Measurements of Two-Particle Correlations with respect to Higher-Order Event Planes in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions at RHIC-PHENIX

Pre-Defense Session

Nov 6th 2013

Takahito Todoroki

High Energy Nuclear Physics Group

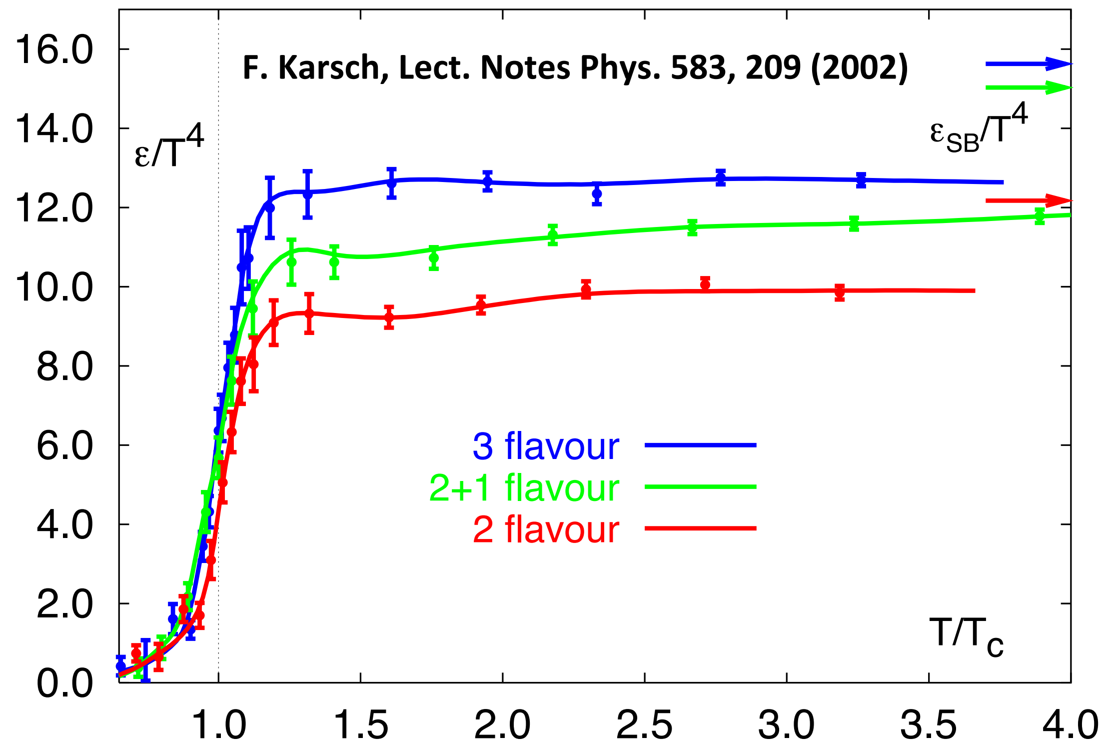
Outline

- Introduction
  - Quark Gluon Plasma (QGP)
  - Previous Measurements and Theoretical Models
  - Higher-Order Flow Contributions in Two-Particle Correlations
- Analysis
  - Data Set & Experimental Set Up
  - Flow and Two-Particle Correlation Measurements
  - Correlations with respect to Event Planes
- Results & Discussion
  - Inclusive Trigger Correlations
  - Event Plane Dependent Correlations
- Summary

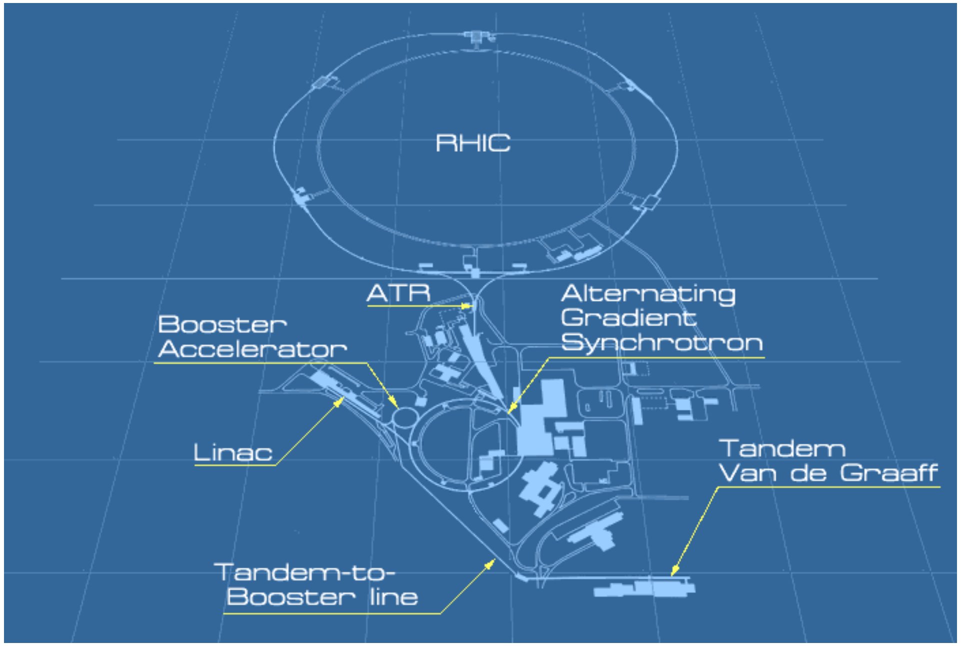
INTRODUCTION

Quark Gluon Plasma (QGP)

- A fluid of quark and gluons deconfined from hadrons at high energy-density ε & temperature T
- Predicted transition ε & T by Lattice-QCD
  - ε_c ~ 1.0 [GeV/fm^3]
  - T_c ~ 170 [MeV]
- Relativistic Heavy Ion Collisions at RHIC
  - ε ~5.0 - 15.0 [GeV/fm^3]



Relativistic Heavy Ion Collider



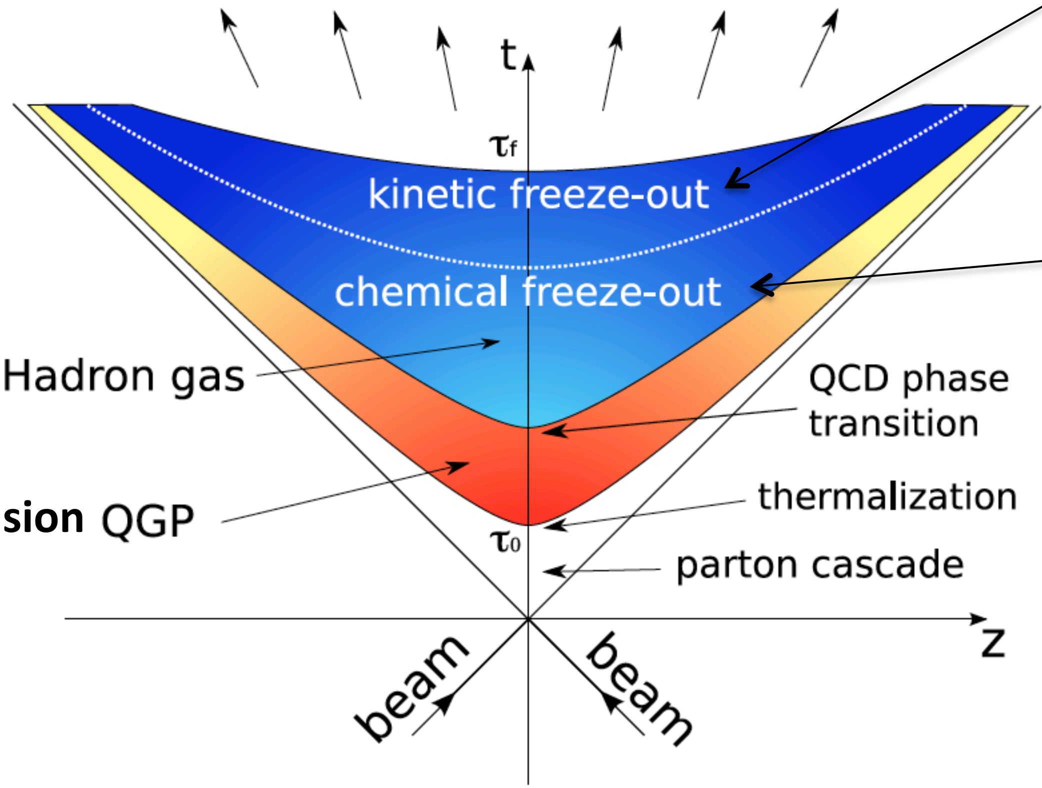
PHENIX Run Summary

	Year	Species	√s [GeV]	∫Ldt	N_{tot} (sampled)	Data Size
Run1	2000	Au - Au	130	1 ub^{-1}	10 M	3 TB
Run2	2001/02	Au - Au	200	24 ub^{-1}	170 M	10 TB
		Au - Au	19		< 1 M	
		p - p	200	0.15 pb^{-1}	3.7 B	20 TB
Run3	2002/03	d - Au	200	2.74 nb^{-1}	5.5 B	46 TB
		p - p	200	0.35 pb^{-1}	6.6 B	35 TB
Run4	2003/04	Au - Au	200	241 ub^{-1}	1.5 B	270 TB
		Au - Au	62.4	9 ub^{-1}	58 M	10 TB
Run5	2005	Cu - Cu	200	3 nb^{-1}	8.6 B	173 TB
		Cu - Cu	62.4	0.19 nb^{-1}	0.4 B	48 TB
		Cu - Cu	22.4	2.7 ub^{-1}	9 M	1 TB
		p - p	200	3.8 pb^{-1}	85 B	262 TB
Run-6	2006	p - p	200	10.7 pb^{-1}	233 B	310 TB
		p - p	62.4	0.1 pb^{-1}	28 B	25 TB
Run-7	2007	Au - Au	200	813 ub^{-1}	5.1 B	650 TB
Run-8	2007/08	d - Au	200	80 nb^{-1}	160 B	437 TB
		p - p	200	5.2 pb^{-1}	115 B	118 TB
		Au - Au	9.2		few k	

- Accelerators at Brookhaven National Laboratory
  - Tandem van de Graaff
  - Linear Accelerator
  - Booster Synchrotron
  - Alternating Gradient Synchrotron
  - Relativistic Heavy Ion Collider

- p+p : 510 GeV
- d+Au, Cu+Cu, Cu+Au, Au+Au: 200GeV
- U+U : 193 GeV

Space-Time Evolution

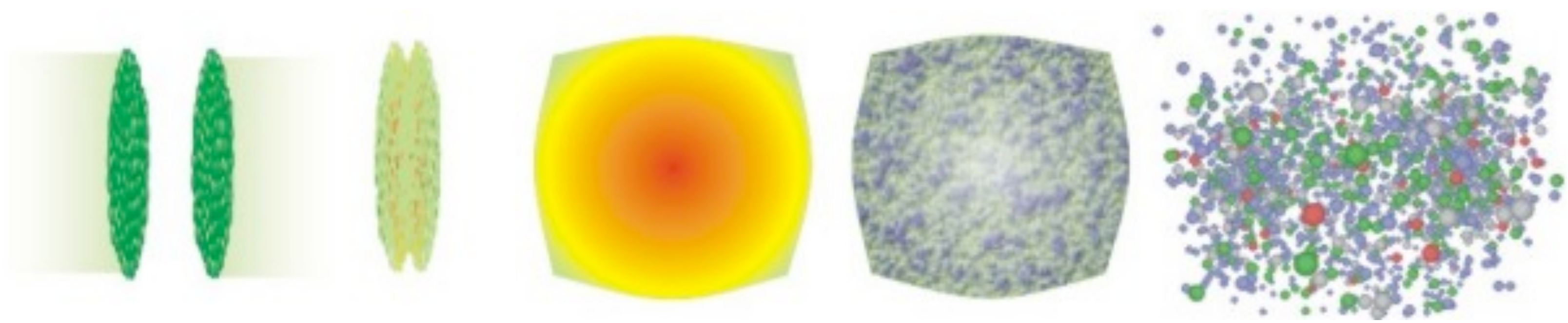


Break of Kinetic Equilibrium

Number & Species of Particles Fixed (Kinetic Equilibrium)

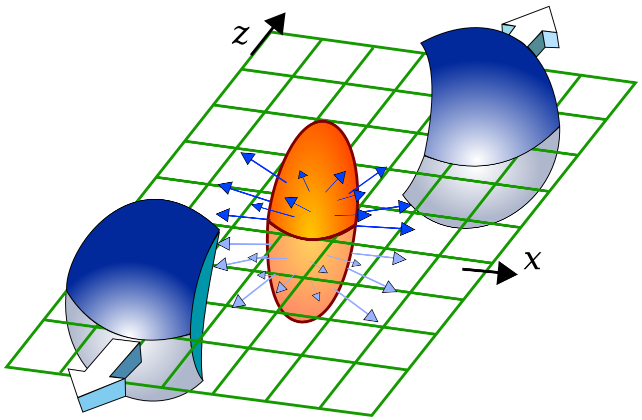
Hydrodynamic Expansion

$$\partial_\mu T^{\nu\mu} = 0$$
$$\partial_\mu j^\mu_B = 0$$



Collective Expansion

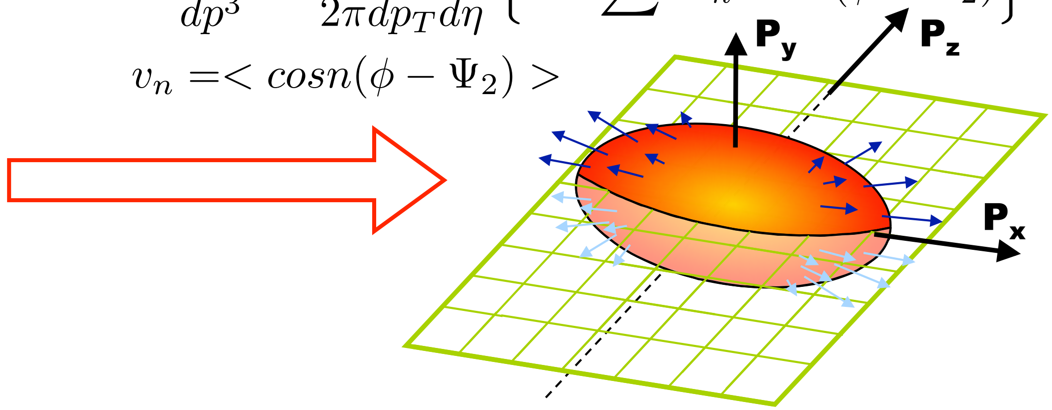
Smooth Parton Density



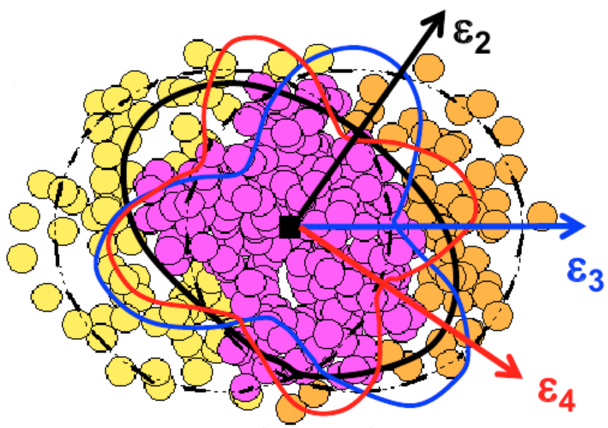
- Pressure Gradient due to small λ/R<<1

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi dp_T d\eta}\left\{1+\sum 2v_n \cos n(\phi-\Psi_2)\right\}$$

$$v_n = < cosn(\phi - \Psi_2) >$$



Fluctuating Parton Density



PRC81.054905 (2010)

- Expansion with respect to Ψ_n

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi dp_T d\eta}\left\{1+\sum 2v_n \cos n(\phi-\Psi_n)\right\}$$

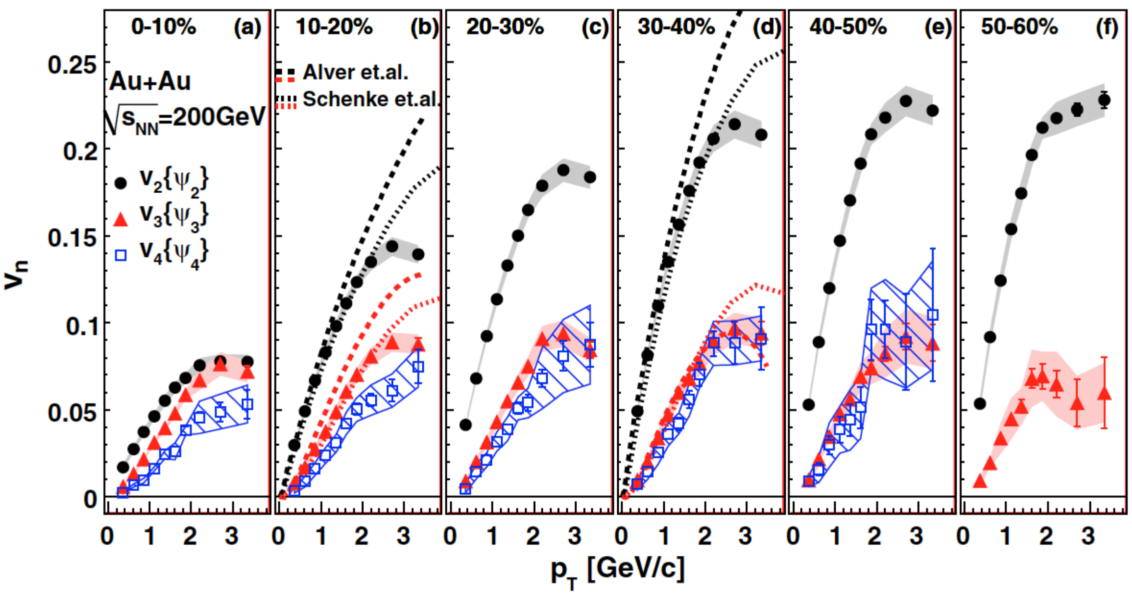
$$v_n = < cosn(\phi - \Psi_n) >$$

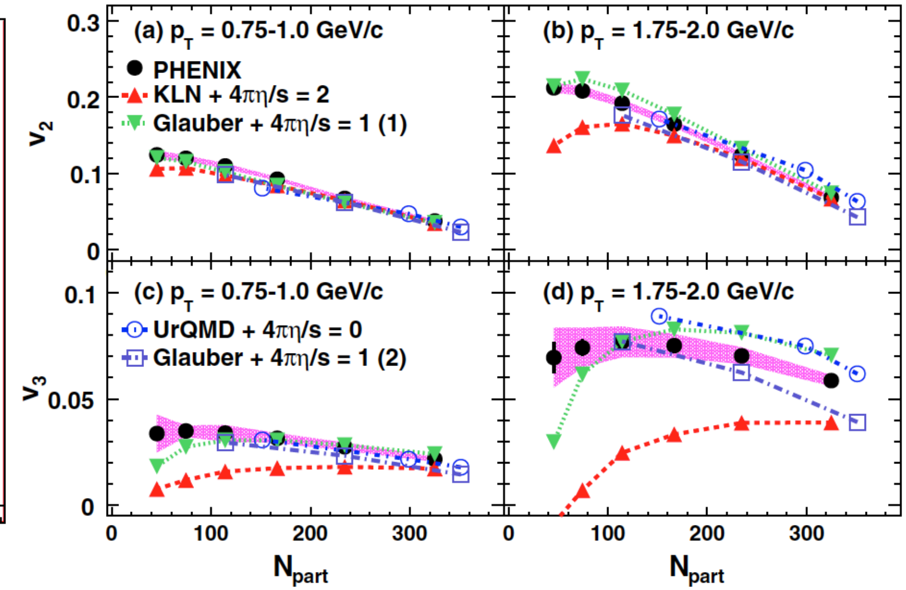
ϕ : azimuthal angle of emitted particles

Ψ : azimuthal angle of event plane

Higher-Order Flow Harmonics

PRL107.252301 (2011)

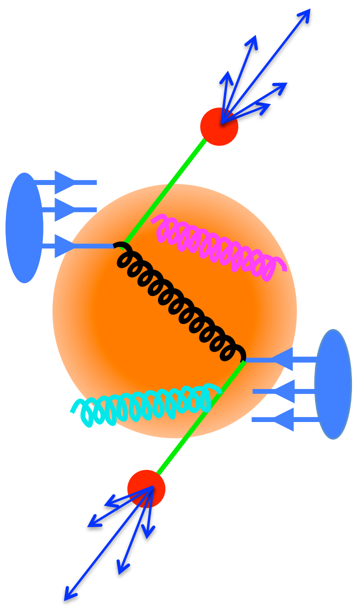


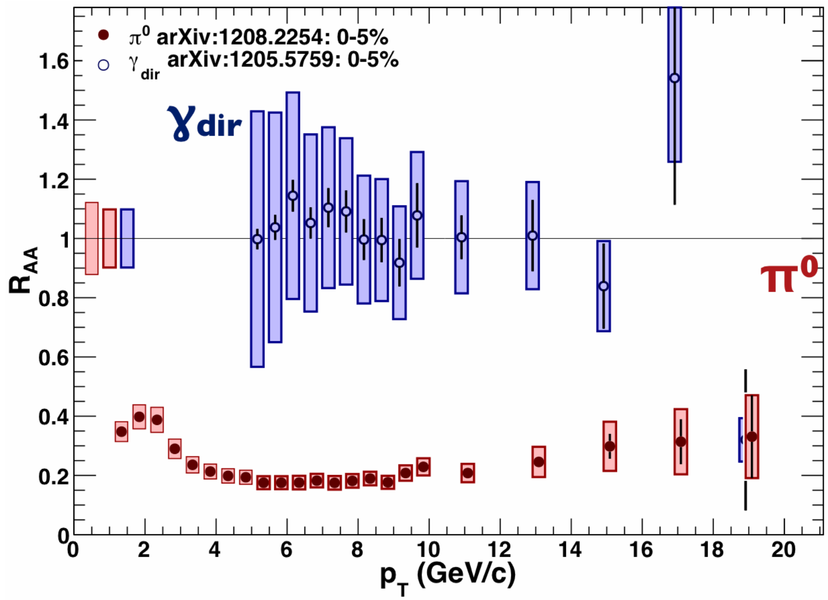


- None-zero v_n(n>2)
- Disentanglement of a degeneracy among models
  – Initial Condition, Sheer Viscosity in Hydrodynamics
- Backgrounds in correlation studies

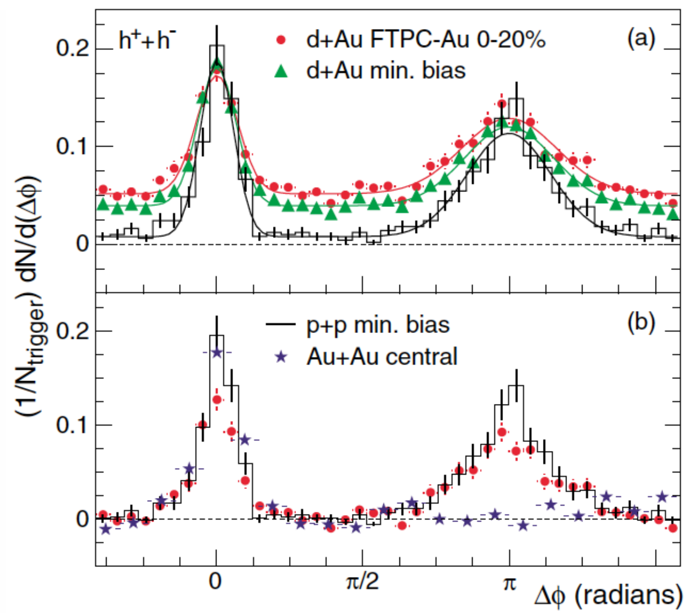
Jet-Quenching

Au+Au





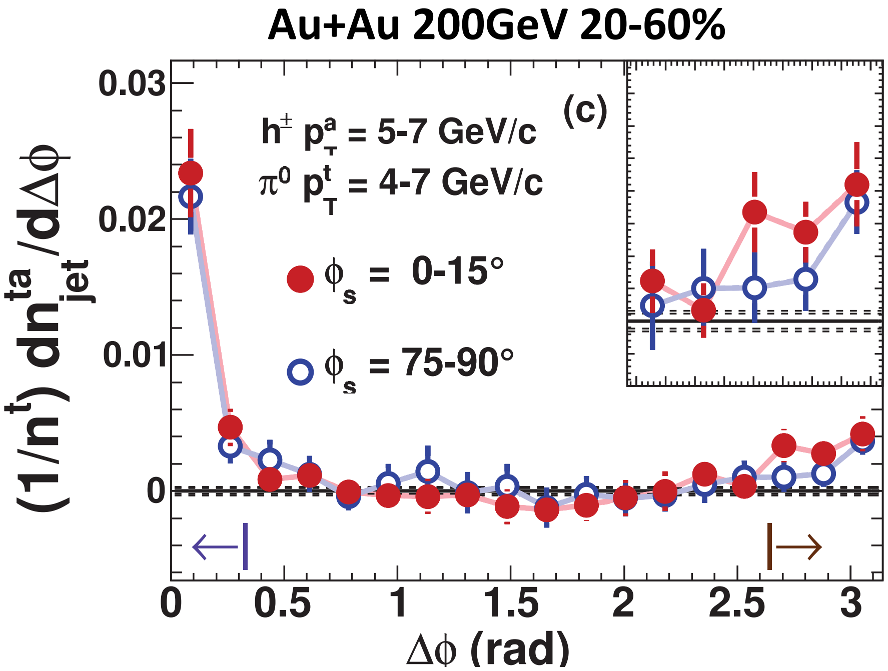
PRL91.072304 (2003)

