High-p_T suppression phenomena in nucleus-nucleus collisions within the Parton Quenching Model (PQM)

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based on work in collaboration with:

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Outline

- High-pt suppression at RHIC
- Phenomenology of Parton Energy Loss
- Details of the Parton Quenching Model
  - BDMPS-Z-SW quenching weights
  - Glauber geometry
  - Parton-by-parton approach
- Confrontation with RHIC data
- Heavy-Quark energy loss at RHIC (*)
- Opacity problem

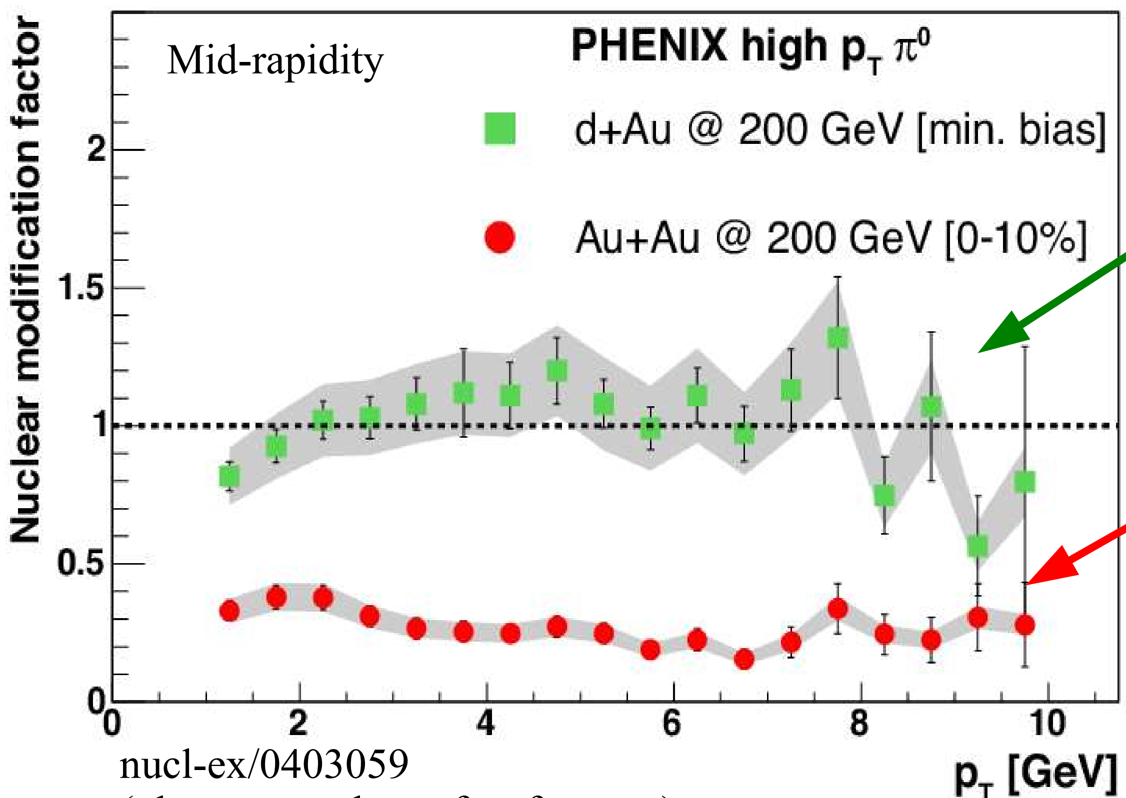
(*) if there is time

Leading-particle suppression at RHIC

Compare p_T distributions of leading particles in pp, dAu and AA (for different centralities)

Nuclear modification factor

$$R_{AB}(,p_T,\eta)=\frac{1}{N_{coll}}\times\frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}(p_T,\eta)$$



nucl-ex/0403059
(plus many other refs, of course)

Control measurement in d+Au no suppression ($R_{dA} \approx 1$)

Central Au+Au collision up to factor 5 suppressed (R_{AuAu} = 0.2)

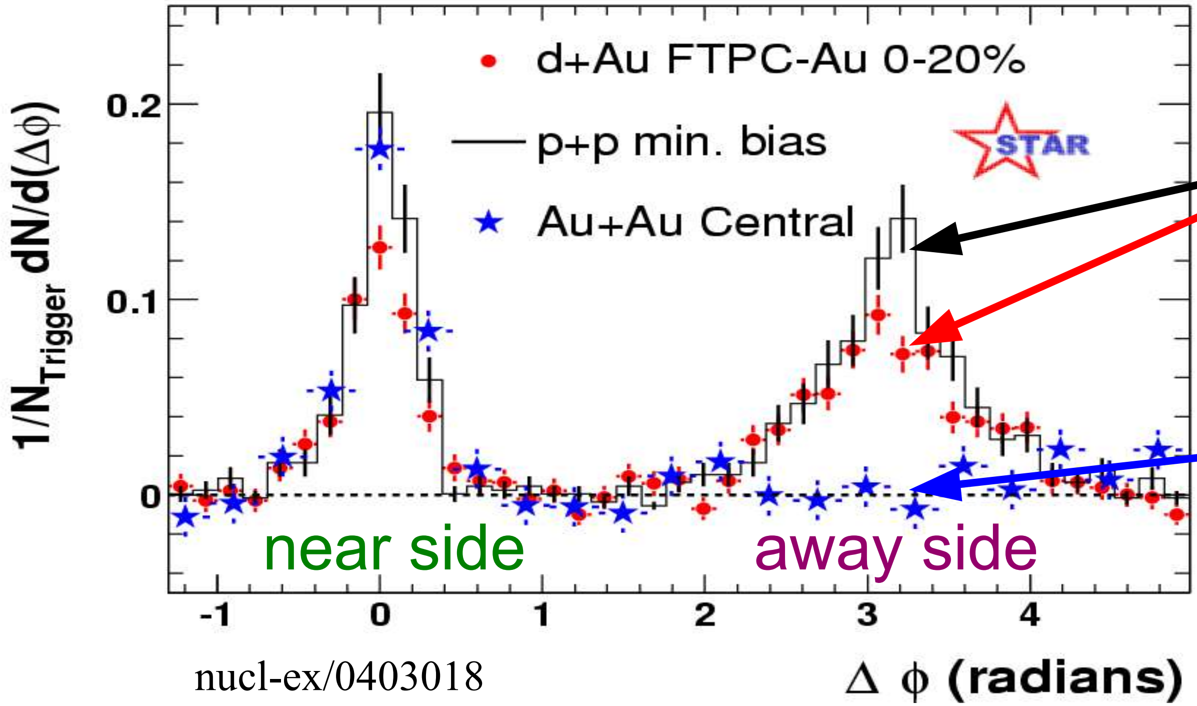
Final-state effect

Disappearance of away-side correlations at RHIC

- Trigger: highest p_T track with p_T>4 GeV
- $\Delta\phi$ distribution: 2 GeV < p_T < $p_T^{trigger}$
- Normalize to number of trigger particles

Suppression factor

$$I_{AB}^{away} = \int_{away} dN_{AB} / \int_{away} dN_{pp}$$



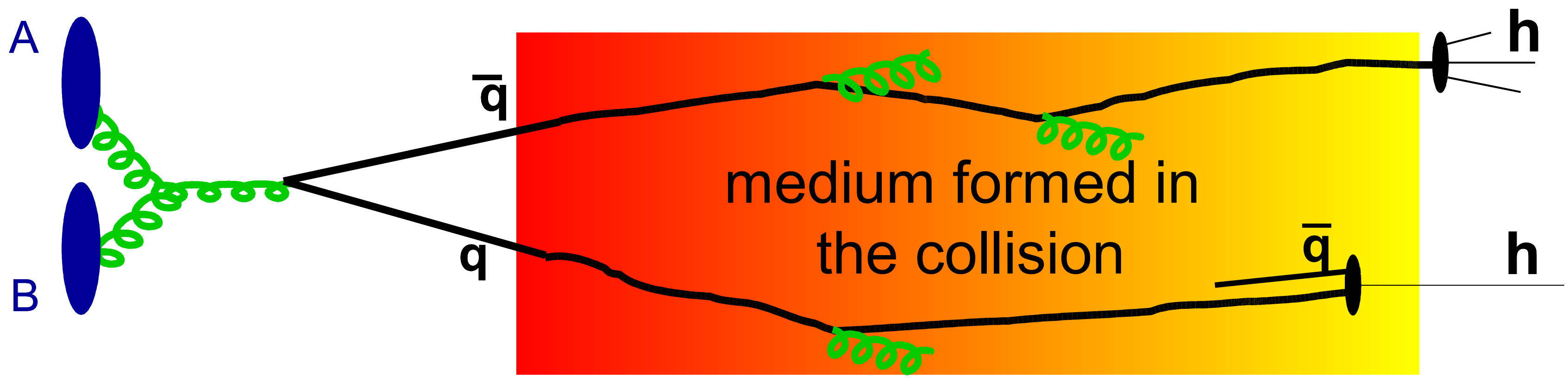
nucl-ex/0403018
(plus many other refs, of course)

Measurement in pp and d+Au not suppressed ($I_{AA} \approx 1$)

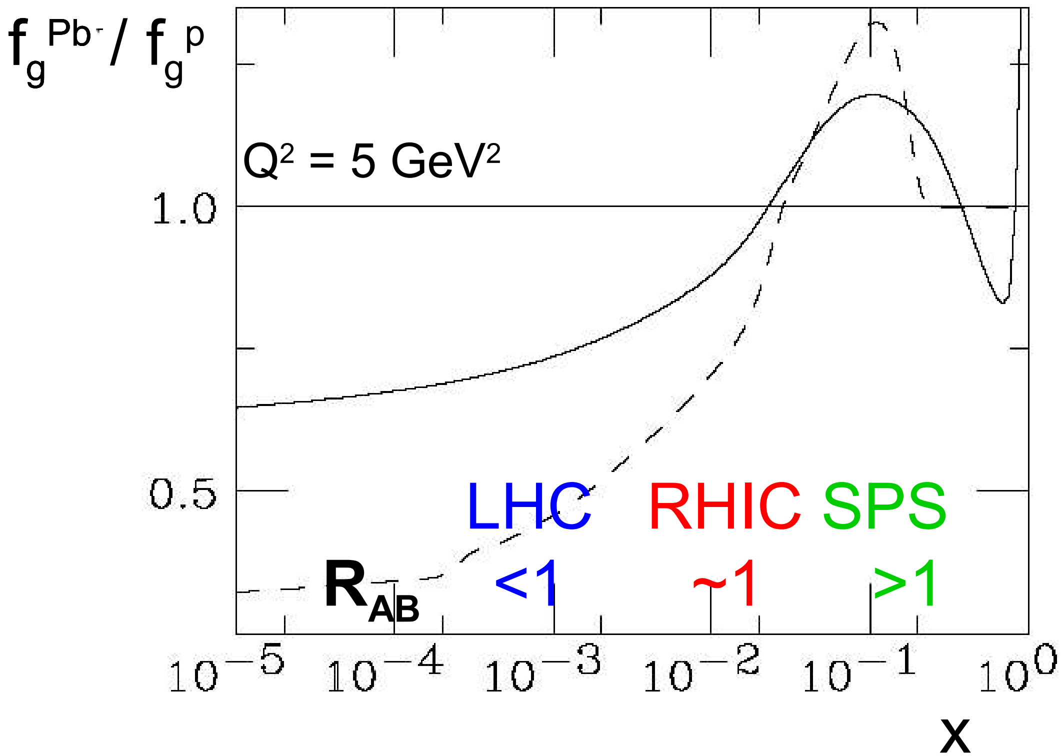
Central Au+Au collision strongly suppressed ($I_{AA} \approx 0.1$)

Final-state effect

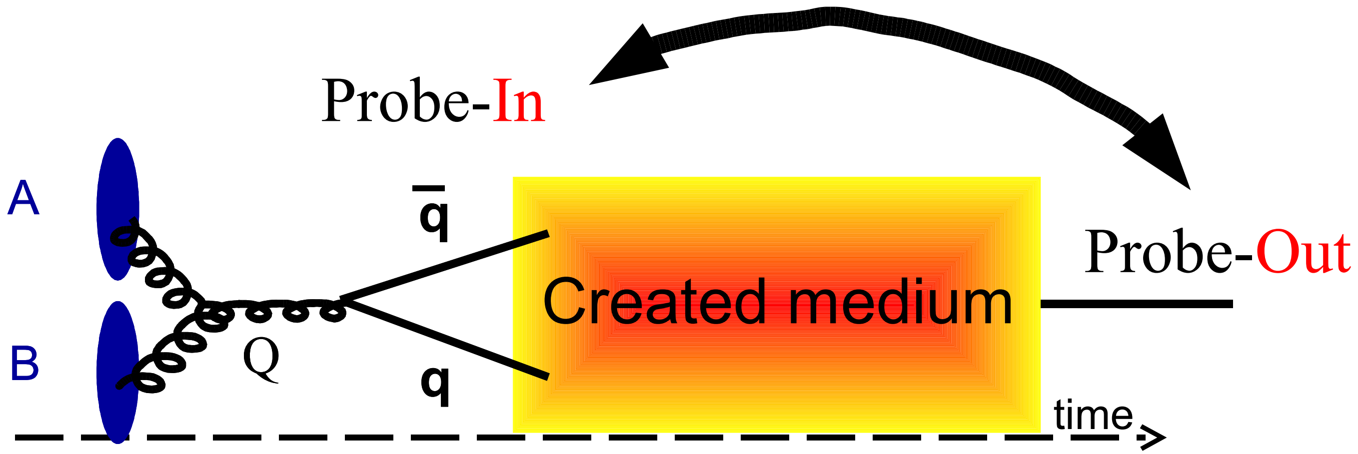
High-p_T particle production in A+B collisions



