Jets and jet quenching in high energy nuclear collisions

Hirschegg 2005

Kleinwalsertal, Austria, Jan. 19, 2005

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Overview

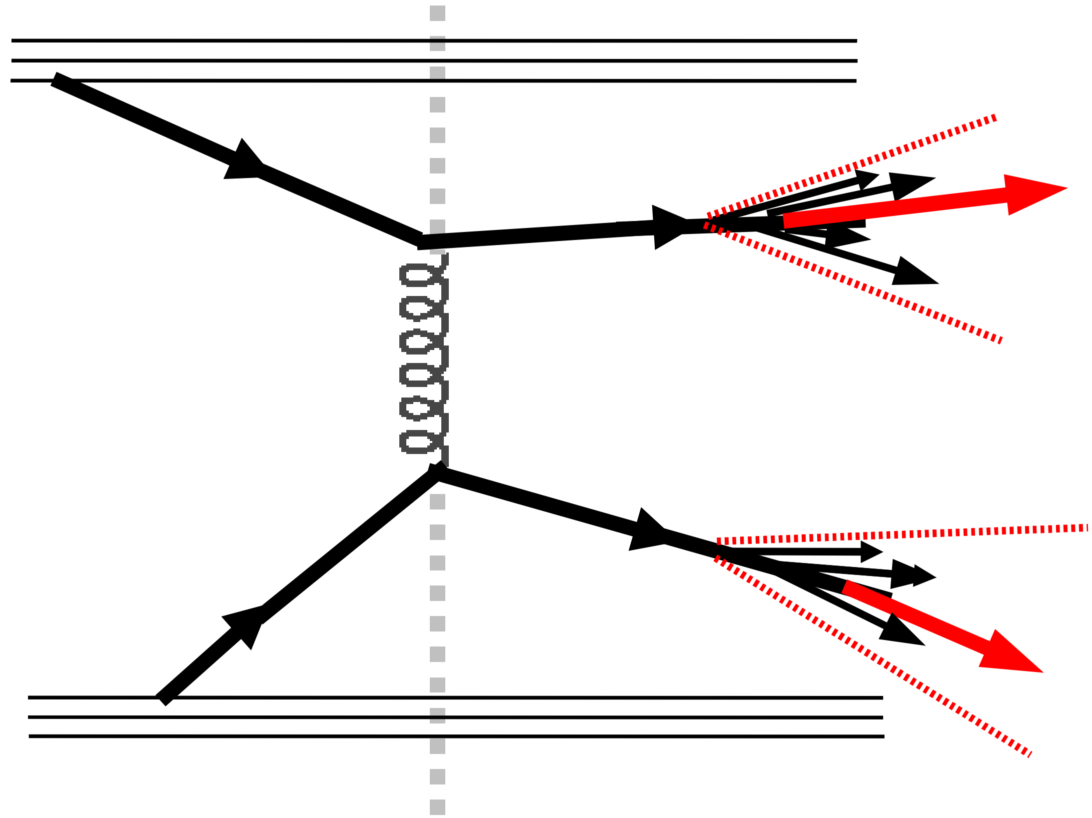
- Introduction:
  - Jet production in pp, pA and AA collisions.
  - What can be learnt about high-energy-density QCD via jet physics in AA collisions ?

- Results I: Leading hadron production in pp, dAu, AuAu @ RHIC:
  - High p_T hadro-production in baseline pp collisions (data vs. pQCD)
  - High p_T suppression in central AuAu: p_T-, sqrt(s)-, reaction-plane dependence.
  - Physics [Final state (FS) effects]: Parton energy loss $\rightarrow$ QCD medium properties.

- Results II: Jet production in QCD vacuum (pp) & cold QCD medium (dAu):
  - Full jet reconstruction (pp).
  - Dijets via dihadron $\Delta\varphi$ correlations (pp, dAu).
  - Extraction of jet properties: j_T, k_T
  - Physics [Initial state (IS) effects]: multiple scattering in cold nuclear matter

- Results III: Jet production in a hot & dense QCD medium (AA):
  - Dijets: away-side disappearance: sqrt(s)-, reaction-plane dependence.
  - Extraction of jet properties (j_T, k_T, “FFs”).
  - Dihadron $\Delta\eta$ correlations.
  - Physics [Final state (FS) effects]: Jet quenching $\rightarrow$ QCD medium properties.

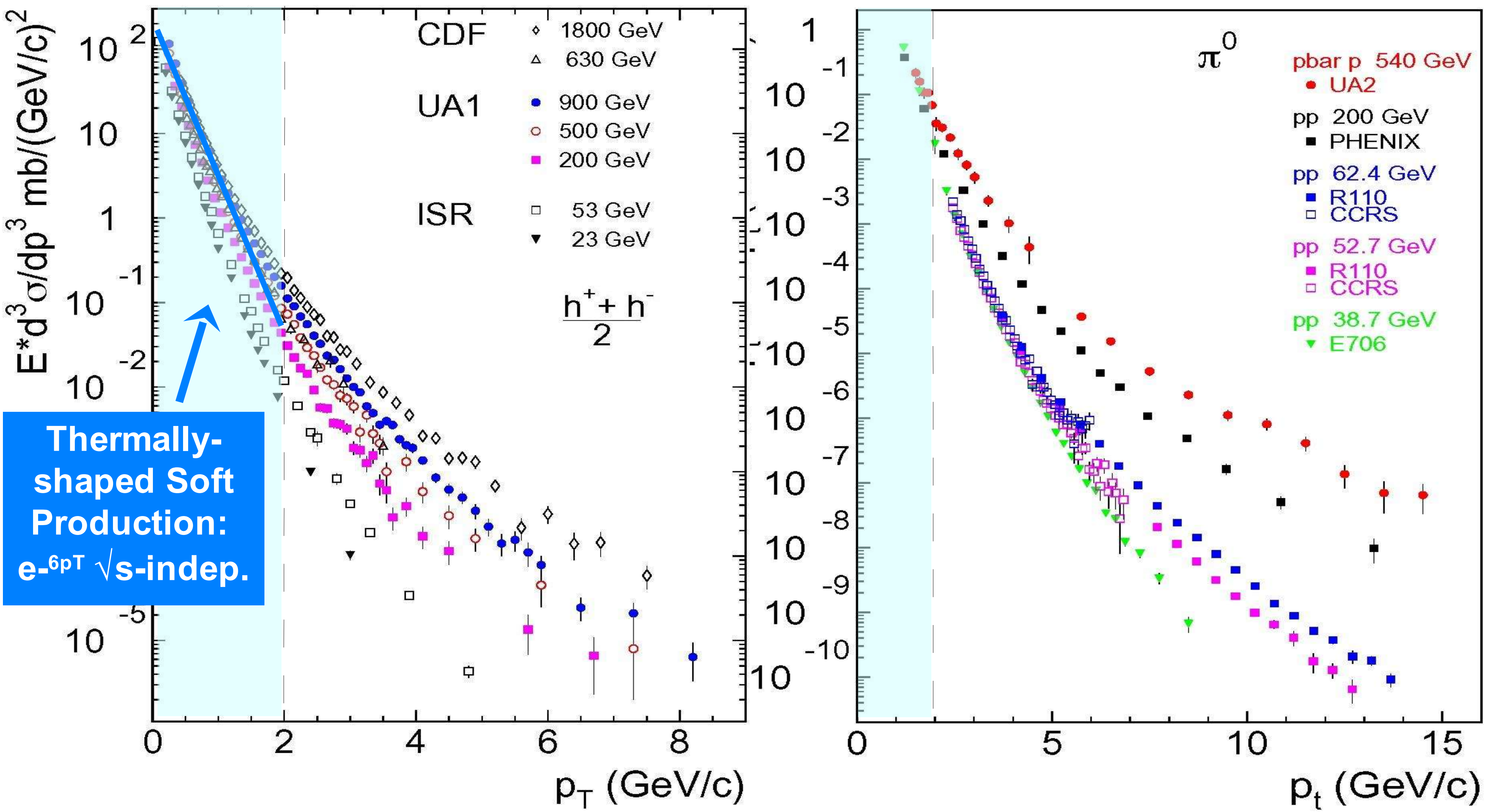
Jet production in pp collisions



- Jet : Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~ 0.7) with 4-momentum of original fragmenting parton:

  (i) Leading hadron takes away large fraction (**<z>** ~0.6 –0.8 @ RHIC) of parent parton p_T

N.B.(1) -- High p_T (leading) hadron: pp, ppbar



- $p_T < 2$ GeV/c: Expo. ($Ed^3\sigma/d^3p \sim e^{-6p_T}$) w/ constant inv. slope: ~ 160 MeV ~ T_{crit}

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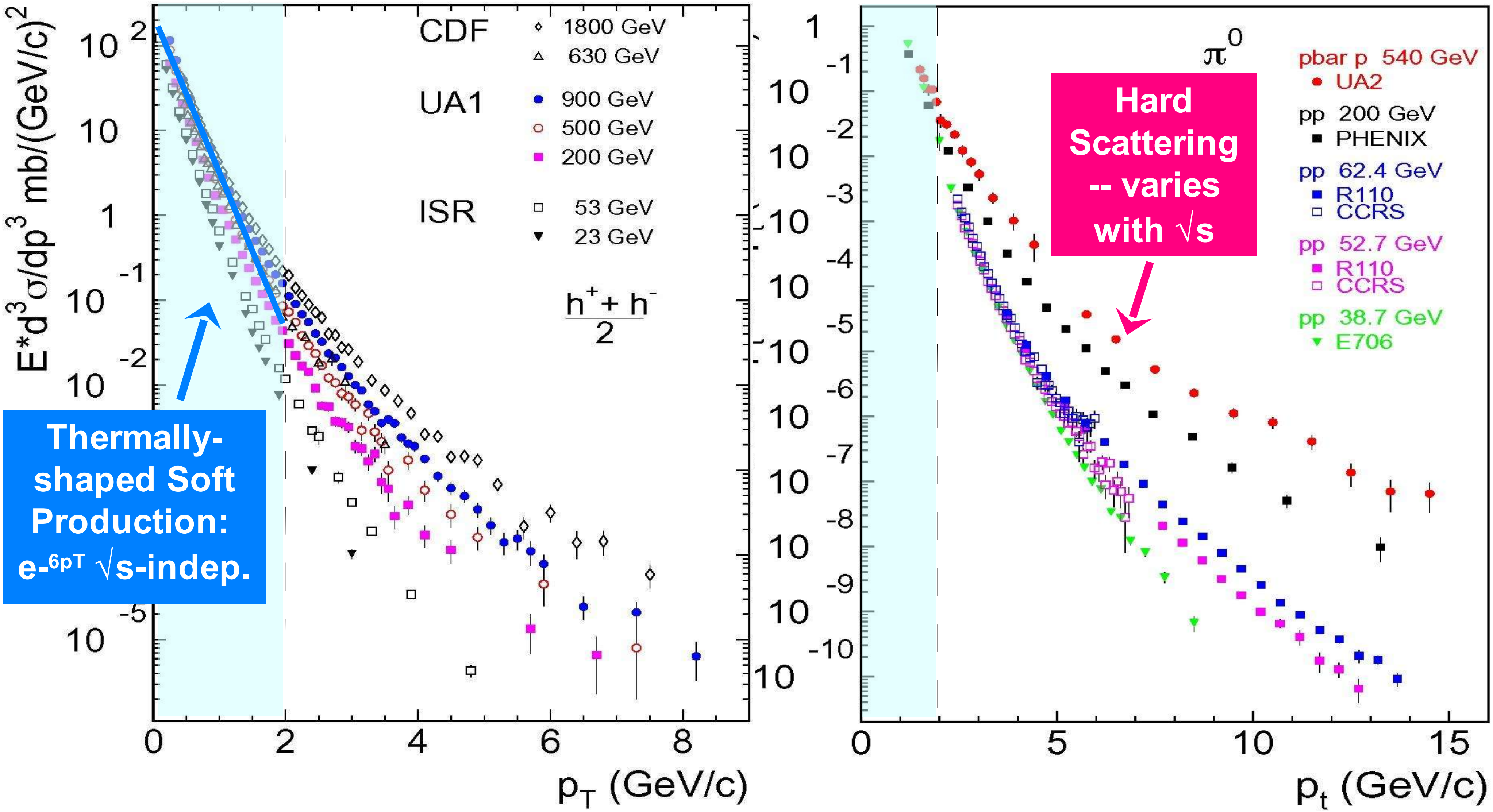
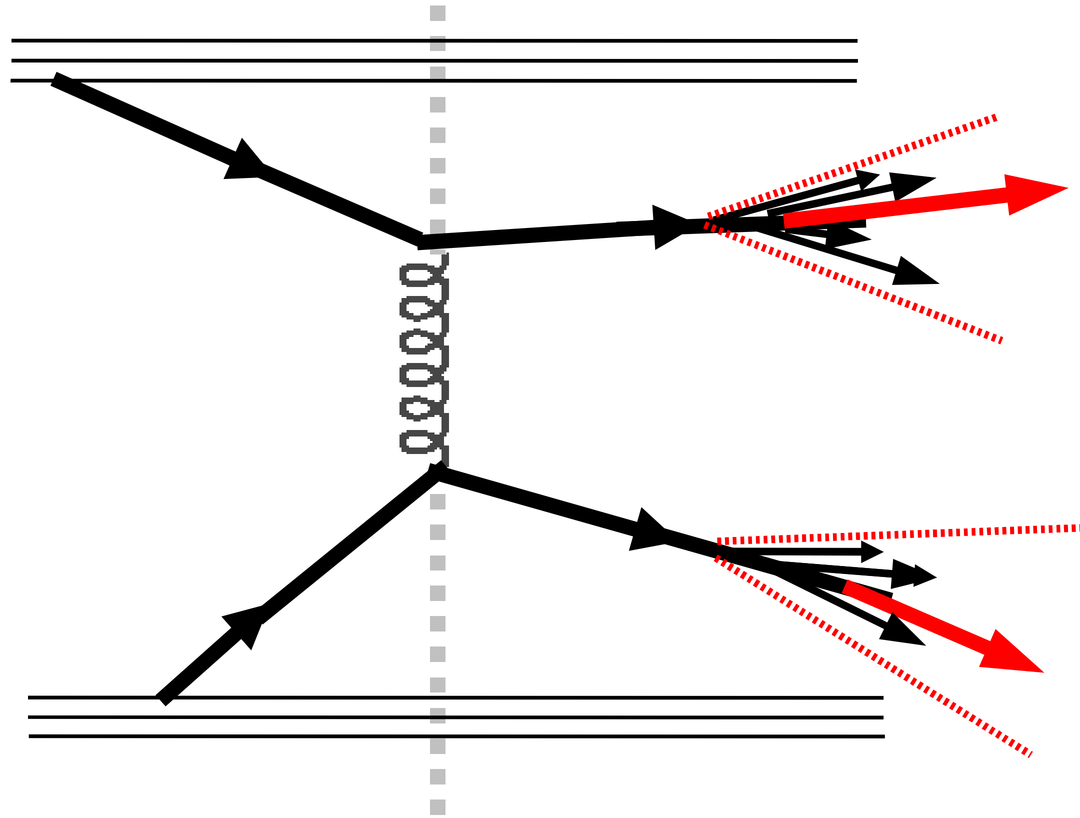


- p_T< 2 GeV/c: Expo. ($Ed^3\sigma/d^3p \sim e^{-6p_T}$) w/ constant inv. slope: ~ 160 MeV ~ T_{crit}
- p_T> 2 GeV/c: Power-law ($Ed^3\sigma/d^3p \sim 1/p_T^n$, n~ 6 -10) with strong $\sqrt{s}$-dependence.

Jet production in pp collisions



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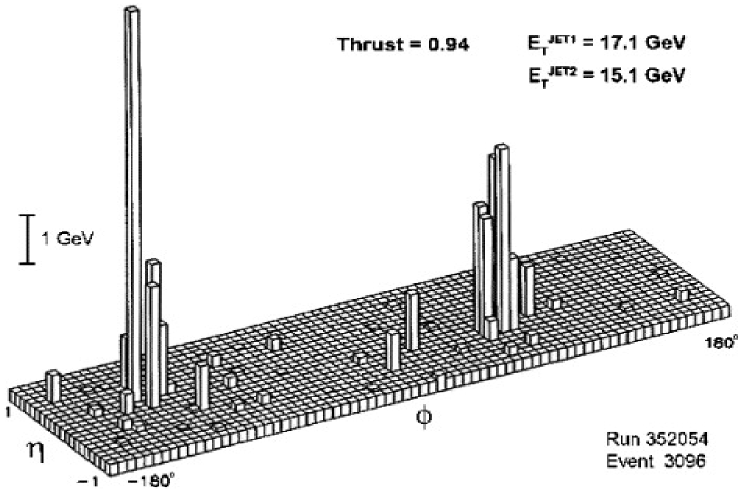
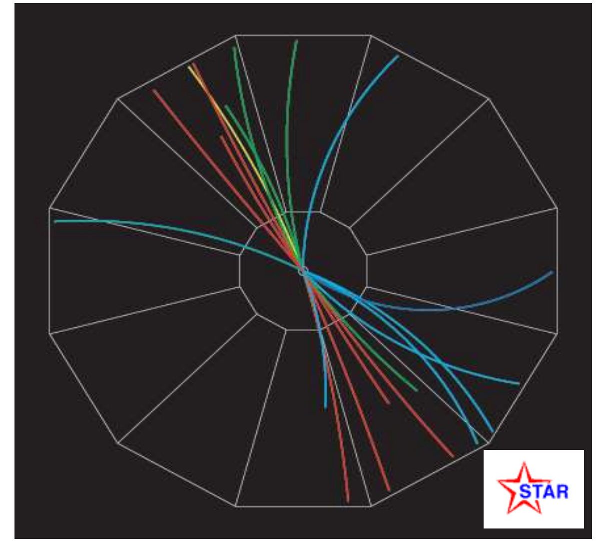
- Jet is balanced back-to-back by other hard-scattered "parton" (jet, direct γ, ...)

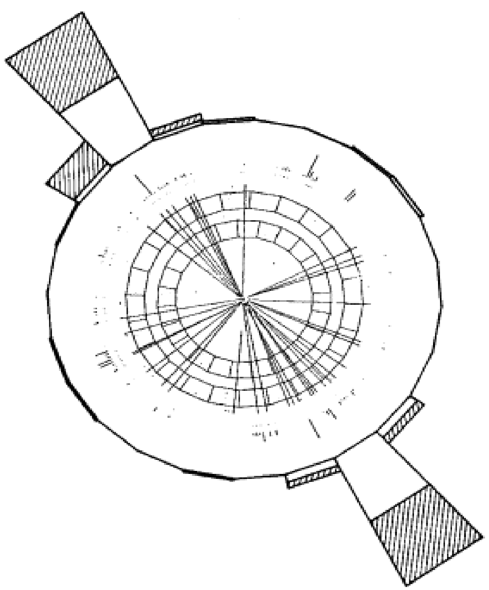
N.B.(2) -- Jets in pp, ppbar collisions



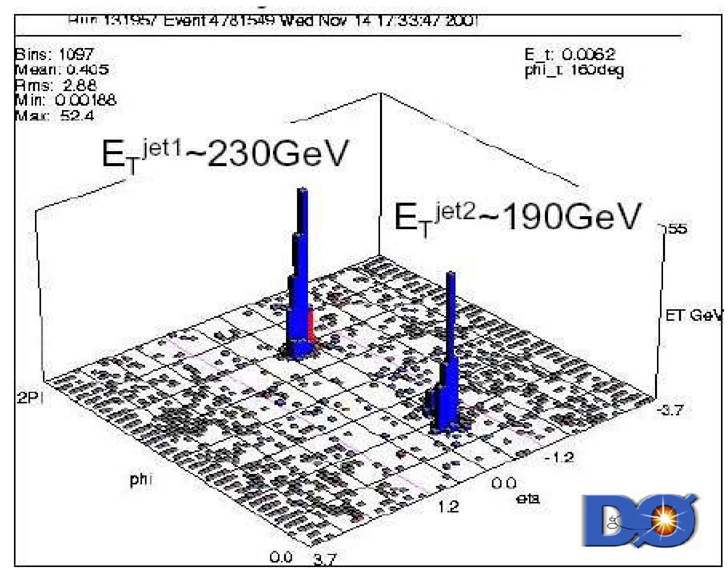
p+p → jet+jet [√s = 63 GeV]
AFS @ CERN-ISR (1982)



p+p → jet+jet [√s = 200 GeV] – STAR @ RHIC (2003)

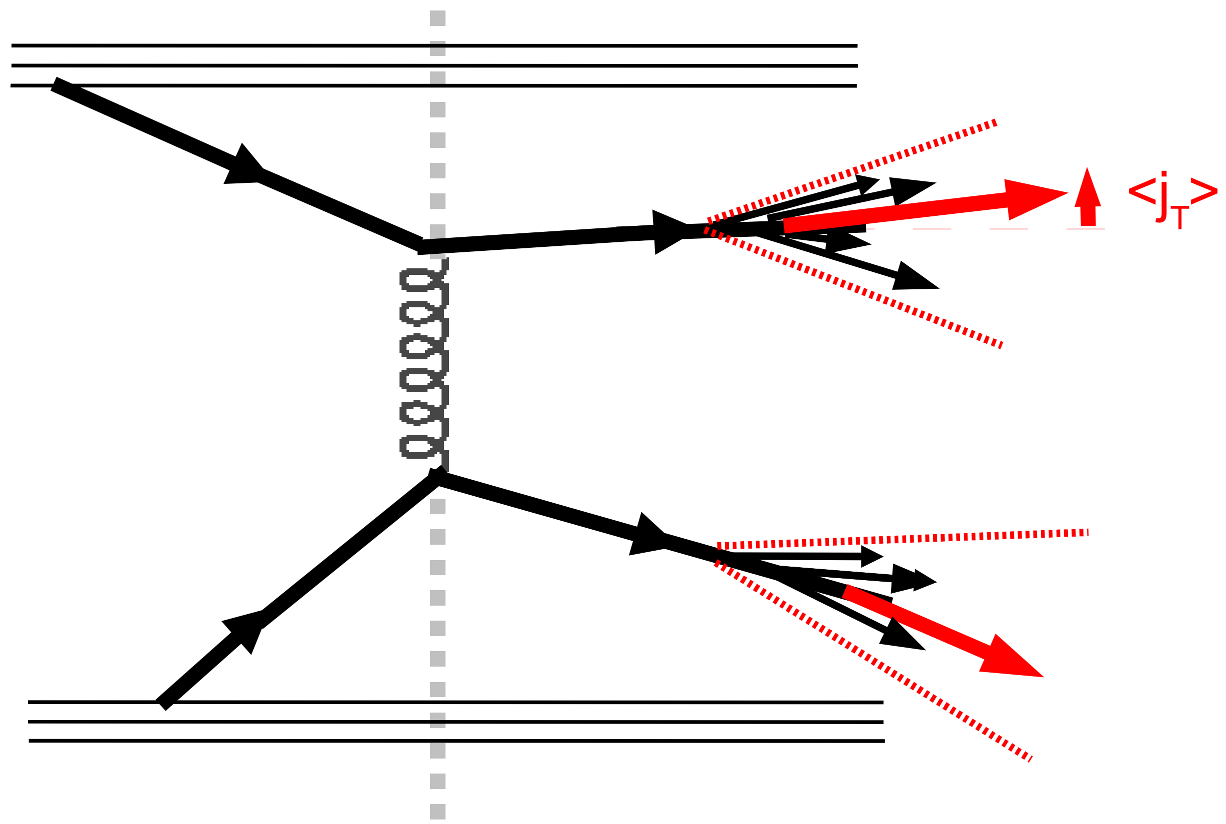


p+pbar → jet+jet [√s = 560 GeV]
UA2 @ CERN-SppS (1983)



p+pbar → jet+jet [√s = 1.96 TeV] – D0 @ Tevatron (2001)

Jet production in pp collisions



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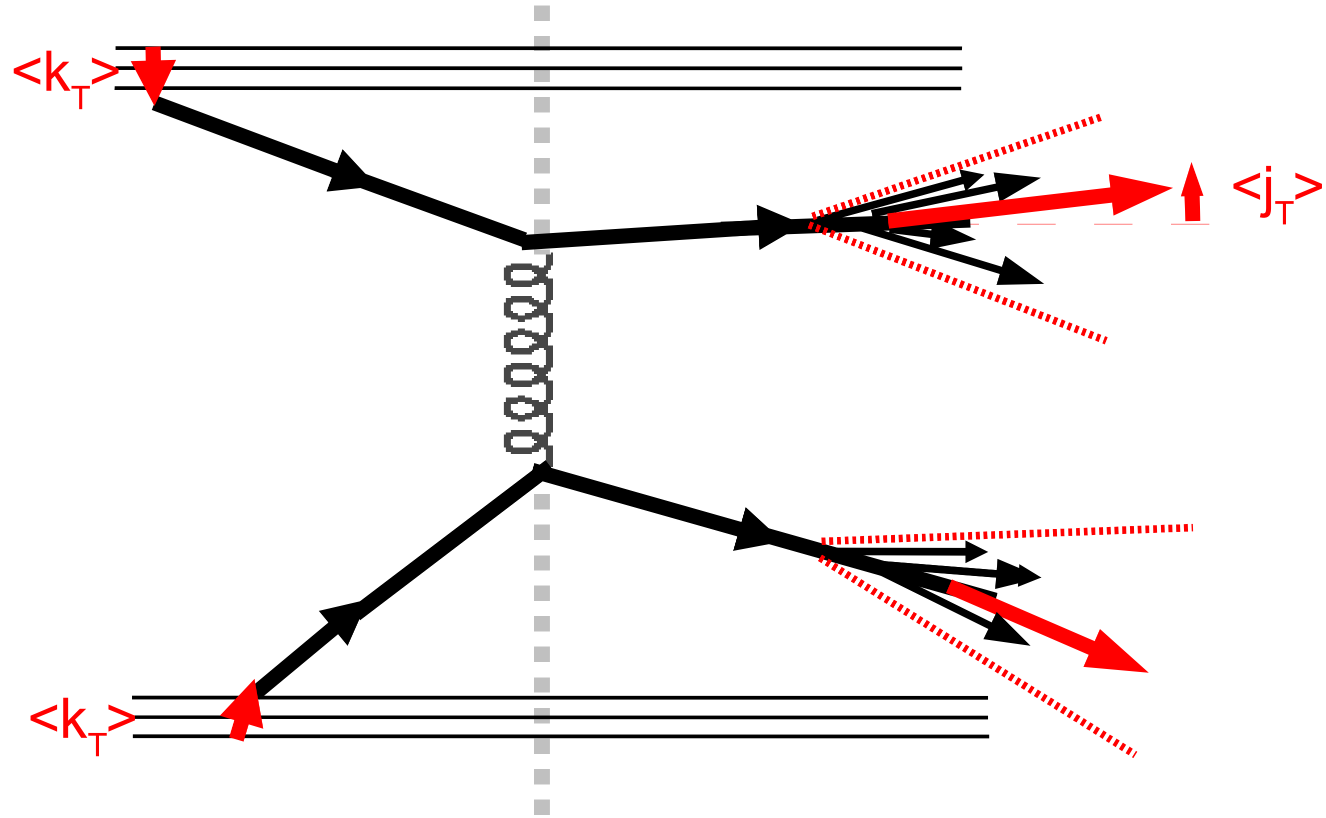
  (ii) Average jet fragmentation transverse momentum (jet "width"): **$\langle j_T \rangle$**
- Jet is balanced back-to-back by other hard-scattered "parton" (jet, direct γ, ...)

Jet production in pp collisions



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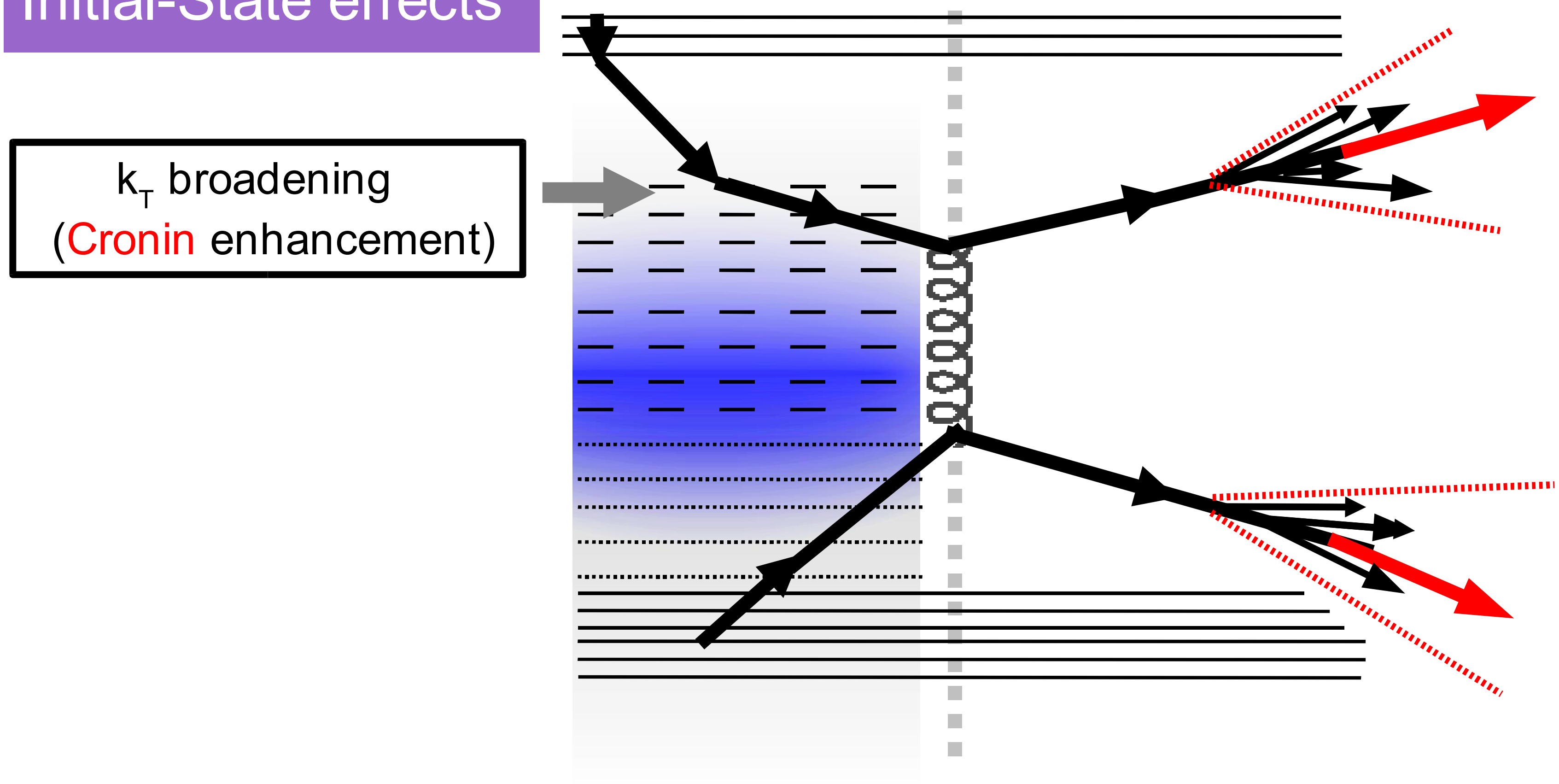
  (i) Leading hadron takes away large fraction (**<z>** ~0.6 –0.8 @ RHIC) of parent parton p_T
  (ii) Average jet fragmentation transverse momentum (jet "width"): **$\langle j_T \rangle$**
- Jet is balanced back-to-back by other hard-scattered "parton" (jet, direct γ, ...) A (small) acoplanarity appears due to intrinsic transv. k_T (parton Fermi motion + *g* rad.).

