Jet quenching at RHIC: experimental perspective

Workshop on Parton Propagation through Strongly Interacting Matter

ECT*, Trento, October 2nd, 2005

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Overview

- Physics motivation:

  Jet production in QCD medium (AA) vs. QCD vacuum (pp) as a signature of QGP formation at RHIC.

  "Jet physics"@RHIC (w/o full jet reco): Inclusive high p_T spectra, 2-hadron correls.

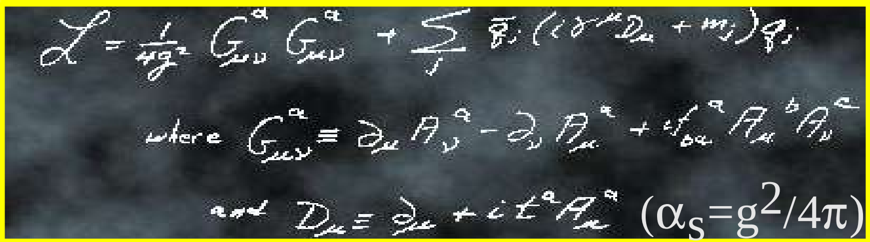
- High p_T (leading) hadron suppression data in central AA confronted to non-Abelian radiative energy loss "paradigm":

  1. Magnitude ⇒ Very dense medium: $dN^g/dy \sim 1000$ ($\sim dN_{ch}/d\eta$). **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. Baryon vs. meson suppression. **OK ?**
  10. Heavy vs. light quark suppression. **OK ?**

- Summary

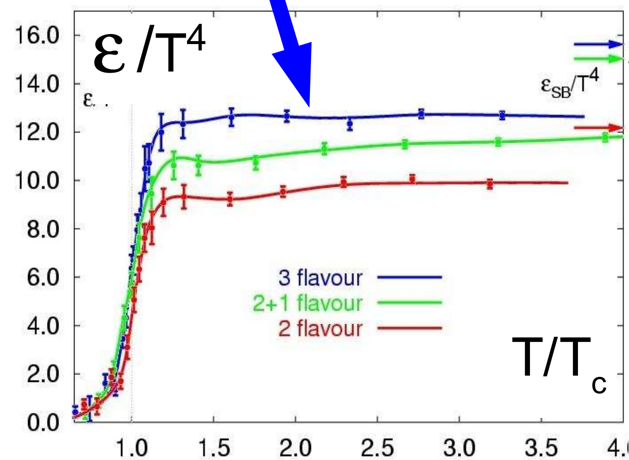
High-energy heavy-ion physics program (in 4 plots)

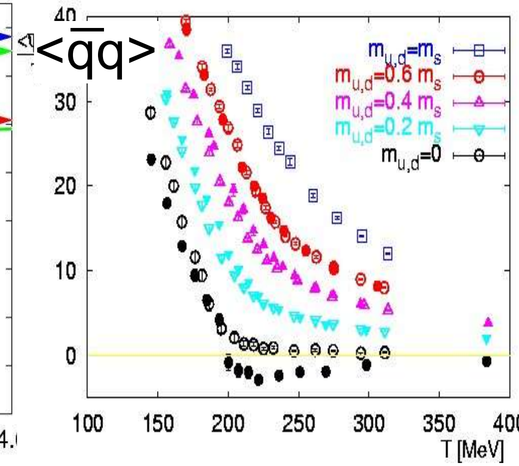


$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

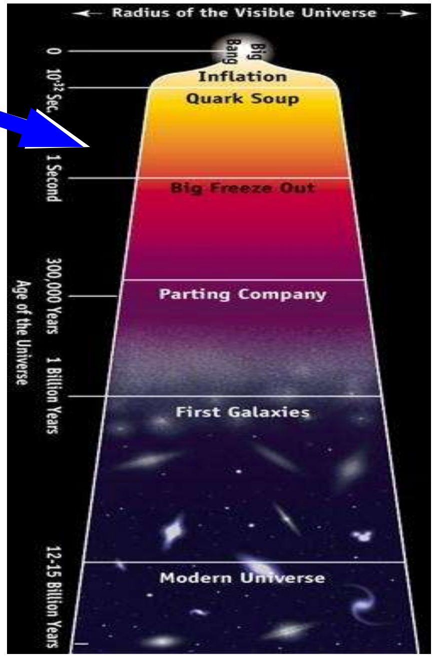
1. Learn about 2 basic properties of strong interaction: (de)confinement, chiral symm. breaking (restoration)

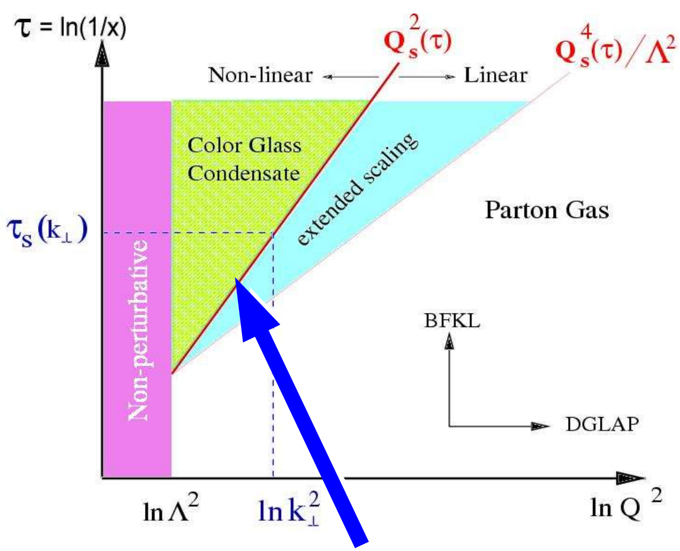
2. Study the collective dynamics of q&g (QCD phase diagram): produce & study the QGP





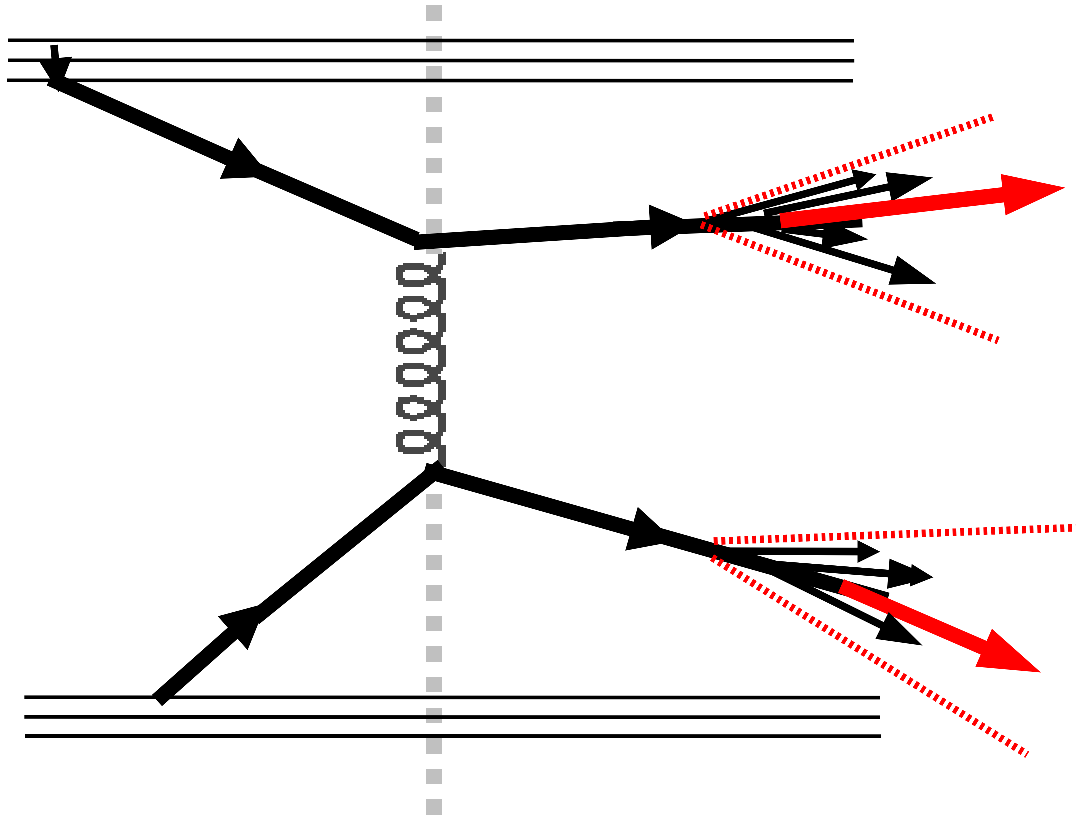
3. Probe quark-hadron phase transition of the primordial Universe (few μsec after the Big Bang)





4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

Jet production in the “QCD vacuum” (pp collisions)



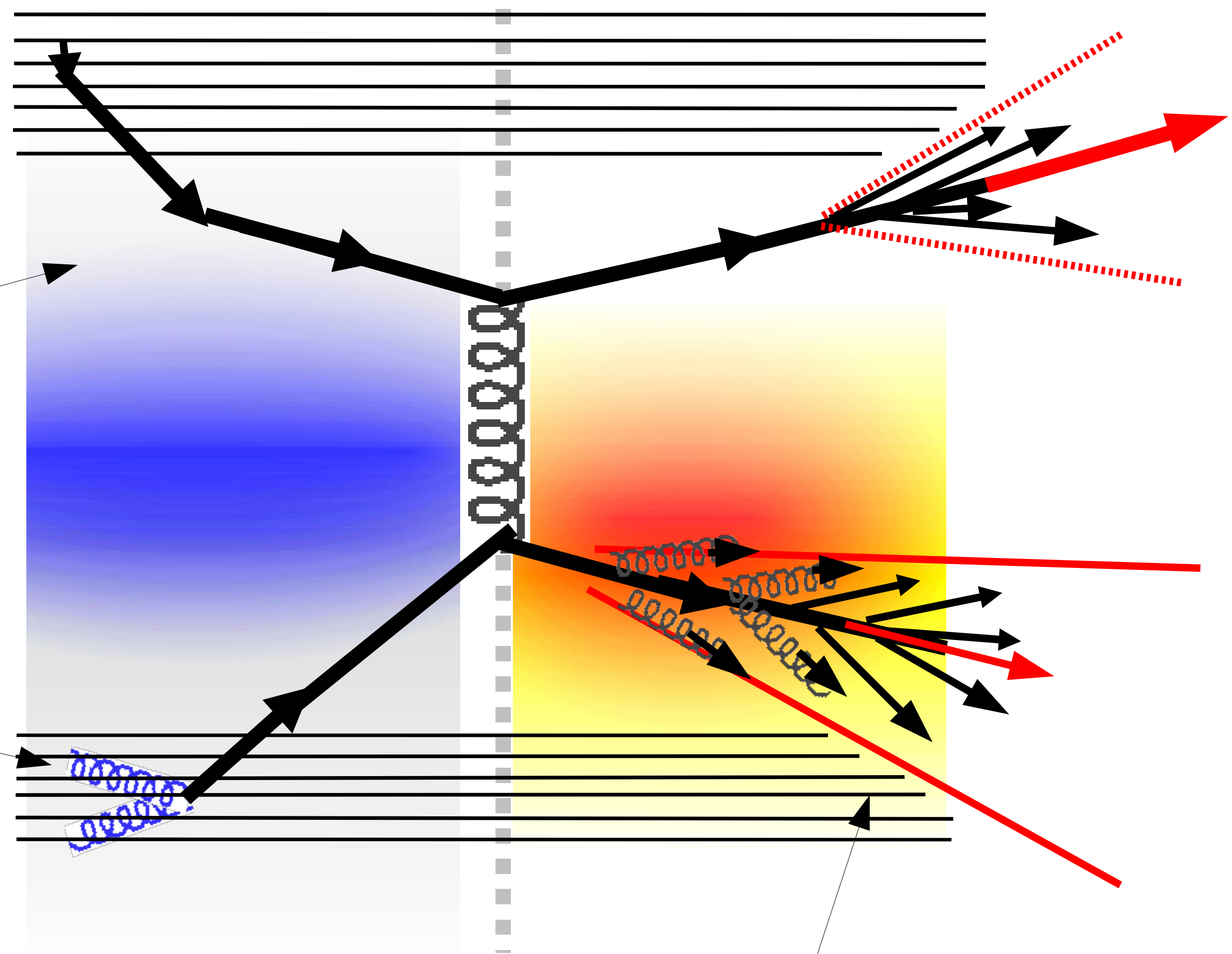
- Jet : Collimated spray of hadrons in a cone ($R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ ~ 0.7) with 4-momentum of original fragmenting parton
- Leading hadron takes away large fraction (**<z>** ~0.6 –0.8 @ RHIC) of parent parton p_T
- Jet balanced back-to-back by other hard-scattered "parton" (jet, direct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

"Jet quenching" as a QGP signal

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

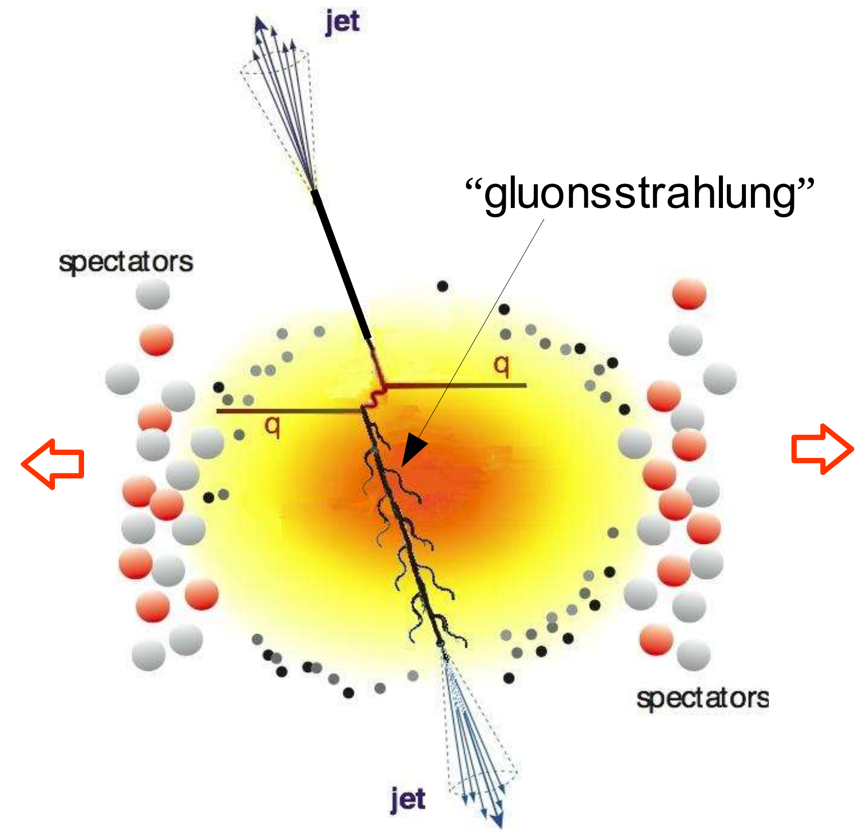
- Parton energy loss ∝ medium properties:

$$\Delta E \simeq \int d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_s C_R \omega_c = \alpha_s C_R \hat{q} L^2/2$$

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

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

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



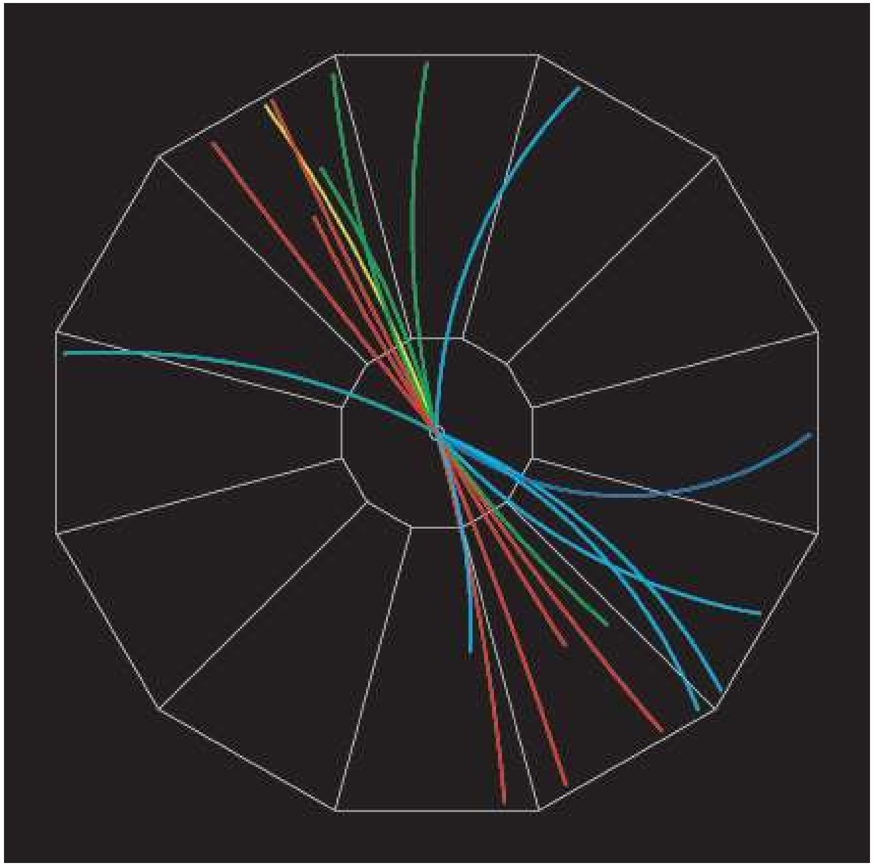
- Different energy losses: $\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (mass effect)

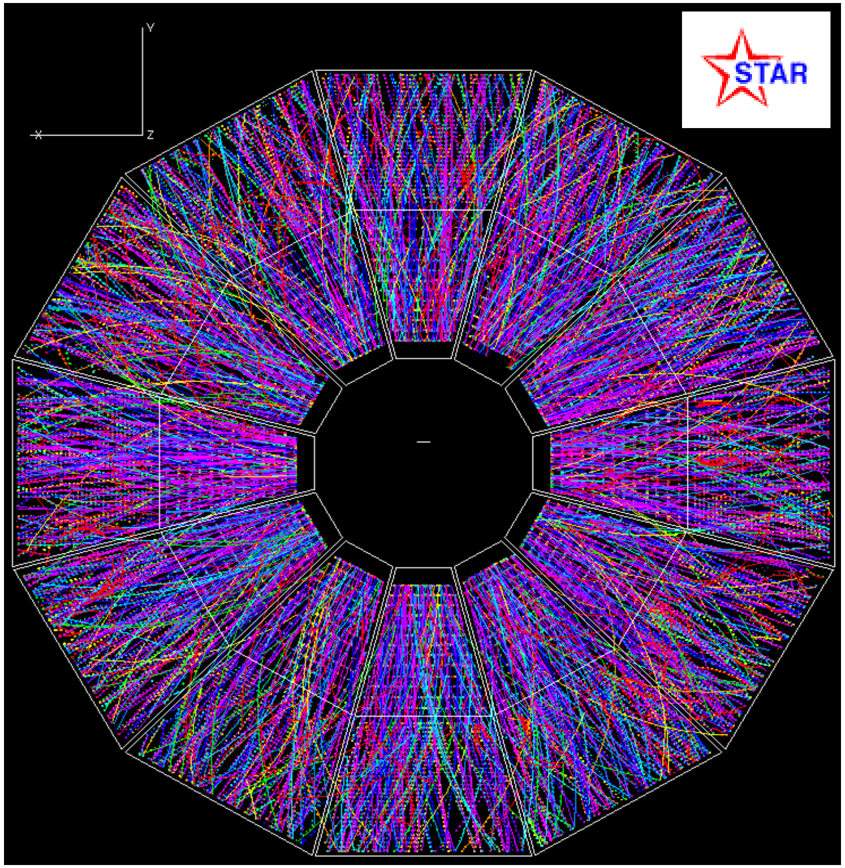
- Prediction I: Suppression of high p_T leading hadrons: dN/dp_T ◄ SPS,RHIC,LHC
- Prediction II: Modification of (di)jet correlations: $d^2N_{pair}/d\varphi d\eta$ ◄ RHIC,LHC
- Predition III: Modified energy- & particle- flow within full jet ◄ LHC

Jet physics at RHIC: full jet reconstruction ?

