# “Jet quenching”: Latest news from RHIC

CERN Heavy-Ion Forum

CERN, April 13th, 2005

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# Overview

- Physics motivation.

- Latest experimental results on
  AA single (leading) hadron spectra at high $p_T$:

  (1) Excitation function of leading hadron suppression: $R_{AA}(\sqrt{s})$

  (2) Reaction-plane dependence of hadron suppression: $R_{AA}(\varphi)$

  (3) High $p_T$ single electrons & heavy-quark energy loss: $R_{AA \rightarrow Q}(p_T)$

- Latest experimental results on
  AA di-hadron $\phi$-, $\eta$-correlations at high $p_T$:

  (1) Strong modif. ("dip") in away-side di-hadron azim. corrs.: $dN_{pair}/d\varphi$

  (2) Enhanced di-jet acoplanarity. "Thermalized" away-side $dN_{pair}/d\varphi$

  (3) Di-jet pseudo-rapidity broadening: $dN_{pair}/d\eta$

- Summary

# Physics motivation

- Multiple final-state non-Abelian (gluon) radiation off the produced hard parton induced by the dense QCD medium.

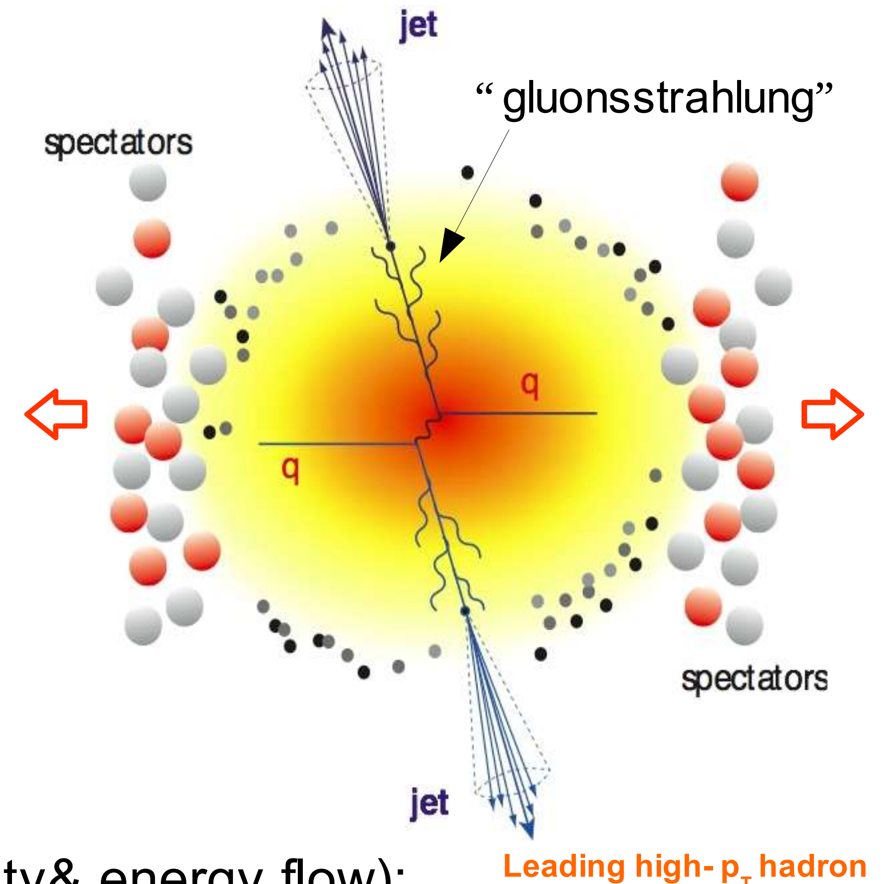
- Parton energy loss $\propto$ medium properties:

  $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)

  $\Delta E_{loss} \sim \Delta L^2$ (medium length)

- Energy is carried away by gluonsstrahlung inside (broader) jet cone (modified multiplicity& energy flow):

  $dE/dx \sim \alpha_s \langle k^2_T \rangle$

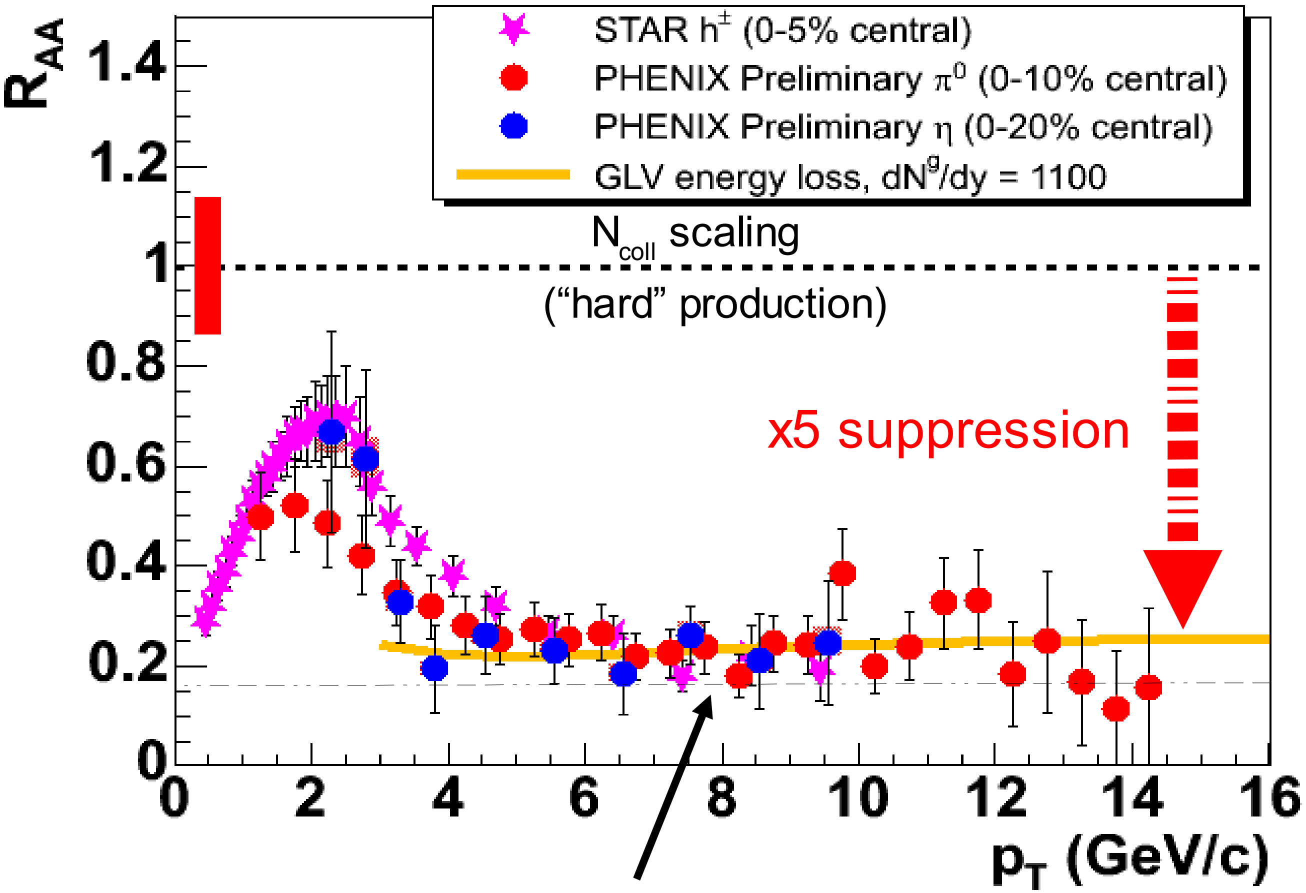



- Prediction I: Suppression of high $p_T$ leading hadrons: $dN/dp_T$
- Prediction II: Modification of (di)jet correlations: $d^2N_{pair}/d\varphi d\eta$

# High $p_T$ leading hadron $p_T$ spectra in high-energy AA collisions

# Suppressed high $p_T$ hadroproduction in AuAu (central) colls.

PHENIX Collab.
PRL 88, 022301 (2002)
nucl-ex/0109003



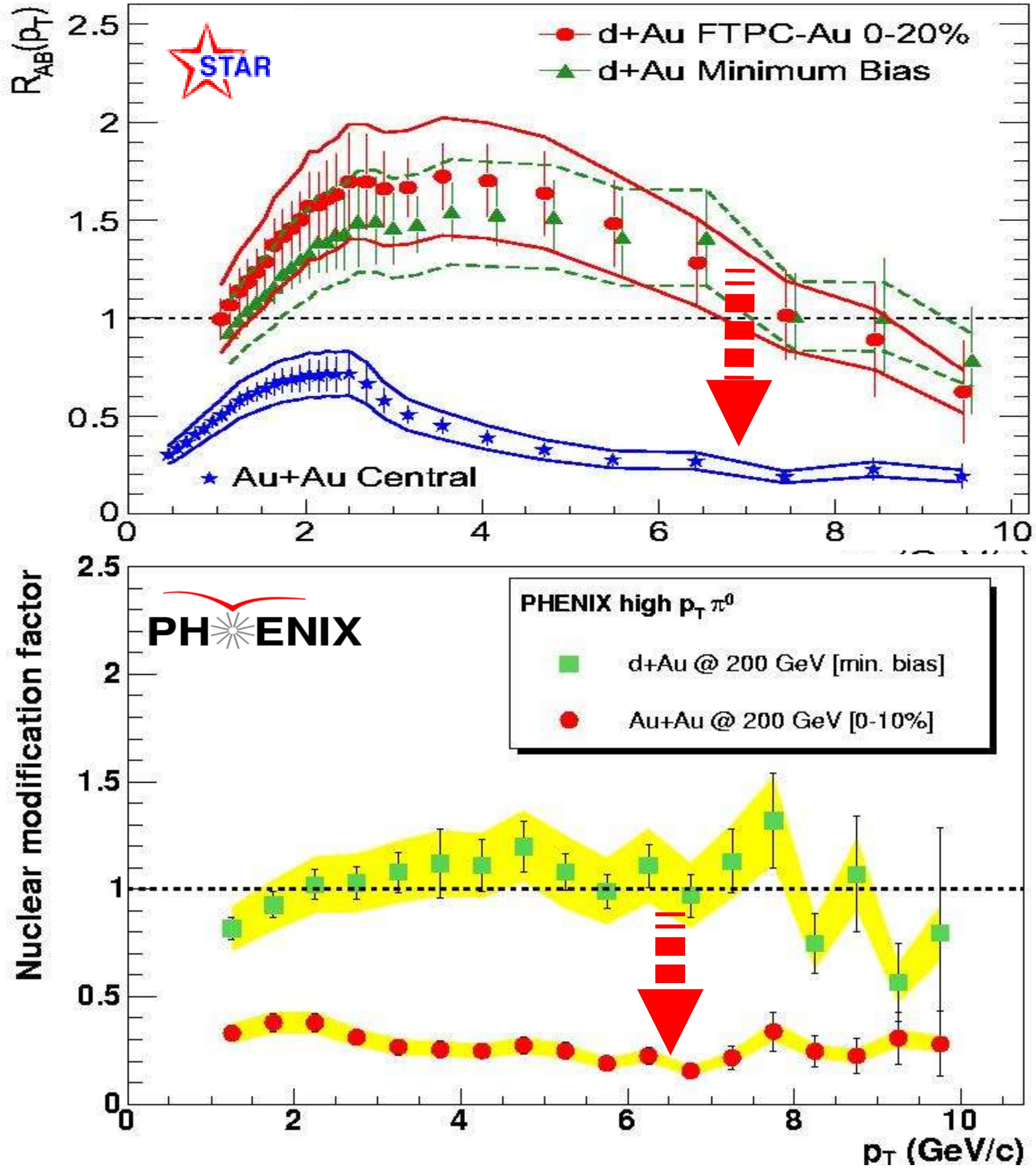

$N_{part}$ scaling
(surface emission)

D.d'E., HP'04
nucl-ex/0504001

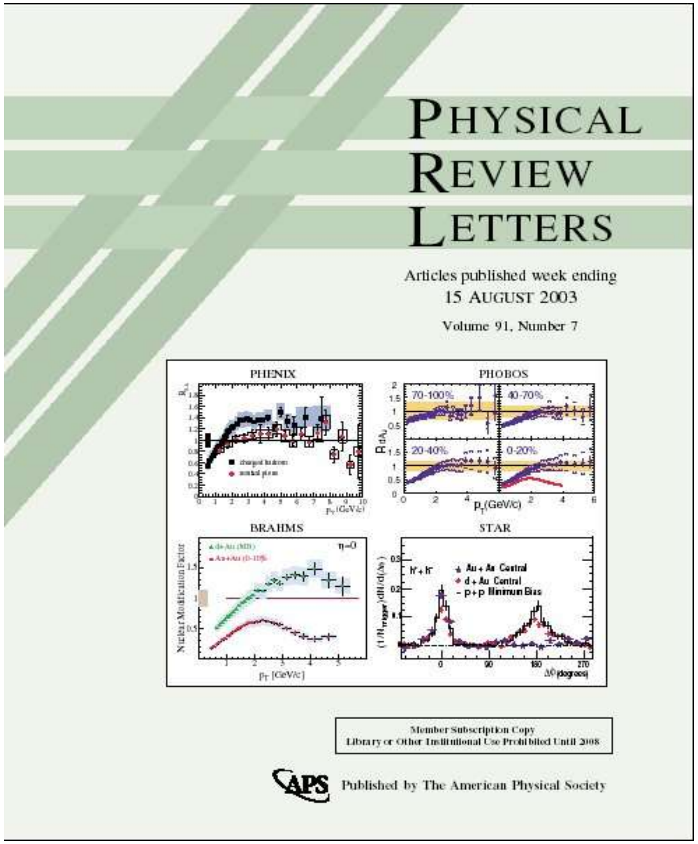

Discovery of
high $p_T$ suppression
(one of most significant
results @ RHIC so far)

- “Universal” (pid-wise) suppression: $R_{AA}$~0.2 up to $p_T$ ~ 14 GeV/c for $\pi^0$, $\eta$, $h^{\pm}$ well below pQCD expectations for hard cross-sections

# Unquenched high $p_T$ hadroduction in dAu collisions




STAR.
PRL91, 072304 (2003)

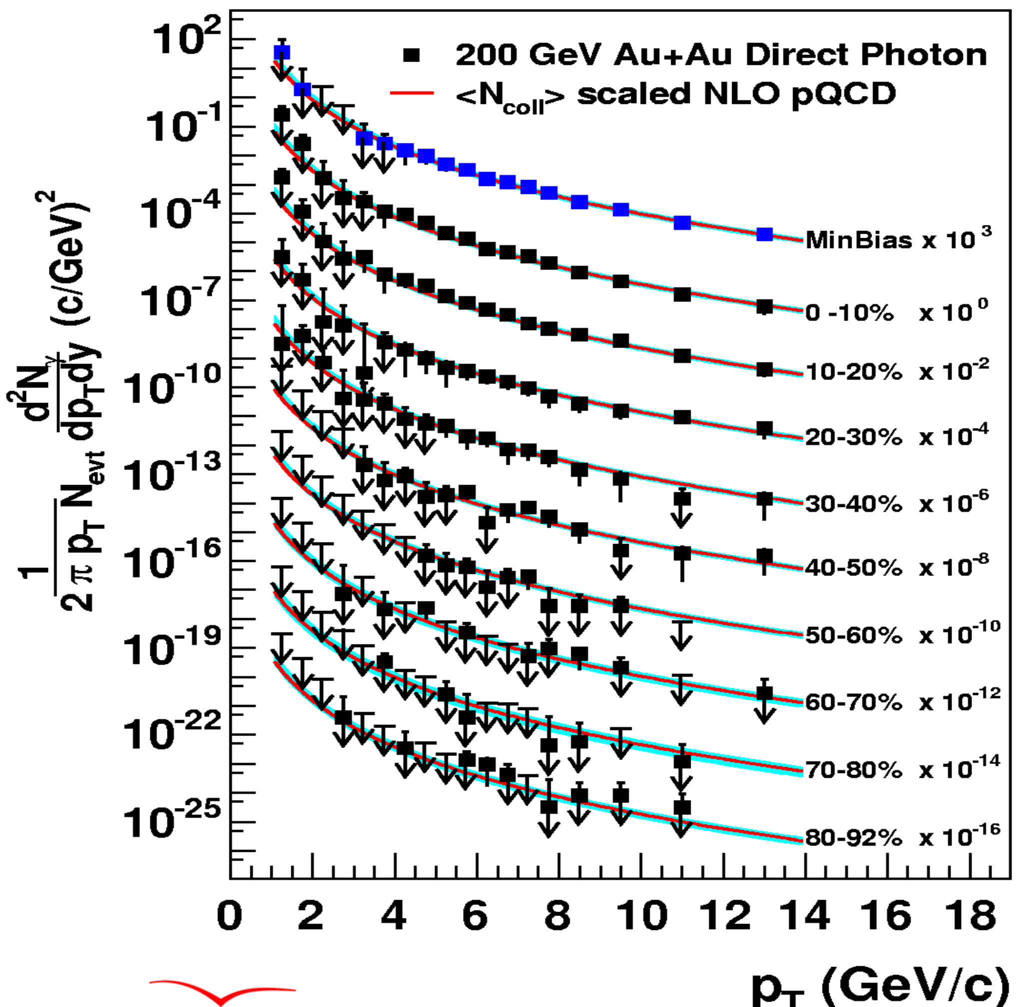



PHENIX.
PRL91, 072303 (2003)

- High $p_T$ suppression in central AuAu due to final-state effects (absent in "control" dAu experiment)

# Unquenched direct photons in AuAu collisions

- Direct photon production in Au+Au (all centralities) consistent w/ p+p incoherent scattering ("NN-scaled" pQCD) predictions:

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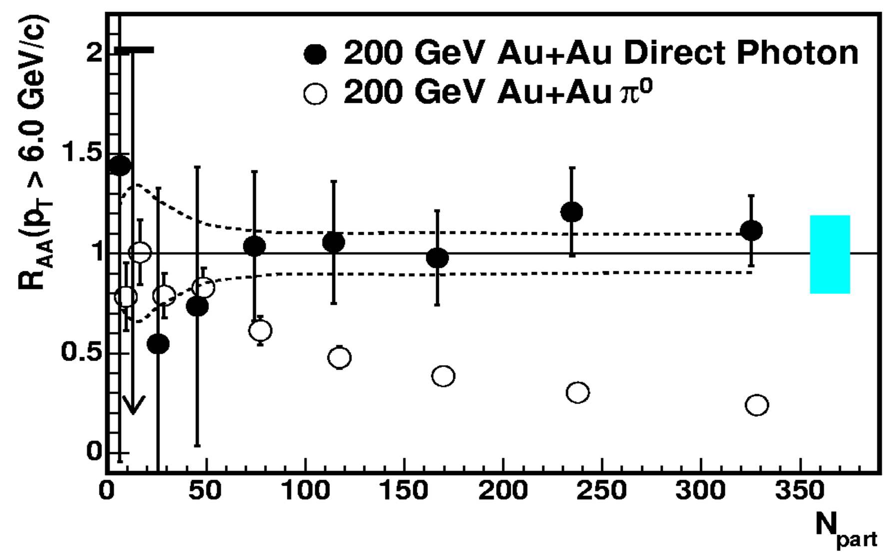
Submitted to PRL
nucl-ex/0503003

