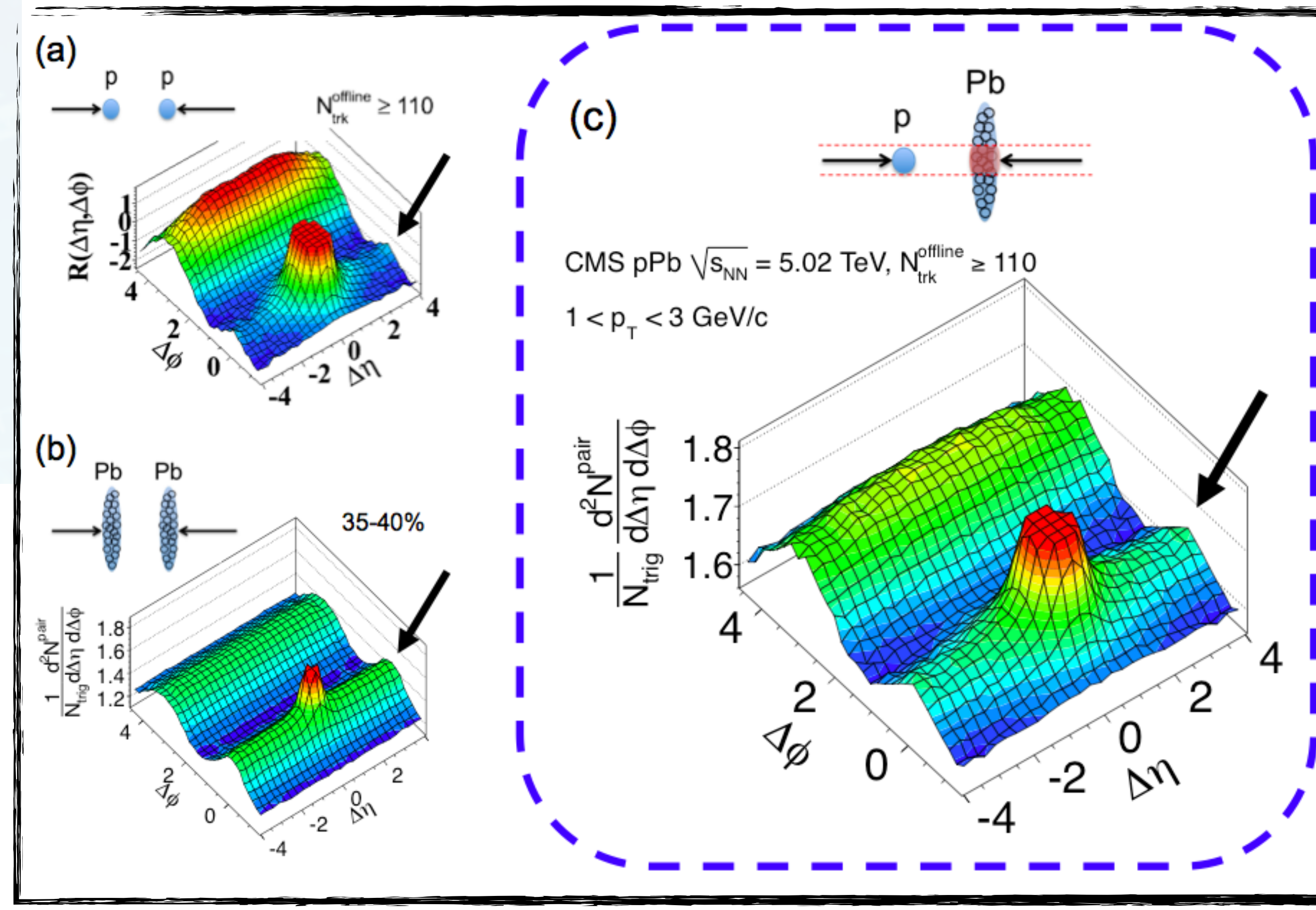

“Ridge” structures have been discovered in small systems (pp and p-A collisions). See e.g.

CMS, JHEP 1009 (2010) 091
ALICE, PLB 719 (2013) 29
ATLAS, PRL 110 (2013), 182302
LHCb, PLB 762 (2016) 473

In heavy-ion collisions it is interpreted as a signature of the collective expansion of the system

Initial or final state effect?

The origin of the effect in small systems is still unclear. Different models: a) final state interactions (assuming QGP), b) initial state effects related to gluon saturation, c) parton transport models

See e.g. **PRC 85 (2012) 014911** (a), **PRC 87 (2013) 064906** (b), **PRL 113 (2014) 252301** or **arXiv:1805.04081** (c)

- How reliable is hydrodynamics applied to small non-equilibrium systems?
- How large are the initial state correlations in realistic simulations and to what extend do they survive subsequent final state interactions?

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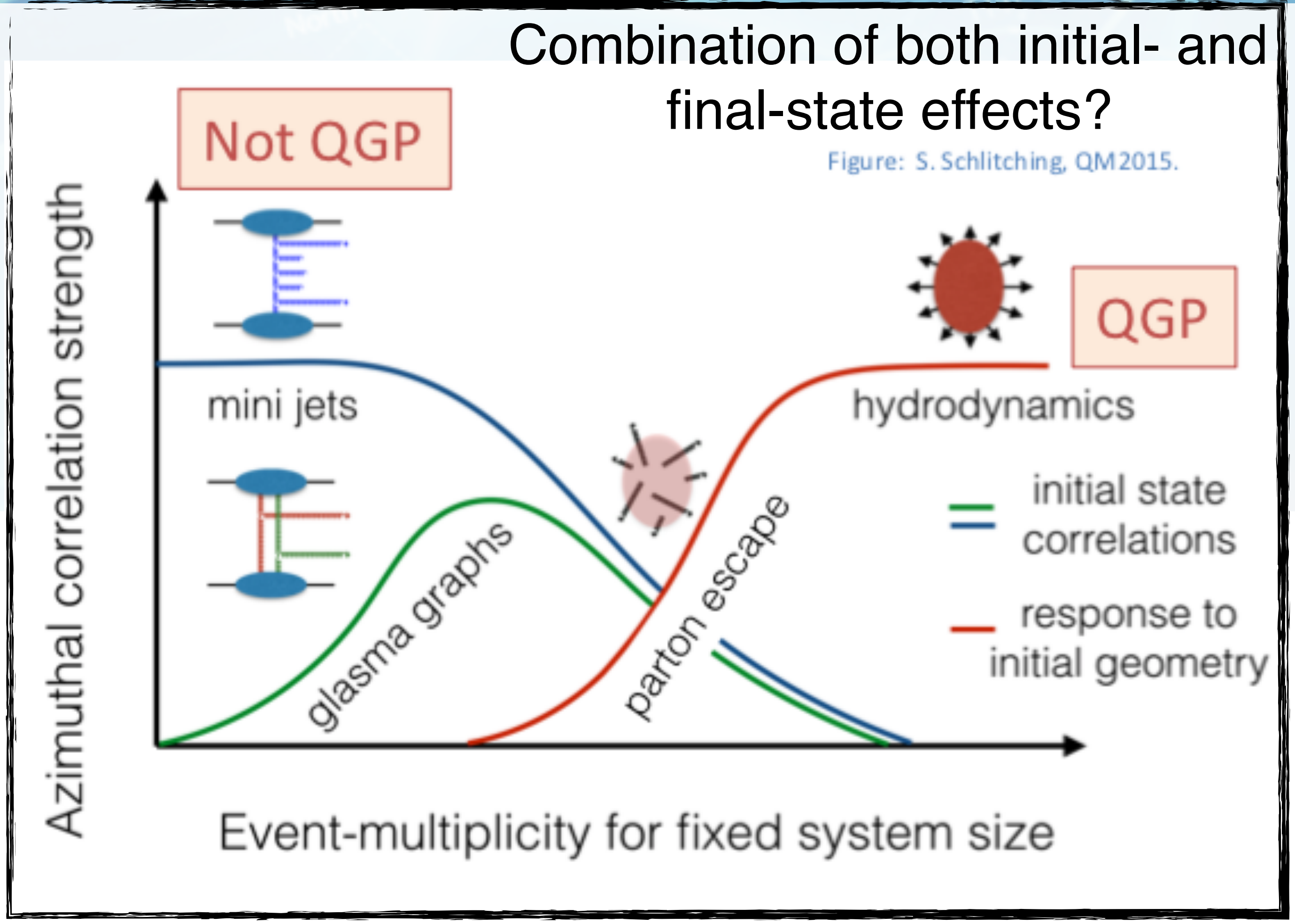

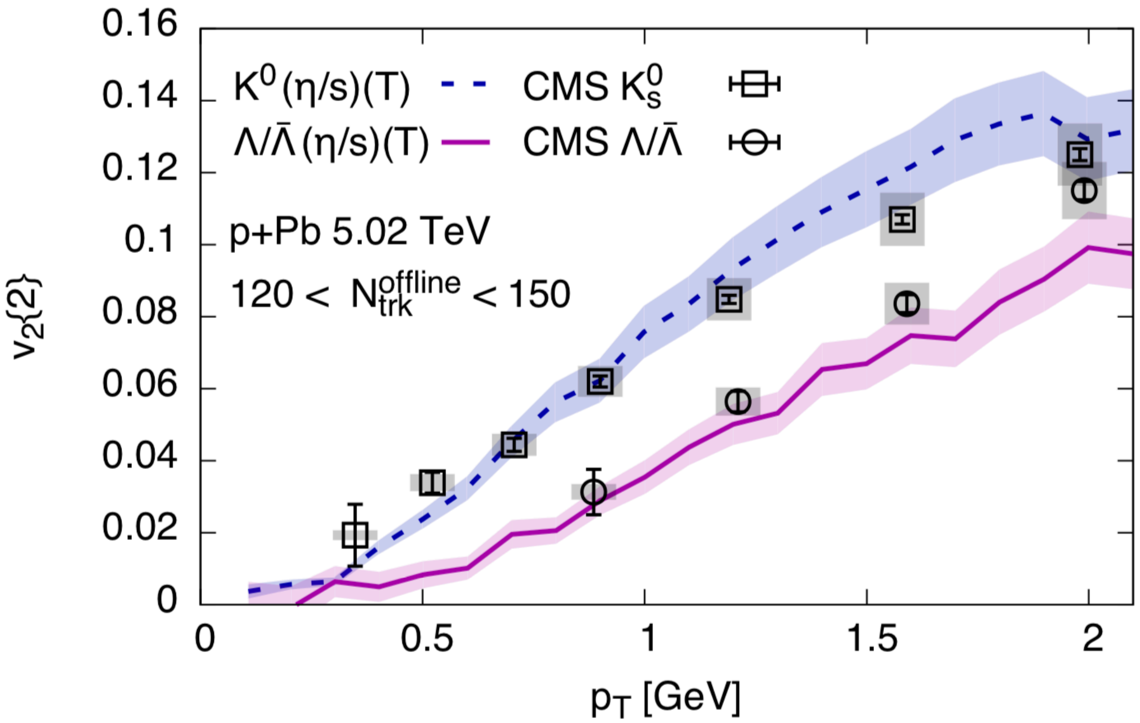

PLB 772 (2017) 681

IP-Glasma + hydrodynamics + UrQMD (importance of sub-nucleon scale fluctuations in the p projectile)

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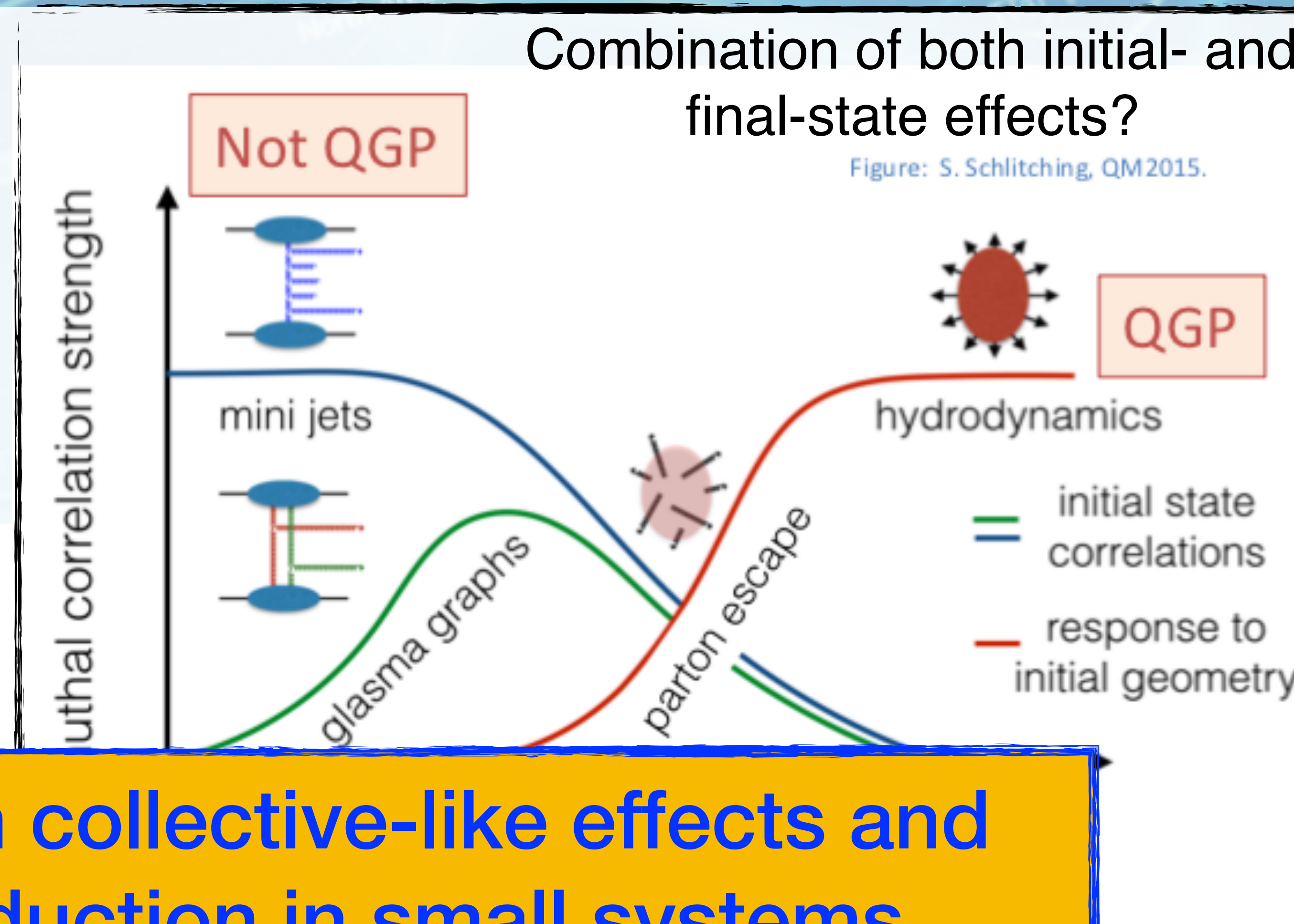


This talk: LHC results on collective-like effects and identified particle production in small systems

Theory reports:
- Theory overview talk (**Derek Teaney** / Plenary / Wednesday 22, 9:00)
- Theory on collective effects and MC simulations (**Patrick Kirchgaesser** / QCD parallel session / Thursday 23, 11:50)

PLB 772 (2017) 681

IP-Glasma + hydrodynamics + UrQMD (importance of sub-nucleon scale fluctuations in the p projectile)

