Collective flow: experiment vs theory

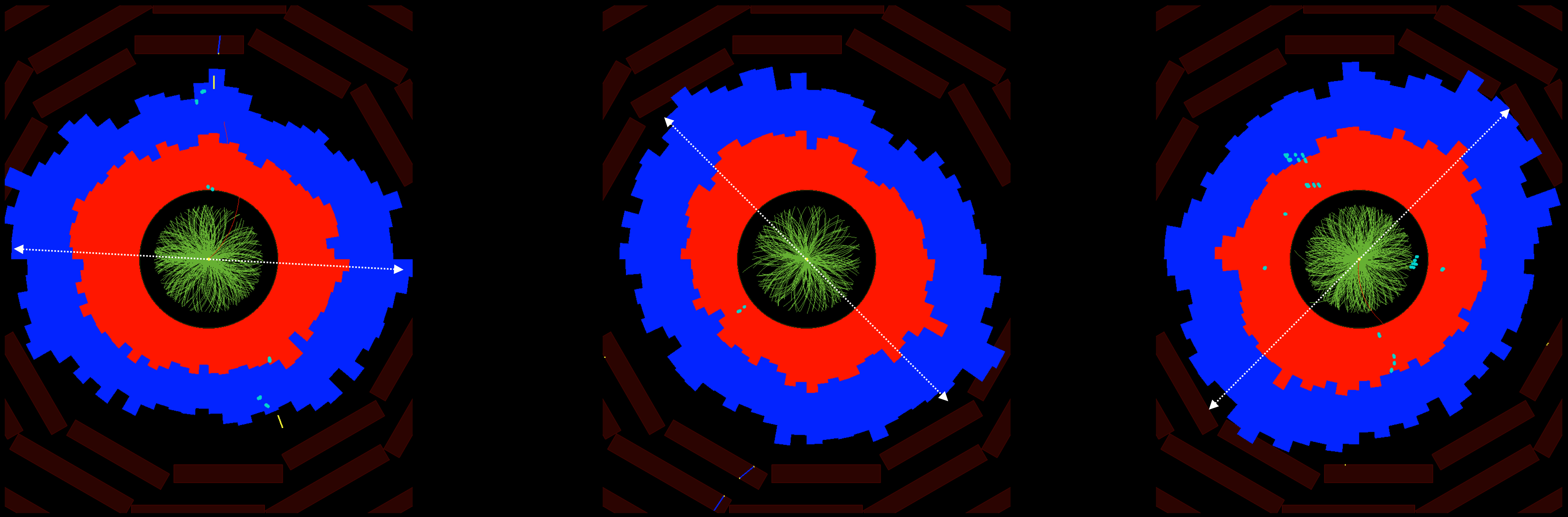
Gunther Roland

Berkeley, Jan 6 2018

JETSCAPE Winter School

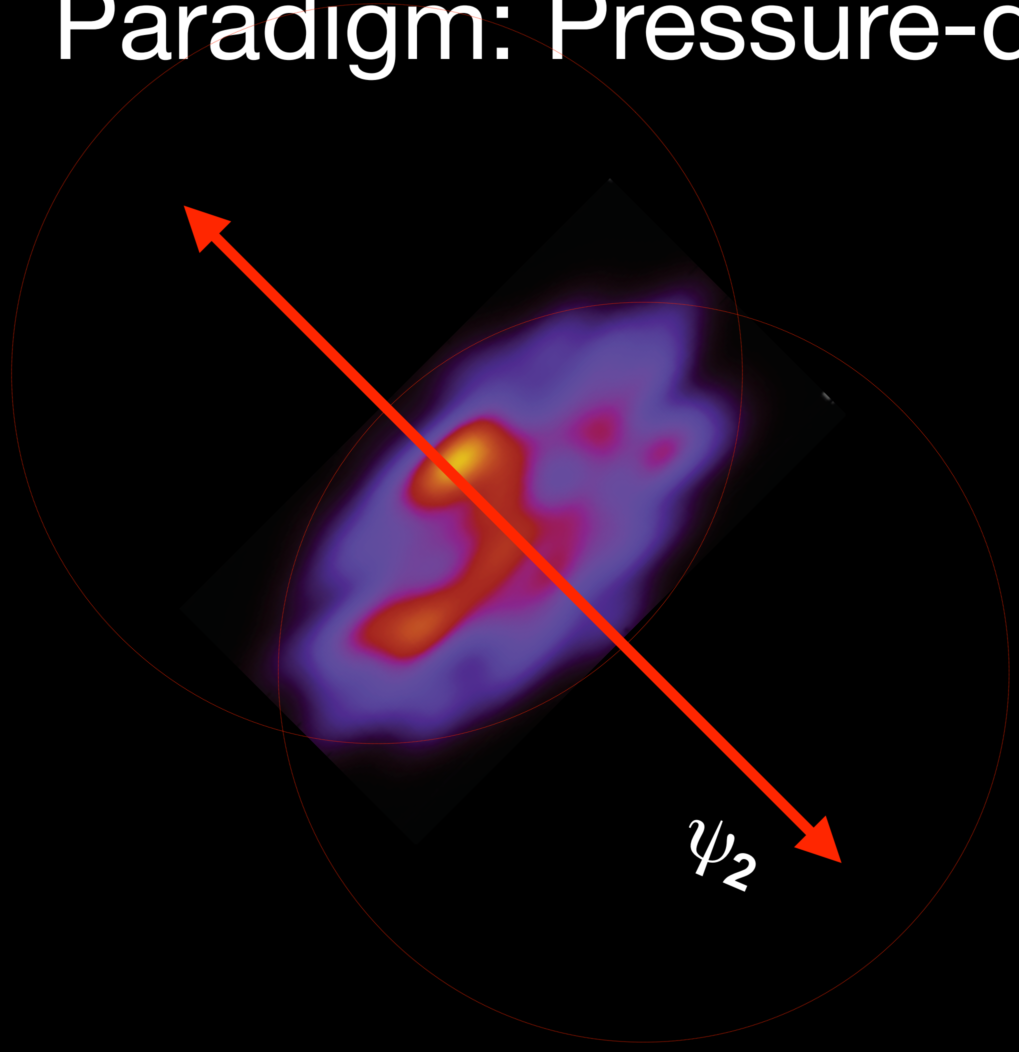
Is there collectivity?

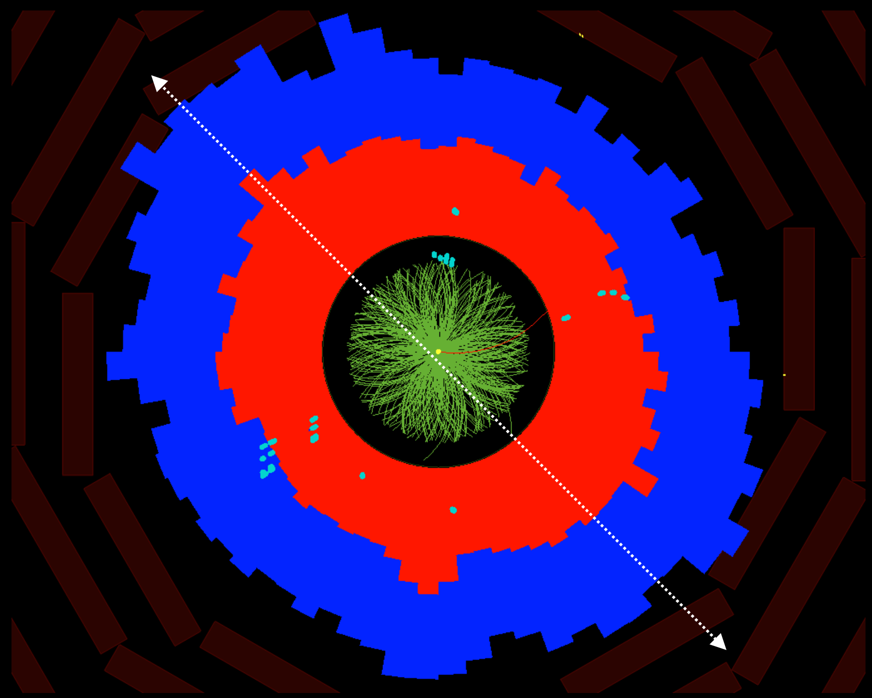
Projections of single event calorimeter distributions - O(10^4) particles - onto transverse plane



Particles are emitted in preferred directions event-by-event
Modulation of ± 15% or more

Paradigm: Pressure-driven hydrodynamic expansion





Initial nuclear overlap defines direction
(anisotropic pressure gradients)

Final state momentum distribution reflects
initial overlap geometry

Hydrodynamic expansion translates initial configuration space
anisotropy into final state momentum distribution

A brief history of collective flow

$$S^{\perp}_{ij} = \sum_{\nu=1}^{M} p_i(\nu)\, p_j(\nu)$$

Voloshin, Zhang,

Z.Phys. C70 (1996) 665-672

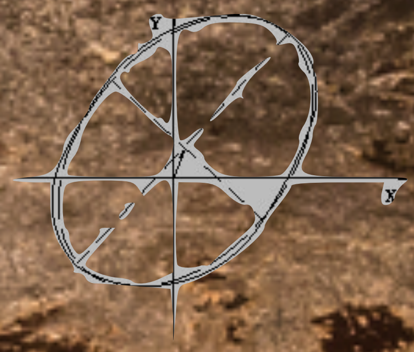
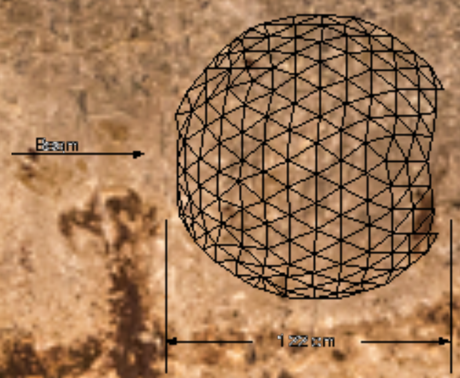


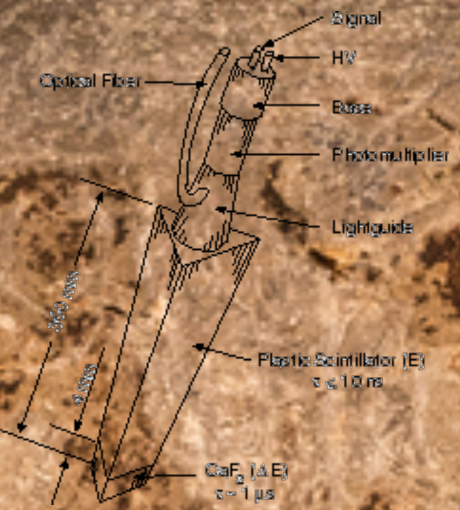
Figure 1:

Ollitrault

Phys.Rev. D46 (1992) 229-245

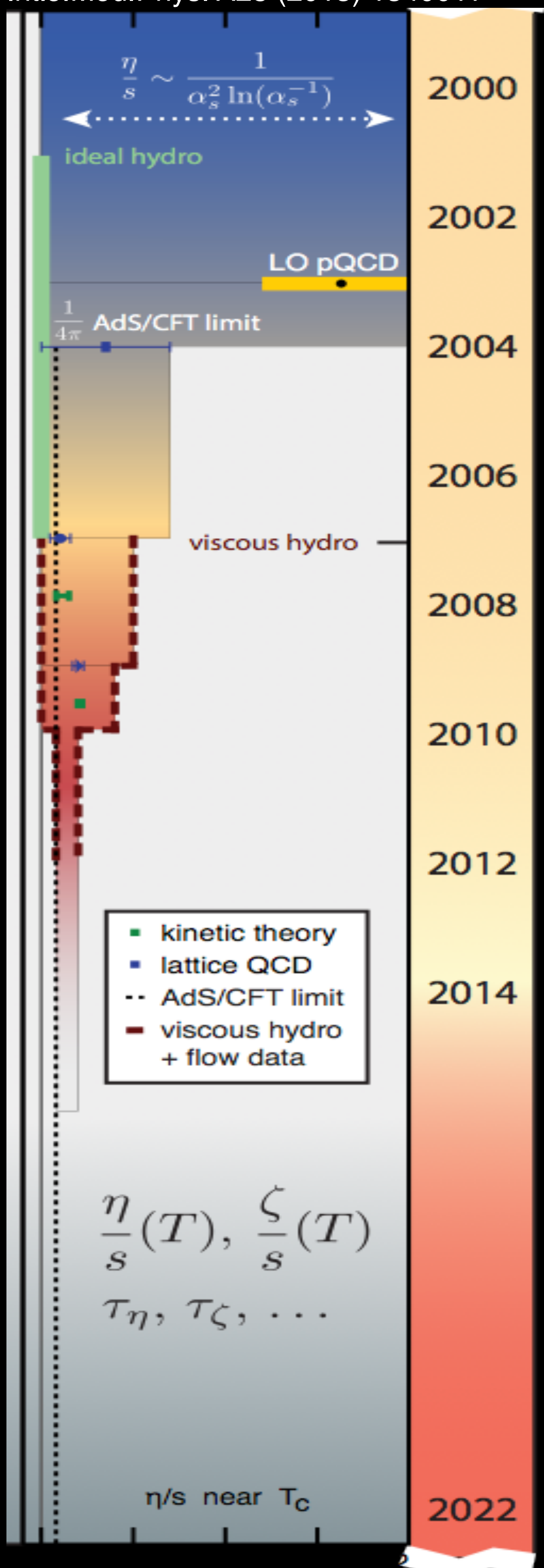


Bevatron Plastic Ball



Modern times: 2000-2015

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



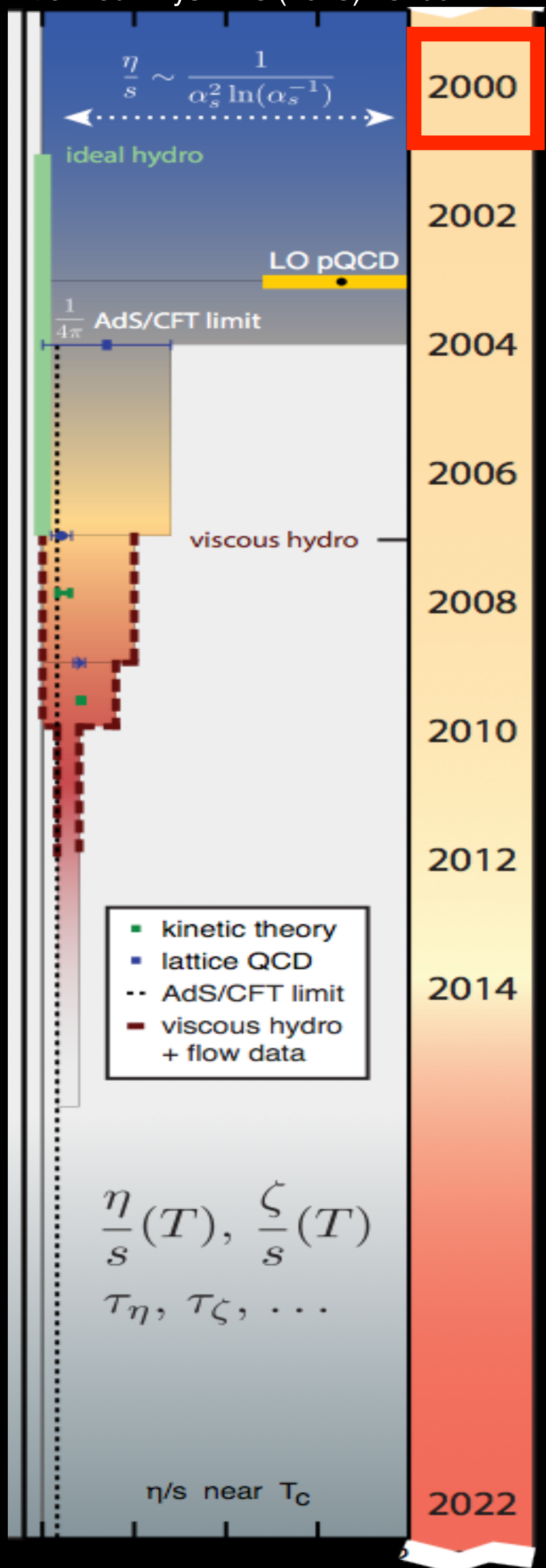
Key experimental and theoretical developments

Precise extraction of QGP transport coefficient η/s

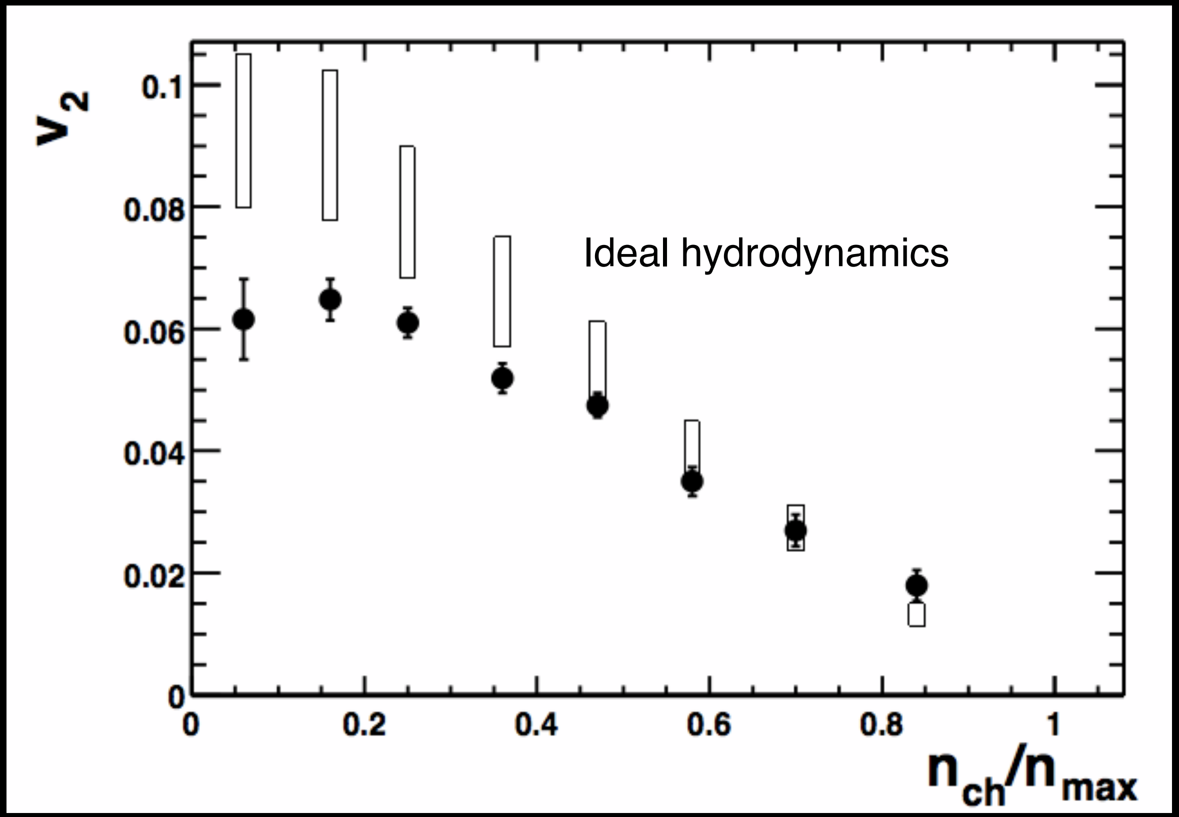
Understanding the structure and fine structure of collective motion through correlations

2000

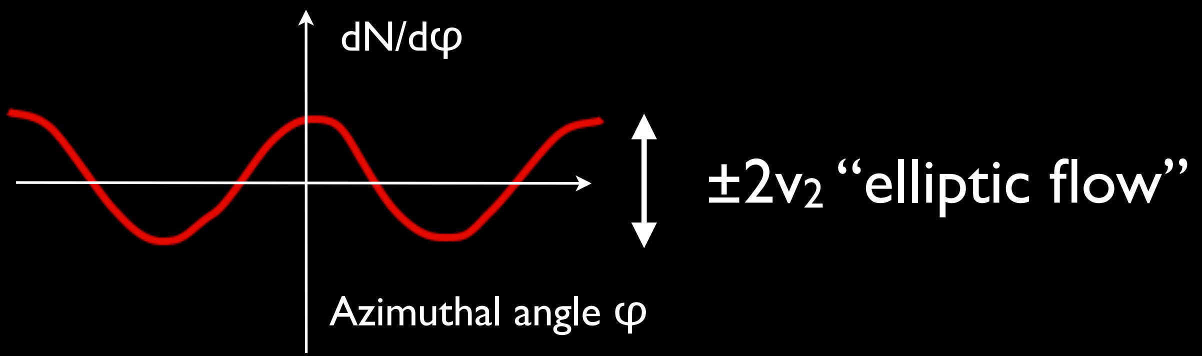
Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



STAR Phys.Rev.Lett. 86 (2001) 402-407

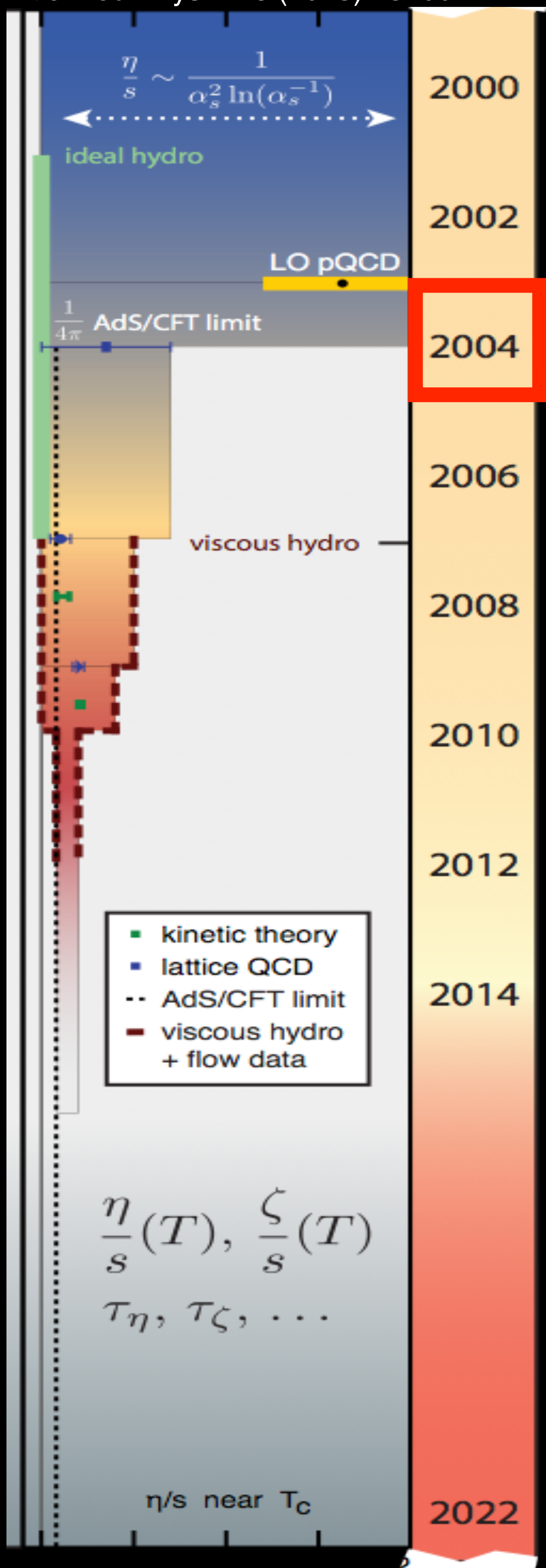


Elliptic flow in mid-central Au+Au collisions reaches values predicted in ideal (non-viscous) hydrodynamics