Jet production in pA collisions

Initial-State effects



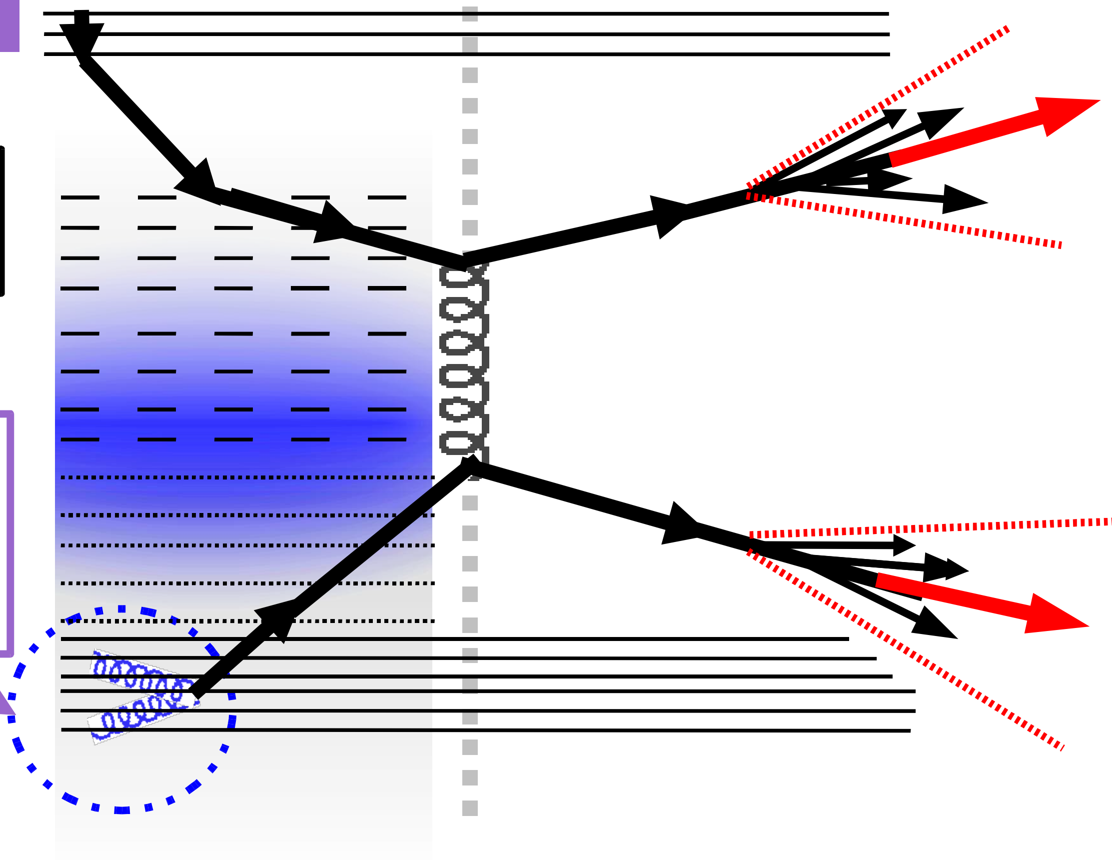
- Extra nuclear k_T broadening due to multiple scattering in the nuclear medium (Cronin enhancement of leading hadron).

Jet production in pA collisions

Initial-State effects

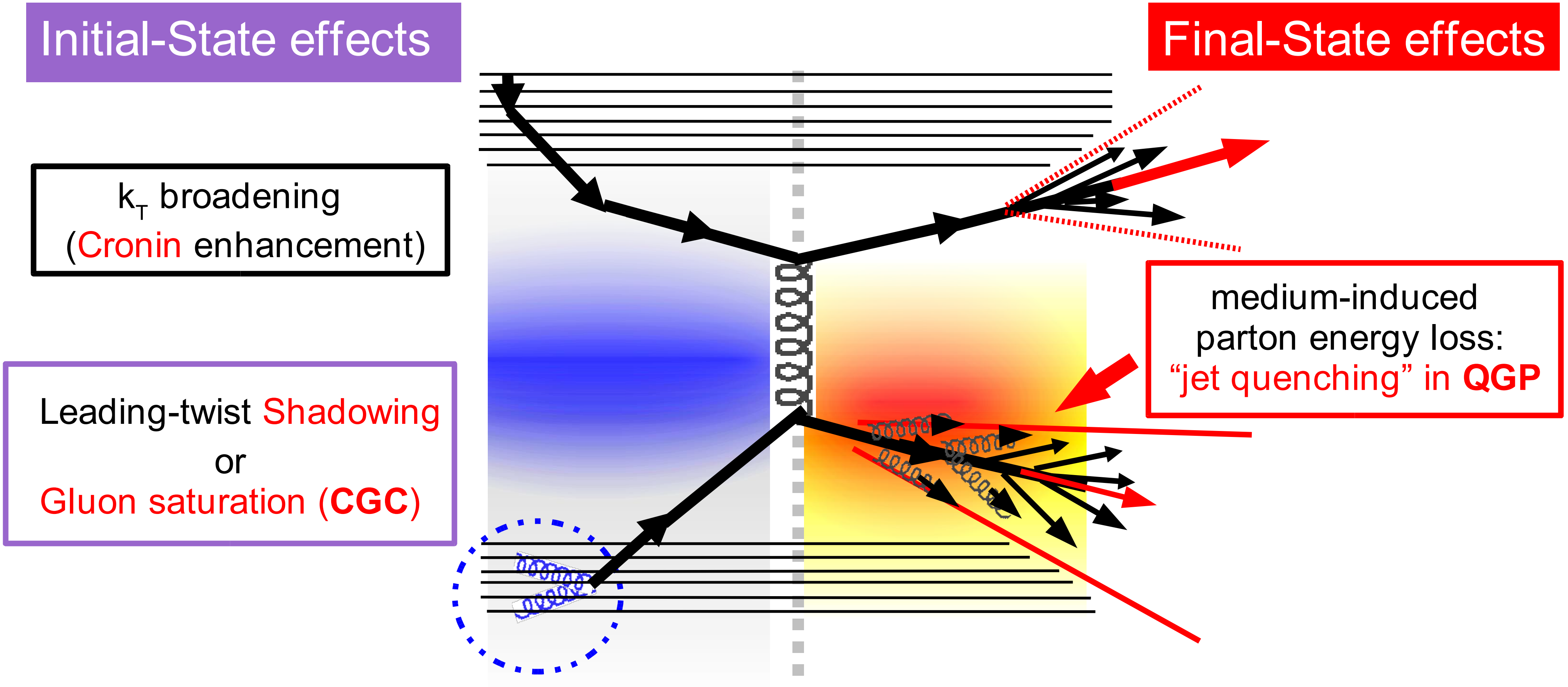
k_T broadening
(Cronin enhancement)

Leading-twist Shadowing
or
Gluon saturation (**CGC**)



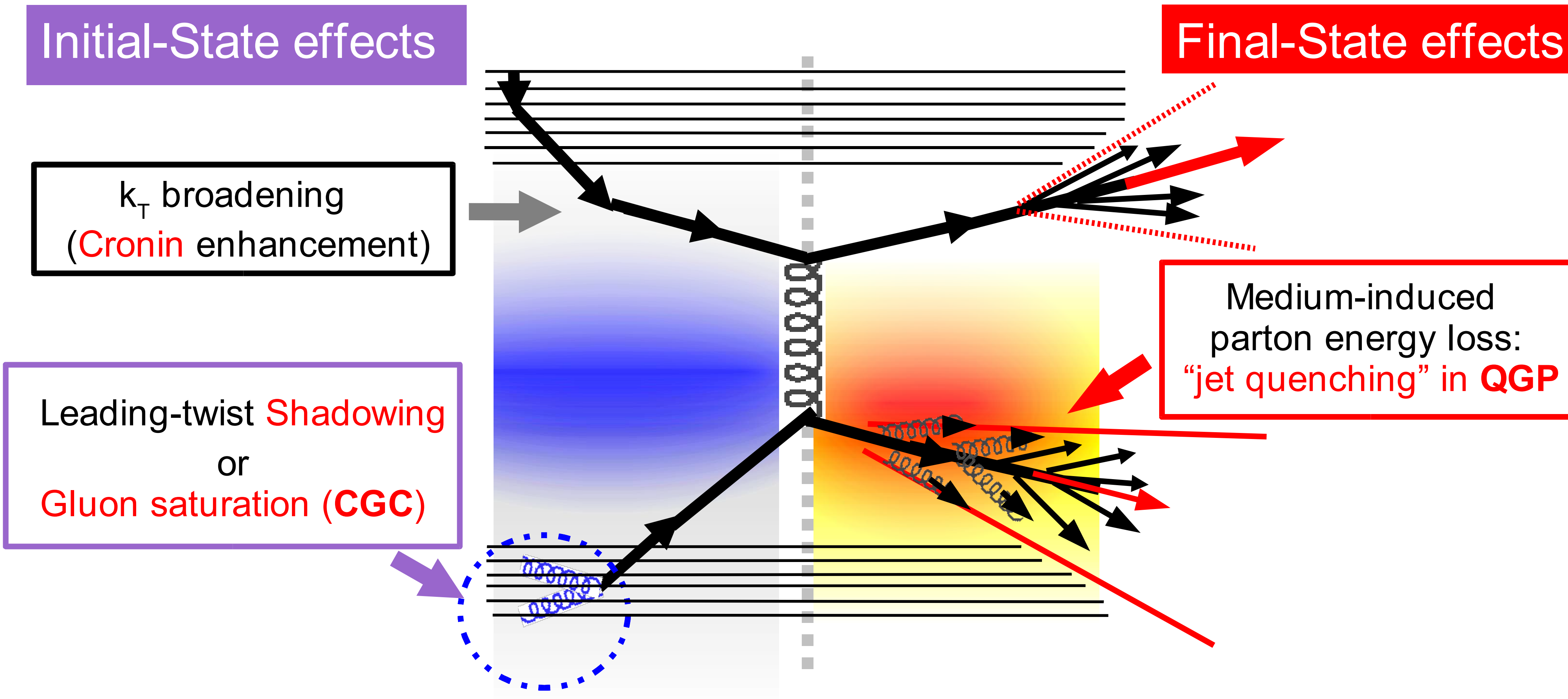
- Extra nuclear k_T broadening due to multiple scattering in the nuclear medium (Cronin enhancement of leading hadron, dijet broadening).
- At (very) small-x values (forward rapidities) there is a reduced effective number of parton scattering centers due to gluon-gluon fusion processes.

Jet production in AA collisions



- Parton energy loss due to final-state gluon-strahlung in dense medium:
  (i) Reduces energy of the leading hadron: high p_T hadron suppression,
  (ii) Modifies (di)jet shape properties: k_T, j_T, dN/dx_E, ...

Jet production in AA collisions



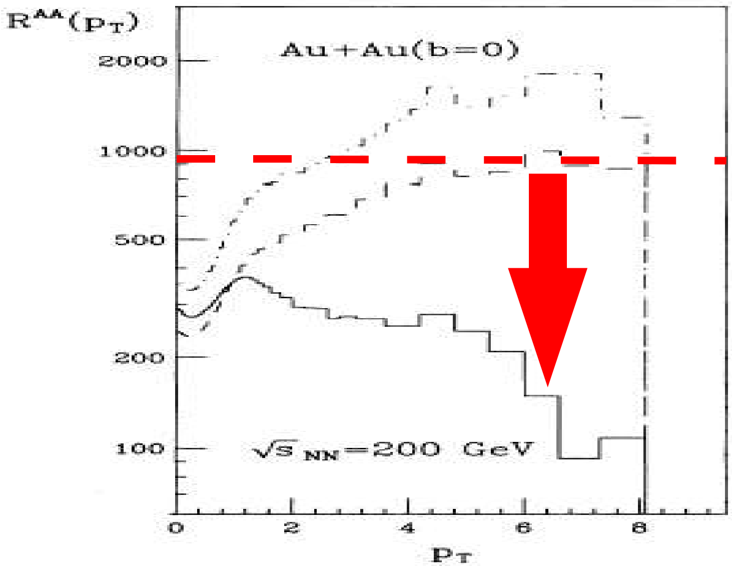
- <u>Approach</u>: Compare jet production in p+p,d+A & A+A :
  - I. Inclusive leading hadron: dN/dp_T
  - II. Di-hadron correlations: $dN_{pair}/d\varphi$, $dN_{pair}/d\eta$
  - III. Obtain (di)jet properties: k_T, j_T, dN/dx_E (~FF)

... to learn about transport & thermodyn. properties of dense QCD medium.

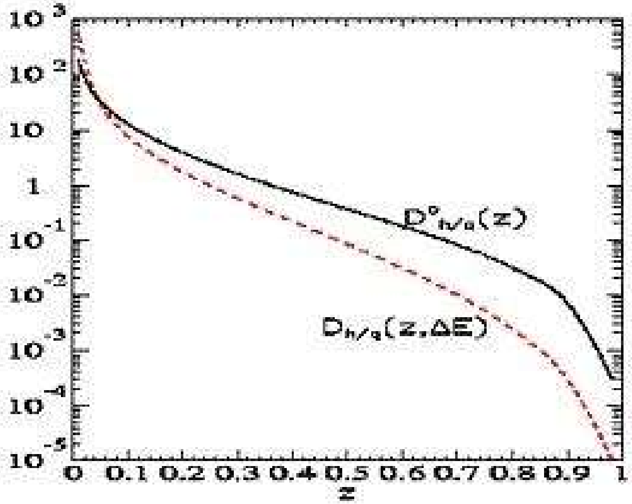
Jet production in AA : (a few) theoretical expectations

- Leading hadron suppression:

Wang&Gyulassy PRL 68, 1480 (1992)



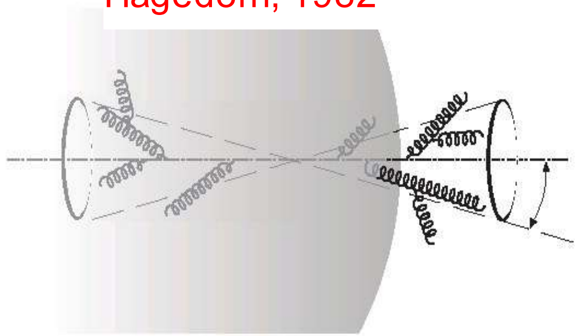
- Medium-modified FFs:



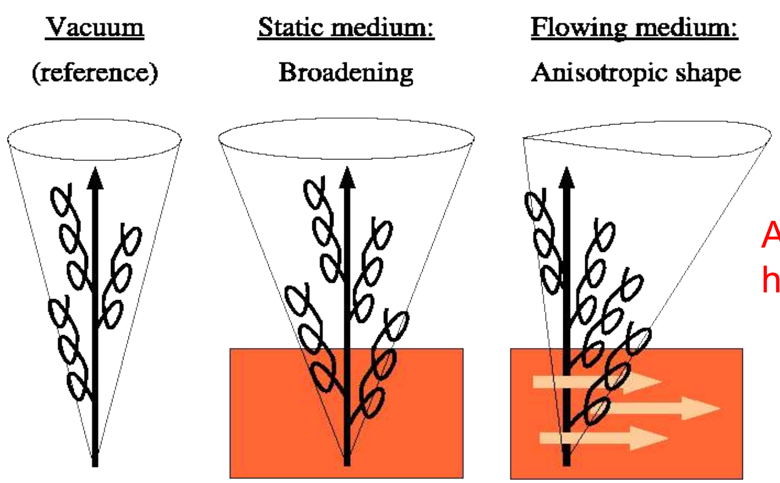
X.N.Wang; Salgado&Wiedem. Arleo, ...

- Mono-jets:

Hagedorn, 1982



- Jet broadening in eta:



Armesto et al hep-ph/0405301

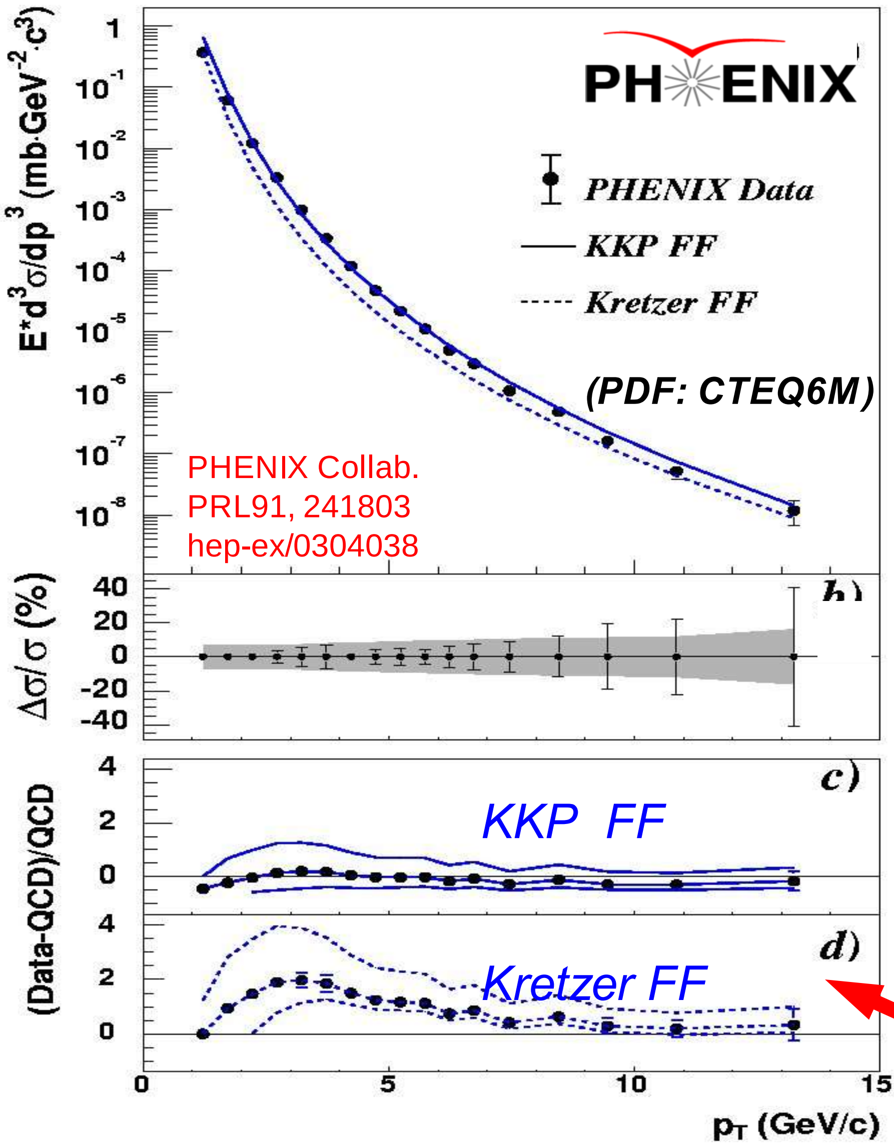
➔ Valuable diagnostic tools of QCD medium (dN^g/dy, $<q_0>$, ...)

Leading hadron production at RHIC: pp, dAu, AuAu

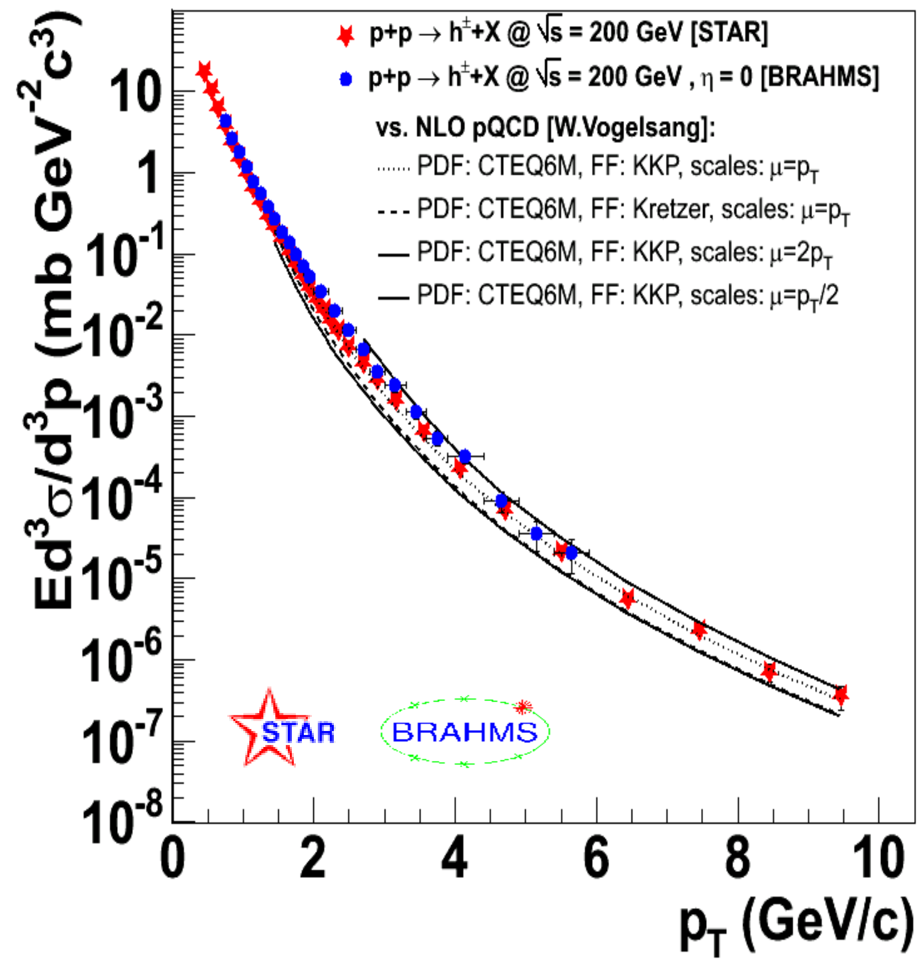
Leading hadron spectra: pp @ 200 GeV

- High p_T π^0,$h^\pm$ spectra up to ~15 GeV/c. Good theoretical (NLO pQCD) descript.

$p+p \rightarrow \pi^0 X$



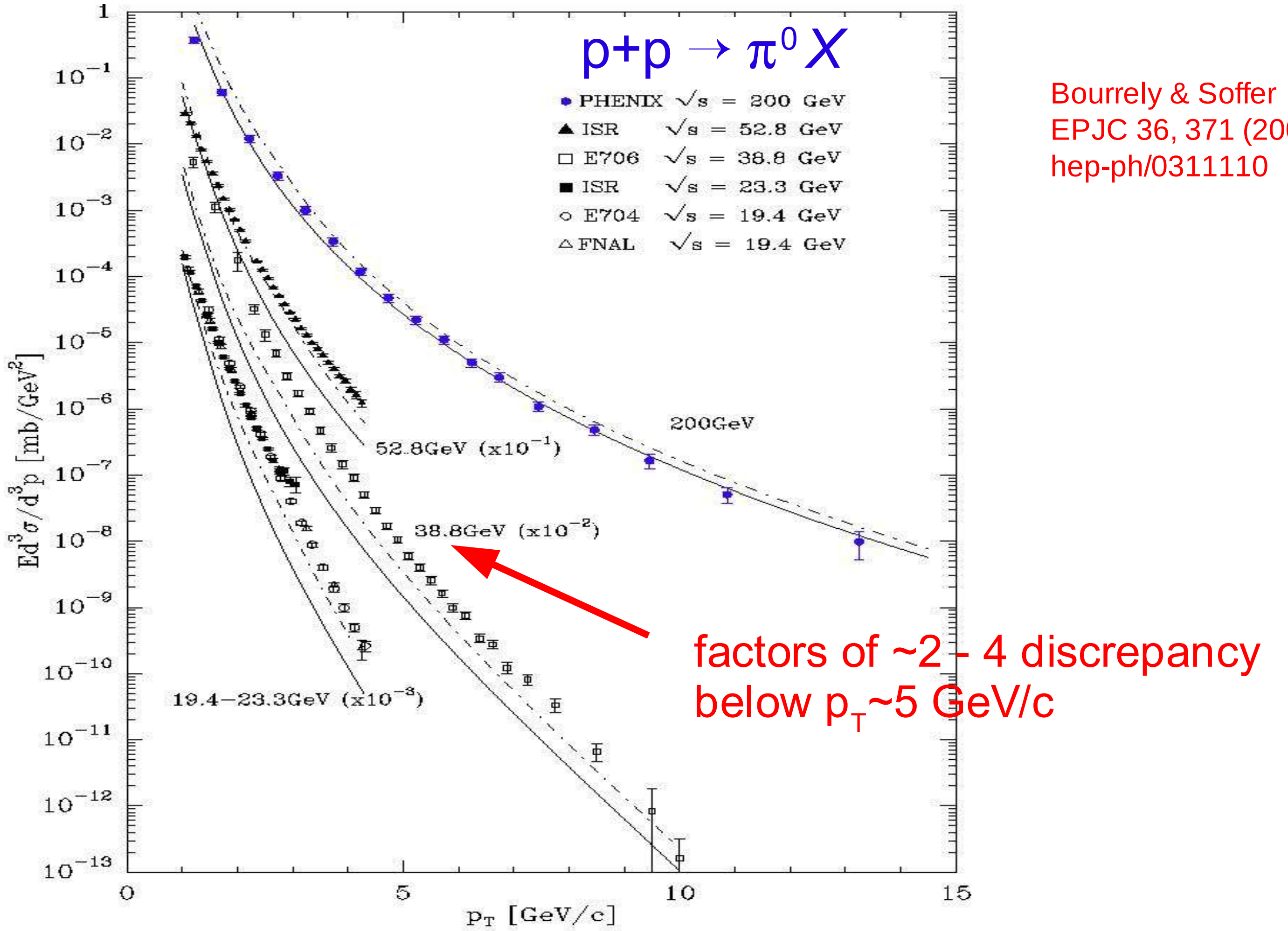
$p+p \rightarrow h^\pm X$ (non singly diffractive)



- High quality data: sensitive to different parametrizations of gluon FF

Leading hadron spectra: pp @ 200 GeV

- High p_T π^0 well described by collinear NLO pQCD: No apparent need of large intrinsic k_T (though this is maybe FF-dependent) at variance w/ lower sqrt(s) results:



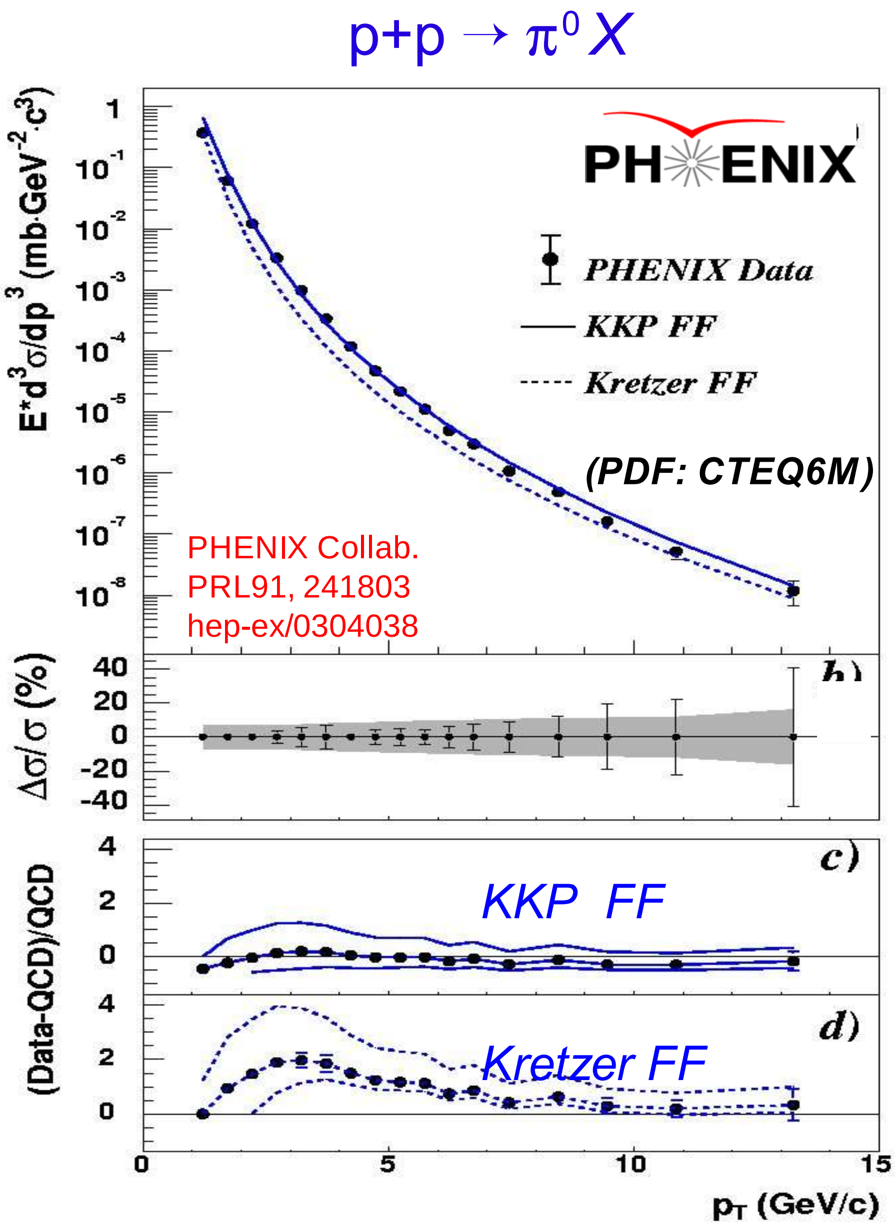
Bourrely & Soffer
EPJC 36, 371 (2004)
hep-ph/0311110

