“Collective flow and two particle correlations at RHIC and LHC”

Phenomenology and Experiments at RHIC and LHC

Takahito Todoroki

University of Tsukuba

RIKEN Nishina Center

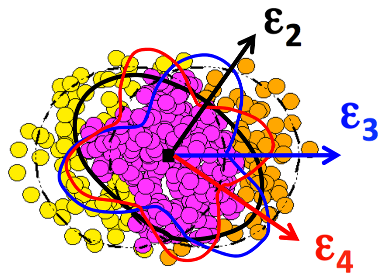
Collective flow

- ✧EP correlations
- ✧Event by event v_n
- ✧N_q scaling
- ✧ v_2 in geometry controlled collisions
- ✧Direct photon v_2
- ✧High p_T & jet v_2

Event plane correlations

Measured planes : Ψ_n

True planes : Φ_n



Desired correlator

Observed correlator

$$\langle \cos k(\Phi_n - \Phi_m)\rangle = \frac{\langle \cos k(\Psi_n - \Psi_m)\rangle}{\mathrm{Res}\{k\Psi_n\}\mathrm{Res}\{k\Psi_m\}}$$

arXiv: 1105.3928
PHENIX but no corrections for reso.

Resolution for individual planes

$$\mathrm{Res}\{k\Psi_n\} = \langle \cos(k\Psi_n - k\Phi_n)\rangle$$

- Can generalize into multi-plane correlations

Variable: $c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l$ satisfying: $c_1 + 2c_2 ... + lc_l = 0$

arXiv:1104.4740, Bhalerao, Luzum, Ollitrault

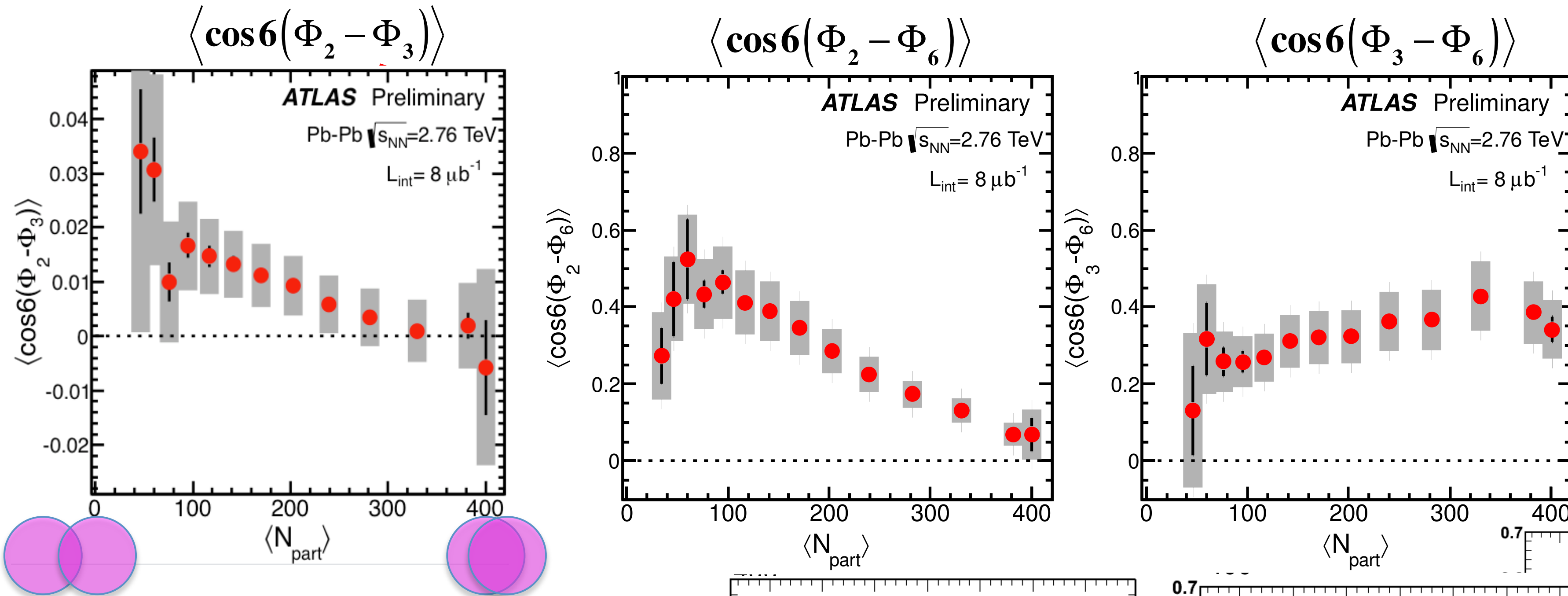
$$\langle \cos(c_1\Phi_1 + ... + lc_l\Phi_l)\rangle = \frac{\langle \cos(c_1\Psi_1 + ... + lc_l\Psi_l)\rangle}{\mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}}$$

$$\mathrm{Res}\{c_n n\Psi_n\} = \langle \cos c_n n(\Psi_n - \Phi_n)\rangle$$

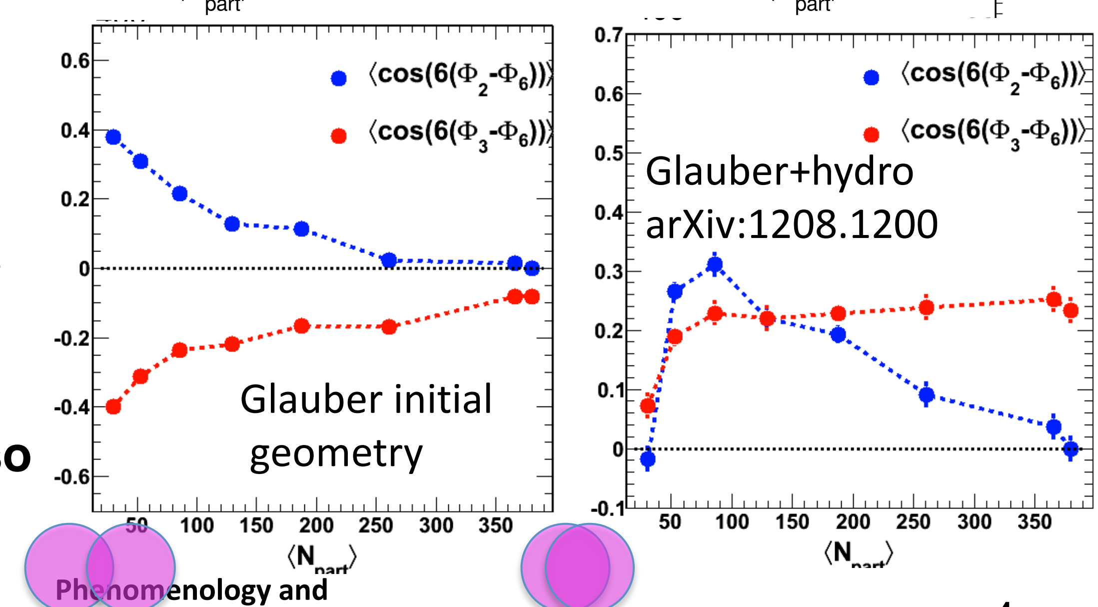
arXiv:1203.5095
1205.3585

$$\mathrm{Res}\{(c_1\Psi_1 + ... + lc_l\Psi_l)\} = \mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}$$

Two plane correlations

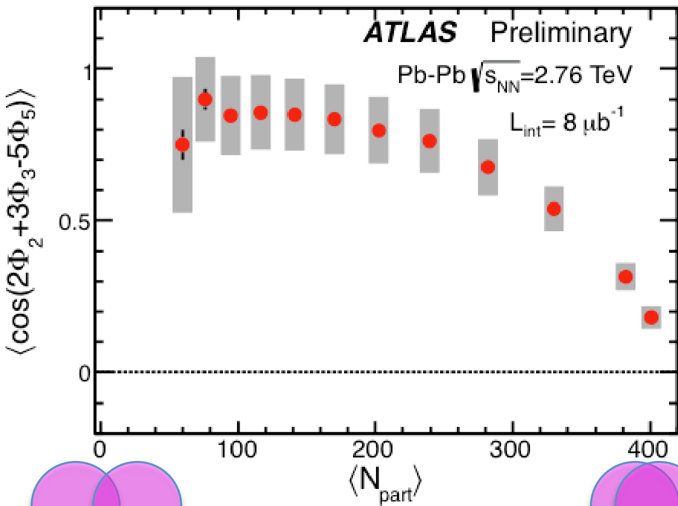


- ✧ $\Phi_{2,3}$ weakly correlated both strongly correlated with Φ_6
- • Alignment between Φ_{23} & Φ_6
- ✧ Hydro. expansion qualitatively reproduce EP cor.
- • Parameters in hydro. would also take main role in EP cor.

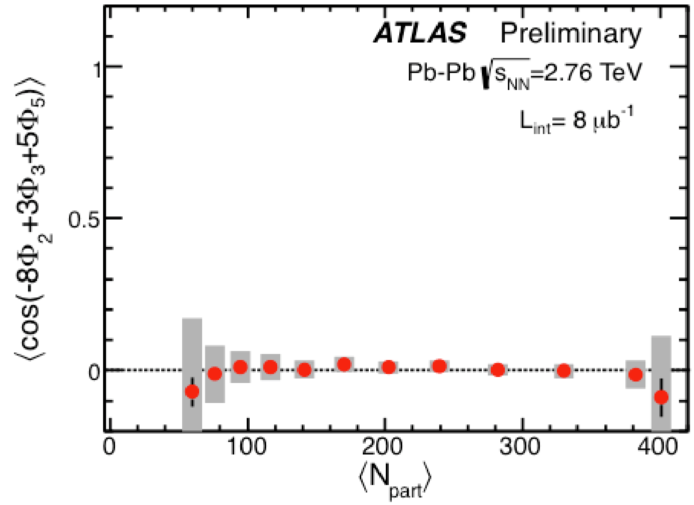


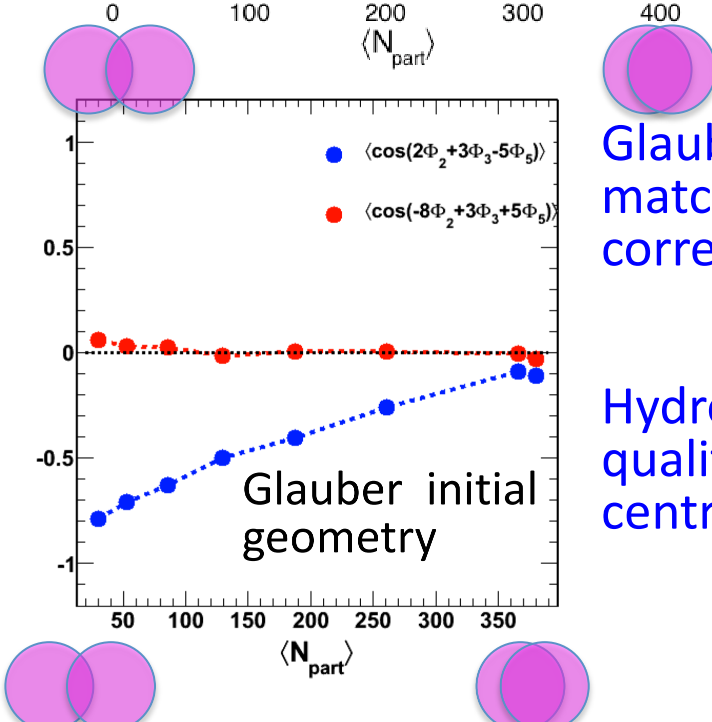
Three plane correlations

$$\left\langle \cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi_5\right)\right\rangle$$



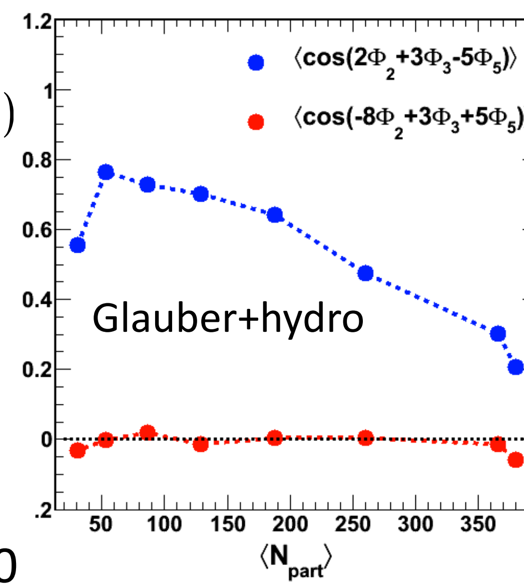
$$\left\langle \cos\left(-8\Phi_2 + 3\Phi_3 + 5\Phi_5\right)\right\rangle$$





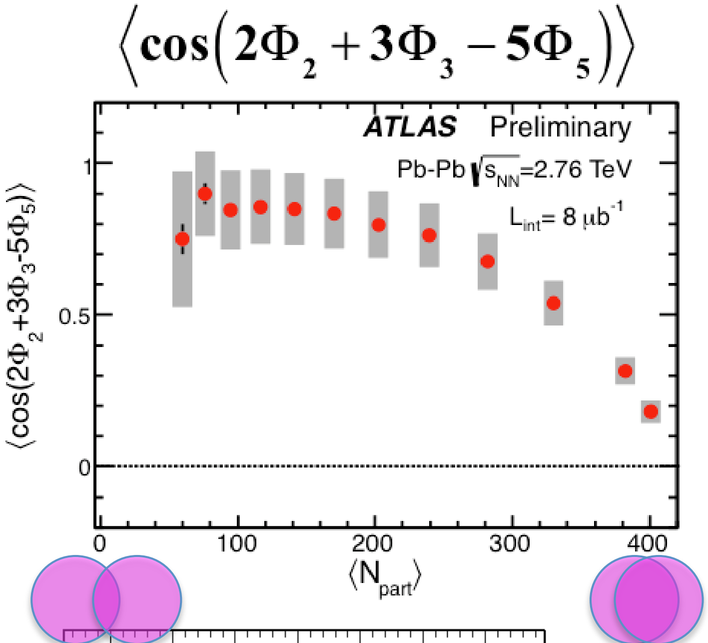
Glauber geometry does not match the $\cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi5)\right)$ correlation

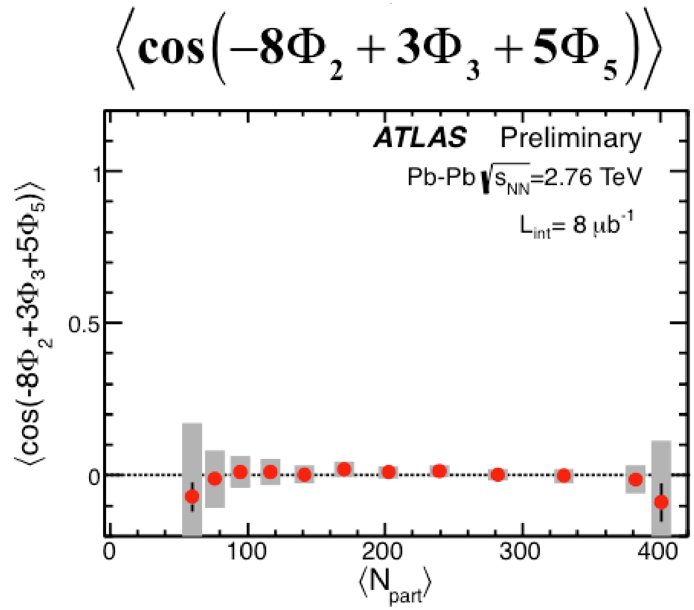
Hydro evolution qualitatively reproduces the centrality dependence