- Proton-Proton baseline (pQCD)
- Initial-state effects
  - Nuclear PDF (anti-/shadowing)
  - K_T broadening (Cronin)
- Final-state effects
  - Energy loss
  - In-medium hadronization (coalescence)



Hard probes in nucleus-nucleus collisions

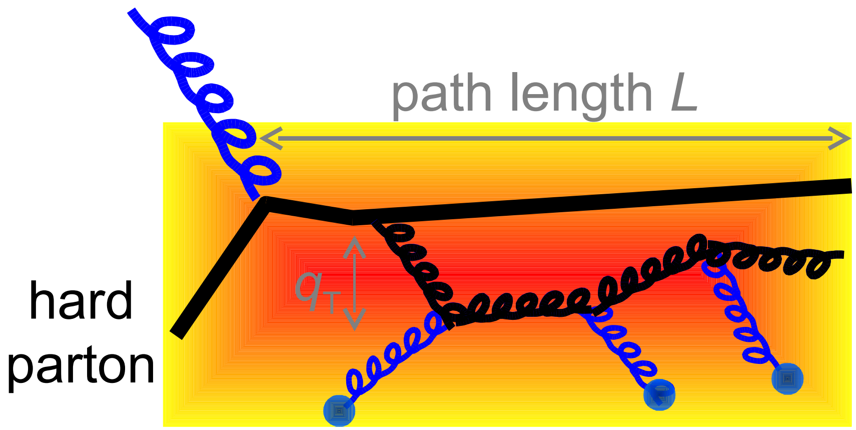


- Large virtuality Q leads to
  small "formation time" $\Delta t \sim 1/Q$ and small α_s
- Initial yields and p_T distributions in A+B may be predicted by
  pp measurements + pQCD + collision geometry (Glauber)
  + additional "known" nuclear (initial state) effects (e.g. nPDFs)
- Deviations from such predictions are attributed to the medium

Parton energy loss inspired by pQCD

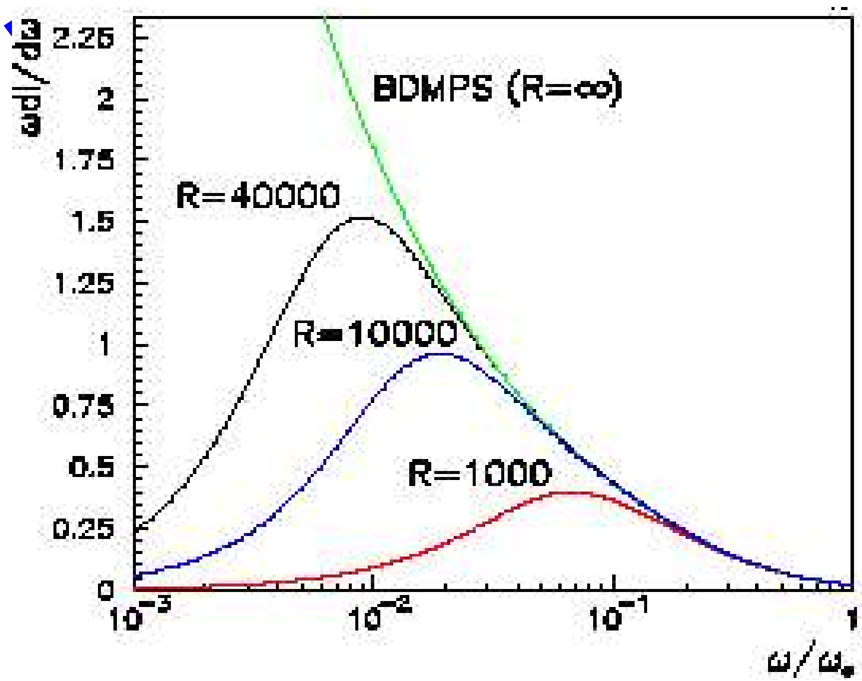
- Partons travel a few fm in the high color-density medium
- Bjorken (`82): energy loss due to elastic (collisional) scattering
- Successive calculations (`92++) revealed/suggested that medium-induced gluon radiation (QCD bremsstrahlung) dominates:

  Coherent wave-function gluon acummulates k_T due to multiple inelastic scatterings in the medium until decoheres and is radiated off the original hard parton



Bjorken, Gyulassy, Plümer, Thoma, Wang, Wang, Baier, Dokshitzer, Müller, Peigne', Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann, ...

Parton energy loss in pQCD (BDMPS-Z)



STATIC MEDIUM

BDMPS-Z formalism

$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{dI}{d\omega} \propto \alpha_S C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geqslant \omega_c \end{cases}$$

C_R	Casimir coupling factor: 4/3 for q, 3 for g
$\omega_c = \hat{q} L^2 / 2$	determines the scale of the radiated energy
$R = \omega_c L$	related to constraint $k_T < \omega$ and controls shape at $\omega << \omega_c$

Baier, Dokshitzer, Müller, Peigne‘, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

Calculating the energy loss

$$\langle \Delta E \rangle \approx \int_0^{\omega_c} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_S\, C_R\, \omega_C \propto \alpha_S\, C_R\, \hat{q}\, L^2$$

$$\langle \Delta E \rangle \propto \hat{q} \propto \rho \int dq_T^2 q_T^2\, d\sigma / dq_T^2$$

(gluons volume-density and interaction cross section)

Probe the medium

Finite parton energy (qualitatively)

- If E< ω_c (e.g. small p_T with traversing large L) :

$$\langle \Delta E \rangle \approx \int_0^{E} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_S\, C_R\, \sqrt{E\, \omega} \propto \alpha_S\, C_R\, \sqrt{E}\, \sqrt{\hat{q}}\, L$$

  - Introduces dependence on parton energy
  - Reduces sensitivity to density
  - Leads to linear dependence on path length

Expanding medium

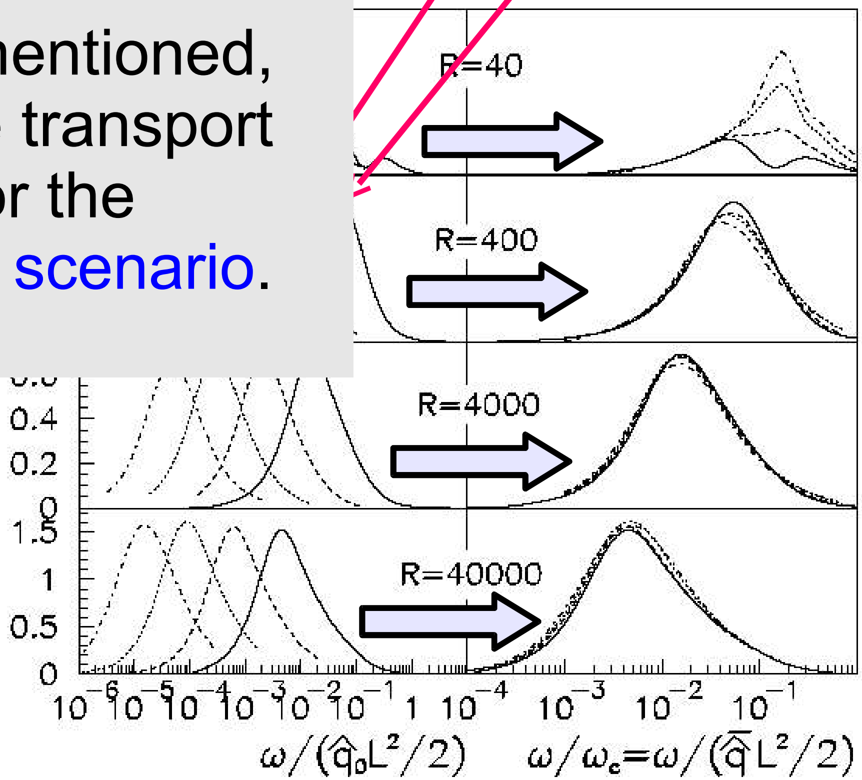
- Time-dep. density of scattering centers

$$\hat{q}(\tau) = \hat{q}_0 \times \left(\frac{\tau_0}{\ }\right)^{\alpha}$$

- Dynamical sc… same spectru… for an equiva… transport coe…

$$\bar{\hat{q}} = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau \,(\tau - \tau_0)\, \hat{q}(\tau)$$

If not explicitly mentioned, all values for the transport coefficient are for the equivalent static scenario.



→ **Calculations for a static scenario apply for also for expanding systems**

Salgado, Wiedemann, PRL 89 (2002) 092303.

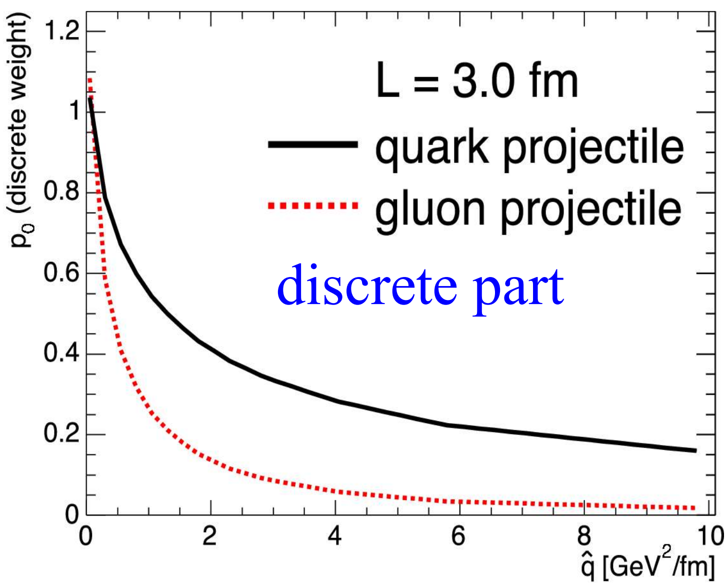
Quenching weights

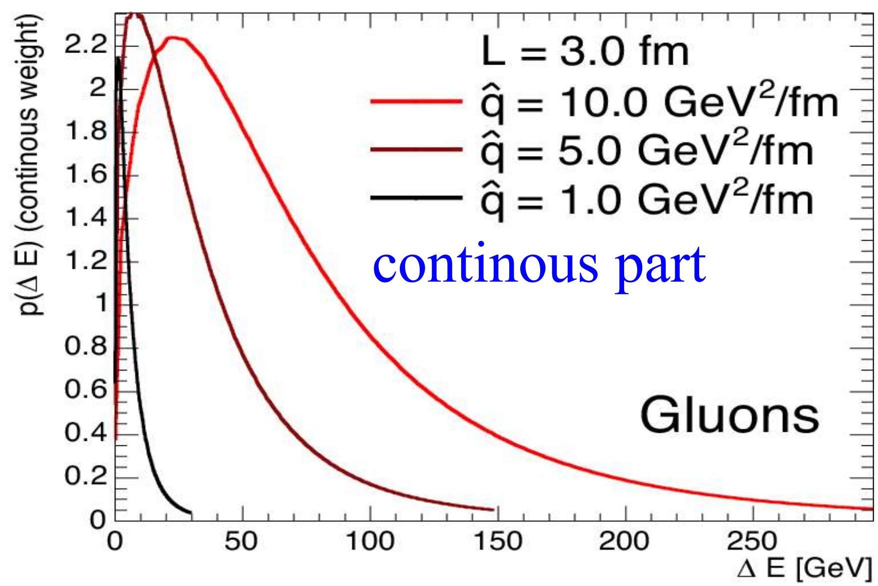
- Compute energy loss probability distributions

$$P(\Delta E) = \sum_{n=0}^{\infty} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=0}^{n} \omega_i \right) \exp\left[-\int d\omega \frac{dI}{d\omega} \right]$$

- Calculated from $\omega\, dI/d\omega$ in the $E \to \infty$ approximation (no E dep.)

$$P(\Delta E; C_R, \hat{q}, L) = p_0(C_R, \hat{q}, L) + p(\Delta E; C_R, \hat{q}, L) \qquad \left[\alpha_S = 1/3\right]$$





