Recent measurements of azimuthal anisotropy v_n in heavy ion collisions

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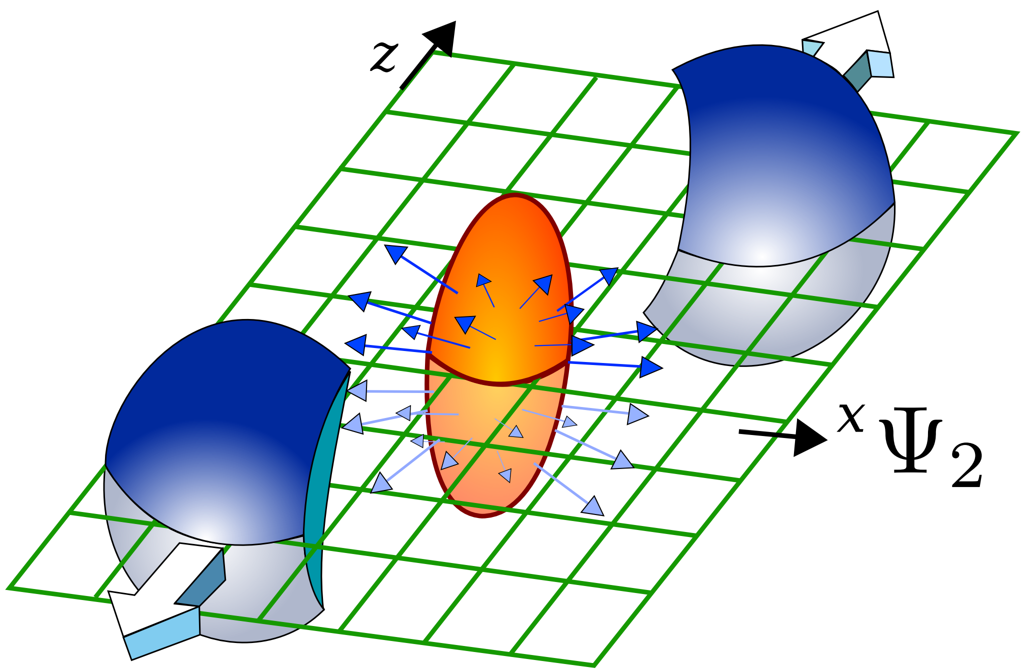
Outline

- Azimuthal anisotropy in p(d)+A collisions
- HBT measurements in p(d)+A collisions
- Event shape control study in A+A collisions

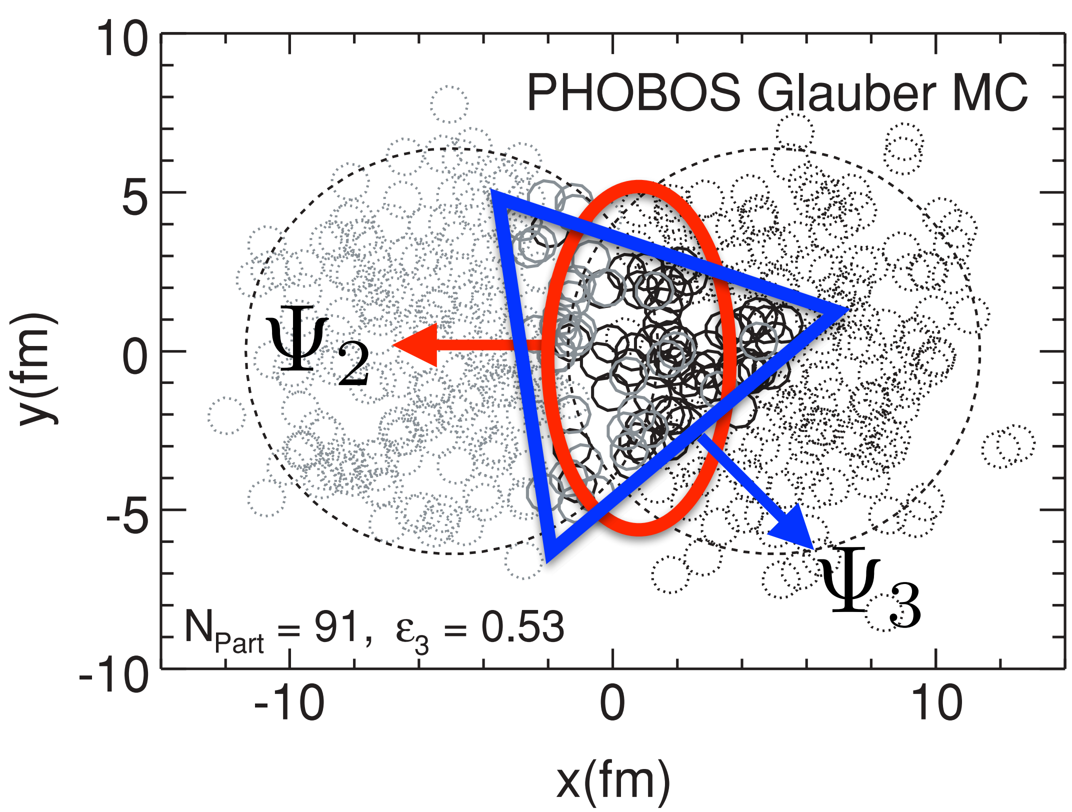
Initial Fluctuations



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

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

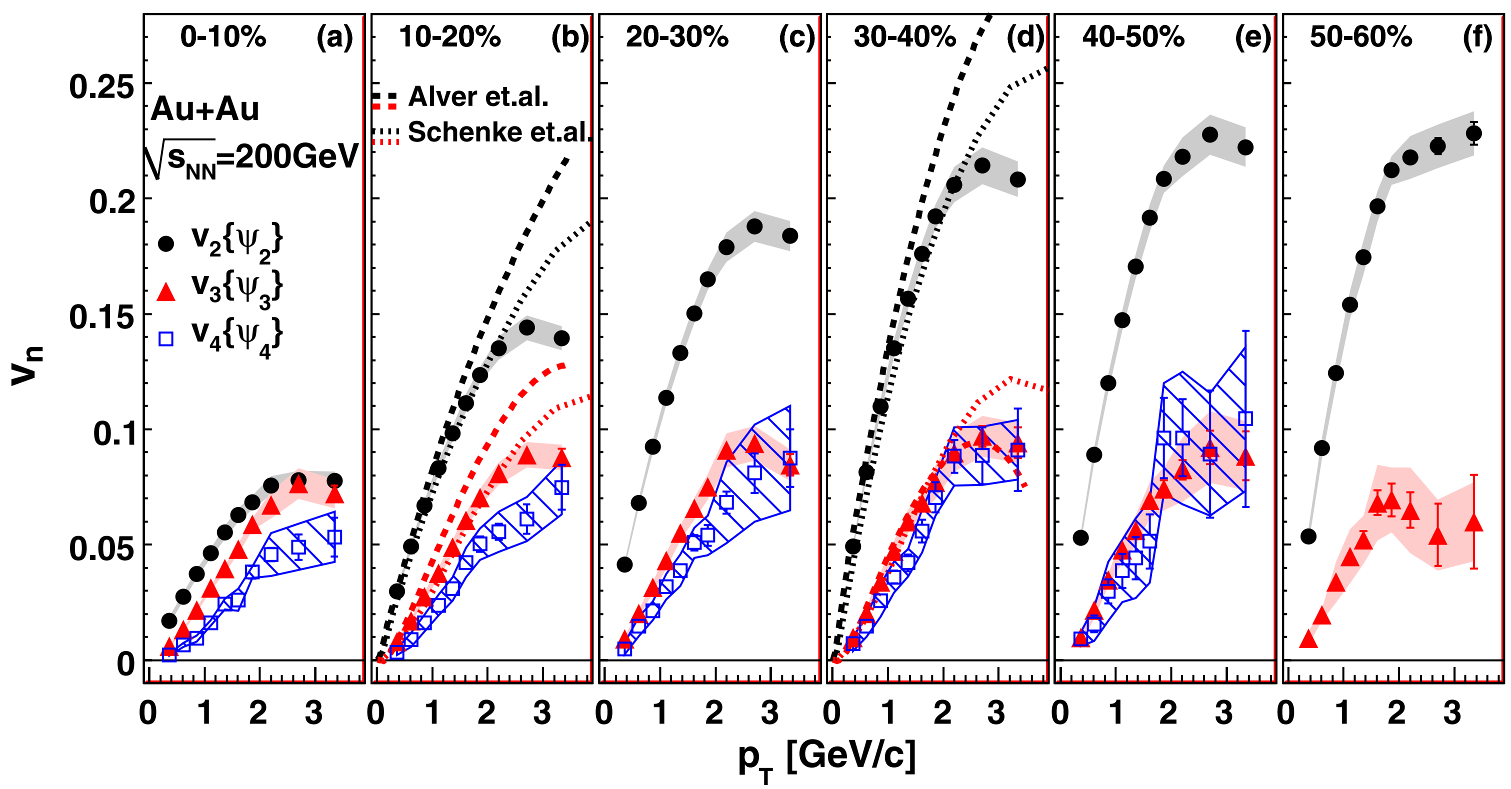
$$\varepsilon_n^{part} = \frac{\sqrt{\langle r^2 \cos n\phi_{part}\rangle^2 + \langle r^2 \sin n\phi_{part}\rangle^2}}{\langle r^2 \rangle},$$

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

Differential v_n measurements

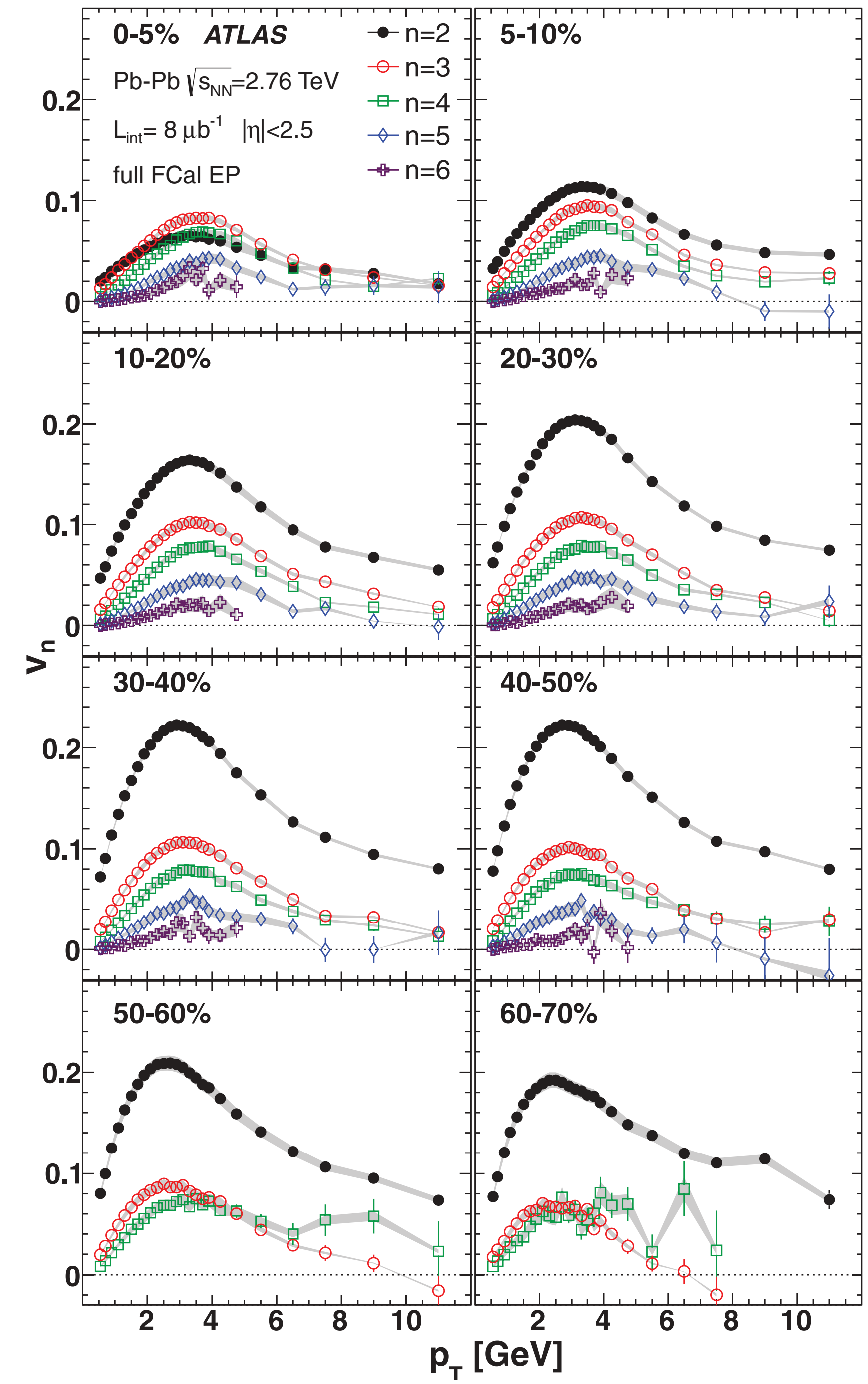
RHIC

PHENIX PRL107.252301



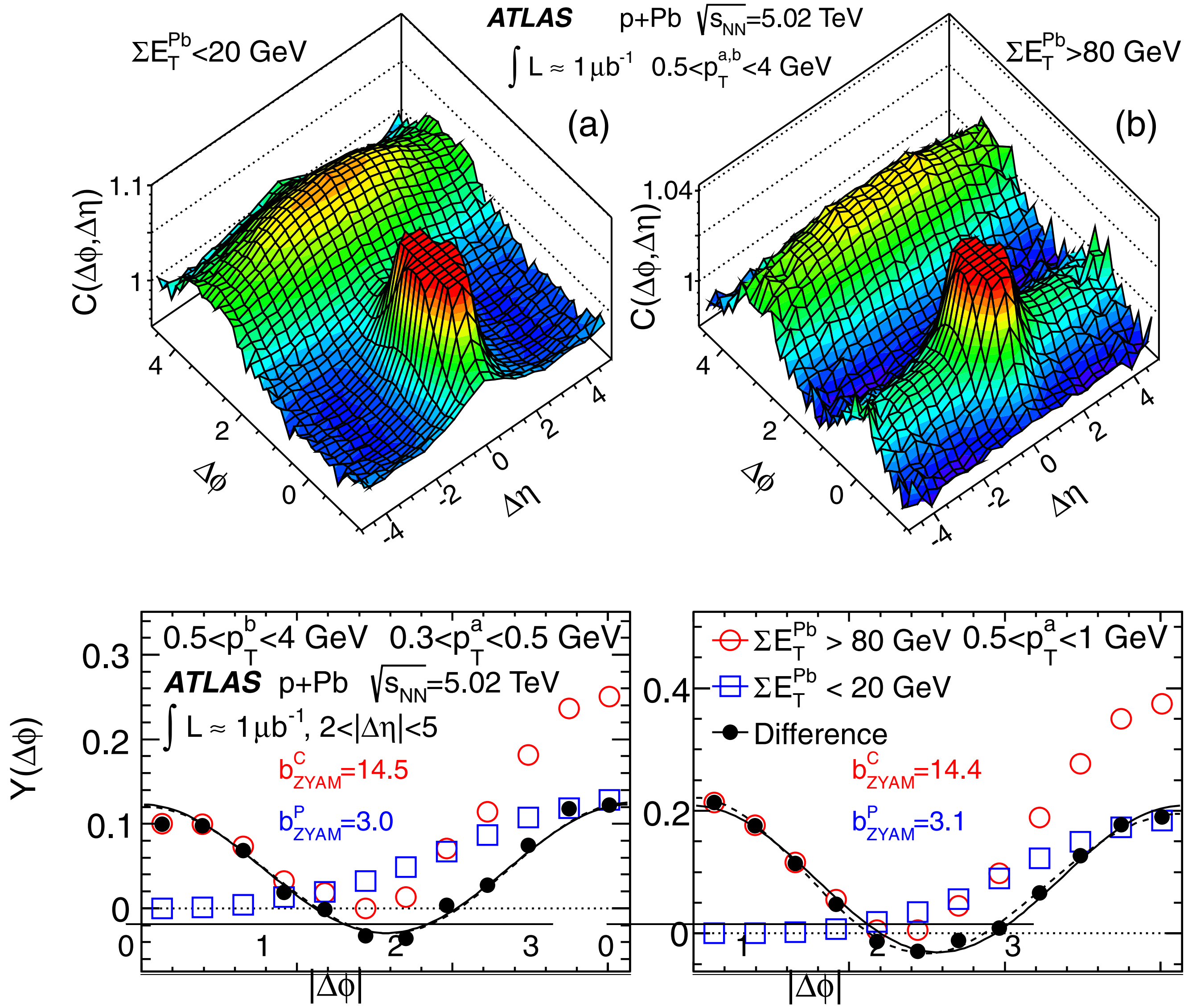
LHC

ATLAS PRC86.014907

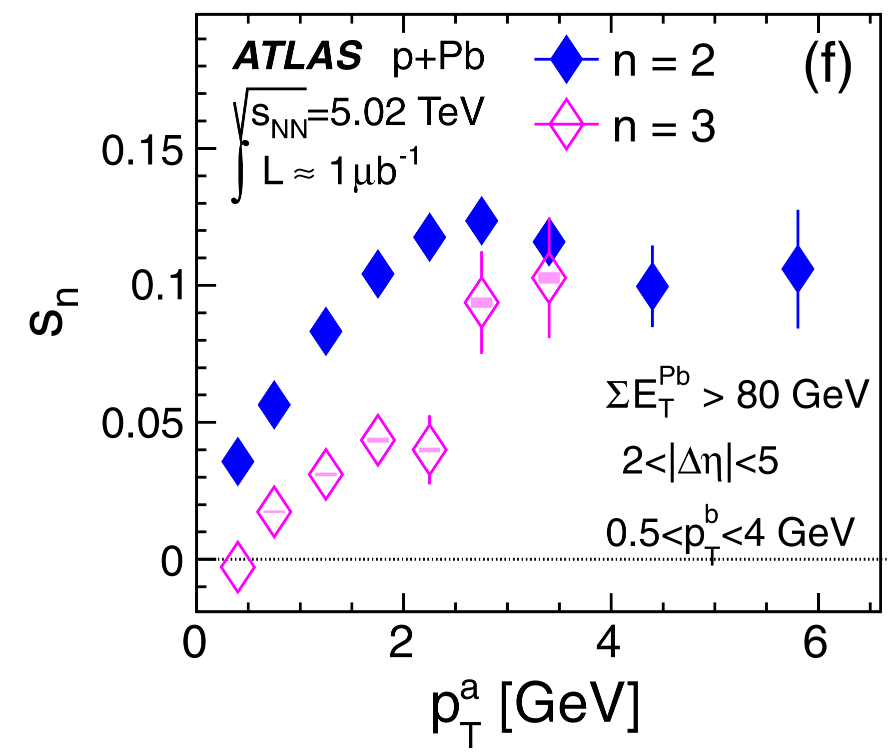


- Substantial higher order flow harmonics v_n is observed in both RHIC and LHC energy ranges

Ridge & v_n in p+Pb collisions

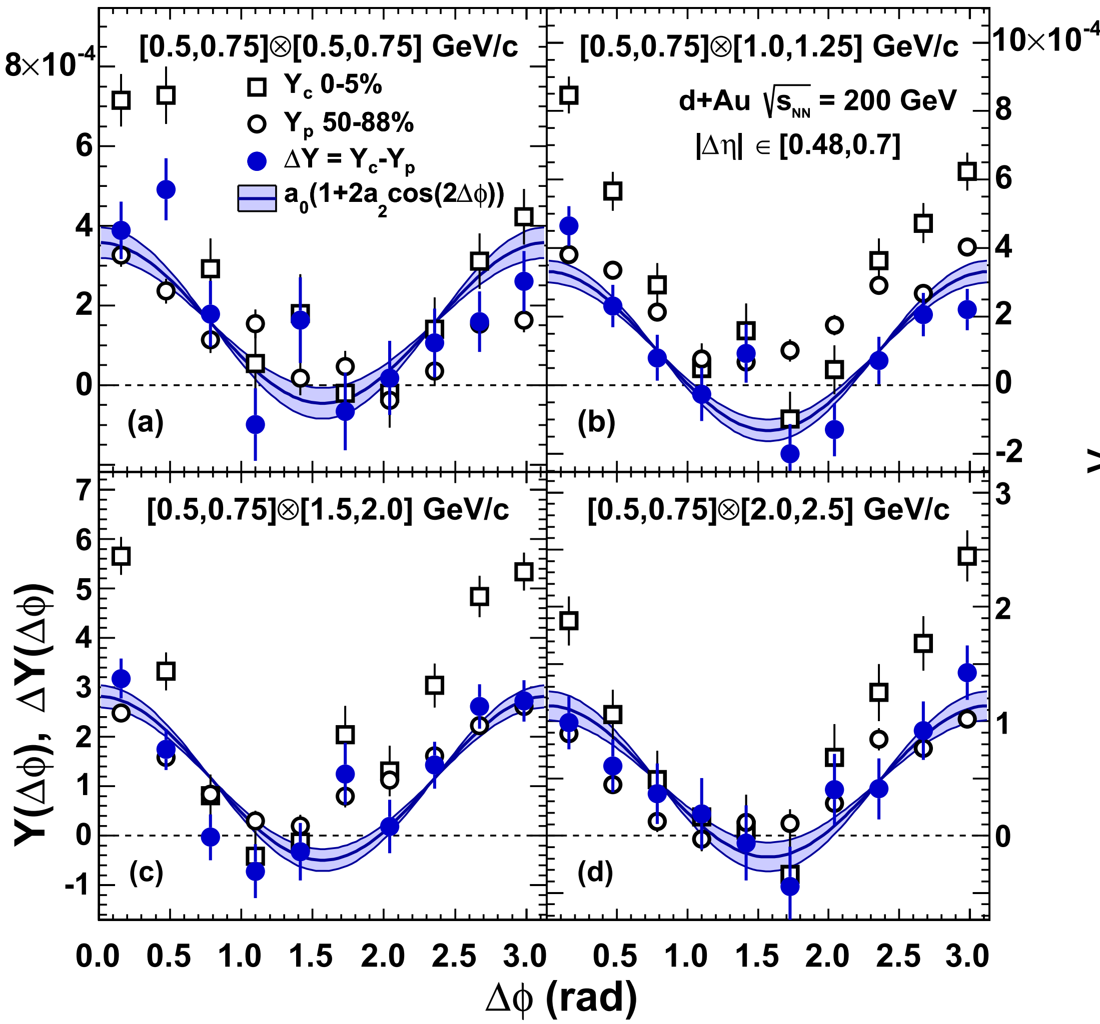


ALICE: Physics Letters B 726 (2013)
ATLAS: Phys. Rev. Lett. 110(2013)
CMS: Phys. Lett. B 7198(2013)

