Jet quenching au RHIC: résultats expérimentaux

Journée thématique "Jet quenching"

IPN-Orsay, November 14th, 2005

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LLR – Ecole Polytechnique, IN2P3, Paris

Overview

- "Jet physics" results @ RHIC (w/o full jet reco):

  (1) Inclusive high p_T spectra, (2) di-hadron φ,η high-p_T triggered correlations.

  confronted to non-Abelian radiative energy loss in QGP "paradigm".

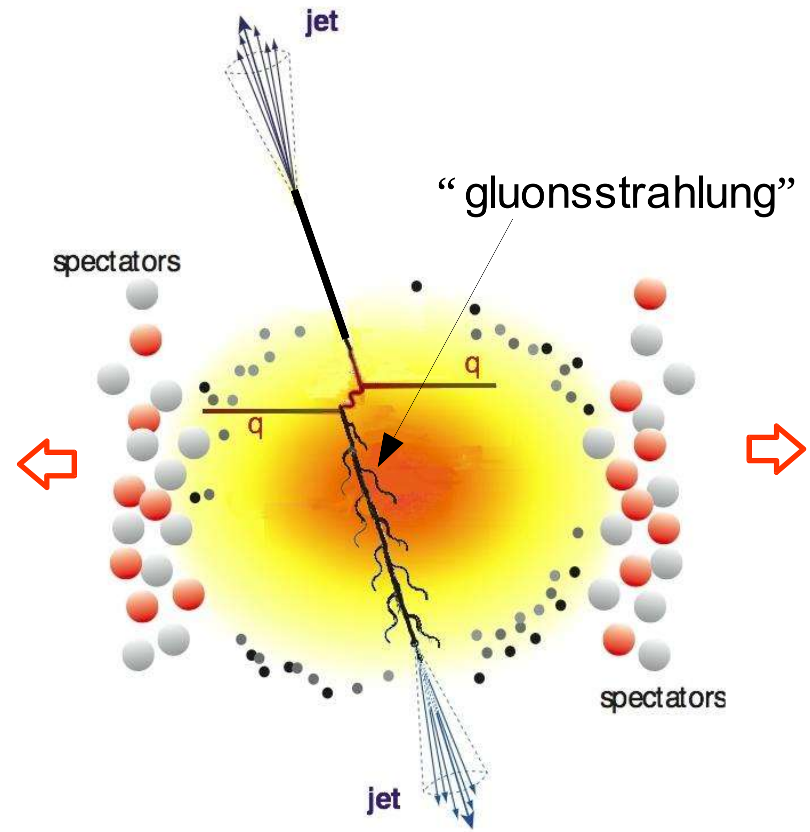
- High p_T (leading) hadron suppression data in central AA:

  1. Magnitude ⇒ Very dense medium: dN^g/dy ~ 1000 (~ $dN_{ch}/d\eta$). **OK**
  2. Transverse momentum dependence: flat p_T . **OK**
  3. Centrality dependence. **OK**
  4. Light-meson species dependence (π^0 vs. η). **OK**
  5. Center-of-mass energy dependence (SPS-20 GeV, RHIC-62,200 GeV). **OK**
  6. Non-Abelian radiation. **OK**
  7. Path-length dependence. **OK ?**
  8. System-size (CuCu vs. AuAu) dependence. **OK ?**
  9. Heavy vs. light quark suppression. **OK ?**

- Modified high p_T di-hadron (φ,η) correlations in central AA:

  1. Disappeareance of away-side azimuthal dijet peak. **OK**
  2. Enhanced ("volcano"-like) away-side associated yield at lower p_T. **(?)**
  3. Broadening of near-side pseudo-rapidity correlations. **OK**

"Jet quenching" as a QGP signal



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

- Parton energy loss ∝ medium properties:

GLV: $\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp}\frac{dN^g}{dy} L \propto$ (g density, L)

BDMPS Wiedemann: $\langle \Delta E \rangle \propto \alpha_S C_R \langle \hat{q} \rangle L^2 \propto$ ($\hat{q}$ coeffic., L^2)

- Flavor dependent energy losses:

$\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

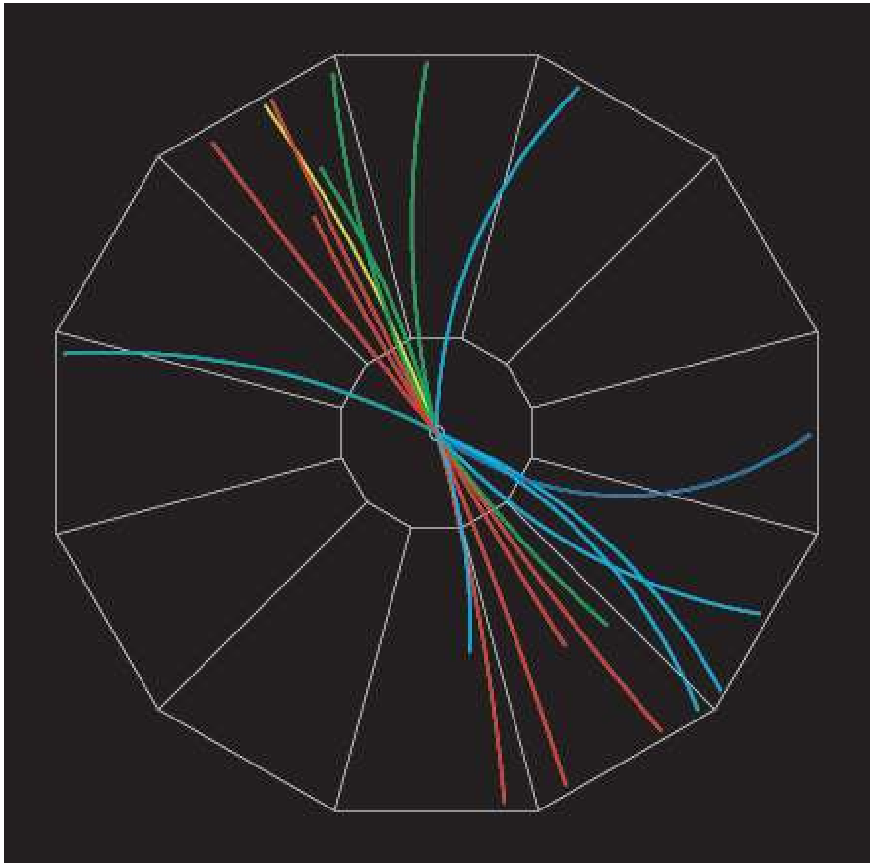
(color factor) (mass effect)

- Energy is carried away by gluons emittted inside (broader) jet cone: $dE/dx \sim \alpha_s \langle k_T^2 \rangle$

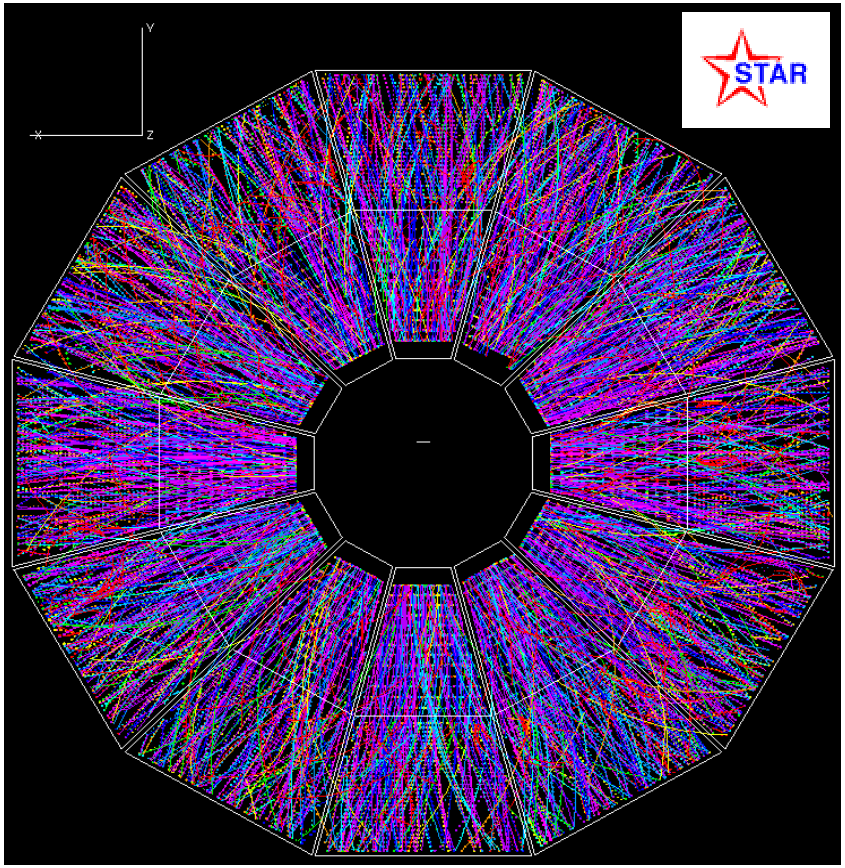
- Prediction I: Suppression of high p_T leading hadrons: dN/dp_T ◄ SPS,RHIC,LHC
- Prediction II: Modification of (di)jet correlations: $d^2N_{pair}/d\varphi d\eta$ ◄ RHIC,LHC
- Predition III: Modified energy- & particle- flow within full jet ◄ LHC

Jet physics at RHIC: experimental limits

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



p+p $\rightarrow$ jet+jet [$\sqrt{s}$ = 200 GeV]

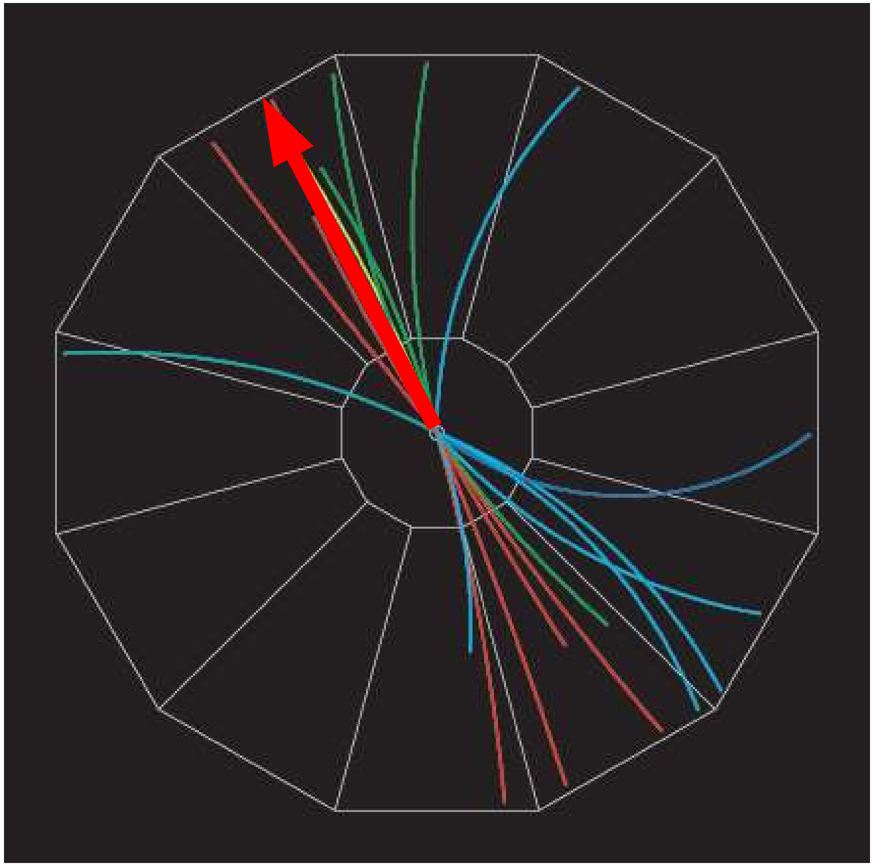


Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]

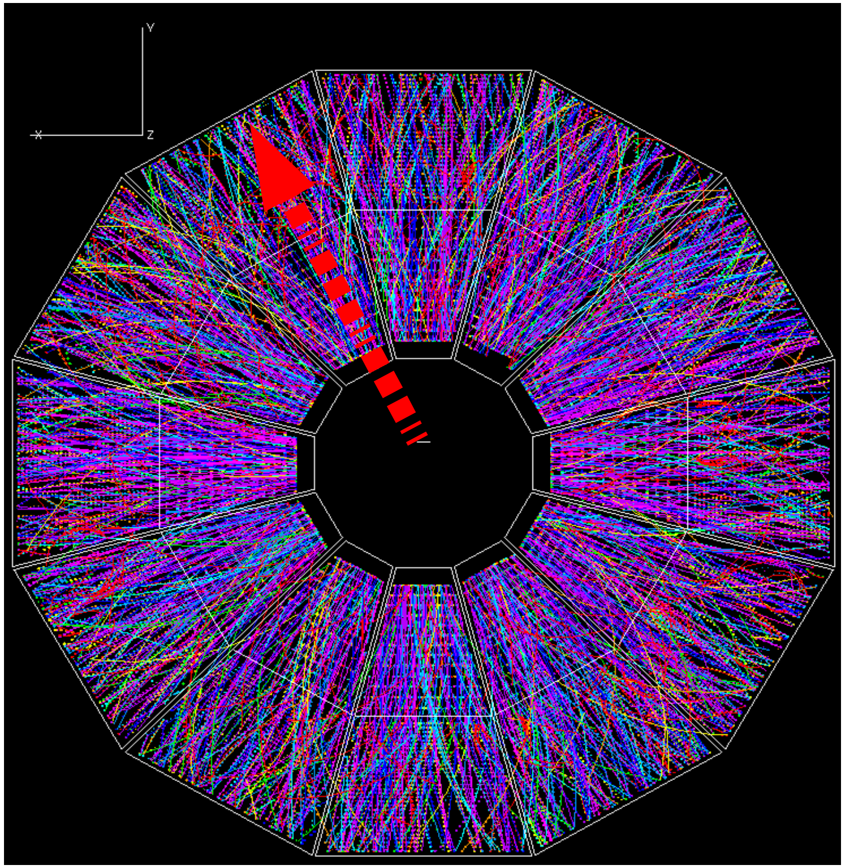
- Feasible at LHC for E_{jet} >~ 50 GeV

"Jet physics" at RHIC (I): Single inclusive high p_T spectra

- Alternative I : Study the energy modifications suffered by the highest p_T hadron in the event ("leading" hadron of the jet) in AA (compared to pp):



$p+p \rightarrow h+X$ [$\sqrt{s}$ = 200 GeV]

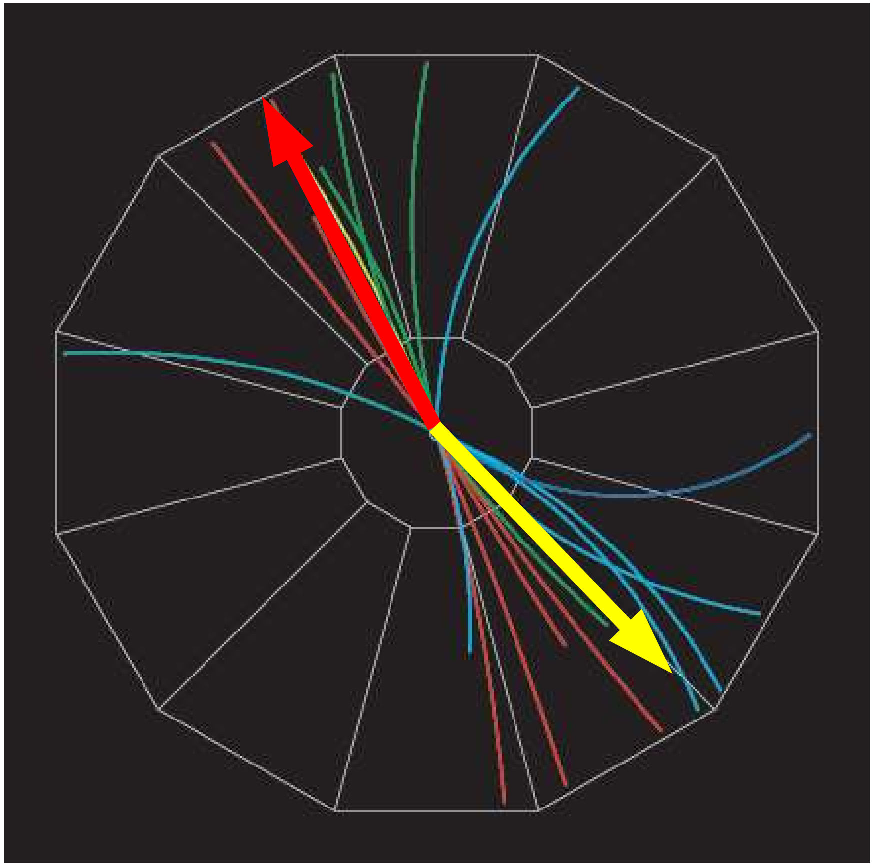


$Au+Au \rightarrow h+X$ [$\sqrt{s_{NN}}$ = 200 GeV]

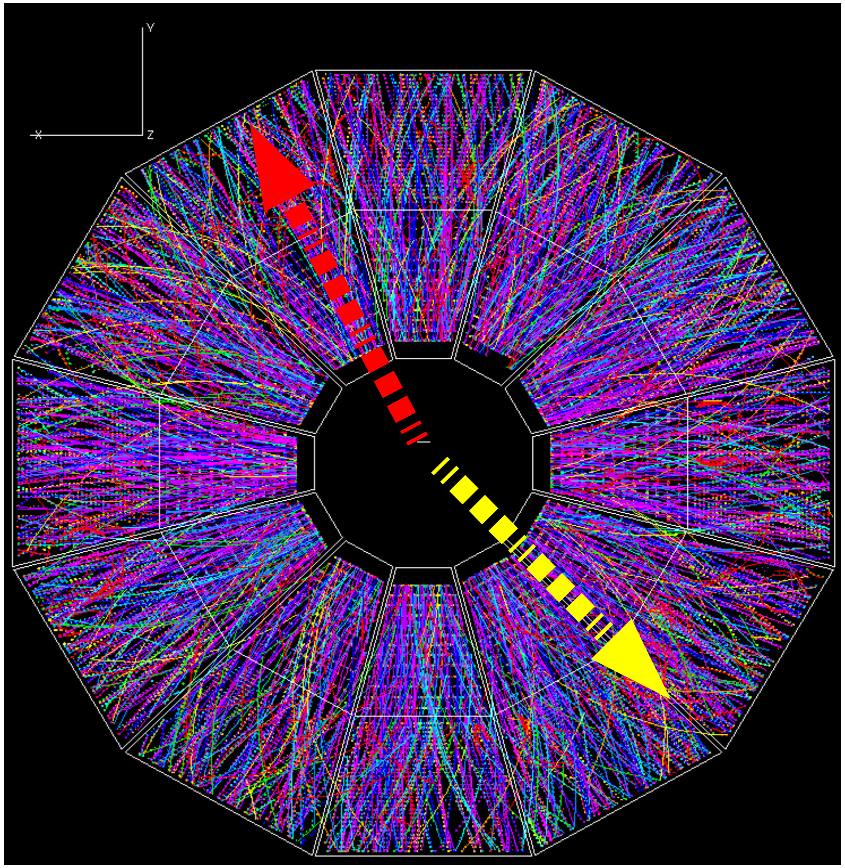
- Many interesting results obtained from this "first-order" approach !

"Jet physics" at RHIC (II): Di-hadron azimuthal correlations

- Alternative II : Study the azimuthal correlations in AA relative to pp between highest p_T hadron ("trigger") & any other "associated" hadron:



$p+p \rightarrow h_1+h_2+X$ [$\sqrt{s}$ = 200 GeV]



$Au+Au \rightarrow h_1+h_2+X$ [$\sqrt{s_{NN}}$ = 200 GeV]

"Jet physics" at RHIC (II): Di-hadron azimuthal correlations

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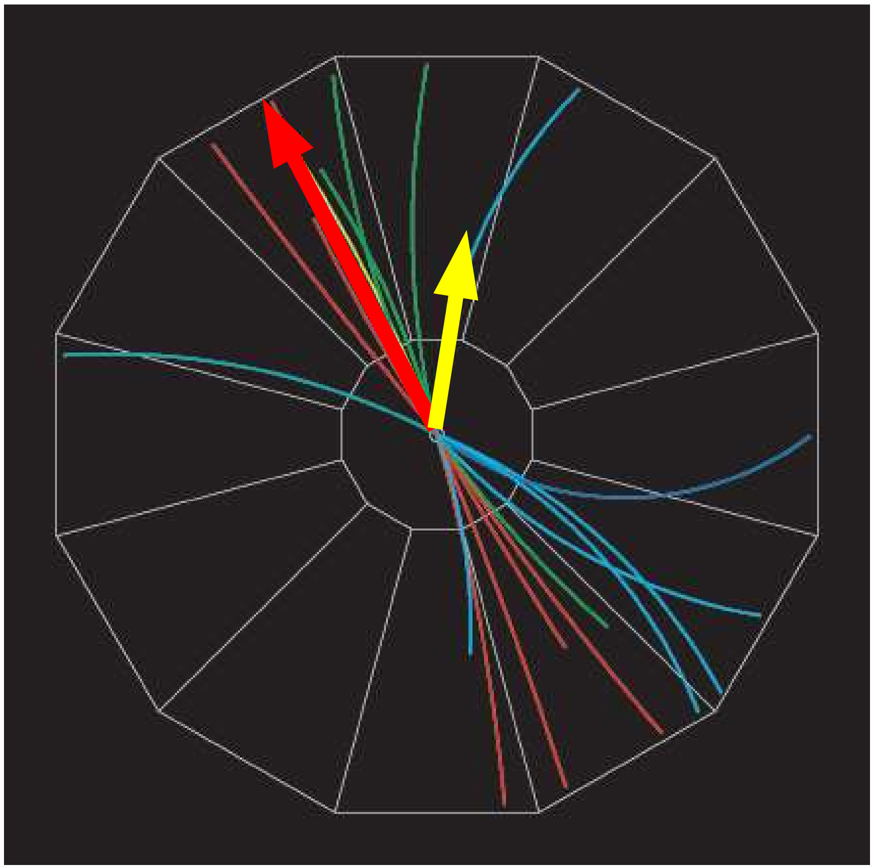
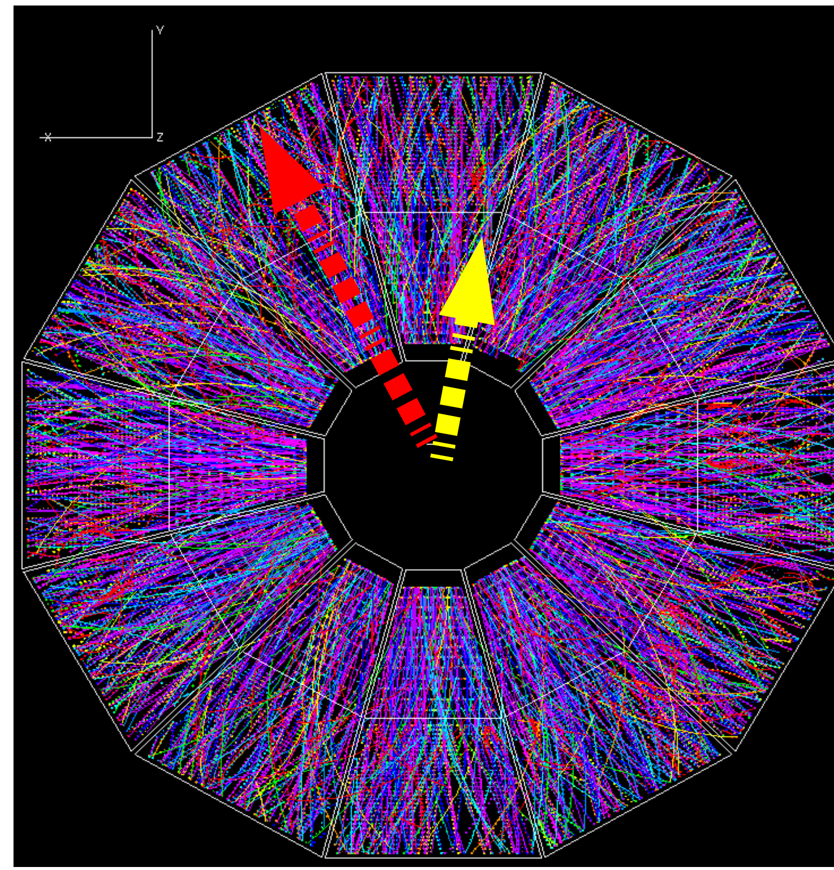


$p+p \rightarrow h_1+h_2+X$ [$\sqrt{s}$ = 200 GeV]



$Au+Au \rightarrow h_1+h_2+X$ [$\sqrt{s_{NN}}$ = 200 GeV]

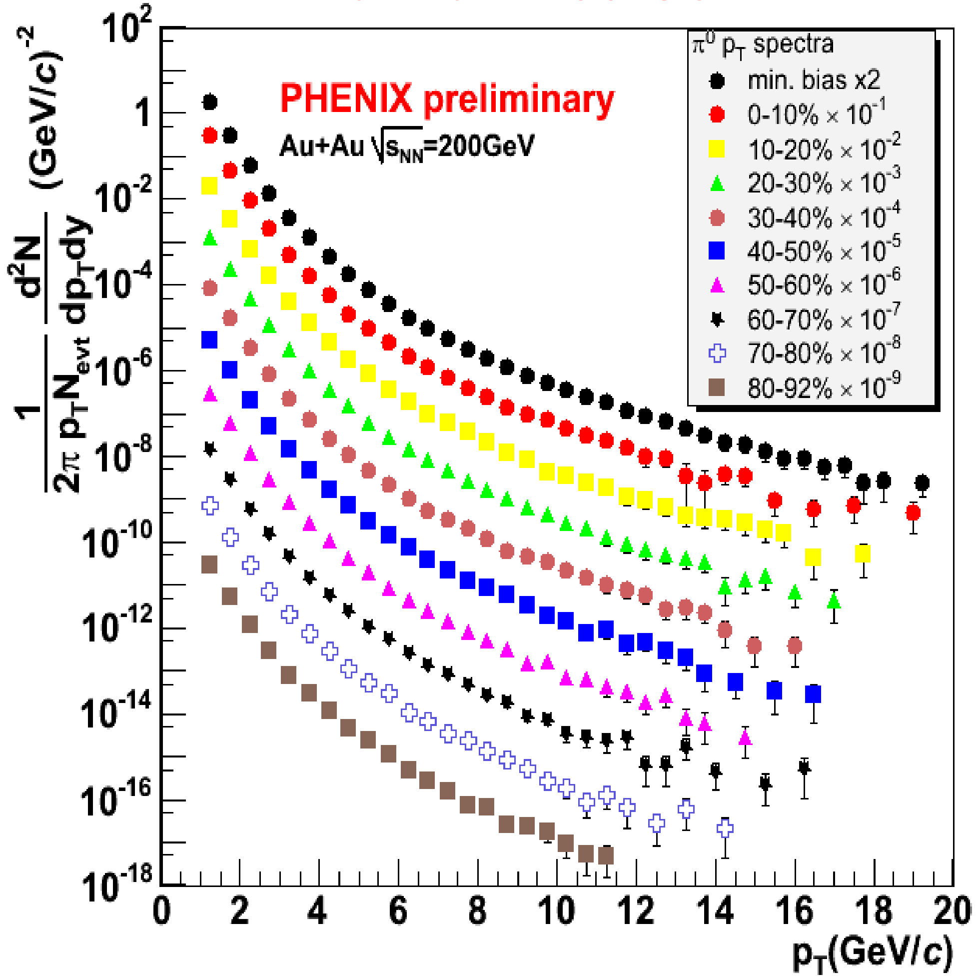
- Many interesting results also obtained from this "2nd-order" approach !

