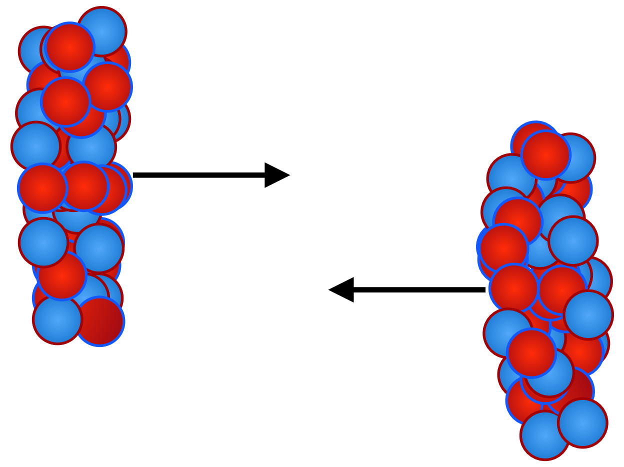
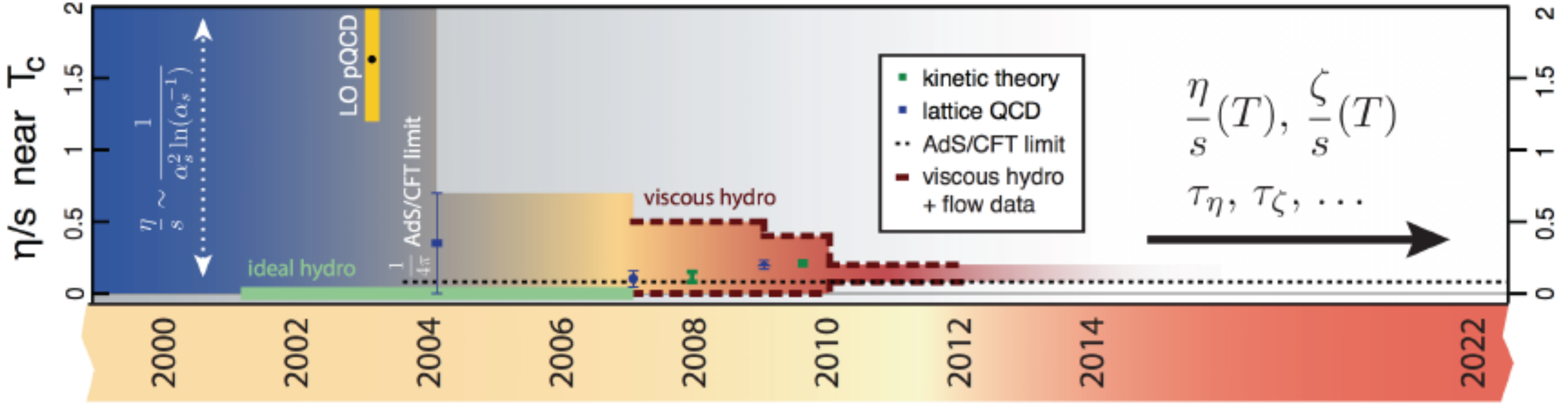
ANISOTROPIC FLOW STUDIES





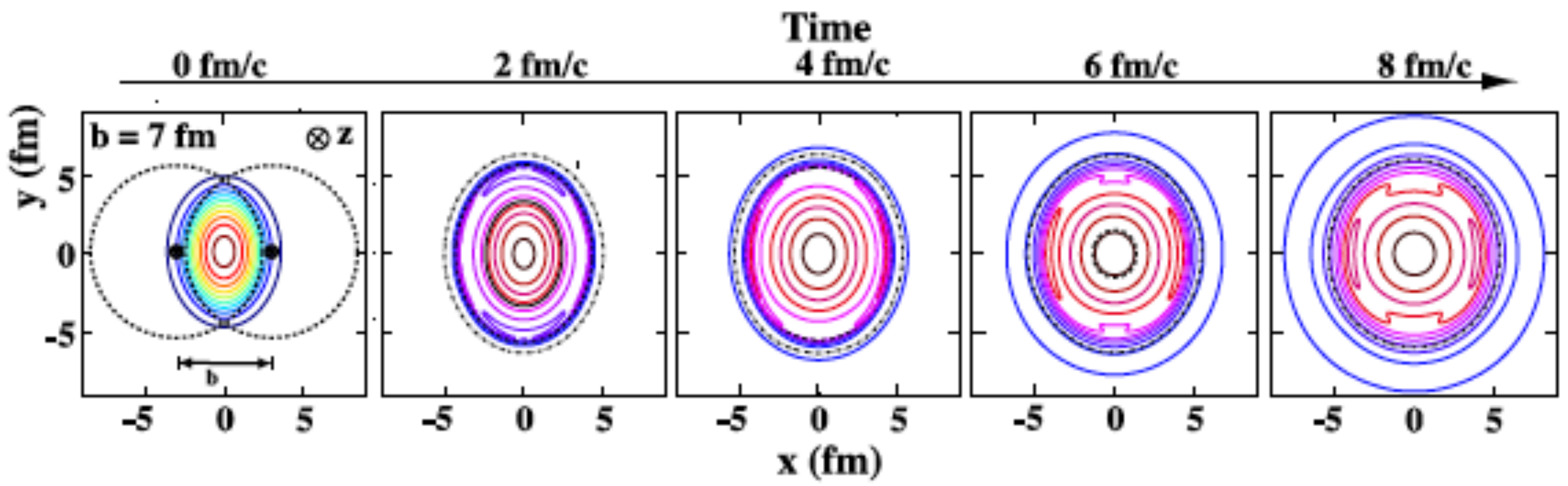
Panos Christakoglou

Nikhef and Utrecht University

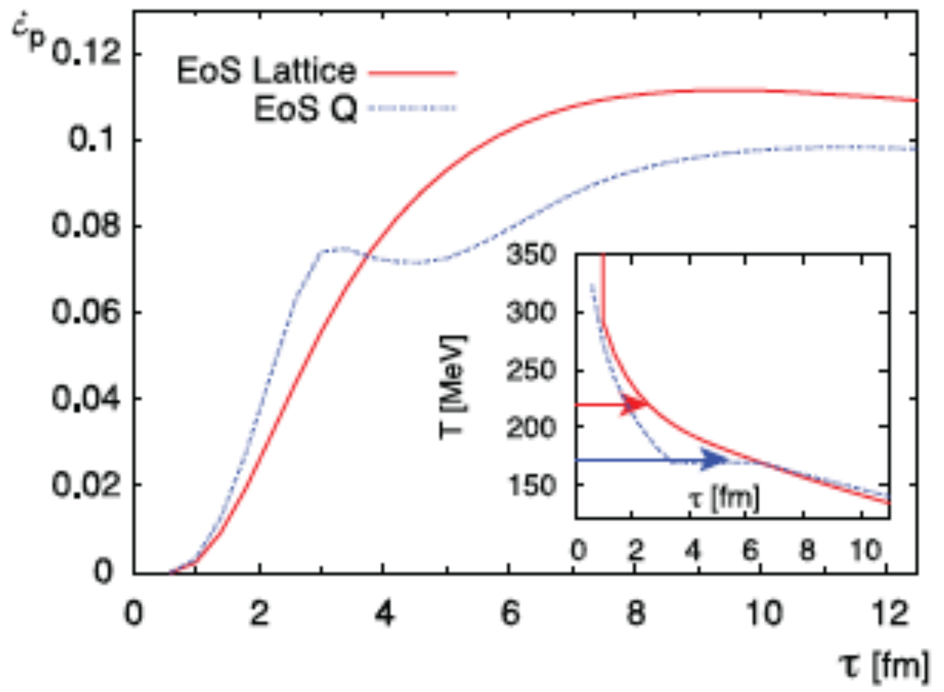
Nikhef

ANISOTROPIC FLOW

Coordinate space: eccentricities



Momentum space: flow harmonics



Anisotropies in coordinate space

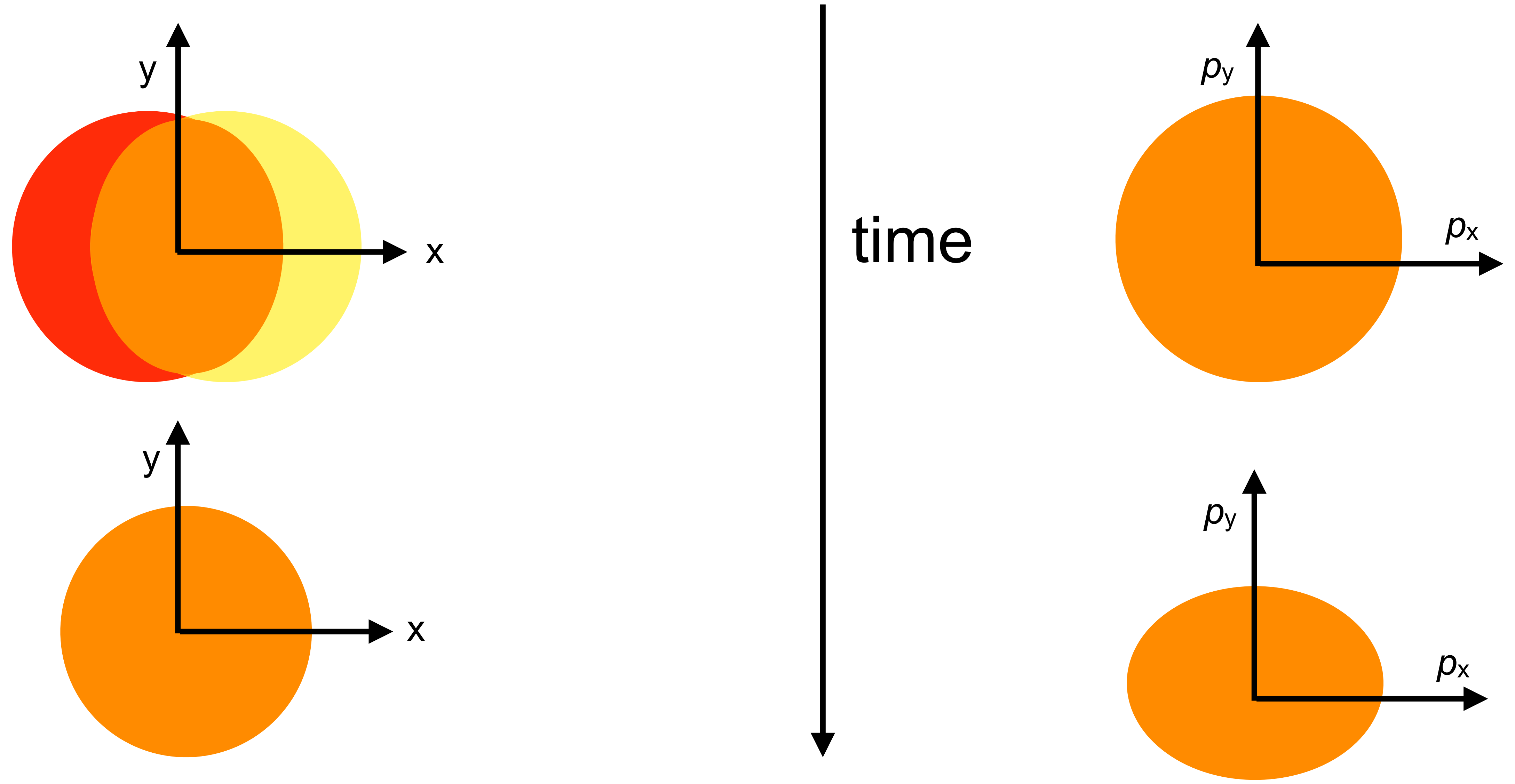
- Initial geometry and its fluctuations

Transferred to anisotropies in momentum space

Quantified by Fourier coefficients v_n

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$\epsilon_P = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$

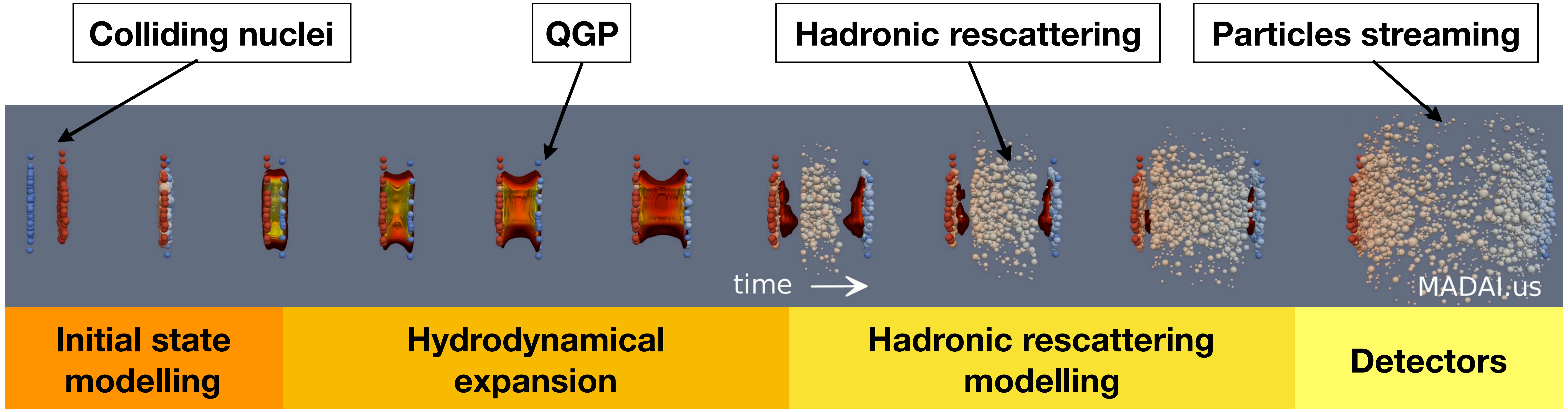


$$E\frac{d^3}{dP^3} = \frac{1}{2\pi}\frac{d^2N}{p_\mathrm{T}dp_\mathrm{T}d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_\mathrm{n}(p_\mathrm{T},\eta)\cos[n(\varphi - \Psi_\mathrm{n})]\right]$$

$$v_\mathrm{n} = \langle \cos[n(\varphi - \Psi_\mathrm{n})] \rangle$$

Voloshin and Zhang, Z. Phys. **C70** (1996) 665

ANISOTROPIC FLOW AS A PROBE OF:



Initial State (IS)

Equation of State (EoS)

Viscous hydrodynamical expansion + transport properties

- $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$,…

Highly dissipative hadronic rescattering phase

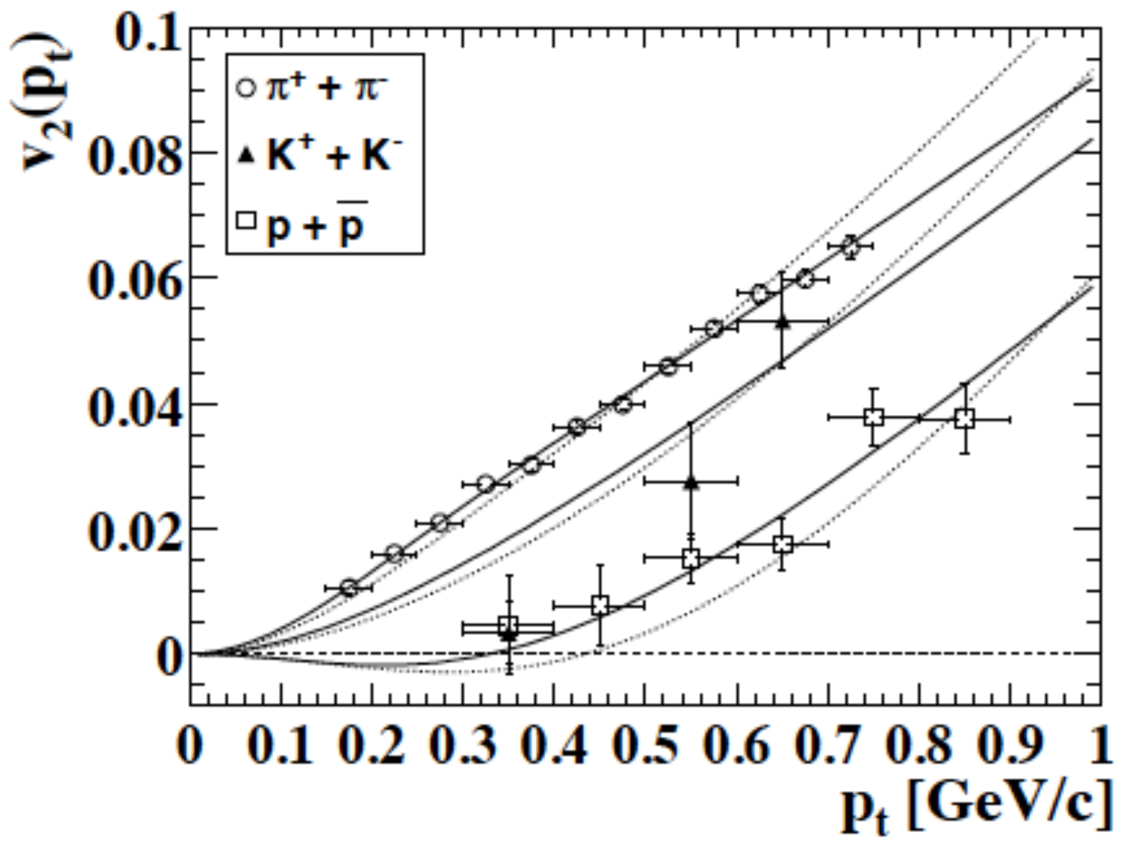
Can also probe the opacity of the system