Glauber+hydro
arXiv:1208.1200

Three plane correlations





Glauber geometry does not

$$2\Phi_2 + 3\Phi_3 - 5\Phi_5 = 3(\Phi_3 - \Phi_2) - 5(\Phi_5 - \Phi_2)$$

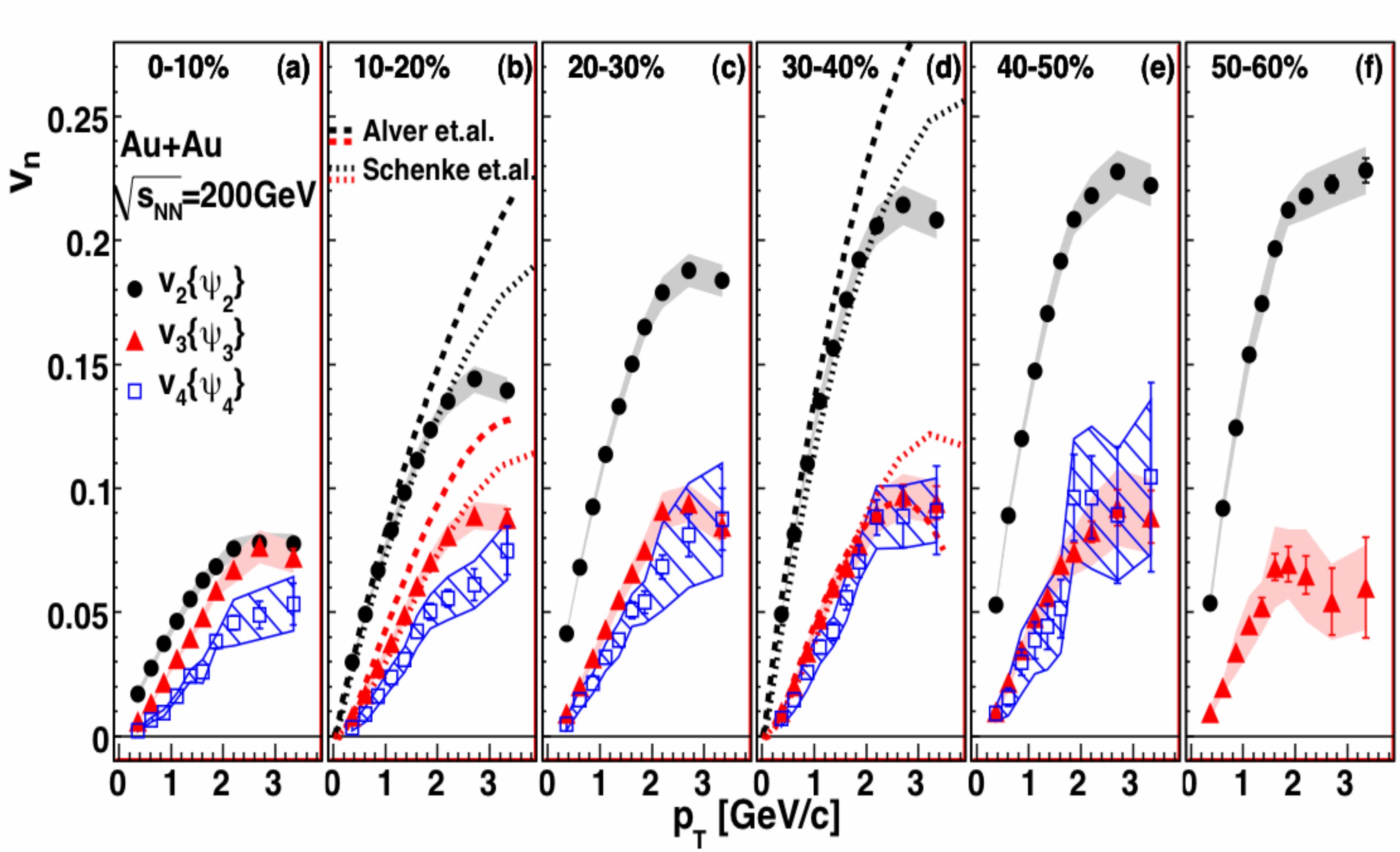
$$-8\Phi_2 + 3\Phi_3 + 5\Phi_5 = 3(\Phi_3 - \Phi_2) + 5(\Phi_5 - \Phi_2)$$

$$\langle \sin 3(\Phi_3 - \Phi_2) \sin 5(\Phi_5 - \Phi_2) \rangle = \frac{1}{2}(\langle \cos 2\Phi_2 + 3\Phi_3 - 5\Phi_5 \rangle) - \langle \cos -8\Phi_2 + 3\Phi_3 + 5\Phi_5 \rangle)$$

$$\langle \cos 3(\Phi_3 - \Phi_2) \cos 5(\Phi_5 - \Phi_2) \rangle = \frac{1}{2}(\langle \cos 2\Phi_2 + 3\Phi_3 - 5\Phi_5 \rangle) + \langle \cos -8\Phi_2 + 3\Phi_3 + 5\Phi_5 \rangle)$$

arXiv:1208.1200

p_T differential v_n at RHIC



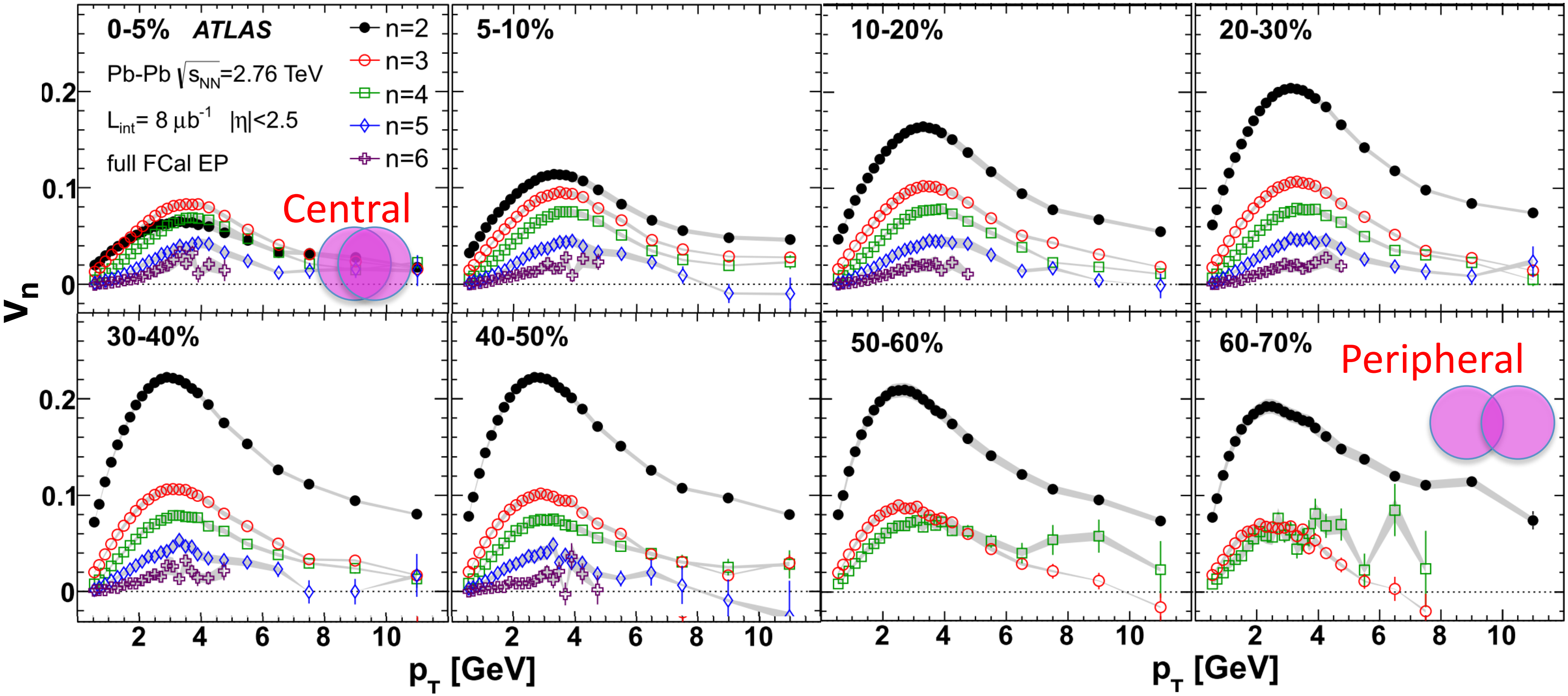
PRL.107.252301

Charged hadron v_n : $|\eta|<0.35$
Event plane Φ_n : $|\eta|$=1.0~2.8

- ✧ v_3 & v_4 comparable to v_2 in most central
- ✧ Stronger centrality dependence of v_2

p_T differential v_n at LHC

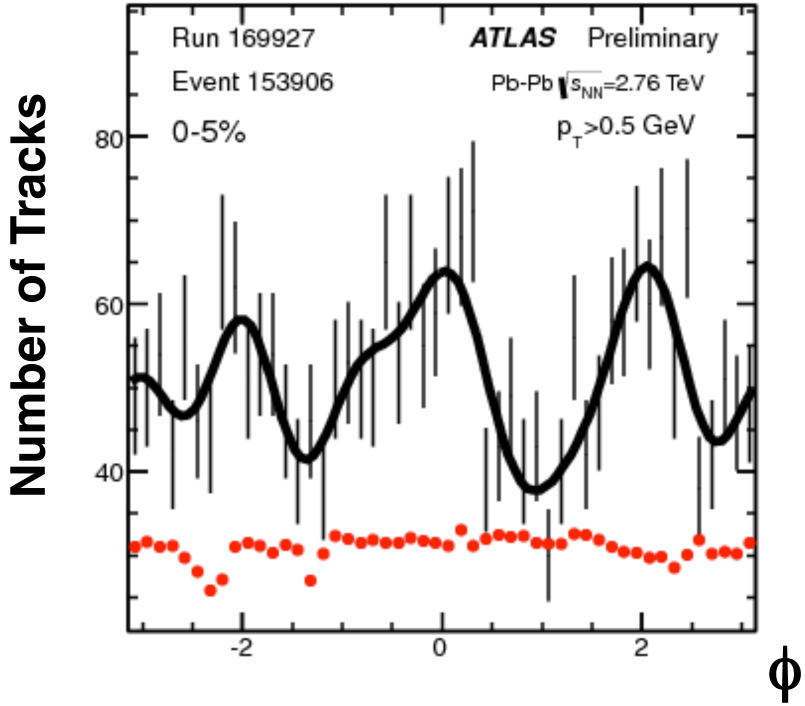
ATLAS, Phys. Rev. C 86, 014907 (2012)



- Significant v_n up to n=6
- In most central collisions(0-5%): v_3 & $v_4 > v_2$
- Stronger centrality dependence of v_2

Event-by-Event v_n

Singles



- Event by Event single particle distributions

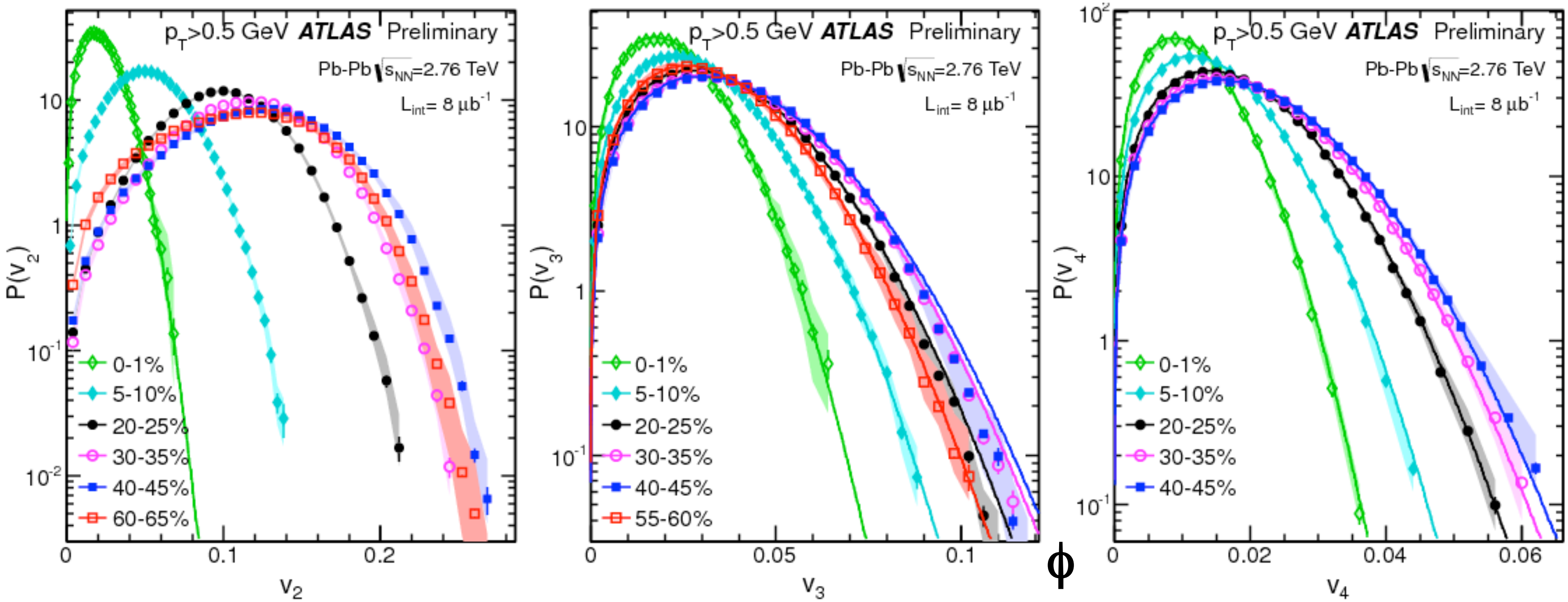
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\mathrm{obs}} \cos n(\phi - \Psi_n^{\mathrm{obs}}) = 1 + 2\sum_{n=1}^{\infty}\left(v_{n,\mathrm{x}}^{\mathrm{obs}} \cos n\phi + v_{n,\mathrm{y}}^{\mathrm{obs}} \sin n\phi\right)$$

- Obtaining amplitude, Correction & unfolding on statistics

$$\vec{v}_n^{\,\mathrm{obs}} = (v_{n,\mathrm{x}}^{\mathrm{obs}}, v_{n,\mathrm{y}}^{\mathrm{obs}})$$

- Provides constraints to model calculations

Event-by-Event v_n



ϕ

✧ **Event by Event single particle distributions**

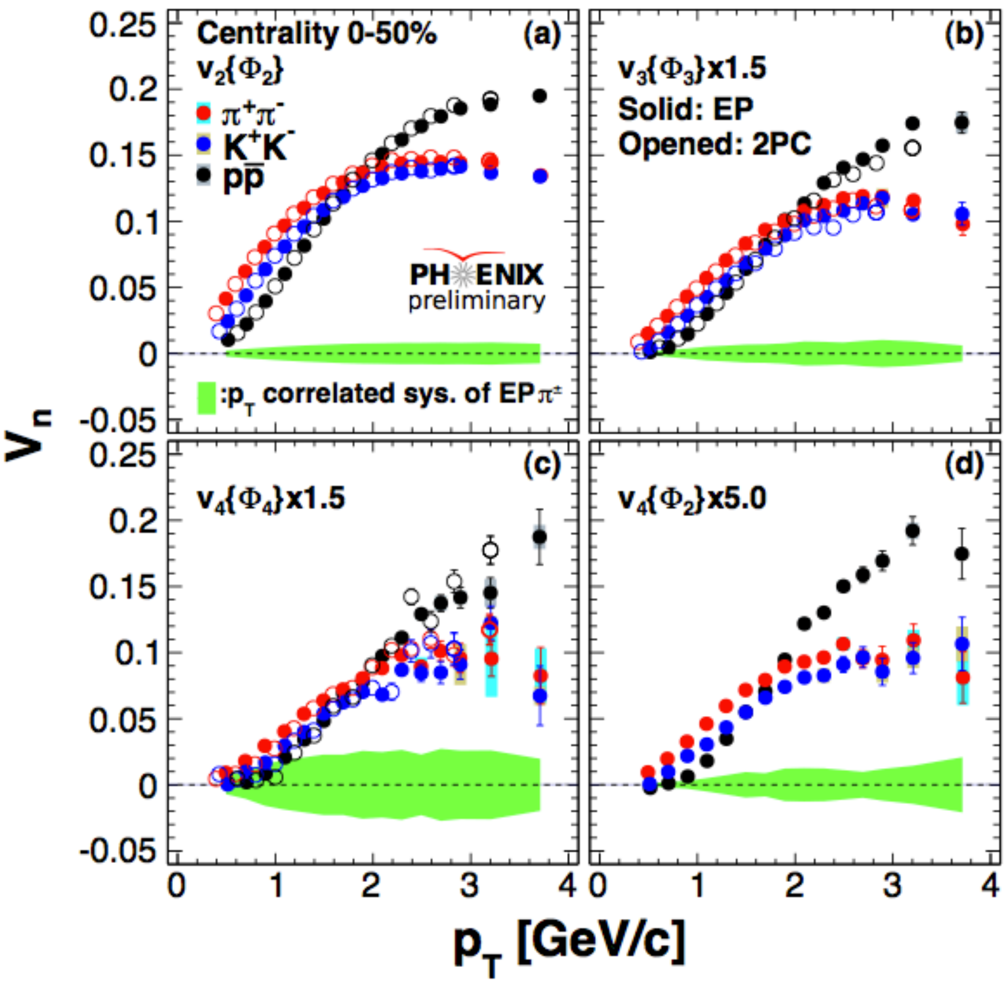
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\mathrm{obs}} \cos n(\phi - \Psi_n^{\mathrm{obs}}) = 1 + 2\sum_{n=1}^{\infty}\left(v_{n,\mathrm{x}}^{\mathrm{obs}} \cos n\phi + v_{n,\mathrm{y}}^{\mathrm{obs}} \sin n\phi\right)$$

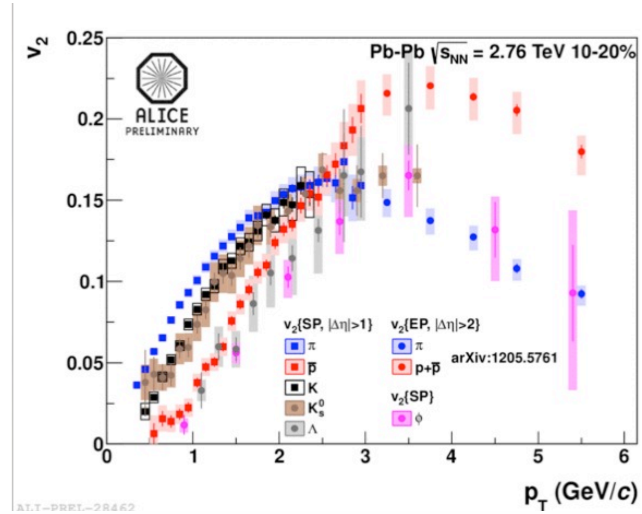
✧ **Obtaining amplitude, Correction & unfolding on statistics**