BDMS, JHEP 0109 (2001) 033
Salgado, Wiedemann, PRD 68 (2003) 014008

→ **Constrained weights**

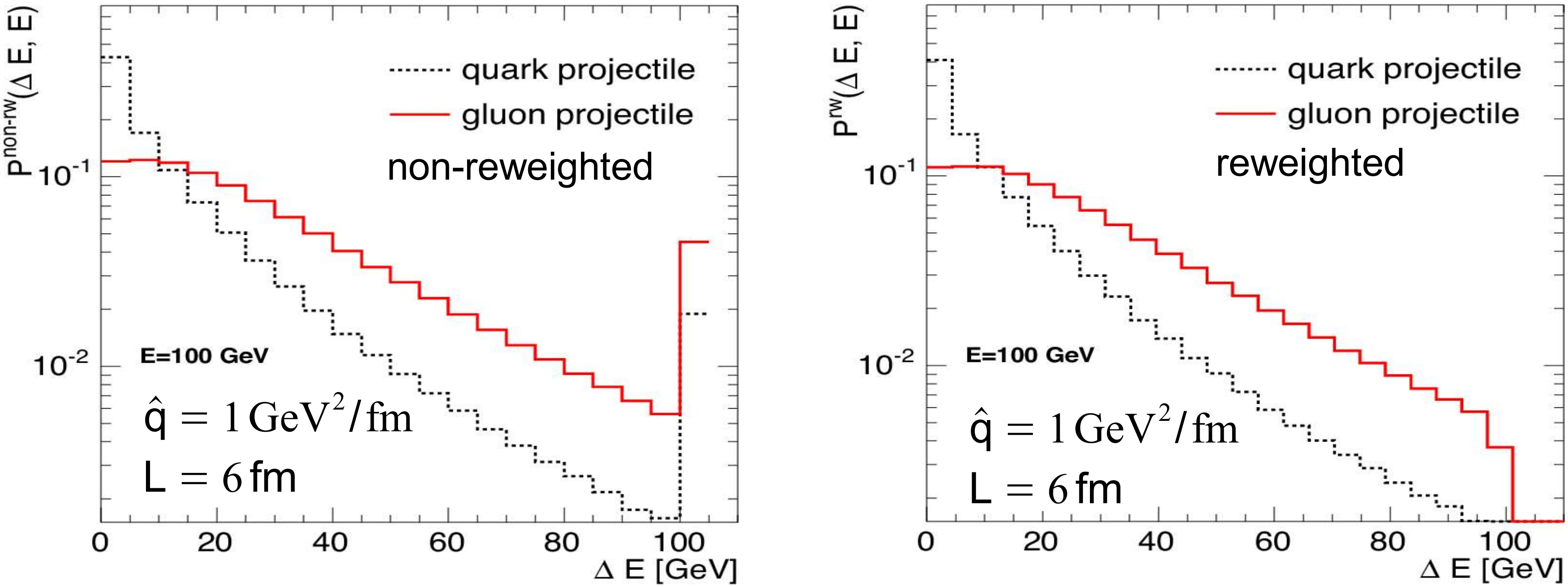
Constrained quenching weights

Construct constrained weights from quenching weights

$$P(\Delta E; C_R, \hat{q}, L, E) \quad \text{with} \quad \Delta E \leq E$$

a) non-reweighted weight
(thermalize for ΔE>E)

b) reweighted weight
(truncate + renormalize at ΔE=E)



Calculating unquenched particle spectra

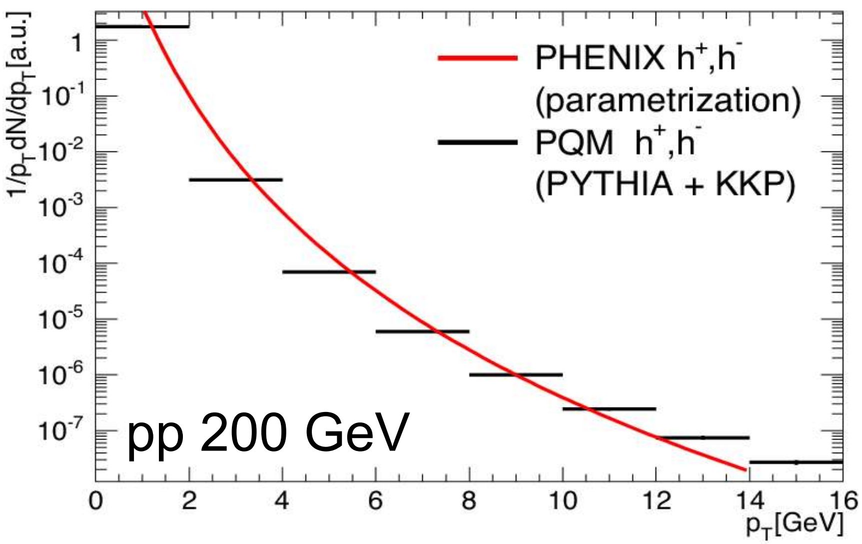
Standard pQCD + collinear factorization + vacuum fragmentation

$$\left.\frac{d^2\sigma^h}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j} \int dF_{ab} \qquad dz_j \left.\frac{d^2\sigma^{ab\to jX}}{dp_{T,j}\,dy}\right|_{y\approx 0} \times \frac{D_{h/j}(z_j)}{z_j^2}$$

Monte Carlo approach:

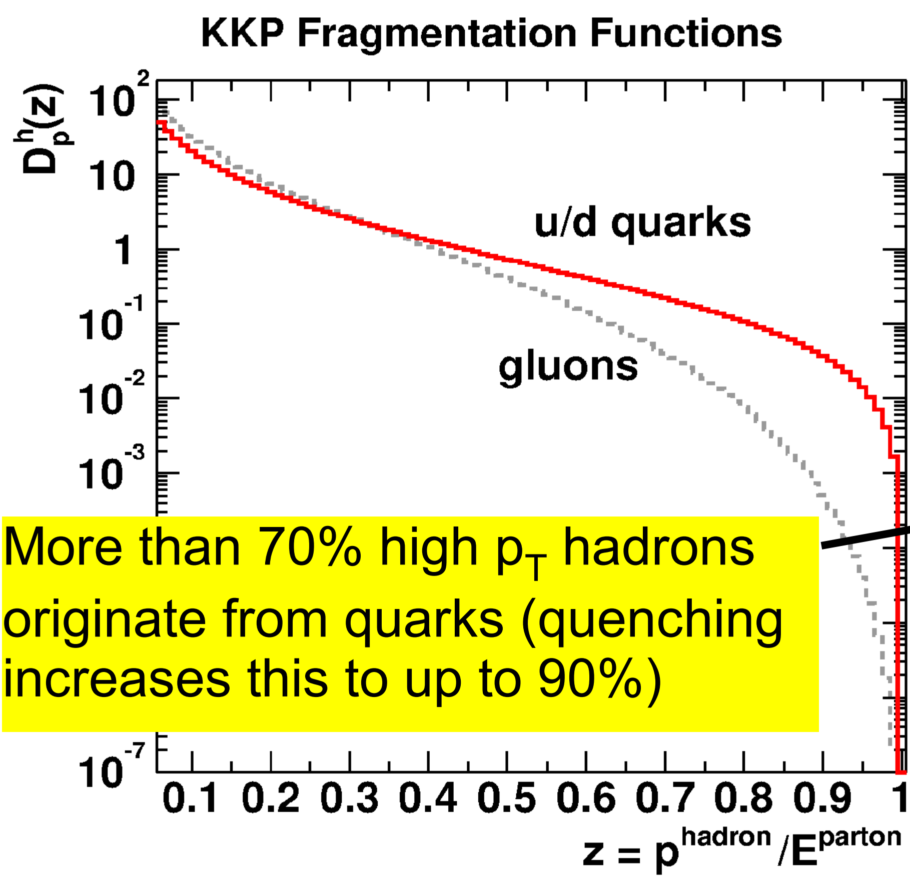
Verify shape with PHENIX parametrization for pp

$$\frac{1}{p_T}\frac{d^2N}{dp_T} = C\left(1+\frac{p_0}{p_T}\right)^n + r\left(p_T\right)$$

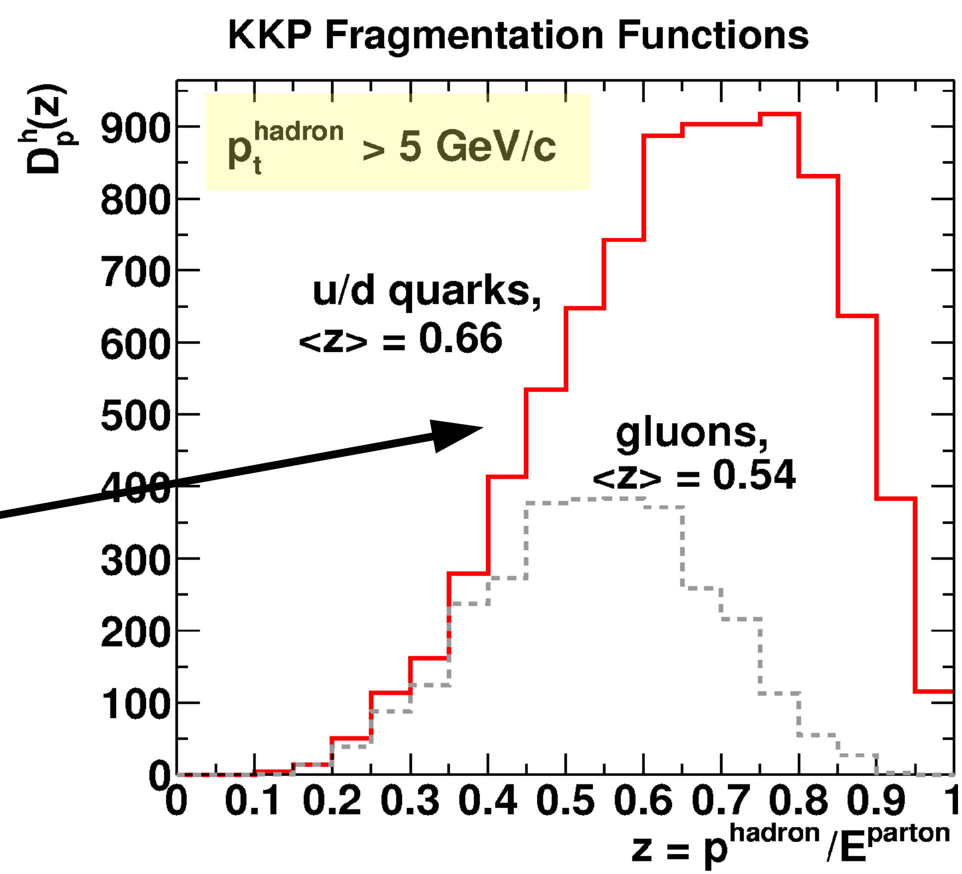


PYTHIA + KKP fragmentation

PYTHIA p_T parton distributions + relative ratio of quarks-to-gluons at 200 GeV cms energy using CTEQ 4L + KKP at LO



More than 70% high p_T hadrons originate from quarks (quenching increases this to up to 90%)

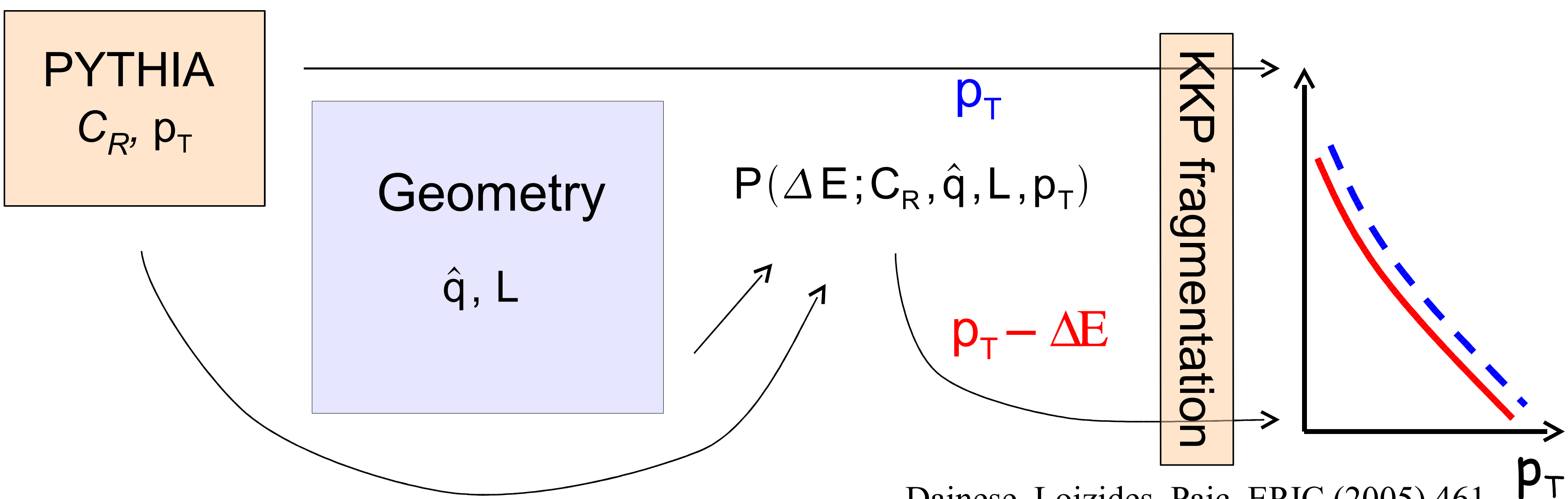


Calculating quenched particle spectra

Factorized pQCD + final state quenching + vacuum fragmentation

$$\left.\frac{d^2\sigma^{h}_{\mathrm{quenched}}}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j}\int dF_{ab}\, d\Delta E_j\, dz_j \left.\frac{d^2\sigma^{ab\to jX}}{dp^{\mathrm{init}}_{T,j}\,dy}\right|_{y\approx 0} \times$$
$$\delta(p^{\mathrm{init}}_{T,j}-p_{T,j}-\Delta E_j)\,P(\Delta E_j; C_j, \hat{q}_j, L_j, p_{T,j})\,\frac{D_{h/j}(z_j)}{z_j^2}$$

Monte Carlo approach:



Dainese, Loizides, Paic, EPJC (2005) 461.

