Energy Loss and Medium Response via Two Particle Correlations in Heavy Ion Collisions

Michael P. McCumber for the PHENIX Collaboration

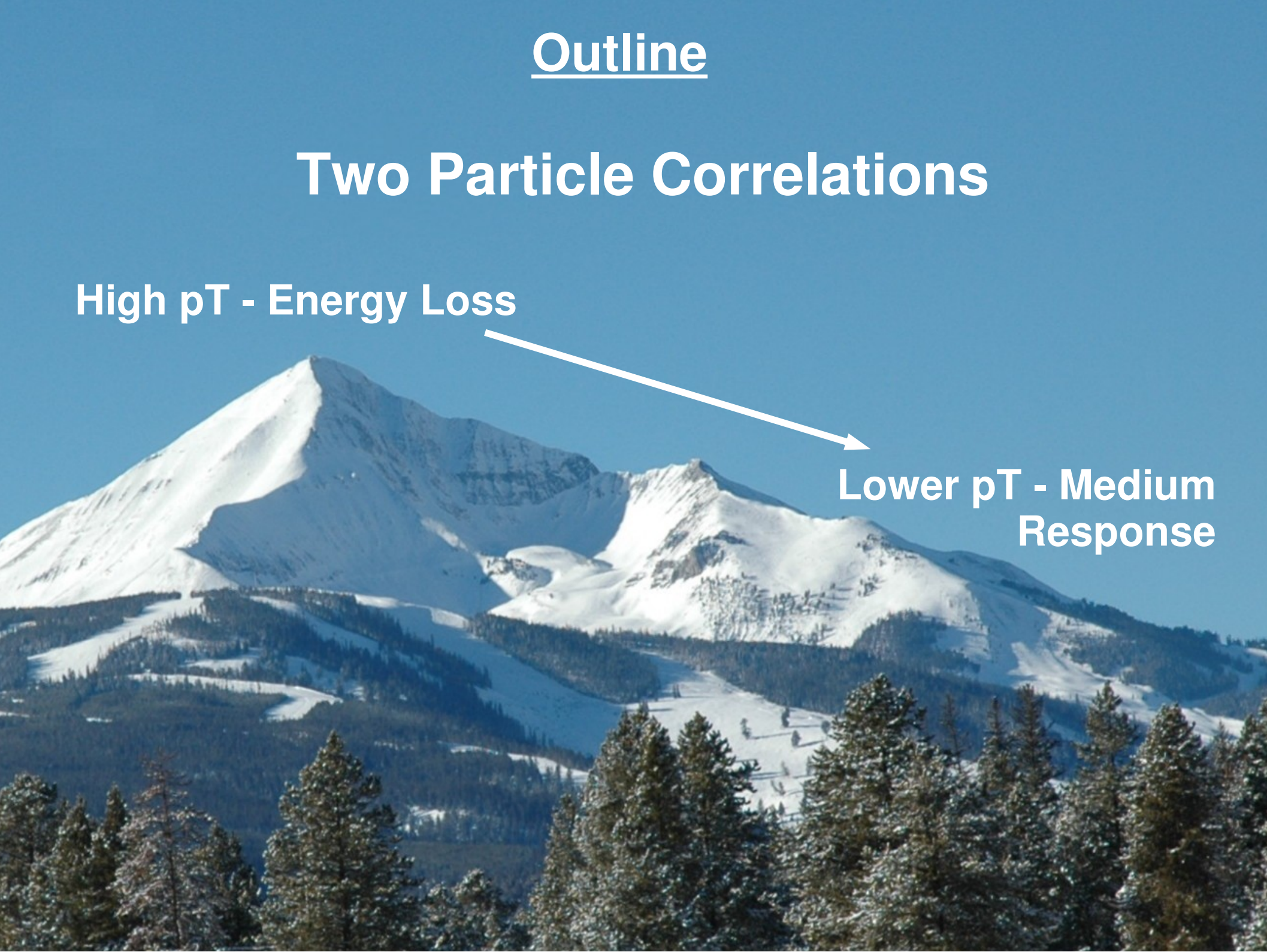
Winter Workshop on Nuclear Dynamics
Big Sky, Montana
4 February 2009

Outline

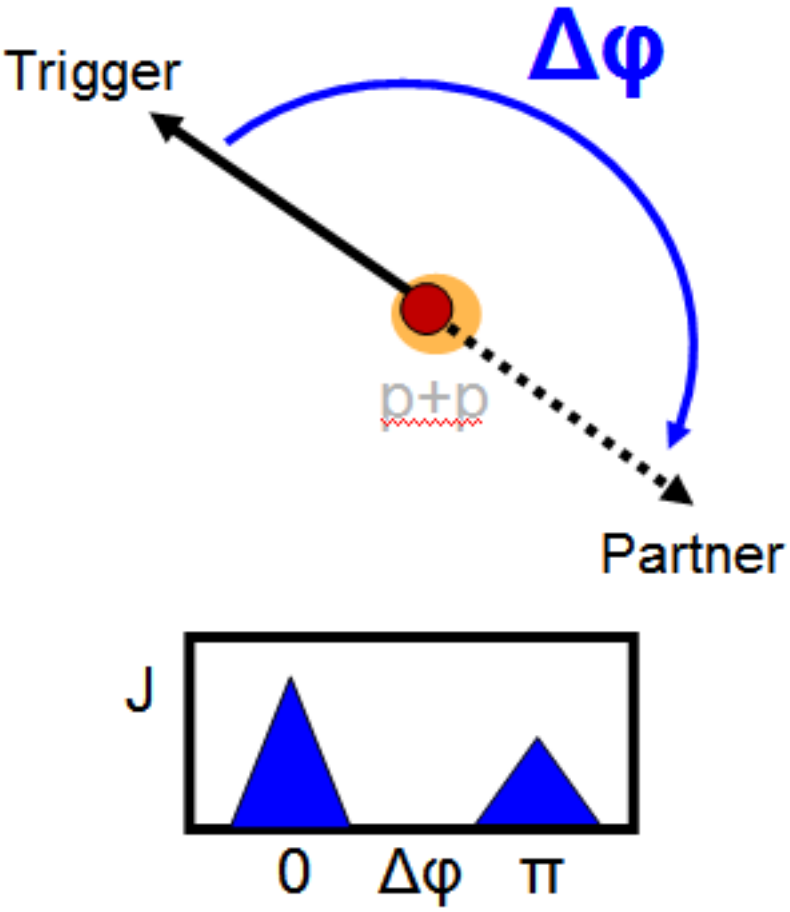
Two Particle Correlations

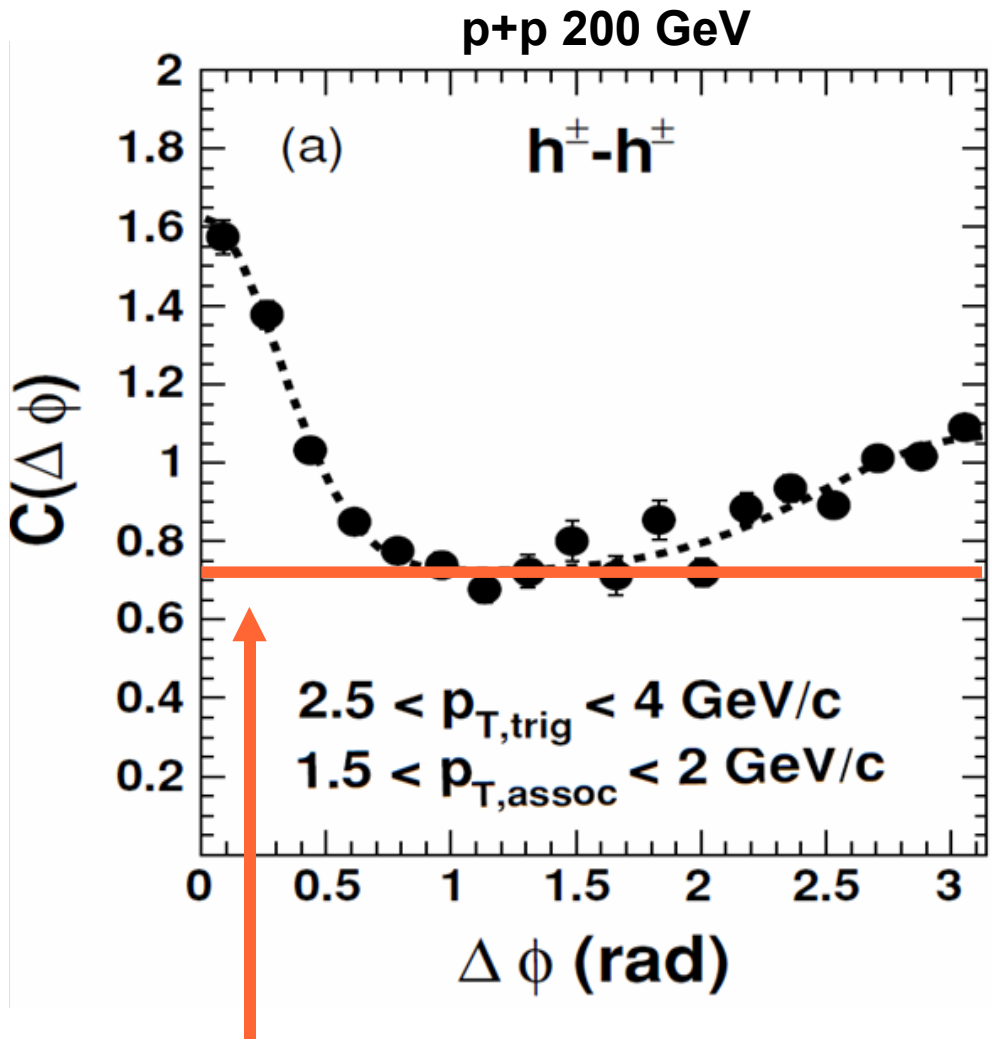
High pT - Energy Loss

Lower pT - Medium Response



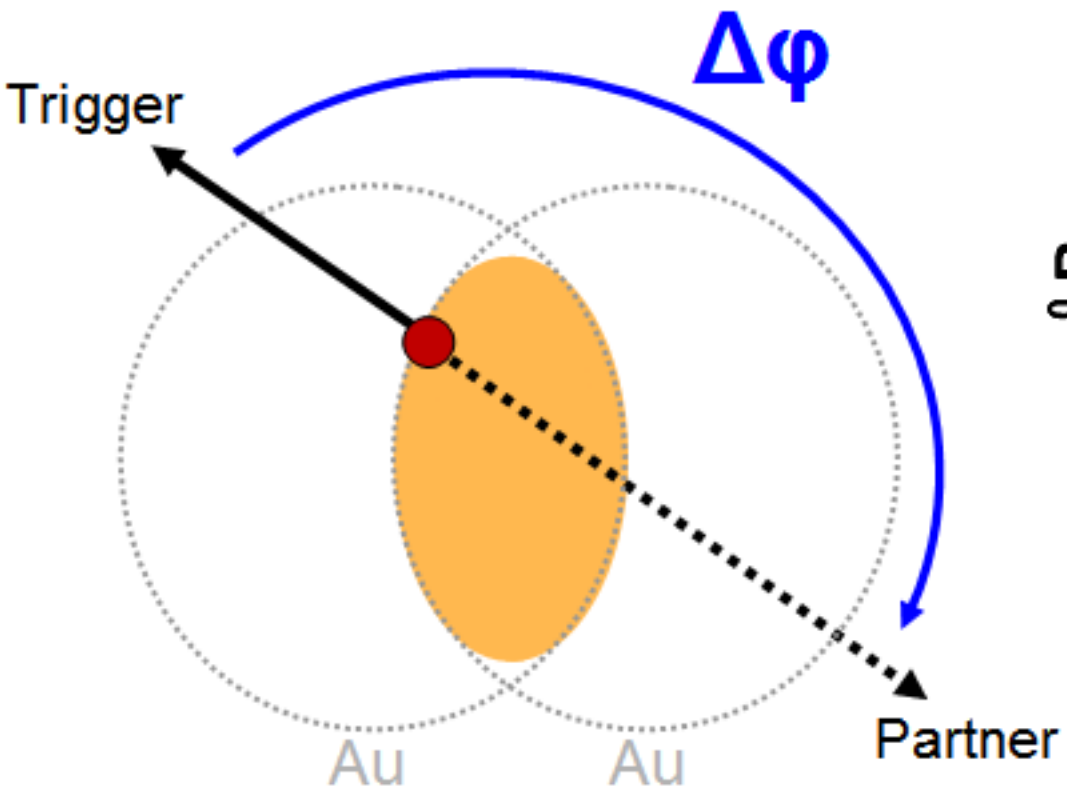
Back-to-Back Jets via Pair Correlations

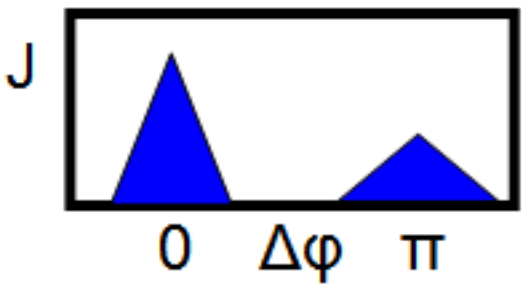




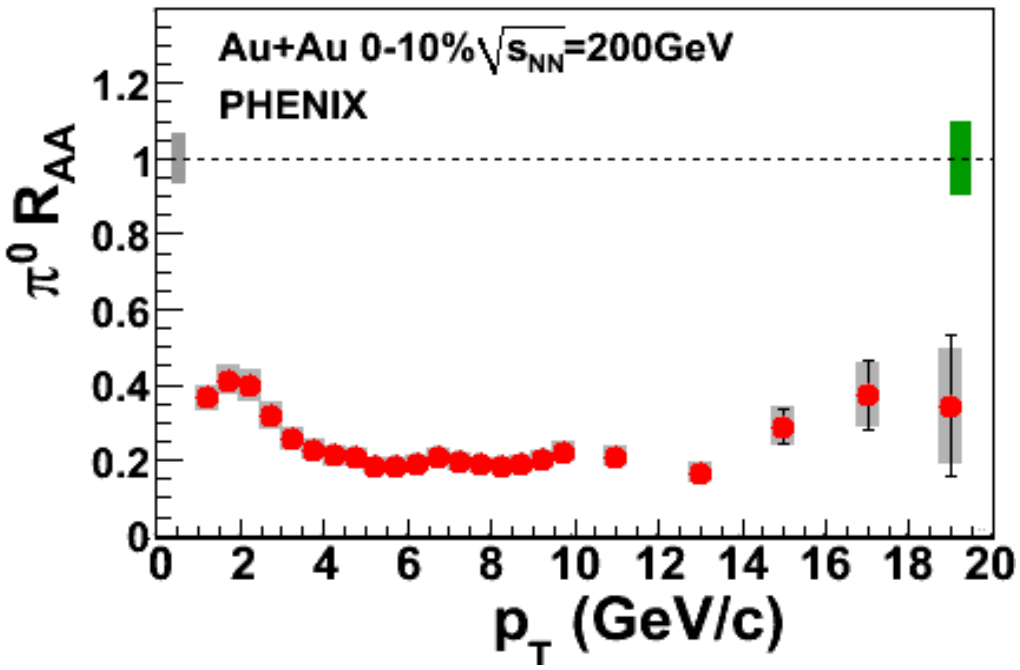
underlying event normalization via ZYAM (Zero Yield at Minimum)

Energy Loss in Heavy Ion Collisions

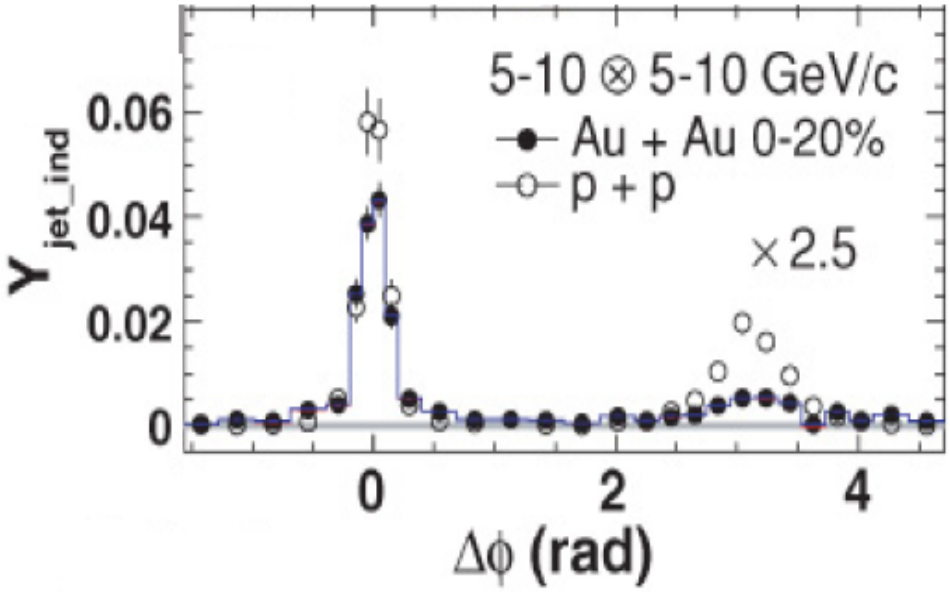




Single particle measurement



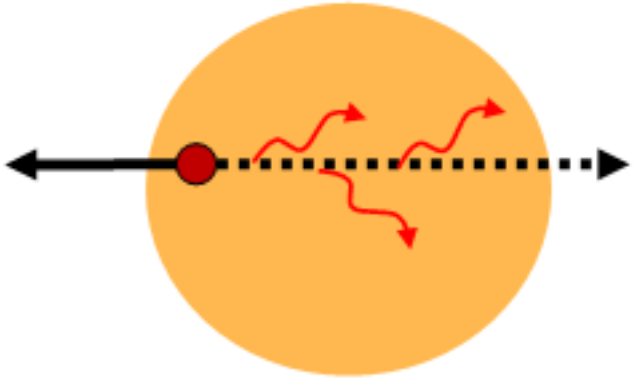
High pT two particle measurement



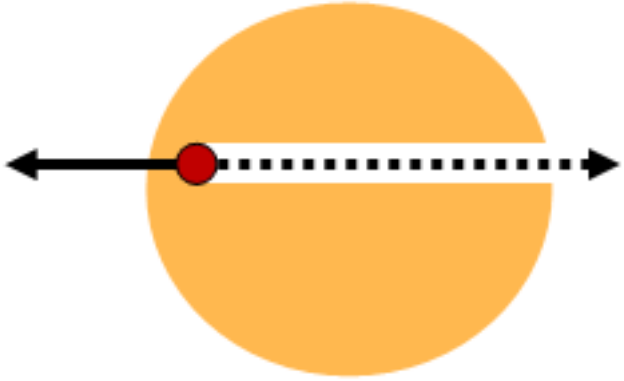
Energy Loss Model Categories

Nuclear Overlap Penetrating

"punch-through"

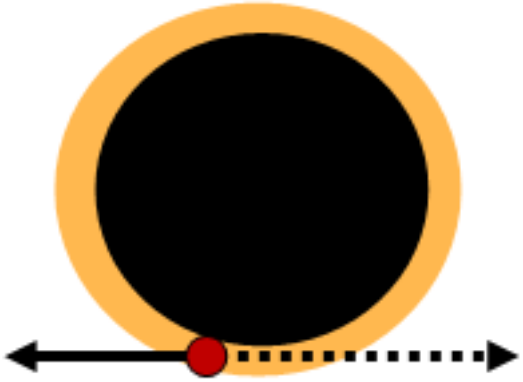


"skip-through"



Tangential Production

"corona"

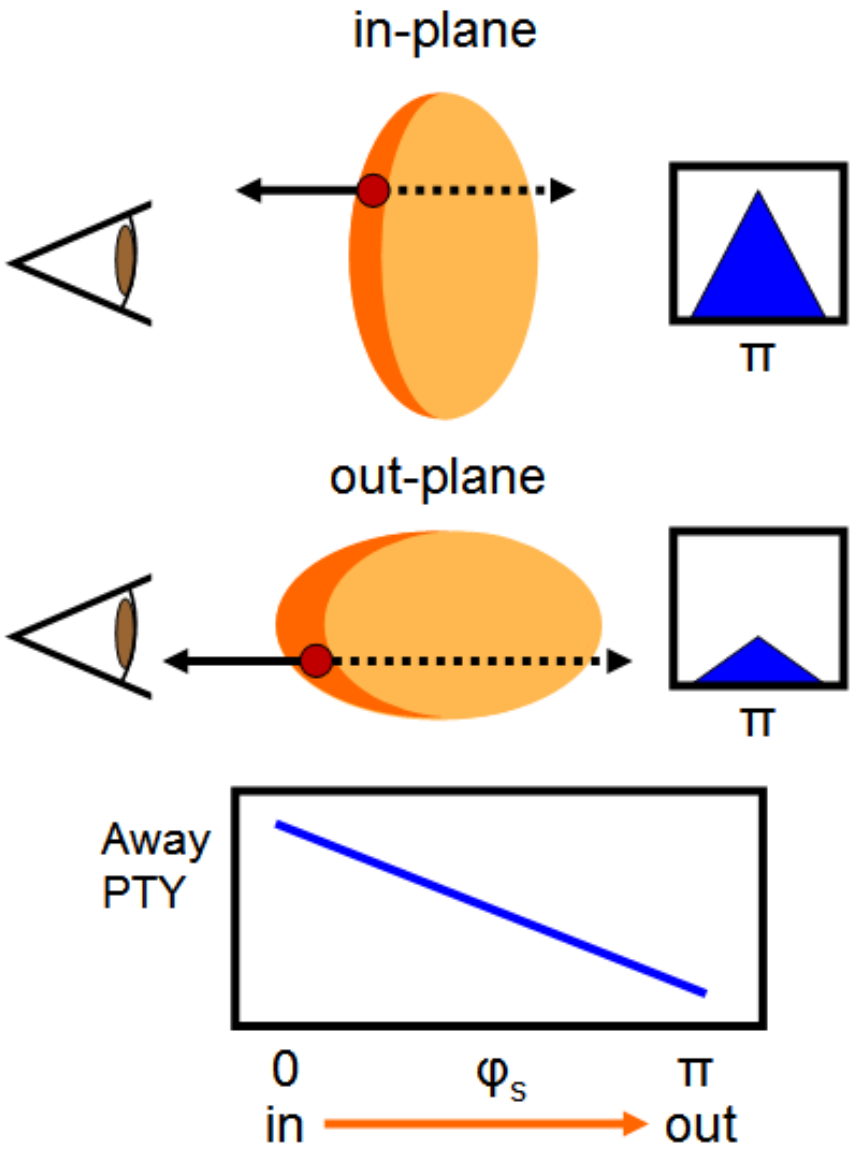


Q: Can a fast parton enter the nuclear overlap and survive?

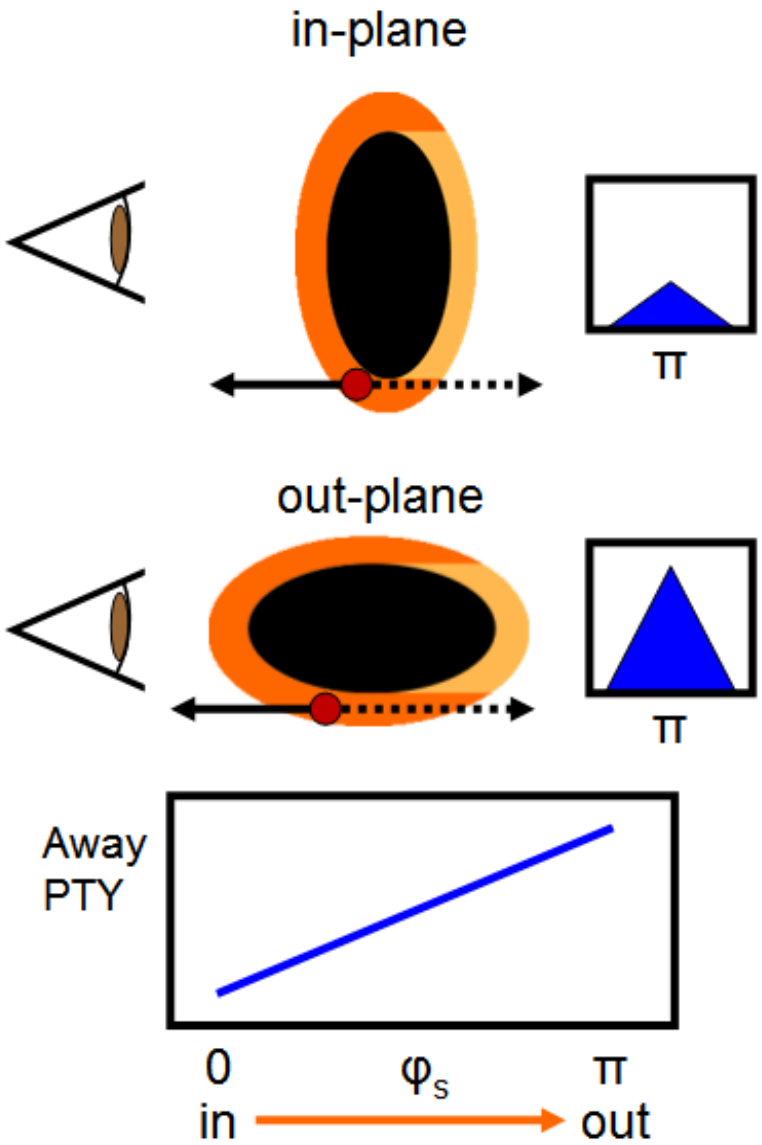
Variation with Reaction-plane

away-side production

Penetrating Production



Tangential Production



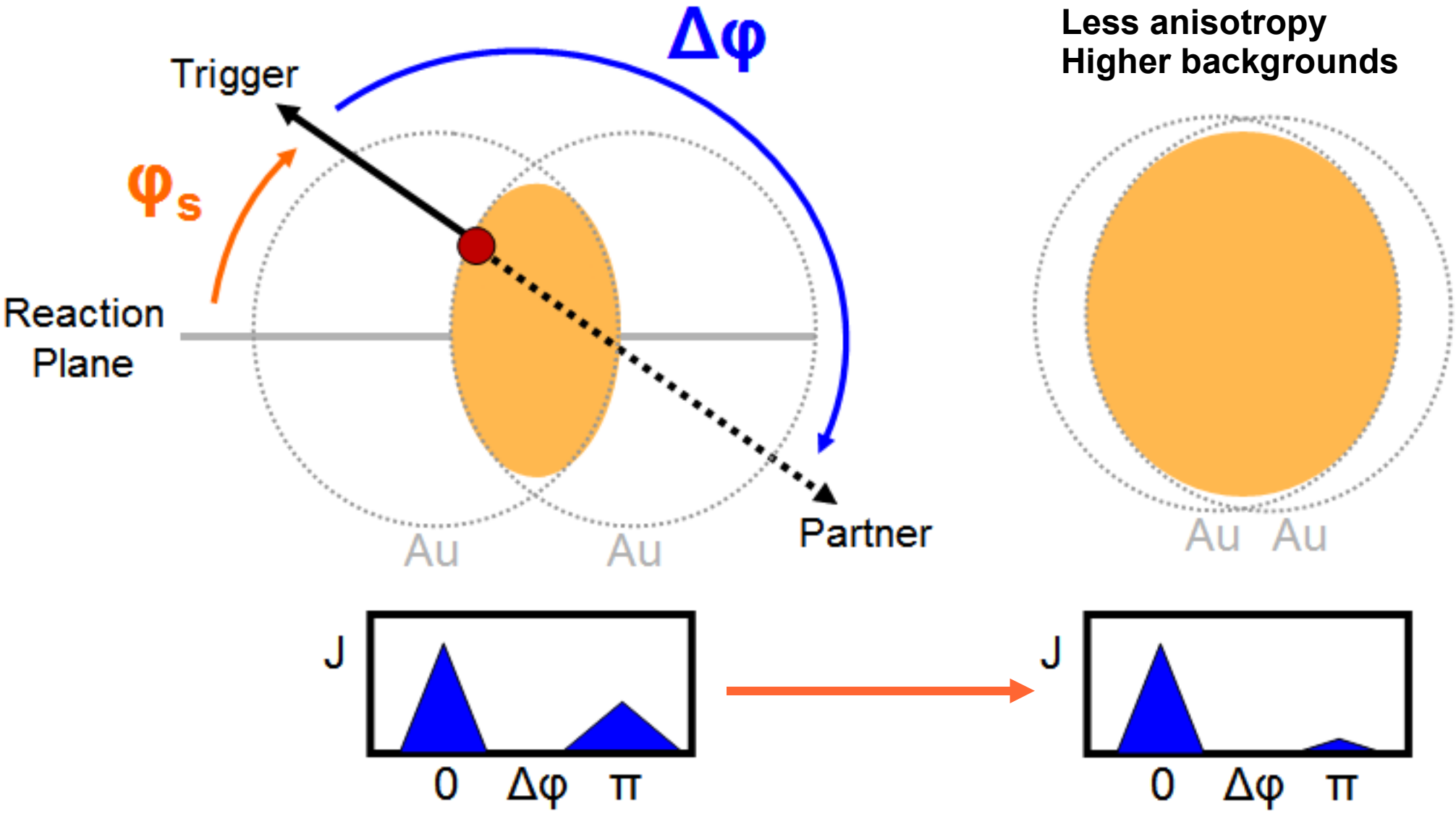
The rp-dependence of away-side PTY can discriminate between models.