- Path length energy loss

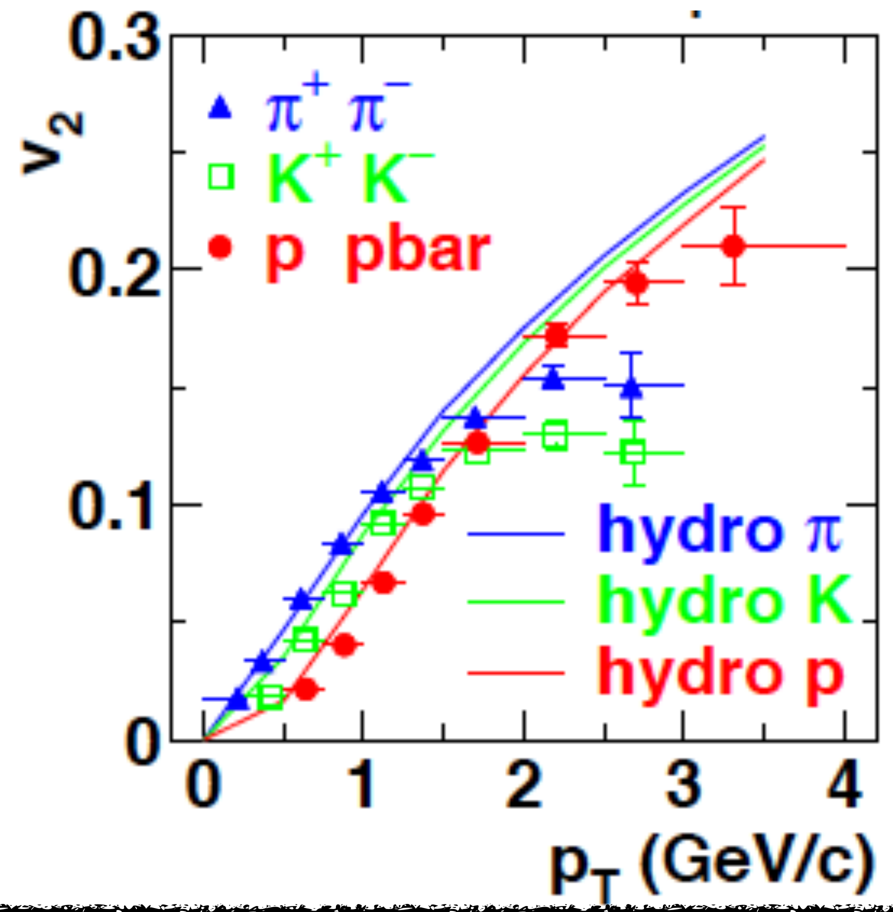
Nikhef

THE BIRTH OF THE S-QGP PARADIGM

(STAR Collaboration): Phys. Rev. Lett. 87 (2001) 182301



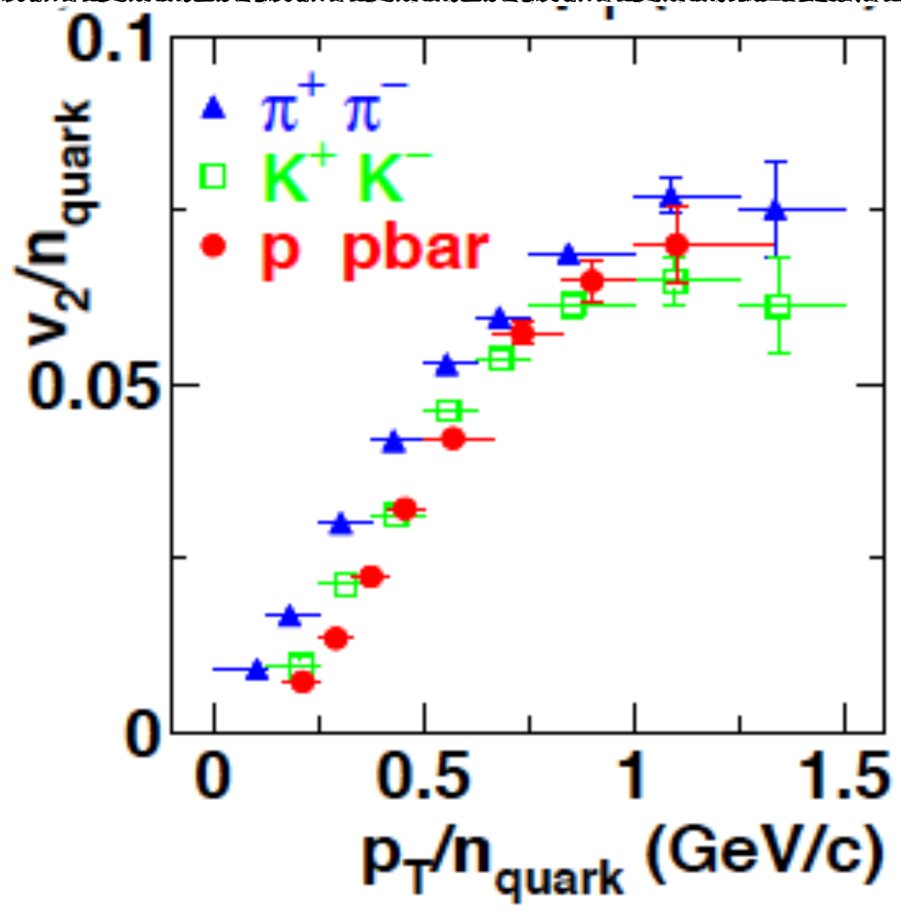
(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



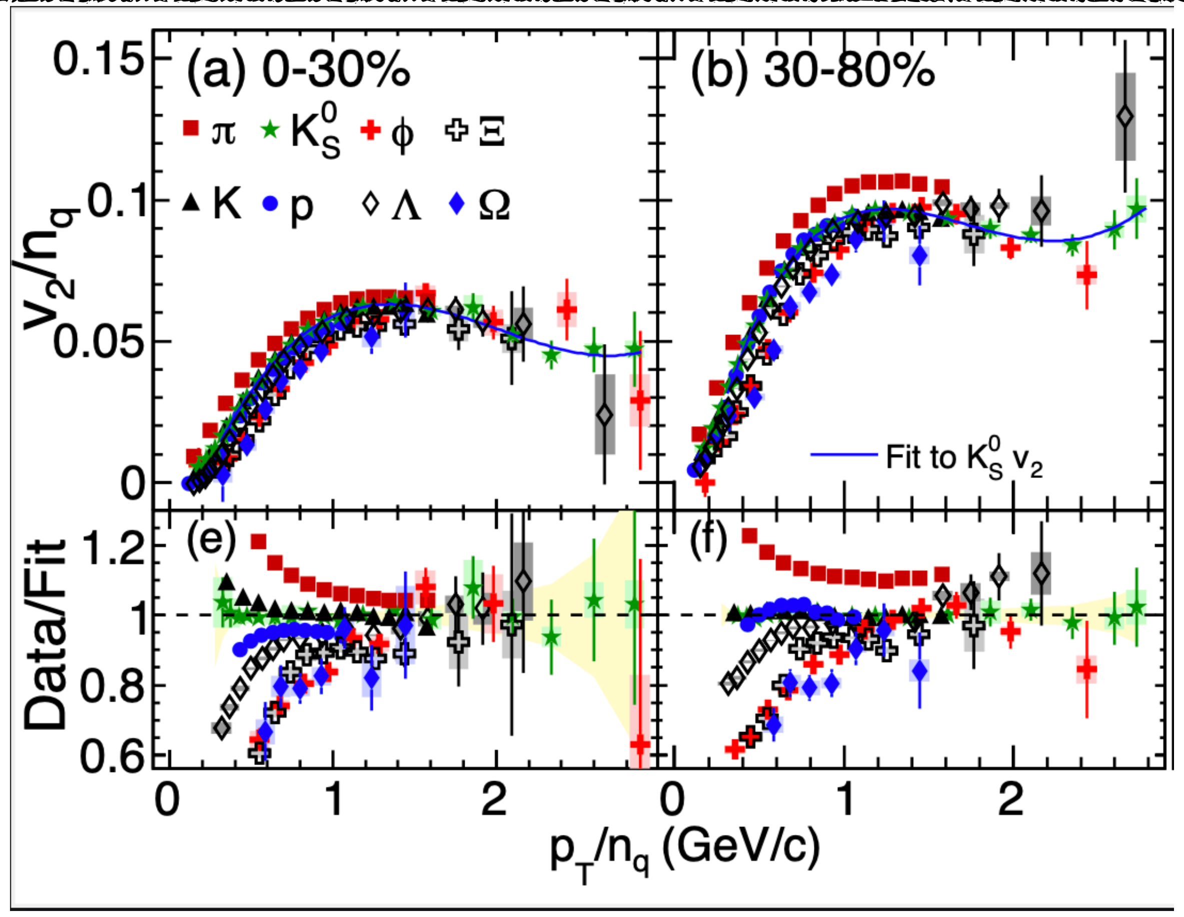
Low p_T region

- Interplay between radial flow and anisotropic geometry → mass ordering

(PHENIX Collaboration): Phys.Rev.Lett.91, 182301,2003



(STAR Collaboration): Phys. Rev. Lett. **116** (2016) 62301

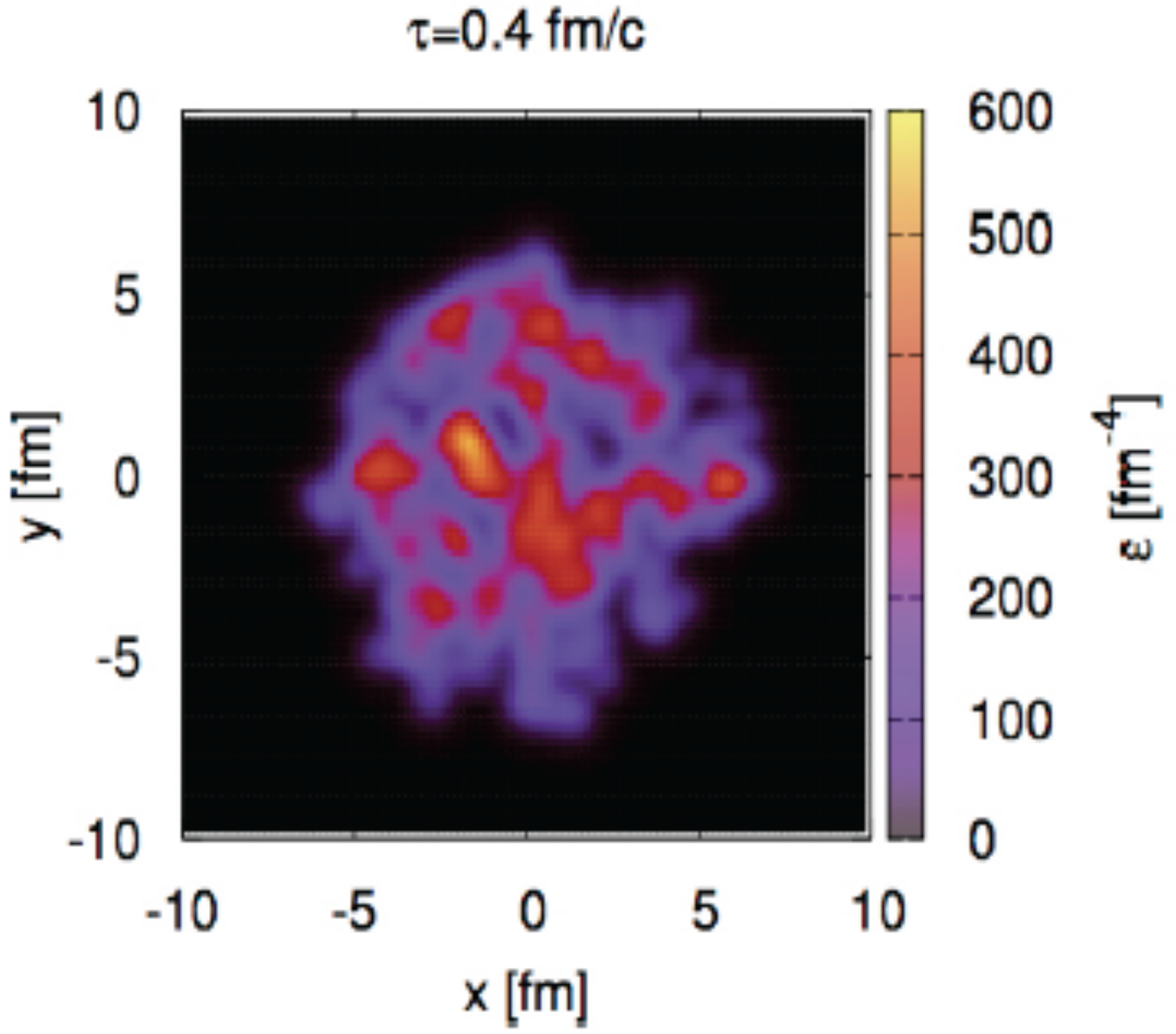


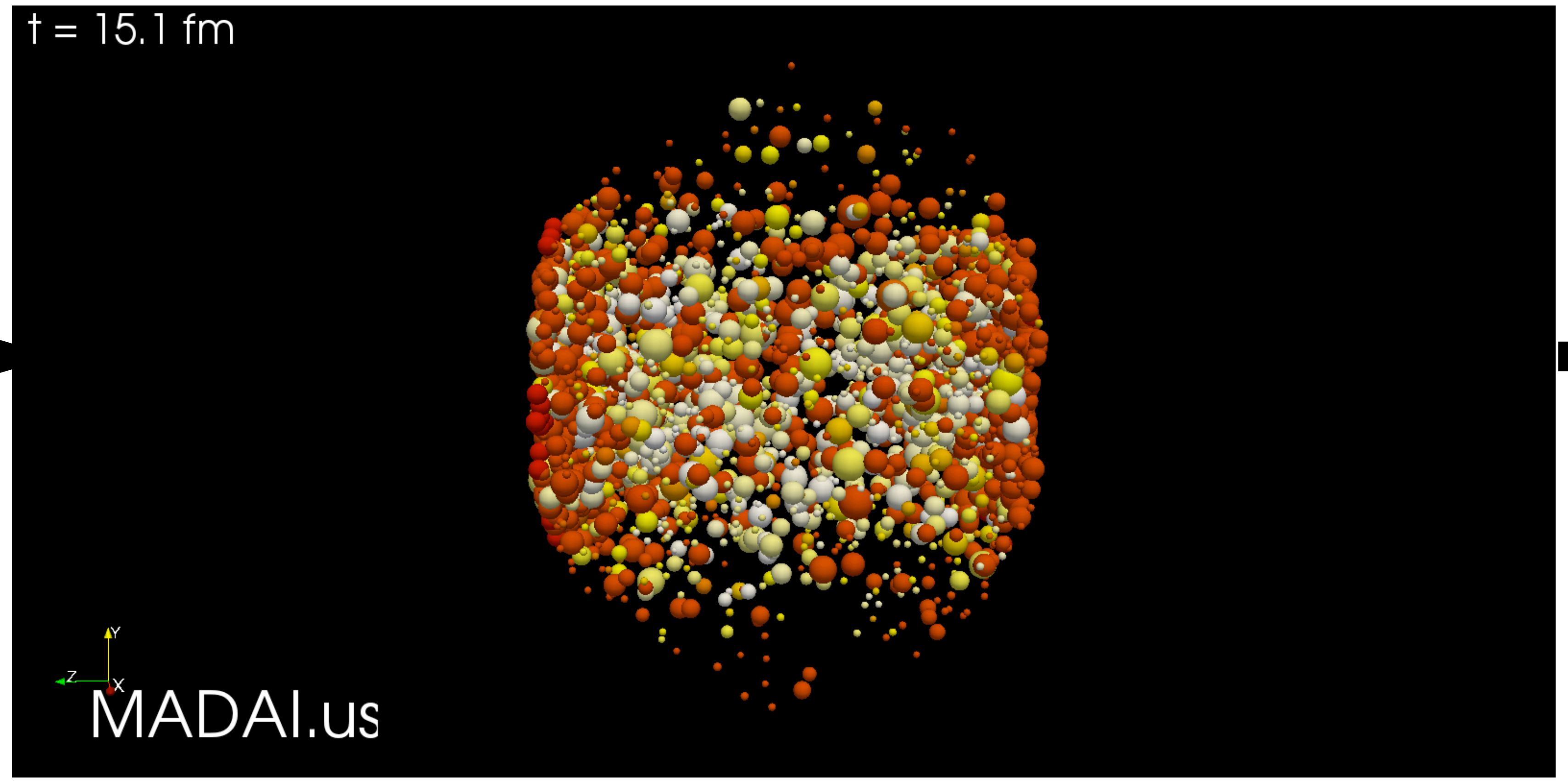
Intermediate p_T region

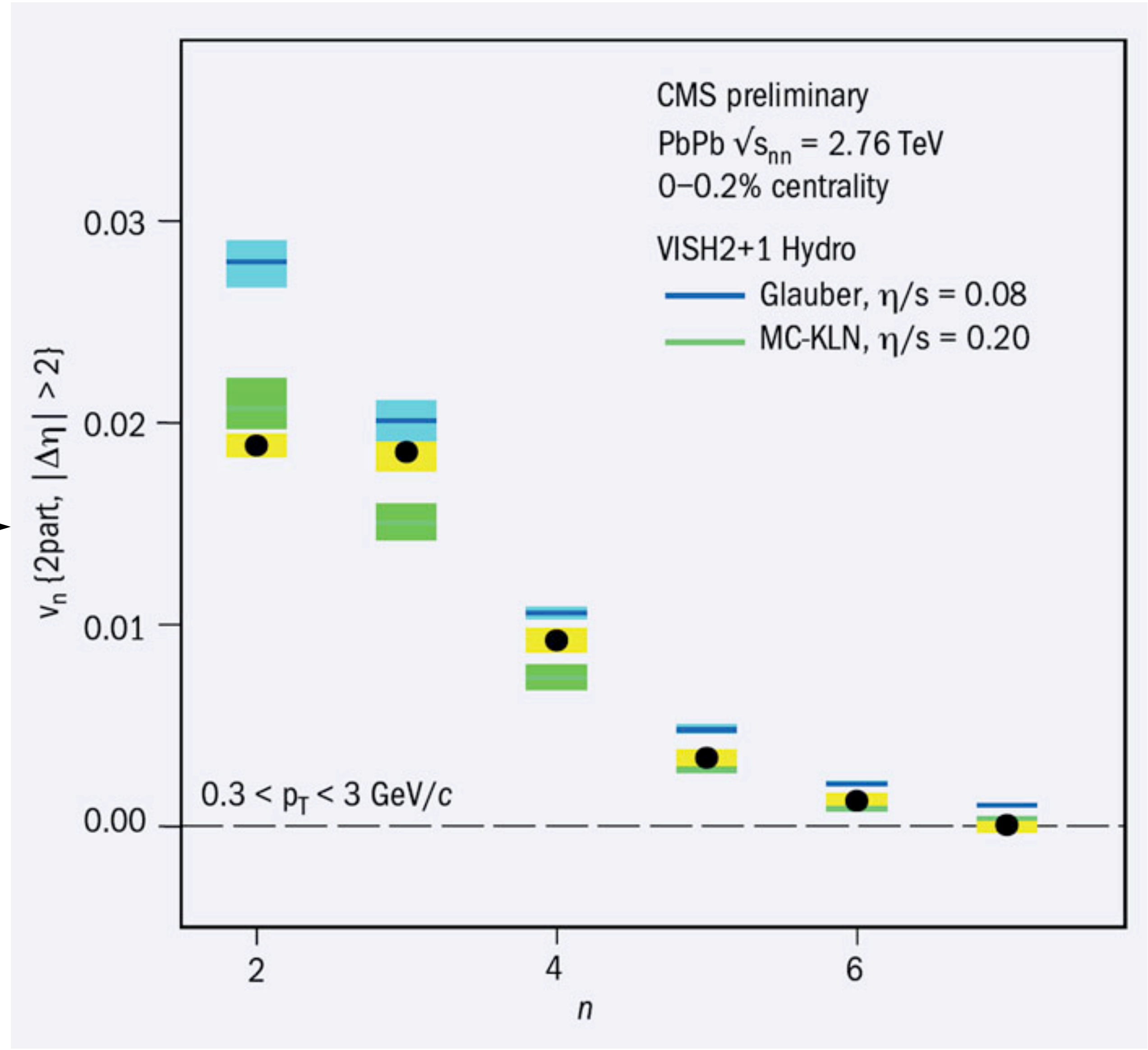
- Coalescence as particle production mechanism (?) → number of constituent quark (NCQ) scaling