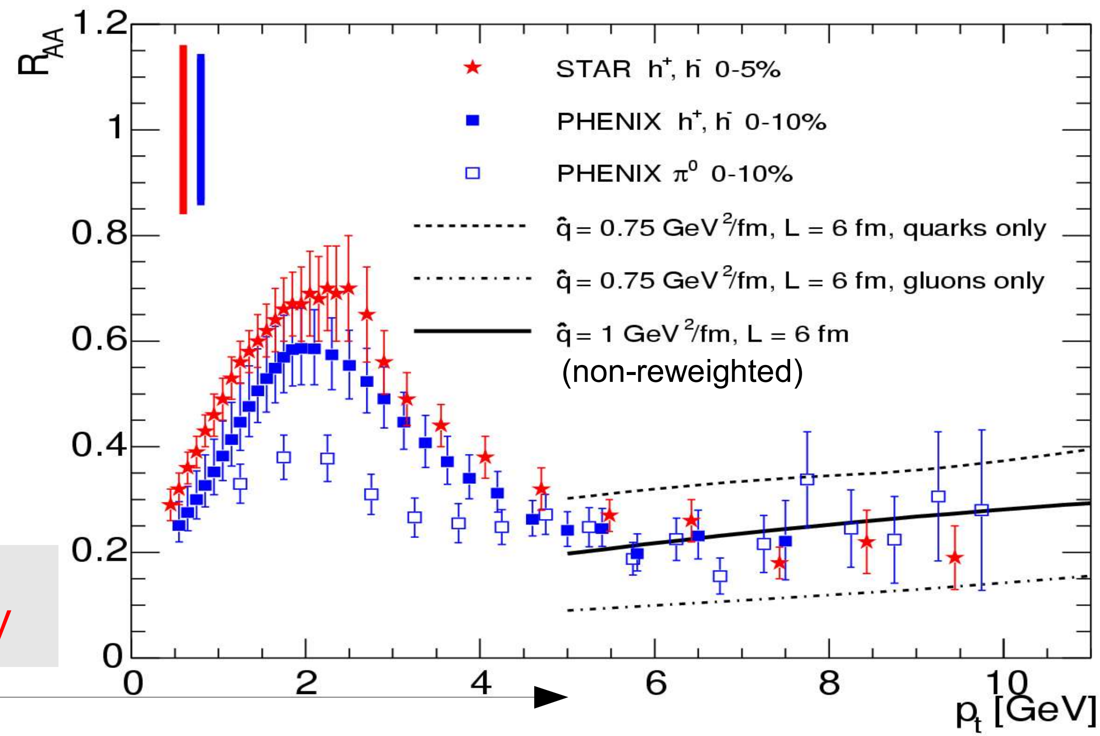
R_{AA} in central Au+Au at 200 GeV

Need

$$\hat{q} = 1\,\mathrm{GeV}^2/\mathrm{fm}$$

to describe the measured suppression in 0-10% Au+Au for <u>fixed length</u> of 6 fm

No initial-state effects and in-medium hadronization: p_T > 5 GeV



PYTHIA

C_R, p_T

FIXED

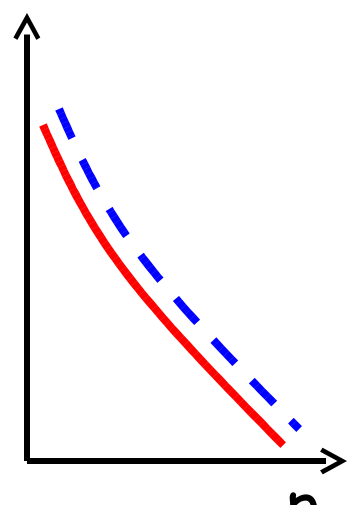
$\hat{q}$, L

$P(\Delta E; C_R, \hat{q}, L, p_T)$

p_T

$p_T - \Delta E$

KKP fragmentation



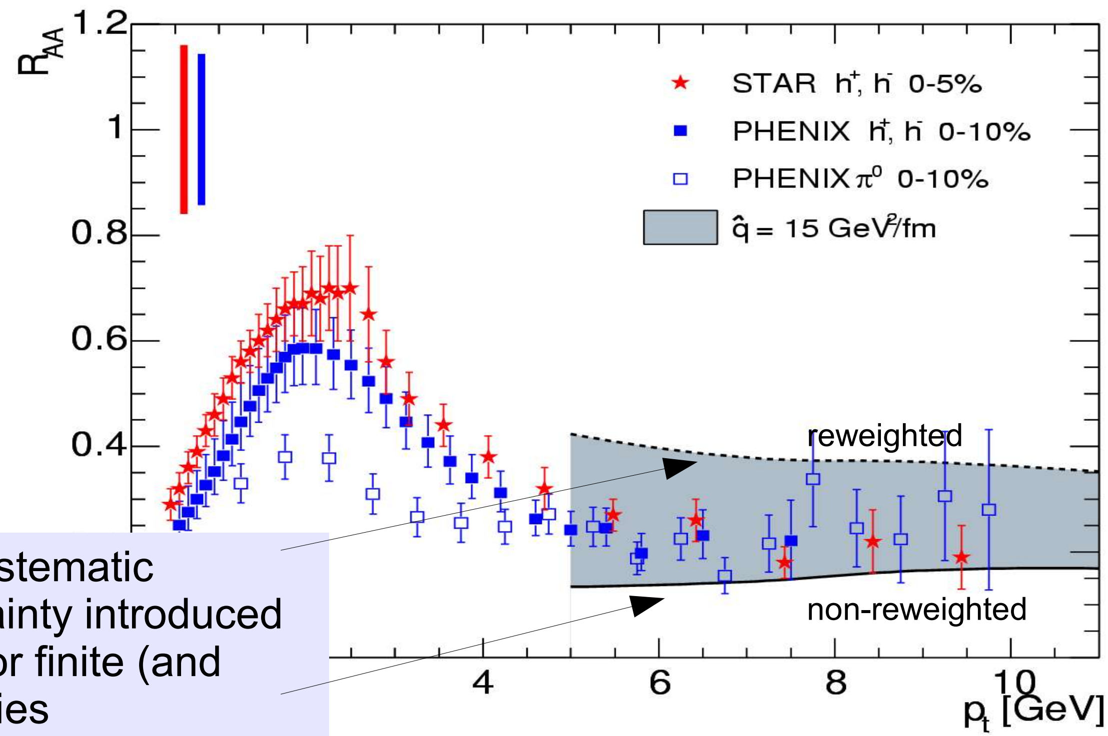
Dainese, Loizides, Paic, EPJC (2005) 461.

R_{AA} in central Au+Au at 200 GeV (2)

Need

$$\hat{q} = 15\,\mathrm{GeV}^2/\mathrm{fm}$$

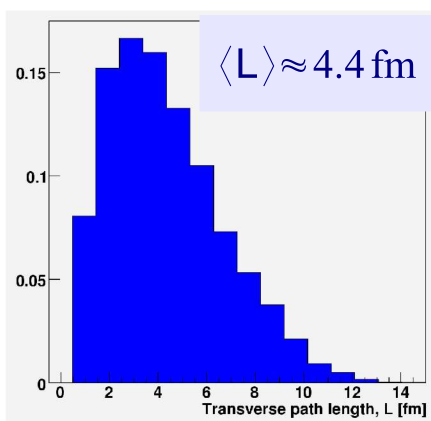
to describe the measured suppression in 0-10% Au+Au for Glauber-based length distribution



Band represents systematic (theoretical) uncertainty introduced by the constraints for finite (and small) parton energies

PYTHIA

C_R, p_T



$\langle L \rangle \approx 4.4\,\mathrm{fm}$

$$L = \frac{\int dl\, l\, \rho(x_0+l, y_0+l; b)}{\int dl\, \rho(x_0+l, y_0+l; b)}$$

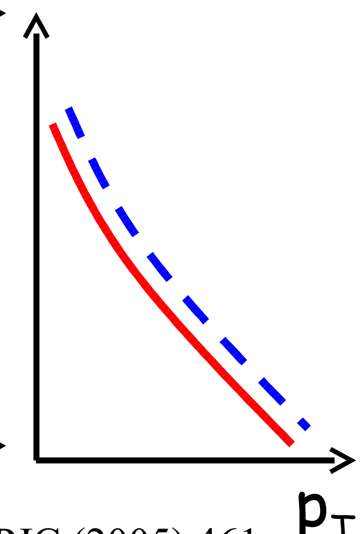
and FIXED $\hat{q}$

p_T

$$P(\Delta E; C_R, \hat{q}, L, p_T)$$

$p_T - \Delta E$

KKP fragmentation



Dainese, Loizides, Paic, EPJC (2005) 461.

Role of collision geometry

- Parton production according to $\rho_{coll}(x, y; b)$
- Parton absorption according:

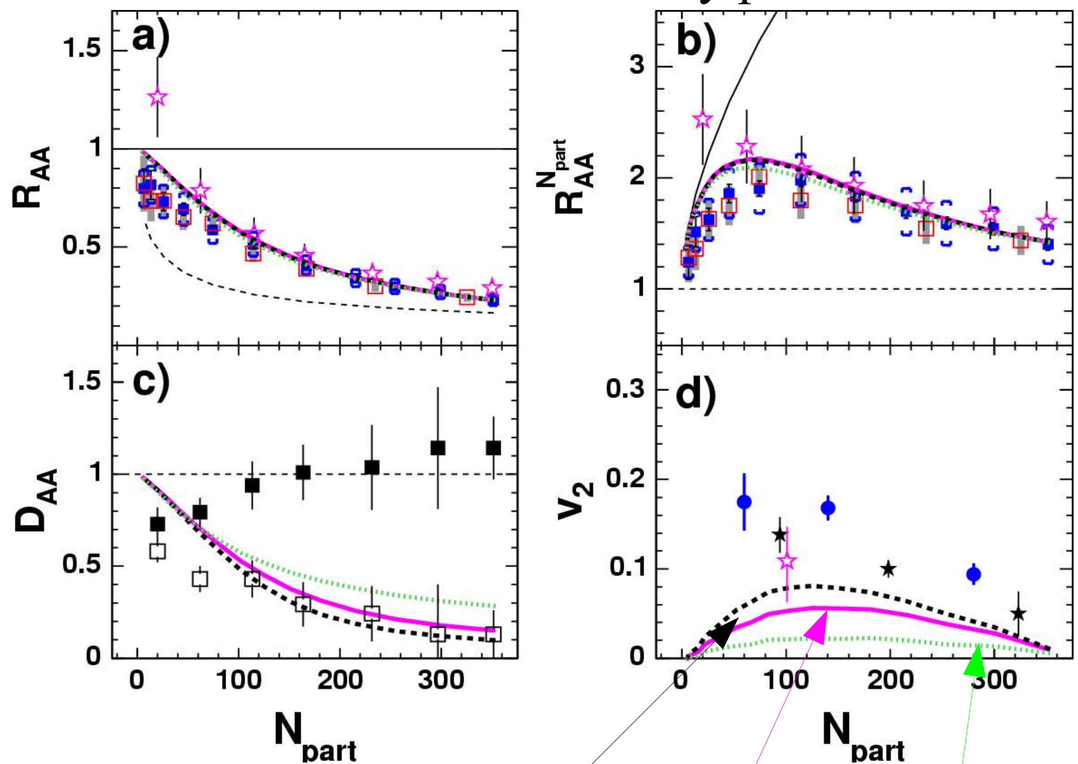
  $$f = \exp(-k\, l)\ ;\ l \propto \int f(l)\,\rho(l)\,dl$$

  independent on p_T

  where l is line-integral over density-profile for different expansion scenarios
- Results relatively independent on detailed modelling of matter (not shown) and absorption patterns

➡ **Opaque medium: geometry (volume) dominates**

Wood-Saxon density profile



L^2 and static

L^2 and longitudinal exp.

L and longitudinal exp.

Drees, Feng, Jia, PRC 71 (2005) 034909.