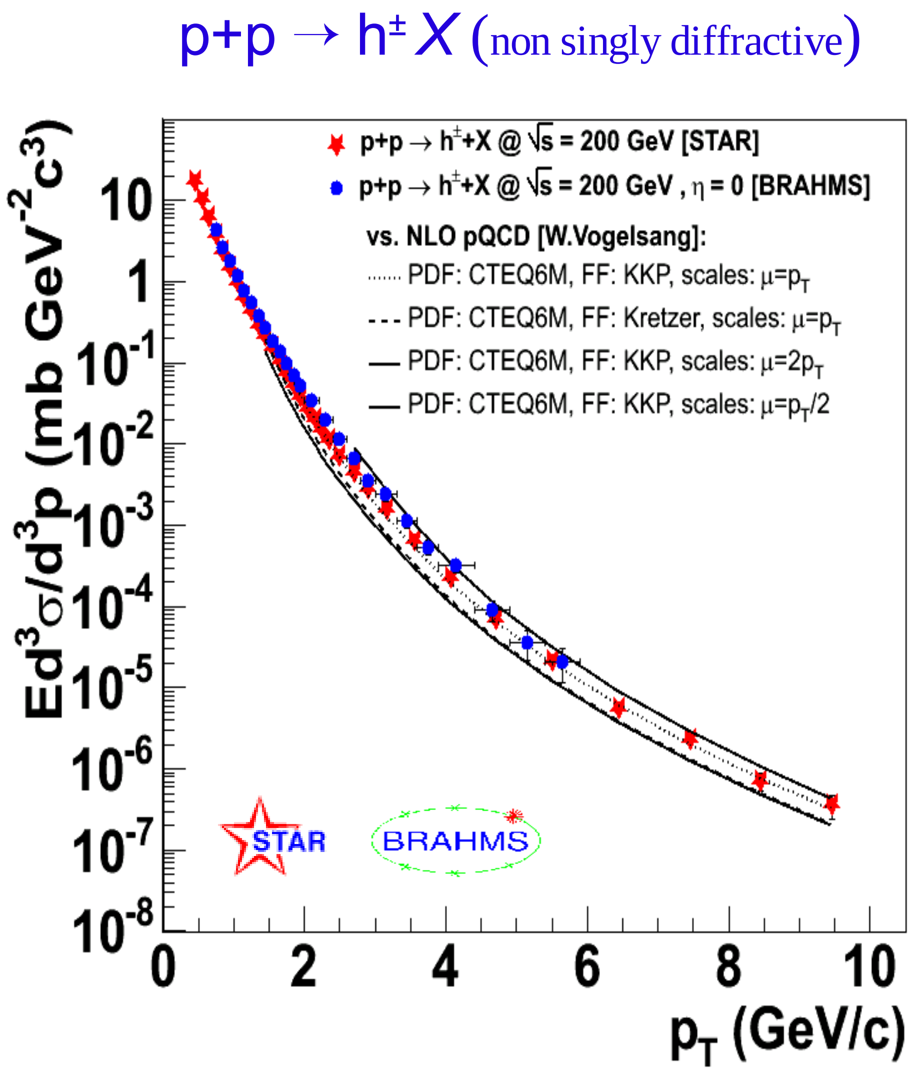
- Higher-order theoretical corrections (soft-*g* rad., threshold resumm.) cure the problem.

[Vogelsang & deFlorian, to be submitted]

Leading hadron spectra: pp @ 200 GeV

- High p_T π^0,$h^\pm$ spectra up to ~15 GeV/c. Good theoret. (NLO pQCD) description.

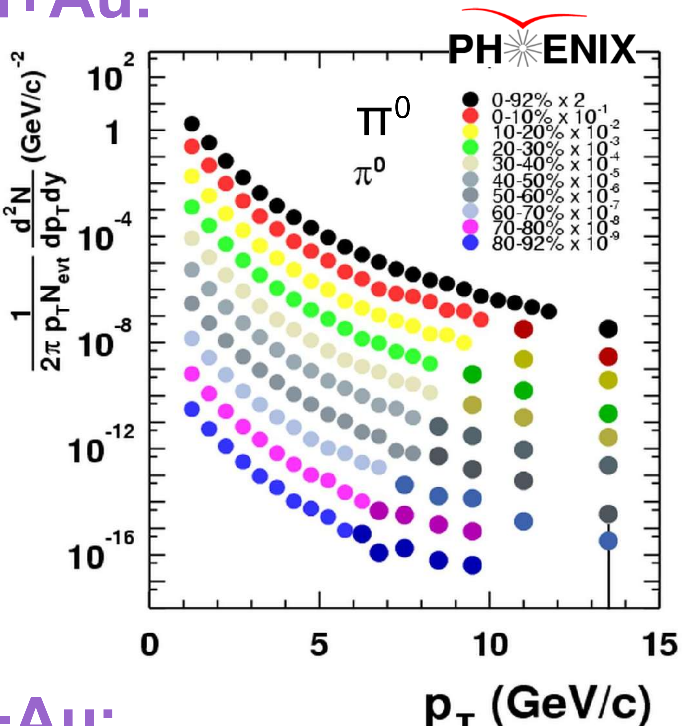


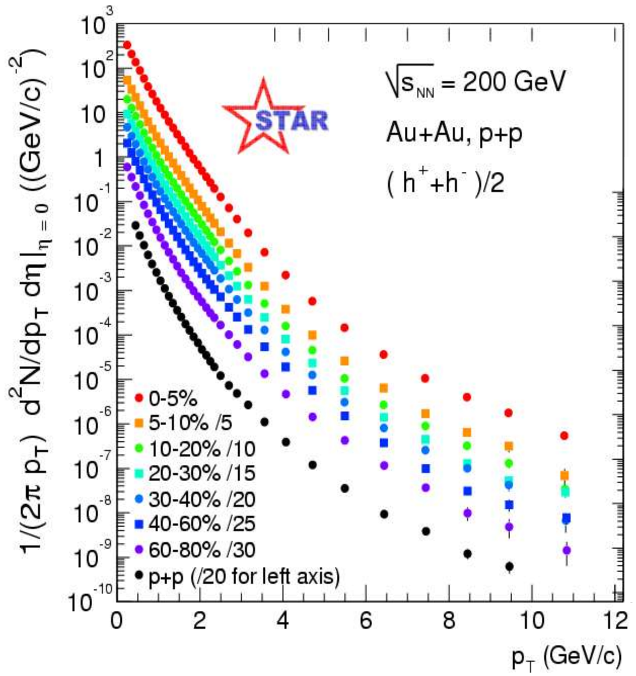


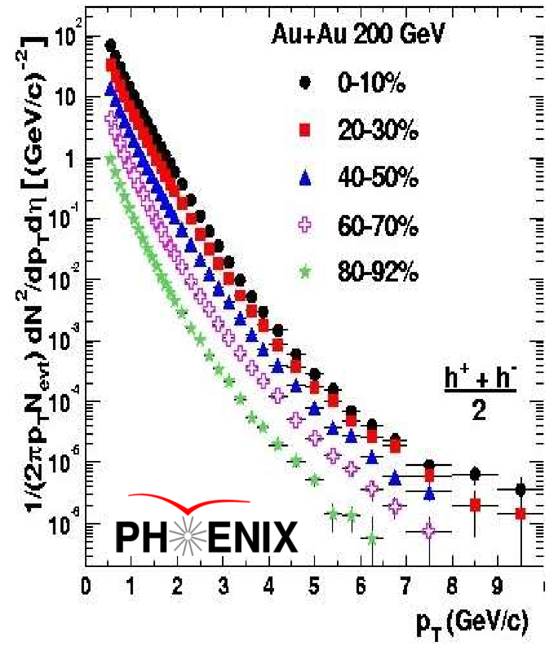
- Well calibrated (experimentally & theoretically) p+p baseline spectra at hand !

Leading hadron spectra: AuAu, dAu @ 200 GeV

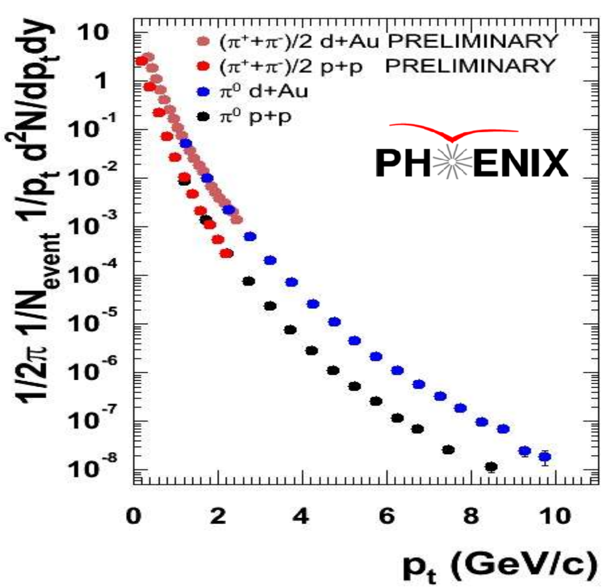
Au+Au:

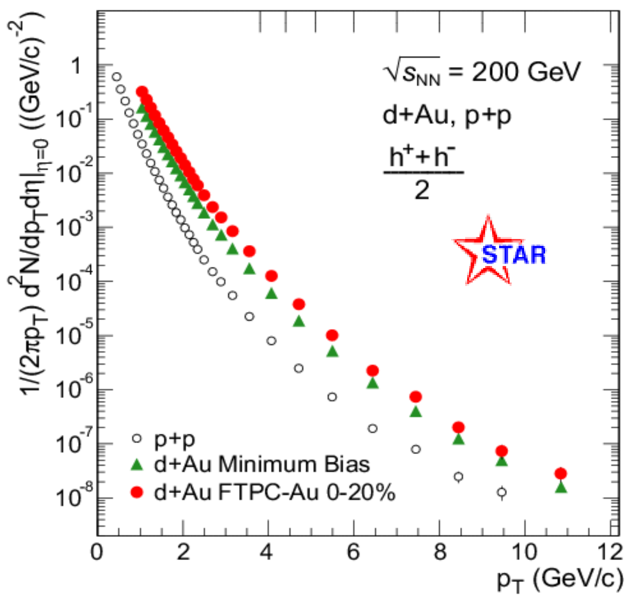






d+Au:





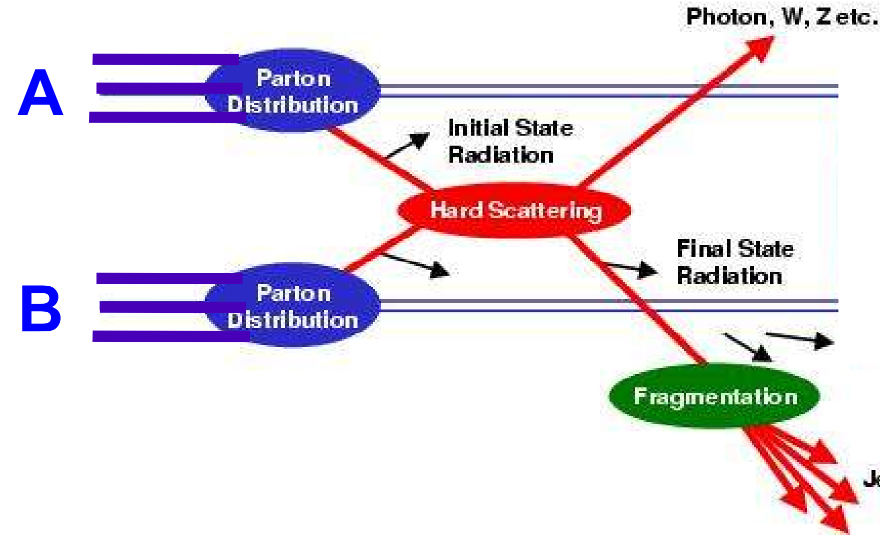
- High p_T π^0, $h^{\pm}$, η, ... spectra (well) above $p_T \sim 10$ GeV/c.

Comparing AA, pA and pp hard inclusive spectra

- Production yields computable in perturbative QCD:

"Factorization theorem":

$$d\sigma_{AB\to hX} = A\cdot B\cdot f_{a/A}(x_a,Q^2_a)\otimes f_{b/B}(x_b,Q^2_b)\otimes d\sigma_{ab\to cd}\otimes D_{h/c}(z_c,Q^2_c)$$



Independent scattering of "free" partons:

$$f_{a/A}(x,Q^2) = A\, f_{a/p}(x,Q^2)$$

A+B = "simple superposition of p+p collisions"

$$d\sigma_{AB\to hard} = A\cdot B\cdot d\sigma_{pp\to hard}$$

$$(d\sigma_{pA\to hard} = A\cdot d\sigma_{pp\to hard})$$

At impact parameter b:

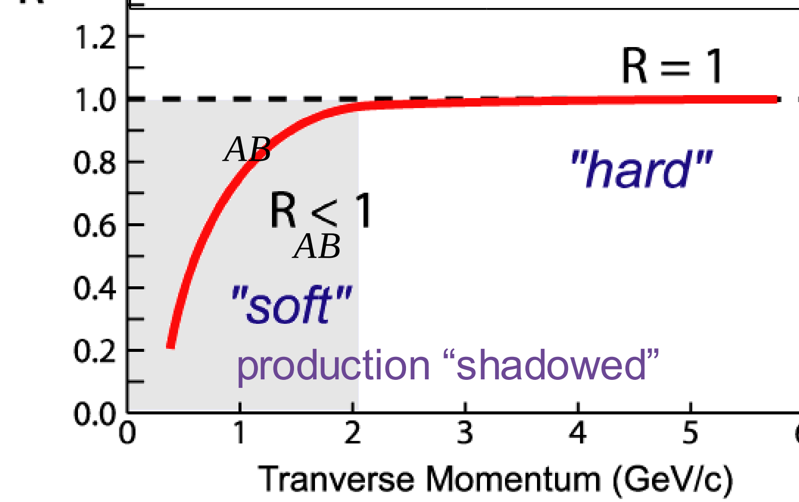
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

T_{AB} ~ # NN collisions ("N_{coll} scaling")

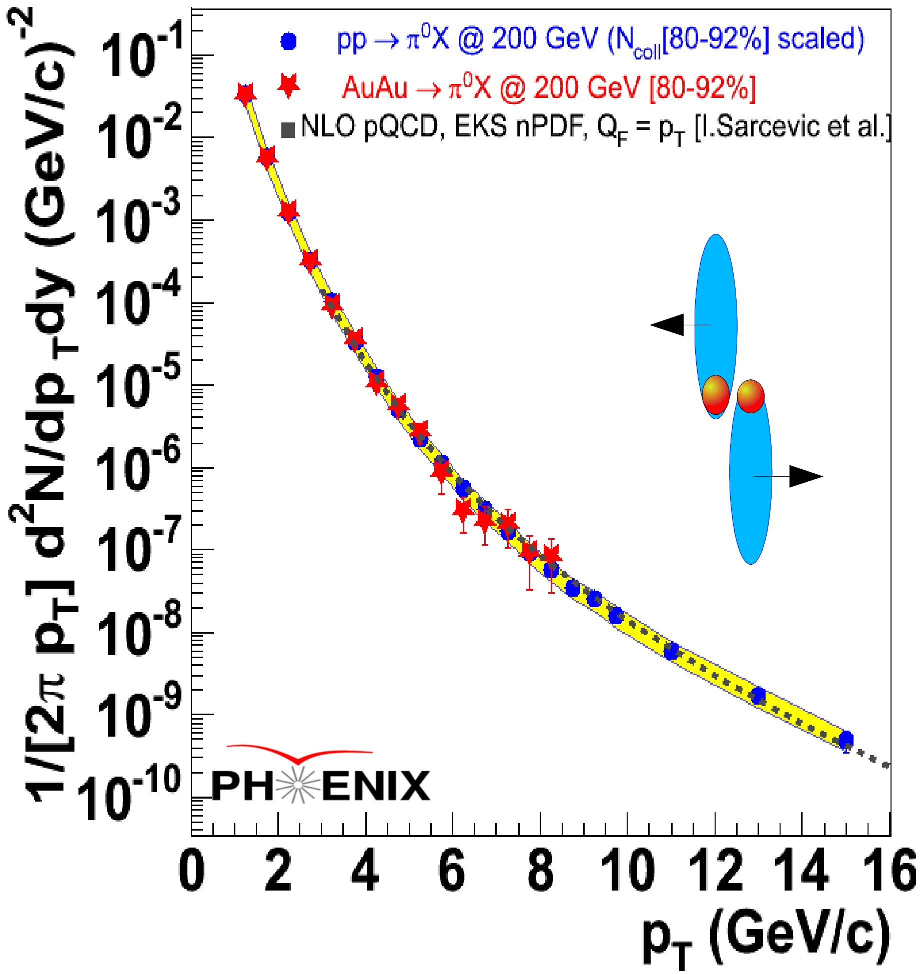
Nuclear Modification Factor:

$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle\cdot d^2\sigma_{pp}/dydp_T}$$

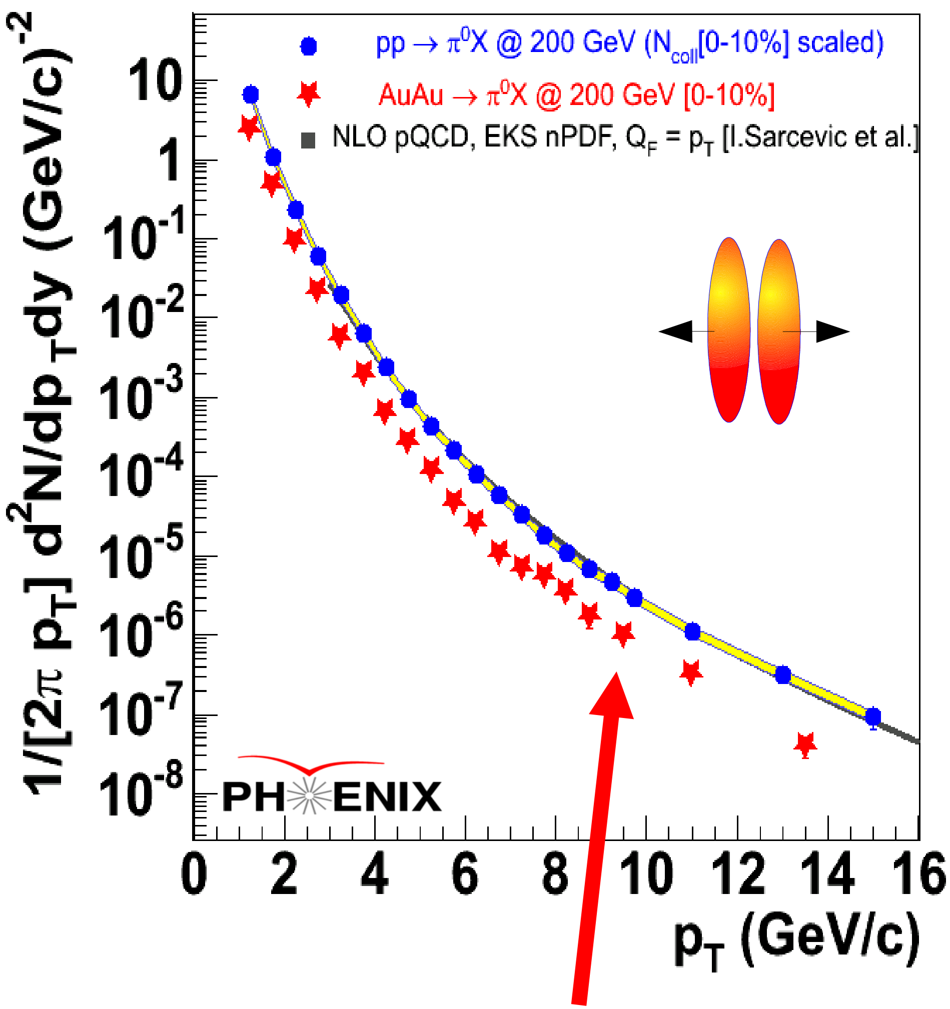


High p_T π^0: AuAu *vs* pp @ 200 GeV

Au+Au→ $\pi^0 X$ (peripheral)



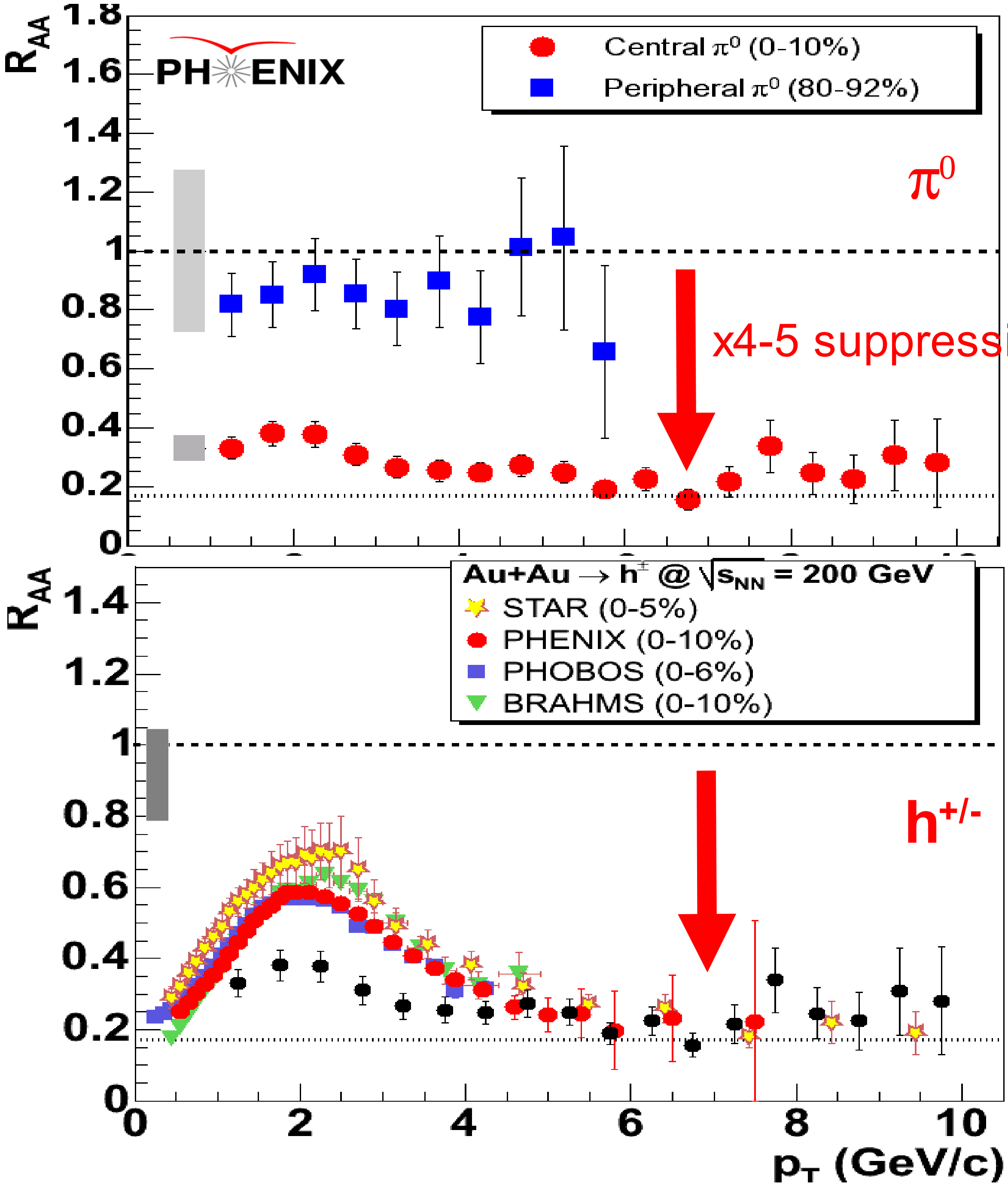
Au+Au→ $\pi^0 X$ (central)



Peripheral data agree well with p+p (data&pQCD) plus N_{coll} scaling

Strong suppression in central Au+Au collisions

AuAu @ 200 GeV (central): high p_T suppression !

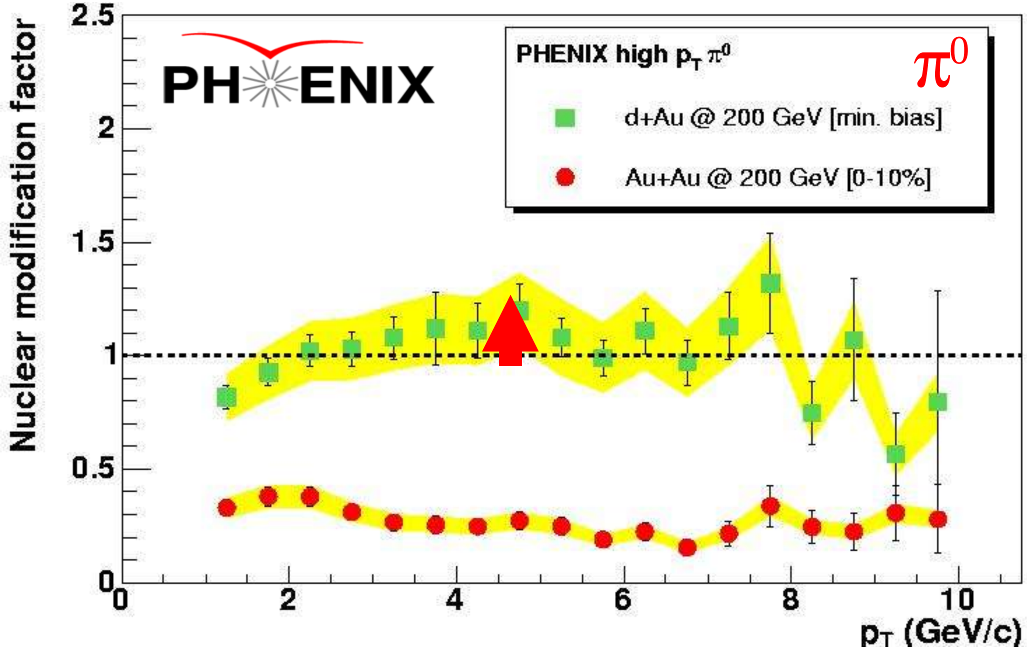


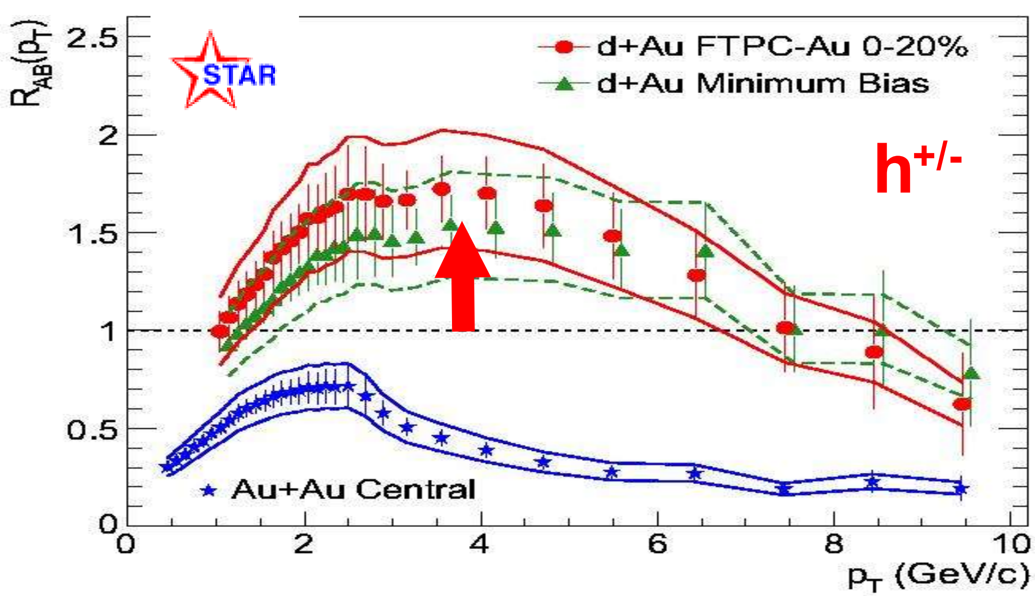
R_{AA} << 1: well below pQCD (factorization) expectations for hard scattering cross-sections

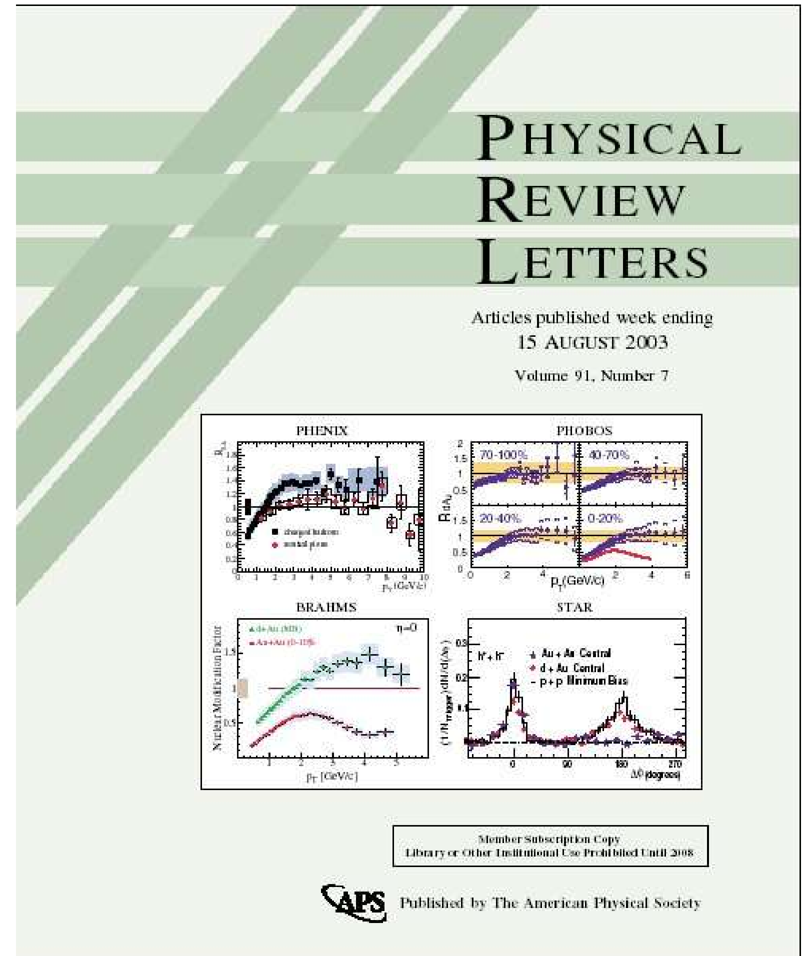
Discovery of high p_T suppression

(one of most significant results @ RHIC so far)

dAu @ 200 GeV: high p_T enhancement !



