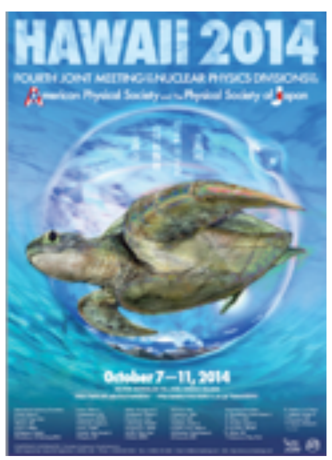
Flow Measurements at the RHIC and LHC, What Have We Learned? What is Needed?

Takahito Todoroki
University of Tsukuba



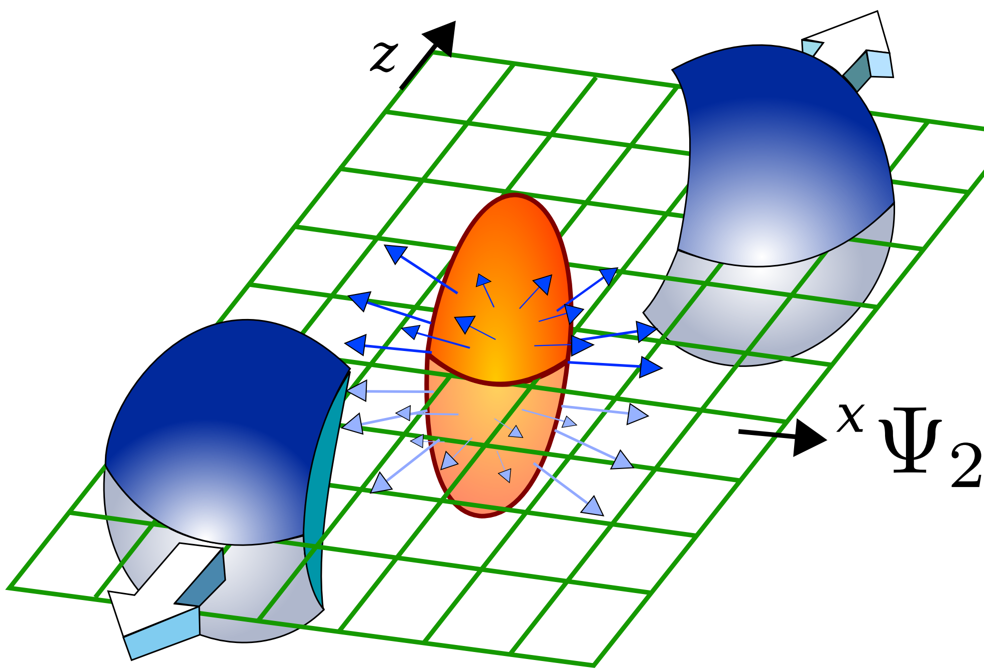
2014 DNP-JPS Joint Meeting
@Hawaii Island
2014/Oct/9th

Session EJ: Mini-Symposium on Flow-Like Observables in Heavy Ion Collisions

Contents

- Overview of previous measurements and calculations in A+A collisions
- Collectivity in p(d)+A collisions
- Event-Shape Study

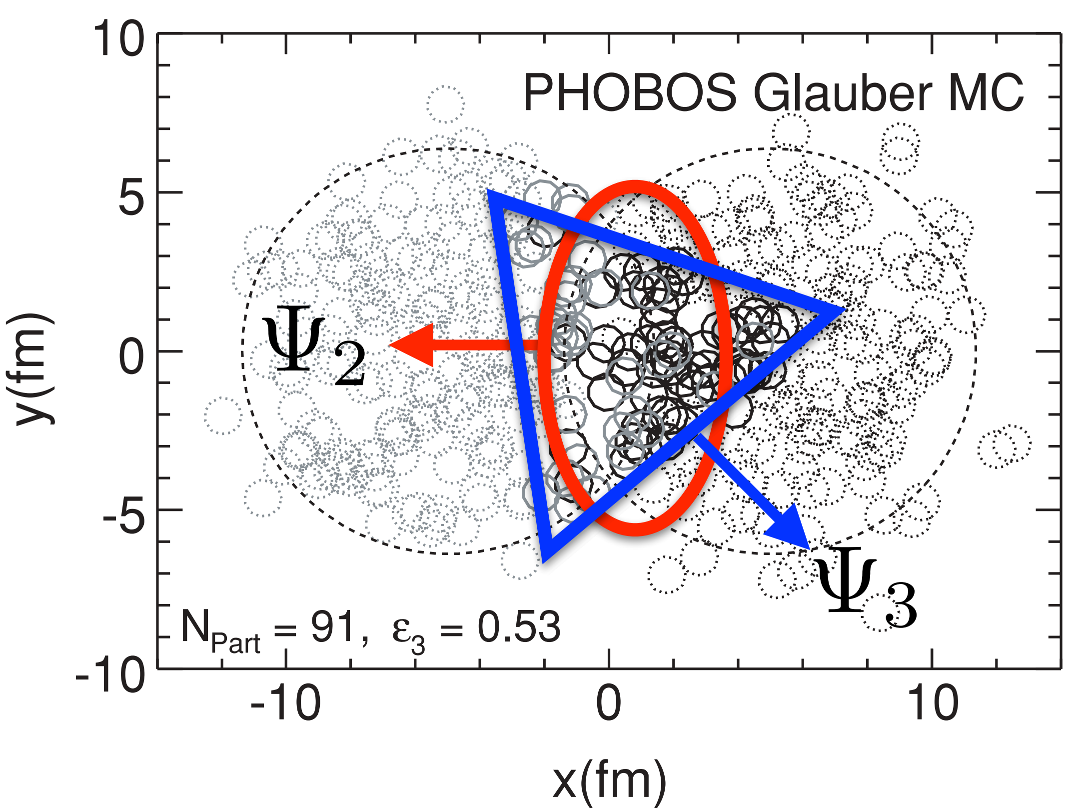
Initial Fluctuations



Simplified Distribution

- Initial spatial anisotropy ⇒ Momentum anisotropy
- Only second-order event-plane

Alver et.al. PRC81.054905



Ev-by-Ev Fluctuating Distribution

- Higher-order event-planes

$$dN/d\phi \propto 1 + \sum 2v_n \cos n(\phi - \Psi_n)$$

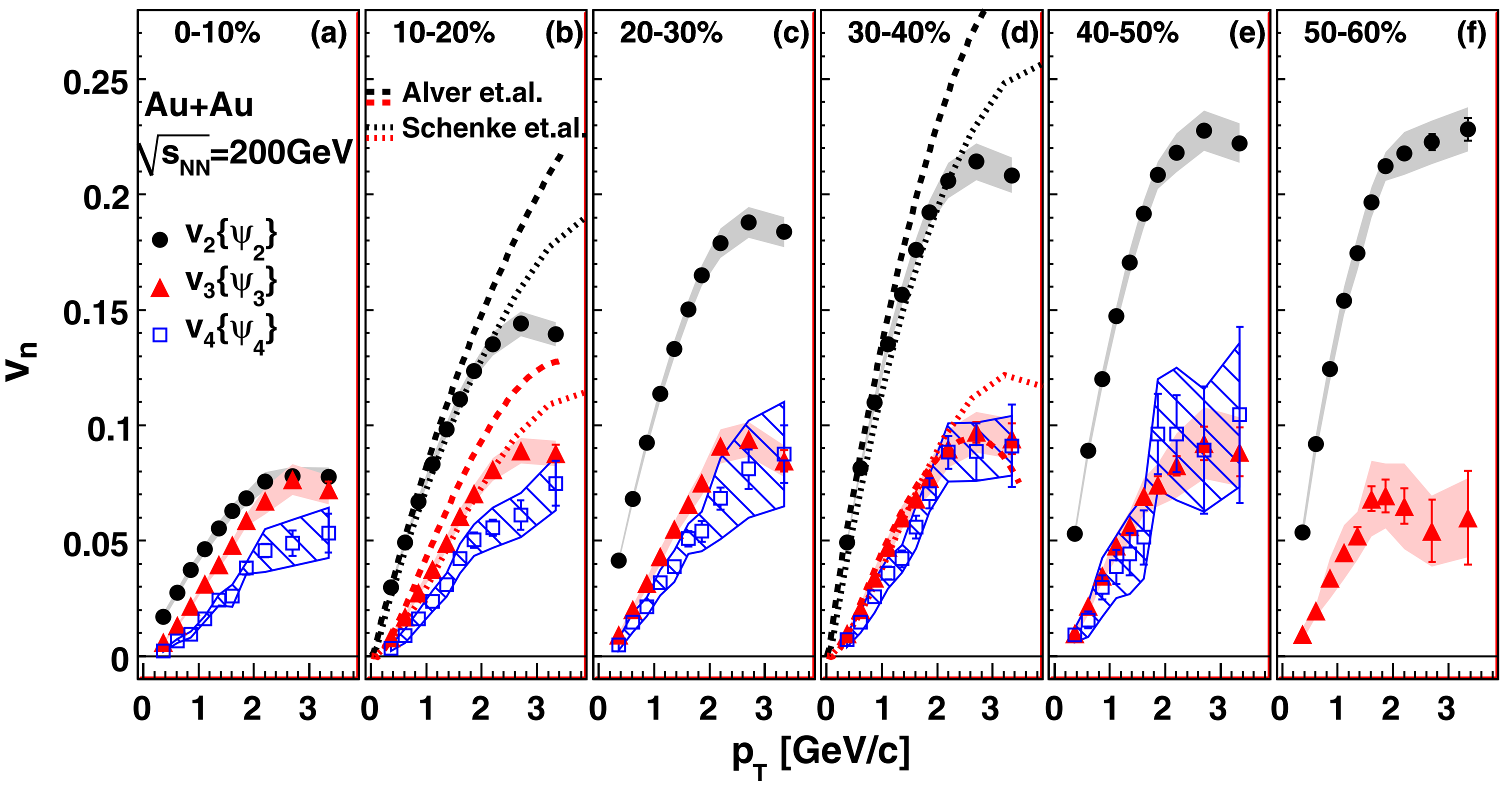
$$\varepsilon_n^{part} = \frac{\sqrt{\langle r^2 \cos n\phi_{part}\rangle^2 + \langle r^2 \sin n\phi_{part}\rangle^2}}{\langle r^2 \rangle},$$

$$\psi_n^{part} = \frac{atan2(\langle r^2 \cos n\phi_{part}\rangle, \langle r^2 \sin n\phi_{part}\rangle) + \pi}{n}$$