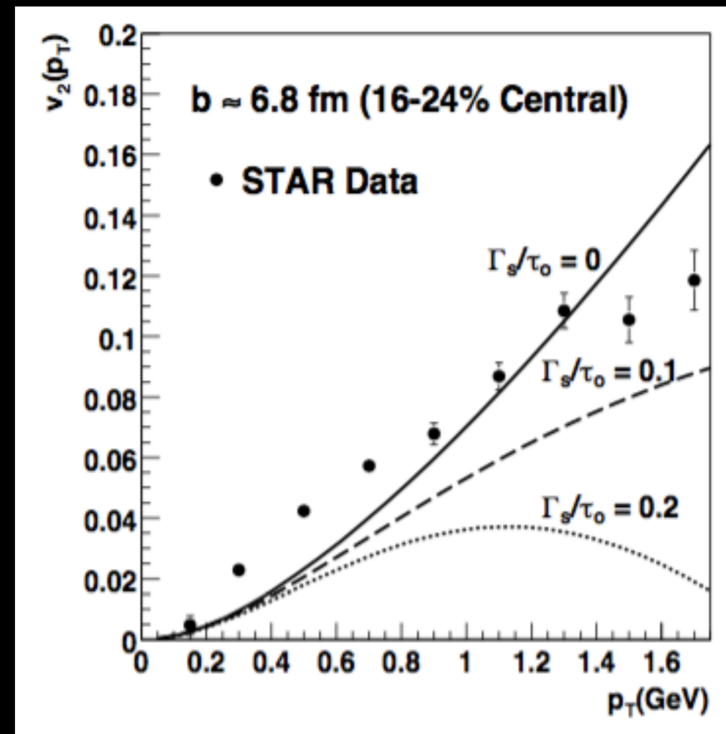


2003-2004

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011

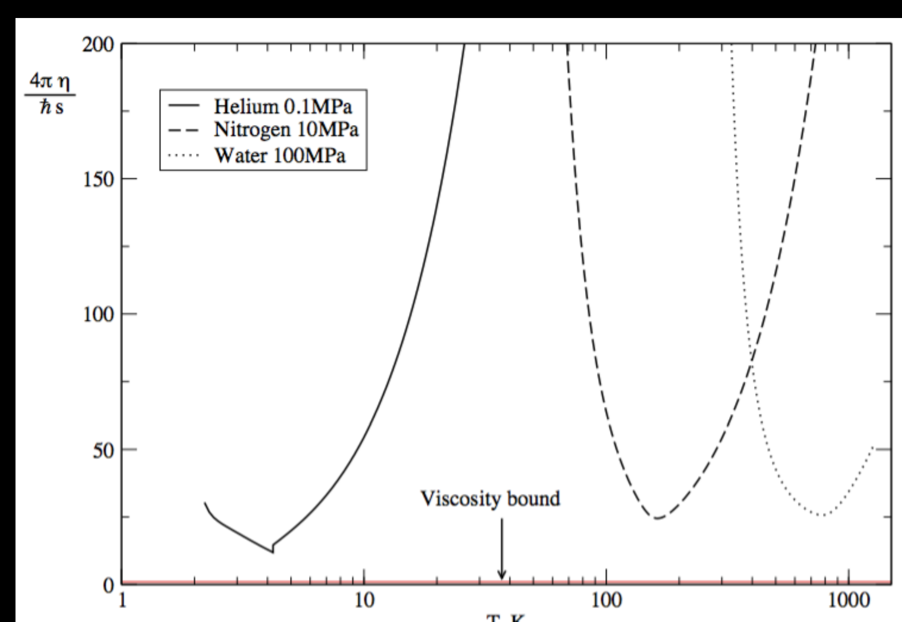


Teaney, Phys.Rev. C68 (2003) 034913



Strength of elliptic flow depends strongly on shear viscosity

Observed signal requires very small shear viscosity



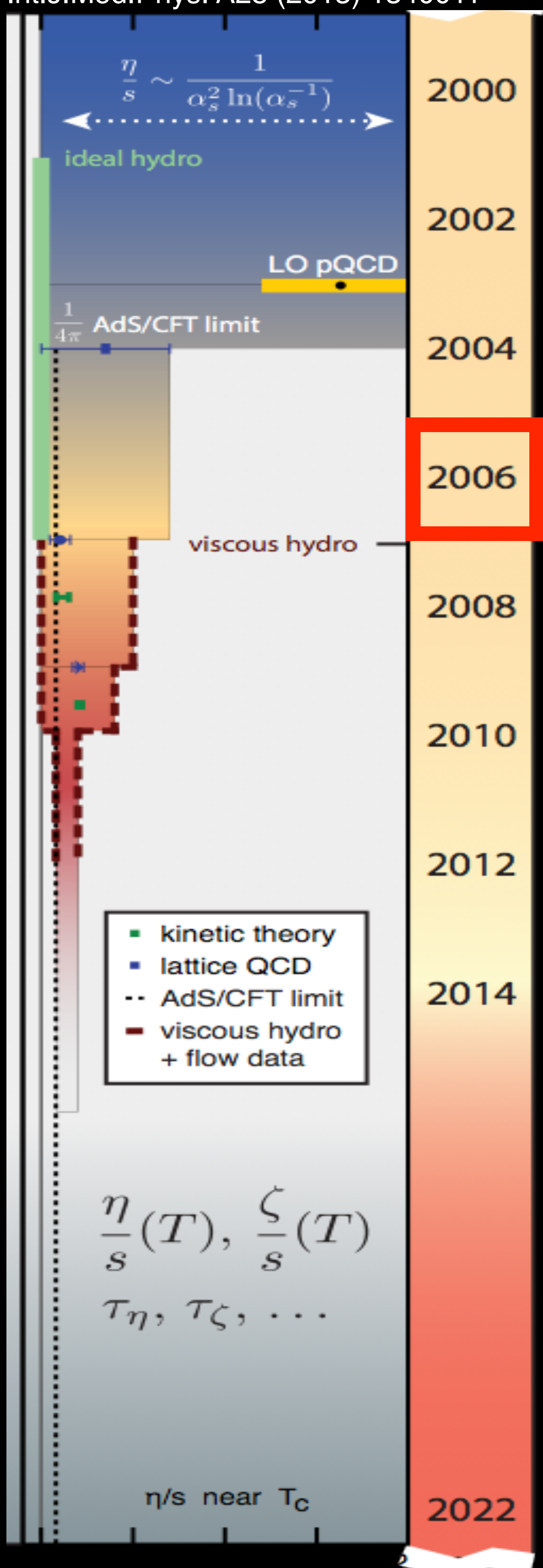
Kovtun, Son, Starinets Phys.Rev.Lett. 94 (2005) 111601

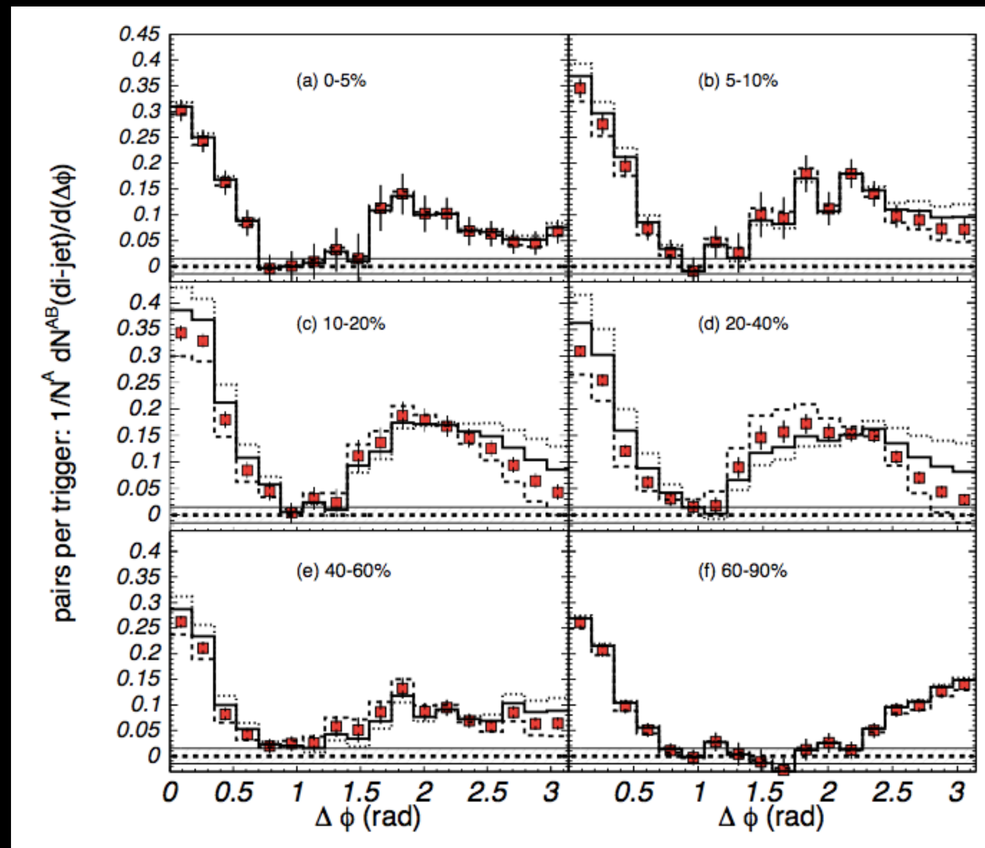
"Viscosity bound" $\eta/s \geqq 1/4\pi$ in string theories with gravity dual in strong coupling limit

Connection between flow in HI and fundamental physics of strongly coupled systems

2005-2007

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011

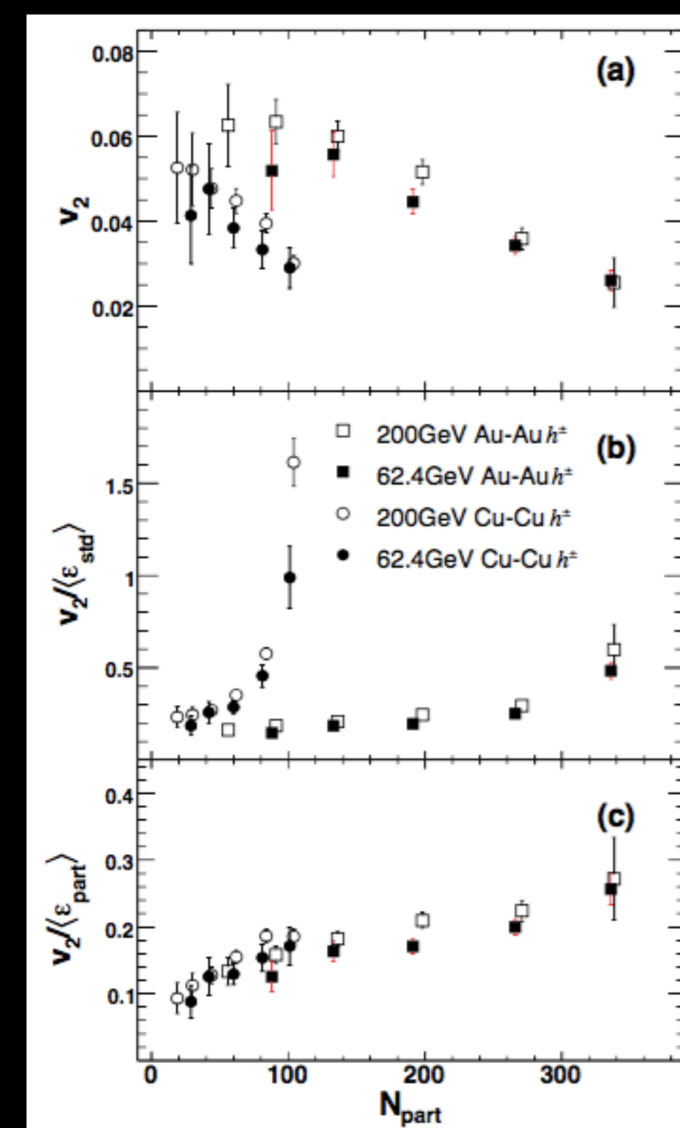




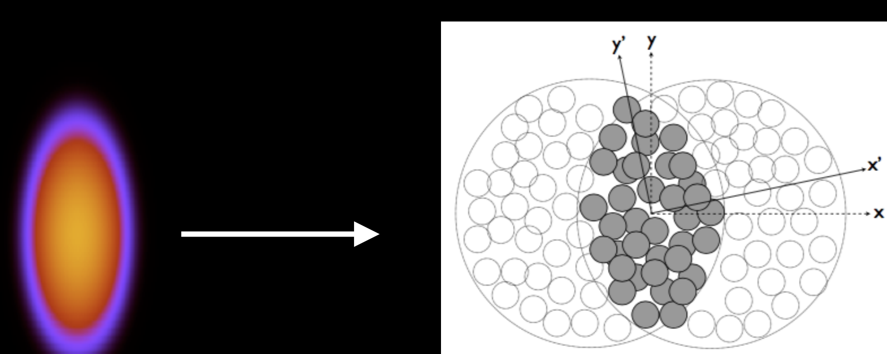
PHENIX Phys.Rev.Lett. 97 (2006) 052301

Correlations after subtraction of v_2 show structure at $\Delta\varphi = \pi \pm 60^\circ$ - Mach cones?

PHOBOS Phys.Rev.Lett. 98 (2007) 242302



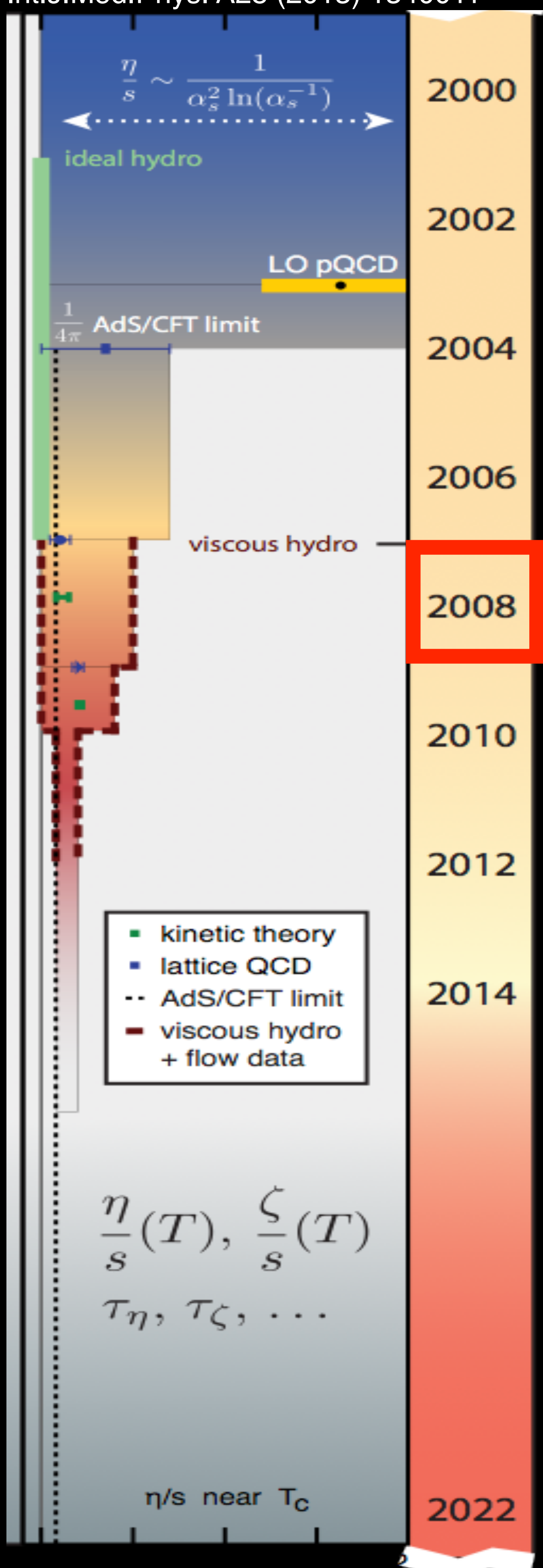
Flow strength in small systems requires fluctuations of initial geometry: Participant eccentricity



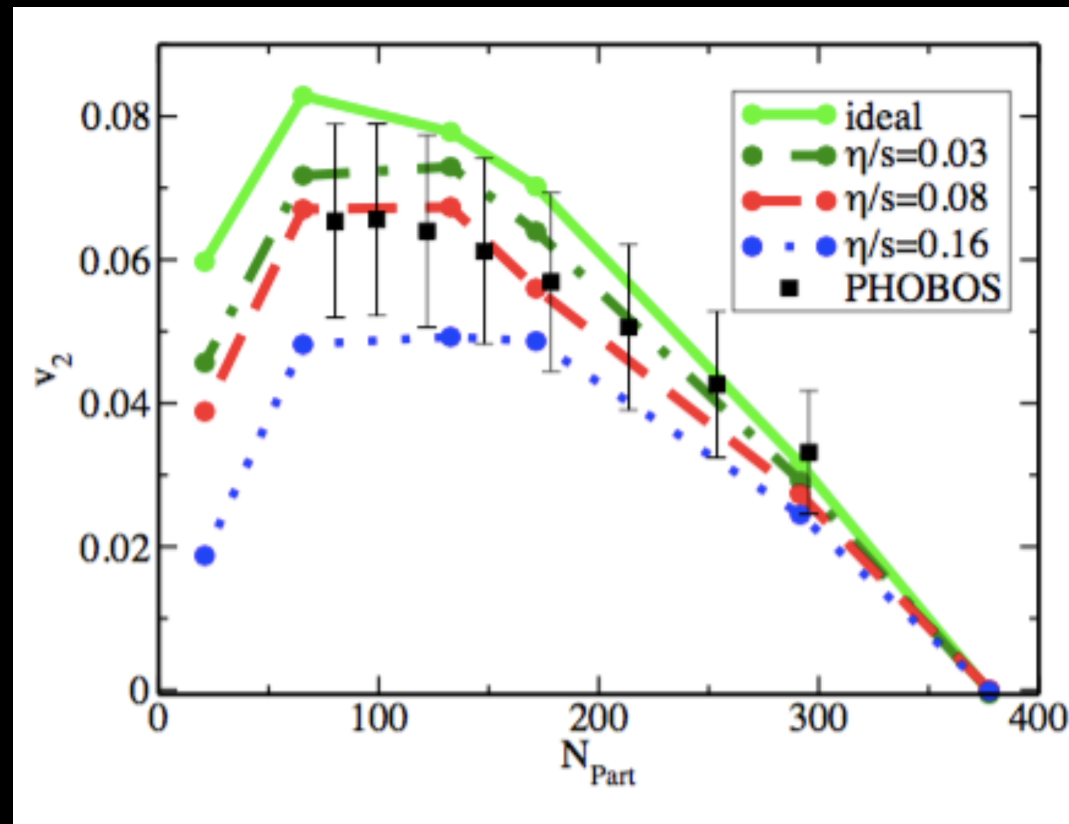
PHOBOS Phys.Rev.C77:014906,2008

2007-2009

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



Romatschke, Romatschke Phys.Rev.Lett. 99 (2007) 172301

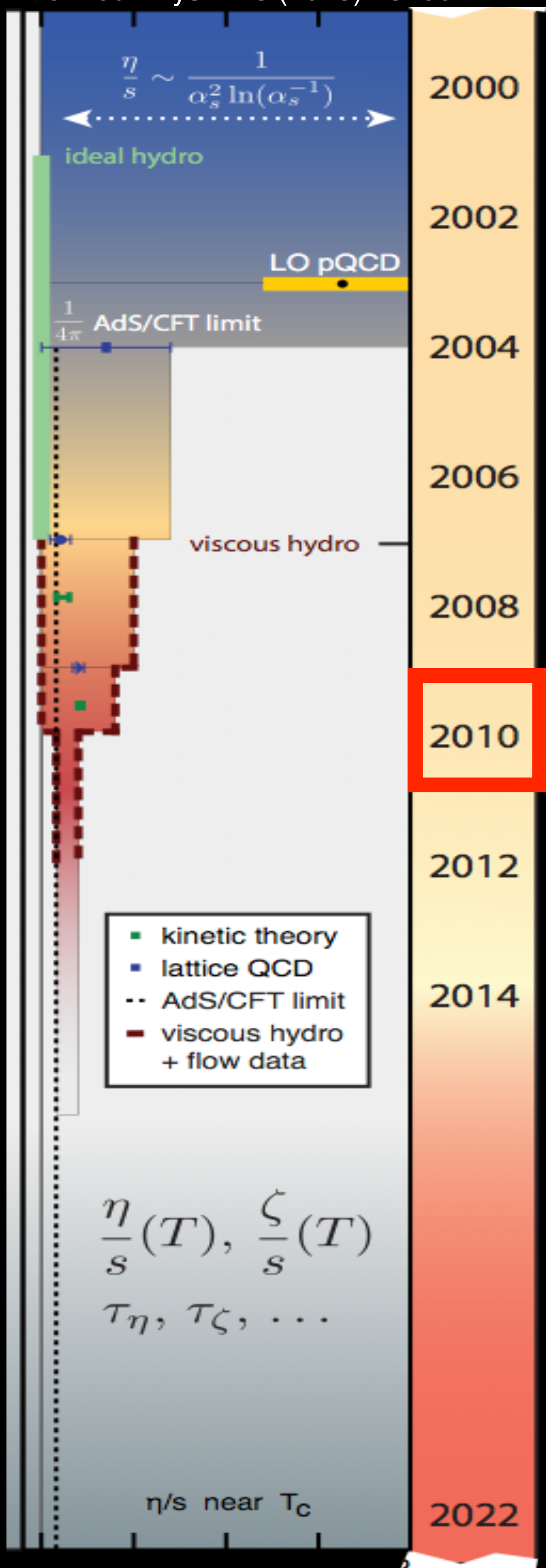


First quantitative comparisons of data with viscous hydro calculations

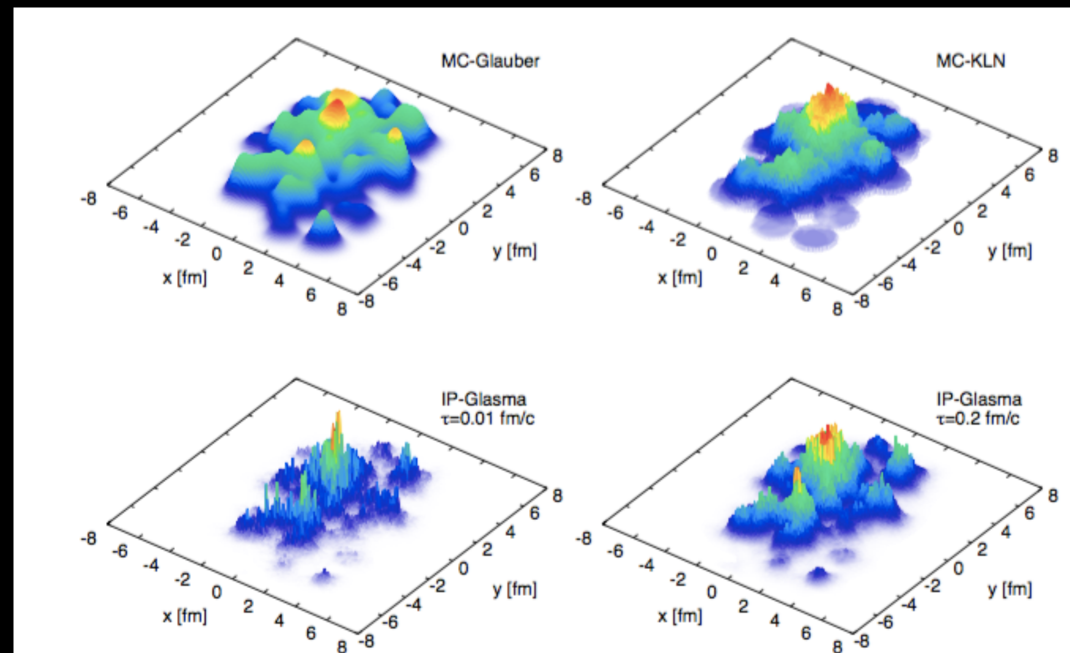
Data imply η/s = few x 1/4π

2010

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011

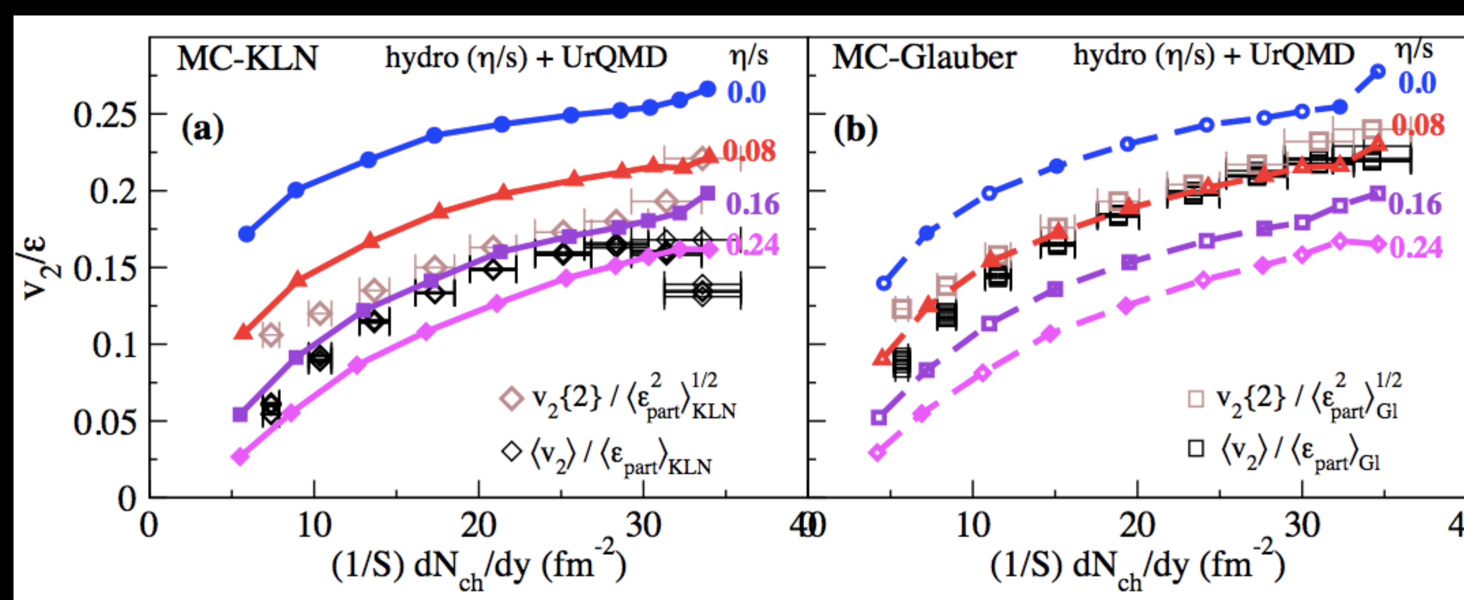


Gale, Jeon, Schenke (Review)
Int.J.Mod.Phys. A28 (2013) 1340011



Variety of models to describe initial state geometry

Heinz, Snellings (Review)
Int.J.Mod.Phys. A28 (2013) 1340011

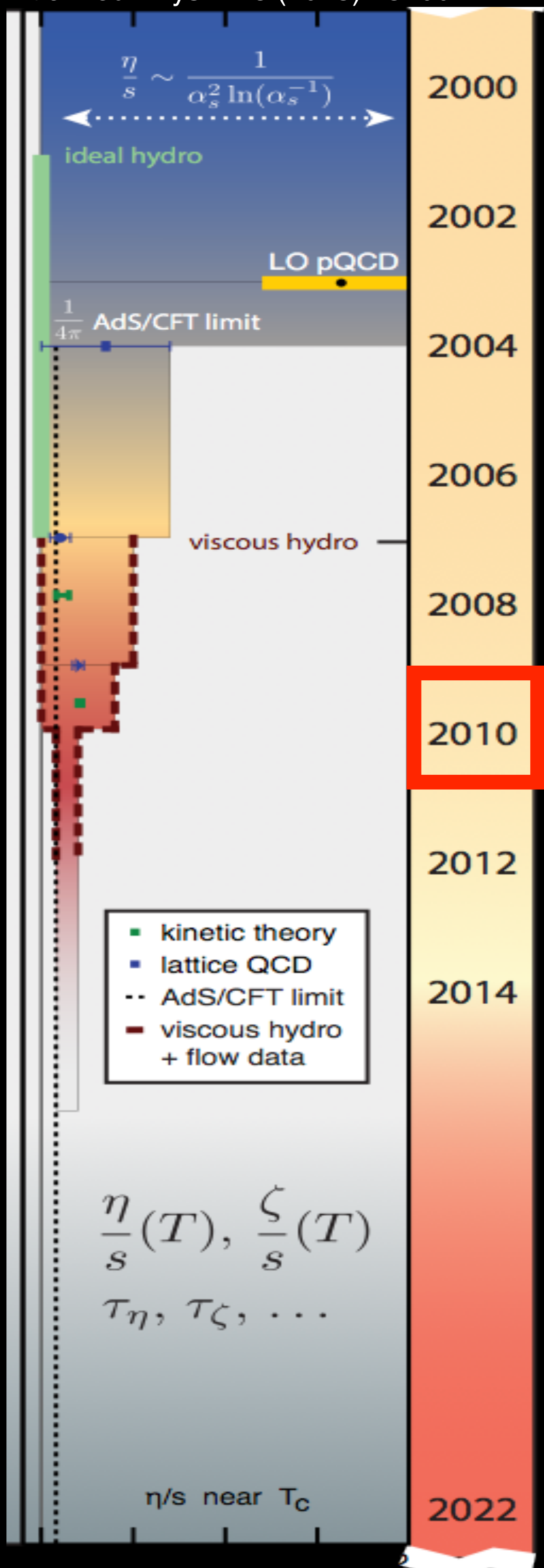


Geometry uncertainty major source of uncertainty on η/s

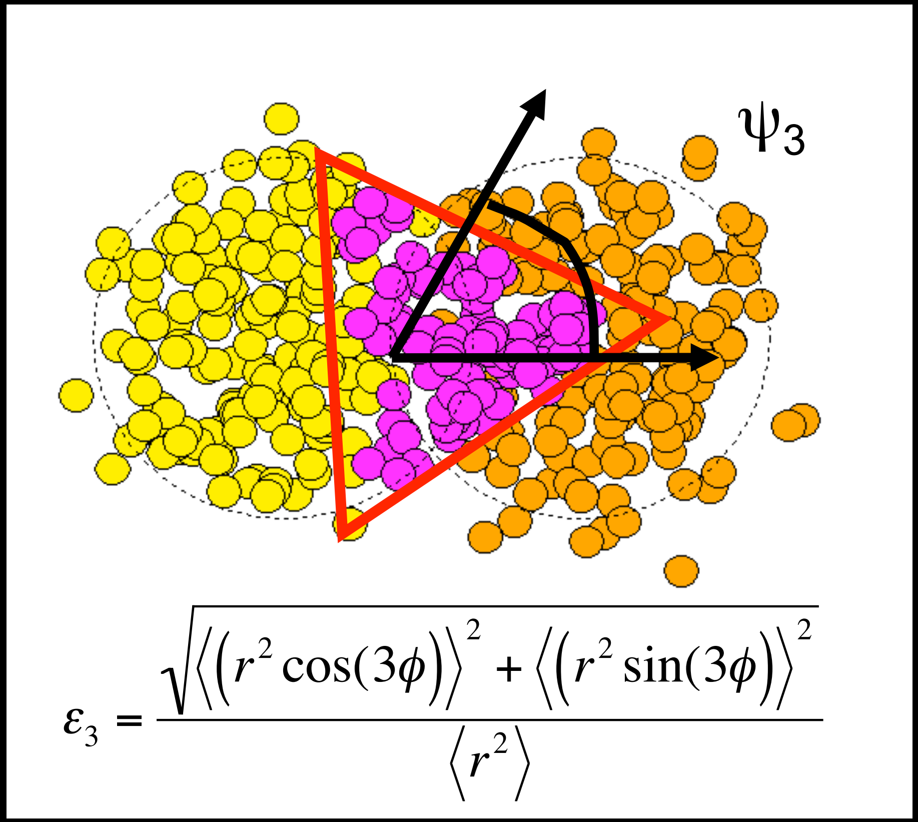
One observable (v_2) - two unknowns (η/s, ε_2)

