THIS IS THESIS RESULTS : NOTHING IN THIS SLIDE REPRESENTS PHENIX COLLABORATION'S OFFICIAL STATEMENT!!

Event shape dependence of jet correlations at RHIC

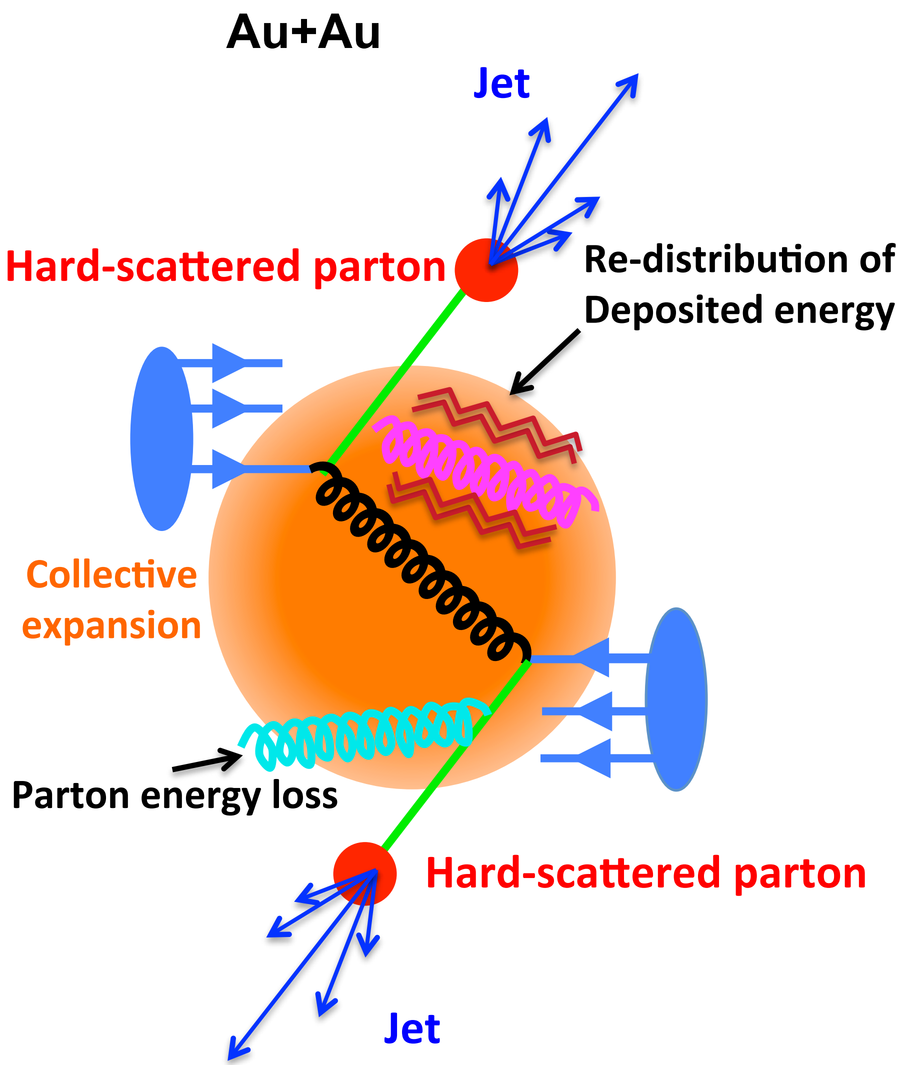
Takahito Todoroki

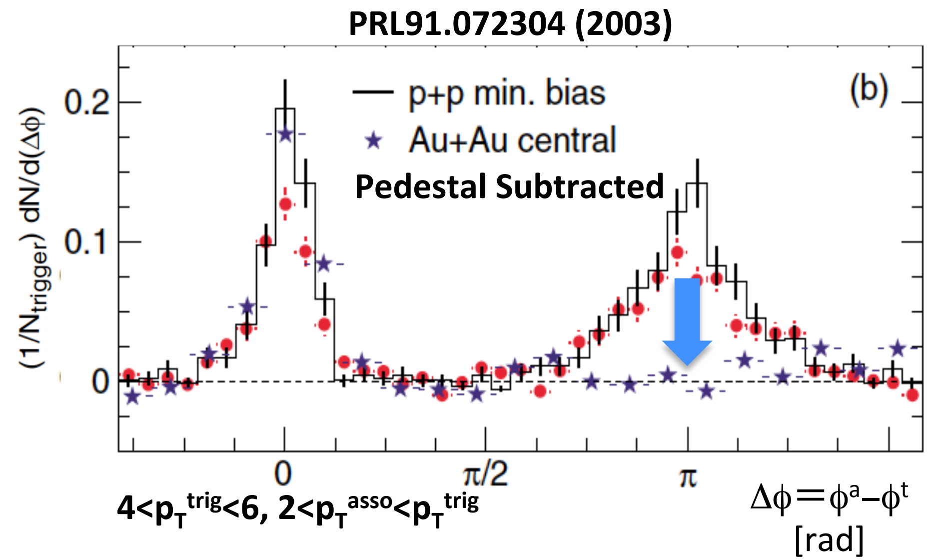
University of Tsukuba

2014/July/19

Heavy Ion Café @ University of Tokyo

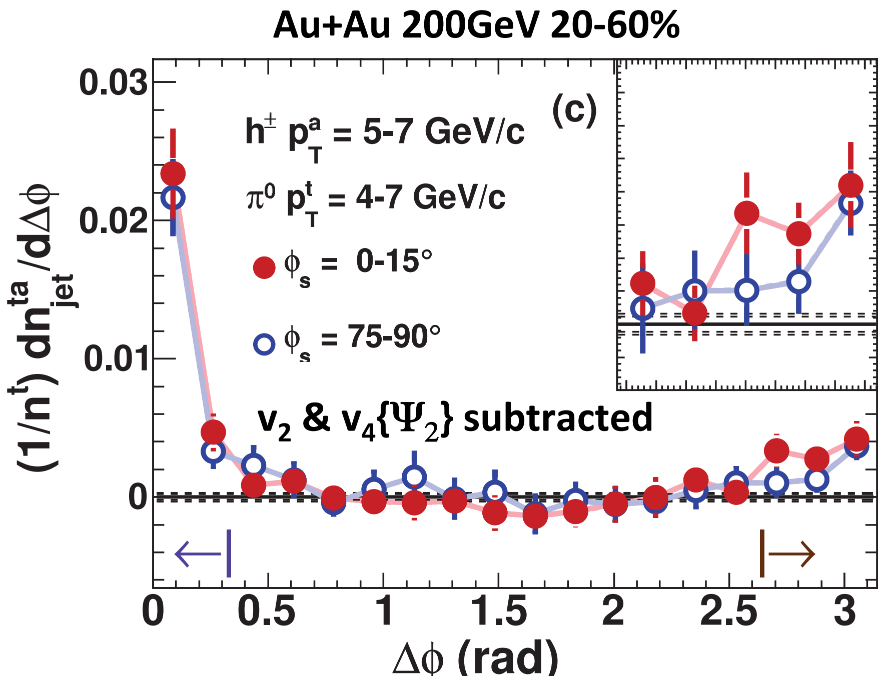
Jet-Quenching

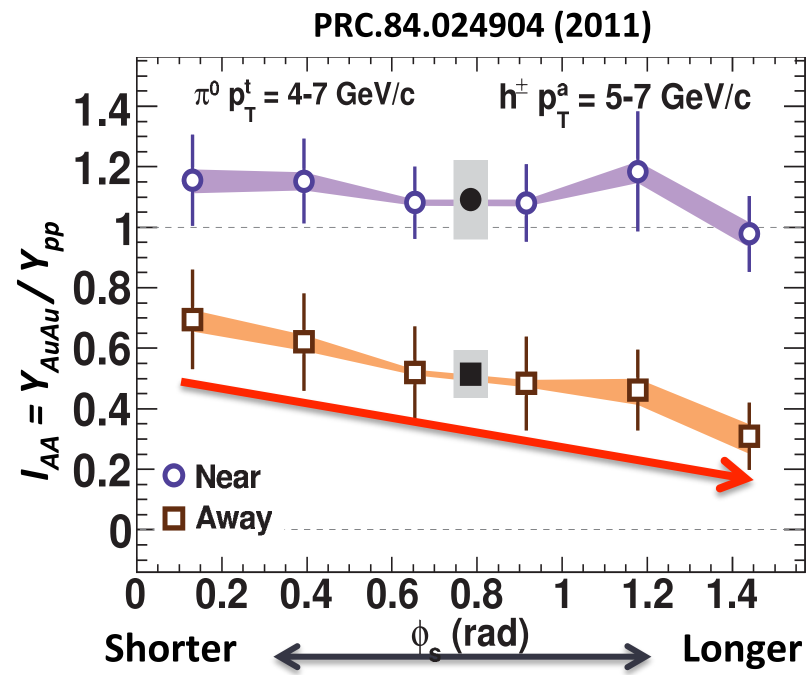


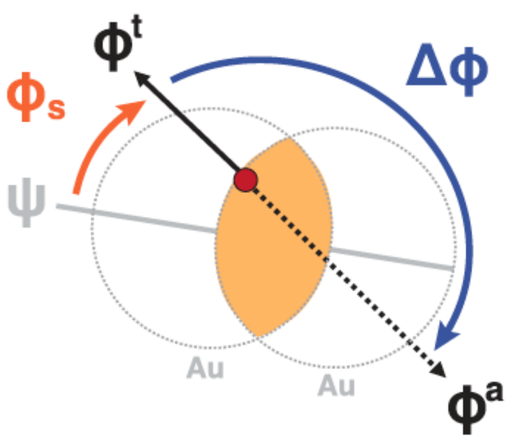


✧ **Suppression of away-side**

Ψ_2 Dependence of Suppression in High p_T correlations



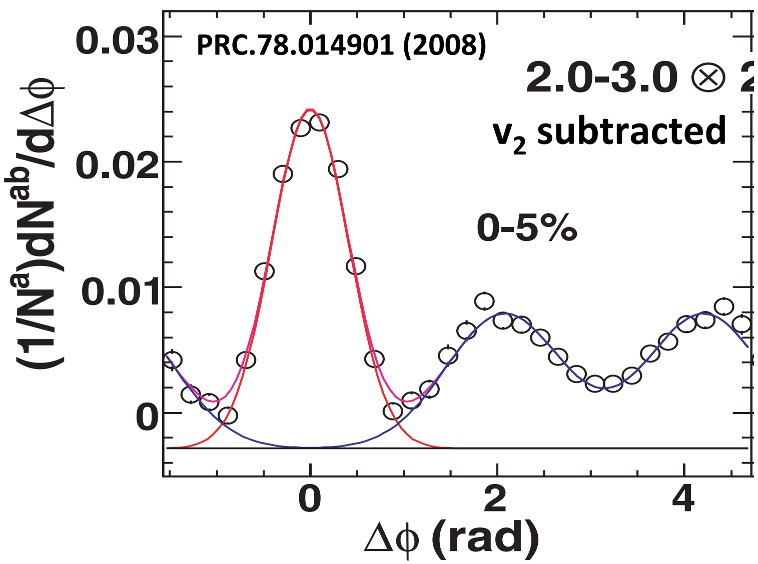




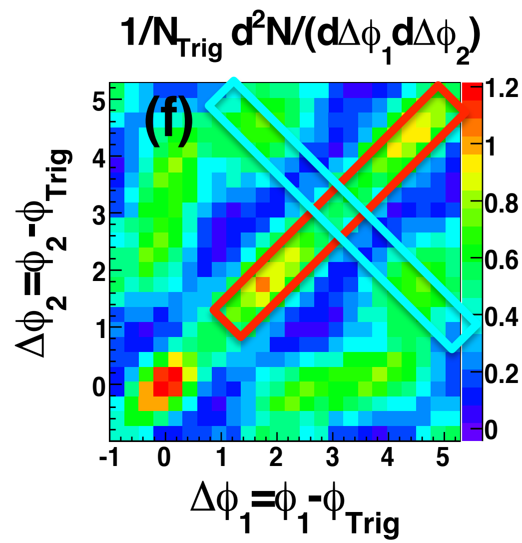
- ✧ Monotonic suppression with increase of path length, which can be taken as “parton energy loss”
- ✧ Where deposited energy goes?

Conical Emission of Intermediate p_T correlations

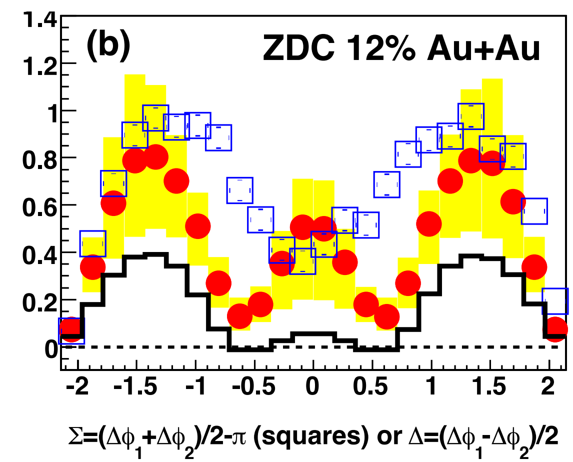
Two-Particle Correlations



Three-Particle Correlations



PRL102.052302 (2009)



- ✧ Away-side double hump in two-particle correlations
- ✧ Conical Emission confirmed by three-particle correlations
- ✧ Seems parton-medium interactions

Models for Double-Hump : 1

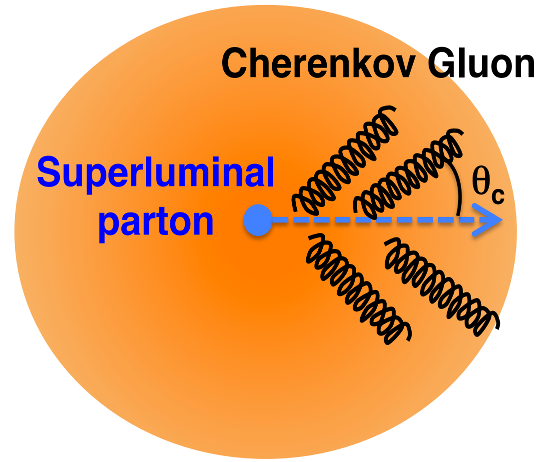
✧ **Cherenkov gluon radiation by superluminal partons**

$$\cos\theta_c = 1/n(p)$$

$n(p)$ **: Index of refraction**

p **: Gluon Momentum**

PRL 96.172302 (2006)



✧ **Shock-wave by supersonic partons**

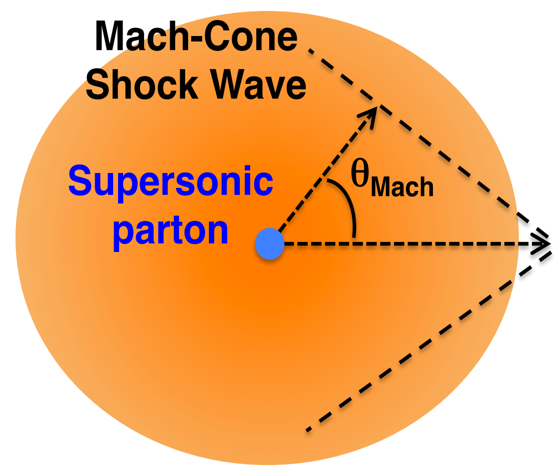
$$\cos\theta_{Mach} = c_s/v_{part}$$

c_s **: Speed of sound**

v_{part} **: Speed of parton**

Phys. Rev. C 73, 011901(R), (2006)

PRL 105.222301 (2010)



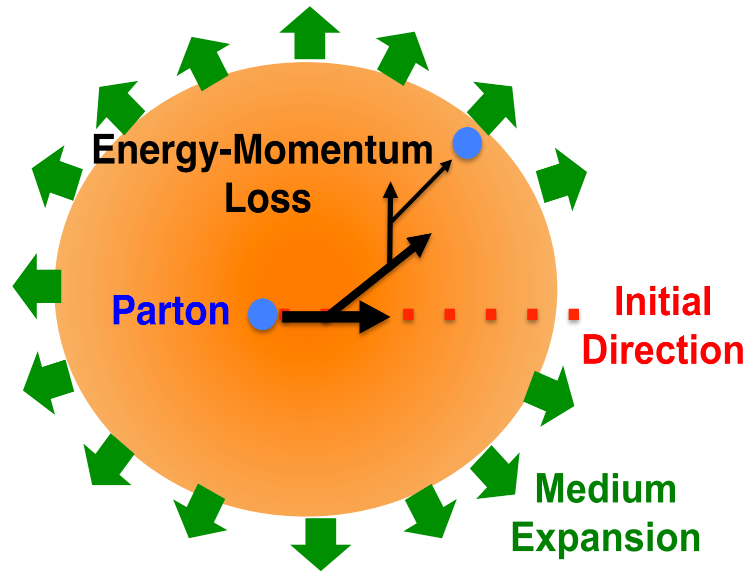
Models for Double-Hump : 2

- ✧ **Energy-momentum loss + expanding medium**

$$\partial_\mu T^{\mu\nu} = S^\nu$$

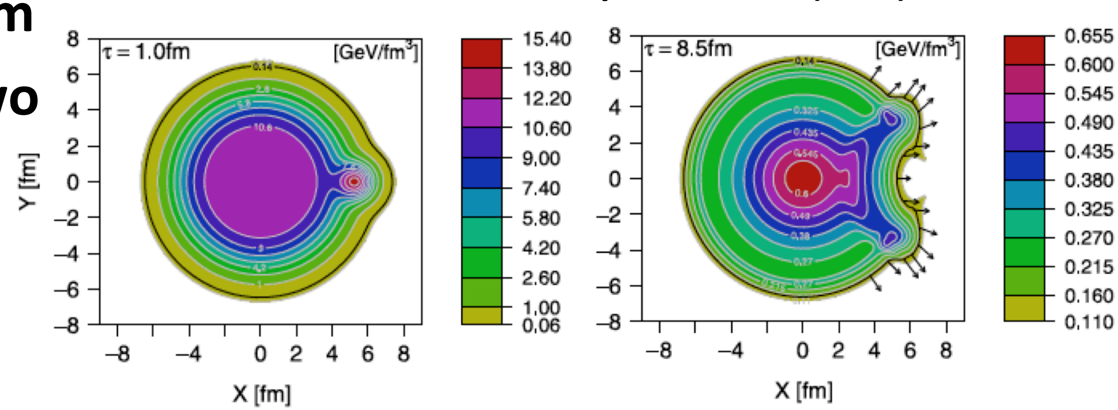
$$S^\nu(t,\vec{x}) = \frac{1}{(\sqrt{2\pi}\sigma)^3}\exp\left[-\frac{[\vec{x}-\vec{x}_{jet}(t)]^2}{2\sigma^2}\right] \times \left(\frac{dE}{dt},\frac{dM}{dt},0,0\right)\left[\frac{T(t,\vec{x})}{T_{max}}\right]^3$$

PRL 105.222301 (2010)



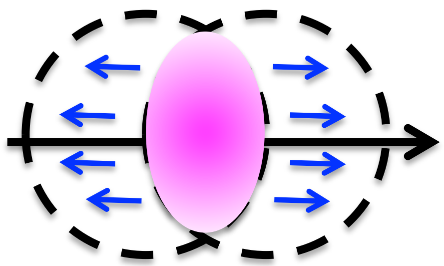
- ✧ **Hot spot+ expanding medium**
  - **Split of the hot spot into two directions**

Phys. Let. B 712 (2012) 226-230



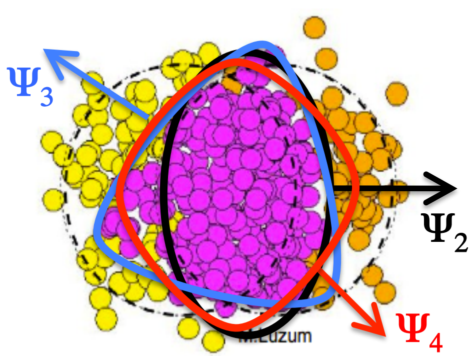
Higher-Order Event-Planes & Flow-Harmonics

Smooth participant density



Expansion to the short-axis direction by pressure gradient

Fluctuating participant density



Expansion to the short-axis directions of event-planes by pressure gradient

✧ **Azimuthal distribution of emitted particles**

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$
$$+ 2v_3 \cos 3(\phi - \Psi_3)$$
$$+ 2v_4 \cos 4(\phi - \Psi_4)...$$
$$v_n = < cosn(\phi - \Psi_n) >$$

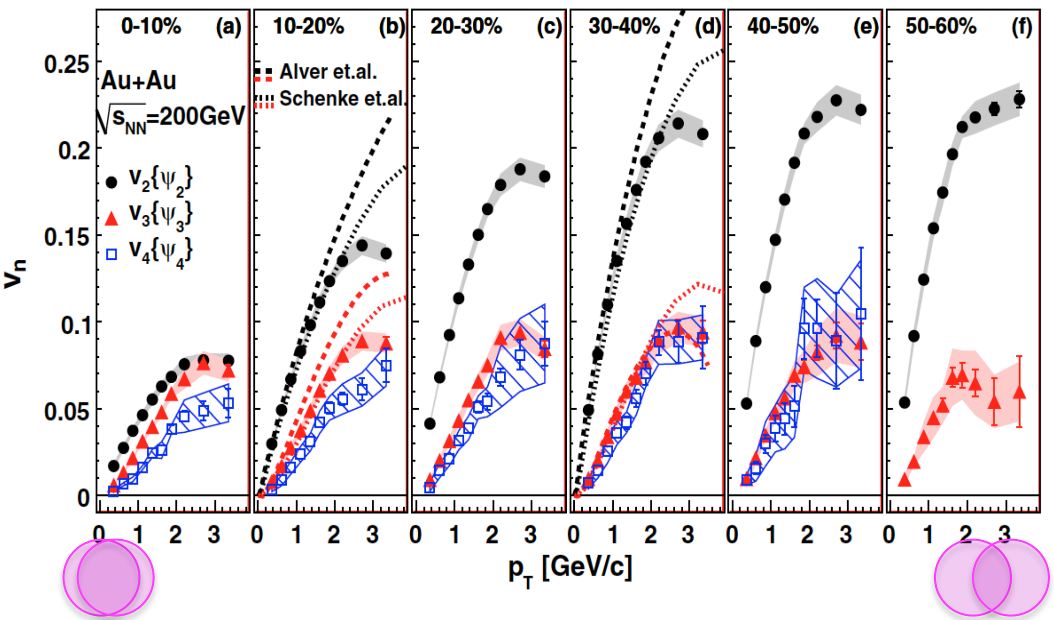
v_n : **Higher-order flow harmonics**

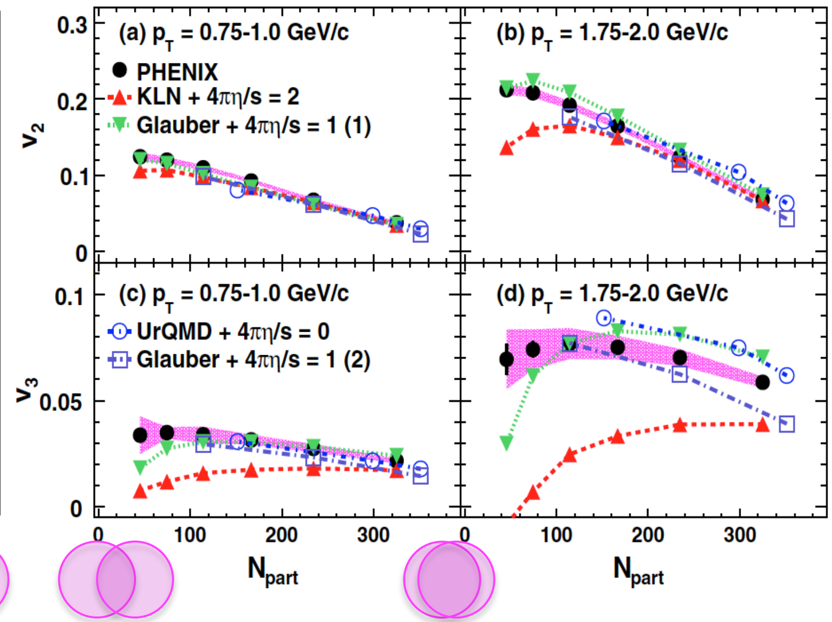
Ψ_n : **Higher-order event planes**

ϕ : **Azimuthal angle of emitted particles**

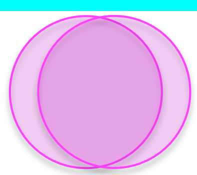
Higher-Order Flow Harmonics

PRL107.252301 (2011)





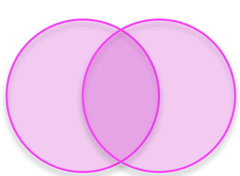
Central Collisions



N_{part} : # of participant nucleons in a collision

Centrality~0%
N_{part} ~394

Peripheral Collisions



Centrality~100%
N_{part} ~2

- ✧ None-zero $v_n(n>2)$ is observed
- ✧ Degeneracy of models disentangled
  - Initial Condition, shear viscosity of QGP, different expansion mechanism between v_2 & v_3
- ✧ Backgrounds in correlation functions

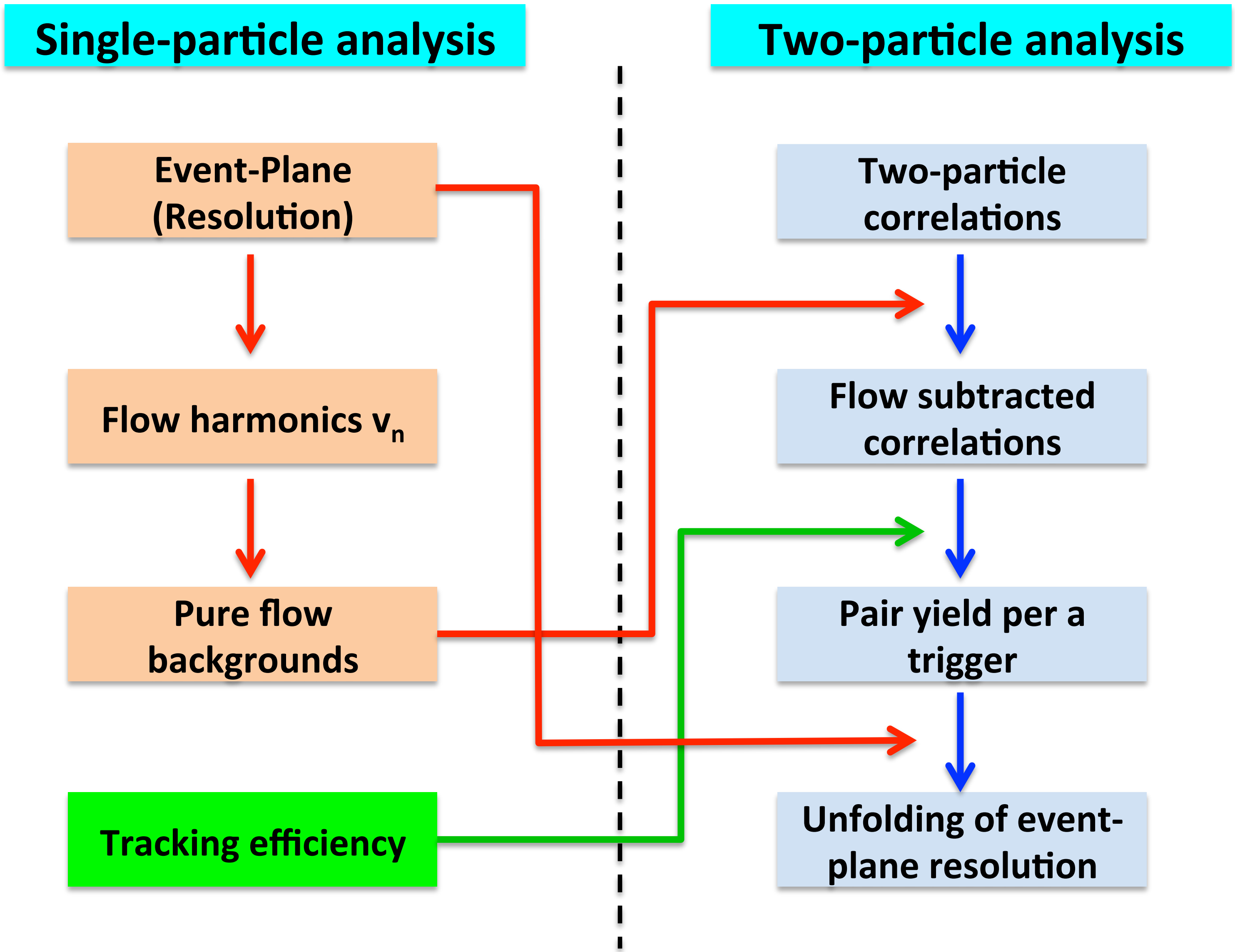
Motivation of analysis

- ✧ Providing experimental results of two-particle correlations after v_n background subtractions

- ✧ Examine the path length dependence of Ψ_2 dependent intermediate-p_T correlations in order to search for deposited energy from high p_T partons

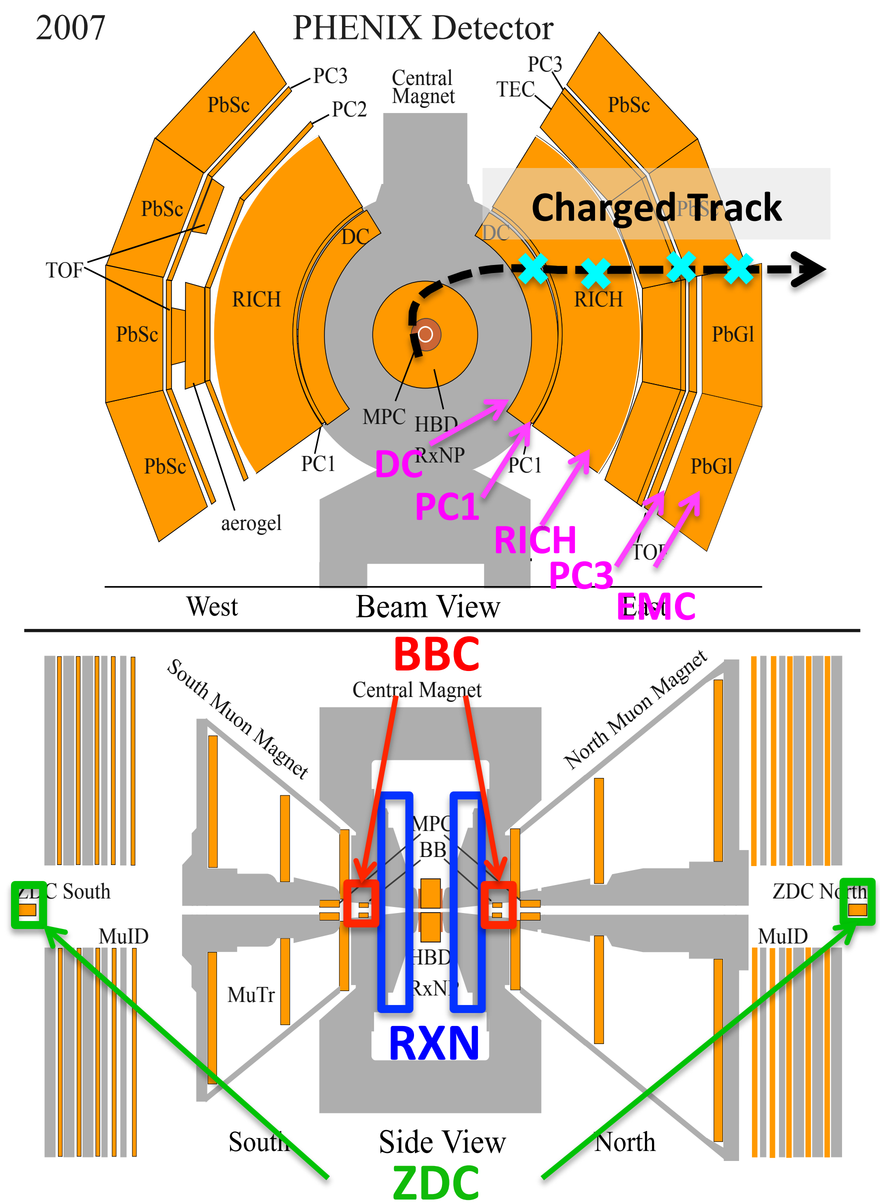
- ✧ Search for differences between Ψ_2 & Ψ_3 dependent correlations which may reflects possible different evolution processes between the 2nd- and 3rd-order geometry planes