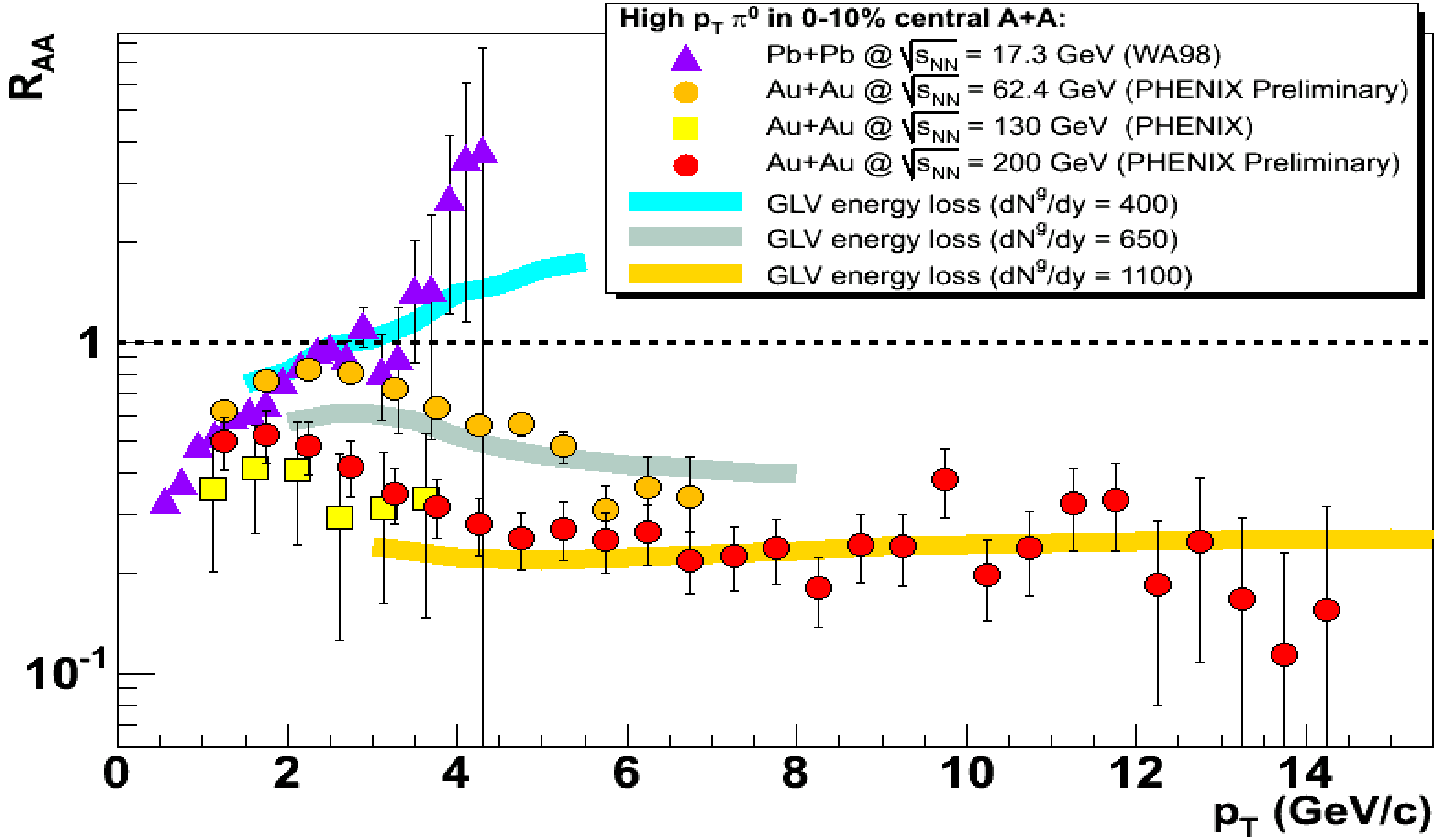
$$R_{AA}(p_T, y; b) = \frac{\text{"hot/dense QCD medium"}}{\text{"QCD vacuum"}} = \\ = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T},$$




- pQCD parton scattering holds for hard (colorless) QCD processes in AuAu (all centralities).

# High $p_T$ suppression: sqrt(s)-dependence (I)

- sqrt(s)- (and $p_T$) dependence in agreement with parton energy loss in increasingly dense (expanding) medium:




[Note: $R_{AA}$ @ SPS uses"revised" pp ref.]

D.d'E., HP'04
nucl-ex/0504001

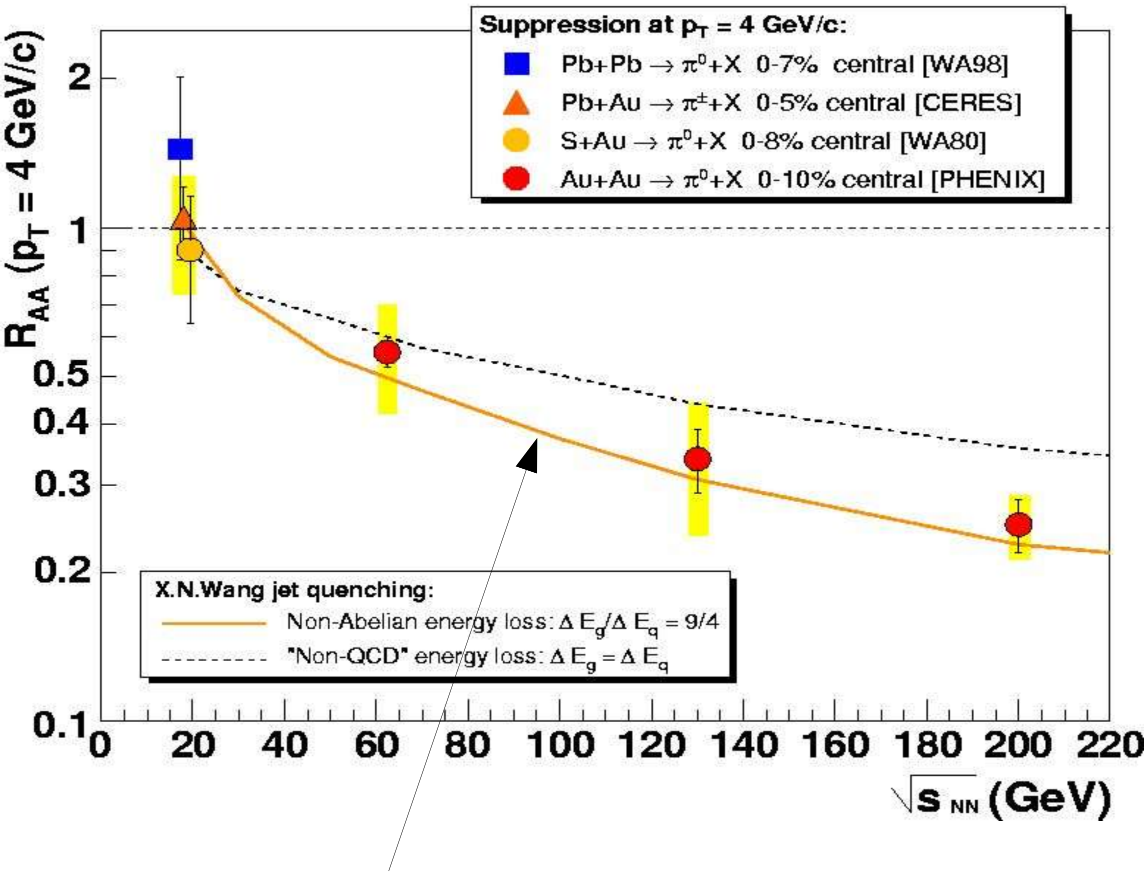
Initial g density: Medium transport coeff.:

$R_{AA}$ ~ 1 @ √s ~ 20 GeV ⇒ $dN^g/dy$ ~ 400 , $\langle q_0 \rangle$ ~ 3.5 GeV/fm$^2$

$R_{AA}$ ~ 0.3 @ √s = 62 GeV ⇒ $dN^g/dy$ ~ 650 , $\langle q_0 \rangle$ ~ 7 GeV/fm$^2$

$R_{AA}$ ~ 0.2 @ √s = 200 GeV ⇒ $dN^g/dy$ ~ 1100 , $\langle q_0 \rangle$ ~ 14 GeV/fm$^2$

- $\sqrt{s}$-dependence (and non-Abelian nature of energy loss) in agreement w/ parton energy loss calculations:
  (i) rising initial density w/ $\sqrt{s}$
  (ii) increasing relative fraction of hard-scattered gluons (for fixed $p_T$) w/ $\sqrt{s}$

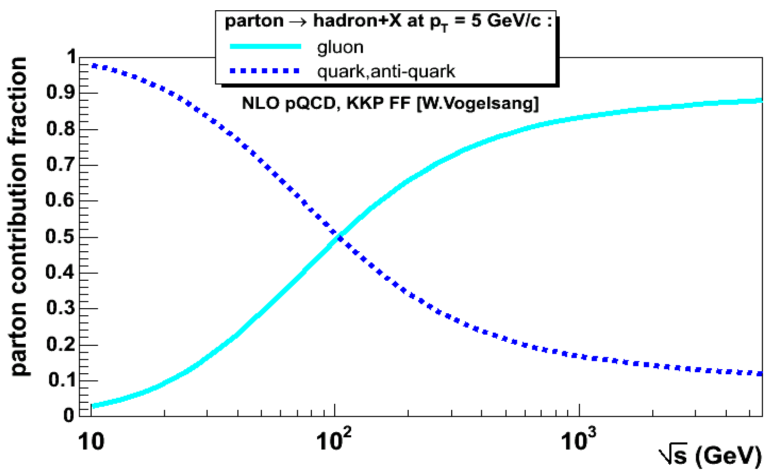



"Jet quenching" model + 2-D longitudinal plasma expansion

QCD radiation probability:

Gluon: $C_A = N_c = 3$
Quark: $C_F = (N_c^2-1)/N_c = 4/3$
$C_A/C_F = 2.25$

Relative fraction of q,g at $p_T$ = 5 GeV/c:

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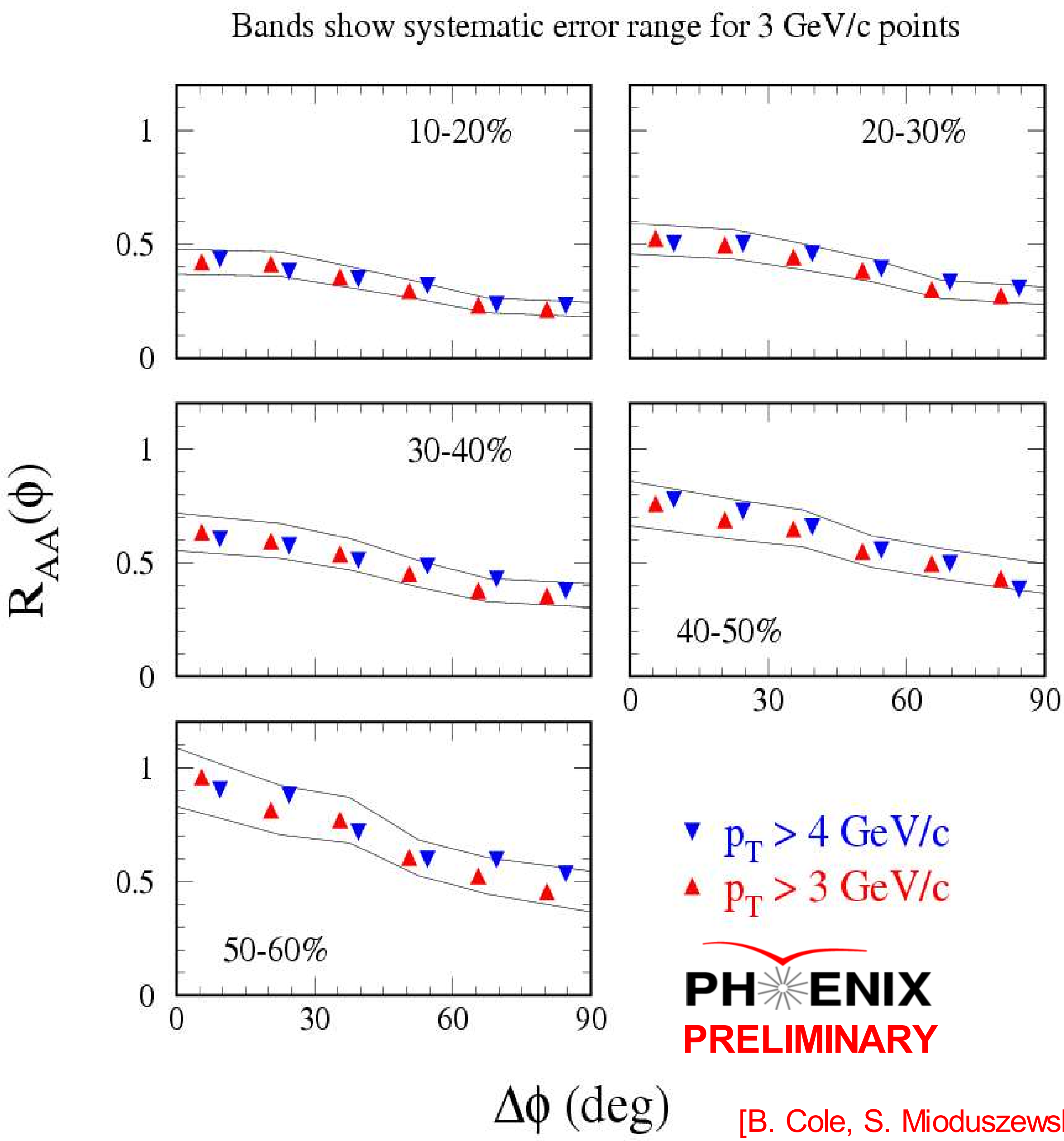
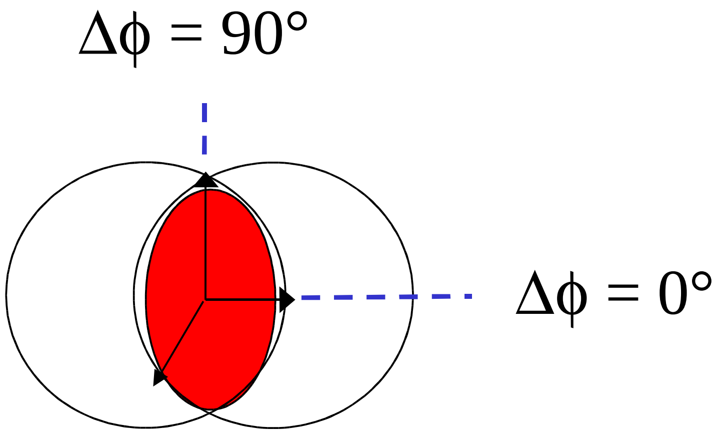
nucl-ex/0504001

# High $p_T$ suppression: Reaction-plane dependence (I)



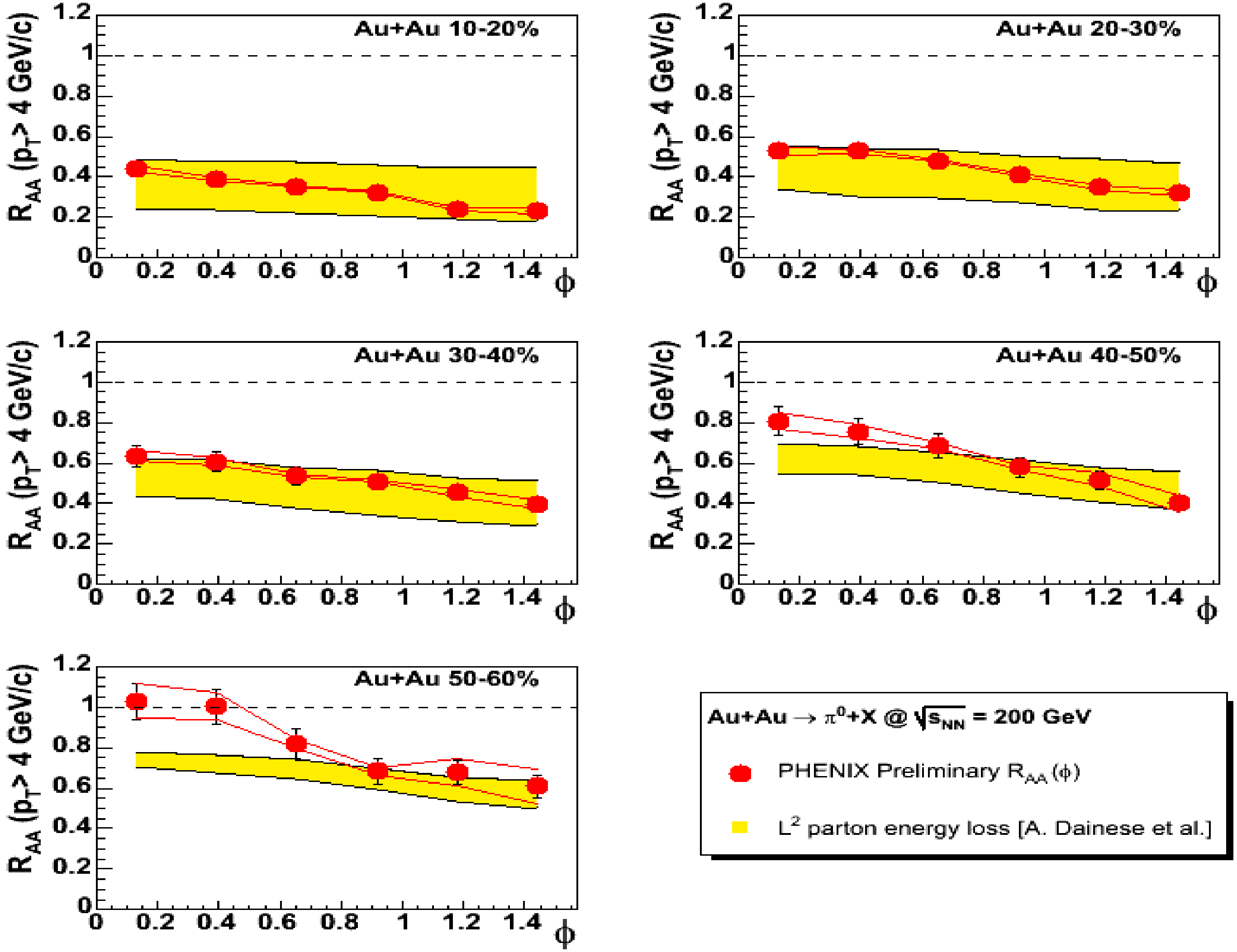

[B. Cole, S. Mioduszewski HP'04]




- Less suppression in-plane ("short" direction).
- More suppression out-of-plane ("long" direction).
- Associated path-length dependence not reproduced by "canonical" $L^2$ (or L) behaviour (in "simple" Glauber model).

