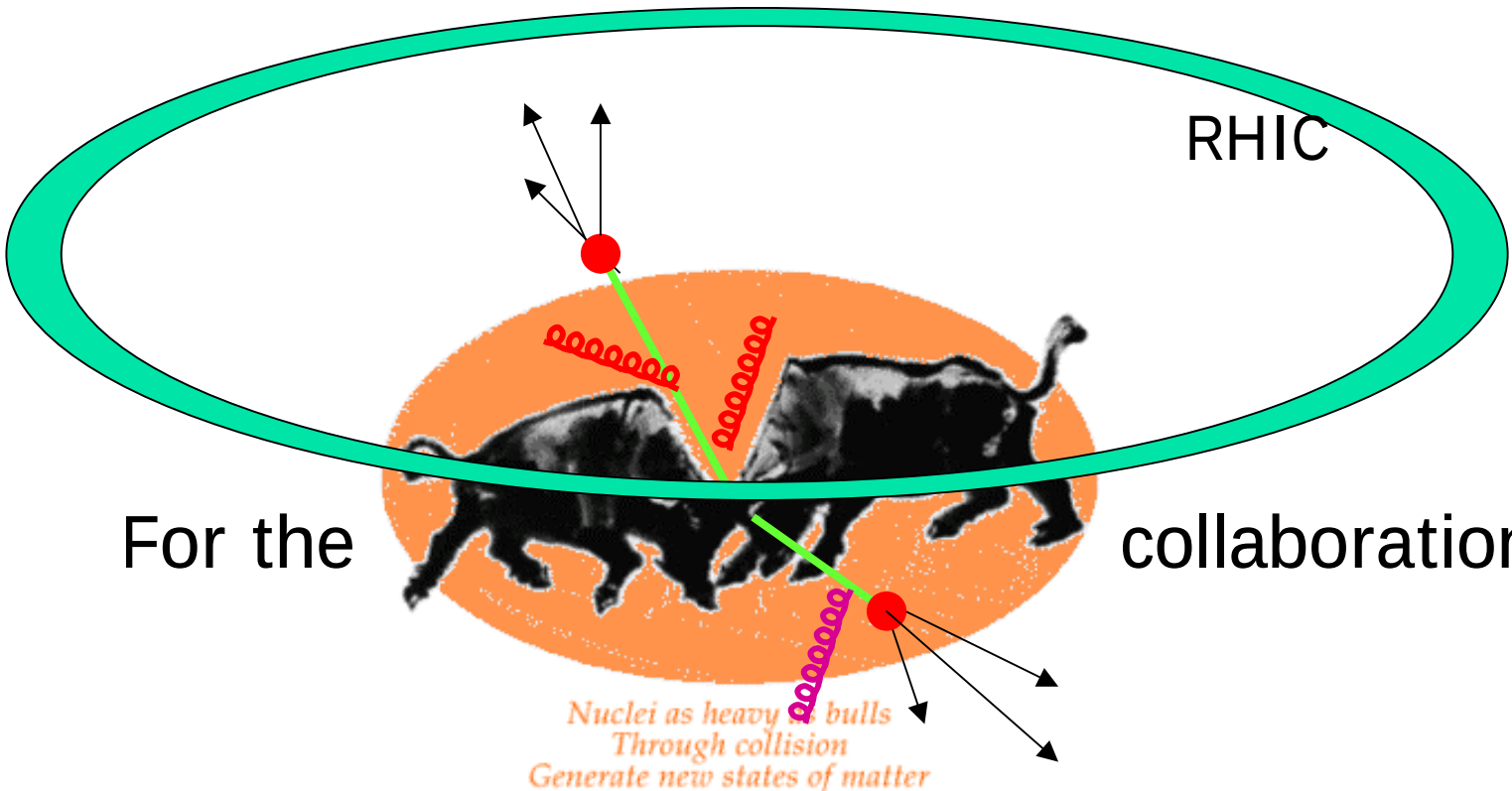
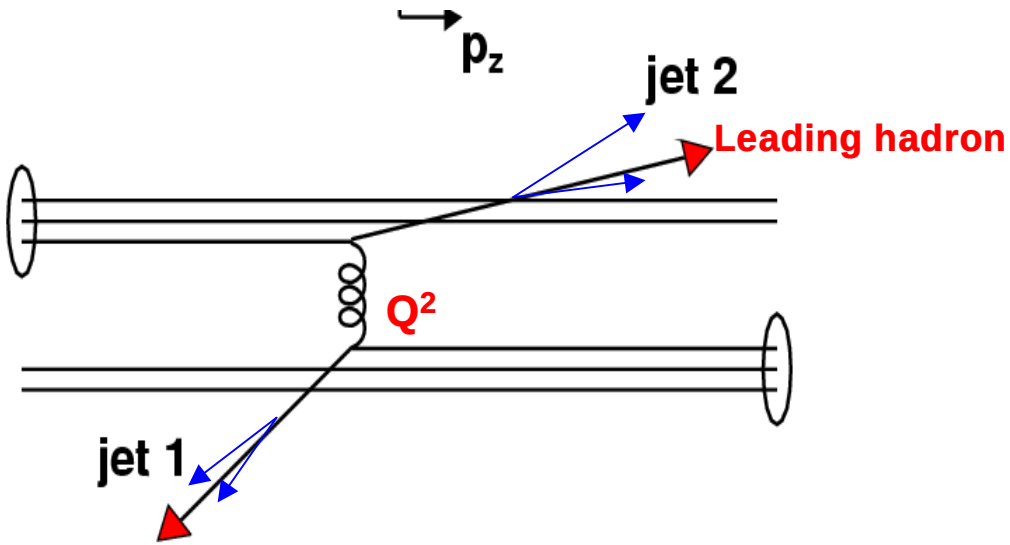
# Jet results in PHENIX

Jiangyong Jia Columbia University, Nevis Labs



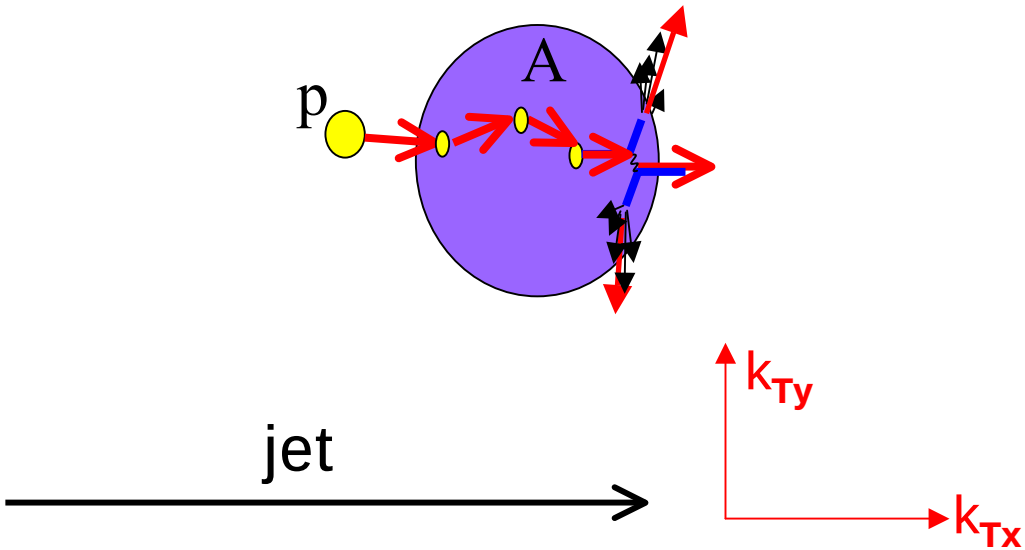

For the collaboration

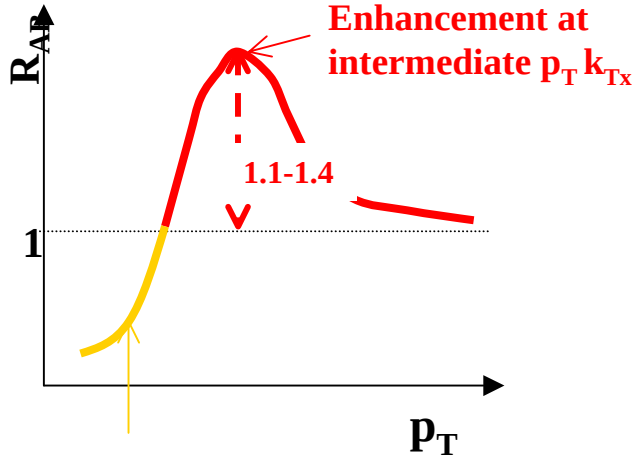
# Hard-scattering and Jet fragmentation

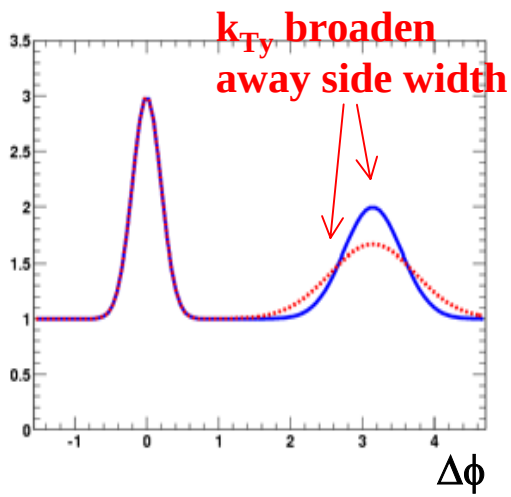



- Properties of di-jet system
  - **The spread of the hadrons around the jet axis and relative orientation of the two jets – jT, kT, Pout**
  - **The multiplicity of hadrons – fragmentation function D(z)**
  - **Well calibrated in pp**
- They can be accessed with two particle correlation in $\Delta\phi$.

# Probing the cold nuclear medium (p+A)



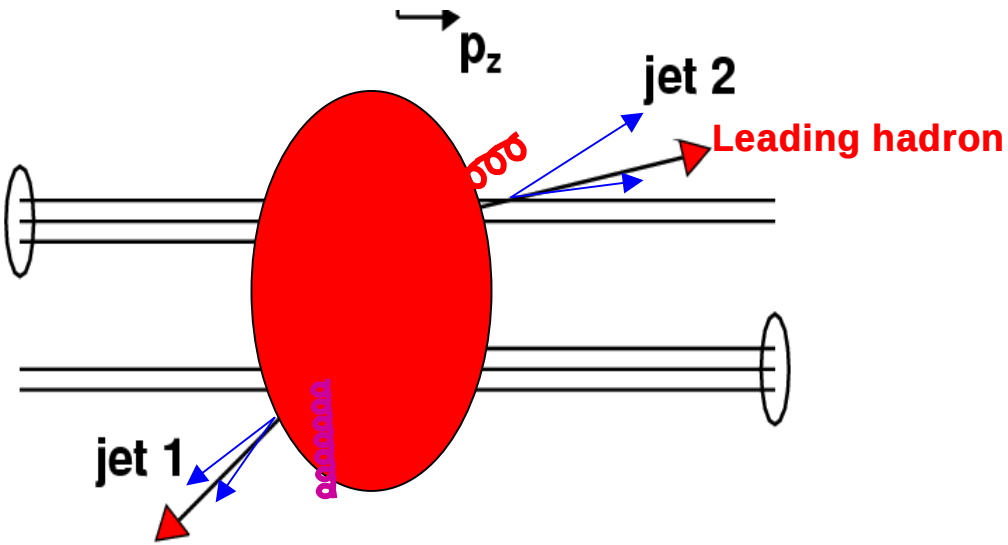




Multiple scattering

- Cronin effect
- Broadening of the back-to-back correlation

# Probing the sQGP (A+A)

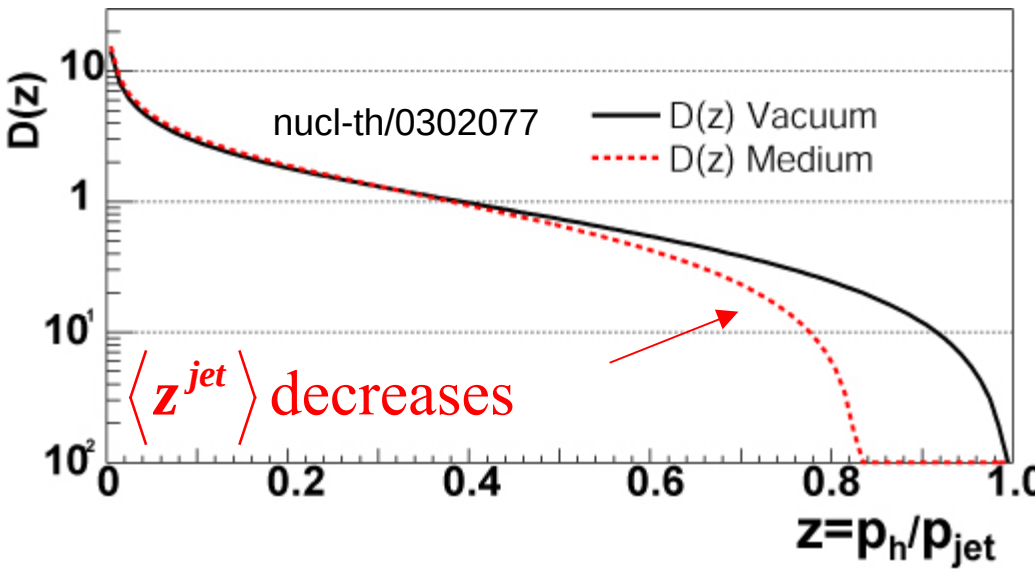



## Induced gluon Radiation

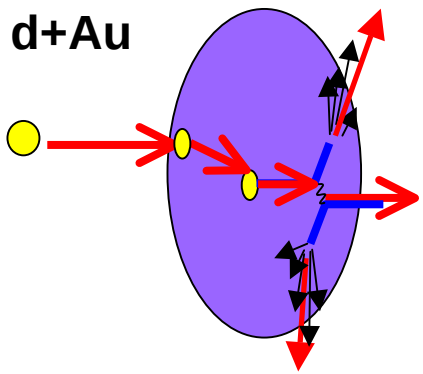
$$\langle \Delta k_T^2 \rangle \sim \int \rho_g(x)\, dx$$

$$\langle \Delta E \rangle \sim \int x\, \rho_g(x)\, dx$$

- ~collinear but broadened
- "Softened" fragmentation

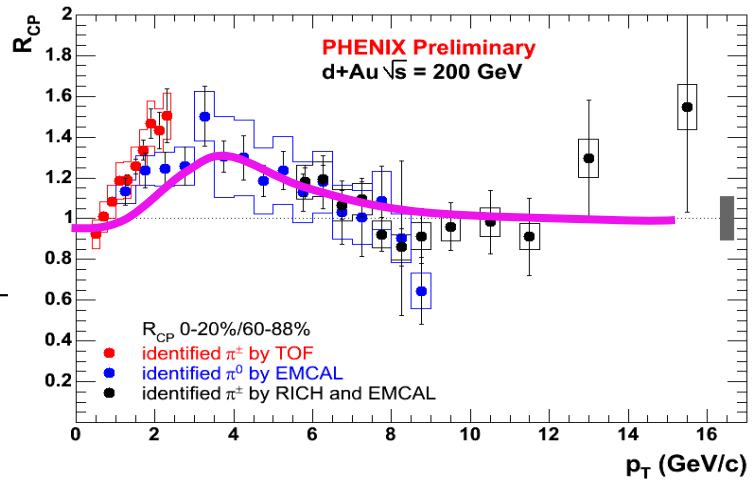


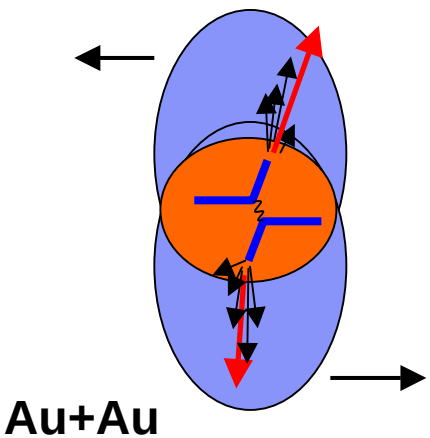
# Hadrons that interact with Medium




- Croning effect

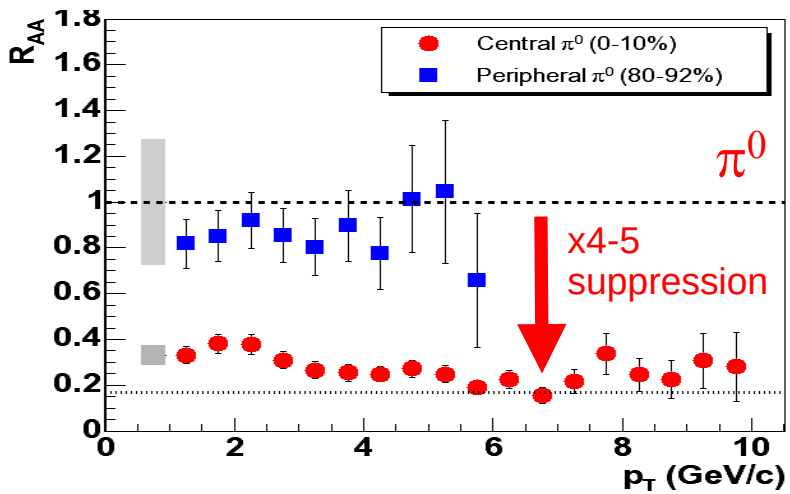
$$R_{cp} = \frac{\text{Yield (Central), scaled}}{\text{Yield (Periph), scaled}}$$



