PHENIX measurement of jet properties and their modification in heavy-ion collisions

Jan Rak

for the PHENIX collaboration

Department of Physics and Astronomy

IOWA STATE UNIVERSITY

Partonic degree of freedom in HI

Highlights from RHIC AuAu program:

- high-p_T particle yield suppression – jet quenching
- disappearance of the back-to-back jet in central collisions
- exceedingly large azimuthal anisotropy v_2

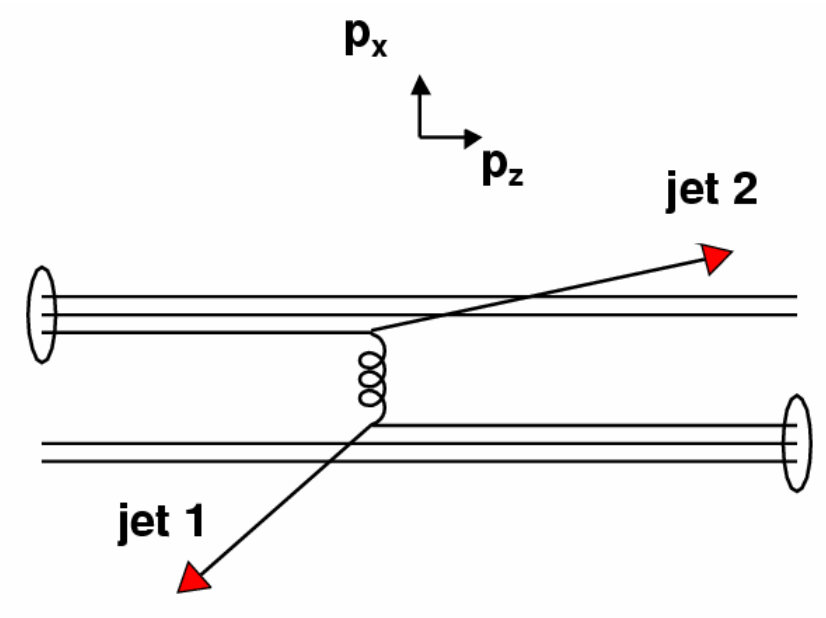
Detailed analysis of parton/jet properties like:

- shape of the fragmentation $D(z)$ and parton distribution function $f_q(p_{Tq})$
- parton transverse momentum $\langle k_T^2 \rangle$

and their modification is vital for understanding of the mechanism of parton interaction with QCD medium formed at RHIC

Hard scattering

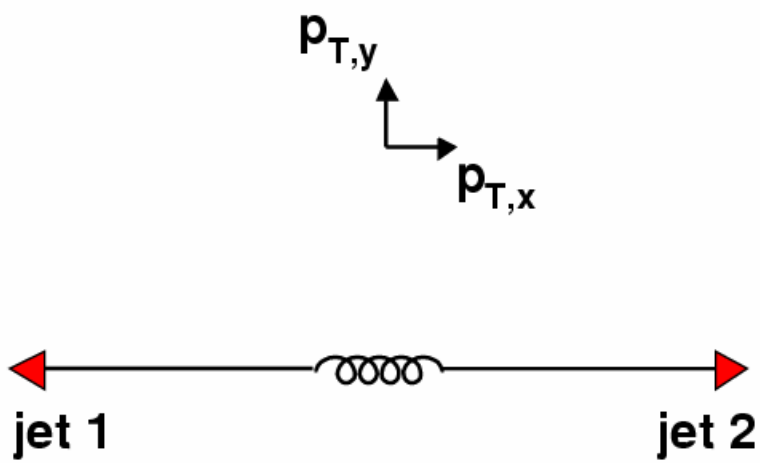
Hard scattering in longitudinal plane



Generally, momentum fraction $\mathbf{x_1 \neq x_2}$. (Not in PHENIX $-0.35<\eta<0.35$)

Hard scattering

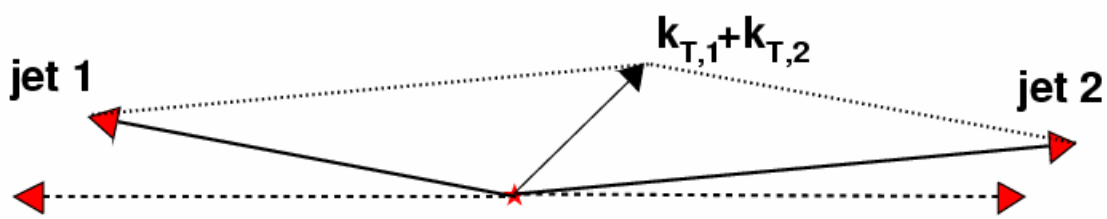
Hard scattering in transverse plane



Point-like partons $\Rightarrow$ elastic scattering $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{0}$

Hard scattering

Hard scattering in transverse plane



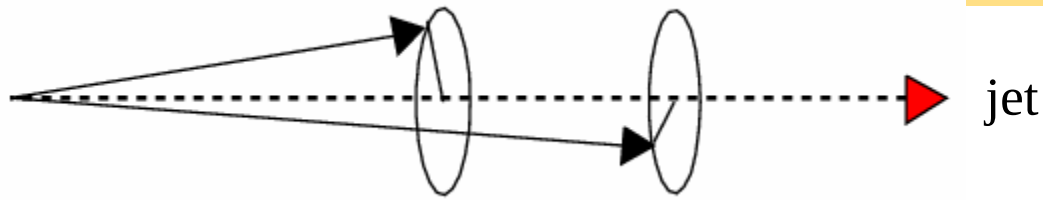
Point-like partons $\Rightarrow$ elastic scattering $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{0}$

Partons have intrinsic transverse momentum $\boldsymbol{k_T}$ $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{k}_{T,1} + \vec{k}_{T,2}$

Jet Fragmentation (width of the jet cone)

Partons have to materialize (fragment) in colorless world

$\vec{j}_T$ = jet fragmentation transverse momentum



j_T and k_T are 2D vectors. We measure the mean value of its projection into the transverse plane $\langle |j_{Ty}| \rangle$ and $\langle |k_{Ty}| \rangle$.

$$\langle | k_{Ty} | \rangle = \sqrt{\frac{2}{\pi}} \sqrt{\langle k^2{}_T \rangle}$$

$\langle |j_{Ty}| \rangle$ is an important jet parameter. It's constant value independent on fragment's p_T is characteristic of jet fragmentation (j_T-scaling).

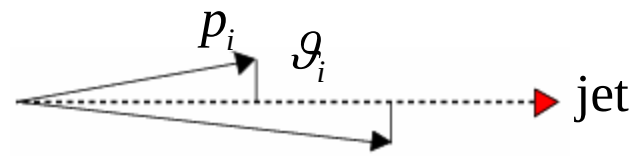
$\langle |k_{Ty}| \rangle$ (intrinsic + NLO radiative corrections) carries the information on the parton interaction with QCD medium.

$$\langle k_\perp{}^2 \rangle_{AA} = \langle k_\perp{}^2 \rangle_{vac} + \langle k_\perp{}^2 \rangle_{IS\ nucl} + \langle k_\perp{}^2 \rangle_{FS\ nucl}$$

p+p p+A A+A

Fragmentation Function (distribution of parton momentum among fragments)

In Principle



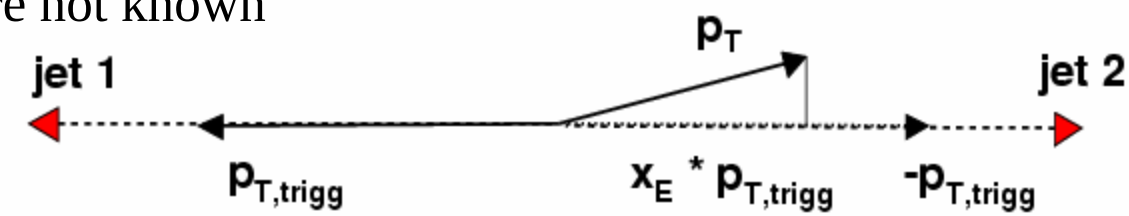
$$\vec{p}_{parton} = \sum_i \vec{p}_i \qquad |\vec{p}_{parton}| = \sum_i |\vec{p}_i| \cos(\vartheta_i)$$

$$z_i = \frac{|\vec{p}_i| \cos(\vartheta_i)}{|\vec{p}_{parton}|} \qquad \sum_i z_i = 1$$

Fragmentation function $D(z) \propto e^{-z/\langle z \rangle}$

In Practice parton momenta are not known

$$x_E = -\frac{\vec{p}_T \cdot \vec{p}_{Ttrigg}}{|\vec{p}_{Ttrigg}|^2}$$

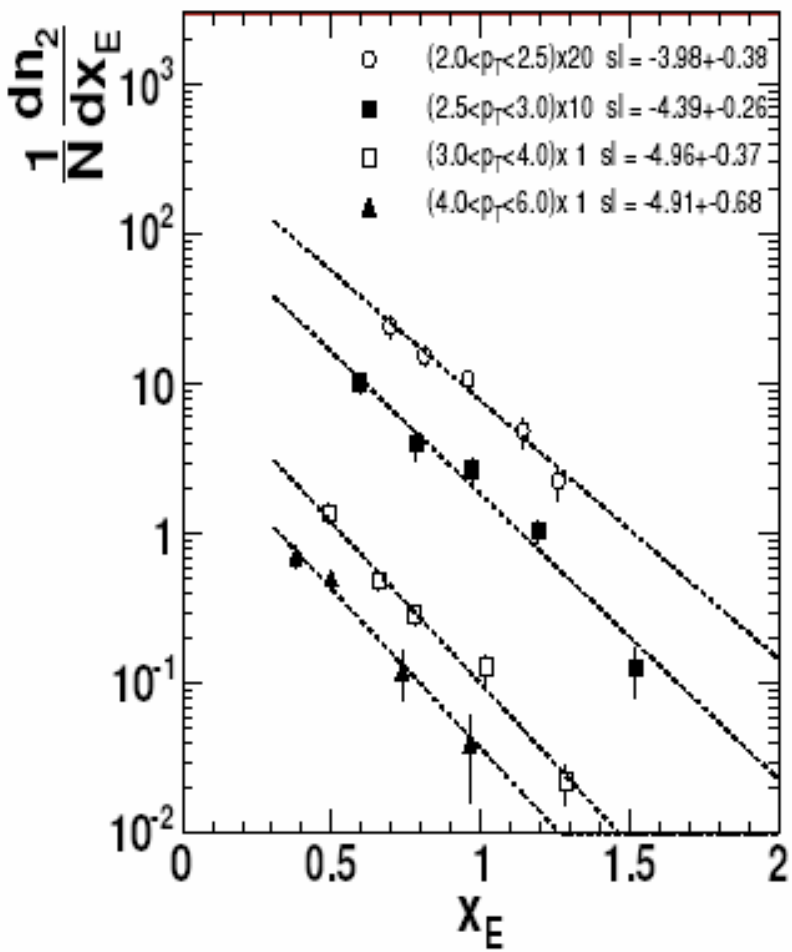


$$x_E z_{trigg} = \frac{p_T \cos(\Delta\varphi)}{p_{parton}} = z$$

$\Rightarrow$ Simple relation $\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$