# High $p_T$ suppression: Reaction-plane dependence (II)

- $R_{AA}(\varphi)$ versus parton energy loss model:

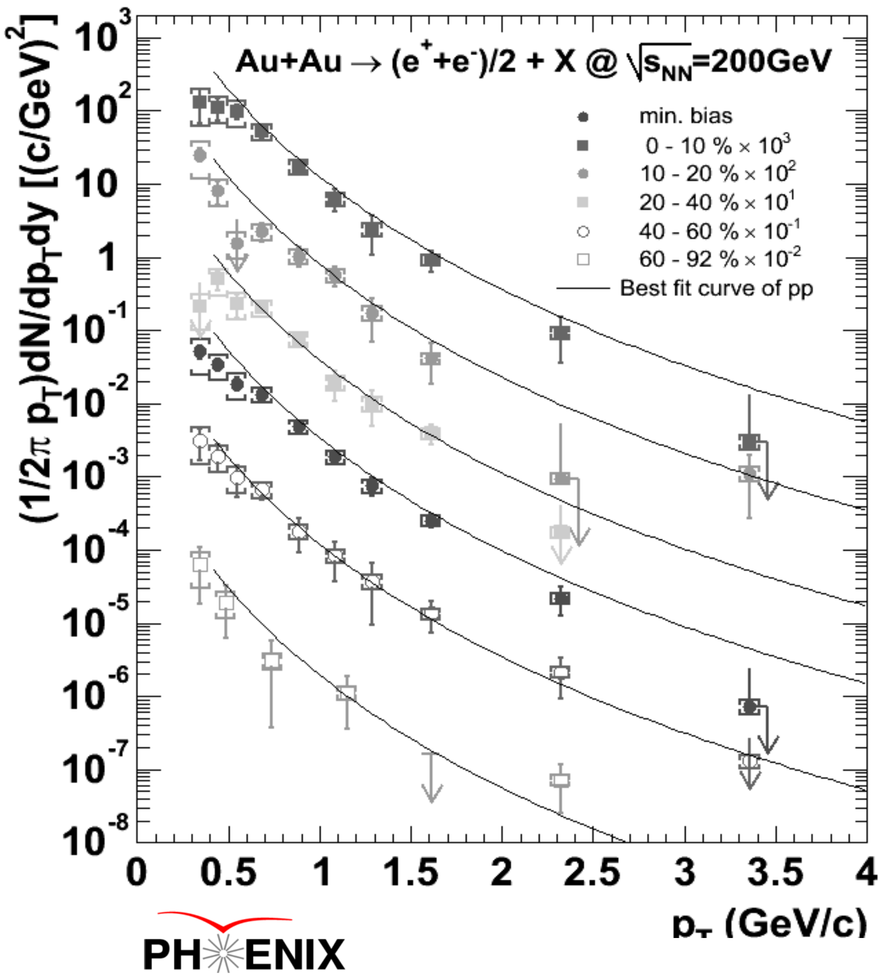



D.d'E., HP'04
nucl-ex/0504001
Dainese et al
Eur.Phys.J. C38
(2005) 461

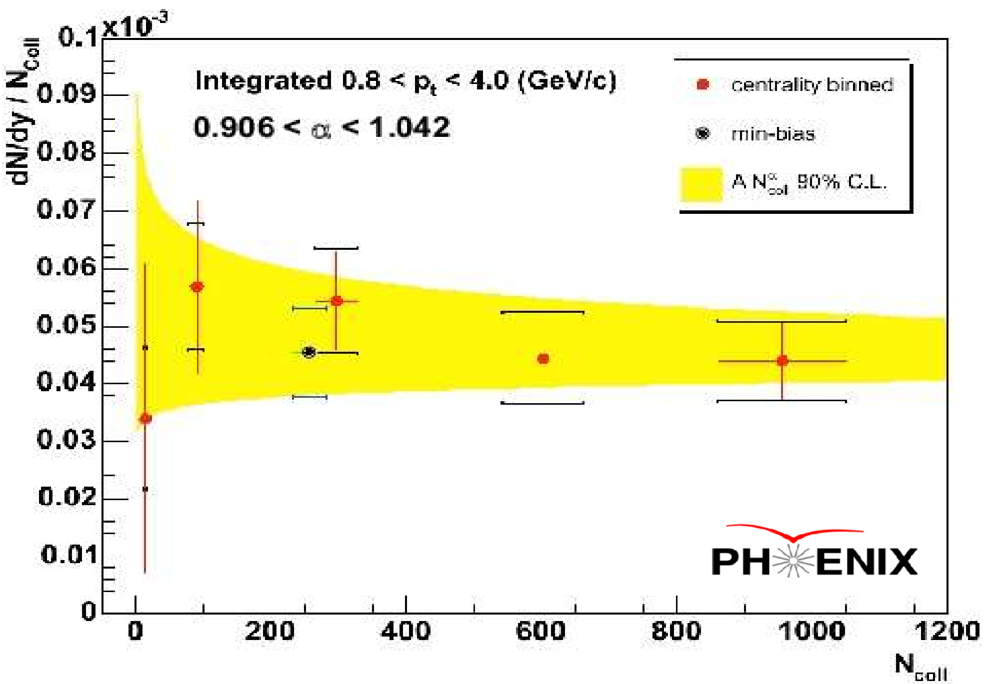
- Data: factor of ~2 more suppression "out-of-plane" than "in-plane".
- Model: predicts only ~50% increased "out-of-plane" vs "in-plane" $\pi^0$ emission

# Charm production in AuAu: "NN scaling"

- Open-charm (indirect) measurement via semi-leptonic channel: $D \rightarrow e^{\pm} + X$
- Single $e^{\pm}$ AuAu spectra ($p_T$ ~ 0.3 – 2 GeV/c) & total cross-section consistent w/ $N_{coll}$ -scaled pp charm production:




$$N_{charm}^{AuAu} = (N_{coll})^{\alpha} * A$$

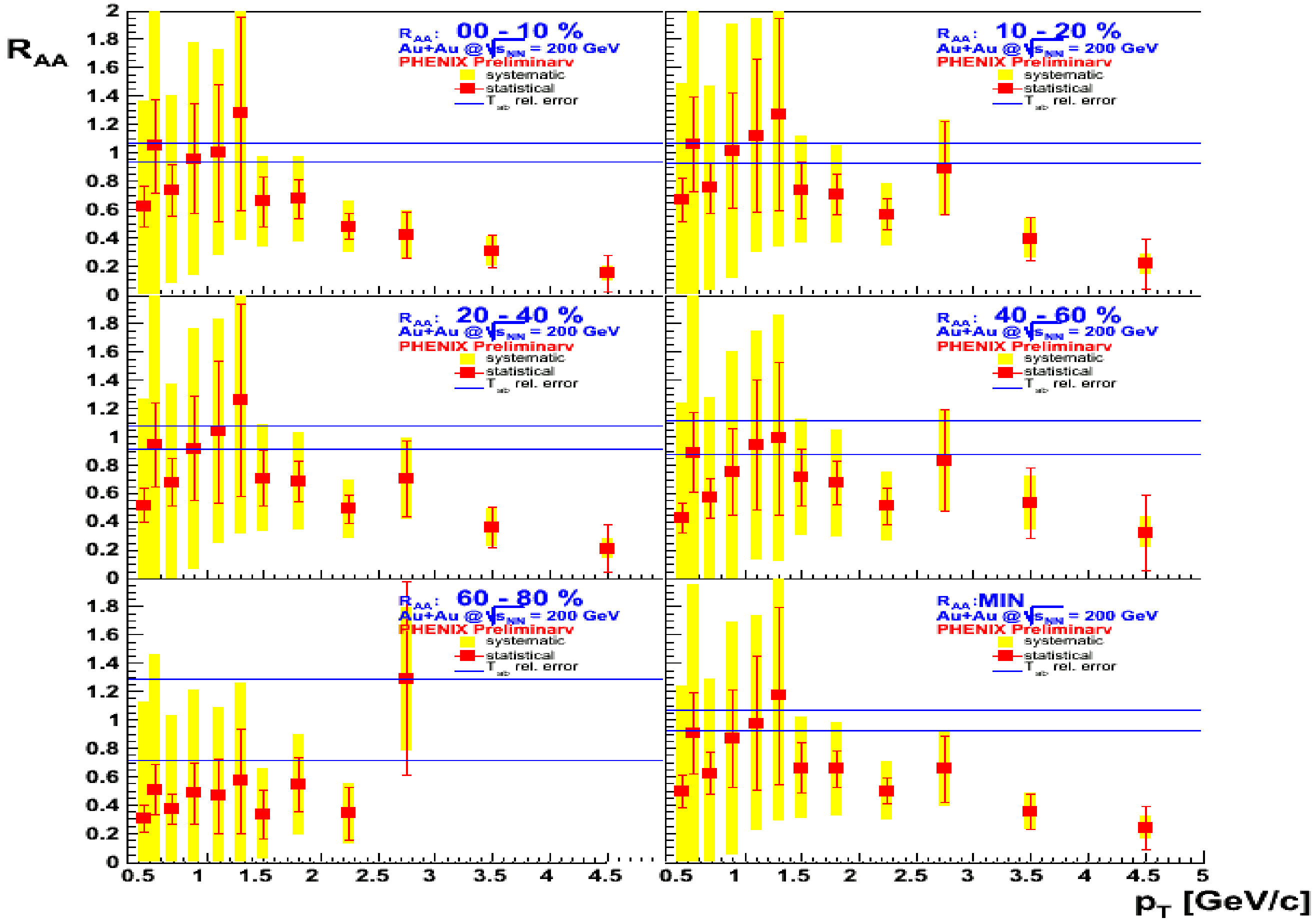



Note: $\alpha = (0.906 - 1.042) \Rightarrow$
$N_{coll}^{\alpha} \approx (0.6 - 1.2) * N_{coll}$

PHENIX.
PRL94, 082301 (2005)

# Charm quark suppression at high $p_T$ ?

- Latest single $e^{\pm}$ $R_{AA}$ at higher $p_T$ < 4.5 GeV/c (large uncertainties still @ low $p_T$):




PHENIX Preliminary

- Suppressed charm production above $p_T$~2 GeV/c ?

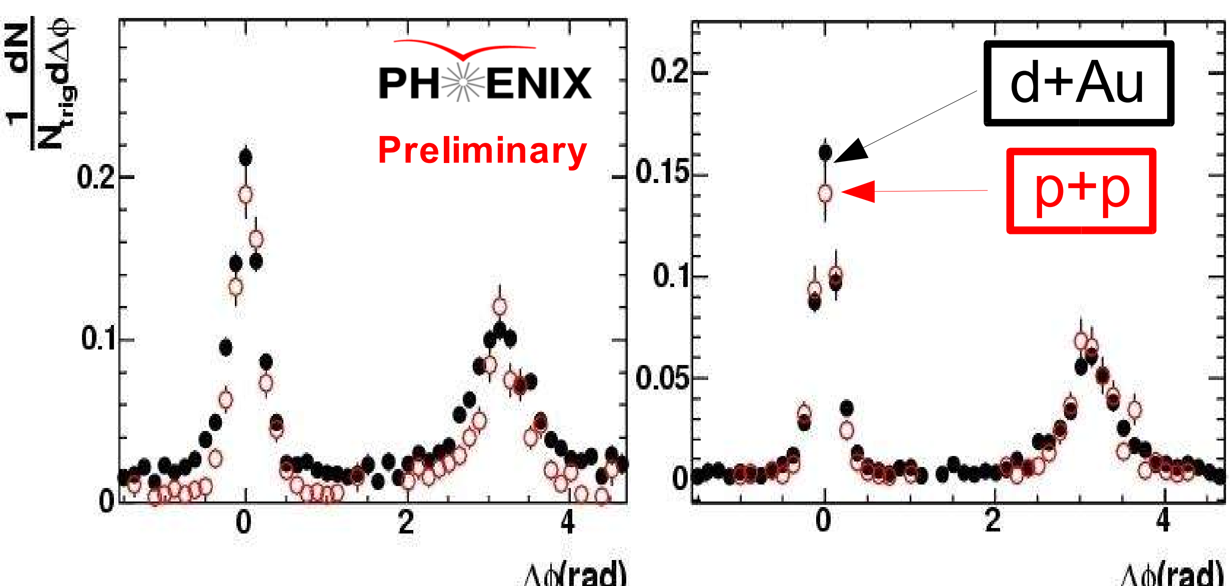
See next talks by A. Dainese & R. Turrisi

- New kinematic domain accessible with heavy-Q: Hard production at low $p_T$
- $R_{AA}$(lo $p_T$) ~1 >> $R_{AA}$(hi $p_T$) ~ $R_{AA}(\pi^0)$: Energy loss for <u>fast</u> heavy Q shifts them down to low $p_T$? No en. loss effect for slow Q (flatter charm $dN/dp_T$ at low $p_T$) ?

# High $p_T$ di-hadron $\phi$ correlations in high-energy pp, dAu collisions

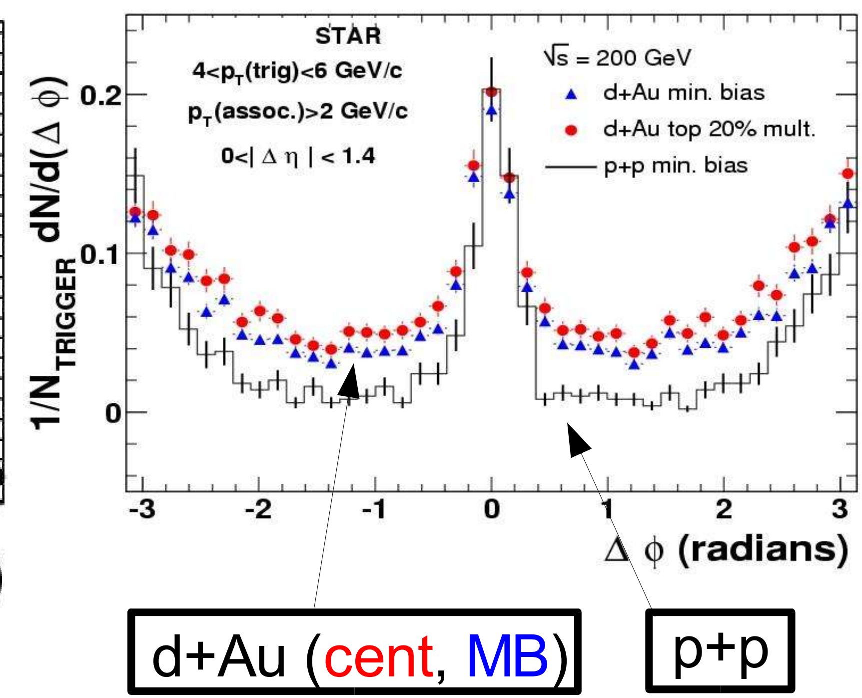
# Dijets via high $p_T$ dihadron azimuthal correlations: pp, dAu

- Two-particle correlations: $h^{\pm} - h^{\pm}$, $\pi^{0,\pm} - h^{\pm}$. Trigger: highest $p_T$ (leading) hadron.
- Associated $\Delta\phi$ distribution (e.g. "assorted": 2 GeV/c < $p_T^{assoc} < p_T^{trigger}$)
- Normalized to number of triggers: $\boxed{\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} = \frac{1}{N_{trig}}\frac{N_{cor}(\Delta\phi)}{N_{mix}(\Delta\phi)}}$
- Clear near- ($\Delta\phi \sim 0$) and away- ($\Delta\phi \sim \pi$) side jet signals:



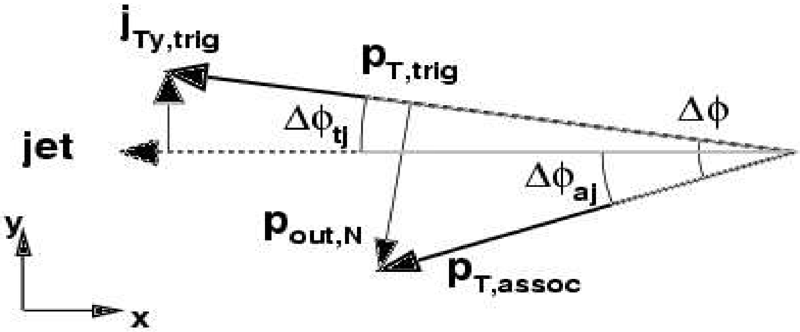

$p_T^{assoc}$ = 2-3 GeV/c

$p_T^{assoc}$ = 3-5 GeV/c



# Jet properties from dihadron correlations

- Jet "width" $j_T$ :

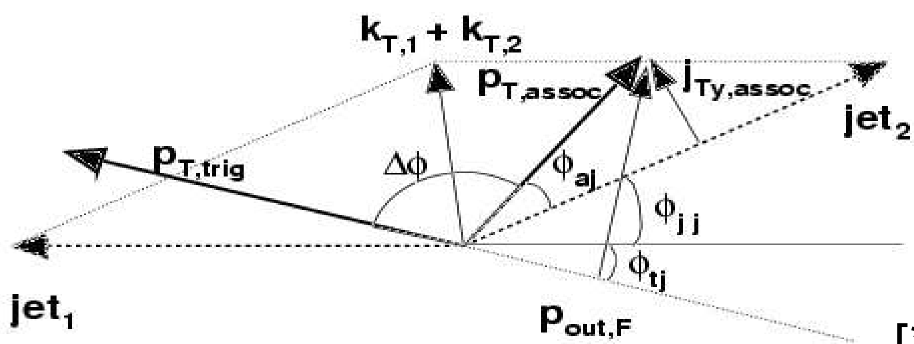



[*]

$$(j_{T_y})_{RMS} \simeq \frac{\sigma_N \langle p_{T,asso}\rangle}{\sqrt{1+\langle x_h^2\rangle}} \simeq \sigma_N \frac{\langle p_{T,trig}\rangle\langle p_{T,asso}\rangle}{\sqrt{\langle p_{T,trig}\rangle^2+\langle p_{T,asso}\rangle^2}}$$

where $x_h = p_{T,asso}/p_{T,trig}$

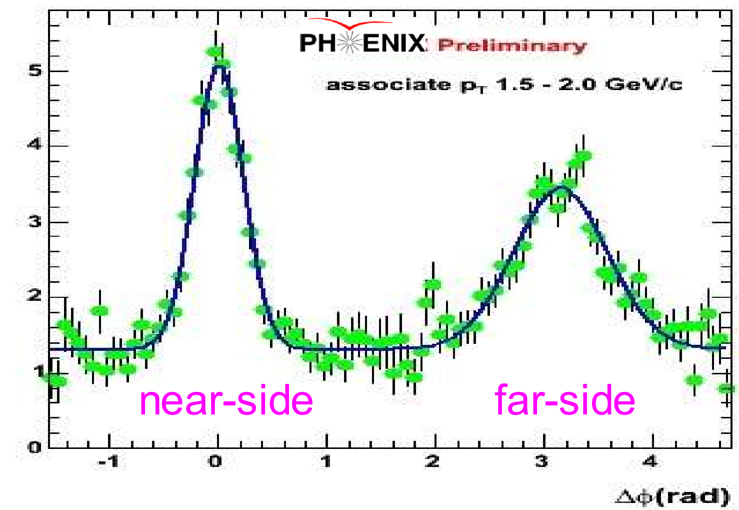
- Di-jet acoplanarity $k_T$:




[**]

$$(k_{Ty} z_{trig})_{RMS} = \frac{1}{\sqrt{2\langle x_h^2\rangle}} \sqrt{\langle p_{T,assoc}\rangle^2 \sin^2\sigma_F - (1+\langle x_h^2\rangle)\,(j_{T_y})^2_{RMS}}$$

(1) 2-hadron correlation function:




(2) Fit to 2-gaussians:

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} = B + \frac{Yield_N}{\sqrt{2\pi}\sigma_N} e^{\frac{-\Delta\phi^2}{2\sigma_N^2}} + \frac{Yield_F}{\sqrt{2\pi}\sigma_F} e^{\frac{-(\Delta\phi-\pi)^2}{2\sigma_F^2}}$$

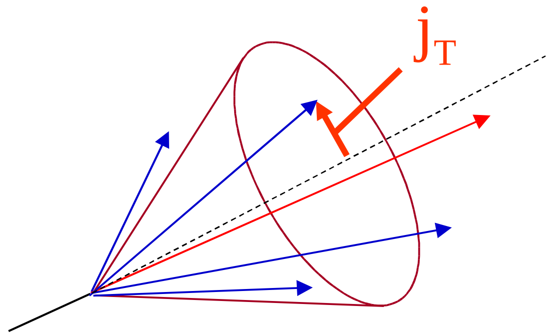
$\Longrightarrow$ near-side $\sigma_N$, far-side $\sigma_F$ widths

(3) Extraction of $j_T$, $k_T$ from $\sigma_N$, $\sigma_F$ via [*], [**] (and $dN/dx_E$ from $Yield_{N,F}$)