Differential v_n measurements

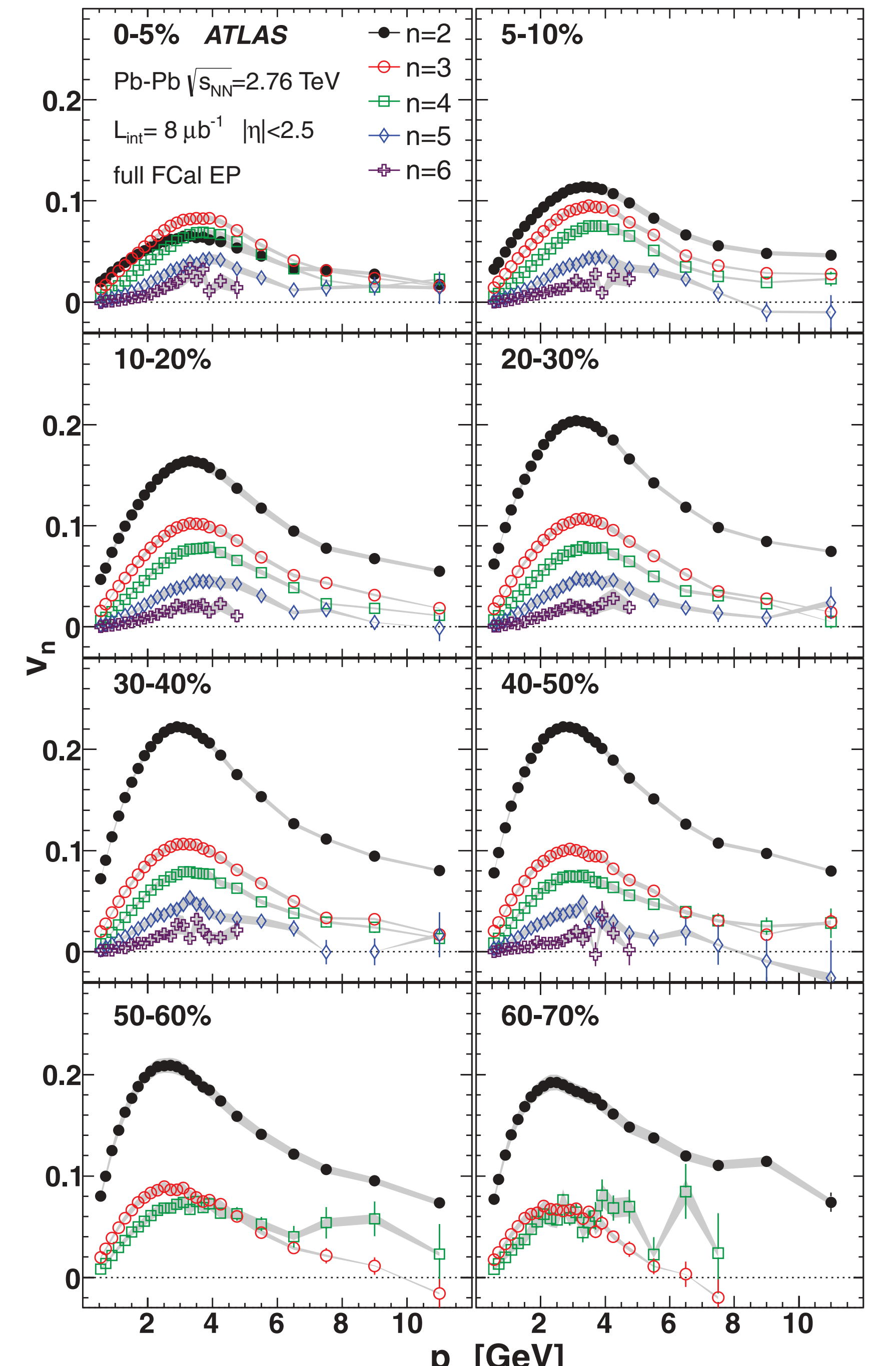
RHIC

PHENIX PRL107.252301



LHC

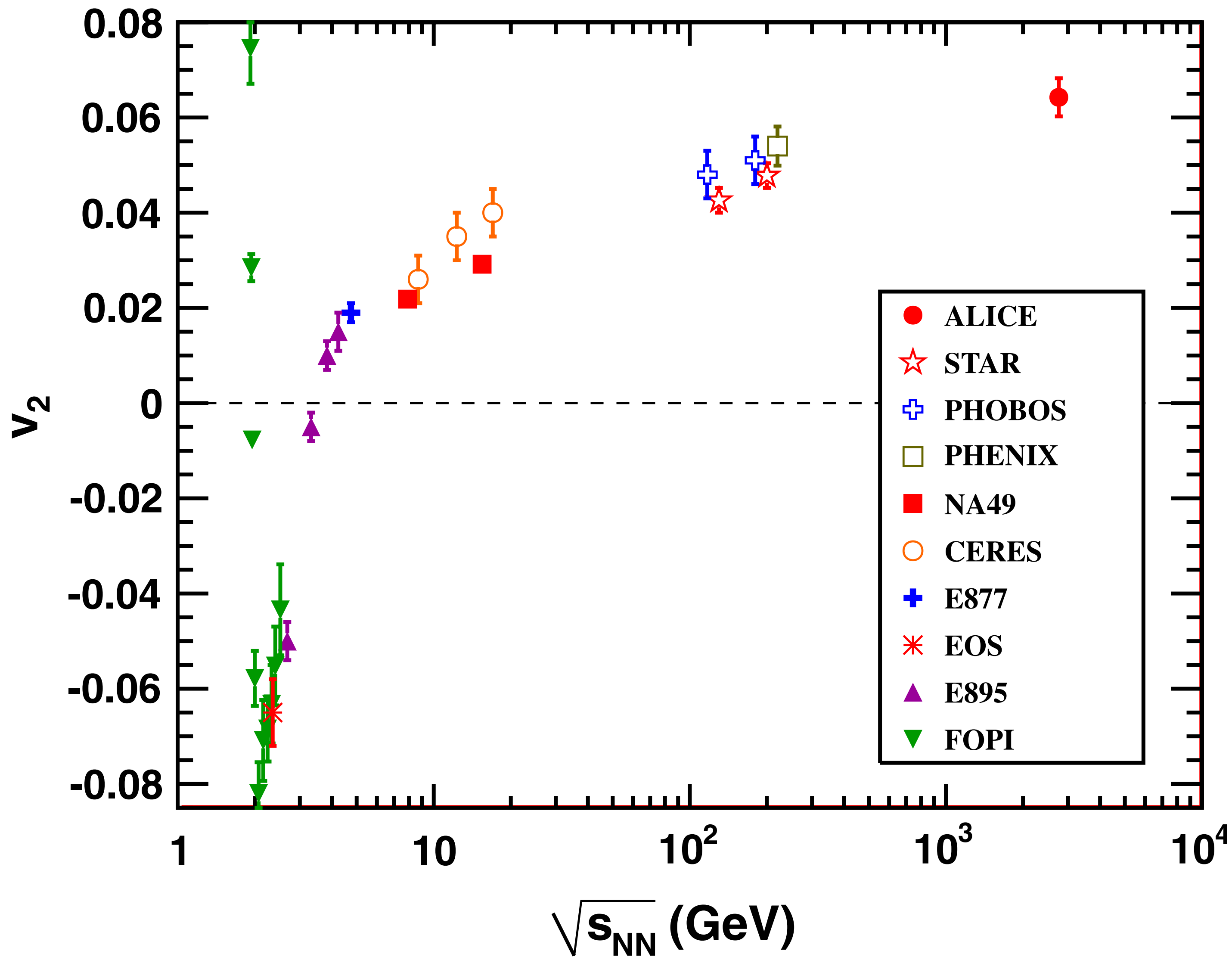
ATLAS PRC86.014907

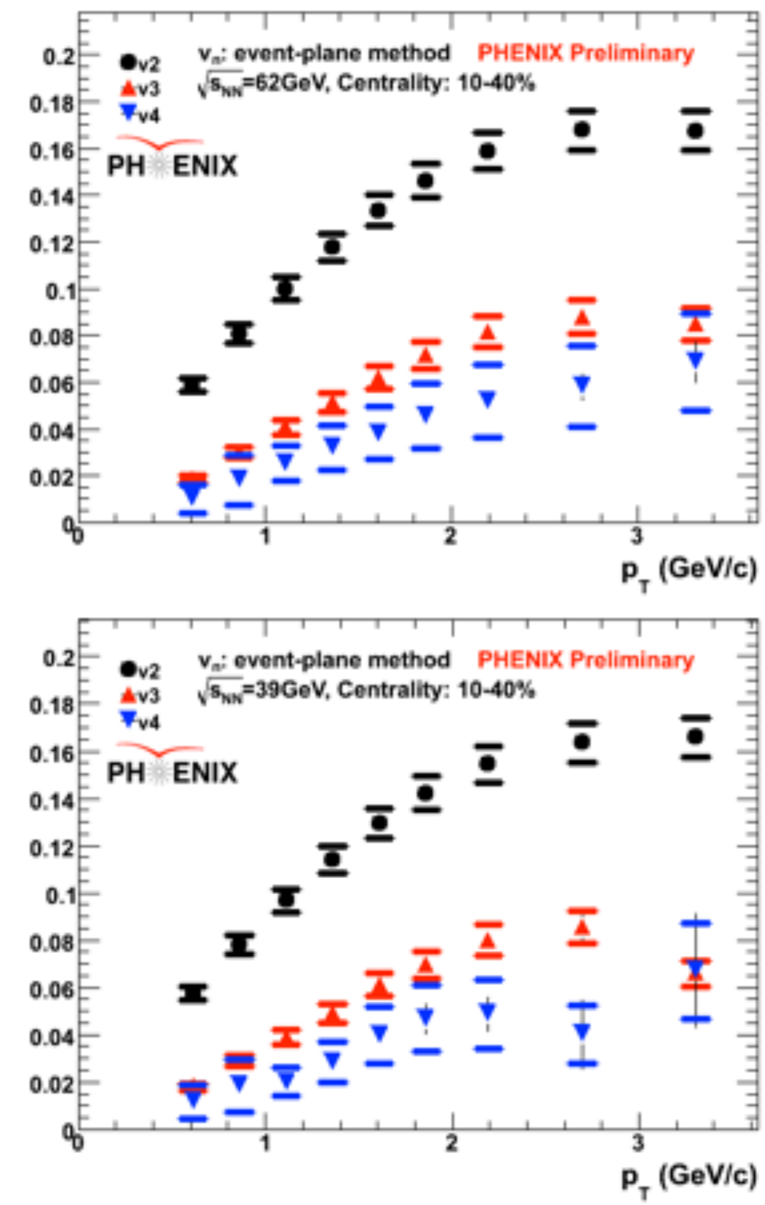


- Sizable higher order flow harmonics v_n is observed in both RHIC and LHC energy ranges

Collision Energy Dependence

ALICE PRL105.252302

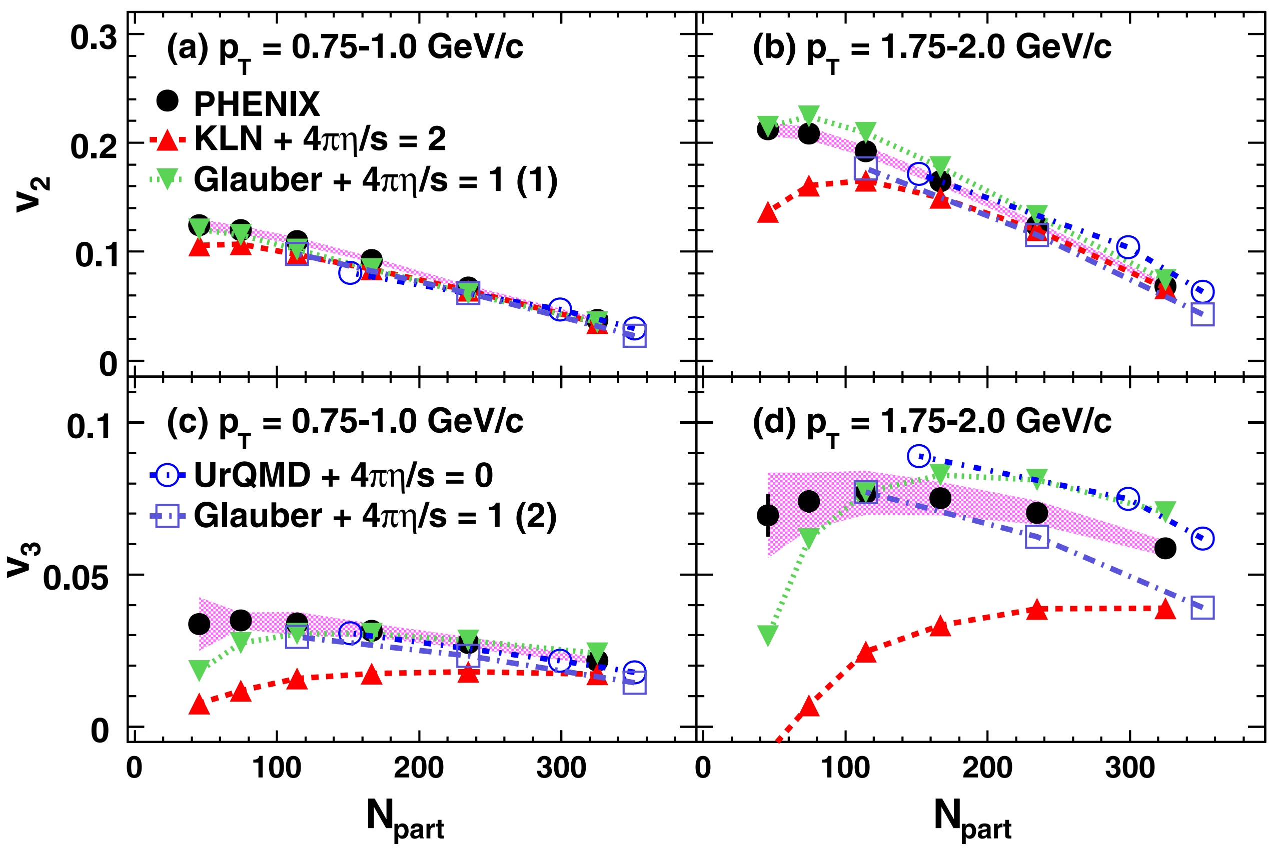




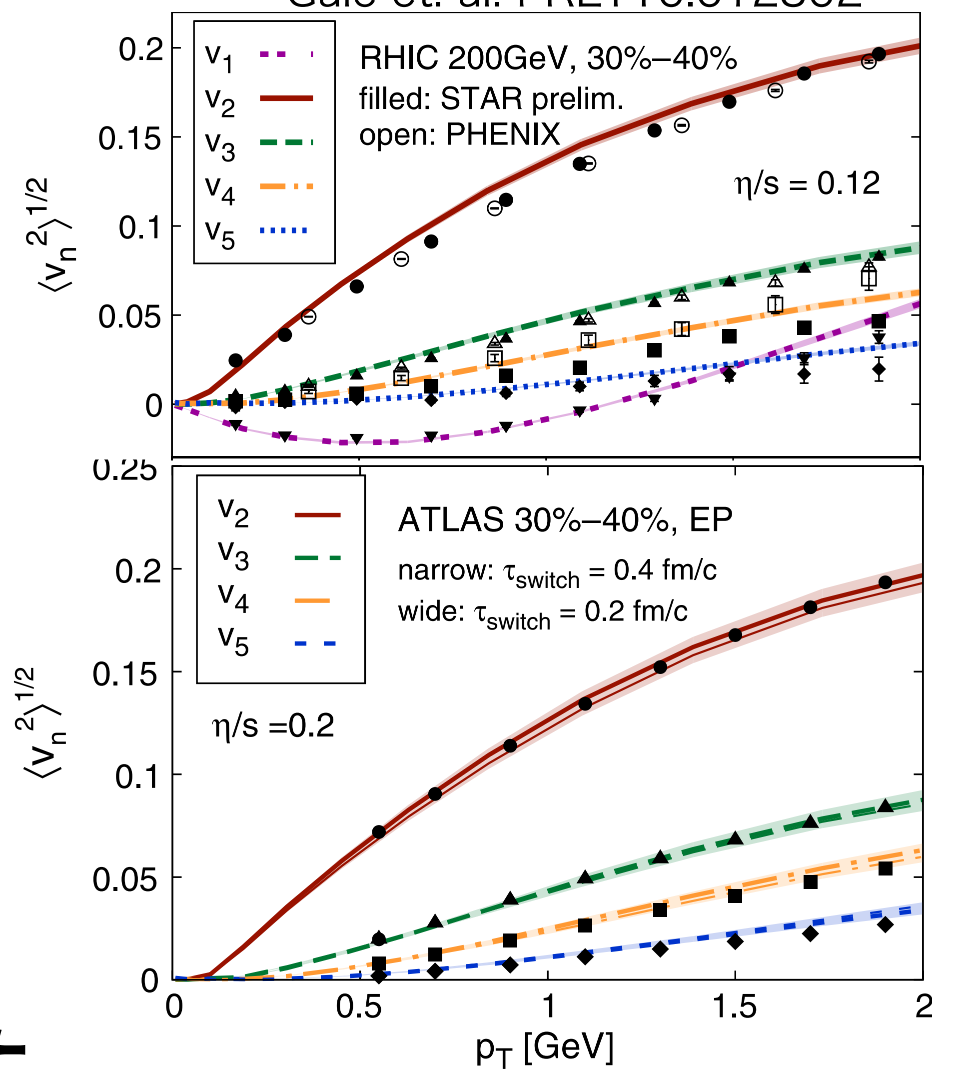
- ~30% increase of v_2 from RHIC to LHC, still not saturated
- More $v_{3,4}$ data will come at ~20 GeV range by RHIC BES