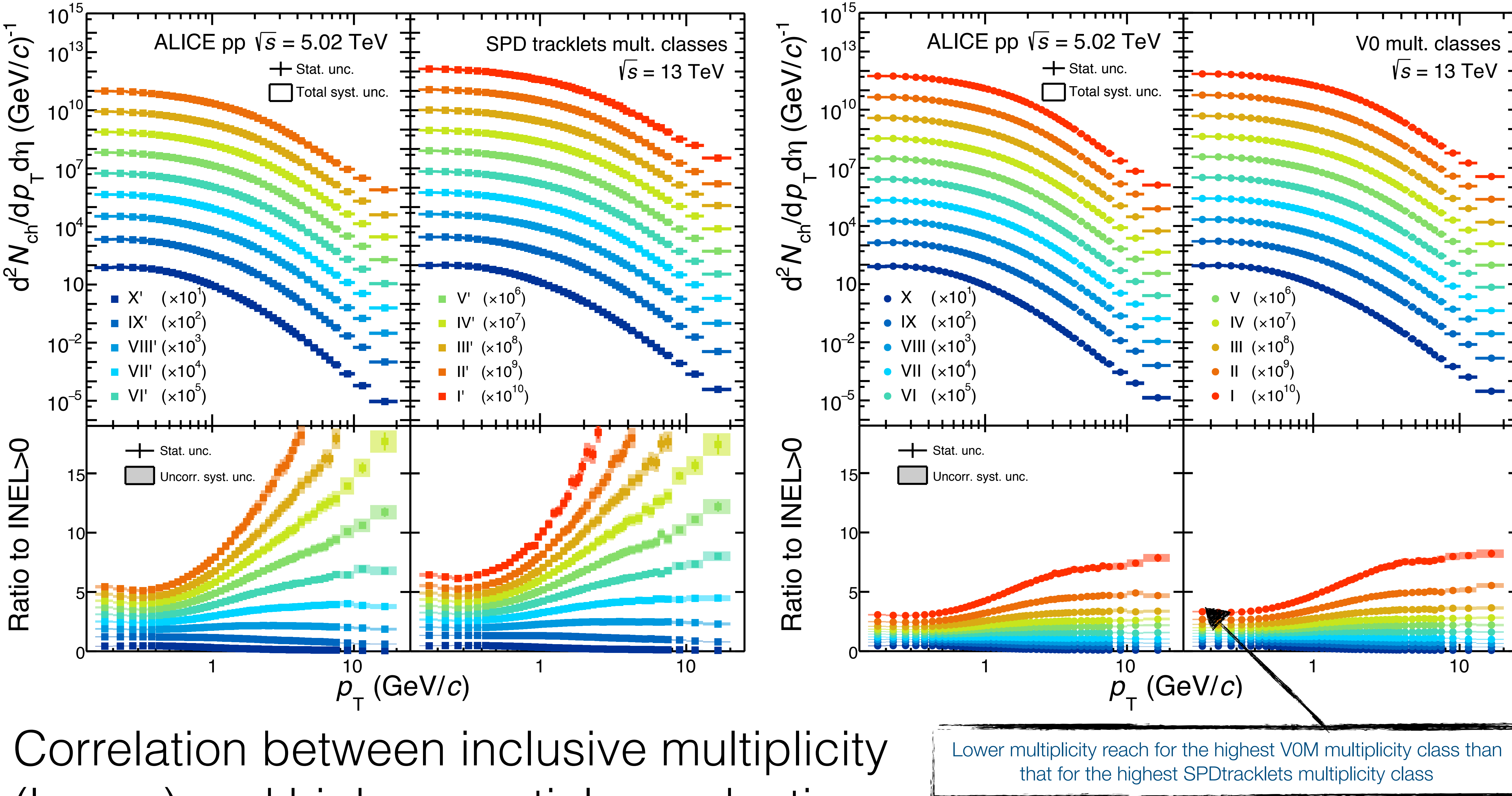
Particle production as a function of multiplicity

Particle production vs N_{ch}

ALICE, arXiv:1905.07208

Multiplicity selection at mid-pseudorapidity

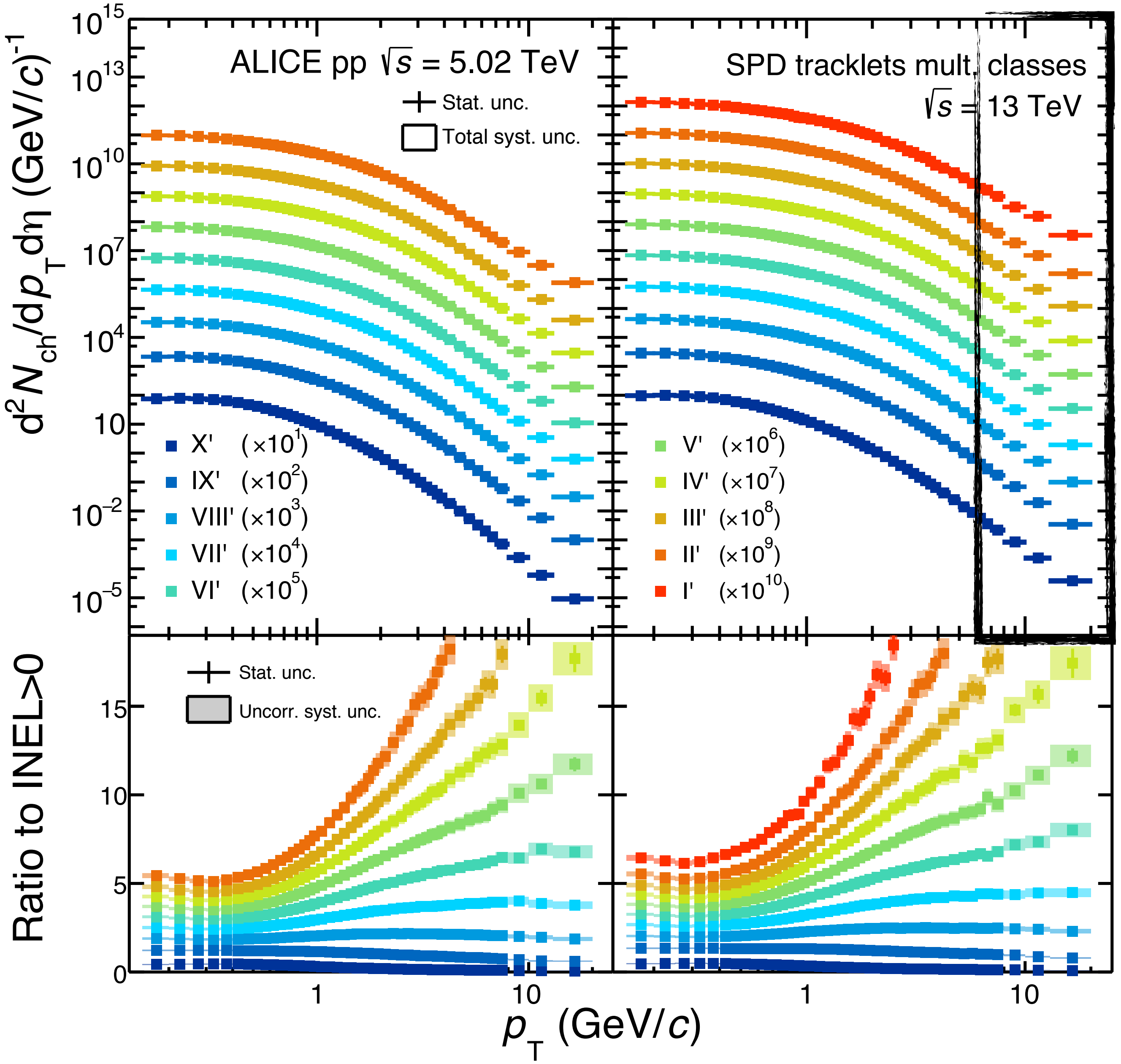
Multiplicity selection at forward rapidity



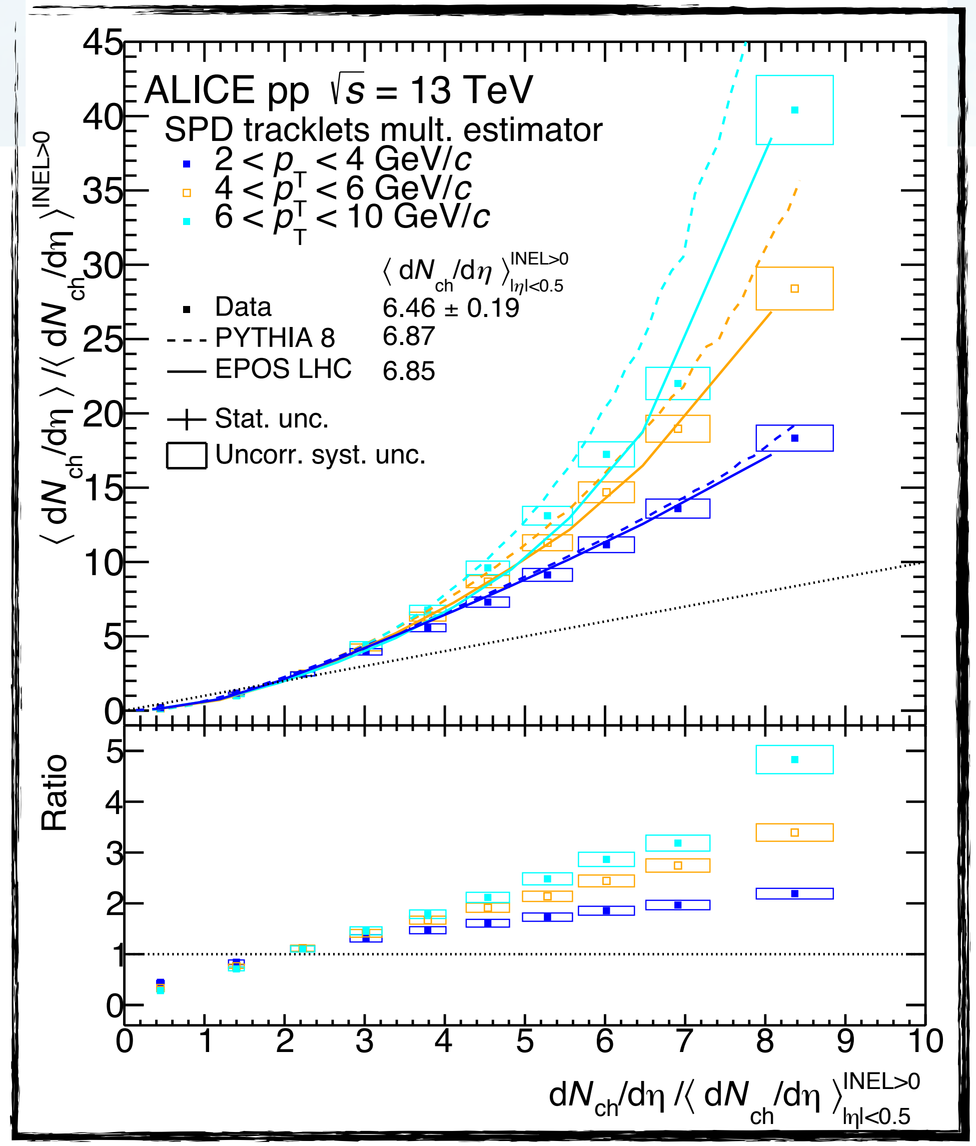
Correlation between inclusive multiplicity (low p_T) and high-p_T particle production

Particle production vs N_{ch}

Multiplicity selection at mid-pseudorapidity



ALICE, arXiv:1905.07208

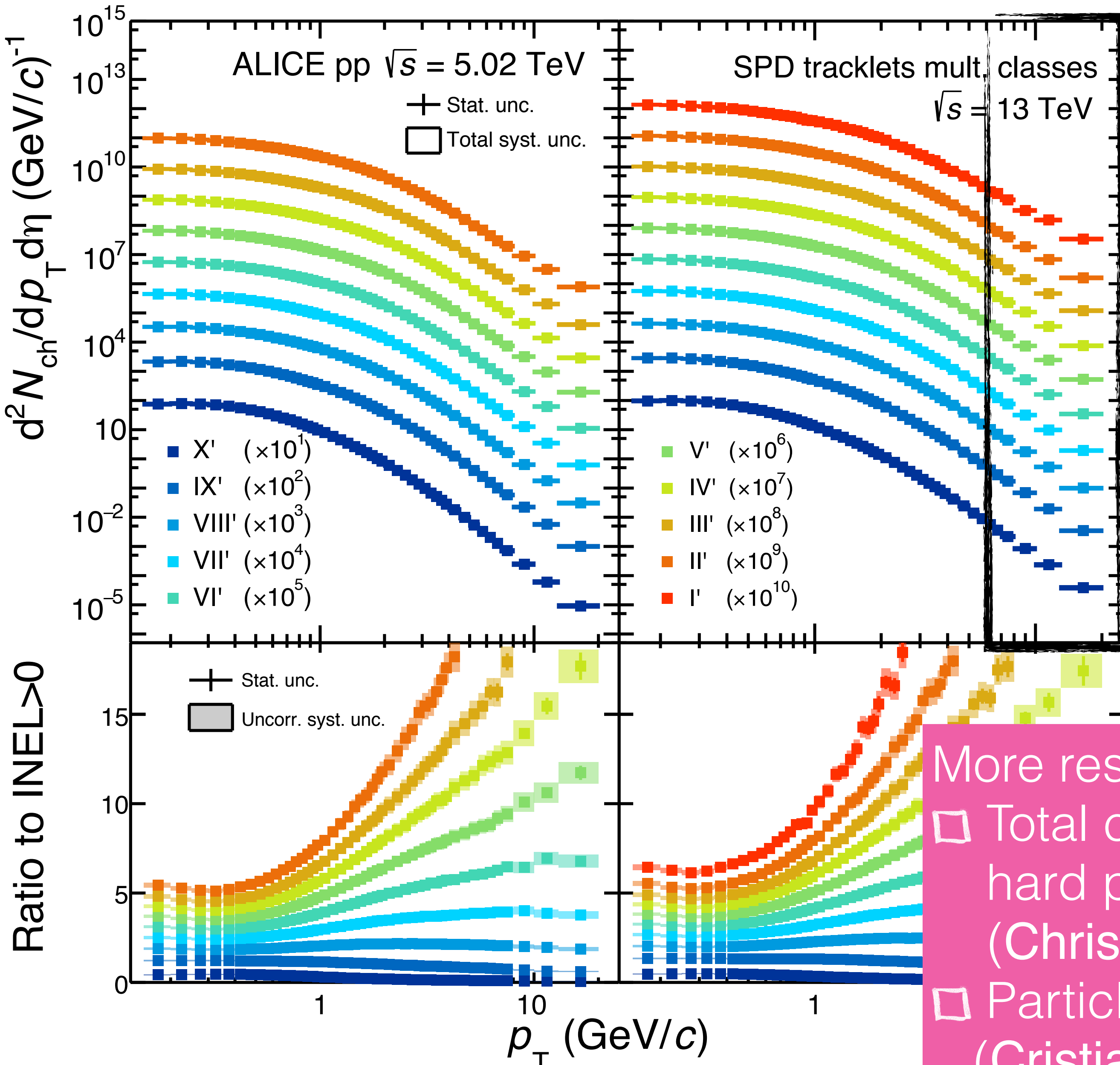


Non-linear increase of the high-p_T particle production as a function of multiplicity. EPOS LHC describes the relative yields better than PYTHIA, but it fails in describing the spectral shapes at high p_T

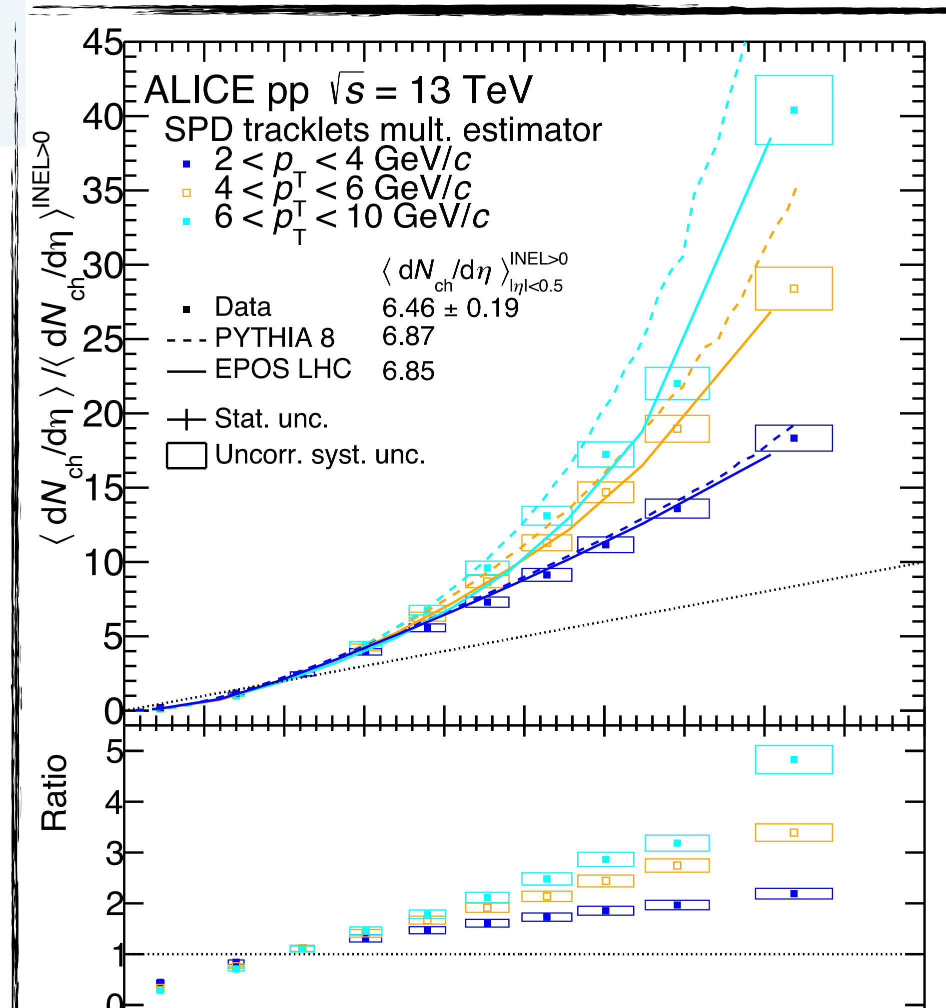
The results illustrate the role of hard physics in high multiplicity events

Particle production vs N_{ch}

Multiplicity selection at mid-pseudorapidity



ICE, arXiv:1905.07208



The results illustrate the role o[f]
physics in high multiplicity eve[nts]

More results on soft QCD in pp collisions:

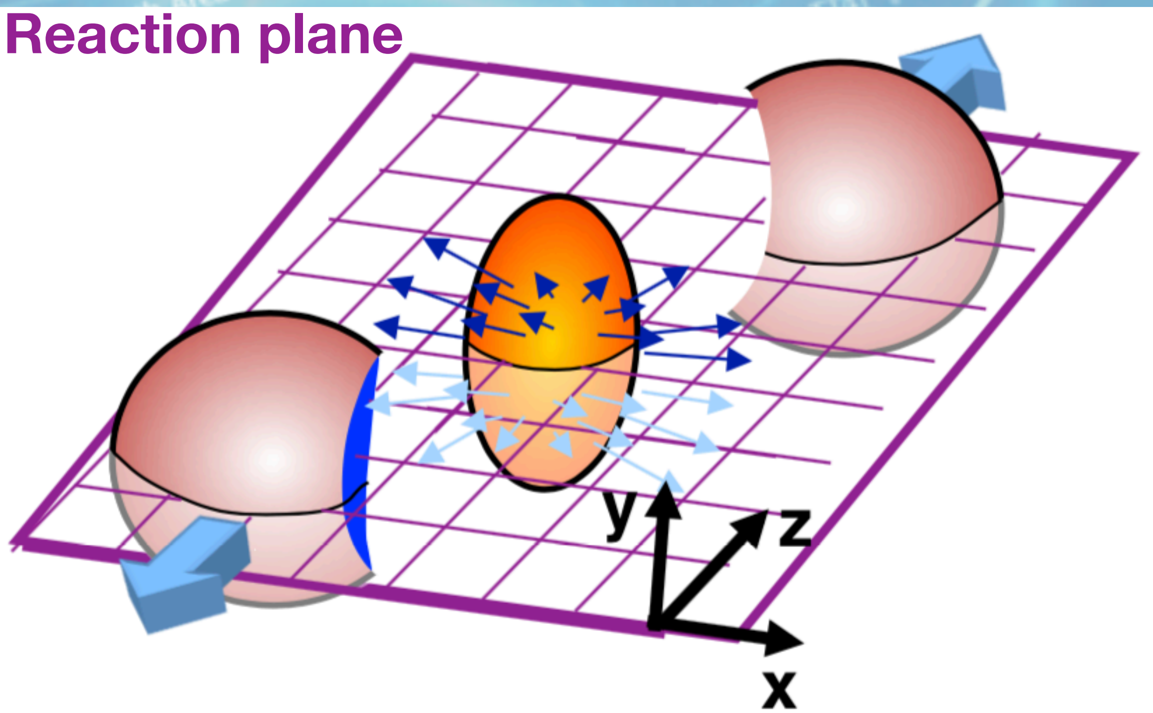
- Total cross-section and particle production in soft and hard processes at the LHC (**Christophe Royon** / Tuesday 21, 18:06)
- Particle production vs multiplicity in pp with ALICE (**Cristiane Jahnke** / Thursday 23, 12:10)
- Recent soft QCD results from ATLAS and CMS (**Valentina Cairo** / Thursday 23, 2:44)

Anisotropic flow

Collectivity in small systems

- **Collective flow**: In heavy-ion collisions (HIC) azimuthal anisotropies established during the hydrodynamic stage in response to initial geometry

  v_2: dominates in non-central HI collisions
  v_{2n+1}: various geometrical configurations arising from initial geometry fluctuations



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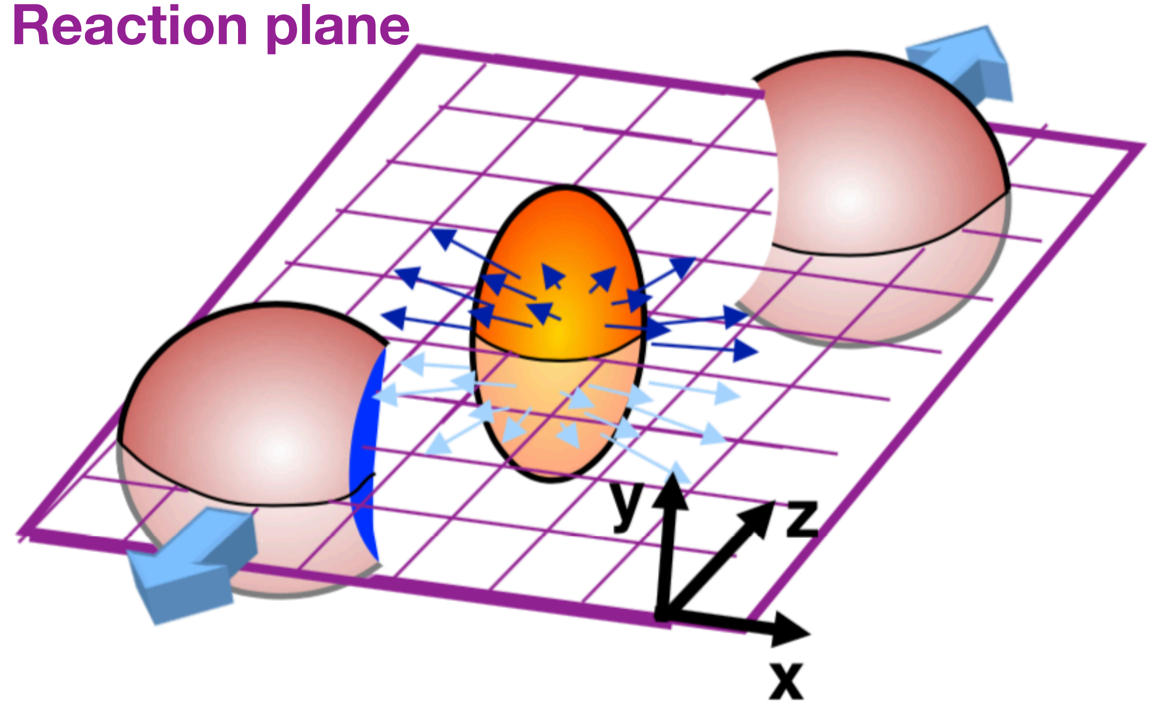
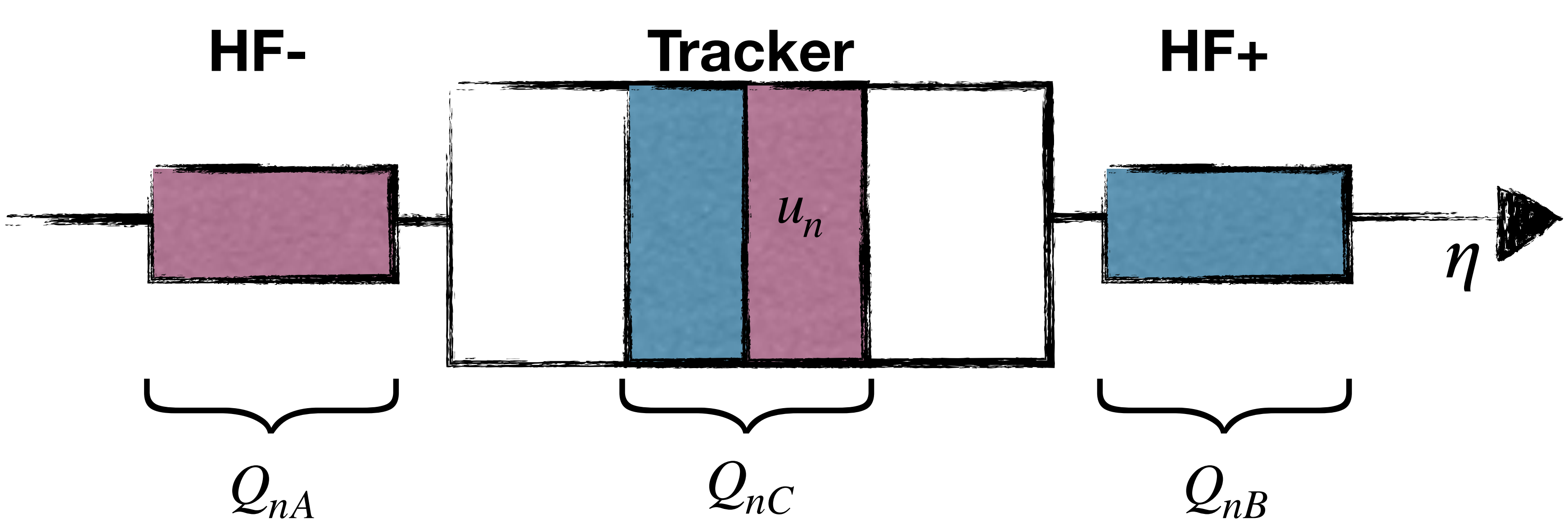


Main challenge for small systems: non-flow contributions (resonance decays, jets). Different techniques have been developed to control non-flow effects (e.g. scalar product method correlating particles from different subevents)

$$Q_n = \sum_{i=1}^{M} \tilde{\omega}_i e^{in\phi_i}$$

$$v_n\{SP\} = \frac{\langle u_n Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$$



Multi-particle cumulants

Multi-particle cumulants from two- and multi-particle azimuthal correlations (standard method)

- k-particle azimuthal correlation $\langle\{k\}\rangle$

$$\langle\{2\}_n\rangle = \langle e^{in(\phi_1-\phi_2)}\rangle \qquad \langle\{3\}_n\rangle = \langle e^{in(\phi_1+\phi_2-2\phi_3)}\rangle$$

$$\langle\{4\}_{n,m}\rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\rangle$$

- 2- and 4-particle cumulants:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle \qquad c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$

where $\langle\{4\}_n\rangle \equiv \langle\{4\}_{n,n}\rangle$

- If cumulants are free of non-flow correlations:

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

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Anisotropic flow coefficients

ALICE, arXiv:1903.01790

v_2(Pb-Pb) > v_2(p-Pb) > v_2(pp)

(as expected if the overall collision geometry dominates)

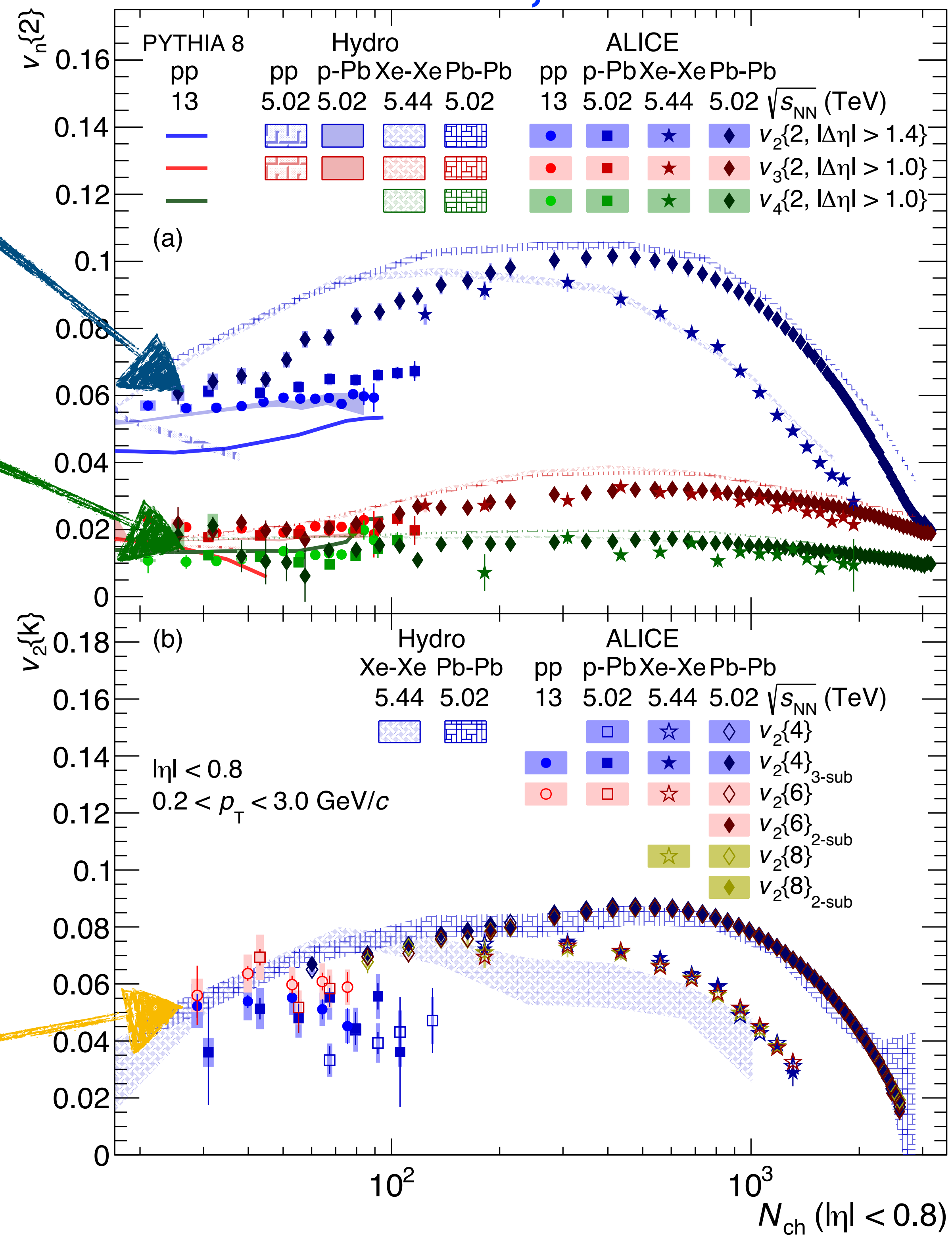
v_3(Pb-Pb) ≈ v_3(p-Pb)

(indicating a similar, fluctuation-driven initial-state geometry)