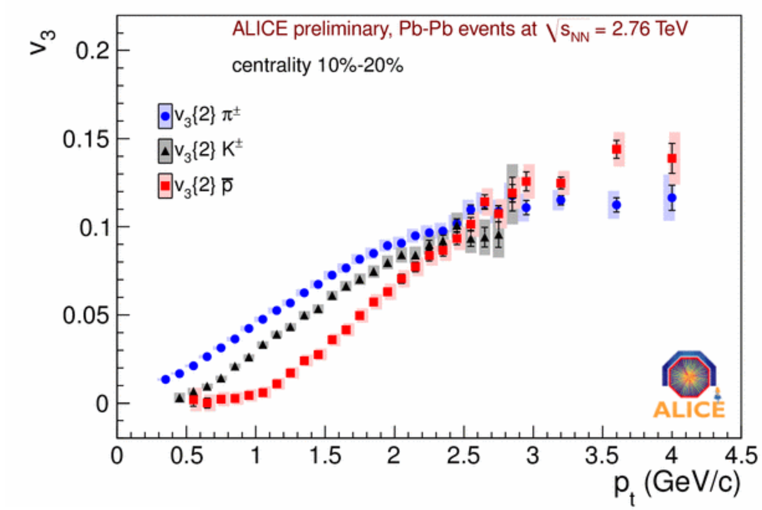
$$\vec{v}_n^{\,\mathrm{obs}} = (v_{n,\mathrm{x}}^{\mathrm{obs}}, v_{n,\mathrm{y}}^{\mathrm{obs}})$$

✧ **Provides constraints to model calculations**

Identified particle v_n



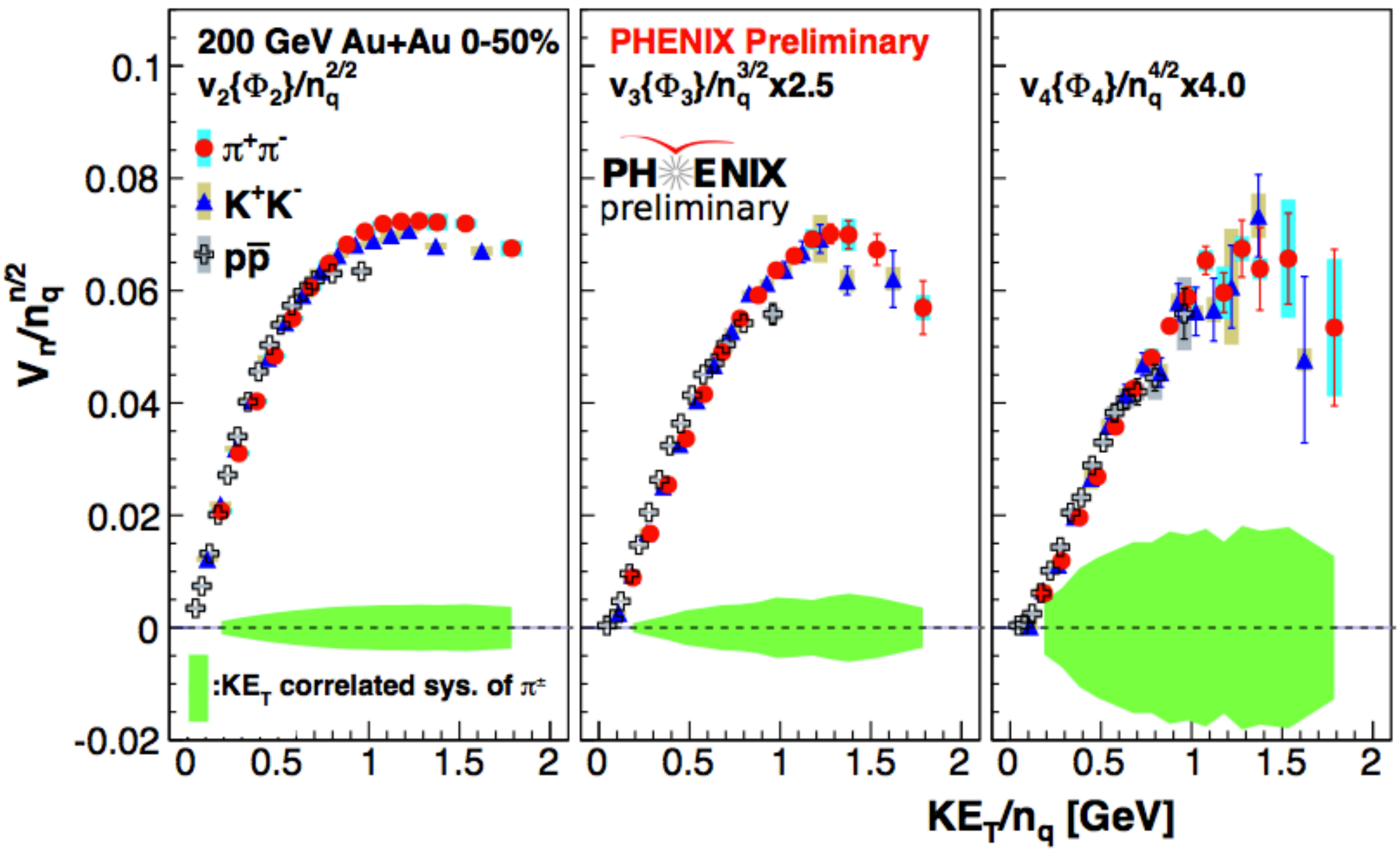




✧ **Mass ordering at low p_T**

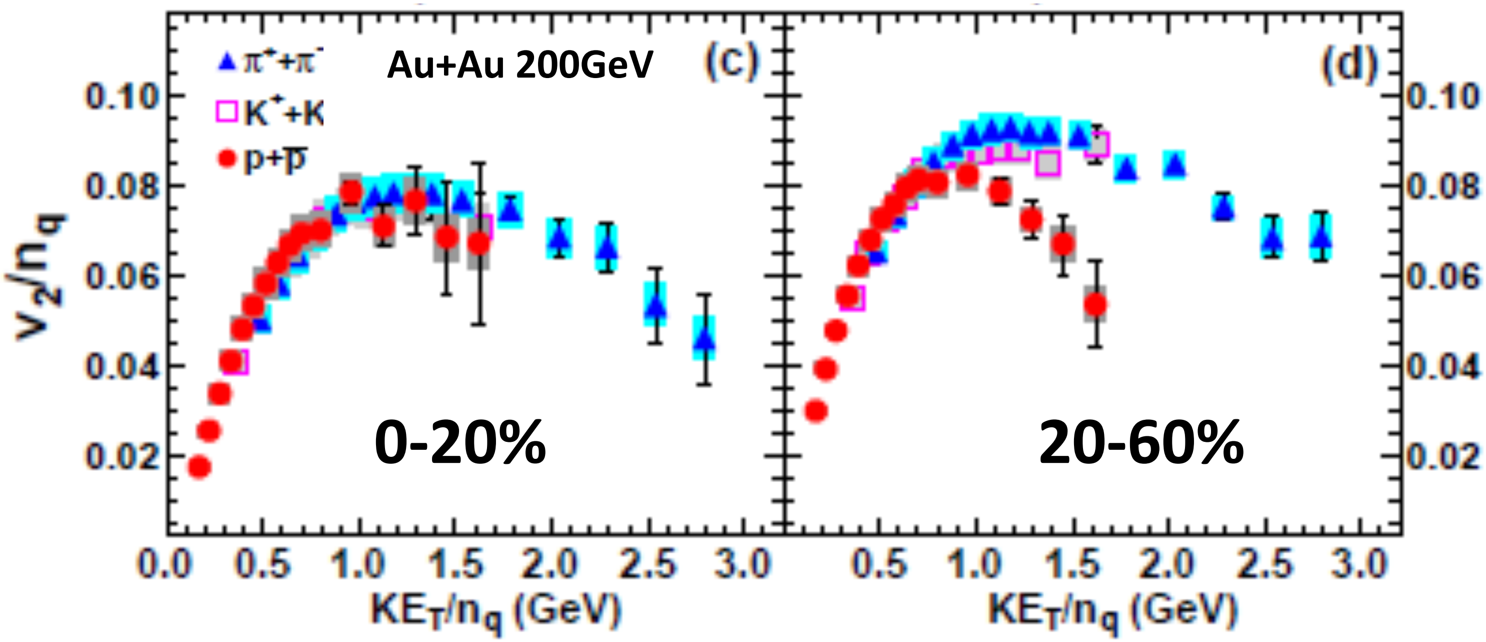
✧ **Coalescence at intermediate p_T**

N_q scaling of vn



✧ N_q scaling up to KE_T/n_q = 0.7 GeV for v_2, v_3, and v_4

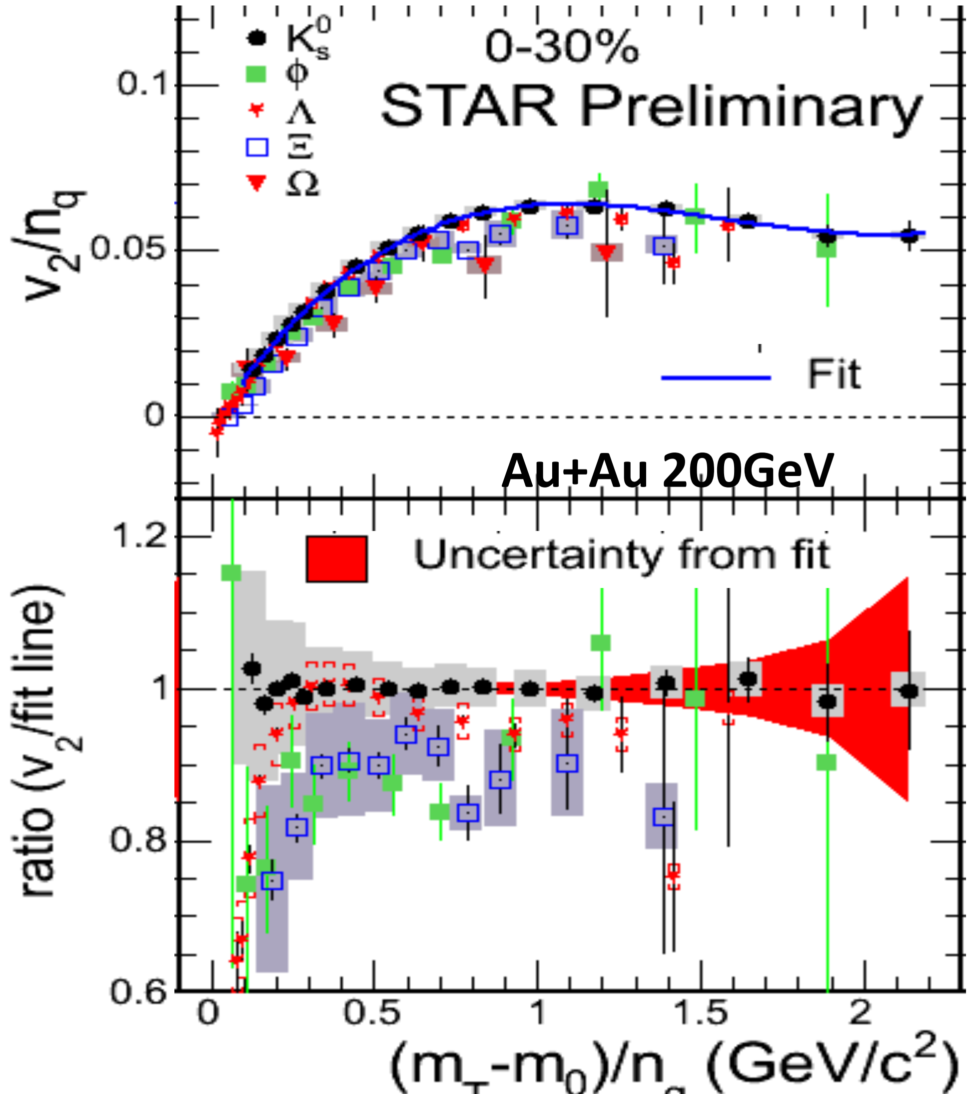
Break of N_q scaling of v_2 at high p_T



PHENIX [PRC 85, 064914 (2012)]

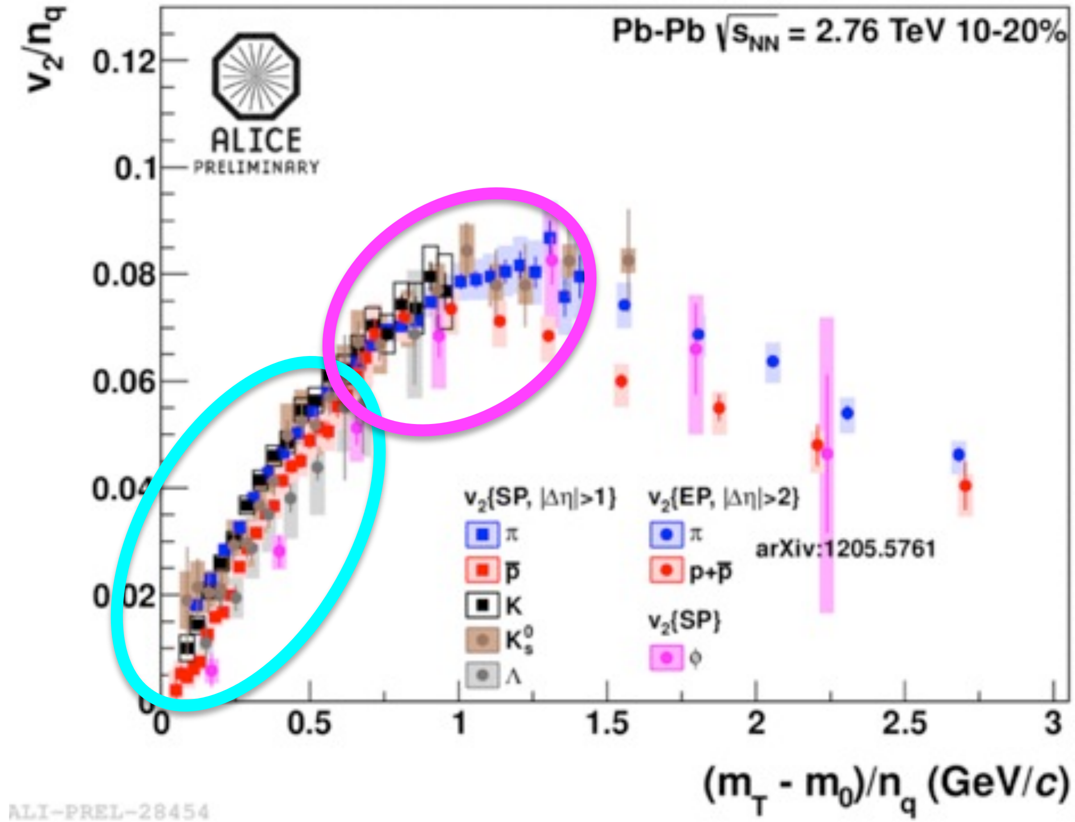
- ✧ **In the 0-20%, scaling is still roughly kept.**
- ✧ **In 20-60% n_q scaling is broken at $KE_T > 0.7$ GeV.**
- ✧ **Different mechanisms for pion and proton production at intermediate p_T for different centralities**

N_q scaling of strange hadron v_2



- ✧ K^0_S follows scaling curve of π, K, & P
- ✧ Multi-strangeness hadrons deviate from K^0_S

N_q scaling of v_2 at LHC

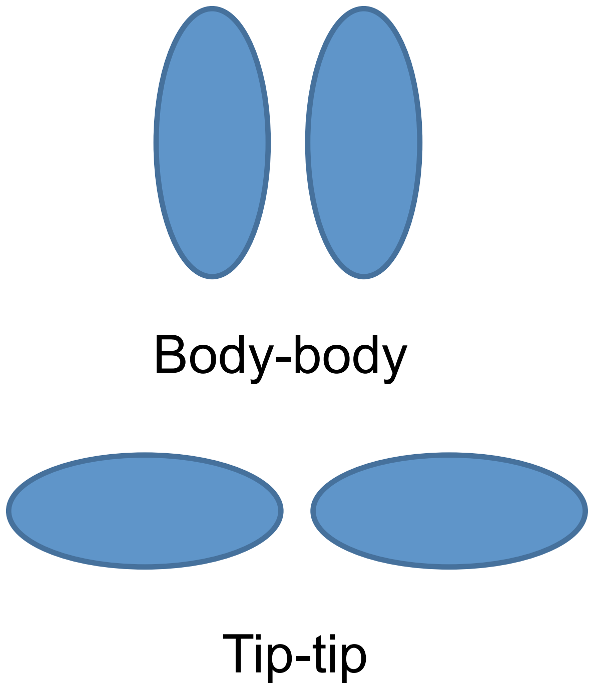


- ✧ P, Λ, ϕ deviate from pi, K at low p_T
  - Might be due to stronger radial flow at LHC than RHIC
  - Realistic parameter describes radial flow effects to hadrons
- ✧ N_q scaling survives at intermediate p_T