- 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]

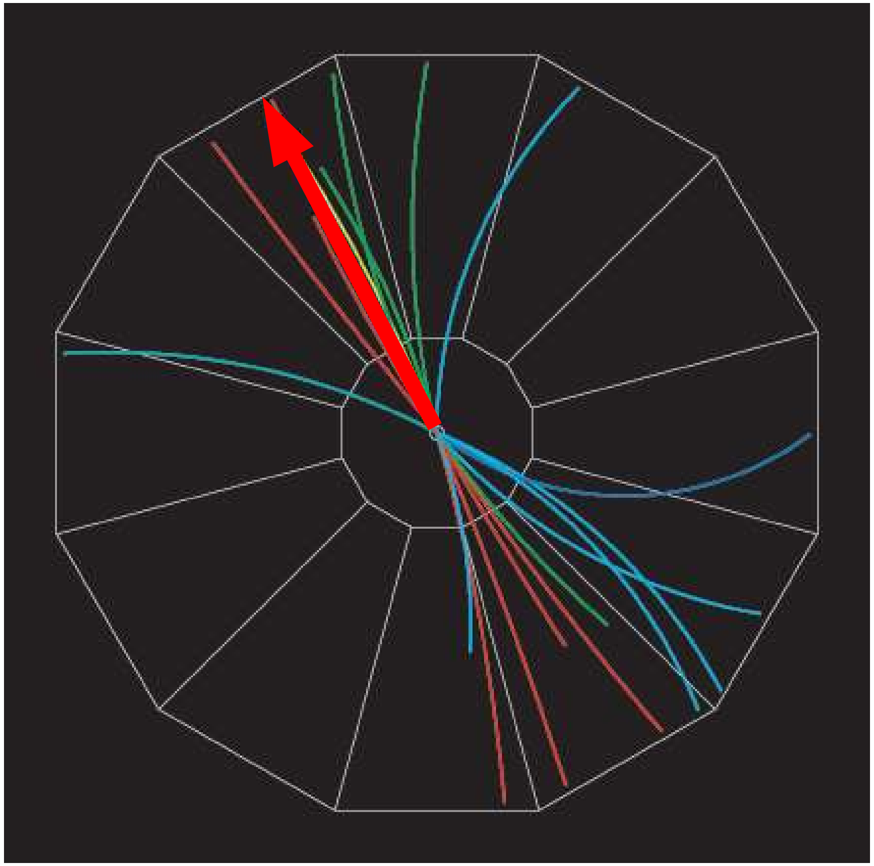


Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]

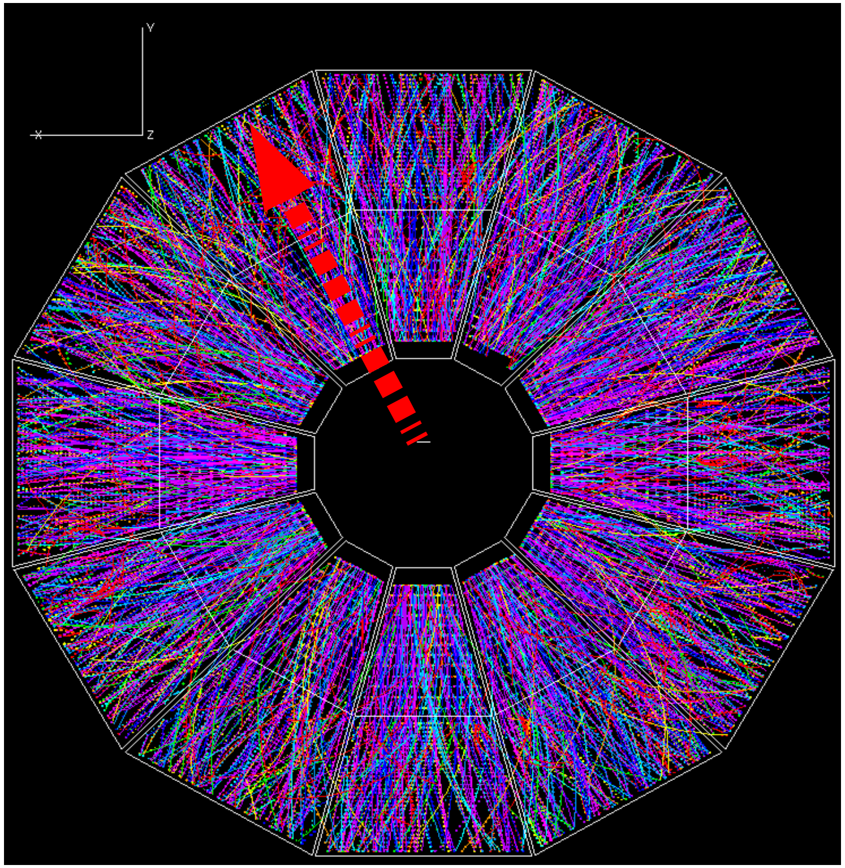
- Feasible at LHC for E_{jet} >~ 50 GeV

"Jet physics" at RHIC: 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 → h+ X [$\sqrt{s}$ = 200 GeV]

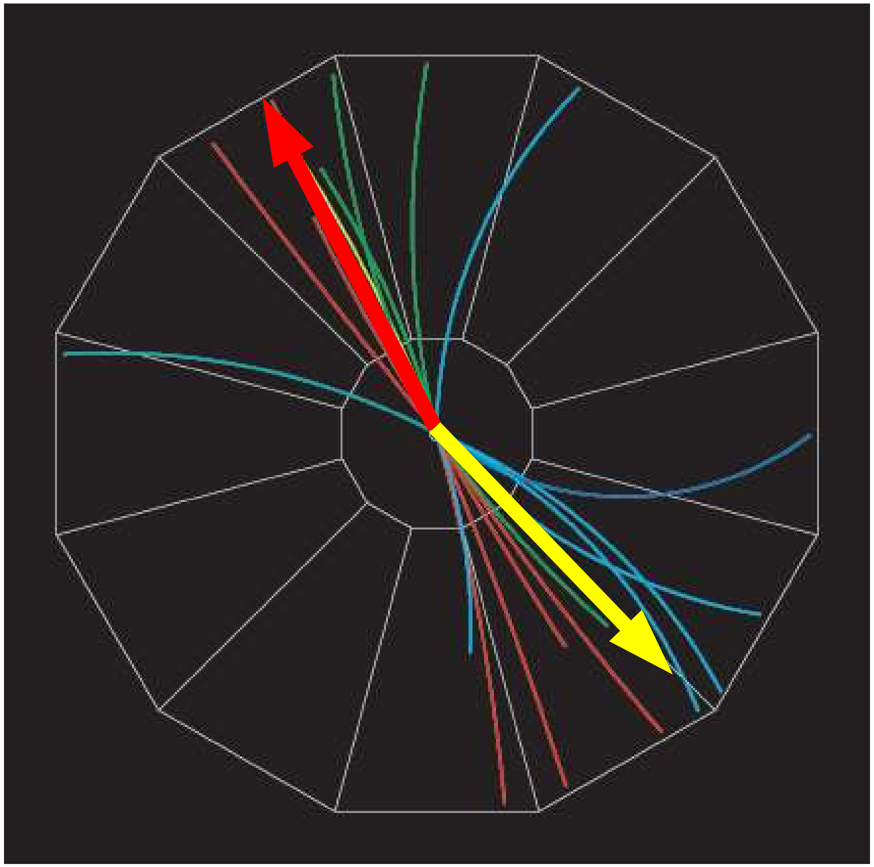


Au+Au → h+X [$\sqrt{s_{NN}}$ = 200 GeV]

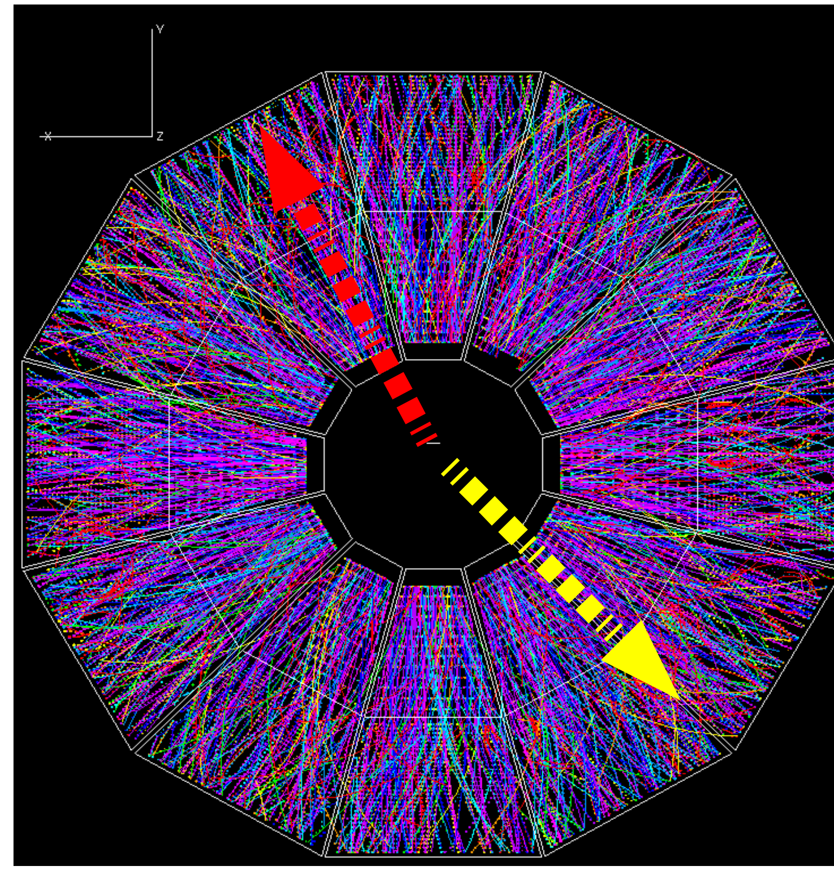
- Many interesting results obtained from this "first-order" approach !

“Jet physics” at RHIC: di-hadron azimuthal correlations

- Alternative II : Study the azimuthal correlations in AA w.r.t. pp between the highest p_T hadron (“trigger”) & any other “associated” hadron:



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



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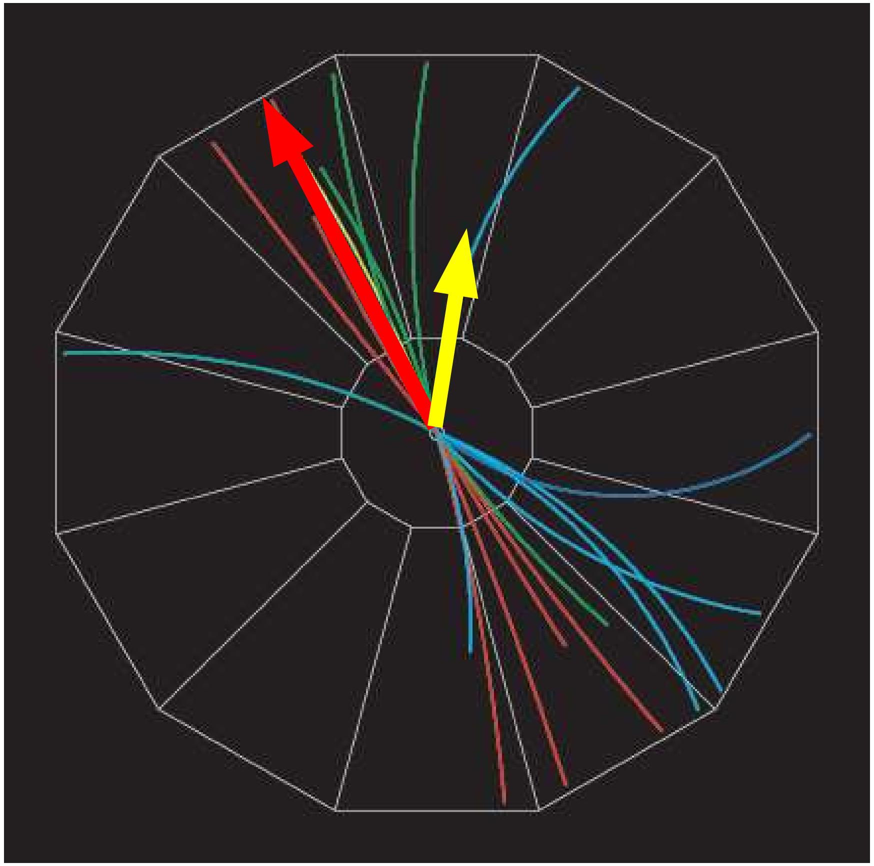
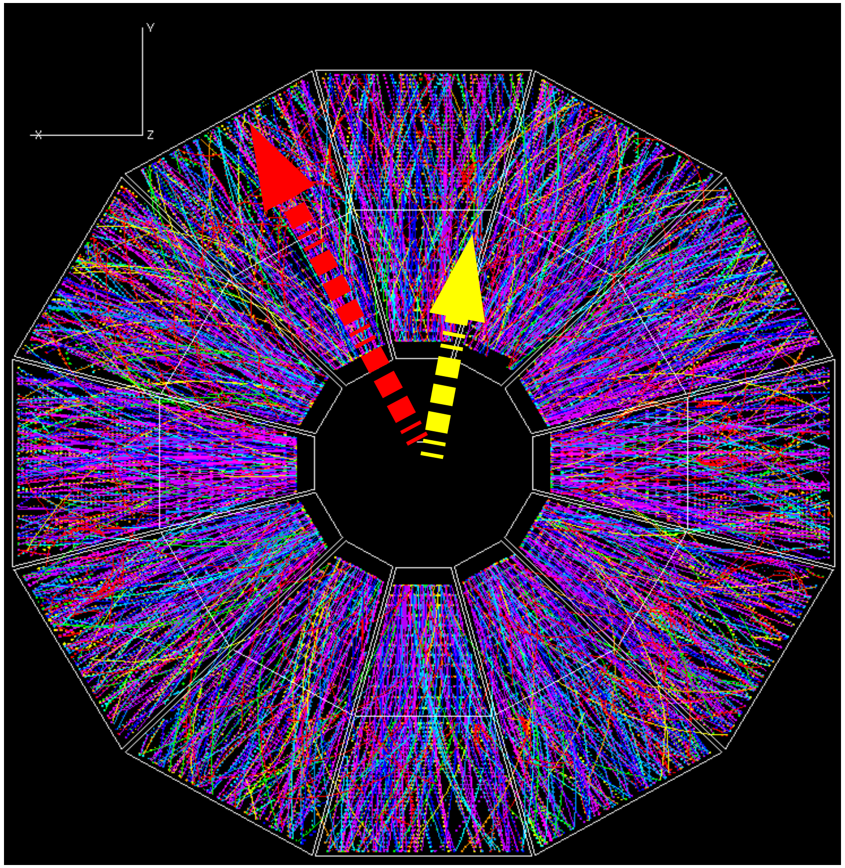


$p+p \rightarrow h_1+h_2+X$ [$\sqrt{s}$ = 200 GeV]



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

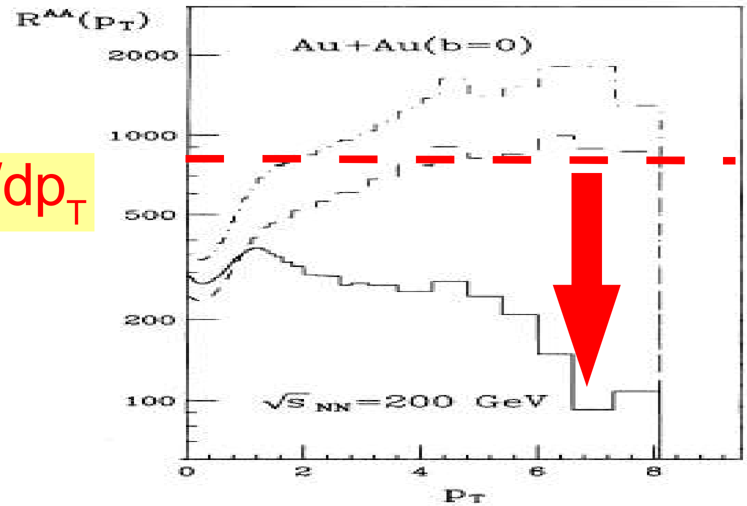
- Many interesting results also obtained from this “2nd-order” approach !

