A brief review of collective effects at the LHC: lessons and puzzles

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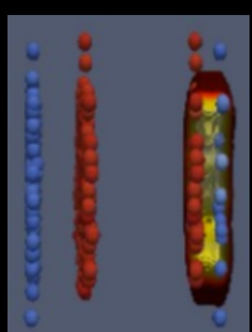
Probing collective effects through anisotropic flow studies

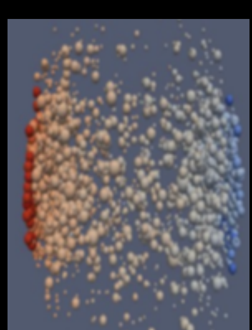
- Anisotropies in momentum space
- Quantified by Fourier coefficients v_n

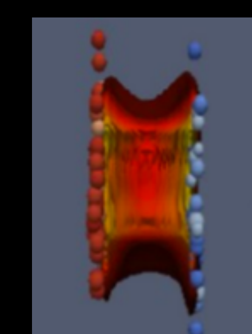
Voloshin and Zhang, Z. Phys. **C70** (1996) 665

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

- Where do these anisotropies come from?
  - From coordinate space anisotropies of the initial geometry and its fluctuations
- Flow harmonics sensitive probes of
  - Initial state
  - EoS
  - Viscous hydrodynamical expansion + transport properties
  - Highly dissipative hadronic rescattering phase



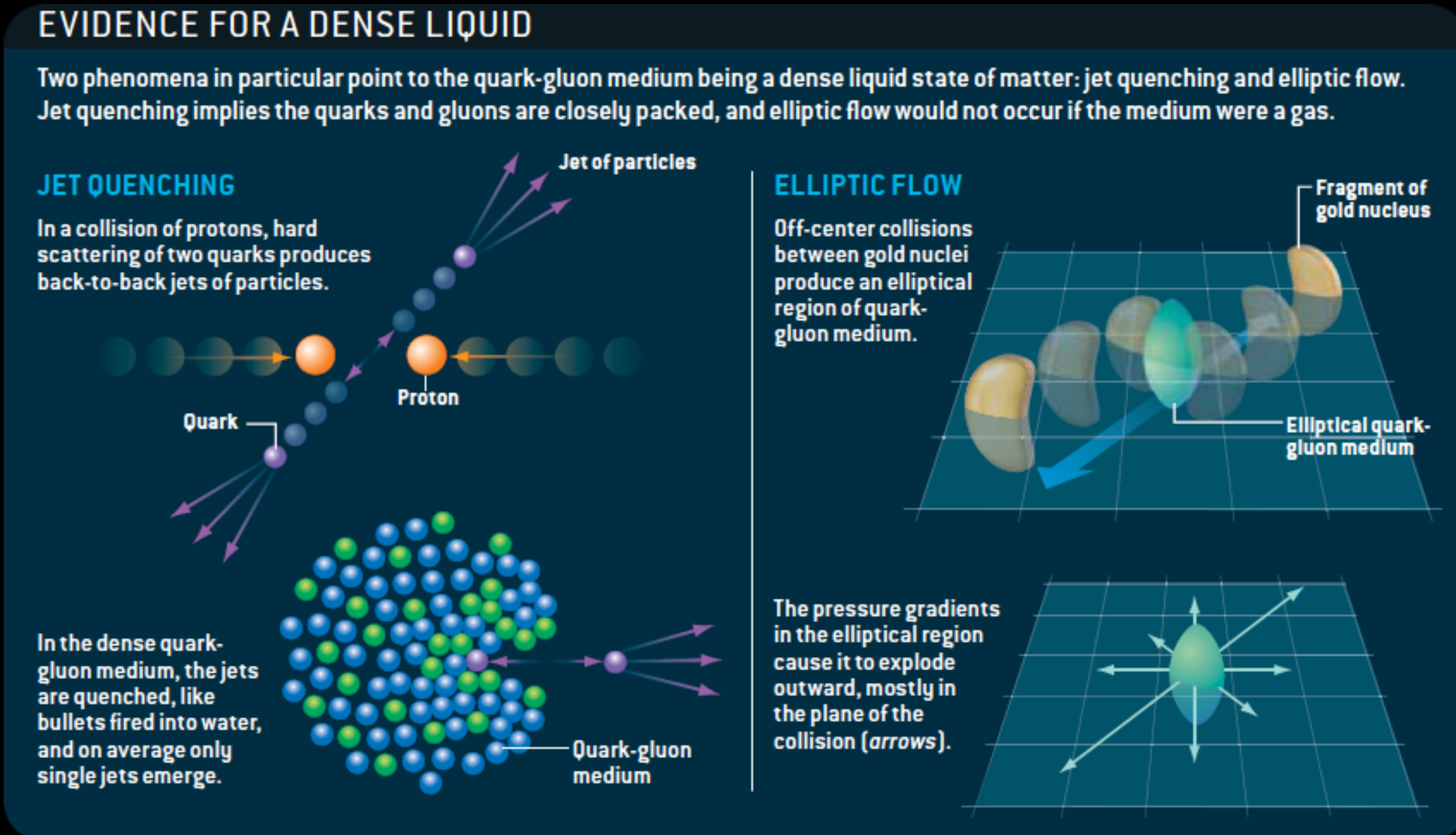




- They can also be used to probe the opacity of the system
  - path length energy loss

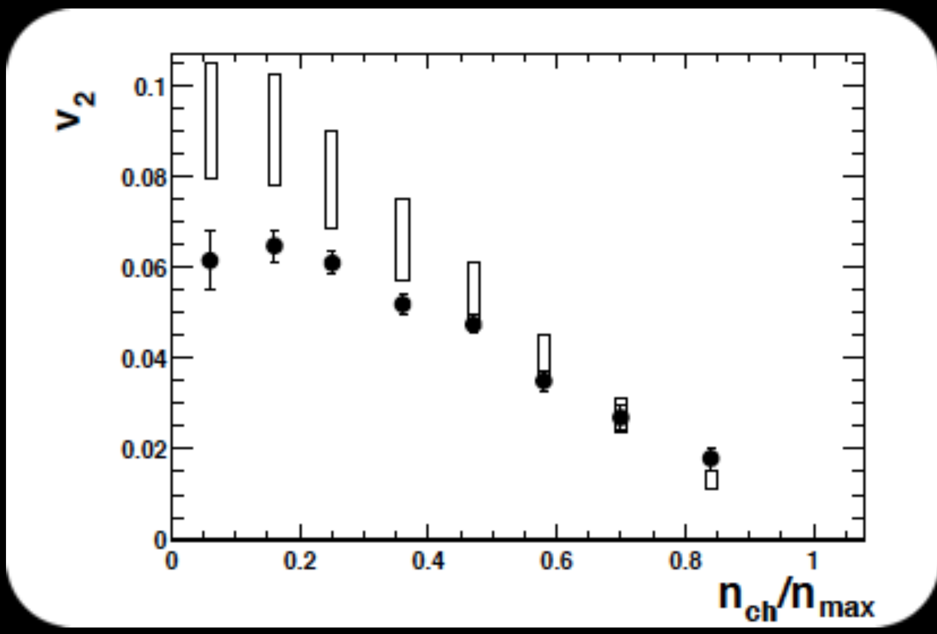
The perfect liquid: the birth of the sQGP paradigm

M. Roirdan and W. Zajc, Scientific American 34A May (2006)

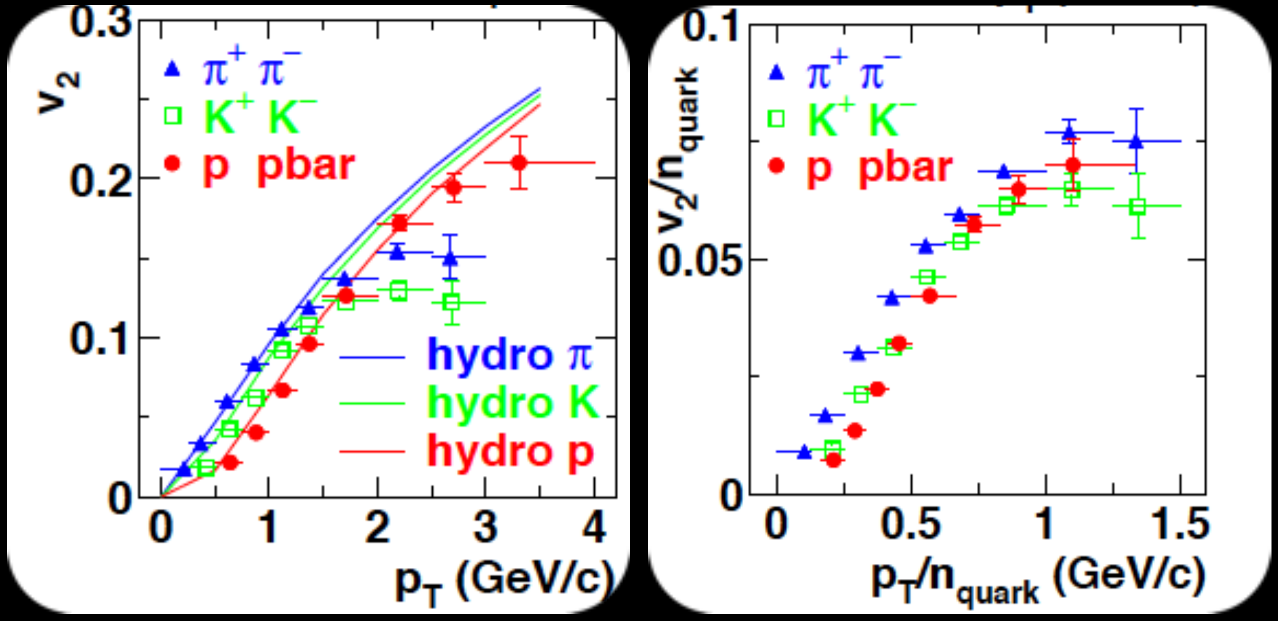


The (hi)story of elliptic flow measurements

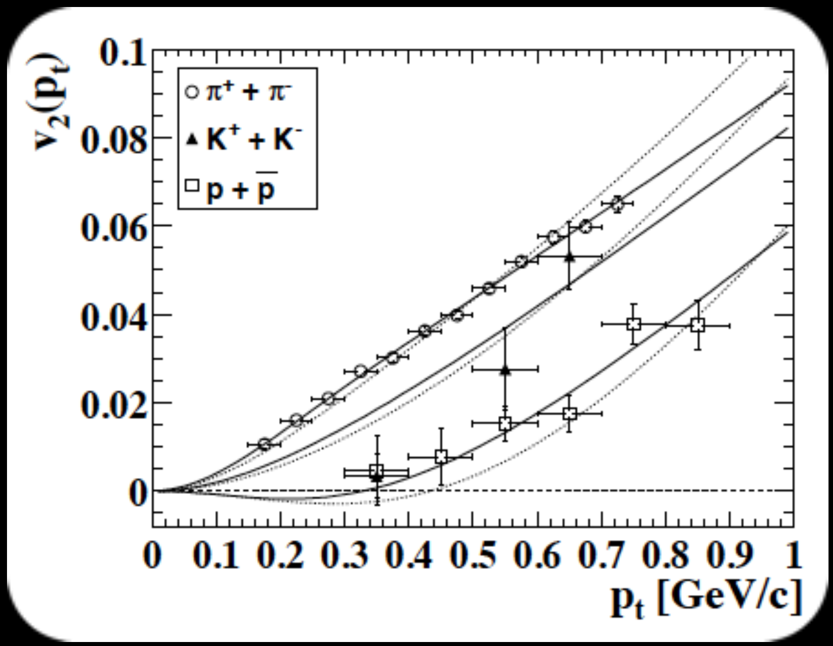
(STAR Collaboration)
Phys. Rev. Lett. 86 (2001) 402



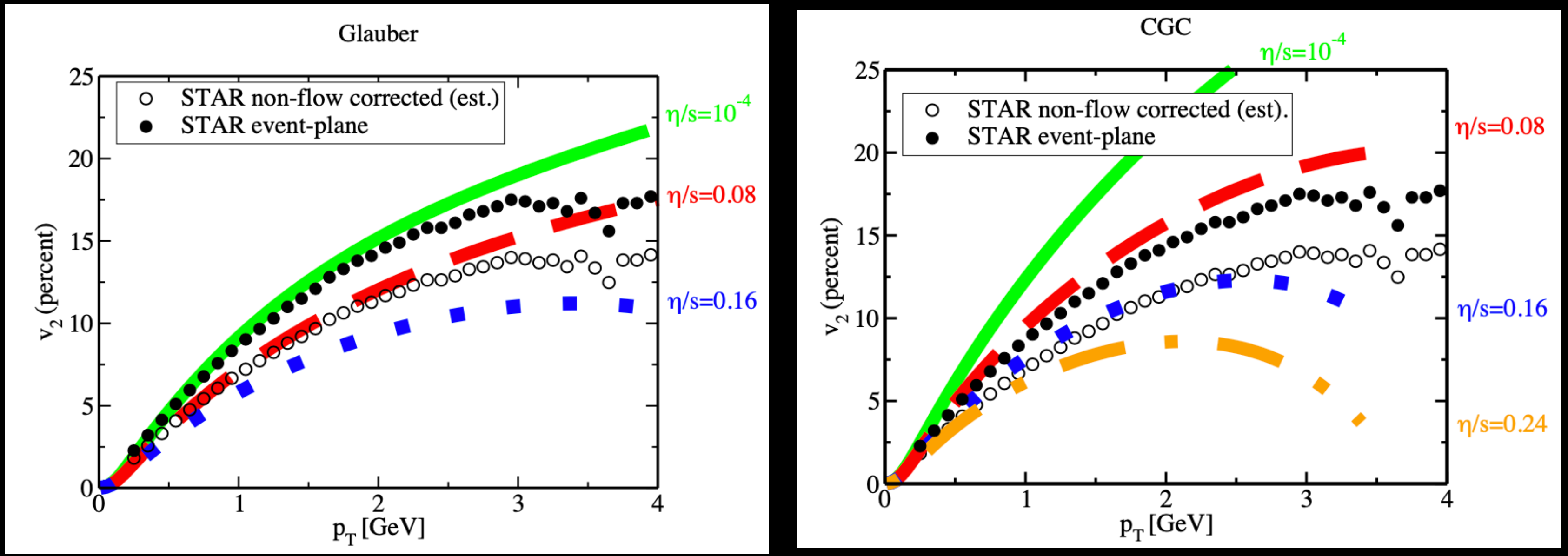
(PHENIX Collaboration)
Phys. Rev. Lett. 91 (2003)182301



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

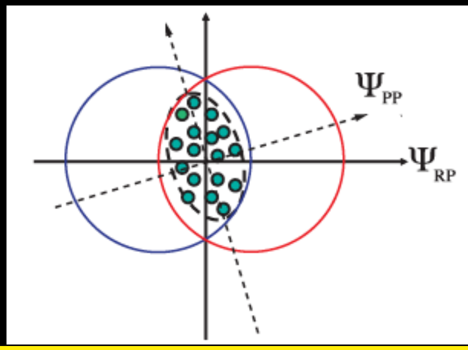


M. Luzum and P. Romatschke
Phys. Rev. **C78** (2008) 034915



Values of η/s not so well constrained since IS was a big unknown

But there is more…: higher (odd) harmonics!

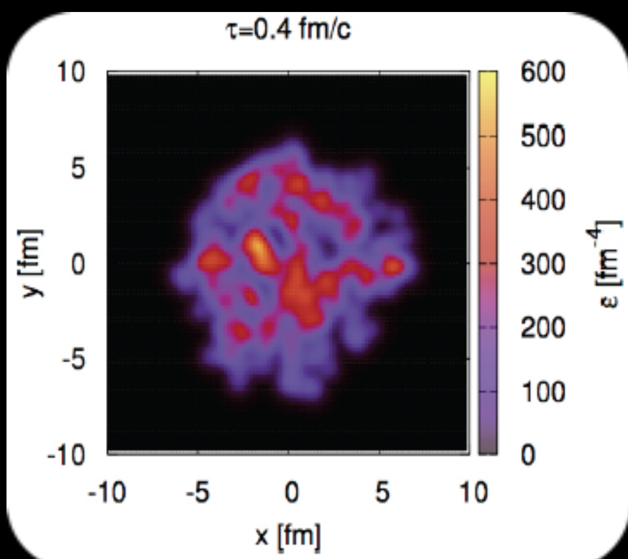


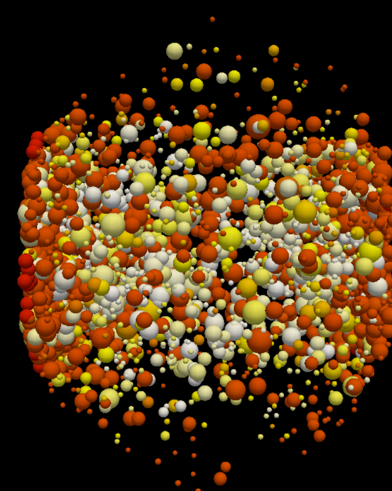
Reaction plane (Ψ_{RP}) → Participant (symmetry) plane Ψ_n

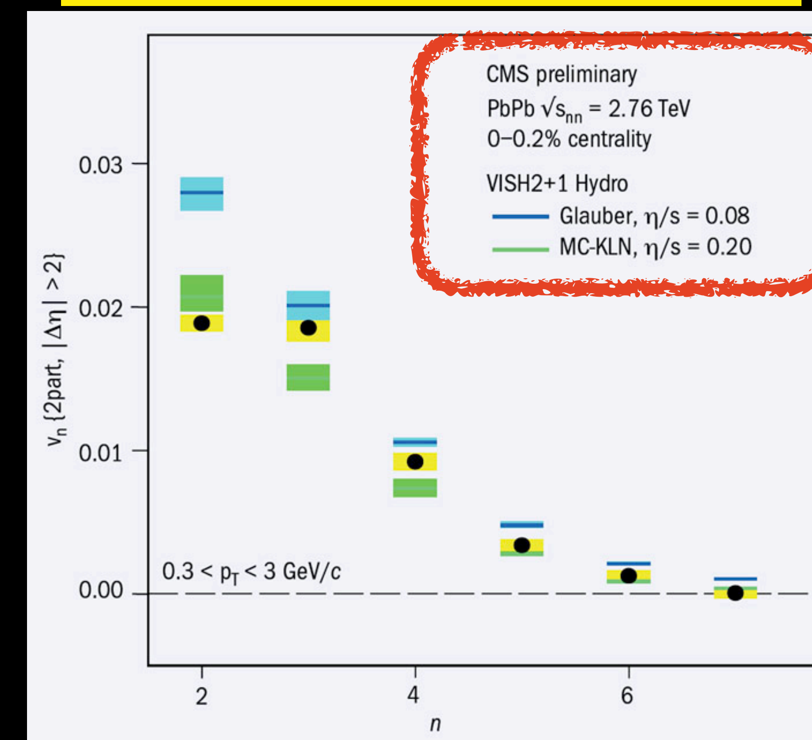
Initial state fluctuations

transferred via the low viscosity QGP

into final state correlations (higher, odd harmonics)



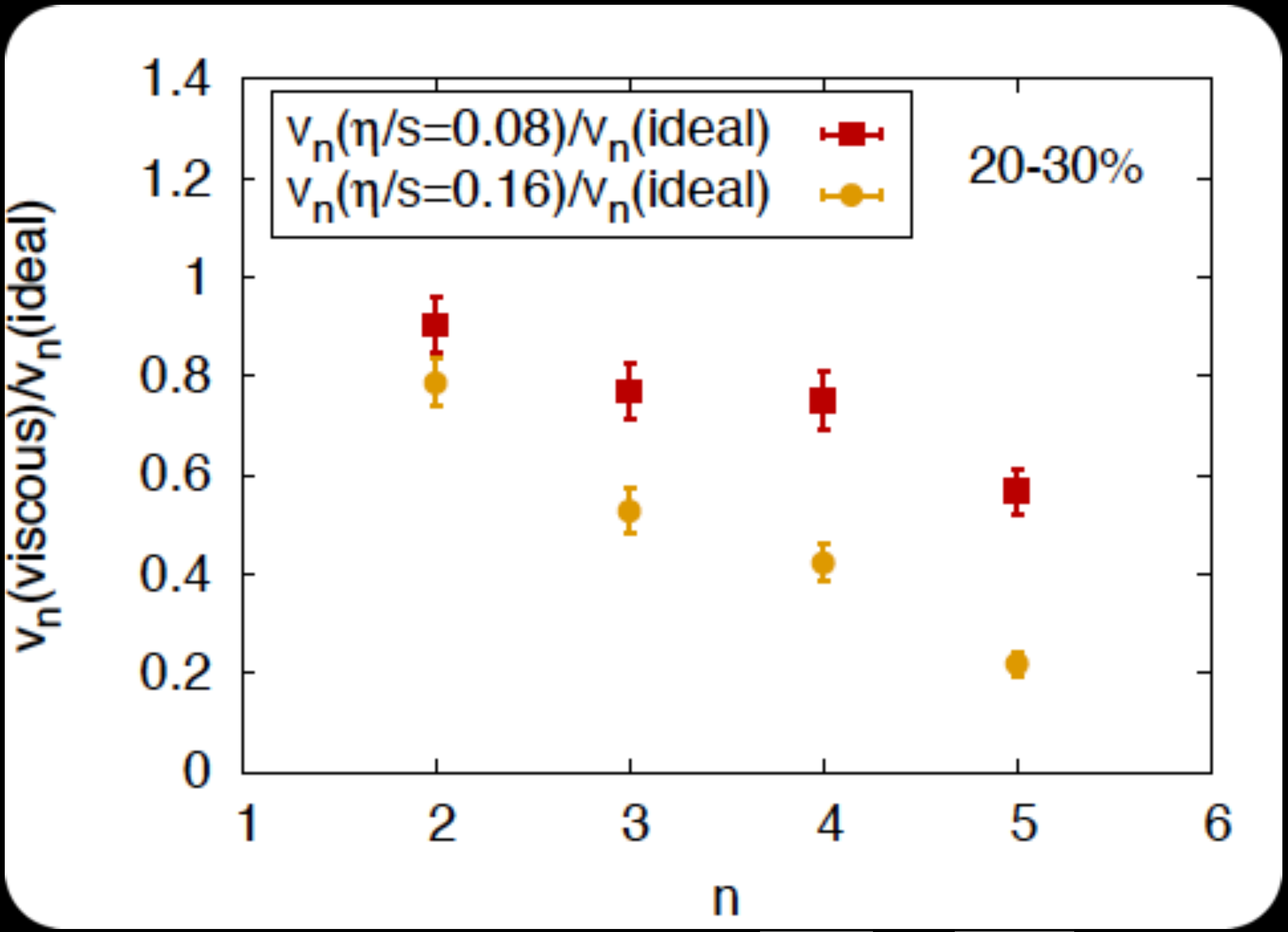


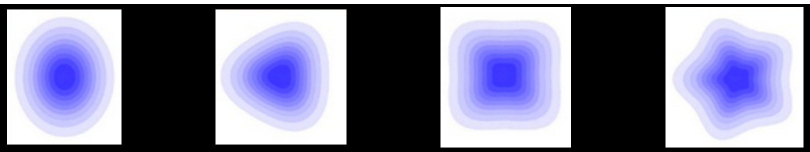


- ✓ Higher harmonics represent modulations in smaller spatial scales
  - More sensitive probes of the QGP transport properties
  - Unique tool to constrain initial state fluctuations

Effect of viscous corrections on higher harmonics

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





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

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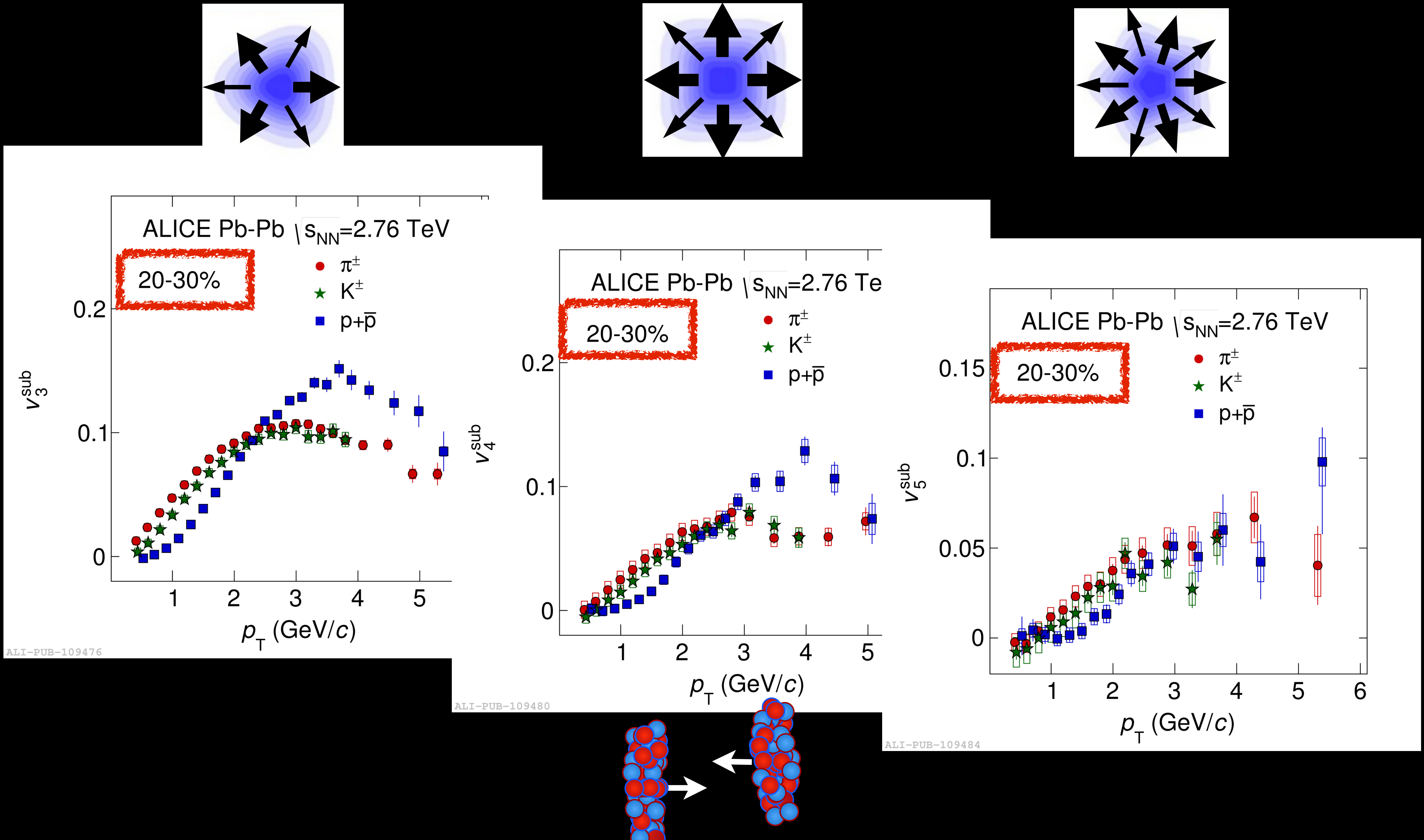
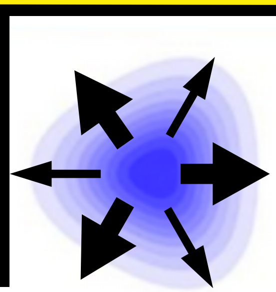
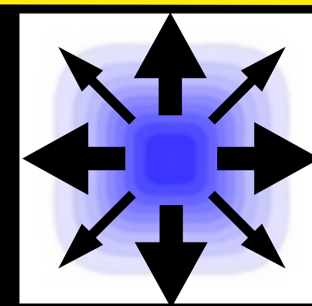
Higher harmonics @ LHC with run 1 data

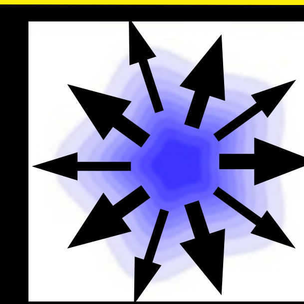


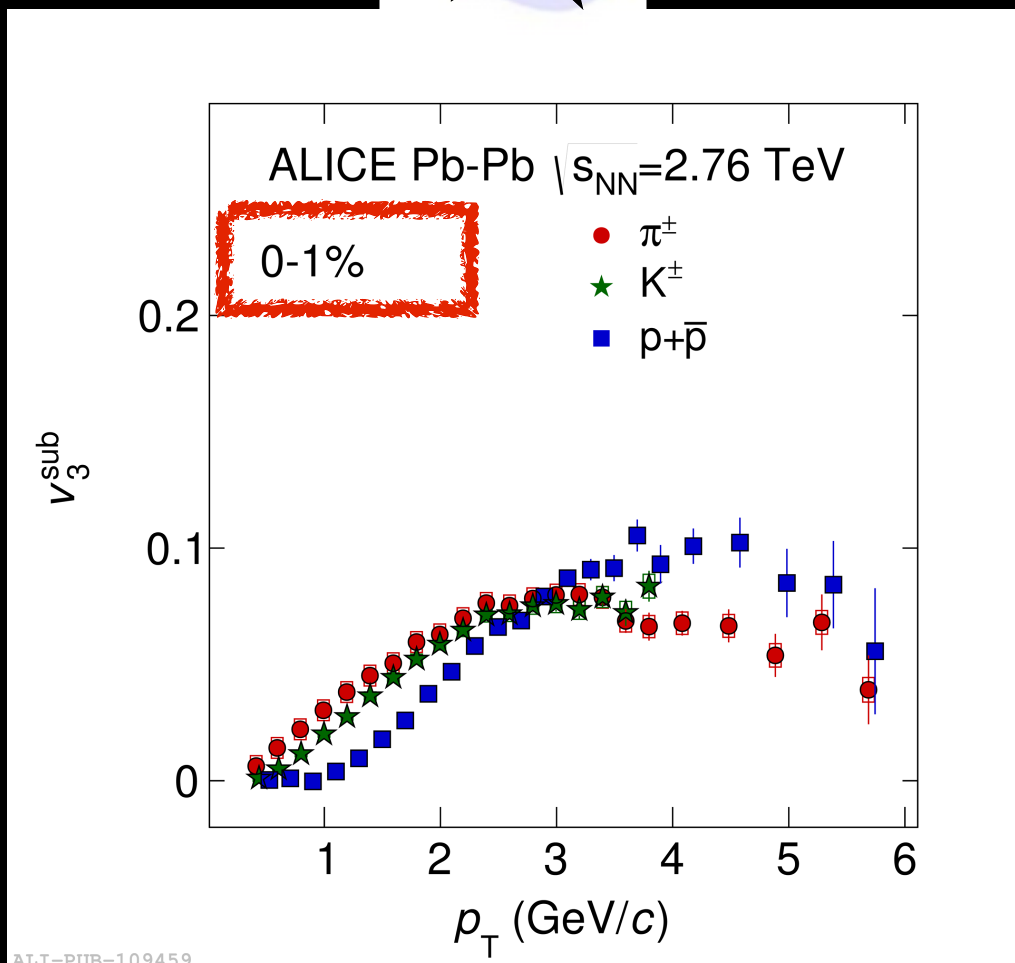
B. Abelev *et al.* (ALICE Collaboration), JHEP **09** (2016) 164