High π^0-h by Reaction-Plane Analysis

"Measurement" Bin
20-60%Centrality

"Control" Bin
0-20%Centrality

Less anisotropy
Higher backgrounds



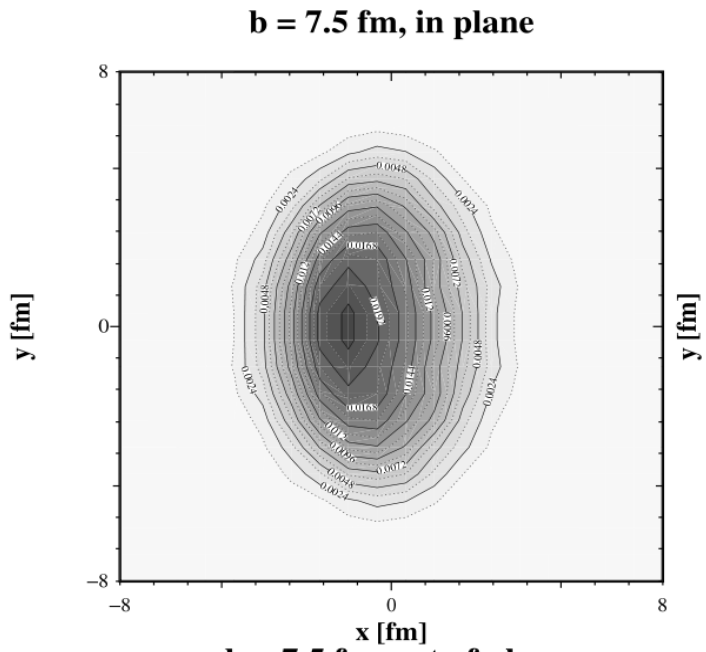
triggers: π^0 4.0-7.0 GeV/c partners: h 4.0-5.0 GeV/c

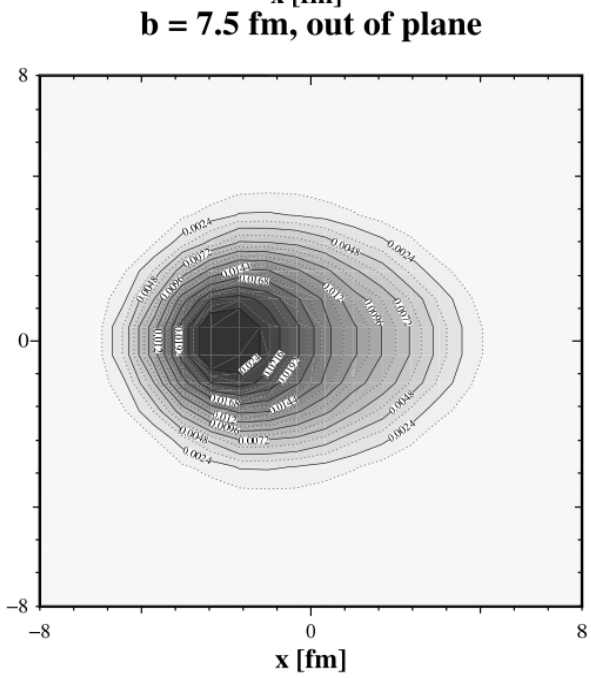
Theory Prediction - Renk

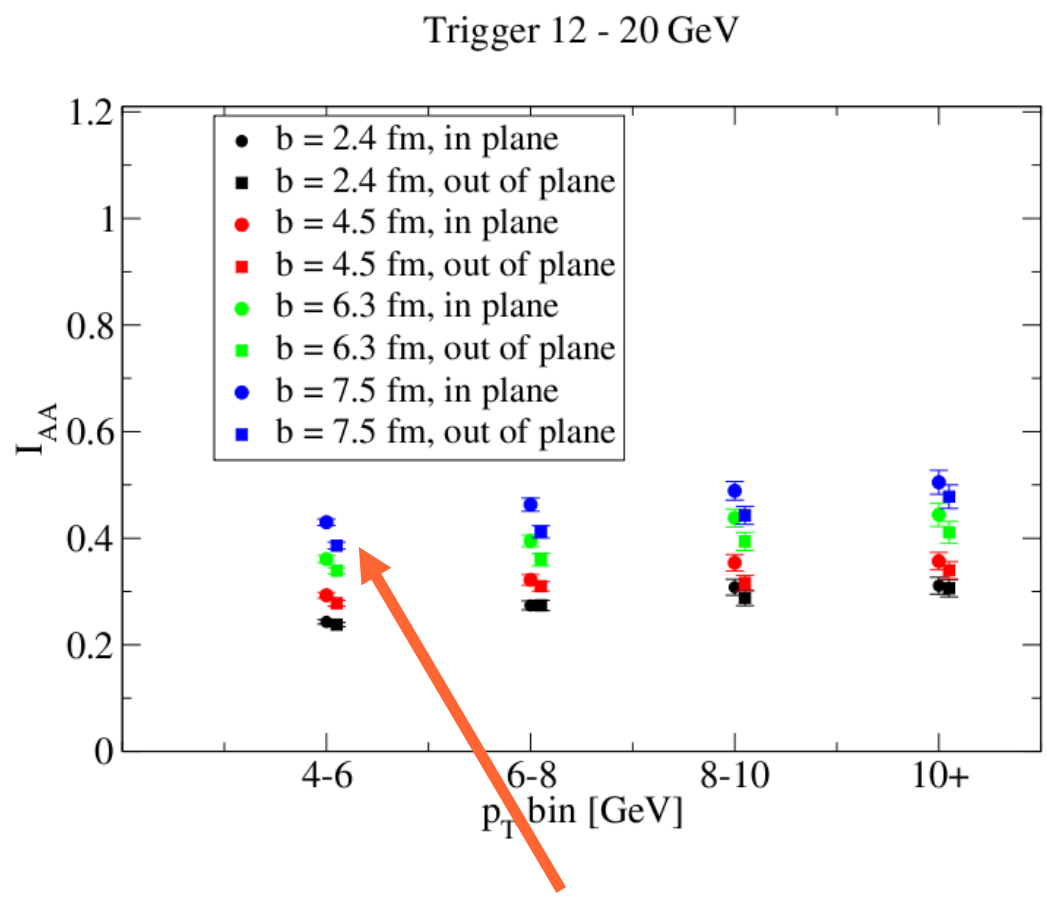
Angular variation of hard back-to-back hadron suppression in heavy-ion collisions

arXiv:0803.0218v2

Thorsten Renk*
Box 35 FI-40014 University of Jyväskylä, Finland and
P.O. Box 64 FI-00014, University of Helsinki, Finland



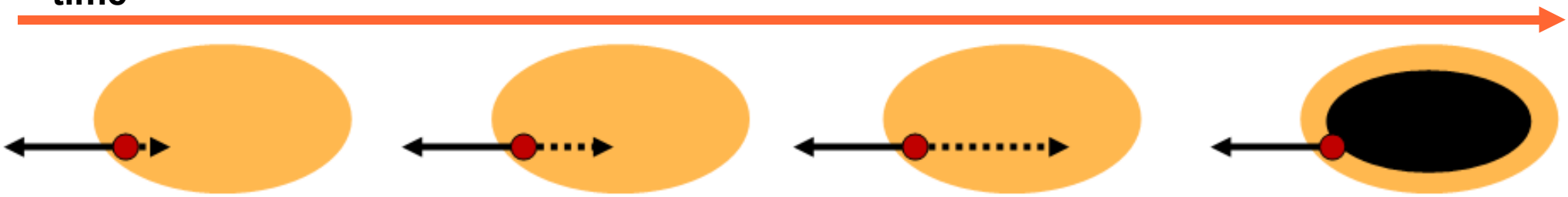




falling with increasing rp-angle
max ~12% variation in mid-central

Theory Prediction - Vlad Pantuev

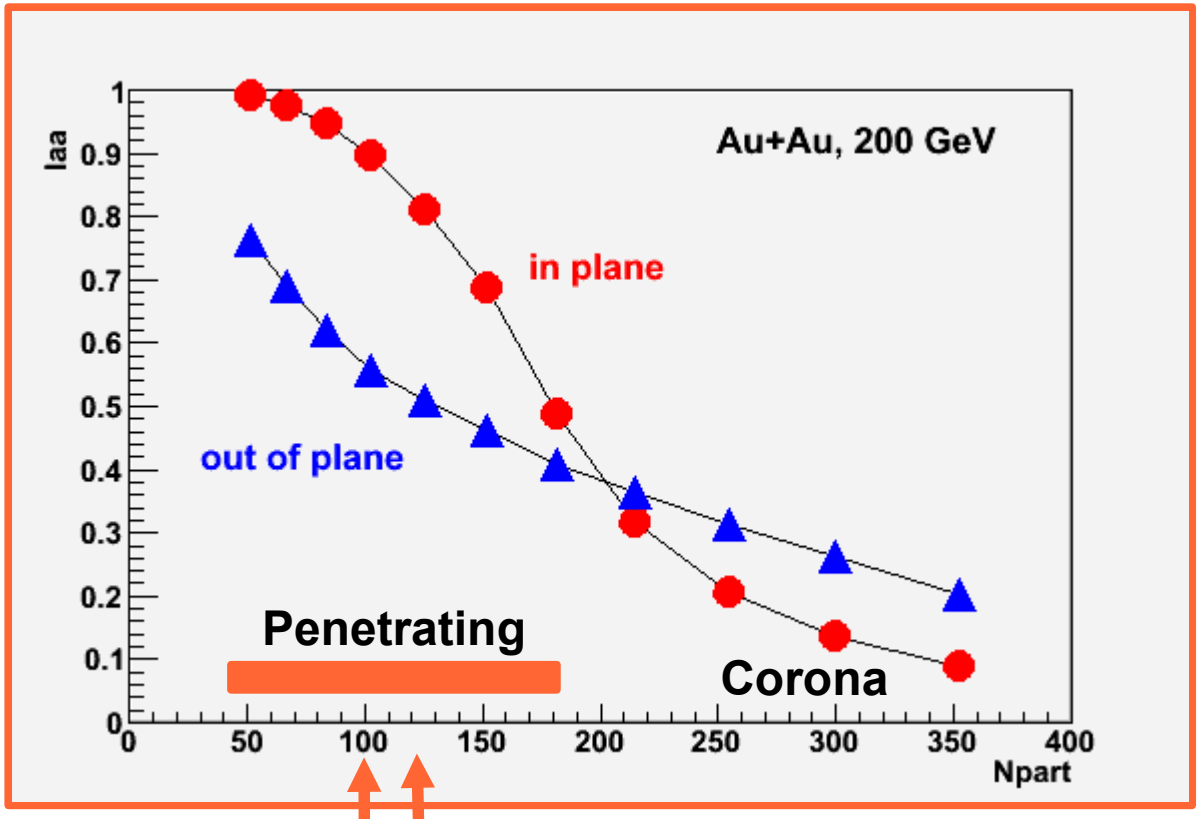
Vlad Pantuev, private communication 2009



Tangential-dominance only in more central collisions

Transition driven by formation time of black core

Large falling variation in mid-central bin
~45%

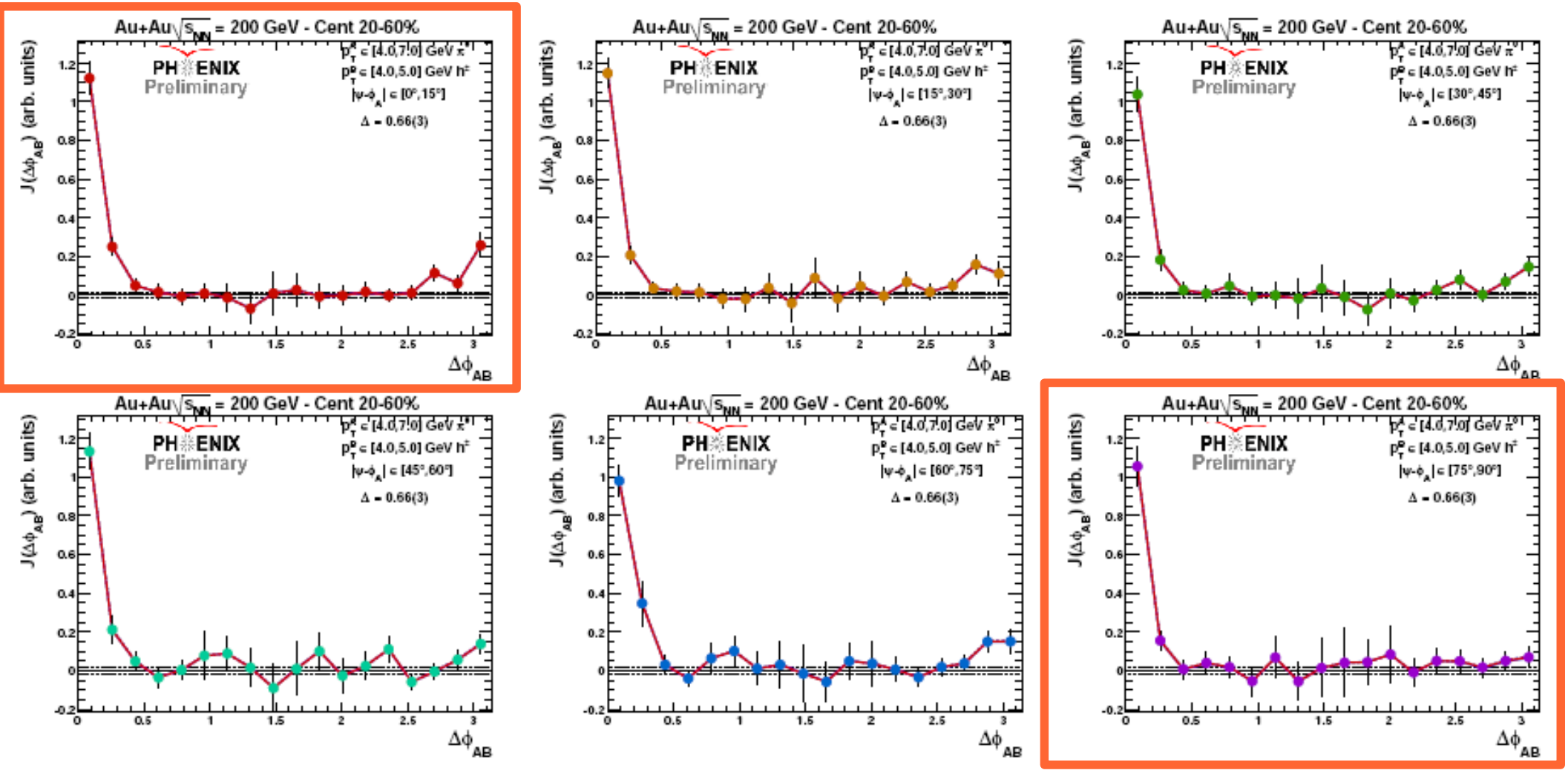


Trigger Weighted
Npart 20-60% ~ 125

Npart 20-60% = 100

J x RXPN – Cent 20-60%

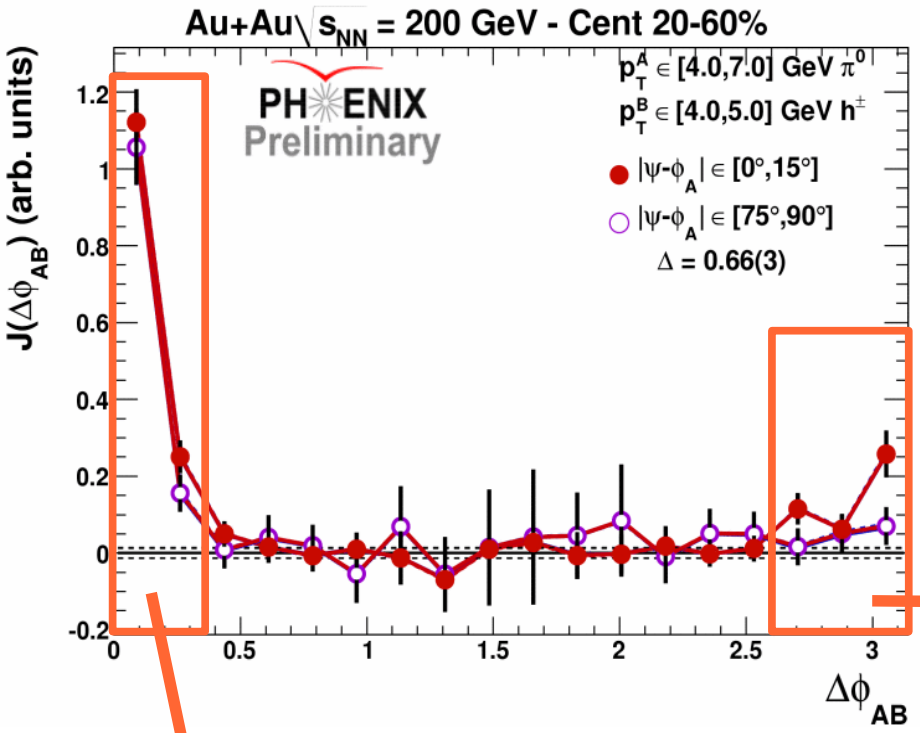
most in-plane

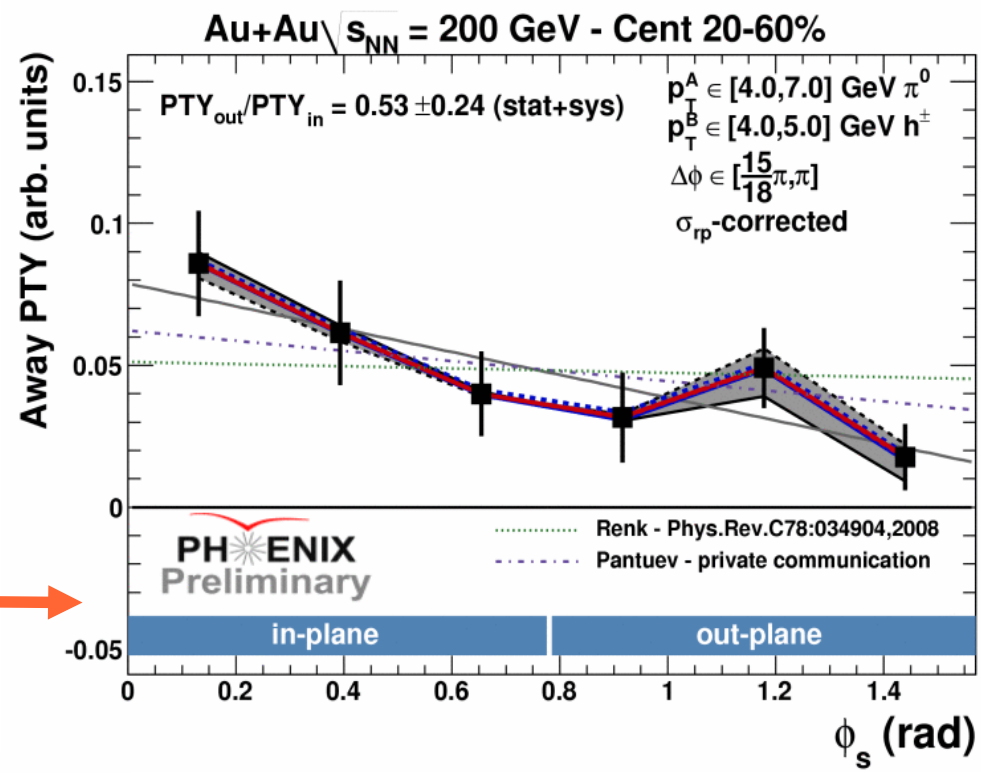


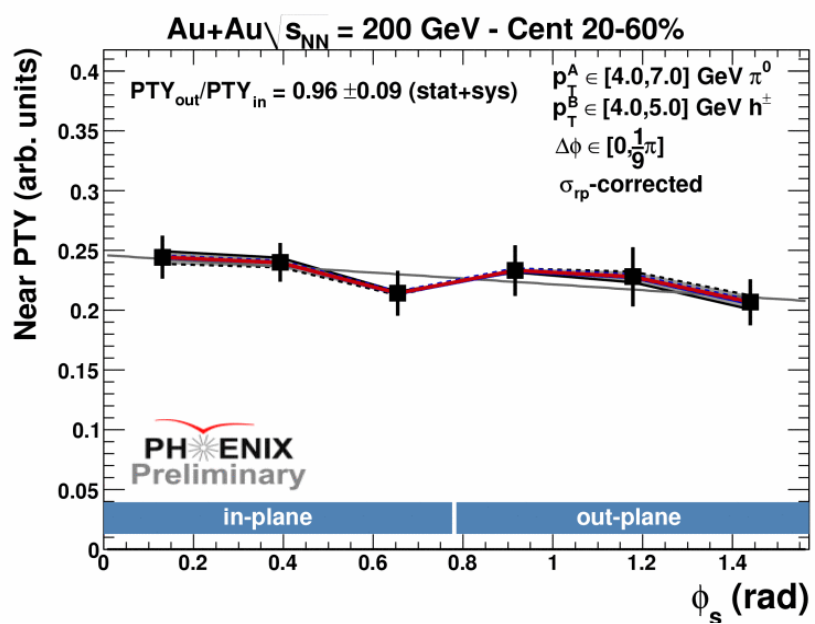
most out-plane

JF Most-in vs. Most-out

Measurement Bin – 20-60%







Measurement:

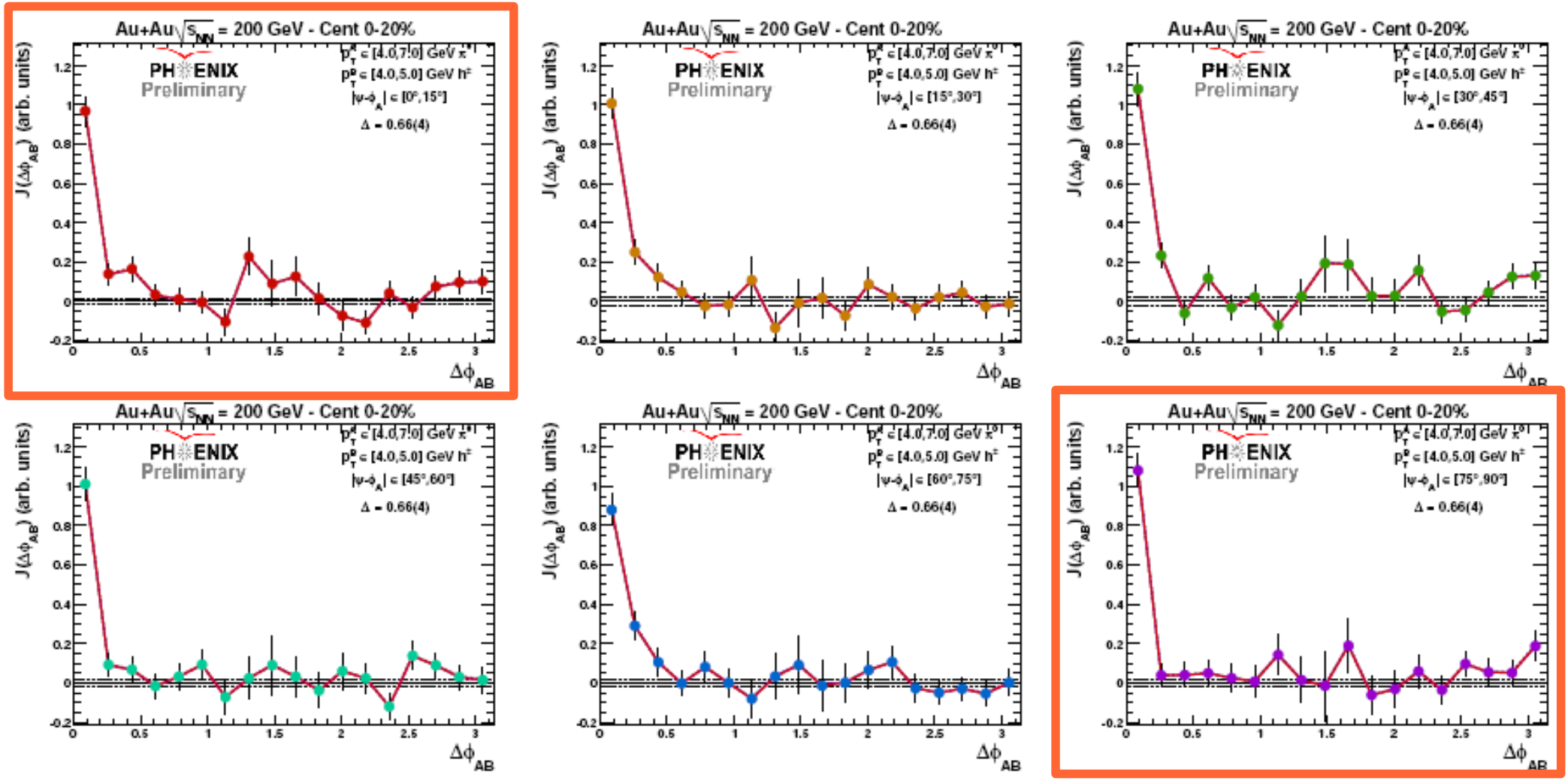
Flat (<1σ) on near-side

Steep falling away-side

2σ significance to away-side dependence

J x RXPN – Cent 0-20%

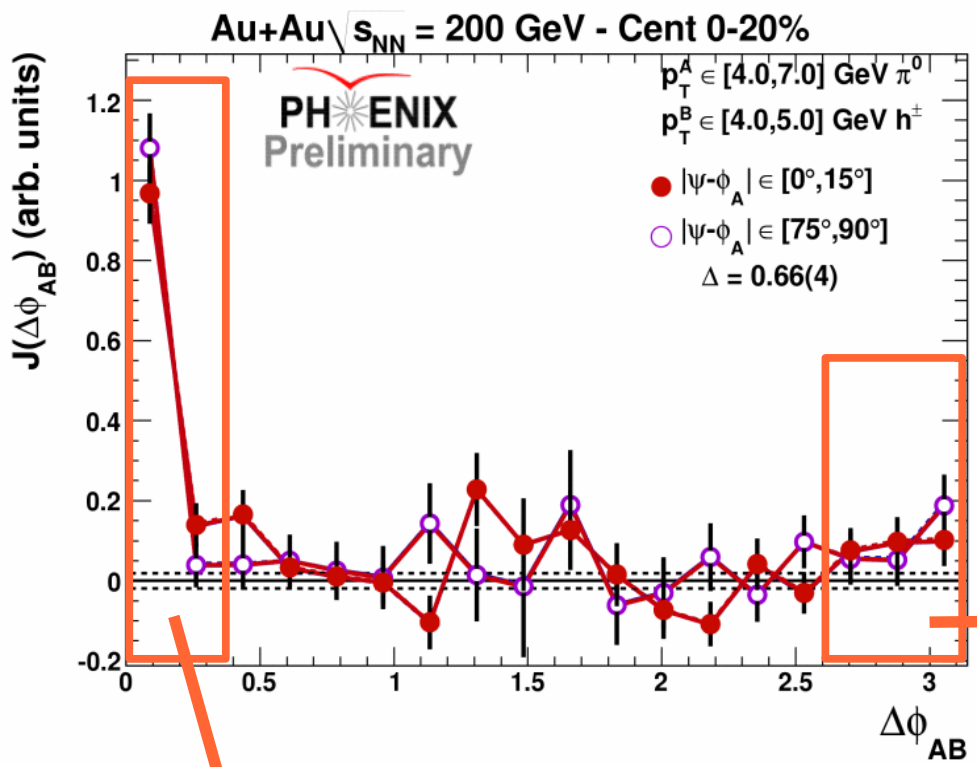
most in-plane

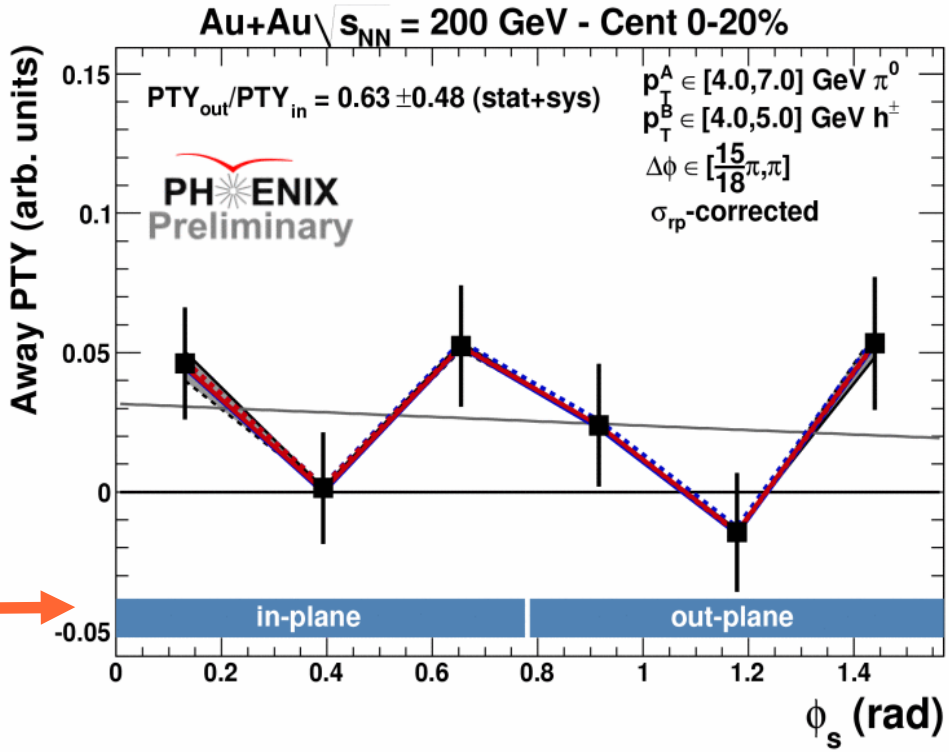


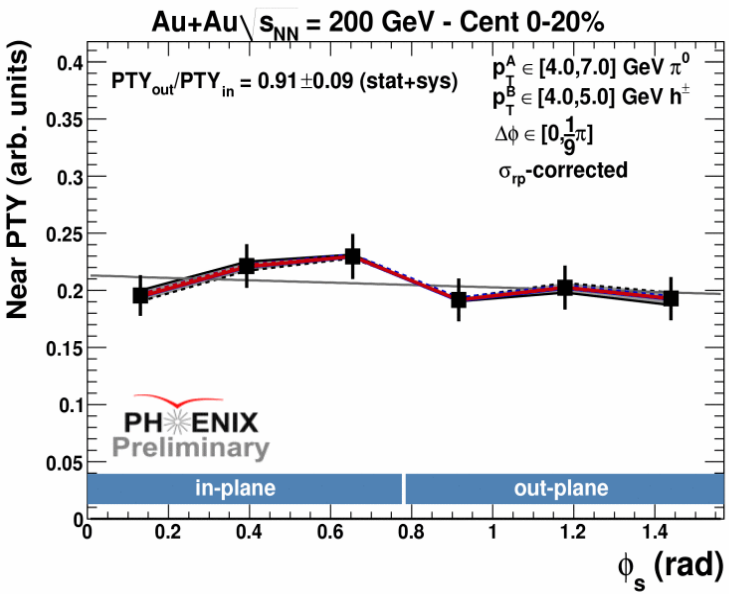
most out-plane

J Most-in vs. Most-out

Control Bin – 0-20%







Control:

