Azimuthal Anisotropy Measurements in Small Colliding Systems

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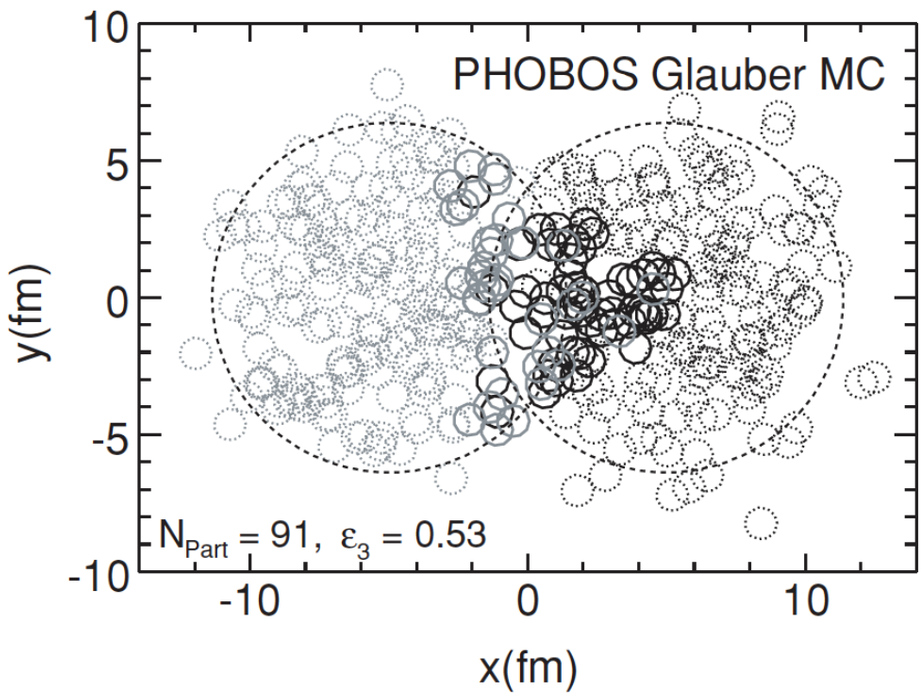
Outline

- Motivation
- Ridge yields
- v_n measurement
- Summary

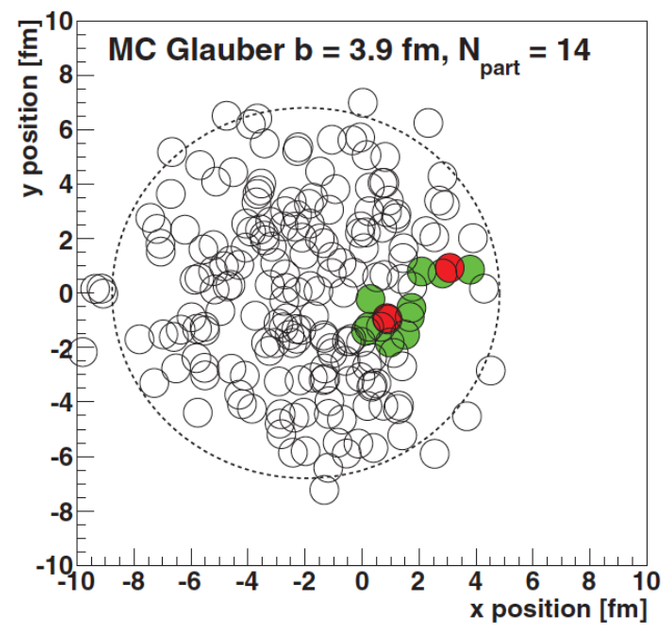
Large vs Small Colliding Systems

Au+Au 200 GeV



B. Alver and G. Roland PRC 81, 054905 (2010)

d+Au 200 GeV



PHENIX, PRC 90, 034902 (2014)

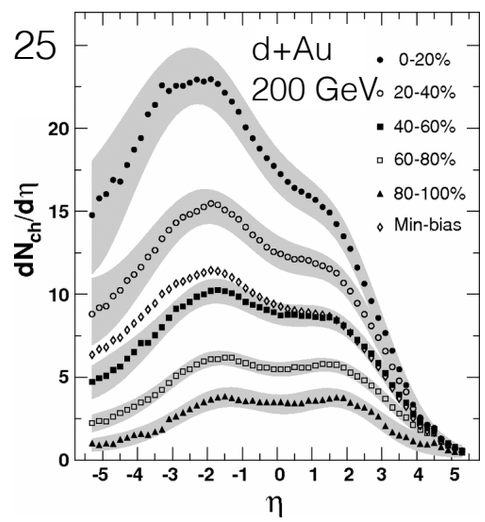
- PbPb ~ 15 fm
- AuAu ~ 14 fm

> "Large"

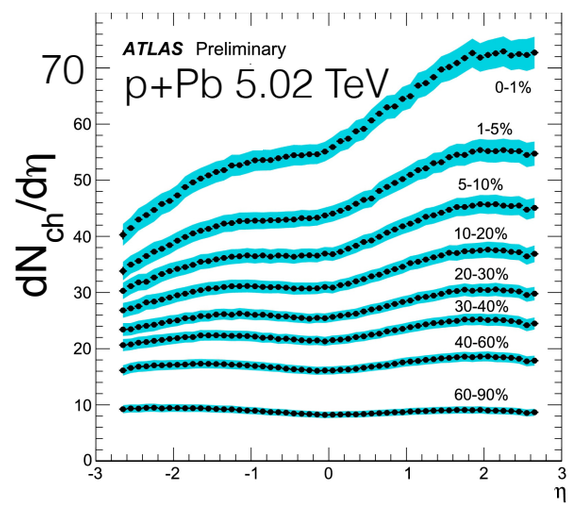
- dAu, pAu, pPb ~ a few fm
- pp ~ 1 fm

> Small

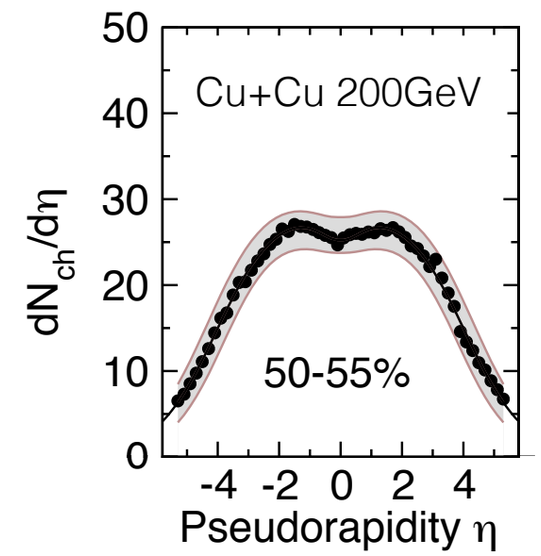
Large vs Small Colliding Systems

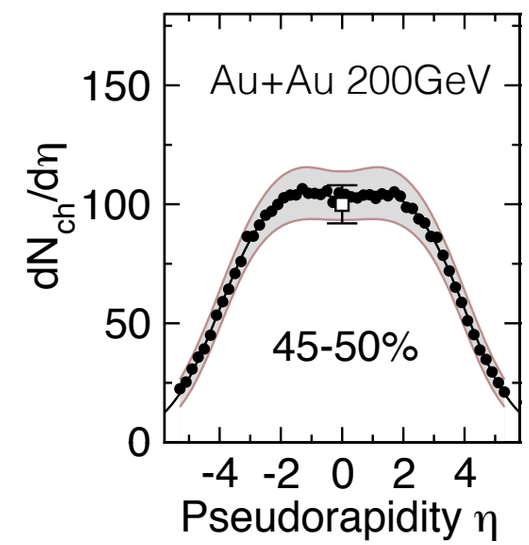


PHOBOS, PRC 72, 031901 (2005)



ATLAS, NPA 932 (2014) 404–408



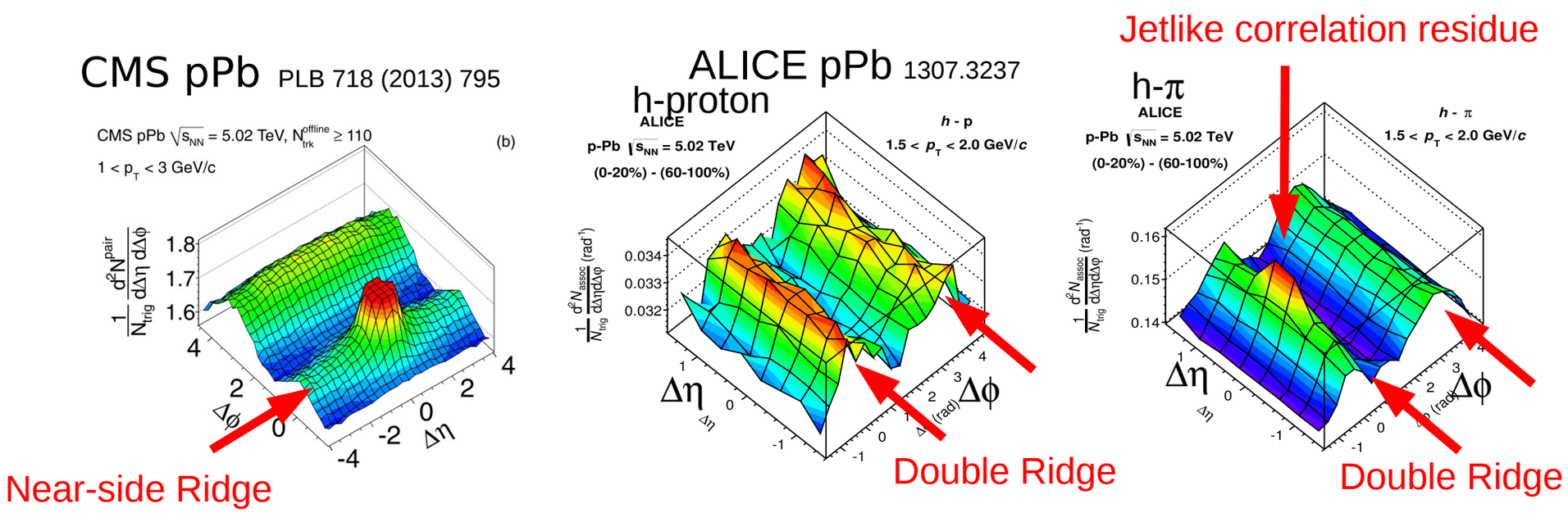


PHOBOS, PRC 83, 024913 (2011)

- Charged particle multiplicity
  in high-multiplicity p+A ~ peripheral heavy ion collisions

Ridge in Small Systems

Ridge in Small Systems

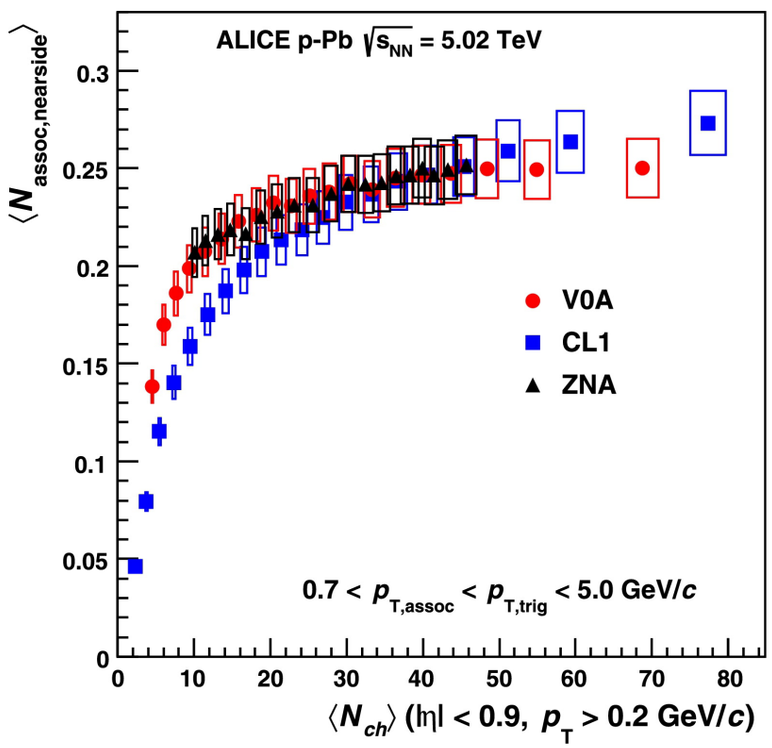


- Near-side ridge in pPb
- Double-ridge in high-mult. – low-multiplicity (for jets)
- Near-side jetlike yield multiplicity dependence?