Jet production in AA : (a few) theoretical expectations

- Leading hadron suppression:

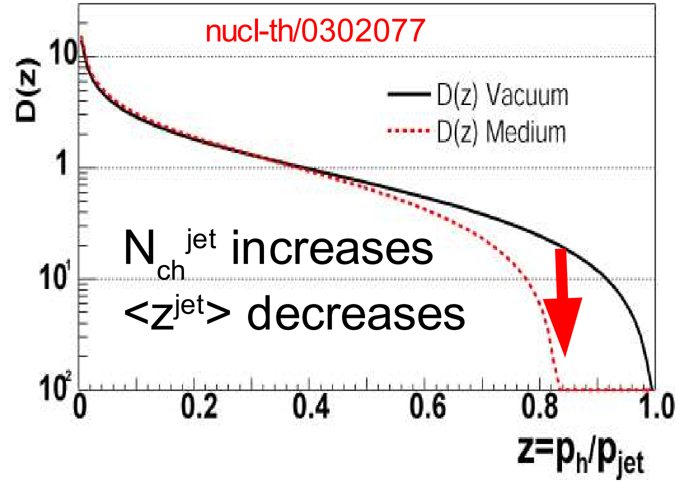
X.N.Wang&M.Gyulassy PRL 68, 1480 (1992)

dN/dp_T



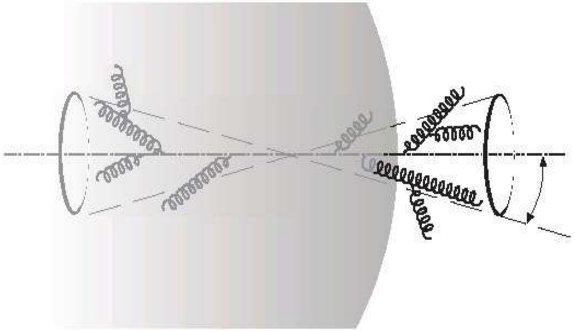
- Medium-modified FFs:

dN/dz_T



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

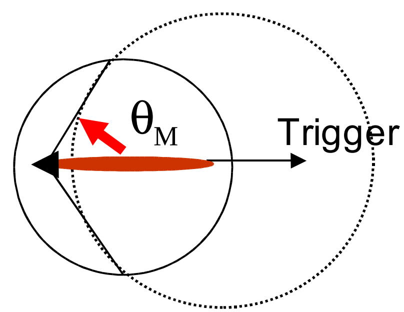
- Mono-jets: $dN_{pair}/d\varphi$



Bjorken, 1982

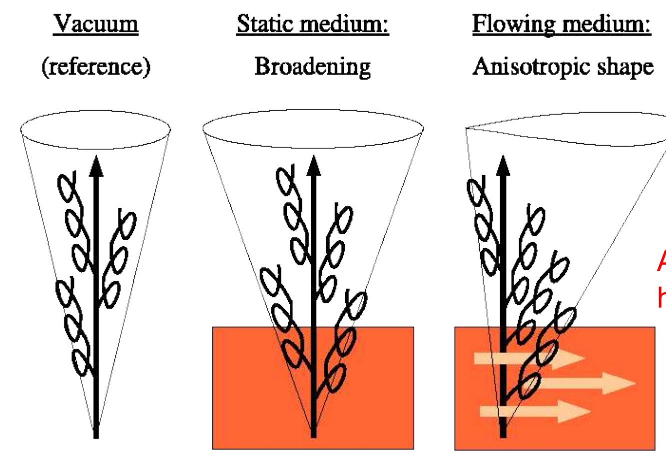
- "Mach cone":

$$\cos\Theta_M = c_s$$



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

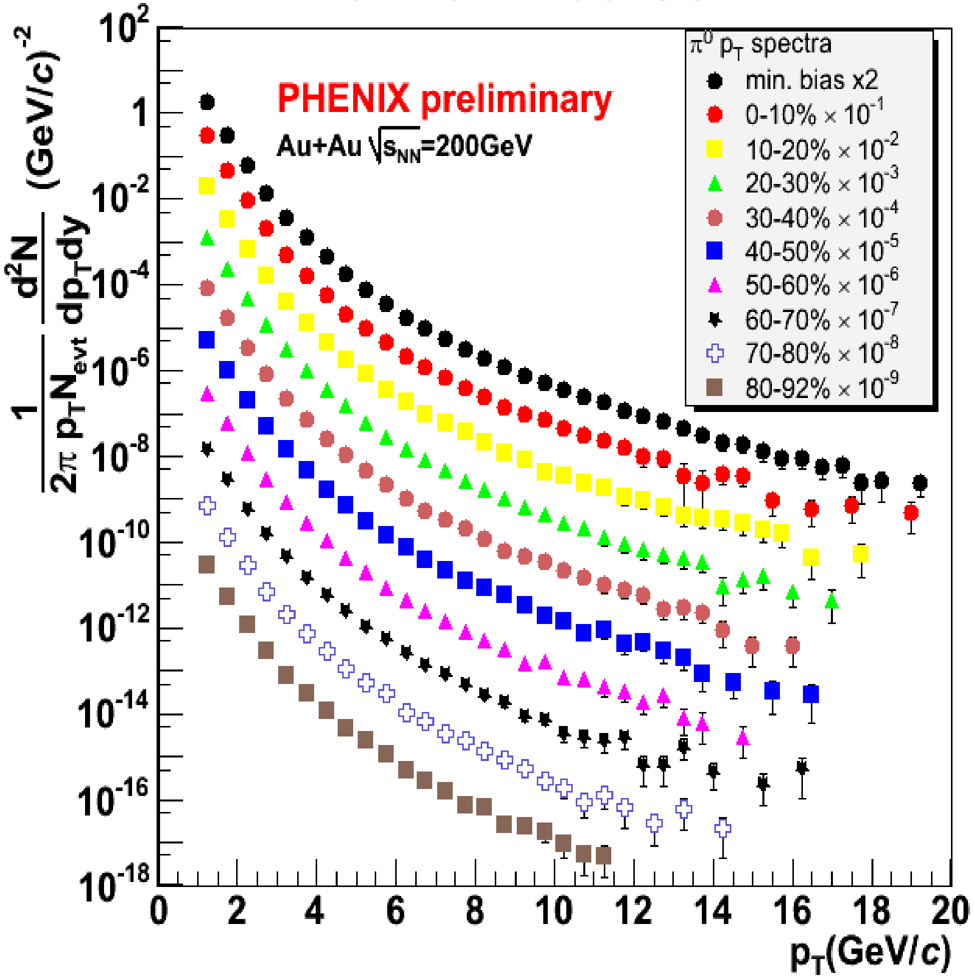
➜ Valuable diagnostic tools of QCD medium properties (dN^g/dy, <q_0>, c_s, ...)

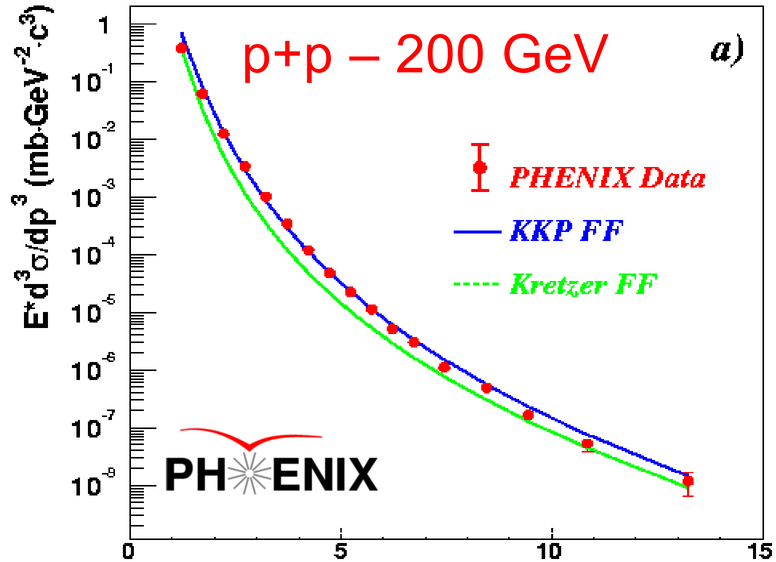
High p_T leading hadron spectra at RHIC & jet-quenching models: Good agreement data ↔ theory

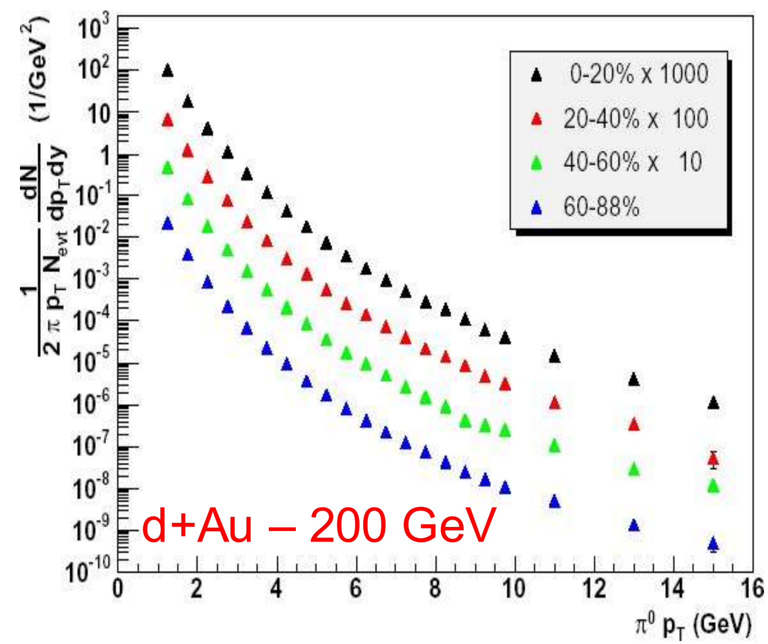
Inclusive single spectra at high p_T (AA, dA, pp)

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

Au+Au – 200 GeV





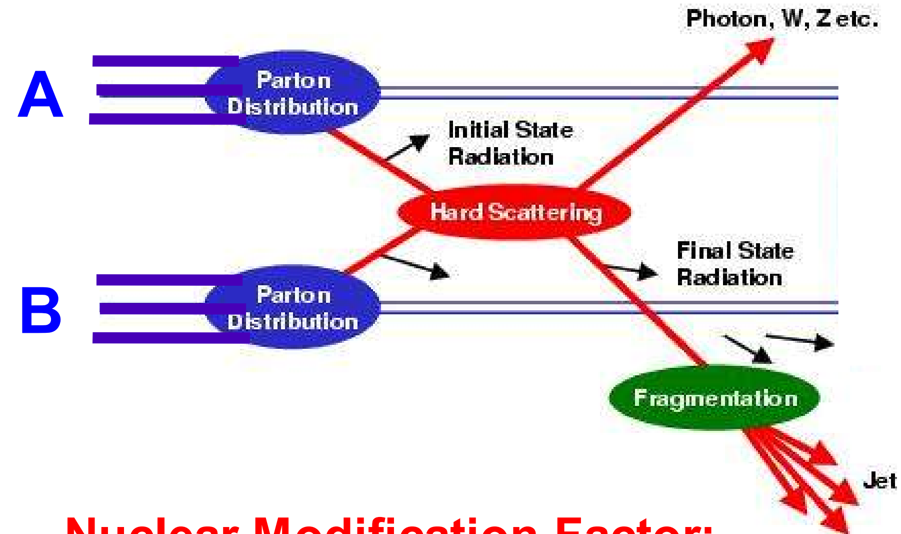


How to compare high p_T spectra in AA and pp ?

- 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:

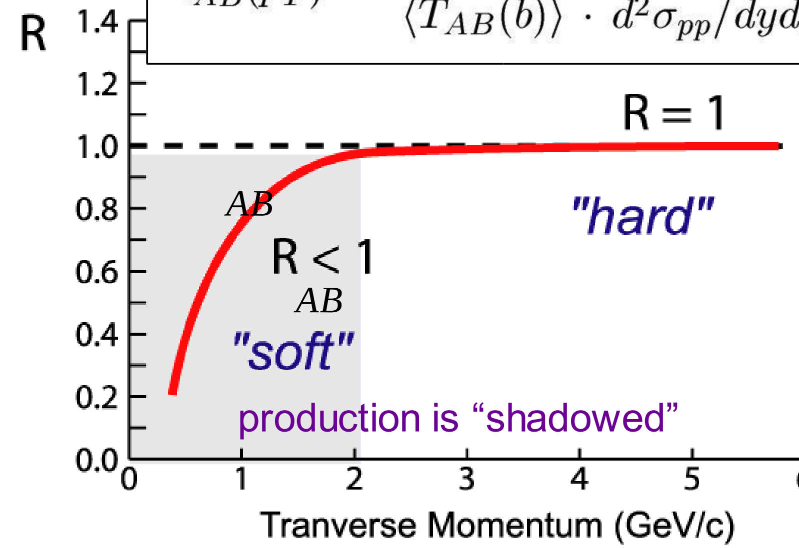
$$dN_{AB\to hard}(b) = T_{AB}(b)\cdot d\sigma_{pp\to hard}$$

geom. nuclear overlap at b

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

Nuclear Modification Factor:

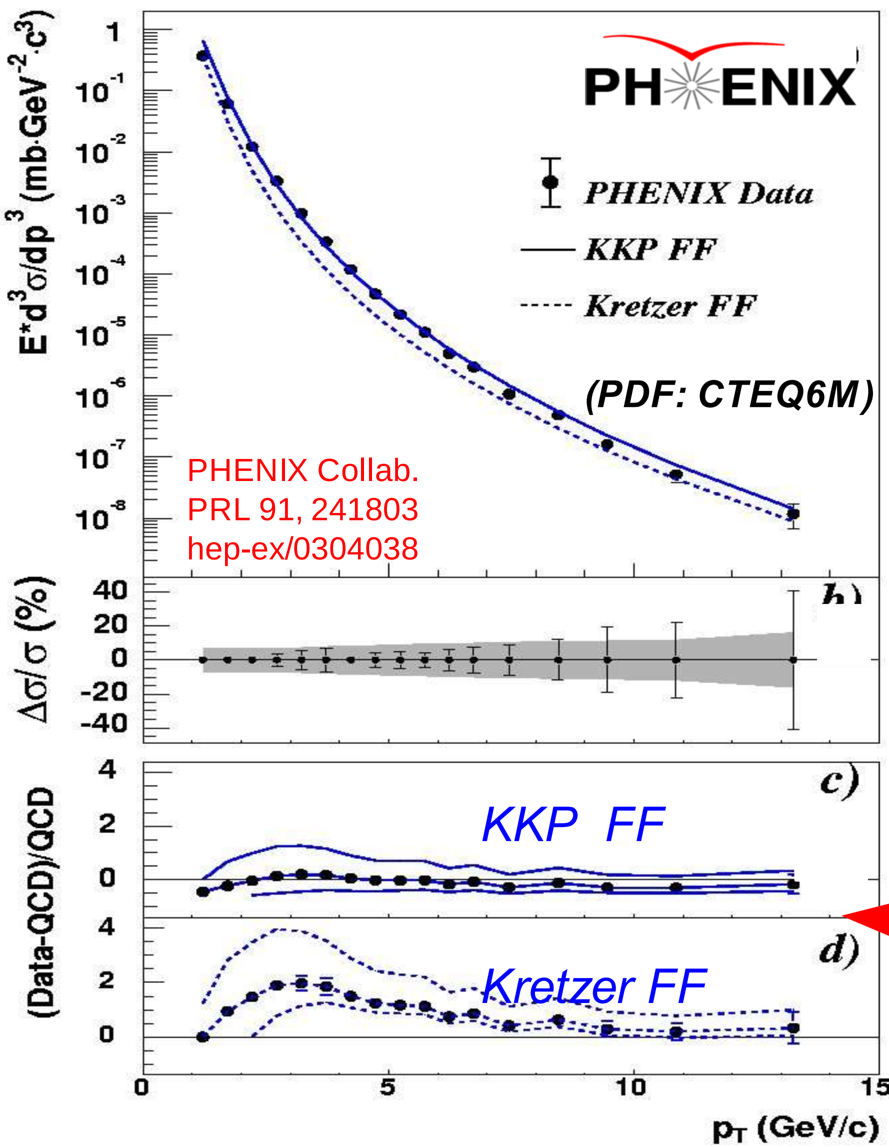
$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle T_{AB}(b)\rangle\cdot d^2\sigma_{pp}/dydp_T}$$



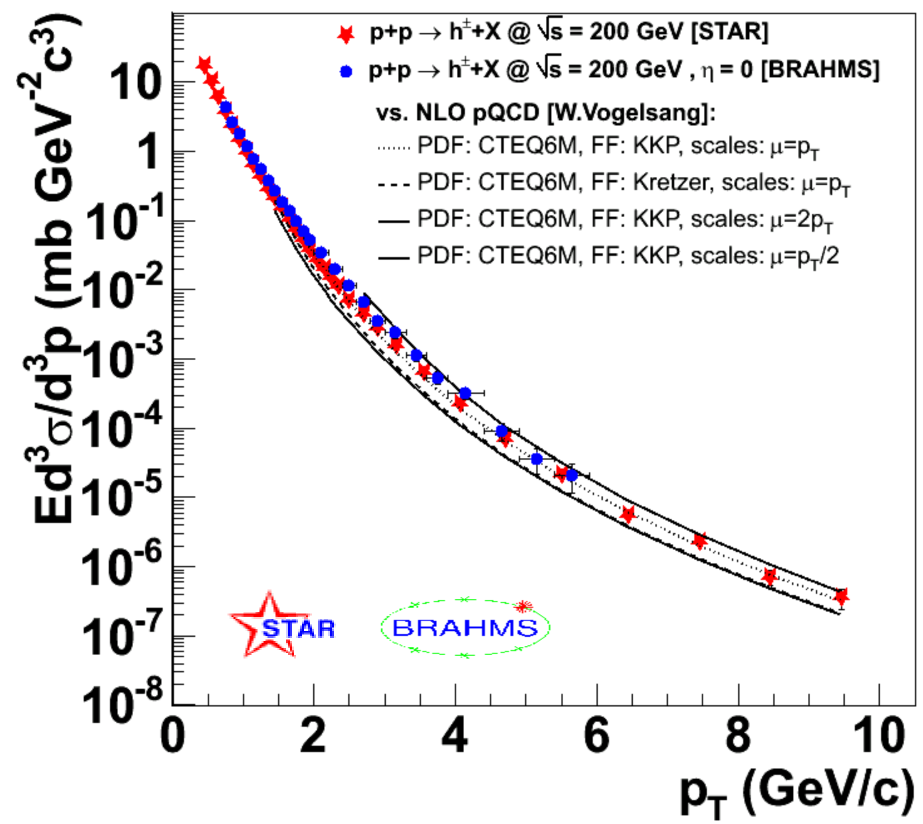
Leading hadron spectra in free space: pp @ 200 GeV