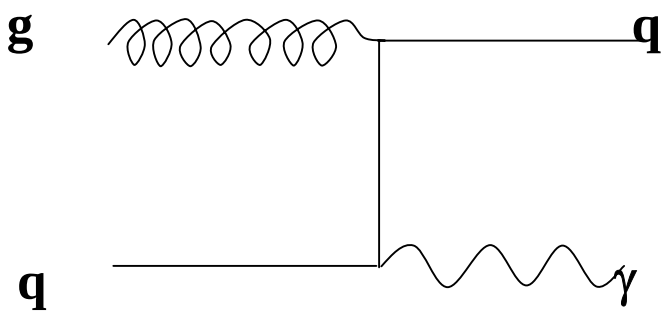

- Medium-induced energy loss

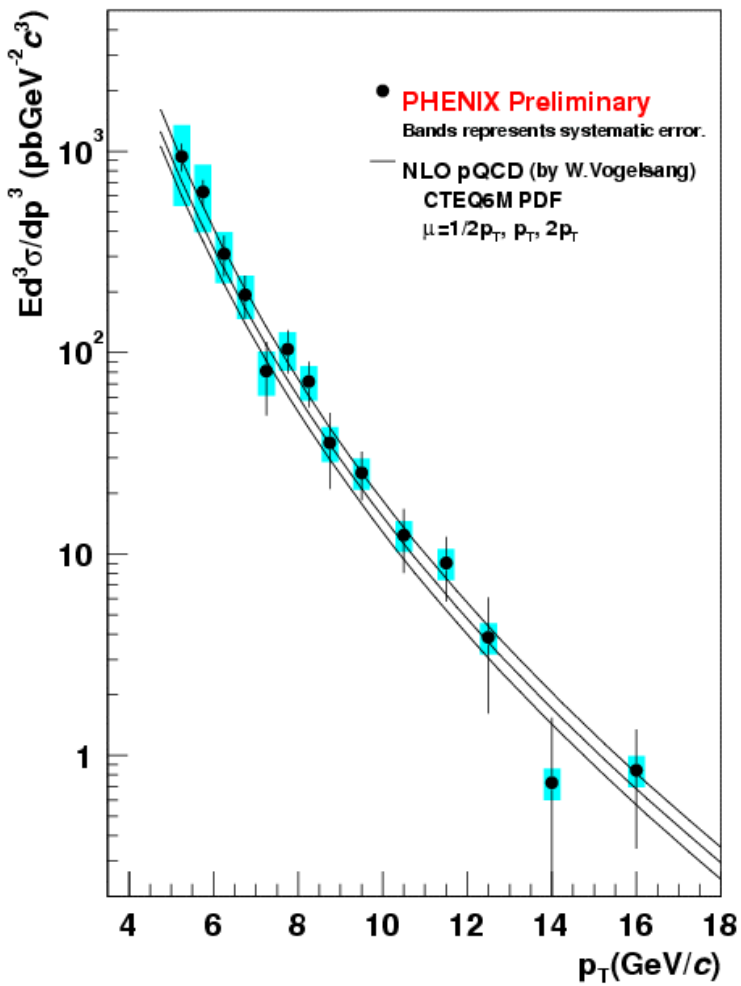
$$R_{AA} = \frac{\text{Yield}(AA)\text{, scaled}}{\text{Yield}(pp)}$$



# Direct γ: pQCD

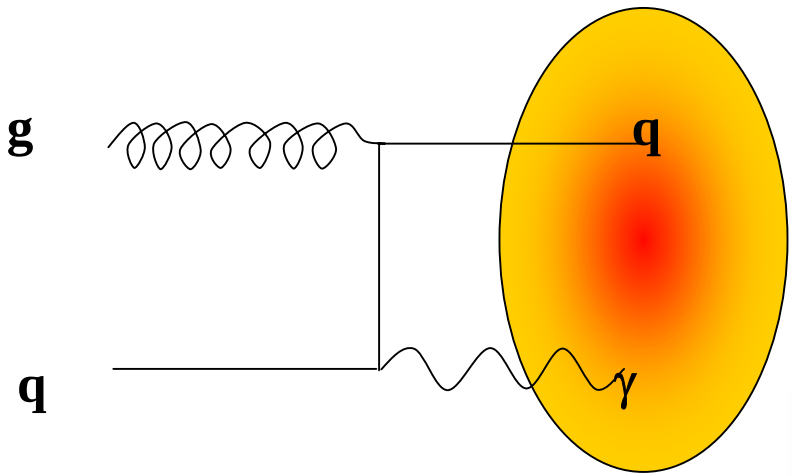
**Quark gluon Compton scattering**



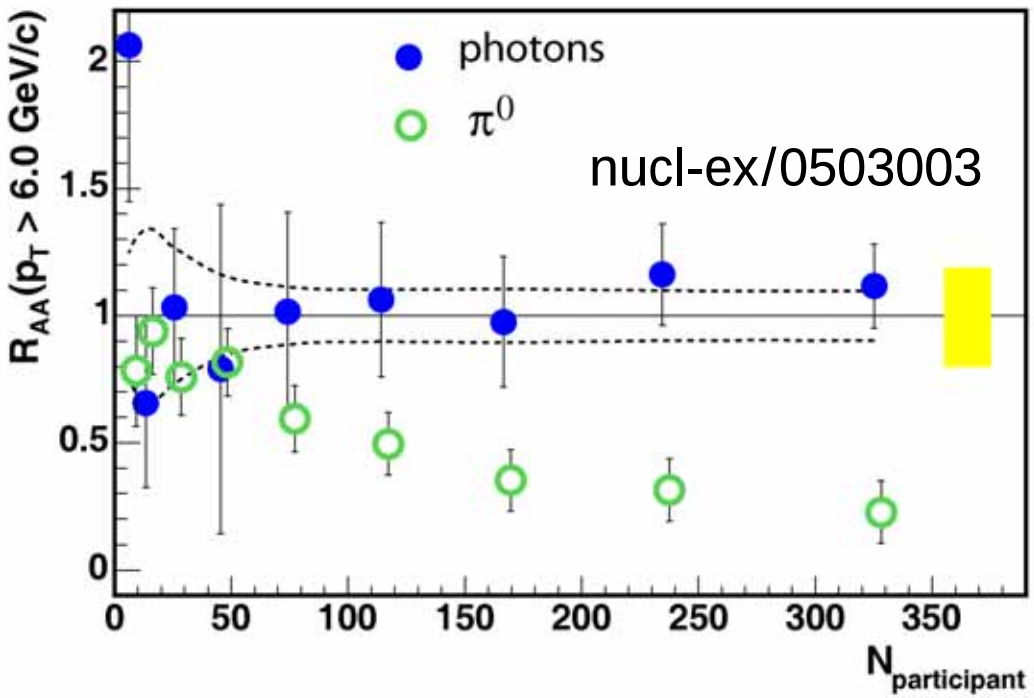

<u>good agreement with pQCD calculation</u>

# Direct $\gamma$: pQCD + Binary scaling




<u>High pT $\gamma$</u>

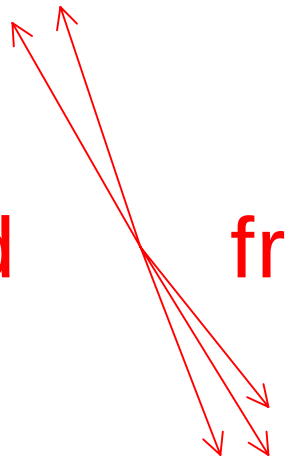
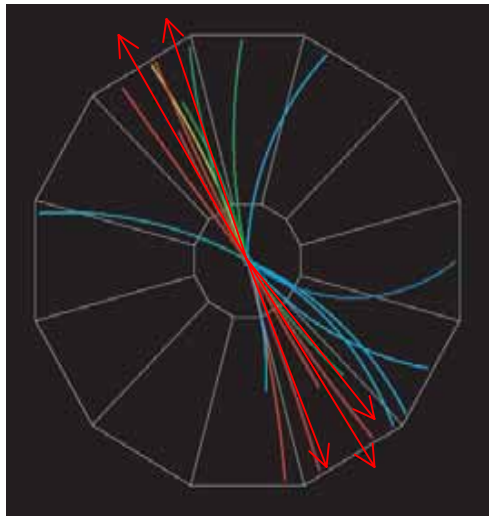
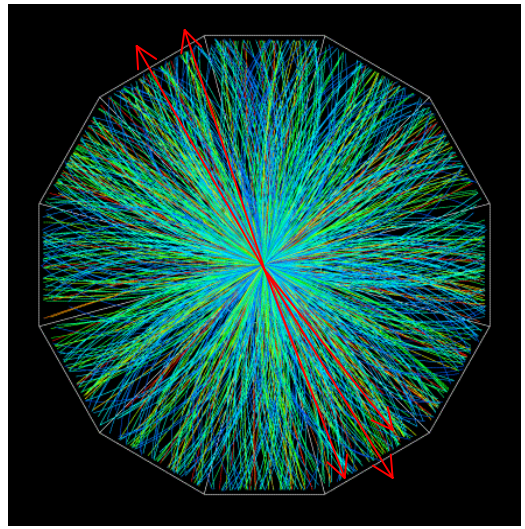
- Dominated by direct photon(>6 GeV/c)
- Initial state partons not suppressed




Hadron($\pi^0$) suppression is a final state effect

# Probing the nuclear medium with jets

Probes

Find  from  and  !

- How to measure jets in PHENIX P. Stankus
- Jet modifications, RP and flavor dependence in AuAu

  P. Stankus, W. Holzmann, B. Jacak
- Jet properties in pp and dAu J. Rak, N. Grau
- OutLook and summary

# Two particle correlation in PHENIX

# Two particle correlation in PHENIX

1) In ideal acceptance, real pair distribution in $\Delta\phi$, $\Delta\eta$ is

$$dN_0^{real} / d\Delta\phi d\Delta\eta = \lambda + jet(\Delta\phi, \Delta\eta)$$

2) It is modulated by PHENIX pair acceptance function $Acc(\Delta\phi, \Delta\eta)$.

$$dN^{real} / d\Delta\phi d\Delta\eta = Acc(\Delta\phi, \Delta\eta)(\lambda + jet(\Delta\phi, \Delta\eta))$$

3) Pair acceptance function can be determined from event mixing technique

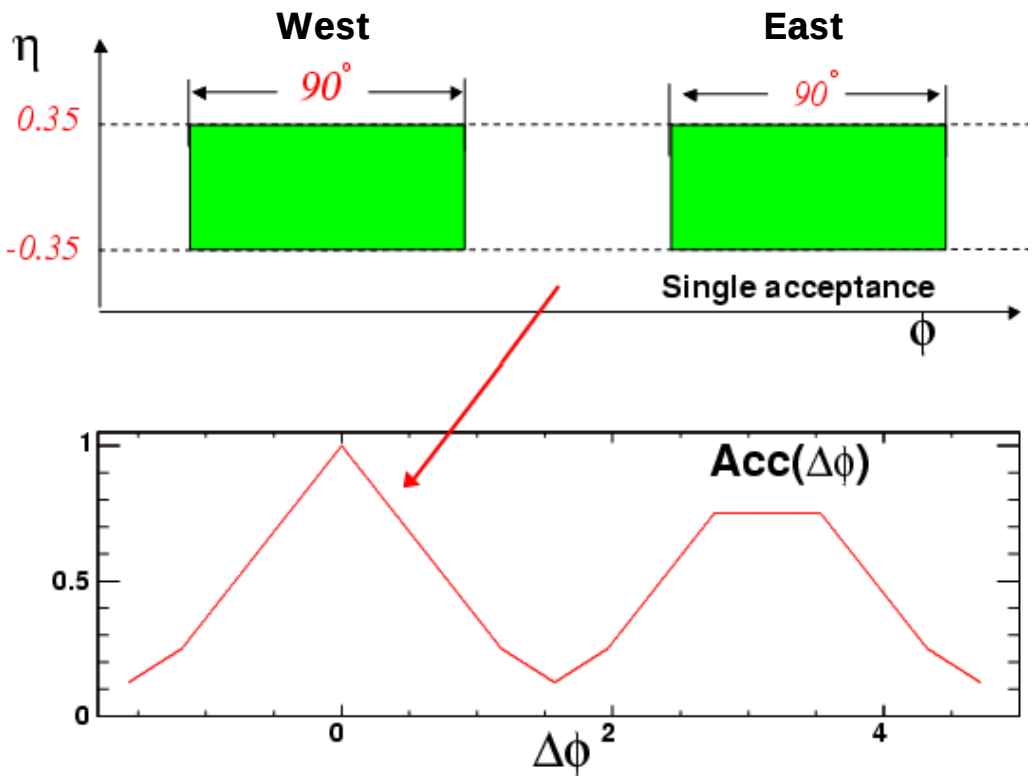
$$dN^{mix} / d\Delta\phi d\Delta\eta \propto Acc(\Delta\phi, \Delta\eta)$$

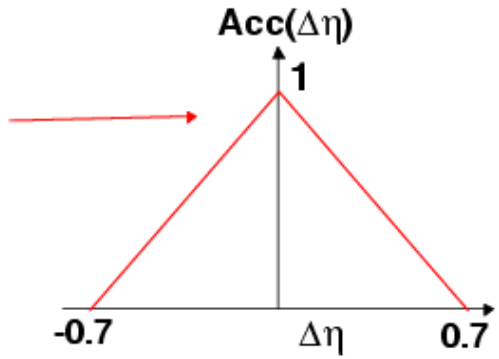
4) Real/mix gives the acceptance corrected CY.

$$\frac{1}{N_{Trig}^0} \frac{dN_0^{real}}{d\Delta\phi d\Delta\eta} \propto \frac{dN^{real} / d\Delta\phi d\Delta\eta}{dN^{mix} / d\Delta\phi d\Delta\eta} \propto \lambda + jet(\Delta\phi, \Delta\eta)$$

1D correlation function: $dN/\Delta\phi$ or $dN/d\Delta\eta$.

# Pair acceptance function ACC in PHENIX



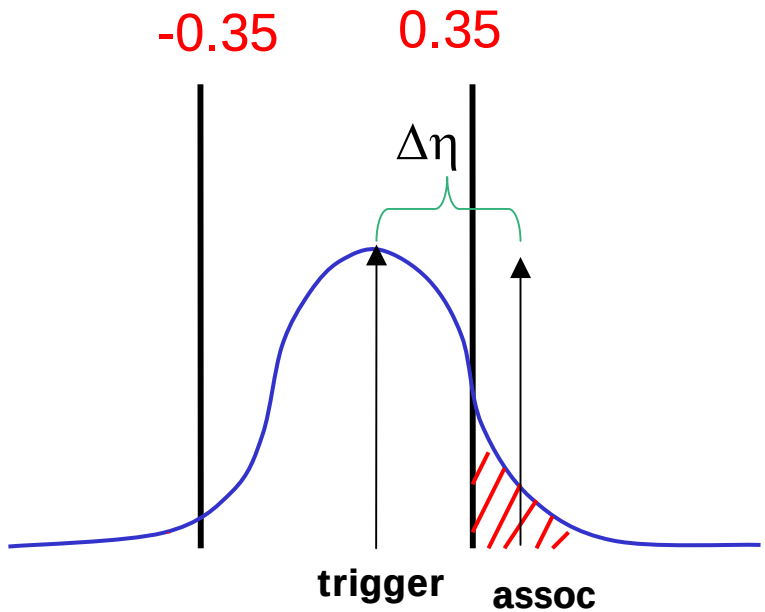



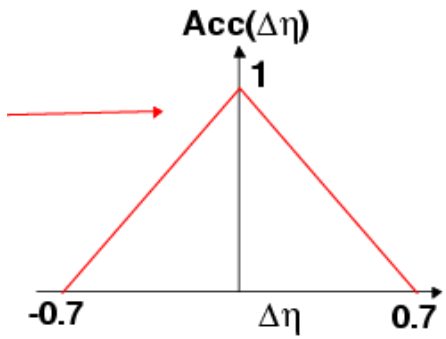

Shape from overlapping four triangles:

**west1-west2, east1-east2, west1-east2, east1-west2**

Pair effi is 100% at $\Delta\phi=0$, $\Delta\eta=0$. average is 25%

# The correction in $\Delta\eta$




Pair acceptance is limited by single acceptance: $|\eta|<0.35 \Rightarrow |\Delta\eta|<0.7$

- If we know the jet shape in $\Delta\eta$, we can correct back to true yield in $|\Delta\eta|<0.7$

$$R_{\Delta\eta} = \frac{\int_{-\infty}^{+\infty} d\Delta\eta\, jet(\Delta\eta) Acc(\Delta\eta)}{\int_{-\infty}^{+\infty} d\Delta\eta\, jet(\Delta\eta)}$$

Convoluted with pair acceptance

- In pp/dAu collisions, jet shape is the same in $\Delta\phi$ and $\Delta\eta$. (AuAu is different!)