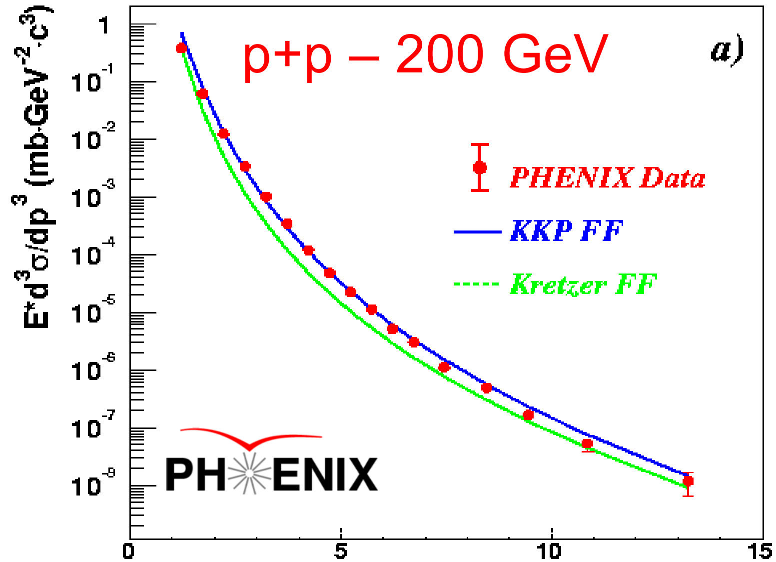
High p_T leading hadron spectra at RHIC & jet-quenching models: Good agreement data ↔ theory

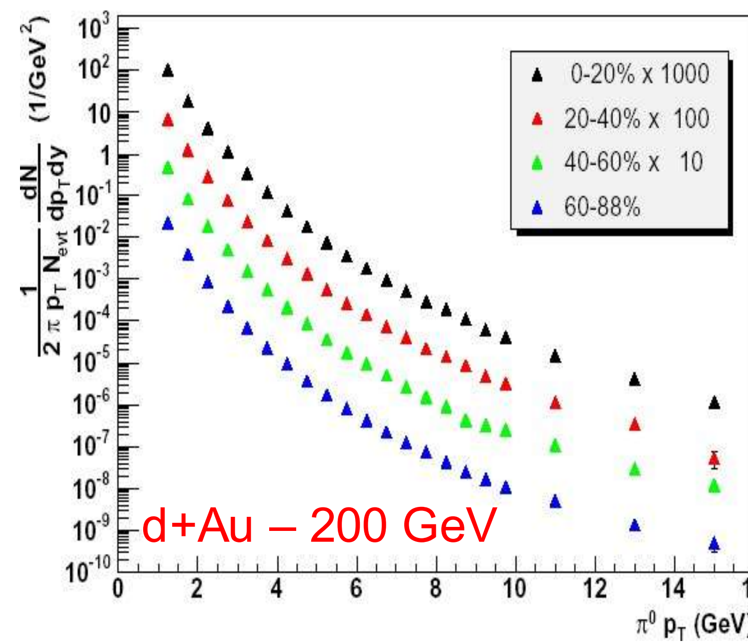
Inclusive single spectra at high p_T (AA, dA, pp)

- High quality large-p_T data (up to ~20 GeV/c) available in pp, dA and AA collisions:

Au+Au – 200 GeV



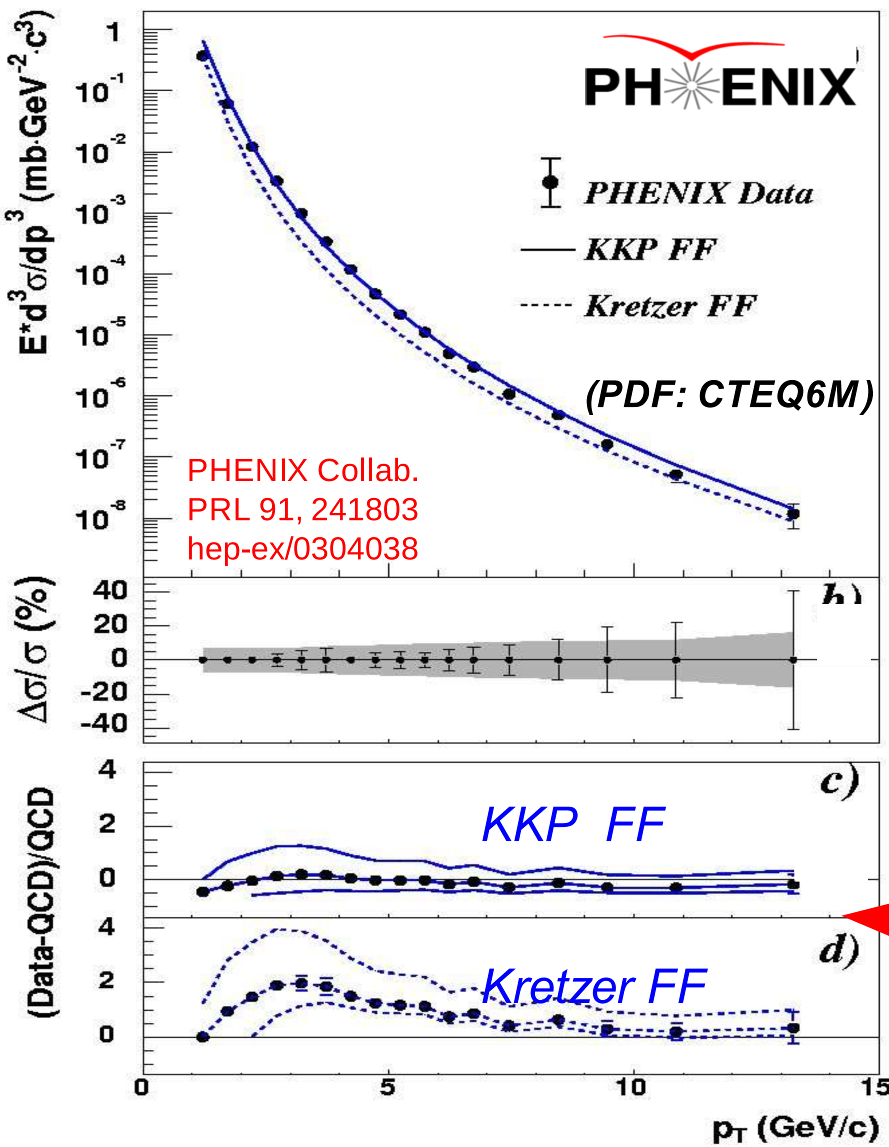


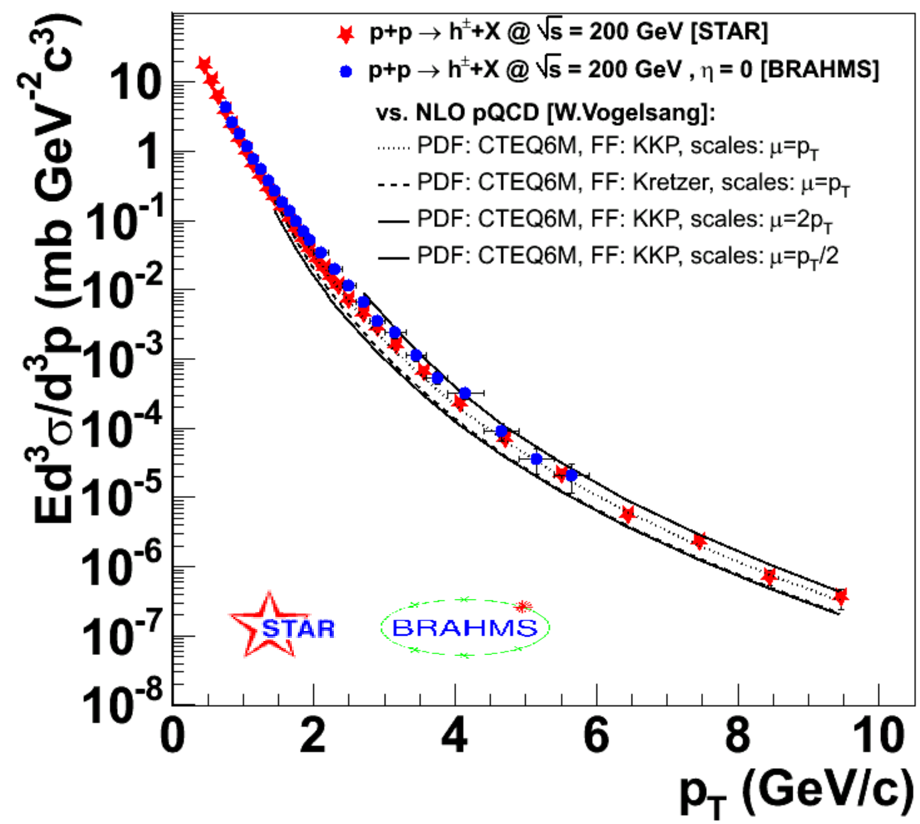


Leading hadron spectra in free space: pp @ 200 GeV

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

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

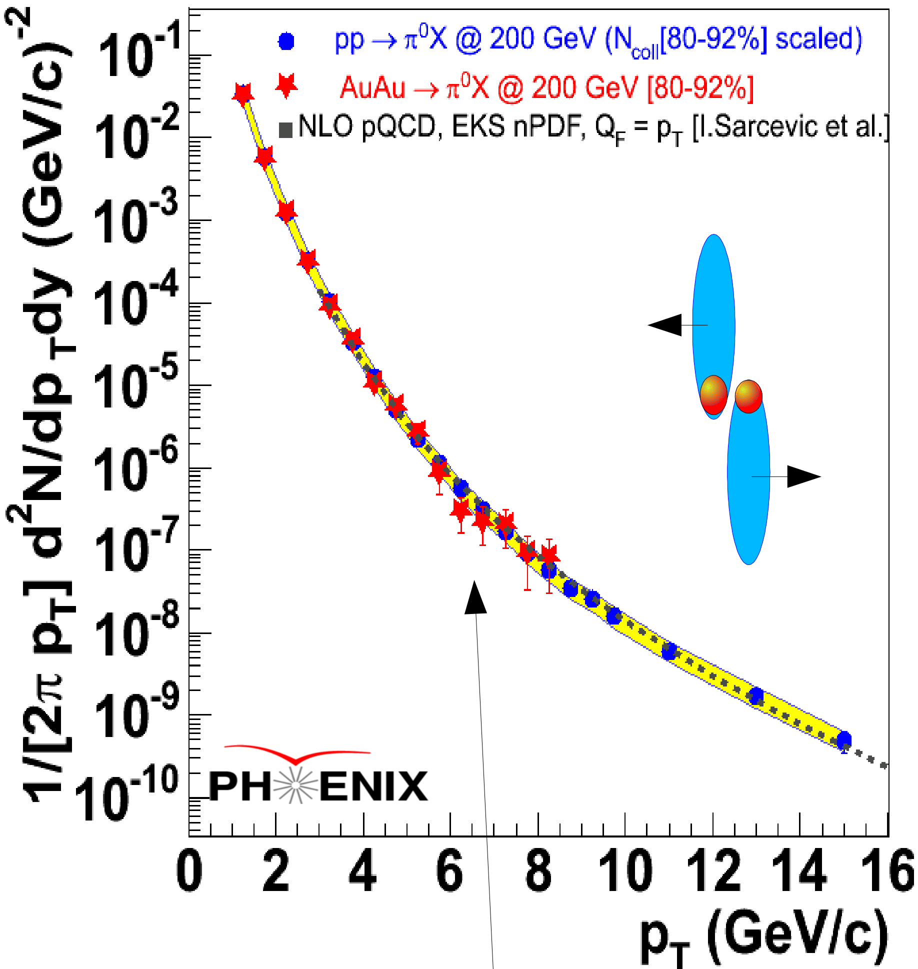




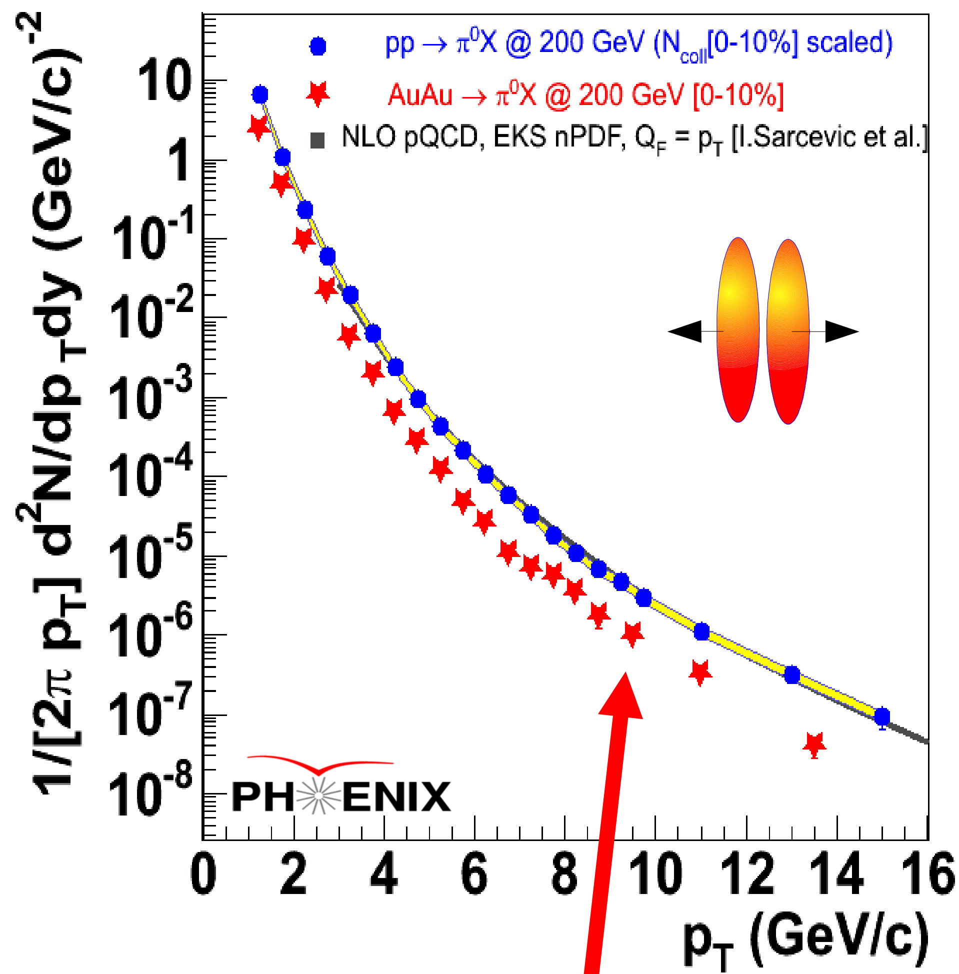
- High quality data: sensitive to different parametrizations of gluon FF
- Well calibrated (experimentally & theoret.) p+p baseline spectra at hand.

Leading hadron spectra in AuAu @ 200 GeV

Au+Au→ $\pi^0 X$ (peripheral)



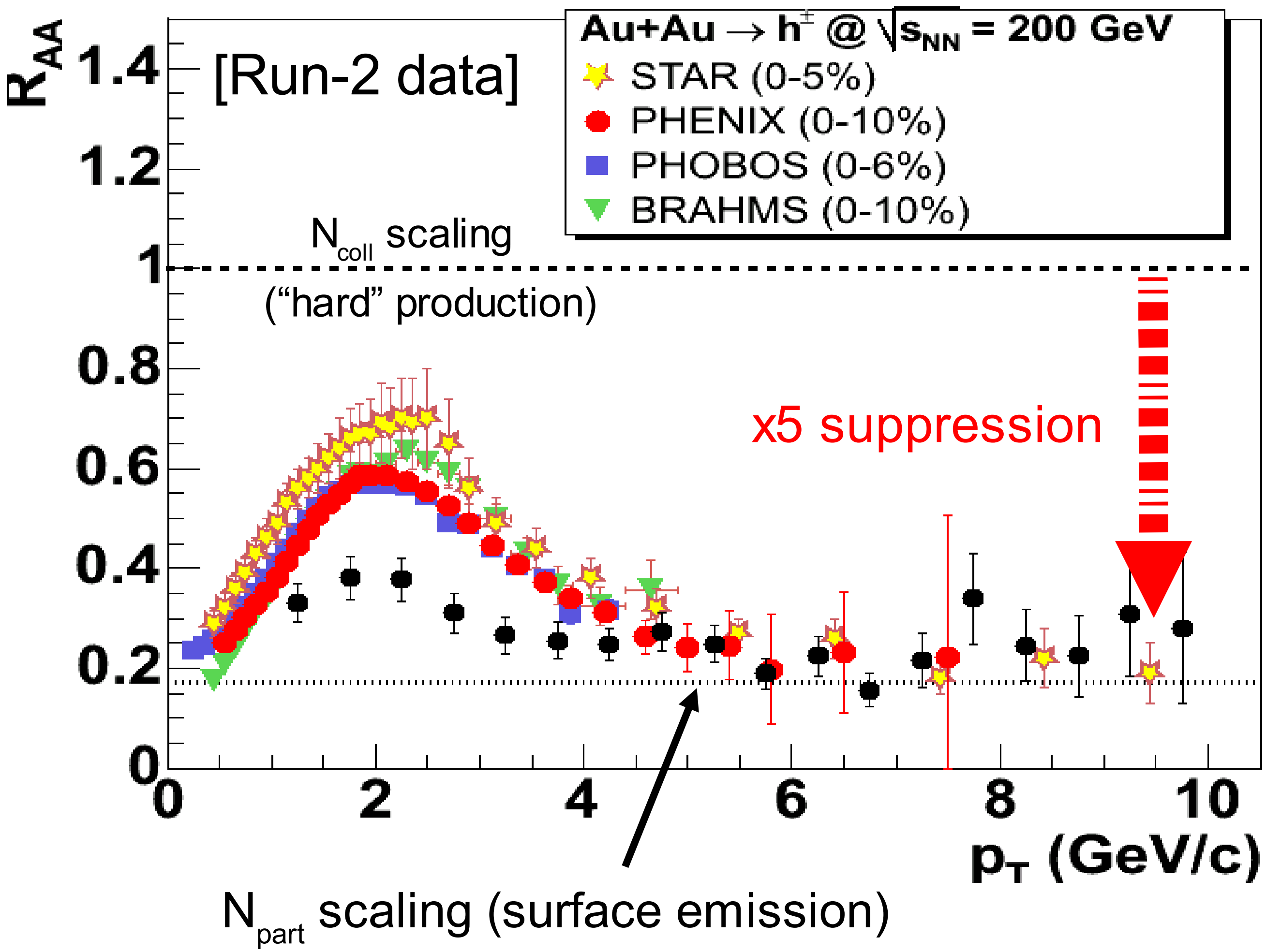
Au+Au→ $\pi^0 X$ (central)



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

Strong suppression in central Au+Au collisions !

Suppressed high p_T hadroproduction in central AuAu

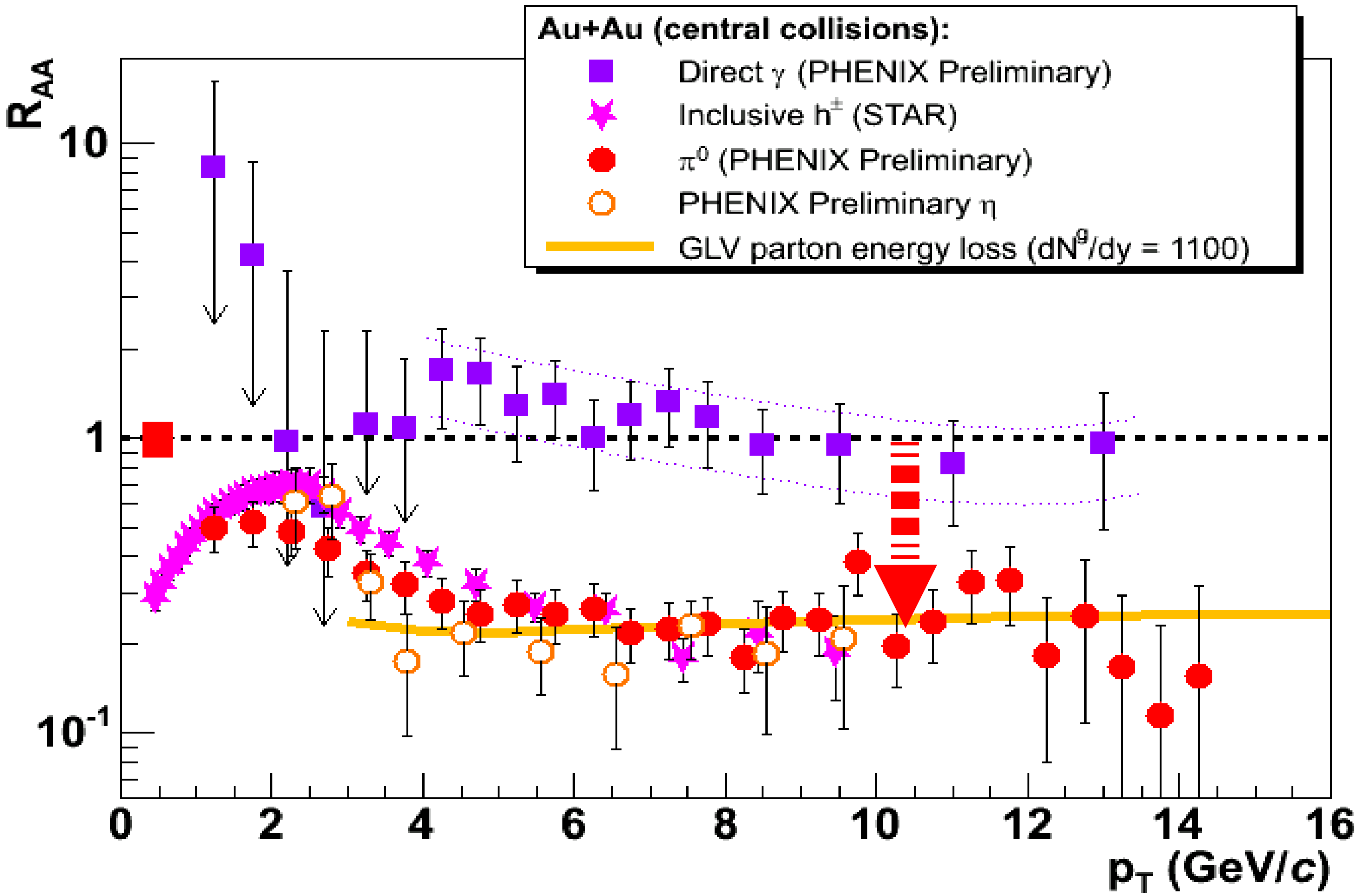


PHENIX Collab.
PRL 88, 022301 (2002)
nucl-ex/0109003

- Very strong suppression (R_{AA} ~ 0.2 !) up to p_T ~ 10 GeV/c for π^0 $h^{\pm}$, well below incoherent scattering expectations for hard cross-sections

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

Hadrons are suppressed. Photons are not.