Event Selection Effect on Jet

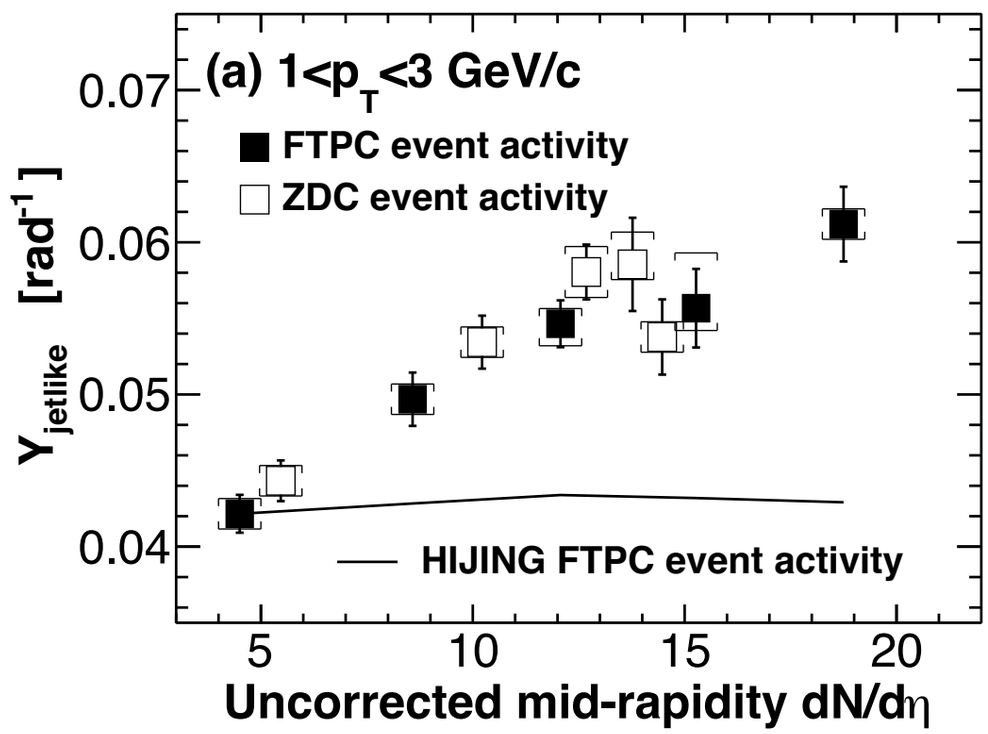
p+Pb

ALICE, PLB 741 (2015) 38–50



d+Au

STAR, PLB 743 (2015) 333

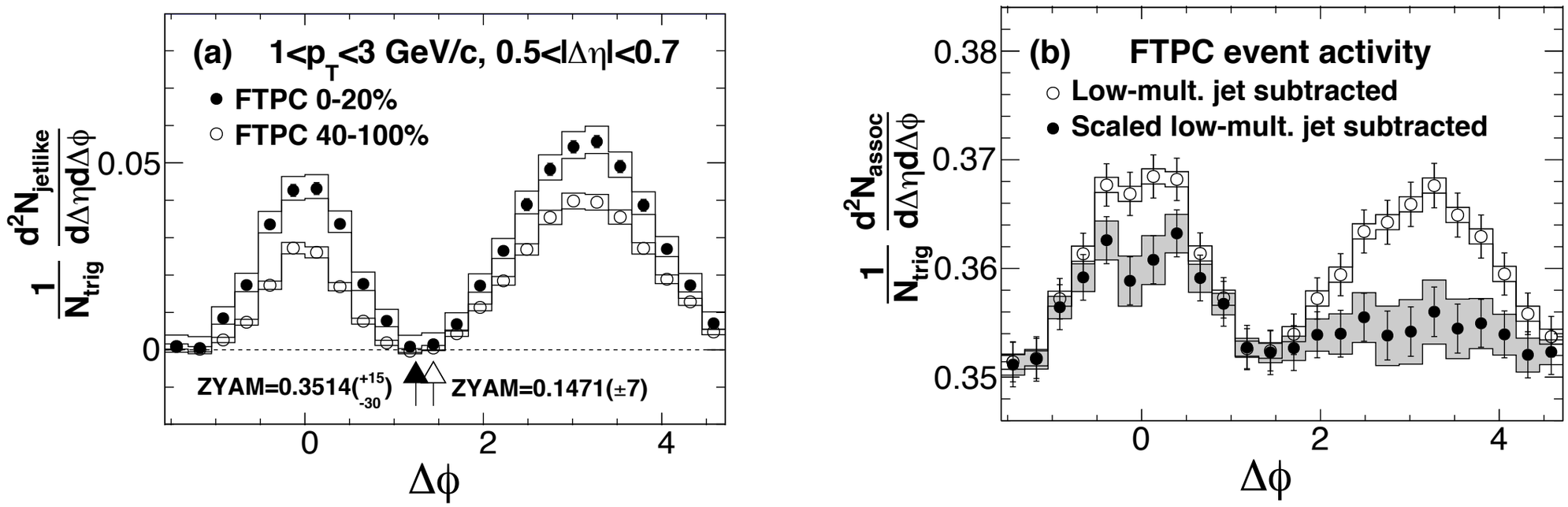


- High-multiplicity selects on jet with larger yield

Near-side Jetlike Correlation Subtraction

d+Au

STAR, PLB 743 (2015) 333



- High-mult. – jet in low-mult. → Double Ridge
- High-mult. – scaled jet in low-mult. → Away-side diminished

Ridge and Jet Multiplicity Dependence

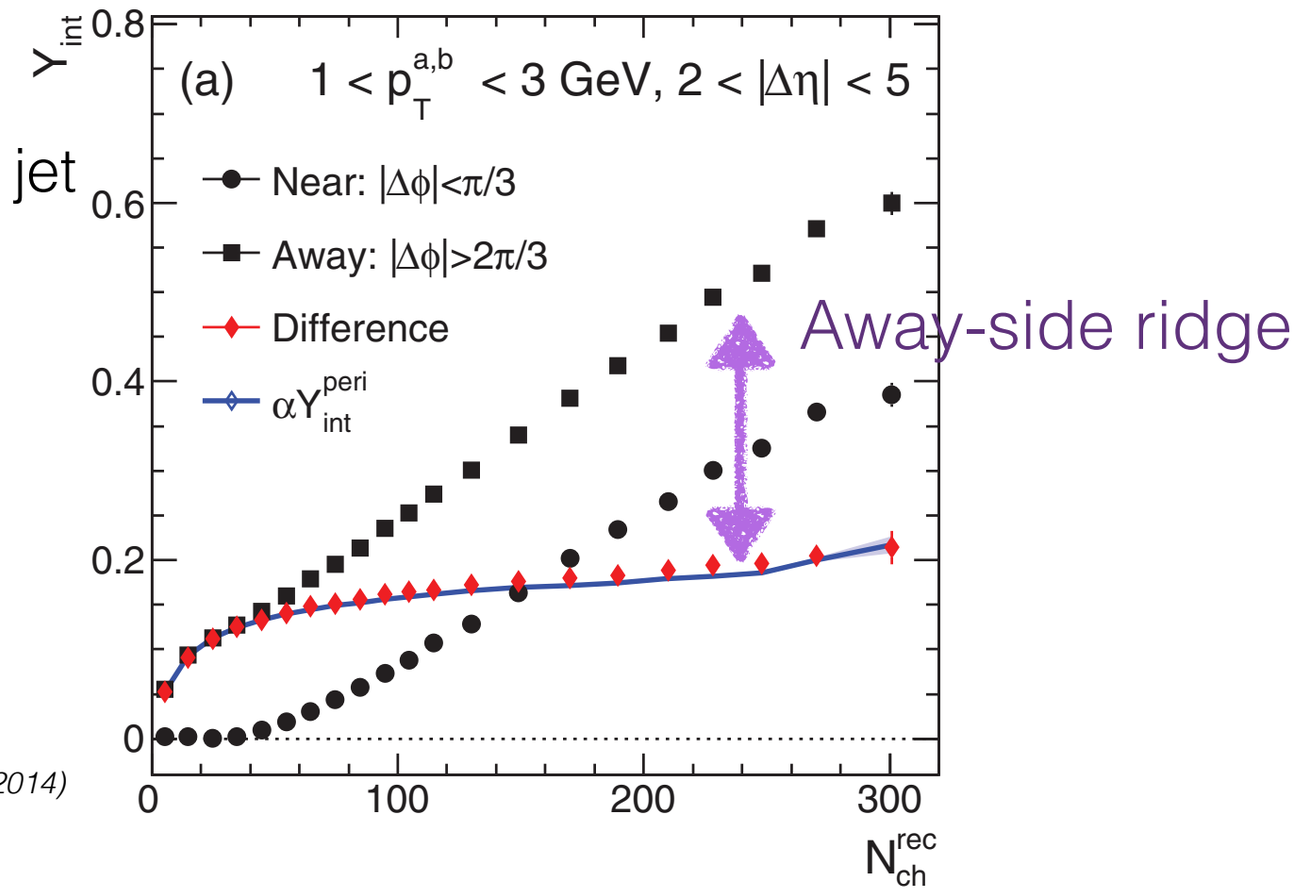
p+Pb 5.02 TeV

Away-side ridge + jet

Near-side ridge

Away-side jet

Near-side jet

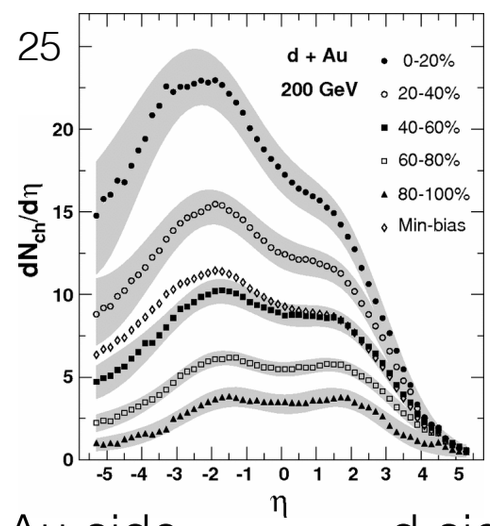


ATLAS, PRC 90, 044906 (2014)

- Ridge and jet have different multiplicity dependence in p+Pb

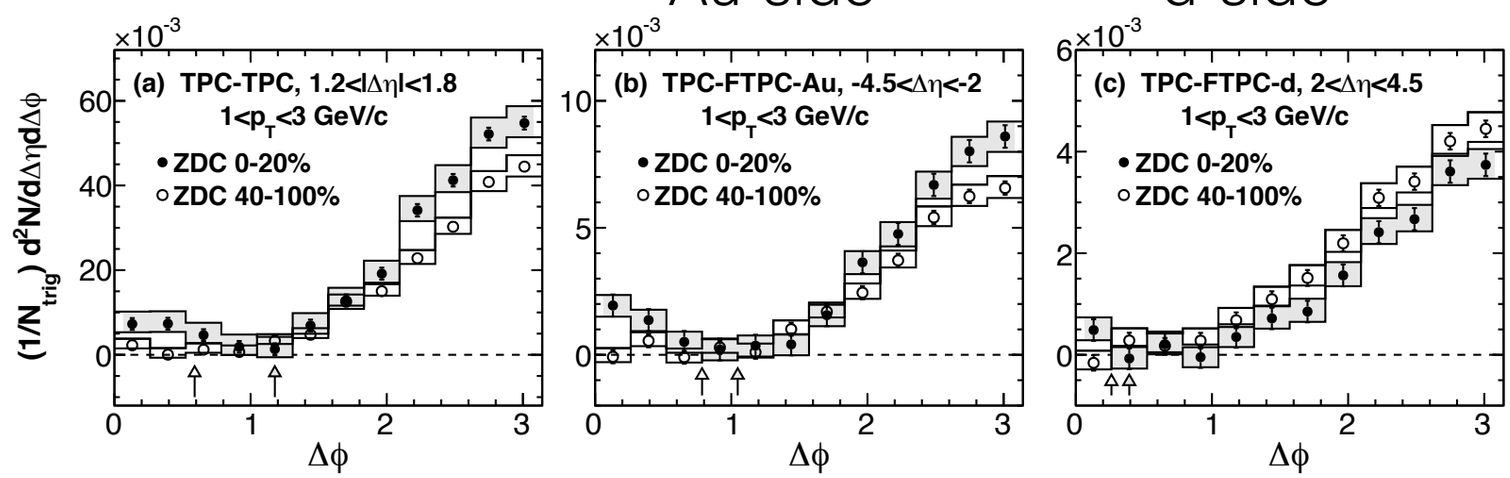
Ridge in d+Au

PHOBOS, PRC 72, 031901 (2005)

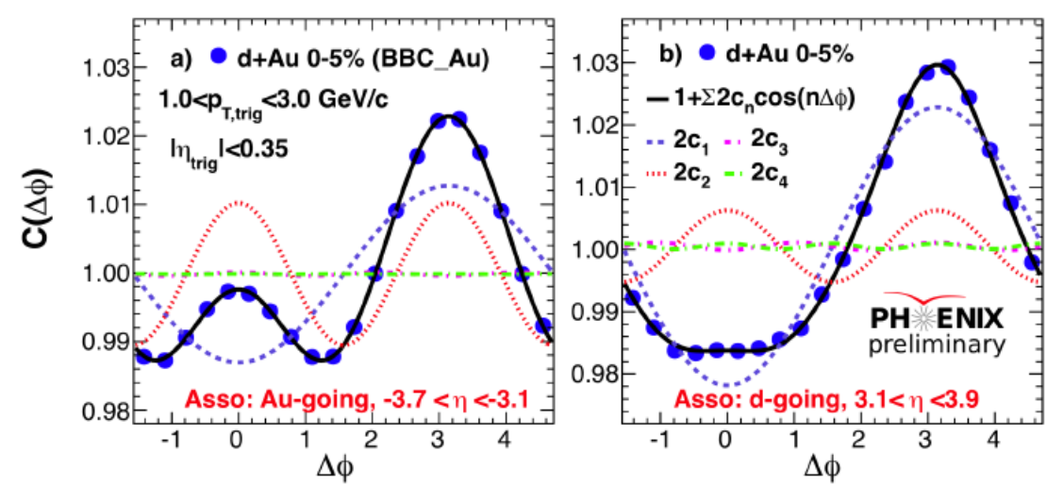


Au-side d-side

Au-side d-side



STAR, PLB

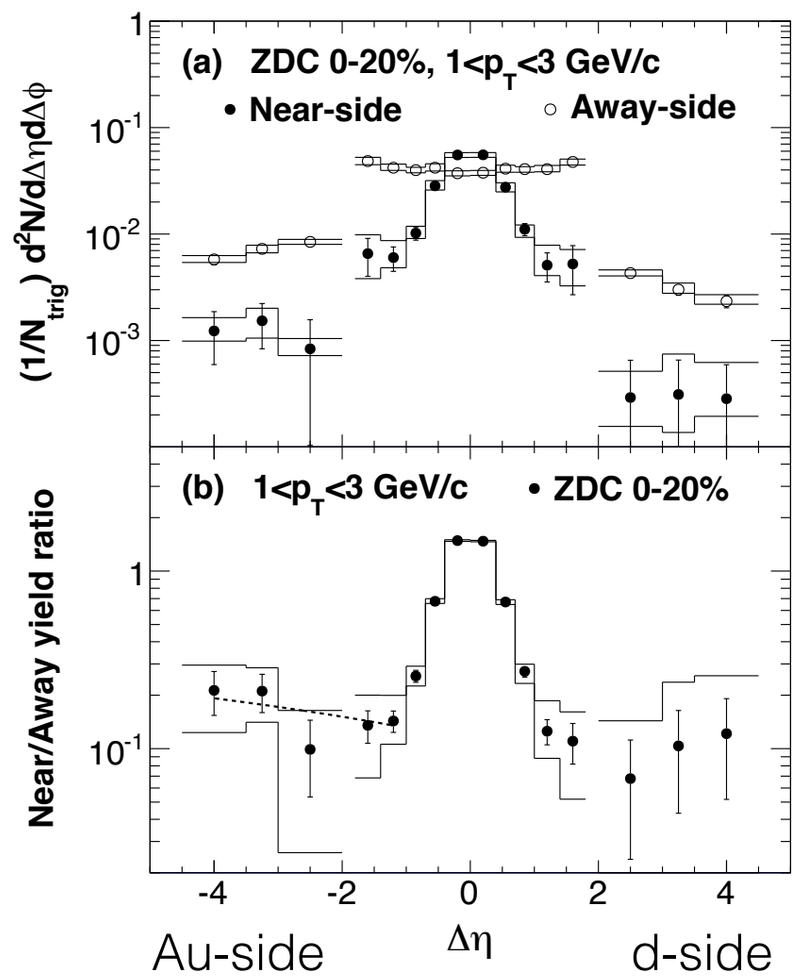


PHENIX, PRL 114, 192301 (2015)