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

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



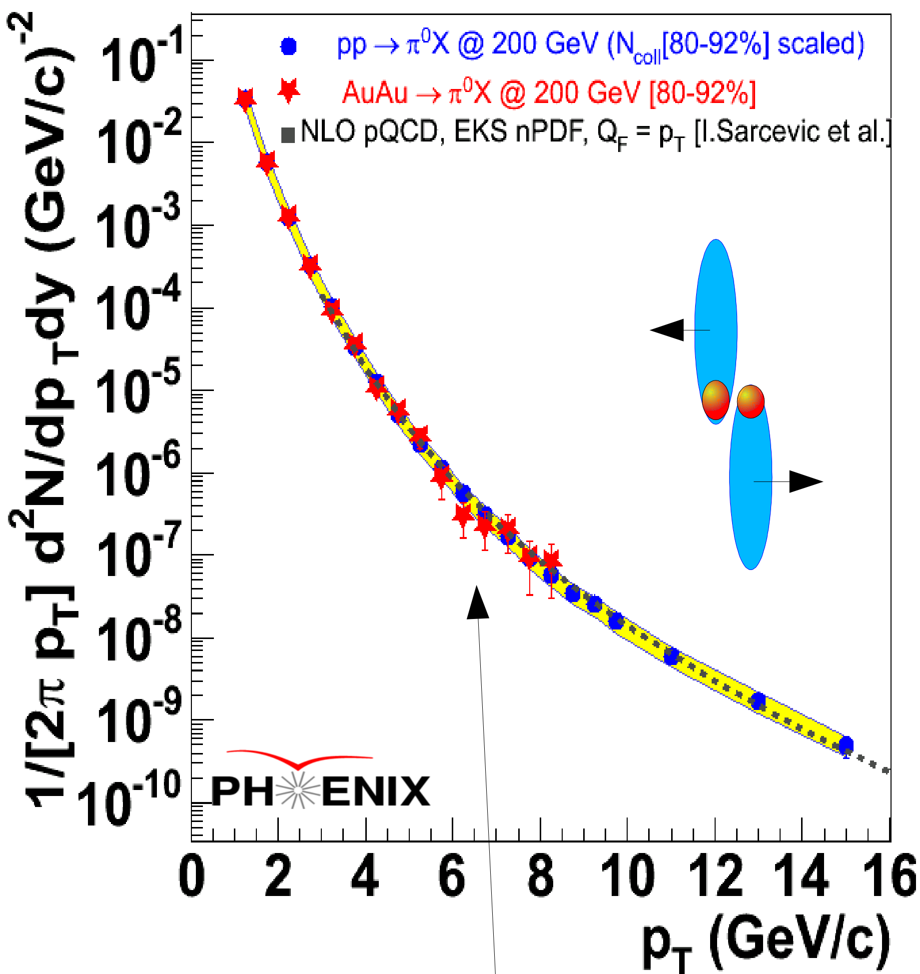
$p+p \to h^\pm X$



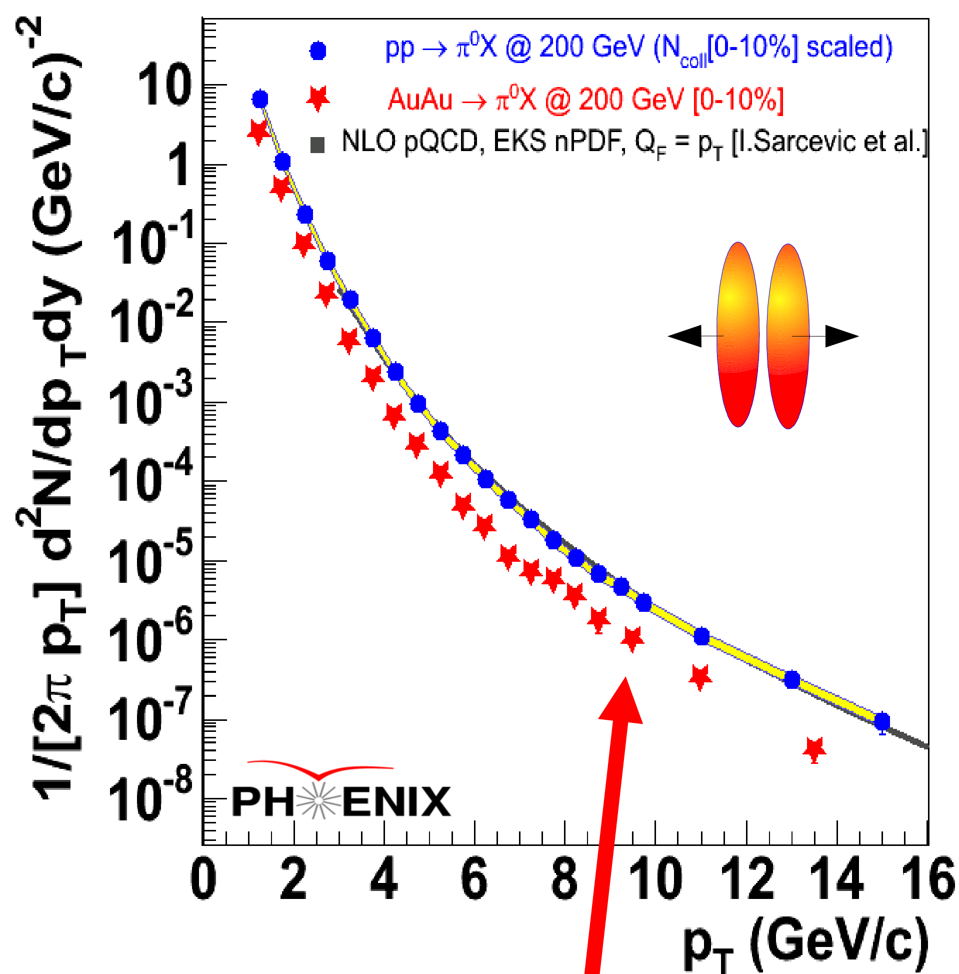
- High quality data: sensitive to different parametrizations of gluon FF
- Well calibrated (experimentally & theoret.) p+p baseline spectra at hand.

Leading hadron spectra in AuAu @ 200 GeV

Au+Au→ $\pi^0 X$ (peripheral)



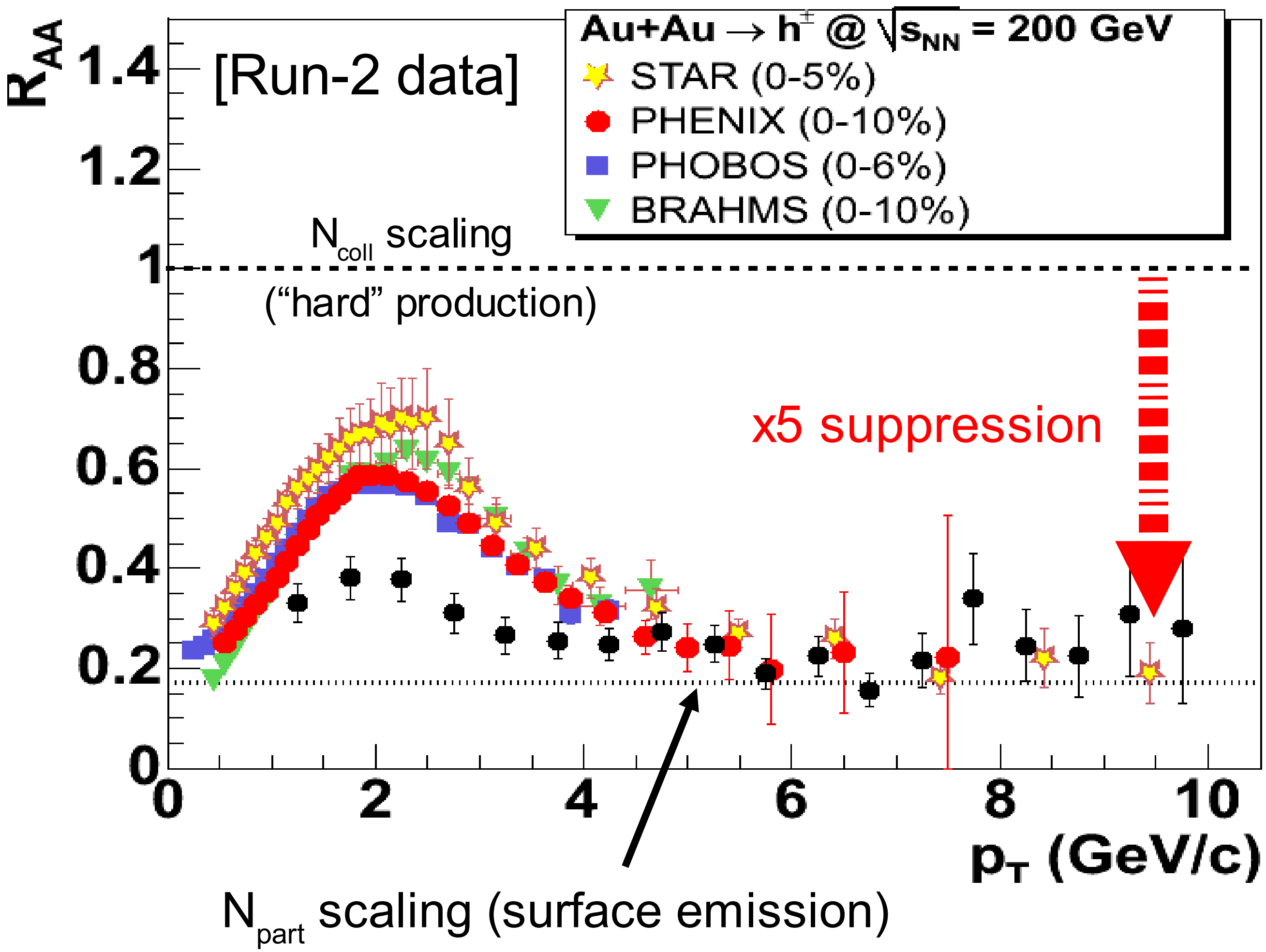
Au+Au→ $\pi^0 X$ (central)



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

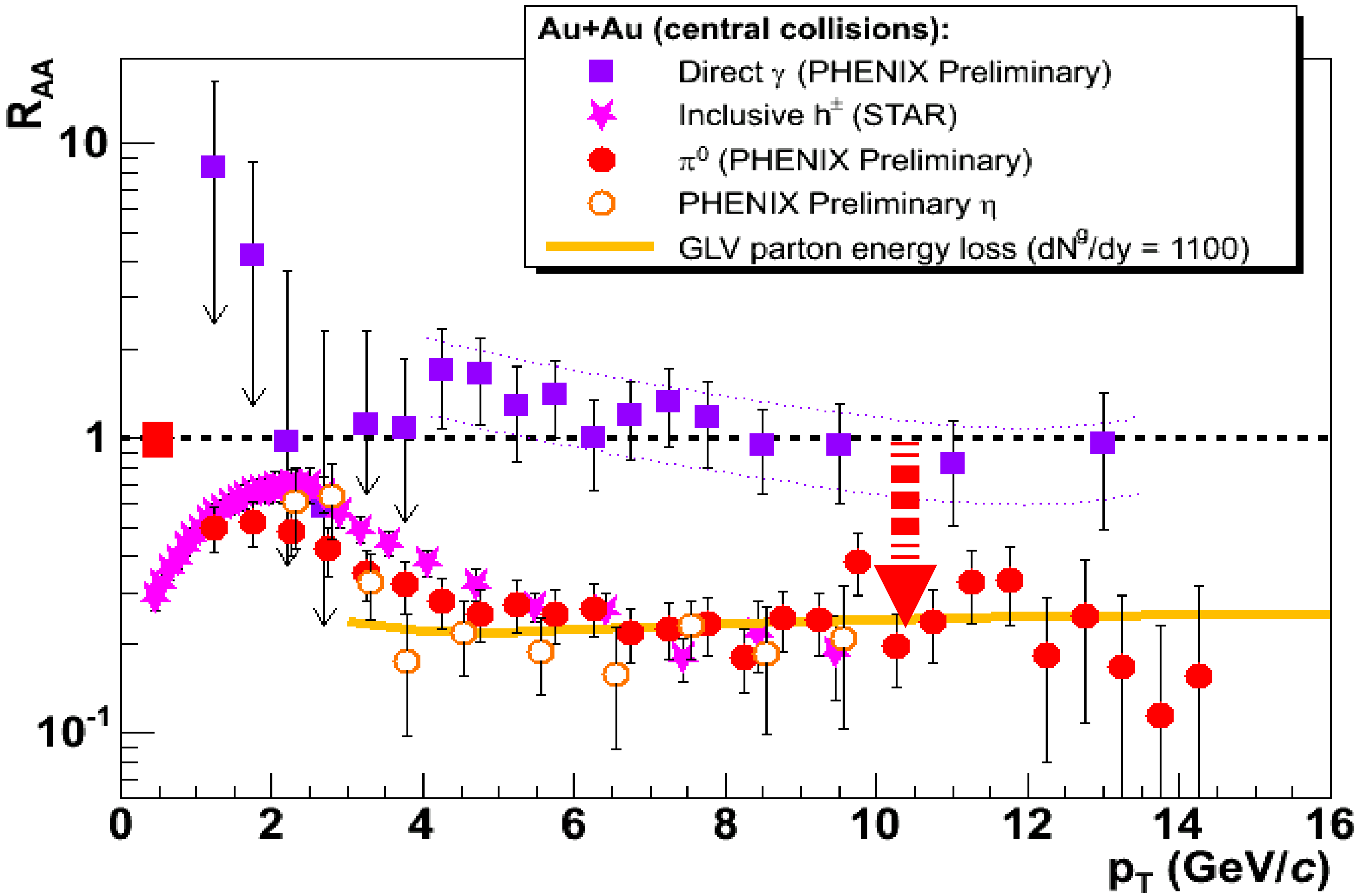


PHENIX Collab.
PRL 88, 022301 (2002)
nucl-ex/0109003

- Very strong suppression (R_{AA} ~ 0.2 !) up to p_T ~ 10 GeV/c for π^0 $h^{\pm}$, well below pQCD 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.

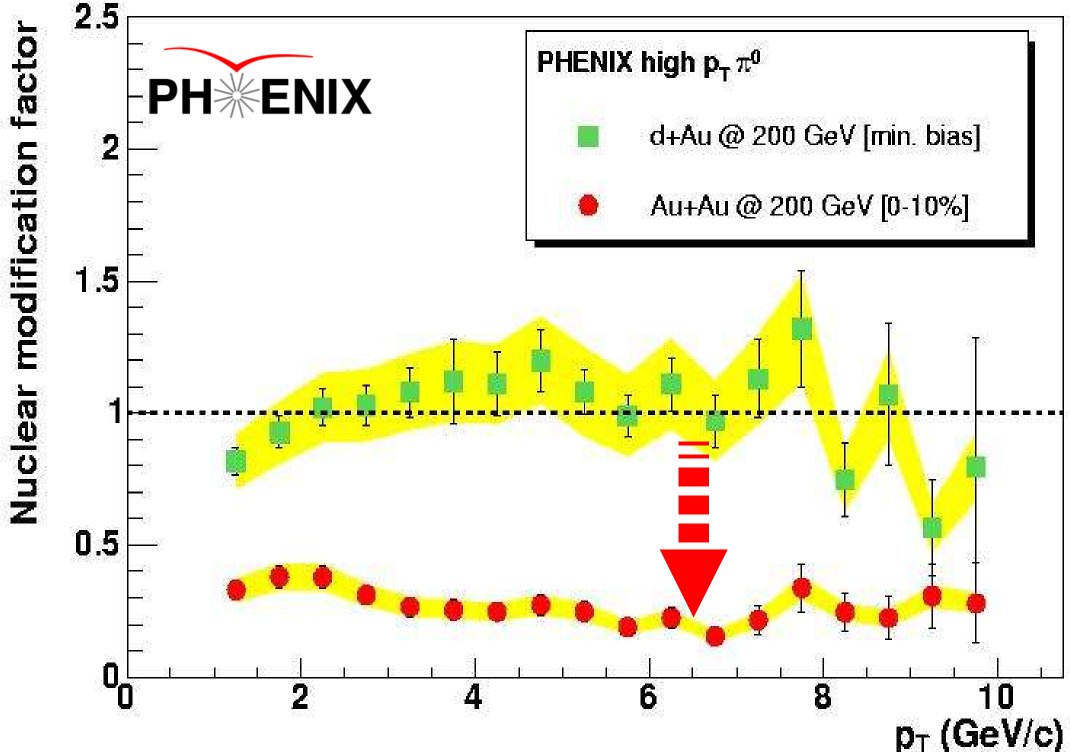


PHENIX. PRL 94, 232301

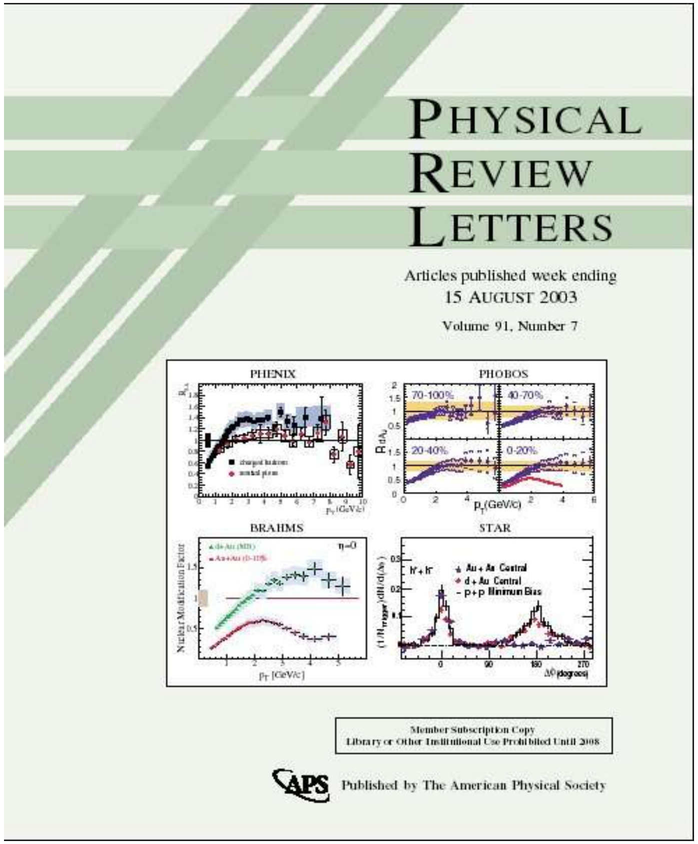
D.d'E, HP'04
EPJ C to appear
(nucl-ex/0504001)

- 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)

Magnitude of the suppression: medium properties

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

  - Initial gluon densities:

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

  - Opacities:

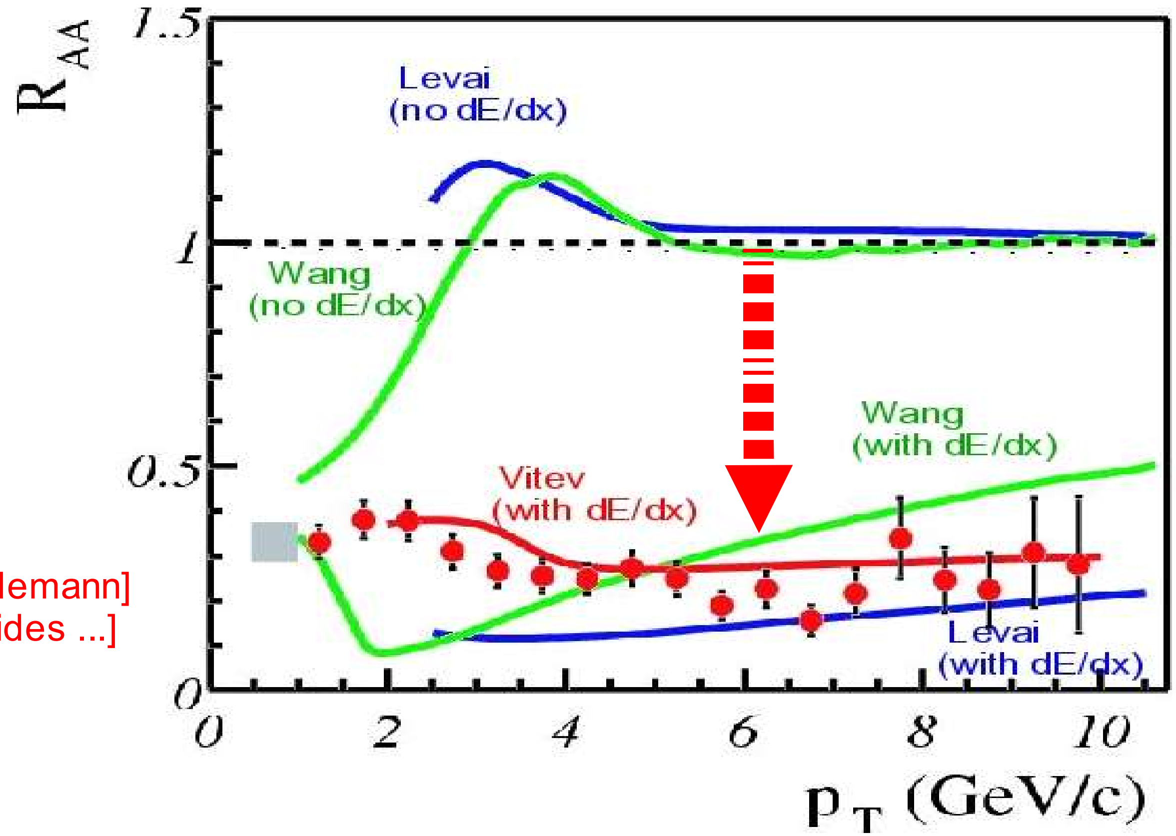
    $\langle n \rangle = L/\lambda \approx 3 - 4$ [Levai et al.]