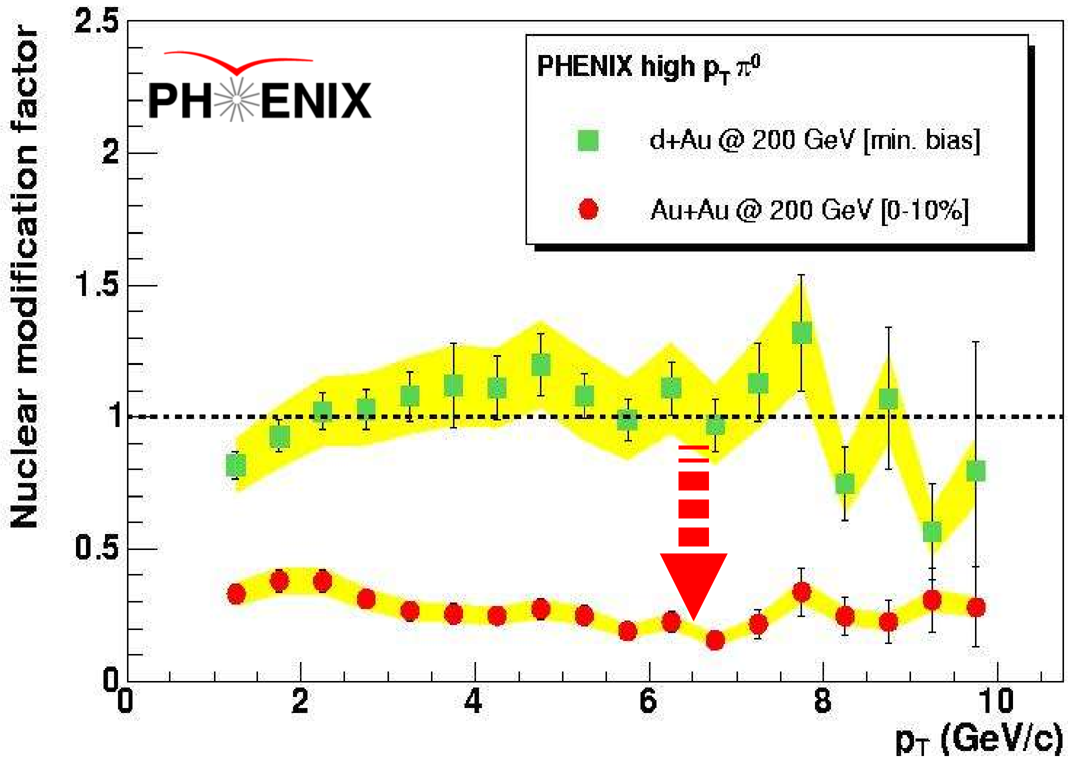
PHENIX.
PRL 94, 232301

D.d'E, HP'04
EJP C 43 (2005)295

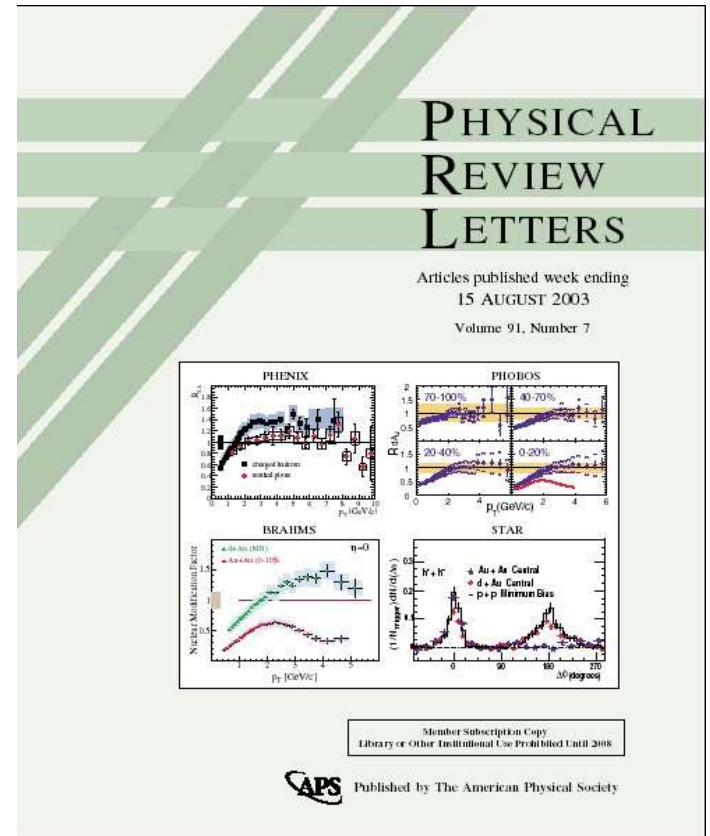
- Colorless hard probes (direct γ insensitive to final-state) are unsuppressed.

- Confirms that AuAu collision = incoherent sum of pp collisions (i.e. "N_{coll} scaling" expectation is valid) for perturbative probes.

Hadrons are suppressed in AuAu. Not in dAu.



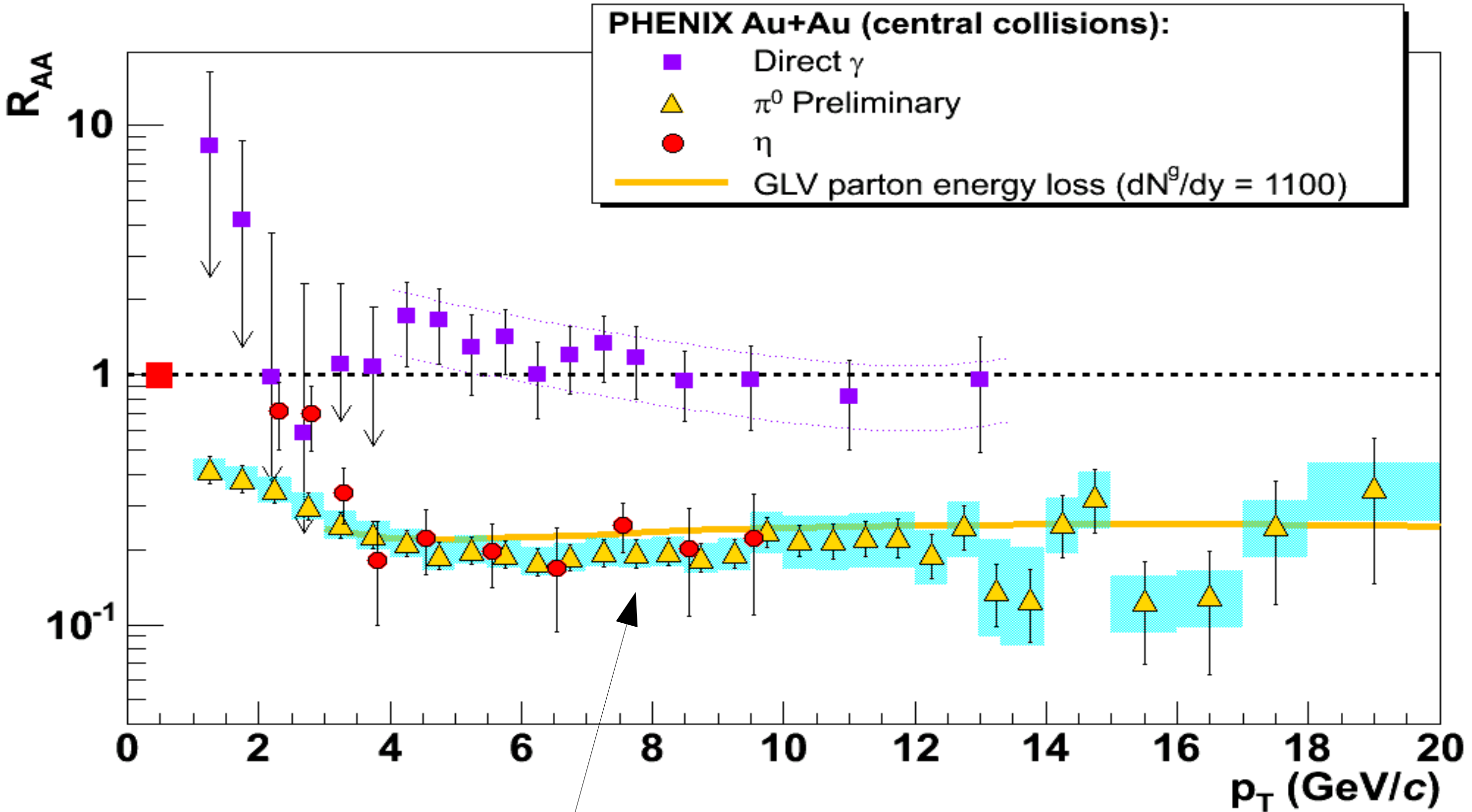
PHENIX.
PRL 91, 072303 (2003)



- Initial-state cold nuclear matter effects (shadowing, Cronin) are small at RHIC mid-rapidity.
- High p_T suppression in central AuAu is due to final-state effects (absent in "control" dAu experiment)

High p_T suppression: "Universal" for all light mesons

- Common suppression pattern (magnitude, p_T, centrality, ... dependence) for π^0 and η:



- Same flat R_{AA} ~ 0.2 up to 10 GeV/c

- Universal suppression for light mesons indicates it is at partonic level prior to q,g fragmentation into leading meson according to vacuum FFs.

Magnitude of the suppression: medium properties

- Data vs. models (pQCD+ non-Abelian parton energy loss) comparison:

  - Initial gluon densities:

    $$\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp}\frac{dN^g}{dy} L$$

    $dN^g/dy \sim 1000$ [Vitev & Gyulassy]

  - Opacities:

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

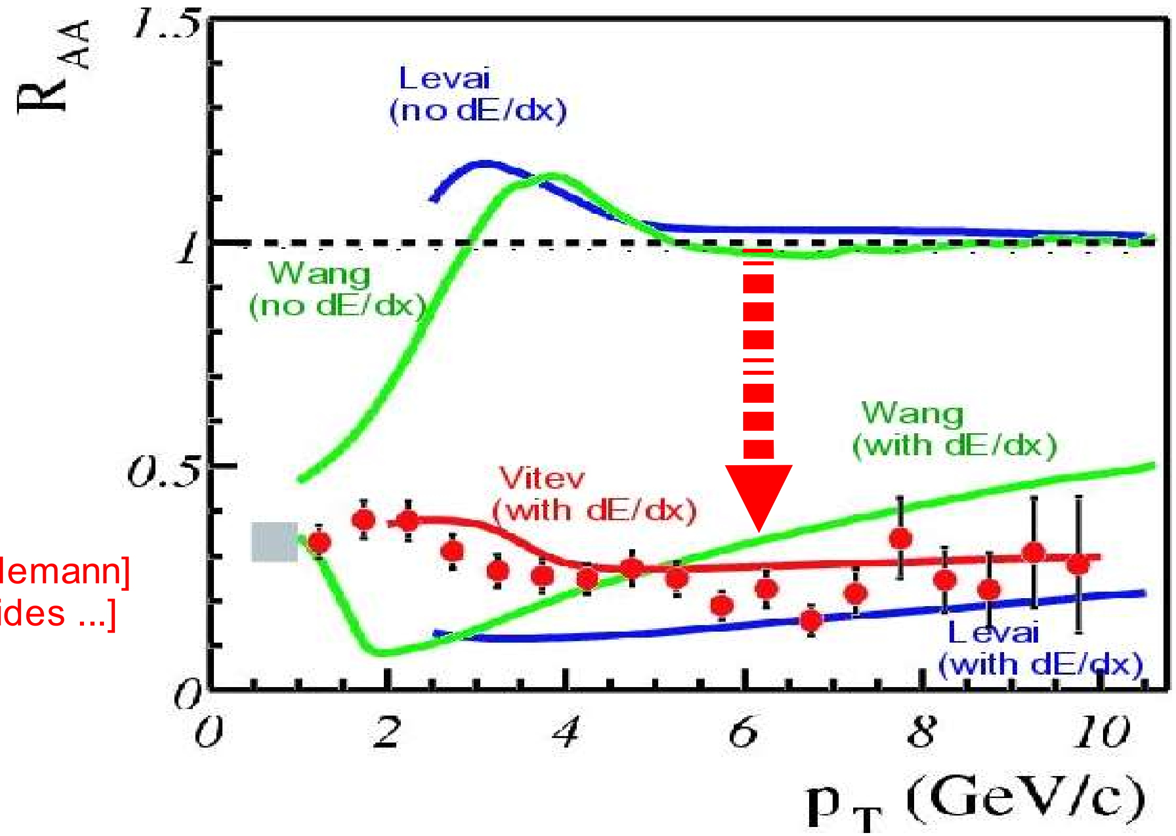
  - Transport coefficients:

    $$\langle \Delta E \rangle \propto \alpha_S C_R \langle \hat{q} \rangle L^2$$

    $\langle q_0 \rangle \sim 14$ GeV²/fm [BDMPS] [Salgado-Wiedemann] [Dainese, Loizides ...] [Arleo]

  - Medium-induced radiative energy losses:

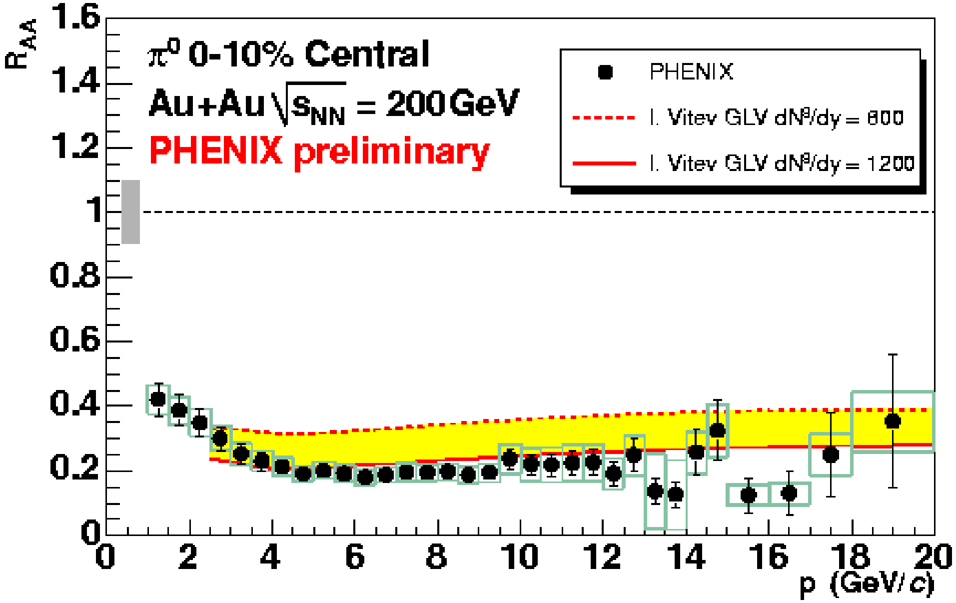
    dE/dx ≈ 0.25 GeV/fm (expanding)
    $dE/dx|_{eff}$ ≈ 14 GeV/fm (static source) [X.N.Wang]



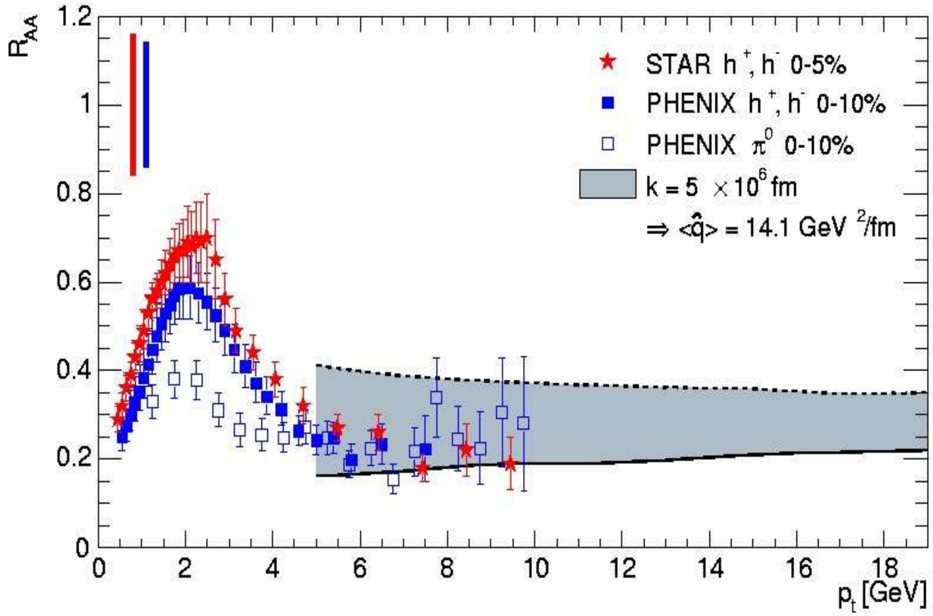
- Very large gluon densities: dN^g/dy~1000 consistent w/ measured $dN_{ch}/d\eta$ ~700
- All medium properties imply energy densities >> $\varepsilon_{crit\ QCD}$ (assuming thermalizat.)

High p_T suppression: p_T-dependence

- Flat p_T- dependence described by parton energy loss models:



GLV – I. Vitev 2005



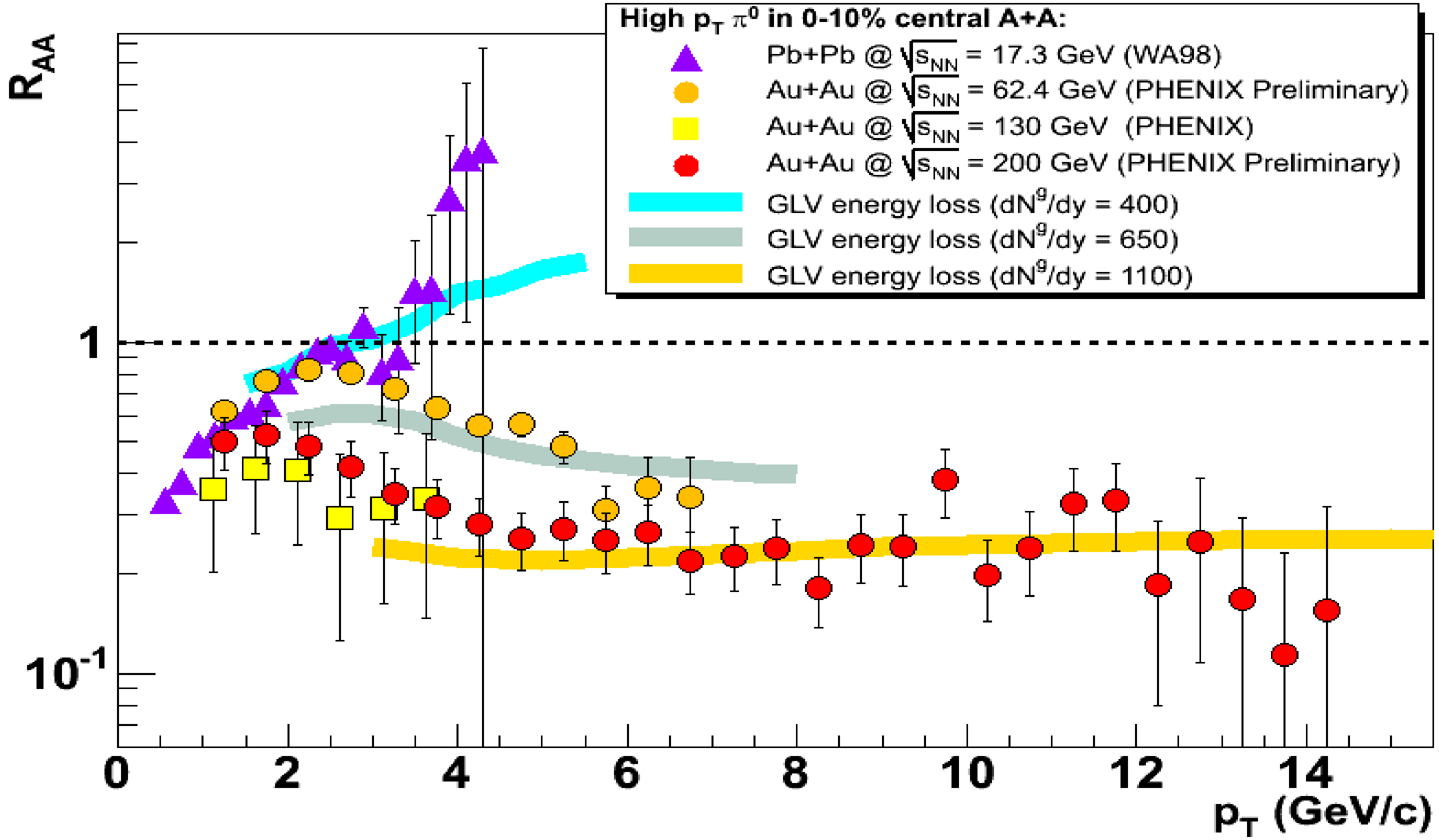
PQM – A. Dainese, C. Loizides, G. Paic
EPJ C 38, 461(2005)

- Underlying LPM interference for single gluon bremsstrahlung would give: $\Delta E_{loss} \sim \log(p_T)$

- Combination of different effects (convolution w/ realistic gluon energy distribution, local parton p_T slope, ...) yields constant suppression factor.

High p_T suppression: √s-dependence

- √s- dependence in agreement with parton energy loss in increasingly dense (expanding) medium:



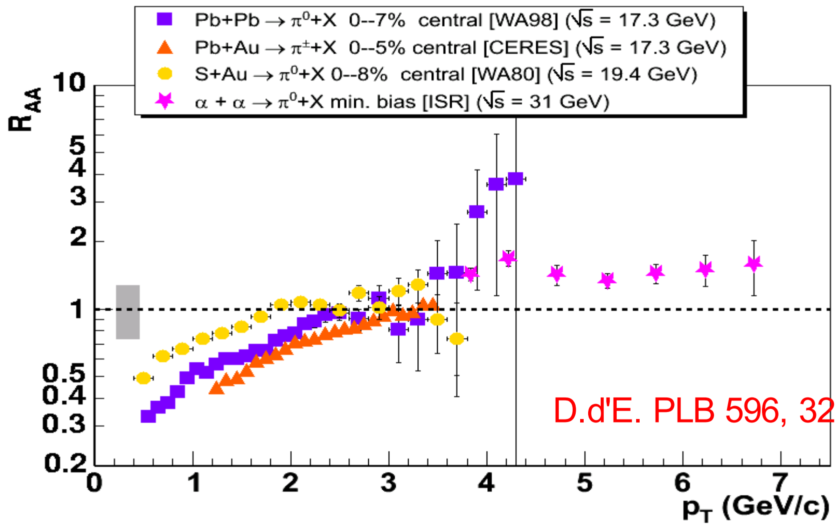
[Note: R_{AA} @ SPS uses "revised" pp ref.]