2010

Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



B. Alver, GR, Phys.Rev. C81 (2010) 054905

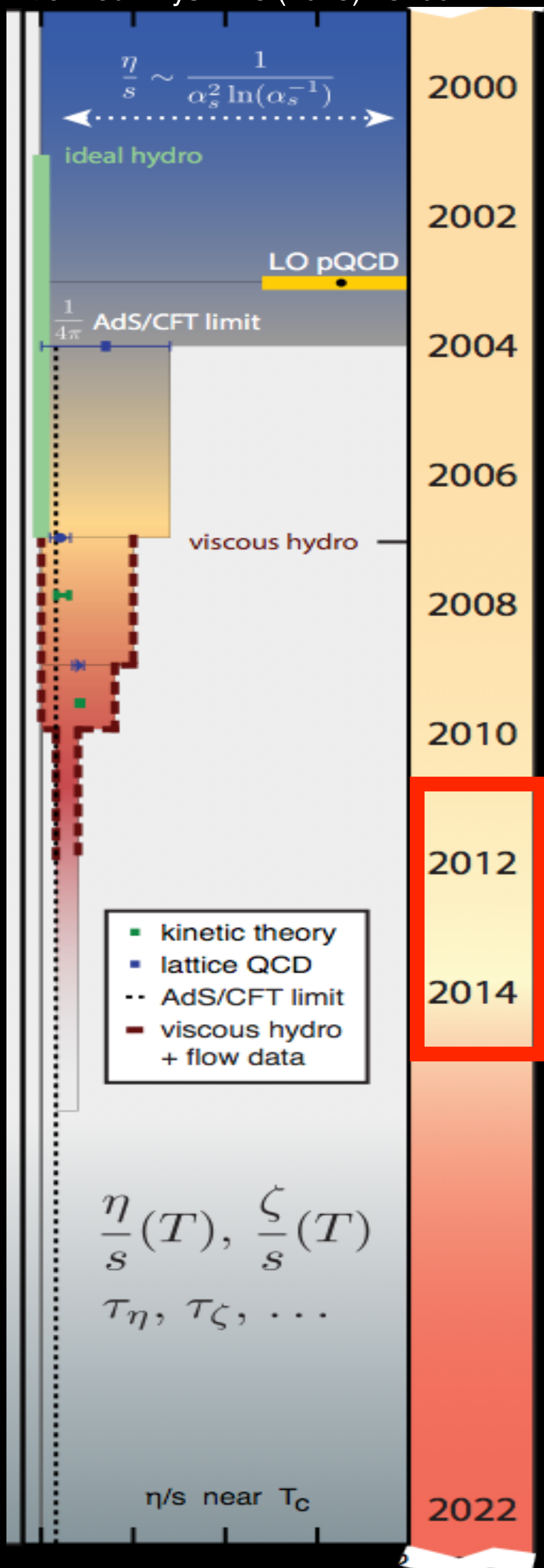


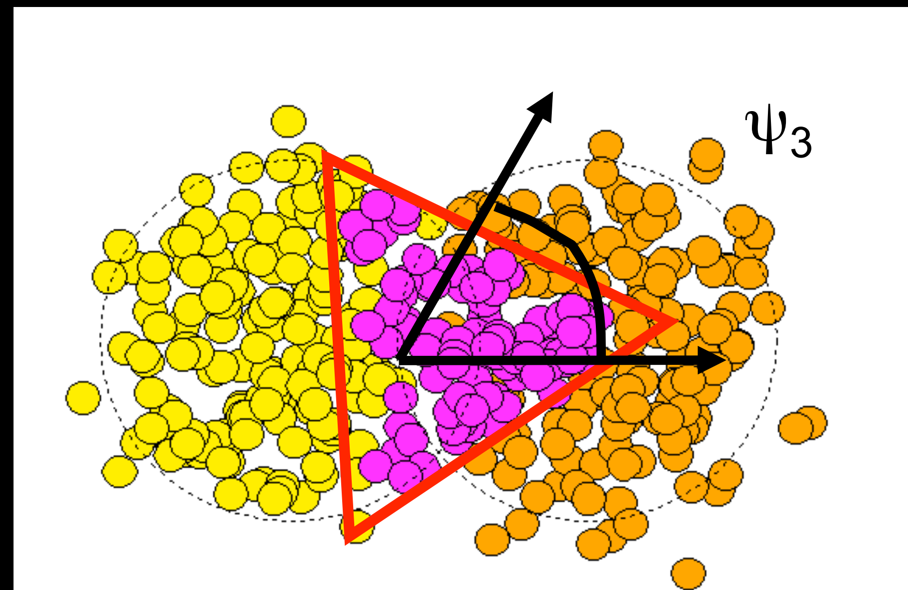
Initial geometry fluctuations break two-fold symmetry → Odd flow components, in particular triangular flow (v_3)

Provides independent observables to constrain geometry and η/s simultaneously

2011-

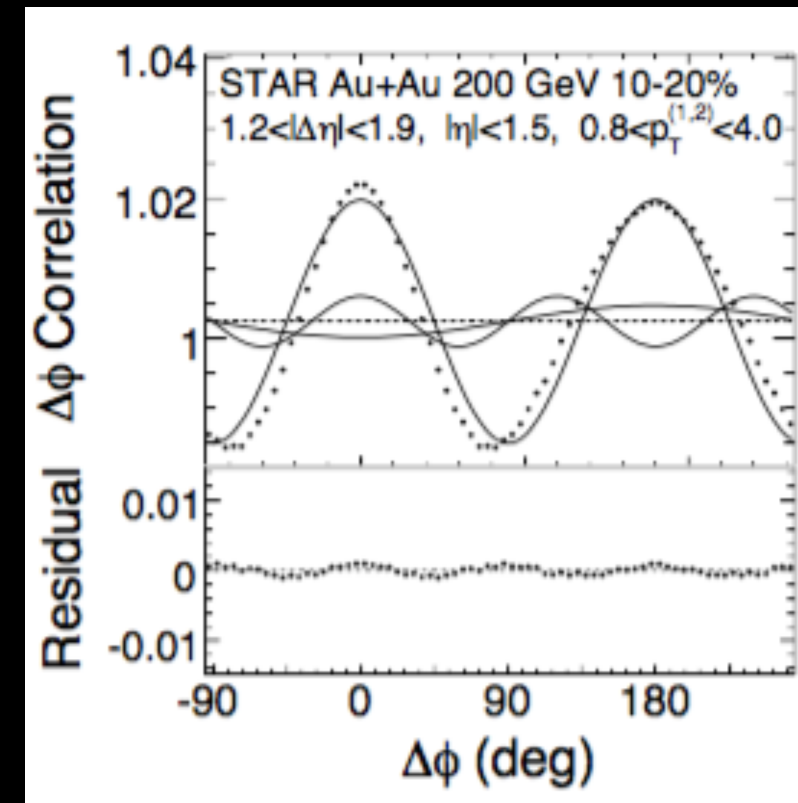
Gale, Jeon, Schenke
Int.J.Mod.Phys. A28 (2013) 1340011



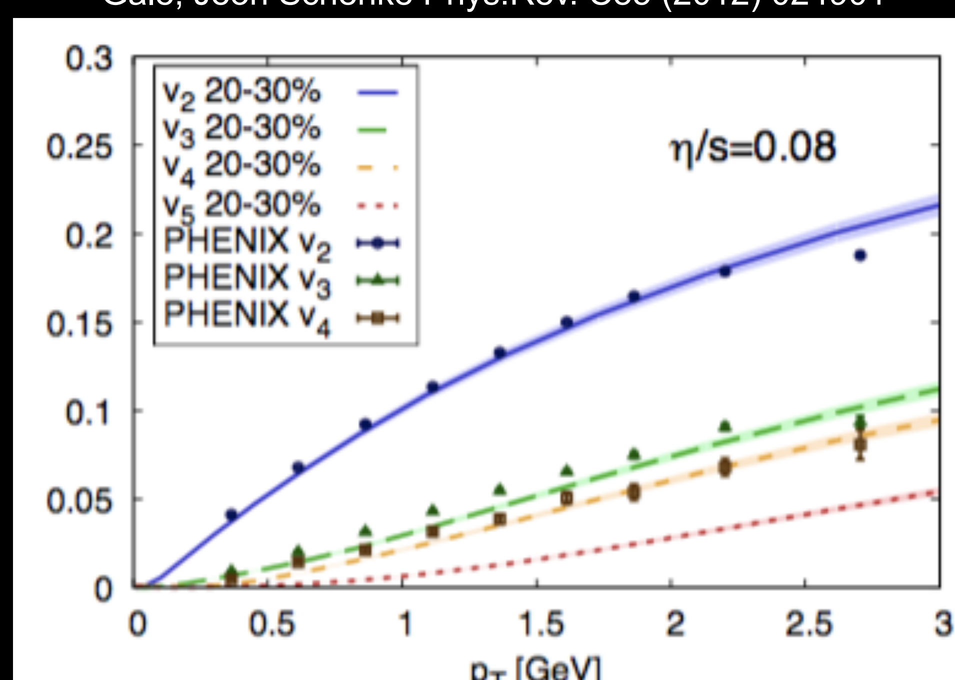


$$\varepsilon_3 = \frac{\sqrt{\left\langle\left(r^2\cos(3\phi)\right)\right\rangle^2 + \left\langle\left(r^2\sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2\right\rangle}$$

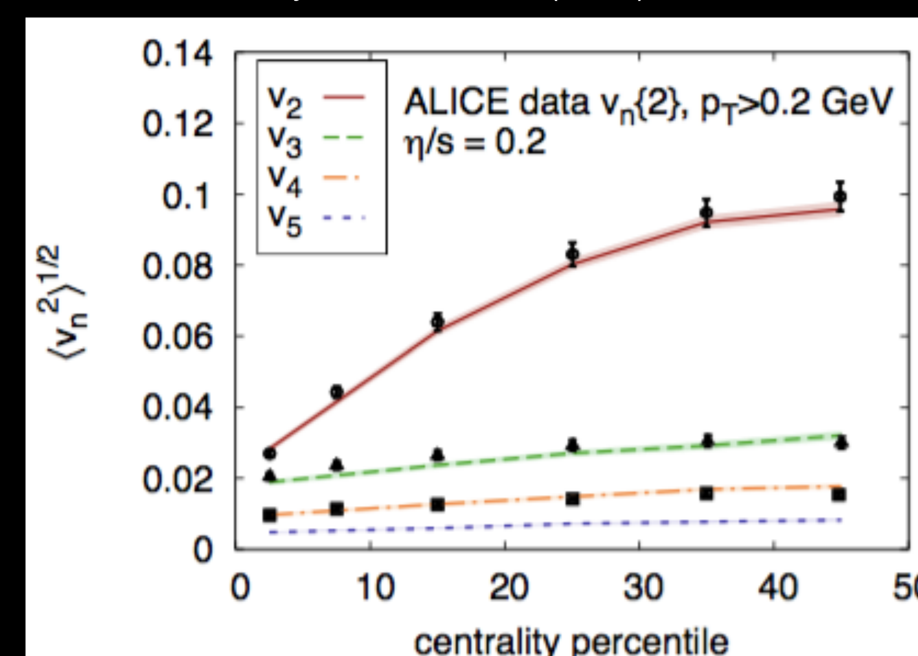
B. Alver, GR, Phys.Rev. C81 (2010) 054905



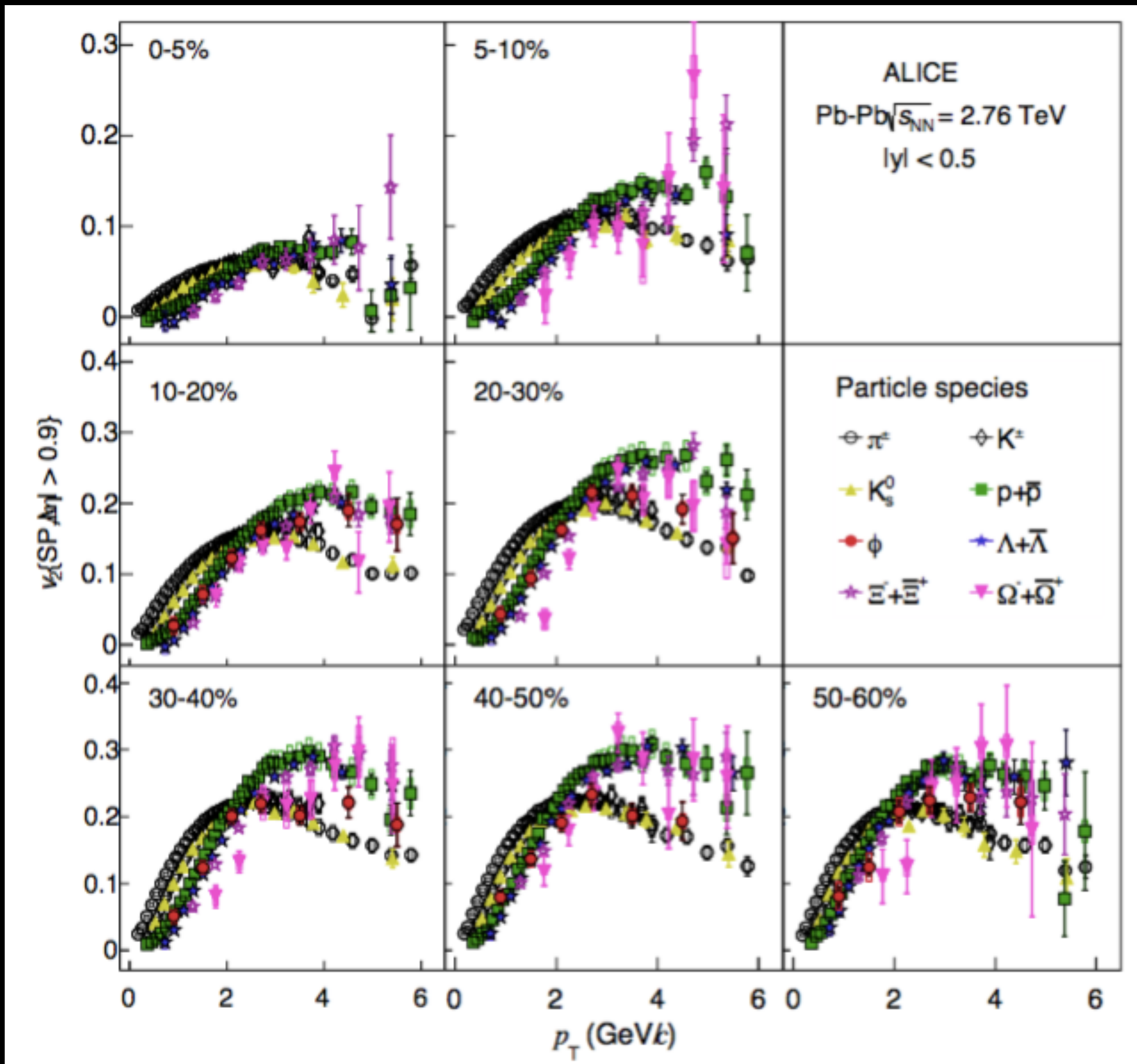
Gale, Jeon Schenke Phys.Rev. C85 (2012) 024901



Gale et al, Phys.Rev.Lett. 110 (2013)



Mass dependence of $v_2(p_T)$



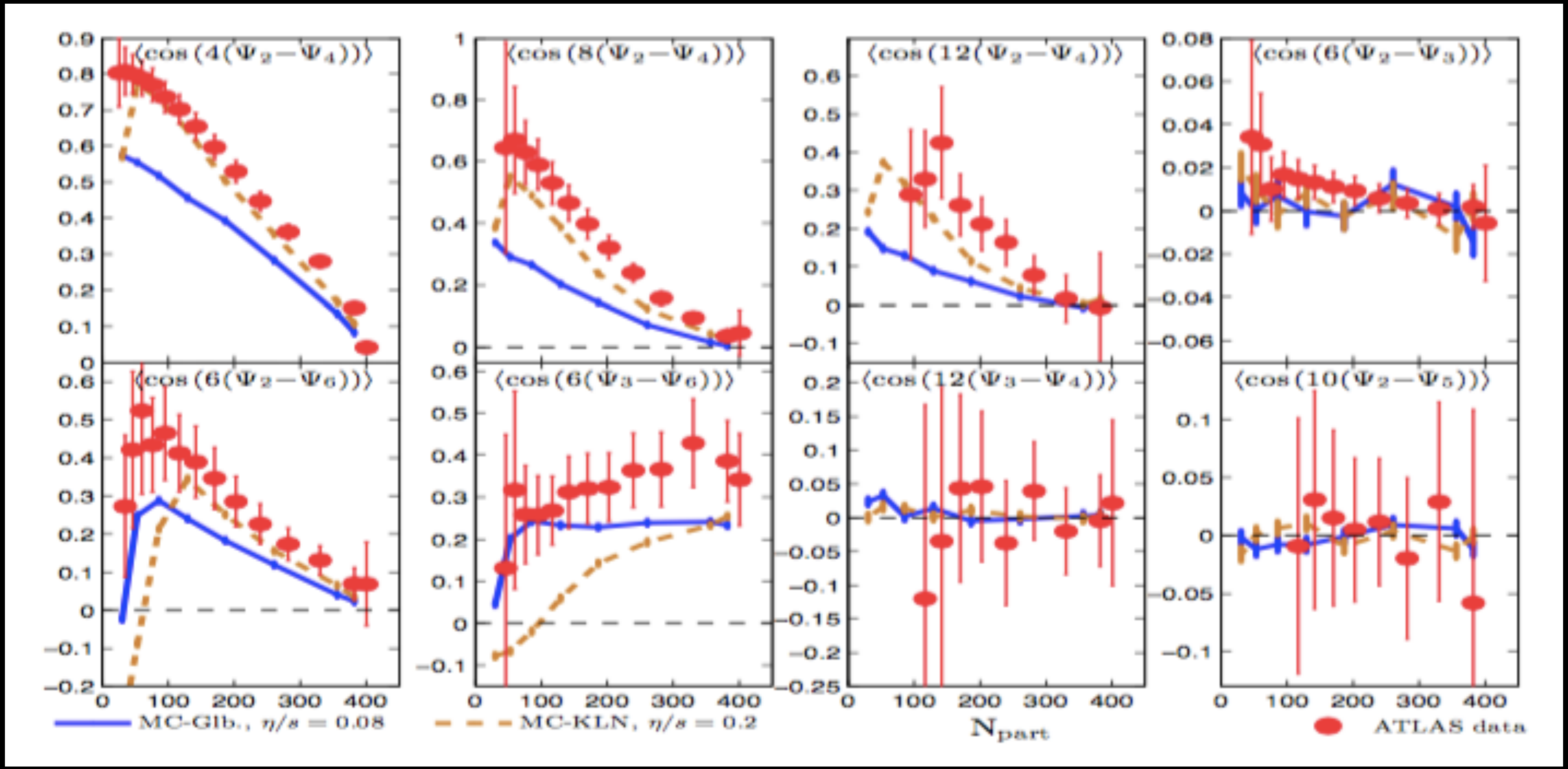
Measurement of v2(pT) for identified hadrons

Origin of correlations from common underlying anisotropic velocity field in hydro picture implies mass ordering

Mass ordering seen in data at LHC, similar to prior RHIC measurements by STAR, PHENIX

ALICE
JHEP 1506 (2015) 190

Event-plane angle (Ψ_n) correlations



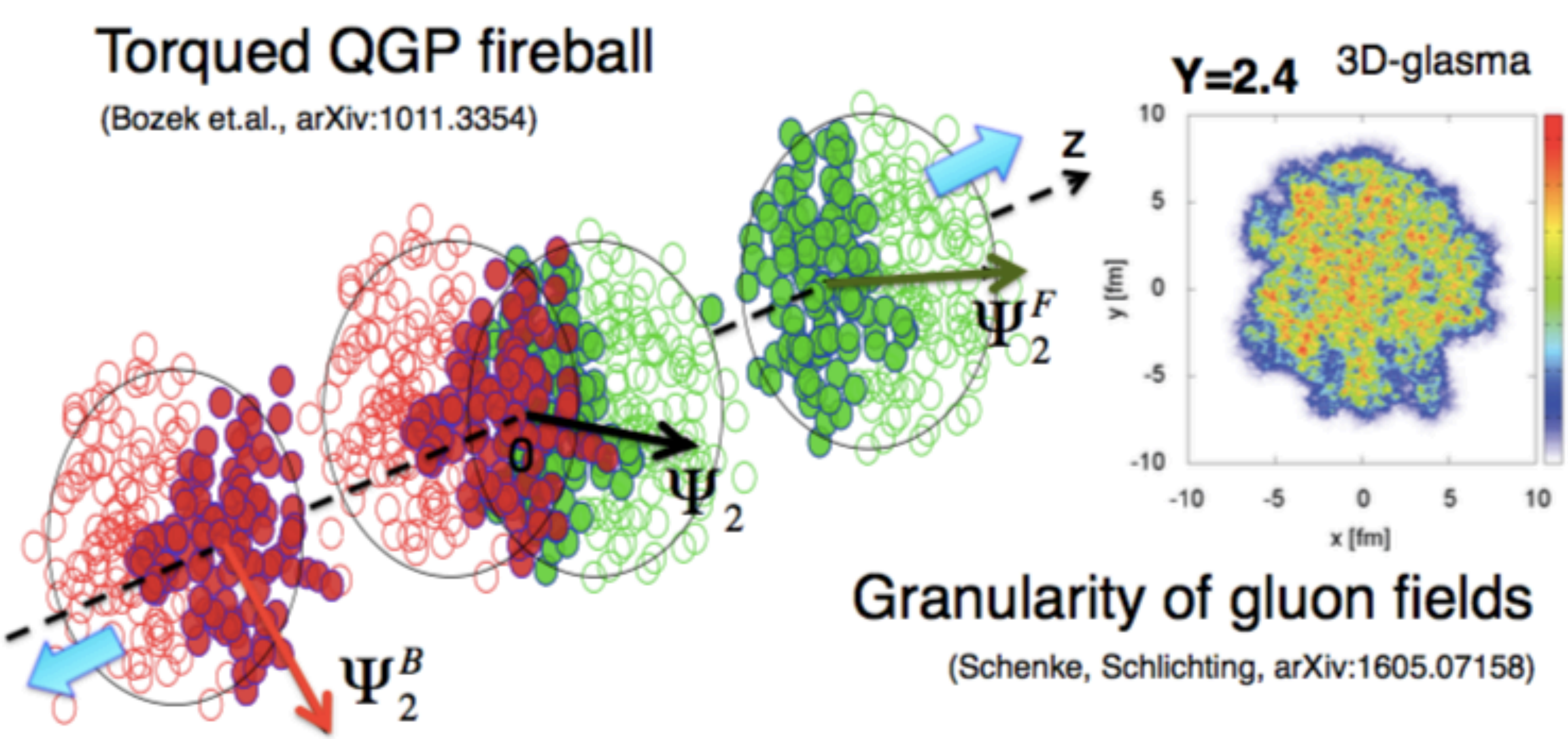
Heinz, Snellings (Review)
Int.J.Mod.Phys. A28 (2013) 1340011

ATLAS pioneered studies of correlations between event-plane angles (Ψ_n) of different flow harmonics v_n

Some of these correlations are purely geometrical, while others arise only in the evolution of the system.