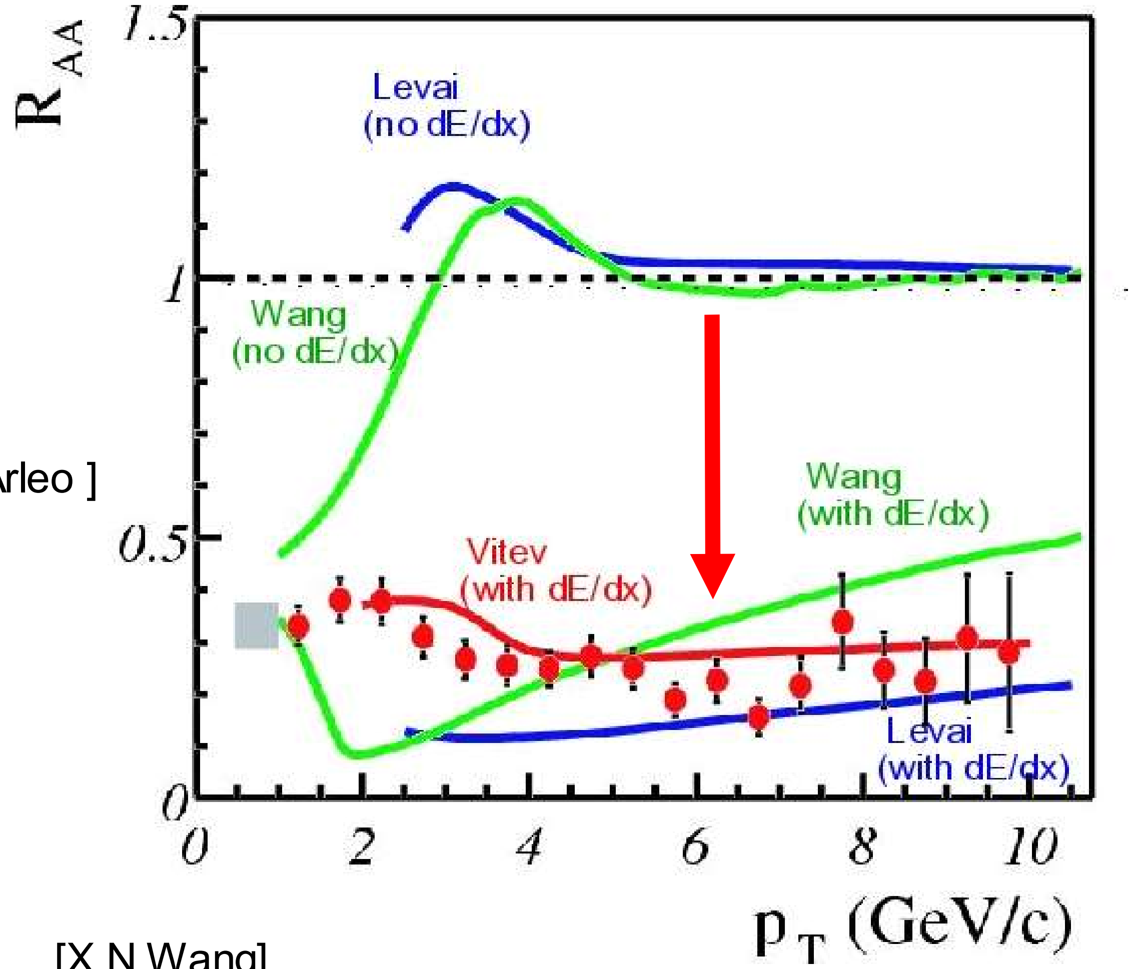




- Conclusion: Suppression in central Au+Au is due to final-state effects.

High p_T suppression: QCD medium properties

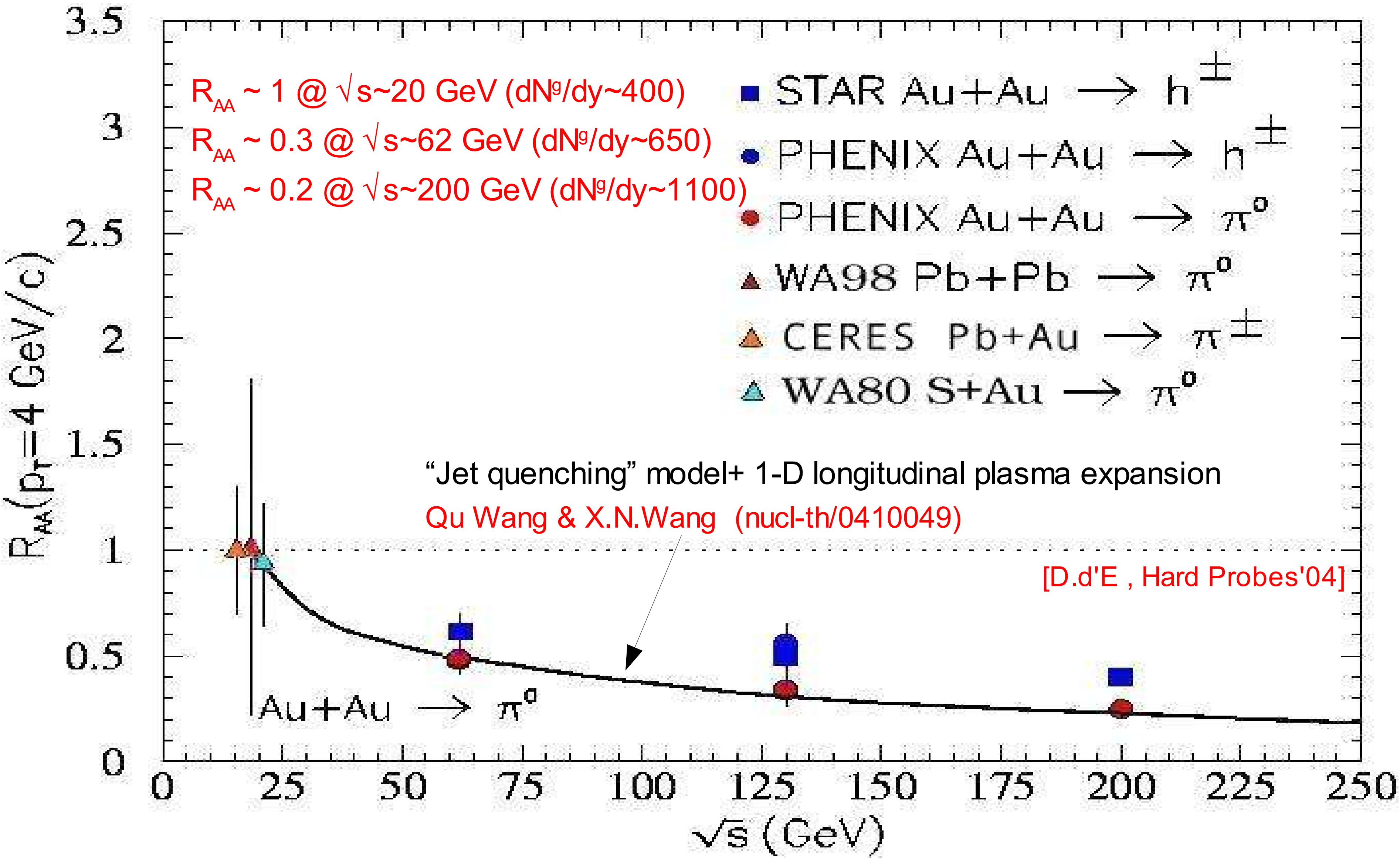
- Medium properties according to "jet quenching" models:
  - Initial gluon densities:
    $dN^g/dy \sim 1100$ [Vitev & Gyulassy]
  - Opacities:
    $<n> = L/\lambda \approx 3 – 4$ [Levai et al.]
  - Transport coefficients:
    $<q_0> \sim 3.5$ GeV/fm^2 [BDMPS, F.Arleo]
  - Plasma temperatures:
    T ~ 0.4 GeV [G. Moore]
  - 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]



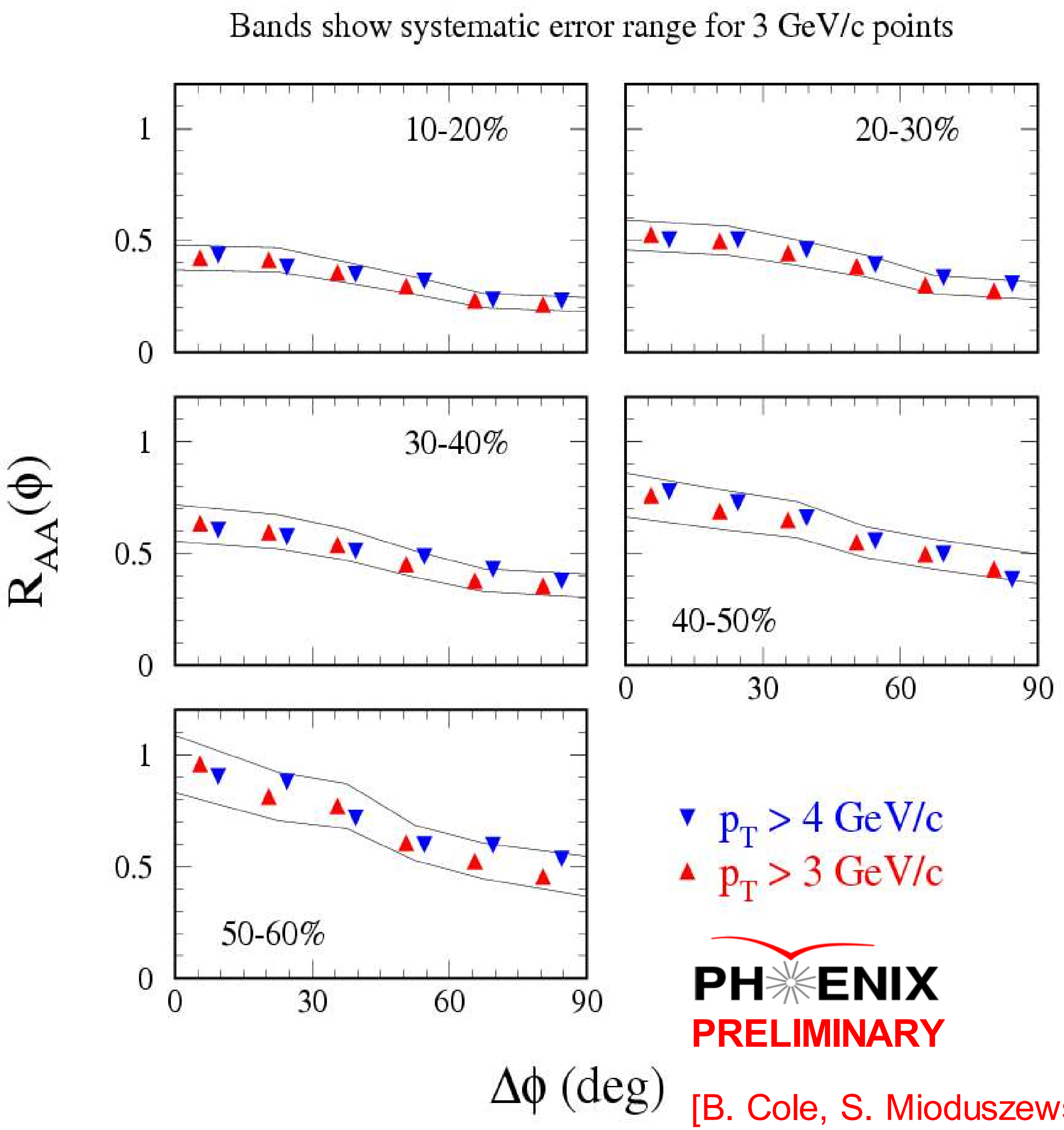
- Large opacities imply fast thermalization.
- All these values imply energy densities well above $\varepsilon_{crit\ QCD}$ in thermalized syst.

High p_T suppression: Excitation function

- sqrt(s)-dependence of R_{AA} consistent w/ parton E_{loss} models (ΔE_{loss}~ dN/dy) + Bjorken expansion:

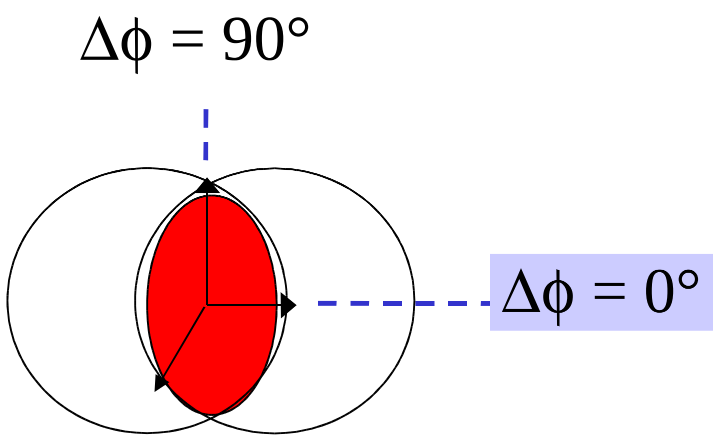


High p_T suppression: Reaction-plane dependence



PHENIX PRELIMINARY

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



- Observe:

  Less suppression in-plane ("short" direction).

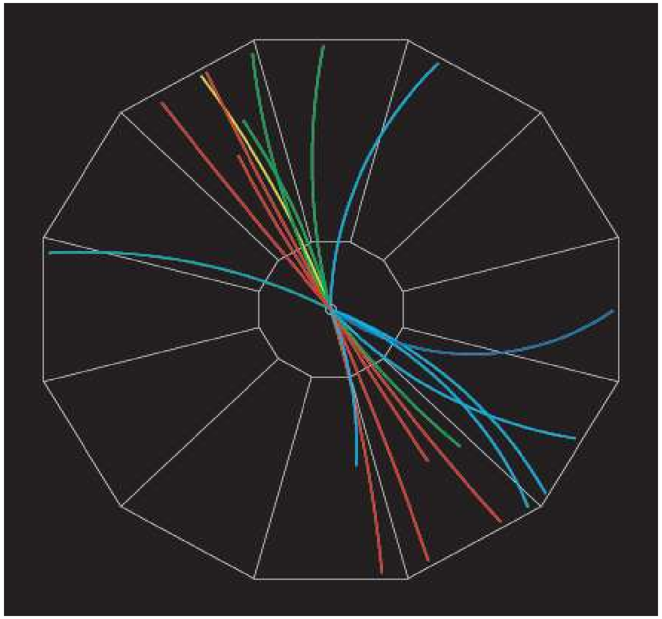
  More suppression out-of-plane ("long" direction).

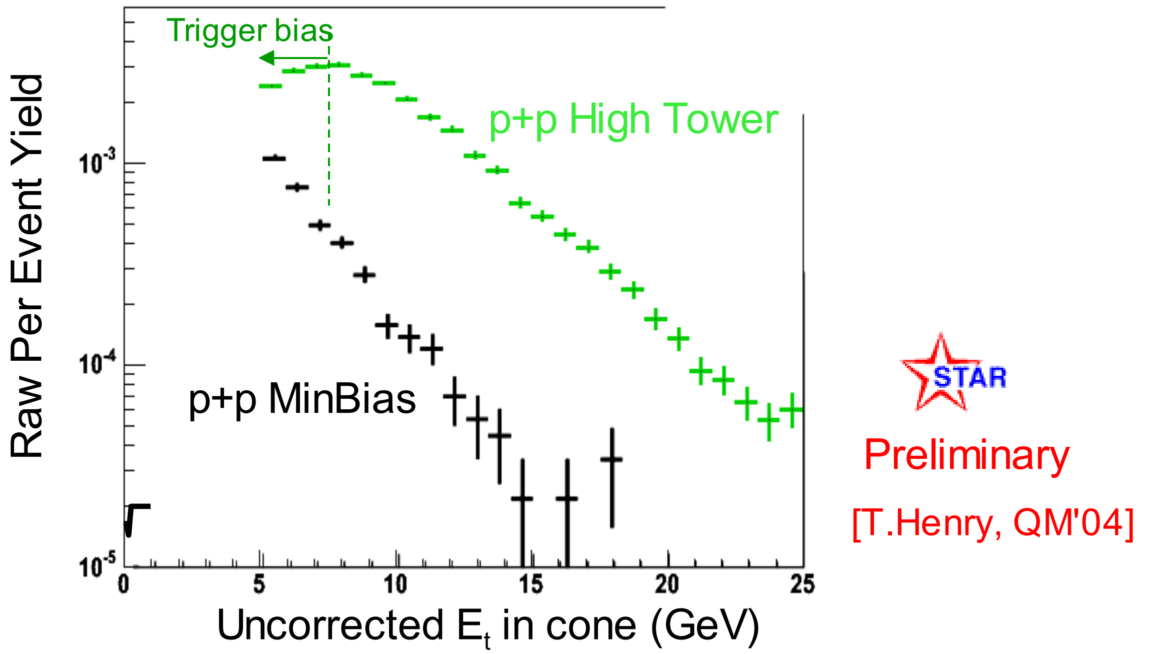
  Ongoing study to constraint path-length dependence (L, L^2?) of energy loss.

Jet production:
QCD vacuum (pp) versus
cold QCD medium (dAu)

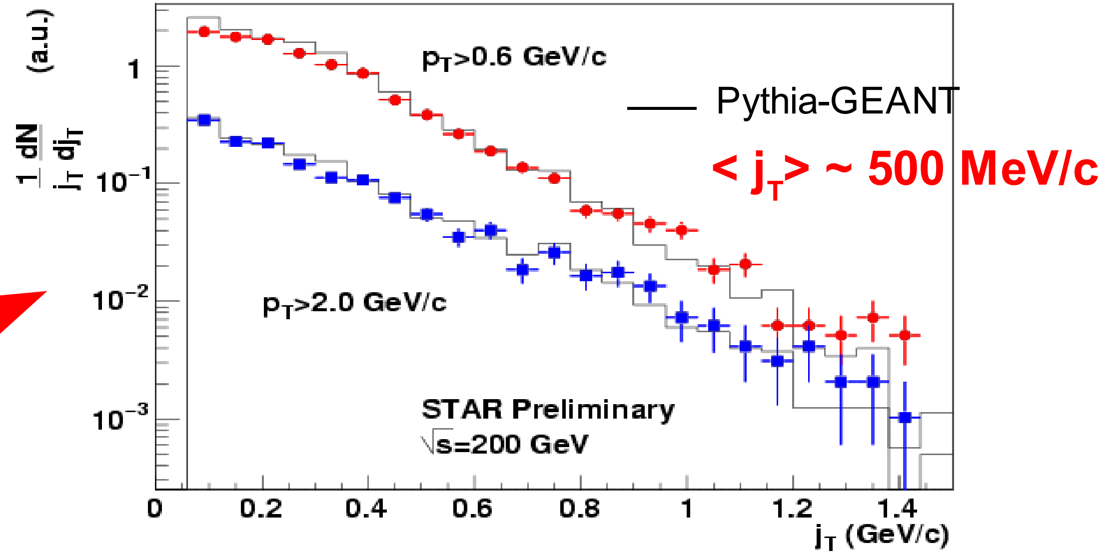
Full jet reconstruction in pp

- First attempt to fully reconstruct jets @ RHIC (p+p @ √s = 200 GeV)



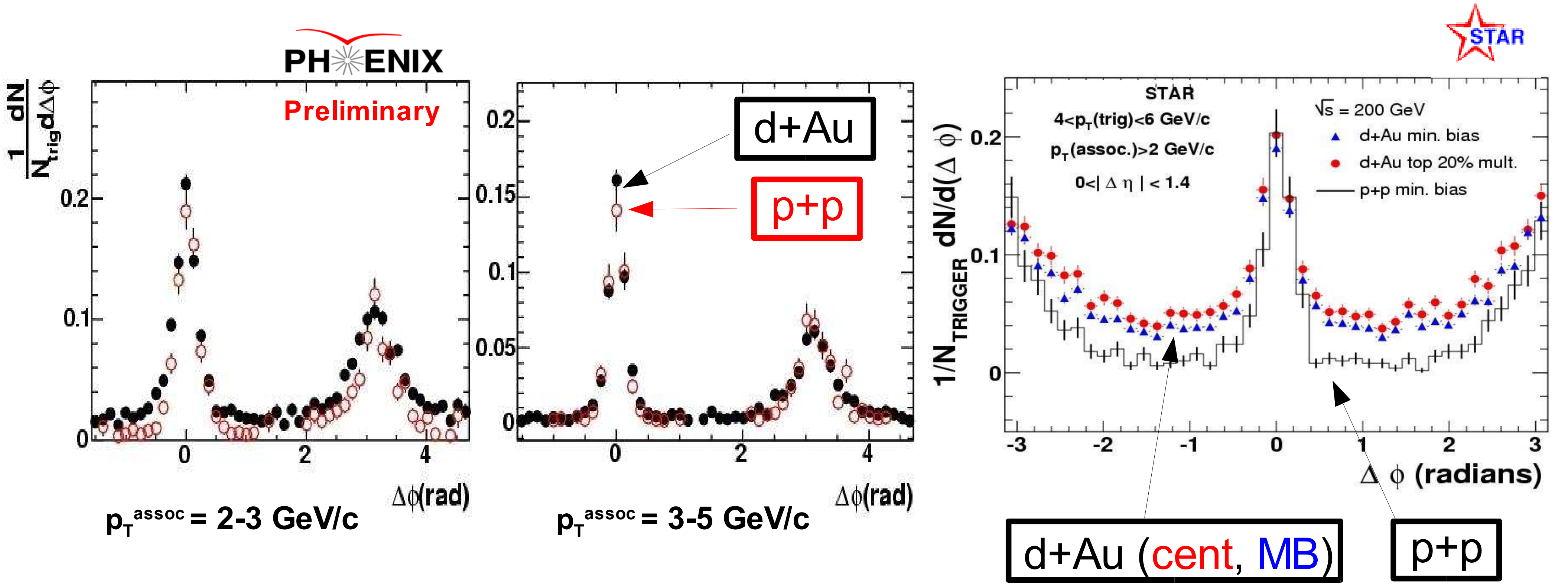


- Uses STAR EMC (neutral) + TPC (charged).
- Two different triggers.
- "Cone algorithm" (R=0.7)
- Obtained j_T spectrum (*see later*)



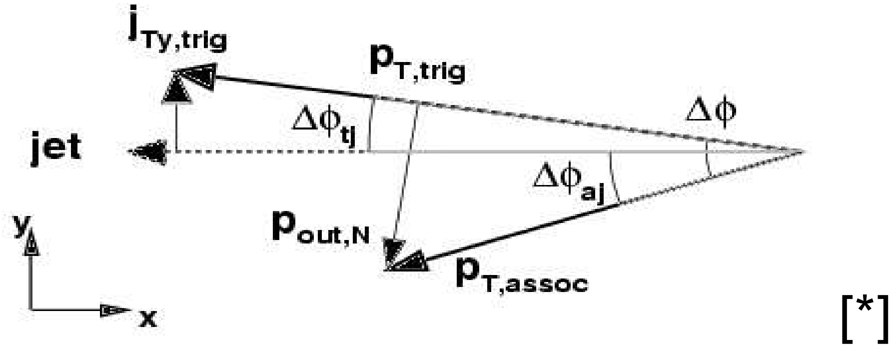
Dijets via dihadron azimuthal correlations: pp, dAu

- 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: $$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} = \frac{1}{N_{trig}}\frac{N_{cor}(\Delta\phi)}{N_{mix}(\Delta\phi)}$$
- Clear near- ($\Delta\phi$ ~ 0) and away- ($\Delta\phi$ ~ π) side jet signals:



Jet properties from dihadron correlations

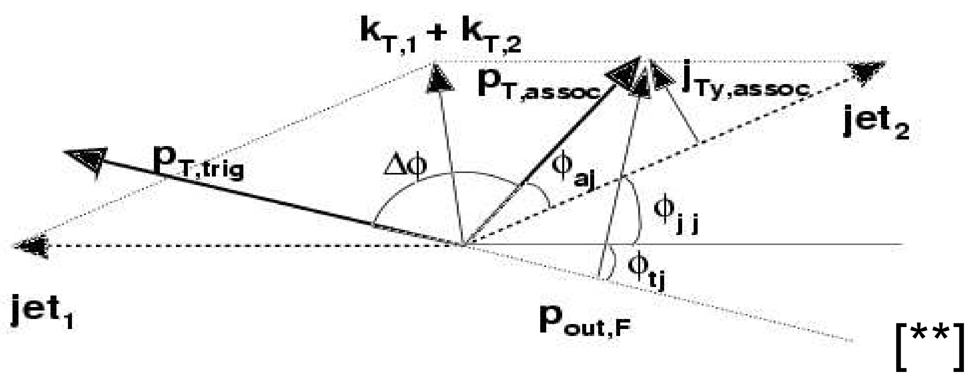
- Jet "width" j_T :



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

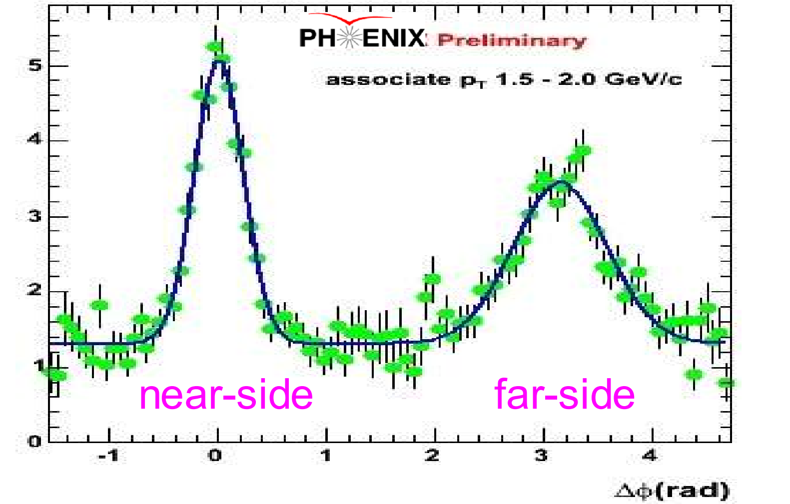
where $x_h = p_{T,asso}/p_{T,trig}$

- Di-jet acoplanarity k_T:



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

(1) 2-hadron correlation function:



(2) Fit to 2-gaussians:

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

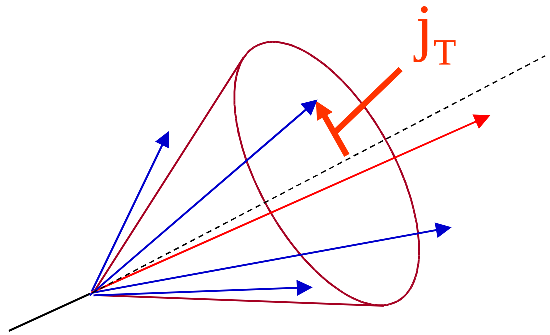
$\Rightarrow$ near-side σ_N, far-side σ_F widths