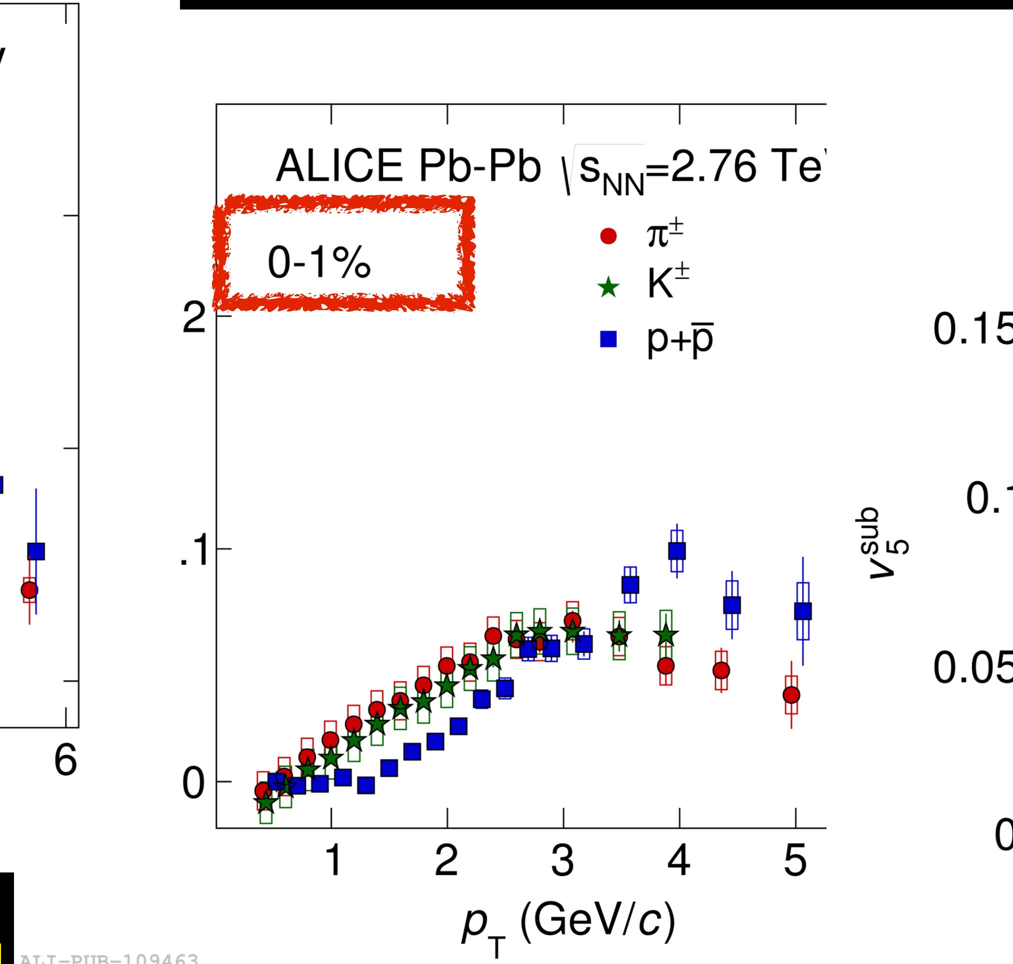
Higher harmonics @ LHC with run 1 data (ultra-central events)

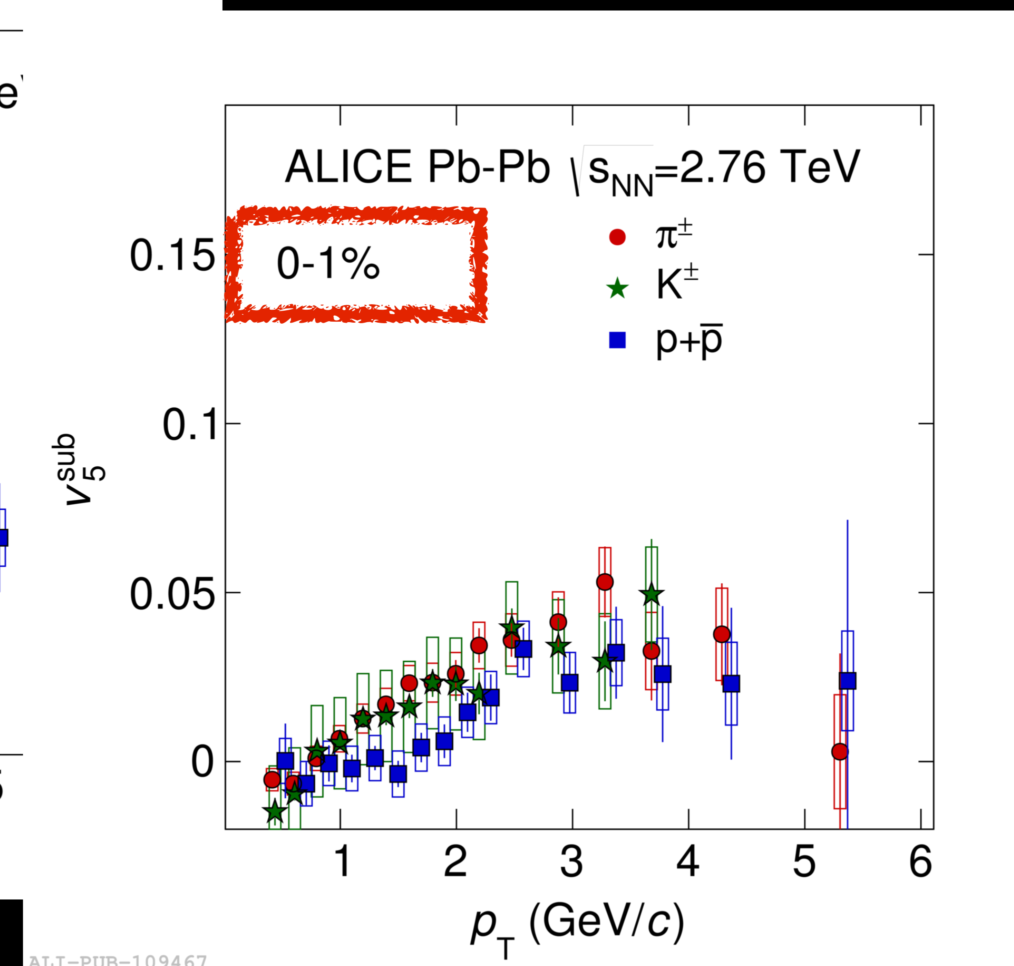




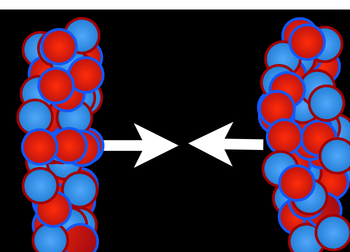








Same features for different v_n (up to v_5!) even for ultra-central collisions



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

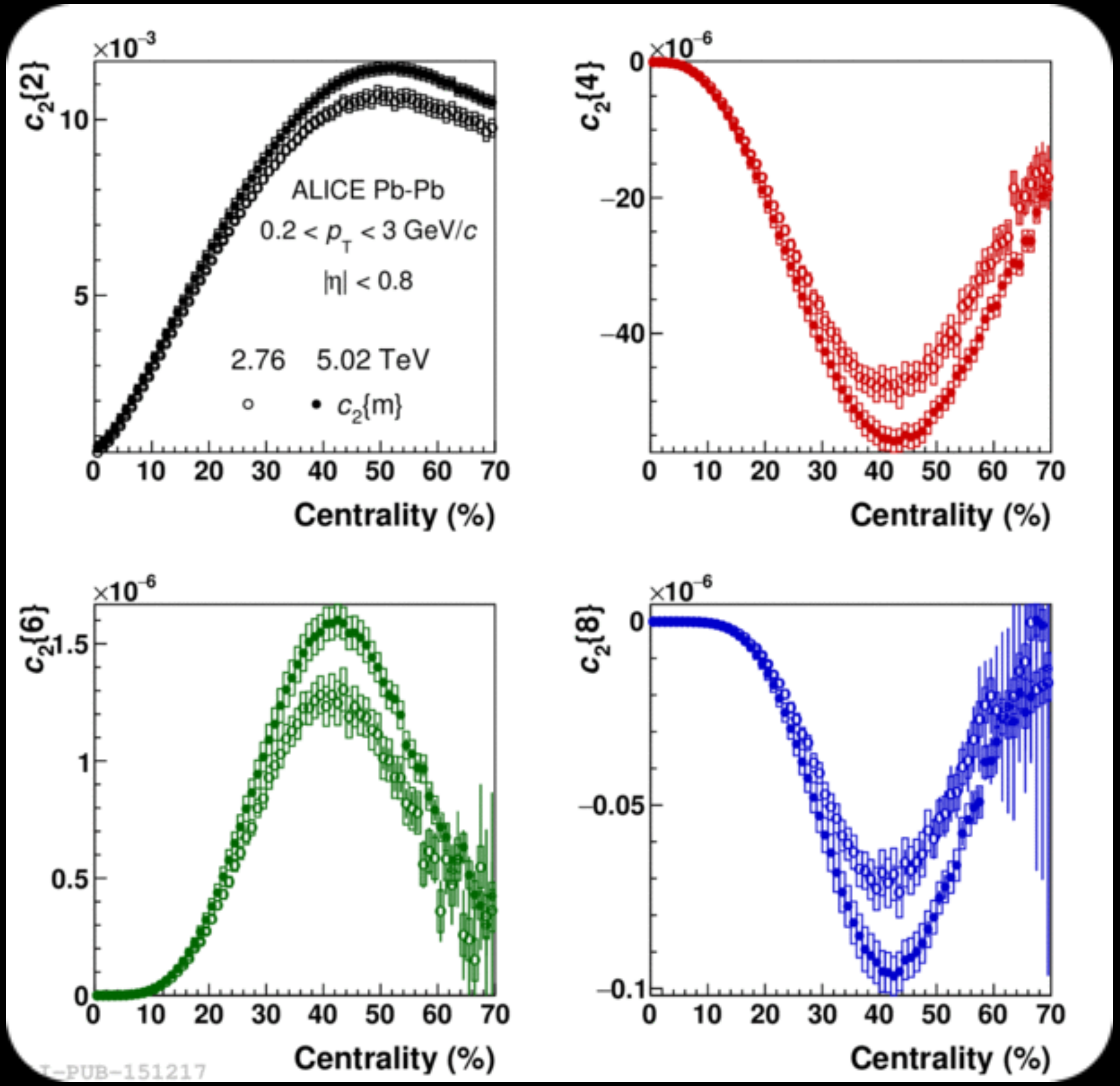
Constraining the IS with fluctuations

- ✓ What is the underlying probability distribution function (p.d.f.) of v_n, $P(v_n)$?
- ✓ The magnitude of v_n is proportional (for n < 4; for n > 4 non-linear terms come into play) to ε_n
- ✓ $P(v_n)$ ~ Bessel-Gaussian but (small) deviations have already been reported
  - Sensitivity to details of initial state!

ALICE Collaboration, JHEP 07 (2018) 103

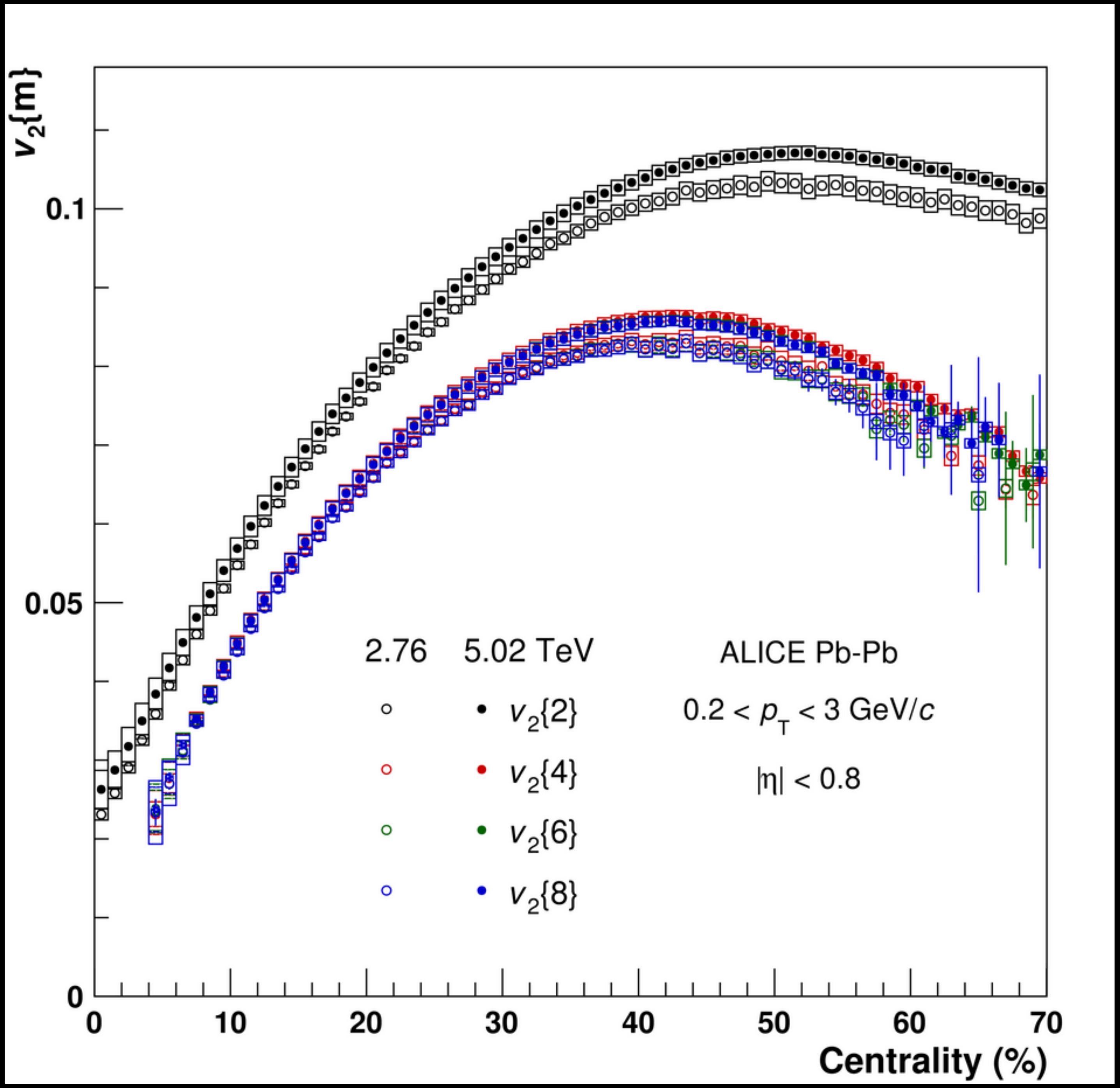
Using cumulants

$$v_n\{2\} = \sqrt[2]{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$
$$v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$



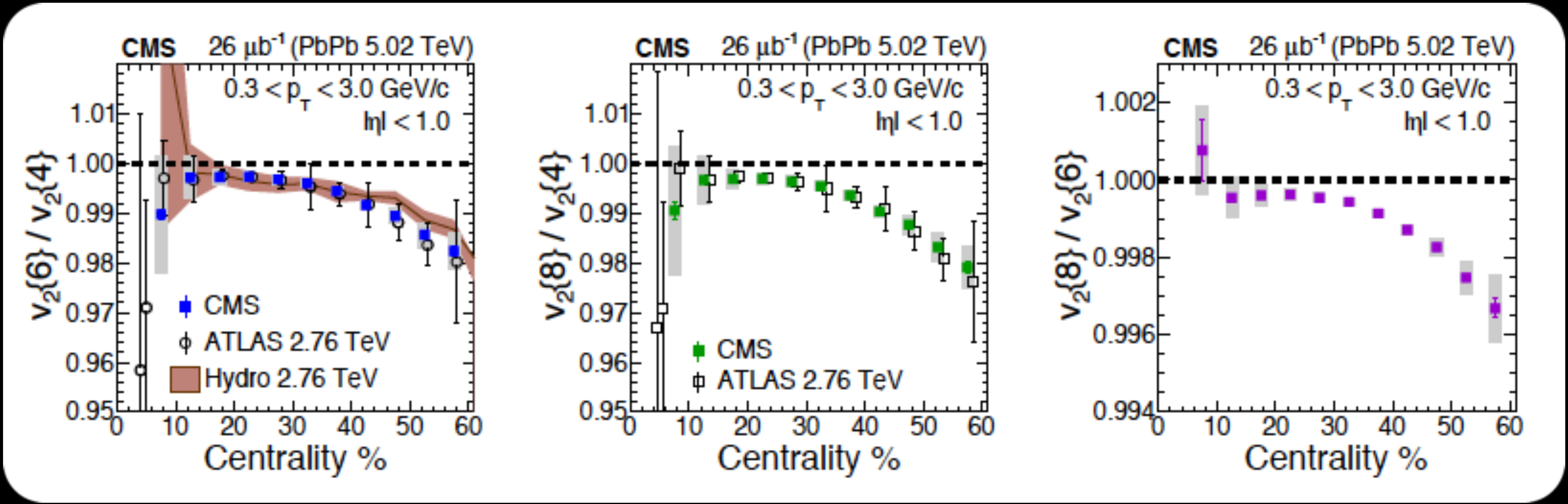
Measurements @ 5.02 TeV

ALICE Collaboration, JHEP 07 (2018) 103



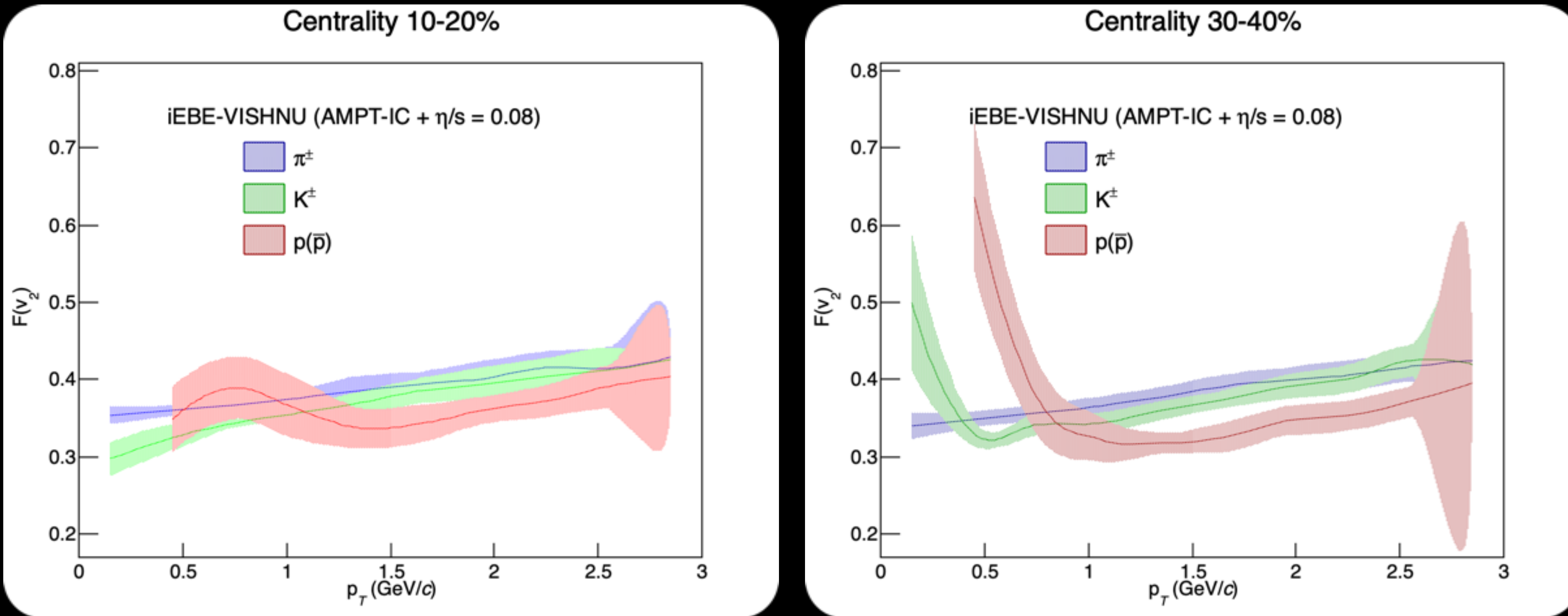
Measurements @ 5.02 TeV

CMS Collaboration, Phys. Lett. **B789** (2019) 643



- ✓ Results do not show any significant energy dependence
  - Consistent with expectations for no significant differences in eccentricities between the two energies
- ✓ Ratios of multi-particle results deviate from unity for peripheral events
- ✓ Results for central events (fluctuations only region) are compatible with a Bessel-Gaussian $P(v_2)$
- ✓ Skewness estimated from the fine-splitting of $v_2\{m\}$

What about different particle species?



W. Zhao et al., EPJC77, (2017)

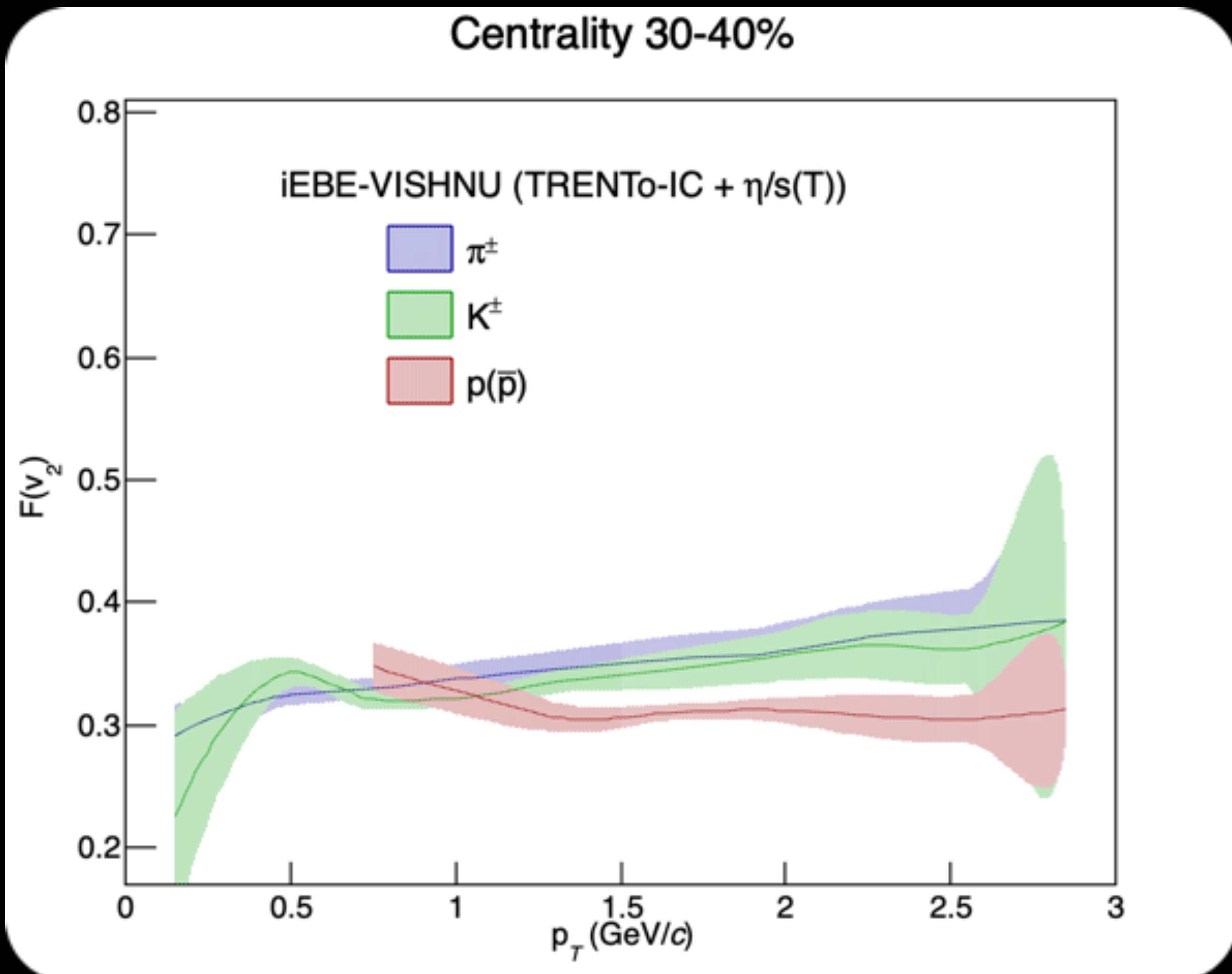
$$\langle v_n \rangle \approx \sqrt{(v_n^2\{2\} + v_n^2\{4\})/2}$$

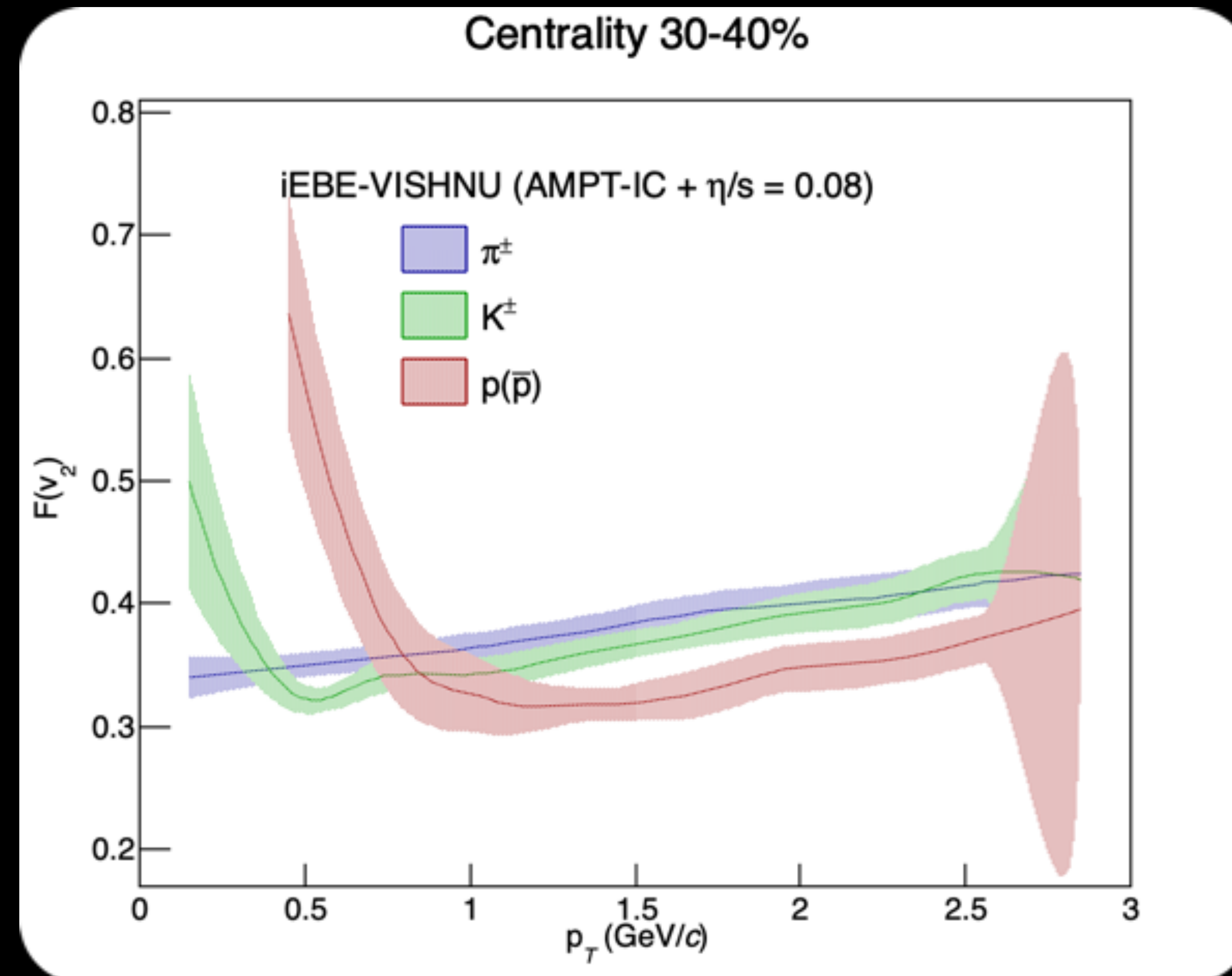
$$\sigma_{v_n} \approx \sqrt{(v_n^2\{2\} - v_n^2\{4\})/2}$$

- ✓ Interesting dependence on particle mass expected by some calculations
  - Is it due to IS? Hydro evolution? Hadronic rescattering?

$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

What about different particle species?