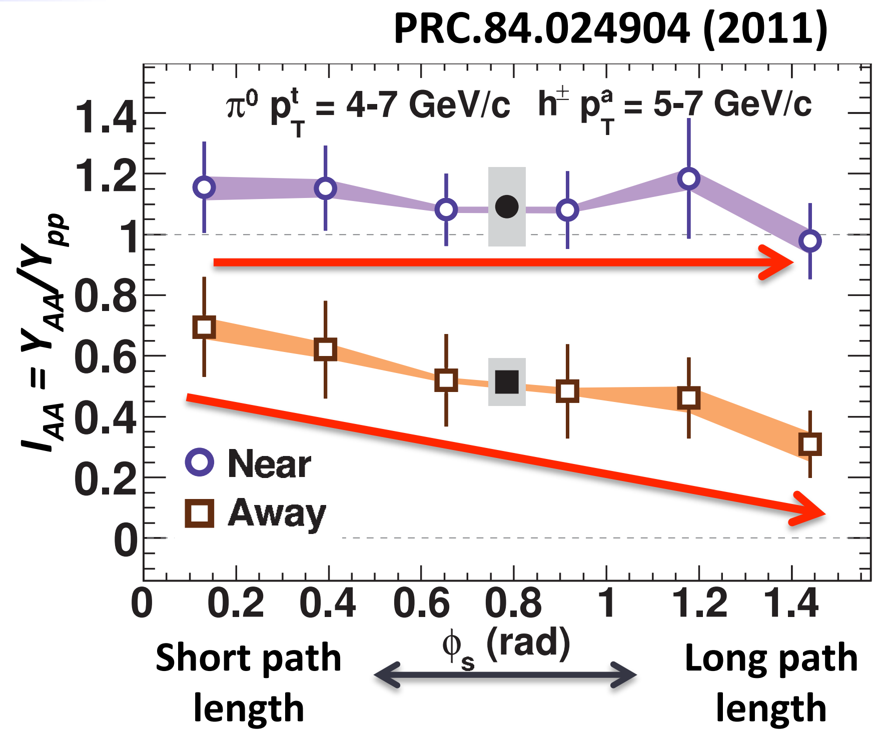


- Suppression of particles compared to p+p collisions
  - Nuclear modification Factor R_{AA}<1
  - Away-Side suppression of Correlations

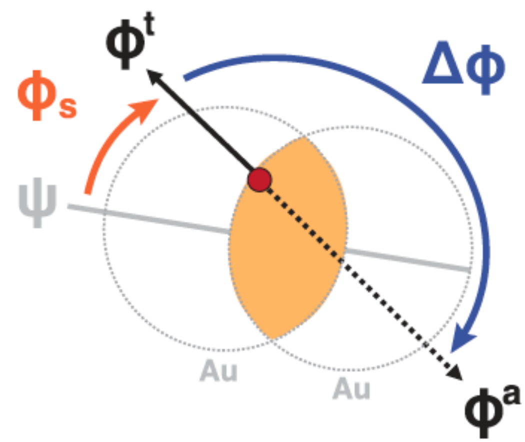
$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{pp}/dp_T d\eta}$$

Path Length Dependence of High p_T Correlations



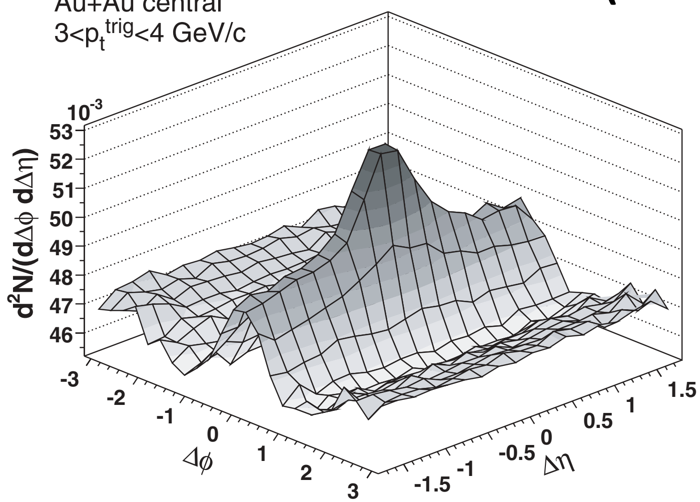


- v_2 and $v_4\{\Psi_2\}$ subtracted
- Monotonic suppression of away-side
- Parton Energy Loss depending on path length

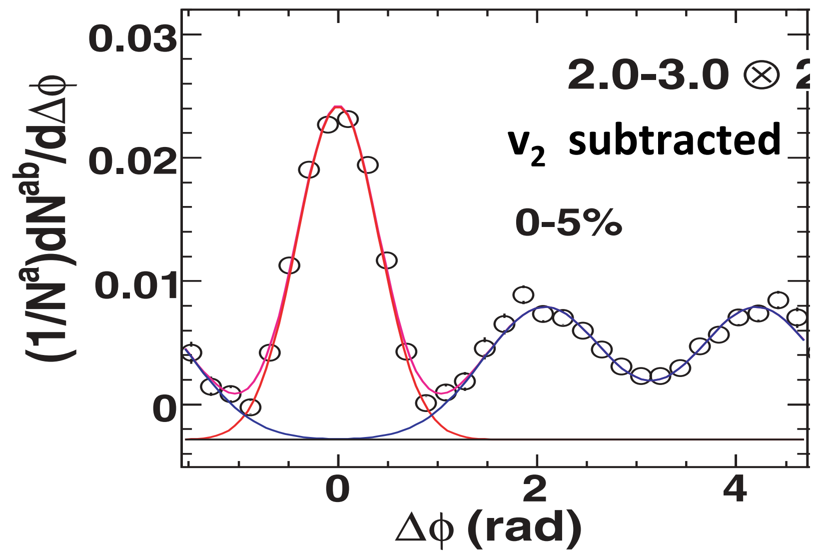


Double-Humps & Ridge of Interm. p_T Correlations

PRC.80.064912 (2009)



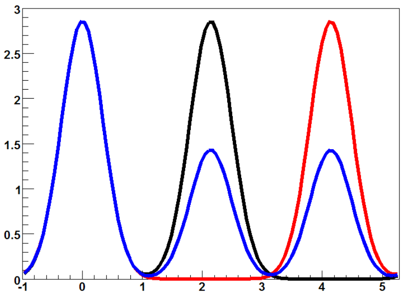
PRC.78.014901 (2008)

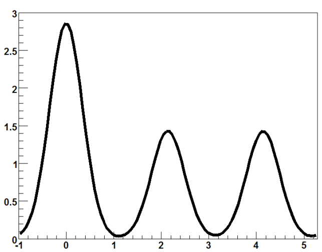


- Near-side long-range rapidity correlations (Ridge)
- Away-side double-humps of azimuthal correlations
  - v_2 contribution subtracted
- Additional Effect to Parton Energy-Loss
  - Lost Energy-Redistribution
  - Boost of jet by medium expansion

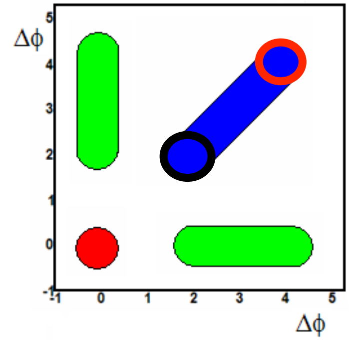
Conical Emission of Away-Side

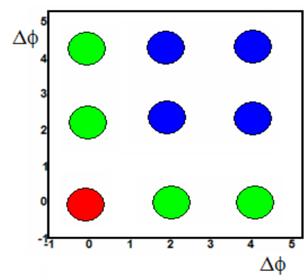
2-particle correlation



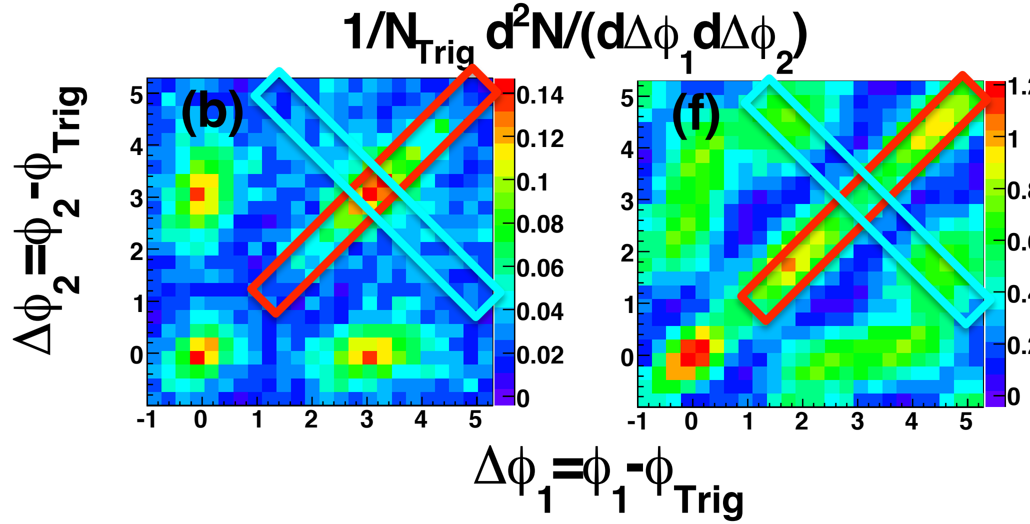


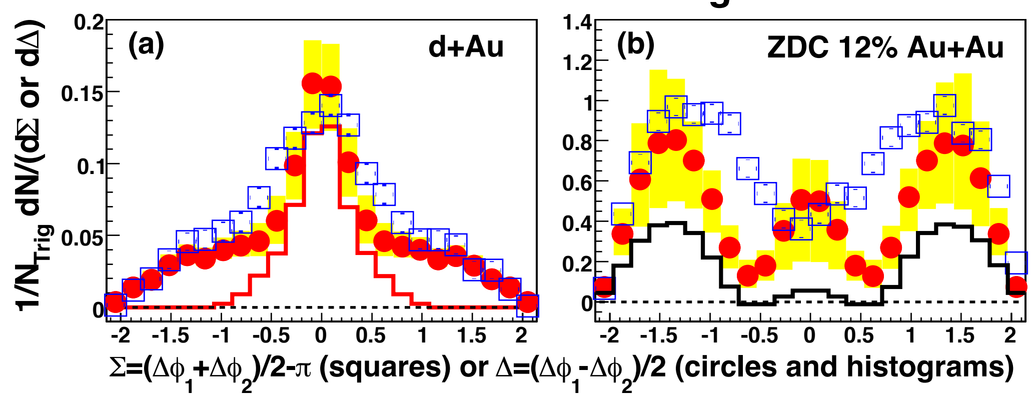
3-particle correlation





Experimental Data





PRL102.052302 (2009)

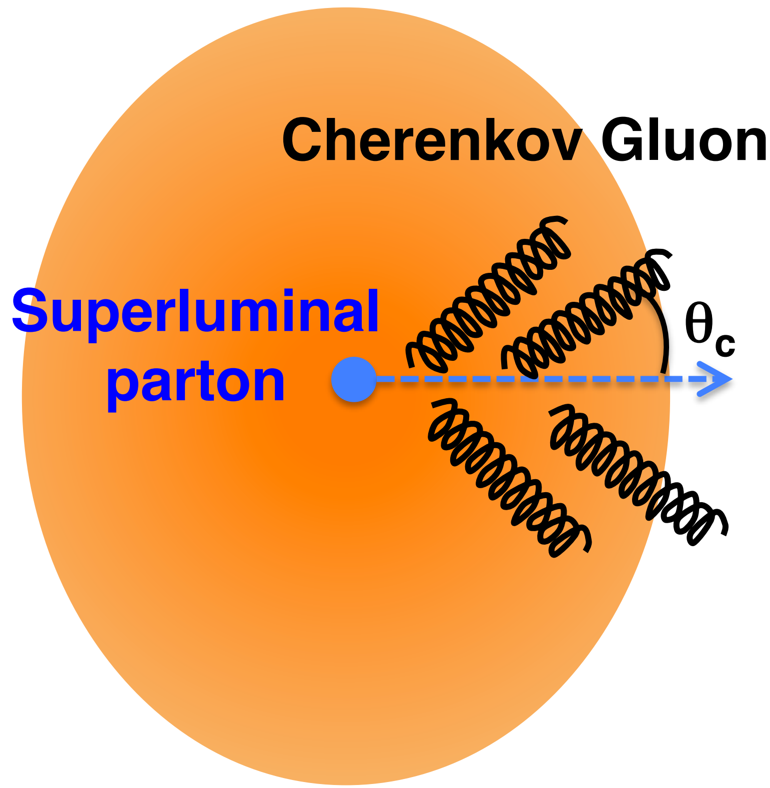
Cherenkov Gluon Radiation

- Gluon Radiation from a superluminal parton
- Momentum dependence of gluon opening angle

$$\cos\theta_c = c/n(p)v_{part} \simeq 1/n(p)$$

v_{part}~ c at GeV/c scale

$$n(p) = p/p_0$$ **: Index of Reflection**



PRL96.172302 (2006)

Mach Cone Shock Wave

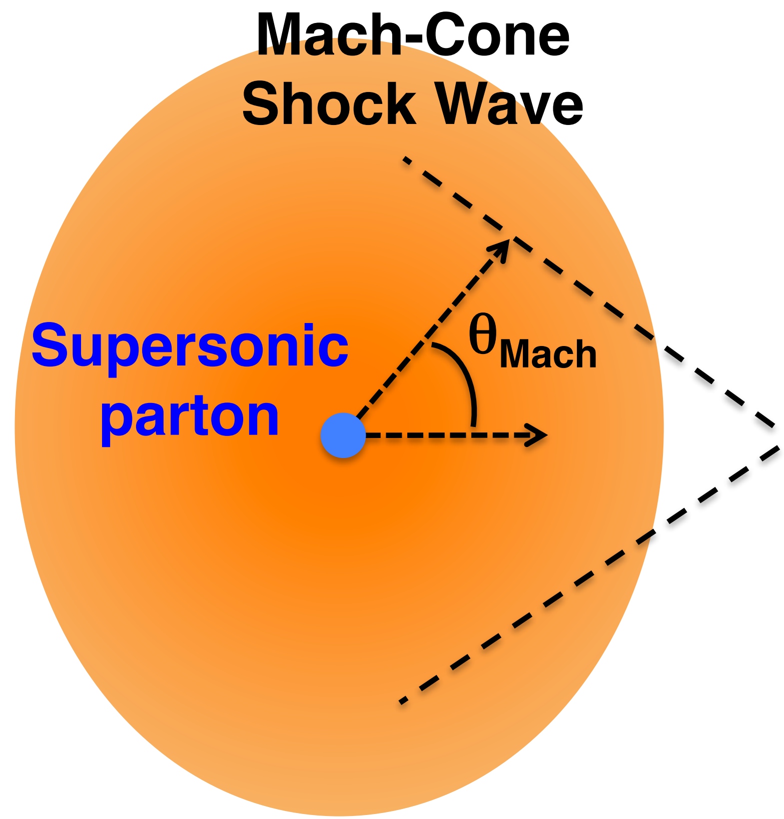
- Shock Wave from a supersonic parton

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

c_s **: speed of sound**

- p_T independence of double-hump position
  - v_{part} ~ constant at GeV scale
  - c_s ~ constant at Au+Au 200 GeV

PRC73.011901(R) (2006)



Jet Deflection

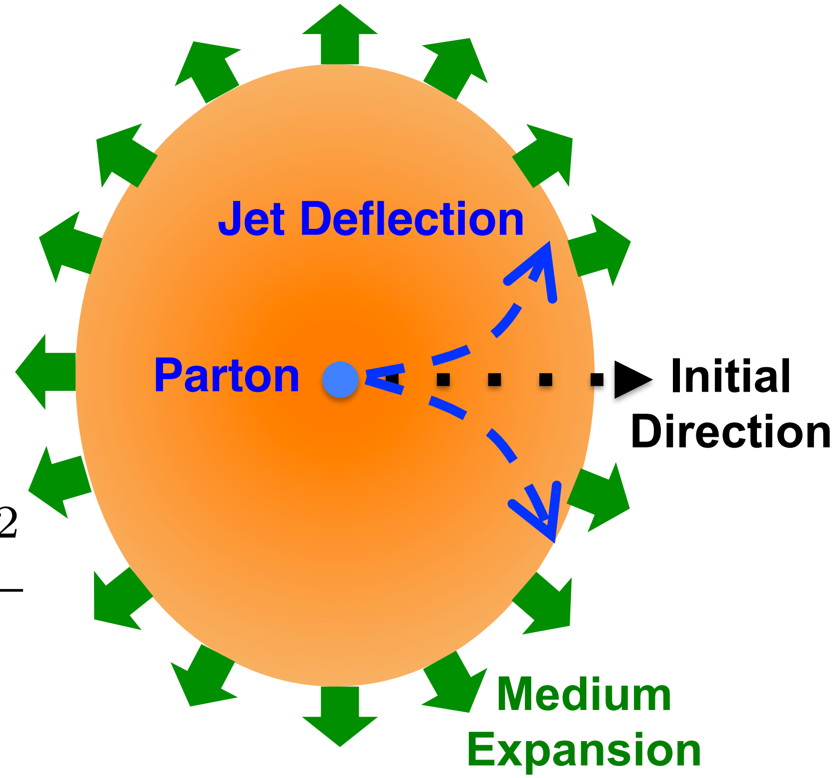
- Deflection from initial direction
  - Boost by medium expansion
  - Energy-momentum loss
- Hydro + Energy-Momentum Loss

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

$$S^\nu(t,\vec{x}) = \frac{1}{(\sqrt{2\pi}\sigma)^3} \exp -\frac{[\vec{x}-\vec{x}_{jet}(t)]^2}{2\sigma^2}$$

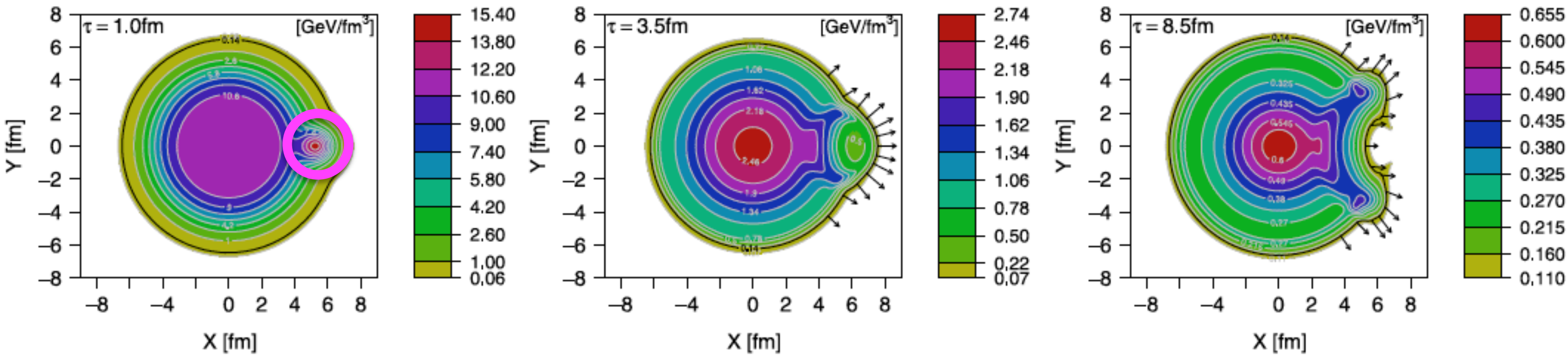
$$\times \left(\frac{dE}{dt}, \frac{dM}{dt}, 0, 0\right) \left[\frac{T(t,\vec{x})}{T_{max}}\right]^3$$

PRL105.222301 (2010)



Hot-Spot Model

PLB712.226 (2012)



- Hot-Spot : domain of high parton density
- Hot-Spot + Hydrodynamic Expansion
- Double-humps without hard-scattered partons

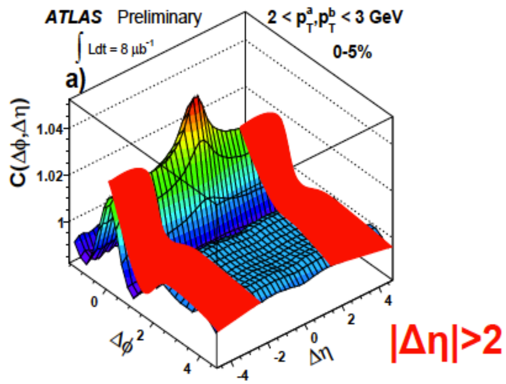
Contributions of v_n (n>2) in correlations

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

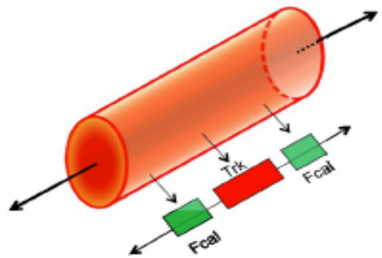
From 2PC method

From EP method

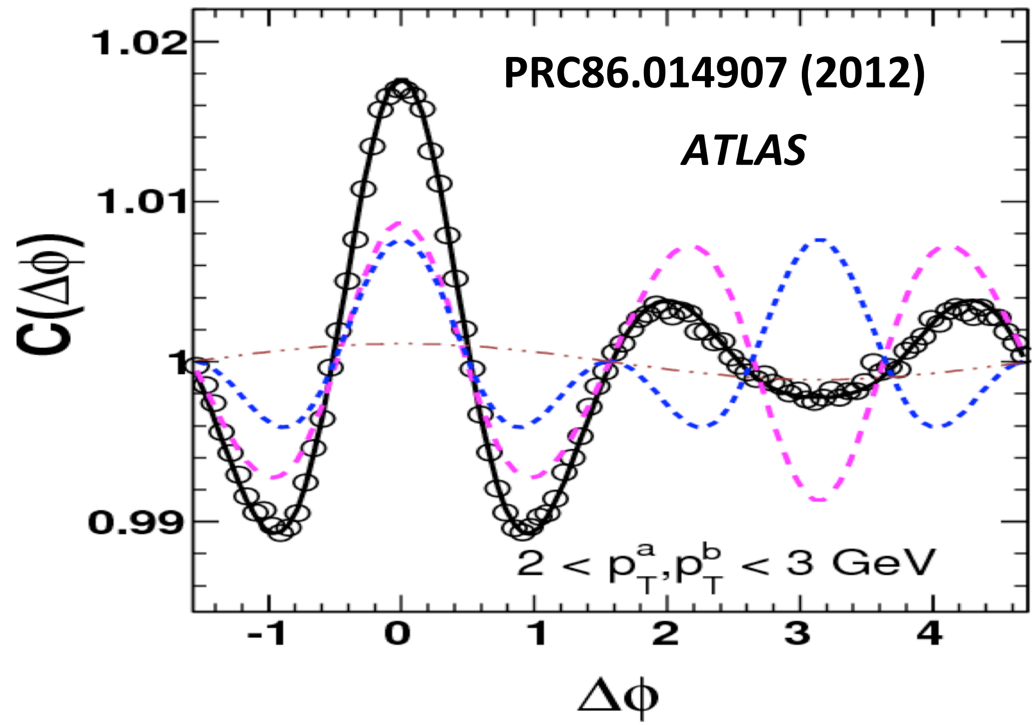
2Par. Correlation



v_n with EP Method



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



- Double-hump & ridge of long-rapidity correlation explained
- Short-rapidity correlation with v_n subtraction to discuss parton behavior