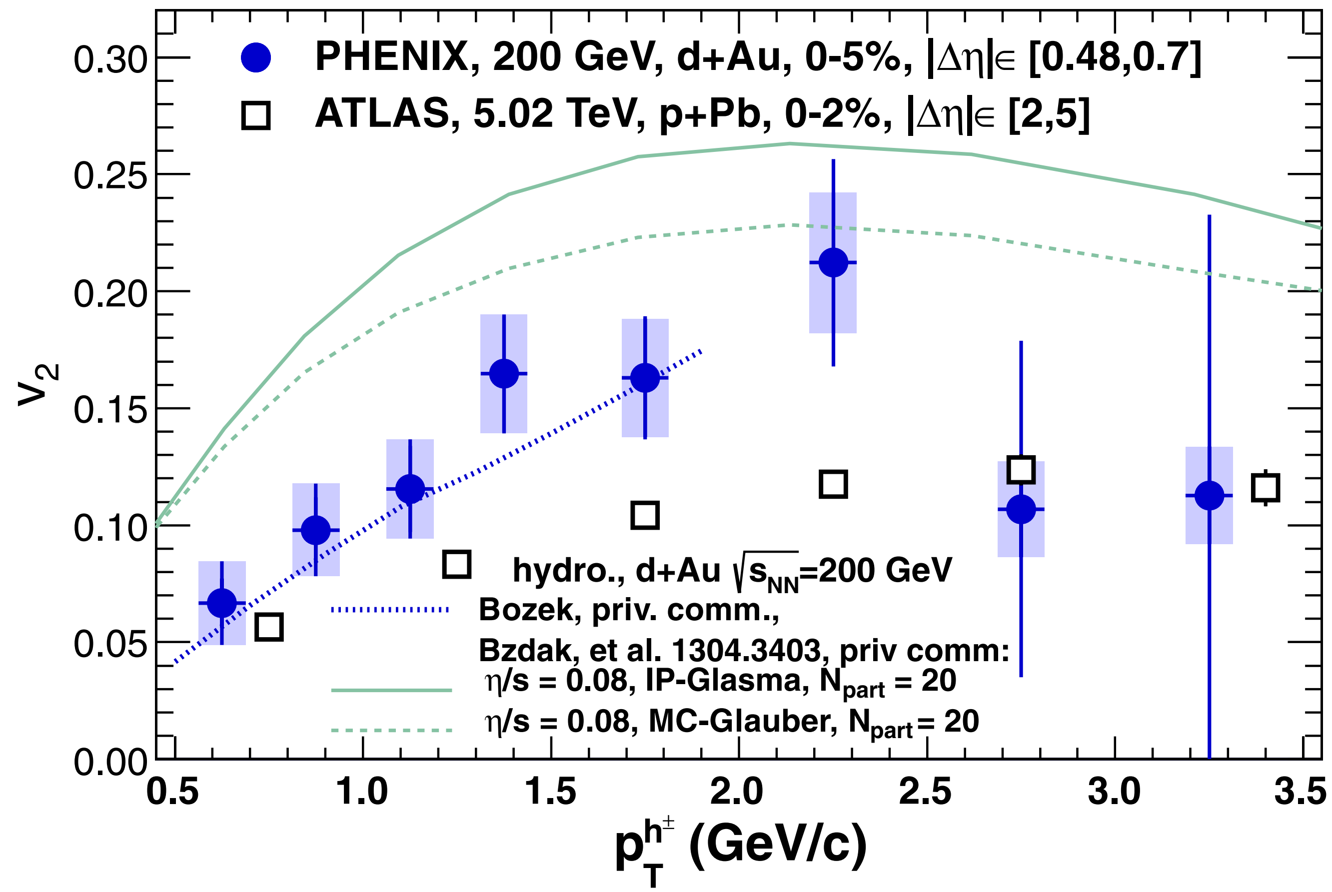


- Ridge and $v_{2,3}$ are observed in high multiplicity p+Pb collision events

Ridge and v2 in d+Au collisions

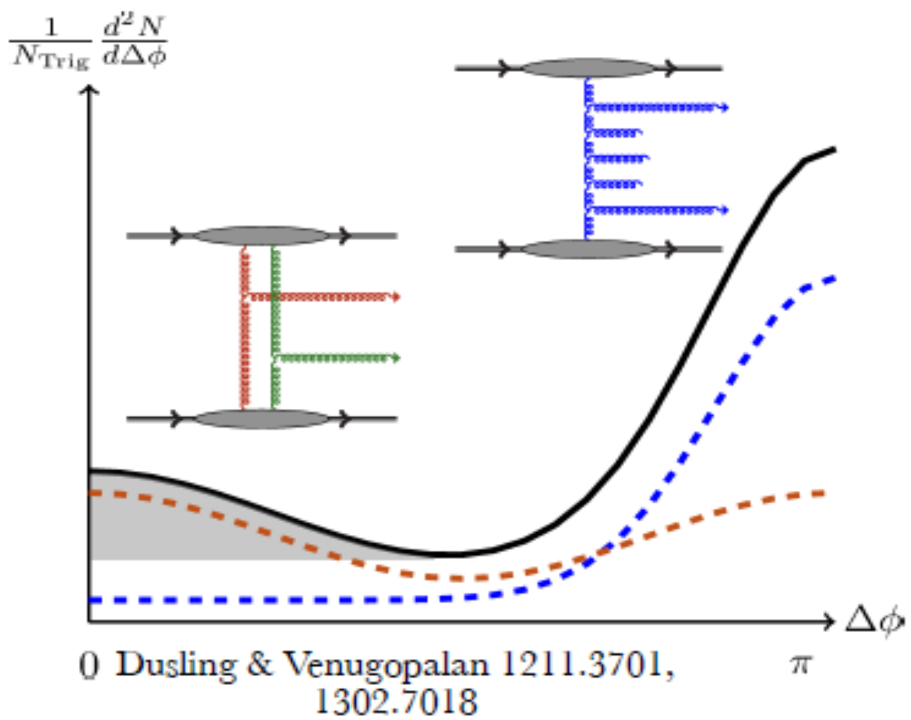


PRL111.212301(2013)

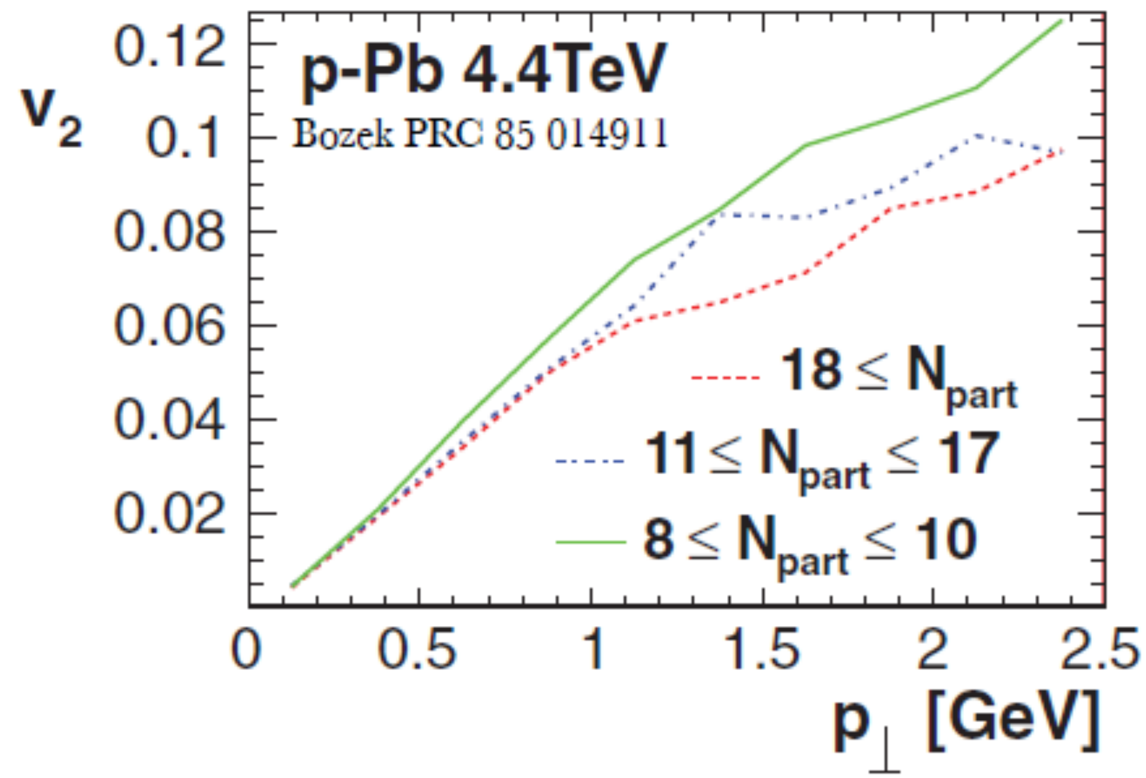


- Peripheral subtraction at $0.48<|\Delta\eta|<0.7$
- None zero v_2 is observed in 0-5% d+Au collisions,
  - Similar p_T dependence of v_2 in 0-2% p+Pb collisions
  - Consistent with hydrodynamics calculations

Initial or Final State Effect?



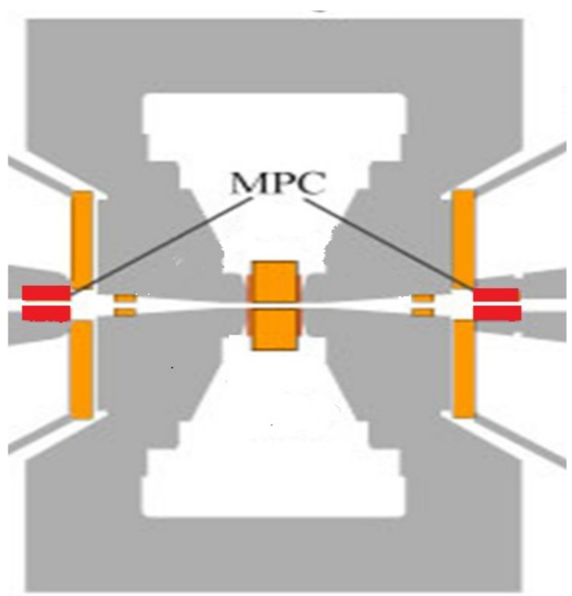
CGC

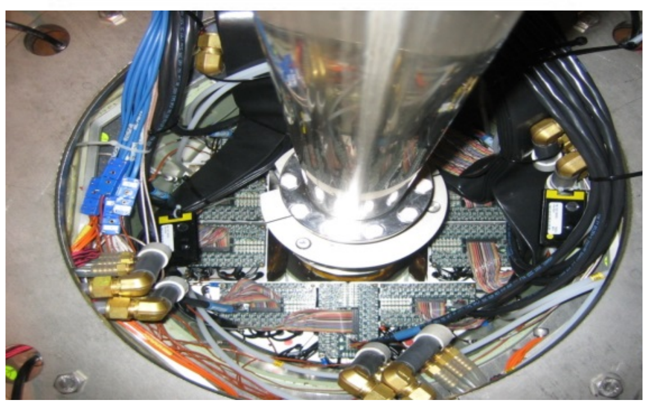


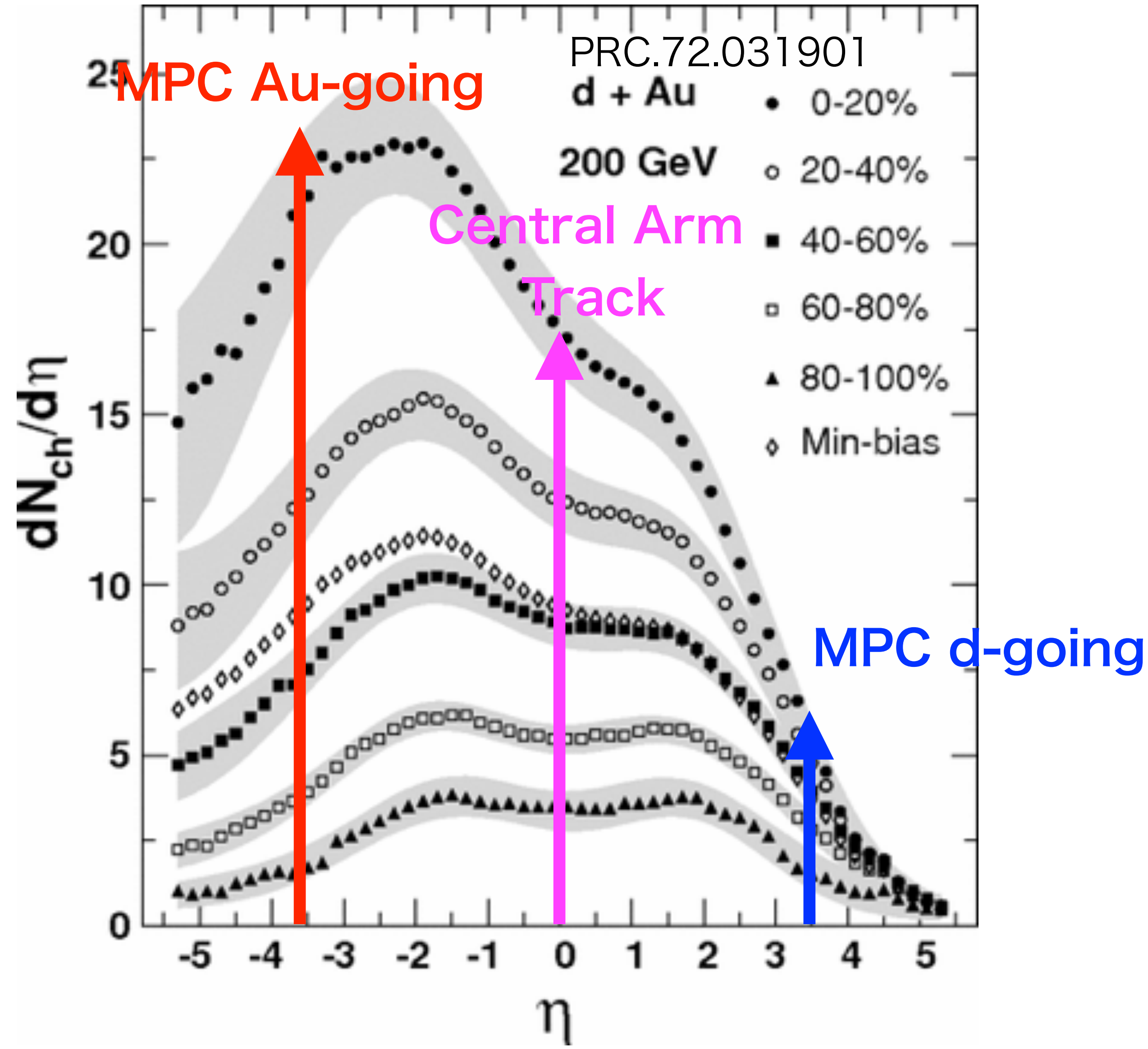
Hydrodynamics

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

Long-range rapidity correlations







- Muon Piston Calorimeter (MPC) : at $3<|\eta|<4$
- Rapidity separation of $|\Delta\eta|>2.75$ is achieved by measuring correlations between tracks ($|\eta|<0.35$) and MPC towers

Track-tower angular correlations

$$s(\Delta\phi) = \frac{d(\omega_{tower} N_{same}^{track-tower})}{d(\Delta\phi)}$$: Track-Tower correlations in same events

$$\Delta\phi = \phi_{tower} - \phi_{track}$$

ω_{tower} : Transverse Energy of each tower (Proportional to multiplicity)

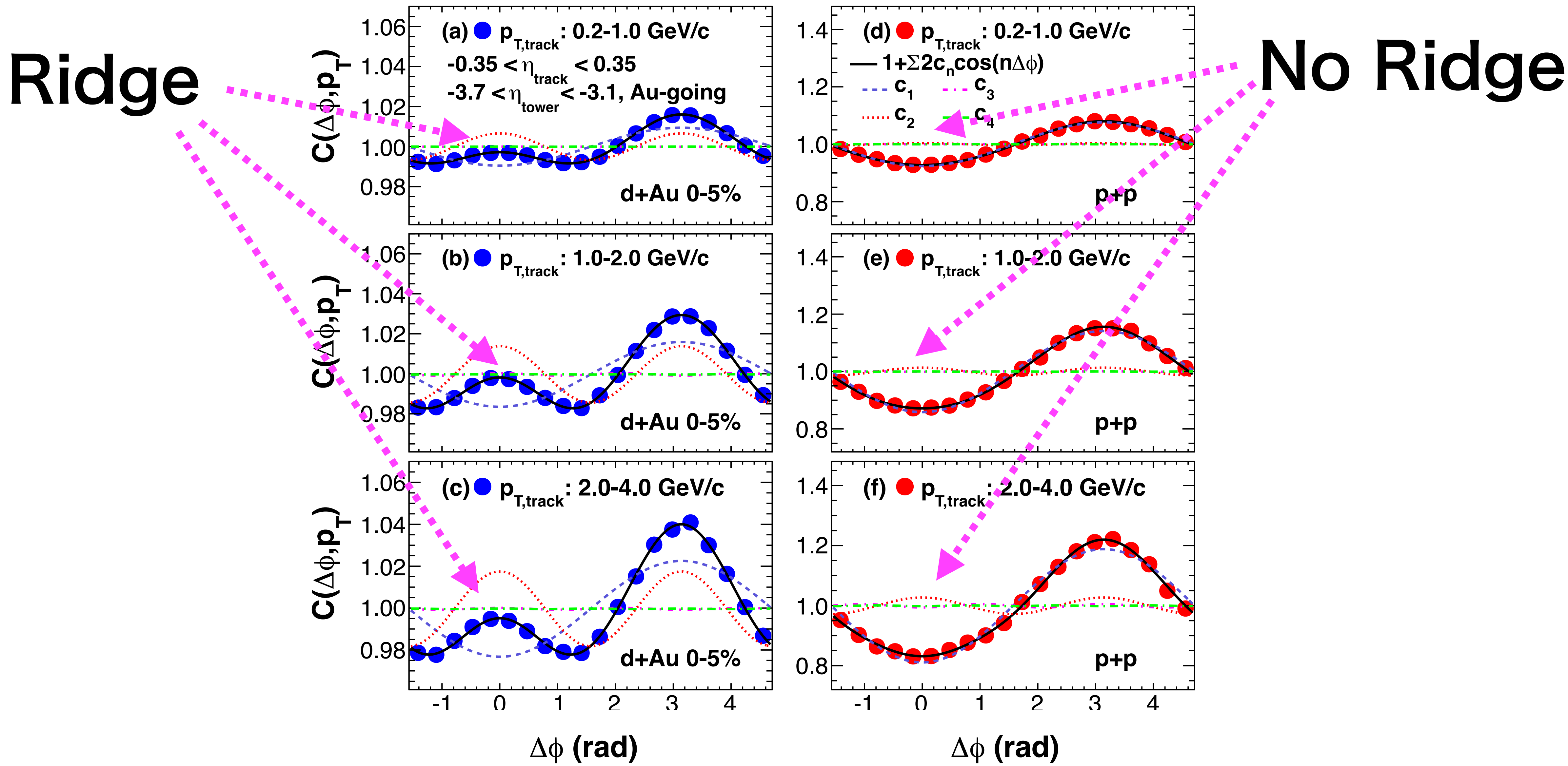
$N_{same}^{track-tower}$: Number of Track-Tower Pairs in same events

$M(\Delta\phi)$: Track-Tower correlations in mixed events

$$C(\Delta\phi) = \frac{S(\Delta\phi) \int M(\Delta\phi)}{M(\Delta\phi) \int S(\Delta\phi)}$$: Correlation Function by Event Mixing

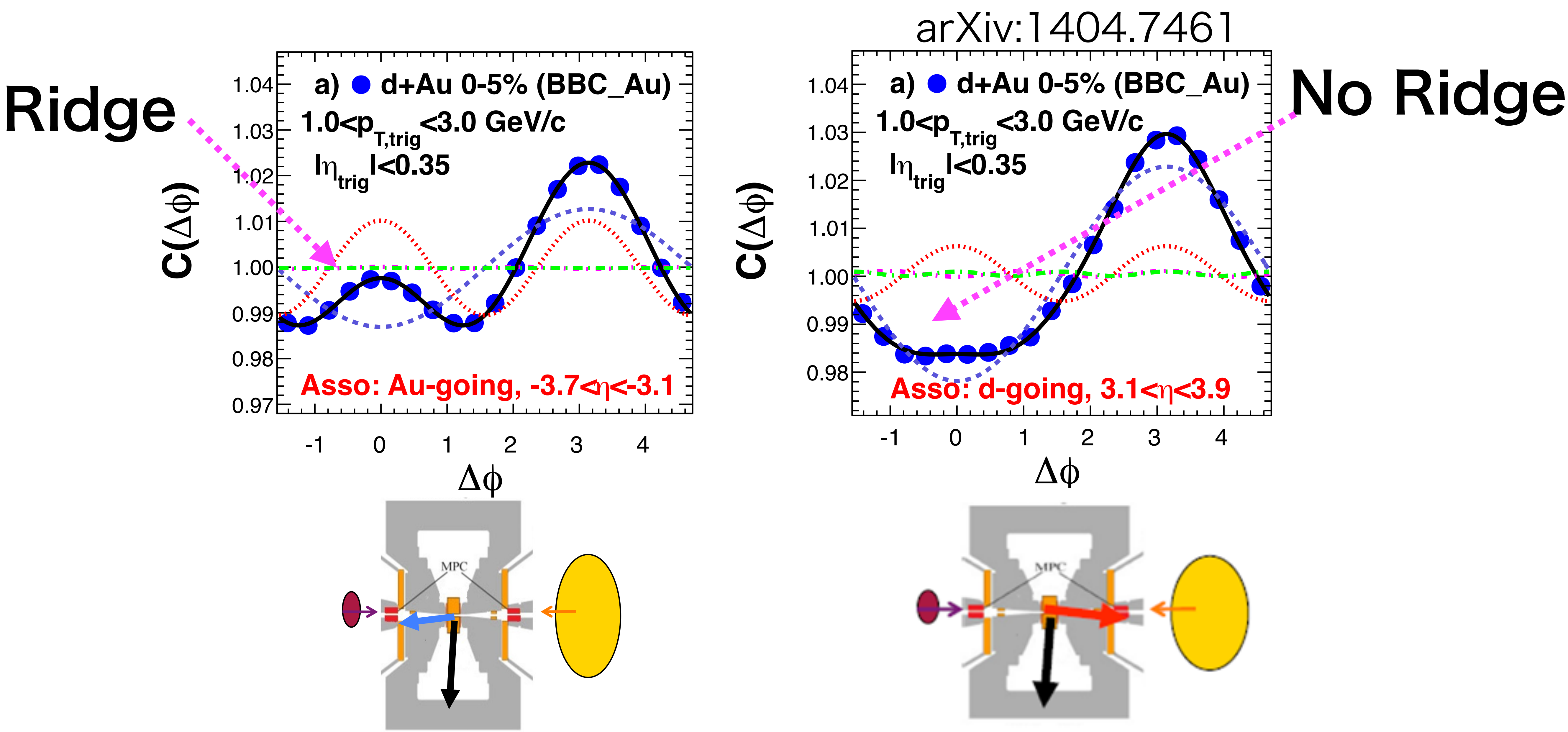
Correlations in p+p and 0-5% d+Au collisions

arXiv:1404.7461



- Ridge is observed in 0-5% d+Au collisions, which is not observed in p+p collisions

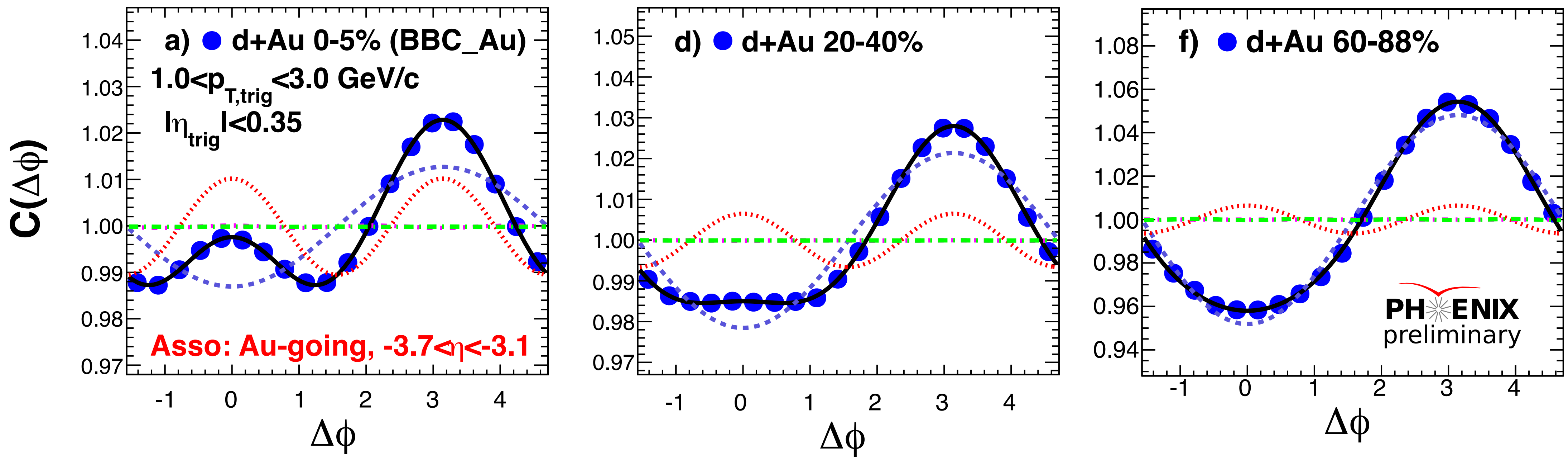
“Au-going” & “d-going”

