Flow Phenomena in dA and pA at RHIC and LHC

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Goal of Heavy Ion Physics

- QGP medium properties
  - Soft probes: collectivity, initial condition, thermal and transport properties (flow etc.)
  - Hard probes: modification of energetic partons, heavy quark bound states (Jet, quarkonium etc.)
  - Use pp and pA/dA as reference

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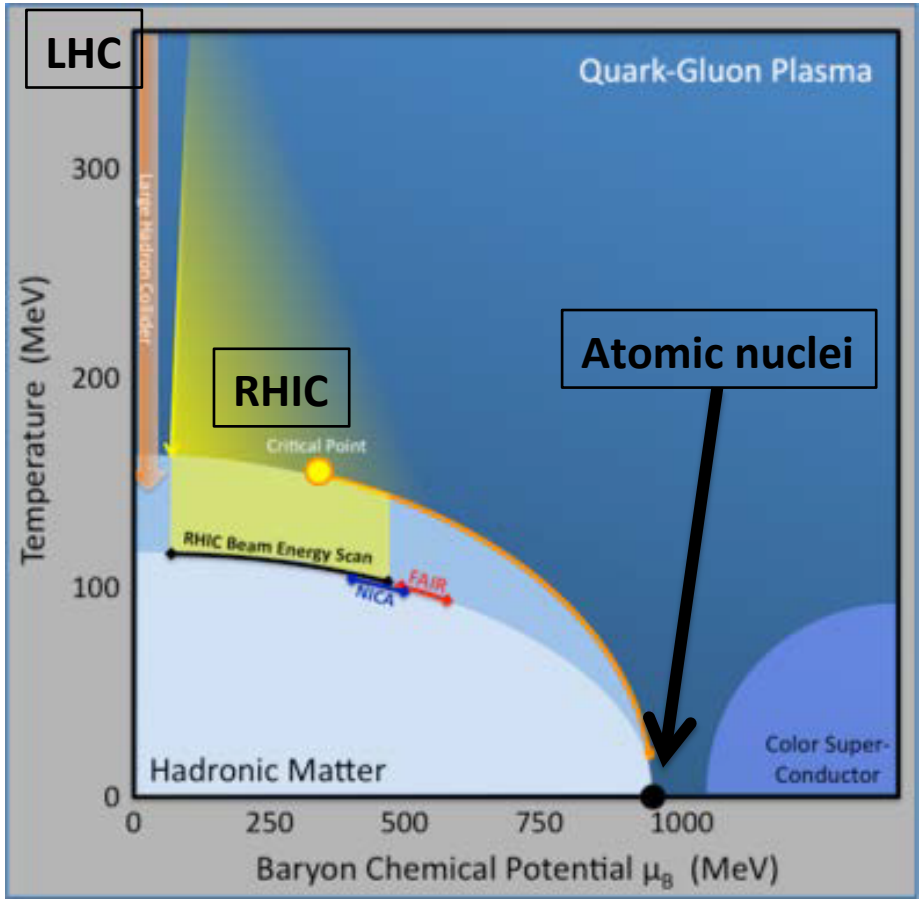
  - Use pp and pA/dA as reference
- Why p(d)A collisions?
  - Cold nuclear effect, QGP not formed in small system?
  - 200 GeV dAu at RHIC
  - 5.02 TeV pPb at LHC

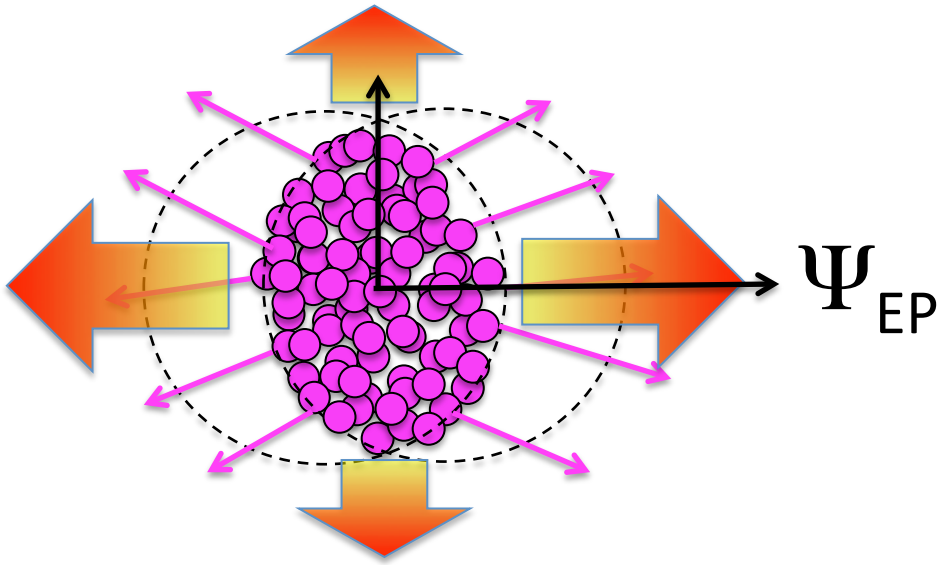
Discoveries of Heavy Ion Physics

- Soft-QCD, the least understood in SM
  - Hot nuclear matter
  - Deconfined and strongly interacting plasma at RHIC/LHC



Discoveries of Heavy Ion Physics

- Anisotropy of initial geometry to final-state particle momentum distribution



$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots$$

Discoveries of Heavy Ion Physics

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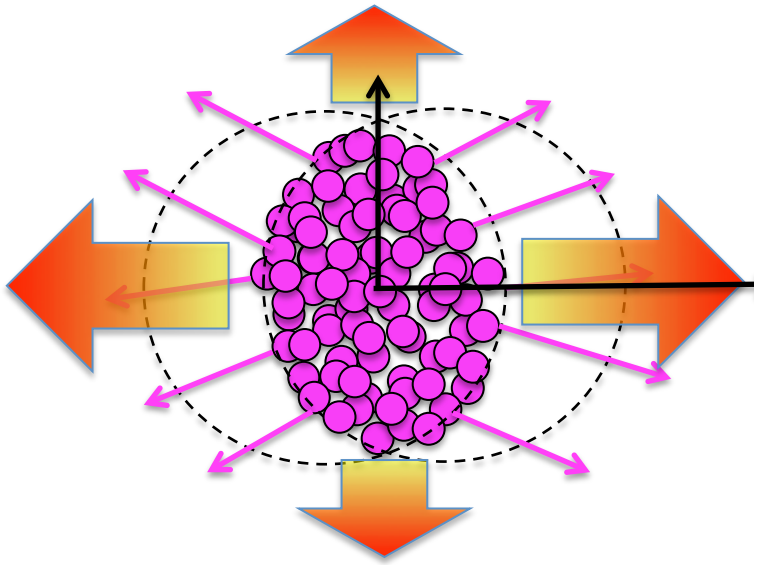

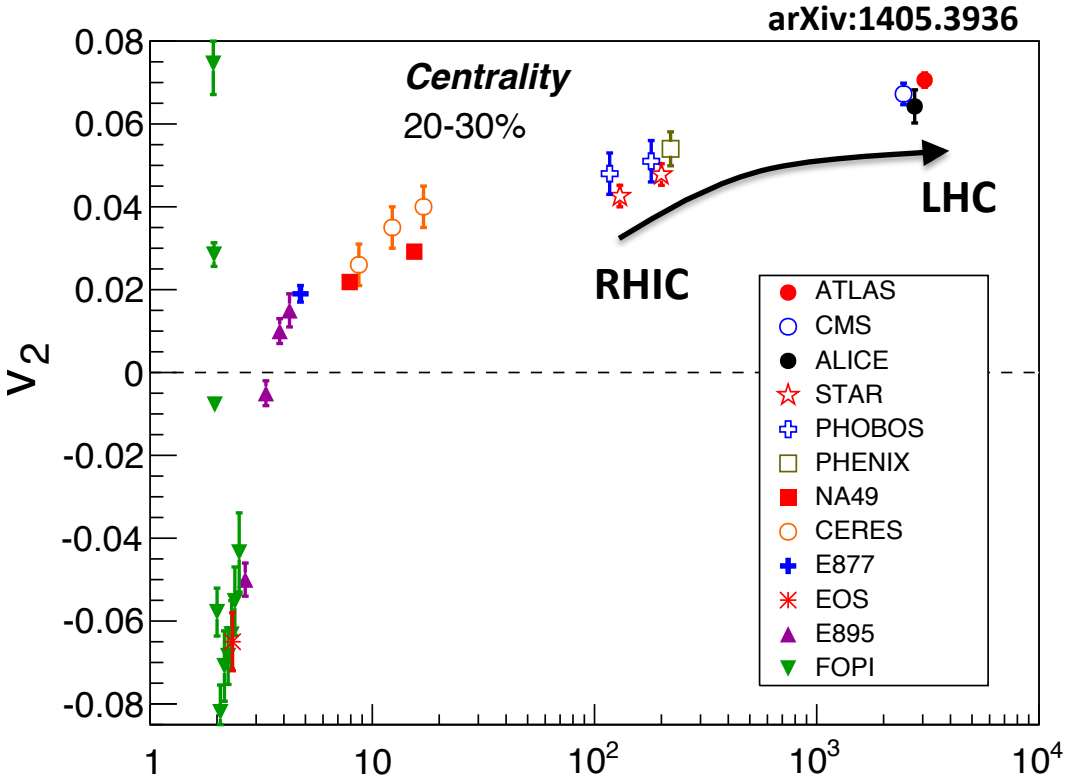

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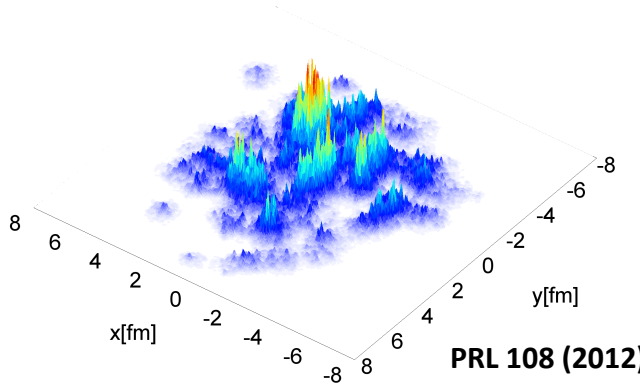
Discoveries of Heavy Ion Physics

- Evolution of the medium

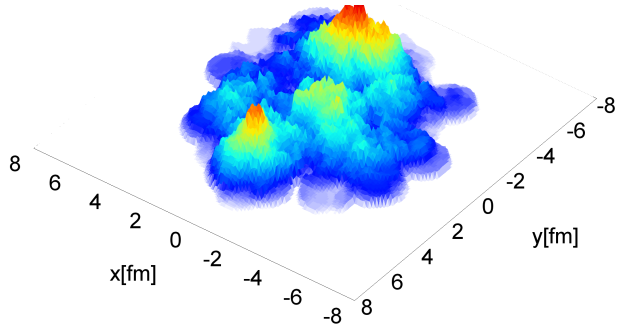
  - Initial Condition
    Glauber, CGC

IP-Glasma

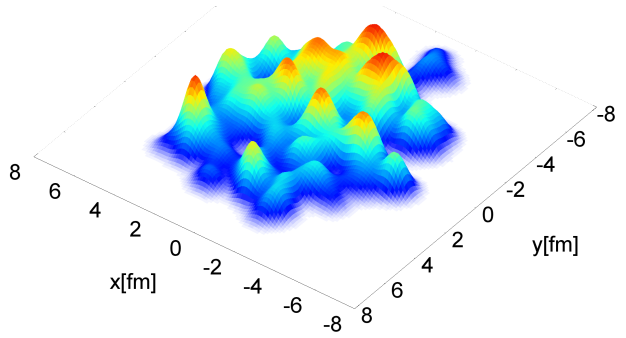


PRL 108 (2012) 252301

MC-KLN



MC-Glauber

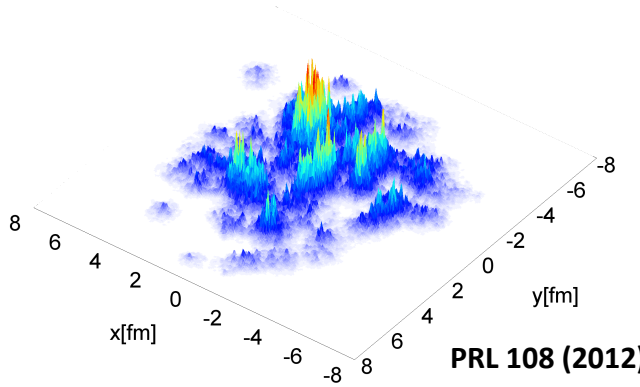


Discoveries of Heavy Ion Physics

- Evolution of the medium

  - Initial Condition
    Glauber, CGC
  - QGP Phase
    η/s 3+1D Hydrodynamics
  - Hadronic Phase
    $\eta/s(T)$
  - Freeze-out
    Cooper-Frye

IP-Glasma



PRL 108 (2012) 252301

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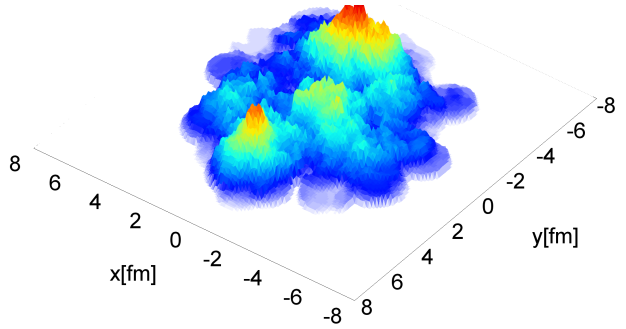

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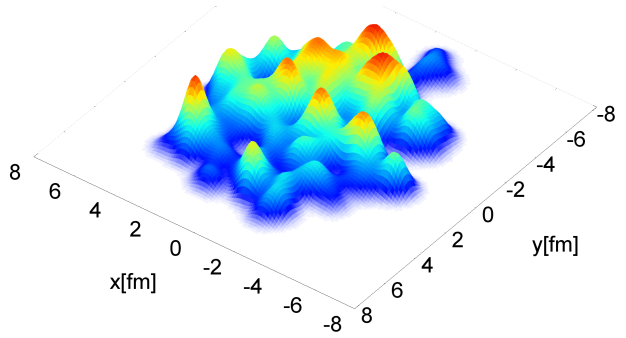
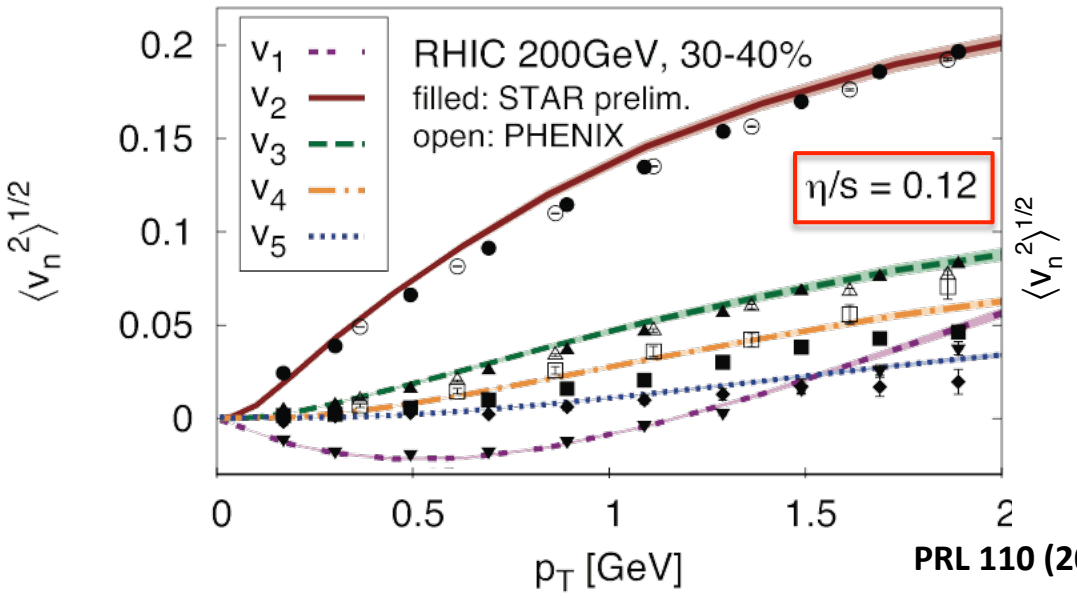


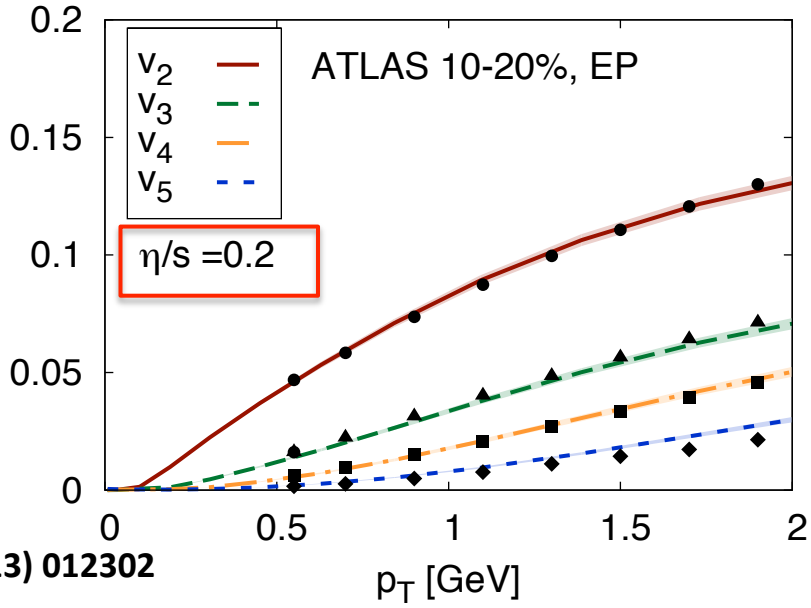
Discoveries of Heavy Ion Physics

- Nearly "perfect" liquid
  - $\eta/s \rightarrow$ Quantum limit $1/4\pi = 0.08$

RHIC AuAu 0.2 TeV



LHC PbPb 2.76 TeV

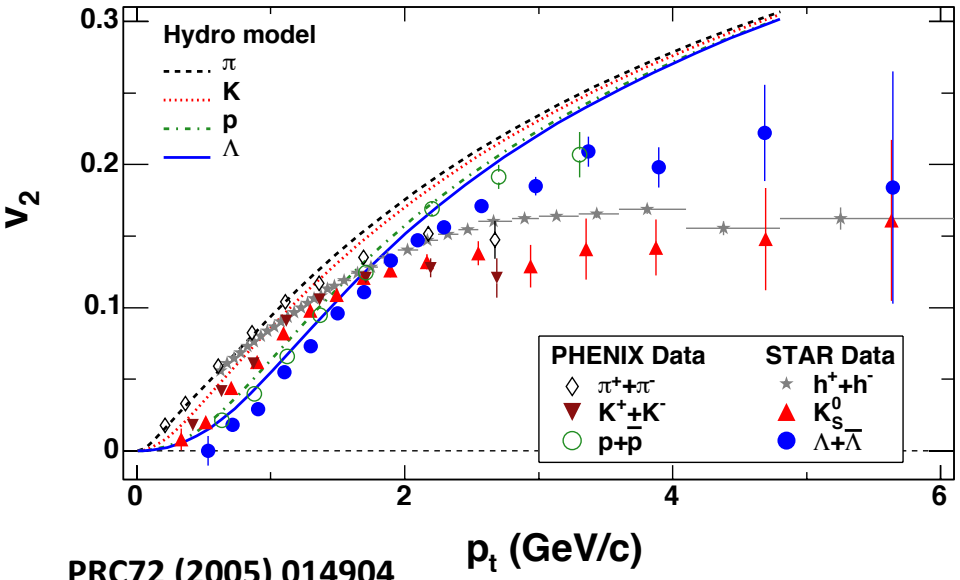


PRL 110 (2013) 012302

Discoveries of Heavy Ion Physics

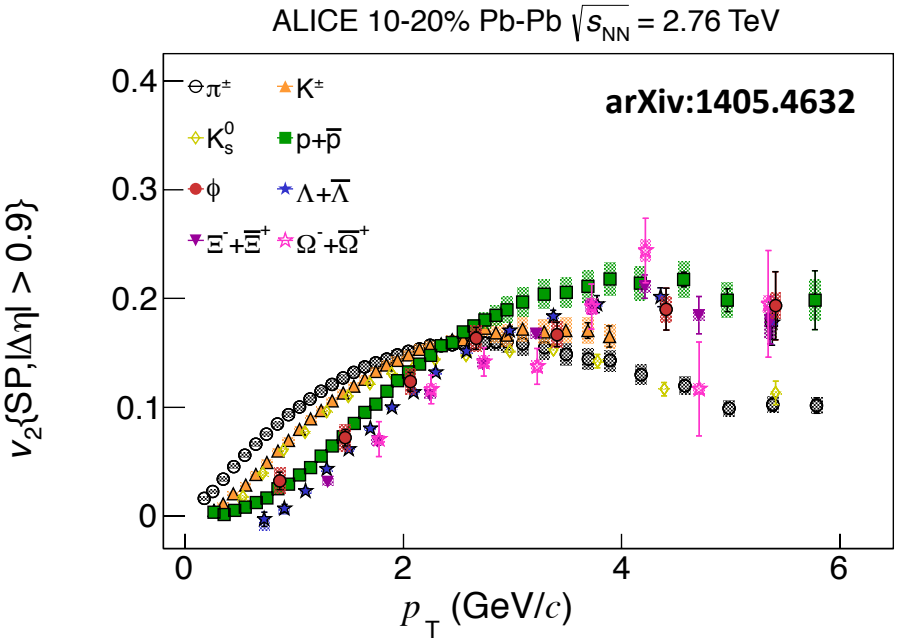
- Mass ordering

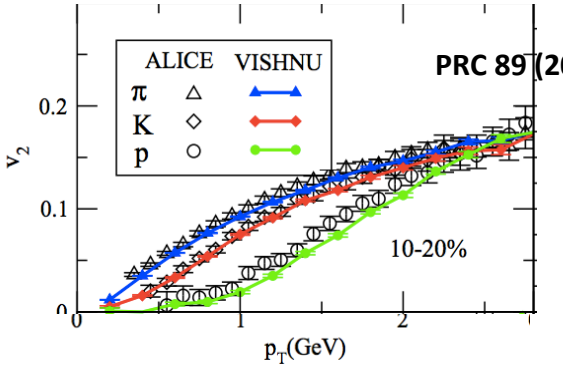
RHIC AuAu 0.2 TeV



PRC72 (2005) 014904

LHC PbPb 2.76 TeV





PRC 89 (2014) 034919

- Low p_T: light hadron larger v_2
- High p_T: v_2{baryon} > v_2{meson}

Why pA(dA) Collisions?