x_E in pp collisions

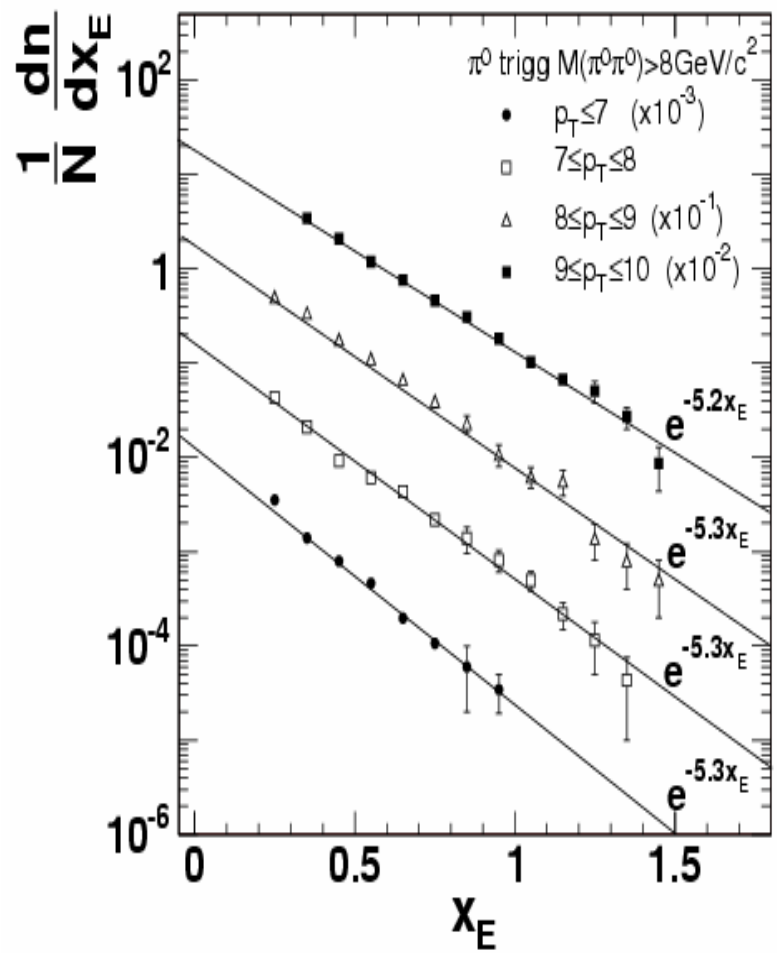
PHENIX preliminary



$1/\langle x_E \rangle \approx -4$ to -5

CCOR (ISR) $\sqrt{s}$ = 63 GeV

see A.L.S. Angelis, Nucl Phys B209 (1982)



$1/\langle x_E \rangle \approx -5.3$

⟨z⟩ extracted from pp data

We measured x_E and

$$\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$$

$x_{Ttrigg}=2.p_{Ttrigg}/\sqrt{s}$

$$\langle z_{trigg} \rangle \propto \int_{x_{Ttrigg}}^{1} z \cdot e^{-z/\langle z \rangle} f_q(p_T / z) \cdot z^{-2} dz$$

FFn *D(z)*

⟨z⟩ extracted from pp data

We measured x_E and

$$\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$$

$x_{Ttrigg}=2.p_{Ttrigg}/\sqrt{s}$

$$\langle z_{trigg} \rangle \propto \int_{x_{Ttrigg}}^{1} z \cdot e^{-z/\langle z \rangle} f_q(p_T / z) \cdot z^{-2} dz$$

final state parton distrib.
extracted from PHENIX
$p+p \rightarrow \pi^0 + X$

⟨z⟩ extracted from pp data

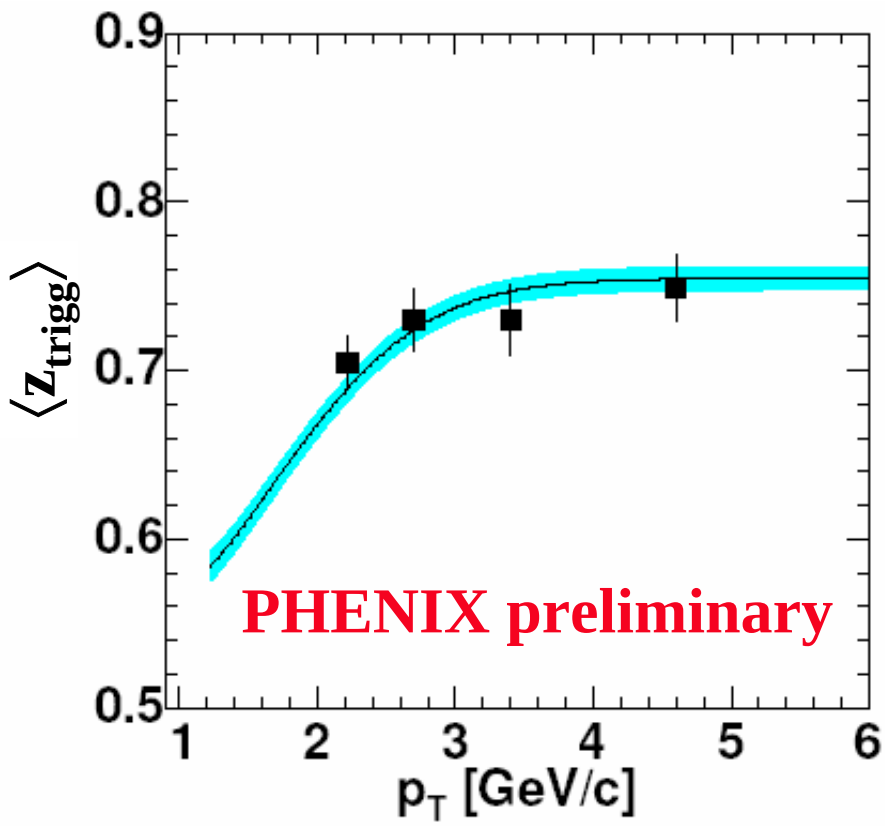
We measured x_E and

$$\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$$

$x_{Ttrigg}=2.p_{Ttrigg}/\sqrt{s}$

$$\langle z_{trigg} \rangle \propto \int_{x_{Ttrigg}}^{1} z \cdot e^{-z/\langle z \rangle} f_q(p_T / z) \cdot z^{-2} dz$$

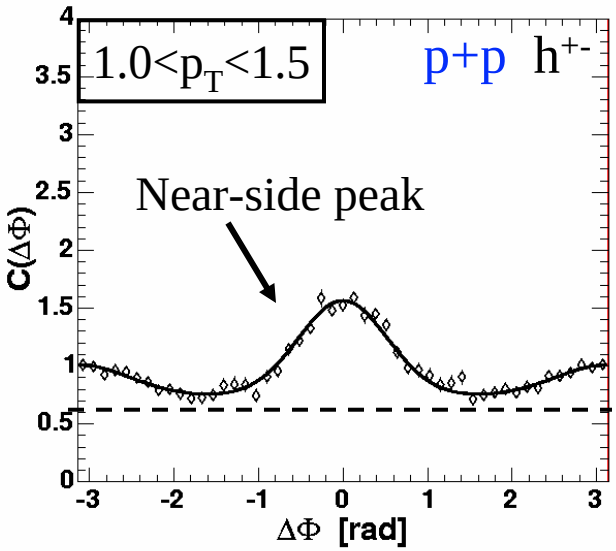
Only one unknown variable ⟨z⟩ ⇒ iterative solution

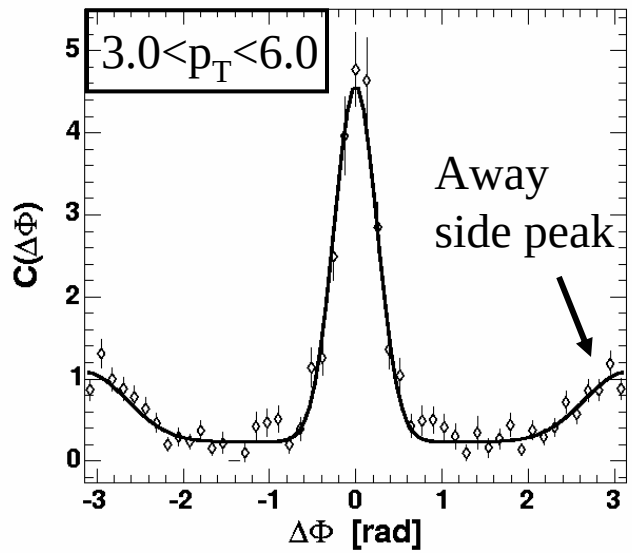


Slope of the fragmentation function in p+p collisions at √s=200 GeV

$$\frac{1}{\langle z \rangle} = 6.16 \pm 0.32$$

pp and dAu correlation functions



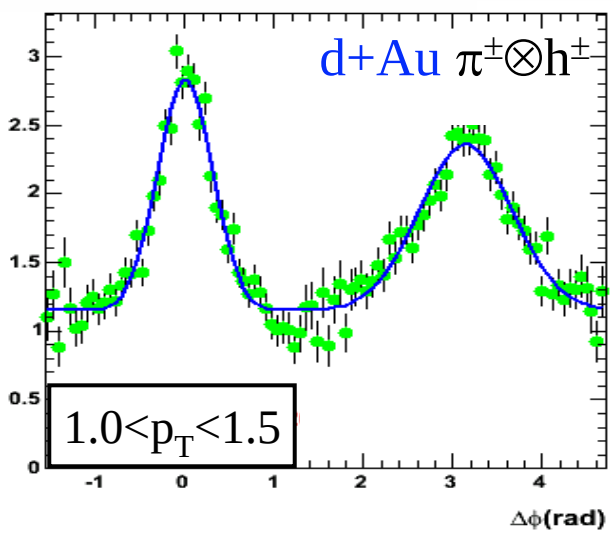


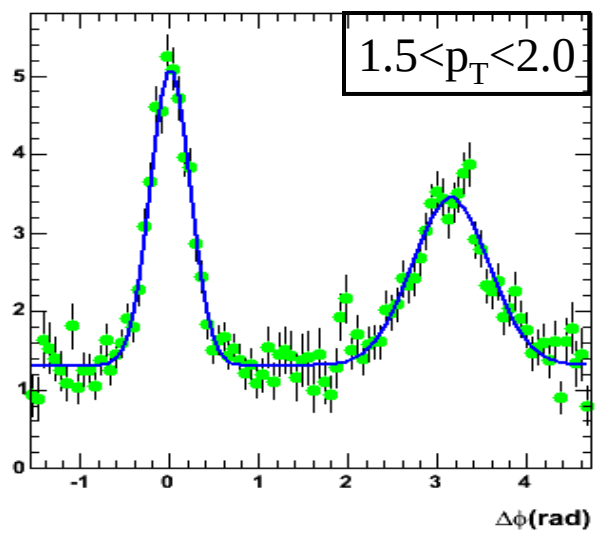
Fixed correlation:

both p_{Ttrigg} and p_{Tassoc} are in the same range

Assorted correlation:

p_{Ttrigg} and p_{Tassoc} different





$5.0<p_{Ttrigg}<16.0$ GeV/c

Jet function assumed to be Gaussian

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$

→ Fit = const + Gauss(0)+Gauss(±π)

σ_N, σ_A , $\langle|j_{Ty}|\rangle$, $\langle|k_{Ty}|\rangle$ relations

Knowing σ_N and σ_A it is straightforward to extract $\langle|j_{Ty}|\rangle$ and $\langle z_{trigg}\rangle\langle|k_{Ty}|\rangle$

In the high-p_T limit ($p_T >> \langle|j_{Ty}|\rangle$ and $p_T >> \langle|k_{Ty}|\rangle$)

$$\left\langle \left| j_{\perp y} \right| \right\rangle = \langle p_\perp \rangle \sin \frac{\sigma_N}{\sqrt{\pi}}$$

$$\left\langle \left| k_{Ty} \right| \right\rangle \approx \langle p_T \rangle \sqrt{\sigma_A^2 - \sigma_N^2}$$

