Experimental overview of collectivity in small systems

soft probes

Roberto Preghenella
Istituto Nazionale di Fisica Nucleare, Bologna

Strangeness in Quark Matter 2019
Bari, Italy
14 June 2019

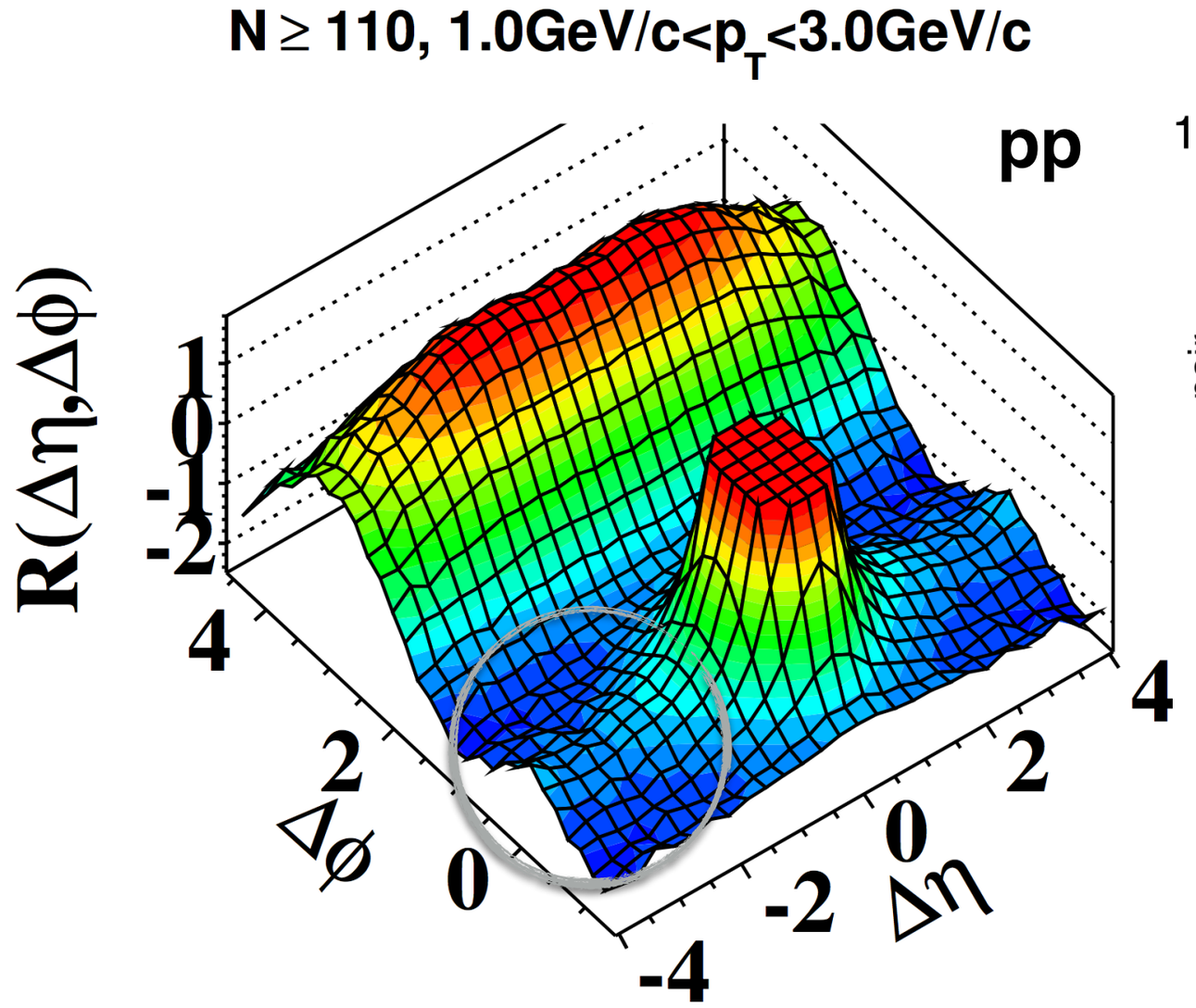
preghenella@bo.infn.it

Unexpected phenomena

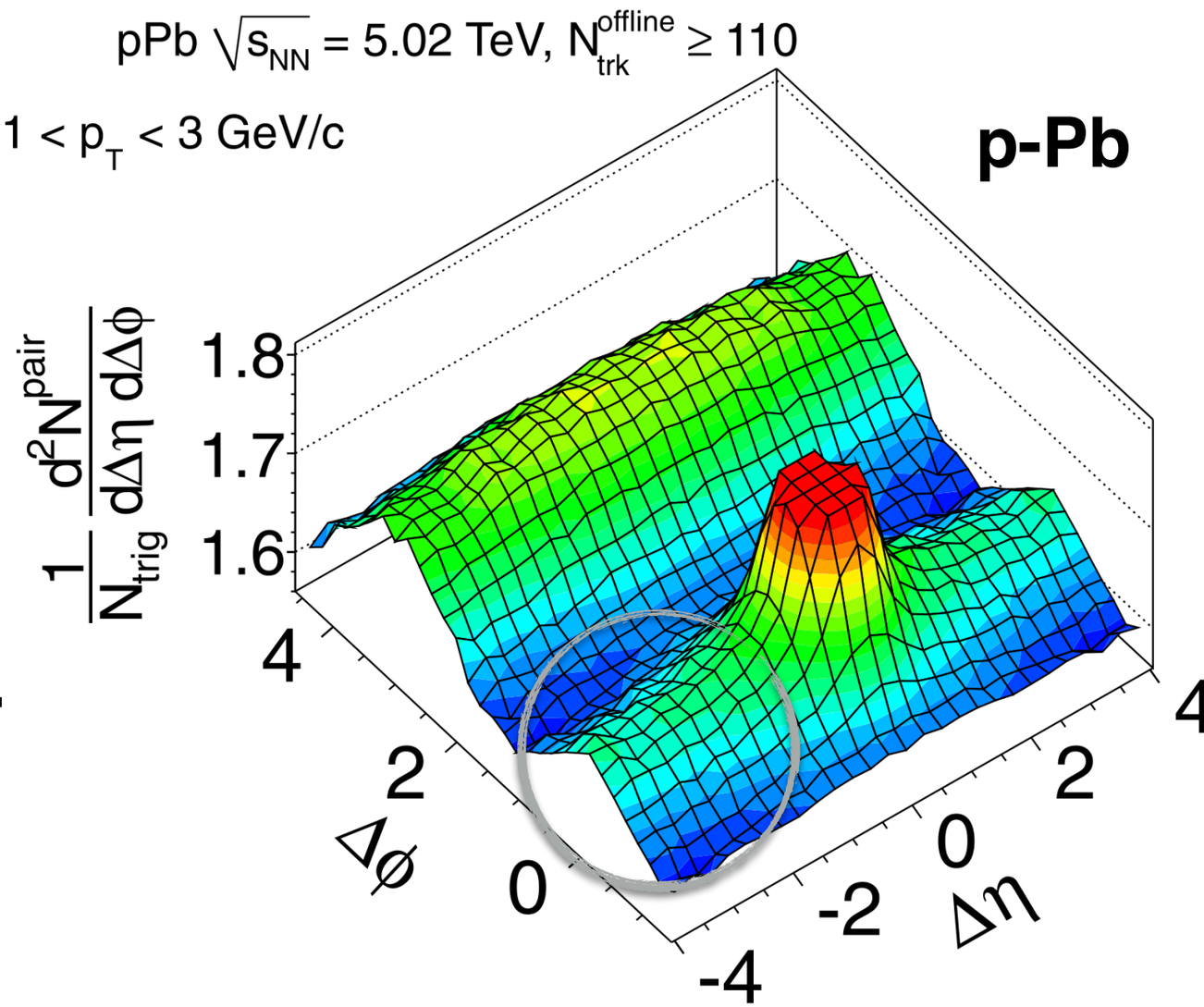
results from small systems are
showing new **unexpected phenomena**

The ridge

study of two-particle correlations led to the observation of **long-range** ($2 < |\Delta\eta| < 4$), **near-side** ($\Delta\phi \approx 0$) angular correlations in high-multiplicity pp and p-Pb events



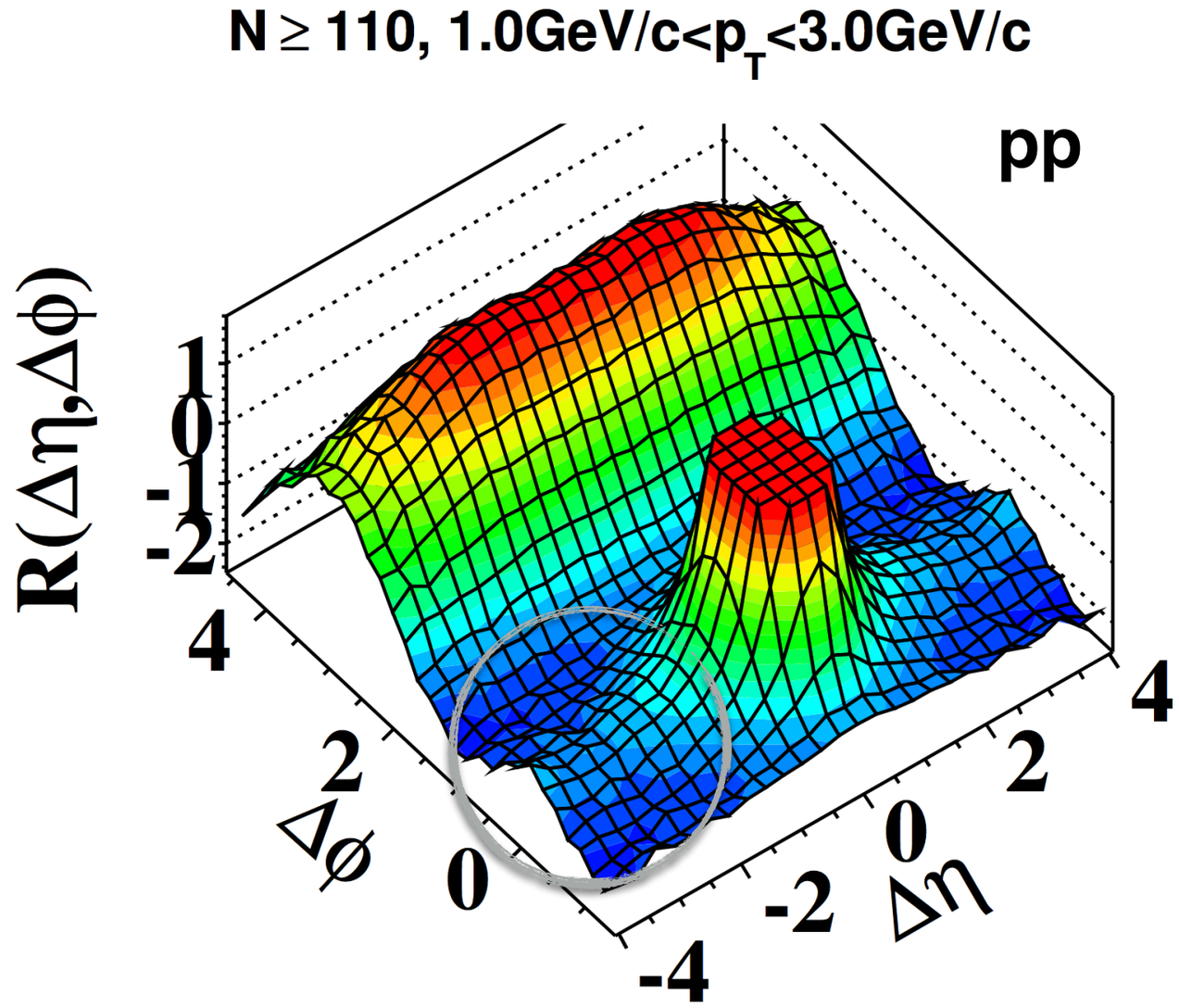
CMS, JHEP 09 (2010) 091



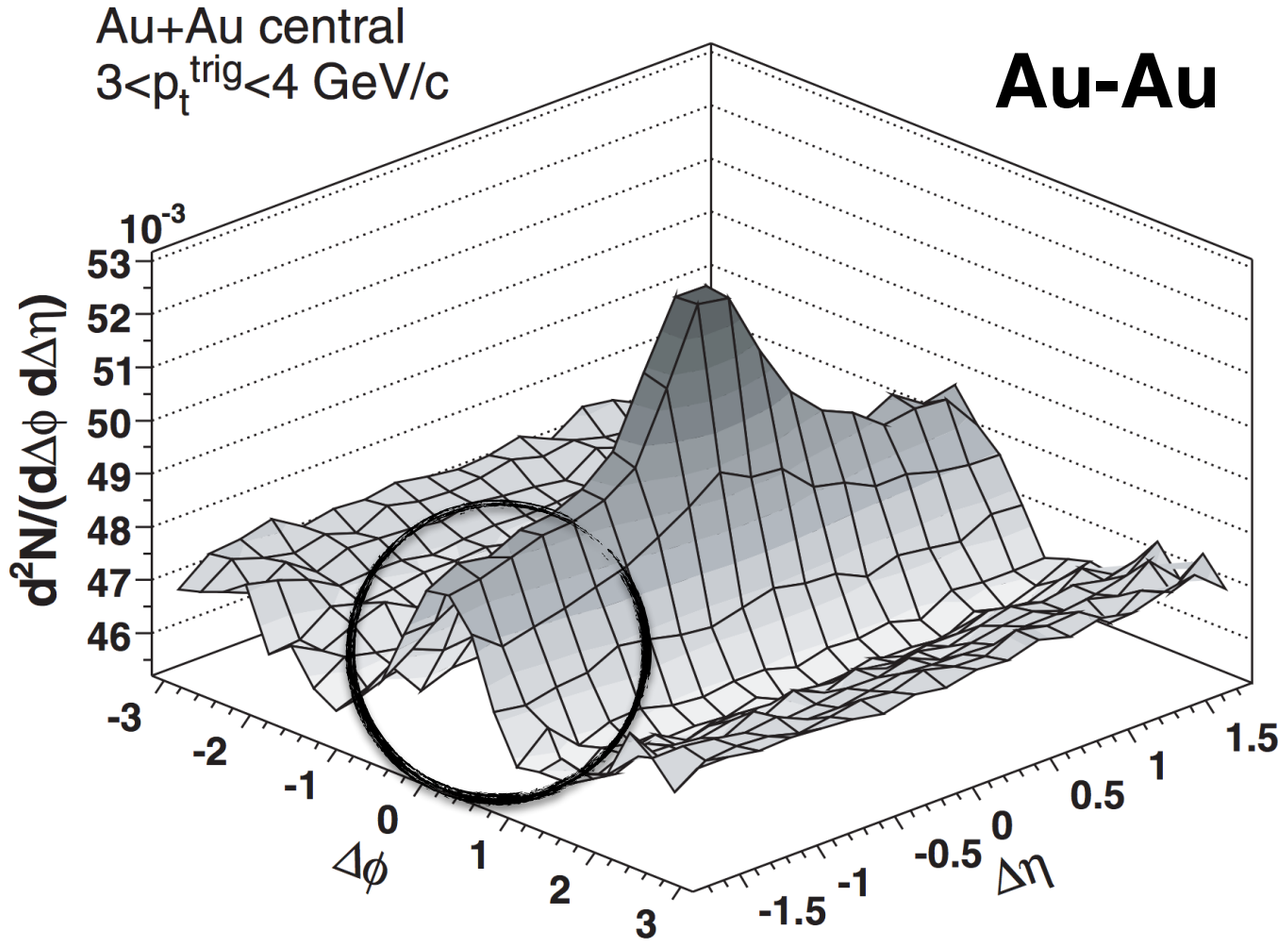
CMS, PLB 718 (2013) 795

The ridge

resembles the ridge-like correlation seen in A-A collisions interpreted as consequence of **hydrodynamic flow**



CMS, JHEP 09 (2010) 091



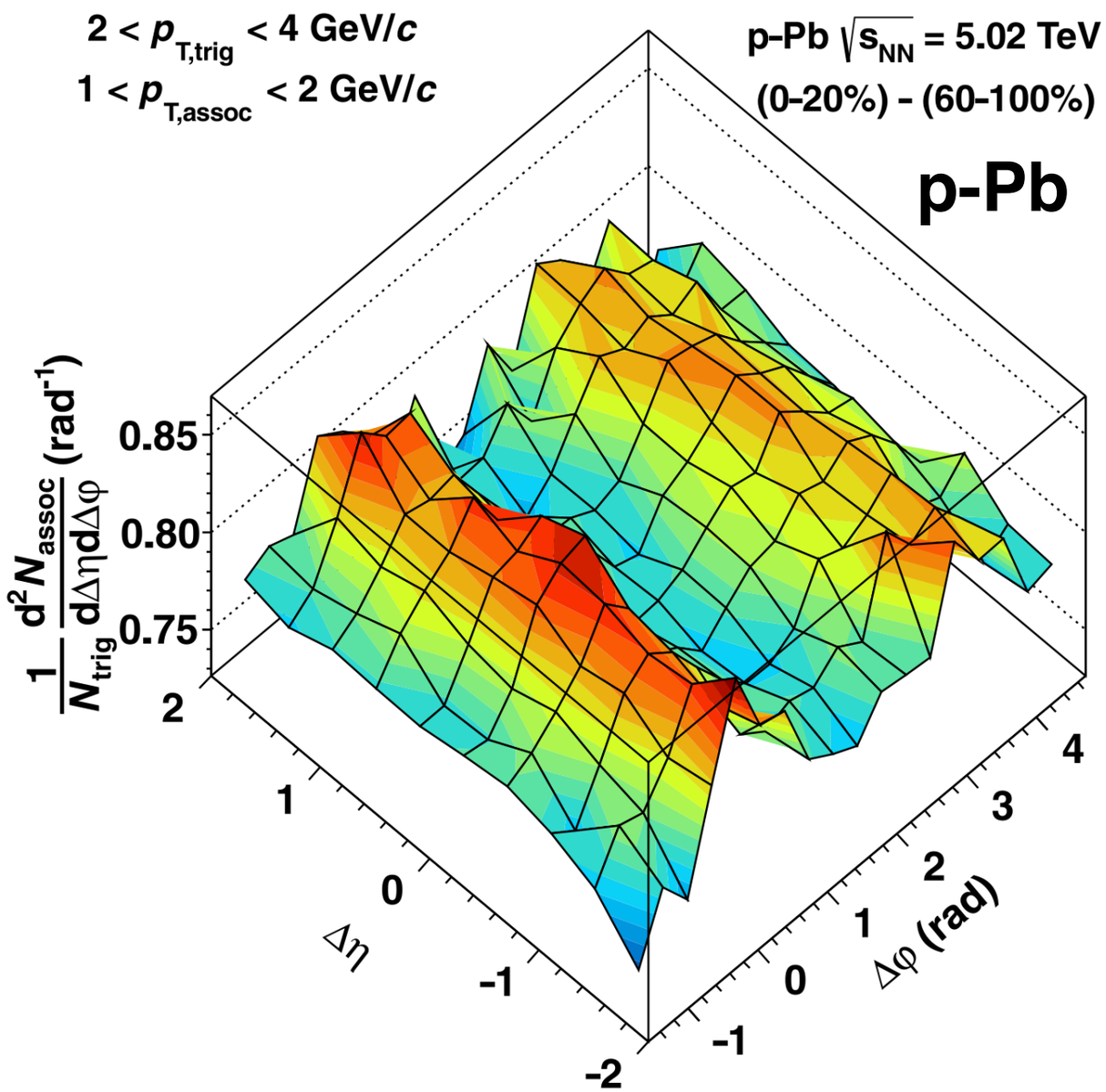
STAR, PRC 80 (2010) 064912

The double ridge

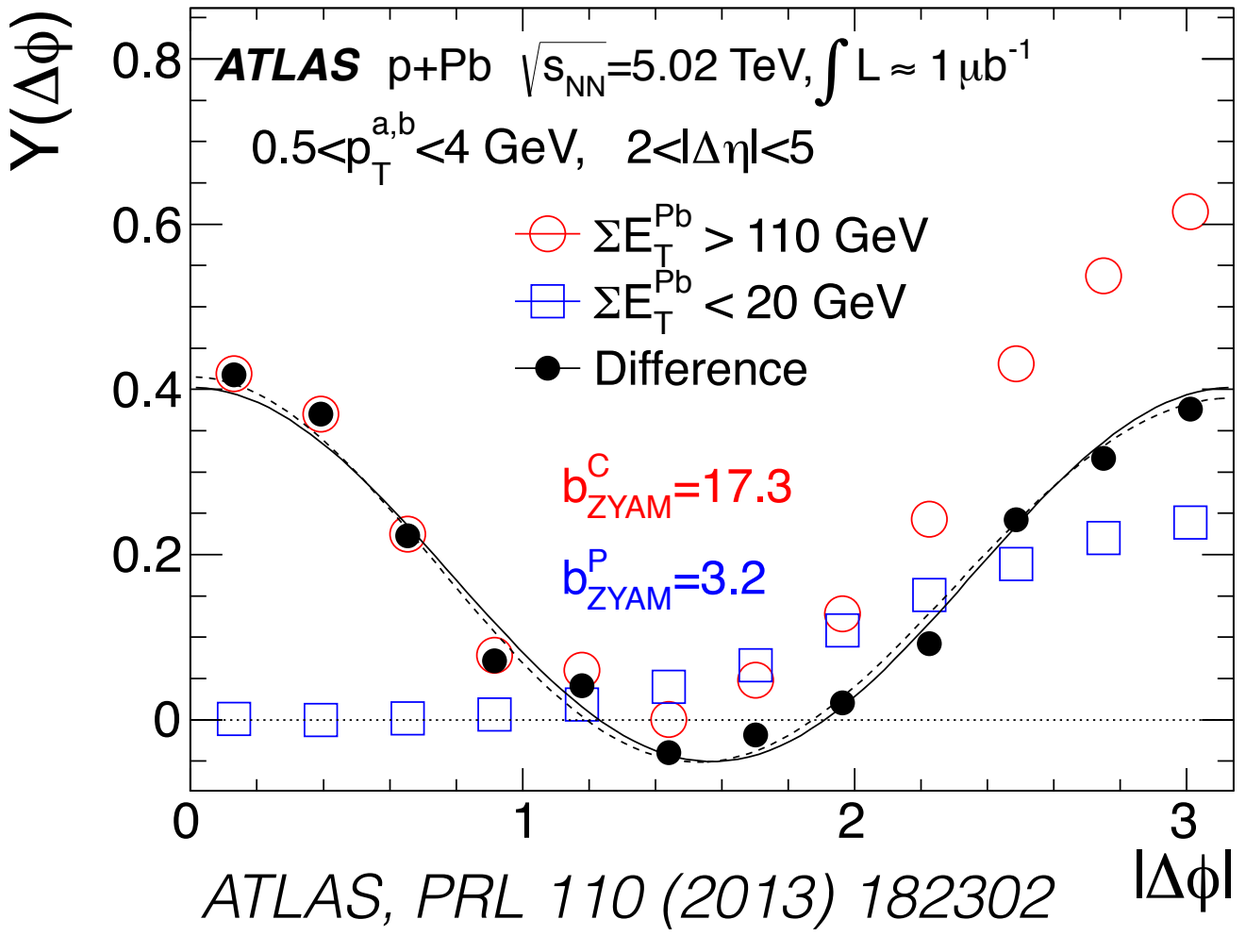
the observation of the ridge triggered further investigations

jet contribution removed by subtracting low-multiplicity events

a **double-ridge** structure **was revealed**



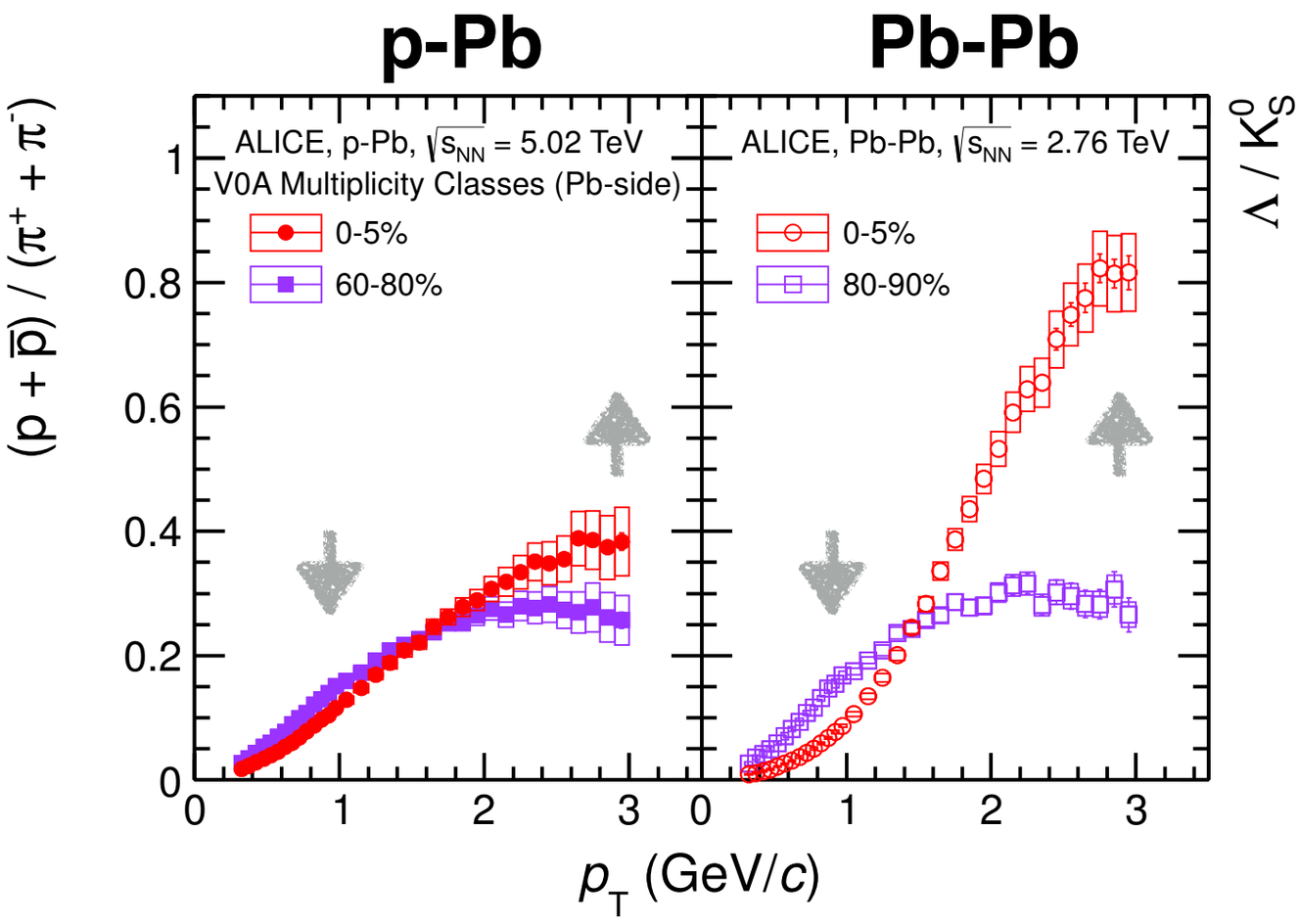
looks so much like flow

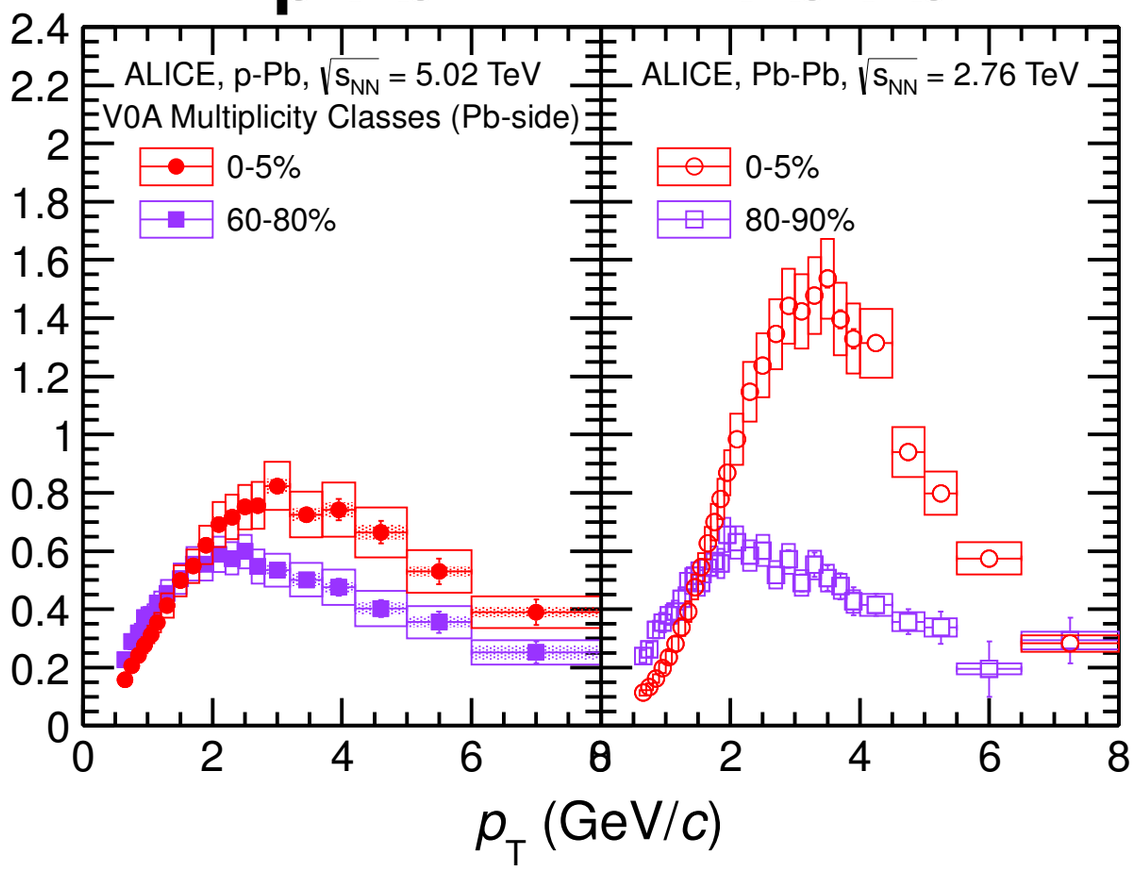


ATLAS, PRL 110 (2013) 182302

ALICE, PLB 719 (2013) 29

Baryon enhancement





significant centrality/multiplicity dependence of the ratios

enhancement at mid p_T with increasing multiplicity

corresponding depletion in the low-p_T region

reminiscent of A-A observations

commonly understood in terms of collective flow / quark recombination

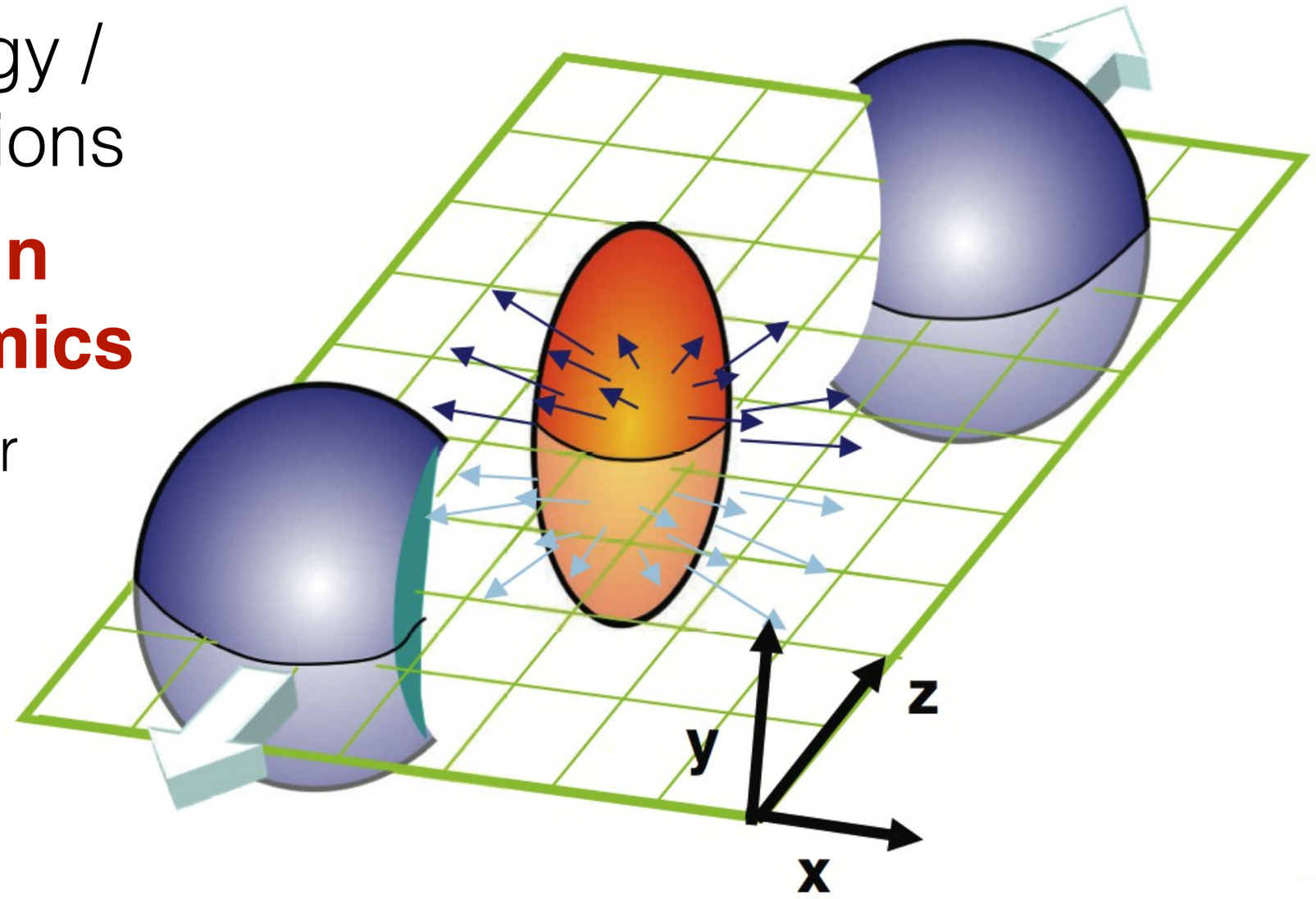
ALICE, PLB 728 (2014) 25

Collective phenomena

if the **bulk of the matter** created in high-energy / high-multiplicity collisions

can be described in terms of hydrodynamics

- strongly-interacting matter
- rapid expansion
- collective flows develop
- system cools down
- final decoupling

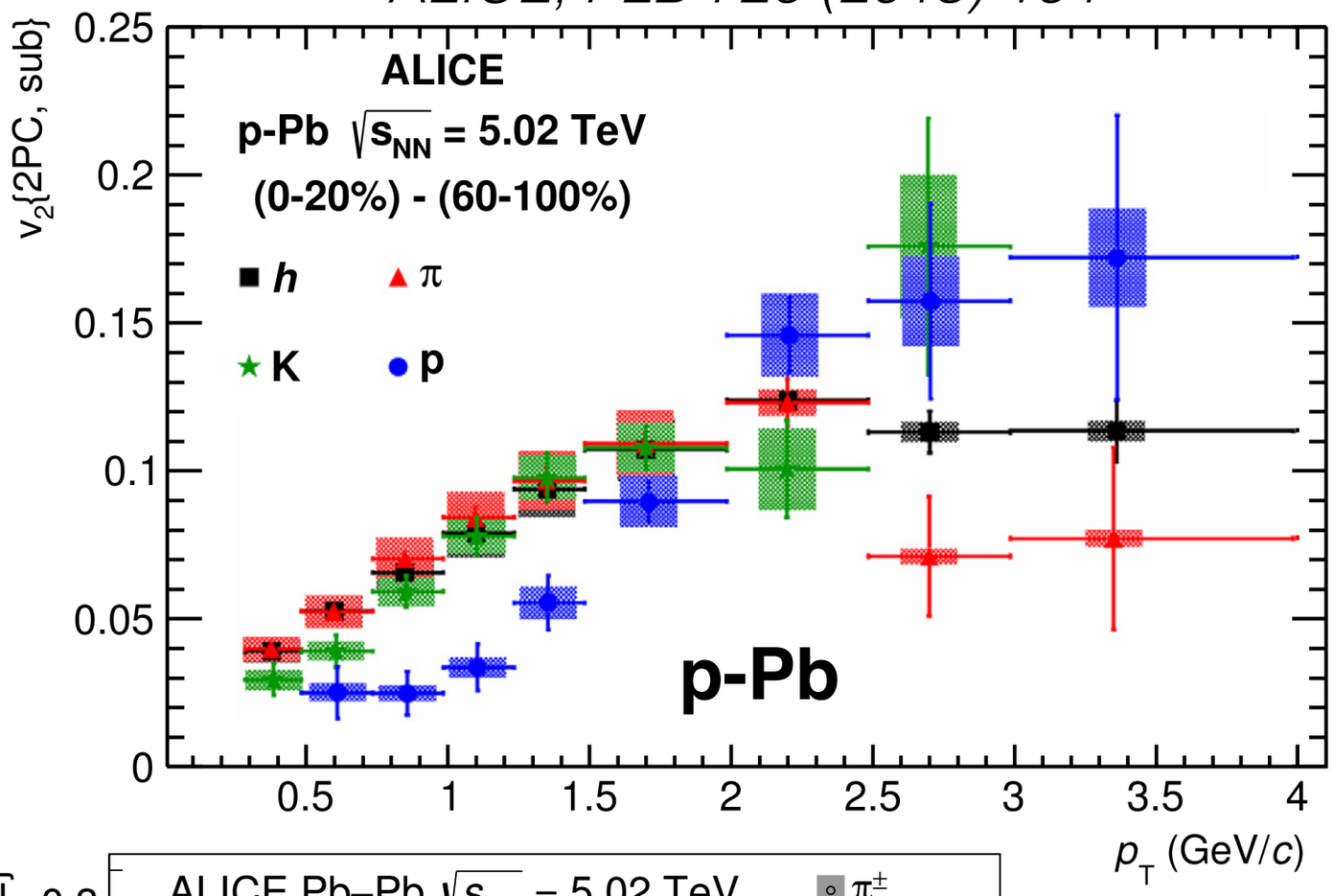


one would expect to observe

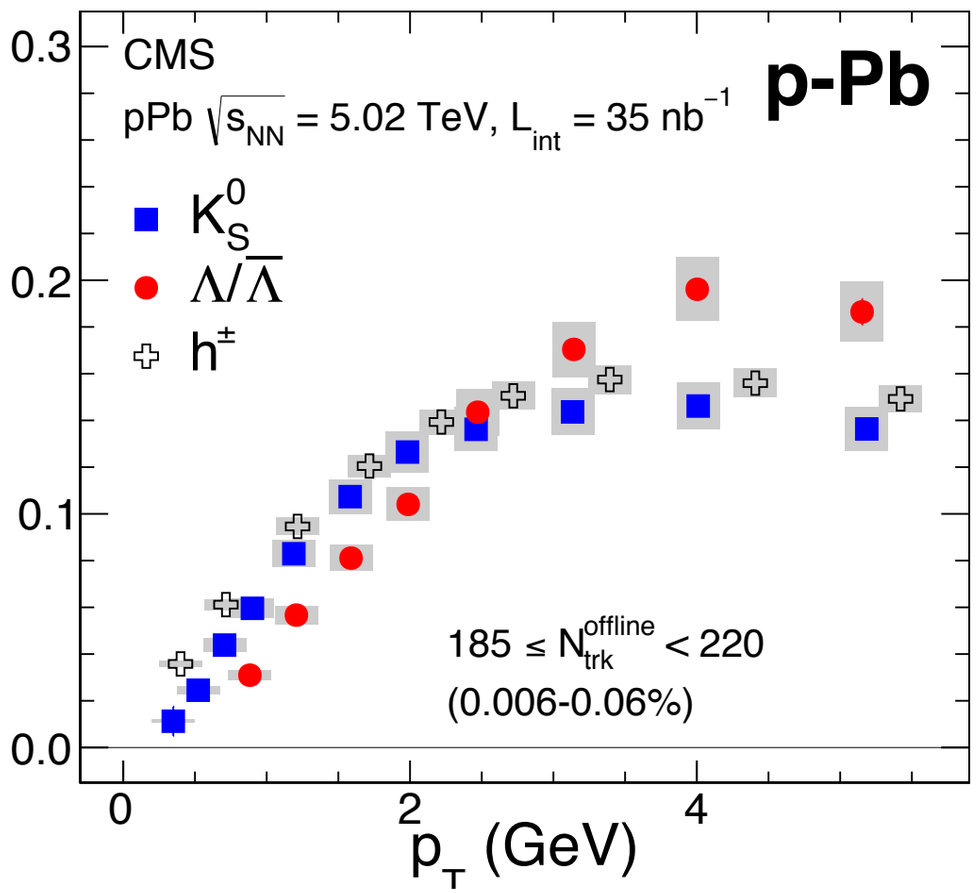
- <u>azimuthal anisotropic flow patterns (initial spatial anisotropy)</u>
- dependence of the shape of the p_T distribution on the particle mass

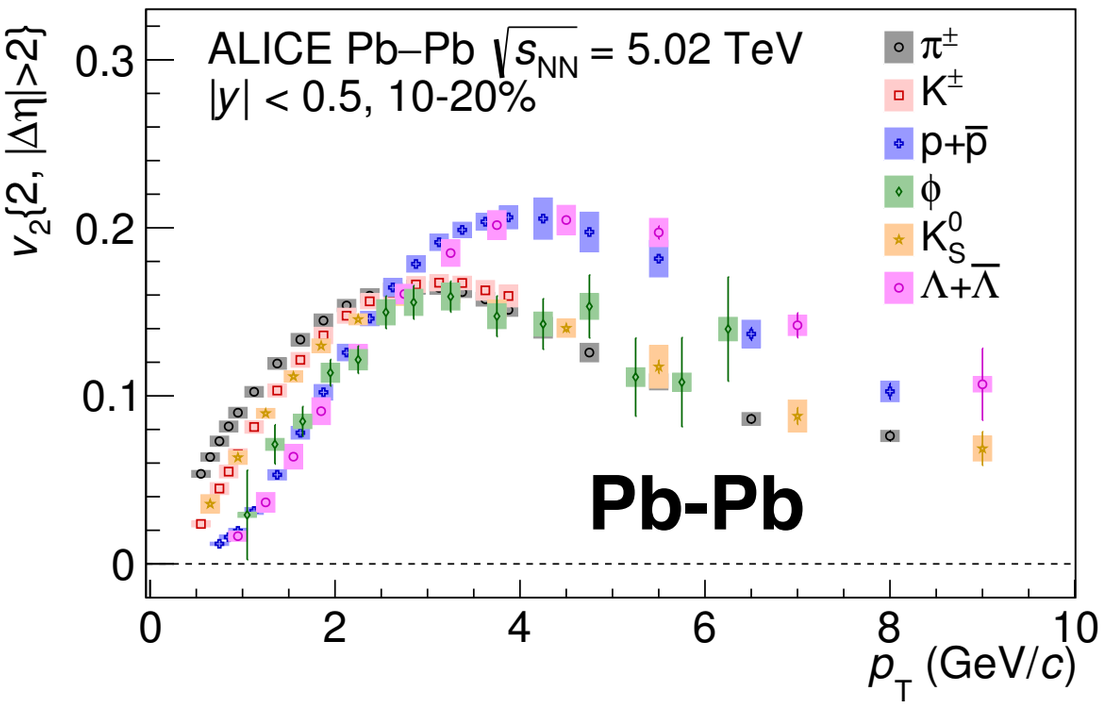
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PLB 742 (2015) 200