Motivation of this Dissertation

- Focus on azimuthal two-particle correlations
- Provide robust experimental results after v_n subtraction
  - Centrality & p_T dependence, double-humps etc.
  - Revisit of previous models

- Diagnose correlation phenomena at intermediate-p_T with control of parton path length with respect to event-planes (Ψ_2,Ψ_3)
  - Parton-Energy Loss
  - Re-distribution of lost energy from partons
  - Possible boost of Jet by medium expansion

My Contributions

Activity Categories

*Oral (intern.) *Oral (Domestic) *Experimental *Analysis *Service work

M1,2 : AY 2008~2009

D1 (RIKEN JRA) : AY 2010

DNP-JPS Joint Meeting

PHENIX Run9 PHENIX Run10

Detector Maintenance

Heavy Ion Pub

preliminary request

Au+Au ridge analysis

D2 (RIKEN JRA) : AY 2011

D3 (RIKEN JRA) : AY 2012

JPS Fall

WPCF2011

PHENIX Run12

Detector Maintenance

JPS Spring

HIC•HIP

Hard Probes2012

Quark Matter2012 PHENIX Run13

Nagoya-Mini Workhop2012

preliminary request

Au+Au vn-correlation

preliminary request

Au+Au PID vn

preliminary request

Au+Au correlations w.r.t. EP

vn EP calibration

Detector Maintenance

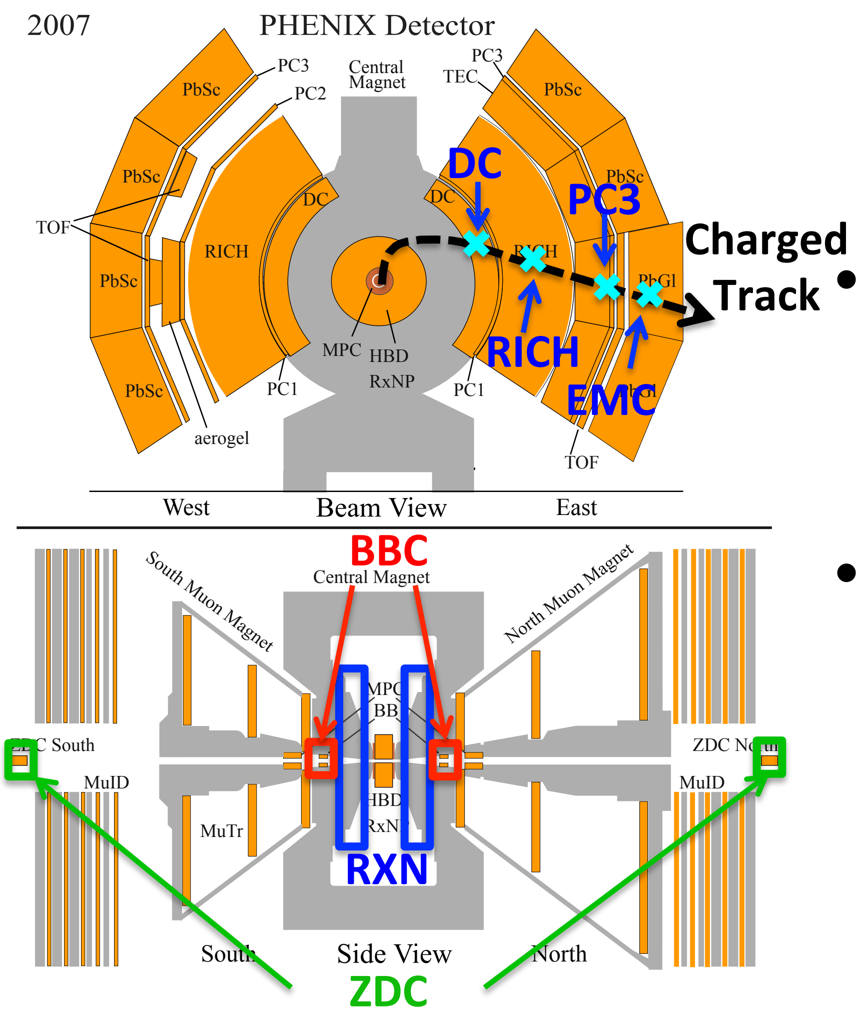
D4 : AY 2013

ANALYSYS

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 Matching Cut
  - Electron Veto
  - Energy/Momentum cut for High p_T particles
    - Background rejection
  - Pair cut of miss-reconstructed hadron pairs

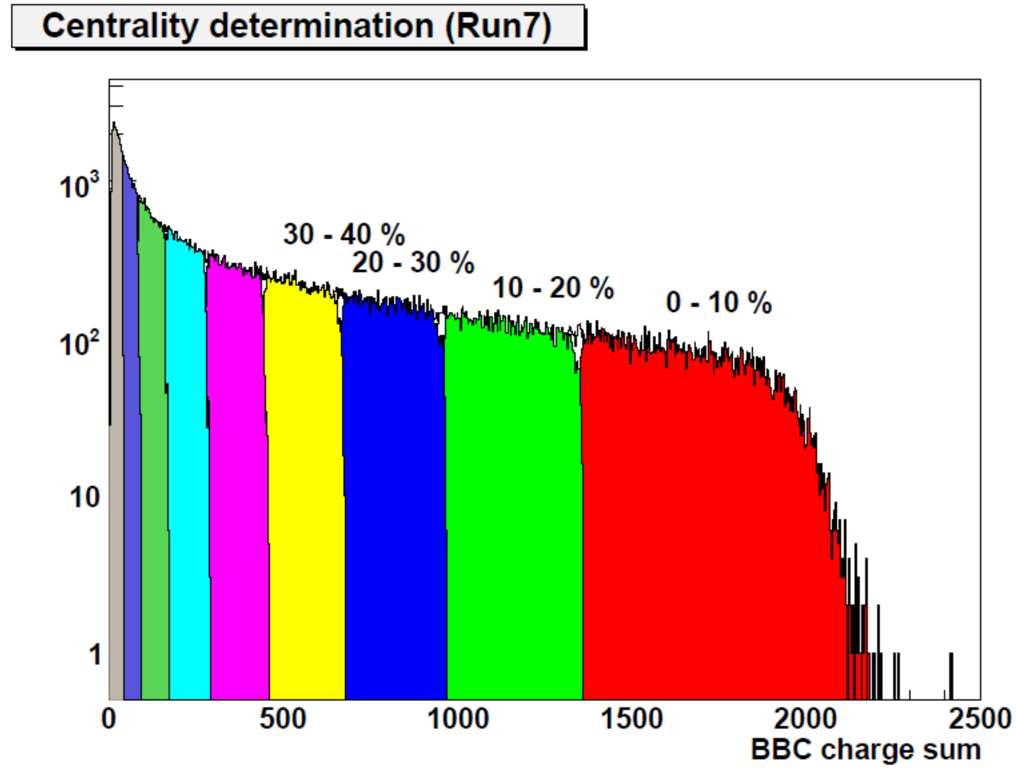
PHENIX Detector - 2007 Experiment

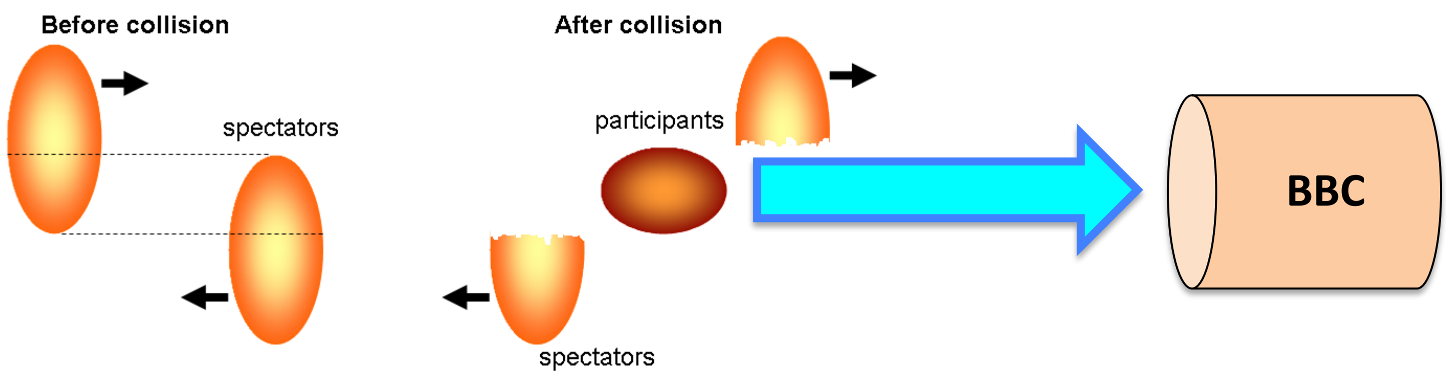


- Trigger, collision vertex, centrality
  - Beam-Beam-Counter (BBC)
  - Zero-Degree-Calorimeter(ZDC)
- Event Plane
  - BBC
  - Reaction-Plane-Detector(RXN)
- Central Arm, $\Delta\phi=\pi$ $|\eta|<0.35$
  - Momentum, Tracking, Electron Veto
    - Drift Chamber (DC)
    - Pad Chamber(PC)
    - Electromagnetic Calorimeter(EMC)
    - Ring Image Cherenkov Detector(RICH)

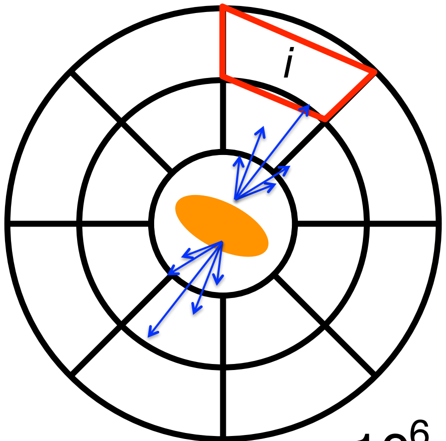
Centrality

- BBC charge sum divided in percentile
  - Same number of events in each bins



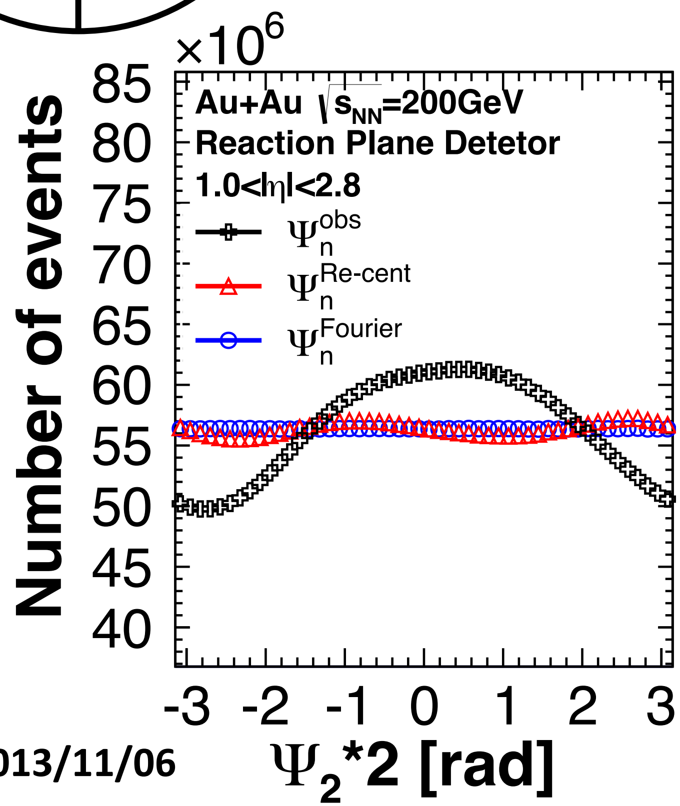


Event Plane Calibration



ϕ_i : Azimuthal angle

w_i : Weight (Charge etc.)



Raw distribution

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

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

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 & v_n Measurements

EP Resolution

PRC58.1671

- Resolution +/-η

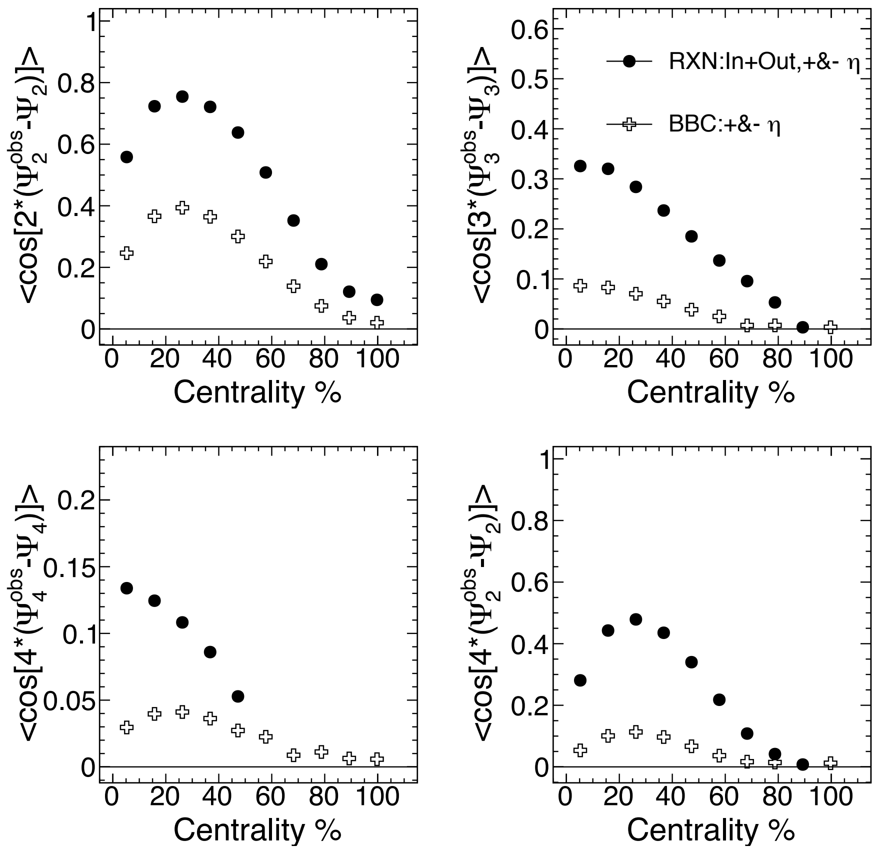
$$\sigma_n^{EP} = \langle \cos kn(\Psi_n^{EP\pm\eta} - \Psi_n) \rangle$$
$$= \sqrt{\langle \cos kn(\Psi_n^{EP(+\eta)} - \Psi_n^{EP(-\eta)}) \rangle}$$
$$= \frac{\pi}{8}\chi_n^2 \left[I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right) + I_{(k+1)/2}\left(\frac{\chi_n^2}{4}\right) \right]^2$$

- Resolution +&-η
  - $\chi \to \sqrt{2}\chi$

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

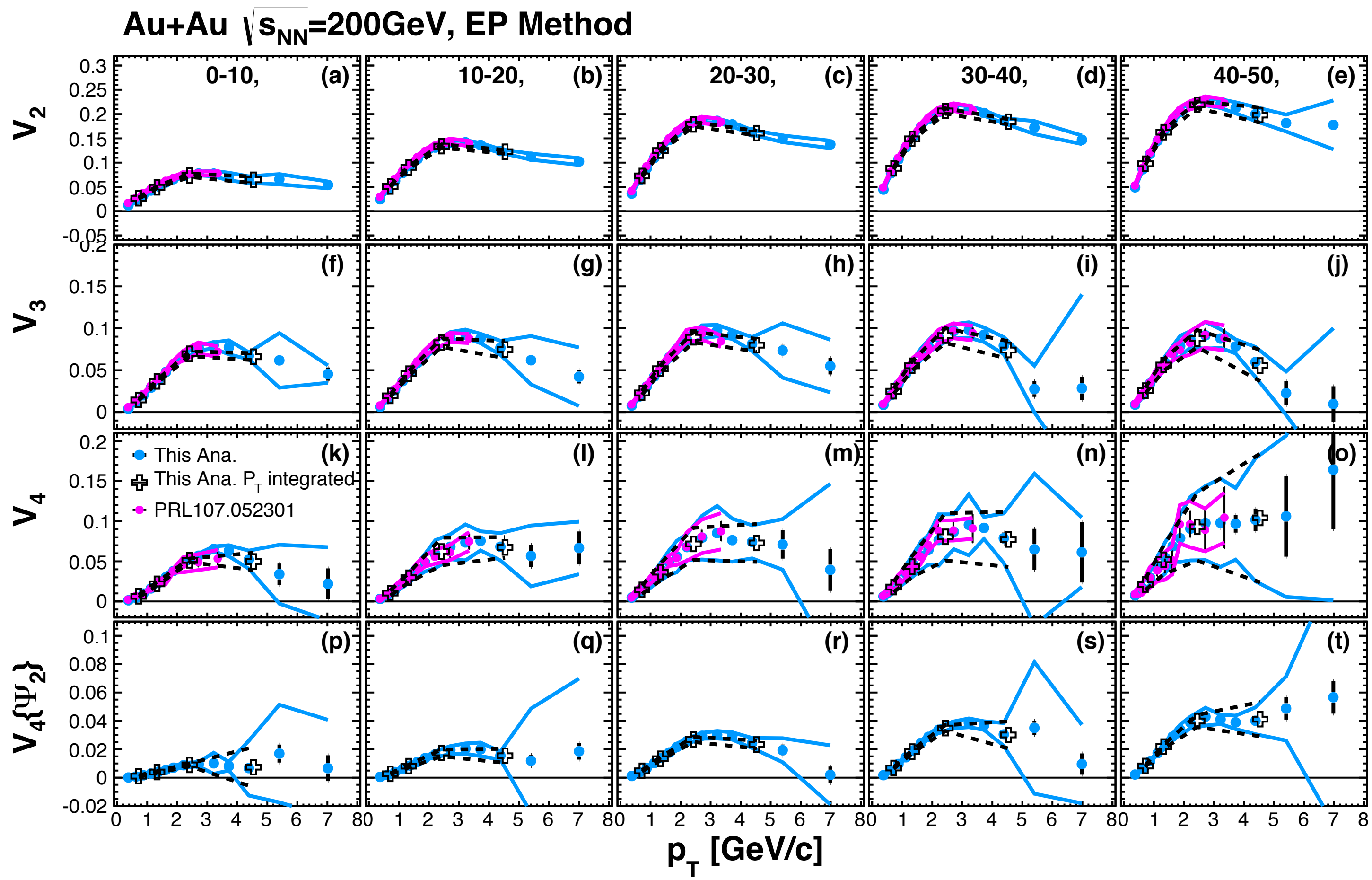
- v_n measurements

$$v_n = \frac{v_n^{obs}}{\sigma_n^{EP}} = \frac{\langle \cos n(\phi - \Psi_n^{EP}) \rangle}{\langle \cos n(\Psi_n^{EP} - \Psi_n) \rangle}$$



v_n Results

- Consistent results with previous measurements
  - Used for background subtraction

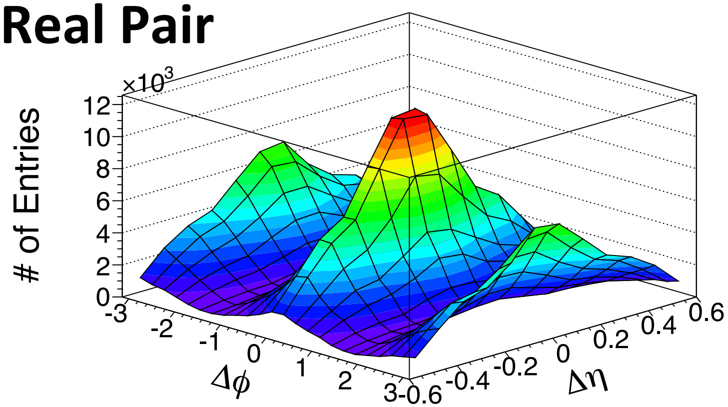


Two Particle Correlations

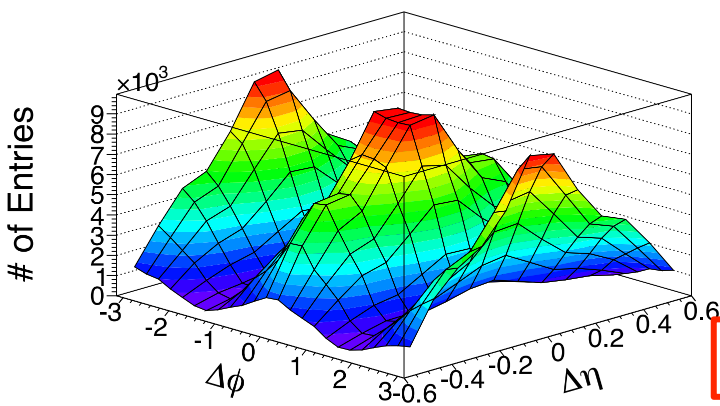
- Pair distributions in real and mixed events

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

Real Pair

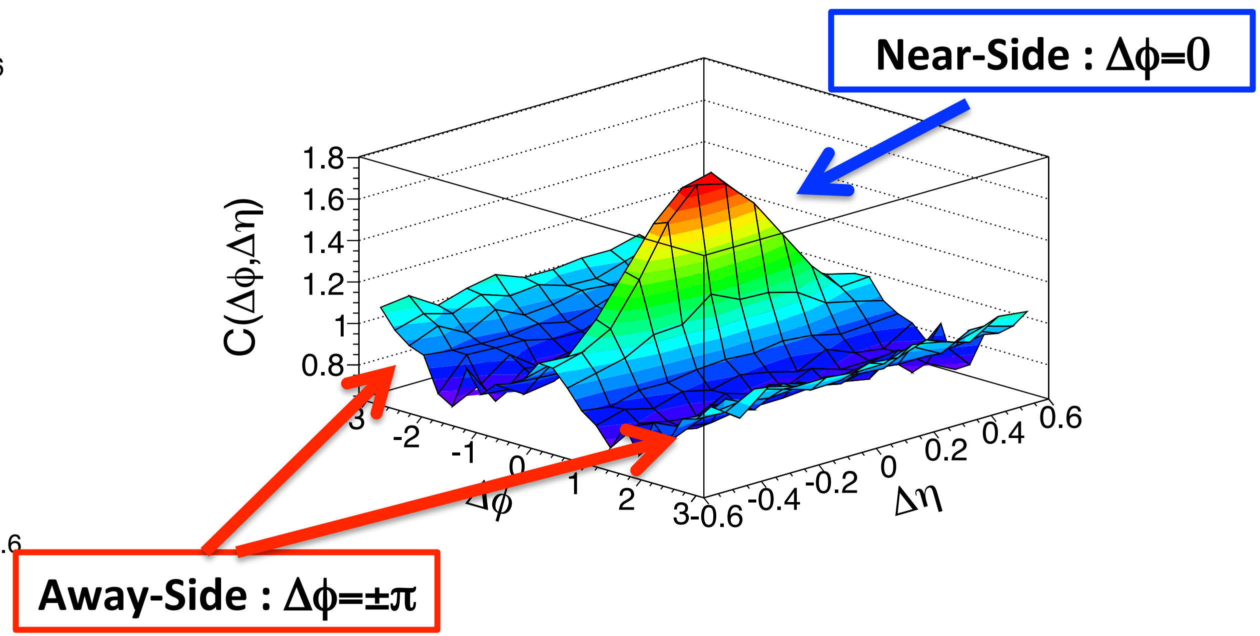


Mixed Pair

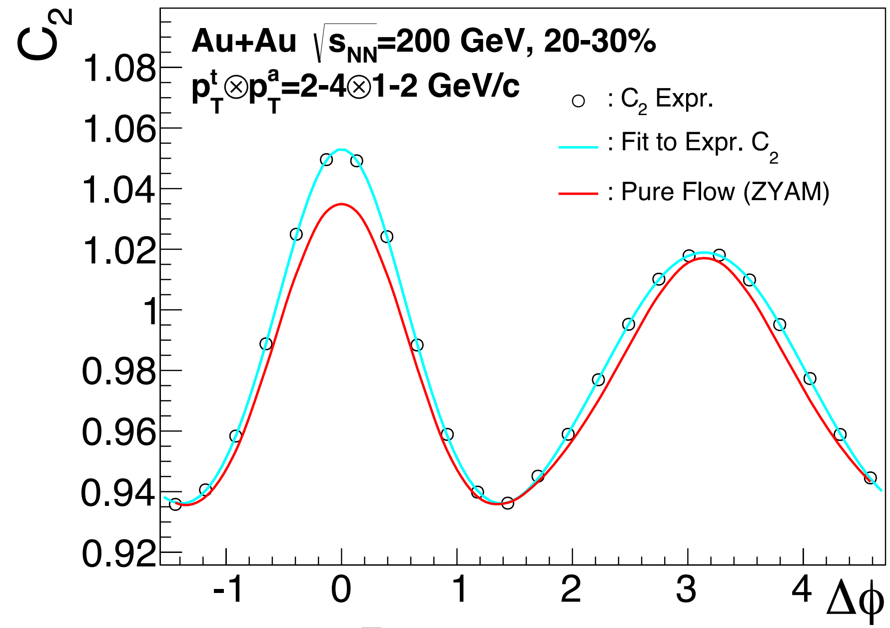


- Two-Particle Correlations

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



Flow Subtraction & Pair Yield per a Trigger (PTY)