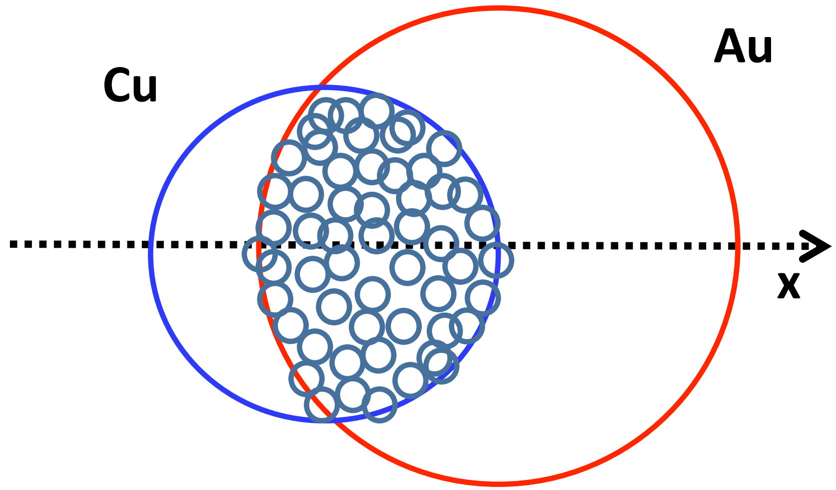
Geometry controlled collision systems

4A, Huang

U+U collisions



Cu+Au collisions

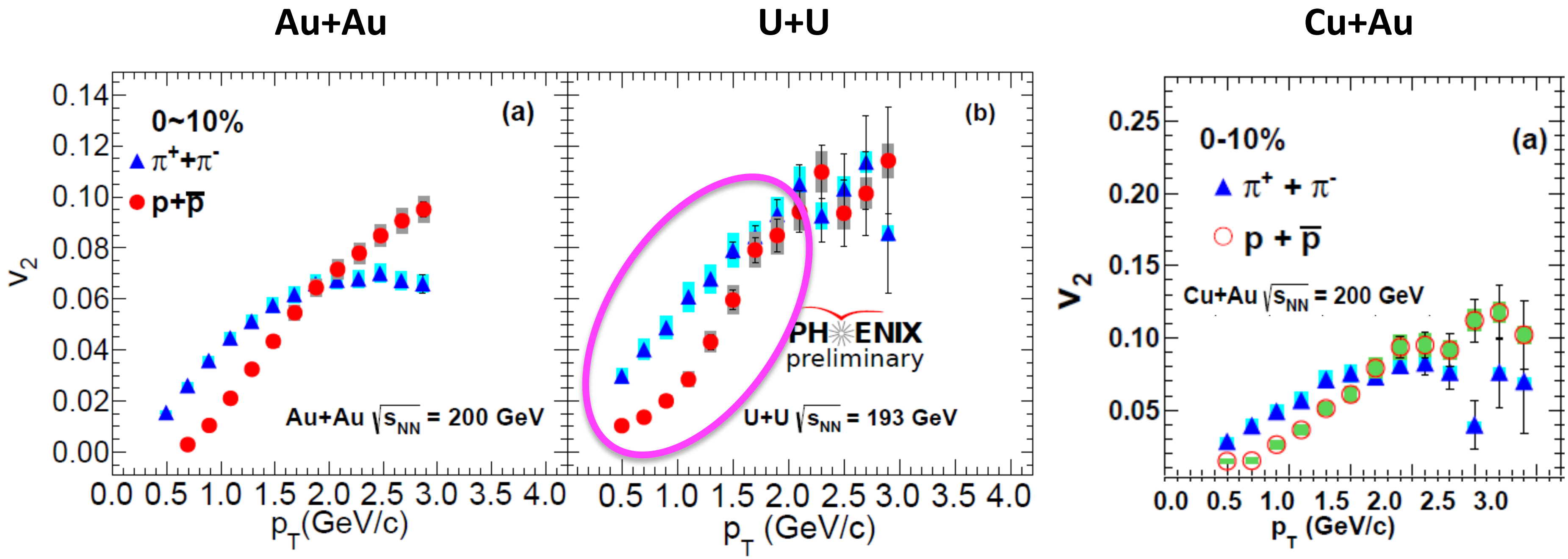


✧ **Various collision geometry**

✧ **The geometry separation in progress**

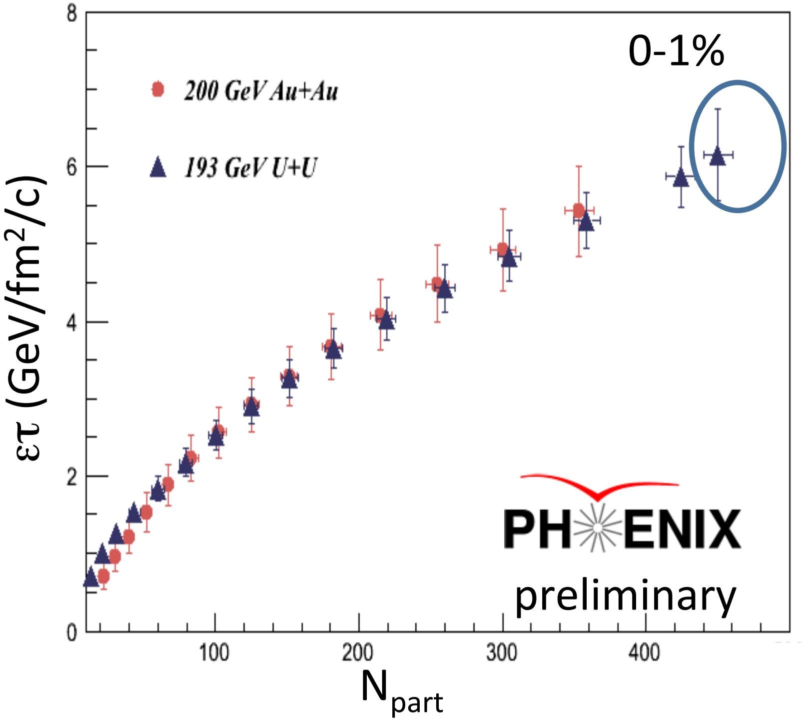
- **This time only centrality is selected**

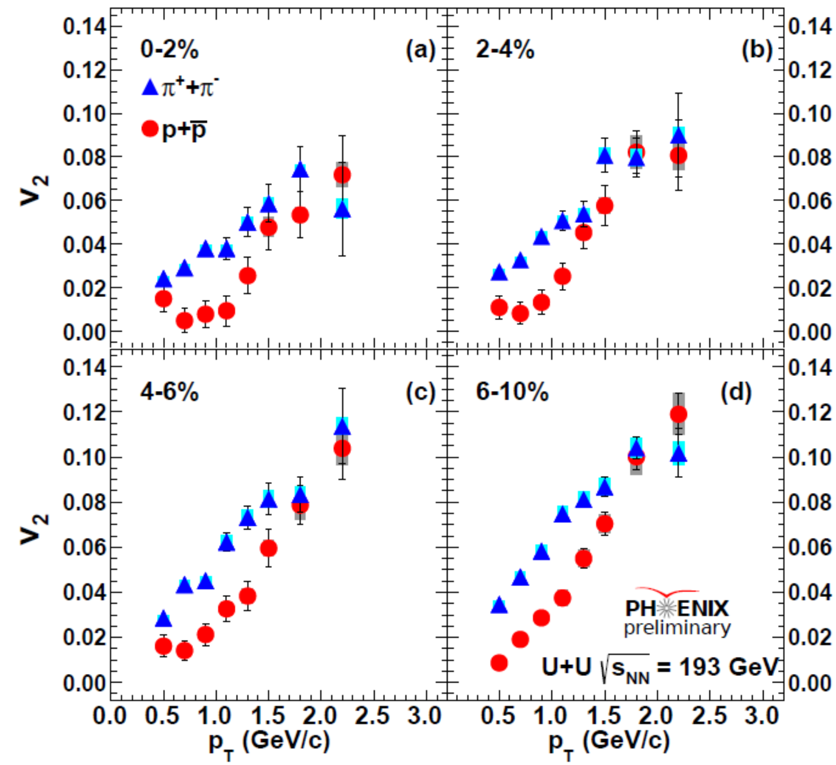
Stronger mass ordering in central U+U collisions



✧ **Not seen in other centrality and collision systems**

π & p v_2 in 0-6% central U + U collision

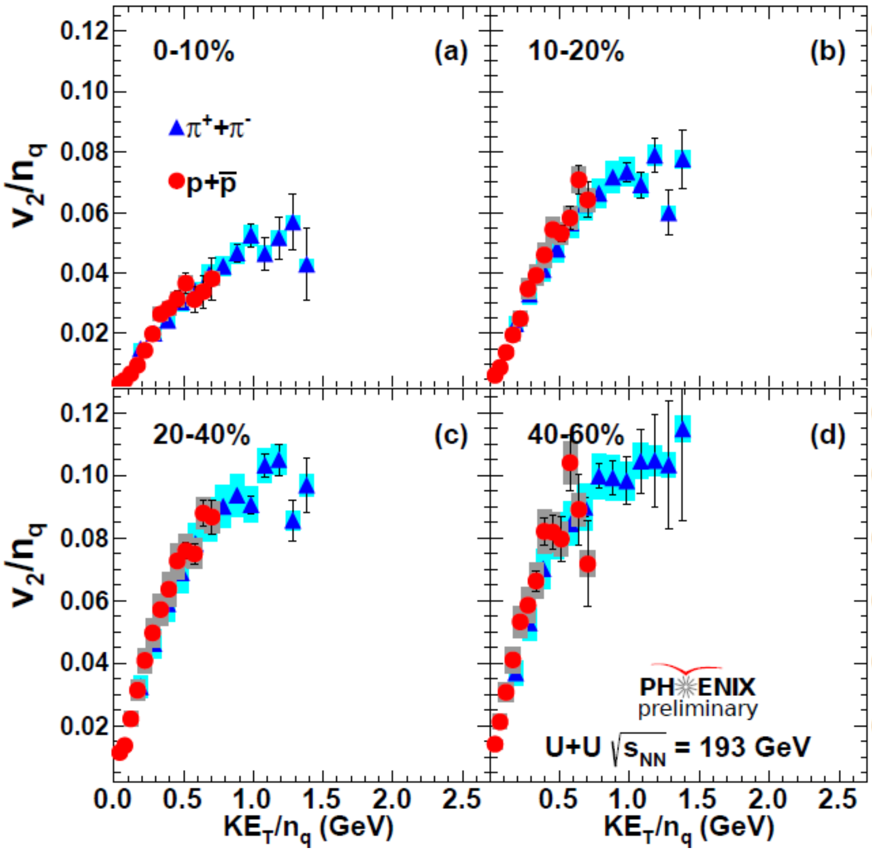




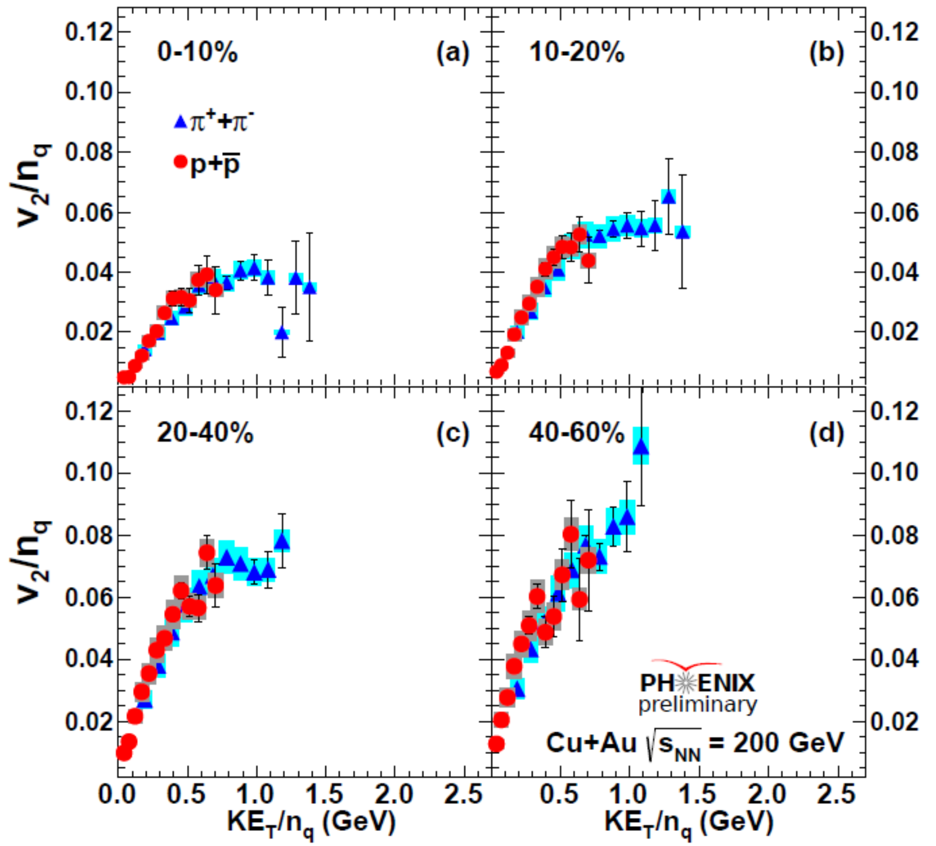
- ✧ **From 0-10% Au+Au to 0-1% U+U collisions**
  - ✧ **ετ increase about 20%**
- ✧ **Strong mass ordering in 0-6% centrality despite of relatively small increase of ετ.**
- ✧ **Radial flow or collision geometry?**