Flat dependencies on both near- and away-side

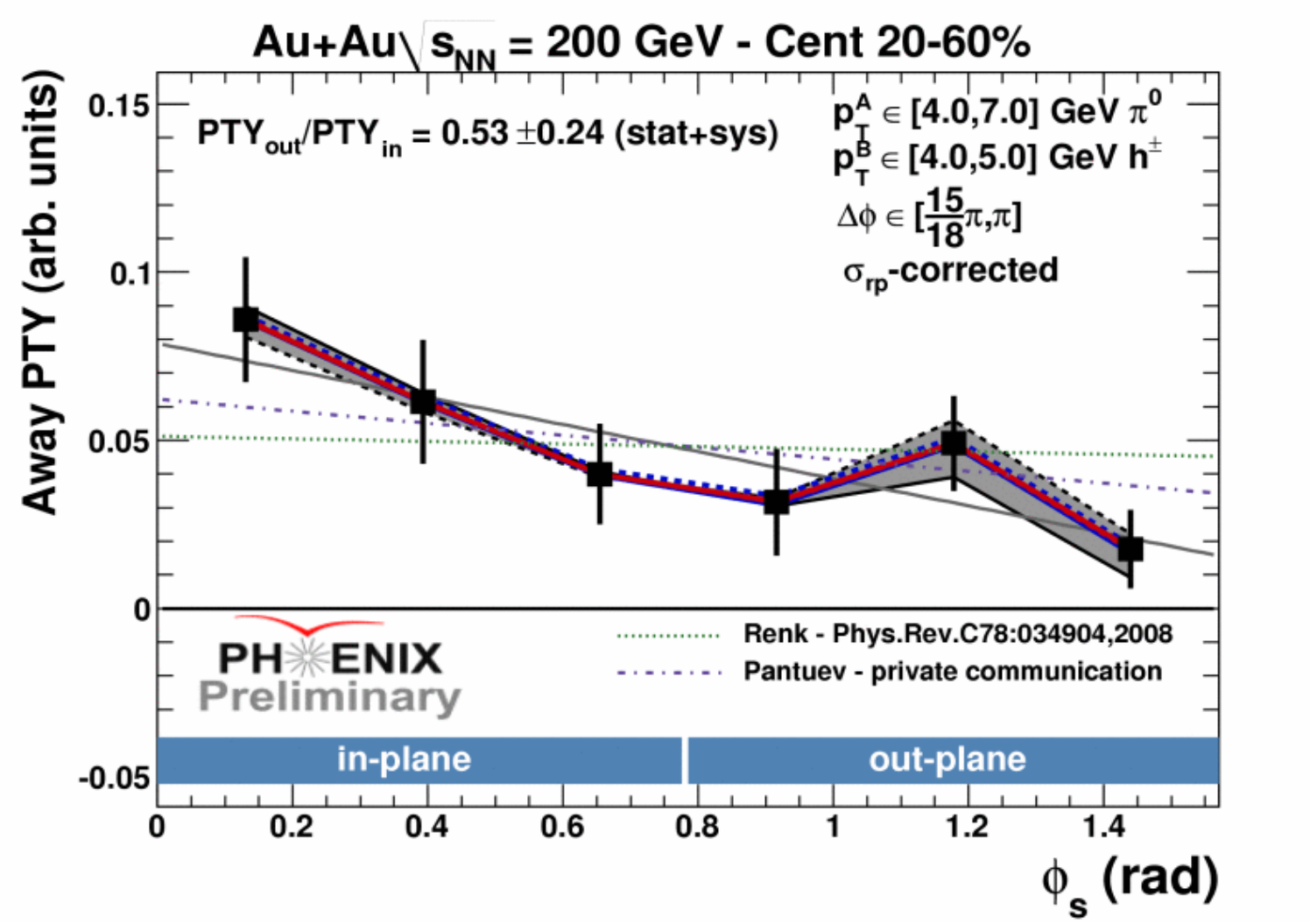
Little yield on away-side

Background under control

Little systematic error due to flow at high pT (red and blue lines)

Mid-Central Back-to-Back Production

"Penetrating production favored over tangential production in mid-central as dominant form for the survival of back-to-back jets at the 2σ level (40:1)."



γ_{dir}-h Correlations

In the black core model:

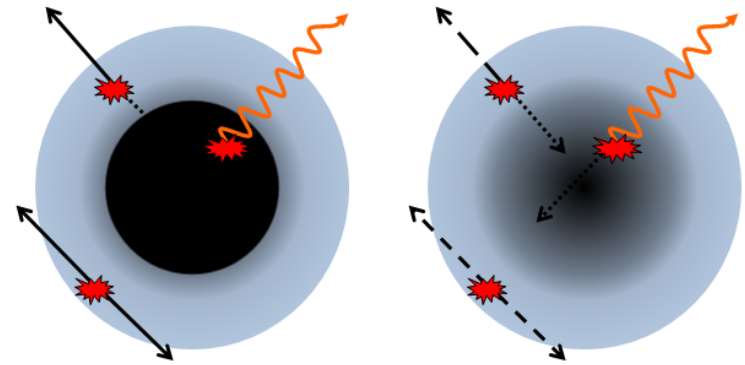
γ-h $I_{AA} \approx$ h R_{AA}

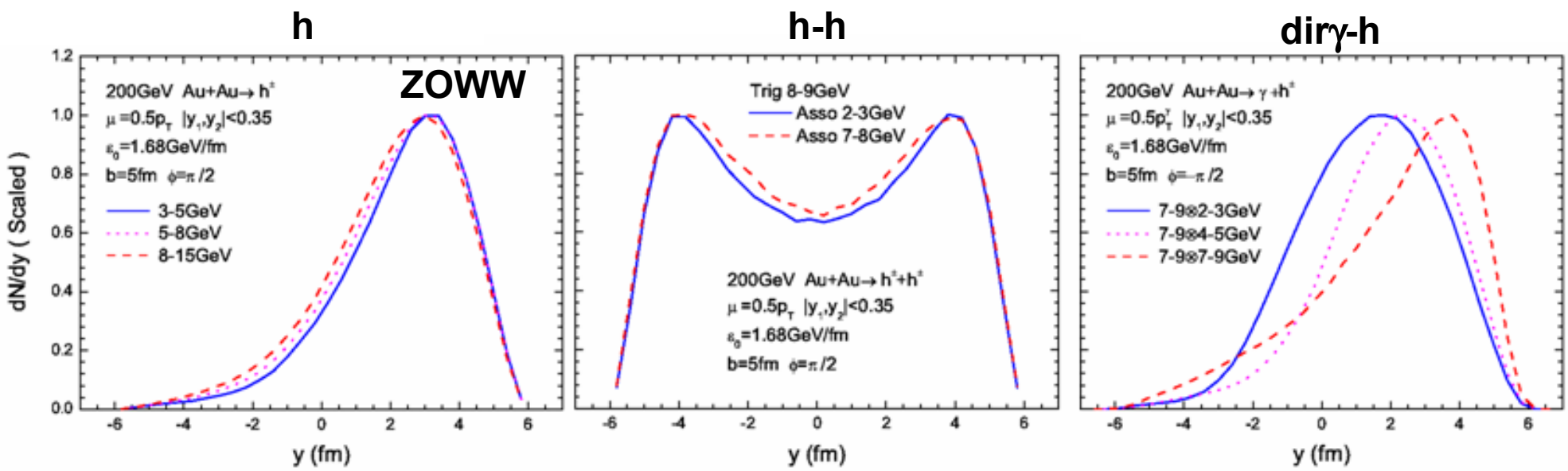
In a penetrating model:

γ-h probes a different set of path lengths through the medium than either h or h-h suppression

Happens because the direct γ better constrains the parton energy

Black Core / Corona vs. Diffuse Medium





EPJC (2008) + ref's therein

γ_{dir}-h Correlations

In the black core model:

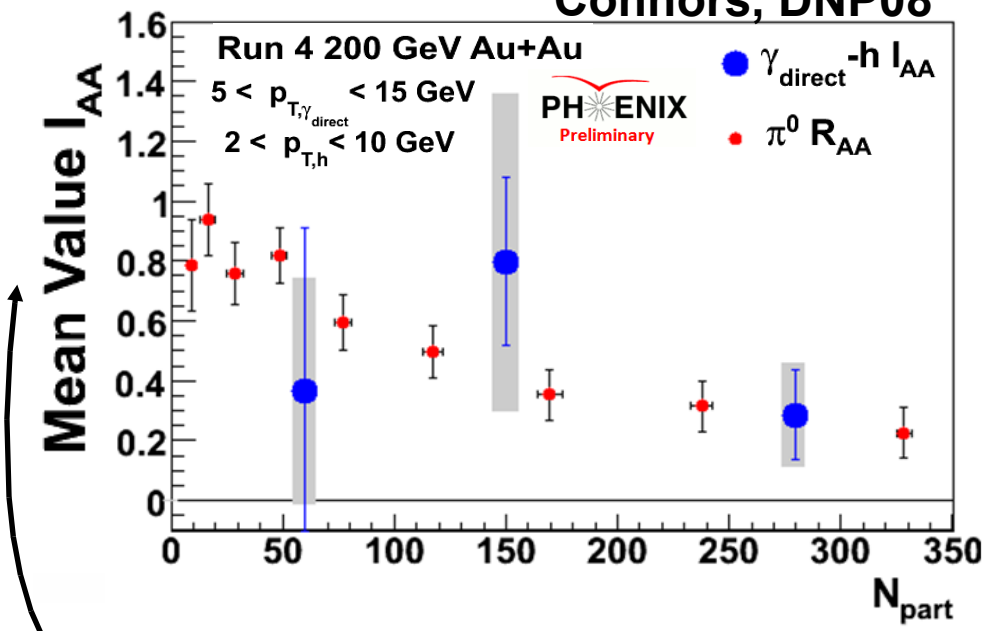
γ-h $I_{AA} \approx$ h R_{AA}

In a penetrating model:

γ-h probes a different set of path lengths through the medium than either h or h-h suppression

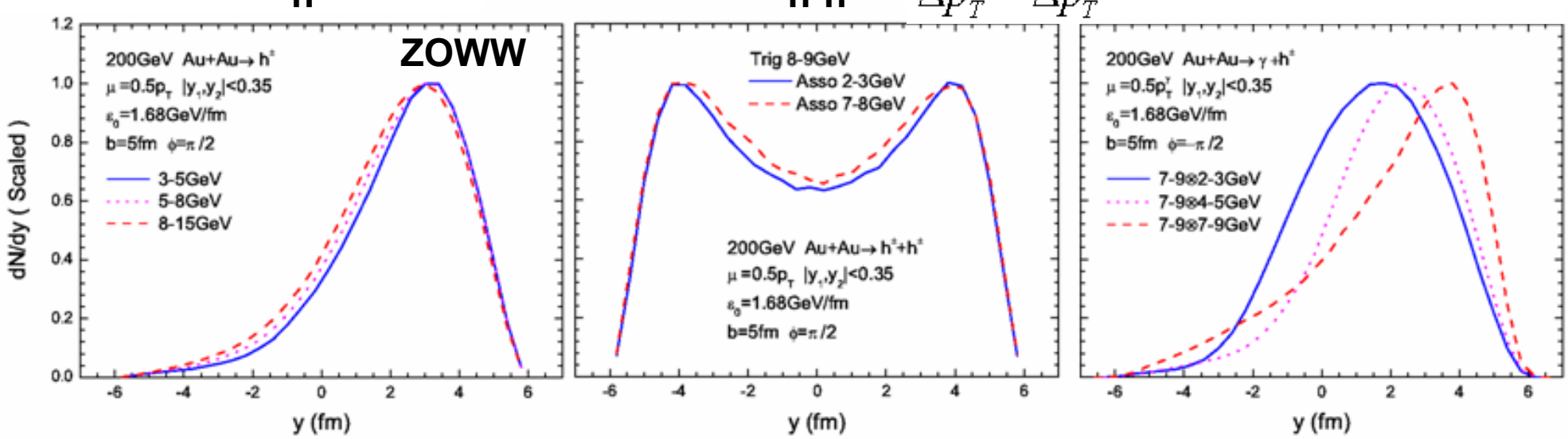
Happens because the direct γ better constrains the parton energy

Connors, DNP08



$$\frac{1}{\Delta p_T^{assoc}\,\Delta p_T^{\gamma\,trig}}\int I_{AA}(p_T^{assoc}, p_T^{\gamma\,trig})\,dp_T$$

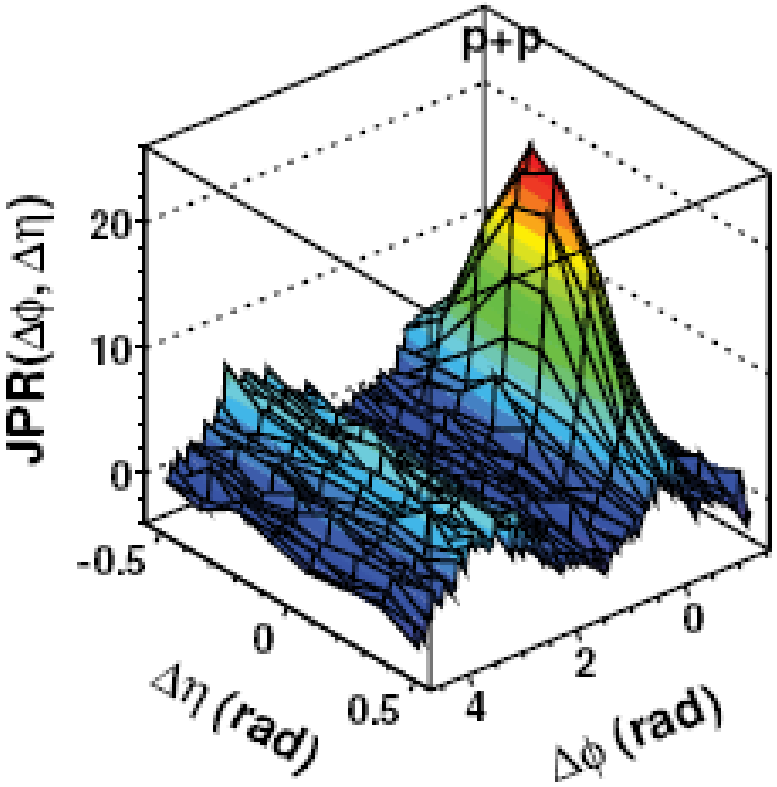
h **h-h**



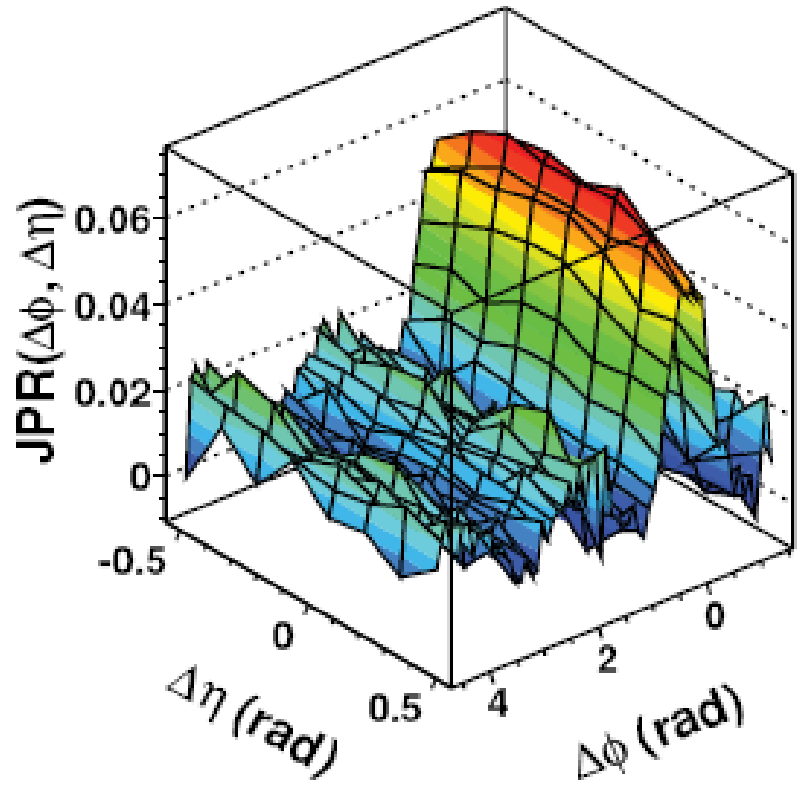
EPJC (2008) + ref's therein

Energy Loss to Medium Response

p+p (similar in peripheral Au+Au)



central Au+Au



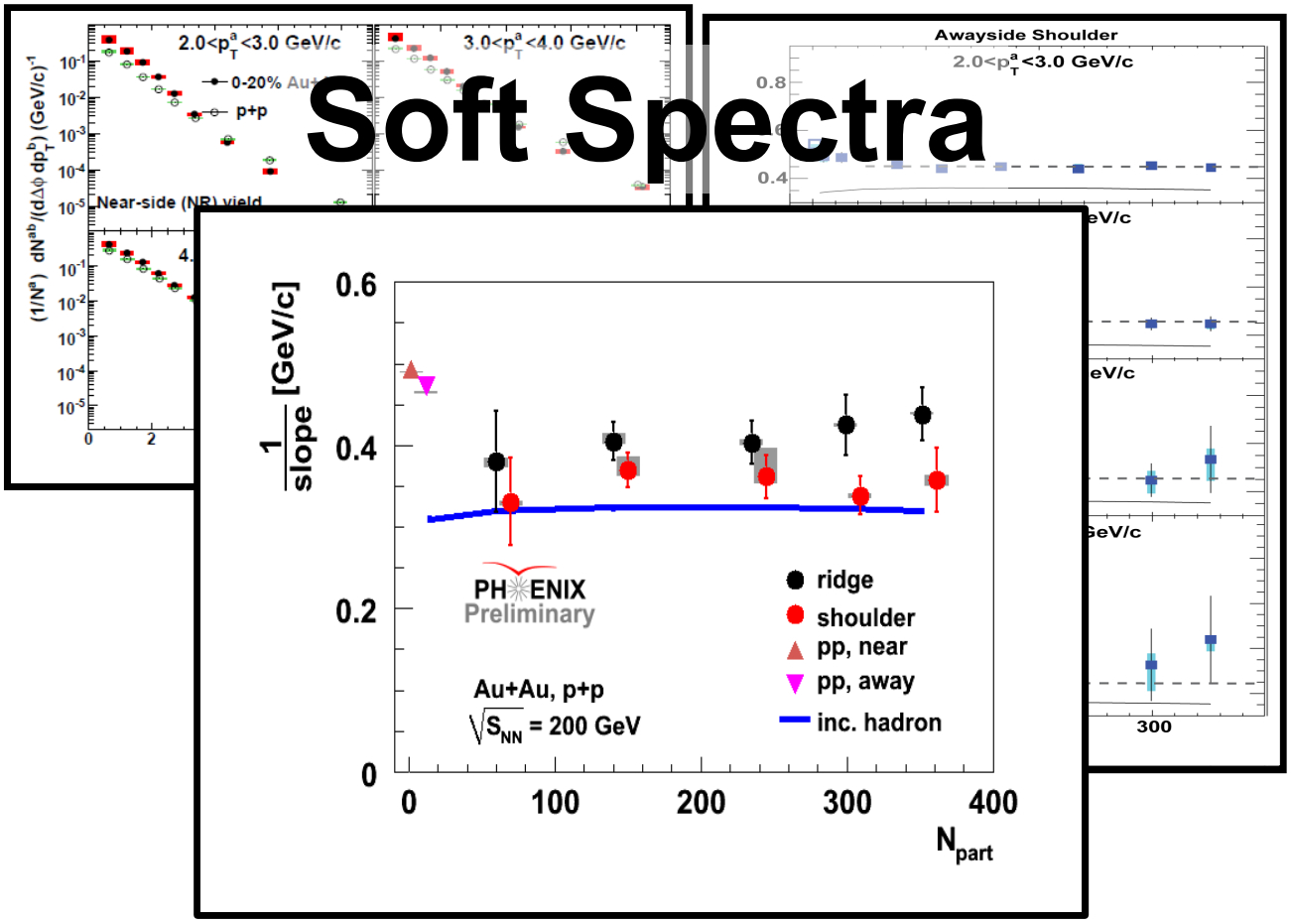
<u>Typical:</u>
- **Near-side Jet**
- **Away-side Jet - "Head"**

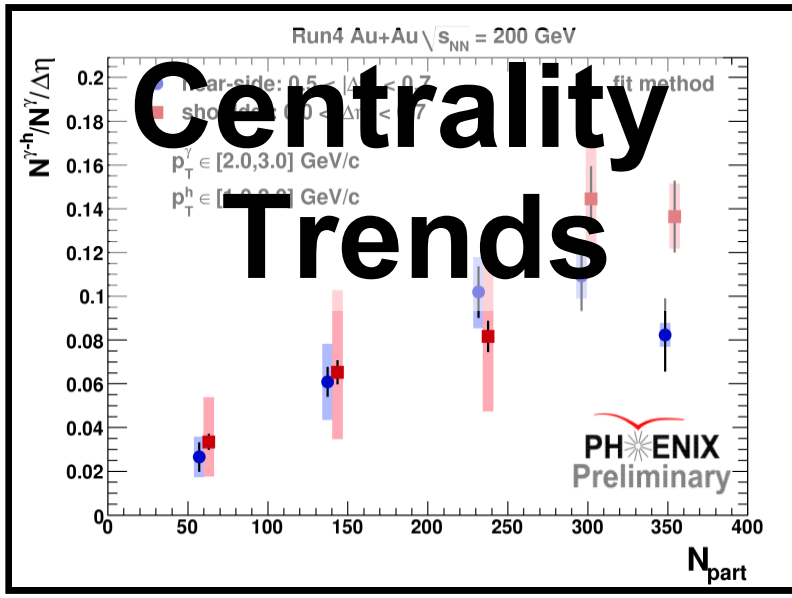
<u>New:</u>
- **Near-side Modification- "Ridge"**
- **Away-side Modification - "Shoulder"**

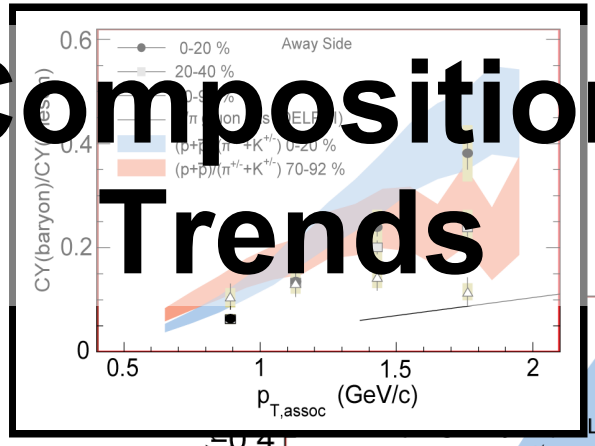
Near-side Ridge theories: Boosted Excess, Backsplash, Local Heating, …

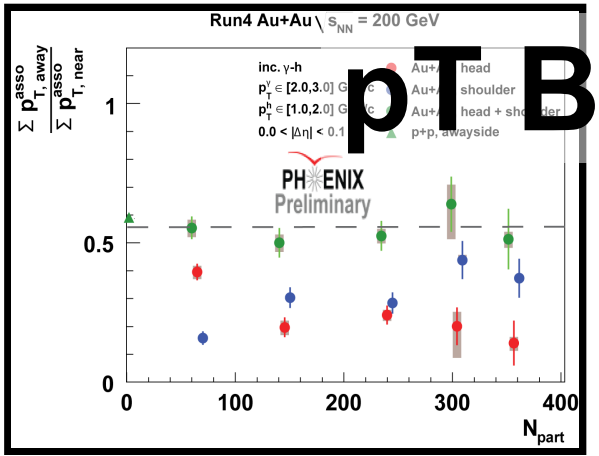
Away-side Shoulder theories: Mach, Jet Survival + Recom, Coherent Scattering,...