Hydrodynamic calculations reproduce these correlations for both cases (semi-) quantitatively

Transverse and longitudinal source structure



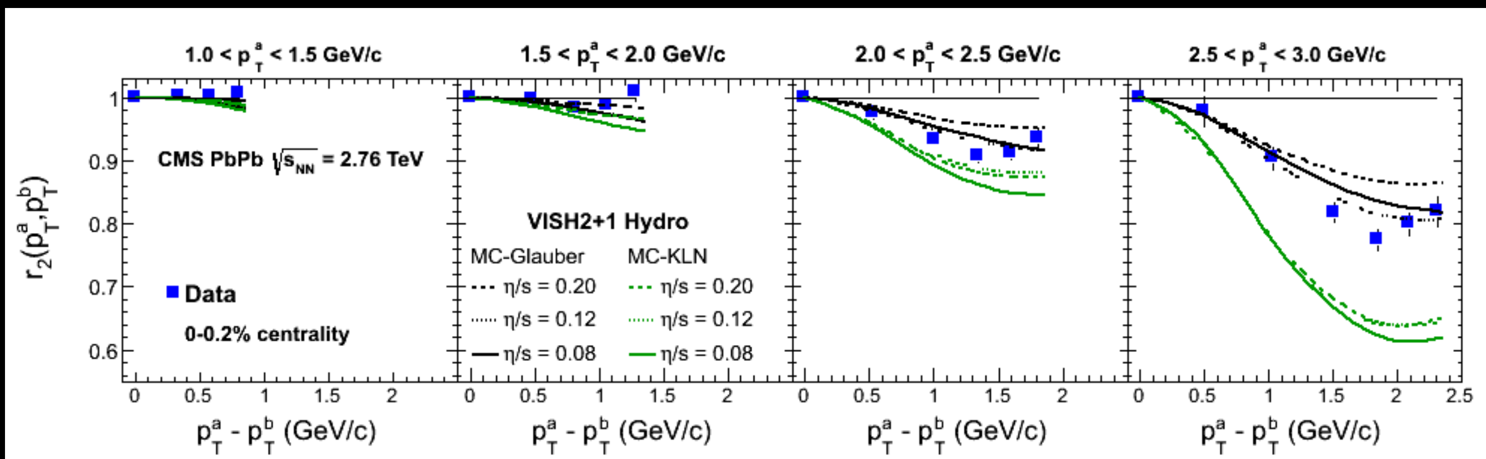
$$\langle \vec{\varepsilon}_n(\eta_1^s)\vec{\varepsilon}_n^*(\eta_2^s)\rangle \Rightarrow \langle \vec{V}_n(\eta_1)\vec{V}_n^*(\eta_2)\rangle$$

Wei Li, QM'17

– rapidity-correlated flow fluctuations

Transverse and longitudinal source structure

Factorization breaking vs transverse momentum difference



CMS PRC 92 (2015) 034911

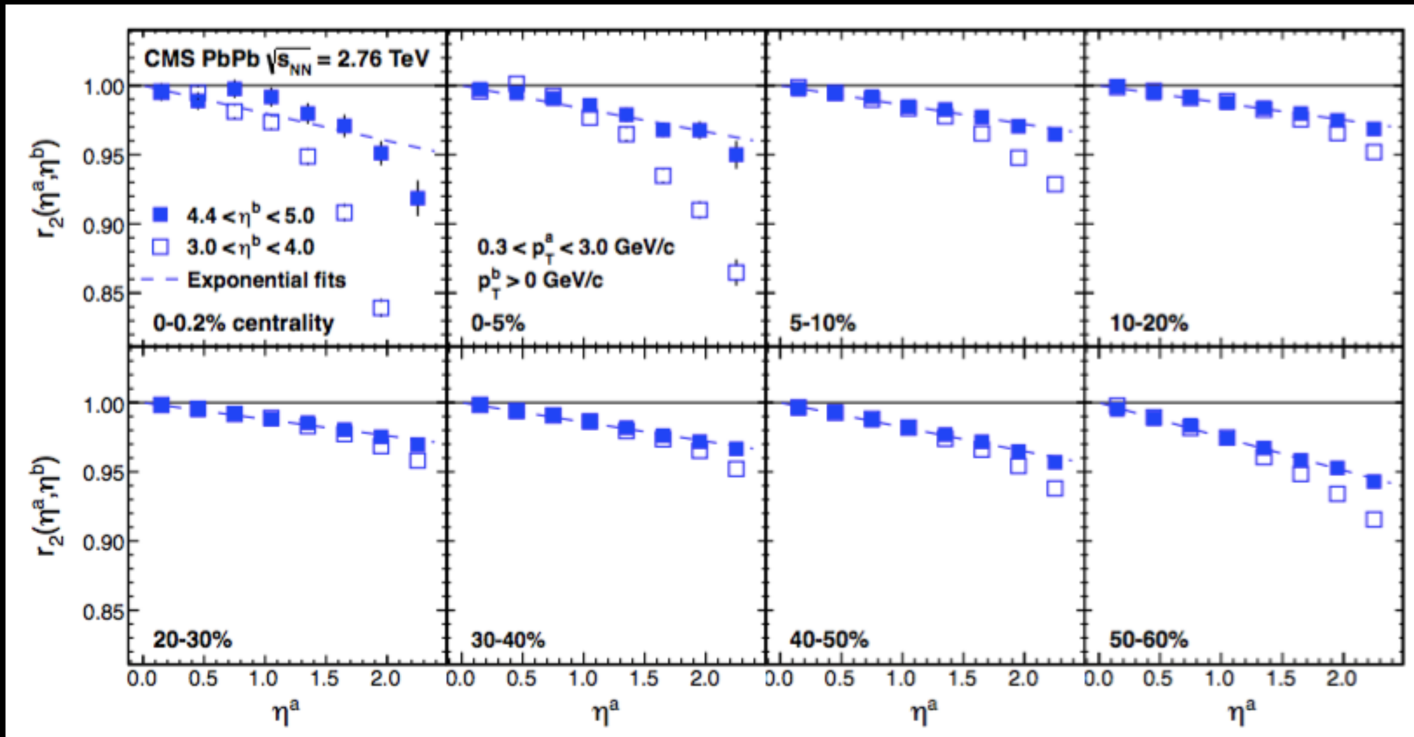
If v_n pure single particle effect wrt common event plane angle expect factorization, i.e. $r_n = 1$

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)}}$$

Due to local geometrical fluctuations and space-momentum correlations, hydro calculations *predicted* factorization breaking

Heinz et al, Phys. Rev. C 87 (2013) 034913

Factorization breaking vs rapidity gap



Semi-quantitative agreement between data and prediction for $r_2(p_T^a, p_T^b)$

Collective Flow in Large Systems

Wide range of correlation measurements in qualitative/semi-quantitative or quantitative agreement with viscous hydro calculations with sensible initial conditions/transport coefficients

- Azimuthal anisotropies v_n
- Characteristic $v_n(p_T)$ shape
- Mass ordering of $v_n(p_T)$
- Multiplicity dependence
- Weak rapidity dependence
- Connection to initial geometry
- Higher order (n>4) correlations
- Factorization breaking
- Mass ordering of p_T spectra
- Event angle correlations

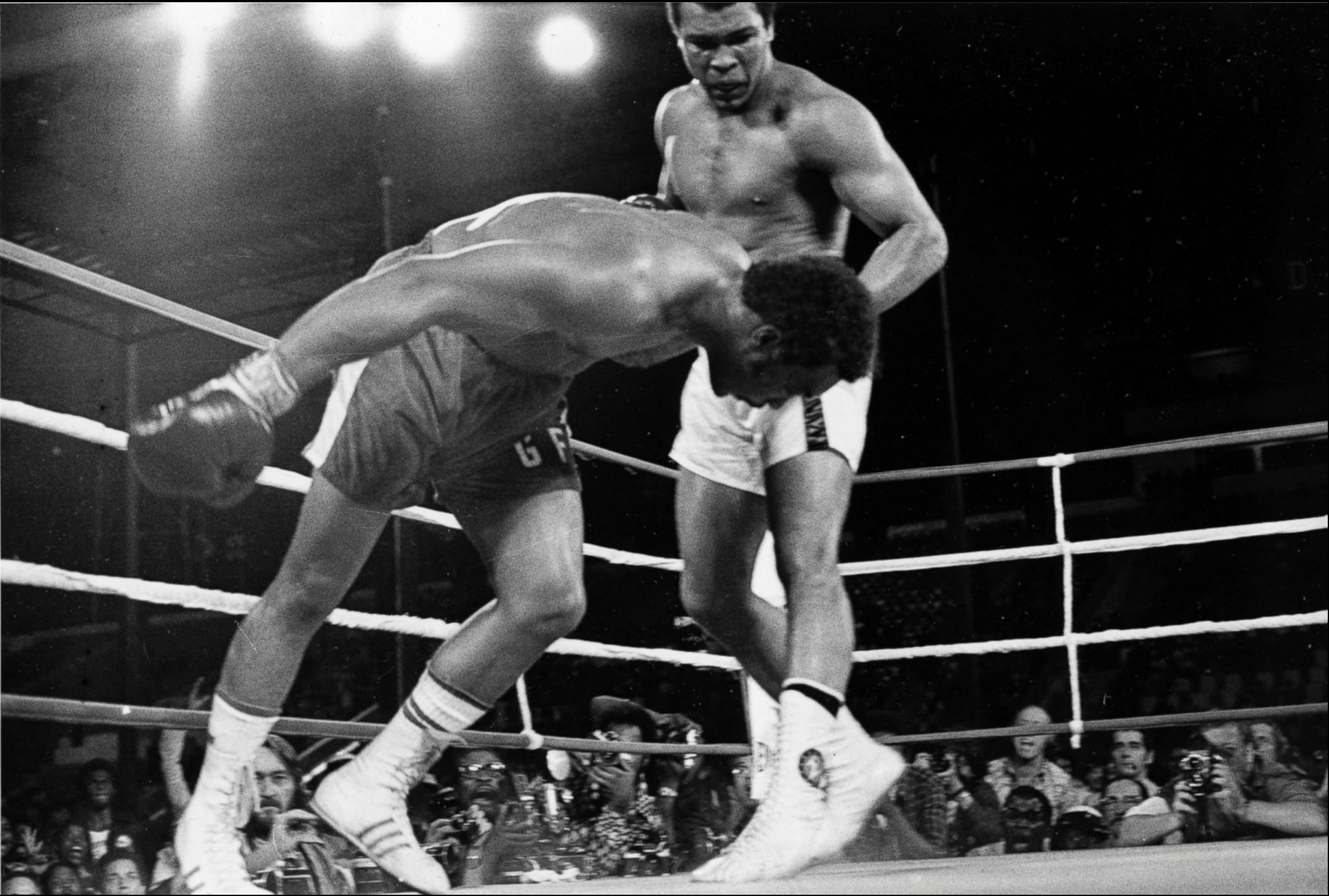
Heinz, Chen arXiv:1507.01558

Precision: Comparison to hydro codes yields $1 \lesssim (\eta/s)/4\pi \lesssim 2.5$

Accuracy: Do we have control of initial and final state physics?
Most importantly: Independent evidence for "perfect fluid"?

Experiment vs Theory

Experiment vs Theory

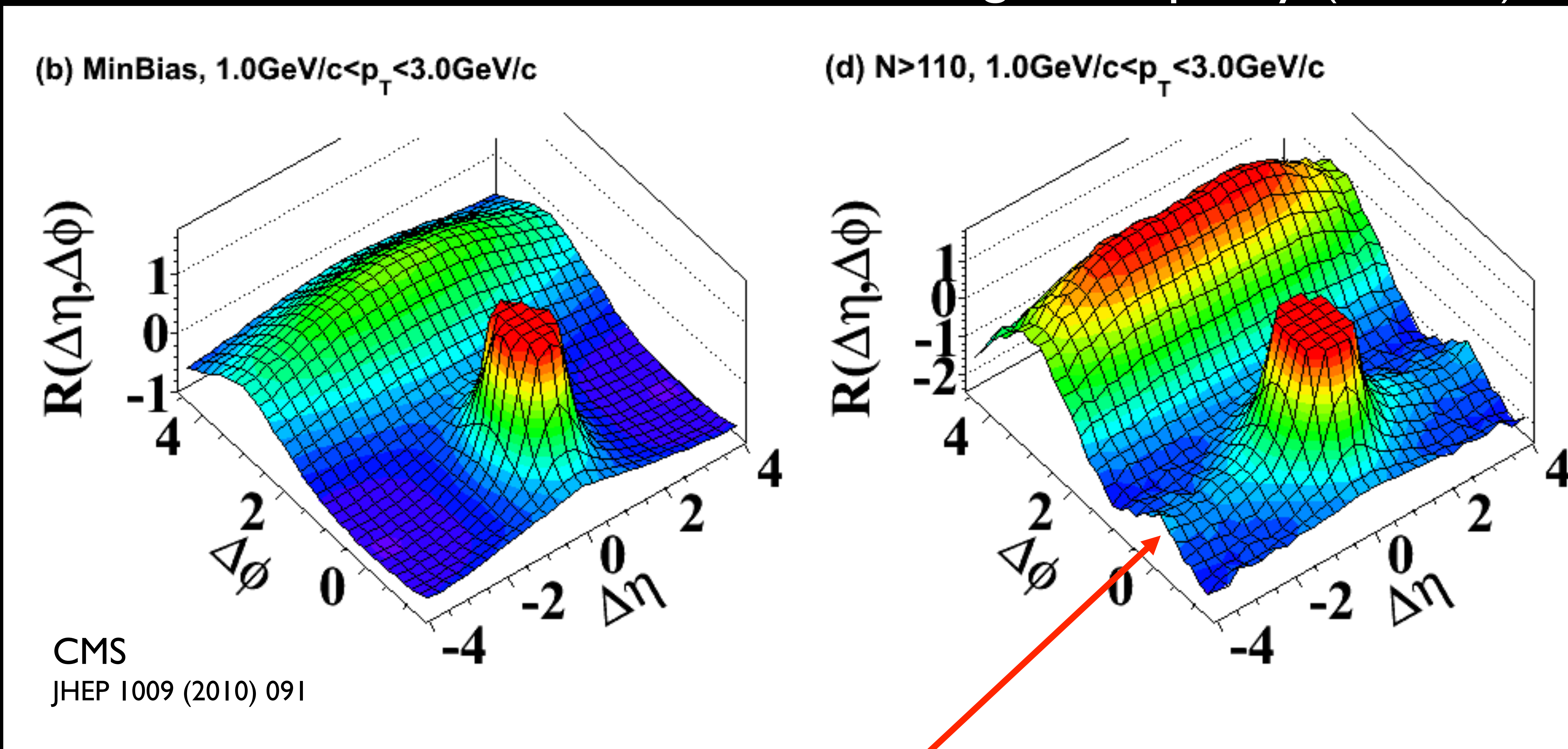


Two-Particle Correlations in 7TeV pp (2010)

Results based on 1fb^{-1},
i.e. sampling 50billion pp events
with high multiplicity trigger

Intermediate p_T: 1-3 GeV/c

MinBias | high multiplicity (N>110)

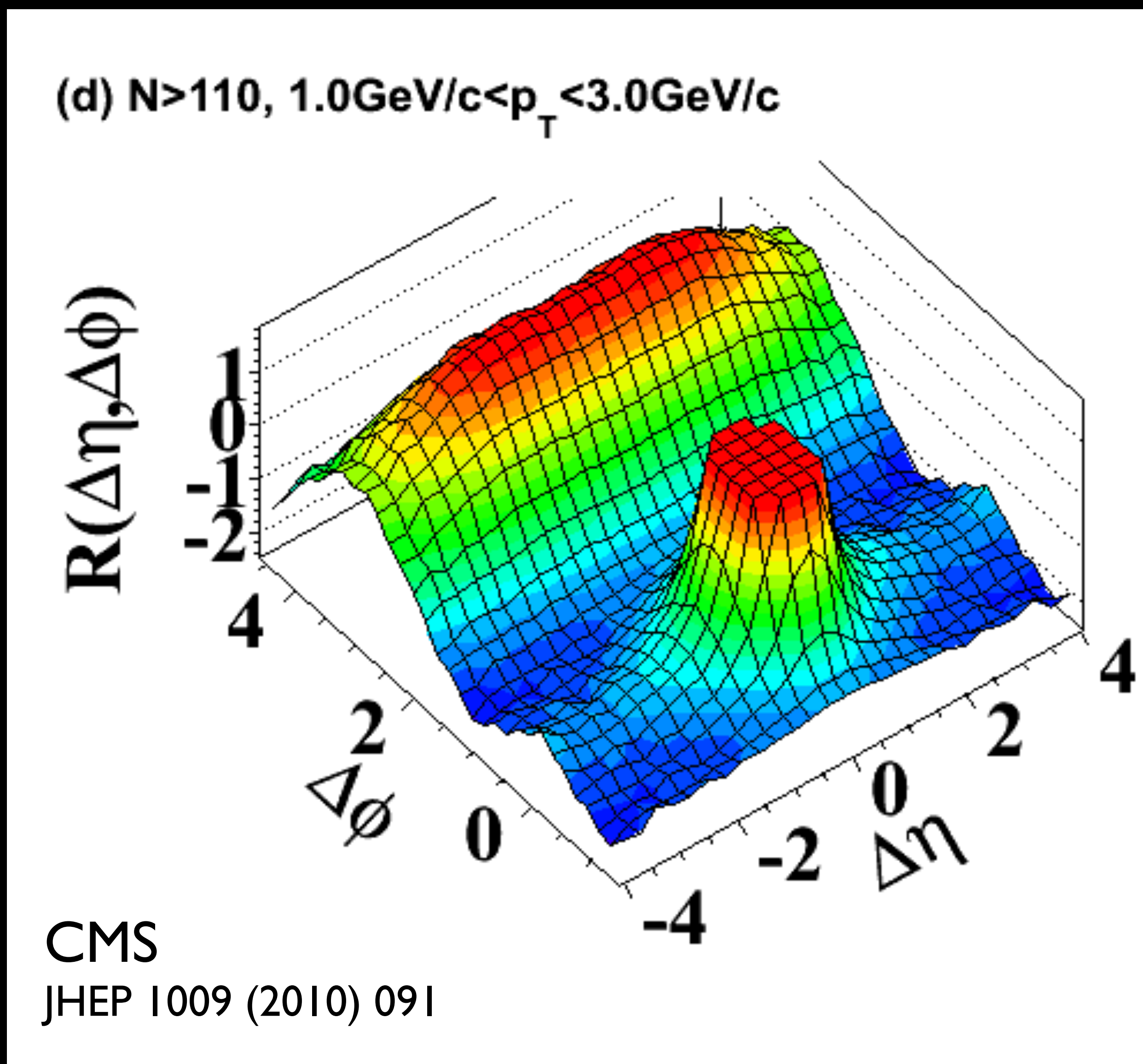


Pronounced structure at large δη around δφ ~ 0 !

Two-Particle Correlations in 7TeV pp (2010)

High multiplicity (N>110)

~100 citations within a year



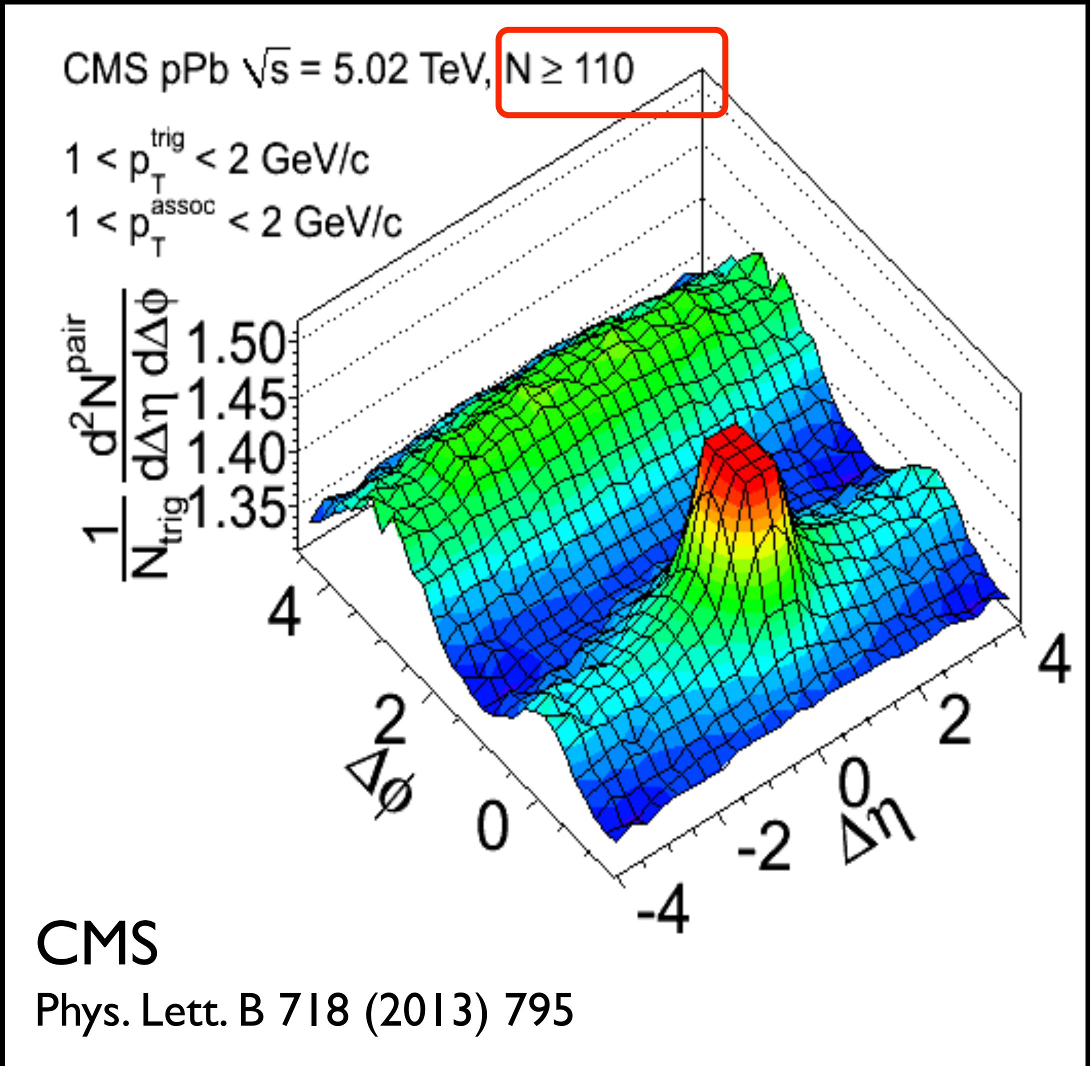
Multiplicity in these events is dominated by jet contribution.

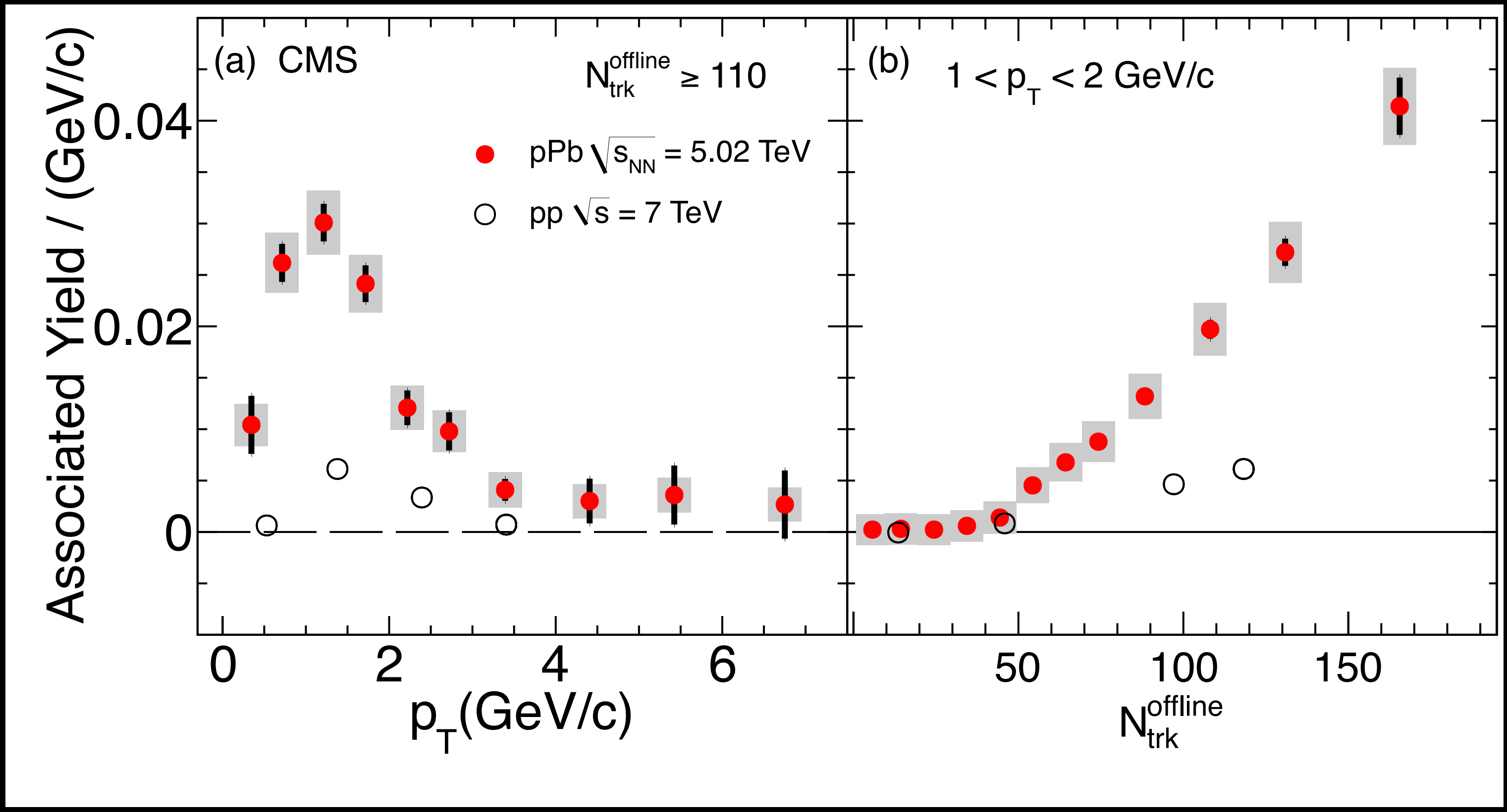
Interpretation:

Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections
Jet-remnant connections + medium
Glasma correlations
Quantum entanglement
Angular momentum conservation
Angular momentum conservation + medium
Hydrodynamic flow

?