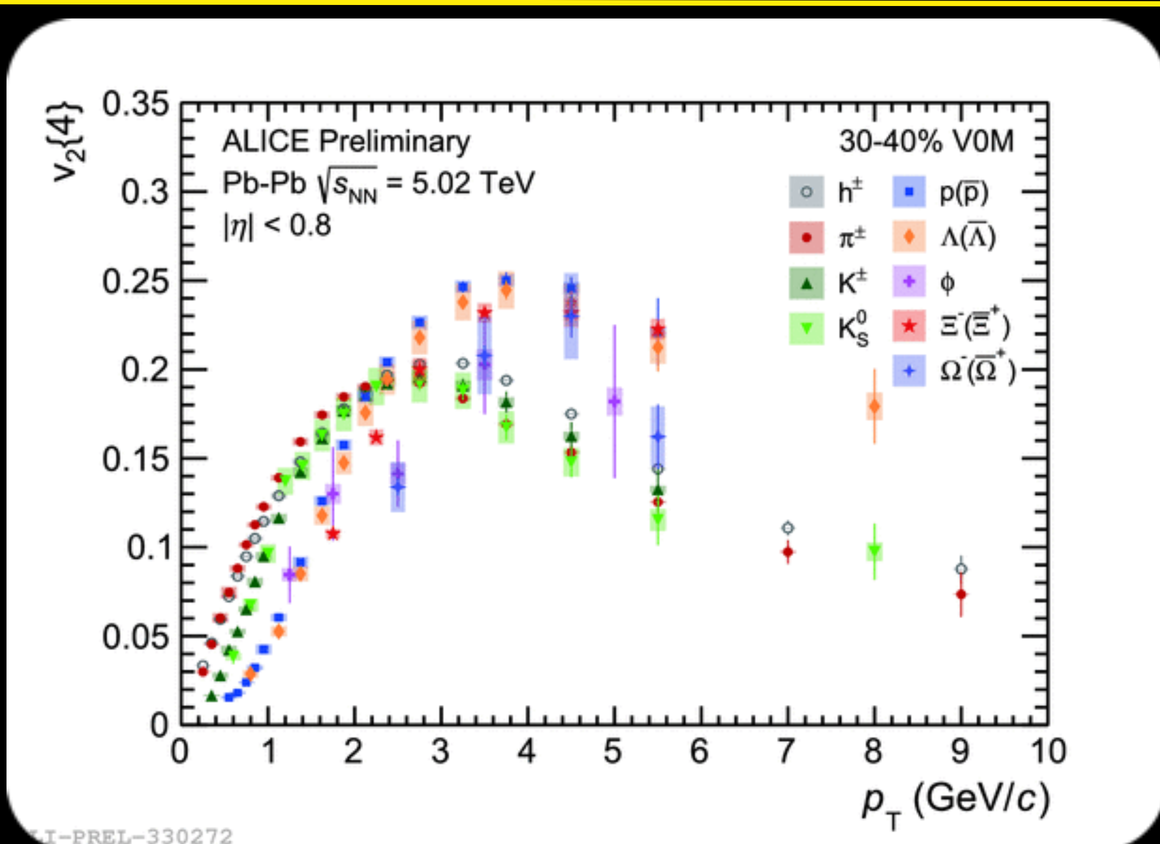
W. Zhao et al., EPJC77, (2017)

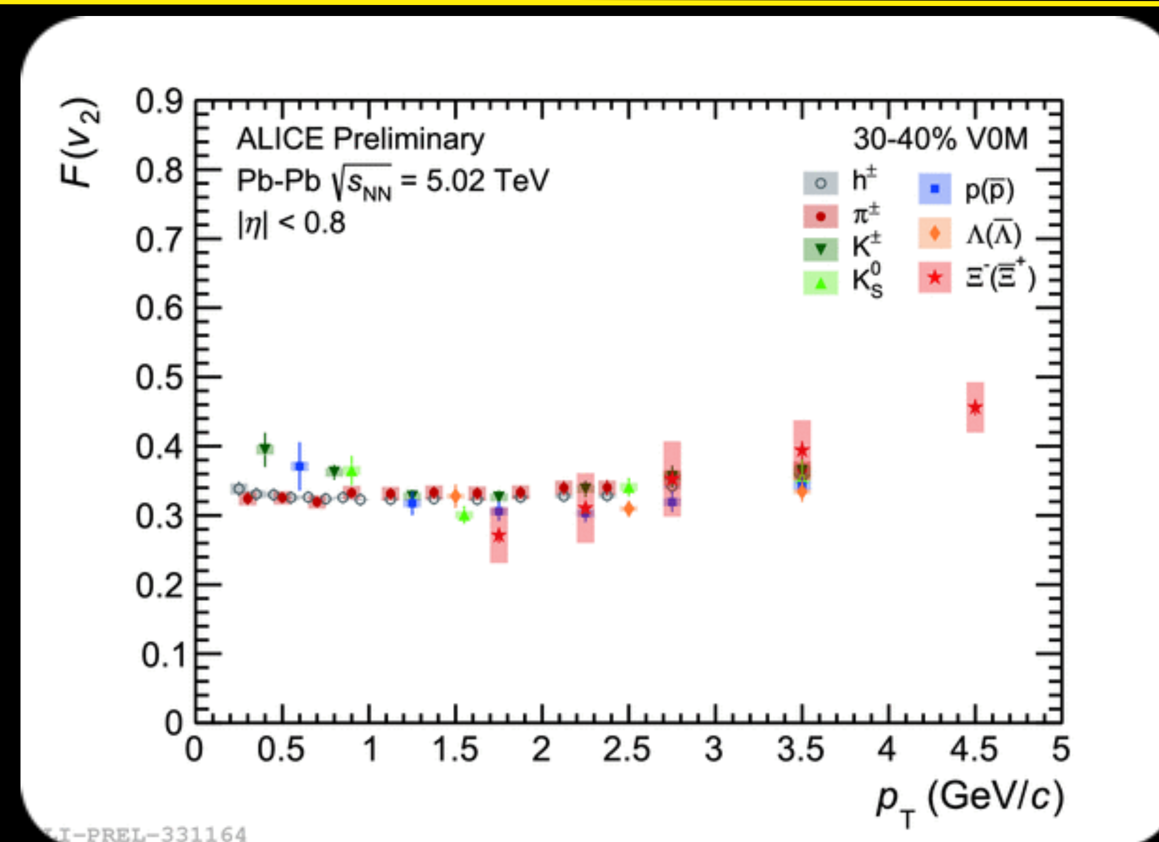
✓ Interesting dependence on particle mass expected by some calculations

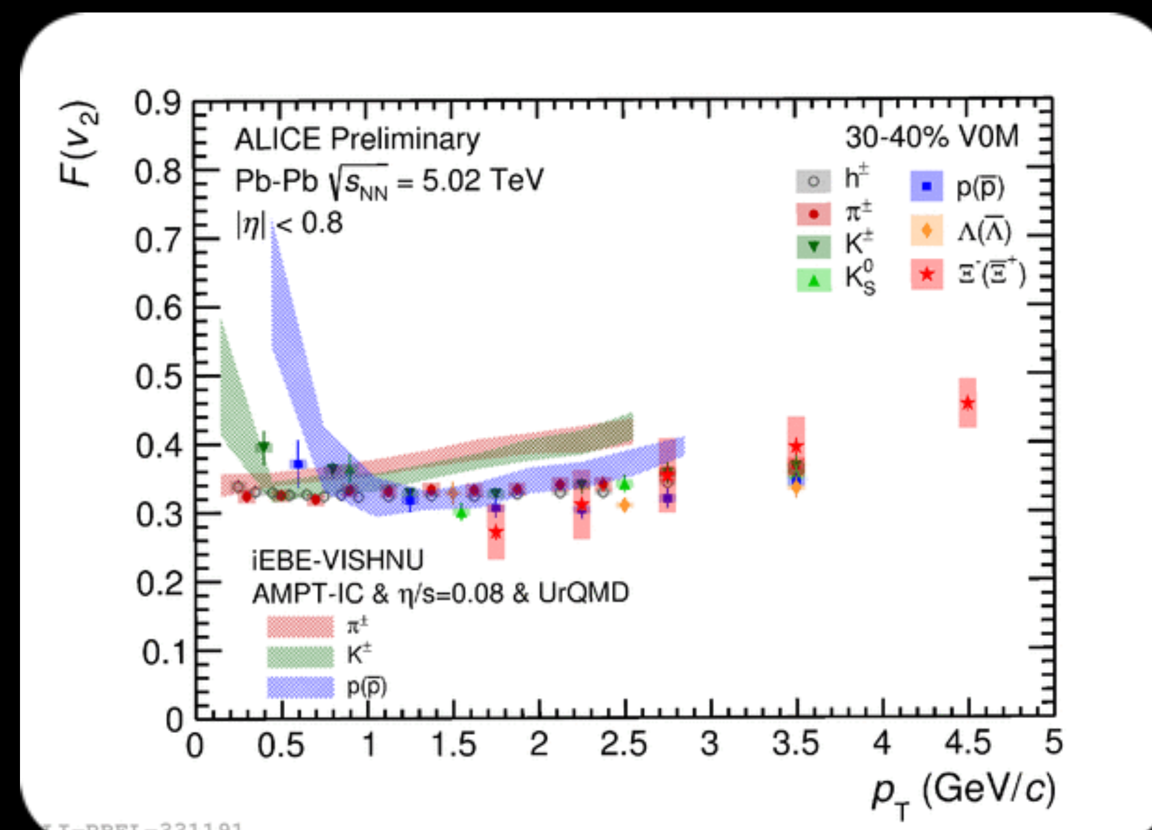
- Is it due to IS? Hydro evolution? ~~Hadronic rescattering?~~ ← Probably not

Interesting to see what the data show

Relative fluctuations for different particle species

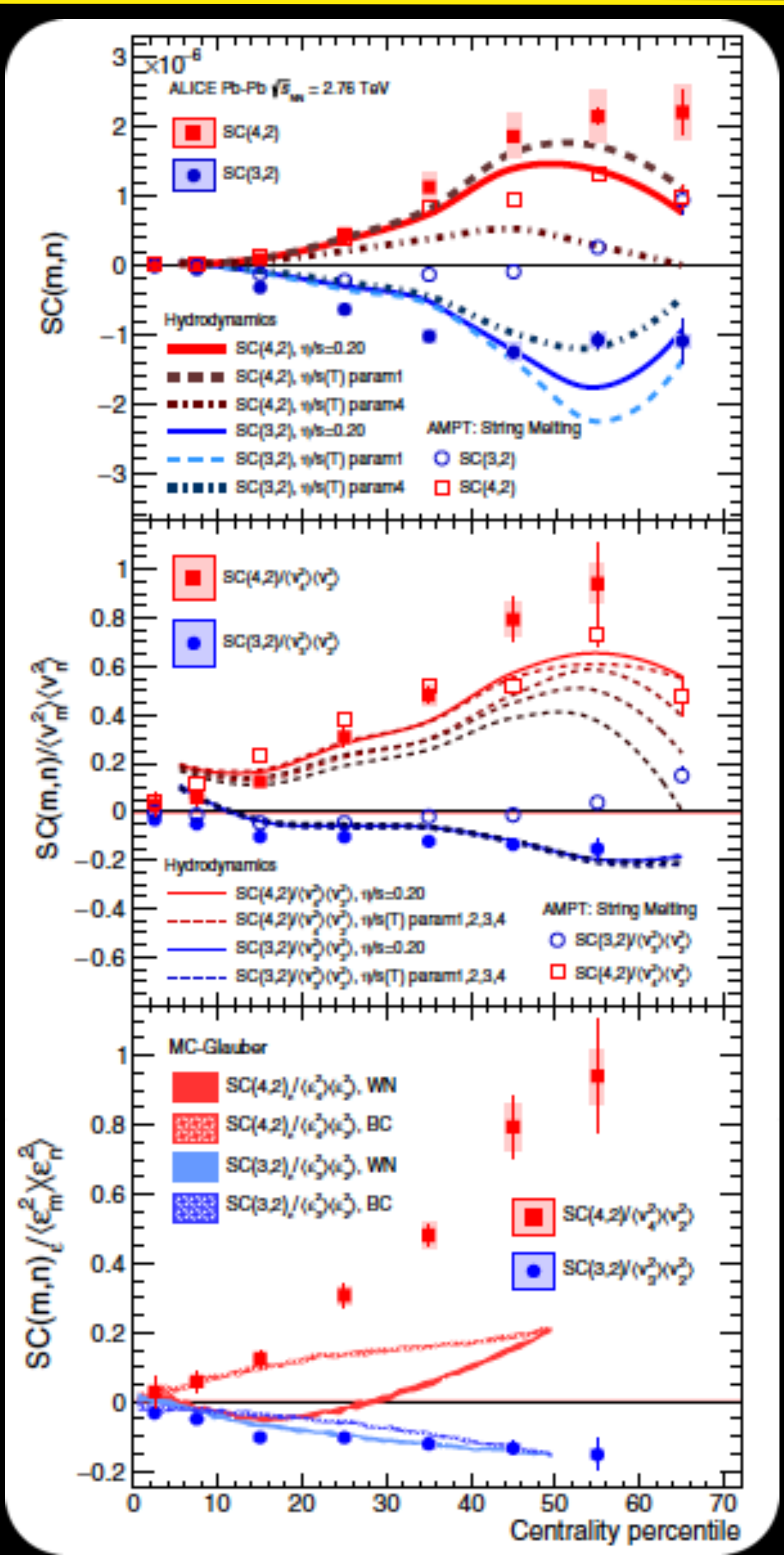






- ✓ First measurements of $v_2\{4\}$ for various particle species
- ✓ Relative fluctuations do not show any strong p_T or particle species dependence
- ✓ Models do not describe the general trends of data (p_T and centrality dependence)

Correlations between harmonic amplitudes

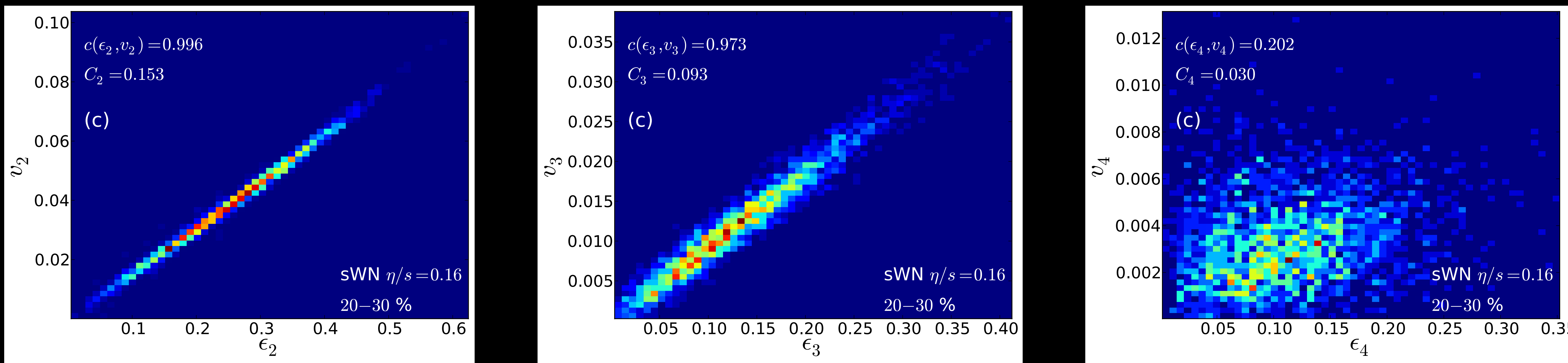


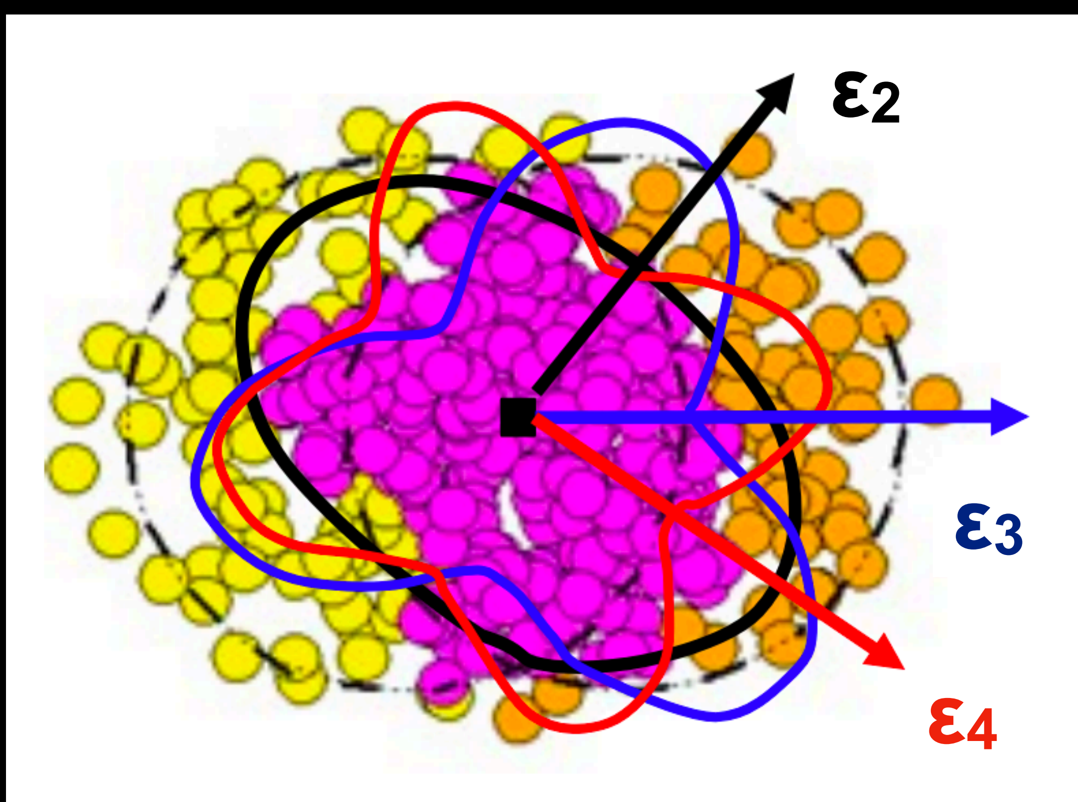
ALICE Collaboration, Phys. Rev. Lett. **117**, (2016) 182301

- Some new clever ways of disentangling the effects of the initial state from the transport properties of the QGP
  - Example: study symmetric cumulants (SC) ➡ probe correlations between the magnitudes of different flow harmonics
  - Magnitudes of v_2 and v_3 and anti-correlated
  - Magnitudes of v_2 and v_4 and correlated
- Normalised symmetric cumulants (NSC) cancels out the dependence of vn on IS or transport properties
  - NSC(3,2) sensitive to IS ➡ v_3 mainly dominated by IS fluctuations
  - NSC(4,2) sensitive to transport properties ➡ v_4 has a non-linear contribution from v_2

Non-linear flow modes

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



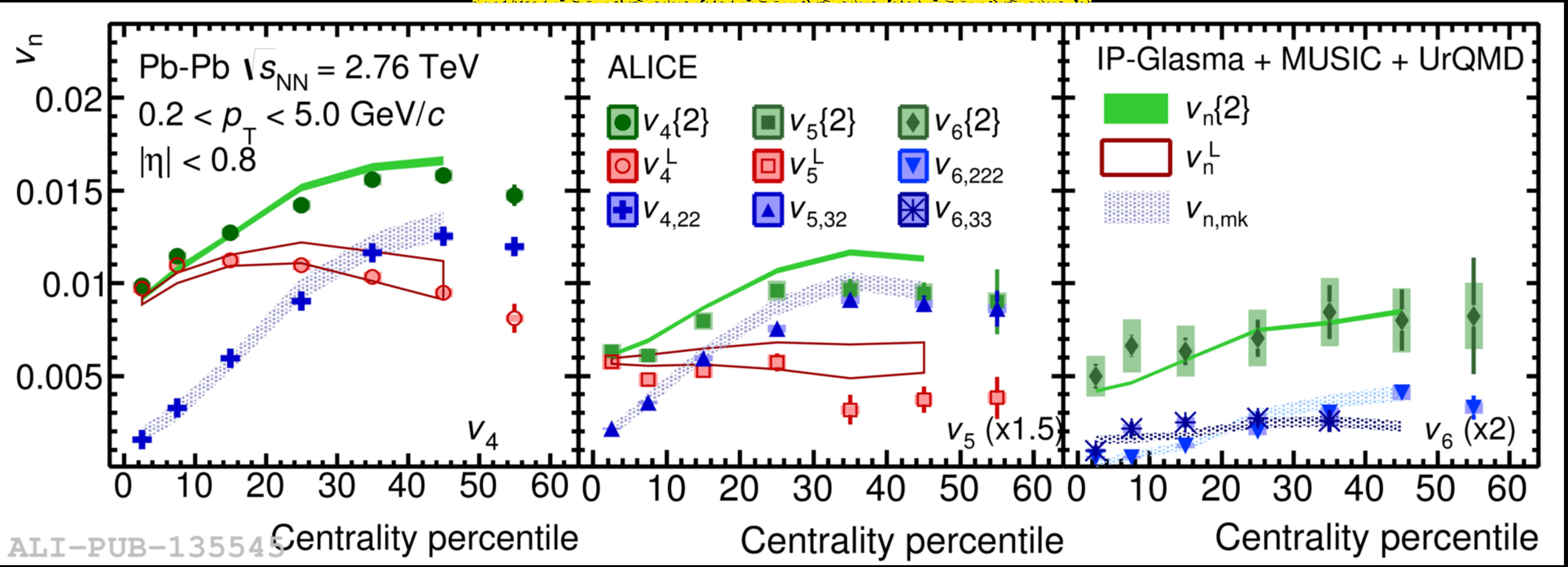


$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} \quad (n > 3)$$

Linear response   Non-linear response

Non-linear flow modes: charged particles

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



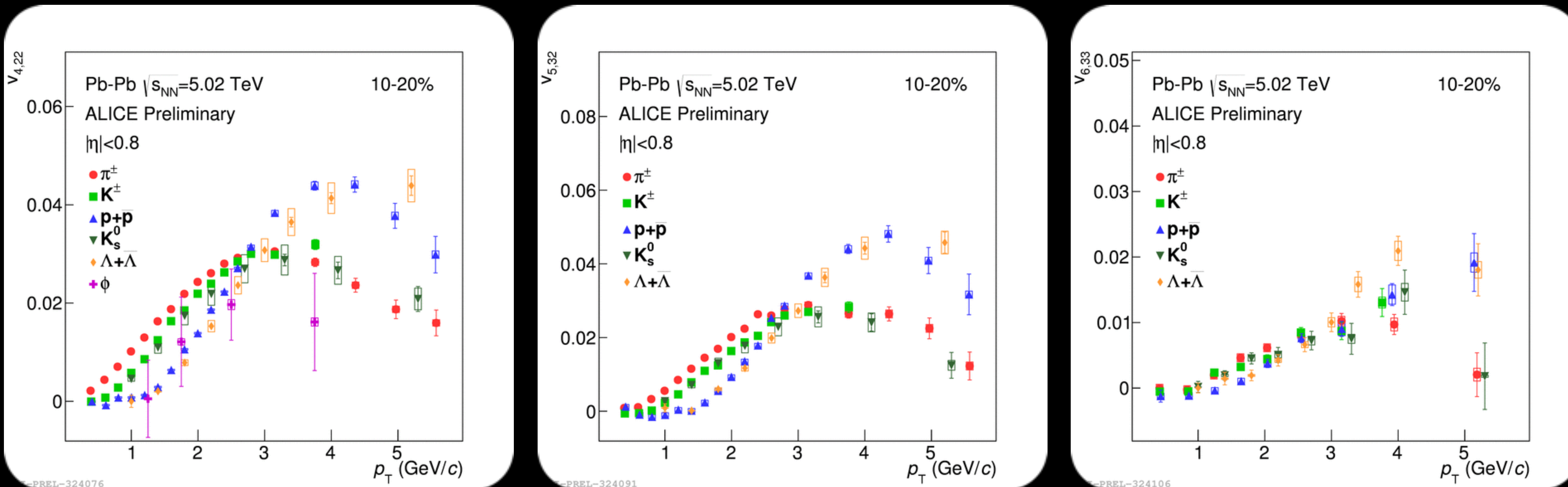
$$v_4^{\mathrm{L}} = \sqrt{v_4^2 - v_{4,22}^2}$$

$$v_5^{\mathrm{L}} = \sqrt{v_5^2 - v_{5,32}^2}$$

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

Non-linear flow modes: identified particles

(ALICE Collaboration) arXiv:1912.00740

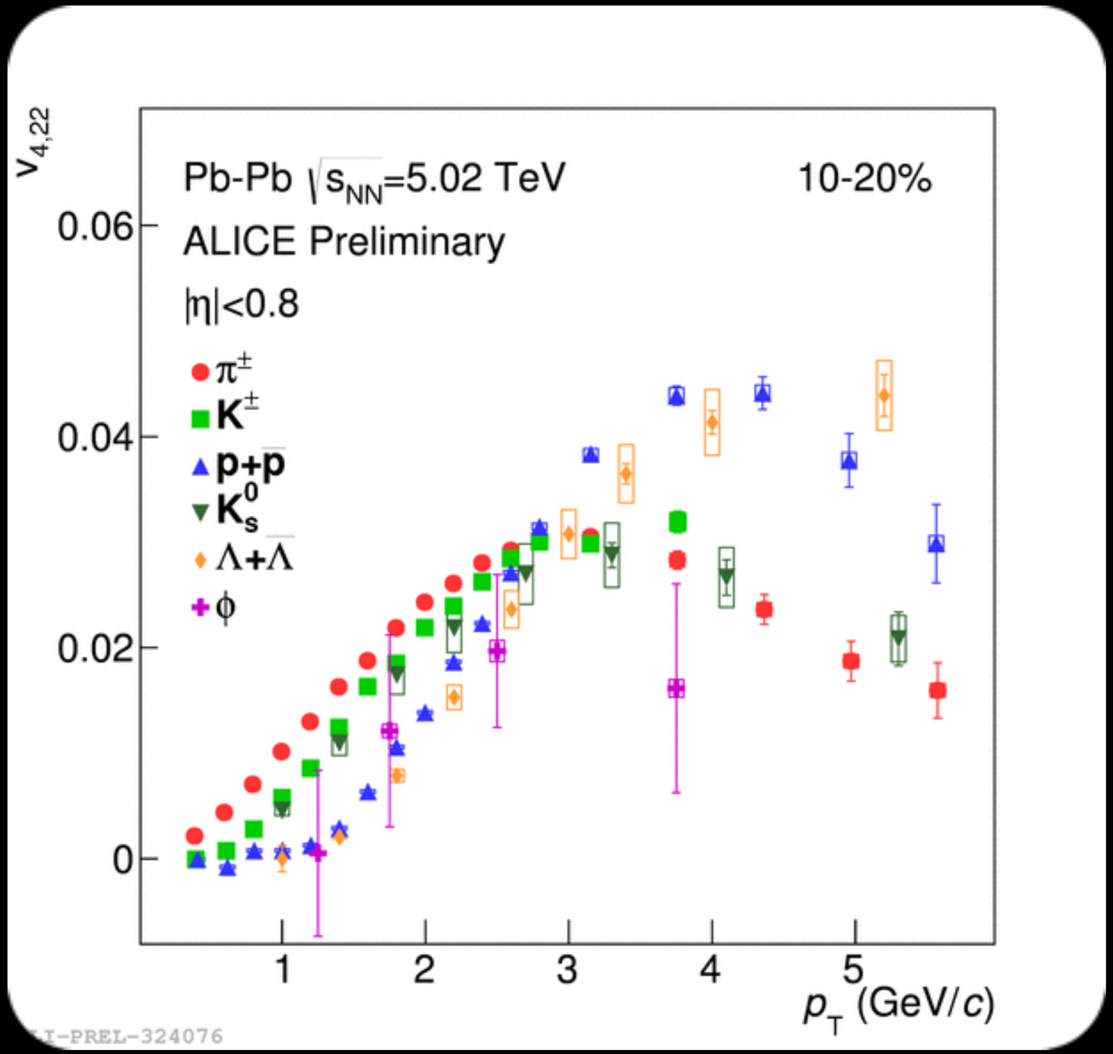


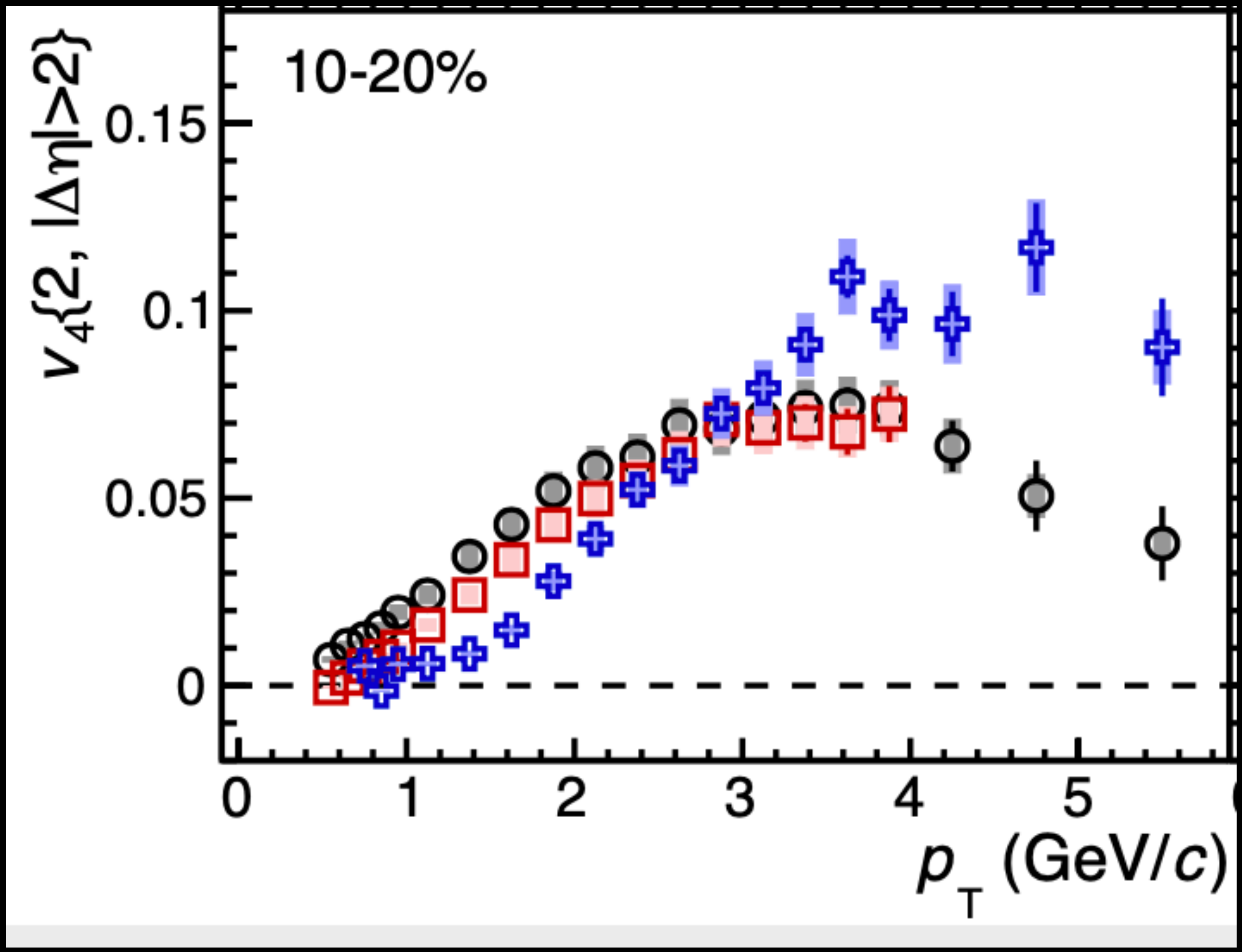
✓ Similar features as in total v_n measurements

- Mass ordering at low p_T → interplay between radial flow and anisotropic geometry
- Particle type grouping at intermediate p_T → coalescence as particle production mechanism?

Are there any differences between total and NL v_n?