  - Transport coefficients:

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

  - Medium-induced radiative energy losses:

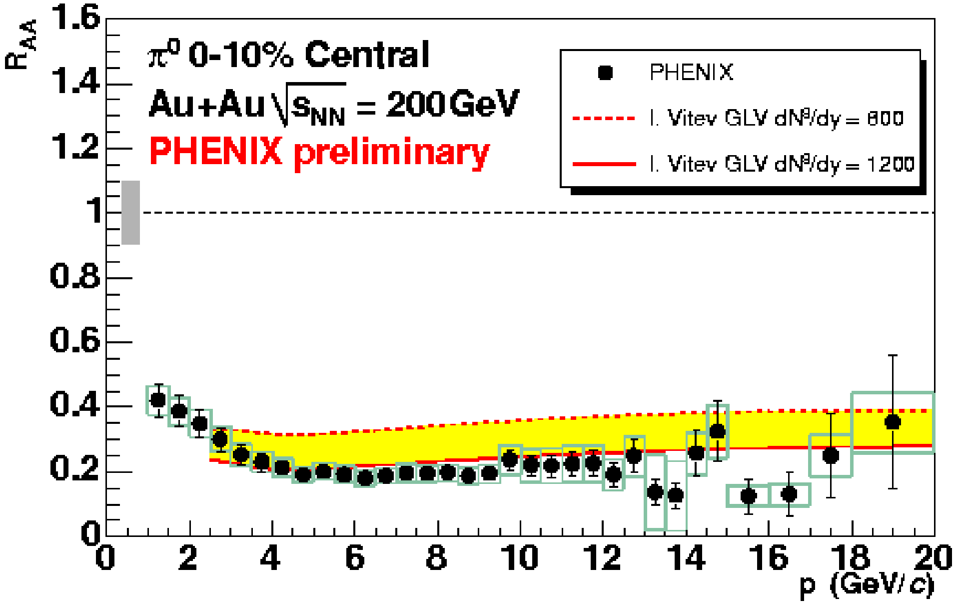
    $dE/dx \approx 0.25$ GeV/fm (expanding)
    $dE/dx|_{eff} \approx 14$ GeV/fm (static source) [X.N.Wang]



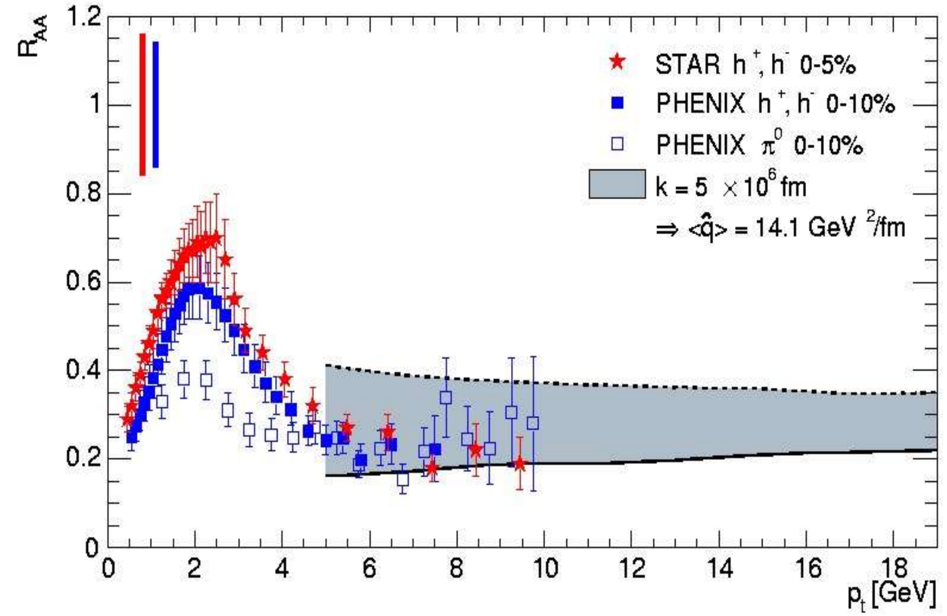
- Very large gluon densities: dN^g/dy~1000 consistent w/ measured $dN_{ch}/d\eta$ ~700
- All transport & thermodynam. values imply energy densities well above $\varepsilon_{crit\ QCD}$

High p_T suppression: p_T-dependence

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



GLV – I. Vitev 2005

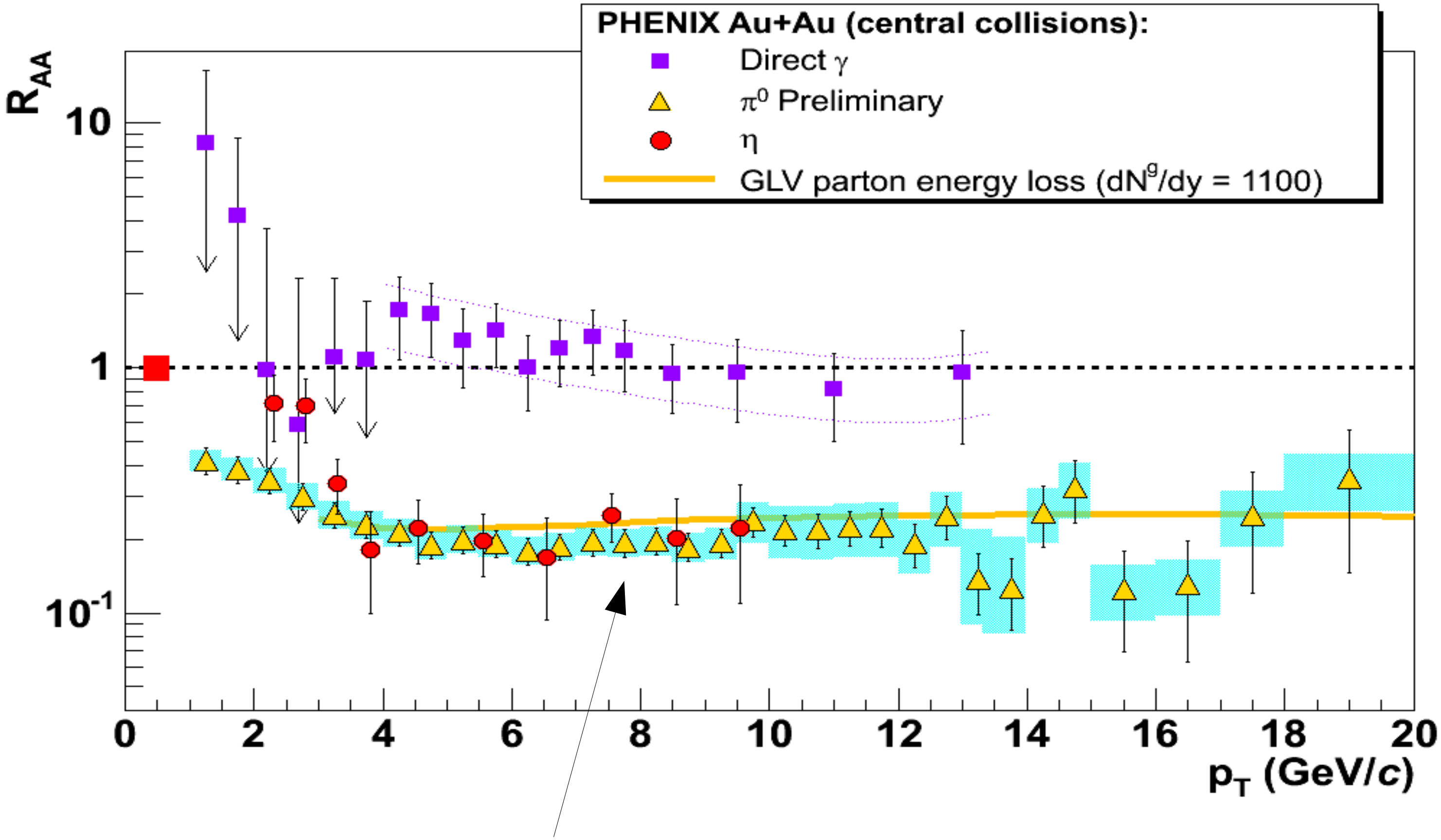


PQM – A. Dainese, C. Loizides, G. Paic
EPJ C 38, 461(2005)

- 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.
- Question ... What about running α_s ?

High p_T suppression: "Universal" for all light mesons

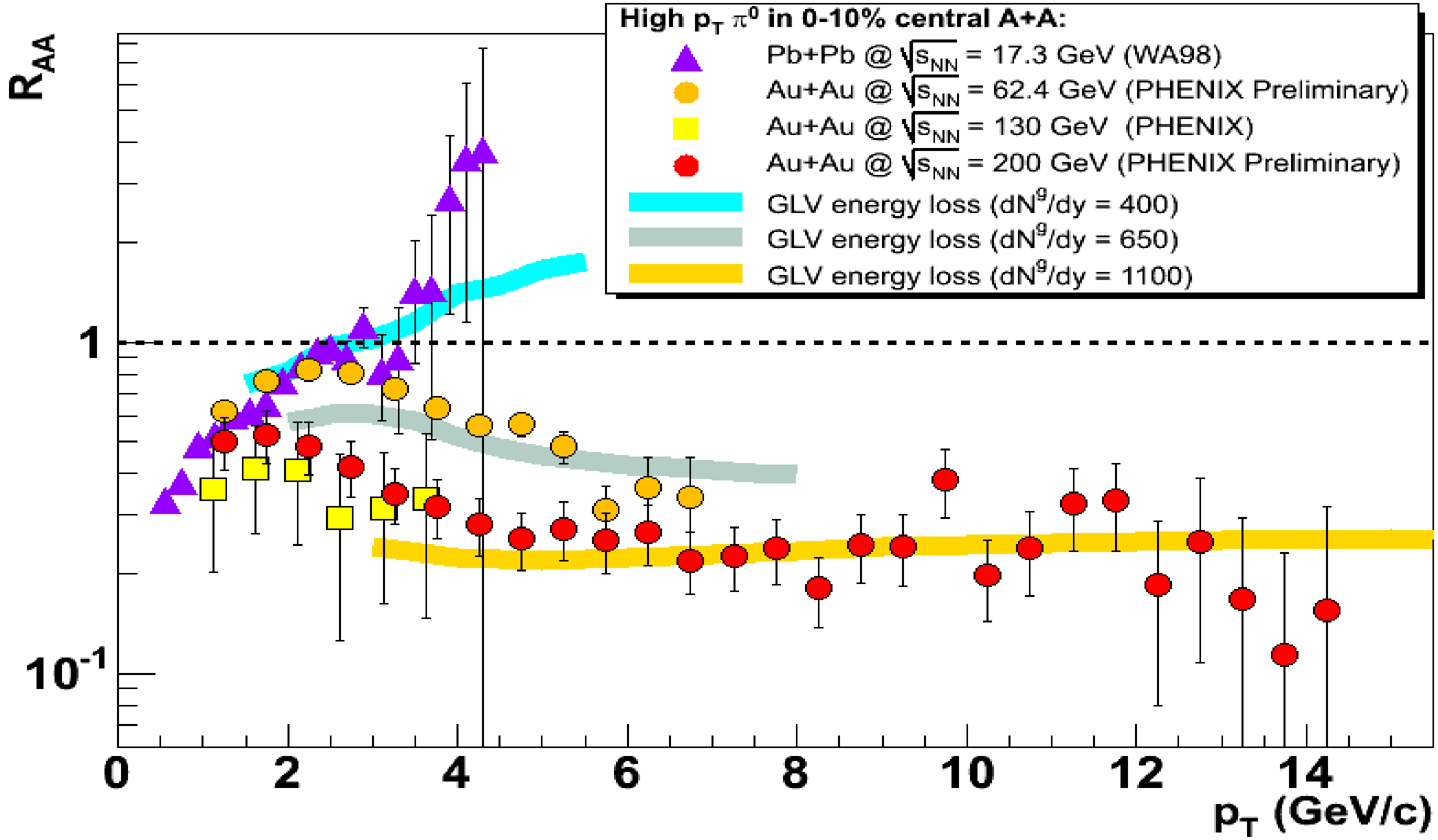
- Common suppression pattern (magnitude, p_T, centrality, ... dependence) for π^0 and η:



- Same flat R_{AA} ~ 0.2 up to 10 GeV/c
- Universal suppression for light mesons indicates it is at partonic level before q,g fragments into leading meson according to vacuum FFs.

High p_T suppression: $\sqrt{s}$-dependence

- $\sqrt{s}$- dependence in agreement with parton energy loss in increasingly dense (expanding) medium:



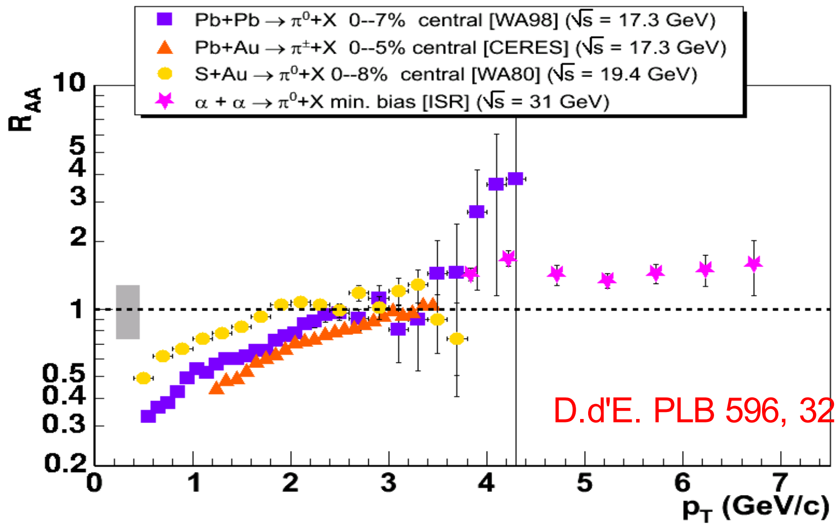
[Note: R_{AA} @ SPS uses "revised" pp ref.]

D.d'E., HP'04
EPJ C to appear
nucl-ex/0504001

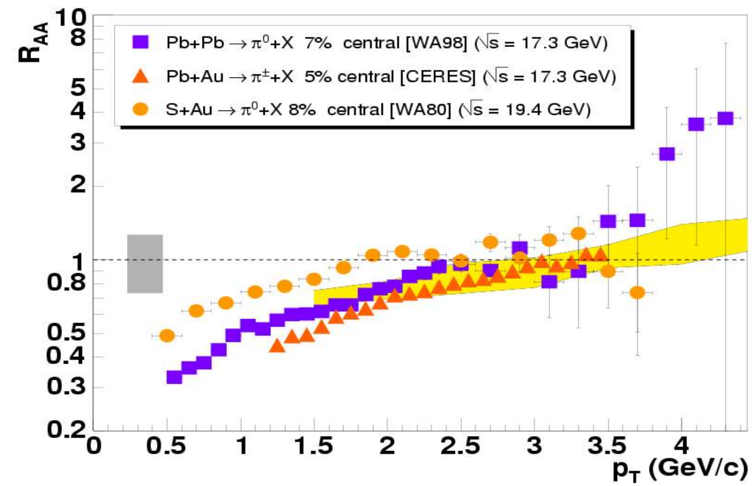
		Initial gluon density:		Medium transport coeff.:
SPS	R_{AA} ~ 1 @ $\sqrt{s}$ ~ 20 GeV	$\Rightarrow$ dN^g/dy ~ 400	,	$\langle q_0 \rangle$ ~ 3.5 GeV/fm^2
RHIC	R_{AA} ~ 0.3 @ $\sqrt{s}$ = 62 GeV	$\Rightarrow$ dN^g/dy ~ 650	,	$\langle q_0 \rangle$ ~ 7 GeV/fm^2
RHIC	R_{AA} ~ 0.2 @ $\sqrt{s}$ = 200 GeV	$\Rightarrow$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

High p_T meson suppression in AA @ 17.3 GeV ?