IC and η/s determination

PHENIX PRL107.252301

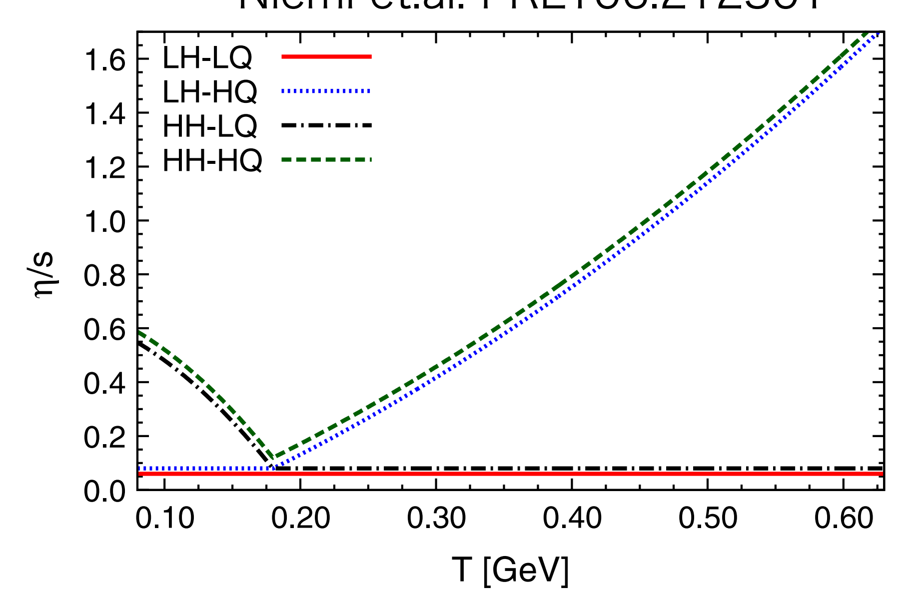


Gale et. al. PRL110.012302

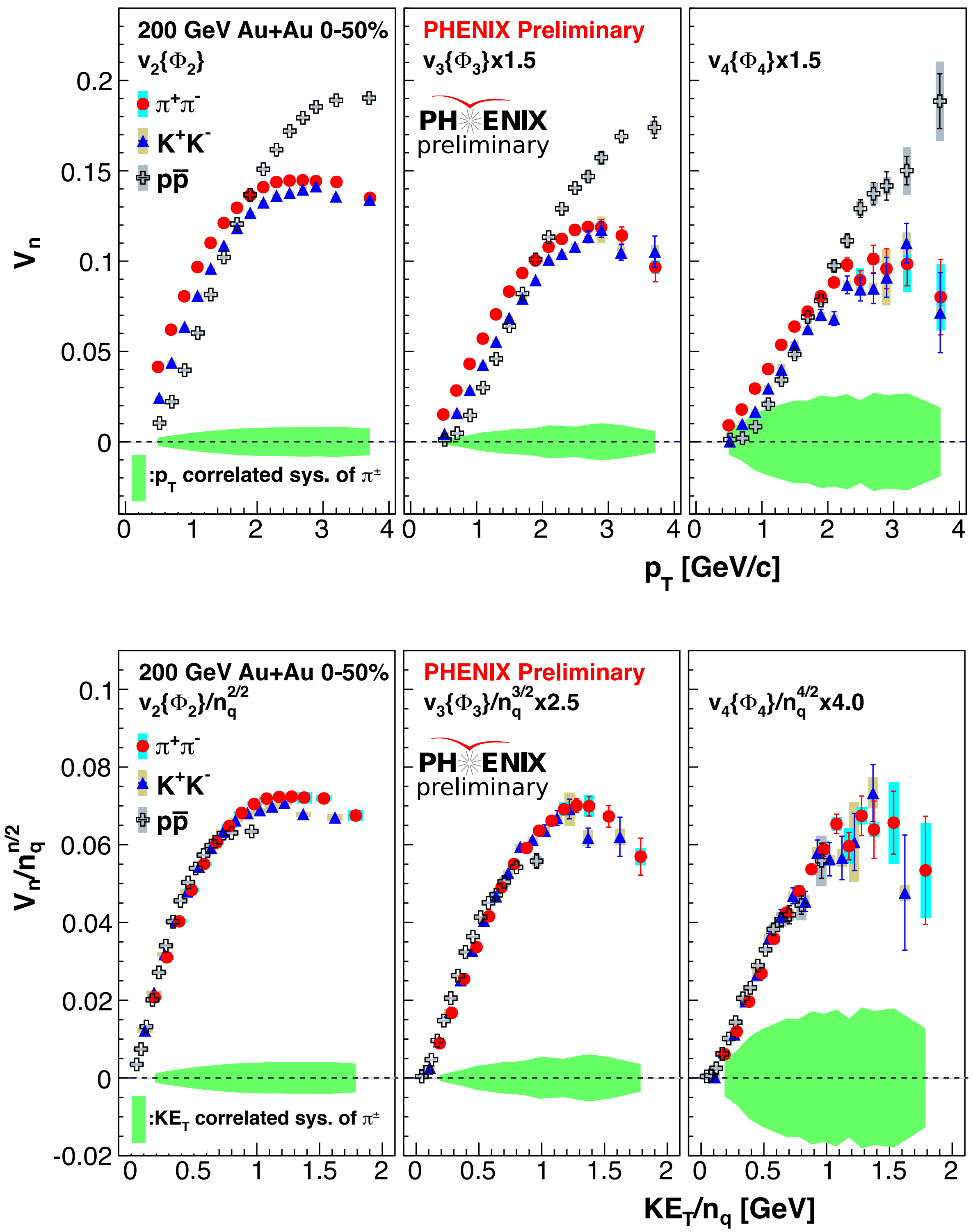


- Stringent constraints to IC and shear-viscosity by higher-order harmonics
  - Still Multiple Combinations
- Temperature dependence of viscosity $\eta/s(T_{\mathrm{RHIC}}) < \eta/s(T_{\mathrm{LHC}})$

Niemi et.al. PRL106.212301



Identified Hadron v_n



- Mass dependence
- Constituent quark number dependence
- Empirical Scaling of v_n

$$v_n/n_{cq}^{n/2} \quad \text{vs} \quad KE_T/n_{cq}$$

  - v_2 ncq scaling +
  - $v_2^{1/2} \propto v_n^{1/n}$
- Possible acoustic-viscous dumping

Lacey et.al. arXiv:1105.3782
Staig et. al. PRC84.034908

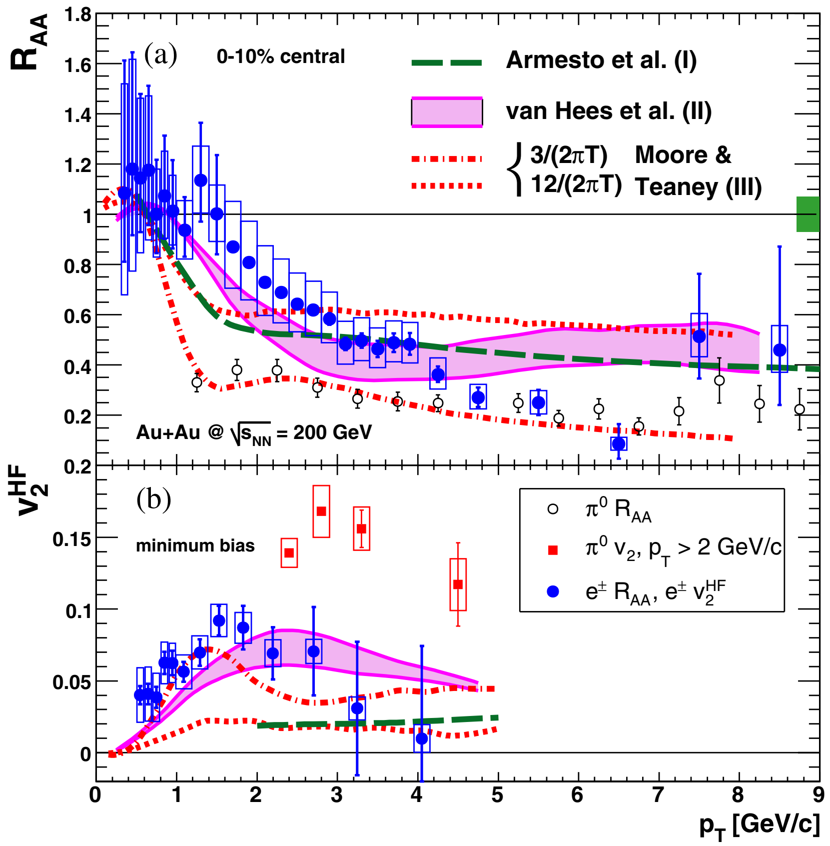
$$\delta T_{\mu\nu}(n,t) = \exp(-\beta' n^2)\delta T_{\mu\nu}(n,0), \quad \beta' = \frac{2\eta}{3s}\frac{1}{\bar{R}^2}\frac{t}{T},$$

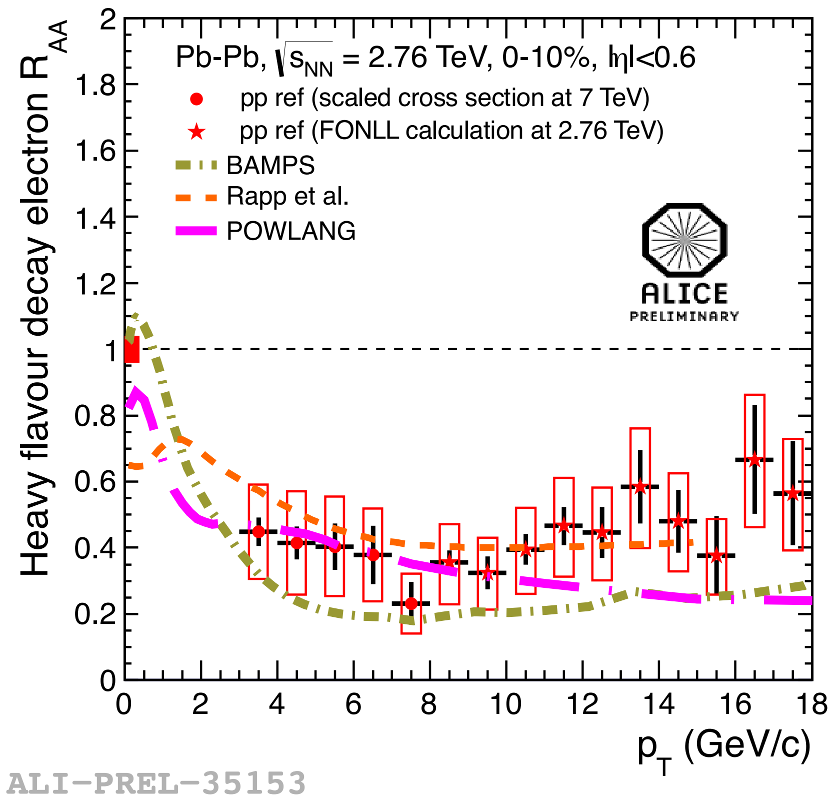
Heavy Flavor v_2

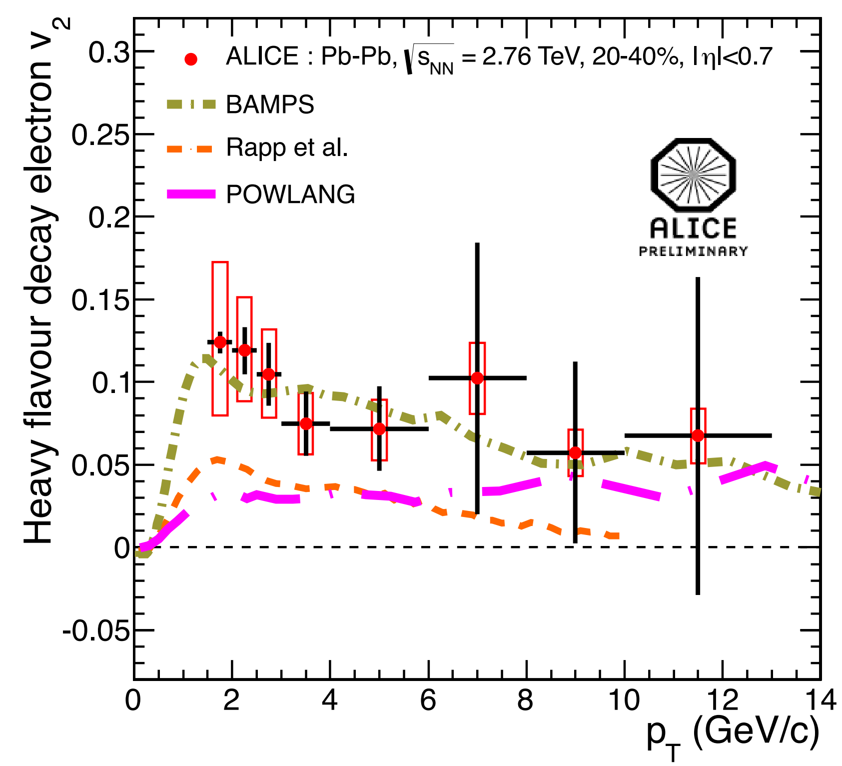
RHIC

LHC

PHENIX PRL98.172301





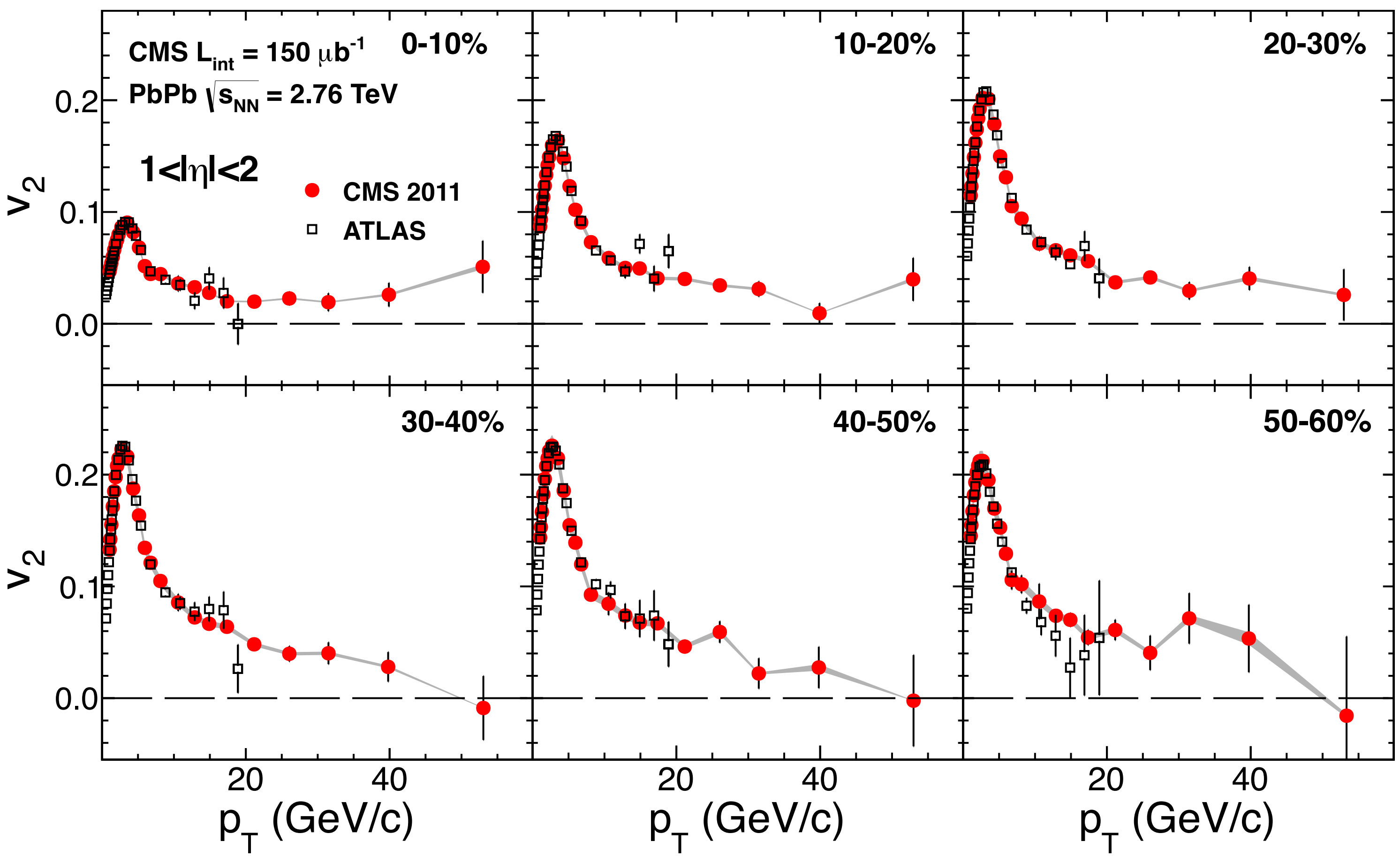


- Suppression of Heavy flavor & none-zero v_2 indicate substantial energy loss in medium and nearly perfect fluid
- Short relaxation time and/or small diffusion coefficients