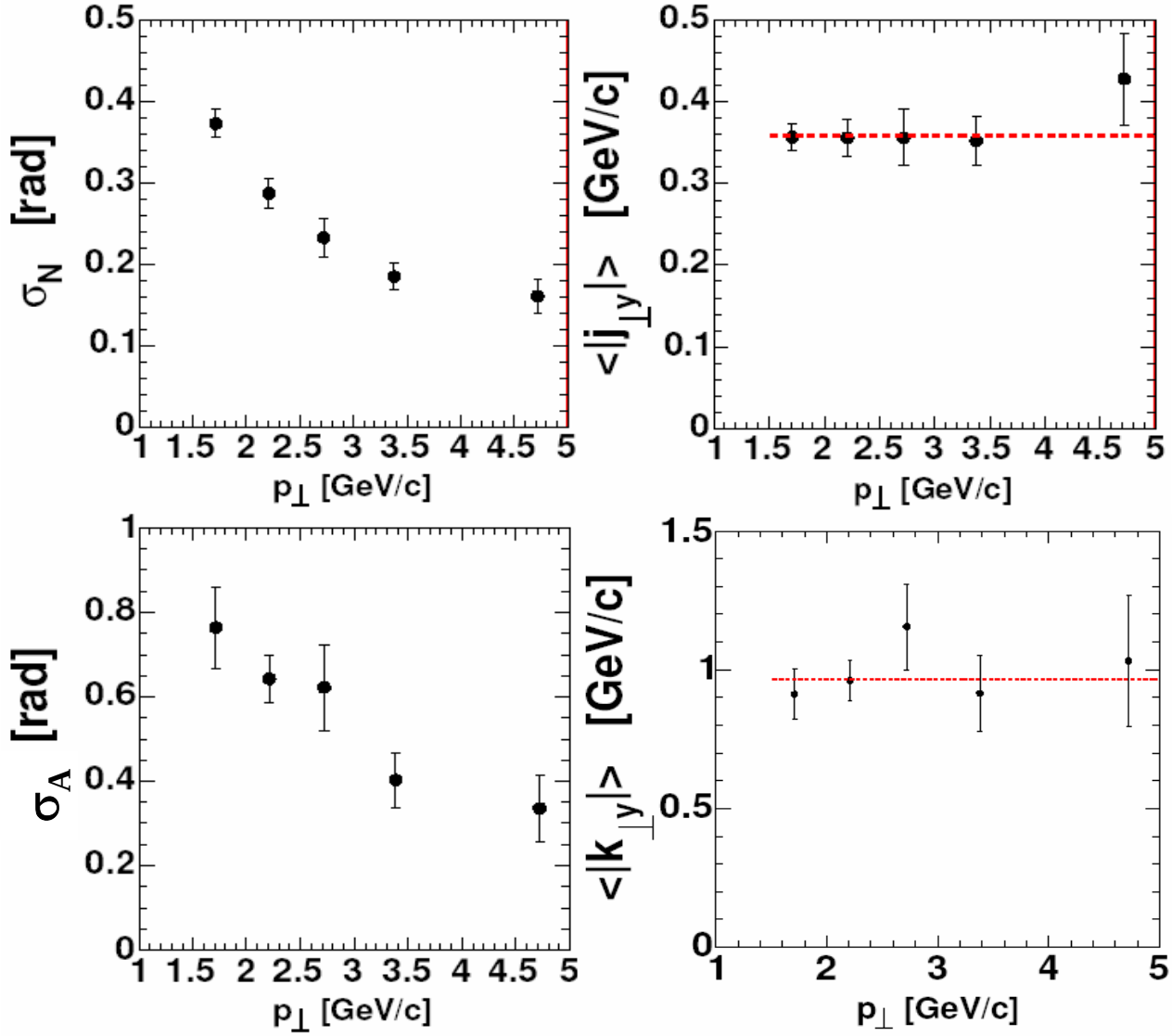
However, inspired by Feynman, Field, Fox and Tannenbaum (see *Phys. Lett. 97B (1980) 163*) we derived more accurate equation

$$\langle z_{trigg} \rangle \langle | k_{Ty} | \rangle = \frac{\langle p_T \rangle}{\sqrt{2}\, x_h} \sqrt{\sin^2 \sqrt{\frac{2}{\pi}} \sigma_A - (1 + x^2{}_h) \sin^2 \frac{\sigma_N}{\sqrt{\pi}}}$$

$x_h = p_{T,assoc} / p_{T,trigg}$

See poster P07, P. Constantin

$\sigma_N, \sigma_A \rightarrow \langle|j_{Ty}|\rangle, \langle|k_{Ty}|\rangle$ in pp data



$$\langle k_\perp^2 \rangle_{pp} = \langle k_\perp^2 \rangle_{vac}$$

PHENIX preliminary

$\langle|j_{Ty}|\rangle = 359 \pm 11$ MeV/c

$\langle|k_{Ty}|\rangle = 964 \pm 49$ MeV/c

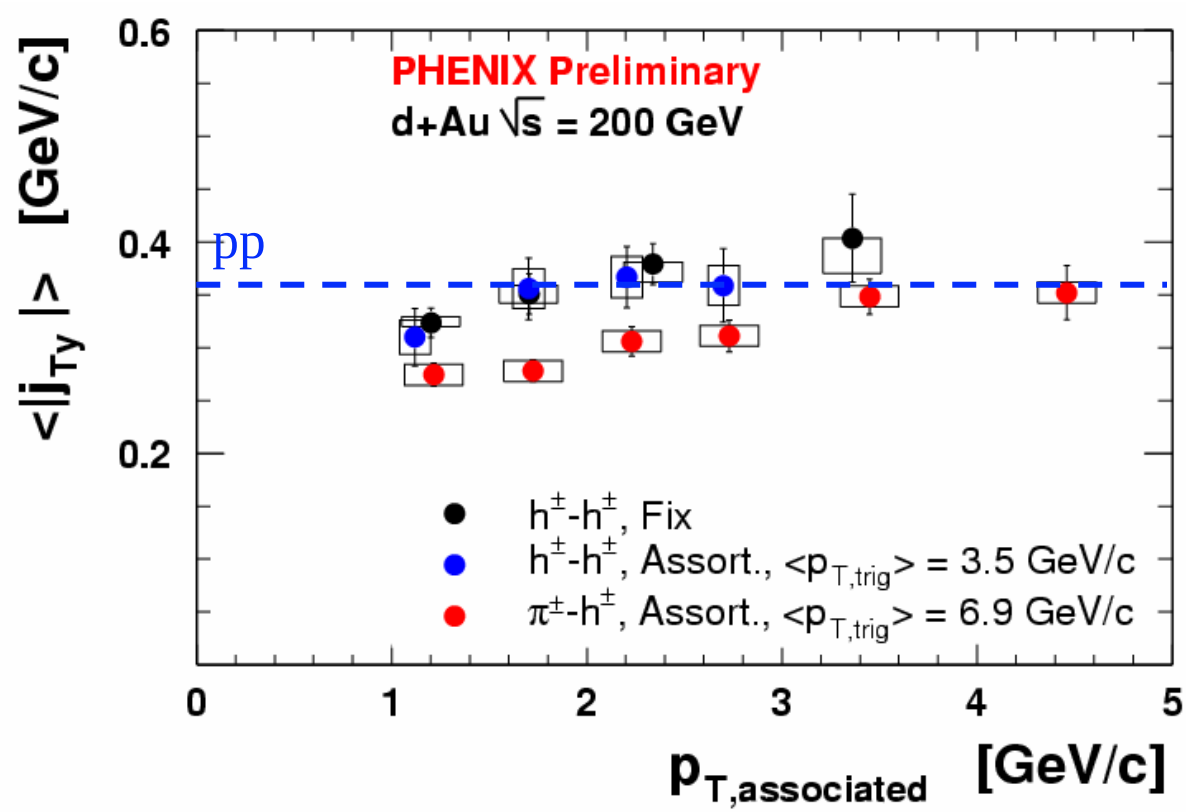
Both $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$ in very good agreement with previous measurements:
PLB97 (1980)163
PRD 59 (1999) 074007

From pp to dAu

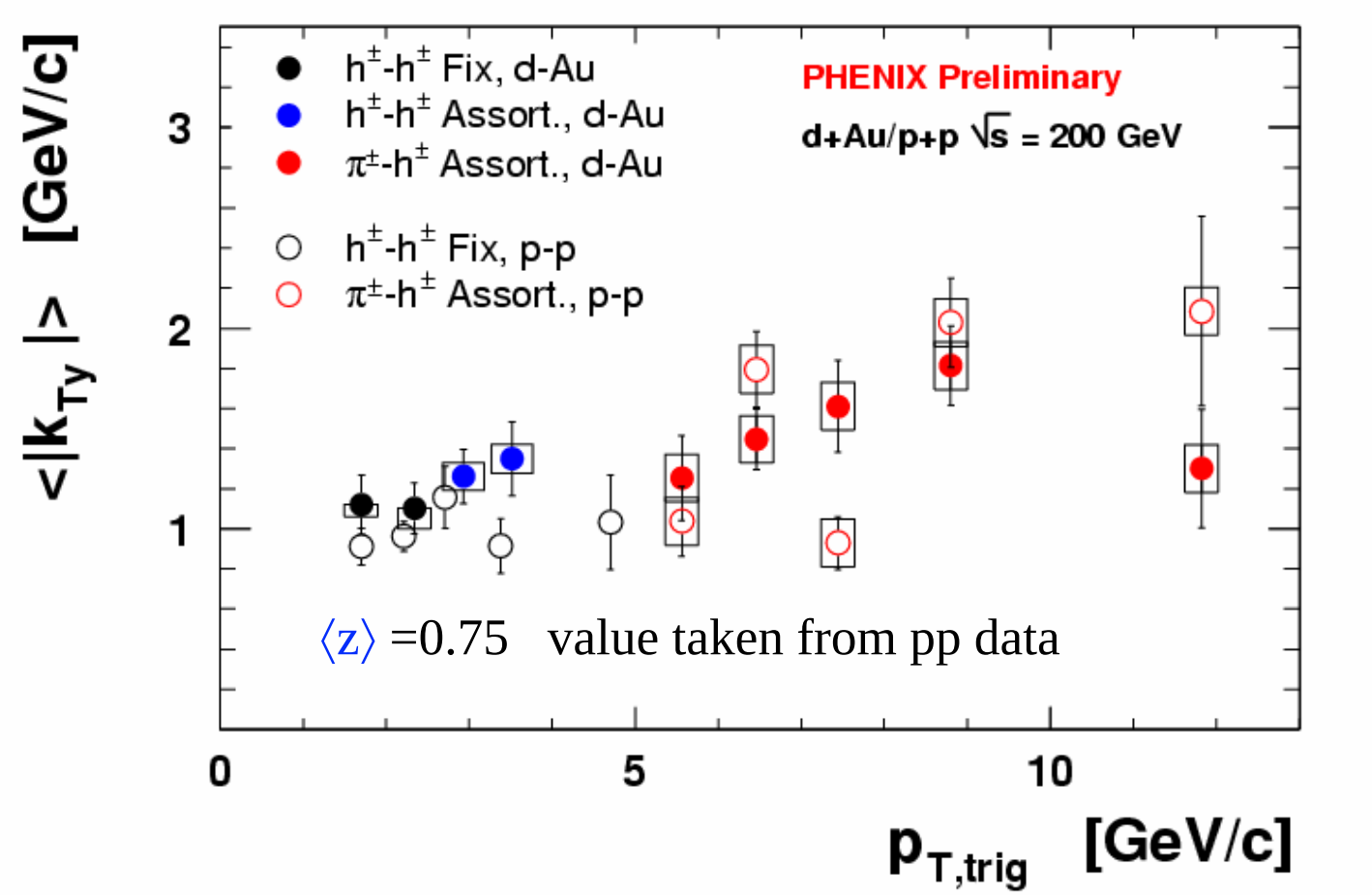
$$\langle k_\perp^2 \rangle_{dAu} = \langle k_\perp^2 \rangle_{vac} + \langle k_\perp^2 \rangle_{IS\ nucl}$$

$\langle |k_{Ty}| \rangle$ carries the information on the parton interaction with cold nuclear matter.