Analysis Flow-Chart

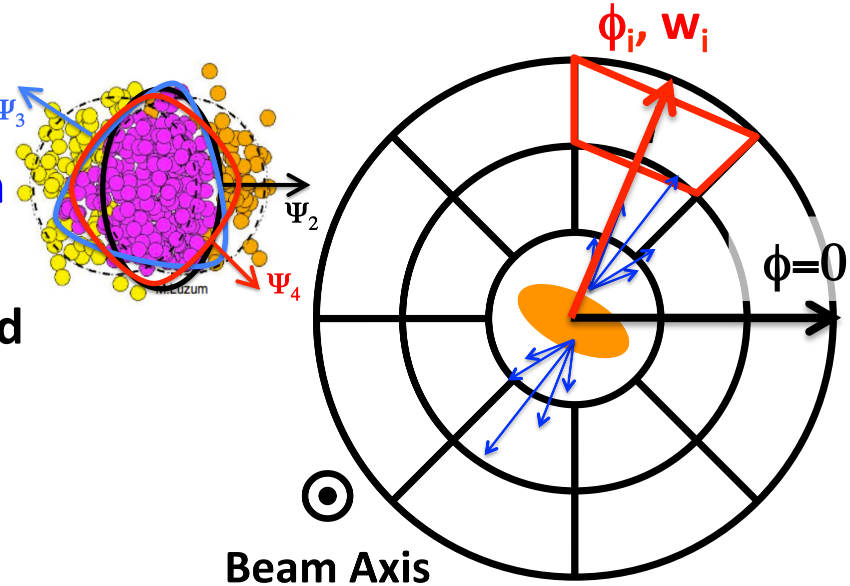


PHENIX 2007 Experiment: Au+Au 200 GeV Collisions

- ✧ **Minimum Bias trigger : 4.4 billion events**
- ✧ **Trigger, collision vertex, centrality**
  - – Zero-Degree-Calorimeter(ZDC)
  - – Beam-Beam-Counter (BBC)
- ✧ **Event-plane**
  - – BBC
  - – Reaction-Plane-Detector(RXN)
- ✧ **Central Arm, $\Delta\phi=\pi$, $|\eta|<0.35$**
  - – Drift Chamber (DC)
  - – Pad Chambers(PC)
  - – Electromagnetic Calorimeter(EMC)
    - • Momentum, charged particle tracking
  - – Ring Image Cherenkov Detector(RICH)
    - • Electron rejection



Event-Plane



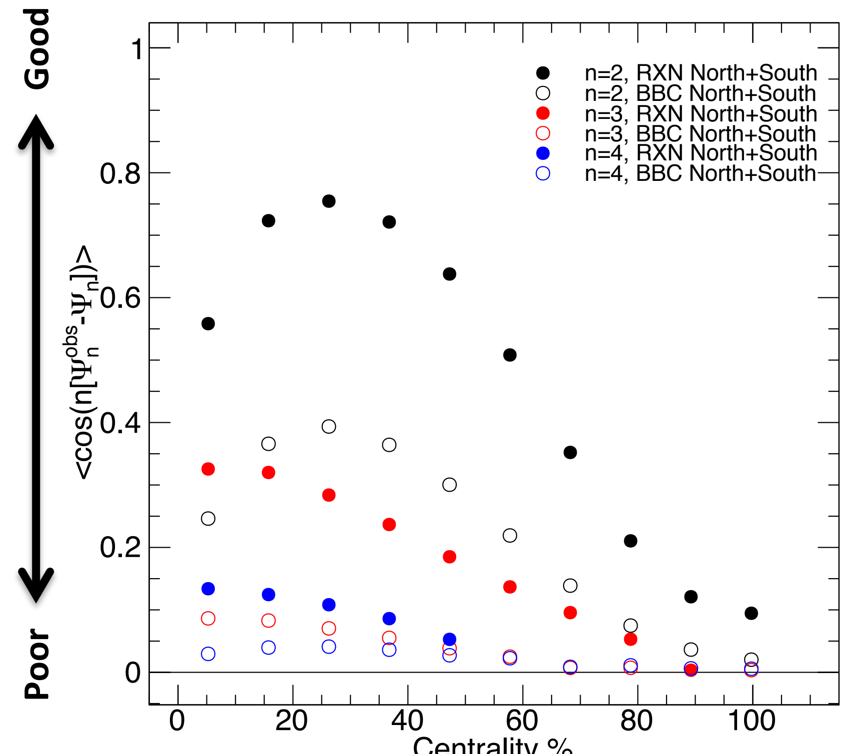
- **Expansion to the initial short-axis direction by pressure gradient**
  - EP is a direction most particles are emitted after freeze-out
  - EP is determined by flow signal itself

- **EP is determined by RXN and BBC detectors**
  - RXN ($1<|\eta|<2.8$) : 24 segments x 2 sectors
  - BBC ($3<|\eta|<3.9$) : 64 segments x 2 sectors

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\sum_i w_i \cos(n\phi_i)/\sum_i w_i}{\sum_i w_i \sin(n\phi_i)/\sum_i w_i}\right)$$

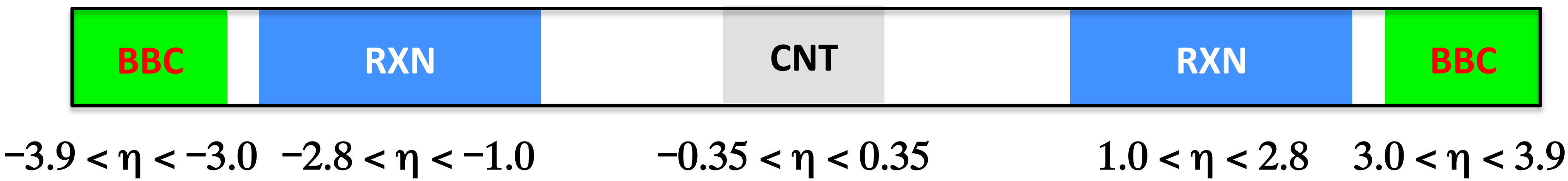
ϕ_i : Azimuthal angle of *i*th segments

w_i : Weight (Charge etc.) of *i*th segments



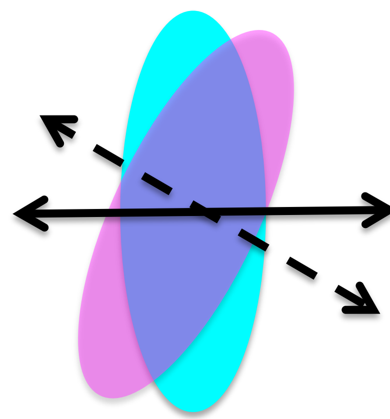
Rapidity Selections in Analysis

- Rapidity ranges of CNT, RXN, & BBC
  - 2PC at $|\Delta\eta|<0.35$
  - Rapidity gap between particles & EP to avoid auto-correlations by jets



- Raw flow harmonics

$$v_n^{raw} = < cosn(\phi - \Psi_n^{obs}) >$$



- Resolution correction
  - Smearing due to limited resolution

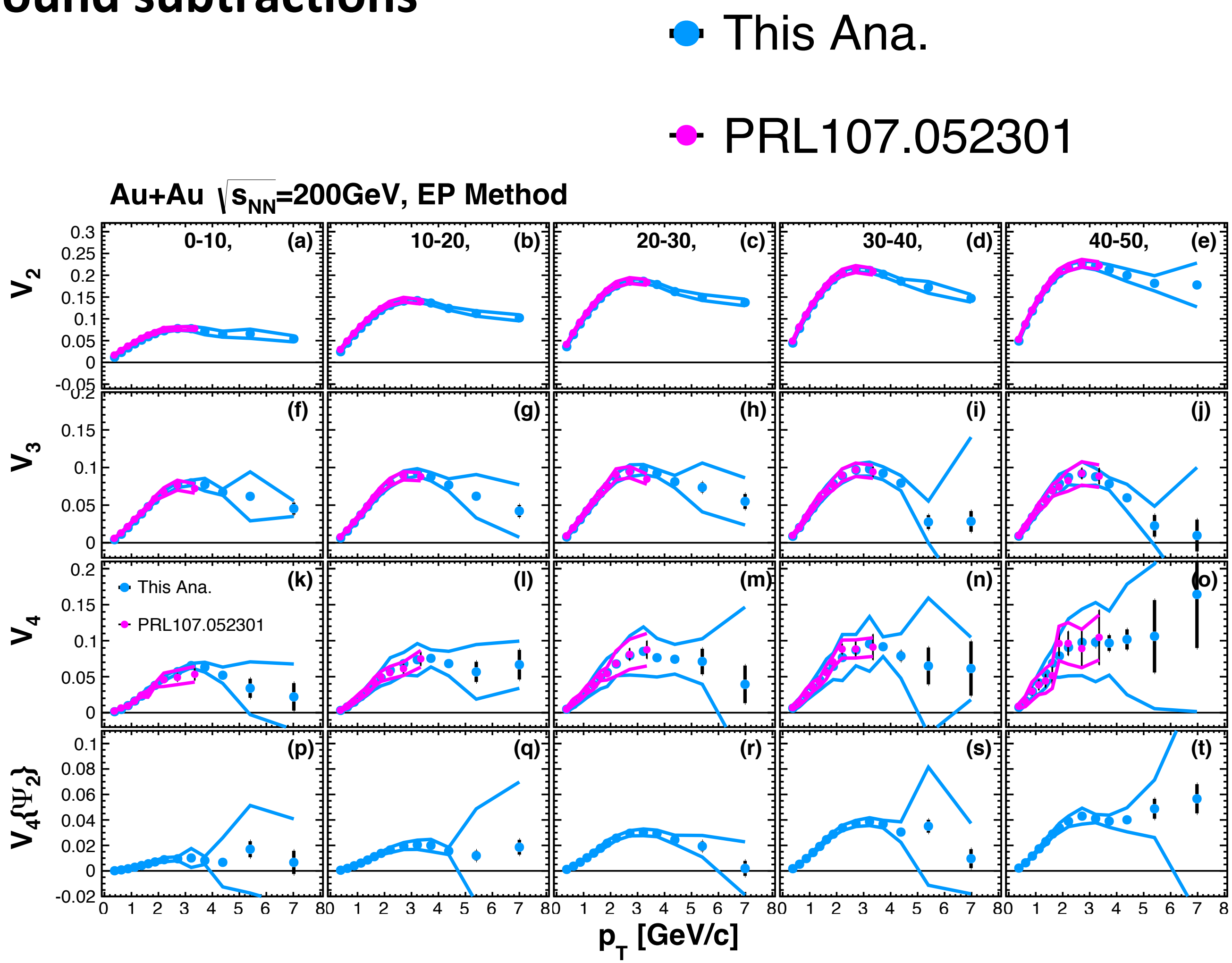
$$v_n = \frac{< cosn(\phi - \Psi_n^{obs}) >}{\boxed{< cosn(\Psi_n - \Psi_n^{obs}) >}}$$

Event-Plane Resolution

v_n Results

✧ **Consistent results with previous PHENIX measurements**

– **Used for background subtractions**



Total systematics (%) at p_T=1-2 GeV/c

Centrality	0-10%	40-50%
v_2	4.3 %	2.7%
v_3	4.9%	12%
v_4	10%	34%
$v_4\{\Psi_4\}$	15%	6.5%

Two-Particle Correlations

Definition

Ratio of two-particle probability over single-particle ones

$$C(\Delta\phi, \Delta\eta) = \frac{P(\phi^a, \phi^t | \eta^a, \eta^t)}{P(\phi^a|\eta^a)P(\phi^t|\eta^t)}$$

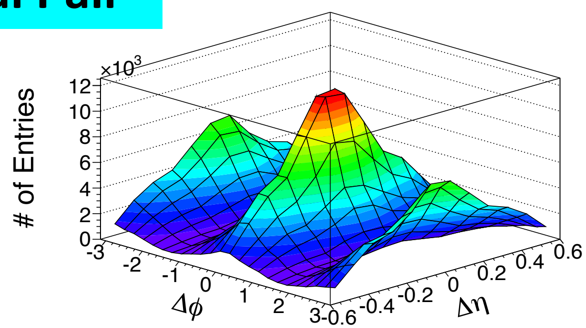
Experimental Def.

Ratio of real pair distribution over mixed one

$$C(\Delta\phi, \Delta\eta) = \frac{N^{ta}_{mix}}{N^{ta}_{real}} \frac{d^2N^{ta}_{real}/d\Delta\phi d\Delta\eta}{d^2N^{ta}_{mix}/d\Delta\phi d\Delta\eta}$$

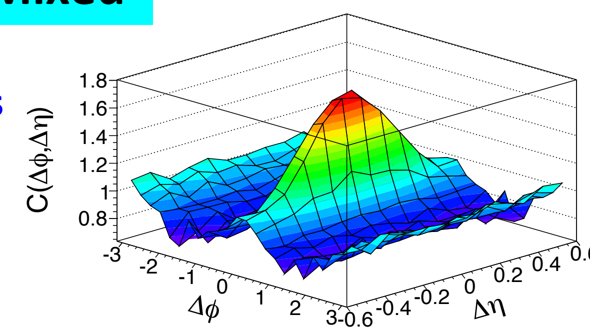
$$\Delta\phi = \phi^a - \phi^t, \Delta\eta = \eta^a - \eta^t$$

Real Pair

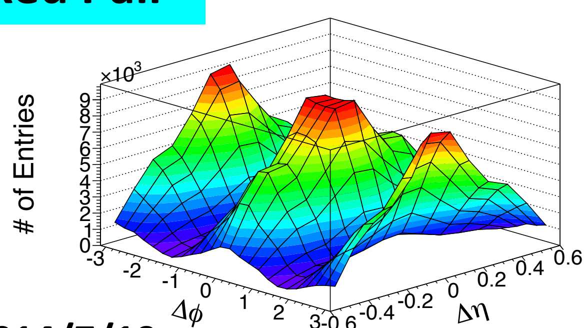


Correlations = Real/Mixed

Event mixing also corrects acceptance effects by choosing similar events: centrality, collision points



Mixed Pair



Pair Yield Per a Trigger

Dimension : Number of Particles

$$\frac{1}{N^t}\frac{d^2N^{ta}}{d\Delta\phi d\Delta\eta} = \frac{1}{2\pi\varepsilon}\frac{N^{ta}}{N^t}C(\Delta\phi, \Delta\eta)$$

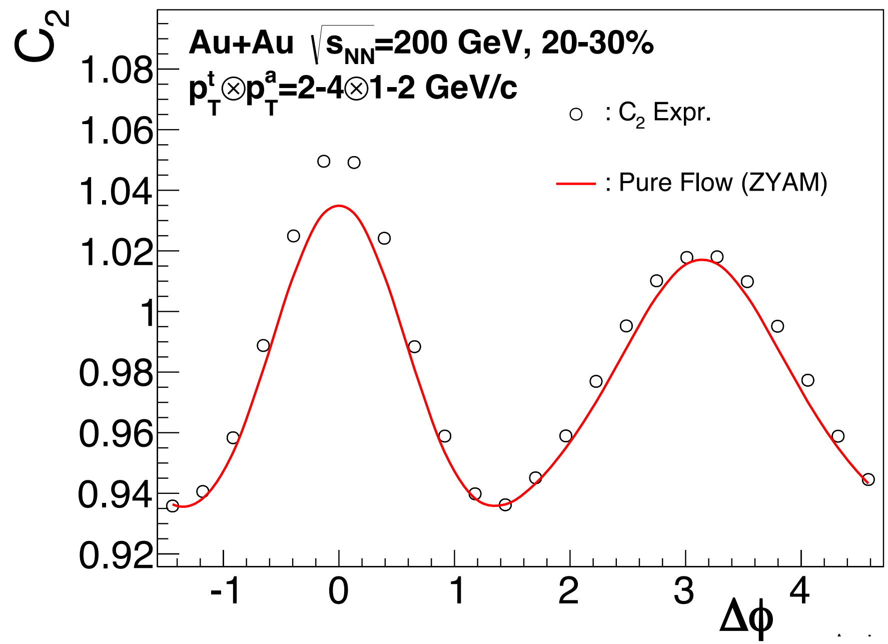
Flow Subtraction & Pair Yield per a Trigger (PTY)

- ✧ **Pure flow background**

$$F(\Delta\phi) = 1 + \sum 2v_n^t v_n^a \cos(n\Delta\phi)$$

- ✧ **Flow subtractions by ZYAM**
  - **Zero Yield At Minimum Assumption**

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



- ✧ **Pair yield per a trigger (PTY)**
  - **Dimension : number of particles**

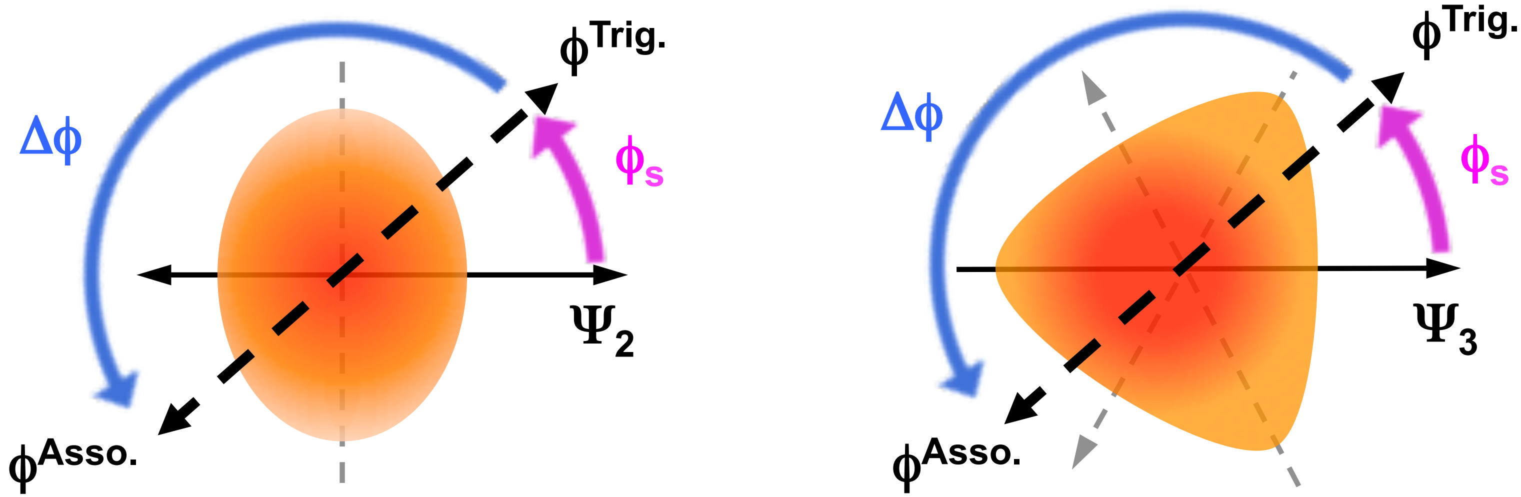
$$\frac{1}{N^t}\frac{dN^{ta}}{d\Delta\phi} = \frac{1}{2\pi\varepsilon}\frac{N^{ta}}{N^t} j(\Delta\phi)$$

ε : **Tracking efficiency of associate particles**

N^t : **Number of triggers**

N^{ta} : **Number of pairs**

Trigger Selection with respect to Event-Plane



- **Expansion to the short-axis direction by pressure gradient**
  - **EP : direction most particles are emitted after freeze-out**
- **Selecting trigger particles with respect to Ψ_2 & Ψ_3**
  - **8 bins :** $\phi^{trig} - \Psi_n : [-\pi/n, \pi/n]$

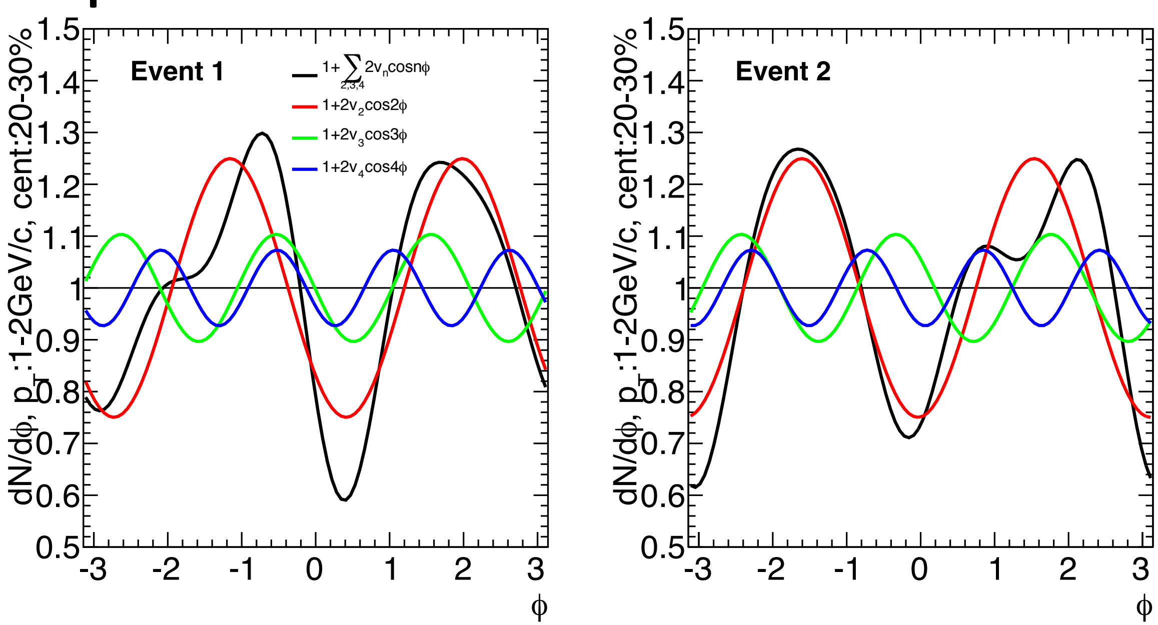
- **Control of path length of trigger and associate particles**
- **Three p_T combinations: 2-4x1-2, 2-4x2-4, 4-10x2-4 GeV/c**

Flow Backgrounds with respect to EP

- ✧ A Monte Carlo simulation employed
- ✧ Azimuthal distribution using
  - Measured v_n
  - Observed correlation between EP
    - $<4(\Psi_2-\Psi_4)>=v_4\{\Psi_2\}/v_4\{\Psi_4\}$
    - $<6(\Psi_2-\Psi_3)>=0$

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=2,3,4} 2v_n \cos n(\phi - \Psi_n)$$

- ✧ Determine trigger particle relative to EP taking into account EP resolutions
- ✧ Calculate two-particle correlations



Flow Backgrounds with respect to EP

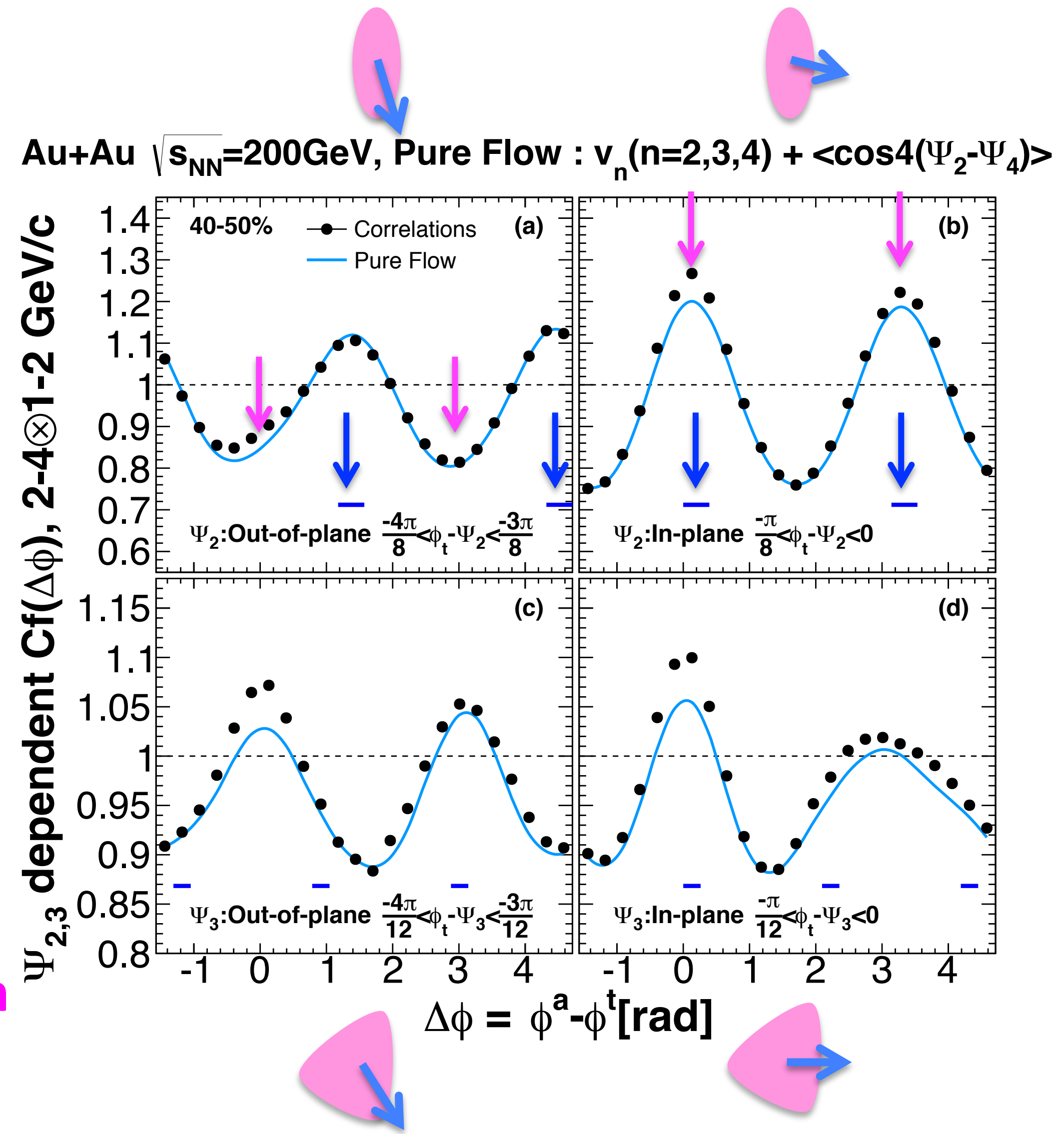
- ✧ **Good reconstruction** of Ψ_2, Ψ_3 dependent correlations by **MC simulation**
  - – Before PTY normalization
- ✧ Except around $\Delta\phi$=0, π where contribution of jet exists

—●— Correlations

— Pure Flow

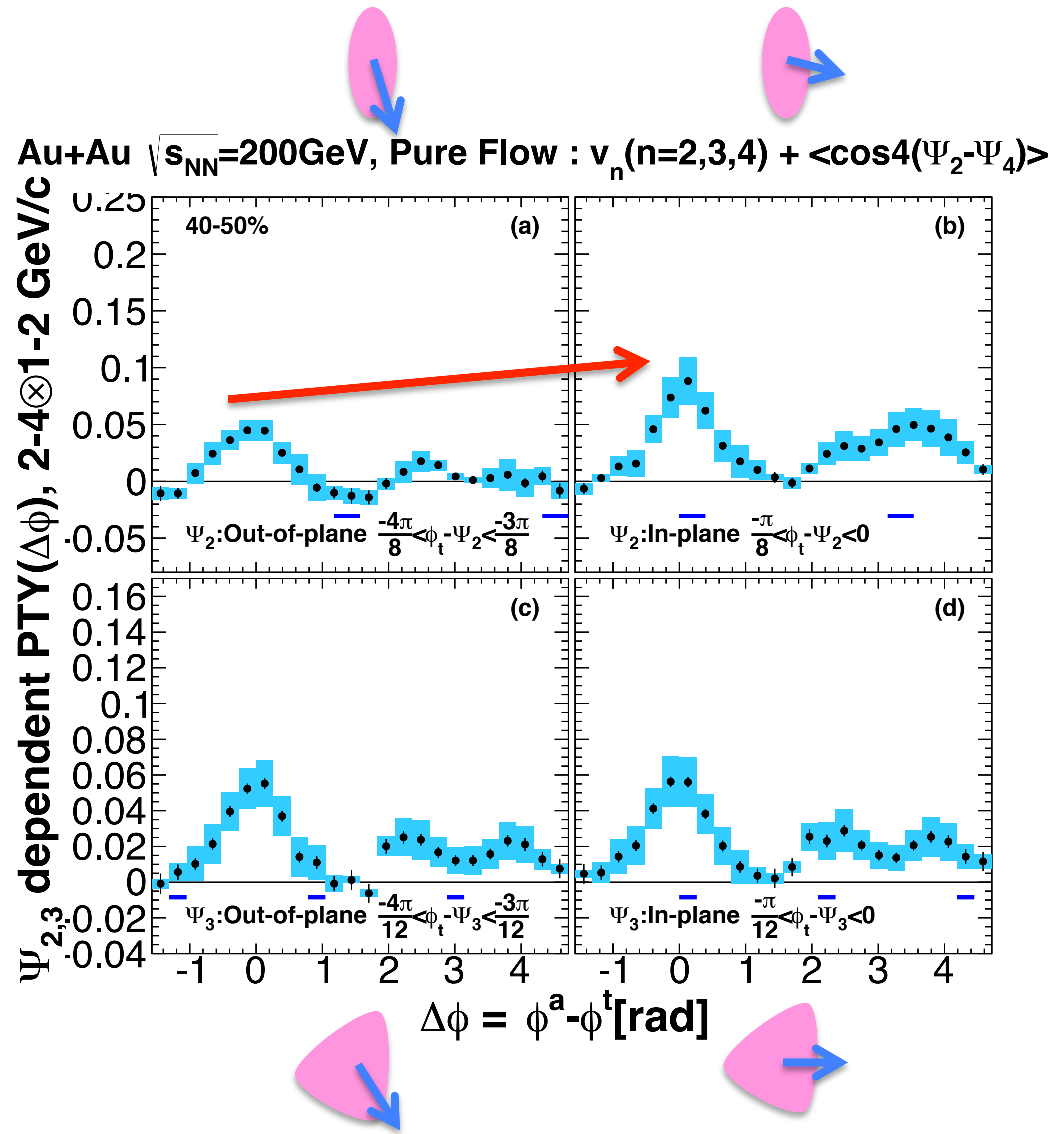
: EP Direction

: Back-to-Back Direction



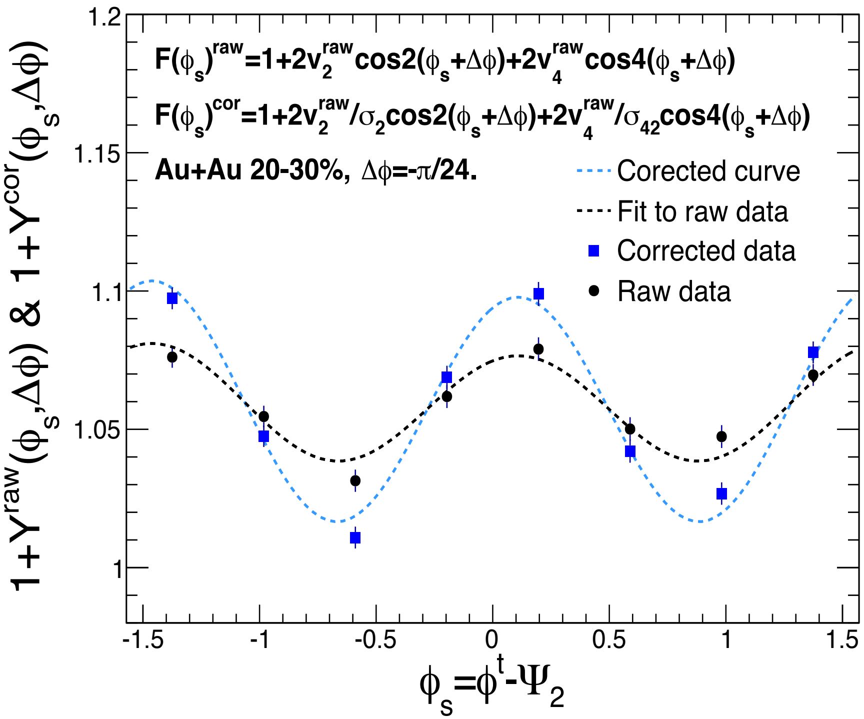
Two-Particle Correlations with respect to EP

- ✧ Flow subtracted Ψ_2, Ψ_3 dependent correlations
- ✧ Clear Ψ_2 dependence
- ✧ No Ψ_3 dependence?
- ✧ Smearing by neighboring trigger bins due to limited EP resolution
  - – Needs unfolding !!