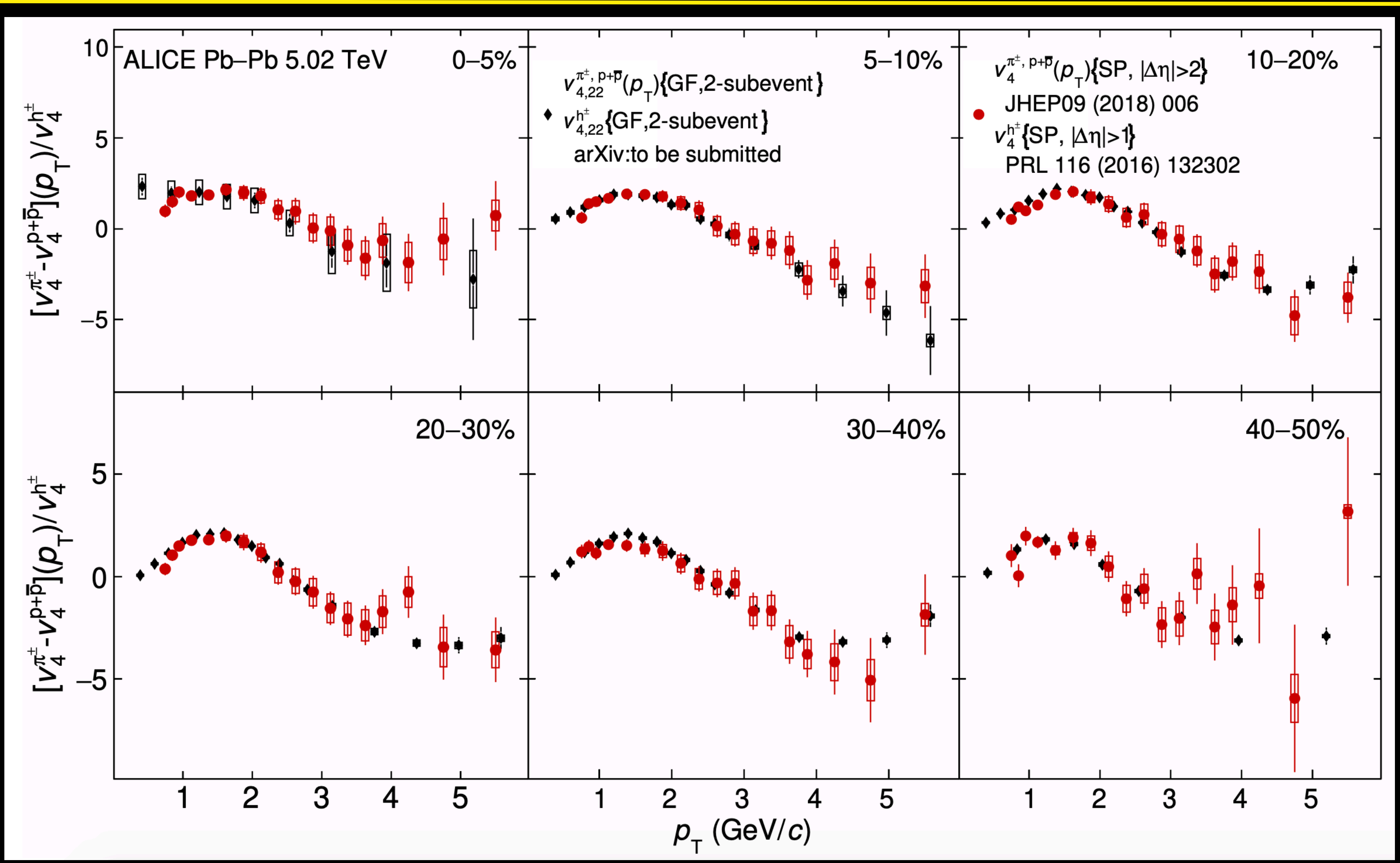
Non-linear flow modes: identified particles





- Unique opportunity to test the two regimes:
  - Mass ordering might develop differently between total and NL v_n
    - v_{422} 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: identified particles



✔ Unique opportunity to test the two regimes:

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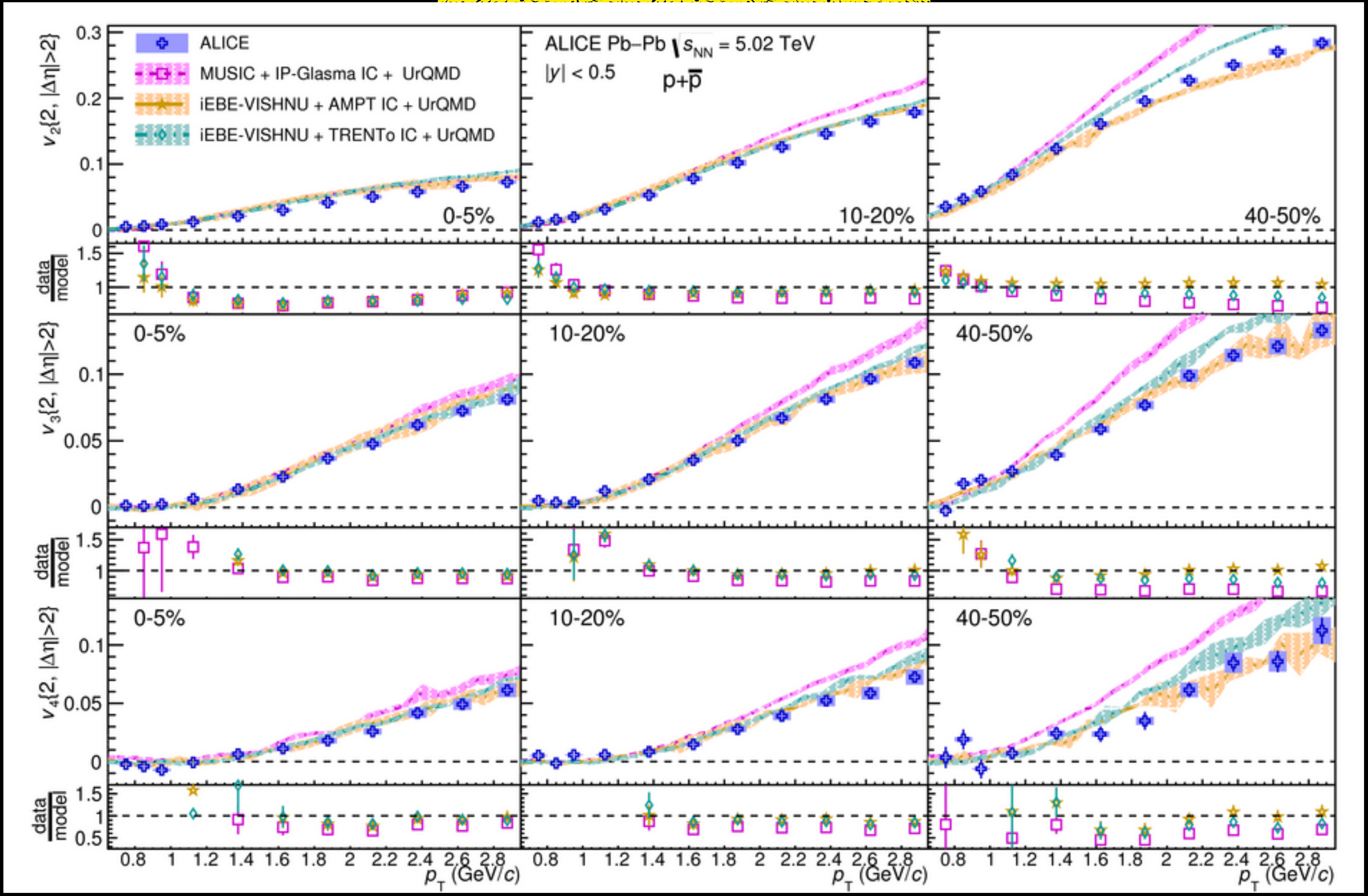
Total flow of identified particles: model comparison

(ALICE Collaboration) JHEP09 (2018) 006



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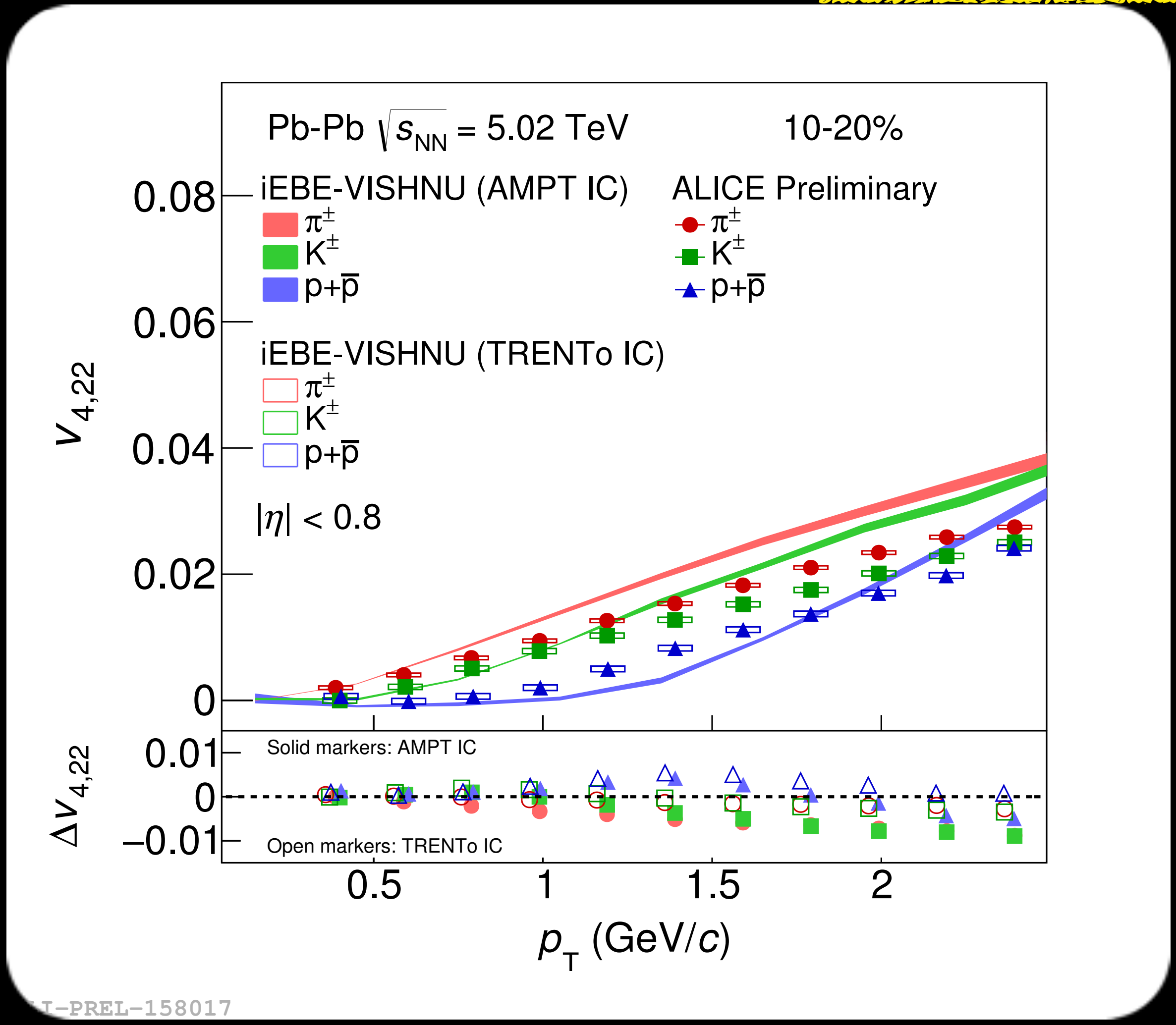
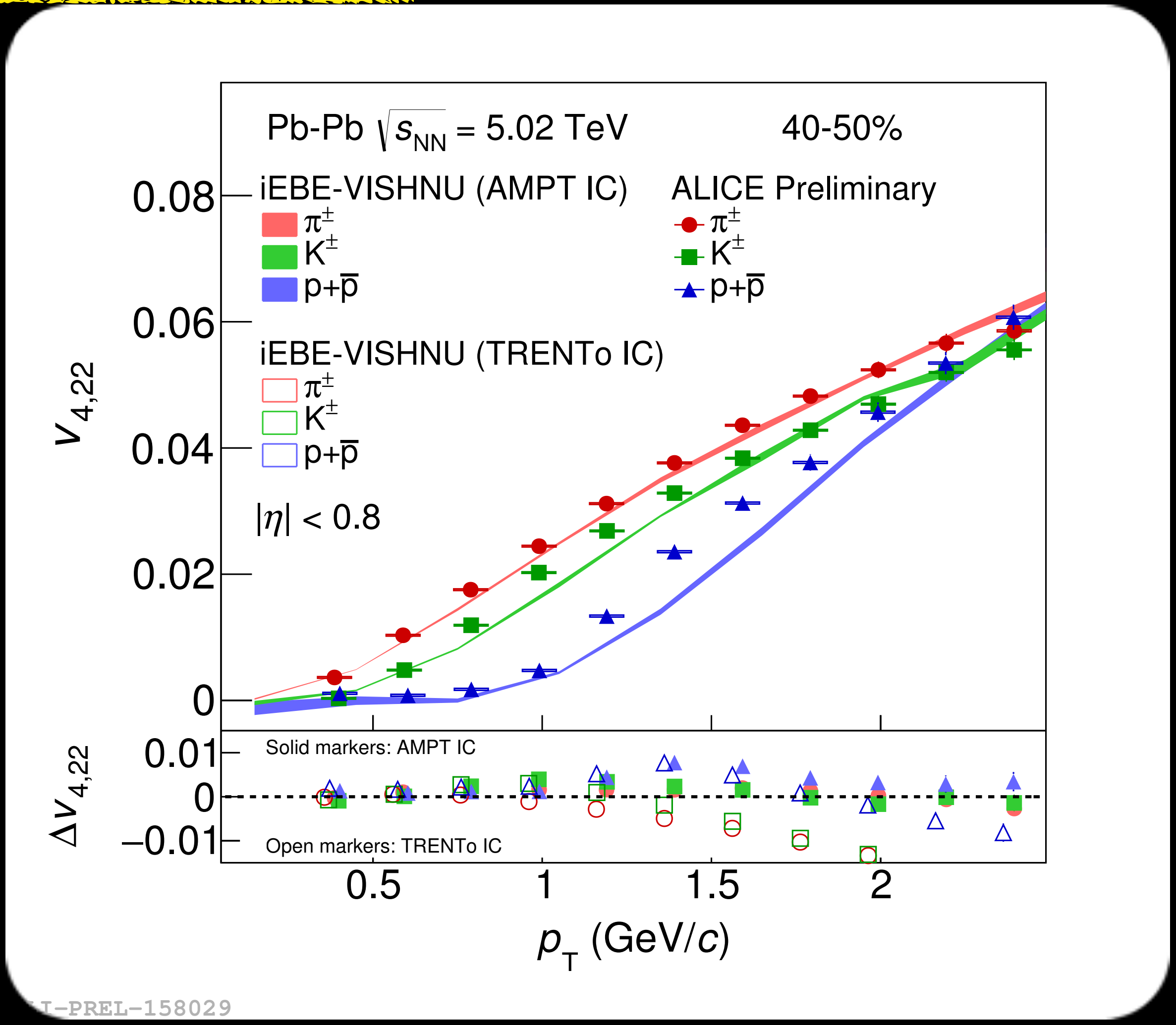
NL flow of identified particles: model comparison

(ALICE Collaboration) arXiv:1912.00740

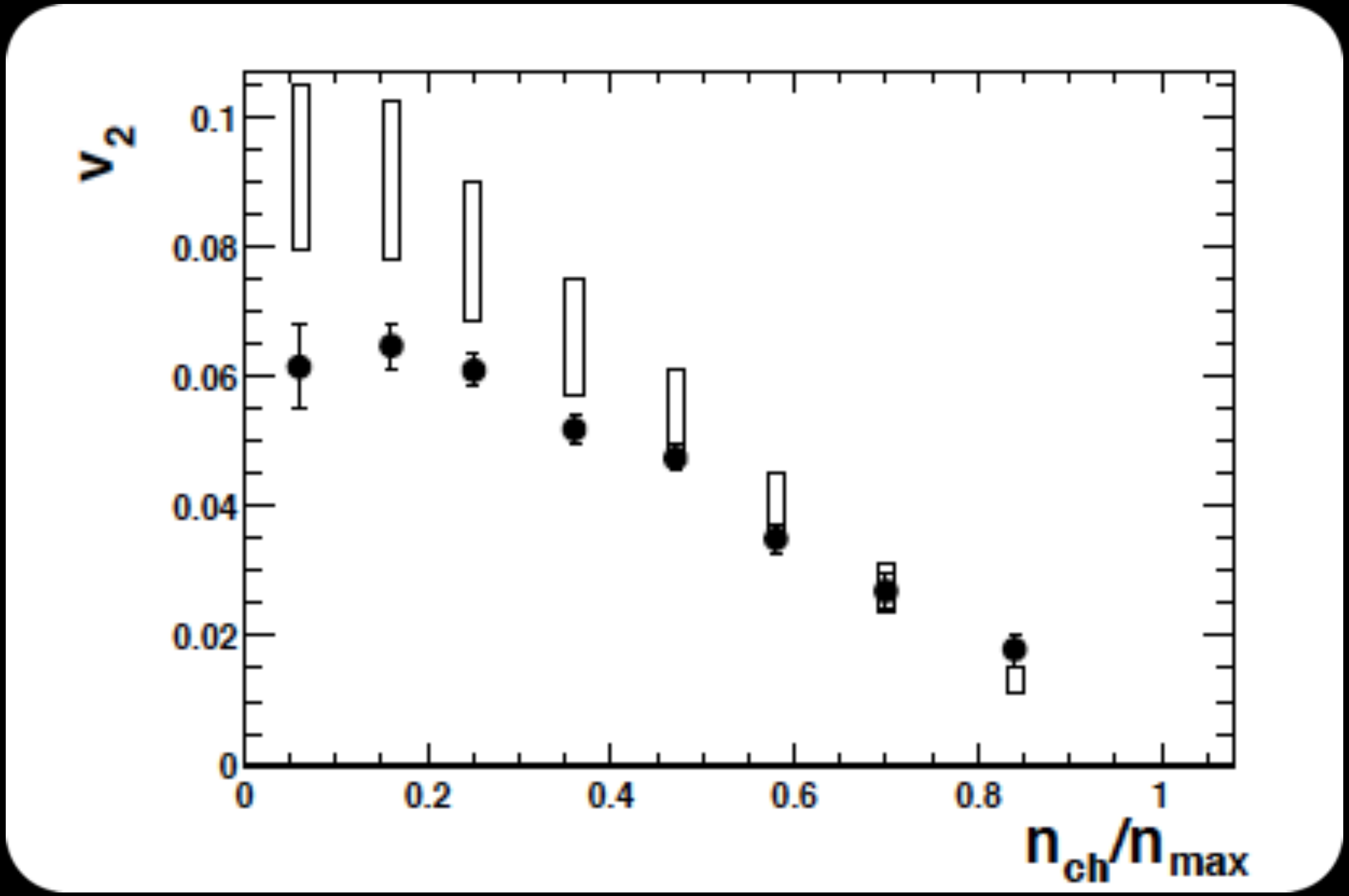




- ✔ In general good description from models
- ✔ Looking at the details:
  - The model with AMPT-IC does slightly better in some cases but trend is not clear
  - Models find it more difficult to describe the NL modes than the total v_n