# Extracting jet properties

- Correlation function in $\Delta\phi$: per-trigger-yield

  correct for pair acceptance , efficiency and $\Delta\eta$ .

$$\frac{1}{N^0_{trig}}\frac{dN^0}{d\Delta\phi} = \frac{1}{N_{trig}}\frac{N_{corr}(\Delta\phi)}{\underbrace{2\pi N_{mix}(\Delta\phi)\Big/\int d\Delta\phi\, N_{mix}(\Delta\phi)}}\frac{R_{\Delta\eta}}{\varepsilon}$$

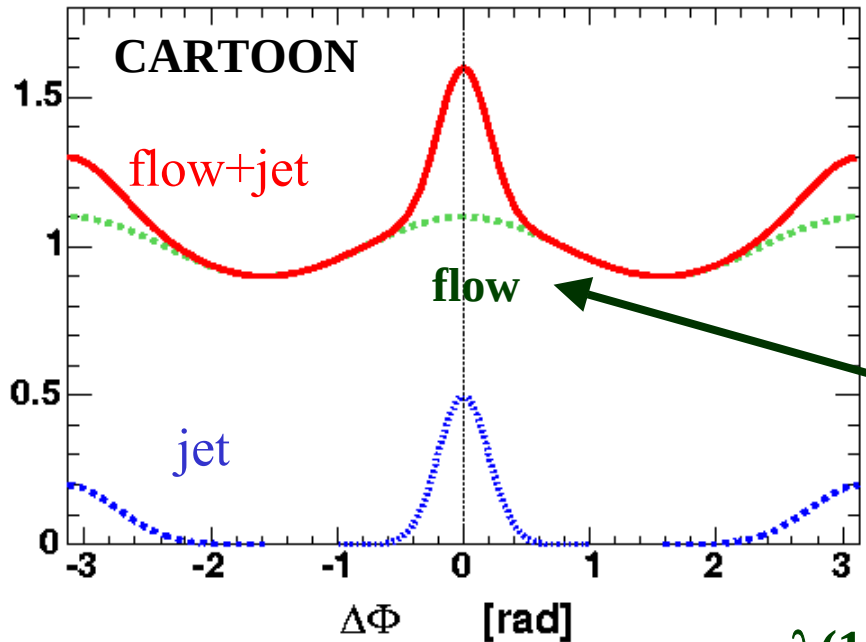
- Fit per-trigger-yield with a double gauss + constant

$$\frac{1}{N^0_{trig}}\frac{dN_0}{d\Delta\phi} = \lambda + \frac{Yield_{Near}}{\sqrt{2\pi}\sigma_N}e^{\frac{-\Delta\phi^2}{2\sigma_N^2}} + \frac{Yield_{Far}}{\sqrt{2\pi}\sigma_F}e^{\frac{-(\Delta\phi-\pi)^2}{2\sigma_F^2}}.$$

Underlying event  Near side jet  Far side jet

# Underlying event in Au+Au

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$$




**combinatorial background is large in Au+Au!**

**And is not constant!**

**elliptic flow causes another correlation in them:**

$$\lambda(1+2v_2(p_T^{trig})v_2(p_T^{assoc})\cos(2\Delta\phi))$$

See P. Stankus's talk for more details

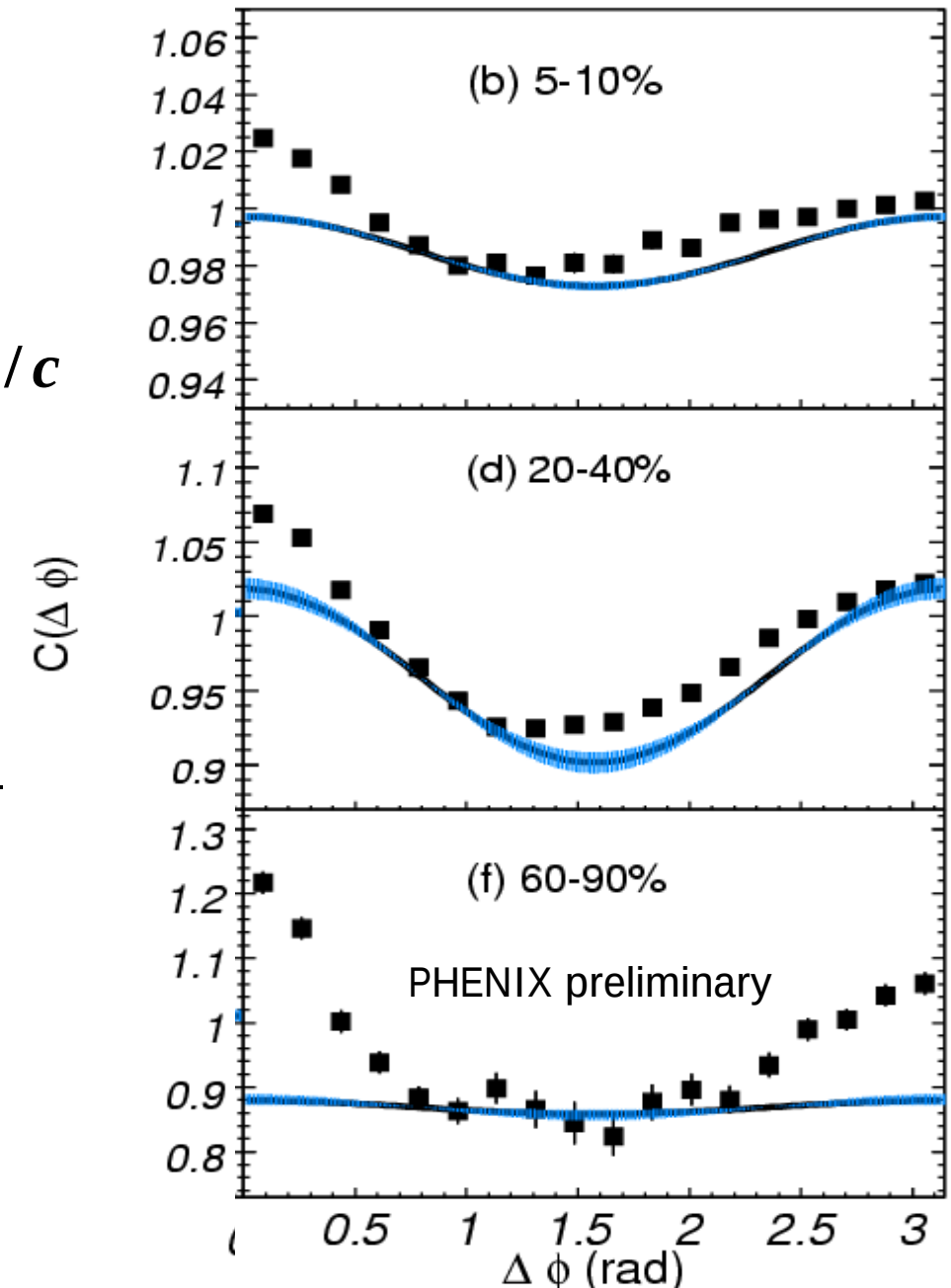
# Results from Au+Au

# Jet correlation in Au+Au

See W. Holzmann and P. Stankus

h-h correlation

$$1 < p_{T,assoc} < 2.5 < p_{T,trig} < 4.0\,GeV/c$$




Intermediate pT correlation

- Jet pair fraction is small
- Jet shape is strongly distorted at away side

# Medium modification

- Assume Zero jet yield at minimum
- Systematics dominated by v2

Wolf and Paul's talk

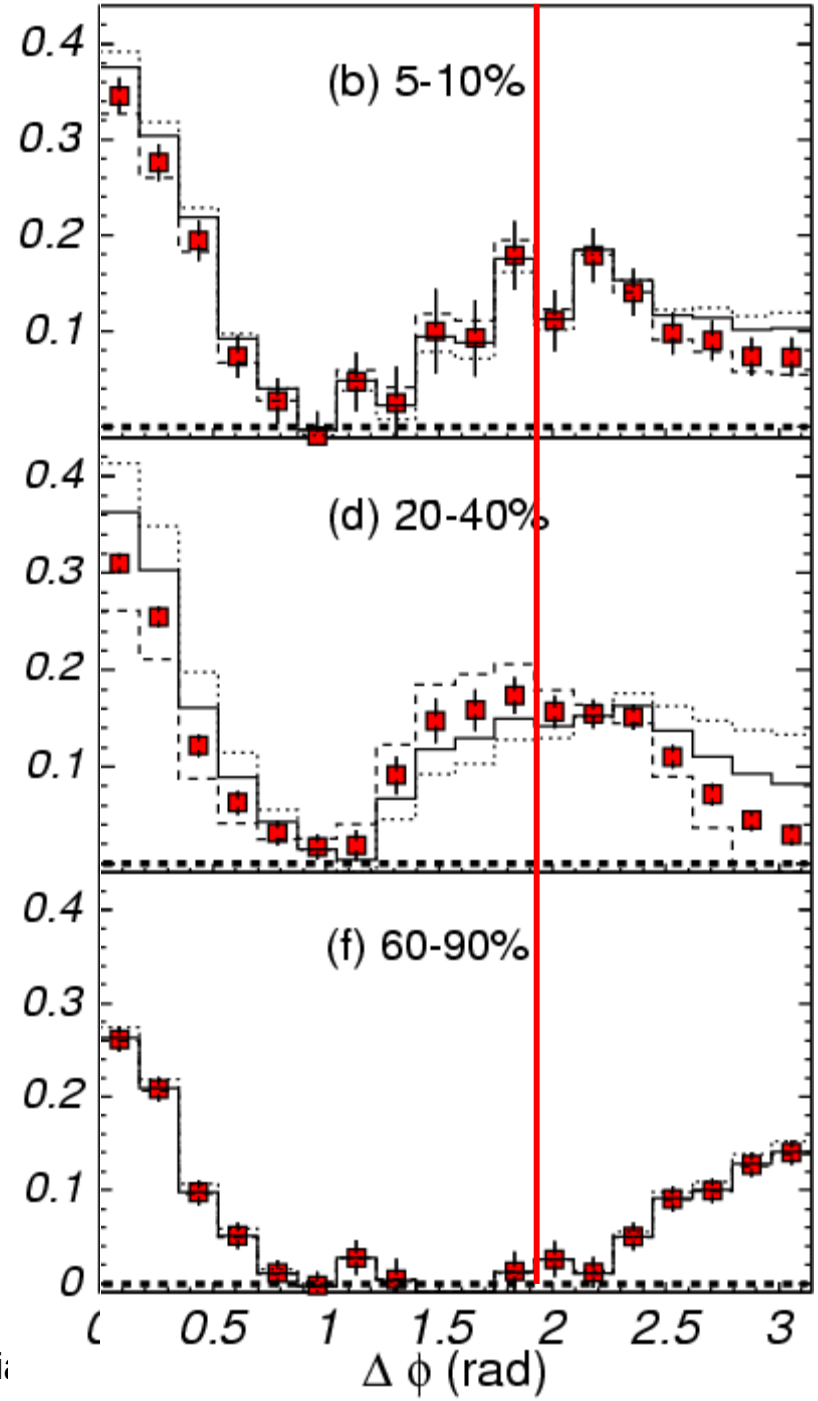
Away side is strongly distorted
2 $\sigma$ dip at $\pi$.

Jet interact with flowing medium

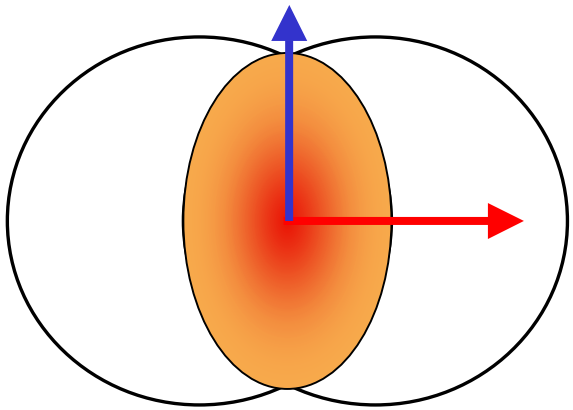
**nucl-th/0312065, S. Voloshin**

**hep-ph/0411315 Shuryak**

**hep-ph/0411341 Armesto,Salgado,Wiedemann**

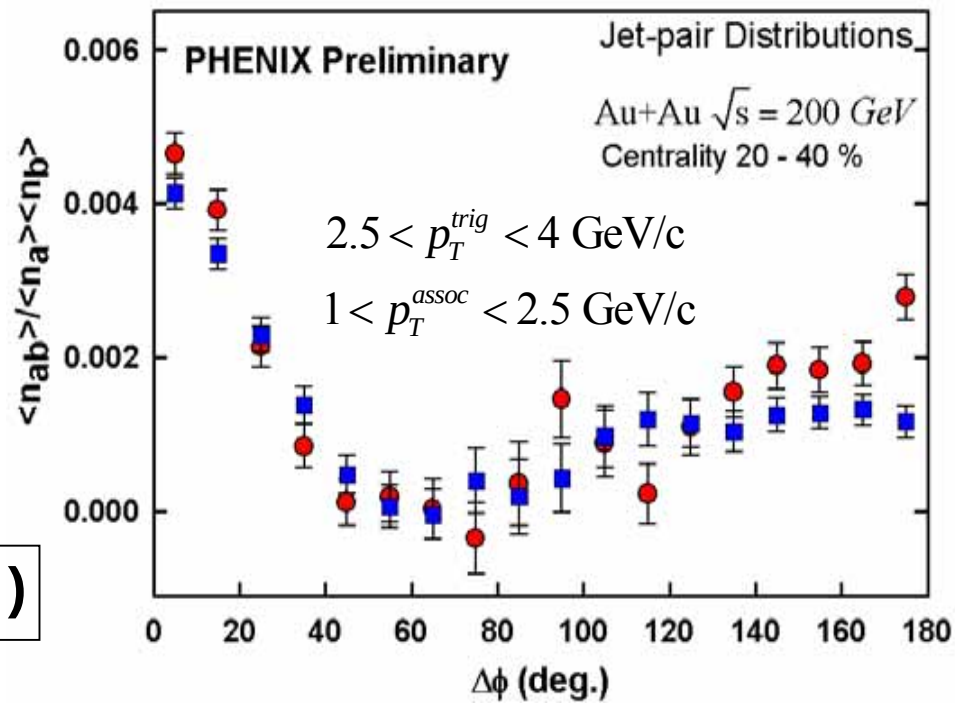


# Path Length Dependence

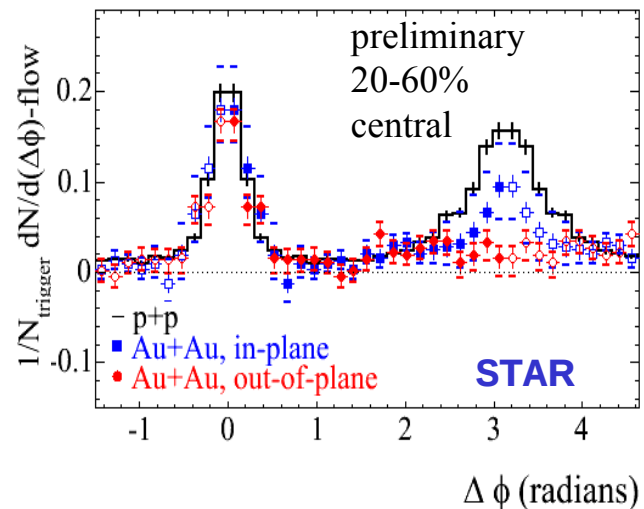


$$\Delta E \propto \int d\tau\, (\tau - \tau_0)\, \rho\big(\tau, r(\tau)\big) \approx L(\phi)$$

di-hadron, 20-40% Central




Difference is still quite qualitative



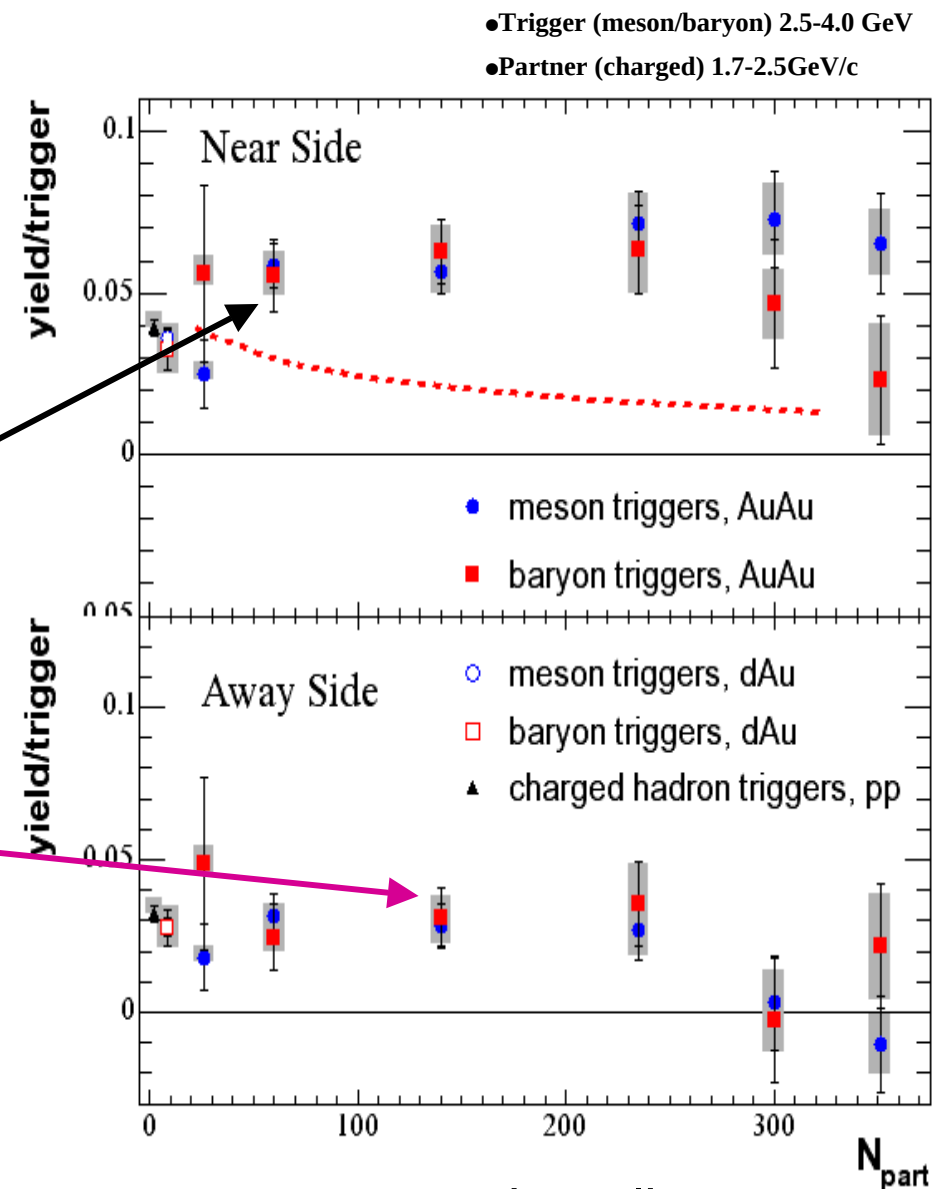
# Leading identified hadron correlation

**nucl-ex/0408007**

Yield integrated in 55°

- Jet partner ~ equally likely for trigger baryons & mesons!
- Larger partner probability than pp, dAu
- Away side: partner rate as in p+p