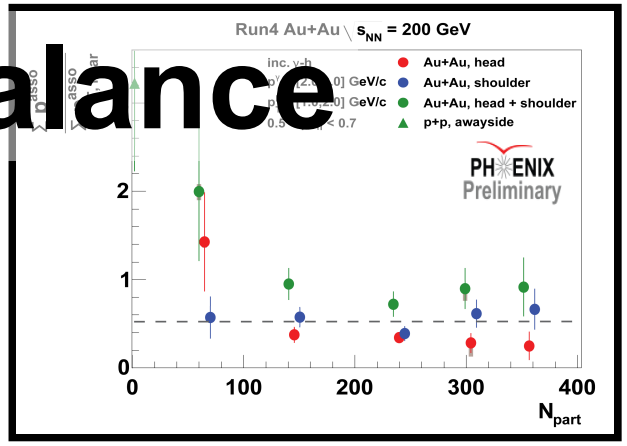
Many Similarities between Ridge and Shoulder

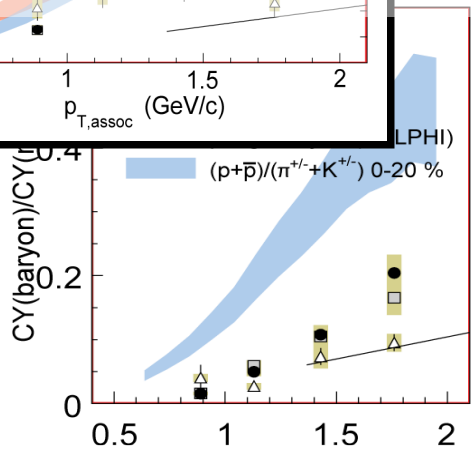










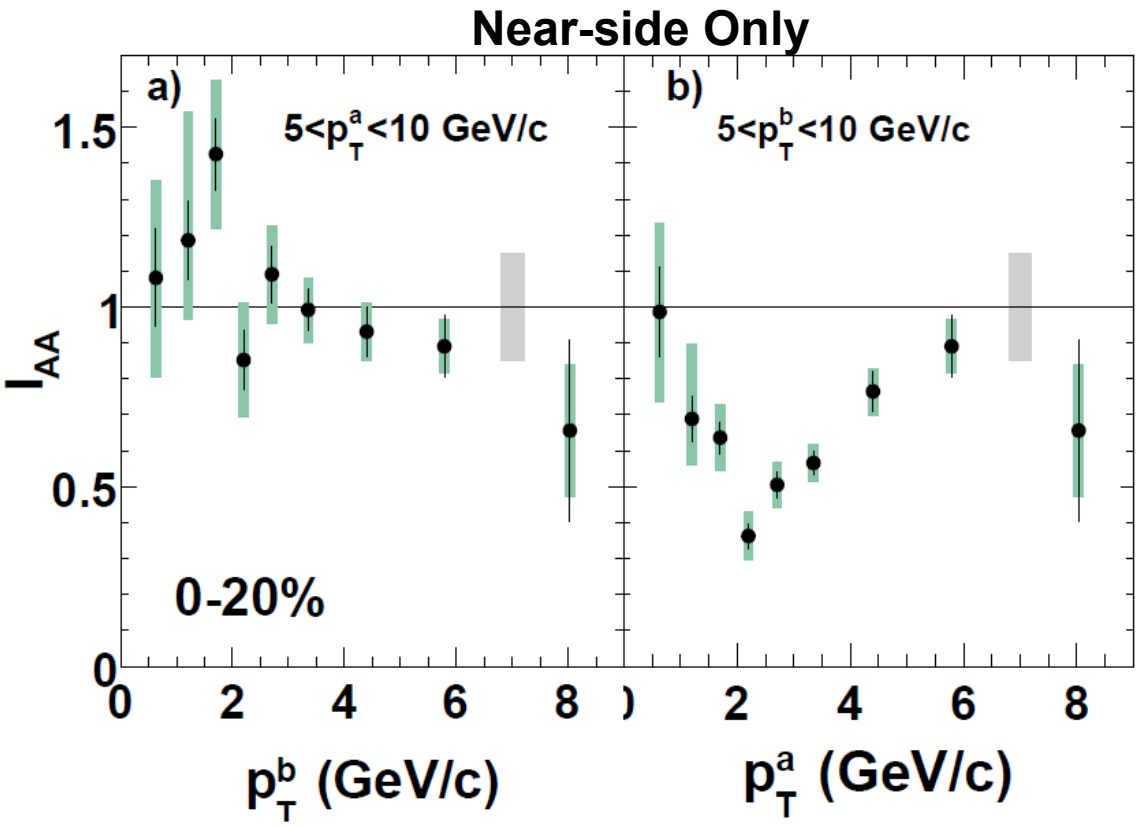


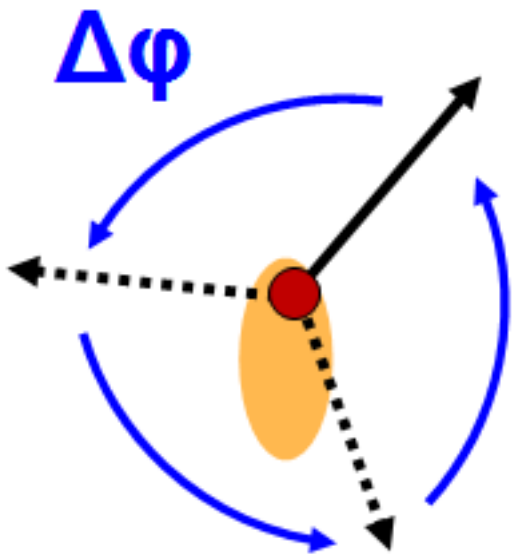
McCumber, QM08 Chen, HP08

Intermediate p_T Triggers

- I_{AA} trigger-partner anti- symmetry indicates not all triggers at intermediate pT are jet fragments

- Some could be from the medium response itself





- 120 deg is a special angle

- Two-sided shoulder mechanisms could create structures at $\Delta\varphi = 0$ and $\Delta\varphi = \pi \pm 1.1$

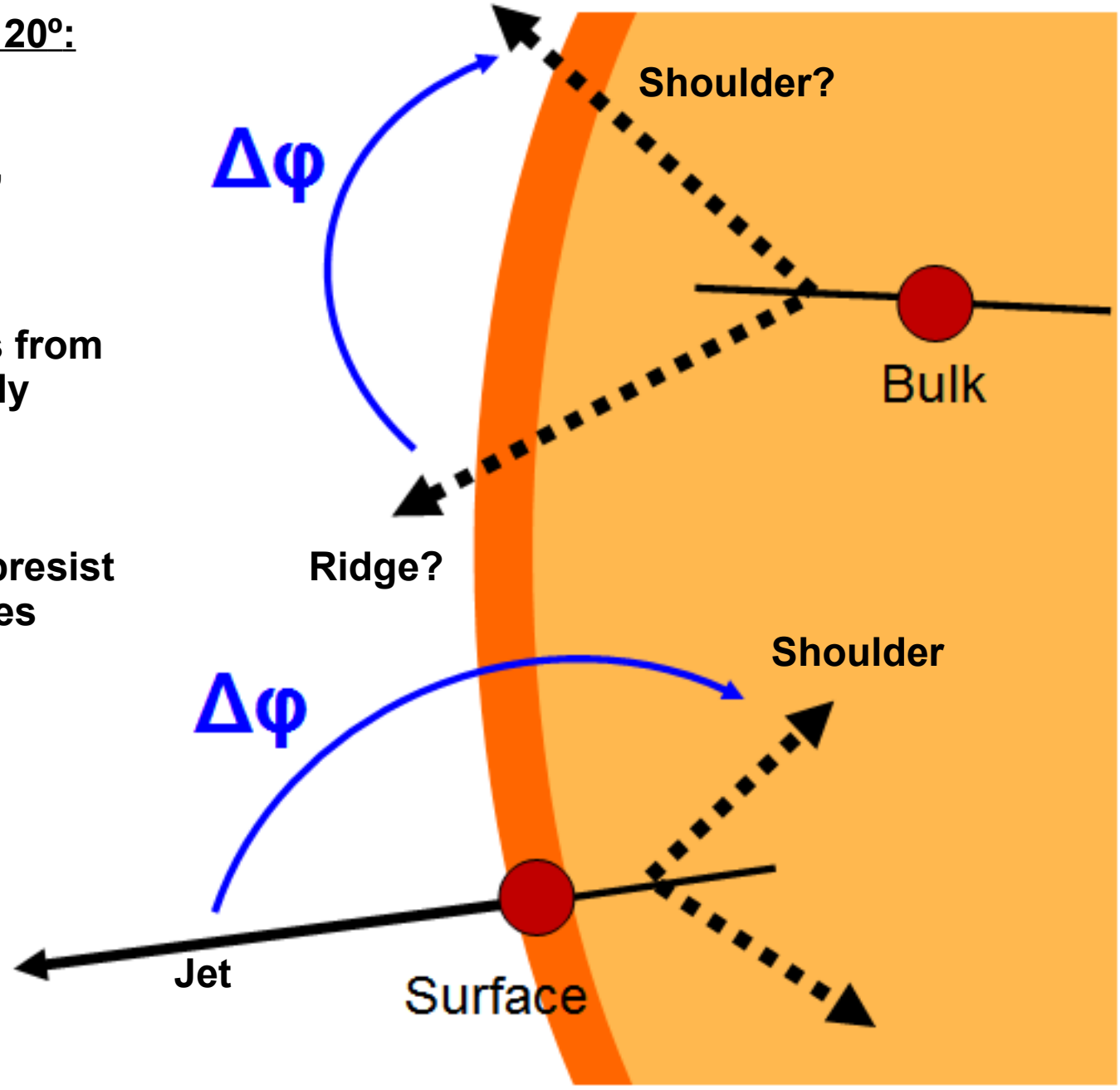
Two-sided Medium Response from the Bulk

<u>If the opening angle is near 120º:</u>

Explains the broad Ridge $\Delta\eta$, Ridge-Shoulder similarities

Pairs from the bulk and pairs from the surface add constructively at 120º

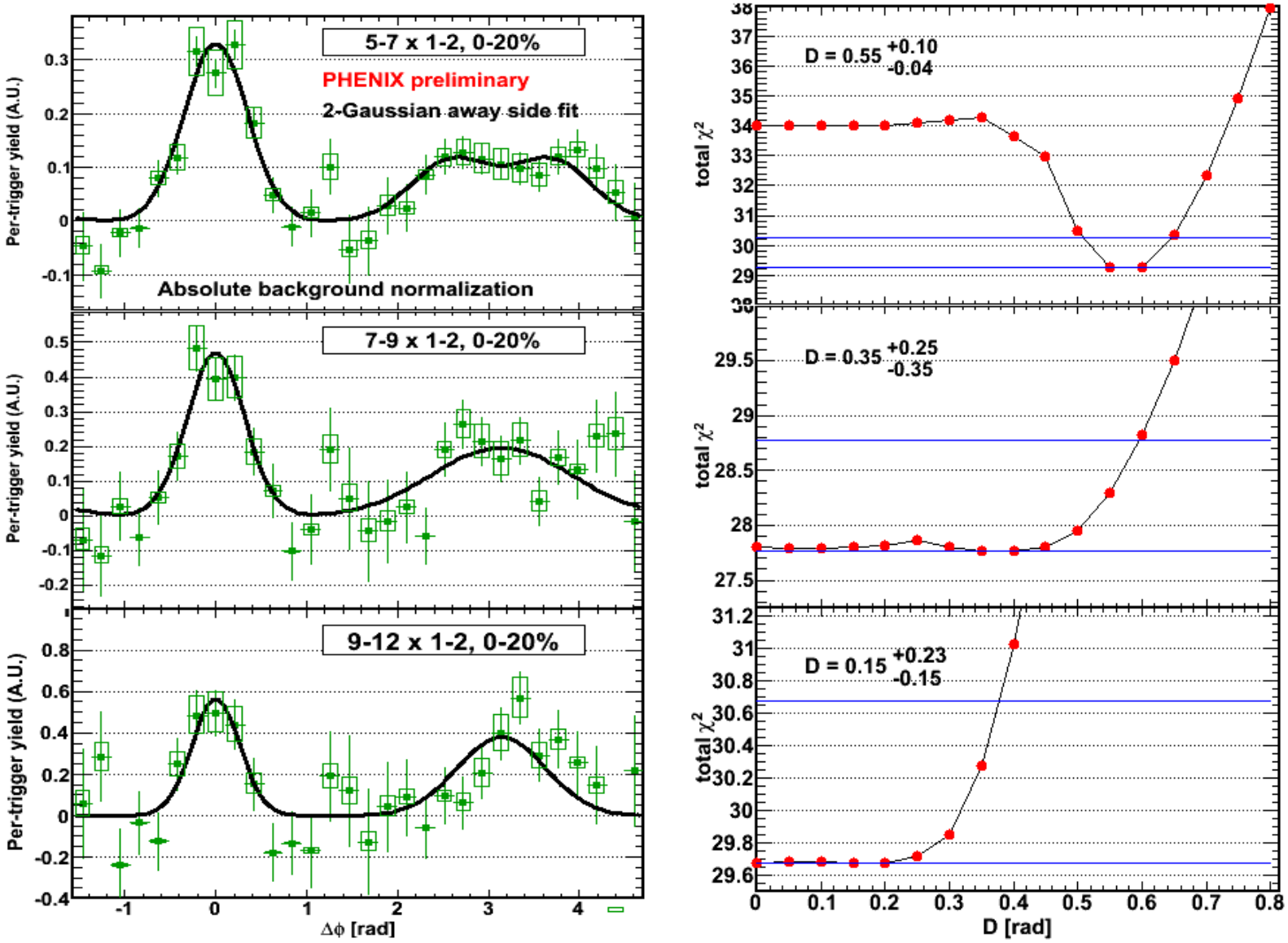
Even if Ridge and Shoulder presist at highest pT, this complicates the intermediate pT correlations



High p_T - Low p_T Correlations

Lower pT trig shows smaller shoulder peak position

Increasing head production as trigger pT increases



Summary

High pT:

We have a new differential "fine knob" with reaction-plane angle

- **Mid-central surviving high p_T back-to-back pairs prefer partons that penetrate the nuclear overlap.**
- **Partner momentum scan required to confirm**

Lower pT:

The Ridge and Shoulder show remarkable similarities and may have a non-trivial relationship at intermediate pT

Intermediate p_T triggers can not be thought of as only jet fragmentation

- **May be triggering on the medium response itself**
- **Complicates the interpretation of the data**

Transition to higher pT triggers needs to be understood

Backup Slides

Begin Backup Slides

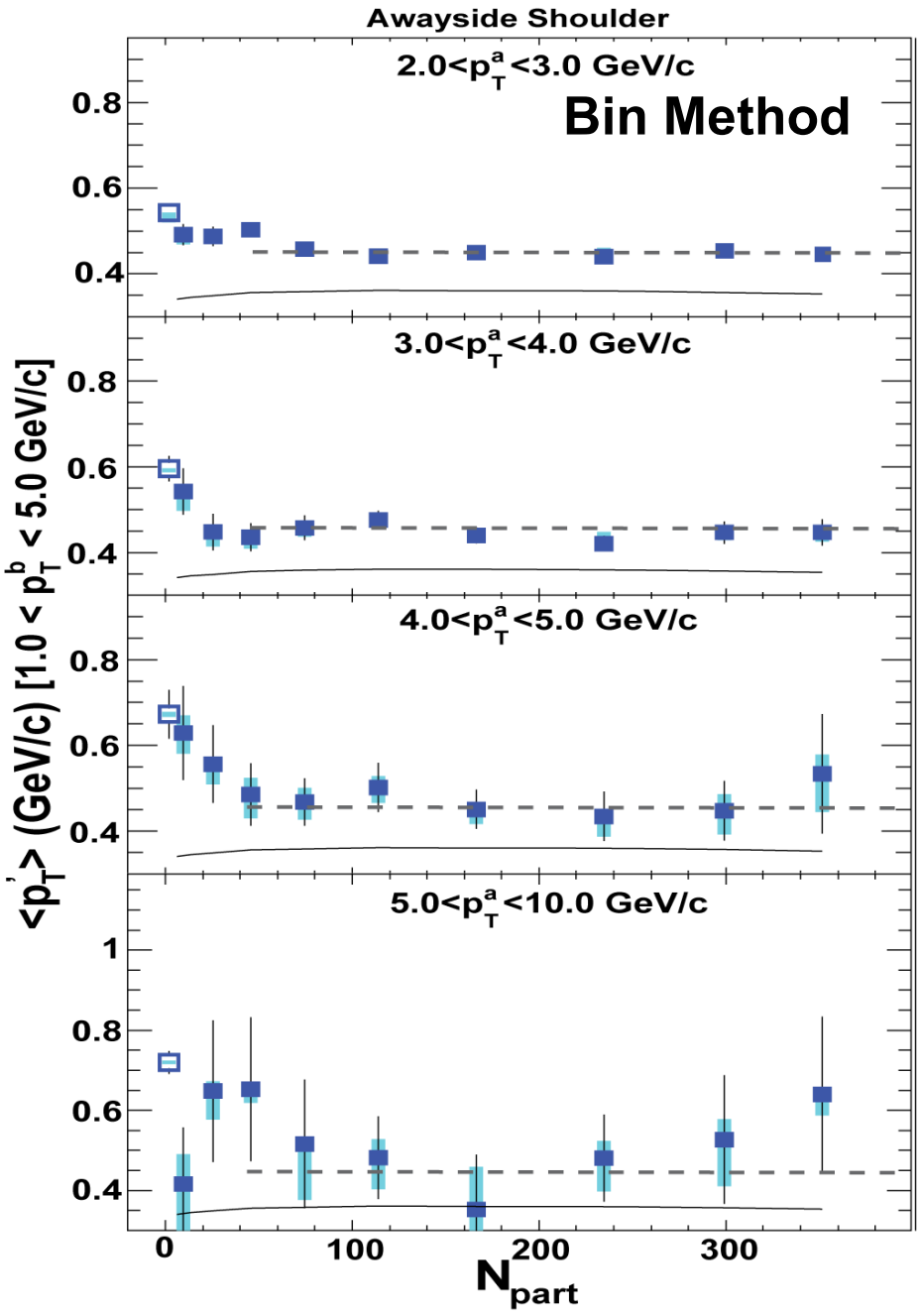
Away-side Shoulder Spectra

p-p baseline:

- Spectral shape depends on trigger p_T selection (0.55 → 0.73 GeV/c)

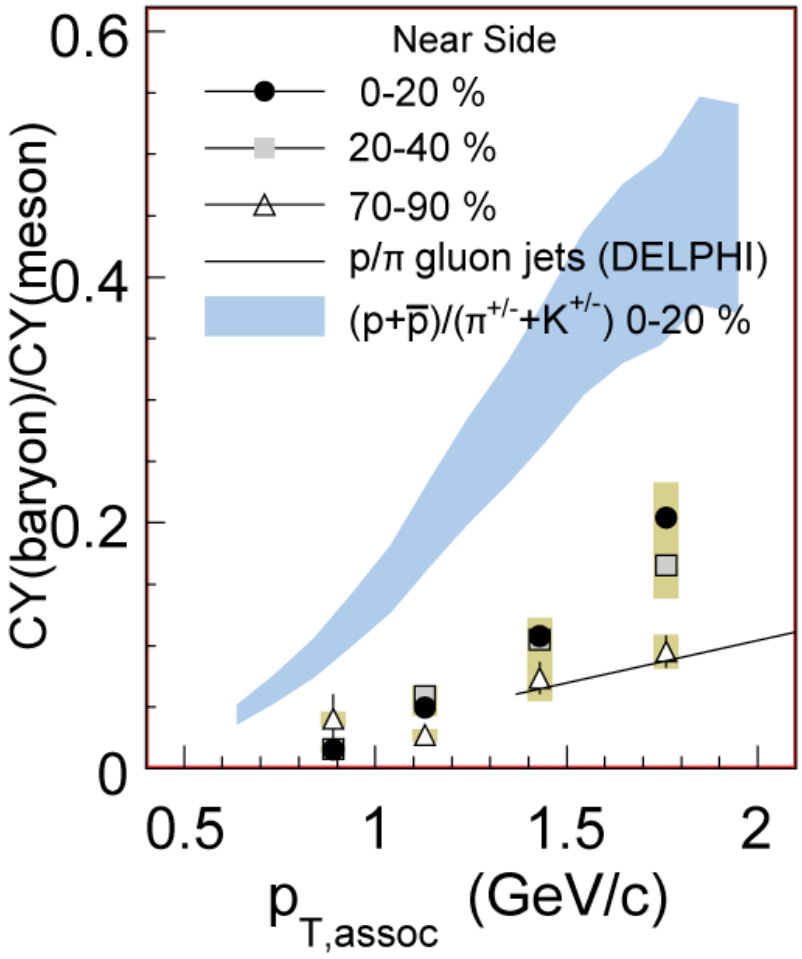
Mid-Central → Central Au-Au:

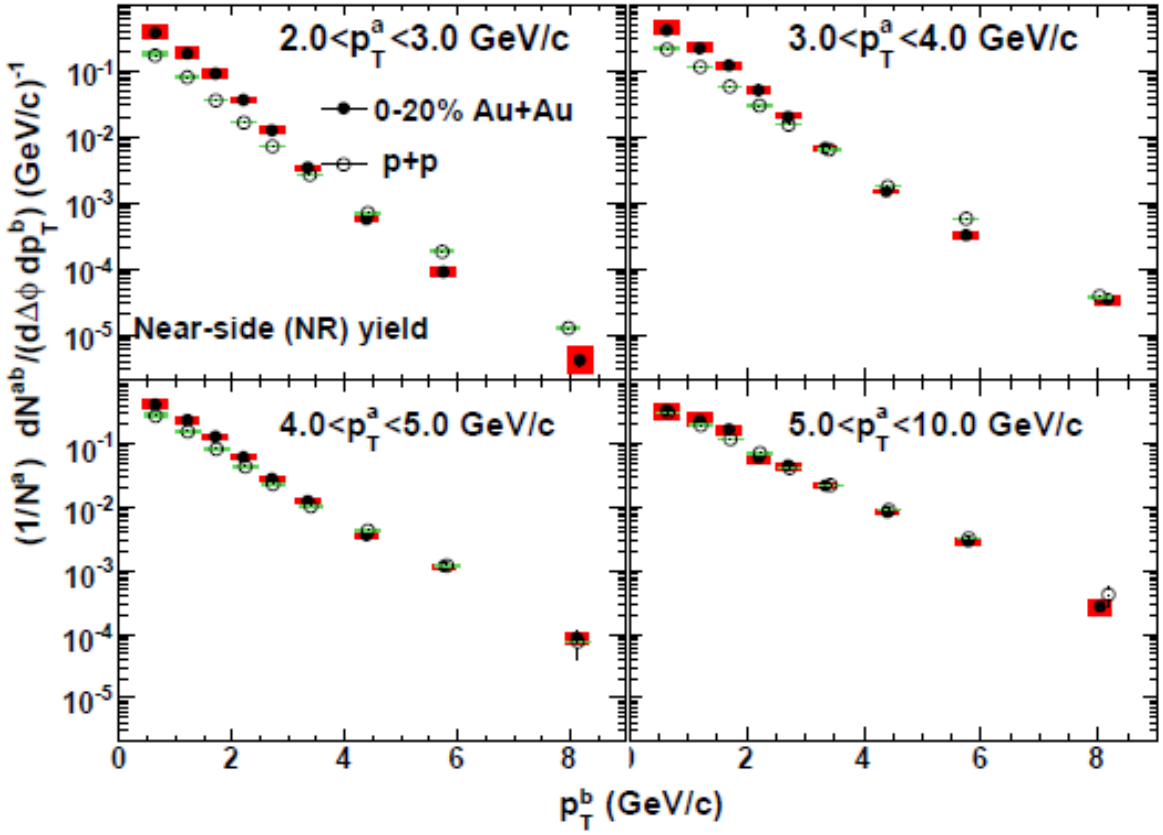
- Medium response dominates the shoulder bin (>50 N_{part})
- Softer than p-p away-side
- Little dependence on trigger p_T selection (~0.45 GeV/c)



Near-side Spectra & Composition

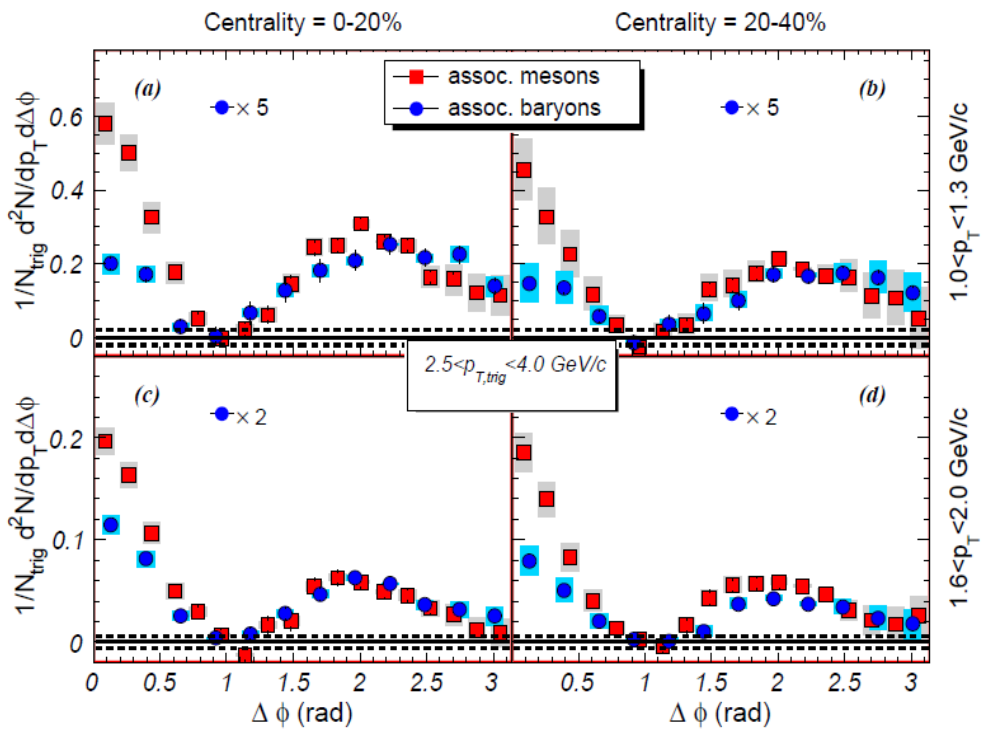
- **Near-side Baryon/Meson ratio increases in central collisions**





- **Near-side spectra are softer than p-p baseline at intermediate p_T**

Away-Side Composition

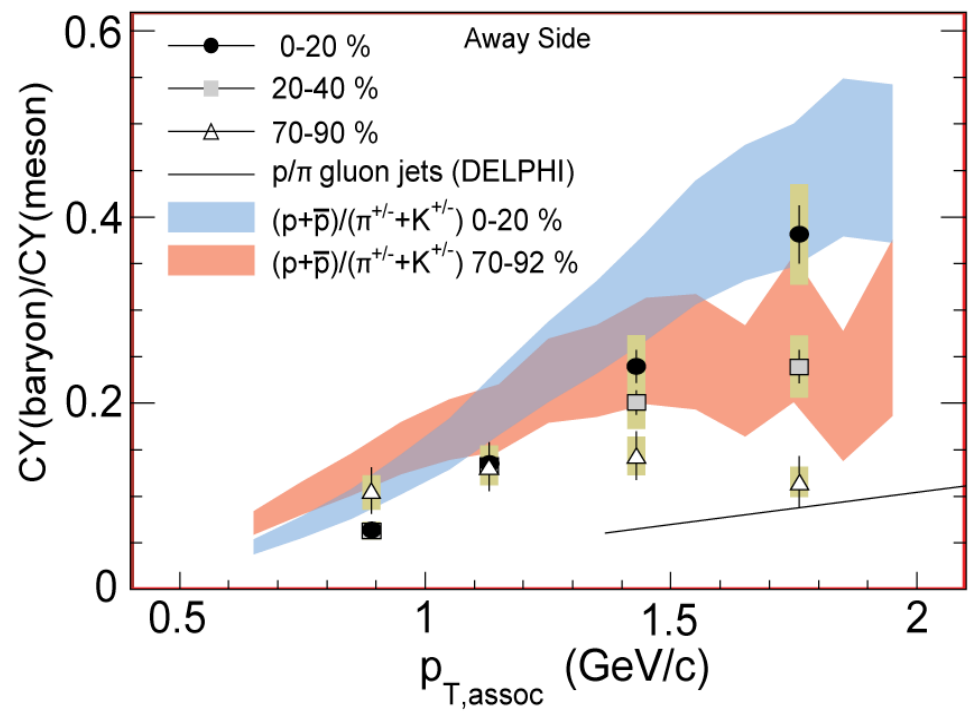


Ratios:

- **Away-side baryon/meson ratios approach inclusive values**
- **Incompatible with in-vacuum fragmentation**

Shapes:

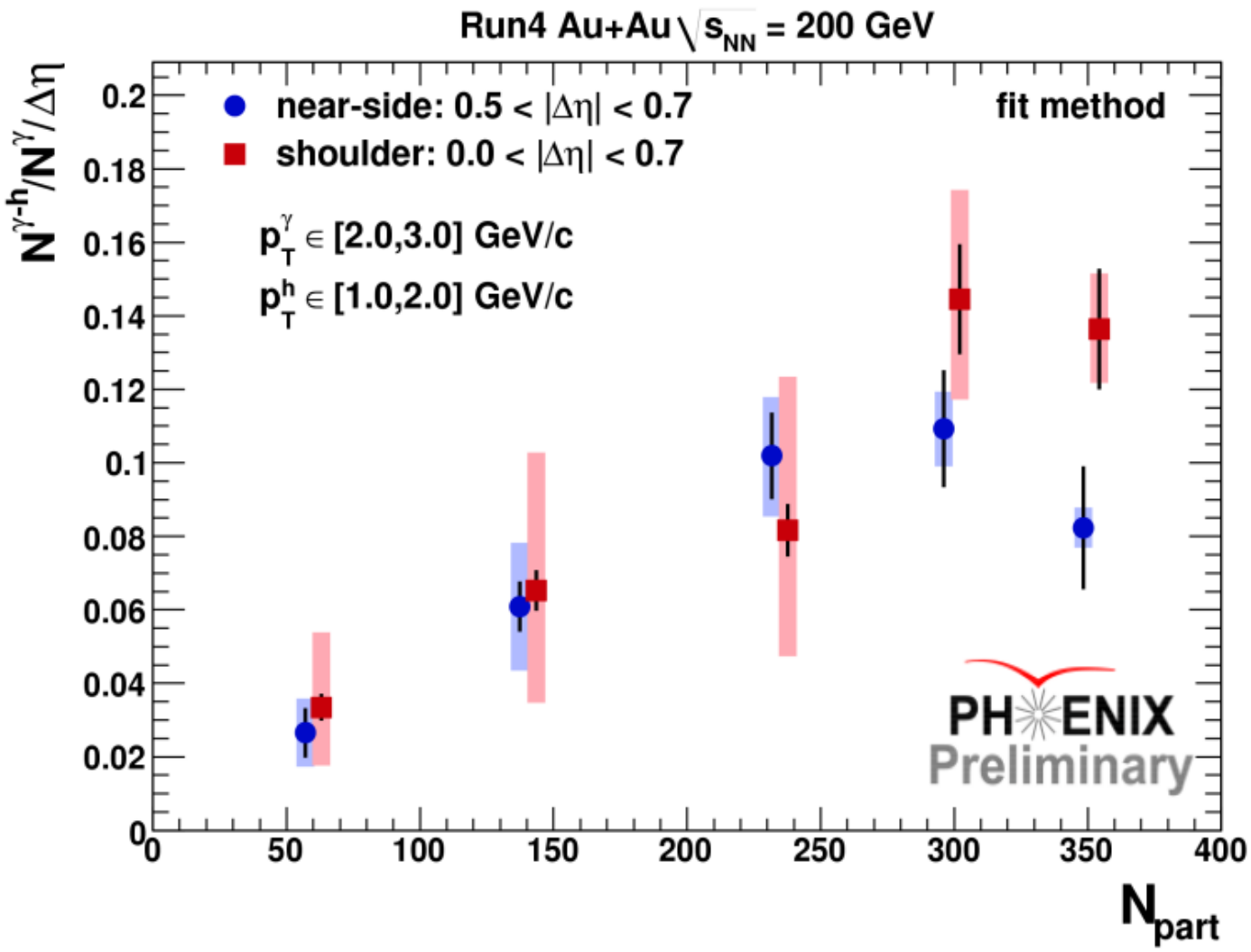
- **Similar shape in away-side mesons and baryons**



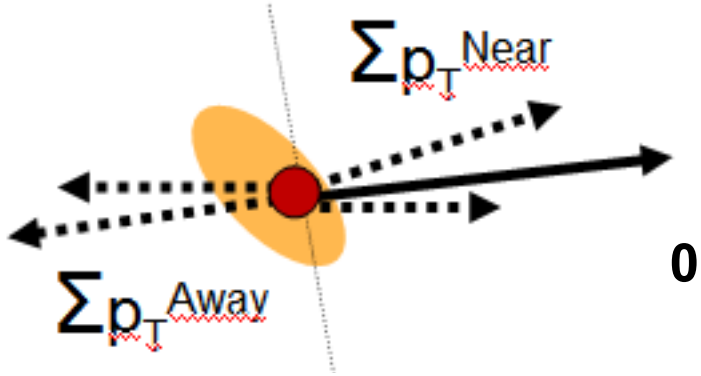
Ridge & Shoulder - Centrality

- Away-side shoulder and near-side ridge share a largely common centrality dependence

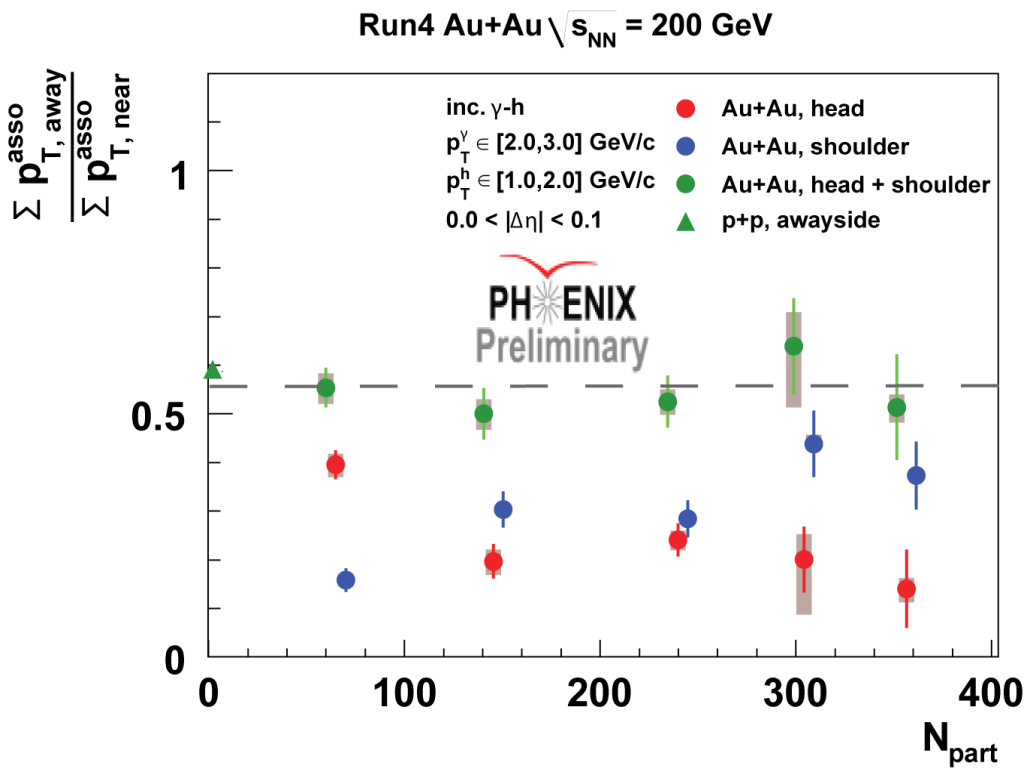
- Scale similarity here is largely a factor of p_T selection



Ridge & Shoulder - Balance

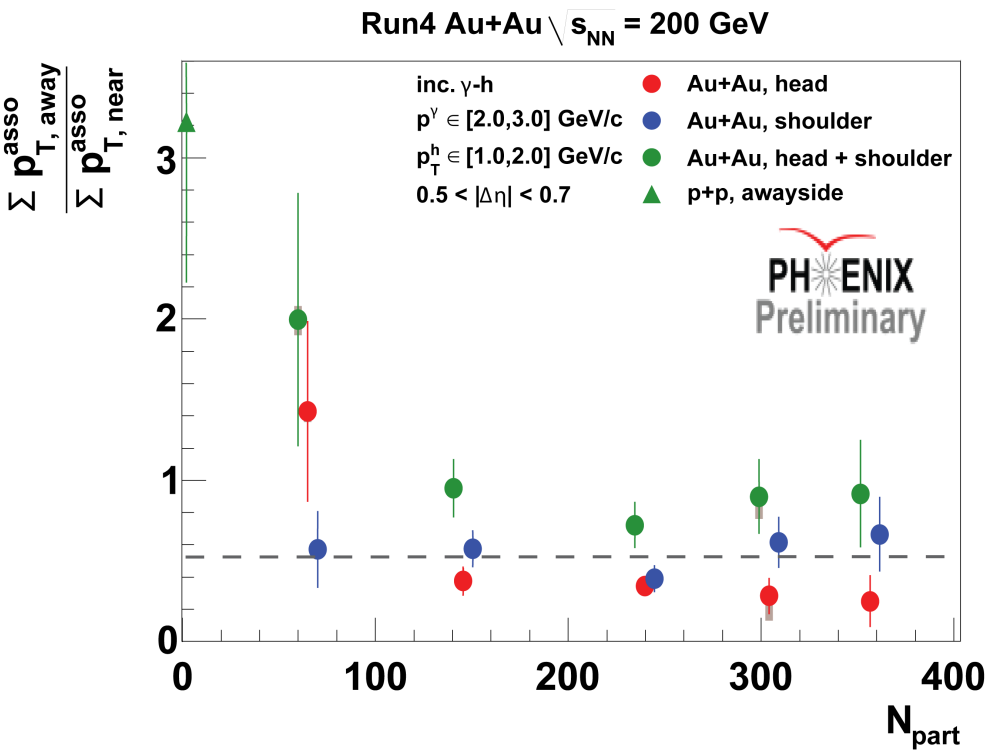


0.0 < |Δη| < 0.1



Jet + Ridge balances Shoulder + Head

0.5 < |Δη| < 0.7



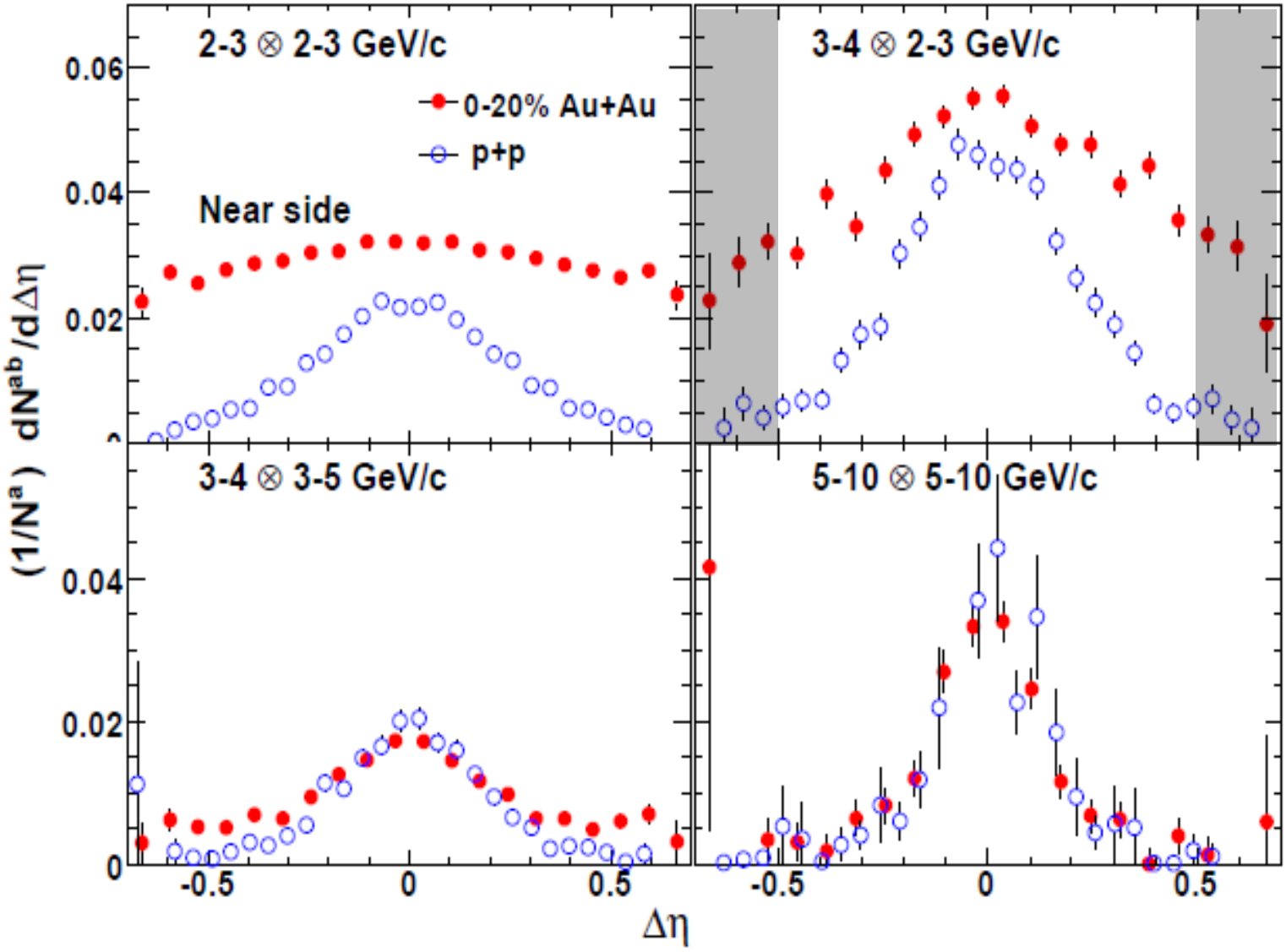
Ridge balances Shoulder!

Near-side Ridge

- Broad Δη near-side enhancement measured in Au+Au collisions at intermediate p_T

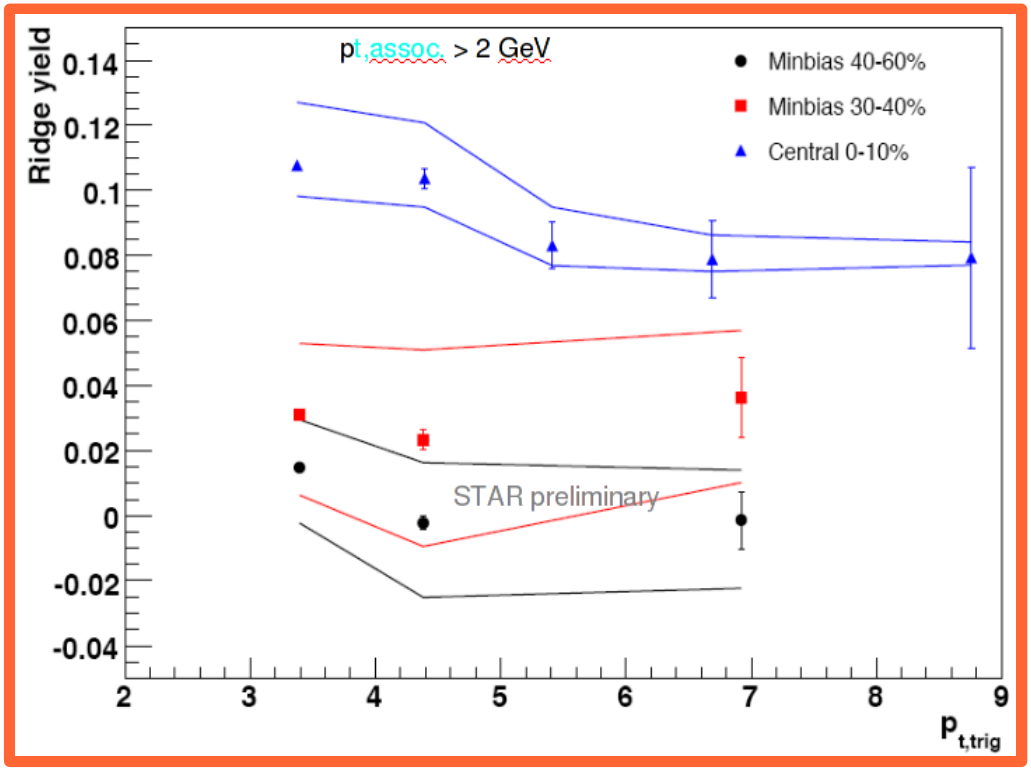
- High p_T near-sides are similar

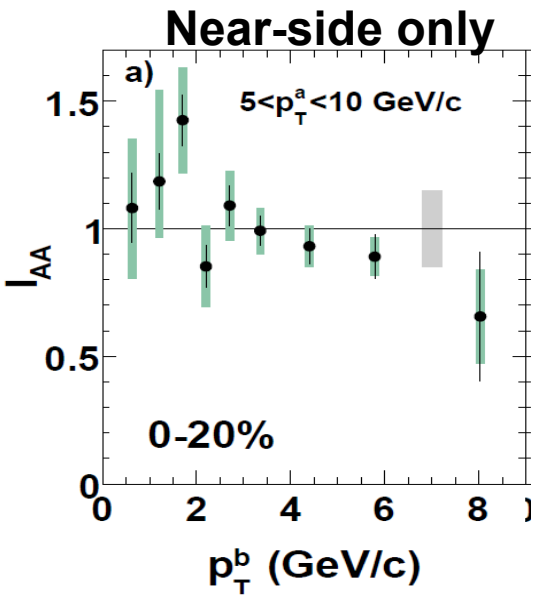
- Intermediate p_T p+p near-side is narrower in Δη than central collisions

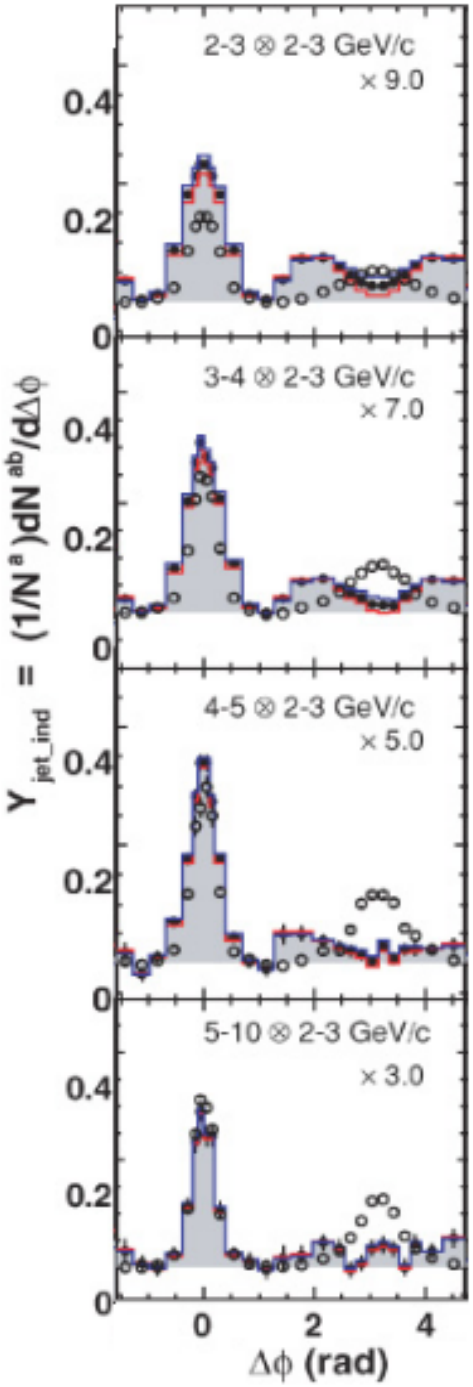


- At intermediate p_T, little p-p jet beyond Δη > 0.5

The Ridge with High p_T Triggers







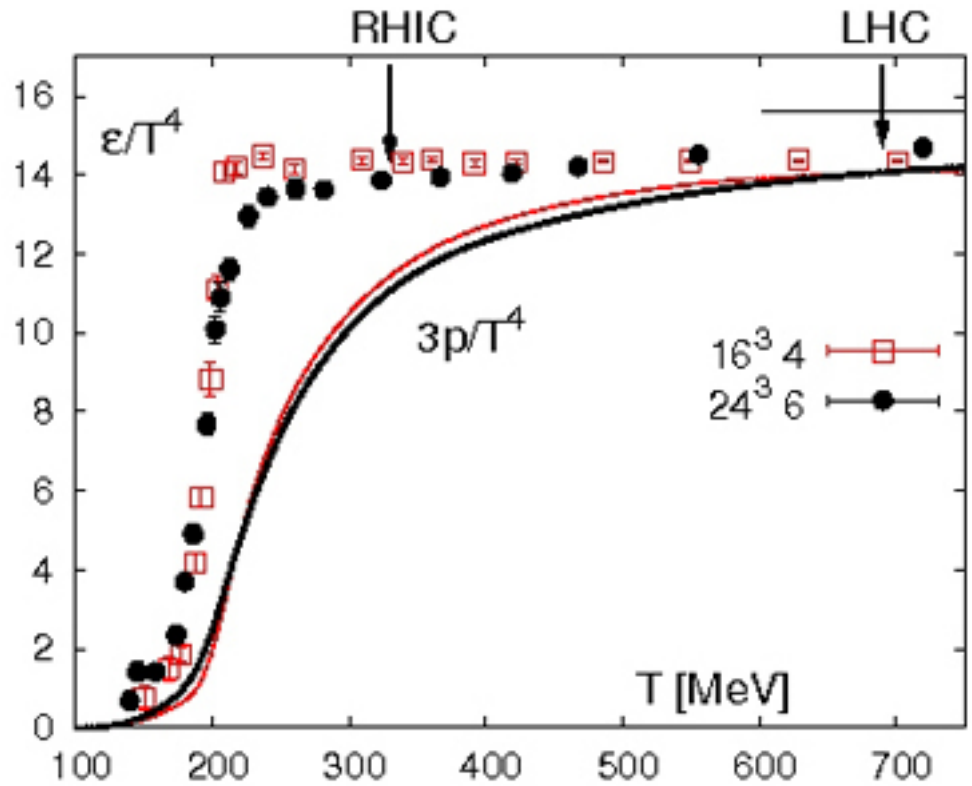
STAR measures relatively flat Ridge yield out to highest pT

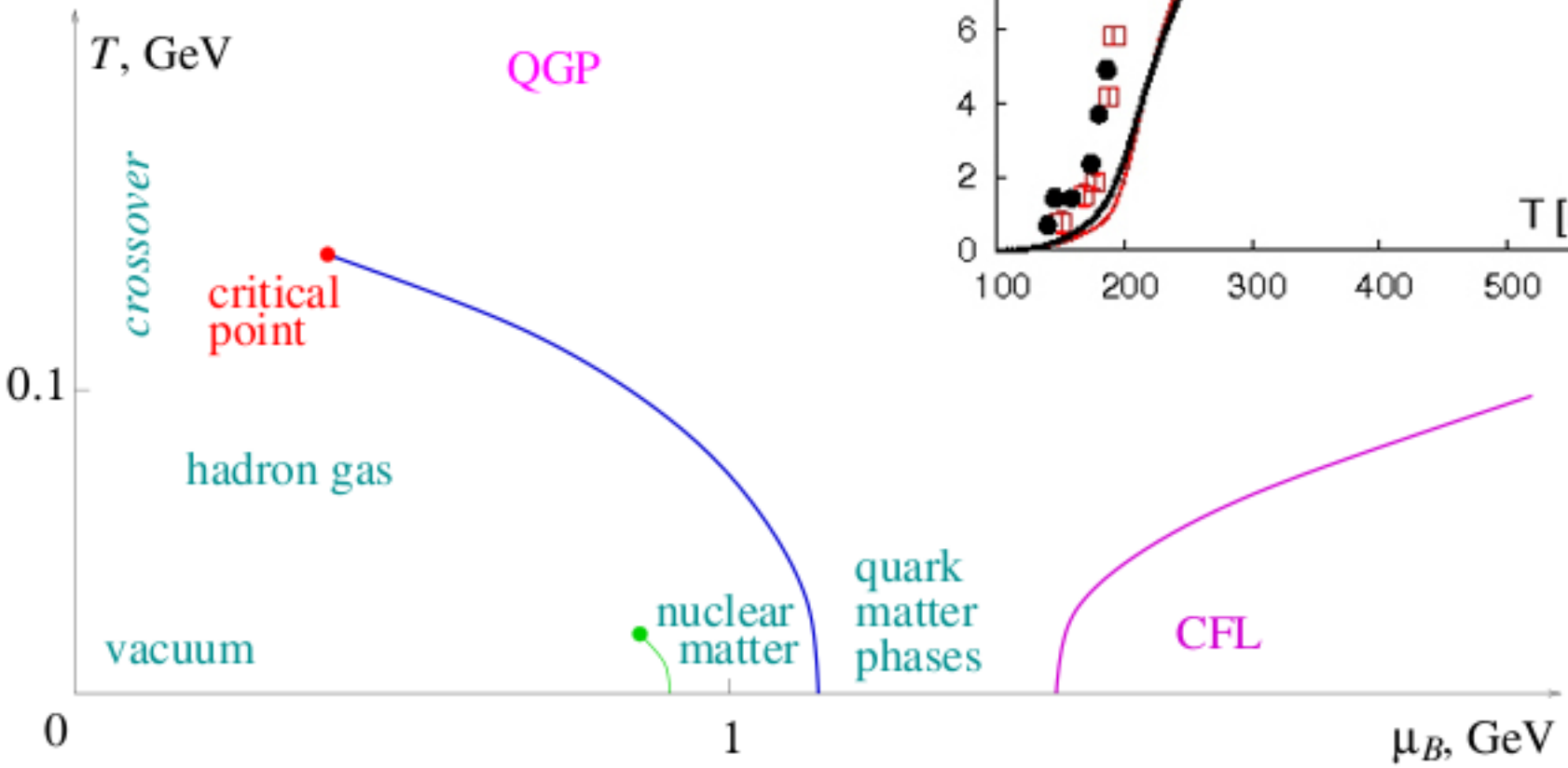
PHENIX sees consistency with p+p yield at highest pT

The QGP Phase Transition

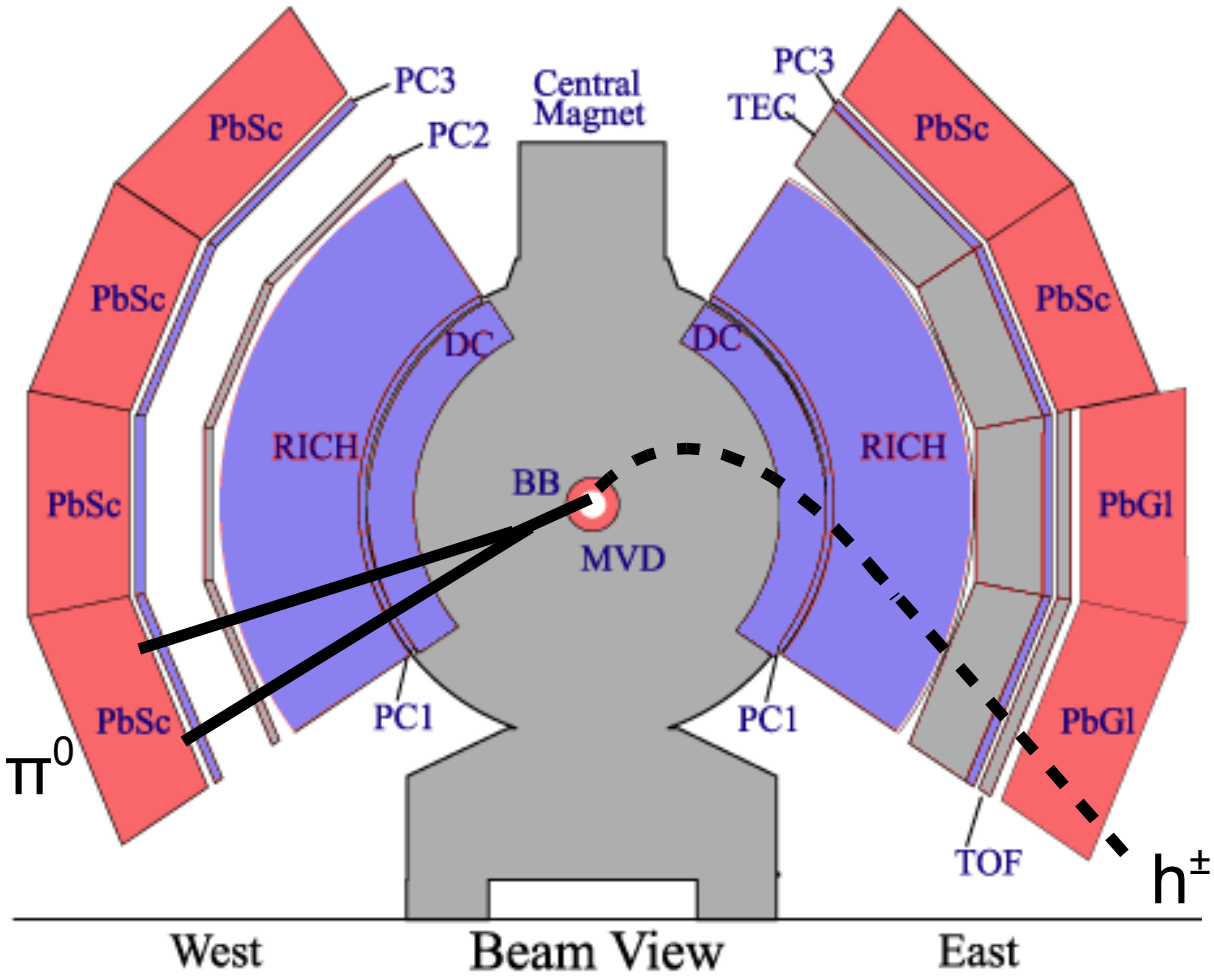
QGP phase transition occurs at large temperature