D.d'E., HP'04
EJP C 43 (2005)295

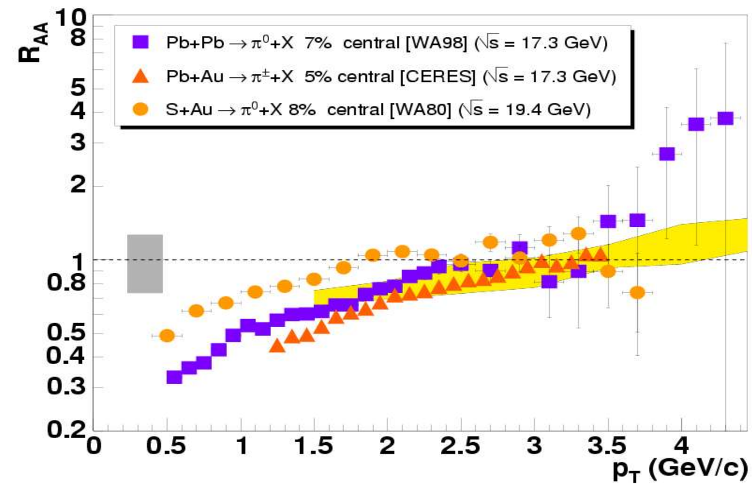
		Initial gluon density:		Medium transport coeff.:
SPS	R_{AA} ~ 1 @ √s ~ 20 GeV	⇒ dN^g/dy ~ 400	,	$\langle q_0 \rangle$ ~ 3.5 GeV/fm^2
RHIC	R_{AA} ~ 0.3 @ √s = 62 GeV	⇒ dN^g/dy ~ 650	,	$\langle q_0 \rangle$ ~ 7 GeV/fm^2
RHIC	R_{AA} ~ 0.2 @ √s = 200 GeV	⇒ dN^g/dy ~ 1100	,	$\langle q_0 \rangle$ ~ 14 GeV/fm^2

High p_T meson suppression in AA @ 17.3 GeV ?

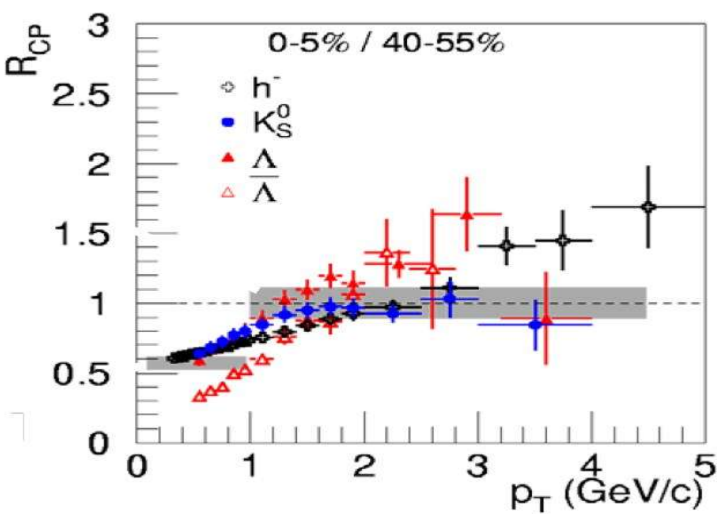
- Revised pp reference: high p_T π^0 production in (0-10%) central PbPb at SPS is slighted suppressed or consistent w/ "N_{coll}-scaling" :

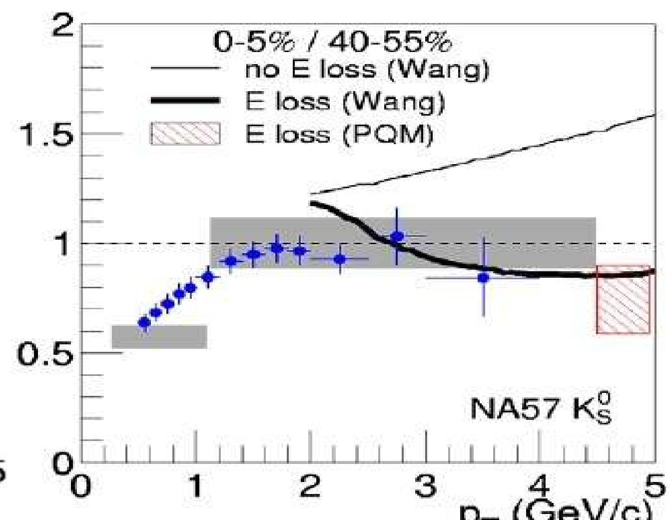


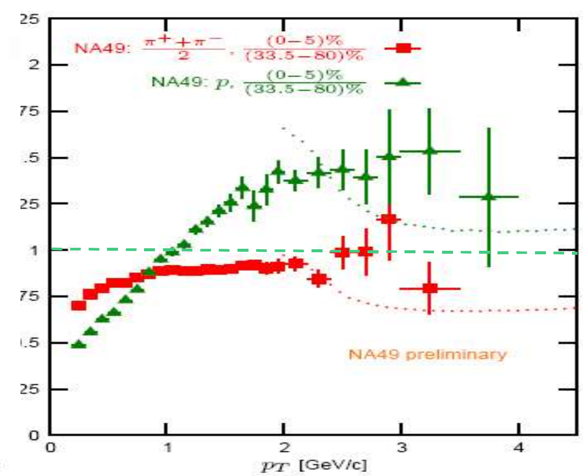
D.d'E. PLB 596, 32 (2004)



- Confirmed by NA57 (& NA49) recent high p_T results in central PbPb at SPS:







NA57, PLB62, 317 (2005)

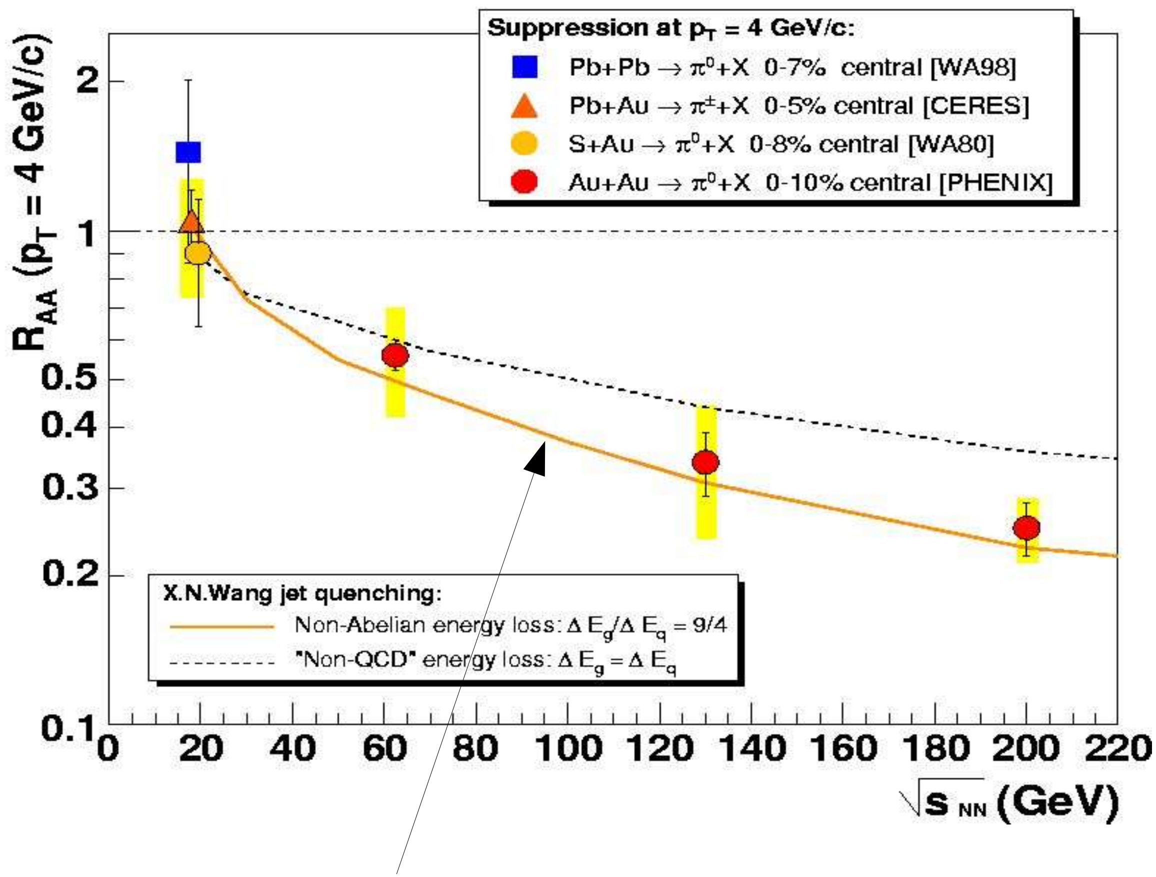
NA49 (A. Lazslo, QM'05)

High p_T suppression: non-Abelian nature

- Excitation function ($\sqrt{s}$-dependence) & non-Abelian nature of energy loss in agreement w/ parton energy loss calculations:

  (i) rising initial parton density with $\sqrt{s}$

  (ii) increasing relative fraction of hard-scattered gluons (at fixed p_T) with $\sqrt{s}$



“Jet quenching” model + 2-D longitudinal plasma expansion

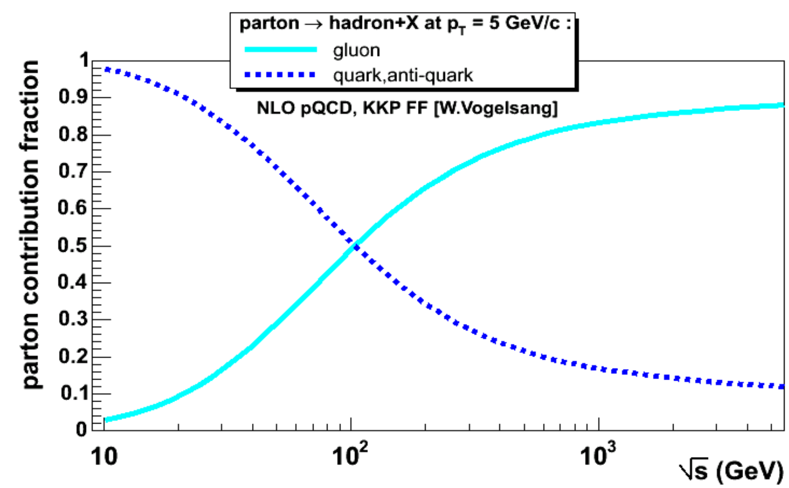
QCD radiation probability:

Gluon: $C_A = N_c = 3$

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

$\Big\}\ C_A/C_F = 2.25$

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



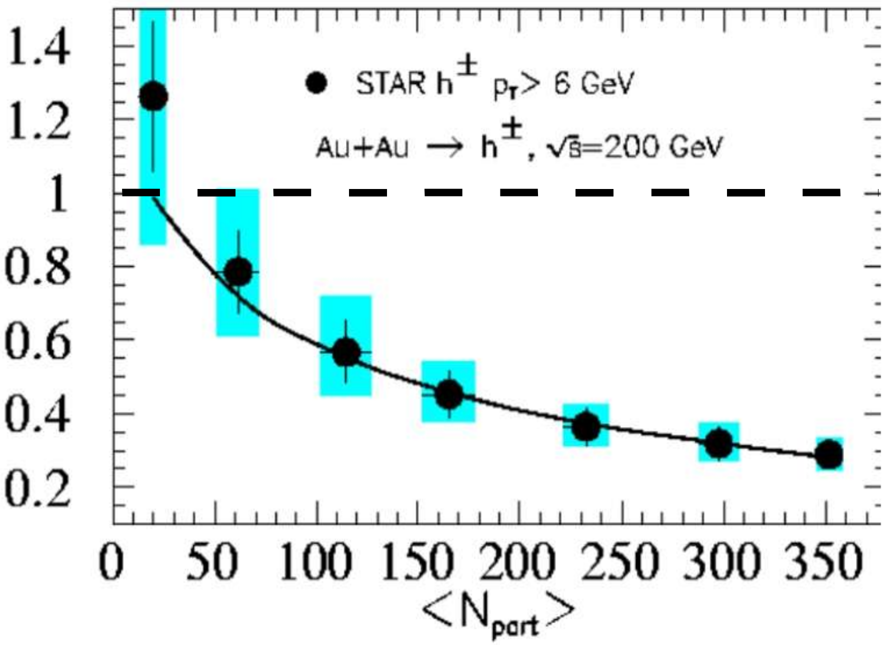
D.d'E. EJP C 43 (2005)295

High p_T suppression: centrality dependence

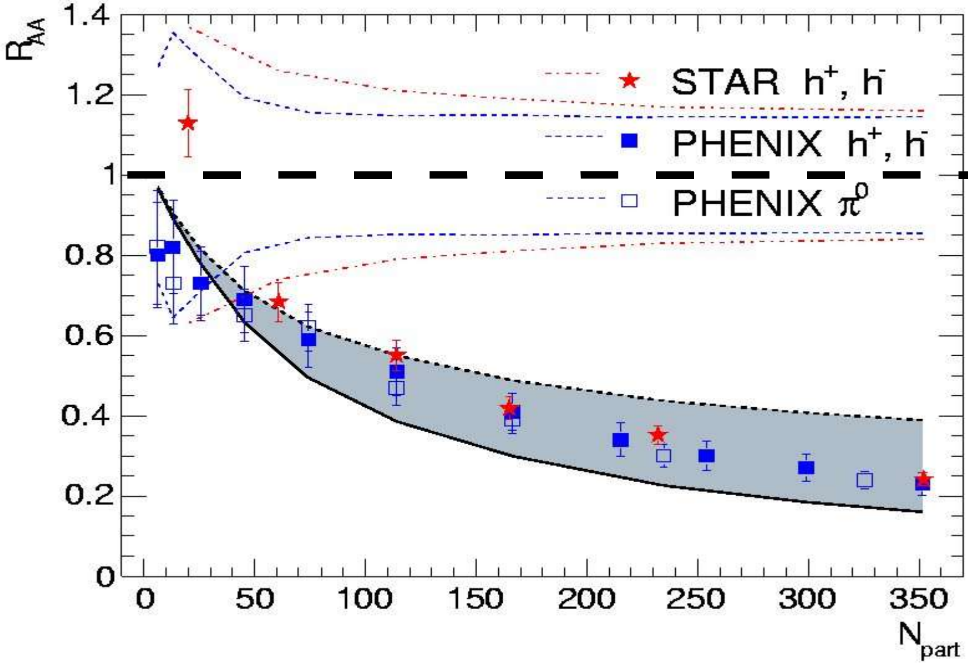
- Increasing centrality (N_{part}) $\Rightarrow$ increased L, ρ $\Rightarrow$ increased suppression

$$\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L$$

$$\langle \Delta E \rangle \propto \alpha_S C_R \langle \hat{q} \rangle L^2$$



X.N. Wang, PLB 2003



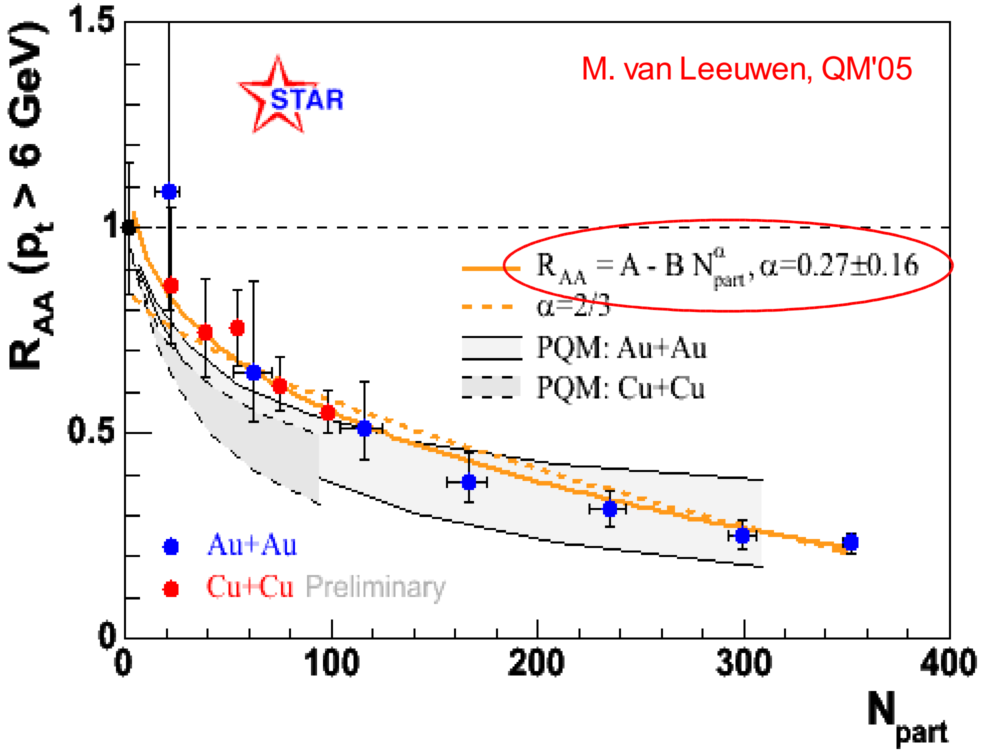
PQM – A. Dainese, C. Loizides, G. Paic
EPJ C 38, 461(2005)

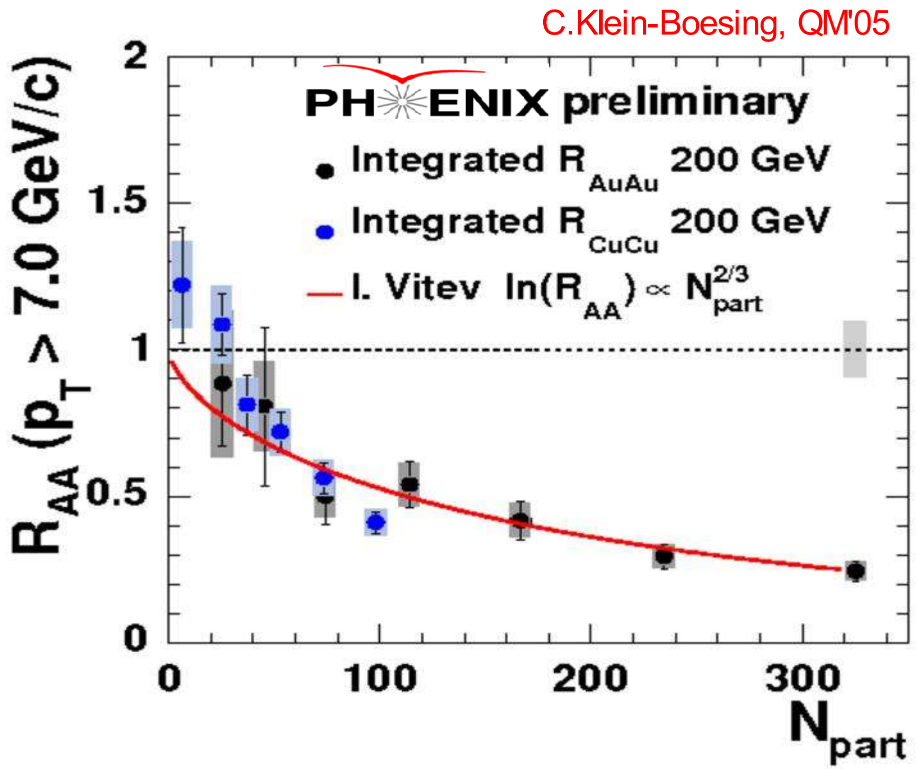
- Agreement data ↔ models as expected for diff. suppressions at different (geometrical) parton production points.

High p_T leading hadron spectra at RHIC & jet-quenching models: Less good agreement data ↔ theory ?

High p_T suppression: system-size dependence

- Smaller CuCu system adds significant precision at intermediate N_{part}~100:
- Theory predicts: $\ln(R_{AA}) \propto N_{part}^{-2/3}$

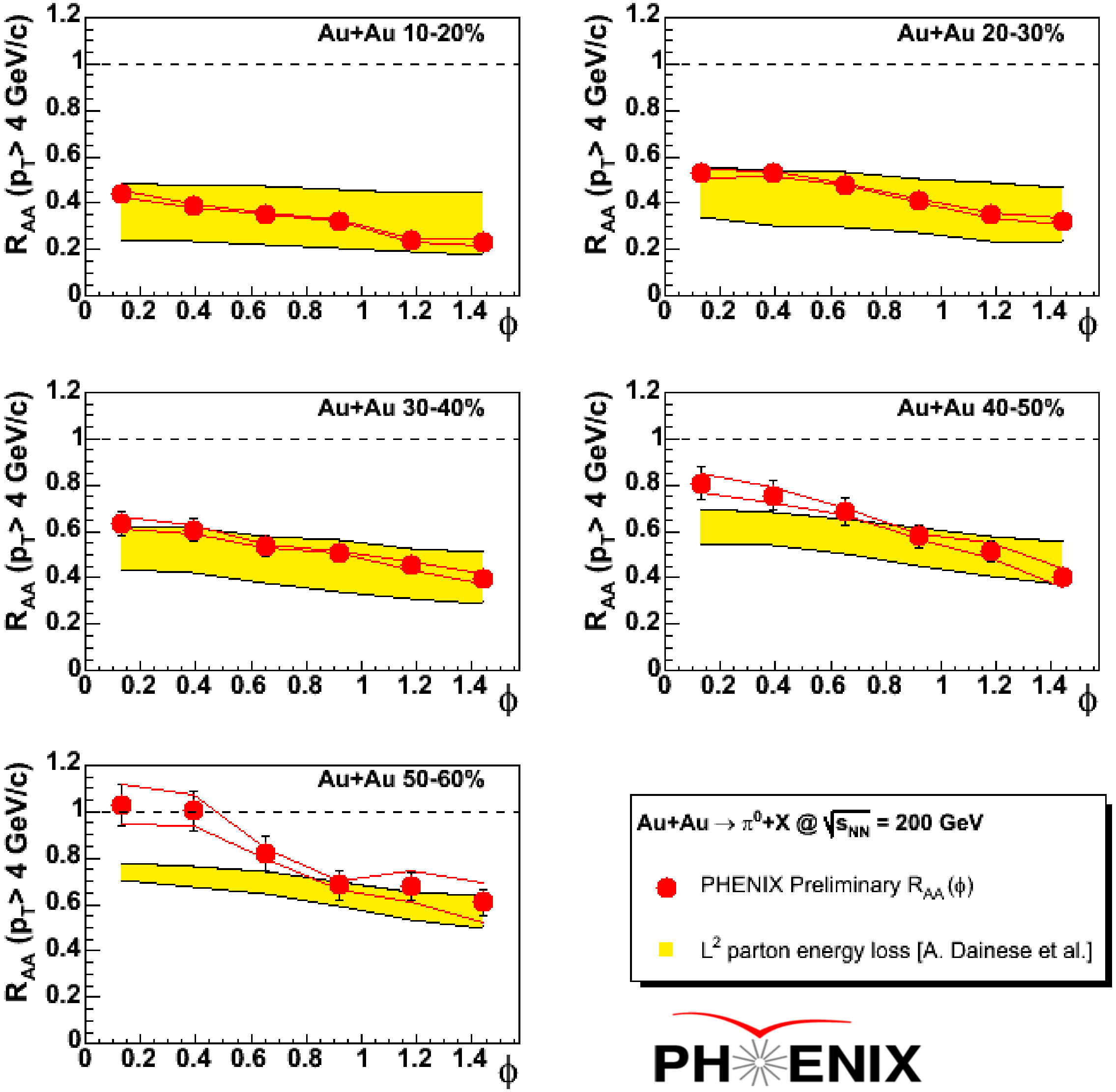




- Both PHENIX & STAR preliminary data seem to exclude α= -2/3
- Fit to STAR N_{part}^{α} prefers α~ -1/3 (circumf./area ~ $A^{-1/3}$ ~ $N_{part}^{-1/3}$?)
- PHENIX data seems to indicate a "steeper" slope at low N_{part}.
- Differences STAR ↔ PHENIX and PQM ↔ GLV still unclear at this point.