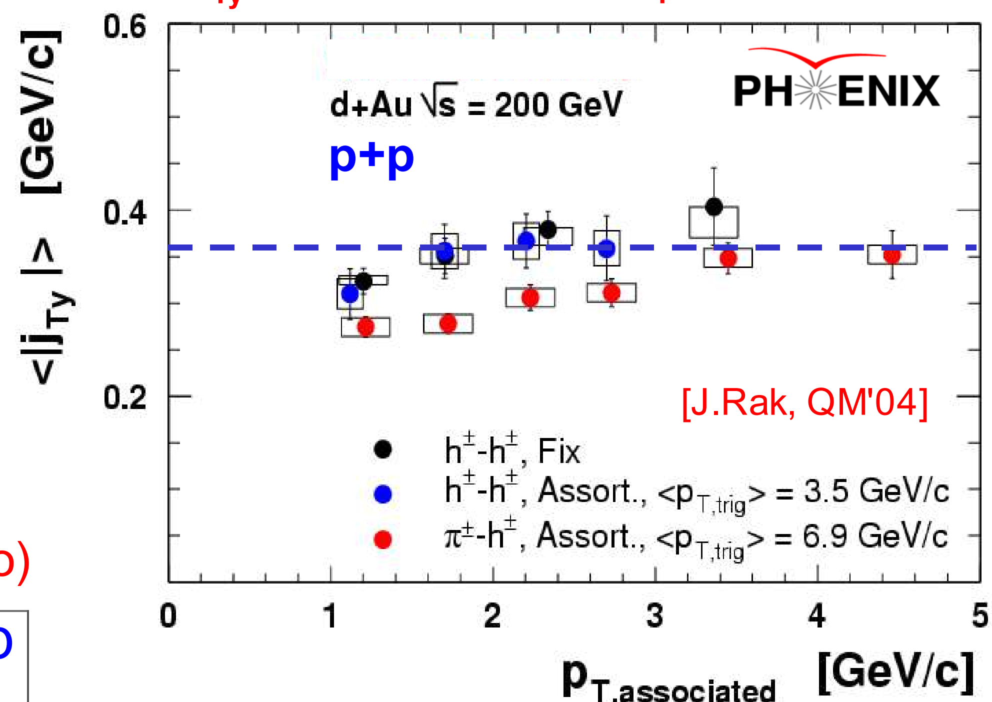
[details in J.Jia, nucl-ex/0409024]

# Mean transverse momentum of jet hadrons ($j_T$): pp, dAu

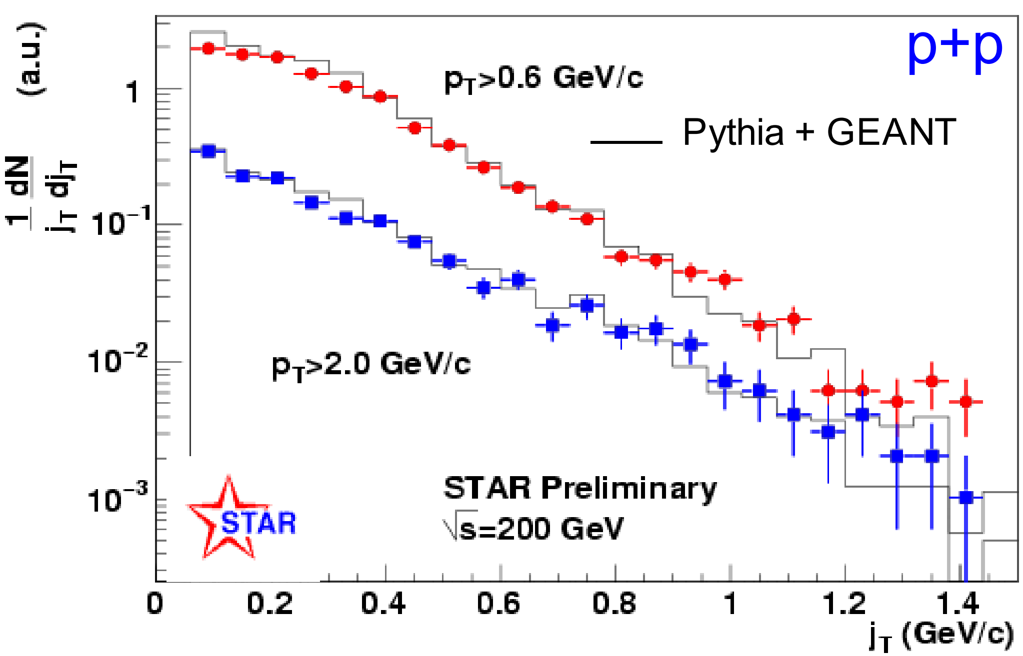
- Jet (near-angle) "width" $j_T$ :




$< j_{Ty} >$ ~350 MeV/c ≡ $< j_T >$ ~ 500 MeV/c



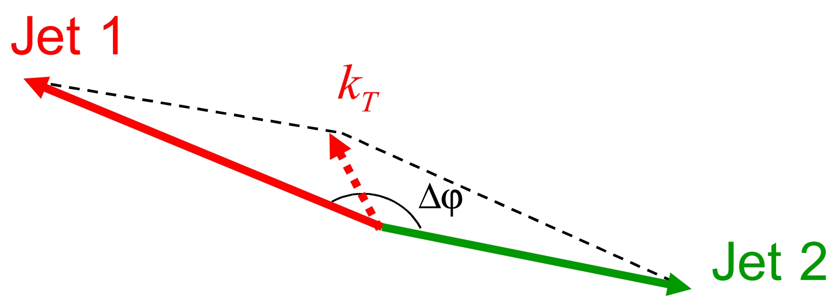

$< j_T >$ ~ 500 MeV/c (from full jet reco)



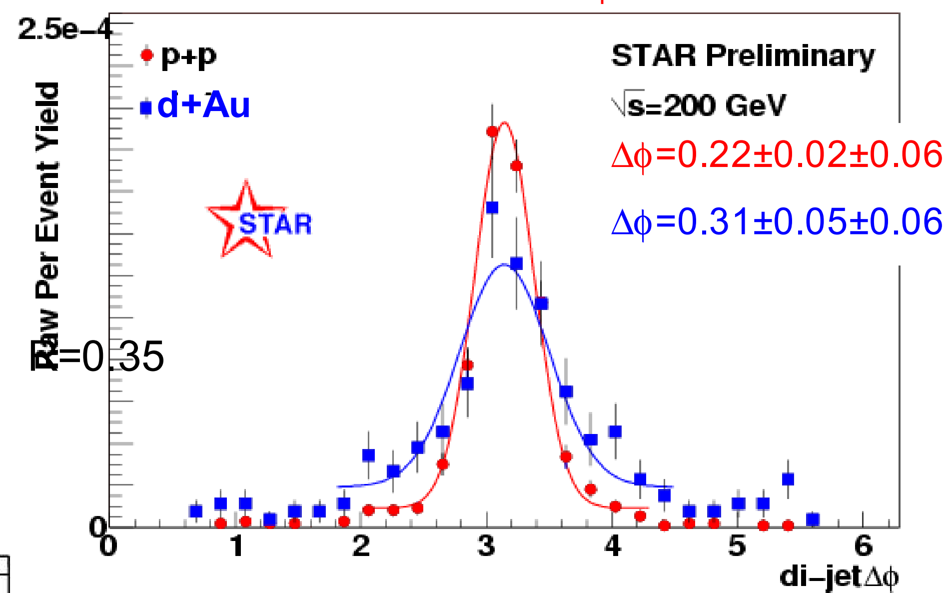

- $< j_T >$ ~ 500 MeV/c: Agreement between RHIC and ISR data.
- No apparent difference between dAu and pp.
- Fragmentation not affected by cold QCD medium.

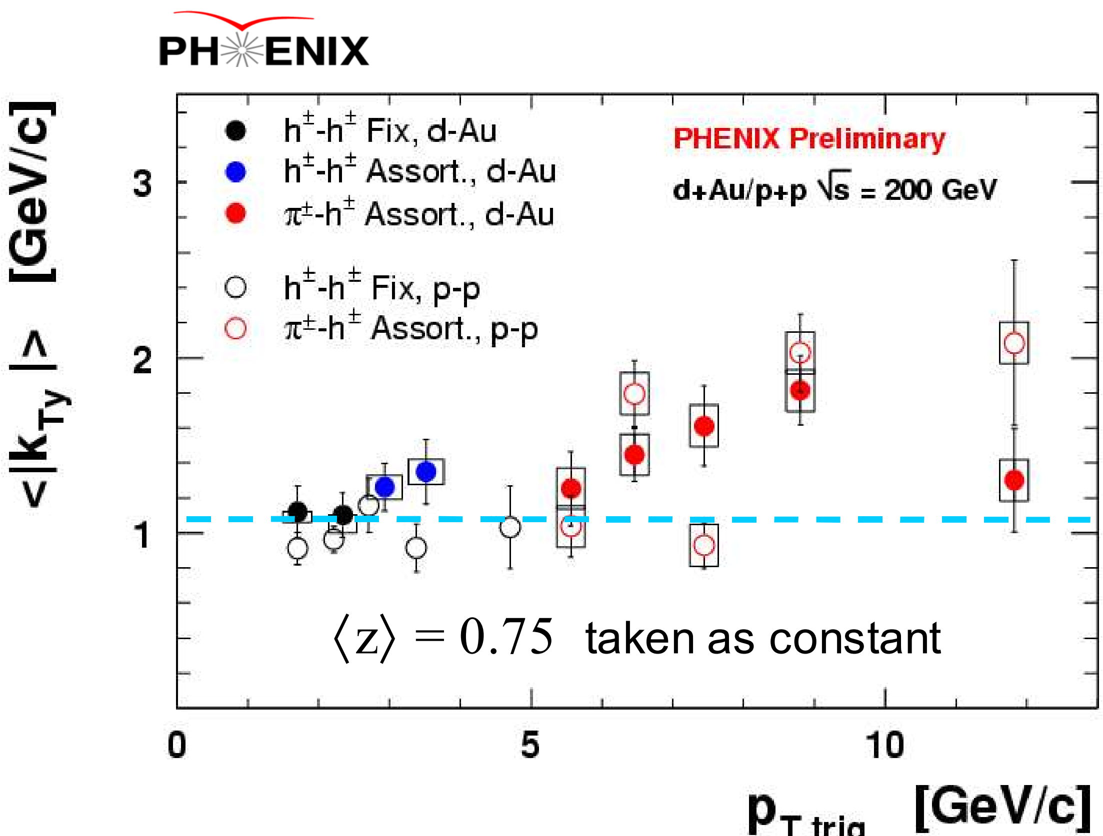
# Di-jet acoplanarity ("intrinsic" $k_T$) : pp, dAu

- Intrinsic $k_T$ (di-jet acoplanarity):




(from full jet reco: $E_T$~13 GeV)

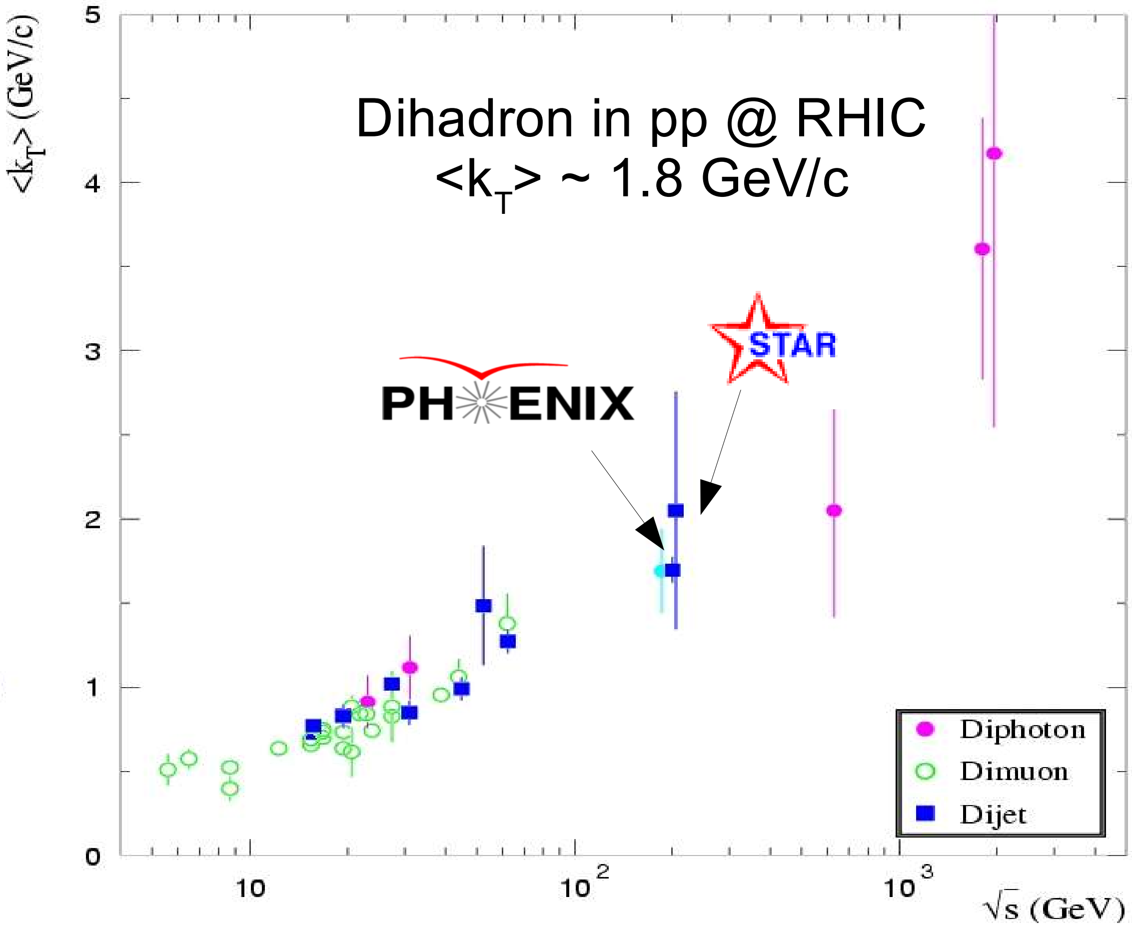



- Non-negligible **$k_T$ broadening in pp: $\langle k_{Ty}\rangle$ ~ 1.1 GeV/c**
- In dAu: $\langle k_T^2\rangle_{dAu} \equiv \langle k_T^2\rangle_{pp} + \langle k_T^2\rangle_{nuclear}$
- Non-null (but small) **$\langle k_T\rangle_{nuclear}$**
  (constraints models of multiple scattering in cold nuclear medium)

# Excitation function of pp di-jet acoplanarity ("intrinsic" $k_T$)

- sqrt(s)-dependence of $<k_T>_{pair}$:

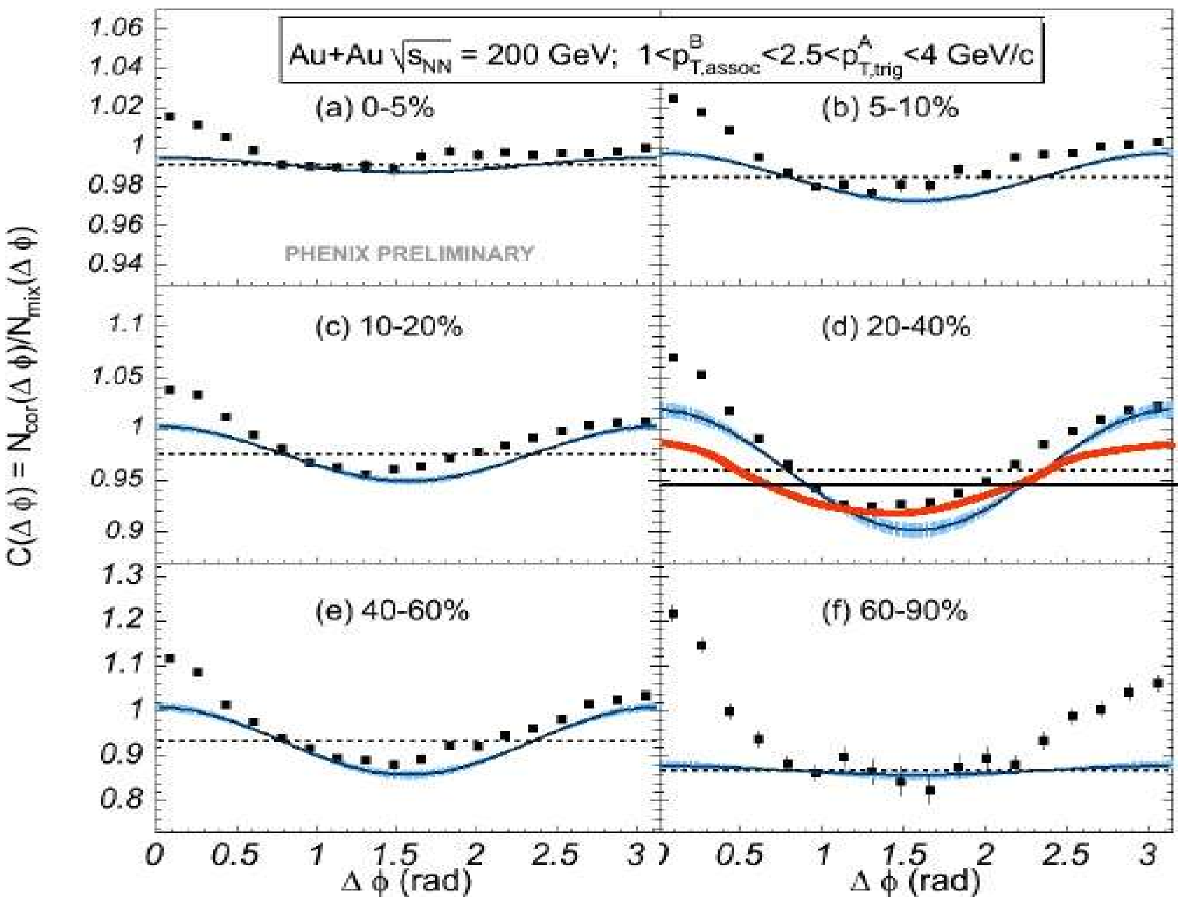



- (Logarithmic) increase with sqrt(s) consistent with growing gluon radiation contribution (not just intrinsic parton Fermi motion).

# High $p_T$ di-hadron $\phi$-, $\eta$- correlations in high-energy AA collisions

# Dijets in AuAu via high $p_T$ dihadron azimuthal correlations

- Same $dN_{pair}/d\varphi$ analysis as in pp (dAu) but 2 extra "complications":
  (1) Increased "underlying event" background: $a_0$
  (2) Elliptic flow subtraction: $H(\Delta\varphi)$




$$\underbrace{C(\Delta\phi)}_{\text{Correlation Function}} = a_0\left[\underbrace{H(\Delta\phi)}_{\text{Harmonic}} + \underbrace{J(\Delta\phi)}_{\text{Jet Function}}\right]$$

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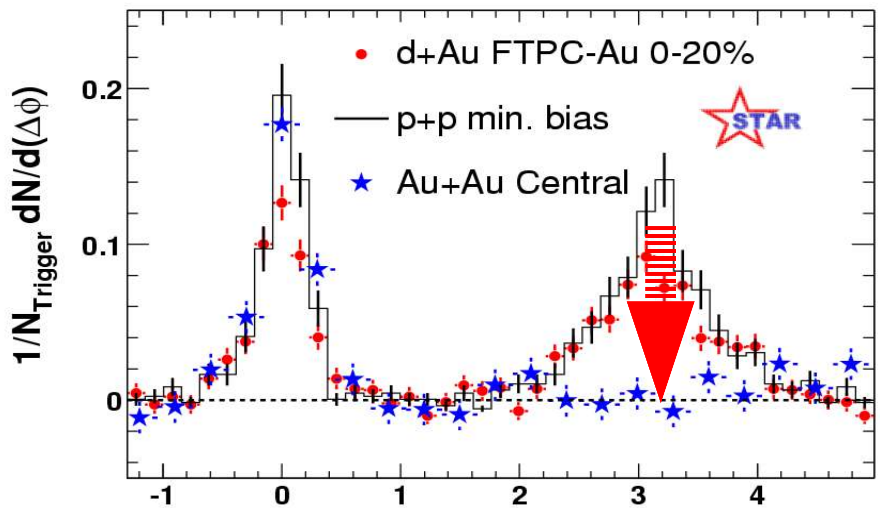
Ajitanand, ICPAQGP'04 and nucl-ex/0501025

- Complex procedure (esp. in finite acceptances) under control now (see e.g. Ajitanand *et al:* nucl-ex/0501025)

# High $p_T$ AuAu dihadron azimuthal correlations

- Near-side: Unmodified (AuAu ~ dAu ~ pp)
- Away-side: Disappearance of high $p_T$ correlations ("monojet"-like topologies) in central AuAu.