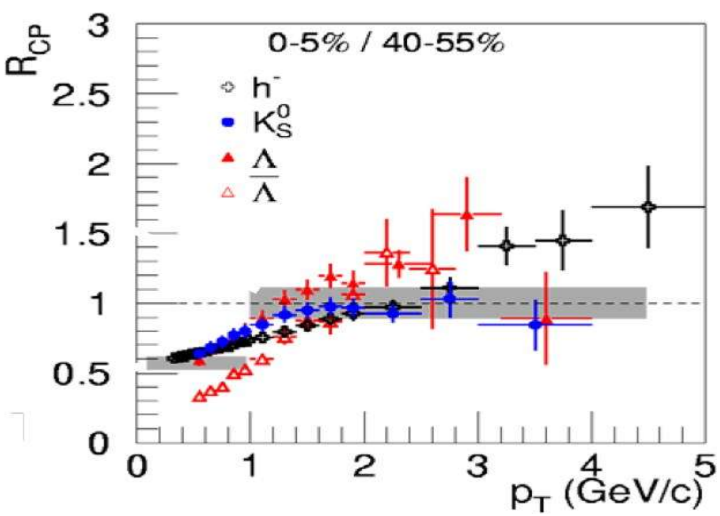
- Revised pp reference: high p_T π^0 production in (0-10%) central PbPb at SPS is slighted suppressed or consistent w/ "N_{coll}-scaling" :

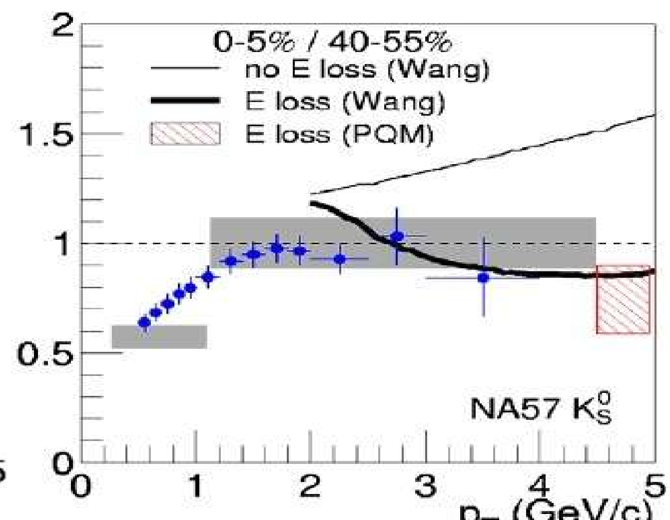


D.d'E. PLB 596, 32 (2004)

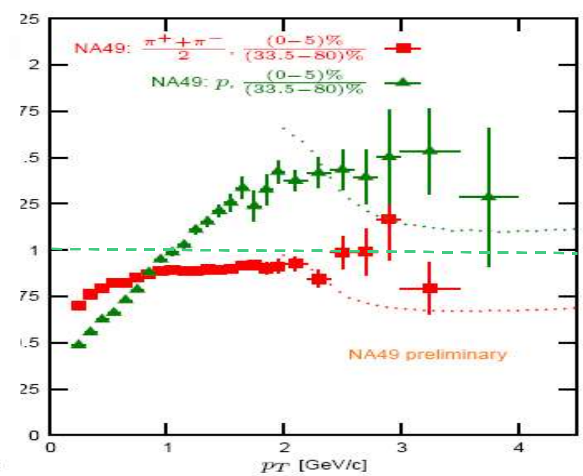


- Confirmed by NA57 (& NA49) recent high p_T results in central PbPb at SPS:





NA57, PLB62, 317 (2005)



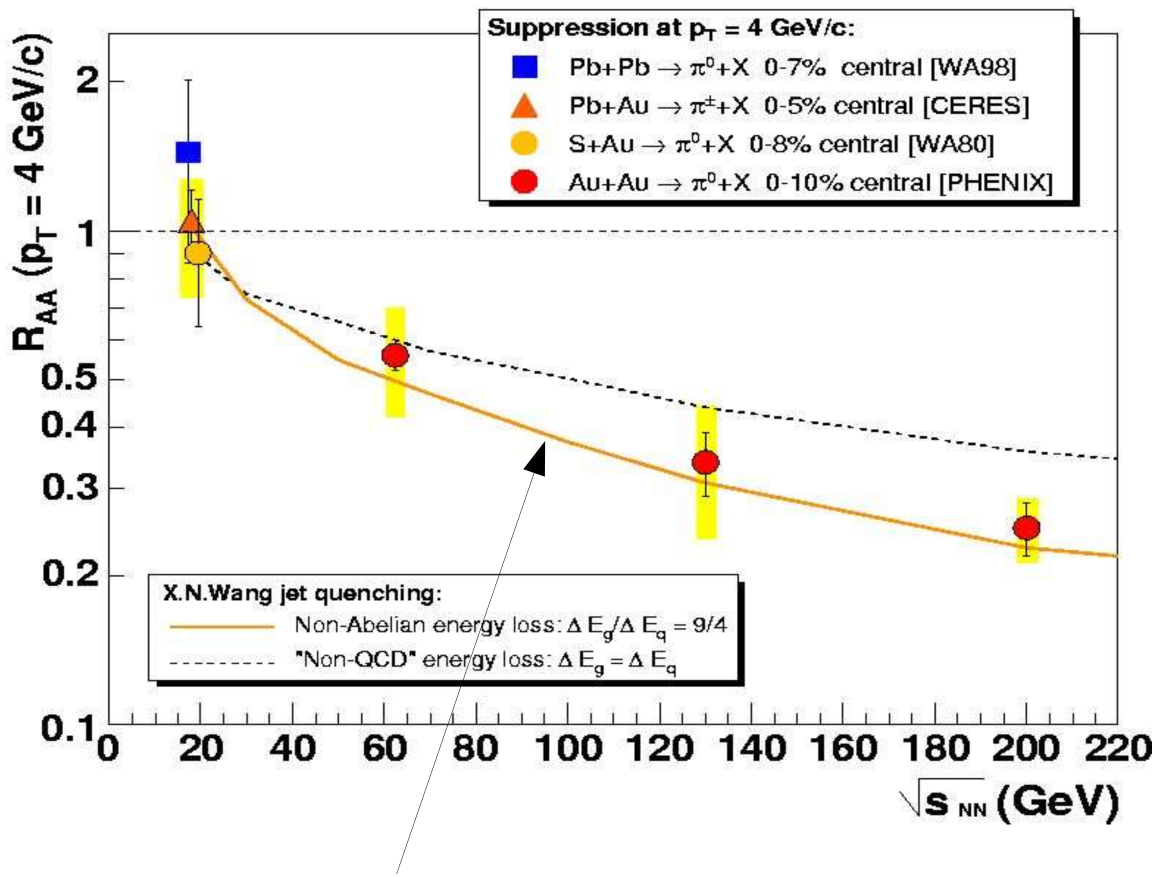
NA49 (A. Lazslo, QM'05)

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

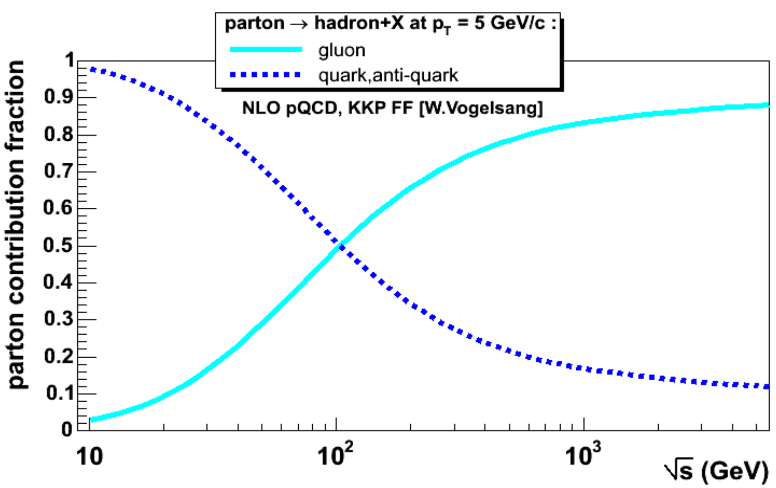
QCD radiation probability:

Gluon: $C_A = N_c = 3$

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

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

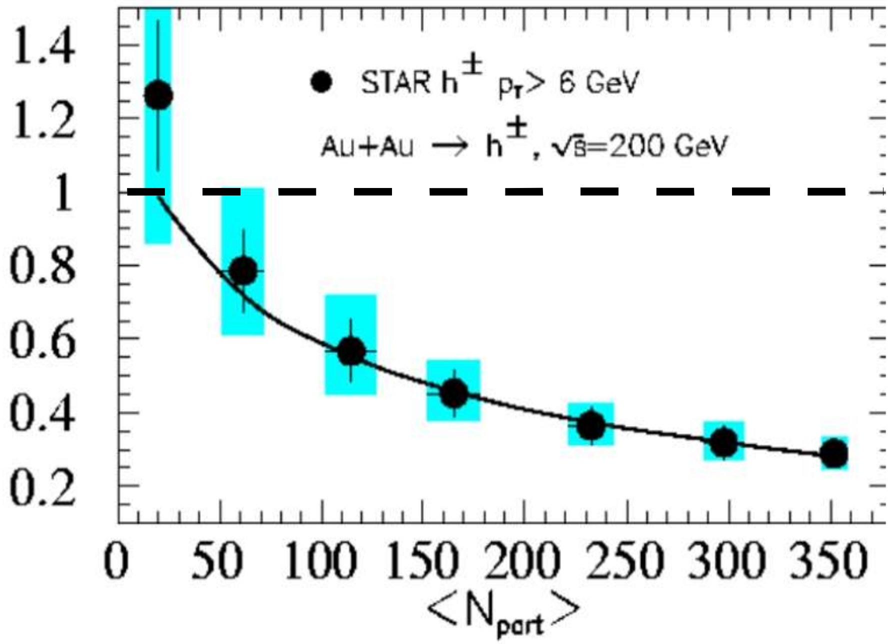
Relative fraction of q,g at p_T = 5 GeV/c:



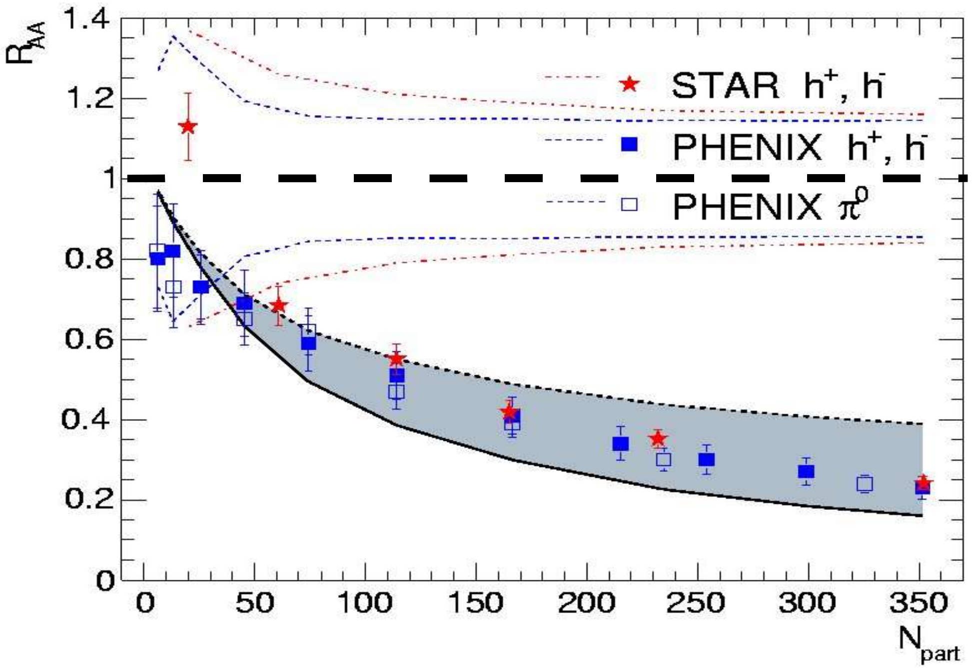
D.d'E. EJP C to appear
nucl-ex/0504001

High p_T suppression: centrality dependence

- Increasing centrality $\Rightarrow$ increased N_{part} $\Rightarrow$ increased suppression



X.N. Wang, PLB 2003



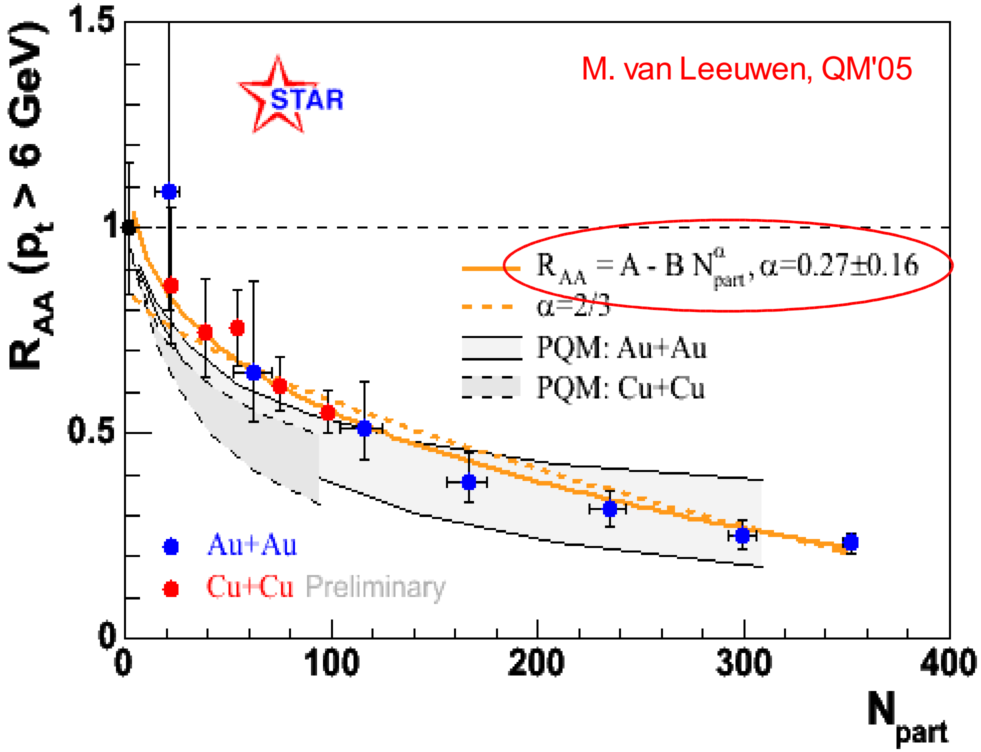
PQM – A. Dainese, C. Loizides, G. Paic
EPJ C 38, 461(2005)

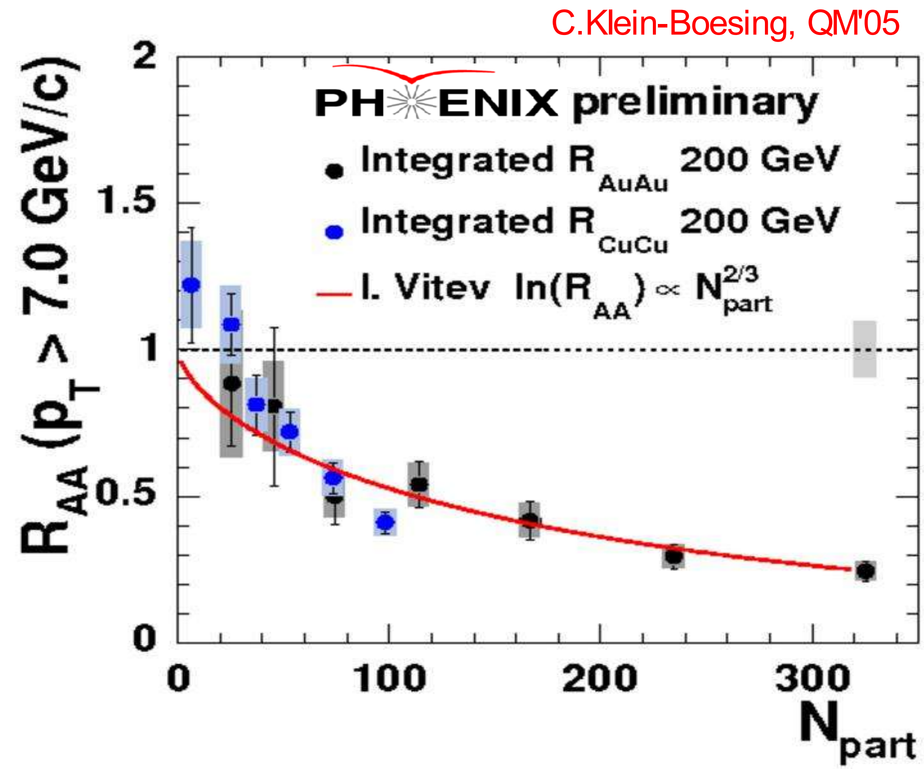
- Agreement data ↔ models OK

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: $\ln(R_{AA}) \propto N_{part}^{-2/3}$

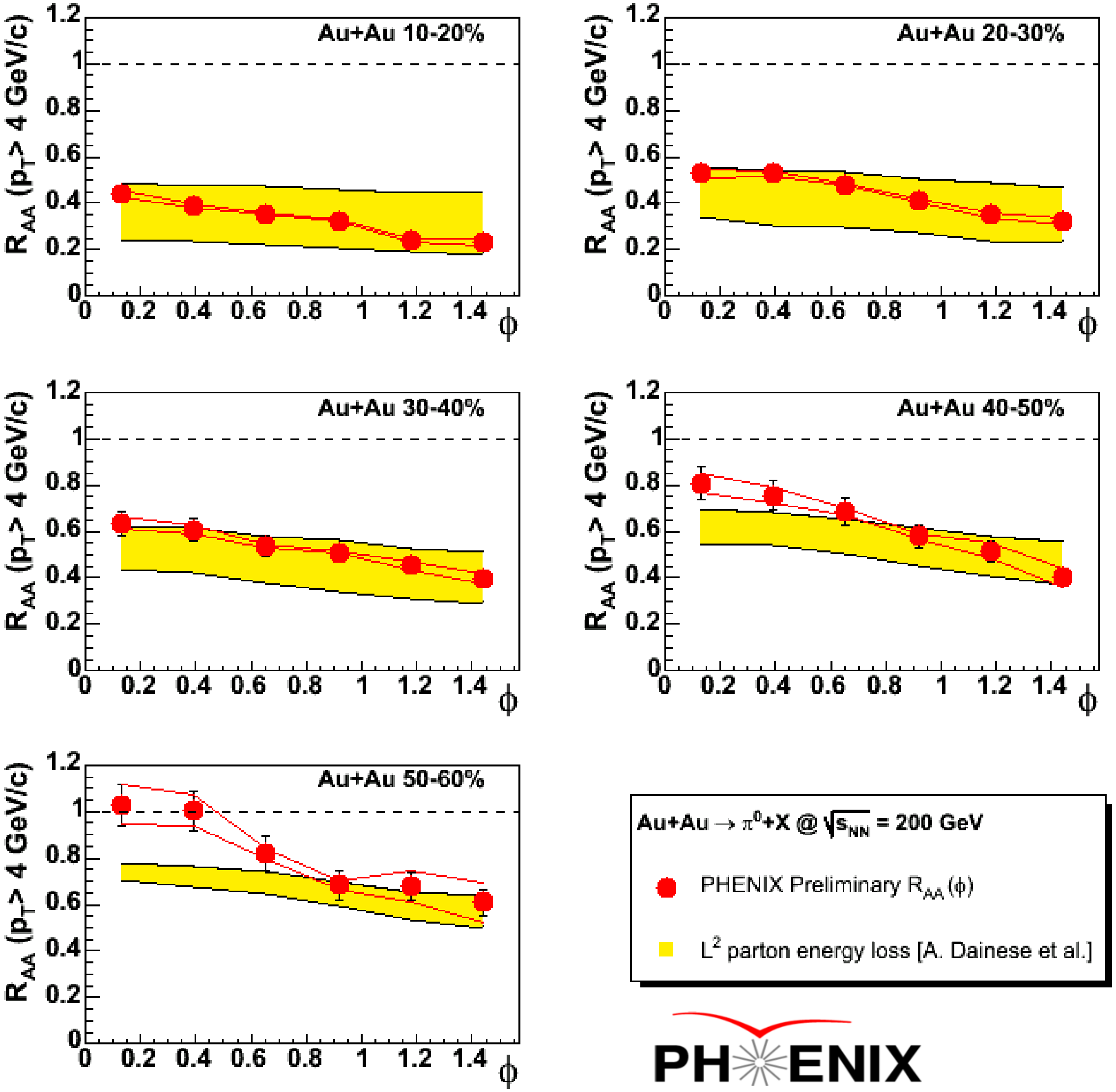




- Both PHENIX & STAR preliminary data seem to exclude α= -2/3
- Fit to STAR N_{part}^{α} prefers "shallower" α~ -1/3 (circumf./area ~ $A^{-1/3}$ ~ $N_{part}^{-1/3}$?)
- PHENIX data seems to indicate a "steeper" slope at low N_{part}.
- Differences STAR ↔ PHENIX and PQM ↔ GLV still unclear at this point.