- Need a gauge to calibrate AA collisions
  - Cold nuclear effect
  - 200 GeV dAu at RHIC
  - 5.02 TeV pPb at LHC

Ridge and Angular Correlations

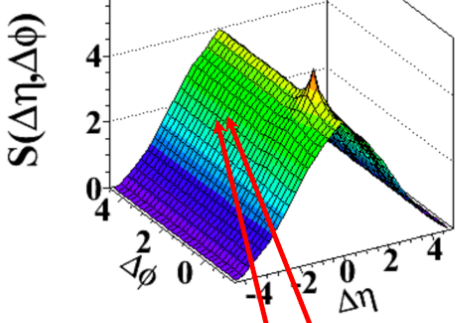
Signal pair distribution:

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

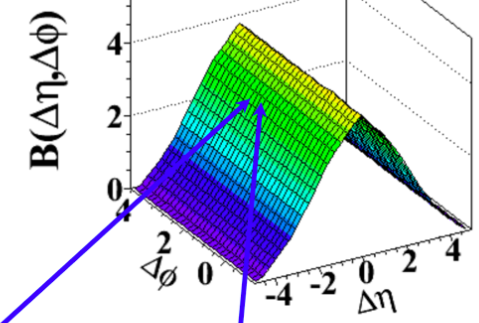
Background pair distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$

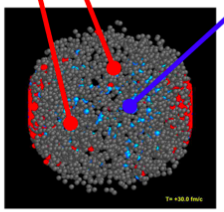
same event pairs



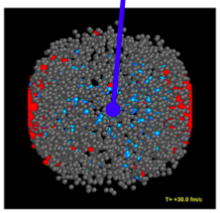
mixed event pairs



Event 1:



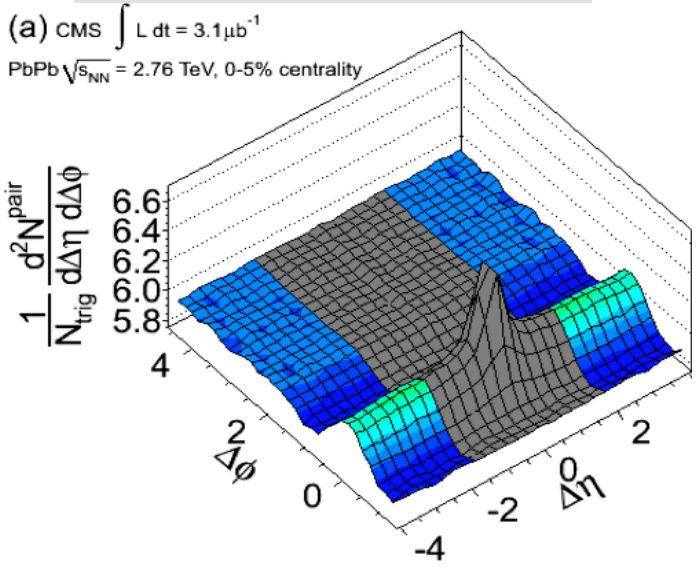
Event 2:

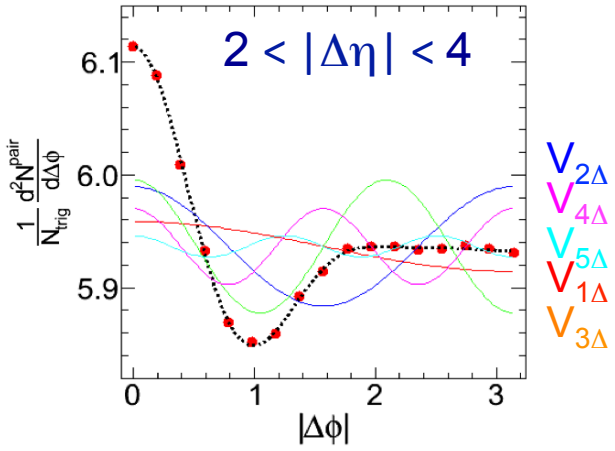


$$\Delta\eta = \eta^{assoc} - \eta^{trig}$$
$$\Delta\phi = \phi^{assoc} - \phi^{trig}$$

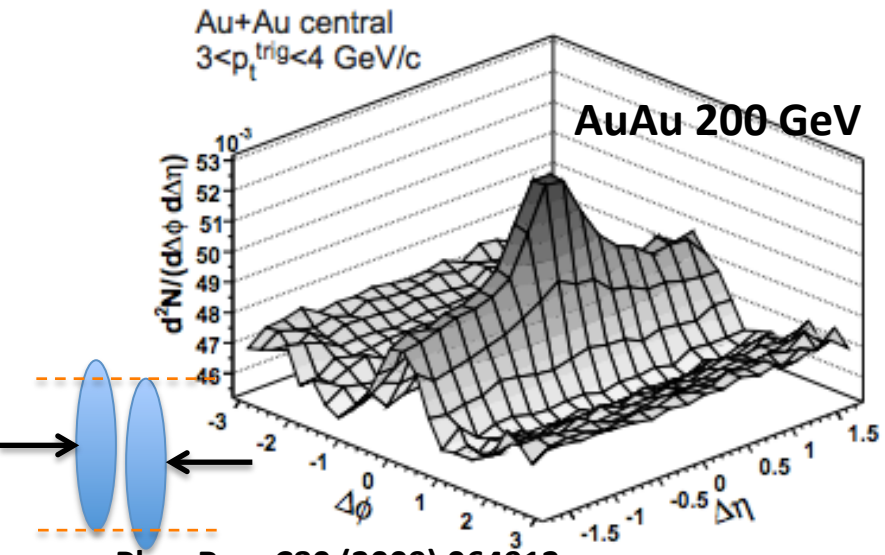
$$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Exclusion region in Δη

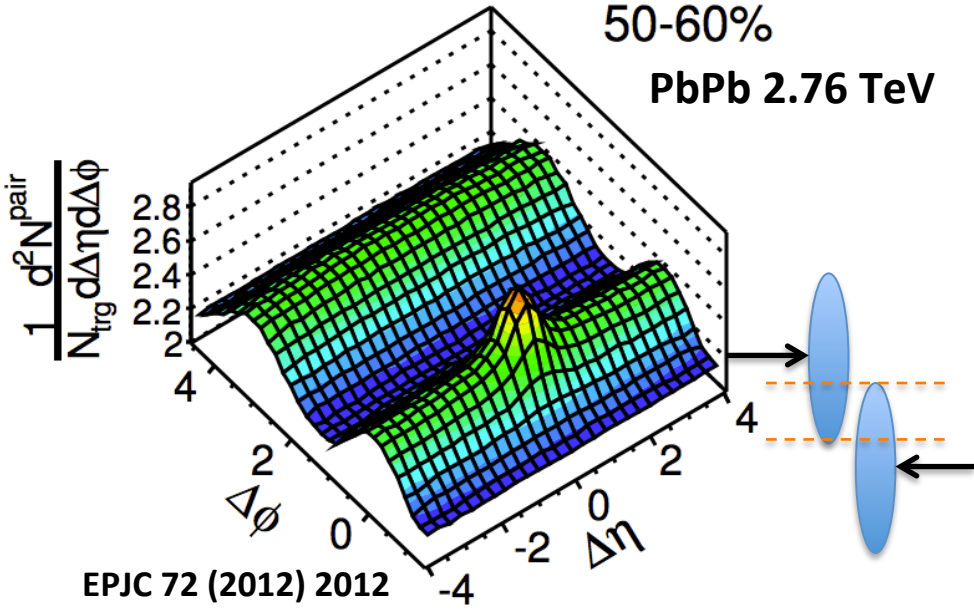




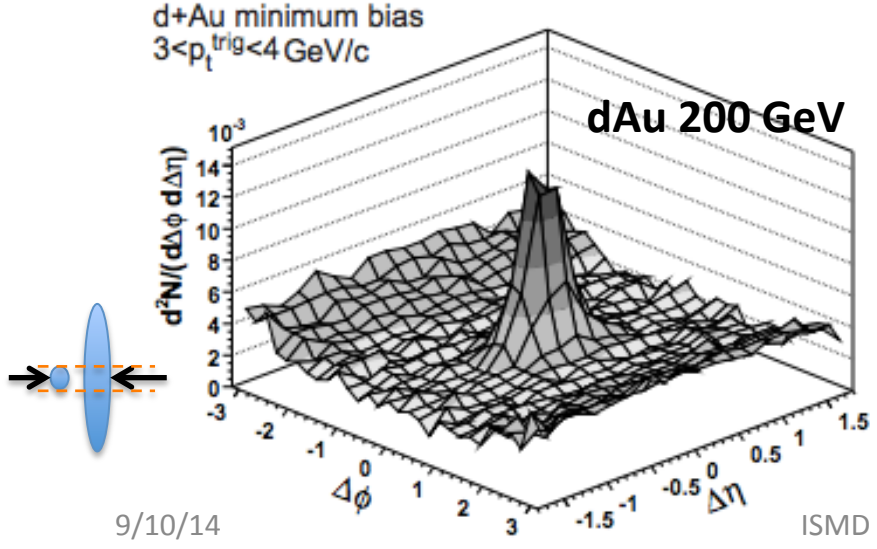
Ridge and Angular Correlations

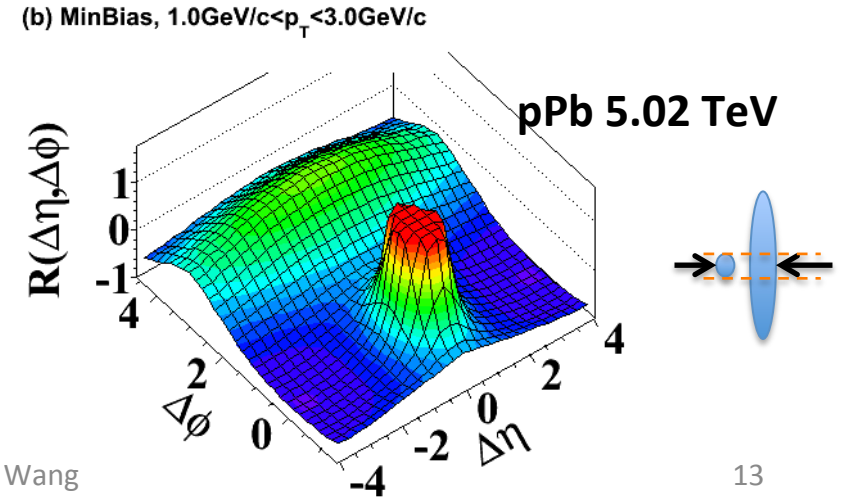


Phys.Rev. C80 (2009) 064912



EPJC 72 (2012) 2012





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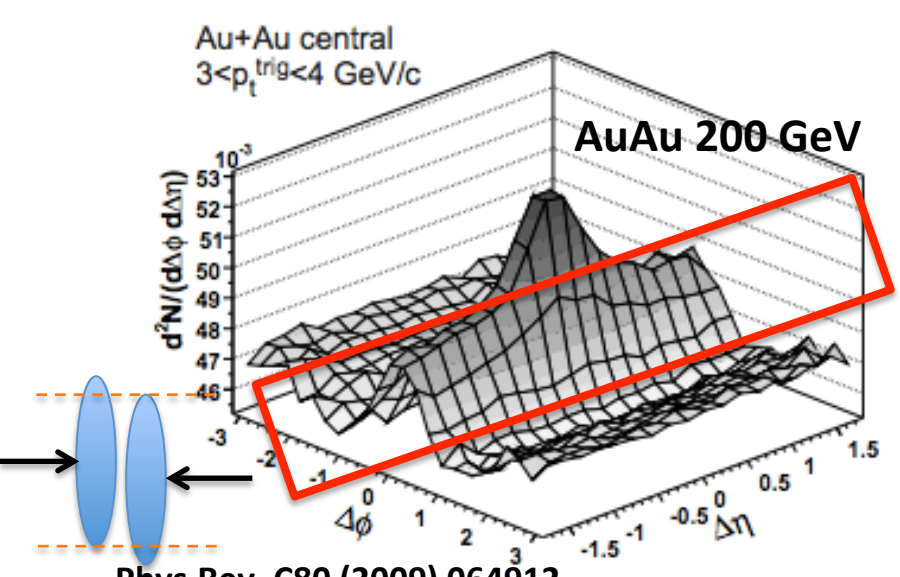

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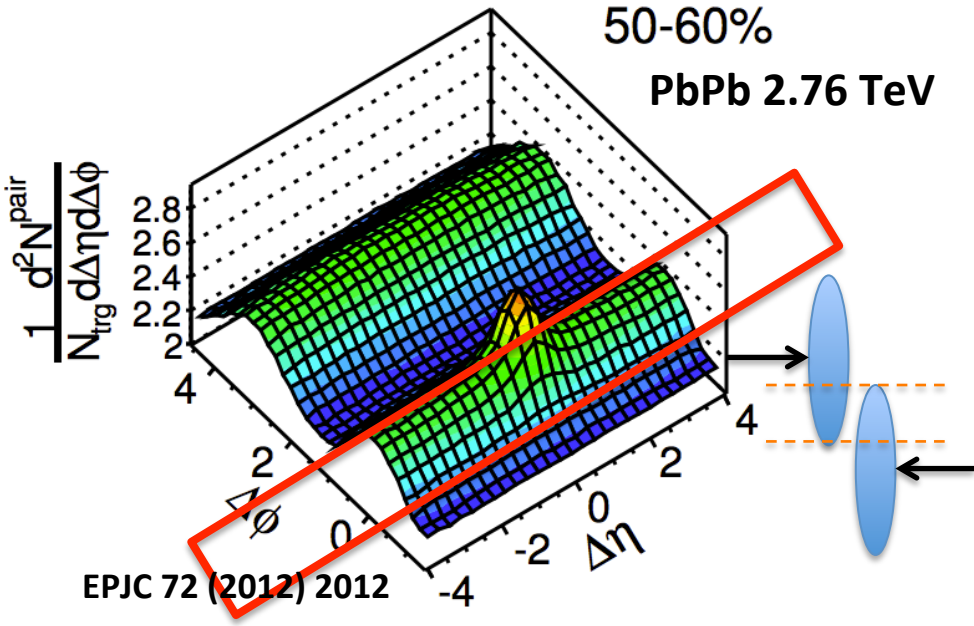
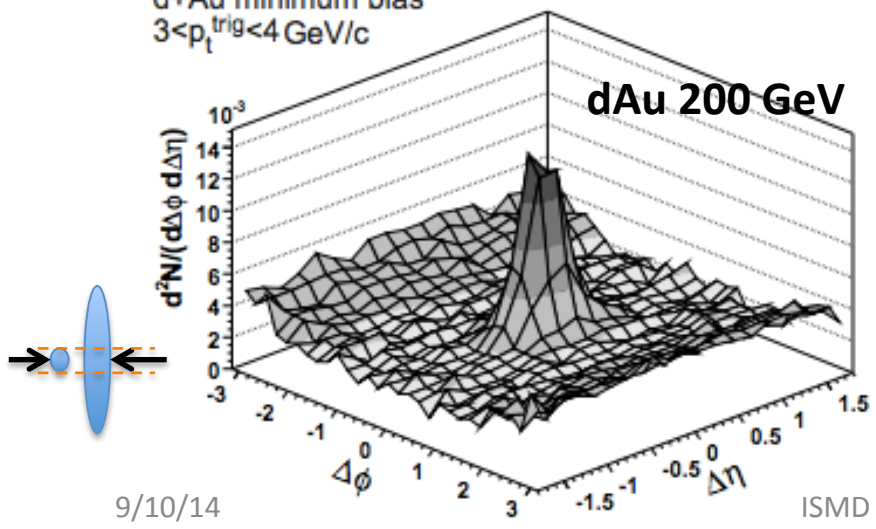
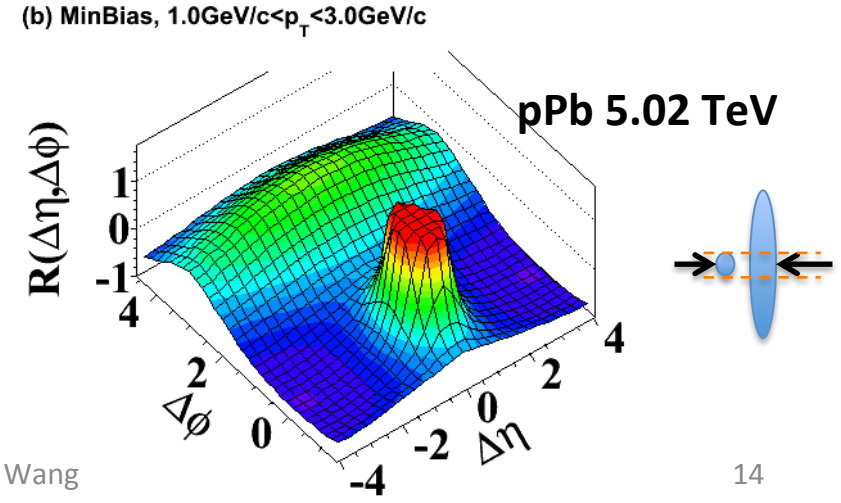


EPJC 72 (2012) 2012





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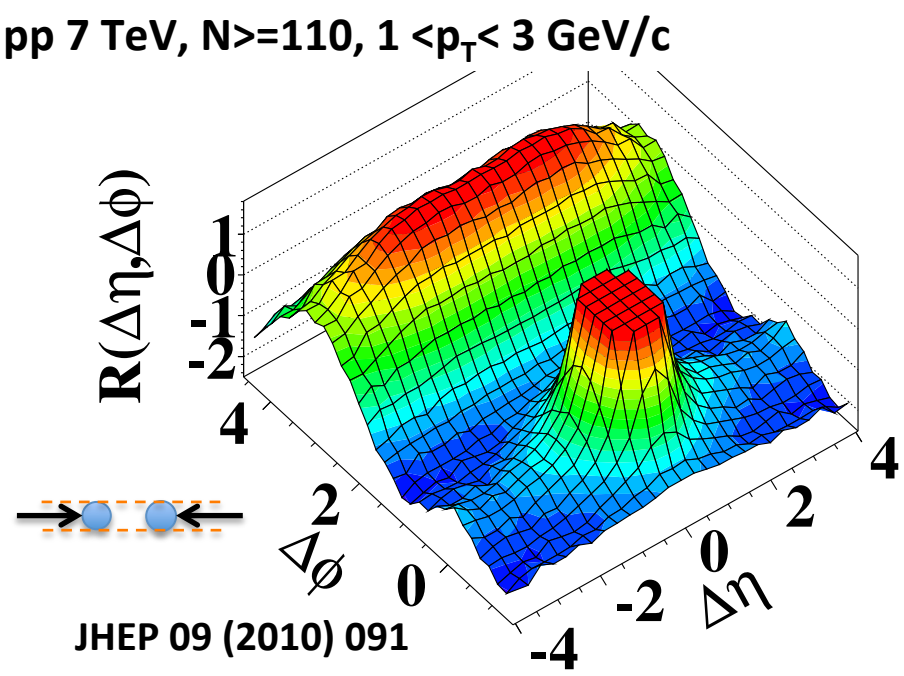