- Near-side ridge yield depends on rapidity

Ridge Yields Pseudorapidity Dependence

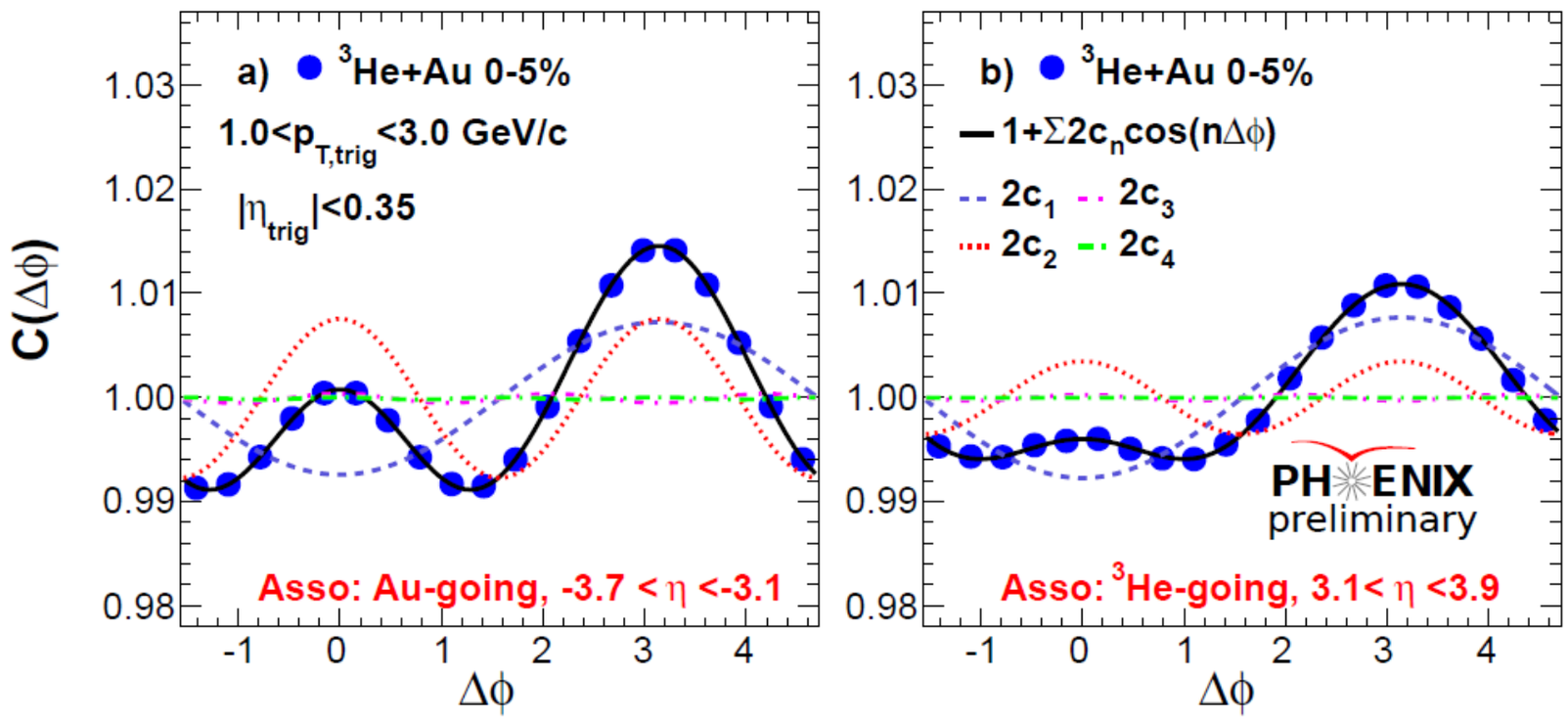
d+Au



STAR, PLB

- Ridge proportional to away-side (ratio independent of Δη)
- Away-side yield dominated by jets

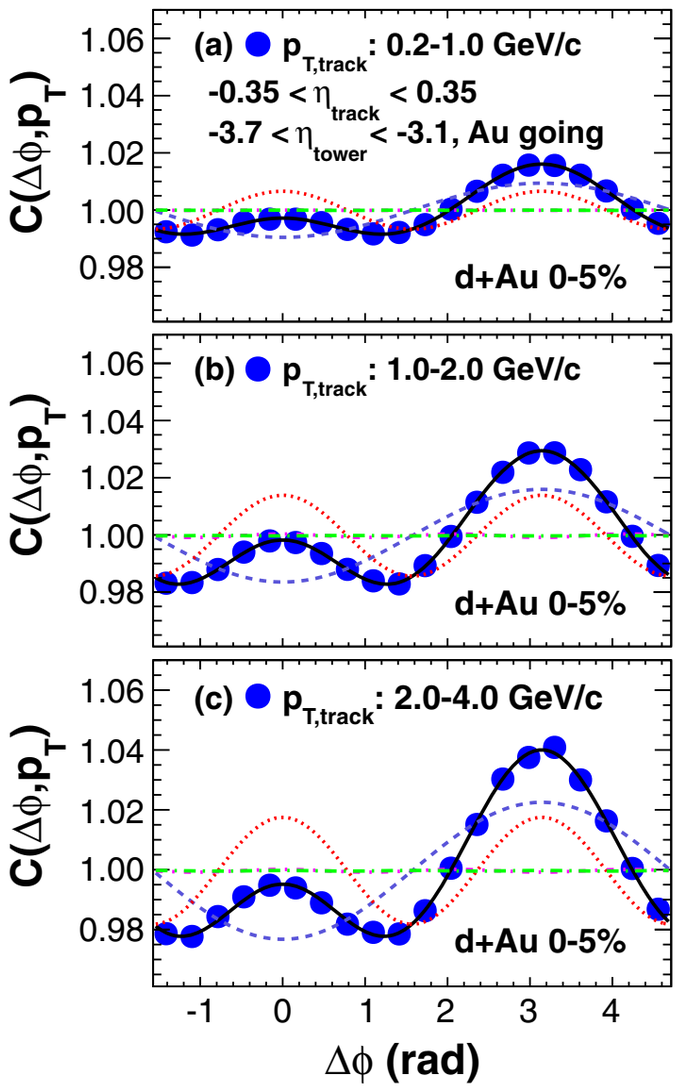
Ridge in He^3+Au



S. Huang IS2014

- Near-side ridge on both Au-side and He^3-side

Ridge p_T Dependence in d+Au



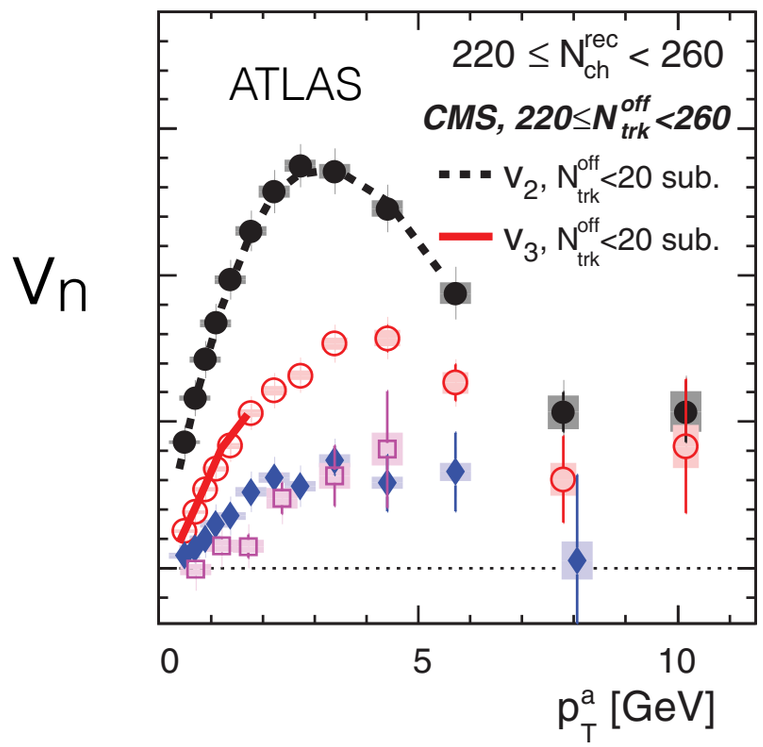
- Near-side ridge yield increases as p_T

PHENIX, PRL 114, 192301 (2015)

v_n Measurements

v_2-$v_5(p_T)$

p+Pb 5.02 TeV



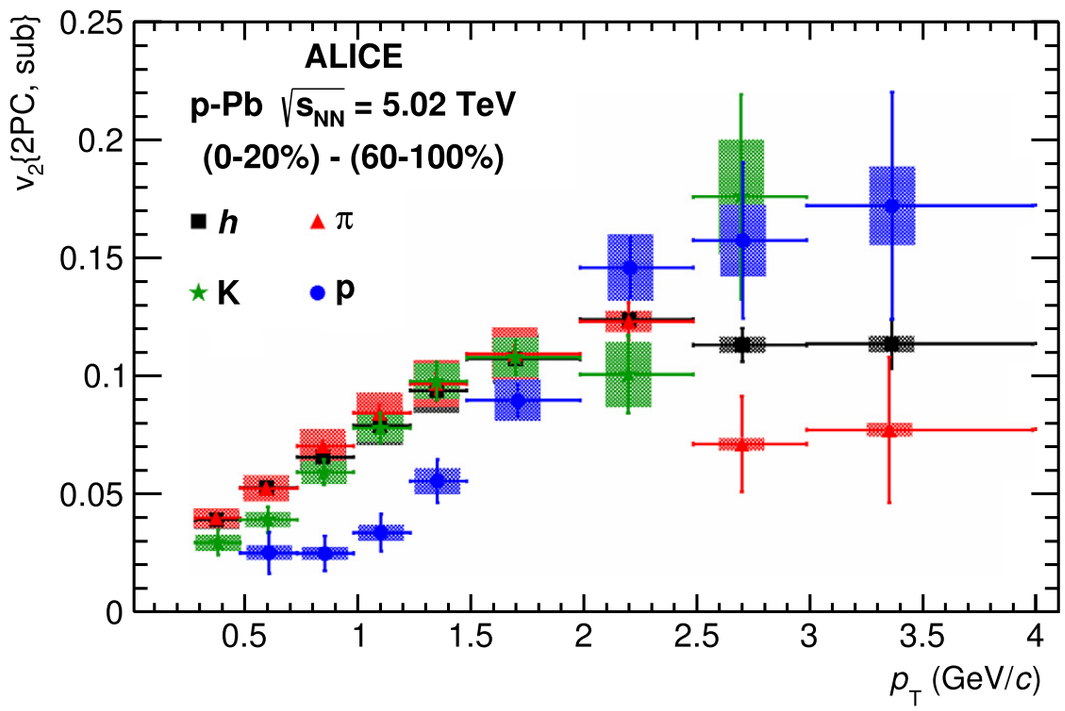
ATLAS, PRC 90, 044906 (2014)

- Higher order v_n is measured
  Good agreement between experiments

- How is non-linear response?