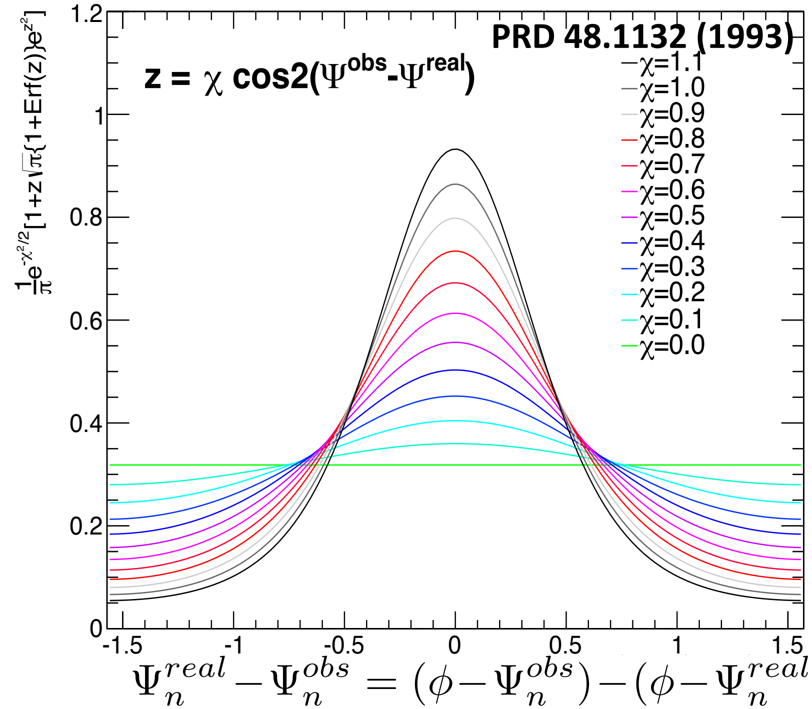


Unfolding Methods of EP Resolution

Fitting Method



Iteration Method



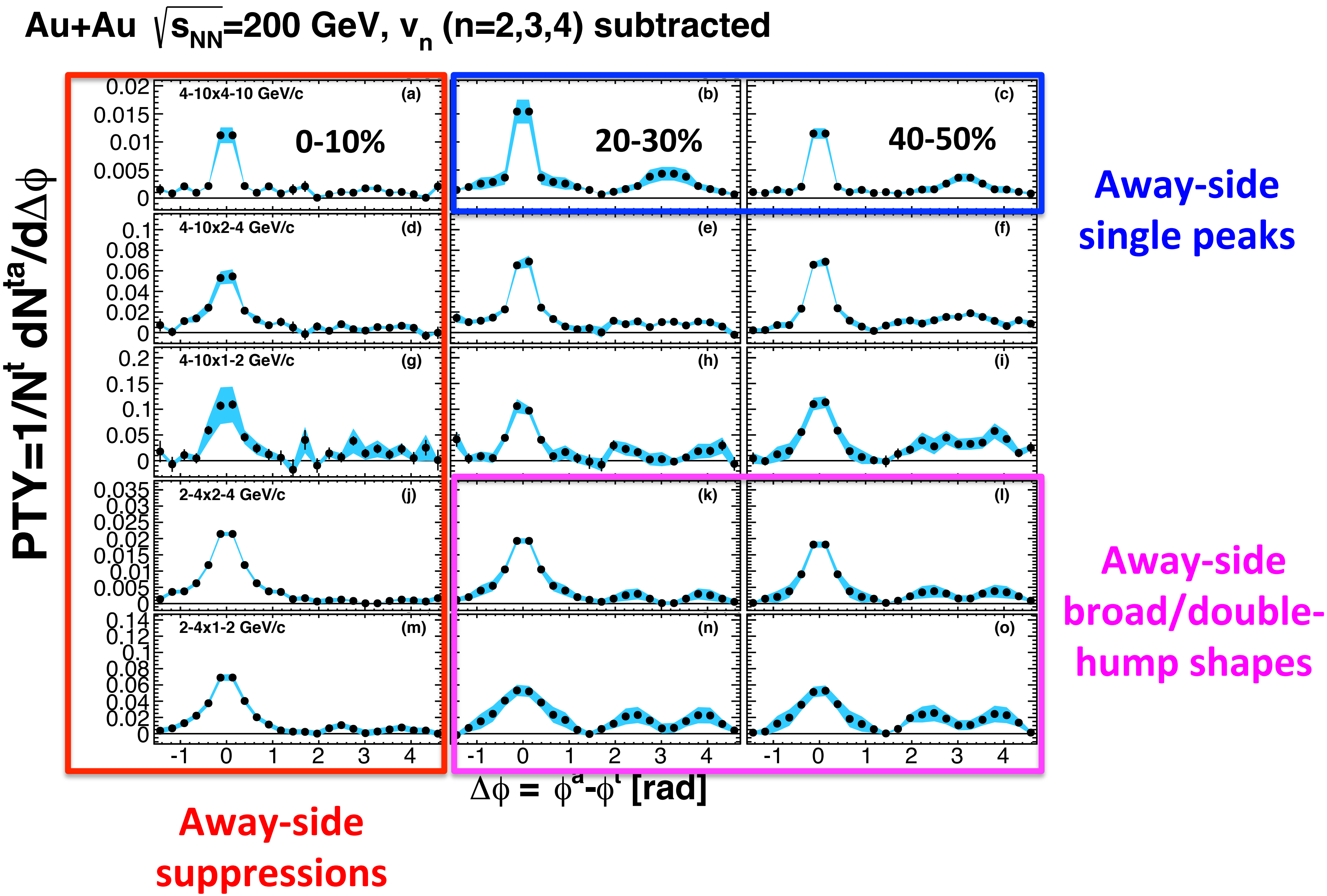
- ✧ **Azimuthal anisotropy of correlation yield corrected by the event-plane resolution**

Method by PRC.84.024904 (2011)

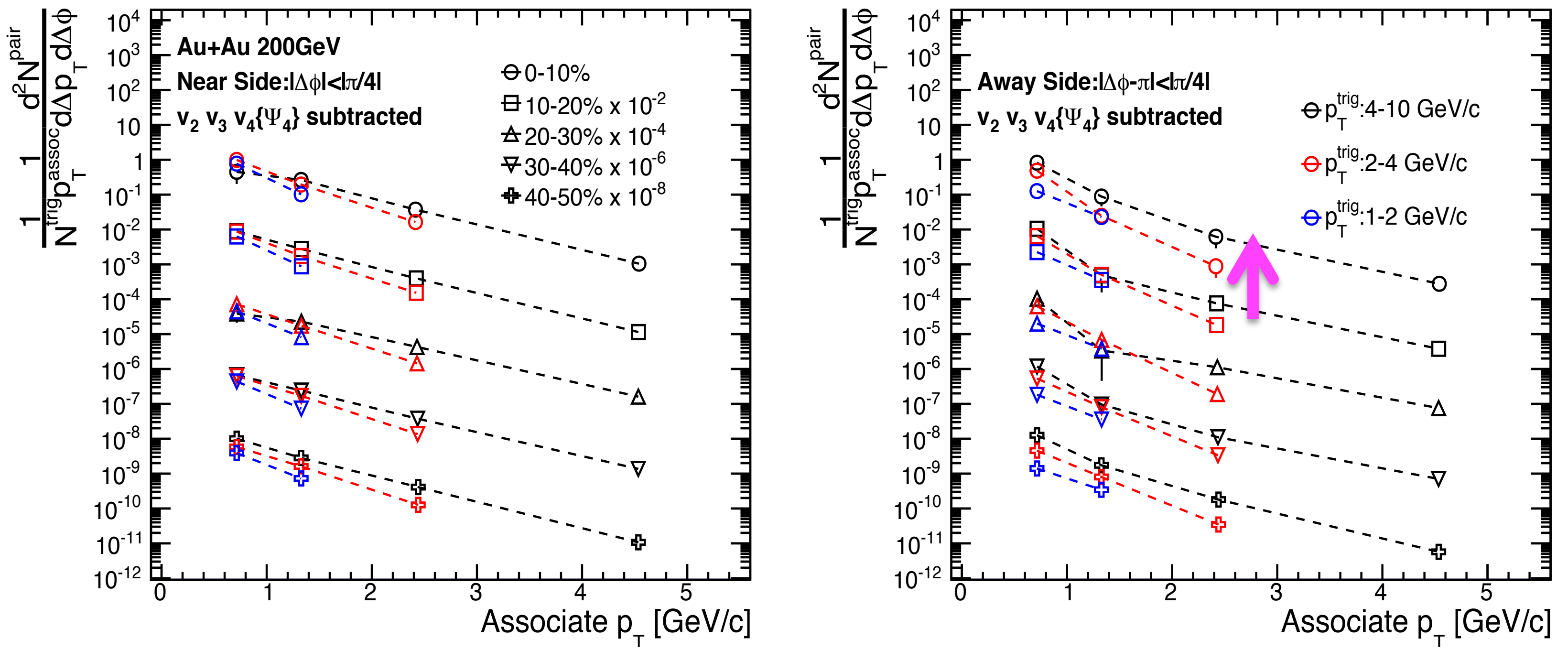
- ✧ **Trigger smearing matrix "*S*"**
- ✧ **True & Observed Correlations "A" & "B"**
  - **Vector elements : Trigger bin**
- ✧ **Solve simultaneous equations via iteration**

$$\mathbf{B}=\mathbf{SA} \Rightarrow \mathbf{A}=\mathbf{S}^{-1}\mathbf{B}$$

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



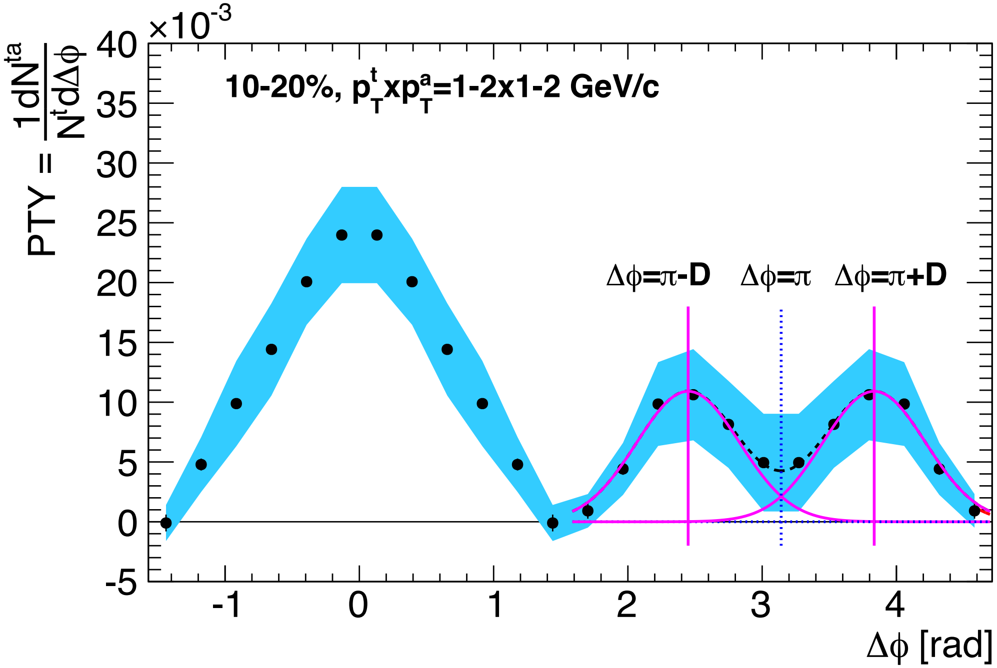
p_T spectra of Per Trigger Yields



✧ **Hardness increases with trigger and associate p_T**

✧ **Existence of high p_T particles enhances lot p_T particles**

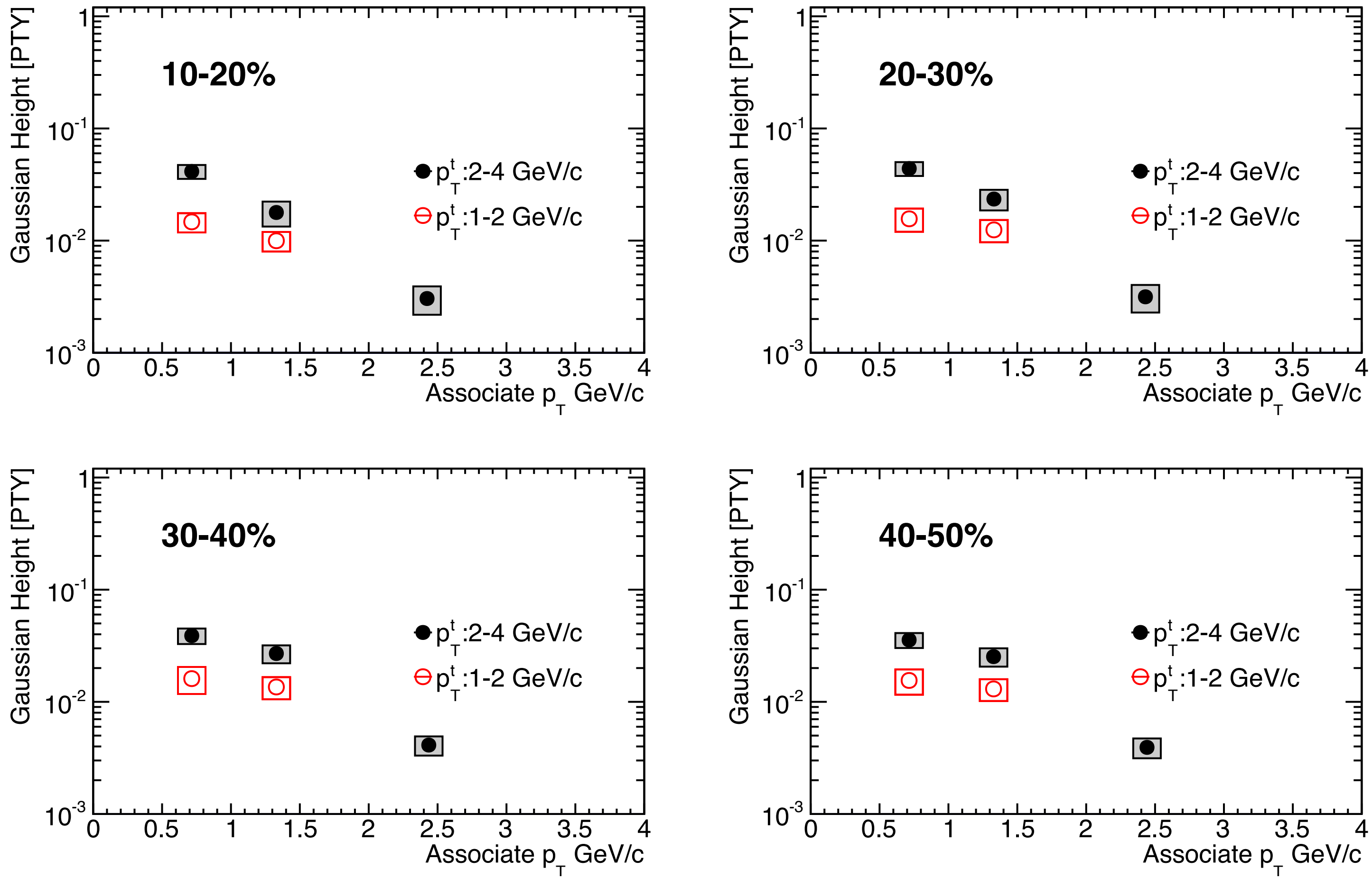
Extraction of Double-Hump Position



✧ **Extraction of double-hump position via two-Gaussian fitting to away-side ($|\Delta\phi - \pi| < \pi$) at centrality 10%>, where double-humps seen**

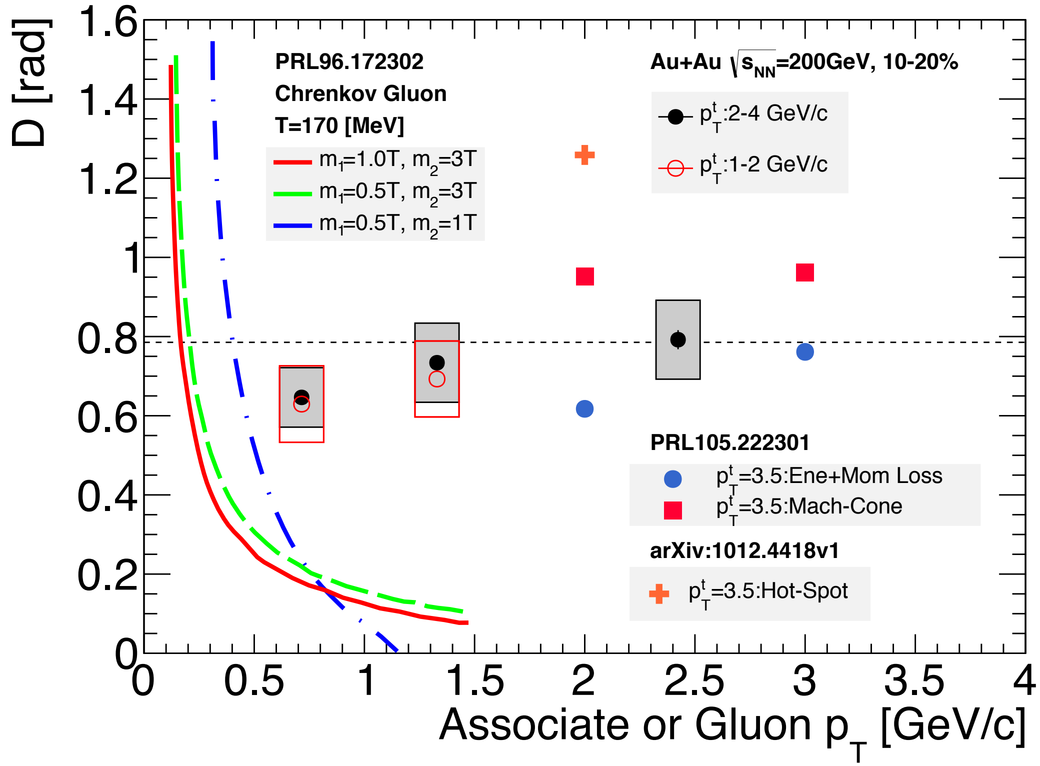
$$F(\Delta\phi) = A e^{-\frac{(\Delta\phi - \pi - \boxed{D})^2}{\sigma^2}} + A e^{-\frac{(\Delta\phi - \pi + \boxed{D})^2}{\sigma^2}}$$

Two-Gaussian Height



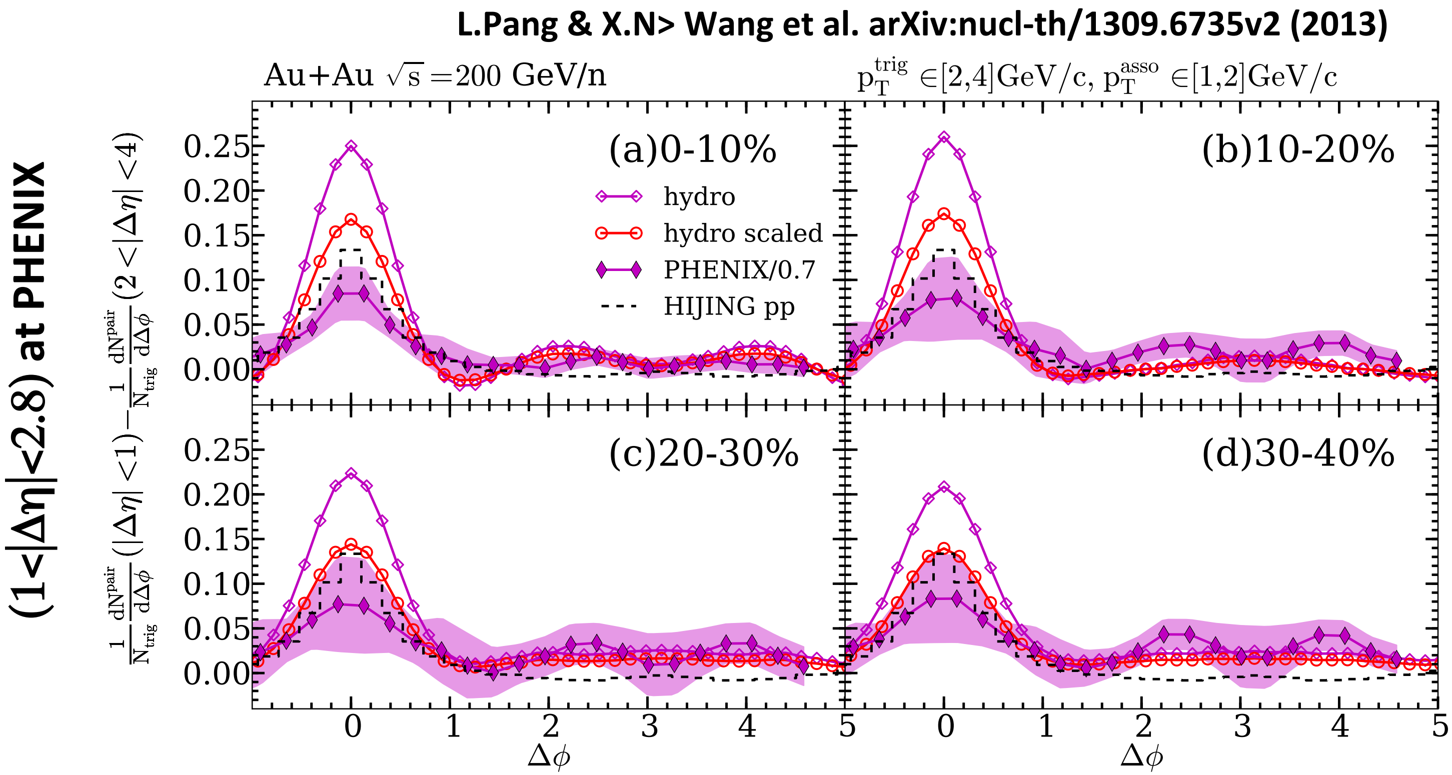
✧ Double-hump height more than one sigma of systematic uncertainties

Comparison with Models



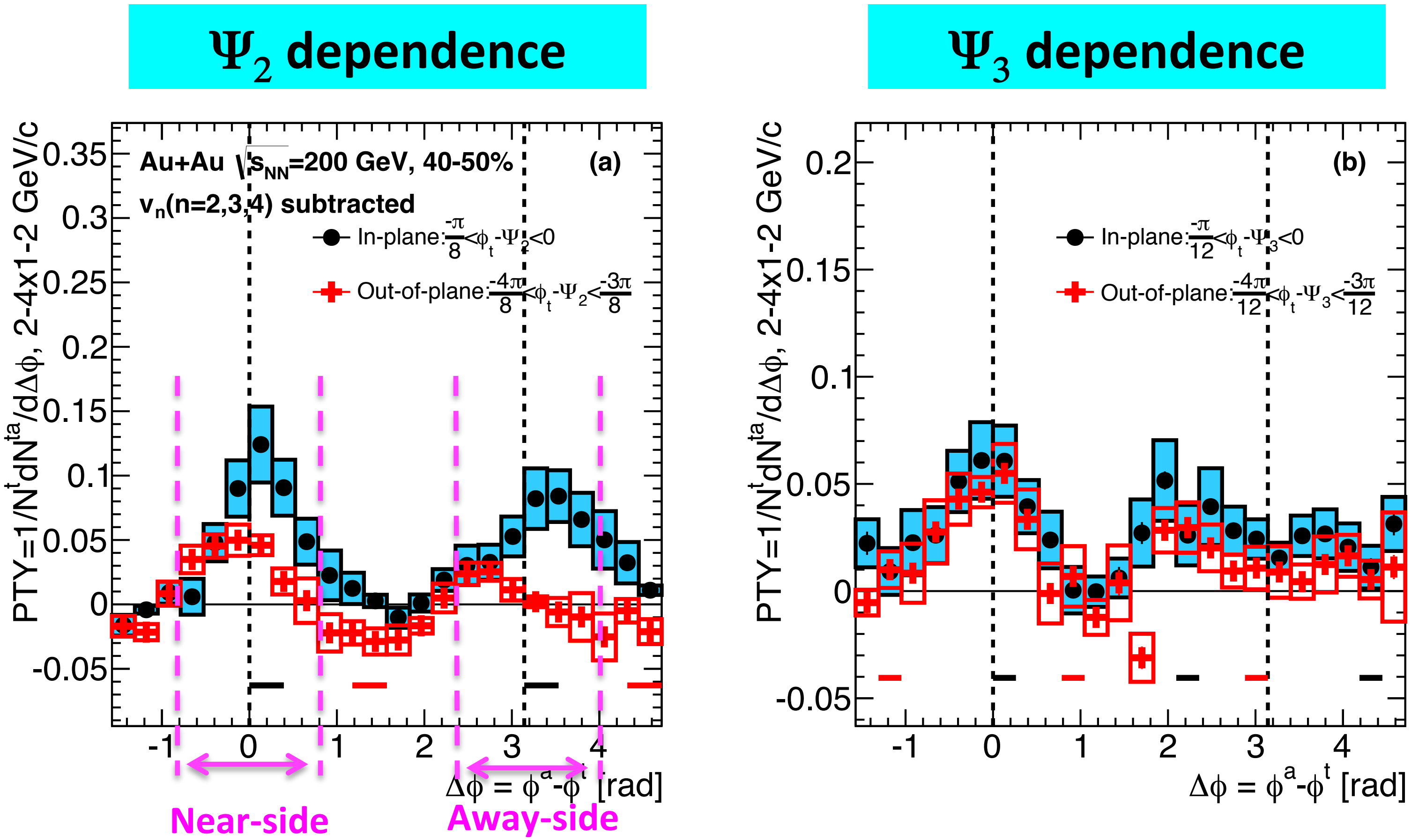
- Cherenkov gluon : <25 % of experimental data at p_T =1 GeV/c
- Mach-cone & Energy-momentum loss :
  - Independence of p_T is similar to the experimental data
  - 20 % larger/smaller than experimental data at p_T =2 GeV/c
- Hot-spot : 50% larger than experimental data

Realistic Model Calculation



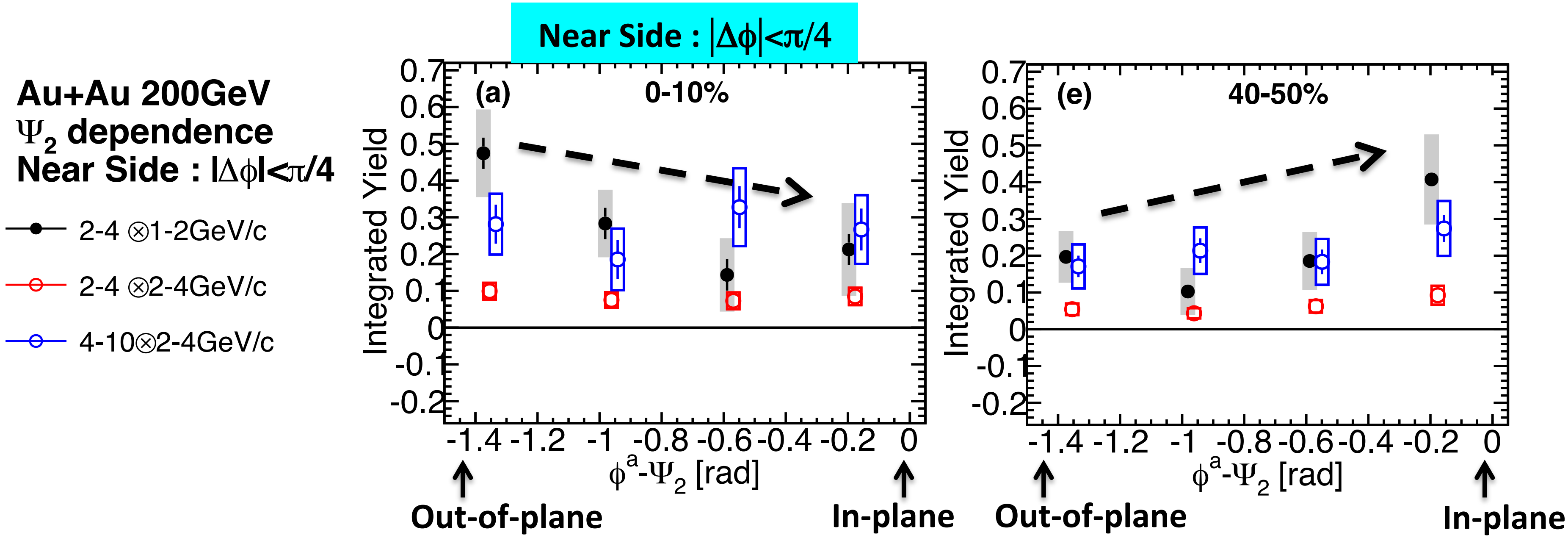
- ✧ **Fluctuations of initial parton energy density**
- ✧ **Parton cascade**
- ✧ **Event-by-event (3+1)D hydrodynamics**
- ✧ **Parton Energy Momentum Loss**

Ψ_2 & Ψ_3 Dependent Correlations at p_T:2-4x1-2 GeV/c

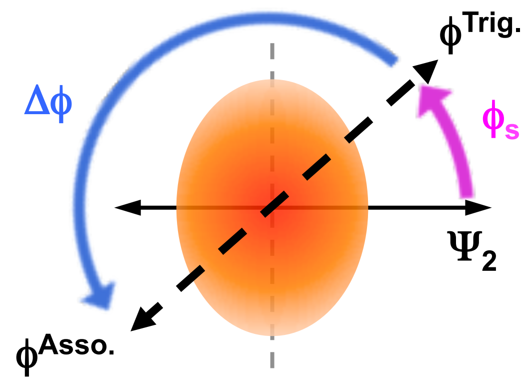


✧ Ψ_2 dependence is observed at intermediate-p_T correlations

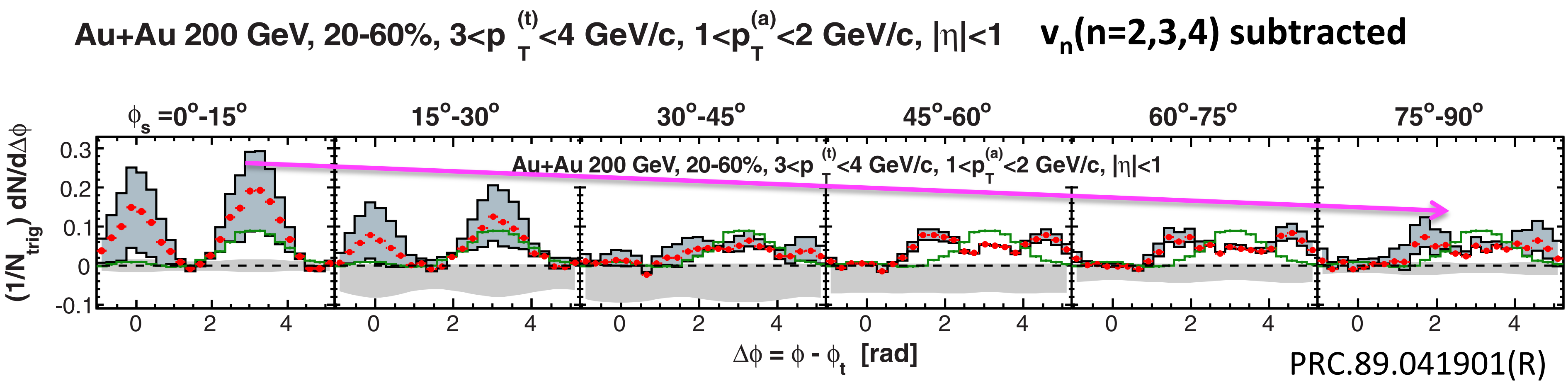
Near-Side Integrated Yield vs Associate Angle from Ψ_2



- ✧ Similar near and away-side trends
- ✧ p_T 2-4x2-4, 4-10x2-4 GeV/c : in-plane >= out-of-plane
  - Consistent with the parton energy loss picture
- ✧ p_T 2-4x1-2 GeV/c
  - 0-10% : Out-of-plane > In-plane
  - 40-50% : In-plane > Out-of-plane
  - More than 1σ significance of total systematics



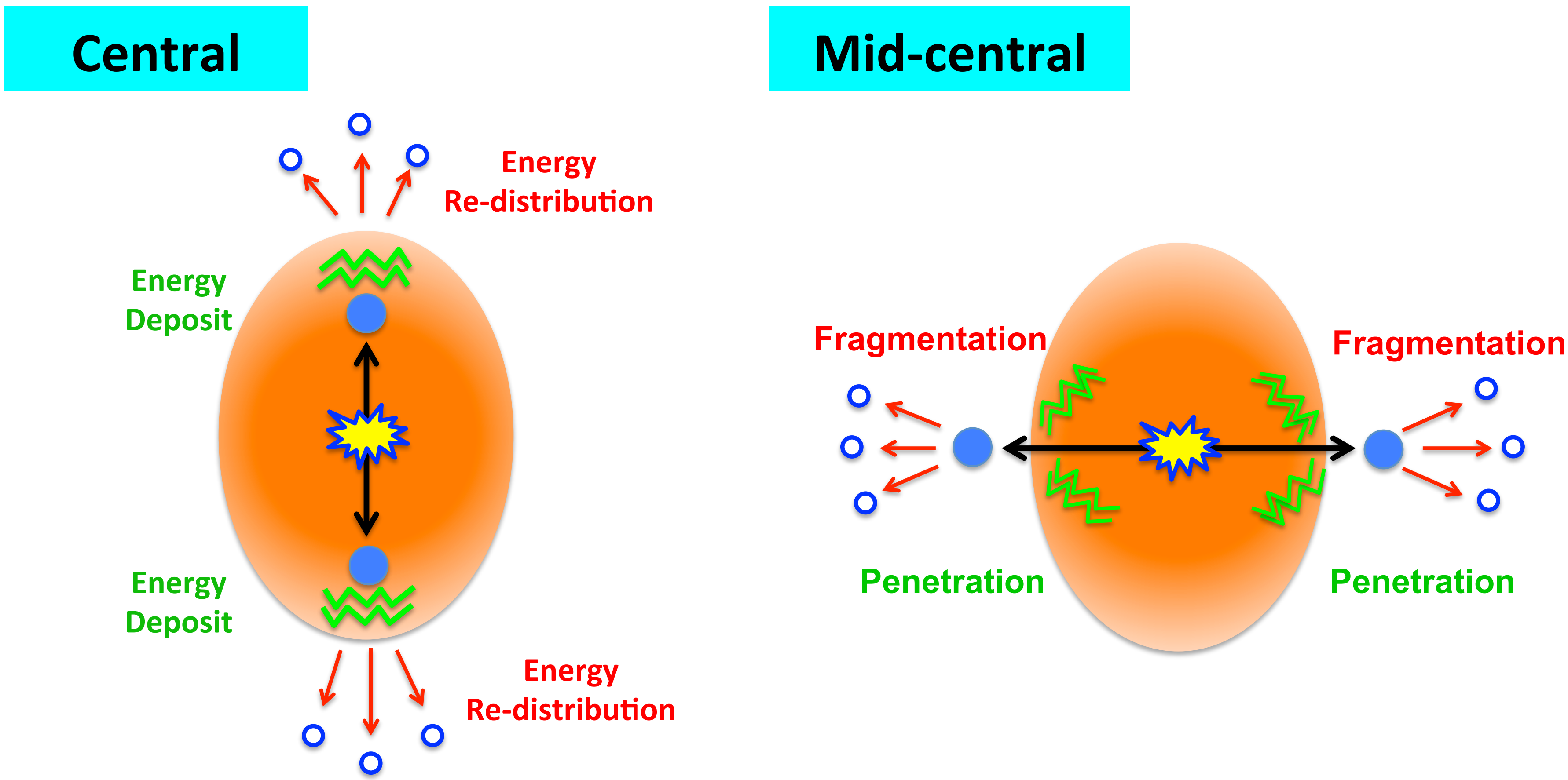
STAR Result of Ψ_2 Dependent Correlations