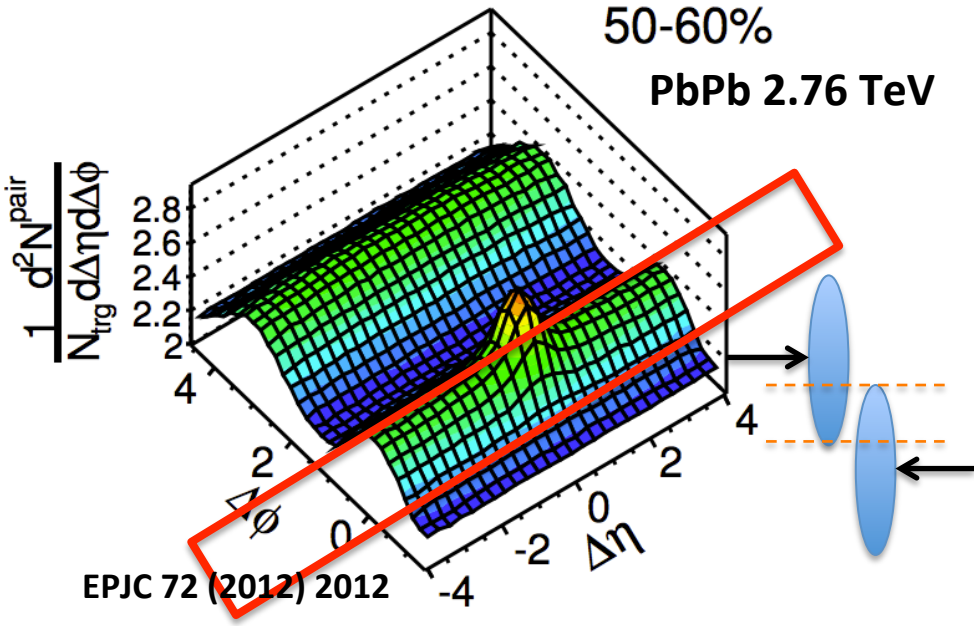

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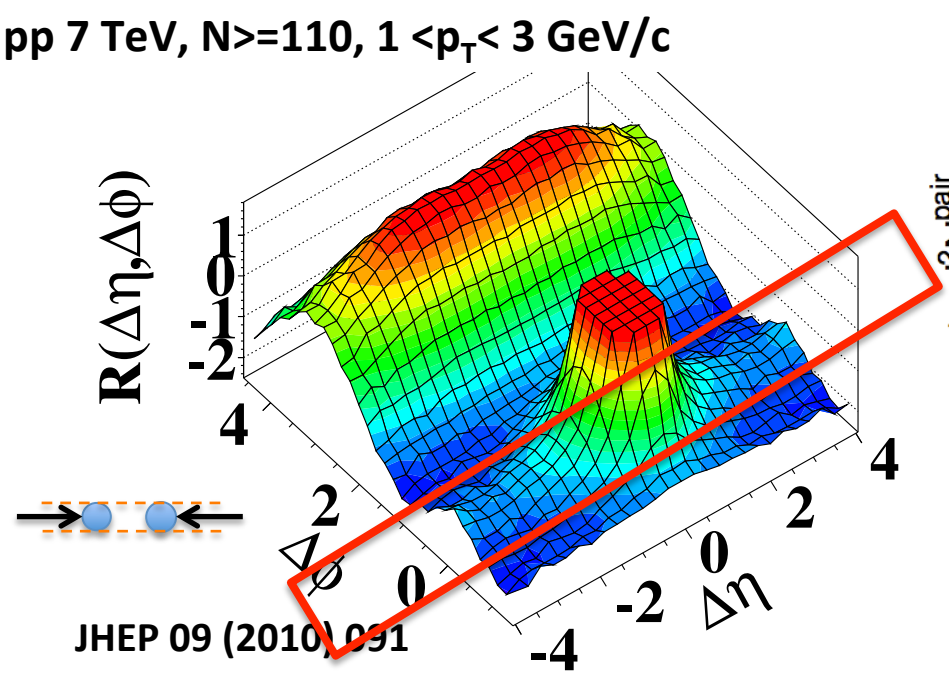
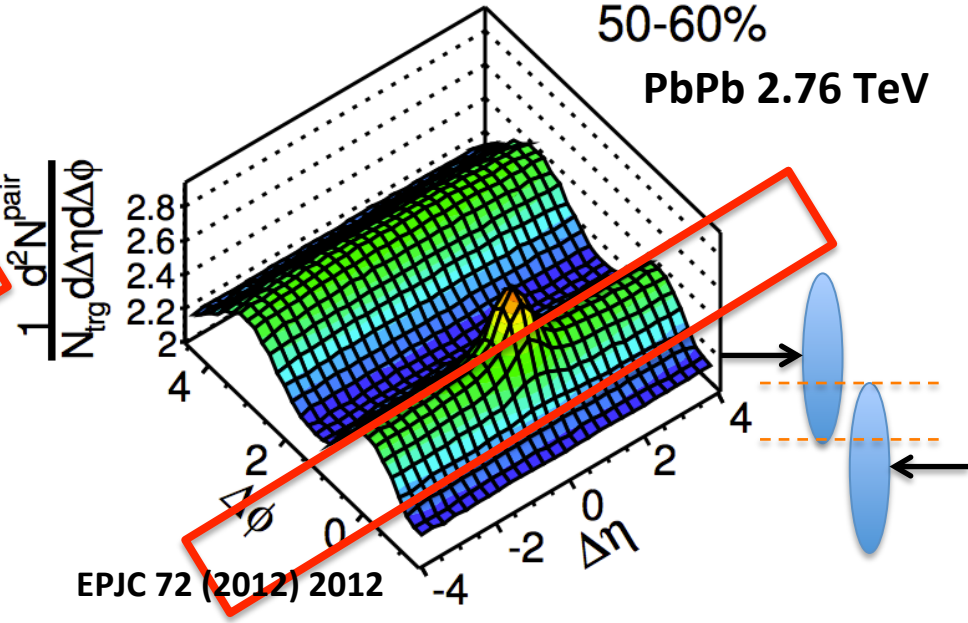
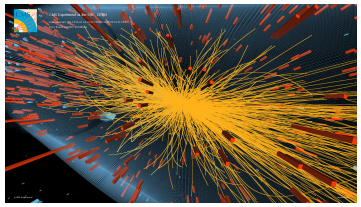
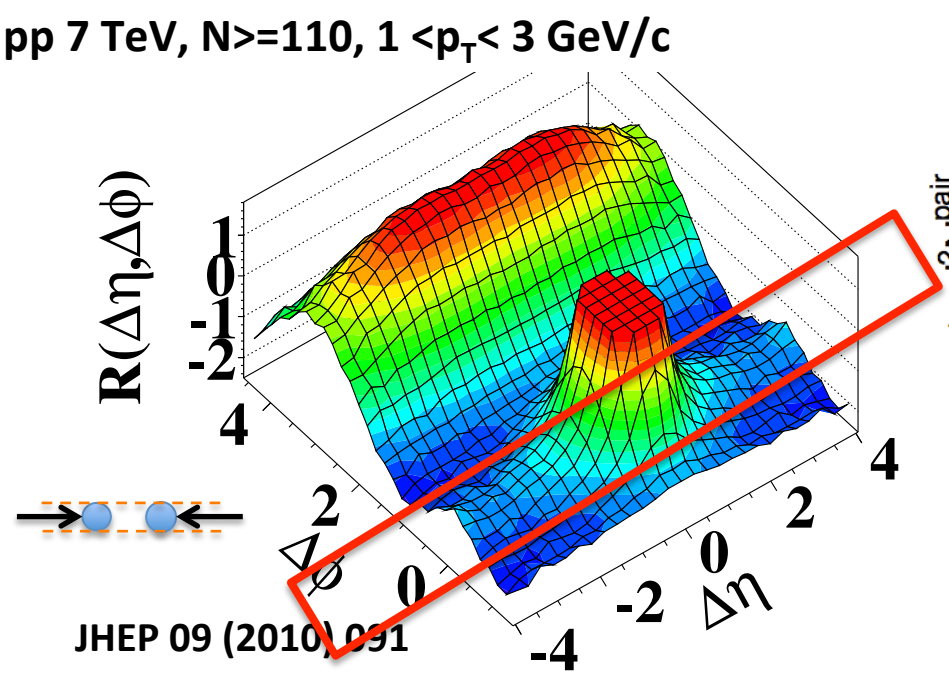


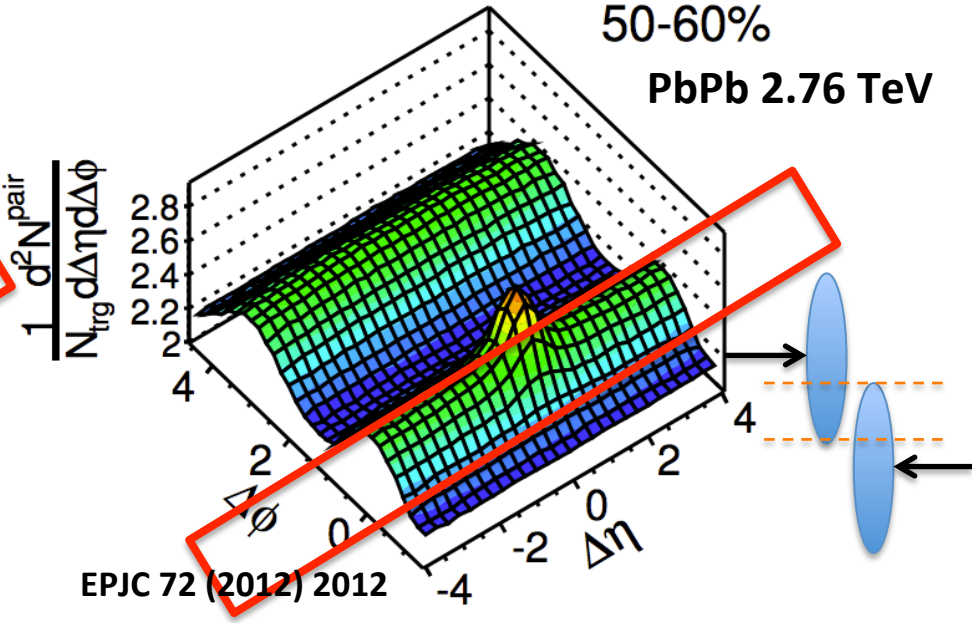


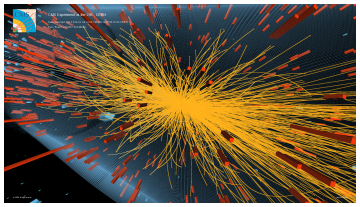


- Ridge in very high multiplicity pp events, N >= 110

Ridge and Angular Correlations

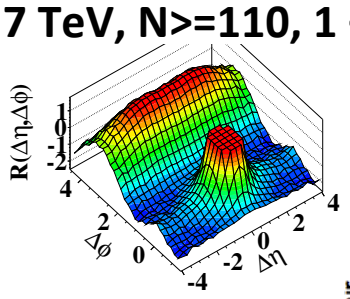


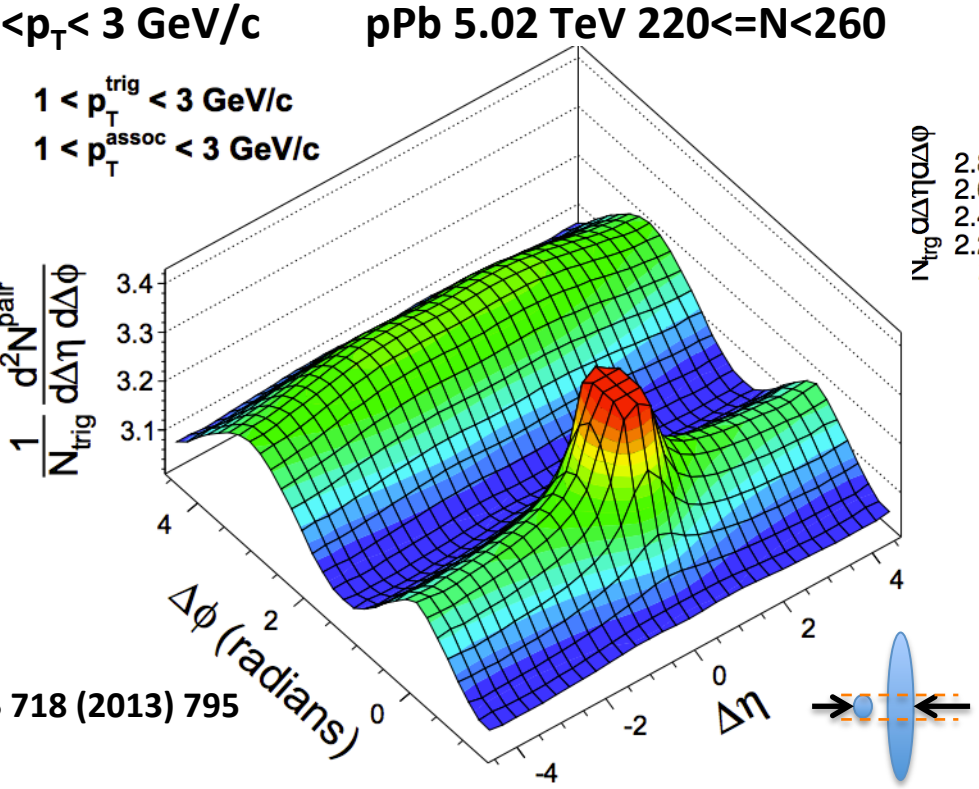


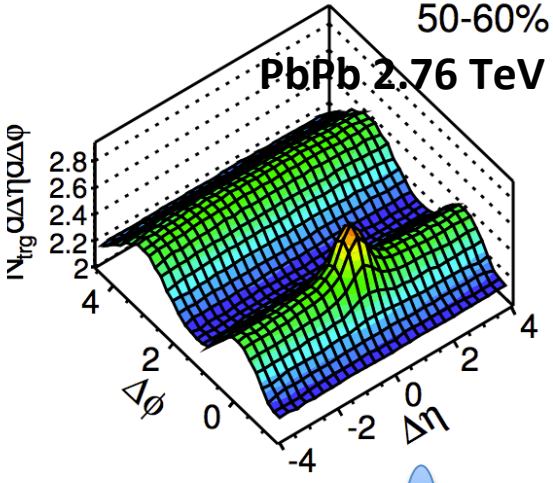


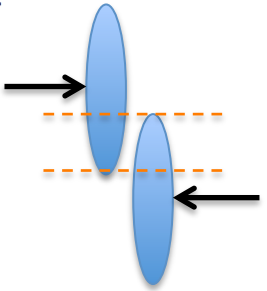
- Ridge in very high multiplicity pp events, N >= 110
- Naturally expect ridge also in pPb high multi events