PID v_n in p+Pb

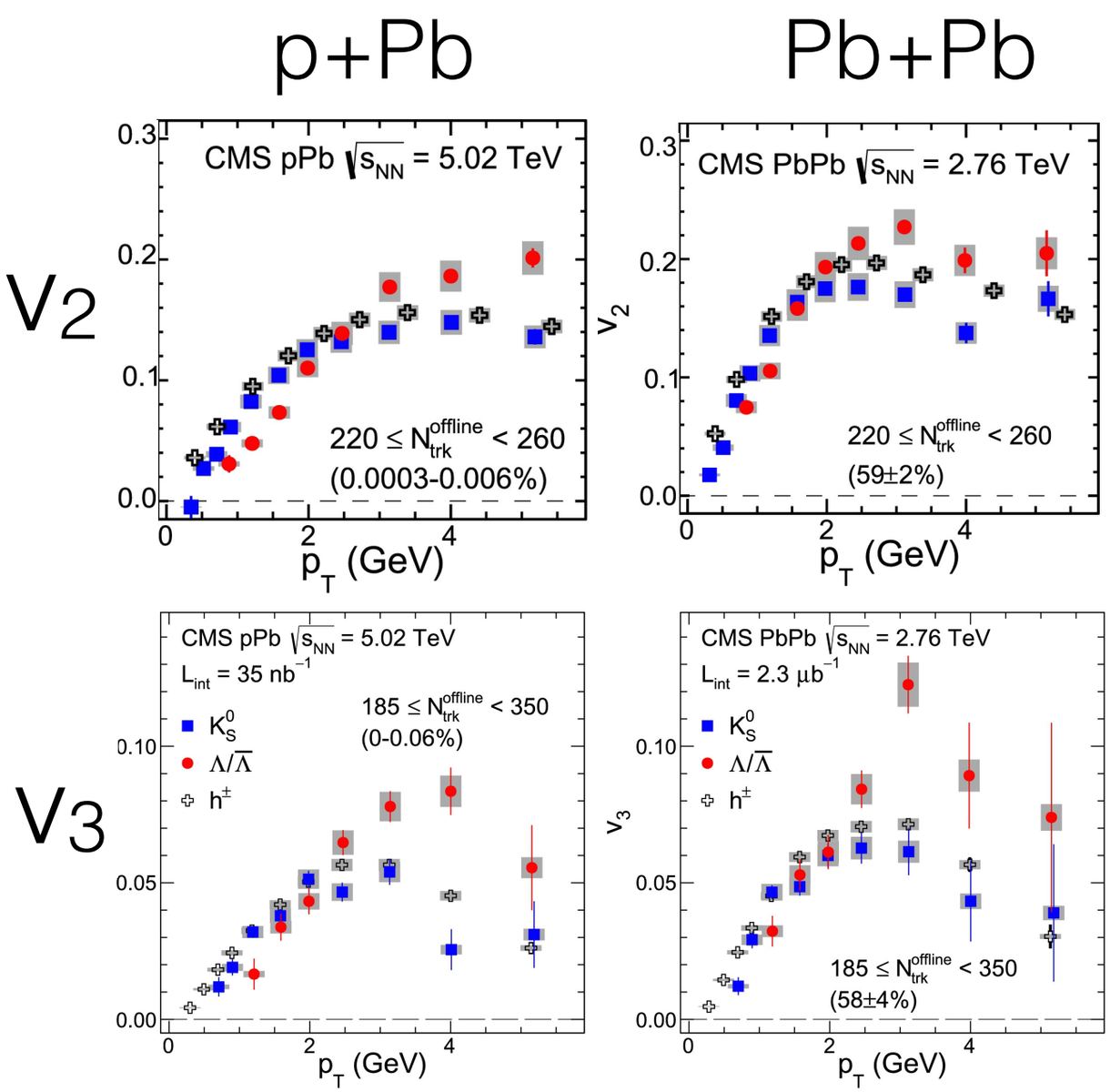
p+Pb 5.02 TeV



ALICE, PLB 726 (2013) 164–177

- v_n mass ordering

Strange Particle Mass Ordering of v_n

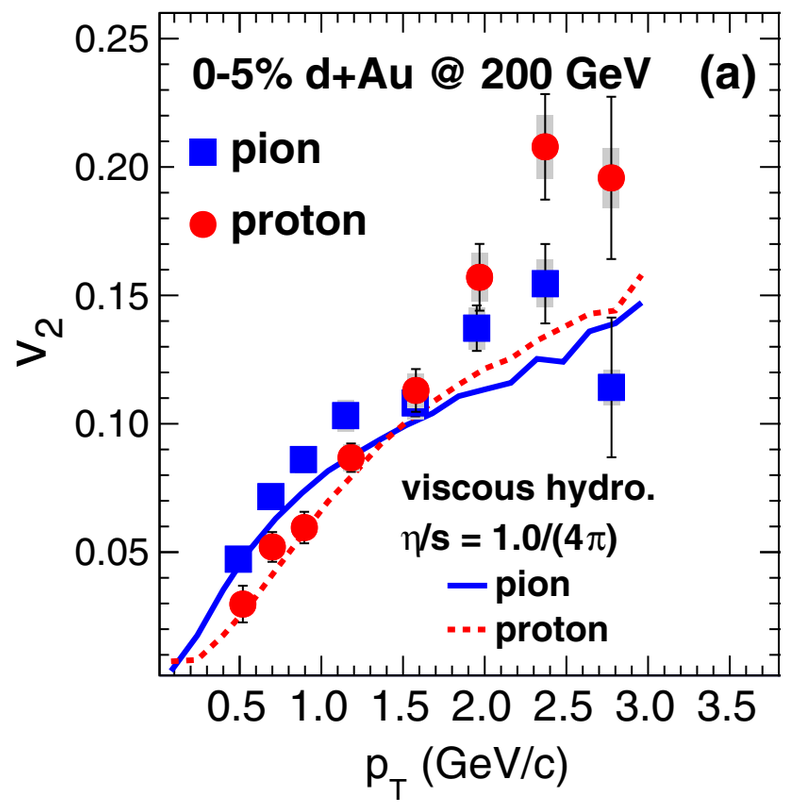


- Smaller v_n but Stronger mass ordering in p+Pb

CMS, PLB 742 (2015) 200

PID v_n in d+Au

d+Au 200 GeV

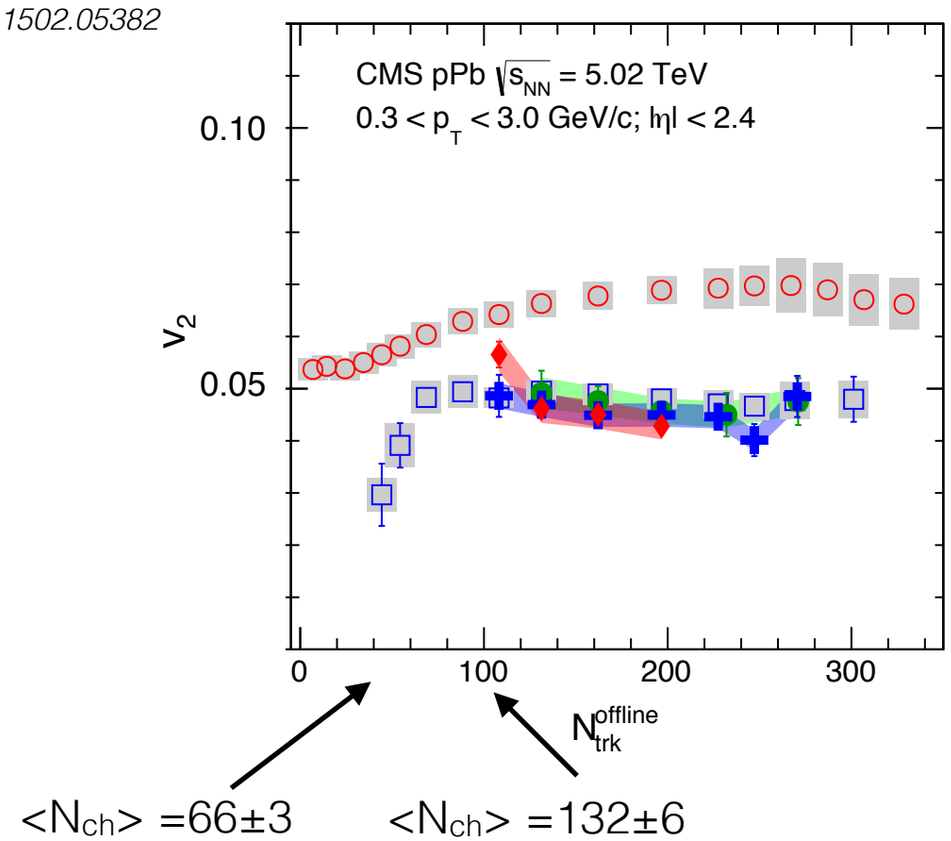


PHENIX, PRL 114, 192301 (2015)

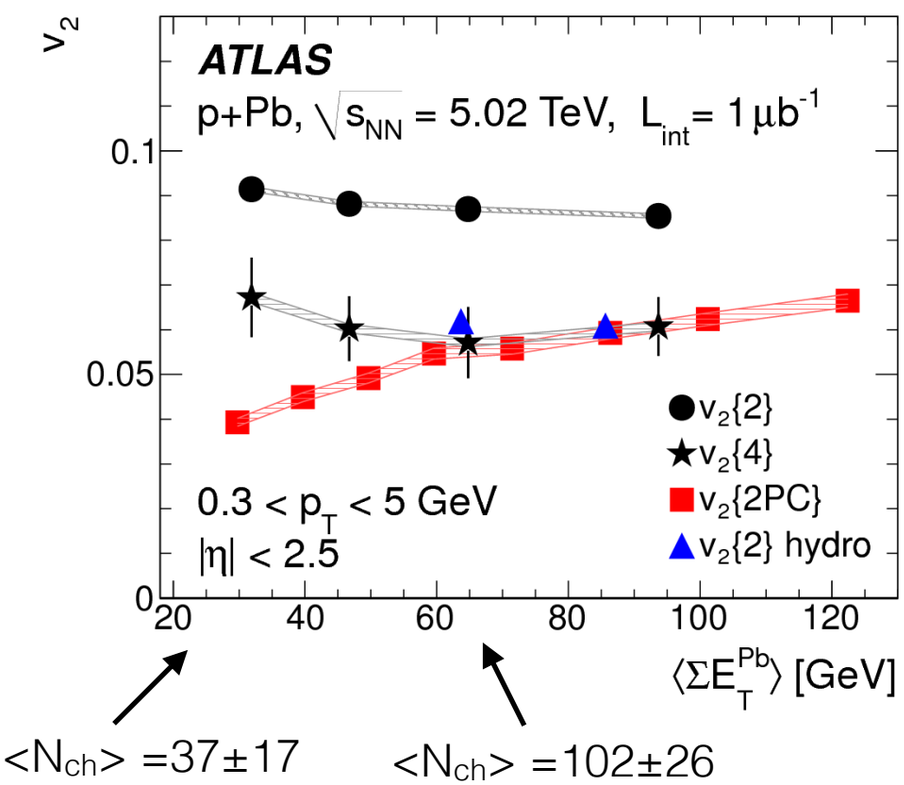
- v_n mass ordering

Multi-particle Correlations v_2 in p+Pb

CMS, arXiv:1502.05382



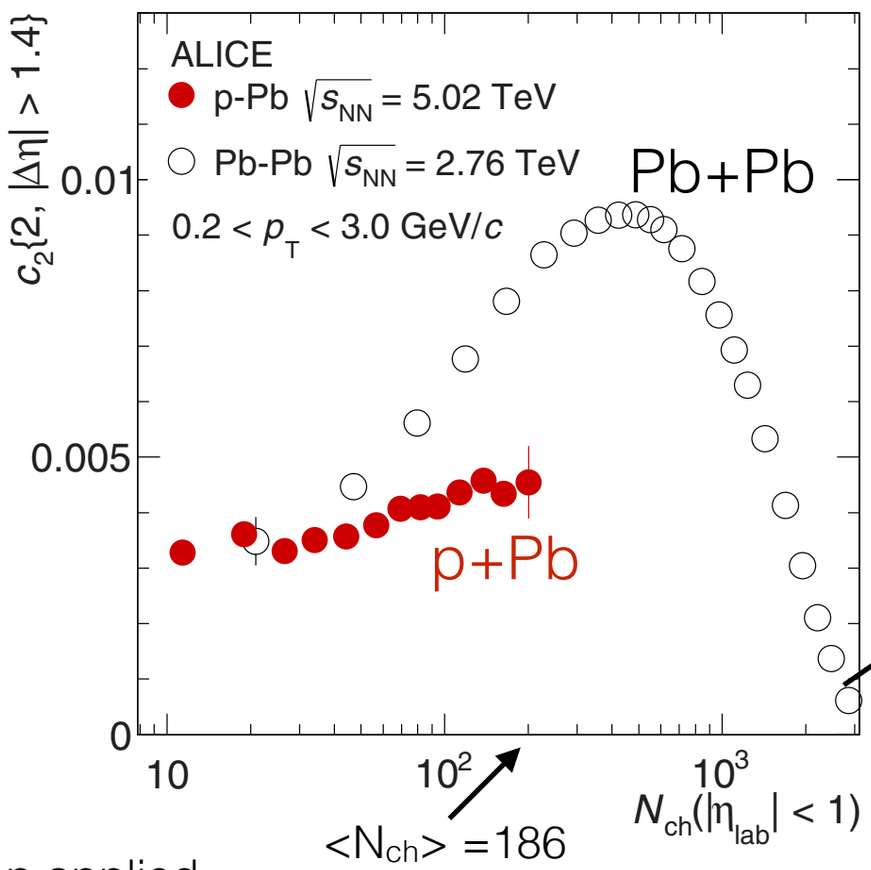
ATLAS, PLB 725 (2013) 60–78



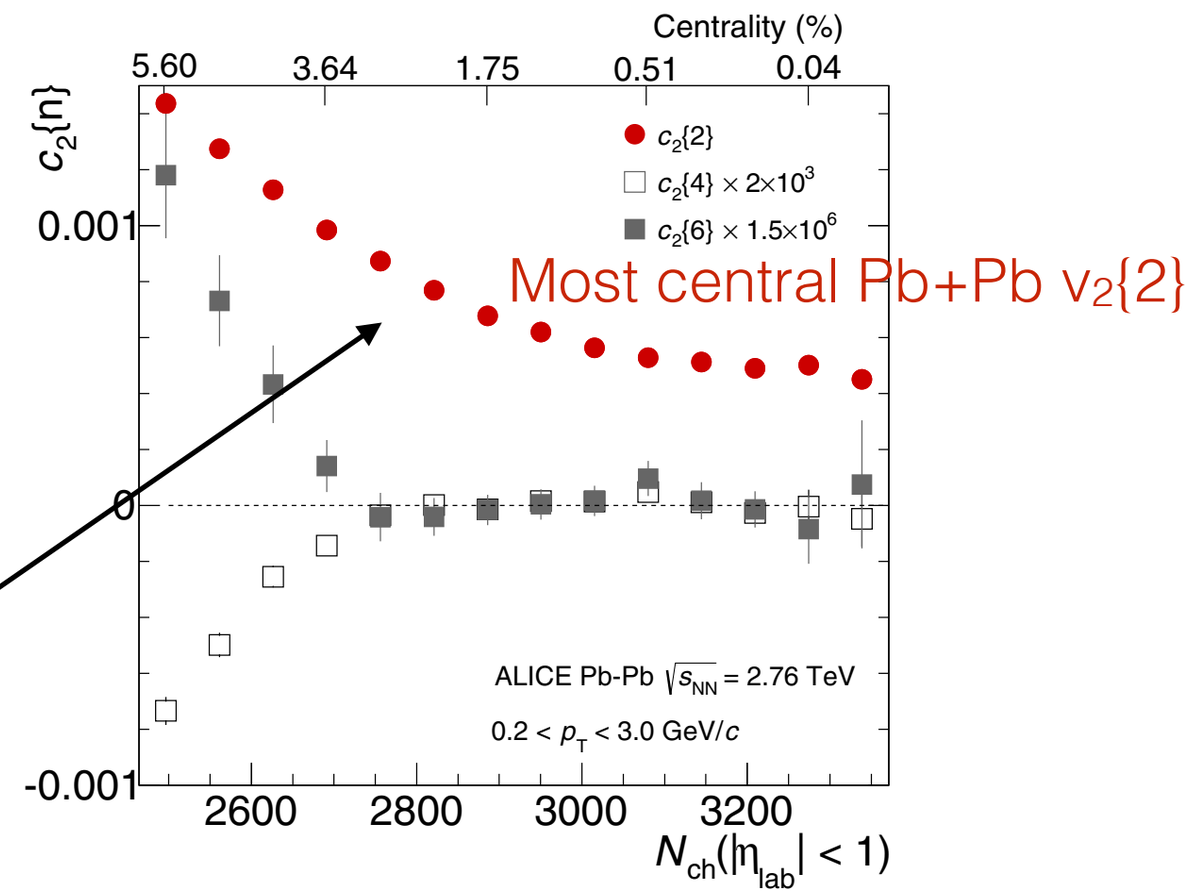
- Multi-particle cumulant needs $v_n\{k\} \gg \mathcal{O}\left(\frac{1}{M^{1-1/k}}\right)$

c_2 in p+Pb, Pb+Pb

$c_n\{2\} = (v_n)^2$



ALICE, PRC 90, 054901 (2014)



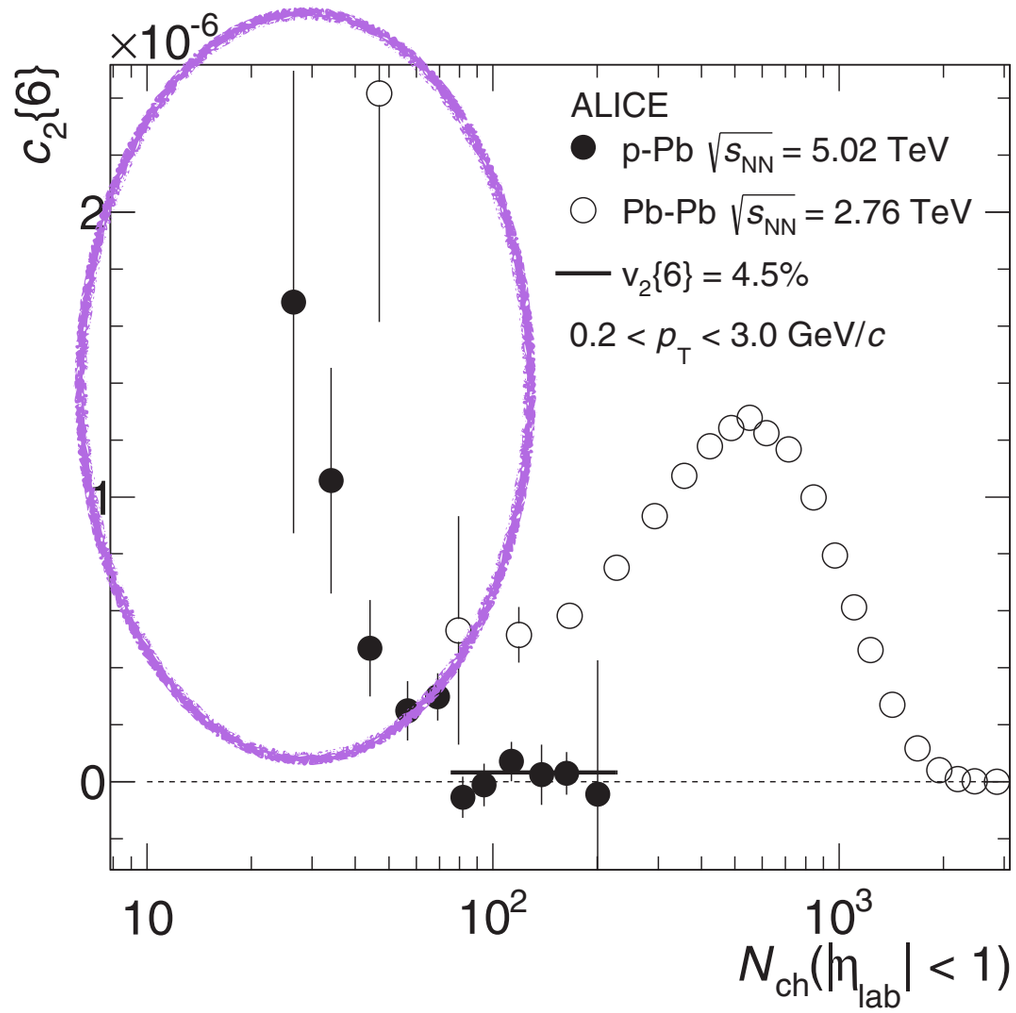
Δη-gap applied
no away-side jet subtraction

- Most central Pb+Pb v_2 from initial fluctuation
- Similarity with p+Pb?