- Analytical Formula of Pure Flow

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

- Flow subtractions
  - Zero Yield At Minimum Assumption

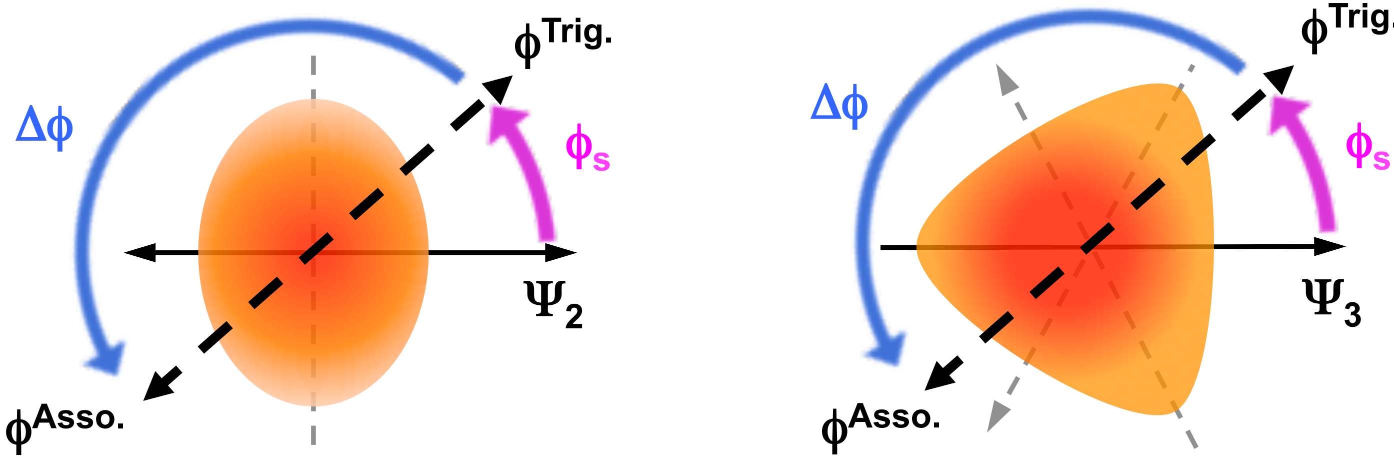
$$j(\Delta\phi) = C(\Delta\phi) - b_0 \left[1 + \sum_{n=1} 2v_n^t v_n^a \cos(n\Delta\phi)\right]$$

- Pair yield per a trigger

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

ε : **Tracking efficiency of associate particles**

Event-Plane Dependence



- Selecting trigger particle w.r.t. Ψ_2 & Ψ_3
- Control of parton path length inside medium
- Sensitivity to each harmonic plane

Flow Contributions with respect to EP

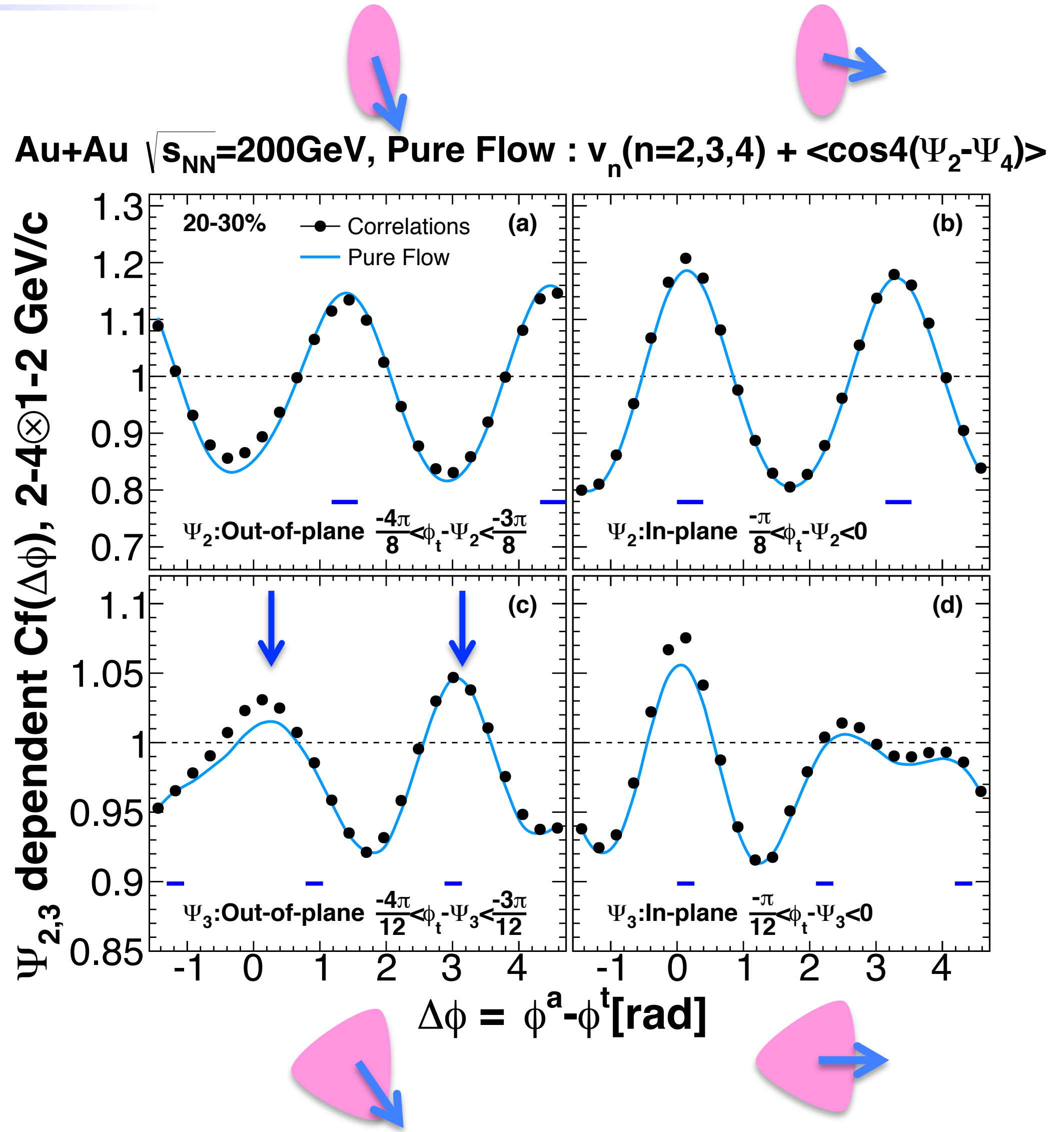
- No analytical formula of pure flow w.r.t EP
- Run a Monte Carlo simulation
- Azimuthal distribution
  - Using Measured v_n

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi dp_T d\eta}\left\{1 + \sum_{n=2,3,4} 2v_n \cos n(\phi - \Psi_n)\right\}$$

- Observed Event Plane Resolution
- Observed correlation between EP
  - $<4(\Psi_2-\Psi_4)>=v_4\{\Psi_2\}/v_4\{\Psi_4\}$
  - $<6(\Psi_2-\Psi_3)>=0$

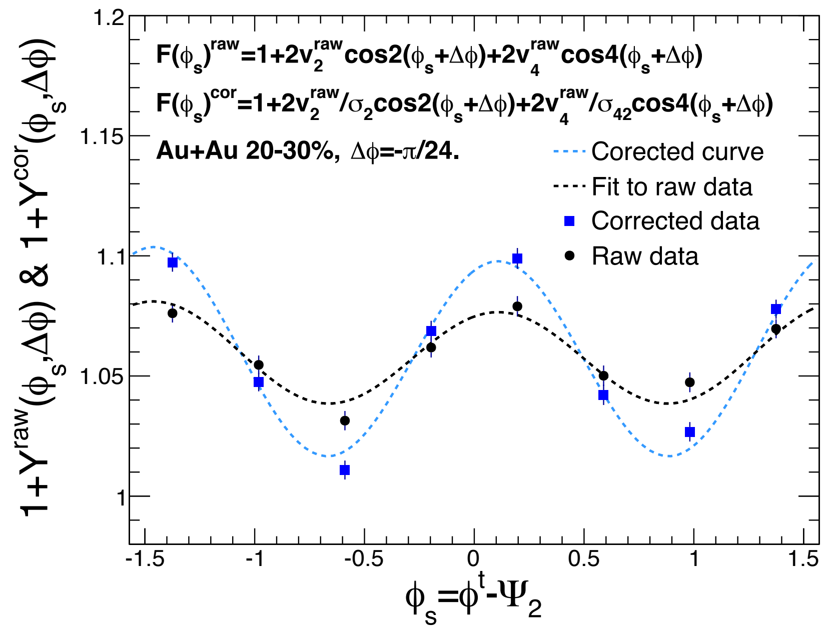
Flow Contributions with respect to EP

- p_T^T : 2-4, p_T^a:1-2 GeV/c
- Good reconstruction of correlation shape by MC simulation for both Ψ_2, Ψ_3 dependence
- Except around $\Delta\phi=0, \pi$ where affected by jet



Resolution Correction for Trigger Selection

- Fitting Method
  - Azimuthal anisotropy of correlations yield
  - Resolution correction in analogous to v_n measurements
- Iteration Method
  - Trigger smearing effect by measured resolution ***S***
  - Correlation Yield ***A***
  - Smeared Correlations ***B***
  - Effective correction coefficient ***C***
  - Iteration until convergence



$$\mathbf{B}^{(\mathbf{n})} = S\mathbf{A}^{(\mathbf{n})}$$

$$\mathbf{C}^{(\mathbf{n})} = \mathbf{A}^{(\mathbf{n})}/\mathbf{B}^{(\mathbf{n})}$$

$$\mathbf{C}\mathbf{A}^{(\mathbf{n})} = \mathbf{A}^{(\mathbf{n+1})}$$

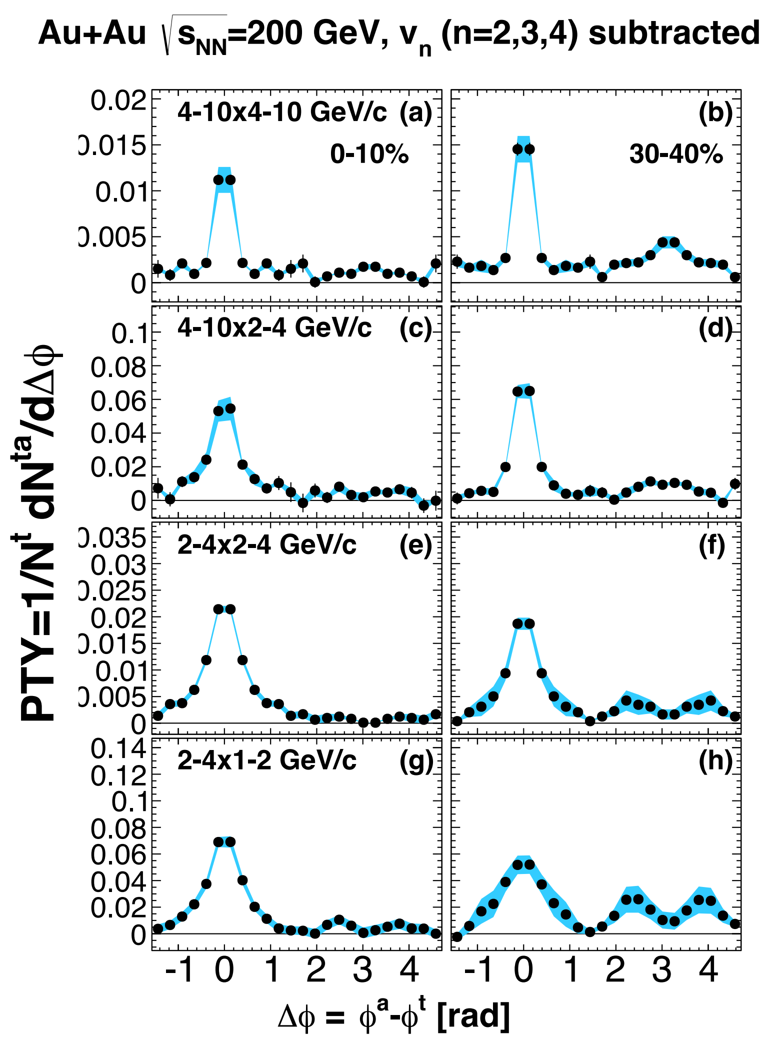
Systematic Uncertainties

- Flow v_n Measurements
  - Fluctuation within RXN EP
  - Rapidity dependence of EP : RXN-BBC difference
  - Matching cut of CNT Particles
- Two-Particle Correlations
  - Systematics from v_n
  - Matching cut of CNT Particles
- Event Plane Dependent Correlations
  - Unfolding Method : Fit & Iteration
  - Parameter in iteration method

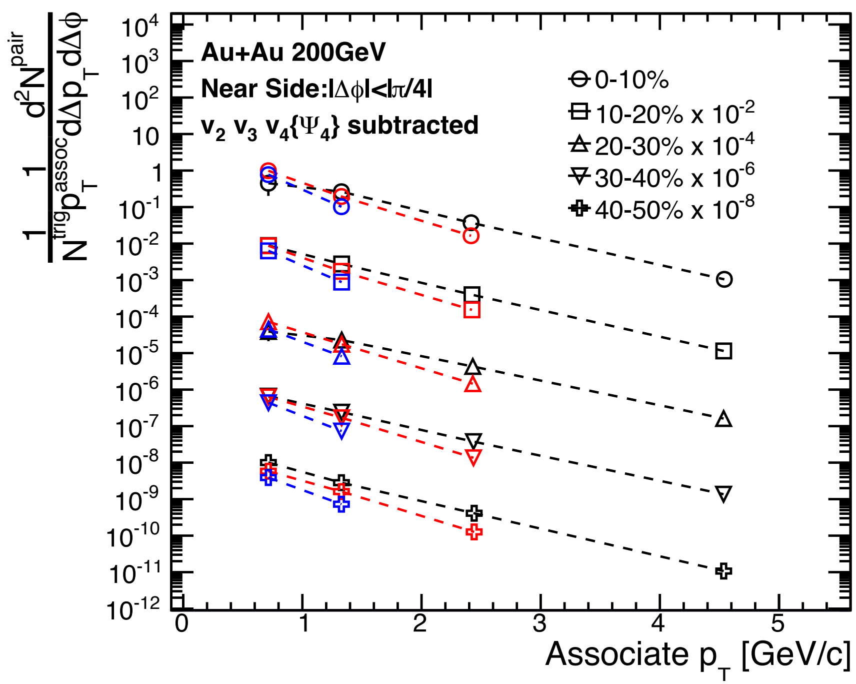
Results & Discussion

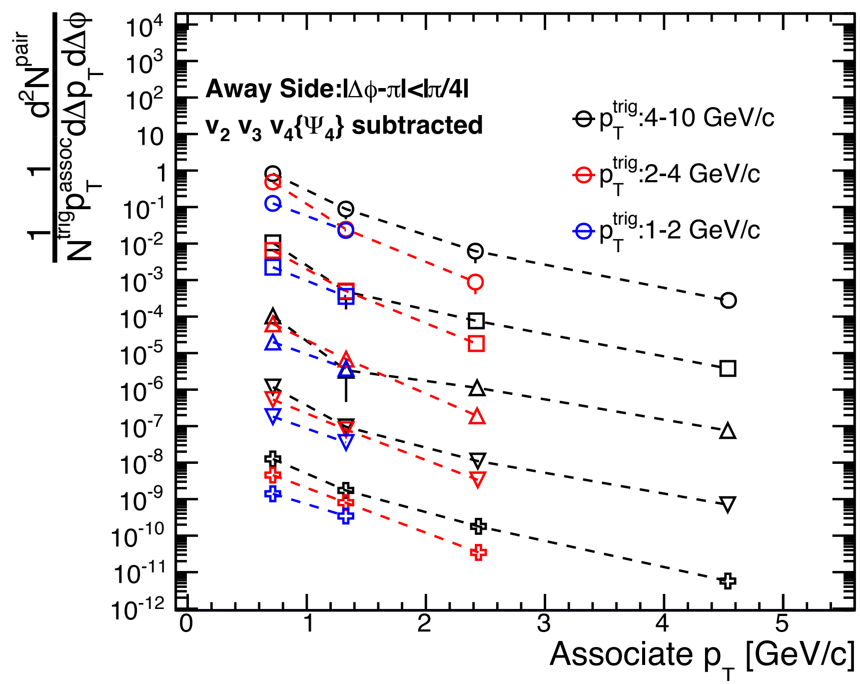
Two-Particle Correlations

- Suppression of Away-Side in most central collisions
- Away-side shape in peripheral collisions
  - Single peak at high p_T
  - Double hump at intm. p_T
- p_T independence of double hump position below p_T<4 GeV/*c*



Hardness of Correlation Yields



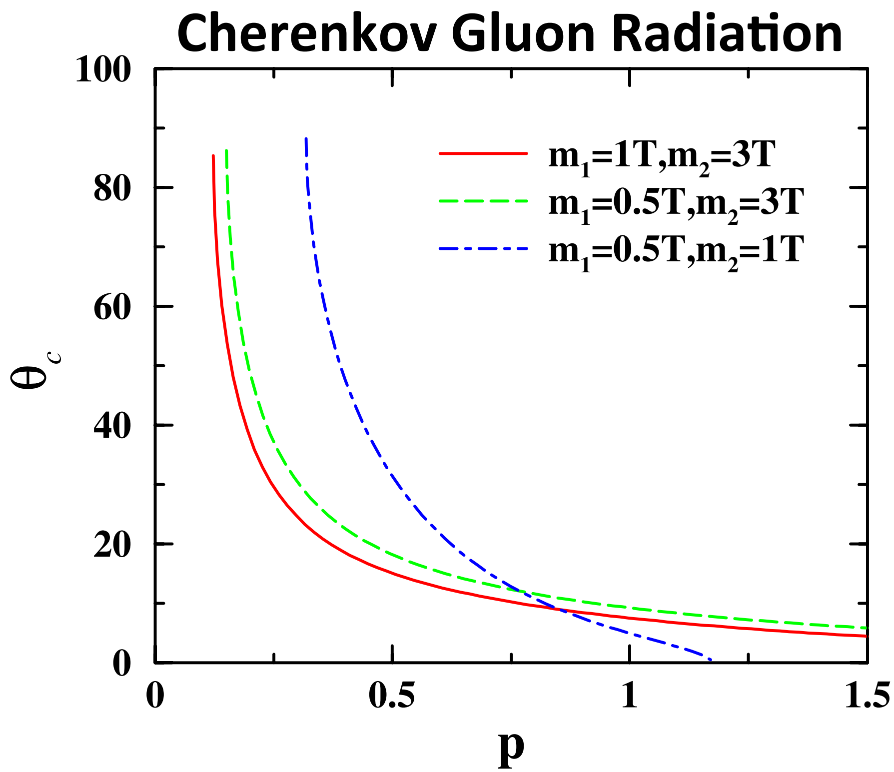


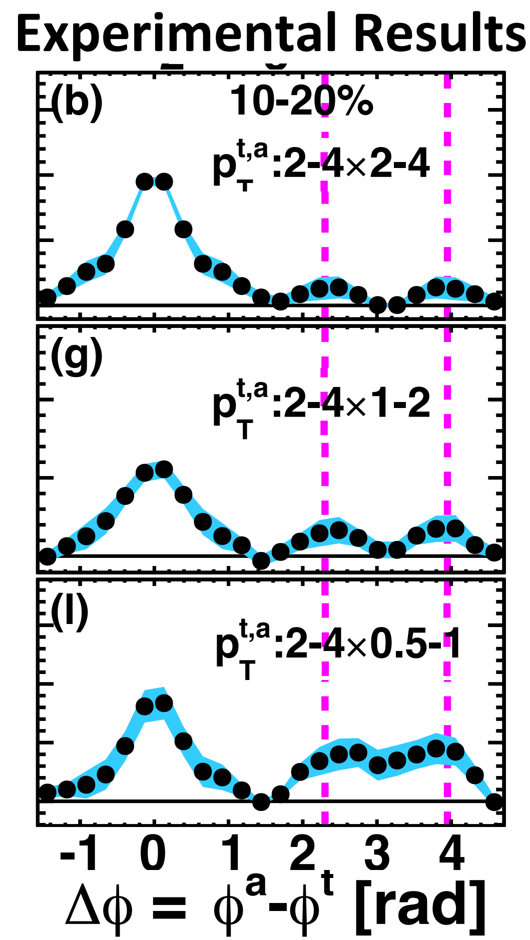
- p_T spectra of correlation yield

$$\frac{1}{p_T^a}\frac{dY}{d\Delta p_T} = \frac{1}{p_T^a}\frac{1}{(p_T^{a,max} - p_T^{a,min})}\int d\Delta\phi \frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$$

- Hardness increase with trigger and associate p_T
  - Different Physics depending on p_T

Comp. w/ Model : Cherenkov Gluon Radiation

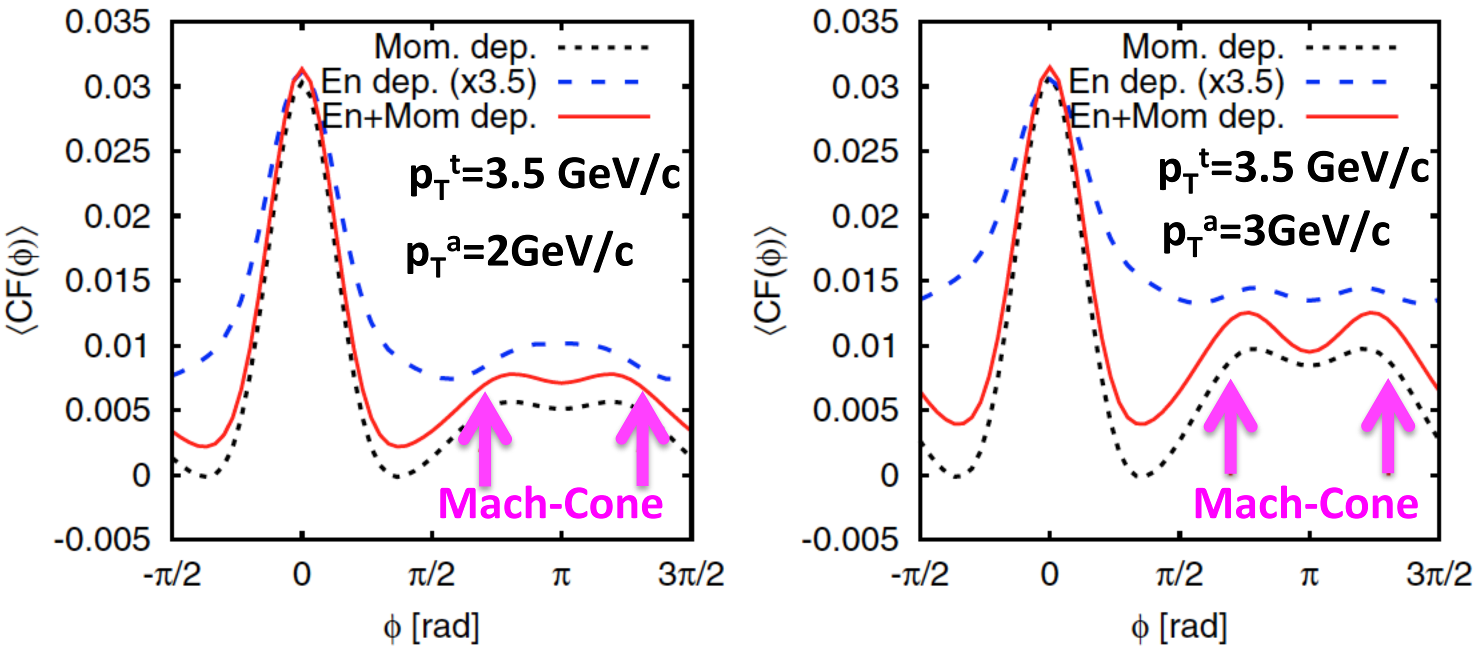




- Strong momentum dependence
- Disfavored by p_T independence of experimental data