N_q scaling in U+U and Cu+Au collisions

U+U

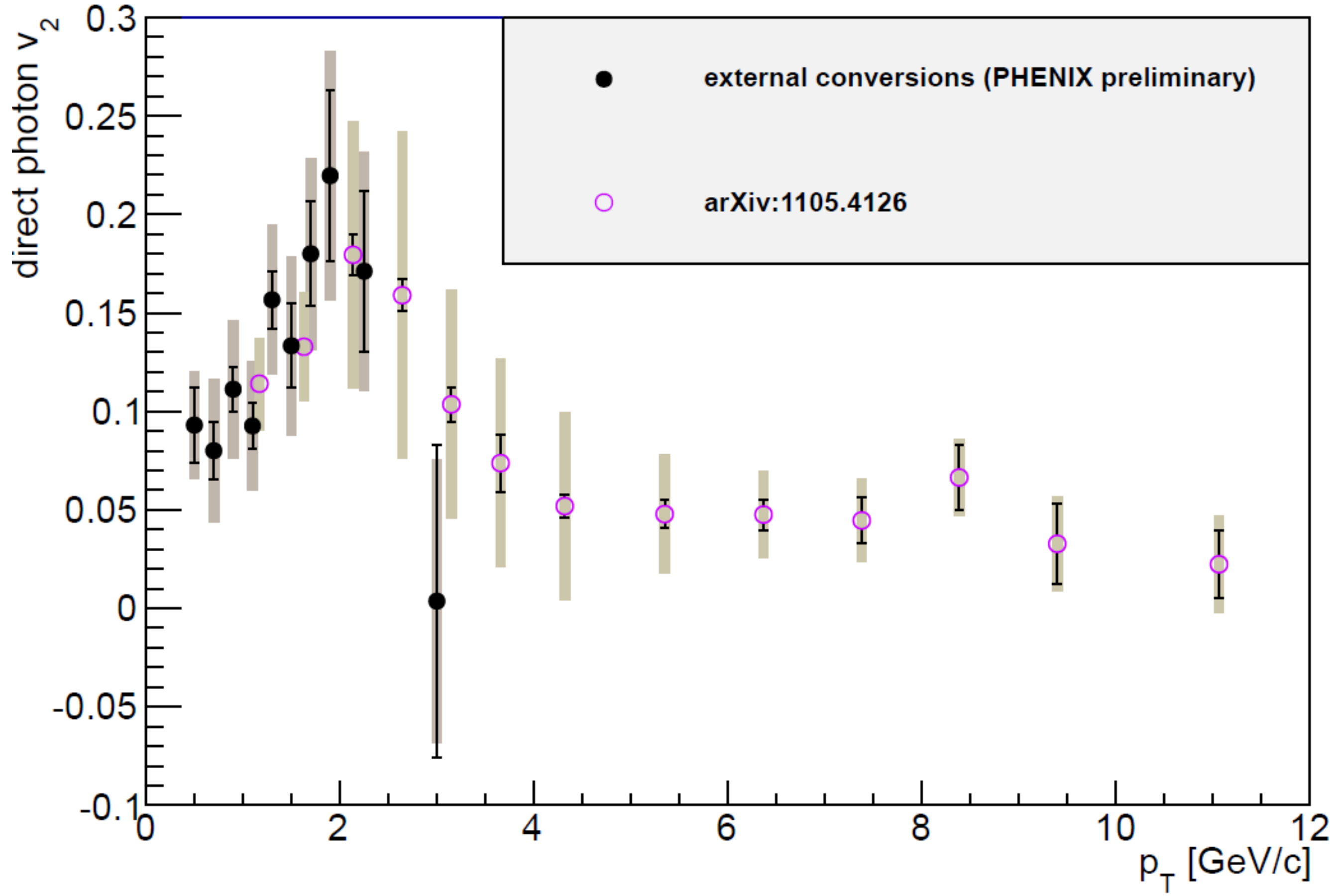


Cu+Au



✧ **N_q scaling works for U+U and Cu+Au for π , P**

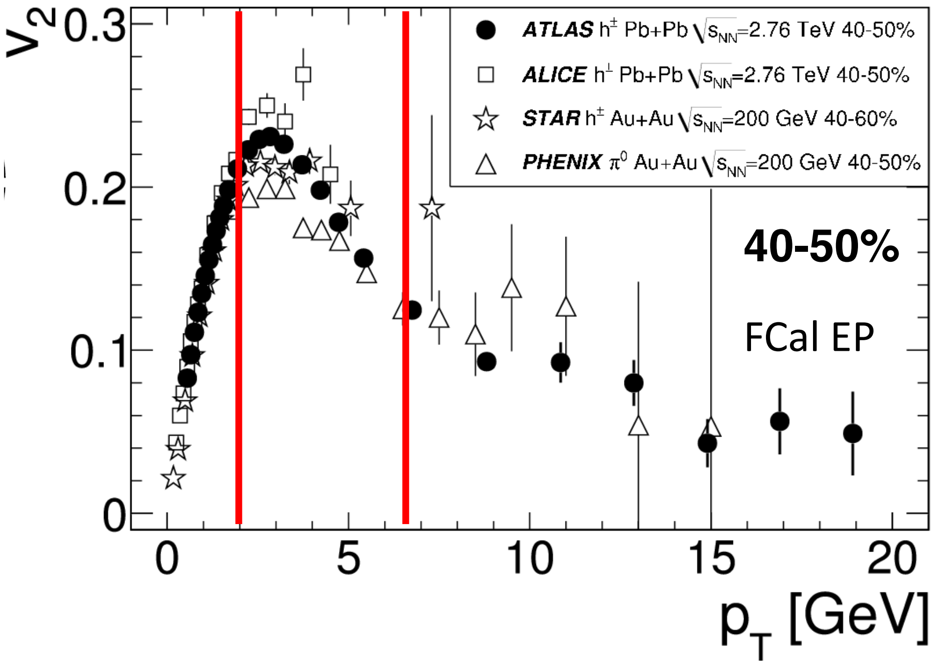
Direct Photon v_2

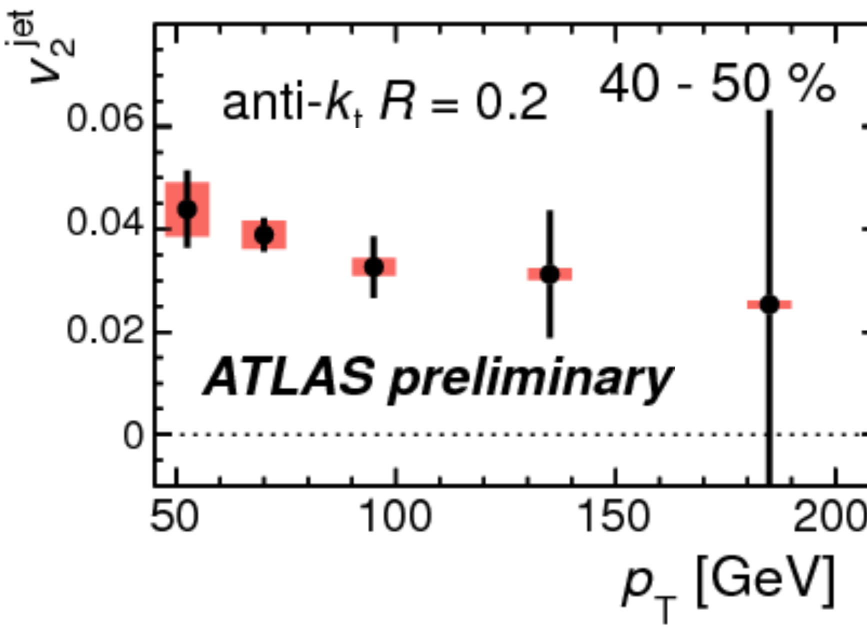


- ✧ v_2 down to 0.5 GeV via external conversion di-electron pairs
- ✧ Consistency check with previous measurements via photon
- ✧ Agreement up to 2 GeV, None-zero v_2 is conclusive

High p_T single hadron and jet v_2

Low p_T: hydro expansion | **Medium p_T:** coalescence | **High p_T:** jet quenching



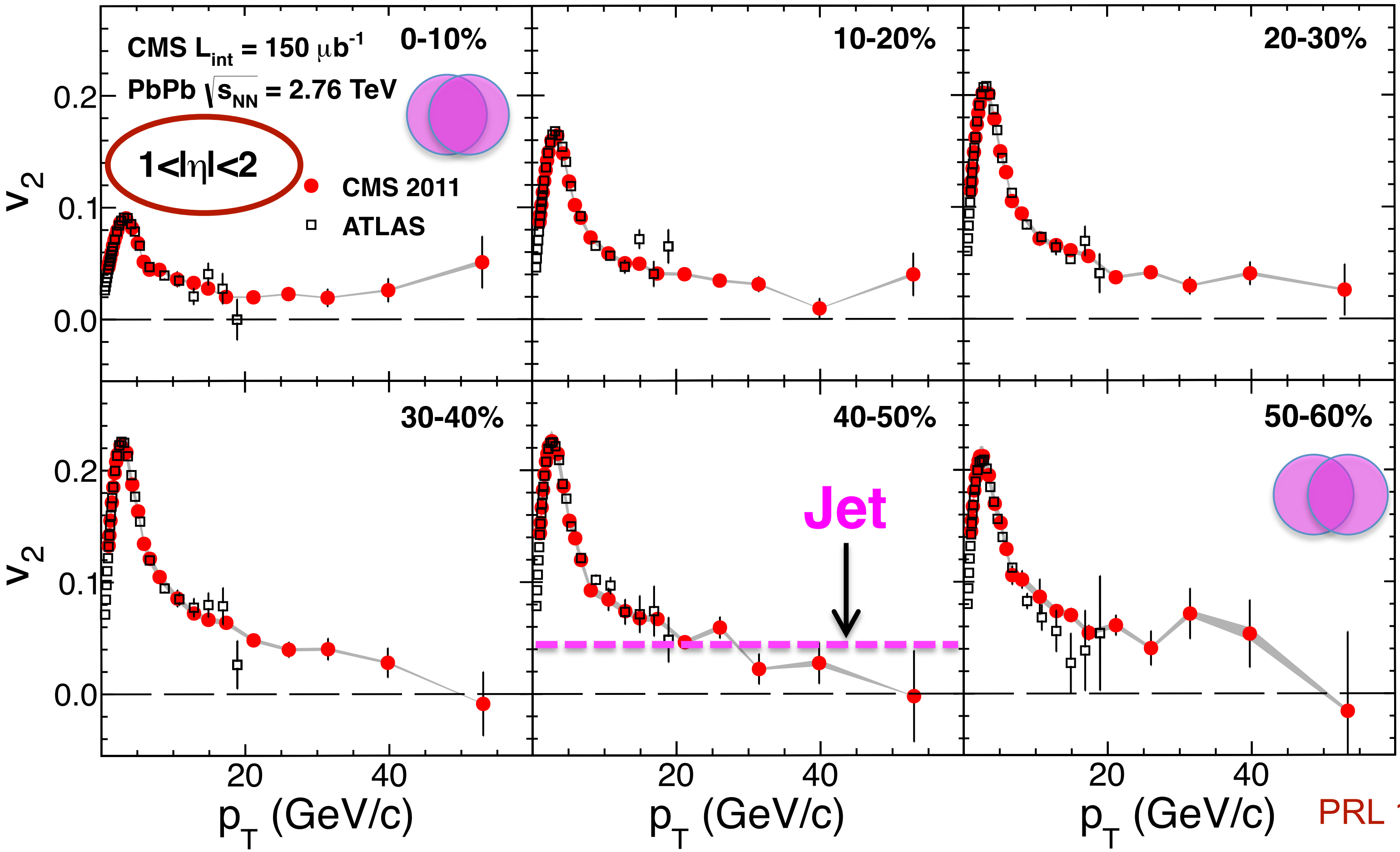


✧ **None-zero v2 of single hadrons at high p_T**

✧ **Jet v2 is qualitatively consistent with hadron v_2**

- **Path length dependence of parton energy loss**

Very high p_T v_2 via 2PC

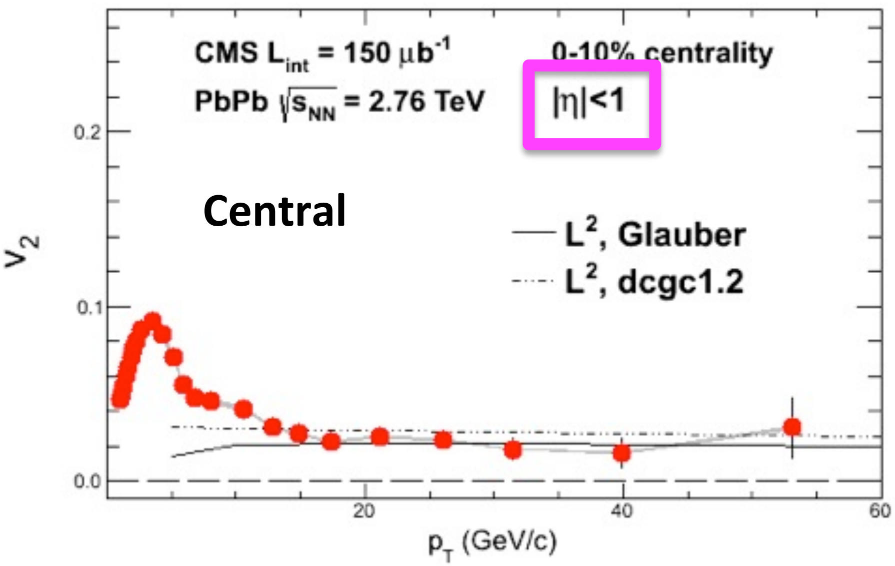


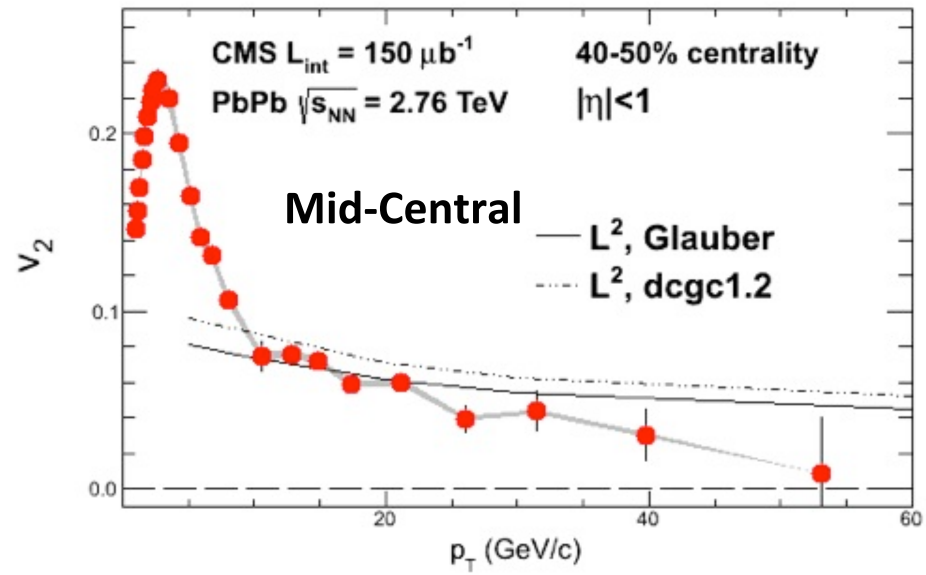
PRL 109, 022301(2012)

- ✧ None zero v_2 up to p_T 40 GeV/c
- ✧ Comparable to jet v_2 above 20 GeV/c

Theory Comparison

Data: PRL 109.022301(2012)





Theory: B.Betz,M.Gyulassy;arXiv:1201.0281

-Data can constrain different theoretical scenarios

✧ **RHIC data supports *L³* dependence**

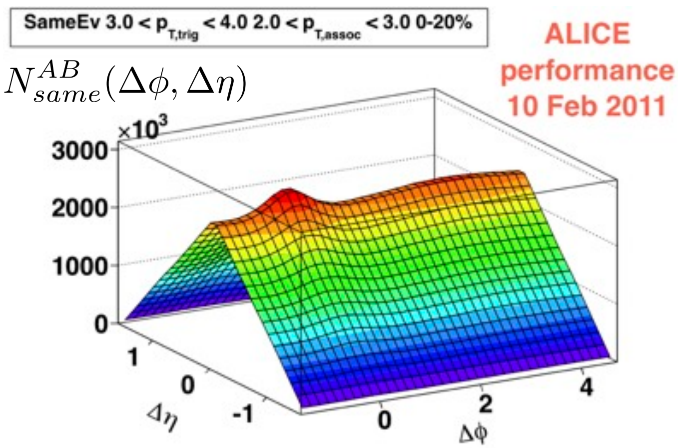
Two-particle correlations

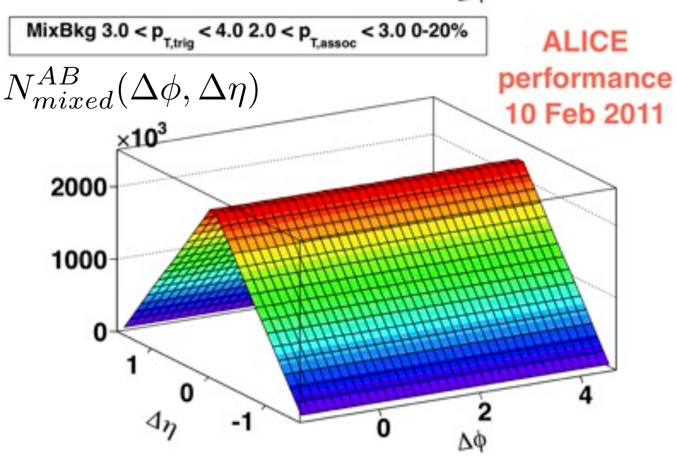
- ✧Correlations with v_n background subtractions
- ✧Correlations with respect to Ψ_2 & Ψ_3

Two-particle correlations

Pair distributions in real & mixed events

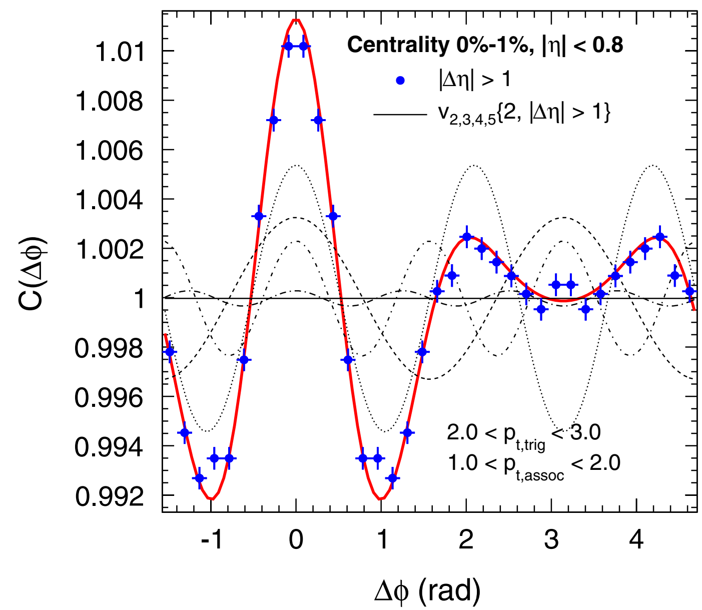
$$\Delta\phi = \phi^a - \phi^t, \Delta\eta = \eta^a - \eta^t$$





Correlation functions

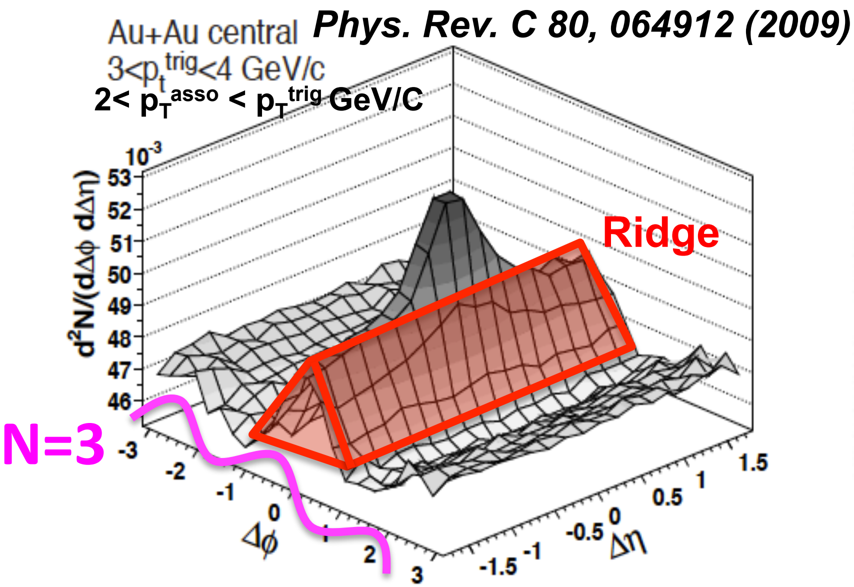
$$C(\Delta\phi) \equiv \frac{N_{mixed}}{N_{real}} \cdot \frac{N_{real}/d\Delta\phi}{N_{mixed}/d\Delta\phi}$$

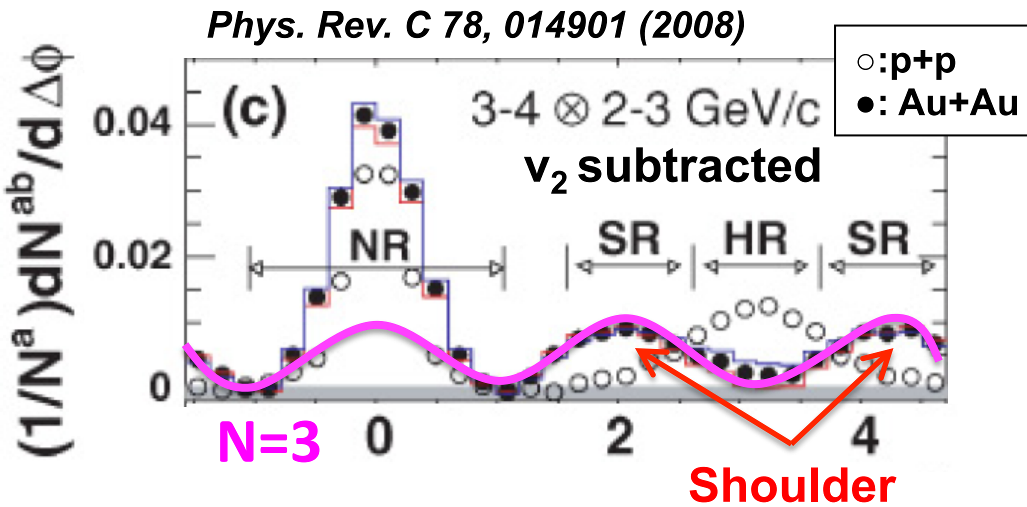


Flow backgrounds in correlations

$$F(\Delta\phi) = b_0 \left[1 + \sum_{n=1} 2 v_n^t v_n^a \cos(n\Delta\phi) \right]$$