$c_2\{6\}$ in p+Pb, Pb+Pb

$c_n\{6\} = 4(v_n)^6$

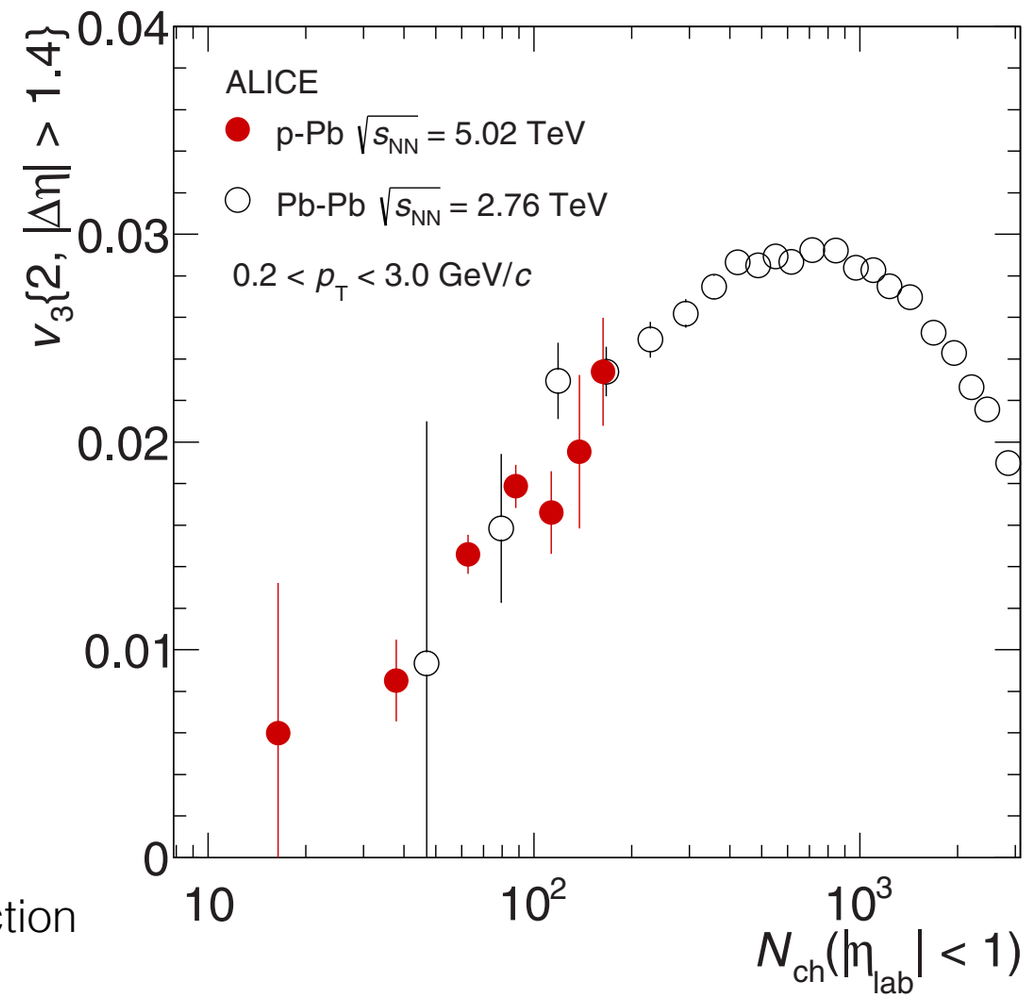
ALICE, PRC 90, 054901 (2014)



- Large $c_2\{6\}$ at jet dominated low-multiplicity
- How much contribution in high-multiplicity

$v_3\{2\}$ in p+Pb, Pb+Pb

ALICE, PRC 90, 054901 (2014)

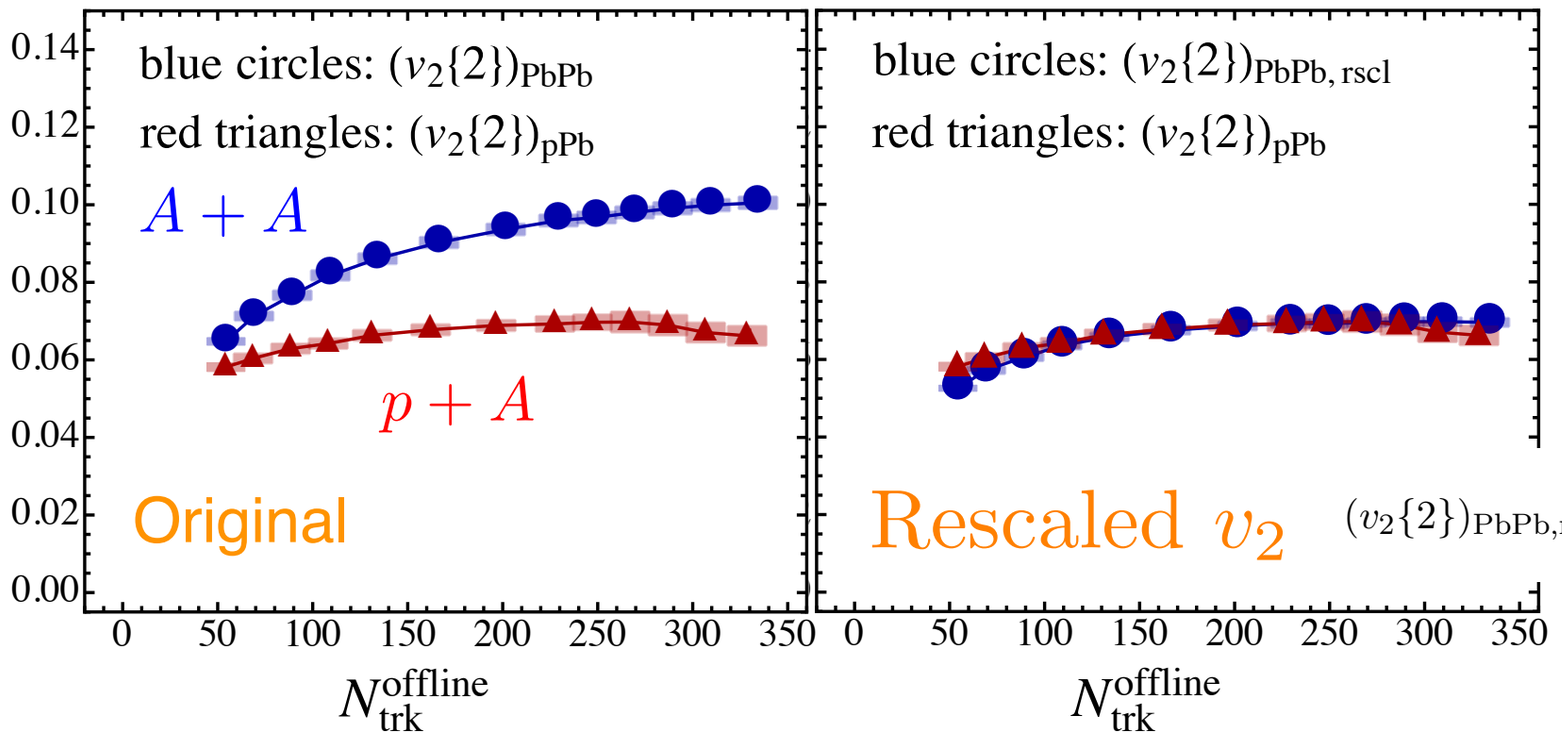


Δη-gap applied
no away-side jet subtraction

- v_3 continuous evolution p+Pb -> Pb+Pb

v_n Scaling from pA -> AA

p+Pb 5.02 TeV



$$(v_2\{2\})_{\mathrm{PbPb,rscl}} \equiv \sqrt{\frac{\langle \delta\epsilon_2^2 \rangle}{(\epsilon_2\{2\})^2_{PbPb}}}(v_2\{2\})_{\mathrm{PbPb}}$$

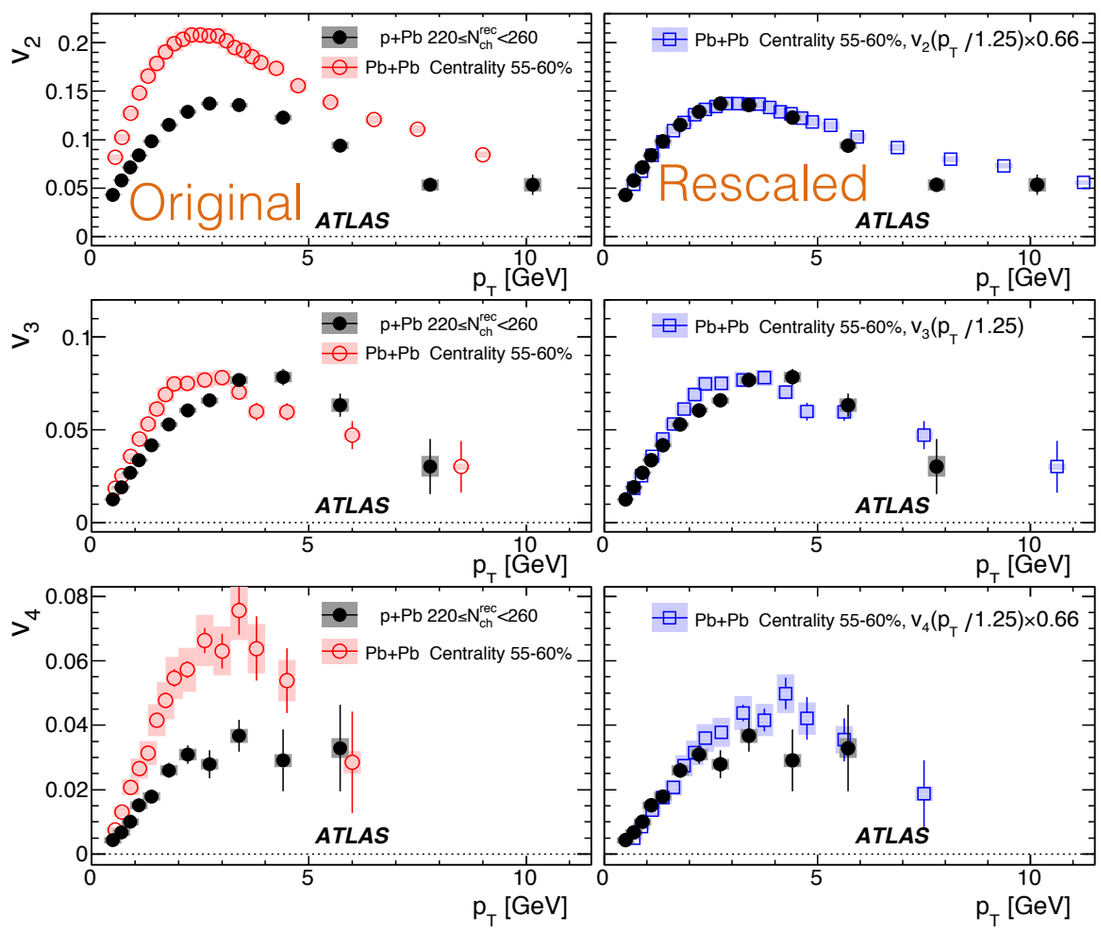
G. Basar & D. Teaney, PRC 90, 054903 (2014)

Data: CMS, PLB 724 (2013) 213

- 'Remove' overall geometry in AA and isolation fluctuation part
- Scaling ratio calculated from Glauber model

v_n(pT) Scaling from pA -> AA

p+Pb 5.02 TeV



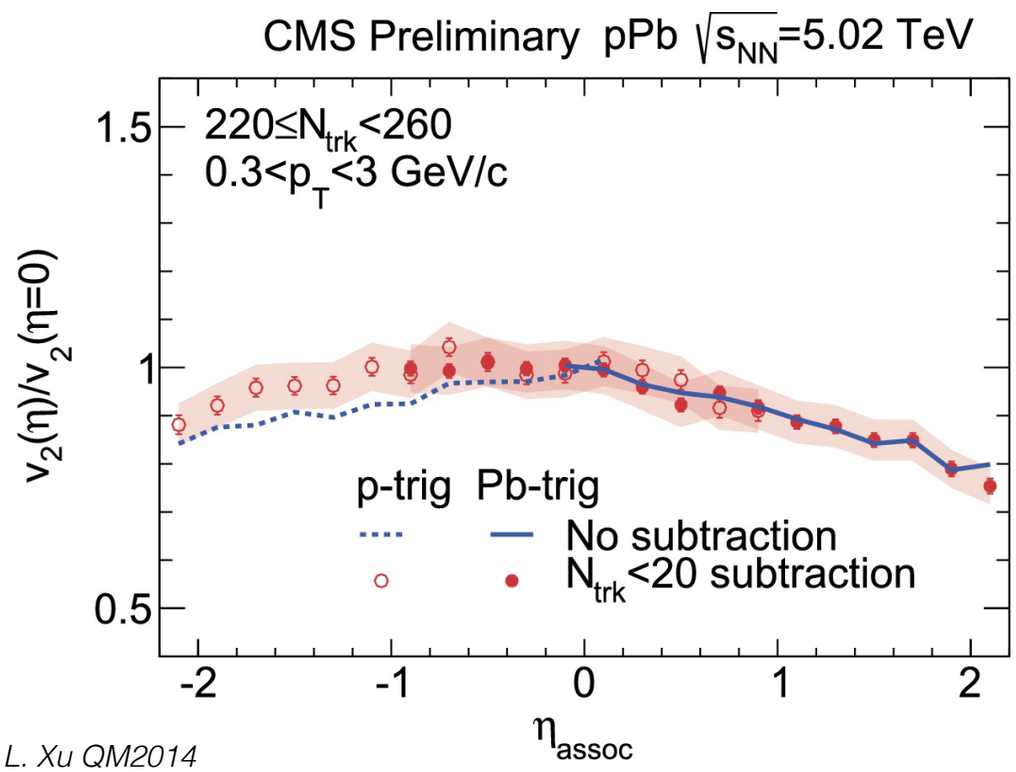
- pA, AA shapes similar with constant scaling
- Mean pT scaling works is not enough: additional x 0.66 for v_2 & v_4

$$v_n(p_T)_{pPb} = v_n(p_T / \frac{\langle p_T \rangle_{pPb}}{\langle p_T \rangle_{PbPb}})_{PbPb}$$

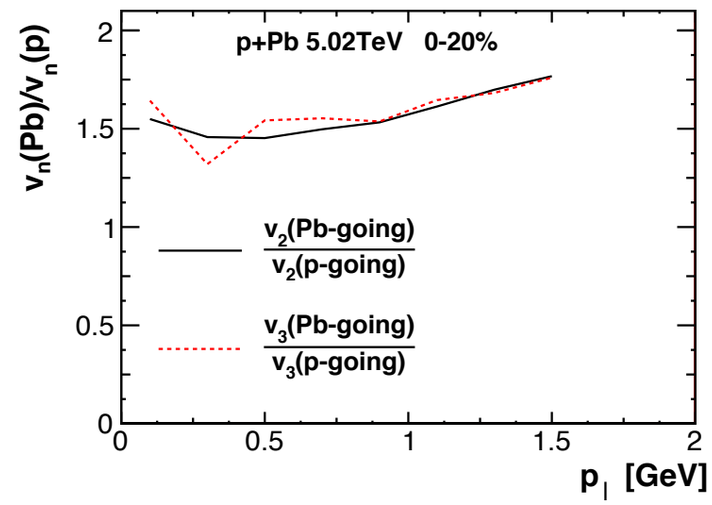
ATLAS, PRC 90, 044906 (2014)