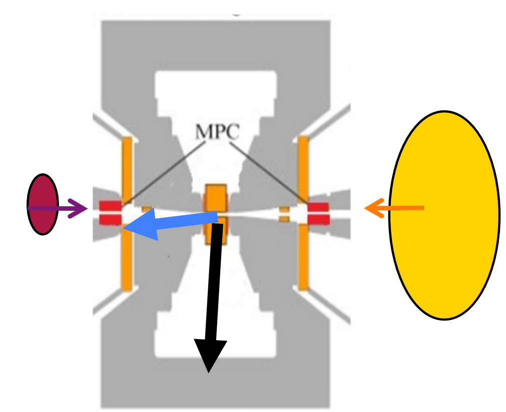


- Ridge is observed in “Au-going” direction
- No ridge is observed in “d-going” direction
- Non-zero cos2Δϕ is observed in both directions

Centrality dependence in "Au-going" direction

arXiv:1404.7461

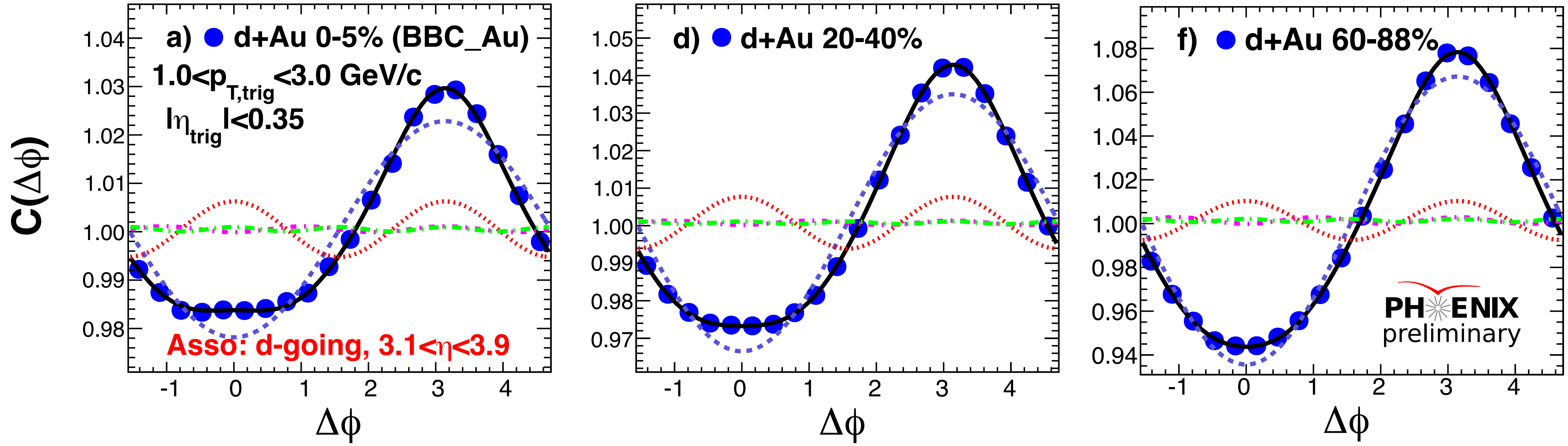




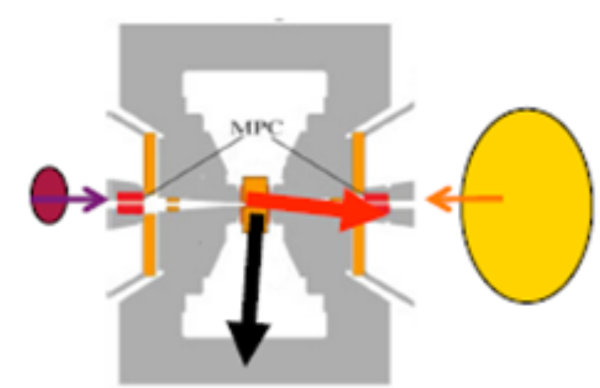
- Ridge is observed only in most-central d+Au collisions
- None-zero cos2Δφ is observed in all centralities

Centrality dependence in “d-going” direction

arXiv:1404.7461

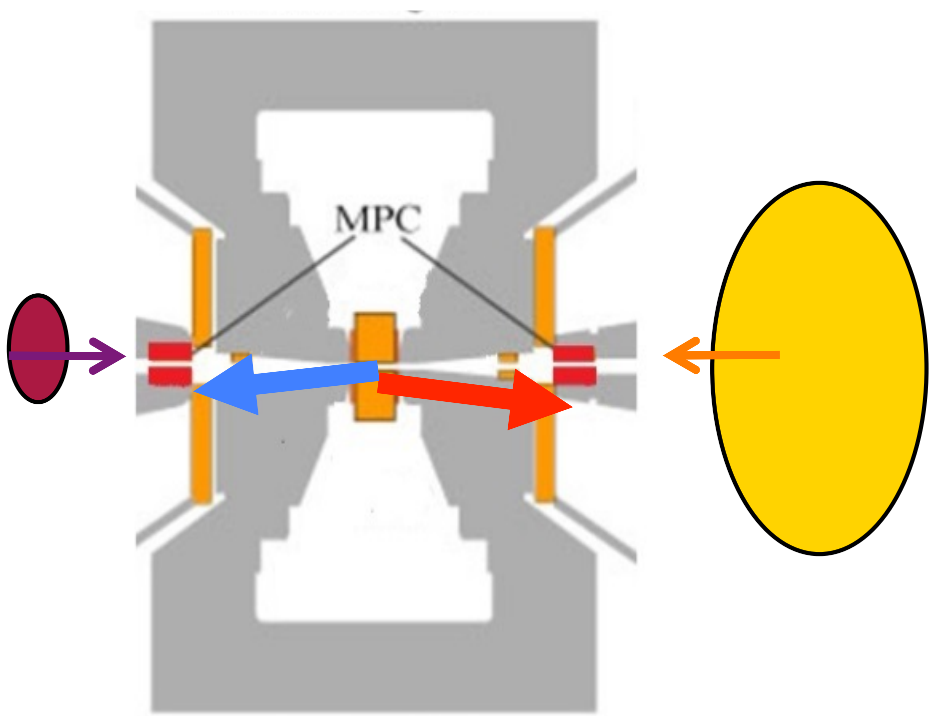


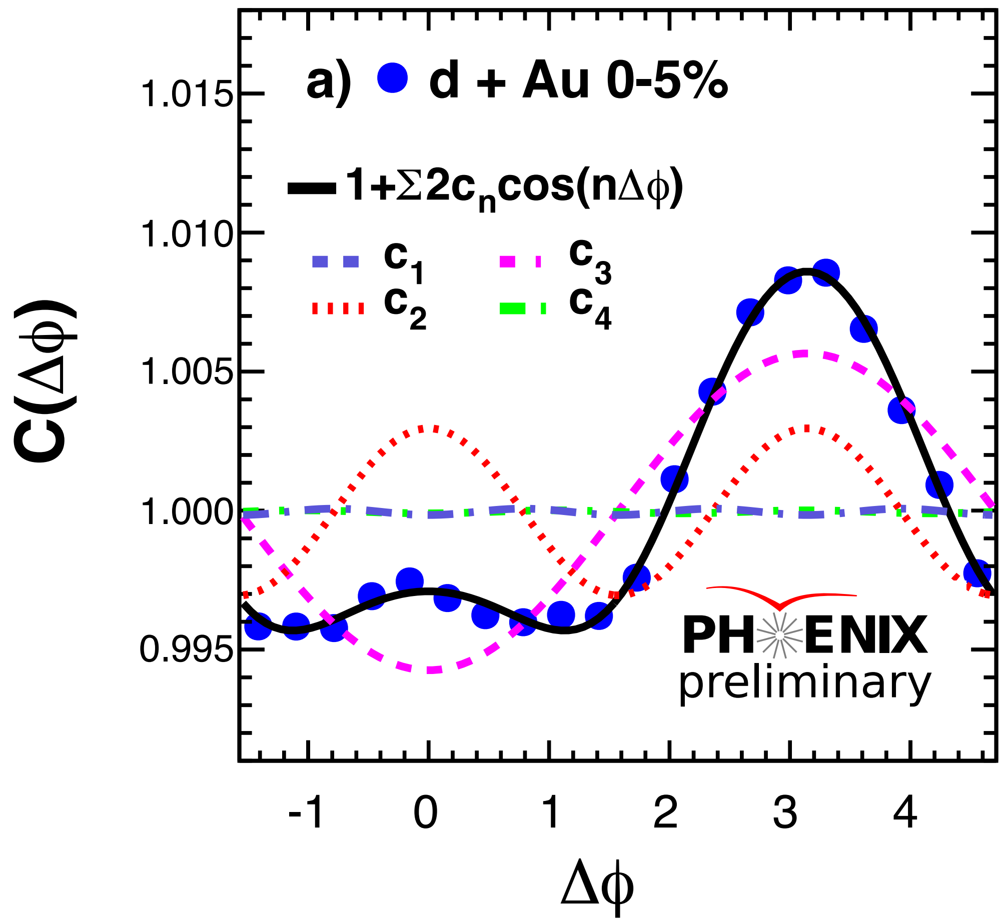
- No ridge is observed even in most-central
- None-zero cos2Δφ is observed in all centralities, cos2Δφ overwhelmed by cos1Δφ
- What if peripheral subtraction?
- Subtraction method appears to be important when discussing correlation shapes



Ridge across $|\Delta\eta|>6$

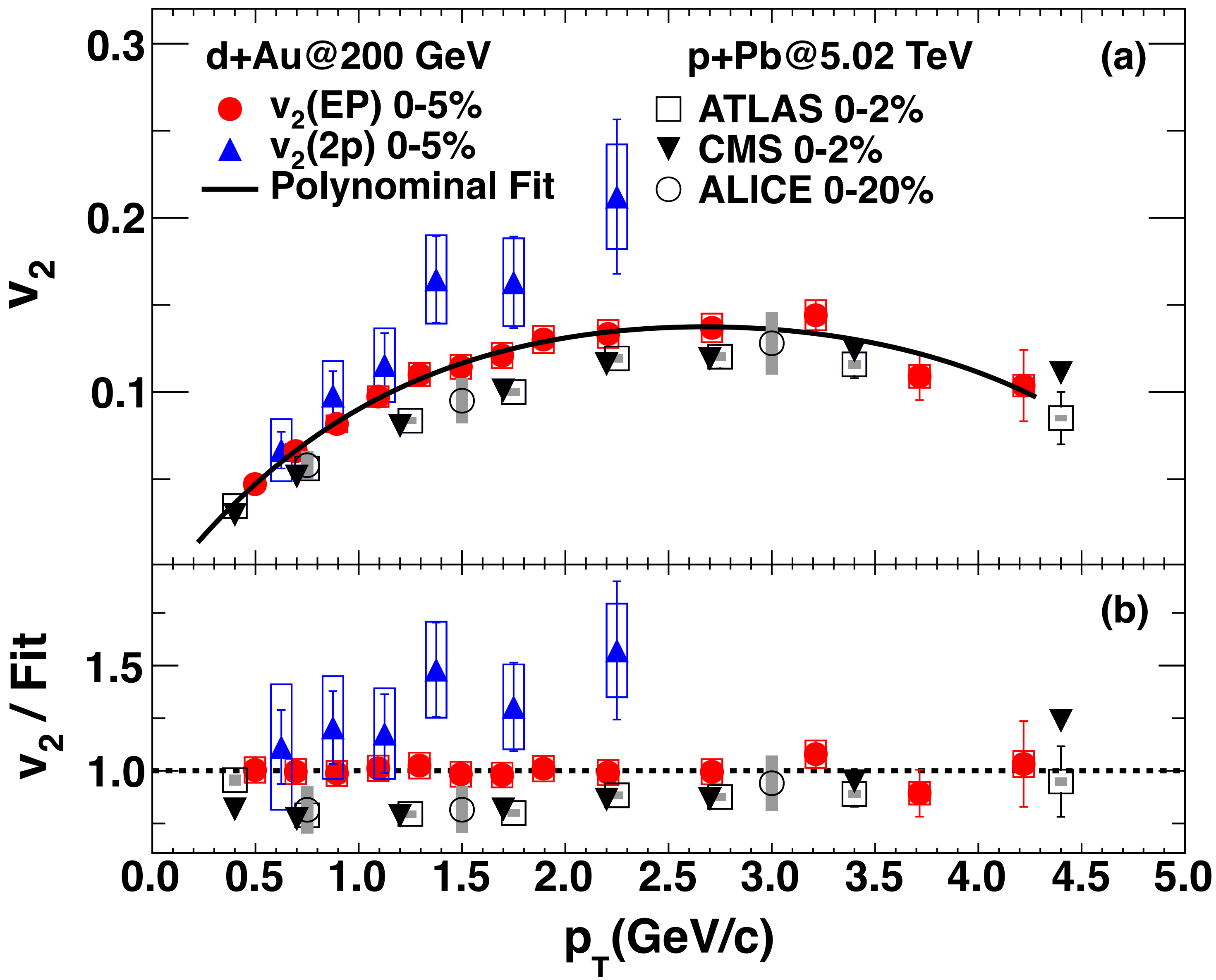
arXiv:1404.7461





- E_T integrated tower-tower correlations
- Forward-Backward correlations show a ridge across $|\Delta\eta|>6$!!
- Unlike jet effects

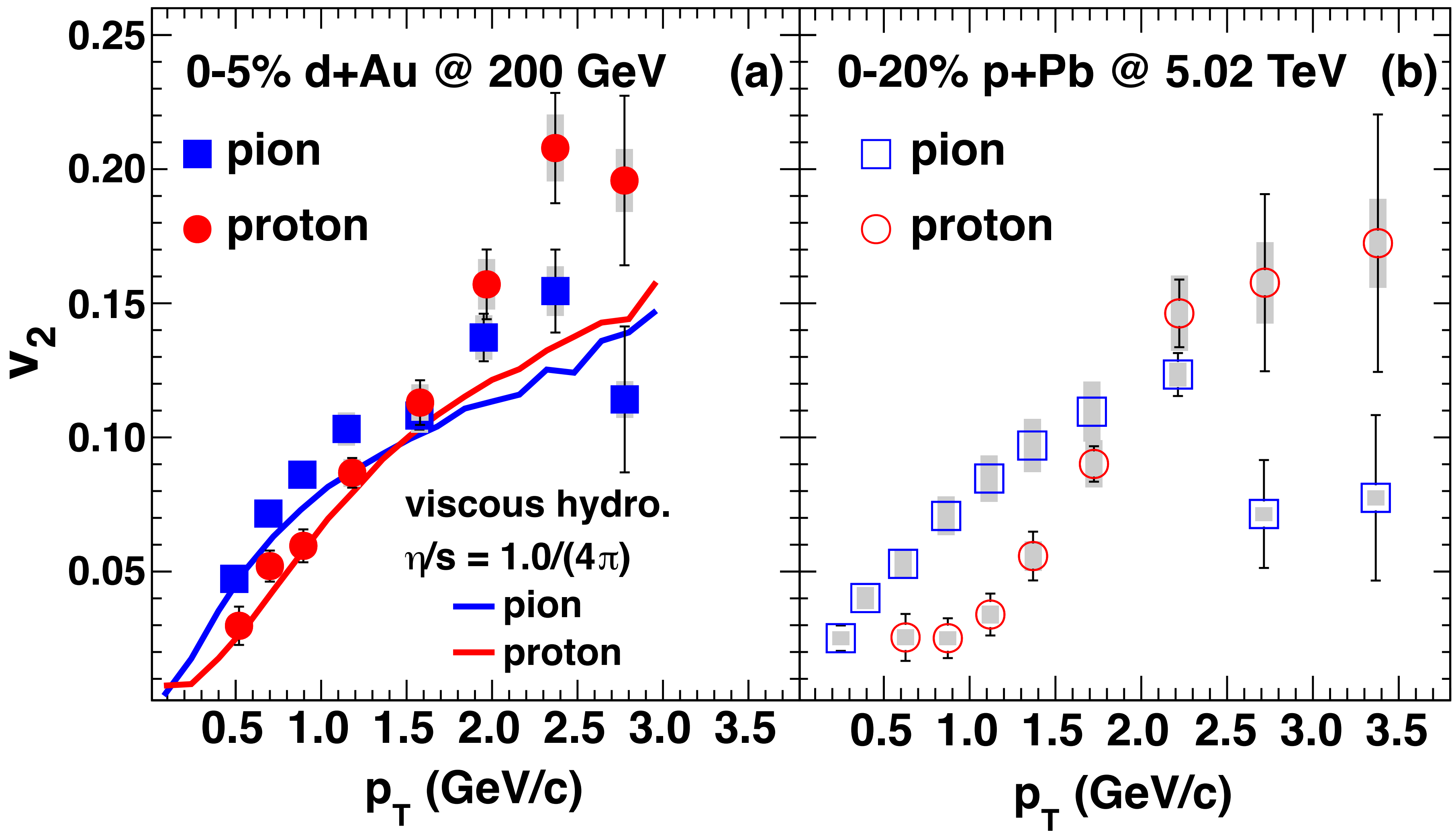
v_2 with more rapidity gap



- EP method using MPC : MPC-CNT rapidity gap $|\Delta\eta|>2.75$
- Sizable v_2 observed across large rapidity gap

PID v_n in p(d)+A

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

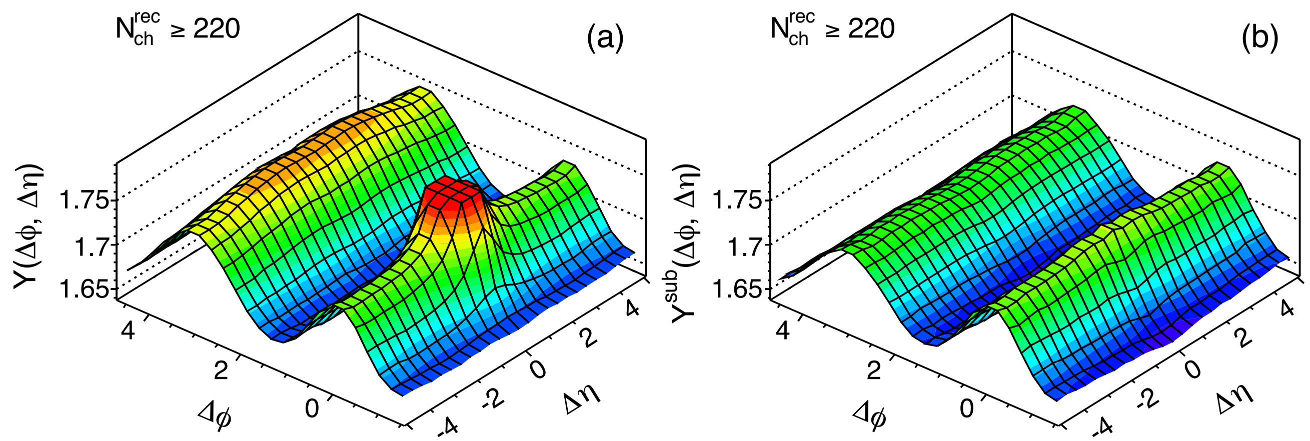


- Mass dependence in low p_T
- Baryon/Meson difference at intermediate p_T
- Qualitatively consistent with hydrodynamics.

Non-flow effects in p+A collisions

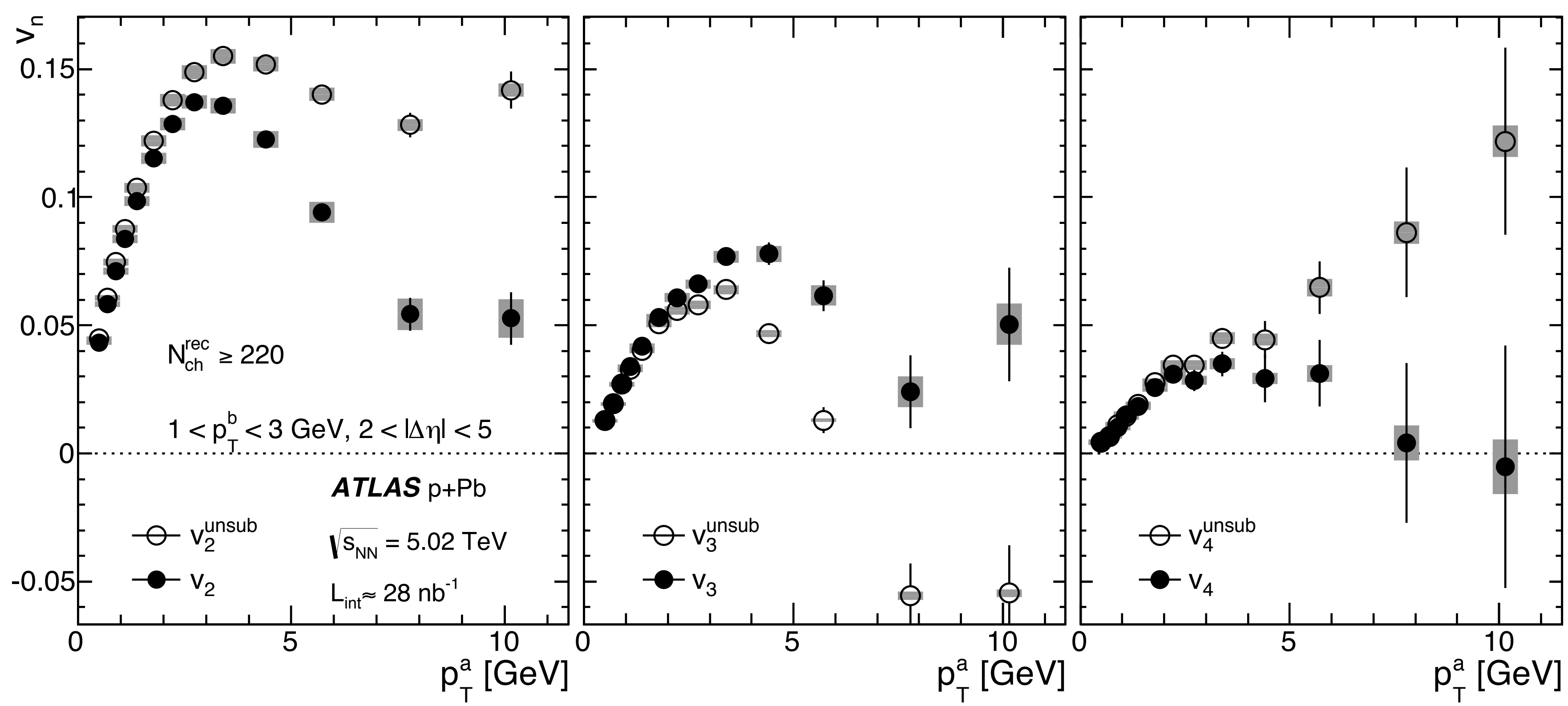
Recoil Jet Subtraction

ATLAS arXiv:1409.1792v1



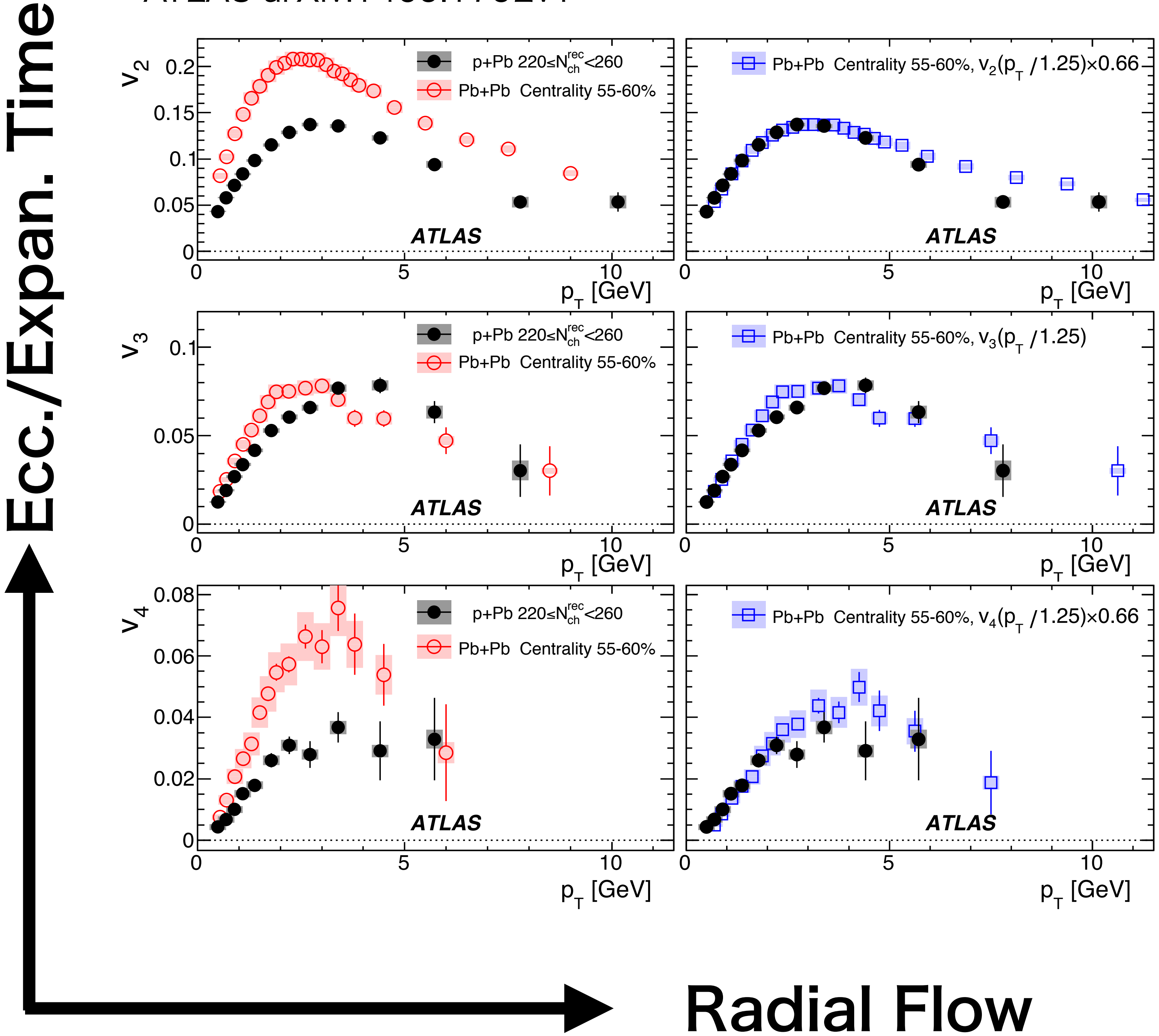
$$Y^{sub}(\Delta\phi) = Y(\Delta\phi) - \alpha Y^{corr}_{peri}(\Delta\phi)$$