PQM parton-by-parton approach

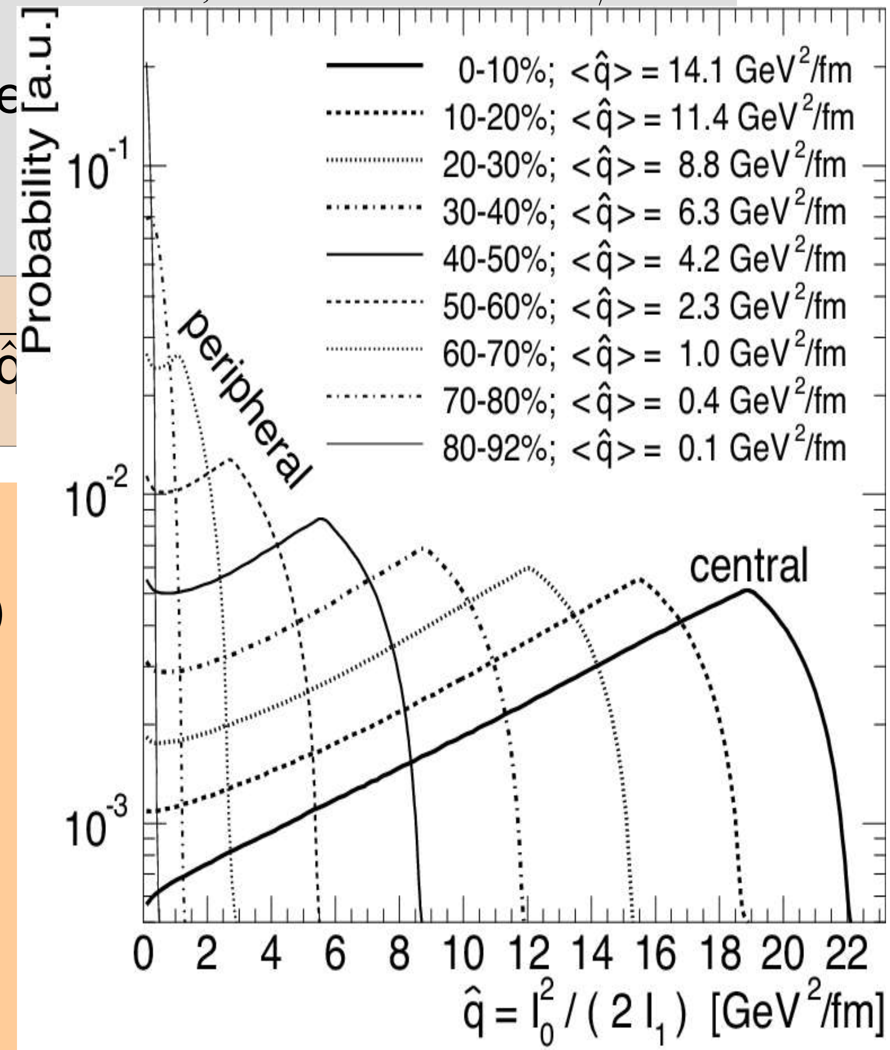
- Define "local" transport coefficient

$$\hat{q}\left(\xi; x_{0,} y_{0,} \phi_0; b\right) = k \times T_A T_B\left(x_0 + \xi \cos\phi_{0,} y_0 + \xi \sin\phi_0; b\right)$$

  - Definition of matter: $\propto \rho_{\text{coll}}$ (note
  - With $I_i = \int_0^\infty d\xi\ \xi^i\ \hat{q}(\xi)$ one gets

parton-by-parton dependent $\bar{\hat{q}}$

- Definition of L independent of k
- Parameter k must be tuned by data (once)
  - Single parameter to set the scale
  - Implicitly depends on systems and energy (see later)
  - Use Glauber to scale to other centralities
  - Report $\langle \hat{q} \rangle \propto k$ for a given centrality range



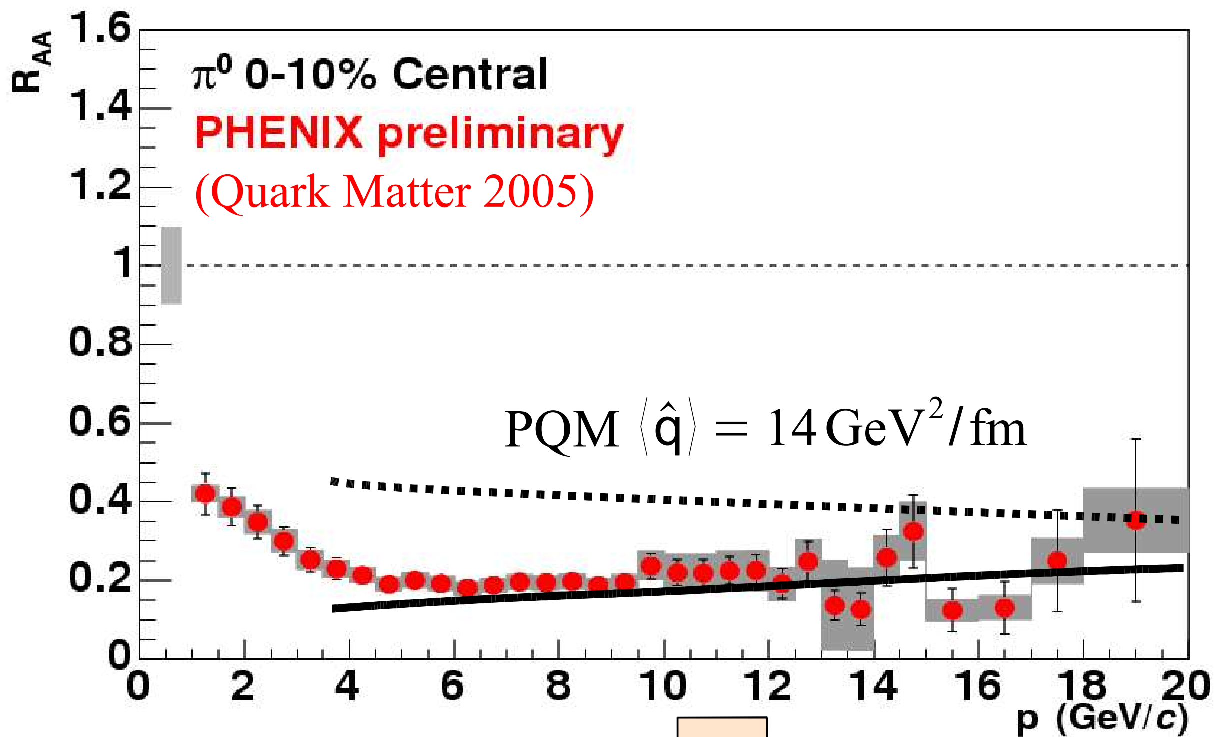
Dainese, Loizides, Paic, EPJC (2005) 461.

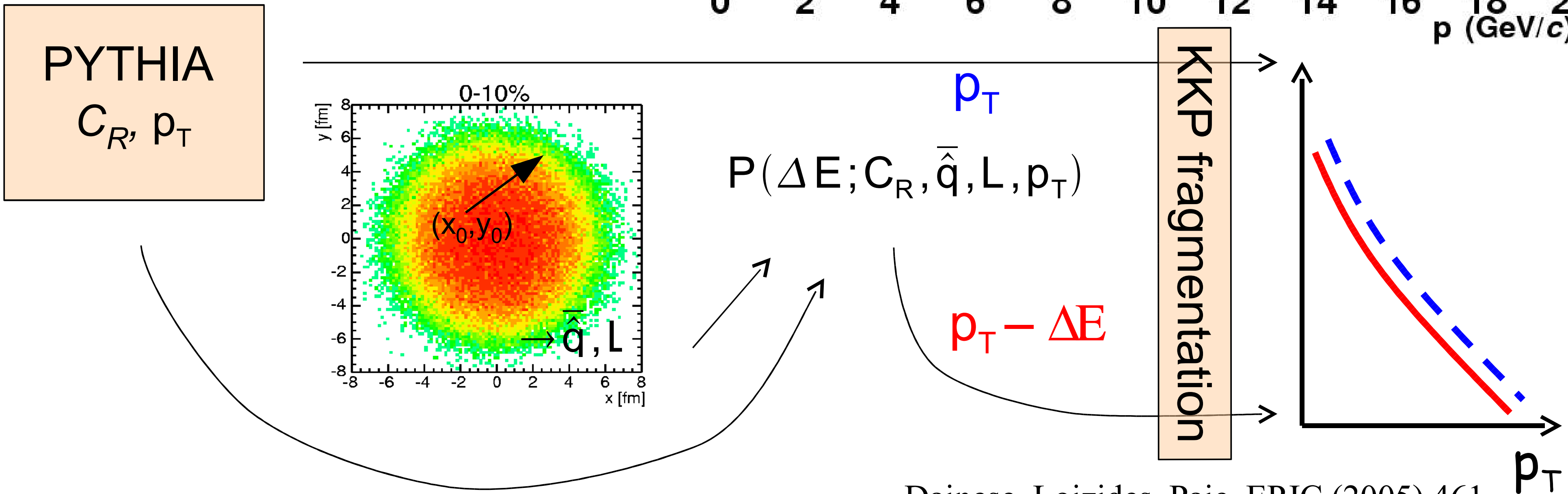
R_{AA} in central Au+Au at 200 GeV (3)

Find

$$\langle \hat{q} \rangle = 14\,\mathrm{GeV}^2/\mathrm{fm}$$

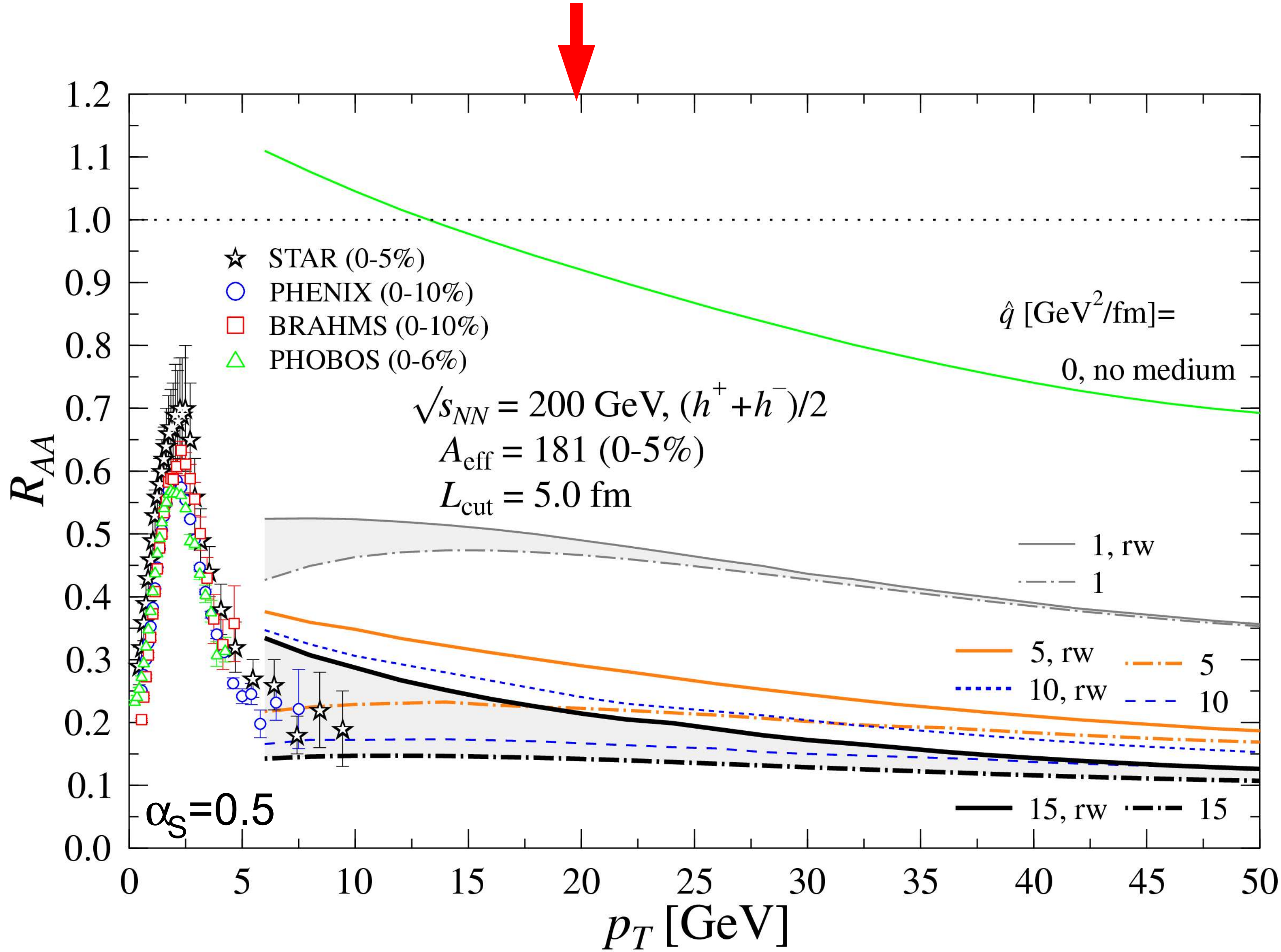
to describe the measured suppression in 0-10% Au+Au for the parton-by-parton approach





Dainese, Loizides, Paic, EPJC (2005) 461.