Comp. w/ Model : Jet-Deflection & Mach-Cone

PRL105.222301 (2010)



Energy-Momentum Loss Rate

$$dE/dt = 1\mathrm{GeV/fm}$$

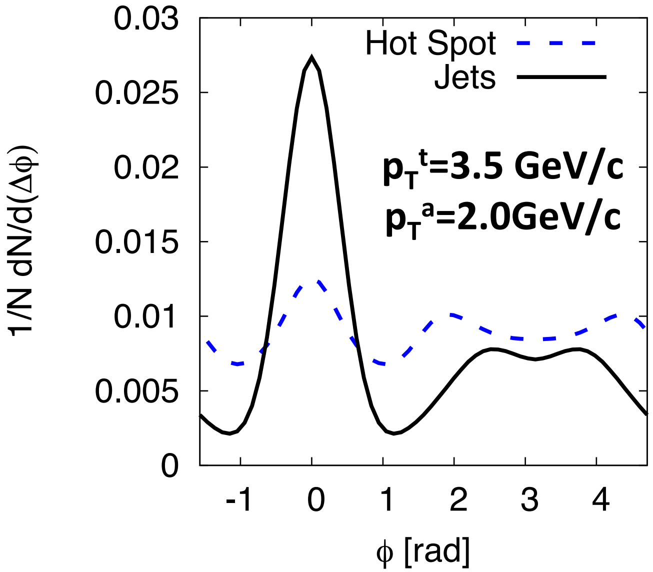
$$dM/dt = (1/v)(dE/dt)$$

$$(v = 0.999)$$

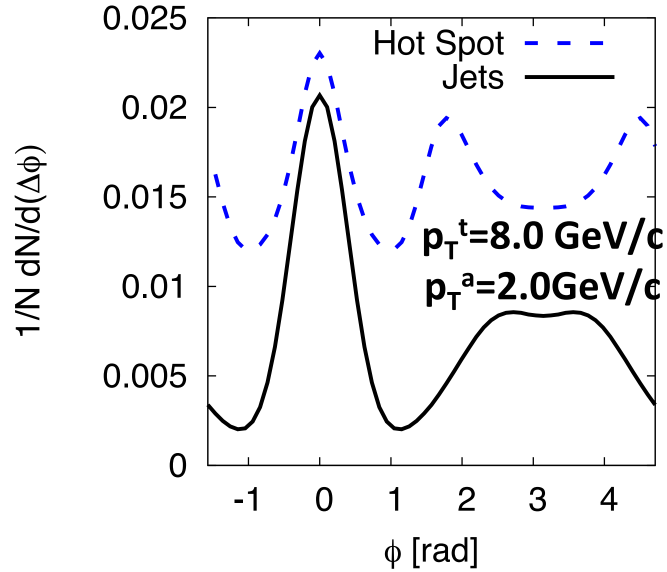
- Momentum Loss to obtain p_T independent Double-hump
  - Energy + Momentum Loss is most realistic
- Mach-Cone also shows p_T independence

Comp. w/ Model : Jet-Deflection & Hot-Spot

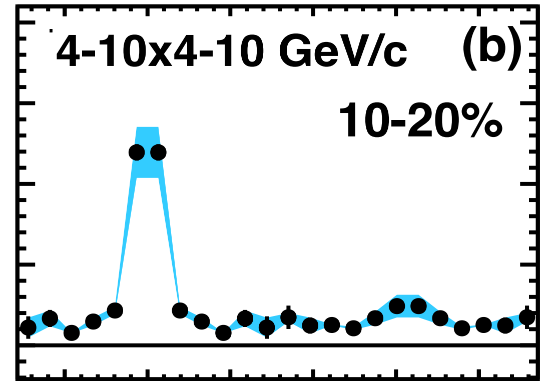
Jet : PRL105.222301 (2010)



Hot-Spot : PLB712.226 (2012)



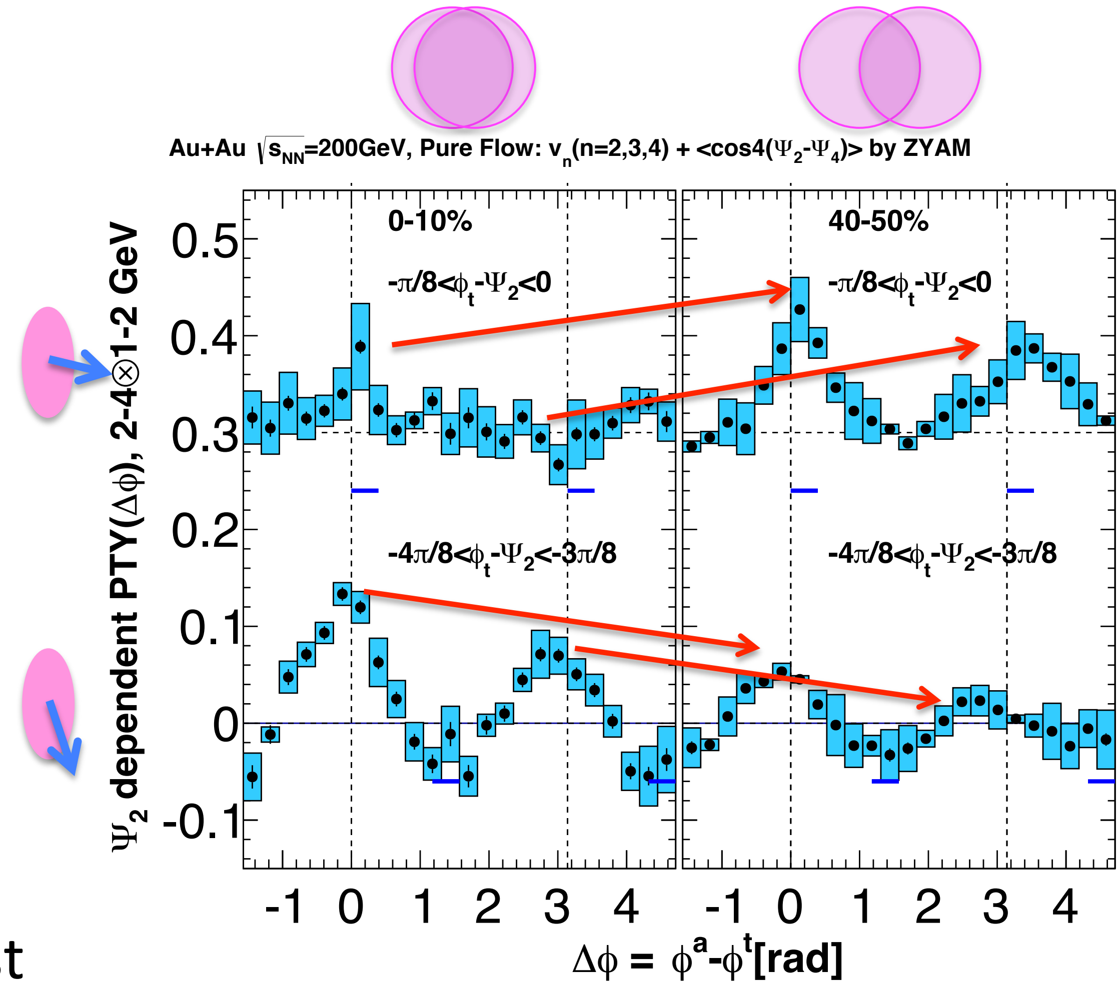
Experimental Results



- Intermediate p_T : Both models consistent with data
- Hot-Spot disfavored by the double-hump at high-p_T
- Consistent with the behavior of p_T spectra

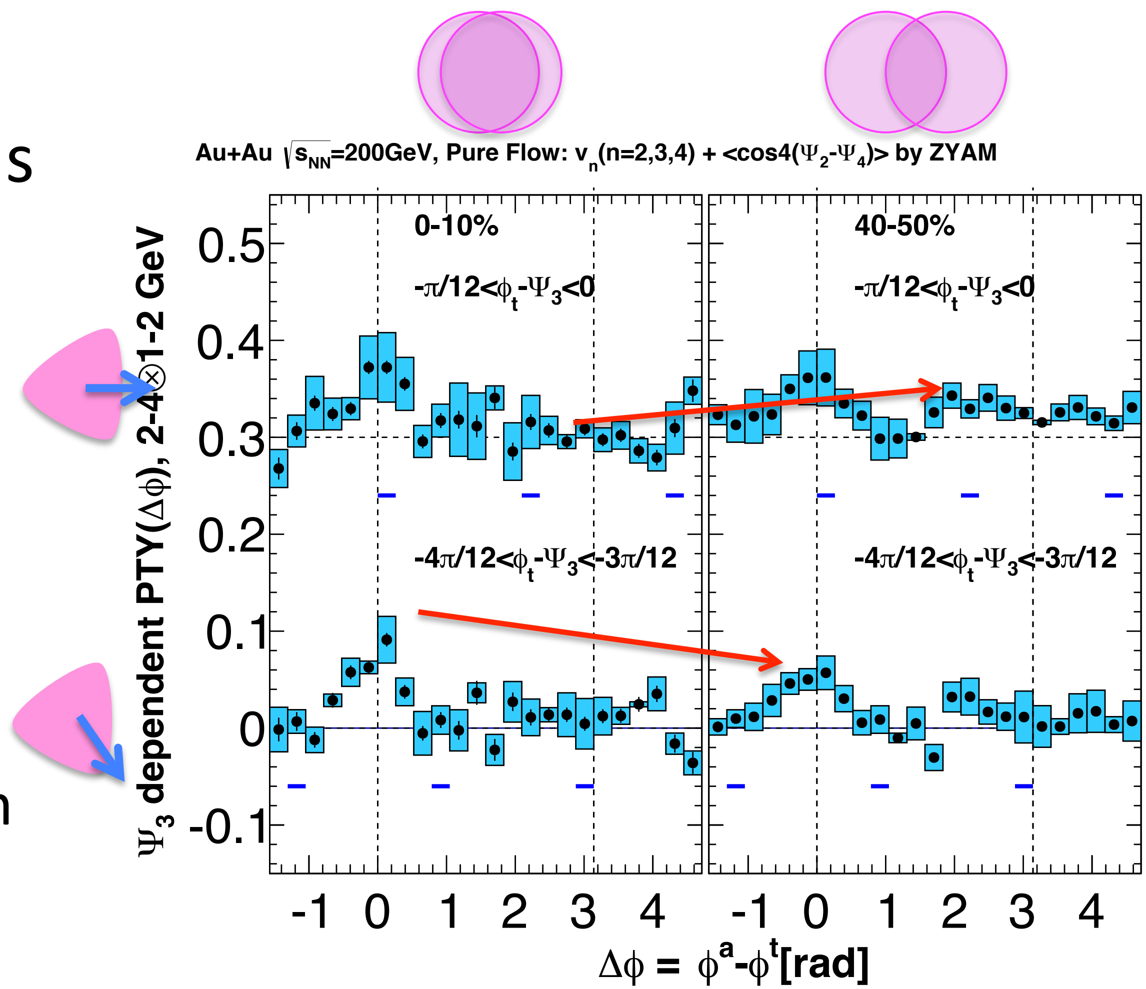
Ψ_2 dependence of PTY

- Mach-Cone disfavored
  - Double-hump must always appear in Mach-Cone
- In-plane trigger
  - Enhance in peripheral collisions: with thin medium
  - Parton Energy Loss
- Out-of-plane trigger
  - Enhance in central collisions: thick medium
  - Energy re-distribution & boost by collective expansion



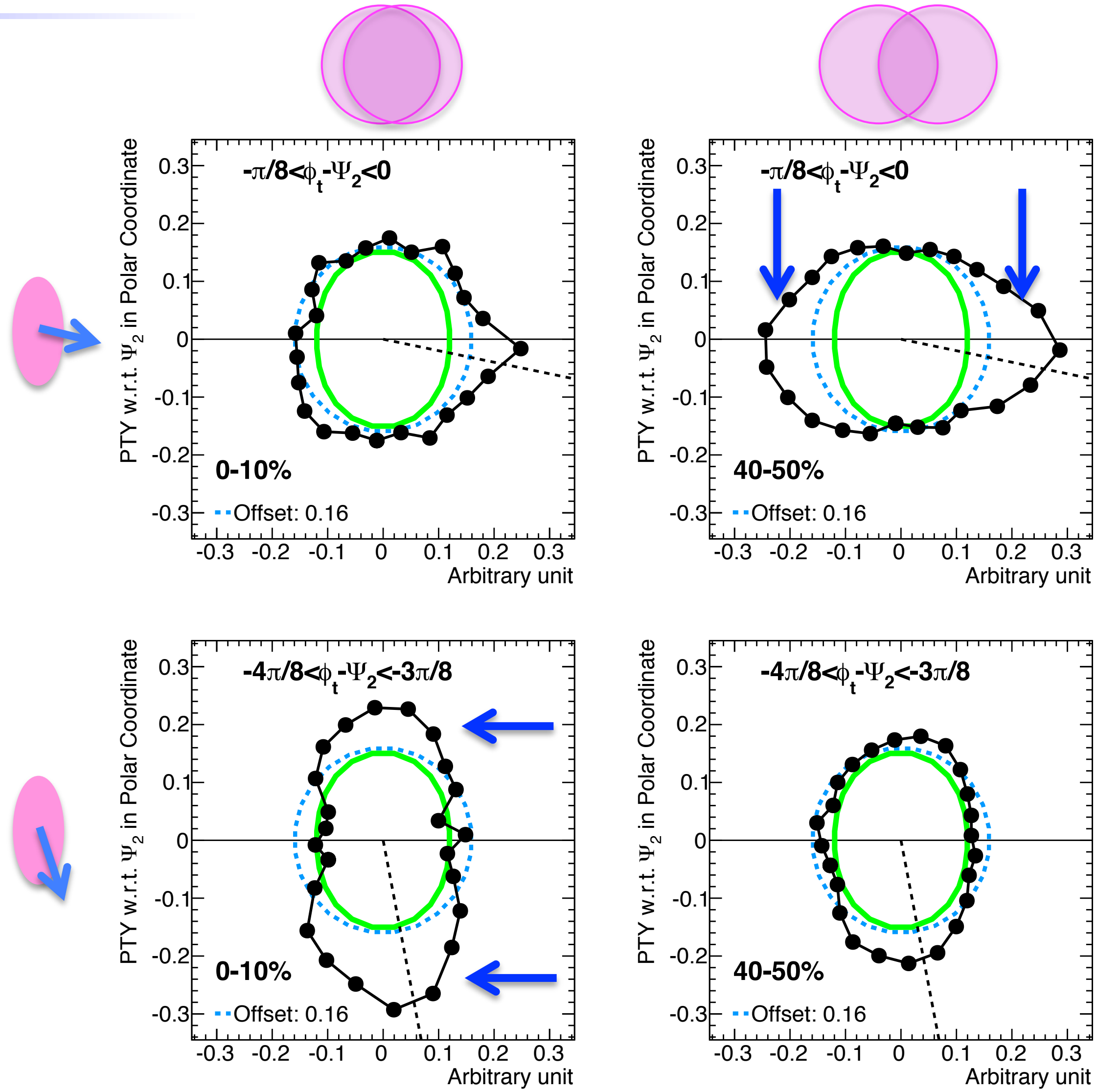
Ψ_3 dependence of PTY

- Similar but weaker trends as Ψ_2 dependence
- In-plane trigger
  - Enhance in peripheral collisions with thin medium
- Out-of-plane trigger
  - Possible enhance in central collisions with thick medium
- Weaker Ψ_3 dependence than Ψ_2



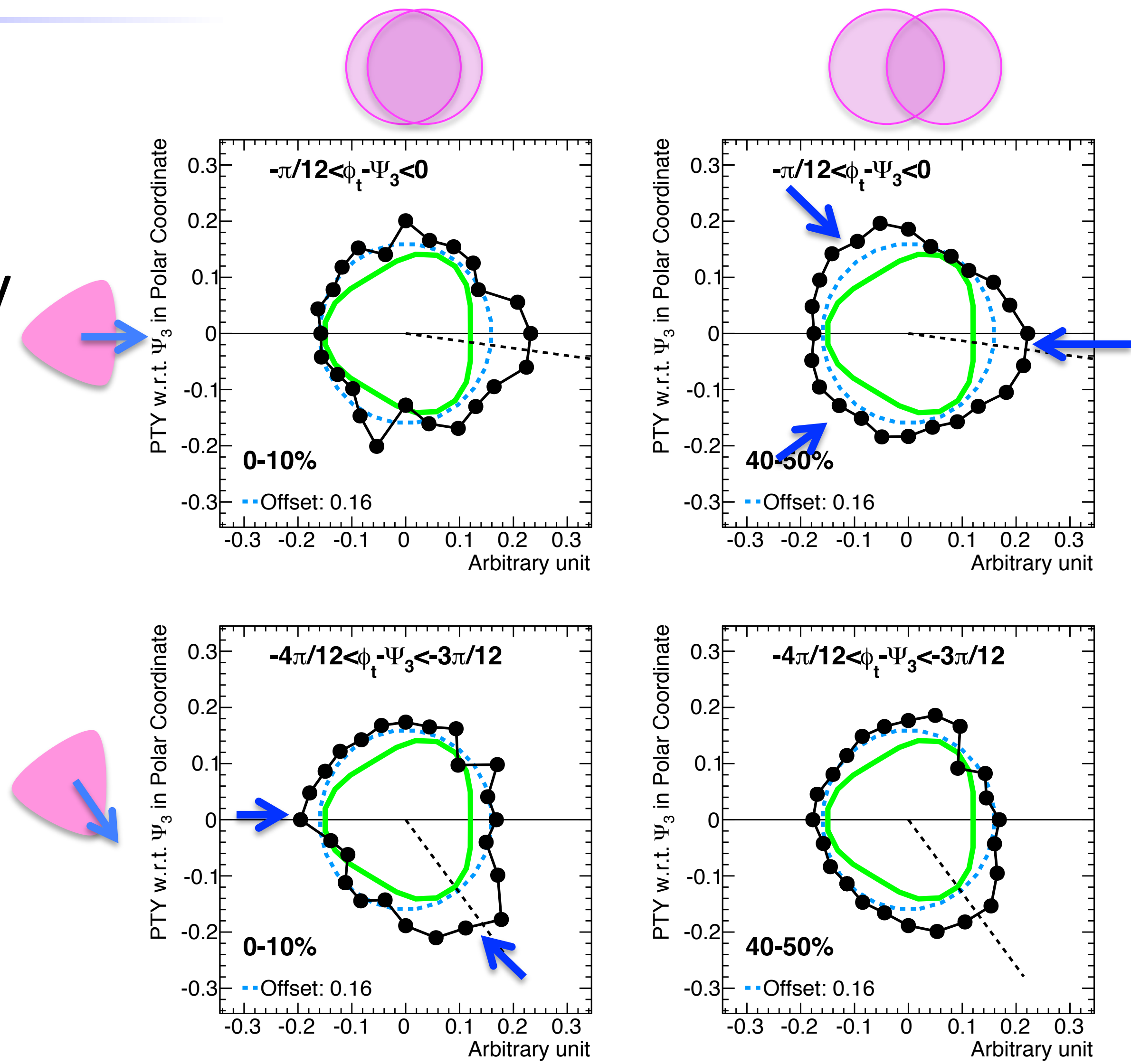
Ψ_2 dependence of PTY (Polar Coordinate)

- Yield correlates with geometry
- Enhance of In-plane yield with increase of centrality
  - Shortest average path length
- Enhance of Out-of-plane yield with decrease of centrality
  - Longest average path length

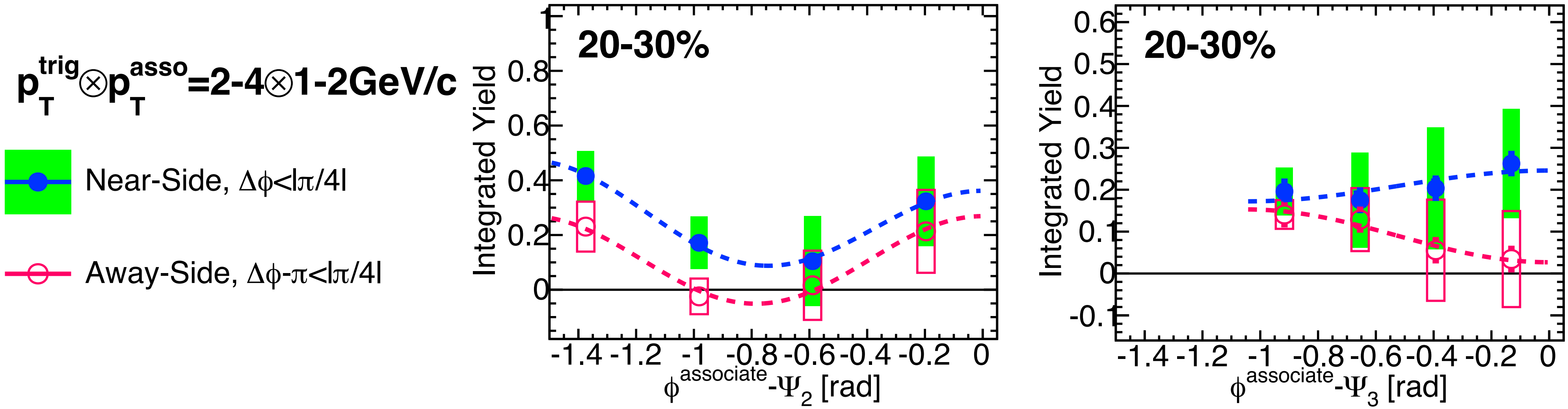


Ψ_3 dependence of PTY (Polar Coordinate)

- Enhance of In-plane yield with increase of centrality
  - Shortest average path length
- Possible enhance of Out-of-plane yield with decrease of centrality



Azimuthal anisotropy of PTY : v_n^{PTY}



- Extraction of v_n^{PTY} by fitting

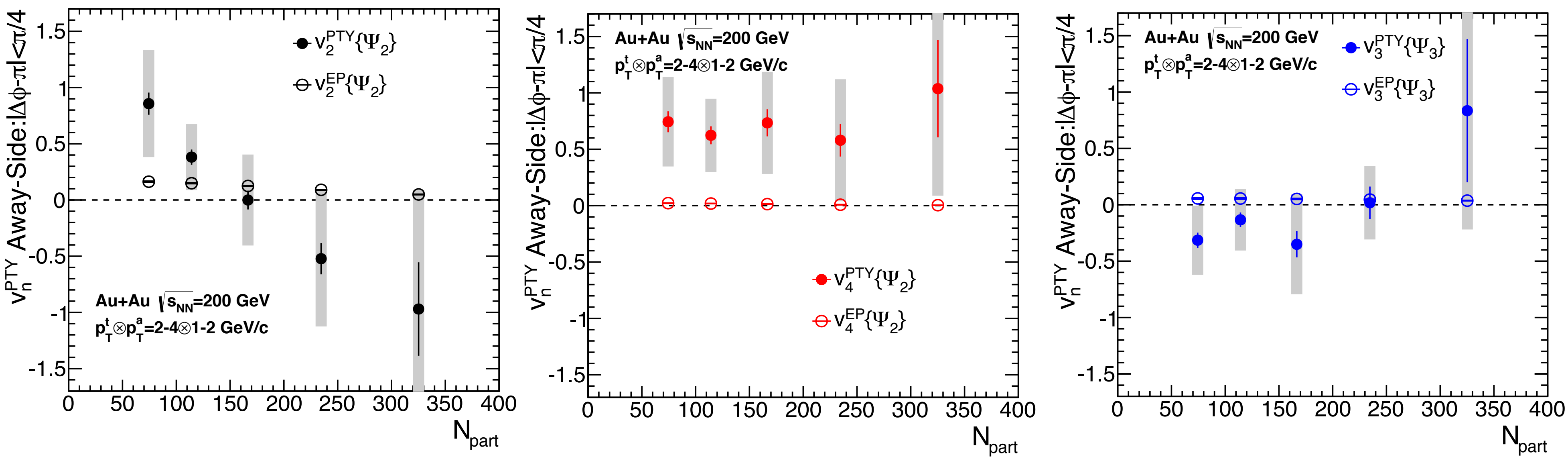
Ψ_2 dependence

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

Ψ_3 dependence

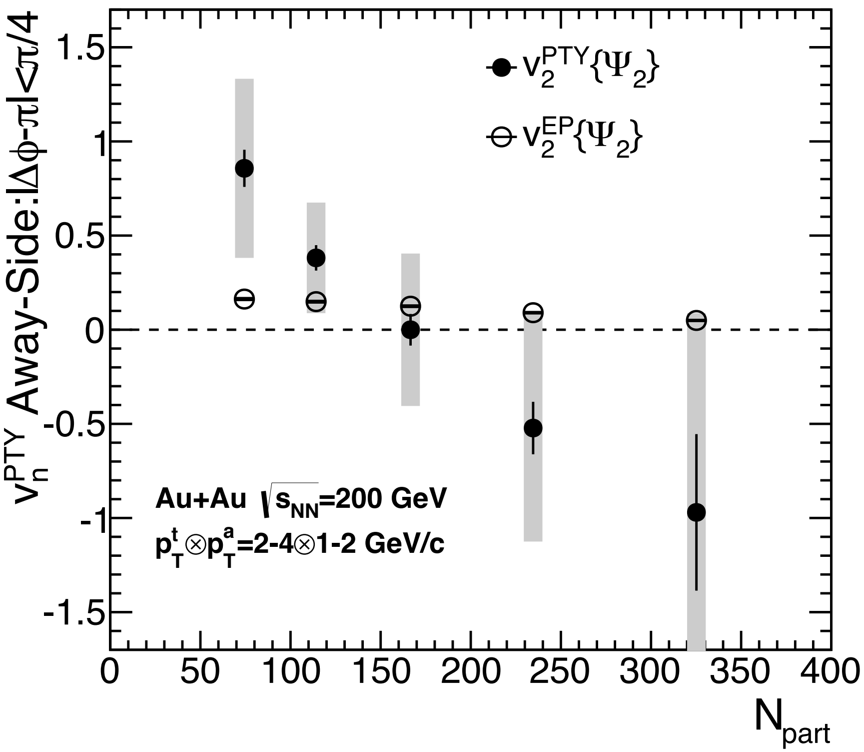
$$F(\phi^a - \Psi_3) = a\{1 + 2v_3^{PTY} \cos 3(\phi^a - \Psi_3)\},$$