Very high p_T v_n at LHC

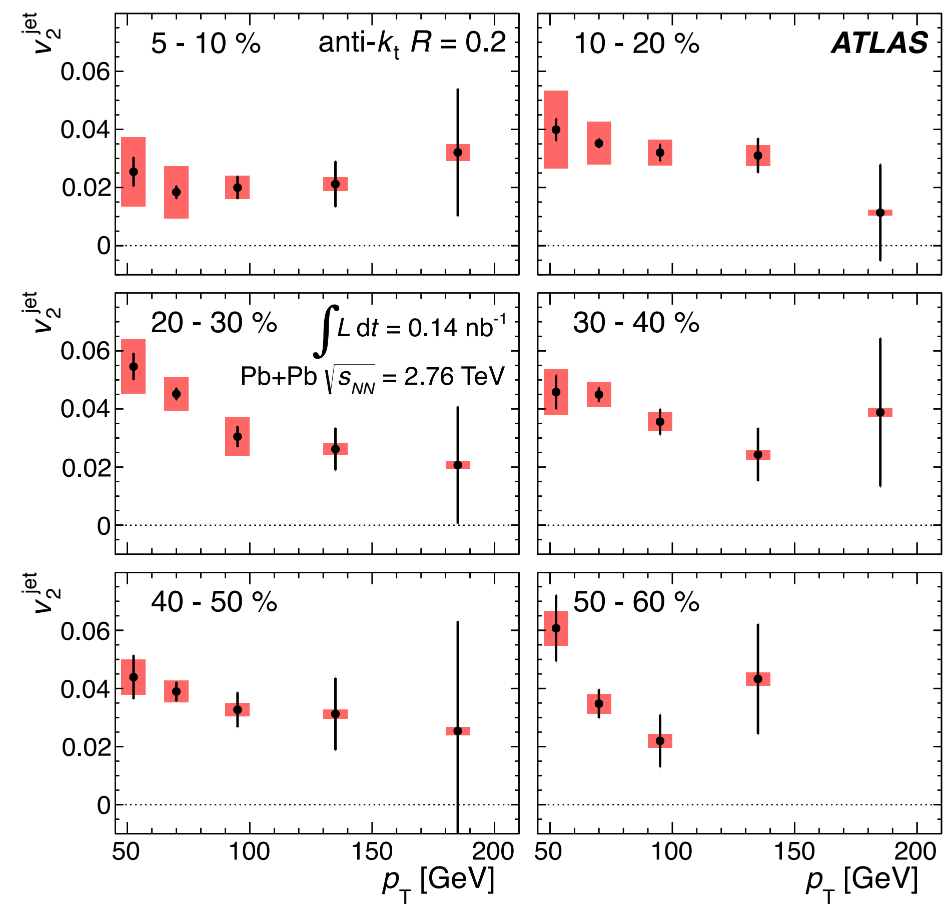
Single Hadron

CMS PRL109.022301



Reconstructed Jet

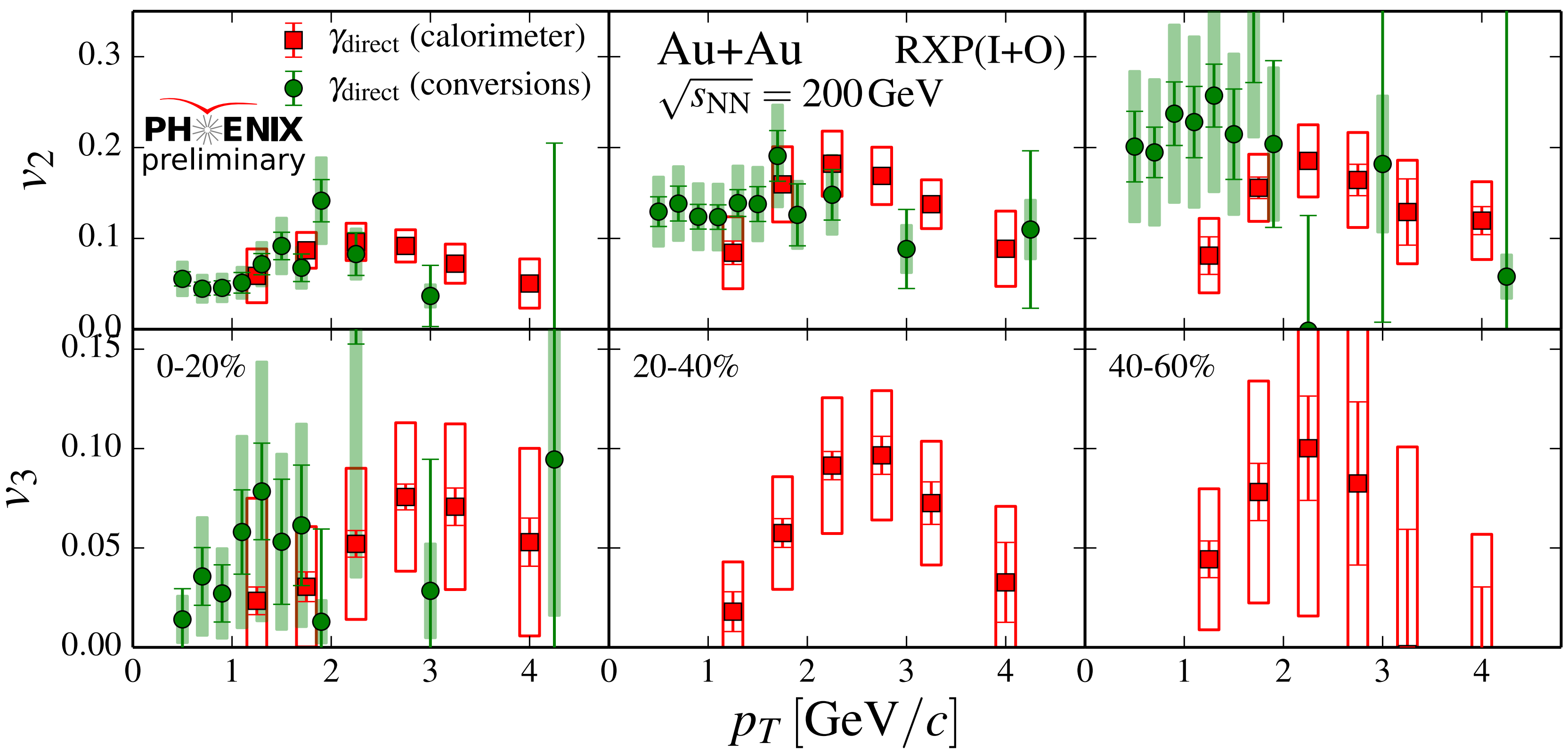
ATLAS PRL111.152301



- None-zero v_2 up to 40 GeV/c for single hadrons and 150GeV for jets at a similar amplitude
- Reflection of path-length dependence in jet quenching

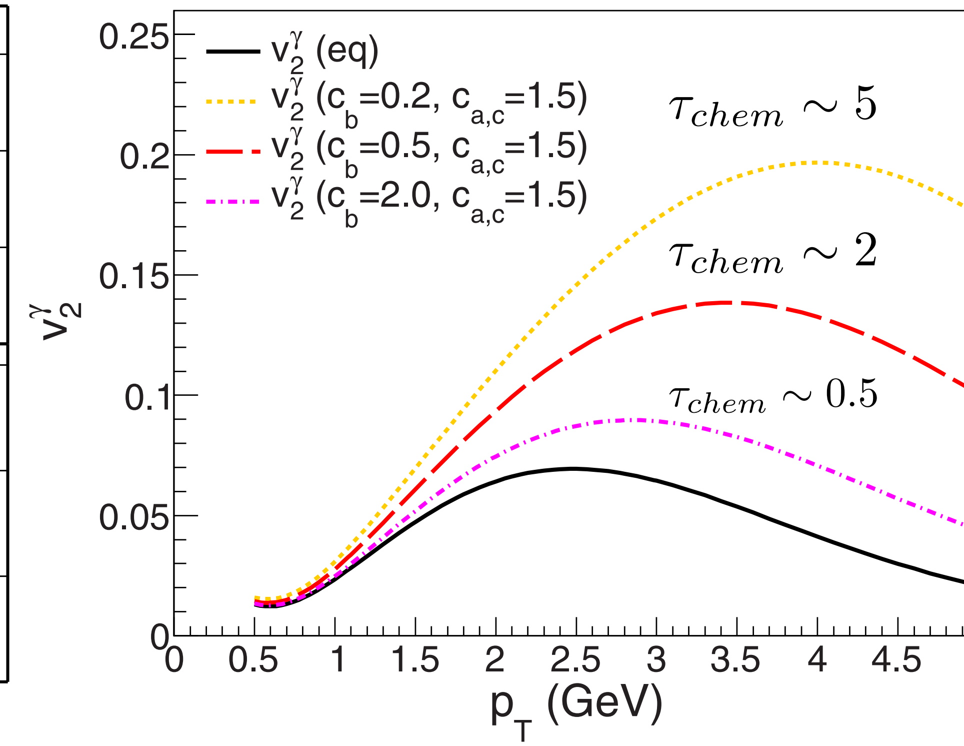
Direct Photon v_n puzzle

See also PHENIX PRL109.122302



Late chemical equilibrium

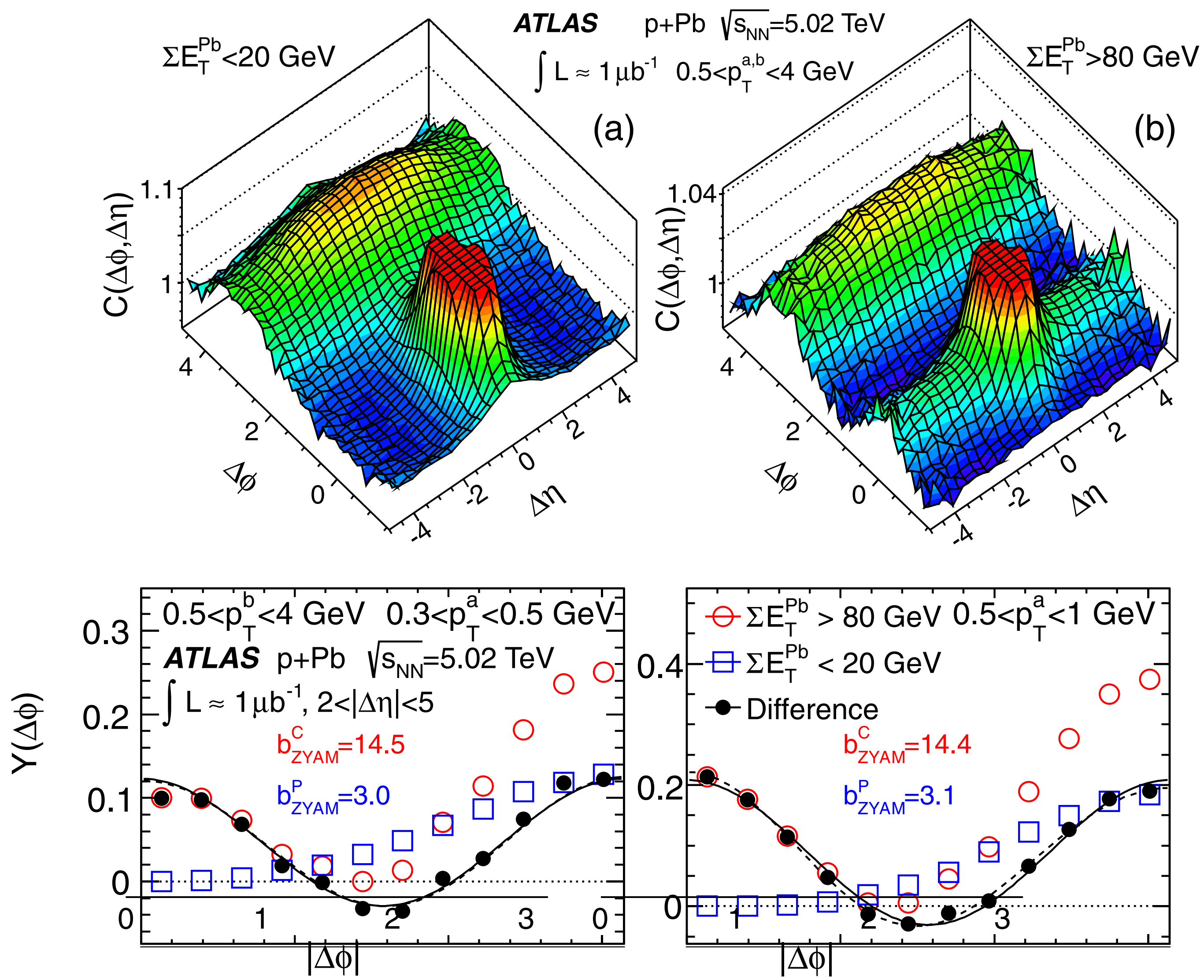
A. Monnai PRC90.021901(R)

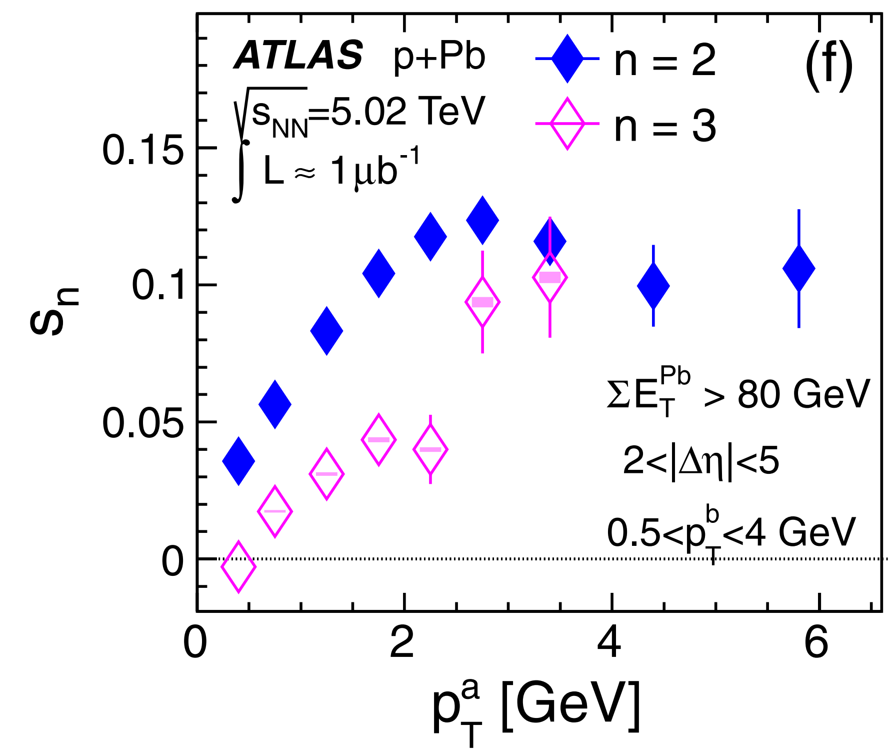


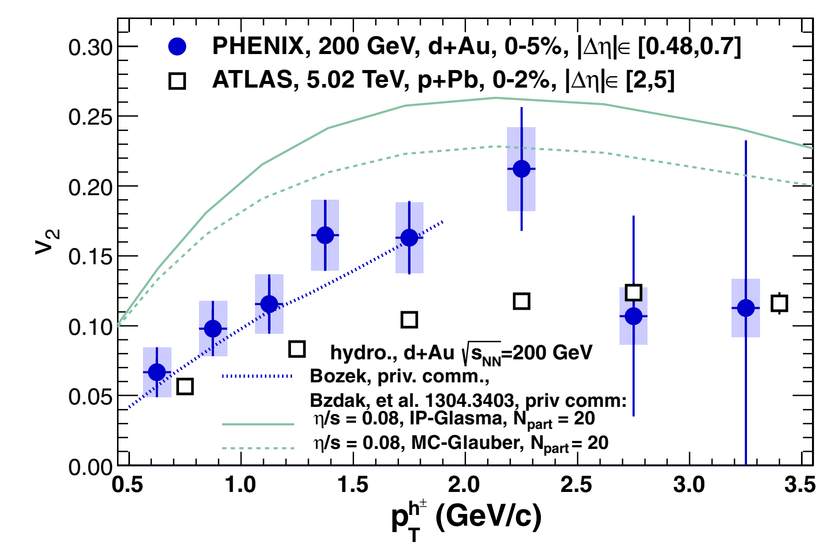
- Most of hydrodynamic models failed
- Magnetic field is also disfavored due to none zero v_3; Third-order plane very weakly correlated with reaction plane where the field is generated
- New Idea: Thermal photon by slow quark chemical equilibrium