mass ordering observed at low p_T

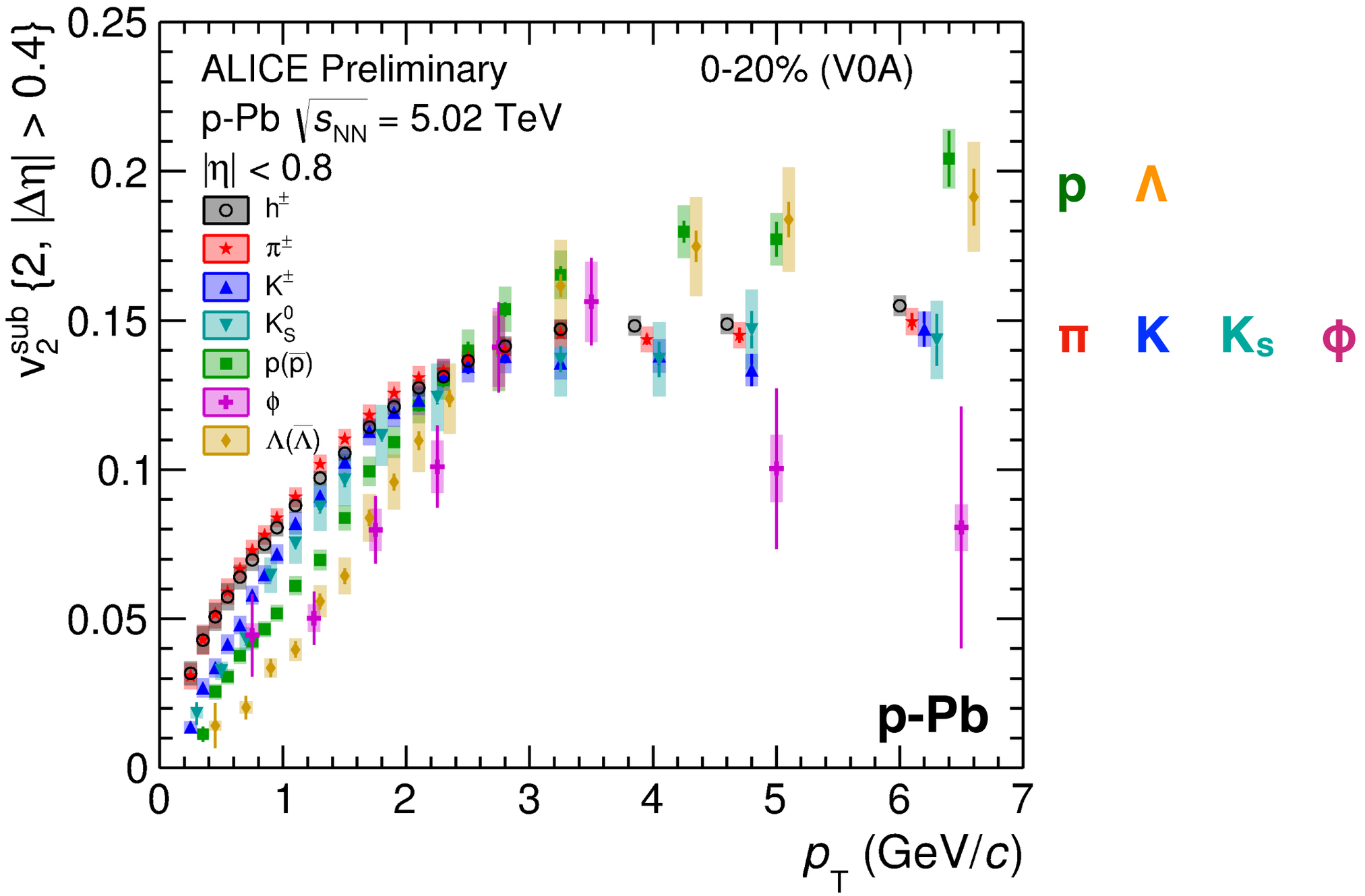
lower v_2 for heavier particles

crossing at higher p_T

reminiscent of A-A observations

ALICE, JHEP 09 (2018) 006

v_2 of many identified particles

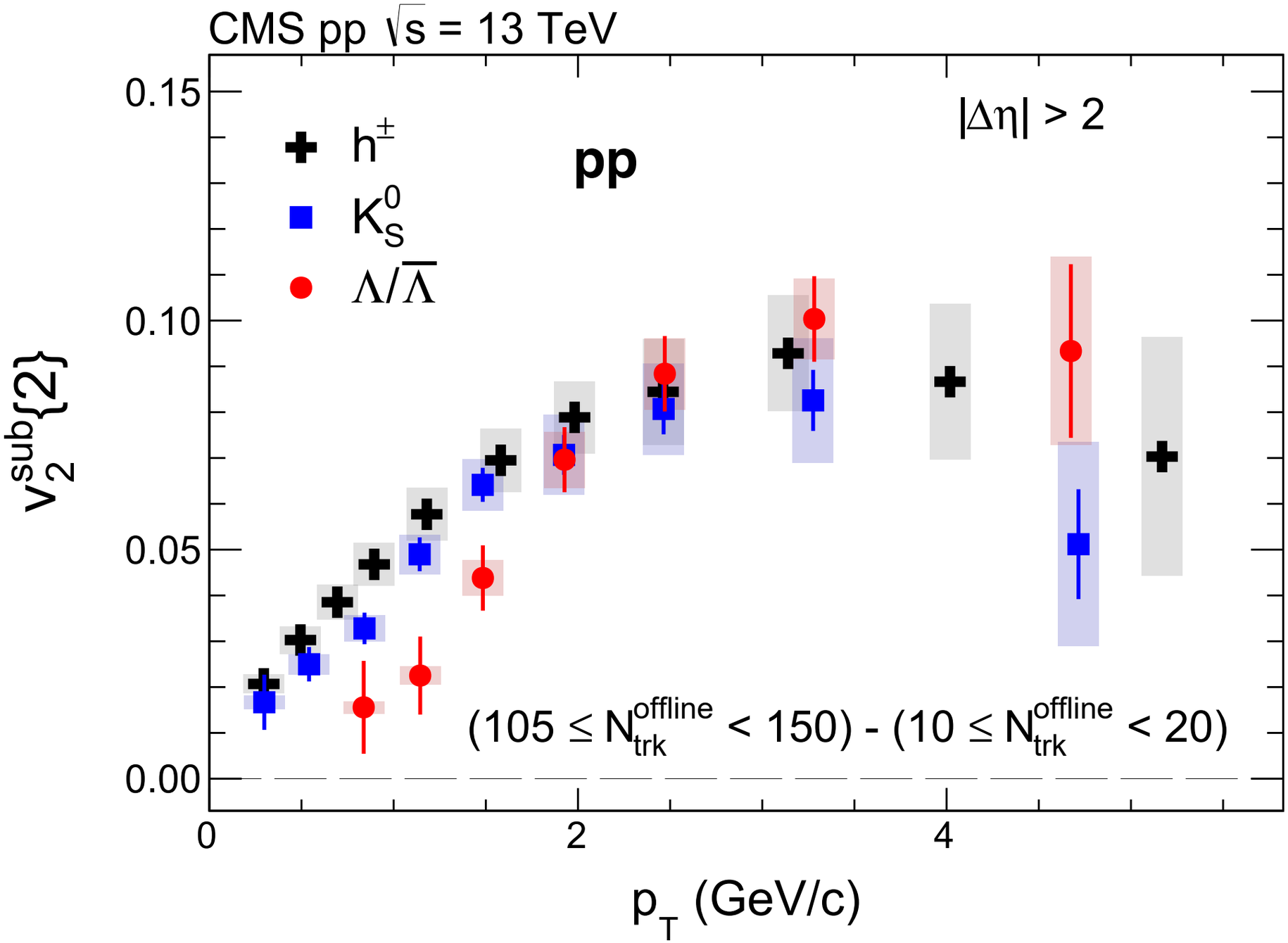


mass ordering observed at low p_T

baryon/meson grouping at mid p_T

ALICE, NPA 982 (2019) 451

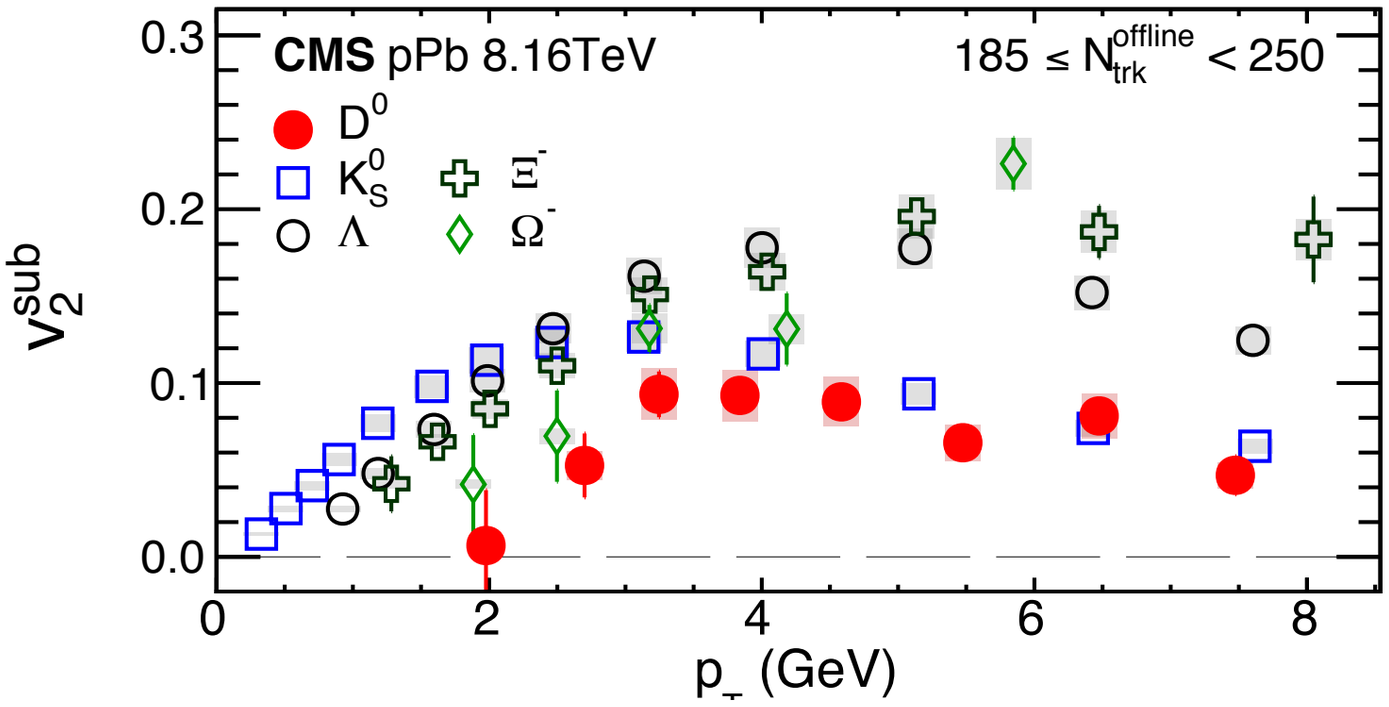
v_2 of identified particles in pp



mass ordering observed at low p_T
also in pp collisions

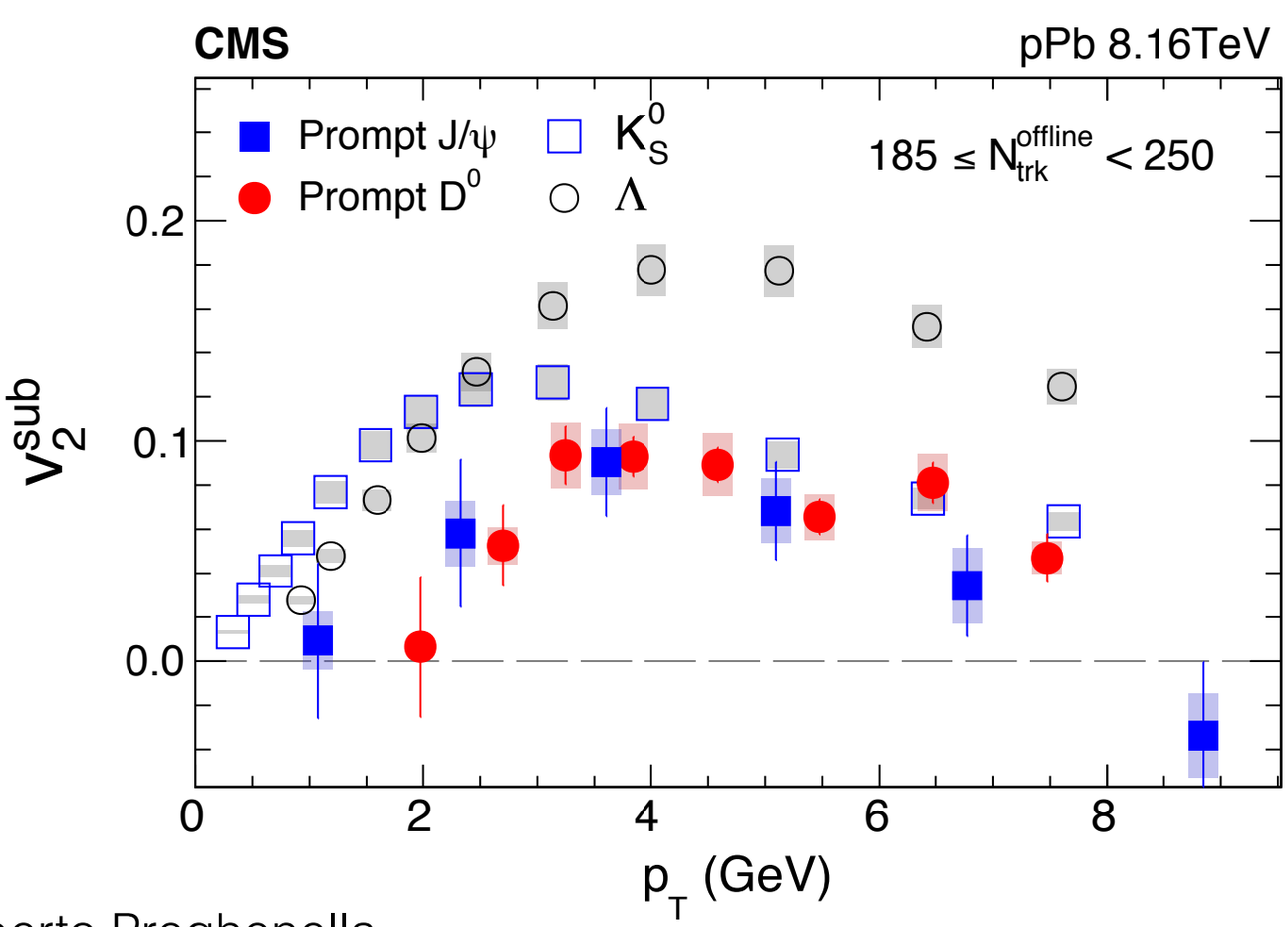
CMS, PLB 765 (2017) 193

Also charm flows!



p-Pb

CMS, PRL 121 (2018) 082301



p-Pb

CMS, PLB 791 (2019) 172

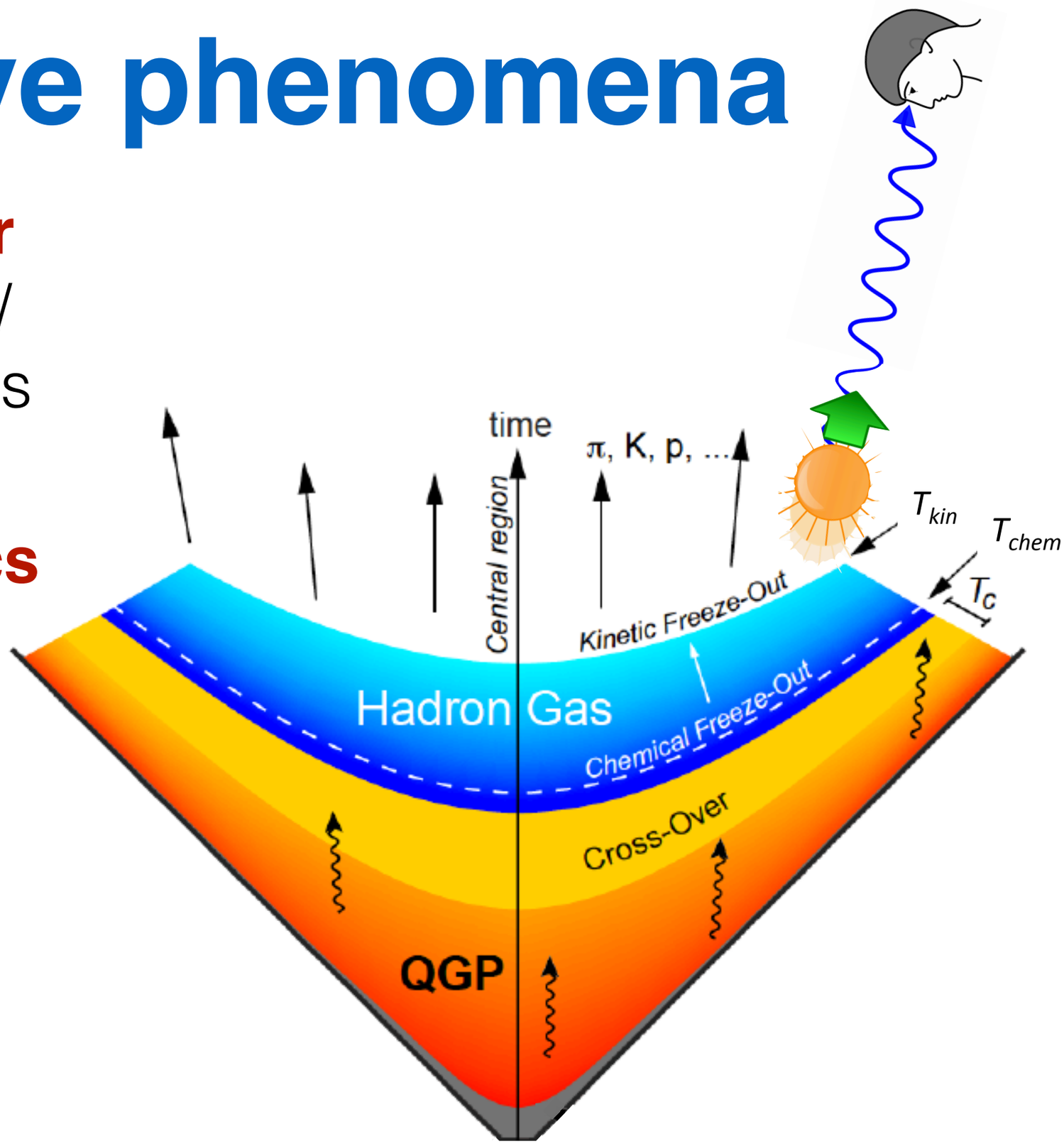
see next talk E. Chapon

Collective phenomena

if the **bulk of the matter** created in high-energy / high-multiplicity collisions

can be described in terms of hydrodynamics

- strongly-interacting matter
- rapid expansion
- collective flows develop
- system cools down
- final decoupling

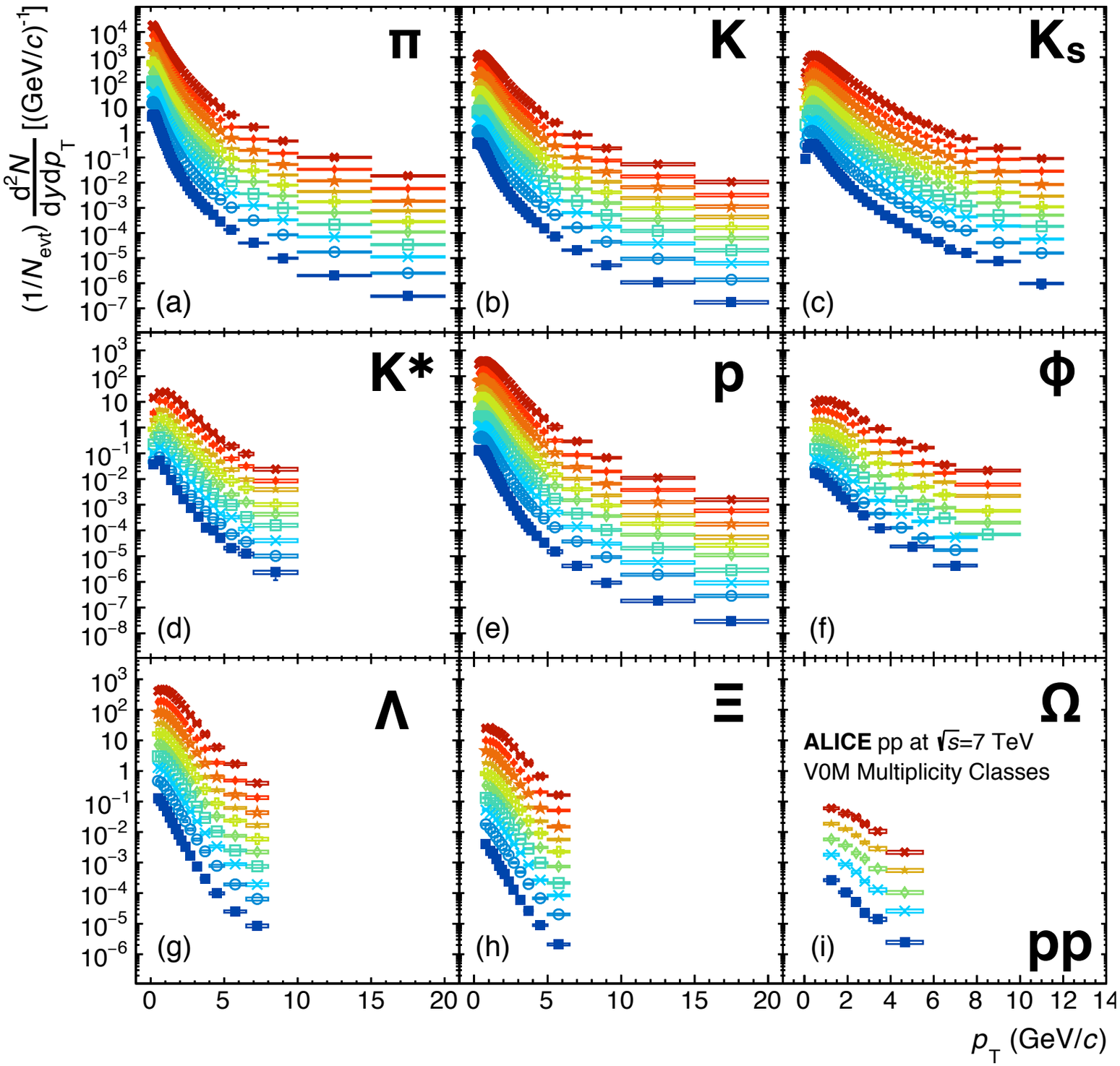


one would expect to observe

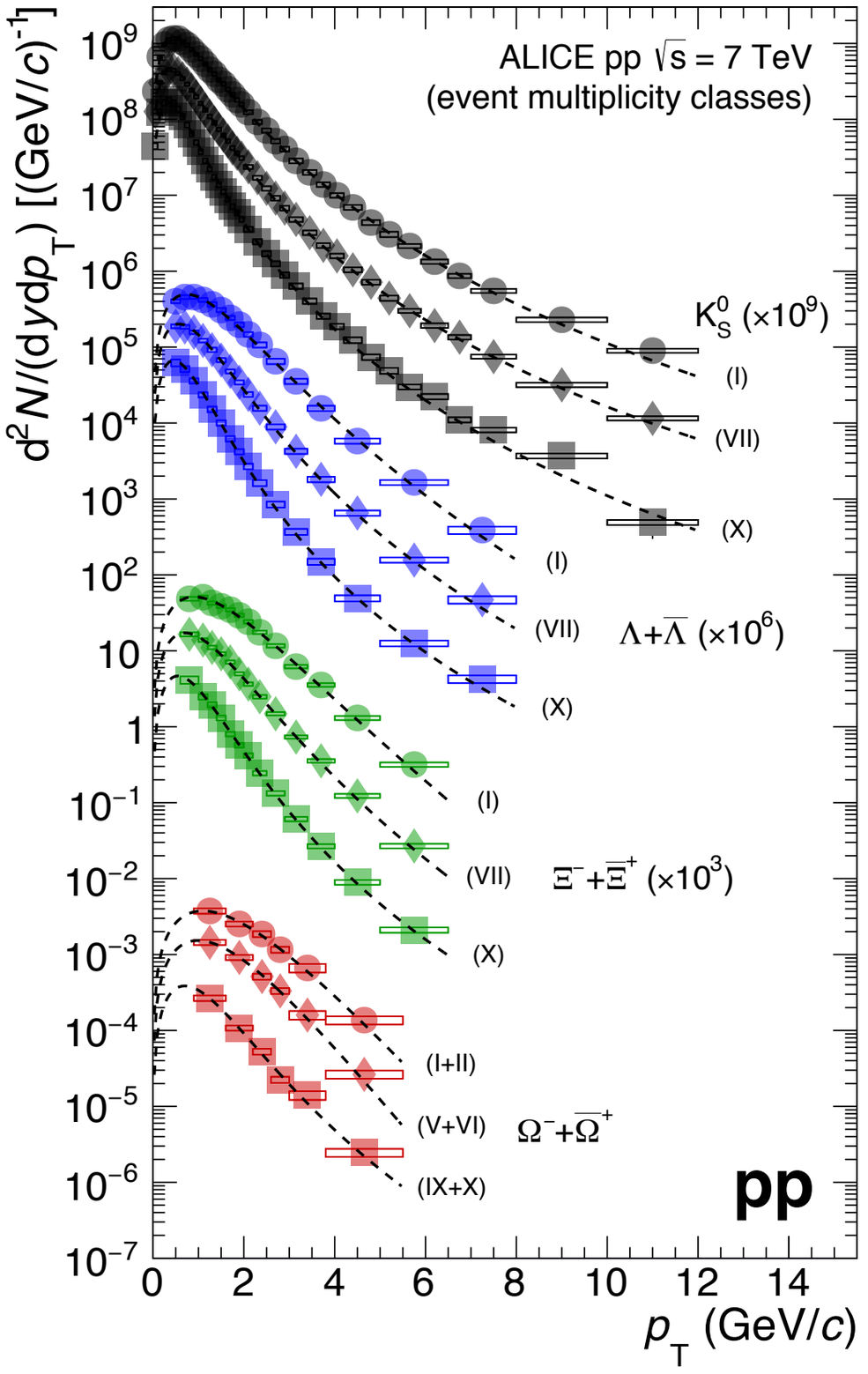
- azimuthal anisotropic flow patterns (initial spatial anisotropy)
- dependence of the shape of the p_T distribution on the particle mass

Identified hadron p_T spectra

ALICE, PRC 99 (2019) 024906

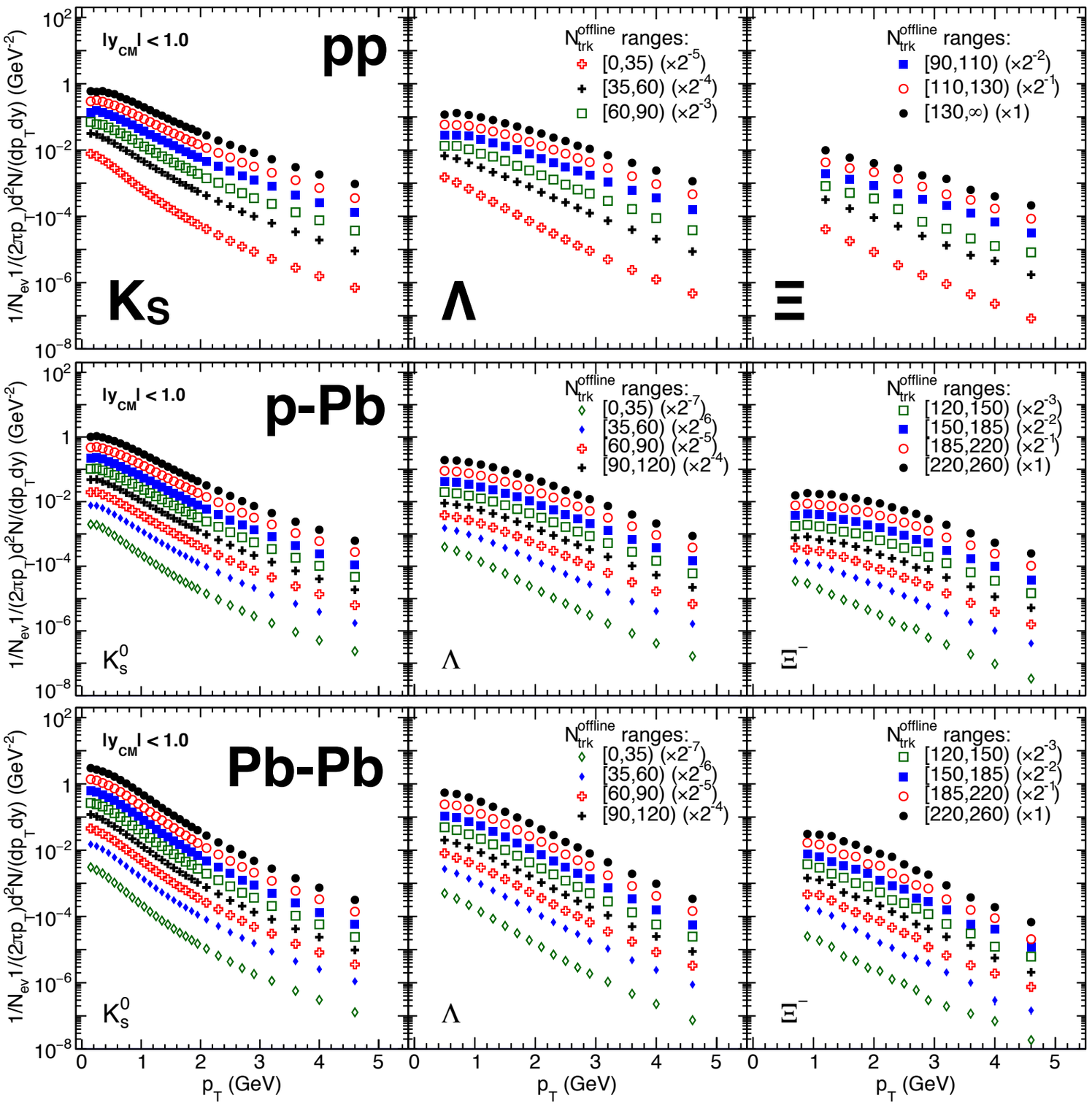


ALICE, Nature Phys. 13 (2017) 535

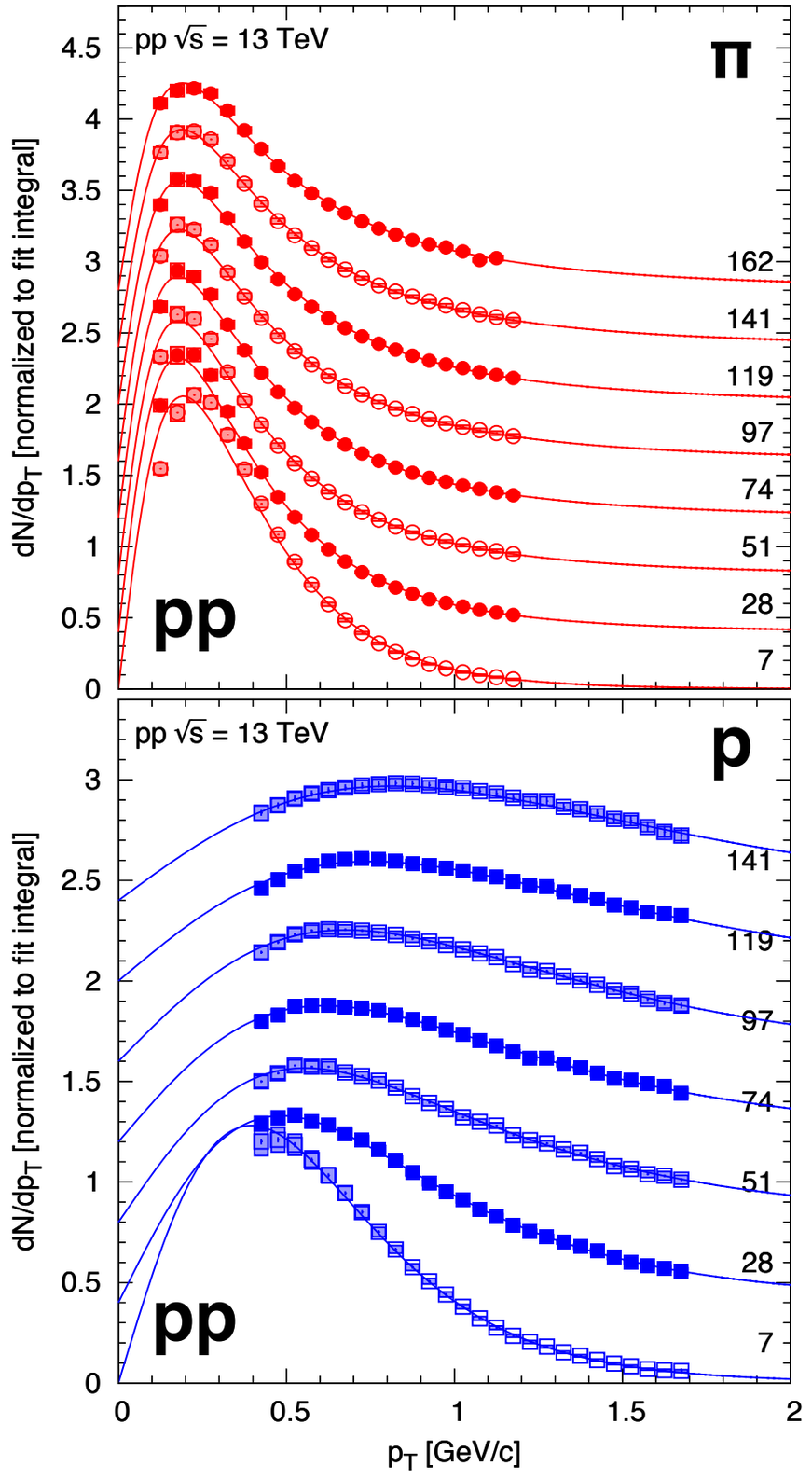


Identified hadron p_T spectra

CMS, PLB 768 (2017) 103

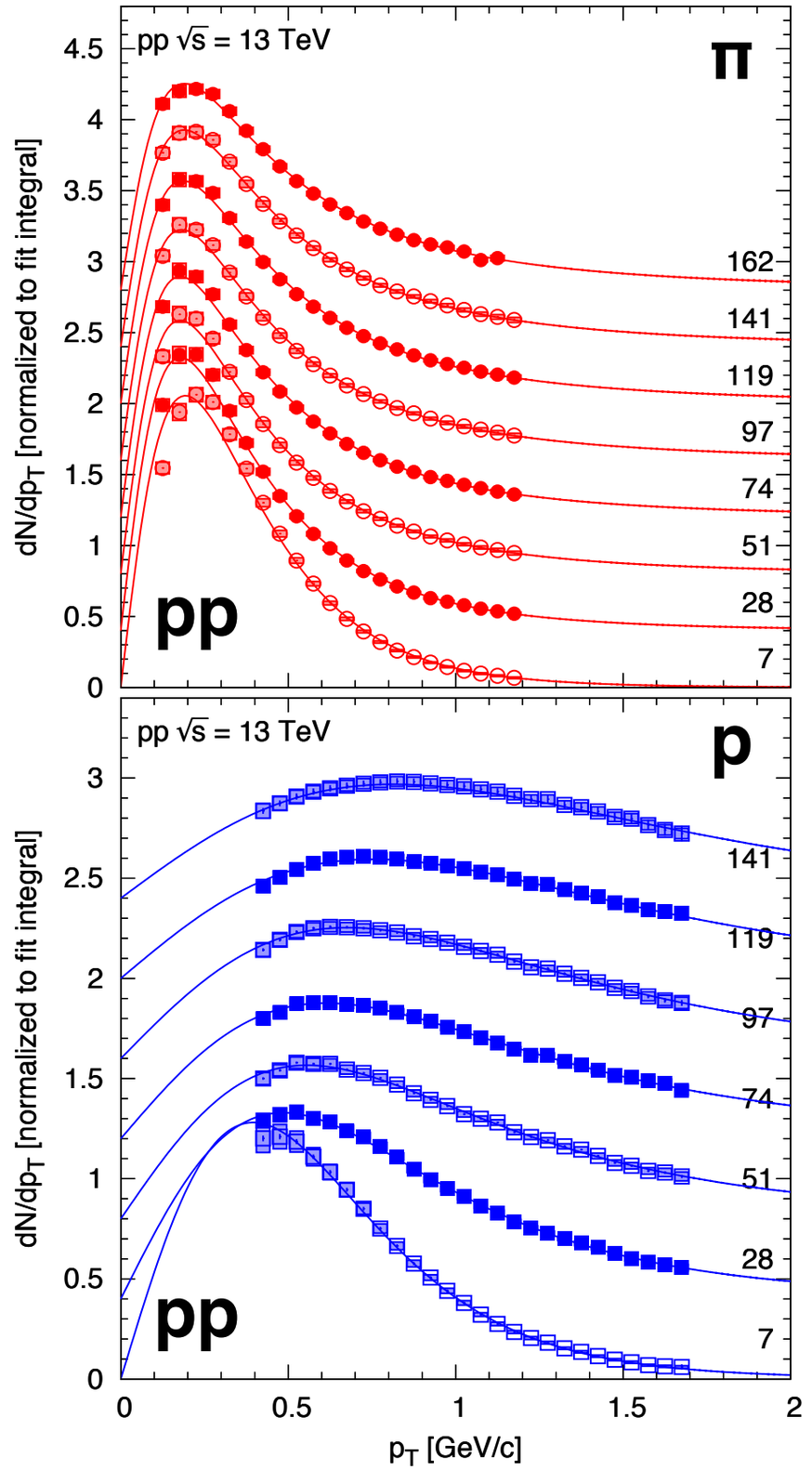


CMS, PRD 96 (2017) 112003



Mass-dependent evolution

CMS, PRD 96 (2017) 112003



clear evolution of particle spectra
become flatter with increasing N_{ch}

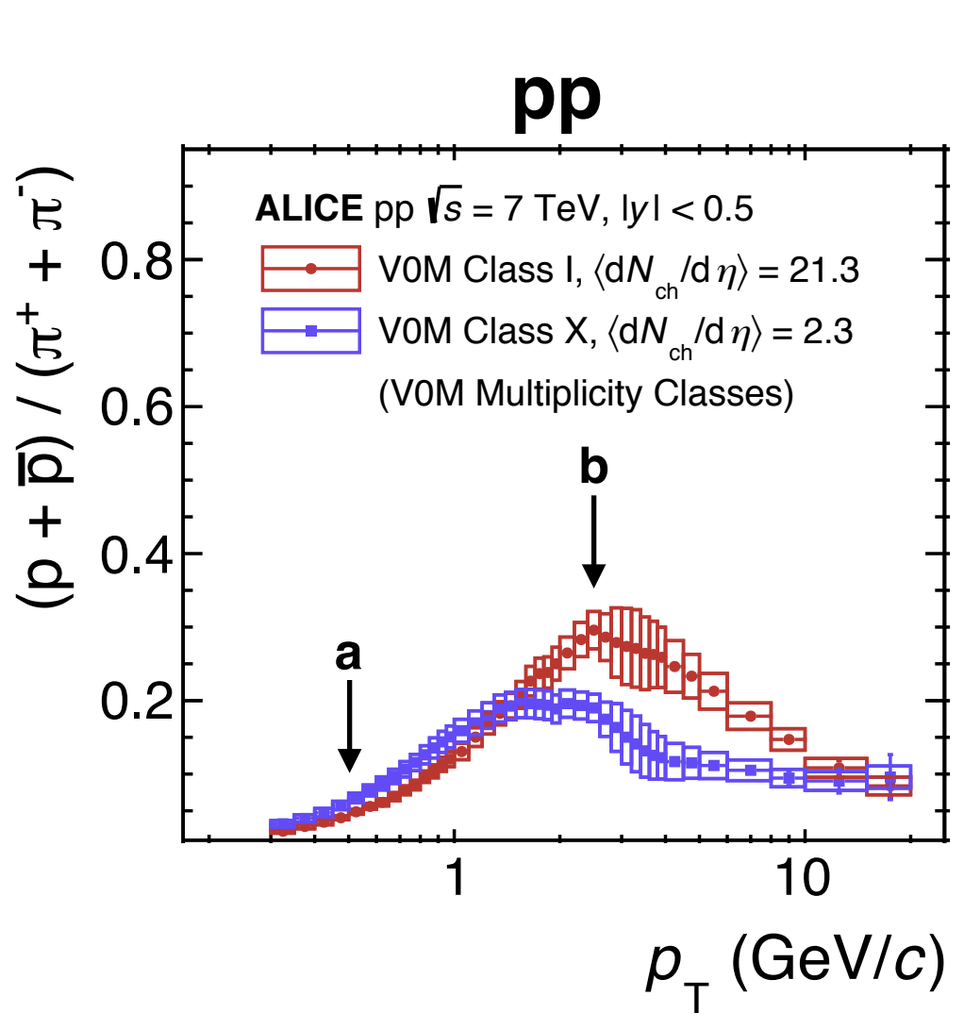
significantly more pronounced for protons than for pions

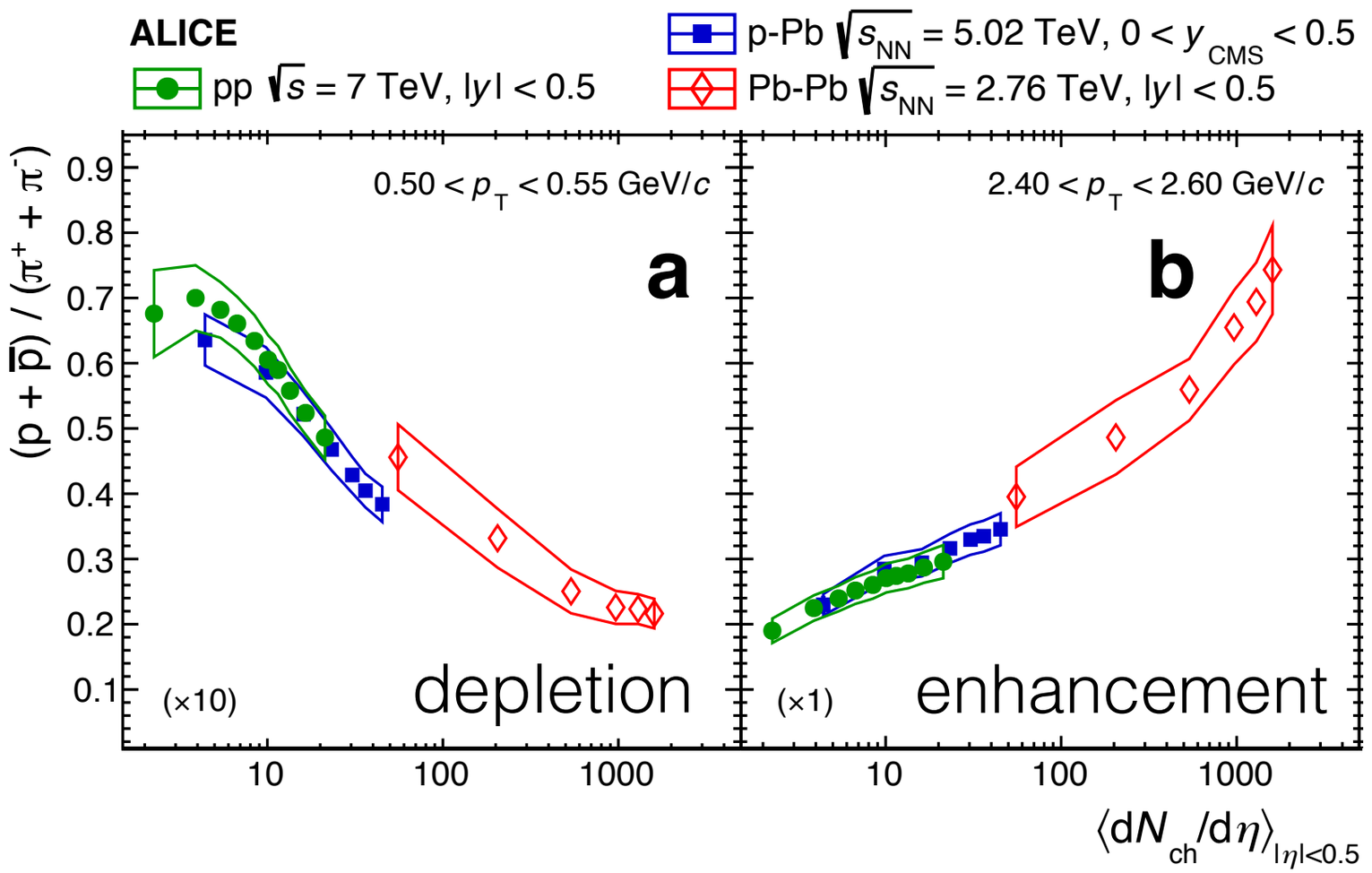
mass ordering as expected from collective hydro expansion

Multiplicity dependence

N_{ch}-dependence of **p/π ratio at fixed p_T**

points towards a universal (soft) mechanism driven by final state $dN_{ch}/d\eta$





rather **smooth evolution across different systems** at low and mid p_T

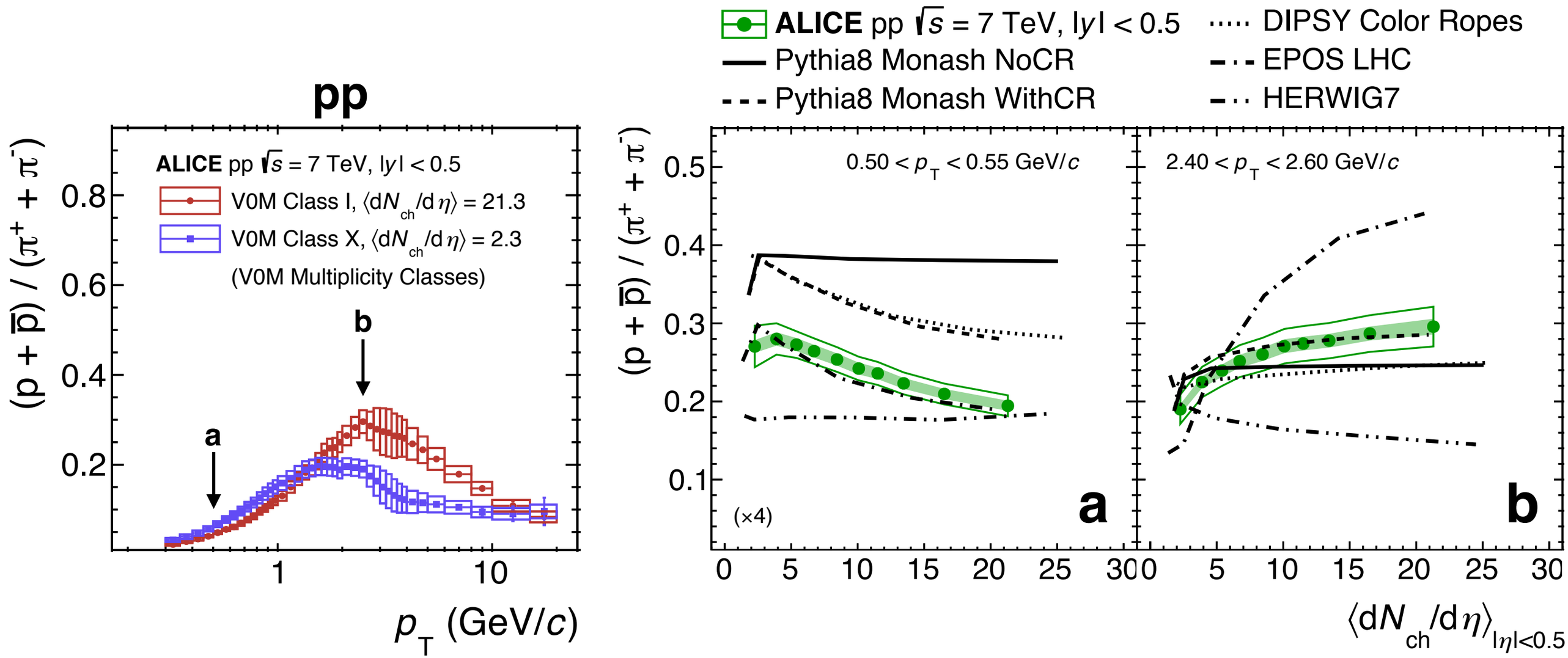
(not shown) high-p_T hard fragmentation does not feel $dN_{ch}/d\eta$

ALICE, PRC 99 (2019) 024906

Multiplicity dependence

N_{ch}-dependent ratios **compared to a large set of generators**

no model gets everything right, so far



colour-reconnection (PYTHIA, DIPSY) and **collective expansion** (EPOS, core-corona) **models** are the most viable options

ALICE, PRC 99 (2019) 024906

Nuclear modification factors

measured for **strange-hadrons in p-Pb** collisions

can provide critical information about initial/final state effects

Cronin-like enhancements

are visible at intermediate p_T

clear **mass ordering**

consistent with radial flow in hydro picture

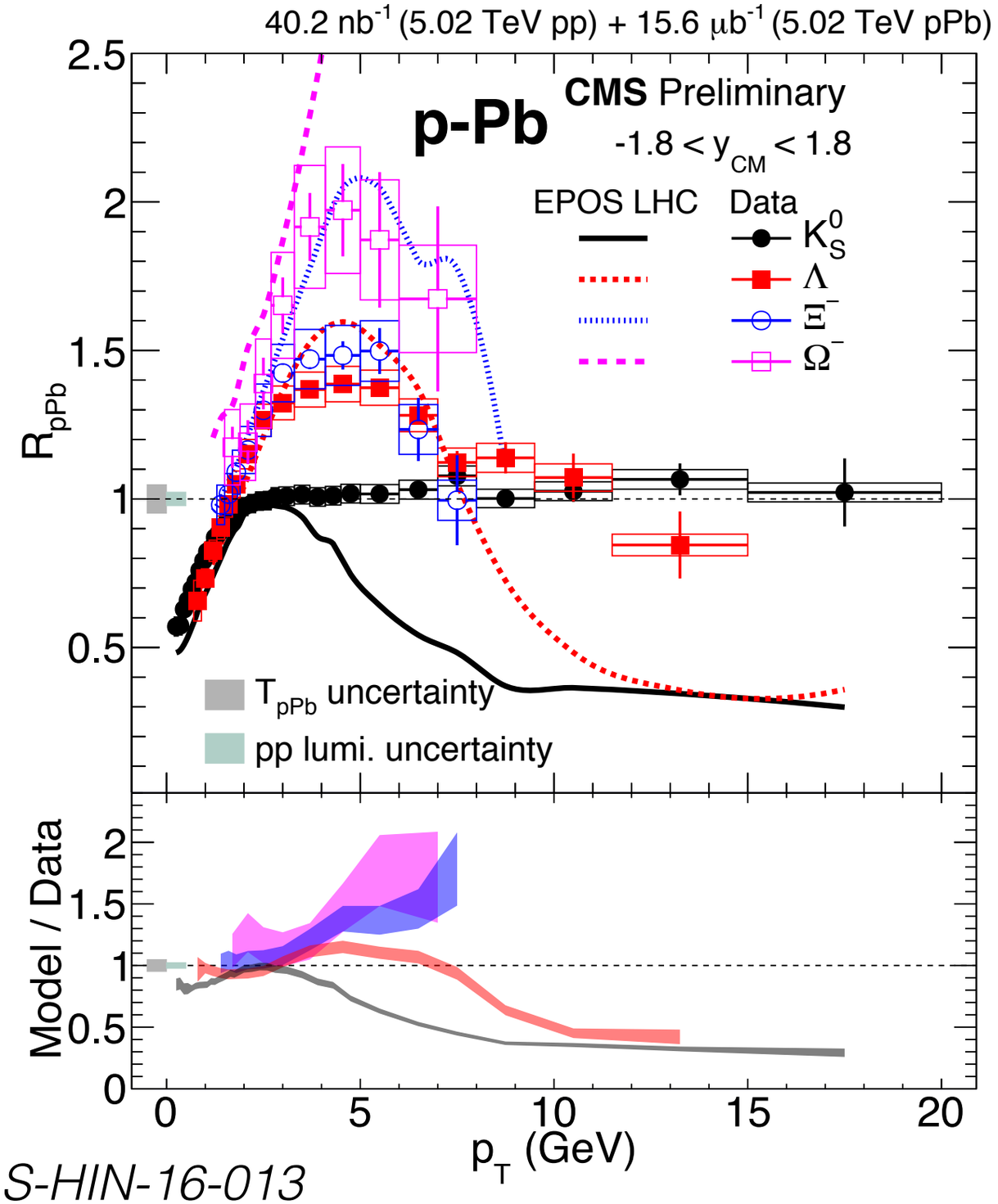
EPOS-LHC

includes collective flow in pp and p-Pb

predicts (stronger) mass ordering

agrees for $p_T < 3$ GeV

much below the data at high p_T

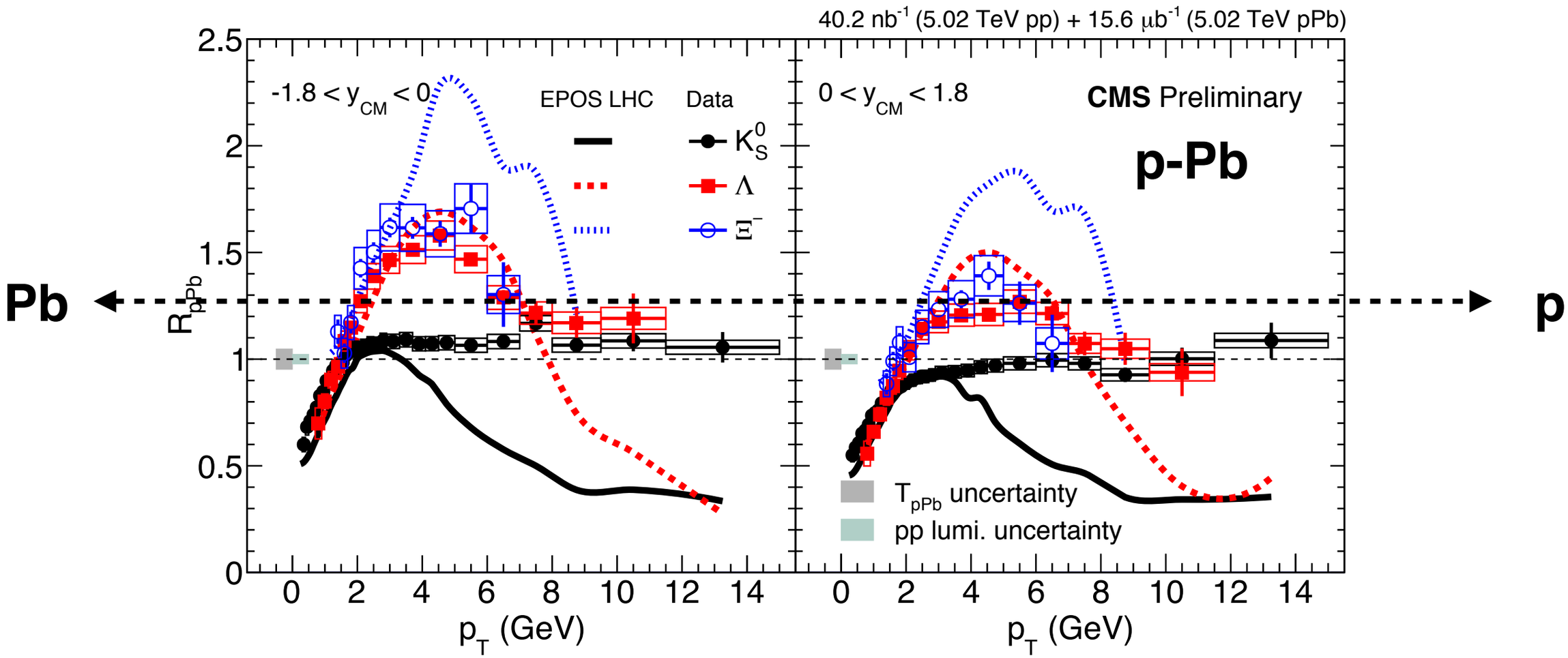


CMS, CMS-PAS-HIN-16-013

Nuclear modification factors

measured for **strange-hadrons in p-Pb** collisions

both in the p-going and Pb-going directions, separately



R_{pPb} is **larger in the Pb-going** direction (stronger mass ordering)