PRC.89.041901(R)

✧ Consistent with the results in mid-central collisions by PHENIX

Interpretation of Ψ_2 Dependent Correlations



Re-distribution Dominance

Penetration Dominance

Hydro + energy redistribution

Purposes and Methods

- *Purpose of this study*

Study the collective response to jet propagation in QGP
transport of the jet's lost energy

- *Method*

Hydrodynamical simulations of di-jet asymmetric events in heavy ion collisions

- *Relativistic hydrodynamic equations with source terms*

Hydrodynamic equations with incoming energy and momentum

$$\boxed{\partial_\mu T^{\mu\nu} = J^\nu}$$

$T^{\mu\nu}$: energy-momentum tensor of the QGP fluid

J^ν : **source term** (energy-momentum deposit from jets)

QM'14 Y. Tachibana

- *Source terms*

Assume sudden thermalization of deposited momentum inside a fluid cell

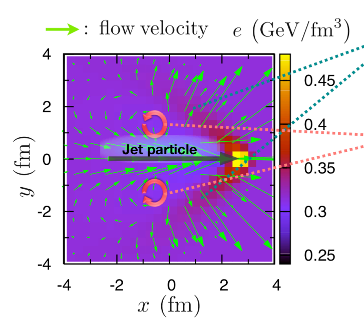
$$J^\mu(x) = -\sum_a \frac{dp_a^\mu}{dt}\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_a(t))$$

a: index for each jet particle

- *Collective flow induced by a jet*

YT and T. Hirano, Nucl.Phys.A904-905 2013 (2013) 1023c-1026c

Test study result in the case of 1-jet traveling through a uniform fluid

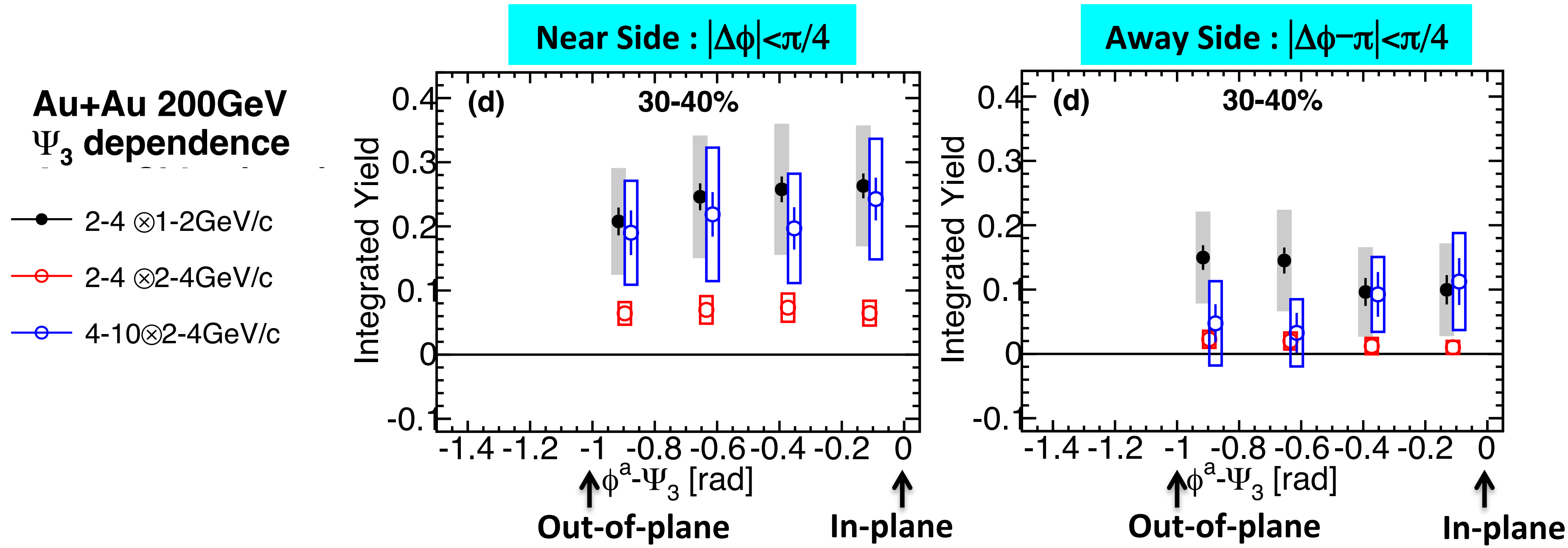


Mach cone
Interference of sound waves induced by a source moving at supersonic speed

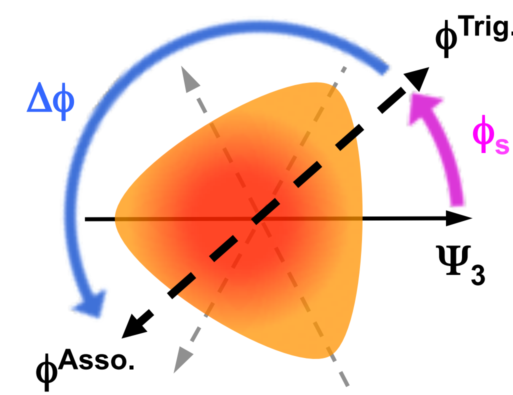
Vortex
Vortex ring around the jet passage in 3-D space

Mach cone carries information about jet energy loss and properties of QGP

Integrated Yield vs Associate Angle from Ψ_3



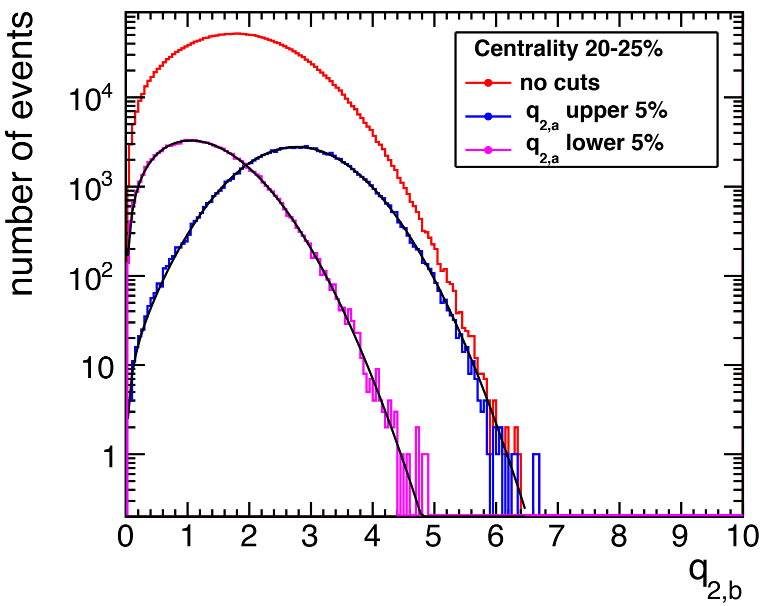
- ✧ **Weak centrality dependence**
- ✧ **Event-plane dependence is not clearly seen**
  - – **Flat within systematic uncertainties**

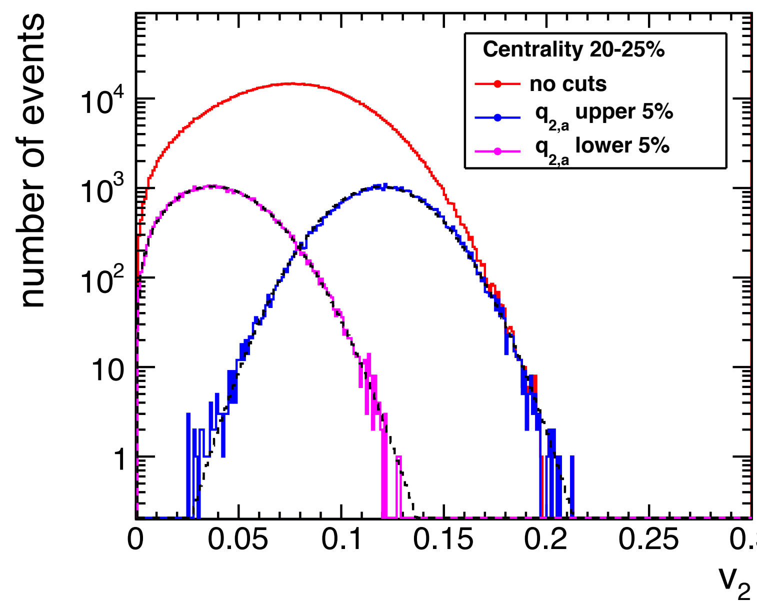


Out Look : Event-Shape Engineering

✧ Q-vector

$$Q_{n,x} = \sum_{i}^{M} \cos(n\phi_i); \; Q_{n,y} = \sum_{i}^{M} \sin(n\phi_i);$$





✧ Selection of flow rich events

✧ Differential analysis of medium response

Summary

- ✧ v_n subtracted correlations are presented

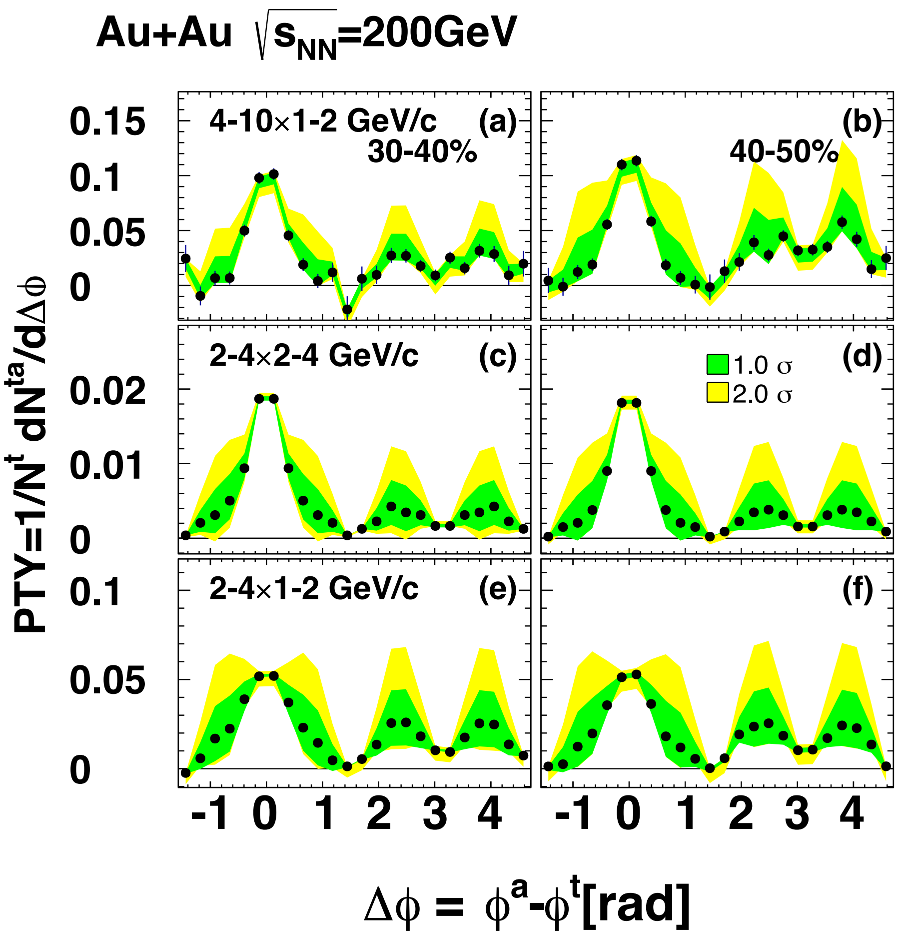
- ✧ Non-monotonic path-length dependence is seen in Ψ_2 dependent correlations at low p_T
  - Can be taken as re-distribution of deposited energy?

- ✧ Non-Ψ_3 dependence is observed due to large systematics

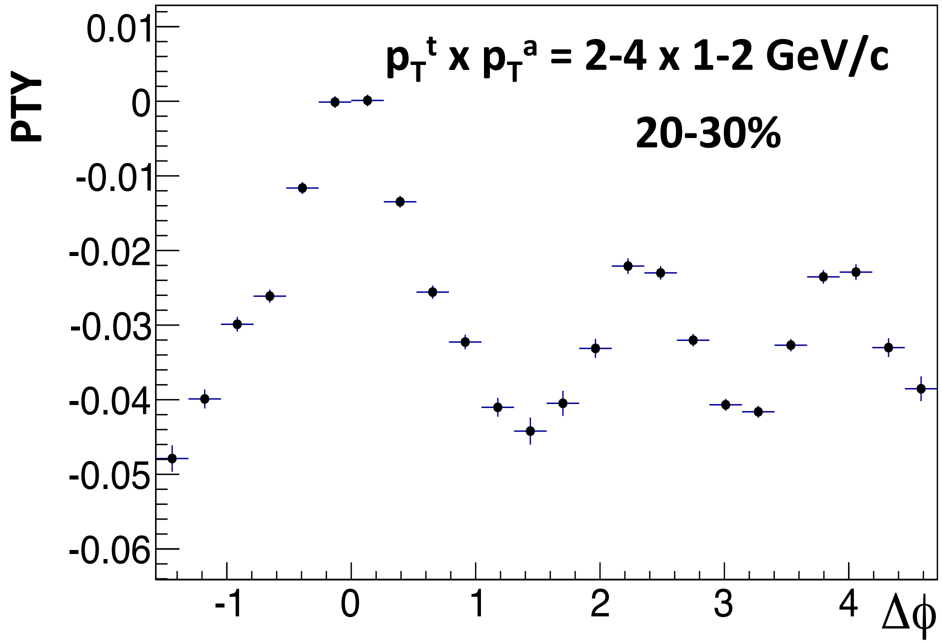
BACK UP

Significance of Double-Hump

- ✧ Examined the significance of Double-Hump in terms of v_4 systematics
- ✧ v_2 and v_3 are fixed in flow subtractions but v_4 is varied $\pm1\sigma$
- ✧ Lower boundary of yellow band covers that of green band
- ✧ Significance is $\pm1\sigma$ level of v_4 systematics



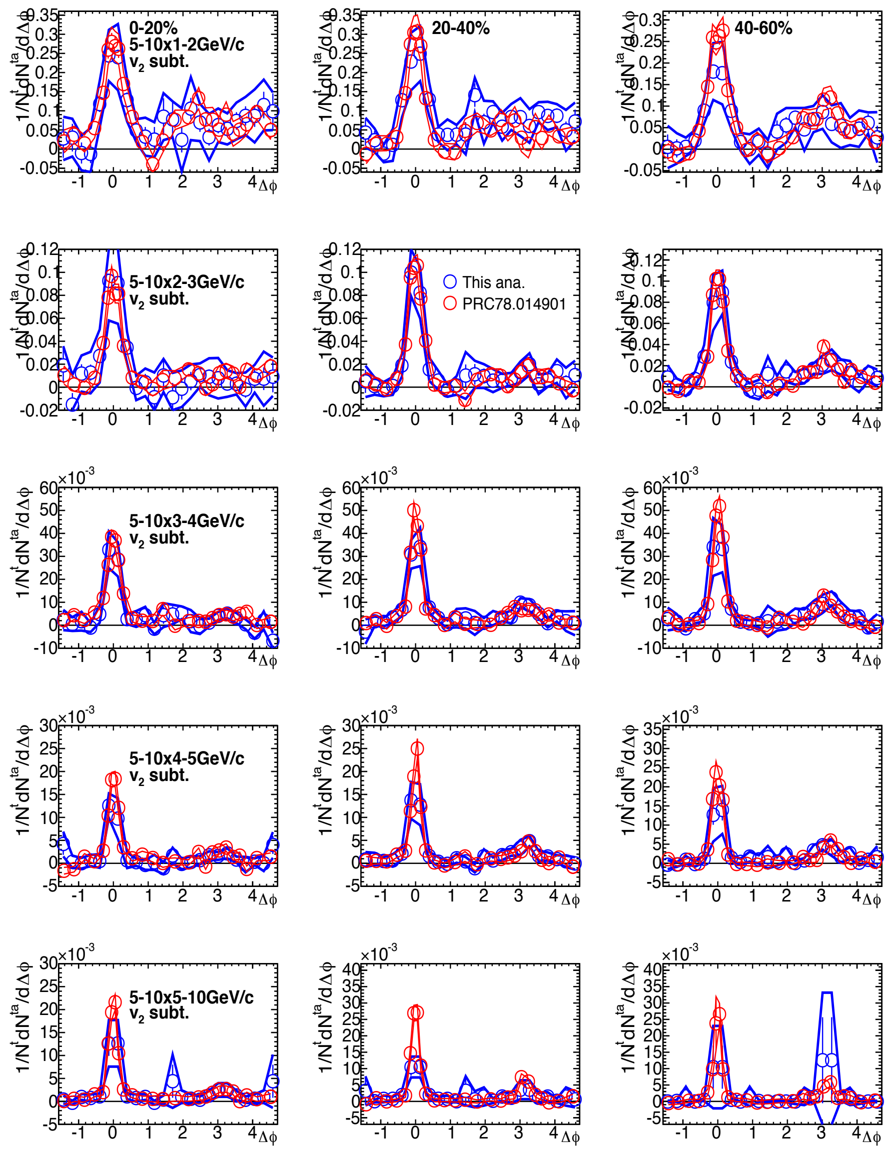
Zero Yield at Near-Side



- ✧ **Correlation and Pure Flow is fitted at $\Delta\phi=0$**
- ✧ **Double-hump is not so sensitive to flow subtraction**

Consistency check : high-p_T trigger

- ✧ Three-Centralities
  - – 0-20, 20-40,40-60%
- ✧ Particle Selections
  - – Trigger p_T:5-10 GeV/c
  - – Associate p_T : 1-10 GeV/c
- ✧ Subtracted Backgrounds
  - – Only v_2
- ✧ Consistent with previous PHENIX results (PRC78.014901)

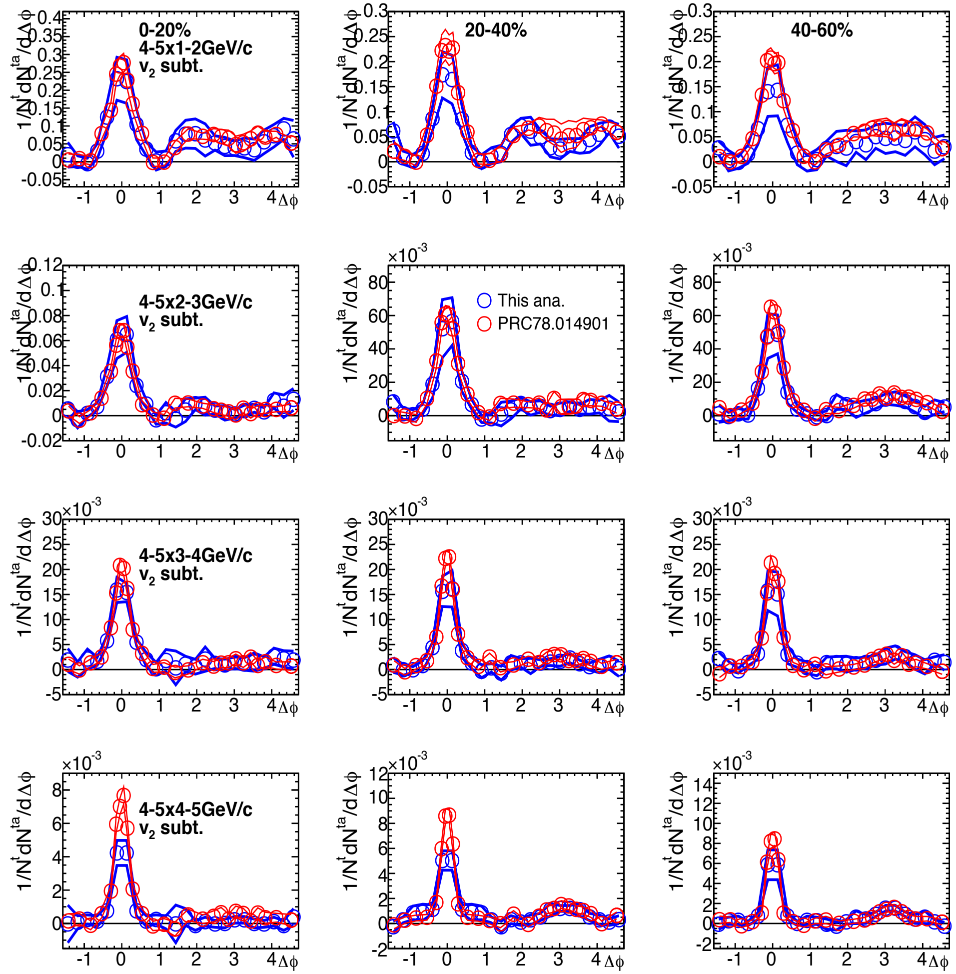


: This Analysis

: PRC78.014901

Consistency check : mid-p_T trigger

- ✧ Three-Centralities
  - – 0-20, 20-40,40-60%
- ✧ Particle Selections
  - – Trigger p_T: 4-5 GeV/c
  - – Associate p_T : 1-5 GeV/c
- ✧ Subtracted Backgrounds
  - – Only v_2
- ✧ Consistent with previous PHENIX results (PRC78.014901)

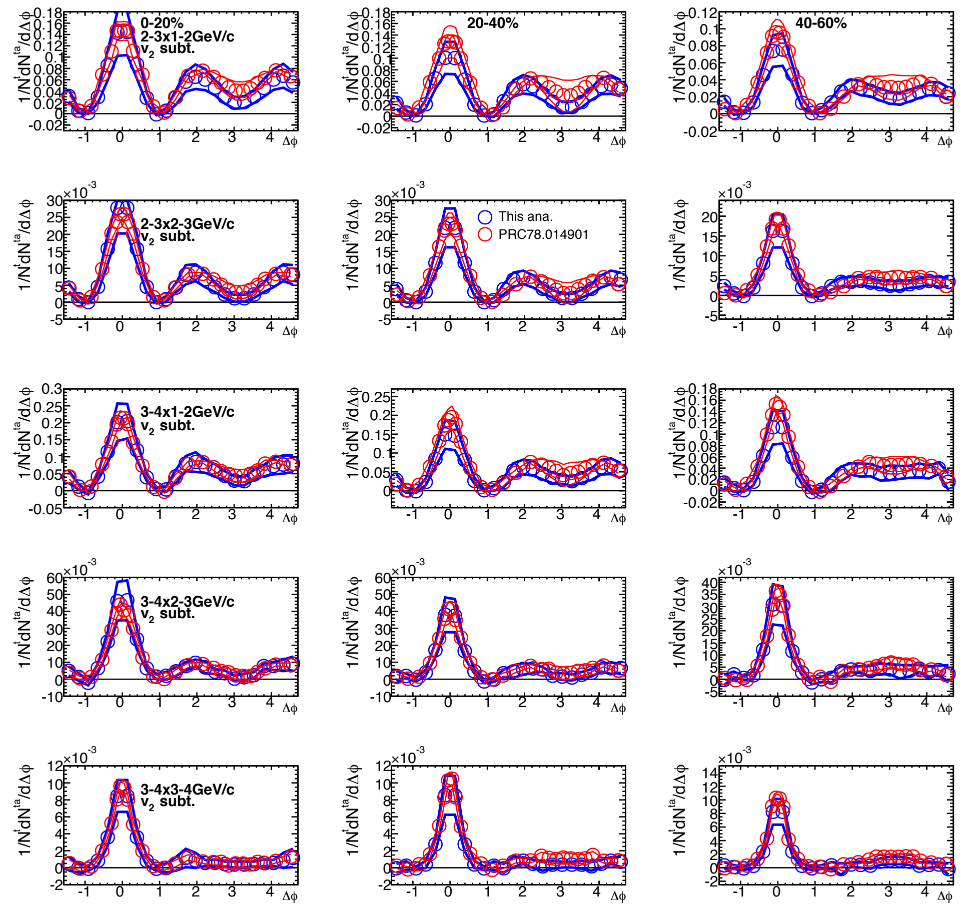


: This Analysis

: PRC78.014901

Consistency check : low-p_T trigger

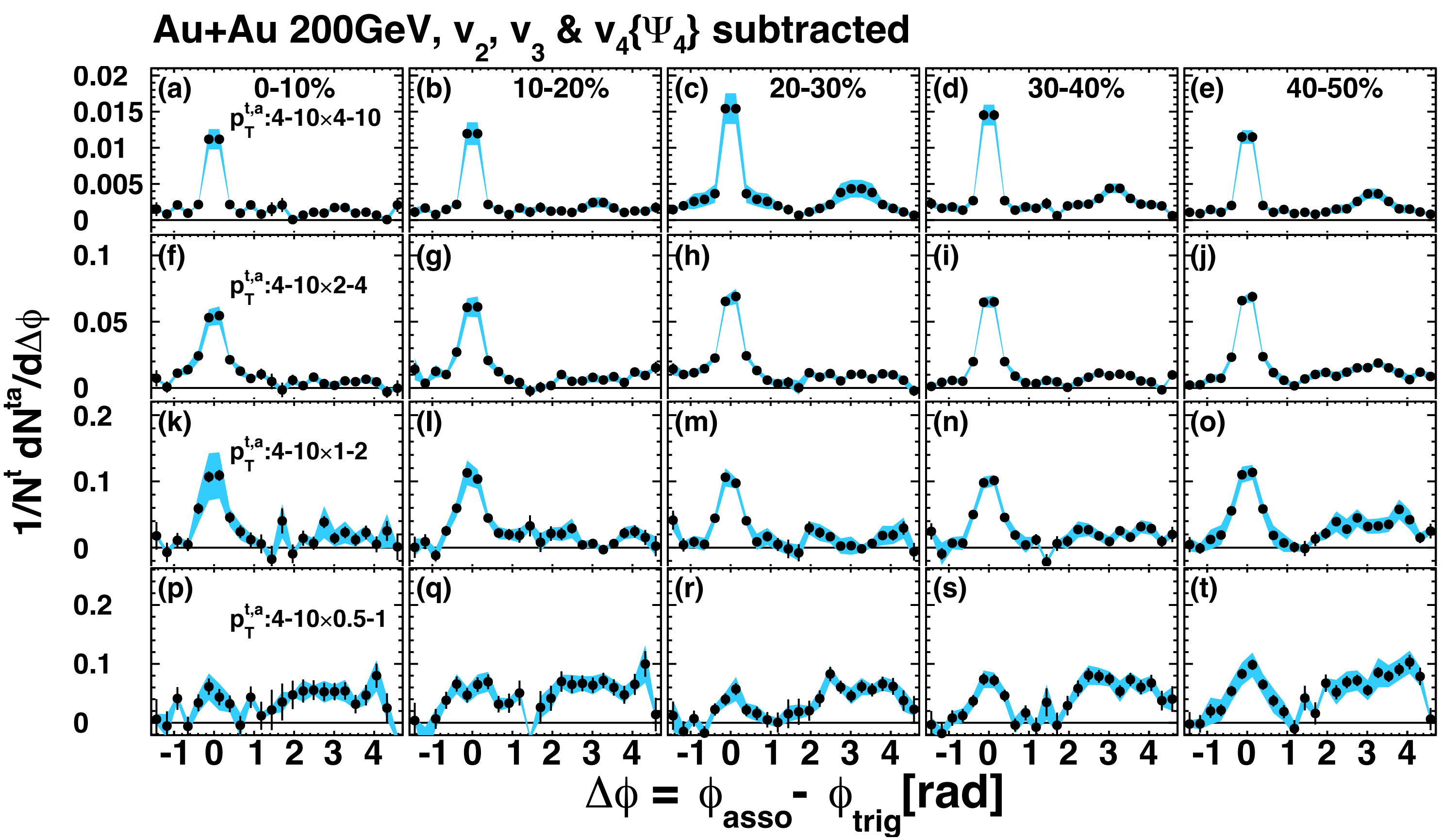
- ✧ Three-Centralities
  - – 0-20, 20-40,40-60%
- ✧ Particle Selections
  - – Trigger p_T: 2-4 GeV/c
  - – Associate p_T : 1-4 GeV/c
- ✧ Subtracted Backgrounds
  - – Only v_2
- ✧ Consistent with previous PHENIX results (PRC78.014901)



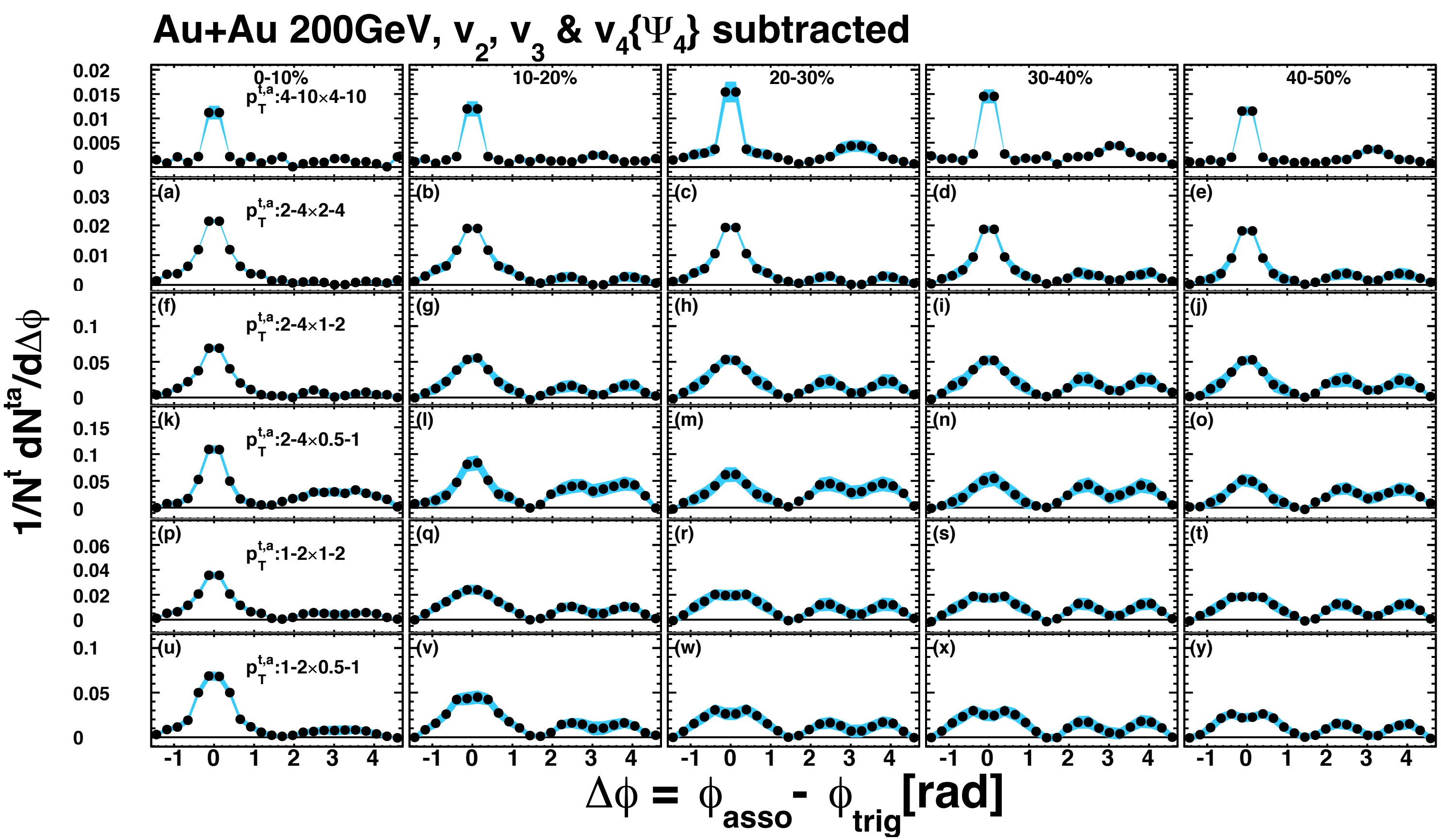
○ : This Analysis

○ : PRC78.014901

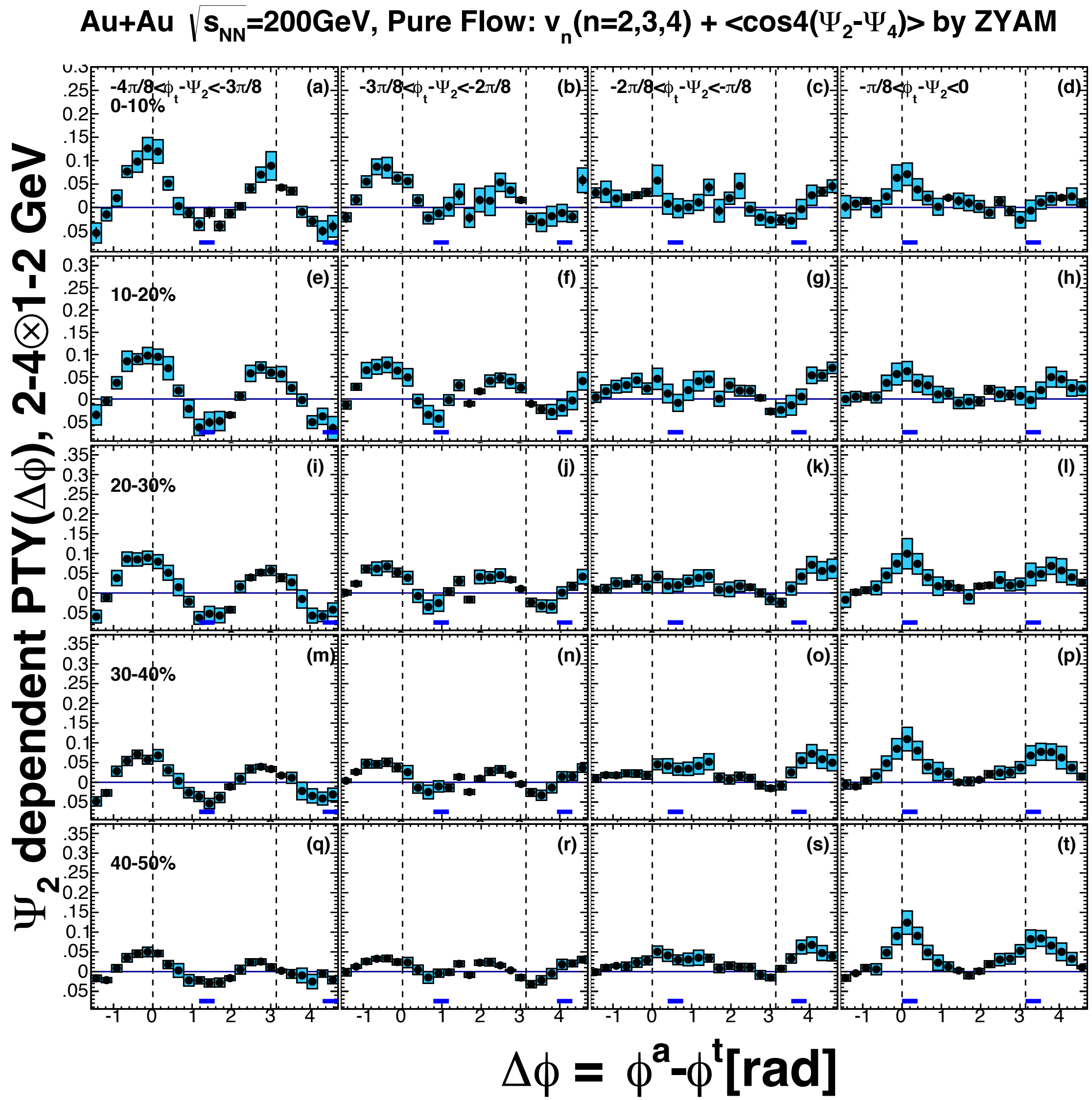
High p_T Trigger Two-Particle Correlations