Se also: **CMS, arXiv:1901.07997**

The analysis has also been extended to the subevent method

v_2>0 for small systems



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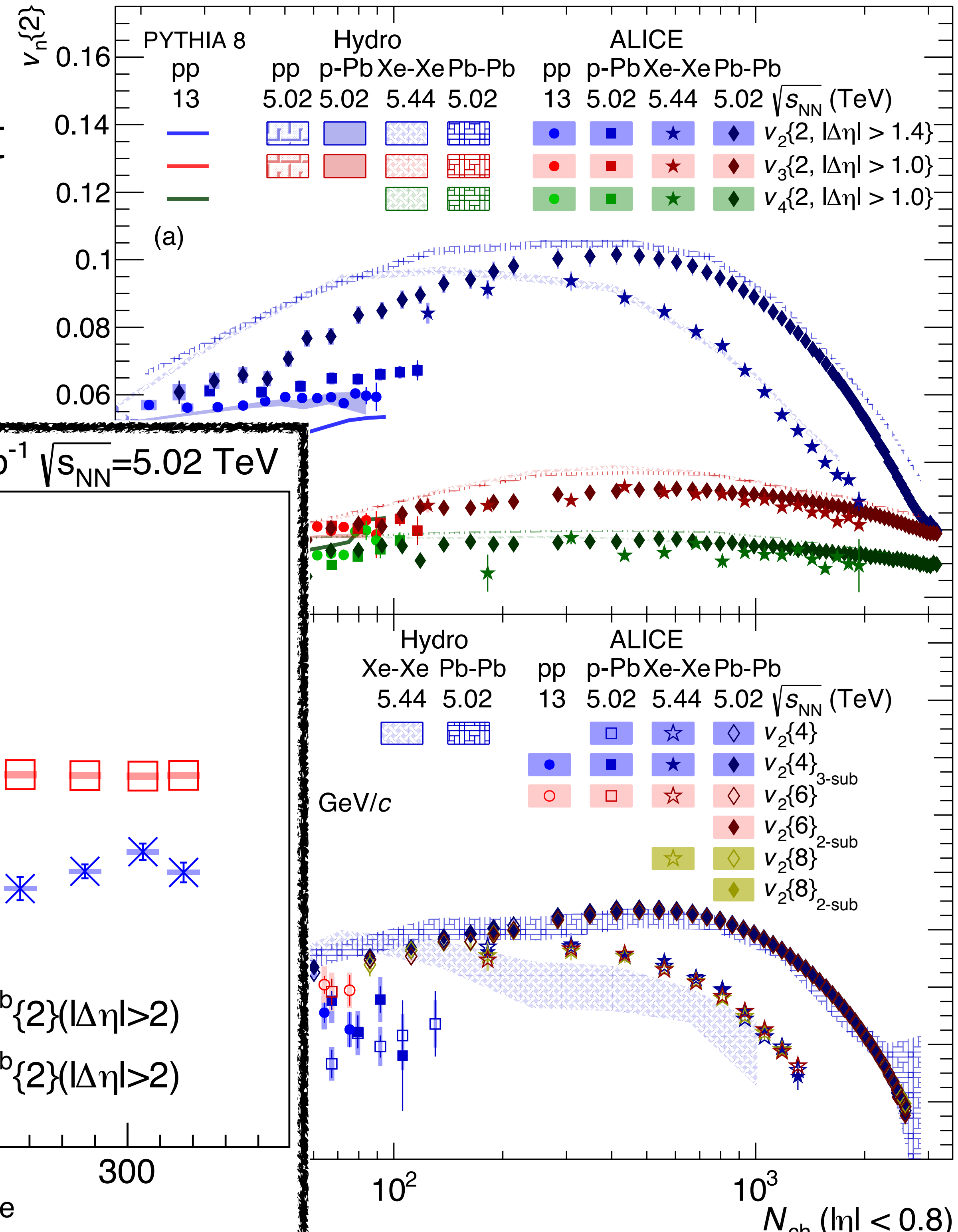
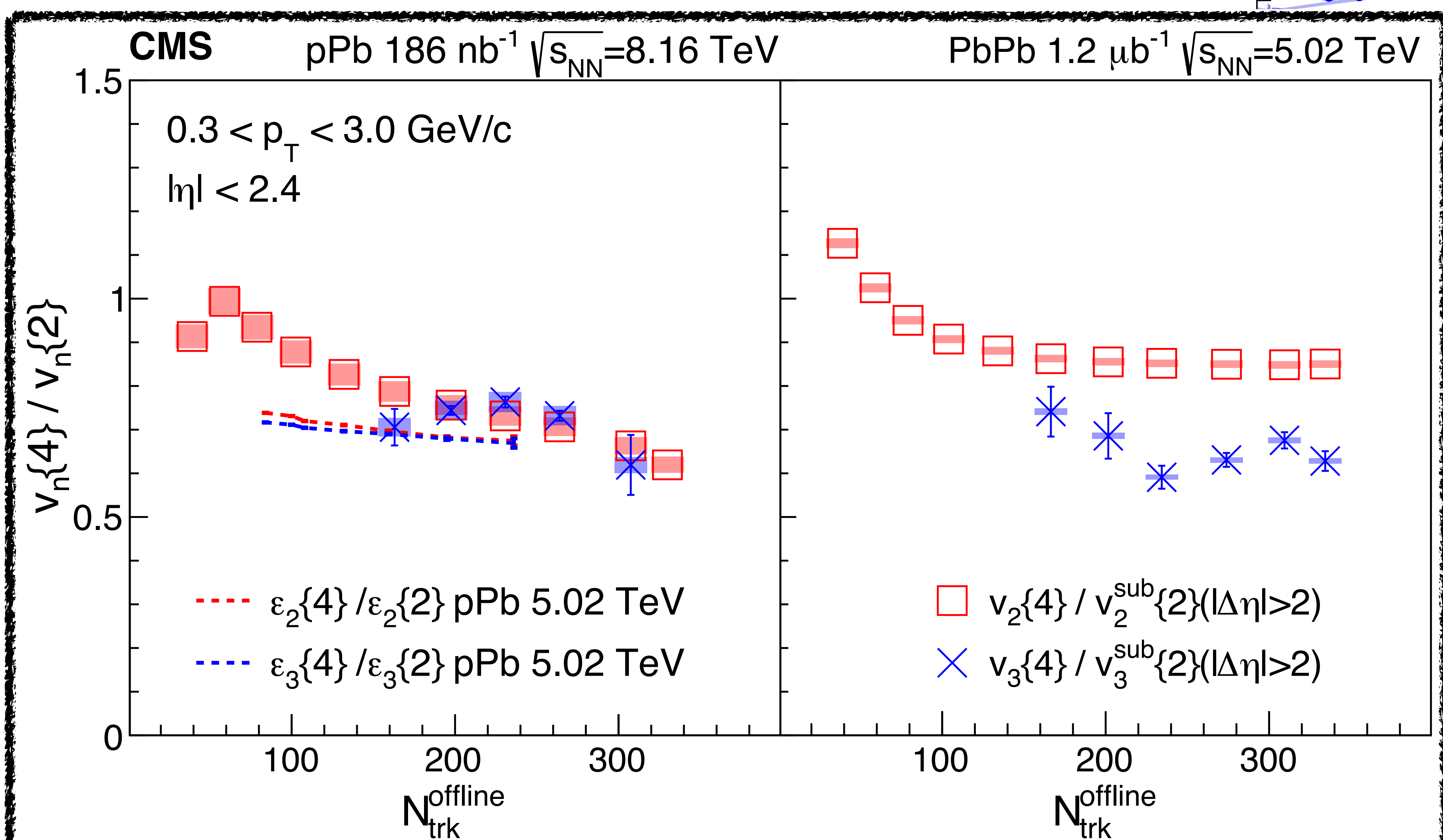
Anisotropic flow coefficients

For p-Pb collisions, the ratios $v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$ are comparable, consistent with a purely fluctuation-driven origin for the azimuthal asymmetry

CMS, arXiv:1904.11519





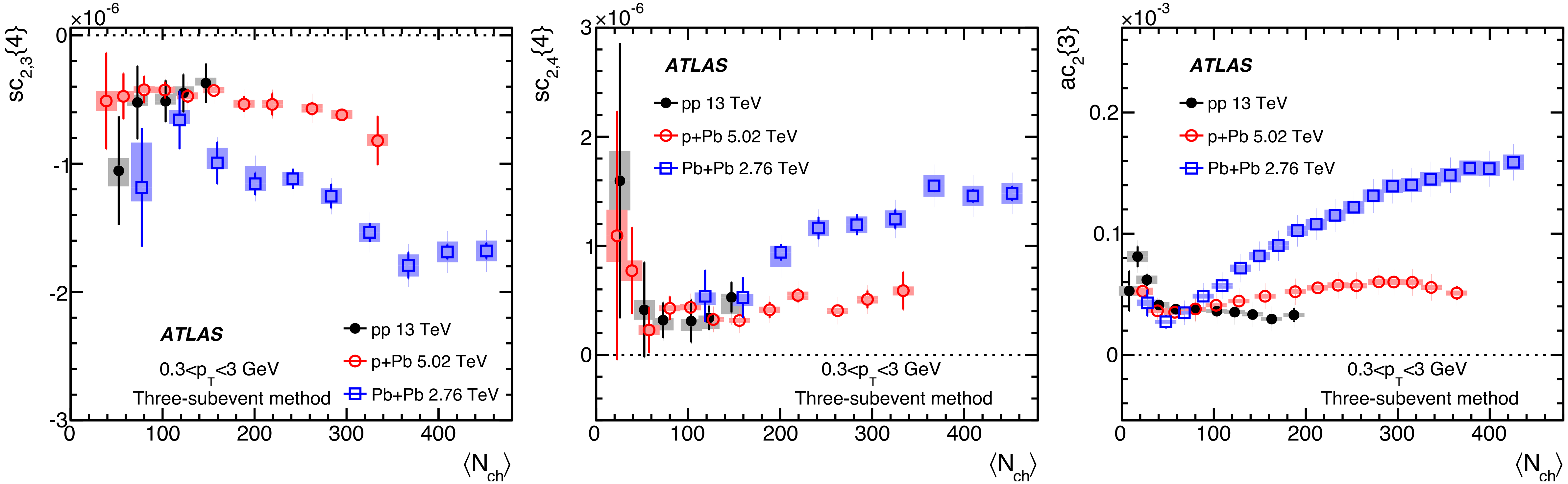
Symmetric and asymmetric cumulants

Results for pp, p-Pb and Pb-Pb collisions using subevent cumulants: 2-, 3- and 4-subevents

ATLAS, PLB 789 (2019) 444-471

$sc_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$ → quantifies the lowest-order correlation between v_n^2 and v_m^2

$ac_n\{3\} = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \rangle$ → quantifies the correlation between v_n and flow phase Φ_n

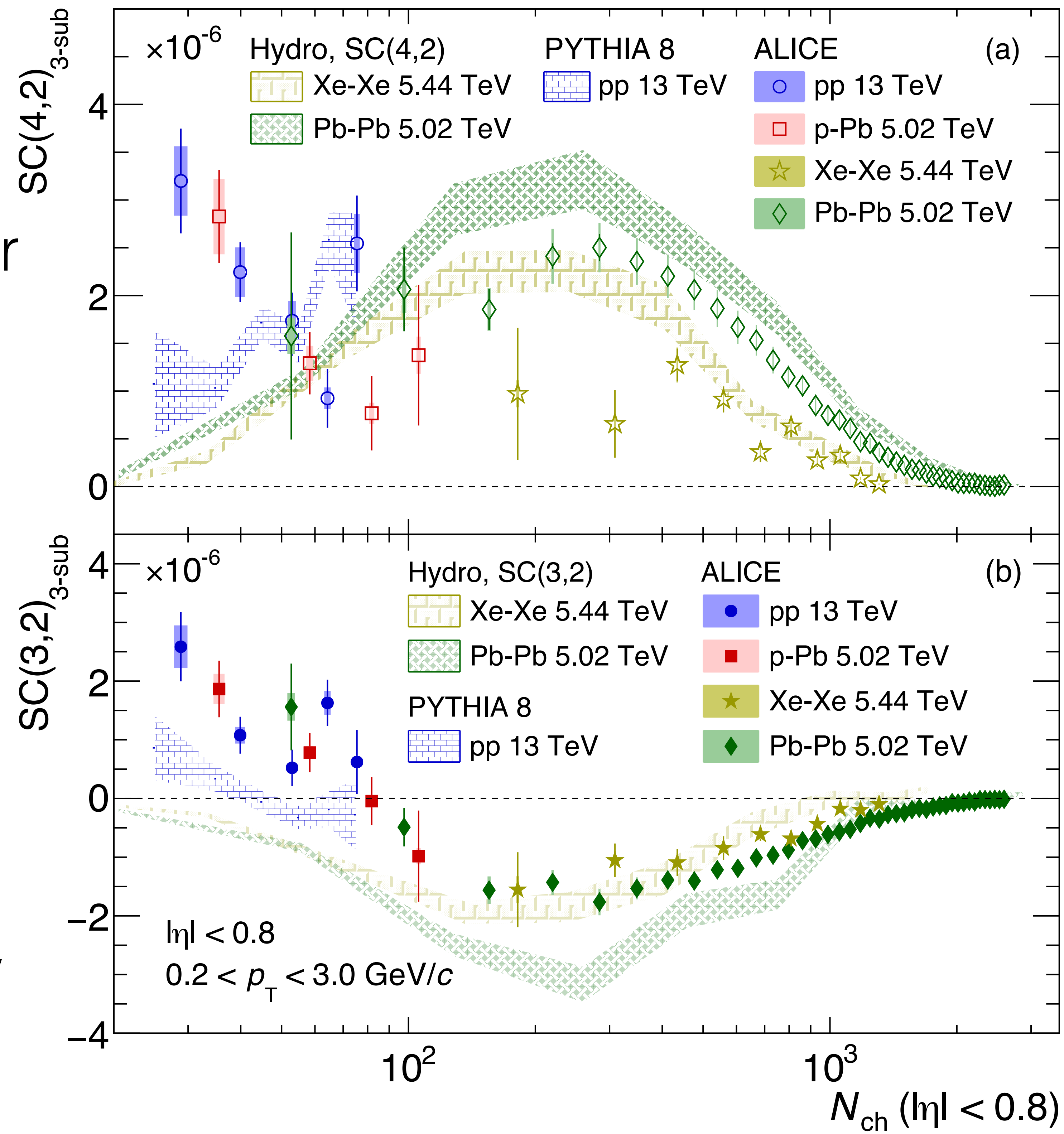


- Methods with three or more subevents are sufficient to reject now-flow correlation from jets
- For small systems: negative correlation between v_2 and v_3, positive correlation between v_2 and v_4. Same patterns already observed in large collision systems. Further evidence that the ridge is a long range collective phenomena

pp, p-Pb, Xe-Xe and Pb-Pb

ALICE, arXiv:1903.01790

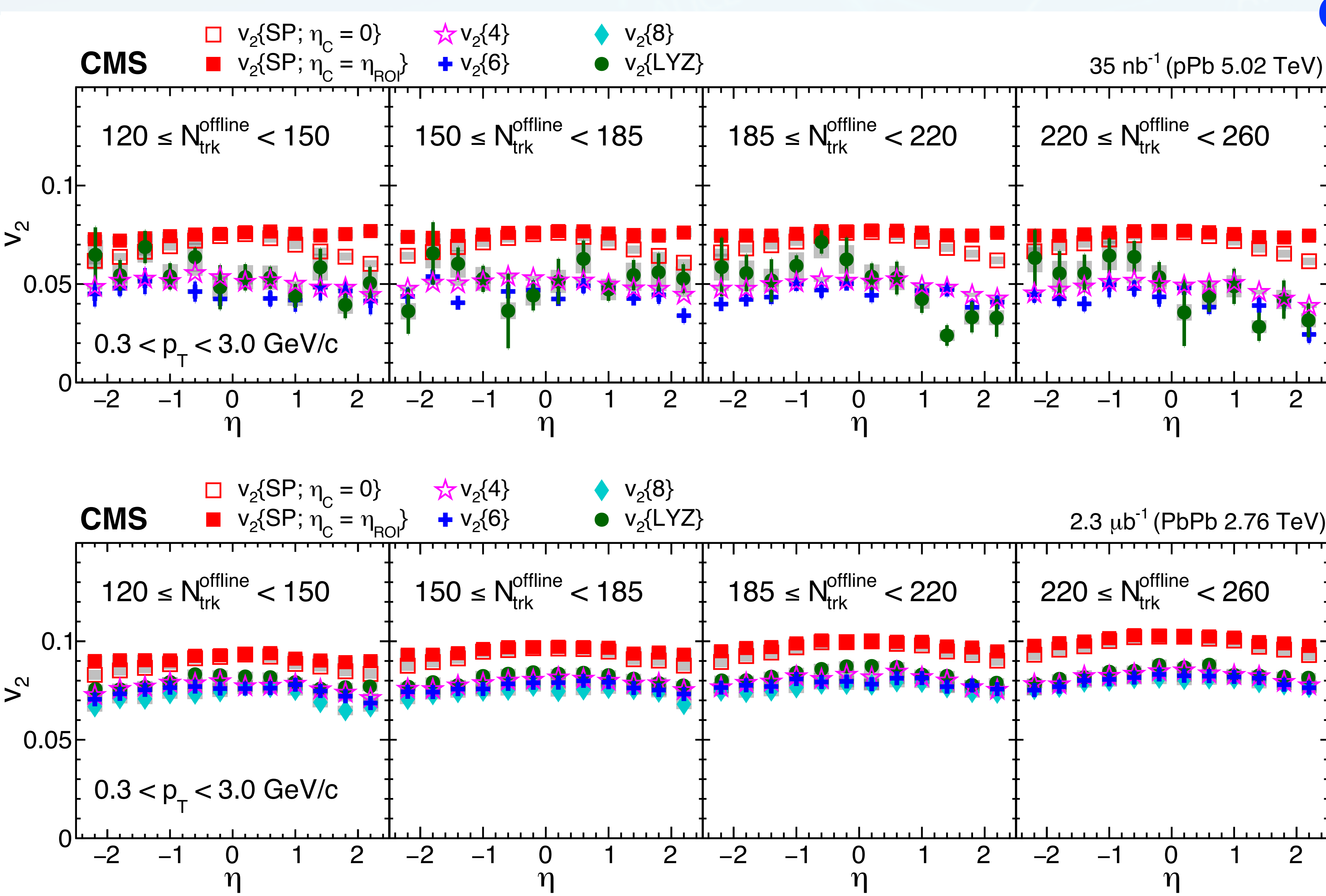
- Positive SC(4,2) in Xe-Xe and Pb-Pb collisions (well reproduced by the hydro model). Same sign is found for pp and p-Pb collisions
- SC(3,2) goes from negative (anticorrelation between v_2 and v_3) to positive values at N_{ch}~100. Same tendency found for pp and p-Pb collisions. Different behavior observed by ATLAS and CMS (different $|\eta|$, different non-flow contributions?)