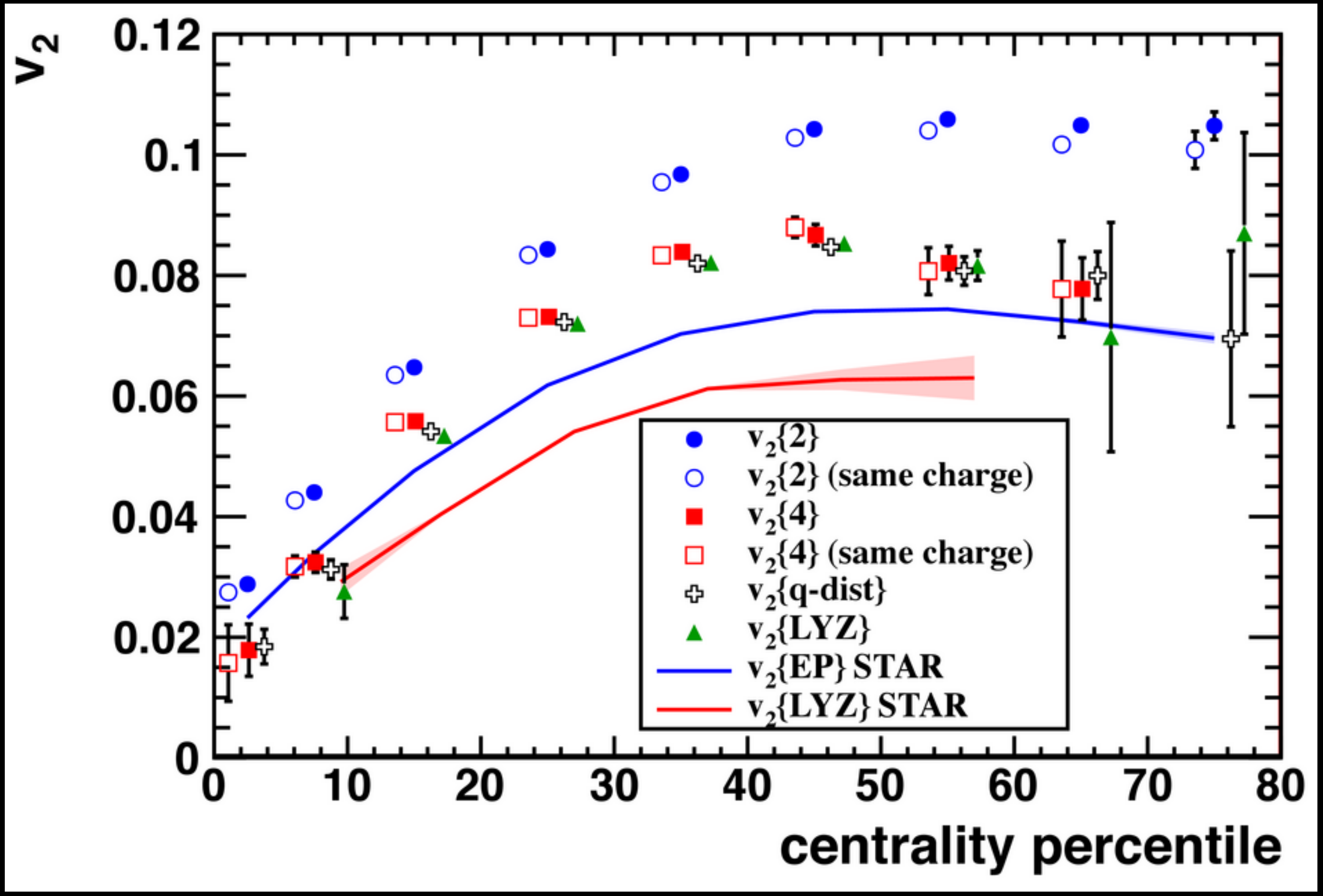
We've come a long way…from this

(STAR Collaboration) Phys. Rev. Lett. 86 (2001) 402



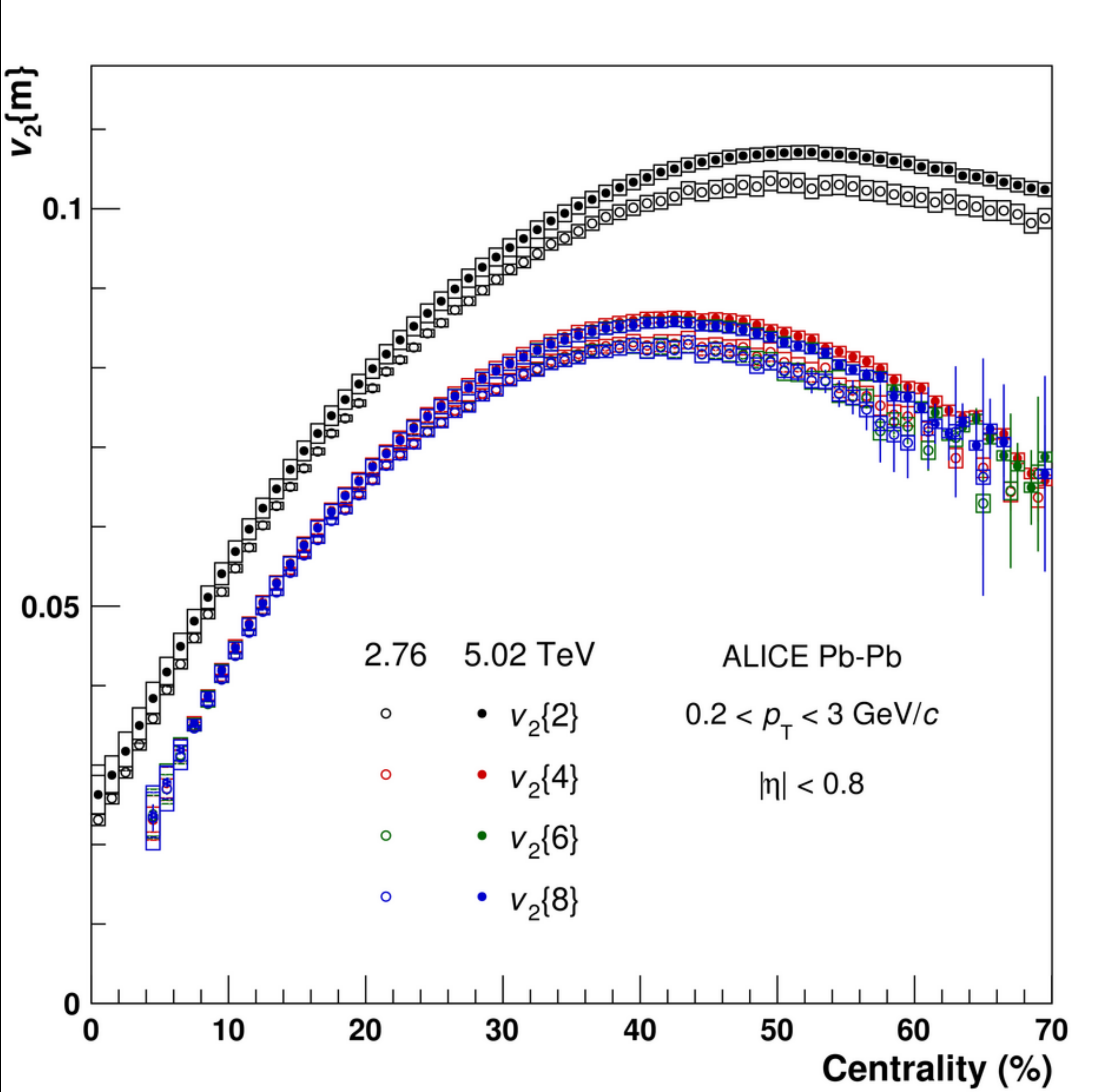
We've come a long way…to this

ALICE Collaboration, Phys. Rev. Lett. 105 (2010) 252302

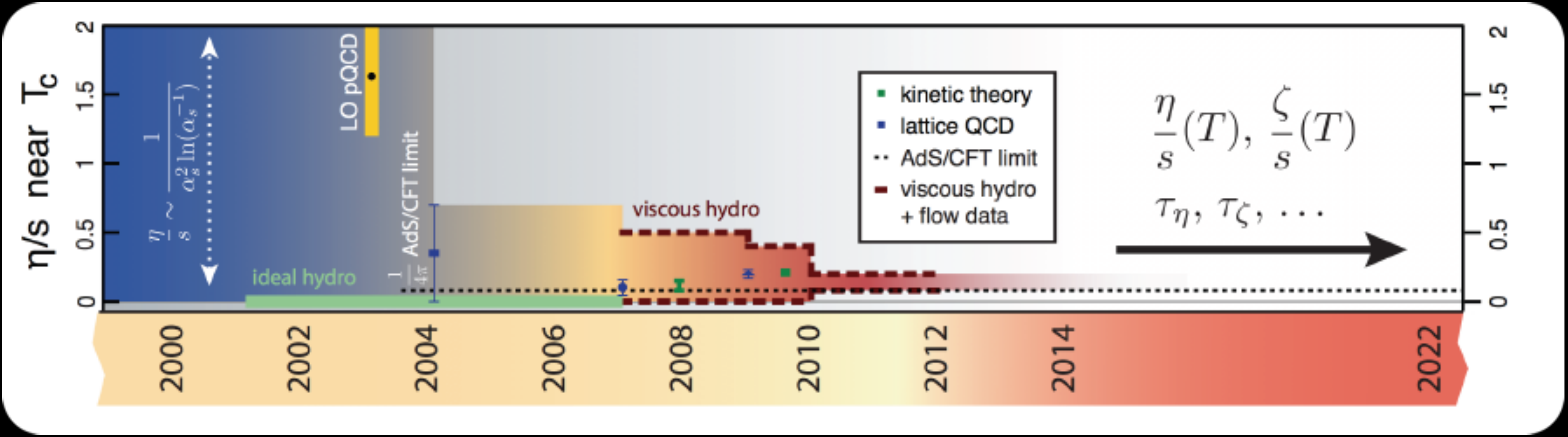


We've come a long way…and now to this

ALICE Collaboration, JHEP 07 (2018) 103

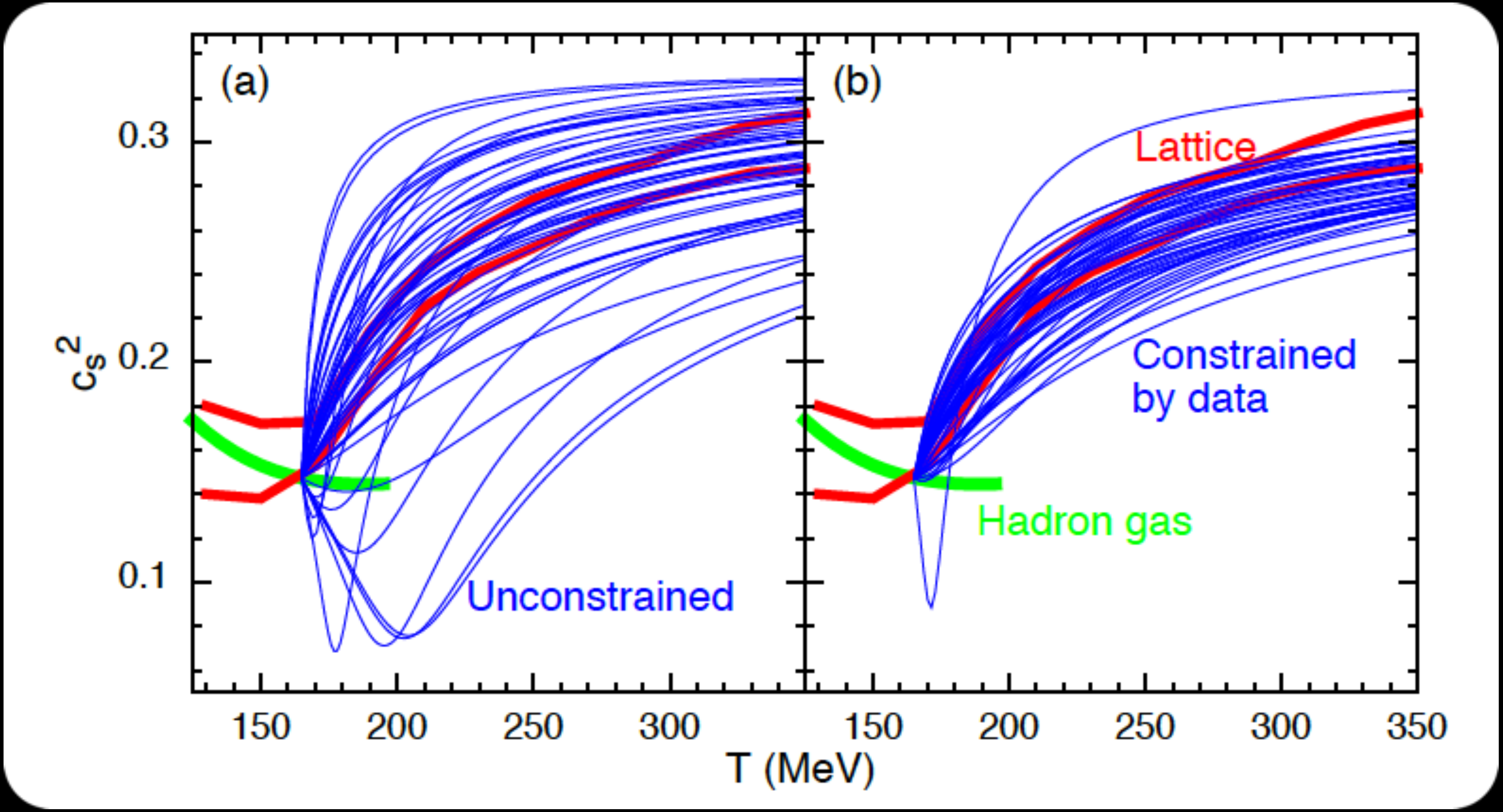


We've come a long way…and now to this



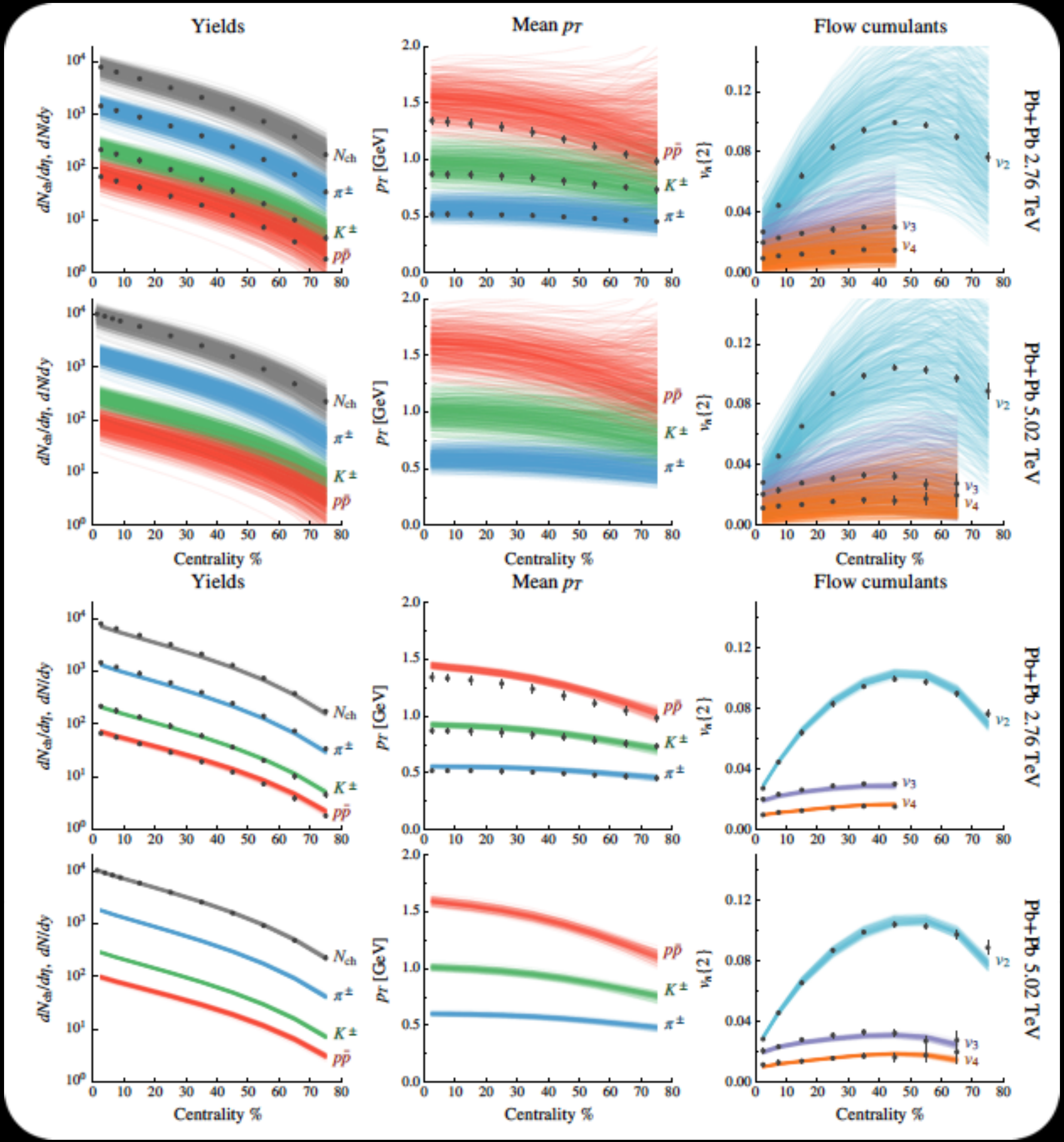
We've come a long way…and now to this

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



We've come a long way…and now to this

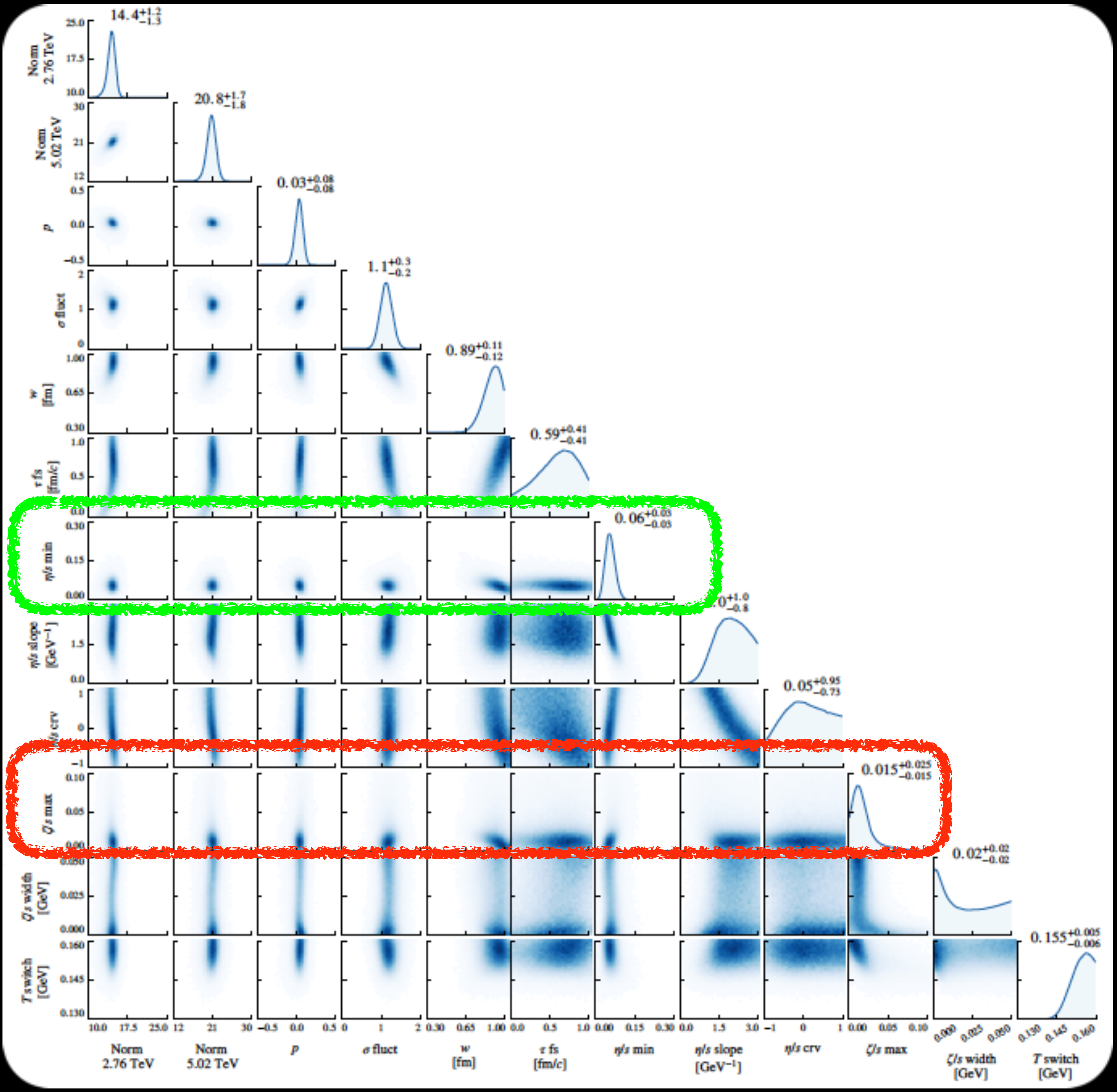
S. Bass *et al.*, Phys.Rev. C94 (2016), 024907



Nikhef

Constraining η/s(T) and ζ/s(T) from data

S. Bass *et al.*, Phys.Rev. C94 (2016), 024907



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Constraining η/s(T) and ζ/s(T) from data

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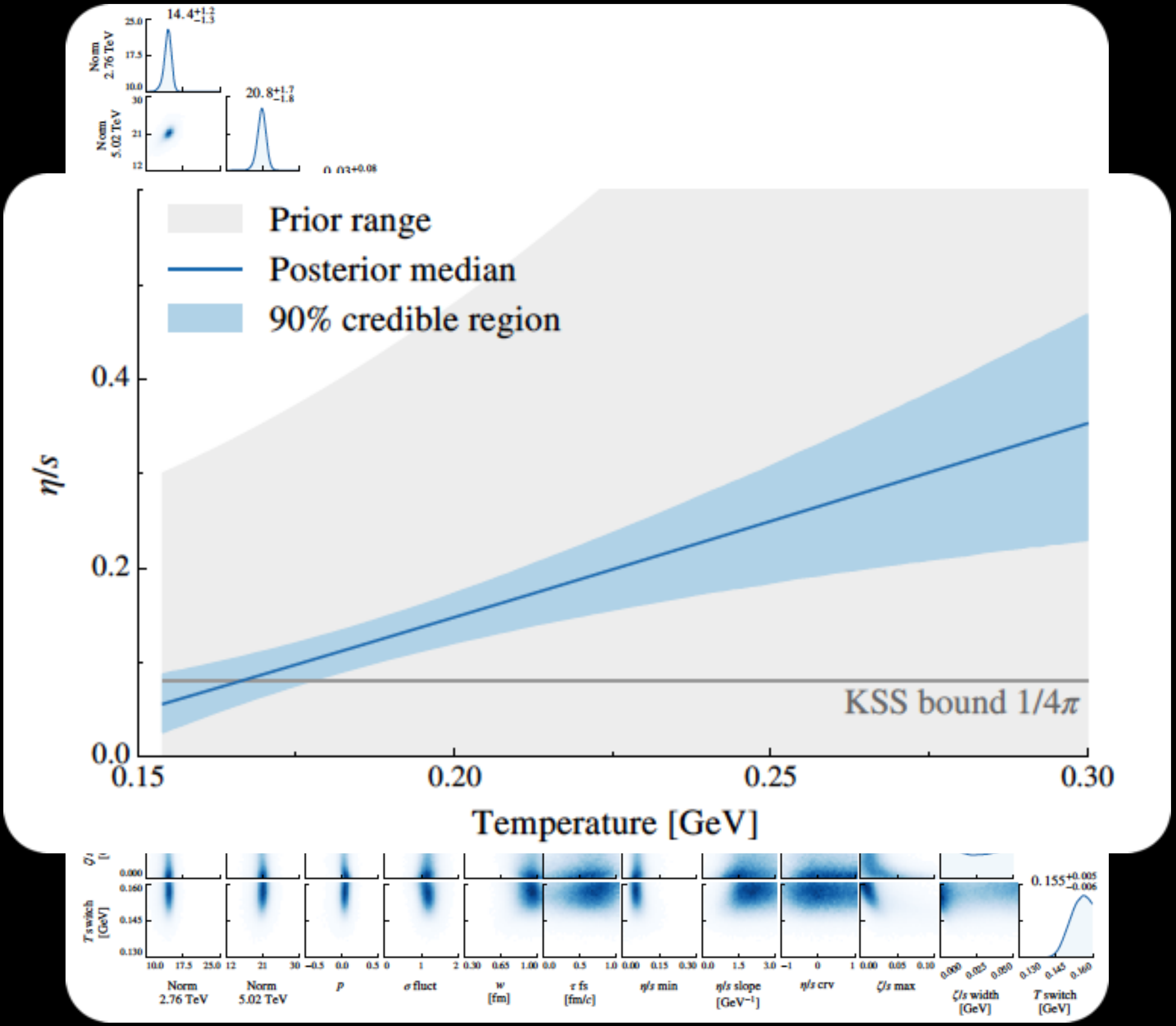
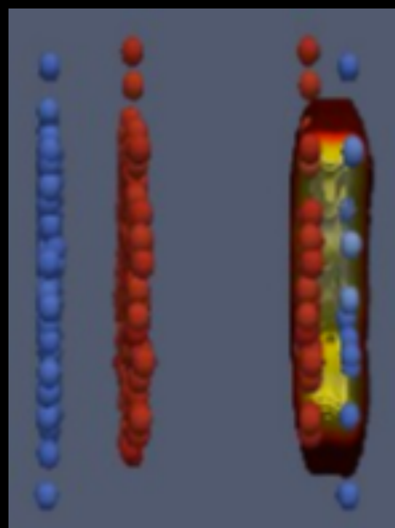


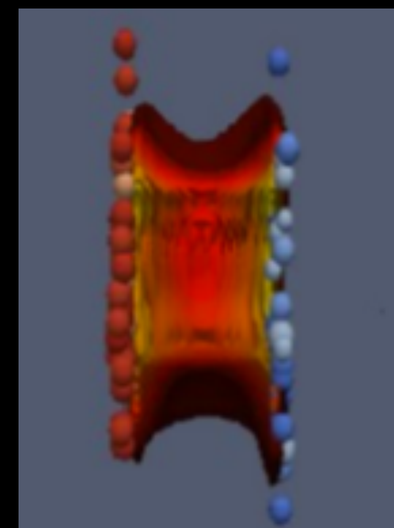
Instead of a summary: an attempt to confuse you more

Initial state



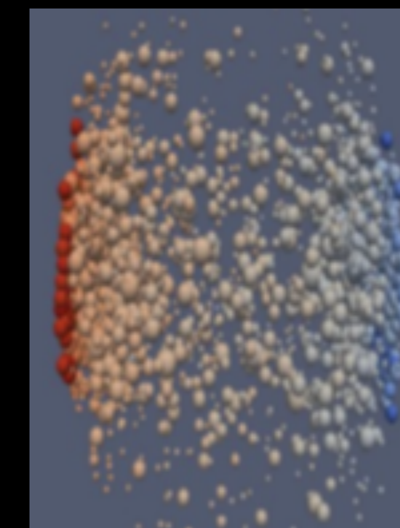
Thermalization

Hydrodynamical evolution



Hadronization

Hadronic rescattering



IP-Glasma, AMPT, EKRT, Glauber…?
How can we constrain the model?

EoS
η/s(T), ζ/s(T),…?

Coalescence, fragmentation,…?

x-sections, duration,…?

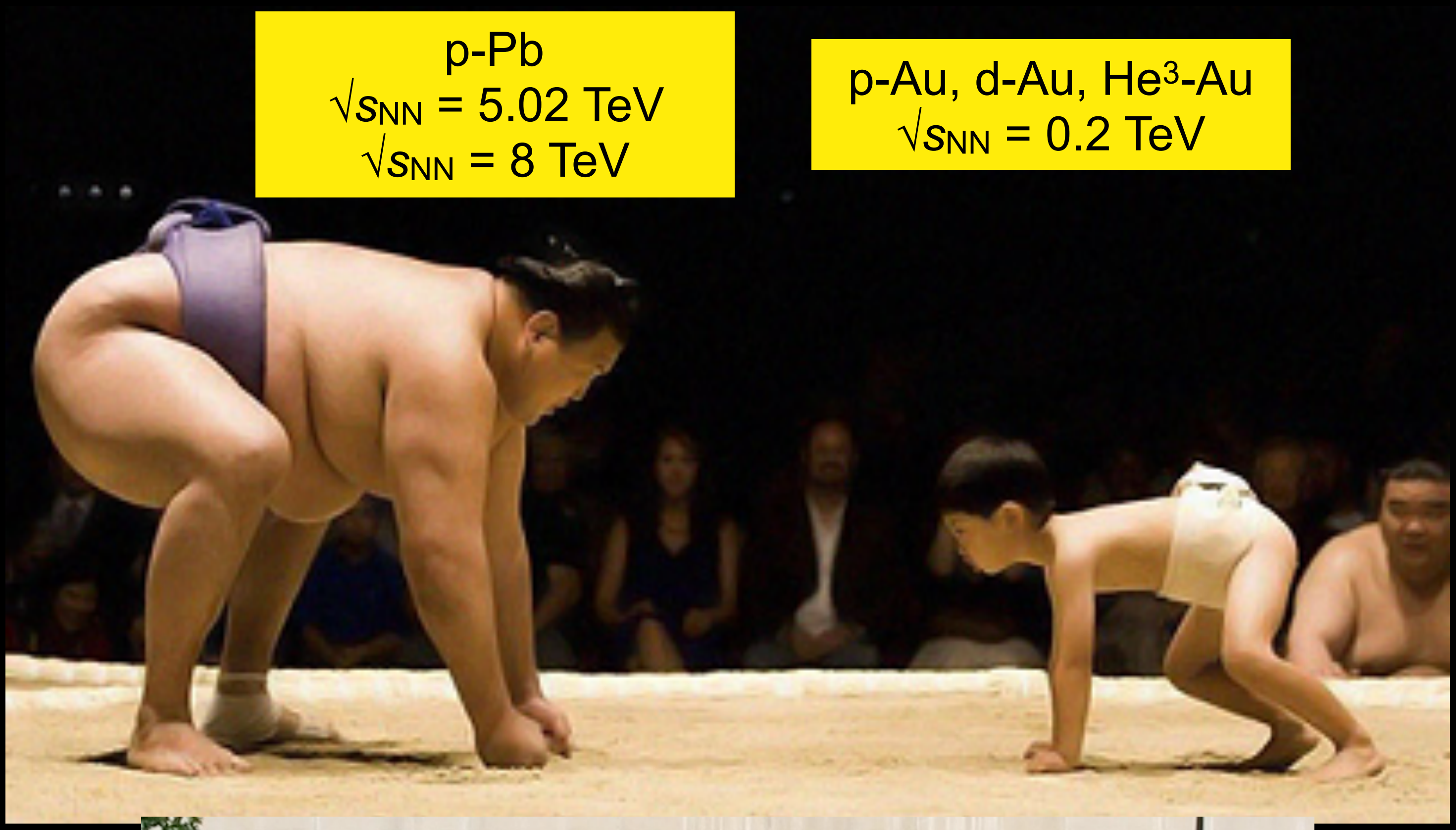
(in)famous quotes

- There are
  - known knowns
  - Known unknowns
  - Unknown knowns

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!!!

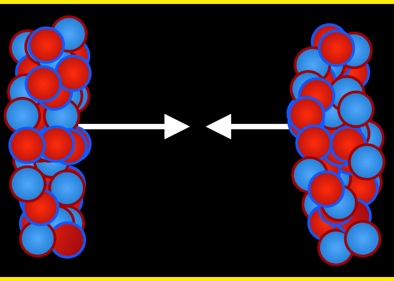
From large to small colliding systems…



p-Pb
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8 TeV

p-Au, d-Au, He^3-Au
$\sqrt{s_{NN}}$ = 0.2 TeV

Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV



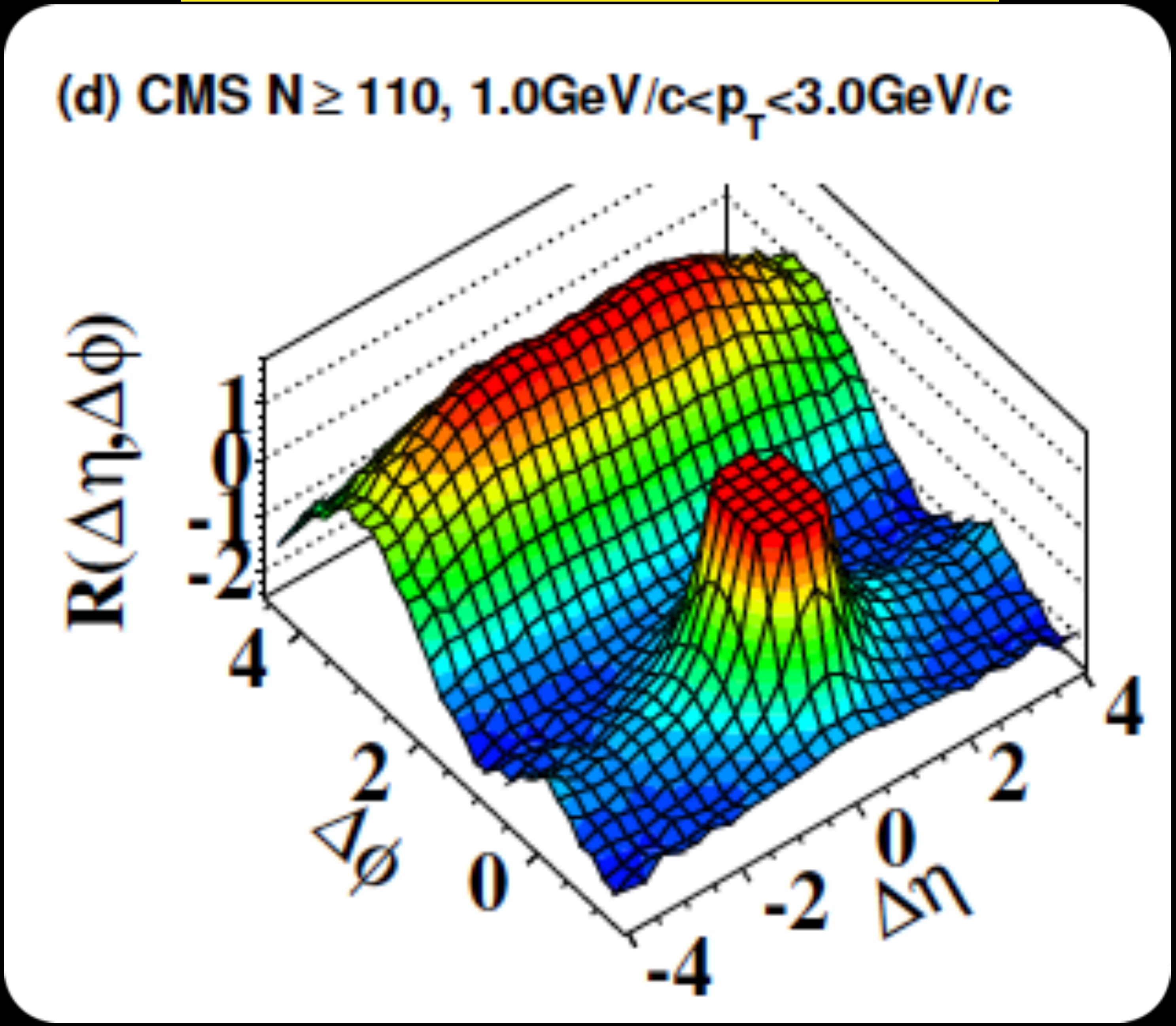
Xe-Xe
$\sqrt{s_{NN}}$ = 5.44 TeV

pp
$\sqrt{s}$ = 2.76 TeV
$\sqrt{s}$ = 5.02 TeV
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV

Where things got started…

Ridges in pp collisions: when pp collisions stopped being just a reference for the heavy-ion physics programs

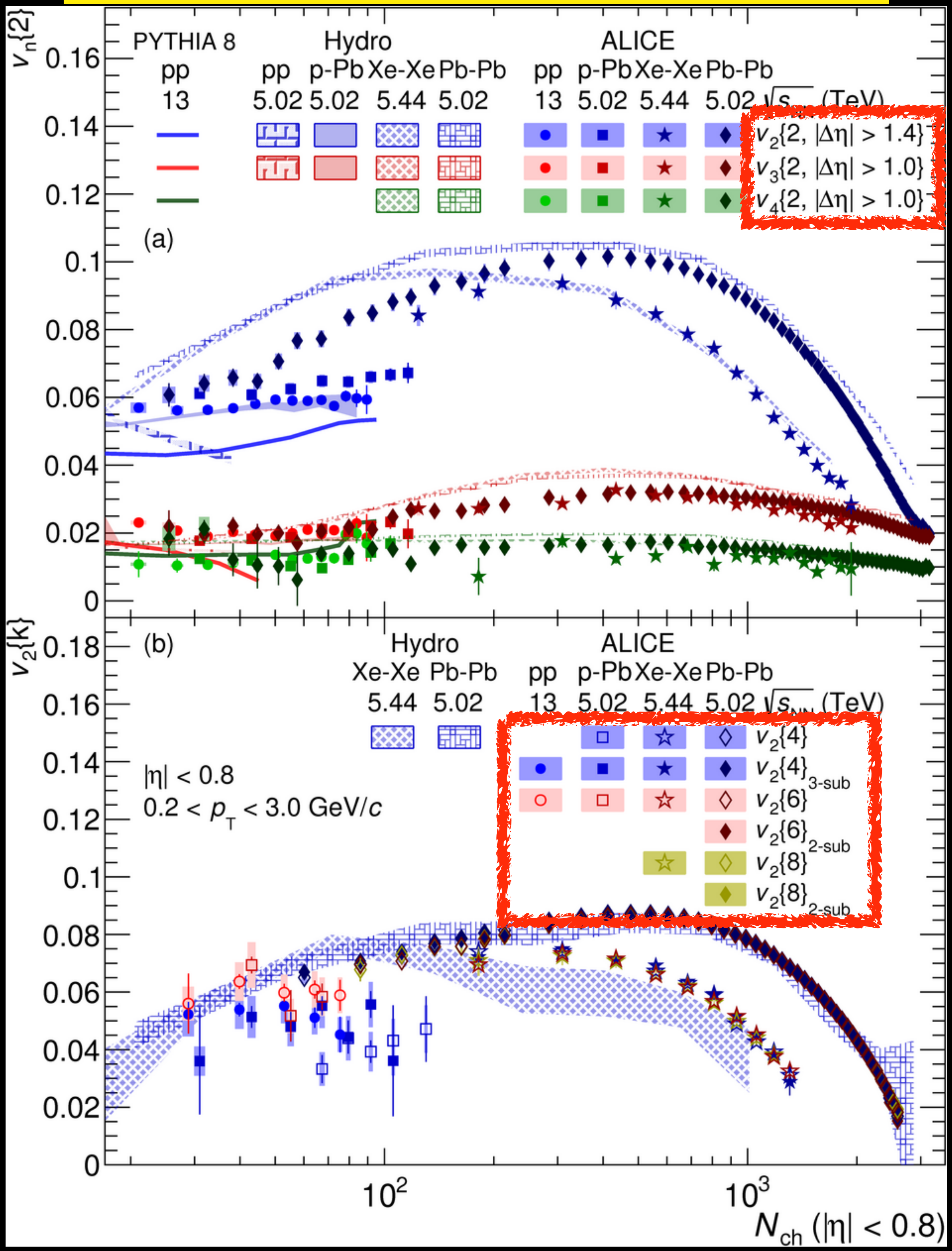
(CMS Collaboration) JHEP 09, (2010) 091



pp collisions @ √s = 7 TeV

Multi-particle collectivity in small systems

ALICE Collaboration, (accepted by PRL)



Correlations are characterised by their long range nature

Long range

- ✓ Results show typical "flow-like" sign: +,-,+,- for 2-, 4-, 6- and 8-particle cumulants
- ✓ 2-particle correlations in p-Pb and pp collisions
  - comparable $v_n\{2\}$ with Pb-Pb at low N_{ch} with weak multiplicity dependence
  - ordering $v_2 > v_3 > v_4$
  - results could not be reproduced by either PYTHIA or hydrodynamics

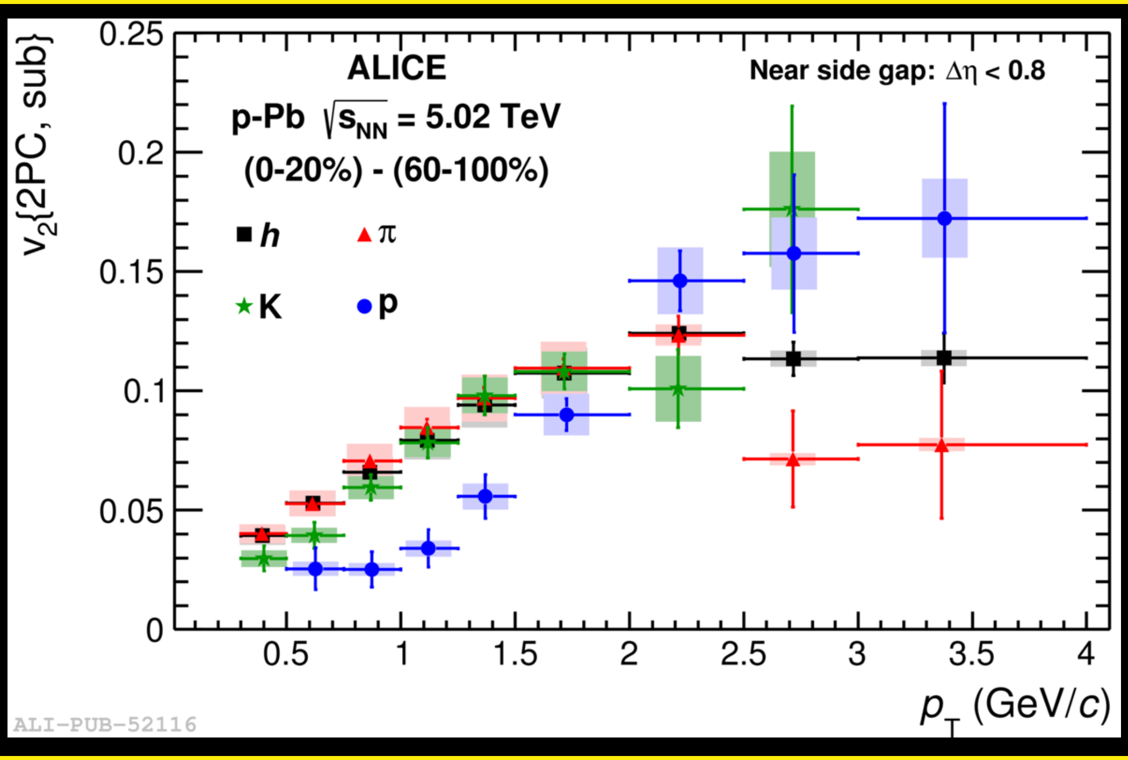
Correlations are shared between many particles

Multiparticle

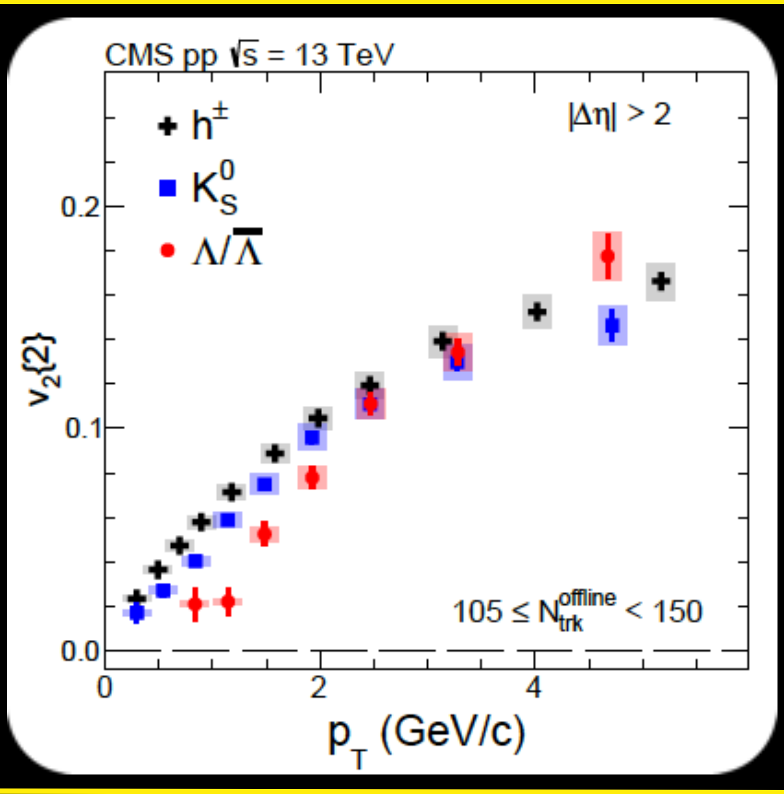
- ✓ Multi-particle cumulants with sub-event method (further non-flow suppression)
  - $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$

Everything flows (?)