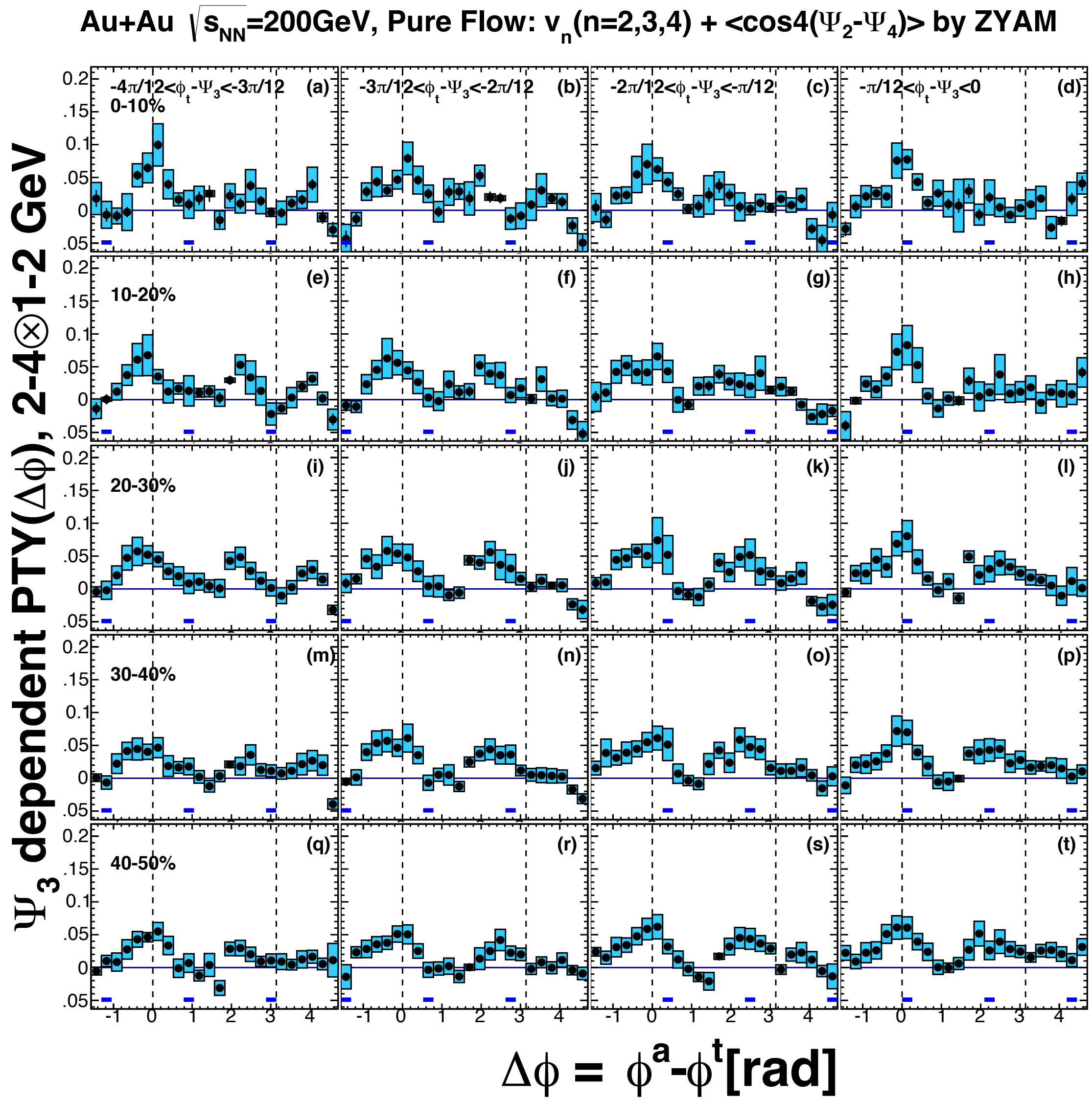
Intermediate p_T Two-Particle Correlations



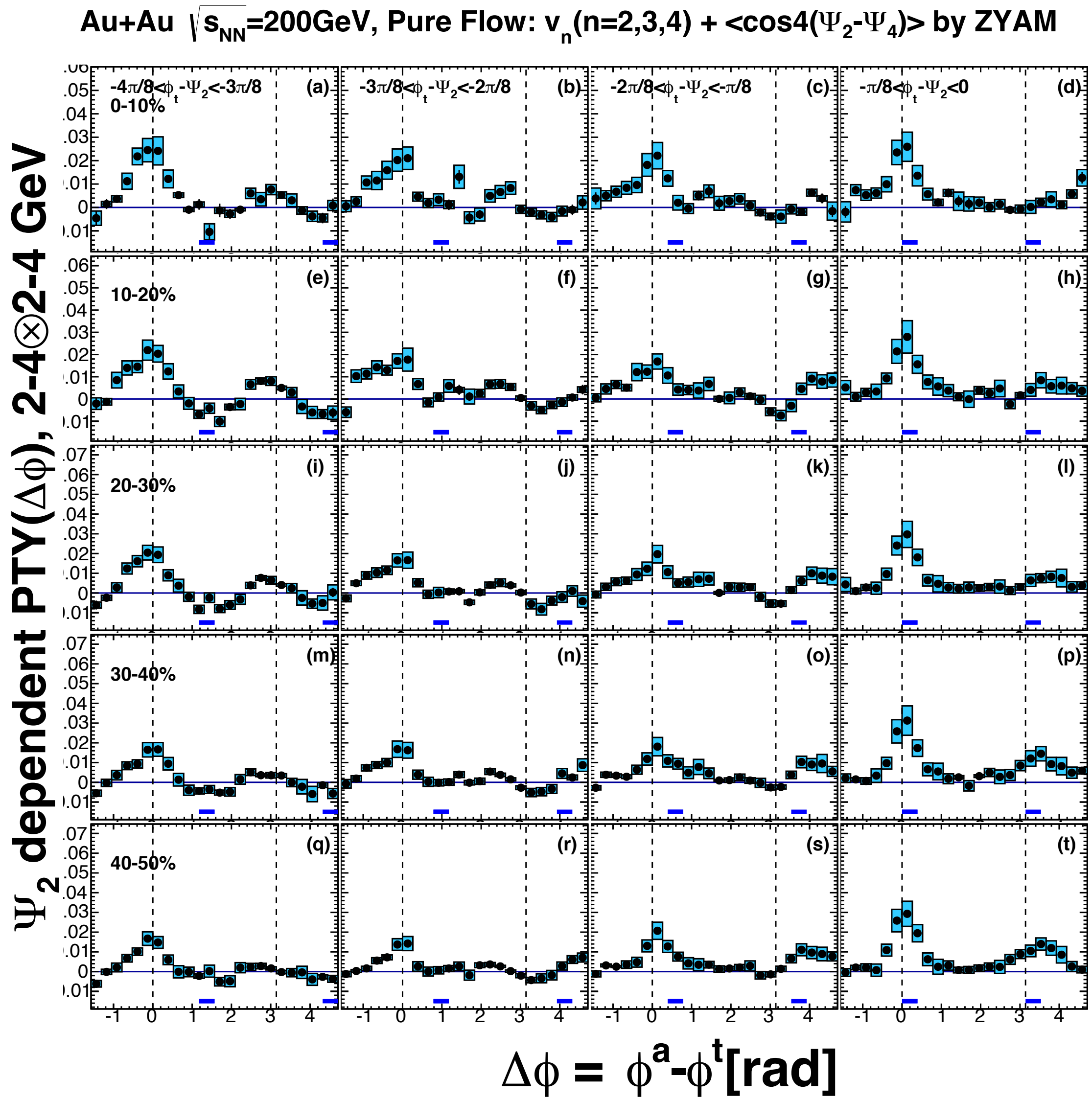
Ψ_2 Dependent Correlations : p_T 2-4x1-2 GeV/c



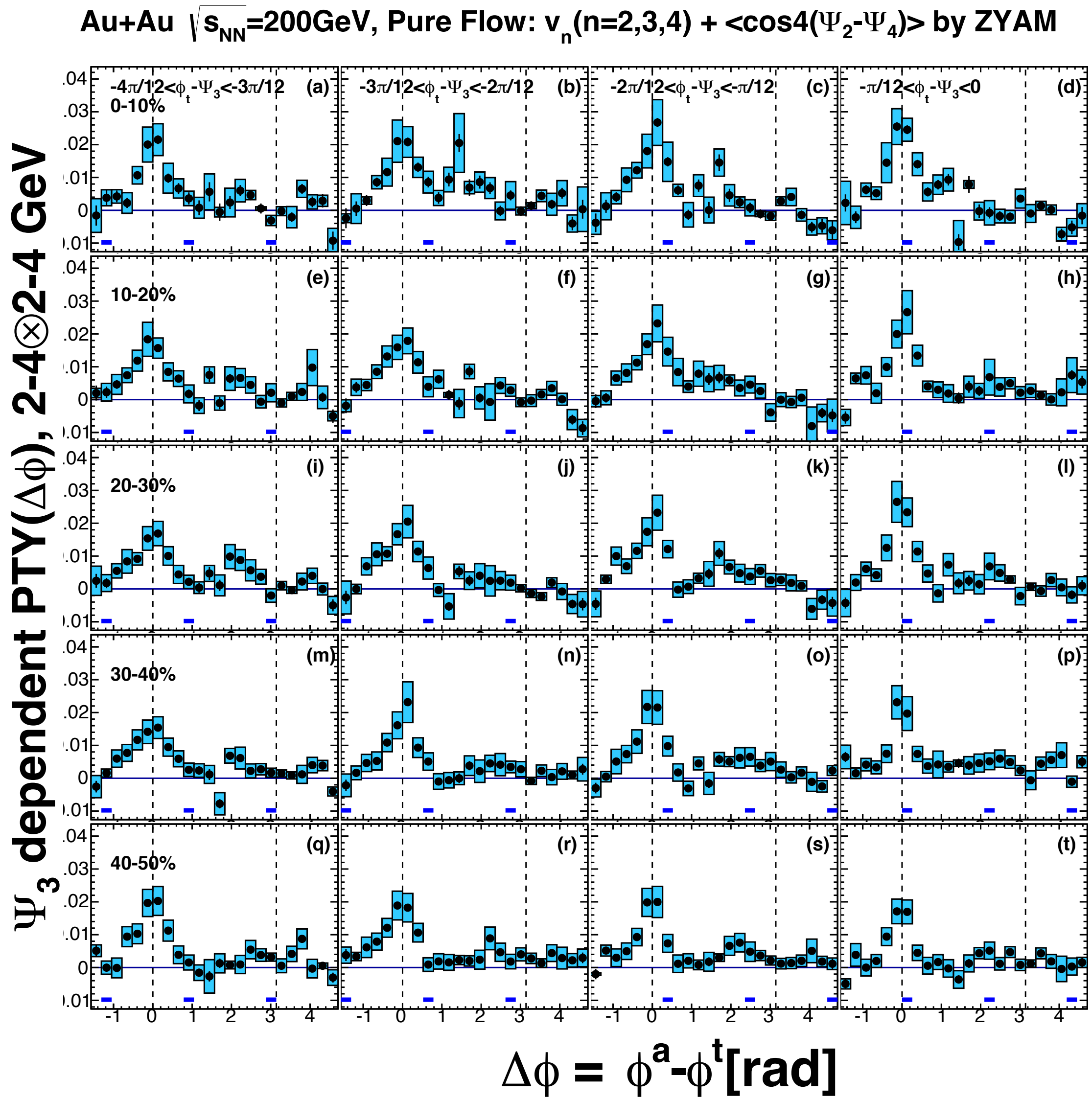
Ψ_3 Dependent Correlations : p_T 2-4x1-2 GeV/c



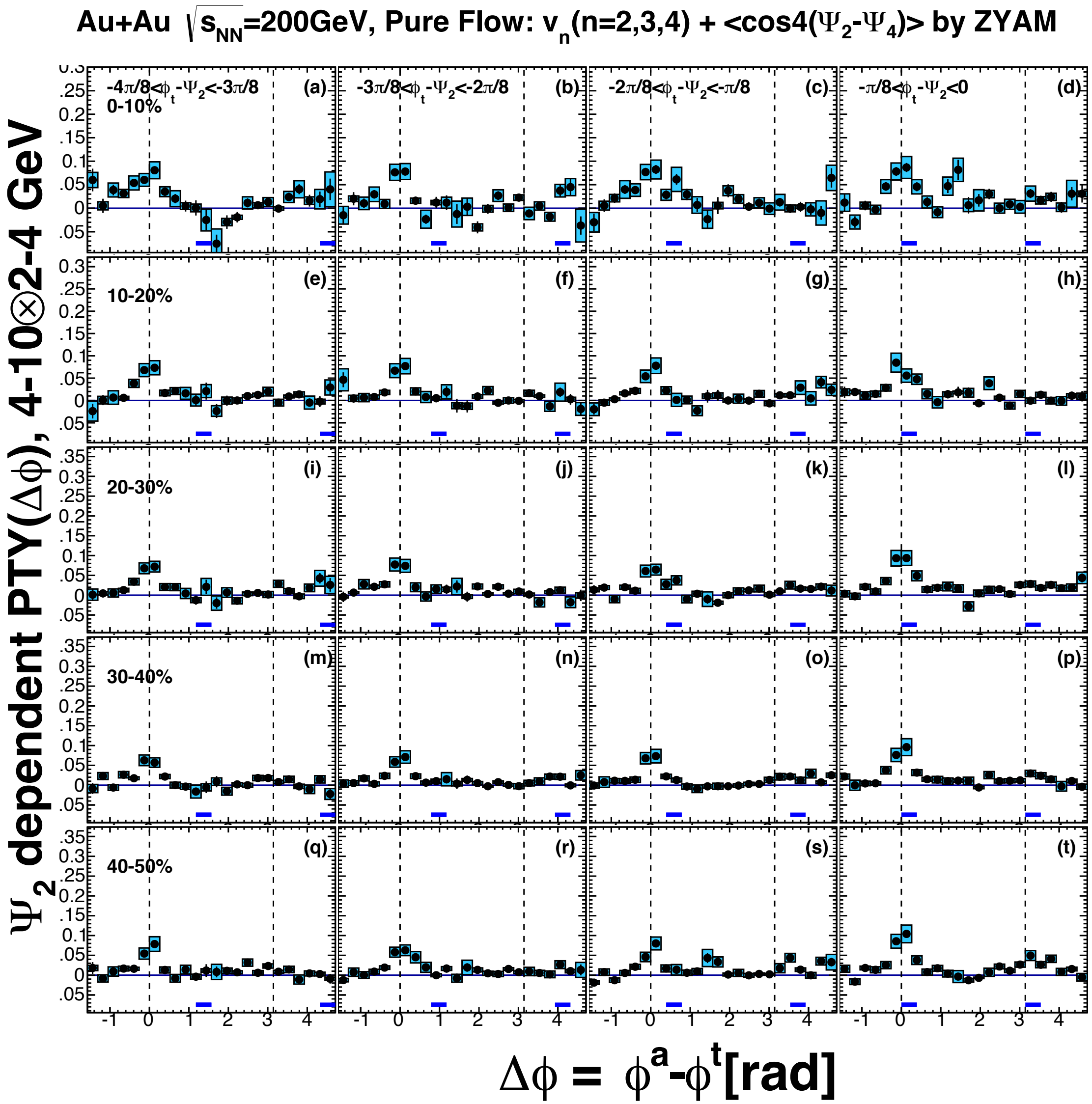
Ψ_2 Dependent Correlations : p_T 2-4x2-4 GeV/c



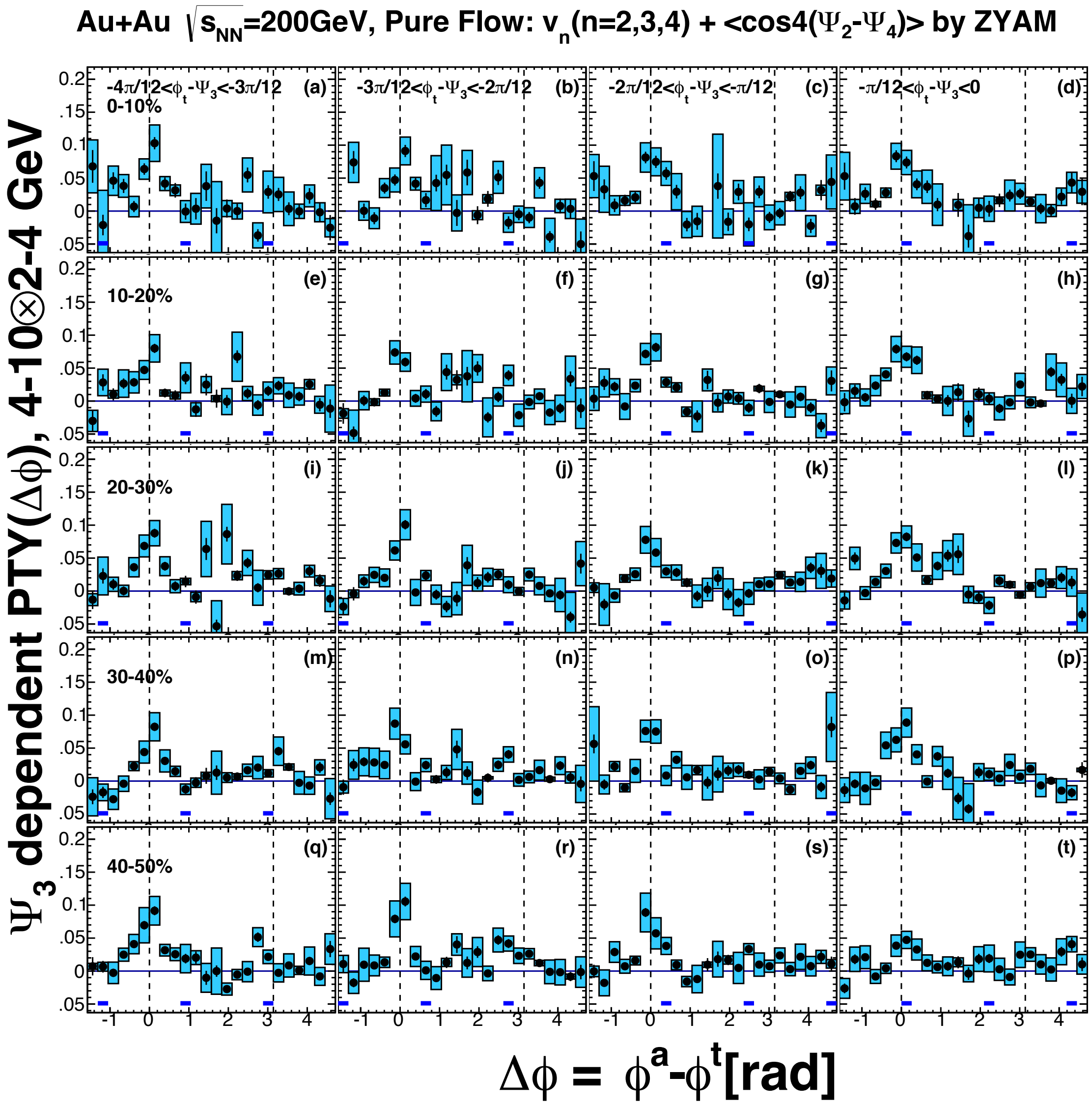
Ψ_3 Dependent Correlations : p_T 2-4x2-4 GeV/c



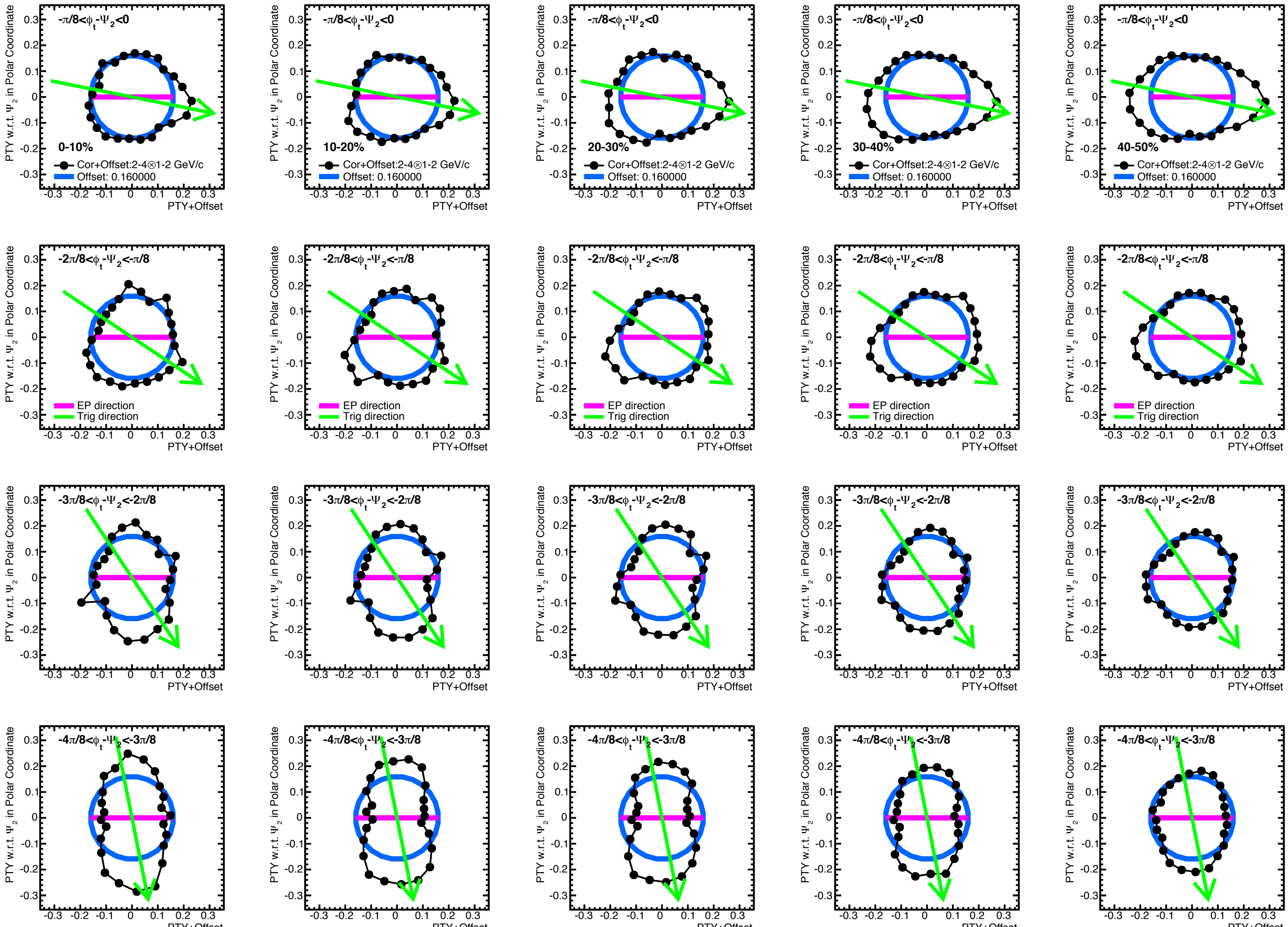
Ψ_2 Dependent Correlations : p_T 4-10x2-4 GeV/c



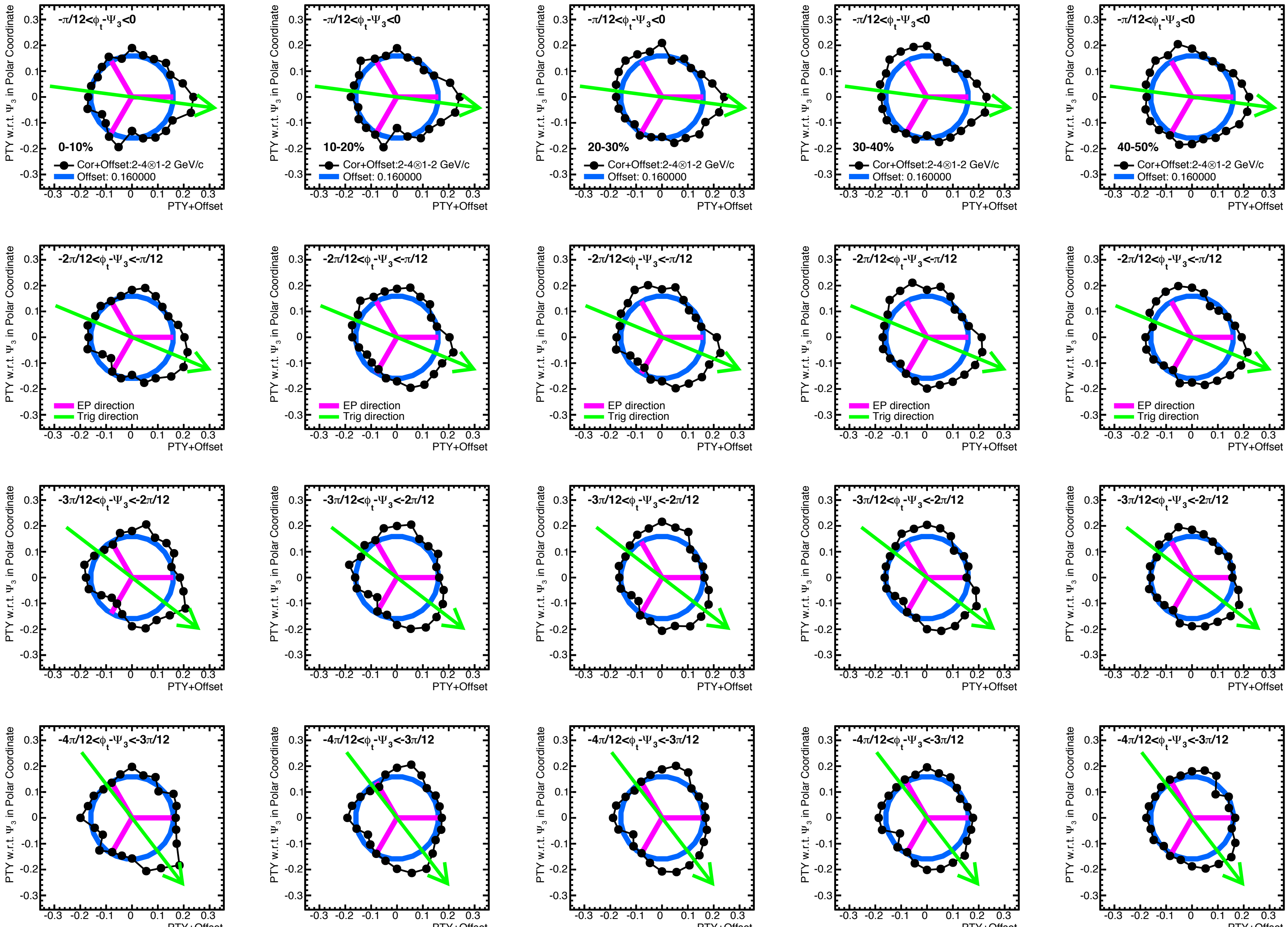
Ψ_3 Dependent Correlations : p_T 4-10x2-4 GeV/c



Ψ_2 Dependent Correlations : p_T 2-4x1-2 GeV/c



Ψ_3 Dependent Correlations : p_T 2-4x1-2 GeV/c



Gravity Position of Two-Particle Correlations

Definition

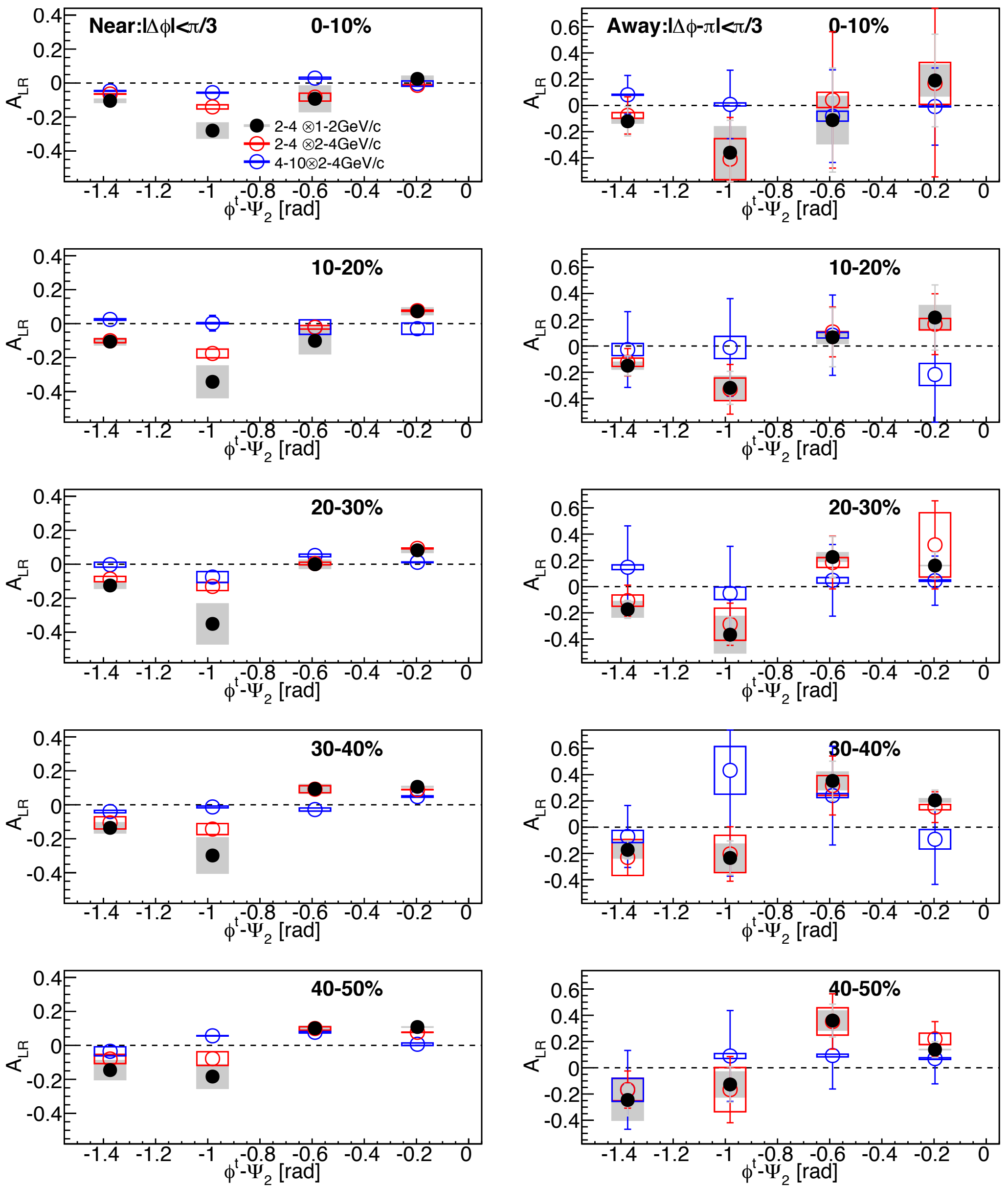
$$A_{LR} = \frac{\int d\Delta\phi \Delta\phi Y(\Delta\phi)}{\int d\Delta\phi Y(\Delta\phi)} - \begin{cases} 0 \text{ if near} - \text{side} \\ \pi \text{ if away} - \text{side} \end{cases}$$