High p_T suppression: path-length dependence

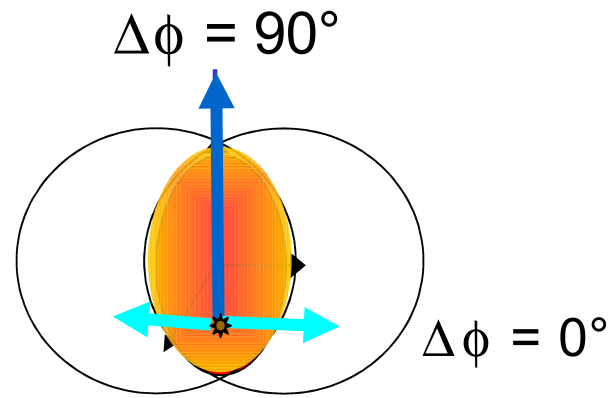
- R_{AA} vs φ w/ respect to reaction plane :



PHENIX PRELIMINARY

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

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



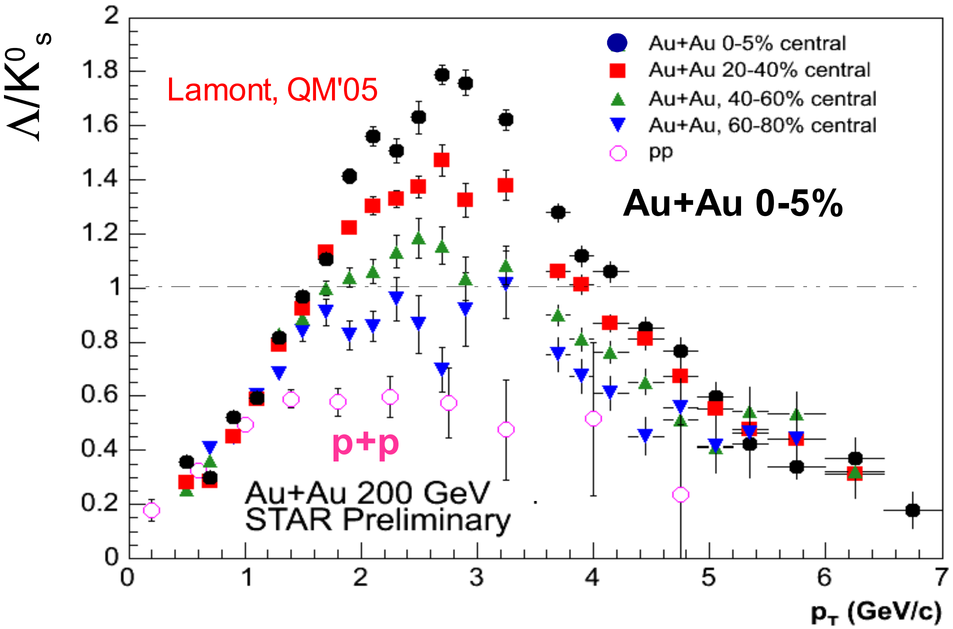
- 2 times more suppression out-of-plane ("long" direction) than in-plane ("short" direction).
- Glauber parton energy loss model predicts only ~50% increased "out-of-plane" vs "in-plane" π^0 emission

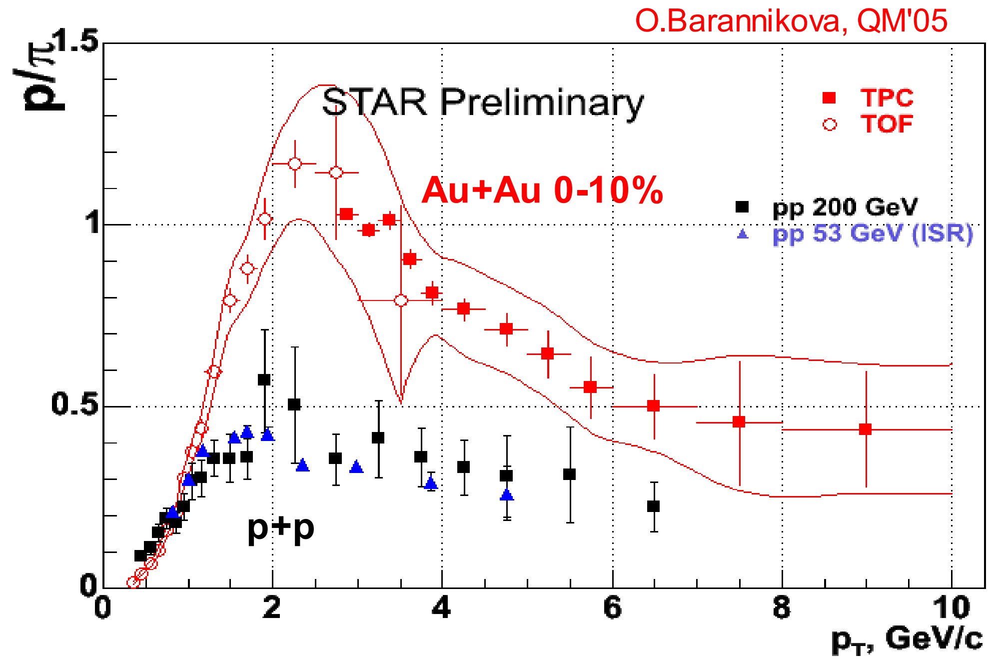
  PQM – Dainese, Loizides, Paic EPJ C 38, 461(2005)

- Azimuthal anisotropy stronger than "canonical" L^2 (or L) path-length dependence.
- Source of extra azim. anisotropy above p_T ~ 4 GeV/c ?

Intermediate p_T mesons suppressed. Baryons are not

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

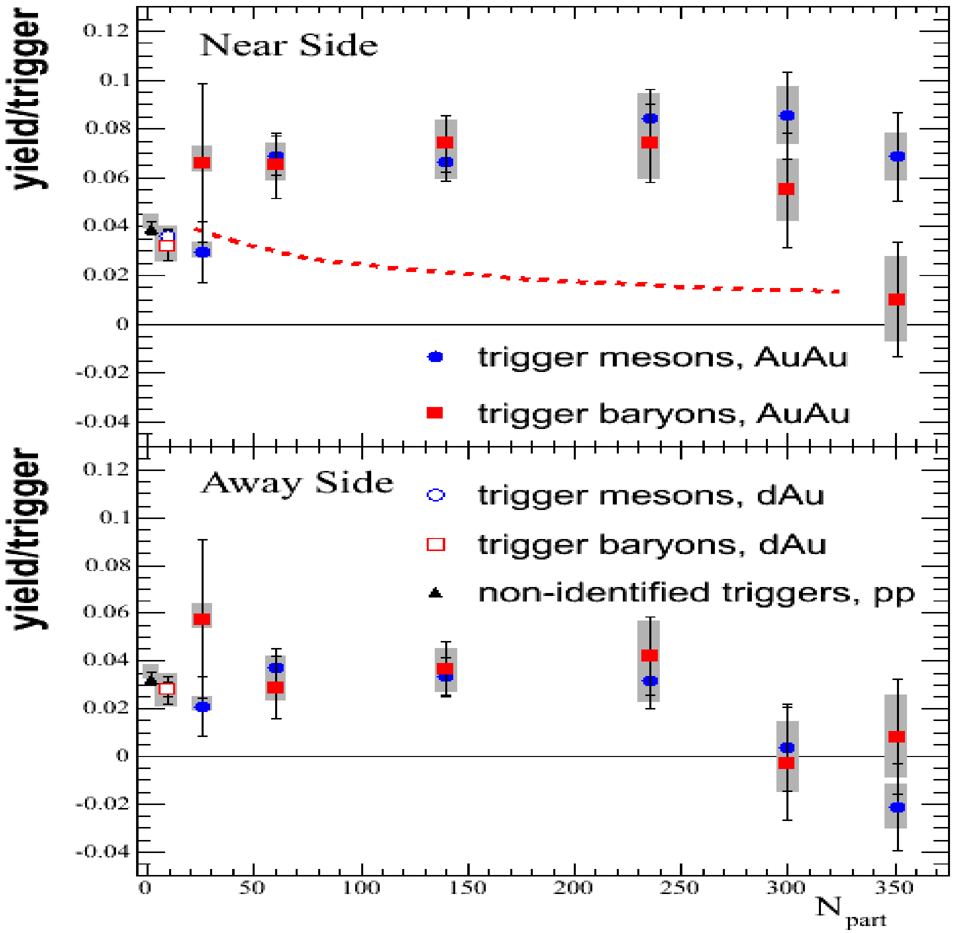




- Strong centrality dependent baryon/meson: ratio well above "perturbative" (pp) ratios.
- Clear deviation from std. vacuum fragmentation functions (large non-pQCD effects) calls for extra baryon production mechanism: recombination.
- Above $p_T \sim 6$ GeV/c: Recovery of "vacuum" fragmentation ratio.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

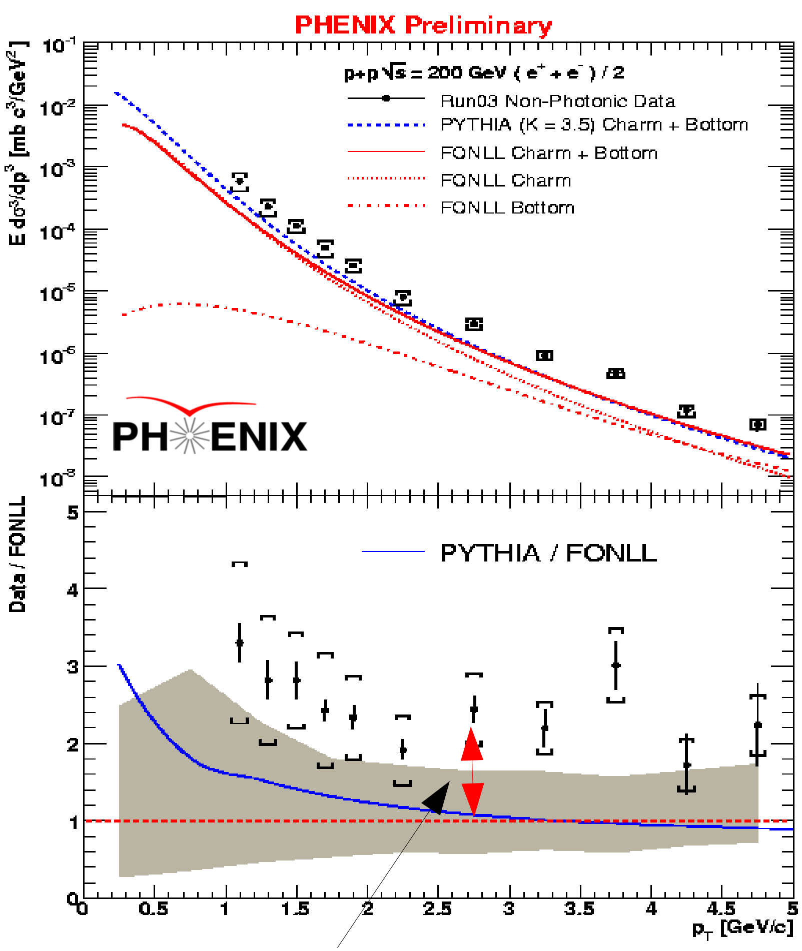
PHENIX
PRC 71, 051902 (2005)

- 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 !?

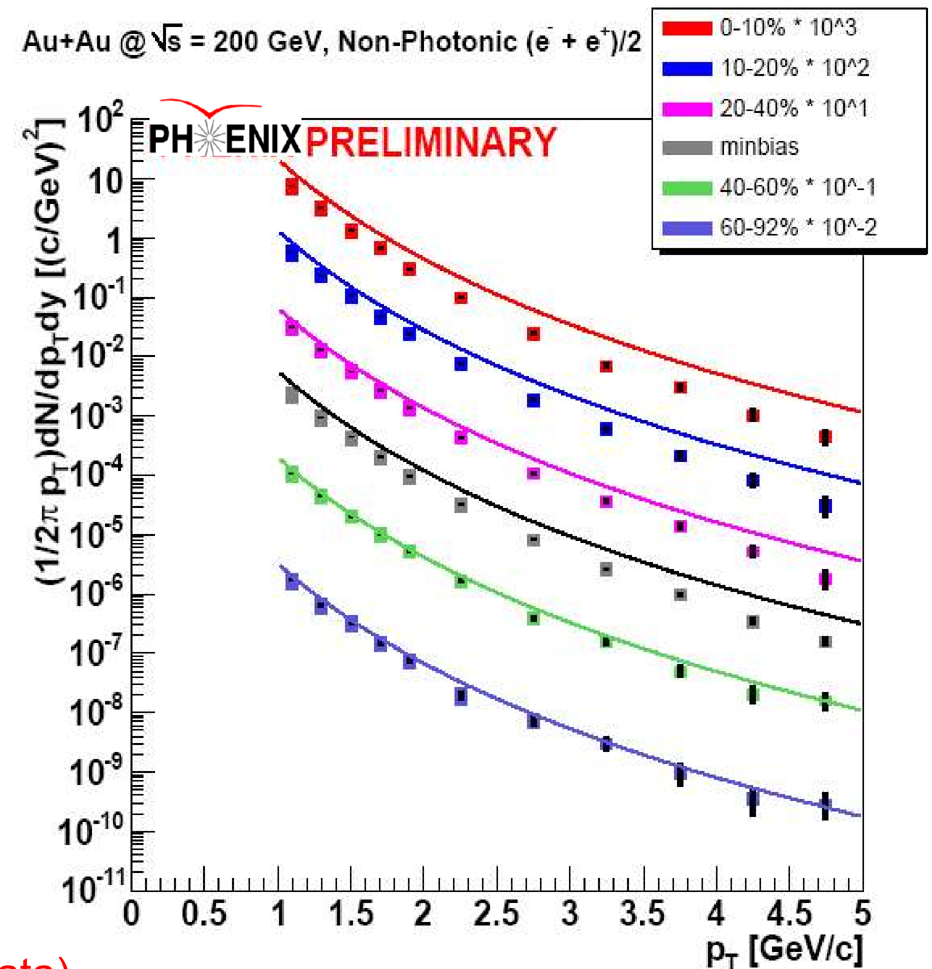
Heavy quark suppression via non-photonic electrons (I)

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

proton-proton baseline:



Au+Au suppression

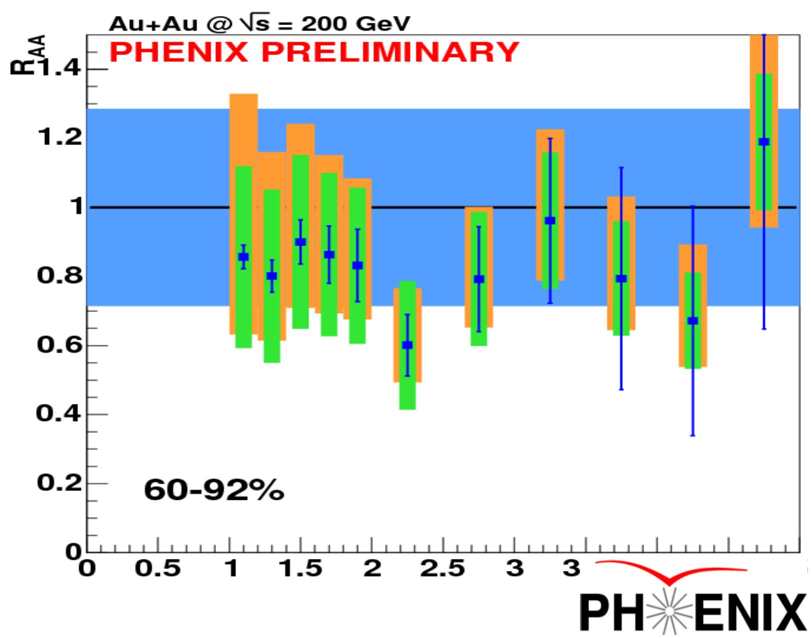


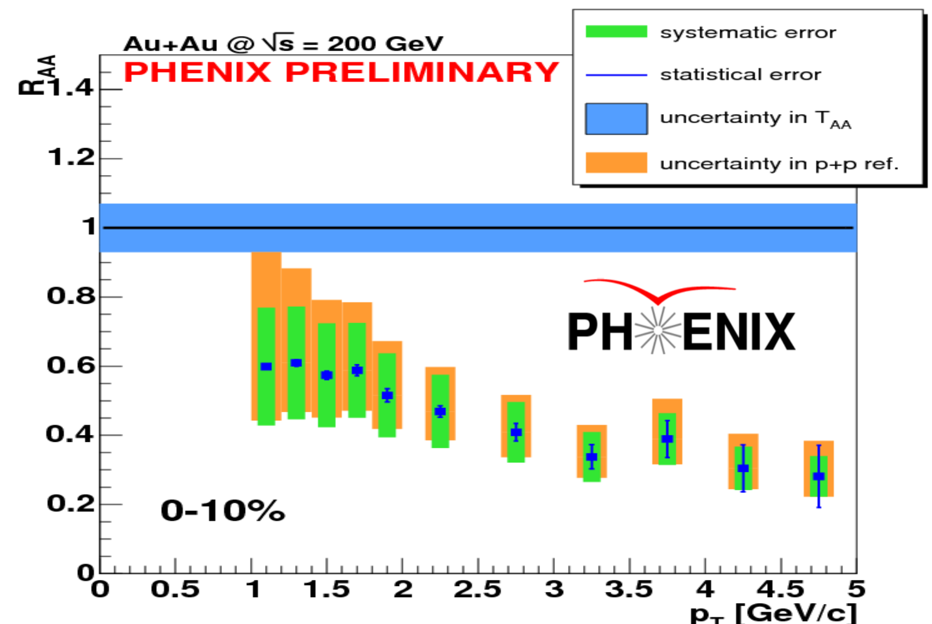
(Note: state-of-the-art theory underpredicts data)

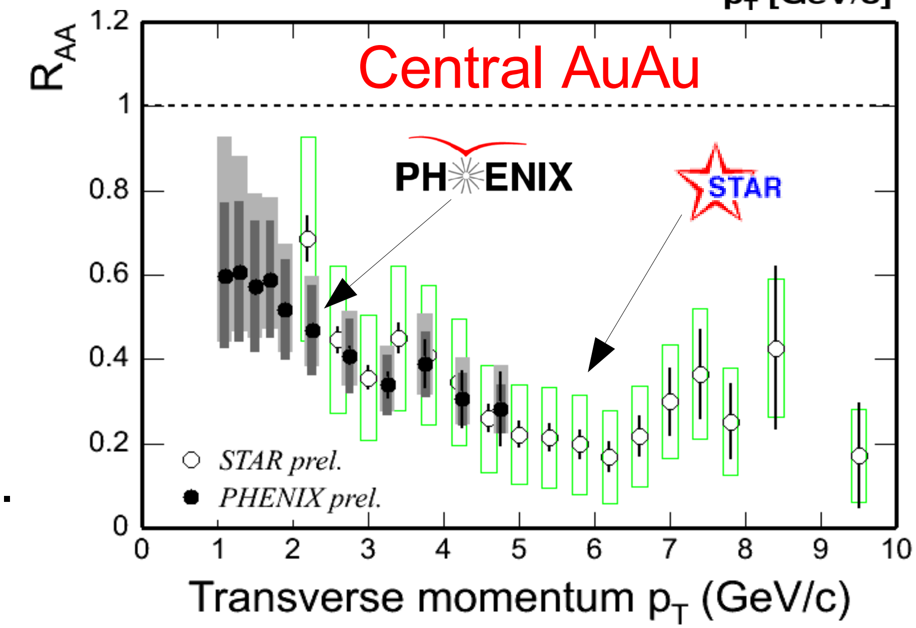
Heavy quark suppression via non-photonic electrons (II)

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

Peripheral AuAu







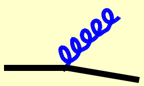
- Note: STAR – PHENIX R_{AA} agrees, but the pp refs are different by ~ 50%.