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

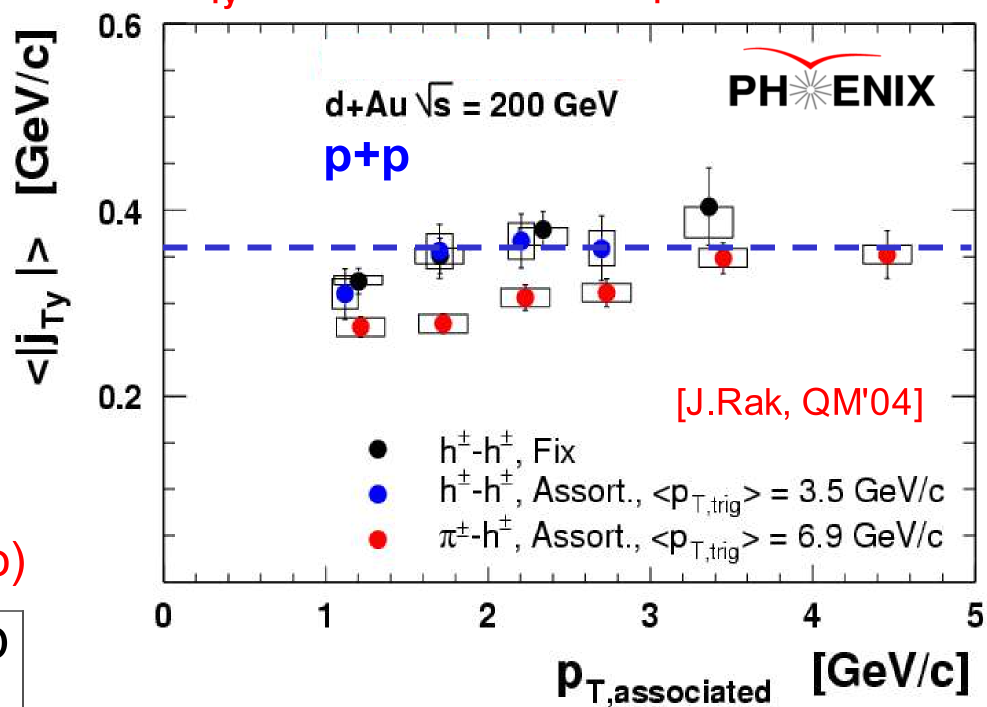
[details in J.Jia, nucl-ex/0409024]

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

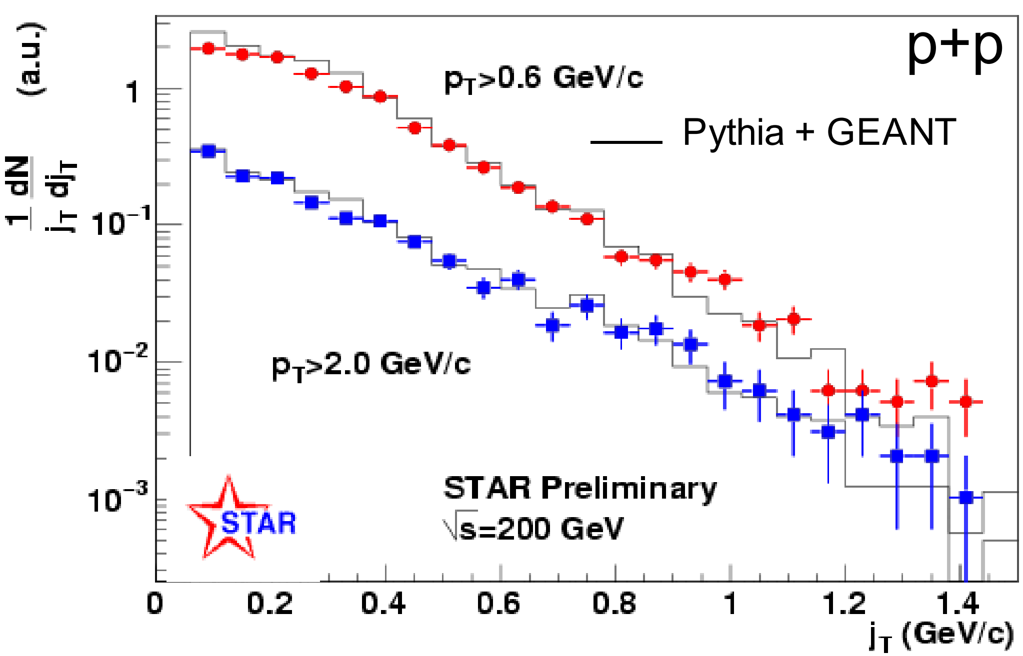
- Jet (near-angle) "width" j_T :



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



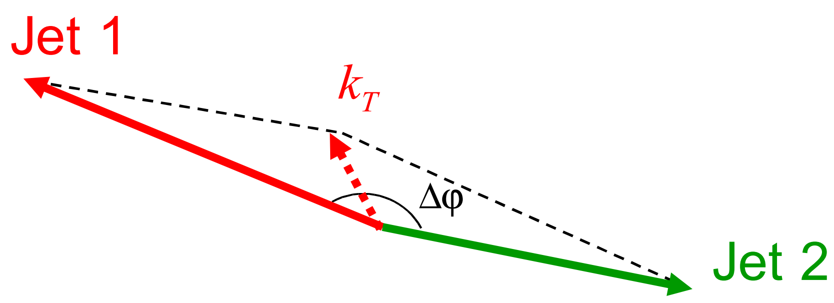
$< j_T >$ ~ 500 MeV/c (from full jet reco)



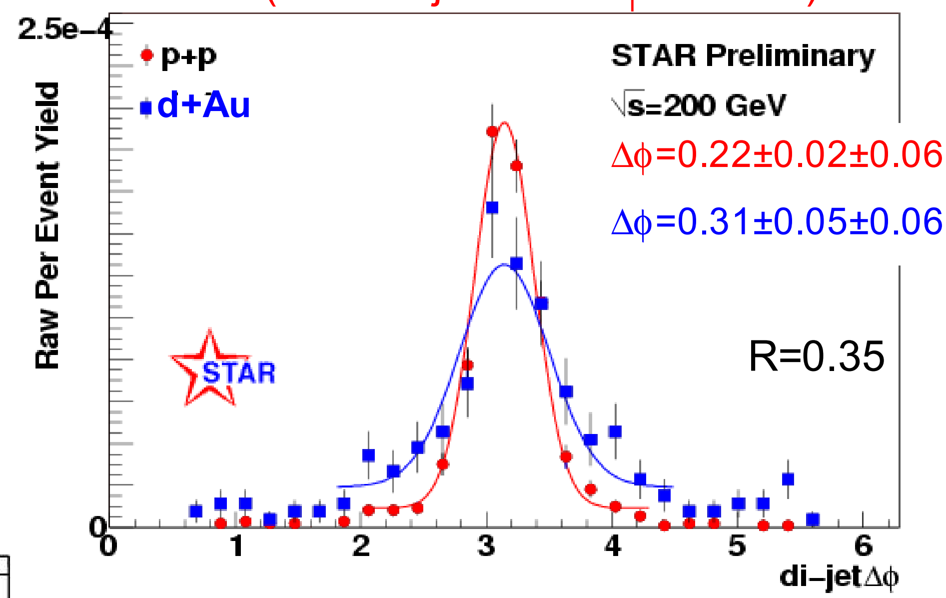
- **$< j_T >$ ~ 500 MeV/c:** Agreement between RHIC and ISR data.
- No apparent difference between dAu and pp.
- Fragmentation not affected by cold QCD medium.

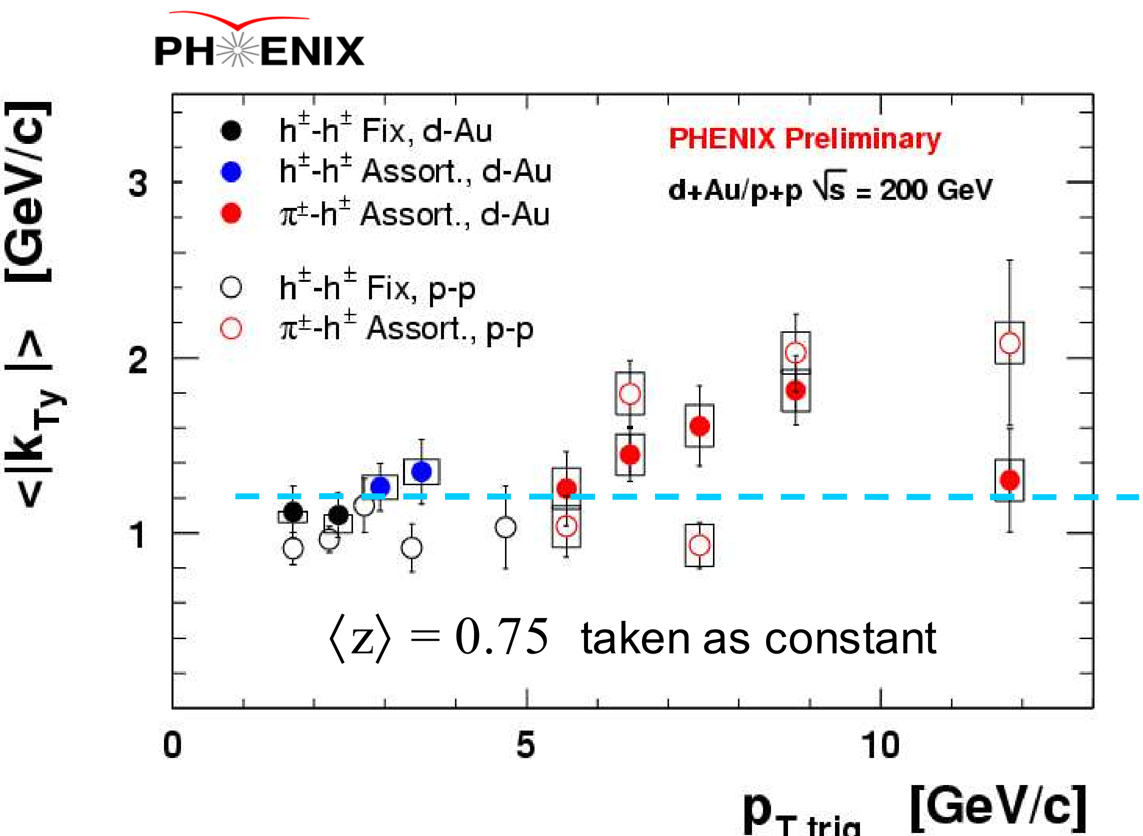
Di-jet acoplanarity (“intrinsic” k_T) : pp, dAu

- Intrinsic k_T (di-jet acoplanarity):



(from full jet reco: E_T~13 GeV)

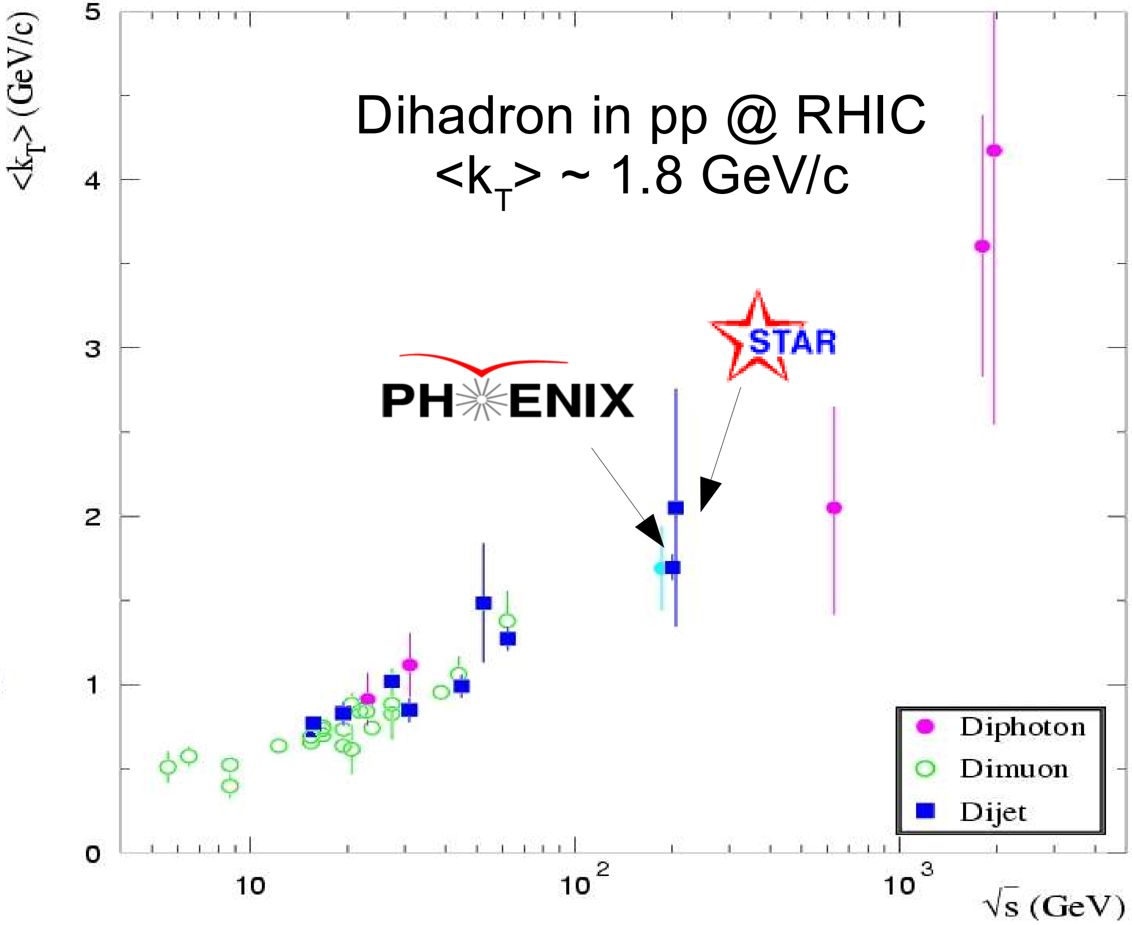




- Non-negligible **k_T broadening in pp: $\langle k_{Ty} \rangle$ ~ 1.1 GeV/c** (“unseen” in inclusive high p_T hadron spectra $\langle k_T \rangle_{pair} \neq \langle k_T \rangle_{incl}$)
- In dAu: $\langle k_T^2 \rangle_{dAu} \equiv \langle k_T^2 \rangle_{pp} + \langle k_T^2 \rangle_{nuclear}$
- Non-null (but small) **$\langle k_T \rangle_{nuclear}$** (constraints models of multiple scattering in cold nuclear medium)

Di-jet acoplanarity ("intrinsic" k_T): Excitation function (pp)

- sqrt(s)-dependence of $\langle k_T \rangle_{pair}$:

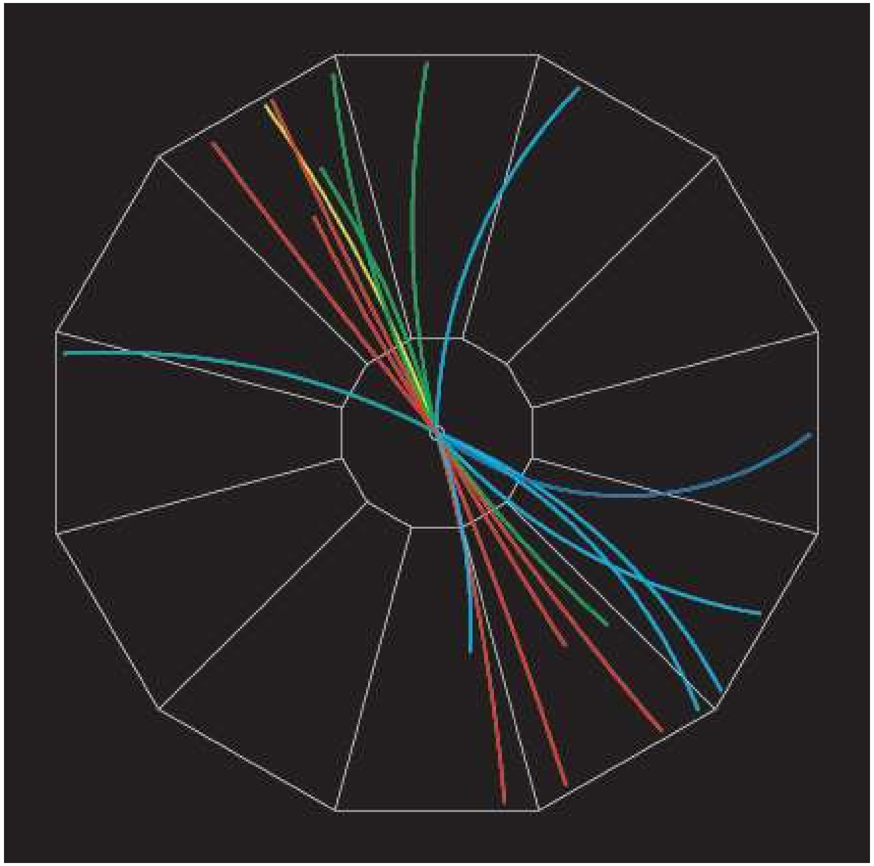


- (Logarithmic) increase with sqrt(s) consistent with growing gluon radiation contribution (not just intrinsic parton Fermi motion).

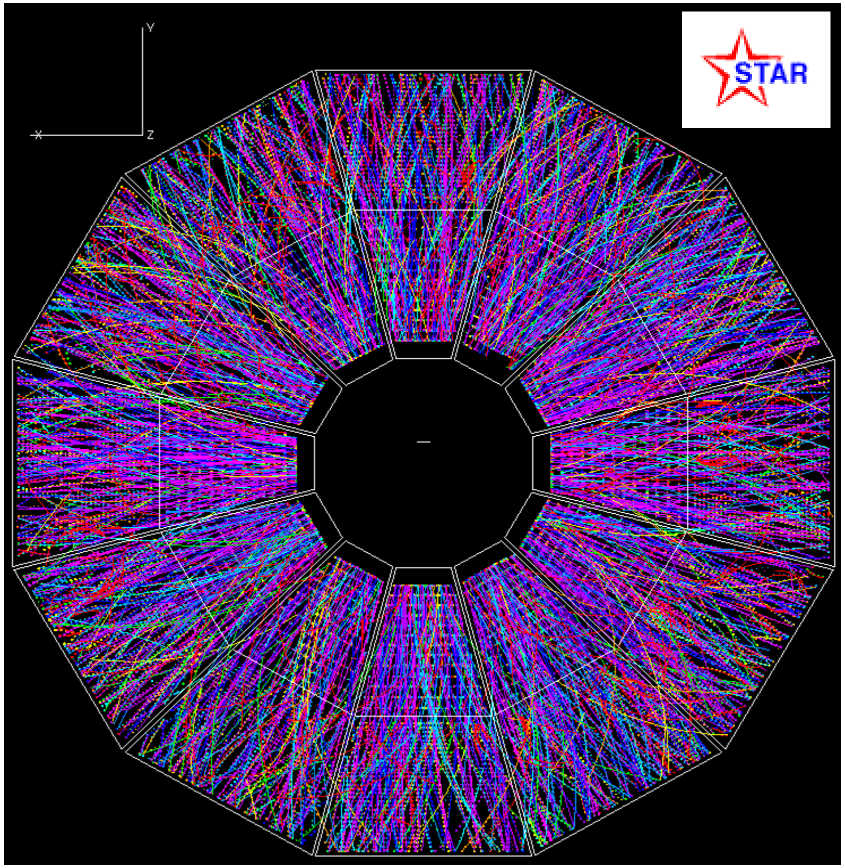
Jet production in hot & dense QCD matter (AA collisions)

Jets in high-energy AA collisions

- Full jet reconstruction w/ standard algorithms is unpractical at RHIC due to huge soft background ("underlying event"):



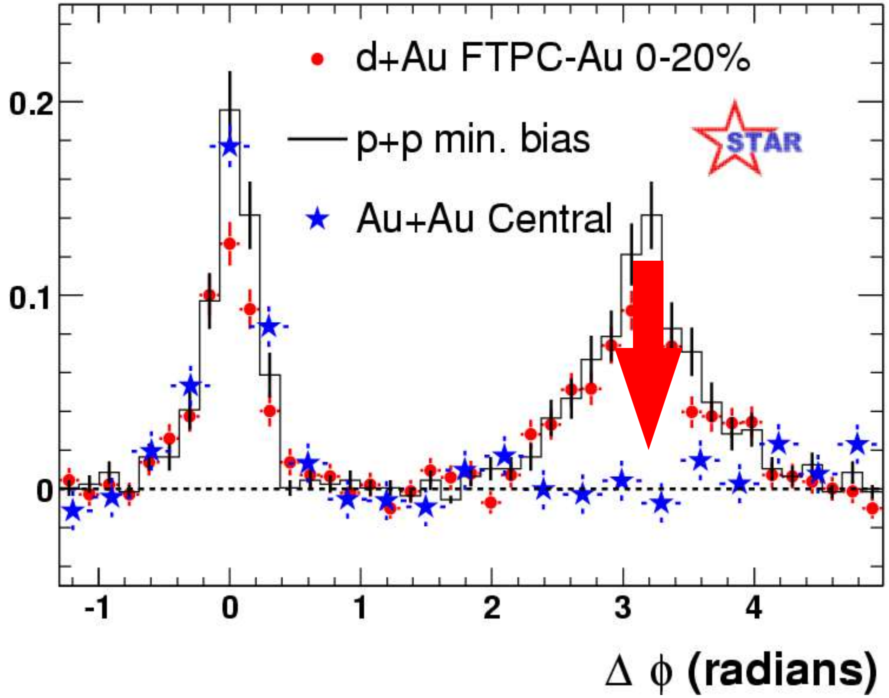
p+p $\rightarrow$ jet+jet [$\sqrt{s}$ = 200 GeV]
STAR @ RHIC (2003)



Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]
STAR @ RHIC (2003)

Dijets via dihadron azimuthal correlations: AuAu (200 GeV)

- [*Same analysis as in pp, dAu plus elliptic flow subtraction*]
- Discovery of "monojet"-like topologies in central AuAu: (disappearance of away-side jet correlations):



STAR, PRL90, 082302 (2003)

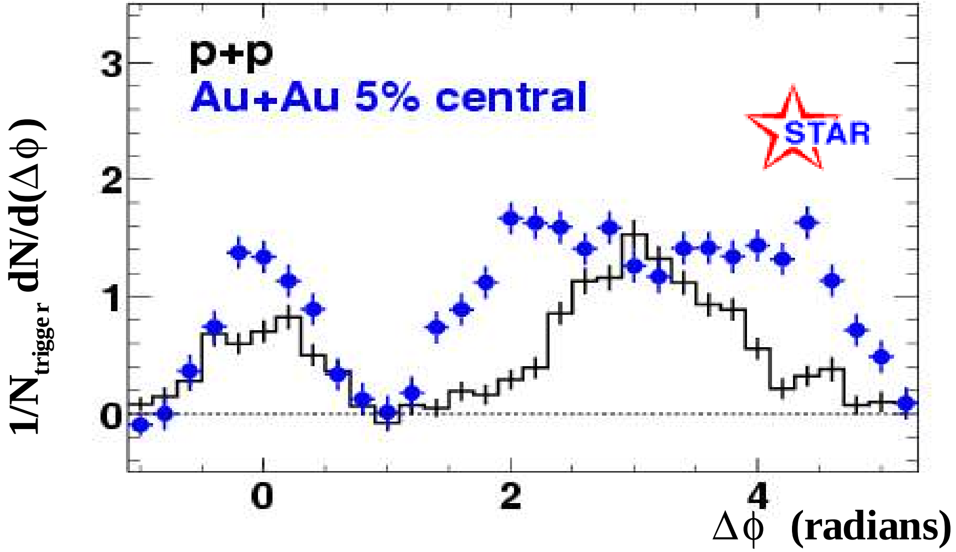
4<p_T(trig)<6 GeV/c

p_T(assoc)>2 GeV/c

- Associated low p_T hadrons ("jet remnants"):

$p_{T\,trigg}$ = 4 – 6 GeV/c

p_{Tassoc} = 0.15 – 4 GeV/c

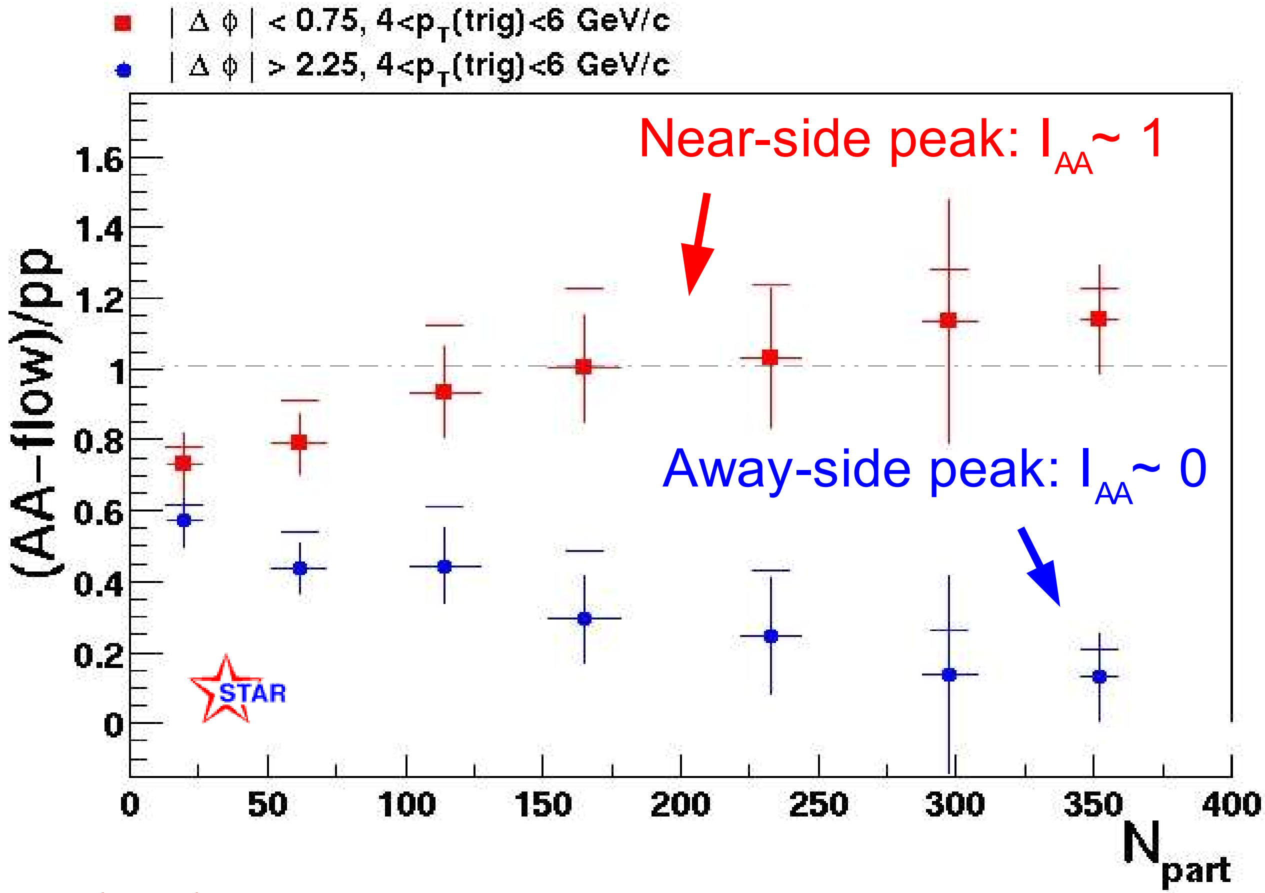


[F.Wang, QM'04]

Dijets via dihadron azimuthal correlations: AuAu (200 GeV)

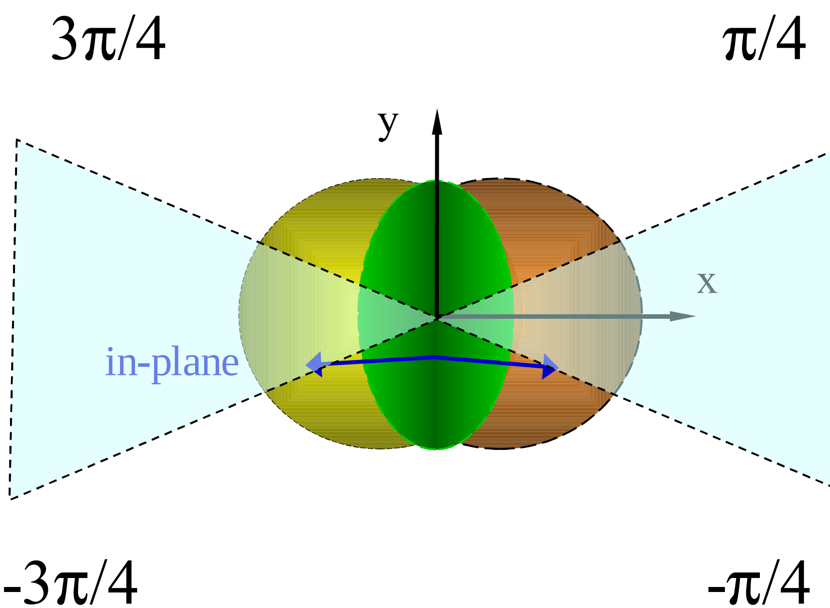
- Centrality dependence of near- and away- side correlations "strengths":