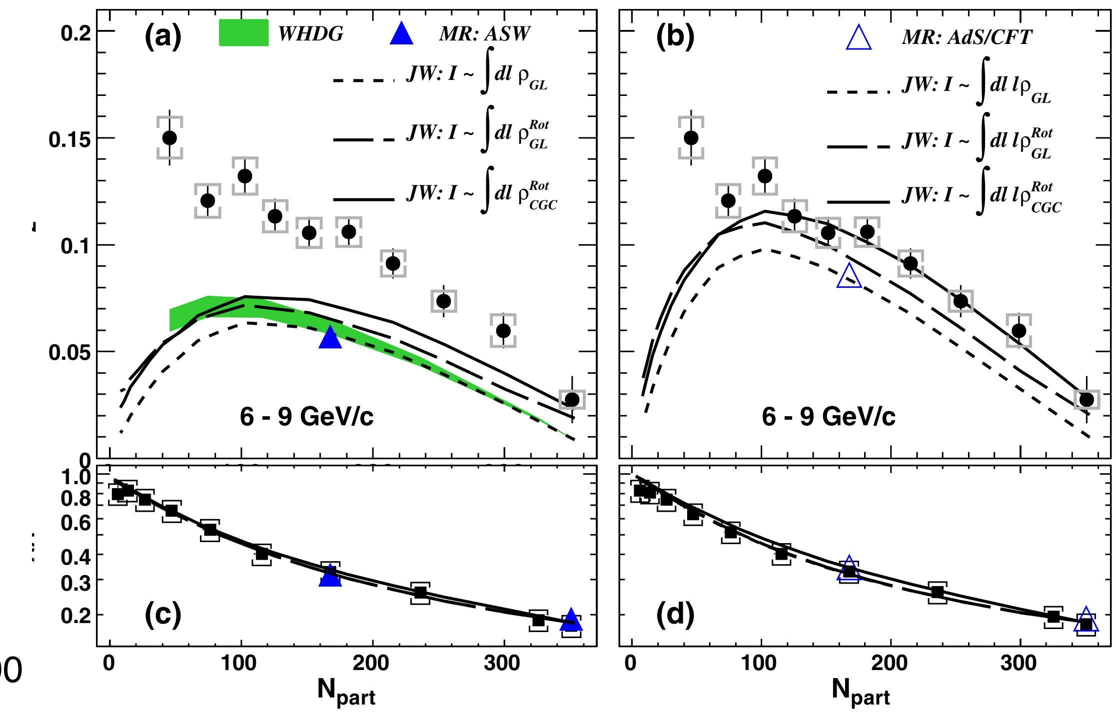
v_n^{PTY} & v_n^{EP}



- v_n^{PTY} is a part of v_n^{EP}
- v_n^{PTY} amplitude is one order larger than v_n^{EP}

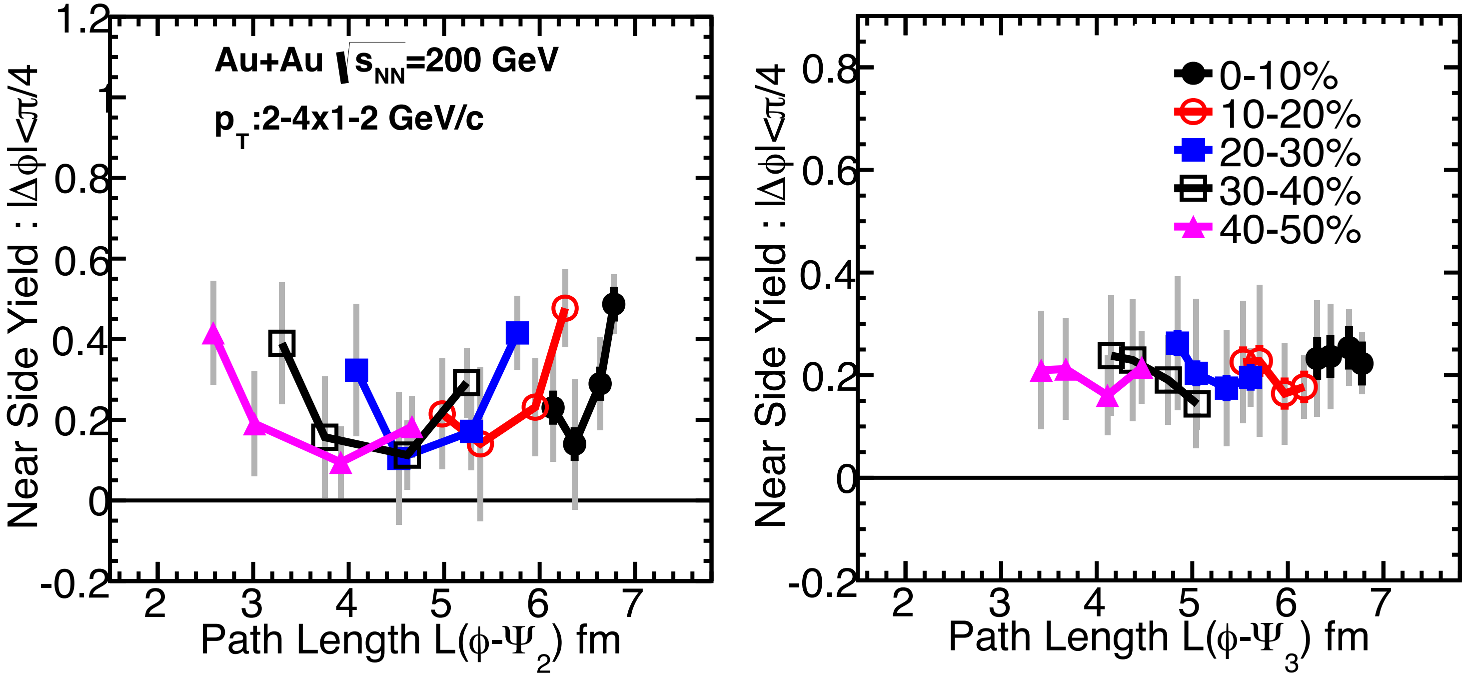
v_2^{PTY} & High-p_T π^0 v_2





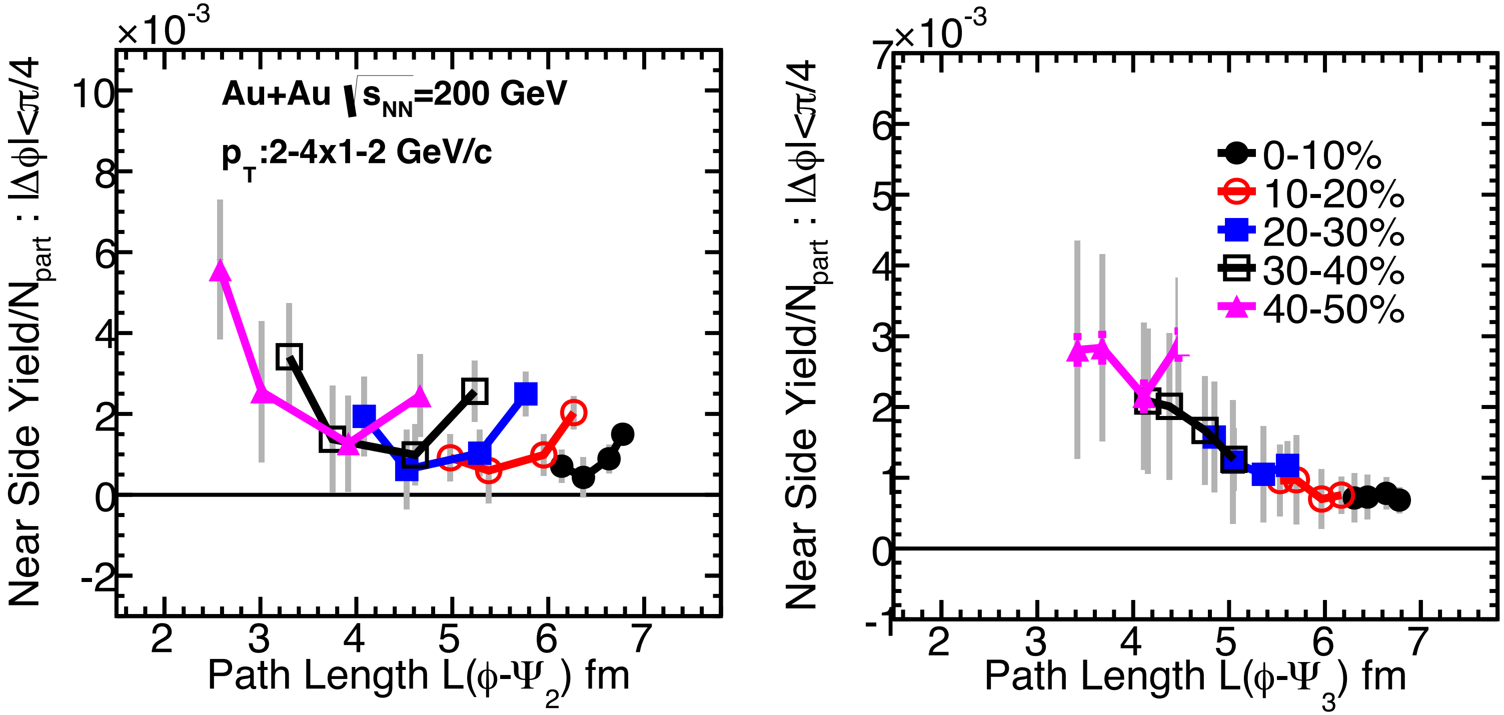
- Models with parton energy-loss provide positive π^0 v_2
- Additional effects required to explain negative v_2

Path length dependence of PTY



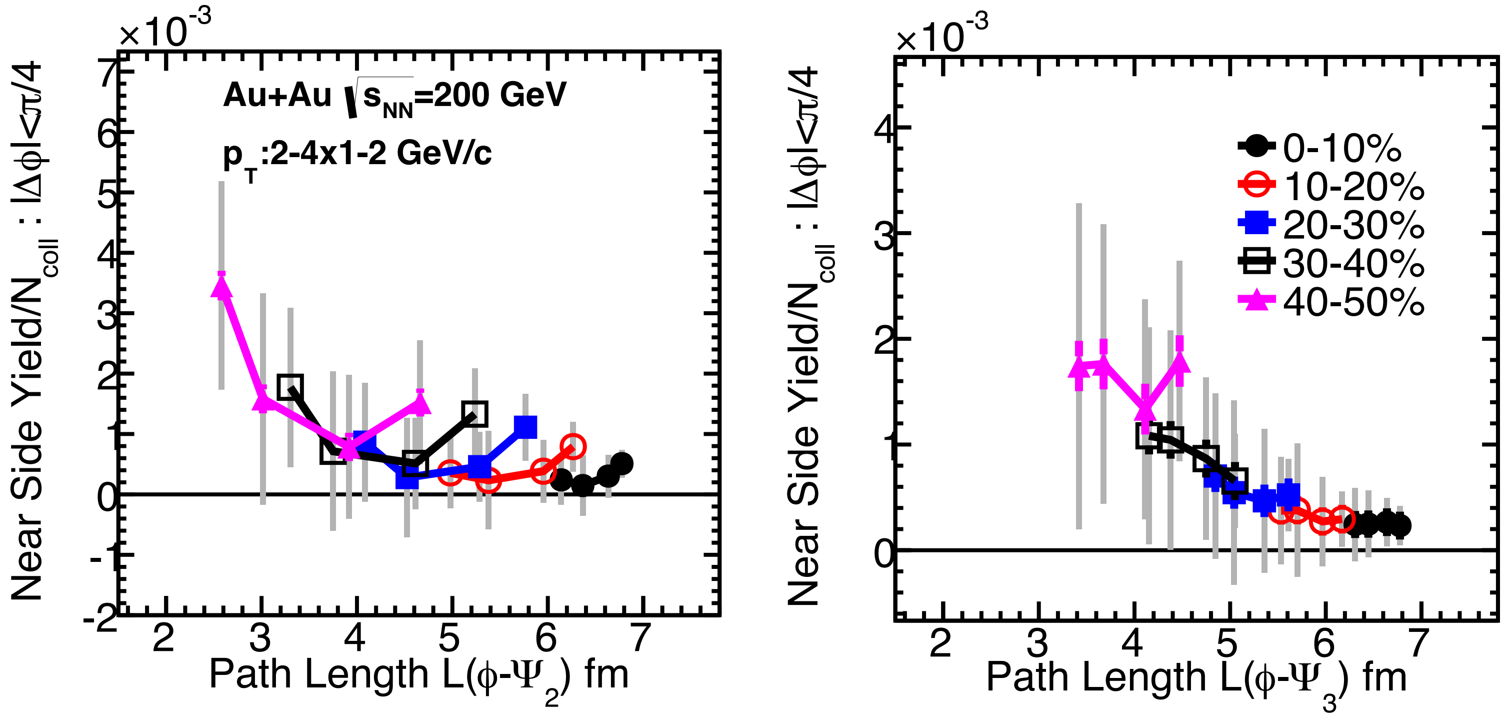
- Angle from EP converted to Path-Length by Glauber Model
- Non-monotonic behavior
- Yields does not scale on a universal curve

Path length dependence of PTY/N_{part}



- Approximately scaled on a curve
- Associate yields from QGP medium

Path length dependence of PTY/N_{coll}



- Also approximately scaled on a curve
- Associate yields from hard-scattering at initial collisions
- Coupling of jet with medium

Summary - I

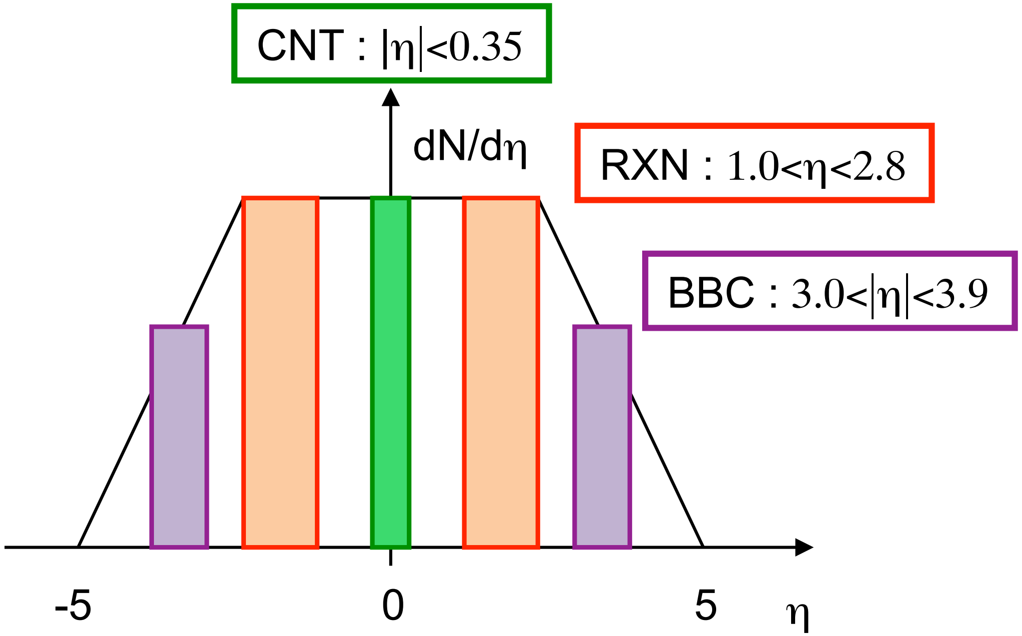
- Two-Particle correlations were measured with subtraction of backgrounds from $v_n(n=2,3,4)$
- New experimental data disfavored theoretical models
  - Cherenkov Gluon Radiation
  - Mach-Cone Shock Wave
  - Hot-Spot Models
- Jet-Deflection model is qualitatively consistent with data

Summary - II

- Event-Plane dependent correlations shows two competing effects
  - Increase / decrease of correlation yield with increase of path-length
- Anisotropy of correlation yield v_n^{PTY}
  - Additional Effect in addition to parton-energy loss
- Scale of Correlation Yield by N_{part} & N_{coll}
  - Jet-Medium Coupling
- Energy-Loss, Energy Re-distribution, and boost of jet by medium need to be considered in future theoretical models

BACK UP

Rapidity Selection in the Measurements



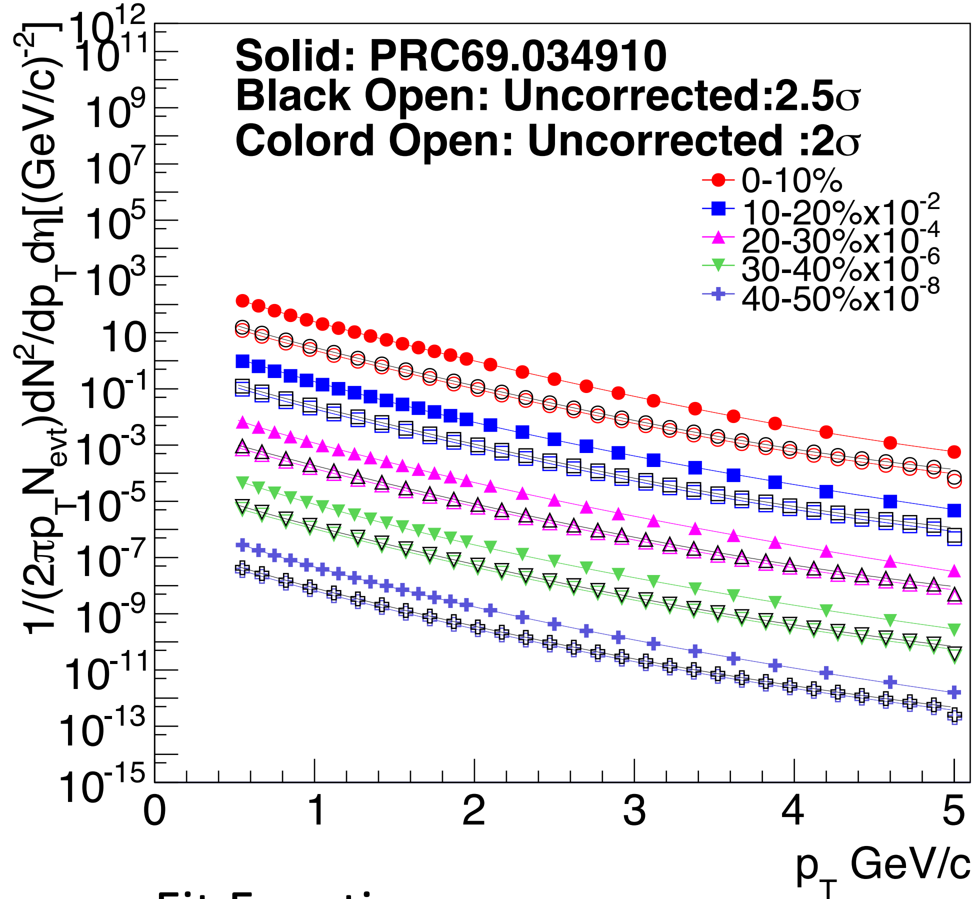
$$v_n =< \cos n(\phi - \Psi_n) >$$

- Two-Particle Correlations at CNT
  - Without rapidity gap, where Jet contribution survives
- Flow Measurements
  - CNT Particle & Forward Event Plane at RXN, BBC
  - Jet contribution suppressed

Tracking Efficiency

- Efficiency correction by ratio of uncorrected invariant yield over corrected ones

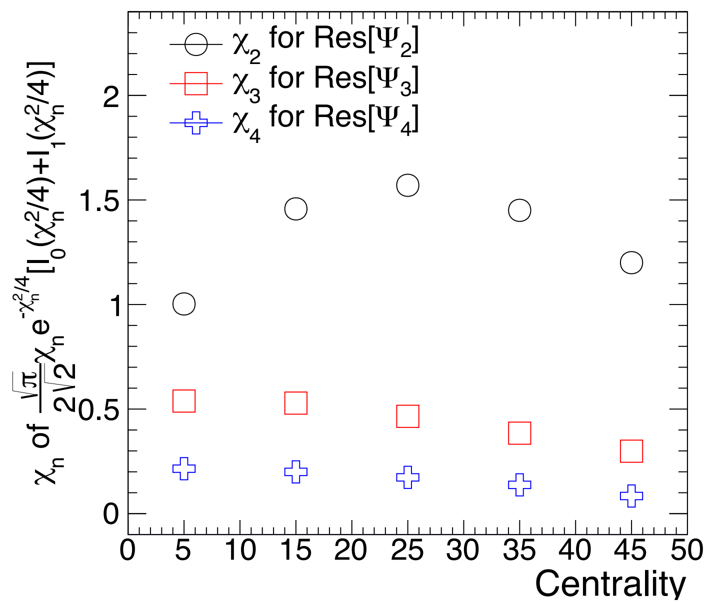
$$\varepsilon = \frac{\sigma^{uncor}}{\sigma^{cor}}$$