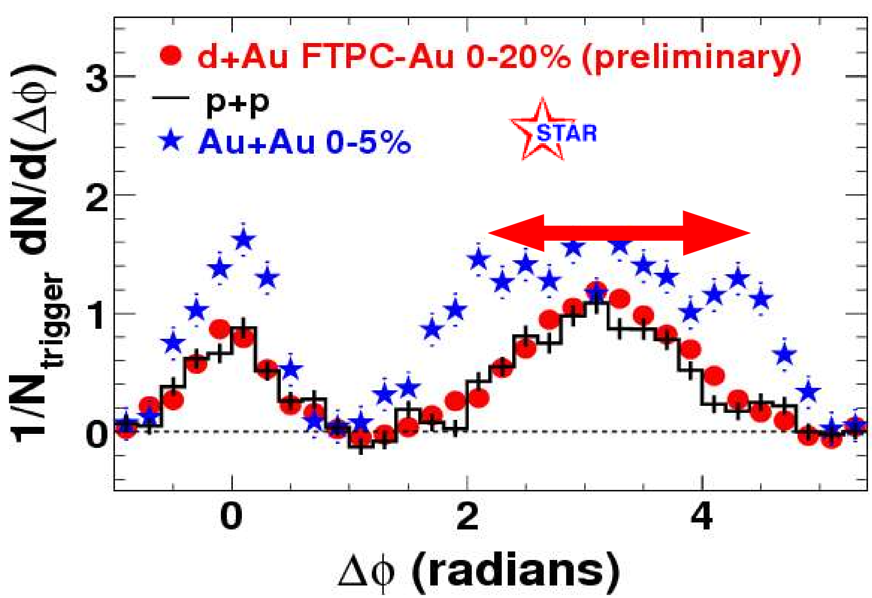
High $p_T$ :




$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ > 2 GeV/c

STAR, PRL90, 082302 (2003)

Lower $p_T$ :




$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ = 0.15 – 4 GeV/c

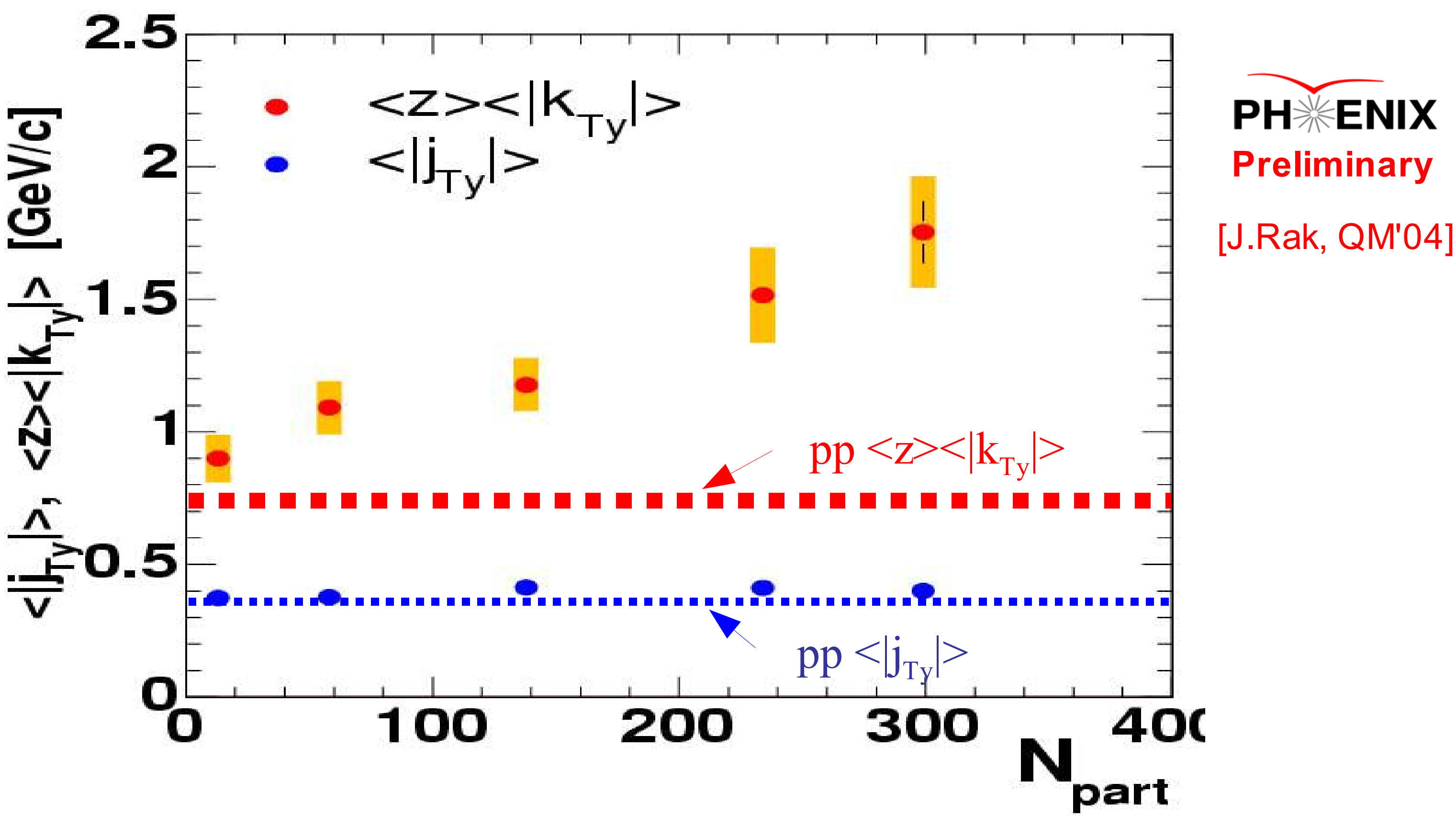
- Away-side: Broadened distribution of associated low $p_T$ hadrons

STAR, submitted to PRL
nucl-ex/0501016

# Centrality dependence of AuAu jet properties: $j_T$, $k_T$

- $\langle j_T \rangle_{AuAu} \approx \langle j_T \rangle_{pp}$: Near-side fragmentation unaffected by QCD medium.

$p_{Ttrigg}$ =2.5 – 4.0 GeV/c , $p_{Tassoc}$ = 1.0 – 2.5 GeV/c

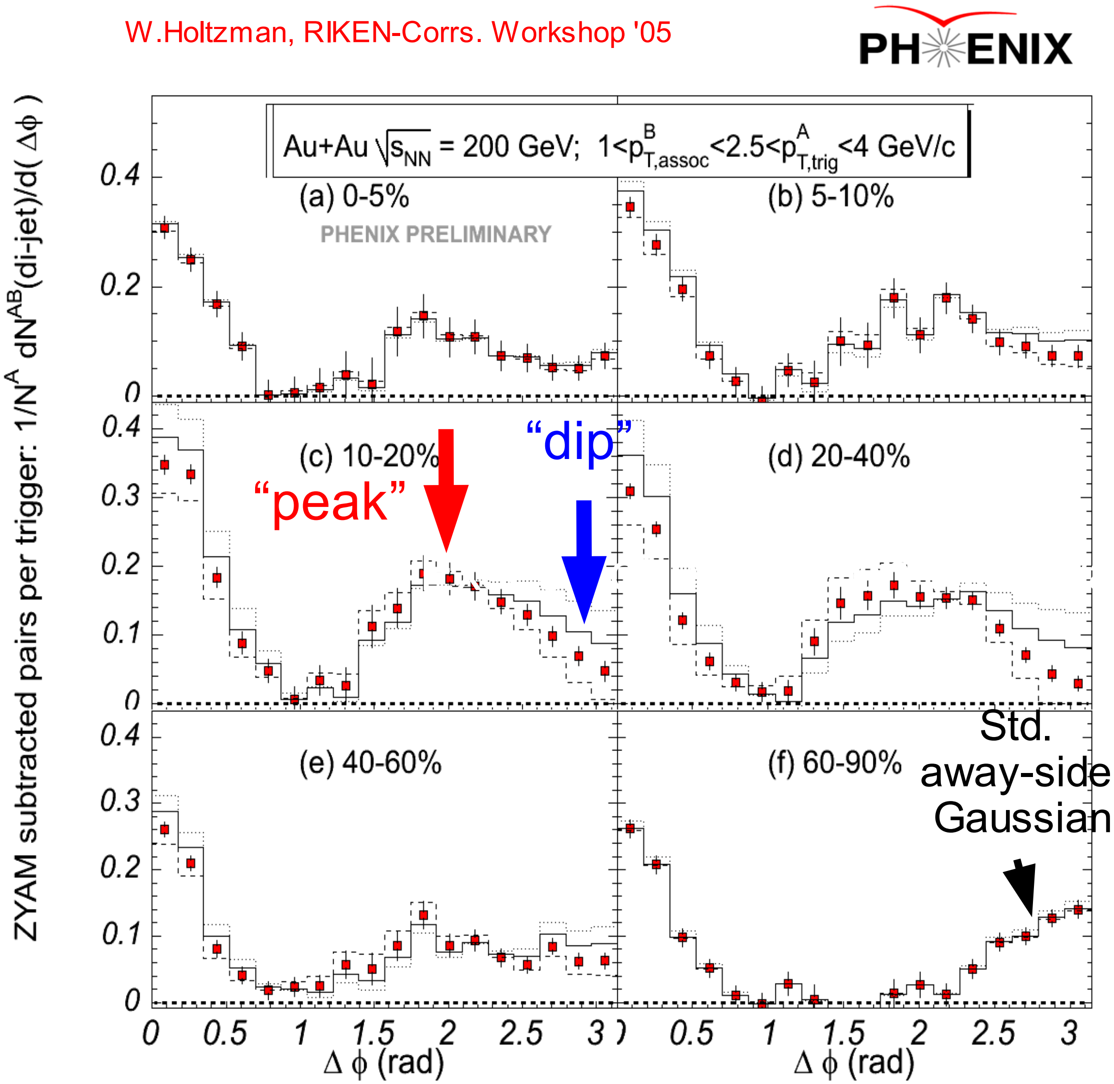



- $\langle k_T \rangle_{AuAu} \approx$ 3 GeV/c: Significant $k_T$ broadening (strongly centrality dependent) indicating substantial final-state rescattering of away-side fragmenting parton.

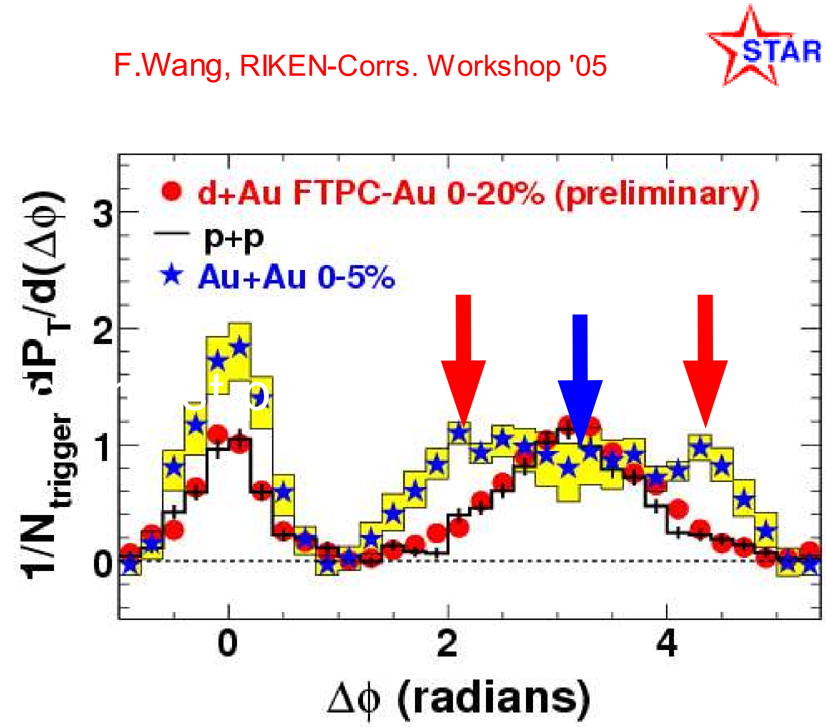
# Away-side AuAu dihadron azimuthal correlations (I)

- Strongly modified away-side $\Delta\varphi$ correlations in central AuAu:

W.Holtzman, RIKEN-Corrs. Workshop '05




F.Wang, RIKEN-Corrs. Workshop '05



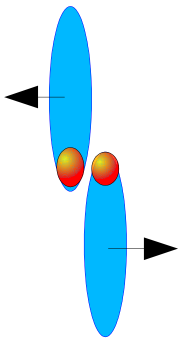

- Away-side ($\pi$) "dip" $\Leftrightarrow$ excess of energy "double peak" at $\pi \pm 1$.
- Broader & double peaked at large $p_T^{assoc}$ (more pronounced for lower $p_T^{trig}$)

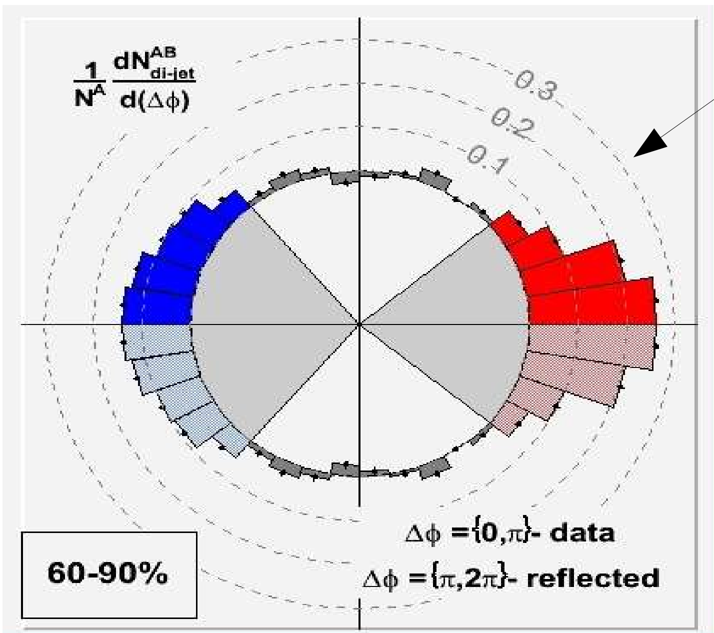
# Away-side AuAu dihadron azimuthal correlations (II)

- Same PHENIX $dN_{pair}/d\Delta\varphi$ result now in polar coords:

Au+Au periph

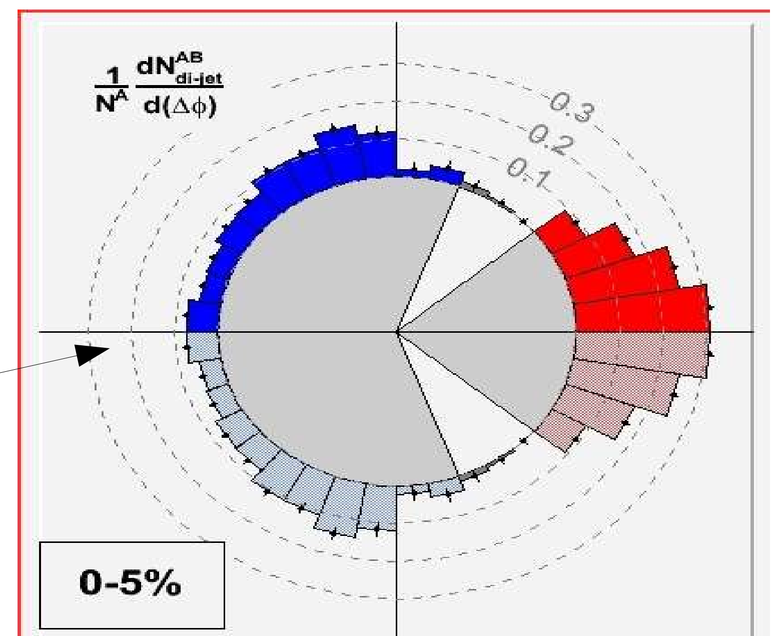
- Standard back-to-back di-jet topology.

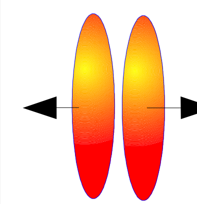





PHENIX Preliminary

Au+Au central



- Strongly non-Gaussian away-side "peak".

PHENIX

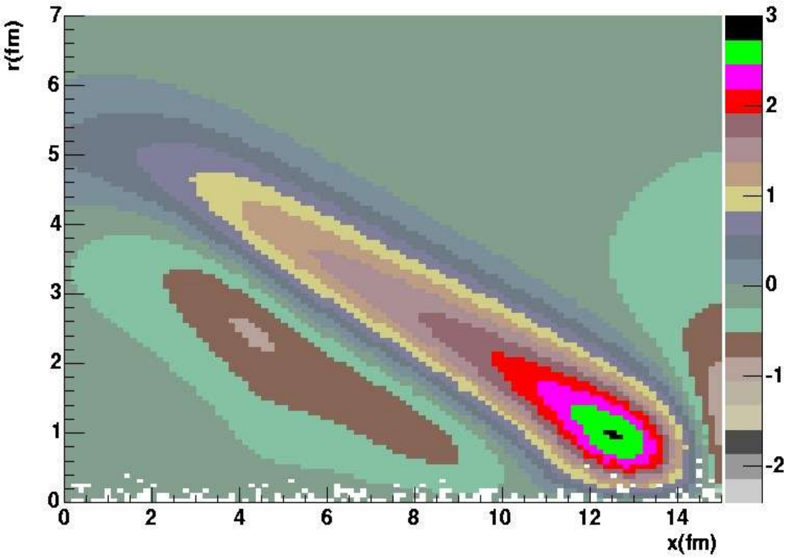
P.Stankus, RIKEN-Correlations Workshop '05

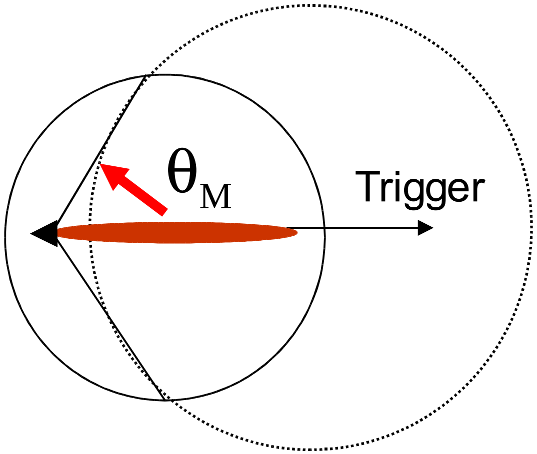
# "Double peak" = Mach wave cone ?

- Double peak structure at at $\pi \pm 1$ rad reminiscent of ...
  Mach wave conical shock ("sonic boom") $\Rightarrow$ speed of sound accessible

Mach cone: $\boxed{\cos\theta_M = c_s}$

Stoecker, Dumitru, nucl-th/0406018.
Casalderrey, Shuryak, Teaney, hep-ph/0411315.