Two-Particle Correlations in pPb (Oct 2012)





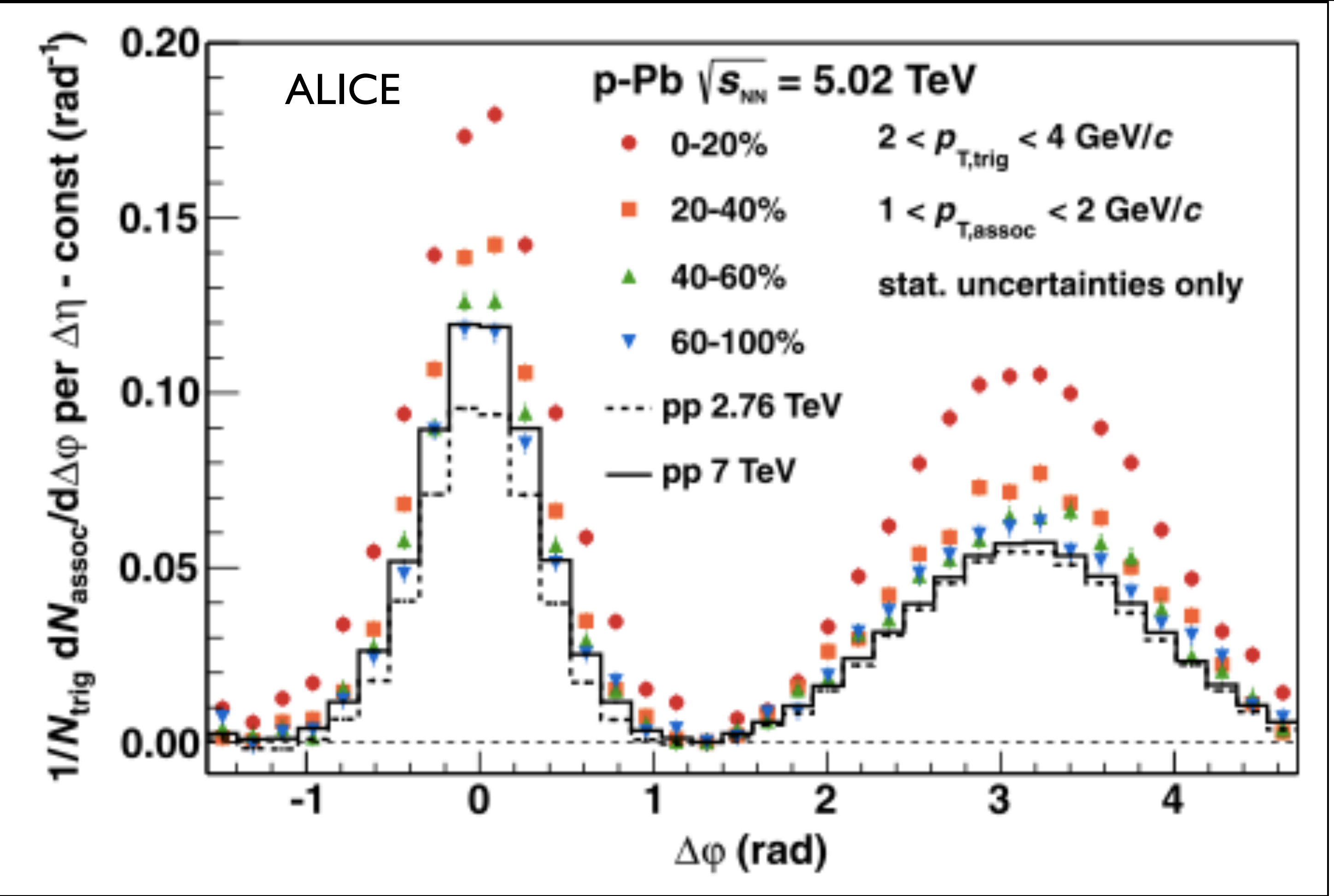
Similar correlations as in high-multiplicity pp, but larger strength (associated yield)

Opinion:
Phenomenology very similar in pp and pPb - same underlying physics

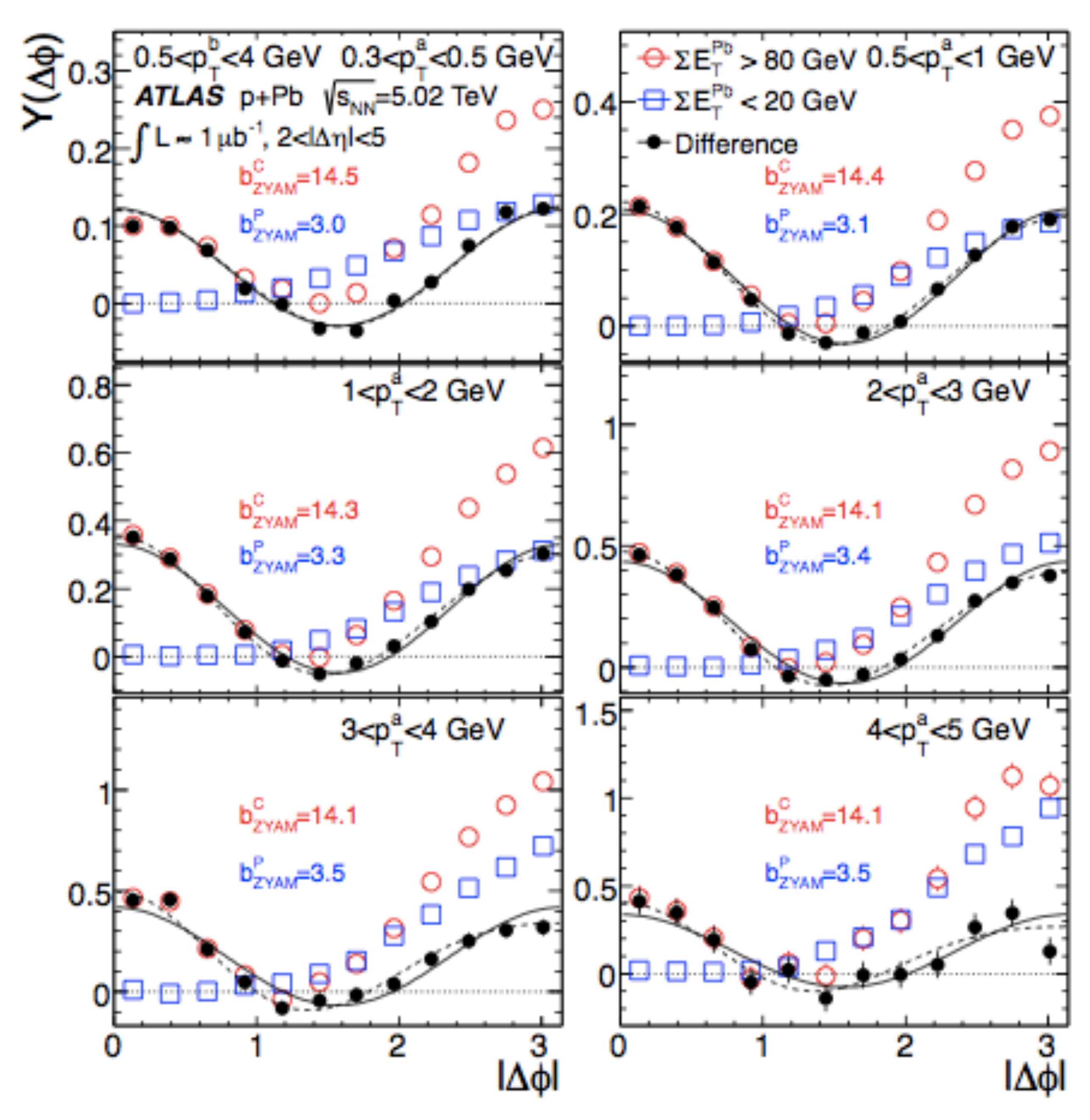
Most models of pp-ridge immediately ruled out

Peripheral subtraction in ALICE and ATLAS

ALICE Phys.Lett. B719 (2013) 29-41



ATLAS Phys. Rev. Lett. 110, 182302 (2013)

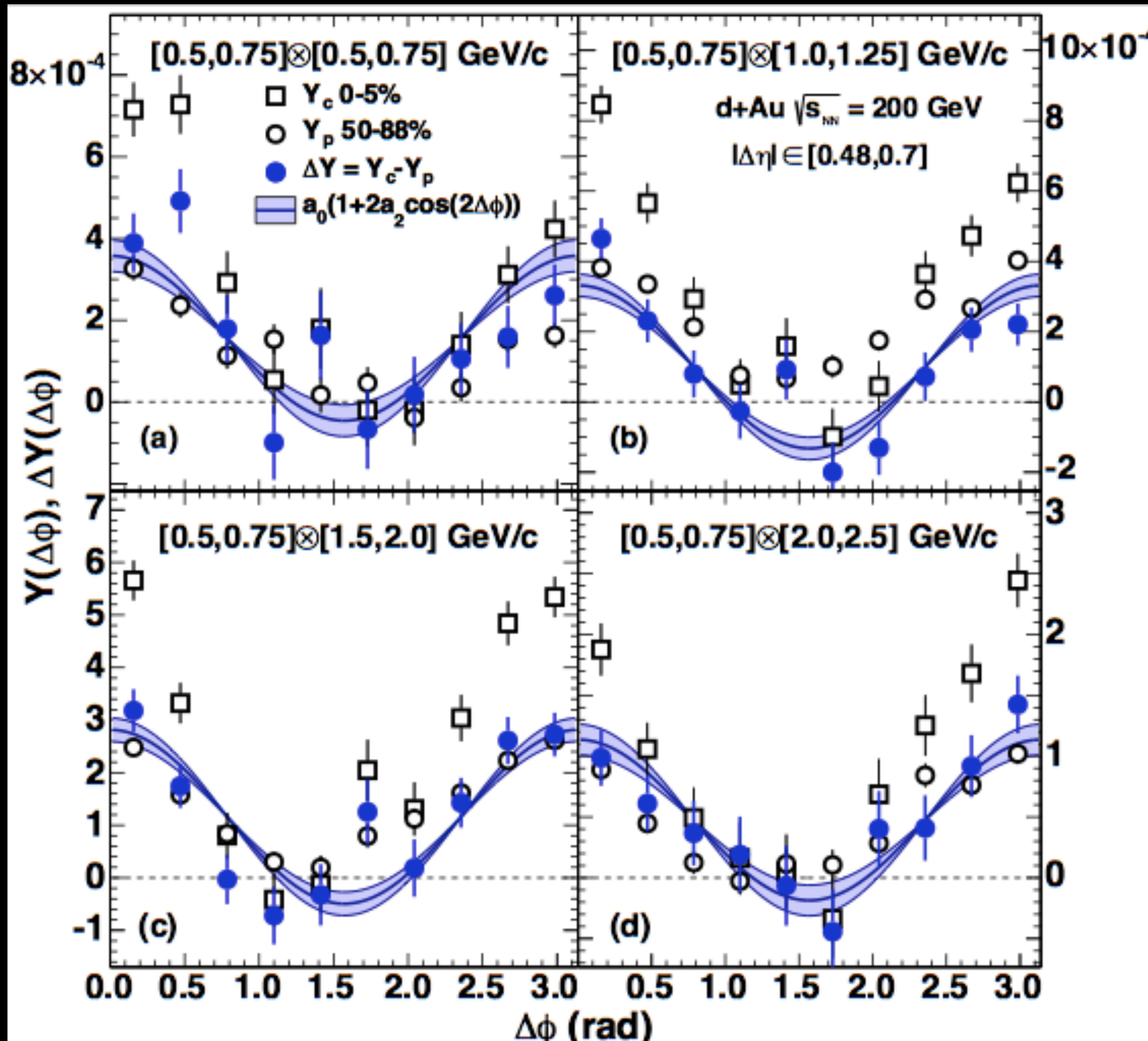


Away side yield in pp and peripheral pPb is very similar (away-side jet)

Subtraction of peripheral pPb correlations reveals nearly symmetric "double-ridge" structure

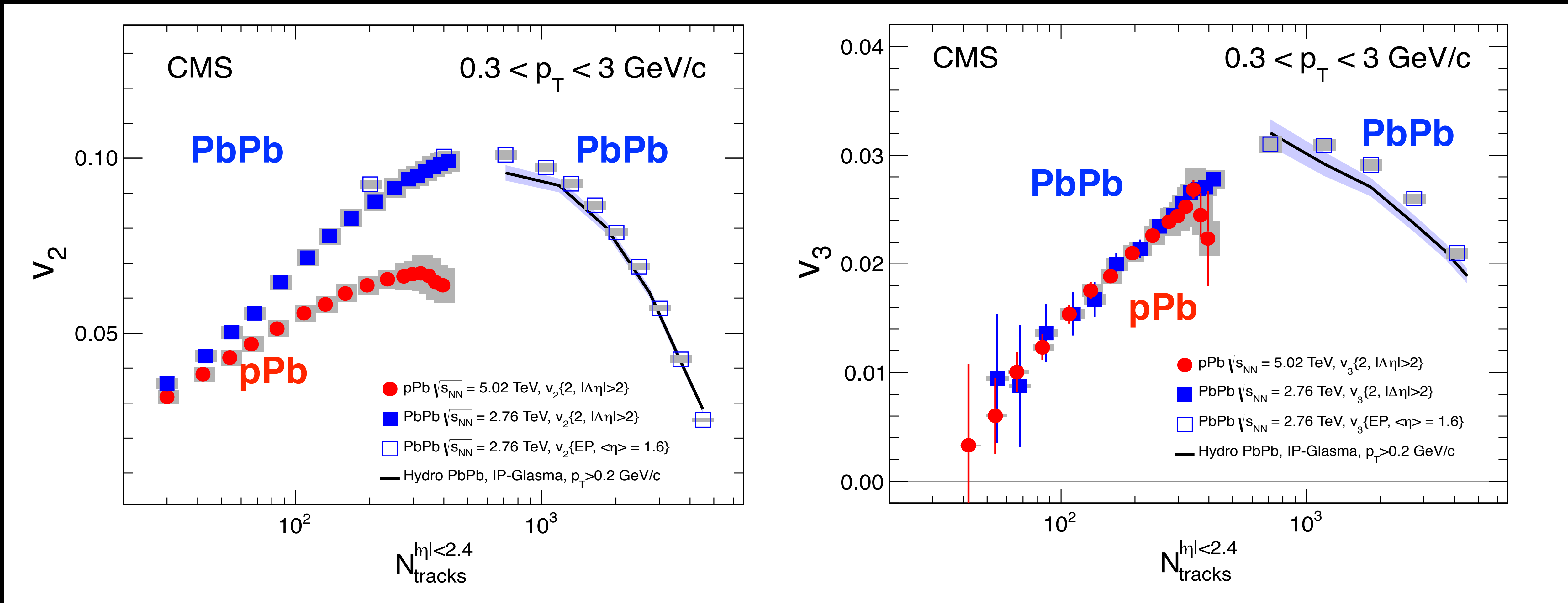
PHENIX dAu correlations

PHENIX
arXiv:1303.1794

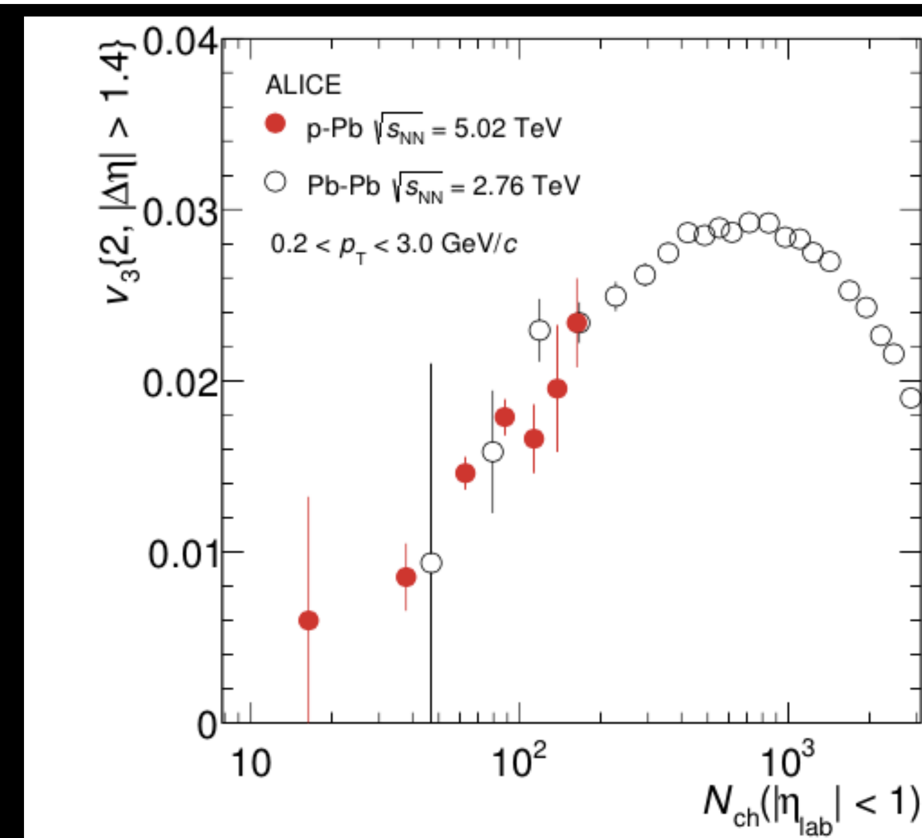


"Quadrupole correlations" seen in dAu as well

Characteristic multiplicity dependence

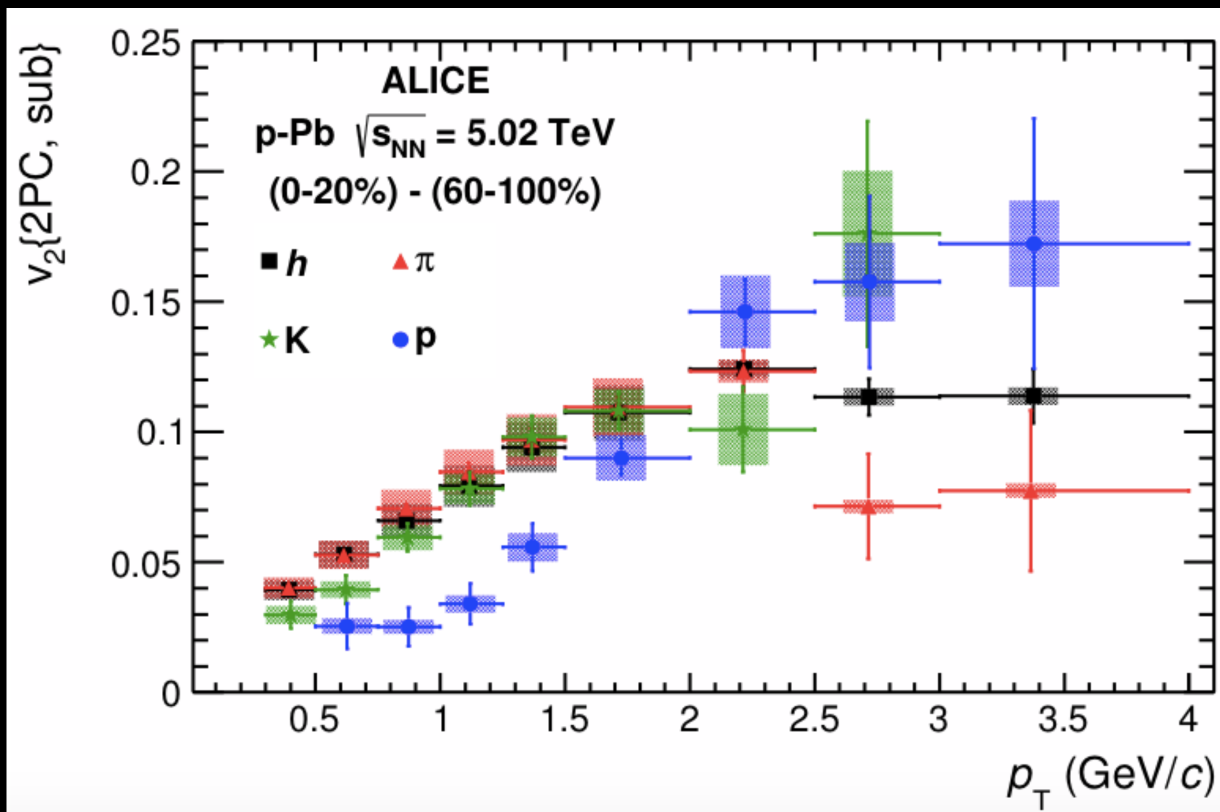


Continuous evolution from "small" (pPb ***and*** PbPb) to "large" (PbPb) system

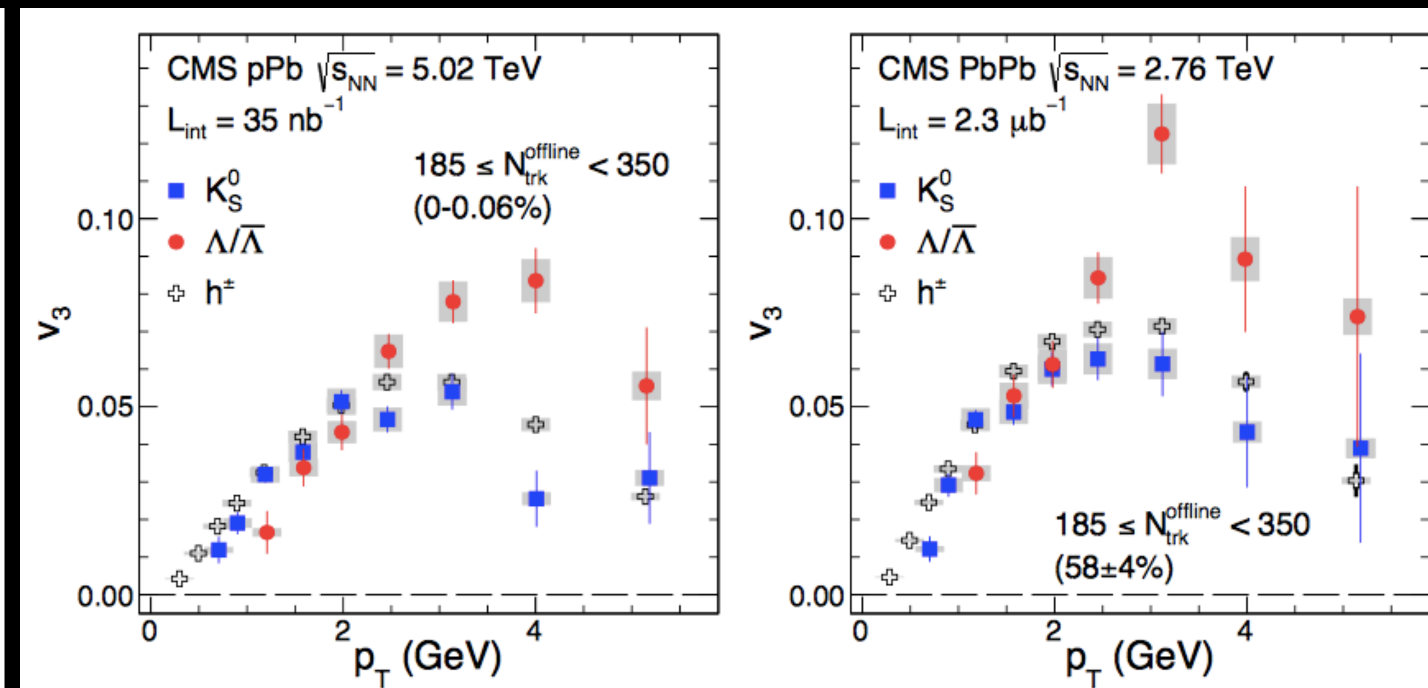


Mass ordering of $v_n(p_T)$

ALICE PLB 726 (2013) 164



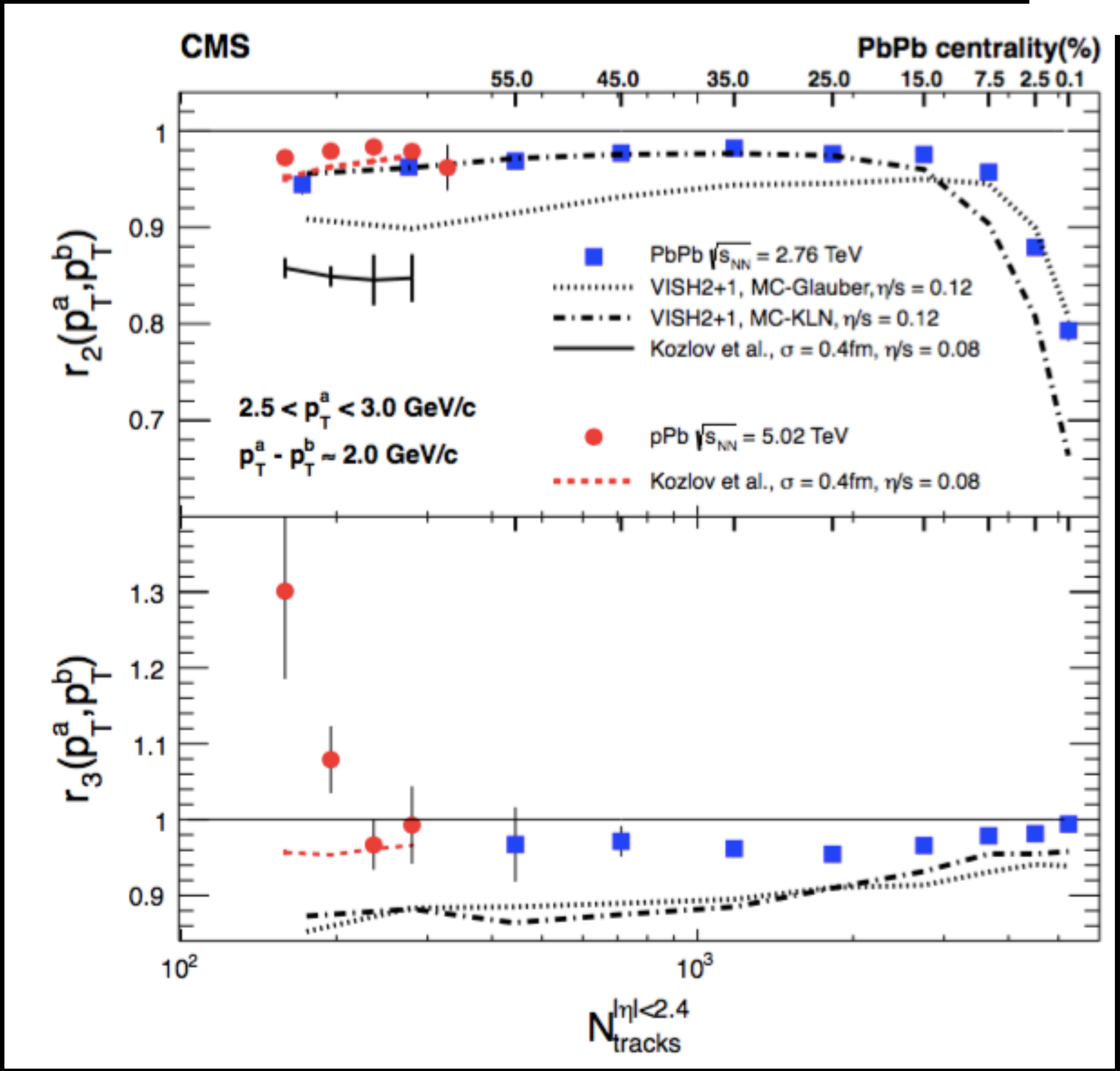
CMS PLB 742 (2015) 200



Mass ordering seen in pPb by ALICE and CMS
(even stronger than in PbPb at the same multiplicity)