Event plane decorrelation effects

It has been reported that the event plane should not be considered a global event observable. The decorrelation between the event plane angles at η_A and η_B has been parametrized by CMS

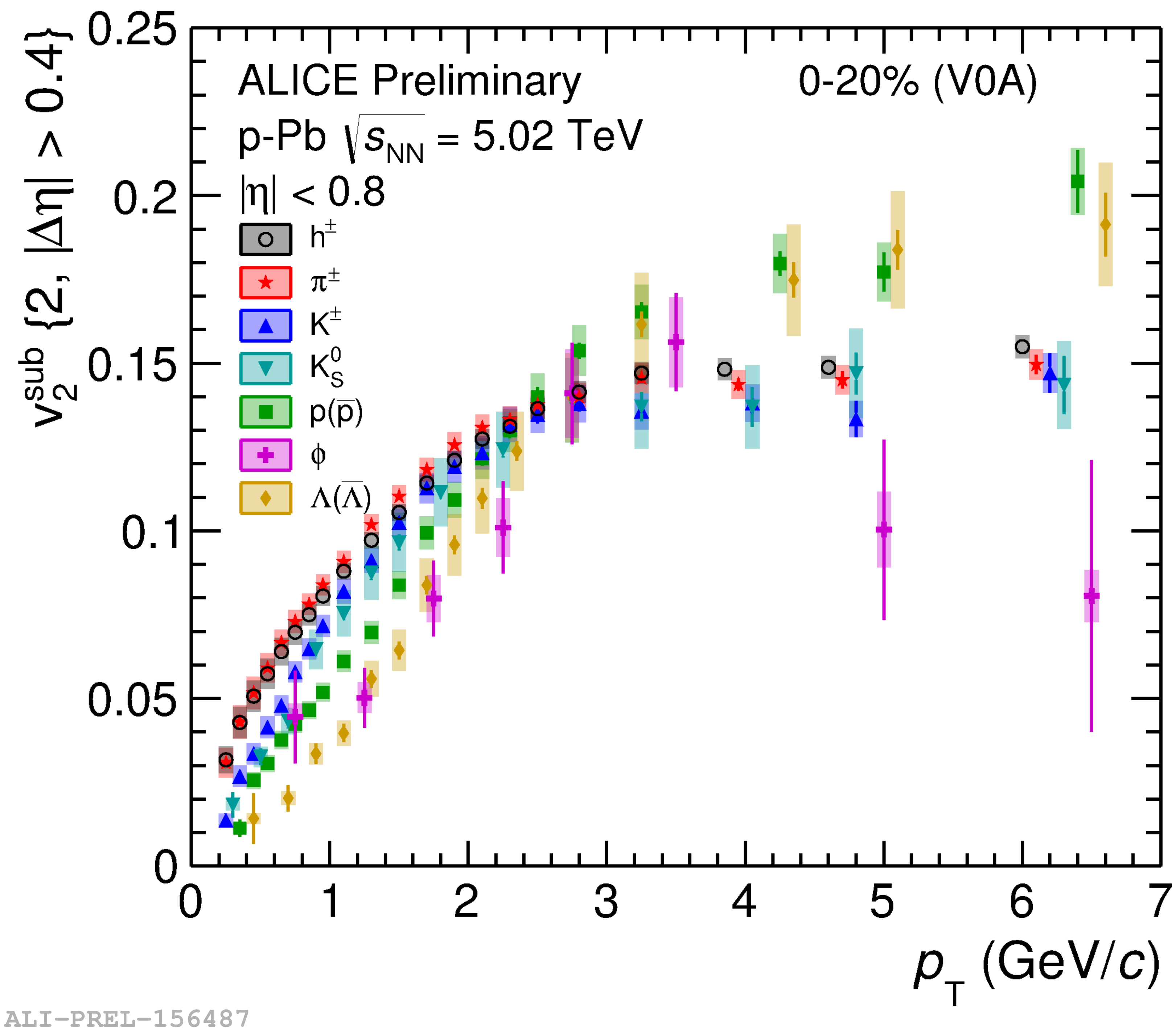
CMS, PRC 98, 044902 (2018)



- Flat v_2 vs η: SP when $\eta_C = \eta_{ROI}$ (partial accounting of the event plane decorrelation behavior)
- η-dependent v_2: SP when $\eta_C = 0$ and for higher order particle correlation analyses

Identified particle v_2 in p-Pb

- In Pb-Pb collisions, low- (intermediate-) p_T v_2 data of identified particles show mass ordering (baryon/meson grouping)
- In p-Pb collisions, most of particle species follow mass ordering at low p_T. For intermediate p_T: baryon v_2 > meson v_2 (partonic flow?)



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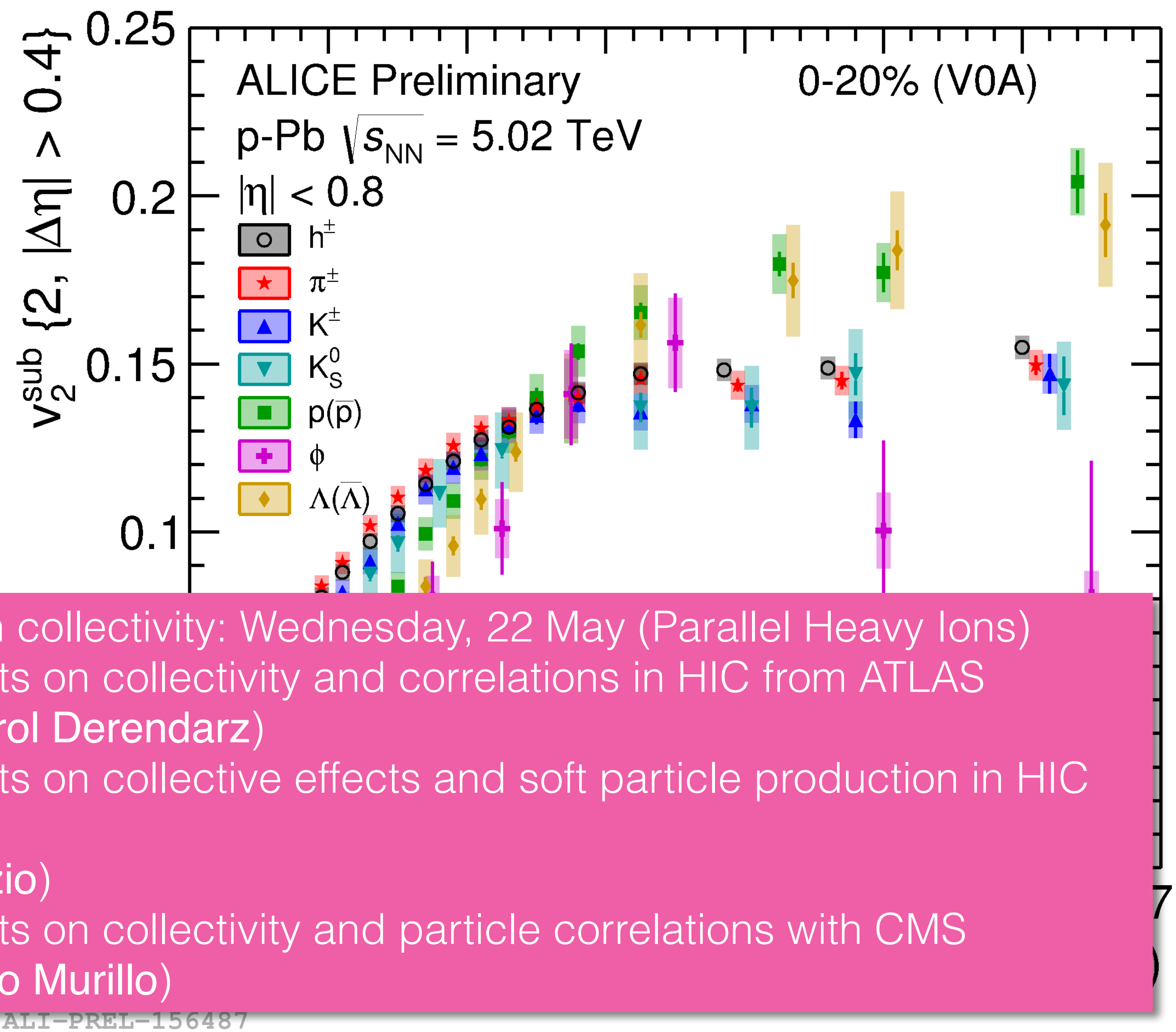


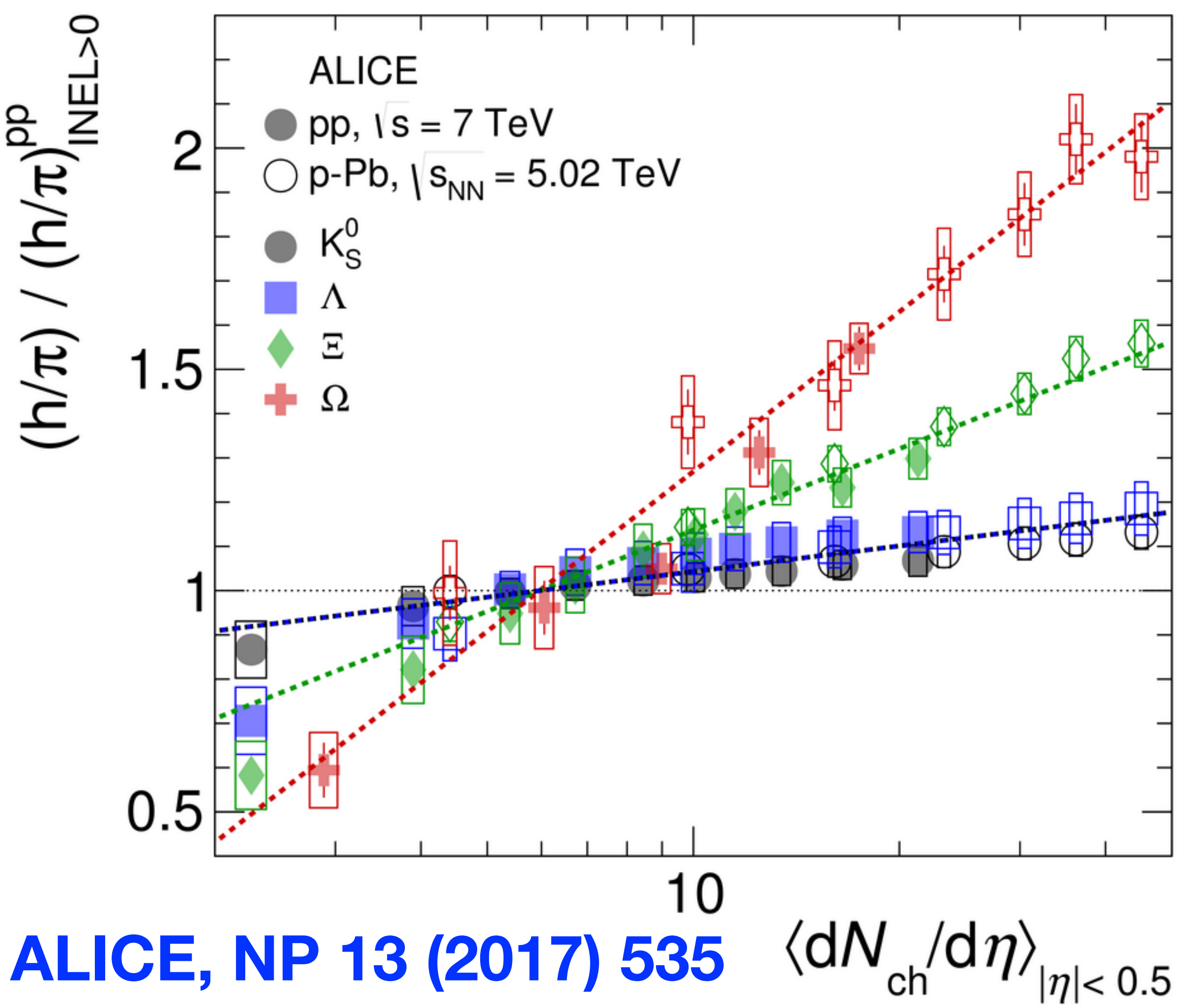
More results on collectivity: Wednesday, 22 May (Parallel Heavy Ions)

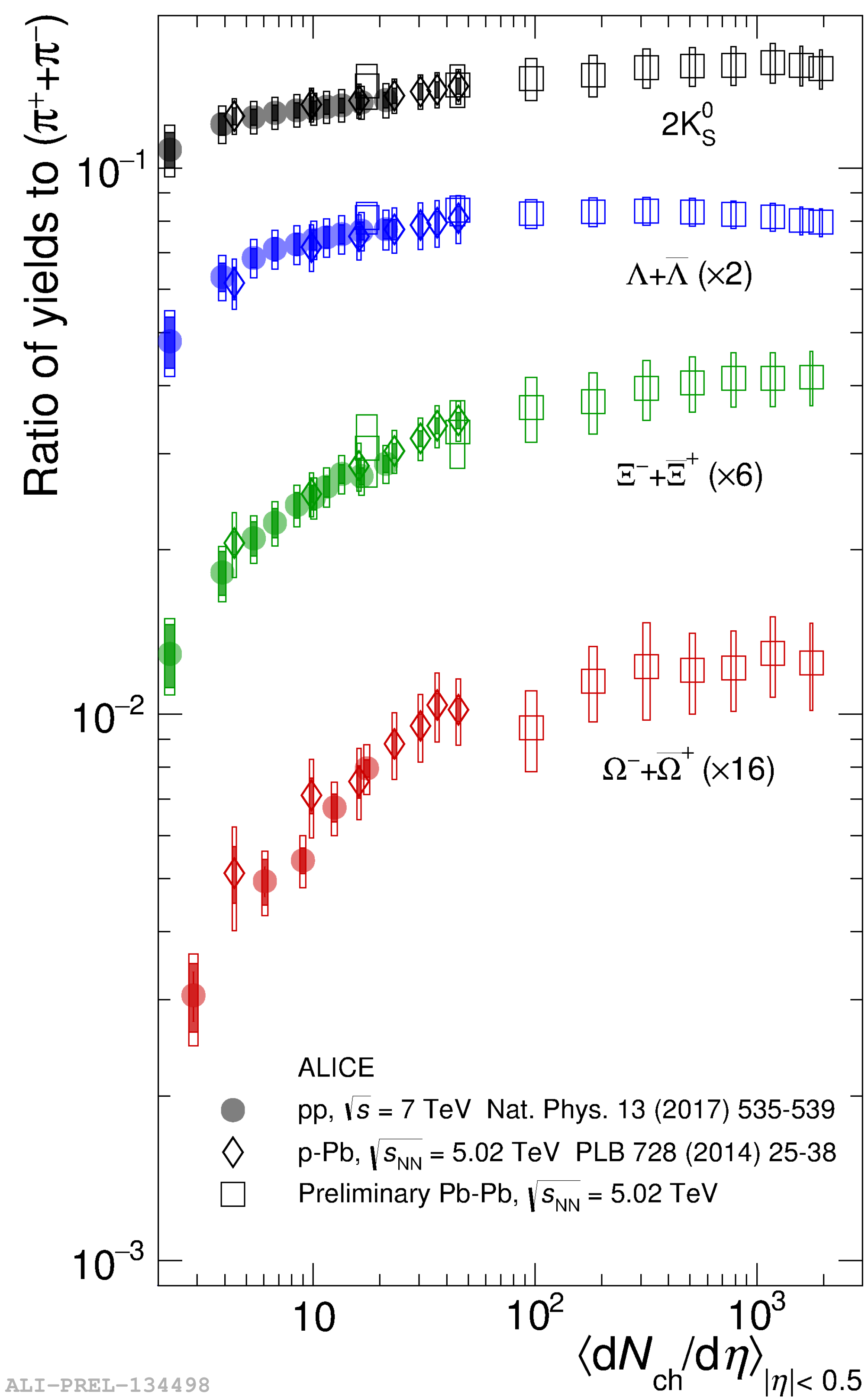
- Recent results on collectivity and correlations in HIC from ATLAS (**Dominik Karol Derendarz**)
- Recent results on collective effects and soft particle production in HIC from ALICE (**Nicolo Jacazio**)
- Recent results on collectivity and particle correlations with CMS (**Javier Alberto Murillo**)

Hadrochemistry and radial flow

Strangeness enhancement

None of microscopic models (string hadronization, core-corona approach) can reproduce the increasing trend. Thermal model picture with canonical suppression can not describe ϕ