$\langle |j_{Ty}| \rangle$ should be the same as in pp – systematic cross check



$\langle |k_{Ty}| \rangle$ from pp and dAu

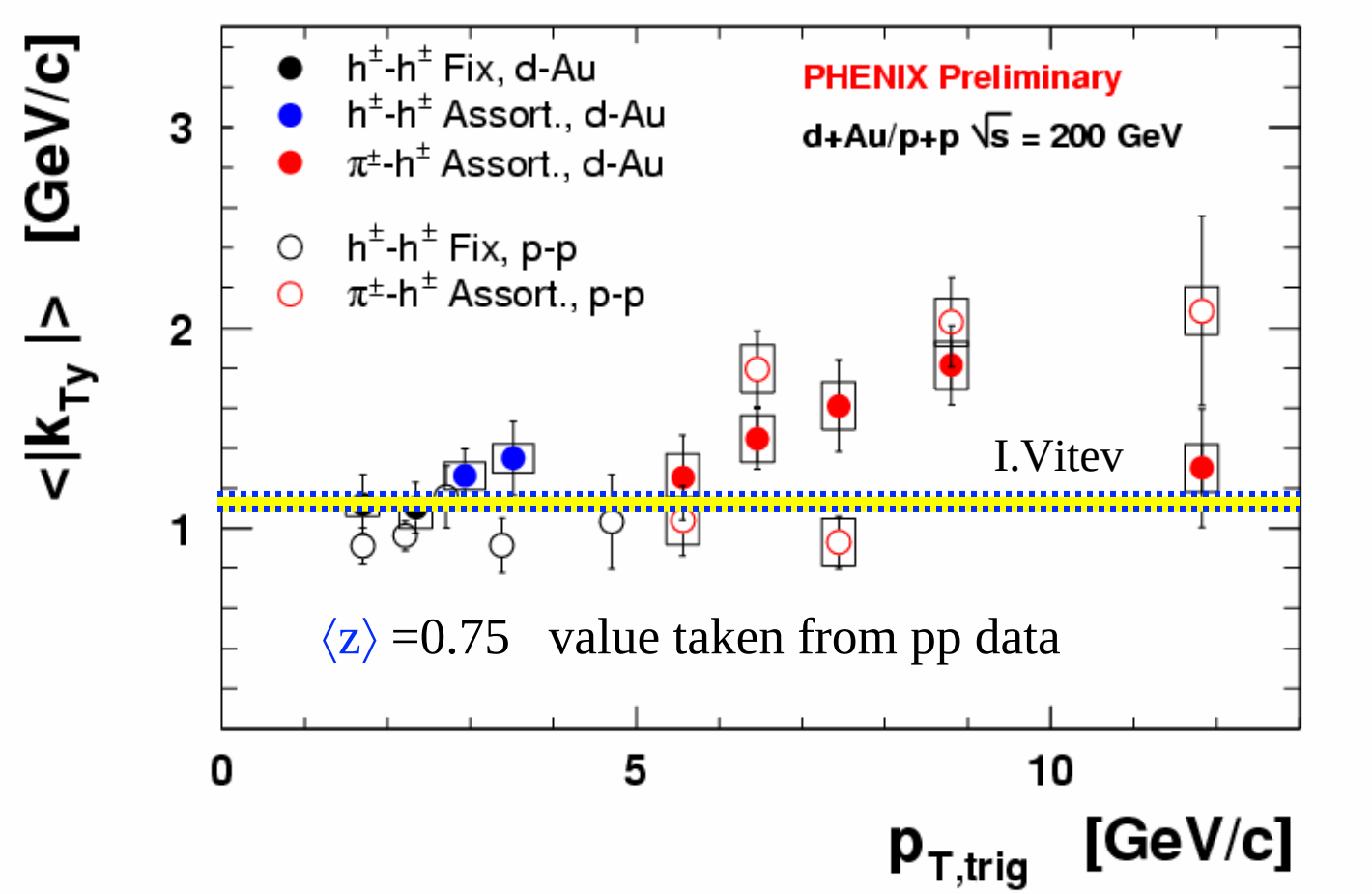


$\langle z \rangle$ =0.75 value taken from pp data

See poster P03 J. Jia and P05 N. Grau

$\langle |k_{Ty}| \rangle$ from pp and dAu

$$\langle \Delta \mathbf{k}_T^2 \rangle_{IS} = \mu^2 / \lambda_{eff} \langle L \rangle_{IS}$$ I.Vitev nucl-th/0306039



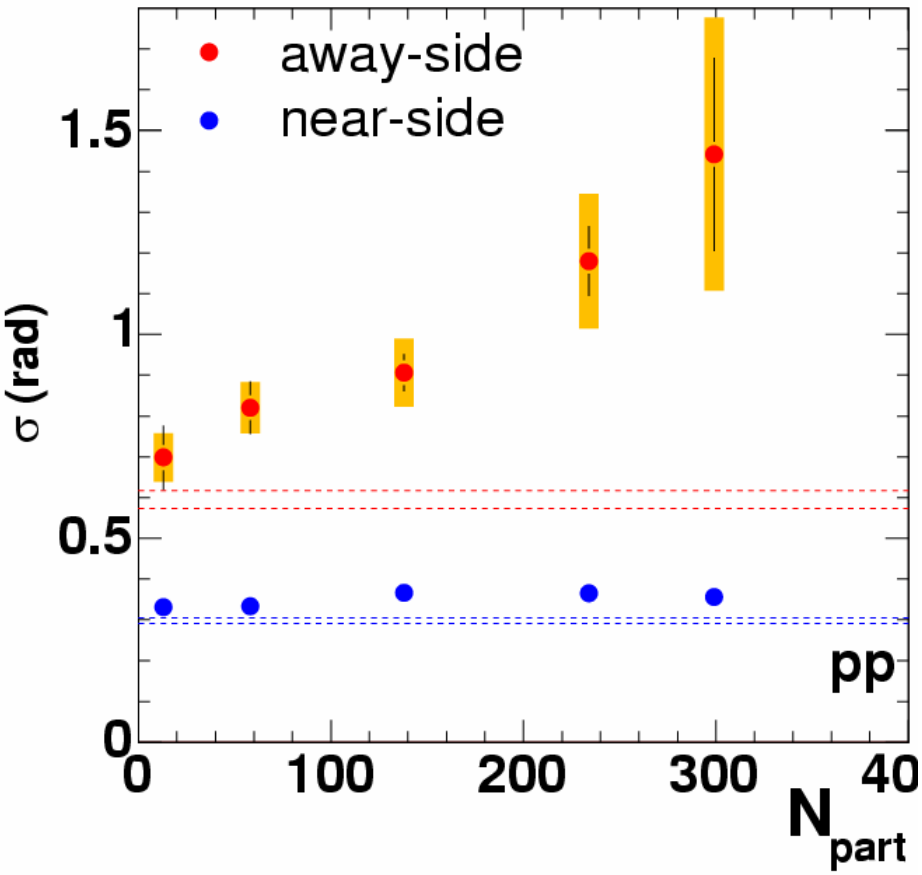
No significant k_T-broadening seen in dAu data

See poster P03 J. Jia and P05 N. Grau

AuAu $\langle|j_{Ty}|\rangle$ and $\langle z\rangle\langle|k_{Ty}|\rangle$ from CF

$$\langle k_\perp^2\rangle_{AA} = \langle k_\perp^2\rangle_{vac} + \langle k_\perp^2\rangle_{IS\ nucl} + \langle k_\perp^2\rangle_{FS\ nucl}$$

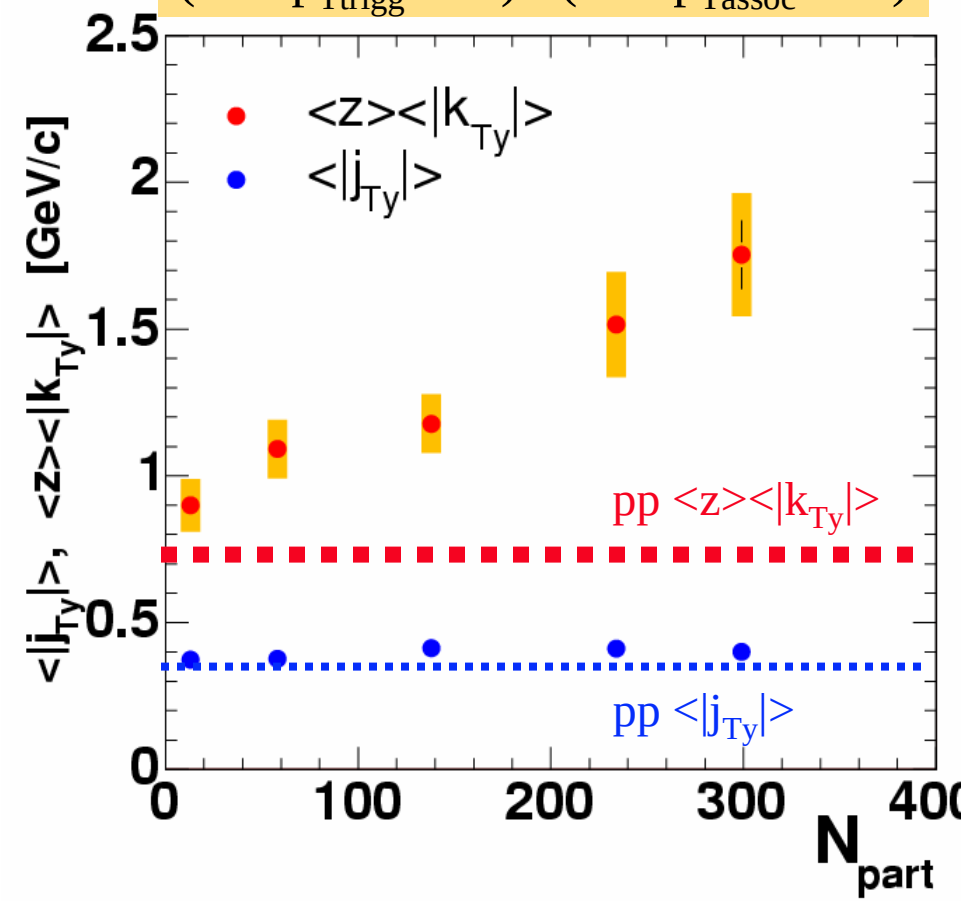
$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$



AuAu $\langle |j_{Ty}| \rangle$ and $\langle z \rangle \langle |k_{Ty}| \rangle$ from CF

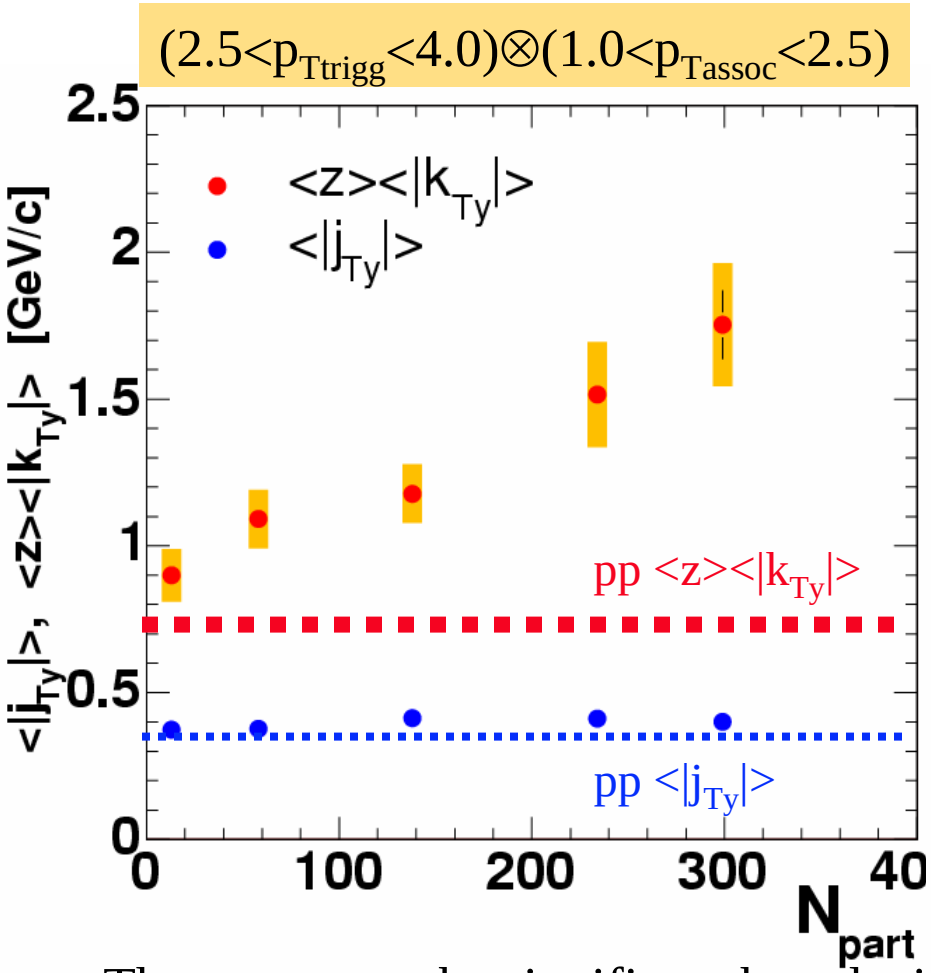
$$\langle k_\perp^2 \rangle_{AA} = \langle k_\perp^2 \rangle_{vac} + \langle k_\perp^2 \rangle_{IS\ nucl} + \langle k_\perp^2 \rangle_{FS\ nucl}$$