High p_T suppression: path-length dependence

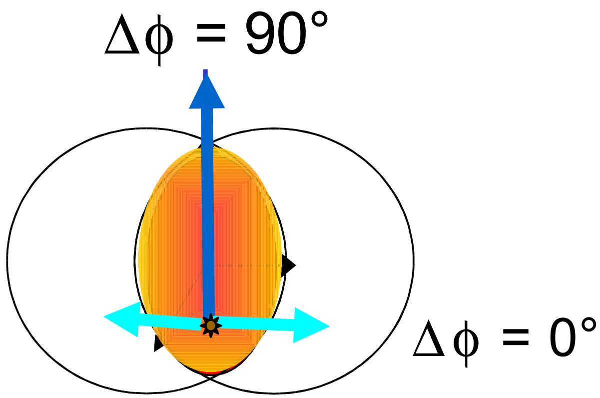
- R_{AA} vs φ w/ respect to reaction plane :



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

[D.d'E, EJP C 43 (2005) 295]

PHENIX PRELIMINARY



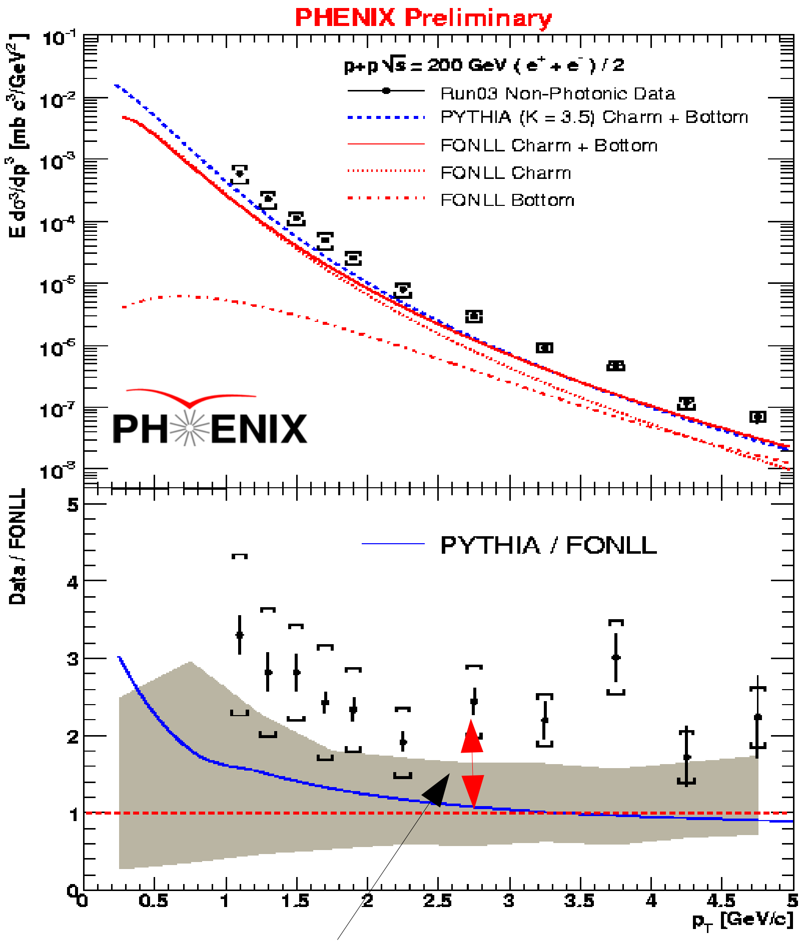
- 2 times more suppression out-of-plane ("long" direction) than in-plane ("short" direction).
- Glauber parton energy loss model predicts only ~50% increased "out-of-plane" vs "in-plane" π^0 emission

  PQM – Dainese, Loizides, Paic EPJ C 38, 461(2005)
- Azimuthal anisotropy stronger than "canonical" L^2 (or L) path-length dependence.
- Source of extra azim. anisotropy above p_T ~ 4 GeV/c ?

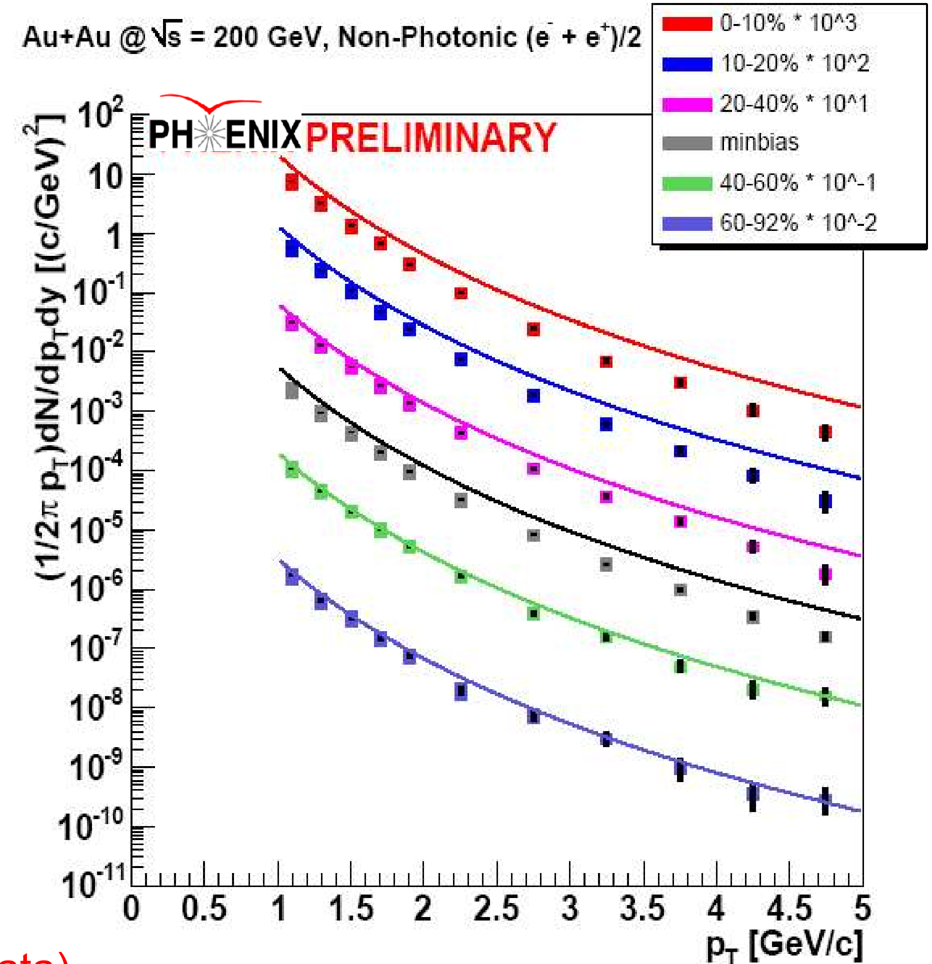
Heavy quark suppression via non-photonic electrons (I)

- Semi-leptonic decays of open charm and bottom mesons = main source of high p_T ("non-photonic") electrons.

proton-proton baseline:



Au+Au suppression

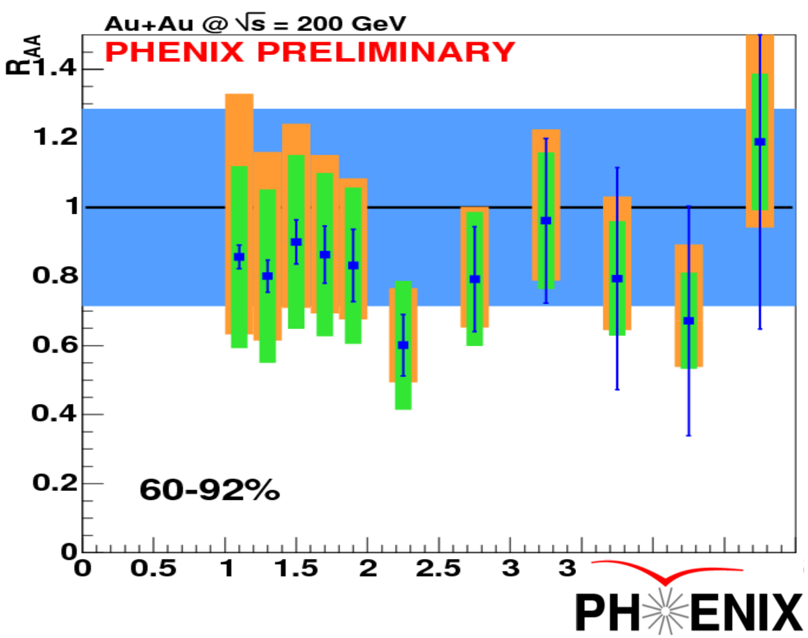


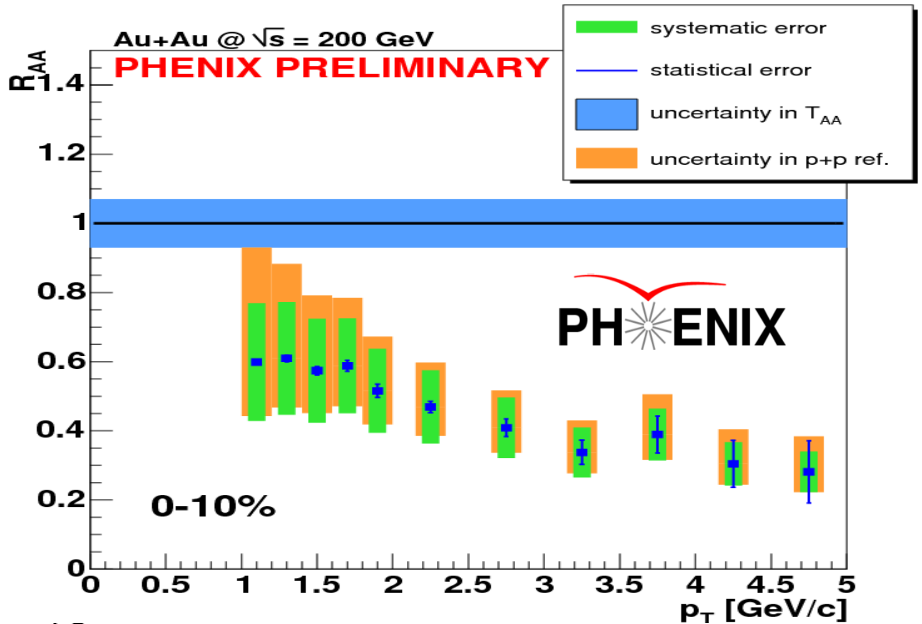
(Note: state-of-the-art theory underpredicts data)

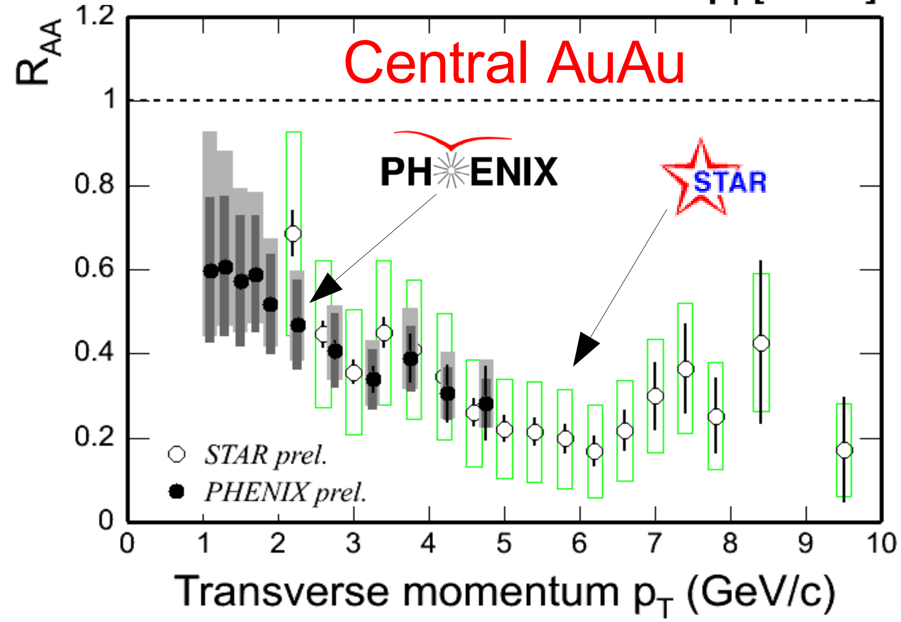
Heavy quark suppression via non-photonic electrons (II)

- Latest single $e^{\pm}$ R_{AA} indicates large suppression in central AuAu:

Peripheral AuAu







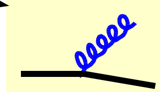
- Note: STAR – PHENIX R_{AA} agrees, but the pp refs are different by ~ 50%.

Heavy quark suppression via non-photonic electrons (III)

- Theory expectations : $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$ — (color factor), (mass effect)

"Dead cone": g rad. suppressed at $\theta < m_Q/E_Q$

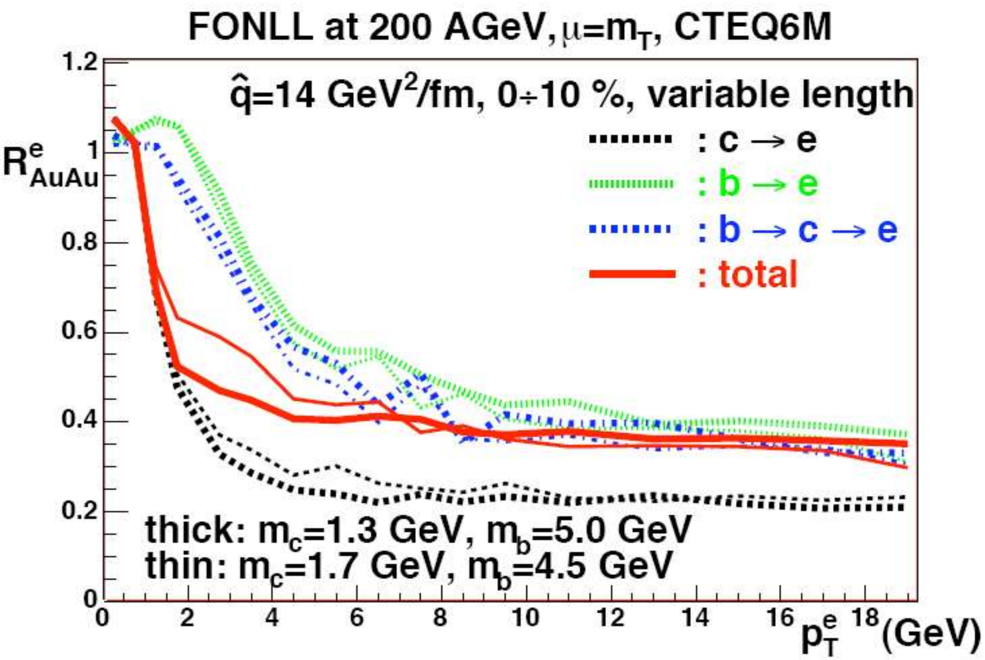
Gluonsstrahlung probability

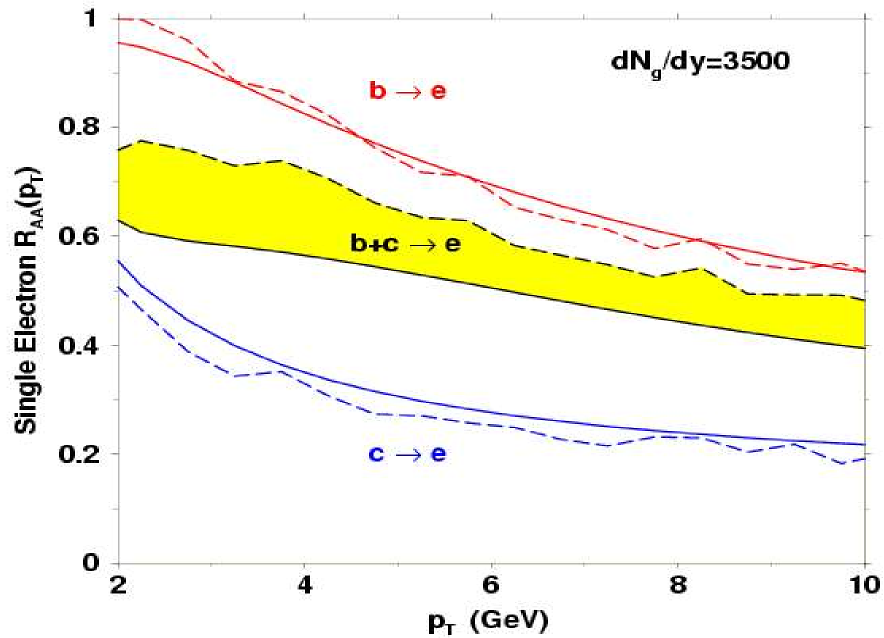


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- Quantitative predictions:

Armesto, Salgado, Wiedemann, QM'05





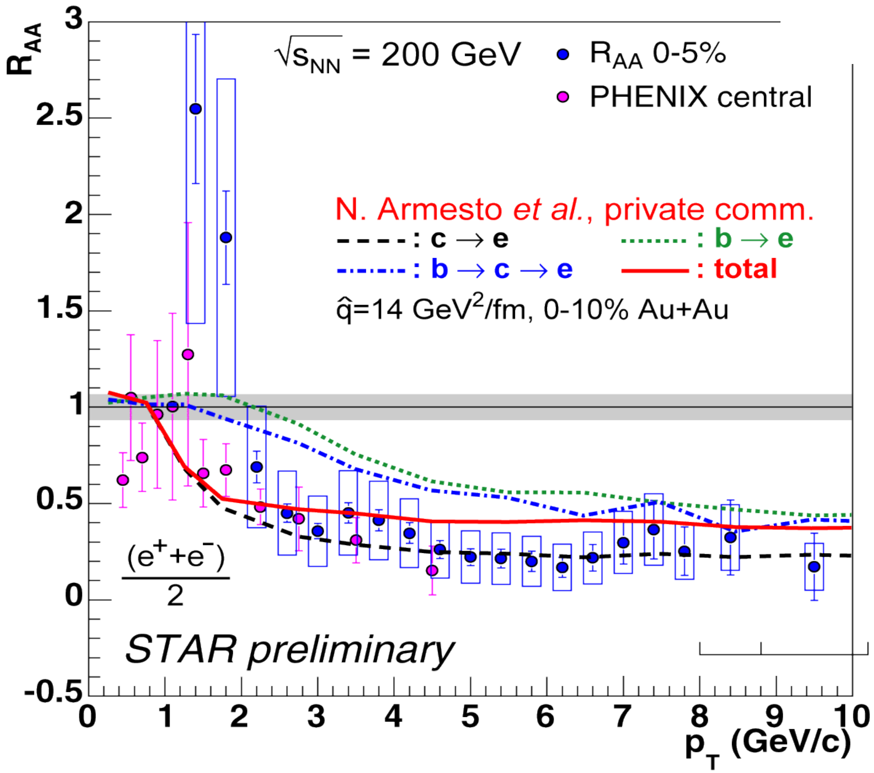
M. Djordjevic et al., nucl-th/0507019

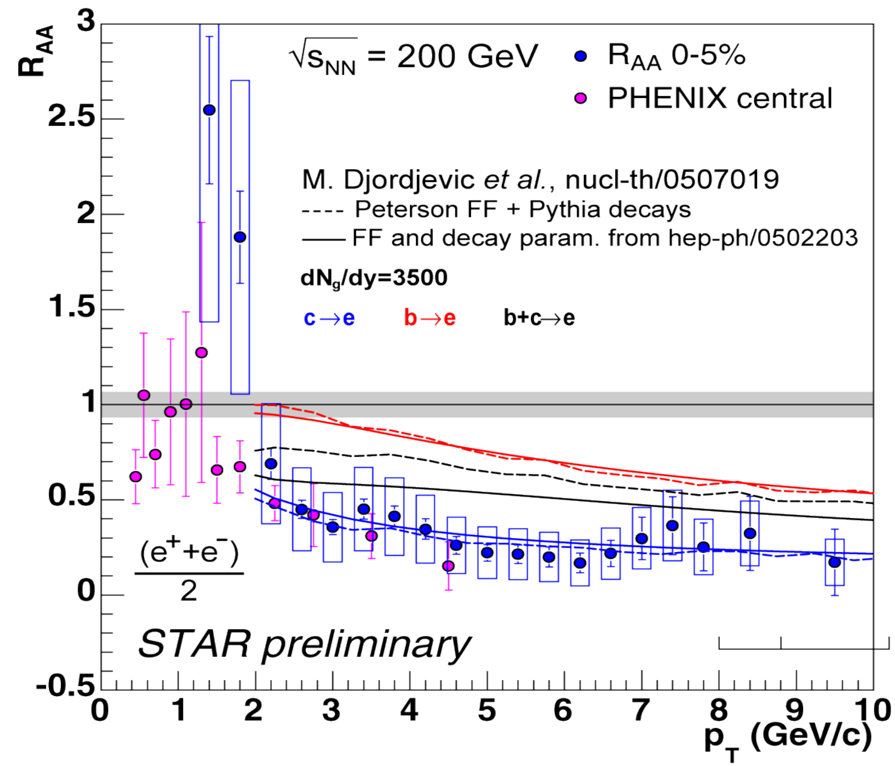
- Charm R_{AA} = 0.2 - 0.3
- Beauty R_{AA} = 0.4 - 0.6

- Models need larger medium densities: $dN^g/dy=3500$, $\langle q \rangle$ = 14 GeV^2/fm than for light mesons R_{AA} to reproduce data ! Unclear consistency w/ $dN_{ch}/dy \sim 600$

Heavy quark suppression via non-photonic electrons (IV)

- Models need too dense medium to account for observed suppression in data:

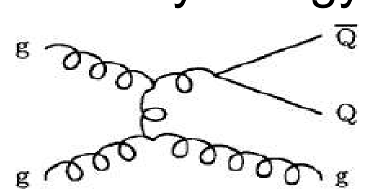




- Possible resolutions of the disagreement (or a combination of them ?):

(1) Larger suppression of beauty …or charm dominance up to electron $p_T \approx$ 10 GeV?

(2) Extra gluon-fragmentation production of charm affected by energy loss ? (would also explain PHENIX proton-proton data ?)



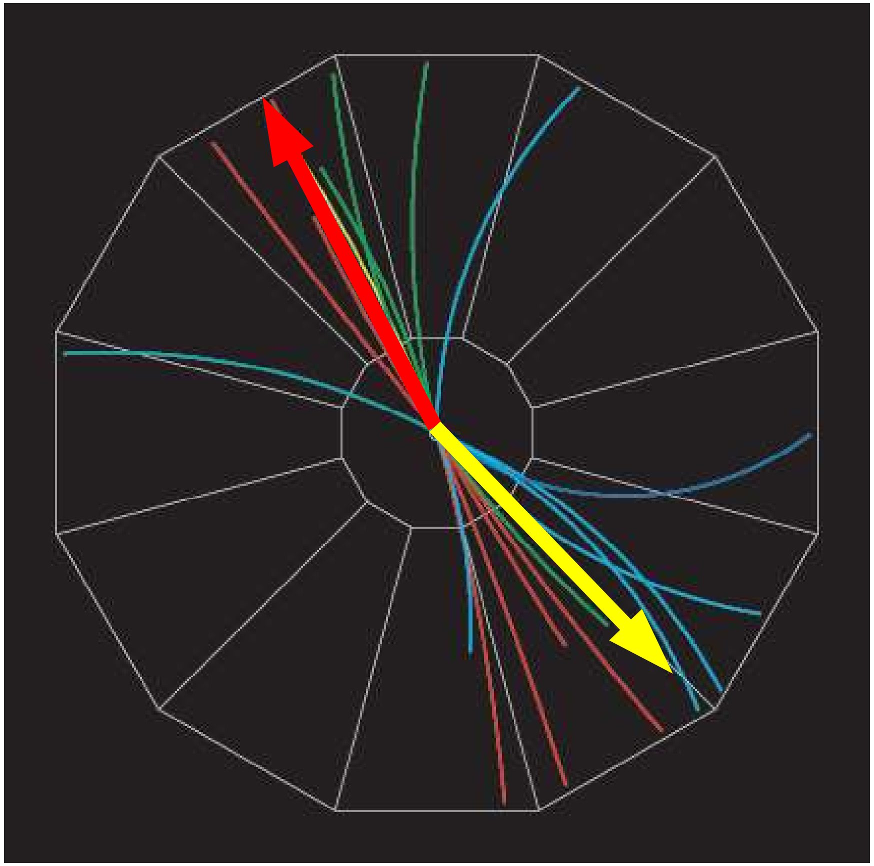
(3) Hadronic (+ partonic) energy loss ?

(4) Radiative + collisional energy loss ? Other ... ?