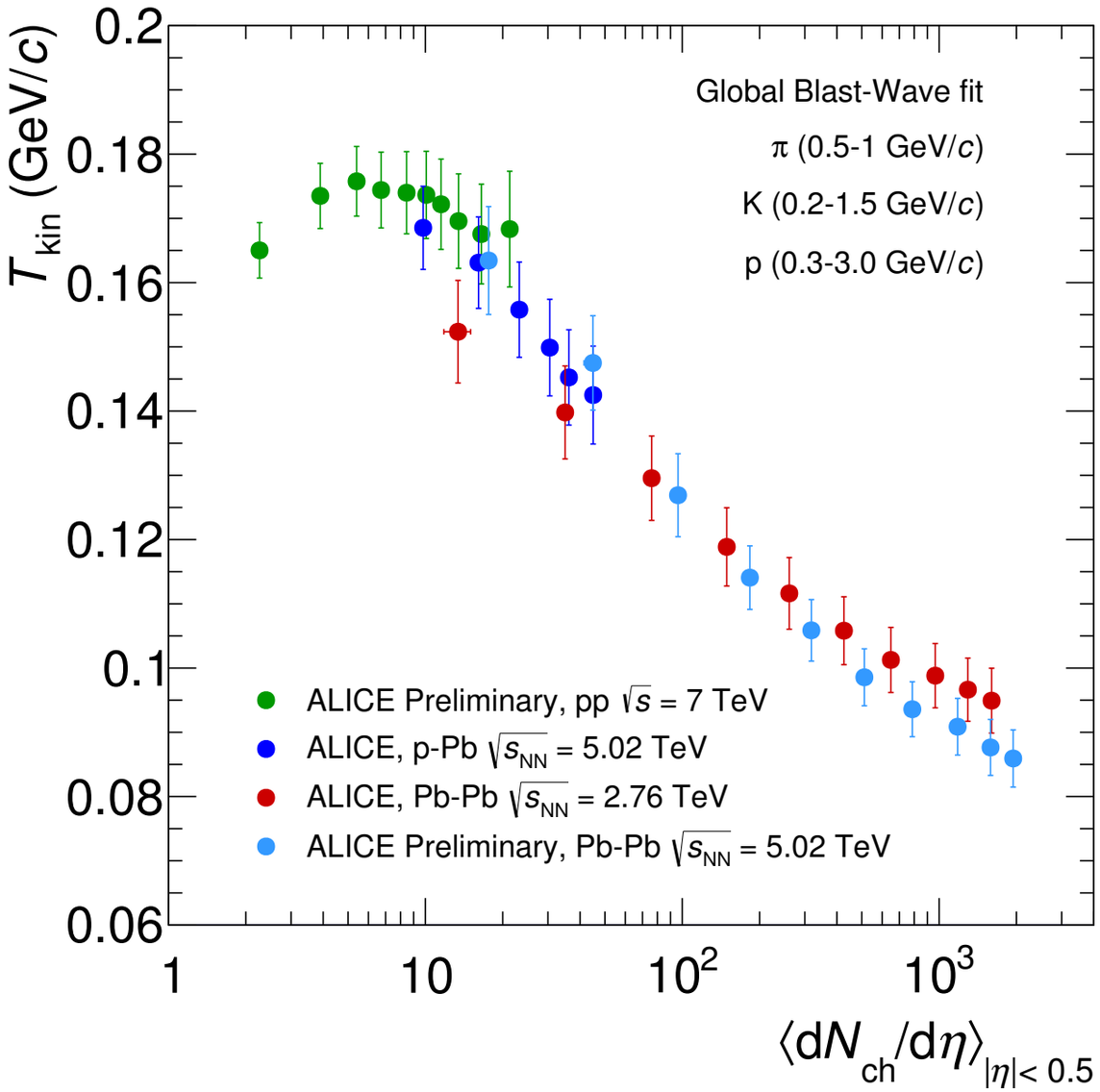
consistent with radial-flow and EPOS-LHC prediction (also with shadowing)

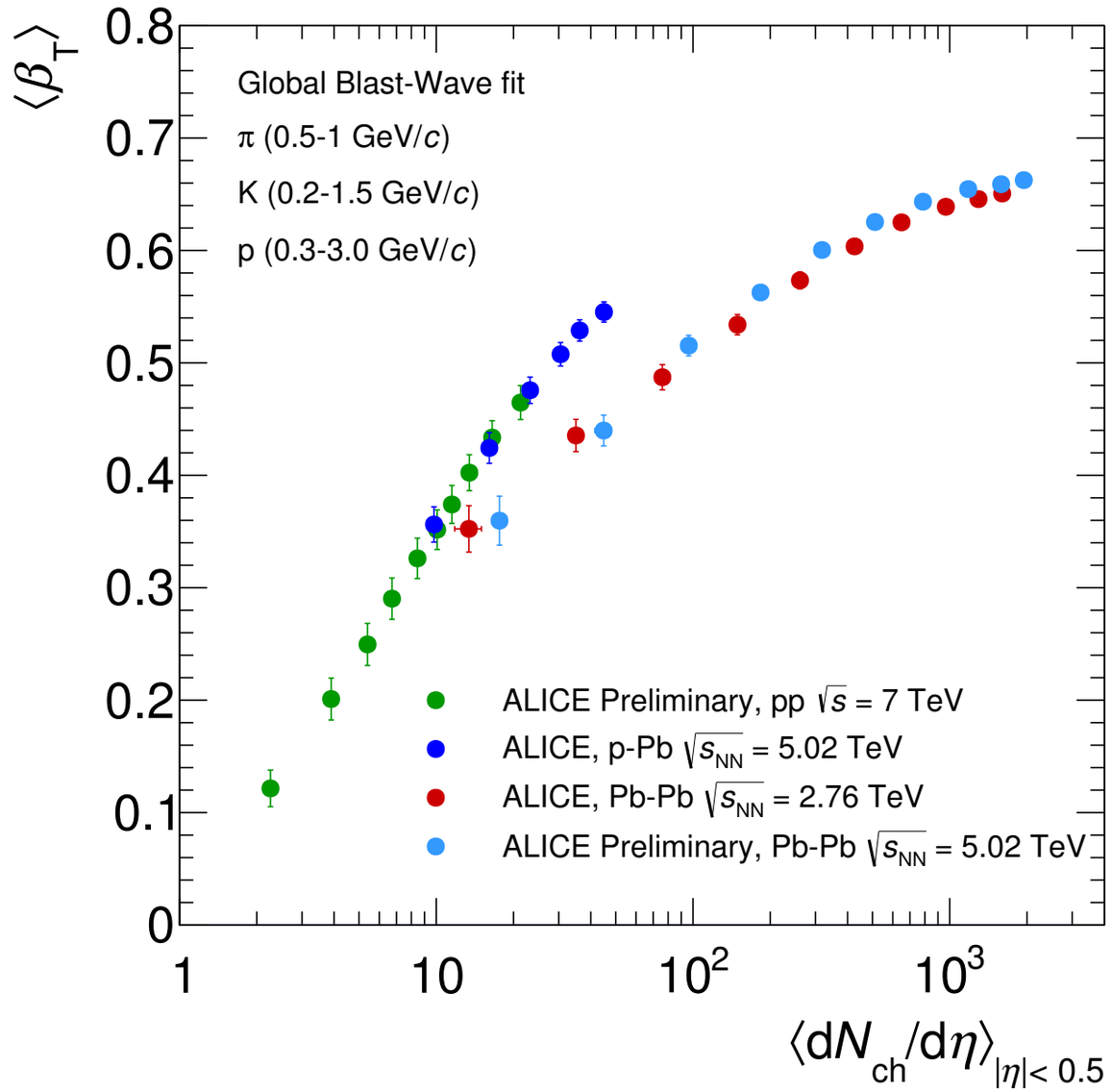
Cronin effect **inconsistent with the data**

should be larger in p-going if initial-state parton (projectile) scatterings

CMS, CMS-PAS-HIN-16-013

Collective radial flow





spectra analysed in the context of the Blast-Wave model

Schnedermann et al., PRC 48 (1993) 2462

when comparing the parameters of different systems at similar $dN_{ch}/d\eta$

T_{kin} values are similar, $\langle\beta_T\rangle$ larger for small systems

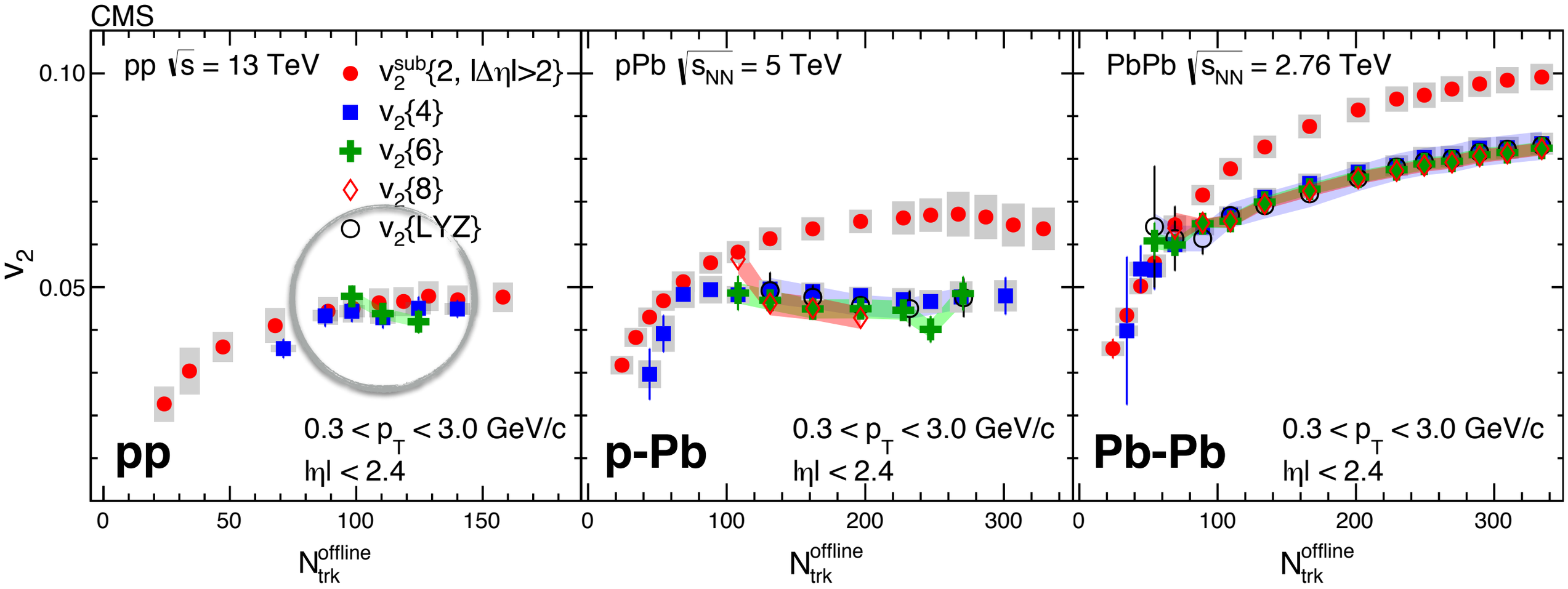
larger radial flow in small system as consequence of stronger gradients

Shuryak et al., PRC 88 (2013) 044915

Evidence of collectivity

v_2 stays large when computed with multi-particle cumulants

v_n{k} have different sensitivity to non-flow effects



there seems to be **true collectivity in p-Pb and in pp**

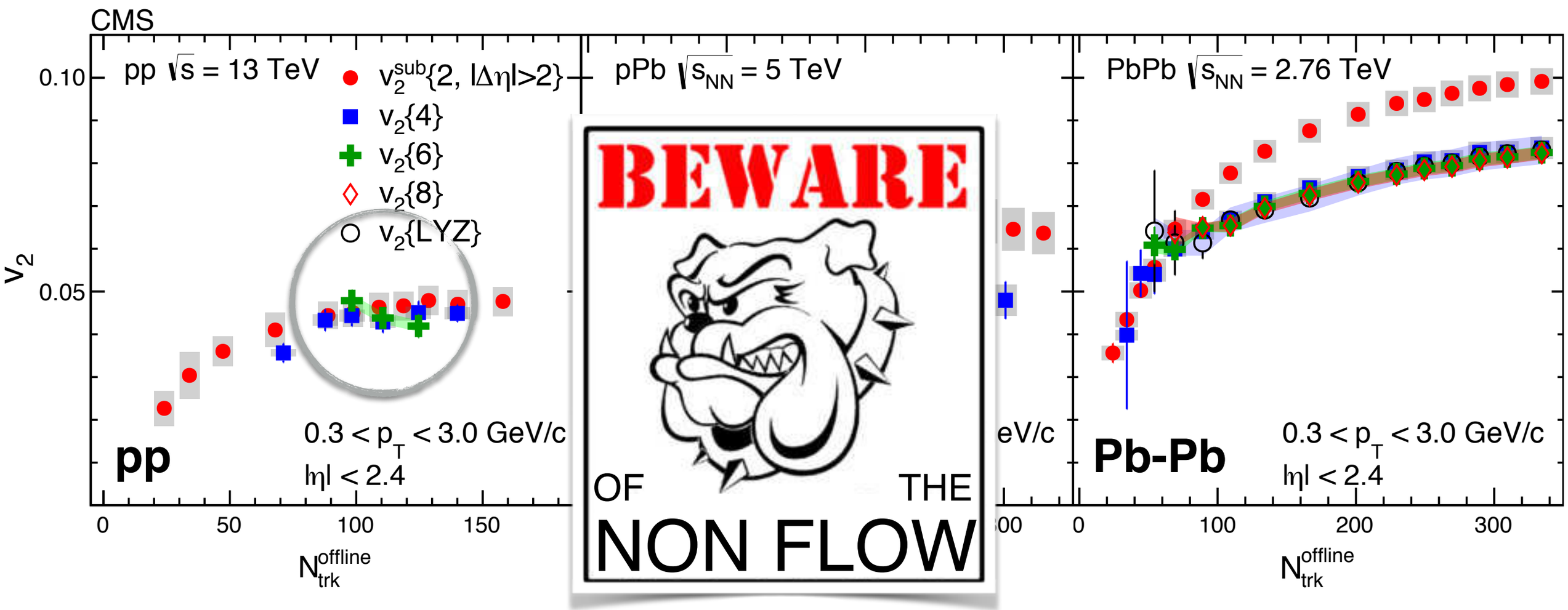
pp: v2{4} = v2{6} , p-Pb: v2{4} = v2{6} = v2{8} = v2{LYZ}

CMS, PLB 765 (2017) 193

Evidence of collectivity

v_2 stays large when computed with multi-particle cumulants

$v_2\{4\} = v_2\{6\} = v_2\{8\} = v_2\{\text{LYZ}\}$ have different sensitivity to non-flow effects



there seems to be **true collectivity in p-Pb and in pp**

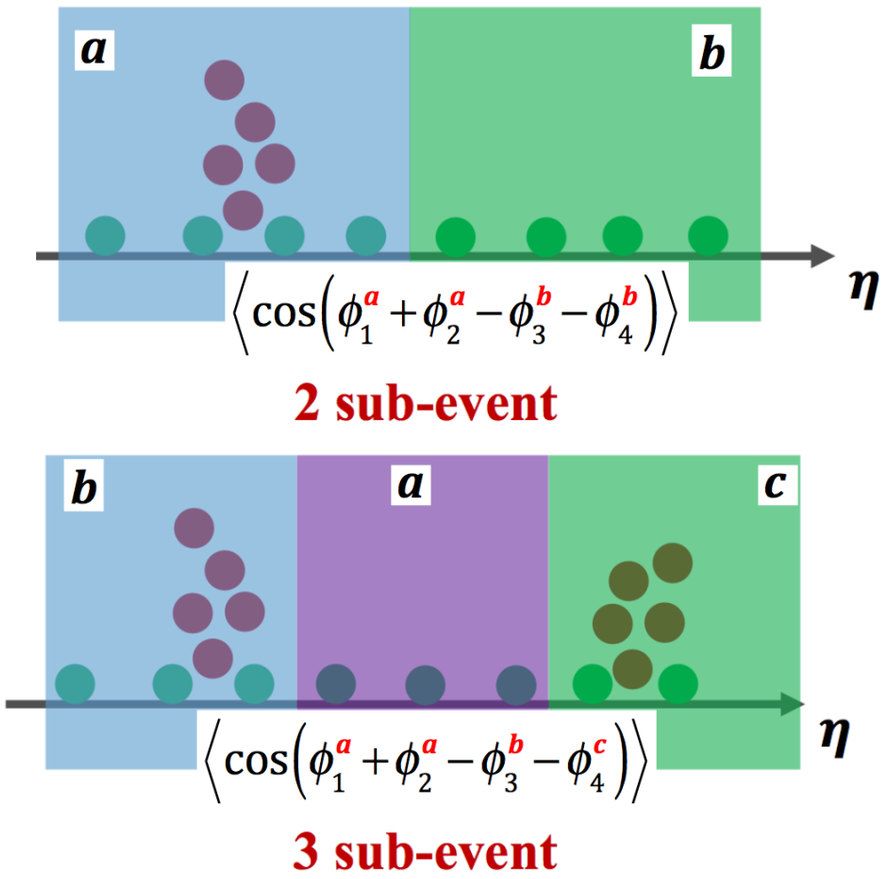
make sure that non-flow is properly suppressed

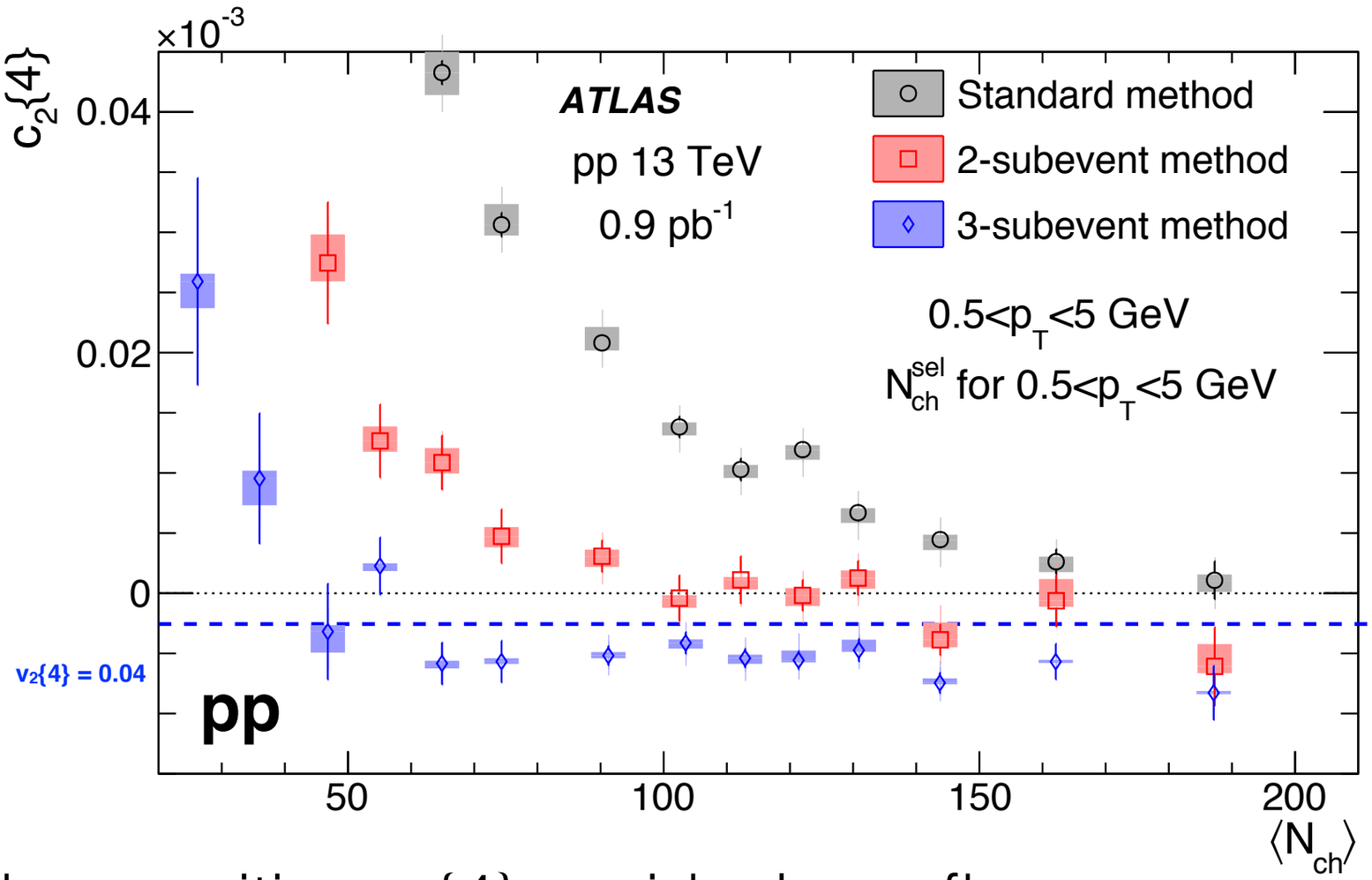
CMS, PLB 765 (2017) 193

The subevent method

minimises biases from **few particle correlations**

aka non-flow (resonances and jets not associated with a collision symmetry plane)





standard method has positive $c_2\{4\}$, residual non-flow

2-subevent method suppresses non-flow, but it is still affected

3-subevent cumulant is more robust against non-flow

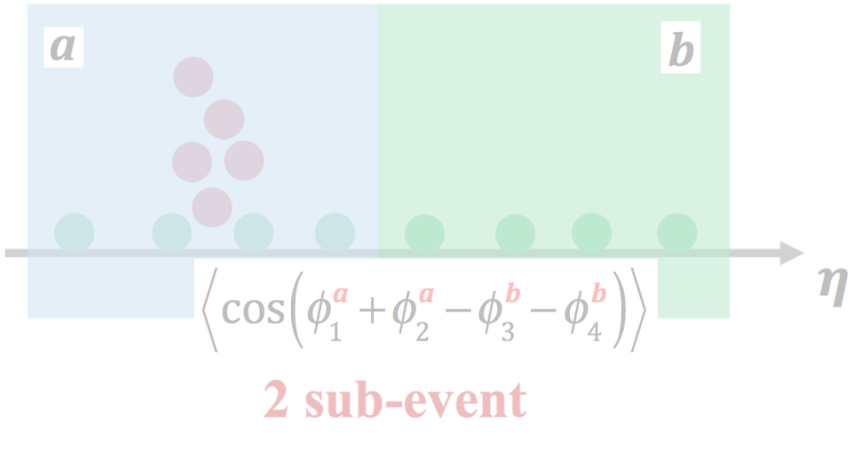
significant flow in a broad range, nearly independent from N_{ch}

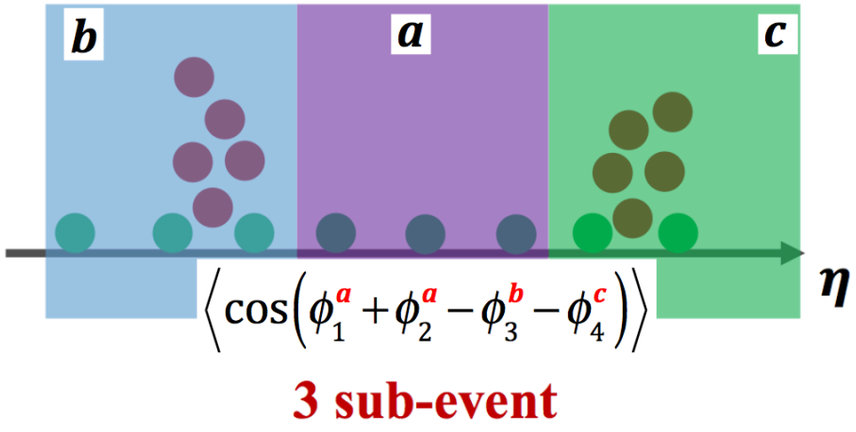
ATLAS, PRC 97 (2018) 024904

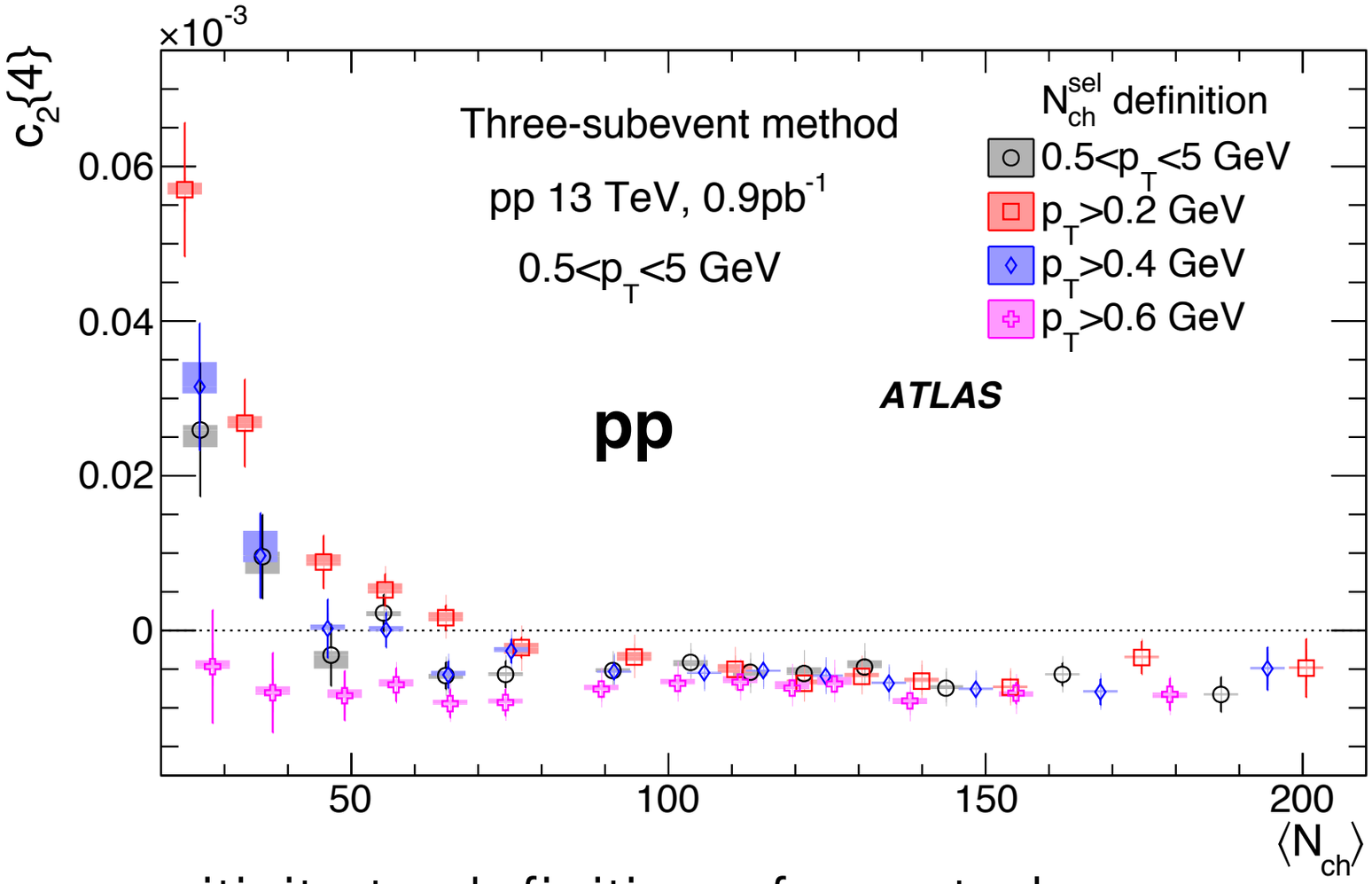
The subevent method

minimises biases from **few particle correlations**

aka non-flow (resonances and jets not associated with a collision symmetry plane)







$c_2\{4\}$ still shows some sensitivity to definition of event-class
but for $N_{ch} > 100$ the values are consistent with each other

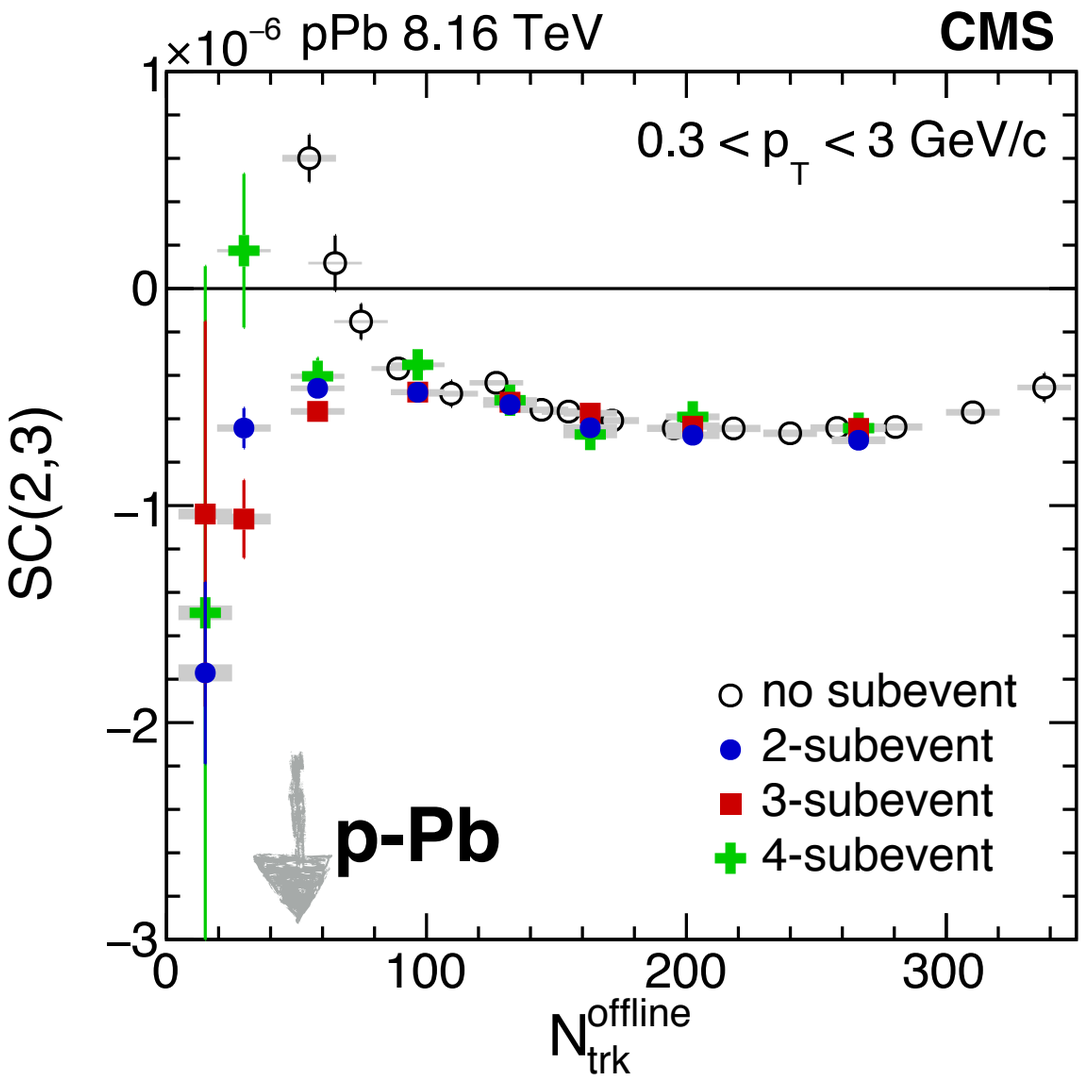
3-subevent cumulant is more robust against non-flow

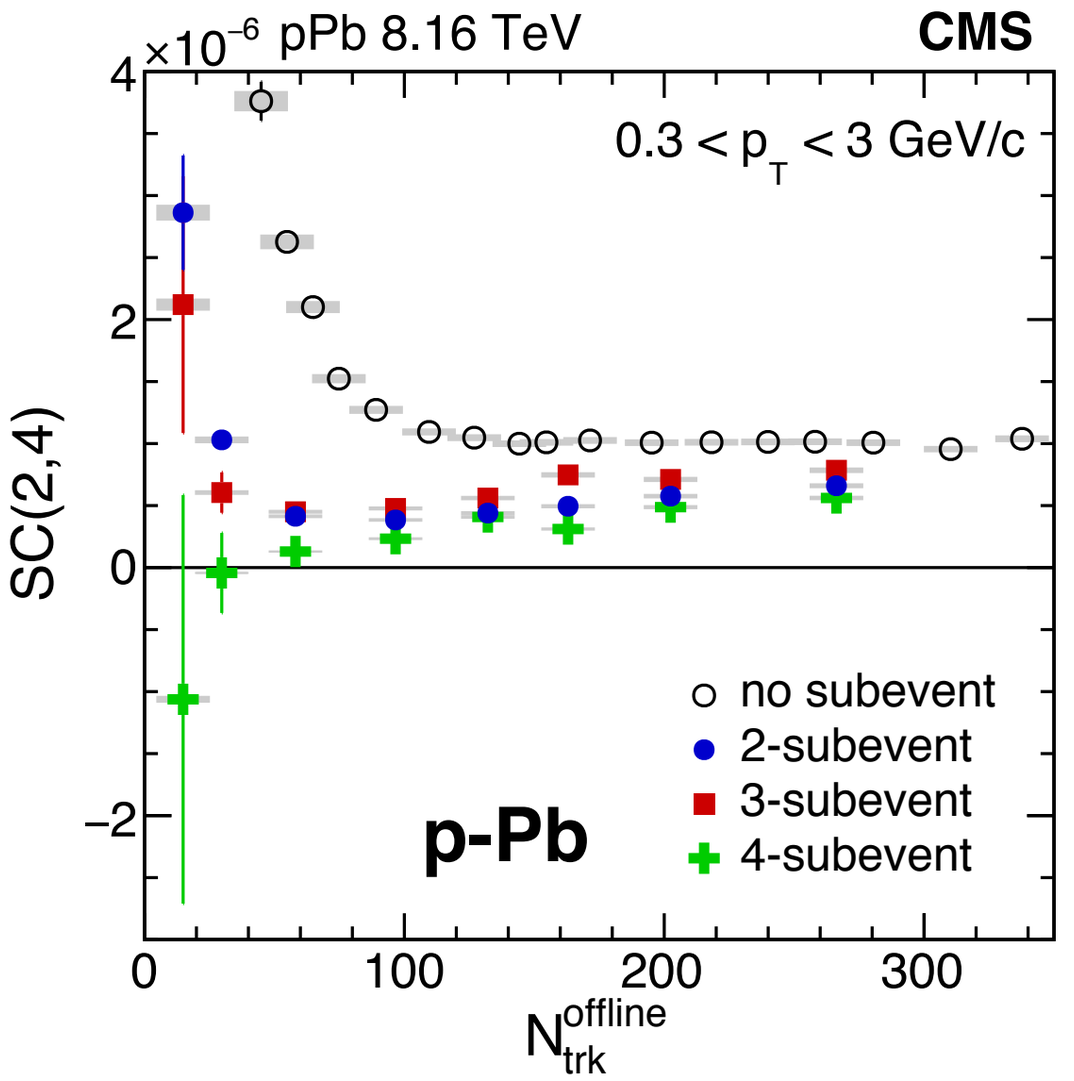
the ridge is indeed a long-range phenomenon involving many particles

ATLAS, PRC 97 (2018) 024904

Symmetric cumulants

with **subevent method** to suppress non-flow correlations





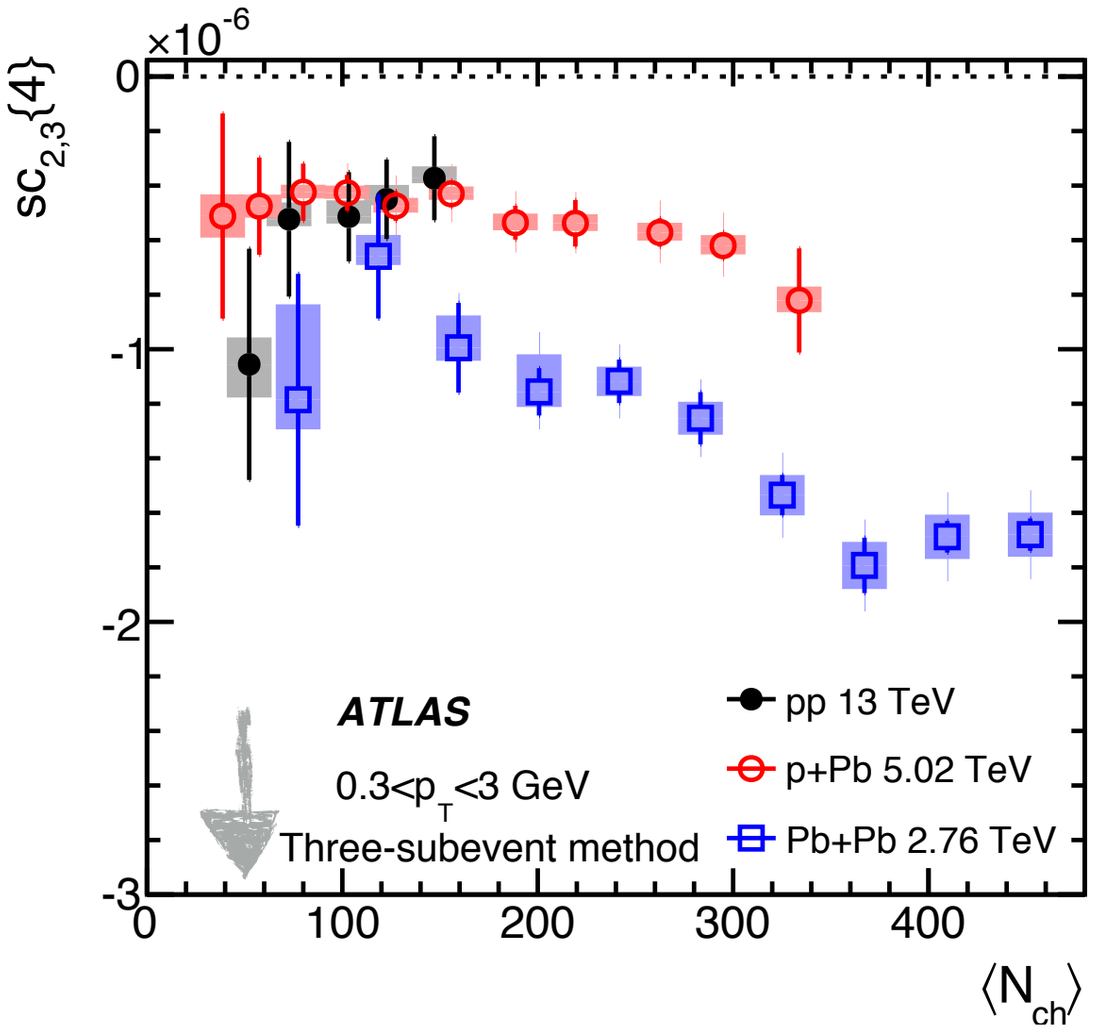
no rising trend at low N_{ch}, **SC(2,3) stays negative**

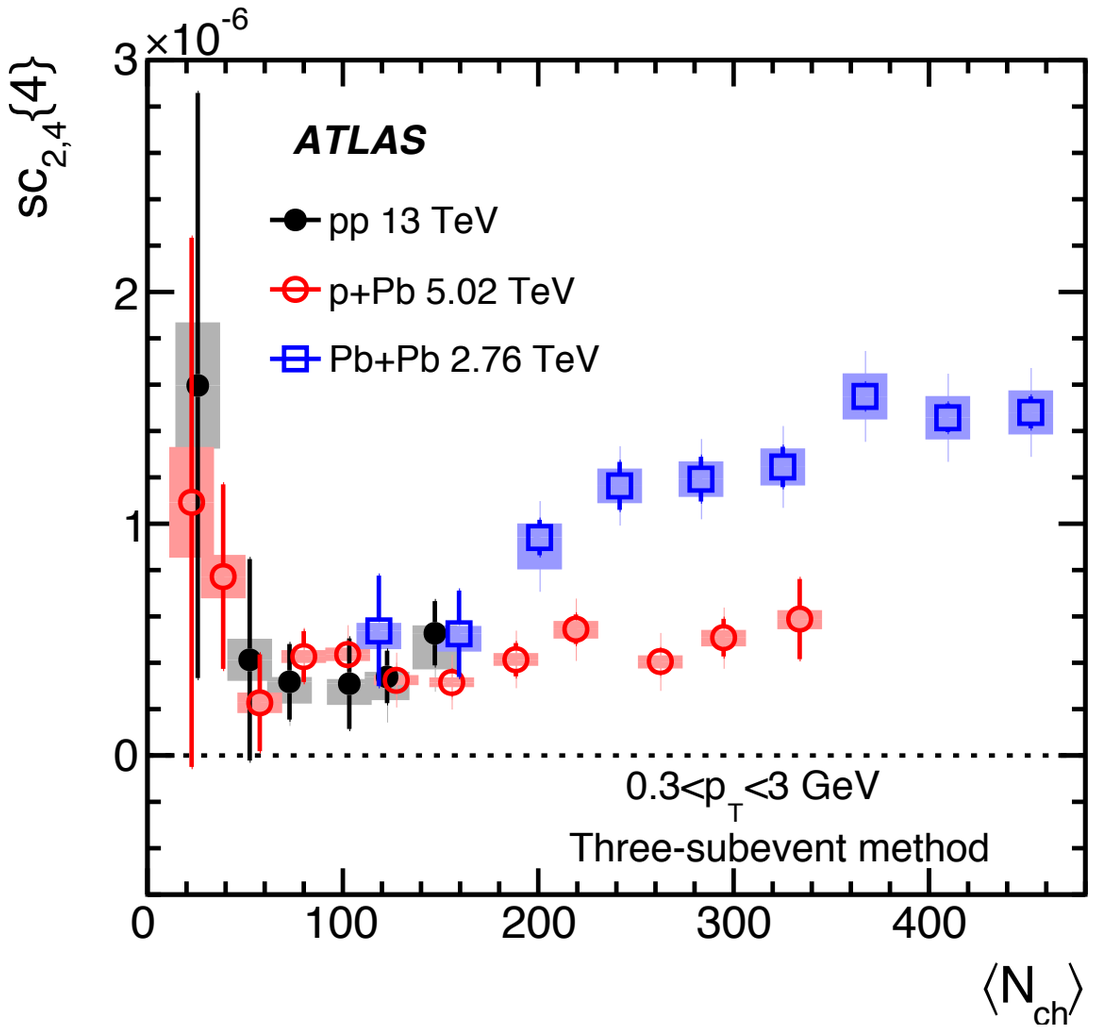
range for possible onset of collectivity down to N_{ch} ~ 50 ($dN_{ch}/d\eta$ ~ 10)

CMS, arXiv:1905.09935 [hep-ex]

Symmetric cumulants

with **subevent method** to suppress non-flow correlations





negative SC(2,3) and positive SC(2,4) for all systems

nature of collective correlations are of the same origin

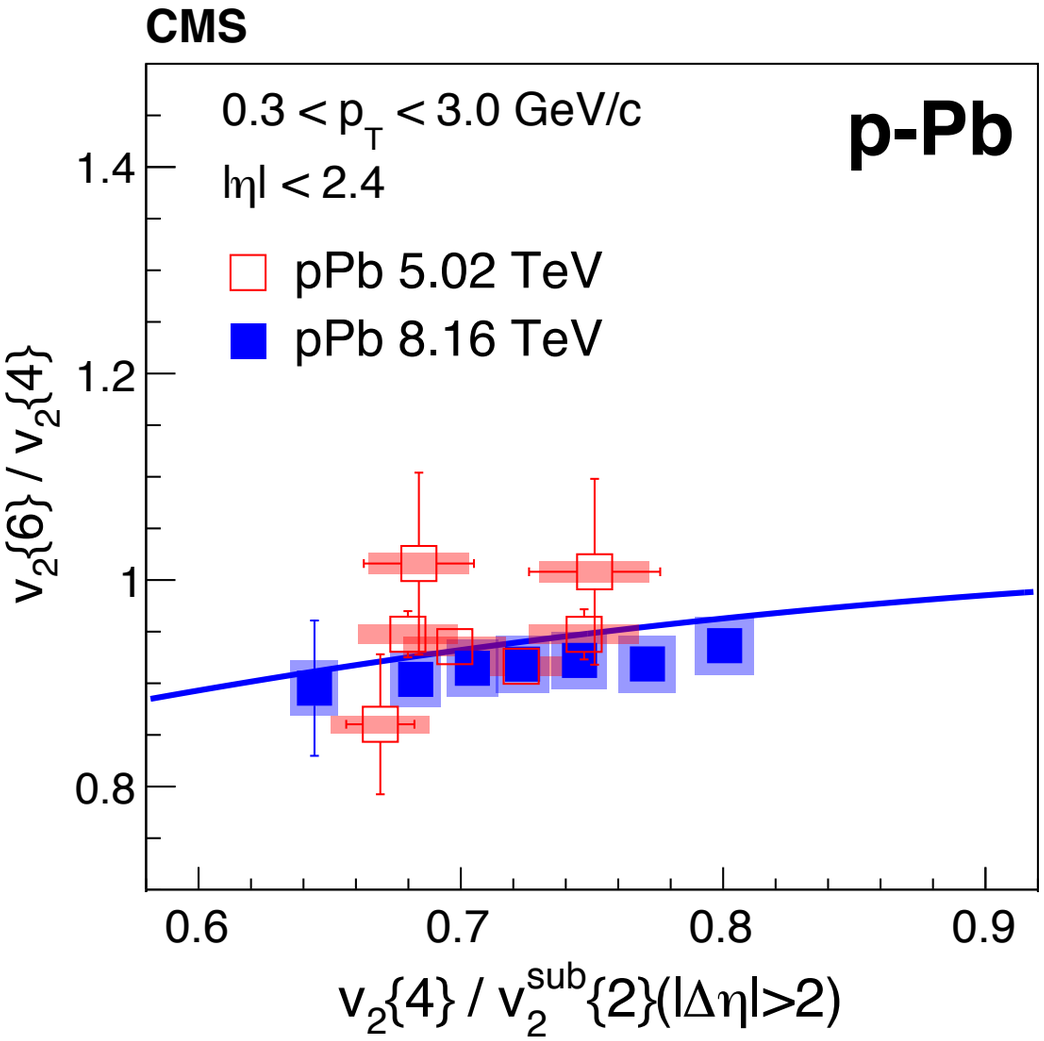
large-small systems: similar(different) magnitude at small(large) N_{ch}