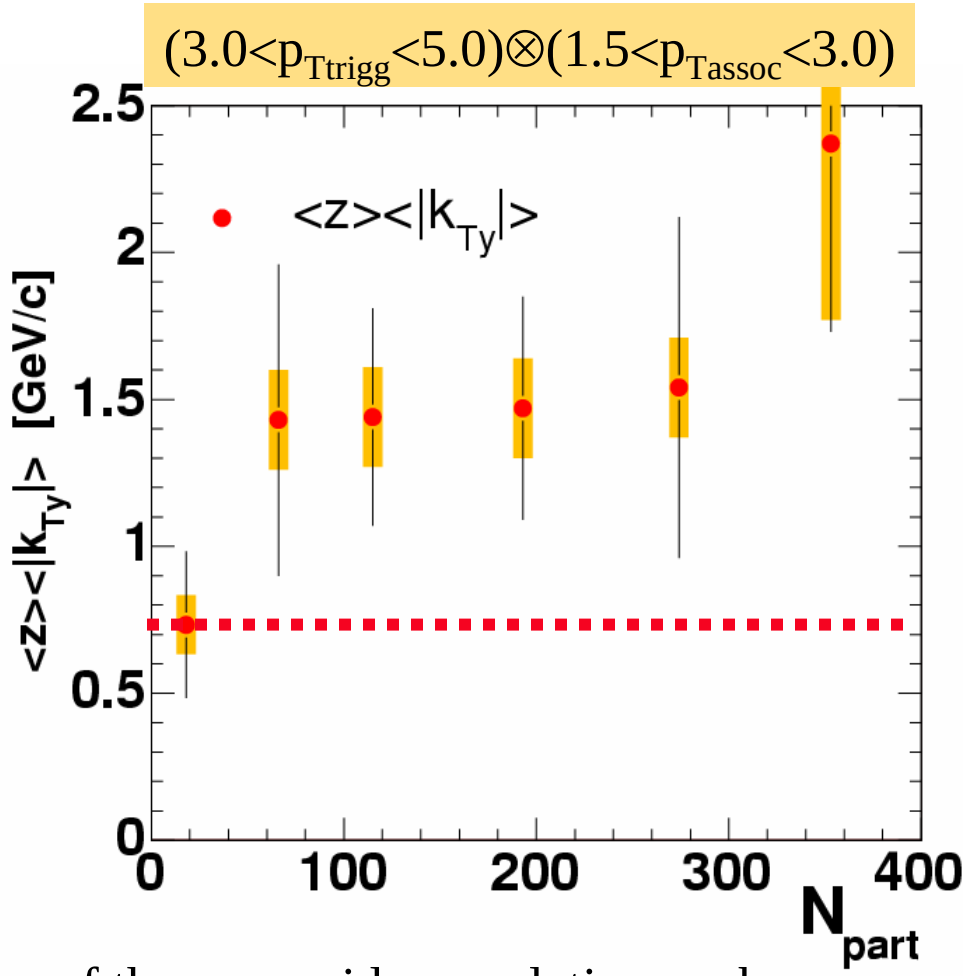
$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$



AuAu $\langle|j_{Ty}|\rangle$ and $\langle z\rangle\langle|k_{Ty}|\rangle$ from CF

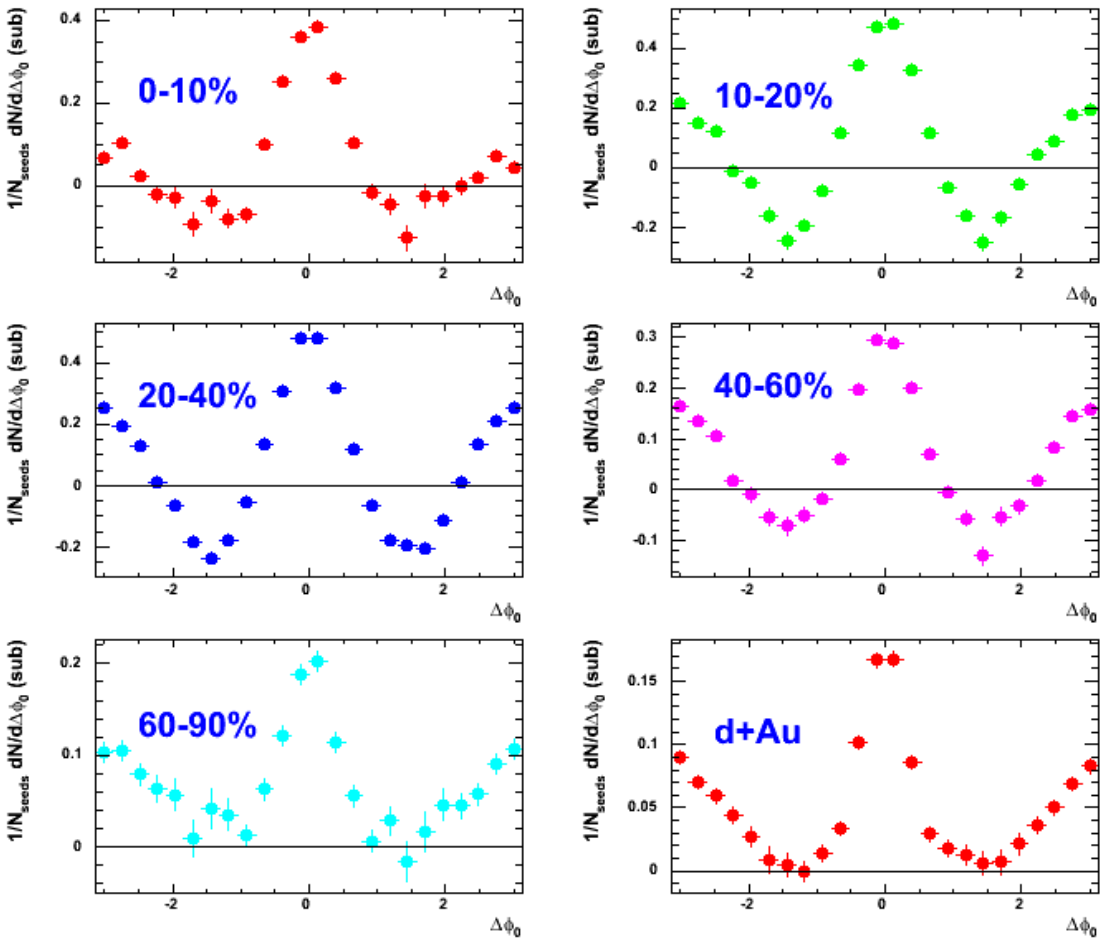
$$\langle k_\perp^2\rangle_{AA} = \langle k_\perp^2\rangle_{vac} + \langle k_\perp^2\rangle_{IS\ nucl} + \langle k_\perp^2\rangle_{FS\ nucl}$$



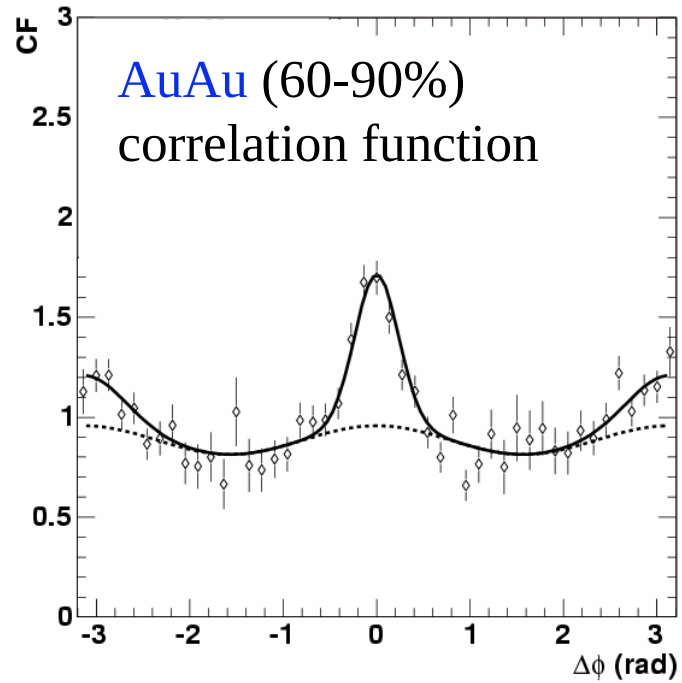


There seems to be significant broadening of the away-side correlation peak which persists also at somewhat higher p_T range.

AuAu yield



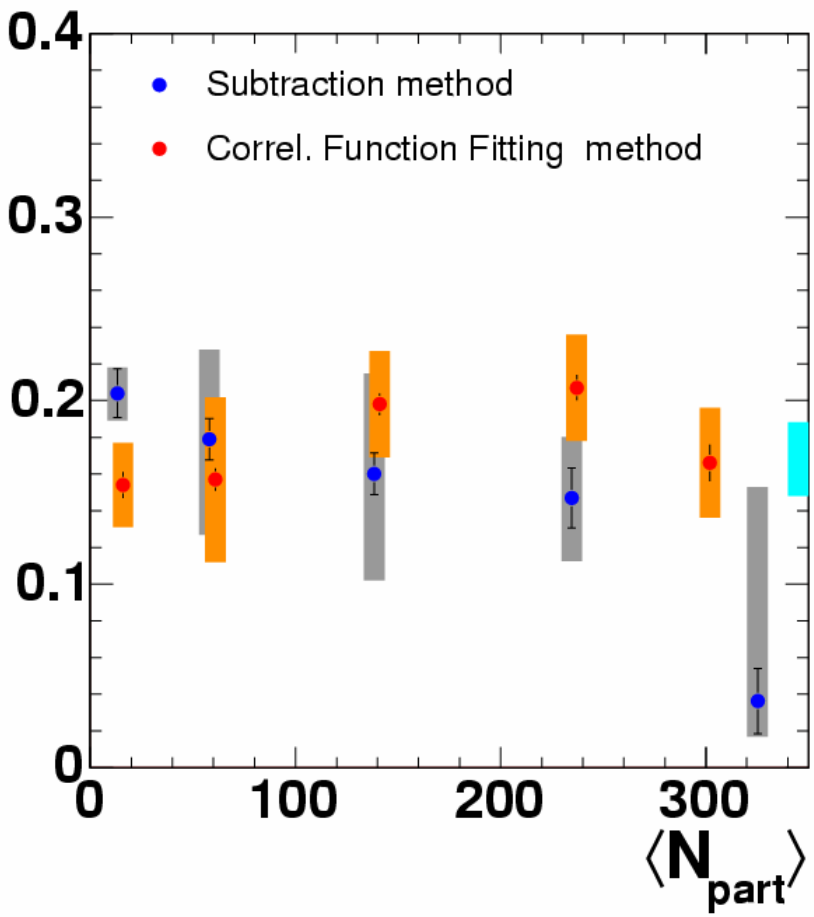
Subtracted $dN/d\Delta\varphi$ integrating from 0-90, 90-180 to remove the v_2 component.