G. Basar & D. Teaney, PRC 90, 054903 (2014)

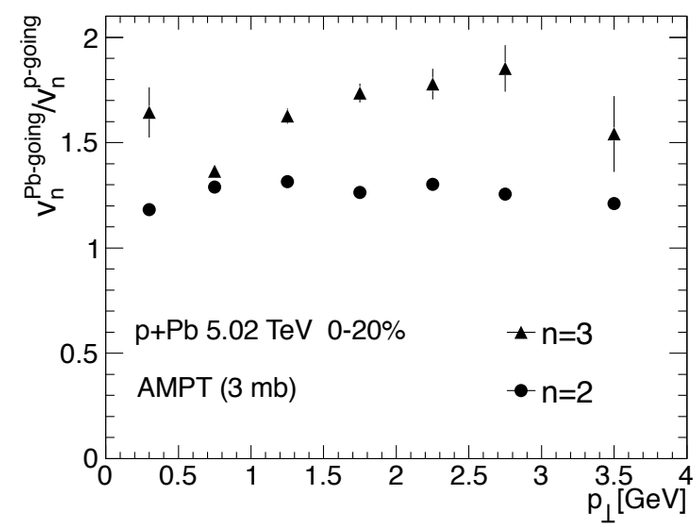
$v_2(\eta)$ in p+Pb



L. Xu QM2014



hydro



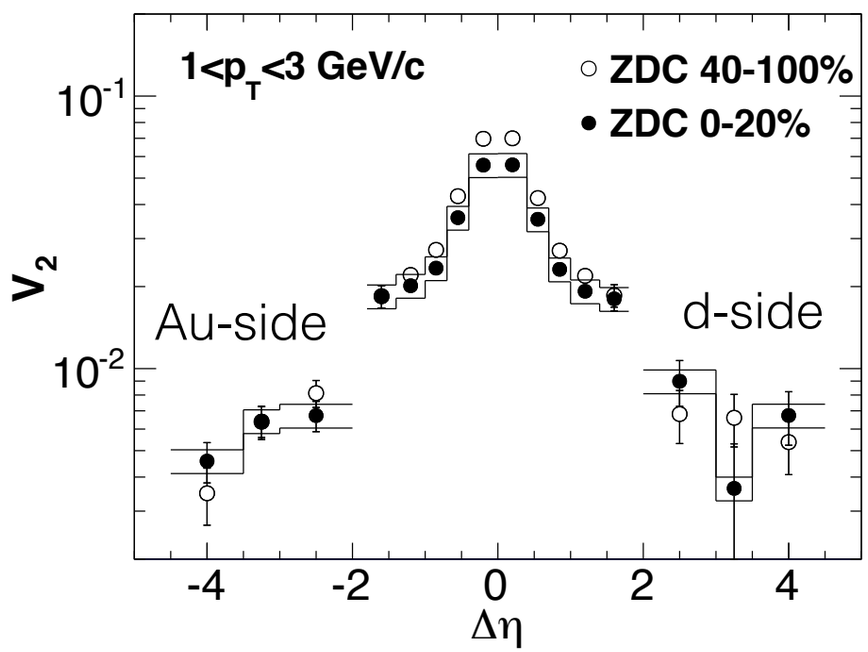
AMPT

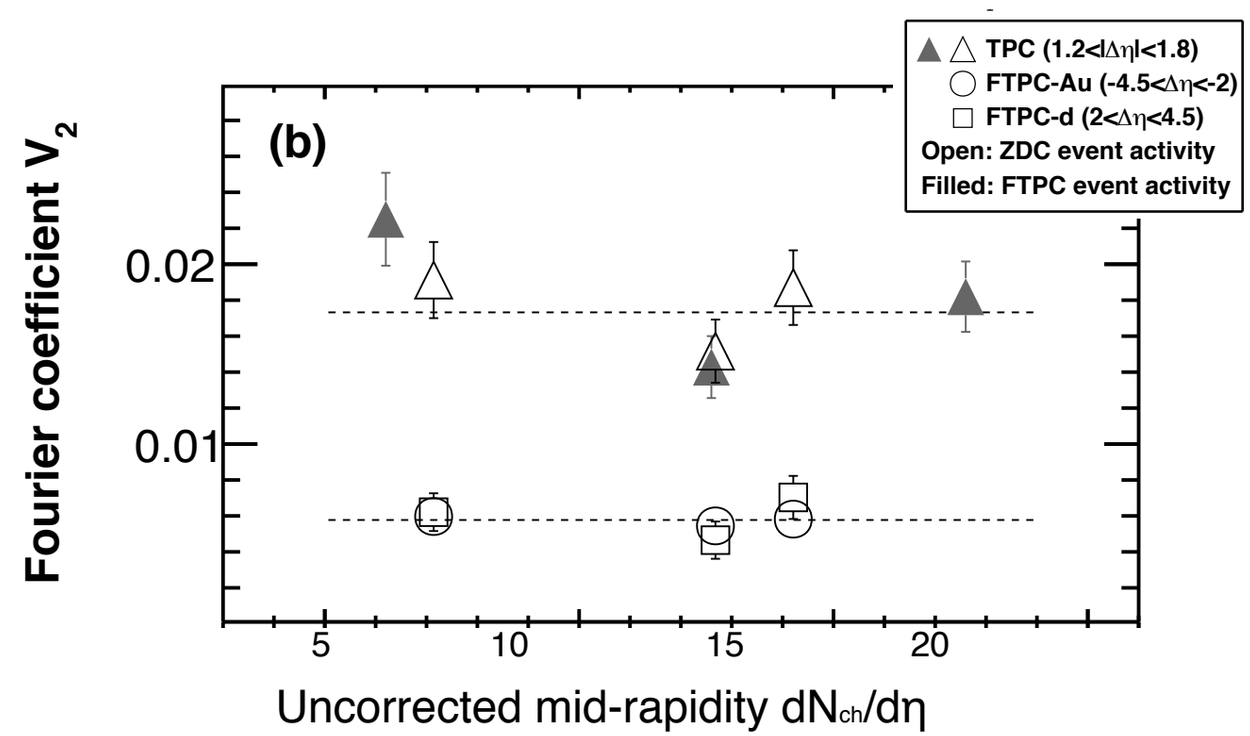
P. Bozek, A. Bzdak, G. MA, arXiv:1503.03655

- v_2 weakly depends on η
- p_T dependence different predications

v_2 Δη & Multiplicity Dependence in d+Au

No jet subtraction

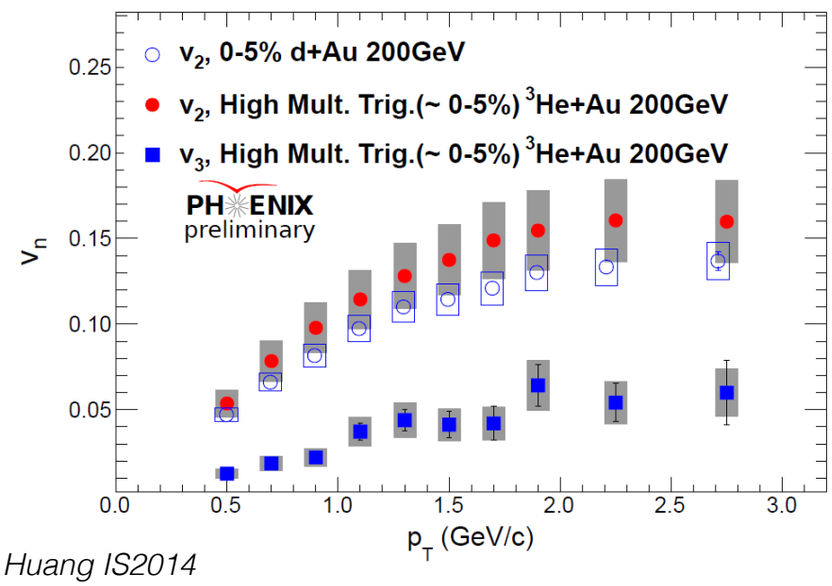




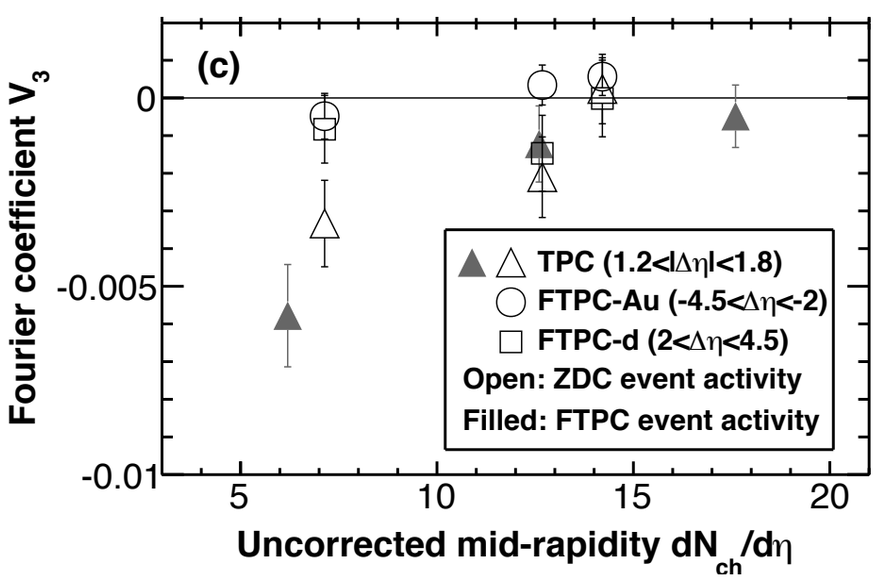
- Similar V_2 on Au-side & d-side while different near-side ridge yield

STAR, PLB

v_2 & $v_3(p_T)$ in d+Au and He^3+Au



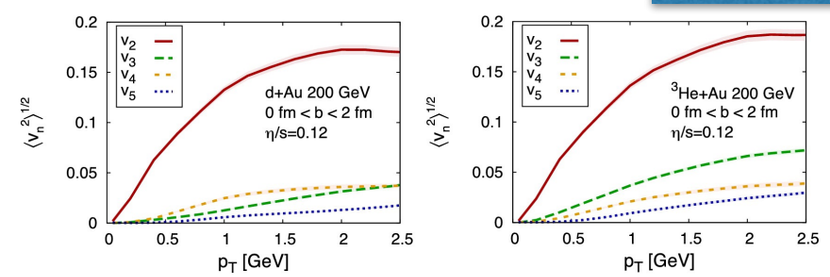
S. Huang IS2014



STAR, PLB

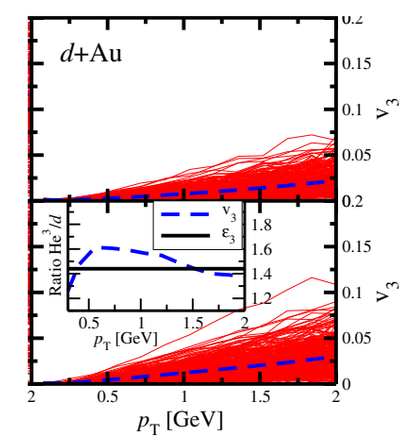
- v_3 in d+Au?

IP-Glasma+music



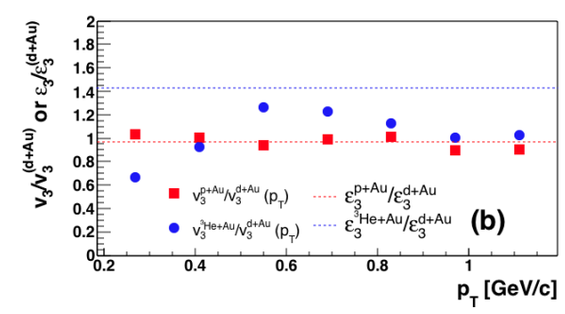
B. Schenke & R. Venugopalan NPA 931 (2014) 1039–1044

Glauber+hydro



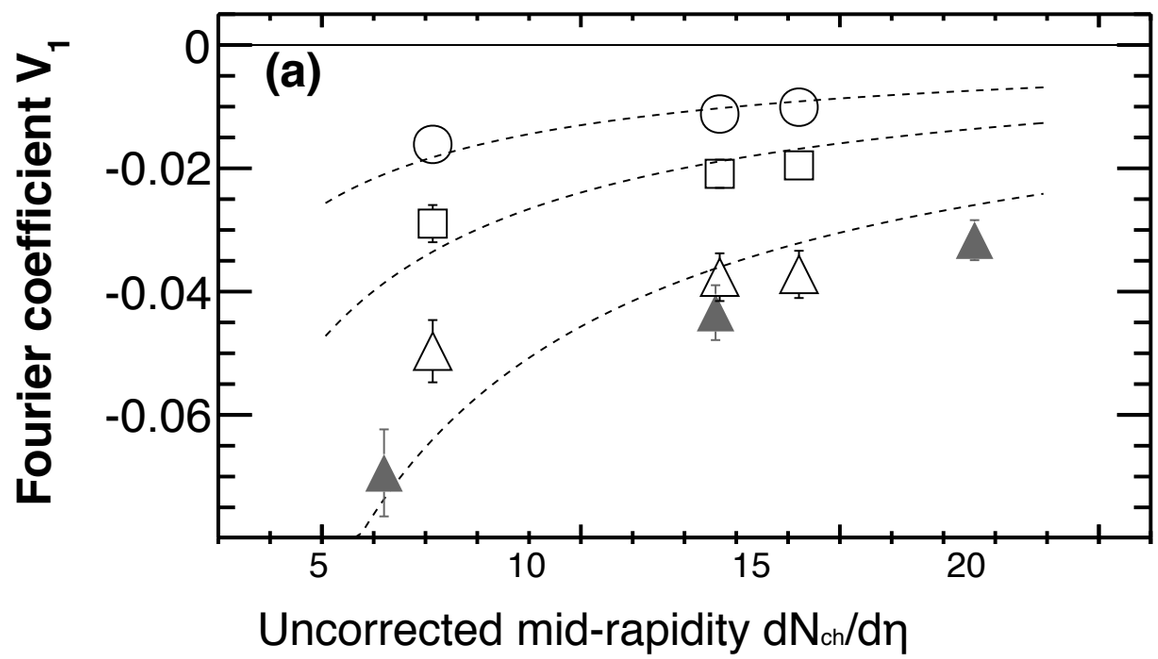
J. Nagle et al, PRL 113, 112301 (2014)

AMPT



J. Nagle et al, arXiv 1501.06880

v_1 Multiplicity Dependence in d+Au



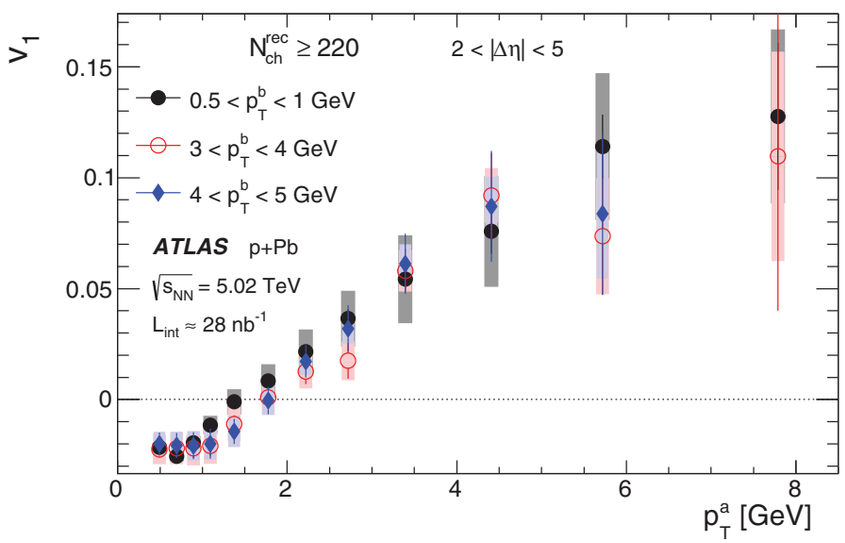
STAR, PLB

- V1 ~ 1/Multiplicity <— Momentum conservation
- + same V2 in low- and high-multiplicity —> Near-side ridge in high-mult. not in low-mult.