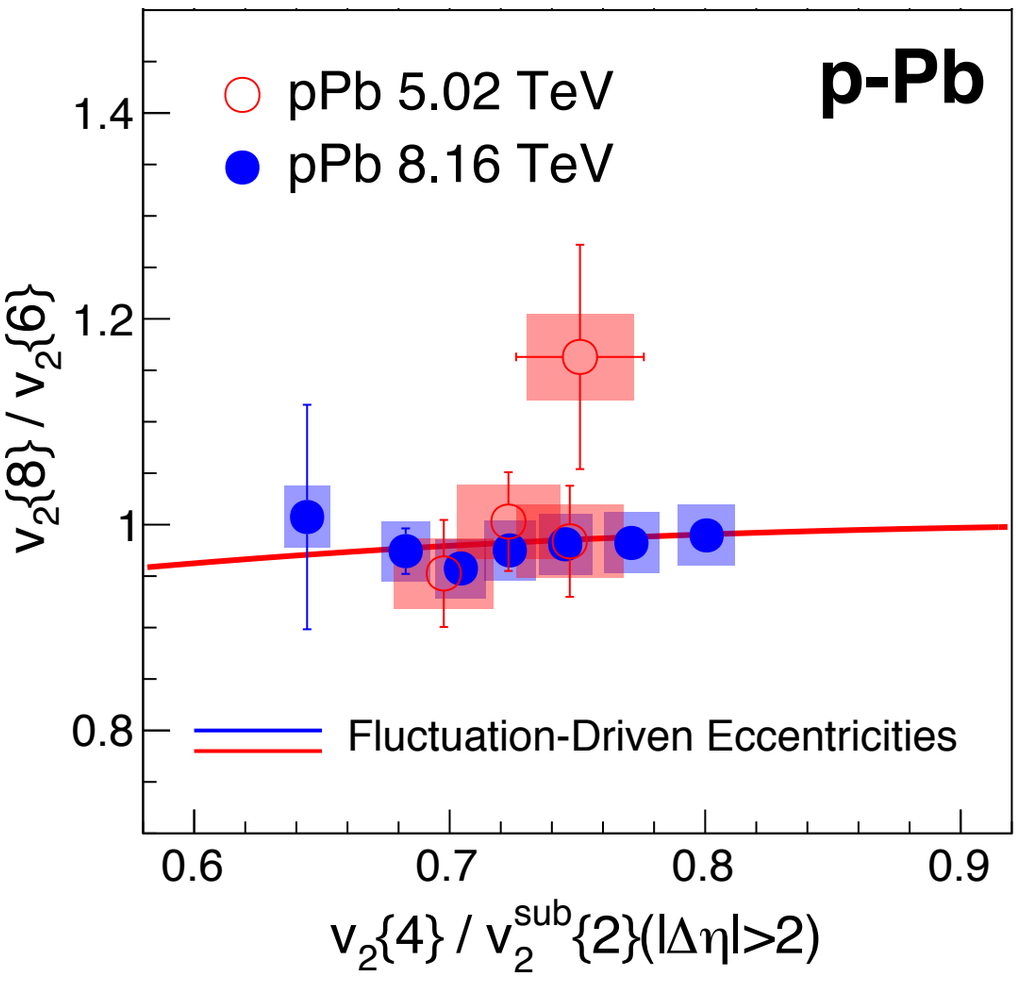
ATLAS, PLB 789 (2019) 444

Fluctuation-driven correlations

high-precision measurement of $v_2\{k\}$, k = 4, 6, 8

ratios compared to fluctuation-driven eccentricity calculations





confirms **correlations originate from source fluctuations**

fundamental assumption for hydro and CGC calculations

CMS, arXiv:1904.11519 [hep-ex]

Quark-Gluon droplets engineered

RHIC versatility: projectile geometry scan

PHENIX, Nature Phys. 15 (2019) 214

initial-state geometry dominantly

p-Au Proton p → Gold ion → **circular**

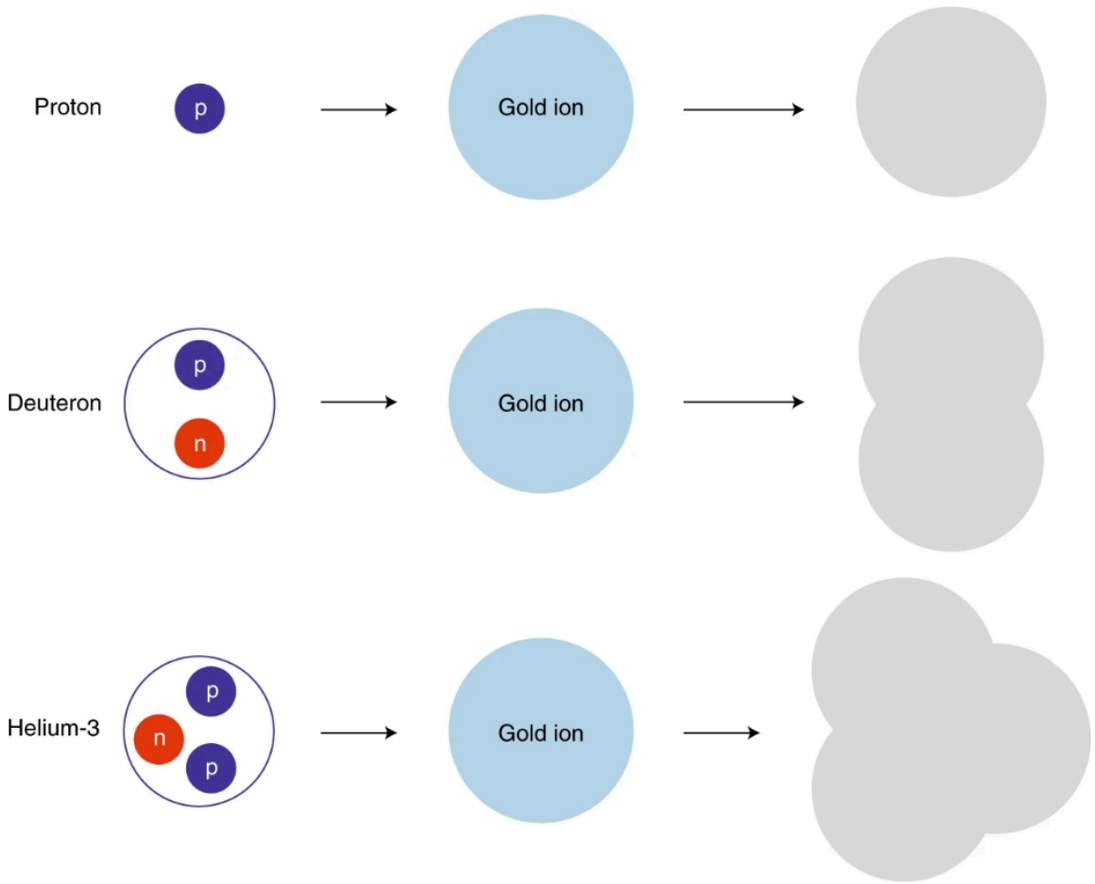
d-Au Deuteron p n → Gold ion → **elliptical**

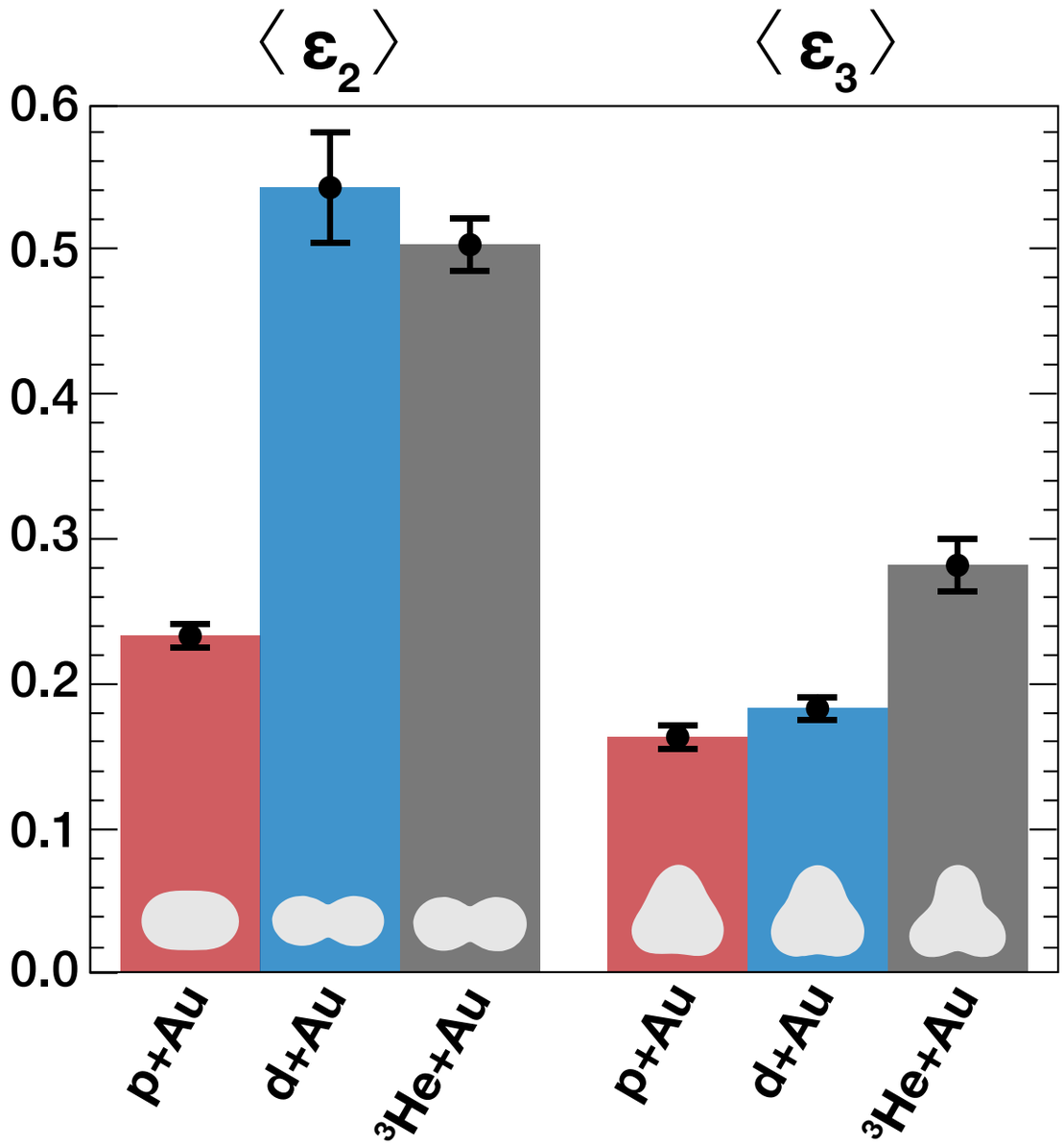
^{3}He-Au Helium-3 p n p → Gold ion → **triangular**

Quark-Gluon droplets engineered

RHIC versatility: projectile geometry scan

initial-state spatial eccentricity (2nd and 3rd order) **fluctuates** E-by-E





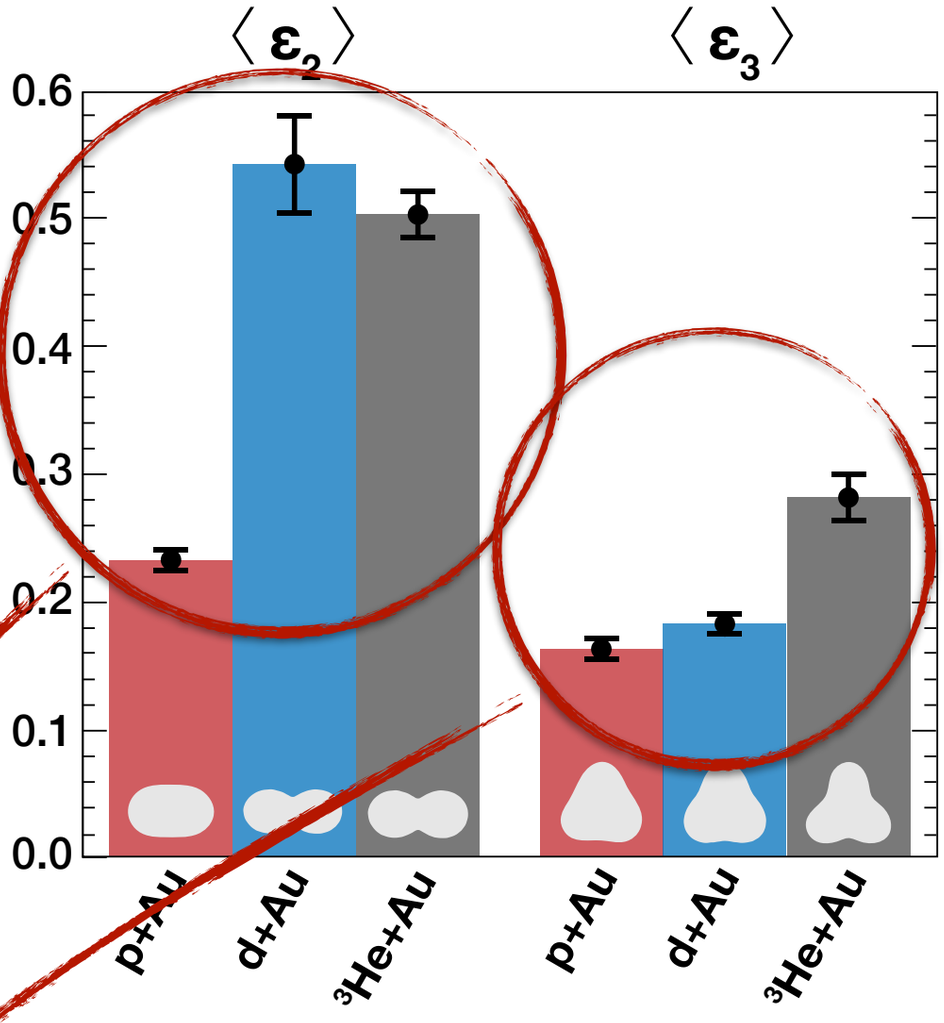
p-Au fluctuation driven, d-Au and ^{3}He-Au geometry driven

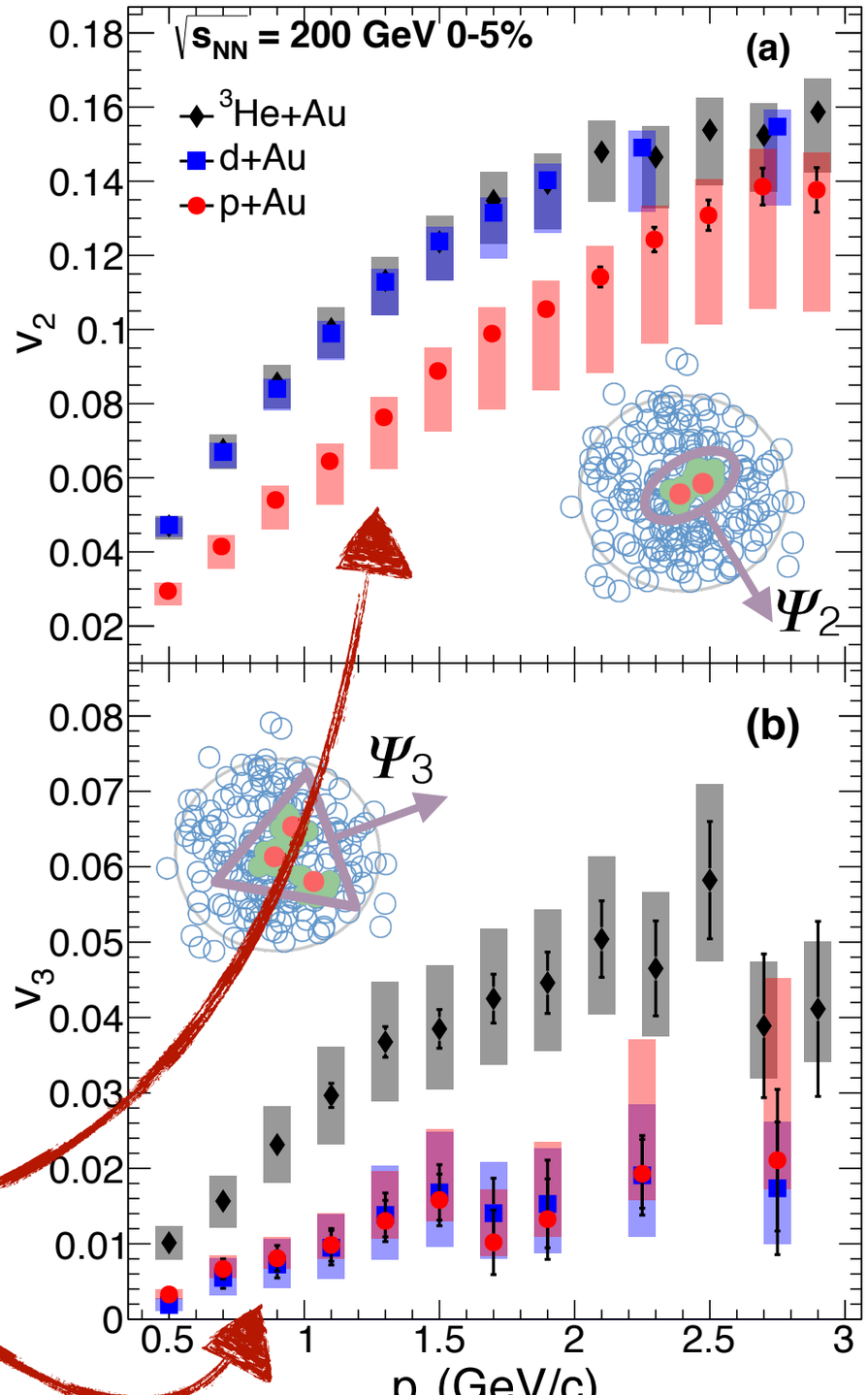
mean values determined from Glauber Monte Carlo

Quark-Gluon droplets engineered

RHIC versatility: projectile geometry scan

measured v_2 and v_3 follow the predicted hydro hierarchy





$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{{}^3He+Au}$$

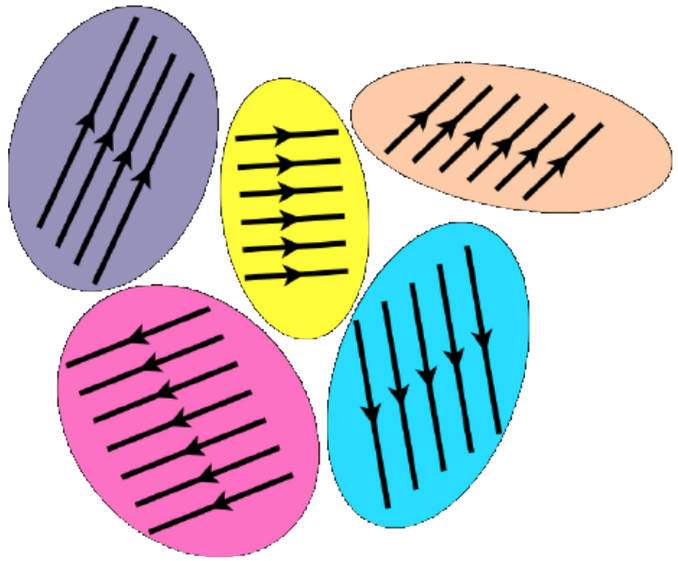
$$v_3^{p+Au} \approx v_3^{d+Au} < v_3^{{}^3He+Au}$$

Quark-Gluon droplets engineered

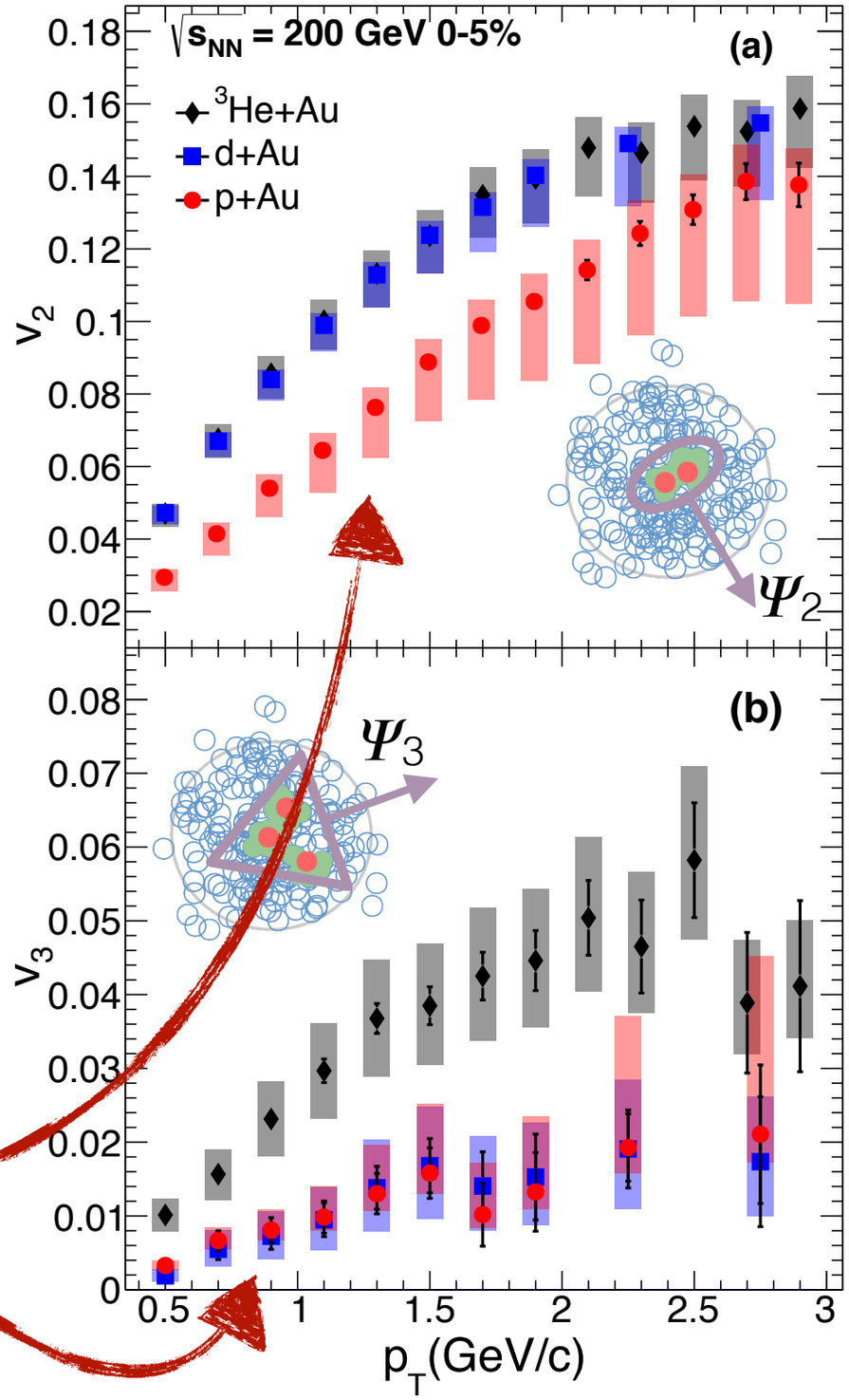
initial-state momentum correlation scenario

rule out "back-of-the-envelop" initial-state correlation scenario

a large-area collision system
(d-Au, ^{3}He-Au)
should exhibit a weaker correlation



if the different individual colour domains are resolved and separated > colour-correlation length because they do not communicate



³He-Au
d-Au
p-Au

³He-Au
d-Au
p-Au

simple prediction
v_2, v_3 ordering

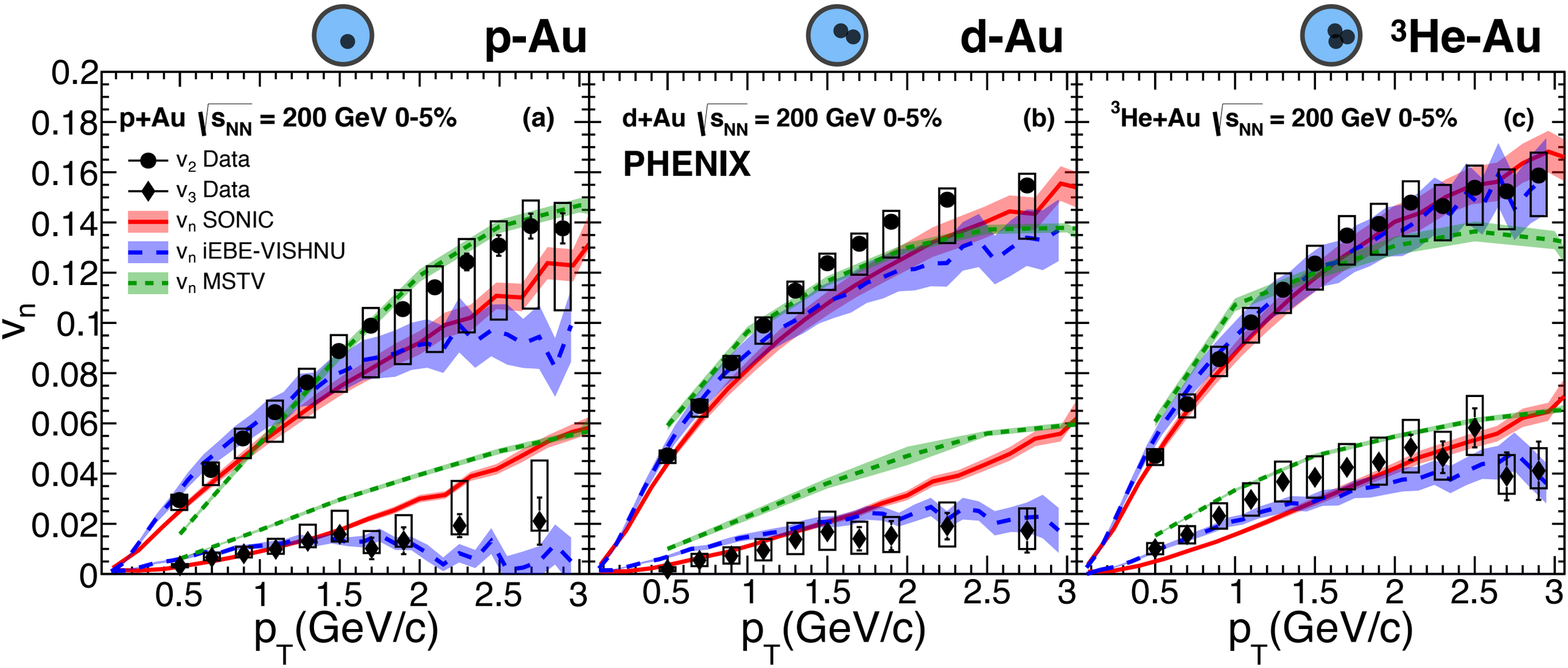
$$v_n^{p+\mathrm{Au}} > v_n^{d+\mathrm{Au}} > v_n^{^3\mathrm{He}+\mathrm{Au}}$$

Quark-Gluon droplets engineered

initial-state momentum correlation scenario

follows hierarchy of the data when performing the actual calculations

Mace et al., PRL 121 (2018) 052301



but for the same N_{ch} ...

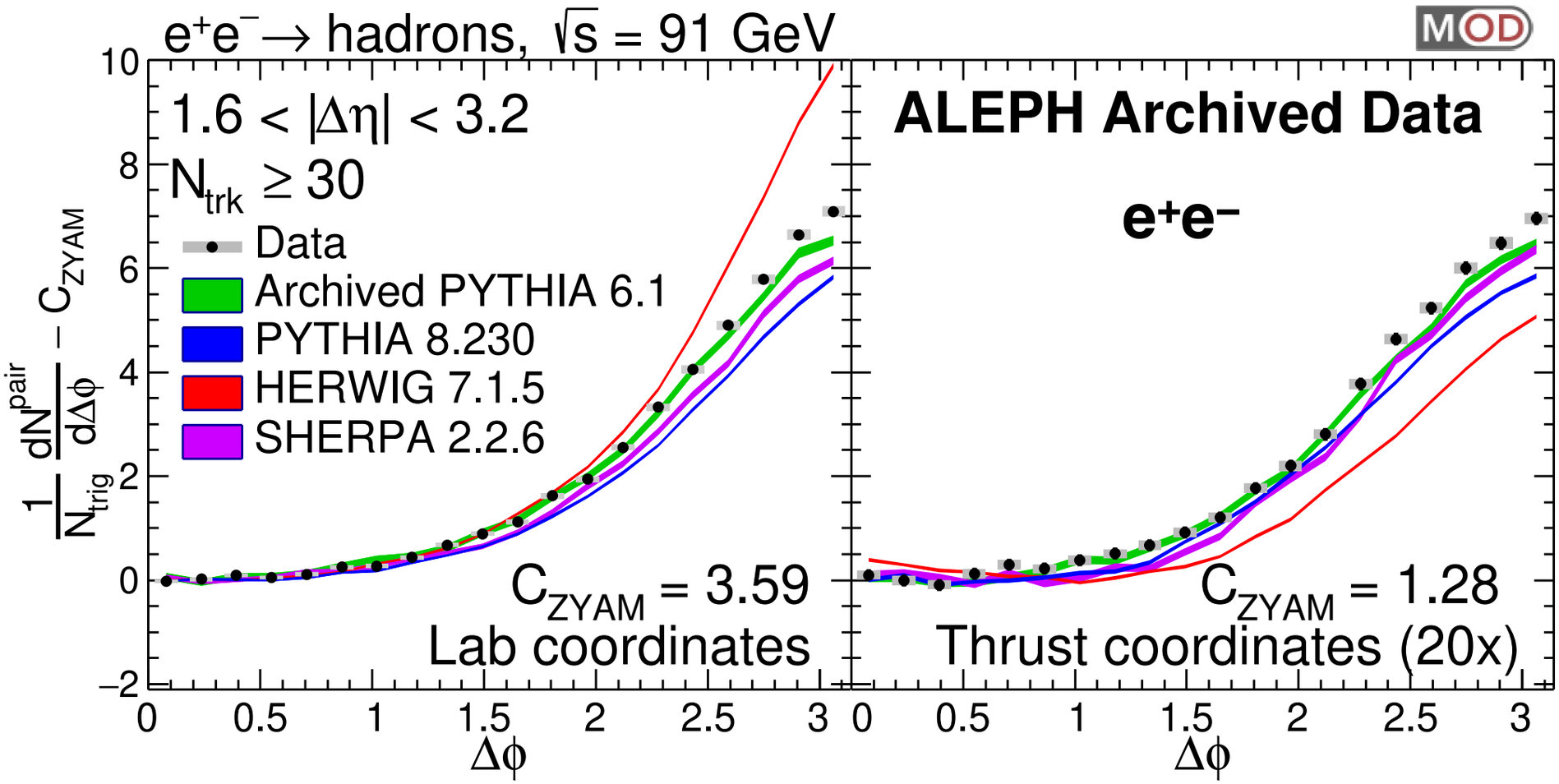
long story to tell today

more on *Nature Phys. 15 (2019) 214* and *arXiv:1901.10506 [hep-ph]*

Is flow unique to h-h collisions?

check in **e^+e^- events** with ALEPH archived data

2-particle correlation measurement in high-N_{ch} hadronic events



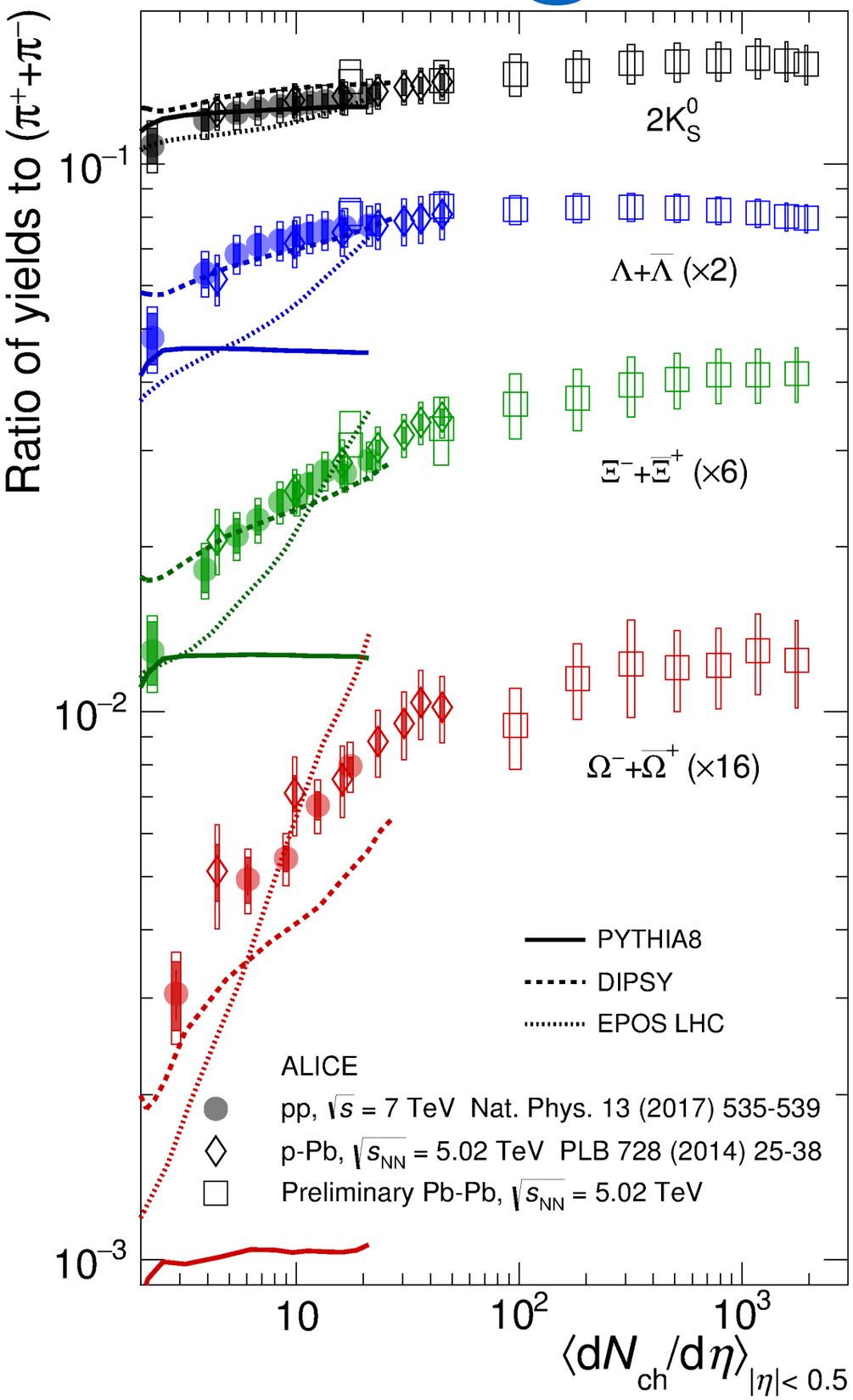
no evidence of long-range correlations

consistent with PYTHIA 6.1, no final state effects

ZEUS $c_n\{2\}$: no evidence of long-range correlations in ep DIS either

Badea et al., arXiv:1906.00489

Strangeness enhancement



one of the first proposed QGP signatures

strange particle production in pp

relative to pions

increases significantly with $dN_{ch}/d\eta$

remarkable agreement with p-Pb

phenomenon related to the final system

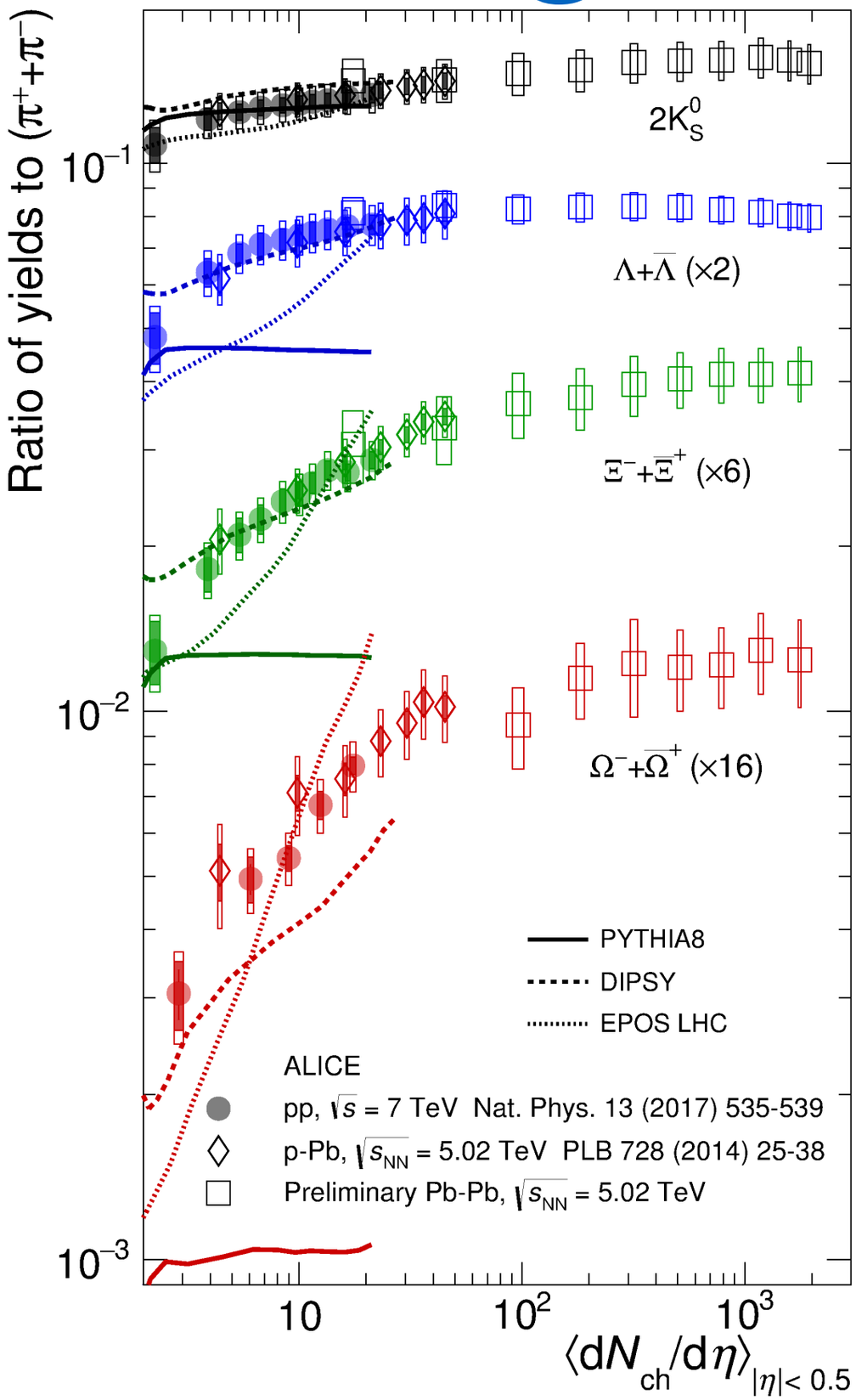
smooth evolution

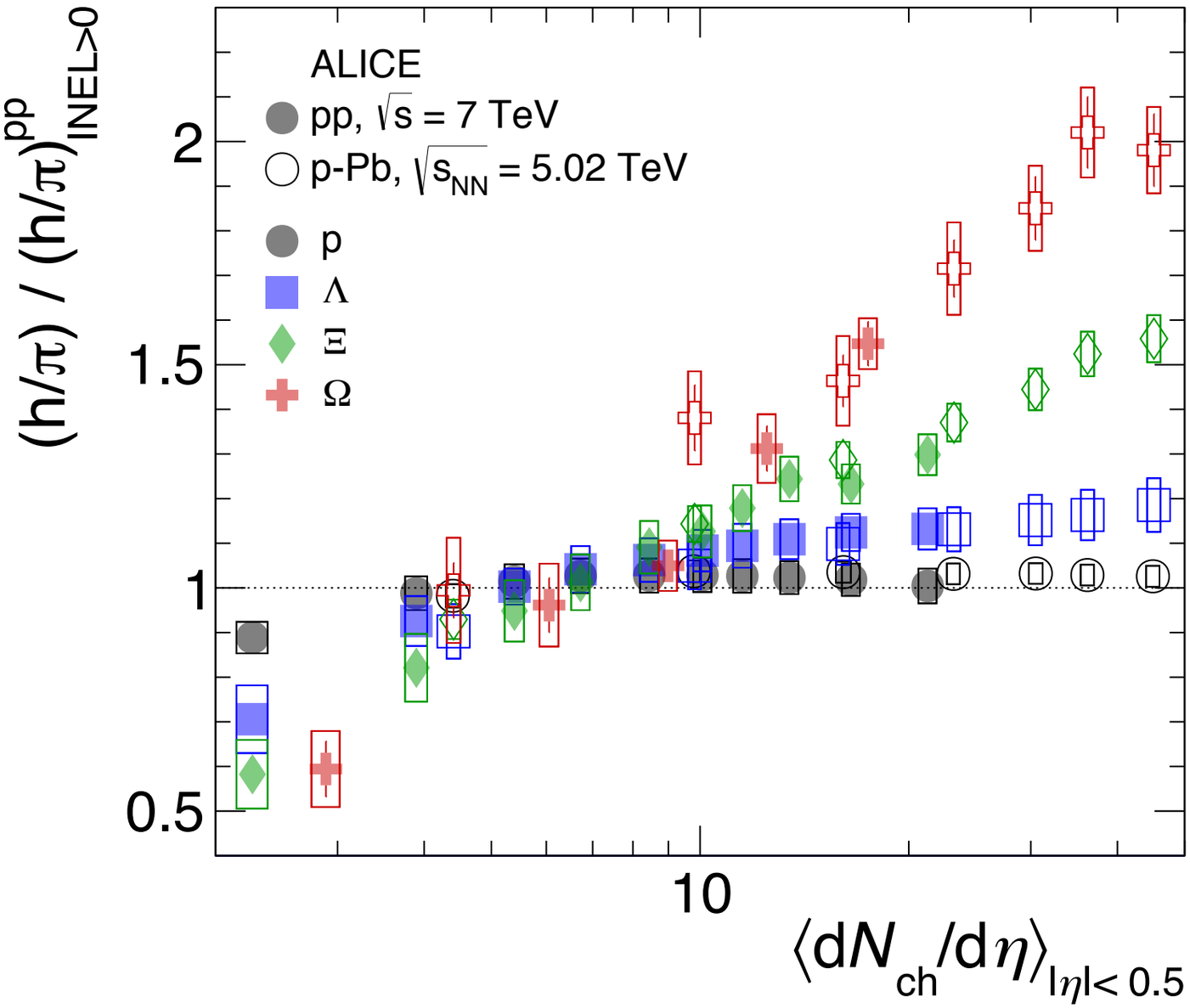
from low-N_{ch} pp to high-N_{ch} p-Pb

reaches Pb-Pb values

ALICE, Nature Phys. 13 (2017) 535

Strangeness enhancement





Ω

Ξ

Λ

p

strangeness hierarchy

not strange? not enhanced!

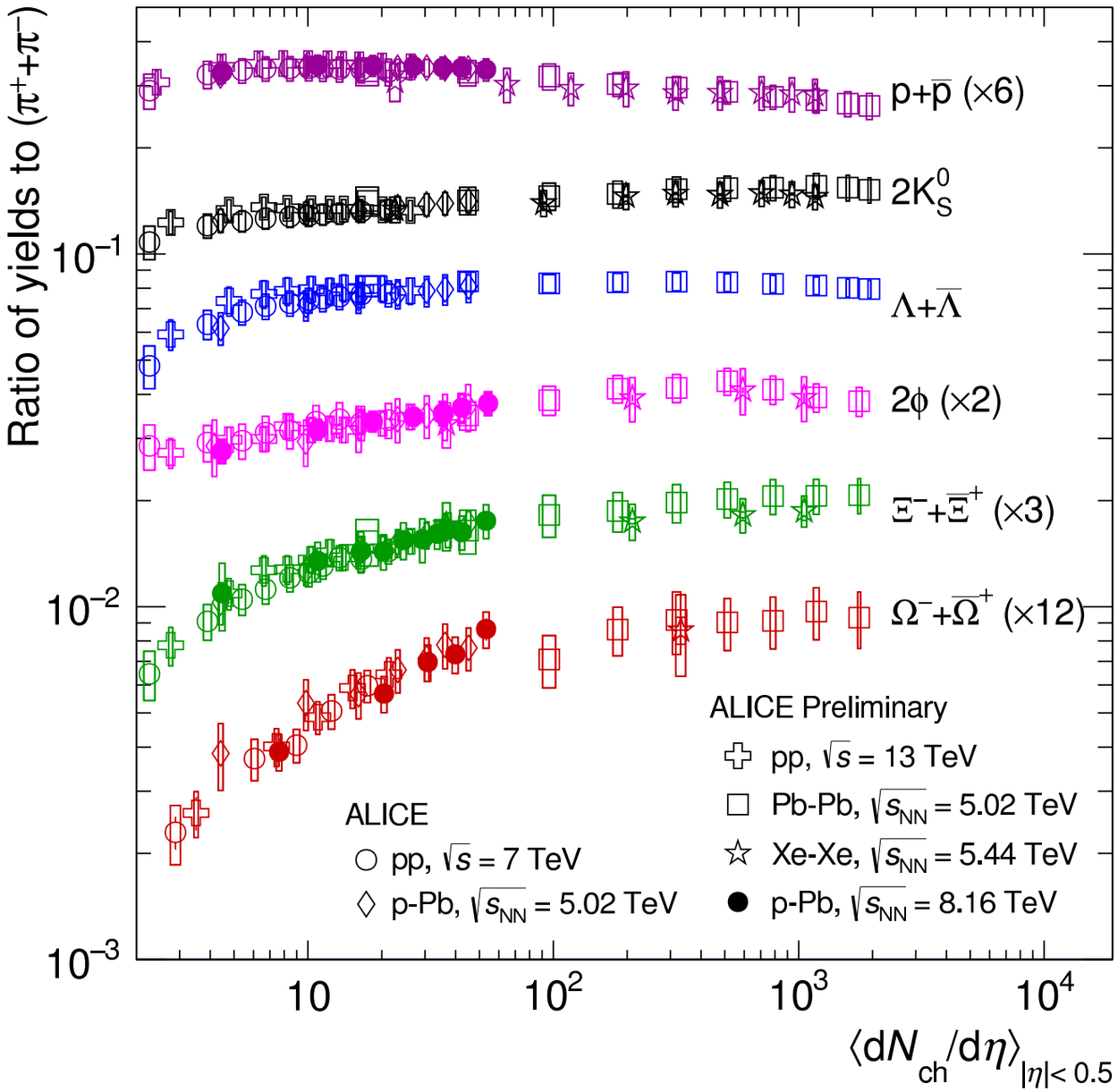
the observed effect is strangeness rather than mass related

ALICE, Nature Phys. 13 (2017) 535

Hadrochemistry evolution

smooth N_{ch} evolution of all particle ratios

from very low N_{ch} pp to very high N_{ch} Pb-Pb

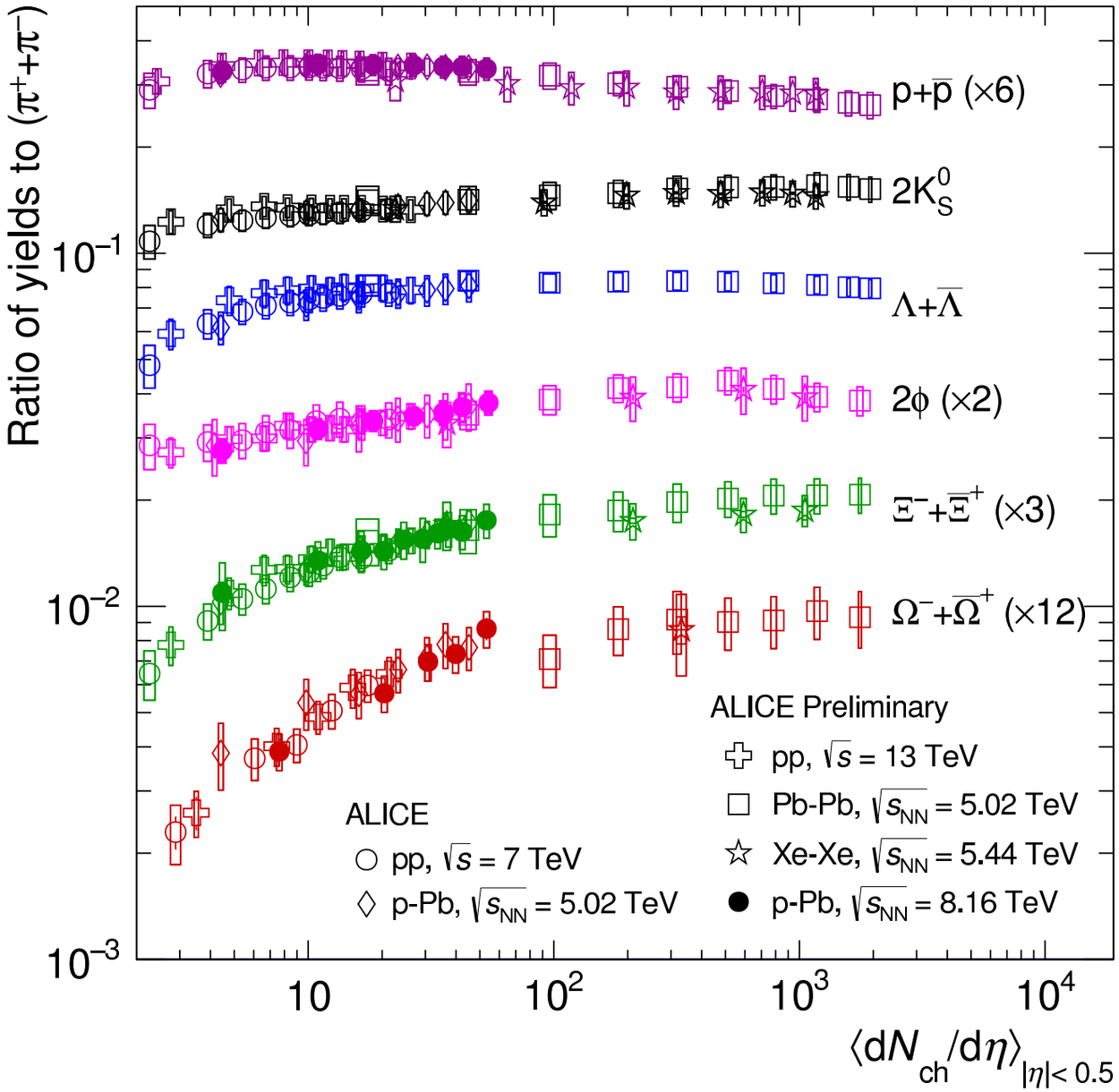


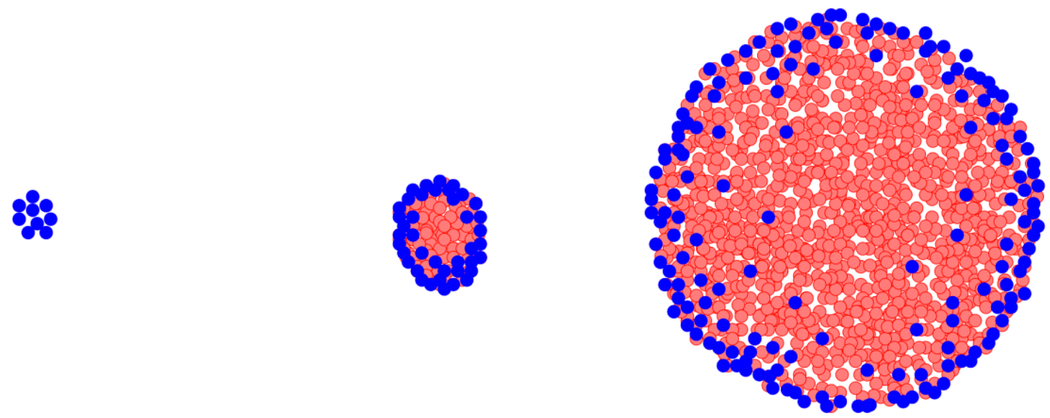
not captured by **jet-universality** principle