- 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



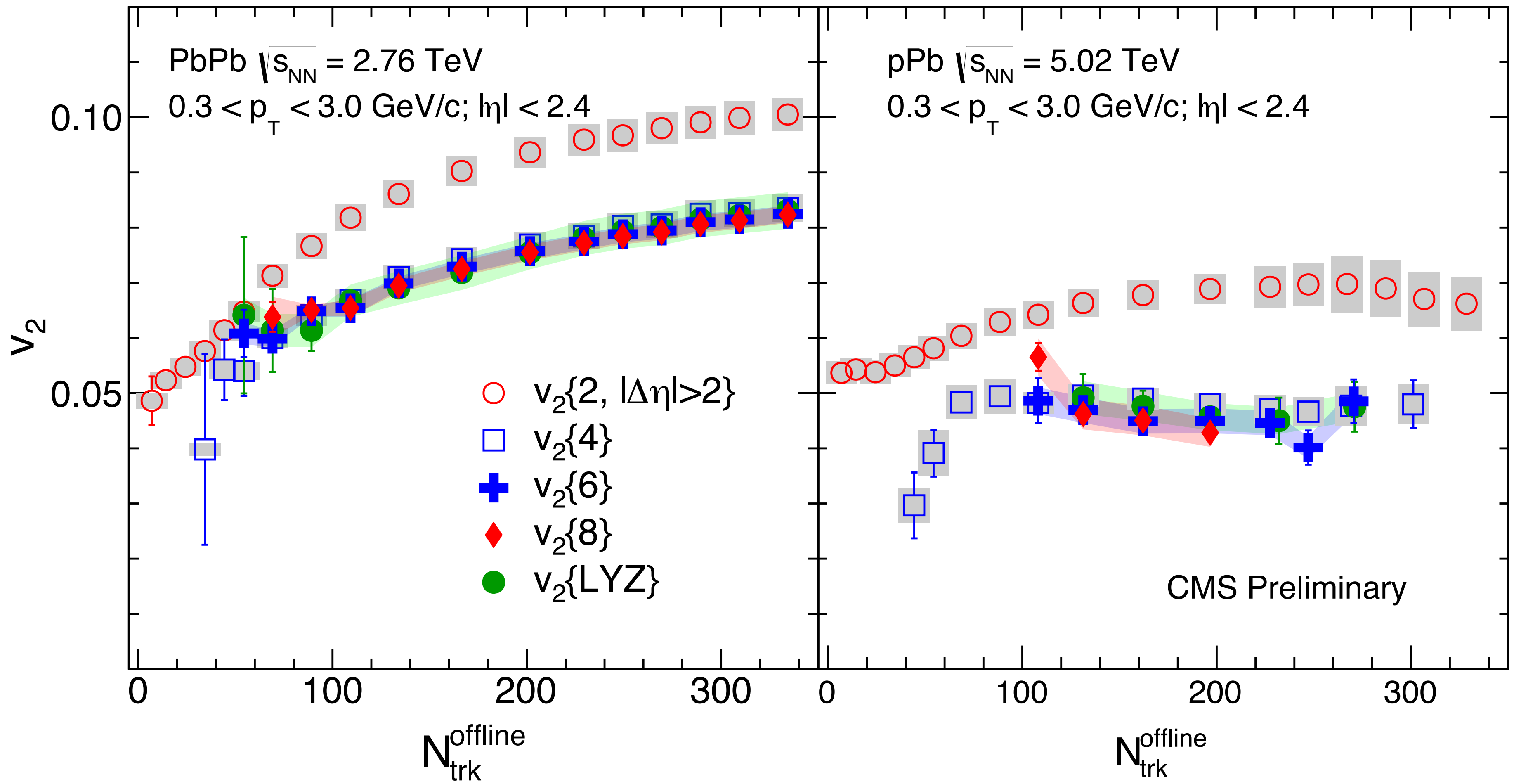
Scaling among p+A and A+A v_n

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

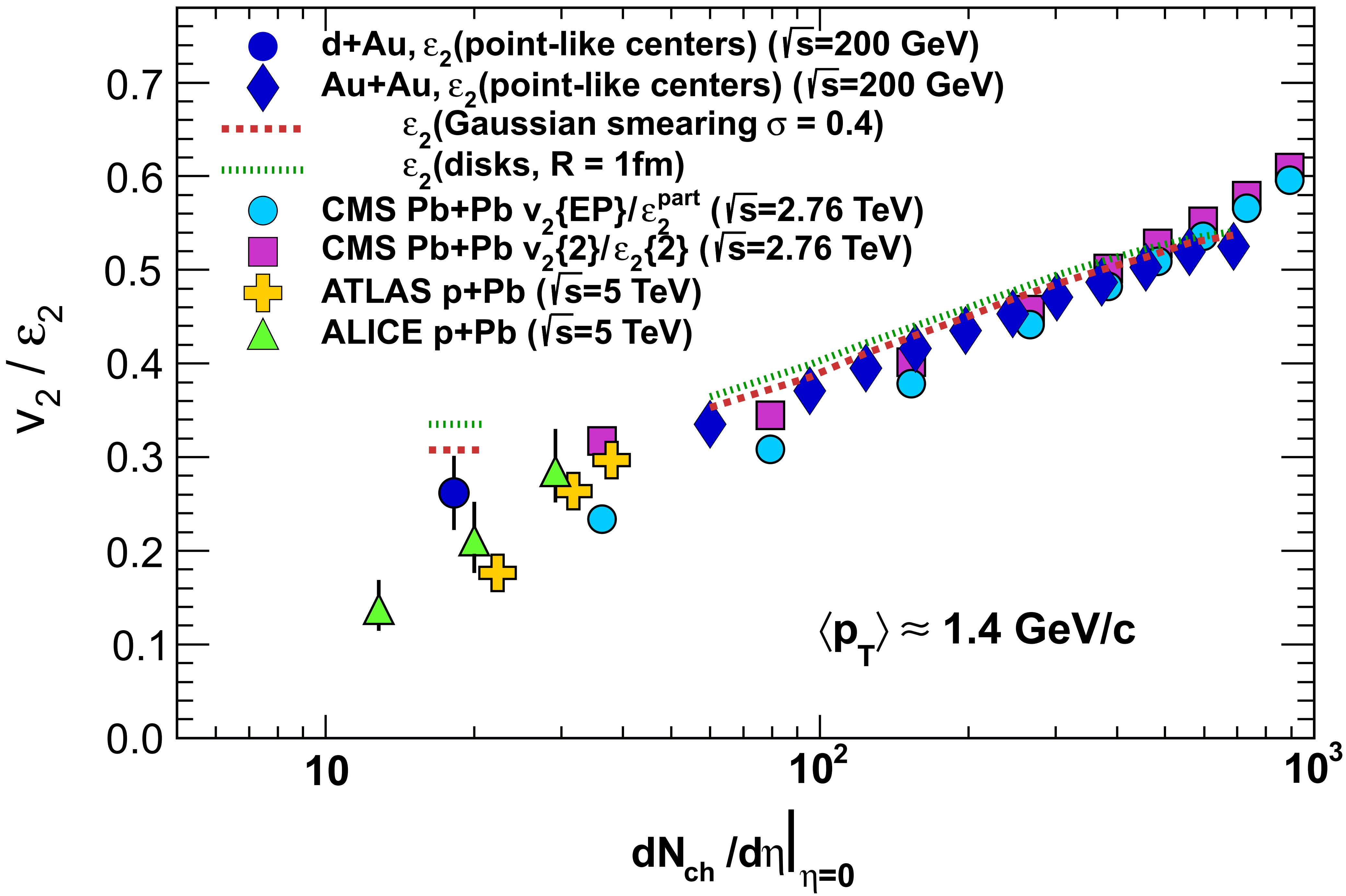
Multi Particle Cumulants



- 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

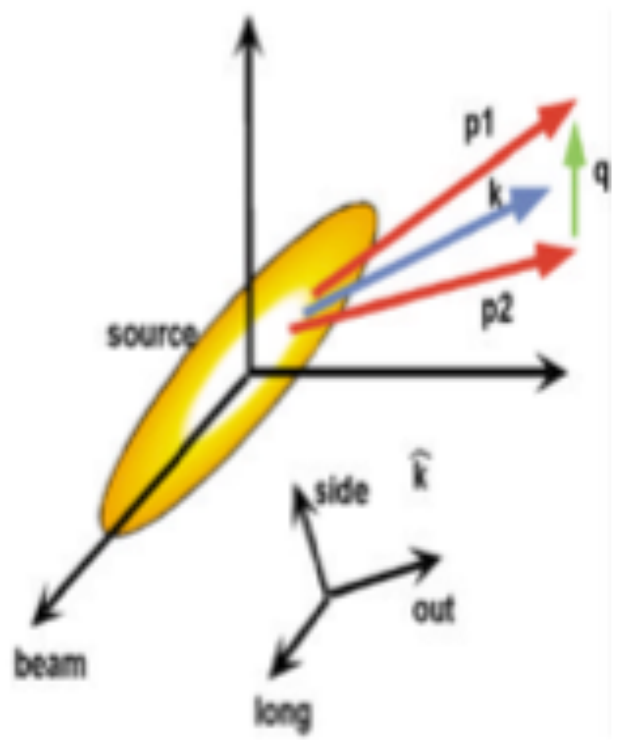
Bzdak et.al. arXiv:1311.7325

v2/ecc



d+Au, ε2(point-like centers) (√s=200 GeV)
Au+Au, ε2(point-like centers) (√s=200 GeV)
ε2(Gaussian smearing σ = 0.4)
ε2(disks, R = 1fm)
CMS Pb+Pb v2{EP}/ε2part (√s=2.76 TeV)
CMS Pb+Pb v2{2}/ε2{2} (√s=2.76 TeV)
ATLAS p+Pb (√s=5 TeV)
ALICE p+Pb (√s=5 TeV)
⟨pT⟩ ≈ 1.4 GeV/c
v2 / ε2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10
10^2
10^3
dNch /dη|η=0

HBT Methodology



LCMS Frame

Space momentum correlation

$$C_2 = P(p_1, p_2)/\{P(p_1)P(p_2)\} \sim 1 + |\rho(q)|^2$$
$$= C_2^{core} + C_2^{halo}$$
$$= [\lambda(1+G)F_{coul}] + [1-\lambda]$$

$$G = \exp\left(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_L^2 q_L^2 - 2R_{os}^2 q_o q_s\right)$$

F_{coul} : coulomb correction factor

λ : fraction of pairs in the core

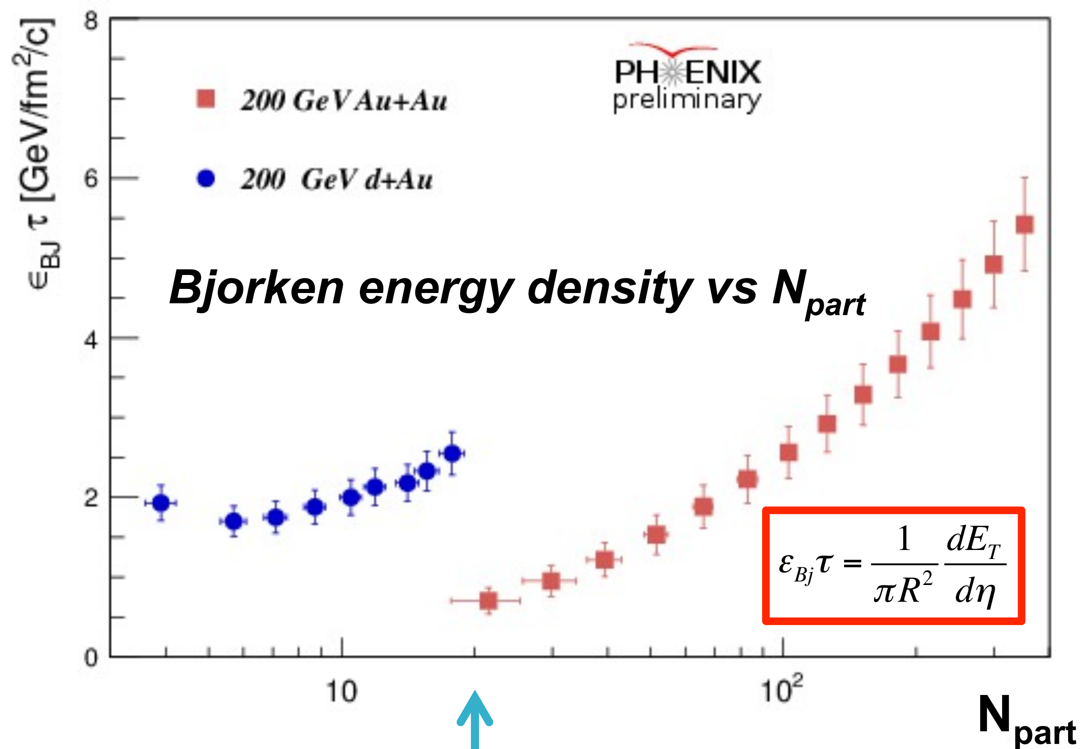
s : (sideward) geometrical size

o : (outward) geometry and time duration

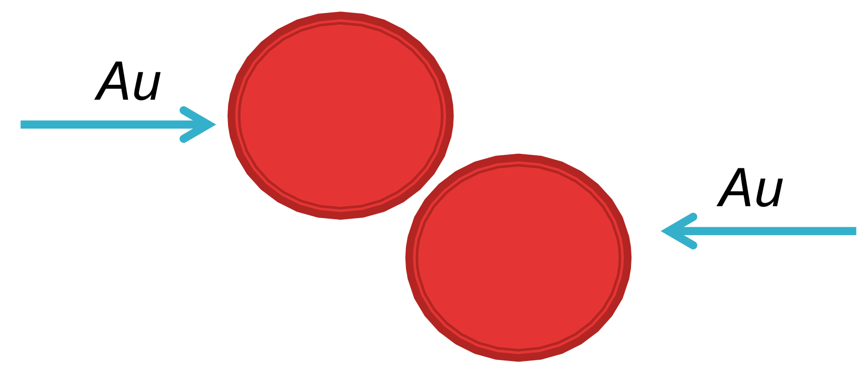
L : (longitudinal) beam direction

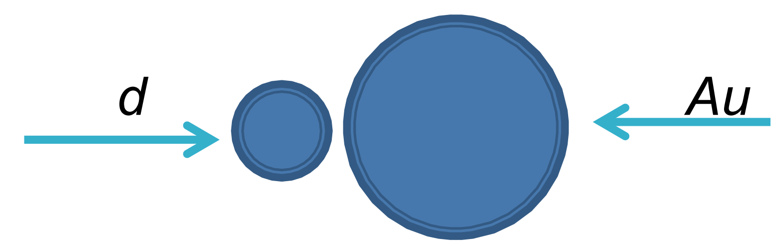
os : outward-sideward cross term

Event selections of d+Au and Au+Au collisions for HBT Analysis



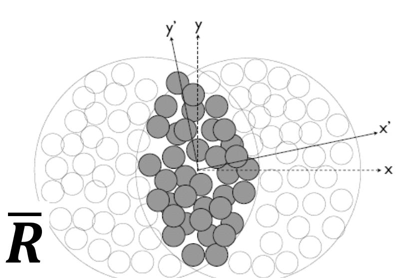
Initial Parameters for peripheral Au+Au and central d+Au





	N_{part}	$dE_T / d\eta$	$\bar{R}$	ε
Au+Au	16.7±1.1	19±.1.5	0.71	0.5
d+Au	15.7±1.6	22±1.5	0.44	2.5

Glauber Model initial size $\bar{R}$



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

σ_x & σ_y → RMS widths of density distribution

Slide from N.Ajit QM'14

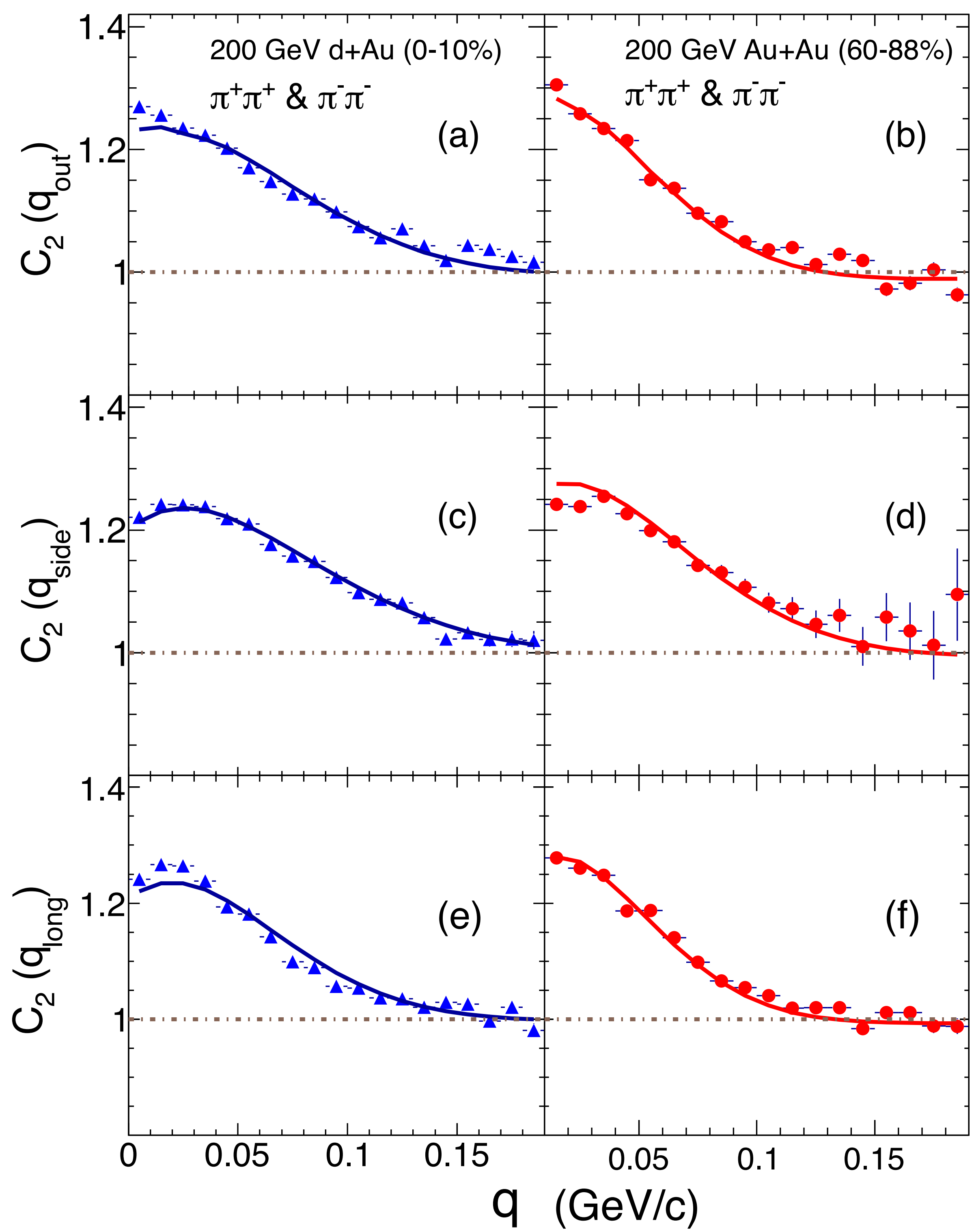
HBT correlation in d+Au & Au+Au

arXiv:1404.5291

- $\pi^{\pm}\pi^{\pm}$ HBT correlations measured at similar N_{part} & k_T

	N_{part}	$<k_T>$
Au+Au	*16.7±1.1*	*0.39*
d+Au	*15.7±1.6*	*0.39*

- HBT correlations in d+Au larger than those in Au+Au imply smaller HBT radii



m_T dependence in d+Au & Au+Au

arXiv:1404.5291

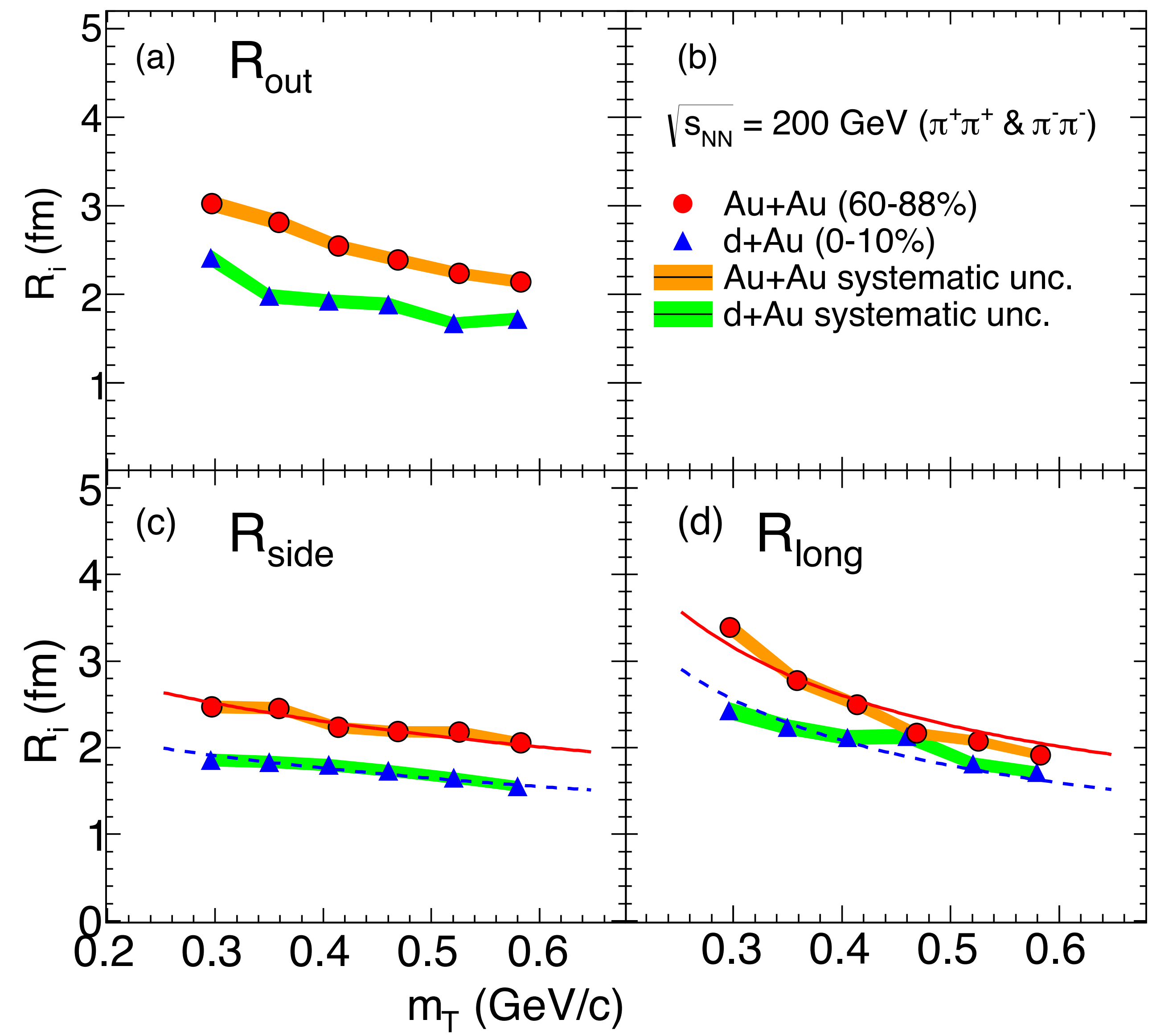
BW fit function

$$R_{\rm side} = R_{\rm geom}/\sqrt{(1+\beta^2(m_T/T))},$$

$$R_{\rm long} = \tau_0\sqrt{(T/m_T)[(K_2(m_T/T))/(K_1(m_T/T))]},$$

TABLE I. Fit parameters

	d+Au	Au+Au
τ_0 (fm/c)	$3.2 \pm 0.04 \pm 0.4$ (syst)	$3.8 \pm 0.04 \pm 0.3$ (syst)
χ^2/ndf	26/5	24/5
$R_{\rm geom}$ (fm)	$2.2 \pm 0.03 \pm 0.2$ (syst)	$2.8 \pm 0.03 \pm 0.2$ (syst)
χ^2/ndf	6/5	4/5