Lattice QCD results show RHIC above the phase transition





The PHENIX Central Arms



Event Classification

BBC, ZDC, RXPN

π^0 Reconstruction

EMCal - PbSc, PbGl

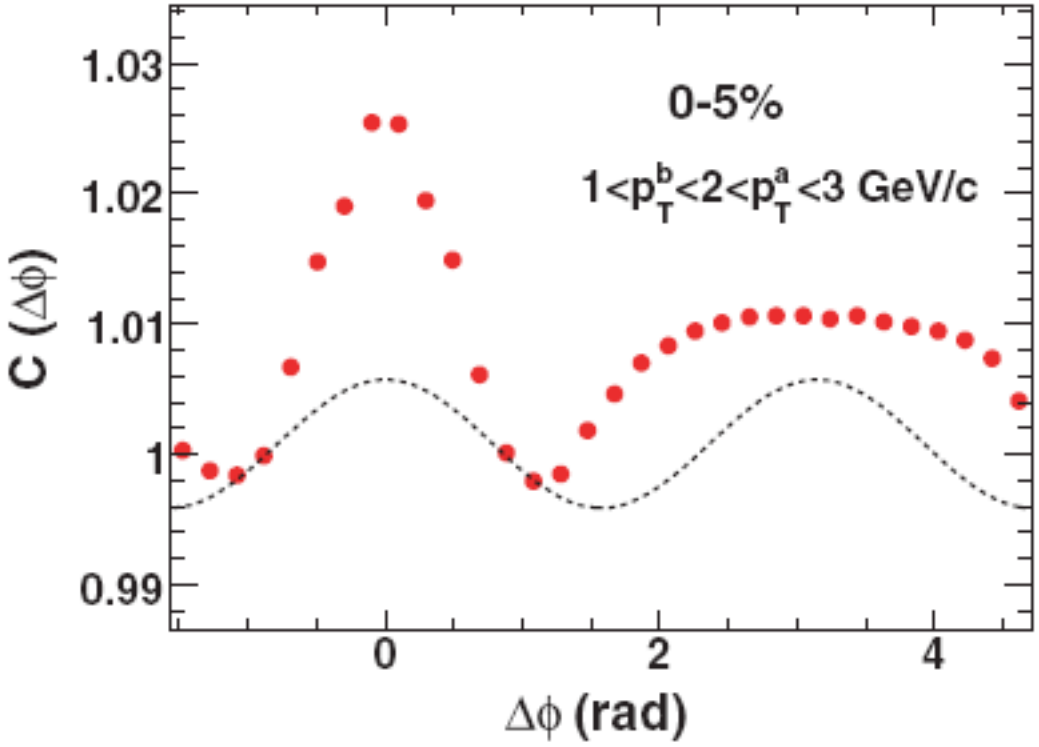
Charged Particle Track Reconstruction

DC, PC1, PC3, RICH

High p_T - EMC

Moving Beyond ZYAM

ZYAM makes non-trivial assumptions about jet behavior in heavy ion collisions



Reliance on any untested jet-shape assumption would be improper without a detailed supporting theory or other supporting evidence

Independent estimations of background level are required to test the validity of the ZYAM assumptions

Basic Jet Pair Mathematics

Two Source Model:

$$\frac{1}{n^A}\frac{dn^{AB}_{jet}}{d\Delta\varphi} = \frac{1}{n^A}\frac{dn^{AB}_{inc}}{d\Delta\varphi} - \frac{1}{n^A}\frac{dn^{AB}_{comb}}{d\Delta\varphi}$$

Pairs correlate in two ways:

direct interactions (jet)

global event properties (comb)

Correlation and
Jet Function Framework:

$$\frac{1}{n^A}\frac{dn^{AB}_{jet}}{d\Delta\varphi} = \frac{1}{\varepsilon^B \kappa}\frac{n^{AB}_{real}}{n^A \int d\Delta\varphi} J(\Delta\varphi)$$

$$C(\Delta\varphi) = \frac{\dfrac{dn^{AB}_{real}}{d\Delta\varphi}}{\dfrac{dn^{AB}_{mix}}{d\Delta\varphi}} \frac{\int \dfrac{dn^{AB}_{mix}}{d\Delta\varphi} d\Delta\varphi}{\int \dfrac{dn^{AB}_{real}}{d\Delta\varphi} d\Delta\varphi}$$

$$J(\Delta\varphi) = C(\Delta\varphi) - b_0\left(1 + 2c_2^{AB}\cos(2\Delta\varphi) + \ldots\right)$$

b_0 sets the background normalization

Absolute Normalization

There are two equivalent methodologies to set b_0

<u>Mixed Event Method:</u>

Count average pair multiplicity in mixed events

Correct for centrality binning

$$n_{comb}^{AB} = n_{mix}^{AB}\xi \qquad b_0 = \frac{n_{mix}^{AB}\xi}{n_{real}^{AB}}$$

<u>Mean-Seeds Mean-Partners Method:</u>

Count singles

Count pair-cut loss in mixed event

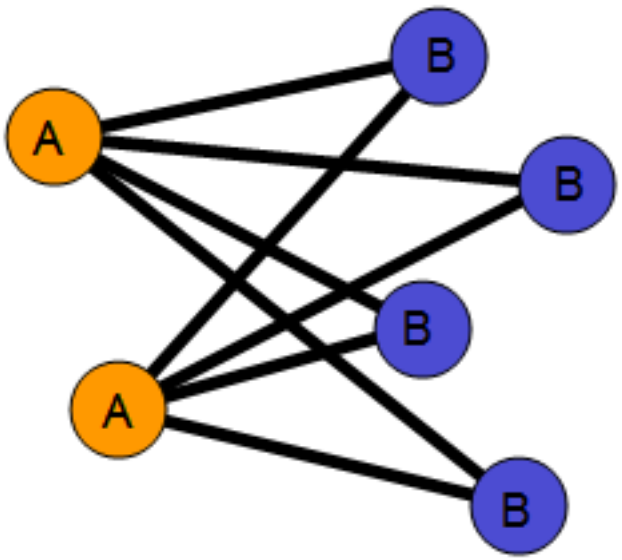
Calculate average pair multiplicity in mixed events

Correct for centrality binning

$$n_{comb}^{AB} = n^{A}n^{B}\kappa\xi \qquad b_0 = \frac{n^{A}n^{B}\kappa\xi}{n_{real}^{AB}}$$

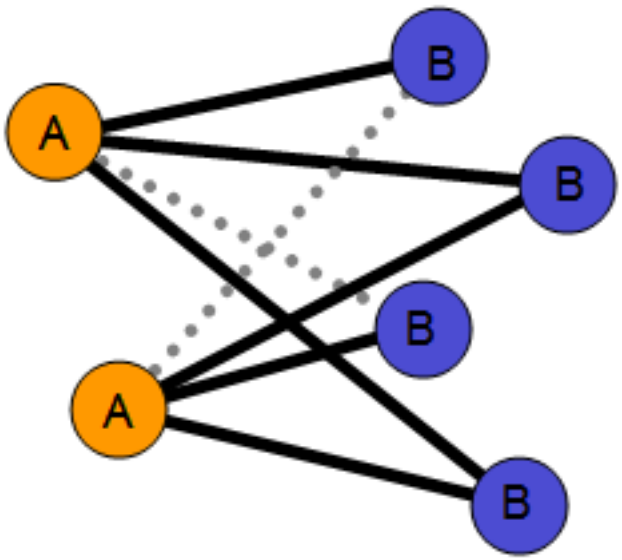
Pair-cut Correction

Calculation without pair cut correction



$$n_{mix}^{AB} \neq n^A n^B$$

Calculation with pair cut correction

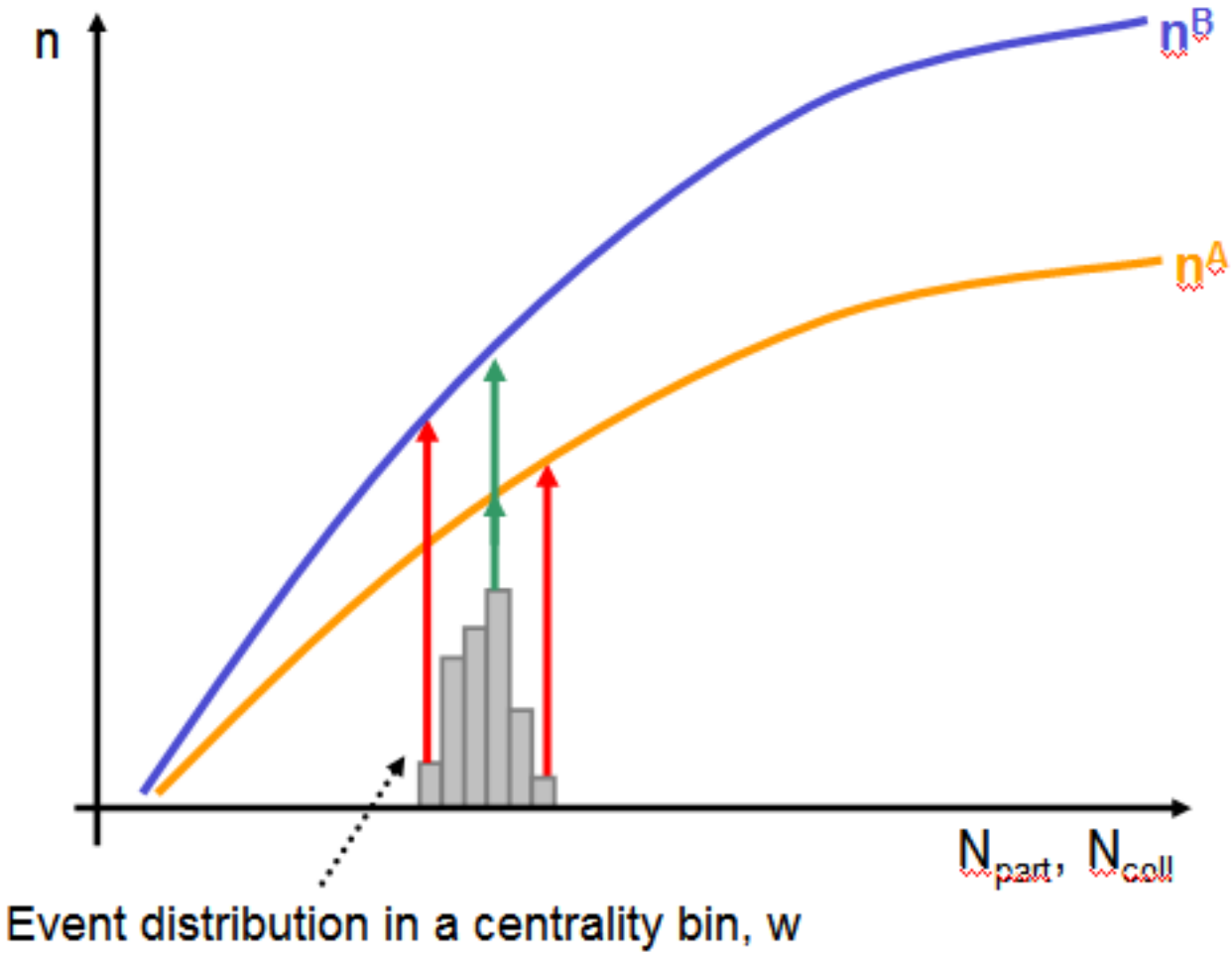


$$n_{mix}^{AB} = n^A n^B \kappa$$

κ, the survival probability, is typically ~99.3% and can be estimated in mixed events

Centrality-Multiplicity Correction, ξ

Calculating (or mixing) for backgrounds in a centrality bin requires a correction for the multiplicity dependence across the bin



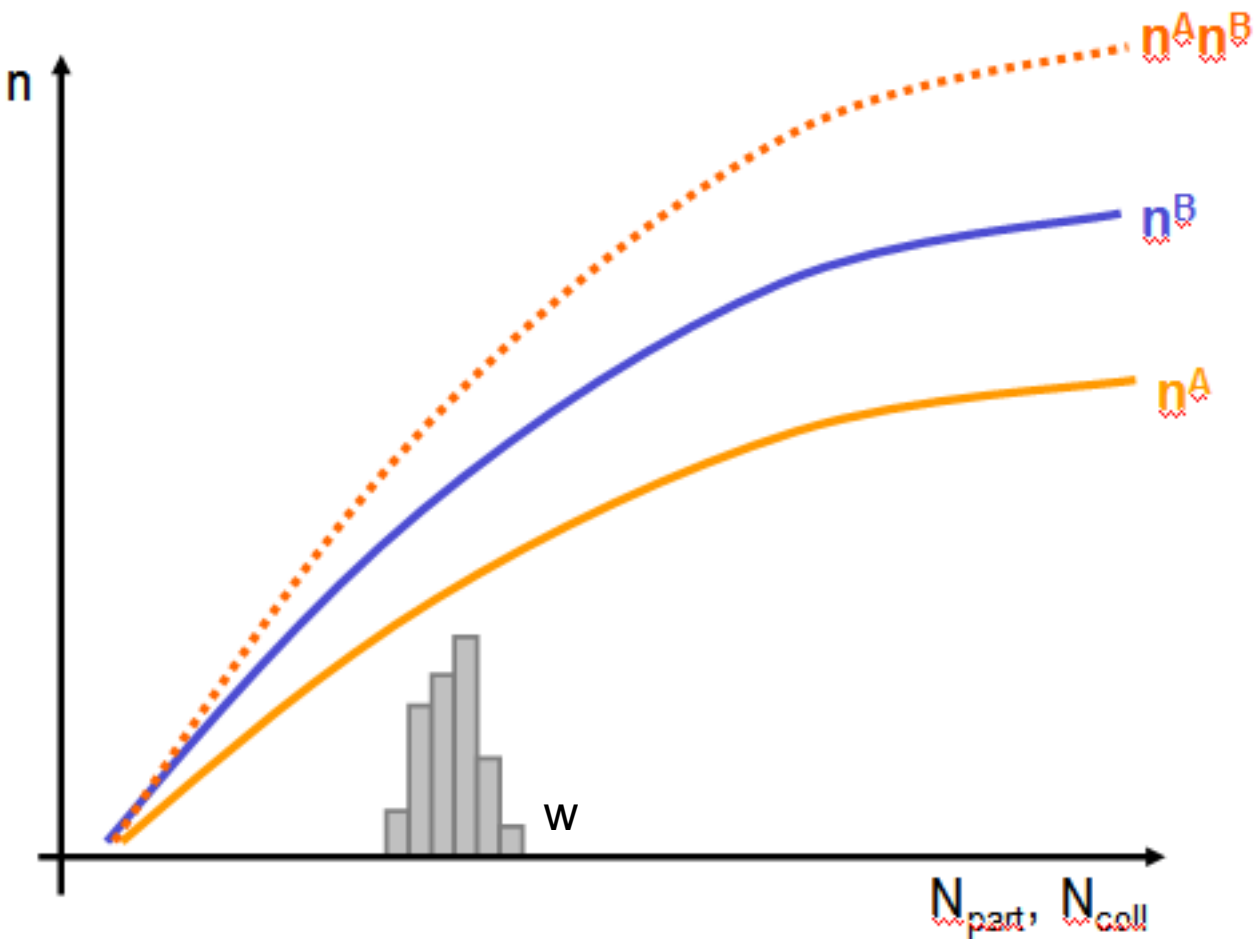
Foreground Events:

Sample particle multiplicities from the same event

Mixed Events:

Sample particles from different multiplicities

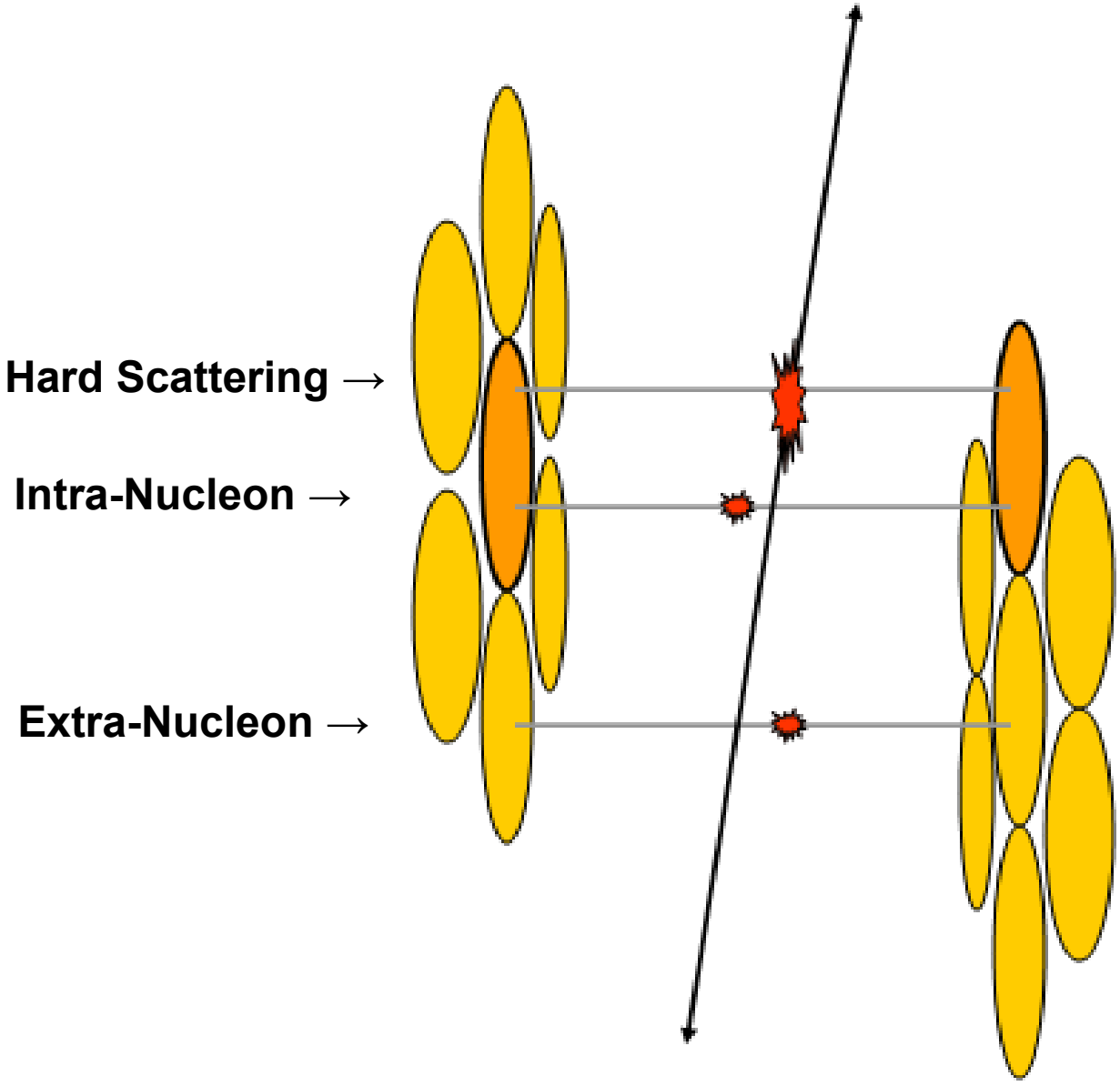
ξ Correction



$$\xi \equiv \frac{\langle n^A \cdot n^B \rangle}{\langle n^A \rangle \langle n^B \rangle} = \frac{\sum n^A n^B w}{\sum n^A w \sum n^B w} \sum w$$

Cent(%)	ξ
0-5	1.0011(4)
5-10	1.0025(6)
10-15	1.0044(9)
15-20	1.007(1)
20-25	1.010(3)
25-30	1.014(4)
30-35	1.019(7)
35-40	1.025(9)
40-45	1.03(1)
45-50	1.05(1)
50-55	1.06(3)
55-60	1.10(6)
60-65	1.15(9)
65-70	1.3(2)
70-75	1.4(3)
75-80	1.5(4)
80+	1.6(5)

Intra- and Extra-Nucleon Background



Two Sources of Background:

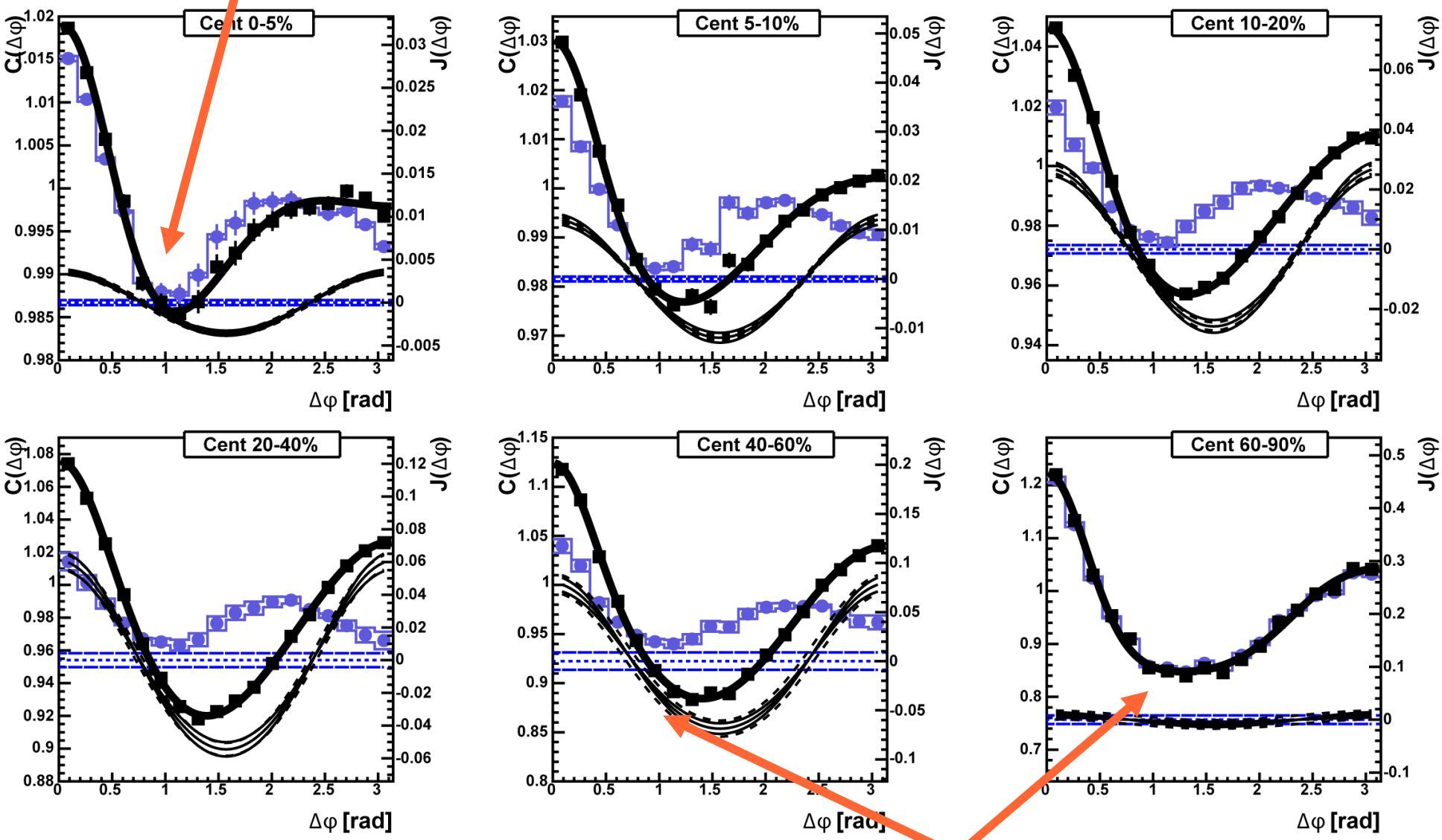
- **Scatterings within the hard-scattering's nucleons or from other nucleon-nucleon collisions**

ξ estimations correct for only the extra-nucleon component

Resulting subtractions in peripheral collisions should look like un-subtracted p-p

Absolute Normalization Results

Confirmation of ZYAM procedure in most central



Black points - Inclusive
Curve - Flow
Blue points - Jet = Inclusive - Flow

Peripheral shows pedestal yield

Away-Side Contributions

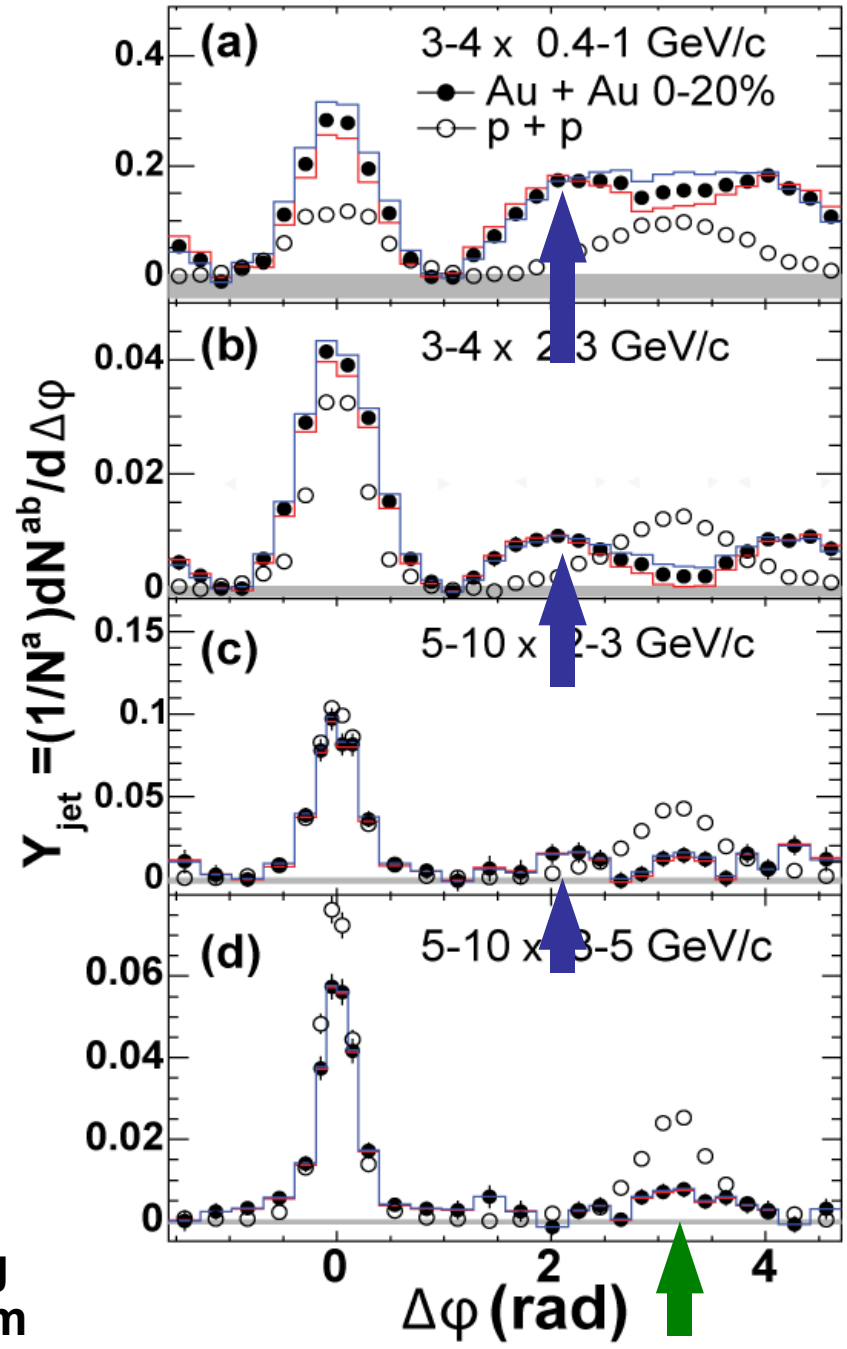
Away-side Head:

- **Suppressed relative to p-p baseline**
- **Dominated by shoulder at low pT**

Away-side Shoulder:

- **Strongest at lower p_T (< 4 GeV/c)**
- **Δφ position largely independent of p_T (~ π ± 1.1)(~120º)**

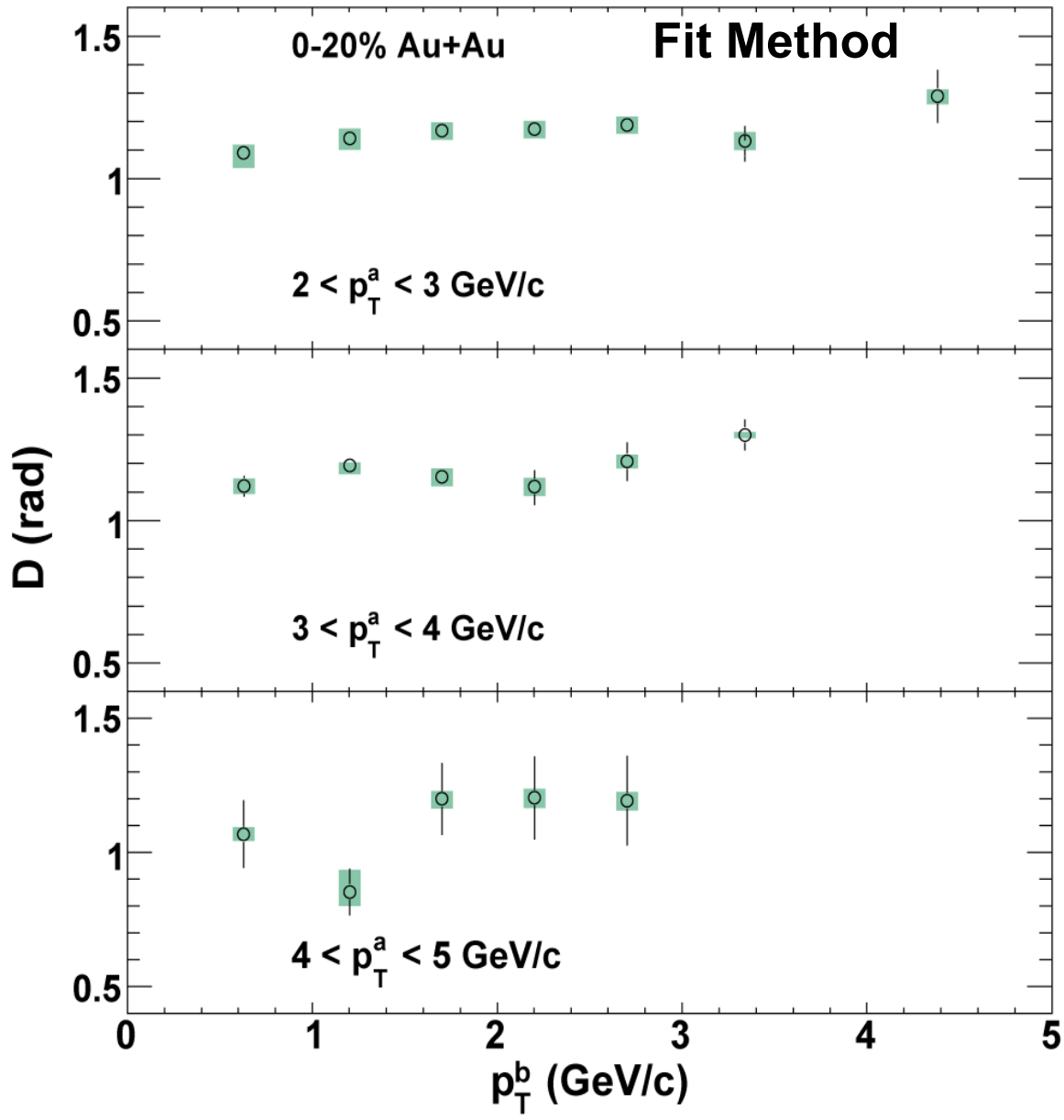
increasing momentum



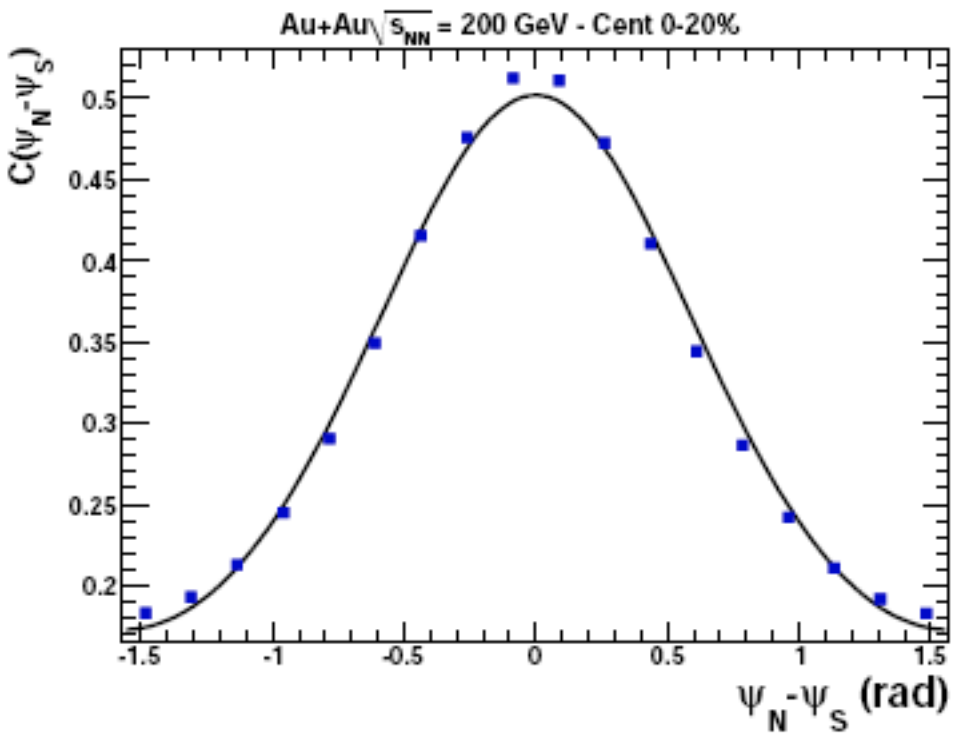
Away-side Shoulder Position

- Head region fitted separately

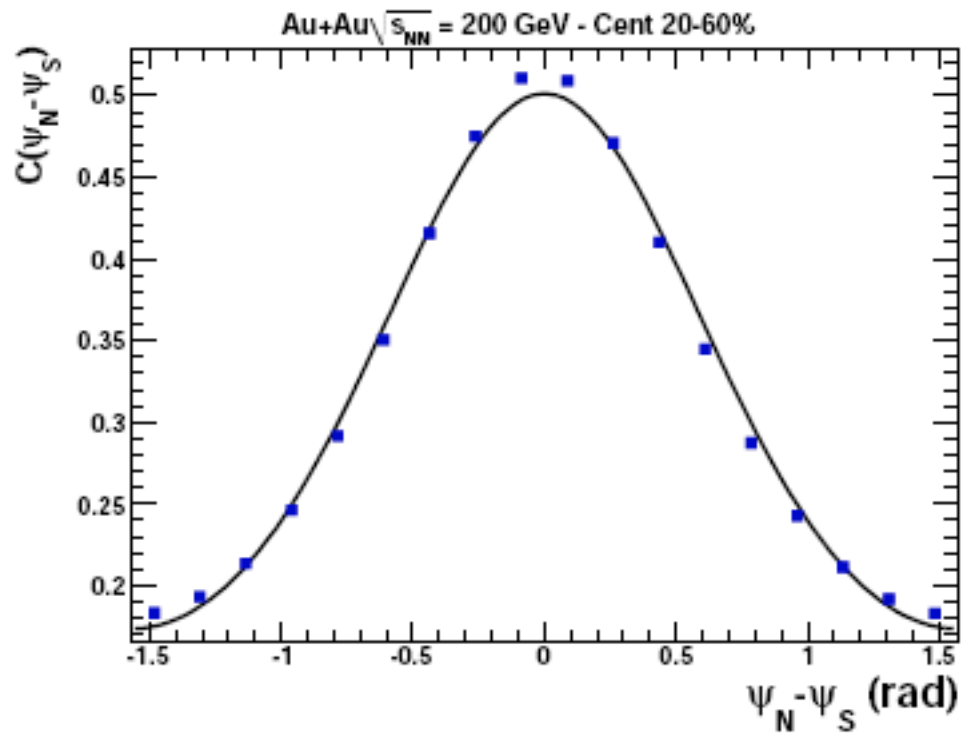
- Position largely independent of both trigger and partner p_T selection (< 5 GeV/c)



Reaction-Plane Resolution



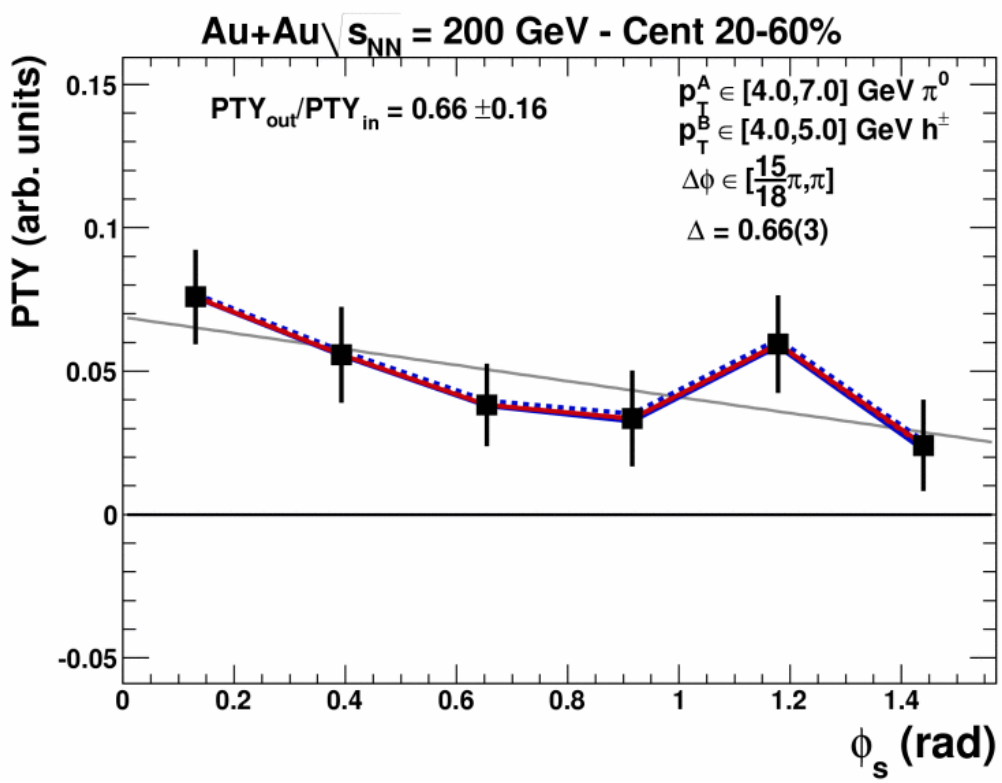
Δ = 0.66(4)

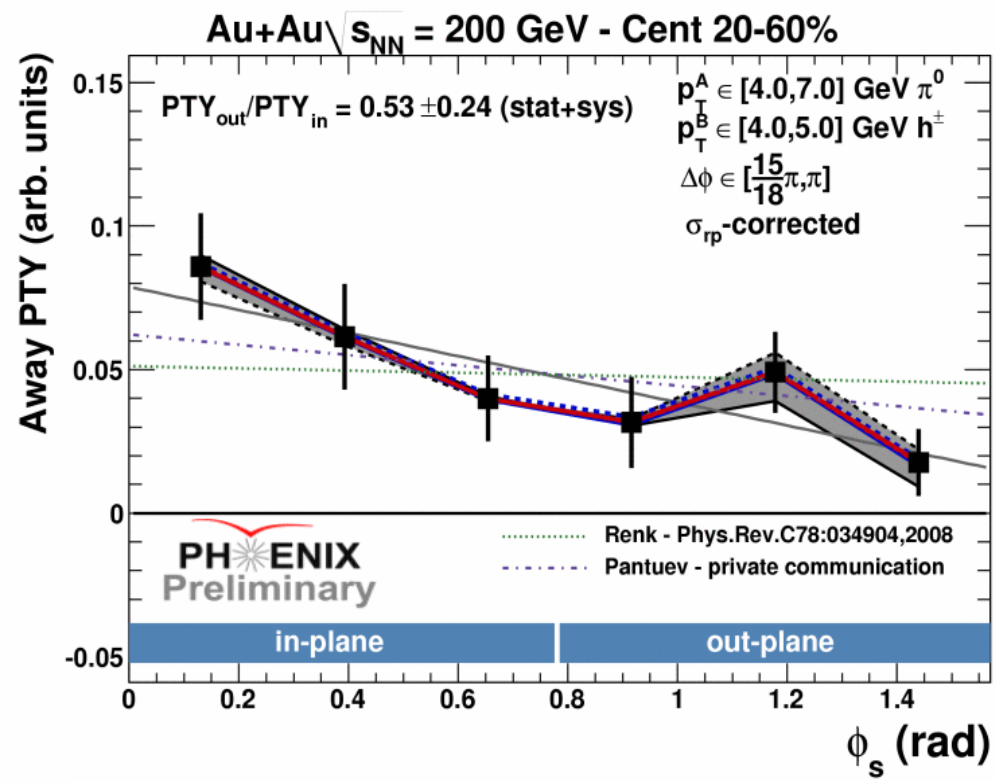


Δ = 0.66(3)

Additional 10% systematic on 0-5% and 5% elsewhere to cover asymmetry in resolution N-S

Resolution Unsmearing





Resolution Unsmearing

$$\frac{Y^{AB}_{corr}(\phi_s)}{Y^{AB}_{raw}(\phi_s)} = \frac{1 + 2A/\Delta cos(\phi_s)}{1 + 2Acos(\phi_s)}$$

Method used in PPG054

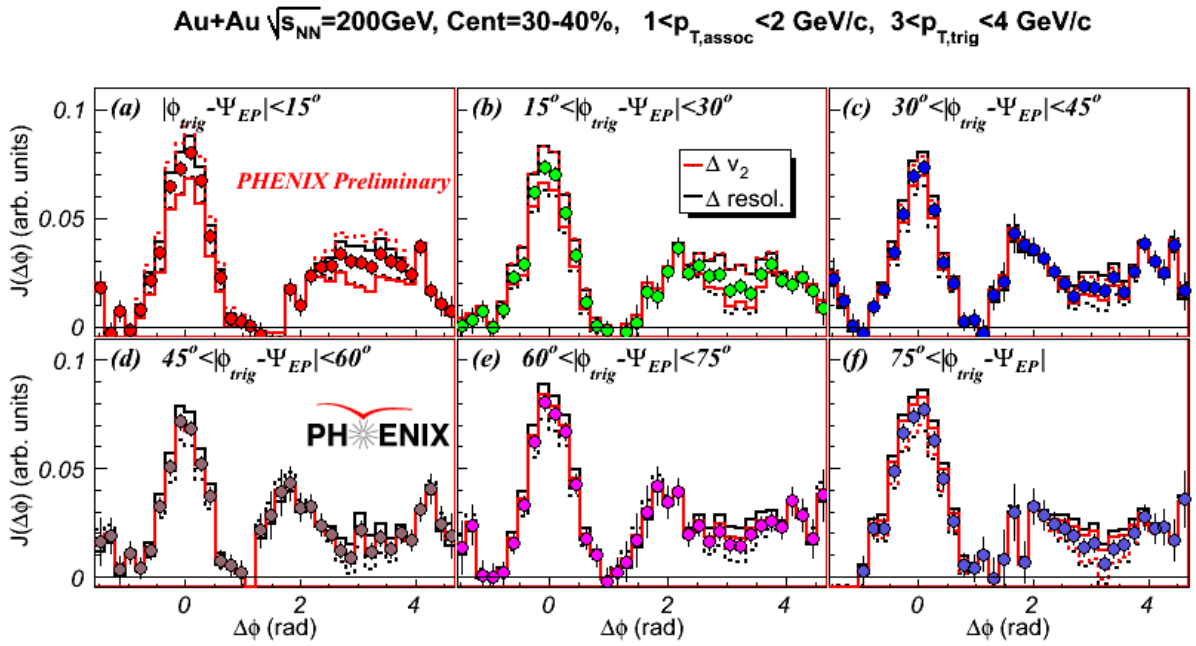
- Same symmetry argument as flow limits functional forms to even-terms
- Assumption that truncating after second-order is reasonable
- New systematic error from fit errors treated as correlated with statistical error in extracted values (somewhat conservative, but reasonable)
- Overall effects of unsmearing are small for this result

Relation to Other PHENIX Analyses

These are PHENIX's highest pT reaction-plane Jet Correlations

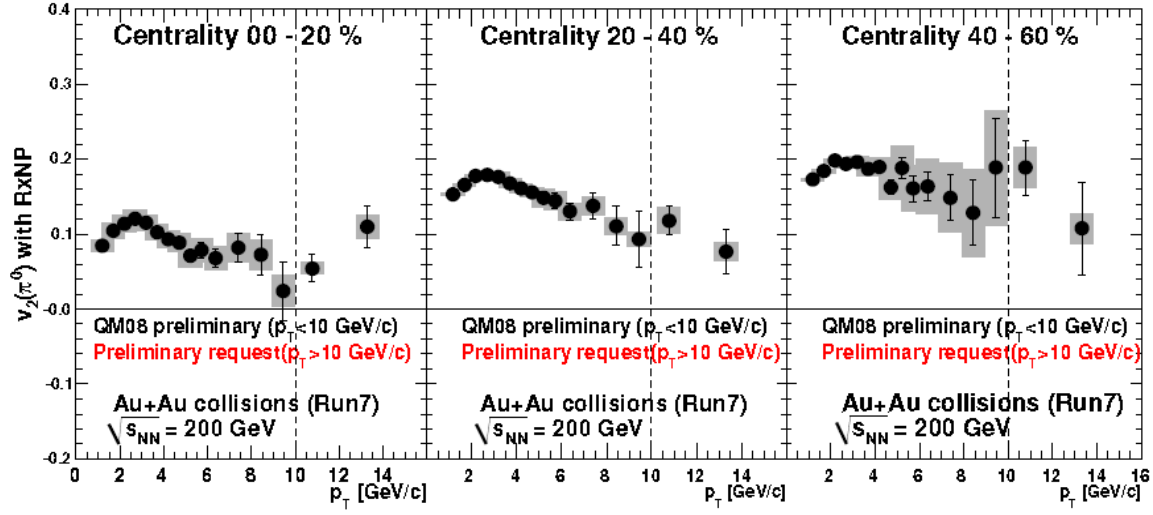
Intermediate pT RP results

h-h, W. Holzmann, QM08



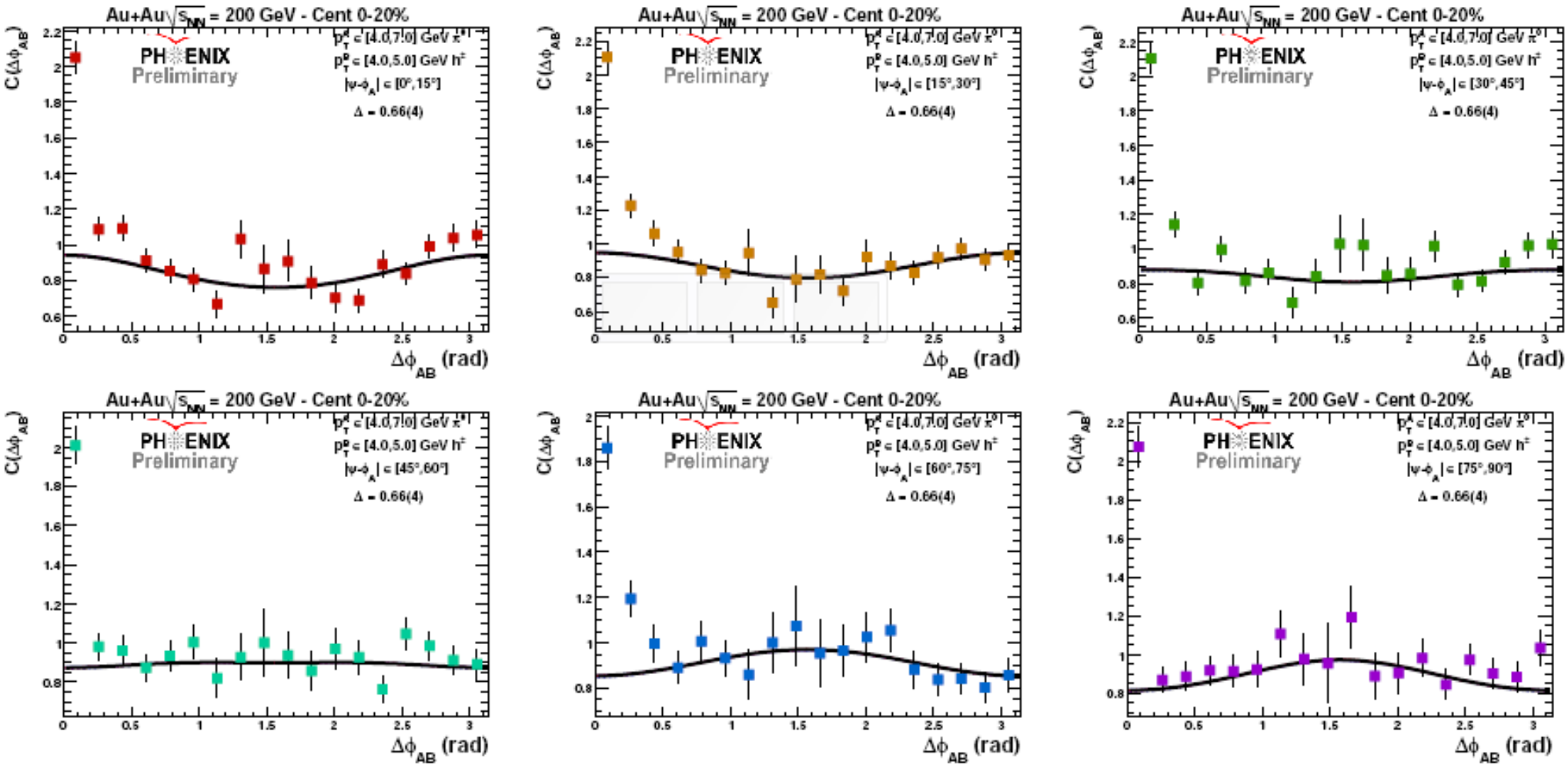
High pT single particle results

pi0, Y. Aramaki, Plenary Nov08



Pi0-h CFs x RXPN – Cent 0-20%

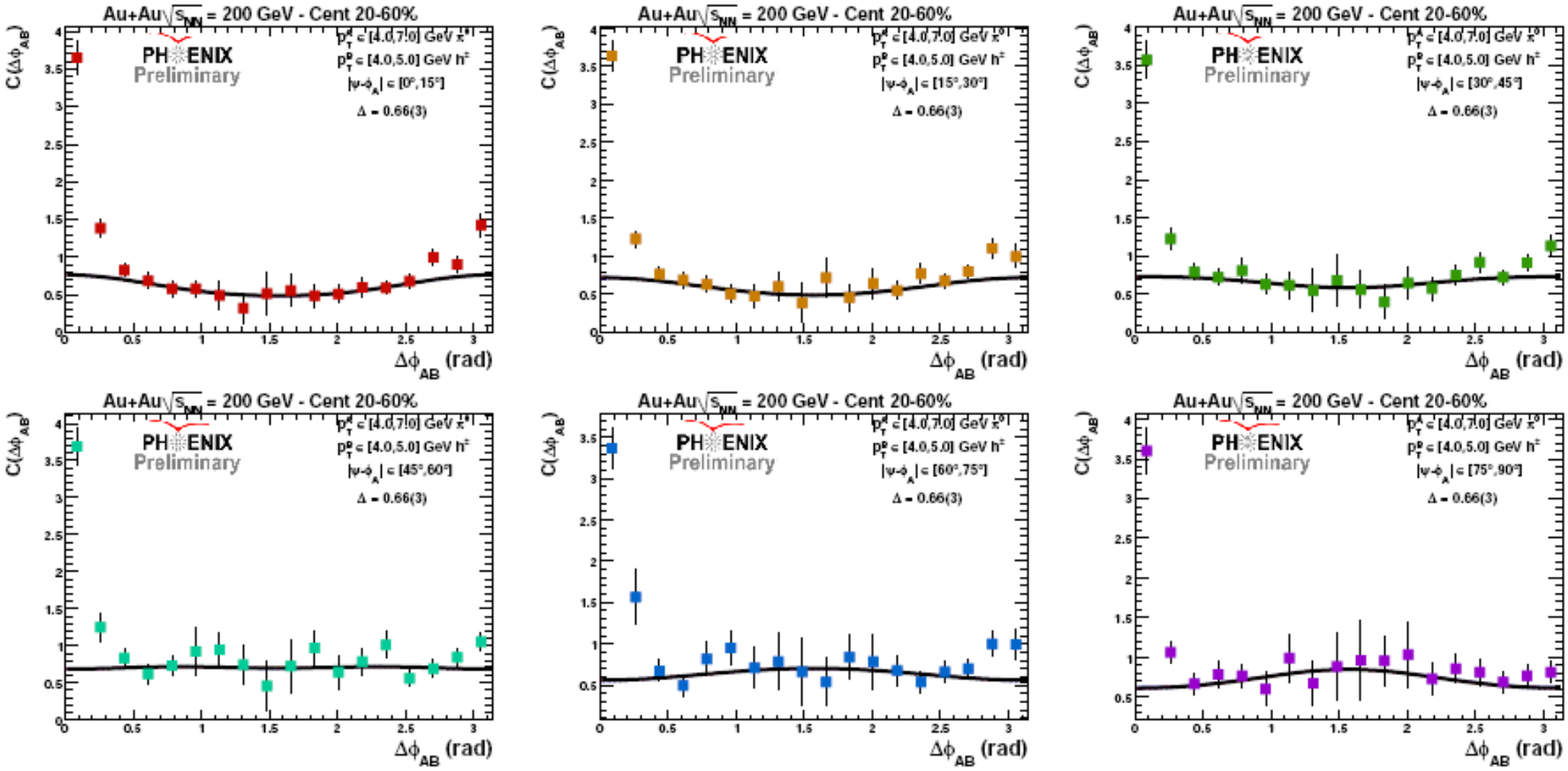
most in-plane



most out-plane

Pi0-h CFs x RXPN – Cent 20-60%

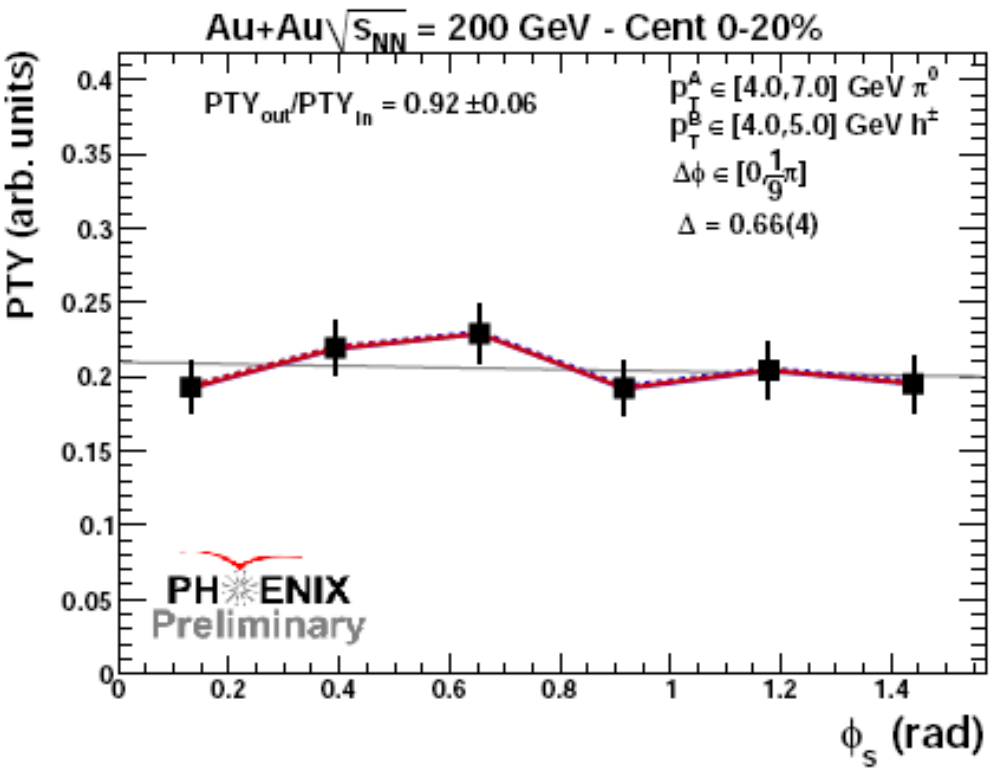
most in-plane



most out-plane

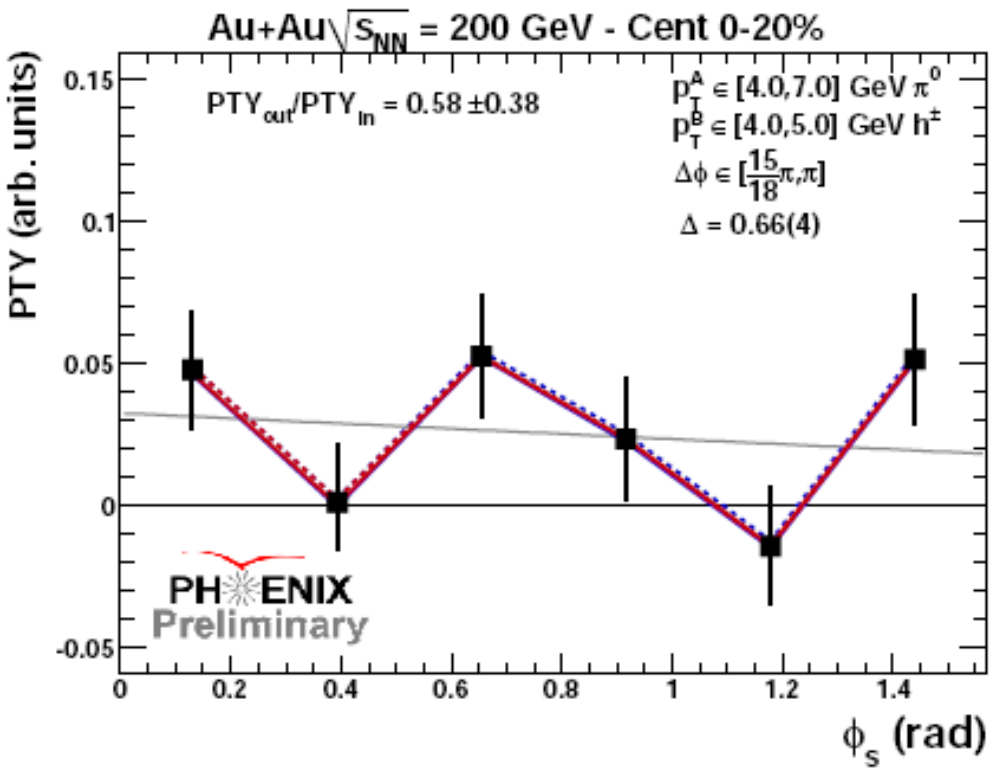
Near- & Away-Side Integrated Yields – 0-20%