Ridge and Angular Correlations

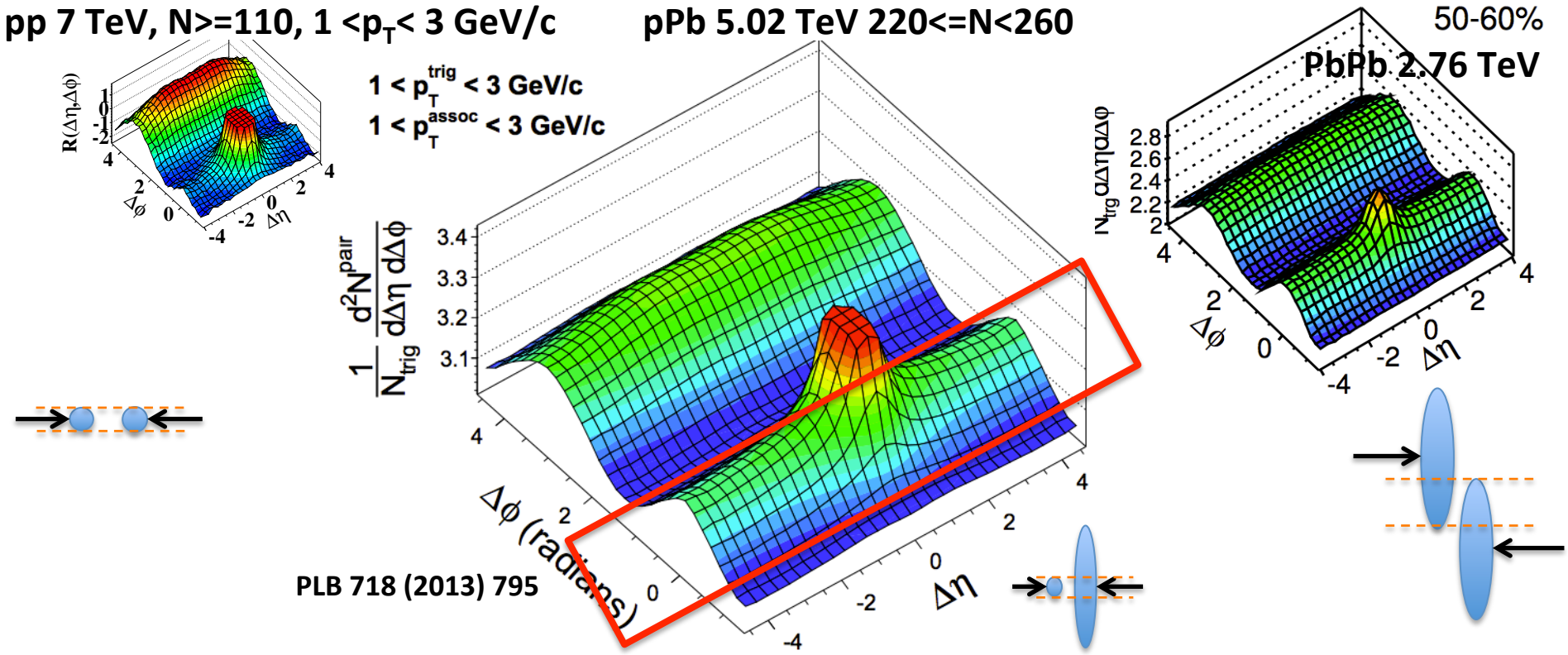








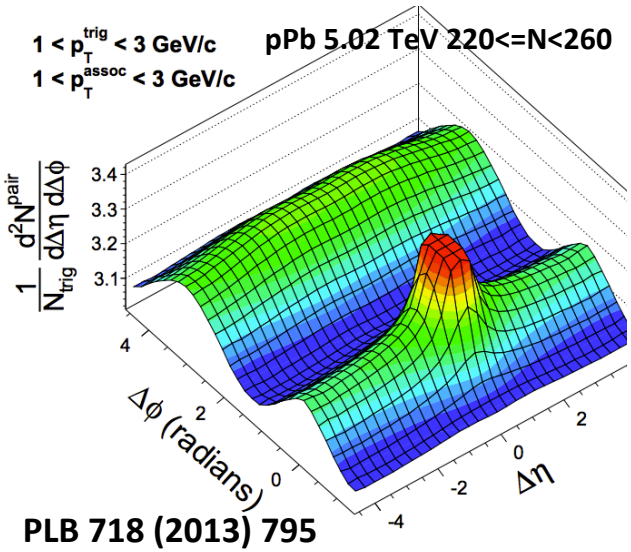
Ridge and Angular Correlations



- **Strongly enhanced** ridge in pPb high multiplicity events

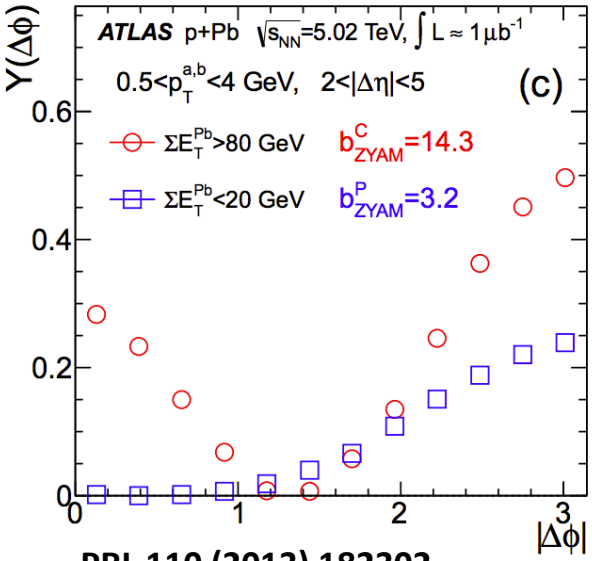
Ridge in pPb at the LHC

CMS



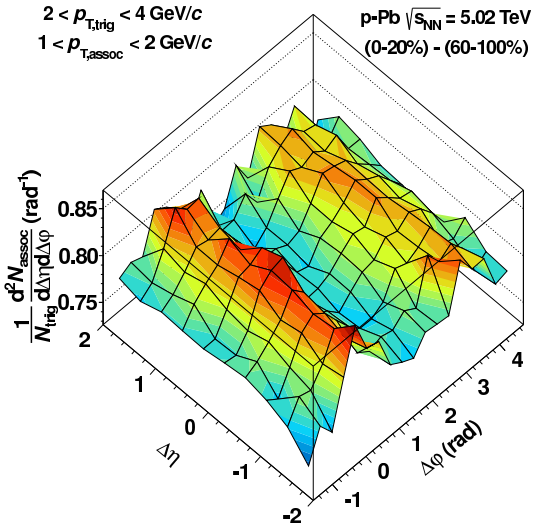
PLB 718 (2013) 795

ATLAS



PRL 110 (2013) 182302

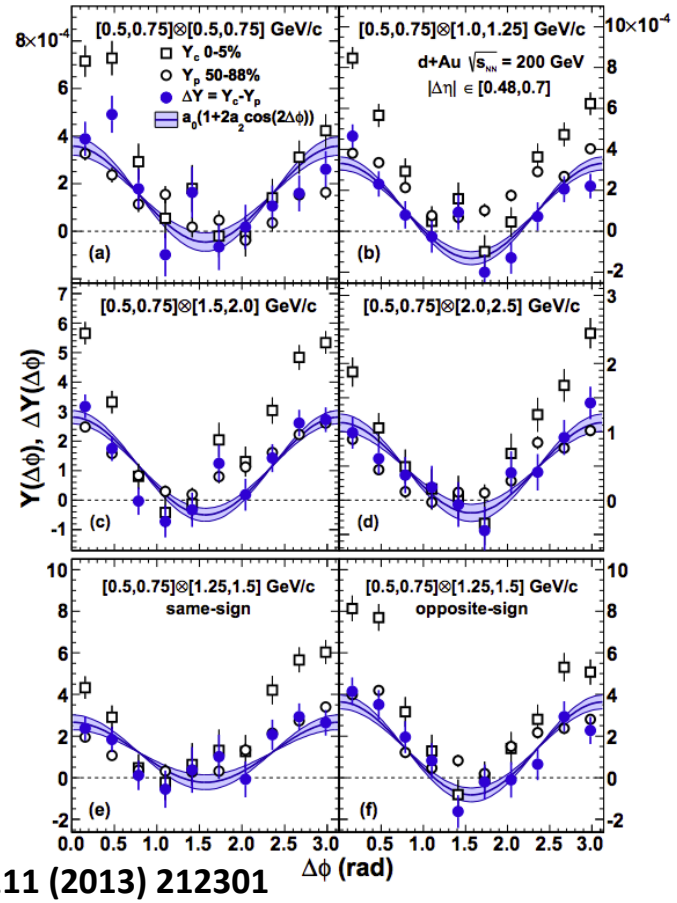
ALICE



PLB 719 (2013) 29-41

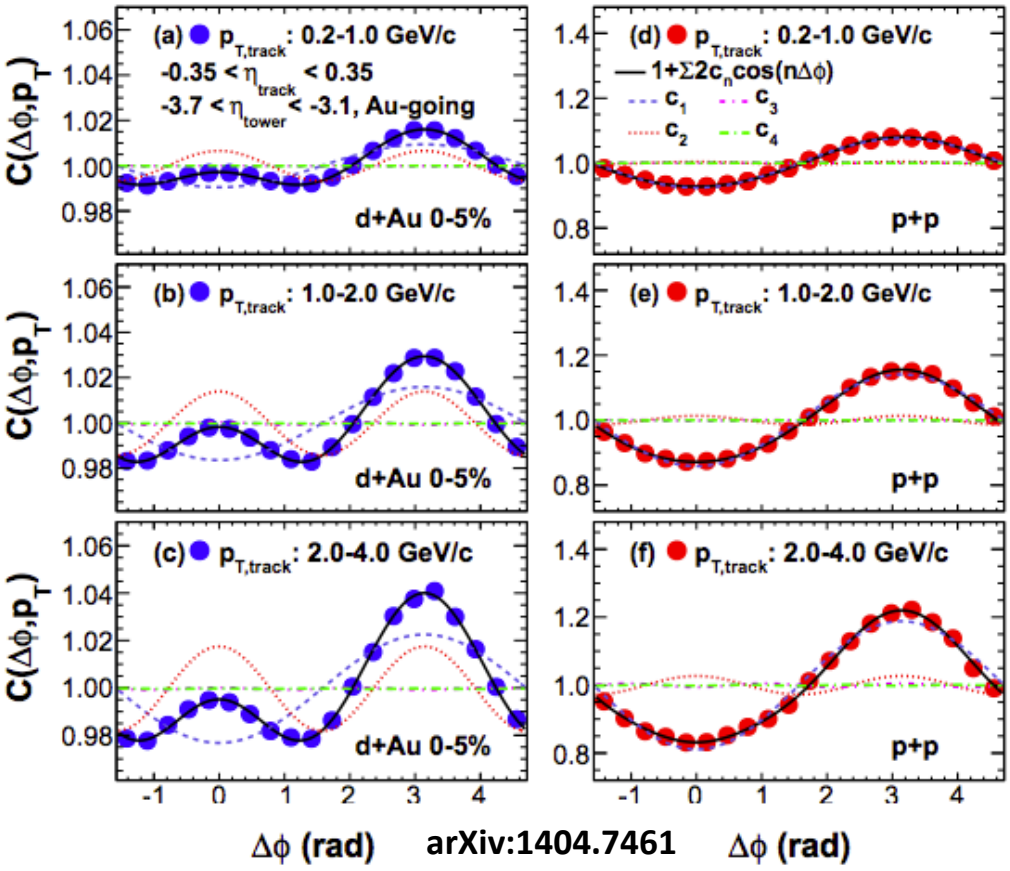
Look Back at dAu

PHNEX dAu 200 GeV



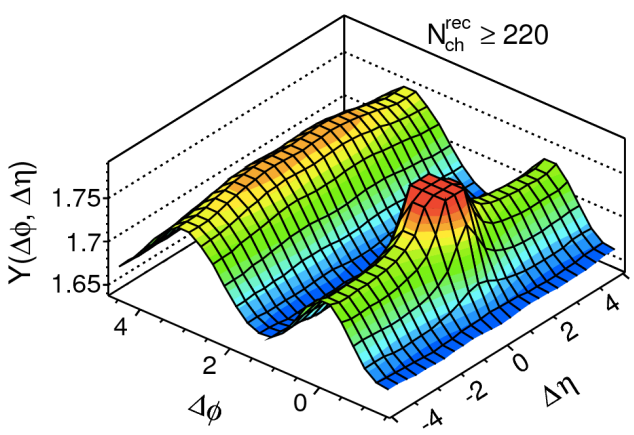
PRL 111 (2013) 212301

PHNEX dAu 200 GeV

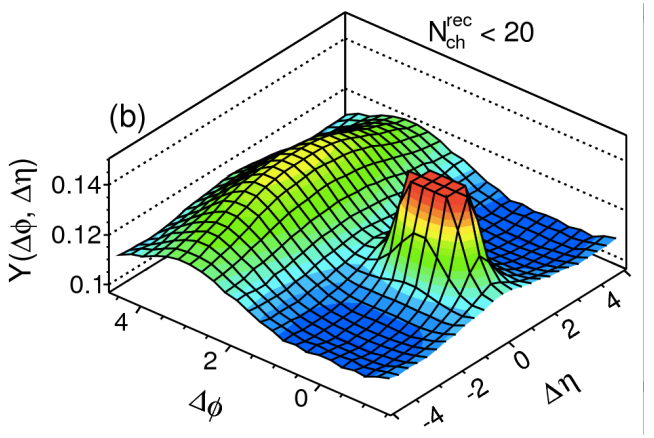


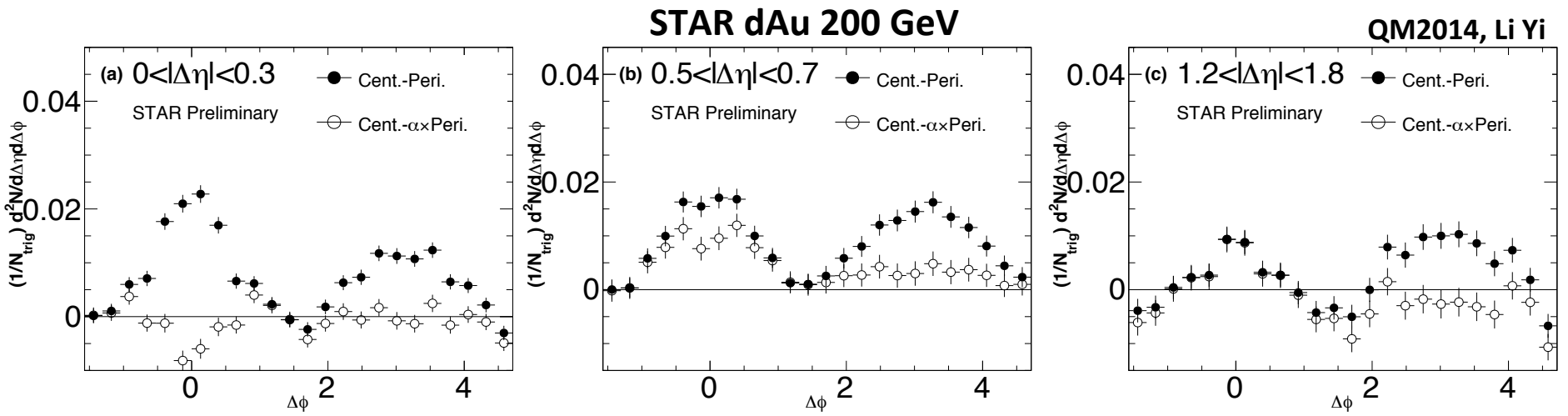
arXiv:1404.7461

Peripheral Subtraction



$- \alpha \times$





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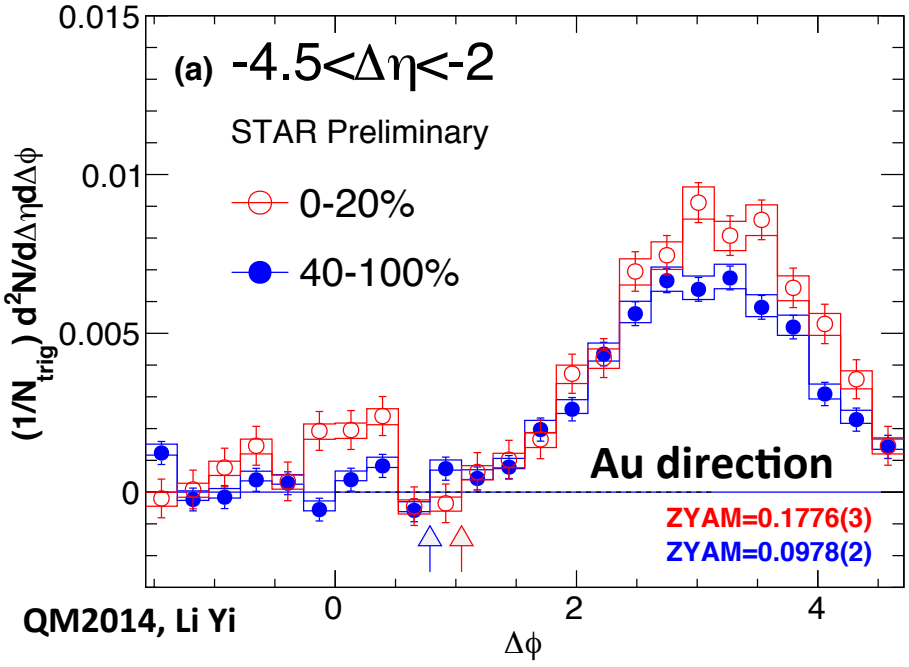
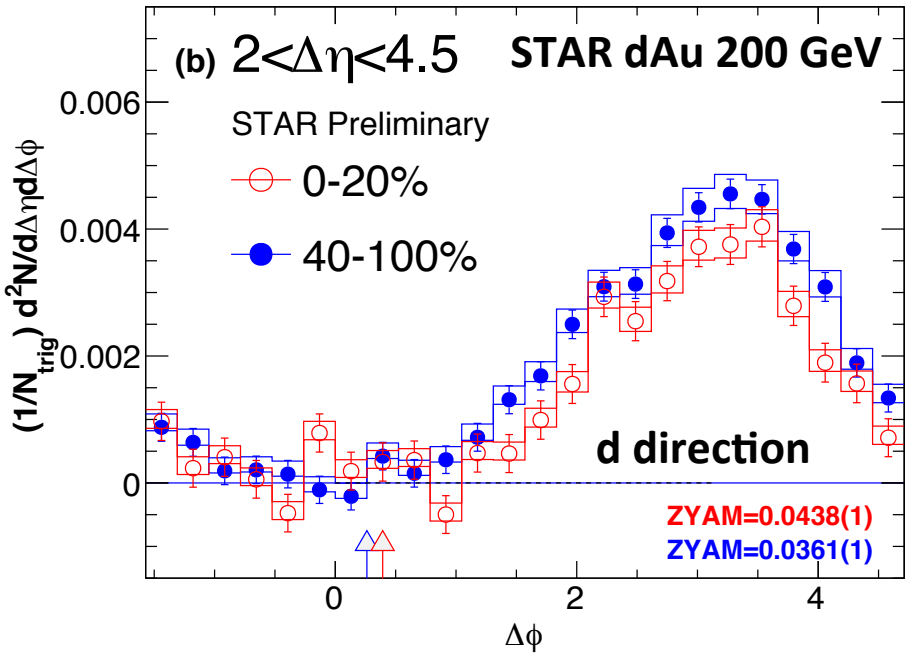
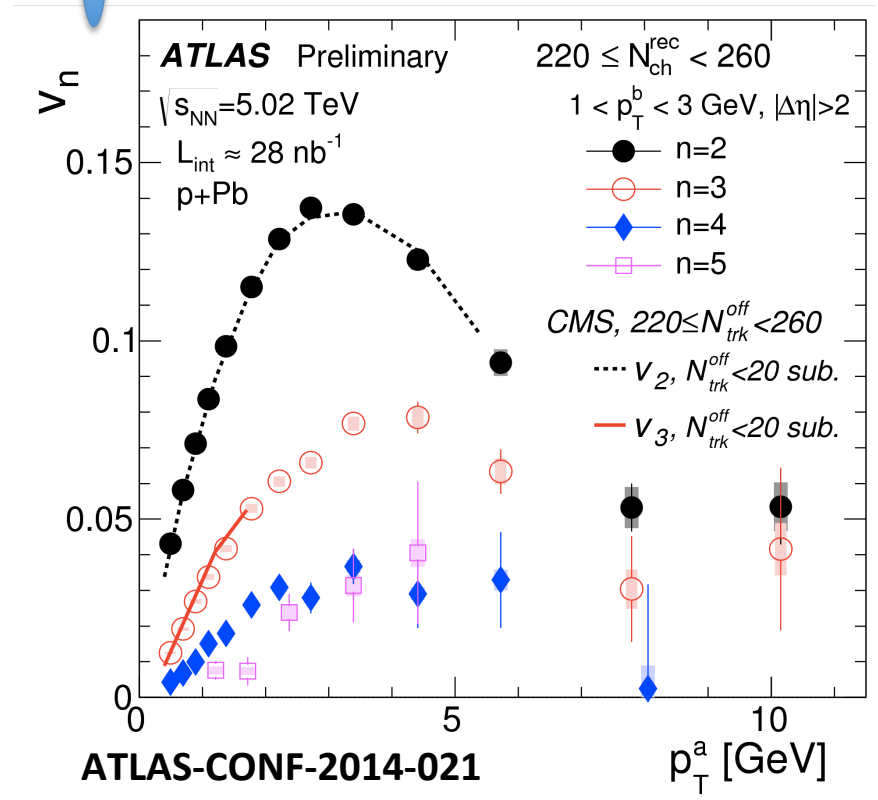


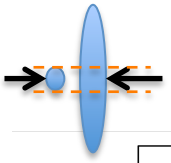


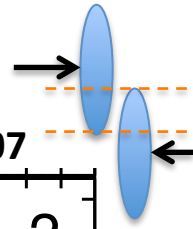
- Ridge in Au direction, but not in d direction
- η dependence of ridge?

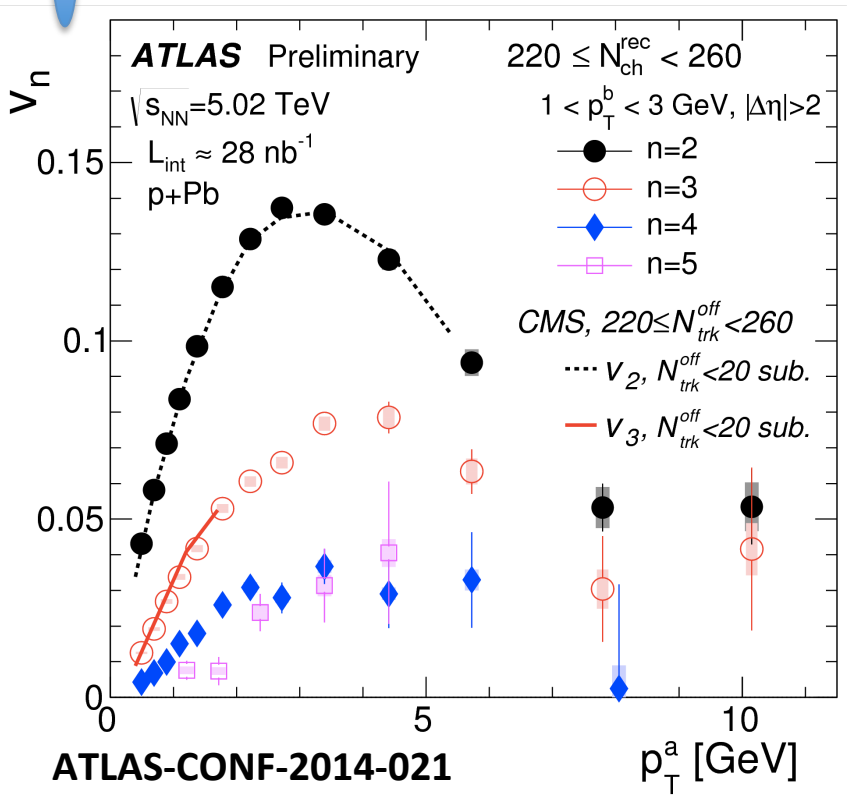
Flow coefficient $v_n(p_T)$

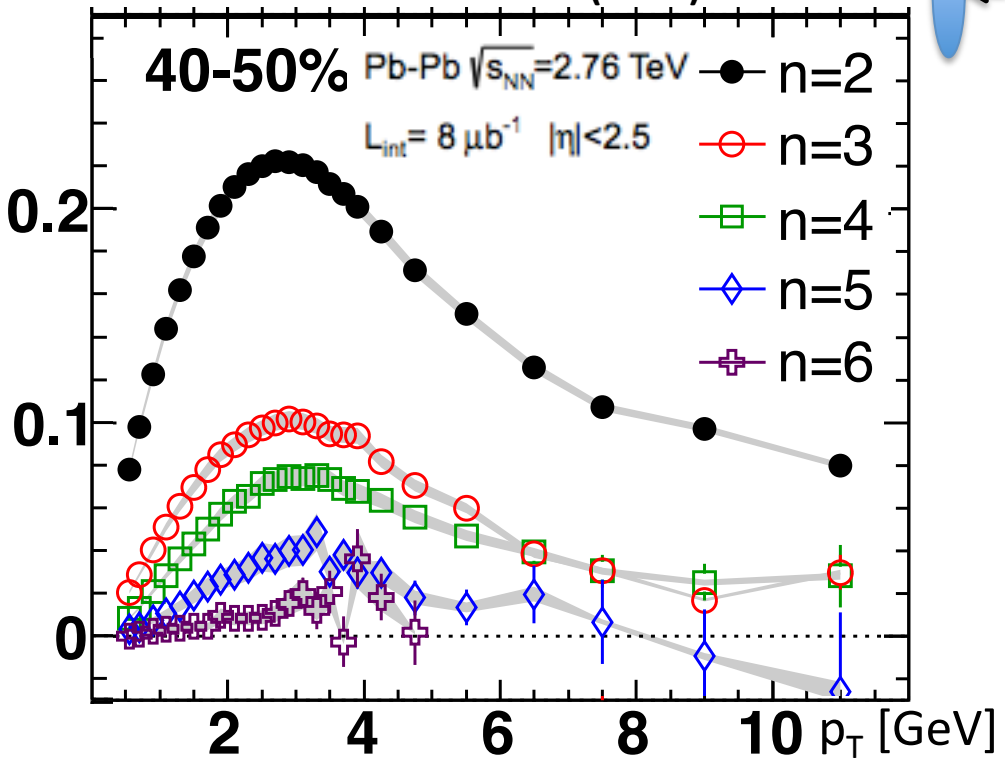


Flow coefficient $v_n(p_T)$

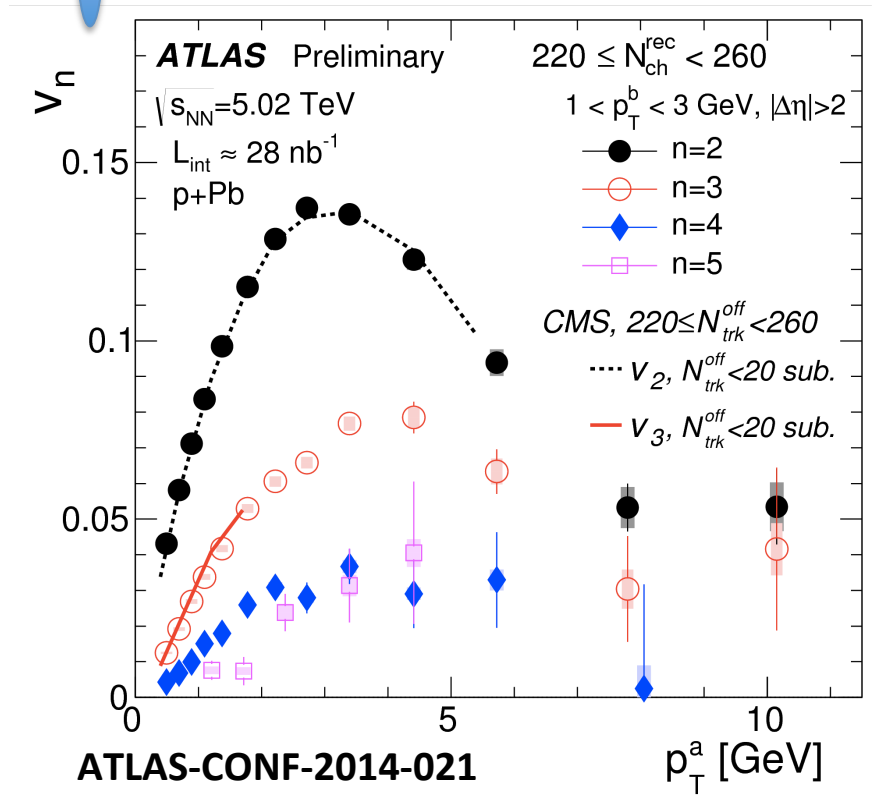


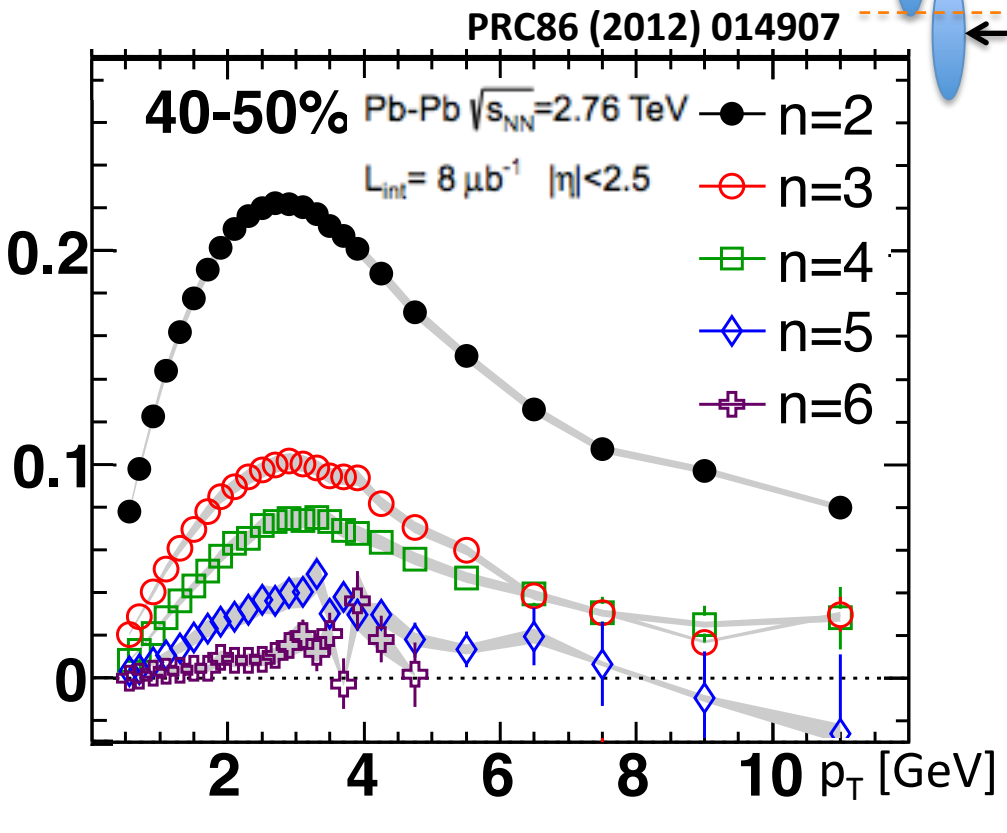






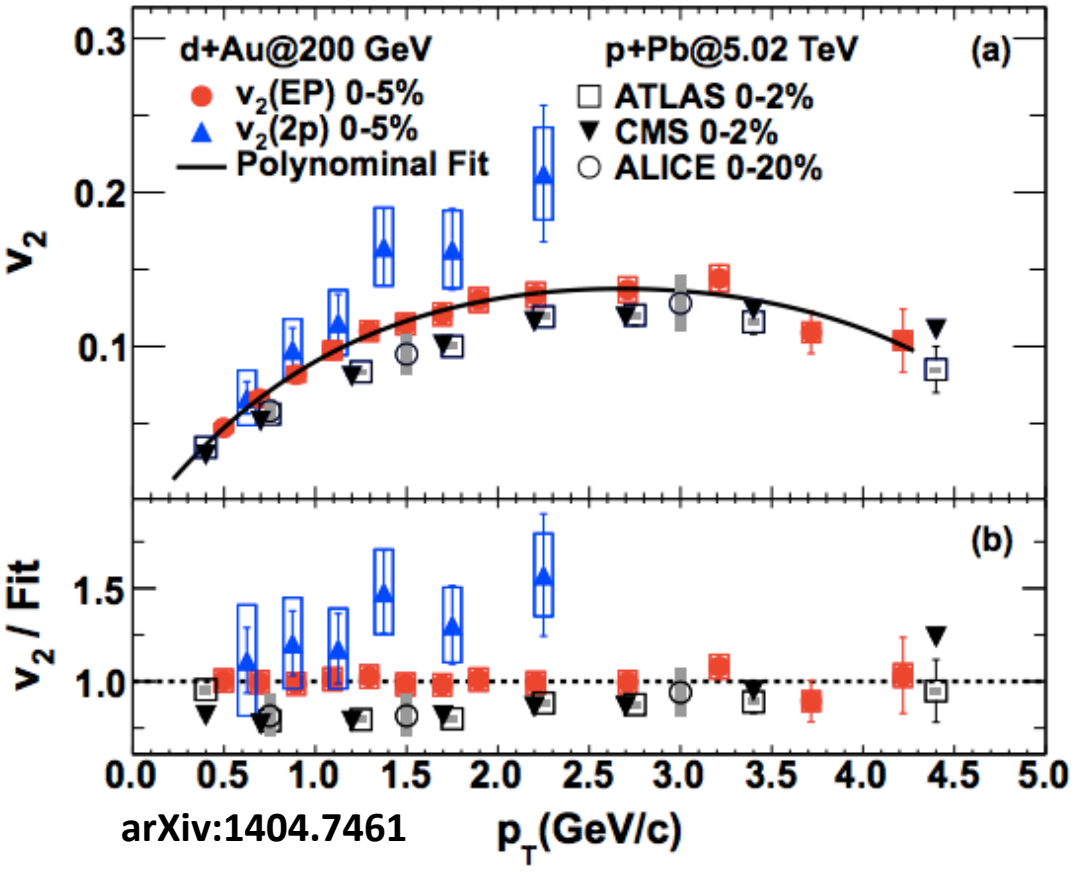
Flow coefficient $v_n(p_T)$



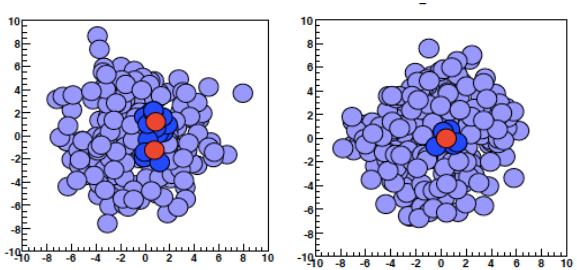


- **Striking similar behavior at similar multiplicity**
- **Same origin?**

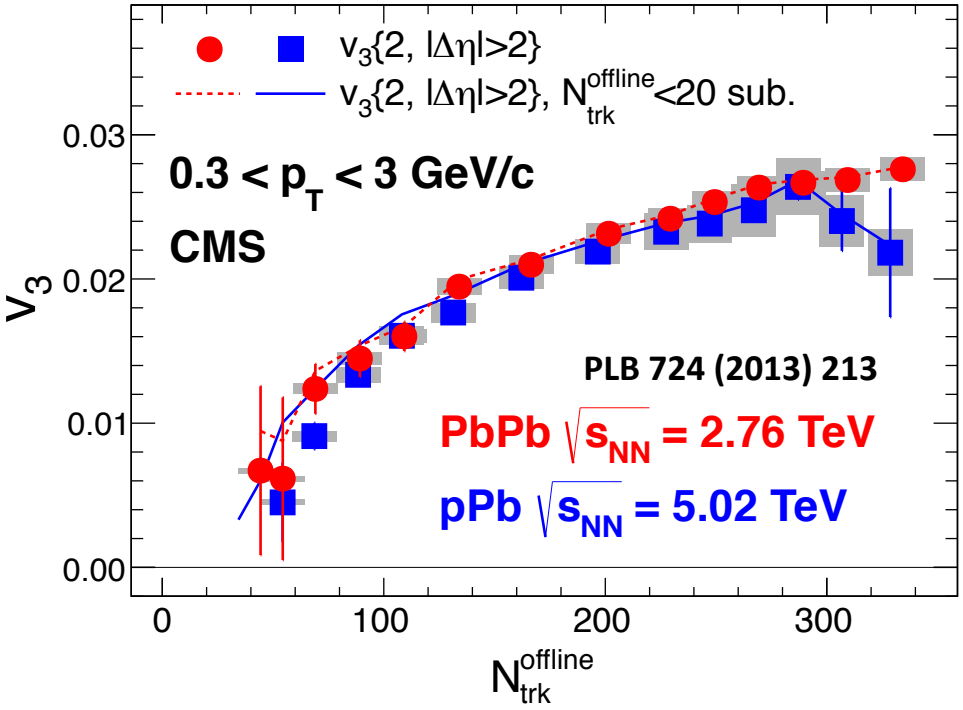
Flow coefficient $v_n(p_T)$



- **Very close v_2 results from RHIC and LHC**
- **Initial conditions are very different**