**recombination of quarks from plasma with jet fragments?**

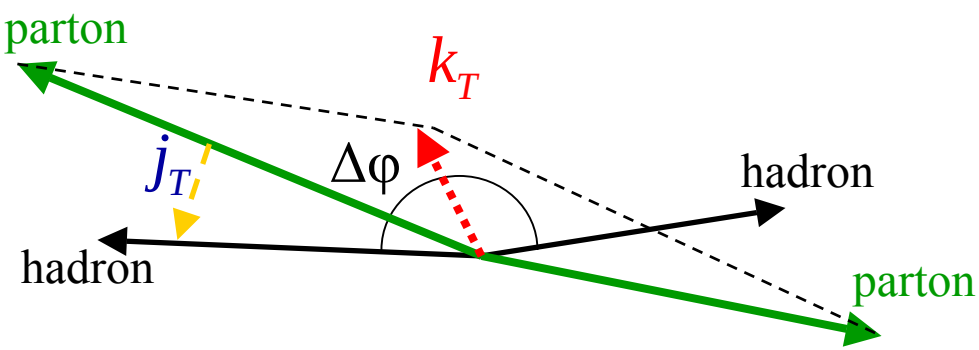



See B. Jacak's talk

# Calibrating the Jet properties in pp and dAu

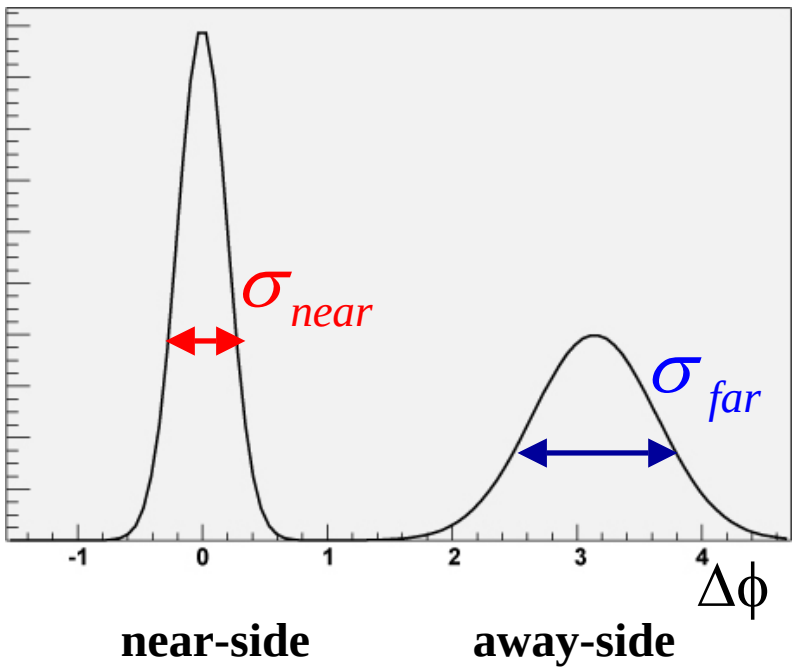
More details in J.Rak and N. Grau's talk

# Di-hadron Fragmentation (shape)




$k_{Ty}$ : total $p_T$ of parton pair

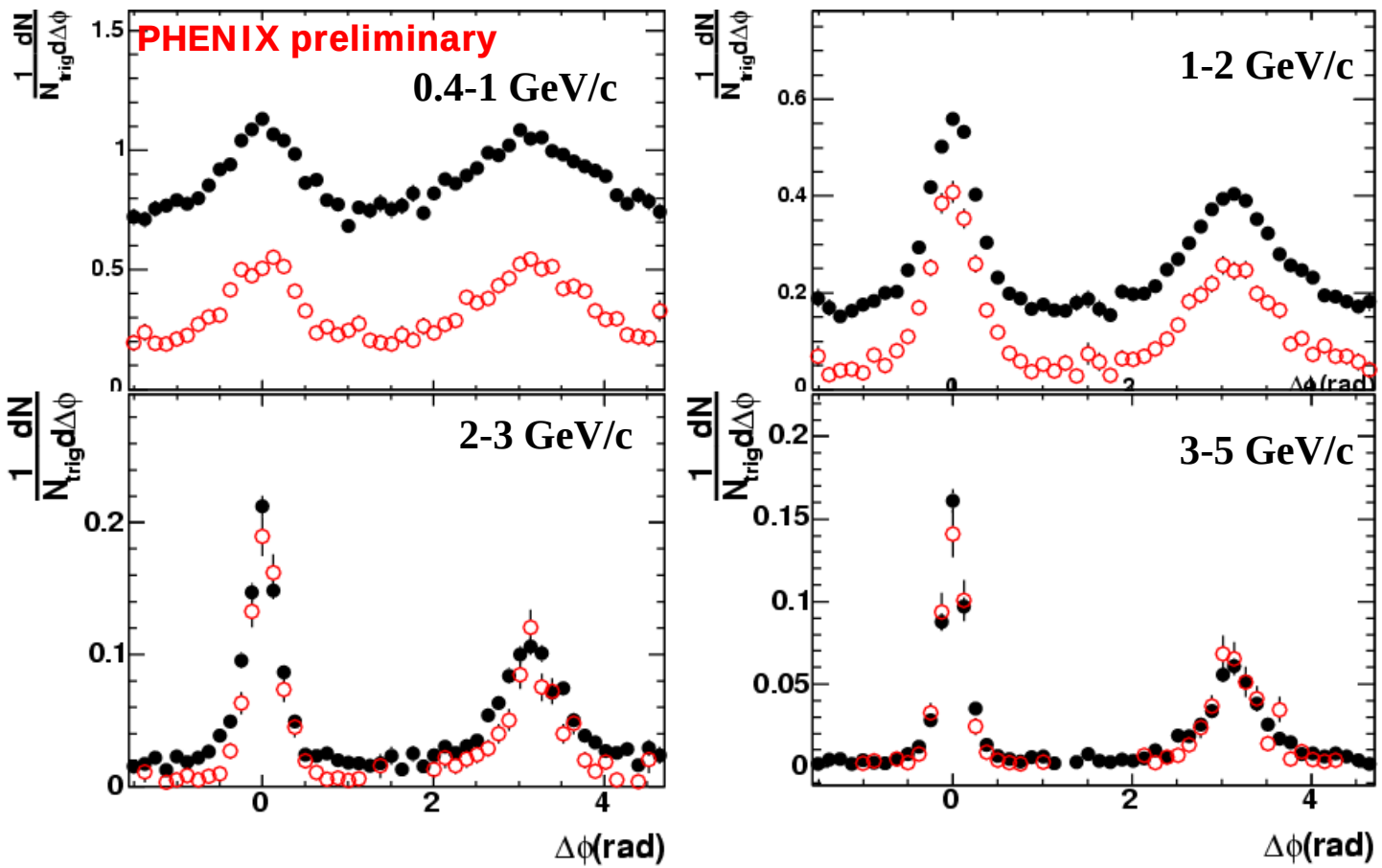
$j_{Ty}$ : $p_T$ of hadron $\perp$ to jet axis




$j_{Ty} \propto \sigma_{near}$ **Jet "width"**

$k_{Ty} \propto \sqrt{\sigma_{far}^2 - \sigma_{near}^2}$ **Jet-coplanarity**

# d-Au/p-p, $\pi^{\pm}$ - h, $\Delta\phi$ Correlations




● d-Au

○ p-p

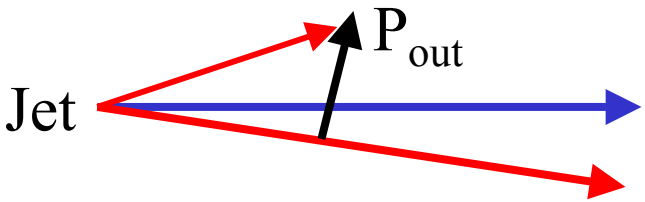
$p_{T,trig}$ > 5 GeV/c

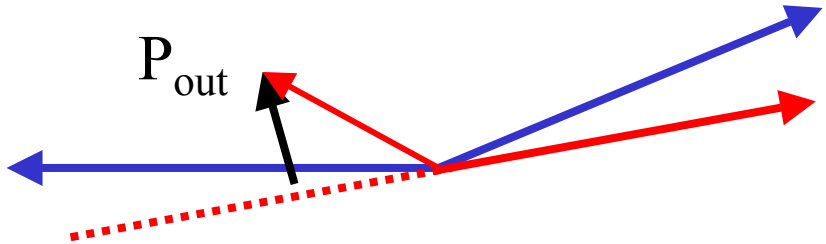
Jet shape is given by the near side and far side width → jT, kT

Jet multiplicity is given by the area under the peak

Jet properties extracted from this figure

# Alternative Method for (di)jet Shape

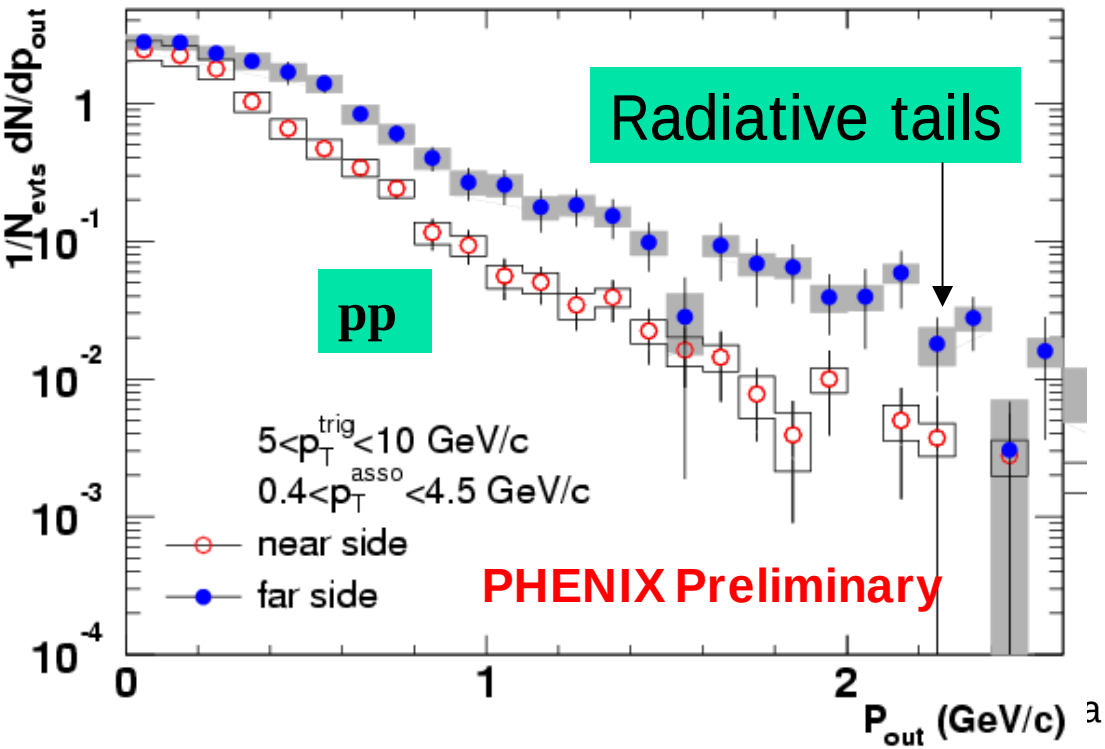



$$\left\langle p_{out}^2 \right\rangle \approx \left\langle j_T^2 \right\rangle + x_E^2 \left\langle j_T^2 \right\rangle \approx \left\langle j_T^2 \right\rangle$$

$$\left\langle p_{out}^2 \right\rangle \approx \left\langle j_T^2 \right\rangle + x_E^2 \left\langle j_T^2 \right\rangle + 2 x_E^2 z^2 \left\langle k_T^2 \right\rangle$$

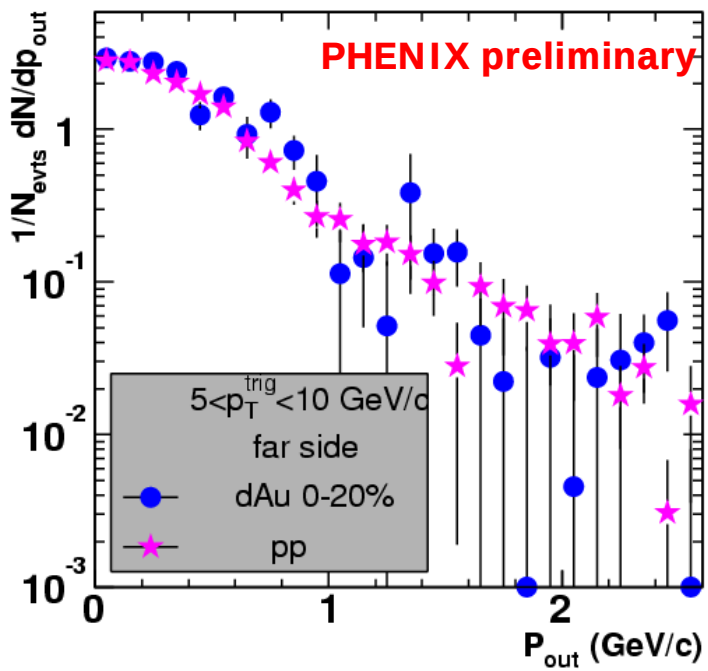
$$2 x_E^2 z^2 \left\langle k_T^2 \right\rangle \approx \left\langle p_{out,far}^2 \right\rangle - \left\langle p_{out,near}^2 \right\rangle$$

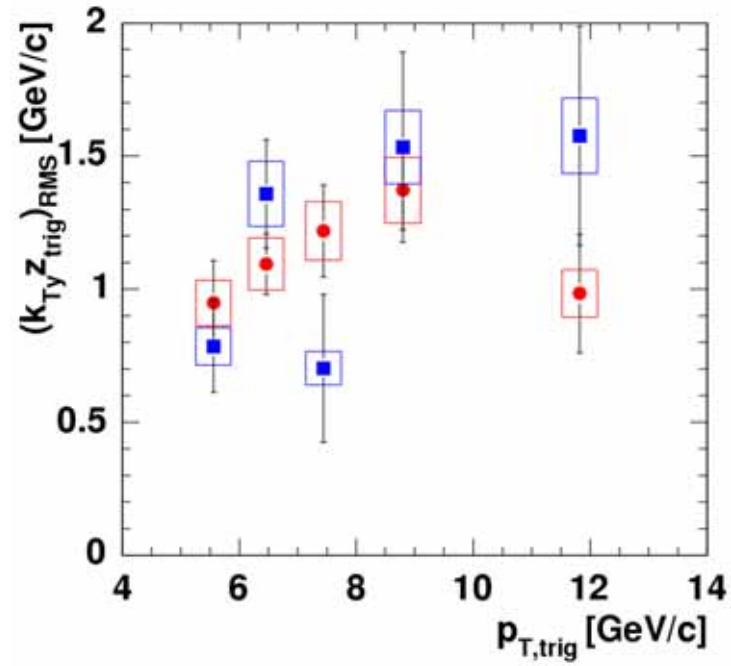



- By measuring pout pair-by-pair, more directly see the shape of the $j_T/k_T$ dist's.
- See non-Gaussian tails – expected due to hard radiation.

# dAu central vs pp

See N. Grau's talk




**No apparent indication of increased $k_T$.**

**No sensitivity to multiple scattering?**

$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) \ .$$

C~ 0.2-0.4

0.8-1.6 $(GeV/c)^2$ in central collisions

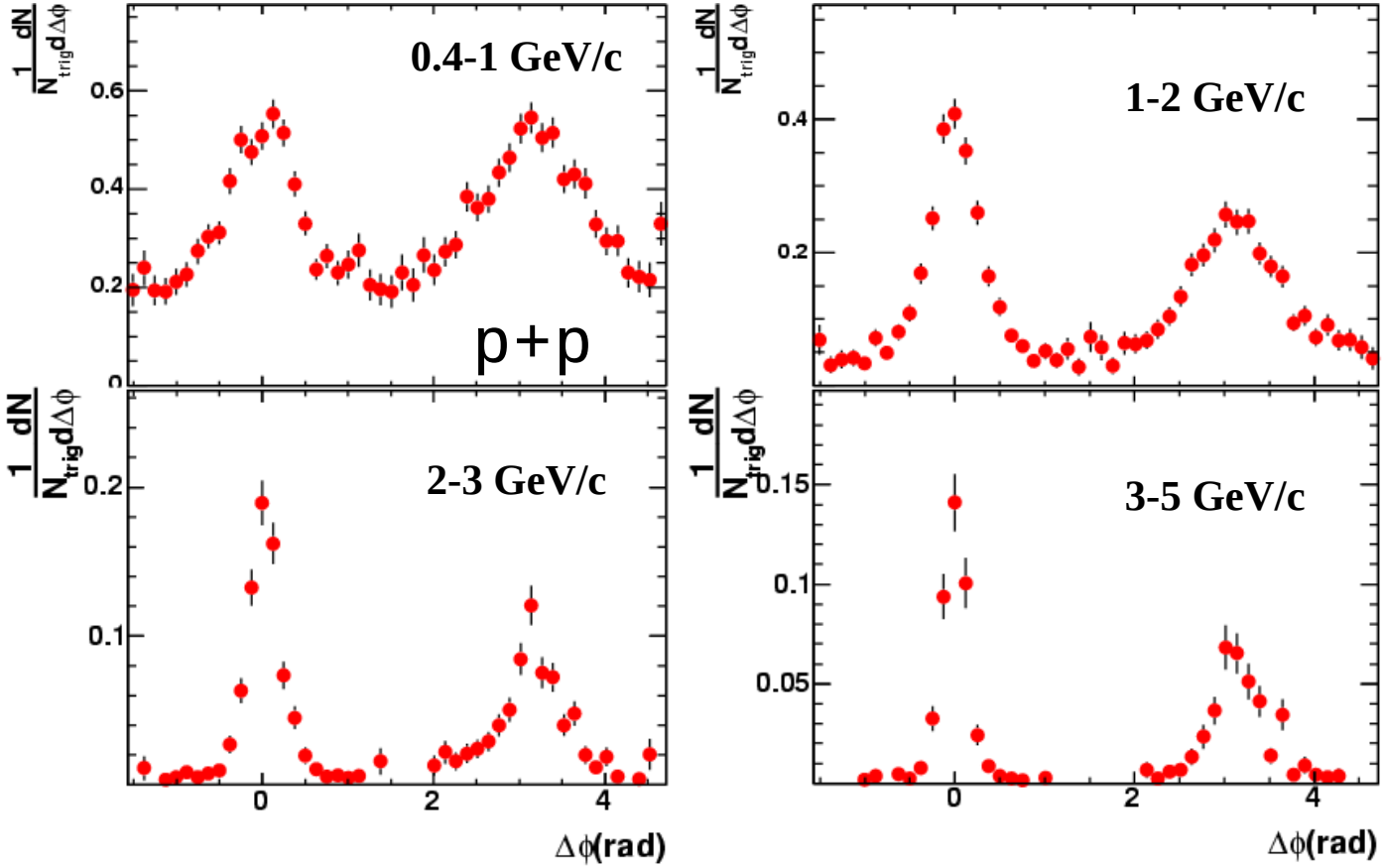
$$\langle k_\perp{}^2 \rangle_{pA} = \langle k_\perp{}^2 \rangle_{Intrisic} + \langle k_\perp{}^2 \rangle_{Radiation} + \langle k_\perp{}^2 \rangle_{multi\text{-}scatter}$$

**<1(GeV/c)²** **≈7(GeV/c)²** **≈1(GeV/c)²**

W.Volgelsang, hep-ph/0312320

I.Vitev, Phys.Lett.B570:161,2003.