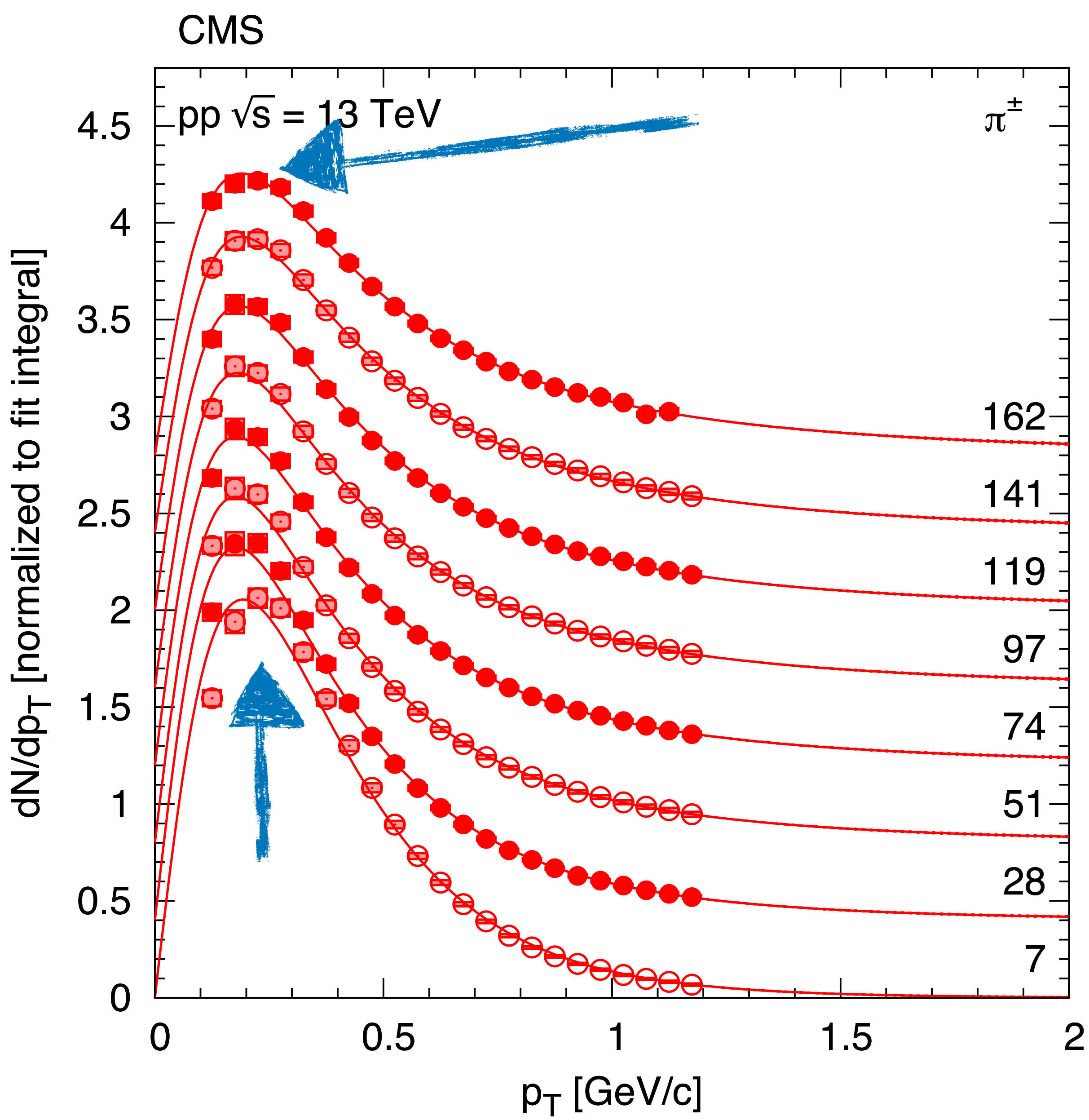




ALICE, NP 13 (2017) 535

π/K/p p_T spectra vs N_{ch}

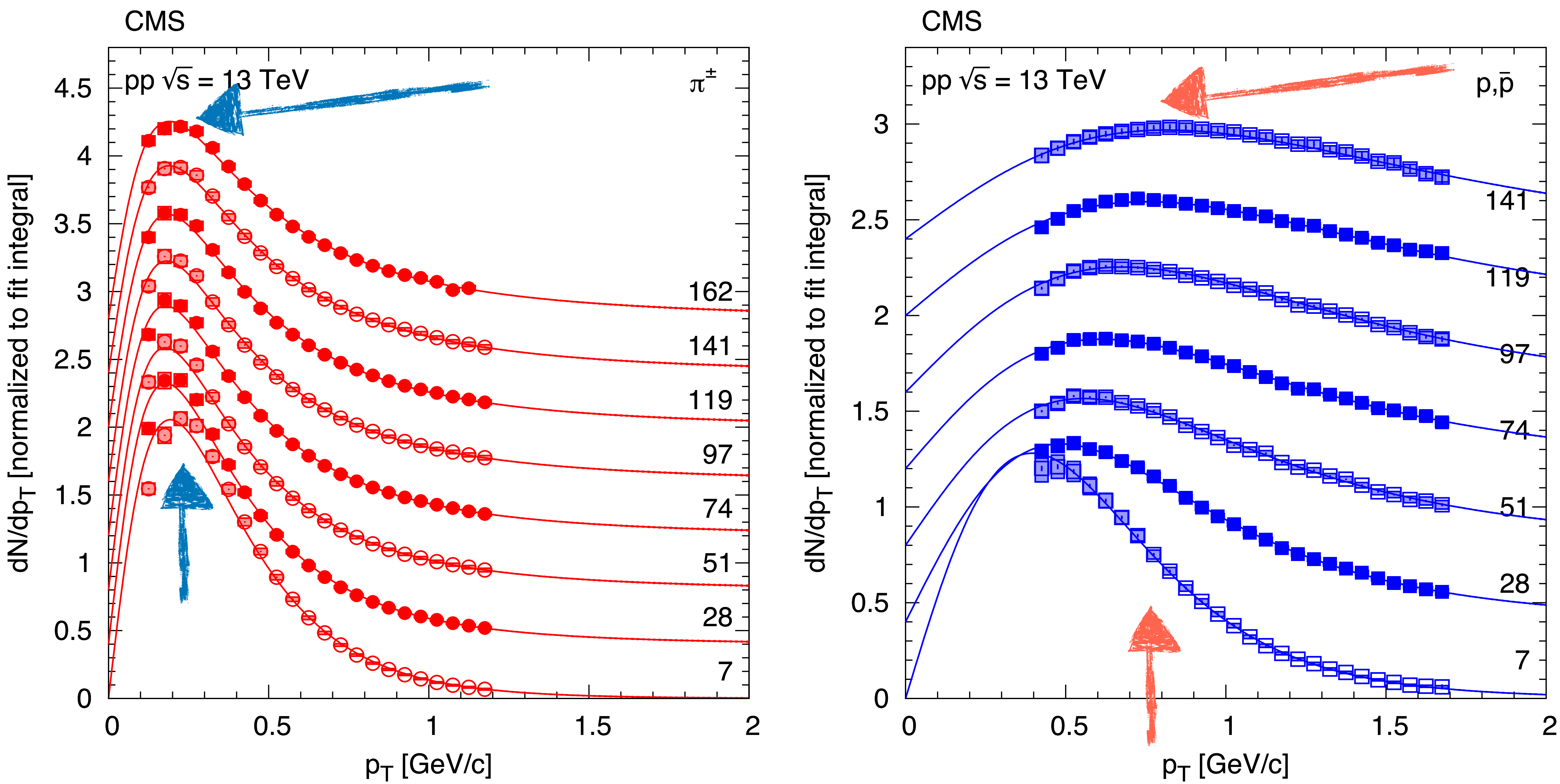
CMS, PRD 96 (2017) 112003



The p_T spectra at low p_T flatten out with increasing event multiplicity

π/K/p p_T spectra vs N_{ch}

CMS, PRD 96 (2017) 112003



The p_T spectra at low p_T flatten out with increasing event multiplicity
The effect is mass dependent as observed in heavy-ion collisions

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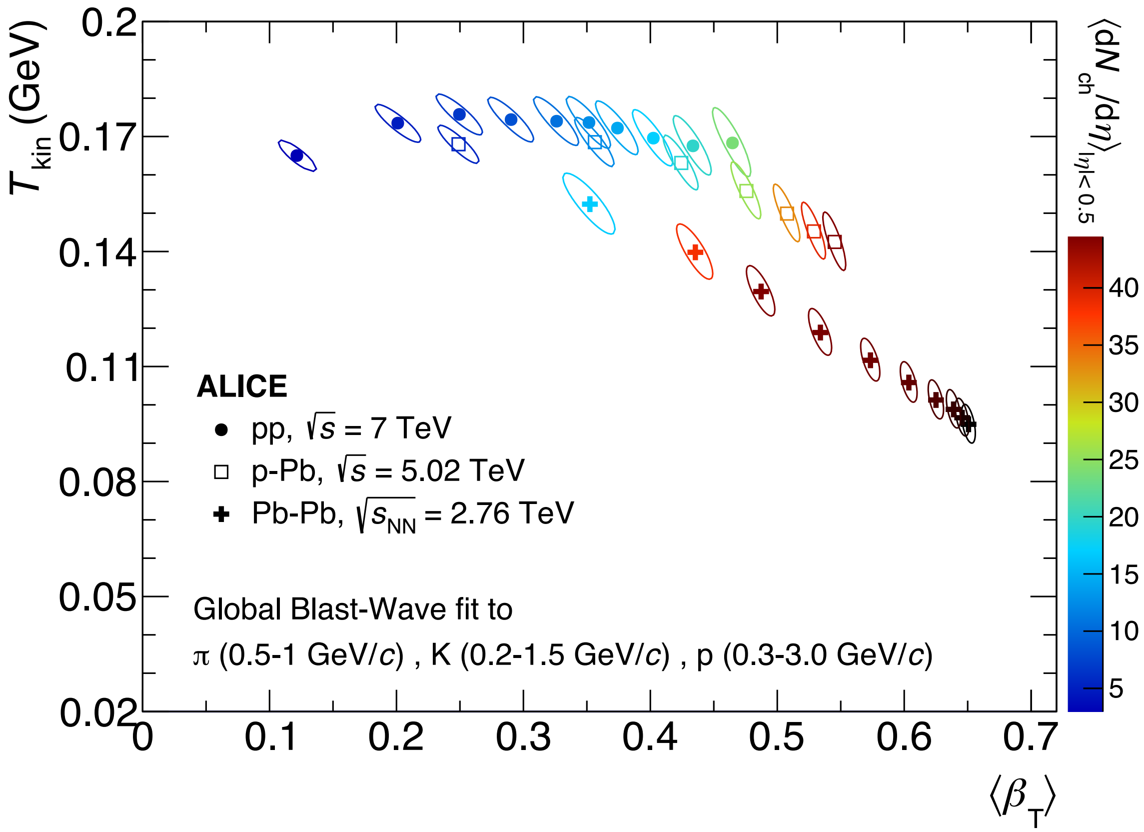
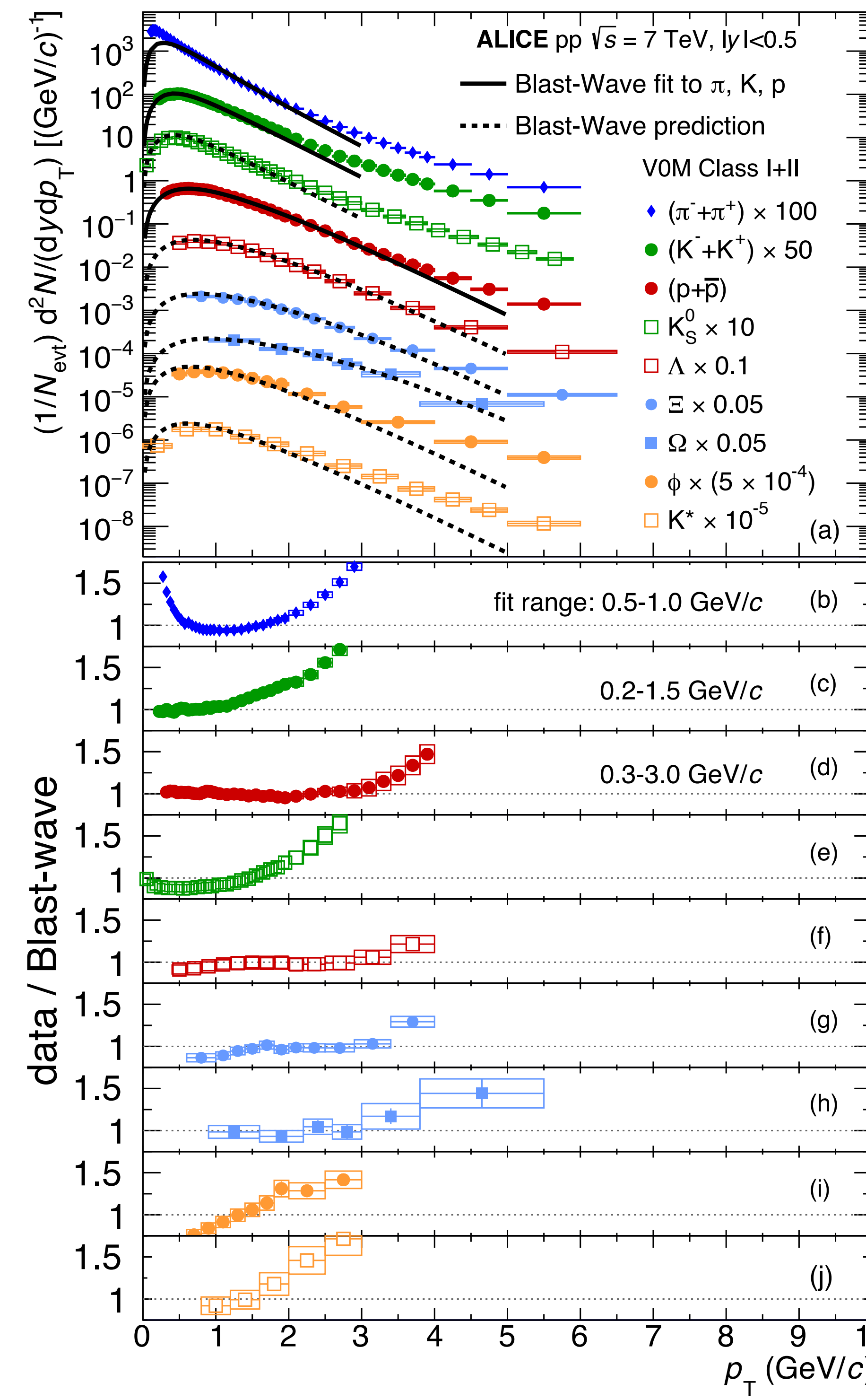
Radial flow

Blast wave: simplified hydro model:

- Assumes common particle expansion with β_T and T_{kin}
- Assumption ~ok for large collision systems
- pp and p-Pb: similar β_T vs T_{kin} behavior



ALICE, PRC 99 (2019) 024906



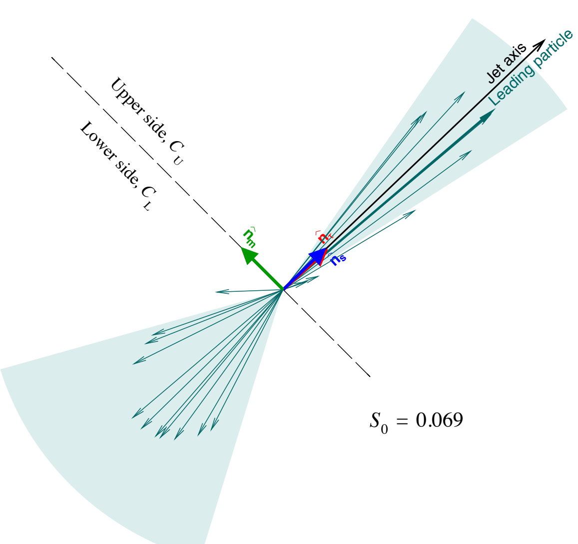
Pythia (color reconnection) can reproduce the same trend: **PRL 111 (2013) 042001**

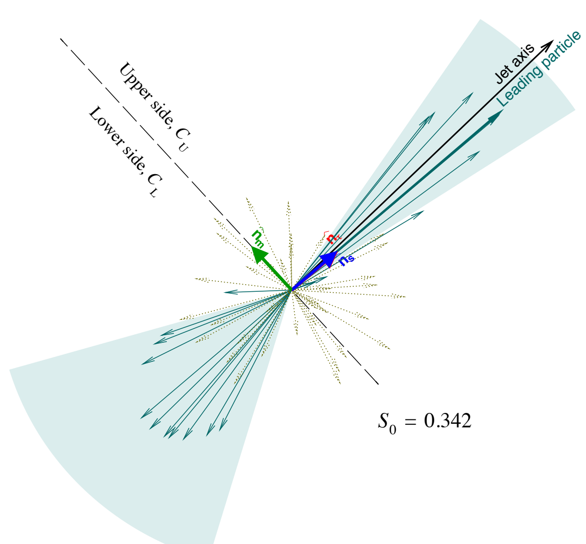
How can we reduce the jet effects?