Motivations





✧ **Dissect interplay of hard-scattered partons and medium**

✧ **Definitive answer what remains after v_n subtractions**

- **Whether Ridge and shoulder survives?**

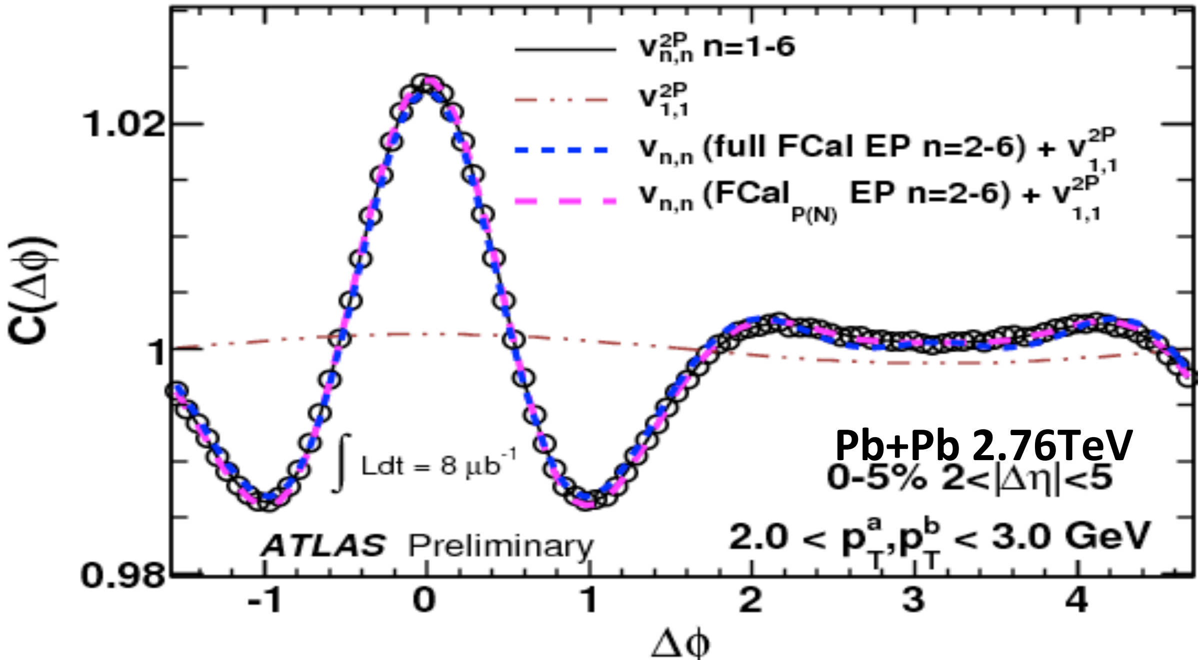
✧ **Test path length dependence of parton energy loss**

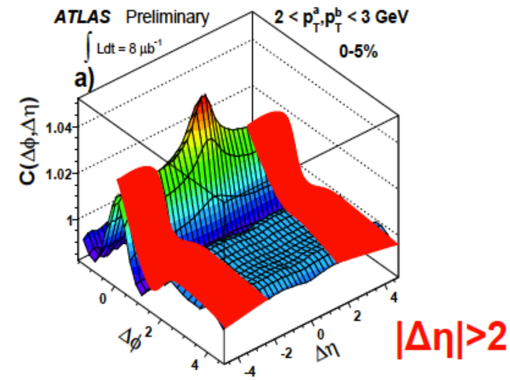
- **Correlations with respect to event planes**

Correlations with large $\Delta\eta$ gap

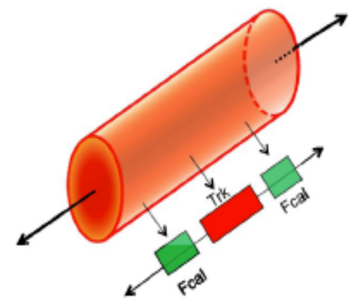
$$C(\Delta\phi) = b^{2P}\left(1 + 2v_{1,1}^{2P}\cos\Delta\phi + 2\sum_{n=2}^{6} v_n^{EP} v_n^{EP}\cos n\Delta\phi\right)$$

From 2PC method   From EP method





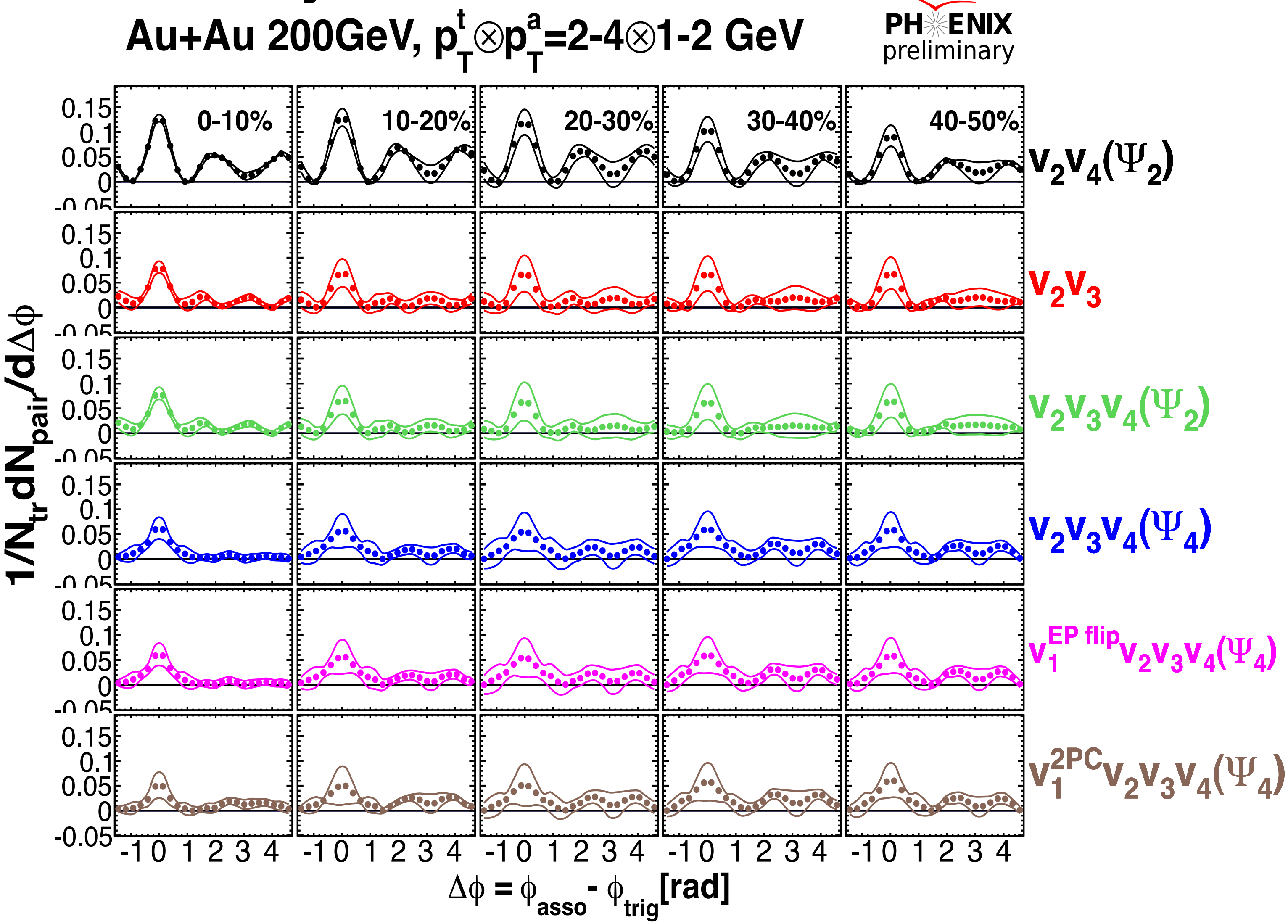
v_n with EP Method



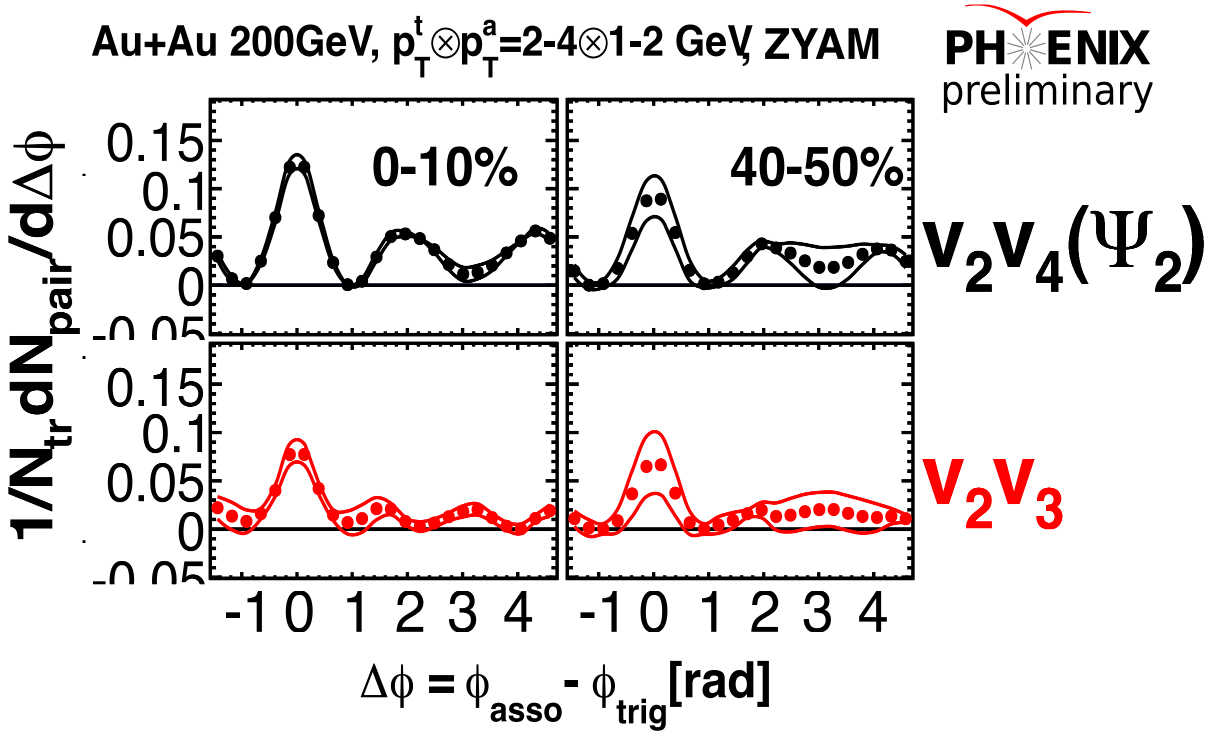
Track at |η|<2.5 with EP from full FCAL 3.3<|η|<4.8

- ✧ Ridge & Shoulder well reproduced at 0-5%
- ✧ Caveat! Correlation and v_n have similar long rapidity gap, very similar information!
- ✧ Consider correlations small rapidity gap where jet contribution survives

Correlations with small Δη gap in wide centrality with various v_n background subtractions by ZYAM



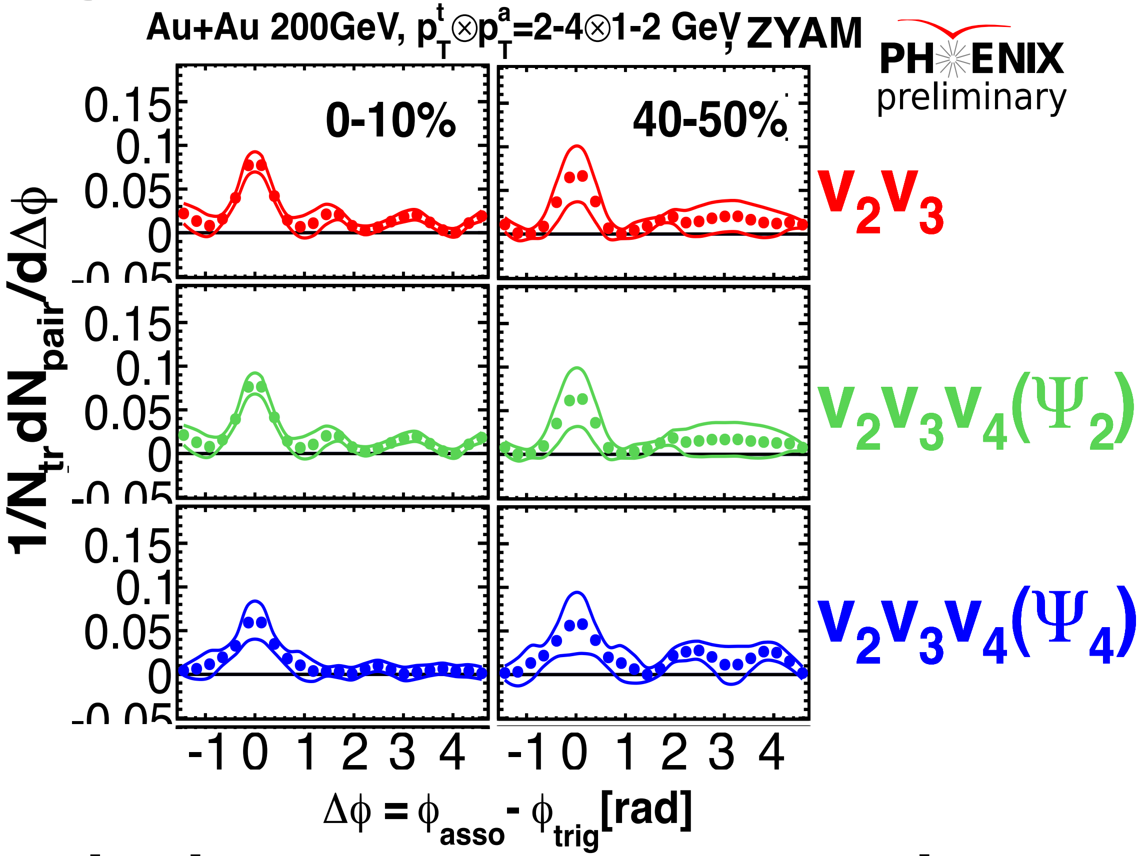
Impact of v_3 to away side residual



✧ v_3 largely reduce away-side shoulder

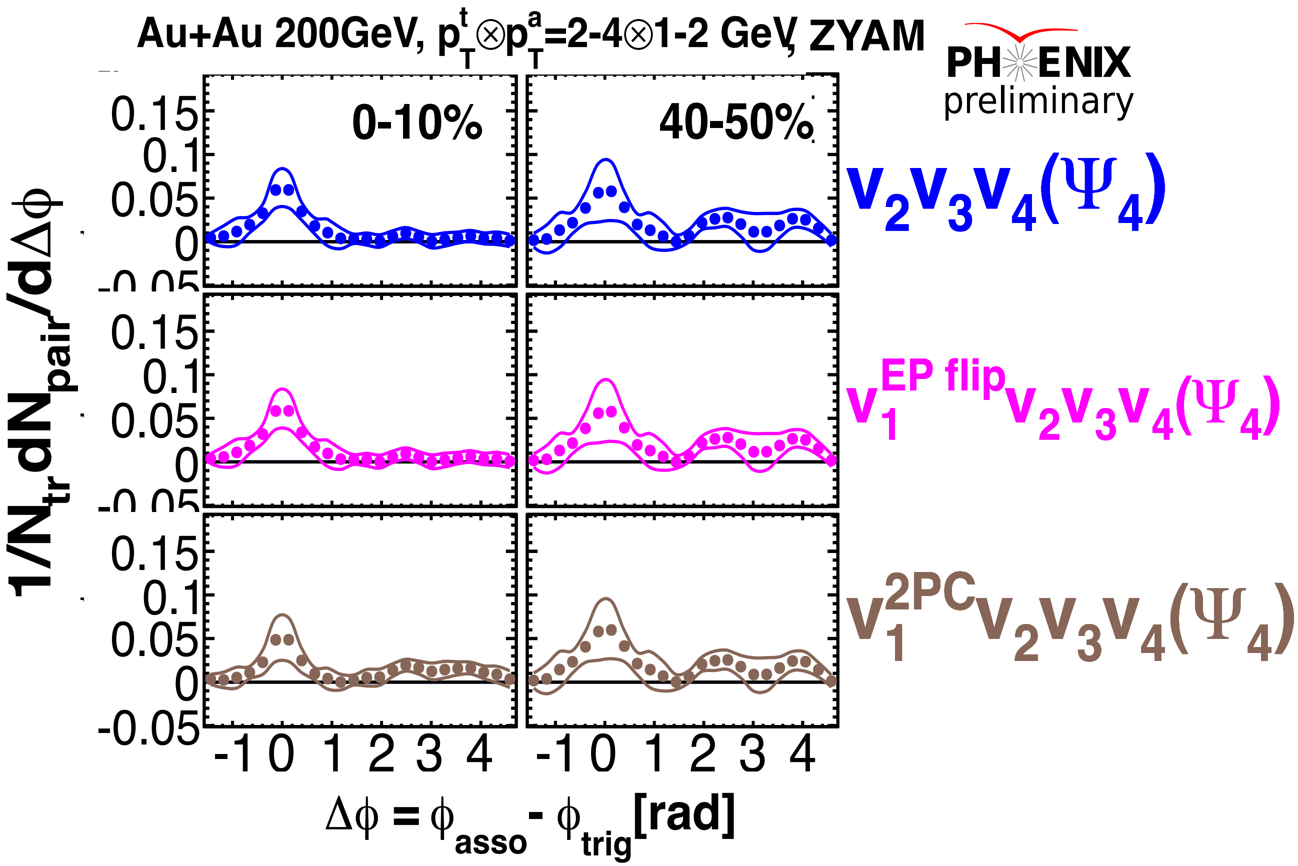
- Small residual at away side in most central
- Double hump almost gone in mid central