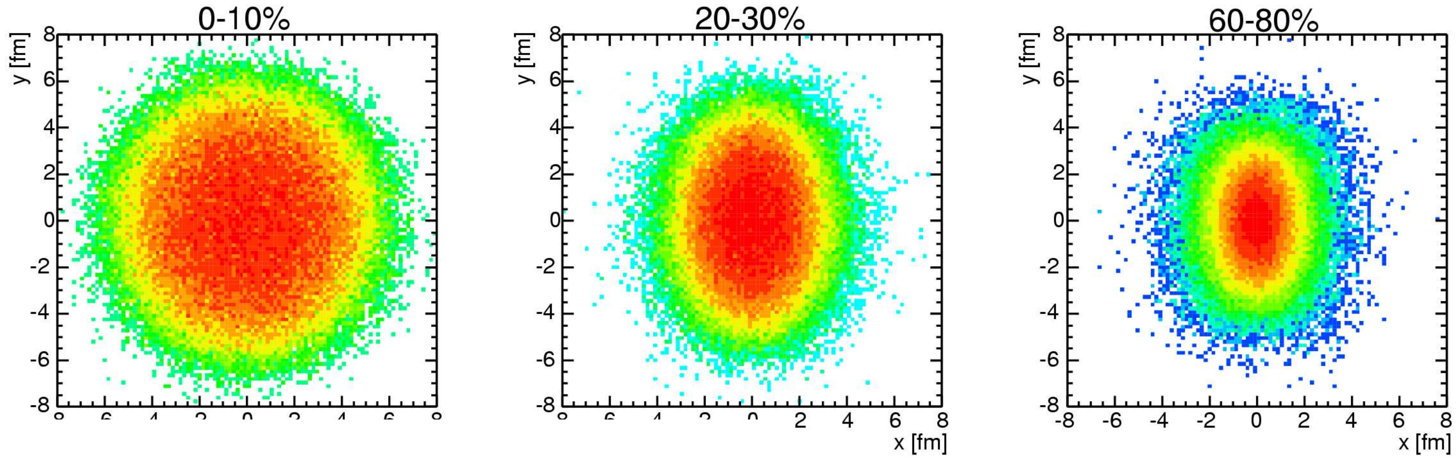
R_{AA} in central Au+Au at 200 GeV (4)

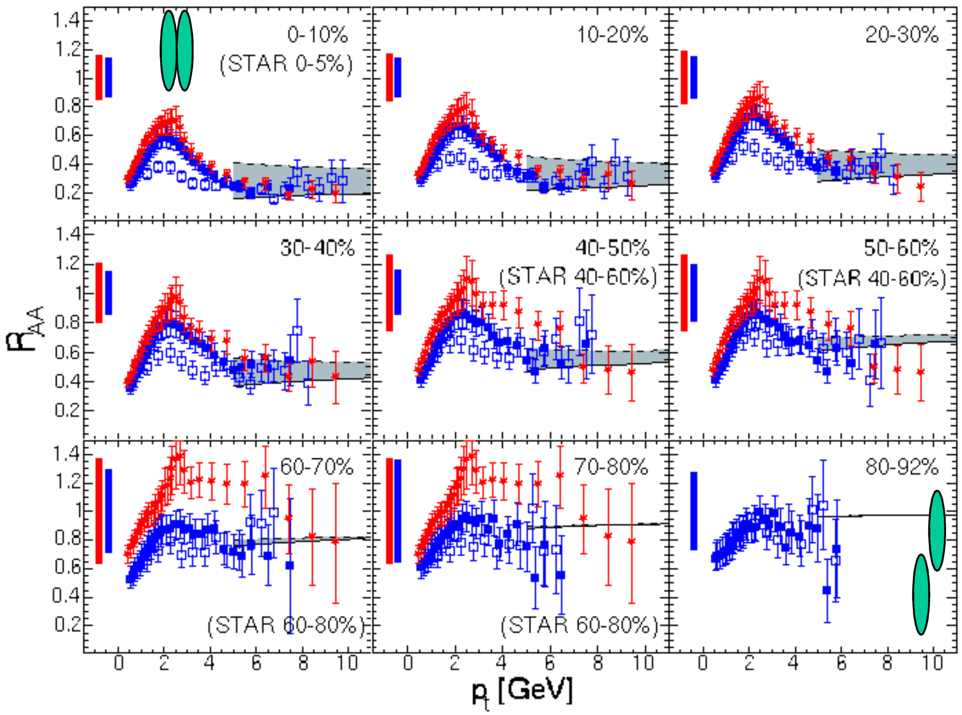


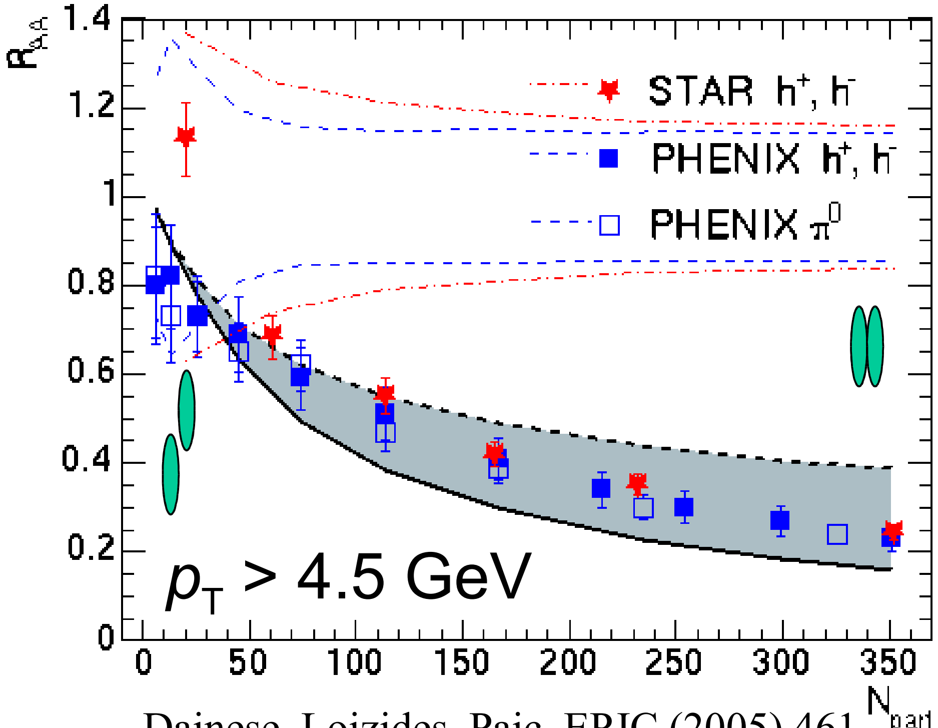
Eskola, Honkanen, Salgado, Wiedemann, NPA 747 (2005) 511.

Centrality dep. of R_{AA} for Au+Au at 200 GeV

Glauber: $\hat{q}(b) = k^{AuAu,200\,GeV} \times T_A T_B(b)$



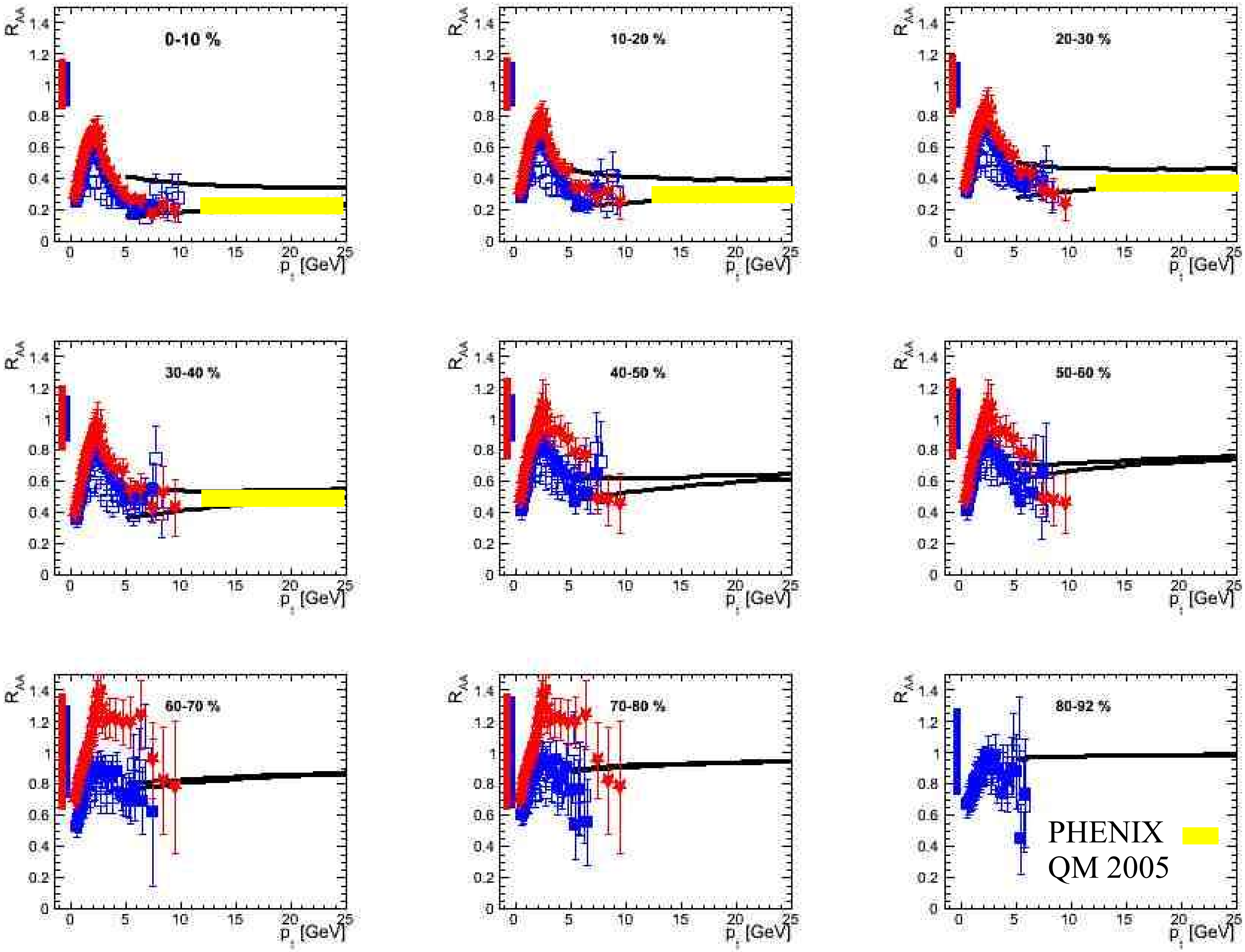




Dainese, Loizides, Paic, EPJC (2005) 461.

Centrality dep. of R_{AA} for Au+Au at 200 GeV (2)

New π^0 R_{AA} data for 200 GeV Au Au from PHENIX



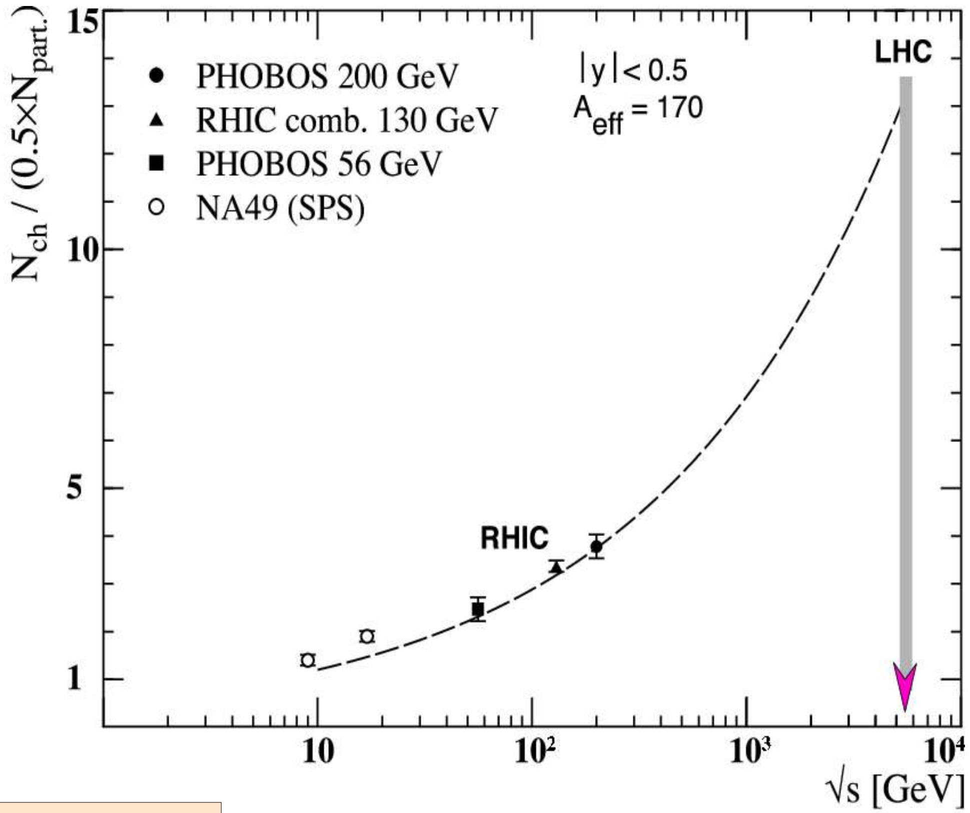
Extrapolation to other systems

The transport coefficient is proportional to the gluon density, which according to the saturation model (EKRT) scales with

$$\langle \hat{q} \rangle \propto n^{\text{gluons}} \propto A^{0.383} \sqrt{s_{NN}}^{\,0.574}$$