Ridge & v_n in p(d)+A collisions

ALICE: Physics Letters B 726 (2013)
ATLAS: Phys. Rev. Lett. 110(2013)
CMS: Phys. Lett. B 7198(2013)
PHENIX PRL111.212301(2013)





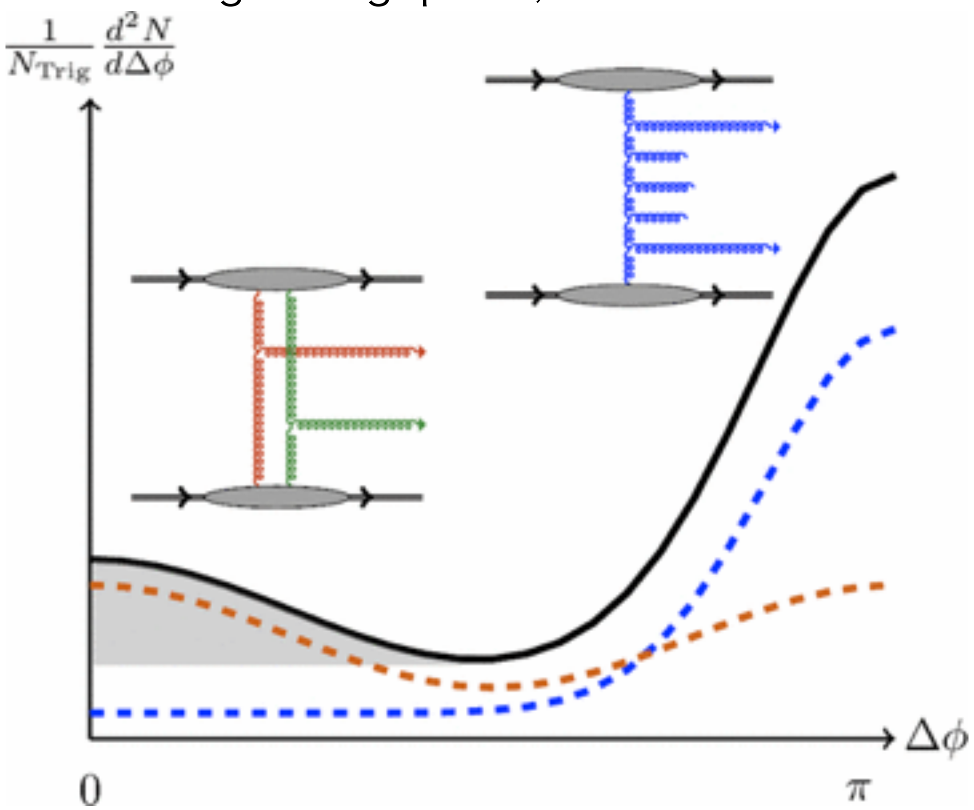


- Ridge and $v_{2,3}$ are observed in high multiplicity events in p(d)+A collisions

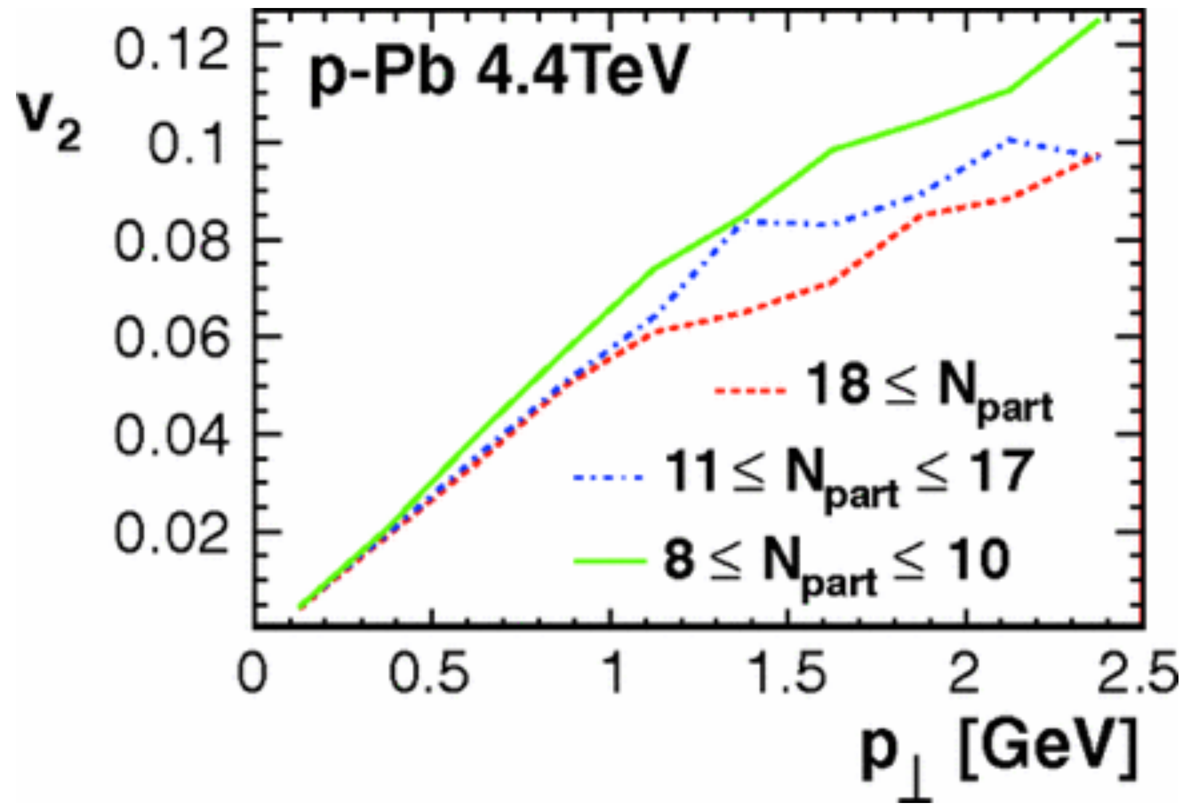
Initial or Final State Effect

CGC | **Hydrodynamics**

Dusling Venugopalan, PRD87.054014



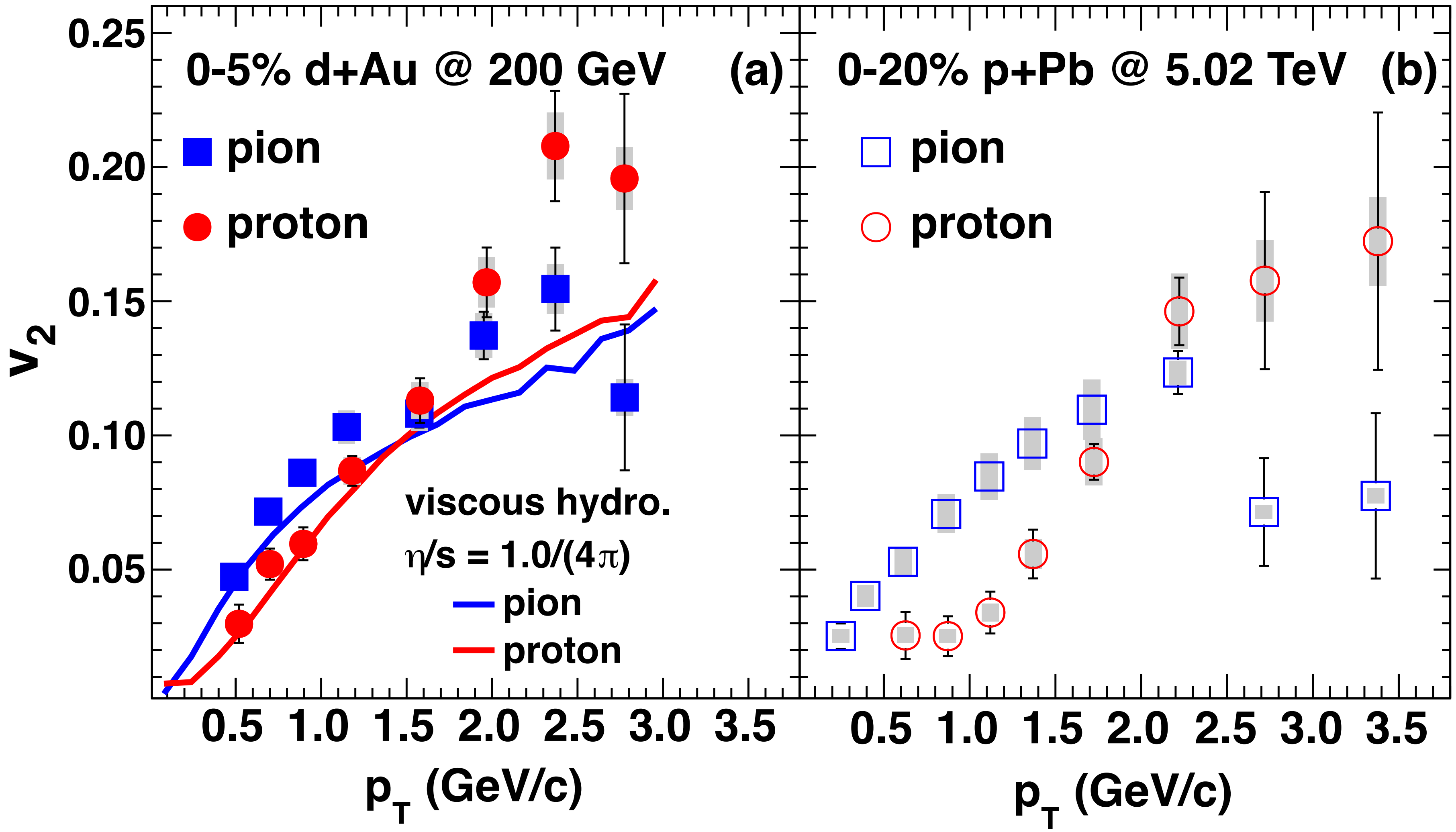
Bozek PRC85.014911



- Both initial state (CGC) and final state (hydro) effects can explain v_n in small collisions systems
- Need more constraints by differential measurements

PID v_n in p(d)+A

PHENIX arXiv:1404.7461v1
ALICE Phys.Let.B726.164-177

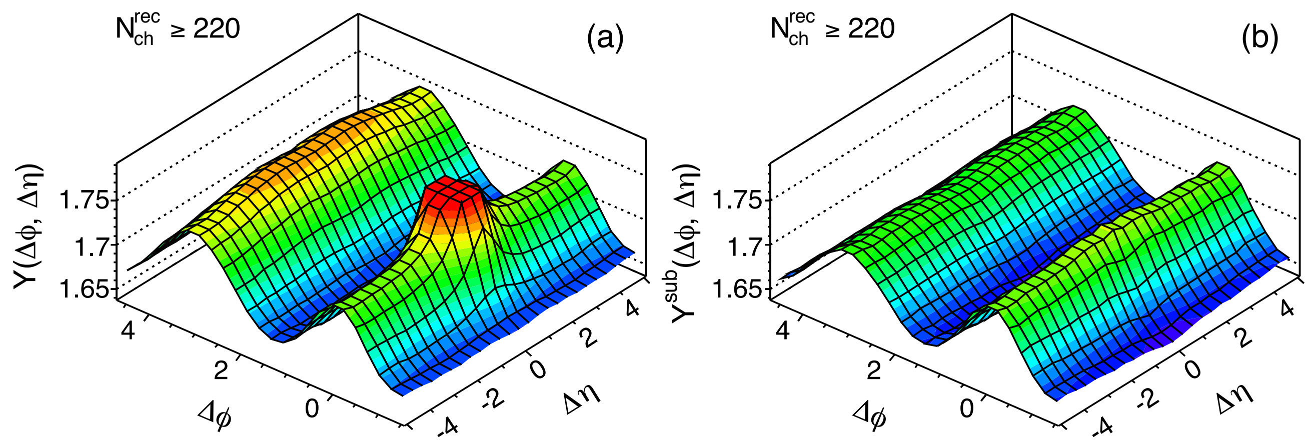


- Mass dependence in low p_T
- Baryon/Meson difference at intermediate p_T
- Qualitatively consistent with hydrodynamics. How about mass dependence in CGC frame work? Not conclusive.