$c^2_s \neq$ constant:

QGP ($1/\sqrt{3}$) $\rightarrow$ phase transition (0.) $\rightarrow$ HRG ($\sqrt{0.2}$)

$$c_s^{av} = \frac{1}{\tau_f}\int d\tau c_s(\tau) = 0.33$$

$\theta = \arccos(c^{av}_s) = 1.2$ rad $= 71^o$ ($\theta_{exp} \sim$ 1. rad ~ 57°)

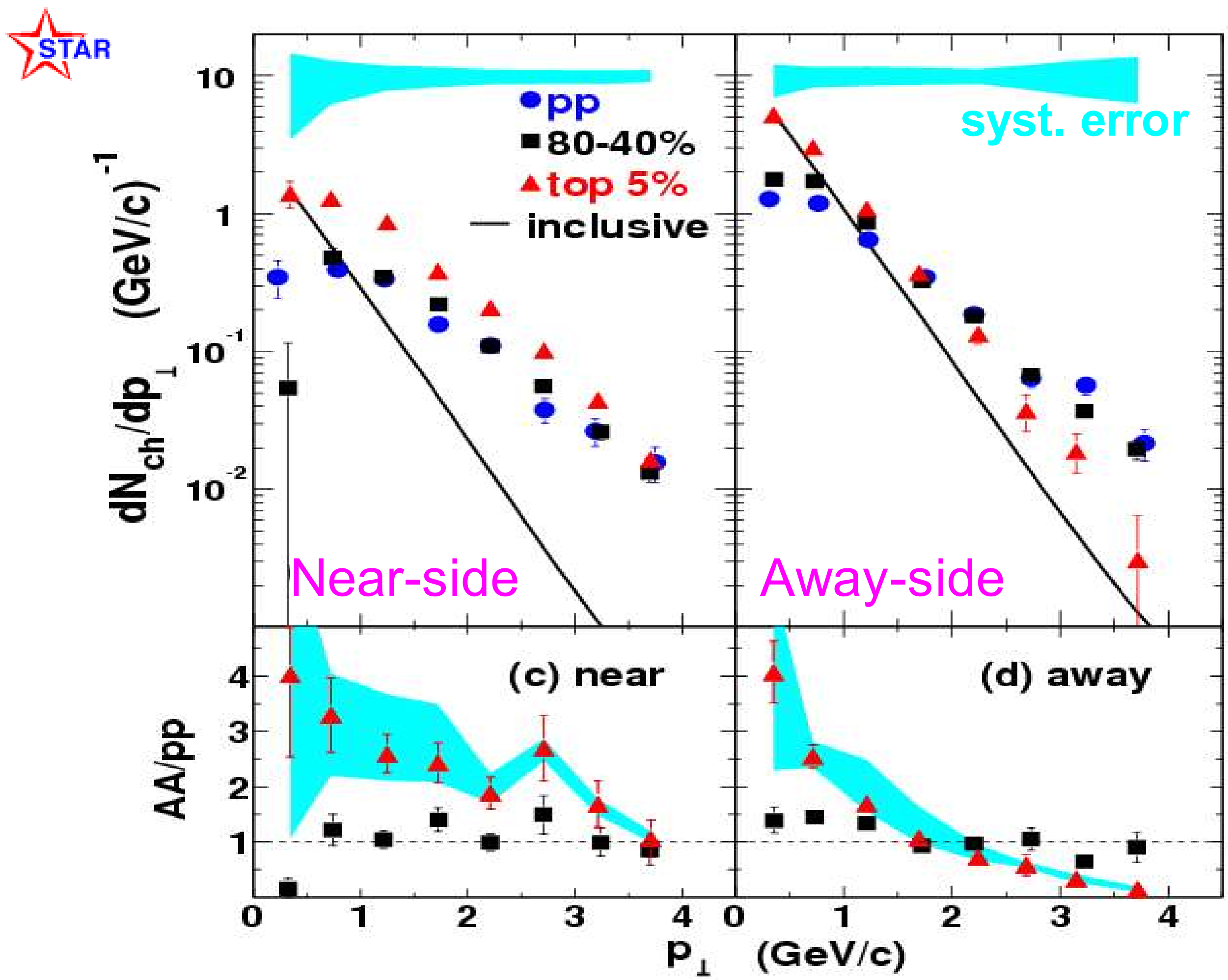
- Caveats:

  (1) Calculations based on collisional energy loss alone (does rad. energy loss fill the cone ?)

  (2) The direction of the Mach cone should change w/ the expansion.

# "Fragmentation functions": Central AuAu

- Associated ($p_{T\,assoc}$ = 0.15 – 4 GeV/c) near- and away- side hadron $p_T$ spectra:



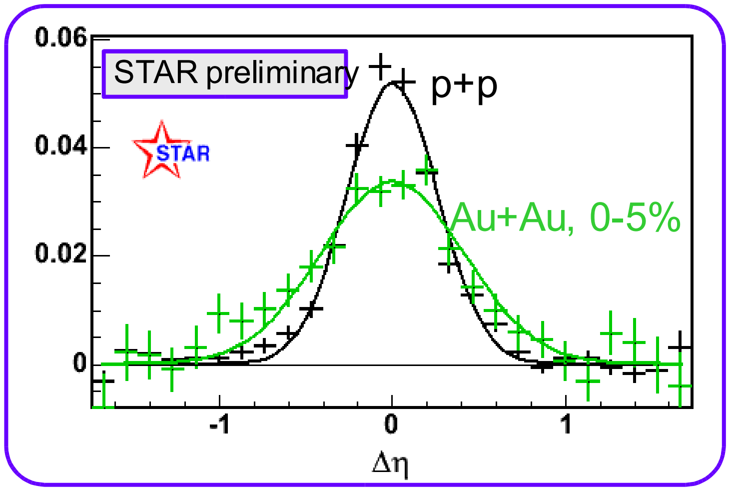

$p_{T\,trigg}$ = 4 – 6 GeV/c
$p_{T\,assoc}$ = 0.15 – 4 GeV/c

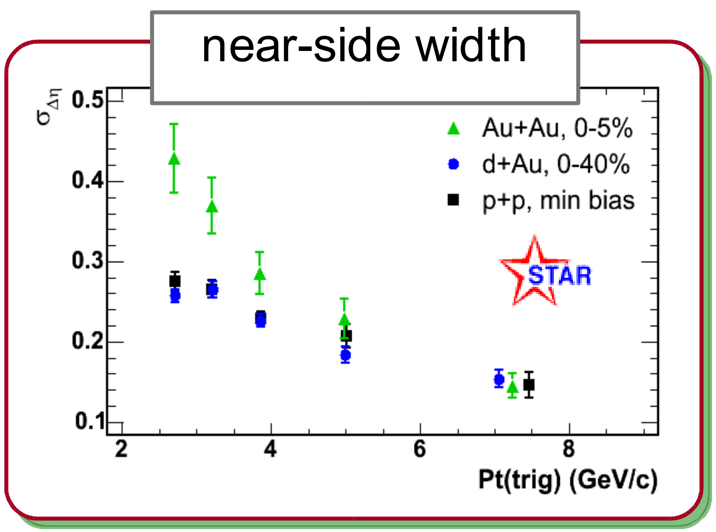
STAR, submitted to PRL
nucl-ex/0501016

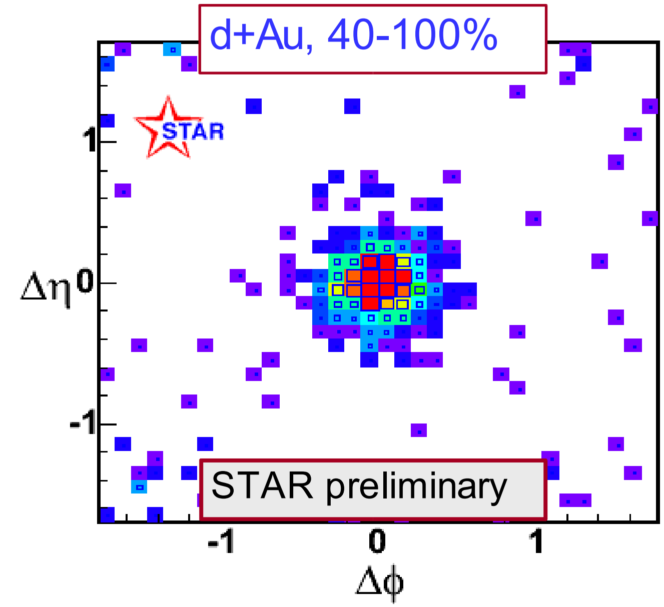
- Associated near-side jet yields overall enhanced (enhanced underlying evt.)
- Associated away-side jet yields "shifted down" in $p_T$: spectra closer to pure "soft" inclusive hadron production ("thermalized")

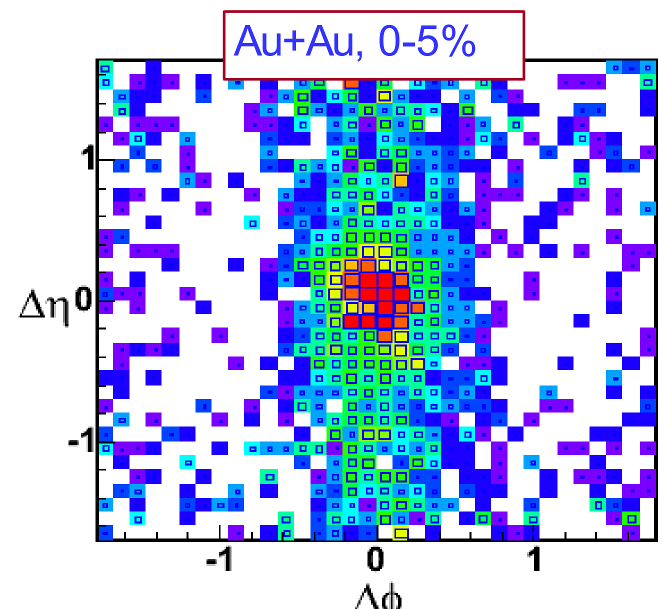
# Dihadron AuAu Δη correlations

- Significant broadening of pseudo-rapidity correlations in AuAu compared to pp,dAu. ("stretching" of jet cone along η).



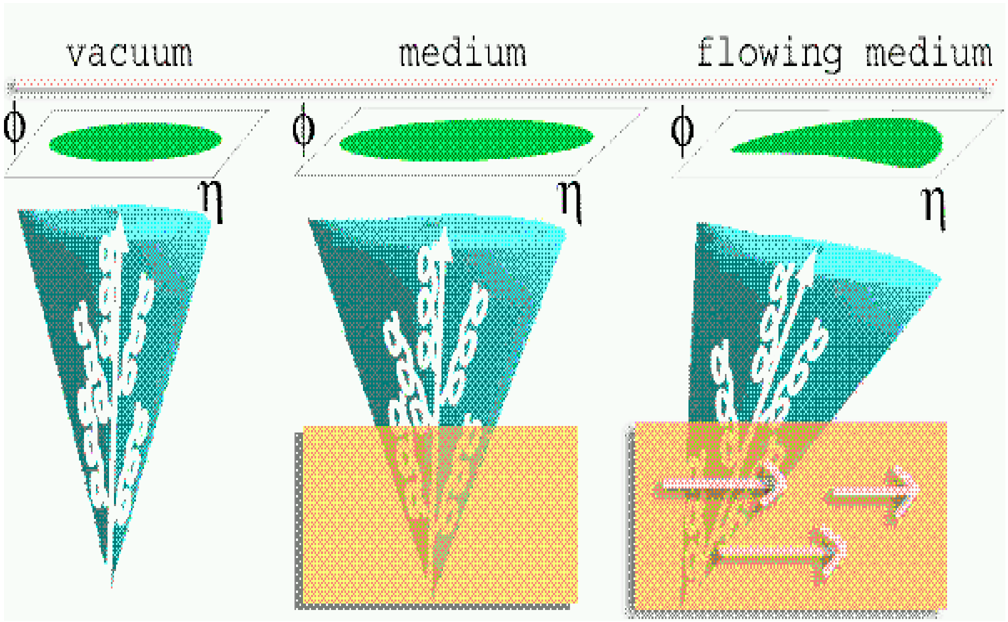

[D. Magestro, HP'04]

$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

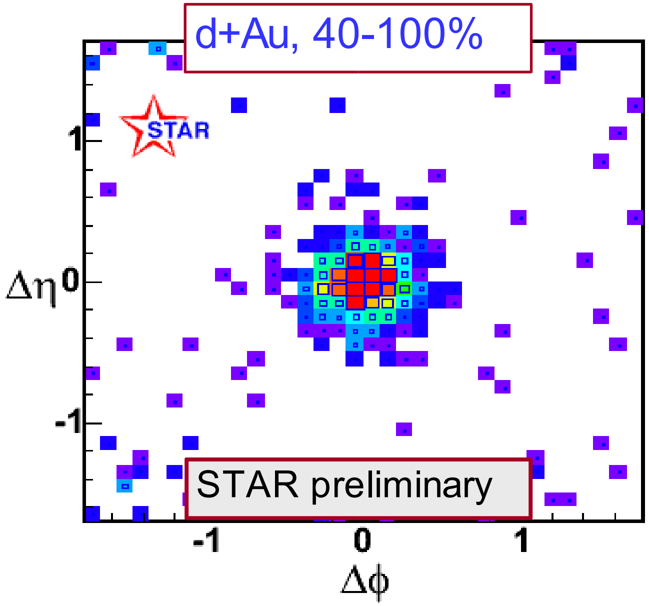
# Dihadron AuAu $\Delta\eta$ correlations

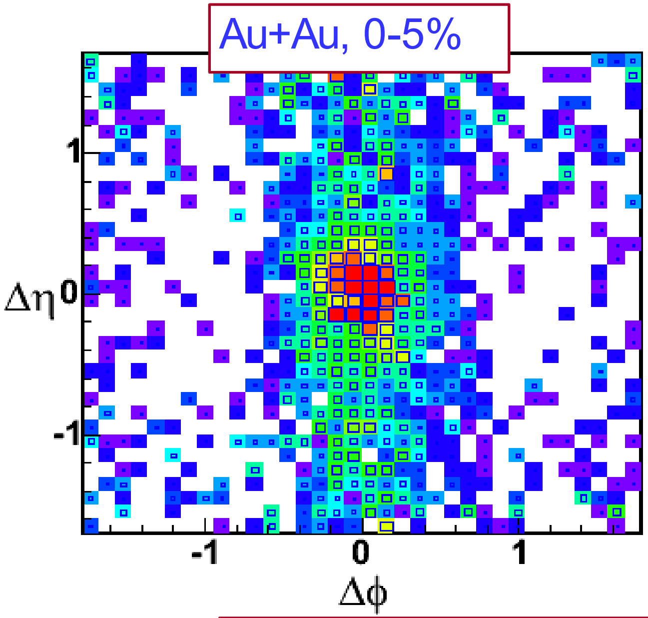
- Significant broadening of pseudo-rapidity correlations in AuAu compared to pp,dAu. ("stretching" of jet cone along $\eta$).

- Coupling of *g* radiation w/ longitudal expanding medium?




Armesto, Salgado, Wiedemann
PRL 93, 242301 (2004)

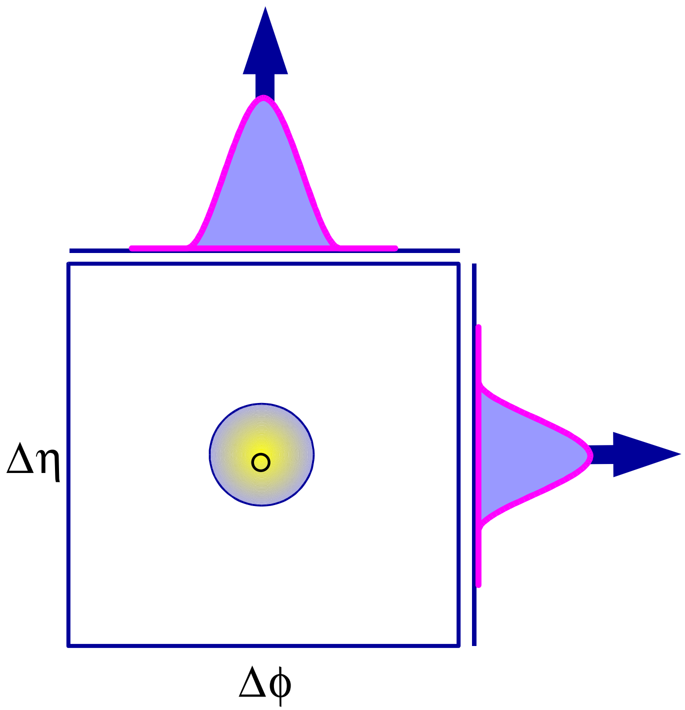



$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

# "Cartoon summary": Jet-quenching at RHIC

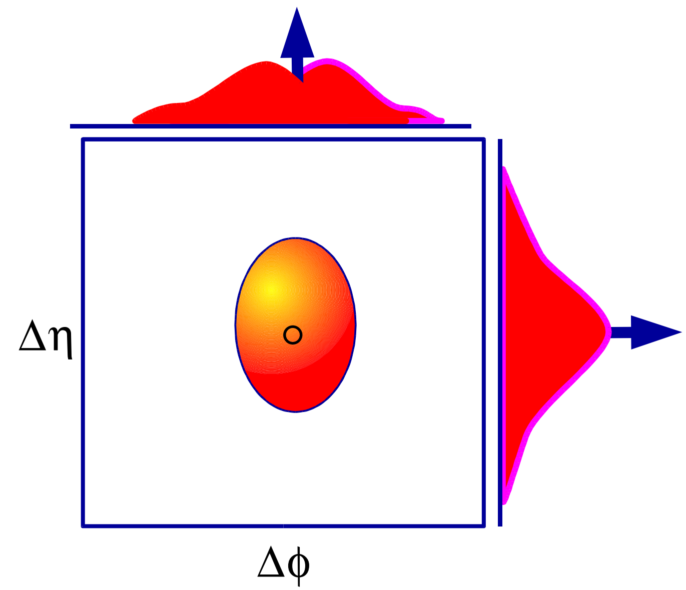
- Jet profile in pp (dAu) collisions:




Near-side width: $\langle j_T \rangle \sim 600$ MeV/c

Dijet acoplanarity: $\langle k_T \rangle \sim 1.8$ GeV/c

- Jet profile in AuAu central collisions:




Factor ~5 suppression of leading hadron.

Unmodified near-side $\Delta\phi$ width: $\langle j_T \rangle_{AuAu} \sim \langle j_T \rangle_{pp}$

Increased dijet acoplanarity: $\langle k_T \rangle \sim 3$ GeV/c

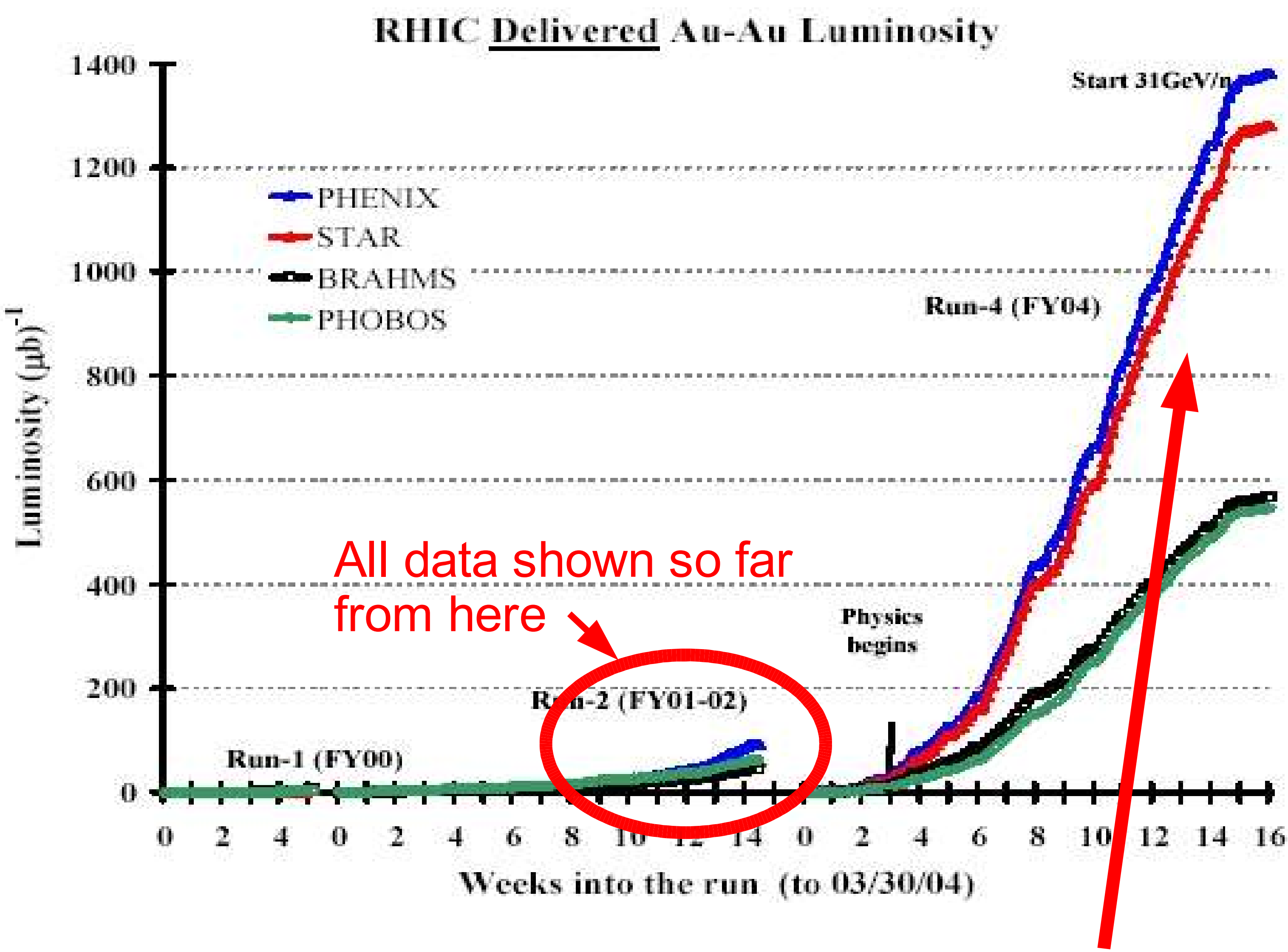
"Dip" (& double peak) structure in away-side $dN/d\Delta\phi$

"Thermalized" associated low $p_T$ yields

Dijet broadening in $\eta$.