- Qualitatively similar m_T dependence in d+Au & Au+Au
  - Similar expansion dynamics?
- Blast-wave fitting defined by expansion velocity & freeze-out temperature works well for R_{side}

Emission duration & freeze-out volume

arXiv:1404.5291

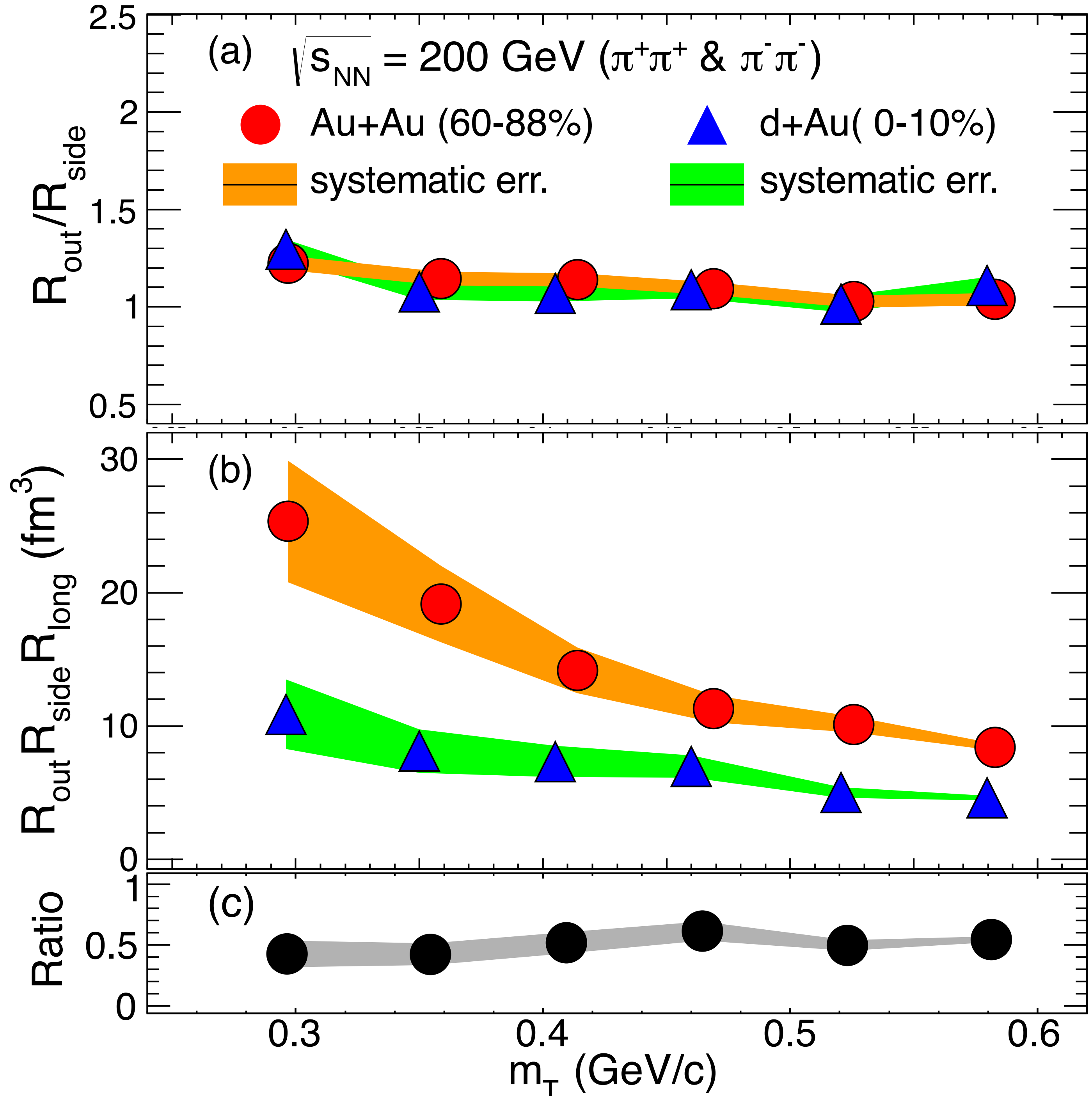
R_{out}/R_{side}~1

Short emission duration

Freeze-out Volume

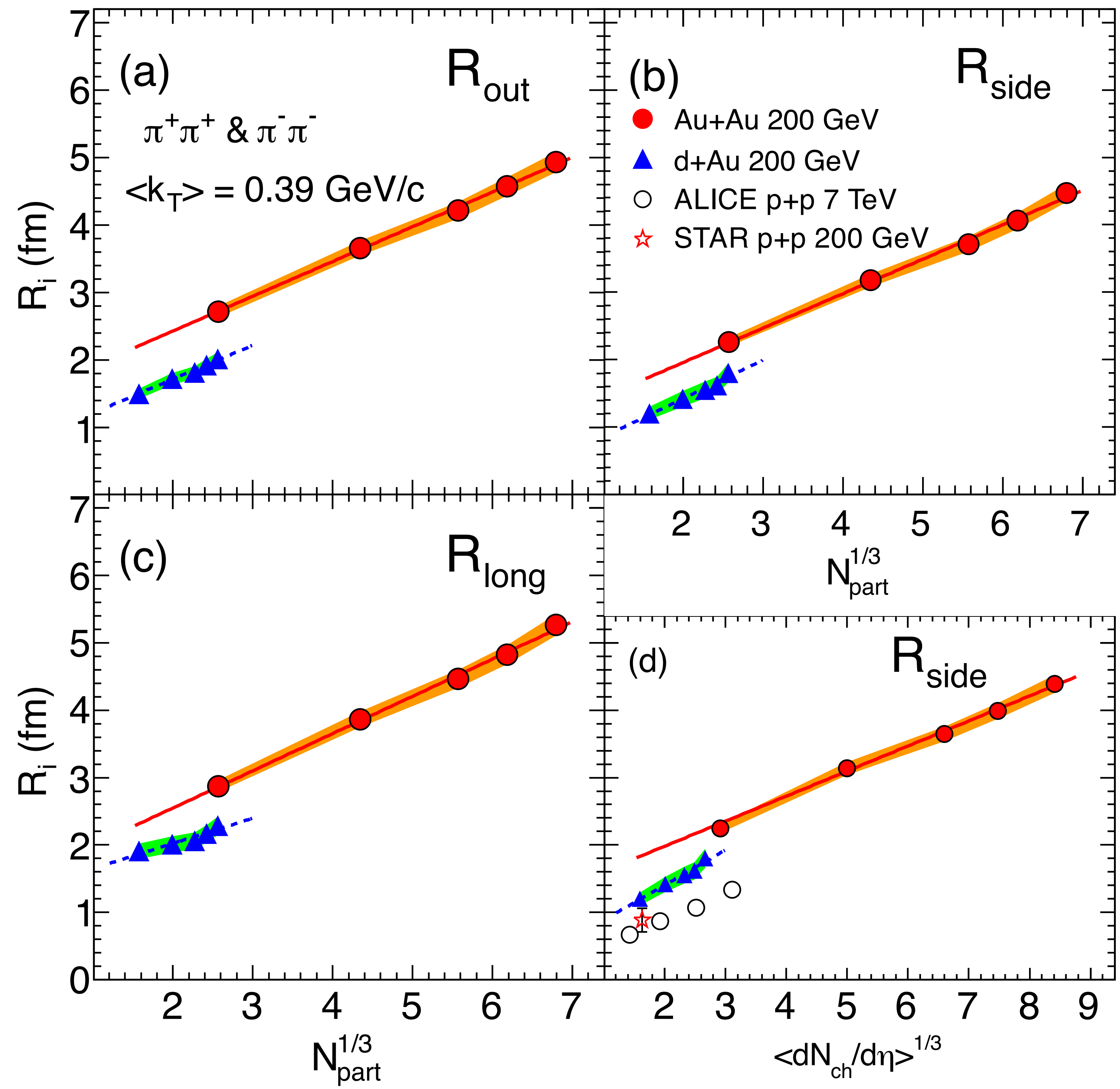
v(dAu)<v(AuAu)

Similar m_T dependence



HBT radii as a function of $N_{part}^{1/3}$

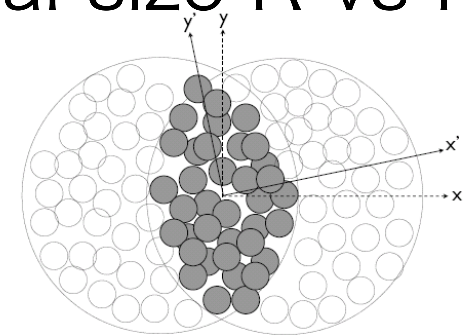
arXiv:1404.5291



- d+Au & Au+Au HBT radii do not scale together but show a similar linearity
- p+p at 7 TeV also show a linearity with respect to $\langle dN_{ch}/\eta \rangle^{1/3}$

Initial R dependence in p+A & A+A collisions

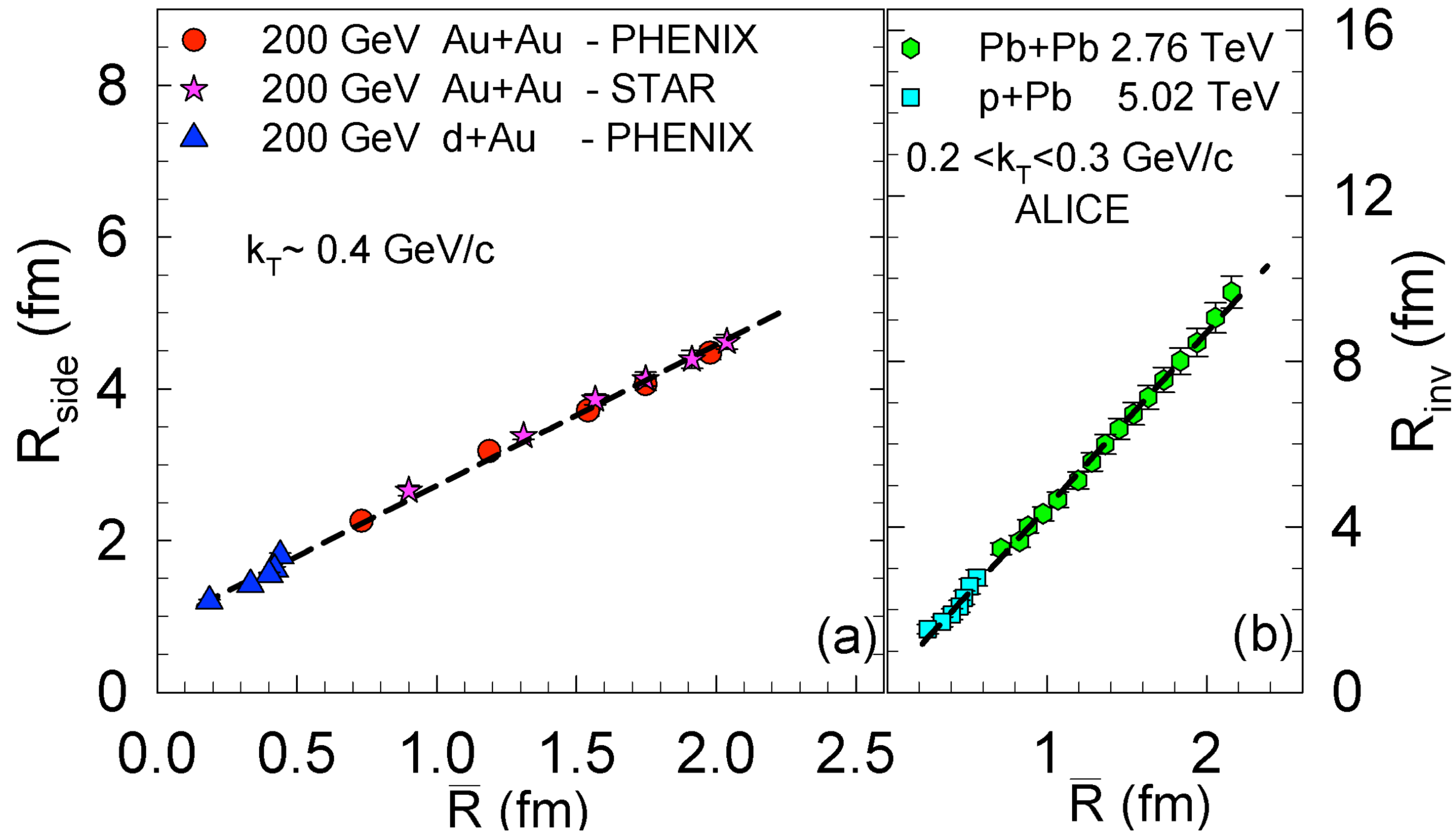
Glauber MC to obtain initial size R vs N_{part}



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

σ_x σ_y : RMS width of density distribution

arXiv:1404.5291

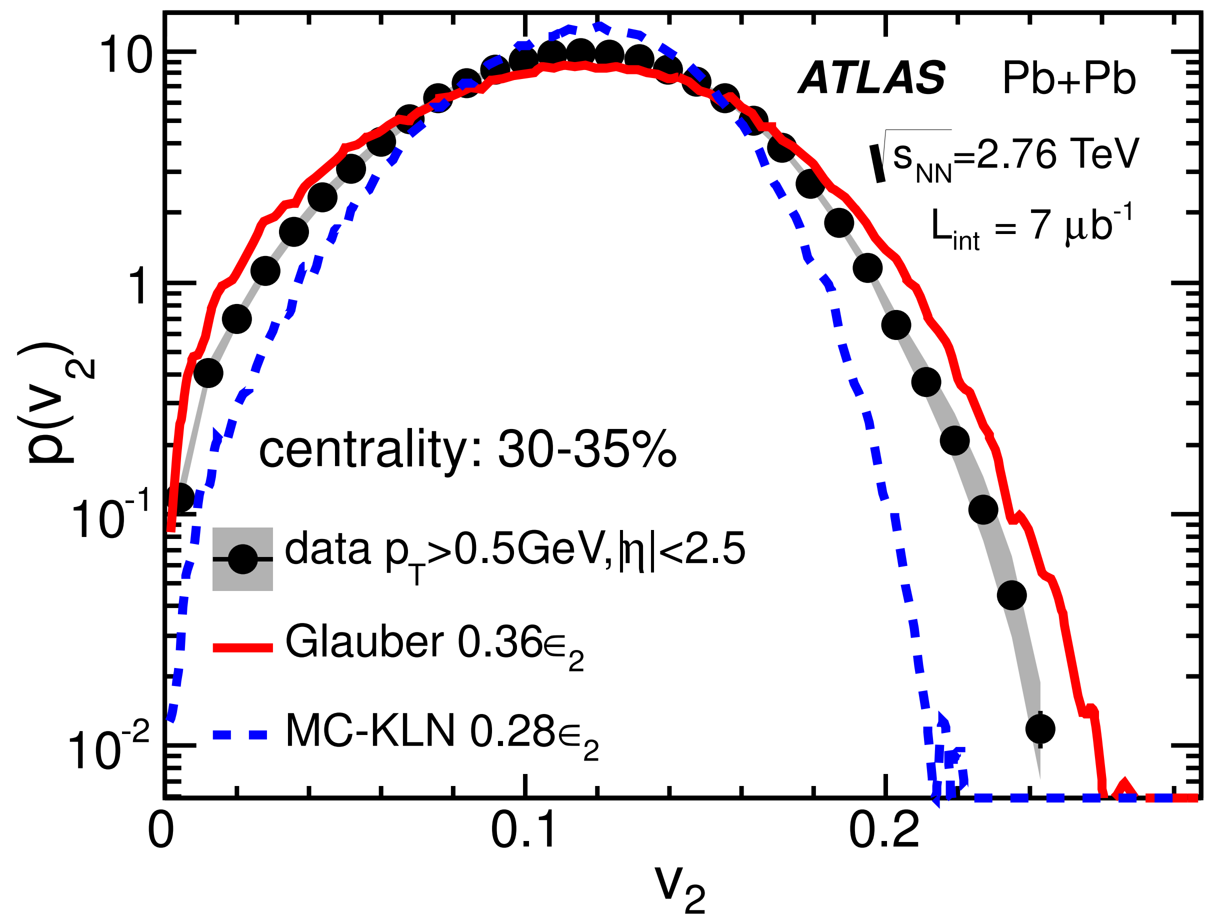


- **Linearity and good scaling are seen in p+A and A+A collisions**
- **Implies possible radial expansion in p+A systems**