Non-flow effects in p+A collisions

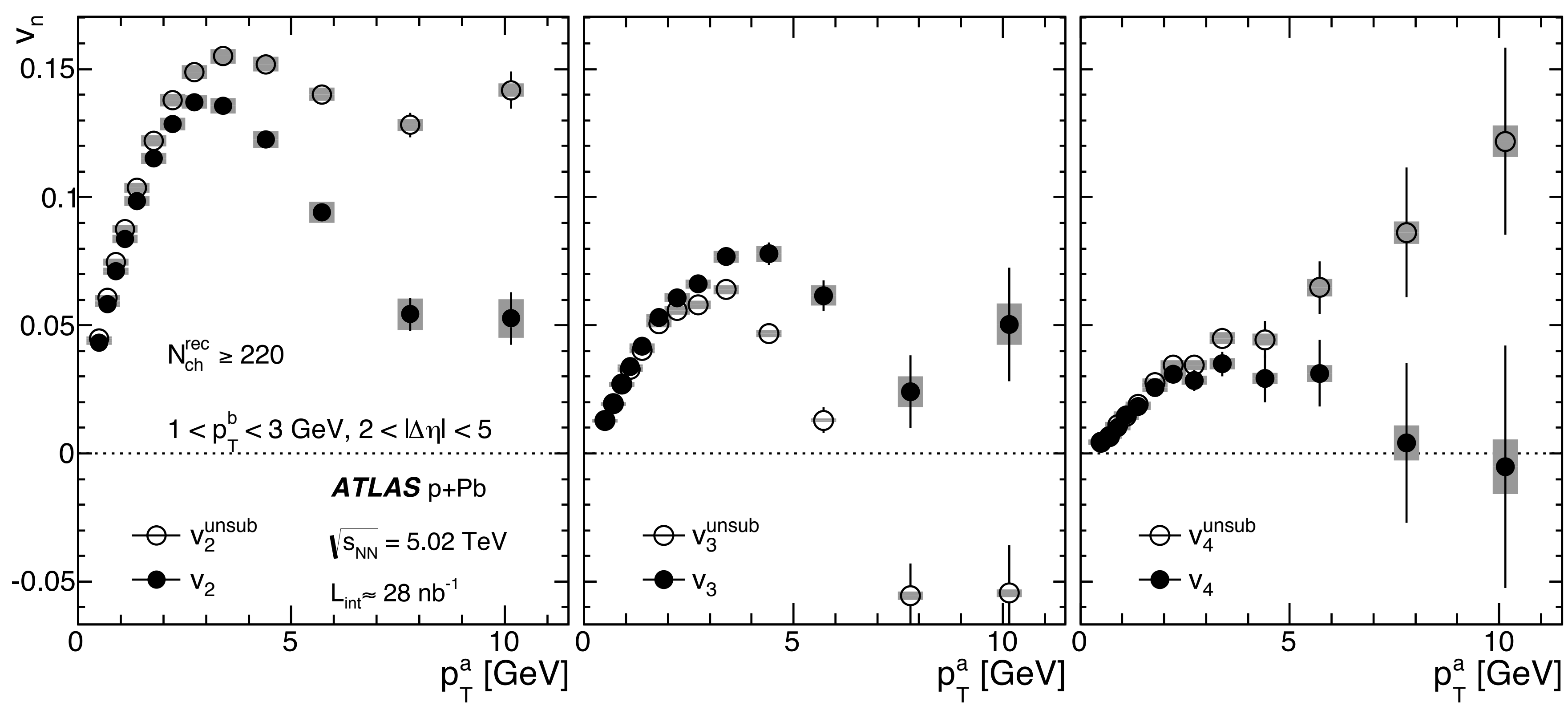
Recoil Jet Subtraction

ATLAS arXiv:1409.1792v1



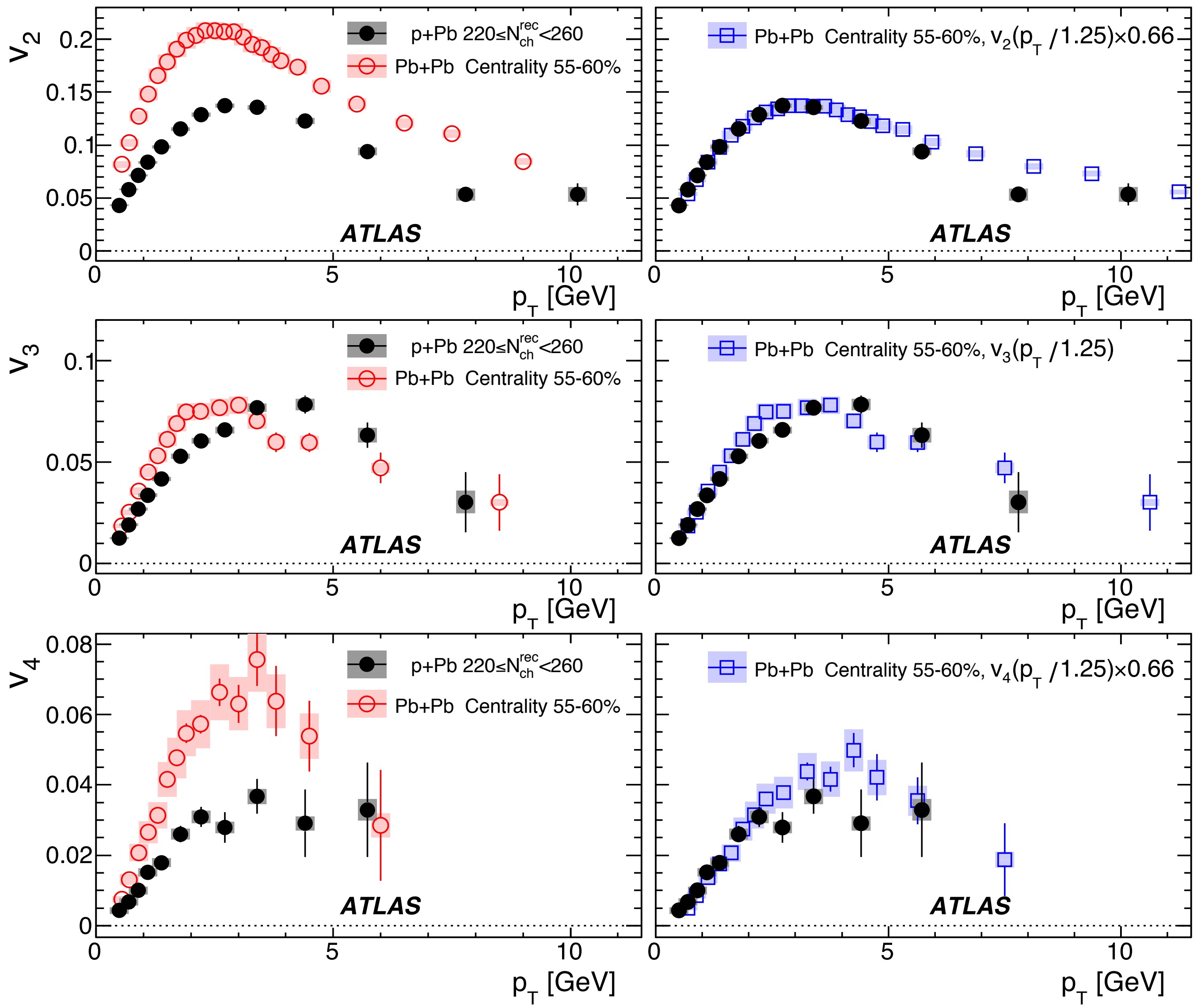
$$Y^{sub}(\Delta\phi) = Y(\Delta\phi) - \alpha Y^{corr}_{peri}(\Delta\phi)$$

- α tuned to completely subtract near-side yield
- Subtraction results in v_n=0~0.05 at high p_T
- ~10% reduction of $v_{2,3}$ at 3 Gev/c



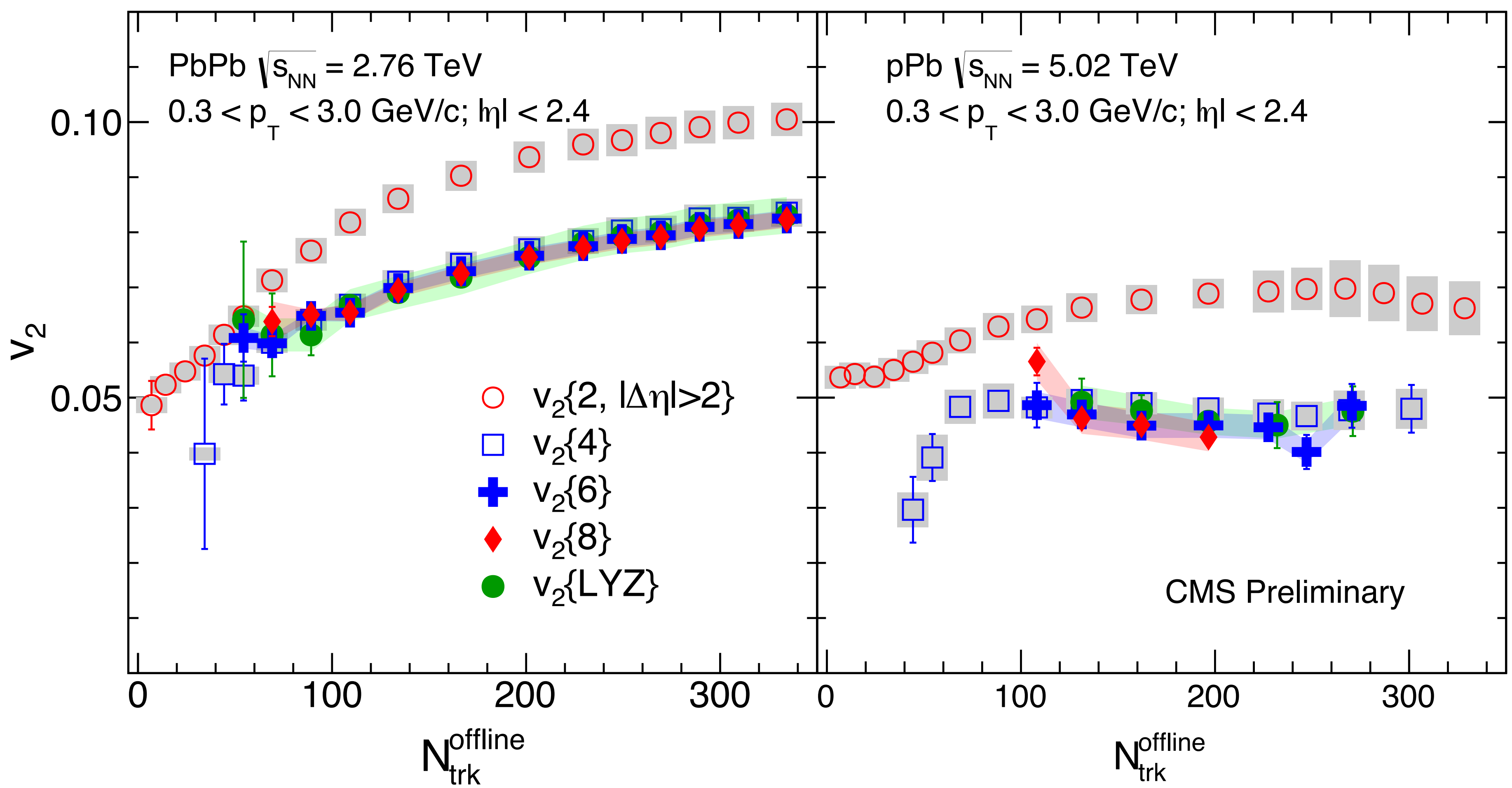
Scaling among p+A and A+A v_n

ATLAS arXiv:1409.1792v1



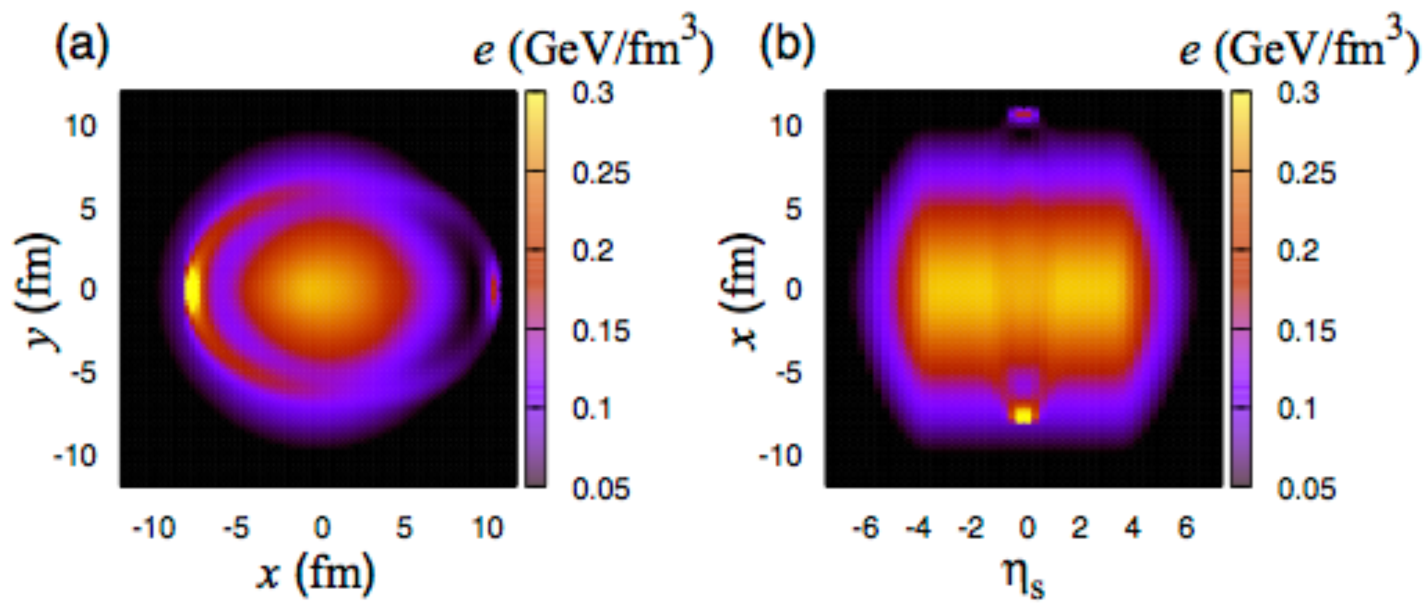
- Scaled v_n in A+A collisions match that in p+A collisions
- Suggests similar origin of v_n in both systems and similar medium response to initial geometry in both systems

Multi Particle Cumulants

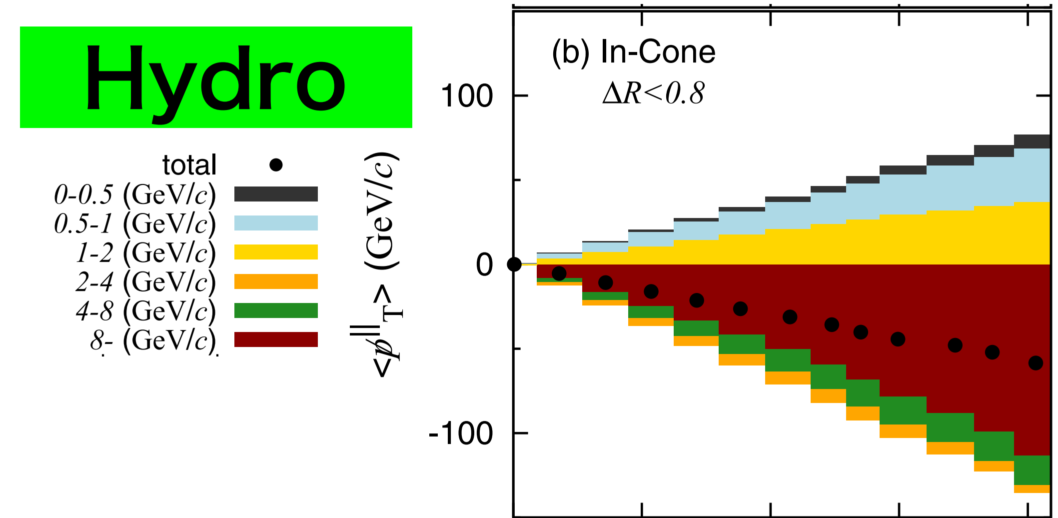


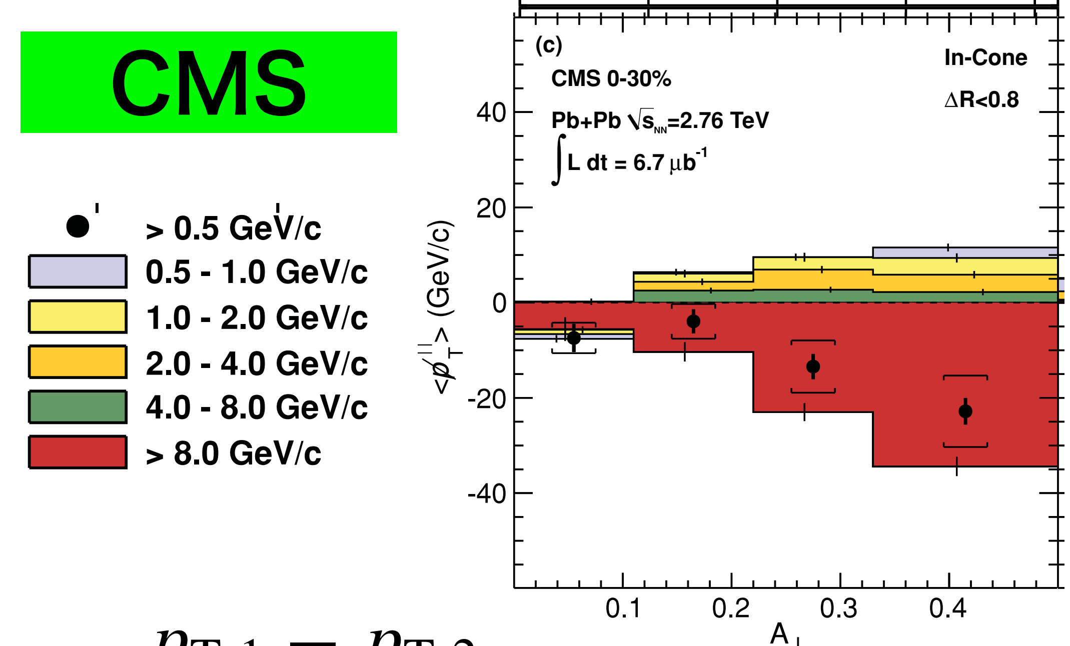
- M.P.C is less sensitive to non-flow than 2-part. cum.
  - ~10% reduction of v_2 in both p+A and A+A collisions
- Convergence in v_2\{n=4,6,8,LYZ\} in p+A and A+A collisions
  - Consistent with hydrodynamics prediction Bzdak et.al. arXiv:1311.7325