Hadrochemistry evolution

smooth N_{ch} evolution of all particle ratios

from very low N_{ch} pp to very high N_{ch} Pb-Pb





core-corona modelling

(implies formation of QGP droplets)

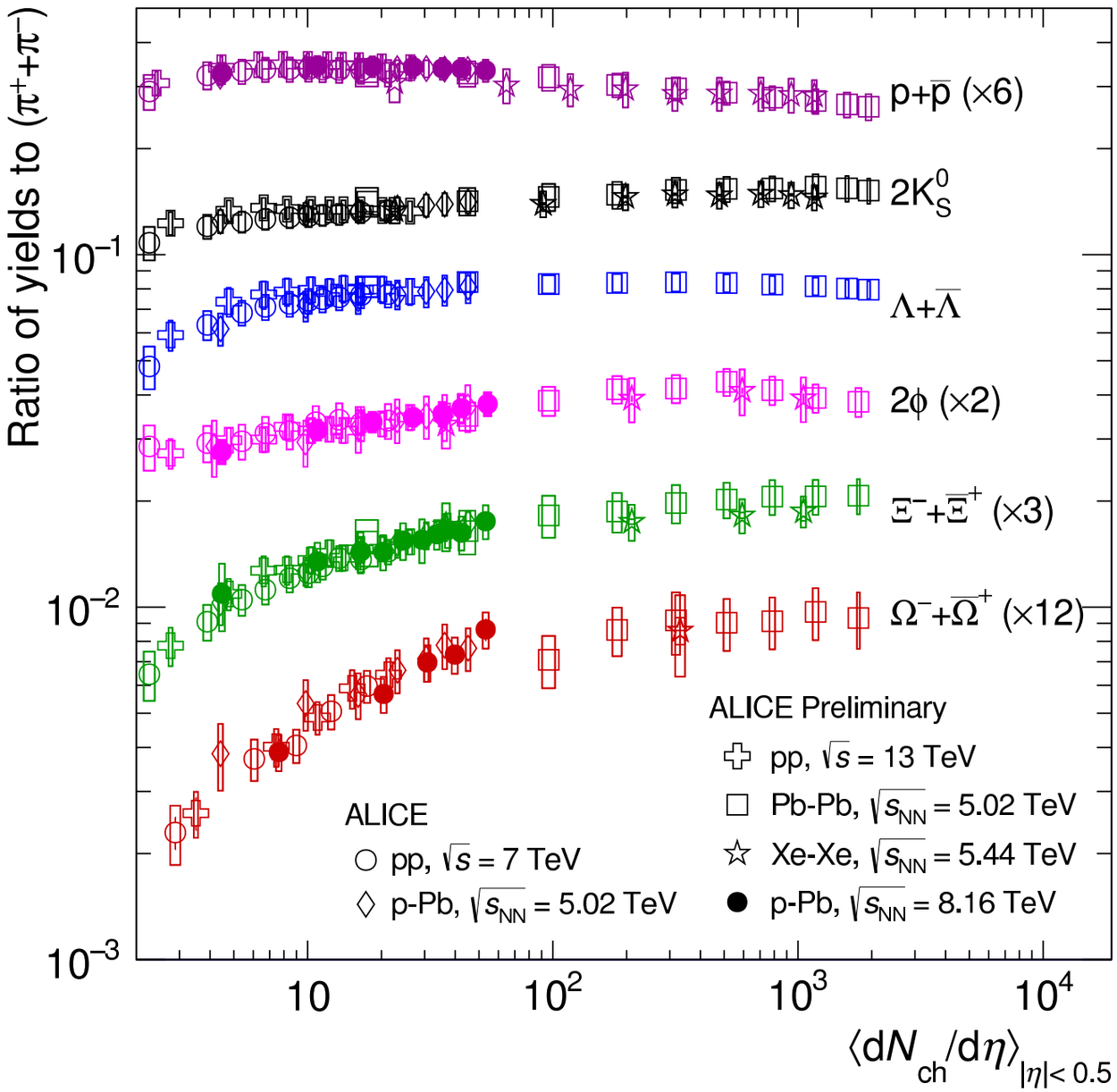
implemented in **EPOS**, allows a smooth transition

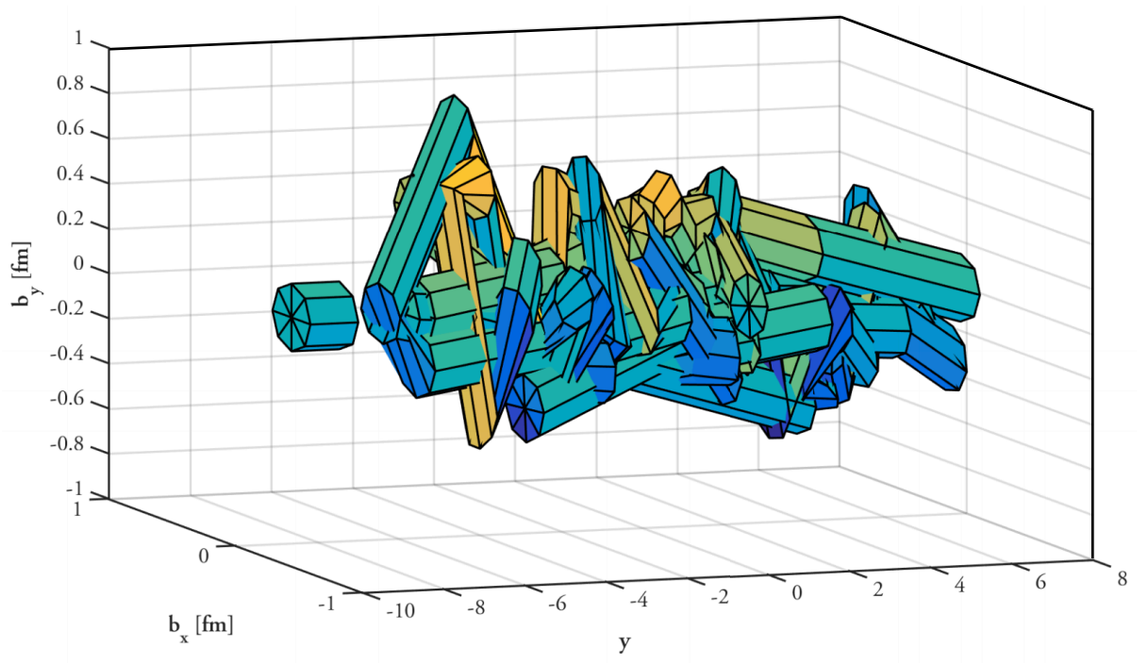
Werner et al., NPA 931 (2014) 83

Hadrochemistry evolution

smooth N_{ch} evolution of all particle ratios

from very low N_{ch} pp to very high N_{ch} Pb-Pb





colour-ropes modelling

(needs coherent overlap strings)

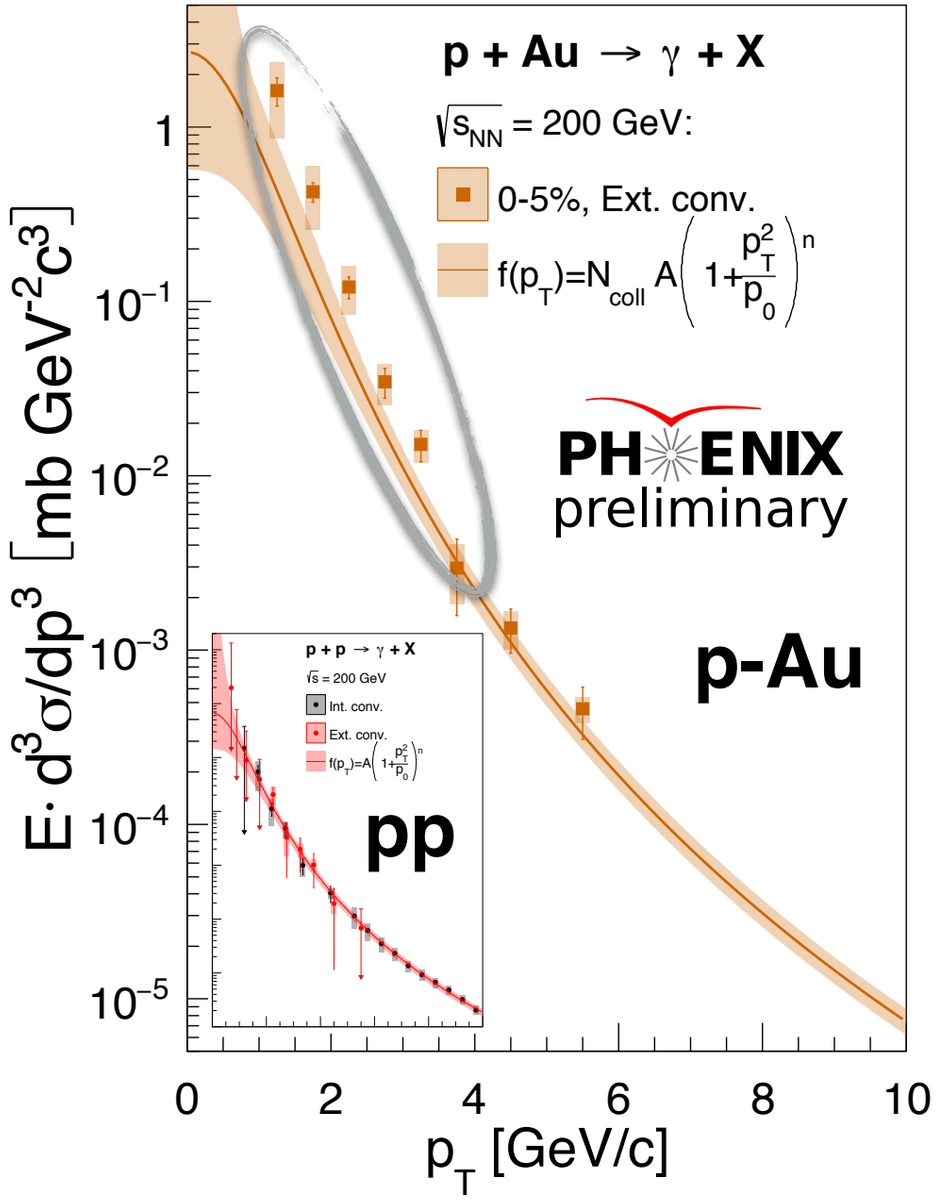
adjust conventional MC, developed in **DIPSY** (available in PYTHIA)

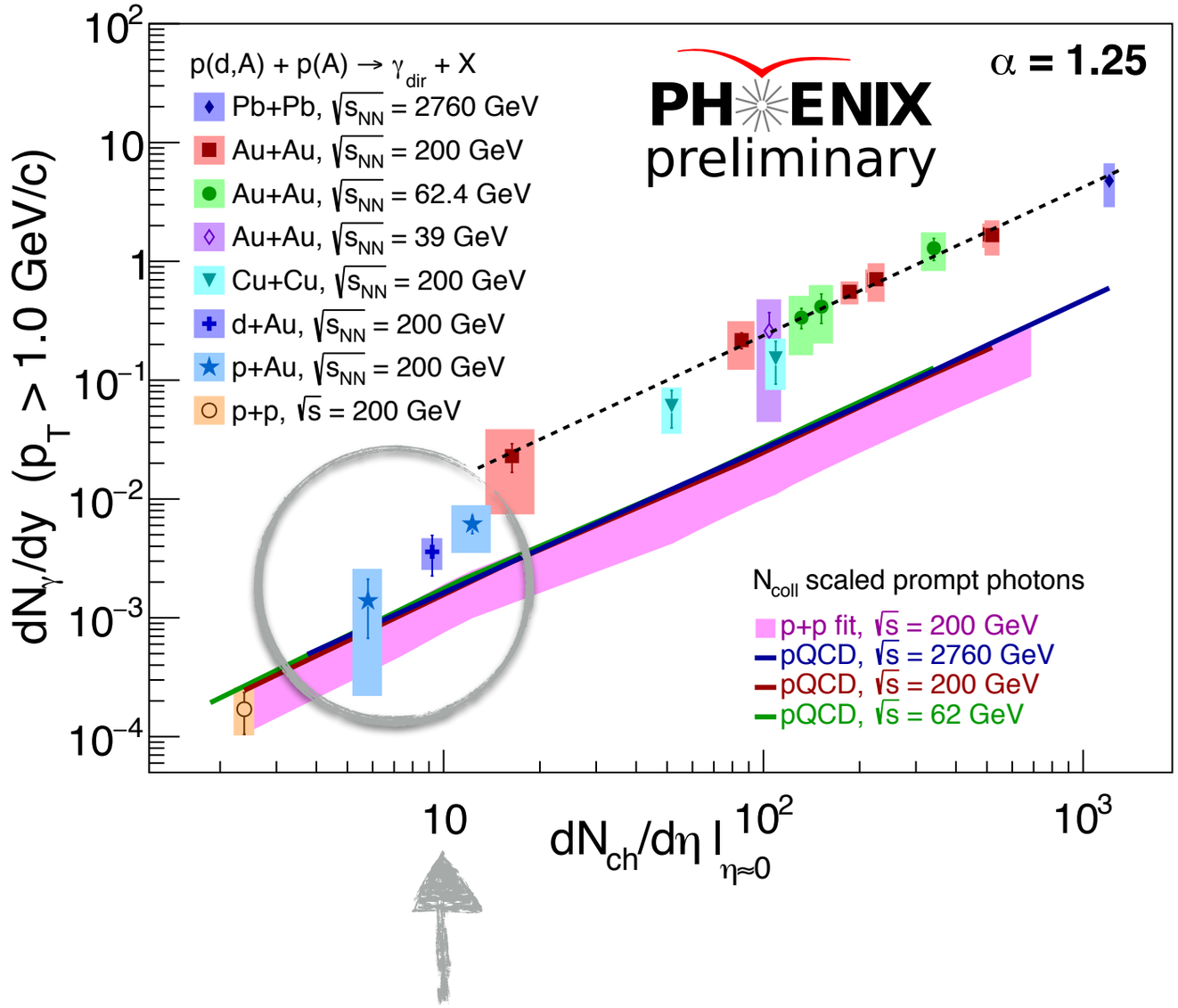
Bierlich et al., JHEP 1503 (2015) 148

Photon radiation

RHIC versatility: different collision systems and energies

excess of direct photons over scaled pp **also in small systems**





p-Au and d-Au data: bridge between pp and A-A

suggests transition from pp to A-A scaling: radiation from QGP droplets?

PHENIX, arXiv:1805.04084 [hep-ex]

Summary

there are **many more results** than these on small systems

always something new! The ridge in pp opened a brand new and very active field

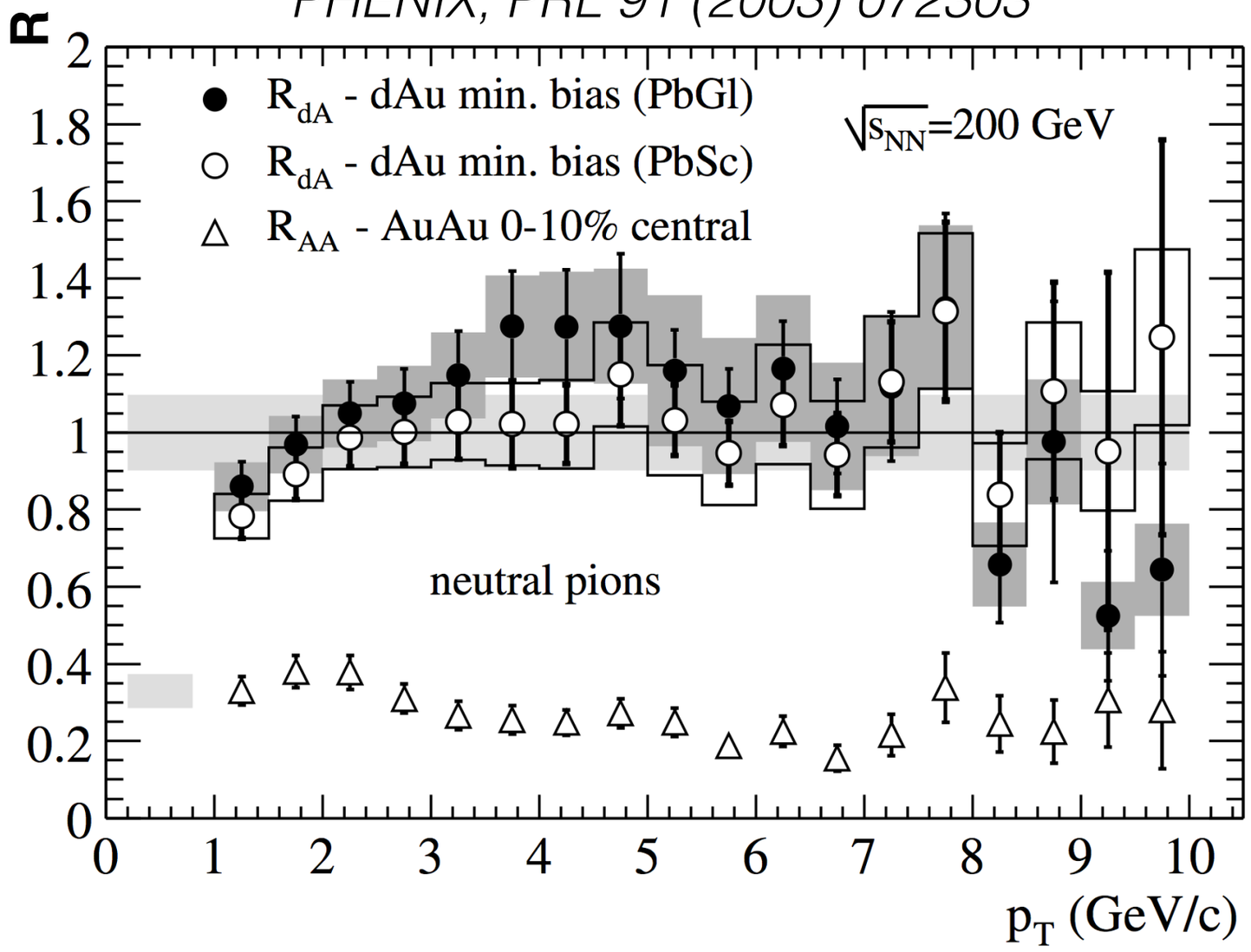
- **multi-particle collectivity in all hadronic systems**
  - initial-state spatial asymmetry + final-state (hydro) interactions?
  - initial-state momentum correlations from gluon saturation (CGC)?
  - new constraints from high-precision measurements

- **strangeness enhancement and direct photon excess**
  - evolves from low-N_{ch} pp to high-N_{ch} p-A towards A-A
  - soft QCD processes sensitive to final-state environment
  - is there a universal underlying microscopic mechanism?

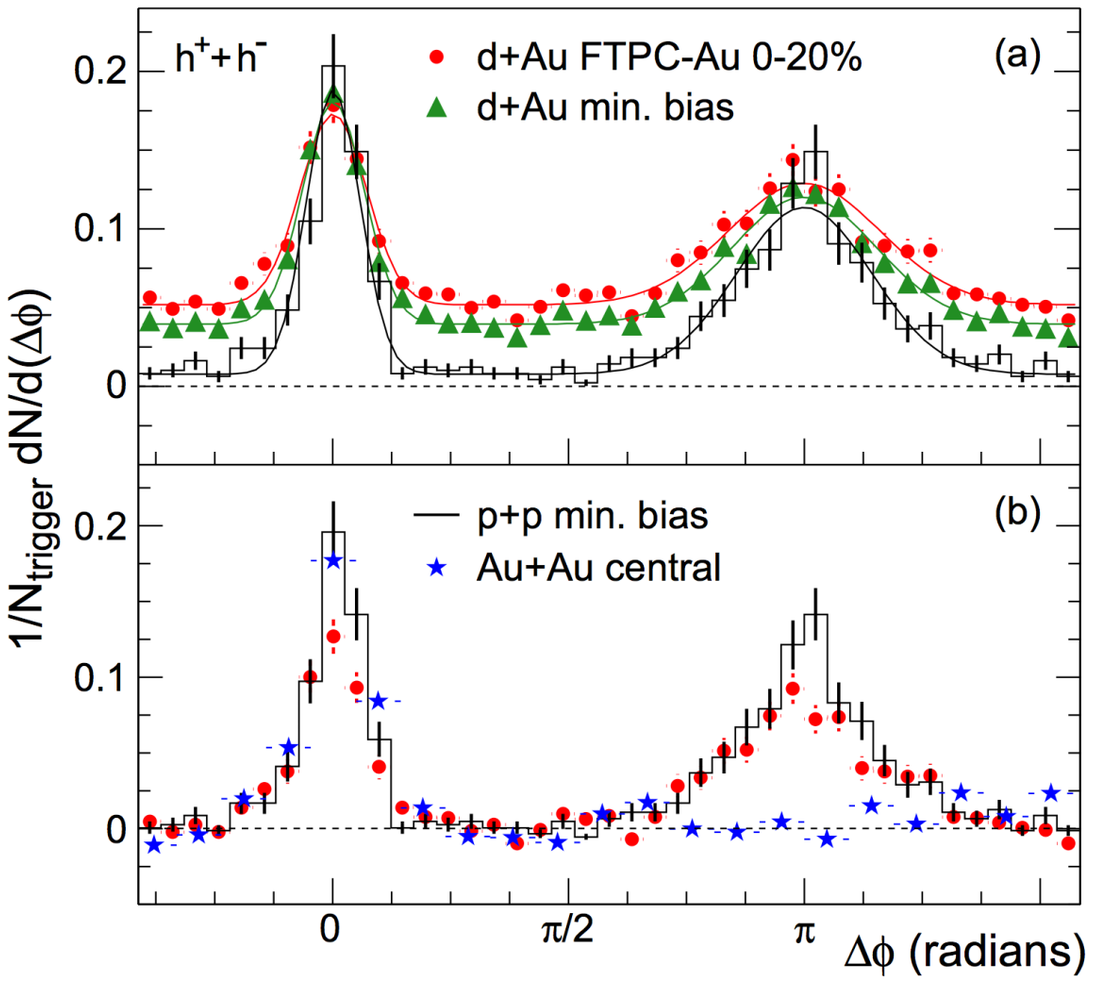
- **formation of Quark-Gluon droplets in small systems**
  - or manifestation of new physics?
  - indication that something starts happening around $dN_{ch}/d\eta$ ~ 10-20
  - keep a critical look at the data and all viable theoretical options

Once upon a time

PHENIX, PRL 91 (2003) 072303



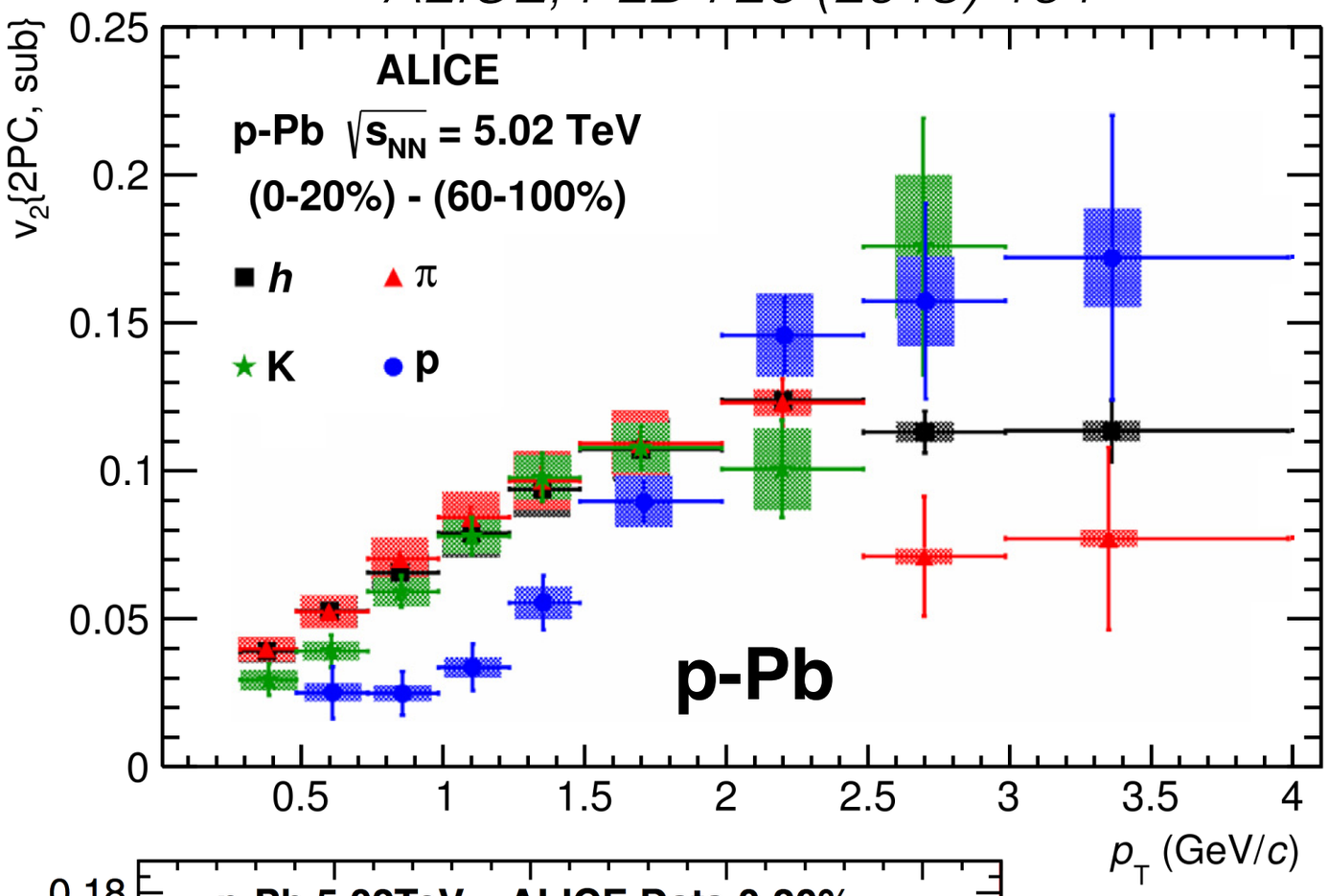
STAR, PRL 91 (2003) 072304



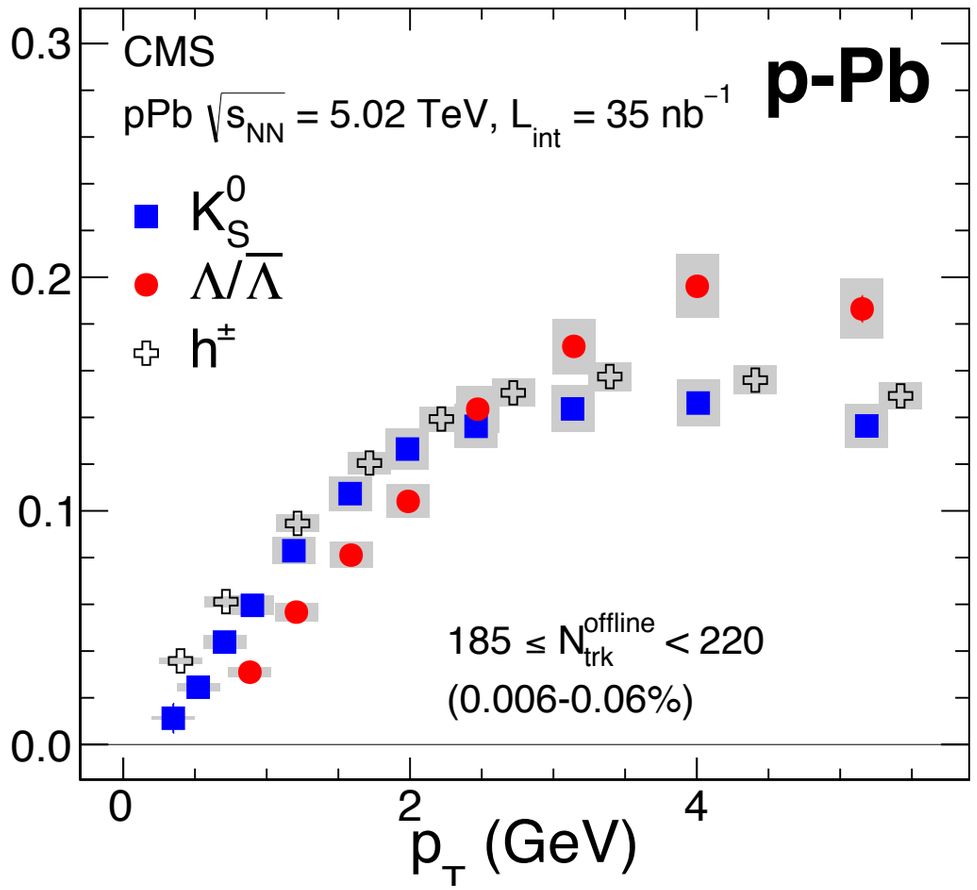
results from small systems provided the **evidence for hot QCD matter** in the final state of A-A collisions

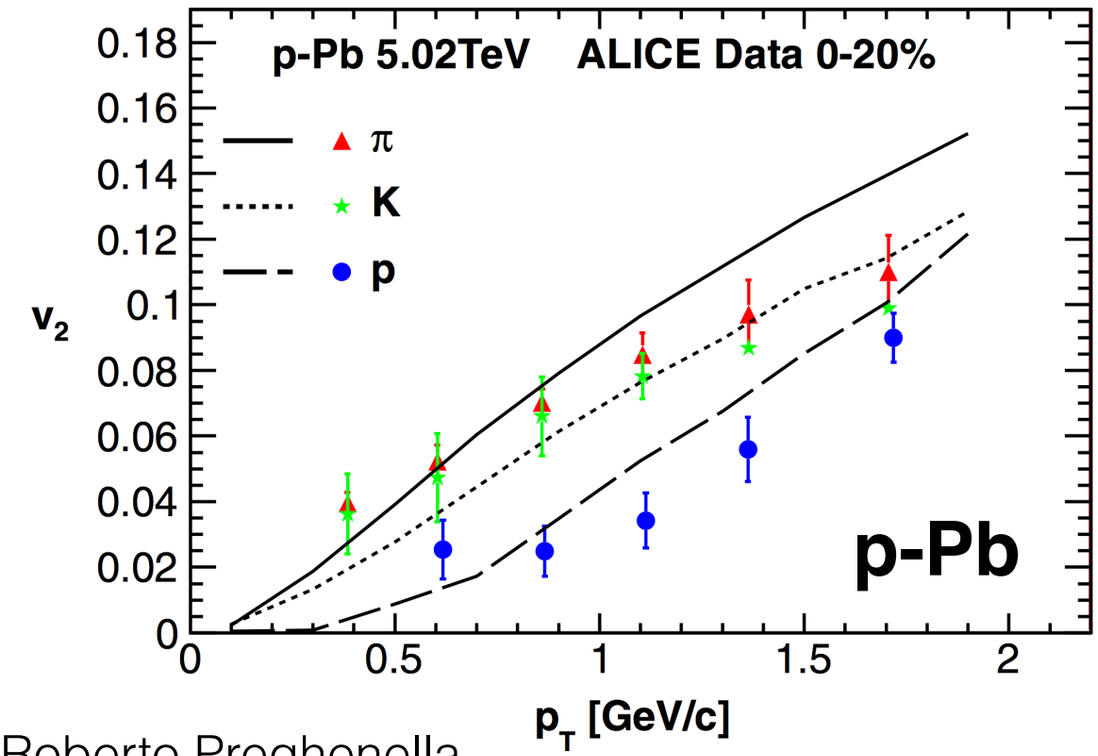
v_2 of identified particles

ALICE, PLB 726 (2013) 164



CMS, PLB 742 (2015) 200





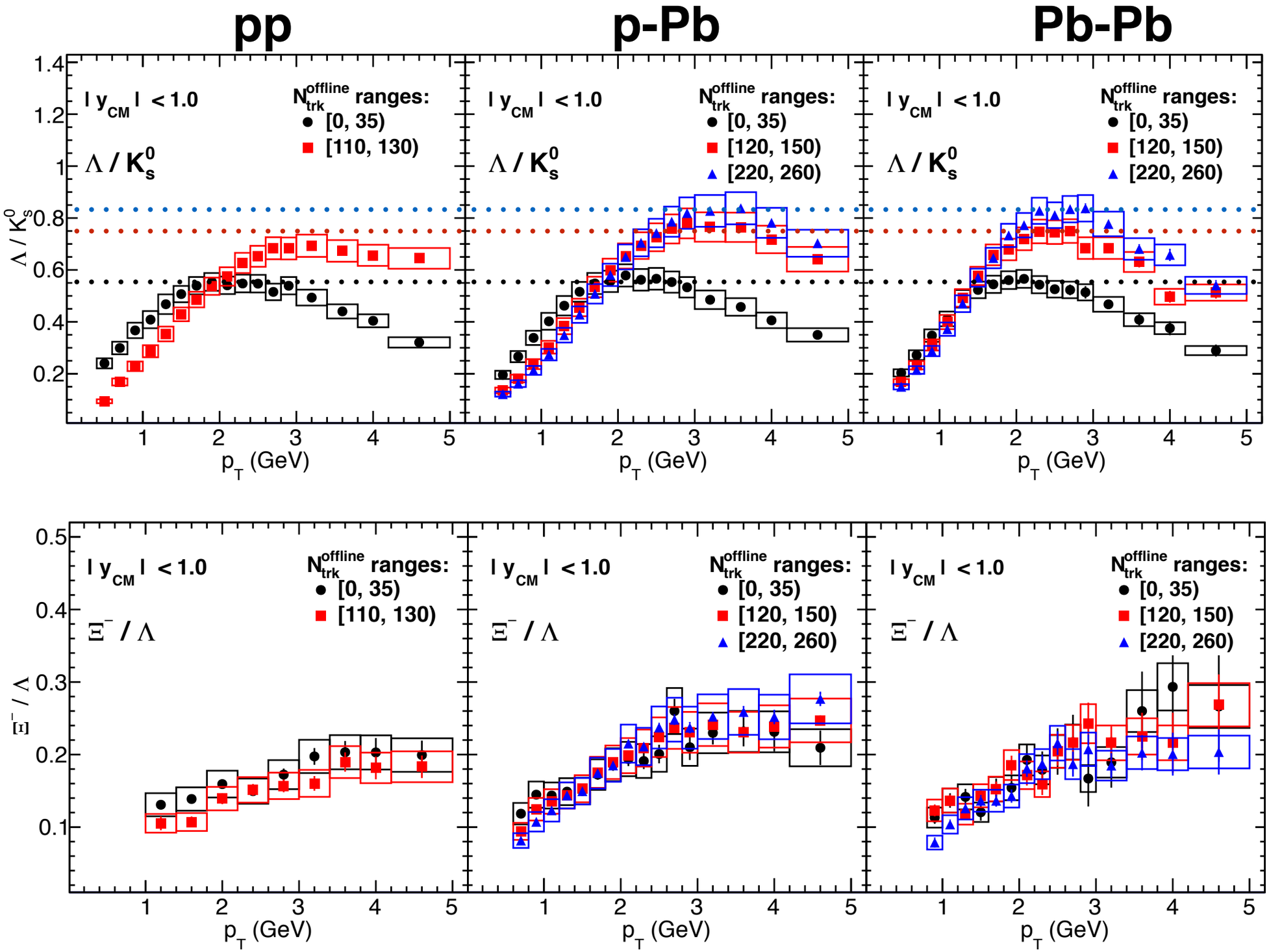
mass ordering observed at low p_T

lower v_2 for heavier particles crossing at higher p_T

consistent with expectations from collective hydro expansion

Bozek et al, PRL 111 (2013) 172303

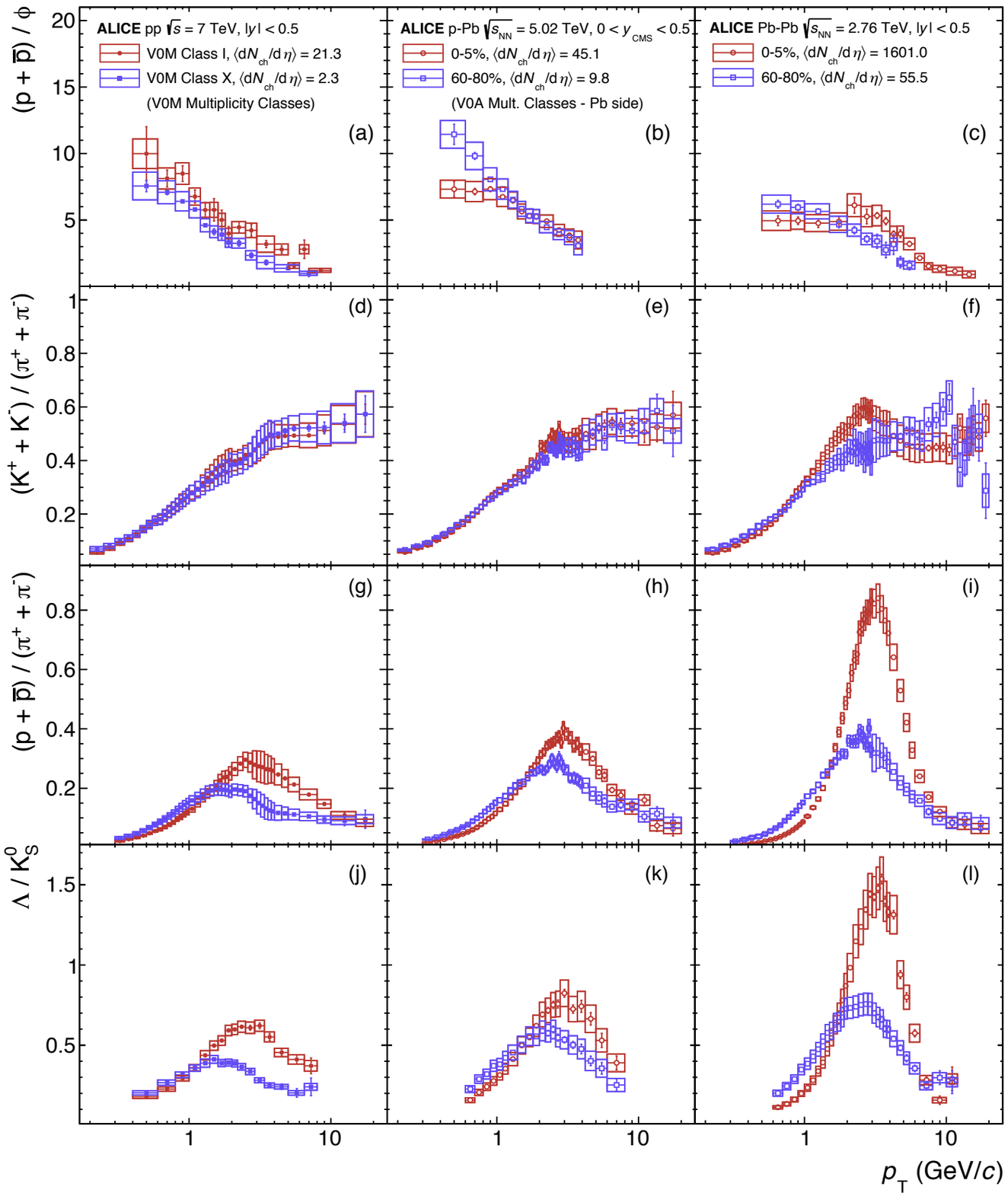
Mass-dependent enhancement

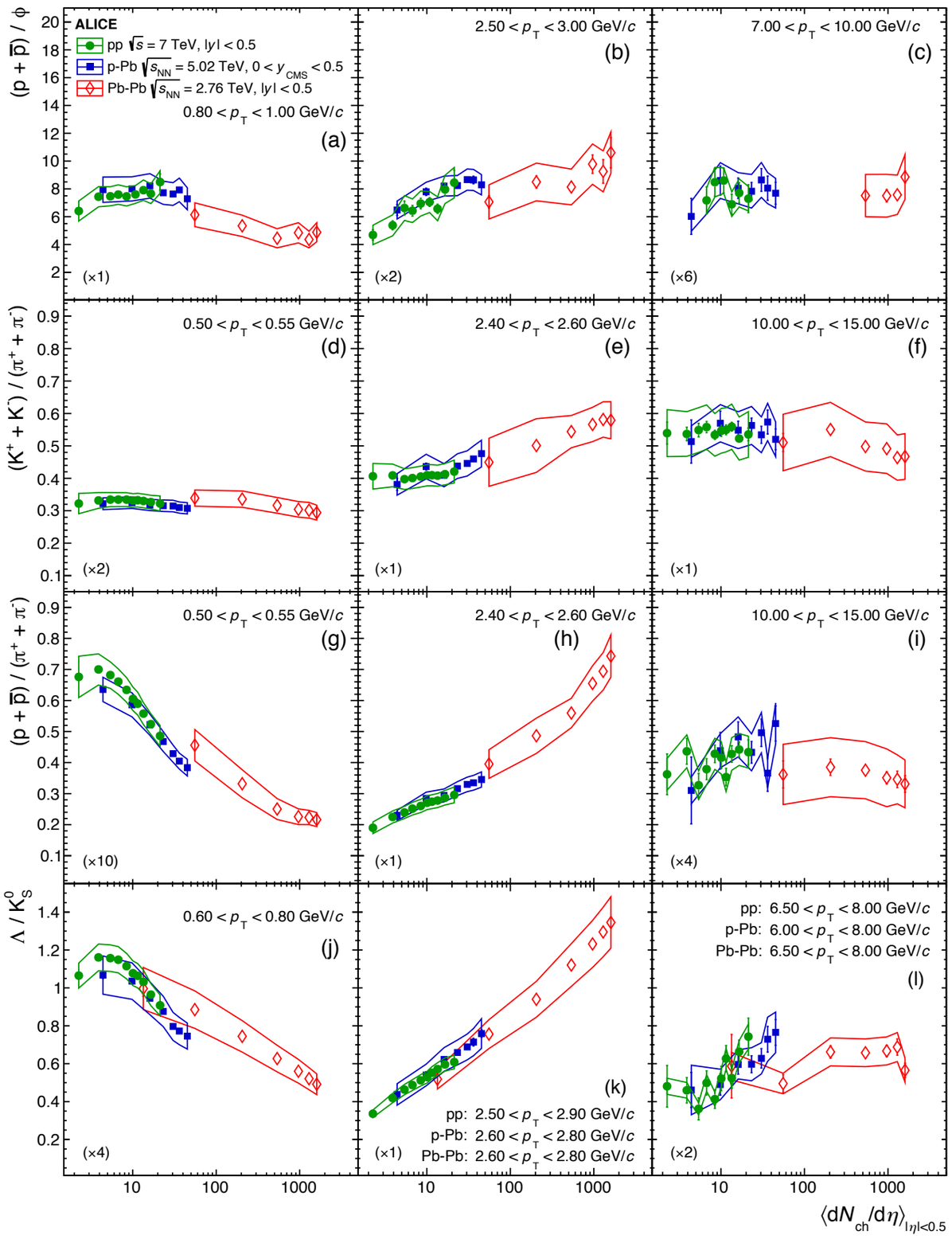


Λ/Ks
maximum at similar N_{ch} has **similar value**

Ξ/Λ
increases and reaches plateau

CMS, PLB 768 (2017) 103

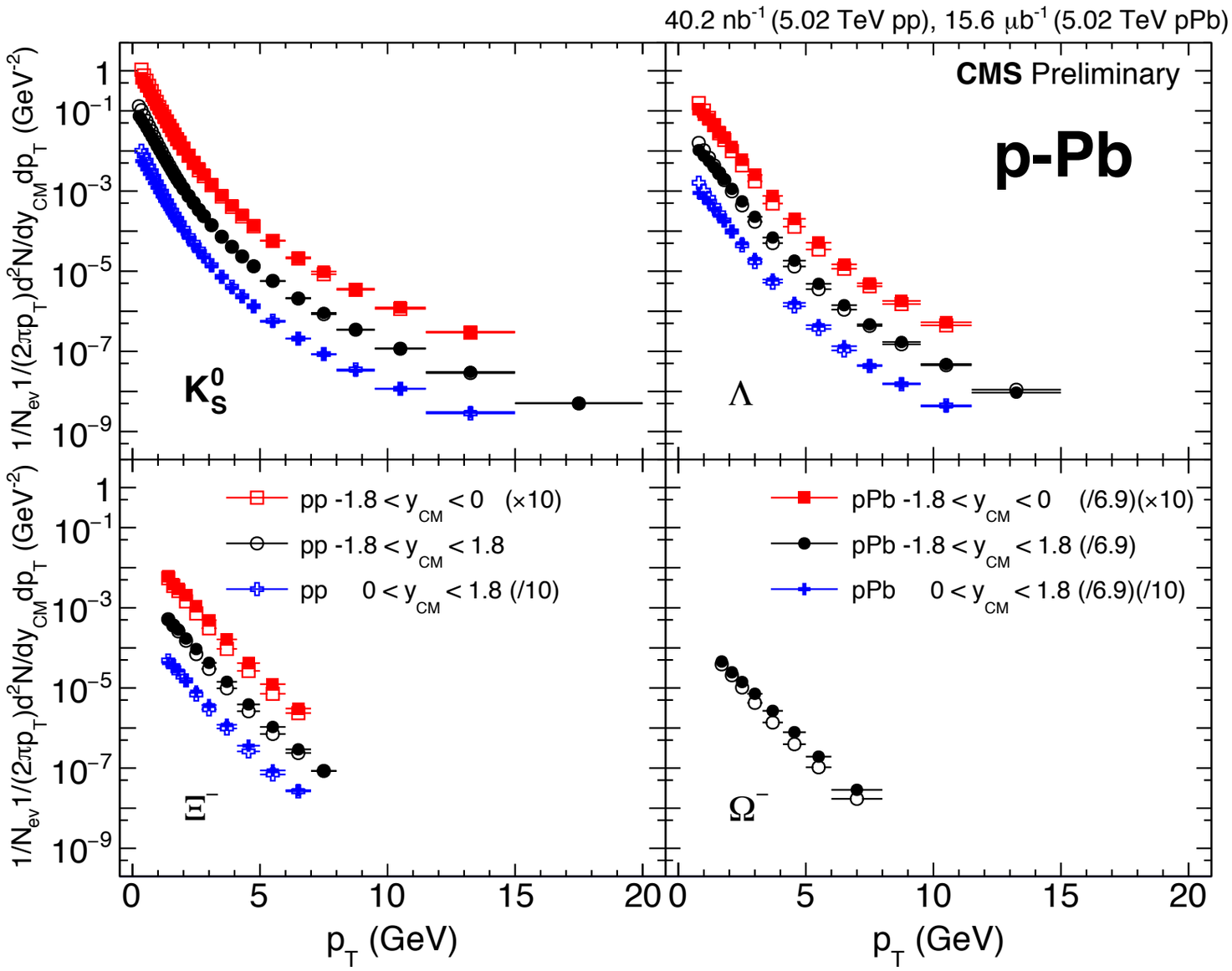

ALICE pp √s = 7 TeV, |y| < 0.5
V0M Class I, ⟨dN_ch/dη⟩ = 21.3
V0M Class X, ⟨dN_ch/dη⟩ = 2.3
(V0M Multiplicity Classes)
ALICE p-Pb √s_NN = 5.02 TeV, 0 < y_CMS < 0.5
0-5%, ⟨dN_ch/dη⟩ = 45.1
60-80%, ⟨dN_ch/dη⟩ = 9.8
(V0A Mult. Classes - Pb side)
ALICE Pb-Pb √s_NN = 2.76 TeV, |y| < 0.5
0-5%, ⟨dN_ch/dη⟩ = 1601.0
60-80%, ⟨dN_ch/dη⟩ = 55.5
(p + p̄) / φ
(K⁺ + K⁻) / (π⁺ + π⁻)
(p + p̄) / (π⁺ + π⁻)
Λ / K⁰_S
p_T (GeV/c)