We have seen that global multiplicity is correlated with hard physics

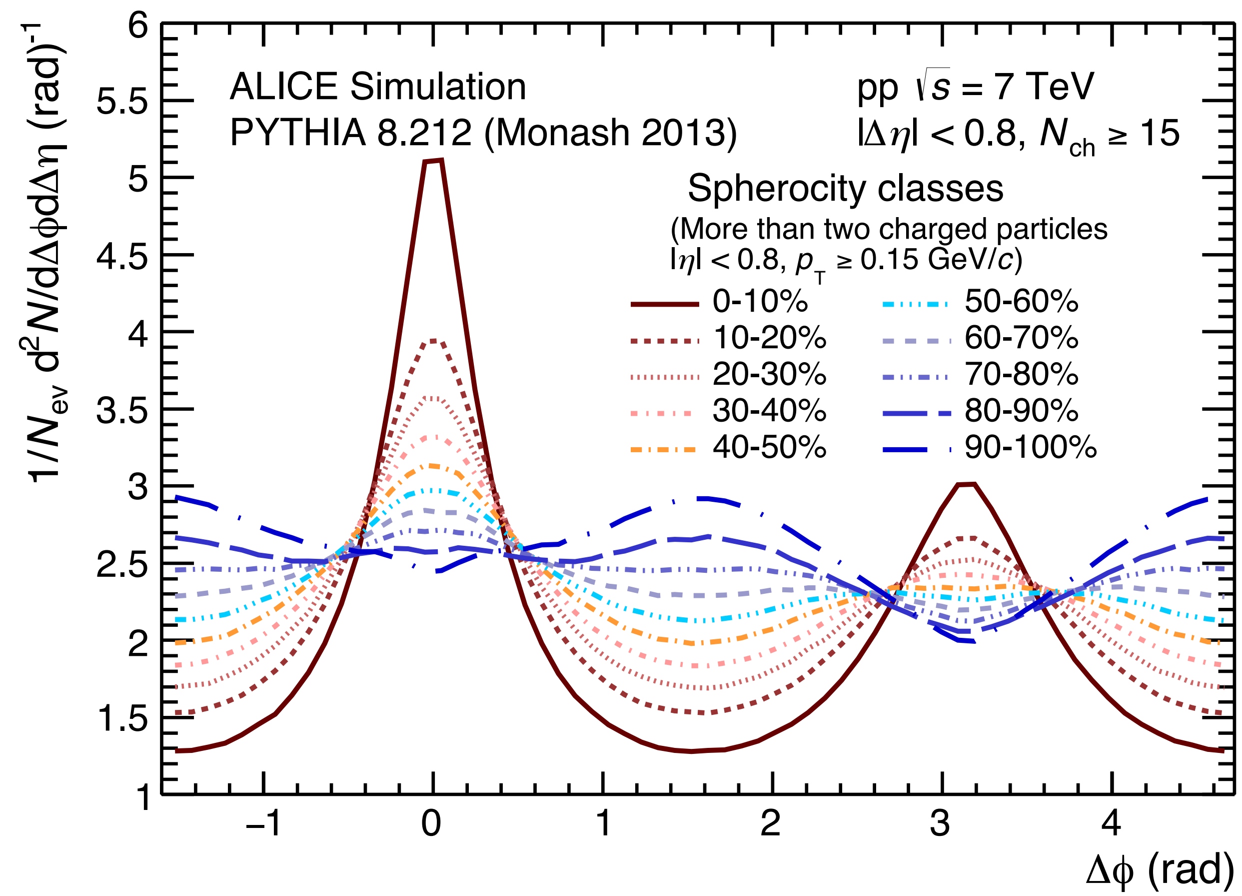
- Event shapes like transverse spherocity can be used to understand the role of jets in high multiplicity pp events
- A selection on multiplicity and transverse spherocity allows the isolation of events with same multiplicity but different content of MPI

$$S_0 \equiv \frac{\pi^2}{4}\left(\frac{\sum_i^{N_{\rm ch}} |\vec{p}_{{\rm T},i} \times \hat{\mathbf{n}}_{\rm s}|}{\sum_i^{N_{\rm ch}} p_{{\rm T},i}}\right)^2$$



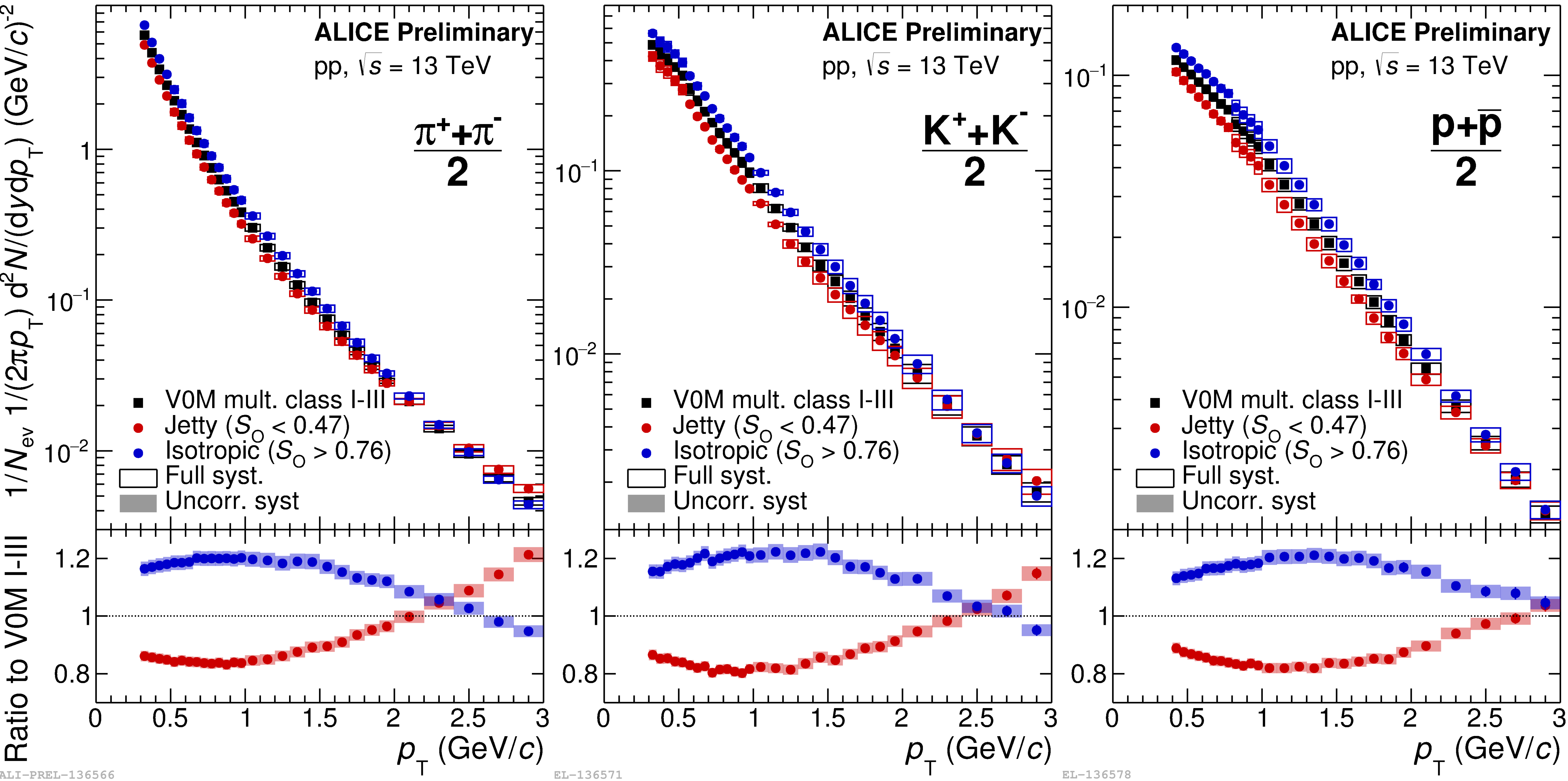


Adv. Ser. Direct. HEP 29 (2018) 343-357



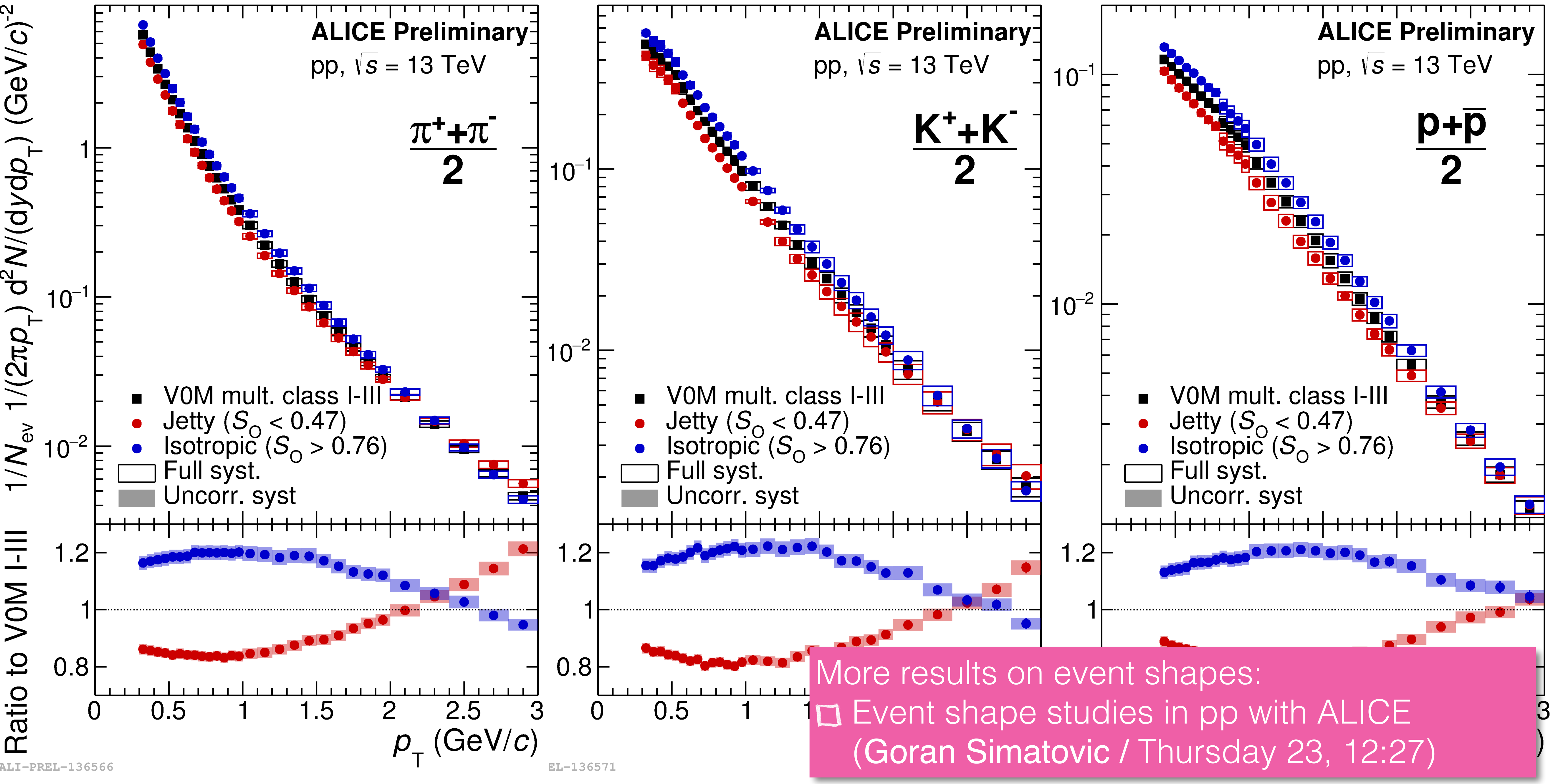
First results for $<p_T>$: **ALICE, arXiv:1905.07208**

p_T spectra vs S_O



Similar charged particle densities but different spherocity classes.
Transverse momentum spectra are harder in jetty events

p_T spectra vs S_O



More results on event shapes:
- Event shape studies in pp with ALICE (**Goran Simatovic** / Thursday 23, 12:27)

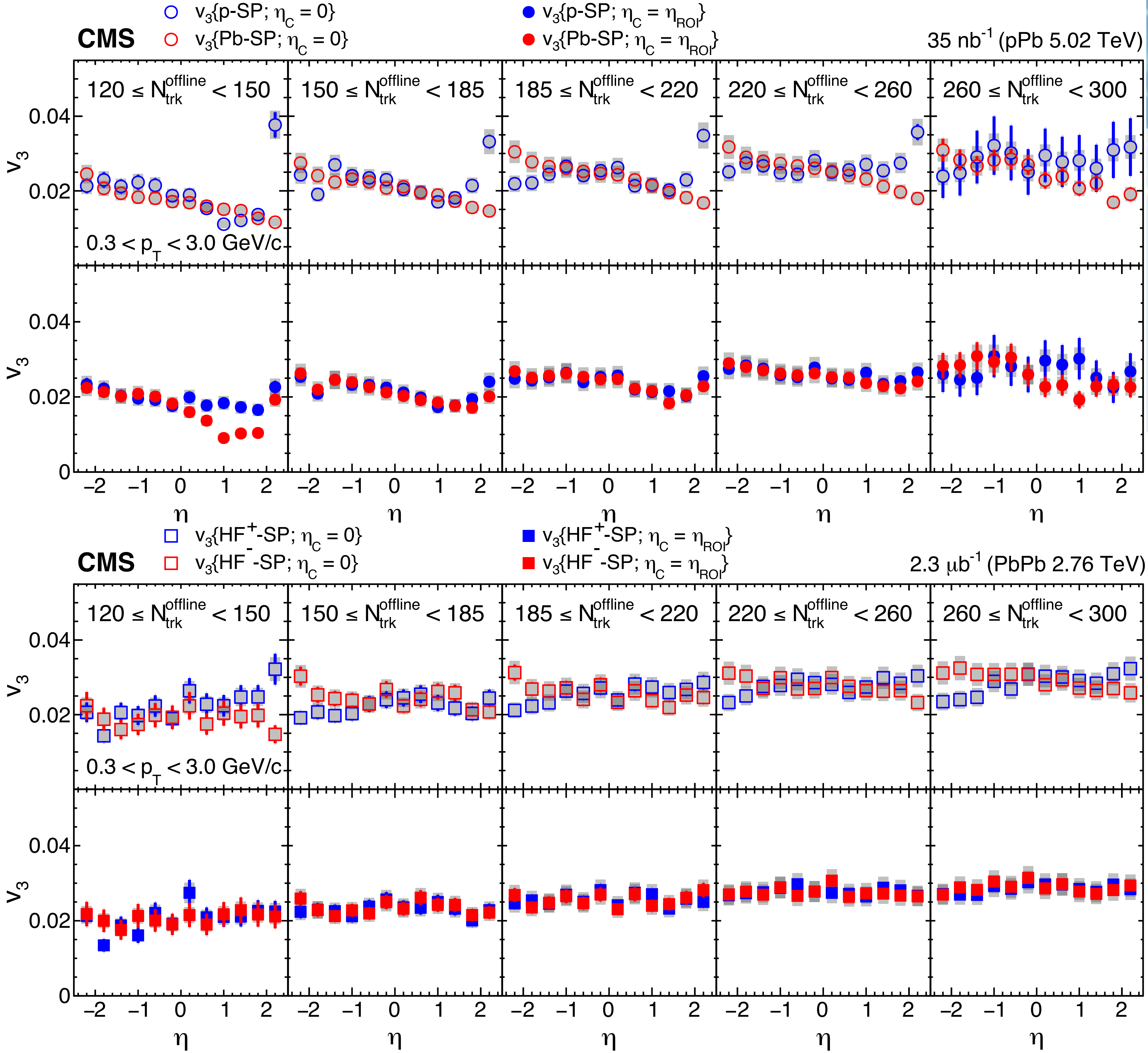
Similar charged particle densities but different spherocity classes. Transverse momentum spectra are harder in jetty events

Summary

Summary

- The correlation between global multiplicity (low-p_T) and high-p_T particle production has been studied: high-p_T particle production increases with increasing multiplicity. The increase is not linear
- Two- and multi-particle correlation analyses have been refined in order to reduce the non-flow effects on flow measurements. Non zero v_2 has been observed for pp and p-Pb collisions in accordance with hydro predictions
- The anti-correlation between v_2 and v_3 (as expected from hydro) in small systems has been reported by ATLAS and CMS
- New results for identified particle production were presented. Transverse spherocity is now used to understand the role of jets for different system sizes. First results look promising. More results will come soon!

Backup


CMS
v_3\{p-SP; η_C = 0\}
v_3\{Pb-SP; η_C = 0\}
v_3\{p-SP; $\eta_C = \eta_{ROI}$\}
v_3\{Pb-SP; $\eta_C = \eta_{ROI}$\}
35 nb^{-1} (pPb 5.02 TeV)
$120 \le N_{trk}^{offline} < 150$
$150 \le N_{trk}^{offline} < 185$
$185 \le N_{trk}^{offline} < 220$
$220 \le N_{trk}^{offline} < 260$
$260 \le N_{trk}^{offline} < 300$
$0.3 < p_T < 3.0$ GeV/c
v_3
η
CMS
v_3\{HF$^+$-SP; η_C = 0\}
v_3\{HF$^-$-SP; η_C = 0\}
v_3\{HF$^+$-SP; $\eta_C = \eta_{ROI}$\}
v_3\{HF$^-$-SP; $\eta_C = \eta_{ROI}$\}
2.3 μb^{-1} (PbPb 2.76 TeV)