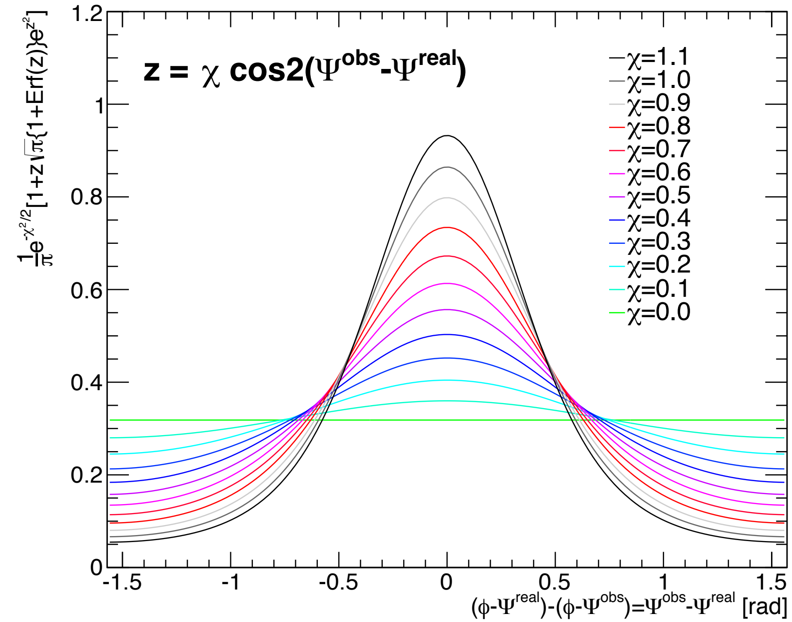


Fit Function

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

EP Resolution in Monte Carlo





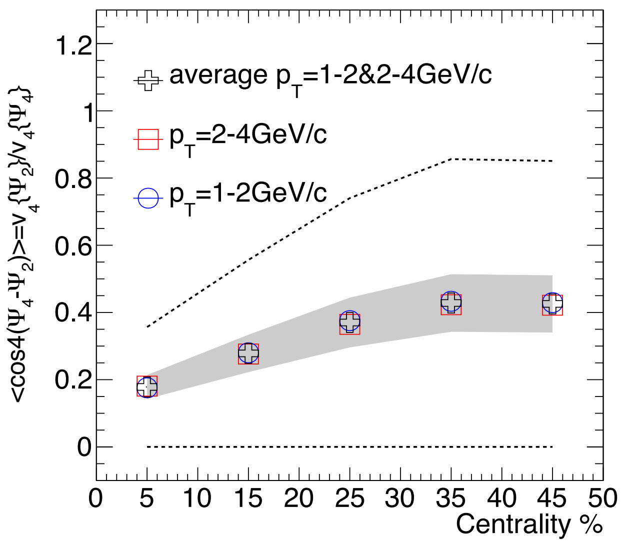
- Convert resolution to χ

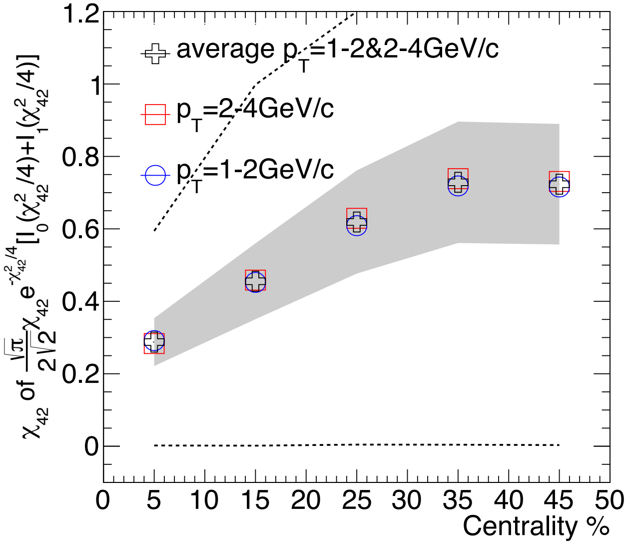
$$\left\langle \cos\left[kn(\Psi_n^{obs} - \Psi_n^{real})\right]\right\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_n e^{-\chi_n^2/4}\left[I_{(k-1)/2}\left(\frac{\chi_n^2}{4}\right) + I_{(k+1)/2}\left(\frac{\chi_n^2}{4}\right)\right].$$

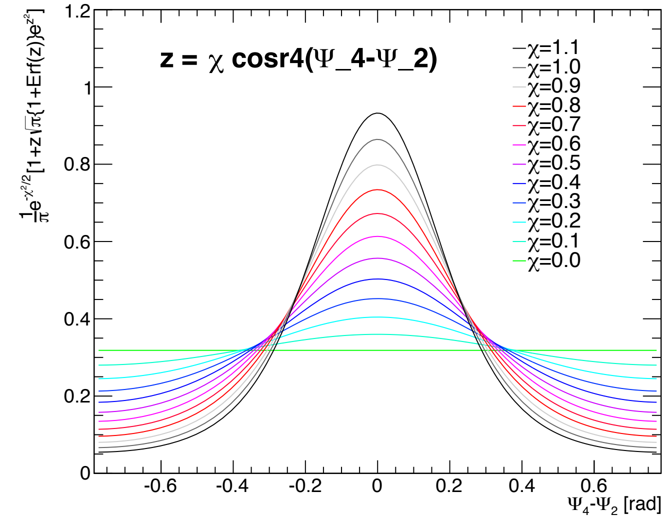
- Distribution between real and observed EP using χ

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

Ψ_2-Ψ_4 correlation in Monte Carlo







- Ψ_2-Ψ_4 correlation : $\langle\cos\left[4(\Psi_2-\Psi_4)\right]\rangle = v_4\left\{\Psi_2\right\}/v_4\left\{\Psi_4\right\}$
- Obtain χ & reconstruct distribution

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

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

Unfolding : Fitting Method

PRC.84.024904 (2011)

Ψ_2 dependent case

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

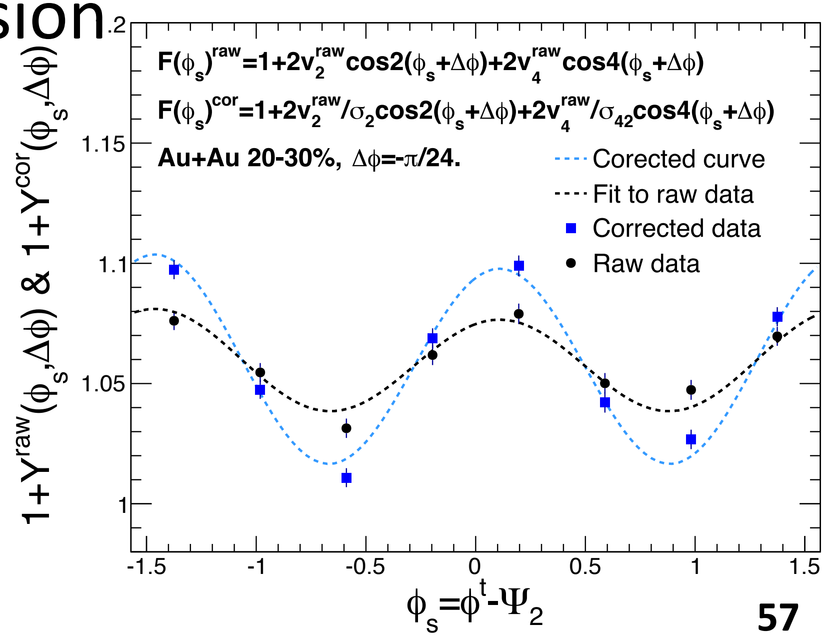
Fitting

Ψ_3 dependent case

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

Fitting

- Offset λ=1.0 to avoid possible division by zero
- Assuming correlation yield has anisotropy w.r.t. EP
- Correction by EP resolution

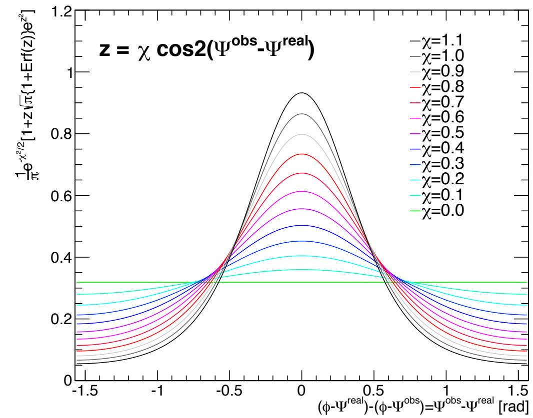


Unfolding : Iteration

Correlation + Offset

Smearing Effect

$$\mathbf{A}(k) = \begin{pmatrix} 1+Y(0,k) \\ 1+Y(1,k) \\ 1+Y(2,k) \\ 1+Y(3,k) \\ 1+Y(4,k) \\ 1+Y(5,k) \\ 1+Y(6,k) \\ 1+Y(7,k) \end{pmatrix}, \qquad S = \begin{pmatrix} s_0 & s_1 & s_2 & s_3 & s_4 & s_3 & s_2 & s_1 \\ s_1 & s_0 & s_1 & s_2 & s_3 & s_4 & s_3 & s_2 \\ s_2 & s_1 & s_0 & s_1 & s_2 & s_3 & s_4 & s_3 \\ s_3 & s_2 & s_1 & s_0 & s_1 & s_2 & s_3 & s_4 \\ s_4 & s_3 & s_2 & s_1 & s_0 & s_1 & s_2 & s_3 \\ s_3 & s_4 & s_3 & s_2 & s_1 & s_0 & s_1 & s_2 \\ s_2 & s_3 & s_4 & s_3 & s_2 & s_1 & s_0 & s_1 \\ s_1 & s_2 & s_3 & s_4 & s_3 & s_2 & s_1 & s_0 \end{pmatrix},$$



- Smearing of measured correlations

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

- Correction factor

$$c_{ii} = A(i,k)/B(i,k)$$
$$c_{ij(i\neq j)} = 0$$

- Corrected yield

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

Unfolding : Iteration

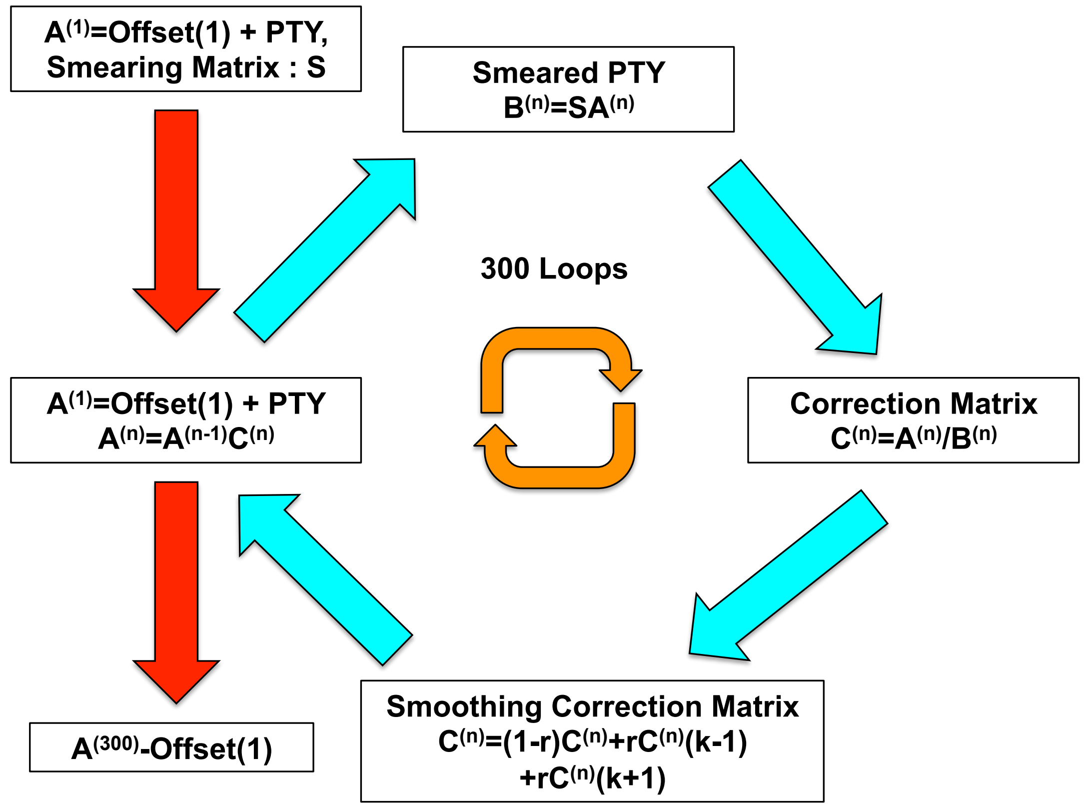
Notation in iteration

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

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

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

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

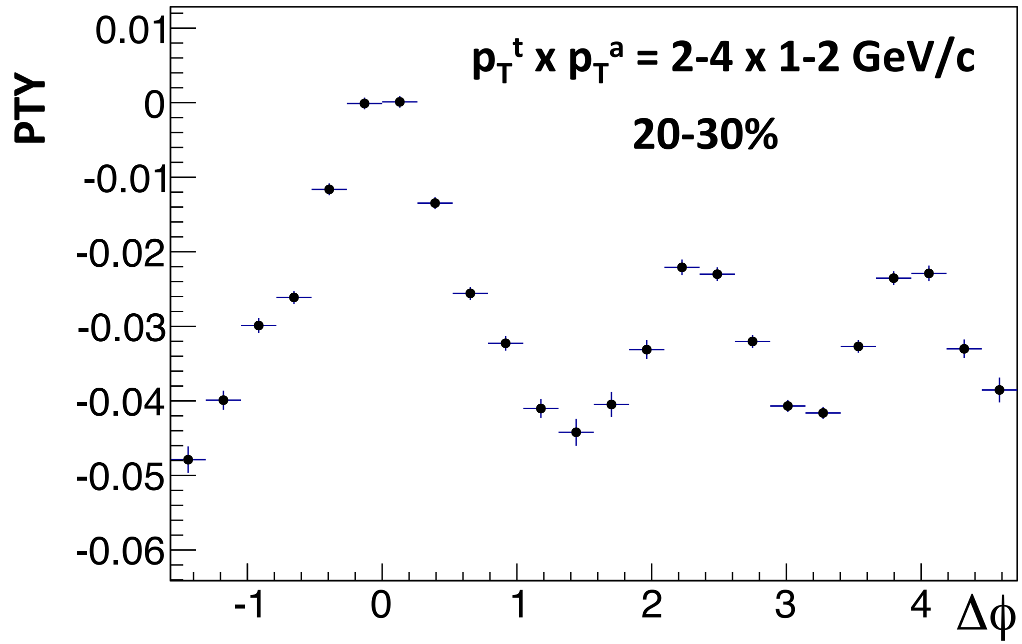


Smoothing

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

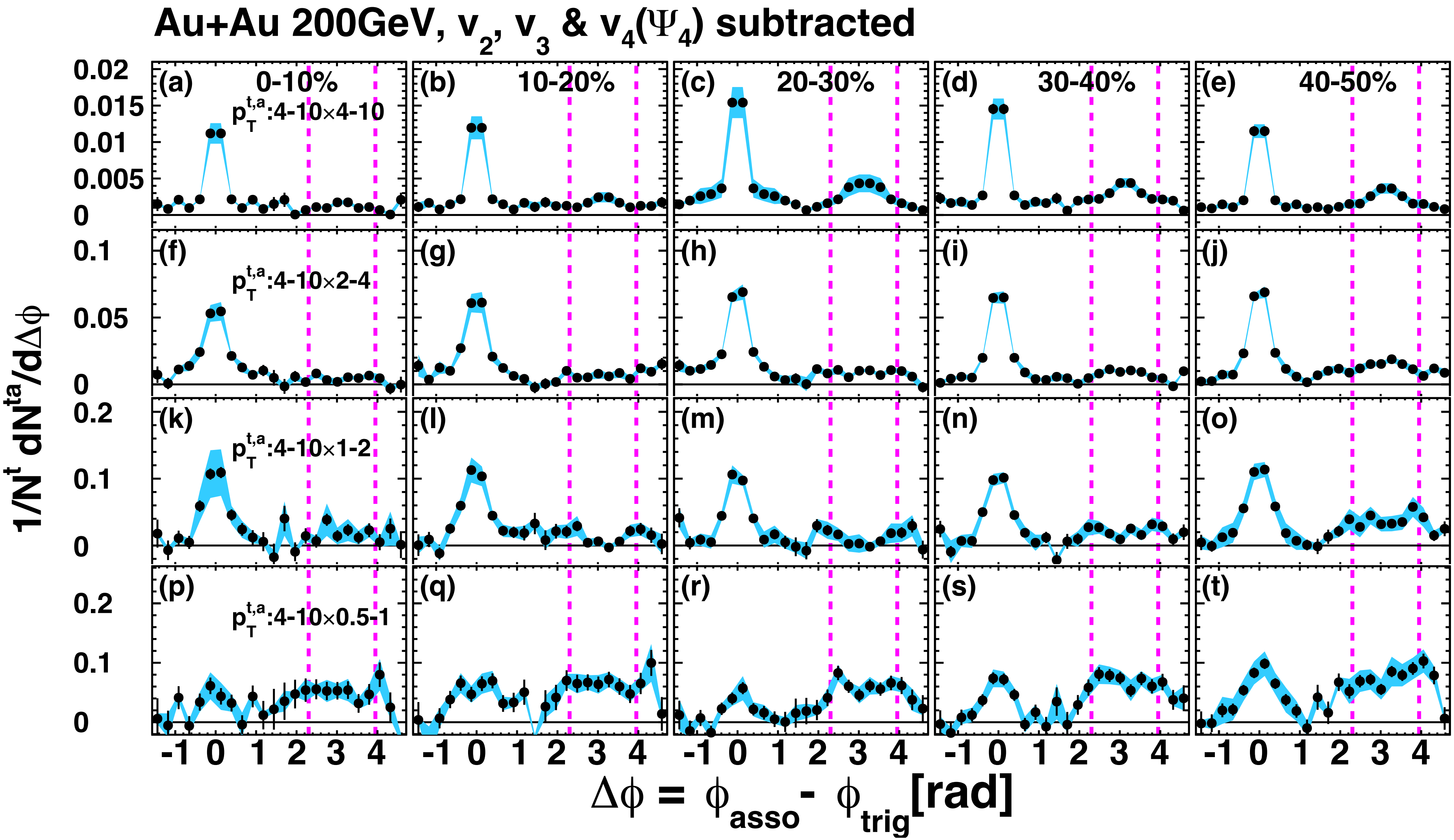
- Iteration until conversion

Zero Yield at Near-Side

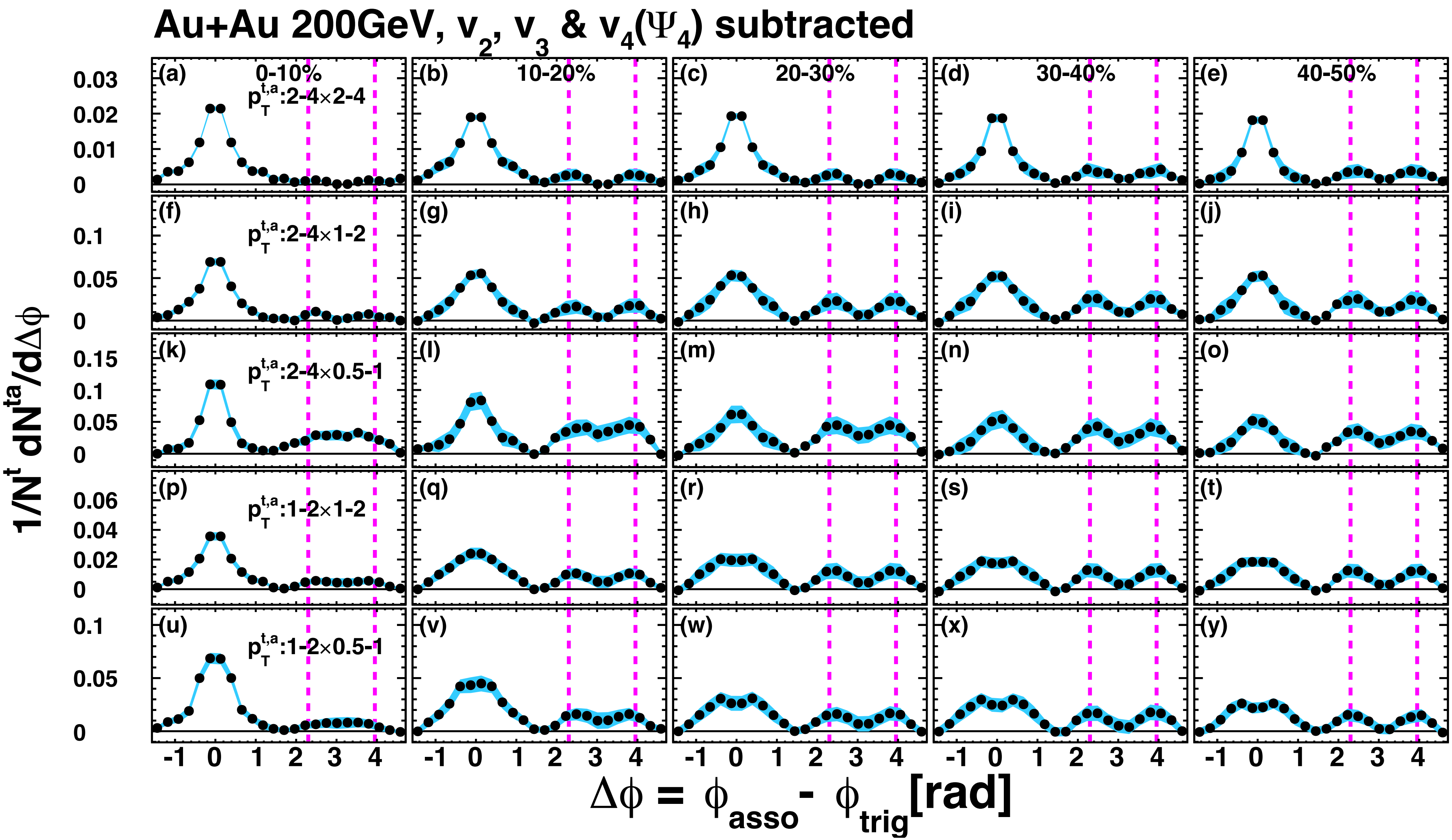


- Correlation and Pure Flow is fitted at $\Delta\phi=0$
- Double-hump is not so sensitive to flow subtraction