# Di-hadron Fragmentation (Yield)




**PHENIX preliminary**

$p_{T,trig}$ > 5 GeV/c

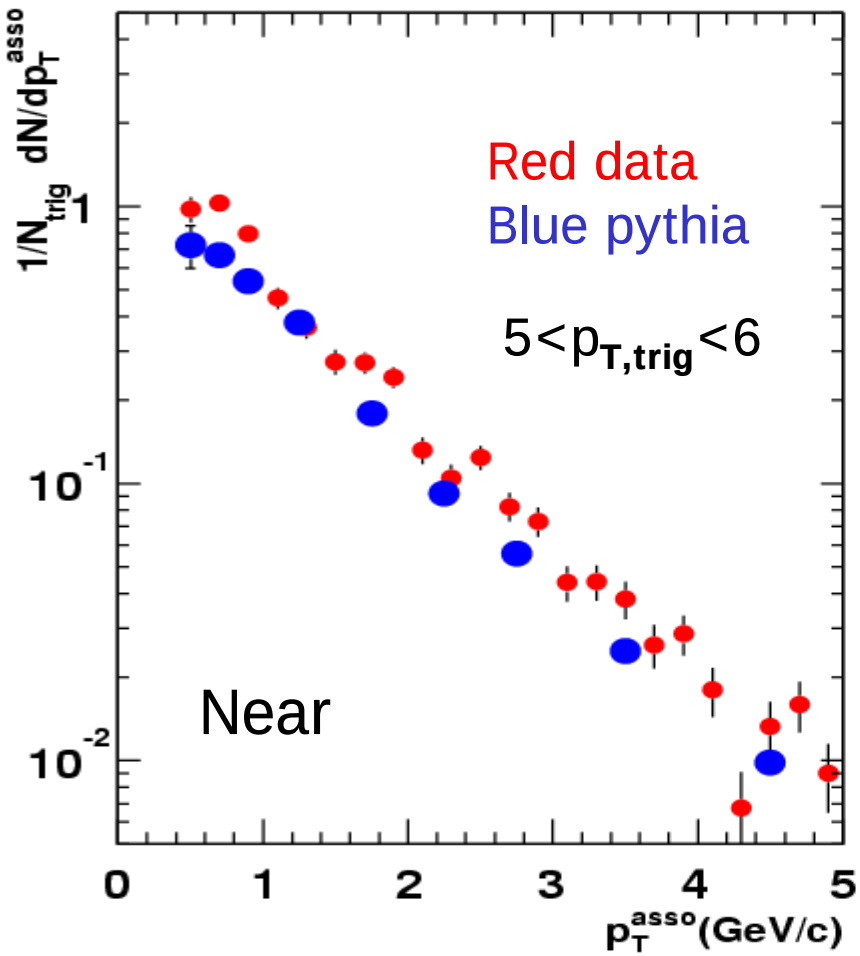
For events with a 5 GeV/c trigger

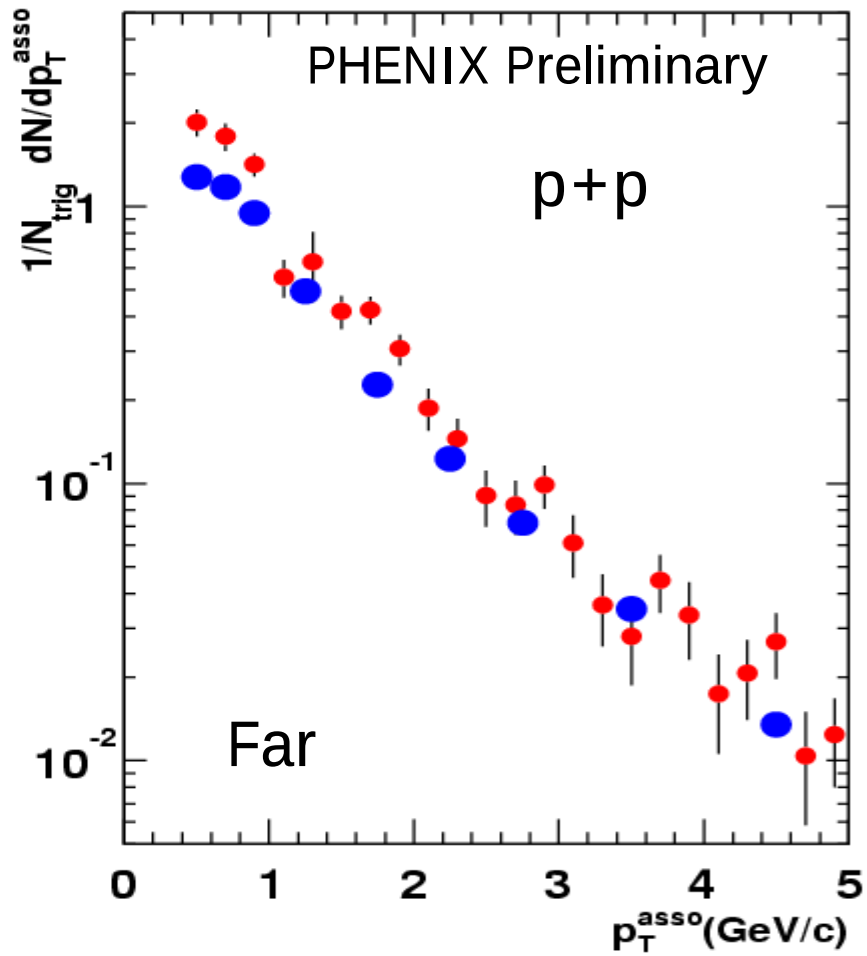
Significant jet contribution down to lowest pT (0.4-1 GeV/c)

Underlying event yield drops quickly, negligible >2 GeV/c

Look at the Jet yield and Underlying event separately

# Compare yield with Pythia 6.131

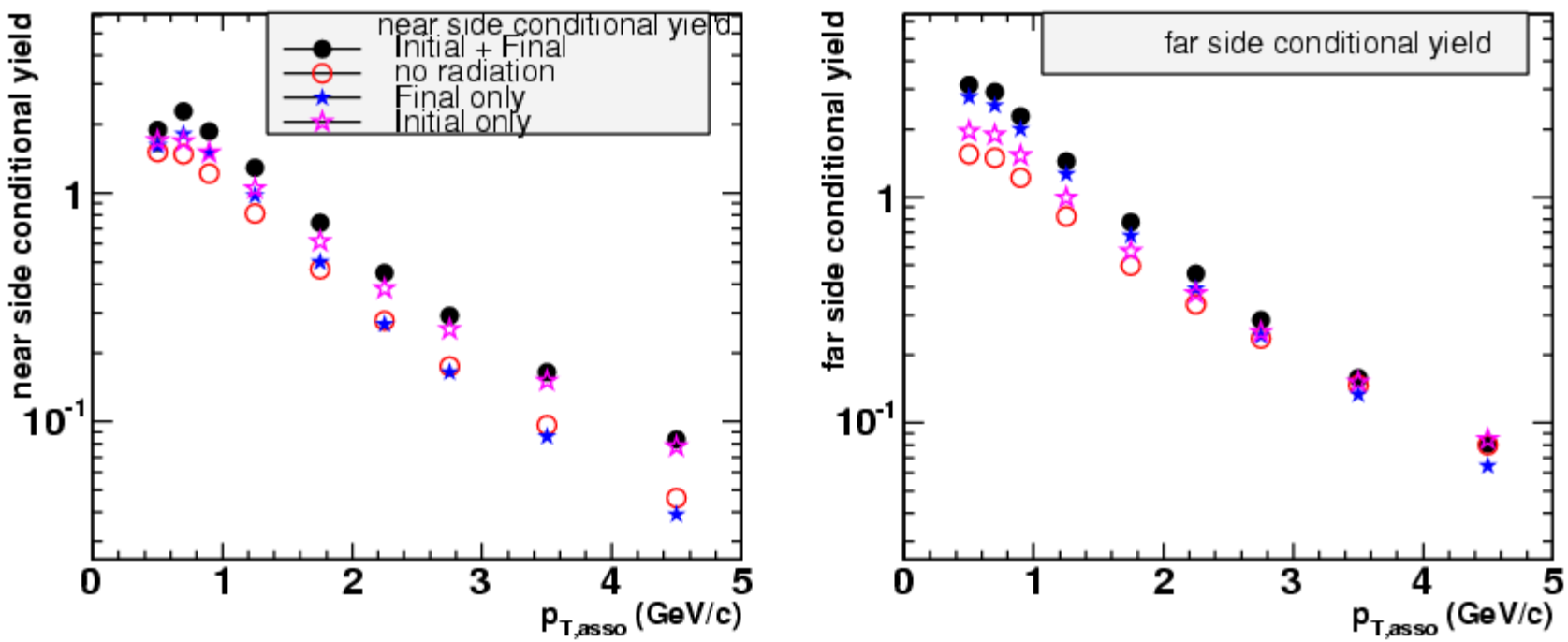


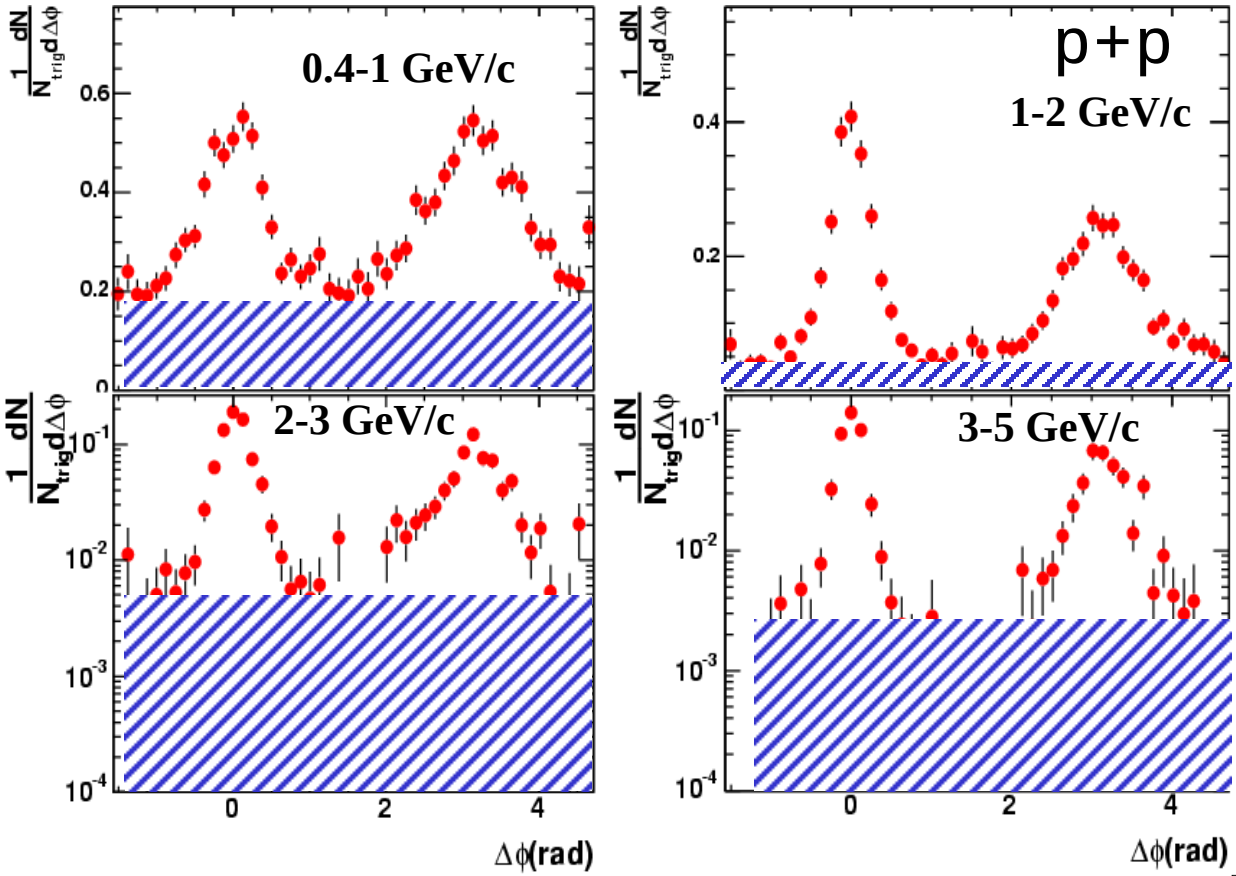

We checked the Pythia high pT hadron yield, it's shape is consistent with PHENIX measurement

# Initial/ final state radiation from Pythia

- Near side : Initial radiation enhance yield at large pT
- Far side : Final radiation enhance yield at low pT



# Underlying event

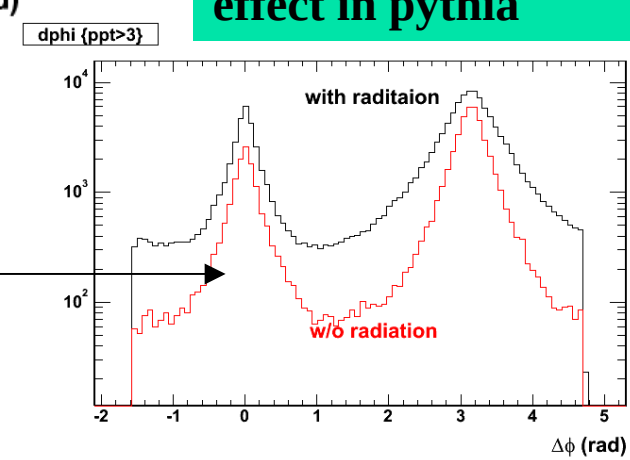



PHENIX preliminary

Linear scale

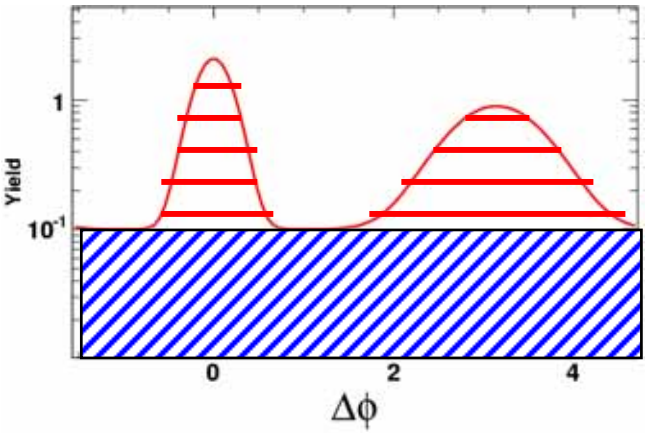
Log scale

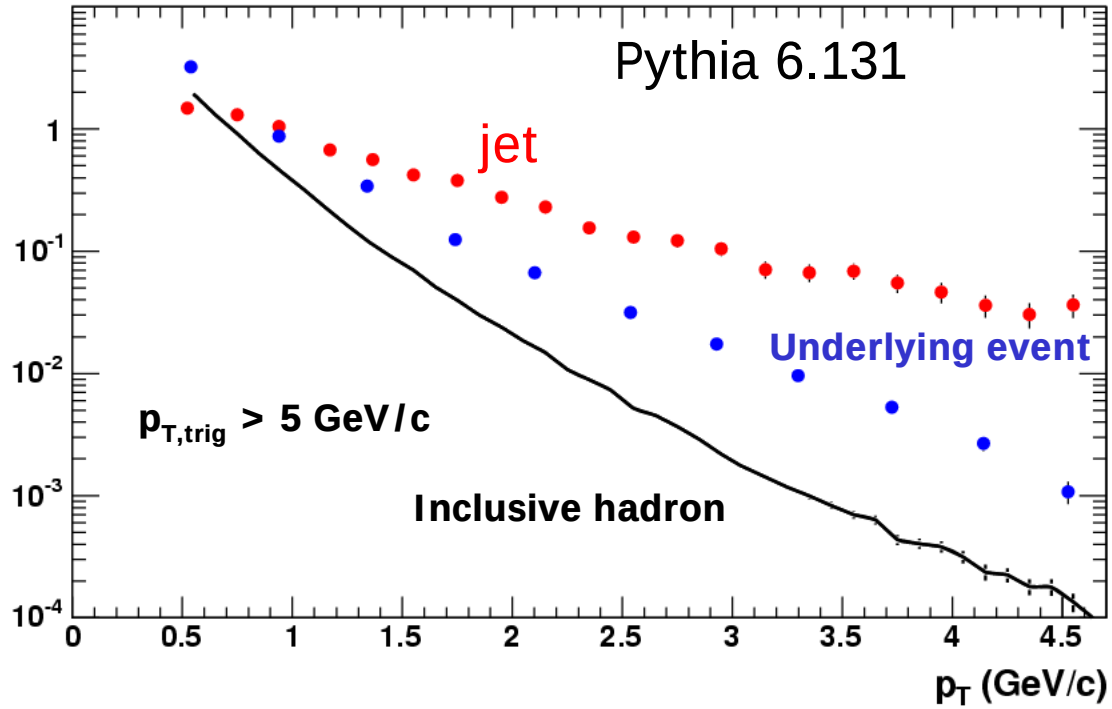
**Initial/final radiation effect in pythia**

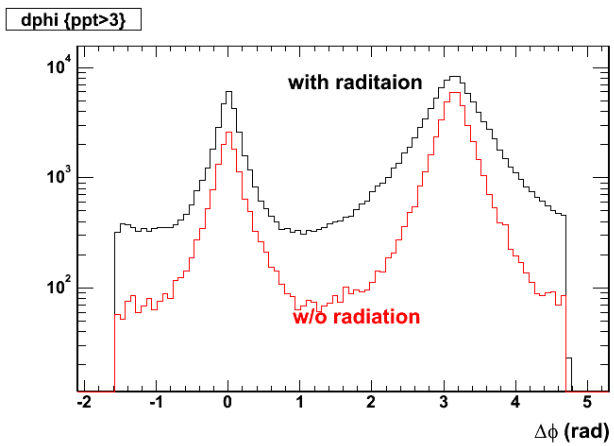



- Underlying event yield drops quickly
- However, Pythia indicates most of the underlying event is from radiative tails

# What Pythia tell us?



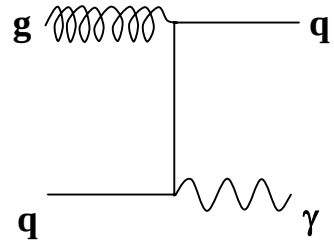




Consistent with radiative contribution

The underlying event is harder than the inclusive!