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

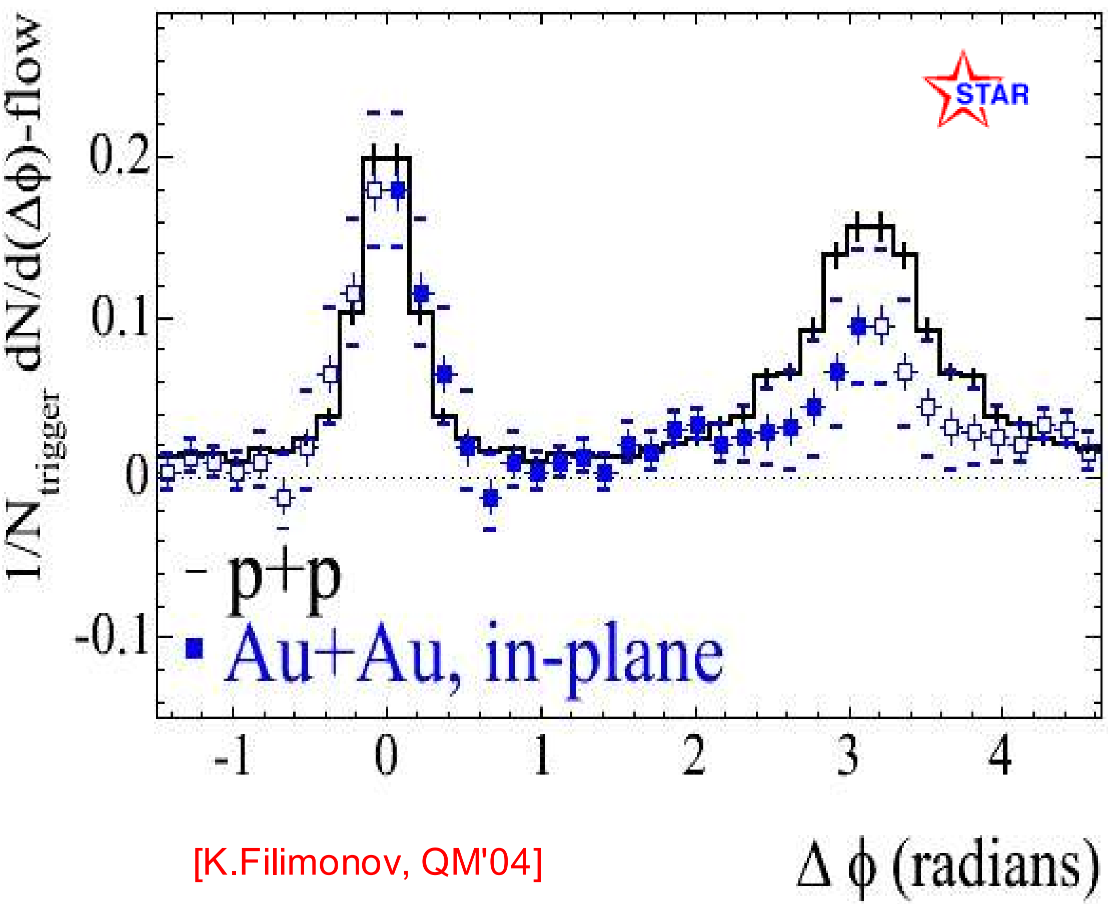


STAR, PRL90, 082302 (2003)

Reaction-plane dependence of away-side dissapeareance

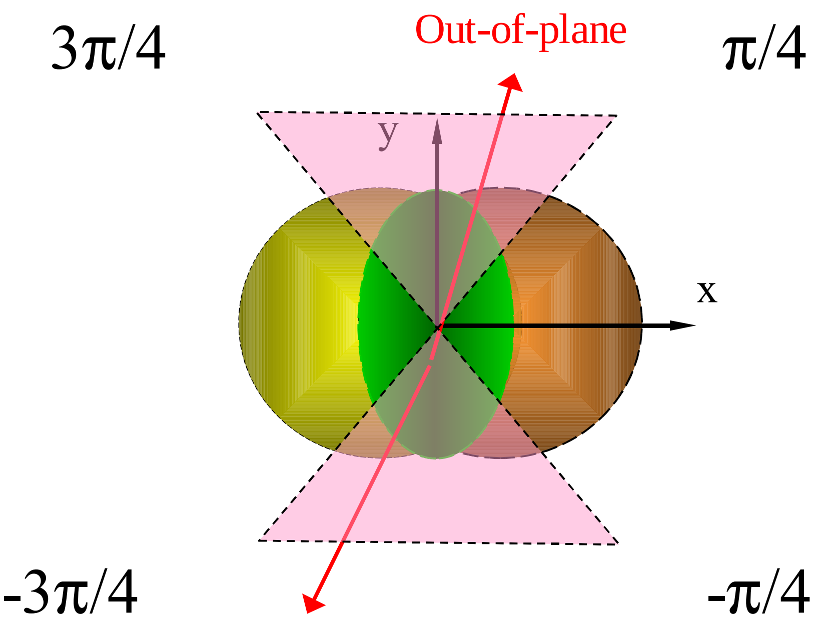


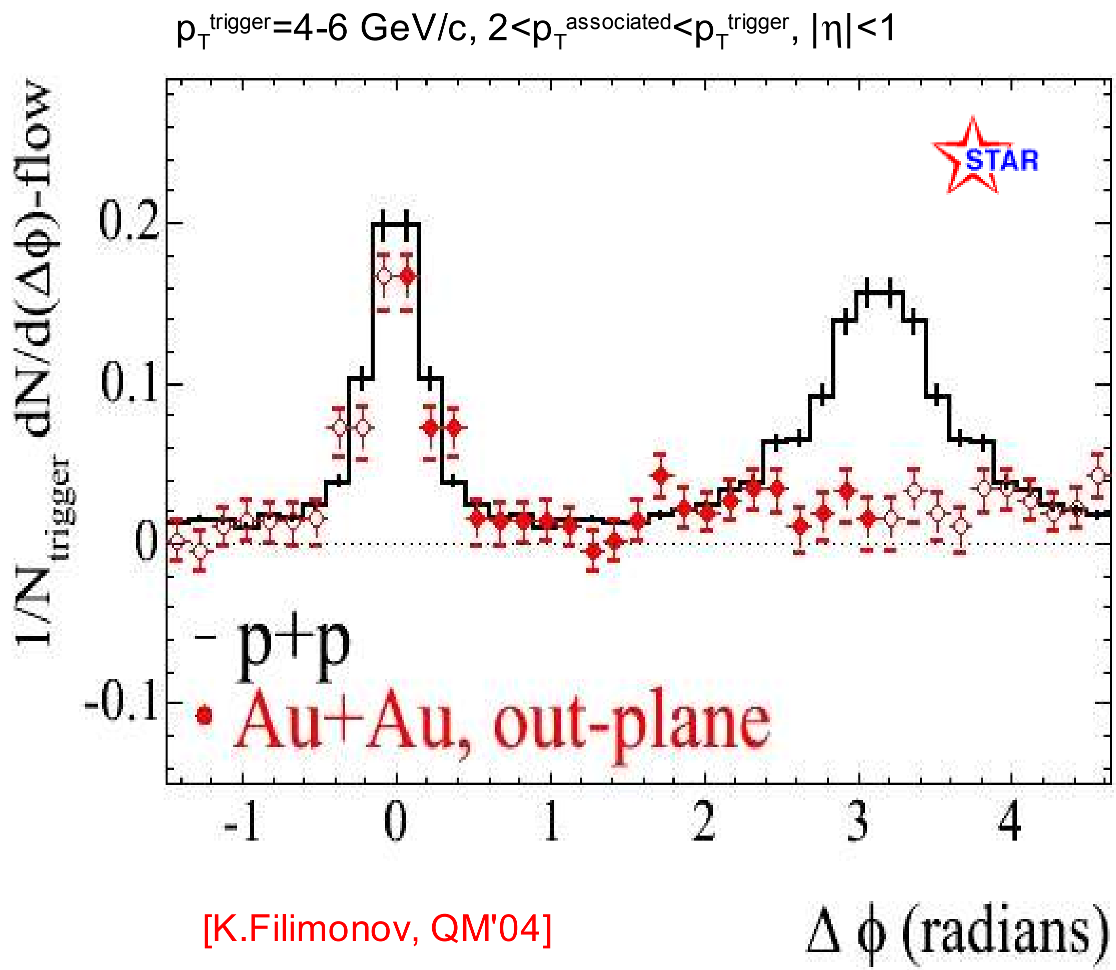
$p_T^{trigger}$=4-6 GeV/c, 2<$p_T^{associated}$<$p_T^{trigger}$, |η|<1



[K.Filimonov, QM'04]

Reaction-plane dependence of away-side dissapeareance

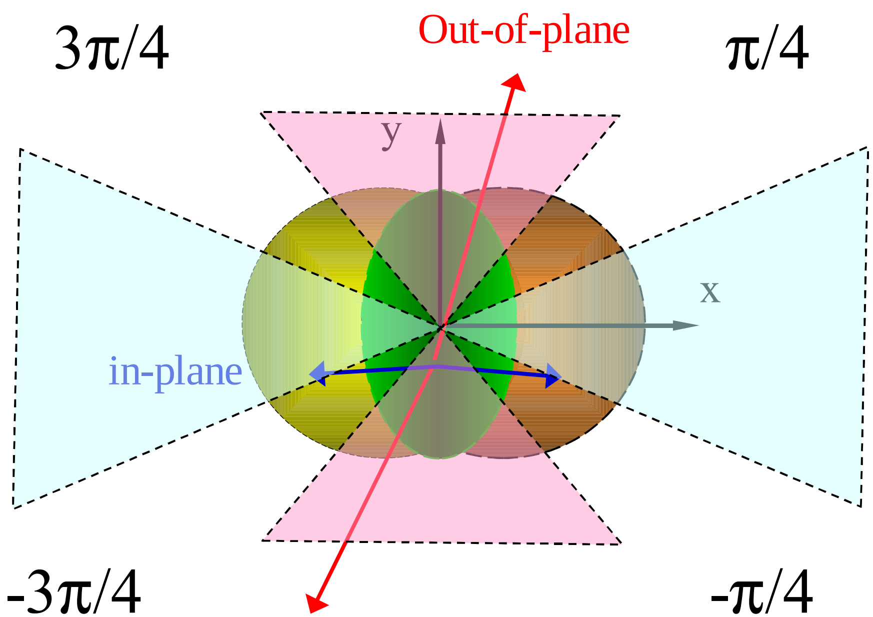




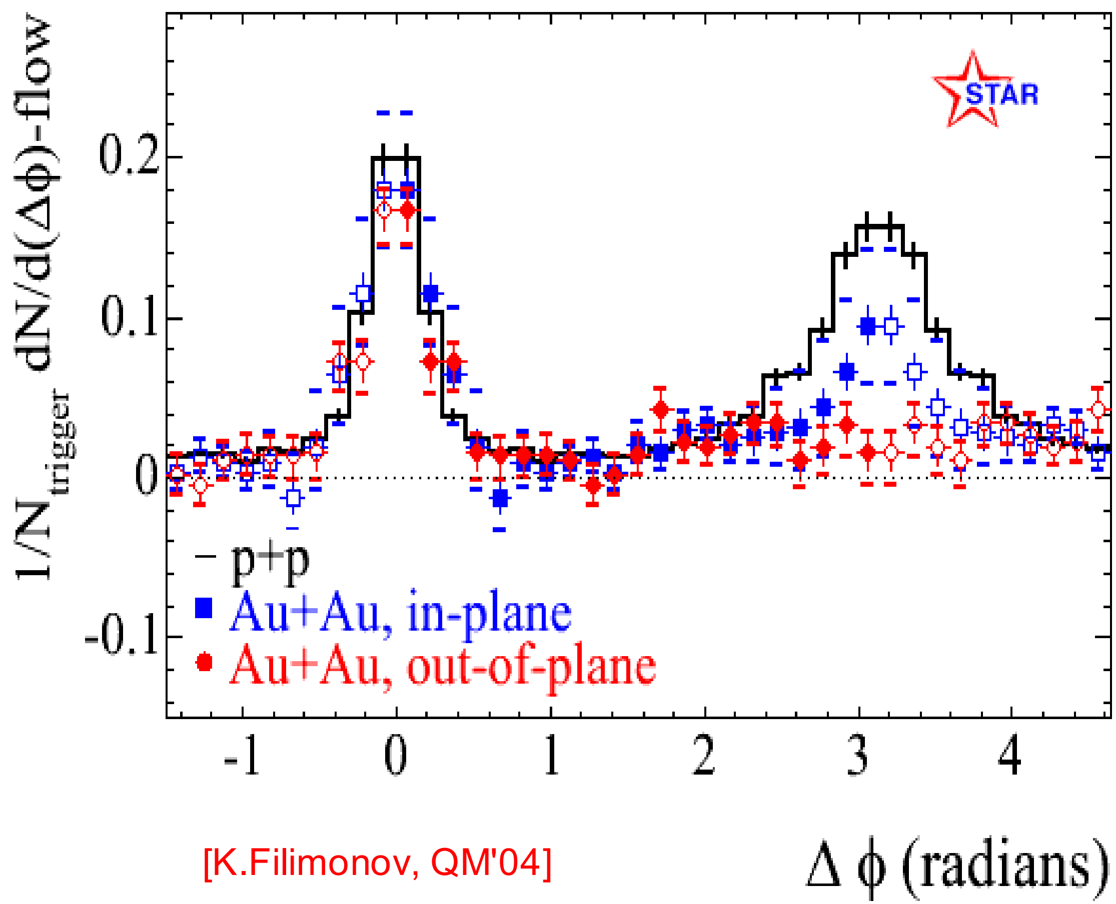
[K.Filimonov, QM'04]

Back-to-back suppression out-of-plane stronger than in-plane
(consistent with increasing energy loss in larger path-length)

Reaction-plane dependence of away-side dissapeareance



$p_T^{trigger}$=4-6 GeV/c, 2<$p_T^{associated}$<$p_T^{trigger}$, |η|<1



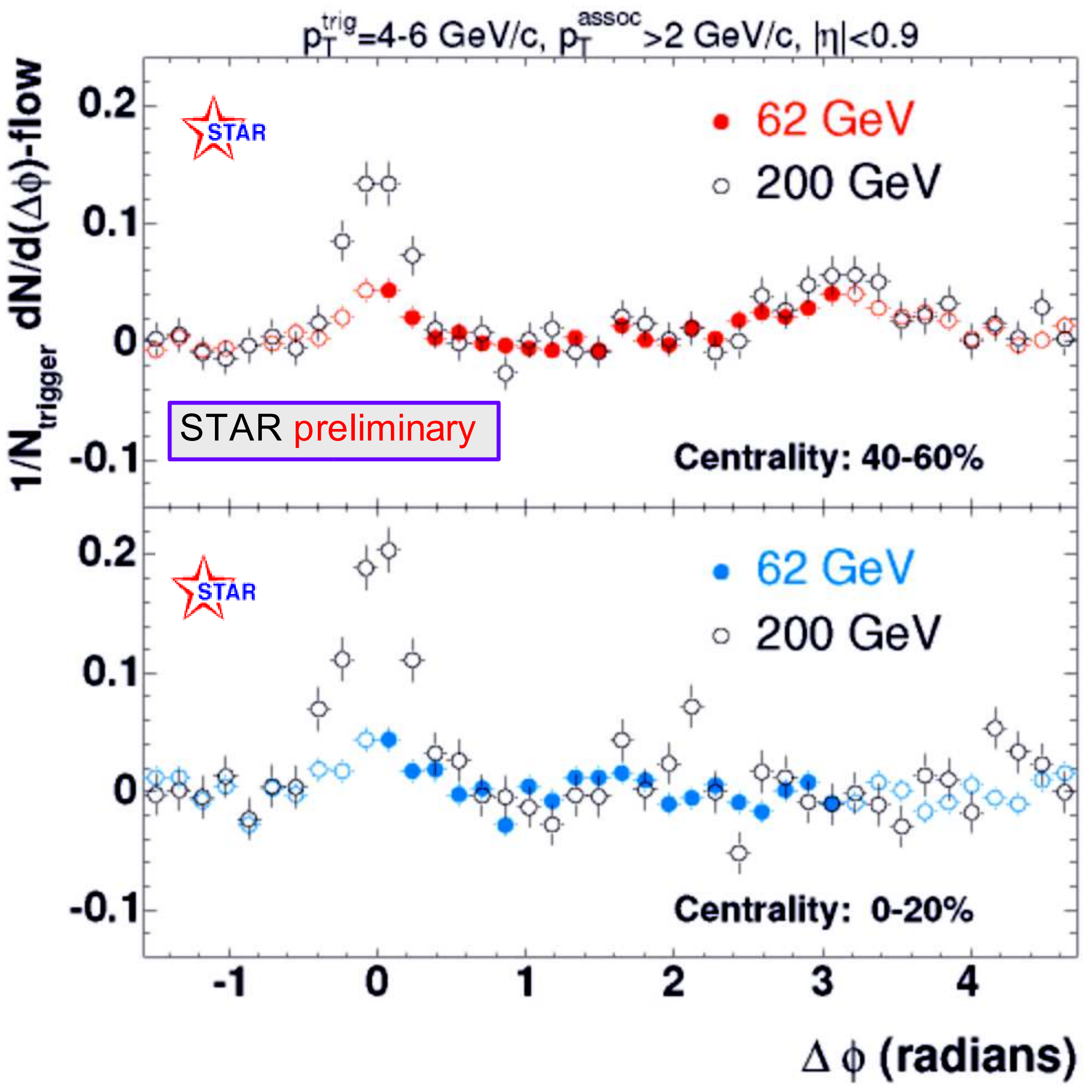
[K.Filimonov, QM'04]

Back-to-back suppression out-of-plane stronger than in-plane (consistent with increasing energy loss in larger path-length)

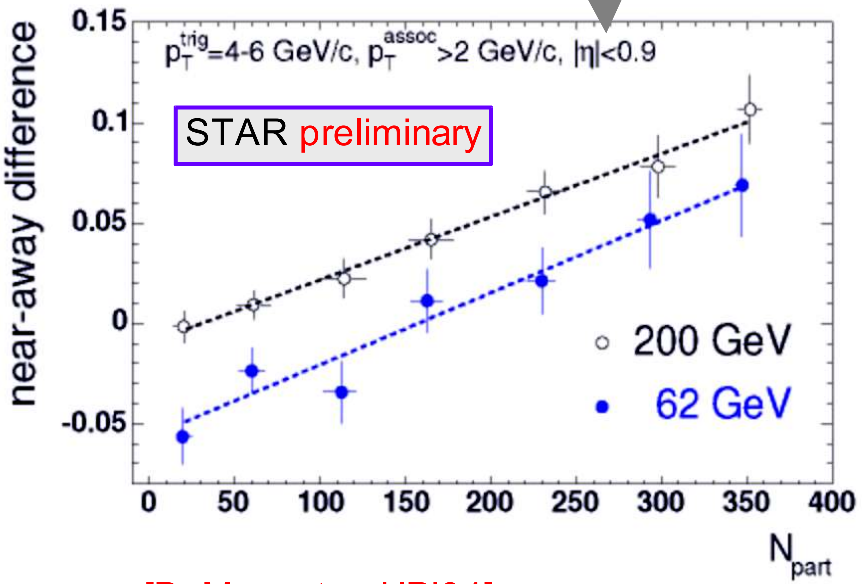
Constraints on path-length dependence of partonic “absorption”

Dihadron azimuthal correlations: AuAu (62 GeV)

- Away-side disappearance also at 62 GeV (statistics limited):



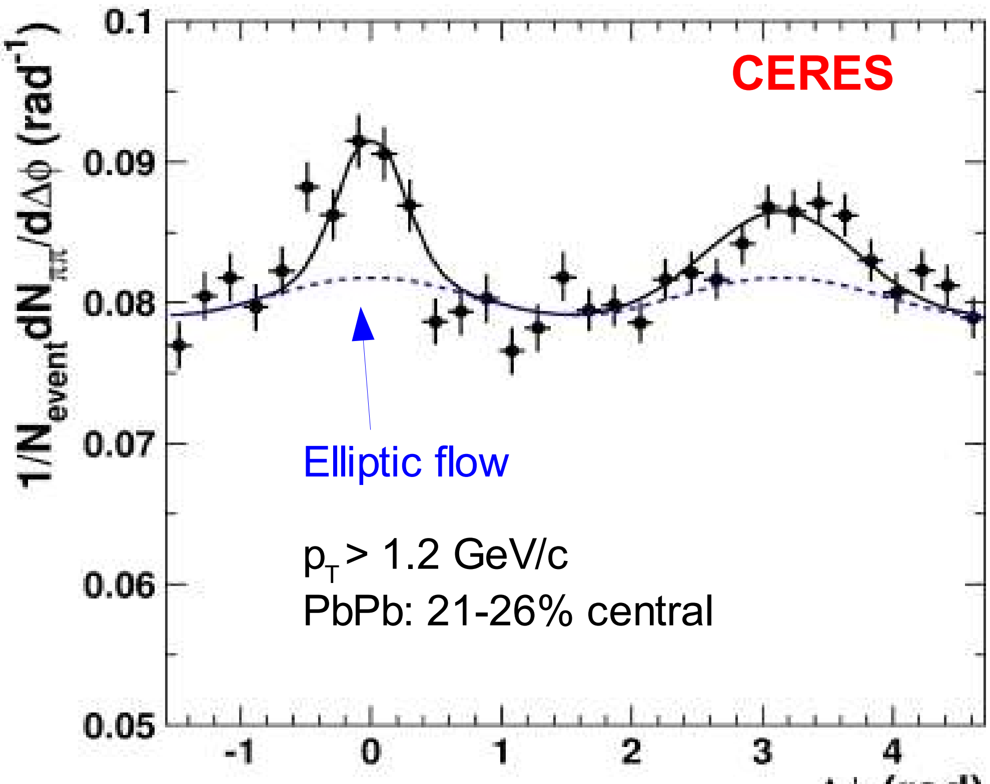
- [near side] – [away side] diff. indicates similar suppression pattern @ 200 and 62 GeV



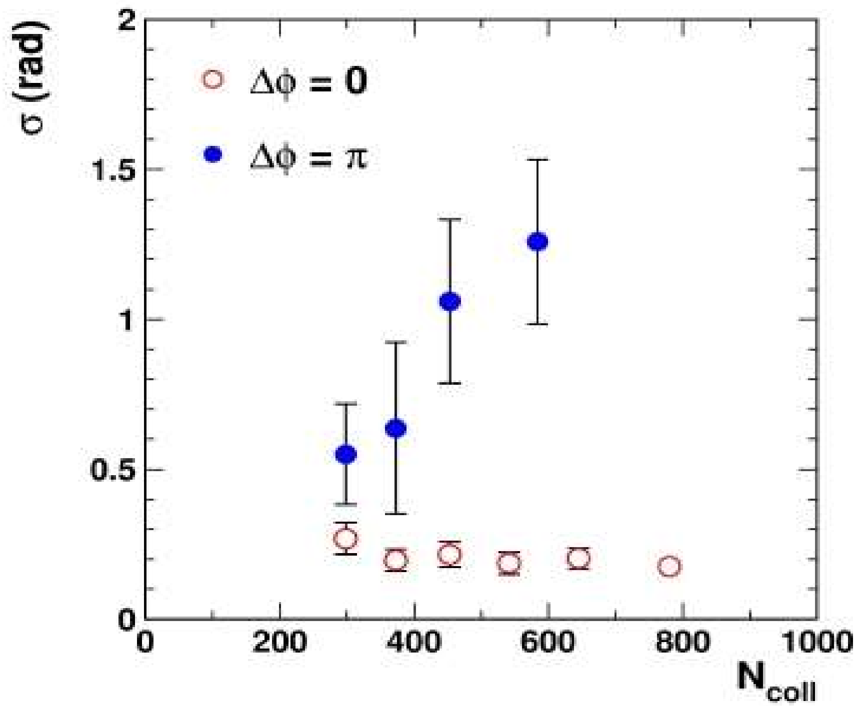
[D. Magestro, HP'04]

Dihadron azimuthal correlations: PbPb (17 GeV)

- Large broadening of away-side correlations seen in di-pion azimuthal correlations at CERN-SPS:



[J. Bielcikova, HP'04]

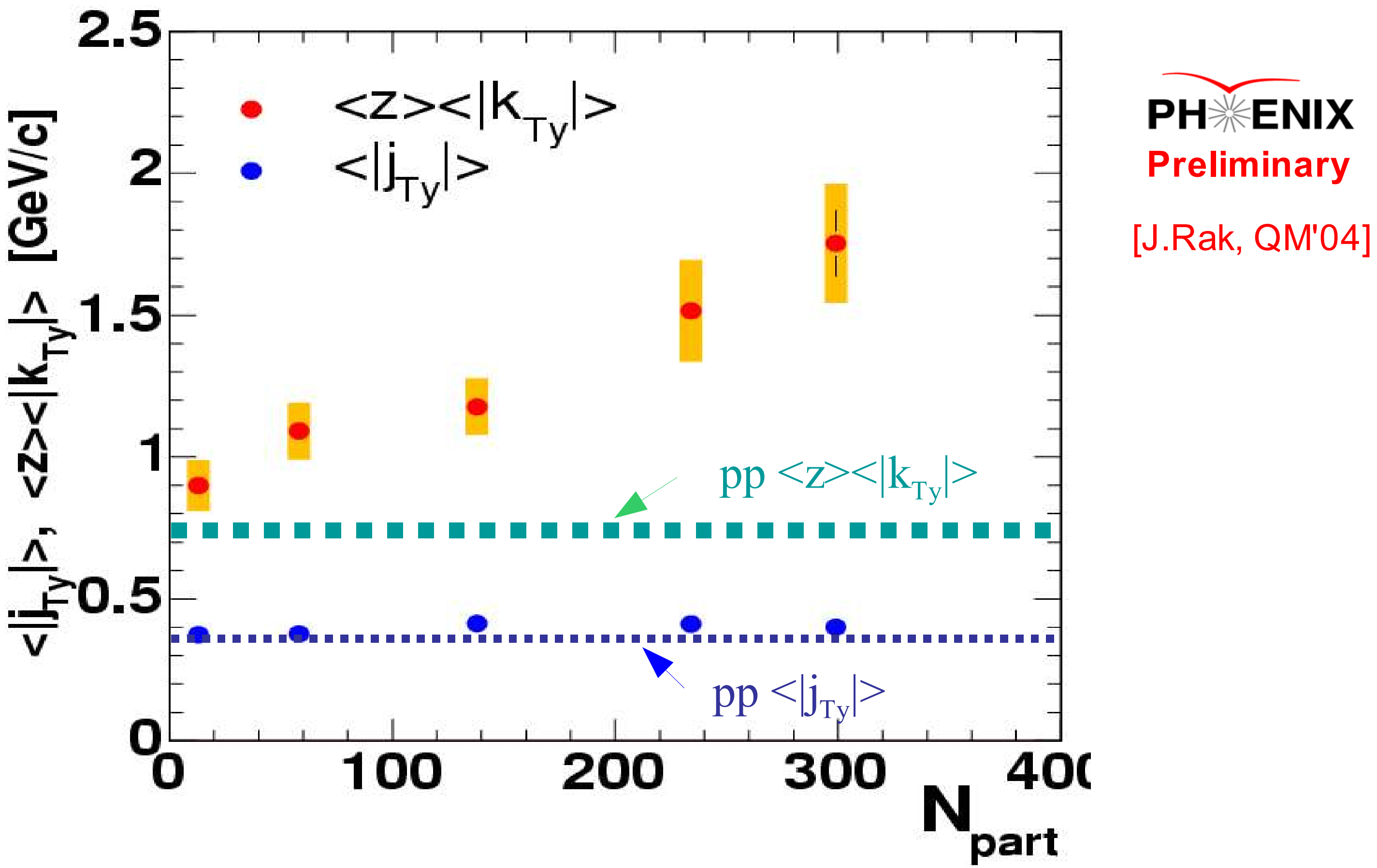


- Gaussian peaks have diff. widths: $\sigma_N = 0.27 \pm 0.05$ rad, $\sigma_F = 0.55 \pm 0.17$ rad.
- Centrality dependence: σ_N is constant, σ_F increases w/ centrality
- Significant k_T broadening: $\langle k_T \rangle = 2.8 \pm 0.6$ GeV/c

Jet properties (j_T, k_T): AuAu (200 GeV)

- Centrality dependence of $\langle|j_{Ty}|\rangle$ and $\langle z\rangle\langle|k_{Ty}|\rangle$ in Au+Au:

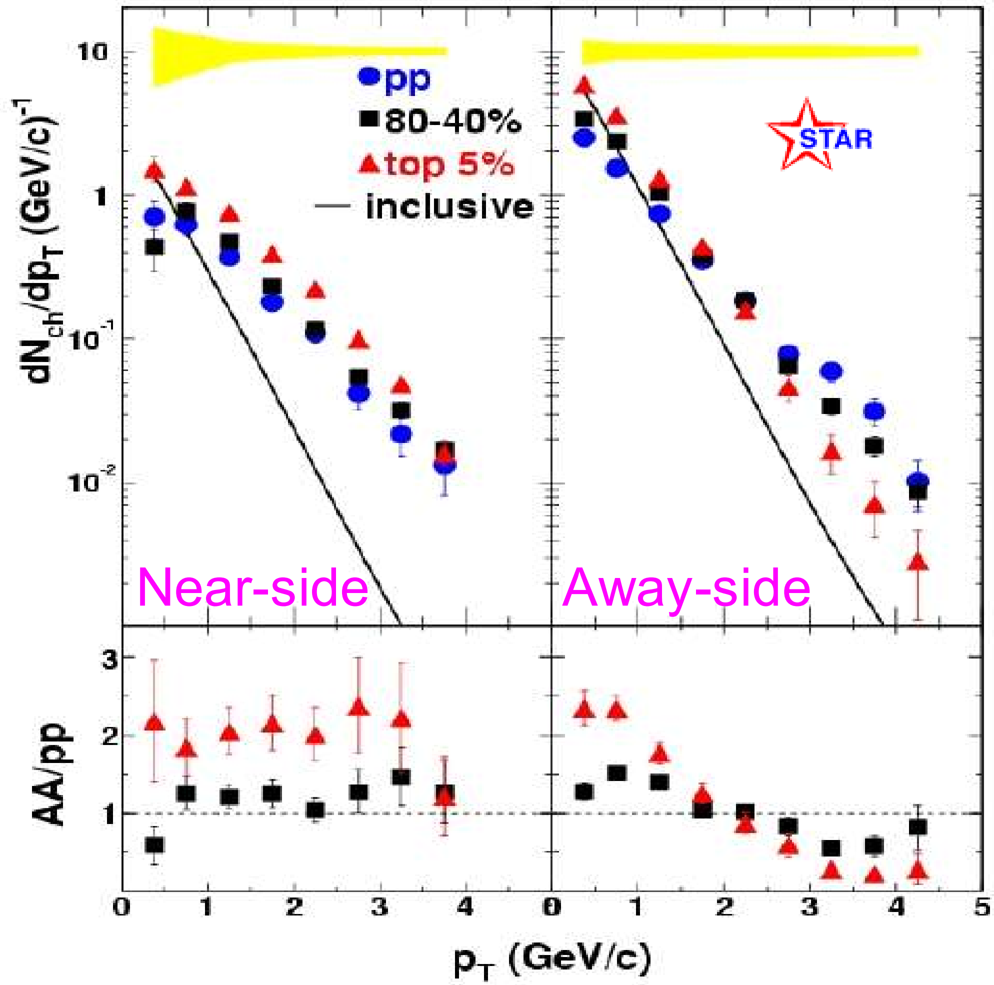
p_{Ttrigg} =2.5 – 4.0 GeV/c , p_{Tassoc} = 1.0 – 2.5 GeV/c



- $\langle j_T\rangle_{AuAu} \sim \langle j_T\rangle_{pp}$: near-side fragmentation unaffected by QCD medium.
- Significant k_T broadening (k_T~3 GeV/c) in AuAu (strongly centrality dependent) indicating substantial final-state rescattering of away-side fragmenting parton.