Sensitivity of away-side residual to v_4



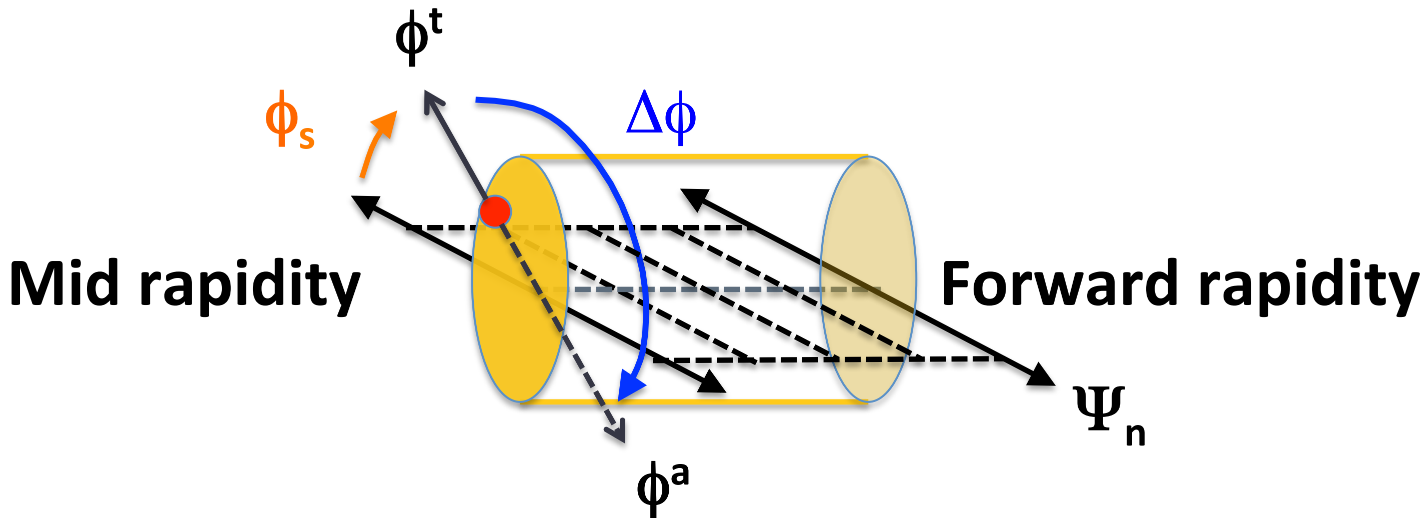
- ✧ $v_4(\Psi_2)$ doesn't change away-side trends
- ✧ $v_4(\Psi_4)$ removes away-side residual in central
  - reproduce double hump in mid-central
- ✧ Mach-cone is possibley induced by jet?

v_n (n=1,2,3,4) subtracted correlations



- Subtraction of v_1 term doesn't change correlations
- Away side double humps in mid-central collision are conclusive

Correlations relative to Ψ_2 & Ψ_3

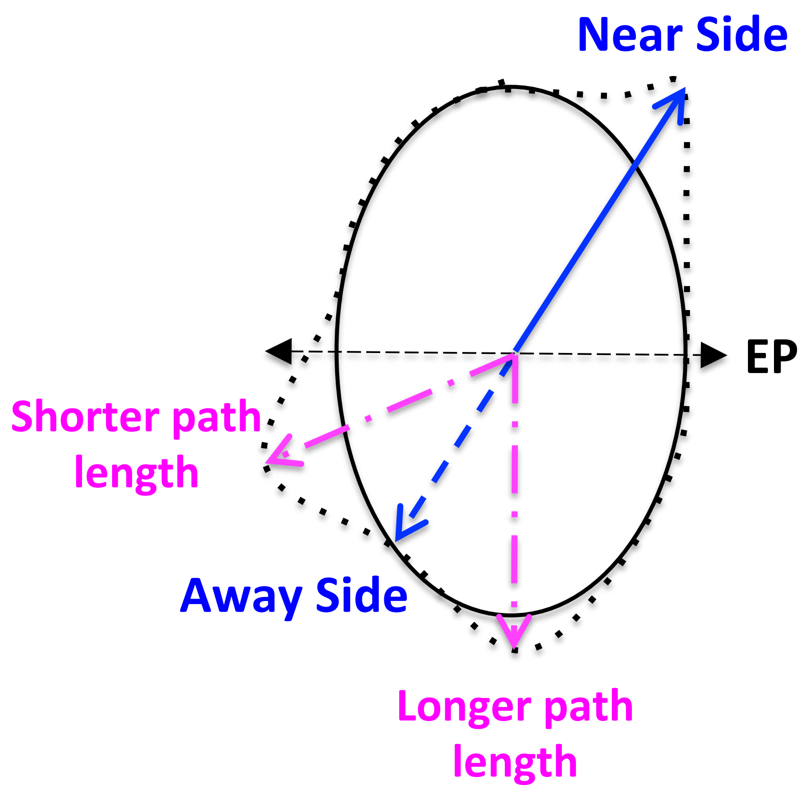


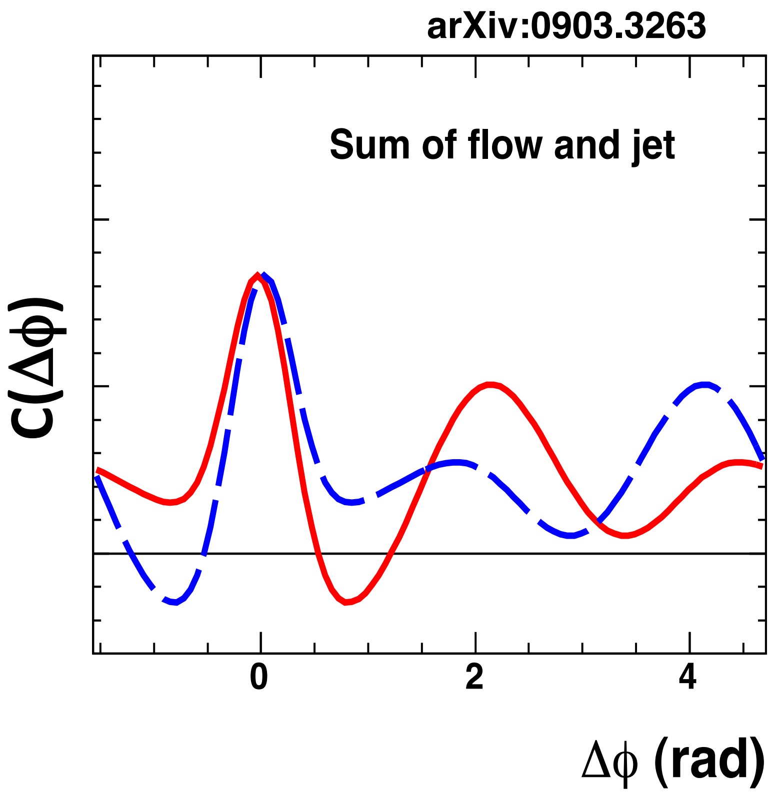
✧ Control parton path length (mainly Ψ_2)

- In-plane : shorter path length
- Out-of-plane : longer path length

✧ Sensitivity of correlations to different harmonic event planes

Parton path length in Left/Right correlations

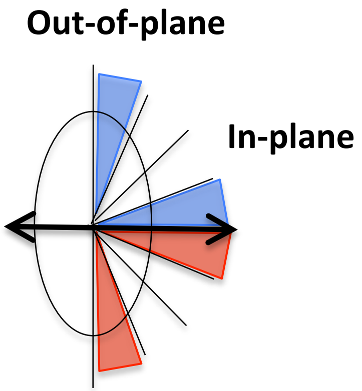


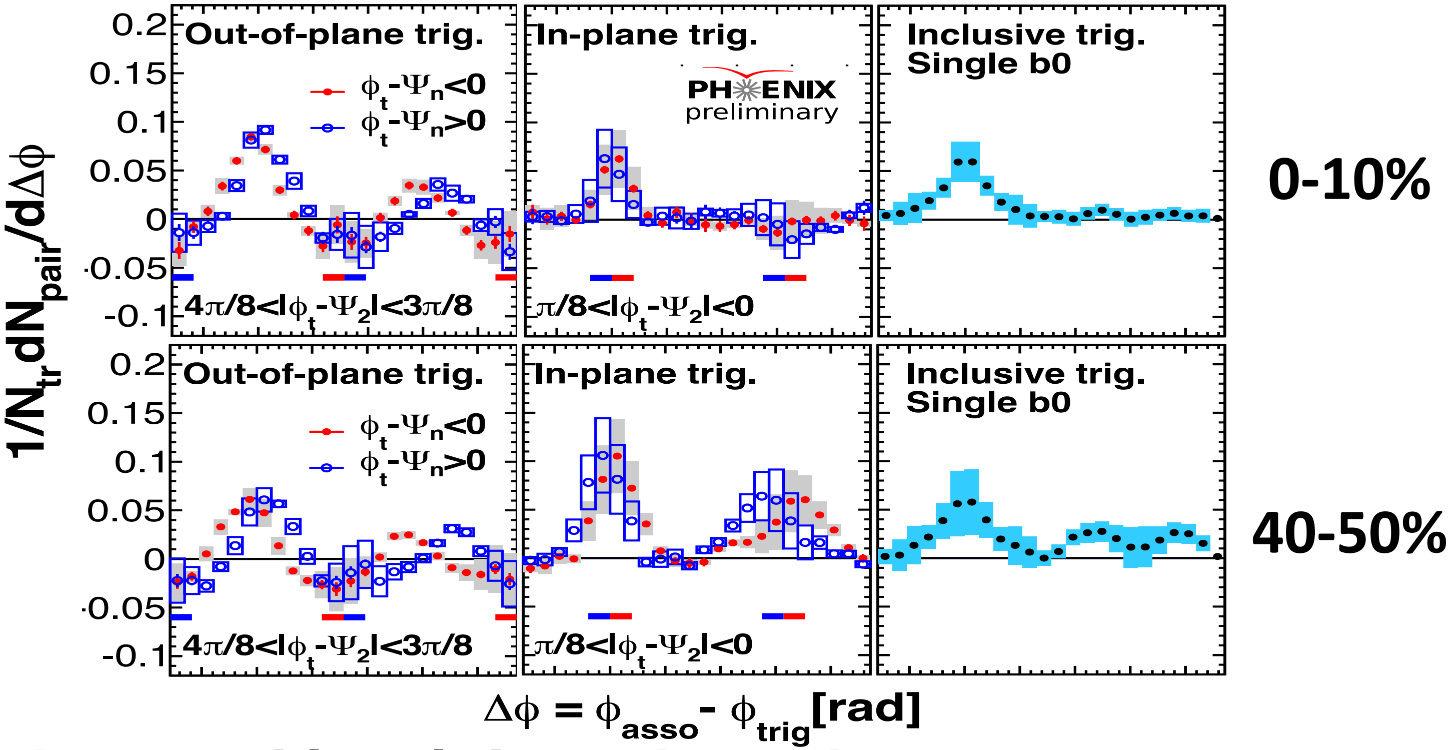


- ✧ Left/Right trigger selection relative to event plane results in non-uniform path length at away-side
- ✧ Expect the modification of away-side as Left/Right asymmetry

Correlations relative to Ψ_2

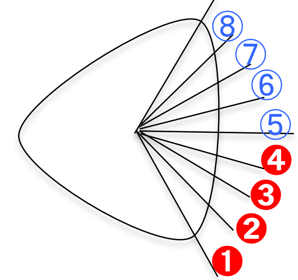
2-4⊗1-2 GeV, $v_2v_3v_4(\Psi_4)$ subtracted with $<\cos4(\Psi_2-\Psi_4)>=v_4(\Psi_2)/v_4(\Psi_4)$ by ZYAM



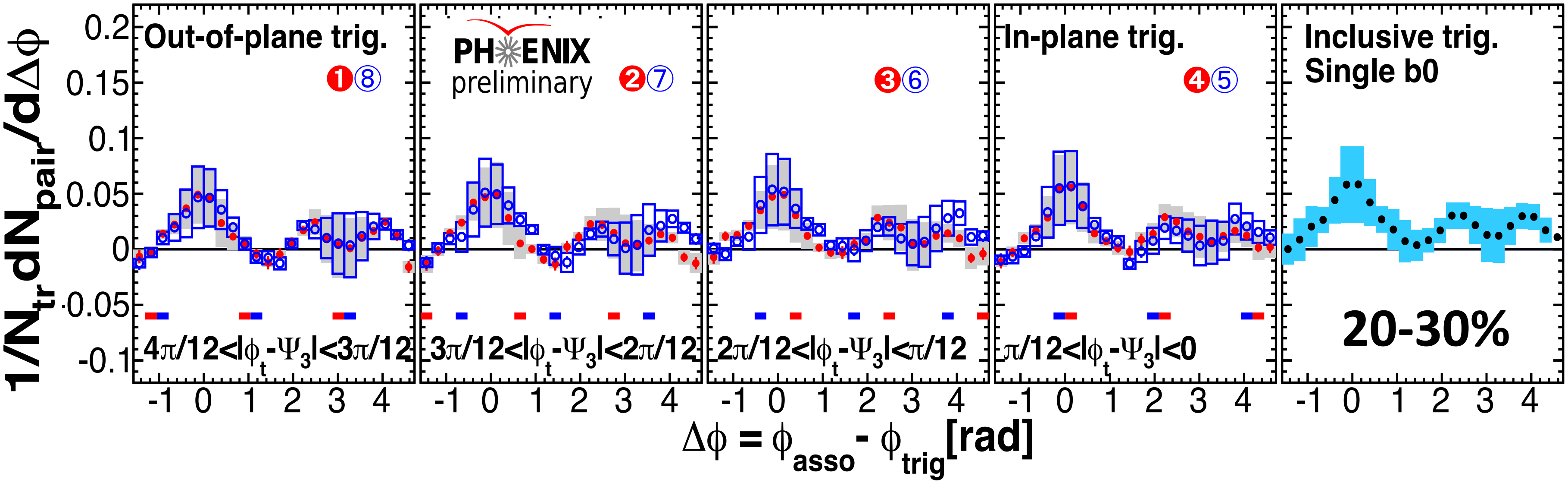


- ✧ Single background level doesn't work
- ✧ Ψ_2 dependence is observed
- ✧ Left/Right asymmetry more pronounced in mid-central
- ✧ Jets pull down v_2 in central collisions
- ✧ Jets push up v_2 in peripheral collisions

Correlations relative to Ψ_3



2-4⊗1-2 GeV, $v_2v_3v_4(\Psi_4)$ subtracted with $\langle\cos4(\Psi_2-\Psi_4)\rangle=v_4(\Psi_2)/v_4(\Psi_4)$ by ZYAM



- ✧ Single background level works
- ✧ Correlations are independent of Ψ_3 within systematics
- ✧ Left/Right correlations are consistent within systematics