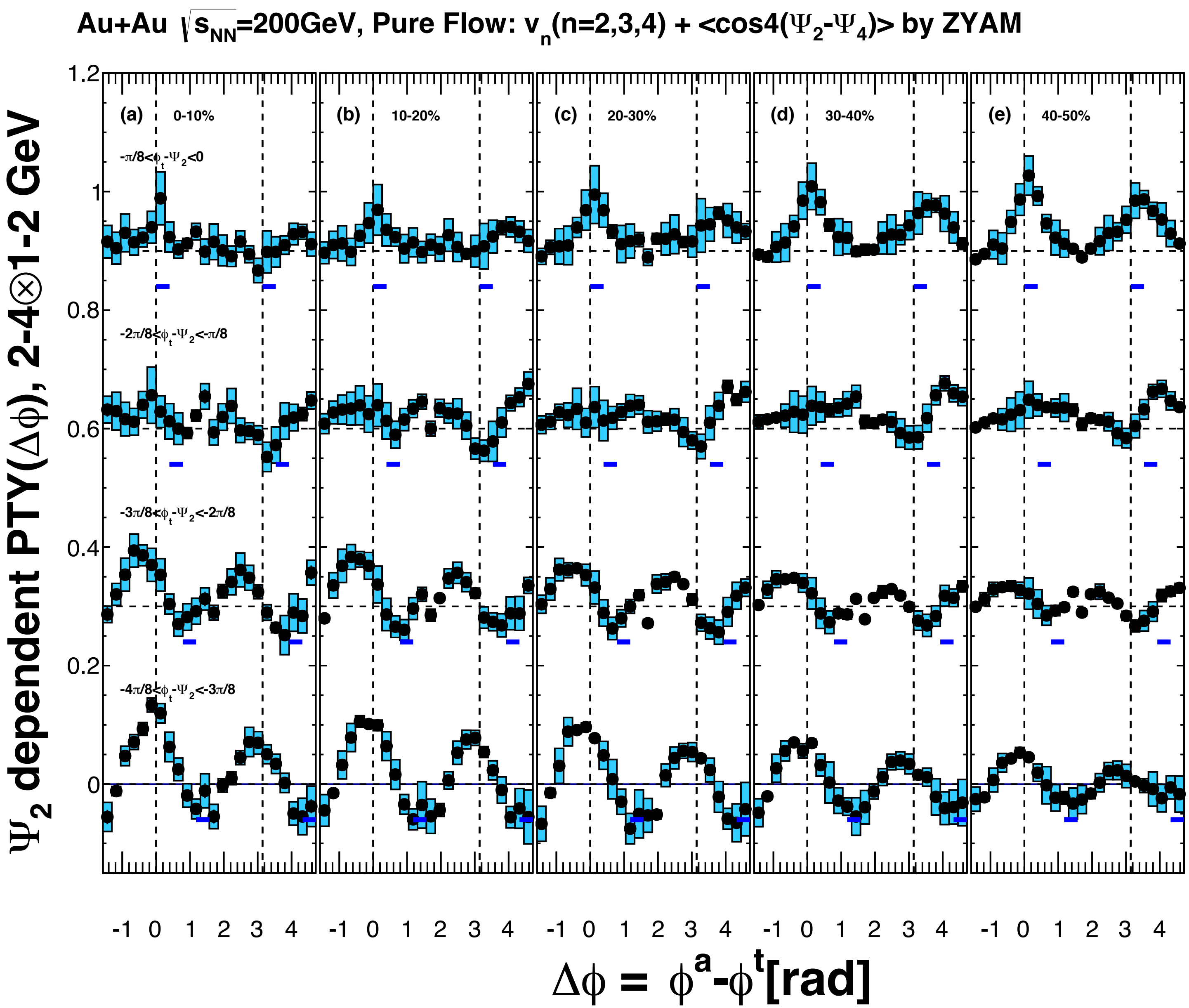
High p_T correlations



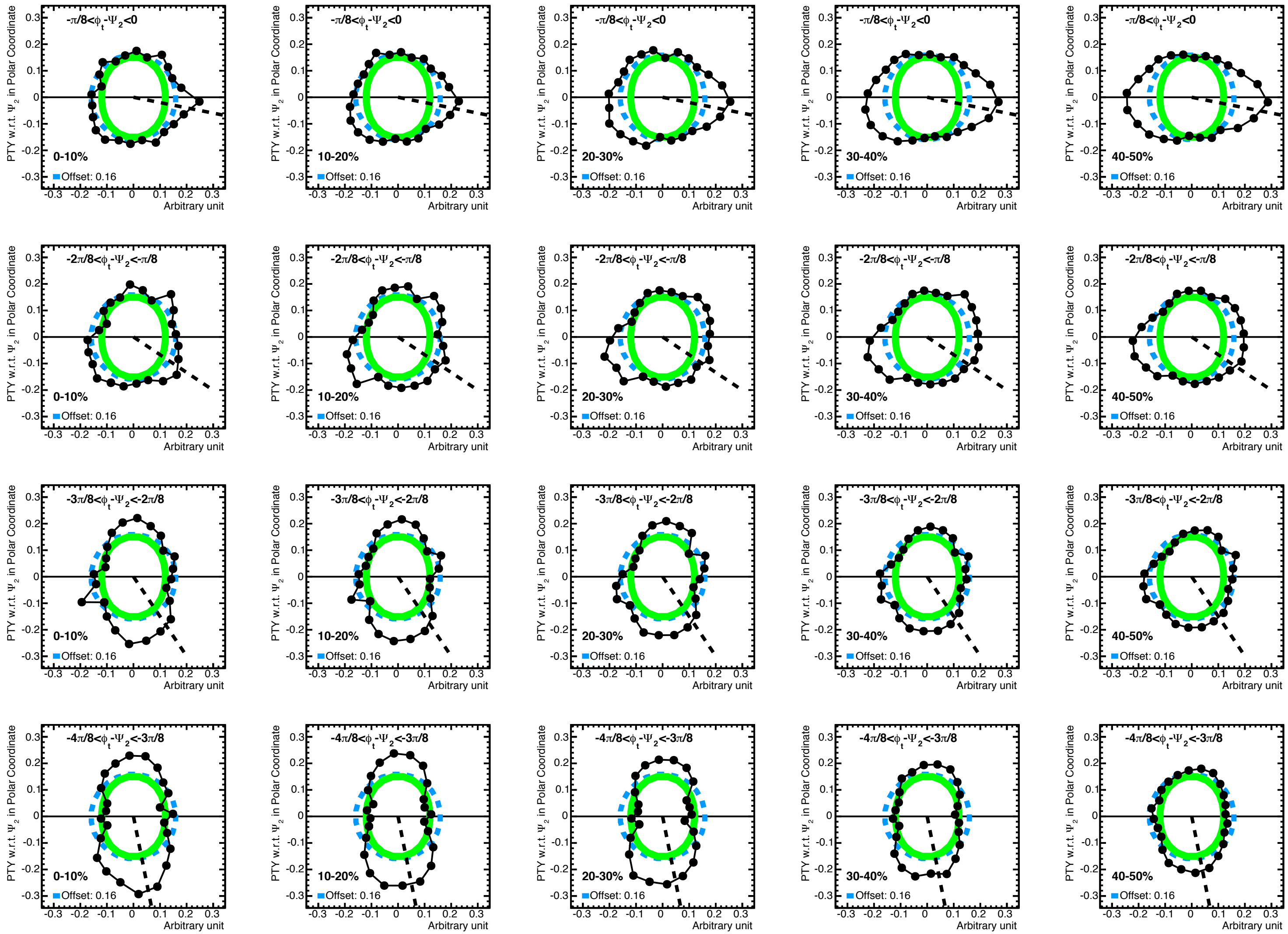
Intermediate p_T correlations



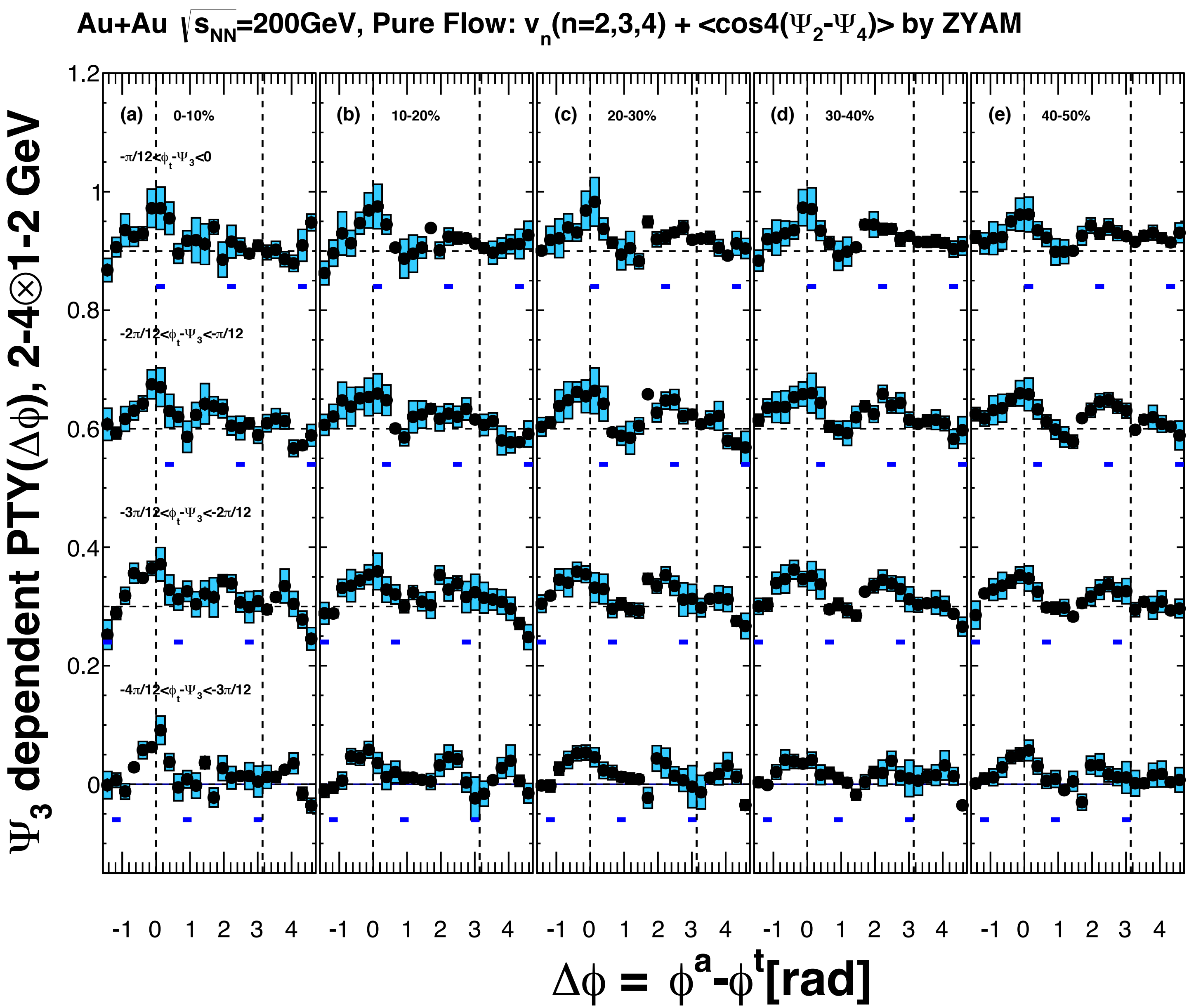
Ψ_2 dependence of PTY



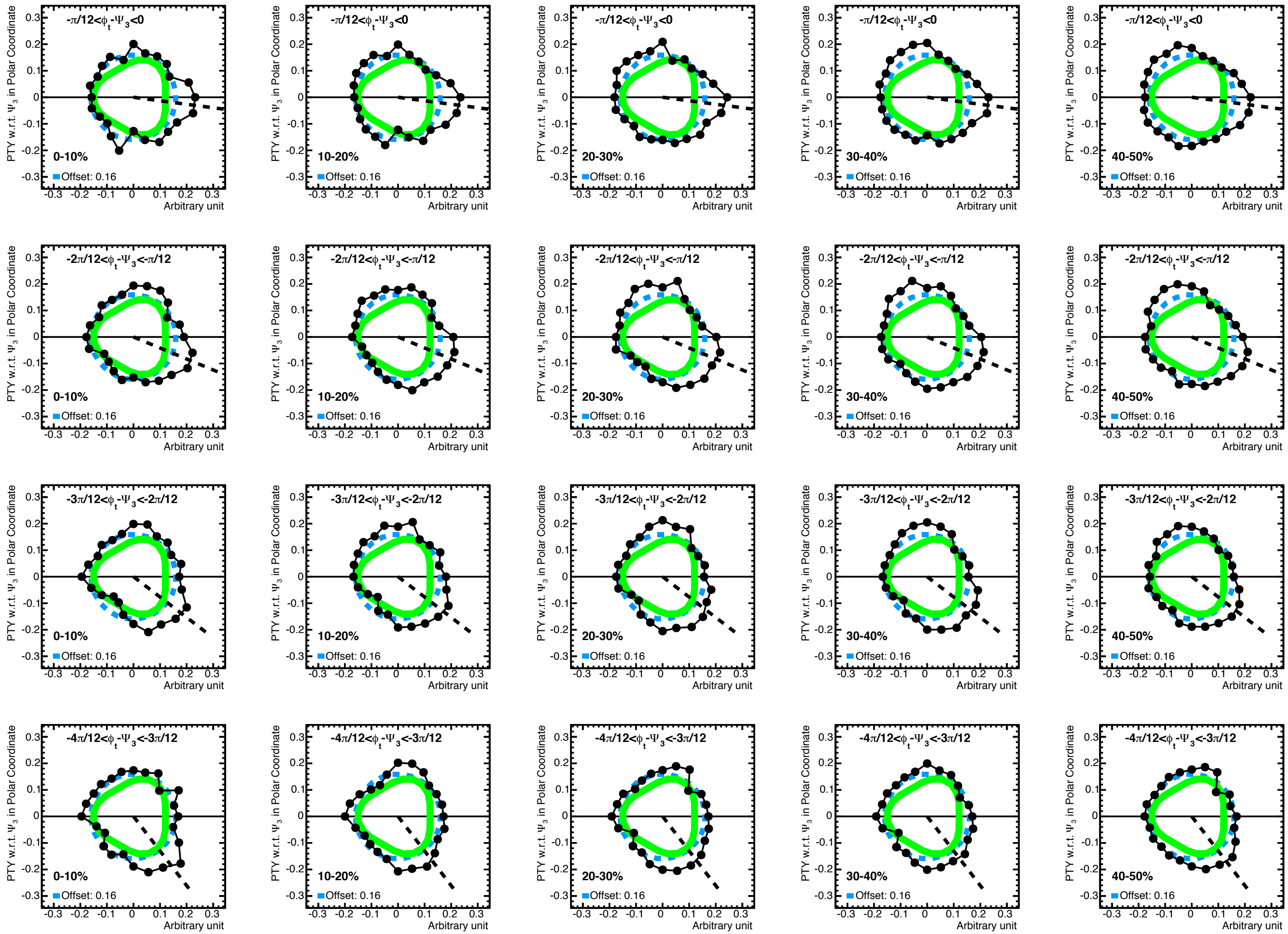
Ψ_2 dependence of PTY (Polar)



Ψ_3 dependence of PTY



Ψ_3 dependence of PTY (Polar)



Glauber Model

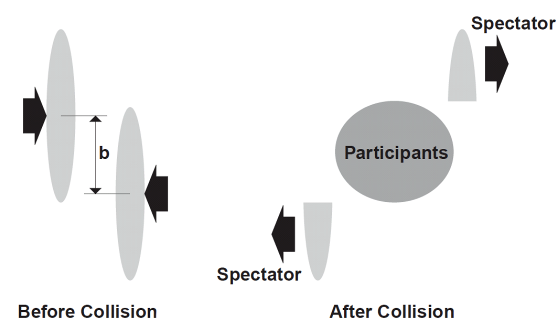
- Woods-Saxon Distribution
  - Nucleon density distribution
- Collision range
- Number of nucleons participated in a collision
- Number of binary nucleons collisions in a collision

$$\rho(r) = \frac{1}{1 + \exp\frac{r - r_a}{a}}$$

$$d < \sqrt{\frac{\sigma_{nn}}{\pi}}, \sigma_{nn} = 42mb$$

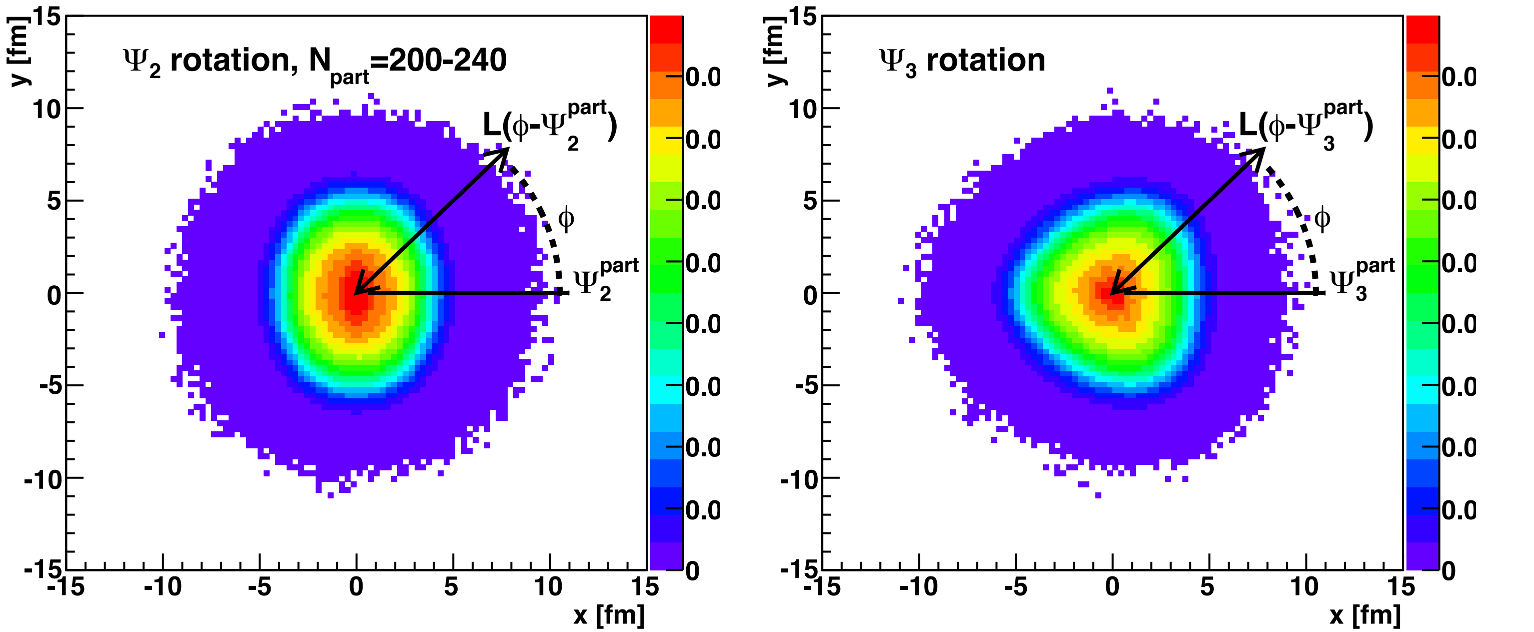
$$N_{part}$$

$$N_{coll}$$

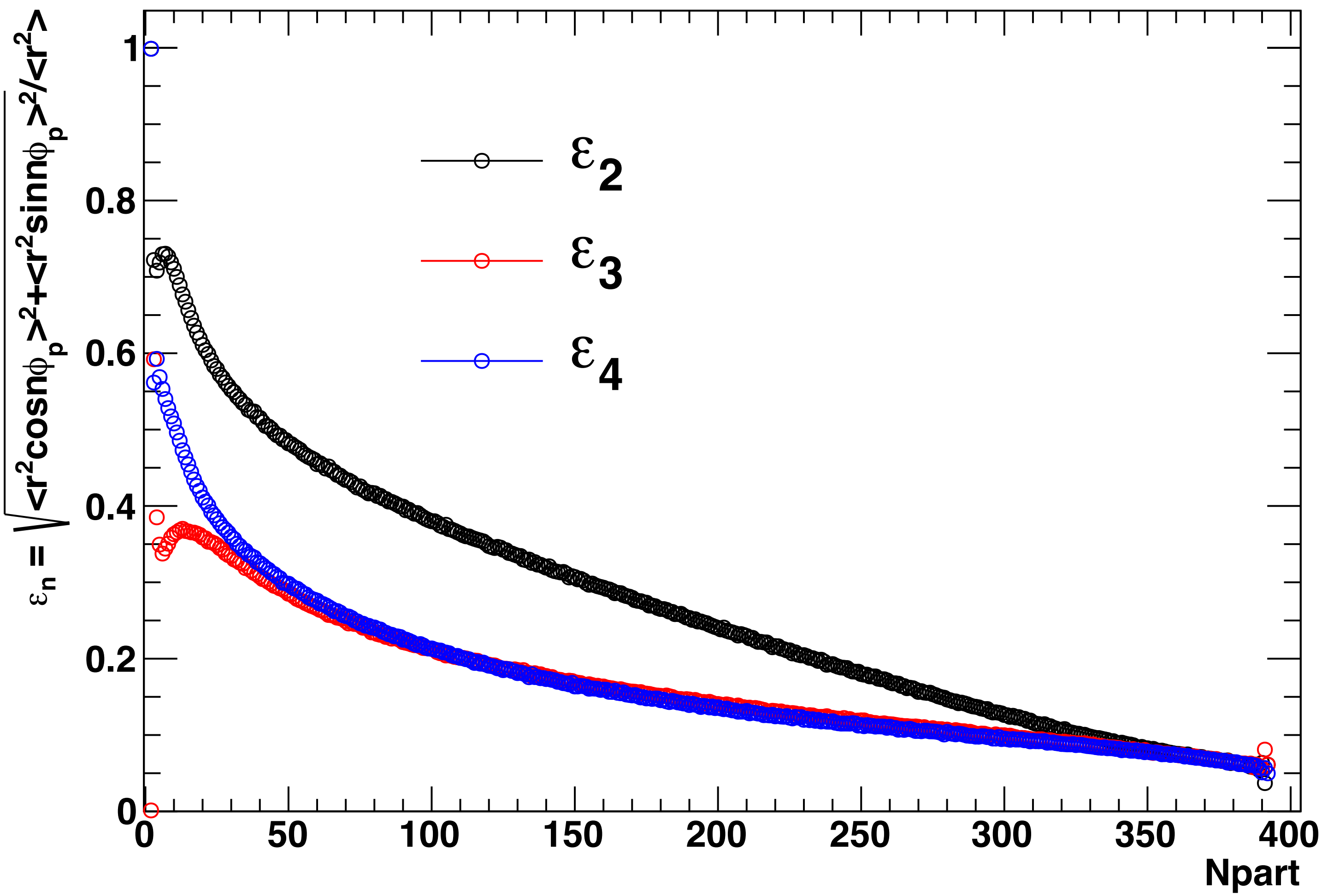


Path-Length based on Glauber MC

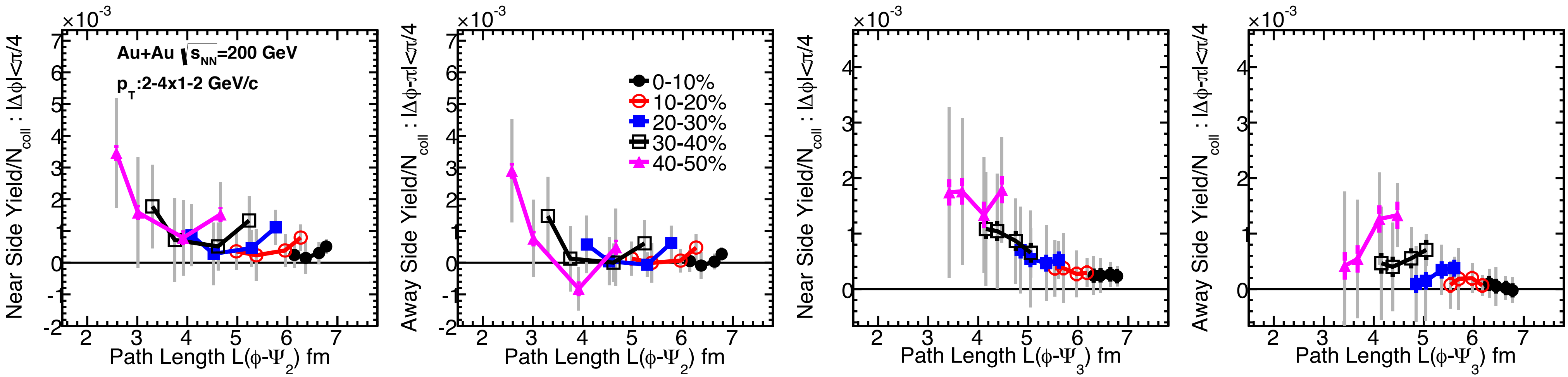
- Path-Length : distance from center to surface as a function of angle form the event-planes



Eccentricity by Glauber Model

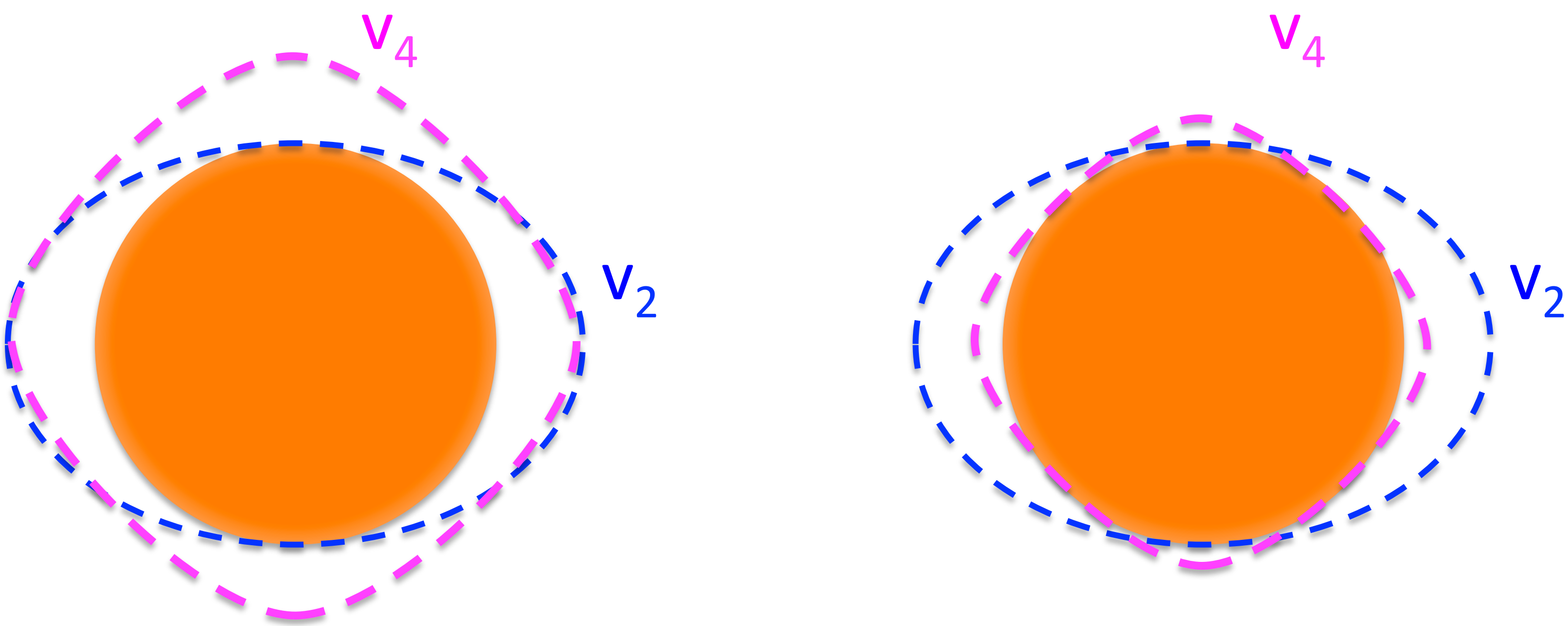


Path length dependence of PTY



- Near & Away-Side of both Ψ_2, Ψ_3 dependent correlations do not form a universal curve

Boost by v_4



Central Collisions

$v_2 = v_4$

Peripheral Collisions

$v_2 > v_4$

- Boost by v_4 to out-of-plane direction in central collisions
- Boost by v_2 to in-plane direction in peripheral collisions