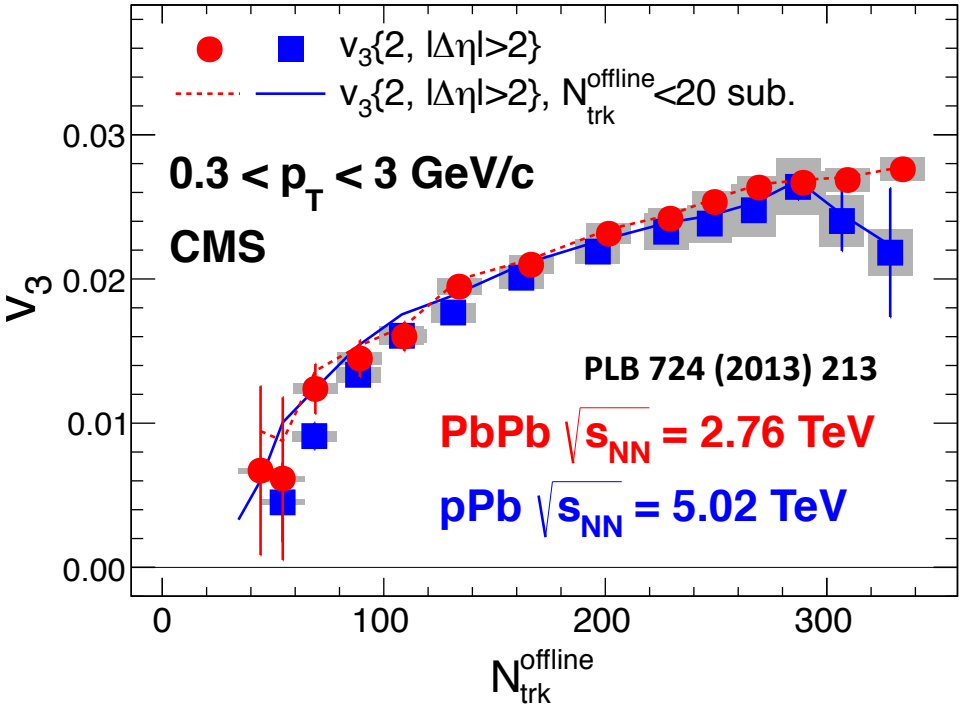


Flow coefficient $v_n(p_T)$



- Intriguing similarity in v_3
- v_3 purely from fluctuation
- System size independent?

Flow coefficient $v_n(p_T)$



- Intriguing similarity in v_3
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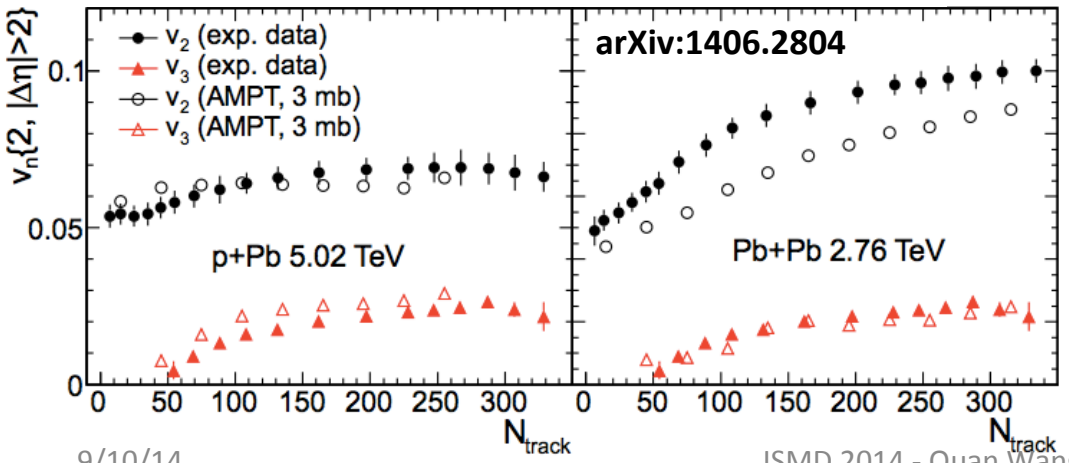
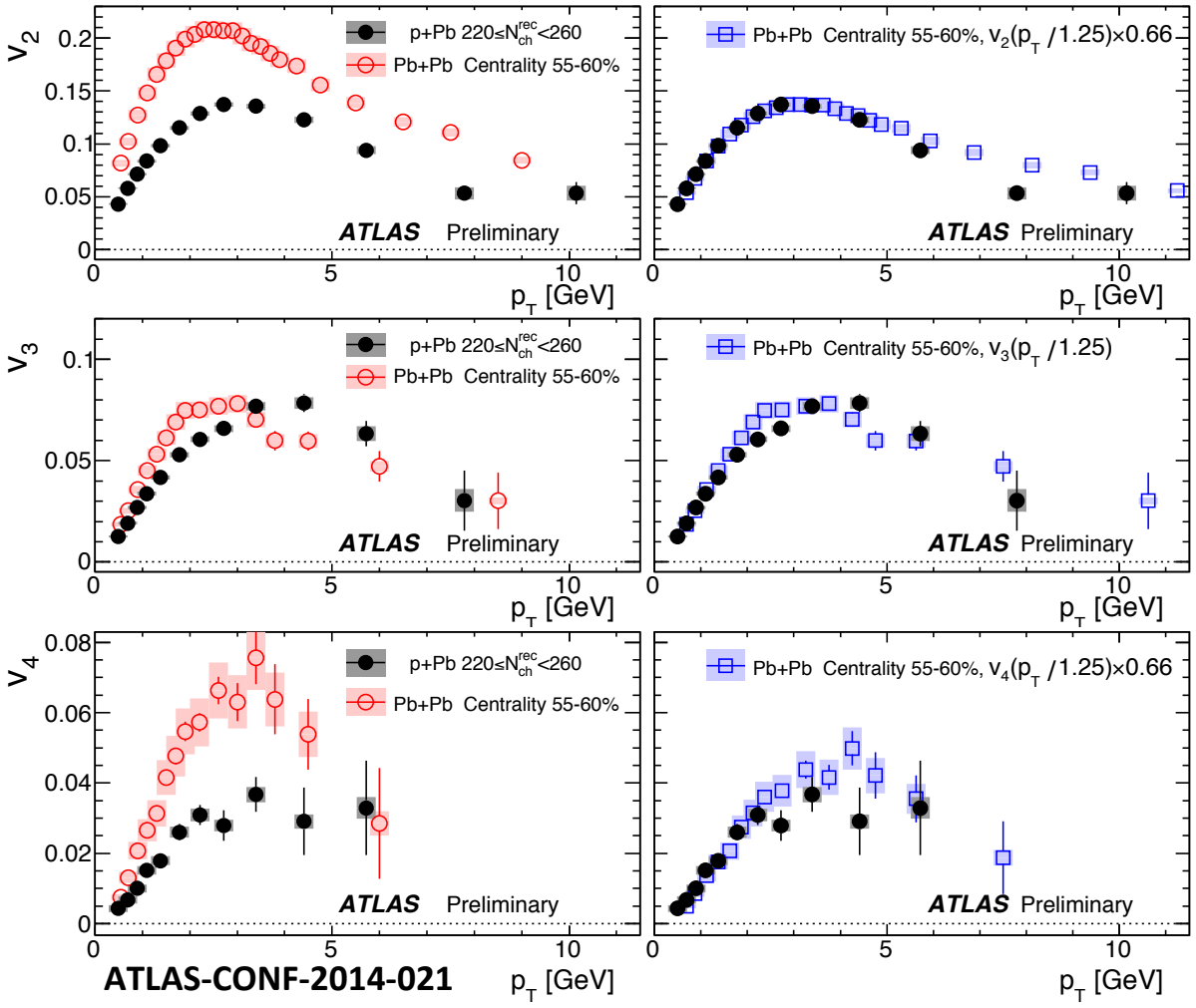
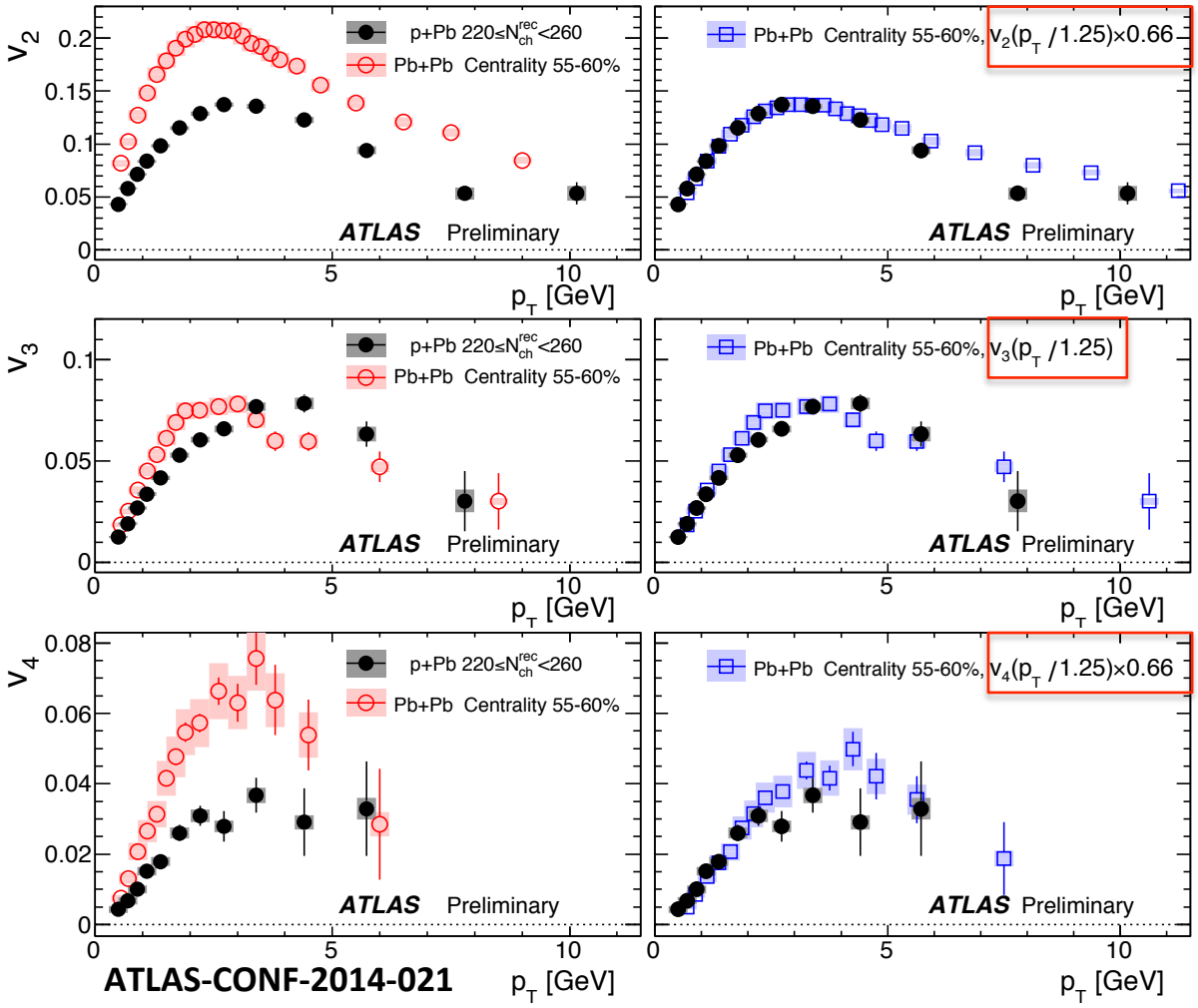


- AMPT with string melting
- Transport model

Flow coefficient $v_n(p_T)$

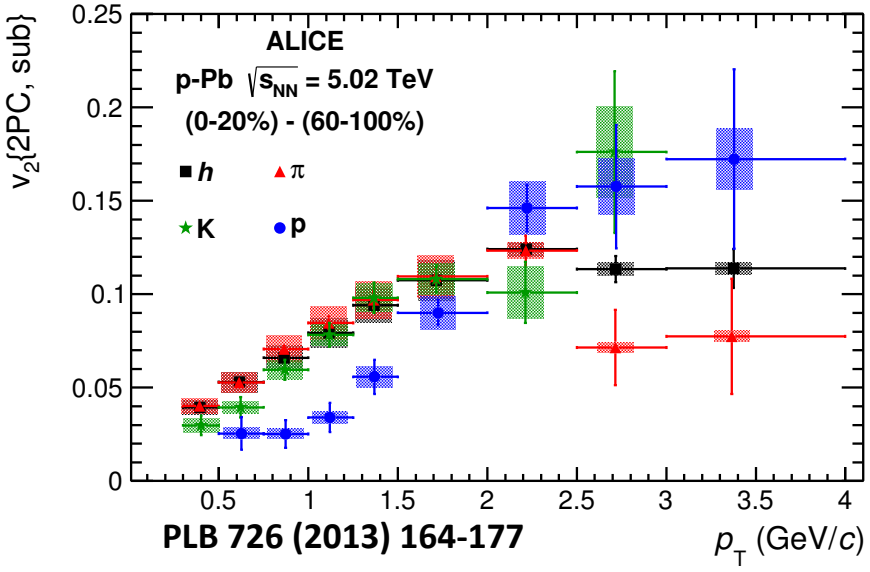


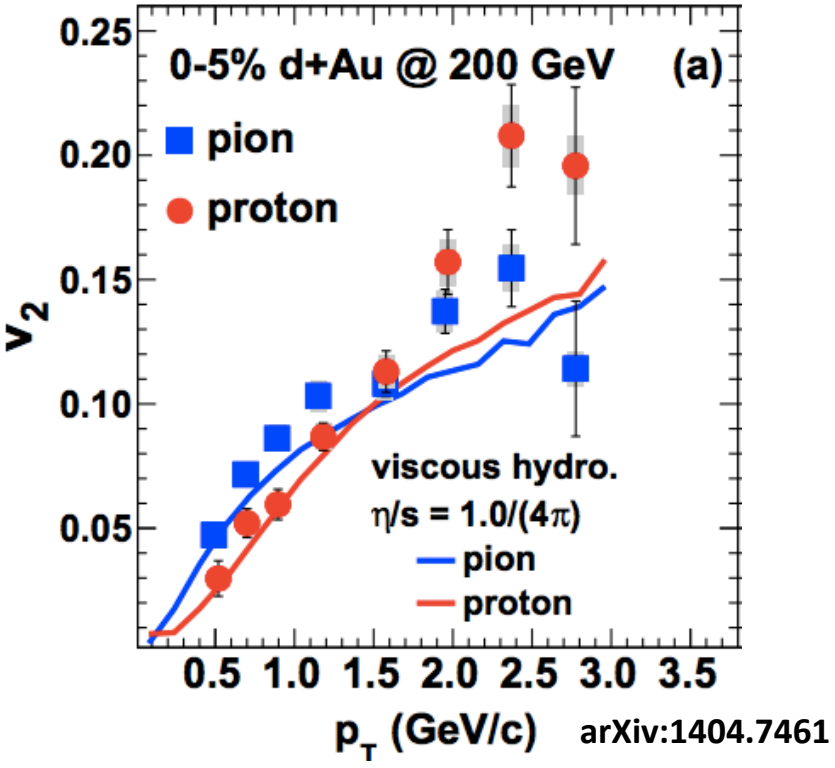
Flow coefficient $v_n(p_T)$

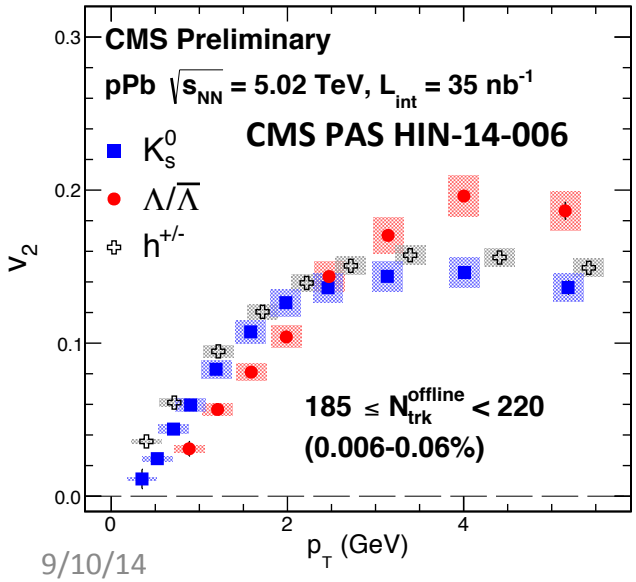


- Rescaling property (arXiv:1312.6770)
- Rescale account for averaged p_T difference of 1.25x

Mass Ordering in Small System

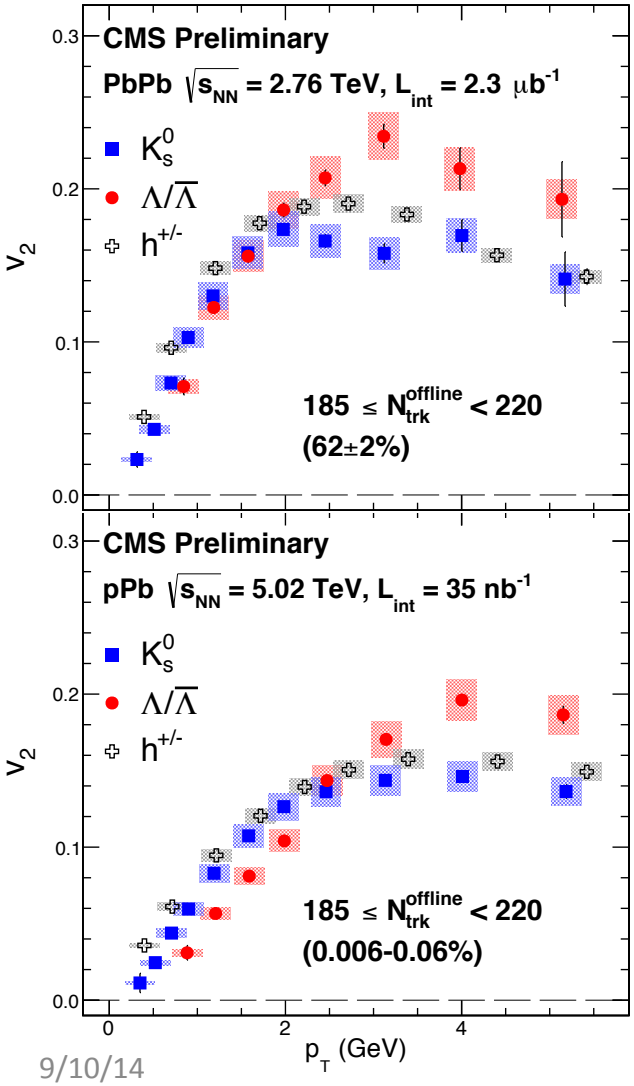


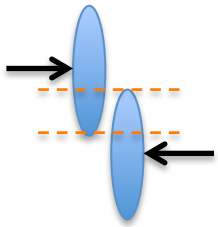


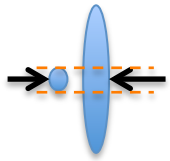


- Mass ordering persists in small system
- Low p_T, light particles have large v_2
- High p_T, v_2{baryon} > v_2{meson}
- Cross over around p_T = 2 GeV/c