Event-by-Event Fluctuations of v_n

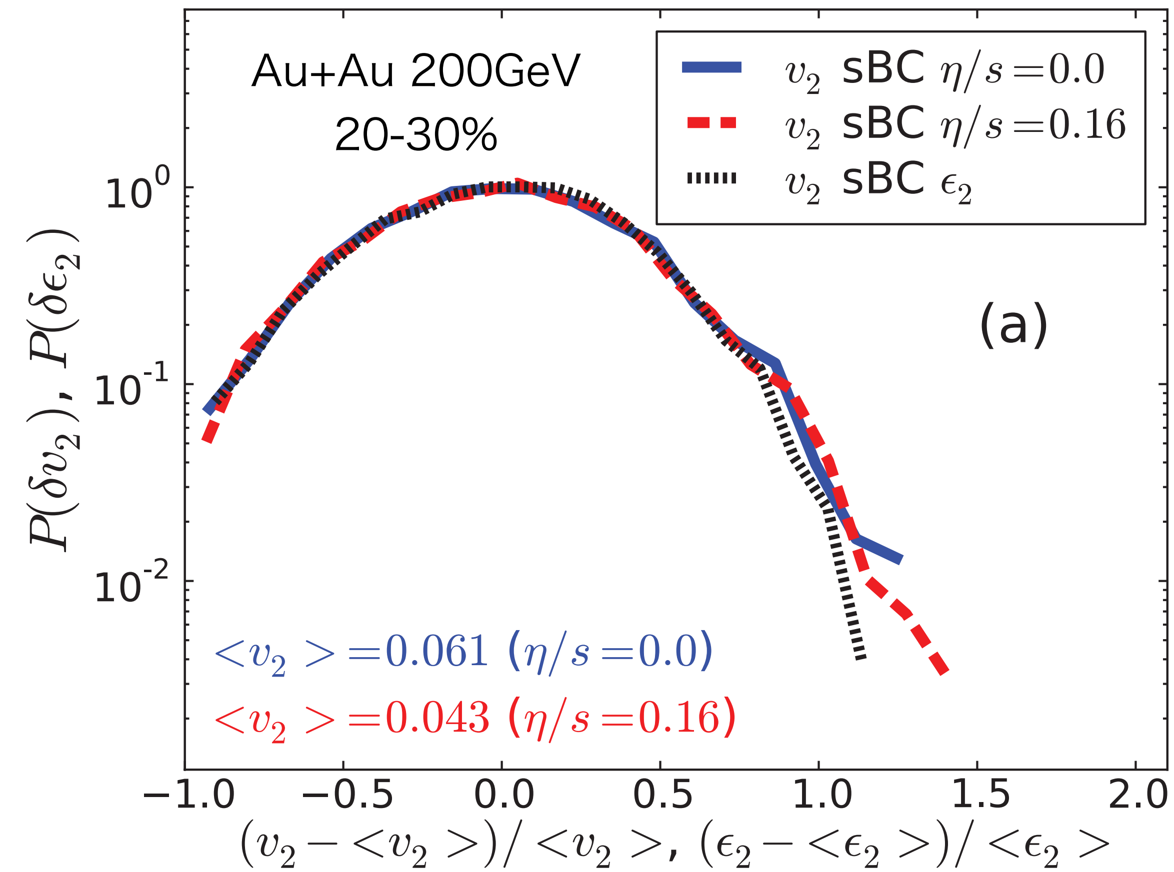
LHC Data

ATLAS:JHEP11(2013)183



Hydro Calculation

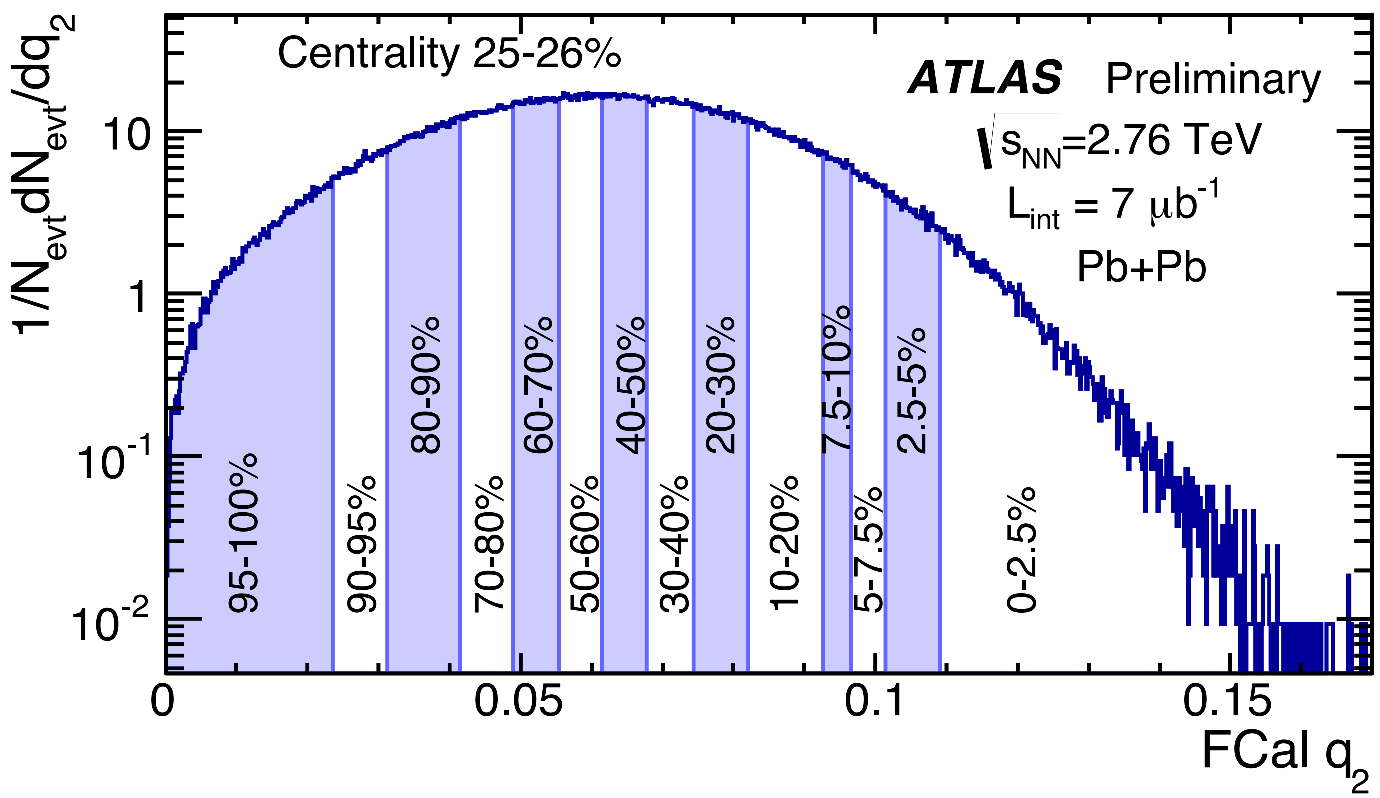
Niemi et.al. PRC87.054901



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

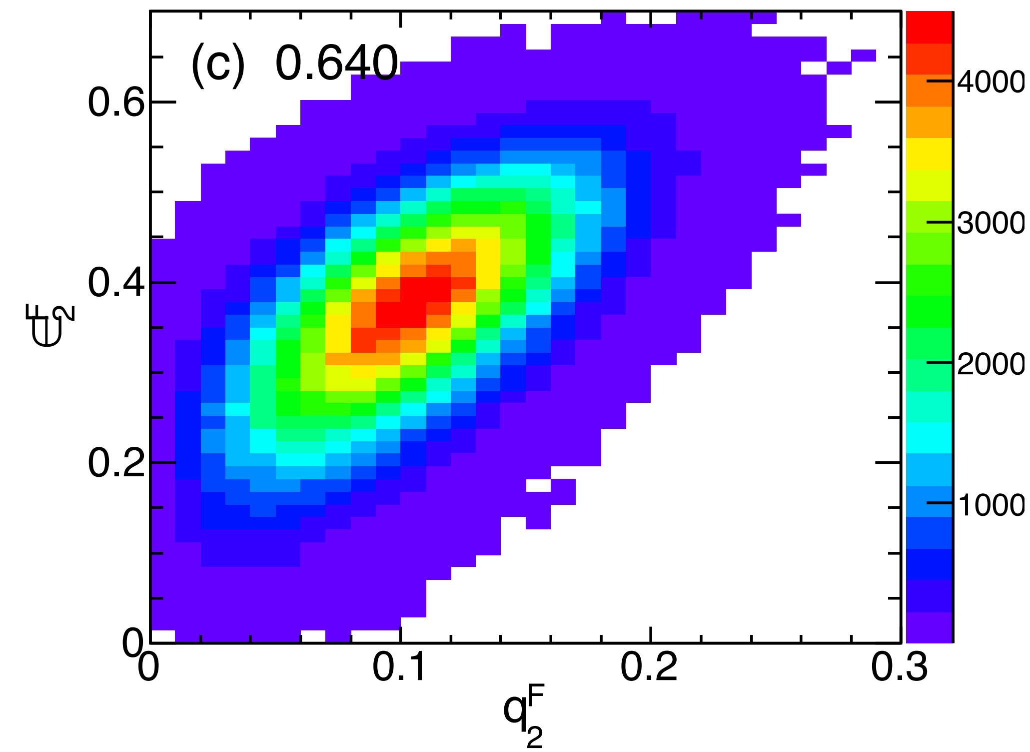
Event-Shape Engineering

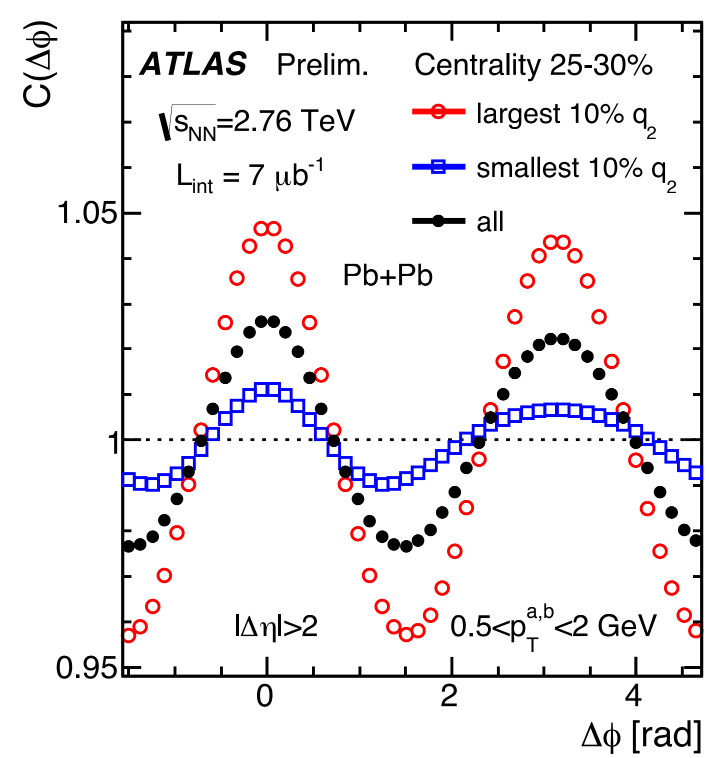
Schukraft et.al: arXiv:1208.4563



AMPT

J.Jia et.al : arXiv:1403.6077





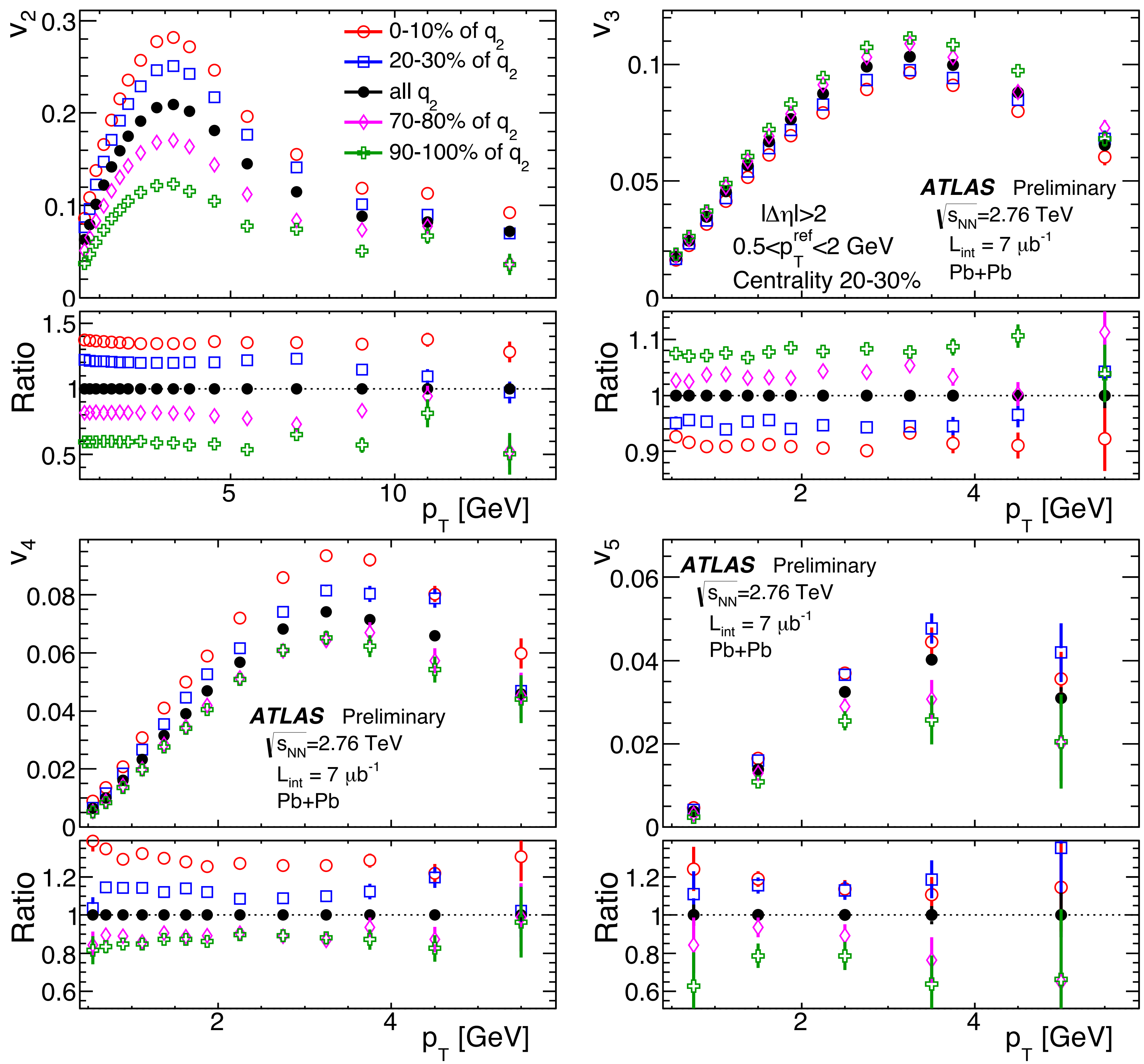
- **$|q_n|$: Strength of Flow**

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

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

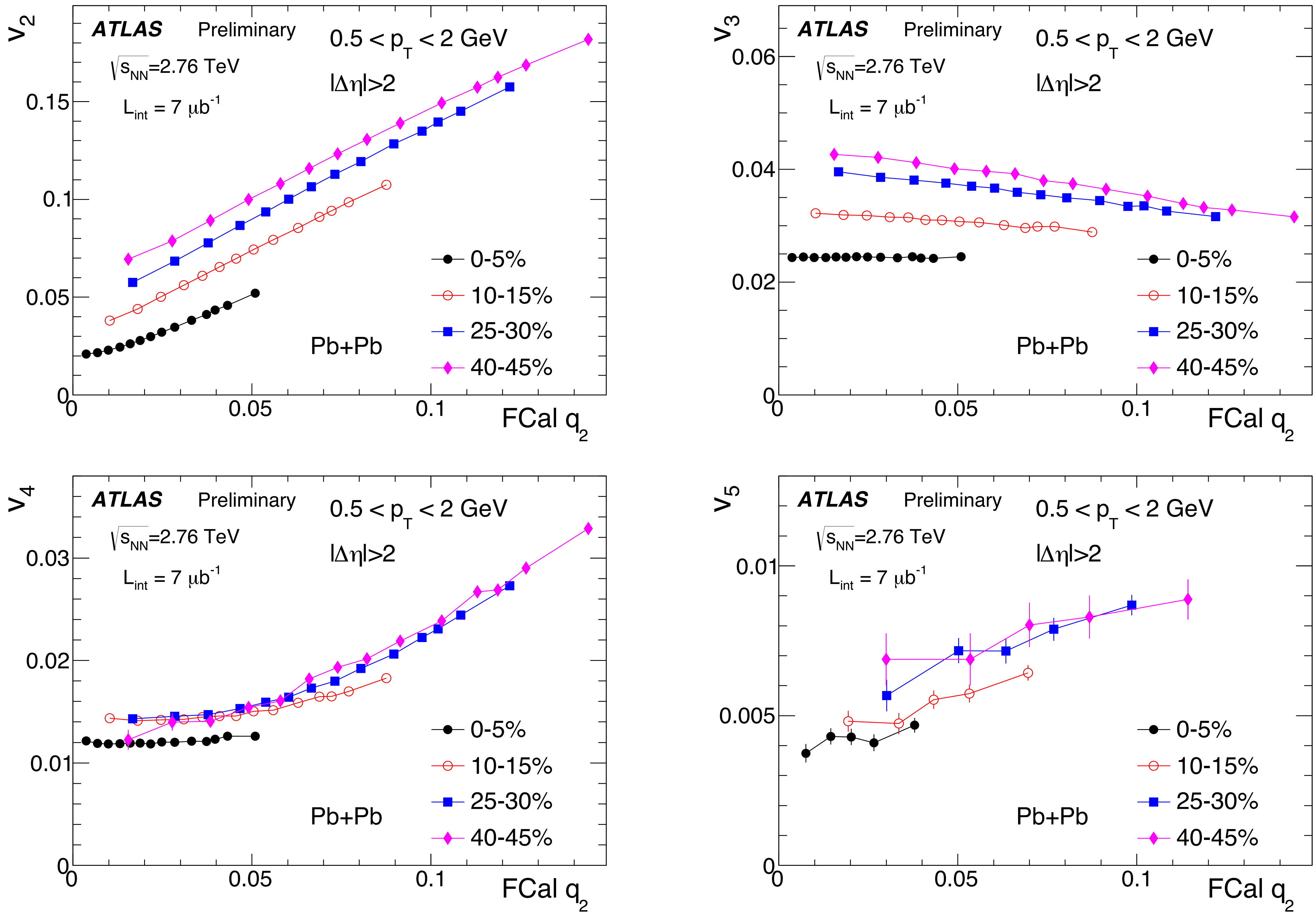
- **Possible control of initial geometry**

$v_n(n=2,3,4,5)$ vs q_2

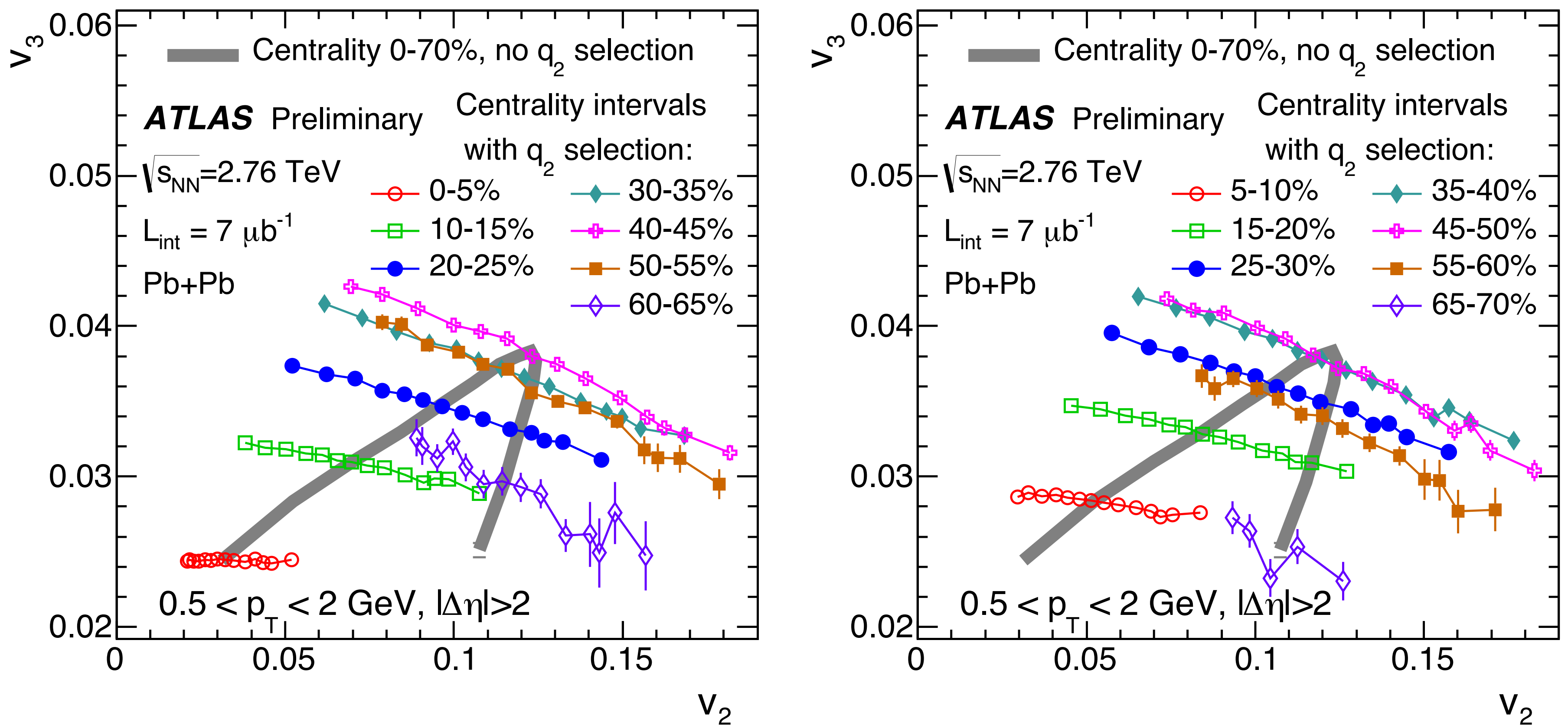


- q_2 dependence for v_2
- Weaker, but q_2 dependence also for $v_n(n=3,4,5)$

v_n(n=2,3,4,5) vs q_2



v_2 - v_3 correlations

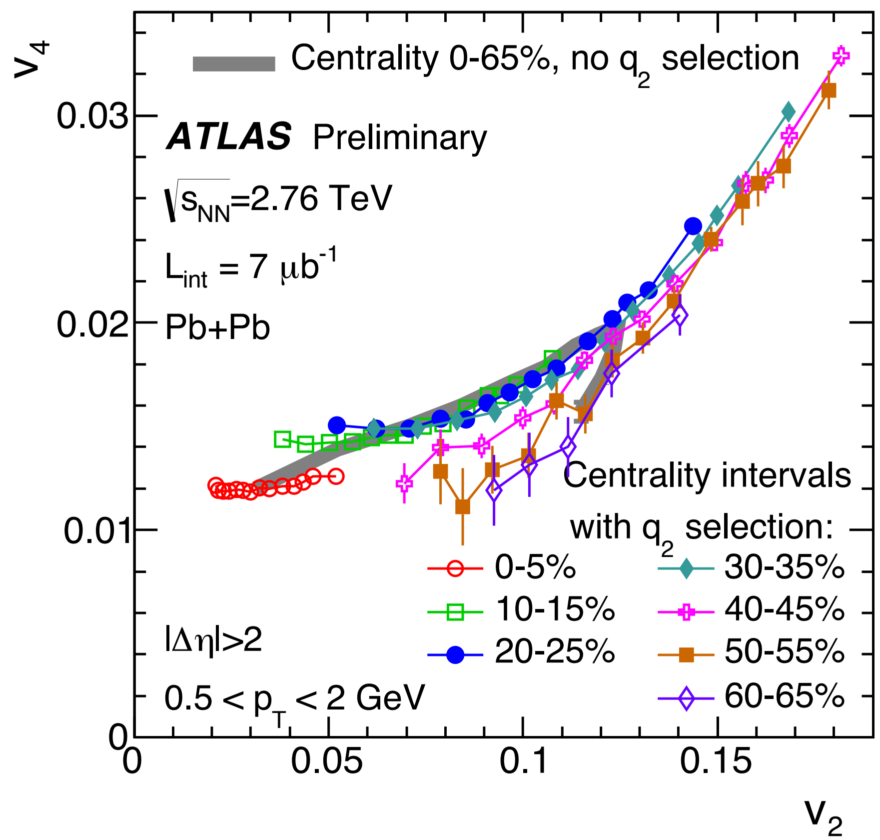


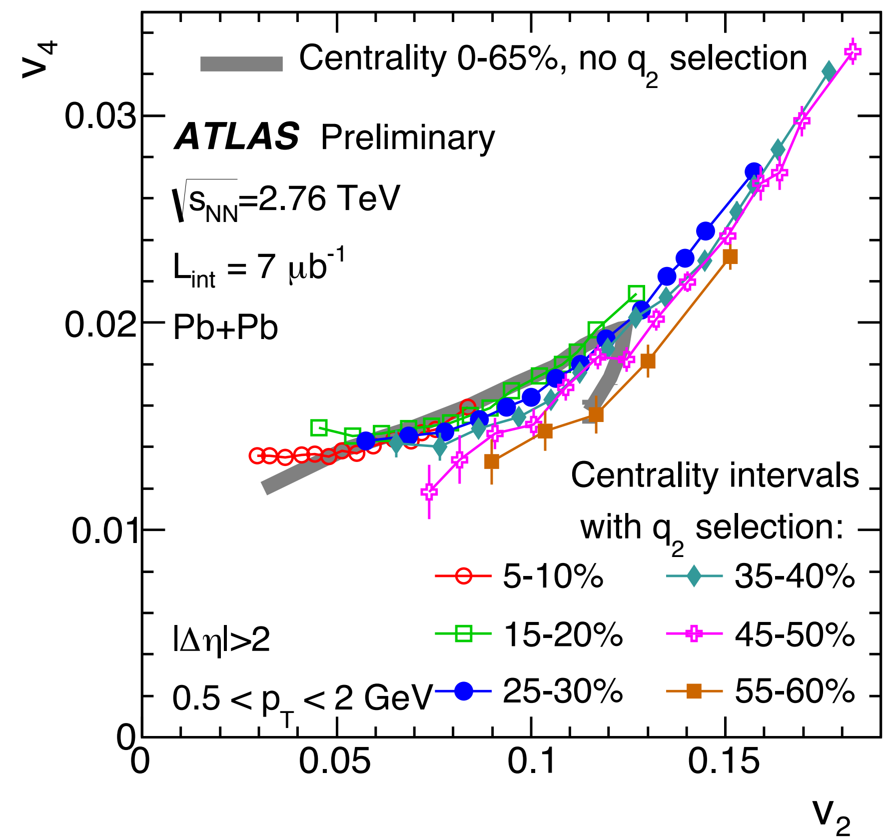
- Negative-correlations between v_2 and v_3 $\quad v_3 = c_0 + c_1 v_2$
- Linear response to initial geometry

$$v_2 e^{i2\Phi_2} = a_0 \epsilon_2 e^{i2\Phi_2^*} \qquad v_3 e^{i3\Phi_3} = a_0 \epsilon_3 e^{i3\Phi_3^*}$$

- Anti correlations at initial eccentricities?

v_2 - v_4 correlations



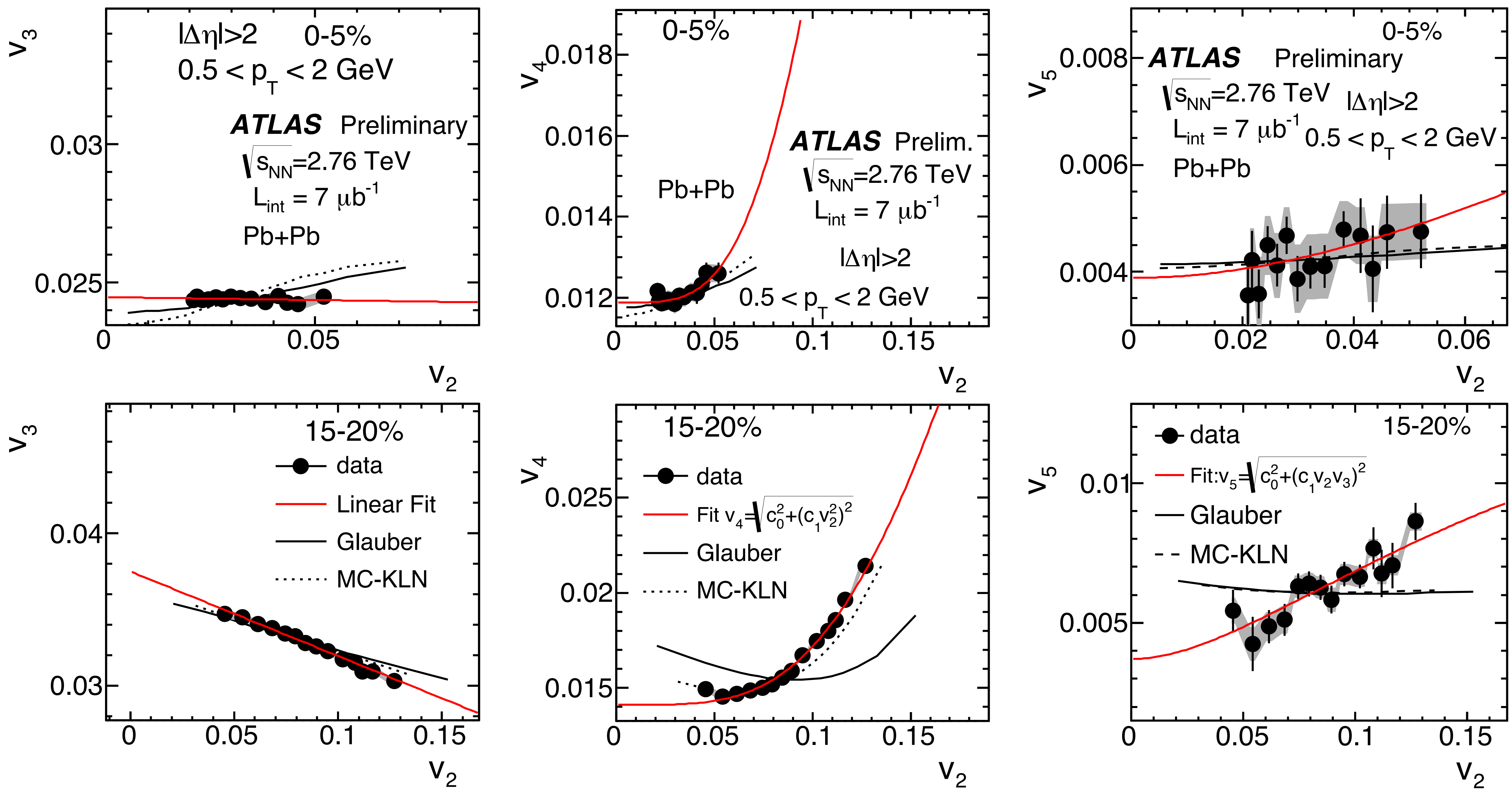


- **Linear-term and non-linear term**
- **Clear non-linear term is seen in data: upward bending**

$$v_4 e^{i4\Phi_4} = a_0 \epsilon_4 e^{i4\Phi_4^*} + a_1 (\epsilon_2 e^{i2\Phi_2^*})^2 + \dots$$
$$= c_0 e^{i4\Phi_4^*} + c_1 (v_2 e^{i2\Phi_2^*})^2 + \dots$$