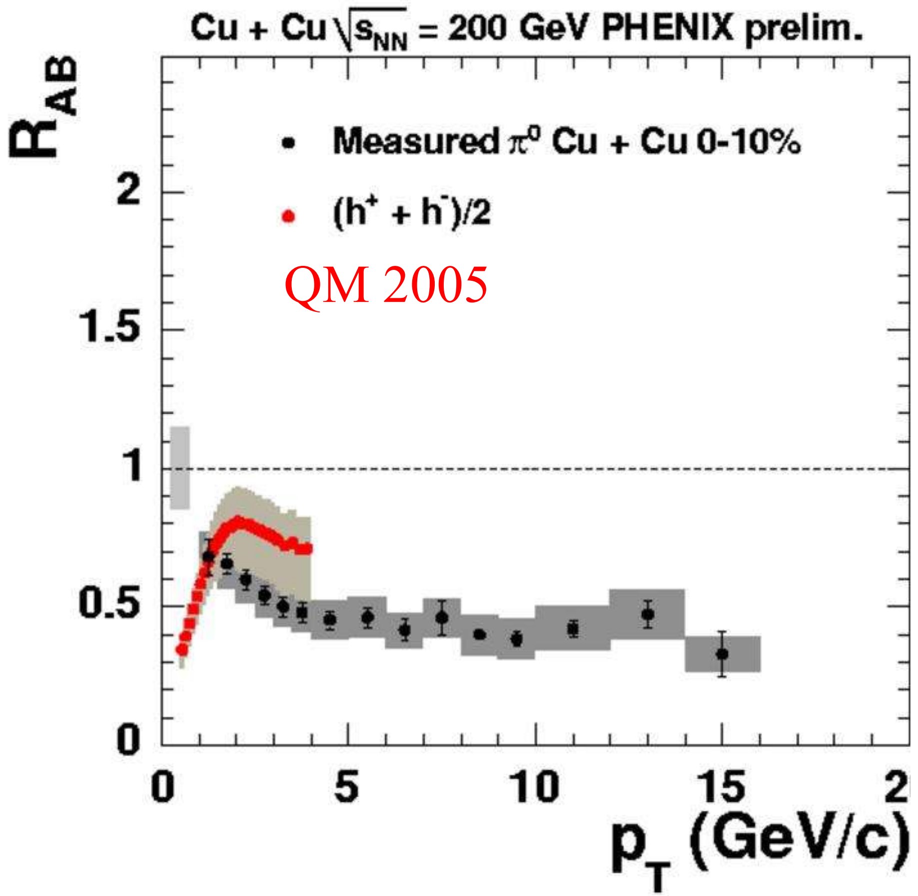
Using the extracted value at Au+Au 200 GeV gives (for 0-10% collisions)

$$\langle \hat{q} \rangle = \left(A/197\right)^{0.383} \left(\sqrt{s_{NN}}/200\right)^{0.574} \times 14 \left[\text{GeV}^2/\text{fm}\right]$$

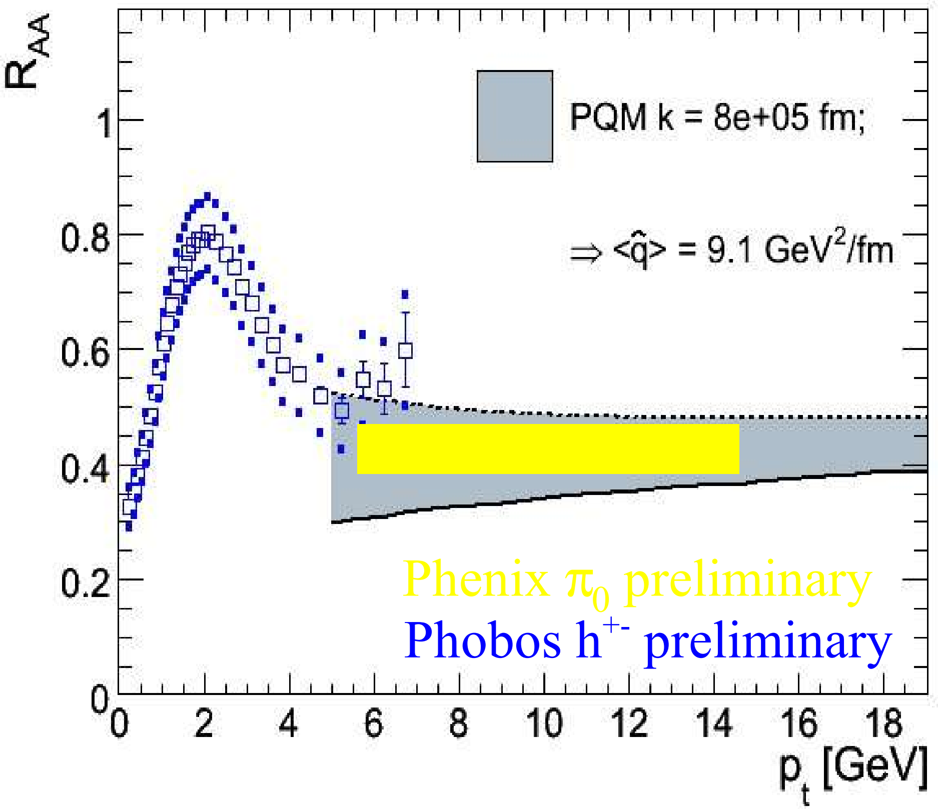


Scale with 0.5 for 62.4 GeV Au+Au;
with 0.63 for 200 GeV Cu+Cu
(Factor 7 for 5.5 TeV Pb+Pb)

Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000) 379.

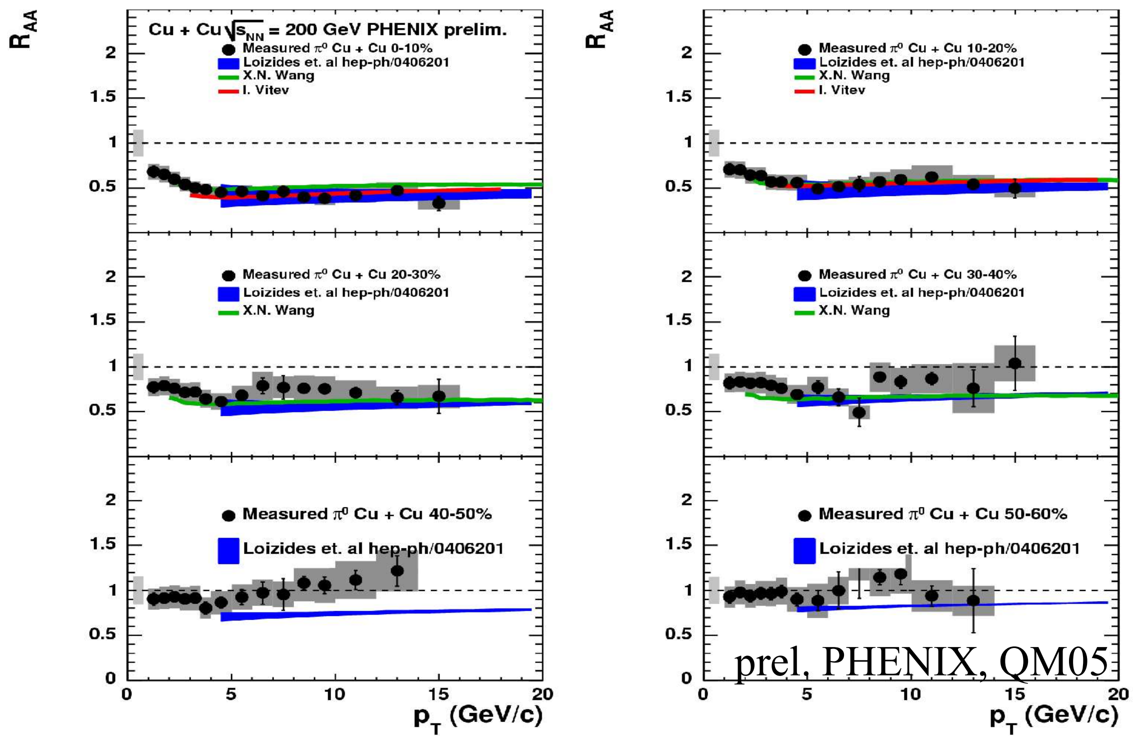


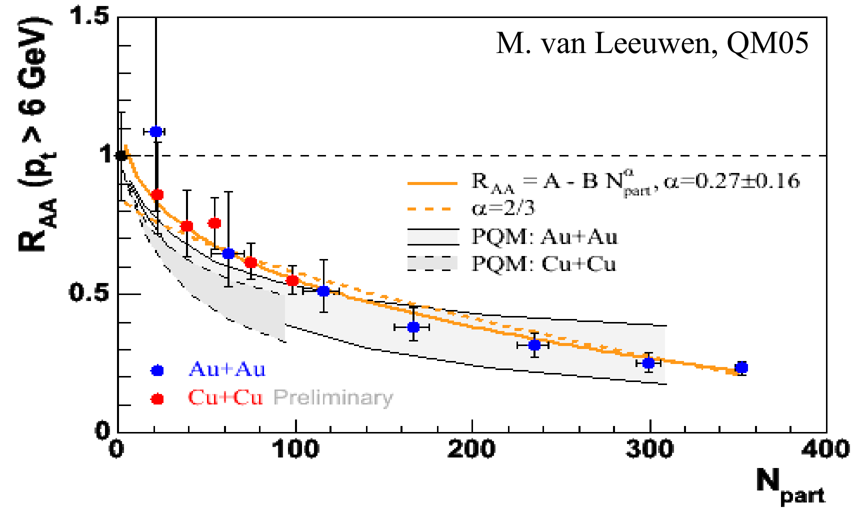
$\langle \hat{q}^{200,CuCu} \rangle = 9\,GeV^2/fm$

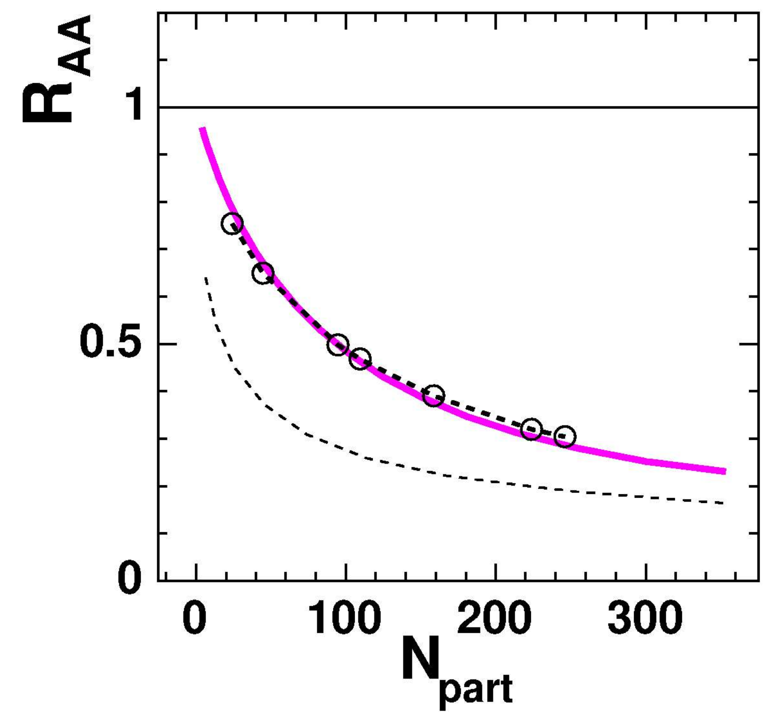


species/energy extrapolation works reasonably well

R_{AA} for Cu+Cu and Au+Au vs centrality



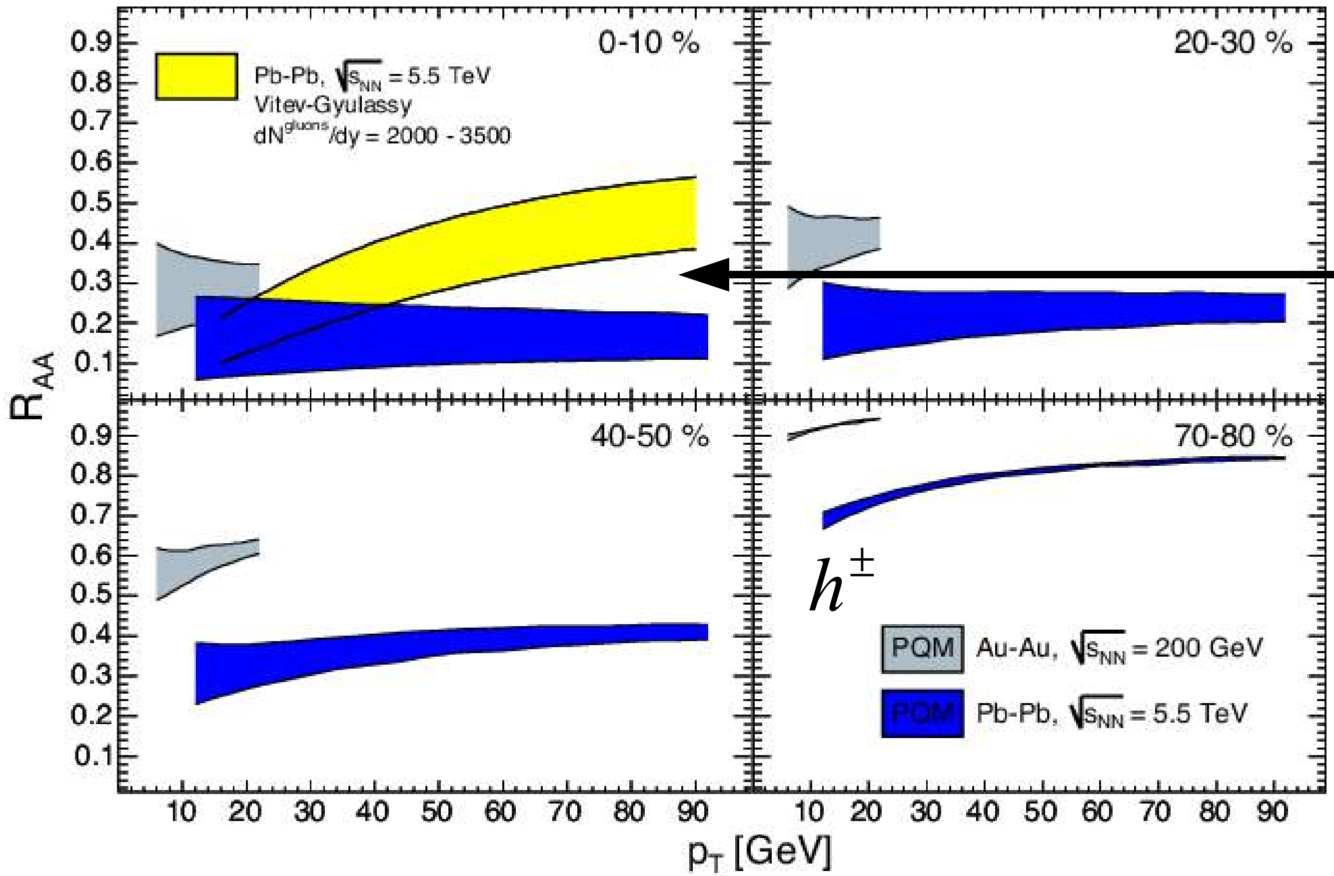




Drees, Feng, Jia, PRC 71 (2005) 034909.