Mass Ordering in Small System

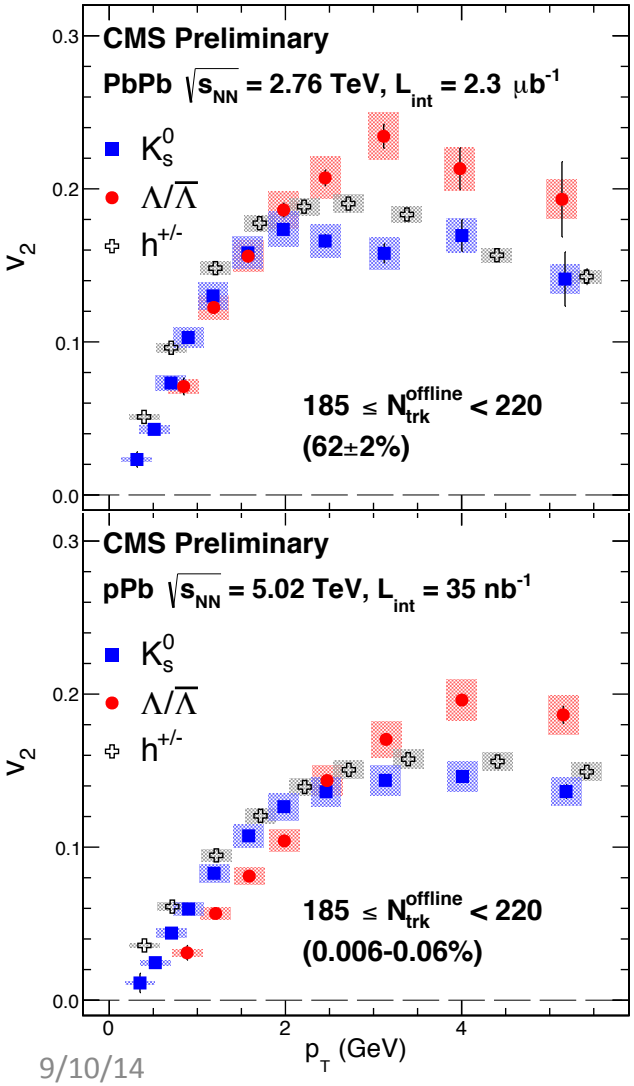




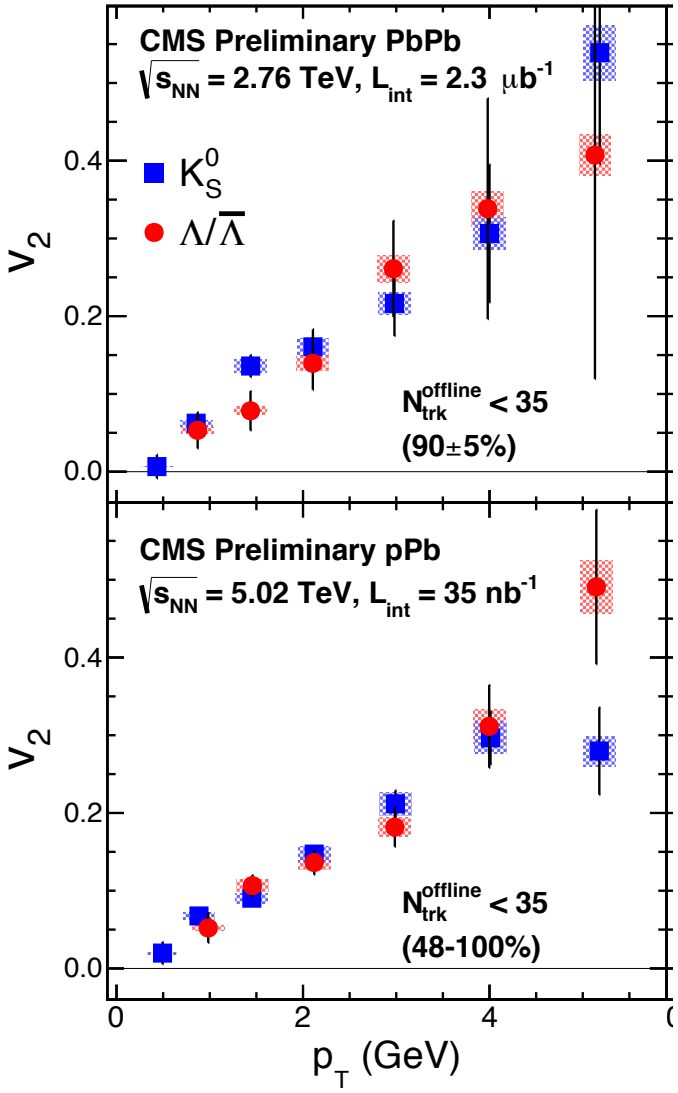


CMS PAS HIN-14-006

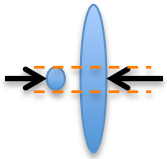
Mass Ordering in Small System



CMS PAS HIN-14-006



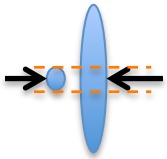
Flow coefficient $v_n(\eta)$



Flow coefficient $v_n(\eta)$

p going

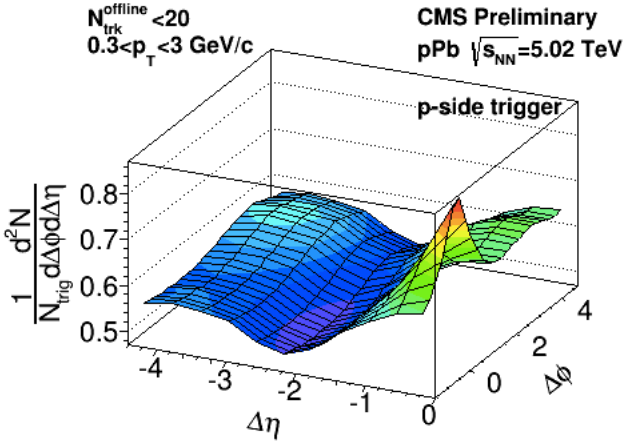
Pb going



Flow coefficient $v_n(\eta)$

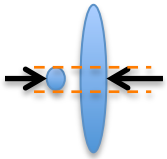
p going

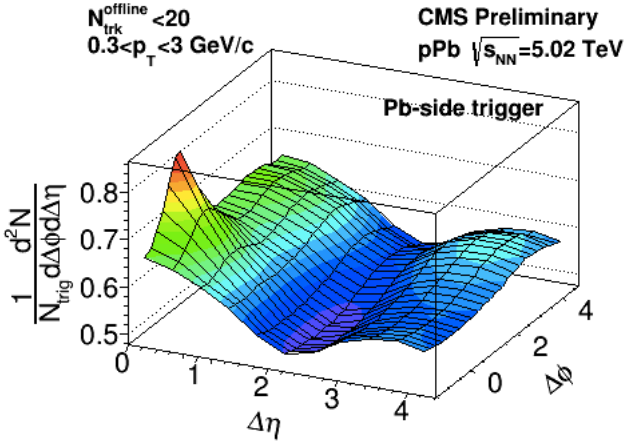
Pb going



CMS PAS HIN-14-008

Low Multiplicity

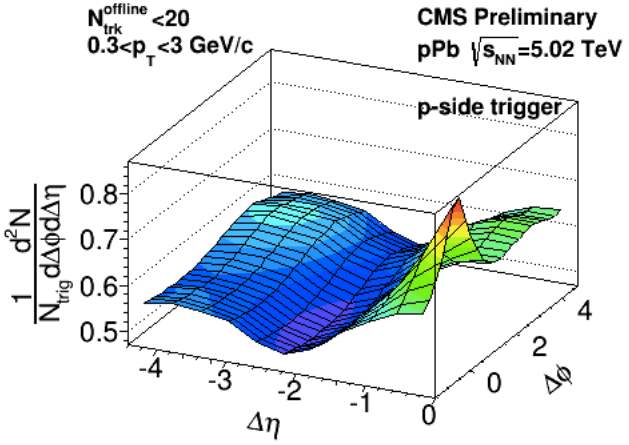




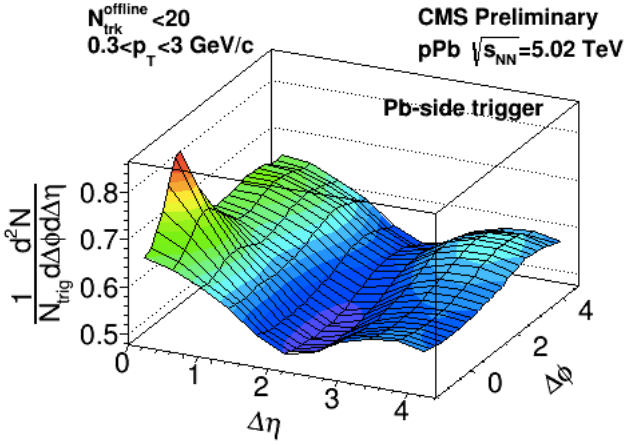
Flow coefficient $v_n(\eta)$

p going

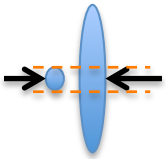
Pb going

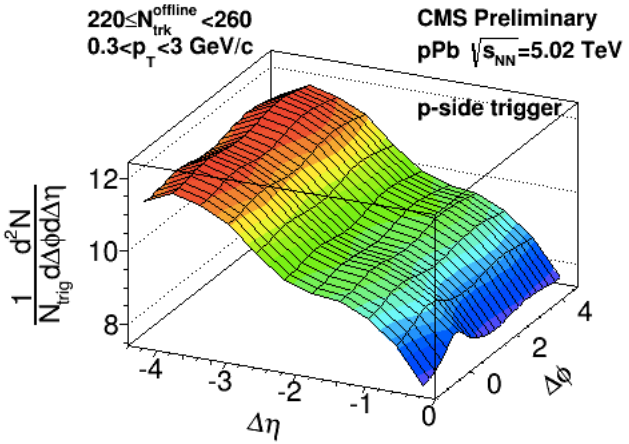


CMS PAS HIN-14-008

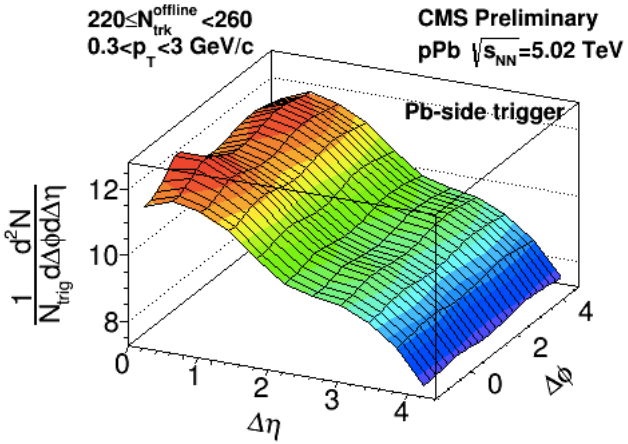


Low Multiplicity





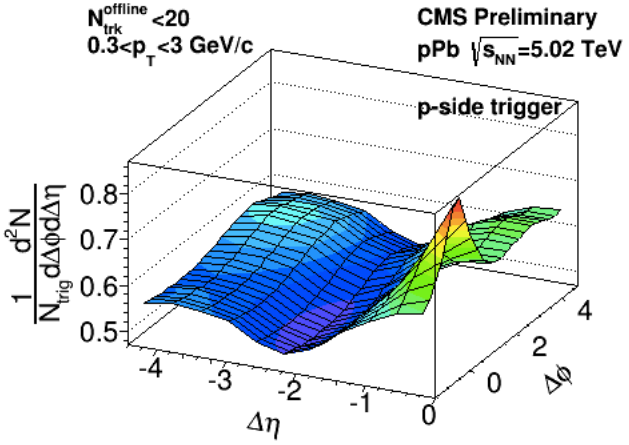
High Multiplicity



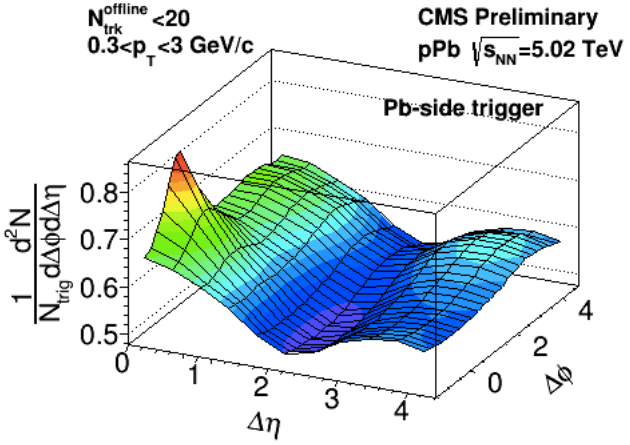
Flow coefficient $v_n(\eta)$

p going

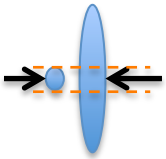
Pb going

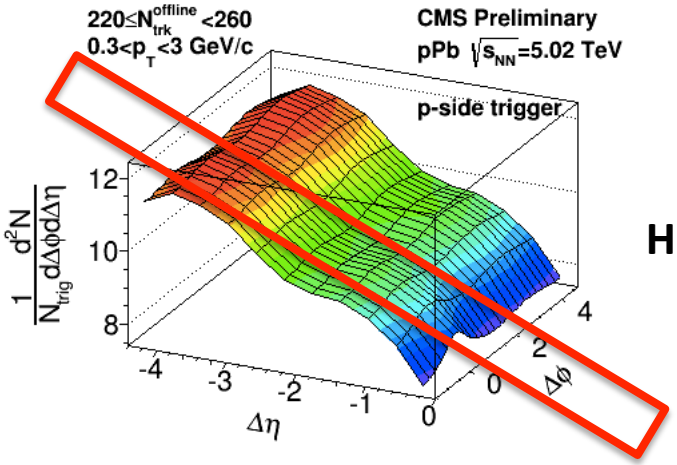


CMS PAS HIN-14-008

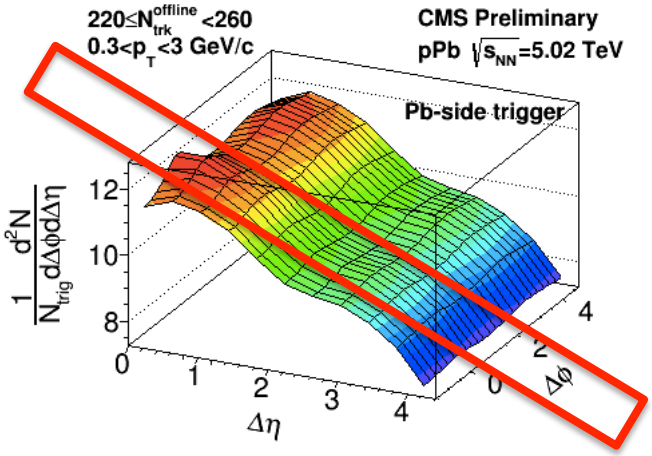


Low Multiplicity

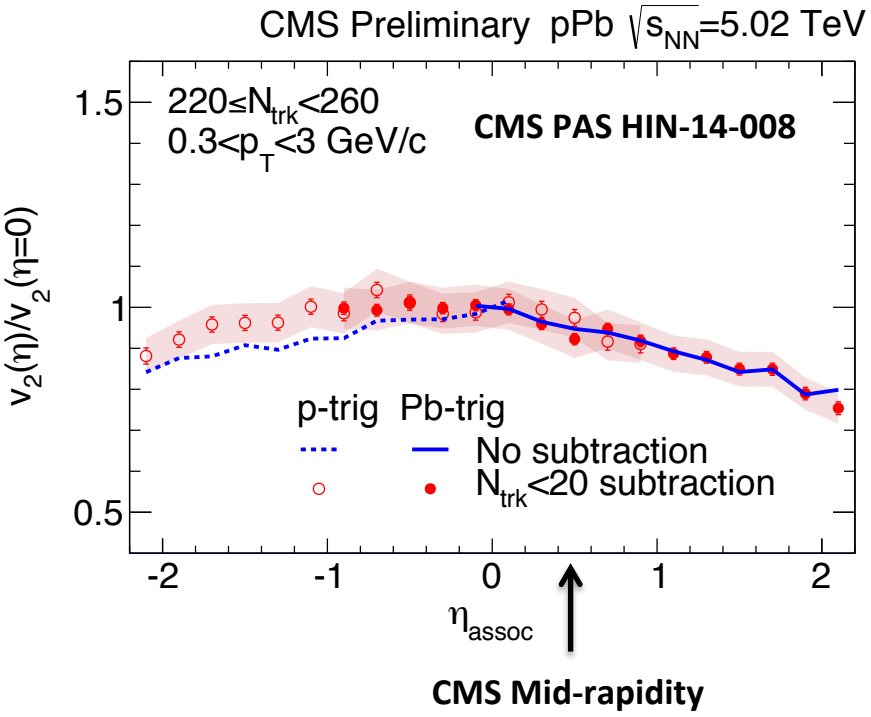


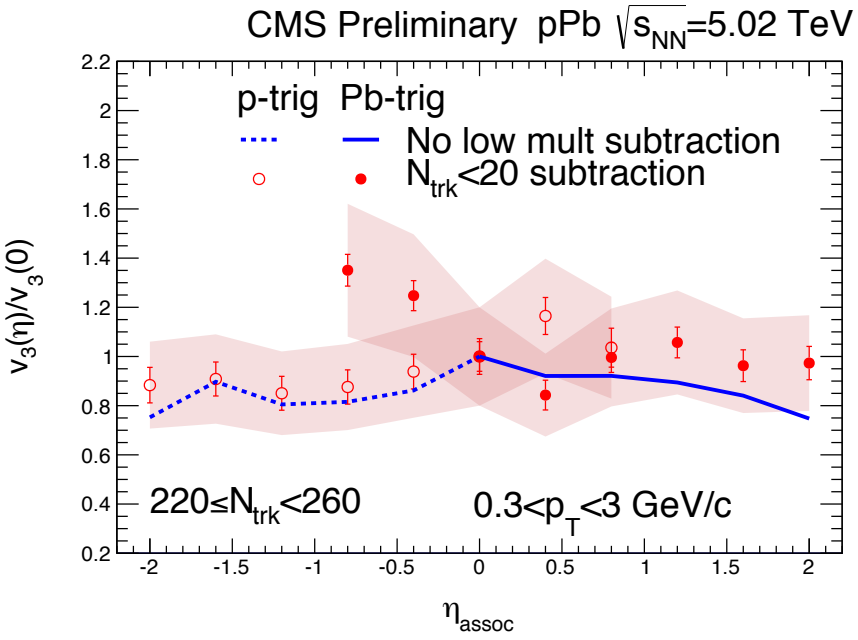


High Multiplicity



Flow coefficient $v_n(\eta)$

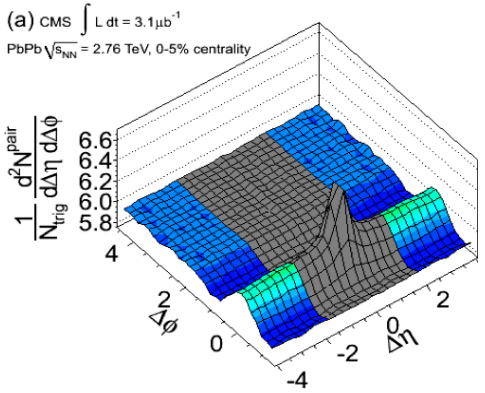




- **Significant η dependence observed for v_2**

Flow Factorization

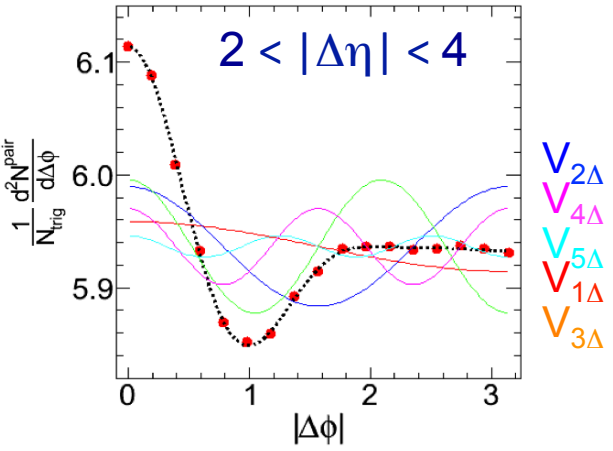
Two particle correlation



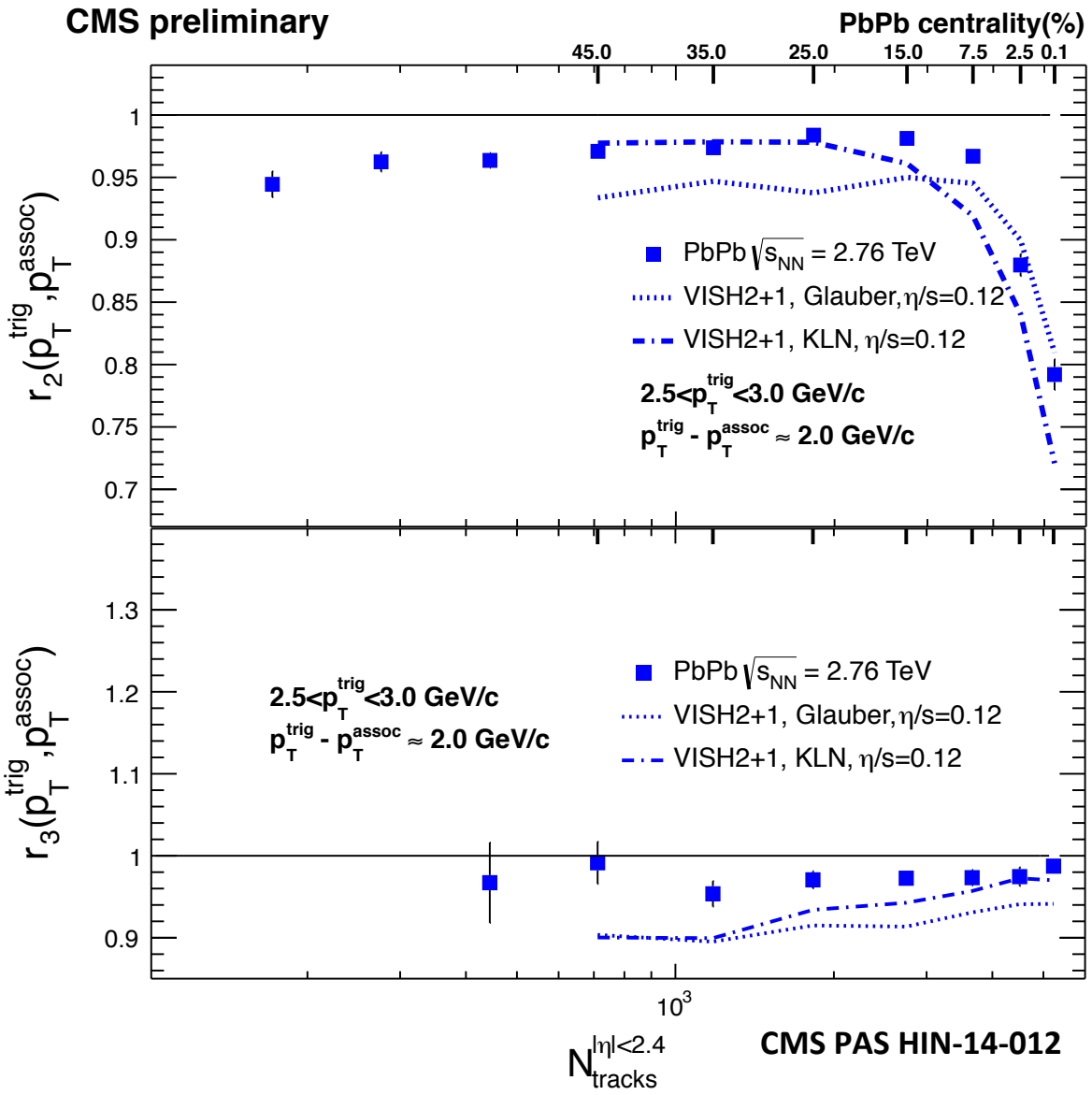
$$\frac{dN}{d\Delta\phi} \sim 1 + 2V_{2\Delta}\cos 2\Delta\phi + 2V_{3\Delta}\cos 3\Delta\phi$$

$$V_{n\Delta}(p_{T1}, p_{T2}) = \left\langle v_n(p_{T1}) v_n(p_{T2}) \cos[n(\Psi_n(p_{T1}) - \Psi_n(p_{T2}))] \right\rangle$$

$$r_n = \frac{V_{n\Delta}(p_{T1}, p_{T2})}{\sqrt{V_{n\Delta}(p_{T1}, p_{T1}) V_{n\Delta}(p_{T2}, p_{T2})}}$$