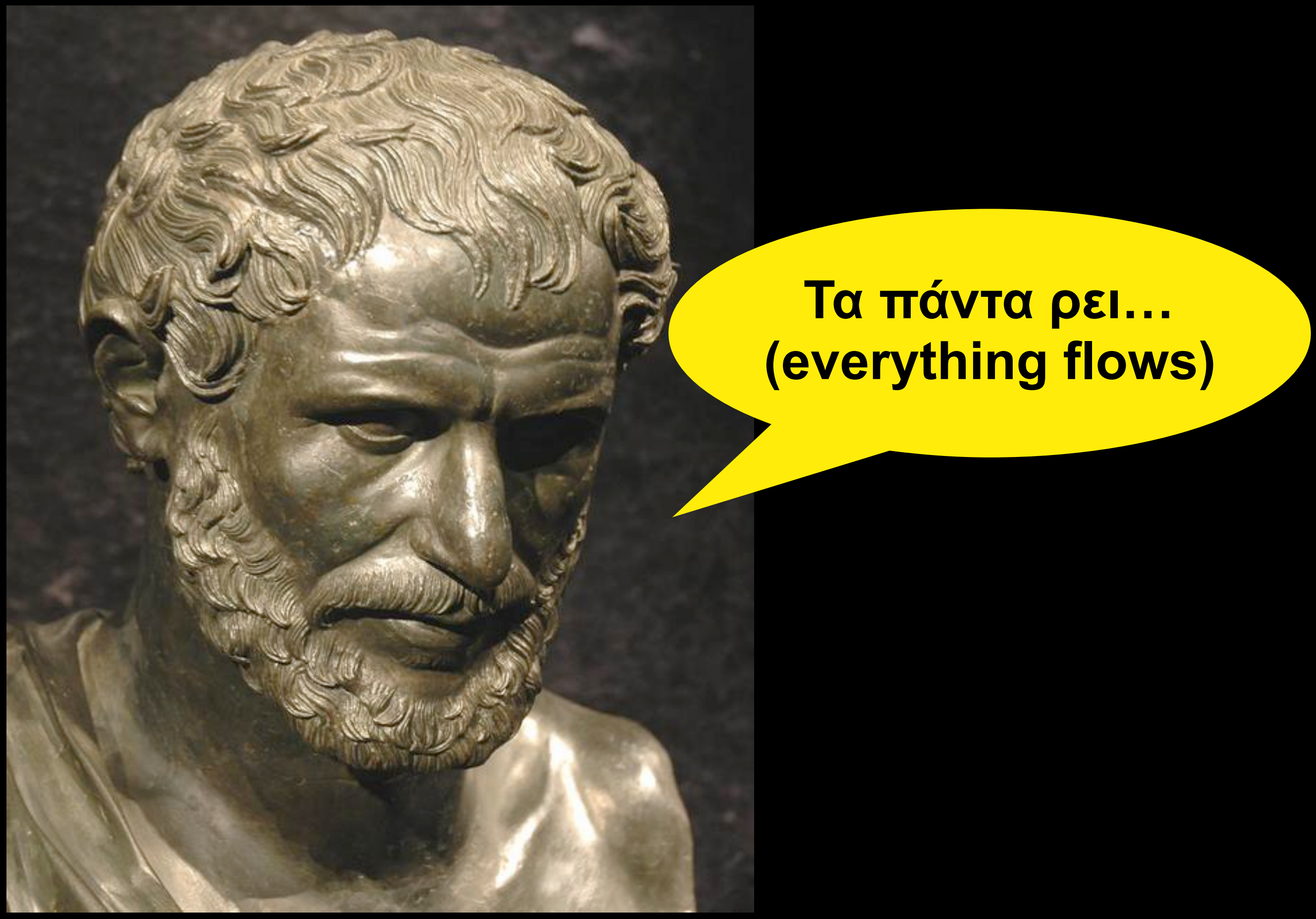
ALICE Collaboration, Phys. Lett. **B726**, (2013) 164



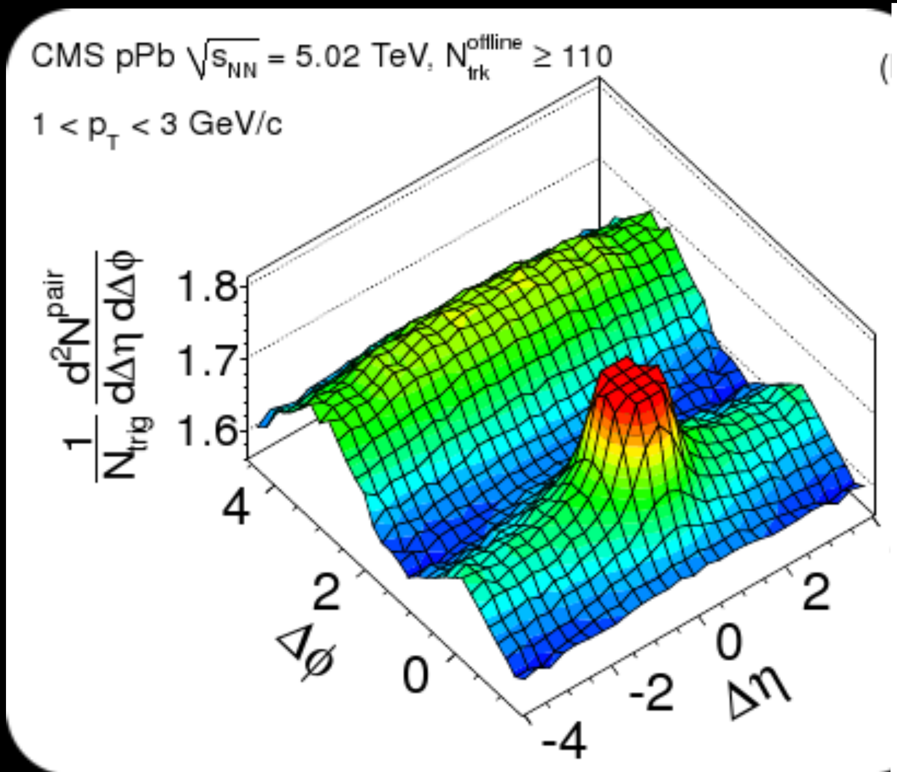
(CMS Collaboration) Phys. Lett. B 765 (2017) 193

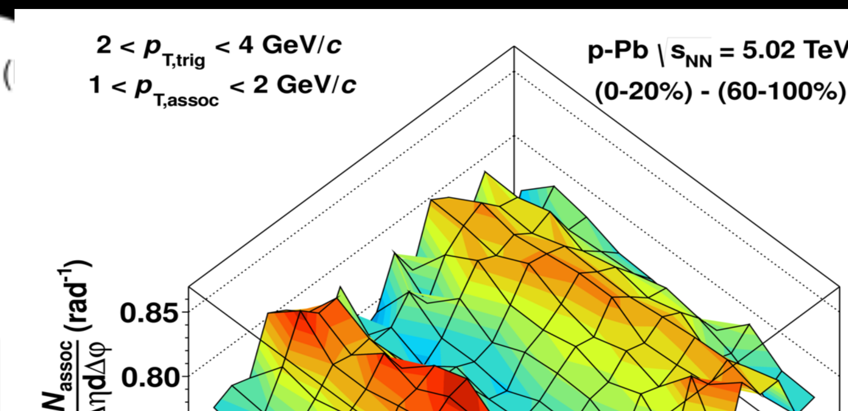


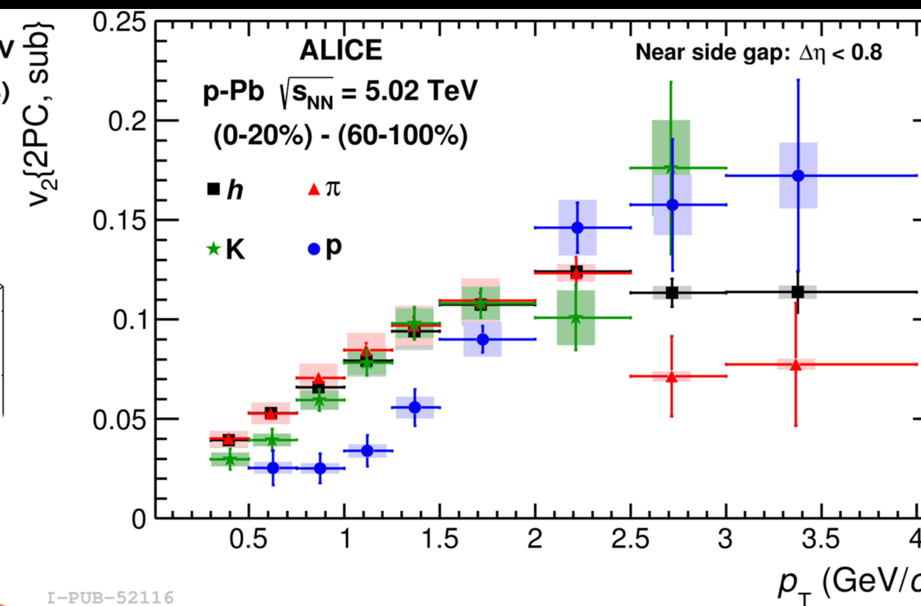
Ηράκλειτος (Heraclitus) ~535 - 475 BC

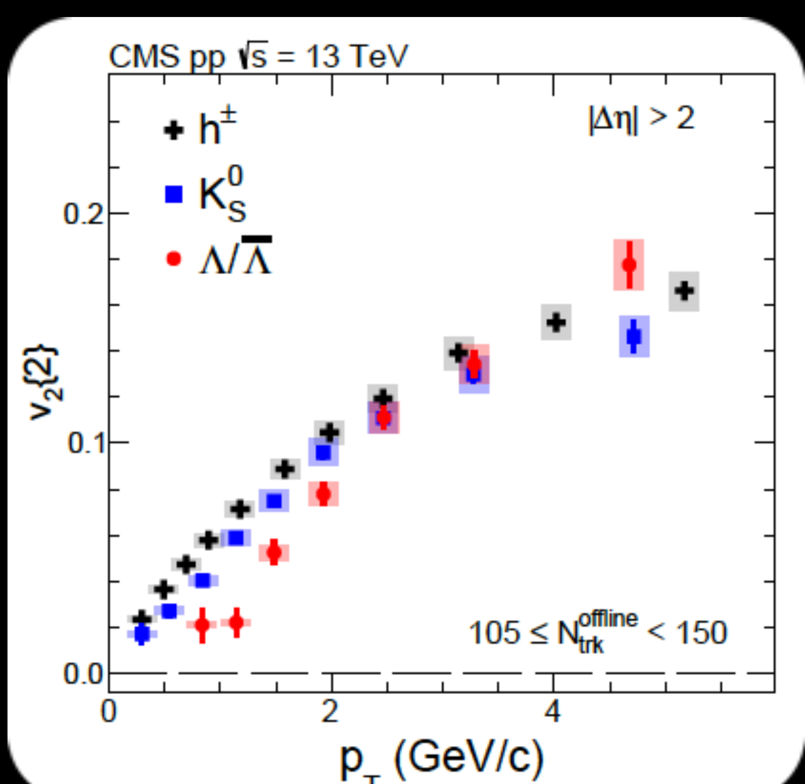


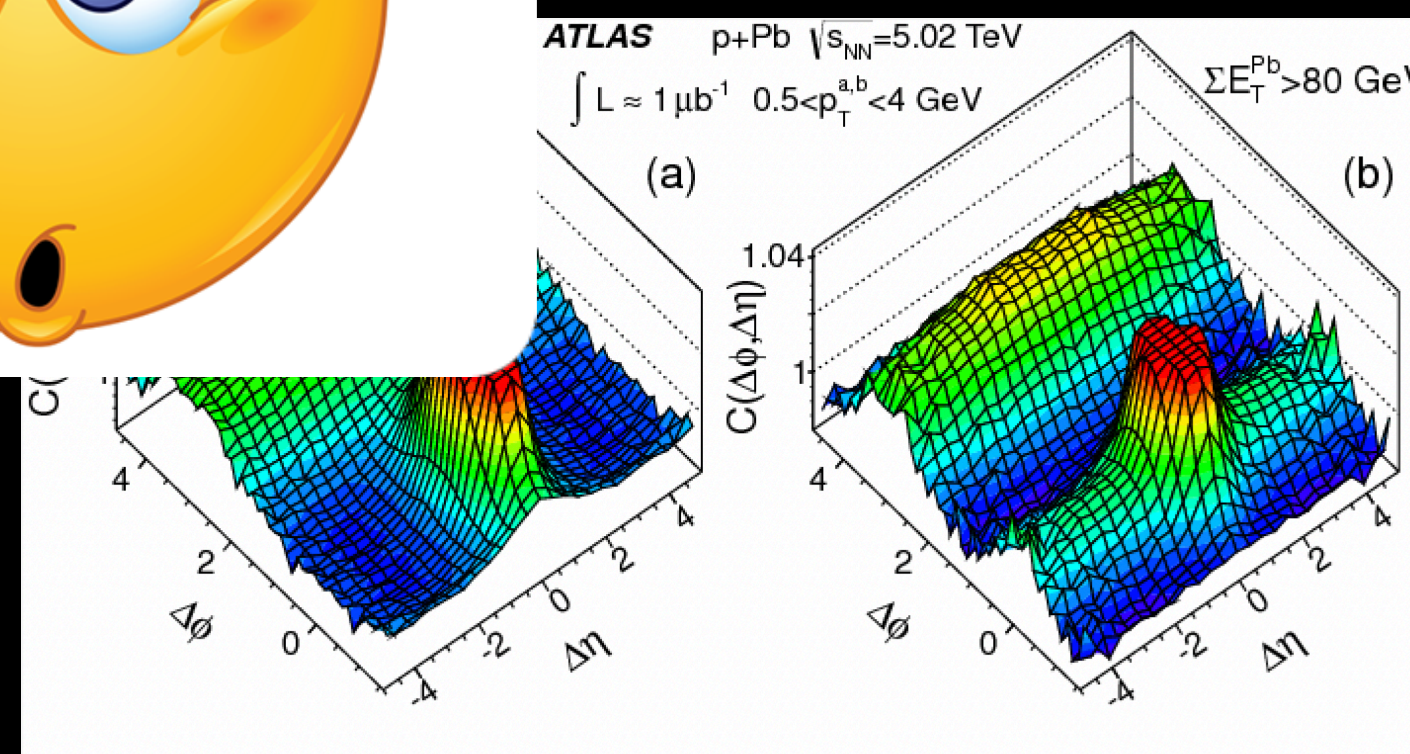
Who ordered these???







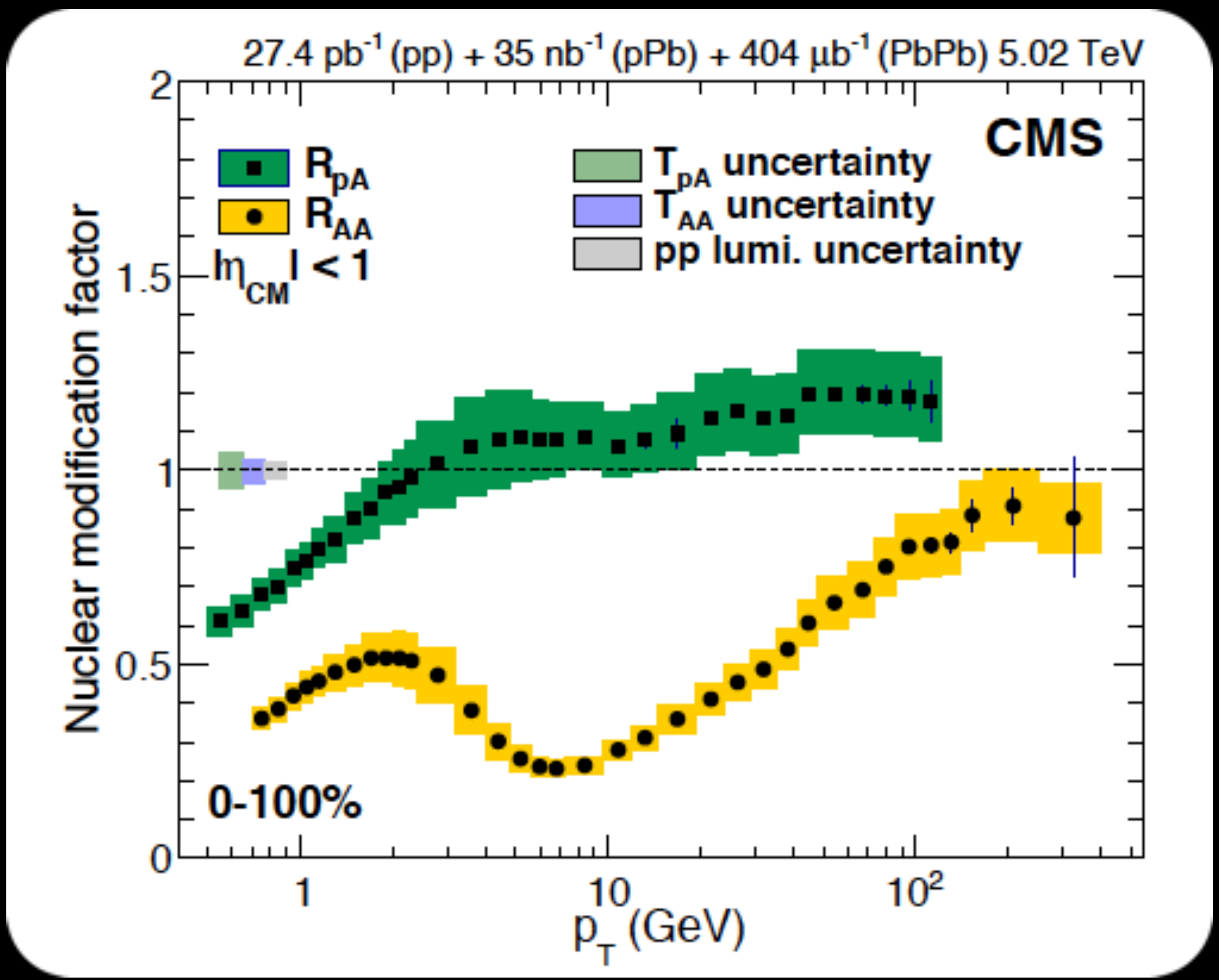




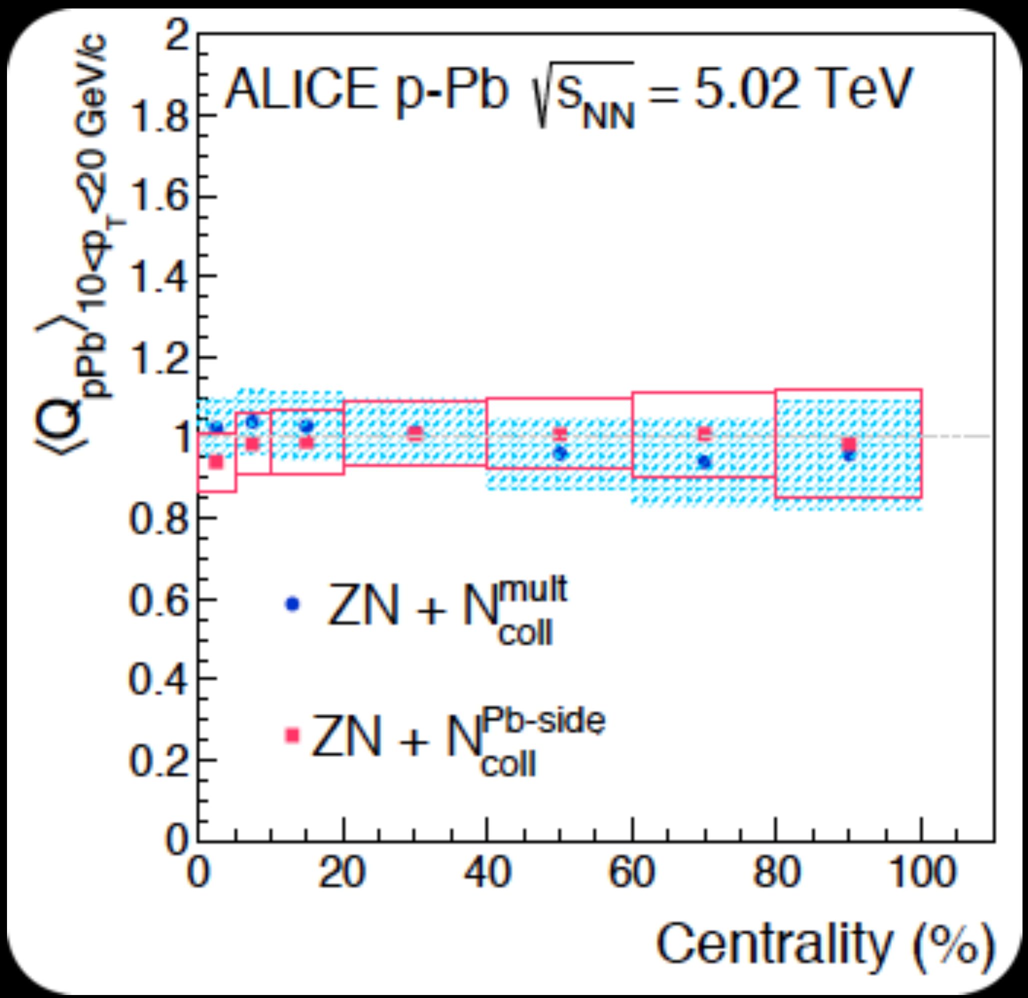
What is missing?

No quenching effects seen so far even if (some) models expect significant effects (~10%)

(CMS Collaboration) JHEP 04 (2017) 039



(Alice Collaboration) Phys.Rev. C91 (2015)



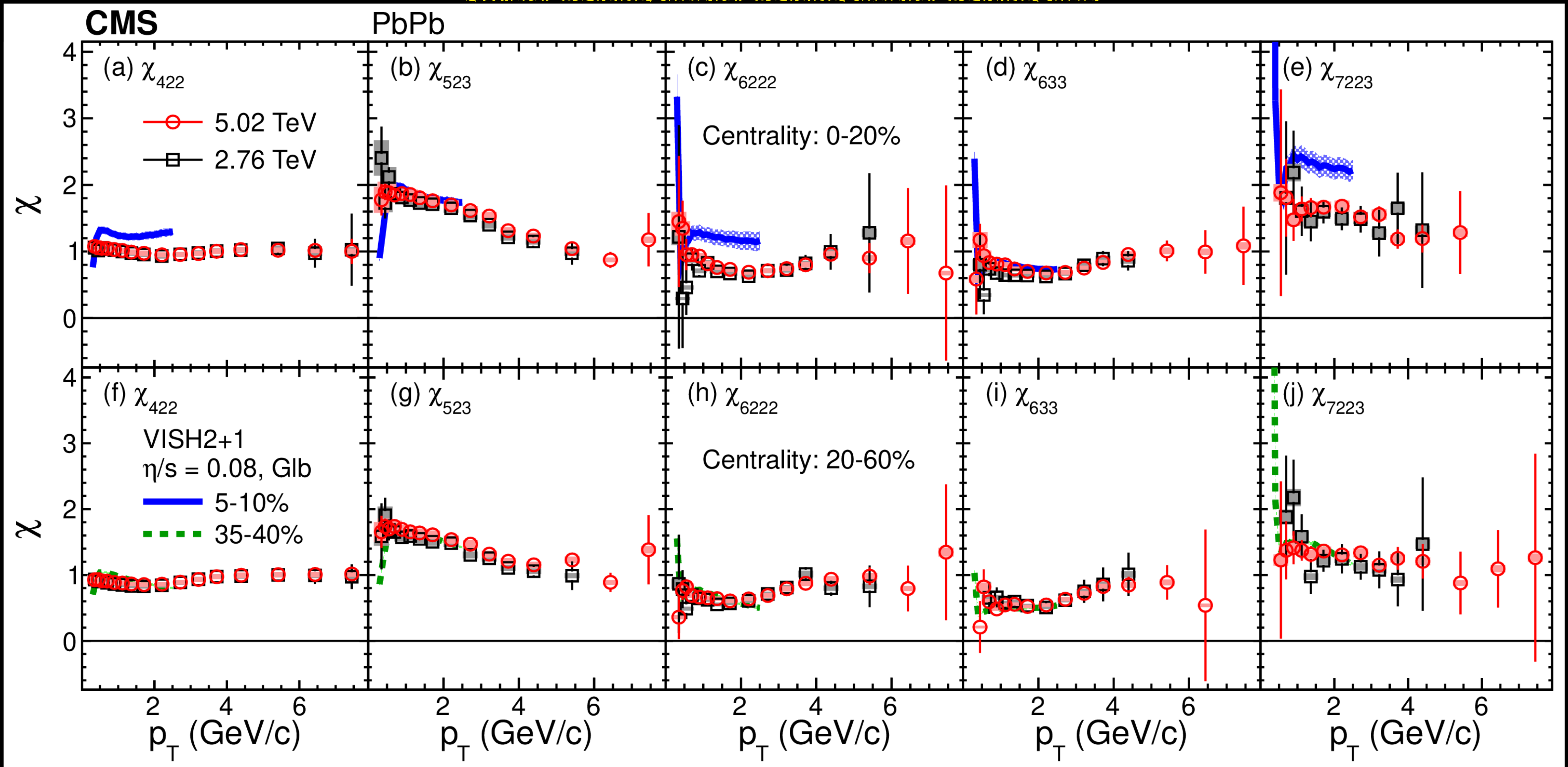
- ✓ R_{pPb} for min. bias collisions consistent with unity above ~2GeV/*c* → suppression is Pb-Pb is not a cold nuclear matter effect
- ✓ "centrality" dependence of R_{pPb} (i.e. Q_{pPb} defined to take into account biases from the multiplicity selection) is also consistent with 1

Many thanks to the organisers for their kind invitation

Backup

Non-linear flow modes: charged particles

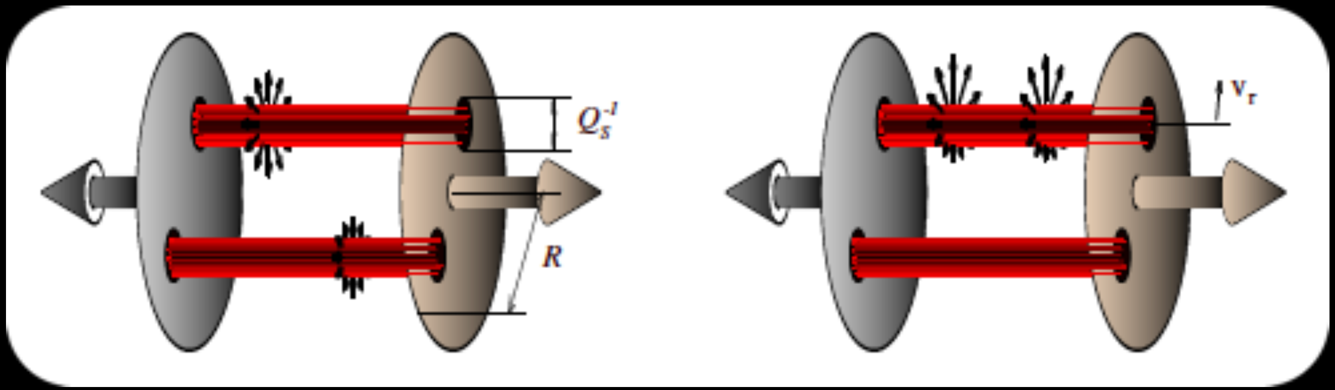
(CMS Collaboration), arXiv:1910.08789 [hep-ex]



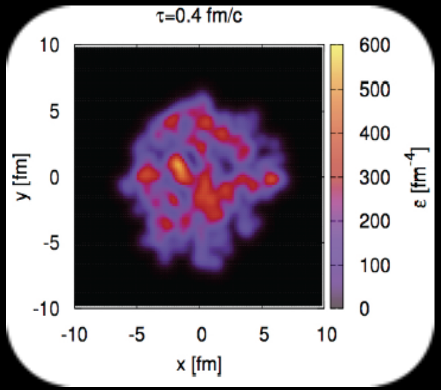
$$V_4 = V_{4L} + \chi_{422} V_2^2,$$
$$V_5 = V_{5L} + \chi_{523} V_2 V_3,$$
$$V_6 = V_{6L} + \chi_{624} V_2 V_{4L} + \chi_{633} V_3^2 + \chi_{6222} V_2^3,$$
$$V_7 = V_{7L} + \chi_{725} V_2 V_{5L} + \chi_{734} V_3 V_{4L} + \chi_{7223} V_2^2 V_3$$

Where do these effects come from?