Near-side



in-plane out-plane

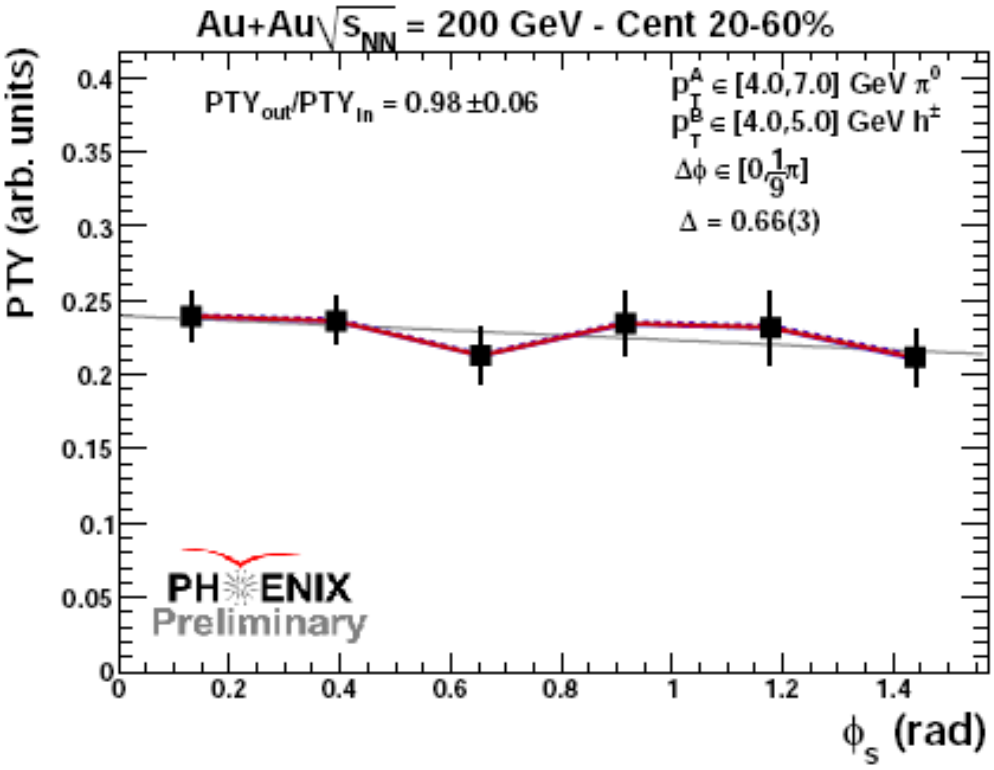
Away-side



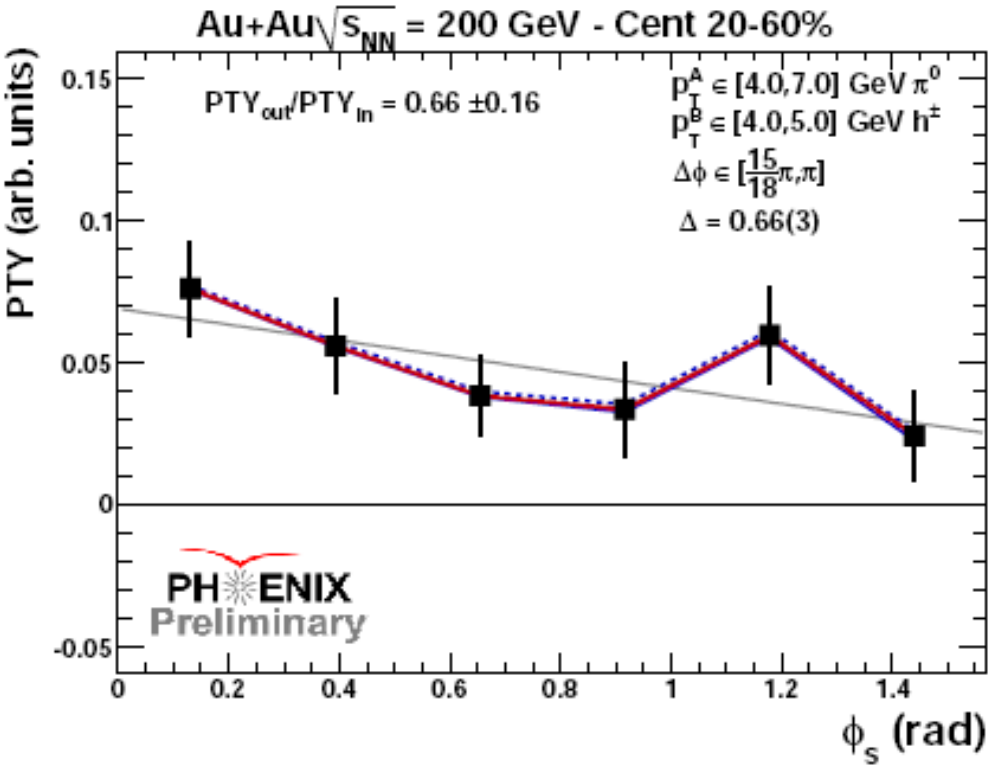
in-plane out-plane

Near- & Away-Side Integrated Yields – 20-60%

Near-side



Away-side



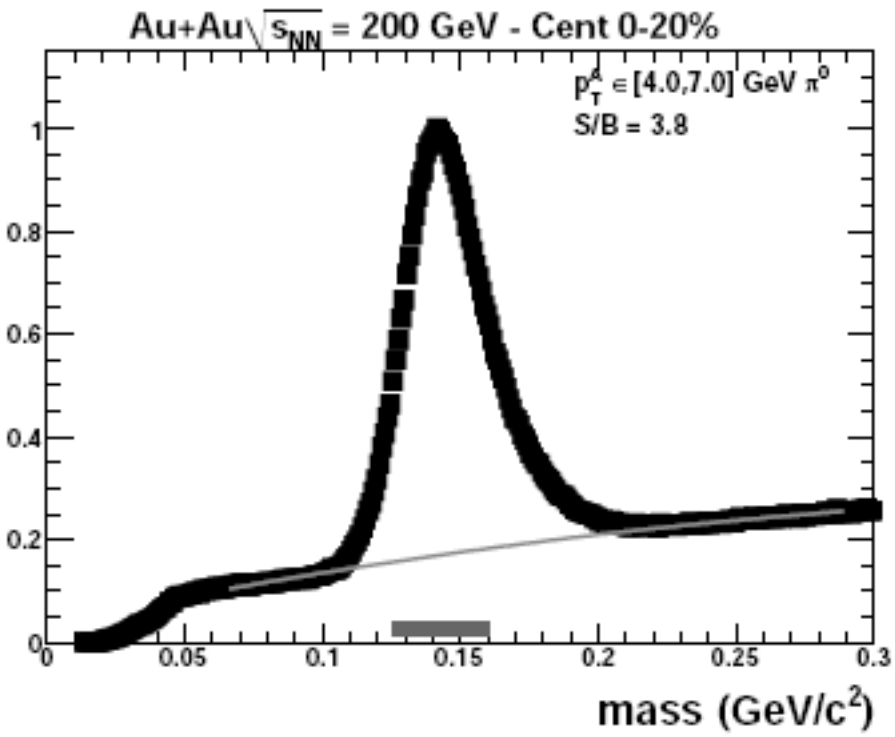
in-plane → **out-plane**

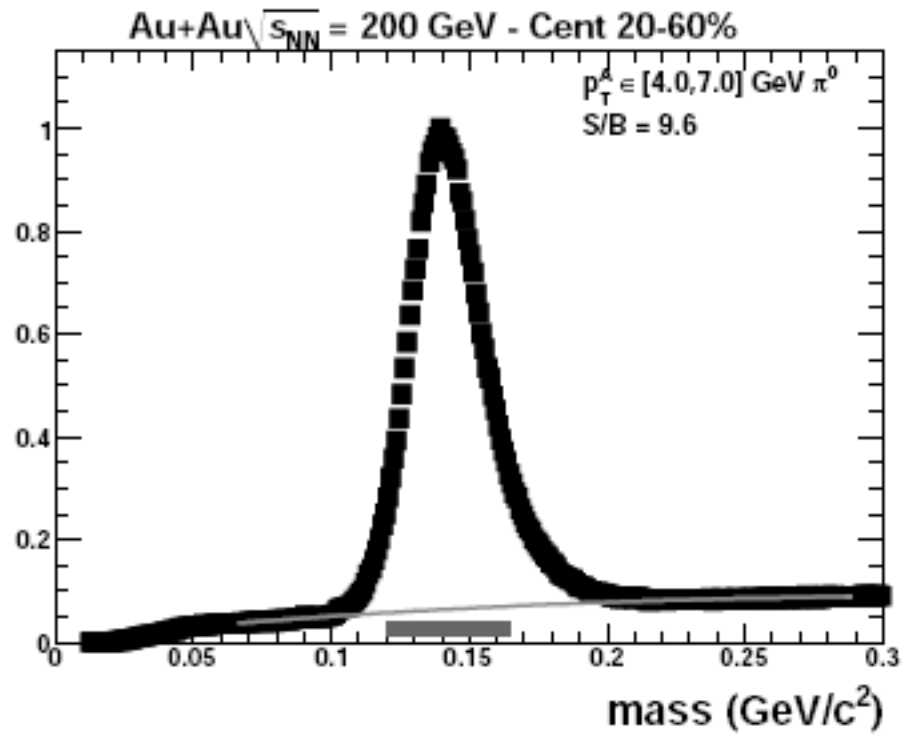
in-plane → **out-plane**

Pi0 Identification

```
// 4.0-7.0 GeV/c Hard pDST pi0 cut
double mass_min = 0.120;
double mass_max = 0.165;
if     (centrality < 20 ){ mass_min = 0.125; mass_max = 0.160; }
```

```
// 4.0-7.0 GeV/c Hard pDST pi0 cut
double asym_max = 0.8;
if     (centrality < 5 ){ asym_max = 0.50; }
else if(centrality < 10){ asym_max = 0.52; }
else if(centrality < 20){ asym_max = 0.54; }
else if(centrality < 40){ asym_max = 0.56; }
else if(centrality < 60){ asym_max = 0.70; }
```





<u>from 3.3B 0-90% Run7 events (full Run7 - QA)</u>

Charged Track Cuts

Similar to cuts for partner charged tracks 5.0-10.0 GeV/c in Run4 (my tracks are 4.0-5.0 GeV/c Run7)

```
// DC Edge Cut...
if (fabs(track->get_zed(itrk)) > 75.0) return false;

// Track Quality Cut...
int quality = track->get_quality(itrk);
if ((quality != 31)&&(quality != 63)) return false;

// Rich Veto... (valid below 5.0 GeV, pions fire above)
if ((pt < 5.0)&&(track->get_n0(itrk) > 0)) return false;
```

New for Run7: PC3 Dead Area Acceptance Cut →

```
// PC3 Matching Cut... Dead area in Run7 masked-true
double phi_dc = track->get_phi(itrk);
double zed_dc = track->get_zed(itrk);
if (( zed_dc < 0.0)||(phi_dc < 2.1)||(phi_dc > 2.6))
  {
    if ( fabs(track->get_pc3sdphi (itrk)) > 2.0 ) return false;
    if ( fabs(track->get_pc3sdz   (itrk)) > 2.0 ) return false;
  }

// EMC Matching Cut...
if ((pt > 3.0)&&( fabs(track->get_emcsdphi (itrk)) > 3.0 )) return false;
if ((pt > 3.0)&&( fabs(track->get_emcsdz   (itrk)) > 3.0 )) return false;
```

Mixed Event Assumptions

Foreground combinatorial pairs-per-event given by corrected mixed-event pairs-per-event

$$n_{comb}^{AB} = n_{mix}^{AB}\xi \qquad b_0 = \frac{n_{mix}^{AB}\xi}{n_{real}^{AB}}$$

Reliance on stochastic hard scattering production

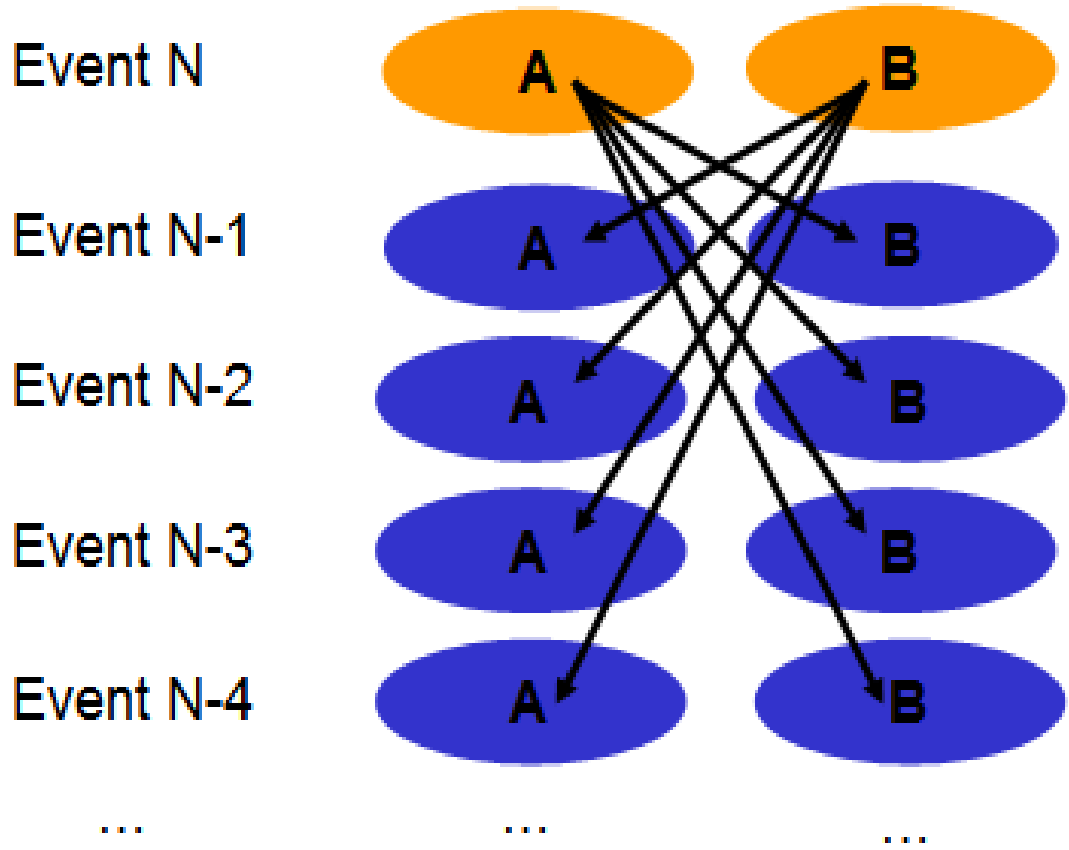
<u>Example of failure scenario:</u>

Every event has 1 and only 1 hard scattering and no other particle production

Mixed Event Construction

Rolling buffer mixing technique

Pooled by Event type:
5cm zvertex
5% centrality



Mixing produces two products:

- Acceptance Correction

- Mixed Event Pair Multiplicity

Measured Flow

π^0 4.0-7.0 GeV/c

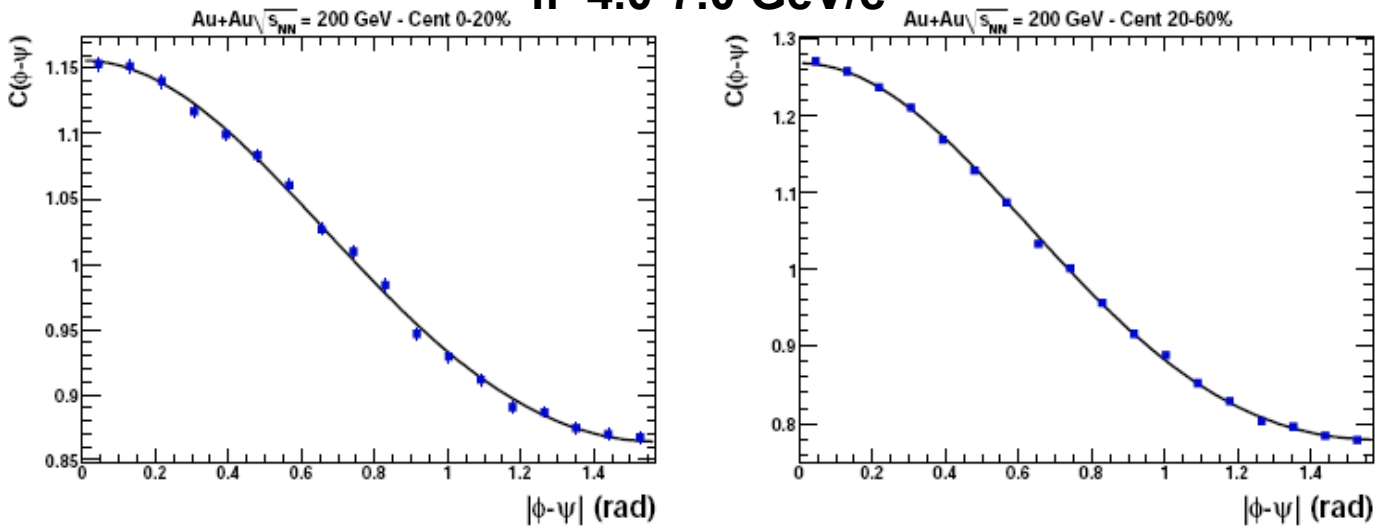


Figure 3: Correlation functions in 0-20% and 20-60% collisions between neutral pions 4.0-7.0 GeV/c and RXPN detector pointings.

$h^{\pm}$ 4.0-7.0 GeV/c

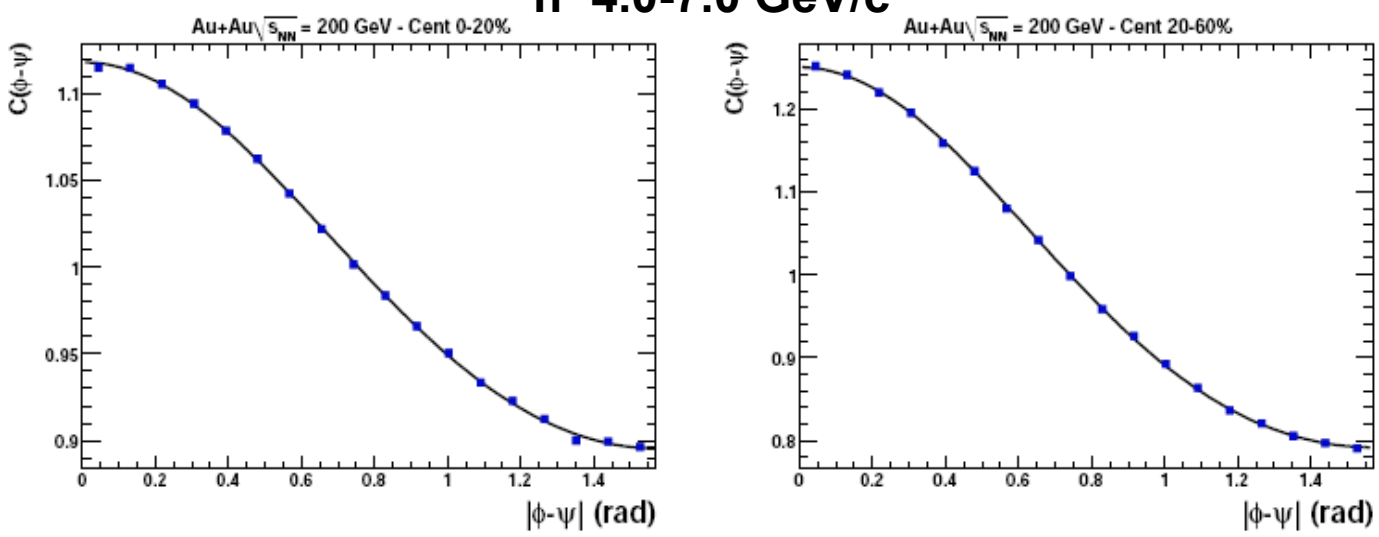


Figure 4: Correlation functions in 0-20% and 20-60% collisions between charged tracks 4.0-5.0 GeV/c and RXPN detector pointings.

Flow Modulation with RP-binning

The values of c_2 and c_4 are fixed to the values given by:

$$c_2 = \frac{\beta}{2\alpha} \tag{2}$$

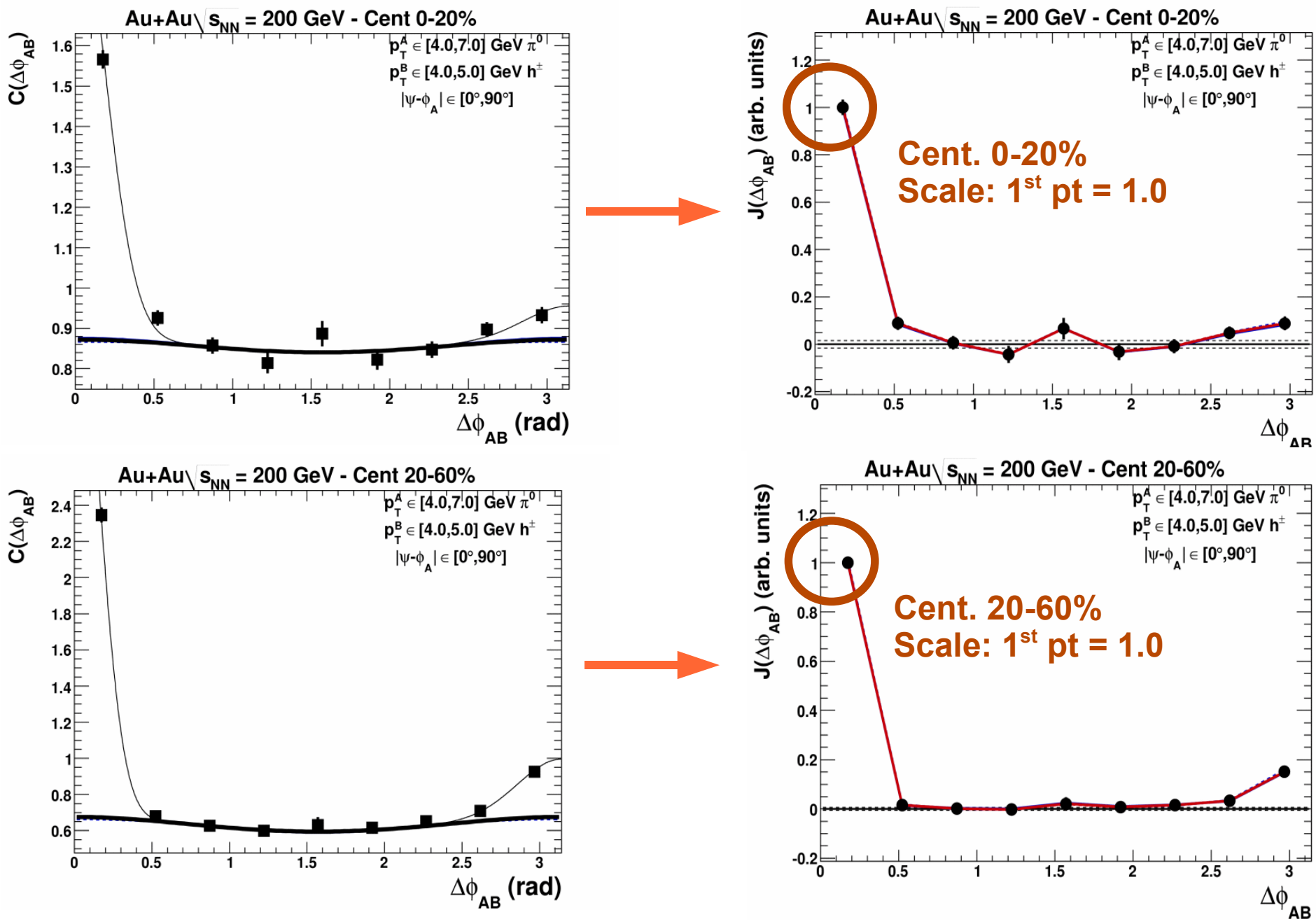
$$c_4 = \frac{\gamma}{2\alpha} \tag{3}$$

where:

$$\alpha = 1 + 2v_2^A cos\left(2\phi_s\right)\frac{sin\left(2c\right)}{2c}\Delta + 2v_2^A cos\left(4\phi_s\right)\Delta_4 \tag{4}$$

$$\beta = 2v_2^A v_2^B + 2v_2^B\left(1 + v_4^A\right) cos\left(2\phi_s\right)\frac{sin\left(2c\right)}{2c}\Delta + 2v_2^A v_2^B cos\left(4\phi_s\right)\frac{sin\left(4c\right)}{4c}\Delta_4 + 2v_2^B v_4^A cos\left(6\phi_s\right)\frac{sin\left(6c\right)}{6c}\Delta_6 \tag{5}$$

$$\gamma = 2v_4^A v_4^B + 2v_4^B\left(1 + v_2^A\right) cos\left(4\phi_s\right)\frac{sin\left(4c\right)}{4c}\Delta_4 + 2v_2^A v_4^B\left(cos\left(2\phi_s\right)\frac{sin\left(2c\right)}{2c}\Delta + cos\left(6\phi_s\right)\frac{sin\left(6c\right)}{6c}\Delta_6\right) + 2v_4^A v_4^B cos\left(8\phi_s\right)\frac{sin\left(8c\right)}{8c}\Delta_8 \tag{6}$$

Requires measurements of obs-v_2, obs-v_4, Δ, Δ_4, Δ_6, Δ_8

Arb. Scale Selection