HIGHER HARMONICS

Initial state fluctuations → transferred via the low viscosity QGP → into final state correlations (higher, odd harmonics)







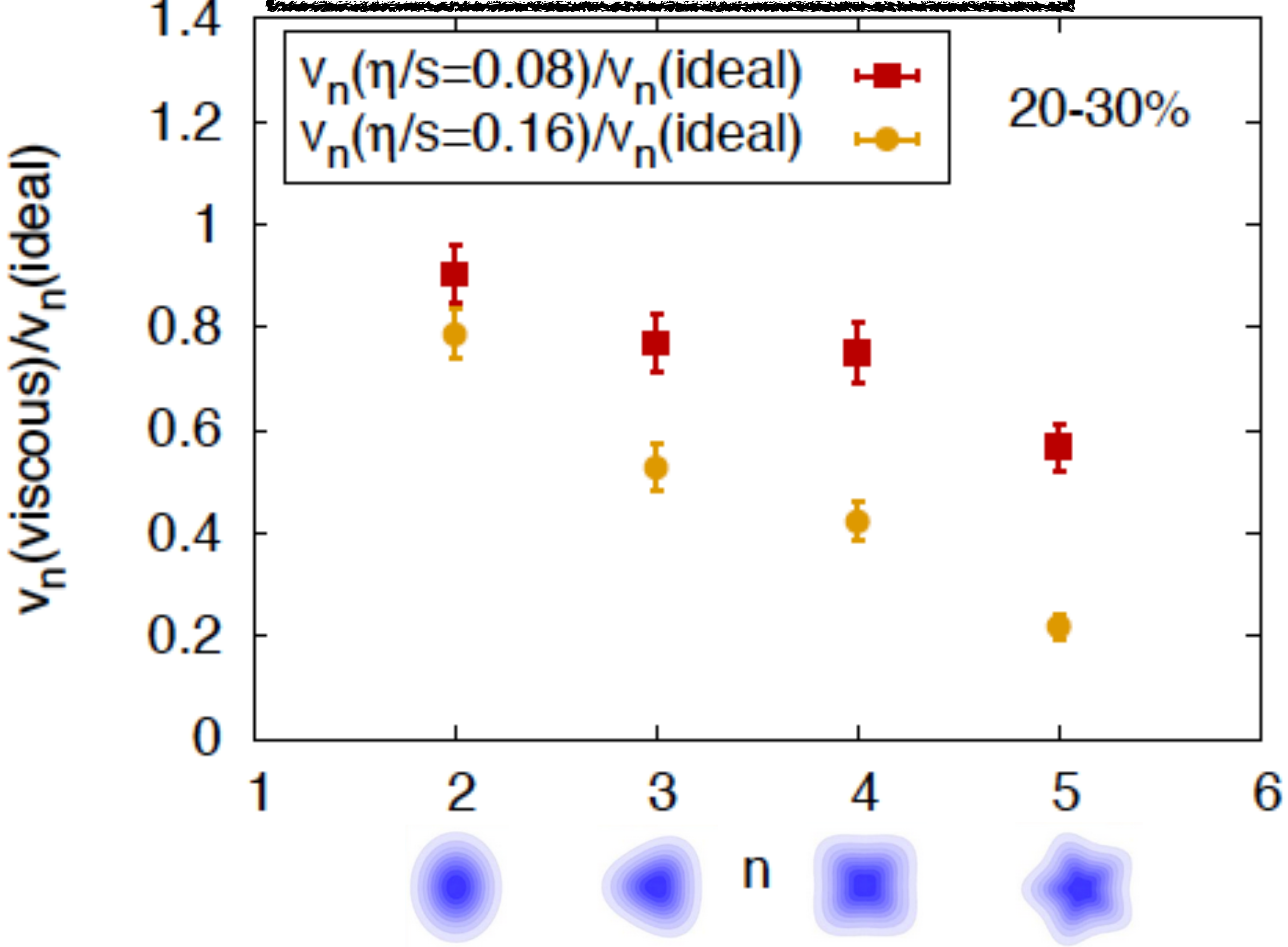
Higher harmonics represent modulations in smaller spatial scales

- More sensitive probes of the QGP transport properties
- Unique tool to constrain the IS

HIGHER HARMONICS

Relative decrease might change if different IS model is used but the trend vs harmonic is qualitatively the same

B. Schenke *et al.*, Phys.Rev. **C85** (2012) 024901

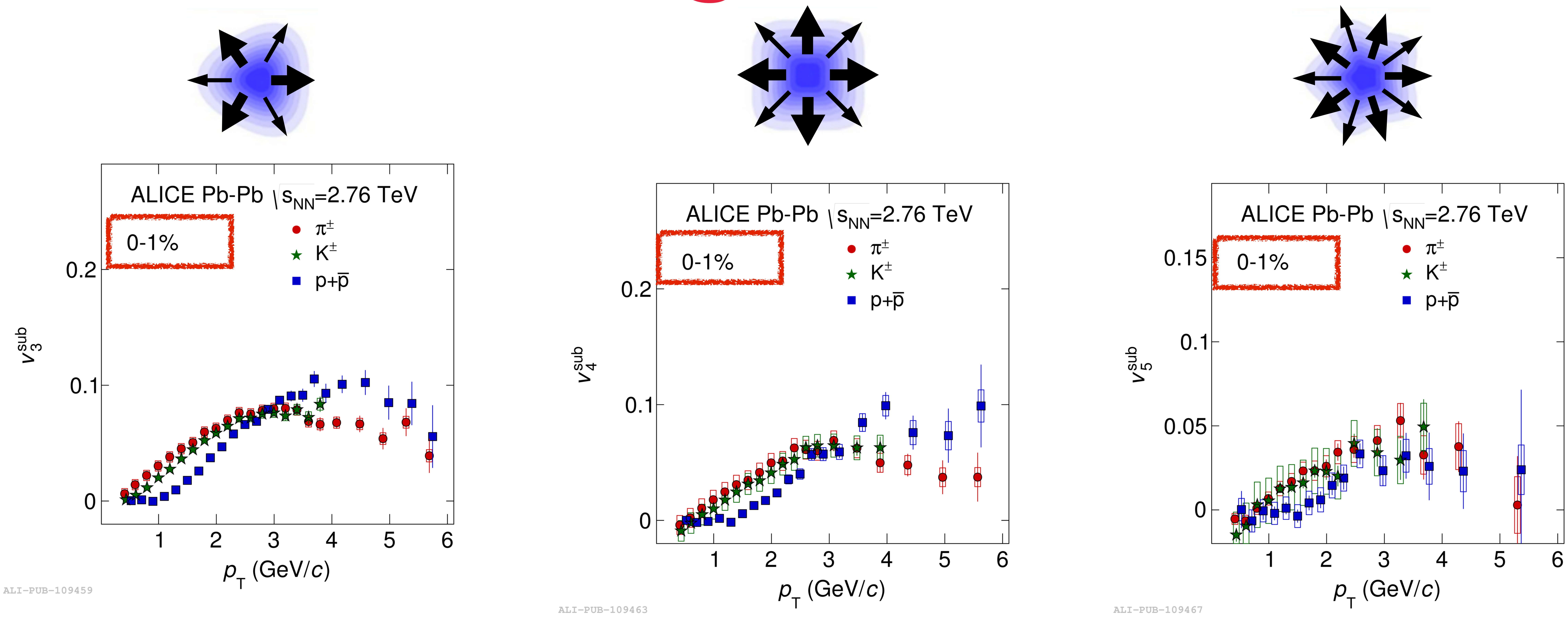


Higher harmonics represent modulations in smaller spatial scales

- More sensitive probes of the QGP transport properties
- Unique tool to constrain the IS

HIGHER HARMONICS @ LHC

B. Abelev *et al.* (ALICE Collaboration). JHEP **09** (2016) 164

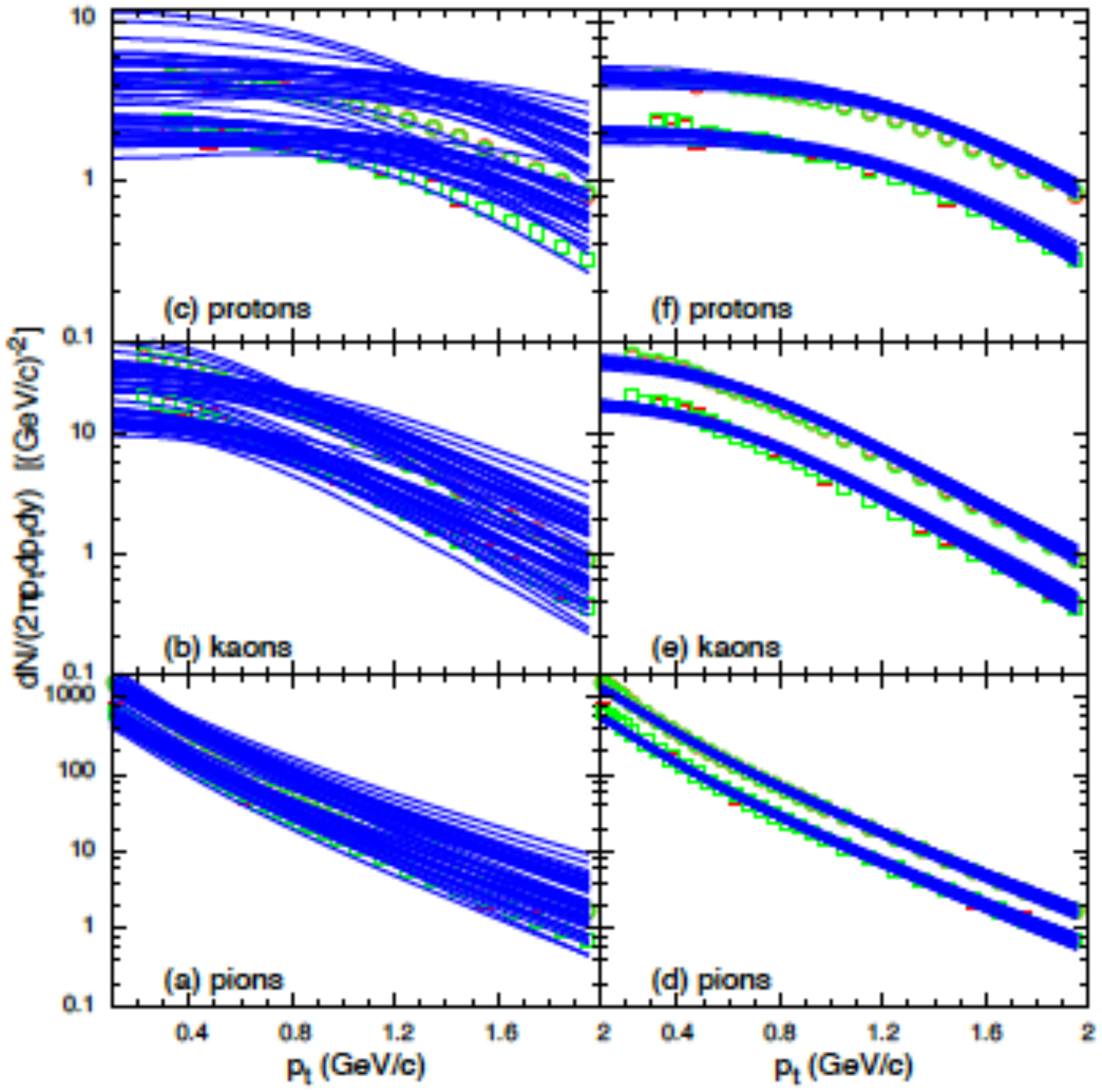


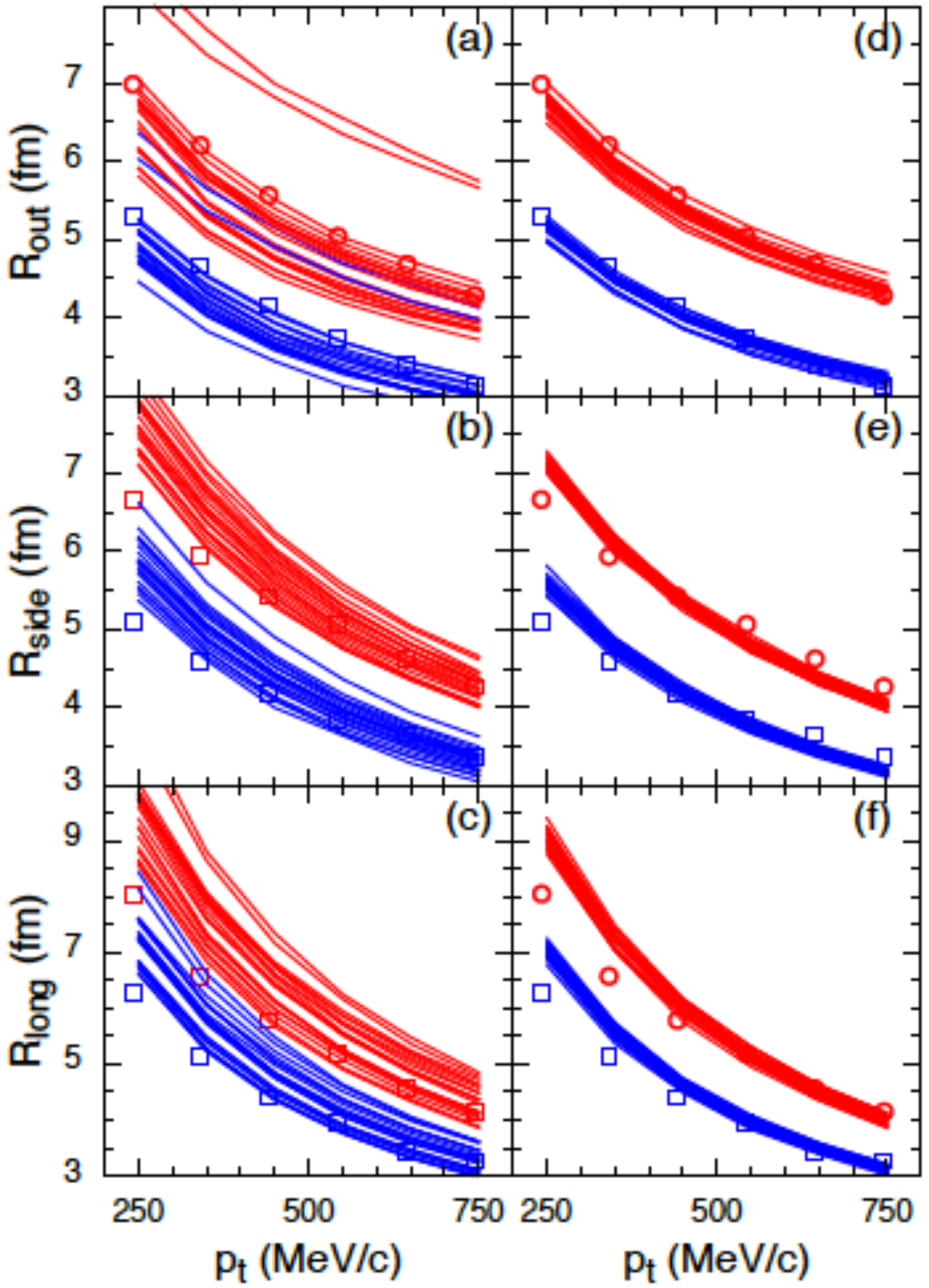
Same features for different v_n (up to v_5!) even for ultra-central collisions