$v_1(p_T)$ in p+Pb and Pb+Pb

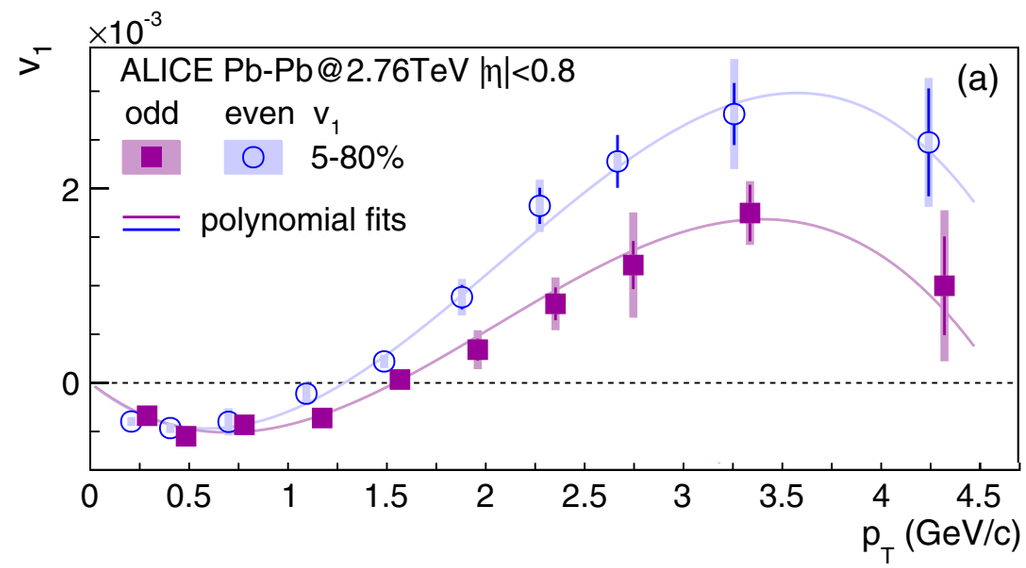
Momentum conservation contribution removed

p+Pb 5.02 TeV



ATLAS, PRC 90, 044906 (2014)

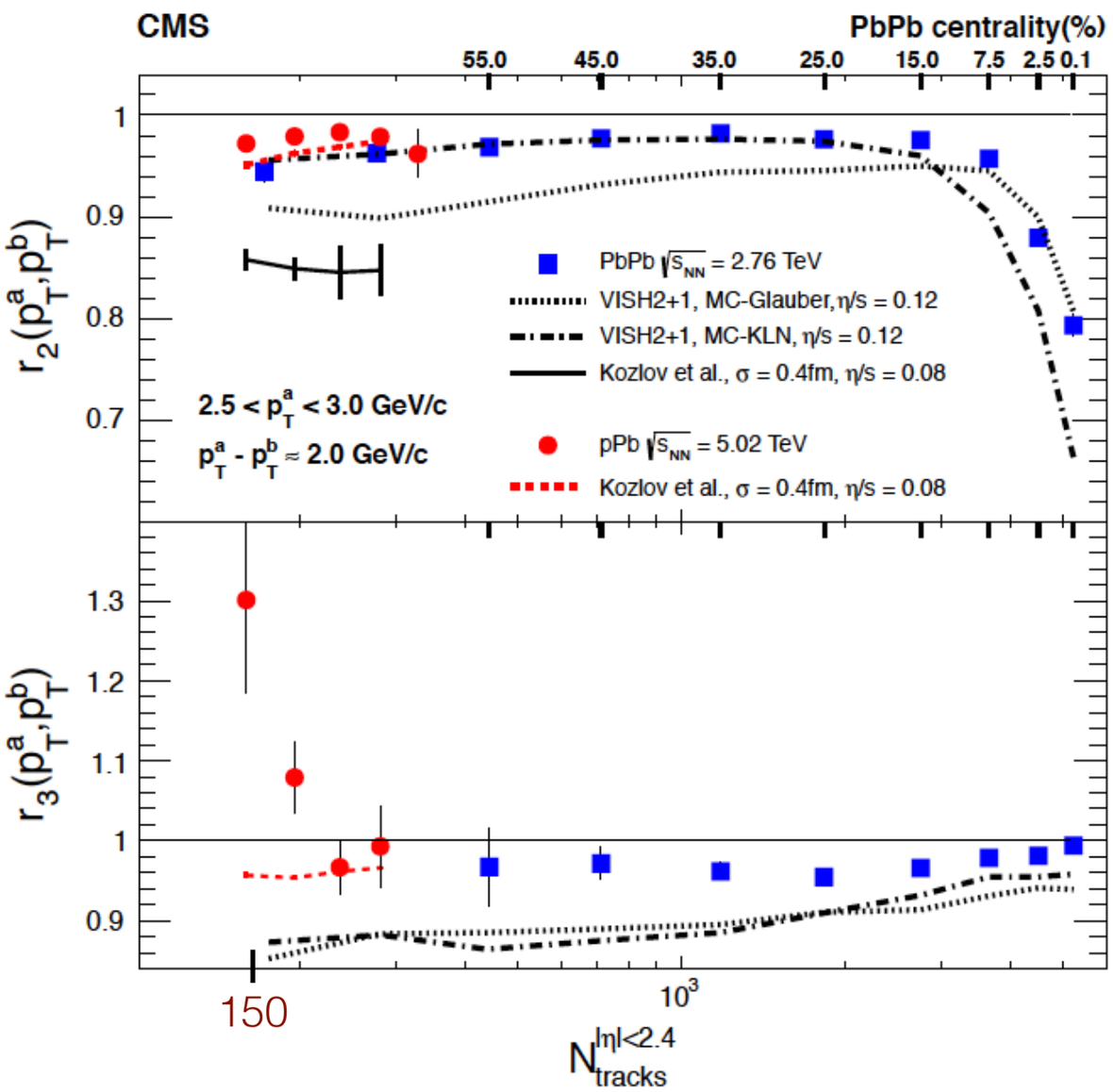
Pb+Pb 2.76 TeV



ALICE, PRL 111, 232302 (2013)

- Similar v_1 trend in p+Pb & Pb+Pb
- Sign change at larger p_T in p+Pb

Transverse Momentum Factorization Breakdown



CMS, arXiv:1503.01692

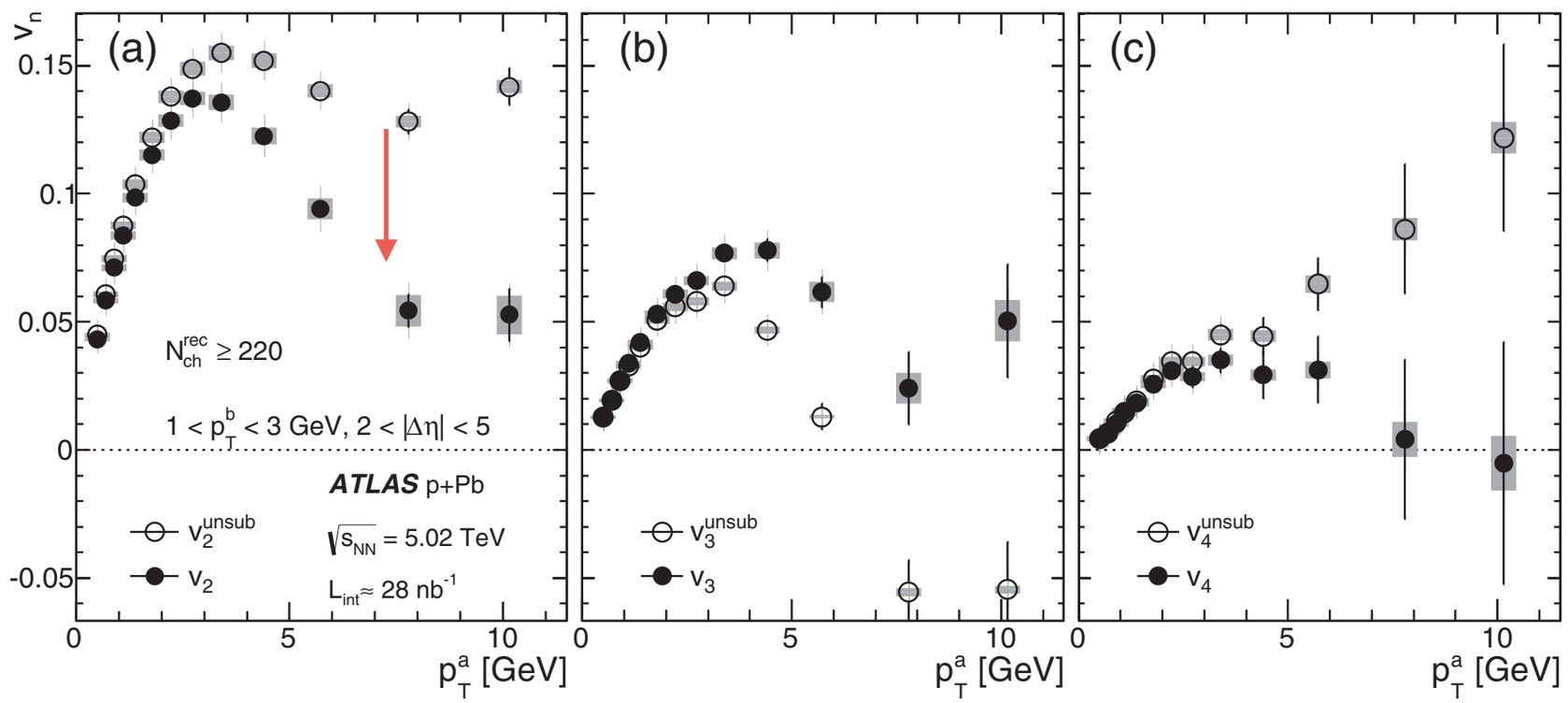
$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)}}$$

- 3+1D hydrodynamic calculation: difficulty to describe the whole picture together

note: the r_n is insensitive to η/s in calculation, can separate initial effect and medium response

Away-side Jet Contribution in v_n

p+Pb 5.02 TeV

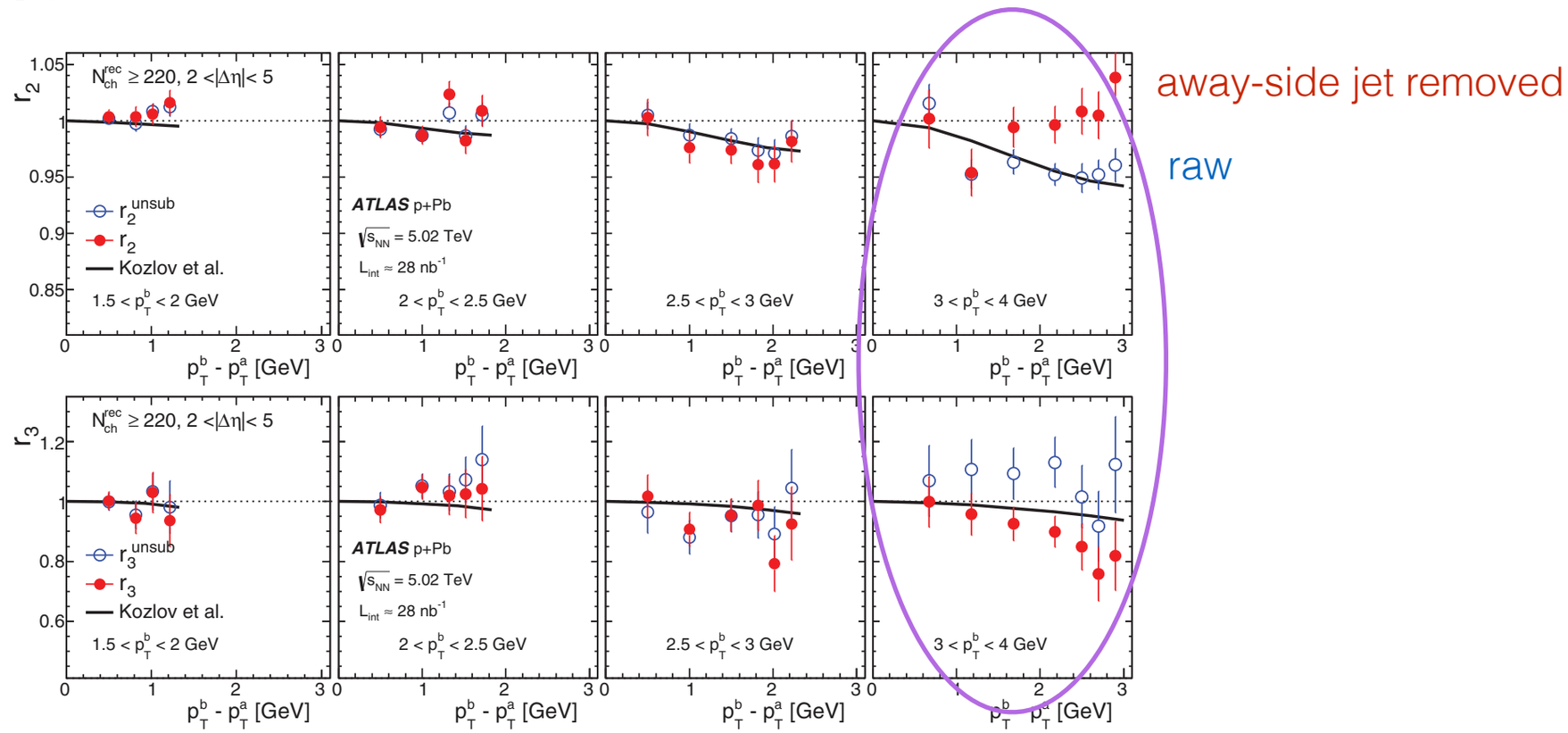


ATLAS, PRC 90, 044906 (2014)

- Large effect for pT > 3 GeV/*c*

Transverse Momentum Factorization Breakdown

p+Pb 5.02 TeV



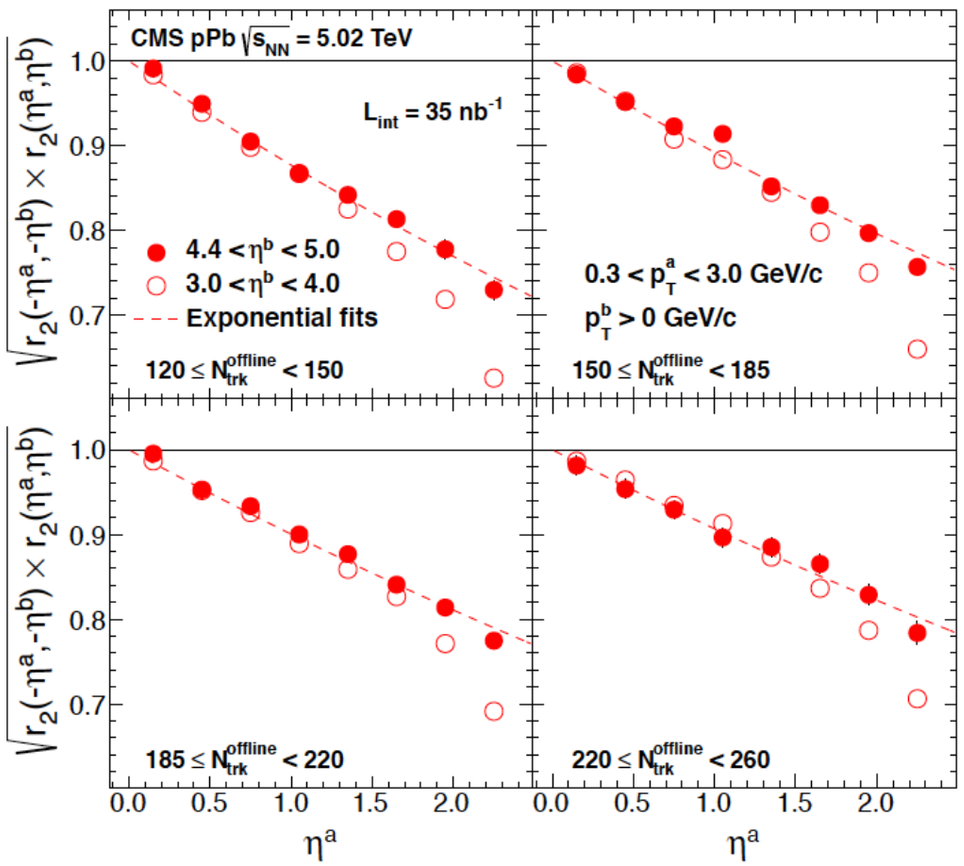
ATLAS, PRC 90, 044906 (2014)

- Some discrepancy between 3+1D hydrodynamic calculation and measurement

Pseudorapidity Factorization Breakdown

p+Pb 5.02 TeV

CMS, arXiv:1503.01692



$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\langle \cos[\Psi_n(-\eta^a) - \Psi_n(\eta^b)]\rangle}{\langle \cos[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\rangle} \frac{\langle \cos[\Psi_n(\eta^a) - \Psi_n(-\eta^b)]\rangle}{\langle \cos[\Psi_n(-\eta^a) - \Psi_n(-\eta^b)]\rangle}}$$

- Event plane fluctuation in pseudorapidity
- Calculation?