Hydrodynamics with Jets



Tachibana et.al PRC90.021902





- Momentum deposit from energized partons
- CMS $p_T^{||}$ vs A_j around jet axis is qualitatively reproduced
- It should also be interesting to see jet effects in soft physics
  - v_n, HBT, low-p_T 2PC

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}},$$

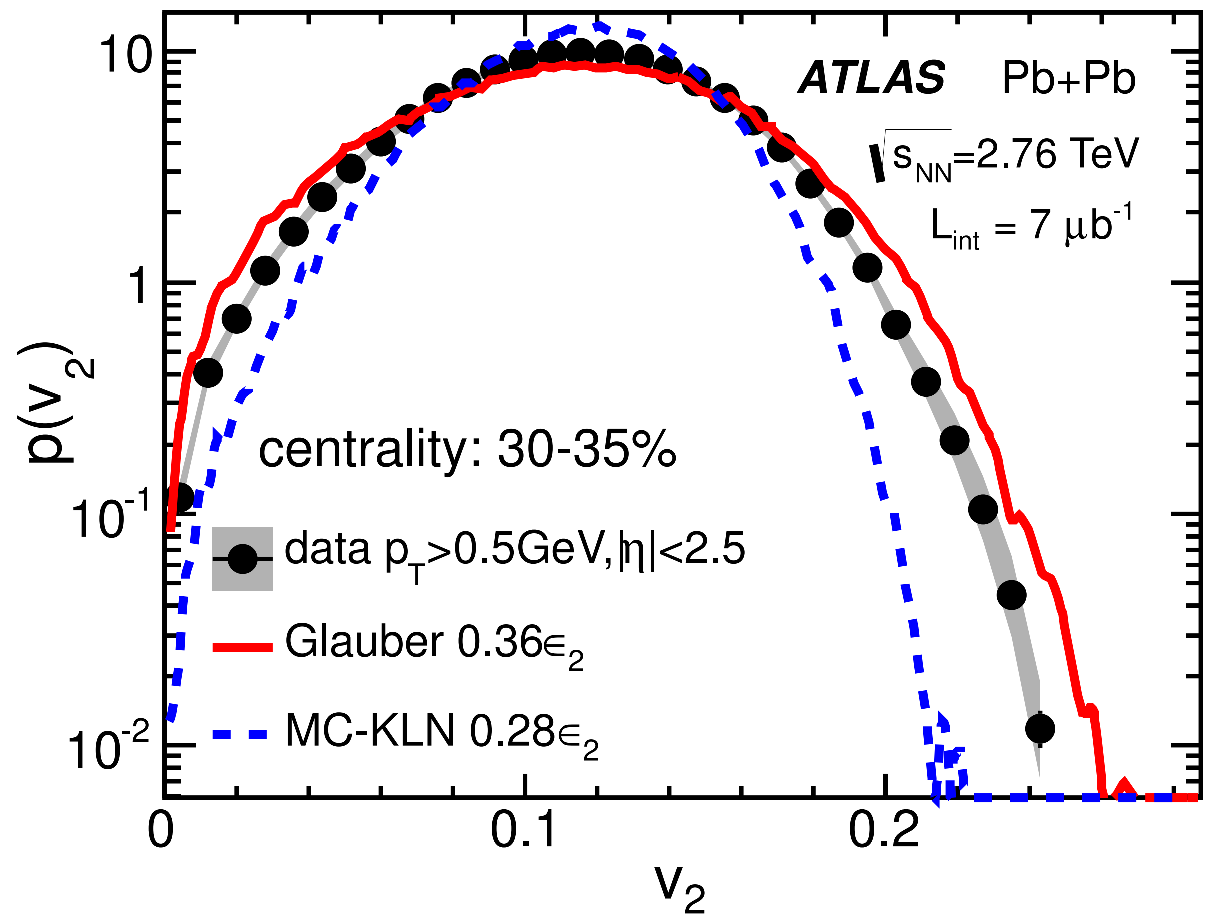
CMS PRC84.024906

$$\not{p}_T^{||} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right),$$

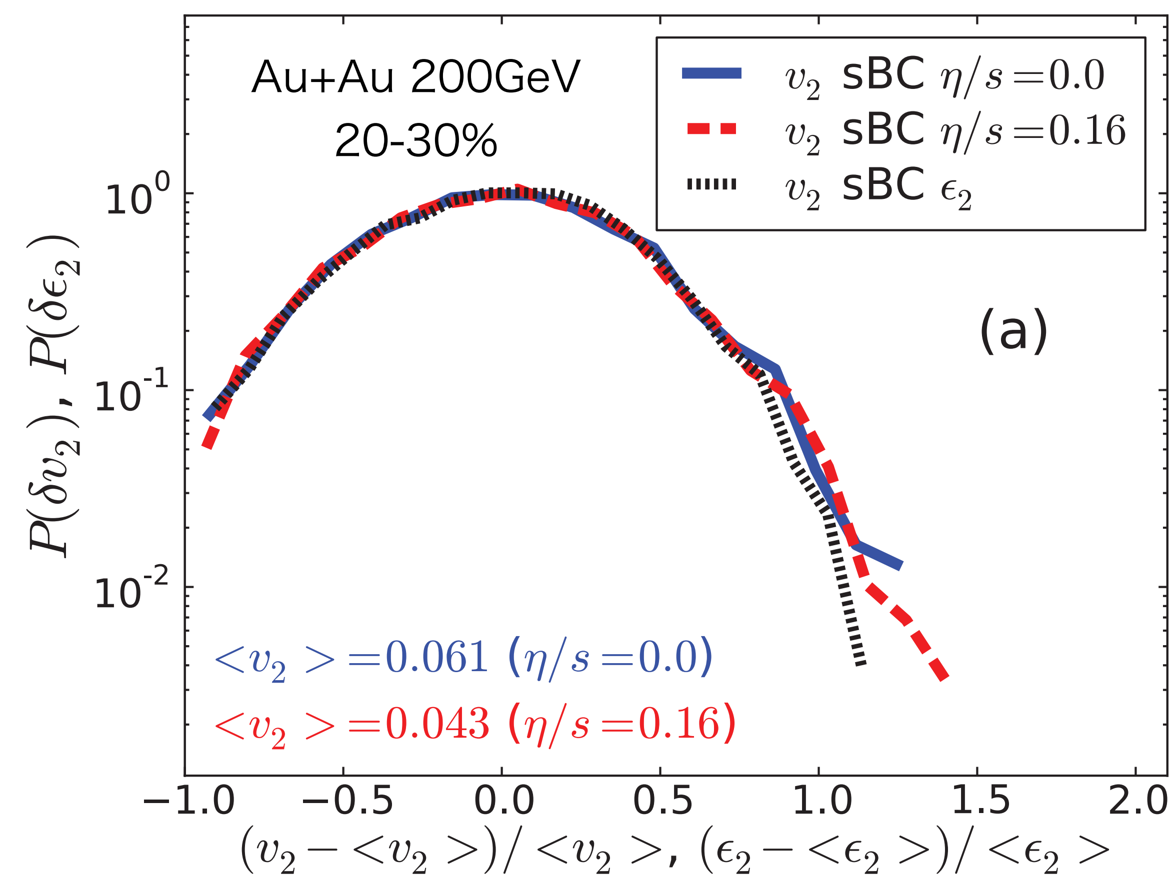
Event-by-Event Fluctuations of v_n

LHC Data | **Hydro Calculation**

ATLAS:JHEP11(2013)183

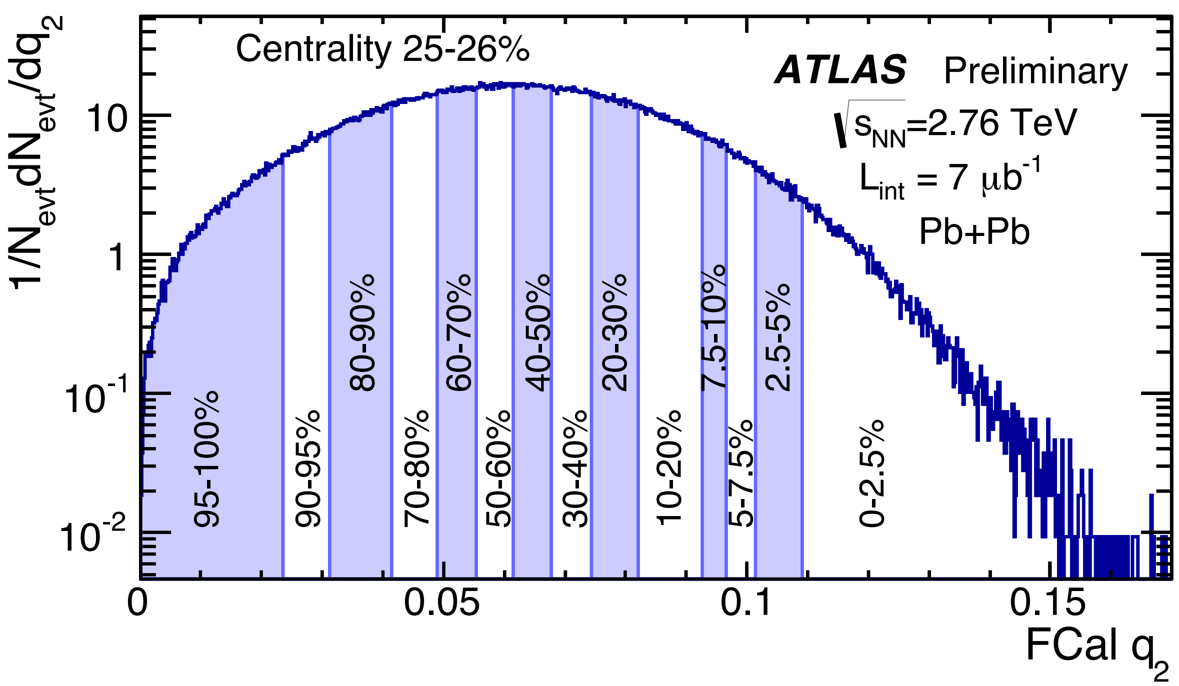


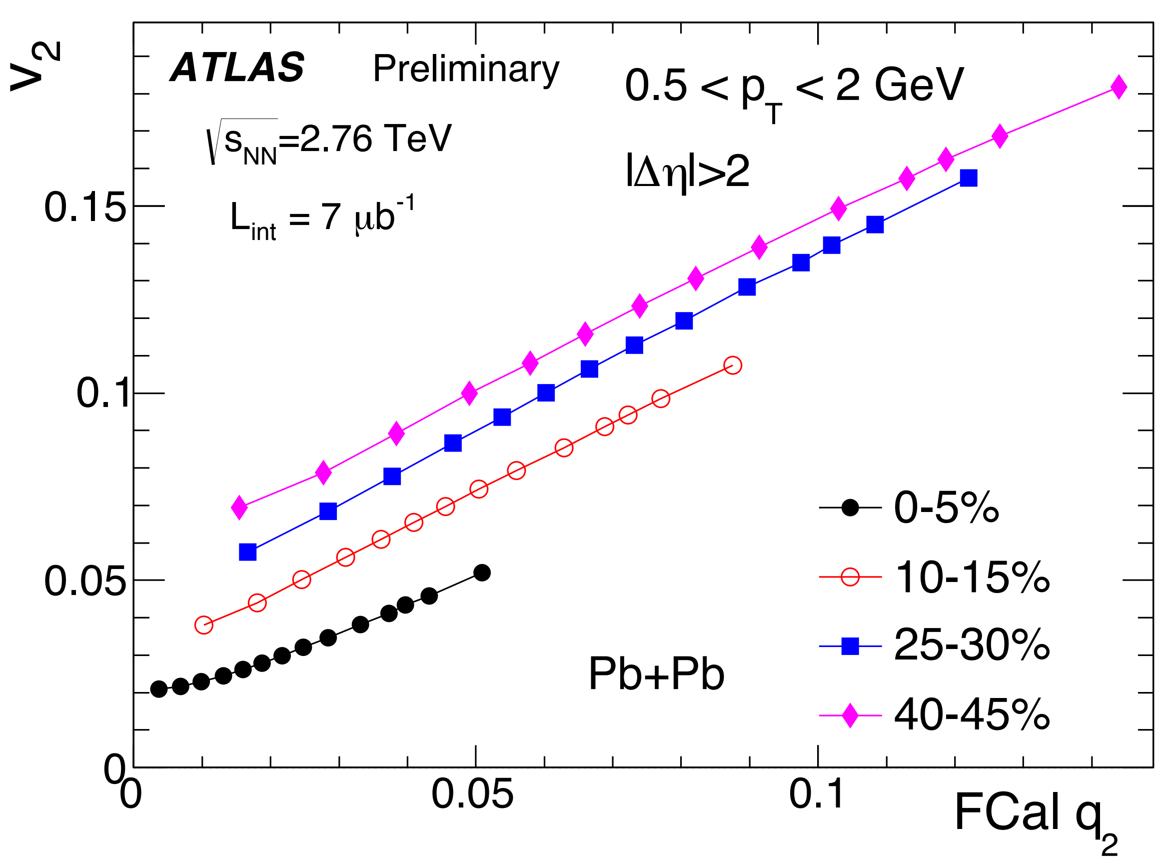
Niemi et.al. PRC87.054901



- **Eve-by-Eve fluctuation seems to be independent of shear-viscosity**
- **Possible probe to access IC**