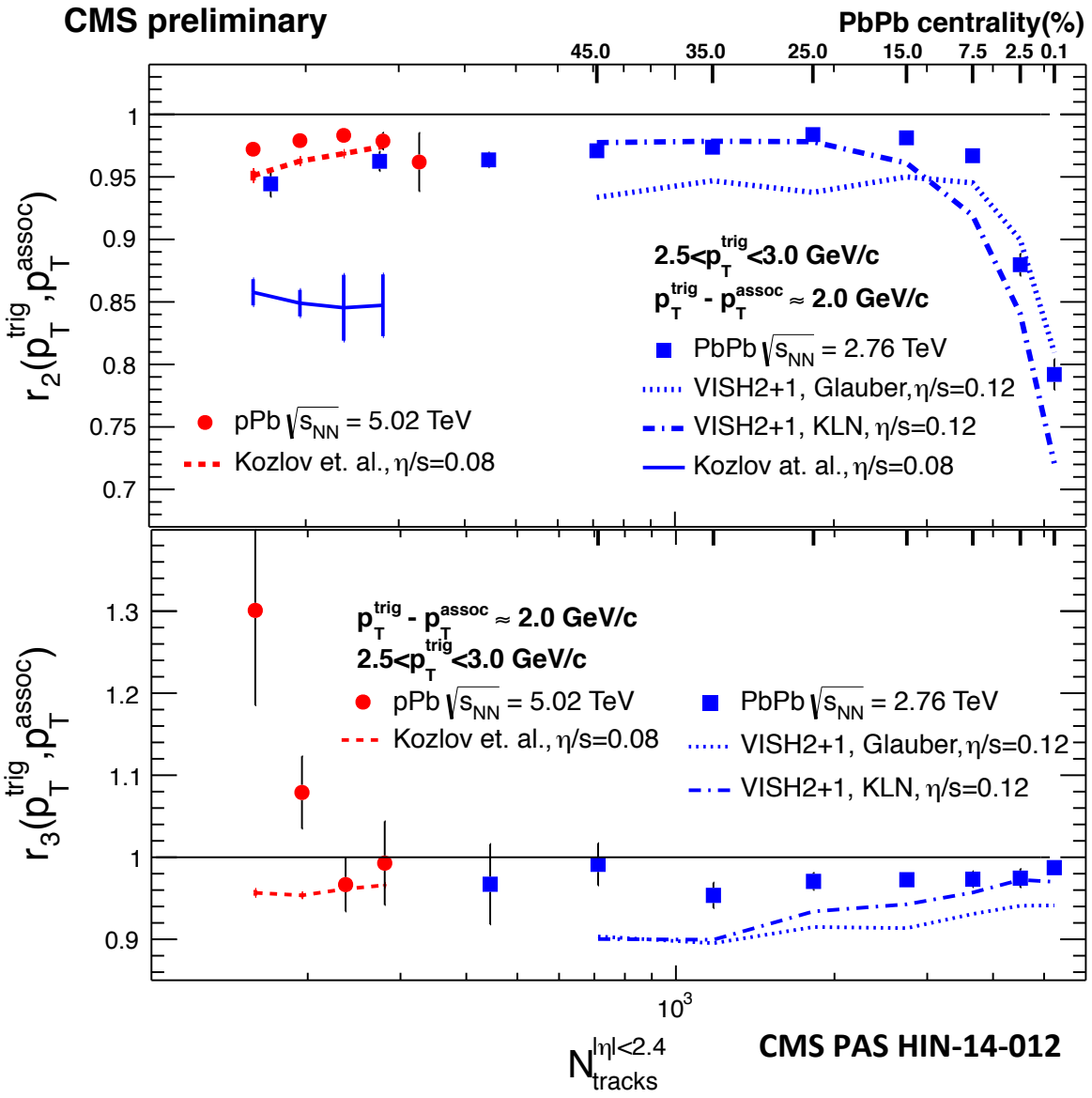


Flow Factorization



- Hydrodynamics Qualitatively consistent with PbPb

Flow Factorization



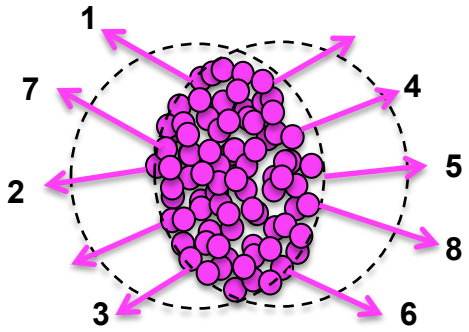
- Hydrodynamics Qualitatively consistent with PbPb and pPb

True Collectivity in pPb?

- So far, analysis are on two-particle correlations
- Question: are the correlations **only** amongst particle **pairs**?
- In hydrodynamics, correlations are expected between all particles

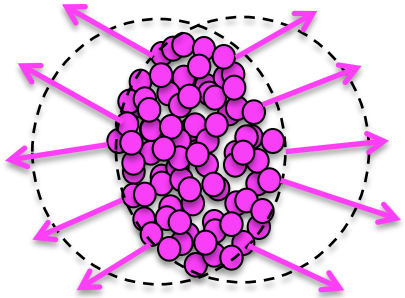
True Collectivity in pPb?

4-, 6- and 8-particle cumulant



- Genuine 4-, 6- and 8-particle correlations
- Insensitive to non-flow contributions from < 4, 6 and 8 particles
- Q-Cumulant suppress higher order interference

Lee-Yang Zeros



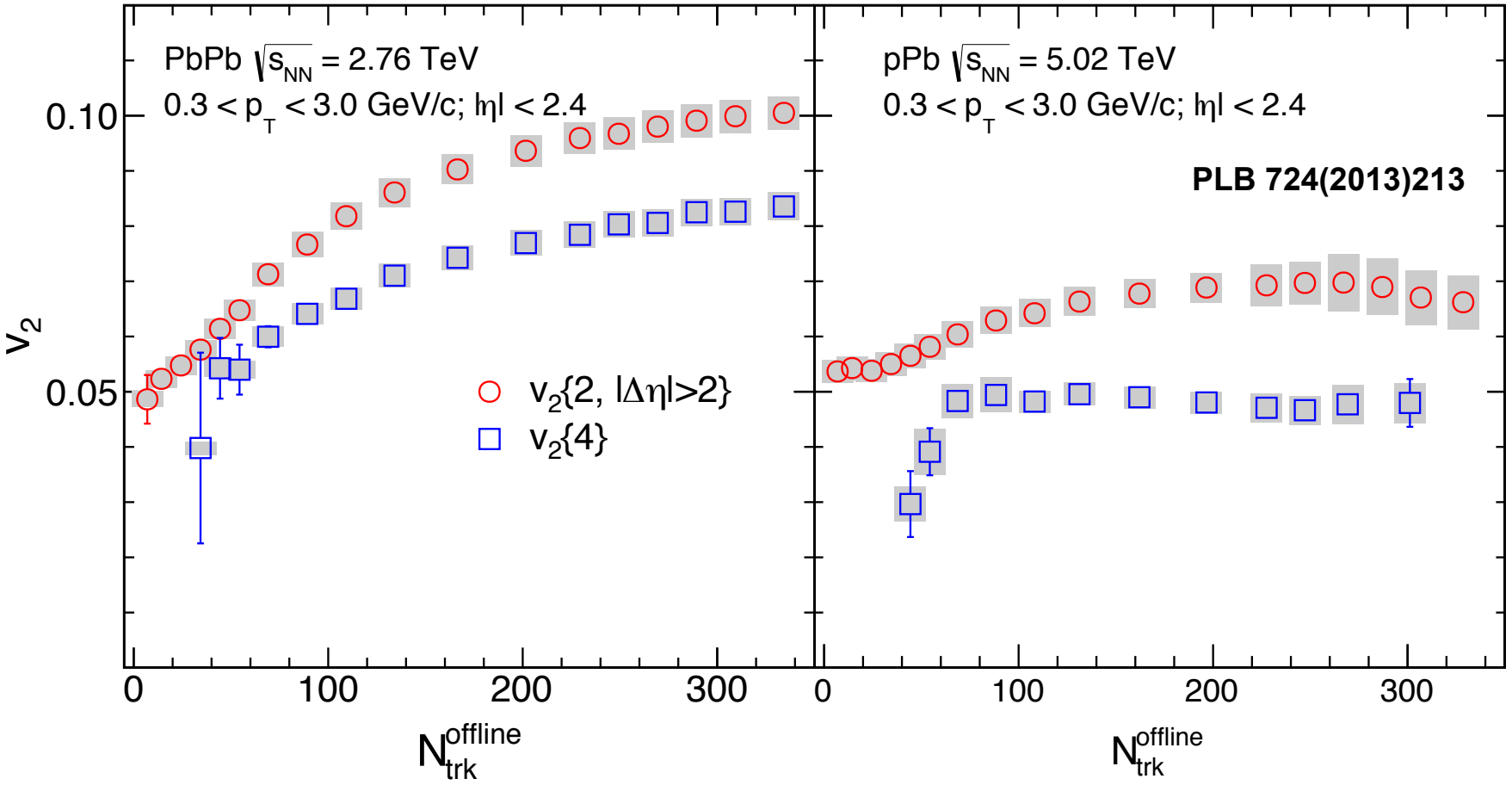
- Genuine all-particle correlation
- Built-in correction for non-uniform distribution

Hydrodynamics:

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$$

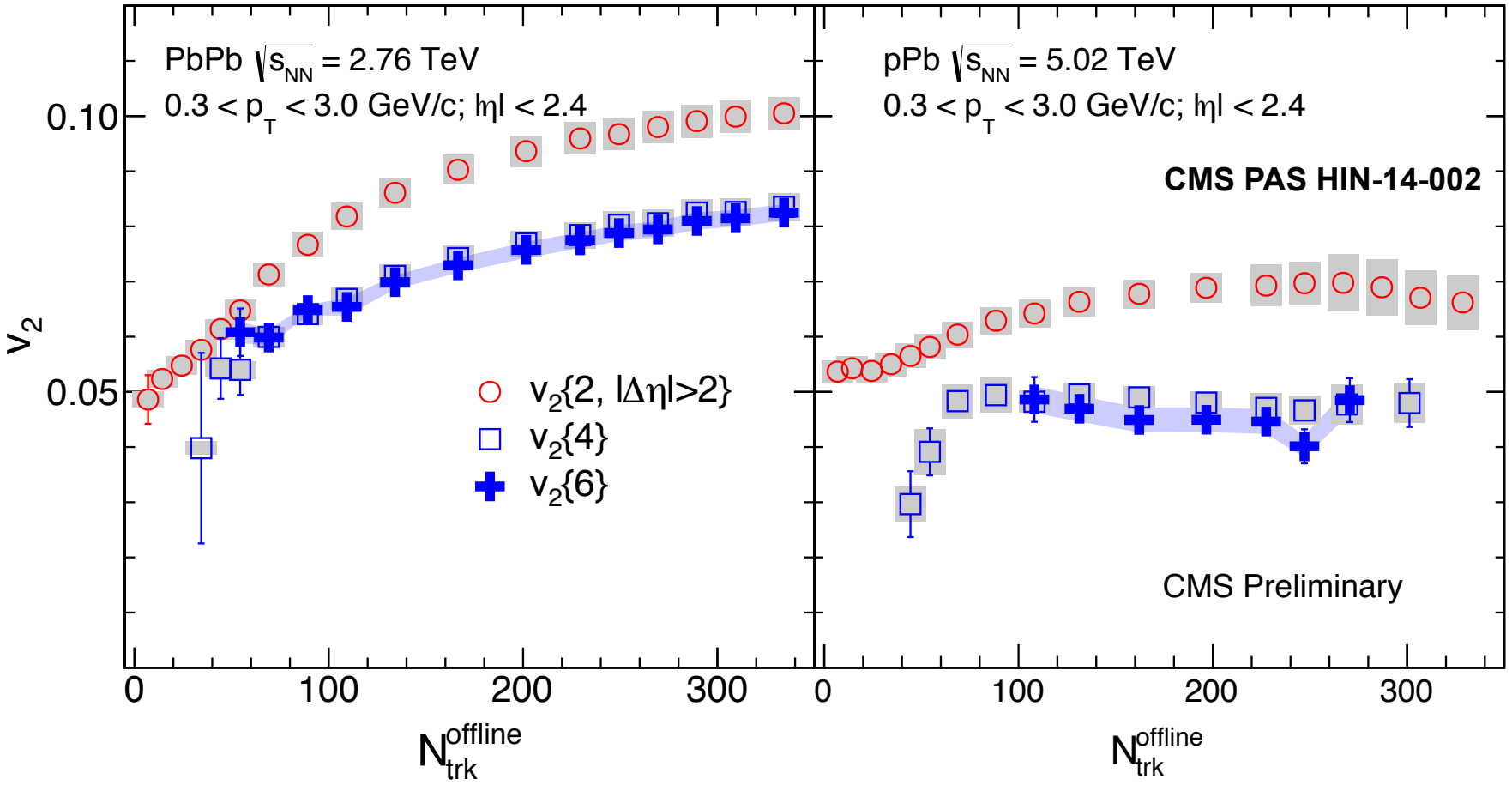
True Collectivity in pPb?

$v_2\{2\} > v_2\{4\}$



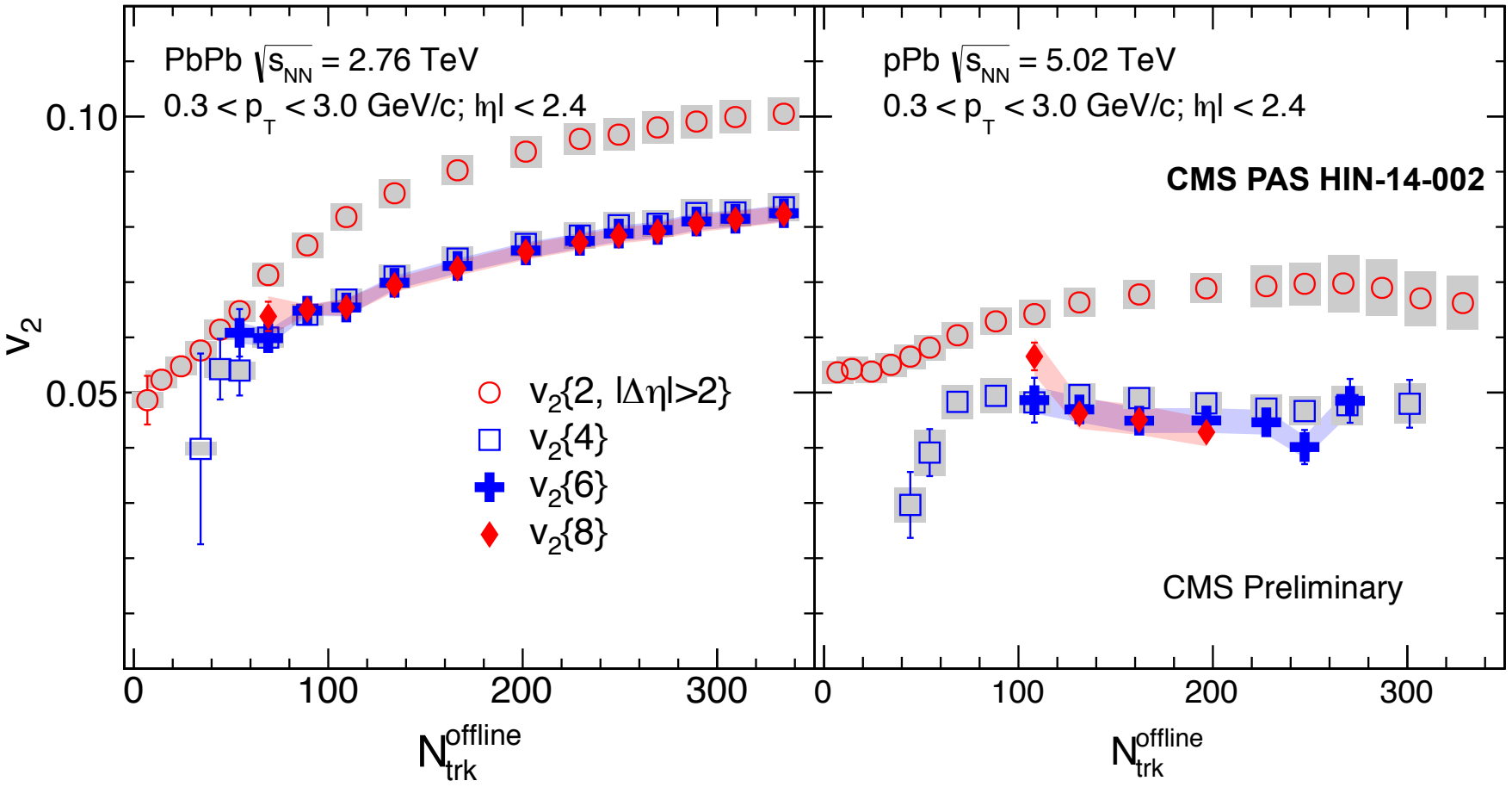
True Collectivity in pPb?

$v_2\{2\} > v_2\{4\} \approx v_2\{6\}$



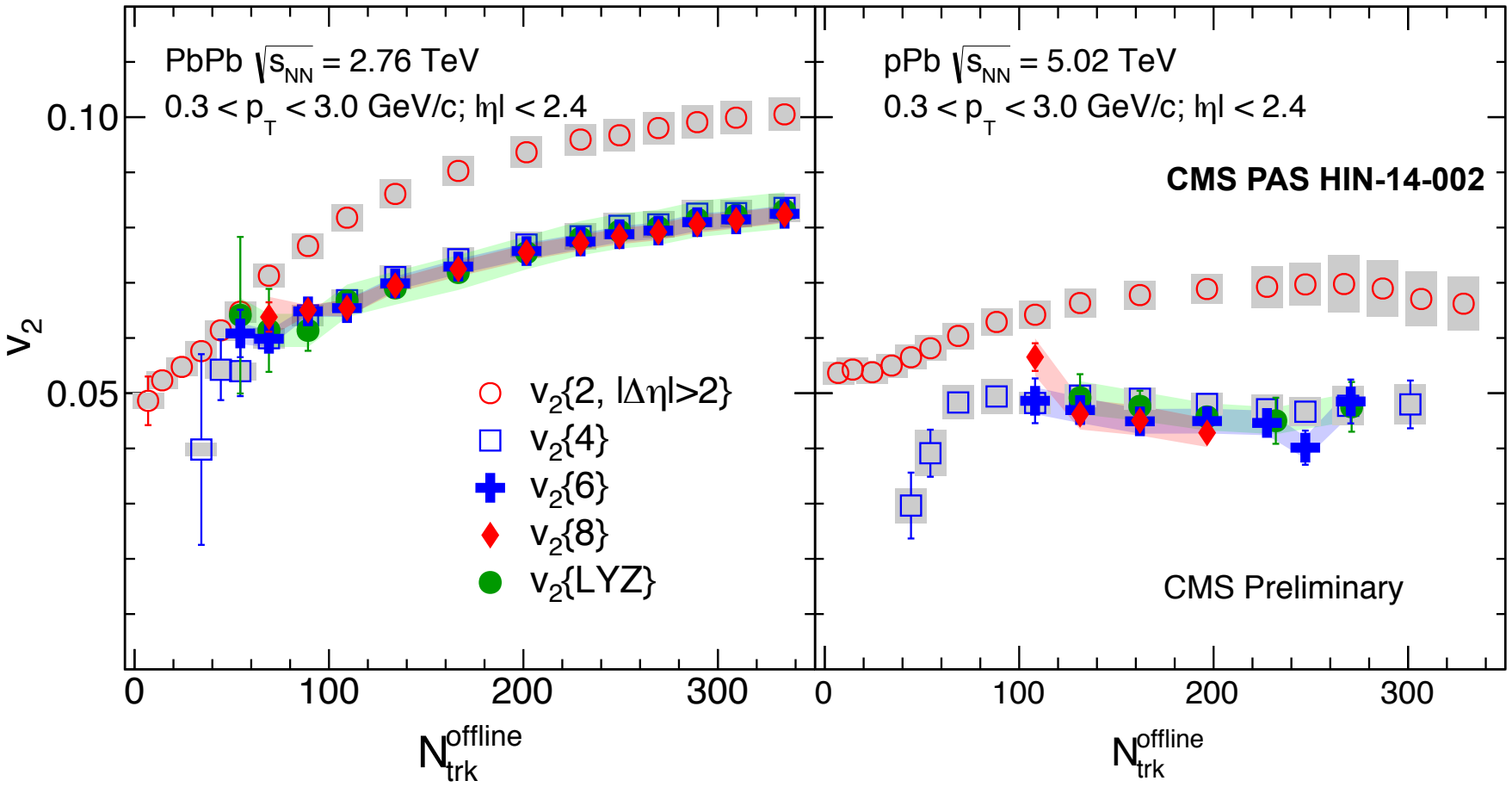
True Collectivity in pPb?

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



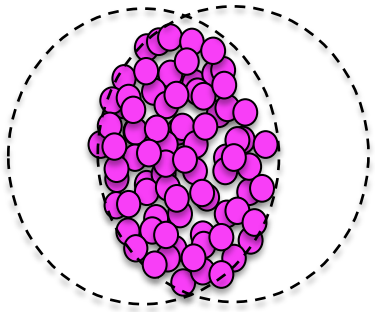
True Collectivity in pPb?

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$



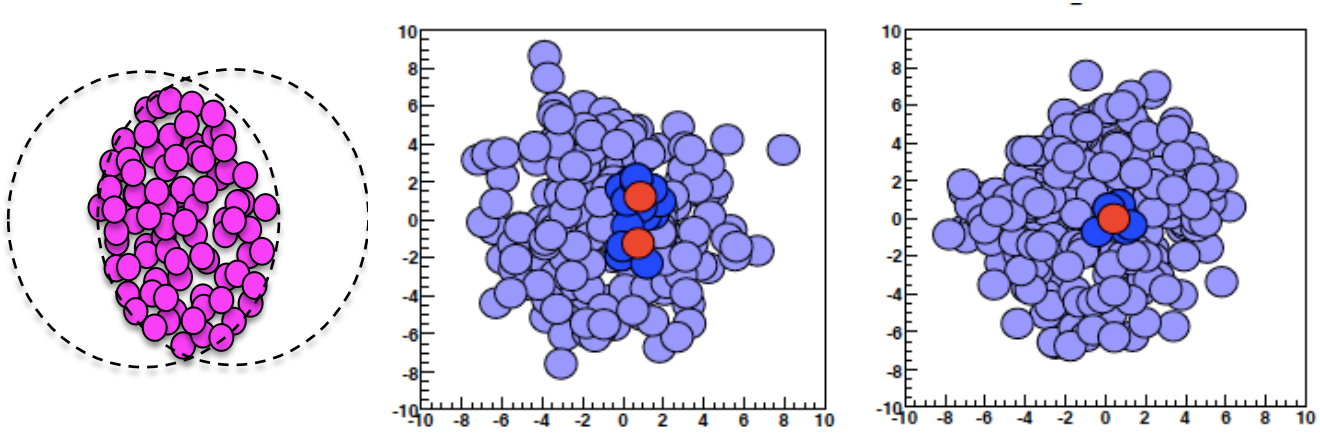
Direct evidence of strong collectivity in pPb!