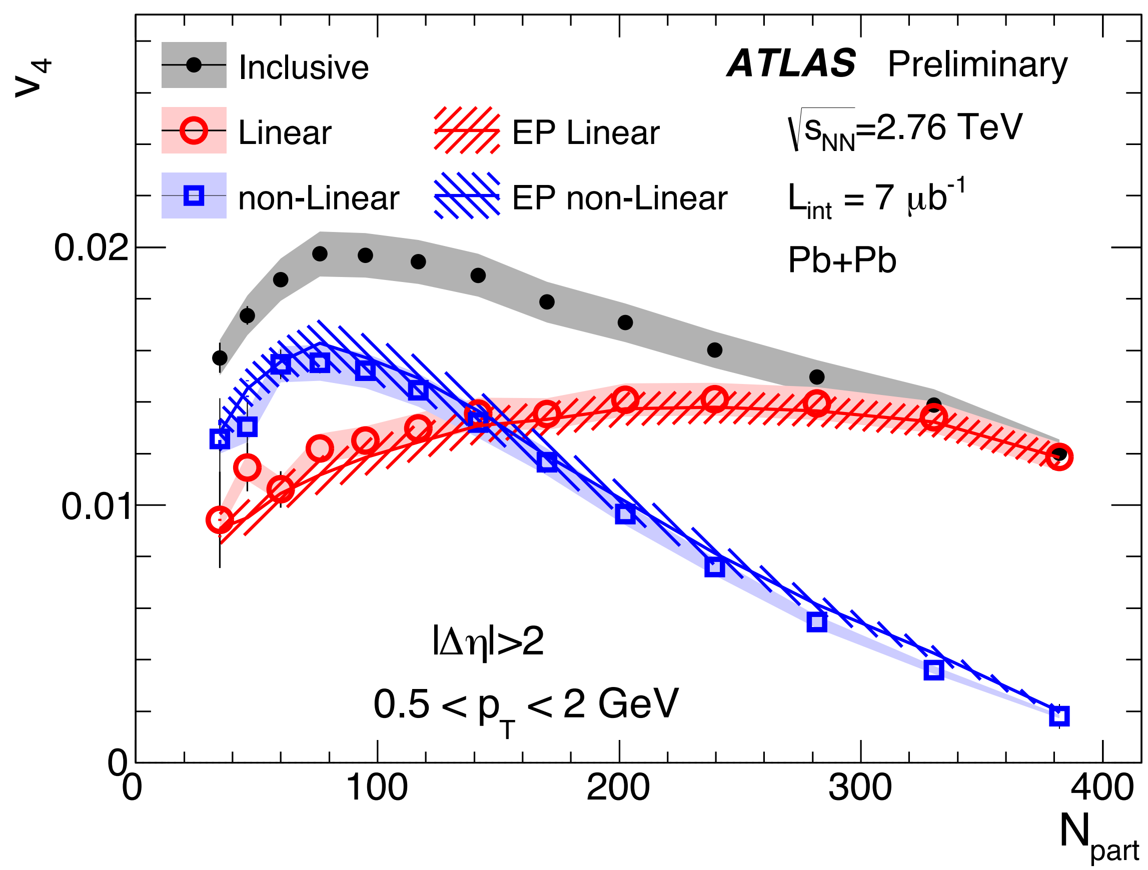
$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

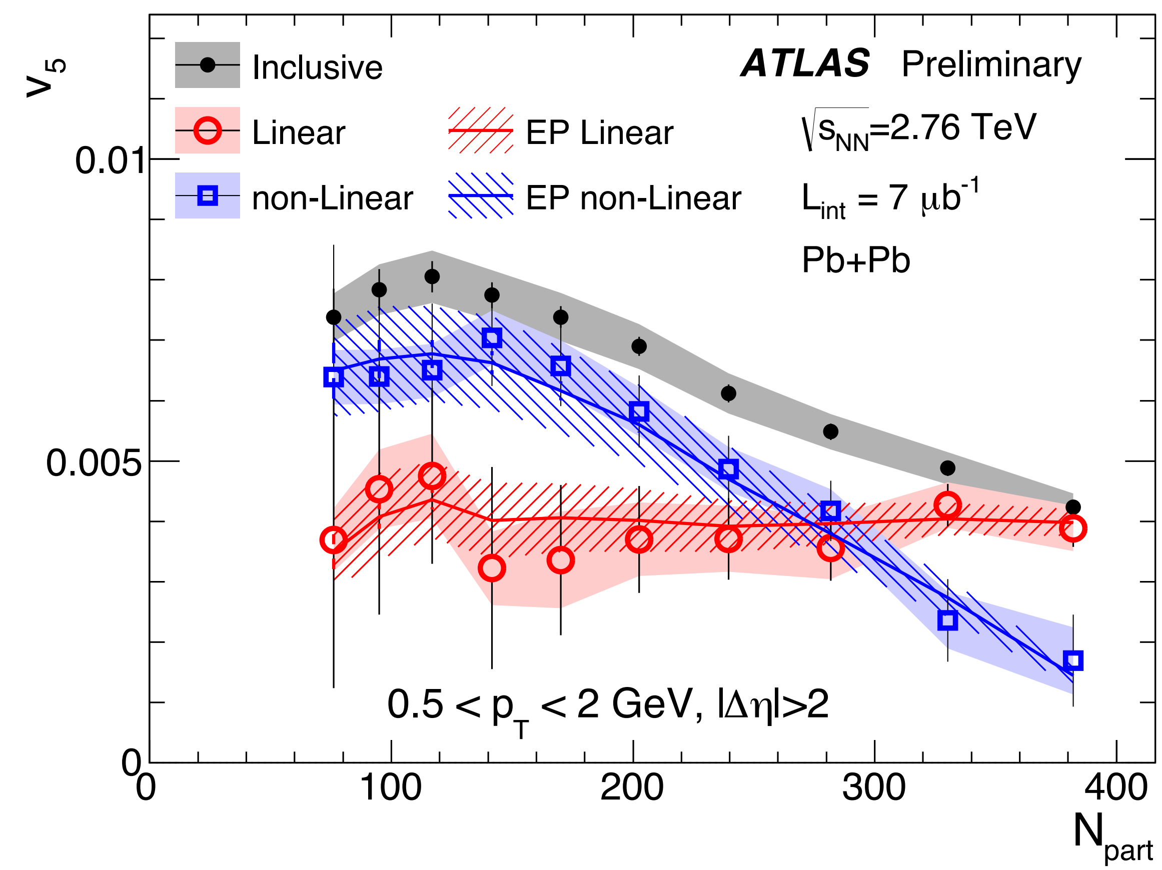
v_2-v_n correlations



- Compared with Glauber and MC_KLN ε_2-ε_n correlations
- Access to IC if a unique hydro response to a given initial correlation

Linear/non-Linear terms





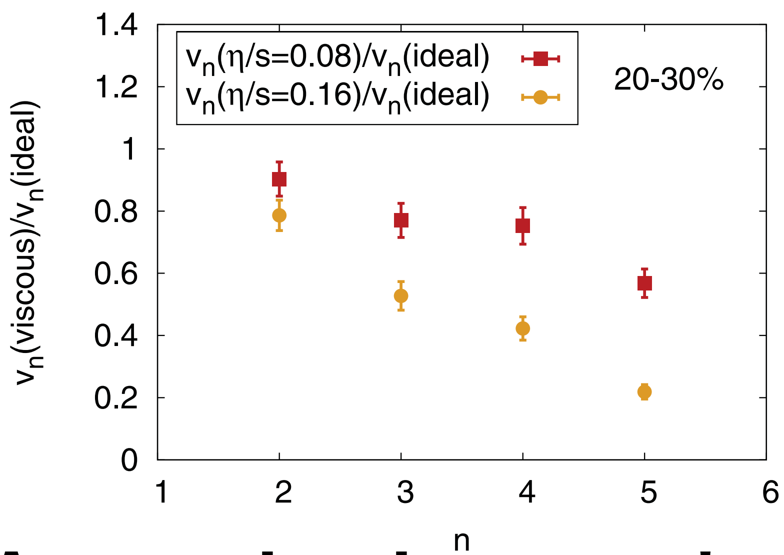
$$v_4^L = c_0, v_4^{NL} = \sqrt{v_4^2 - {v_4^L}^2} \quad v_5^L = c_0, v_5^{NL} = \sqrt{v_5^2 - {v_5^L}^2}$$

- Most-central : v_4 is almost independent of v_2
- NL term increases with centrality
- Similar trends in v_5

Viscous dumping

- Viscous dumping of v_n with “n”

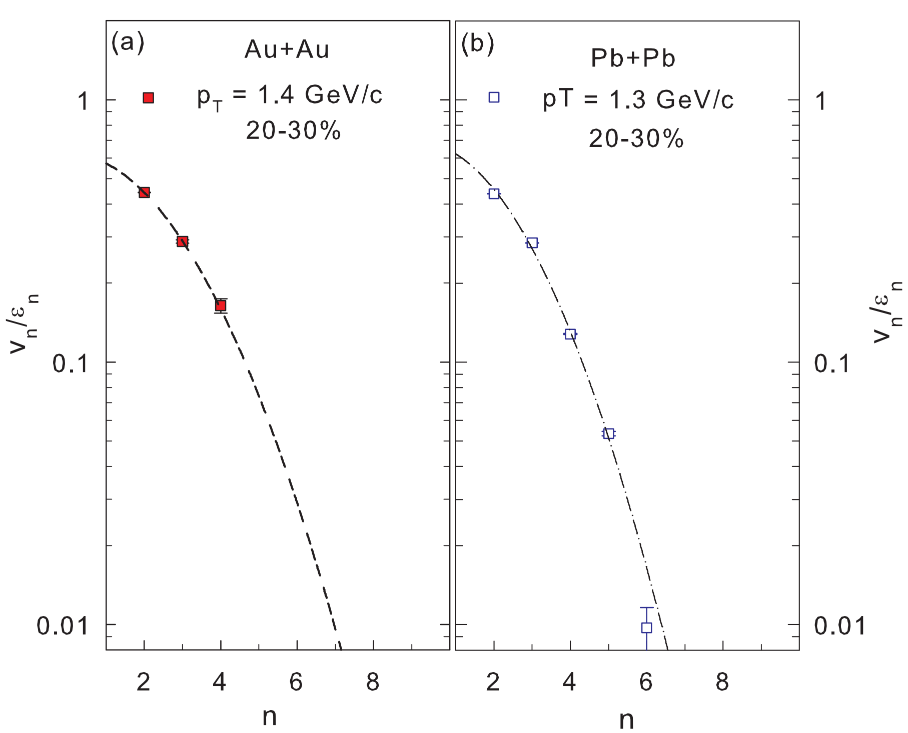
PRC85.024901

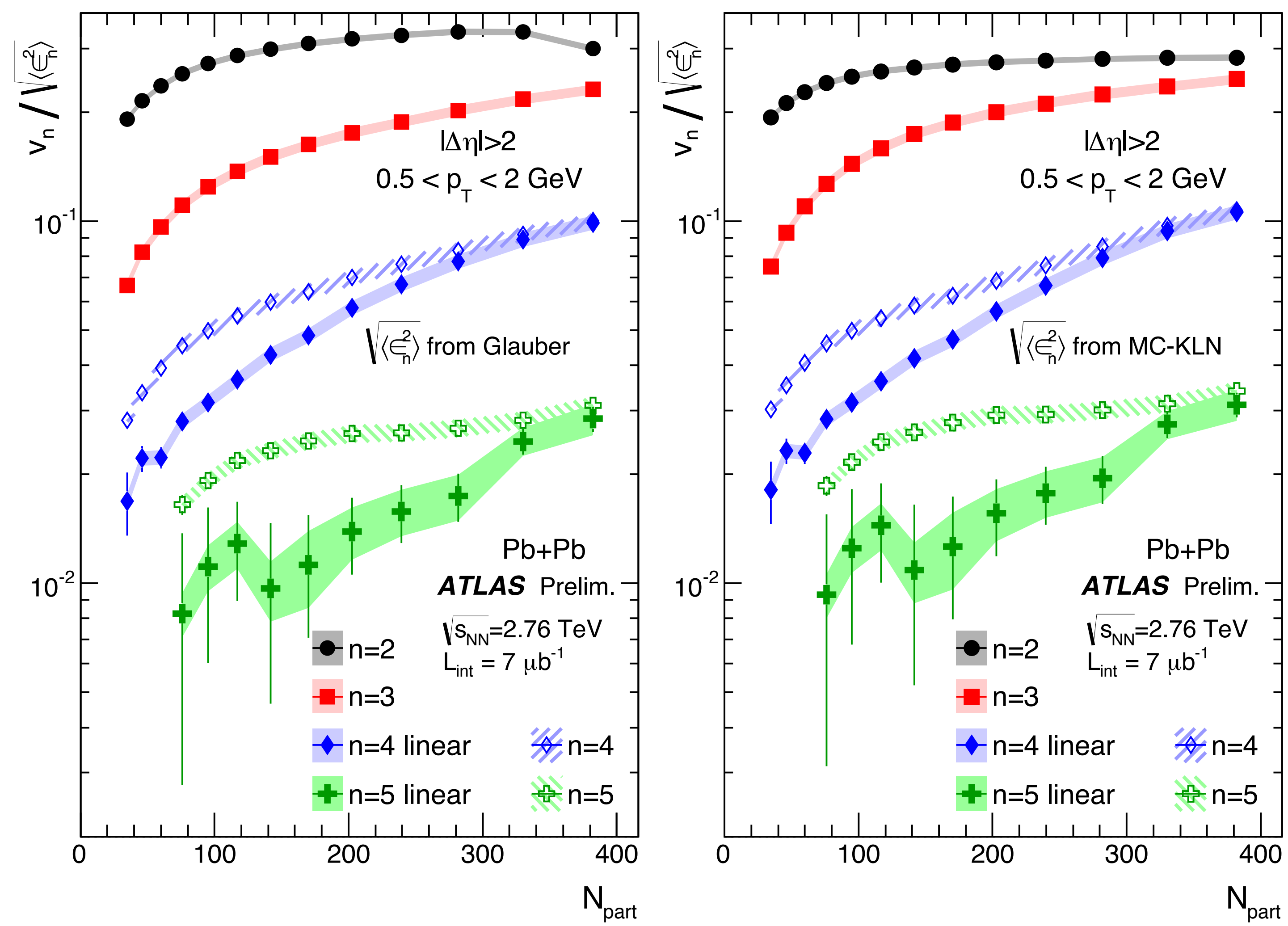


- Acoustic viscous dumping

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

Lacey et.al. 1105.3782, Staig et. al. PRC84.034908

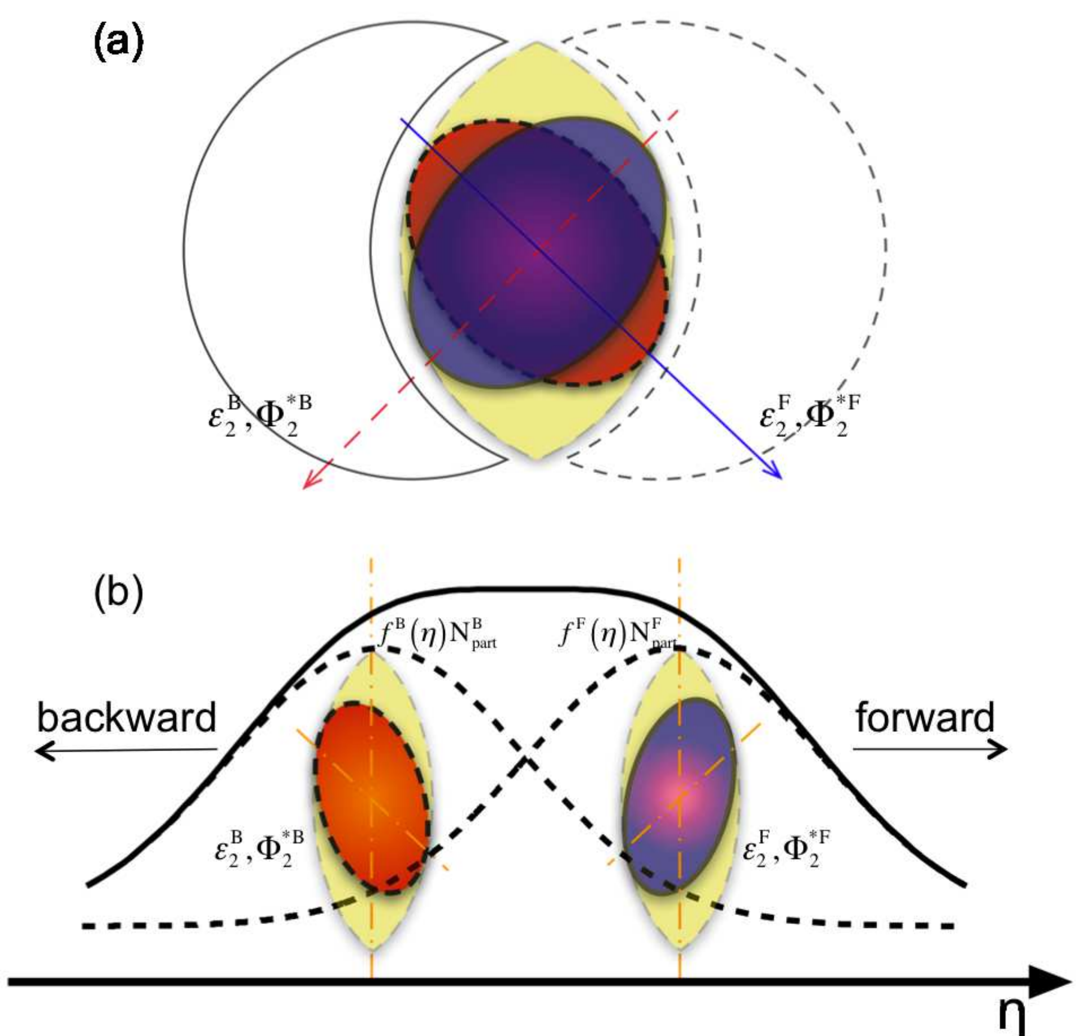




- Dumping pattern may be determine by the data

Twist Effect

Jia et. al. arXiv:1403.6077



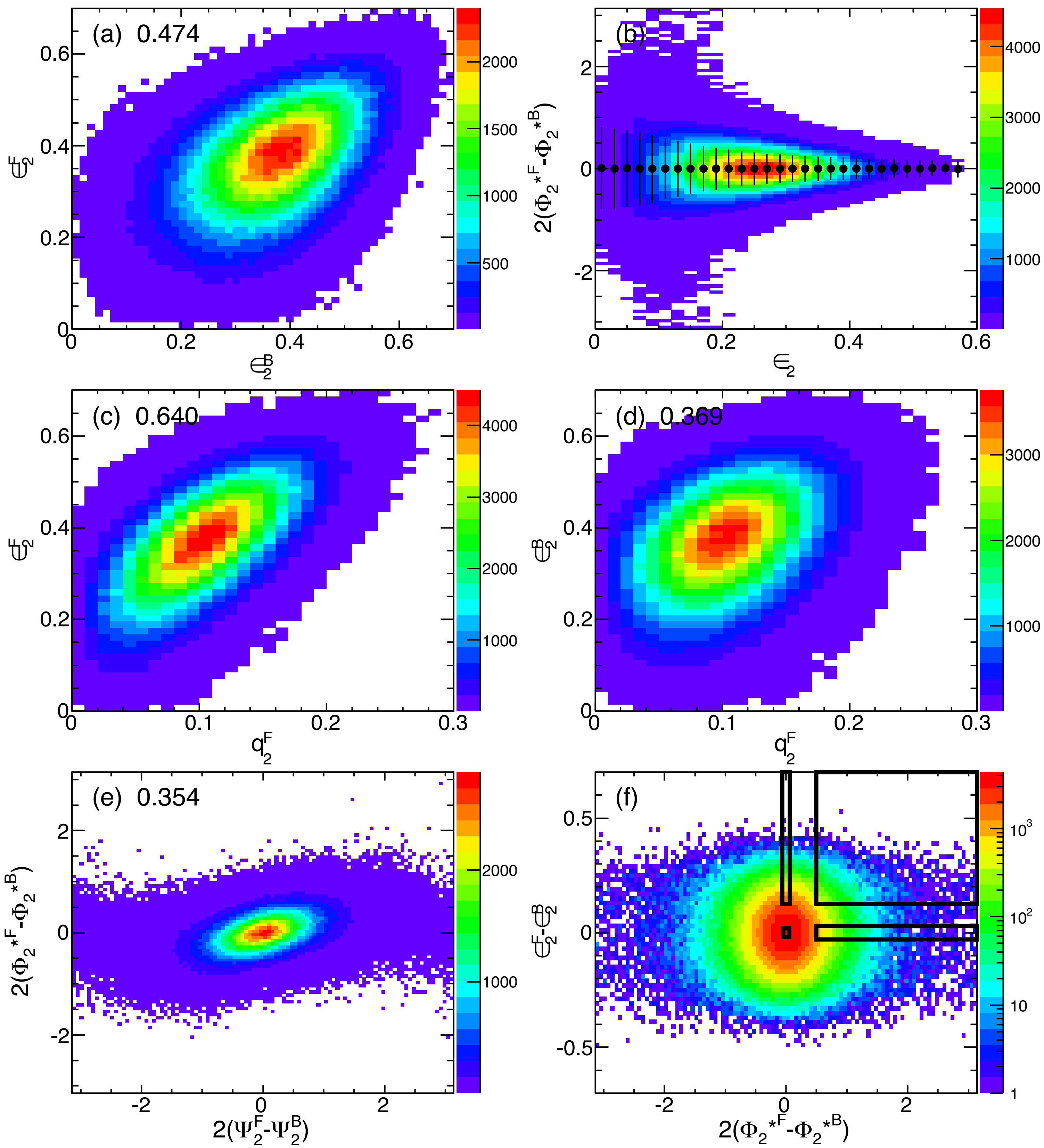
$$N_{part}^{\text{back}} \neq N_{part}^{\text{for.}}$$

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

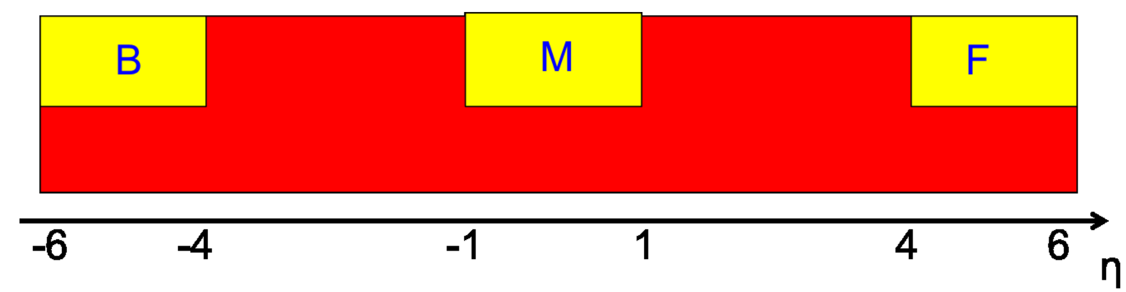
$$\Psi_n^{\text{back}} \neq \Psi_n^{\text{for.}}$$