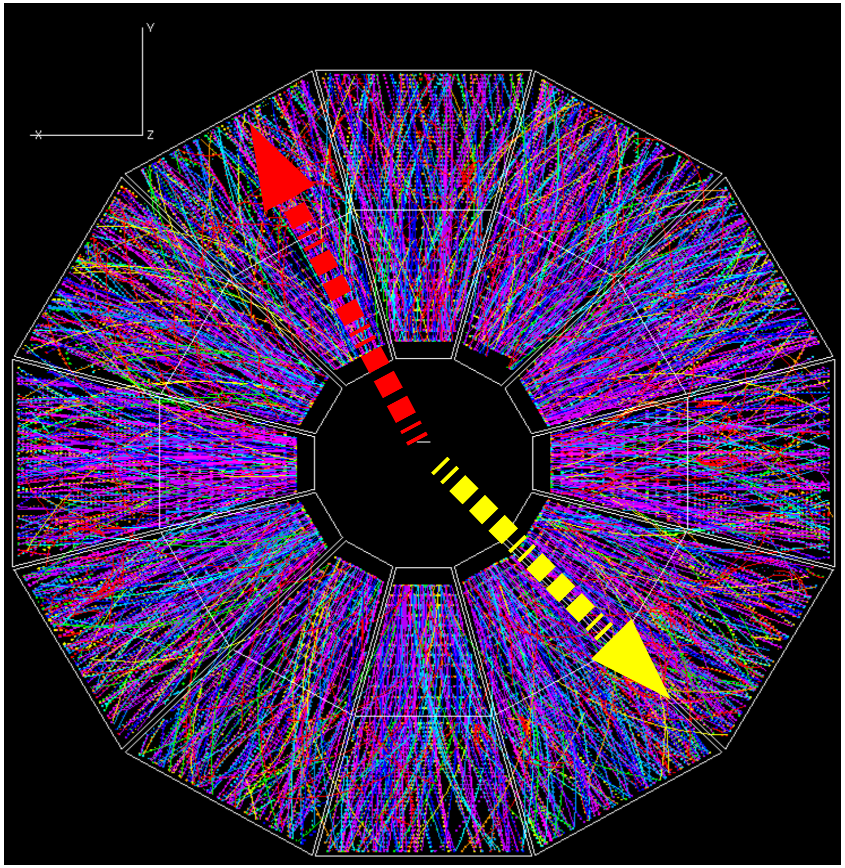
High p_T di-hadron ϕ,η correlations in high-energy AuAu collisions

"Jet physics" at RHIC (II): di-hadron azimuthal correlations

- Study the azimuthal correlations in AA relative to pp between the highest p_T hadron ("trigger") & any other "associated" hadron:



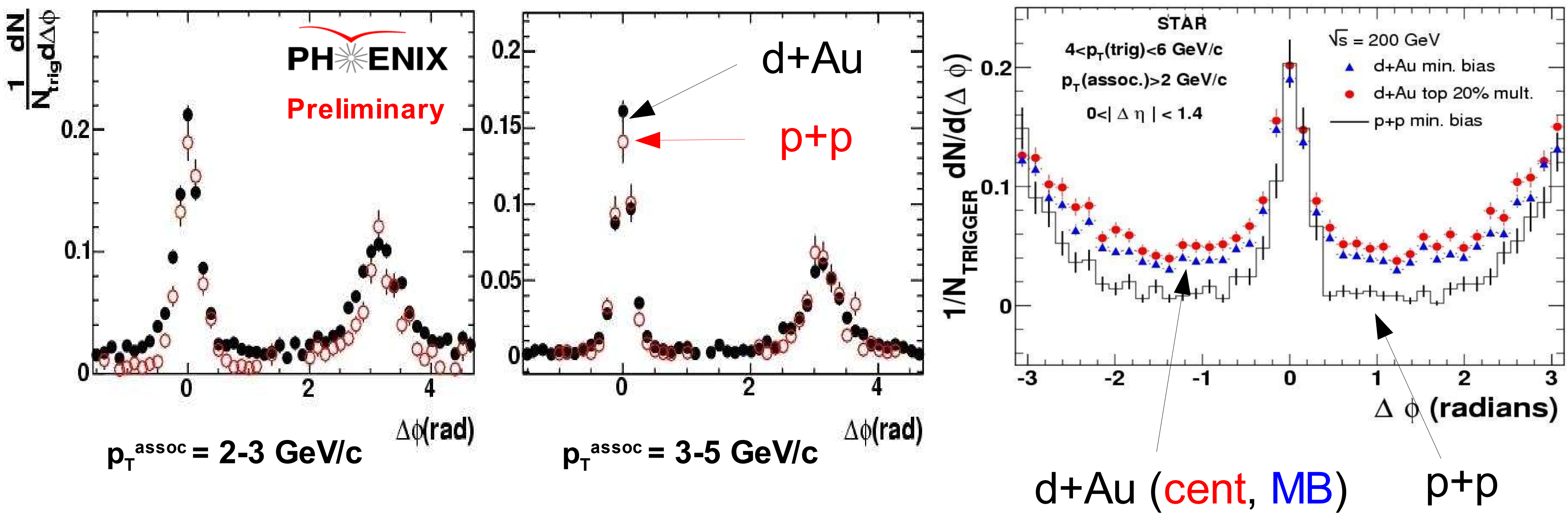
$p+p \rightarrow h_1+h_2+X$ [$\sqrt{s}$ = 200 GeV]



$Au+Au \rightarrow h_1+h_2+X$ [$\sqrt{s_{NN}}$ = 200 GeV]

Dijets via high p_T di-hadron ϕ 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: $$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} = \frac{1}{N_{trig}}\frac{N_{cor}(\Delta\phi)}{N_{mix}(\Delta\phi)}$$



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

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

- Clear near- ($\Delta\phi \sim 0$) and away- ($\Delta\phi \sim \pi$) side jet signals

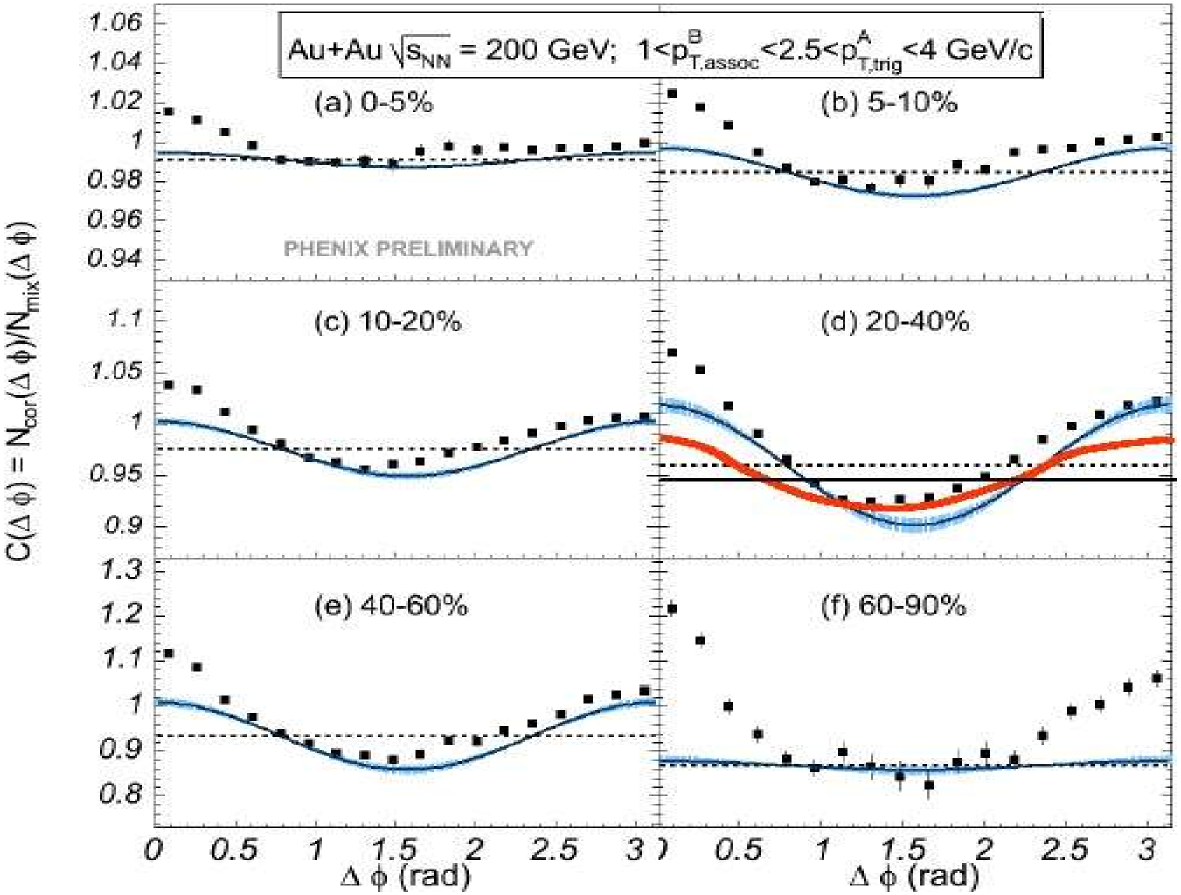
Dijets via high p_T di-hadron ϕ correlations: AuAu

- Same $dN_{pair}/d\varphi$ analysis as in pp (dAu) but 2 extra "complications":

  (1) Increased "underlying event" background

  (2) Collective elliptic flow (harmonic) contribution

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

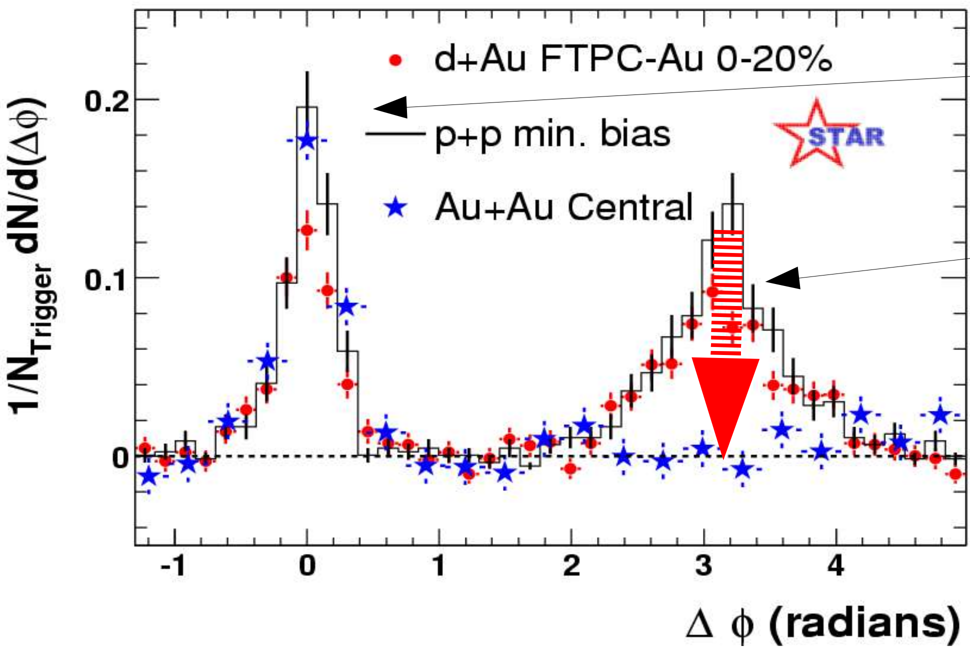


PHENIX

Ajitanand, ICPAQGP'04 and nucl-ex/0501025

- Delicate subtraction procedure (esp. in finite acceptances).

Di-hadron AuAu Δφ correlations: Results at high p_T



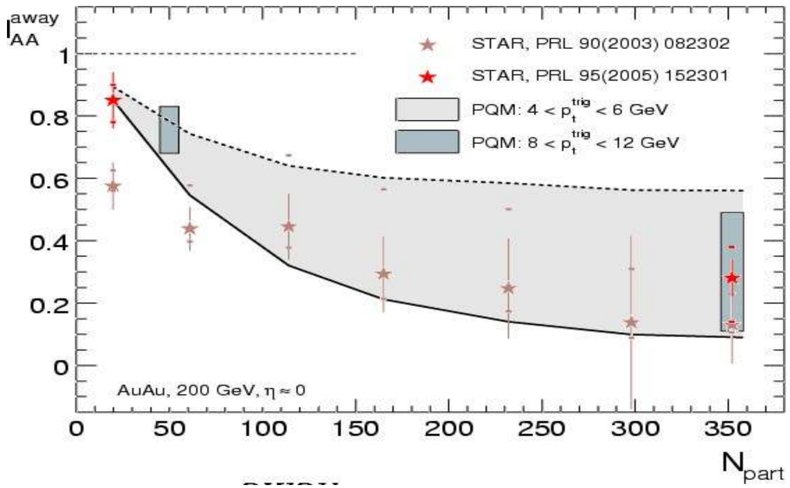
- **Near-side** jet-like Gaussian peak unmodified (AuAu ~ dAu ~ pp)
- **Away-side** peak disappearance: **"monojet"-like** topologies in central AuAu.

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

STAR, PRL 90, 082302 (2003)

- **Centrality dependence** of away-side disappearance globally described by parton energy loss models (increasing medium traversed):

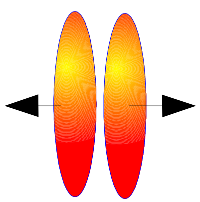
$$I_{AA} = \left(\frac{N^{assoc}}{N^{trig}}\right)_{AA} \Big/ \left(\frac{N^{assoc}}{N^{trig}}\right)_{pp}$$

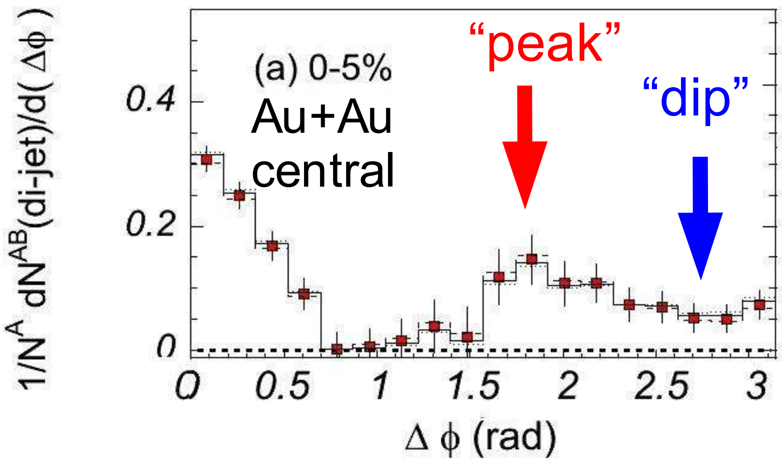


PQM – A. Dainese, C. Loizides, G. Paic
EPJ C 38, 461(2005)

Di-hadron AuAu $\Delta\phi$ correlations: Results at lower p_T

- “Lost” away-side energy is recovered at lower p_T values.
- Strongly modified away-side $\Delta\phi$ correlations in central AuAu:

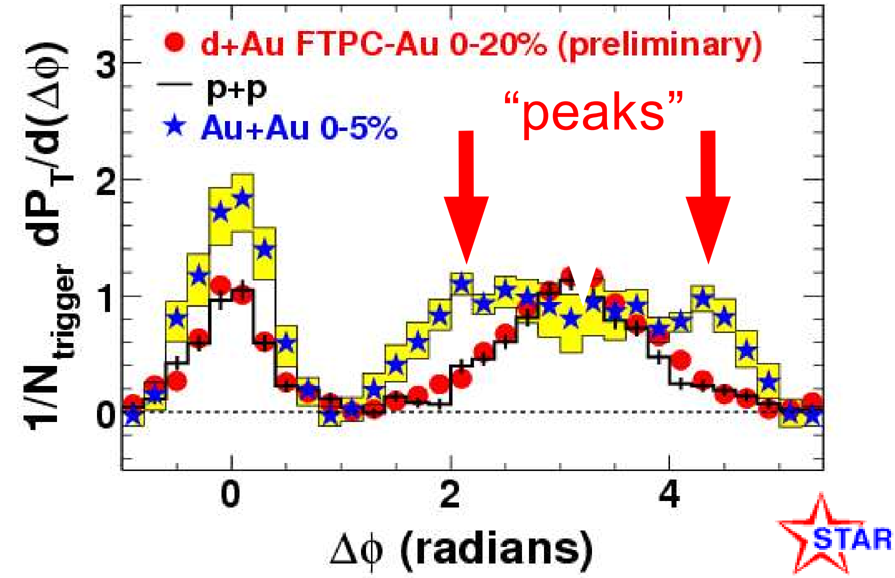




PHENIX Preliminary

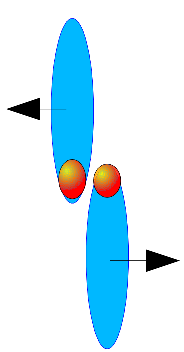
Au+Au $\sqrt{s_{NN}}$ = 200 GeV

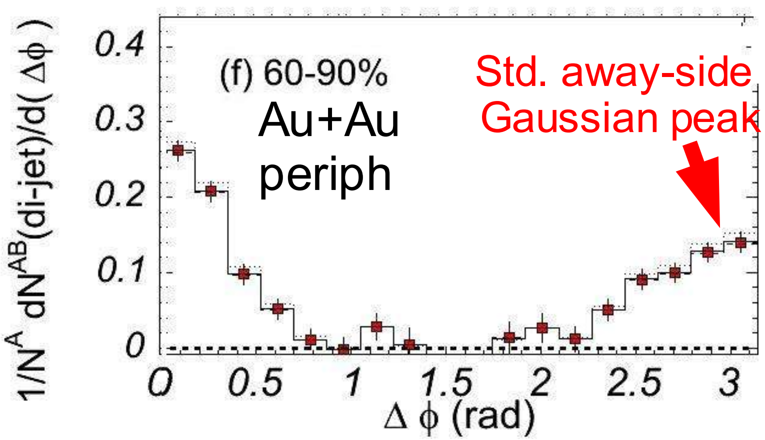
$1<p^B_{T,assoc}<2.5<p^A_{T,trig}<4$ GeV/c



STAR, PRL95,152301(05)
nucl-ex/0501016

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





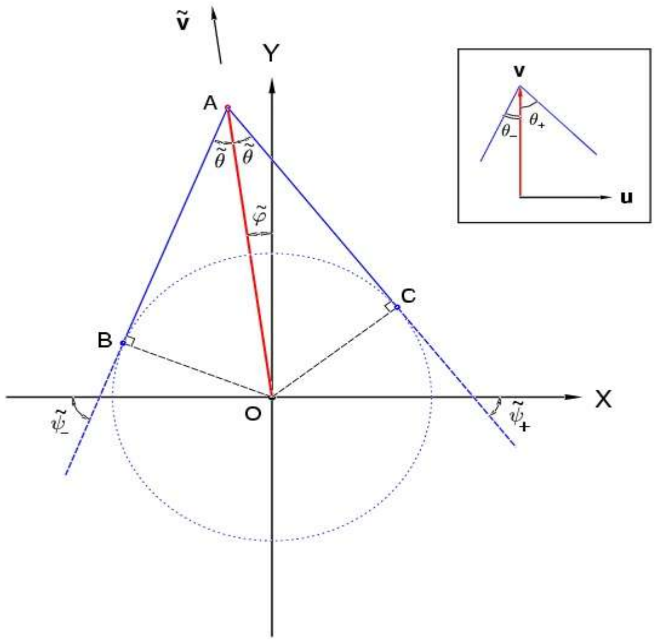
- Away-side (π) “dip” and excess of energy (“double peak”) at:
  PHENIX: $\pi \pm 1.3$ rad
  STAR: $\pi \pm 1.1$ rad

PHENIX, PRLsubmitted, nucl-ex/0507004

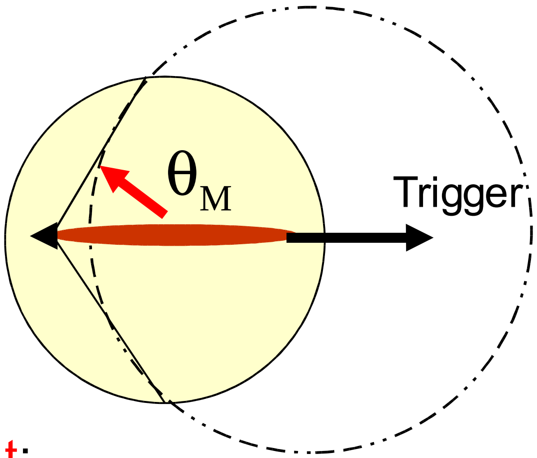
"Double peak" = Mach wave cone ?

- Double peak structure at at $\pi \pm 1.2$ rad reminiscent of Mach wave conical shock ("sonic boom") $\Rightarrow$ speed of sound accessible

Stoecker, Satarov, Mishutin, hep-ph/0505245.
Casalderrey, Shuryak, Teaney, hep-ph/0411315.



Mach cone: $\cos\theta_M = c_s$



$c^2_s \neq$ constant:
QGP ($1/\sqrt{3}$) $\rightarrow$ phase transition (0.) $\rightarrow$ HRG ($\sqrt{0.2}$) :

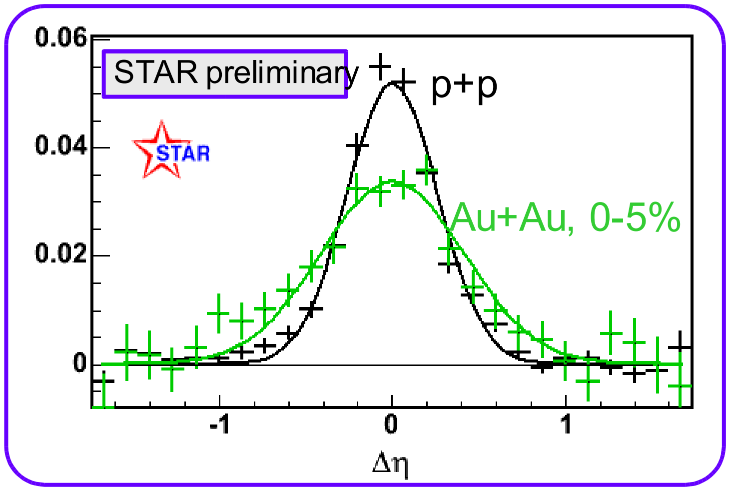
$$c_s^{av} = \frac{1}{\tau_f}\int d\tau c_s(\tau) = 0.33$$

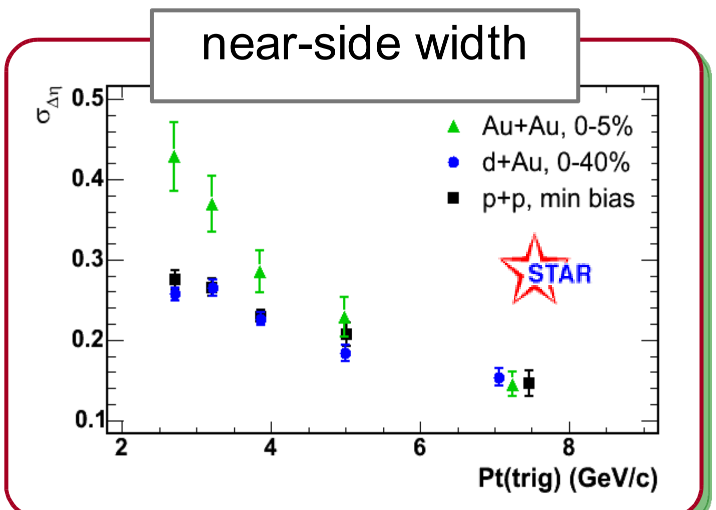
$\theta = \arccos(c^{av}_s) = 1.2$ rad $= 71^{o} \sim \theta_{exp}$

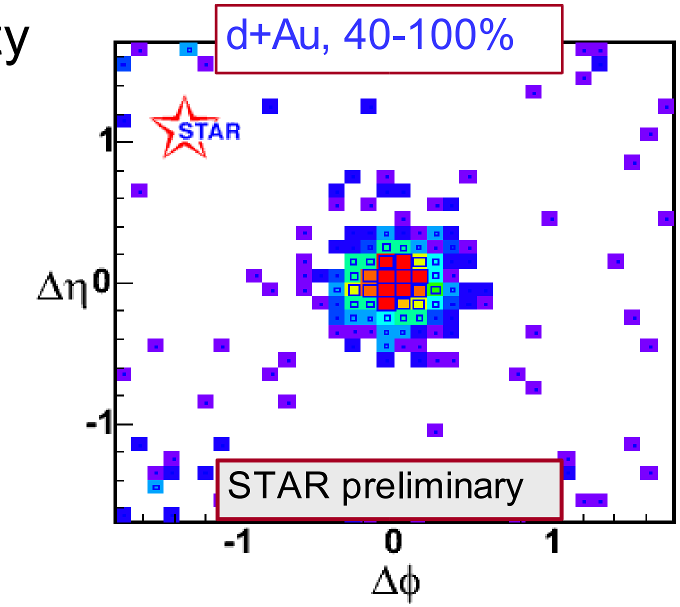
Note: gluon Cerenkov-like emission also proposed [access to medium index refrac. $n=1/\cos(\theta_c)$]

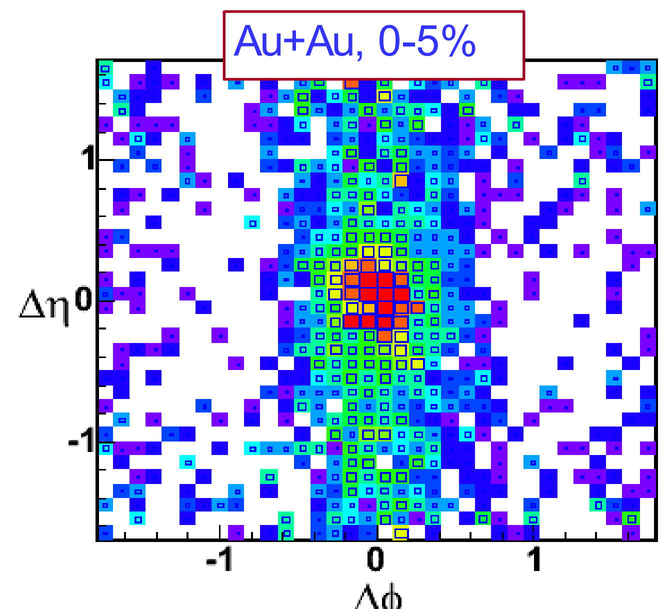
Di-hadron Δη correlations: AuAu, dAu, pp (I)