Event-Shape Engineering : Flow Strength Control





Schukraft et.al: arXiv:1208.4563

- Event Shape Engineering(ESE)
- |qn| : Strength of Flow

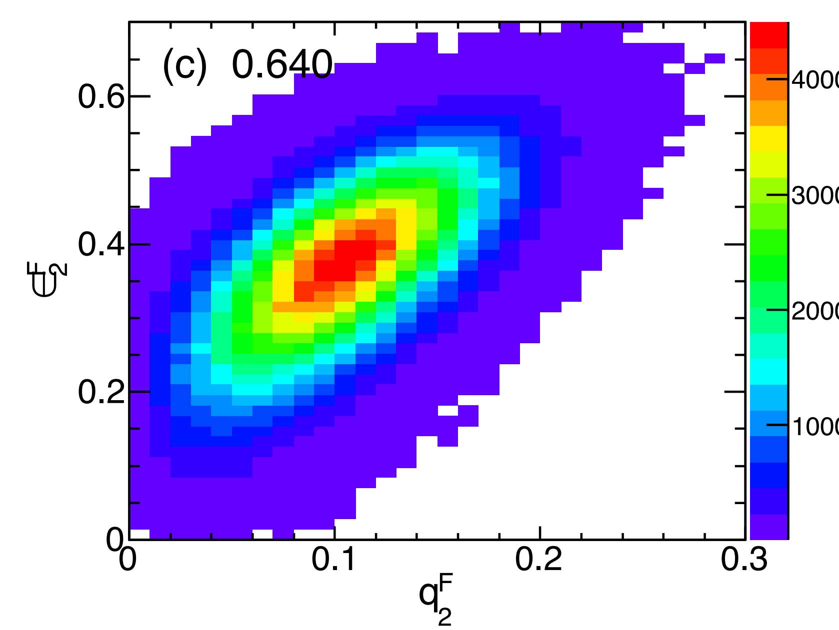
$$(q_n^x, q_n^y) = \frac{1}{\sum_i}\left(\sum_i \cos n\phi_i, \sum_i \cos n\phi_i\right)$$

$$|q_n| = q_n^{x\,2} + q_n^{y\,2}$$

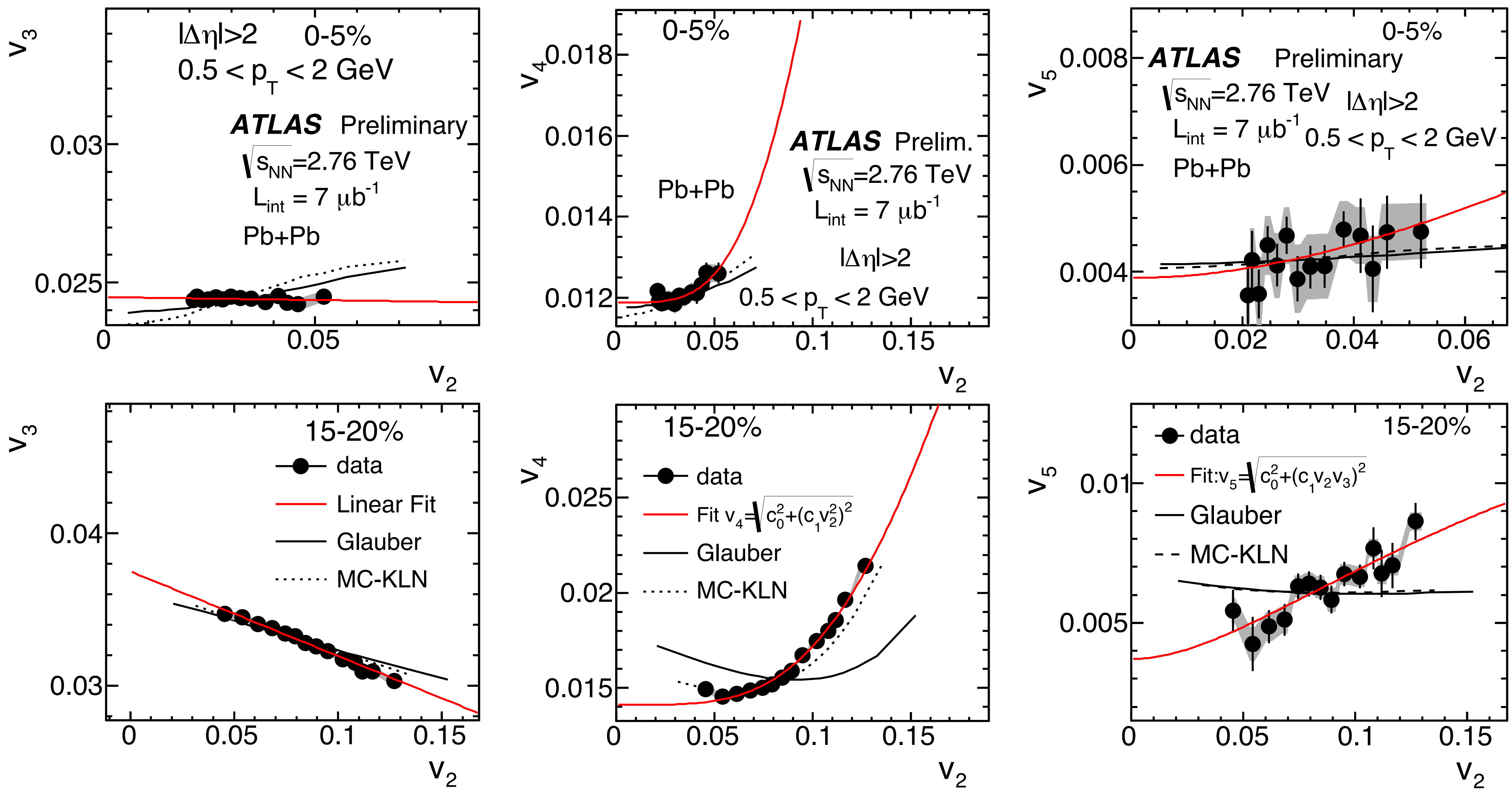
- Selection of e-b-e v_n via strength of flow vector
- Possible control of initial geometry

J.Jia et.al : arXiv:1403.6077

AMPT



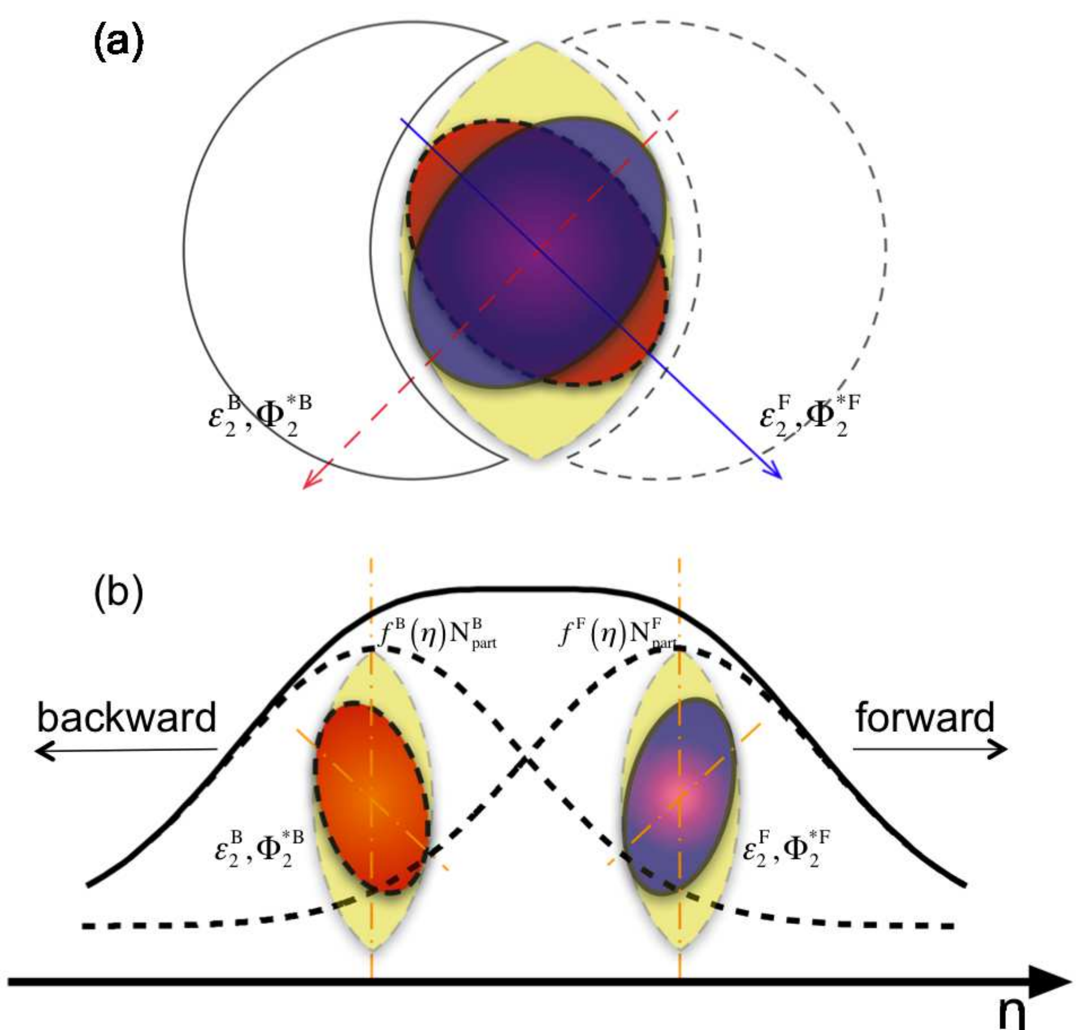
v_n-v_m correlations



- Compared with Glauber and MC_KLN ε_n–ε_m correlations
- Access to IC if linear response to initial eccentricities

ESE : Twist Effect

Jia et. al. arXiv:1403.6077

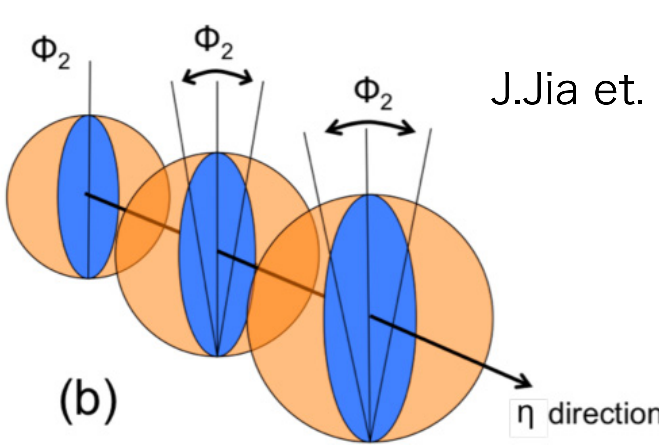


$$N_{part}^{\text{back}} \neq N_{part}^{\text{for.}}$$

$$\varepsilon_n^{\text{back}} \neq \varepsilon_n^{\text{for.}}$$

$$\Psi_n^{\text{back}} \neq \Psi_n^{\text{for.}}$$

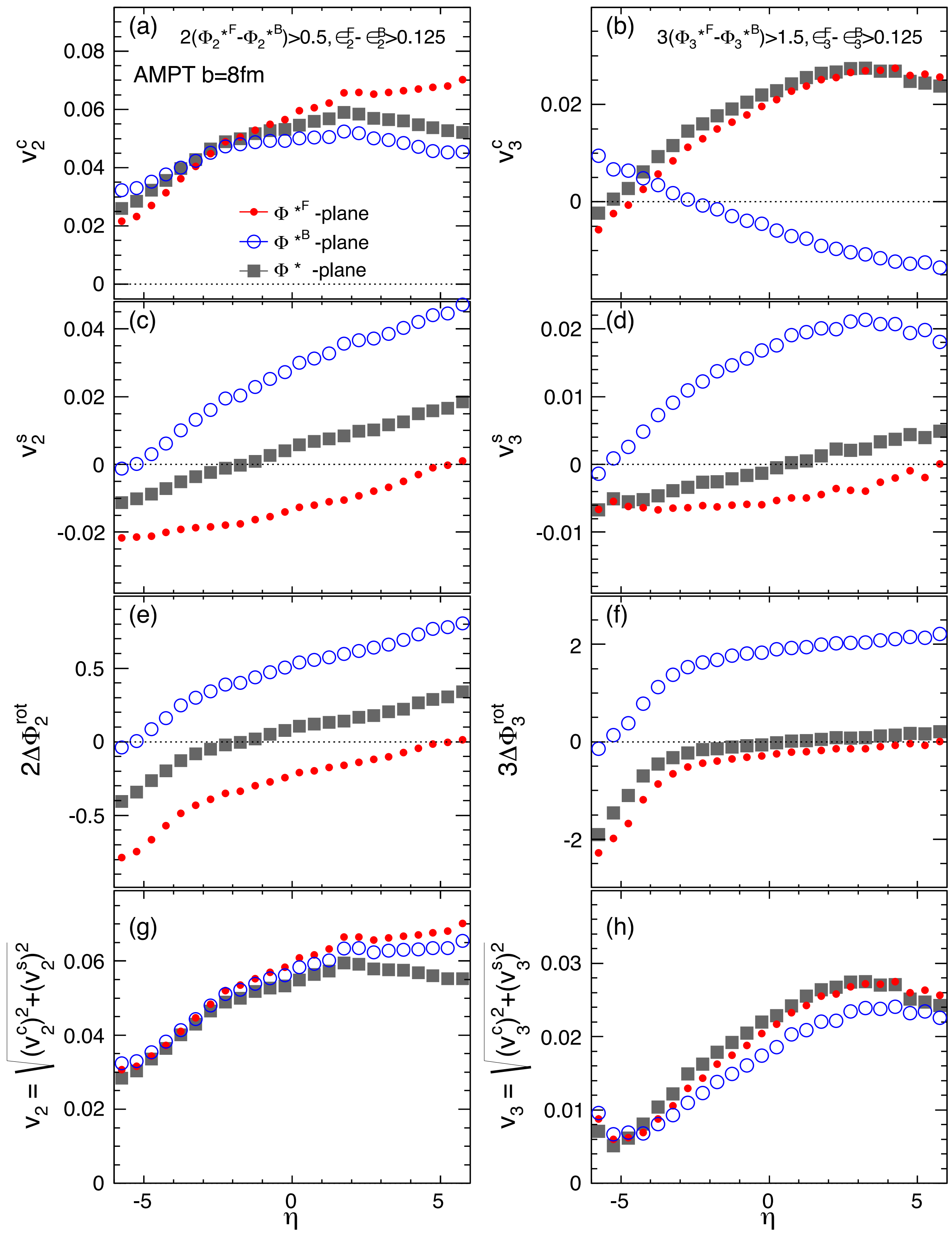
- Twisted medium between forward and backward directions emerging from participant fluctuations
- Possible underestimate of v_n i.e. overestimate of shear-viscosity due to neglecting decorrelated term



J.Jia et. al. PRC90.034905

ESE : Twist Effect

AMPT Simulations Jia et. al. arXiv:1403.6077



Event Selection

$$2(\Psi_2^F - \Psi_2^B) > 0.5 \qquad \varepsilon_2^{\rm back} < \varepsilon_2^{\rm for.}$$

$$3(\Psi_3^F - \Psi_3^B) > 1.5 \qquad \varepsilon_3^{\rm back} < \varepsilon_3^{\rm for.}$$

$$v_n^c = \langle \cos n(\phi - \Psi_n) \rangle / Res\{n\Psi_n\}$$

$$v_n^s = \langle \sin n(\phi - \Psi_n) \rangle / Res\{n\Psi_n\}$$

- Twisted term v_n^s observed
  - Underestimate of v_n
- This study should be done for experimental data

Summary

- Higher-order flow harmonics v_n in A+A collisions
  - More stringent constraints to IC & viscosity
    - Still multiple combinations of those
  - Medium shows possible acoustic-viscous dumping
  - Substantial HF parton energy loss in medium
  - None zero direct photon v_n puzzle
- Collectivity in p(d)+A collisions
  - Flow like features similar to those in A+A collisions
  - Need to see mass dependence of CGC calculation
  - Not Conclusive
  - Jet-Medium coupling study using Jet+Hydro framework
- Event Shape Study is a possible probe to initial conditions