Strong medium effects at work !

# Outlook

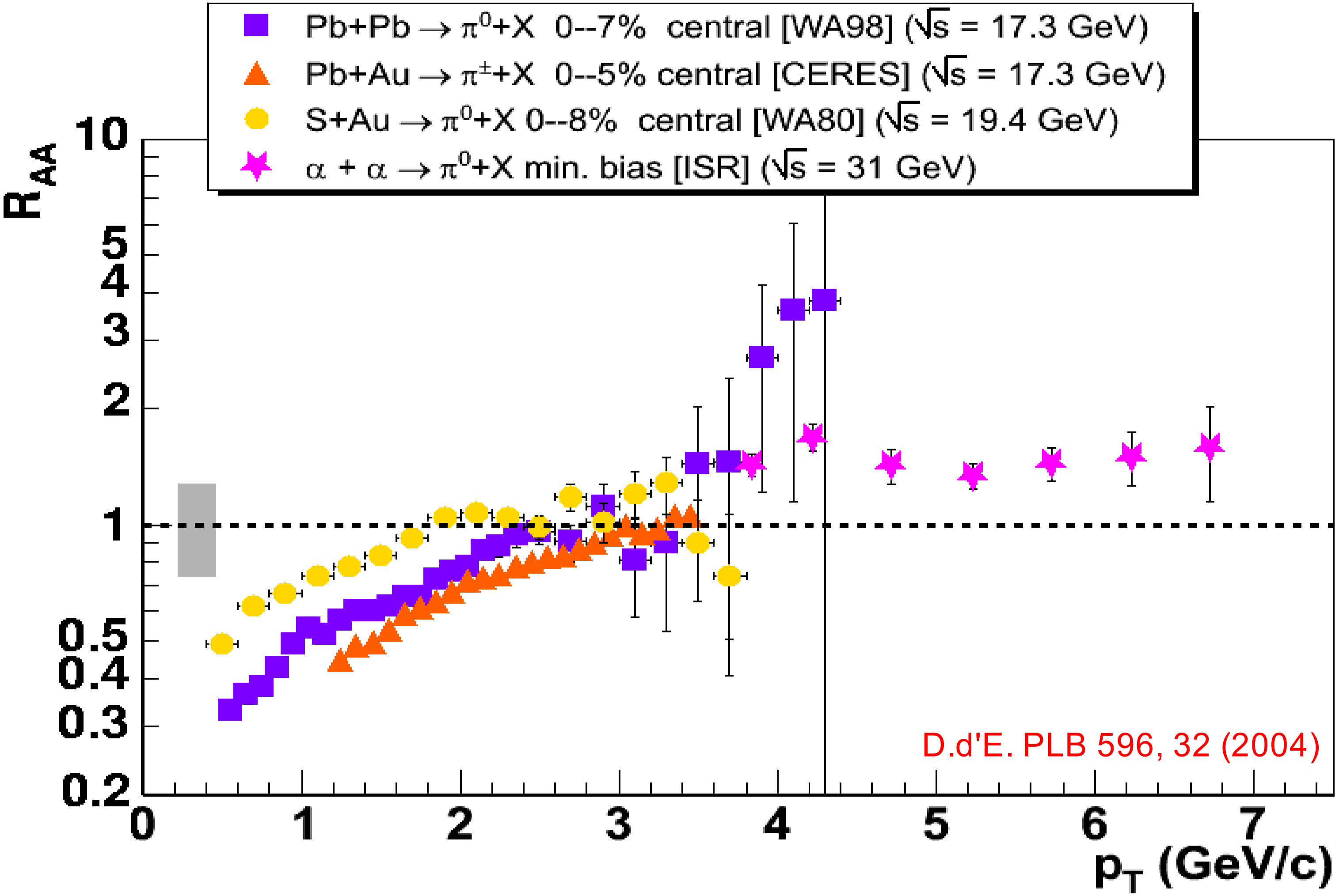



- 15 times more data available (ongoing DST production) !
- .. and exciting jet-physics expected ahead at LHC: γ-, Z-, jet-jet corrs., ...

**backup slides ...**

# "$N_{coll}$ scaling" in A+A @ 17, 31 GeV: High $p_T$ hadrons

- High $p_T$ $\pi^0$ production in (0-10%) central A+A at SPS (and $\alpha+\alpha$ @ ISR) energies consistent w/ "$N_{coll}$-scaling" (or Cronin enhancement):



# “Jet quenching” model vs. data (I)

- Dense medium properties from pQCD+ final-state parton energy loss models:

  - Initial gluon densities:

    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]

  - Opacities:

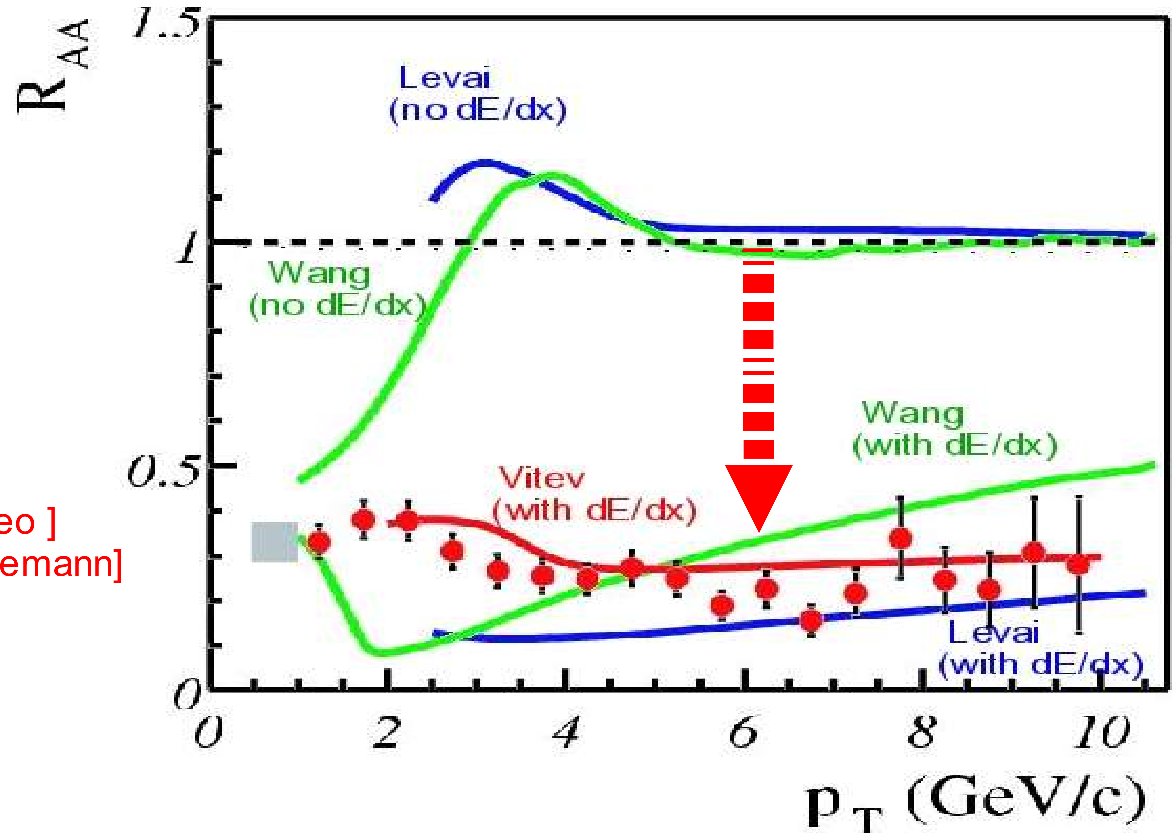
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]

  - Transport coefficients:

    $\langle q_0 \rangle \sim 14$ GeV/fm$^2$ [BDMPS, F.Arleo ] [Salgado-Wiedemann]

  - Medium-induced radiative energy losses:

    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source) [X.N.Wang]




- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\varepsilon_{crit\ QCD}$ (in thermalized syst.)

# High $p_T$ suppression: charm quark (theory)

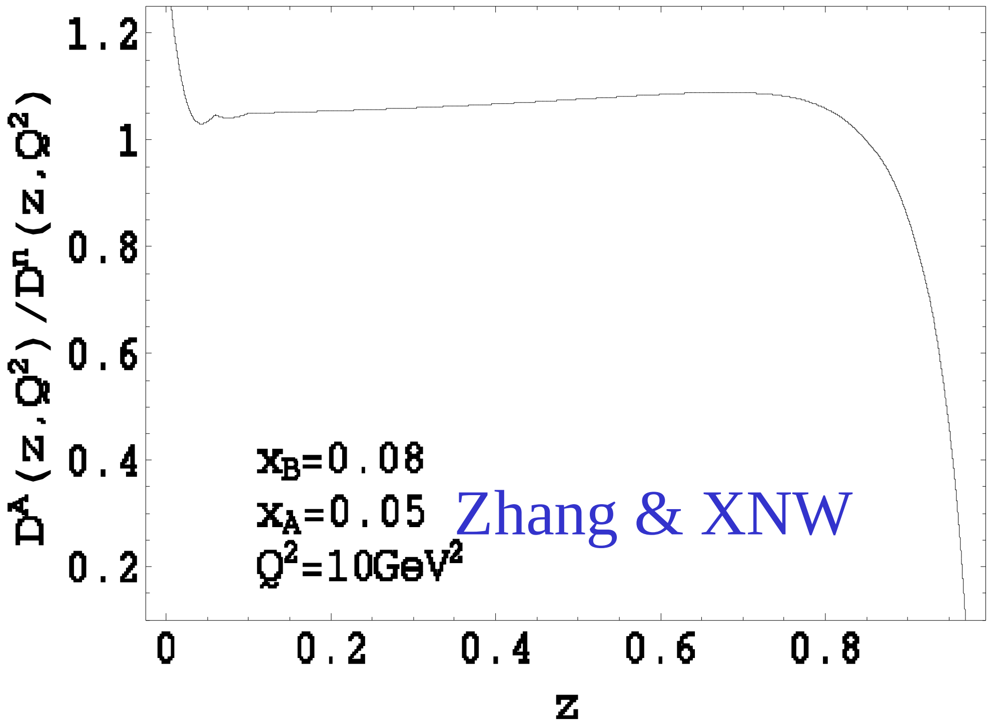
(1) Slow clock for formation time

$$\tau_f^H = \frac{1}{1/\tau_f + (1-z)M^2/2zq^-}$$

(2) Color factor

(3) Dead cone effect

$\Delta E_Q < \Delta E_g,\ \Delta E_q$



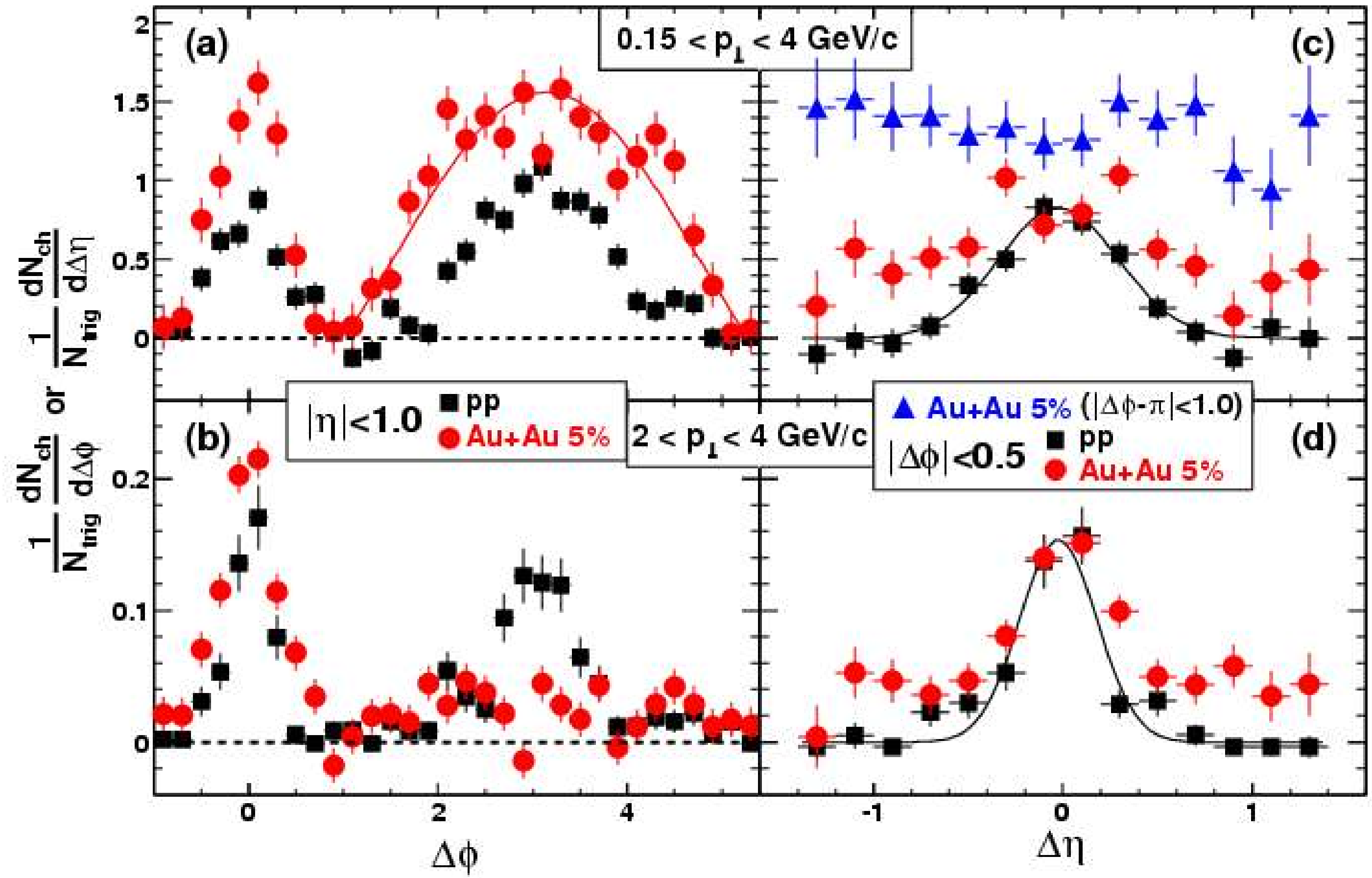

Zhang & XNW

Djordjevic & Gyulassy
Zhang & XNW
Armesto,Dainese,
Salgado & Wiedemann

# "Jet quenching": modified (di)jet structure

- Strongly modified away-side $dN_{pair}/d\varphi$ correlations in central AuAu:

STAR, nucl-ex/0501016.



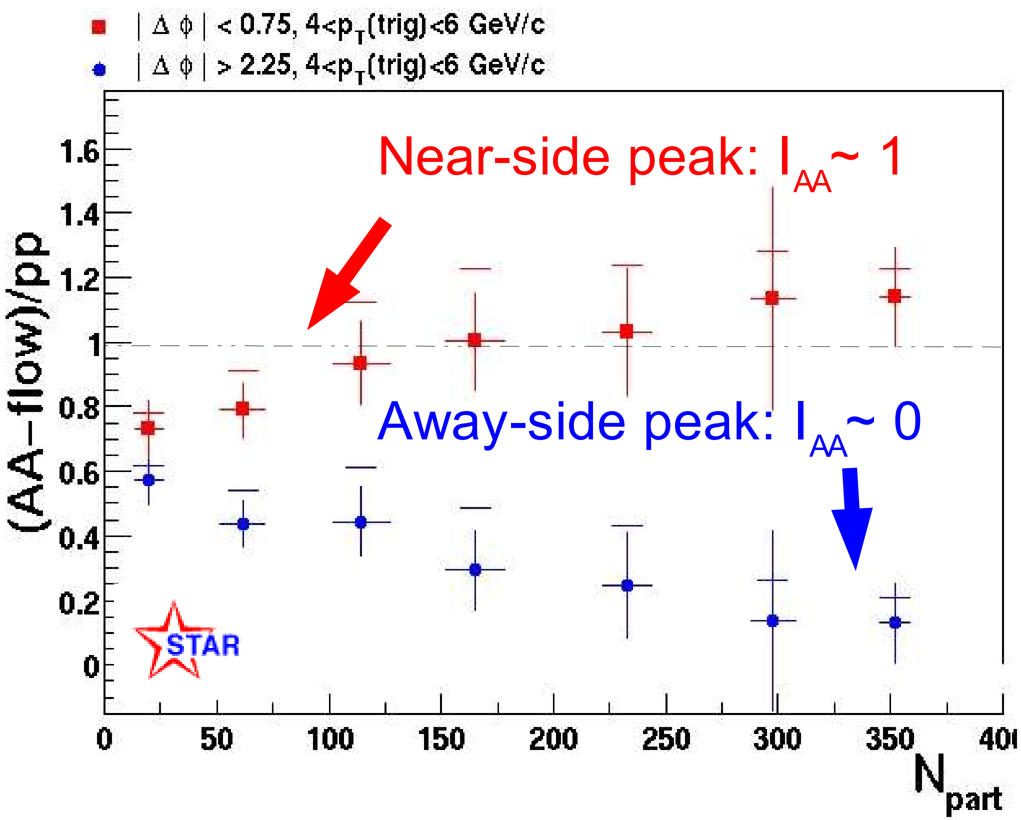

Enhanced and broadened distribution at low pT.

Away side suppression at high pT.