Factorization breakdown

$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}$$

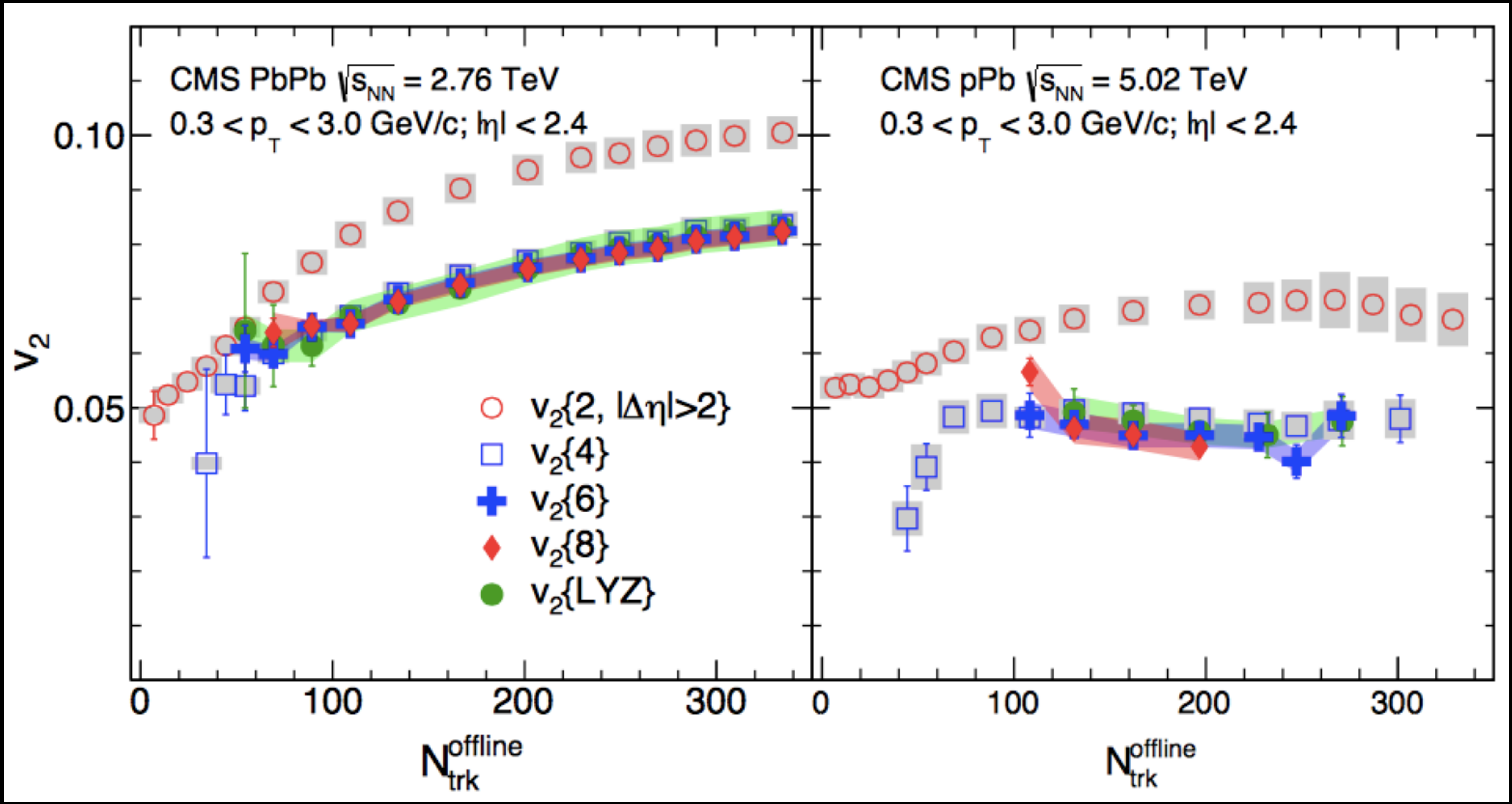


CMS PRC 92 (2015) 034911

Some tension between (pPb) data and predictions

Higher order correlations

CMS PRL 115 (2015) 012301

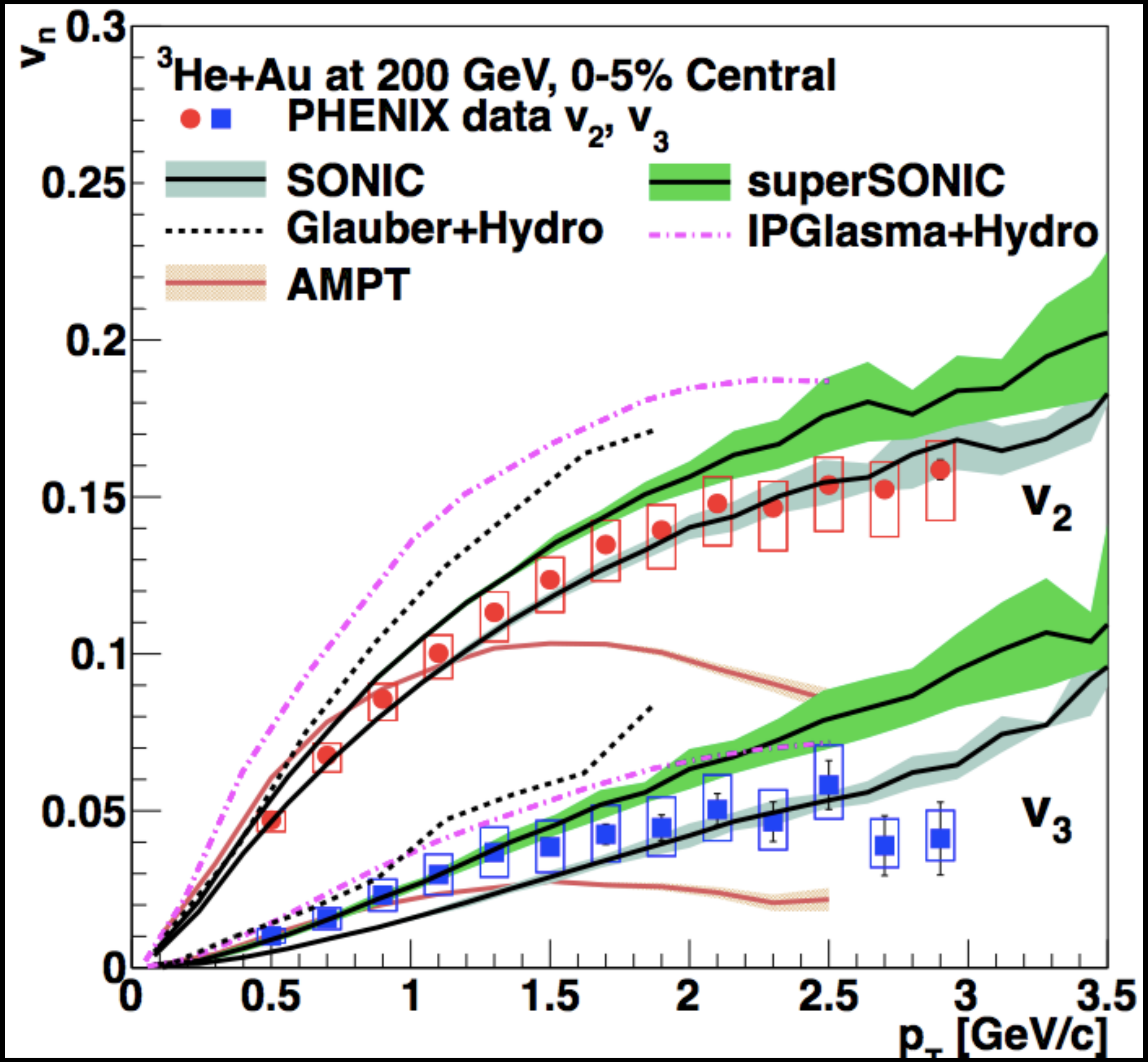


v_2 correlations between "all" particles in the event

Does this define "collectivity"?

Connection to initial geometry

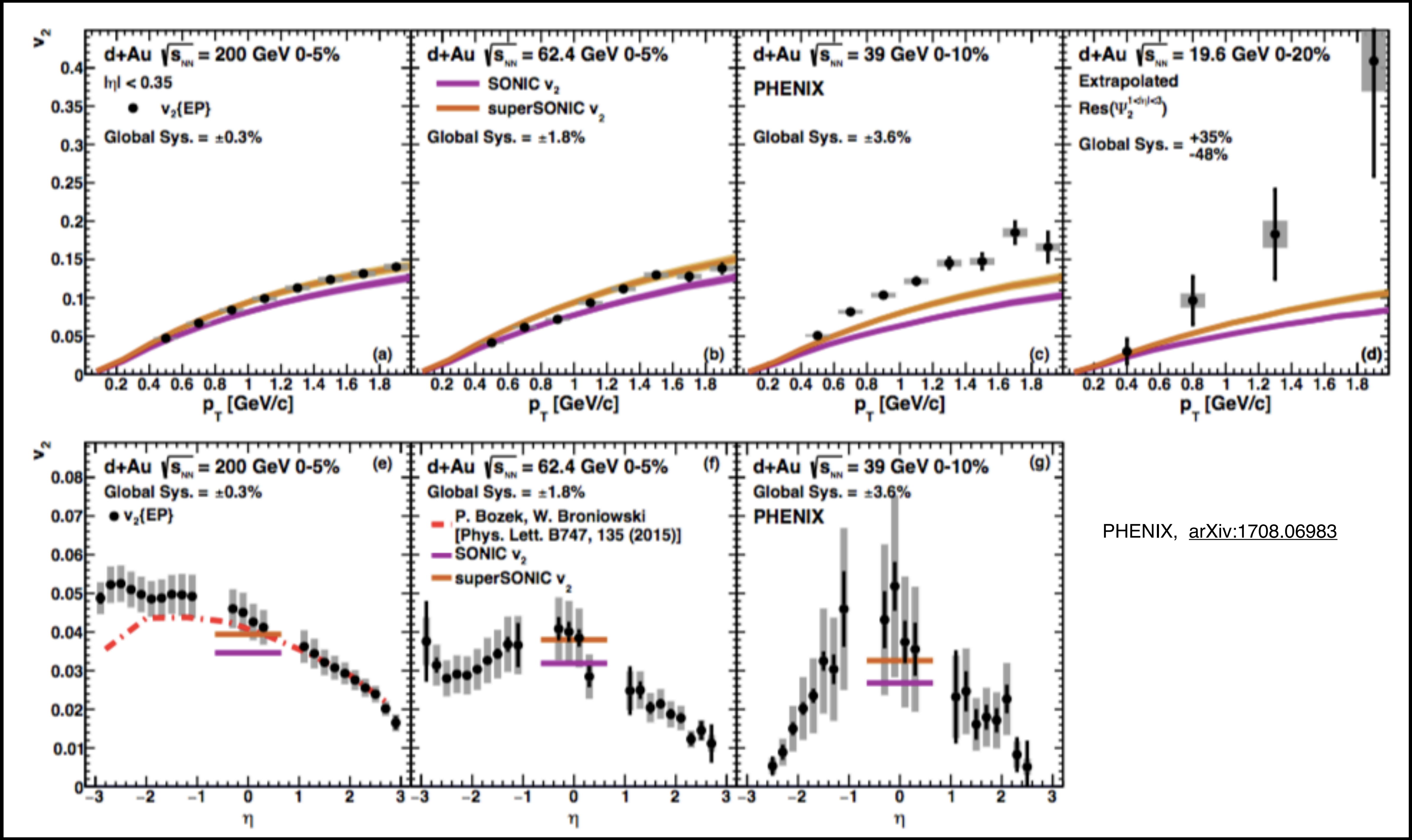
PHENIX Phys.Rev.Lett. 115 (2015) 14, 142301



^{3}He+Au collisions show significant triangular flow as expected based on intrinsic ε_3 of collision system

v_2 and v_3 described by hydro calculations

Energy dependence



PHENIX, arXiv:1708.06983

Comprehensive review of rapidity, p_T and collision energy

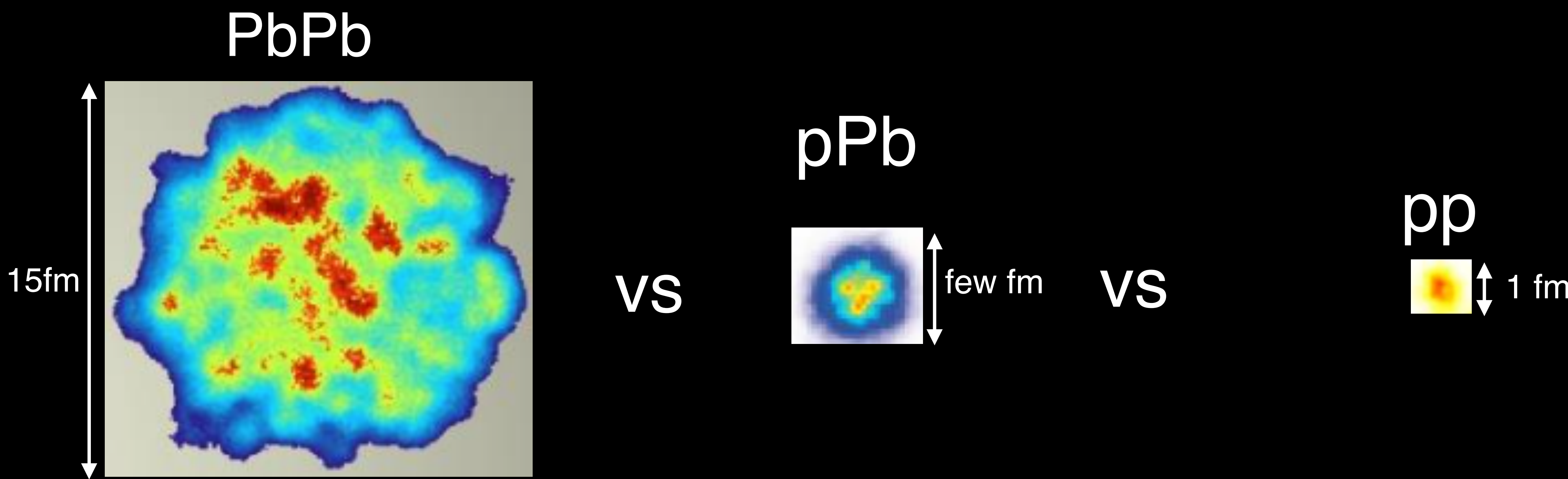
Is there "collectivity" in "small" systems?

- Azimuthal anisotropies v_n ✔
- Characteristic $v_n(p_T)$ shape ✔
- Mass ordering of $v_n(p_T)$ ✔
- Characteristic multiplicity dependence ✔
- Weak rapidity dependence of correlations ✔

- Connection to initial geometry ✔ **LHC?**
- Higher order (n>4) correlations ✔
- Factorization breaking (✔-?)
- Mass ordering of p_T spectra ✔
- Event angle correlations **?**

Experimentally, "collectivity" observables show a smooth evolution from "small" to "large" systems

Hydrodynamics in small systems?



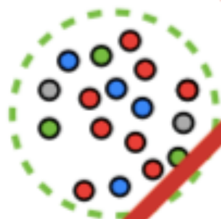
Hydrodynamic calculations (for certain models of initial conditions) successfully reproduce data for pPb, d+Au, He+Au

Is the application of these codes for small systems (large gradients) self-consistent? [Rischke, IS204]

Paul Chesler, QM2015

Concluding thoughts

Common lore:



$$\begin{cases} \tau_{\text{hydro}} \gg \tau_{\text{m.f.t.}} \gg \frac{1}{T}, \\ R \gg \lambda_{\text{m.f.p.}} \gg \frac{1}{T}, \end{cases}$$

Observed extreme domain of hydro:

$$t_{\text{hydro}} \lesssim \frac{1}{T},$$
$$R \lesssim \frac{1}{T}.$$

No theoretical inconsistency with hydro in pp, pA.

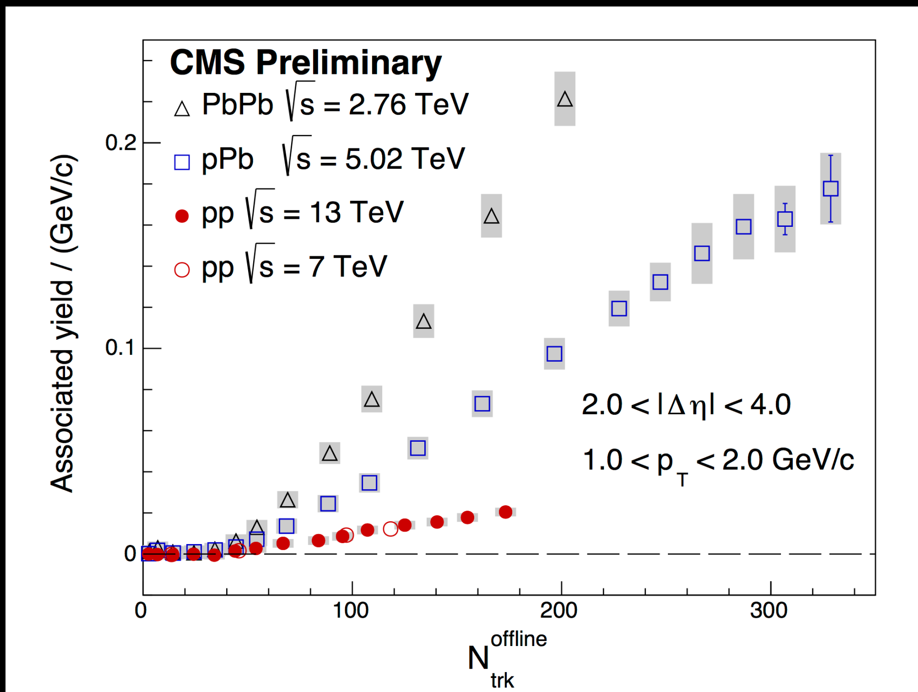
How/when does hydro turn off?

- Must exist critical energy E_c which for $E < E_c$ no black hole forms.
  - **⇒ Hydro evolution for $E > E_c$.**
  - **⇒ No hydro evolution for $E < E_c$.**
- **Universal gravitational dynamics as $E \to E_c$.** [Choptuik 1993]
  - Self-Similar geometry, entropy production $\Delta S \sim (E - E_c)^{3\gamma}$, $\gamma \sim 0.4$.
- **Unstable small black holes and dual liquids?**
- **Interesting to study low energy dynamics!**

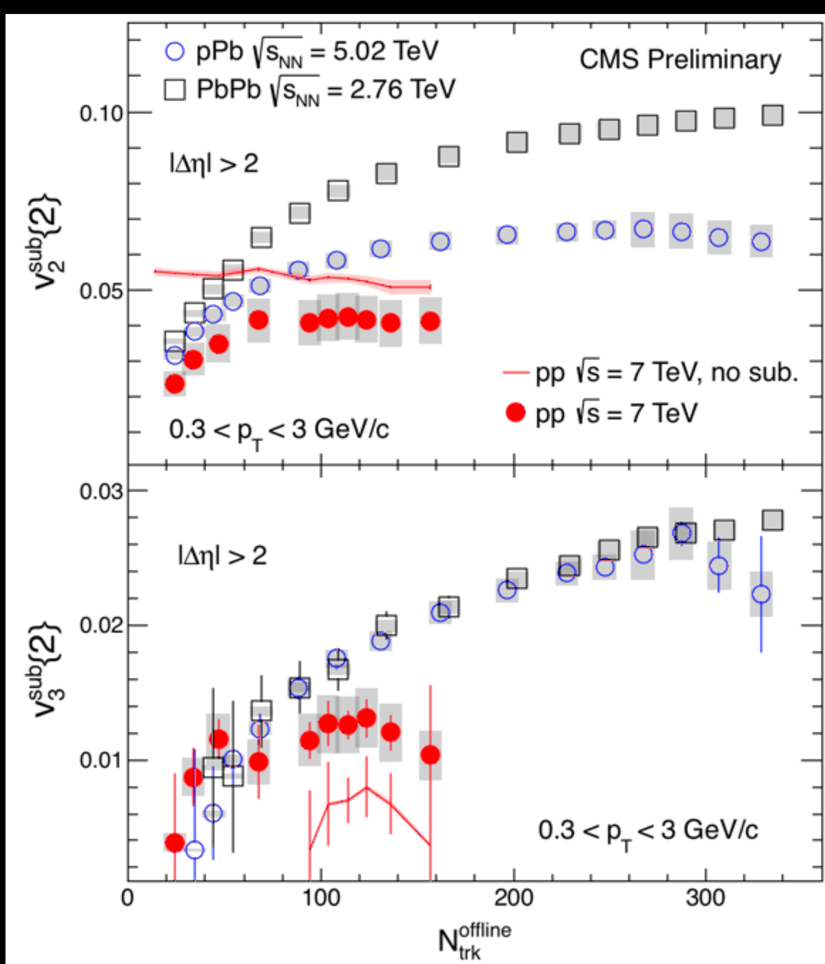
Studied black hole (≈QGP) formation for collision of small sheets/blobs of finite energy density (≈protons) in $\mathcal{N}$=4 SYM in strong coupling limit (classical gravity)

v_n in pp @ 13 TeV

CMS-PAS-HIN-15-009



No energy-dependence of pp "ridge" correlation strength observed

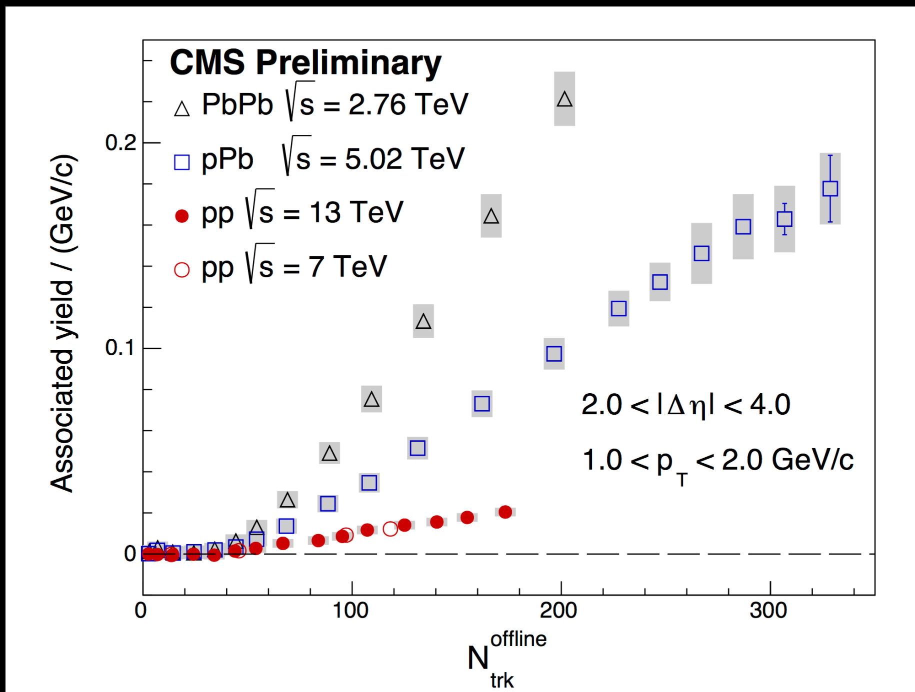


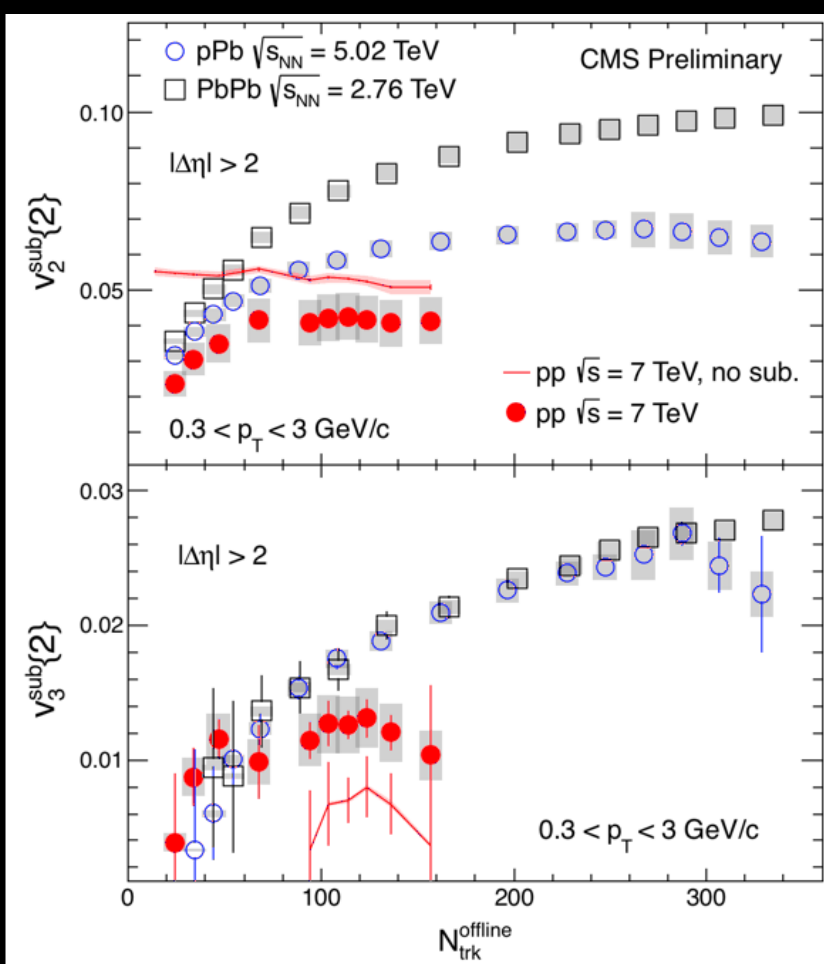
After subtraction of low-multiplicity correlations, clear v_2 and v_3 signals remain