$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c

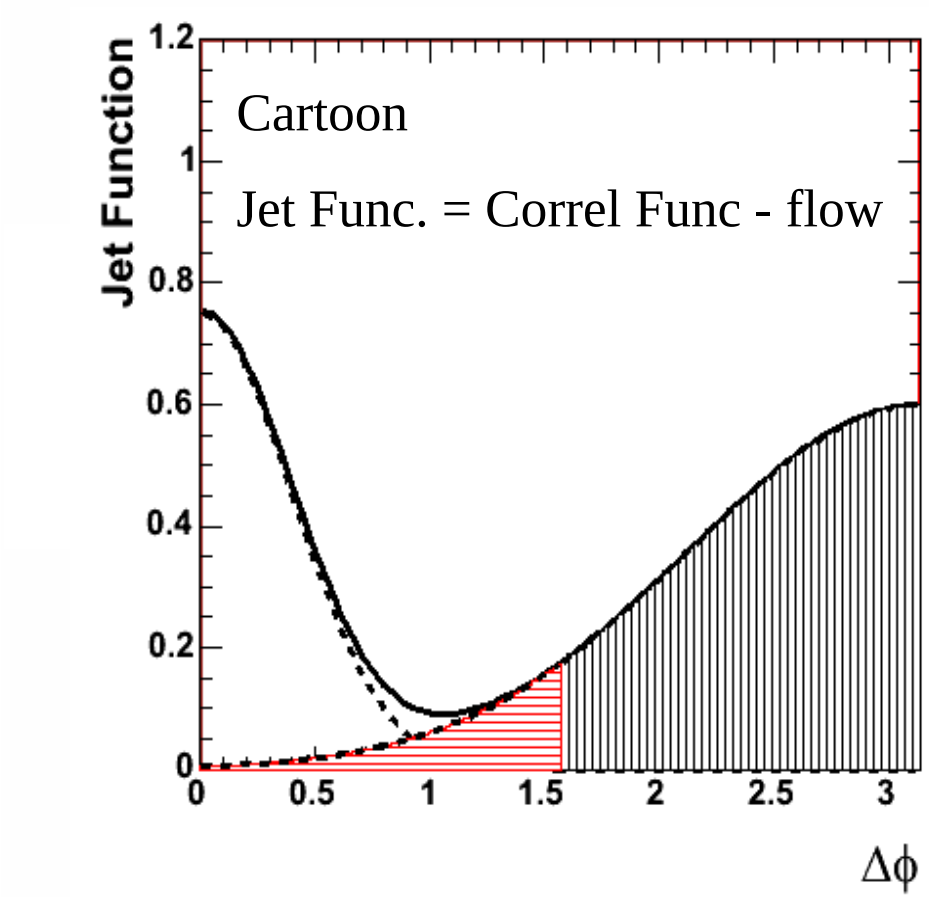
AuAu associated yields

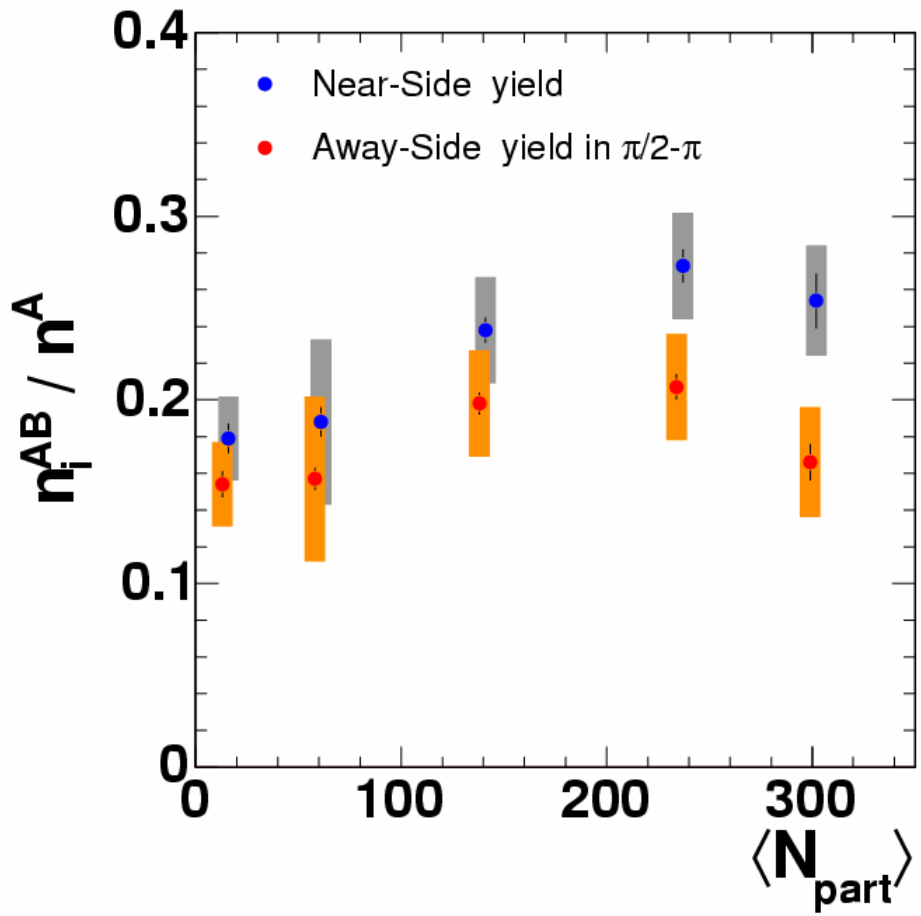
$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c



AuAu associated yields

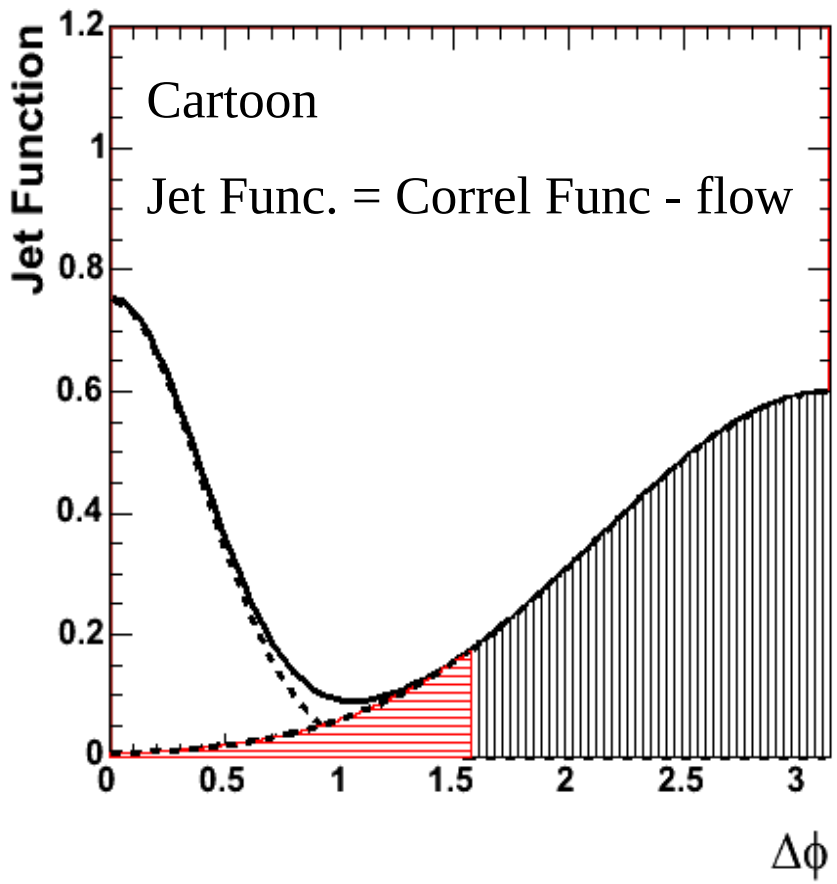
$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c

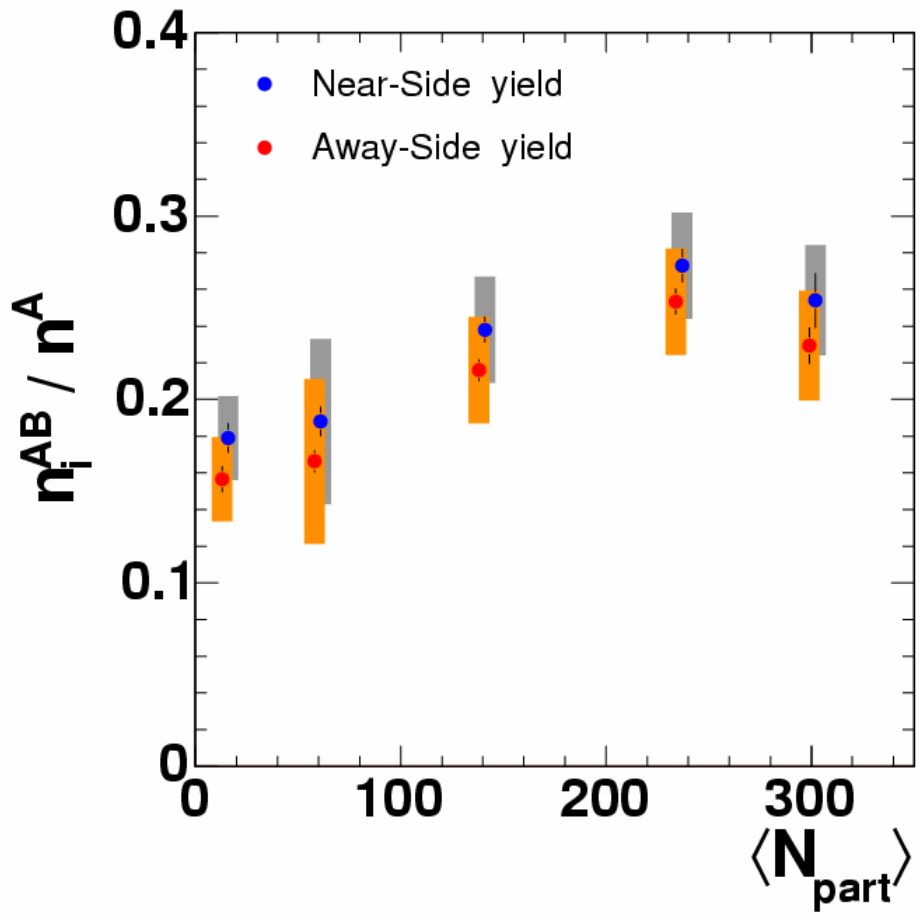




AuAu associated yields

$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c





Note p_T is rather low; associated particle yields increase with centrality

See poster C10, N.N. Ajitanand

Summary and conclusions

Jet production and fragmentation in pp, dAu and AuAu collisions:

- the slope of the fragmentation function in pp
- σ_N , σ_A , $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$ in pp, dAu, AuAu
- Variation of the conditional yield of back-to-back particles with N_{part} in AuAu

We found:

- Good agreement of the jet properties in pp collisions with other experiments
- dAu j_T and k_T consistent with pp
- In AuAu significant k_T - broadening with centrality
- Yield of away side associated particles shows rising trend with N_{part}

Next step:

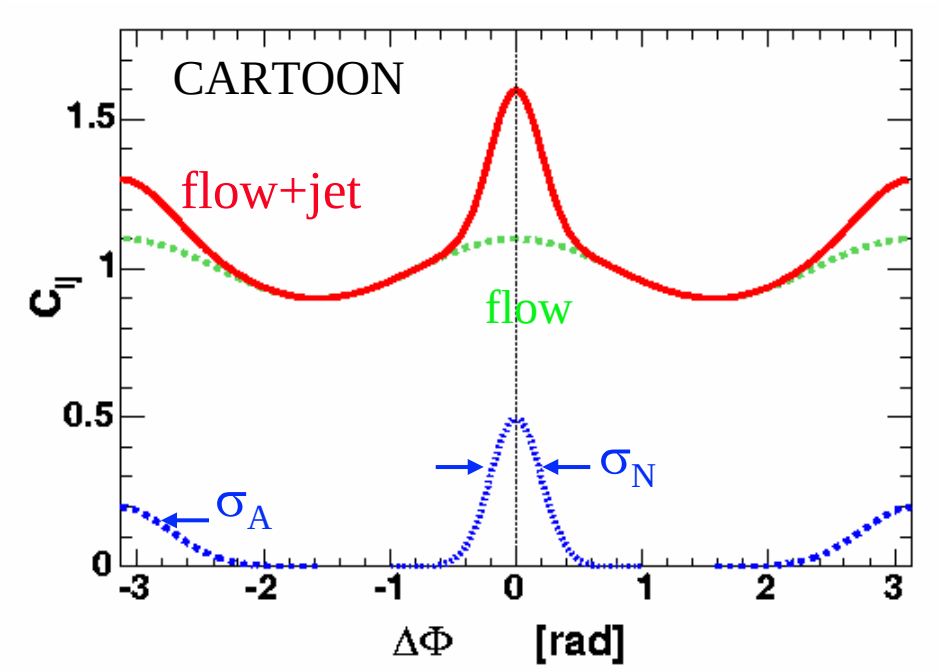
- map out this trend to explore whether this is a hint of jet-quenching balance
- Explore the AuAu fragmentation function

Backup slides

Method – azimuthal correlation function

Now we know the $\langle z \rangle$ - let us measure σ_N and σ_N.
Two particle azimuthal correlation function $\longrightarrow$ $C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$

Unavoidable source of two particle correlations in HI – elliptic flow



"flow" pairs :

$[1+2v_2^2 \cos(2\Delta\varphi)]$

Intra-jet pairs angular width :

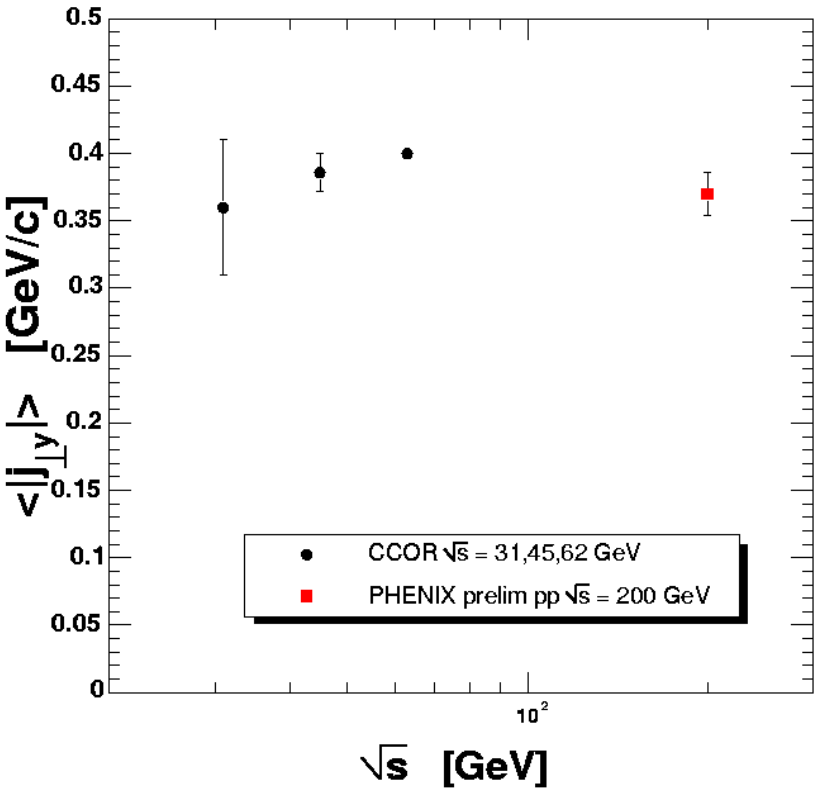
$\sigma_N \rightarrow \langle |j_{Ty}| \rangle$

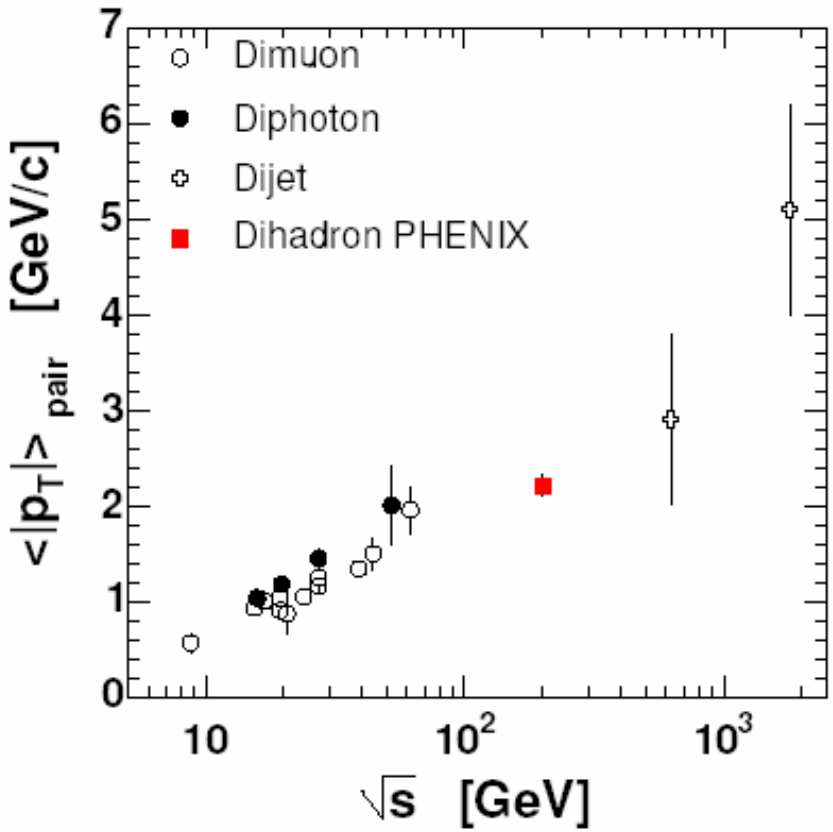
Inter-jet pairs angular width :