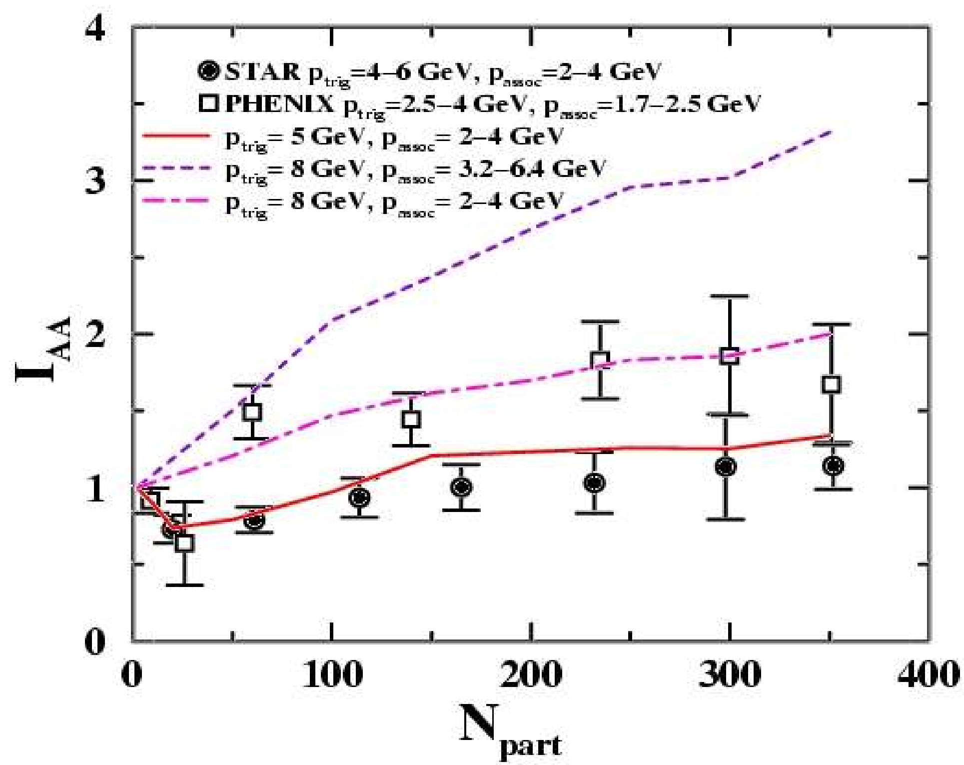
# Dihadron azimuthal correlations: AuAu "mono-jets"

- Centrality dependence of near- and away- side correlations "strengths":

$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)[D^{\mathrm{AuAu}} - B(1 + 2v_2^2\cos(2\Delta\phi))]}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) D^{\mathrm{pp}}}$$




STAR, PRL90, 082302 (2003)




[A.Majumder, nucl-th/041261]

# Dihadron azimuthal correlations: AuAu "mono-jets"

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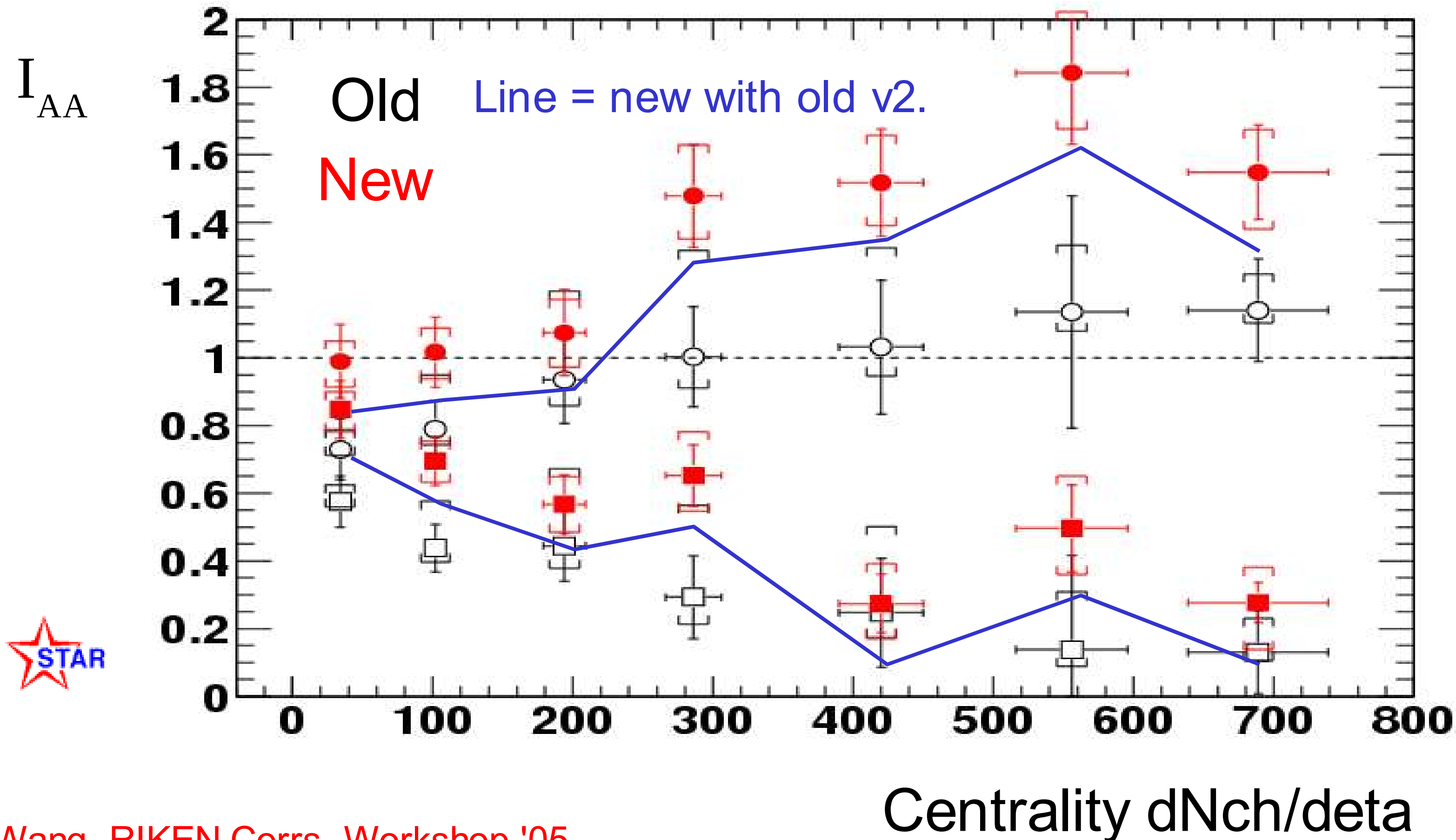
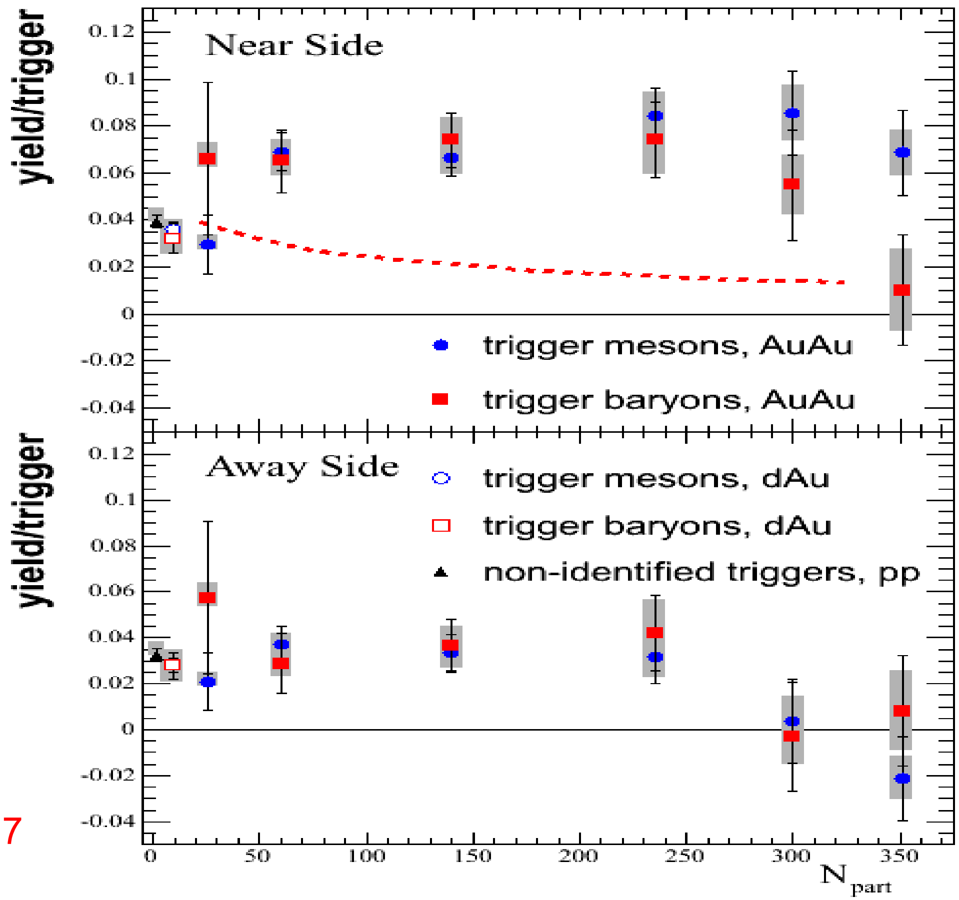



F.Wang. RIKEN Corrs. Workshop '05

# "Fragmentation functions": Central AuAu (200 GeV)

- Baryon-meson dependence of associated near- and away- side hadron $p_T$ spectra:




$p_{T\ trigg}$= 2.5 – 4 GeV/c
$p_{Tassoc}$ = 1.7 – 2.5 GeV/c

Near-side

Away-side

PHENIX
nucl-ex/0408007

- Associated yields similar for meson & baryon triggers (perhaps weak reduction for baryons in very central collisions).
- Slight increase of associated near-side jet yields in mid-central AuAu.
- Jet-like production but different suppression for leading baryons and mesons !?

# “Fragmentation functions”: $x_E$ distributions pp,dAu

- Away-side associated hadron $p_T$ spectra:

  $x_E \sim z/\langle z_{trig}\rangle$ represents away jet fragmentation z

  $\langle z_{trig}\rangle$=0.85 measured*

  $\Rightarrow D^q_\pi(z) \sim e^{-6z}$

$$x_E = \frac{\vec{p}_{T,\mathrm{trig}} \cdot \vec{p}_{T,\mathrm{asso}}}{|\vec{p}_{T,\mathrm{trig}}|^2}$$

$x_E$ variable: Two-particle equivalent of fragmentation variable z

$$x_E \simeq z_{\mathrm{assoc}}/z_{\mathrm{trig}}$$

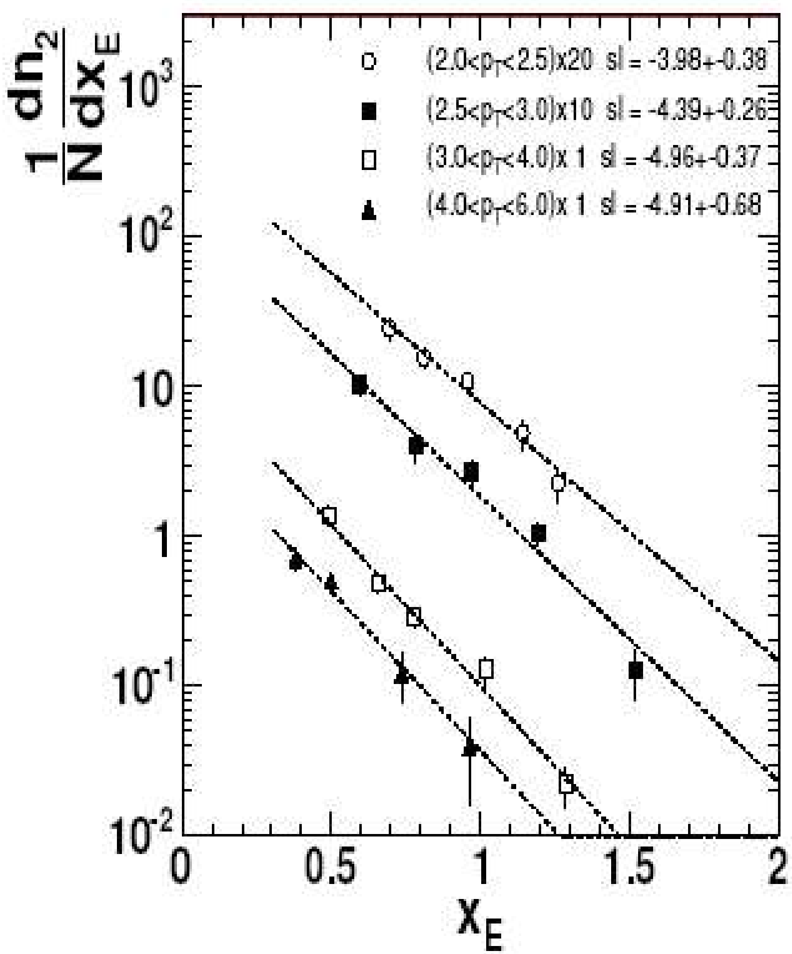
At high $p_T$, i.e. when di-jets are nearly back-to-back.

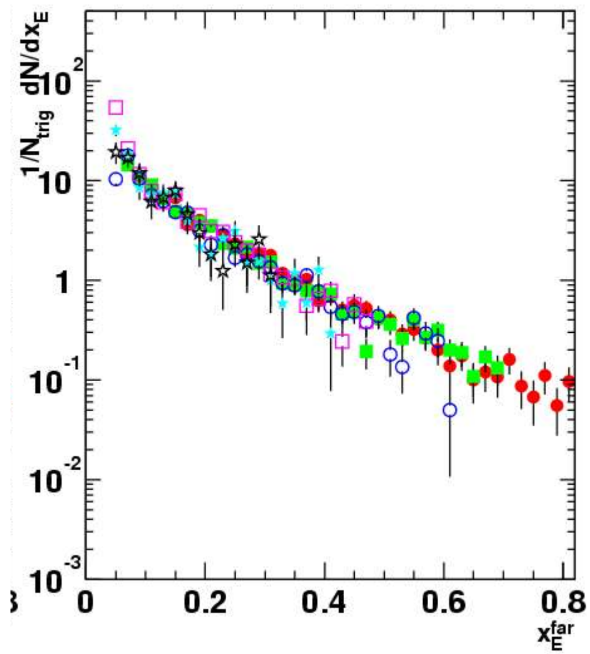
$$\frac{1}{N_{trig}} \frac{dN}{dx_E} \cong \frac{z_{trig}}{N_{trig}} \frac{dN}{dz_{assoc}} \propto z_{trig} D(z_{assoc})$$

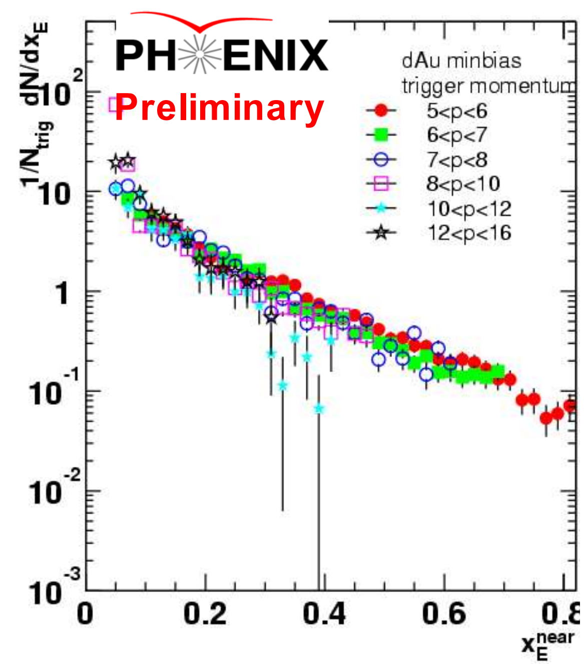
# "Fragmentation functions": $x_E$ distributions pp,dAu

- Away-side associated hadron $p_T$ spectra:

PHENIX preliminary




PHENIX

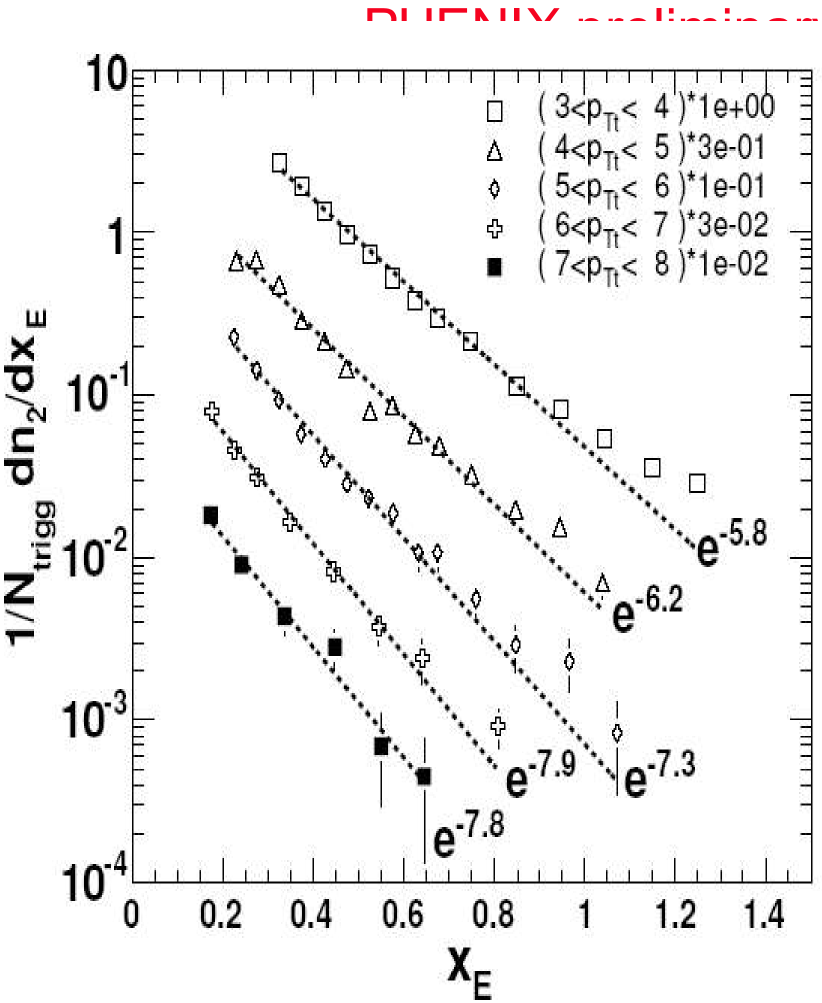
J. Jia

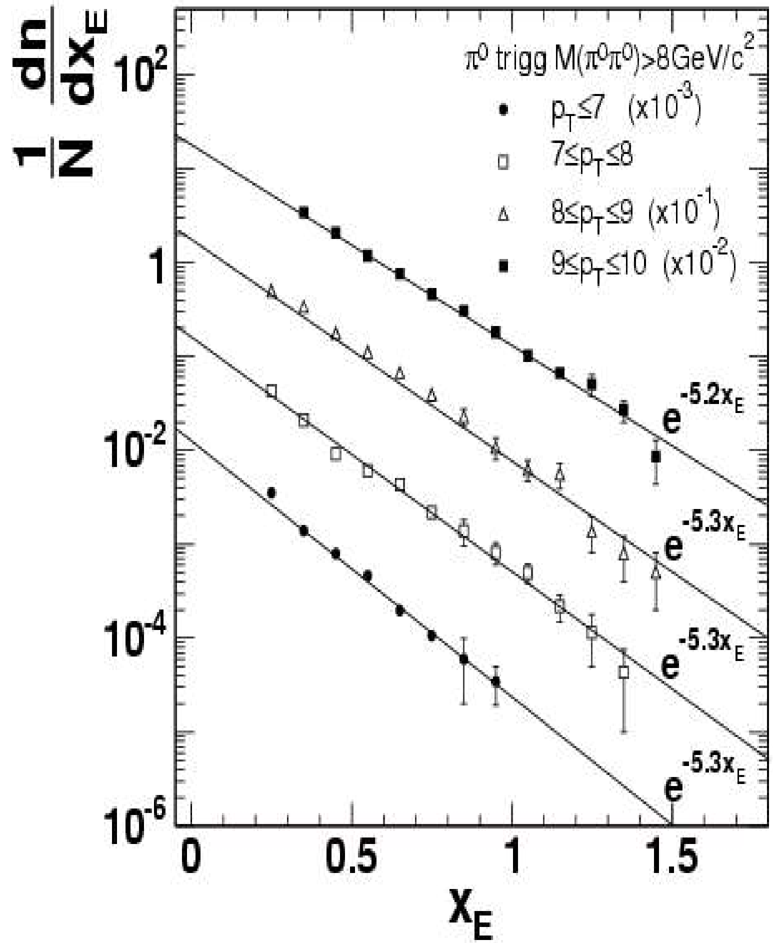
# "Fragmentation functions": $x_E$ distributions pp

- Away-side associated hadron $p_T$ spectra:

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

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




$1/\langle x_E \rangle \approx -5.8$ to $-7.8$

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