- ✓ Initial state effects → "CGC picture"
  - Particles are produced with their momentum-space correlations already "built-in"
  - Target and projectiles described as dense coloured objects
  - Anisotropy induced by scattering off domains of color-electric and magnetic fields that fluctuate from event to event
  - Gluon fields + their evolution/interactions described by classical YM equations



VS



- ✓ Final state effects → "hydrodynamical picture"
  - Particles get their momentum-space correlations from final state interactions during the evolution of the system
    - Conversion of structures/correlations in coordinate space into structures/correlations in momentum space
  - Applicability of hydro
    - $\lambda_{mfp} \ll$ system size
    - $K_{n\theta} \ll 1$ (Knudsen number → ratio of micro to macroscopic scales e.g. relaxation time λ_{mfp} ~ vs inverse of expansion rate

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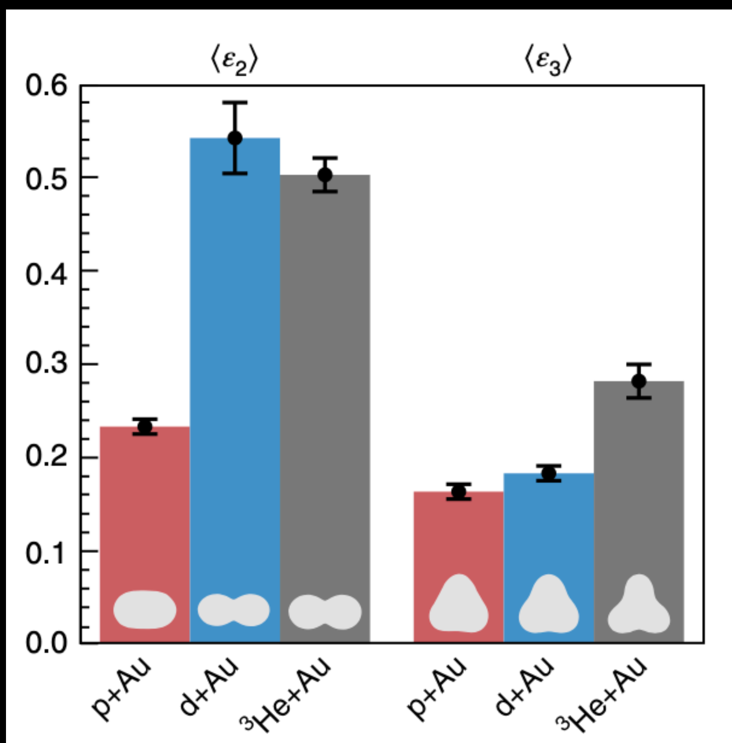
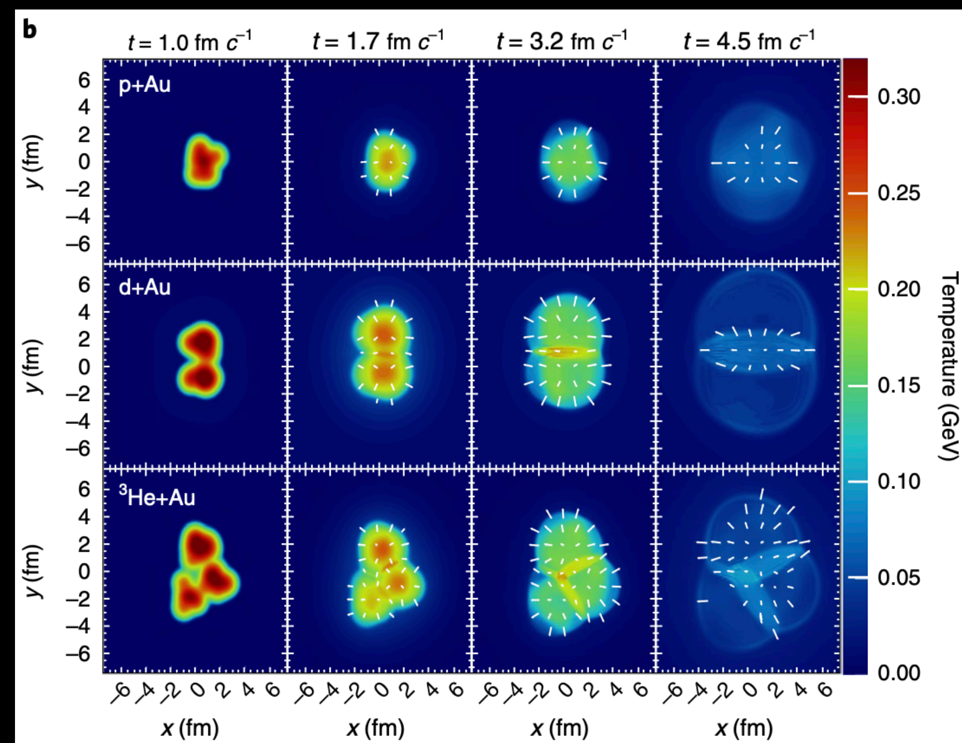
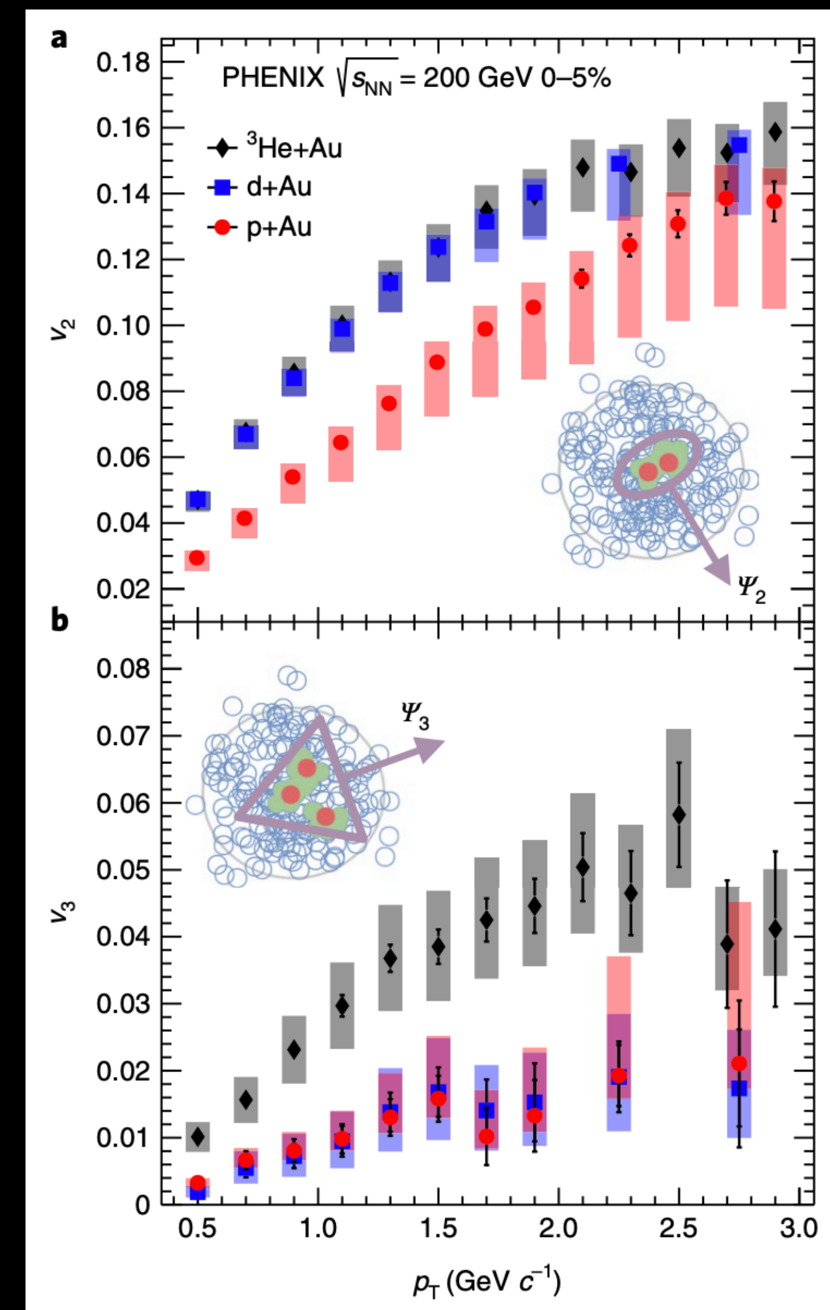
Probing different initial geometries

(PHENIX Collaboration), Nature Phys. 15, 214 (2019)

- ✓ Hydrodynamical models → initial geometry vs IS momentum correlation models
- ✓ Explore different initial collision geometry in p-Au, d-Au and He^3-Au







- ✓ Smaller ⟨ε_2⟩ in p-Au → smaller v_2
- ✓ Larger ⟨ε_3⟩ in He^3-Au → smaller v_3
- ✓ What do the models have to say?

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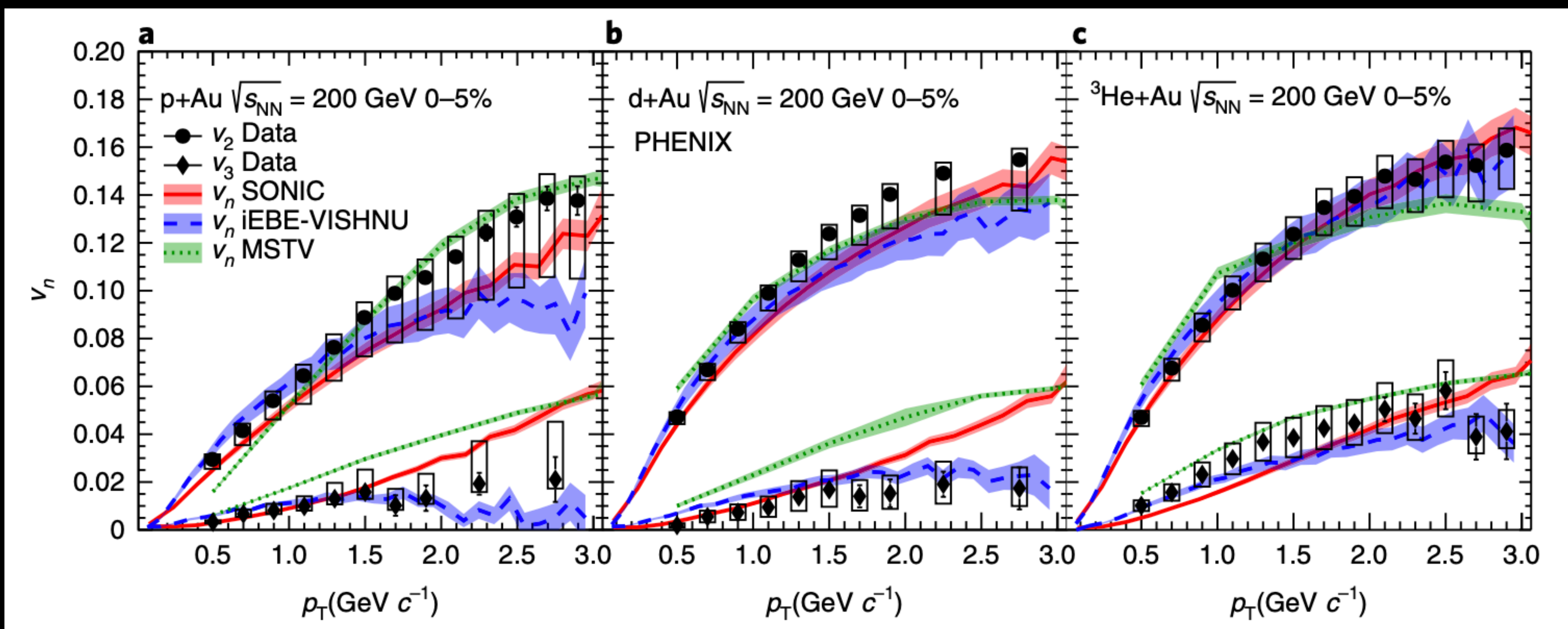
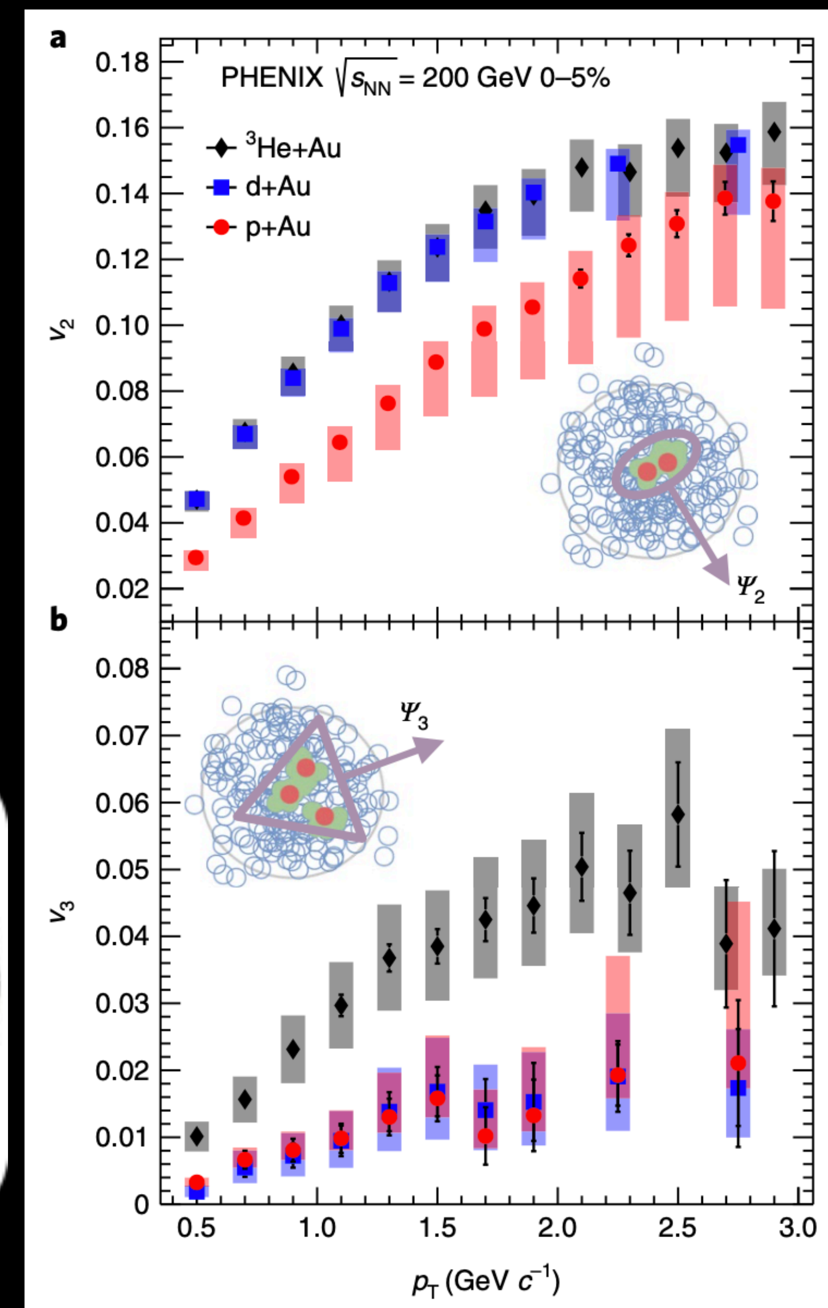


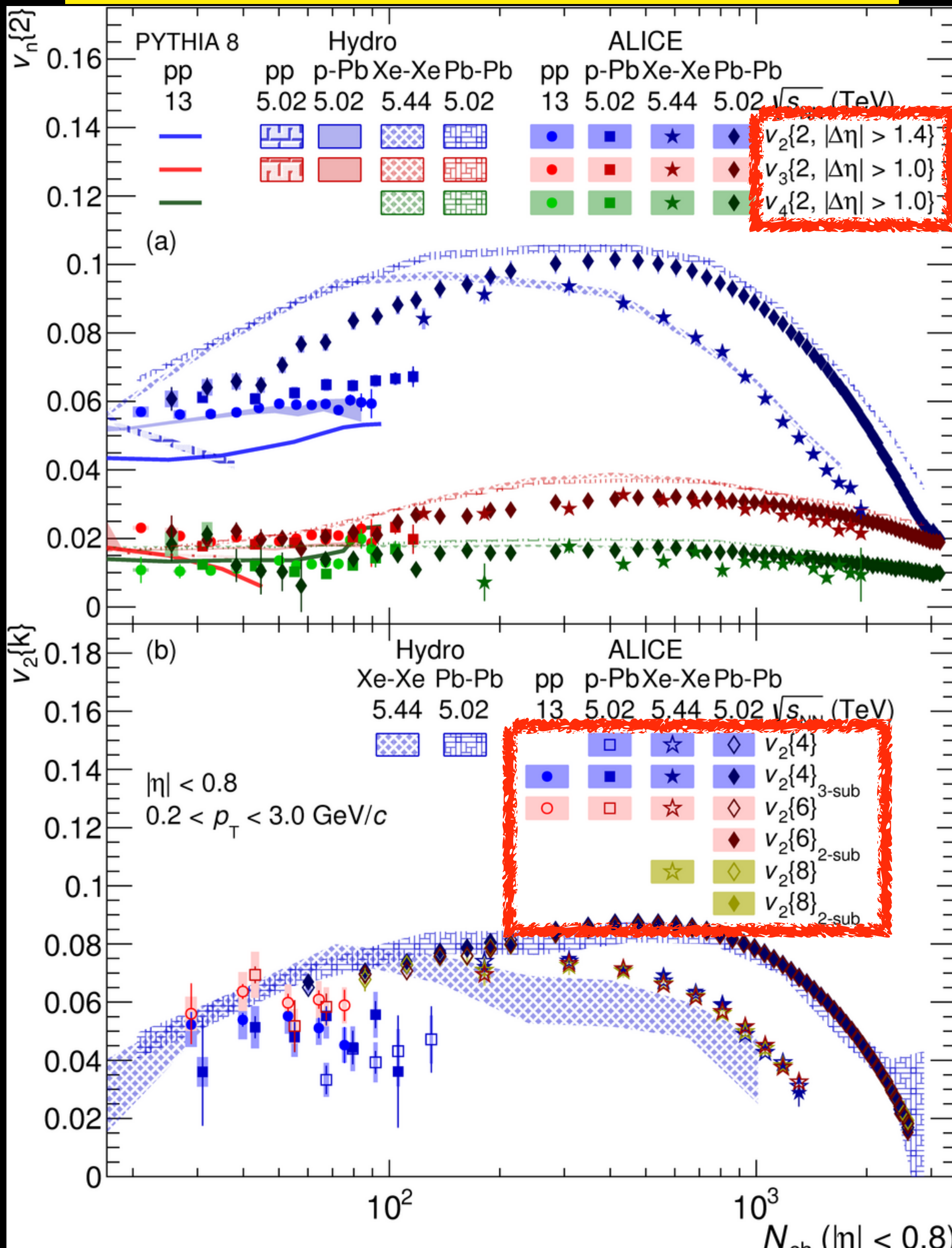


- ✓ Described well by hydrodynamical calculations
- ✓ Results initially described fairly well also by IS model…however…
  - A bug was discovered → IS state model **can not describe** the data

For more details check the slides of Mark Mace

Establishing multi-particle collectivity

ALICE Collaboration, (accepted by PRL)



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Long range

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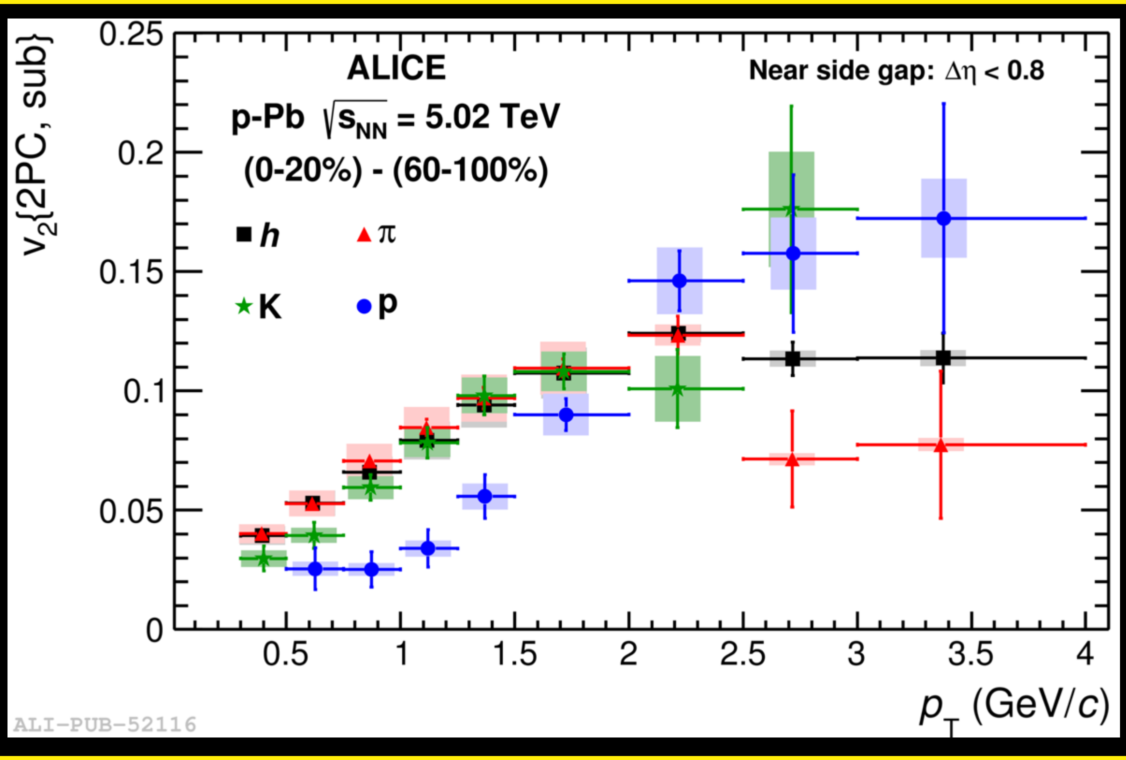
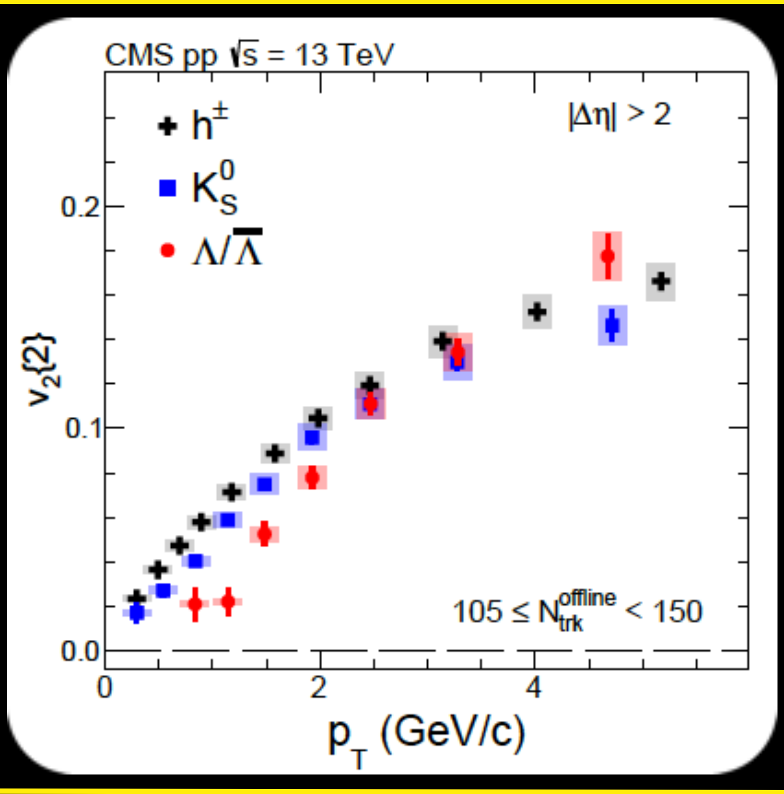
Everything flows (?)

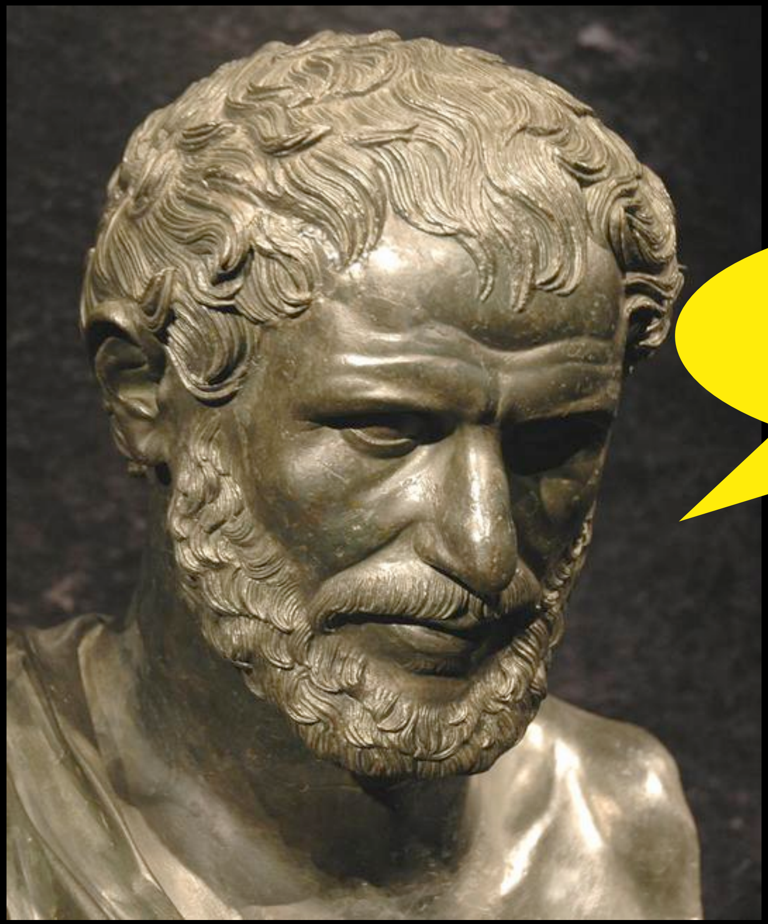
ALICE Collaboration, Phys. Lett. **B726**, (2013) 164



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



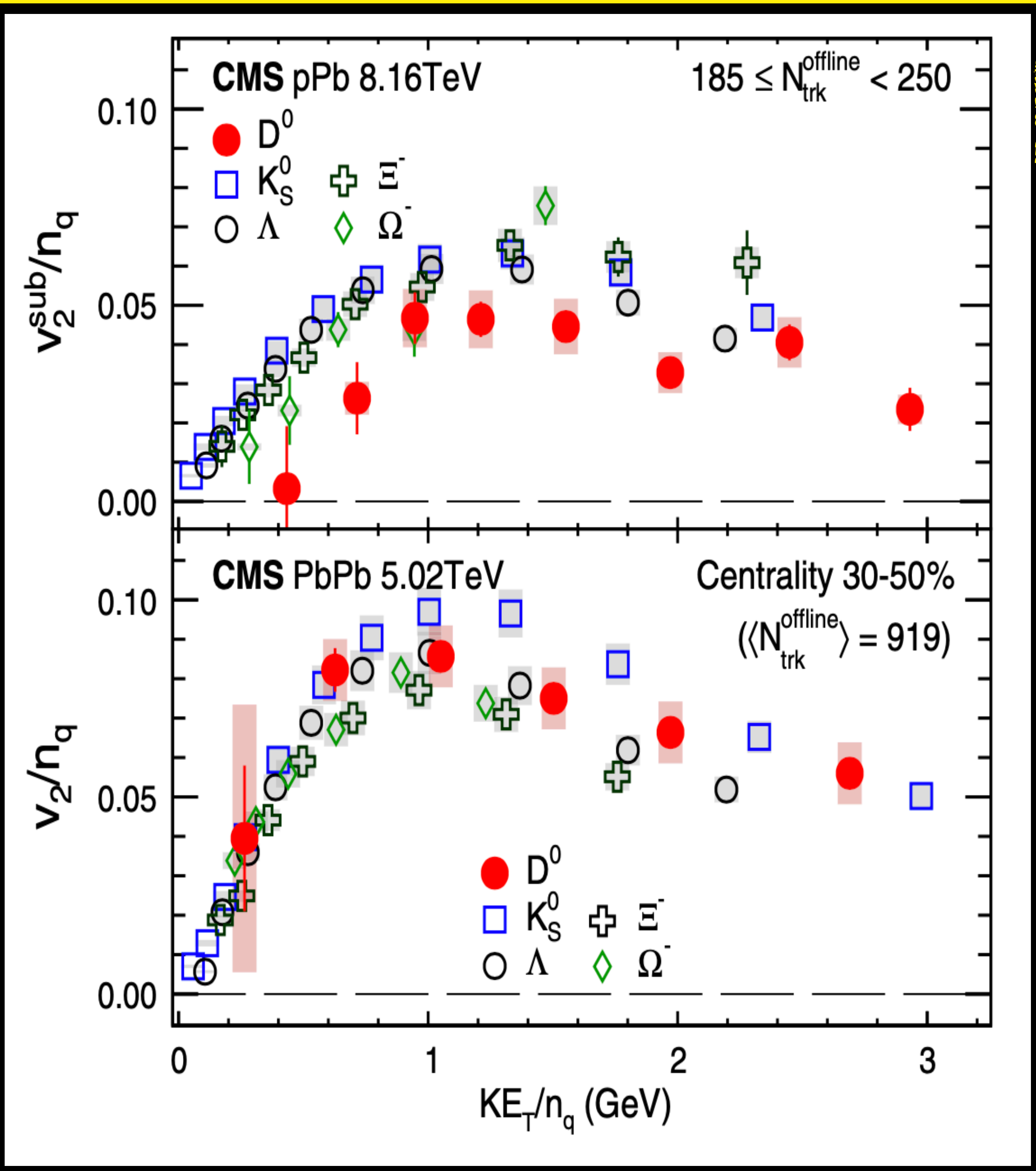
Ηράκλειτος (Heraclitus) ~535 - 475 BC



Τα πάντα ρει…
(everything flows)

Everything flows (?)

(CMS Collaboration) Phys. Rev. Lett. 121 (2018) 082301



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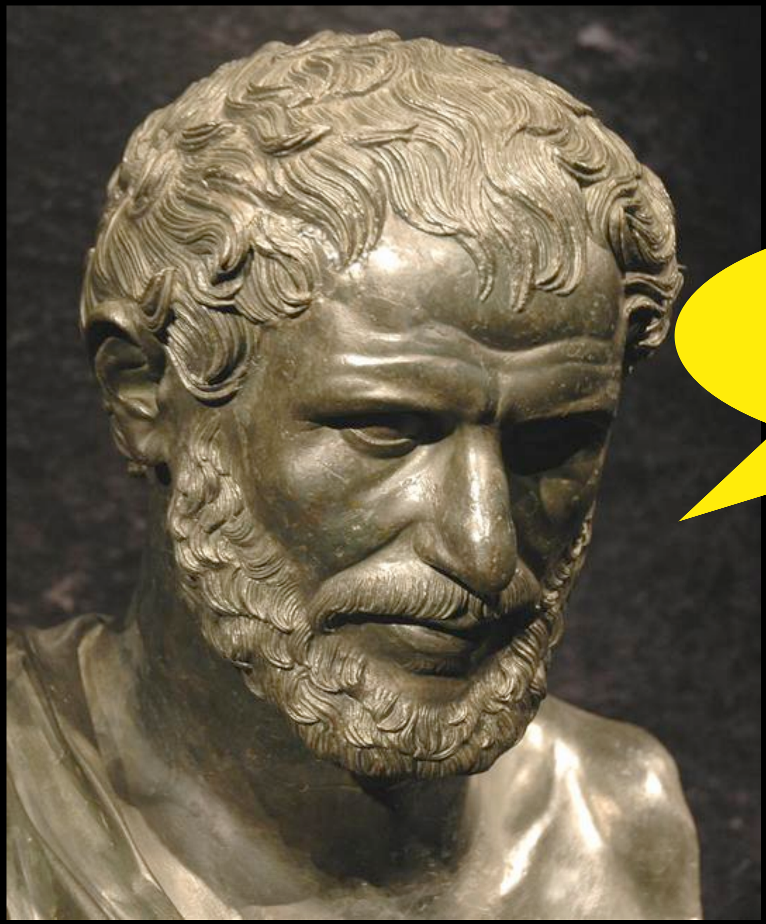

Τα πάντα ρει…
(everything flows)

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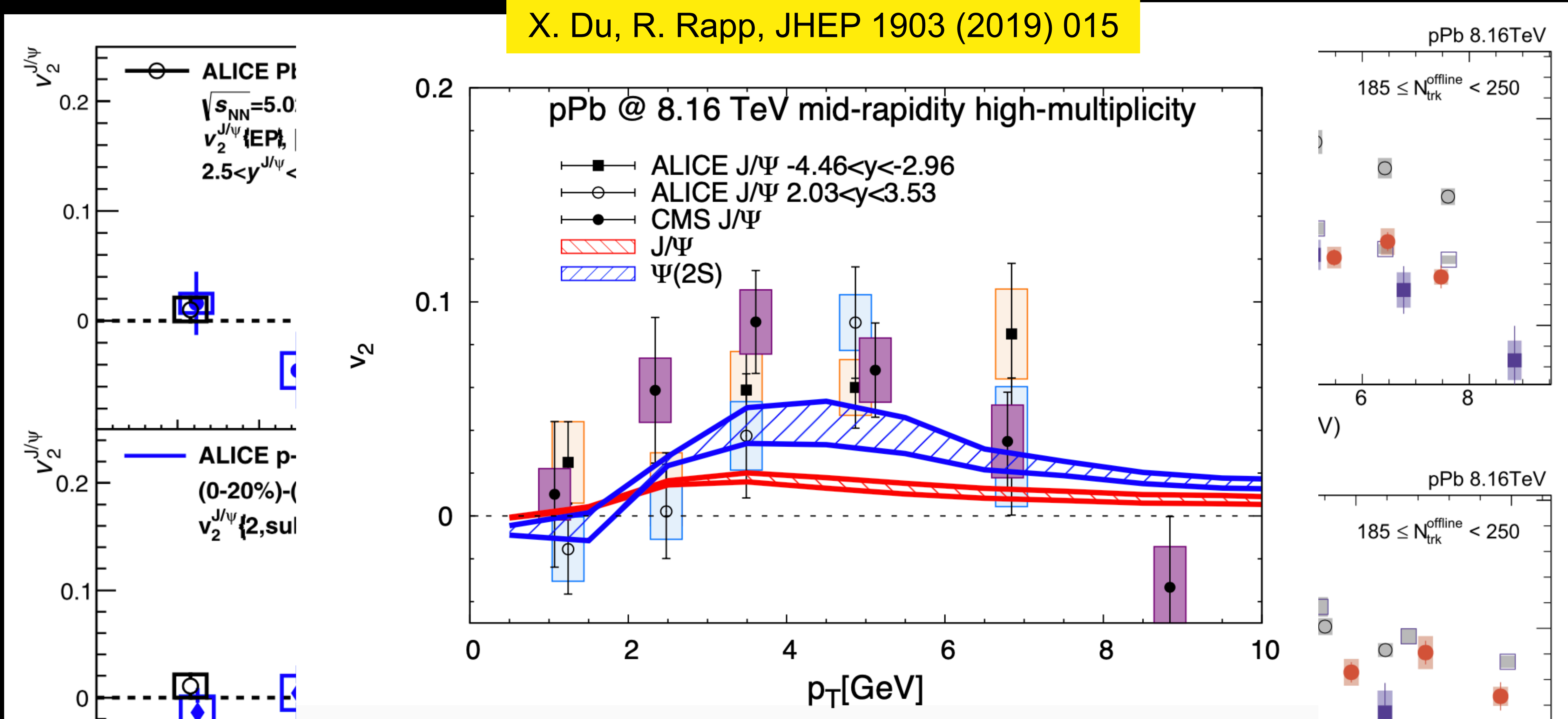
Everything flows (?)