ALICE
pp √s = 7 TeV, |y| < 0.5
p-Pb √s_NN = 5.02 TeV, 0 < y_CMS < 0.5
Pb-Pb √s_NN = 2.76 TeV, |y| < 0.5
0.80 < p_T < 1.00 GeV/c
2.50 < p_T < 3.00 GeV/c
7.00 < p_T < 10.00 GeV/c
0.50 < p_T < 0.55 GeV/c
2.40 < p_T < 2.60 GeV/c
10.00 < p_T < 15.00 GeV/c
0.60 < p_T < 0.80 GeV/c
pp: 2.50 < p_T < 2.90 GeV/c
p-Pb: 2.60 < p_T < 2.80 GeV/c
Pb-Pb: 2.60 < p_T < 2.80 GeV/c
pp: 6.50 < p_T < 8.00 GeV/c
p-Pb: 6.00 < p_T < 8.00 GeV/c
Pb-Pb: 6.50 < p_T < 8.00 GeV/c
(p + p̄) / φ
(K⁺ + K⁻) / (π⁺ + π⁻)
(p + p̄) / (π⁺ + π⁻)
Λ / K⁰_S
⟨dN_ch/dη⟩_|η|<0.5

Nuclear modification factors

measured for **strange-hadrons in p-Pb** collisions

can provide critical information about initial/final state effects

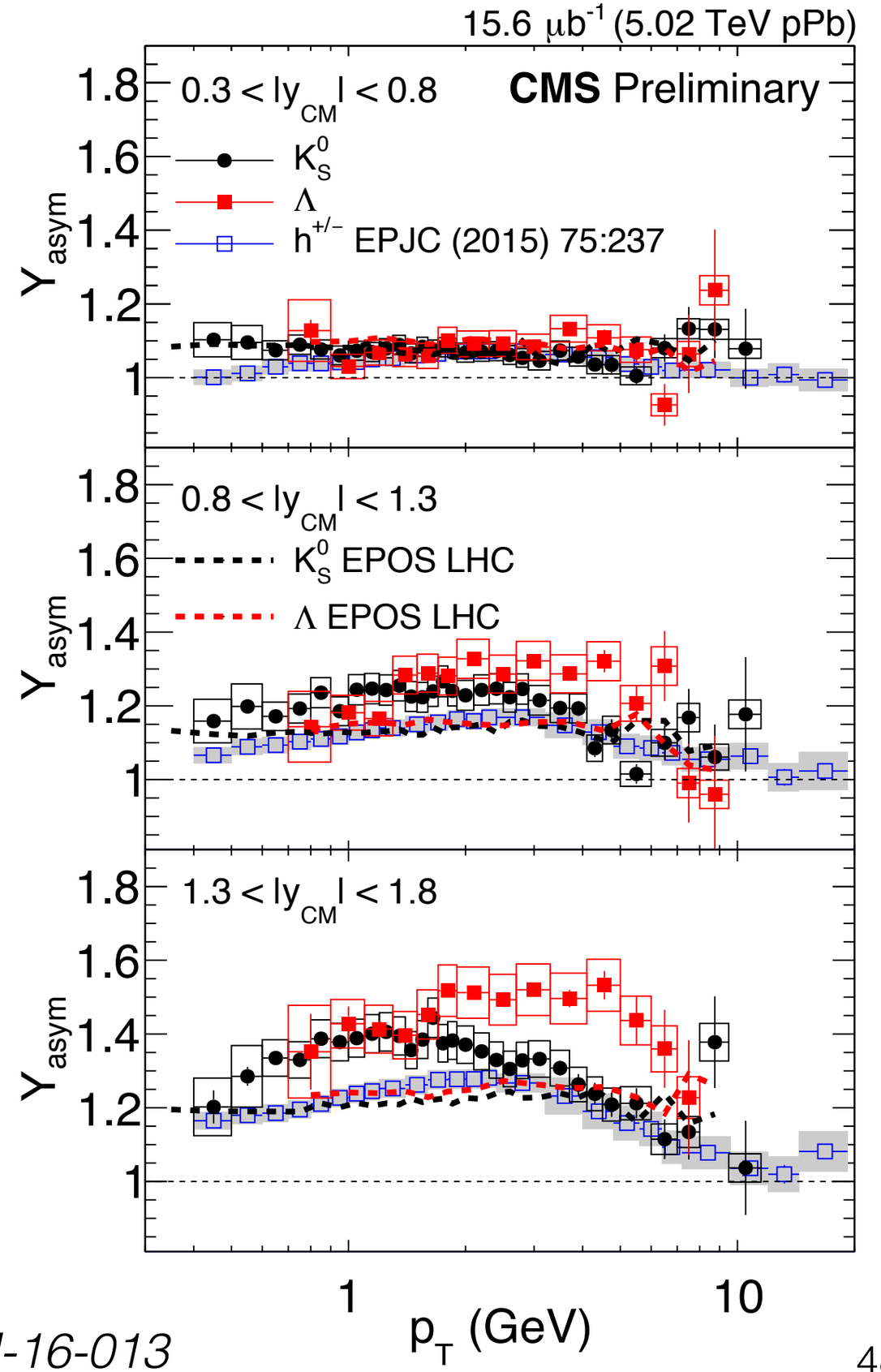


help understanding **collective dynamics** (final state)

probe **Cronin** and **nuclear shadowing** effects (initial state)

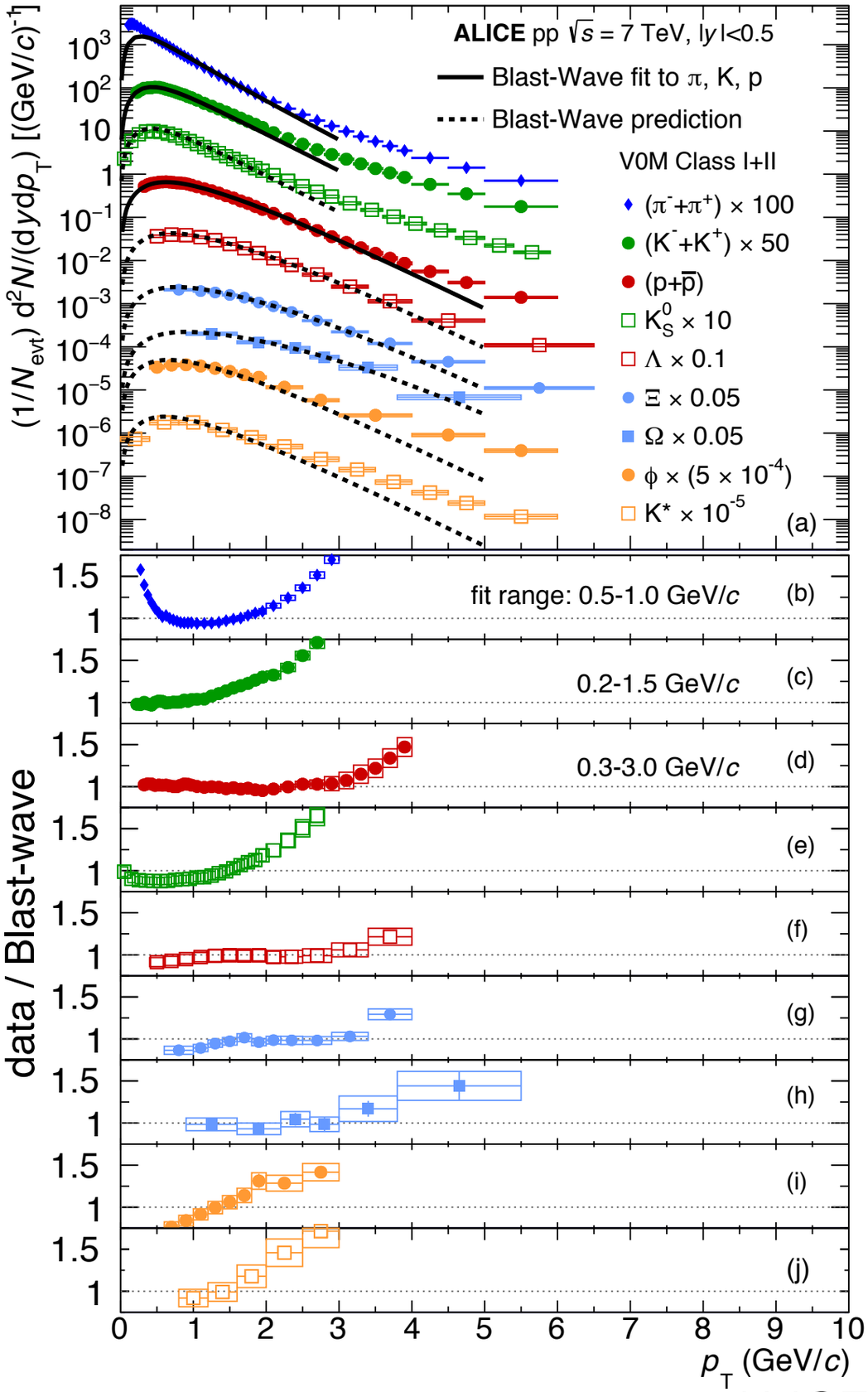
CMS, CMS-PAS-HIN-16-013

Forward-backward asymmetry



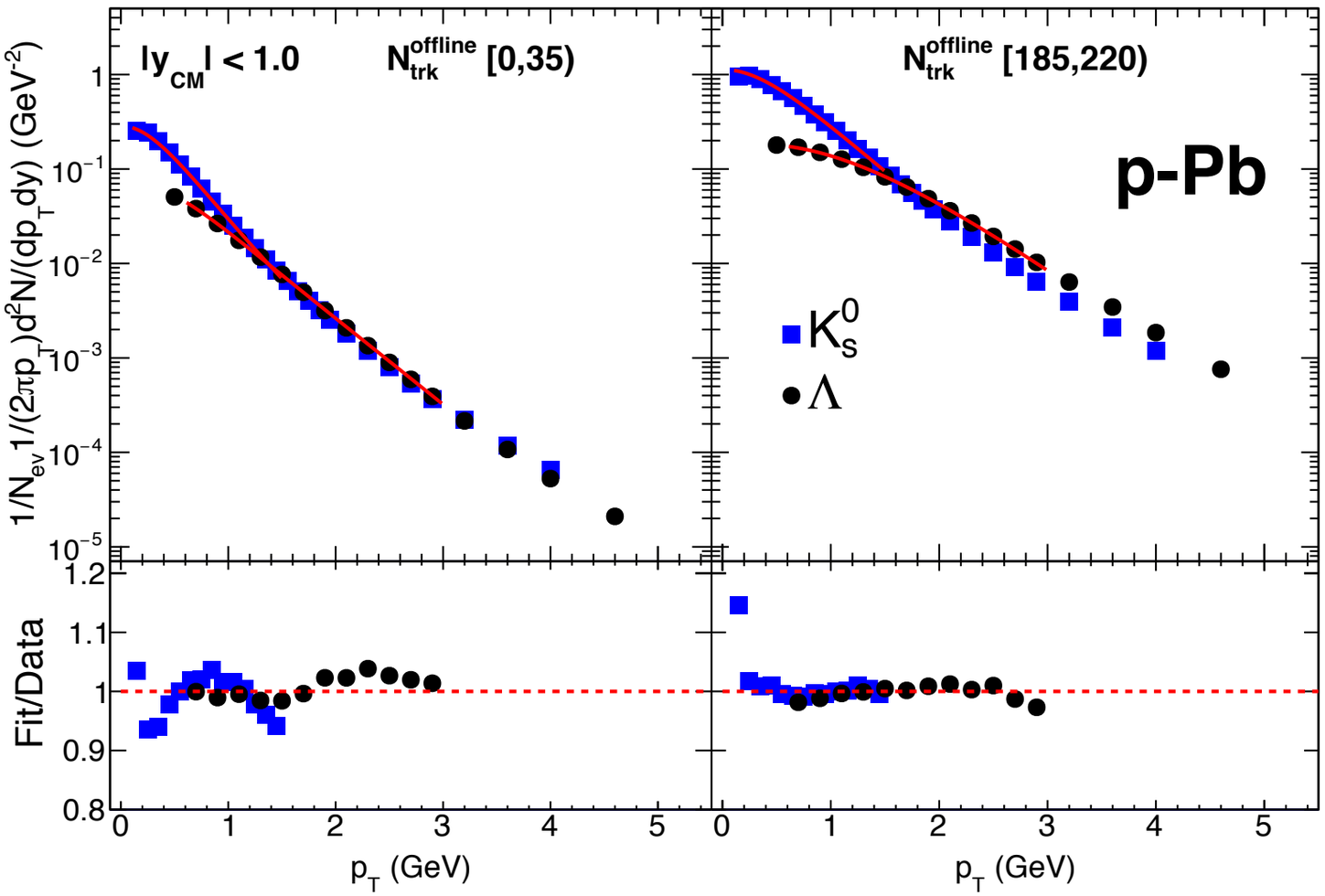
CMS, CMS-PAS-HIN-16-013

Collective radial flow



pp

CMS, PLB 768 (2017) 103



Blast-Wave fits / predictions

useful to characterise spectral shapes and test data against radial flow picture

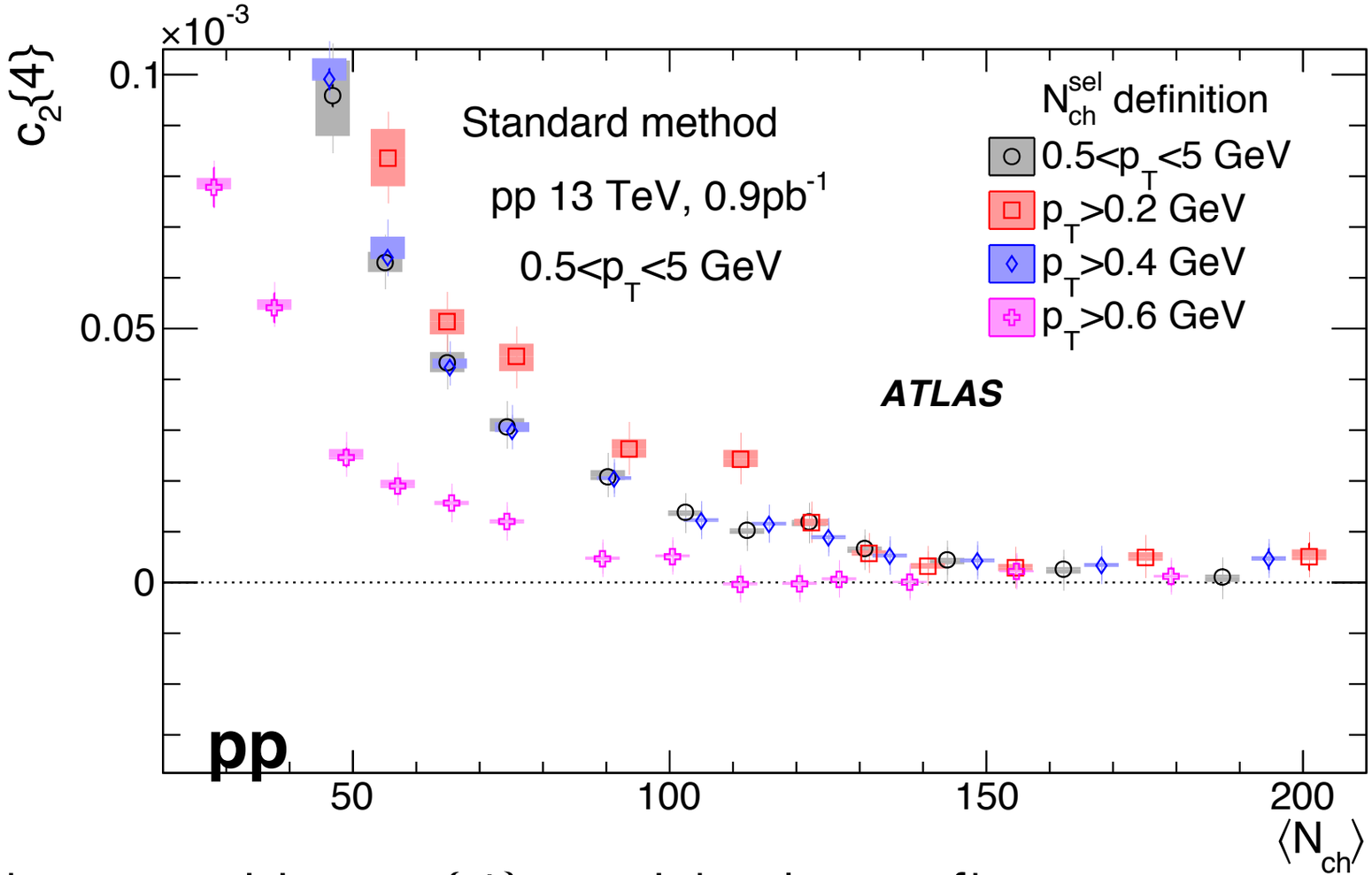
ALICE, PRC 99 (2019) 024906

Dependence on the event-class

multi-particle cumulant sensitivity to **few particle correlations**

aka non-flow (resonances and jets not associated with a collision symmetry plane)

perhaps add a plot showing that p-Pb is not much affected, unless at low Nch



standard method has positive $c_2\{4\}$, residual non-flow

the values change dramatically with the definition of the event-class

this suggests that $c_2\{4\}$ is strongly influenced by non-flow

previous $v_2\{4\}$ $v_2\{6\}$ results in pp might be dominated by non-flow

Correlations of harmonics

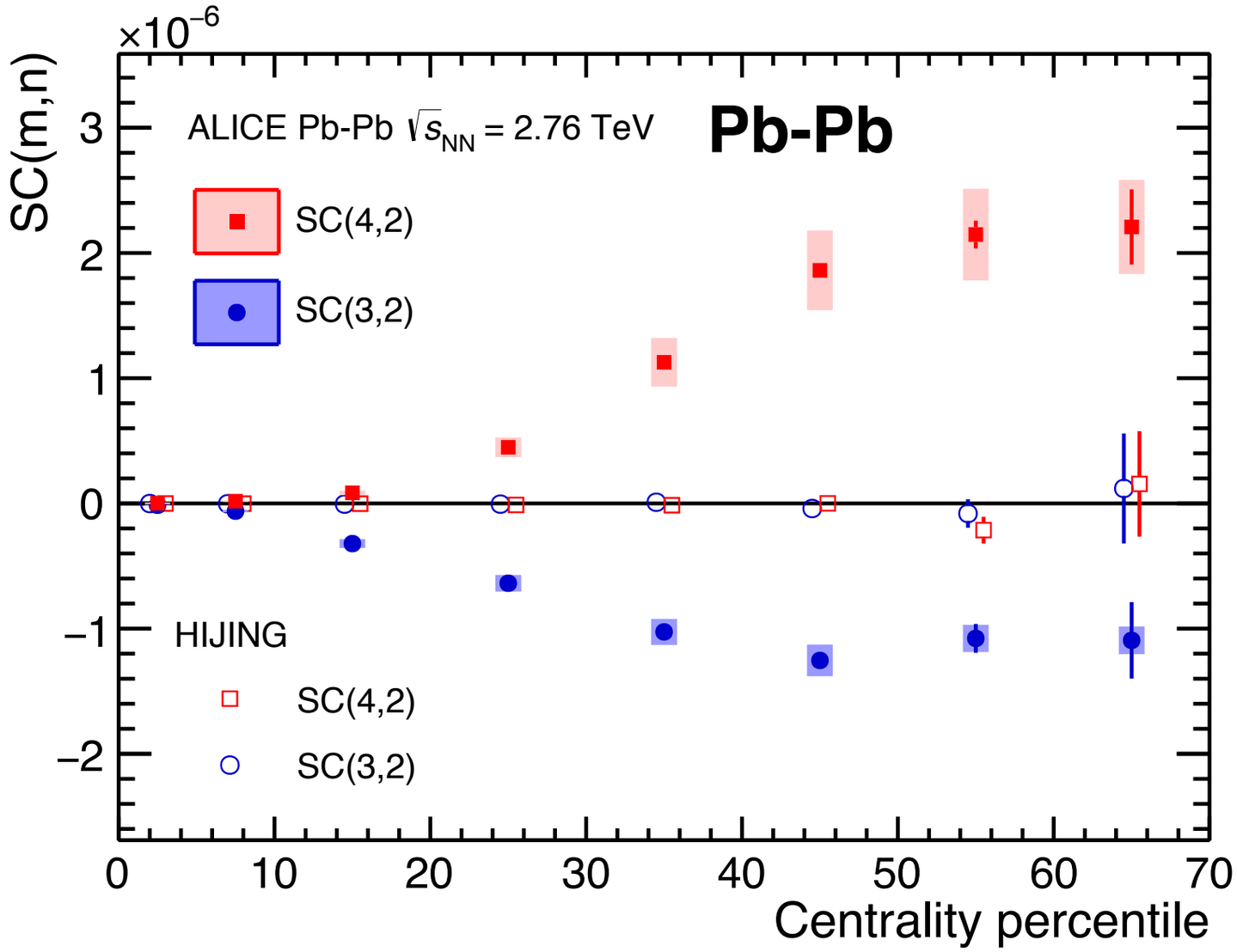
new observable
robust against non-flow

Symmetric cumulants

$$SC(n,m) = \left\langle v_n^2 v_m^2 \right\rangle - \left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$$

developed by ALICE
ALICE, PRL 117 (2016) 182301

particle correlations is a
very active and inventive field!



SC(2,3) < 0

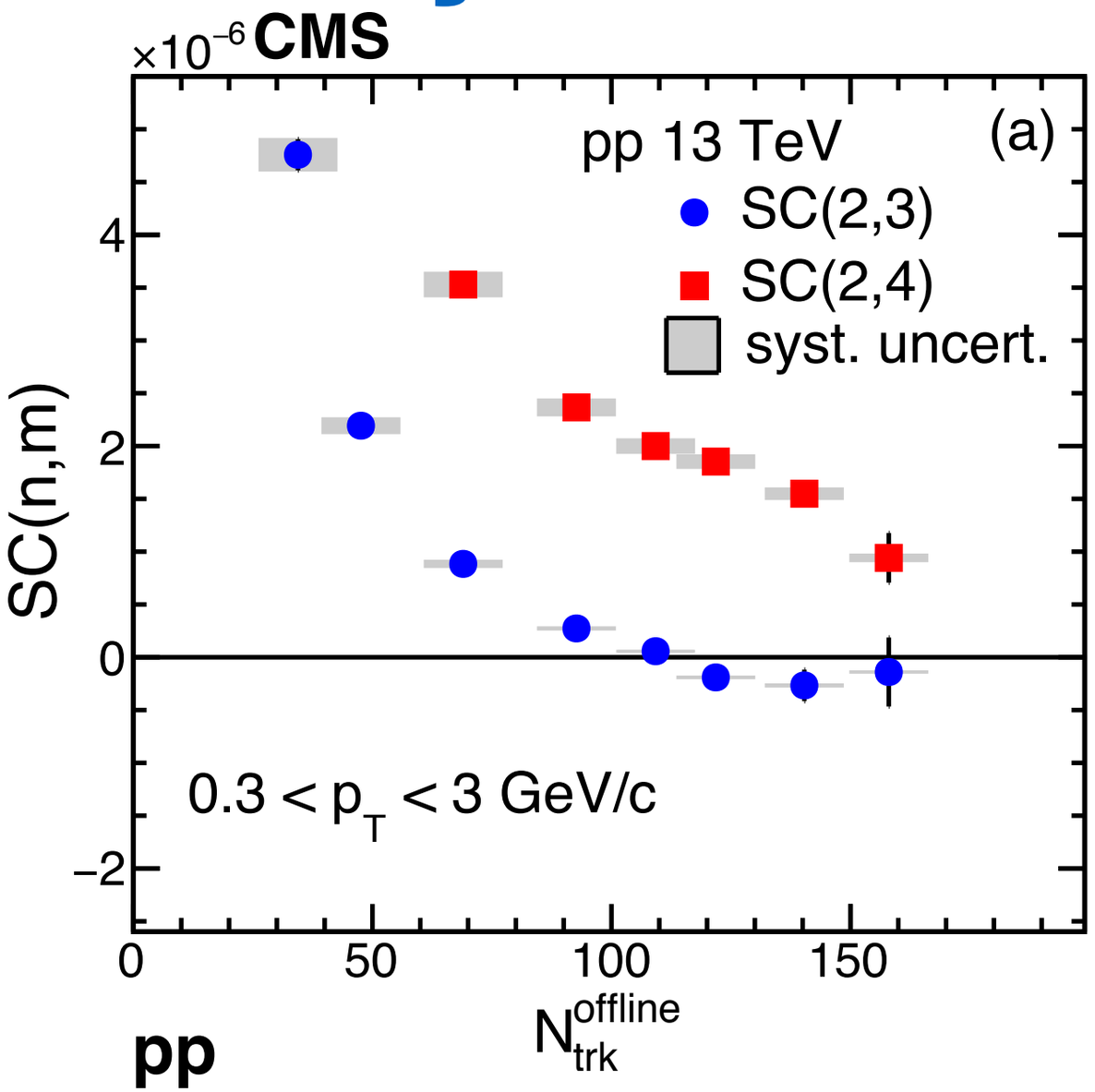
v_2 and v_3 are anti-correlated

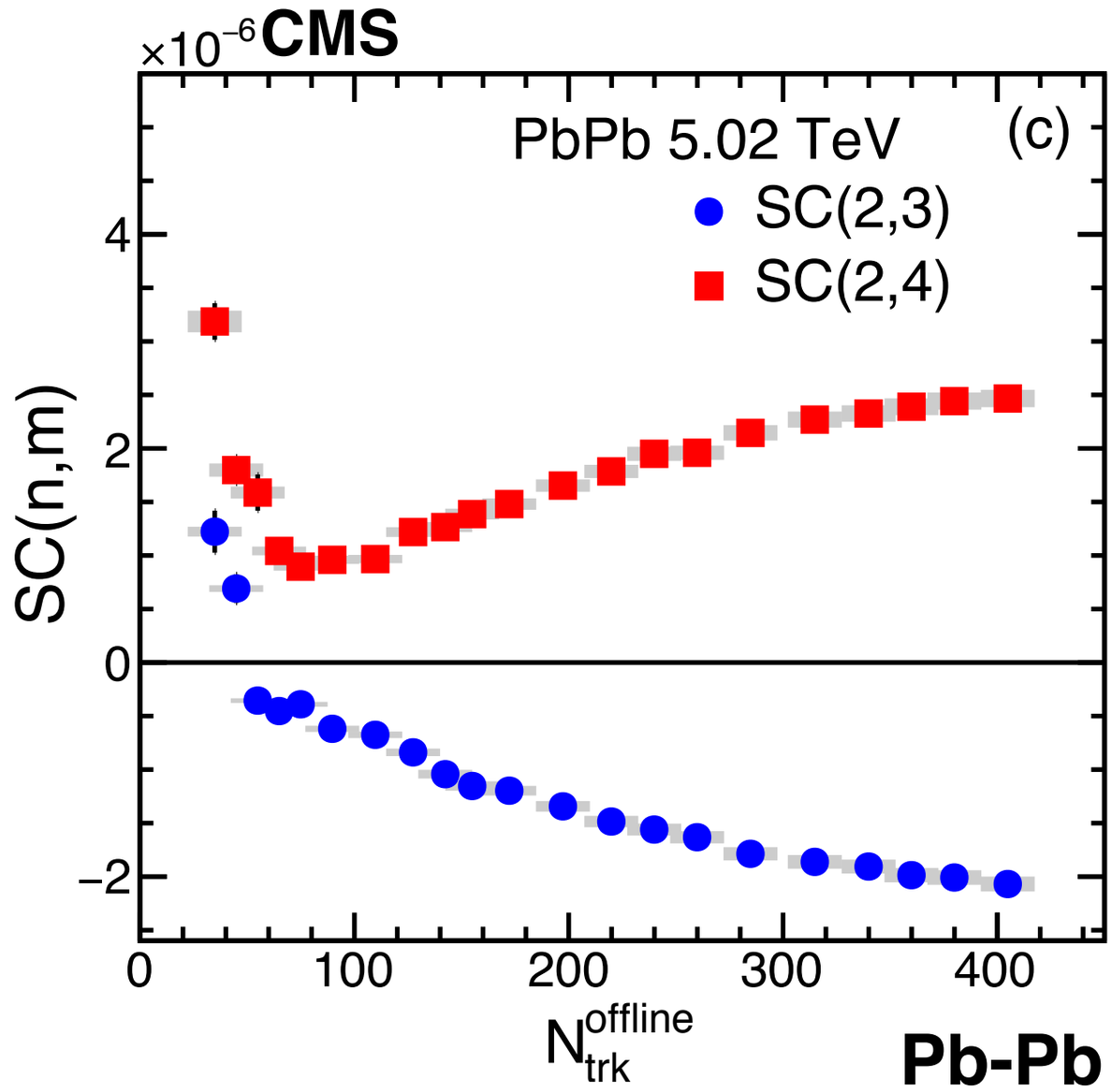
SC(2,4) > 0

v_2 and v_4 are correlated

ALICE, PRL 117 (2016) 182301

Symmetric cumulants





p-Pb and Pb-Pb show similar behaviour

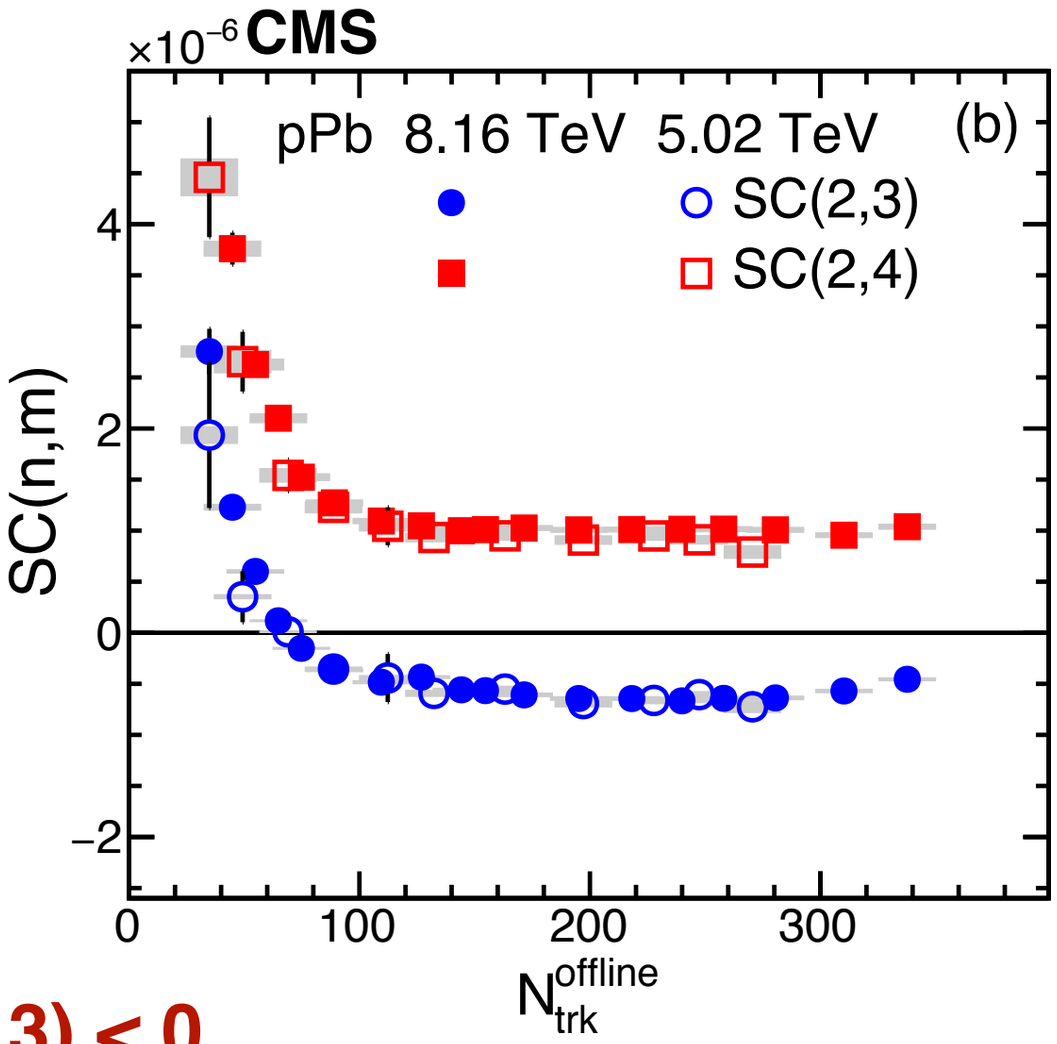
nature of collective correlations in p-Pb and Pb-Pb are of the same origin

hint of **transition to negative SC(2,3)** in pp at large N_{ch}

CMS, PRL 120 (2018) 092301

Symmetric cumulants

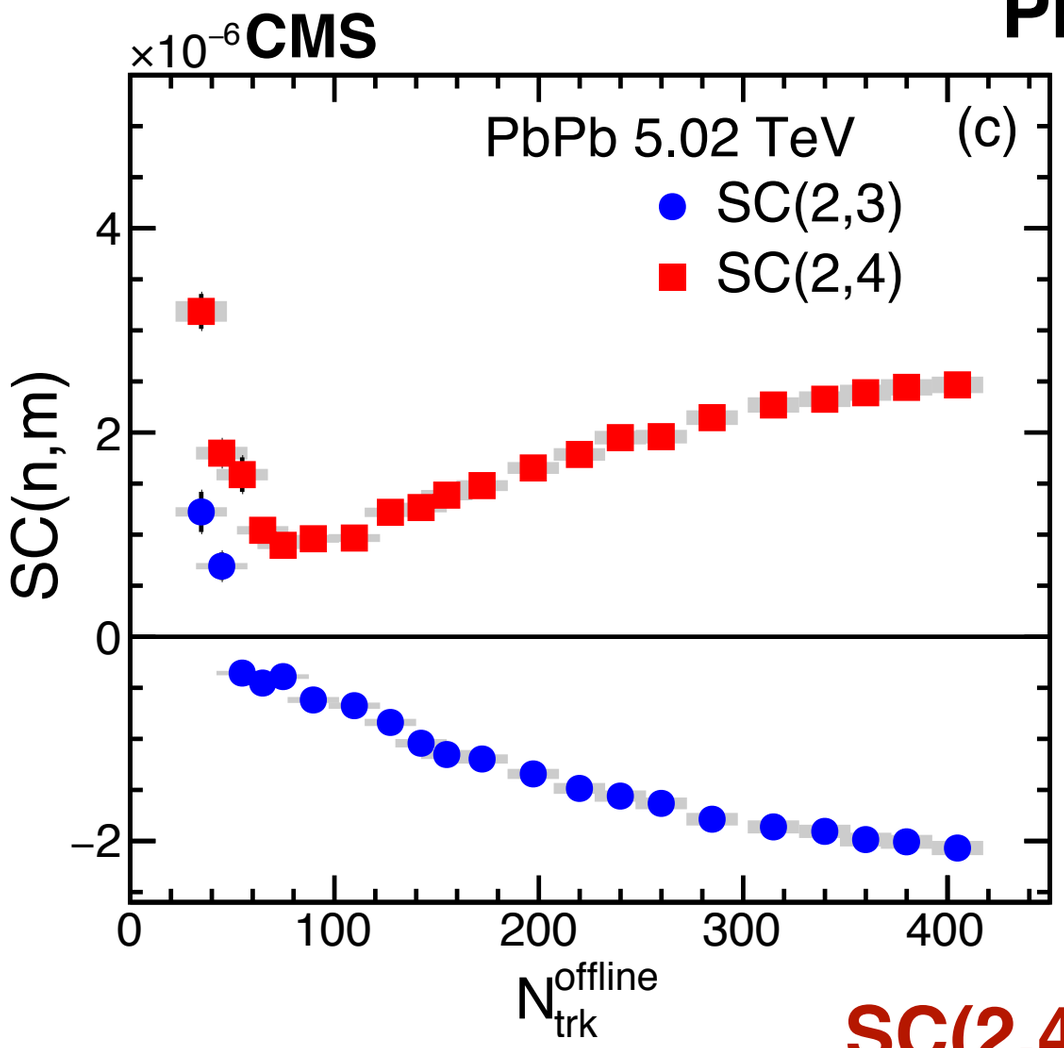
p-Pb



SC(2,3) < 0

v_2 and v_3 are anti-correlated

Pb-Pb



SC(2,4) > 0

v_2 and v_4 are correlated

p-Pb and Pb-Pb show similar behaviour

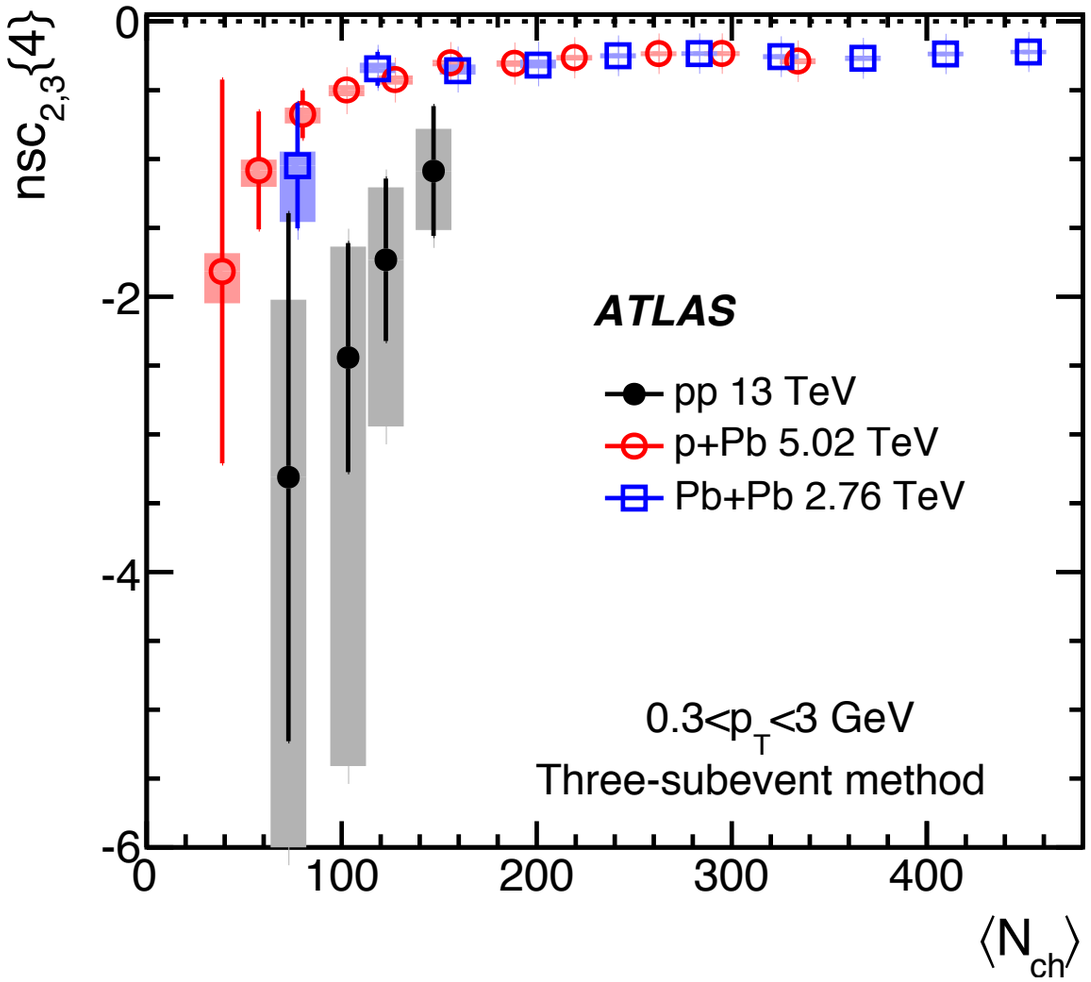
nature of collective correlations in p-Pb and Pb-Pb are of the same origin

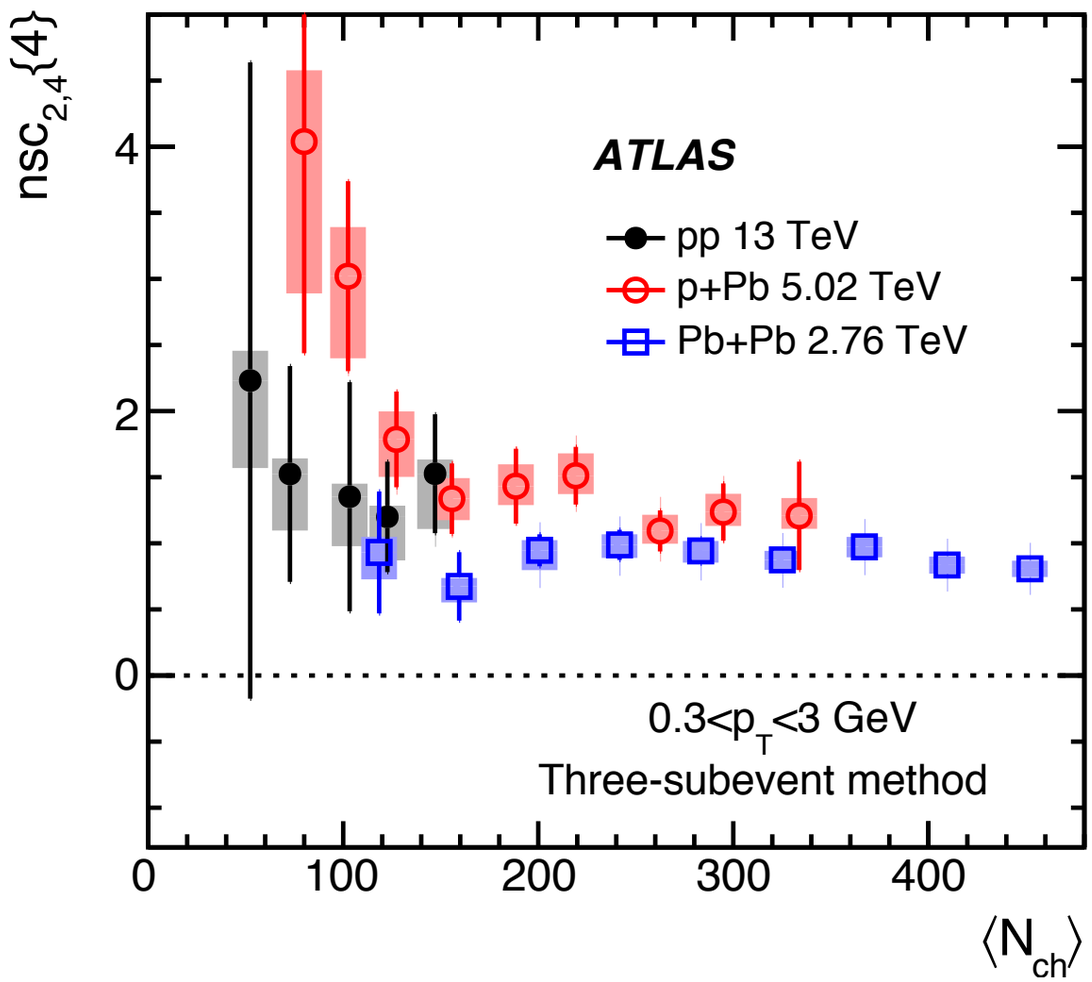
but both SC(2,3) and SC(2,4) **tend to diverge at low N_{ch}**

CMS, PRL 120 (2018) 092301

Symmetric cumulants

with **subevent method** to suppress non-flow correlations





negative SC(2,3) and positive SC(2,4) for all systems

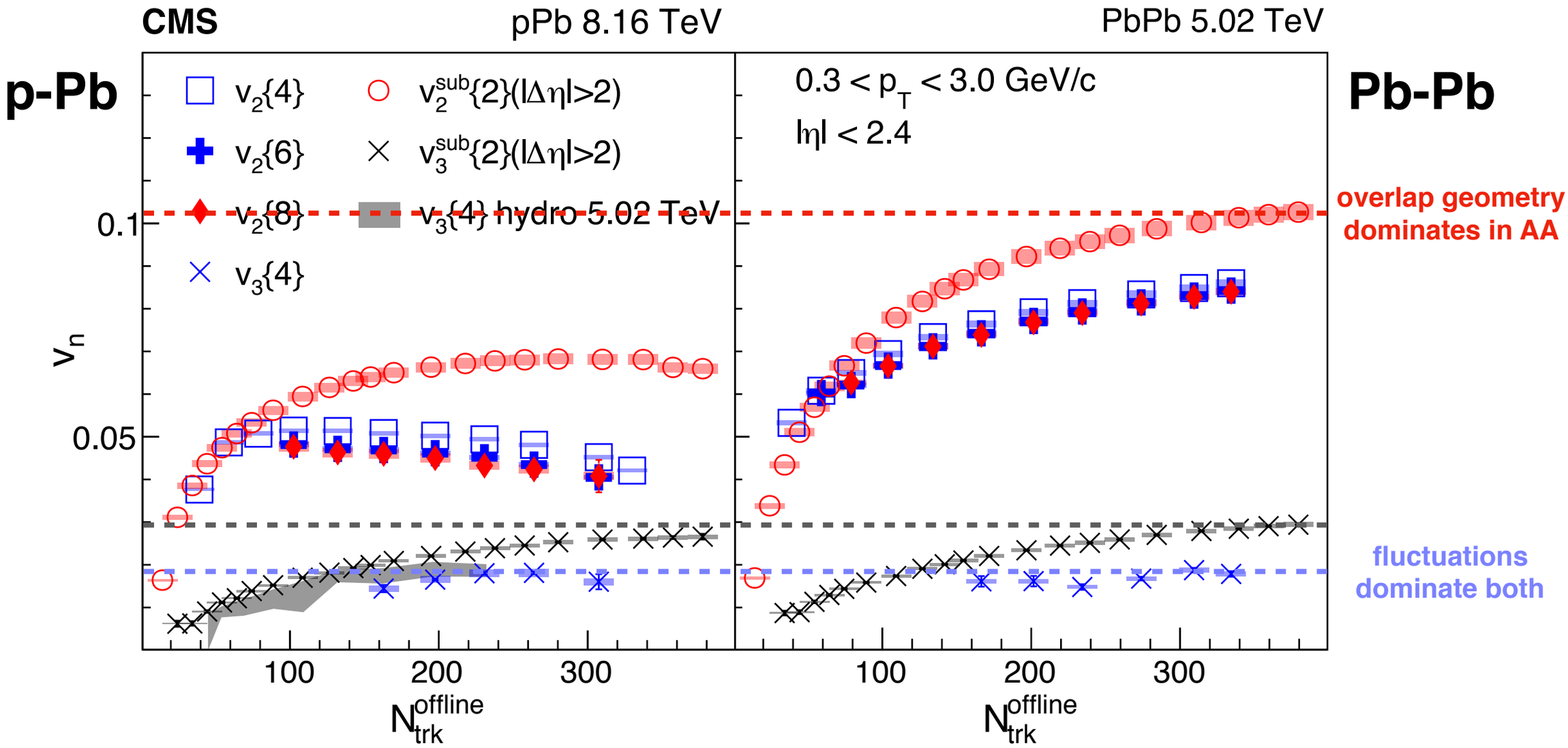
large-small systems: similar(different) magnitude at smalle(large) N_{ch}
much closer to each other after scaling by $\langle v^2_n \rangle$

ATLAS, PLB 789 (2019) 444

Fluctuation-driven correlations

high-precision measurement of $v_2\{k\}$, k = 4, 6, 8

make a direct comparison with eccentricity-fluctuation calculations



third-order triangular harmonic $v_3\{k\}$, k = 4

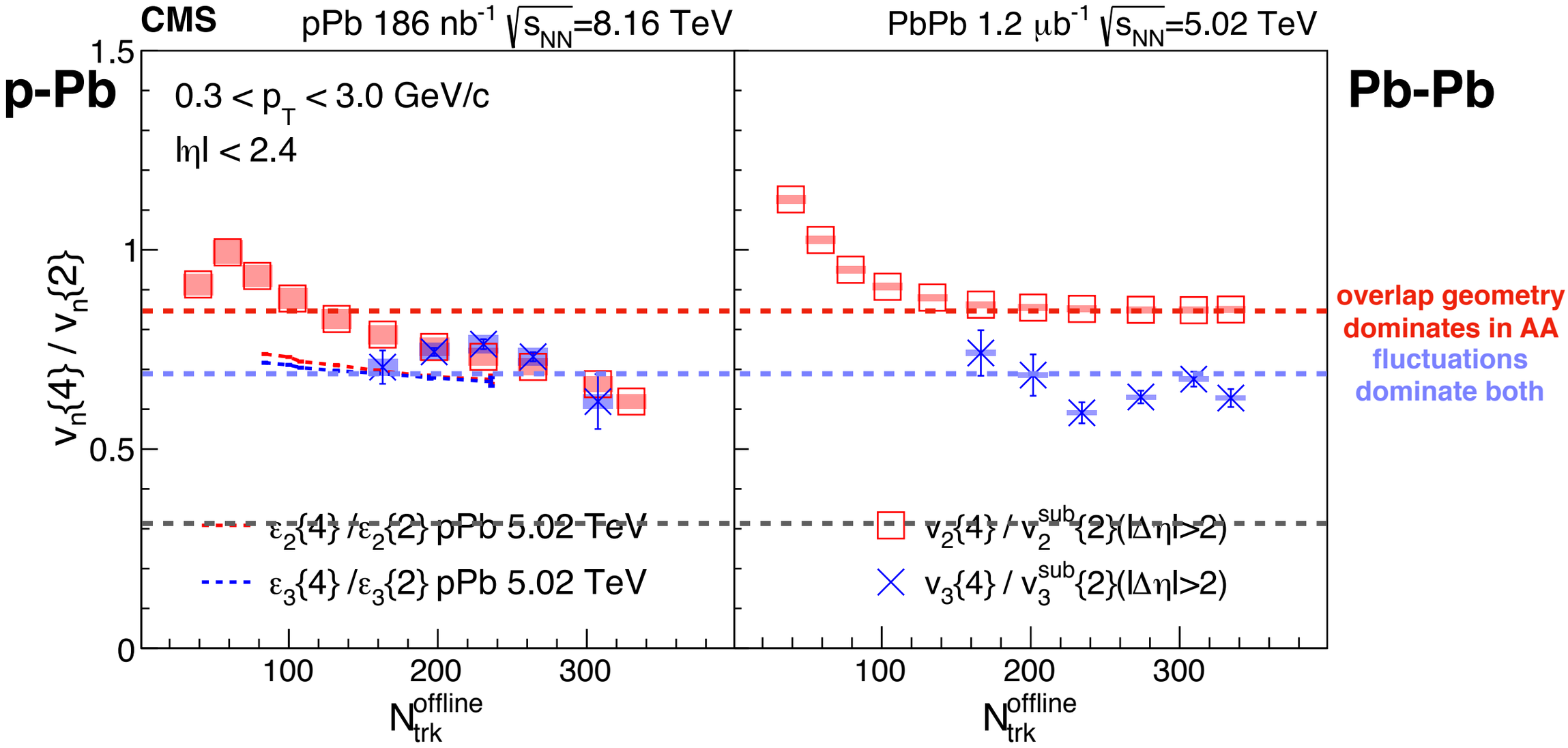
expected to be dominated by fluctuations, measured for the first time