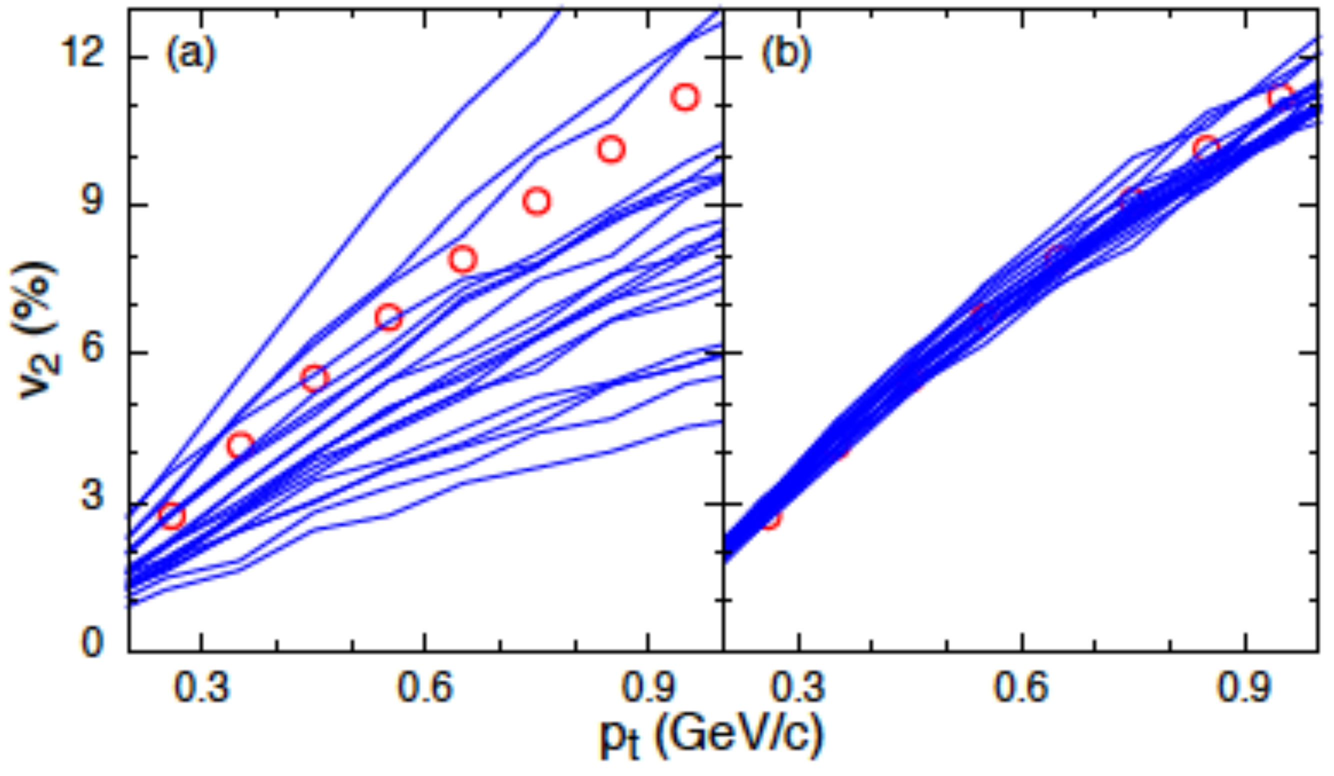
Nikhef

CONSTRAINING EOS

S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301







One of the first attempts for a global fit on data

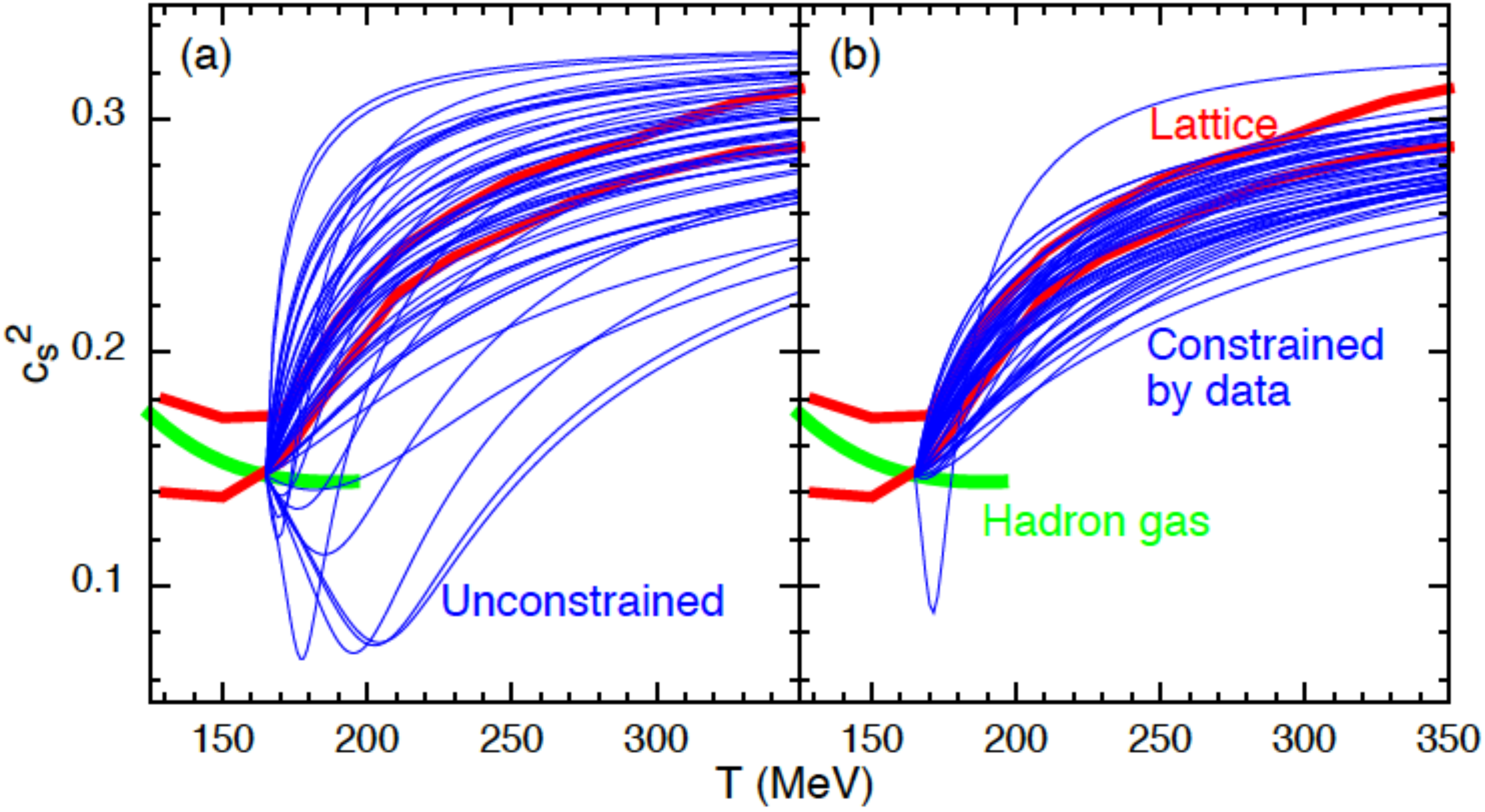
- Spectra
- HBT radii
- $v_2(p_T)$

Nikhef

CONSTRAINING EOS

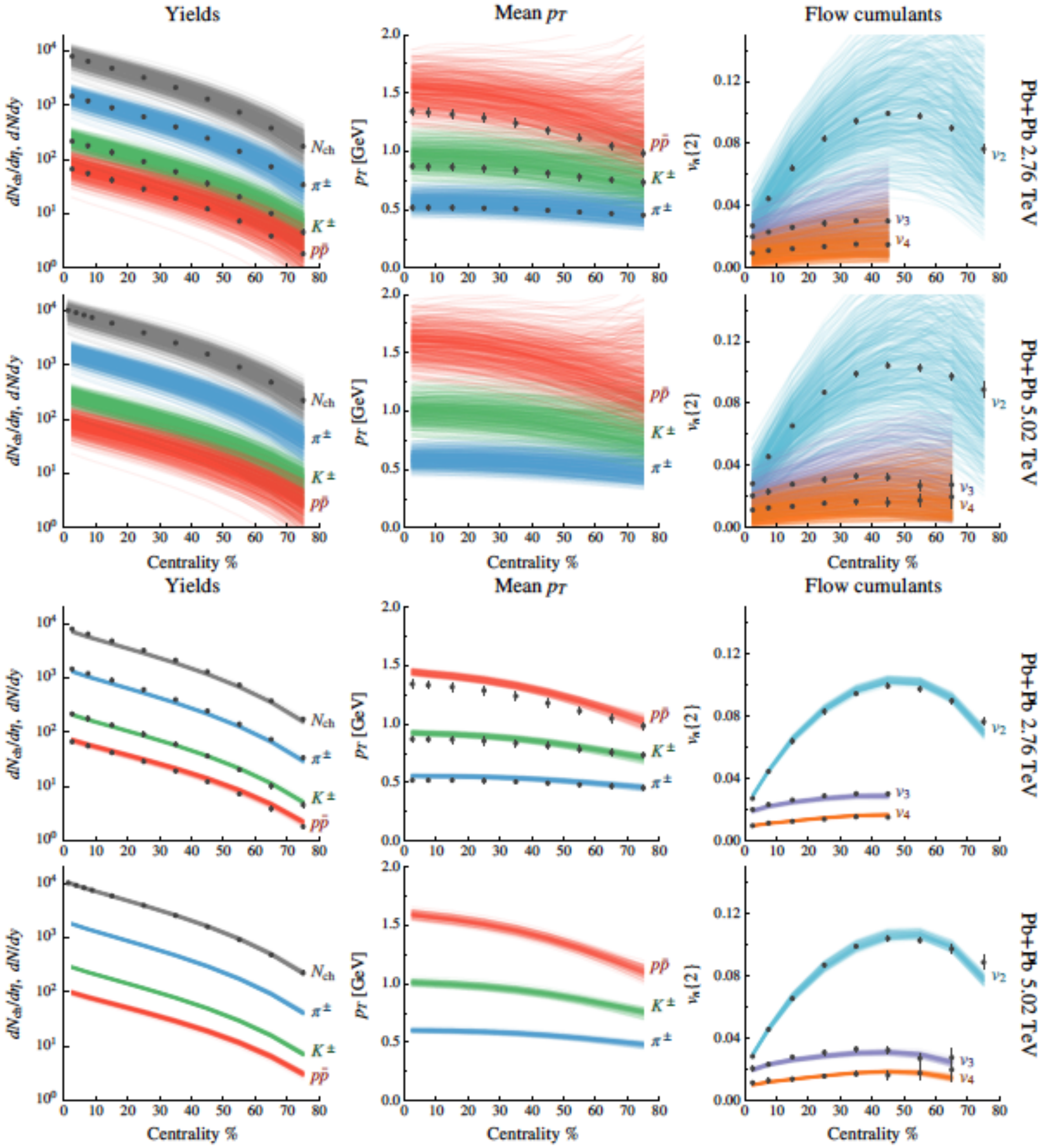
S.Pratt *et al.*, Phys. Rev. Lett. **114**, (2015) 202301

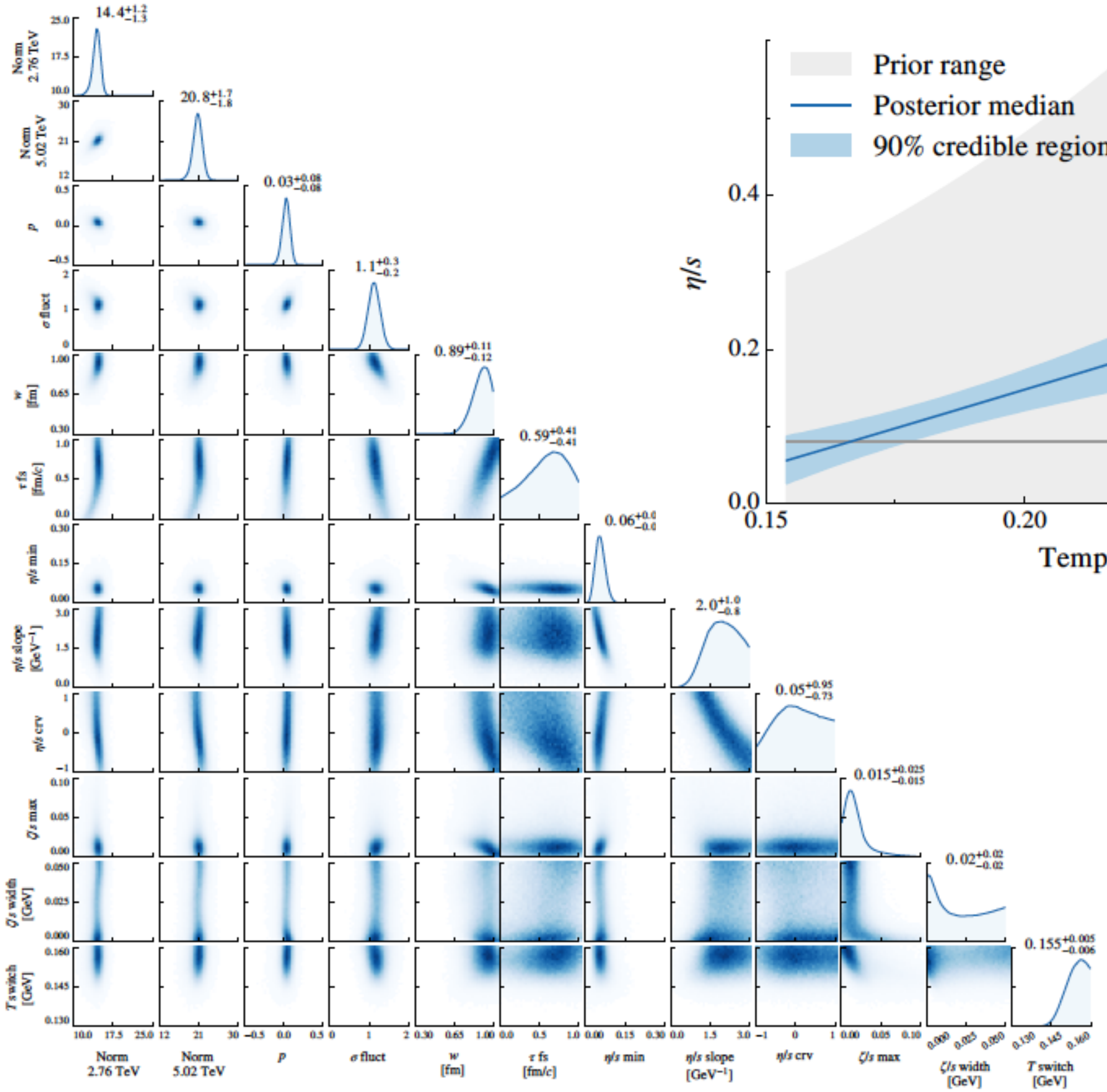
$$c_s^2 = \frac{\partial P}{\partial \epsilon}$$