# Outlook for the Near Future (QM2005)

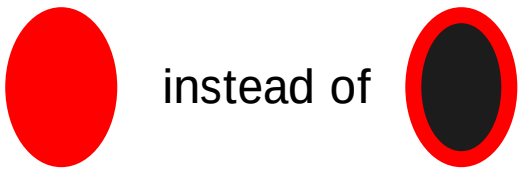
# Direct γ-h correlation




Quark gluon Compton scattering

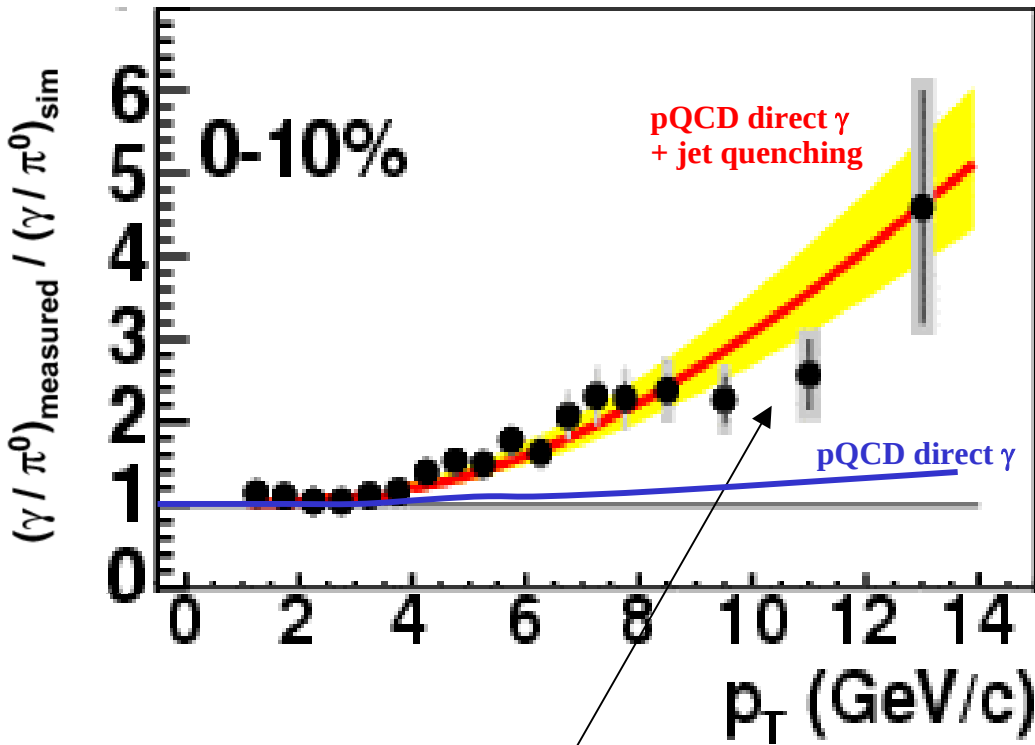
## γ- jet: Real Jet Tomography

1) γ-energy fixes jet energy
2) γ & Jet direction fix kinematics
3) γ generated uniformly, no bias towards surface




4) prompt γ have zero flow (except bremsstrahlung) Away side jet best suited for RP dependence study

measure ΔE as function of:
E, "L", flavor




70% of photons are prompt photons

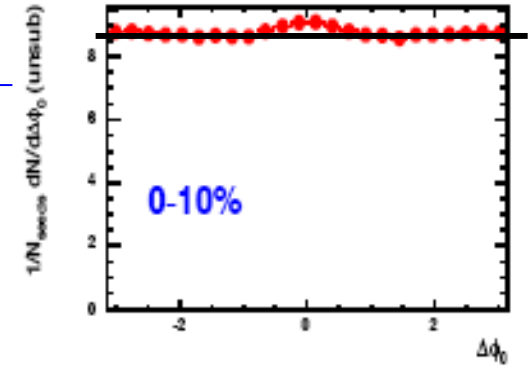
# High pT trigger - h correlation

1) Reduce the combinatory backgrounds: $\propto N_{part} \frac{1}{p_{T,assoc}^{n}}$

Thus avoid the difficulty of subtracting v2 bg

(v2 is only a few % of modulation on the bg)

$$\lambda(1+2v_2(p_T^{trig})v_2(p_T^{assoc})\cos(2\Delta\phi))$$

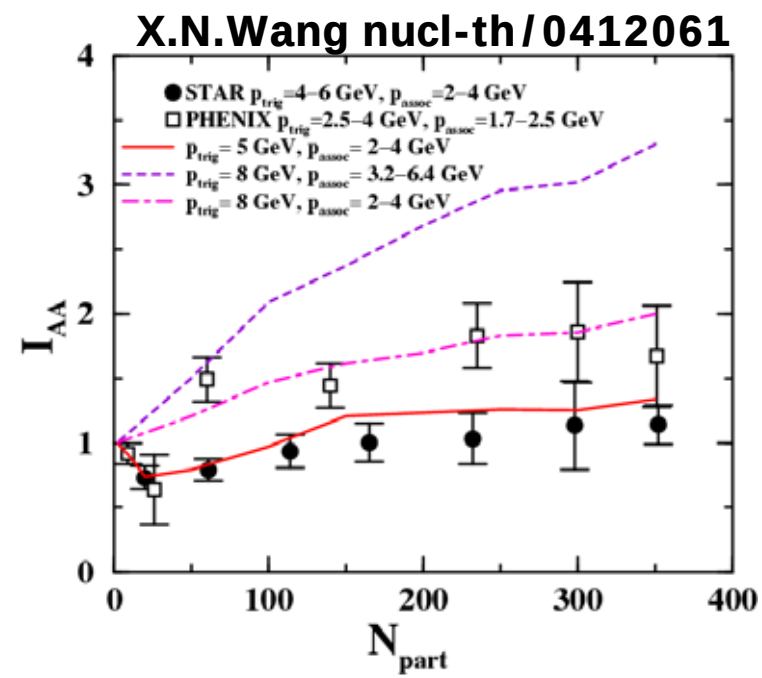



2) Small contamination due to resonance.

Reliable extraction of the near/far side jet!

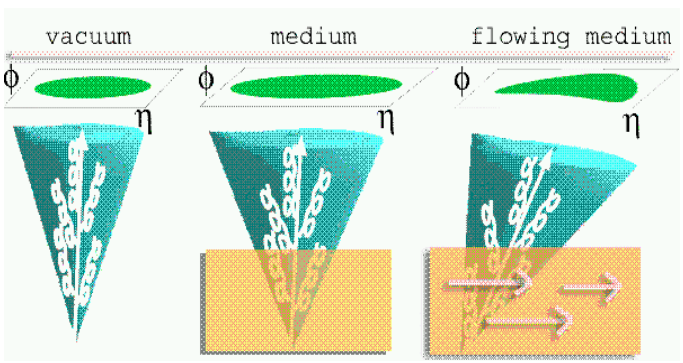
- Trigger in PHENIX includes
  - $\pi^0$, $\pi^{\pm}$, $\gamma$ non-$\pi^{\pm}$ (> 5 GeV/c)
  - p, pbar 4-10 GeV/c (Aerogel)

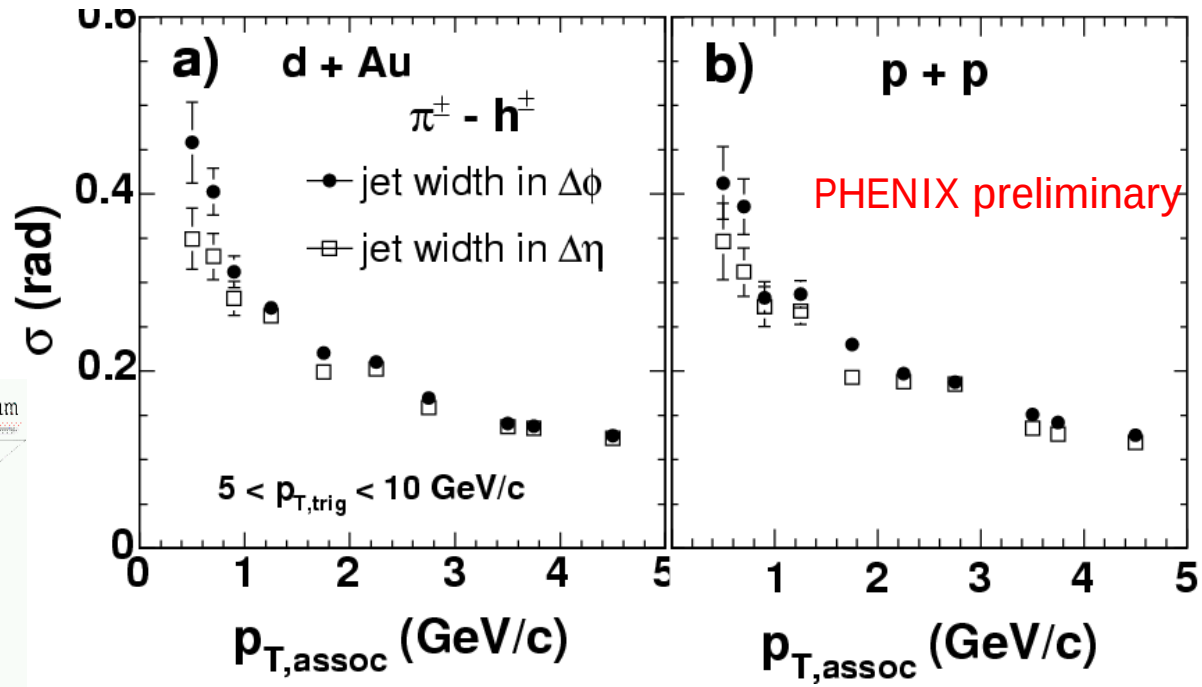
- Many traditional PHENIX intermediate pT jet correlations.



# Study the jet shape in $\Delta\eta$ ($|\Delta\eta|<0.7$)

- PHENIX can measure the jet shape in $\Delta\eta$.
- Top down approach in AuAu: trigger on high pT and study the jet width as function of associated pT, as low as 0.4 GeV/c



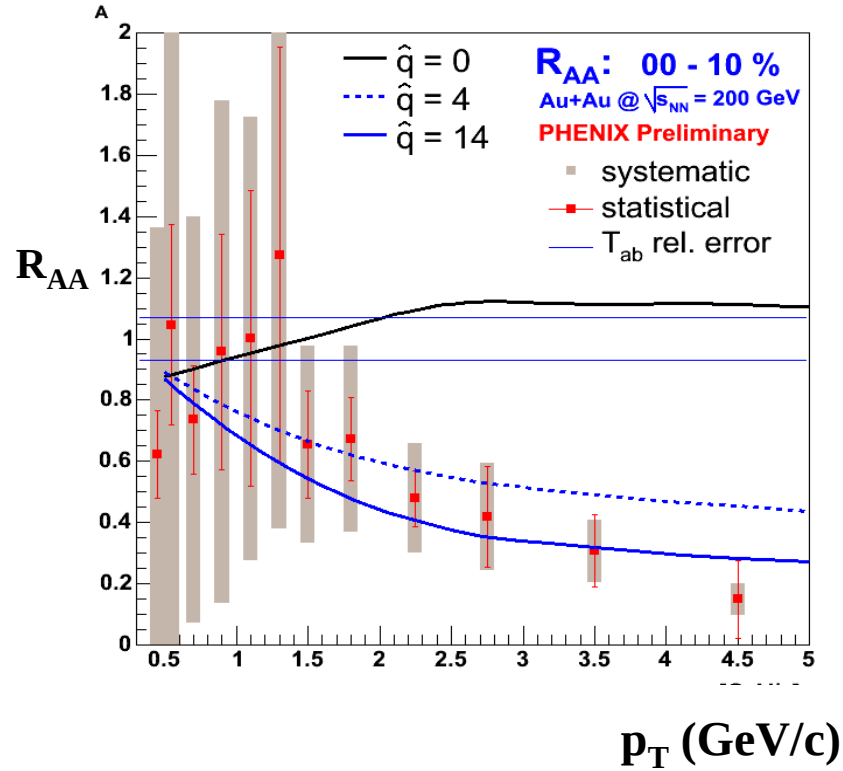




Armesto et al., PRL93, 242301 (2004)
S.A. Voloshin, nucl-th/0312065

# More examples of exotic correlations

## Charm - hadron correlation

- $e^{\pm}$ – h to access charm
- cocktail subtraction similar to single spectra
- study medium modification




## J/psi - hadron correlation

- Origin of J/Psi, in particular the near side correlation
- doable in CuCu and pp

## Muon arm – Central arm correlation

- use $h^{\pm}$ or $\mu^{\pm}$ as trigger
- access the CGC or power correction

# Summary

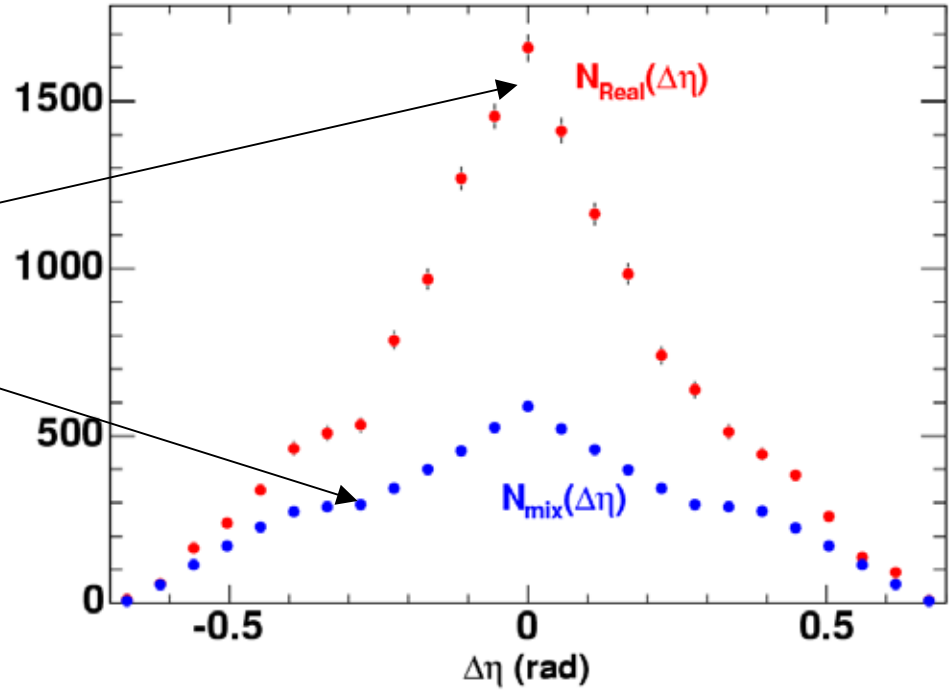
- Two particle correlation method to access the jet properties.
  - Overcome the limited acceptance and access the low pT jet.
- Encouraging results from AuAu
  - Jet shape and jet fragmentation are strongly modified
- Detailed examination of jet properties in pp and dAu is crucial as a baseline
  - Understanding the jet shape and fragmentation function.
  - Understanding the underlying event
- PHENIX will do a lot with RUN4 AuAu and RUN5 CuCu data
  - You just need to wait till QM2005