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 $\theta < m_Q/E_Q$

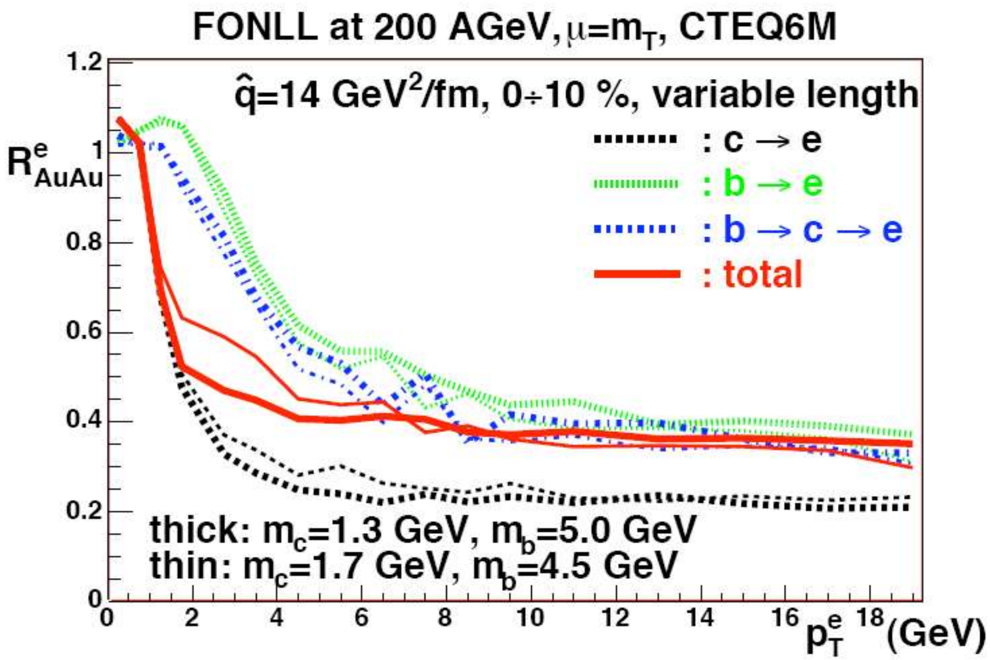
Gluonsstrahlung probability

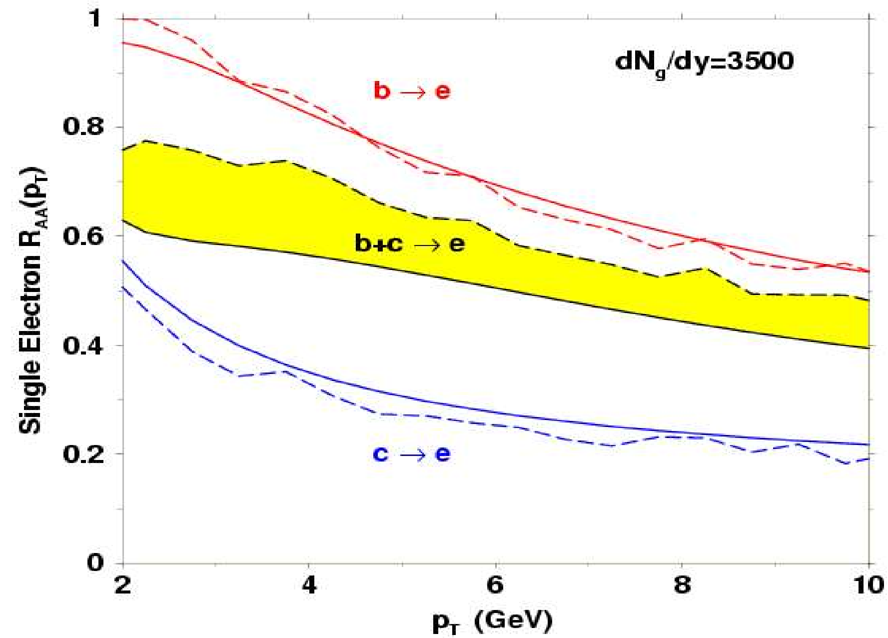


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- Quantitative predictions:

Armesto et al. QM'05





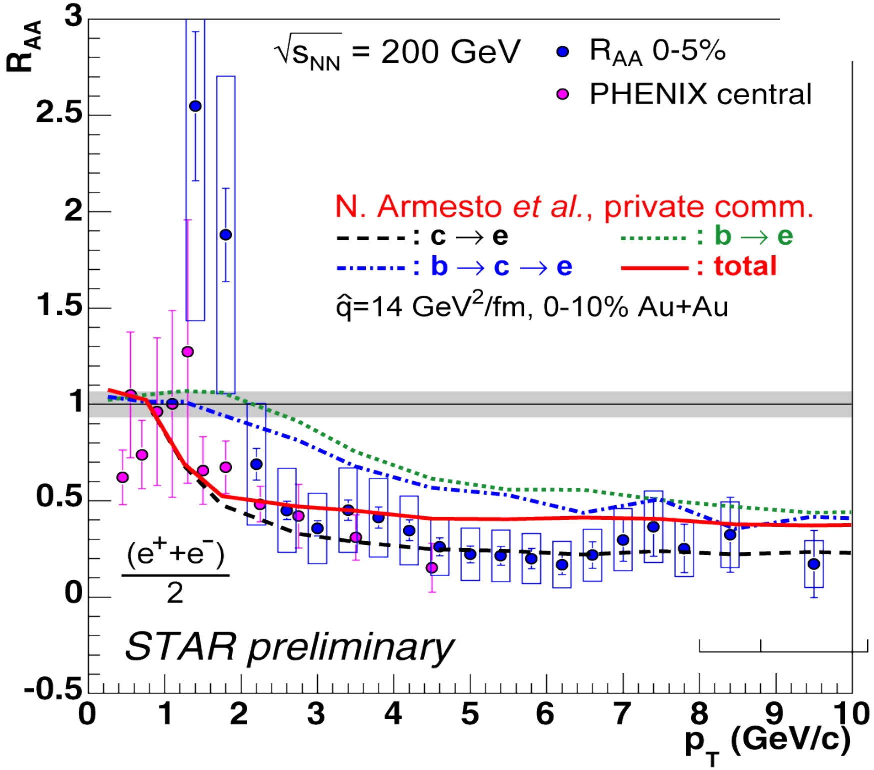
M. Djordjevic et al., nucl-th/0507019

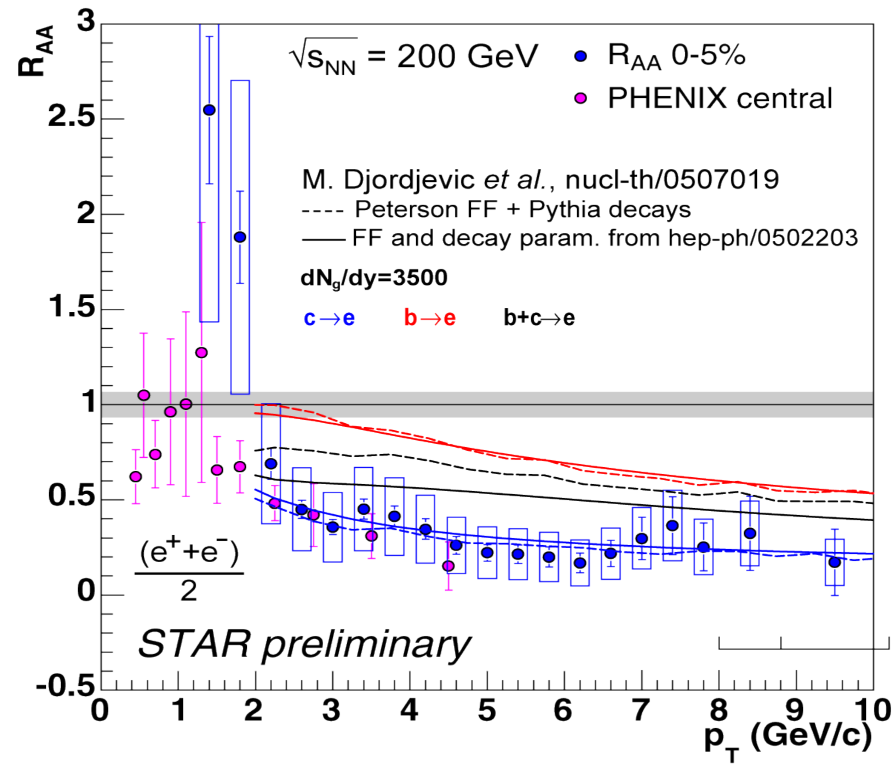
- Charm R_{AA} = 0.2 - 0.3
- Beauty R_{AA} = 0.4 - 0.6

- Note: Using larger medium densities: dN^g/dy=3500, <q> = 14 GeV²/fm than for light mesons R_{AA} ! Unclear consistency w/ dN_{ch}/dy ~ 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 jet-fragmentation production of charm which will be affected by energy loss ?
(supported by PHENIX proton-proton data itself ?)
(3) Hadronic (rather than partonic) energy loss ?
(4) Radiative + collisional energy loss ? Other ... ?

Summary

- Large amount of high precision large-p_T hadron production data at RHIC after 5 years of operation allows to quantitatively address jet physics in QCD medium (w/o full jet reco).

- Details of suppressed hadro-production in central Au+Au provide:
  - stringent constraints on underlying physics.
  - direct access to the density and transport properties of the QCD medium.

- Is jet quenching due to radiative energy loss in a QGP ?
  - Good agreement with calculations on:
    - Magnitude, $\sqrt{s}$, p_T, centrality, (light) species dependence
  - Some tests are weak at present:
    - Few details missing in system-size dependence
    - no sharp test of L^2 dependence yet.
    - unsuppressed (but jet-like) baryon production points to (sthg. more than) recombination ?
    - heavy quark energy loss larger than expected

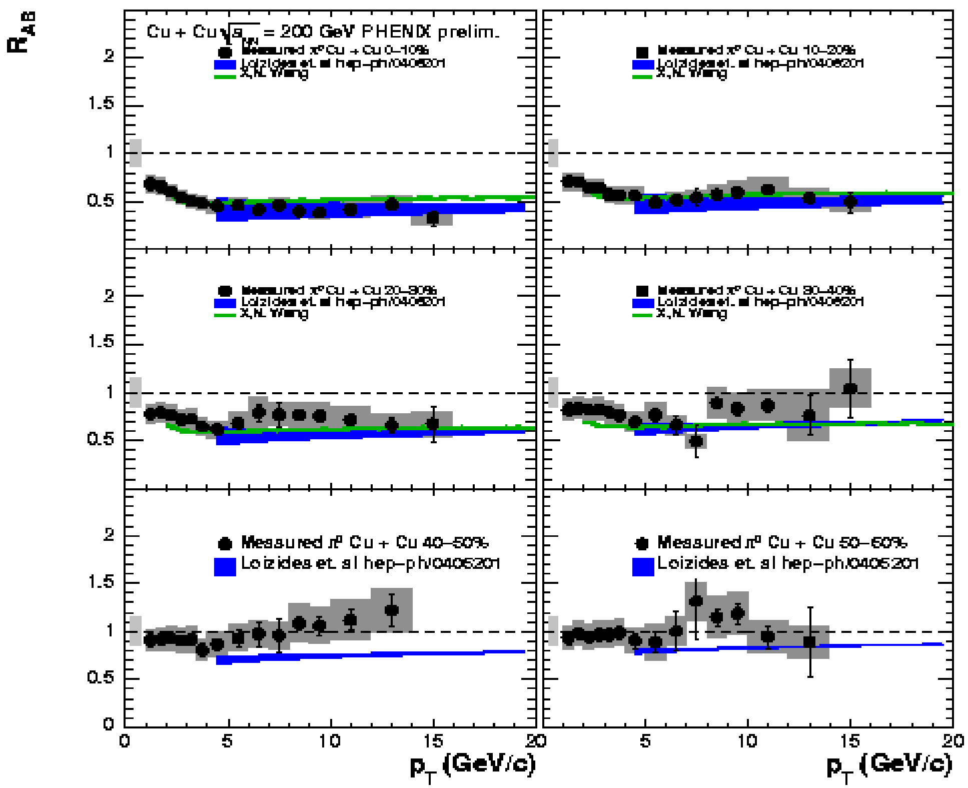
- LHC will provide enormous reach and qualitatively new observables (full jet reco, jet-jet, jet-γ,Z correlations ...)

backup slides ...

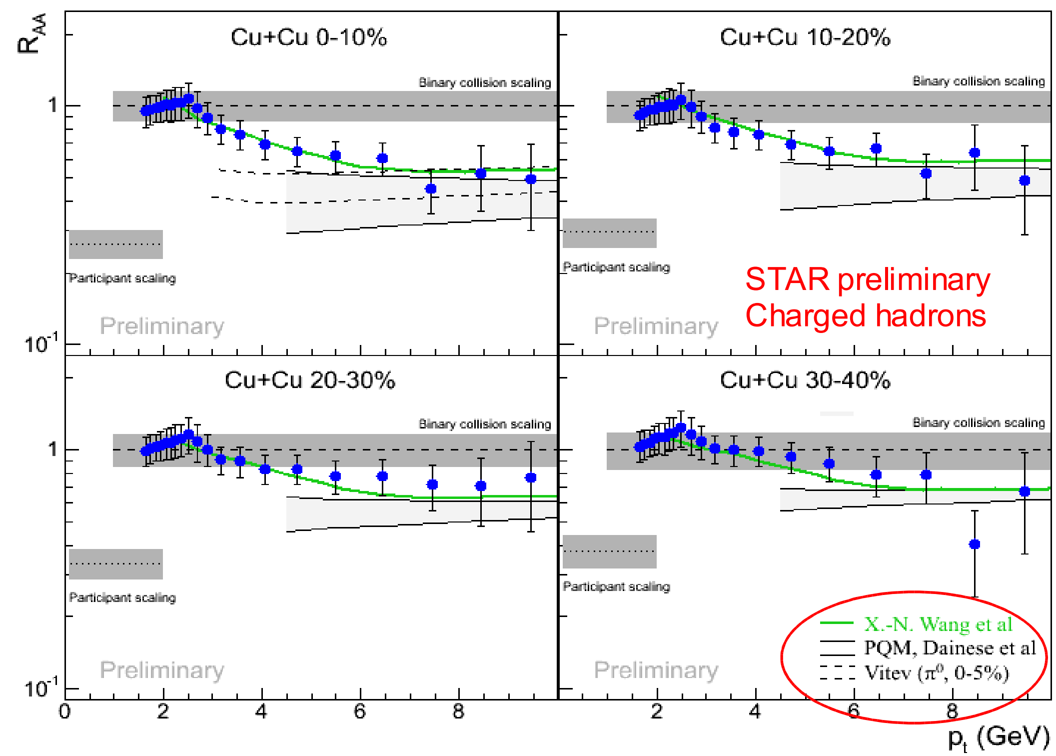
High p_T suppression: system-size dependence

- 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

High p_T suppression: charm quark (theory)

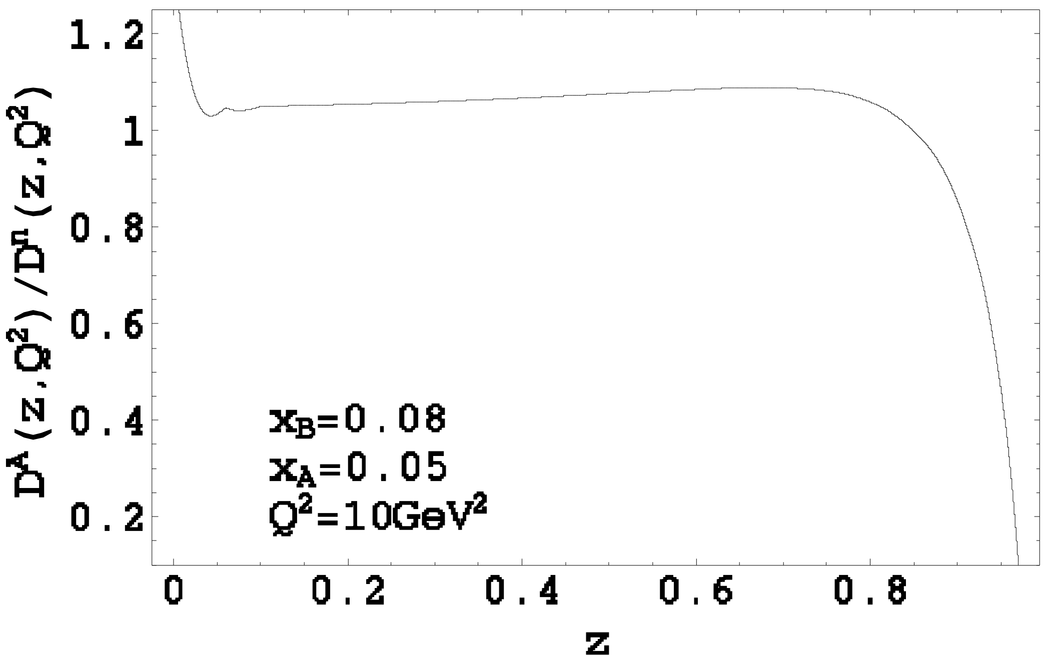
(1) Slow clock for formation time

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

(2) Color factor

(3) Dead cone effect

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



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