(ALICE Collaboration) Physics Letters B 780 (2018) 7

(CMS Collaboration) Physics Letters B 791 (2019) 172

X. Du, R. Rapp, JHEP 1903 (2019) 015

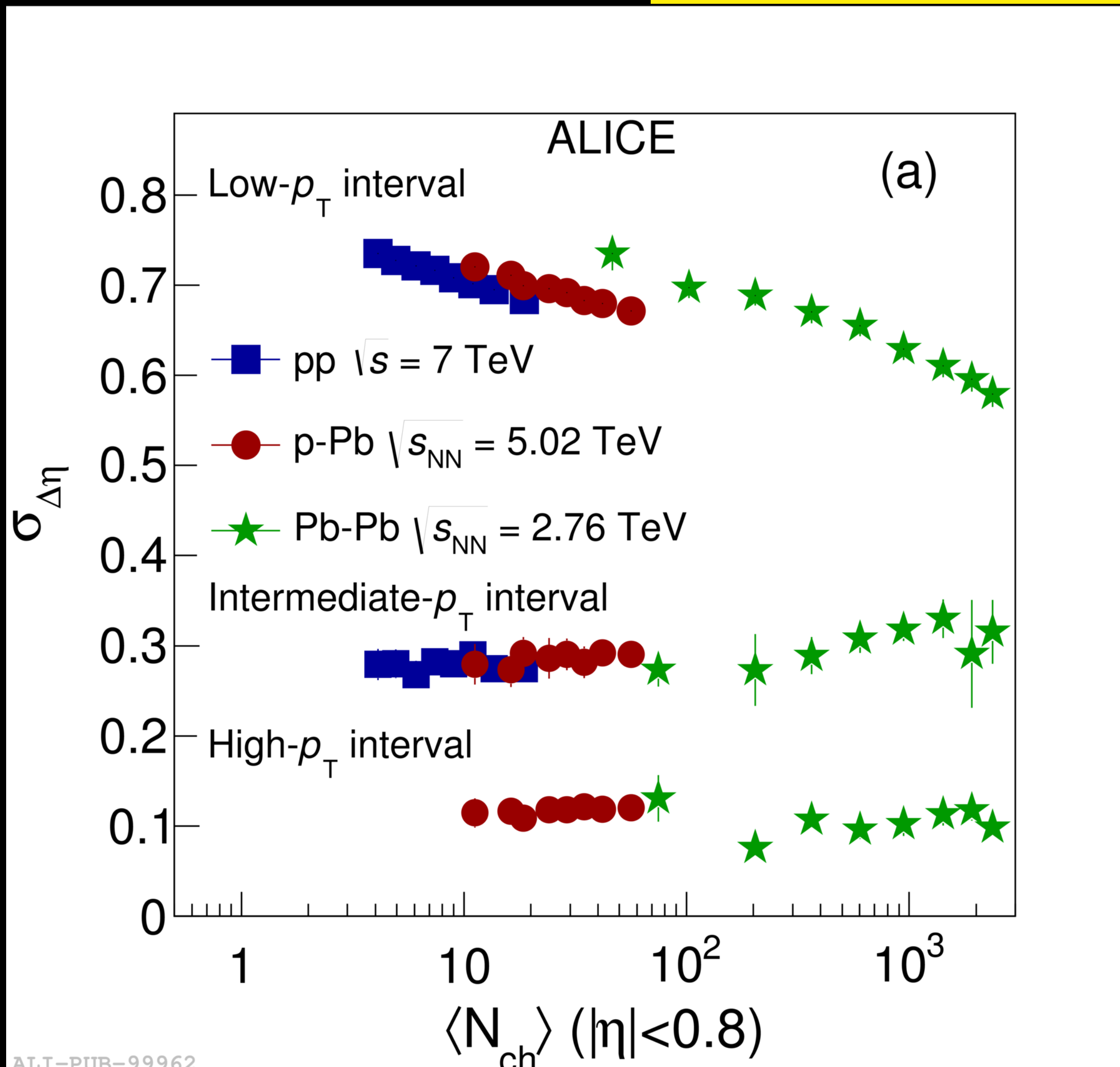


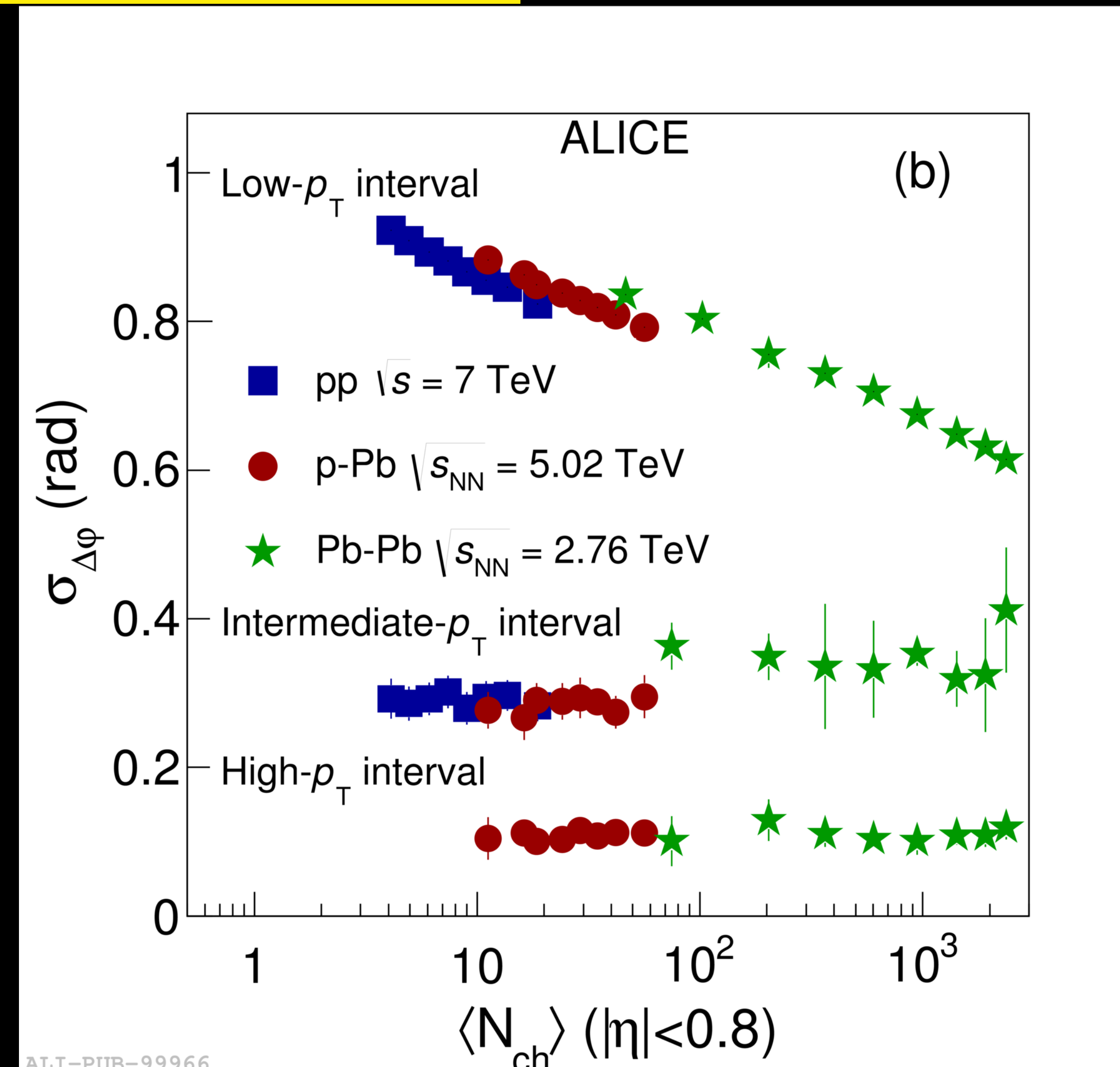
While the R_{pA}s show an overall fair agreement with most of the data, the large v_2 values observed in p-Pb collisions at the LHC cannot be accounted for in our approach. While the former finding generally supports the formation of a near thermalized QCD medium in small systems, the discrepancy in the v_2 suggests that its large observed values are unlikely to be due to the final-state collectivity of the fireball alone.

Nikhef

Width of the balance functions: bulk vs higher p_T

(Alice Collaboration) Eur. Phys. J. C 76 (2016) 86





✓ Narrowing of width (at low p_T) with increasing multiplicity for both large and small systems

✓ Narrowing for large systems explained in terms of

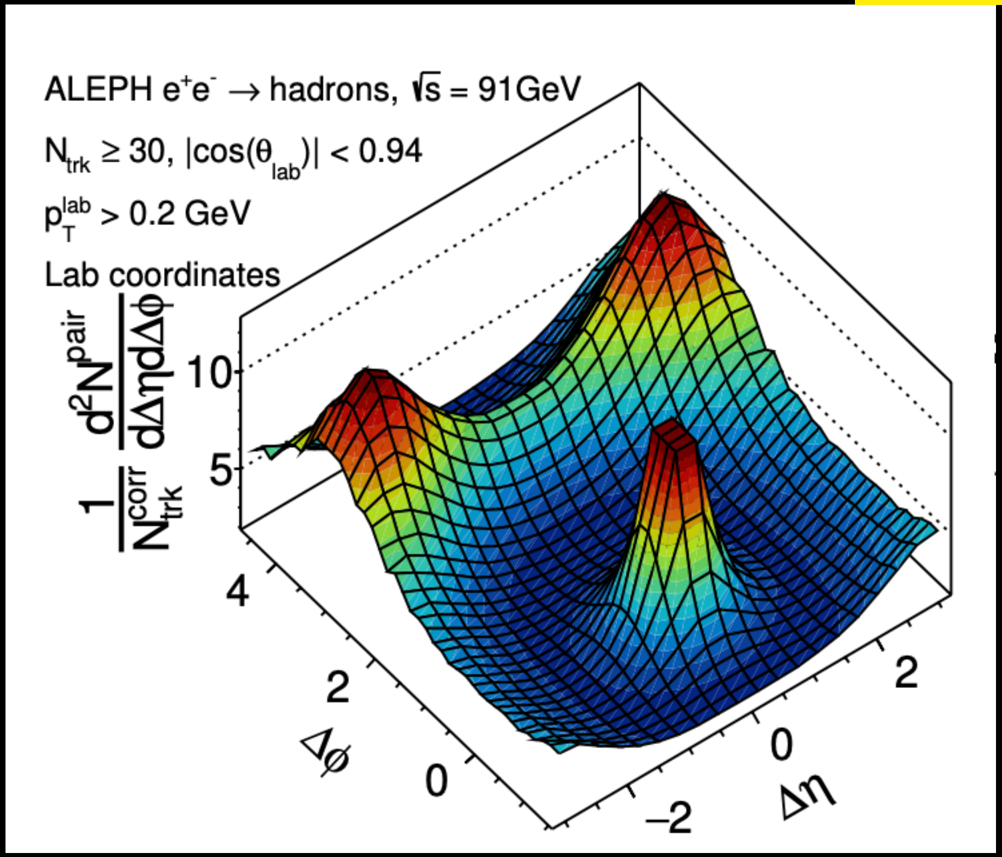
- Radial flow
- Late stage quark production

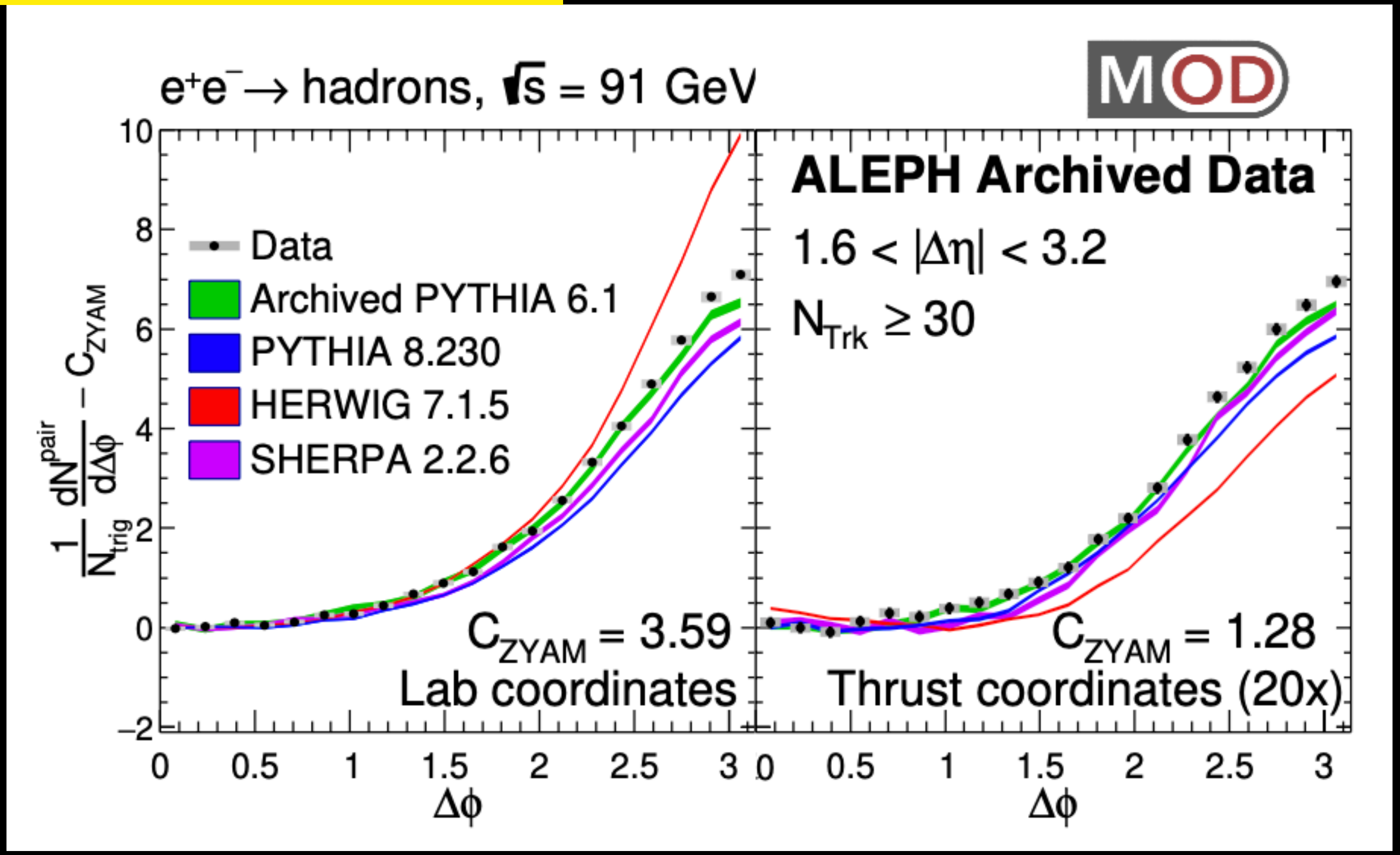
Do these results for small systems point also to collectivity?

See talk by Zhanna Khabanova later

What is missing?

A. Badea et al., arXiv:1906.00489

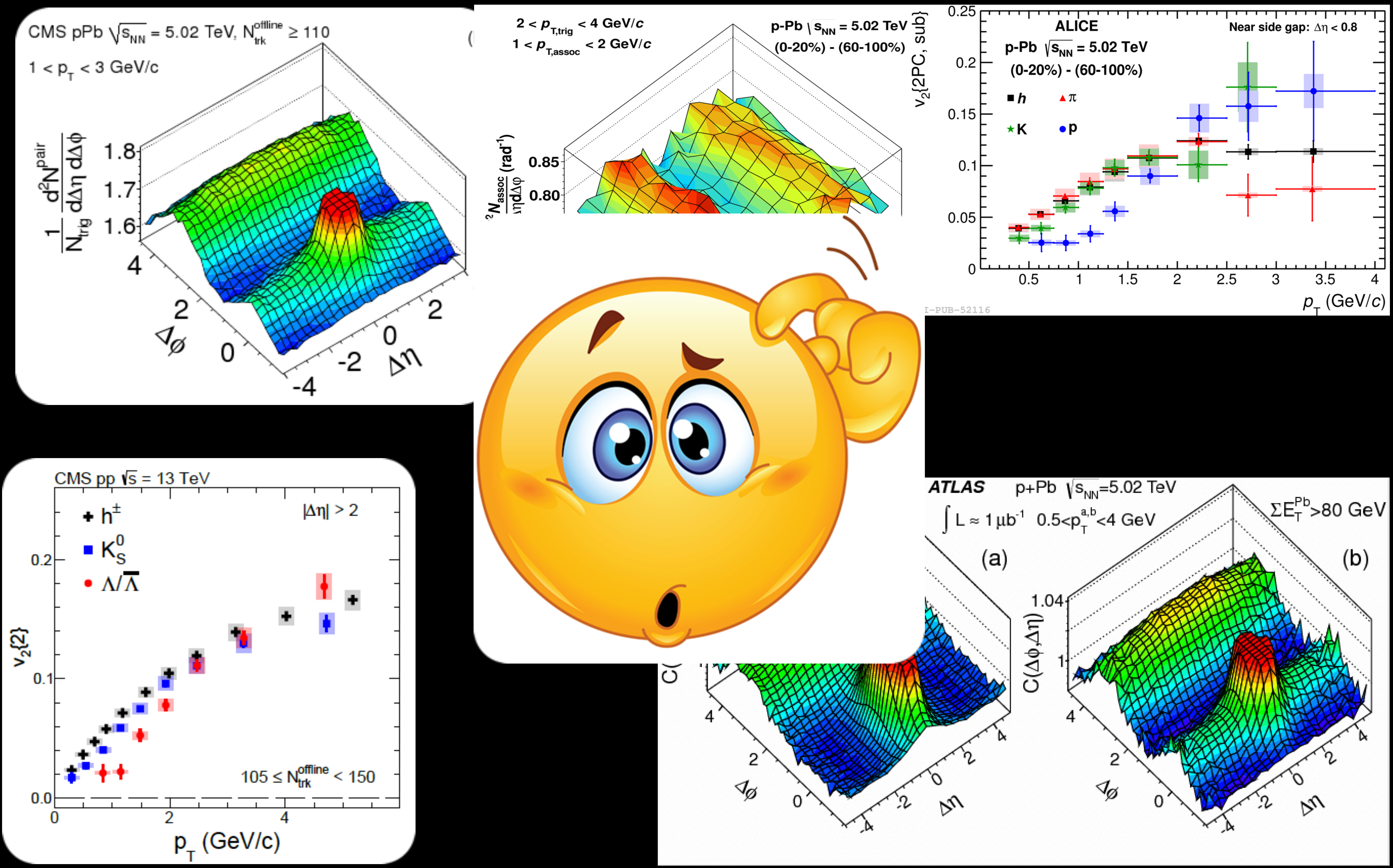




Can we "switch off" these collective effects in pp collisions?

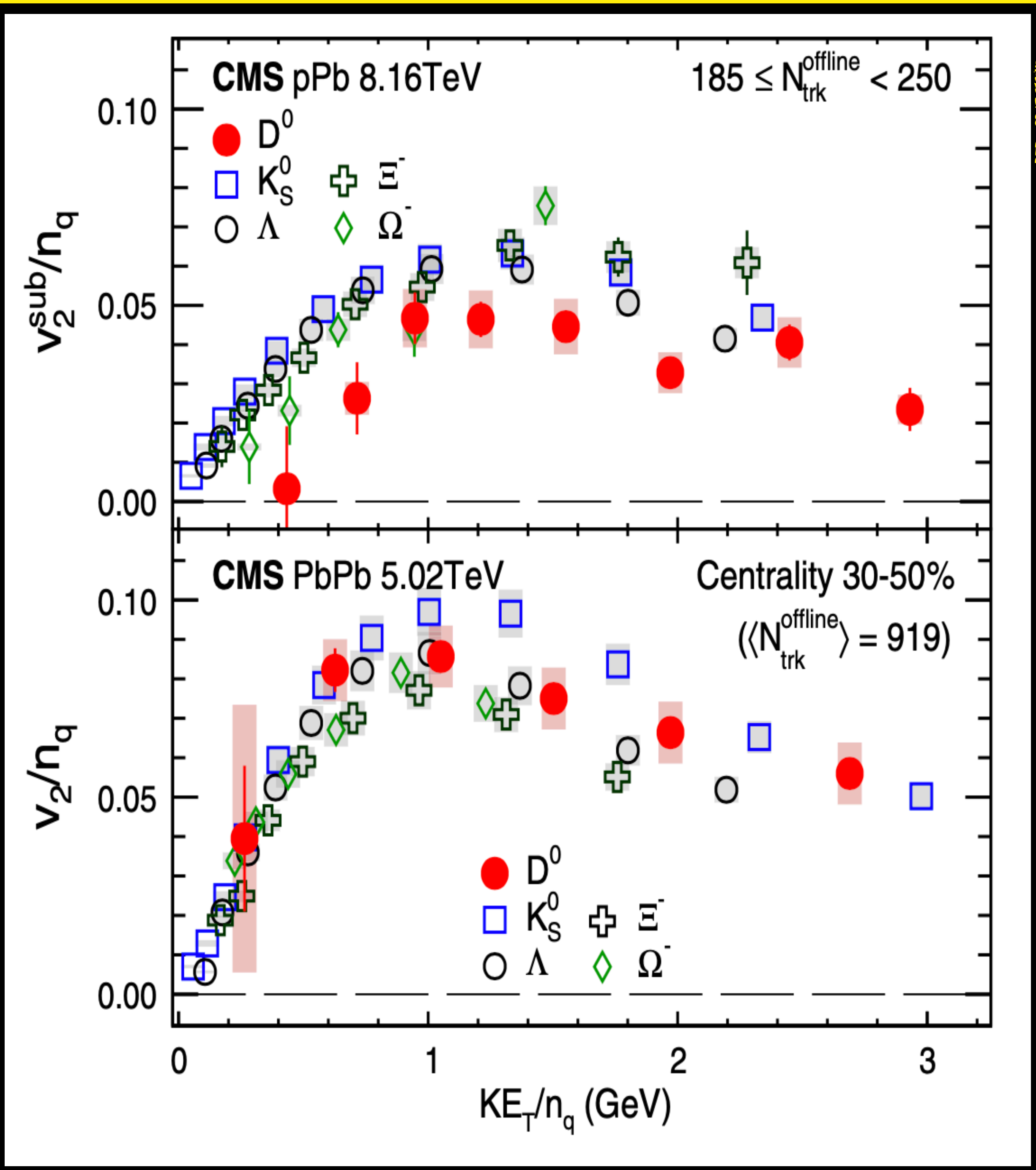
- Do we see the NS ridge in all multiplicity classes of pp collisions?
  - Beware of non-flow, different approaches (e.g. subtraction vs template fits),…
- Is the mass ordering/particle type grouping in v_n measurements still evident in low multiplicity events?
- Are there NL-flow modes and if yes which models can accommodate them?
- What is the underlying pdf?

Who ordered these???



Everything flows (?)

(CMS Collaboration) Phys. Rev. Lett. 121 (2018) 082301



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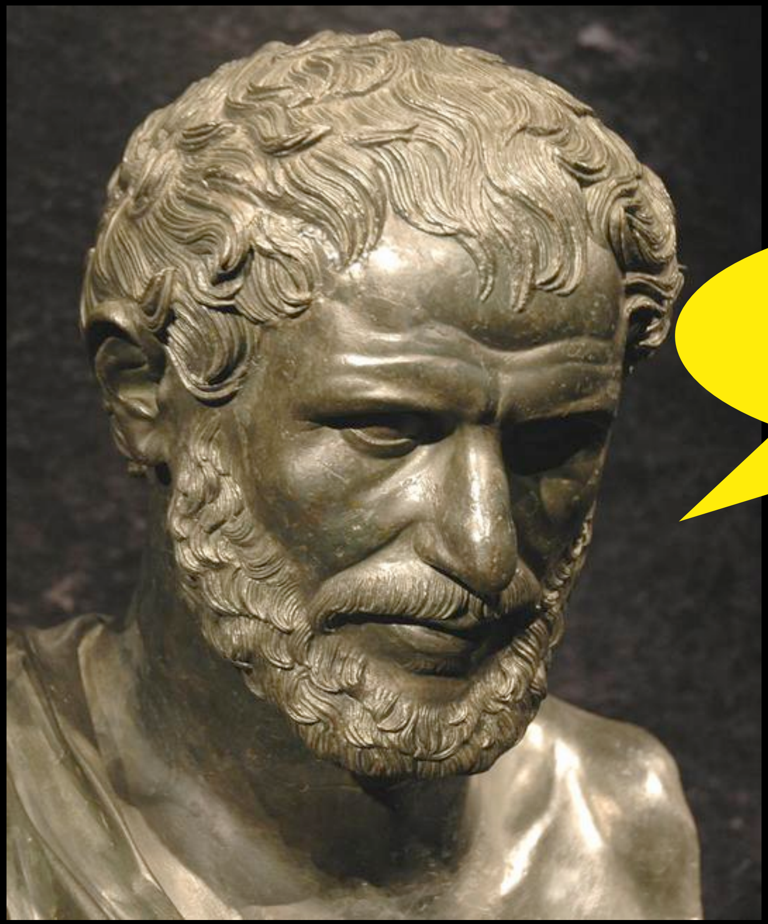


Τα πάντα ρει…
(everything flows)

Some final remarks…

- ✓ There are no smoking guns!!!
  - At least I'm convinced…I used to work on one

- ✓ (some of the) lessons we learned from heavy-ion collisions
  - Look at what all (?) observables, "collectively" tell us
  - Look for theories that point in the same direction as the data in as many variables/probes as possible
  - Look at the details (e.g. more differential analyses, different particle species φ-meson, CME signals)
    - But with caution!!!
  - Physics is not relying on dogmas
    - Do not be afraid to change the paradigm if your data suggest you to do so

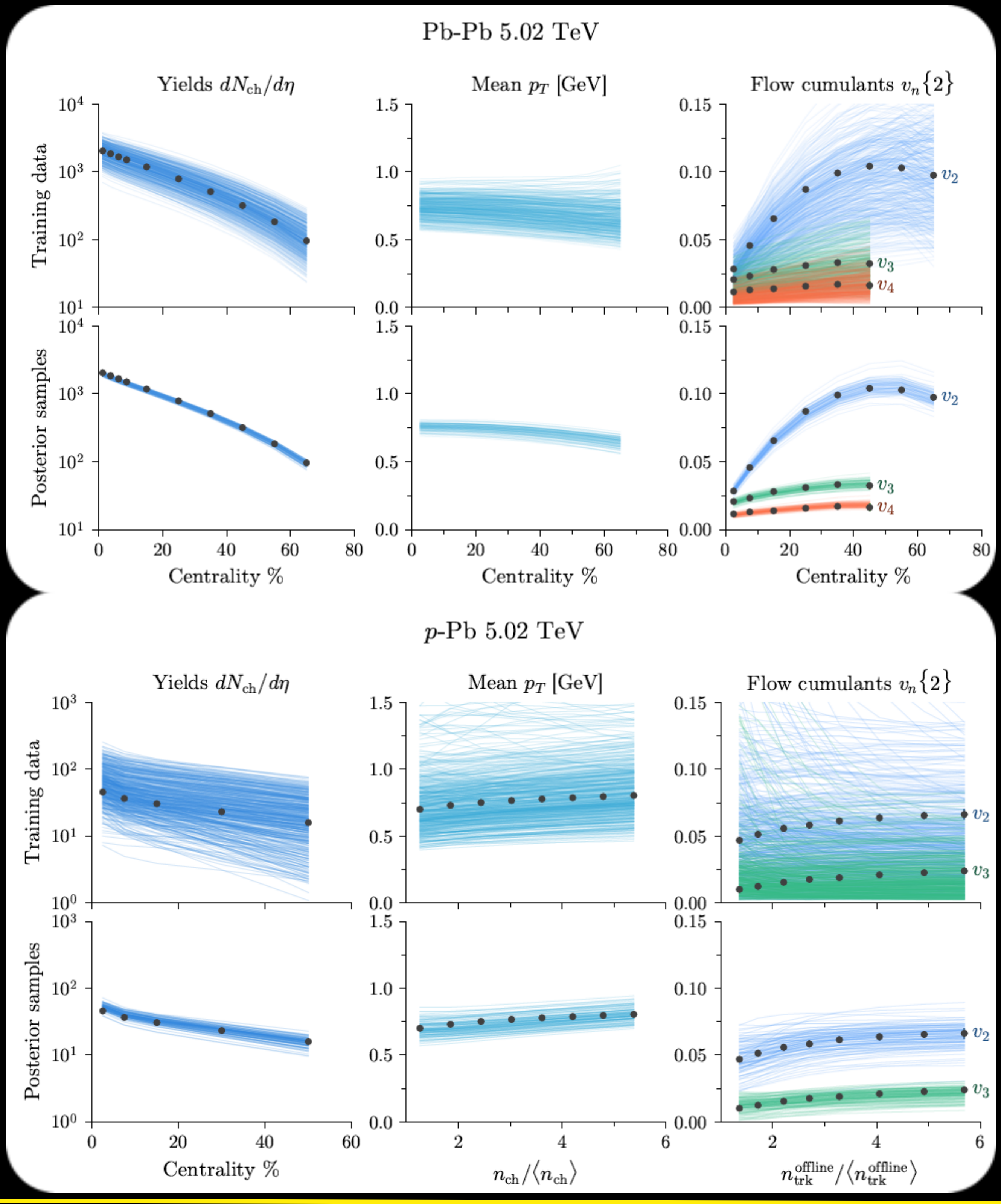
- ✓ The question of whether initial of final state effects are responsible for the observed structures should be just the beginning → connection with heavy-ion system

Personal closing statement

Initial effects should always be there, but it seems that final state effects gain ground

Constraining η/s(T) and ζ/s(T) from data: Pb-Pb and p-Pb

S. Bass *et al.*,arXiv:1808.02106



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