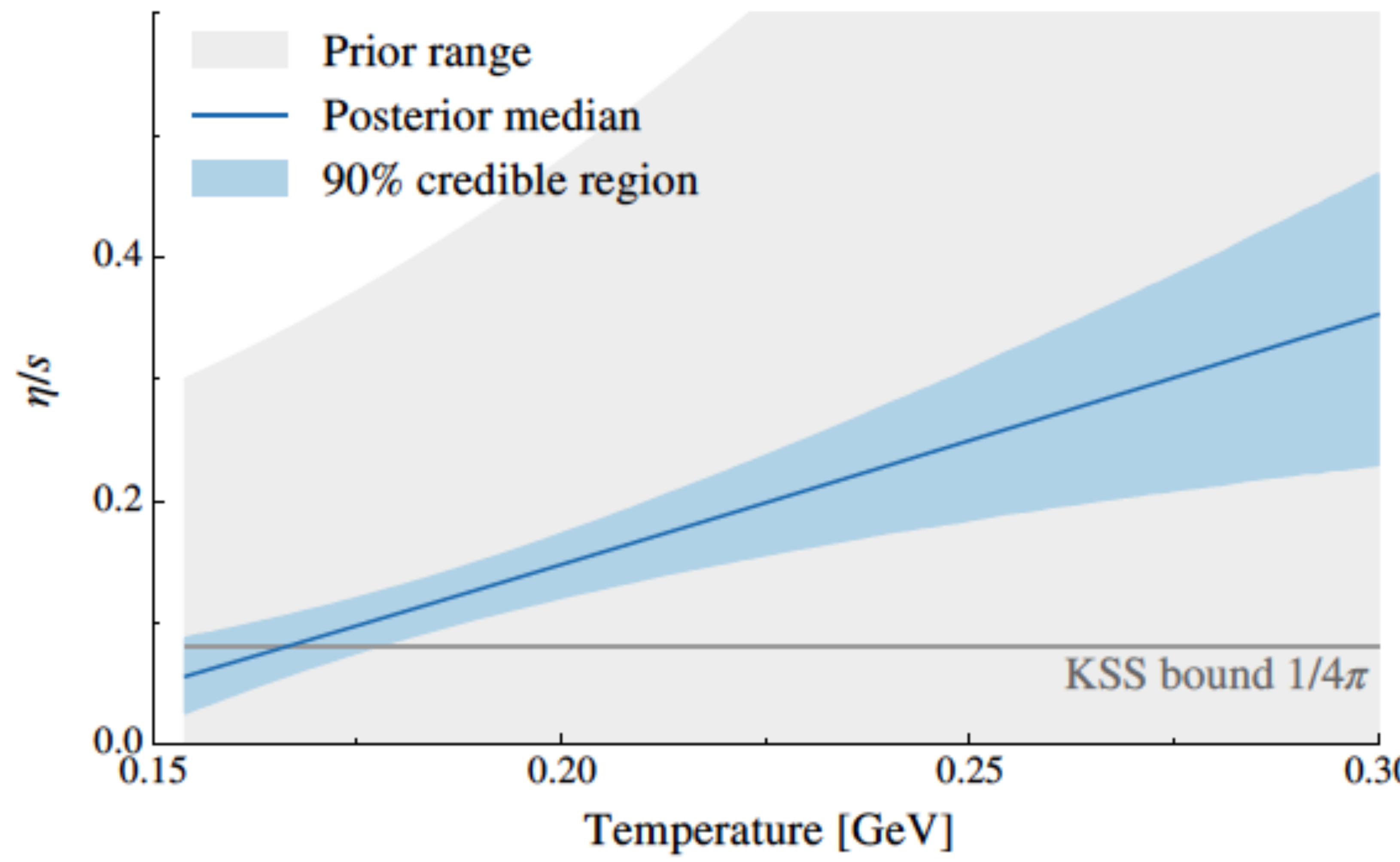


QUANTIFYING QGP TRANSPORT PROPERTIES

S. Bass *et al.*, Nucl. Phys. **A967** (2017) 67





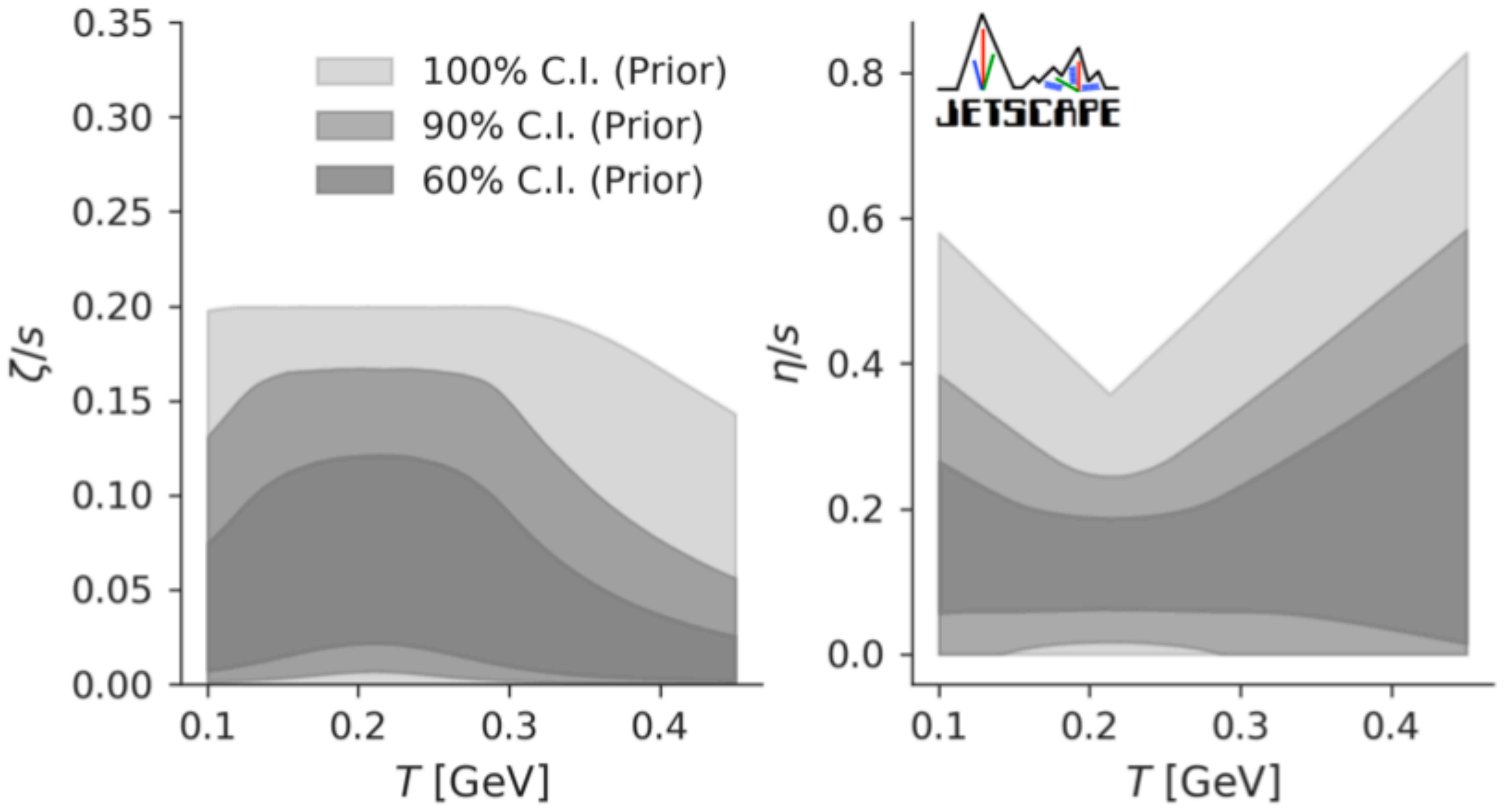


Nikhef

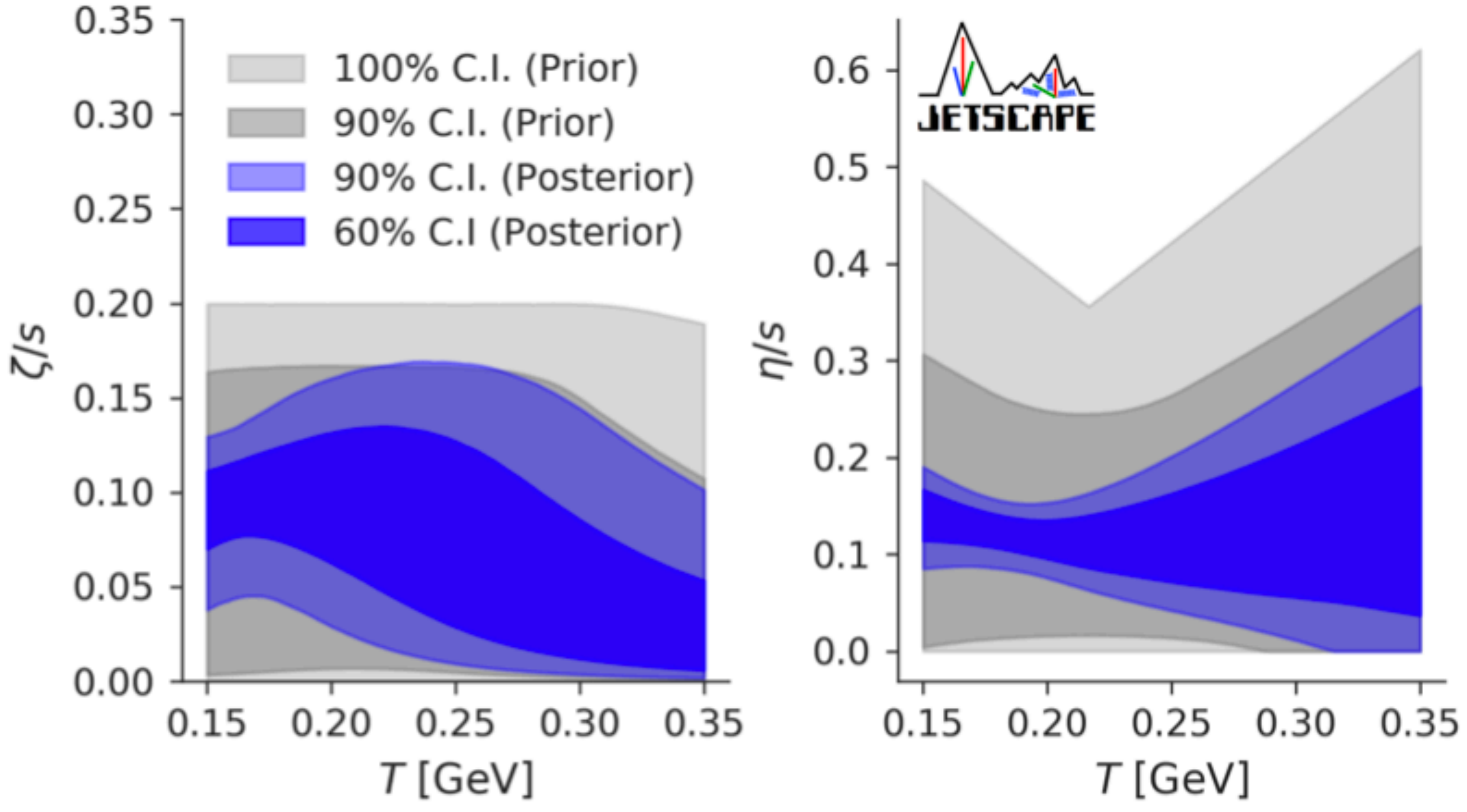
ESTIMATES FROM JETSCAPE

(JETSCAPE Collaboration) arXiv:2011.01430

Prior probability densities



+

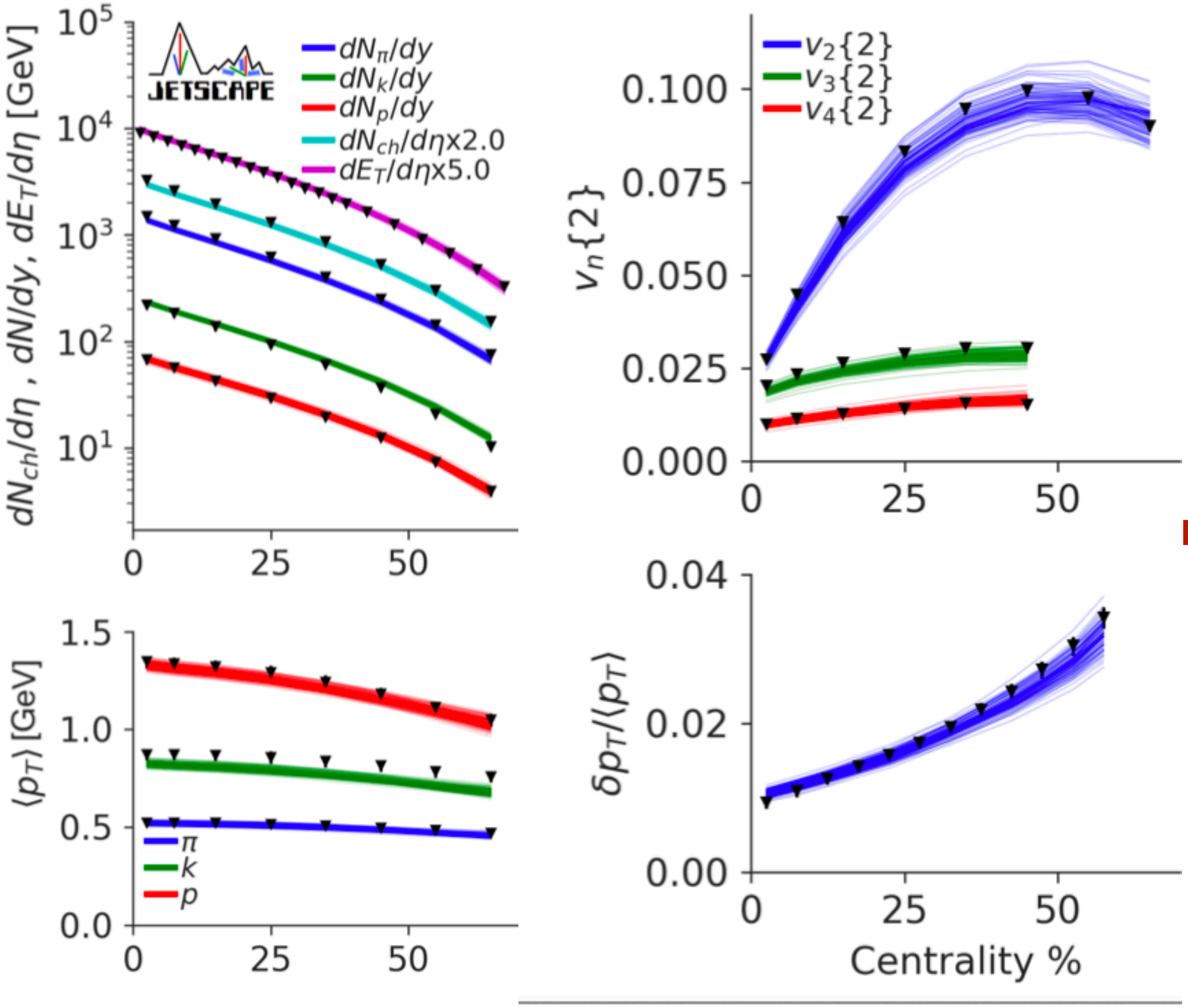


Systematic attempt to quantify (some of) the transport properties of the medium

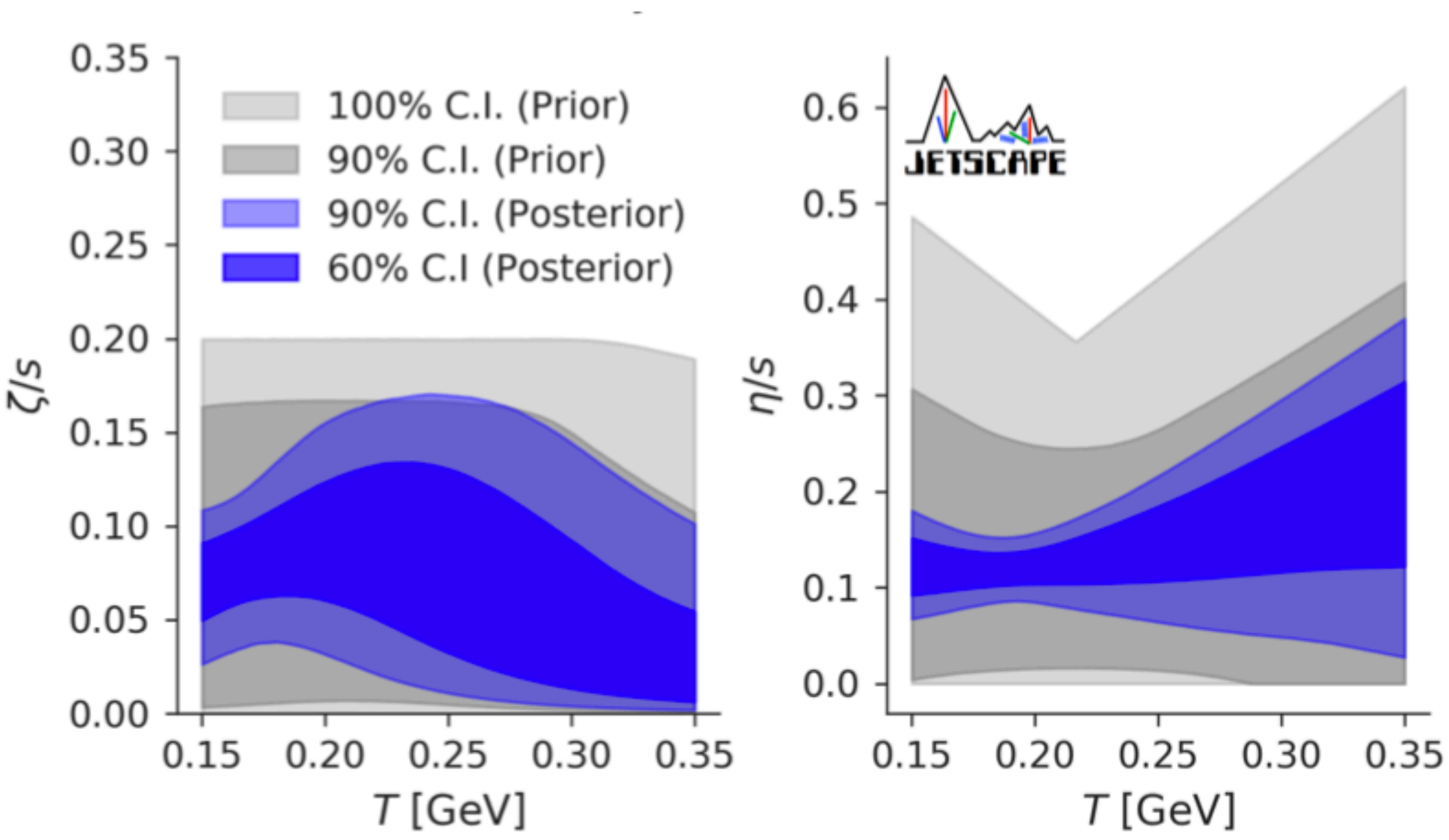
GLOBAL FIT FROM JETSCAPE

(JETSCAPE Collaboration) arXiv:2011.01430

Fit on LHC data



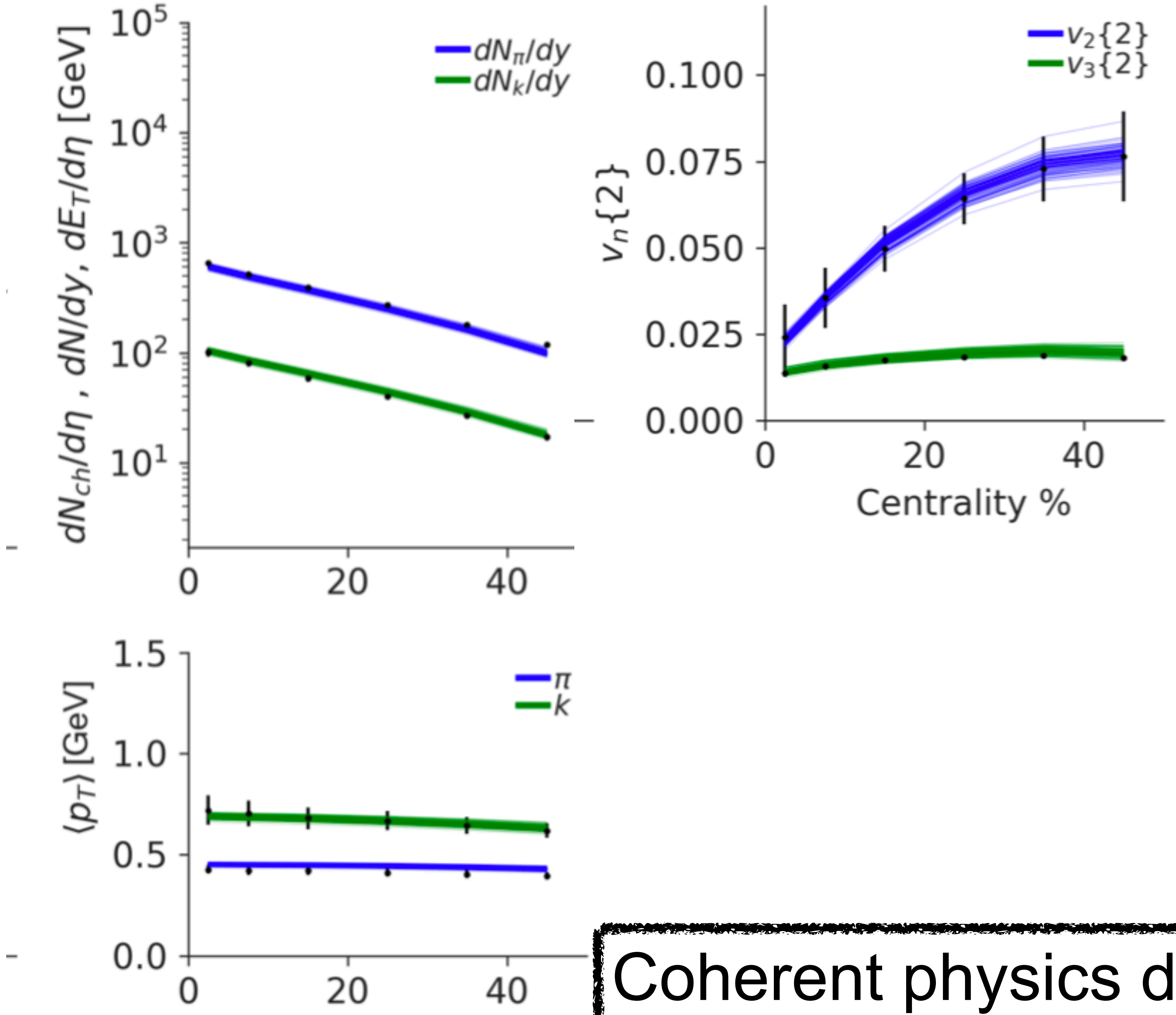
Posterior from LHC data



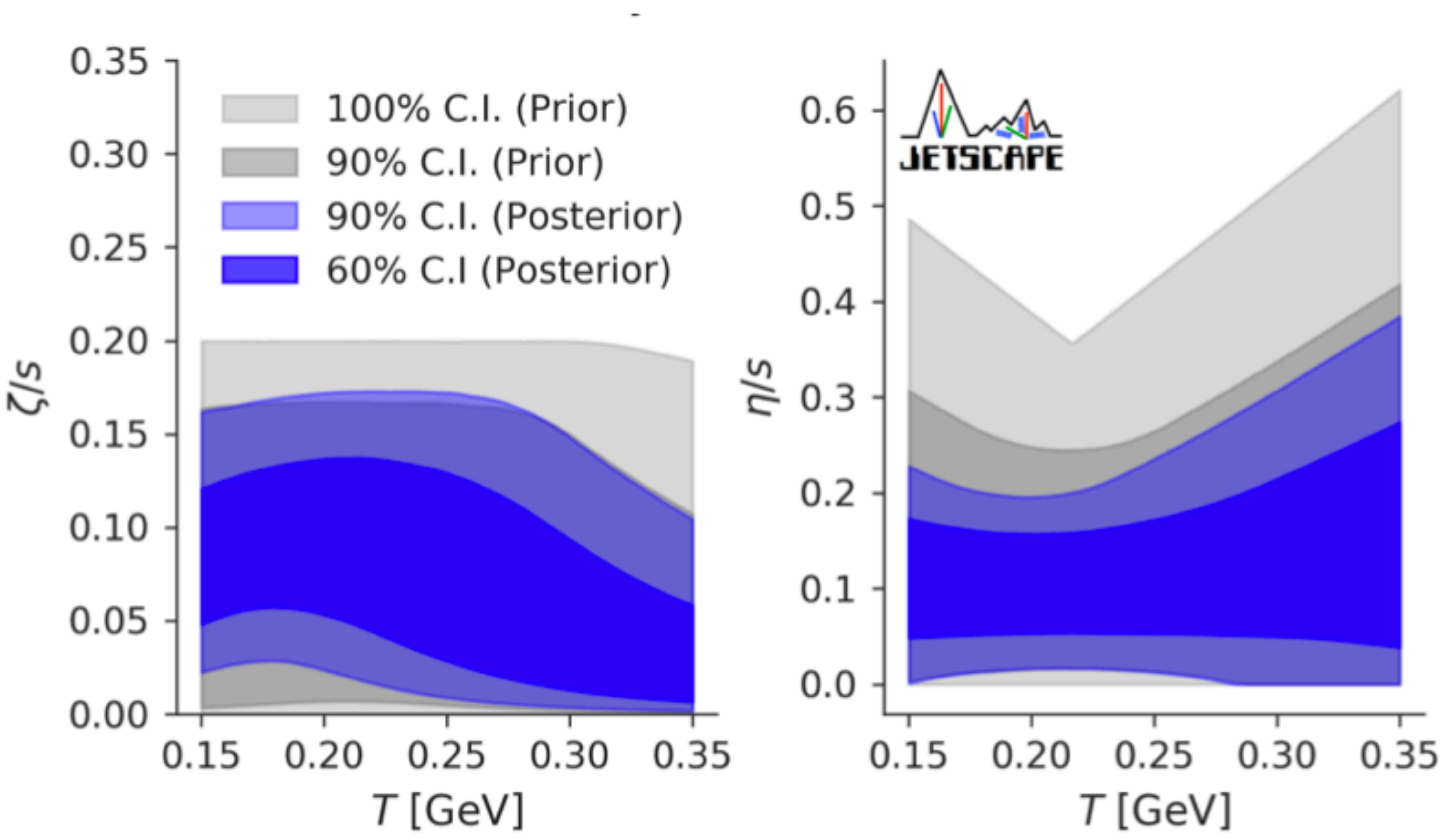
GLOBAL FIT FROM JETSCAPE

(JETSCAPE Collaboration) arXiv:2011.01430

Fit on RHIC data