$\sigma_A \rightarrow \langle |j_{Ty}| \rangle \oplus \langle |k_{Ty}| \rangle$

Comparison to outside world

PHENIX preliminary

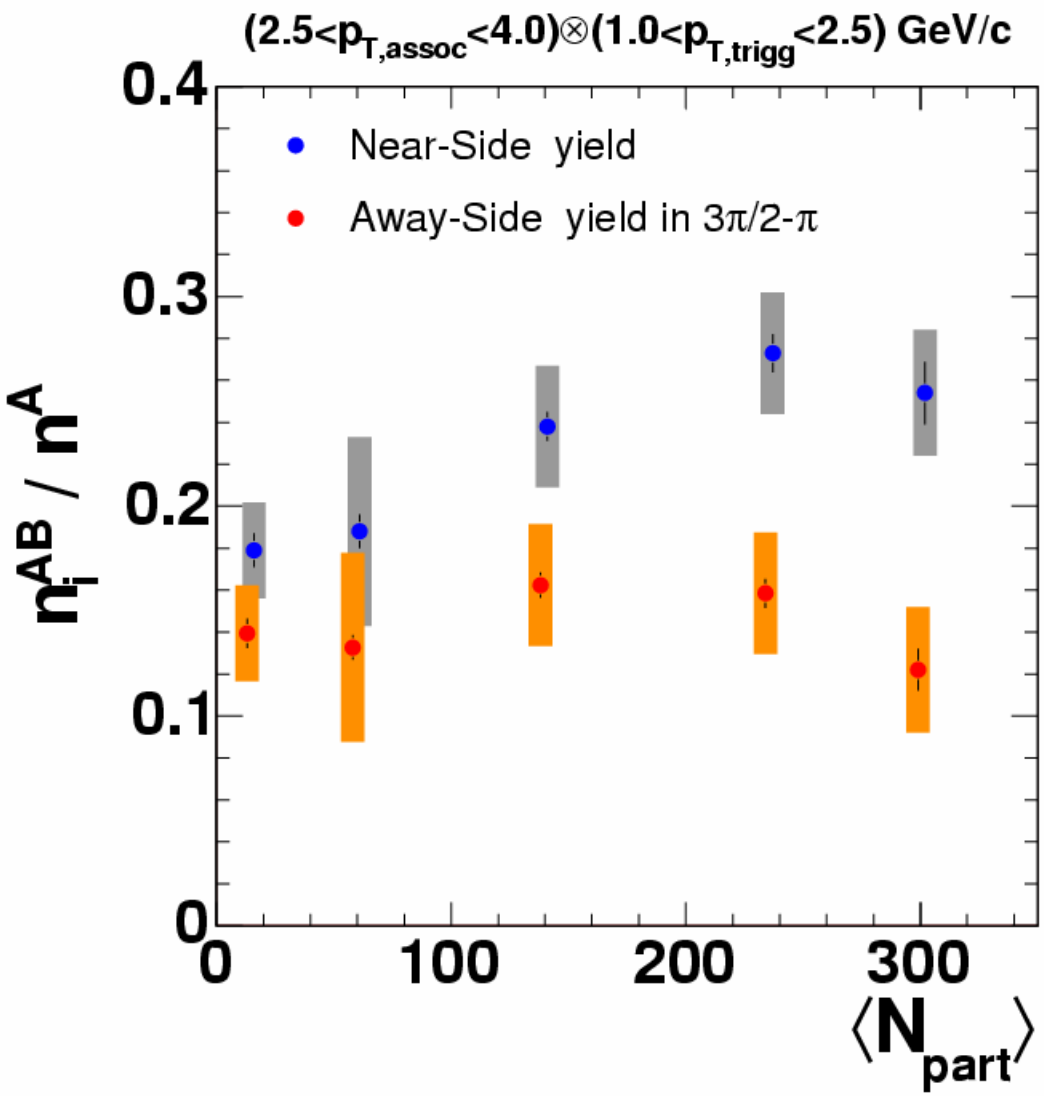




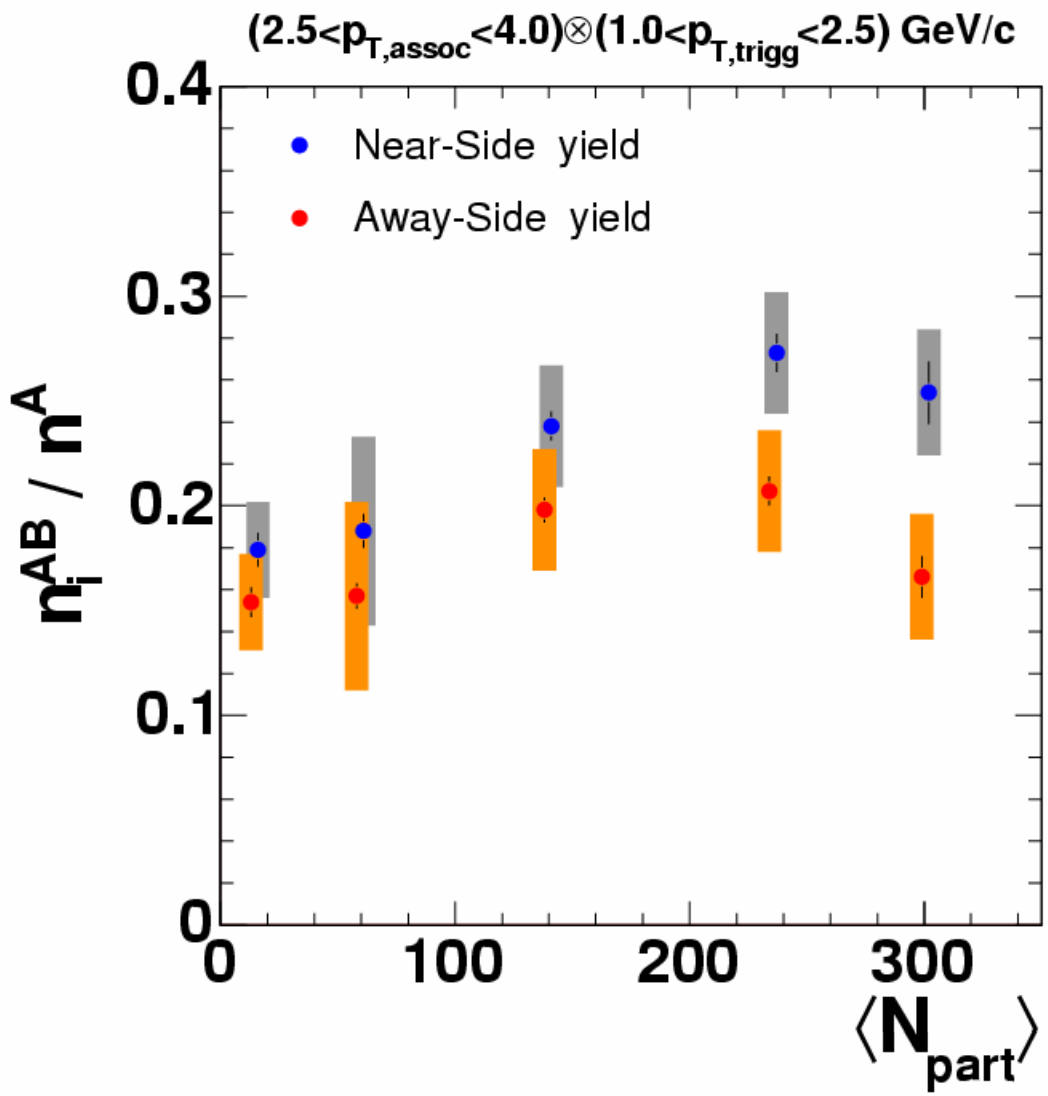
Add the legend – experiment names

Larger markers and legends

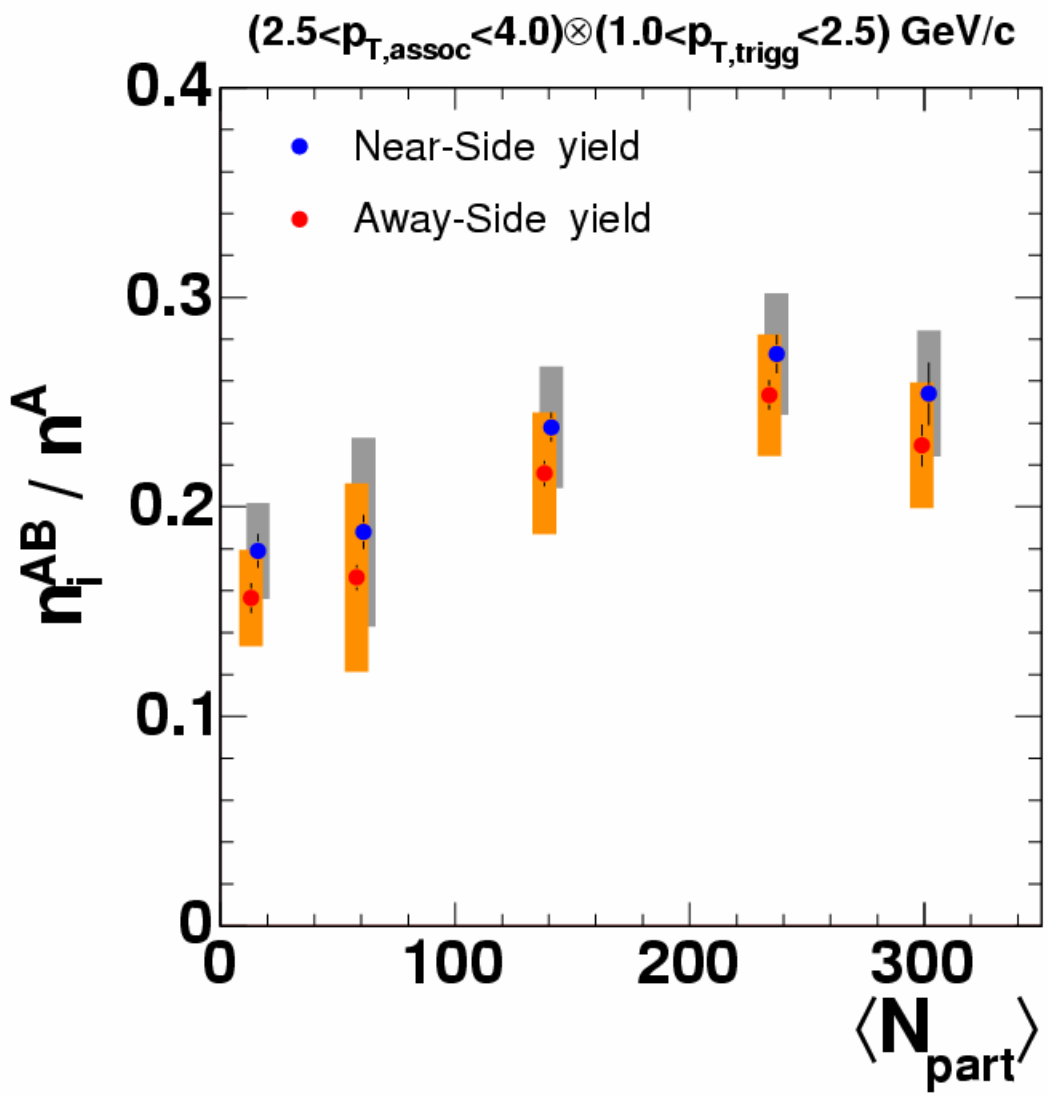
yeilds


(2.5<p_T,assoc<4.0)⊗(1.0<p_T,trigg<2.5) GeV/c
Near-Side yield
Away-Side yield in 3π/2-π
n_i^AB / n^A
⟨N_part⟩
0
0.1
0.2
0.3
0.4
0
100
200
300

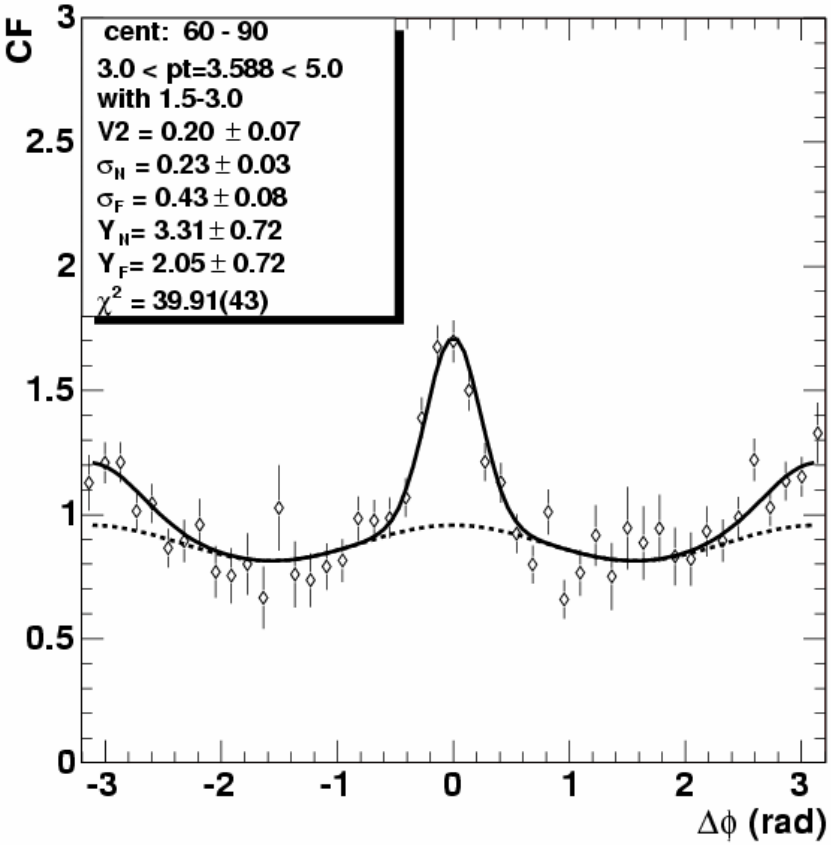
yeilds

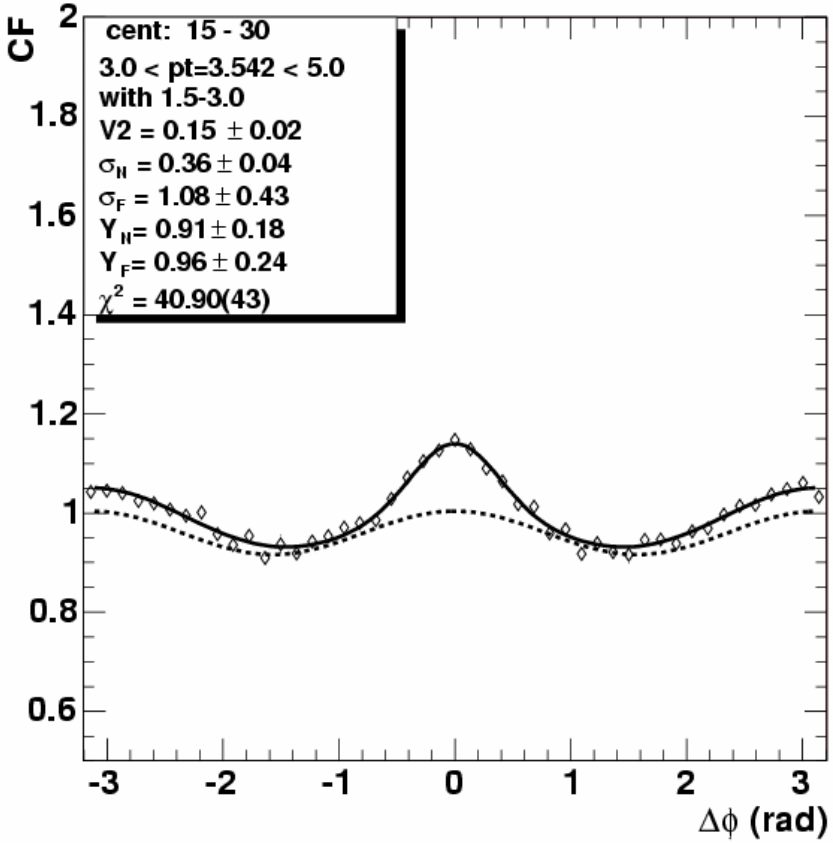

(2.5<p_T,assoc<4.0)⊗(1.0<p_T,trigg<2.5) GeV/c
Near-Side yield
Away-Side yield
n_i^AB / n^A
0.4
0.3
0.2
0.1
0
0
100
200
300
⟨N_part⟩

yeilds


(2.5<p_T,assoc<4.0)⊗(1.0<p_T,trigg<2.5) GeV/c
Near-Side yield
Away-Side yield
n_i^AB / n^A
0.4
0.3
0.2
0.1
0
0
100
200
300
⟨N_part⟩

CF's


cent: 60 - 90
3.0 < pt=3.588 < 5.0
with 1.5-3.0
V2 = 0.20 ± 0.07
σN = 0.23 ± 0.03
σF = 0.43 ± 0.08
YN= 3.31 ± 0.72
YF= 2.05 ± 0.72
χ2 = 39.91(43)
CF
Δφ (rad)


cent: 15 - 30
3.0 < pt=3.542 < 5.0
with 1.5-3.0
V2 = 0.15 ± 0.02
σN = 0.36 ± 0.04
σF = 1.08 ± 0.43
YN= 0.91 ± 0.18
YF= 0.96 ± 0.24
χ2 = 40.90(43)
CF
Δφ (rad)