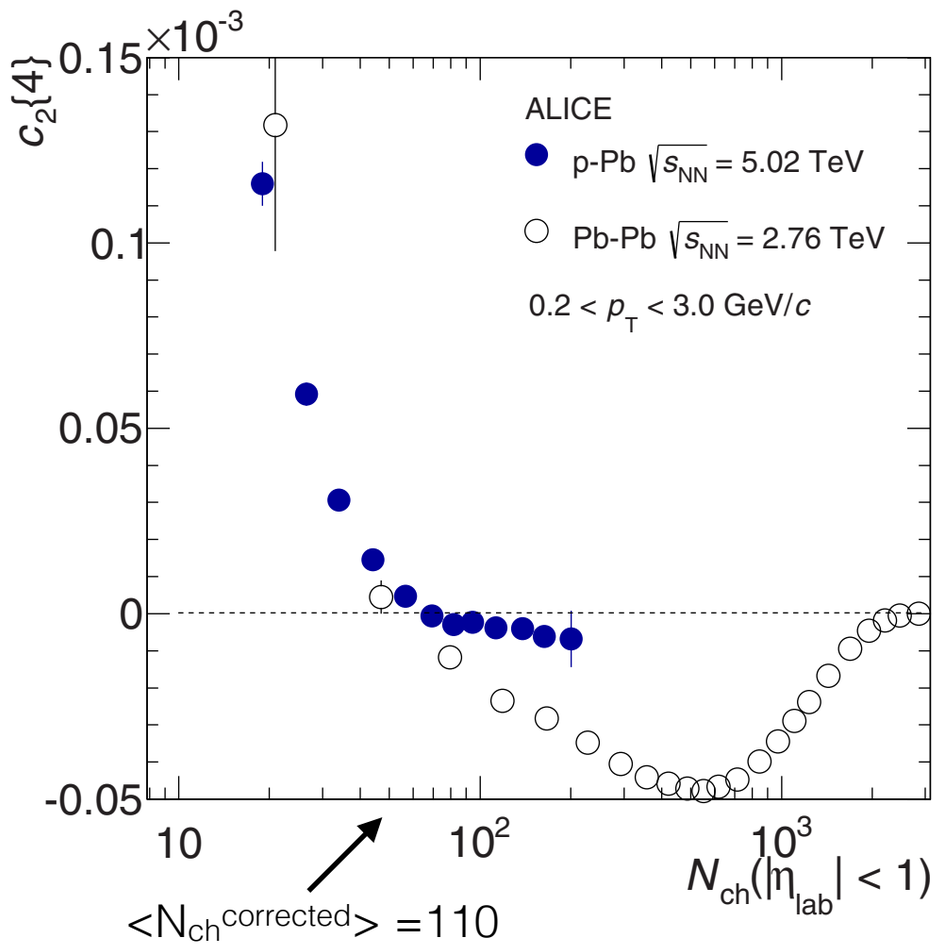
Summary

- Ridge in observed in high-multiplicity pp, pPb, dAu, He^3Au
- v_n measurements in small systems discussed and compared with heavy-ion collisions
- Question remains: the physics mechanism?

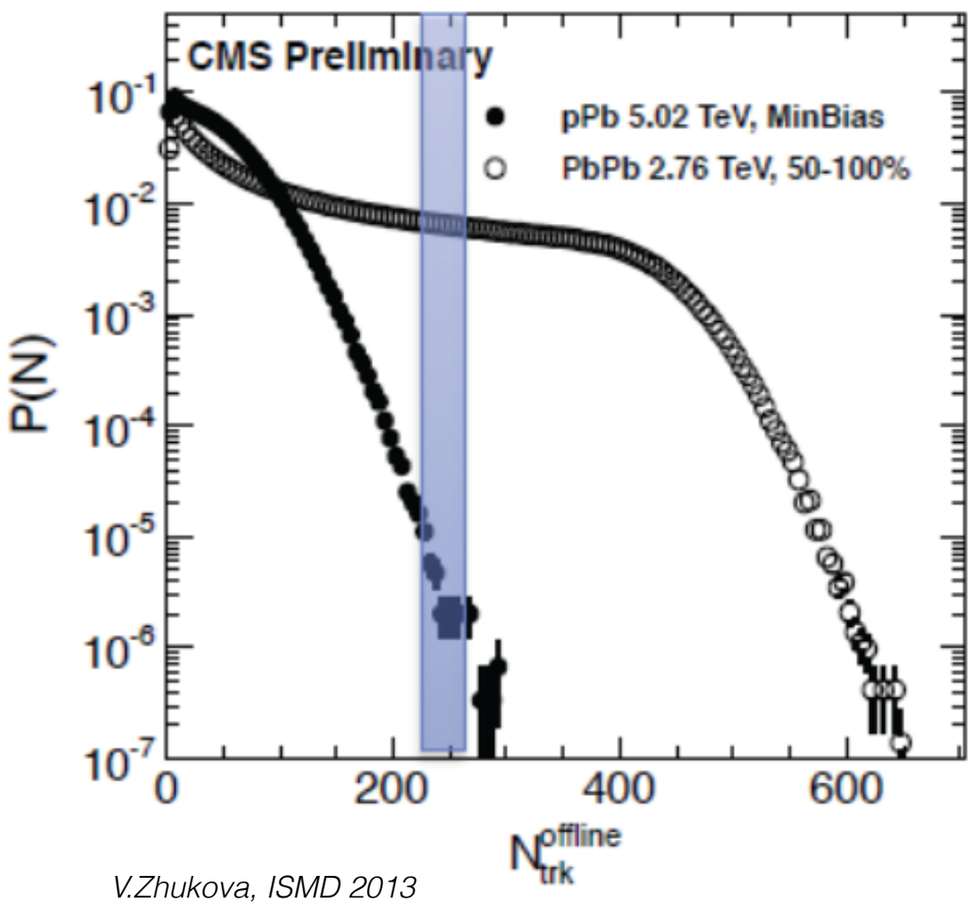
Multi-particle Correlations

ALICE, PRC 90, 054901 (2014)

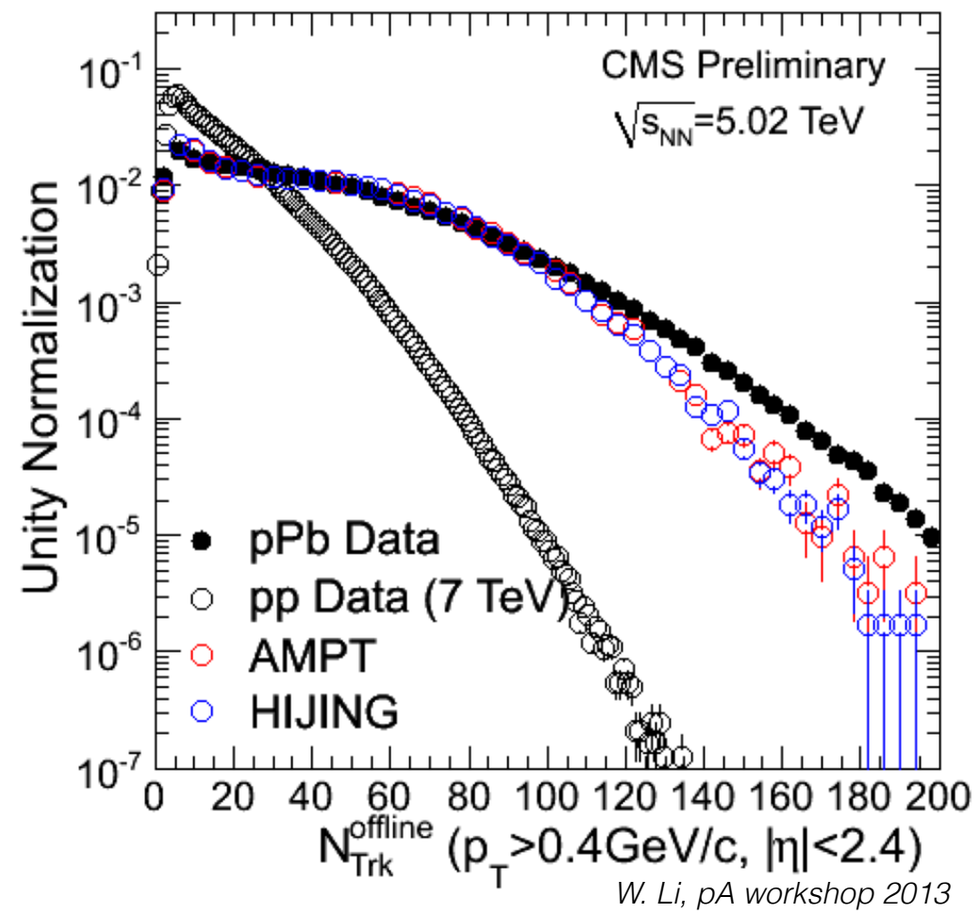
$c_n\{4\} = -(v_n)^4$



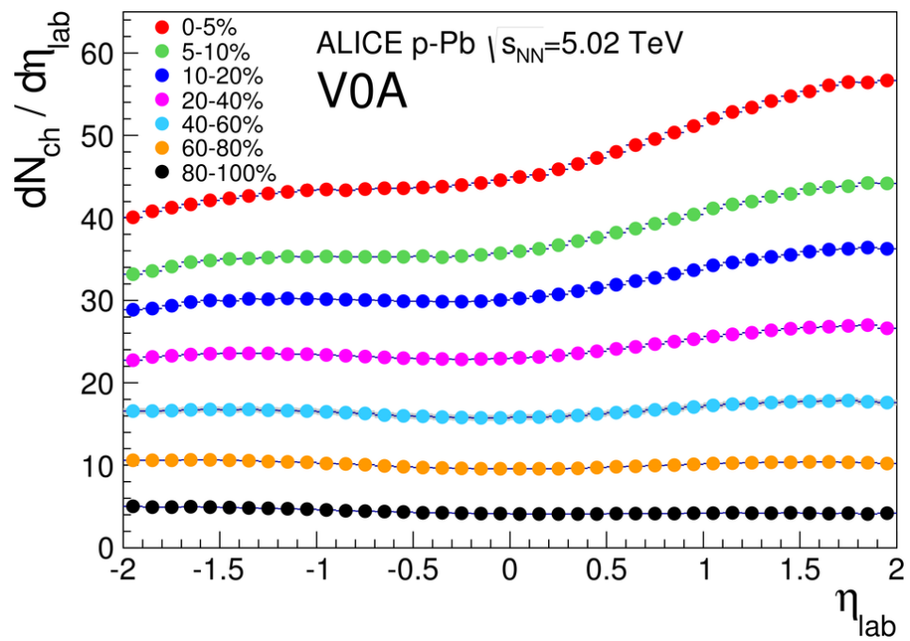
- Multi-particle cumulant needs $v_n\{k\} \gg \mathcal{O}\left(\frac{1}{M^{1-1/k}}\right)$



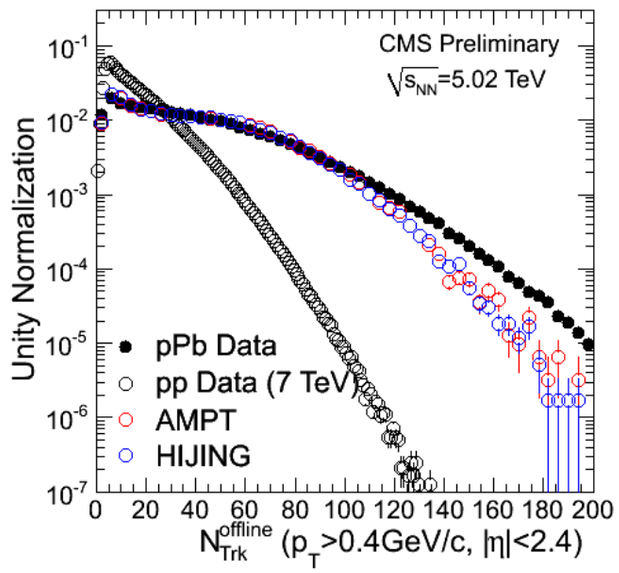
V.Zhukova, ISMD 2013



W. Li, pA workshop 2013



ALICE, Phys. Rev. C 91 (2015) 064905



W. Li pA workshop 2013

Pb+Pb 2.76 TeV

TABLE I.

$dN_{ch}/d\eta$ and $(dN_{ch}/d\eta)/(\langle N_{part}\rangle/2)$ values measured in $|\eta| < 0.5$ for nine centrality classes. The $\langle N_{part}\rangle$ obtained with the Glauber model are given.

Centrality	$dN_{ch}/d\eta$	$\langle N_{part}\rangle$	$(dN_{ch}/d\eta)/(\langle N_{part}\rangle/2)$
0%–5%	1601 ± 60	382.8 ± 3.1	8.4 ± 0.3
5%–10%	1294 ± 49	329.7 ± 4.6	7.9 ± 0.3
10%–20%	966 ± 37	260.5 ± 4.4	7.4 ± 0.3
20%–30%	649 ± 23	186.4 ± 3.9	7.0 ± 0.3
30%–40%	426 ± 15	128.9 ± 3.3	6.6 ± 0.3
40%–50%	261 ± 9	85.0 ± 2.6	6.1 ± 0.3
50%–60%	149 ± 6	52.8 ± 2.0	5.7 ± 0.3
60%–70%	76 ± 4	30.0 ± 1.3	5.1 ± 0.3
70%–80%	35 ± 2	15.8 ± 0.6	4.4 ± 0.4

ALICE, Phys. Rev. Lett. 106, 032301