Integral Ranges

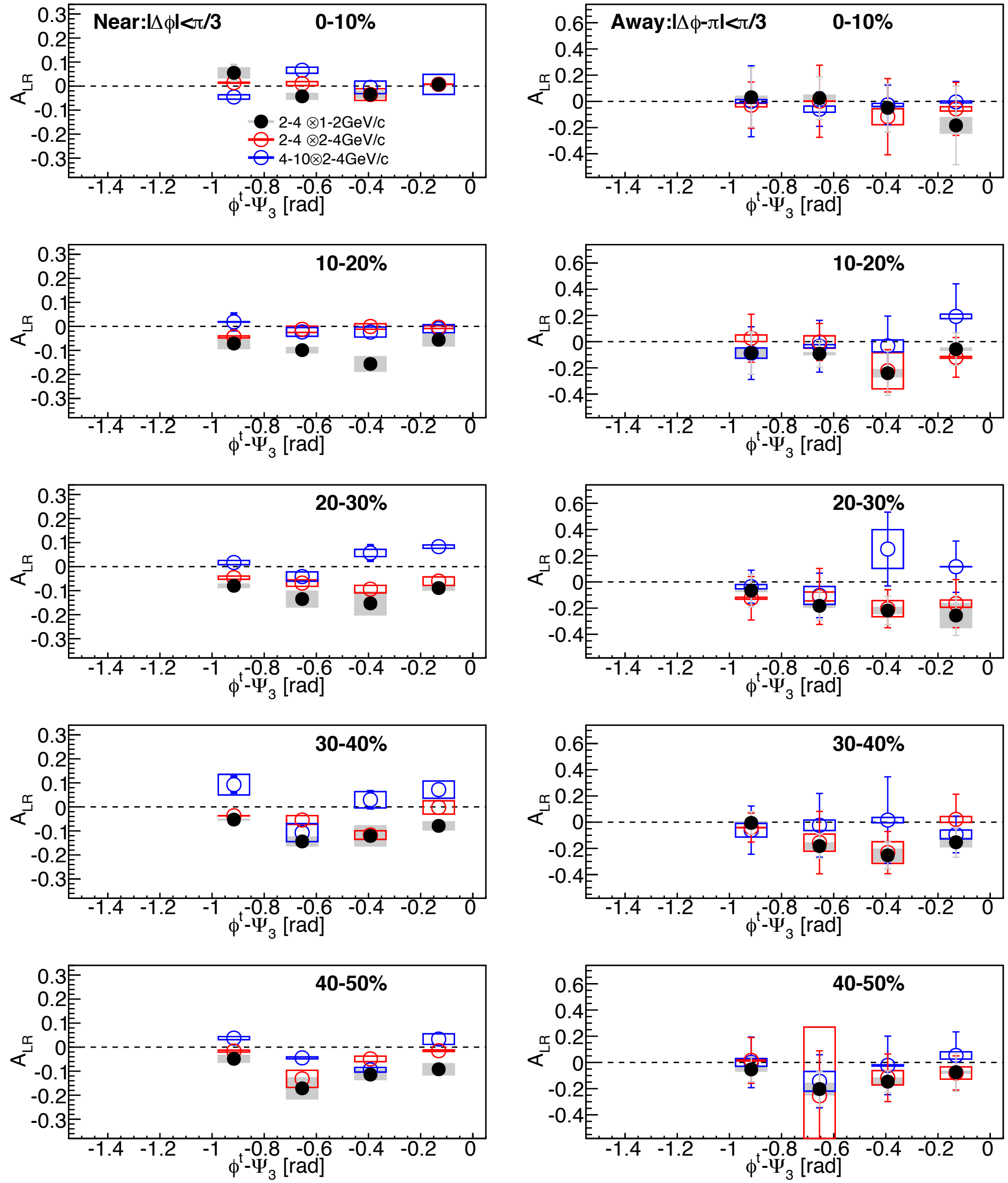
Near – Side : $|\Delta\phi| < \pi/3$

Away – Side : $|\Delta\phi - \pi| < \pi/3$

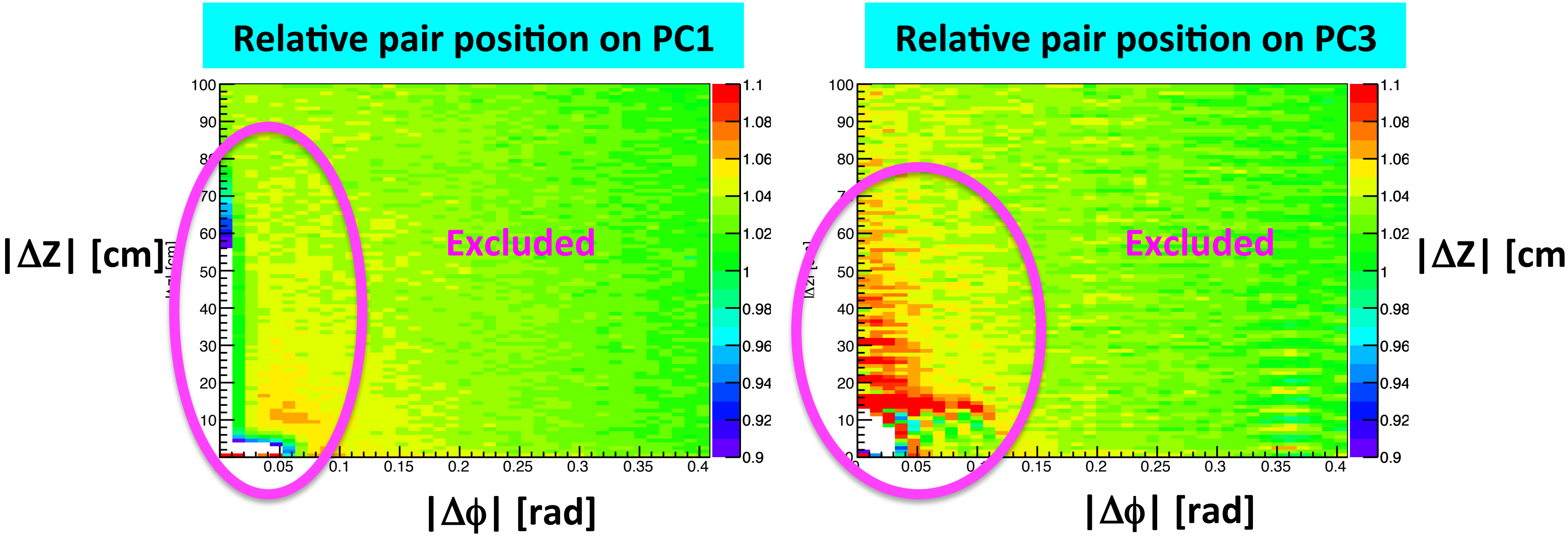
Gravity position vs trigger angle from Ψ_2



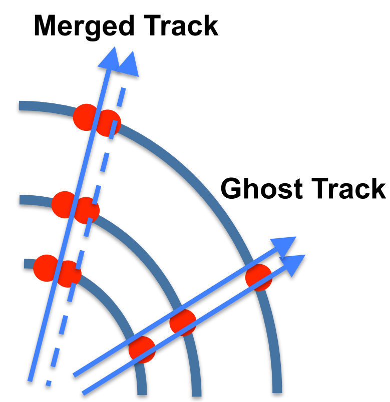
Gravity position vs trigger angle from Ψ_3



Pair Selection on Tracking Detectors



- ✧ **Ghost track**
  - – **A single particle is counted as two tracks**
- ✧ **Merged tracks**
  - – **Two particles are counted as one track**
- ✧ **Real/Mix pair ratio should be 1 if an ideal detector**



Systematic Uncertainties

- ✧ **Flow v_n measurements**
  - Systematic difference within RXN segments
  - Rapidity dependence of EP : RXN-BBC difference
  - Matching cut of CNT particles
- ✧ **Two-particle correlations**
  - Systematics from v_n
  - Matching cut of CNT particles
- ✧ **Unfolding of event plane dependent correlations**
  - Difference of two methods : Fit & Iteration Methods
  - Parameter in the iteration method

Azimuthal Anisotropy of PTY

- Integrated yield vs associate angle from EP is translated into azimuthal anisotropy v_n^{PTY}
- v_n^{PTY} can be compared with single particle v_n because the dimension of PTY is "# of particles"

- v_n^{PTY} is extracted via Fourier fitting

Ψ_2 dependence $F(\phi^a - \Psi_2) = a\{1 + 2v_2^{PTY}\cos 2(\phi^a - \Psi_2) + 2v_4^{PTY}\cos 4(\phi^a - \Psi_2)\}$

Ψ_3 dependence $F(\phi^a - \Psi_3) = a\{1 + 2v_3^{PTY}\cos 3(\phi^a - \Psi_3)\},$

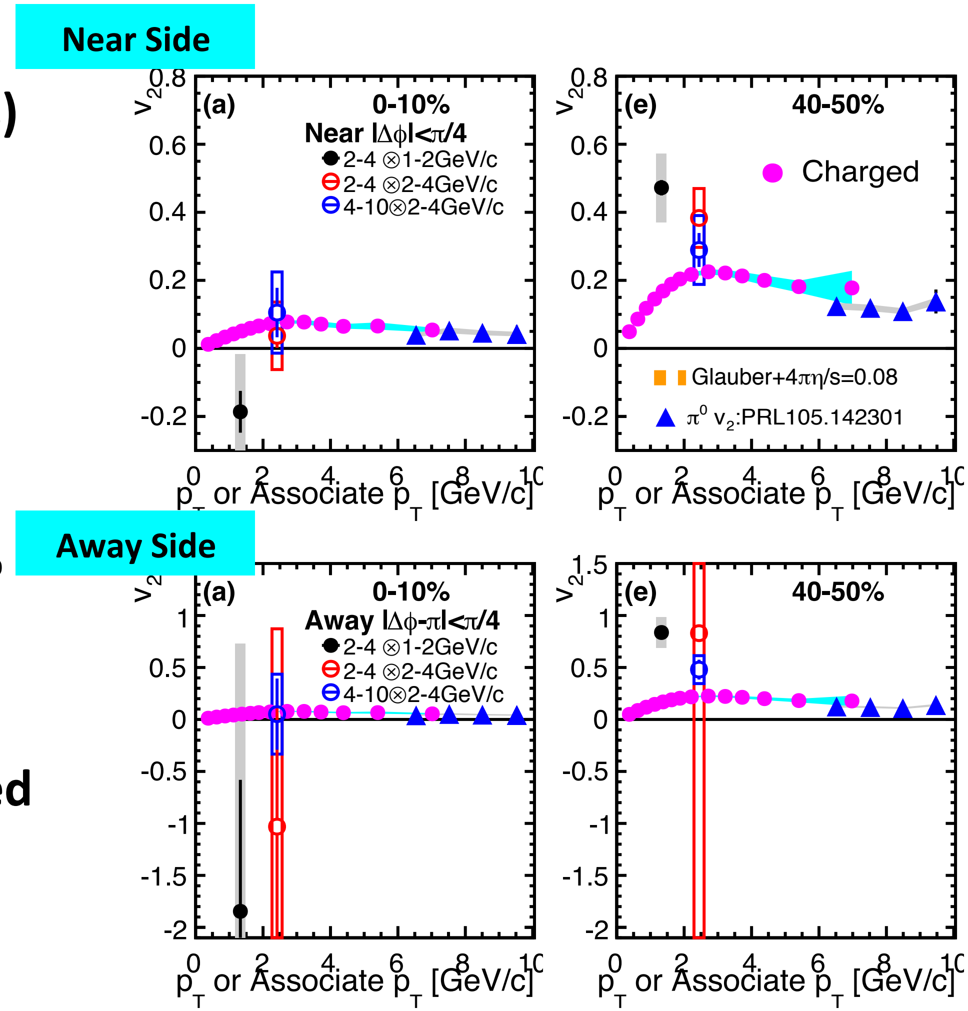
- Anisotropy of associate particles per a trigger ➔ Anisotropy of associate particles per a event

$$v_n^{PTY,cor} = v_n^{PTY} + v_n^{trig}\cos n(\phi^t - \phi^a)$$

v_2^{PTY}

- ✧ Positive hadron v_2 (Hydrodynamics)
- ✧ Positive π^0 v_2 (Parton energy-loss)
  - – Superposition of those assembles only positive v_2
- ✧ Near & away-side v_2^{PTY}
  - – Positive value at 40-50%
  - – Near-side negative value at 0-10%

- ✧ New effects need to be considered
- ✧ Possible re-distribution of deposited energy in longer path direction

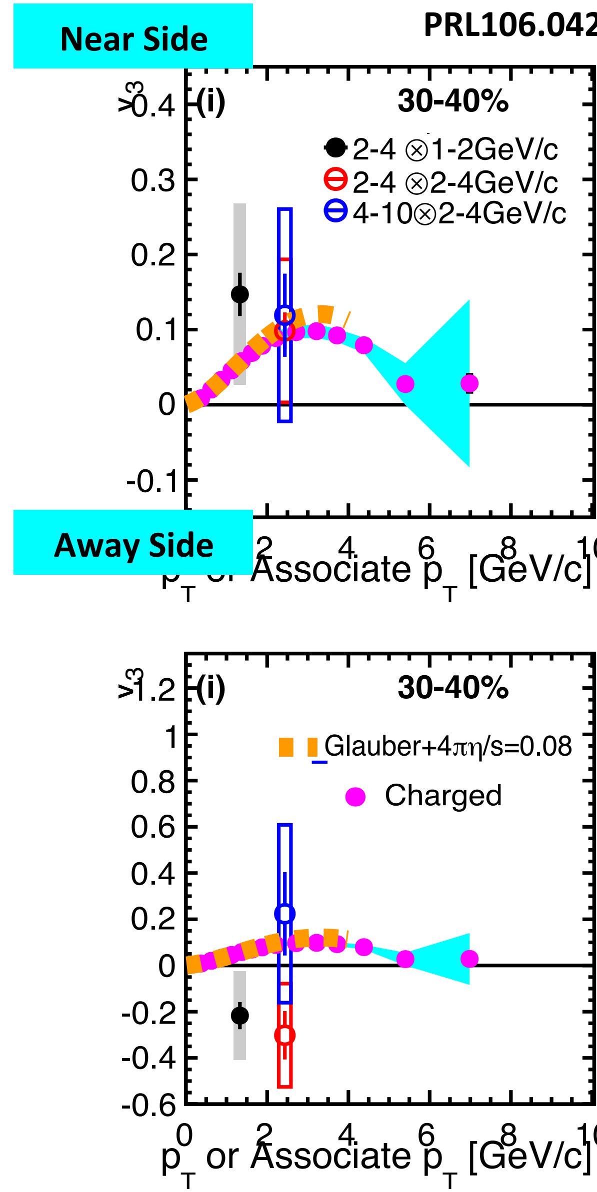


v_3^{PTY}

Hydrodynamics calculation
PRL106.042301 (2011)

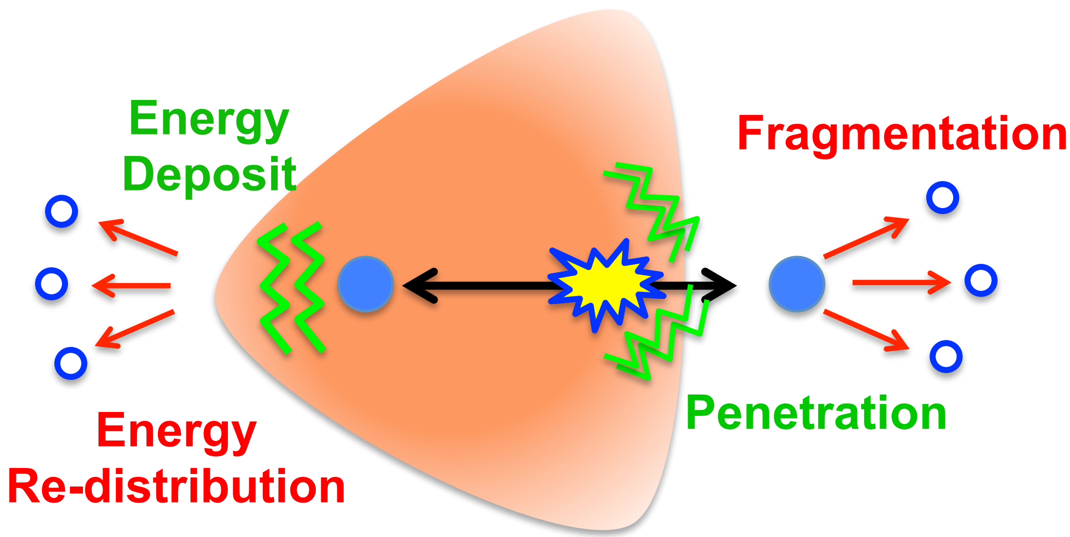
- ✧ Positive hadron v_3 (Hydrodynamics)
- ✧ Near & away-side v_3^{PTY} at 30-40%
  - – Positive near-side
  - – Negative away-side
- ✧ Weak centrality dependence

- ✧ Different near & away-side, as well as centrality dependences from those of v_2^{PTY}
- ✧ Possible different evolution processes between the 2nd- and 3rd-order geometry planes



Interpretation of Ψ_3 Dependent Correlations

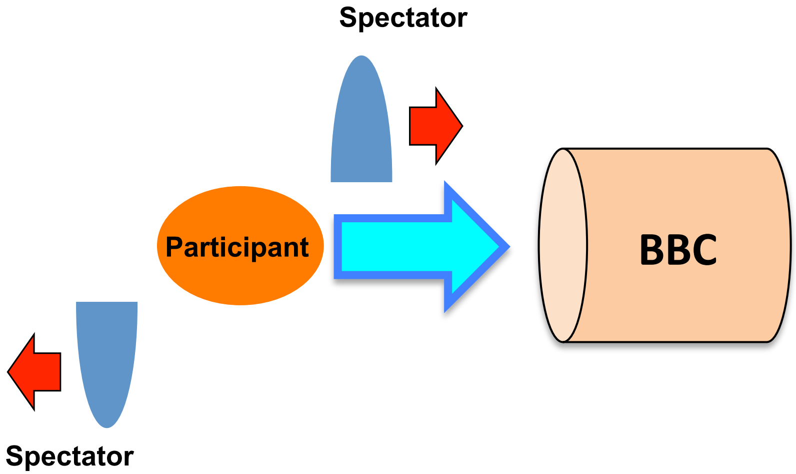
Away-Side | **Near-Side**

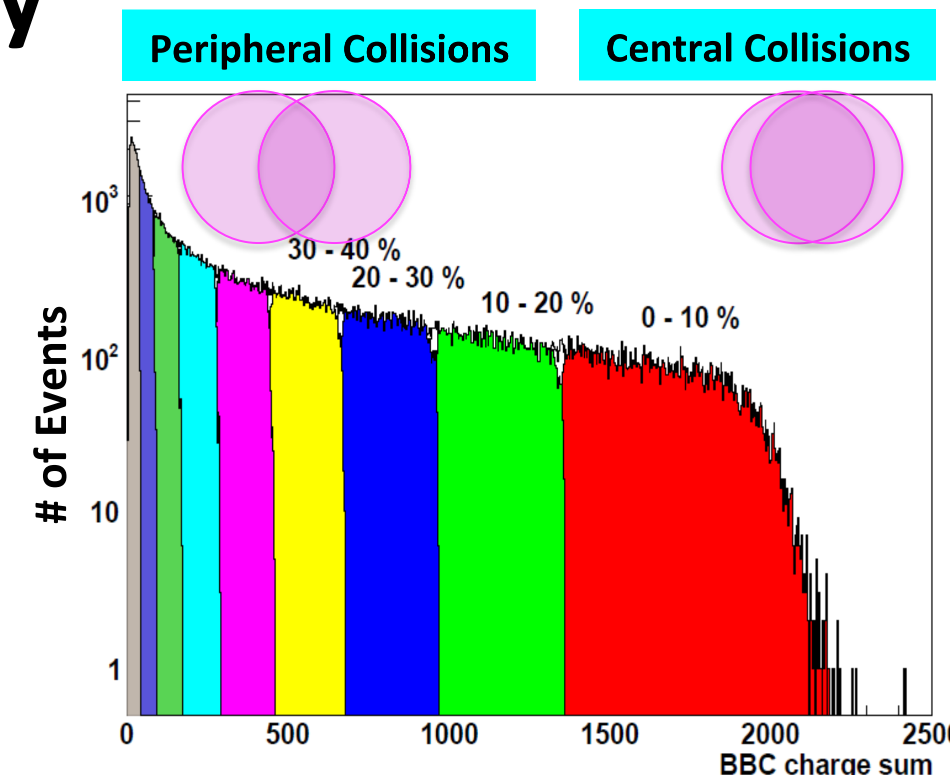


Re-distribution Dominance

Penetration Dominance

Collision Centrality

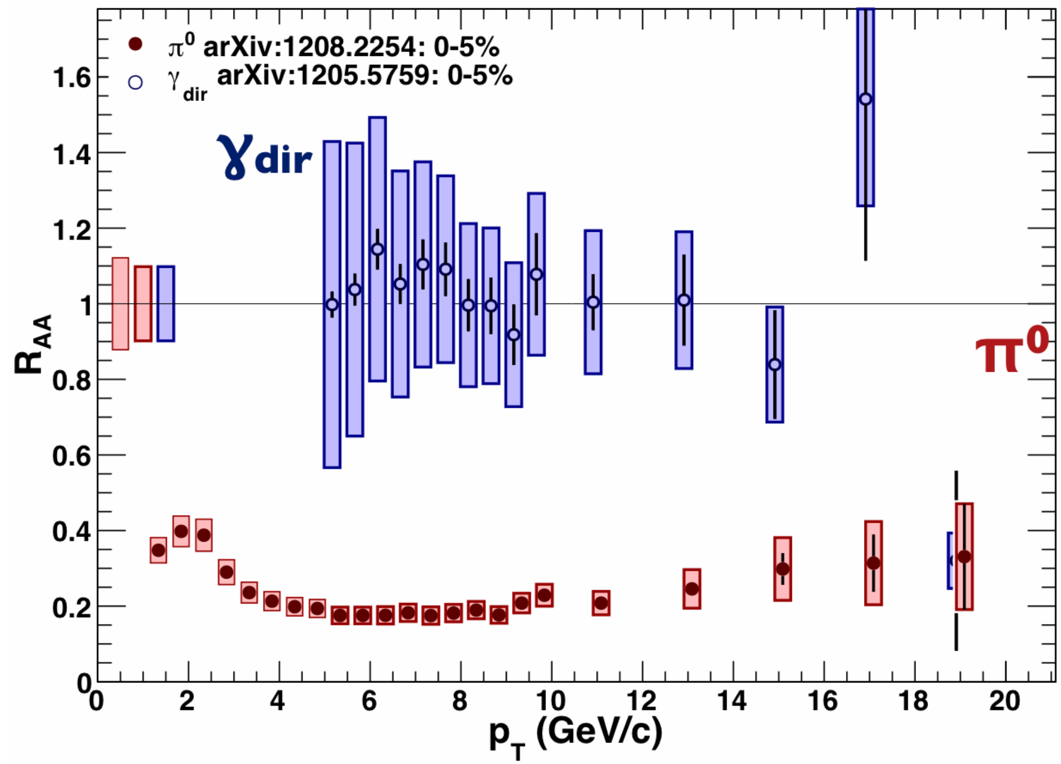




- ✧ **A degree of overlap of two colliding nuclei**
  - **Distance between center of the nuclei ➔ multiplicity ➔ charge deposited in BBC**
- ✧ **Require each percentile contains same # of events**
  - **Most-central Collision : 0%**
  - **Most-peripheral Collision : 100% (PHENIX determines it up to 92%)**

Nuclear Modification Factor R_{AA}

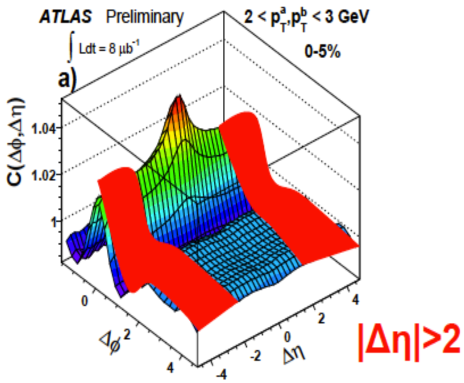
$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{pp}/dp_T d\eta}$$



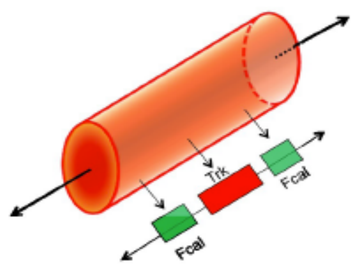
- Ratio of invariant yield scaled by that in p+p collision with scale
  - R_{AA}<1(suppression), R_{AA}=1(no change), R_{AA}>1(enhance)
- Suppression of hadron production
- No suppression of direct photon

Contributions of v_n (n>2) in correlations

2Par. Correlation



v_n with EP Method

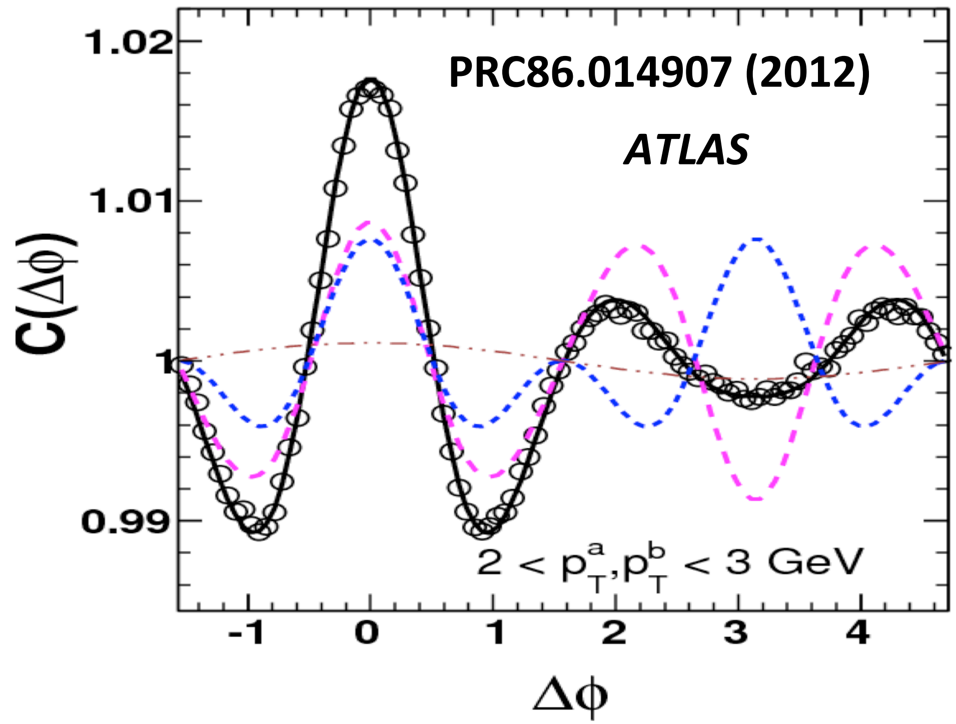


Track at $|\eta| < 2.5$ with EP from full FCAL $3.3 < |\eta| < 4.8$

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

From 2PC method

From EP method



✧ Double-hump & ridge of long-rapidity correlation explained

✧ Short-rapidity correlation with v_n subtraction to discuss parton behavior

Data Set & Particle Selection

- ✧ PHENIX year 2007 Experiment
- ✧ Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
  - Minimum Bias trigger 4.4 billion events
- ✧ Charged hadron selection
  - 2σ cut of track-hit matching
  - Electron veto
  - Energy/momentum cut of high p_T particles for background rejection
    - $E^{EMC}<0.30+0.20*p_T$ rejected for $p_T>5.0$ GeV/c
  - Pair cut of miss-reconstructed hadron pairs

Tracking Efficiency

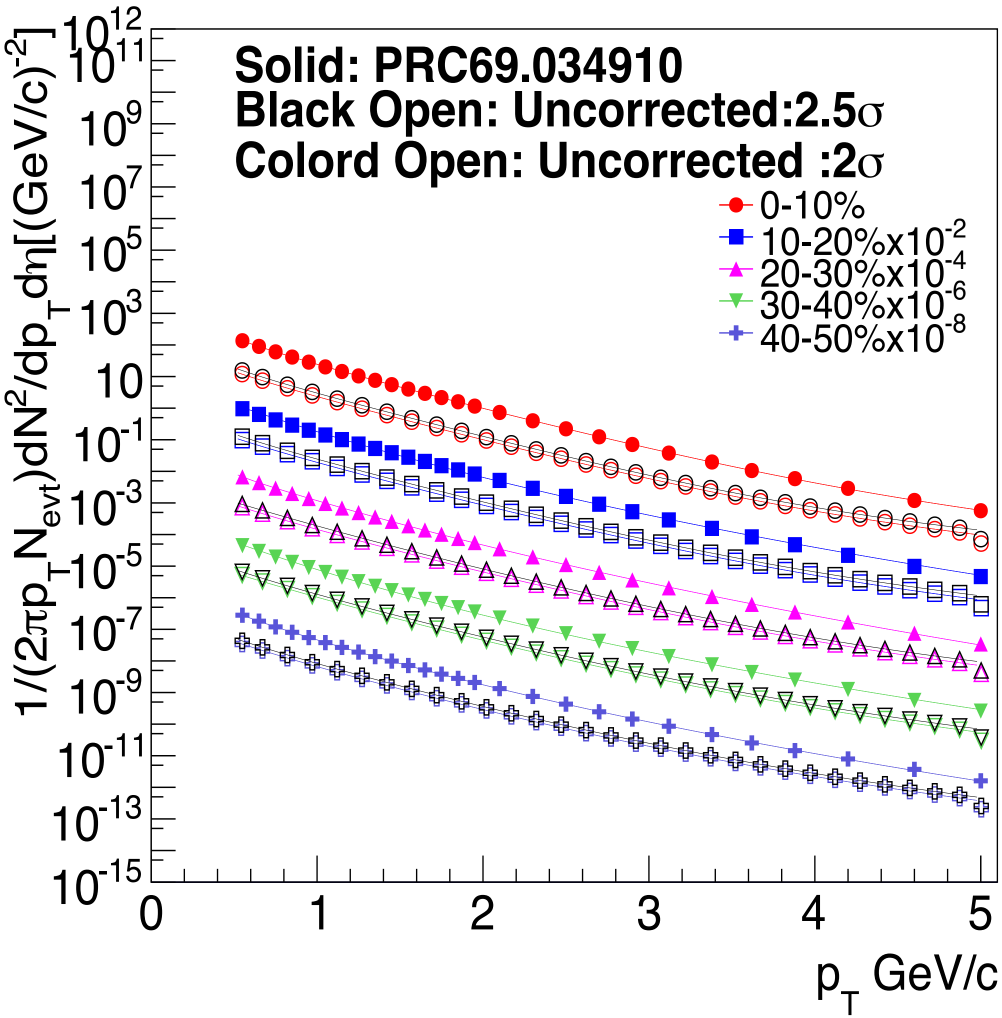
✧ **Efficiency correction by ratio of uncorrected invariant yield over fully corrected ones**

$$\varepsilon = \frac{\sigma^{uncor}}{\sigma^{cor}}$$

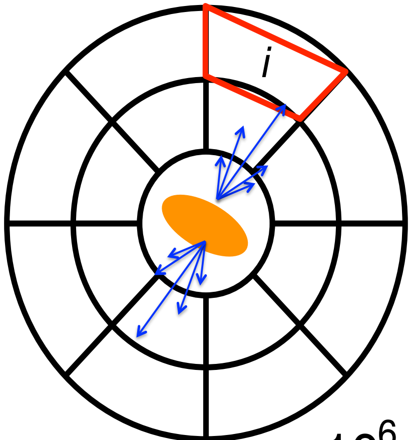
✧ **Ratio calculated by fitting functions to the invariant yields**

Fit Function

$$F(p_T) = p_0 * \left(\frac{p_1}{p_1 + p_T}\right)^{p_2}$$

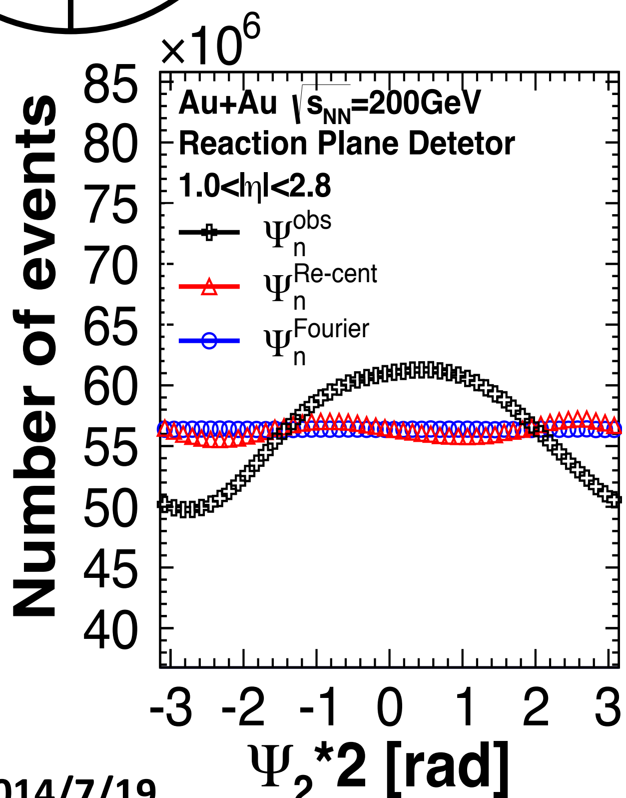


Event Plane Calibration



ϕ_i : Azimuthal angle

w_i : Weight (Charge etc.)