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









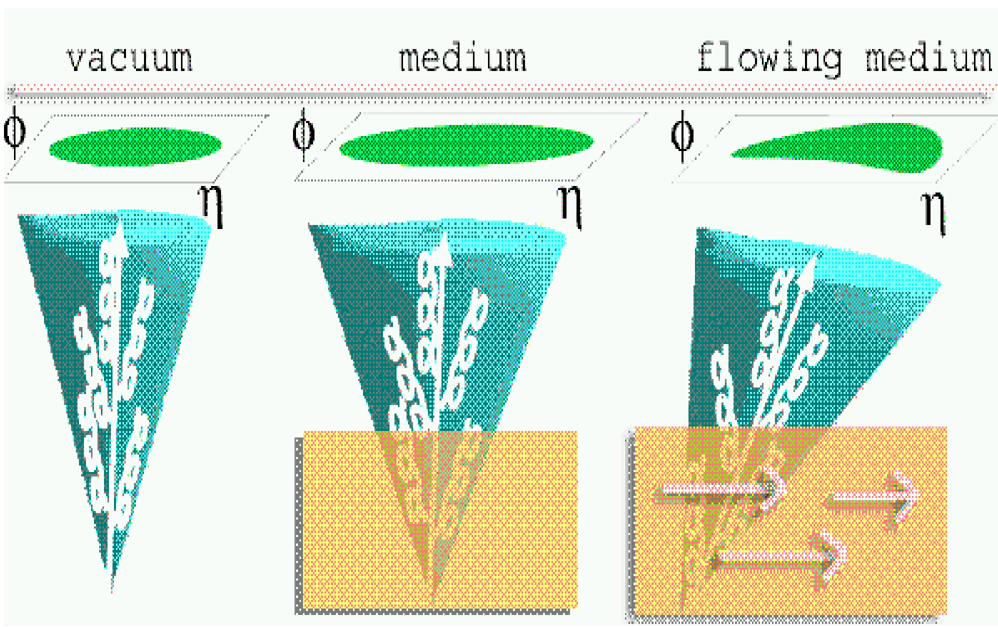
[D. Magestro, HP'04]

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

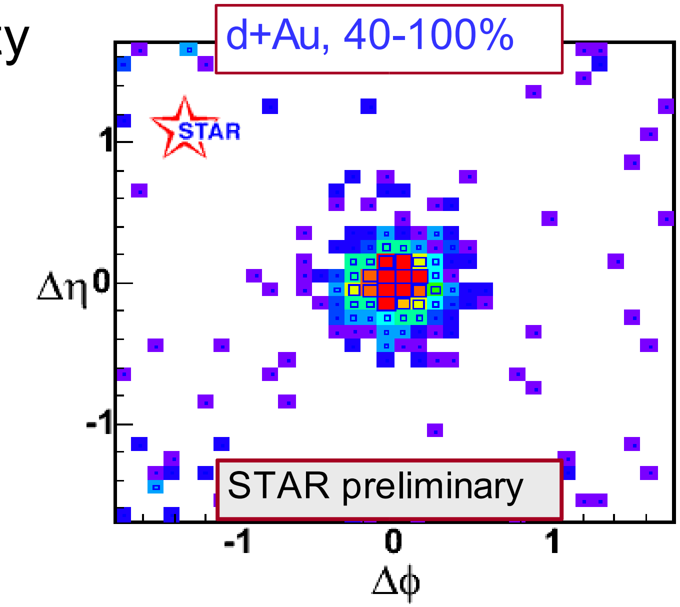
Di-hadron Δη correlations: AuAu, dAu, pp (II)

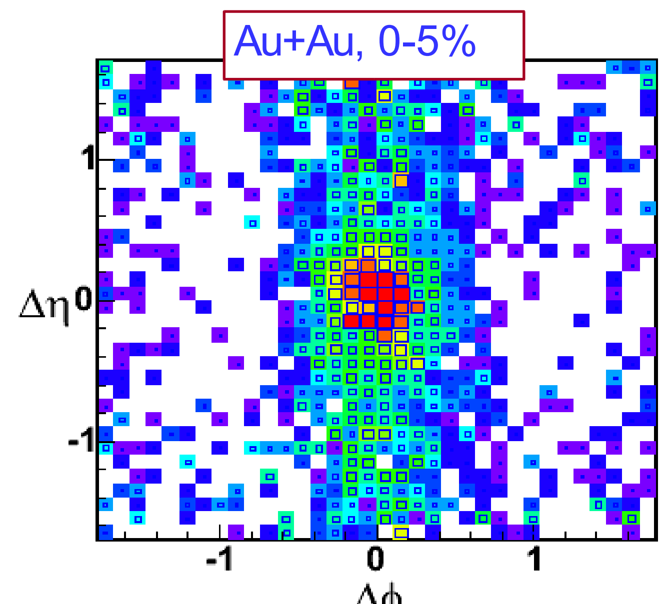
- Significant broadening of near-side pseudorapidity correlations in AuAu compared to pp,dAu. ("stretching" of jet cone along η).

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



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



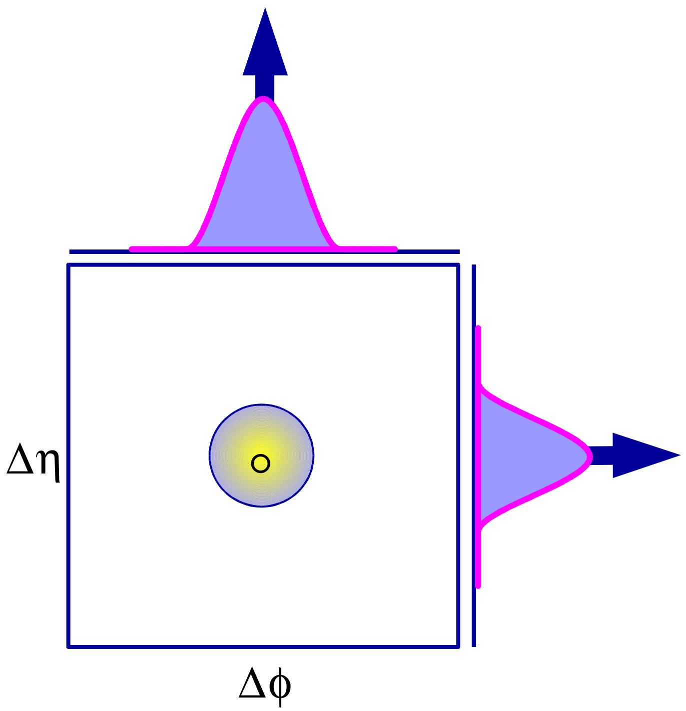


$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

"Cartoon" Summary: Jet-quenching at RHIC

"QCD vacuum" & "cold QCD medium"

- Jet profile in pp (dAu) collisions:

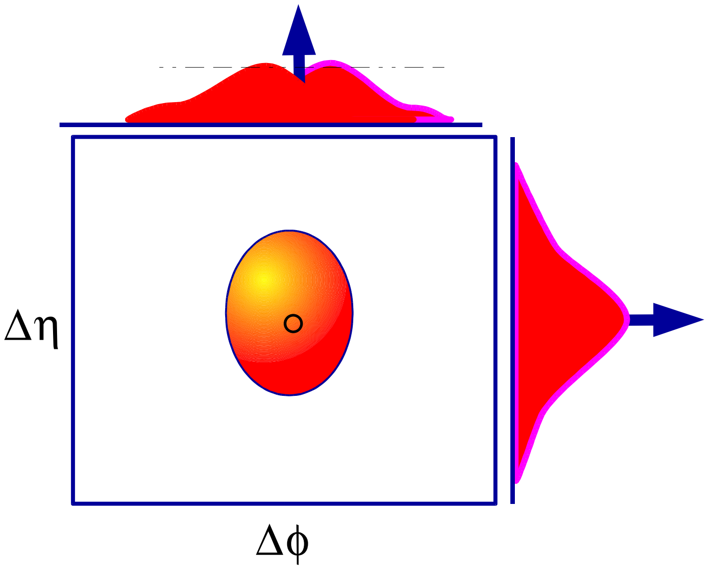


Near-side width: <j_T> ~ 600 MeV/c
unmodified in pp,dAu

Away-side width and acoplanarity
unmodified in pp and dAu

"hot & dense QCD Medium"

- Jet profile in AuAu central collisions:



Factor ~5 suppression of leading hadron
(very large initial parton densities: dN^g/dy~1000)

Disappearance of back-to-back peak ("monojets")

"Double peak" structure at lower p_T in away-side
("sonic boom" in medium ?)

Dijet broadening in η
(coupling of g radiation w/ expanding medium ?)

Strong QCD medium effects at work !

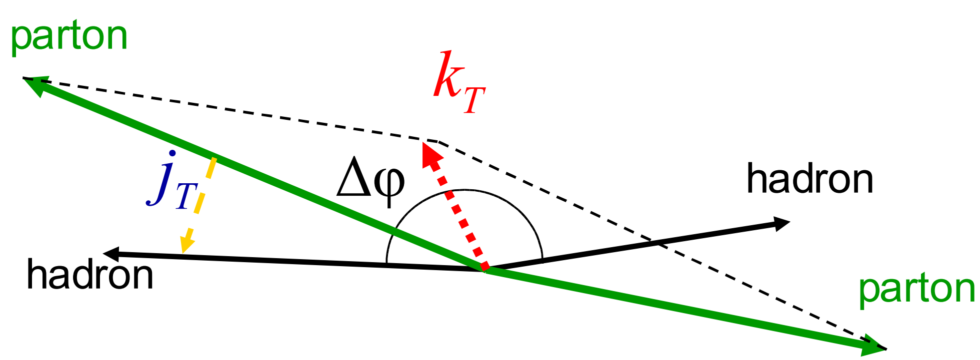
Summary

- Large amount of precision high-p_T hadron production data after 5 years of operation at RHIC allows to quantitatively address jet physics in QCD medium (w/o full jet reco).
- Differential observ. of suppressed hadro-production in central Au+Au provide:
  - stringent constraints on underlying quenching mechanism.
  - direct access to the density & transport properties of QCD medium.
- Are “jet quenching” data due to radiative energy loss in a QGP ?
  - Good agreement with calculations on:
    - Leading hadrons: Magnitude, $\sqrt{s}$, p_T, centrality, (light) species dependence
    - Dihadron correlations: disappeareance of away-side azimuthal dijet peak, Broadening of near-side pseudo-rapidity correlations.
  - Some tests are weak at present:
    - Few details missing in system-size dependence
    - No sharp test of L^2 dependence yet.
    - Heavy quark energy loss larger than expected
- New insights of medium properties from new observables (c_s via “Mach cone”) ?
- LHC = enormous reach, qualitatively new observ. (full jet reco, jet-jet, jet-γ,Z ...)

backup slides ...

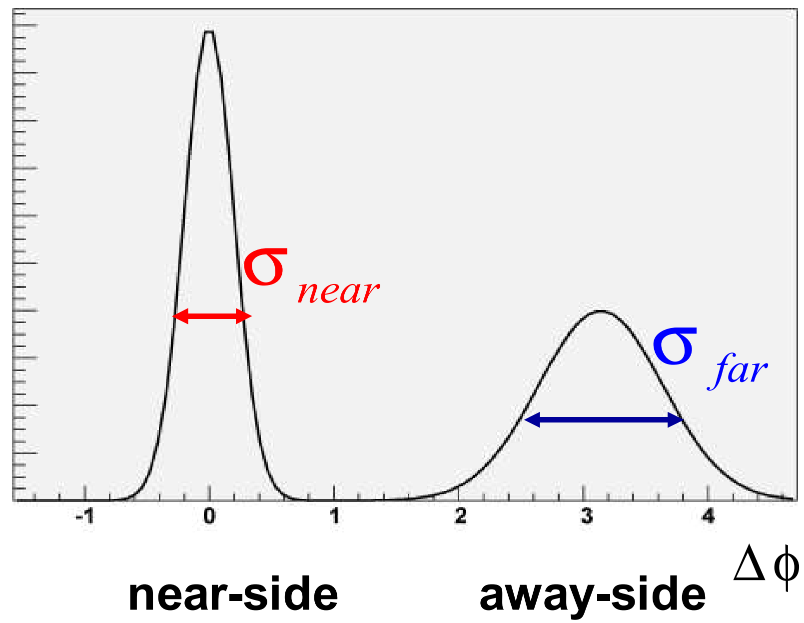
Di-jet properties: experimental observables

- Spread of hadrons around jet axis, relative orientation of the 2 jets: j_T, k_T, p_{out}
- Multiplicity of assoc. hadrons (area under peaks): "fragmentation function" D(z)



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

k_{Ty} : total p_T of parton pair



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

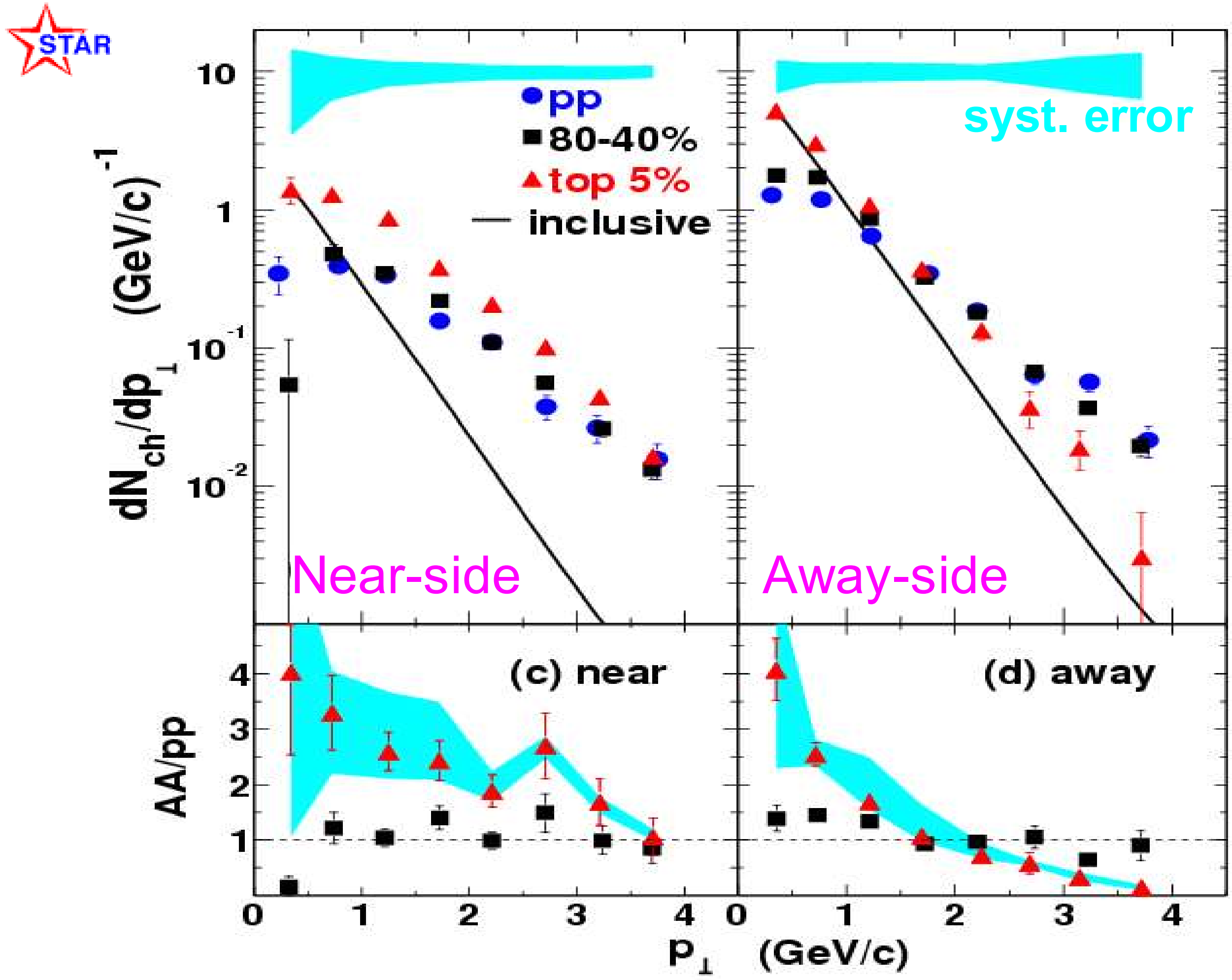
$k_{Ty} \propto \sqrt{\sigma_{far}^2 - \sigma_{near}^2}$ Di-jet acoplanarity k_T

D(z), $z=p/p_{tot}$ "Fragmentation function"

[see e.g. J.Jia, nucl-ex/0409024]

"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

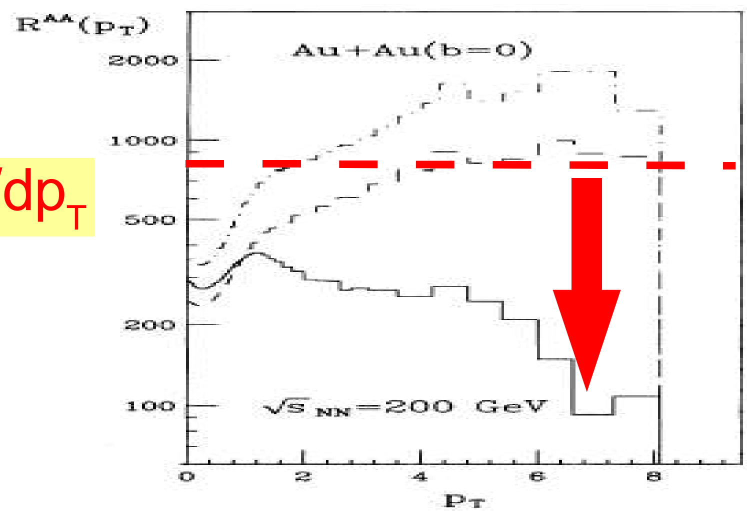
- Associated near-side jet yields overall enhanced (enhanced underlying evt.)
- Associated away-side jet yields "shifted down" in p_T: spectra closer to pure "soft" inclusive hadron production ("thermalized")

Jet production in AA : (a few) theoretical expectations

- Leading hadron suppression:

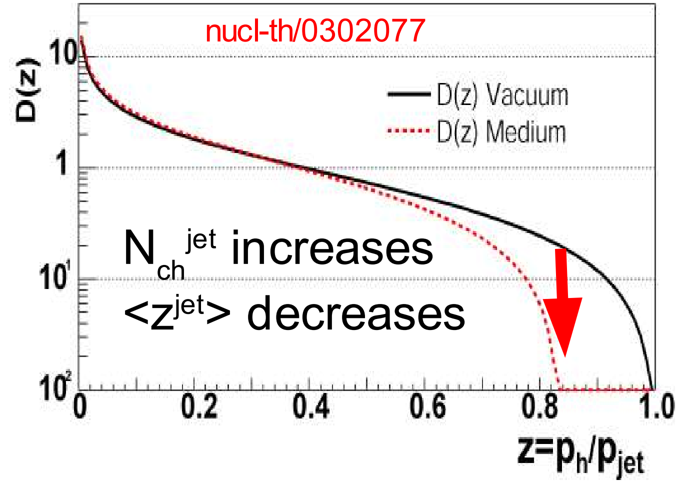
X.N.Wang&M.Gyulassy PRL 68, 1480 (1992)

dN/dp_T



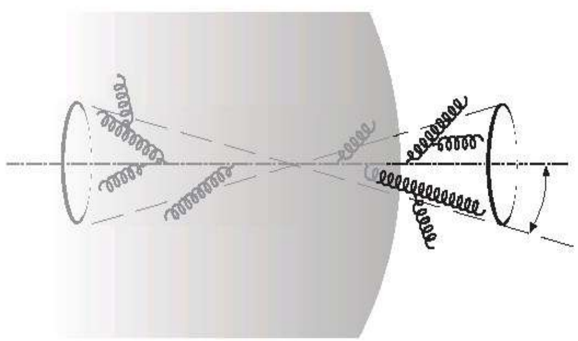
- Medium-modified FFs:

dN/dz_T



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

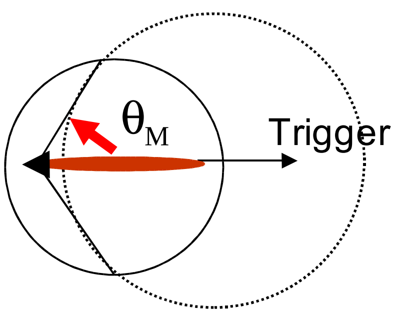
- Mono-jets: $dN_{pair}/d\varphi$



Bjorken, 1982

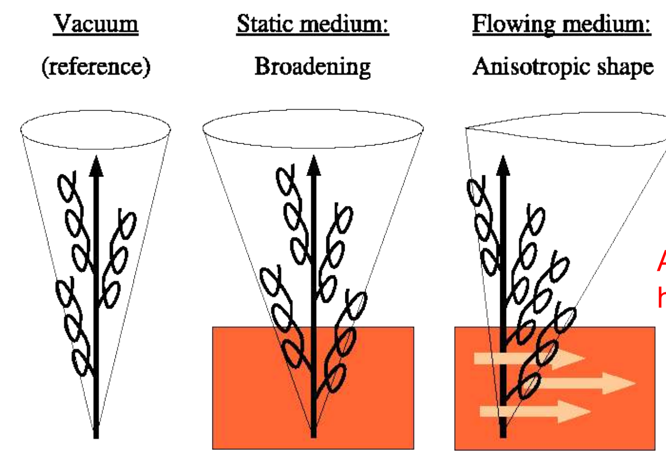
- "Mach cone":

$$\cos\theta_M = c_s$$



Stoecker et al. hep-ph/0505245.
Casalderrey, Shuryak, hep-ph/0411315

- Jet broadening in η: $dN_{pair}/d\eta$

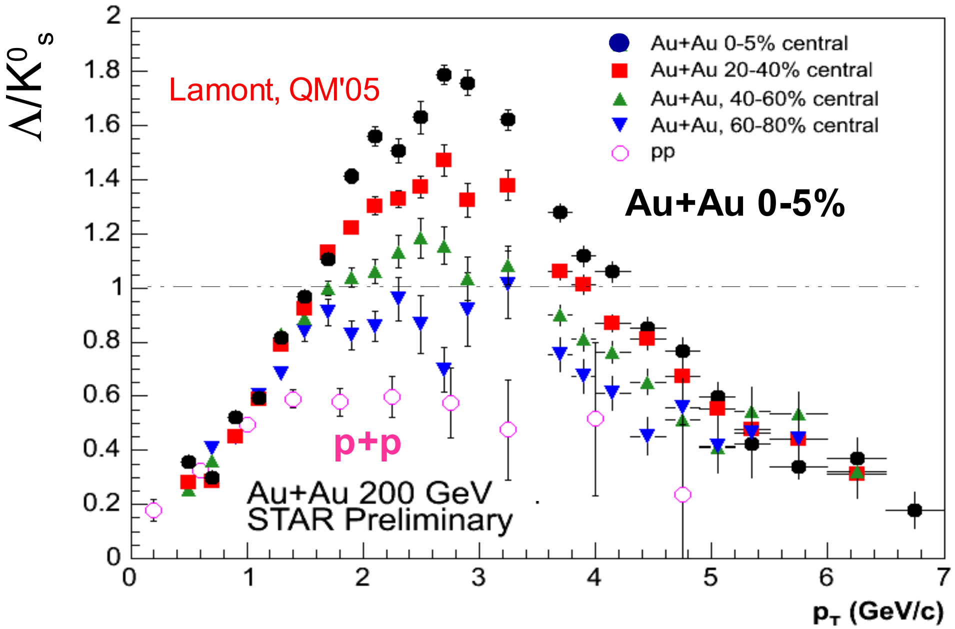


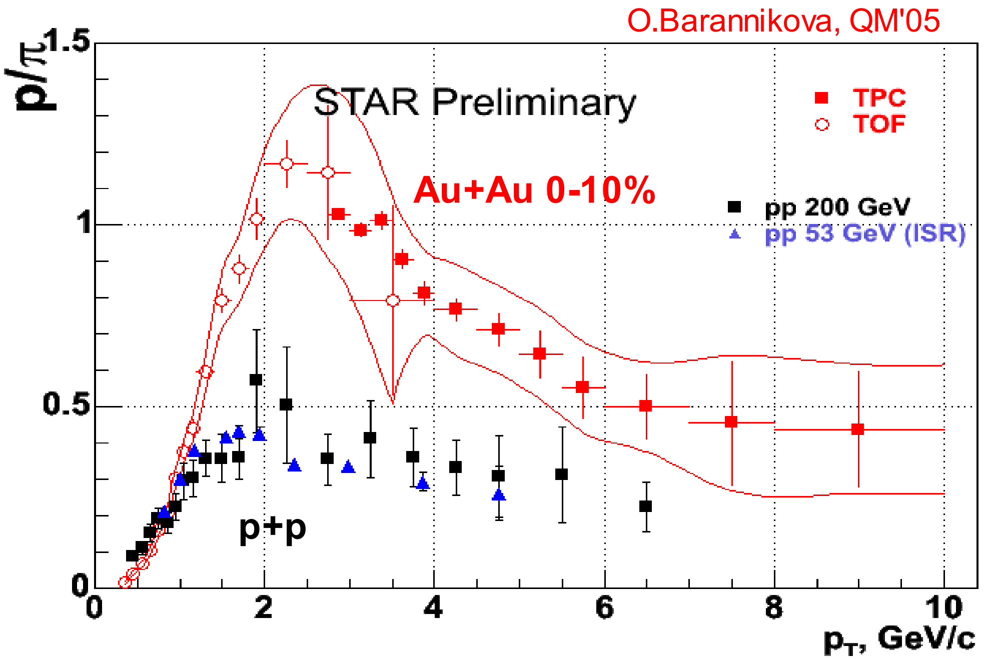
Armesto et al
hep-ph/0405301

➡ Valuable **diagnostic tools** of QCD medium properties (dN^g/dy, $<q_0>$, c_s, ...)