CMS, arXiv:1904.11519 [hep-ex]

Fluctuation-driven

high-precision measurement of $v_2\{k\}$, k = 4, 6, 8

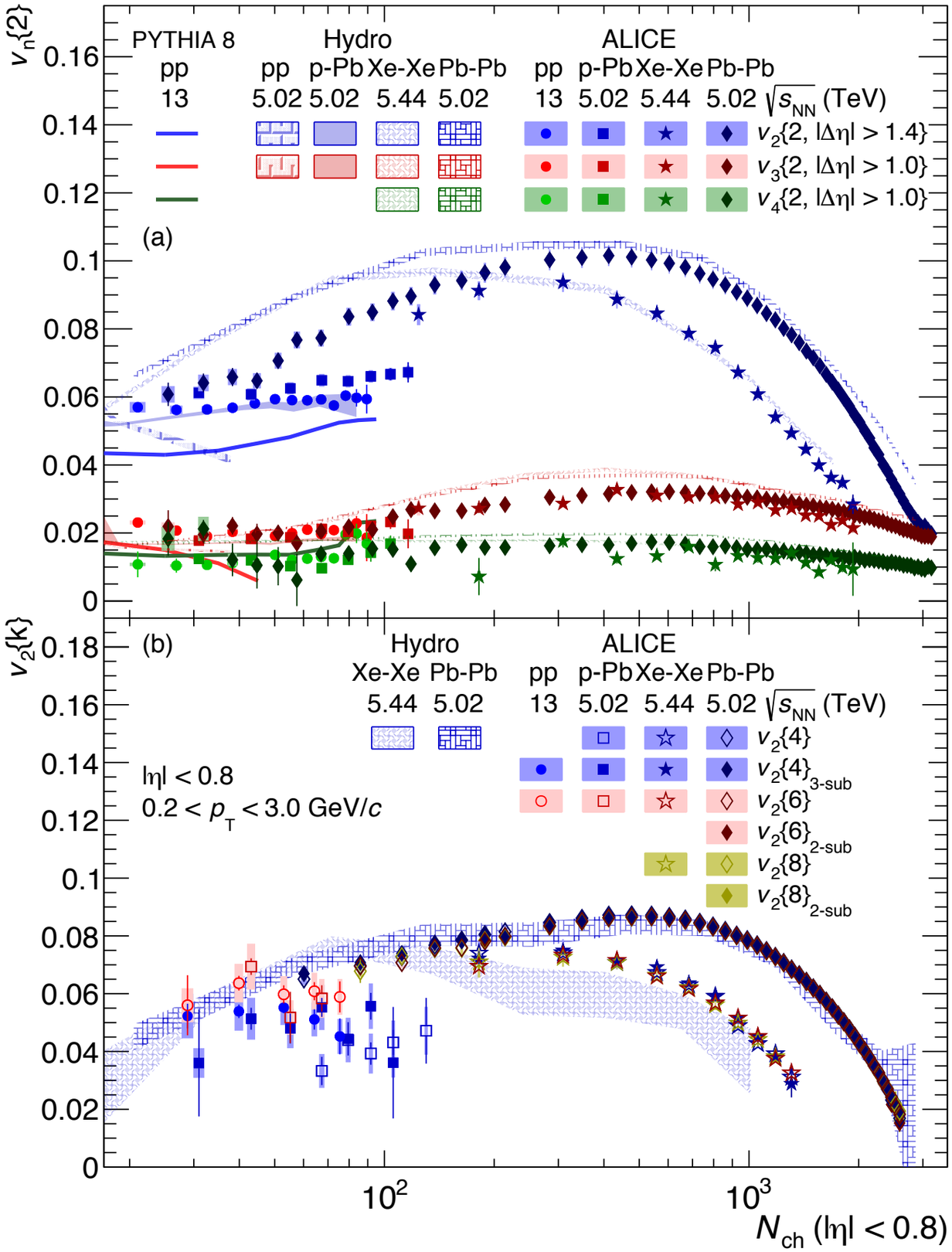
$v_2\{4\}$ / $v_2\{2\}$ and $v_3\{4\}$ / $v_3\{2\}$ ratios



v_2 and v_3 ratios are similar in p-Pb collisions

both harmonic originate from the same initial-state fluctuation mechanism

CMS, arXiv:1904.11519 [hep-ex]

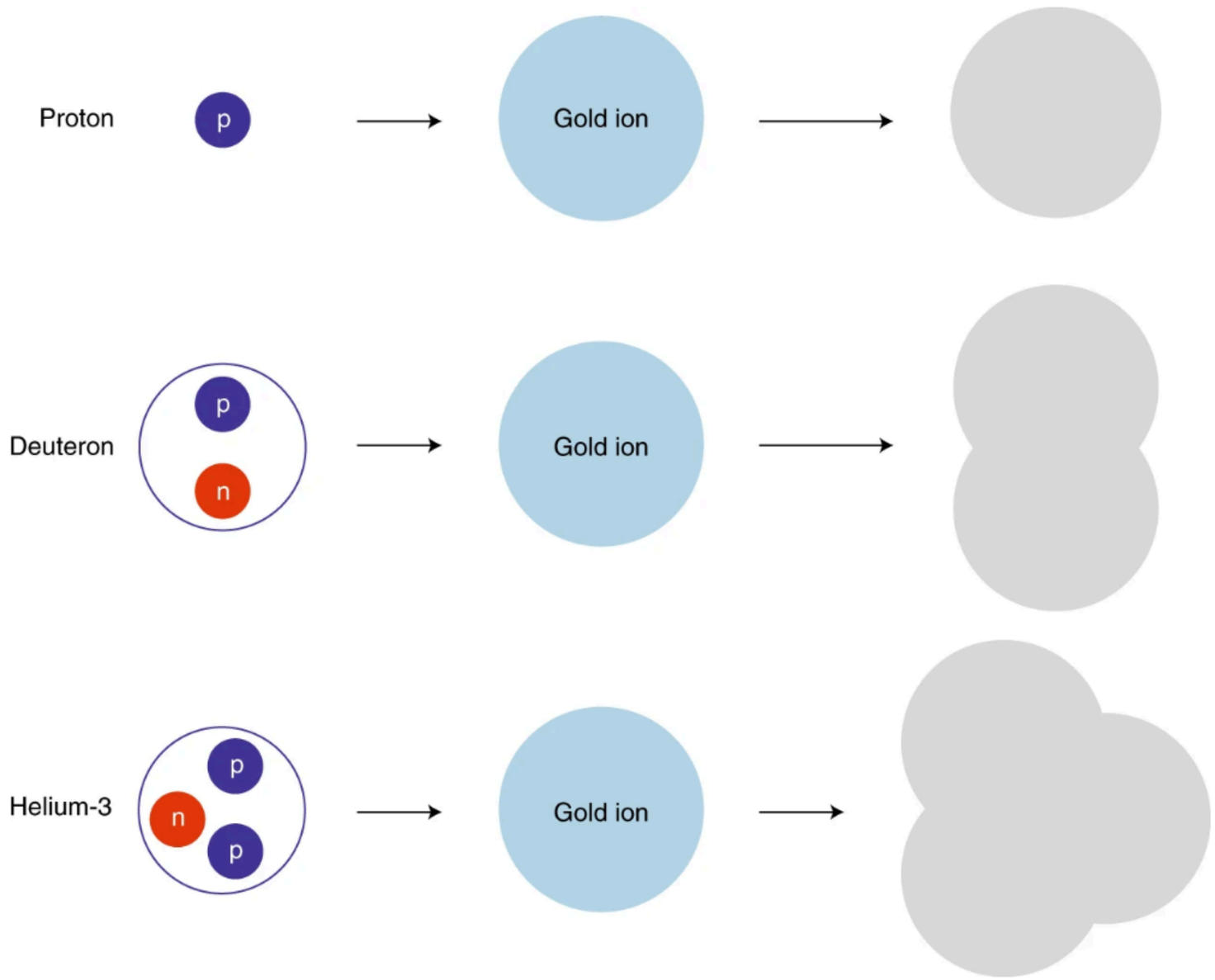


ALICE, arXiv:1903.01790 [nucl-ex]

NUCLEAR PHYSICS

Quark–gluon droplets engineered

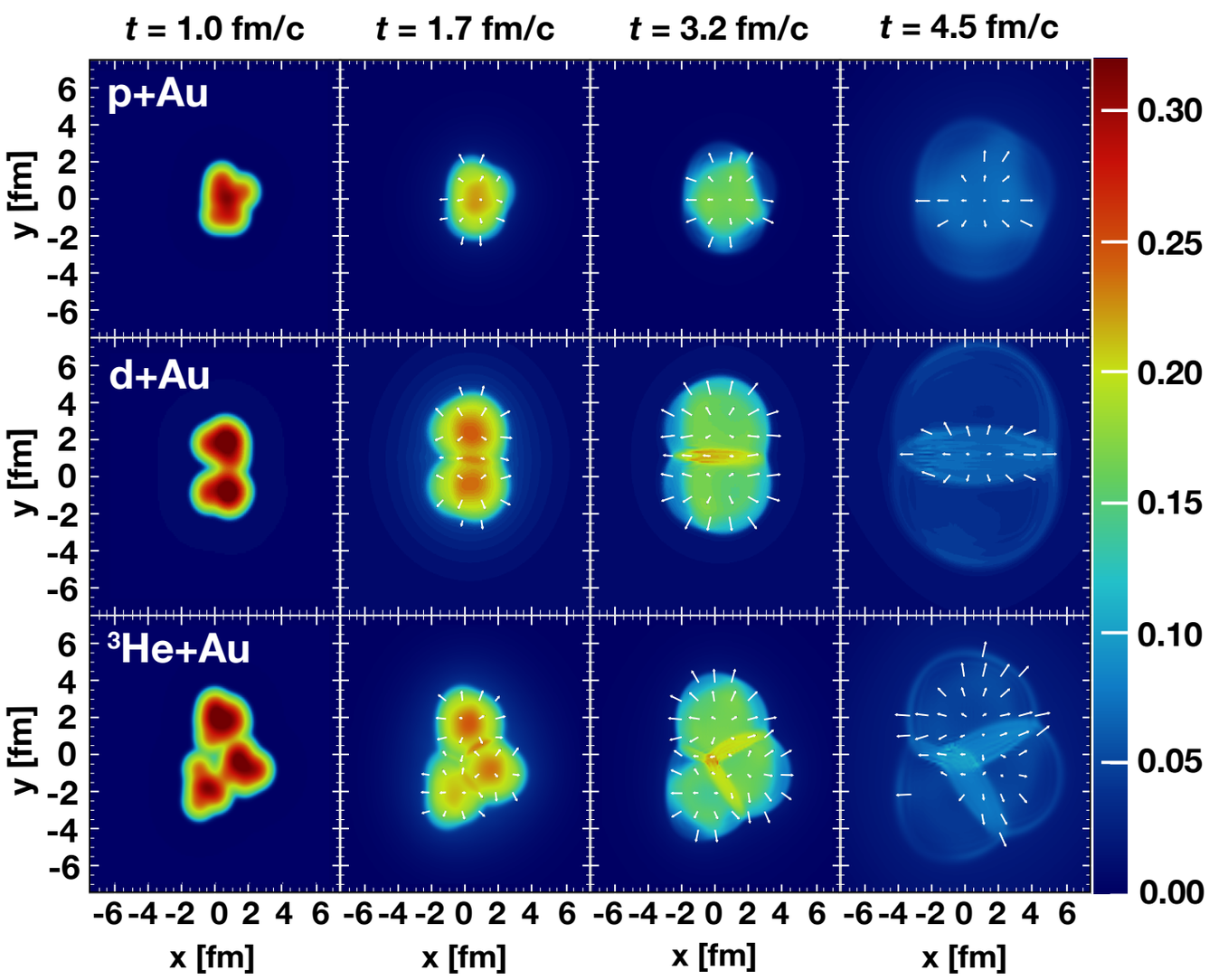
Quark–gluon plasma has been recreated in heavy-ion collisions, providing a glimpse of the very early Universe. The PHENIX Collaboration offers new insights into the possible creation of this state in smaller collision systems.

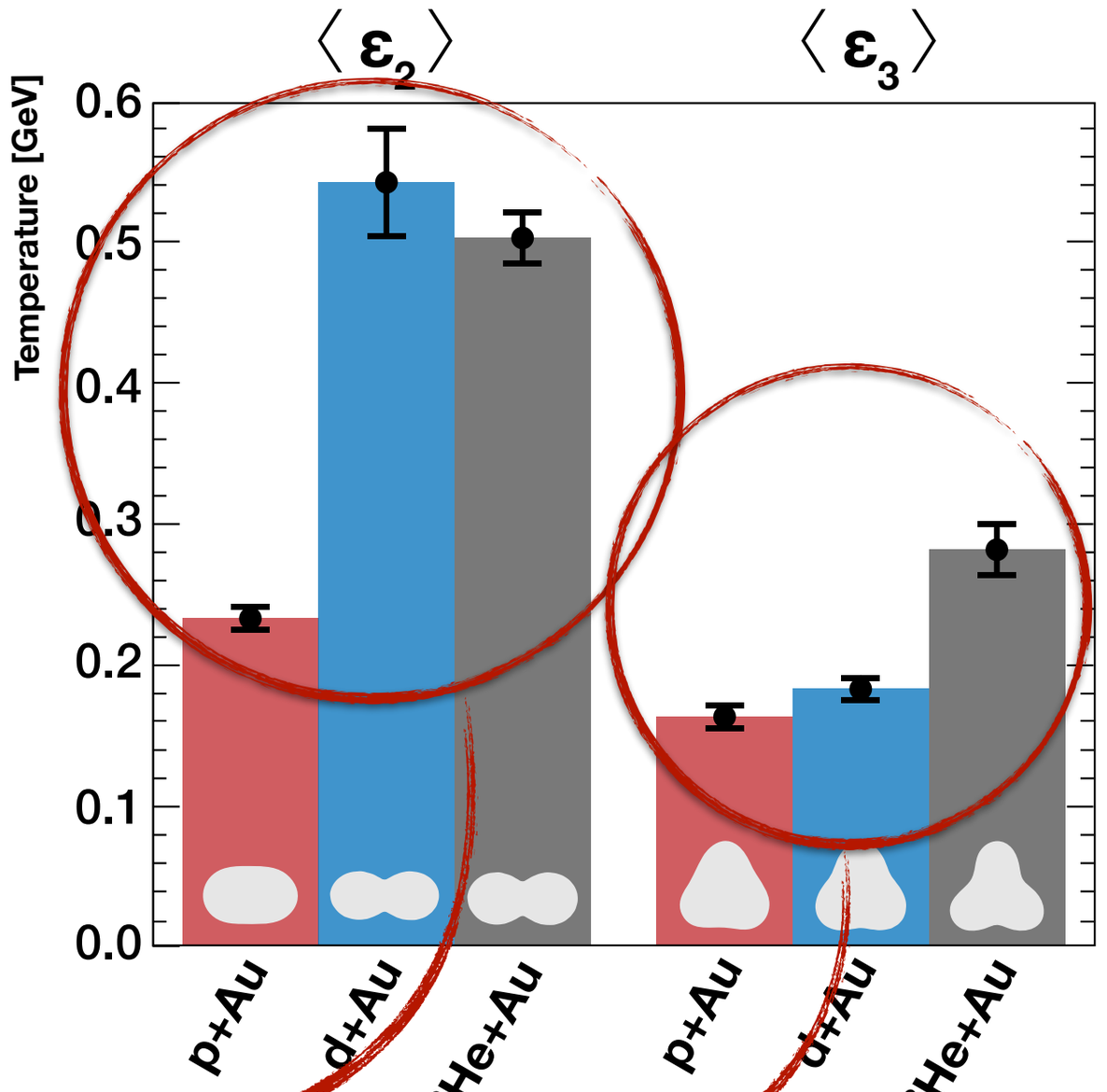


Quark-Gluon droplets engineered

RHIC versatility: projectile geometry scan

ε_2, ε_3 coupled with efficient hydrodynamics





prediction for v_2, v_3 ordering

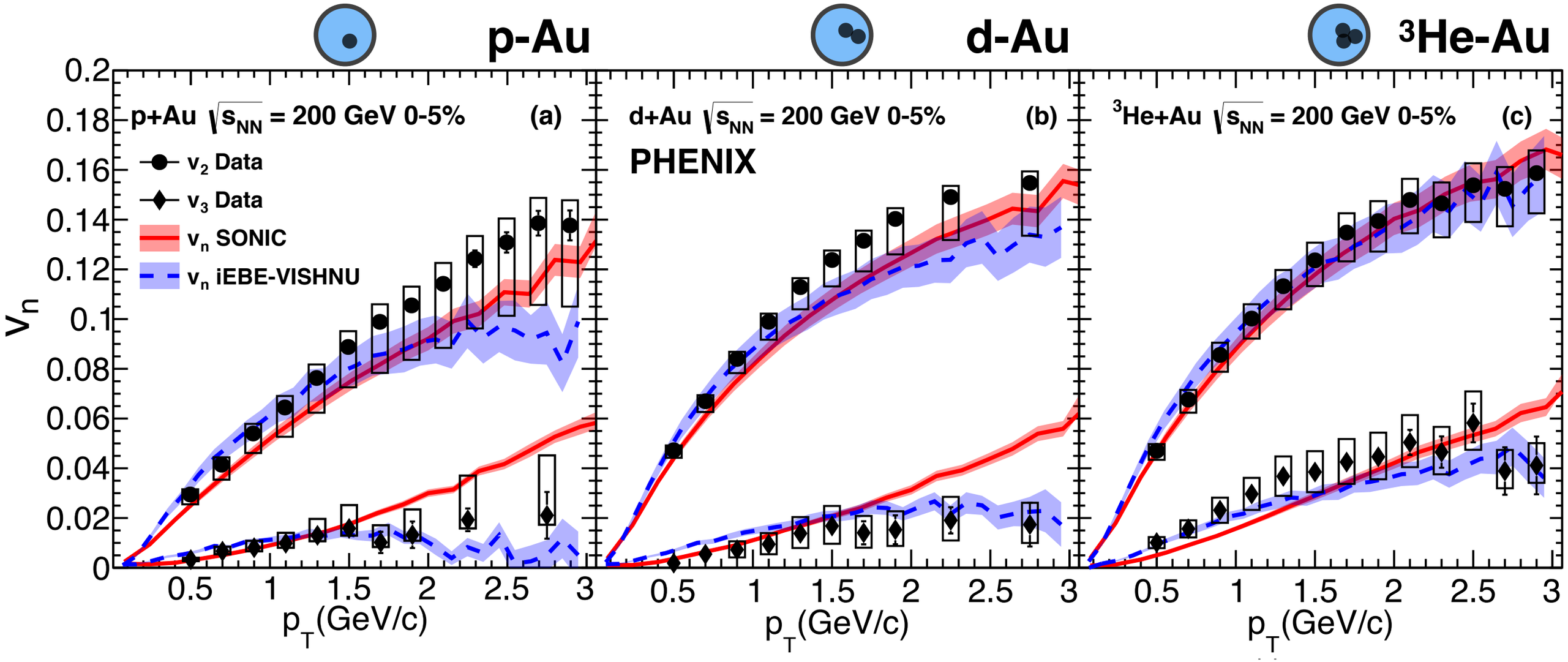
$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \approx v_2^{\ ^3\text{He+Au}}$$

$$v_3^{\text{p+Au}} \approx v_3^{\text{d+Au}} < v_3^{\ ^3\text{He+Au}}$$

Quark-Gluon droplets engineering

RHIC versatility: projectile geometry scan

measured v_2 and v_3 follow the predicted hydro hierarchy

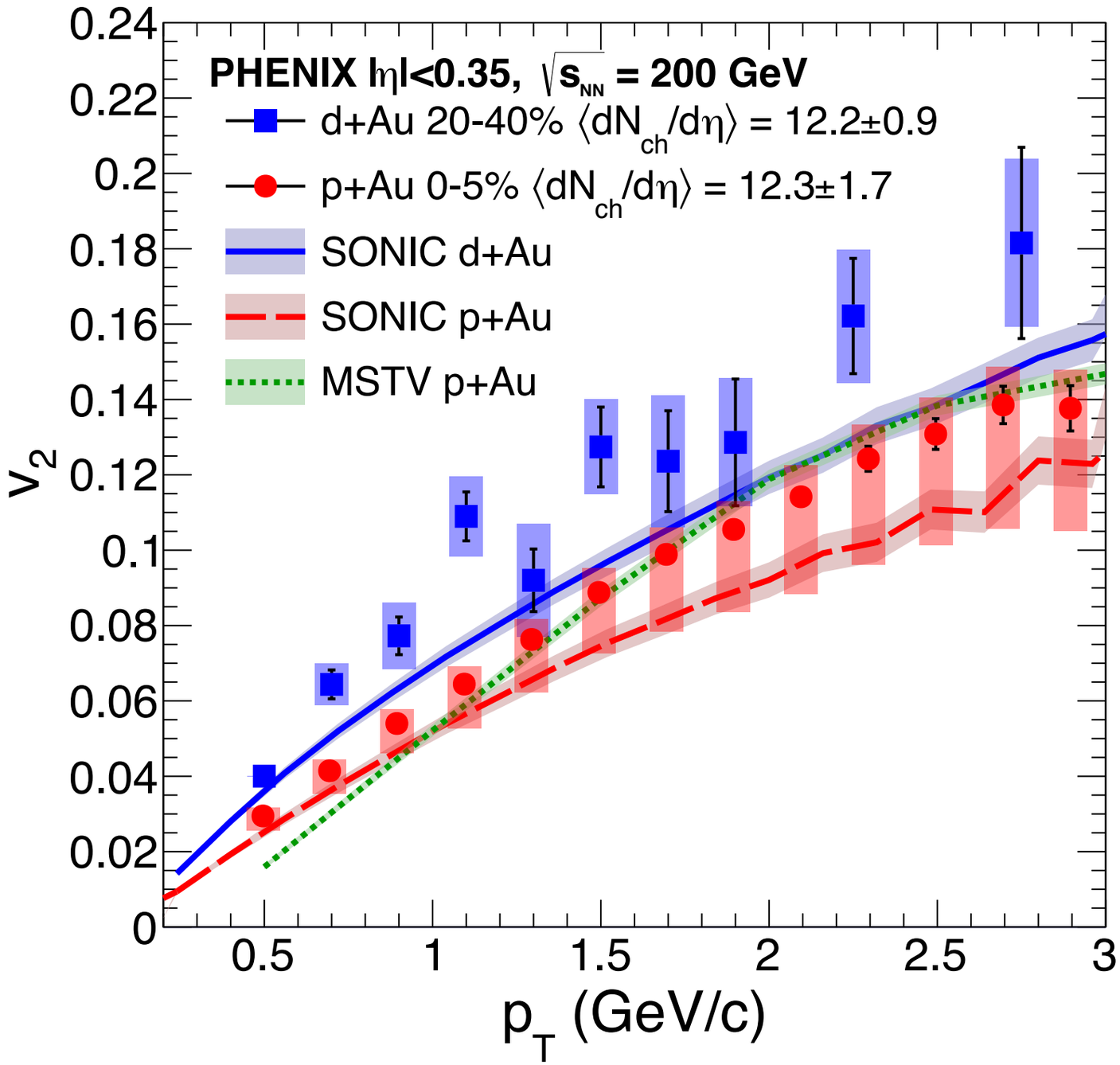


initial conditions → hydro evolution →

→ fluid hadronisation → hadronic rescattering

models with similar core structure, different implementation details

Quark-Gluon droplets engineering

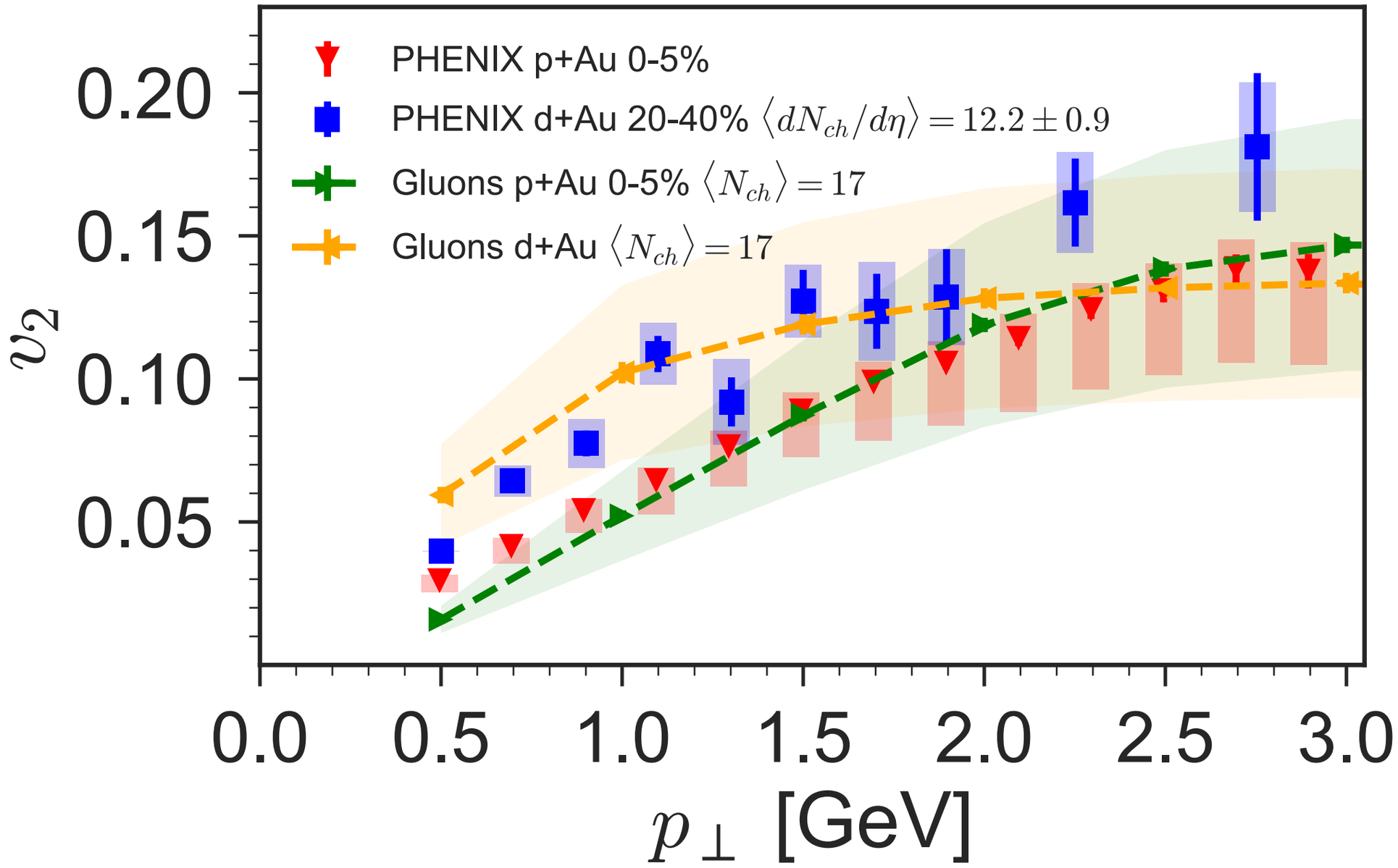


but for the same N_{ch} ...

long story to tell today

more on *Nature Phys. 15 (2019) 214* and *arXiv:1901.10506 [hep-ph]*

Quark-Gluon droplets engineering



but for the same N_{ch} ...

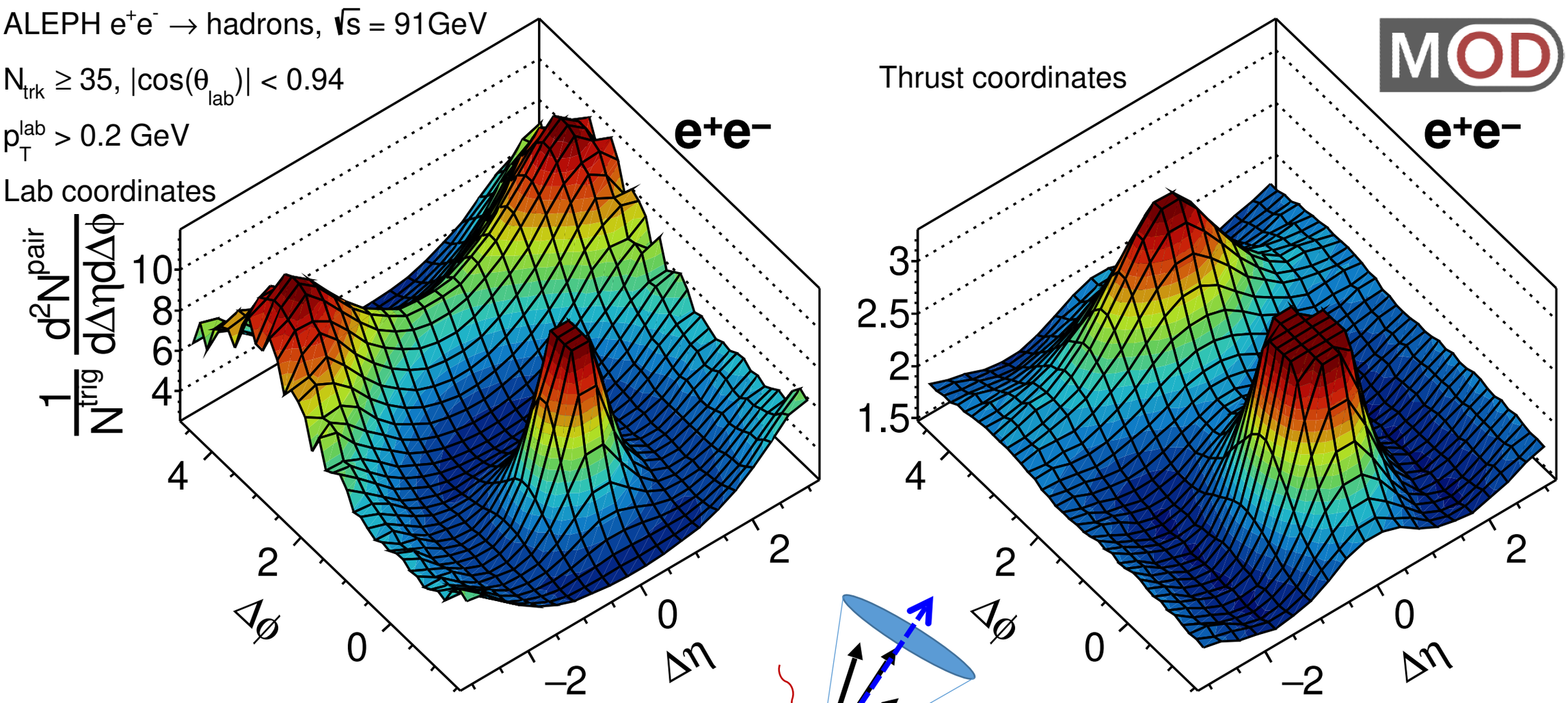
long story to tell today

more on *Nature Phys. 15 (2019) 214* and *arXiv:1901.10506 [hep-ph]*

Is flow unique to h-h collisions?

check in **e⁺e⁻ events** with ALEPH archived data

2-particle correlation measurement in high-N_{ch} hadronic events

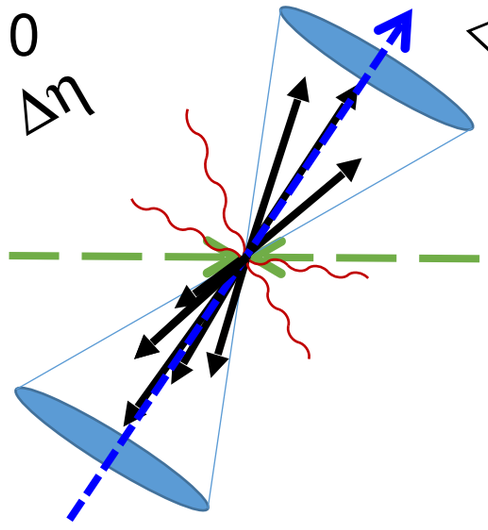


wrt. **beam axis**

as performed in pp, p-A and AA

sensitive to QCD medium

expanding transverse to beam axis



wrt. **thrust axis**

more appropriate for e⁺e⁻

sensitive to QCD medium

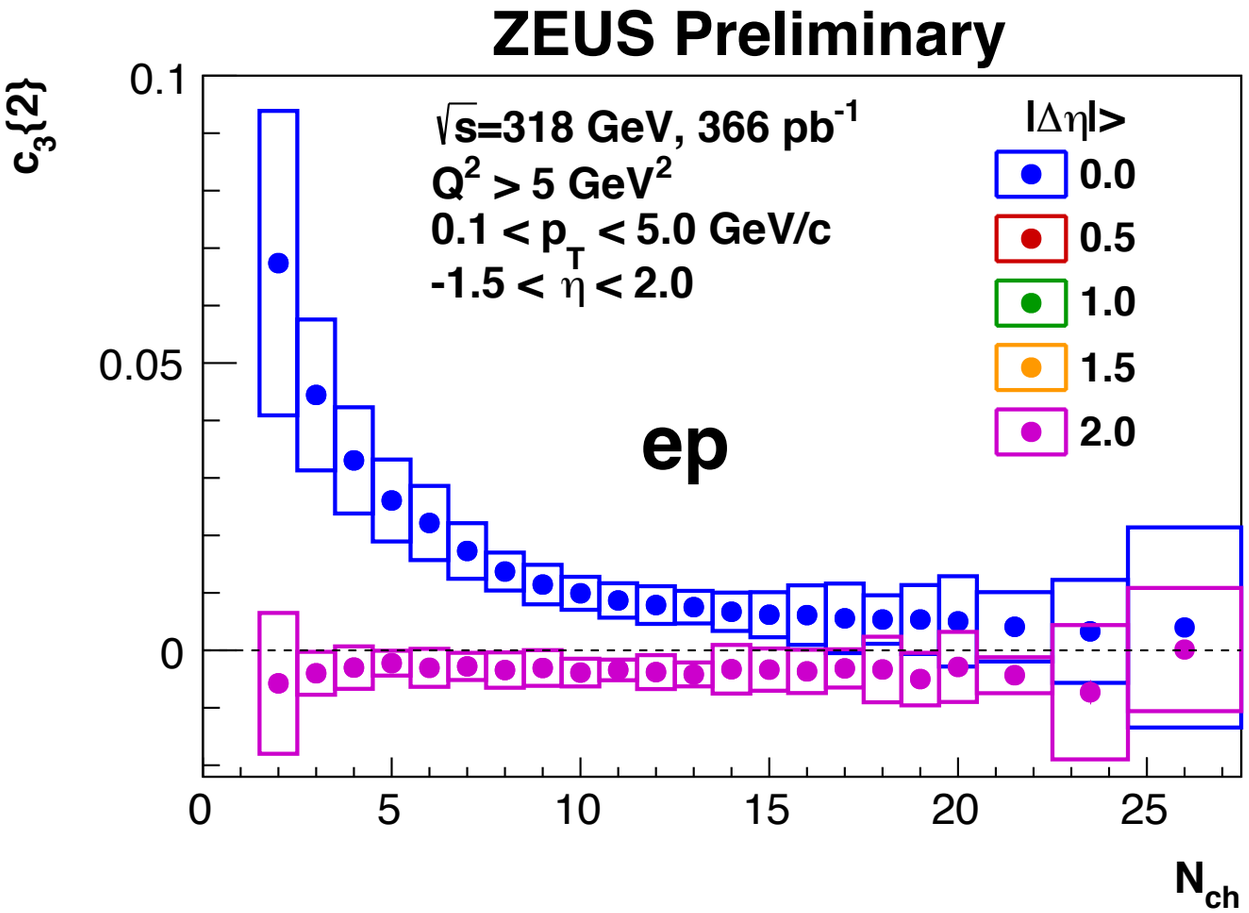
expanding transverse to $q\bar{q}$

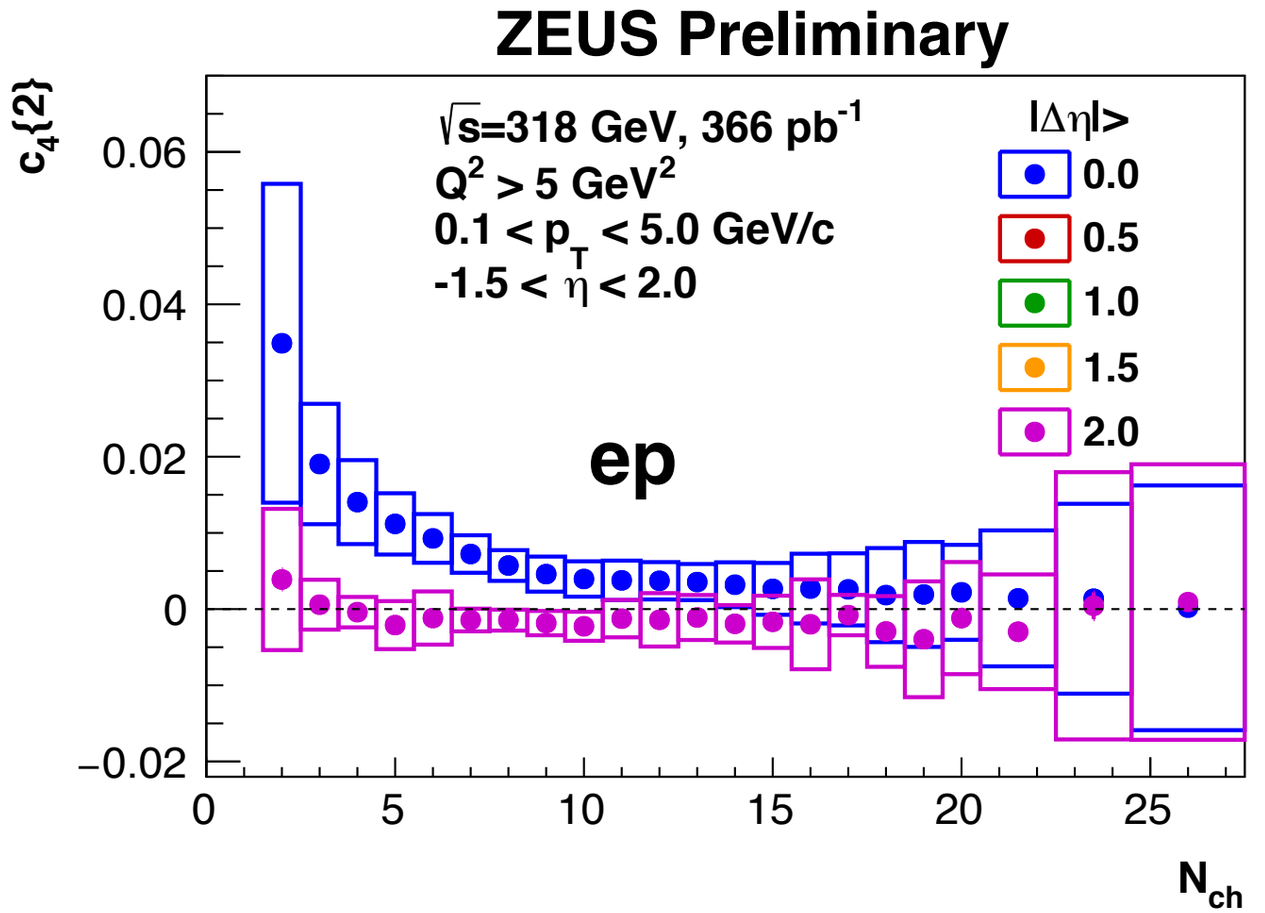
Badea et al., arXiv:1906.00489

Flow is unique to h-h collisions

check in **ep DIS events** with ZEUS archived data

2-particle cumulants vs. N_{ch} with increasing η-gap





no evidence of long-range correlations

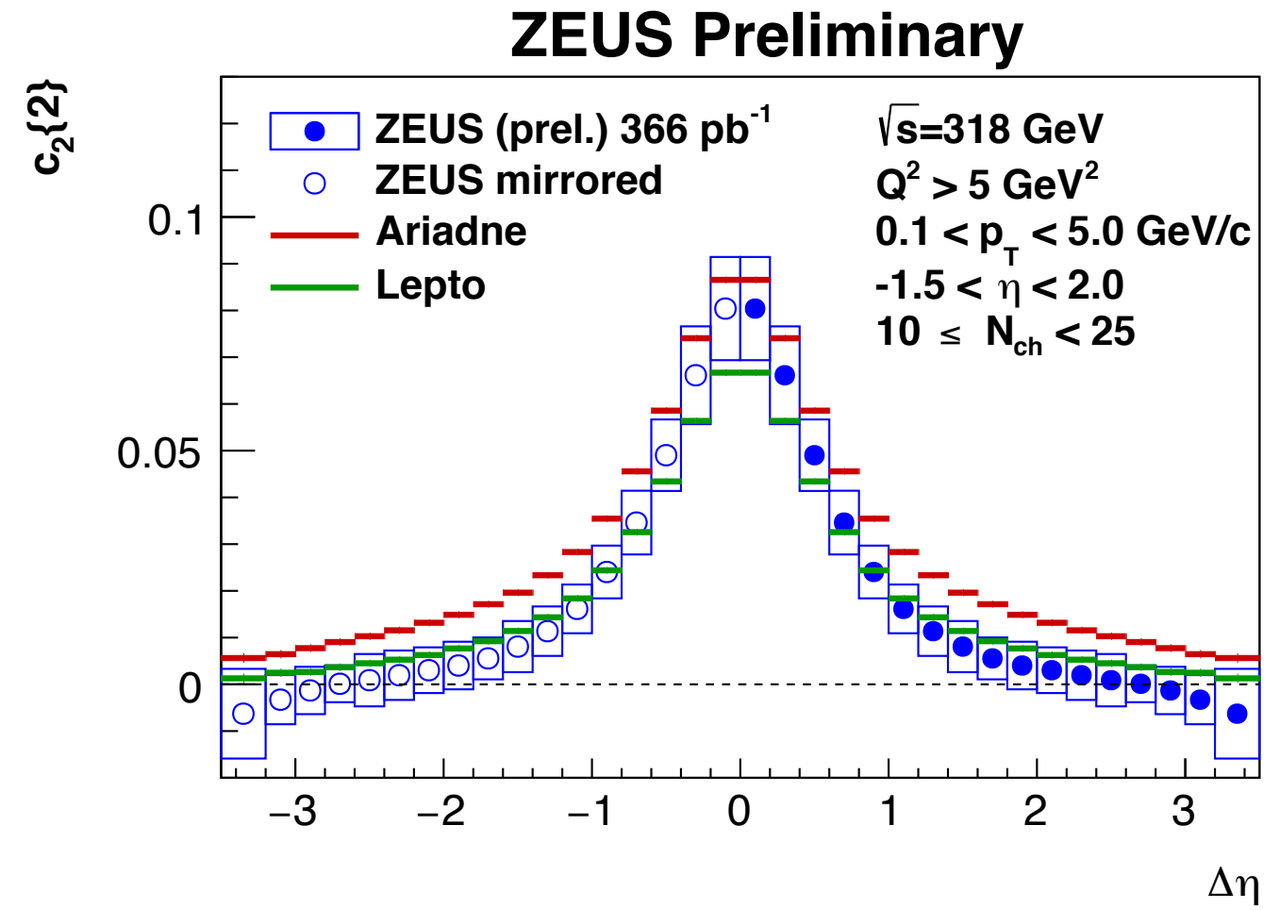
non-flow dominates at low N_{ch} and without η-gap

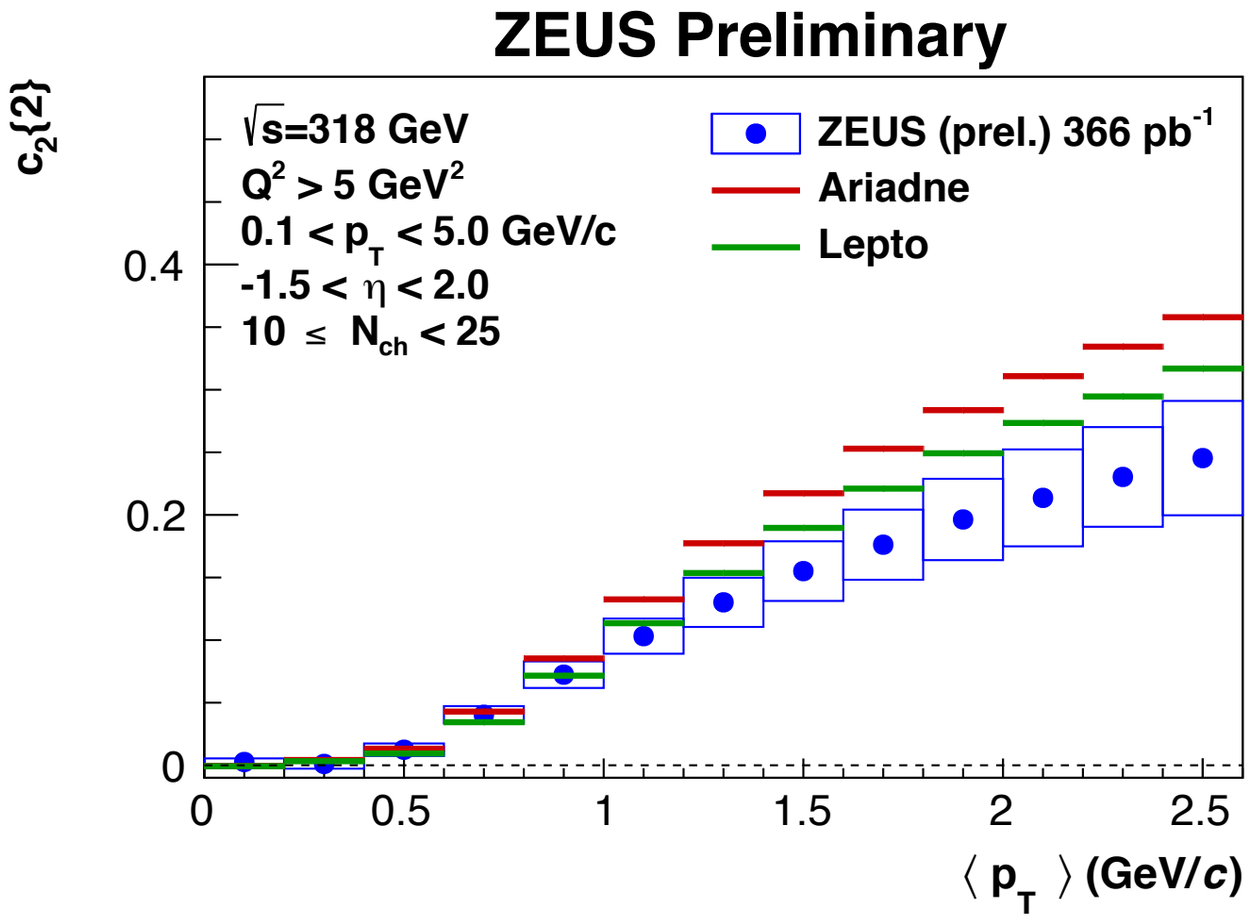
cumulants consistent with zero (no flow) at high N_{ch} and large η-gap

Is flow unique to h-h collisions?

check in **ep DIS events** with ZEUS archived data

2-particle cumulants vs. N_{ch} with increasing η-gap





no evidence of long-range correlations

non-flow dominates at low Nch and without η-gap (a

cumulants consistent with zero (no flow) at high N_{ch} and large η-gap

Strangeness in small systems

one of the first proposed QGP signatures

VOLUME 48, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1982

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

We thus conclude that strangeness abundance saturates in sufficiently excited quark-gluon plasma ($T > 160$ MeV, $E > 1$ GeV/fm^3), allowing us to utilize enhanced abundances of rare, strange hadrons ($\bar{\Lambda}$, $\bar{\Omega}$, etc.) as indicators for the formation of the plasma state in nuclear collisions.