Raw distribution

$$Q_x = \sum_i w_i \cos(n\phi_i), Q_y = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n = \frac{1}{n} \tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

Re-centering

$$Q_x^{Rec} = \frac{Q_x - \langle Q_x \rangle}{\sigma_x}, Q_y^{Rec} = \frac{Q_y - \langle Q_y \rangle}{\sigma_y}$$

$$\Psi_n^{Rec} = \frac{1}{n} \tan^{-1}\left(Q_y^{Rec}/Q_x^{Rec}\right)$$

Fourier correction

$$n\Psi_n^{Fourier} = n\Psi_n^{Rec} + n\Delta\Psi_n$$

$$n\Delta\Psi_n = \sum_k \left\{A_k \cos\left(kn\Psi_n^{Rec}\right) + B_k \sin\left(kn\Psi_n^{Rec}\right)\right\}$$

$$A_k = -\frac{2}{k}\left\langle \cos\left(kn\Psi_n^{Rec}\right)\right\rangle, B_k = \frac{2}{k}\left\langle \sin\left(kn\Psi_n^{Rec}\right)\right\rangle$$

Event Plane Resolution

EP Resolution **PRC 58.1671 (1998)**

- ✧ **Resolution +/-η**

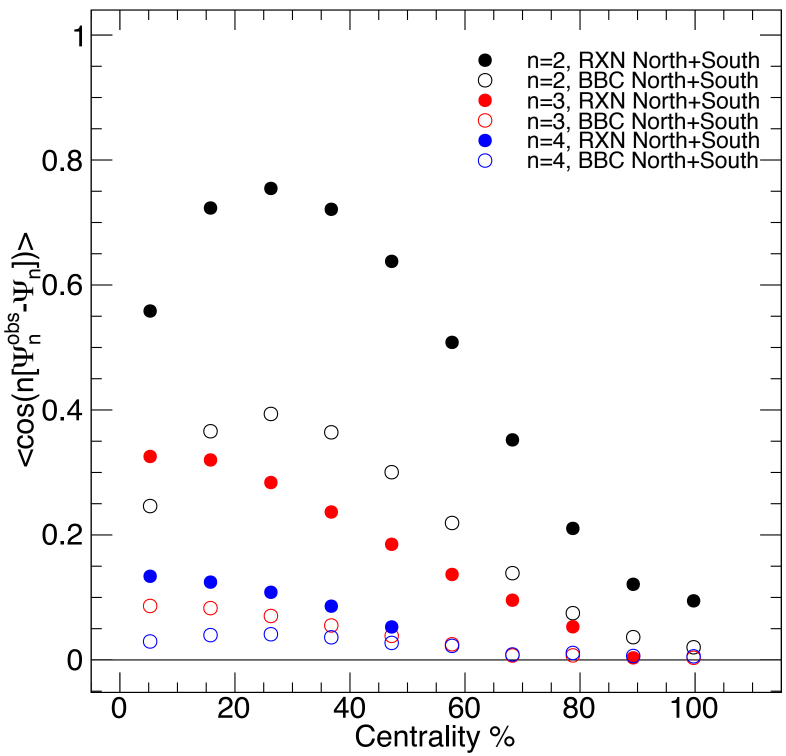
$$\sigma_n^{EP} = \sqrt{\left\langle \cos kn(\Psi_n^{EP(+\eta)} - \Psi_n^{EP(-\eta)}) \right\rangle}$$

$$= \left\langle \cos kn(\Psi_n^{EP+/-\eta} - \Psi_n) \right\rangle$$

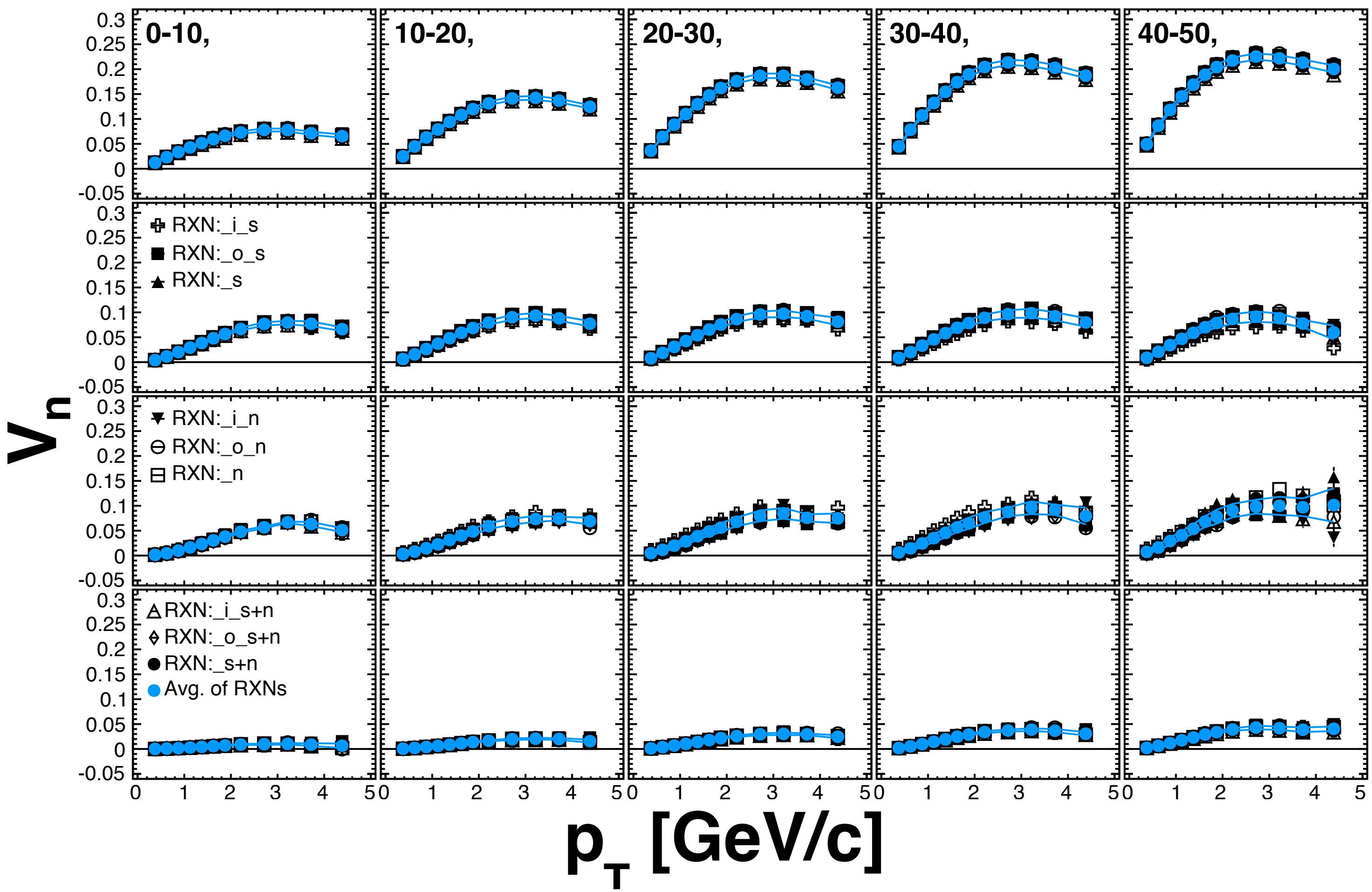
$$= \frac{\pi}{8}\chi_n^2 \left[I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right) + I_{(k+1)/2}\left(\frac{\chi_n^2}{4}\right) \right]^2$$

- ✧ **Resolution +&-η**
  - $\chi_n \rightarrow \sqrt{2}\chi_n$

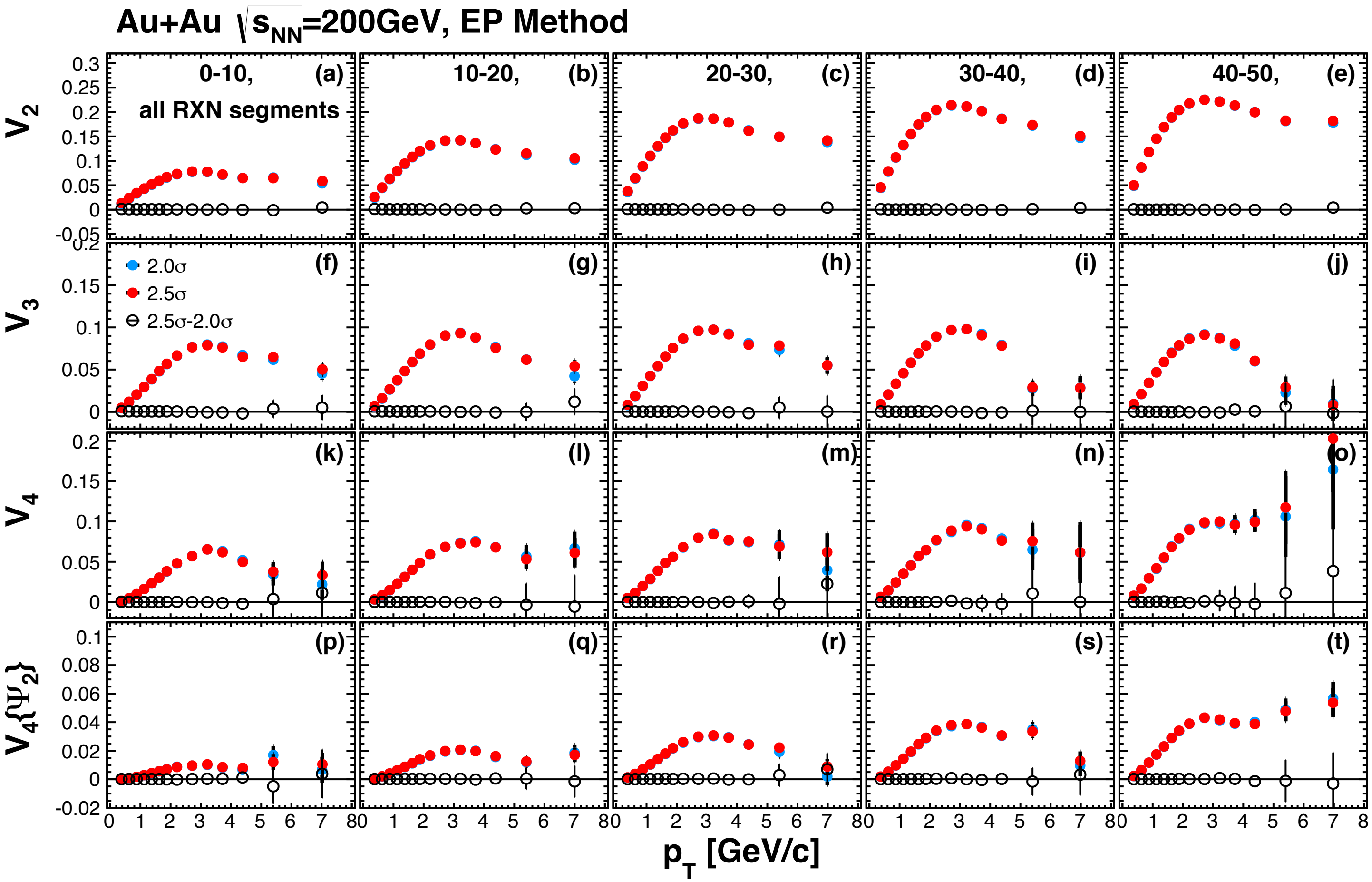
$$\sigma_n^{EP} = \frac{\pi}{8}2\chi_n^2 \left[I_{(k-1)/2}\left(\frac{2\chi_n^2}{4}\right) + I_{(k+1)/2}\left(\frac{2\chi_n^2}{4}\right) \right]^2$$



v_n systematics : RXN segments



v_n systematics : Matching Cut



v_n systematics : RXN-BBC Difference

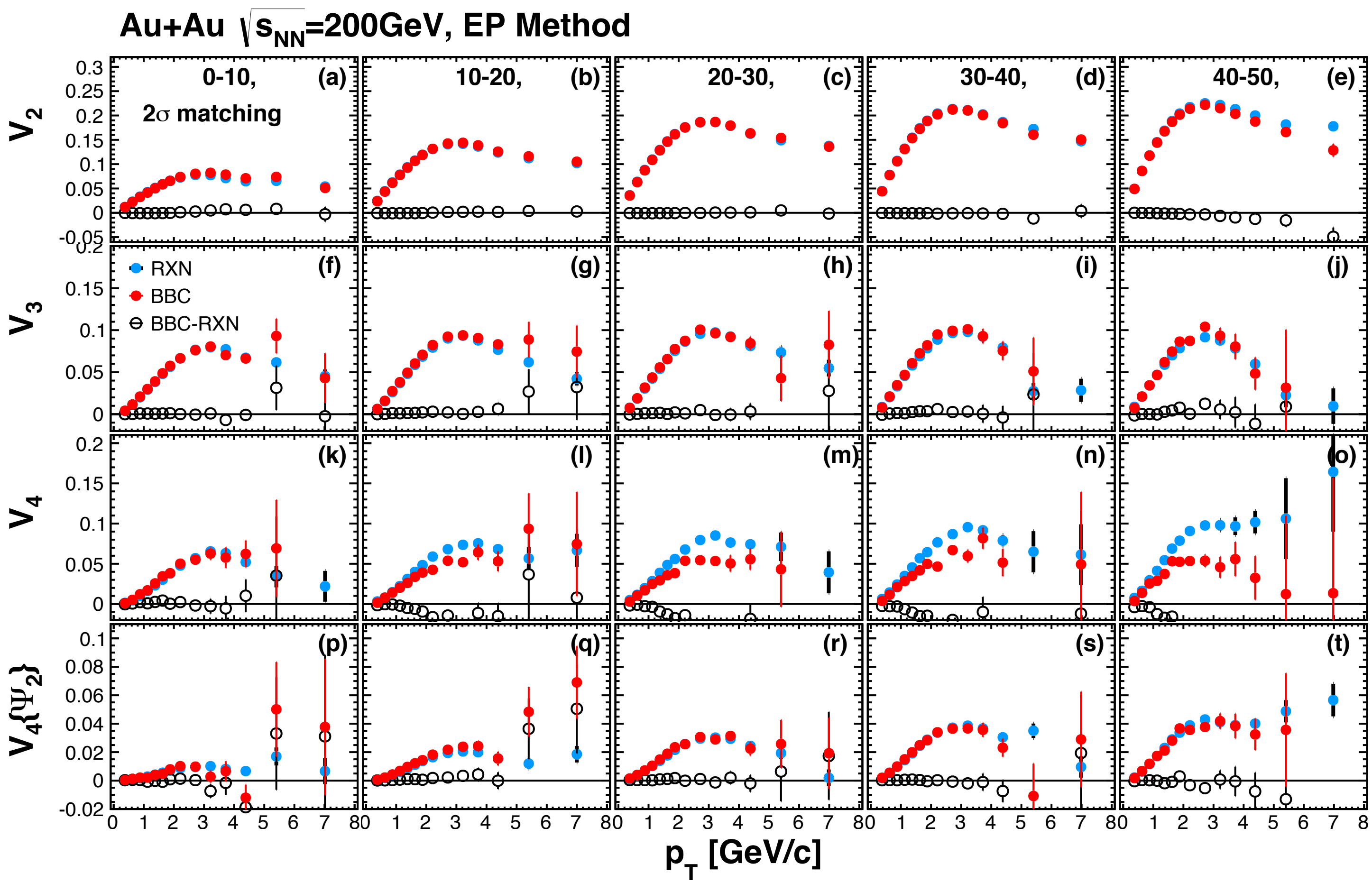


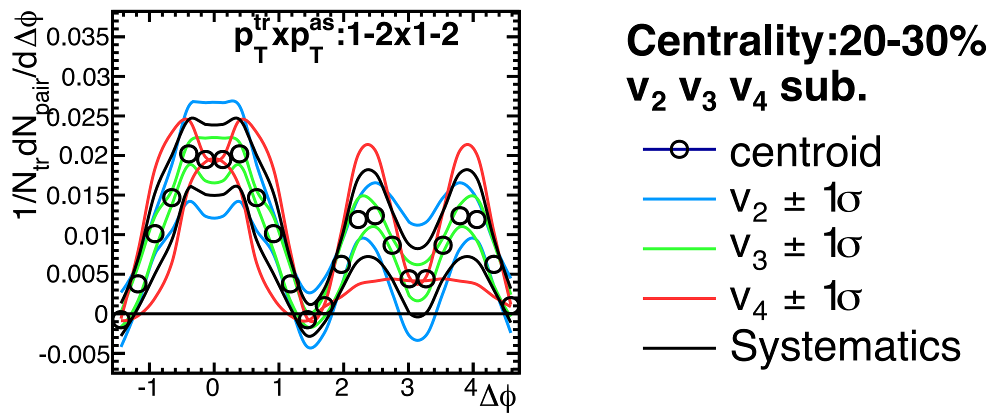
Table of total v_n systematic uncertainties

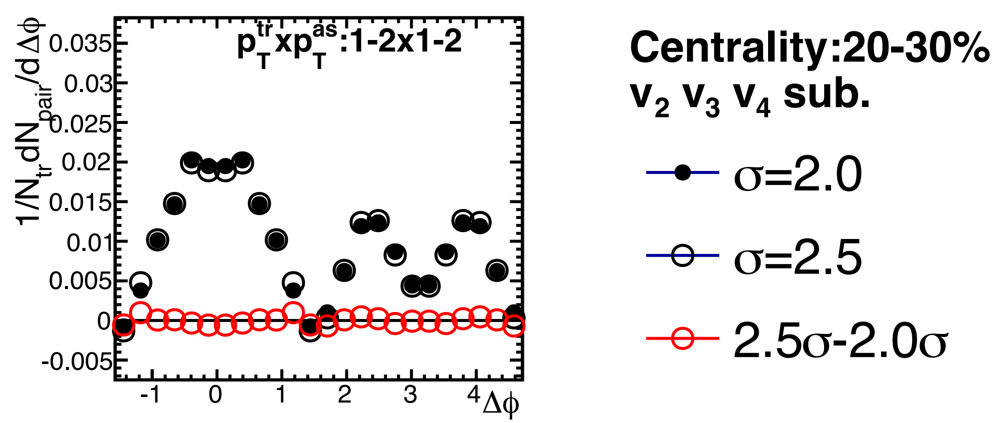
Table 3.8: Summary of percentile ratio of v_n systematic uncertainties

Centrality %	p_T GeV/c	v_2 sys. %	v_3 sys. %	v_4 sys. %	$v_4\{\Psi_2\}$ sys. %
0-10	0.5-1.0	5.449	6.387	24.87	48
	1.0-2.0	4.32	4.911	10.1	14.66
	2.0-4.0	4.536	4.131	4.412	11.39
	4.0-10.0	10.43	6.184	21.67	191.3
10-20	0.5-1.0	3.658	7.992	28.53	12.17
	1.0-2.0	2.891	6.431	20.16	12.27
	2.0-4.0	2.69	6.163	27.64	13.72
	4.0-10.0	3.124	13.62	19.09	32.09
20-30	0.5-1.0	2.811	9.469	35.48	9.633
	1.0-2.0	2.485	7.818	28.85	8.422
	2.0-4.0	2.391	6.822	28.03	6.577
	4.0-10.0	2.98	9.503	32.24	12.21
30-40	0.5-1.0	2.506	12.42	35.81	7.385
	1.0-2.0	2.462	9.695	29.88	6.509
	2.0-4.0	2.556	9.673	36.75	5.913
	4.0-10.0	2.934	14.18	44.32	31.73
40-50	0.5-1.0	2.575	13.8	32.96	6.338
	1.0-2.0	2.688	12.06	34.44	6.479
	2.0-4.0	3.224	11.7	45.4	10.71
	4.0-10.0	7.877	33.53	77.07	29.33

Systematics of Correlations

- Systematics propagated from v_n measurements
  - Varying v_n value ± 1σ (# of harmonics 3 x ± 1σ 2 = 6 combinations)
  - Systematics : RMS of above 6 combinations
- Systematics from matching cut
  - Systematics : Difference between 2.5σ-2.0σ (main)
- Total Systematics
  - Quadrature-sum of above two systematics





EP Resolution in Monte Carlo

- Analytical formula of EP Resolution (RXN:S+N) as a function of χ_n
  - Convert Resolution to χ_n

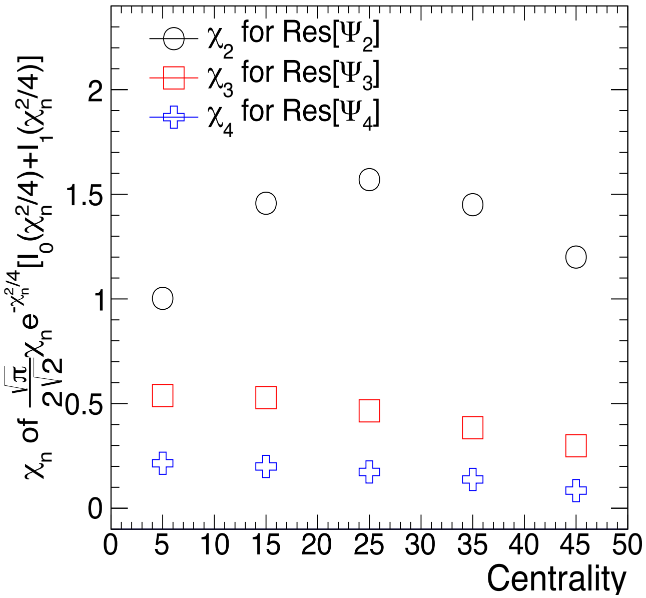
PRC 58.1671 (1998)

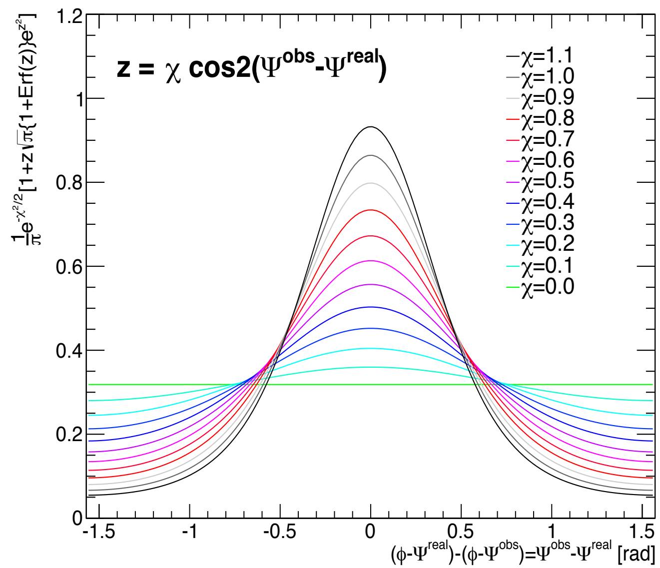
$$\left\langle \cos\left[kn(\Psi_n^{obs} - \Psi_n^{real})\right]\right\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_n e^{-\chi_n^2/4}\left[I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right) + I_{(k+1)/2}\left(\frac{\chi_n^2}{4}\right)\right].$$

- Relative distribution between real and observed EP calculated using χ_n

$$\frac{dN^{eve}}{d[kn(\Psi_n^{obs} - \Psi_n^{real})]} = \frac{1}{\pi}e^{-\chi_n^2/2}\left[1 + z\sqrt{\pi}[1+\mathrm{erf}(z)]e^{z^2}\right] \qquad z = \frac{1}{\sqrt{2}}\chi_n \cos n(\Psi_n^{obs} - \Psi_n^{real})$$

PRD 48.1132 (1993)



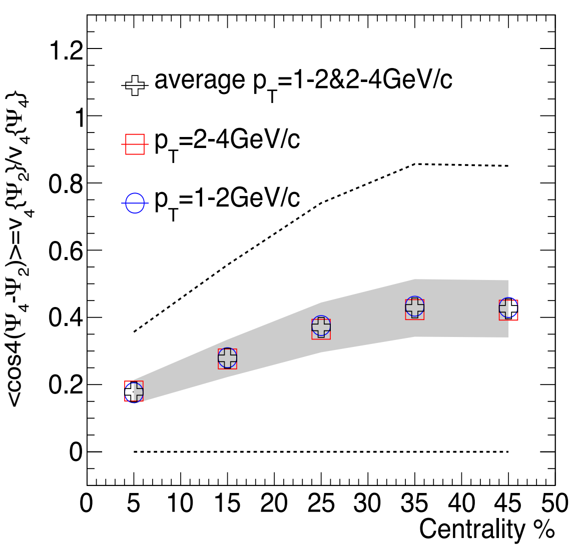


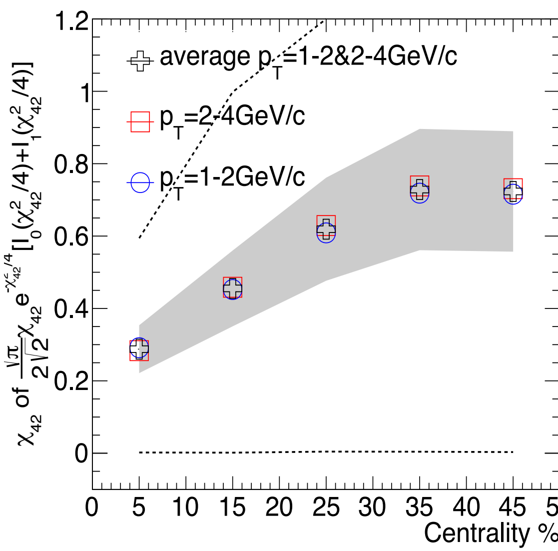
Ψ_2-Ψ_4 correlation in Monte Carlo

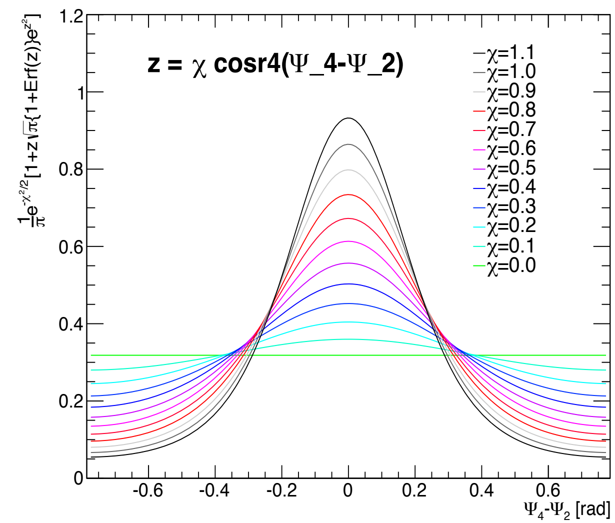
- **Ψ_2-Ψ_4 correlation at p_T 1-2&2-4GeV :** $\langle\cos[4(\Psi_2-\Psi_4)]\rangle = v_4\{\Psi_2\}/v_4\{\Psi_4\}$
  - **To avoid jet contribution to the Ψ_2-Ψ_4 correlation**
- **Obtain χ_{42} & reconstruct relative distribution between Ψ_2 & Ψ_4**

$$\langle\cos[4(\Psi_2-\Psi_4)]\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_{42}e^{-\chi_{42}^2/4}\left[I_0\left(\frac{\chi_{42}^2}{4}\right)+I_1\left(\frac{\chi_{42}^2}{4}\right)\right]$$

$$\frac{dN^{eve}}{d[kn(\Psi_n^{obs}-\Psi_n^{real})]} = \frac{1}{\pi}e^{-\chi_n^2/2}\left[1+z\sqrt{\pi}[1+\mathrm{erf}(z)]e^{z^2}\right] \quad z=\frac{1}{\sqrt{2}}\chi_n\cos n(\Psi_n^{obs}-\Psi_n^{real})$$







Ψ_2-Ψ_3 correlation

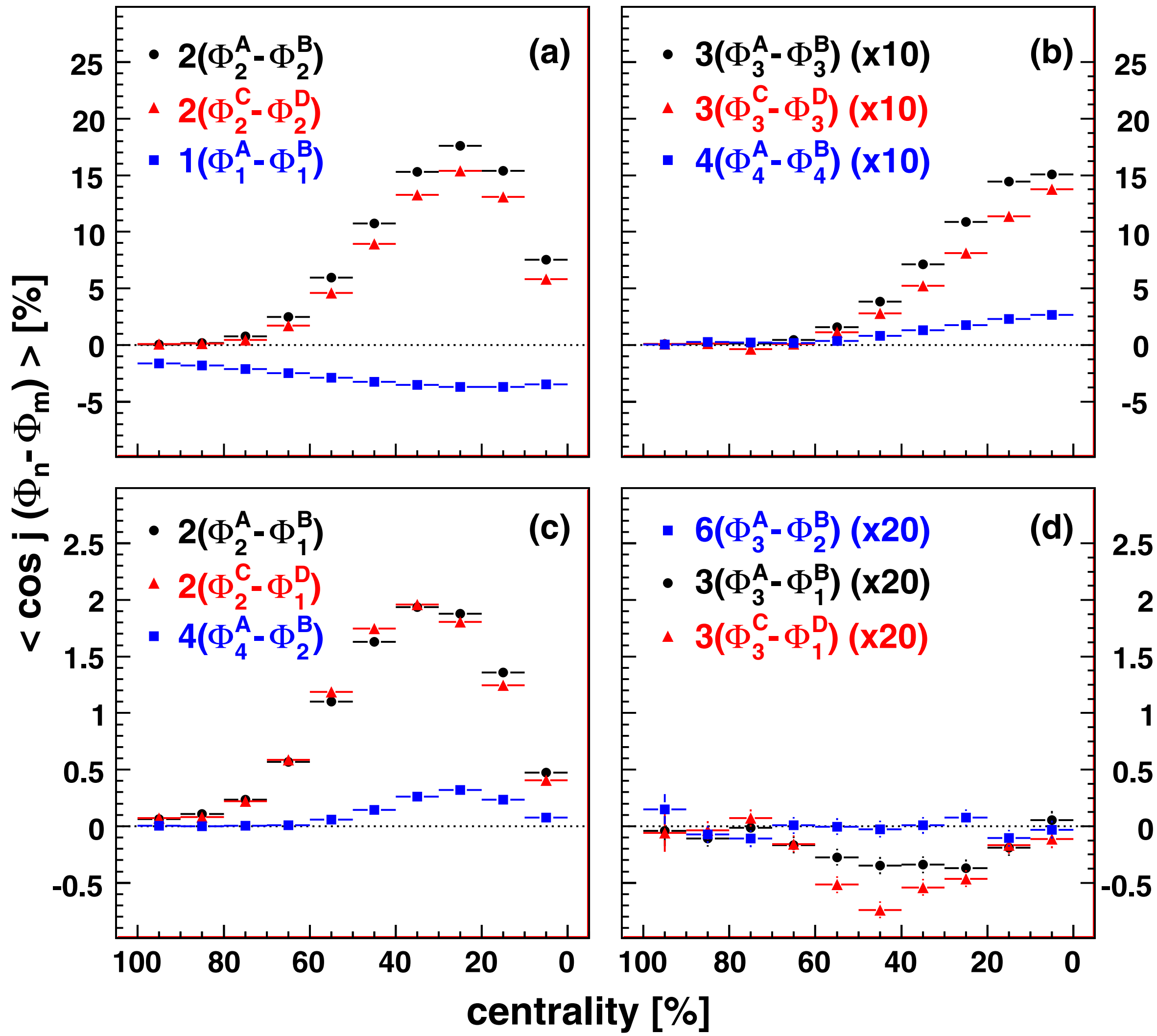
PRL107.252301 (2011)

A : RXN North

B : BBC South

C : MPC North

D : MPC South



EP Resolution Correction : Iteration-1

- Trigger bin is also smeared due to limited EP resolution as v_n
  - Add an offset $\lambda=1.0$ to correlation Y to avoid possible divisions by zero