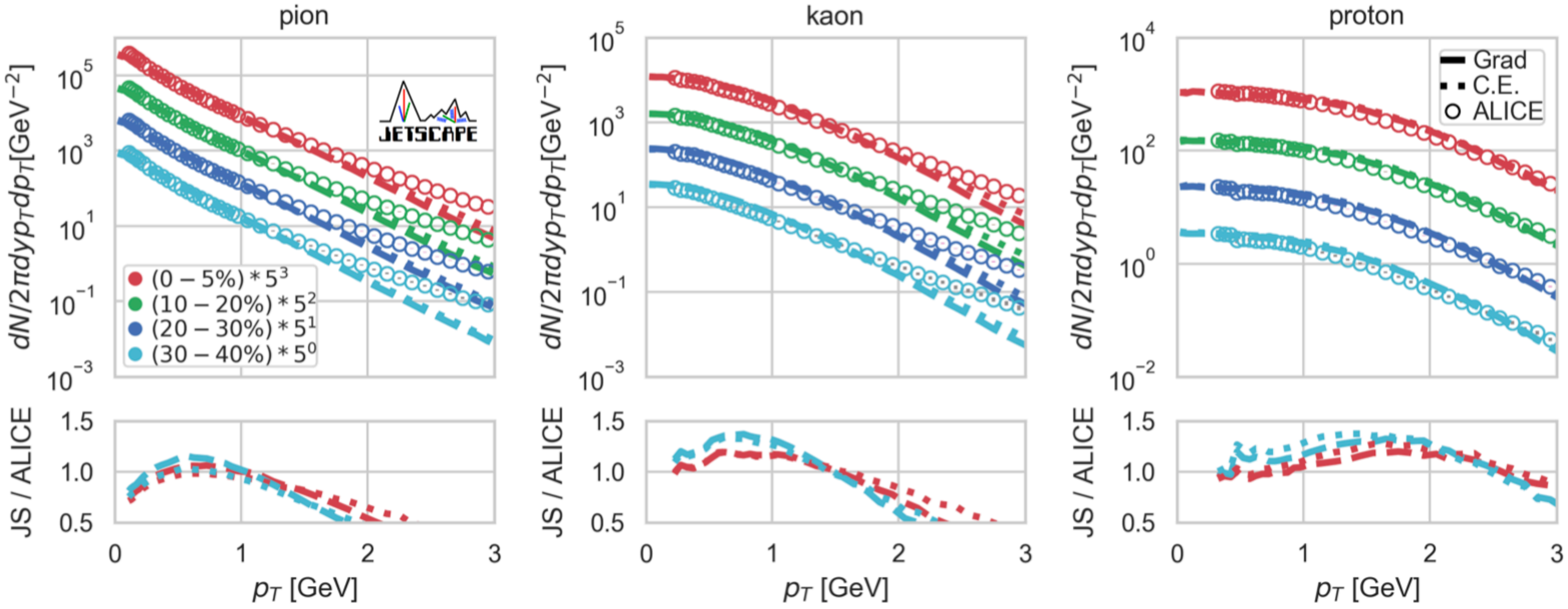
Posterior from RHIC data

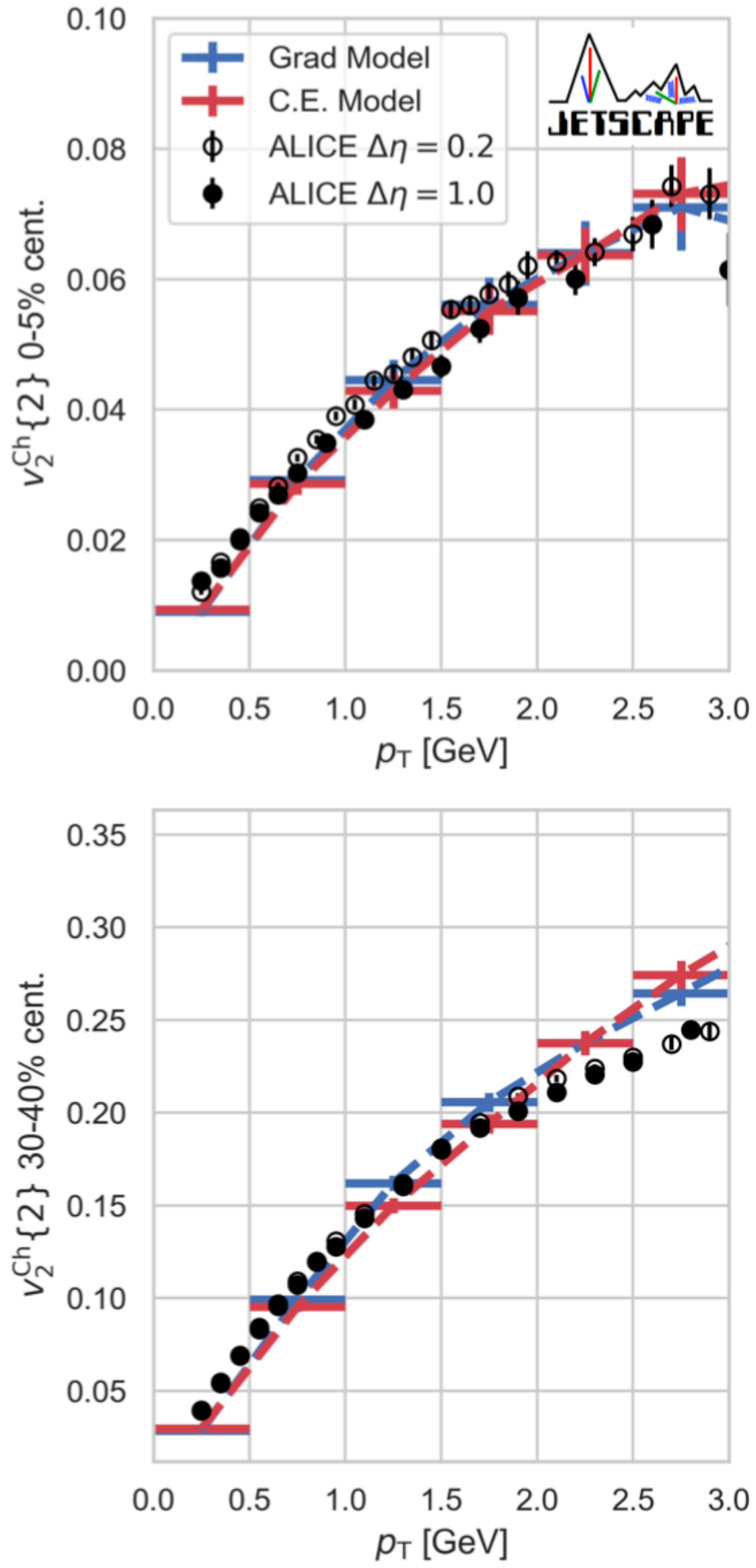


Coherent physics description of experimental data at various energies from a single model with a common set of parameters (except the initial energy density)

ESTIMATES FROM JETSCAPE

(JETSCAPE Collaboration) arXiv:2011.01430

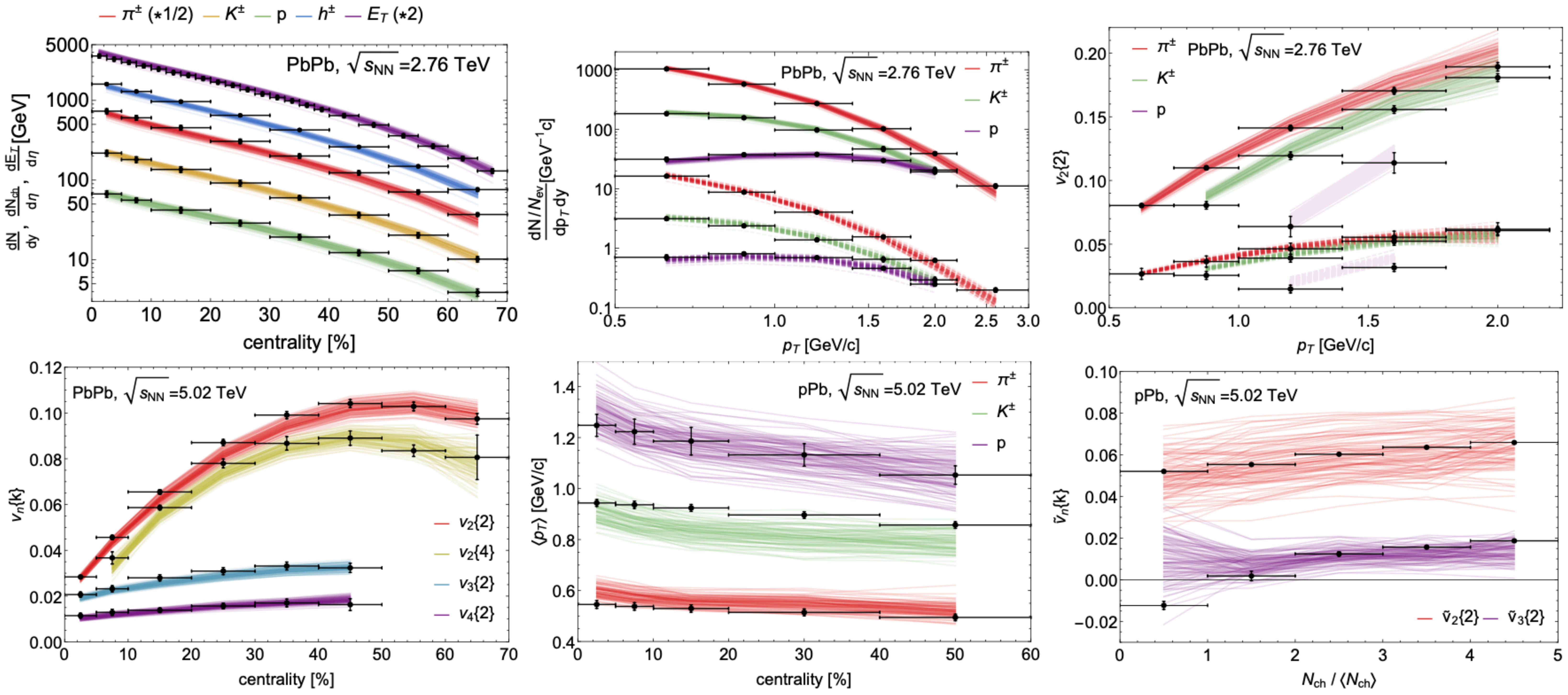


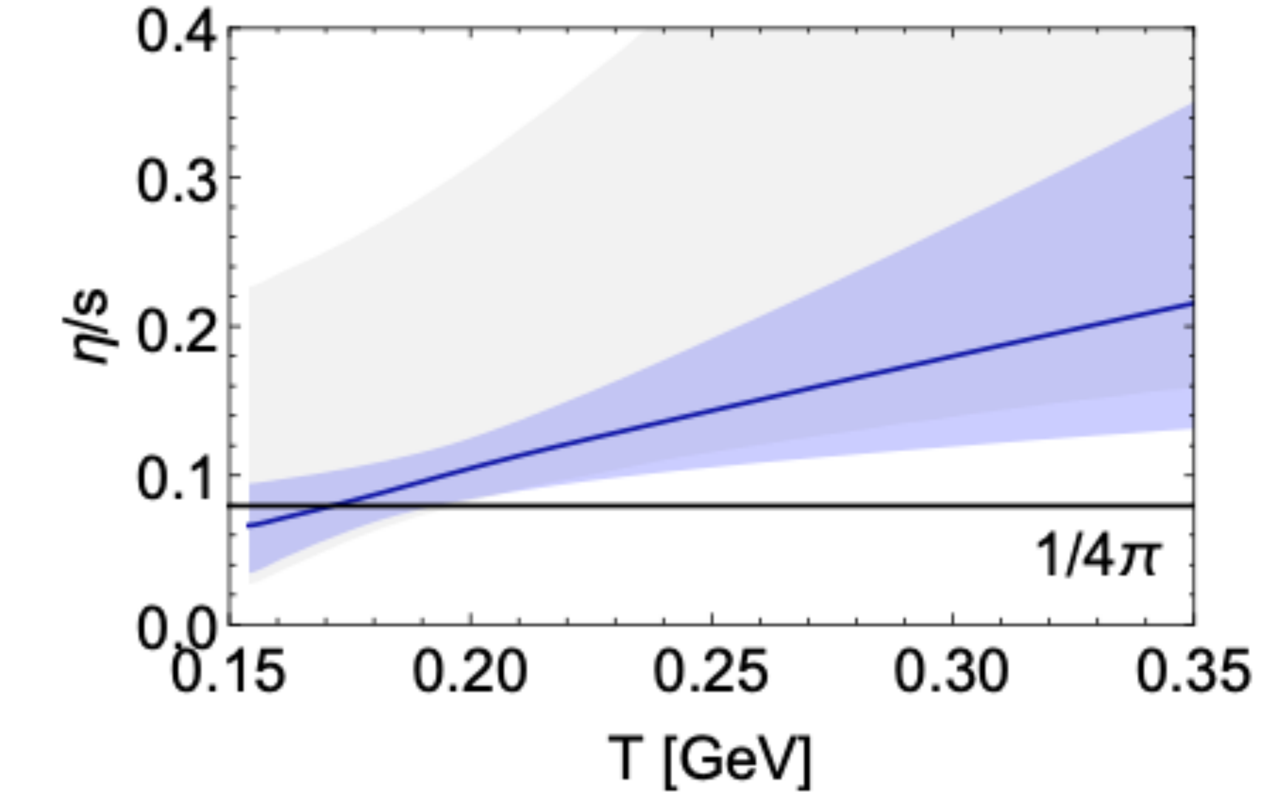


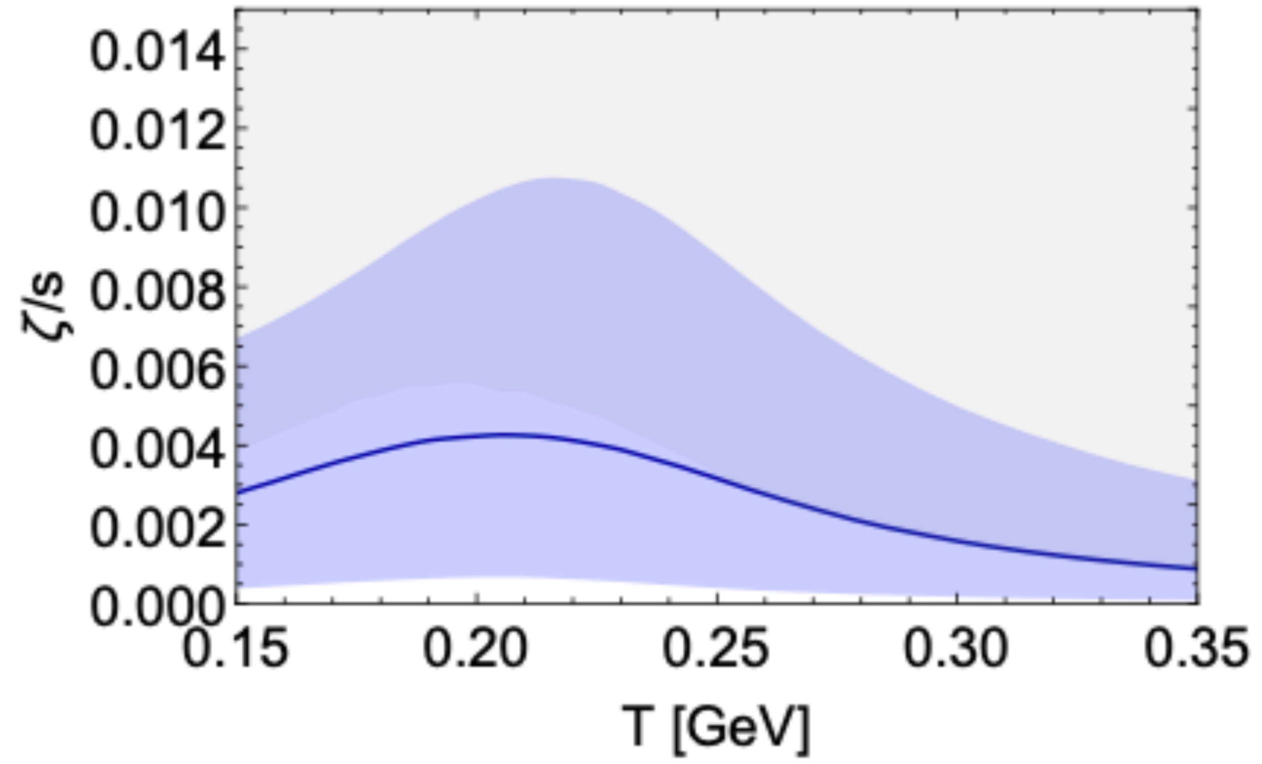
Overall fairly good description for $p_T < 1.5$ GeV/c

ESTIMATES FROM TRAJECTUM

G. Nijs *et al.*, arXiv:2010.01430







First attempt to constrain transport coefficients by including p_T-differential quantities in a global fit

All these attempts use "bread and butter" measurements

- Could they describe "more complicated" observables?