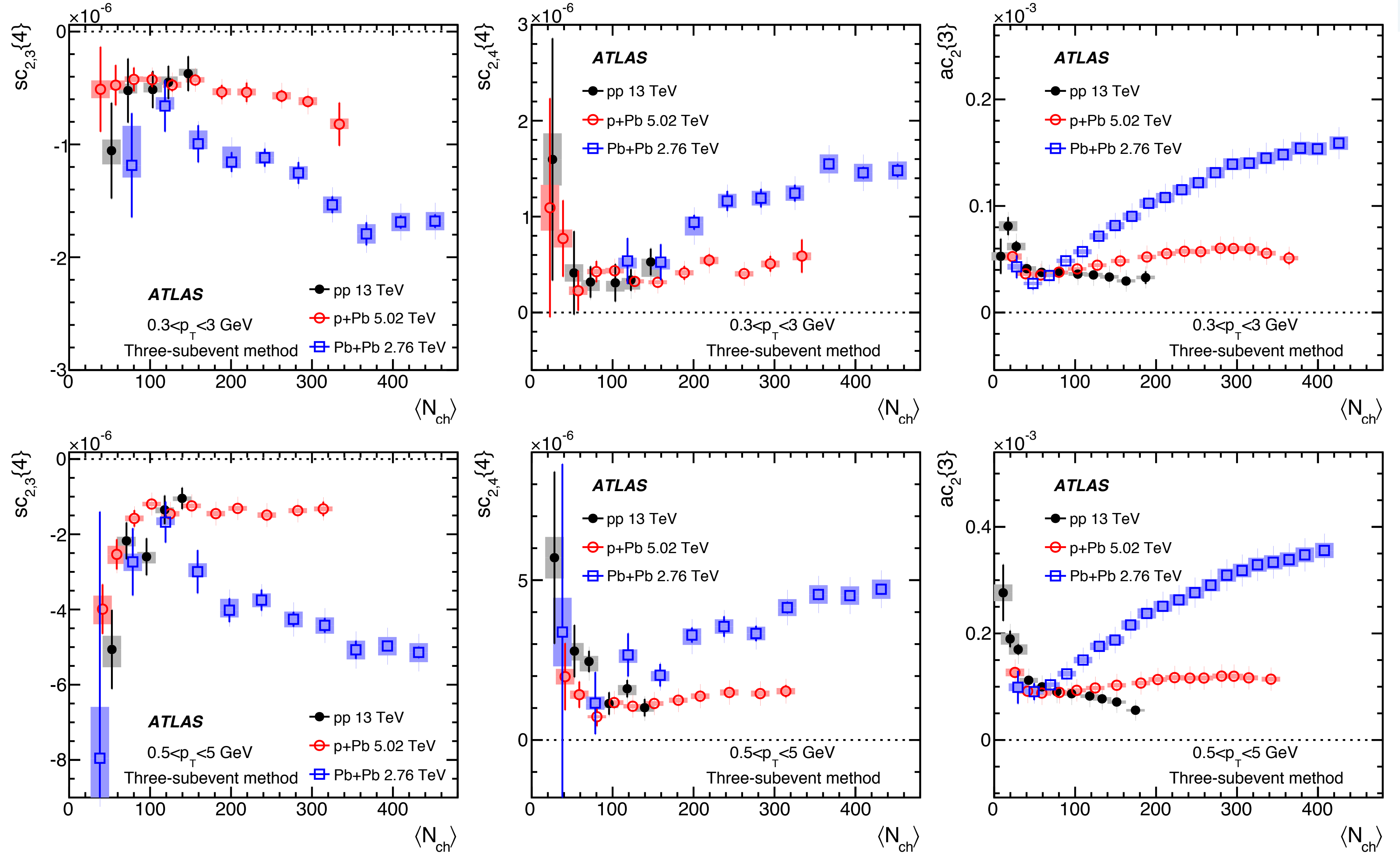
Symmetric cumulants

Results for pp, p-Pb and Pb-Pb collisions using subevent cumulants: 2-, 3- and 4-subevents

ATLAS, PLB 789 (2019) 444-471

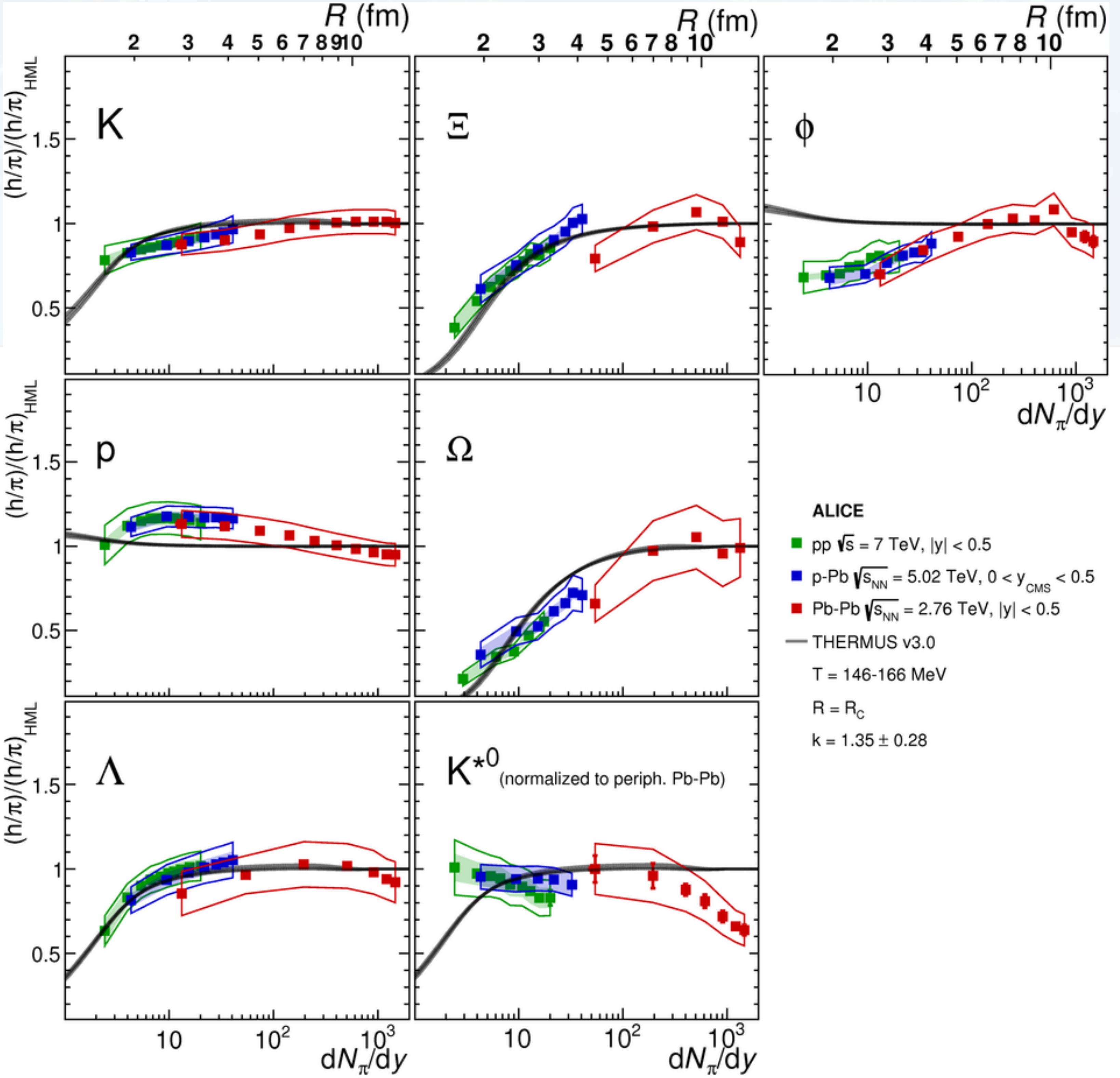
$c_n\{4\} = \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2$ → constrains the width of the probability density distribution which represents the event-by-event fluctuations

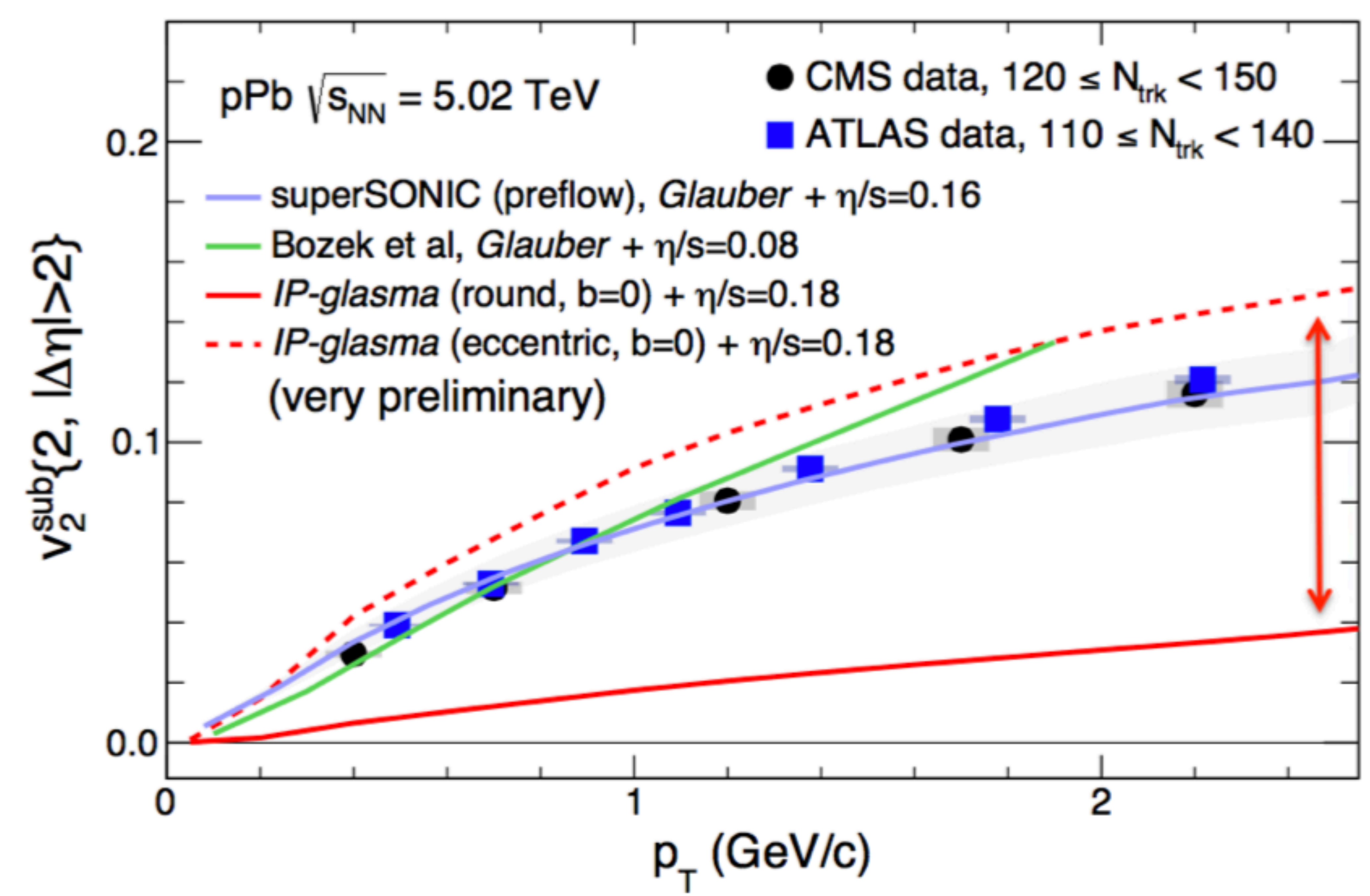
$sc_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$ → quantifies the lowest-order correlation between v_n and v_m



Strangeness enhancement

- Abundances of hadrons produced in heavy-ion collisions have been successfully described by statistical hadronization model over wide range of energies
- For small systems strangeness appears to be significantly suppressed relative to non-strange hadrons. This picture cannot describe the ϕ meson vs N_{ch}



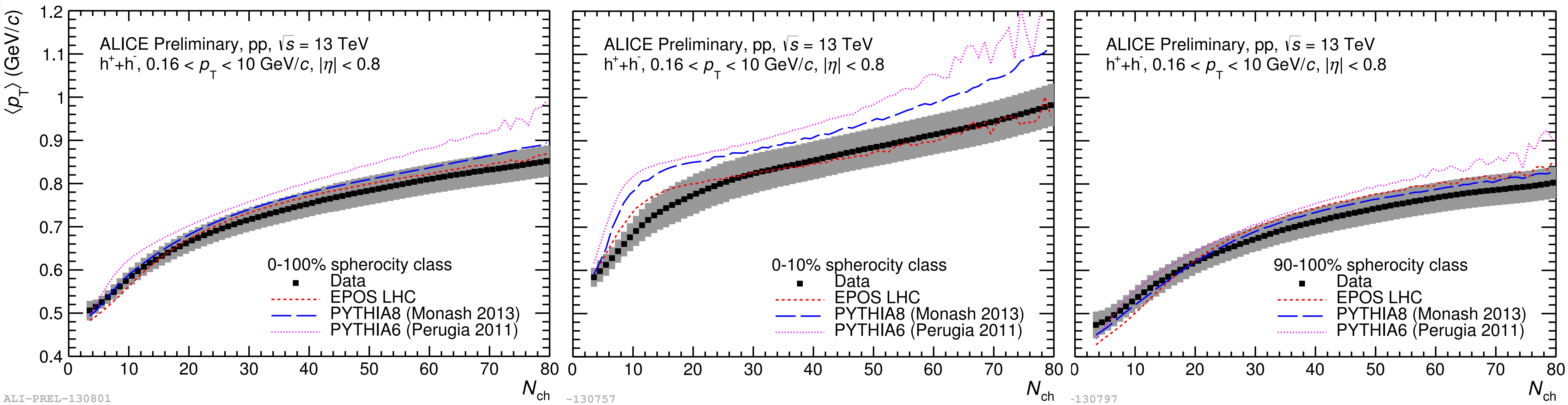

pPb $\sqrt{s_{NN}}$ = 5.02 TeV
CMS data, 120 ≤ N_{trk} < 150
ATLAS data, 110 ≤ N_{trk} < 140
superSONIC (preflow), Glauber + η/s=0.16
Bozek et al, Glauber + η/s=0.08
IP-glasma (round, b=0) + η/s=0.18
IP-glasma (eccentric, b=0) + η/s=0.18
(very preliminary)
$v_2^{sub}\{2, |\Delta\eta|>2\}$
0.0
0.1
0.2
0
1
2
p_T (GeV/c)

Average p_T vs N_{ch}

Events with same N_{ch} can be very different

ALICE, arXiv TO BE ADDED

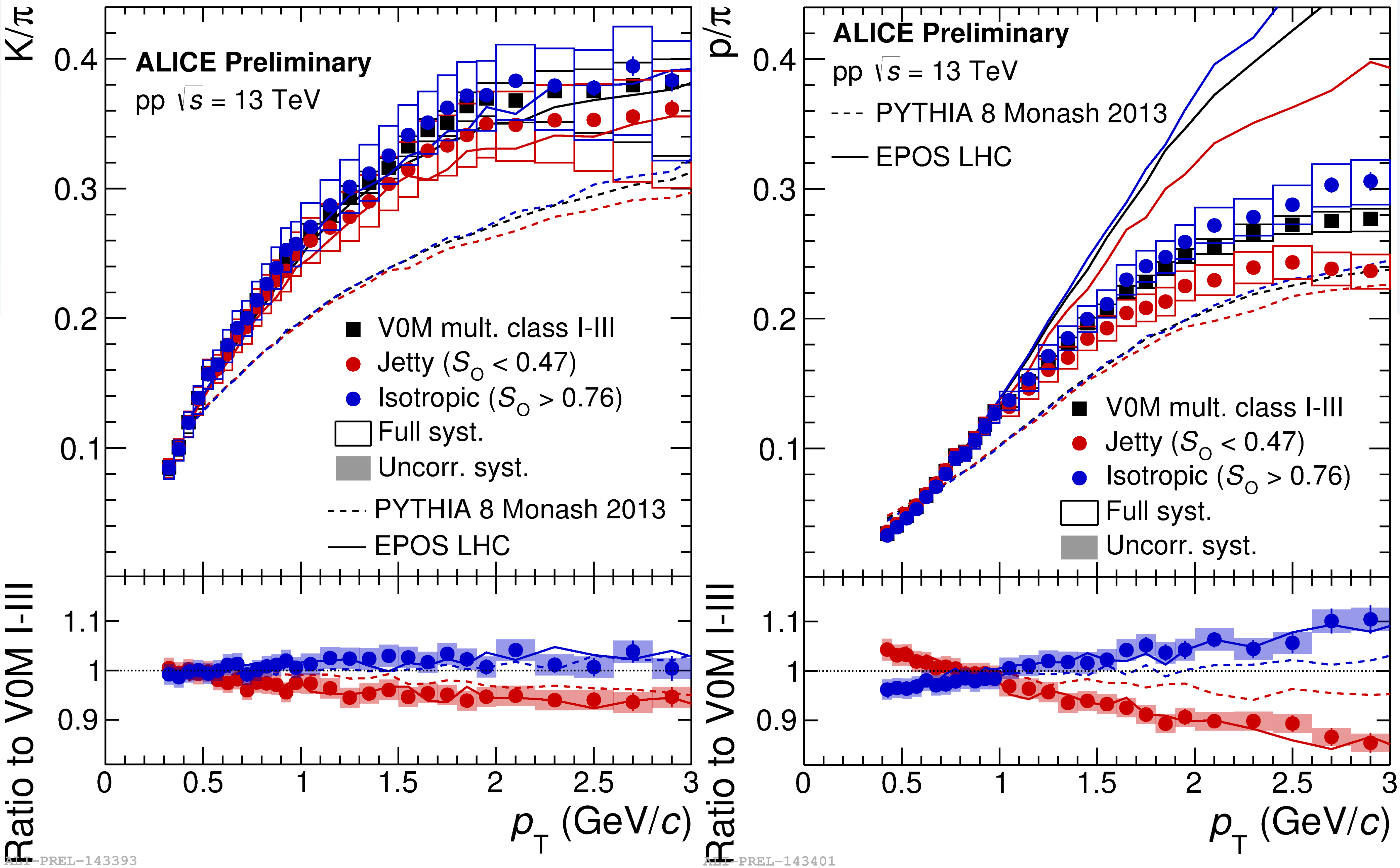
Minimum bias **Jetty** **Isotropic**



Event shapes are now used as a selection variable for better understanding the multiplicity dependent particle production (constrain MPI and color reconnection models)

Instituto de Ciencias Nucleares UNAM

Particle ratios



Particle ratios for isotropic events give larger flow-like effects than jetty ones