"Fragmentation functions": Central AuAu (200 GeV)

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

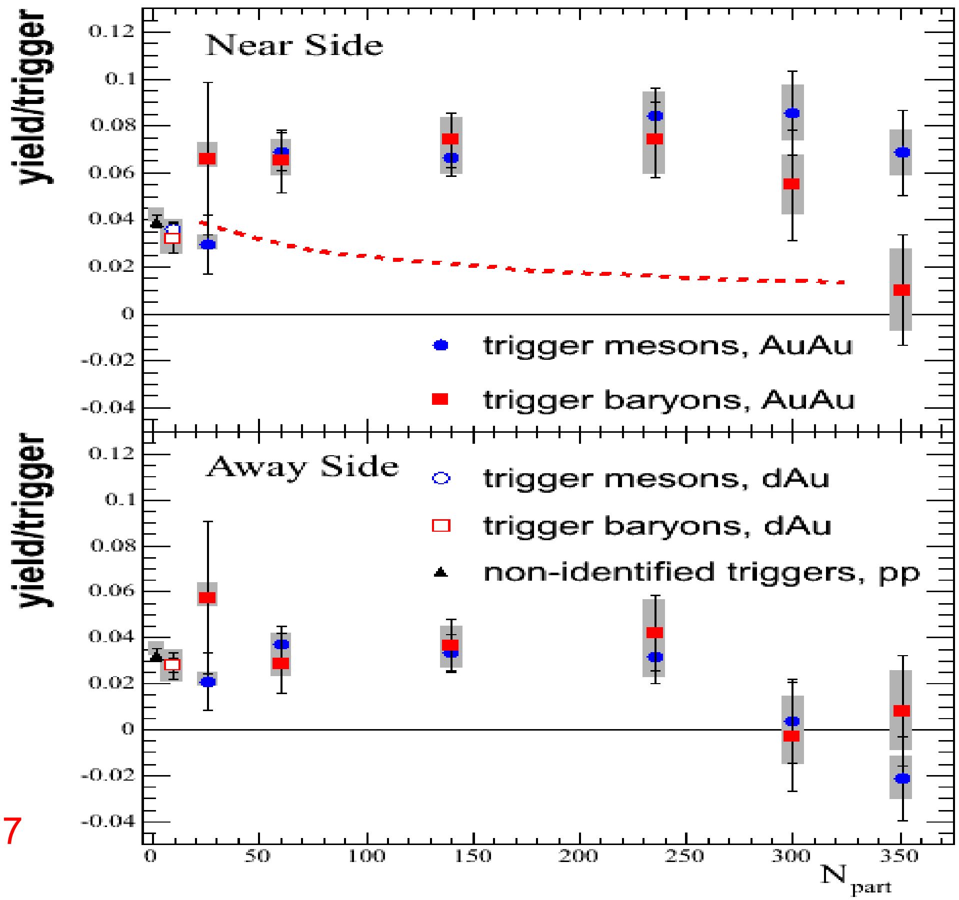


[F.Wang, QM'04]

- Associated near-side jet yields unmodified (pp ~ AuAu)
- Associated away-side jet yields "shifted down" in p_T: spectra closer to pure "soft" inclusive hadron production ("thermalized")

"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
$p_{T assoc}$ = 1.7 – 2.5 GeV/c

Near-side

Away-side

PHENIX
nucl-ex/0408007

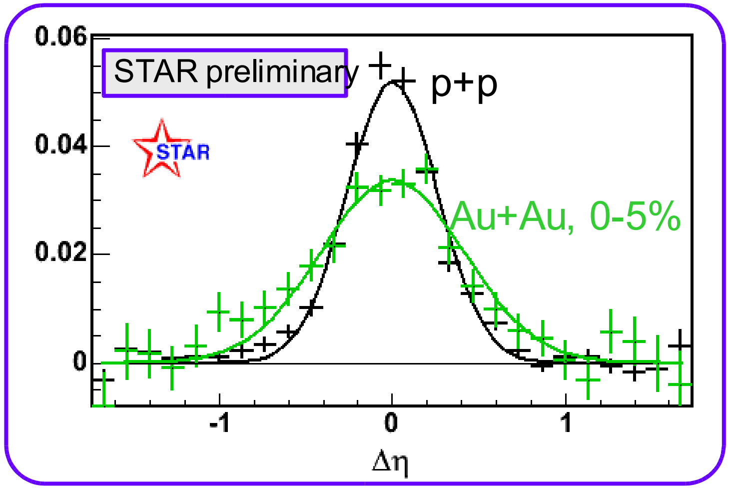
- Associated yields similar for meson & baryon triggers (perhaps weak reduction for baryons in very central collisions).
- Slight increase of associated near-side jet yields in mid-central AuAu.
- Jet-like production but different suppression for leading baryons and mesons !?

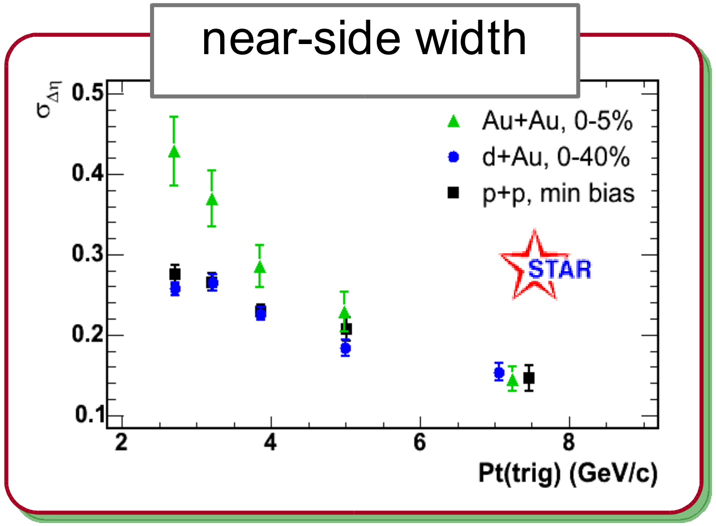
“Fragmentation functions”: AuAu (200 GeV)

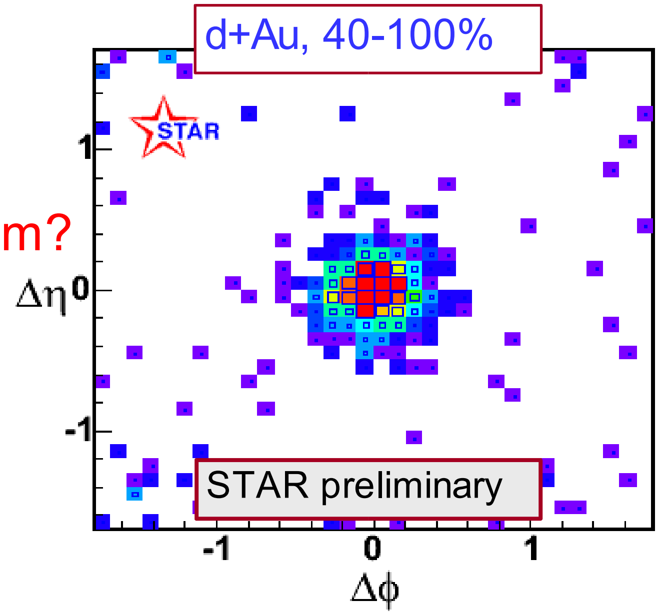
- Associated near- and away-side baryon&meson yields:

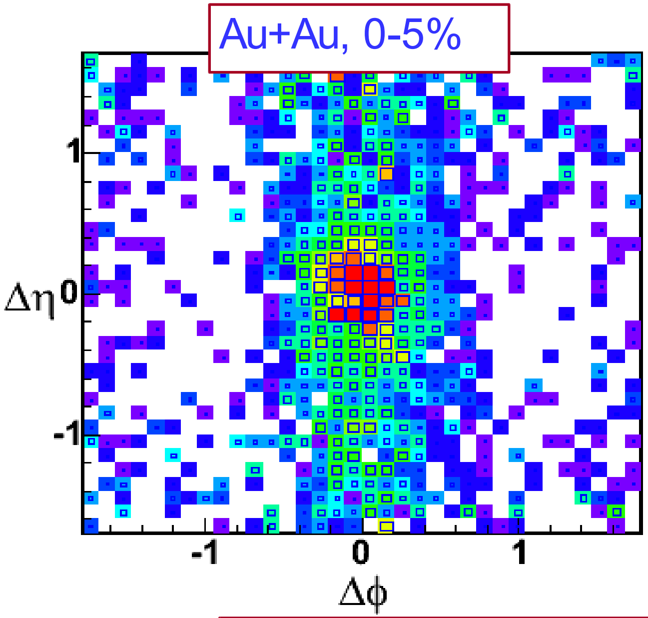
Dihadron Δη correlations: AuAu (200 GeV)

- Significant broadening of pseudo-rapidity correlations in AuAu compared to pp,dAu. ("stretching" of jet cone along η).
- Coupling of *g* radiation w/ longitud. expanding medium?









[D. Magestro, HP'04]

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

Summary

Summary: "Jet quenching" at RHIC

- Results I: Leading hadron production in pp, dAu, AuAu @ RHIC:

  - Strong (factor ~5) high p_T suppression in central AuAu: p_T-, sqrt(s)- dependence consistent with parton energy loss in dense QCD medium ($dN^g/dy \sim 1100$).

  - Reaction-plane dependence of the suppression provides additional constraints to the path-length dependence of the energy loss.

- Results II: Jet production in QCD vacuum (pp) & cold QCD medium (dAu):

  - Small differences on the extracted properties (j_T, k_T) of the jets emitted in pp & dAu
  - Relatively small initial state effects (multiple scattering) in cold nuclear matter.

- Results III: Jet production in a hot & dense QCD medium (AA):

  - Away-side disappearance consistent with:

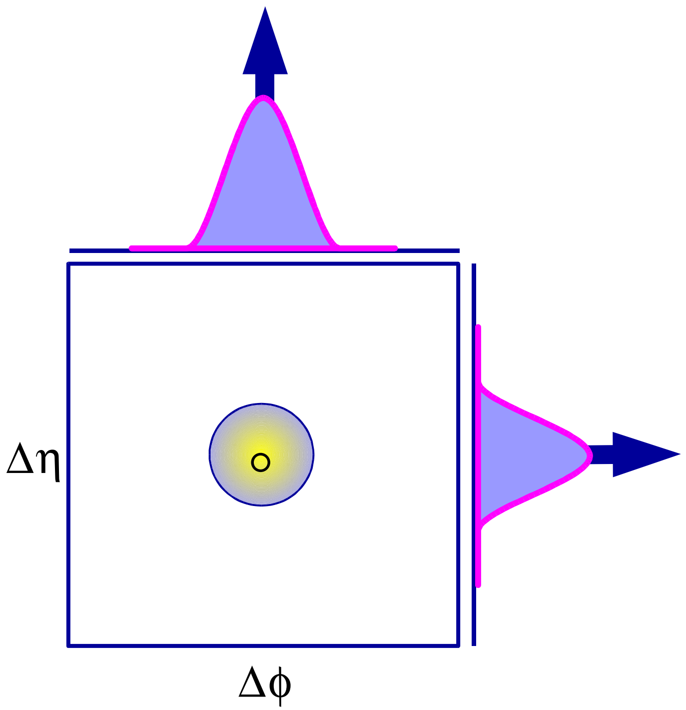
    (i) "Mono-jet" predictions due to high-energy parton "absorption" in dense QCD matter. (enhanced suppression following line of longest path).

    (ii) Large broadening of di-jet acoplanarity ($k_T \sim 3$ GeV/c) due to multiple scattering of away-side parton in the medium. (Can we extract a transport coeffic. consistent w/ the observed dN^g/dy ?).

  - Unmodified near-side azimuth. jet properties (j_T): Vacuum fragm. of unquenched trigger had.
  - No strong flavor dependence at intermediate p_T observed
  - Dihadron eta correlations consistent w/ coupling of *g* rad. w/ longitud. expand. medium

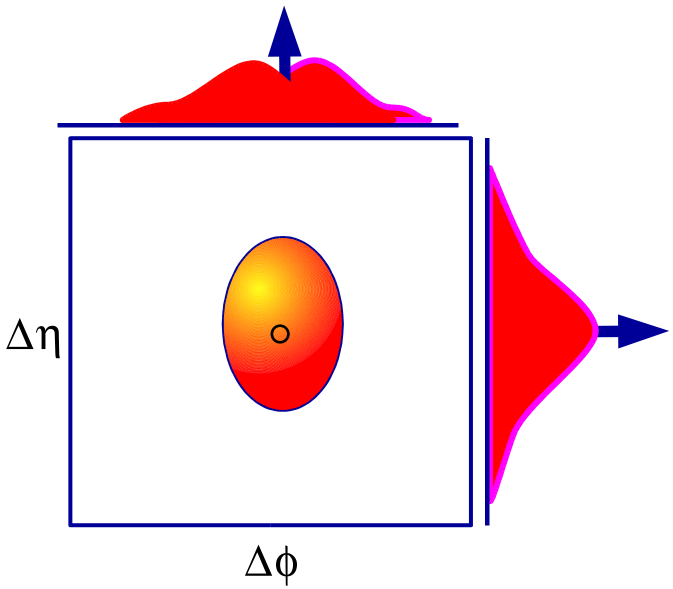
"Cartoon summary": Jet-quenching at RHIC

- 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.
(Increased) dijet acoplanarity: $\langle k_T \rangle \sim 3$ GeV/c
"Thermalized" associated low p_T yields
Dijet broadening in eta.

- ... and exciting jet-physics expected at LHC: γ-, Z-, jet-jet correlations

Backup slides

“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*

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

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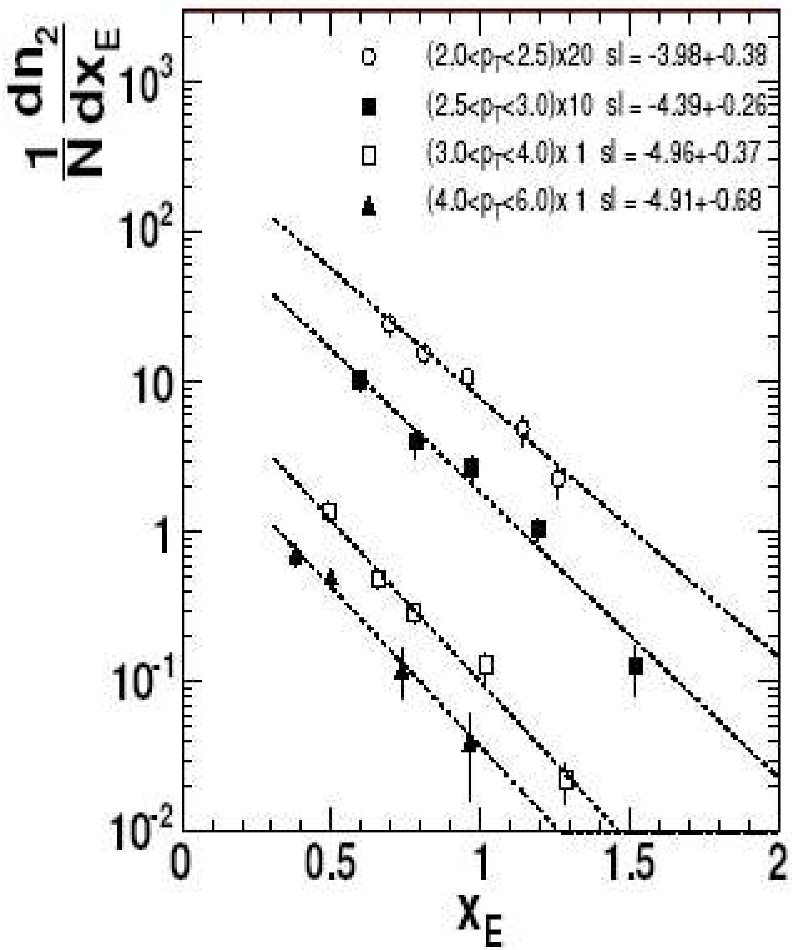
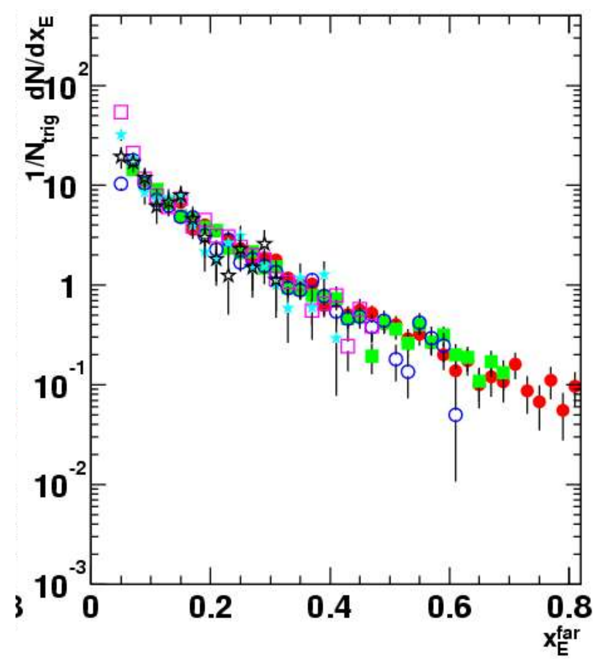
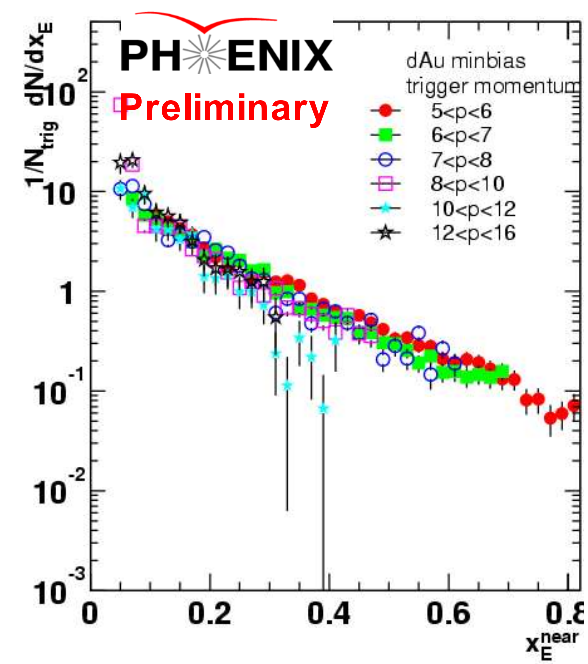




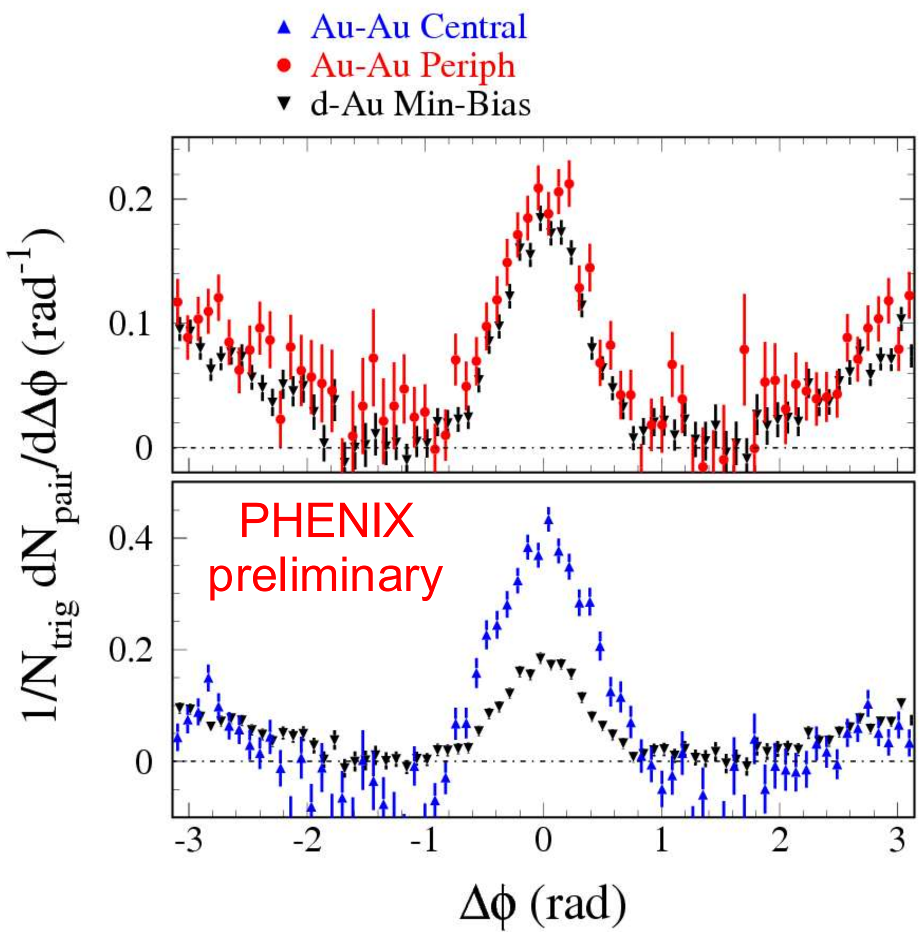


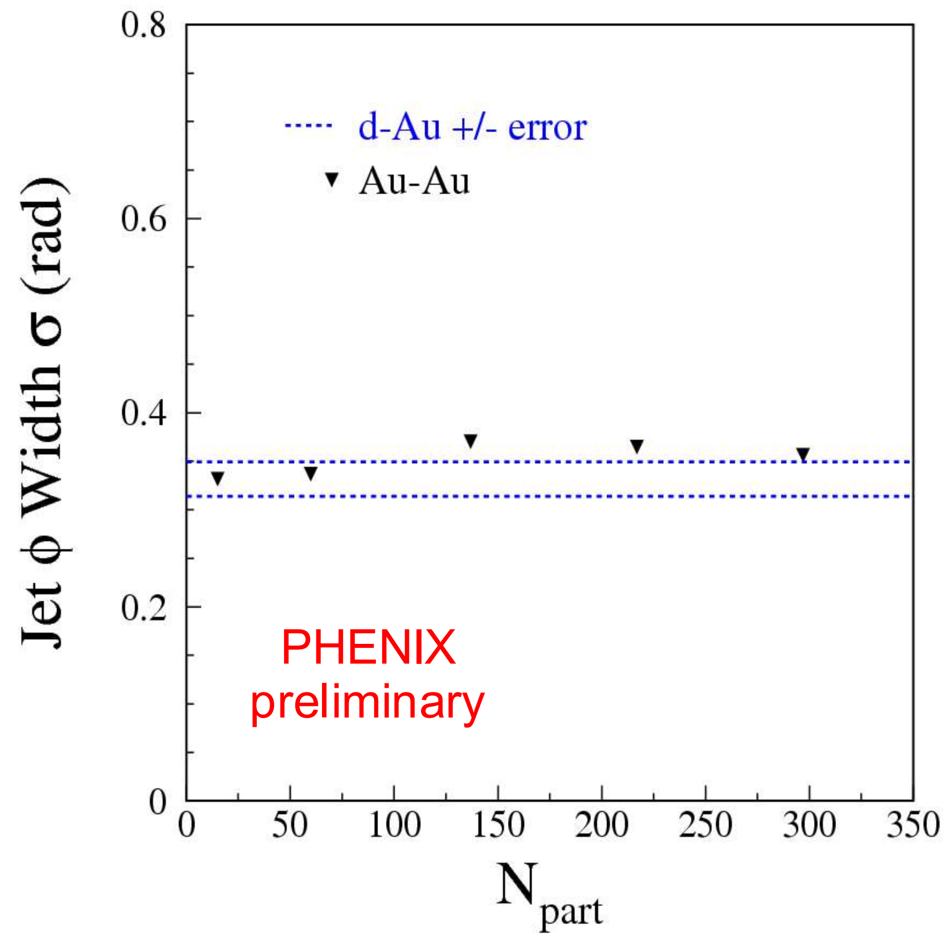
PHENIX

J. Jia

Dijets via dihadron azimuthal correlations: AuAu

- $2.5 < p_T^{trig} < 4$ GeV/c, $1.0 < p_T^{assoc} < 2.5$ GeV/c
  - Additional associated yield in same jet in Au+Au
    - – But same angular width observed !!!





Summary

Jet production and fragmentation:

- Good agreement of the jet properties in pp collisions with other lower s experiments
- dAu j_T and k_T consistent with pp
- In AuAu significant broadening of "effective" k_T - with centrality

- Back-to-back correlations
- Suppression of away-side jet → jet quenching picture
- Suppression dependent on reaction plane orientation
- No strong flavor dependence at intermediate p_T observed
- Near-side correlations
- Evidence for near-side jet broadening in central Au+Au
-

High p_T central Au+Au vs p+p at midrapidity at RHIC:

(1) Inclusive spectra suppressed by a factor of 4-5 at 200 GeV and by a factor of ~3 at 62.4 GeV

(2): Intermediate p_T hadron composition inconsistent with known fragmentation functions in free space.

(3) Disappearance of away-side jet correlations. Enhanced mono-jet pattern following line of longest path.