Canonical suppression

in macroscopic models
(statistical / thermal)

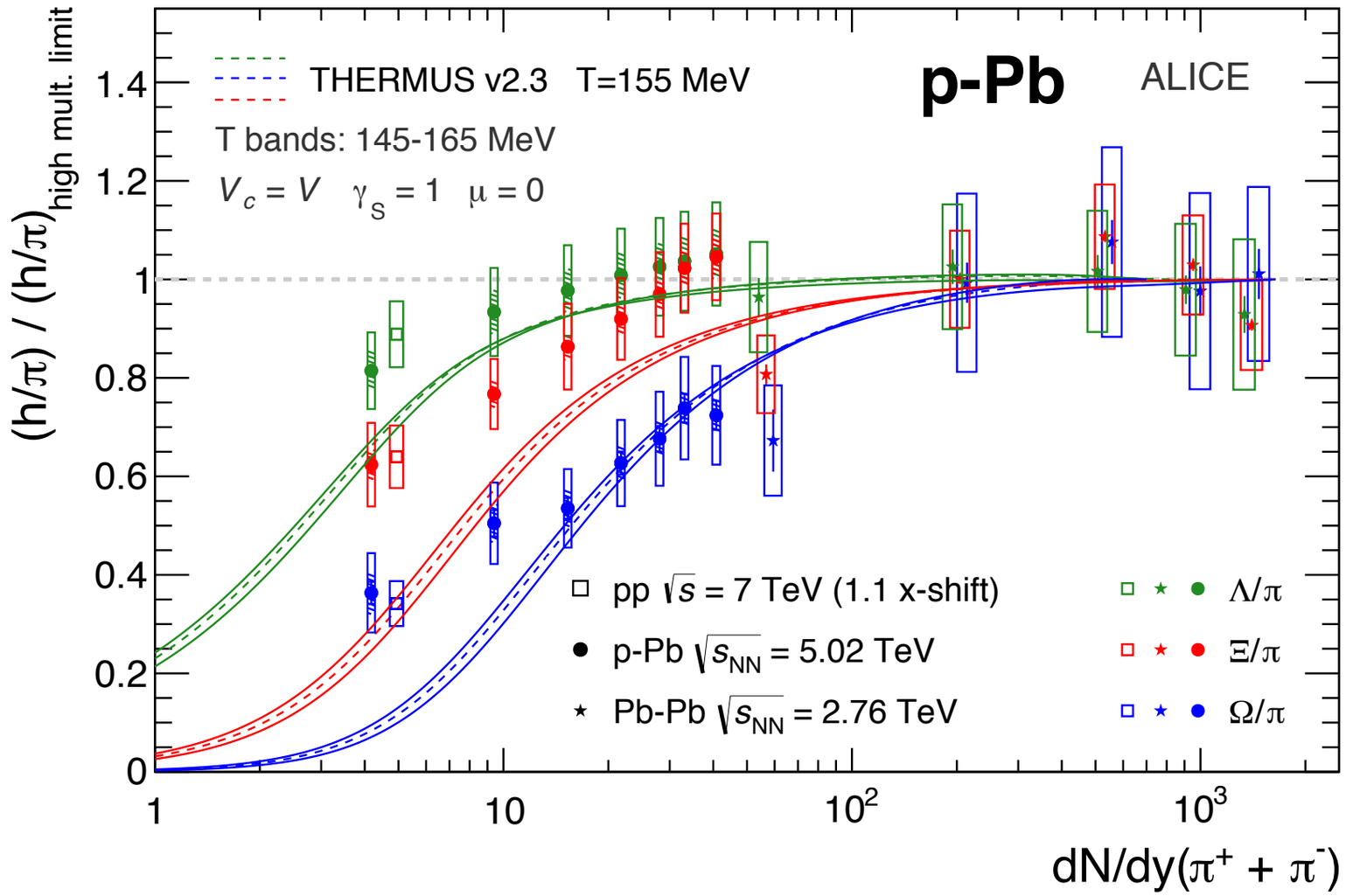
local conservation of strangeness

within a volume V_c

strangeness in small systems suppressed

wrt. grand-canonical limit

magnitude depends on hadron strangeness



calculations from **Strangeness Canonical** model in THERMUS

good qualitative agreement with the data

ALICE, PLB 758 (2016) 389

Canonical suppression

in macroscopic models
(statistical / thermal)

local conservation of strangeness

within a volume V_C

strangeness in small systems suppressed

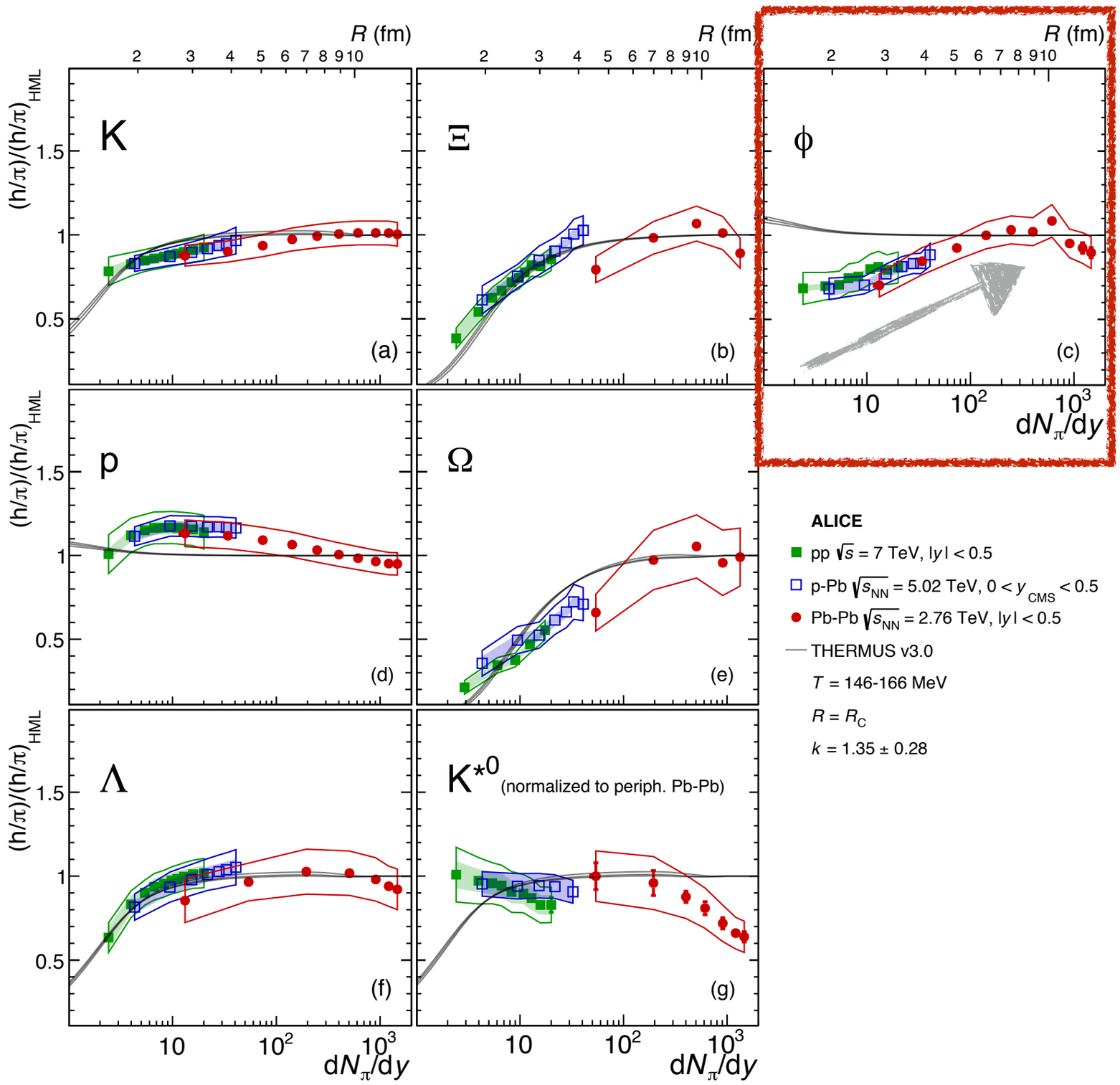
wrt. grand-canonical limit

magnitude depends on hadron strangeness

but the ϕ meson…

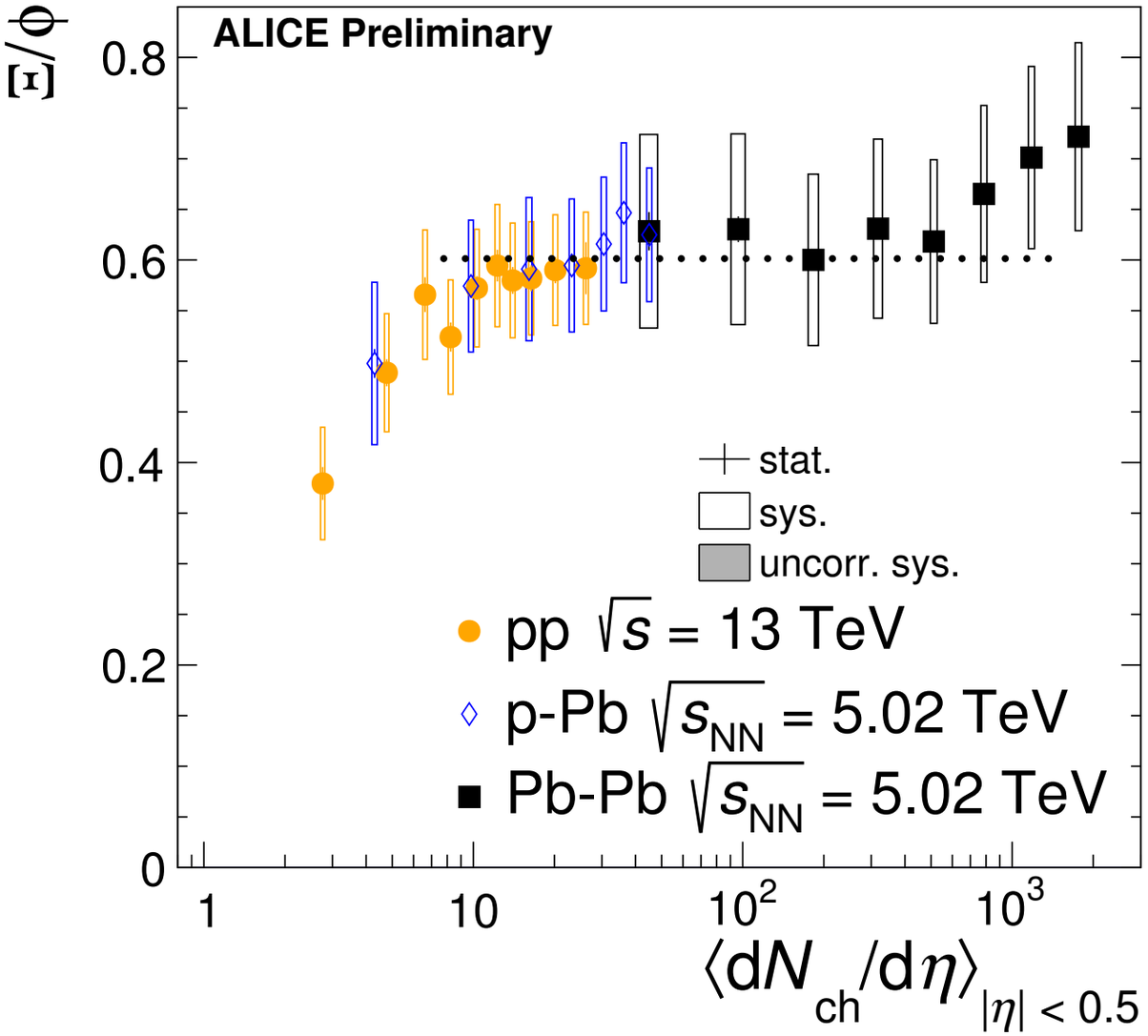
zero strangeness
has multiplicity dependence

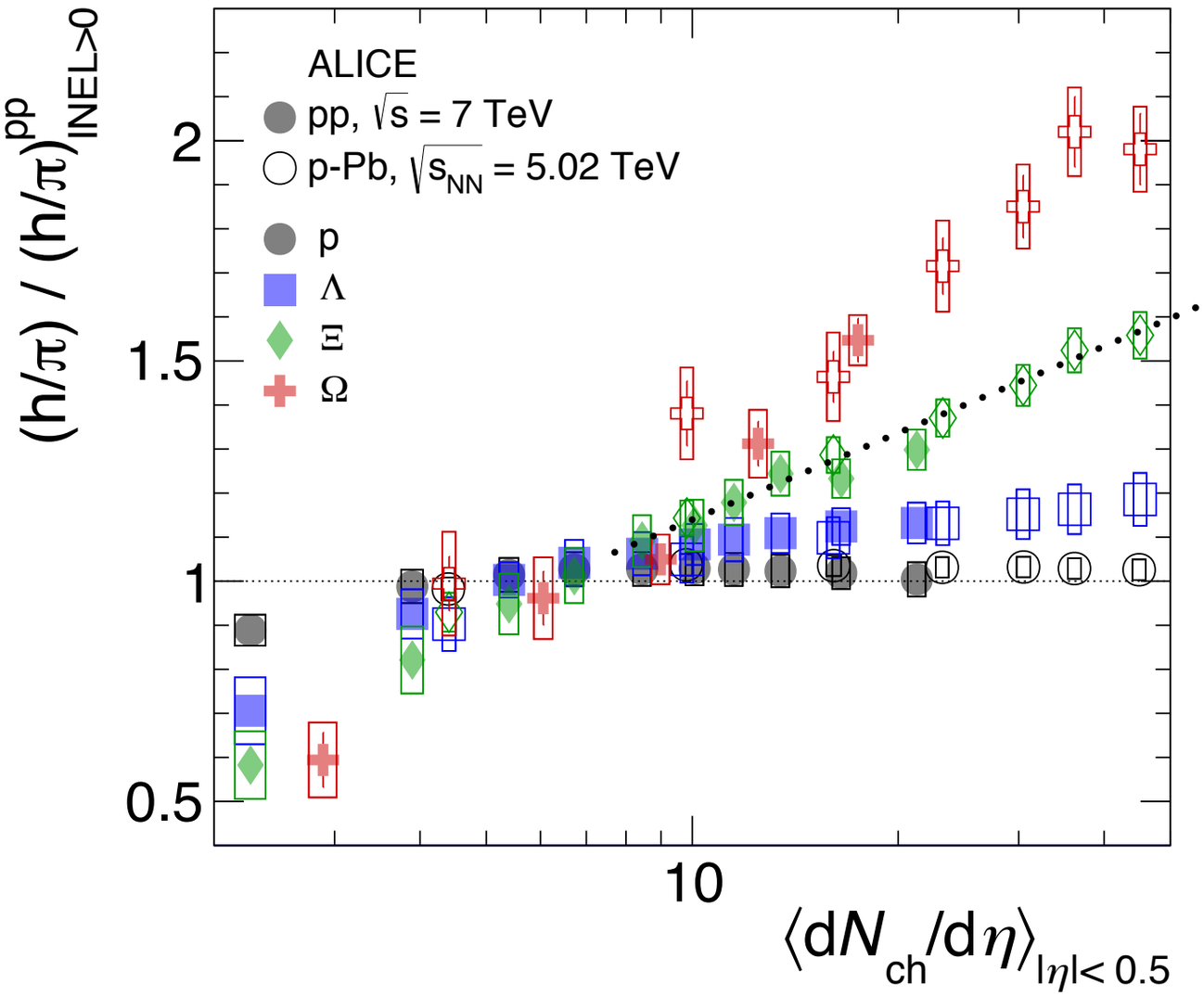
does not fit into this picture



ALICE, PRC 99 (2019) 024906

How does the ϕ behave?





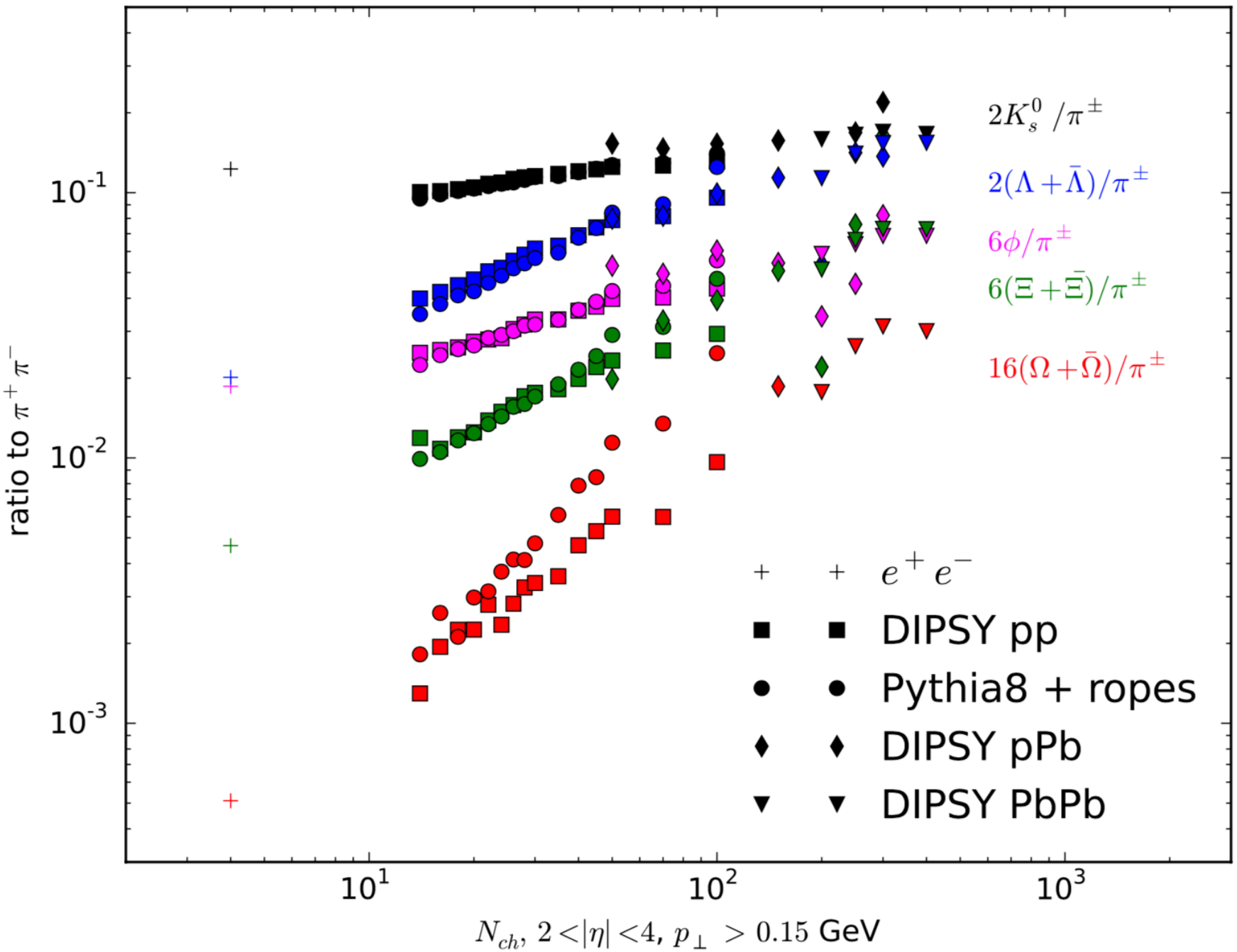
ϕ meson shows enhancement with increasing $dN_{ch}/d\eta$

does not behave as a hadron with zero strangeness quantum number

Ξ/ϕ is constant within uncertainties for $dN_{ch}/d\eta > 10$

the ϕ meson behaves ~ as a particle made of two strange quarks

Colour ropes



high density
string overlap and form colour ropes

larger string tension

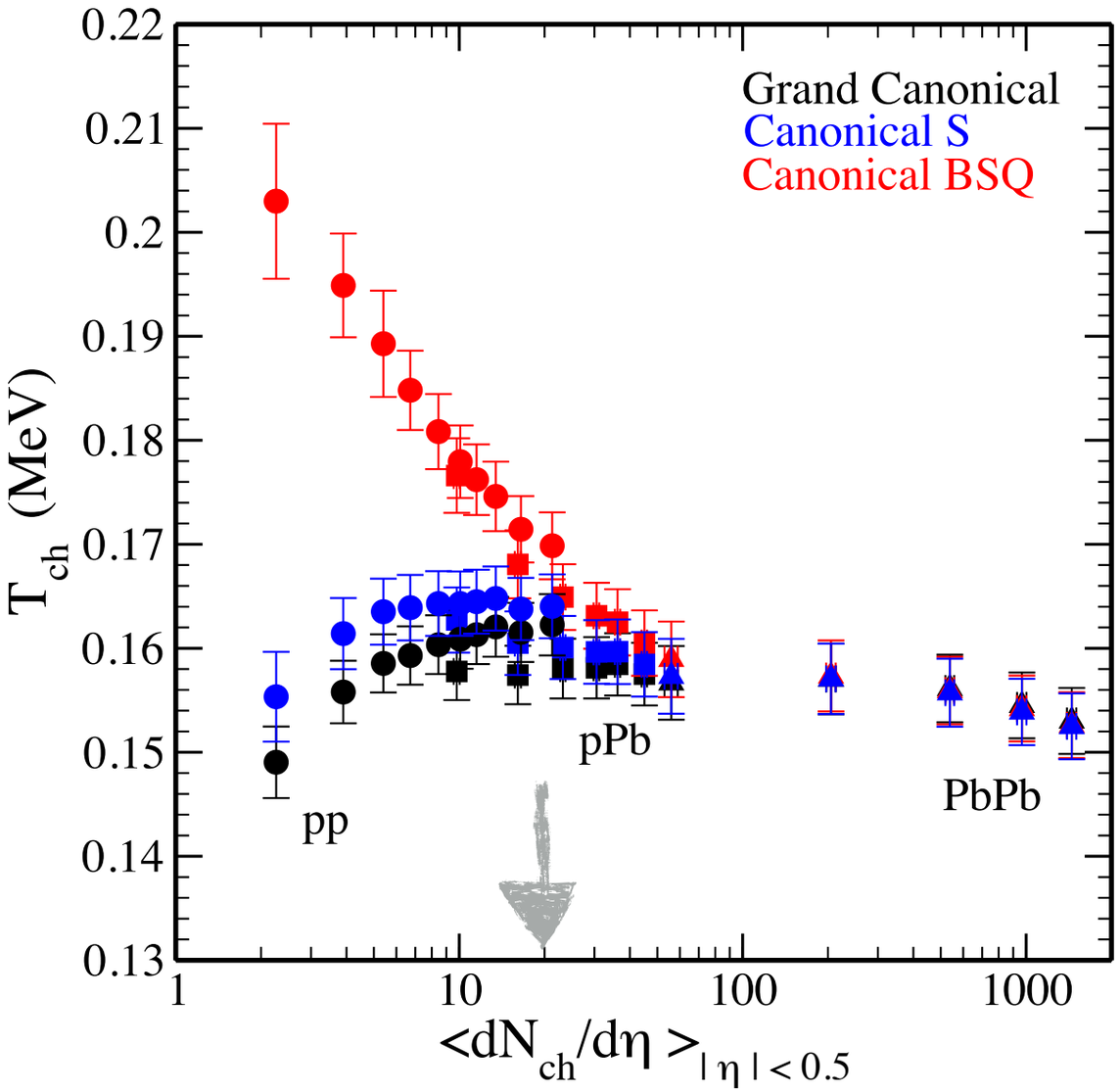
larger production of strangeness

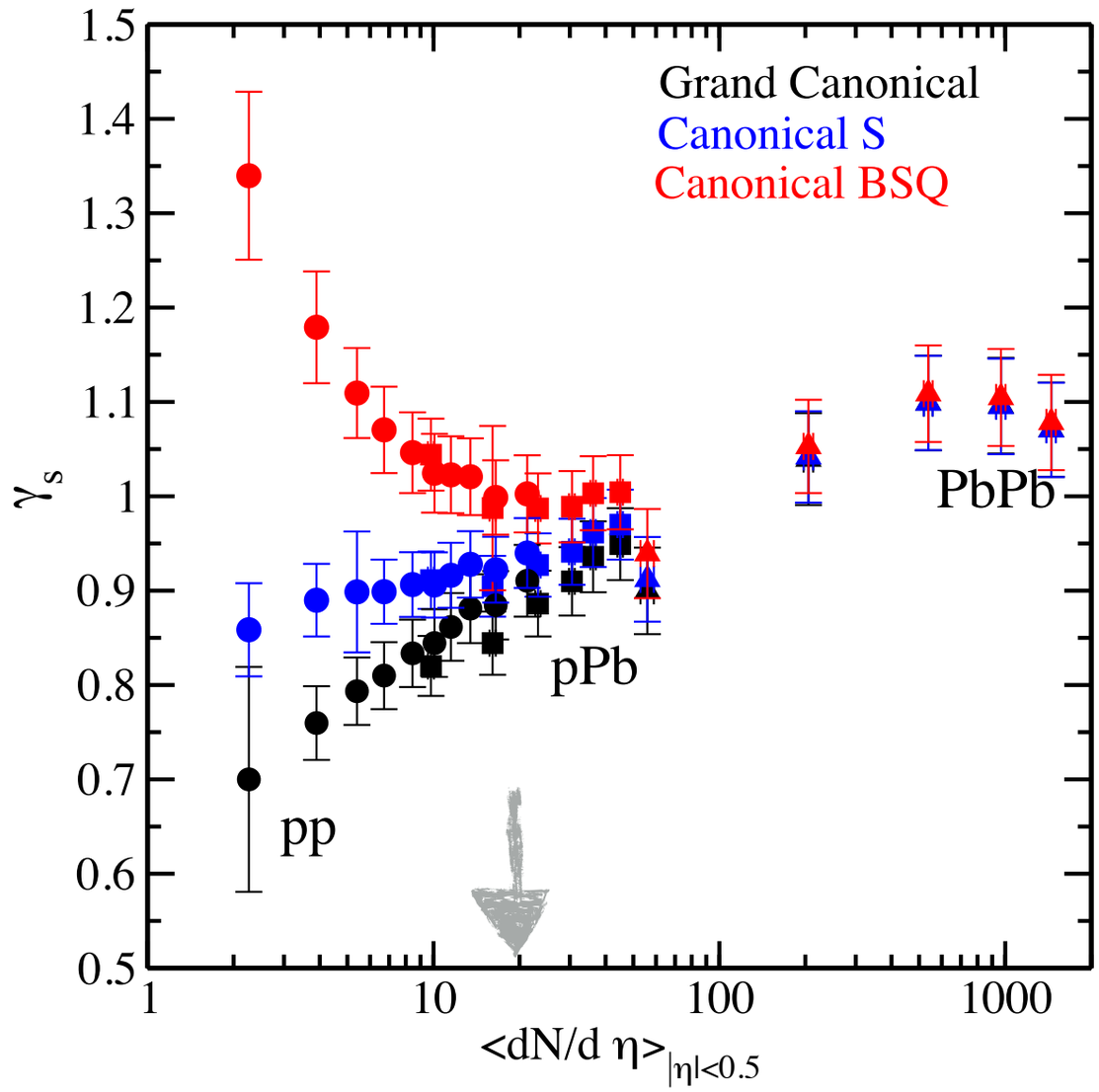
C. Bierlich, https://indico.cern.ch/event/732345

Thermal unification

three different ensembles to analyse pp, p-Pb and Pb-Pb

GC, GC with exact S, GC with B+S+Q conservation





same results for dN_{ch}/dη > 20

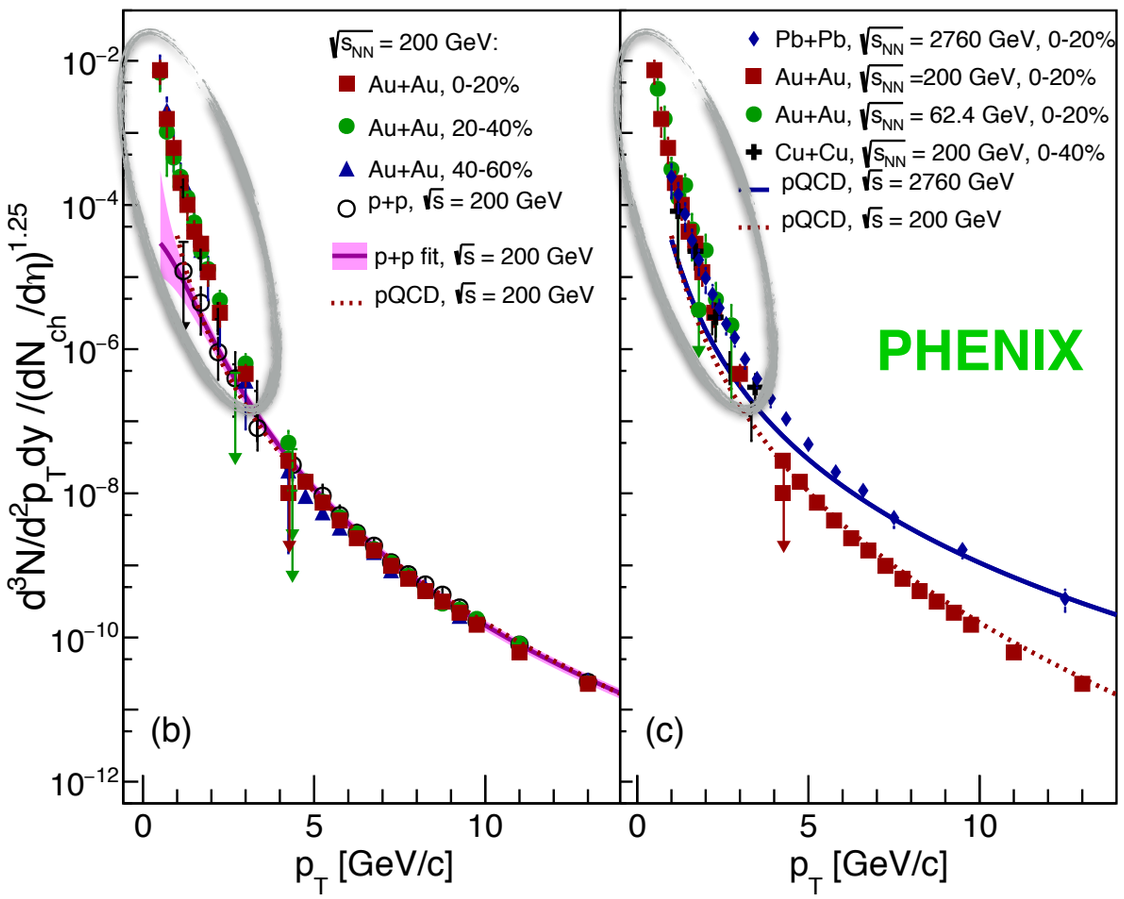
ϕ-meson not included in the fits

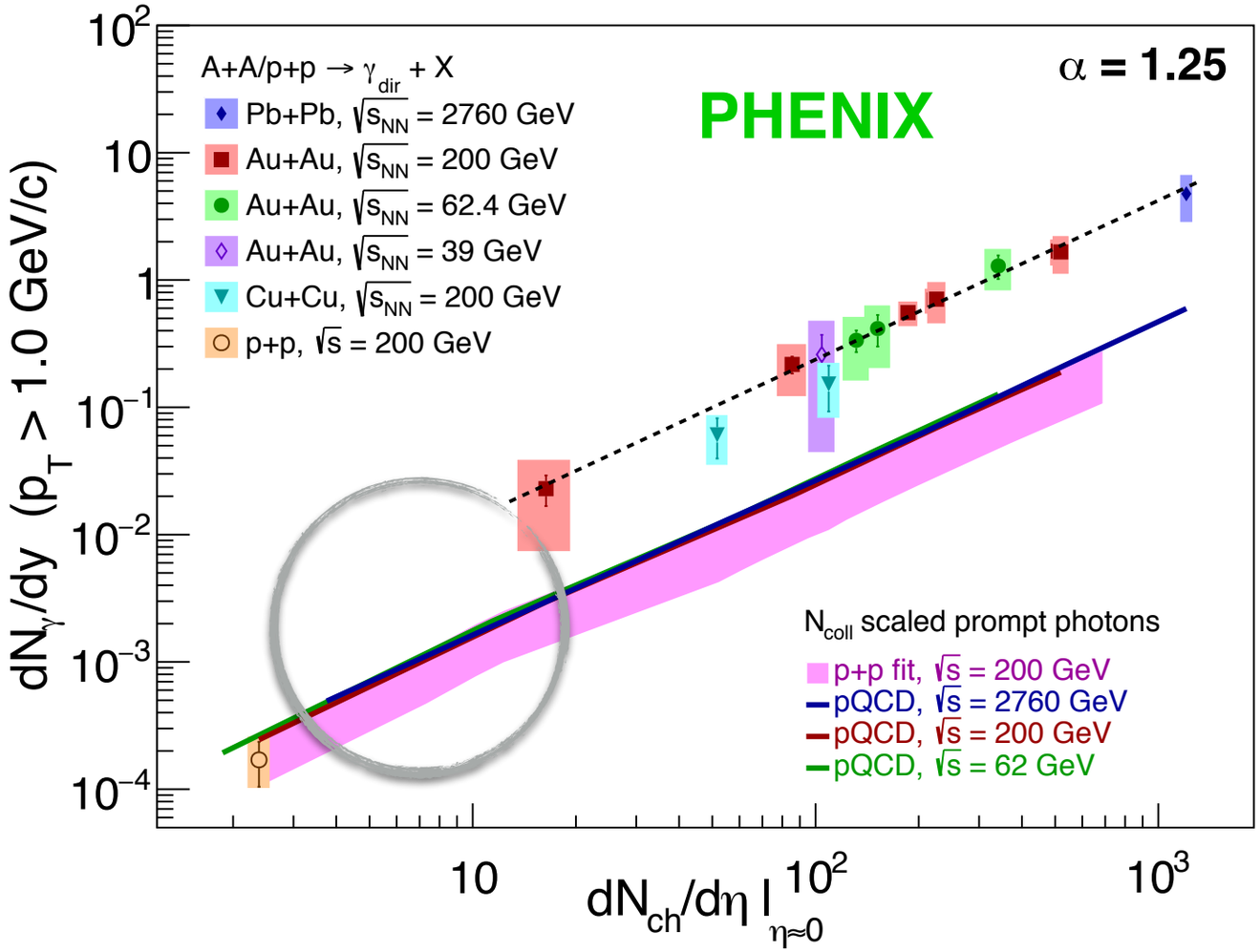
Sharma et al., PRC 99 (2019) 044914

Photon radiation

RHIC versatility: different collision systems and energies

Au-Au and Cu-Cu: large excess of direct photons over scaled pp





low-p_T photon yields: **universal scaling with N_{ch} (a = 1.25) in A-A**
independent of centrality, collision system or energy → from RHIC to LHC

transition with N_{ch} from pp to enhanced A-A yields?

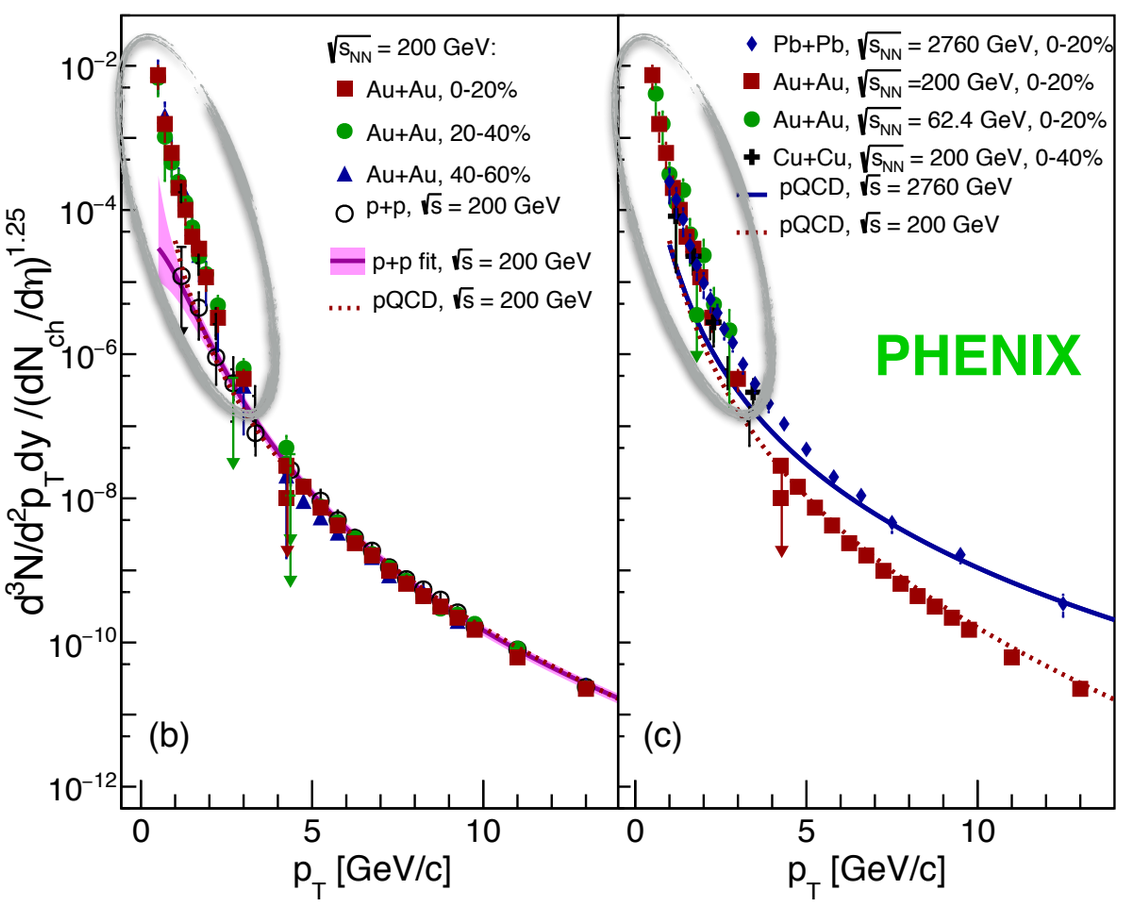
PHENIX, arXiv:1805.04084 [hep-ex]

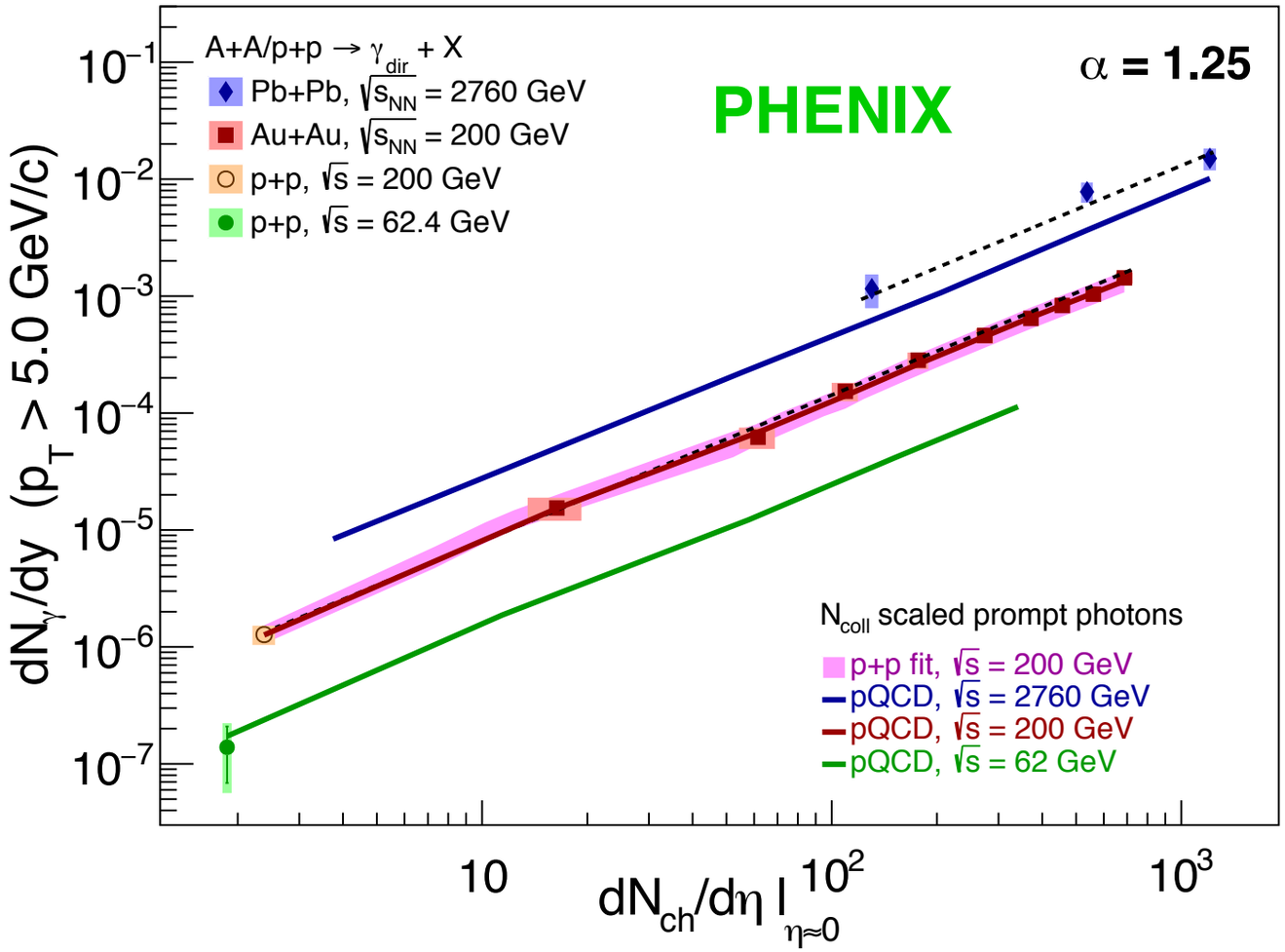
Photon radiation

RHIC versatility: different collision systems and energies

Au-Au and Cu-Cu: large excess of direct photons over scaled pp

PHENIX, arXiv:1805.04084

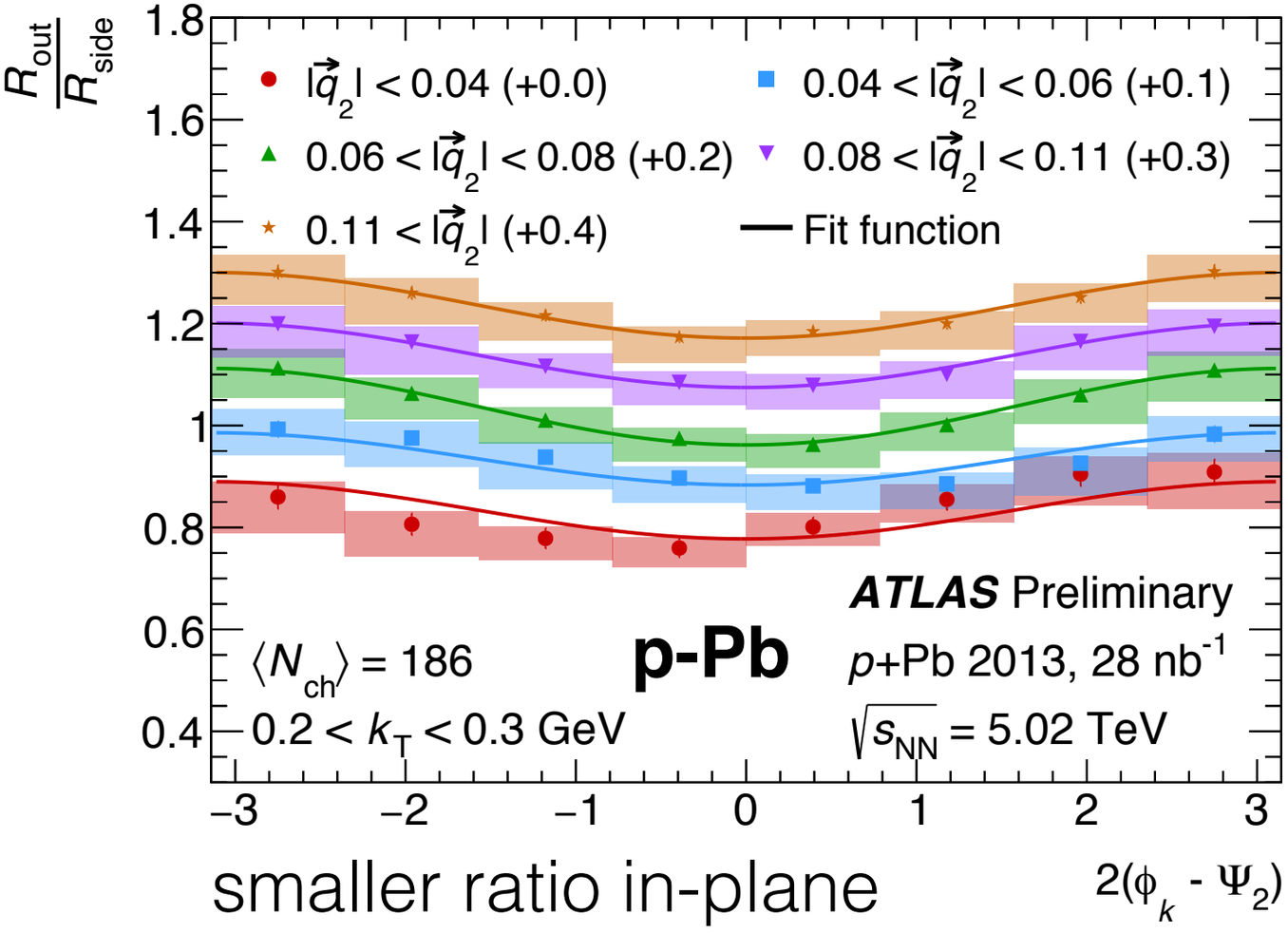




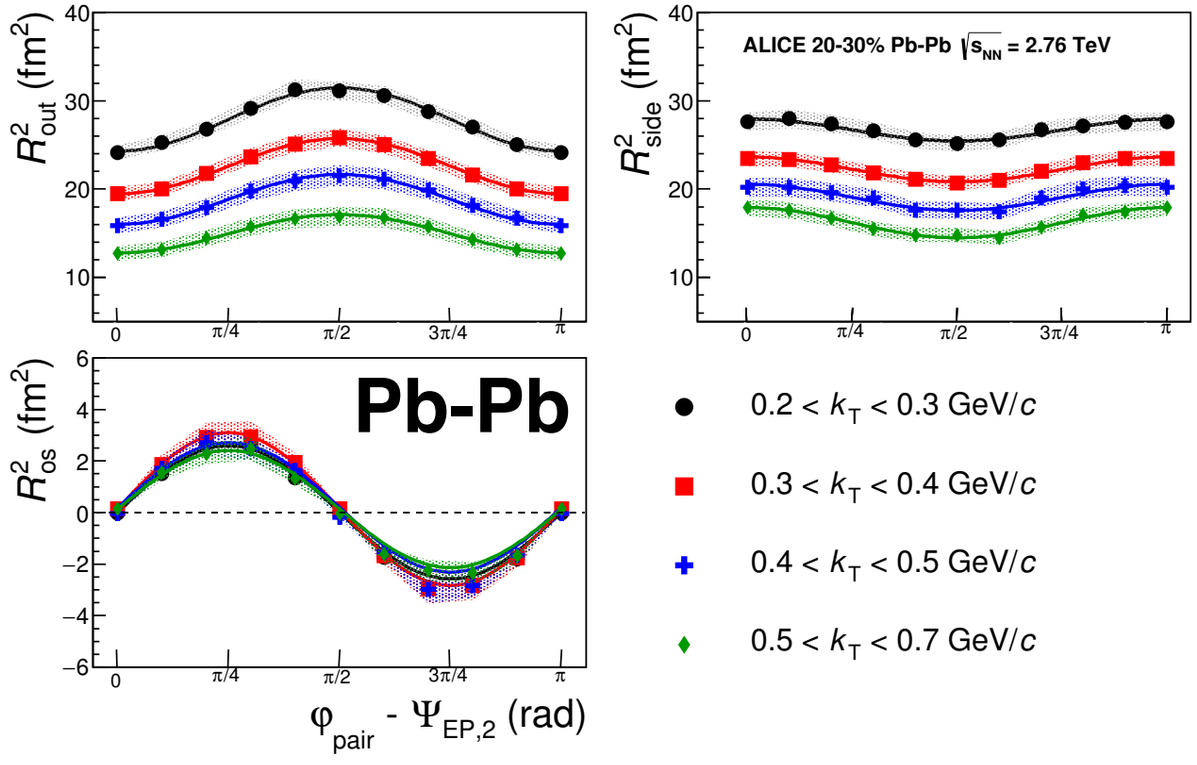
low-p_T photon yields: **universal scaling with N_{ch} (a = 1.25) in A-A**
independent of centrality, collision system or energy → from RHIC to LHC

transition with N_{ch} from pp to enhanced A-A yields?

Azimuthal femtoscopy in p-Pb



ALICE, PRL 118 (2017) 222301



HBT radii wrt. 2nd-order event-plane in p-Pb

measured in central 0-1% events vs. flow vector magnitude $|q_2|$

qualitatively similar to Pb-Pb, consistent within hydro picture

source expands more explosively along the event plane

ATLAS, ATLAS-CONF-2017-008