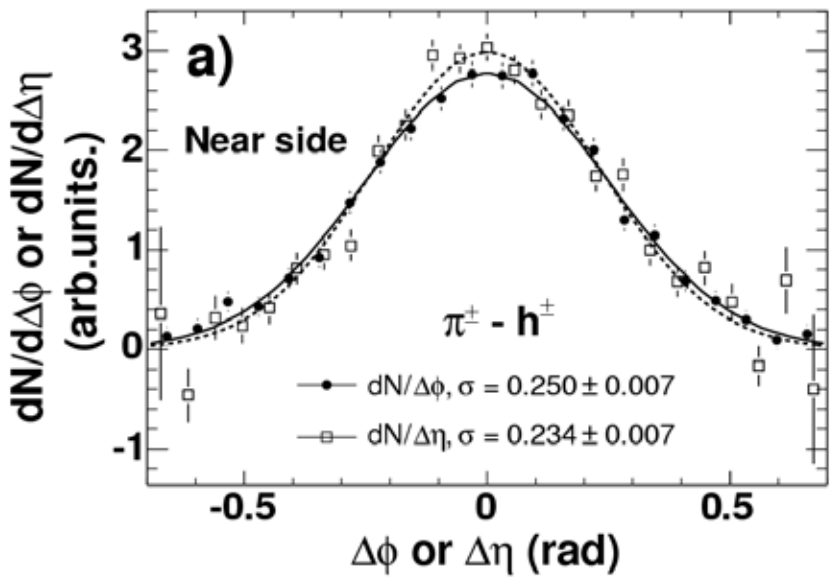
# Backup slides

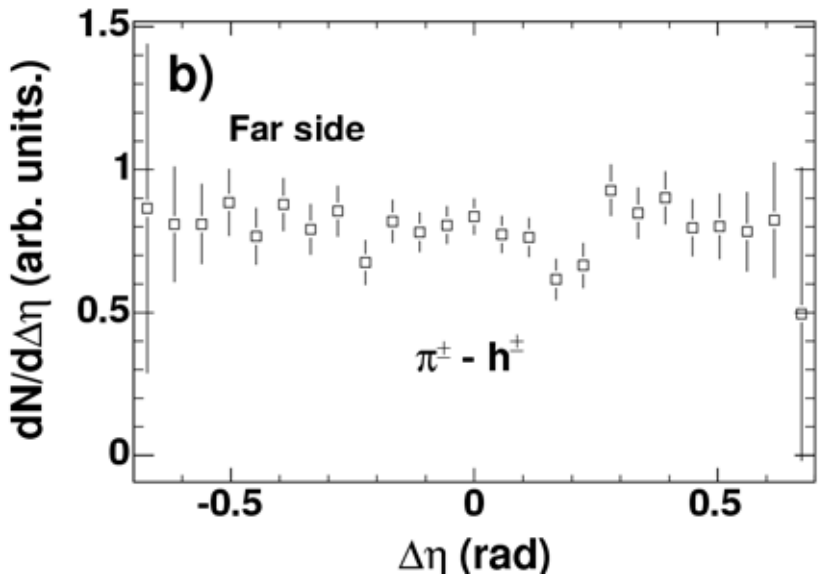
# Correlation in Δη

$$C(\Delta\eta) = \frac{N_{real}(\Delta\eta)}{N_{mix}(\Delta\eta)}$$

$5 < p_{T,trig} < 10$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c

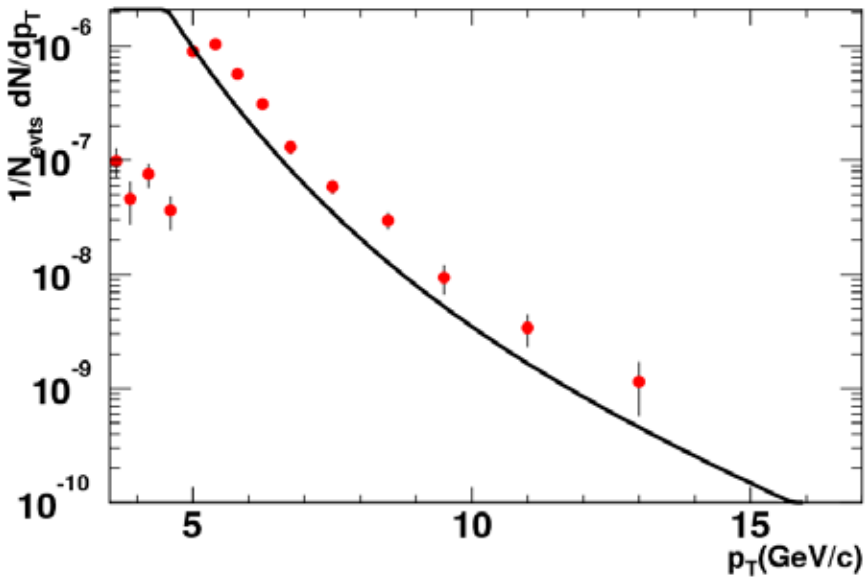


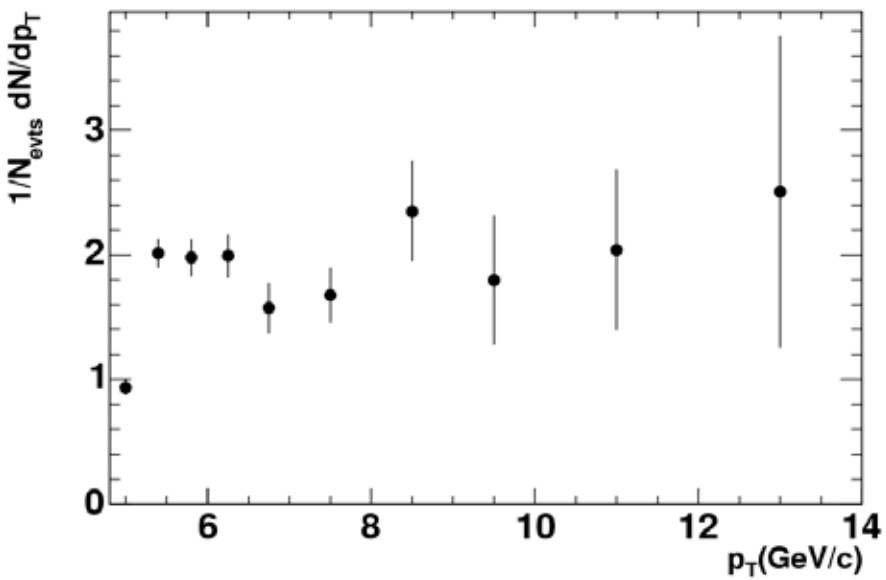
# Pythia Pion yield compared with data

- Line is fit to data
- Red point is pythia pi0 yield




- has the same shape
- Which means that the parton spectra are the same!

$$\frac{dN}{p_T\,dp_T} = \int_{x_T}^{1} D(z)\, f\left(\frac{p_T}{z}\right) \frac{dz}{z^2}$$

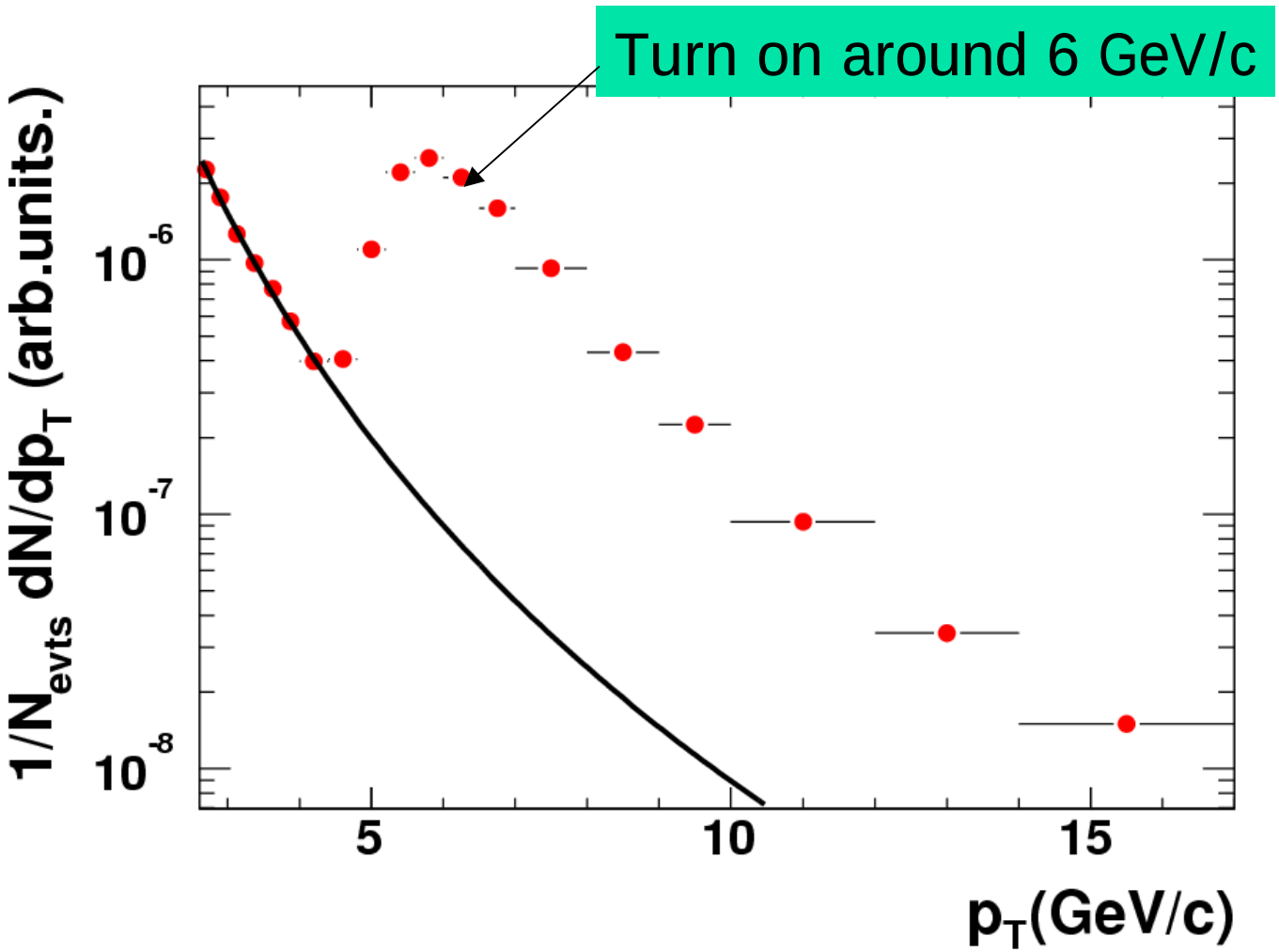


# $\pi^{\pm}$ identification in PHENIX

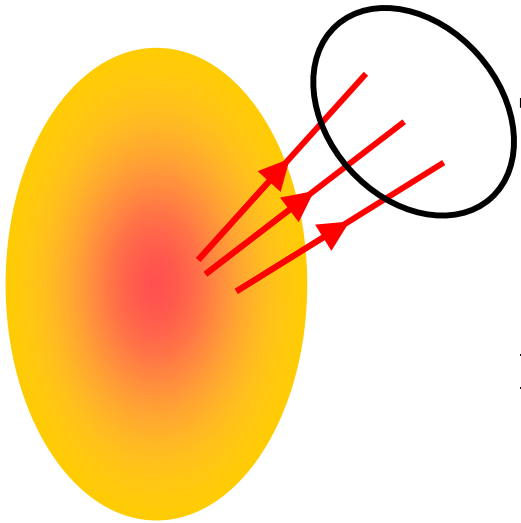
RICH detects $\pi^{\pm}$ at $p_T > 4.7$ GeV/c

EMCal is used to reject high pT background from conversion

Remaining background is less than 5%.



# What's going on?



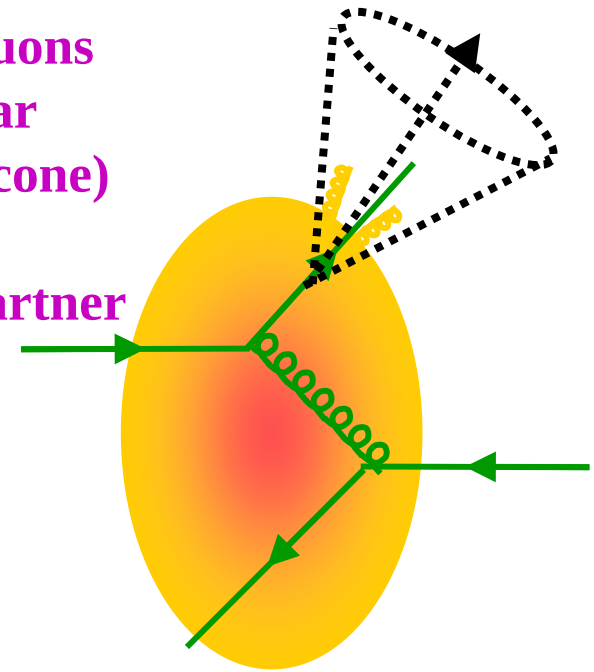
**Thermal quark recombination**

**Dilutes jet partner yield**

Thermal-Thermal

**Radiated gluons are collinear (inside jet cone)**

**Increases partner yield**



Thermal-Shower

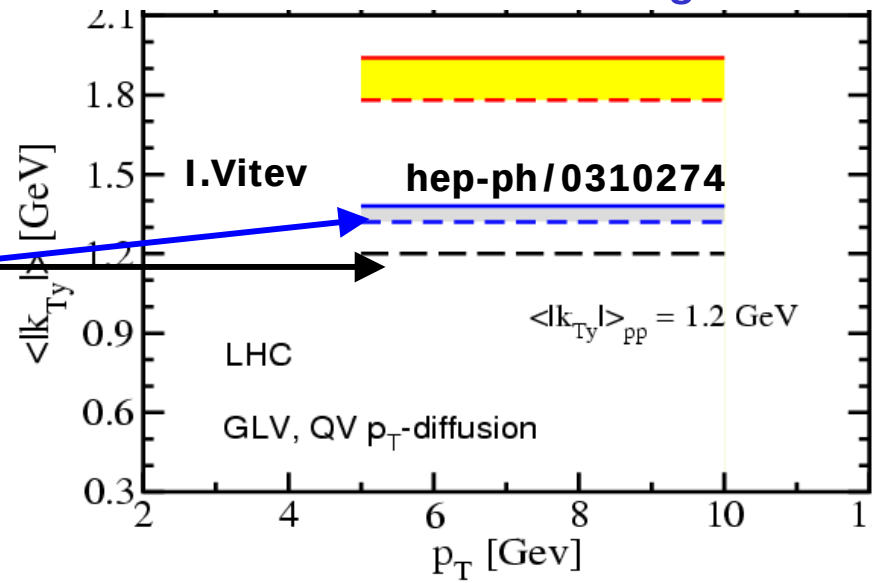
Fries, Bass & Mueller
nucl-th/0407102

**One interpretation: recombination of quarks from plasma with jet fragments**

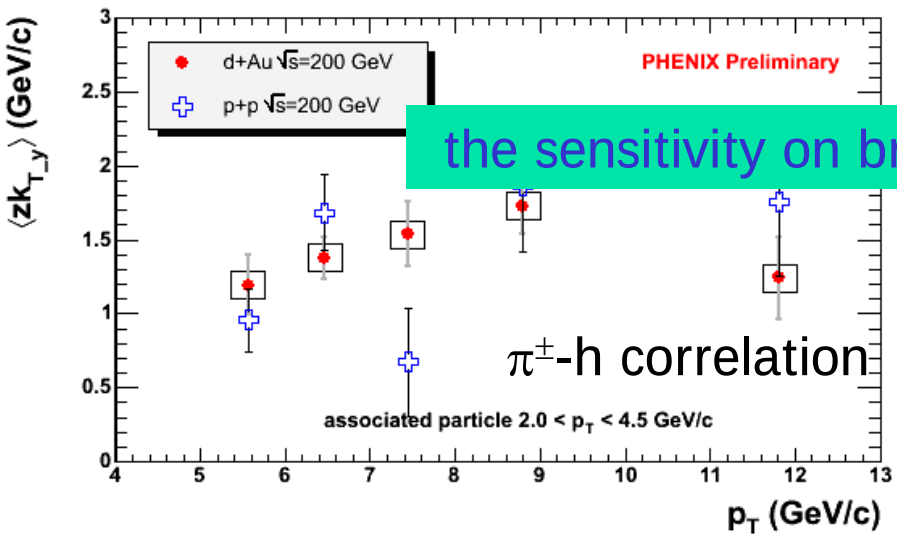
# Is kT in dAu sensitive to broadening?

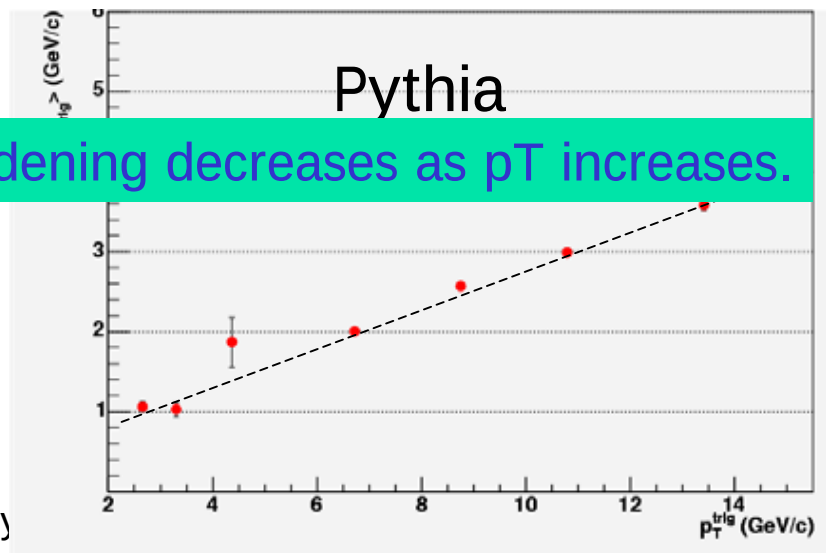
- Seems radiation contribution dominate over the broadening

10% difference between dAu and pp for 4.5 GeV trigger




- Radiation contribution is even stronger at higher pT



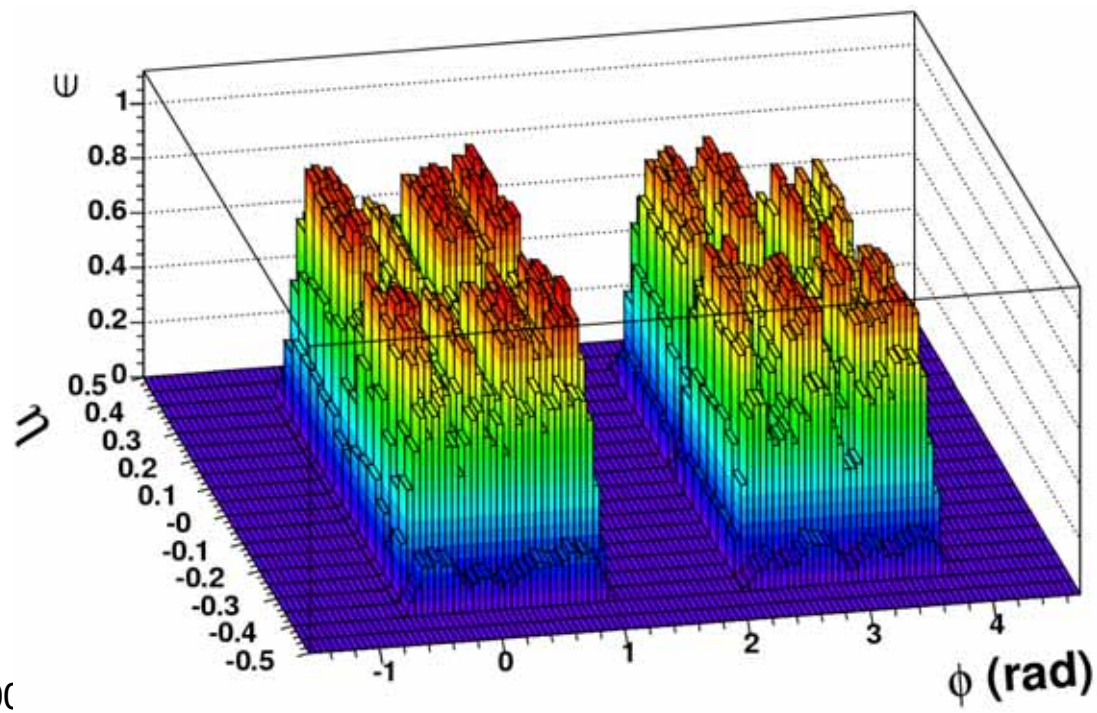

the sensitivity on broadening decreases as pT increases.