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

AMPT : Twist Effect



Jia et. al. arXiv:1403.6077



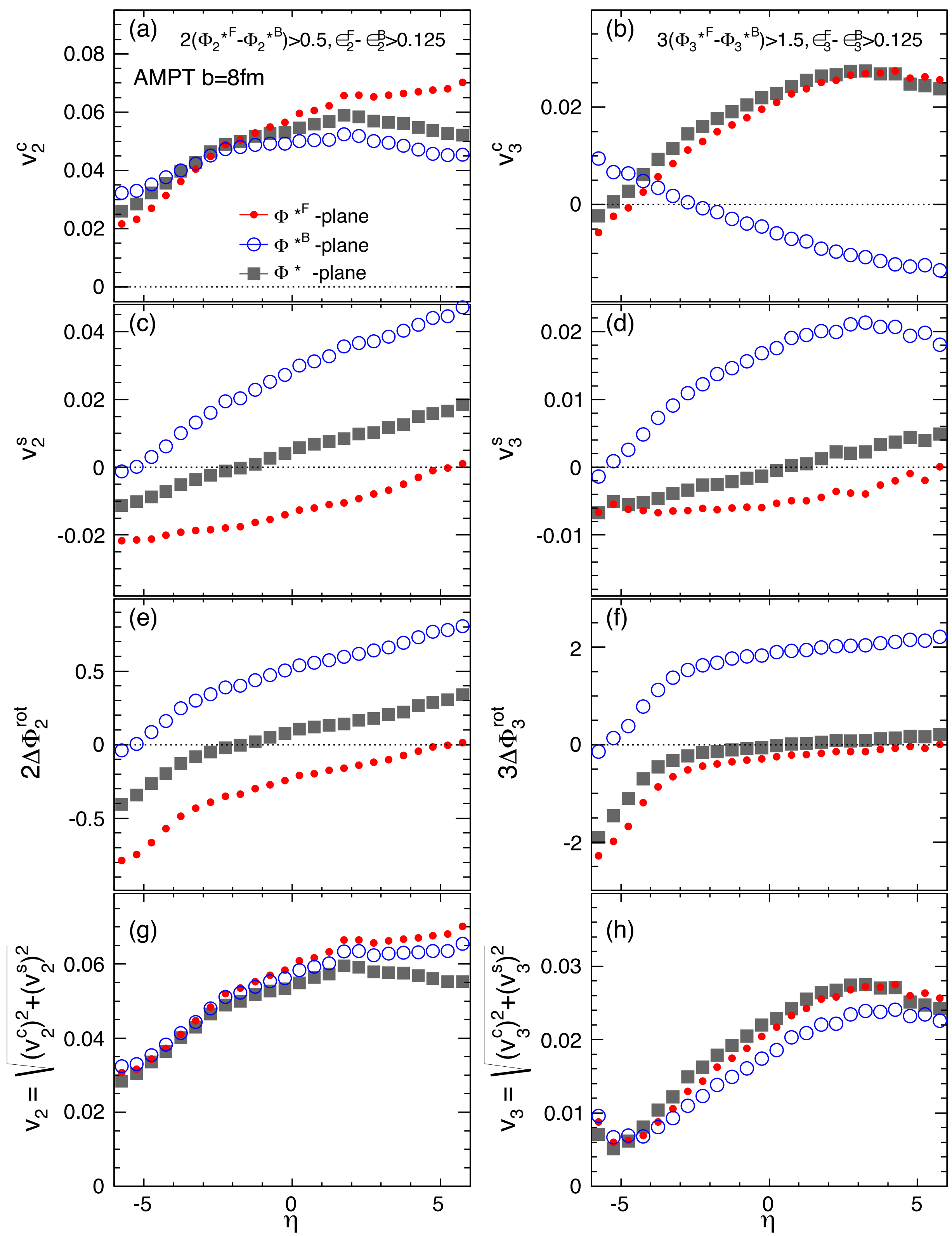
- Event-Plane & Ecc & $q_{2,3}$ determination

$$F : +4 < \eta < +6$$
$$M : -1 < \eta < +1$$
$$B : -6 < \eta < +4$$

- Correlations among EP, ECC, $q_{2,3}$ etc.
- Final twist probes initial twist

AMPT : Twist Effect

Jia et. al. arXiv:1403.6077



Event Selection

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

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

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

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

- Twisted term v_n^s observed i.e. underestimate of v_n
- This study should be done for experimental data

Summary

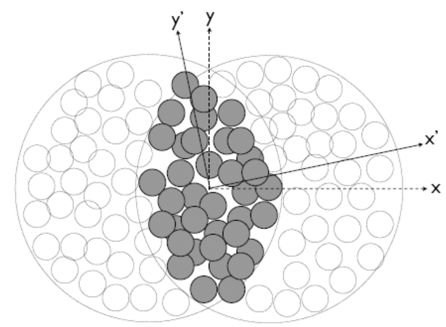
- Similar trends among p(d)+A and A+A collisions in v_n and HBT measurements
  - Observables in p(d)+A collisions are qualitatively consistent with final state effects
  - Hadron mass dependence of CGC?
- Event Shape Control Study is a promising method to address initial geometry of heavy ion collisions
  - Possible access to initial state model

Auxiliary Slides

Hydro models associate a larger expansion time with a larger initial size $\bar{R}$ Does it make a good scaling parameter ?

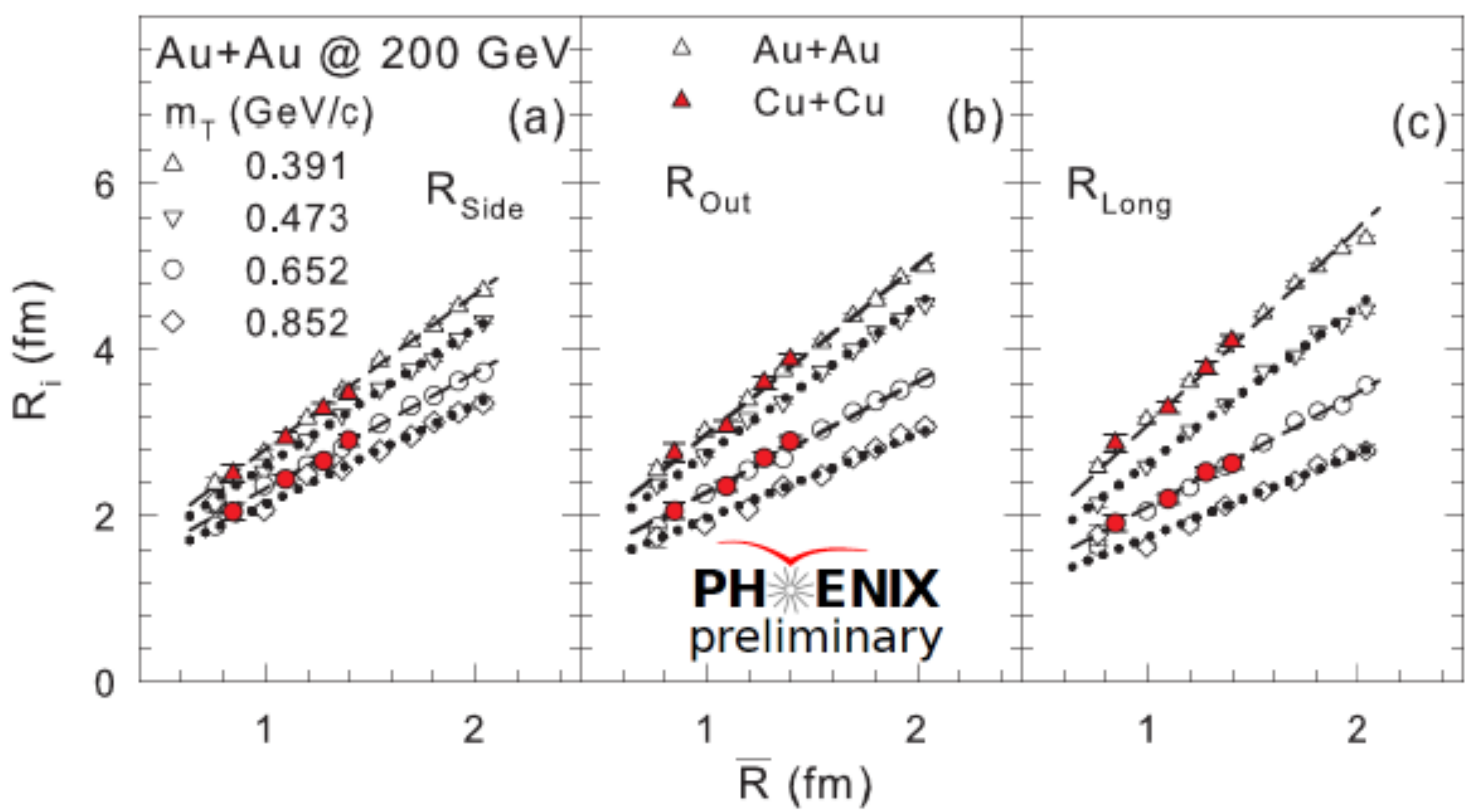
Use Glauber model to get

$N_{part}^{1/3}$ *vs* *initial size* $\bar{R}$



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

σ_x & σ_y → RMS widths of density distribution



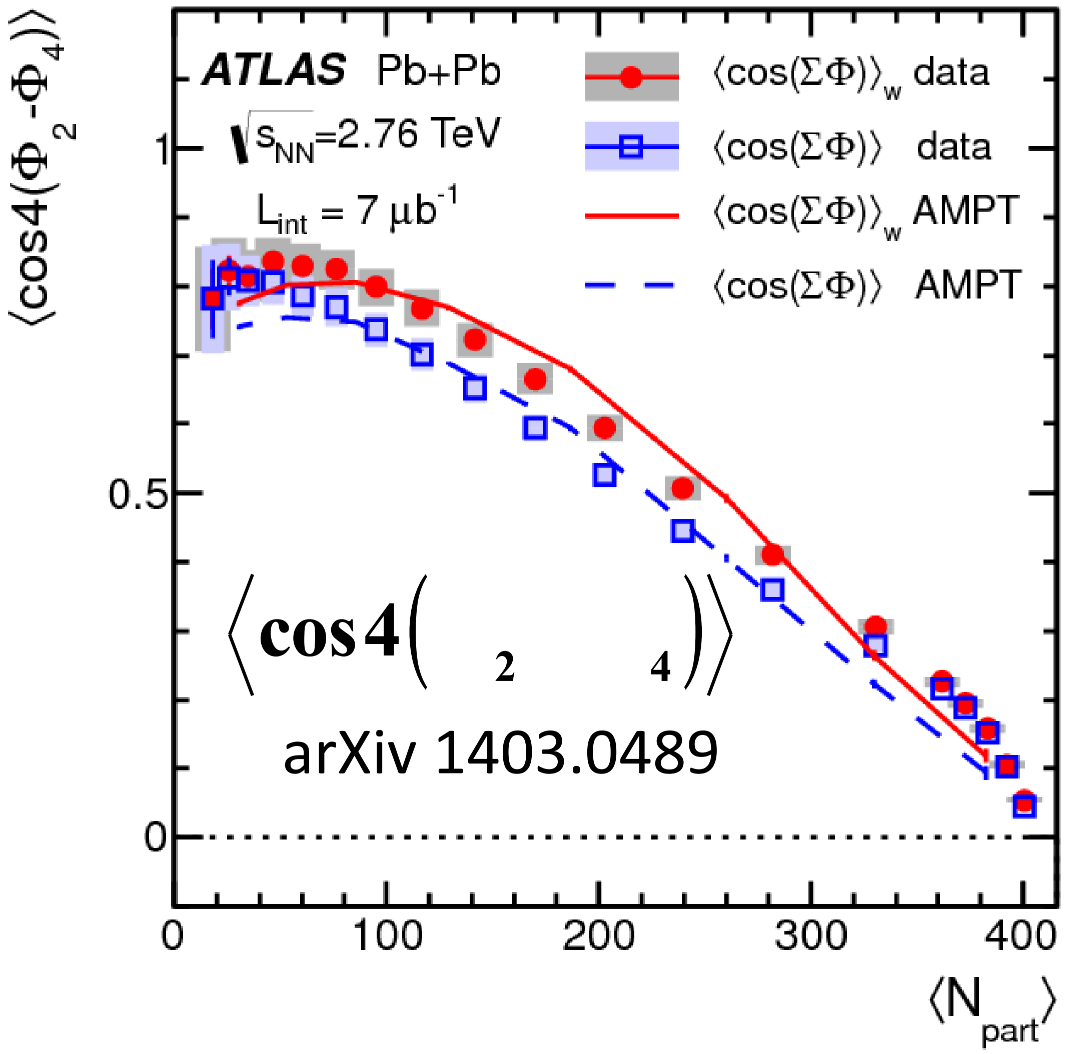
Pion HBT radii scale with $\bar{R}$

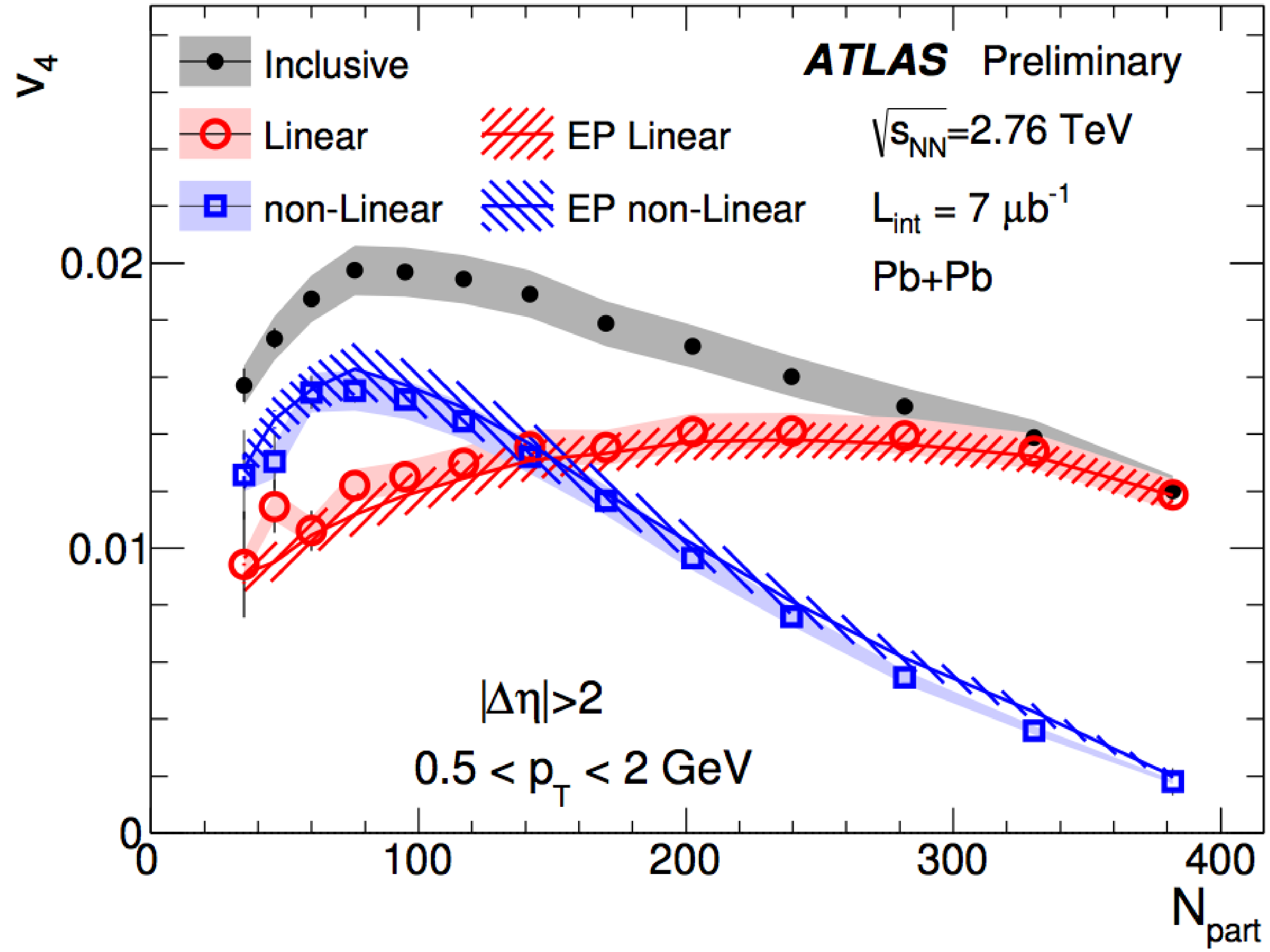
Linear dependence of transverse expansion on initial geometry

Slide from N.Ajit QM'14

14

v_4-v_2 correlations : comparison to EP correlations



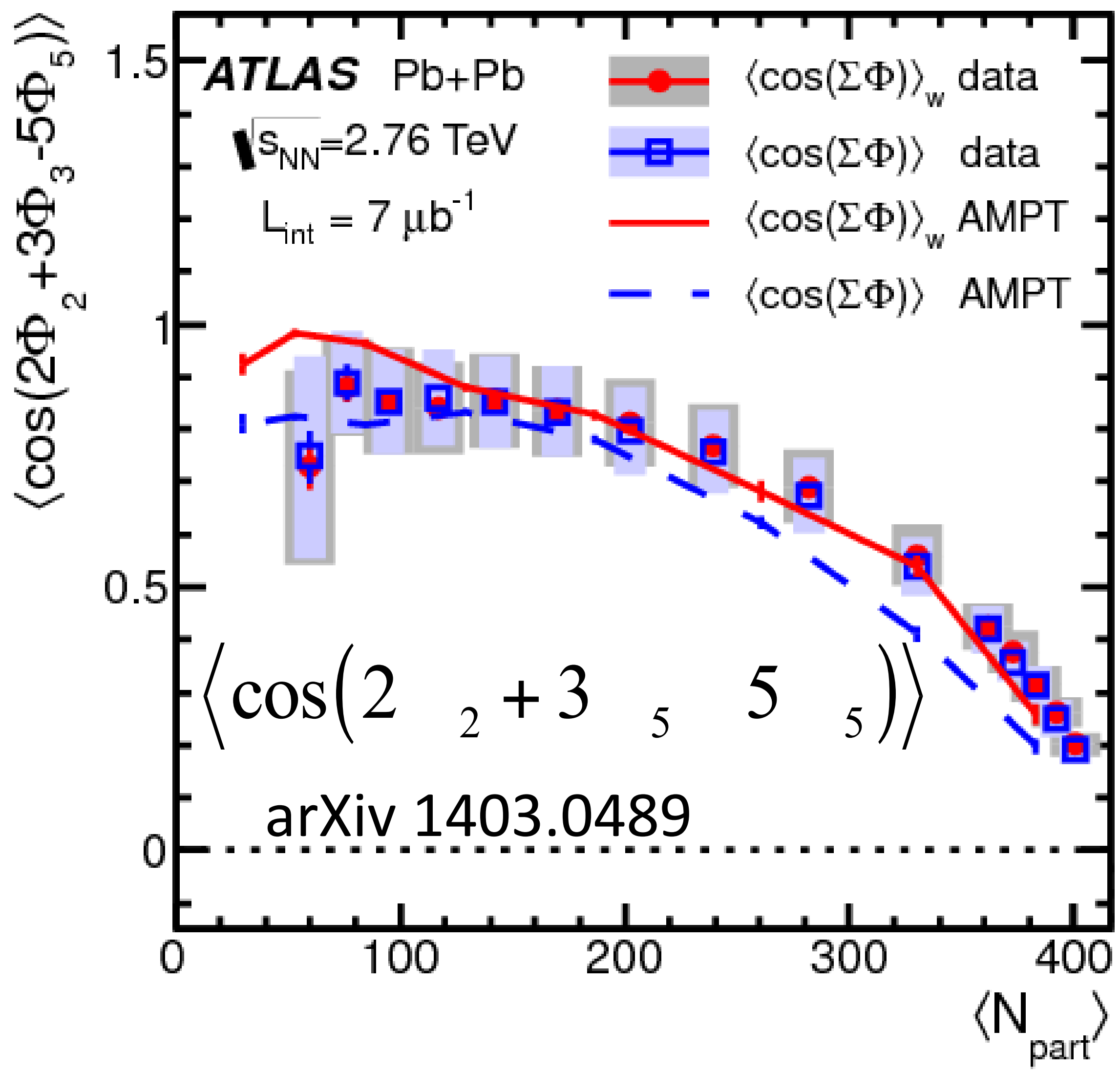


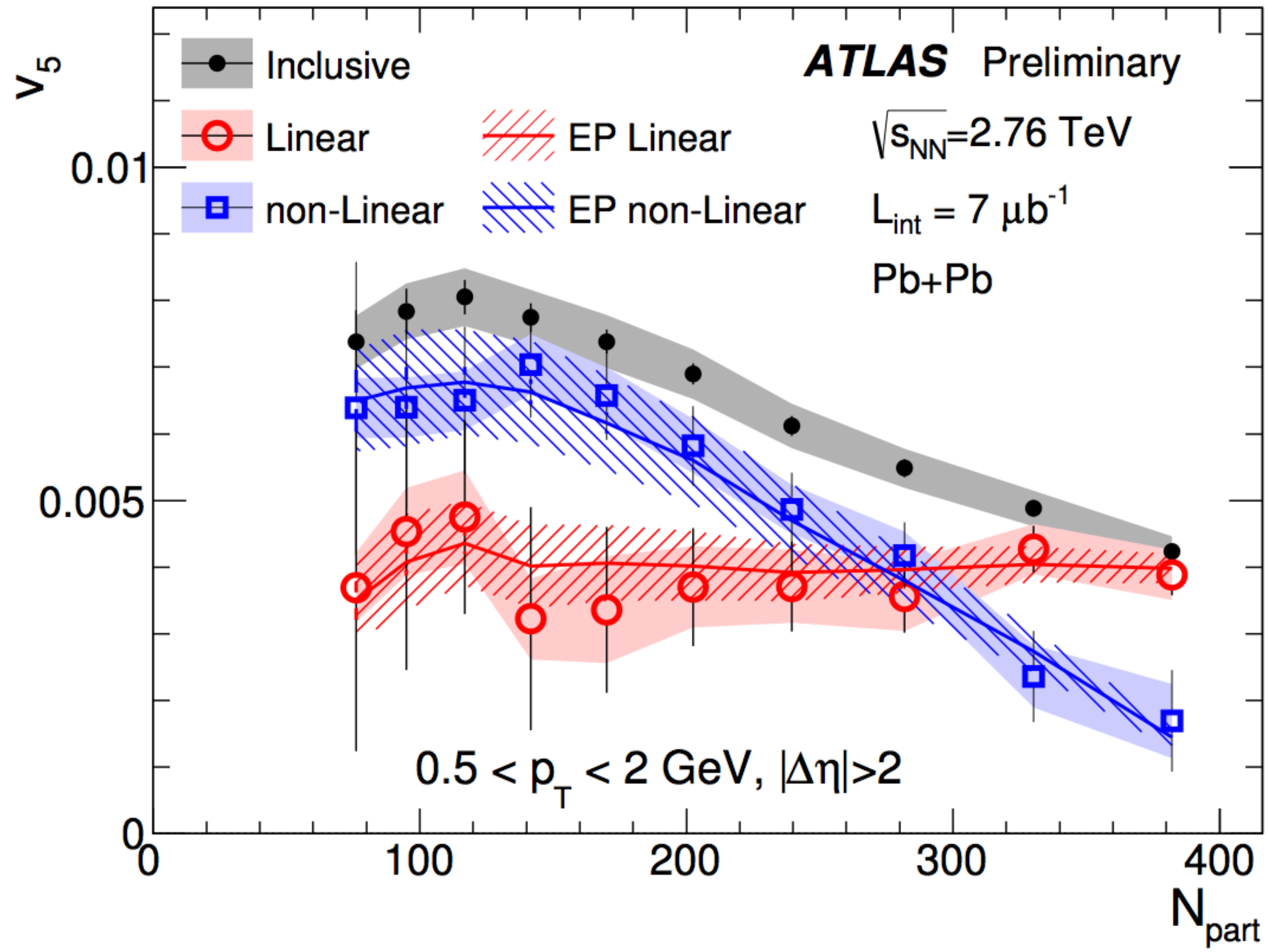
- The non-linear & linear components from EP correlations are obtained as:

$$v_4^{\mathrm{NL}} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle , \quad v_4^{\mathrm{L}} = \sqrt{v_4^2 - (v_4^{\mathrm{NL}})^2}$$

- The results from the two procedures compare quite well
- In most central cases almost all v_4 is uncorrelated with v_2
- Correlated component gradually increases and overtakes linear component as N_{part}~120

v_5-v_2 correlations : comparison to EP correlations





- Compare linear & non-linear components from this analysis to EP correlation results
- The non-linear & linear components from EP correlations are obtained as:

$$v_5^{NL} = v_5 \left\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \right\rangle , \qquad v_5^{L} = \sqrt{v_5^2 - (v_5^{NL})^2}$$