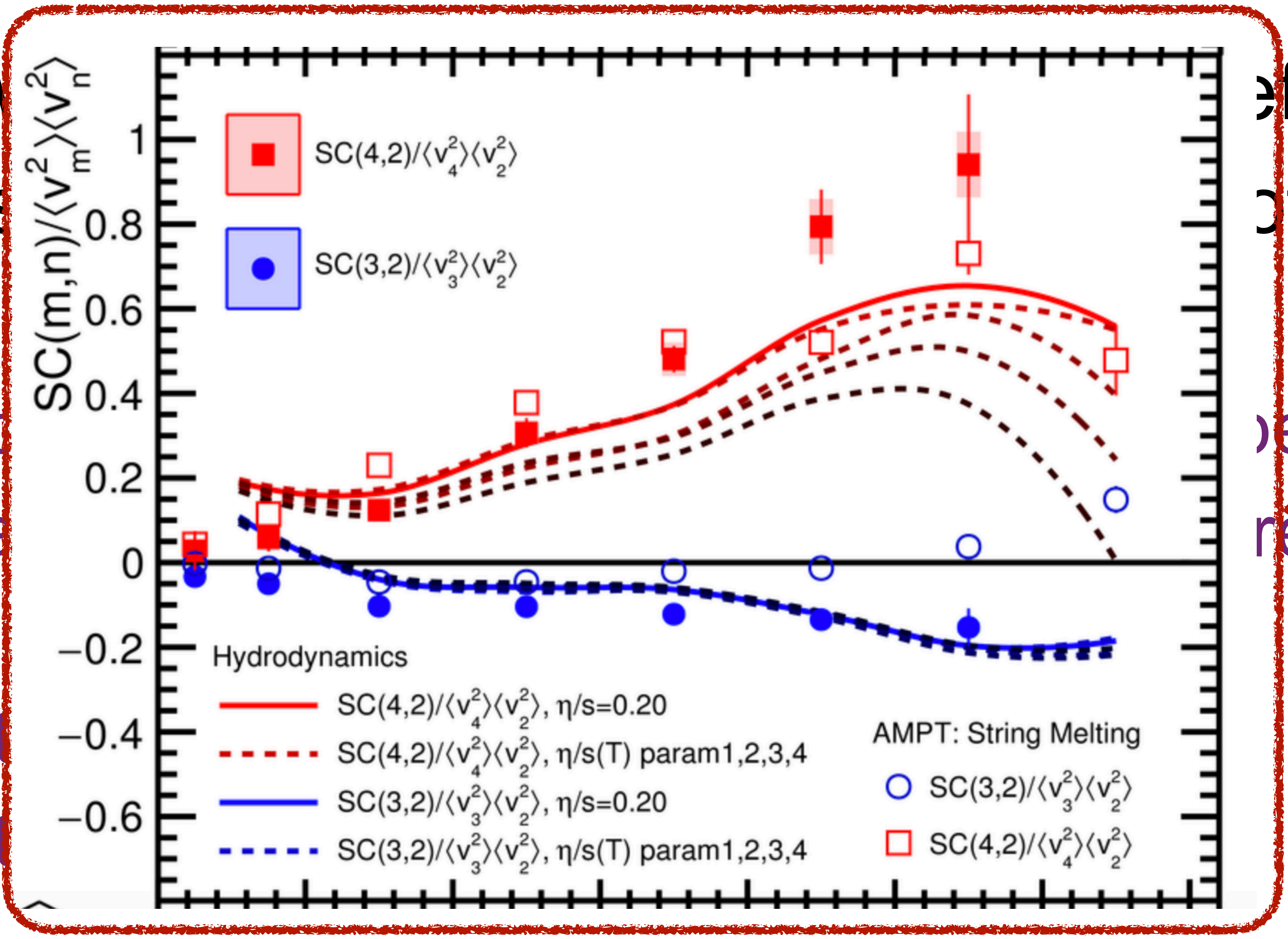
Nikhef

CONSTRAINING IS AND TRANSPORT PROPERTIES

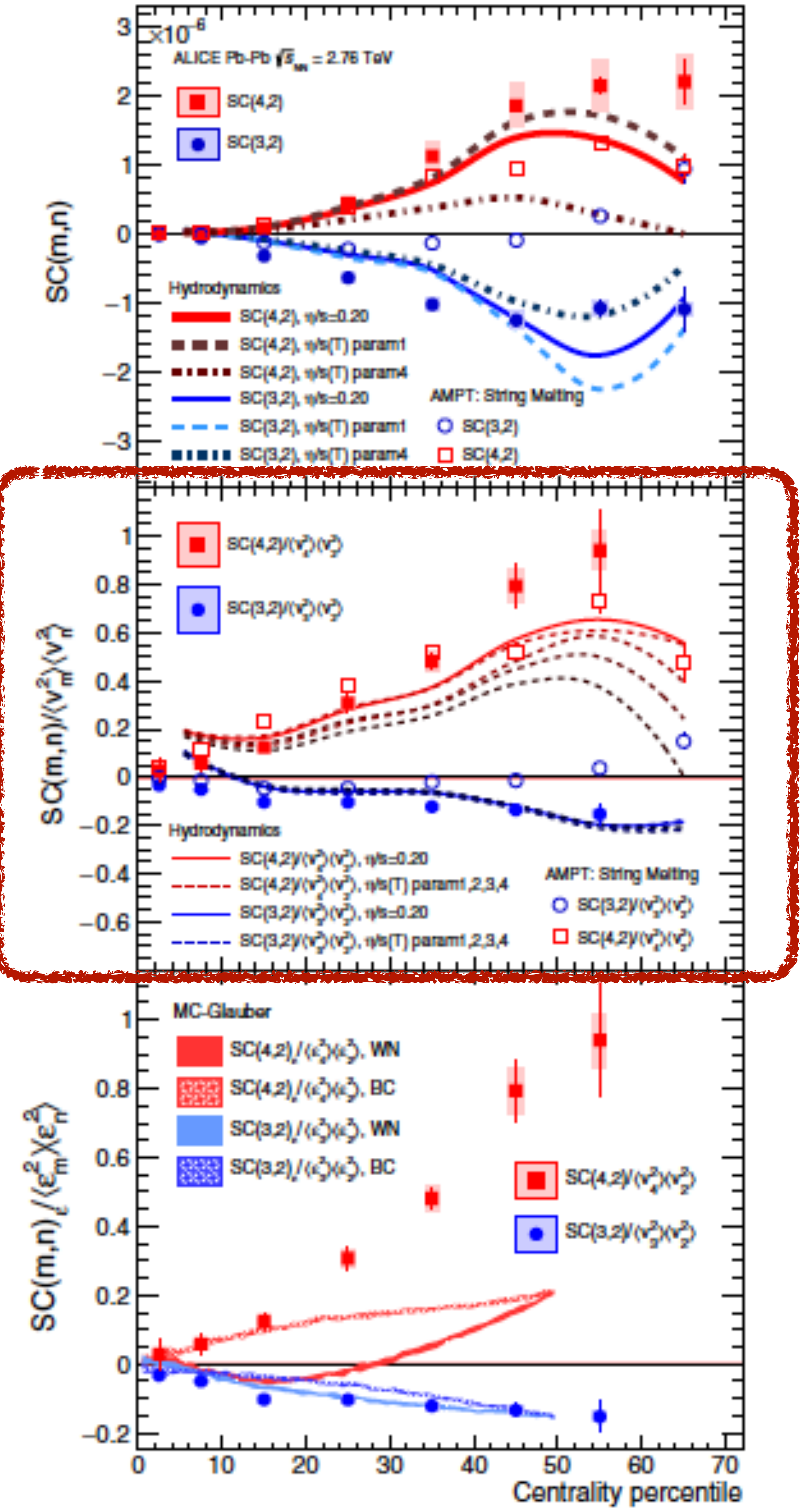
$$SC(m,n) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

Some new … effects of the initial s… of the QGP

- Examp… correla… harmo…
- Magnit…
- Magnit…



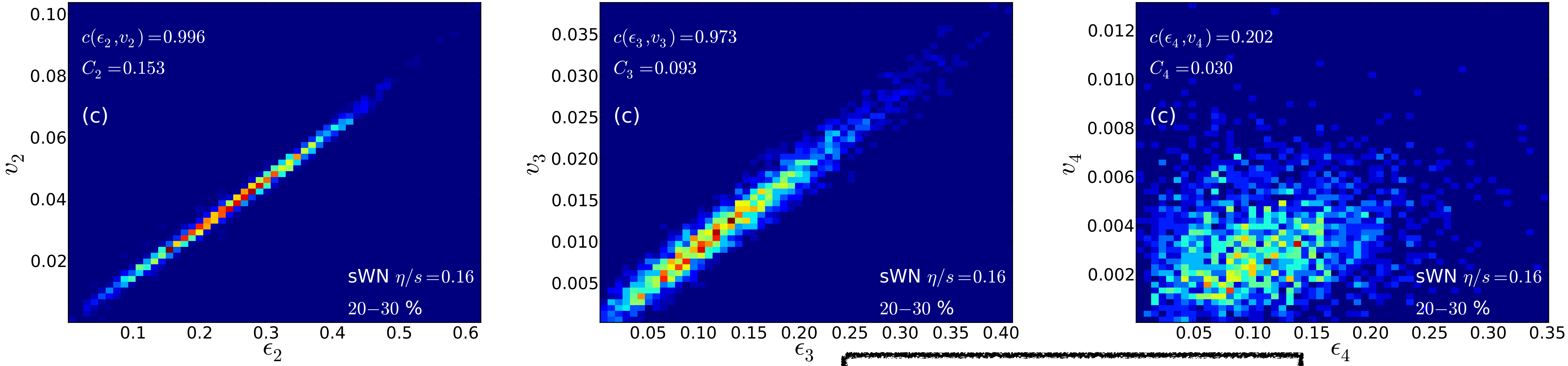
…ent flow



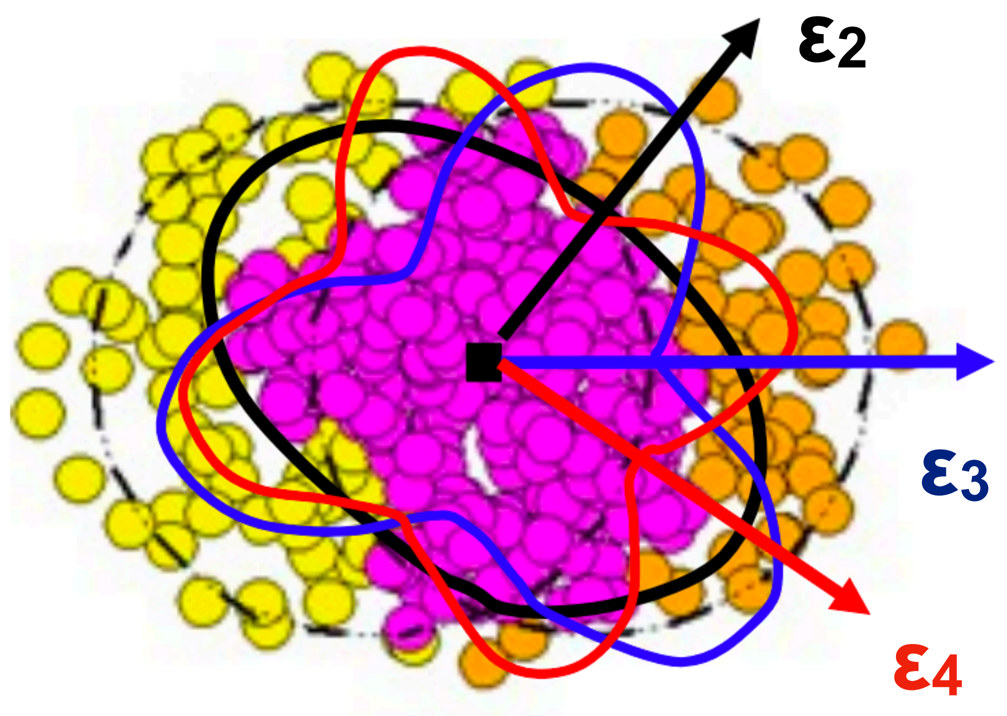
ALICE Collaboration, Phys. Rev. Lett. **117**, (2016) 182301

NON-LINEAR FLOW MODES

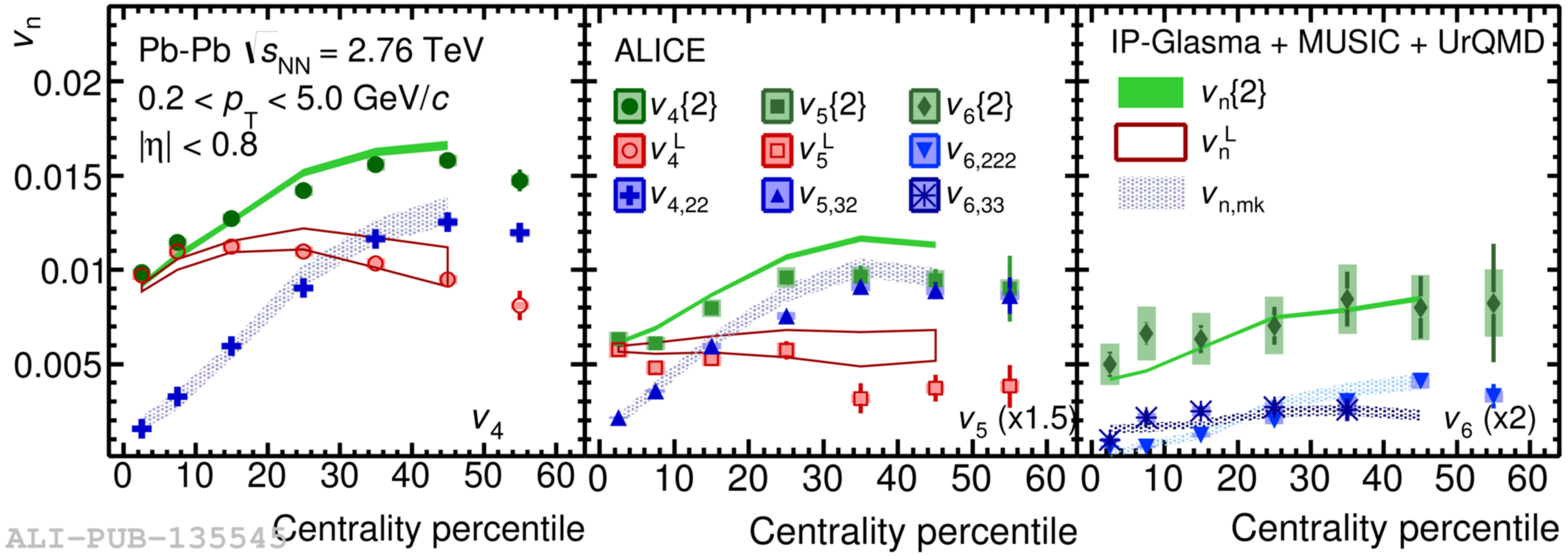
H. Niemi *et al.*, Phys.Rev. C87 (2013), 054901



(ALICE Collaboration) Phys.Lett. **B773** (2017) 68



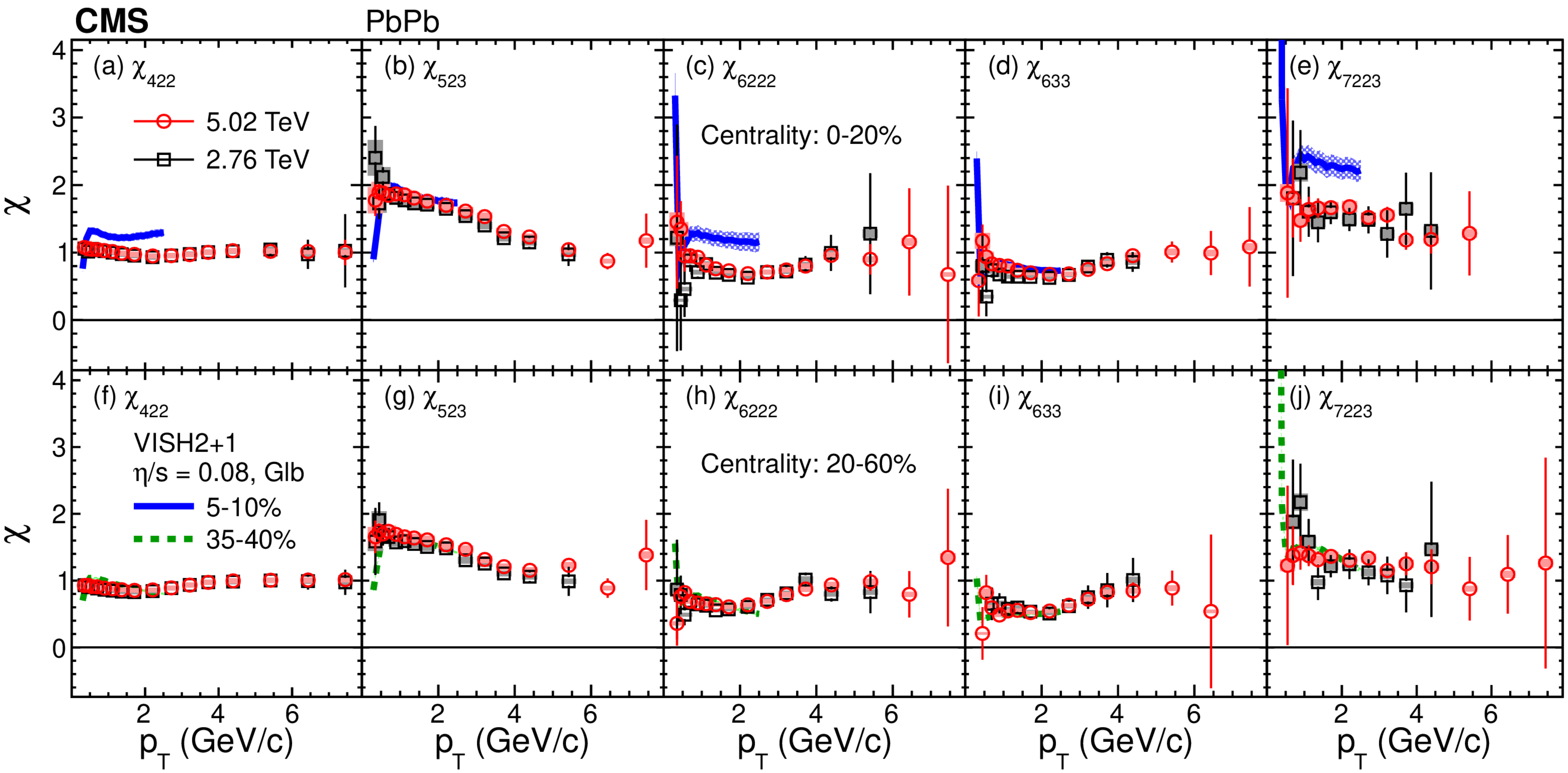
$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} (n > 3)$$