# Test the correction with Pythia simulation

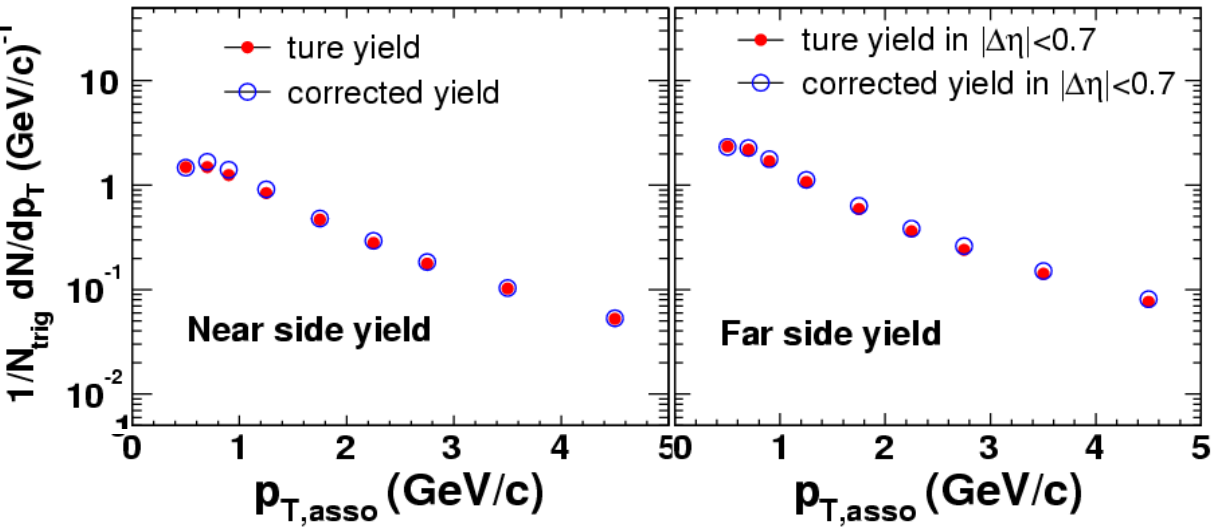
- Generate 1 M triggered events and 1 M minimum bias events.
  - Mixed distribution is obtained by mixing trigger with minbias event.
  - Requiring trigger always has $|\eta|<0.35$.

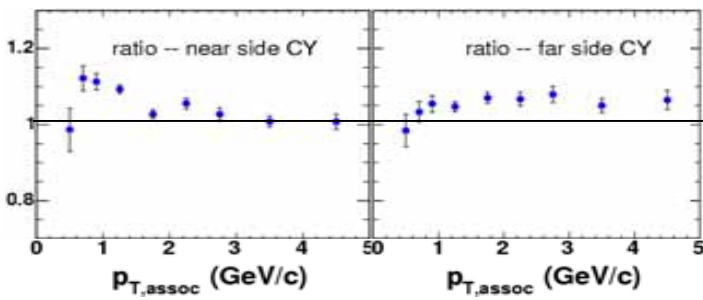
If we don't constrain associated particle, we would get full yield.

- Compare with the jet yield extracted with acceptance filter

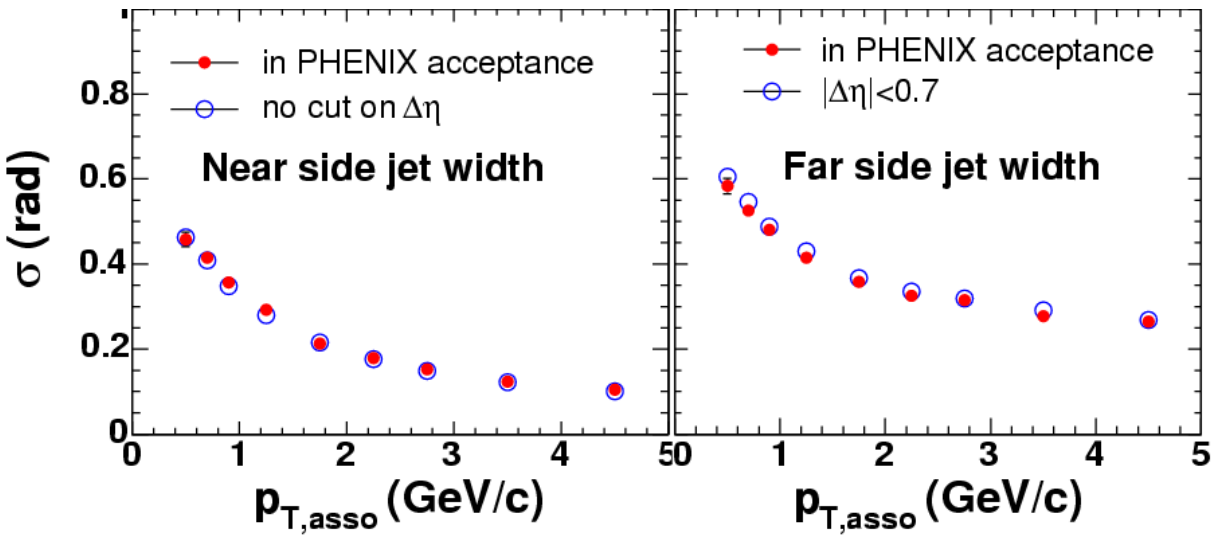


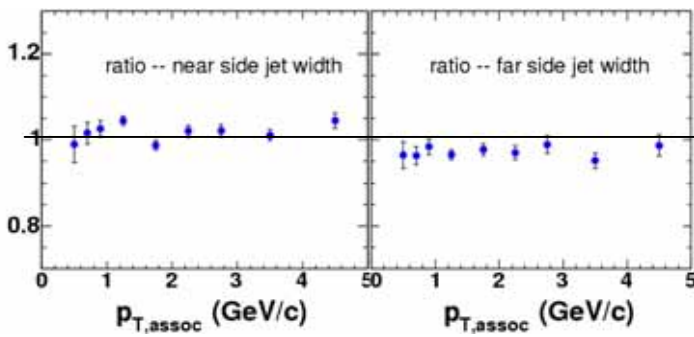
- Compare the yield



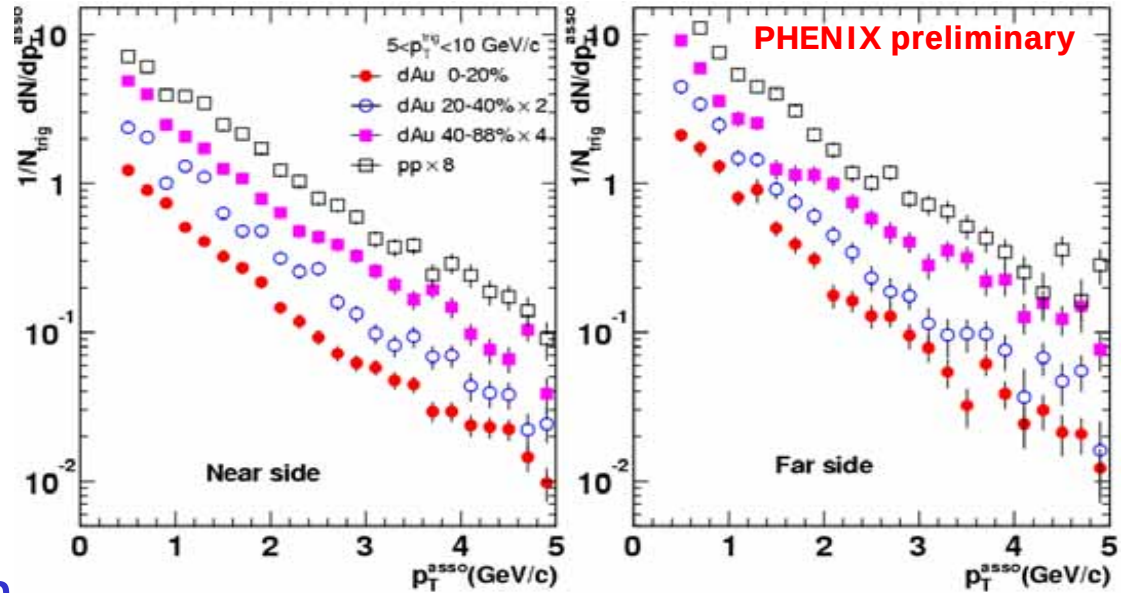

- Compare the width



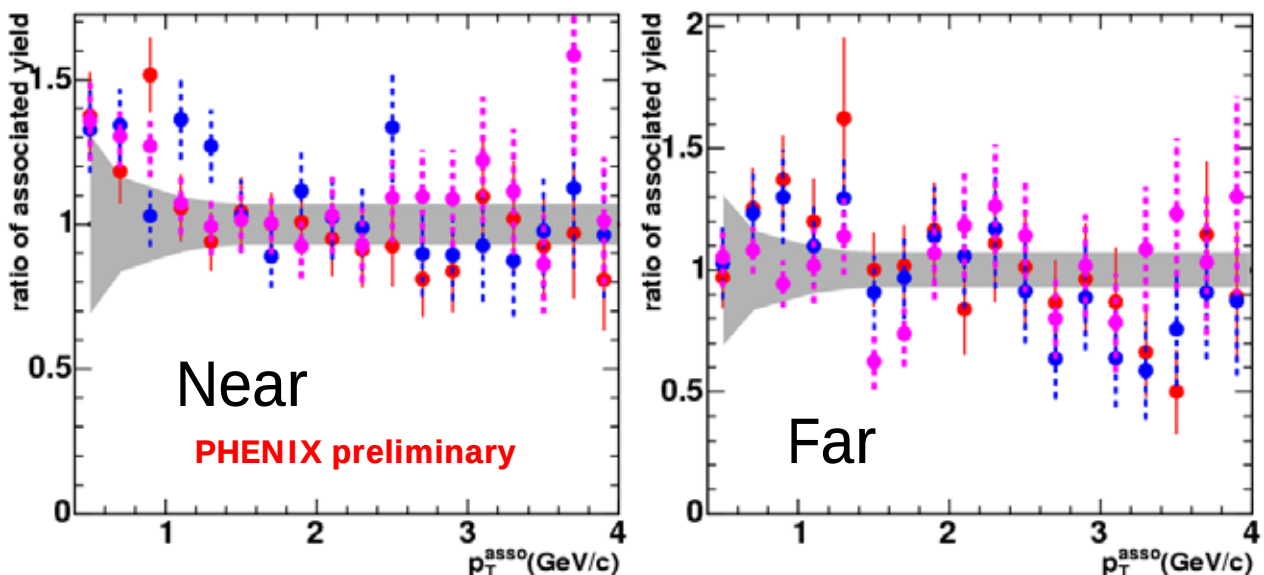



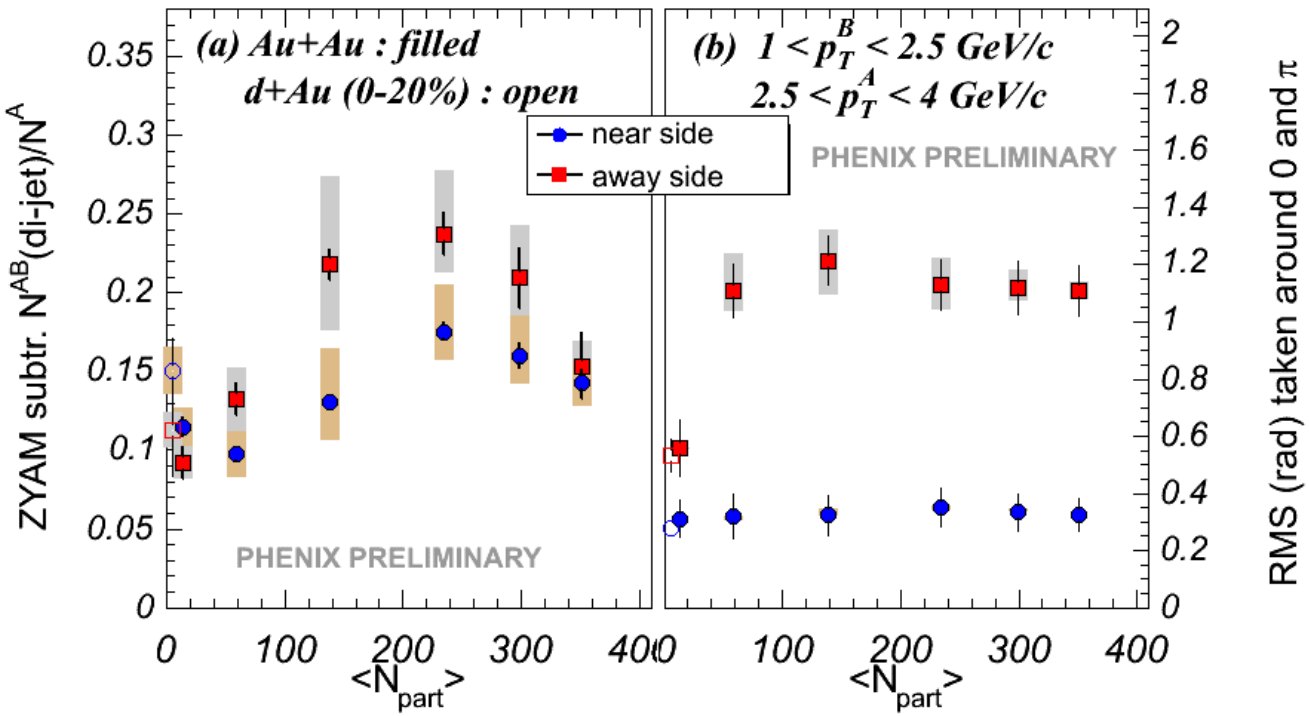
# Jet multiplicity: centrality dependence

- $1/N_{trig}\ dN_h/dp_T$
  - as function of centrality and compare with pp
  - Modification of jet multiplicity in dAu



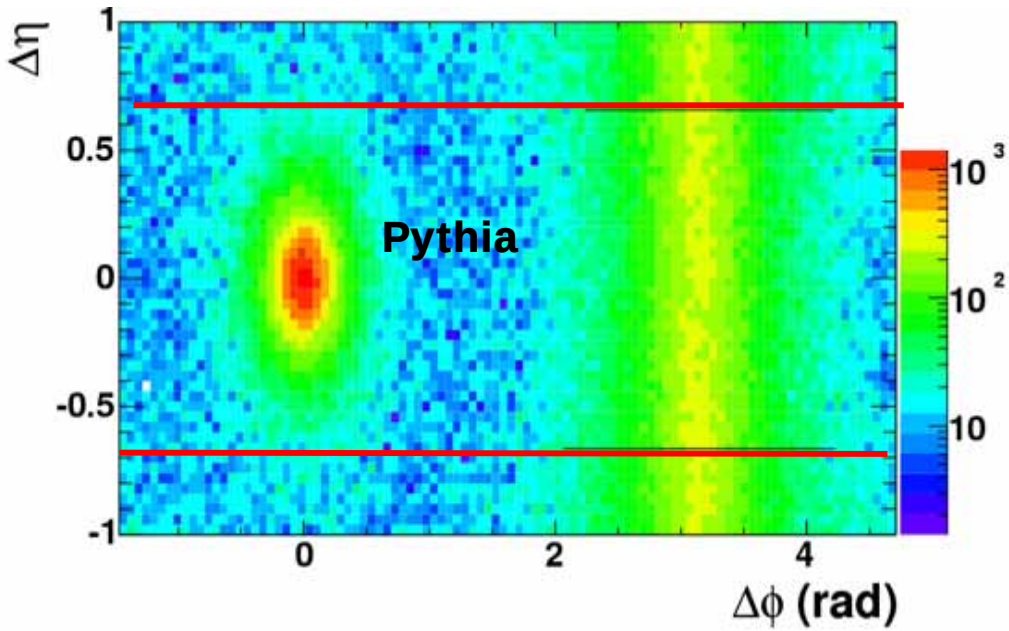

- No change in jet multiplicity is seen within errors

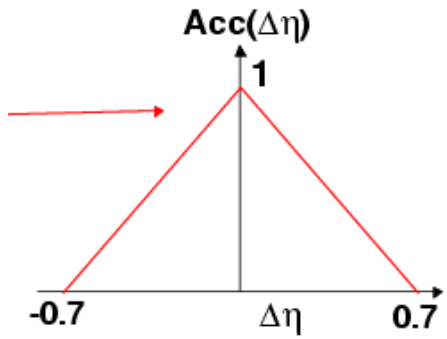





***Compelling Evidence for Modification of Jet-Properties***

# The correction in $\Delta\eta$




Pair acceptance is limited by single acceptance: $|\eta|<0.35 \Rightarrow |\Delta\eta|<0.7$

- If we measure the jet shape, we can correct back to true yield in $|\Delta\eta|<0.7$

$$R_{\Delta\eta} = \frac{\int_{-\infty}^{+\infty} d\Delta\eta\, jet(\Delta\eta) Acc(\Delta\eta)}{\int_{-\infty}^{+\infty} d\Delta\eta\, jet(\Delta\eta)}$$

Convoluted with pair acceptance

- In pp/dAu collisions, jet shape is the same in $\Delta\phi$ and $\Delta\eta$. (AuAu is different!)