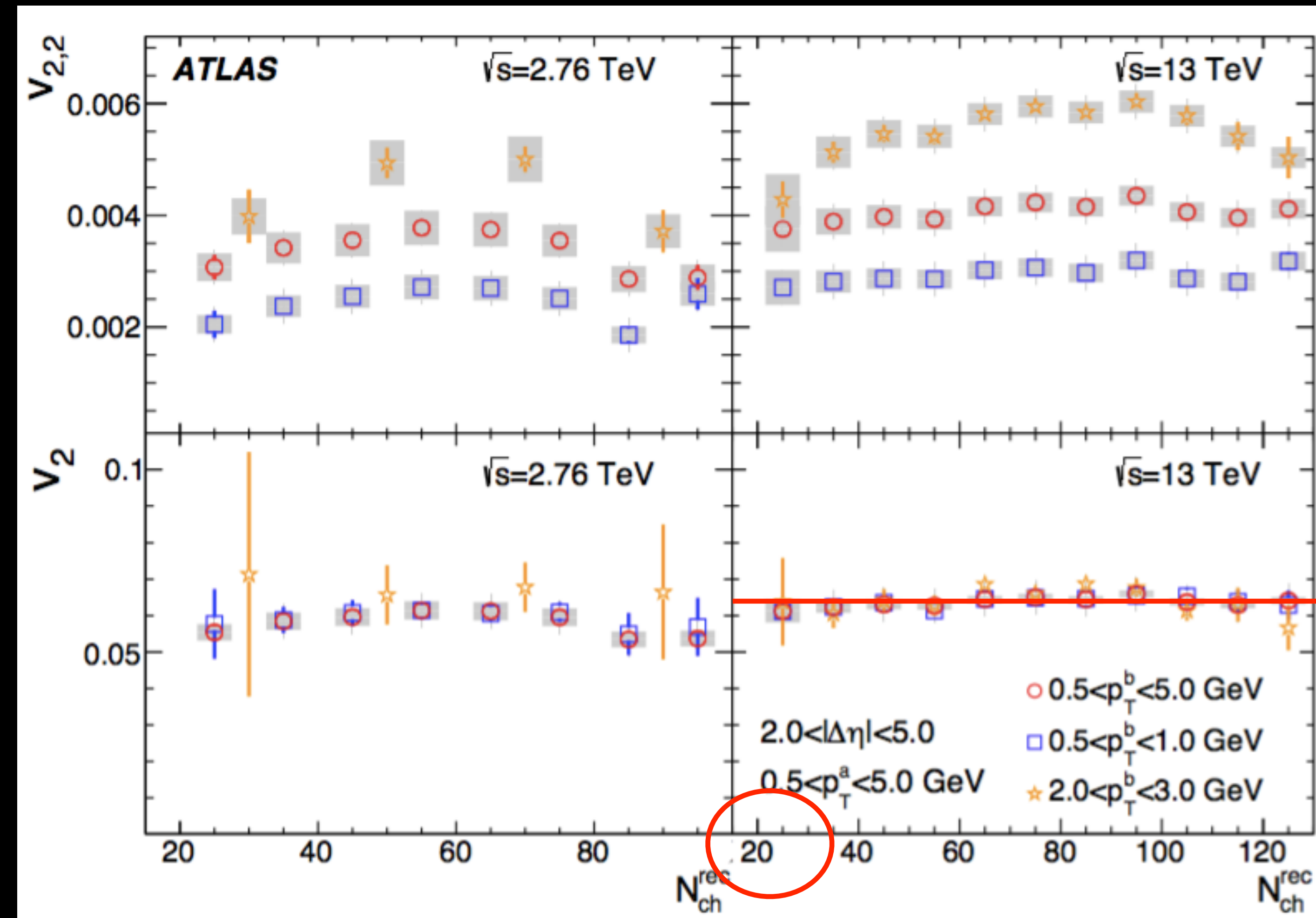
v_n in pp @ 13 TeV

CMS-PAS-HIN-15-009

ATLAS arXiv:1509.04776







ATLAS result without subtraction of low-N correlations (template fit to separate "flow" vs jet correlations)

v_2 strength found to be multiplicity independent!

Contenders

- Several approaches leading to azimuthal anisotropies w/o medium
  - Glasma correlations
  - Escape mechanism
  - Collectivity from interference
  - …
- Full phenomenology (vn, mixed harmonics, rapidity dependence) does not come easy to these approaches
  - e.g. arXiv:1708.06983 for AMPT vs PHENIX data

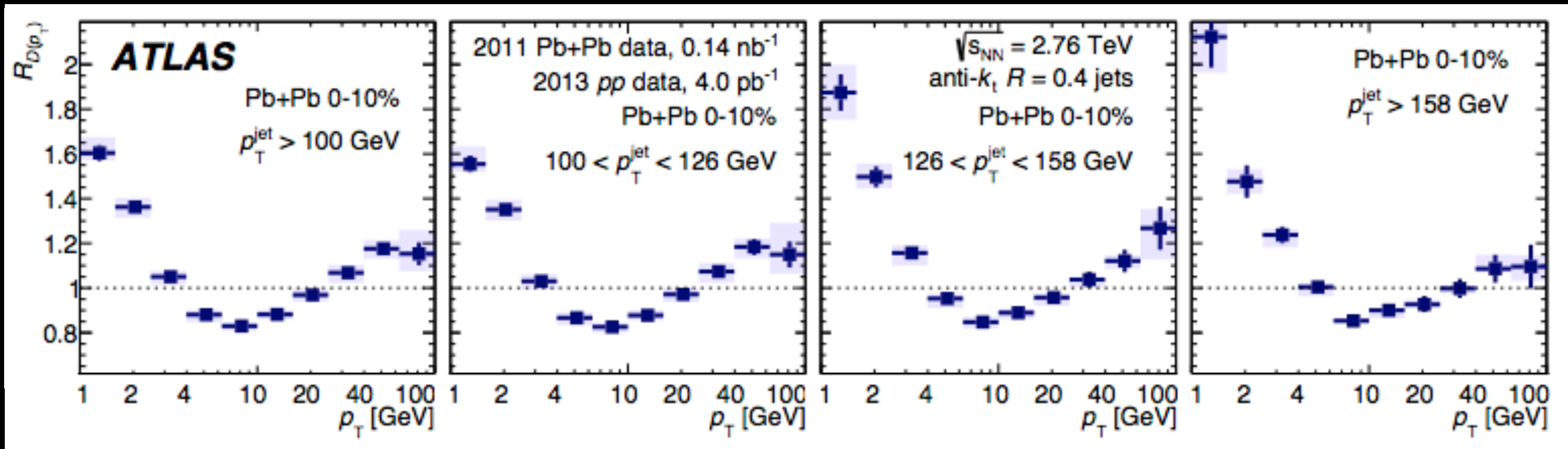
Small system status quo

- Measurements in small systems reproduce nearly all of the hallmarks of collective flow seen in AA
- No conclusive evidence of turn-off of collective flow ("smallest QGP droplet")
  - Flow-like correlations seen in pp @2.76, 7 and 13 TeV
  - ATLAS analysis shows constant v_2 in pp@13TeV down to < 2 x min bias multiplicity
- Are there multiple mechanisms giving identical phenomenology?
  - alternative models struggle, but hard to "disprove"
- Or flow just "is" in QCD systems?

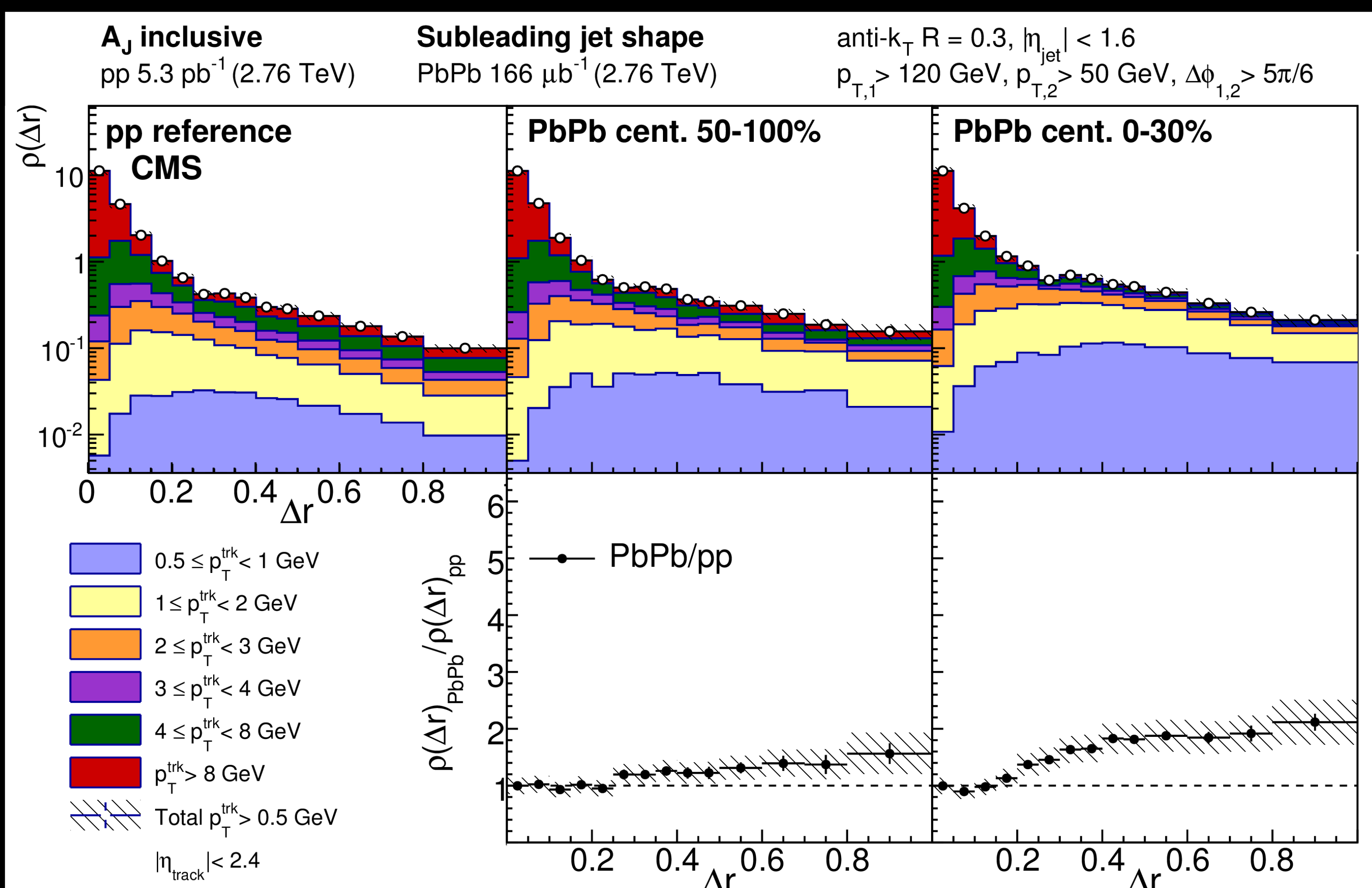
Is there a there there?


Is there a there there?

Modifications of Jet Structure



Longitudinal jet structure (“Fragmentation Function”)



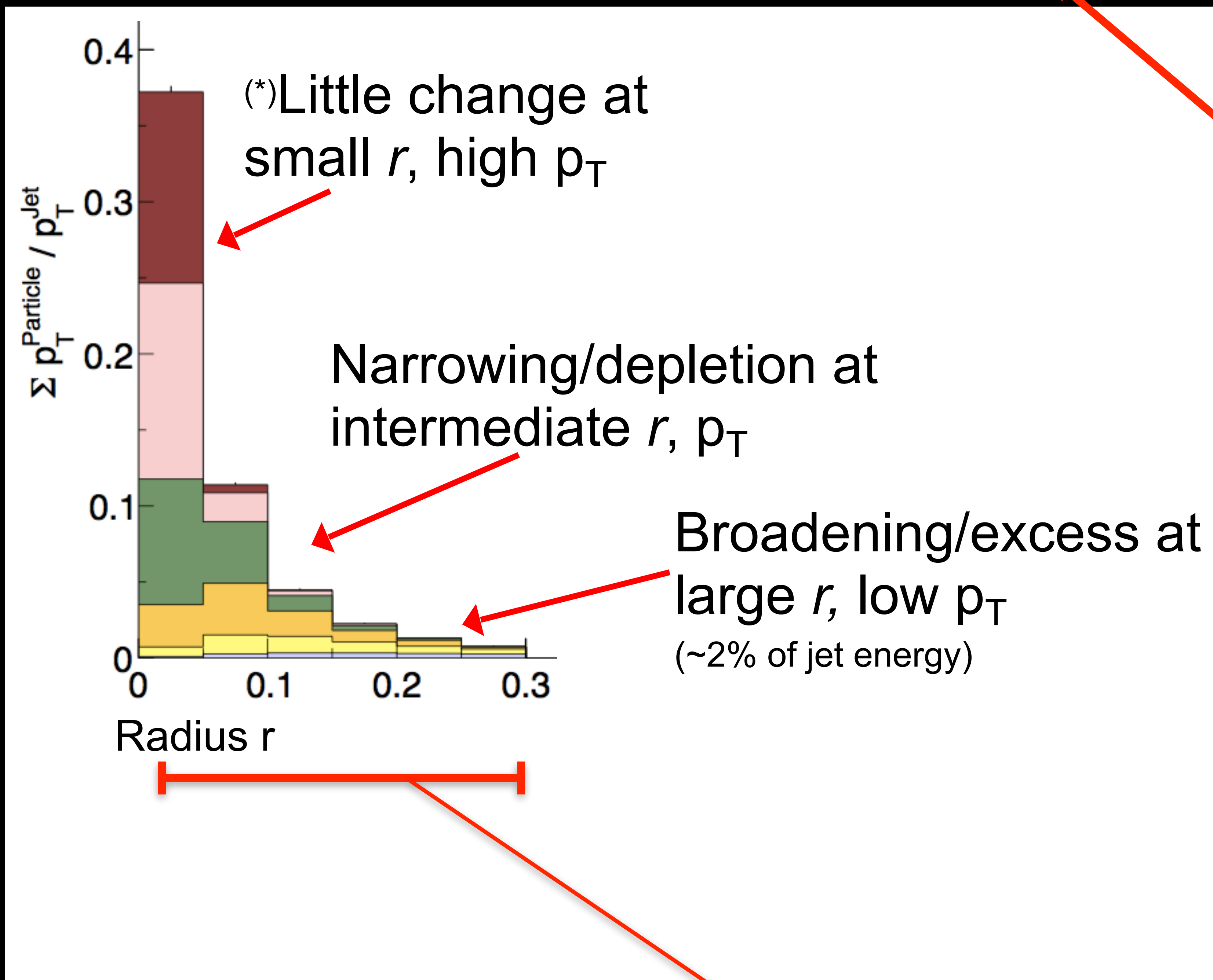
Transverse jet structure (“Jet shape”)

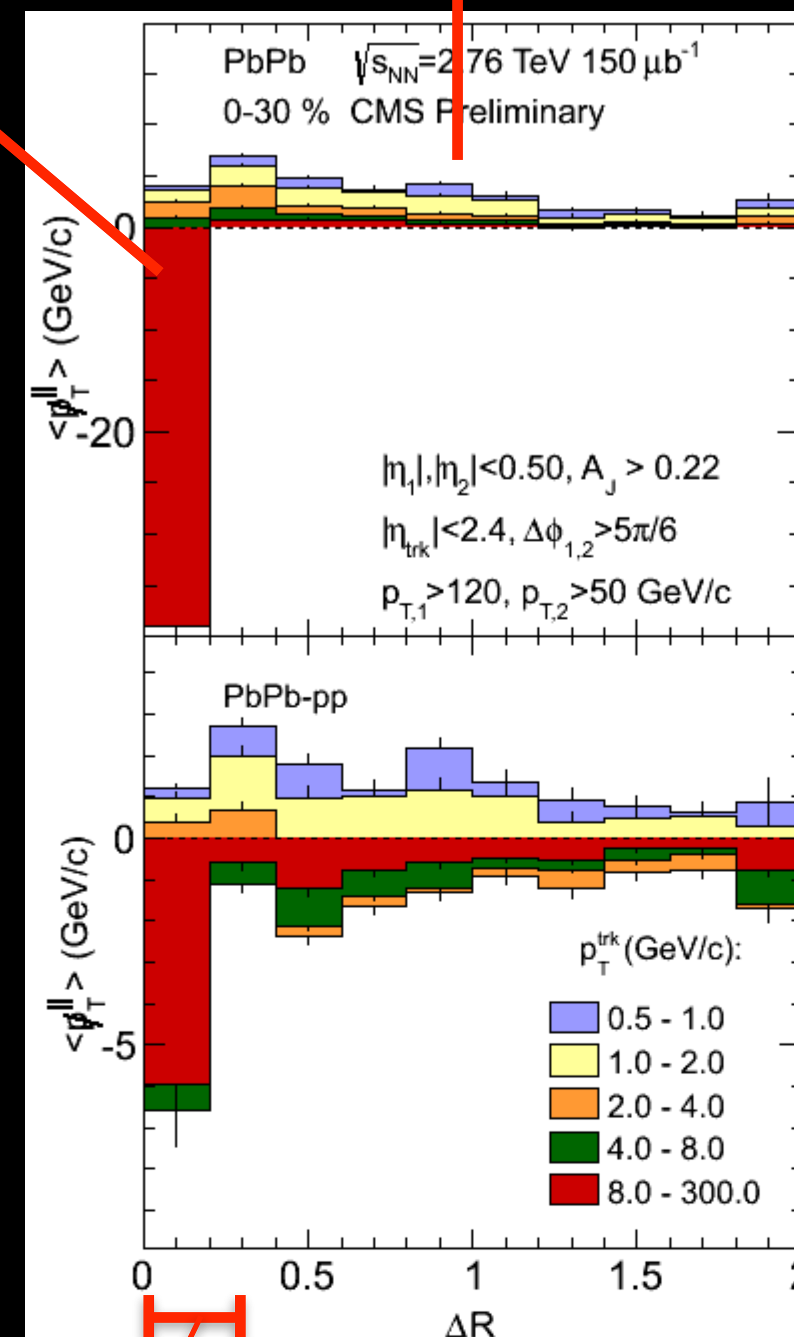
+ many more results from LHC and RHIC

Cheat Sheet: Jets in Medium

In-cone energy difference (leading - subleading jet)

Balanced by low p_T particles at large angles

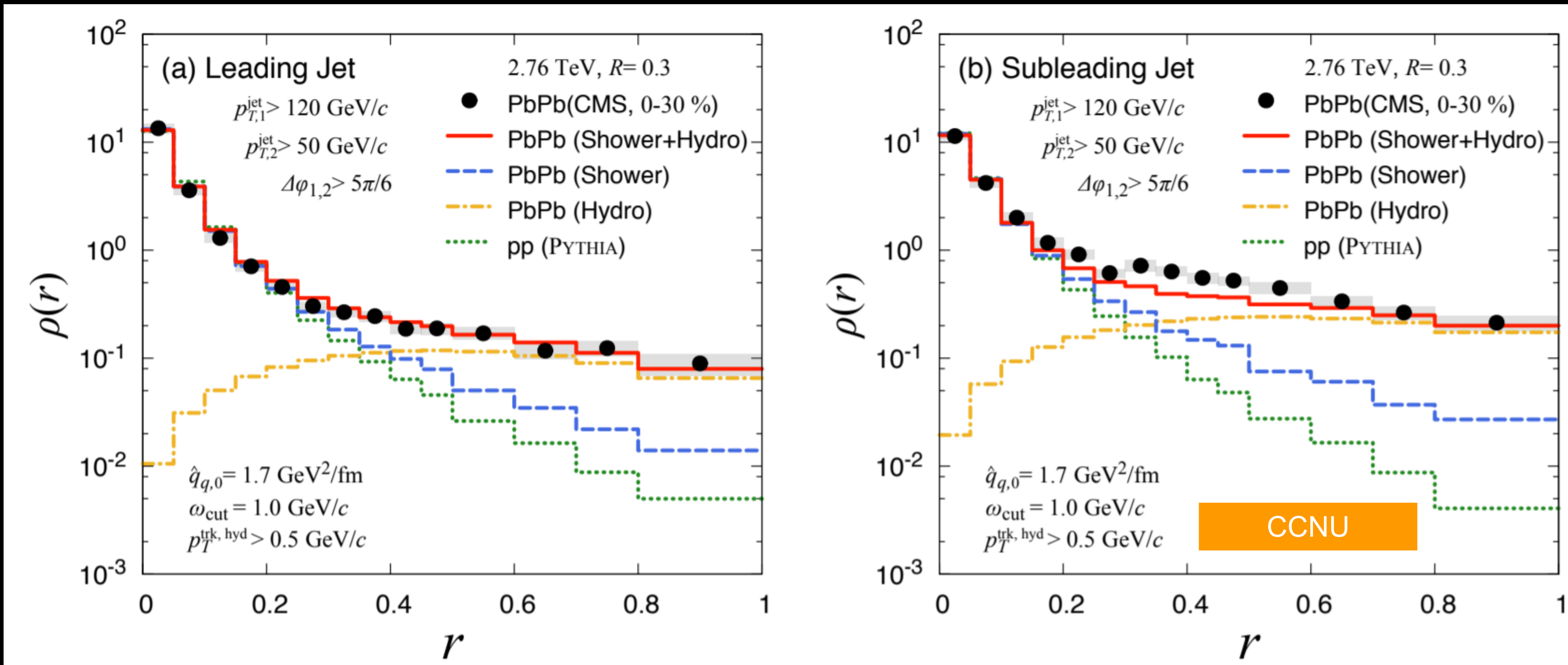




(*) Some tension between ATLAS and CMS results

Open issue: Medium response @ large ΔR?

arXiv:1701.07951



How is energy transported to large ΔR wrt jet axis?

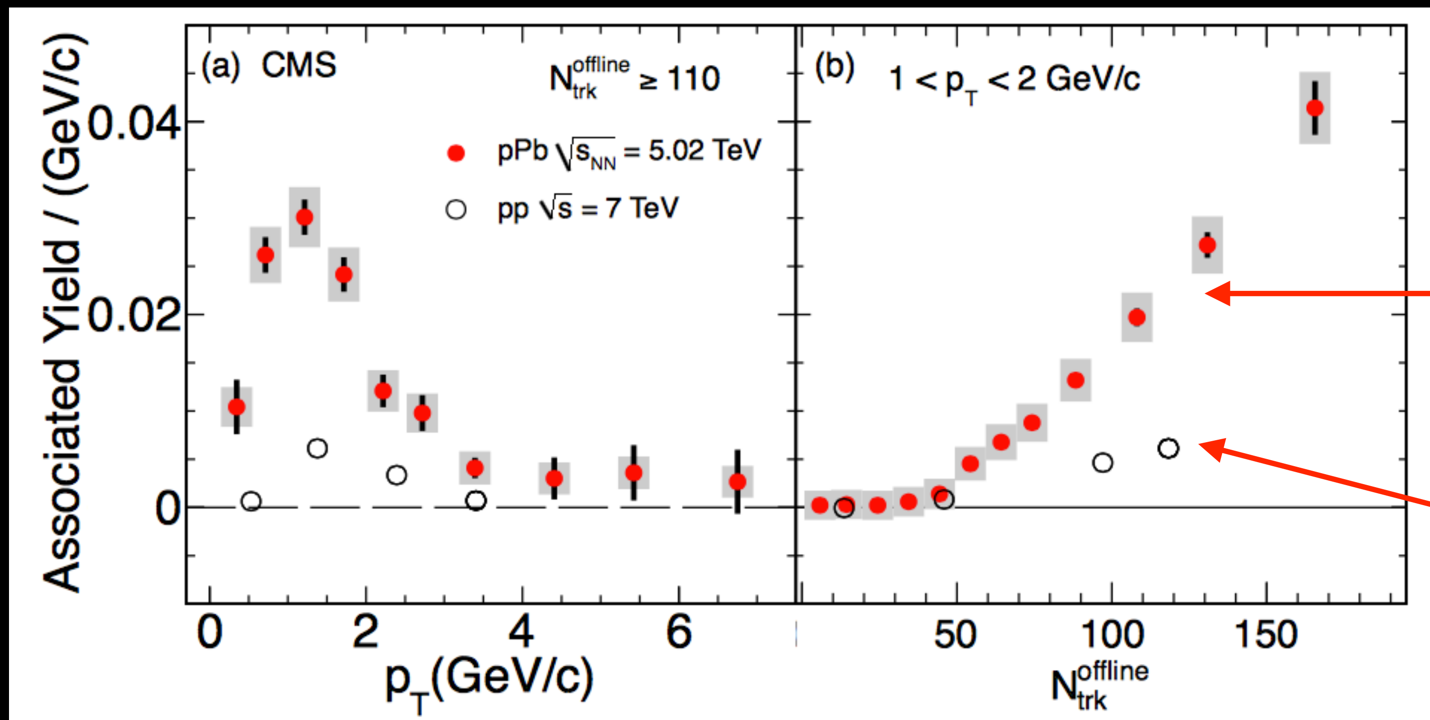
(Large) modification of jet shower in medium *or* hydrodynamic transport of radiated energy?