Full Picture



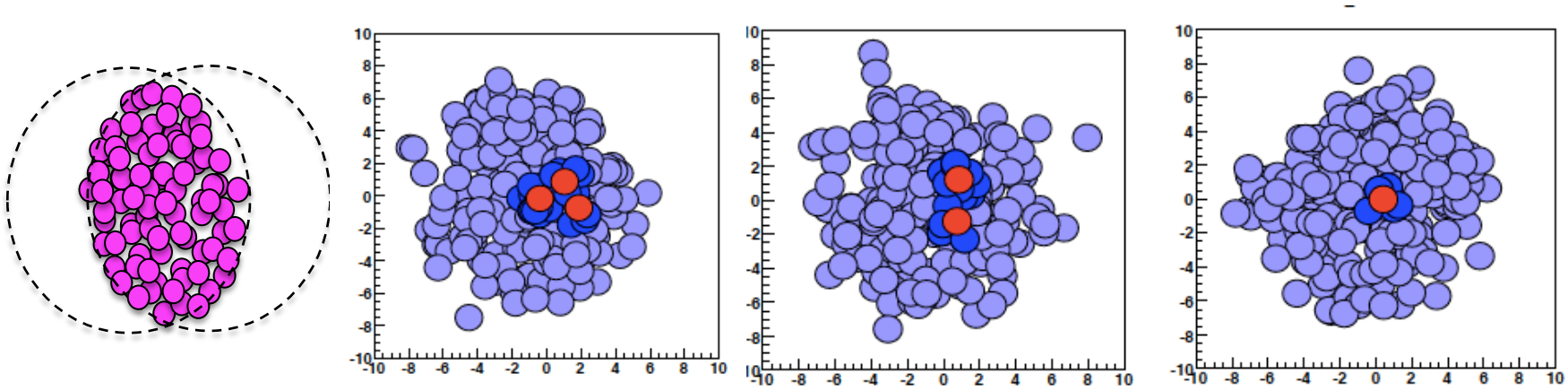
- Hydrodynamics regime in AA

Full Picture



- Hydrodynamics regime in AA
- Hydrodynamics works in p(d)A, although not quite justified. CGC [PRD 87 (2013) 094034], Non-abelian beam jet [arXiv:1405.7825], Transport model [arXiv:1406.2804]

Look Forward



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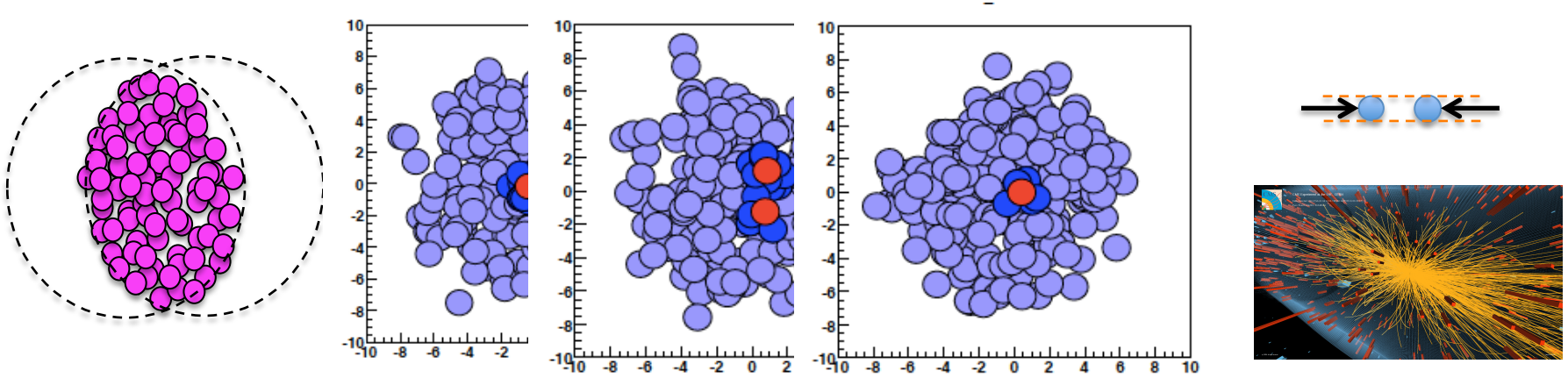
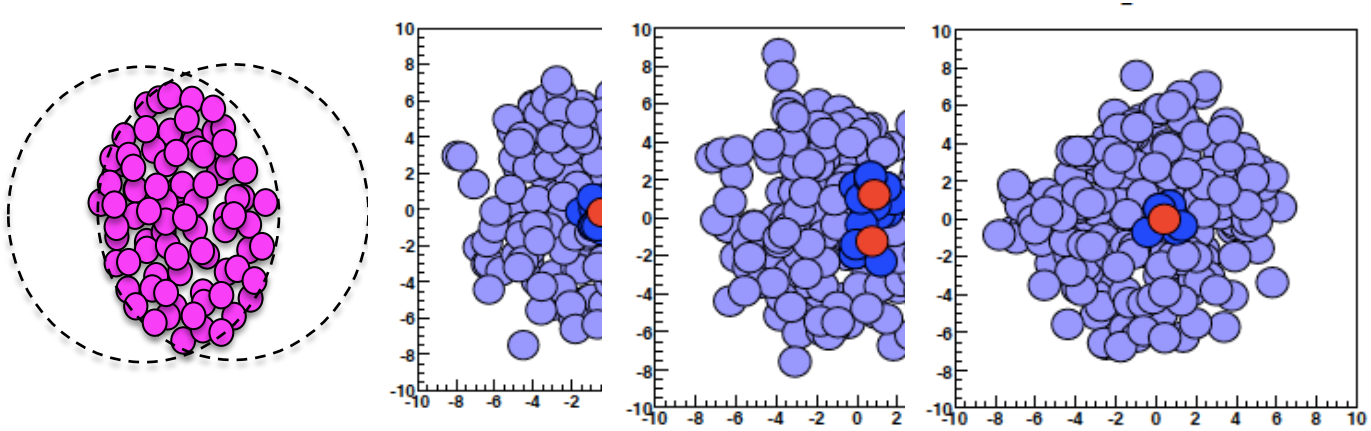
- He^3+Au at RHIC 2015 → Triangularity

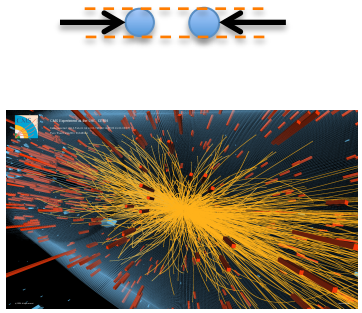
Look Forward



- Hydrodynamics regime in AA
- Hydrodynamics works in p(d)A, although not quite justified. CGC [PRD 87 (2013) 094034], Non-abelian beam jet [arXiv:1405.7825], Transport model [arXiv:1406.2804]
- He^3+Au at RHIC 2015 → Triangularity
- pp at 14 TeV at LHC 2015, energy doubled
  could high multiplicity pp events flow?

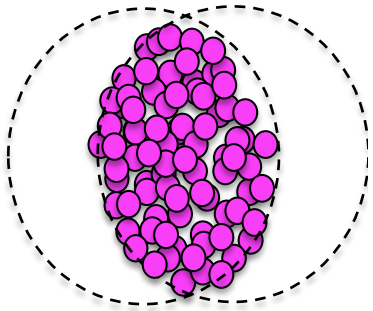
Look Forward

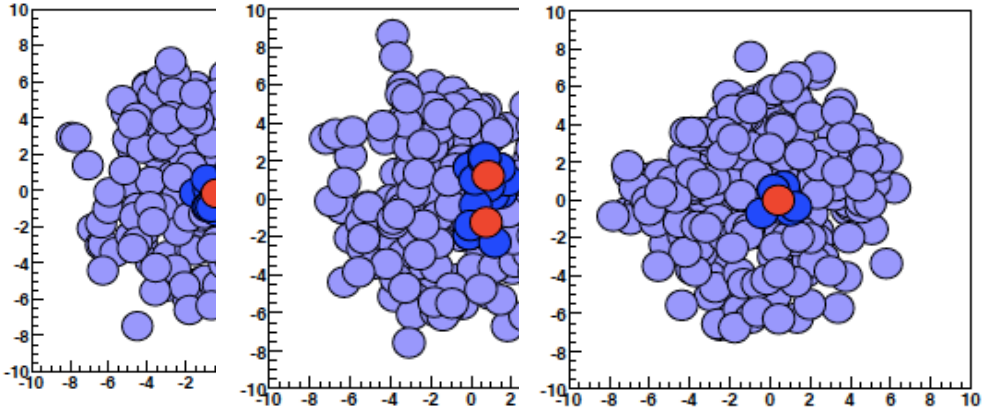


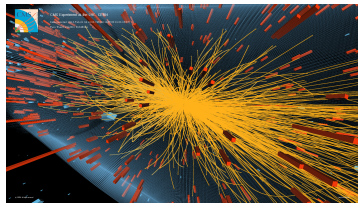


- What do we know about initial state?

Look Forward

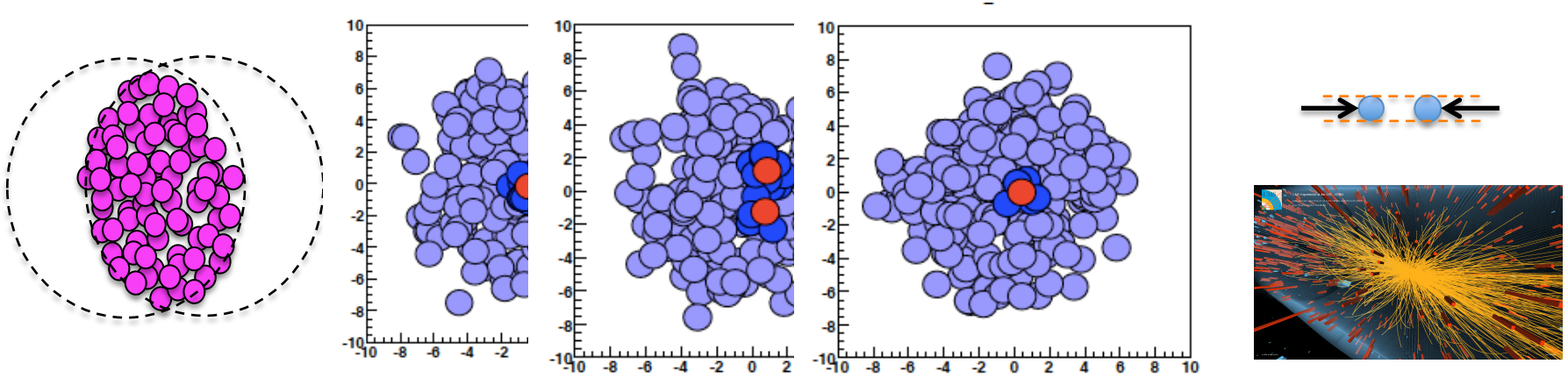






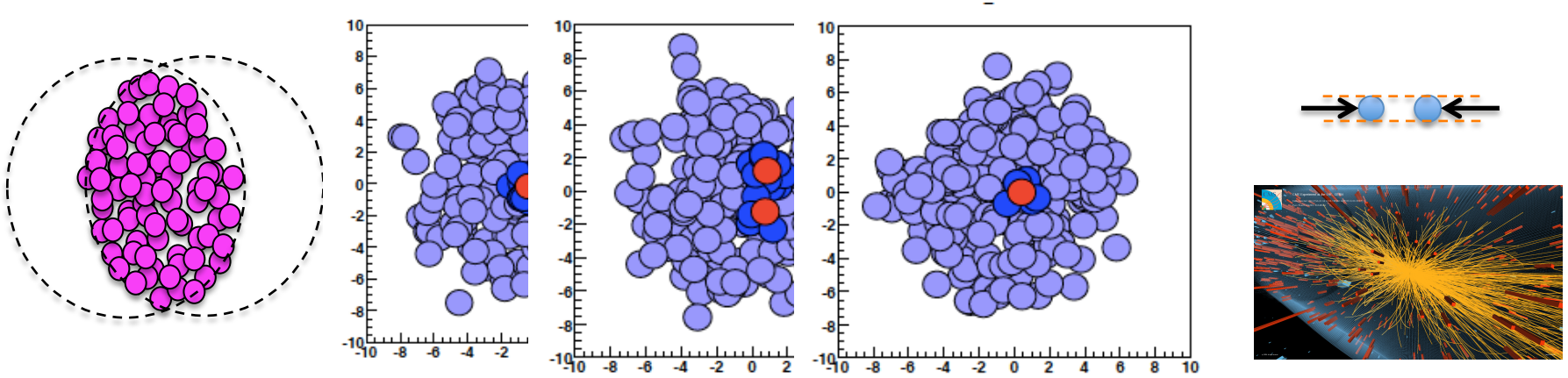
- What do we know about initial state?
- Can the initial condition for the hydrodynamics be determined?

Look Forward



- What do we know about initial state?
- Can the initial condition for the hydrodynamics be determined?
- What is the smallest collision system that behaves collectively, if collectivity is so general?

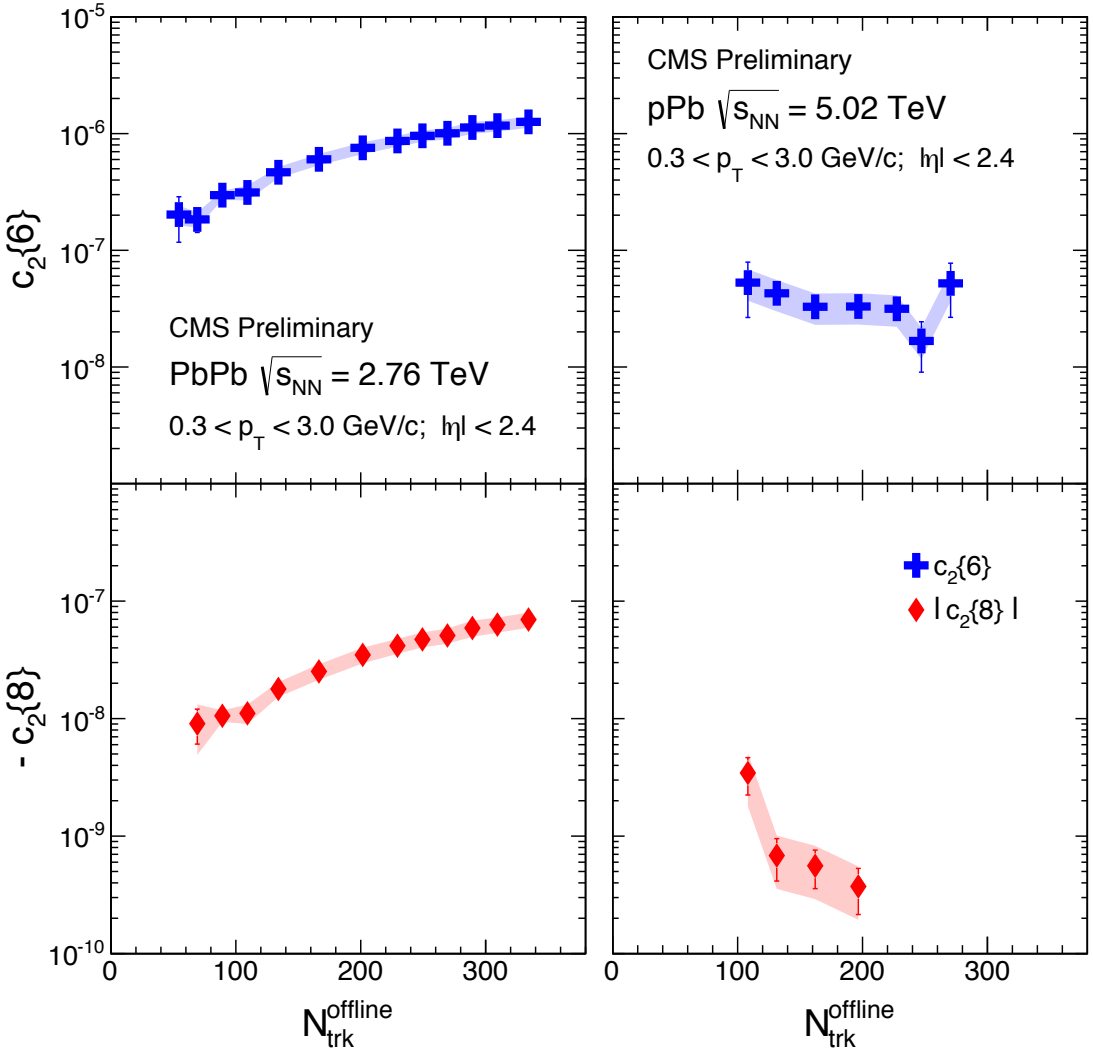
Look Forward



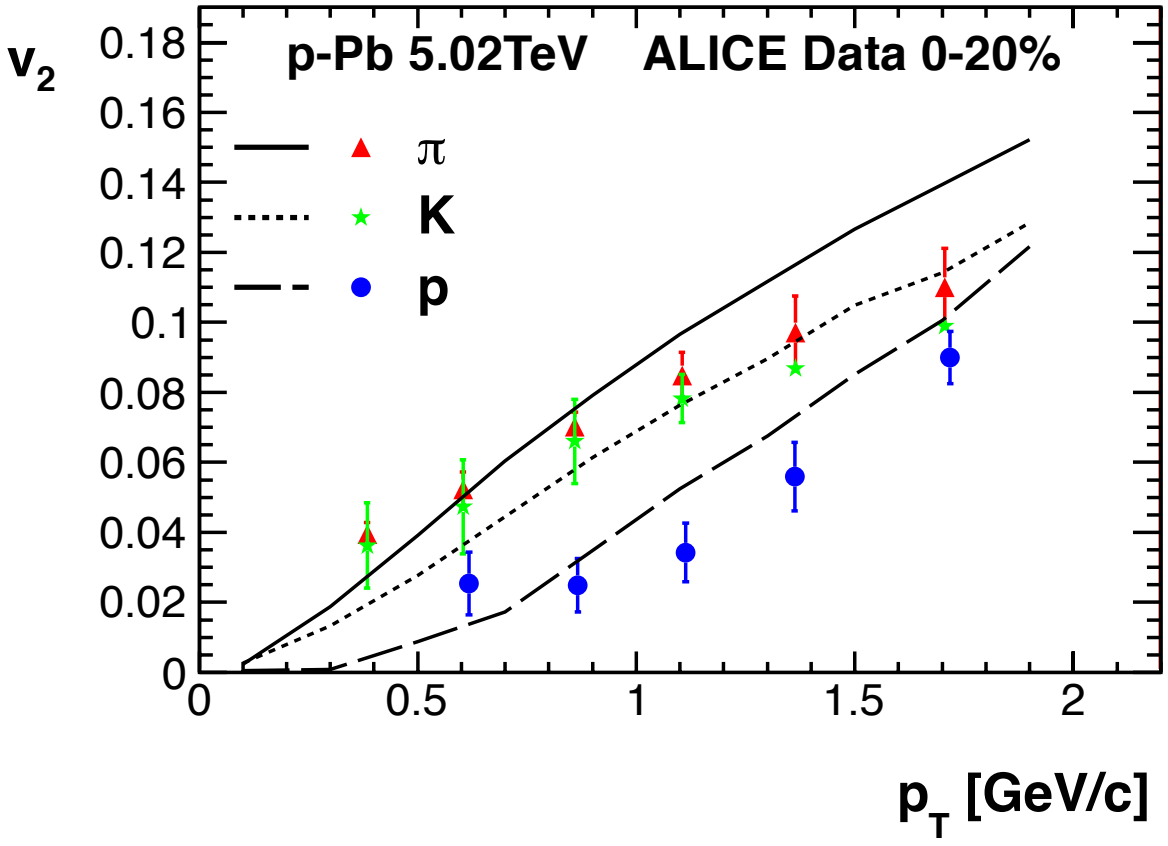
- What do we know about initial state?
- Can the initial condition for the hydrodynamics be determined?
- What is the smallest collision system that behaves collectively, if collectivity is so general?
- I am feeling lucky to be an experimentalist!

Backup

Backup


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
0.3 < p_T < 3.0 GeV/c; |η| < 2.4
$c_2\{6\}$
$-c_2\{8\}$
$c_2\{6\}$
$|c_2\{8\}|$
$N_{trk}^{offline}$
$N_{trk}^{offline}$

Backup



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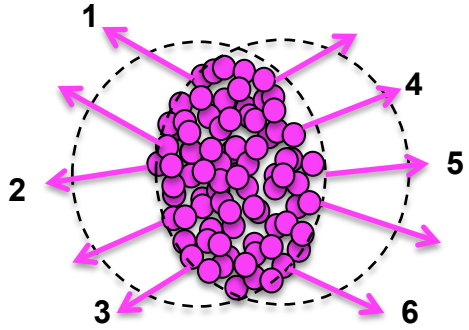
Multi-particle Cumulant

- 6-particle correlator, per event

$$\langle 6 \rangle \equiv \left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \right\rangle$$

$$\equiv \frac{1}{P_{M,6}} \sum_{\substack{i\neq j\neq k \\ \neq l\neq m\neq n}}^{M} e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}$$

Distinctive 6-particle combinations



- 6-particle cumulant, all events

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \bullet \langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle + 12 \bullet \langle\langle 2 \rangle\rangle^3$$

- Q-Cumulant: decompose ➔ flow vector $Q_n \equiv \sum_{i=1}^{M} w_i e^{in\varphi_i}$

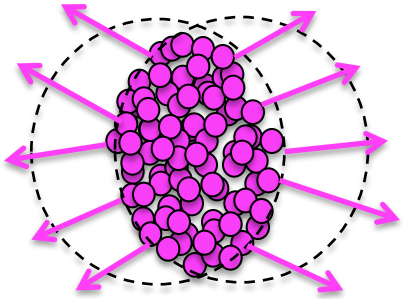
- Cumulant v_n ➔

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

Lee-Yang Zeros

- All-particle correlation, per event

$$g(ir) \equiv \prod_{j=1}^{M}\left[1 + i \cdot r \cdot w_j \cos\left(n(\phi_j - \theta)\right)\right]$$



- Generating function, all events

$$G(ir) = \left\langle g(ir) \right\rangle = \frac{1}{N_{evt}} \sum_{events} g(ir)$$

Decompose

Flow vector:

$$Q_n = (Q_{nx}, Q_{ny})$$

$$Q_{nx} = \sum_{j=1}^{M} w_j \cos(n\phi_j)$$

$$Q_{ny} = \sum_{j=1}^{M} w_j \sin(n\phi_j)$$

- Integrated v_n{LYZ}

$$V_2\{LYZ\} = \frac{j_{01}}{r_0}$$

j_{01}=2.40483
r_0 is the first zero of |G(ir)|