Intermediate p_T mesons suppressed. Baryons are not

- Strongly enhanced baryon (p, Λ) production at $p_T \sim 2 - 4$ GeV/c

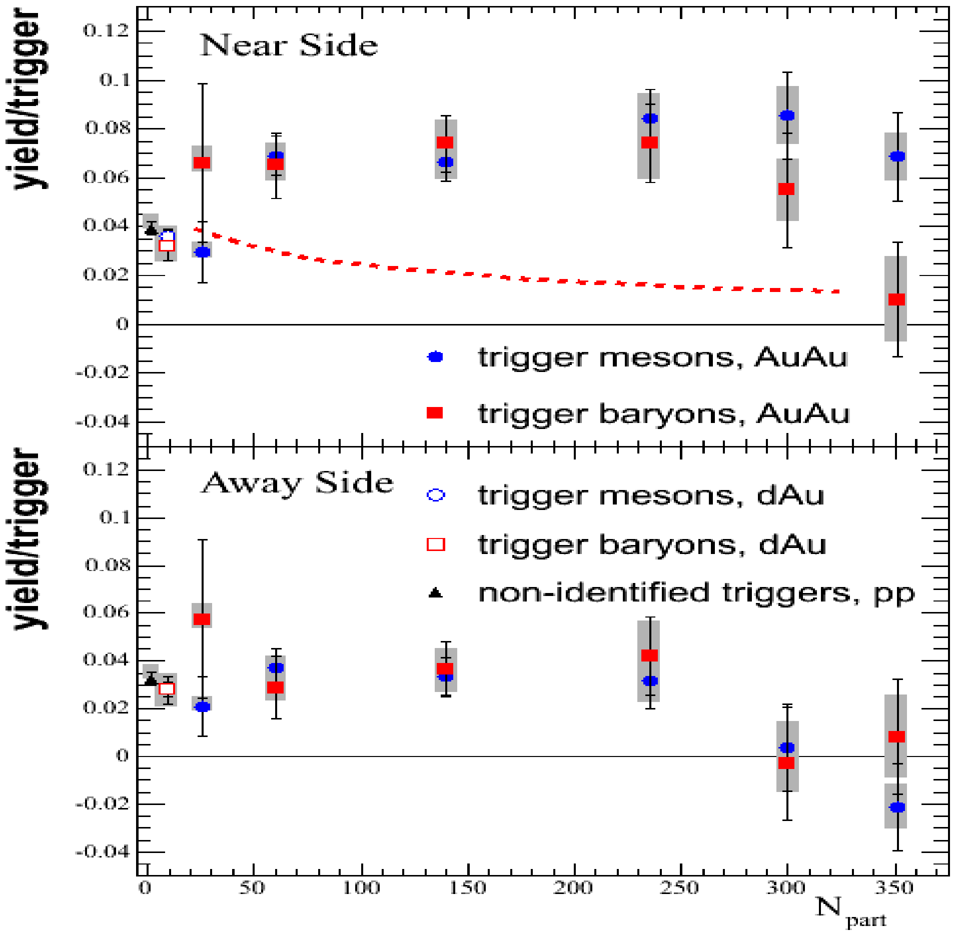




- Strong centrality dependent baryon/meson: ratio well above “perturbative” (pp) ratios.
- Clear deviation from std. vacuum fragmentation functions (large non-pQCD effects) calls for extra baryon production mechanism: recombination.
- Above $p_T \sim 6$ GeV/c: Recovery of “vacuum” fragmentation ratio. Baryons suppressed too.

Baryon vs. meson "fragmentation functions"

- However ... Associated yields similar for meson & baryon triggers.



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

Near-side

Away-side

PHENIX
PRC 71, 051902 (2005)

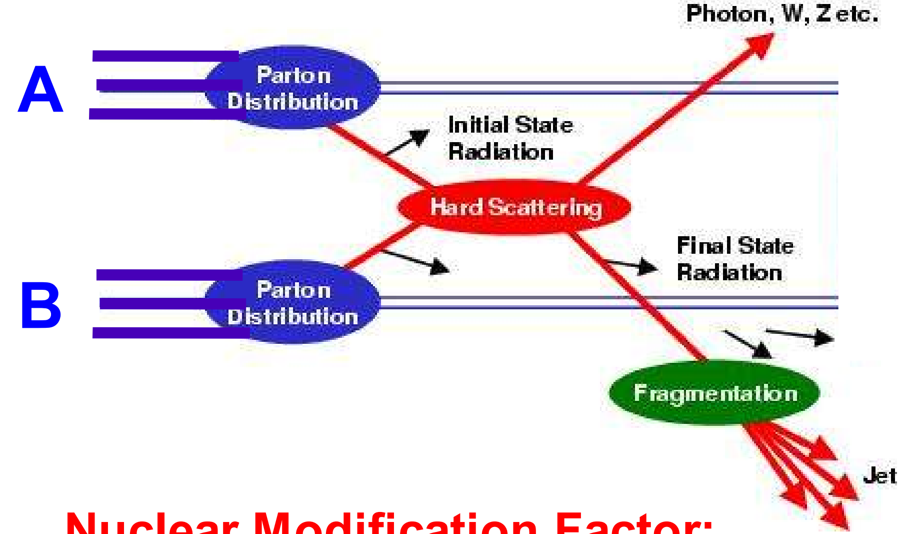
- Magnitude and centrality-dependence of associated (near- & away- side) hadron p_T spectra for baryon & meson triggers show small differences.
- Jet-like production but different suppression for leading baryons and mesons !?

How to compare high p_T spectra in AA and pp ?

- High p_T particles issue from hard scatterings describable by pQCD:

"Factorization theorem":

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



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"

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

At impact parameter b:

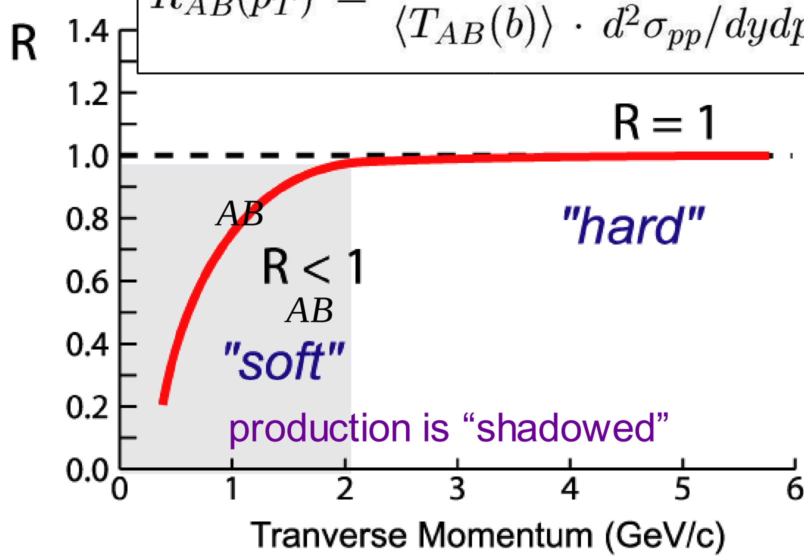
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

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

Nuclear Modification Factor:

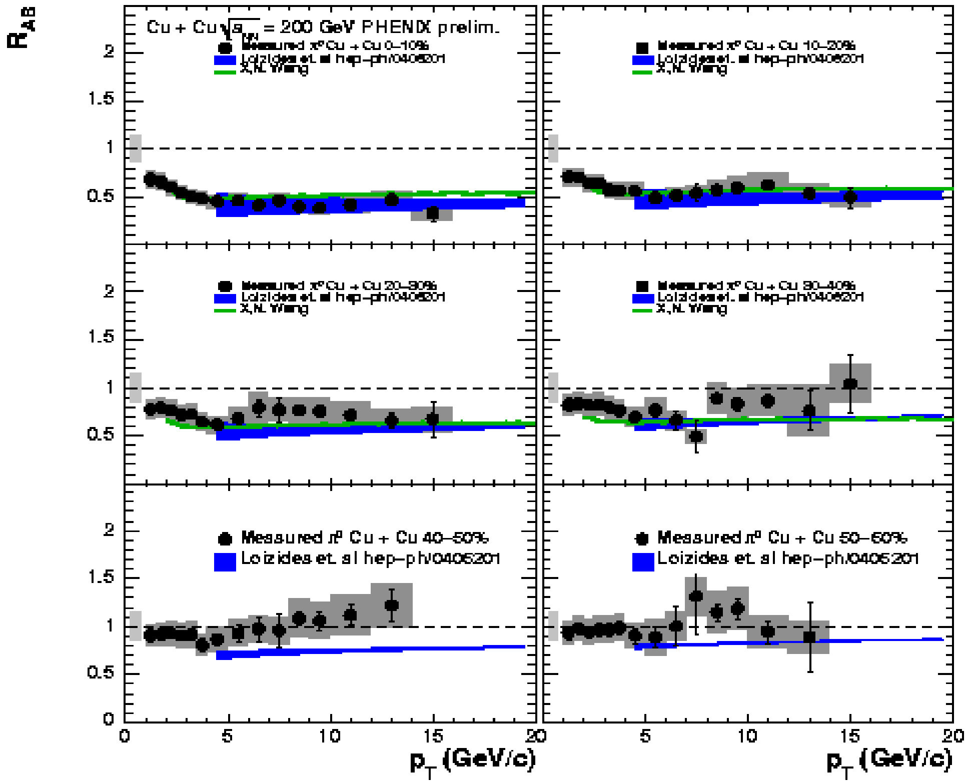
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle\cdot d^2\sigma_{pp}/dydp_T}$$



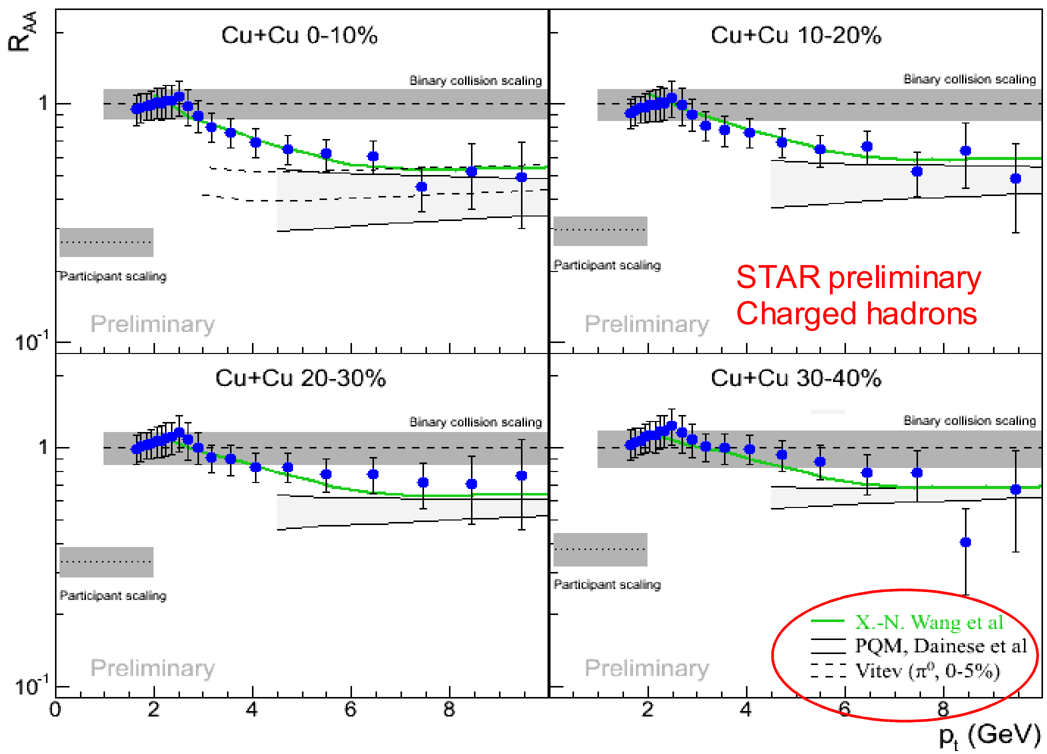
High p_T suppression: system-size dependence

- R_{AA} for Cu+Cu @ $\sqrt{s_{NN}}$ = 200 GeV

M. Shimomura (PHENIX), QM'05



M. van Leeuwen (STAR), QM'05



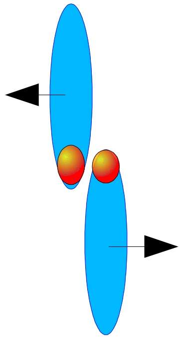
- Suppression observed for central Cu+Cu
- Models scale density from central Au+Au

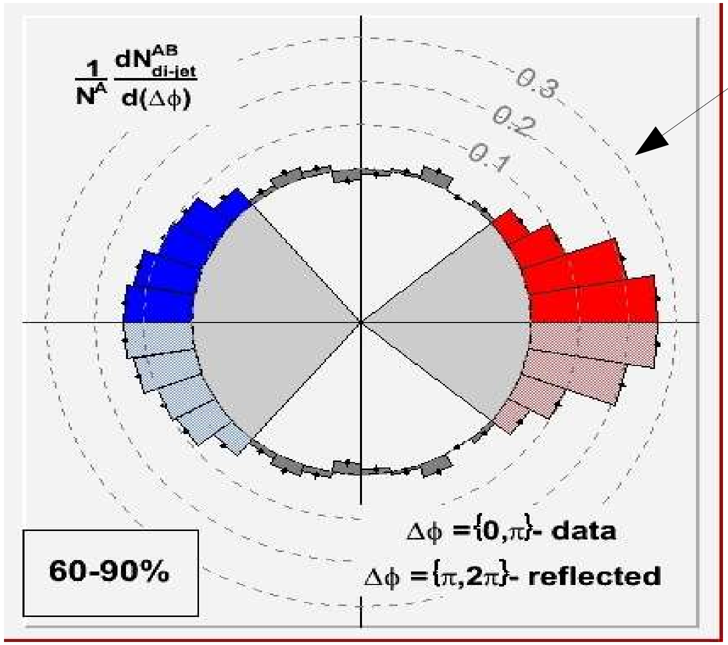
All models show reasonable to good agreement

Di-hadron AuAu: Δφ correlations (III)

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

Au+Au peripheral

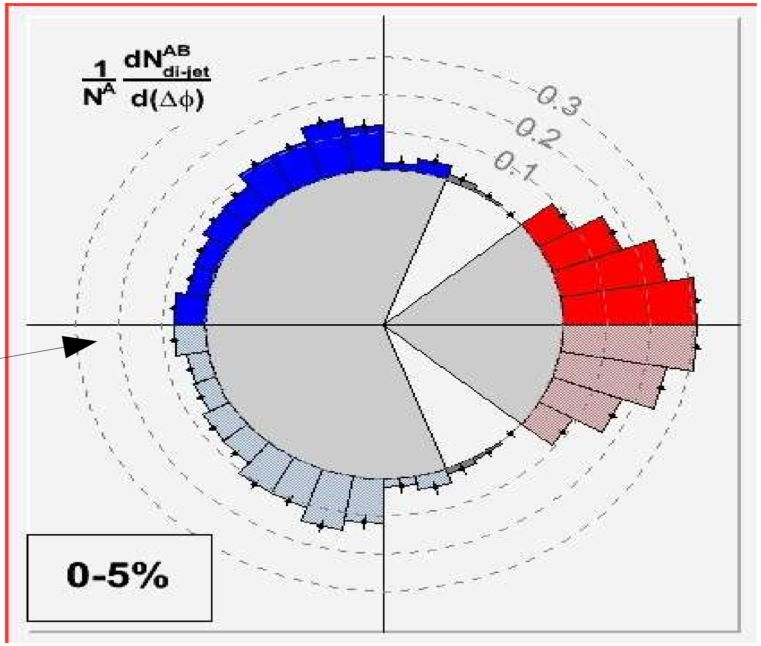


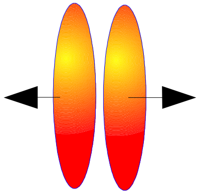


- Standard back-to-back di-jet topology.

PHENIX Preliminary

Au+Au central



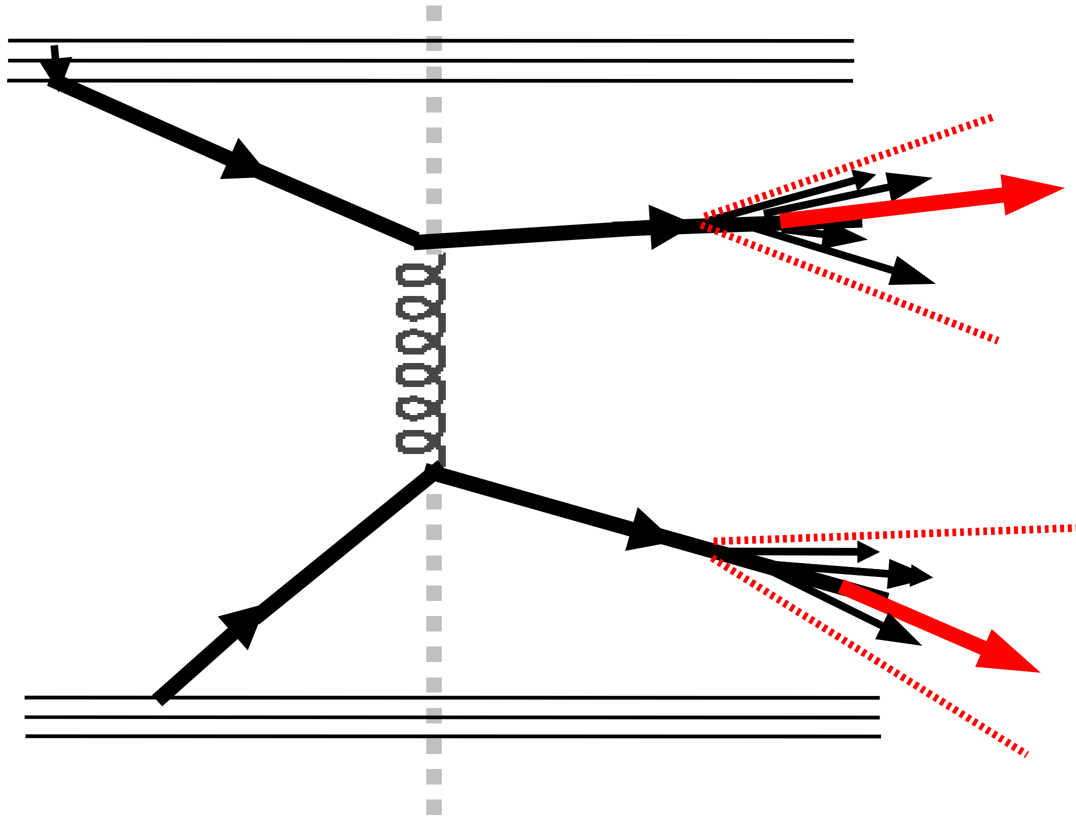


- Strongly non-Gaussian away-side "peak".

PHENIX

PHENIX Collab. PRL to be submitted

Jet production in the "QCD vacuum" (pp collisions)



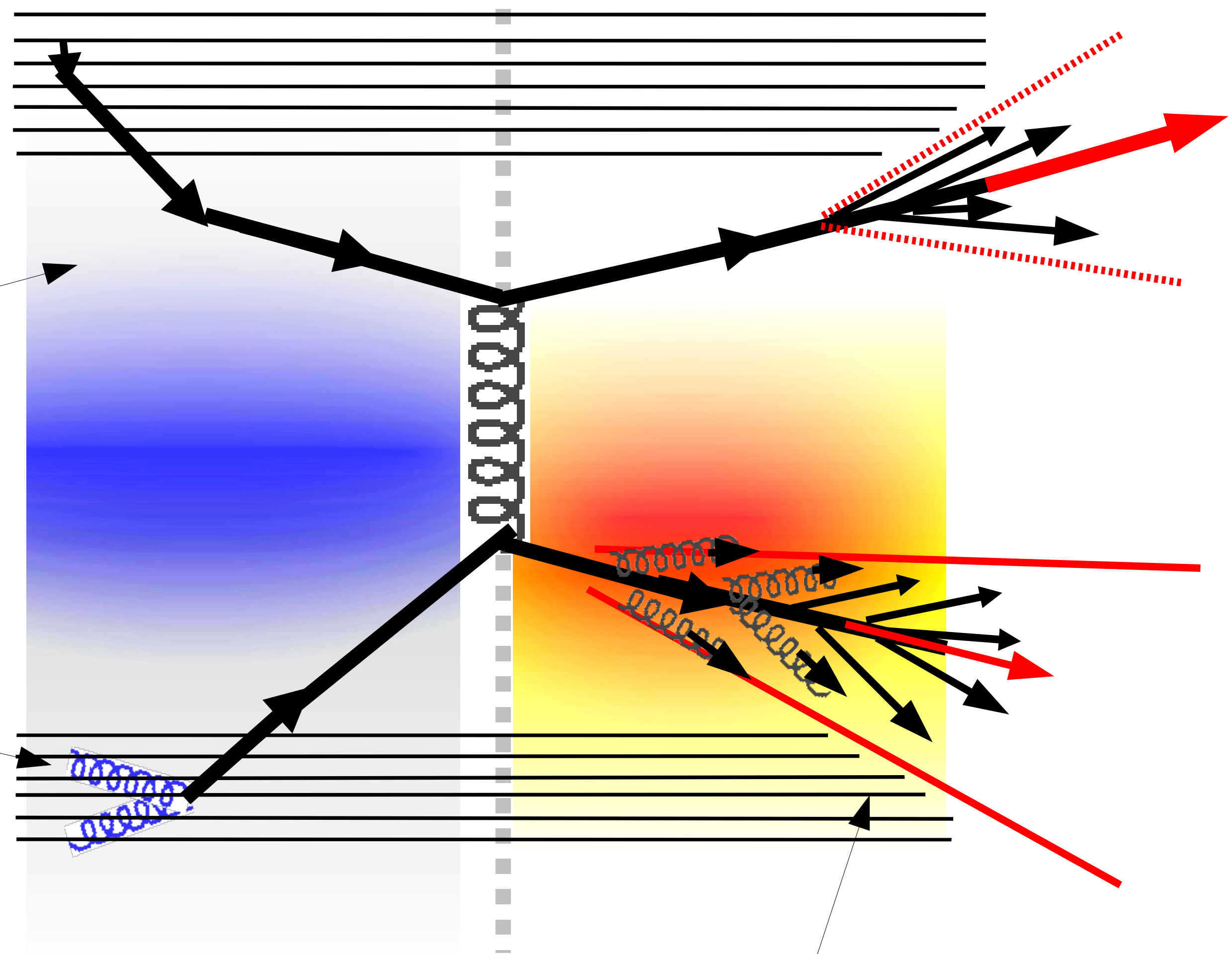
- Jet : Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~ 0.7) with 4-momentum of original fragmenting parton
- Leading hadron takes away large fraction (<z> ~0.6 –0.8 @ RHIC) of parent parton p_T
- Jet balanced back-to-back by other hard-scattered "parton" (jet, direct γ, ...)

Jet production in "QCD media" (pA, AA collisions)

- Initial-state effects
  (accessible via pA colls.):

  k_T broadening
  (Cronin enhancement)

  (Leading-twist) shadowing
  or gluon saturation (**CGC**)



- Final-state effects
  (accessible in AA colls.):

  Parton energy loss due to medium-induced
  gluon-strahlung in hot & dense environment

"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.

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