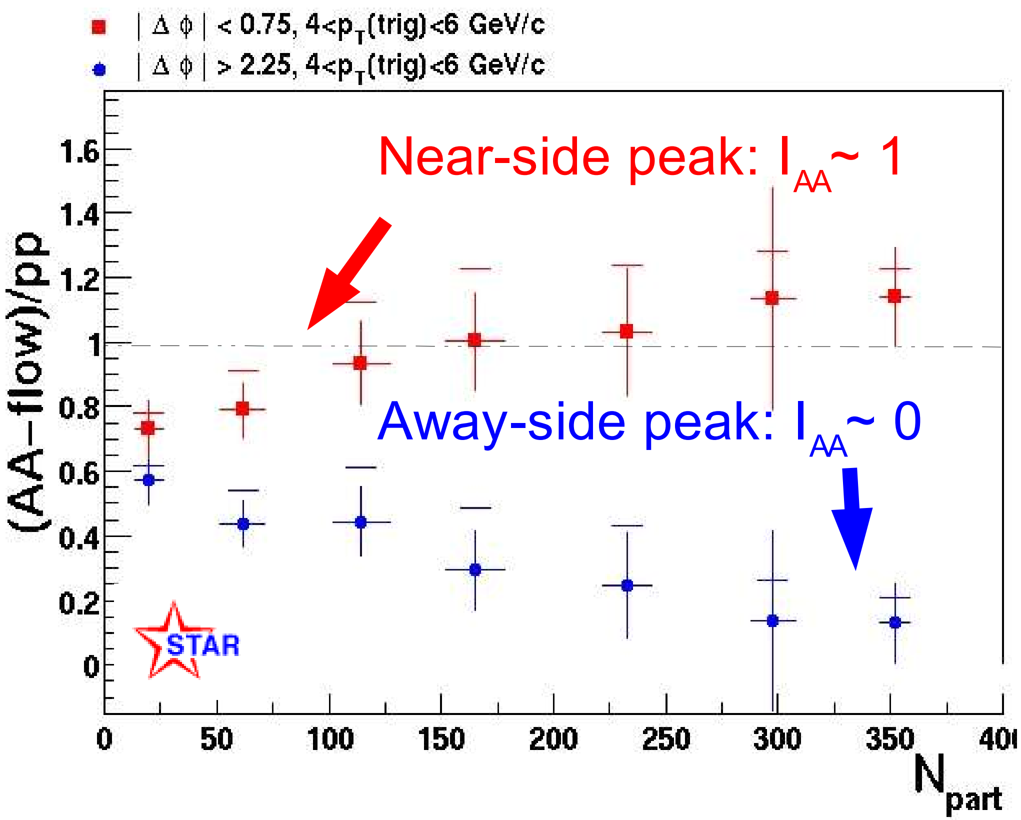
High p_T in d+Au at forward rapidities at RHIC:

(5) Spectra suppressed by a factor ~2

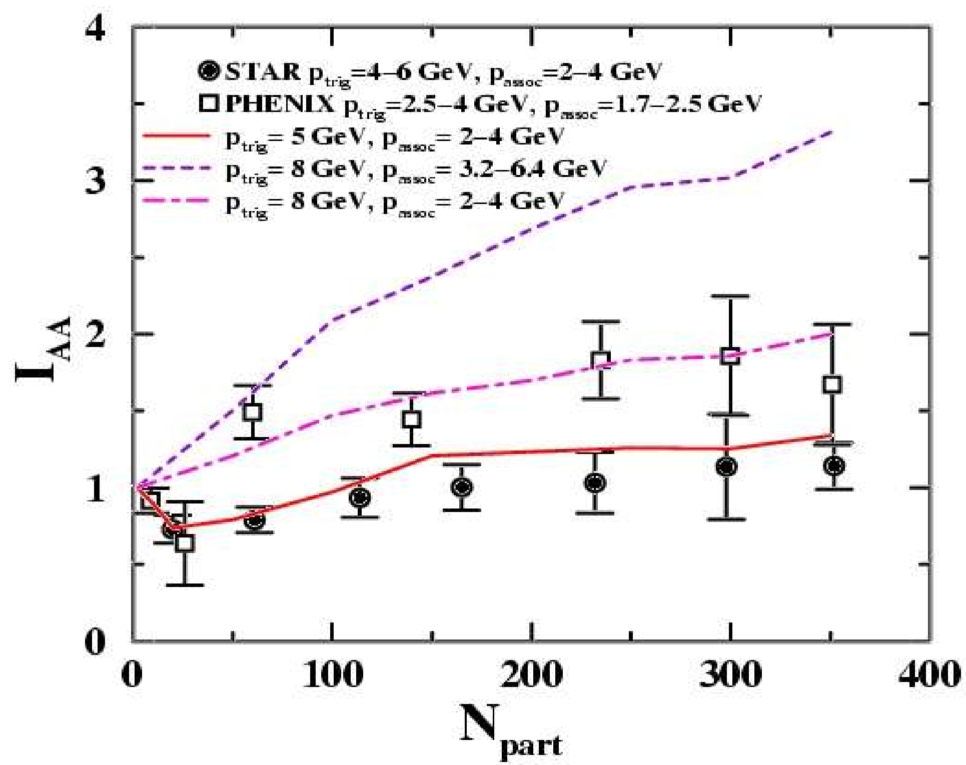
Dihadron azimuthal correlations: AuAu "mono-jets"

- 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]

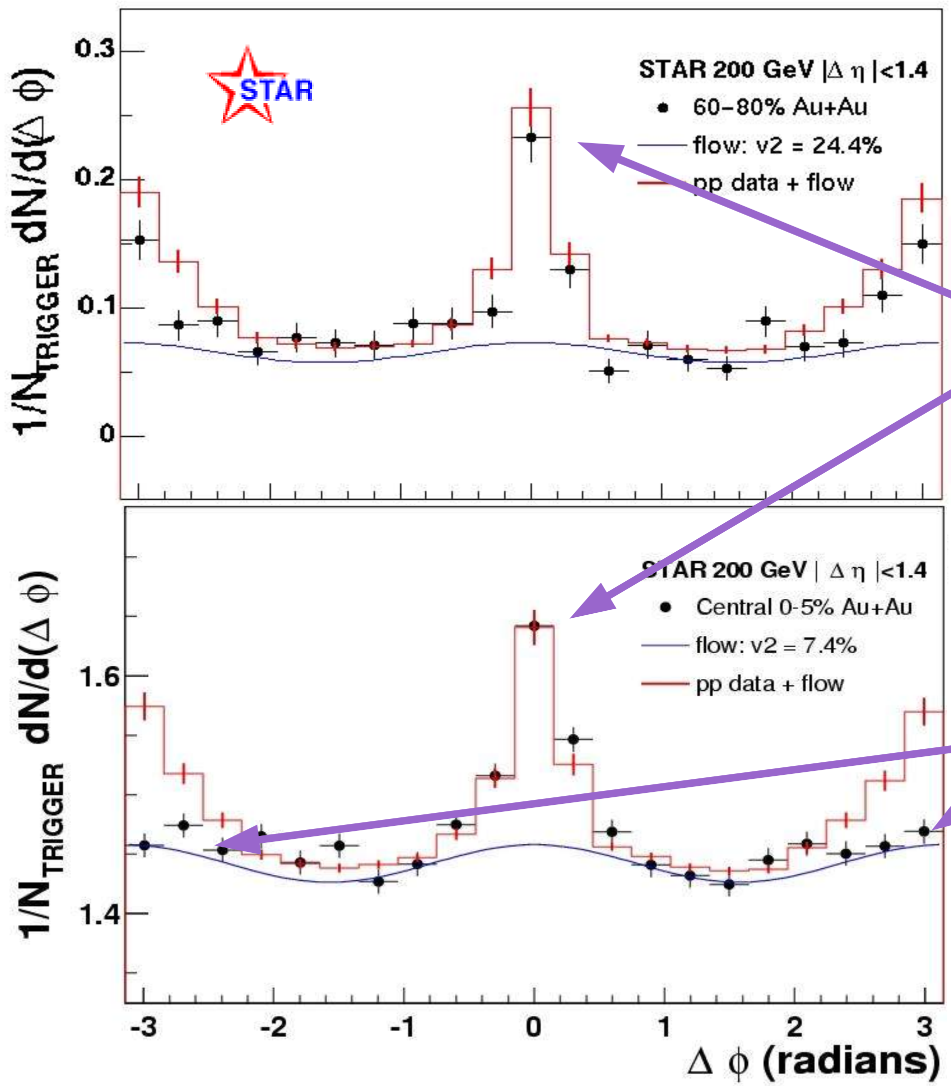
Dijets via dihadron azimuthal correlations: AuAu

- .. $dN_{pair}/d\Delta\phi$ for "trigger" (p_T > 4GeV/c) & associated (p_T = 2- 4 GeV/c) charg. hadrons:

Red histogram: p+p (+flow)
Black points: Au+Au
Blue curve: flow contribution

Periph.:

Central:

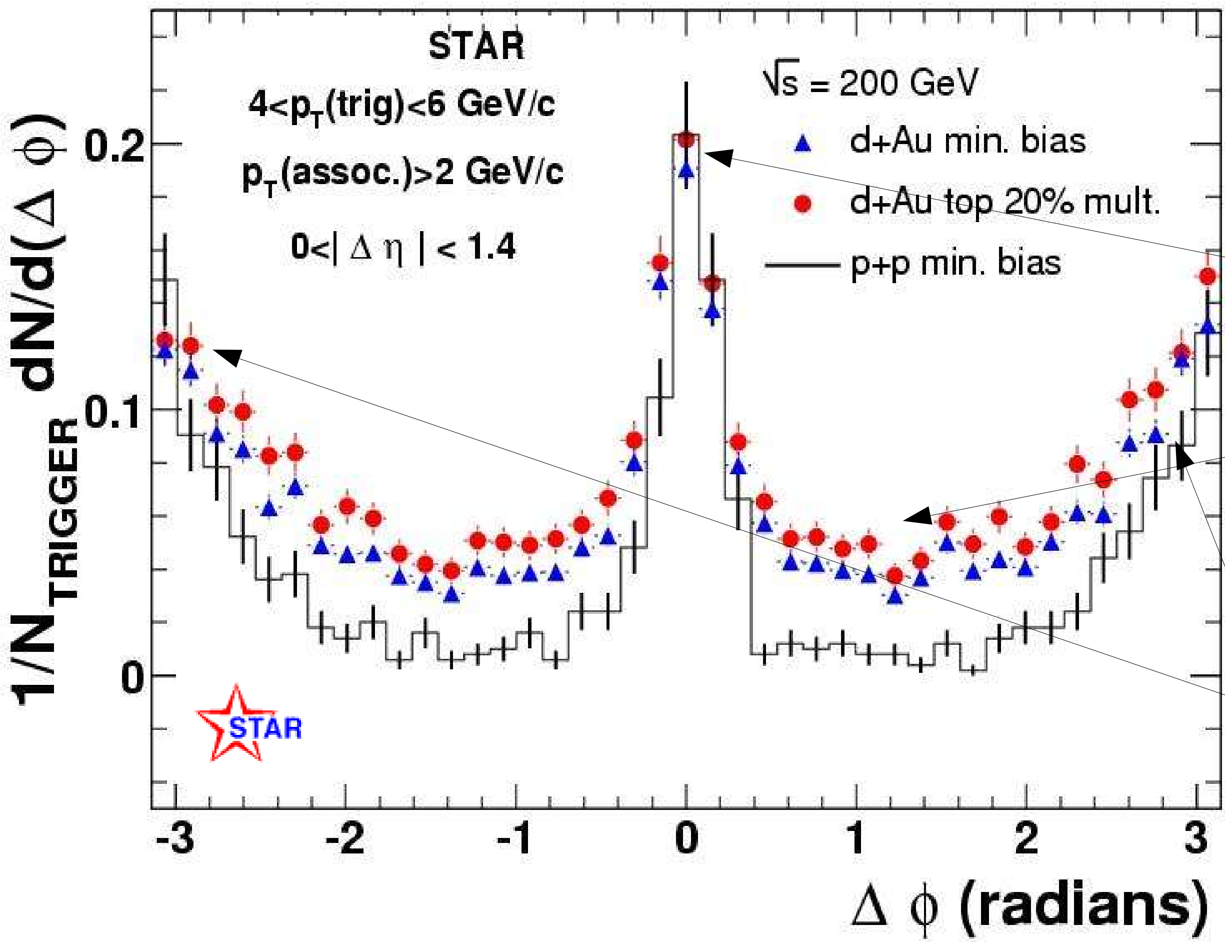


- Near-side peak: Au+Au = p+p.
  Trigger hadrons (p_T > 4GeV/c) from jet fragmentation.

- Away-side peak: Au+Au << p+p
  Back-to-back jets suppressed ("mono-jet") in central Au+Au !

High p_T azimuthal correlations: jets in dAu, pp

- ..

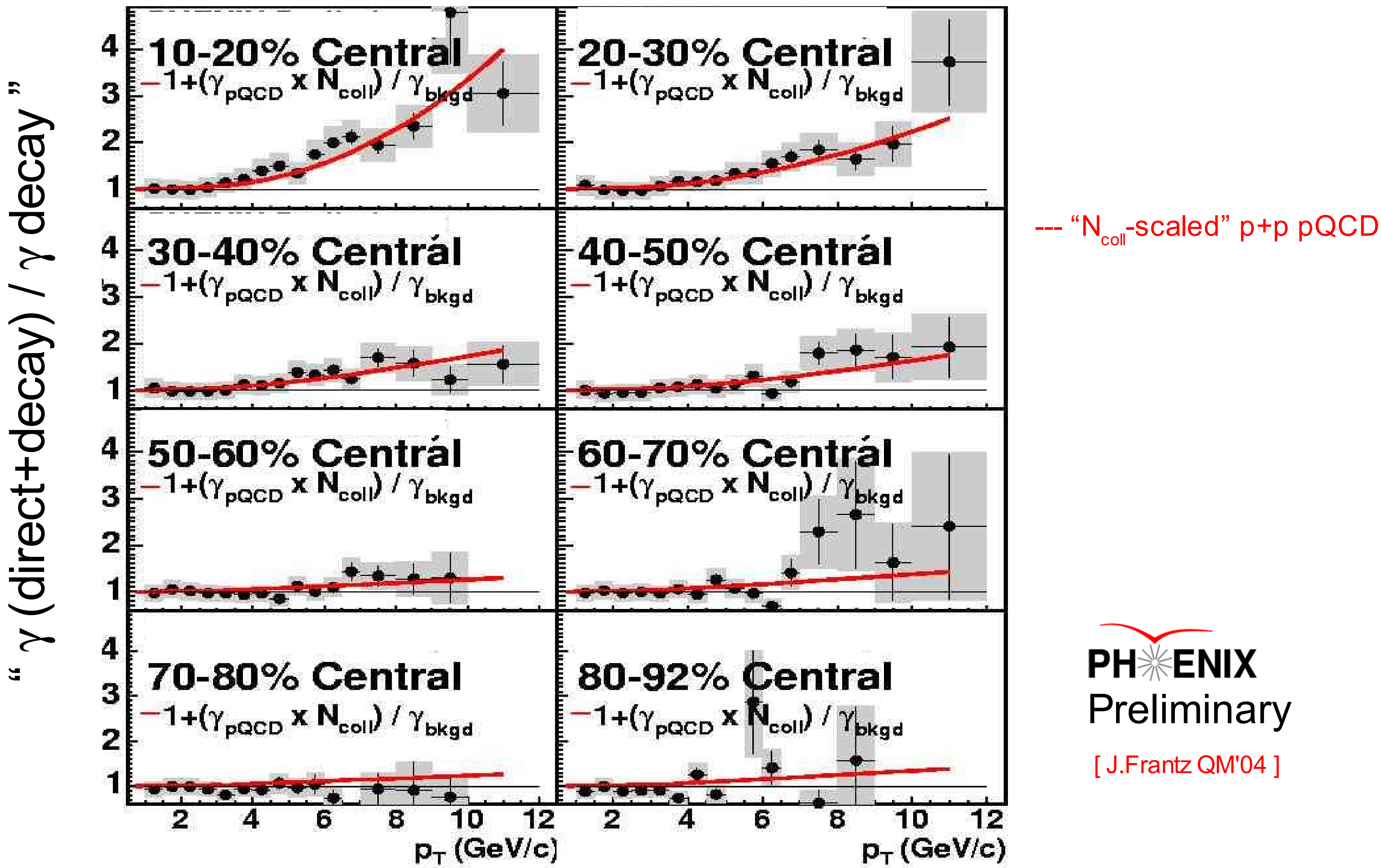


- Near- side: d+Au correlation strength and width similar to p+p (& Au+Au)
- Increasing "underlying event": p+p<d+Au(m.bias)<d+A(central)
- Away-side: d+Au peak broadens but small centrality dependence

- Back-to-back jets do not disappear in central d+Au !

"N_{coll} scaling" in Au+Au @ 200 GeV: Direct Photons

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

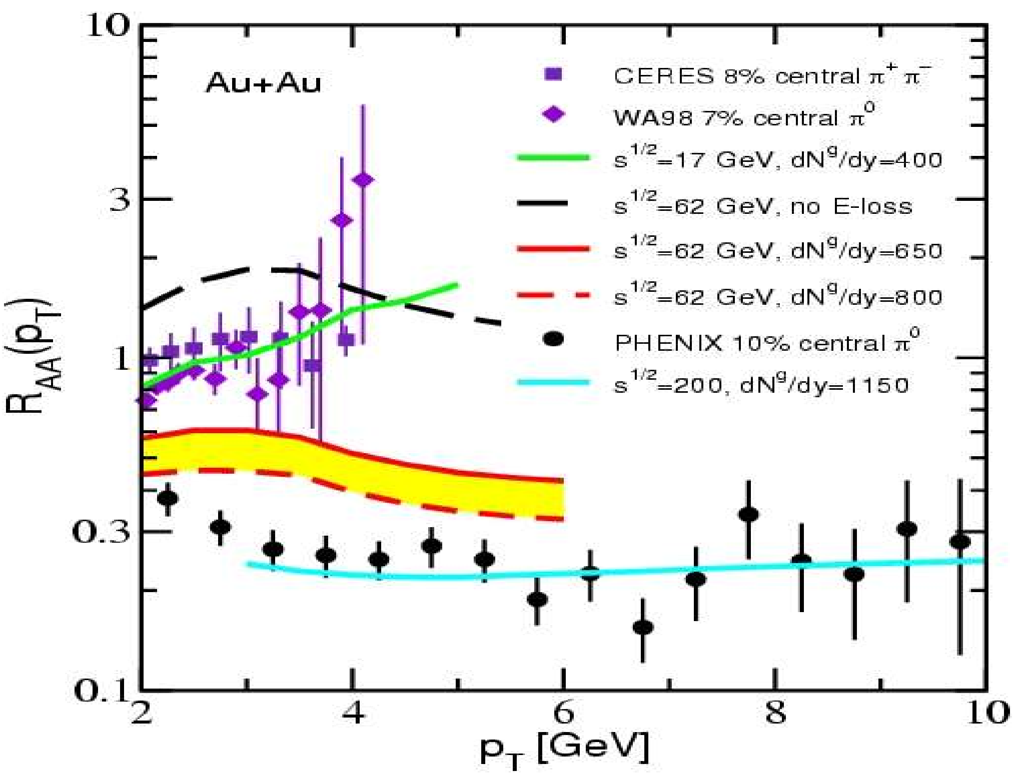


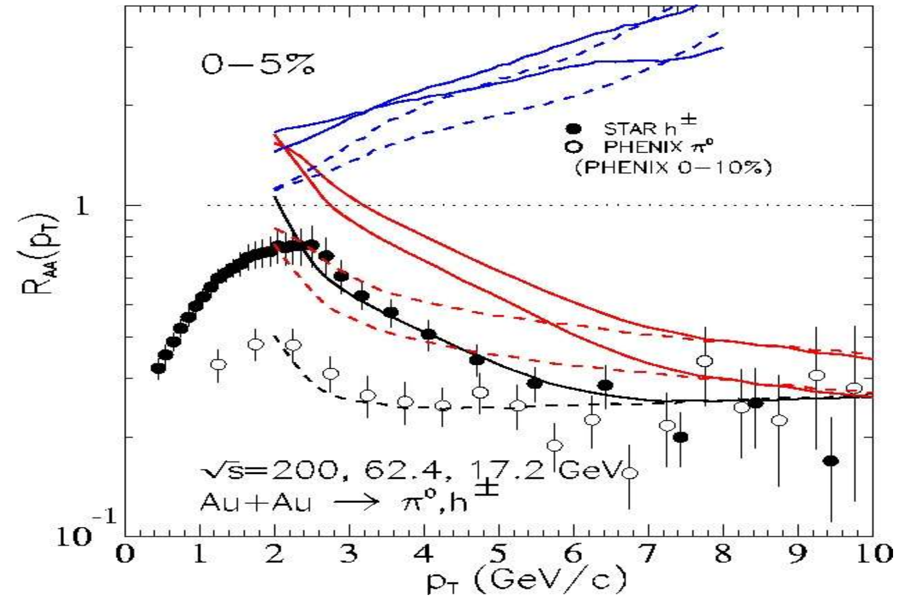
[J.Frantz QM'04]

Au+Au @ 62.4 GeV (central): suppression predictions

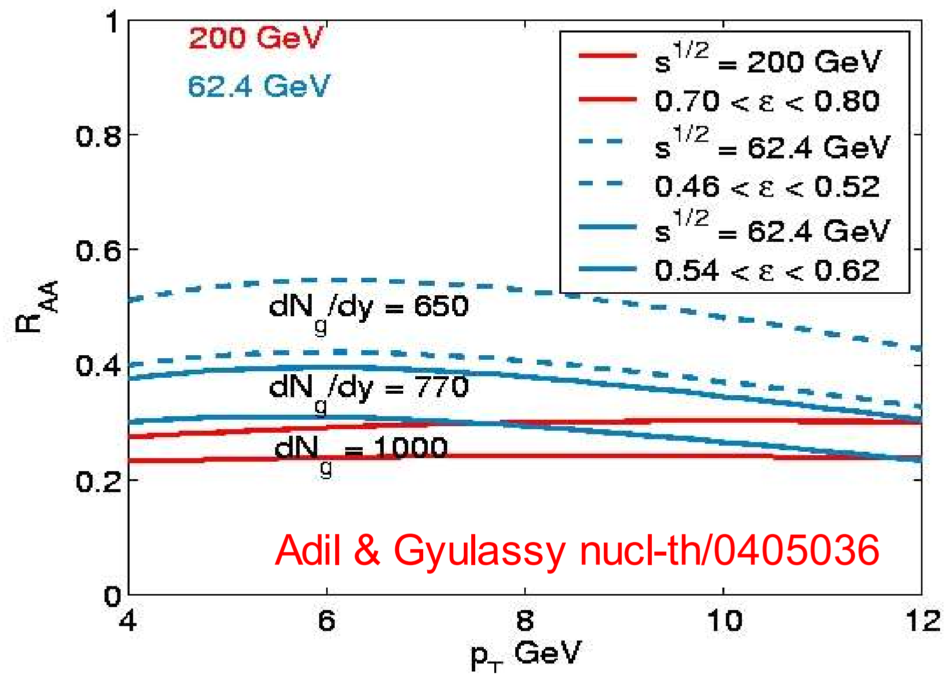
R_{AA} (π^0) ~ 0.5 - 0.3

I. Vitev nucl-th/0404052



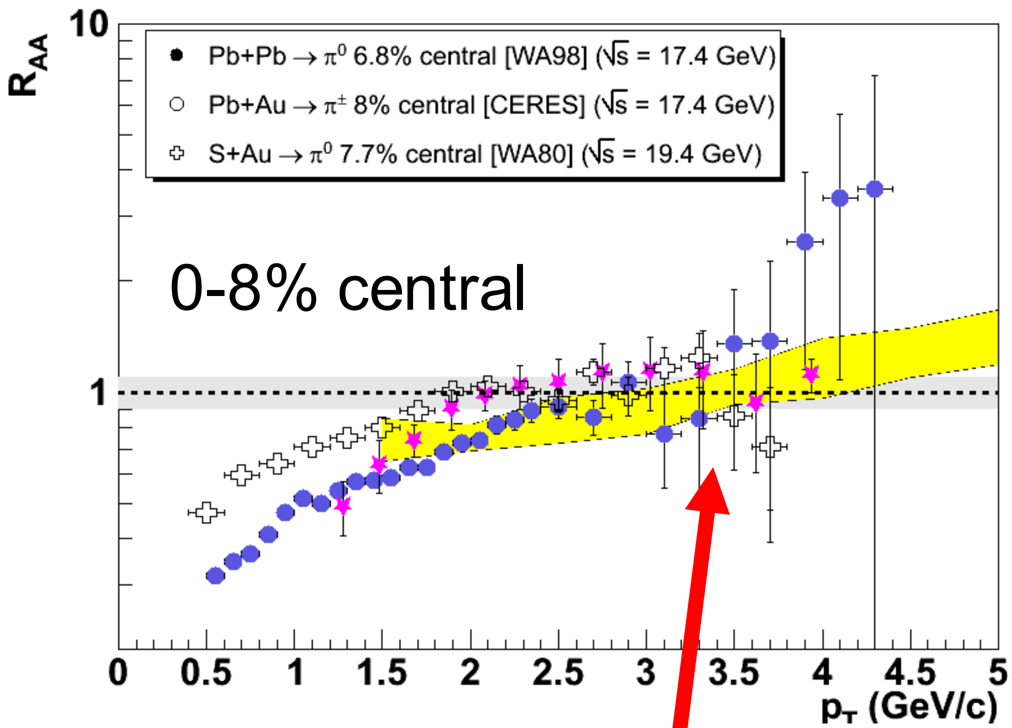


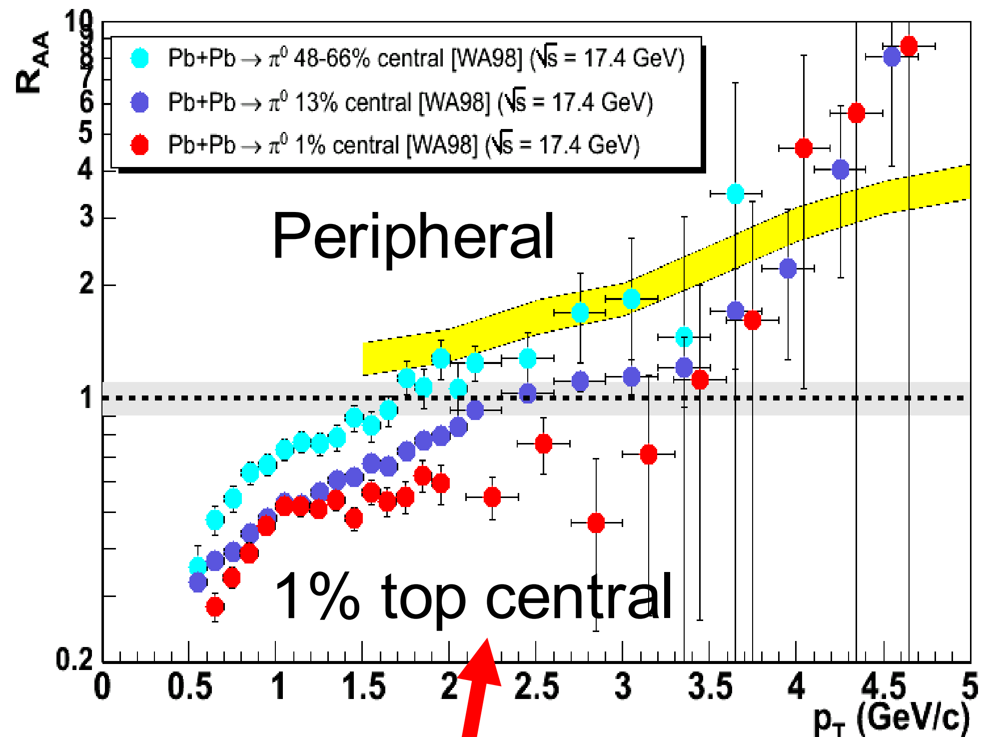
X.N. Wang nucl-th/0405029



High p_T @ CERN-SPS: "Cronin" or "quenching" ?

- New nuclear modification factor (better p+p → π^0 ref. @ $\sqrt{s_{NN}}$ = 17.3 GeV)



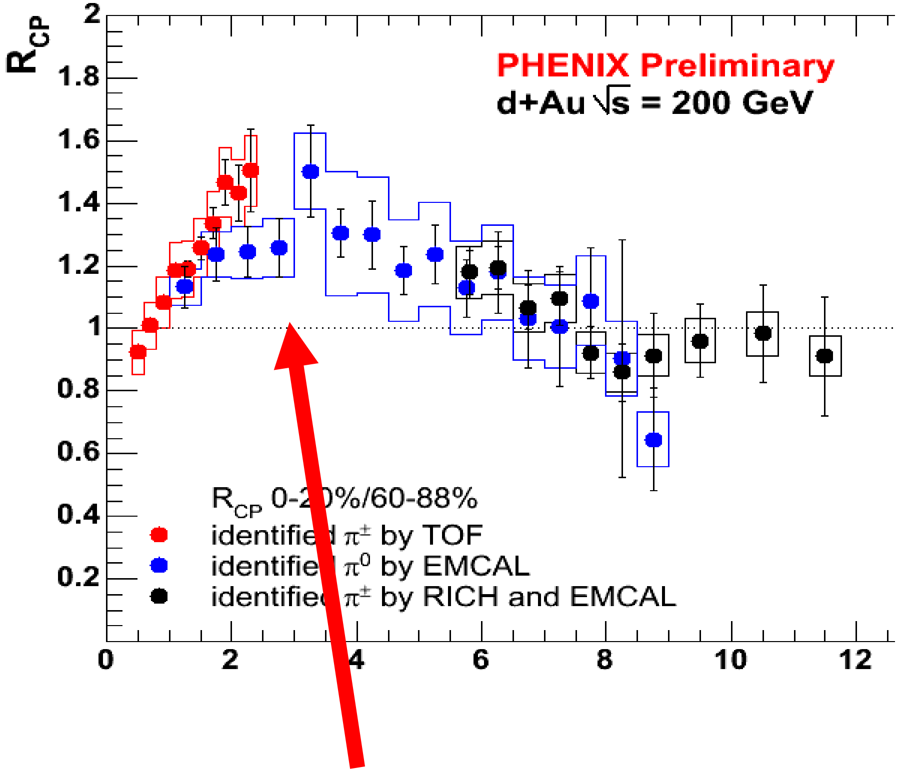


[D.d'E. to be submitted]

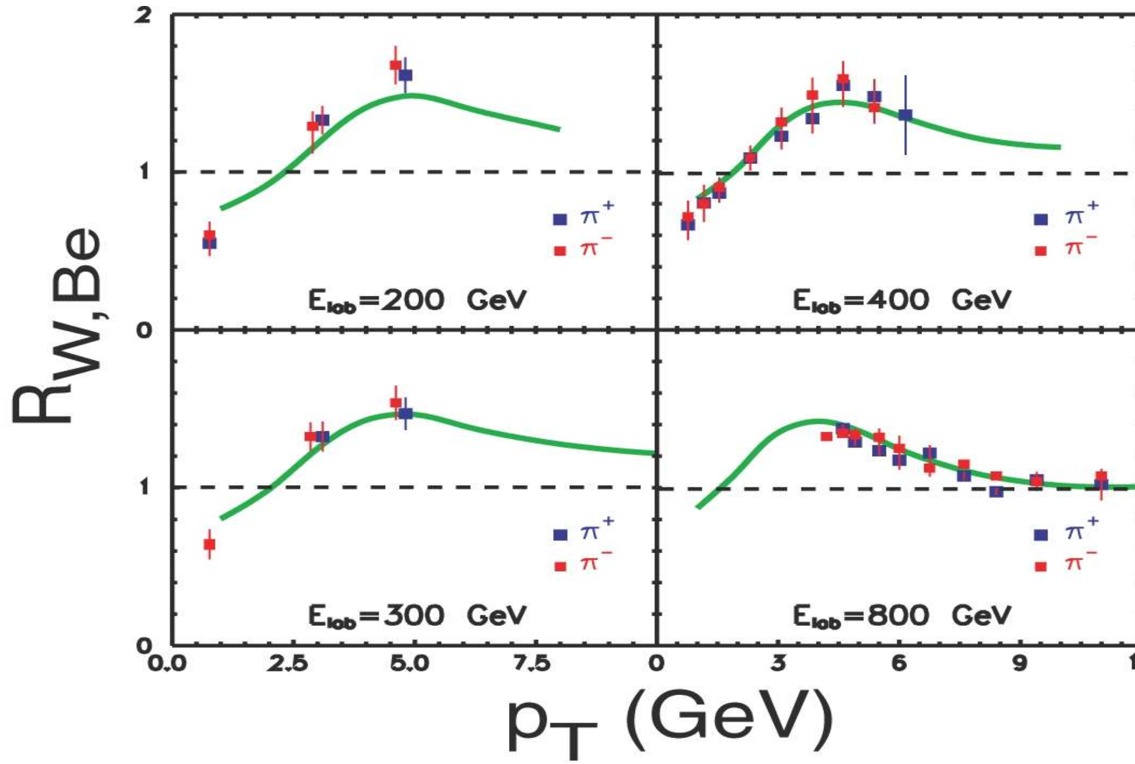
- No "Cronin" effect in central collisions (R_{AA} ~ 1).
- "Cronin" enhancement in peripheral ... and suppression in top central ?
- Look for onset of suppression at RHIC Au+Au, p+p @ $\sqrt{s_{NN}} \approx$ 20 GeV ?

d+Au nuclear modification factor (at y=0)

d+Au @ $\sqrt{s_{NN}}$ = 200 GeV



p+A @ $\sqrt{s_{NN}}$ = 20 - 40 GeV



- High p_T production in d+Au not suppressed but enhanced ! $R_{dAu} > 1$
  as in p+A "Cronin enhancement":
  p_T broadening due to initial-state soft & semihard scattering.
- "pQCD" cross-sections (R_{AA}~1) recovered at p_T > 8 GeV/c
- No Au shadowing effects in kinematic region probed (y= 0).