NON-LINEAR FLOW MODES

$$V_4 = V_{4L} + \chi_{422} V_2^2,$$
$$V_5 = V_{5L} + \chi_{523} V_2 V_3,$$
$$V_6 = V_{6L} + \chi_{624} V_2 V_{4L} + \chi_{633} V_3^2 + \chi_{6222} V_2^3,$$
$$V_7 = V_{7L} + \chi_{725} V_2 V_{5L} + \chi_{734} V_3 V_{4L} + \chi_{7223} V_2^2 V_3$$

(CMS Collaboration), arXiv:1910.08789 [hep-ex]



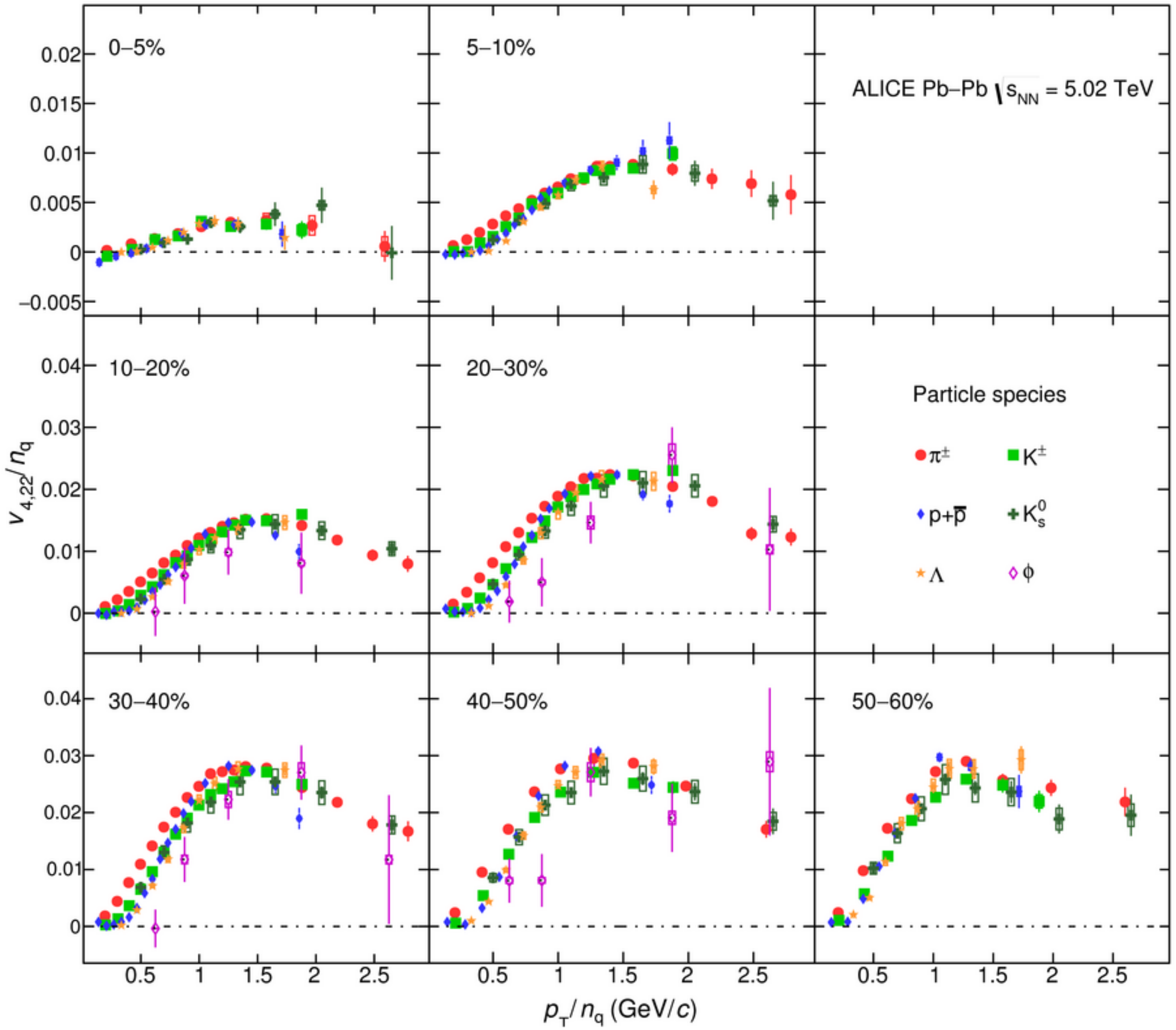
Nikhef

NON-LINEAR FLOW MODES

Similar features as in total v_n measurements

- Mass ordering at low p_T → interplay between radial flow and anisotropic geometry

(ALICE Collaboration) JHEP06 (2020) 147



Are there any differences between total and NL v_n?

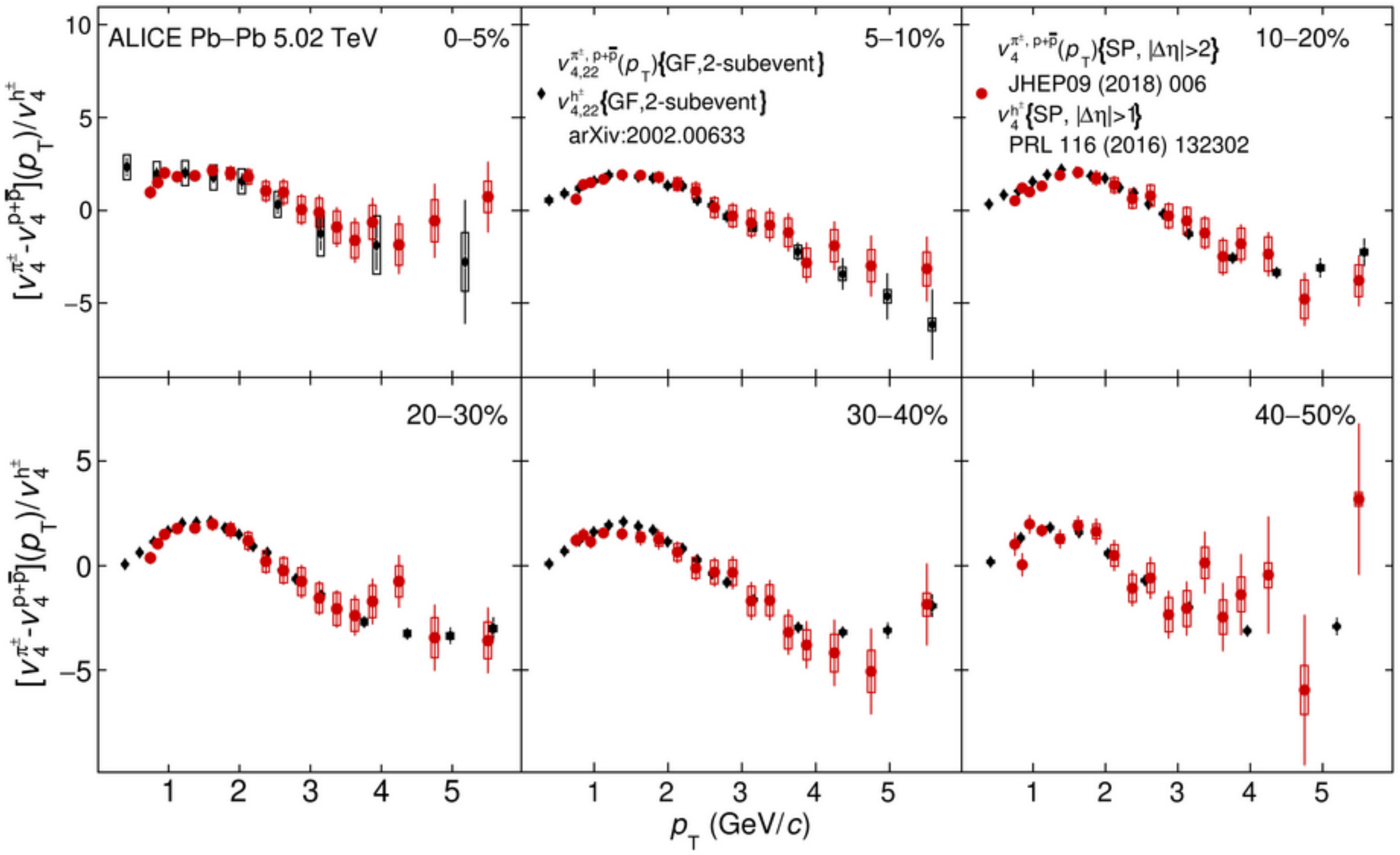
Nikhef

NON-LINEAR FLOW MODES

(ALICE Collaboration) JHEP06 (2020) 147

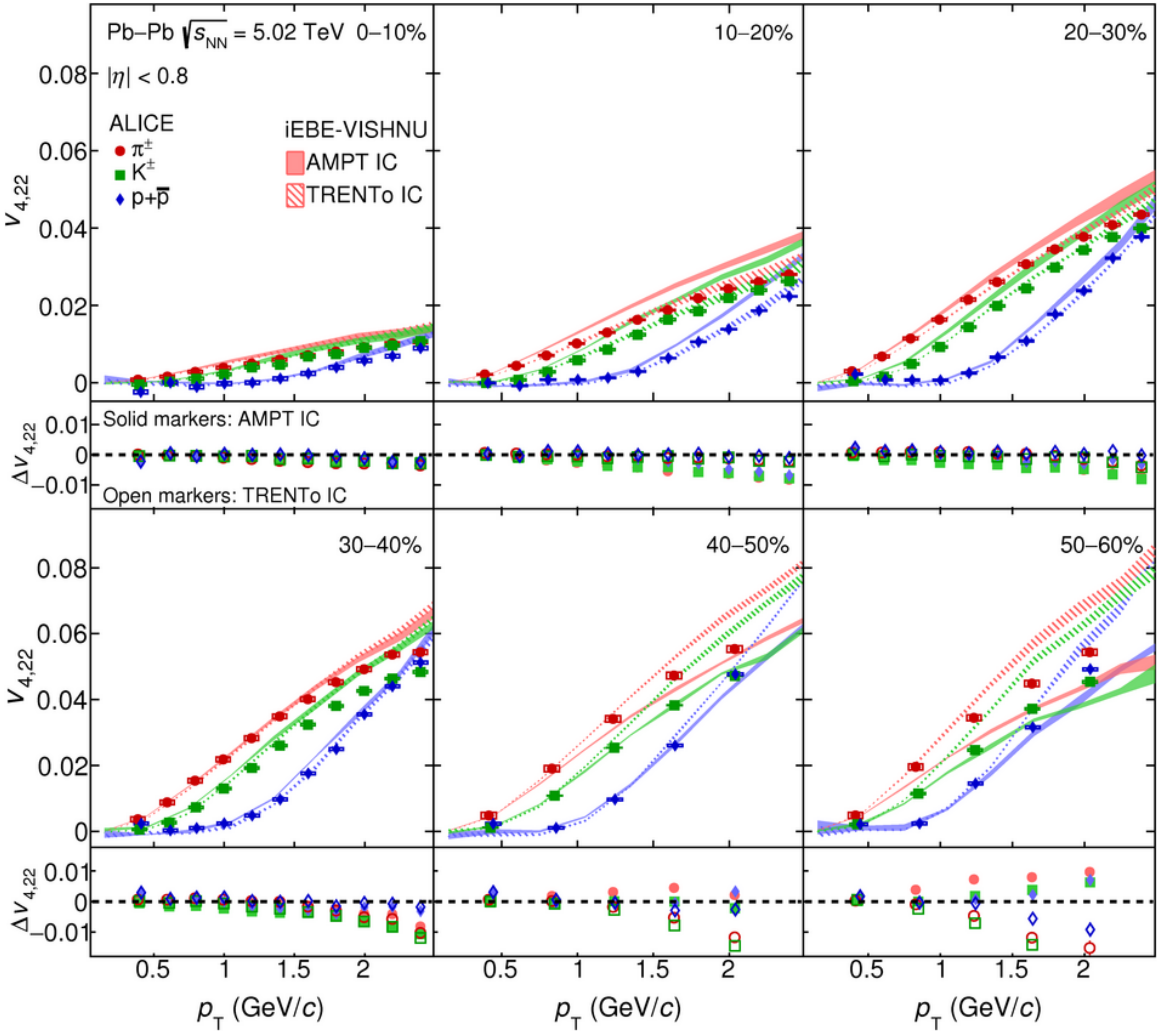
Unique opportunity to test the two regimes:

- Mass ordering might develop differently between total and NL v_n
  - $v_{4,22}$ develops $\sim\varepsilon_2^2$
- Particle type grouping should develop similarly in both modes if coalescence is the reason for this grouping



NON-LINEAR FLOW MODES

(ALICE Collaboration) JHEP06 (2020) 147

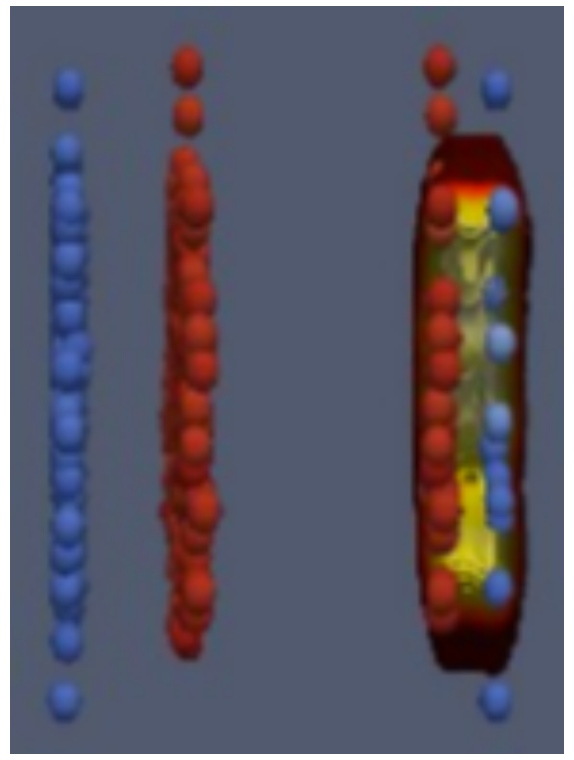
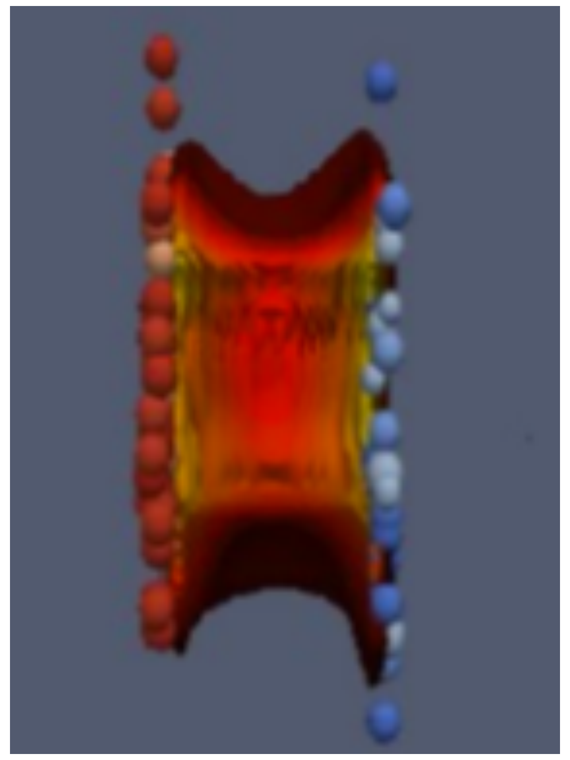
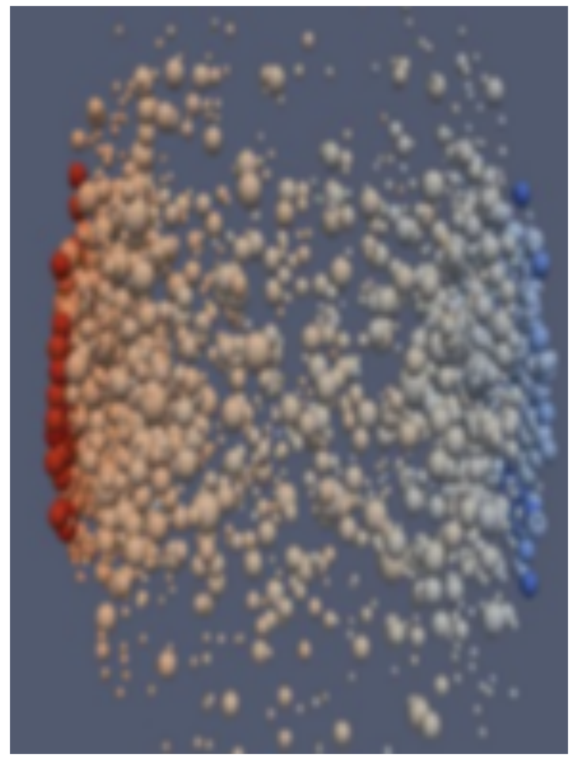


In general good description from models

- Looking at the details:
  - The model with AMPT-IC does slightly better in some cases but trend is not clear
  - Models find it more difficult to describe the NL modes than the total v_n

Nikhef

(AN ATTEMPT FOR A) SUMMARY

Initial state	Thermalization	Hydrodynamical evolution	Hadronization	Hadronic rescattering
				
IP-Glasma, AMPT, EKRT, Glauber…?		EoS η/s(T), ζ/s(T),…?	Coalescence, fragmentation,…?	x-sections, duration,…?

How do
these surprising properties of the QGP emerge
from the fundamental constituents of the theory, the
quarks and gluons.

Still imho a major puzzle!!!

Thank you for your attention!

BACKUP

ZIMÁNYI SCHOOL 2020
20th ZIMÁNYI SCHOOL
WINTER WORKSHOP
ON HEAVY ION PHYSICS
December 7-11, 2020
Budapest, Hungary