Summary

Collective flow

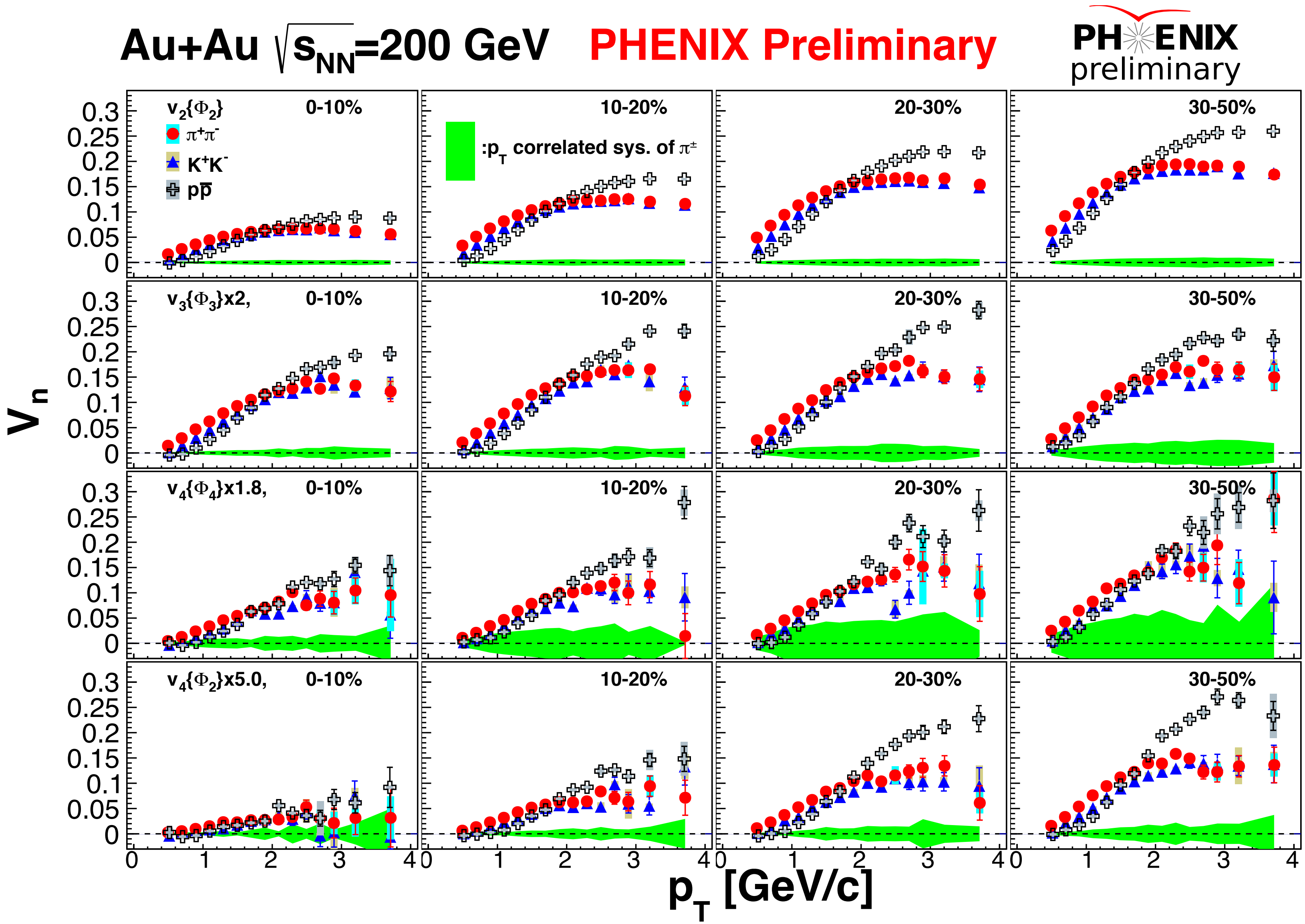
- ✧ EP correlations & event by event v_n provides more constraints to Hydro-models
- ✧ N_q scaling from various aspects
- ✧ v_2 in geometry controlled collisions systems
- ✧ None zero direct photon v_2
- ✧ None zero high p_T hadron & jet v_2

Two-particle correlations

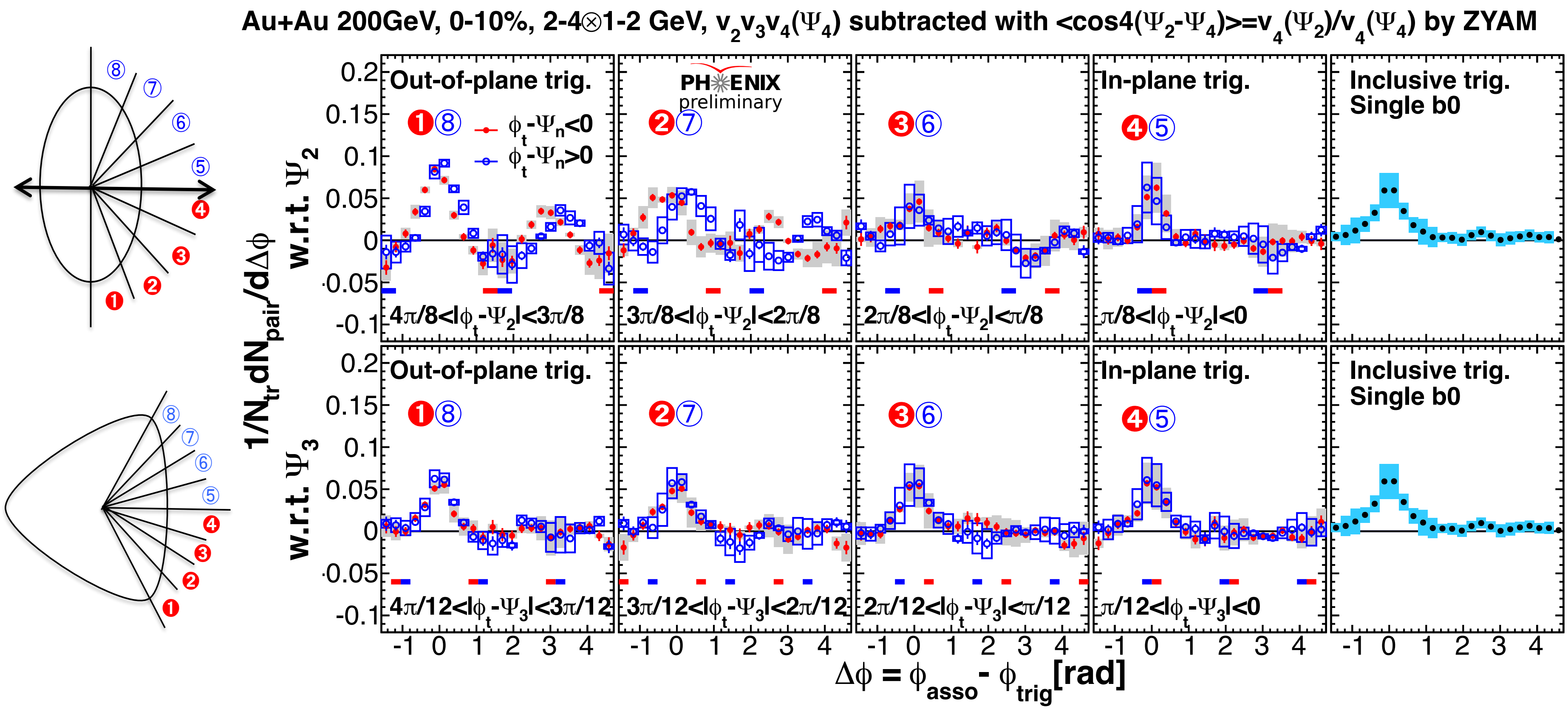
- ✧ Mach-cone like structure is conclusive
  - Difficult to explain by v_n
  - Possibly induced by jet
- ✧ Correlations have different sensitivity to Ψ_2 & Ψ_3

Back Up Slides

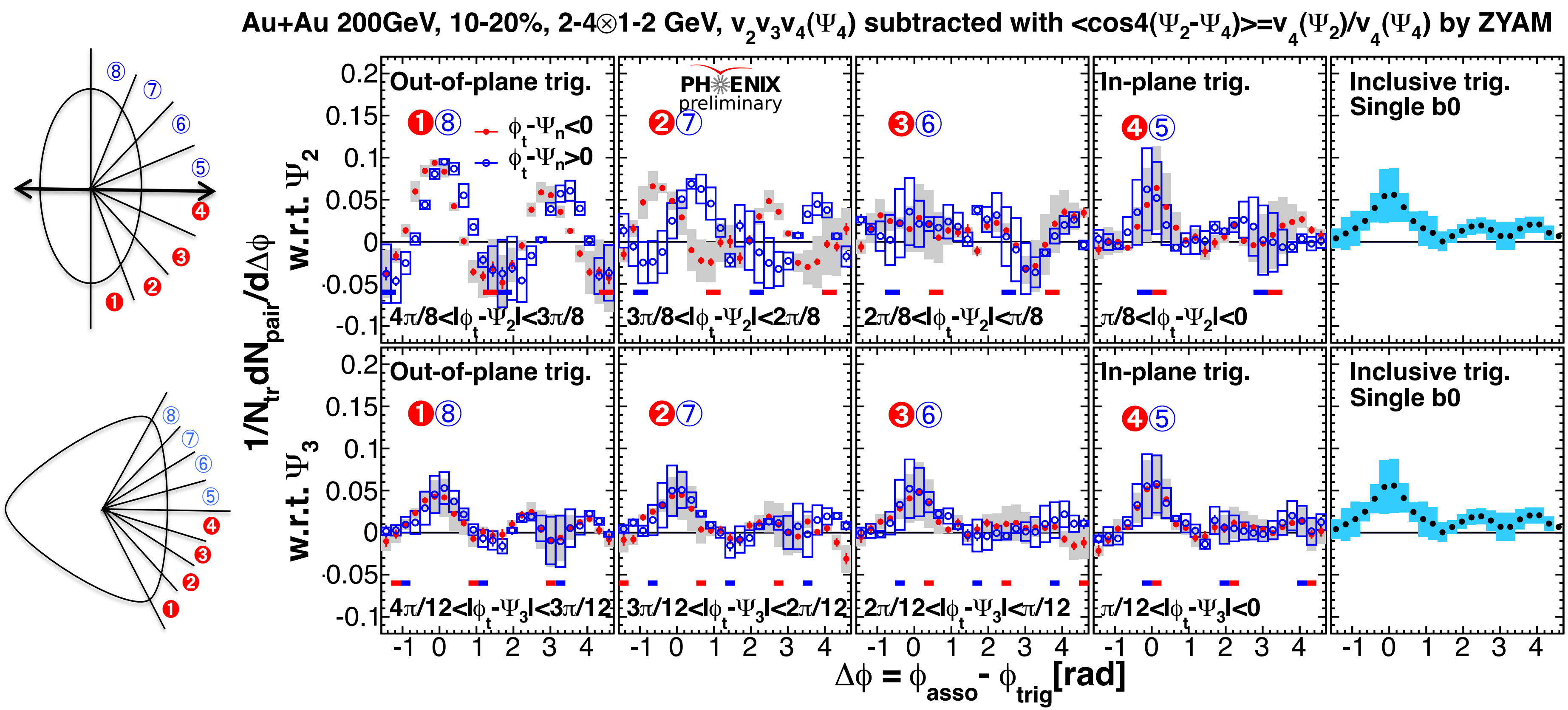
Identified particle v_n



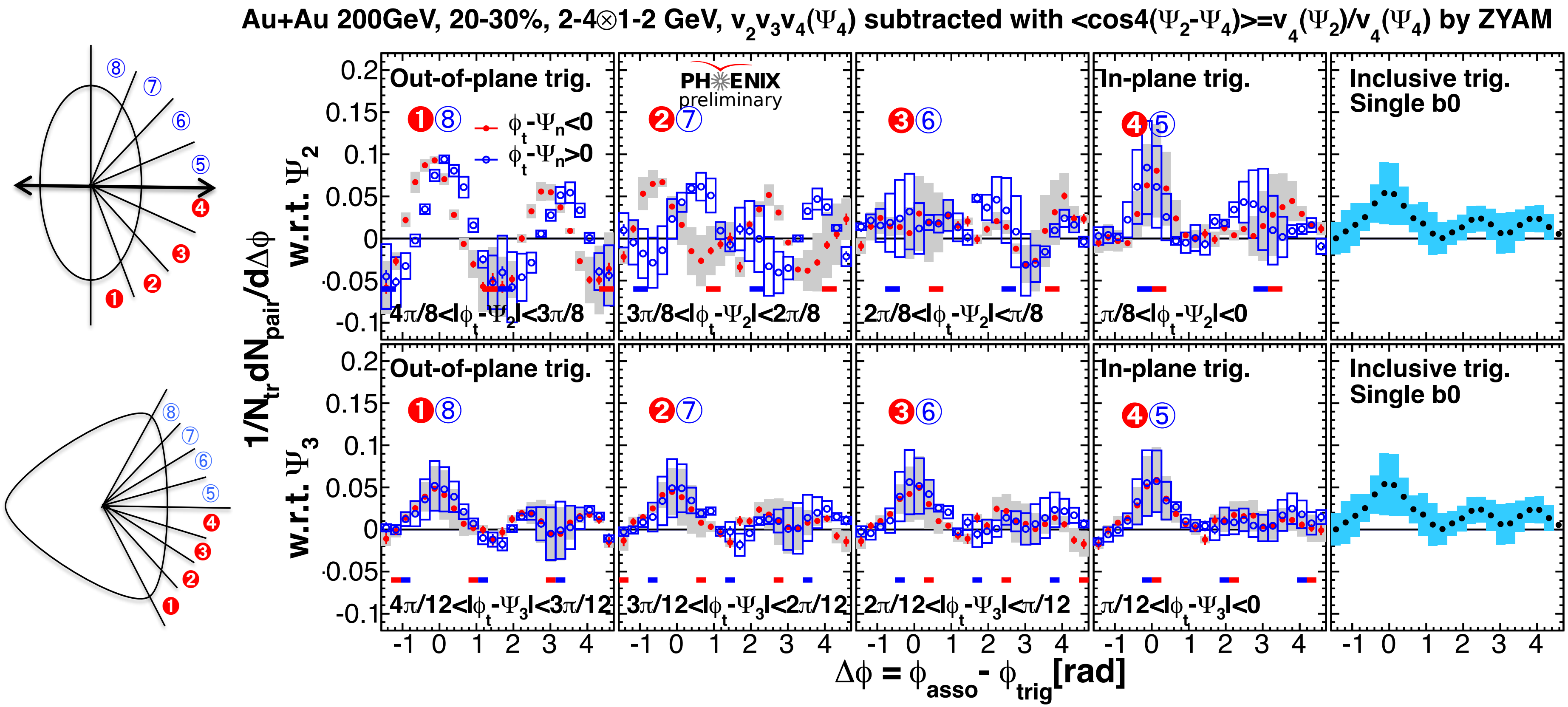
Correlations relative to Ψ_2 & Ψ_3, 0-10%



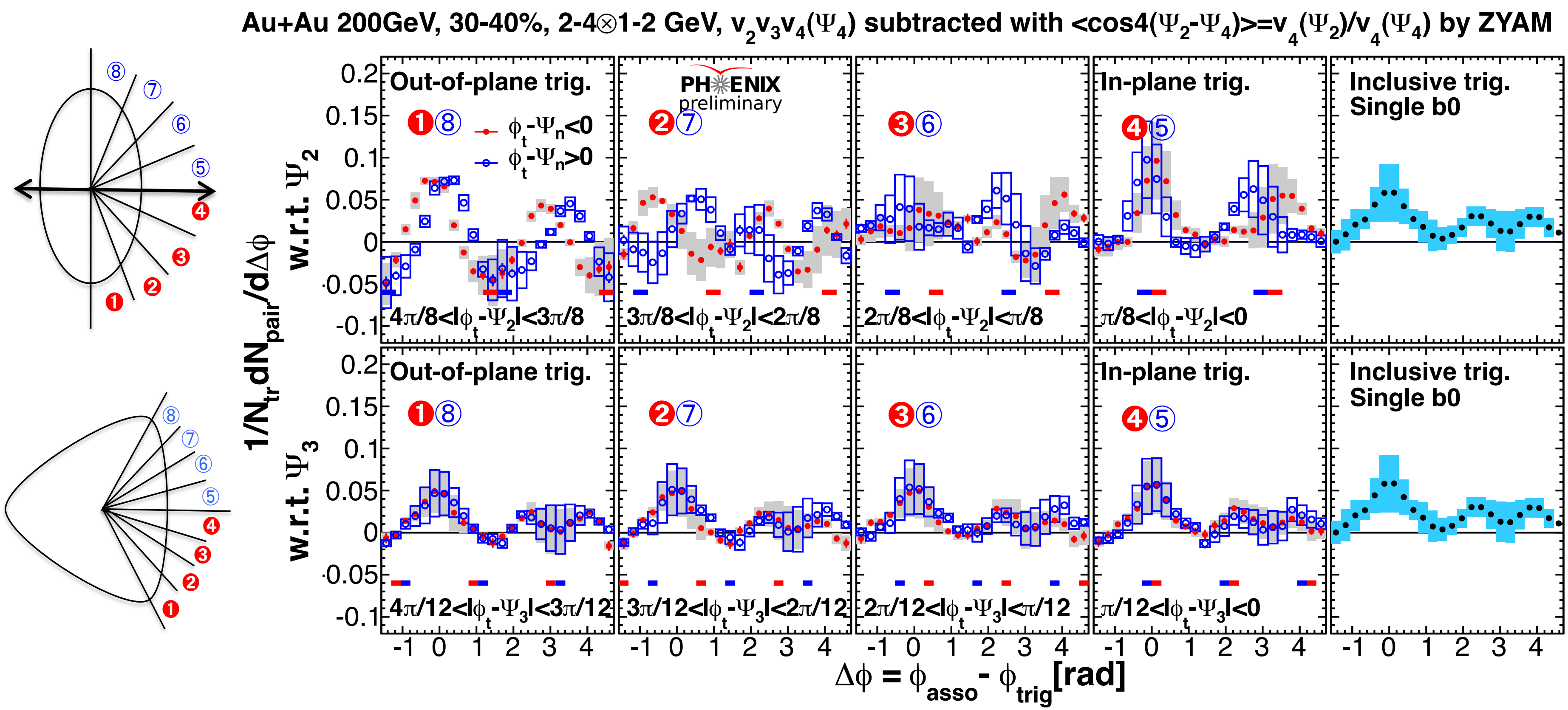
Correlations relative to Ψ_2 & Ψ_3 10-20%



Correlations relative to Ψ_2 & Ψ_3 20-30%



Correlations relative to Ψ_2 & Ψ_3 30-40%



Correlations relative to Ψ_2 & Ψ_3, 40-50%