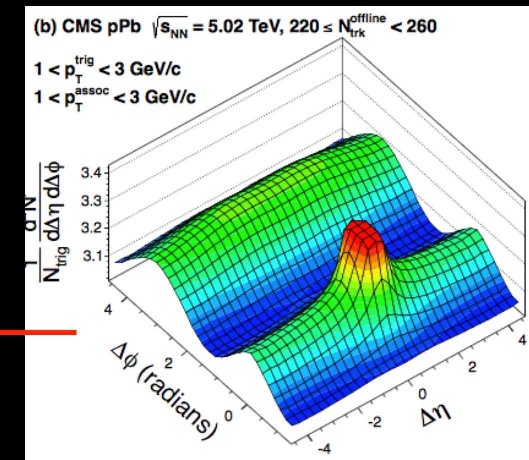
Collective Flow

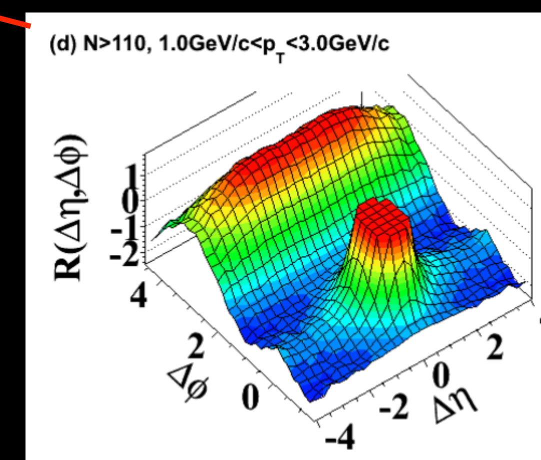
- Hydrodynamic expansion of nearly perfect fluid provides natural explanation of broad range of correlation phenomena in heavy-ion collisions
- Same ansatz also does well for small collision systems
  - is that a bug or a feature?
- Recent set of calculations suggesting evidence for (or at least consistency with) medium response in jet-hadron large angle correlations
  - Unique predictions/features?
- Great successes, but some uneasiness remains

pp vs pPb

Strength of near-side correlations







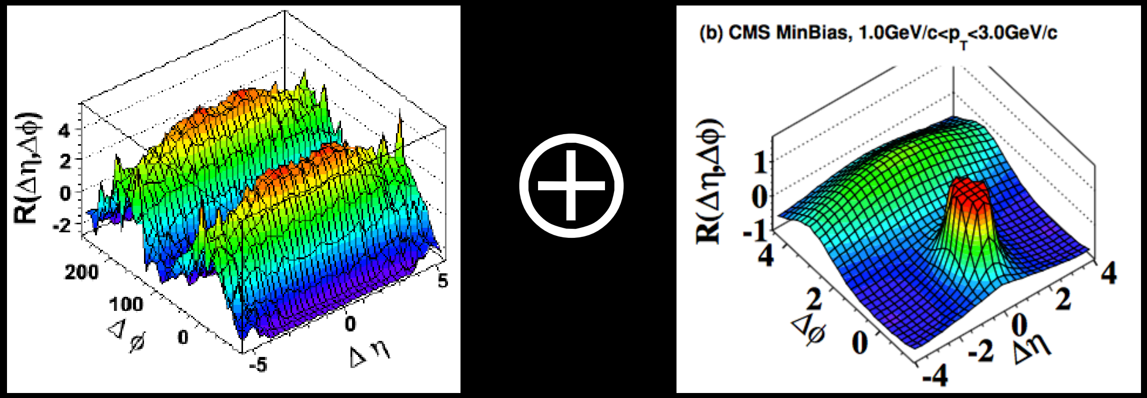
Strength of correlations for same multiplicity much lower in pp than pPb

In pPb (and PbPb), for multiplicity > 50, jet-like correlations are perturbation of flow-like signal

In high multiplicity pp much of final-state multiplicity comes from jet fragmentation
"Flow-like" correlations are perturbations on dominant jet-like structure
Need more data (analyses) to make any judgement on pp

Are pp and pPb "small"?

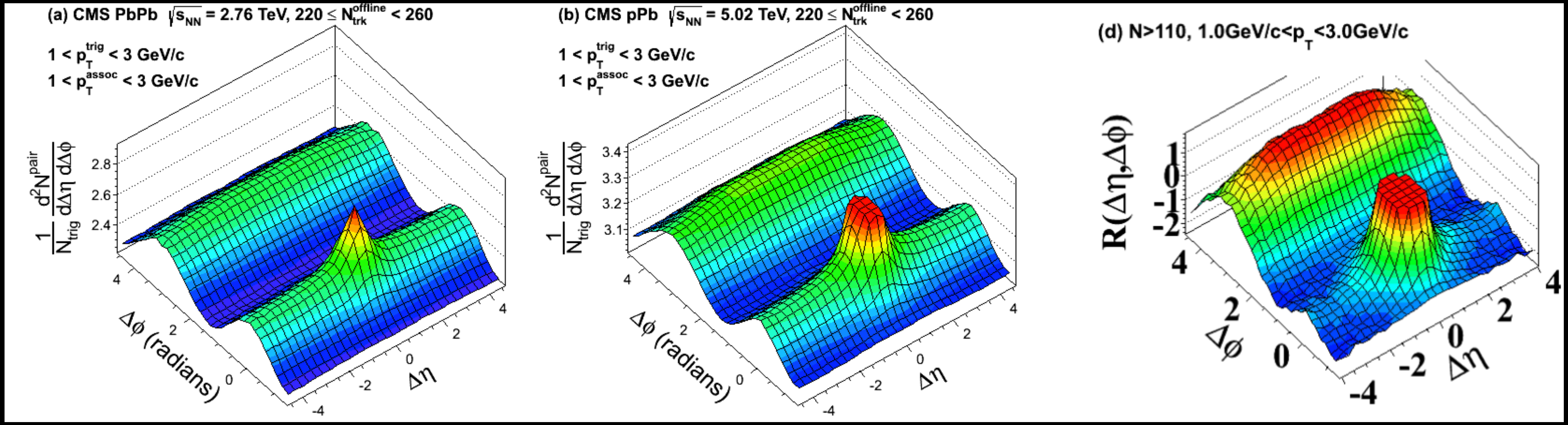
2D CF can be described as superposition of "jet-like" correlations (intra-jet and jet-jet correlations) + weakly rapidity dependent flow harmonics



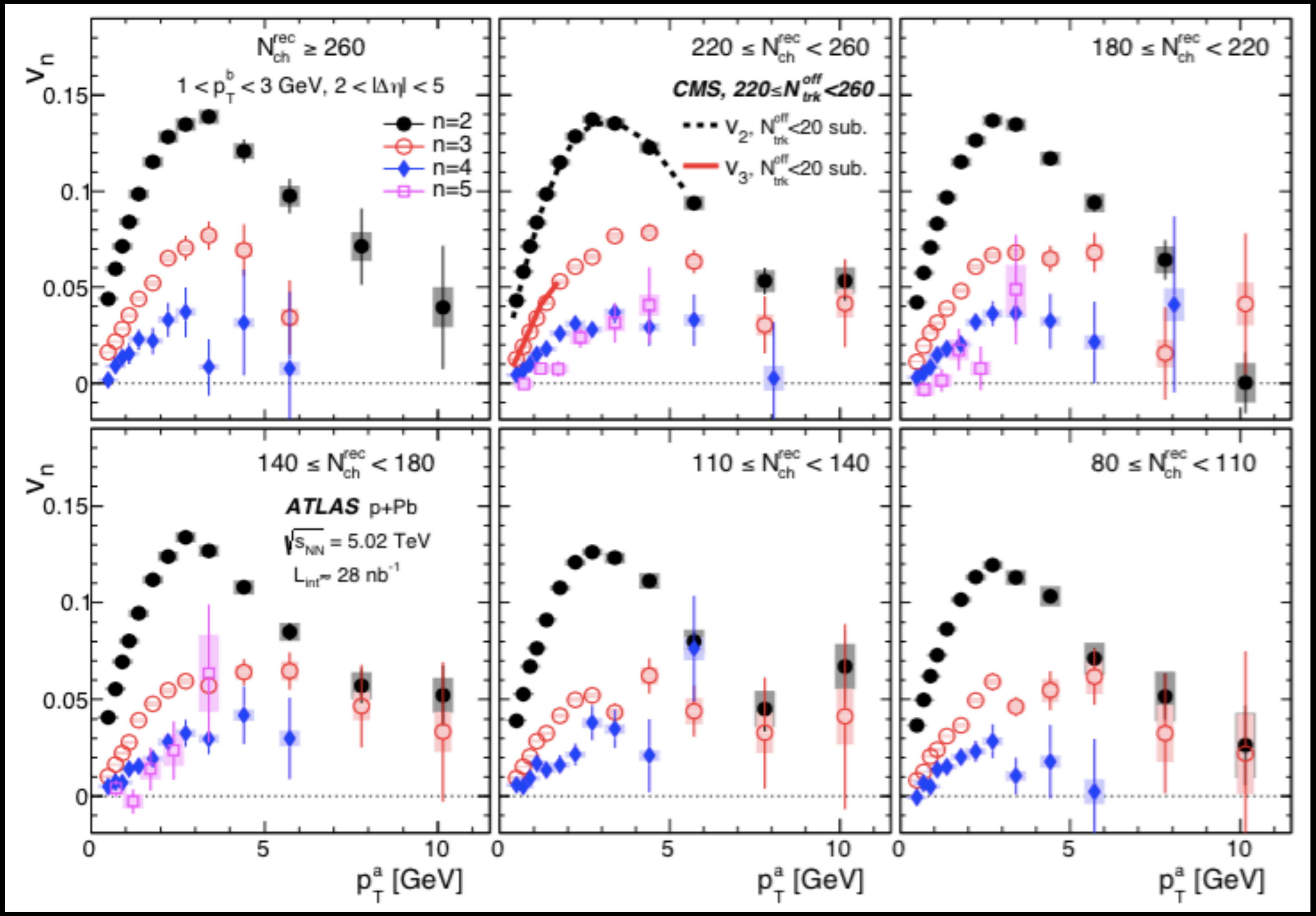
Importance of jet-like correlations drops from pp to pPb to PbPb:

lower collision energy

higher multiplicity



$v_n(p_T)$ in pPb



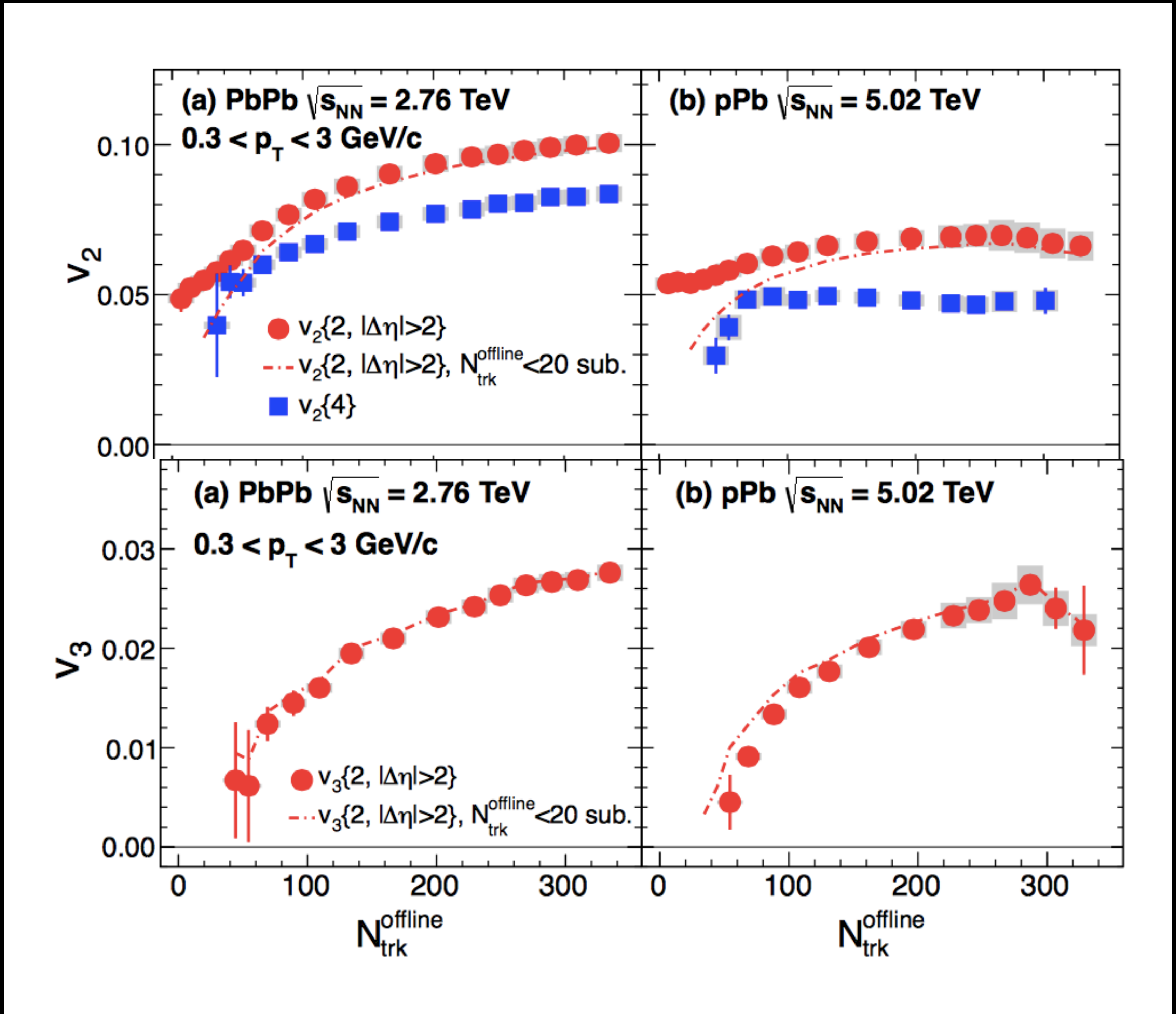
The good:

1. Good agreement with CMS
2. Characteristic $v_n(p_T)$ shape as in PbPb
3. Expected “n” ordering as in PbPb

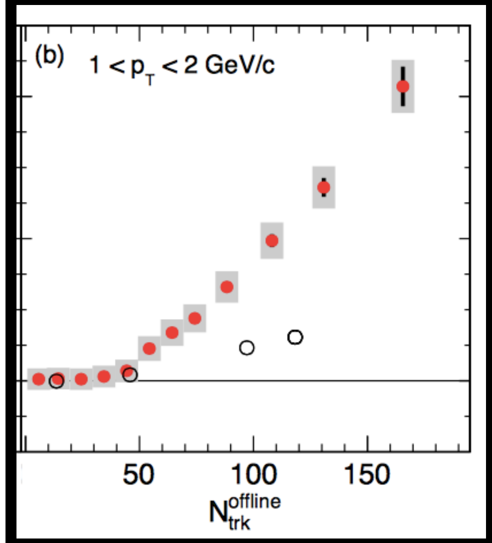
The somewhat confusing:

1. $v_2(p_T=10\text{GeV}) \sim 4\%$

From small to large



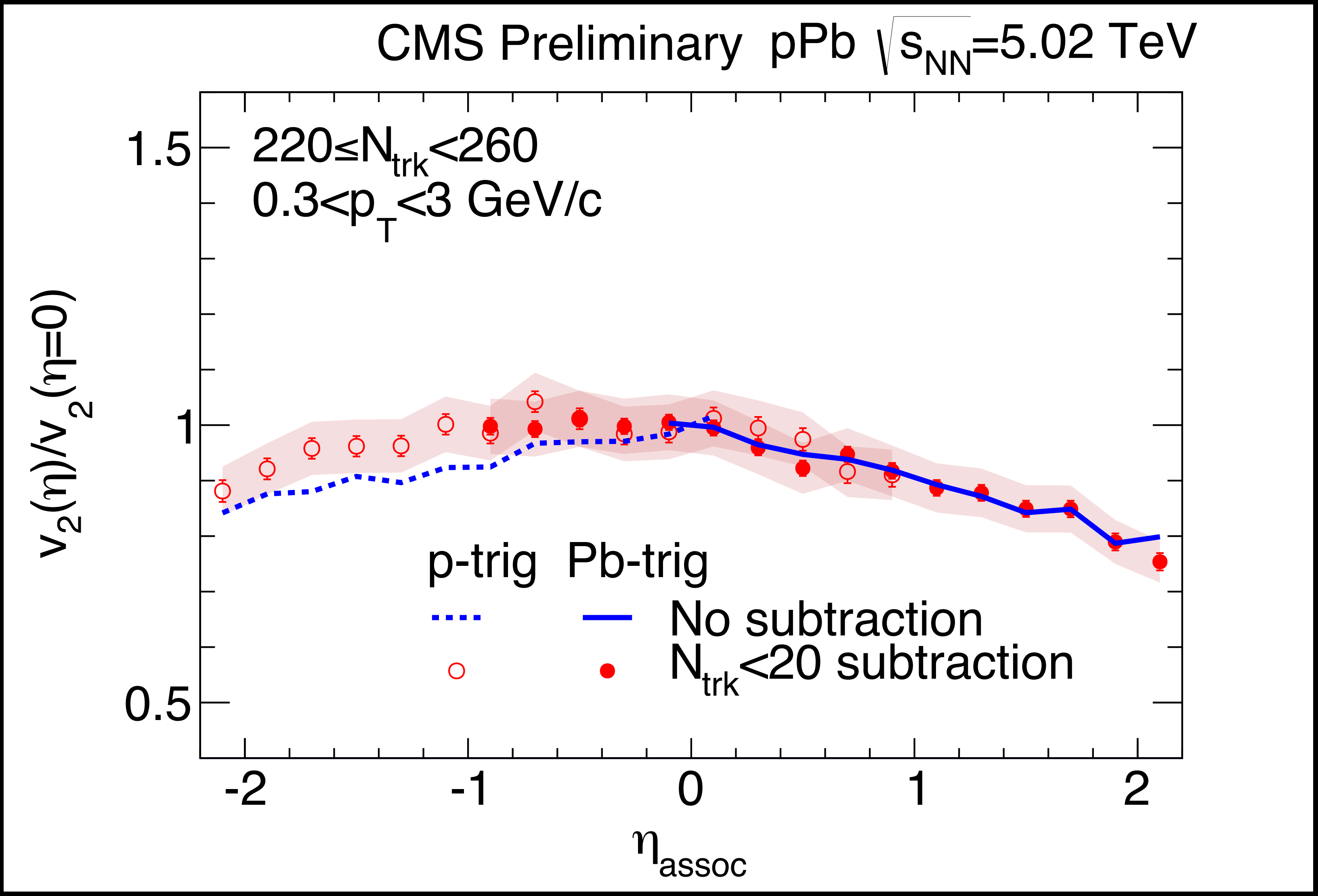
Ridge Yield



No clear evidence for turn-on at low multiplicity

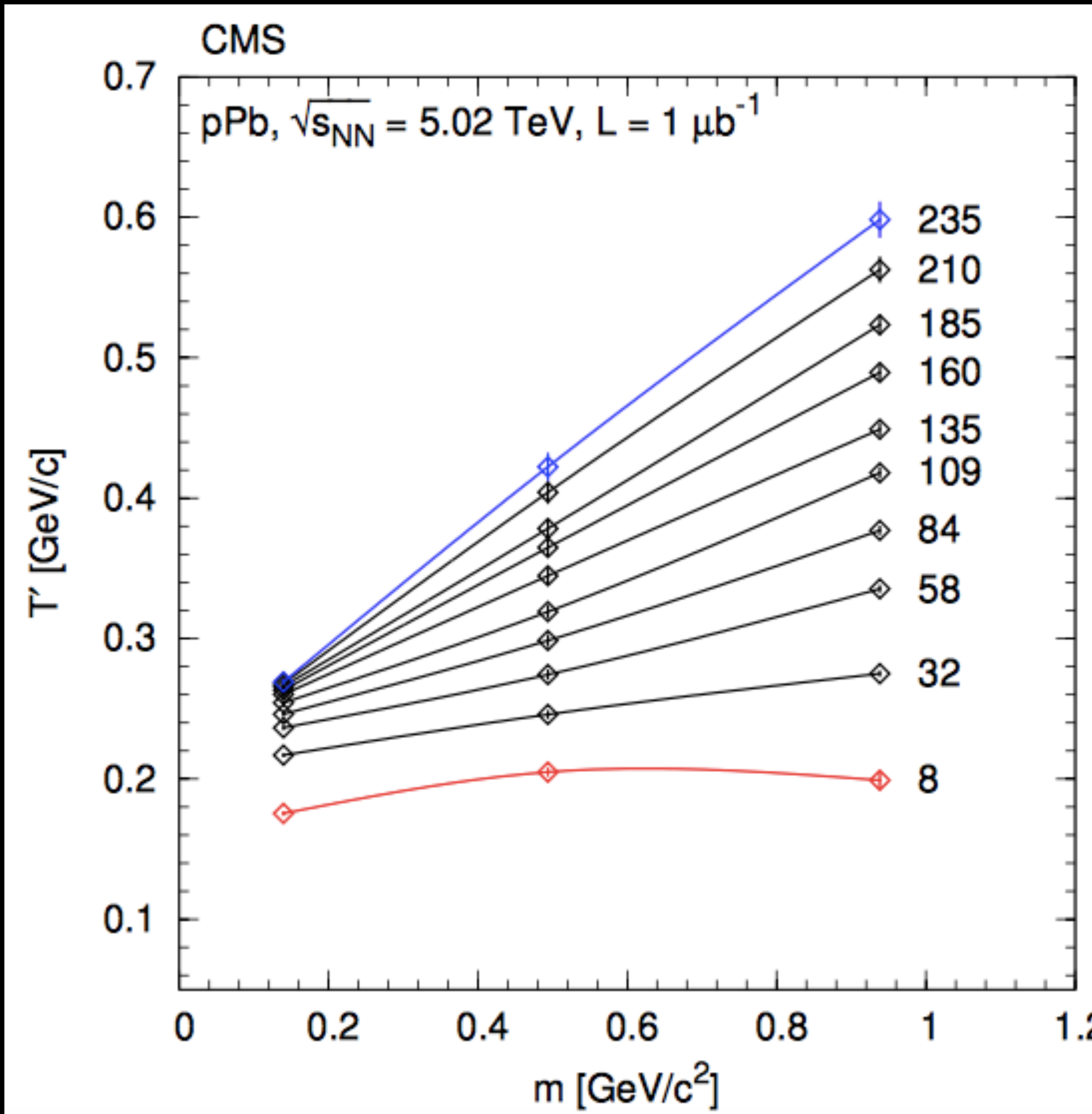
N.b.: at high multiplicity in pPb, “peripheral subtraction” is irrelevant

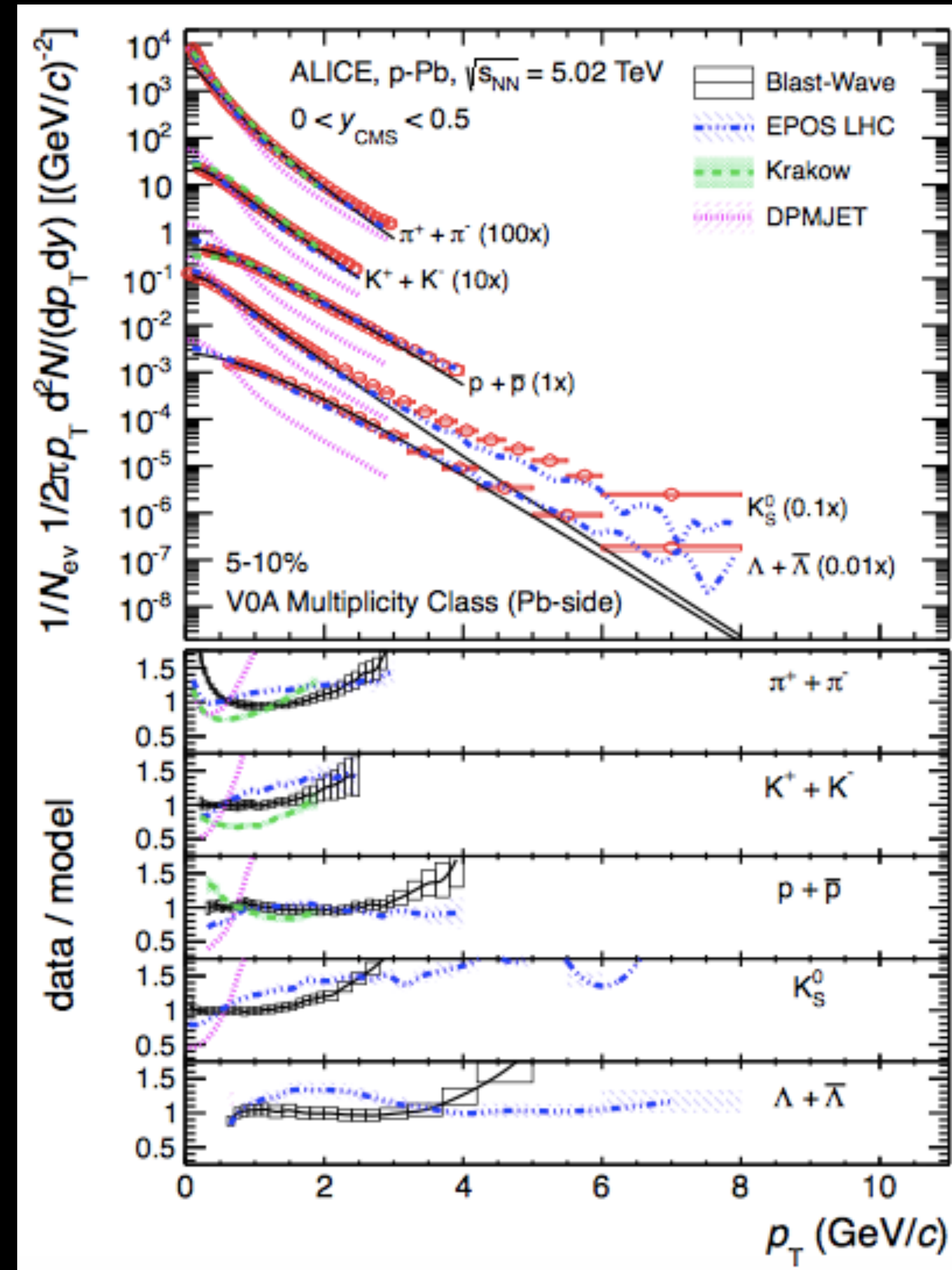
Rapidity dependence



As for PbPb, weak rapidity dependence with maximum near maximal particle density

"Radial flow"?





For completeness: Expected mass ordering of π, K, p spectra