Raw Correlation

Offset Trigger Bin

$$\mathbf{A}(k) = \begin{pmatrix} 1+Y(0,k) \\ 1+Y(1,k) \\ 1+Y(2,k) \\ 1+Y(3,k) \\ 1+Y(4,k) \\ 1+Y(5,k) \\ 1+Y(6,k) \\ 1+Y(7,k) \end{pmatrix},$$

$\Delta\phi$ Bin

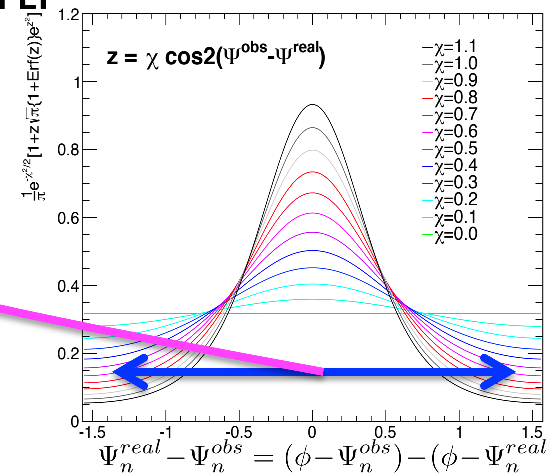
$$k = 0, \cdots, 23$$

Smearing Effect : Calculated by relative distribution between real and observed EP

Trigger Bin

$$S = \begin{pmatrix} s_0 & s_1 & s_2 & s_3 & s_4 & s_3 & s_2 & s_1 \\ s_1 & s_0 & s_1 & s_2 & s_3 & s_4 & s_3 & s_2 \\ s_2 & s_1 & s_0 & s_1 & s_2 & s_3 & s_4 & s_3 \\ s_3 & s_2 & s_1 & s_0 & s_1 & s_2 & s_3 & s_4 \\ s_4 & s_3 & s_2 & s_1 & s_0 & s_1 & s_2 & s_3 \\ s_3 & s_4 & s_3 & s_2 & s_1 & s_0 & s_1 & s_2 \\ s_2 & s_3 & s_4 & s_3 & s_2 & s_1 & s_0 & s_1 \\ s_1 & s_2 & s_3 & s_4 & s_3 & s_2 & s_1 & s_0 \end{pmatrix},$$

$\sum_n s_n = 1$, s_n : Ratio from n[th] away-bin



Smeared Correlation

$$\mathbf{B}(k) = \mathbf{S}\mathbf{A}(k)$$

Correction Matrix

$$\mathbf{C}(\mathbf{k}) = (c_{ij})$$

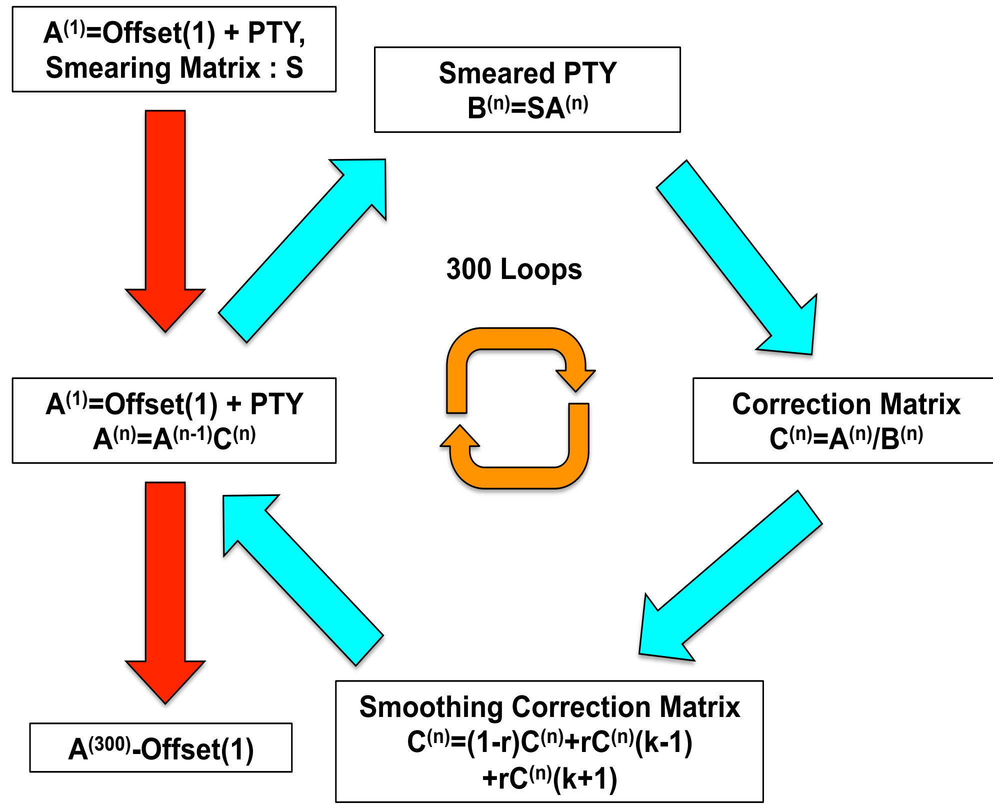
$$c_{ij} = \begin{cases} \frac{A(i,k)}{B(i,k)} & (i=j) \\ 0 & (i \neq j) \end{cases}$$

Corrected Correlation

$$\mathbf{A}^{\mathbf{cor}}(k) = \mathbf{C}(k)\mathbf{A}(k)$$

EP Resolution Correction : Iteration-2

- Start of iteration : experimental results (already smeared once)
- Obtained correction is not true
- Iteration until conversions of each coefficients
  - 300 Loops



Notation in Iteration

$$\mathbf{A} \rightarrow \mathbf{A}^{(\mathbf{n})}$$

$$\mathbf{B} \rightarrow \mathbf{B}^{(\mathbf{n})}$$

$$\mathbf{C} \rightarrow \mathbf{C}^{(\mathbf{n})}$$

$$\mathbf{A}^{\mathbf{cor}} \rightarrow \mathbf{A}^{(\mathbf{n+1})}$$

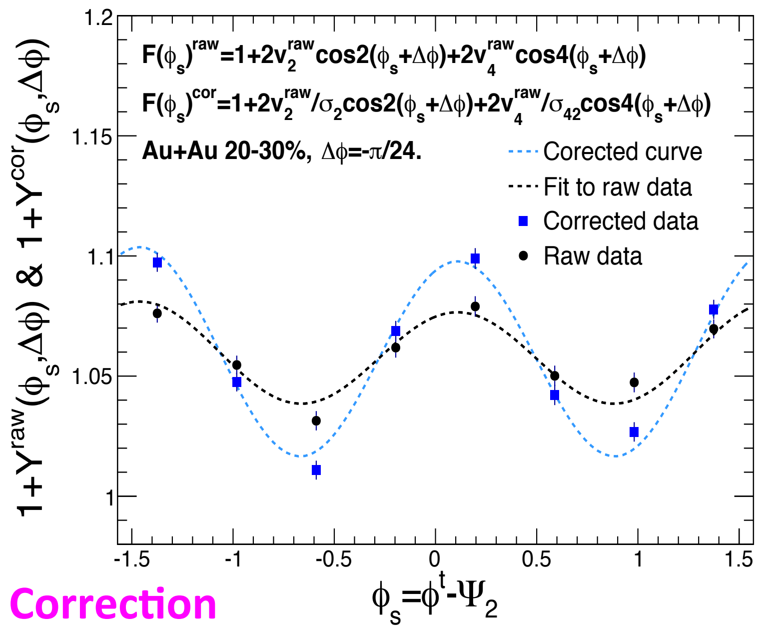
Smoothing

- Preventing a divergence of statistical fluctuations among Δϕ bins
- 2r=0.20 & 0.30

$$c_{ii}^{(n)}(k) = (1-r)c_{ii}^{(n)}(k) + (r/2)\, c_{ii}^{(n)}(k-1) + (r/2)\, c_{ii}^{(n)}(k+1)$$

EP Resolution Correction : Fitting Method

- ✧ Assuming correlation yield has anisotropy with respect to EP
- ✧ Correction by EP resolution as done in v_n measurements
  - Method by PRC.84.024904(2011)
- ✧ Offset λ=1.0 to avoid possible division by zero



EP Resolution Correction

Ψ_2 dependent case

$$\lambda + Y^{cor}(\phi_s,\Delta\phi) = \frac{\lambda + b_0\left[1 + 2v_2^Y/\boxed{\sigma}\cos 2(\phi_s+\Delta\phi) + 2v_4^Y/\boxed{\sigma_{42}}\cos 4(\phi_s+\Delta\phi)\right]}{\boxed{\lambda + b_0\left[1 + 2v_2^Y\cos 2(\phi_s+\Delta\phi) + 2v_4^Y\cos 4(\phi_s+\Delta\phi)\right]}}\boxed{(\lambda + Y(\phi_s,\Delta\phi))}$$

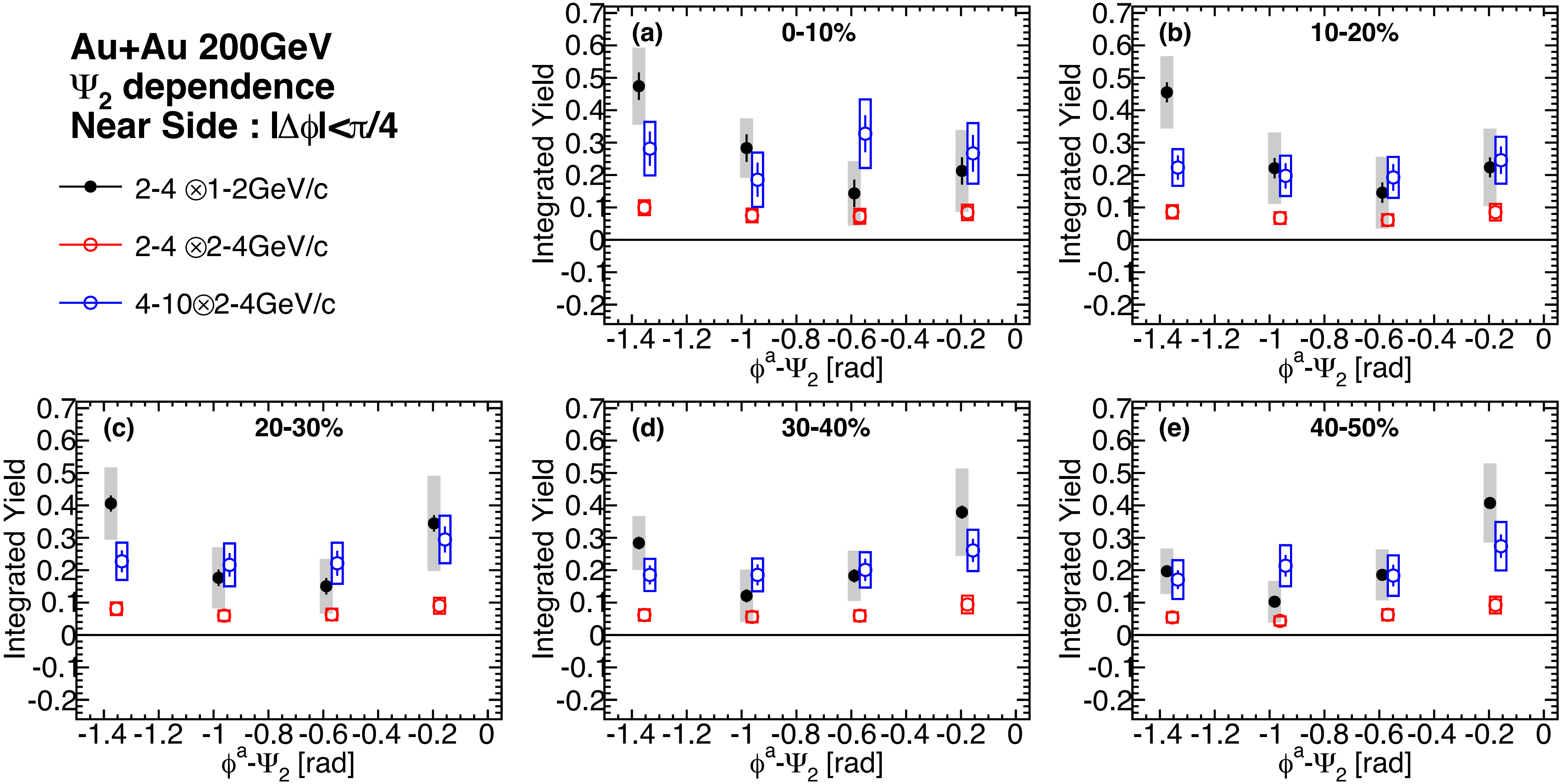
Fitting

Ψ_3 dependent case

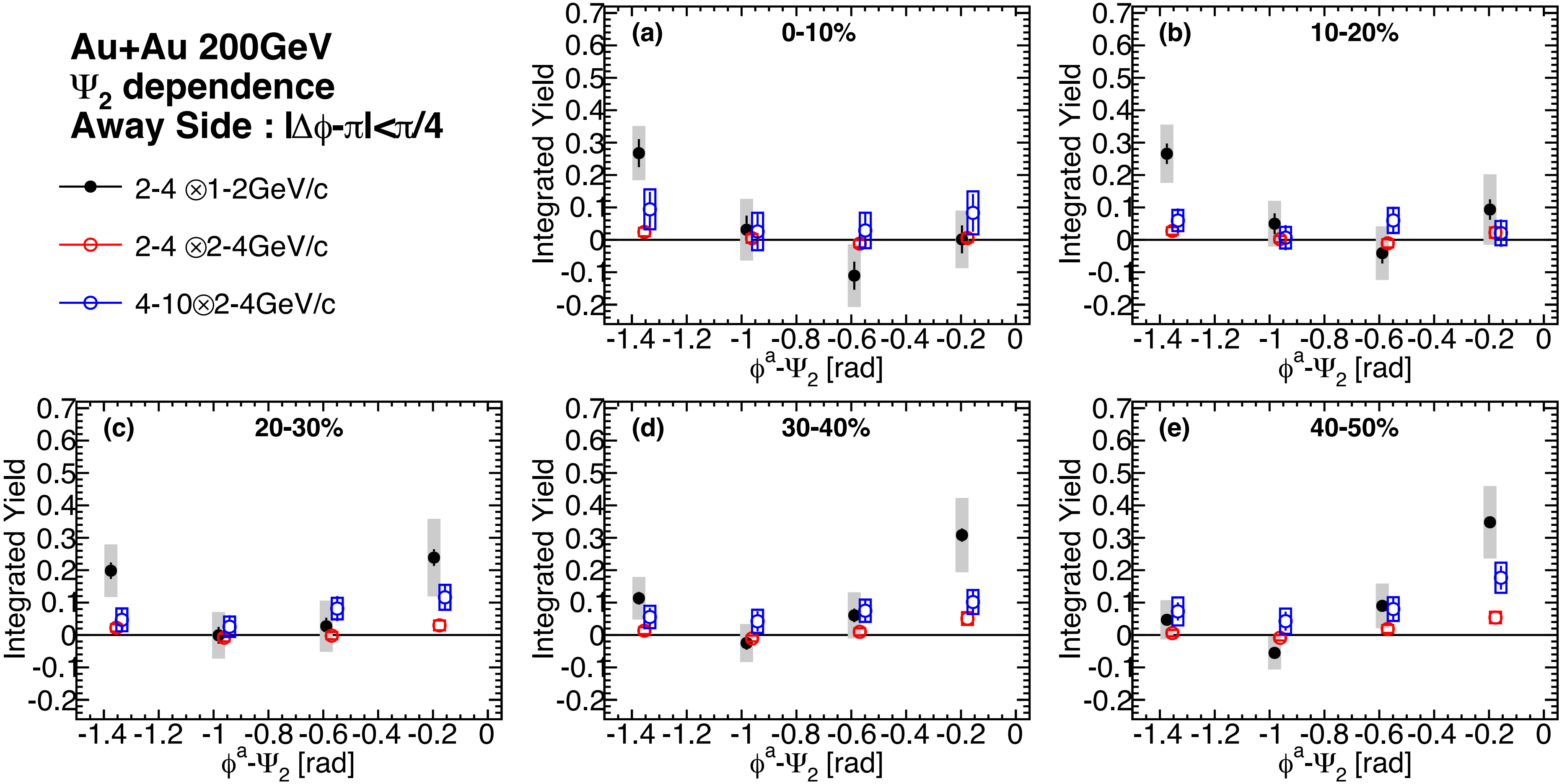
$$\lambda + Y^{cor}(\phi_s,\Delta\phi) = \frac{\lambda + b_0\left[1 + 2v_3^Y/\boxed{\sigma_3}\cos 3(\phi_s+\Delta\phi)\right]}{\boxed{\lambda + b_0\left[1 + 2v_3^Y\cos 3(\phi_s+\Delta\phi)\right]}}\boxed{(\lambda + Y(\phi_s,\Delta\phi))}$$

Fitting

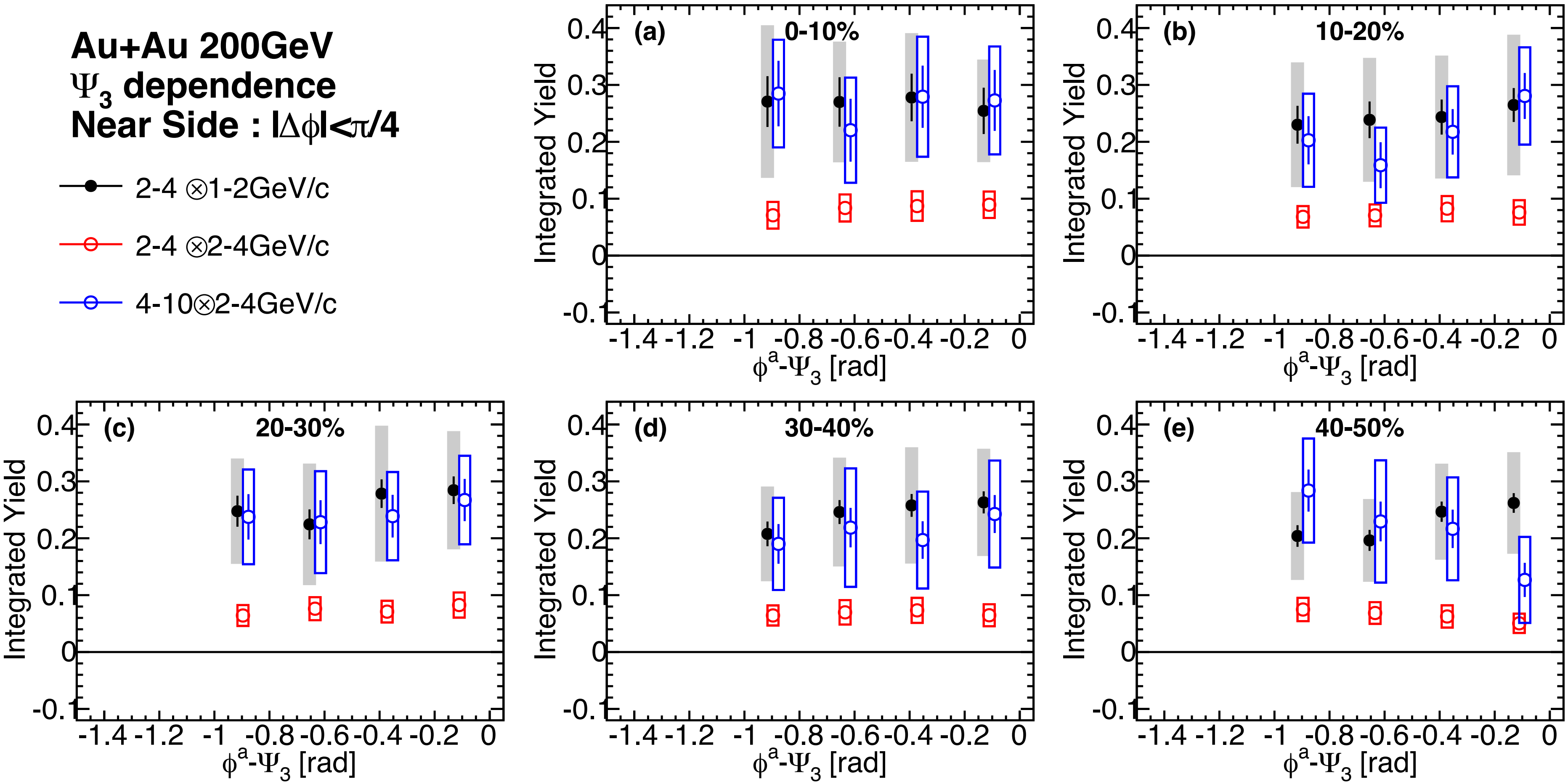
Near-Side Integrated Yield vs Associate Angle from Ψ_2



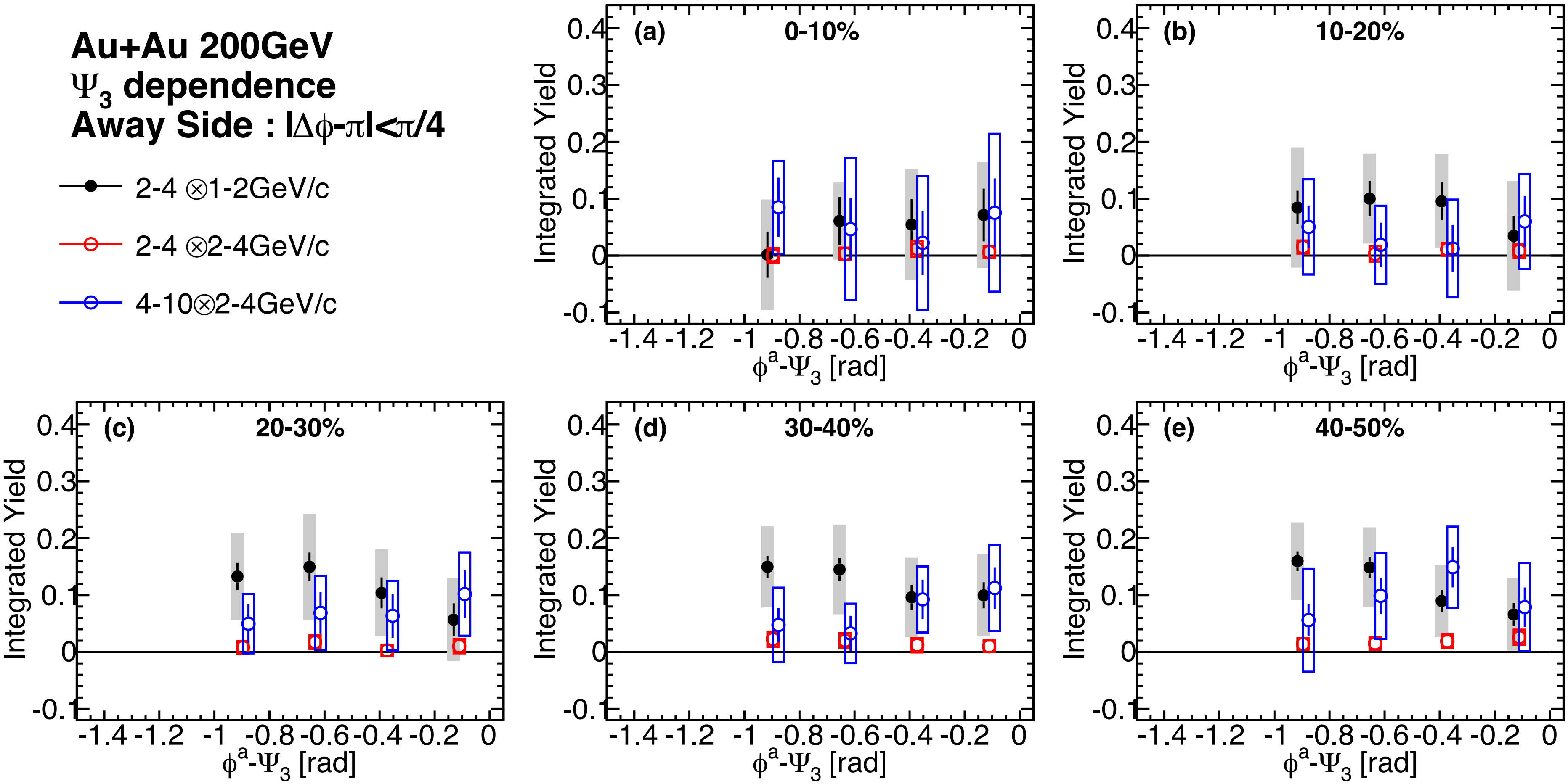
Away-Side Integrated Yield vs Associate Angle from Ψ_2



Near-Side Integrated Yield vs Associate Angle from Ψ_3



Away-Side Integrated Yield vs Associate Angle from Ψ_3

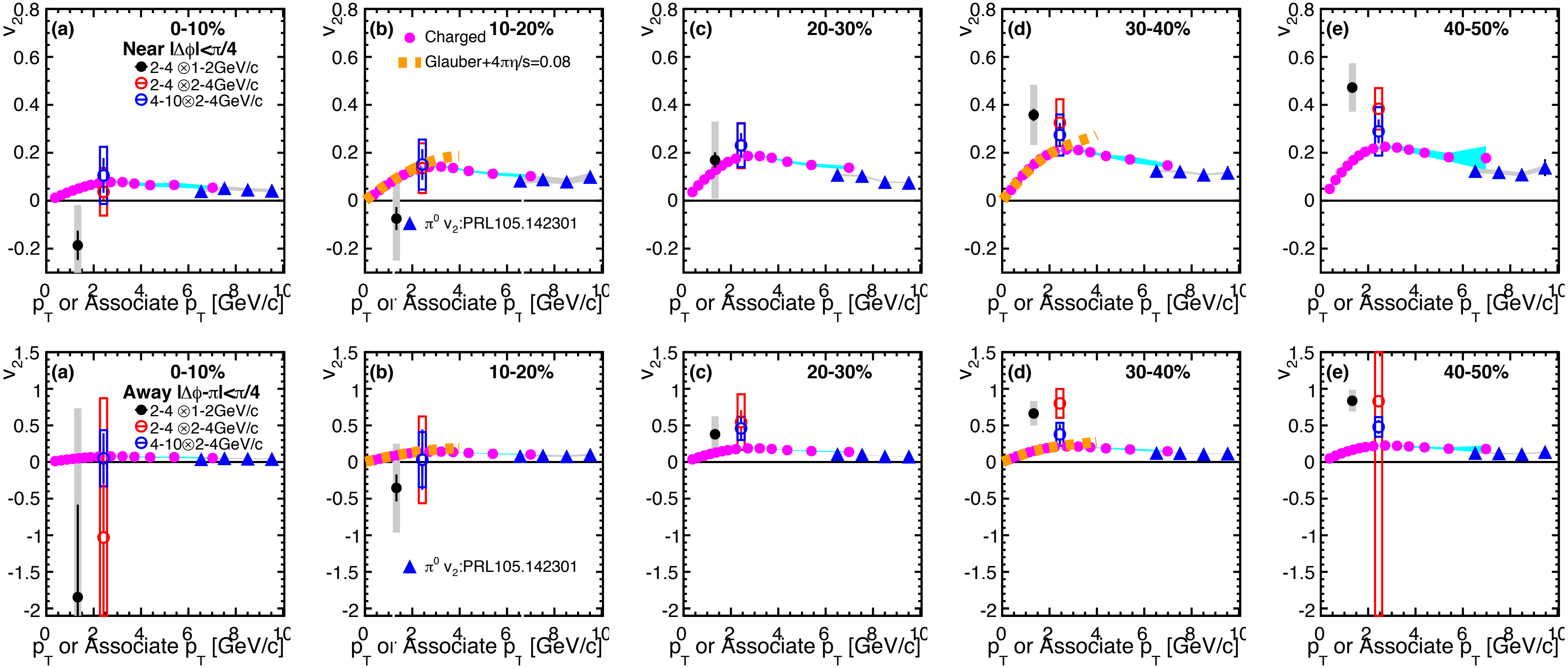


Anisotropy of particles per a jet → Anisotropy of particles per a event

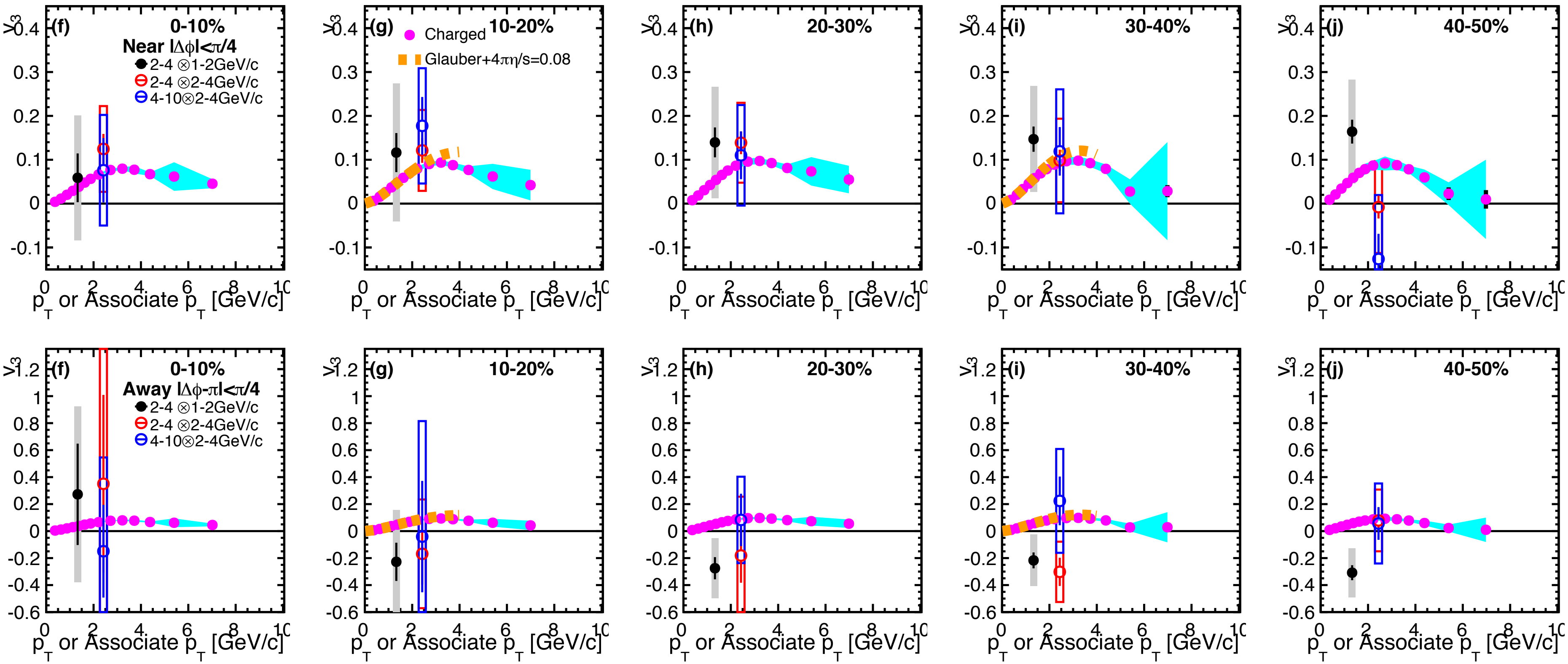
$$
\begin{aligned}
&\{1+2v_n^{PTY}\cos n(\phi^a-\Psi_n)\}\times\{1+2v_n^t\cos n(\phi^t-\Psi_n)\} \\
=&\{1+2v_n^{PTY}\cos n(\phi^a-\Psi_n)\}\times\{1+2v_n^t\cos n(\phi^a-\phi^t)\cos n(\phi^a-\Psi_n)\} \\
\simeq&1+2v_n^{PTY}\cos n(\phi^a-\Psi_n)+2v_n^t\cos n(\phi^a-\phi^t)\cos n(\phi^a-\Psi_n)
\end{aligned}
$$

$$
v_n^{PTY,cor}=v_n^{PTY}+v_n^{trig}\cos n(\phi^t-\phi^a)
$$

v_2^{PTY}


(a) 0-10%
Near |Δφ|<π/4
2-4 ⊗1-2GeV/c
2-4 ⊗2-4GeV/c
4-10⊗2-4GeV/c
(b) 10-20%
Charged
Glauber+4πη/s=0.08
π⁰ v₂:PRL105.142301
(c) 20-30%
(d) 30-40%
(e) 40-50%
(a) 0-10%
Away |Δφ-π|<π/4
2-4 ⊗1-2GeV/c
2-4 ⊗2-4GeV/c
4-10⊗2-4GeV/c
(b) 10-20%
π⁰ v₂:PRL105.142301
(c) 20-30%
(d) 30-40%
(e) 40-50%
v₂
p_T or Associate p_T [GeV/c]

v_3^{PTY}



(f) 0-10%
Near |Δφ|<π/4
2-4 ⊗1-2GeV/c
2-4 ⊗2-4GeV/c
4-10⊗2-4GeV/c
(g) 10-20%
Charged
Glauber+4πη/s=0.08
(h) 20-30%
(i) 30-40%
(j) 40-50%
(f) 0-10%
Away |Δφ-π|<π/4
(g) 10-20%
(h) 20-30%
(i) 30-40%
(j) 40-50%
v_3
p_T or Associate p_T [GeV/c]