R_{AA} prediction for LHC

$\langle \hat{q}^{5500,\mathrm{PbPb}} \rangle \approx 50-100\,\mathrm{GeV}^2/\mathrm{fm}$



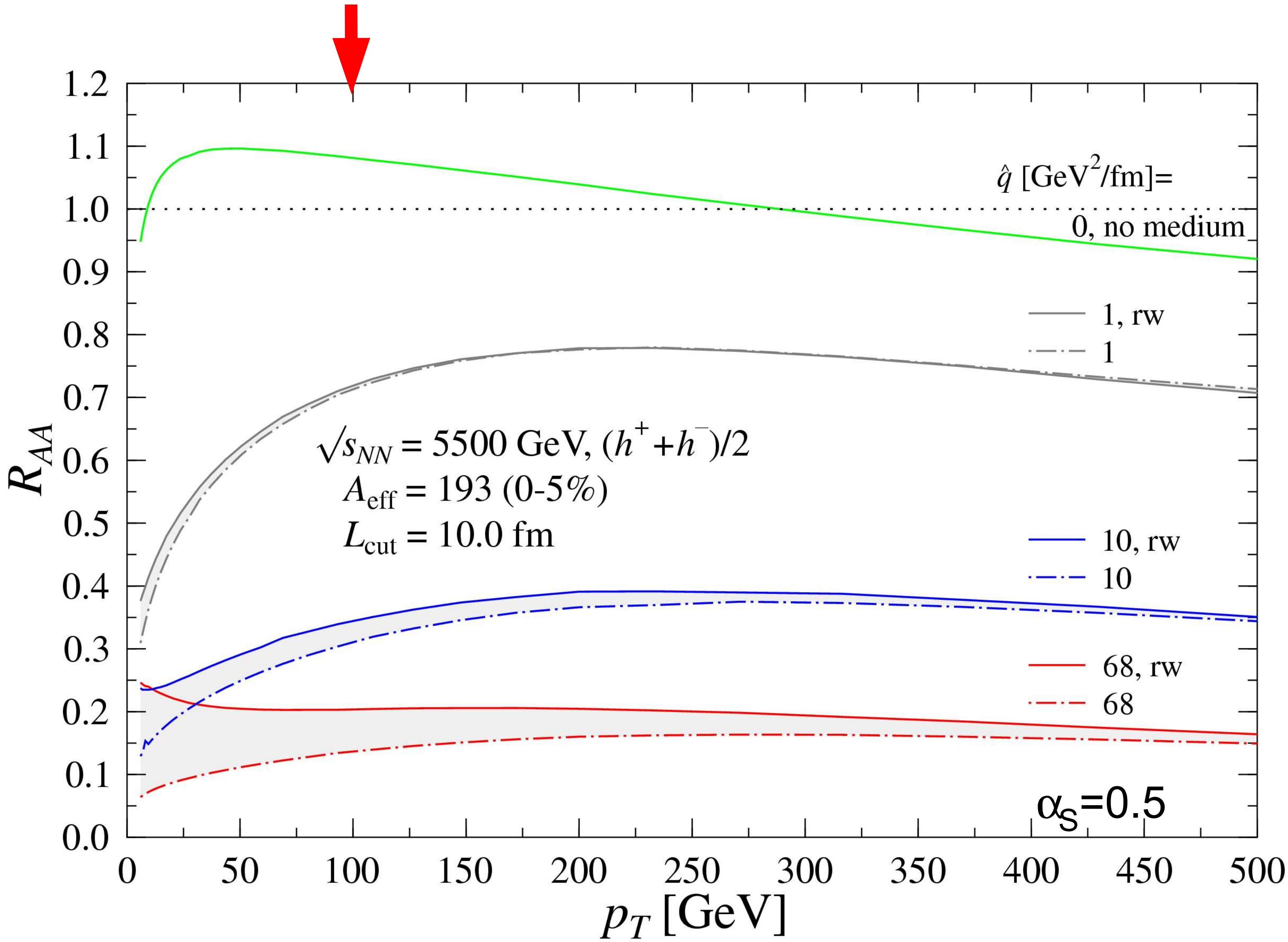
Interesting(?) difference in predictions.

$$R_{AA}^{5.5\ \mathrm{TeV}} \approx \frac{R_{AA}^{200\,\mathrm{GeV}}}{2}$$

PQM predics a rather p_T-independent R_{AA}
(for central collisions)

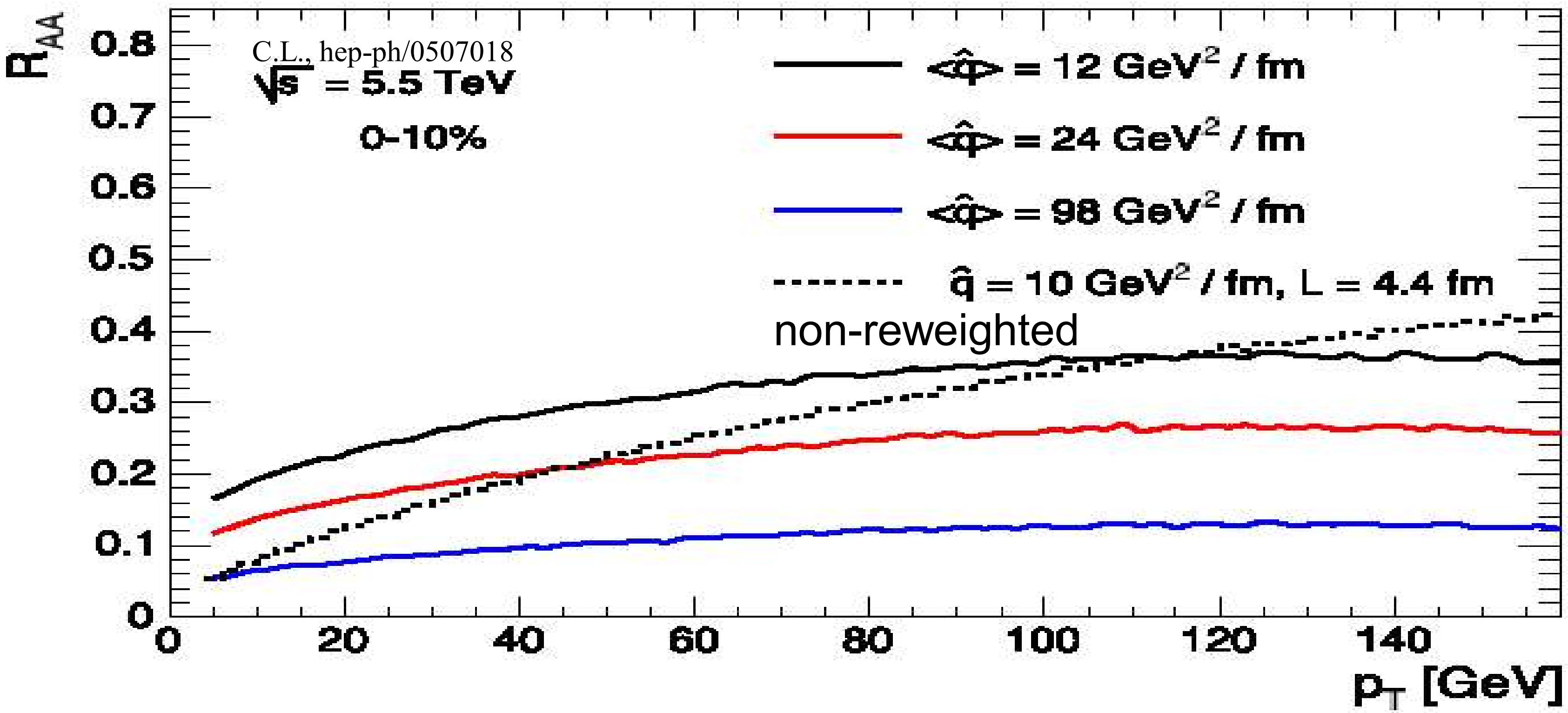
Vitev and Gyulassy, PRL 89 (2002) 252301.
Dainese, Loizides, Paic, EPJC38 (2005), 461.

R_{AA} prediction for LHC (2)



Eskola, Honkanen, Salgado, Wiedemann, NPA 747 (2005) 511.

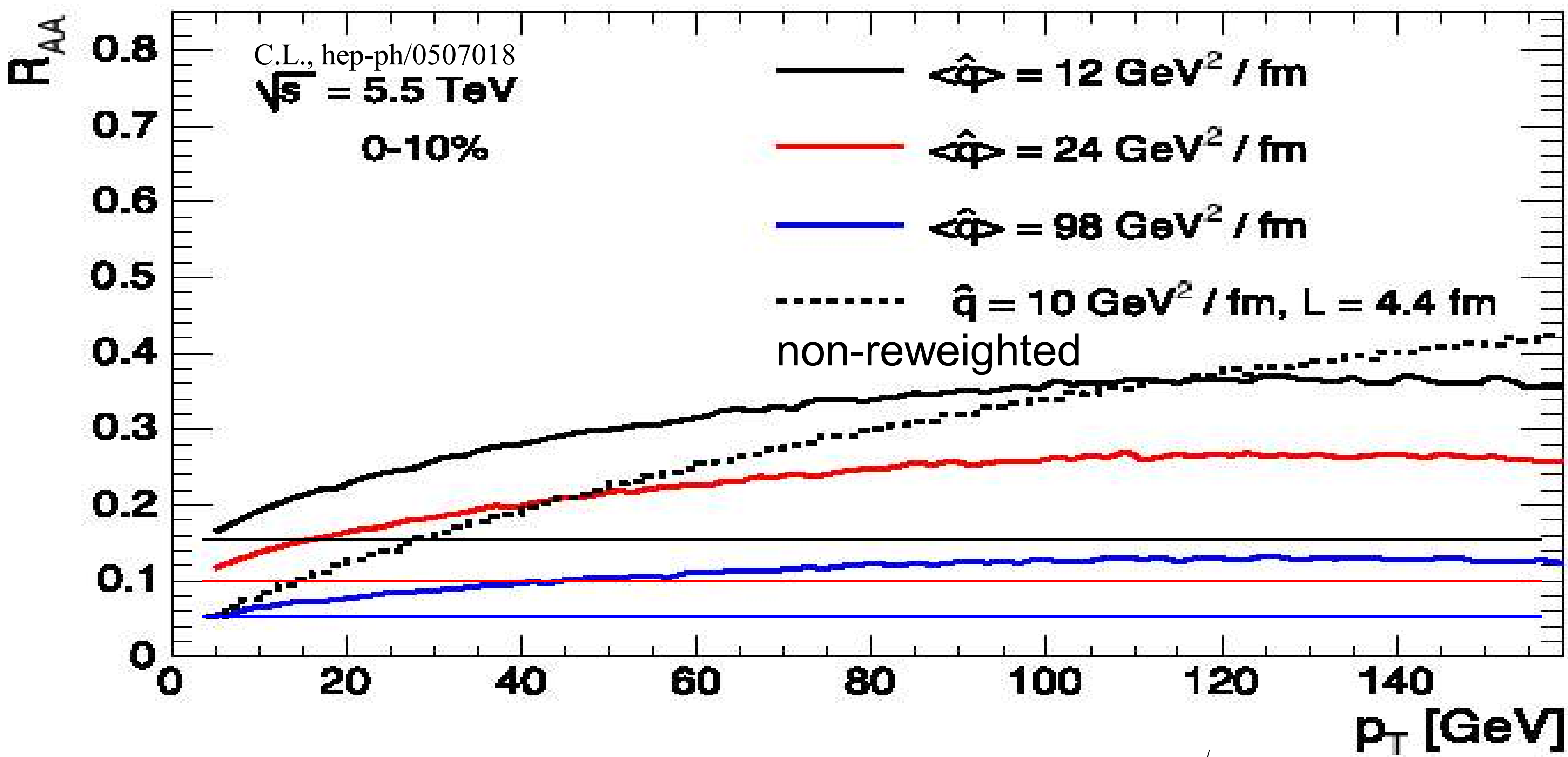
Why is R_{AA} flat?



- The larger the parton energy the longer the possible explorable path length
  - For very large medium density R_{AA} flattens because all partons pay about the same prize for traversing the medium ($\Delta E/E \sim E^{\alpha}$, α >0.5)
  - Check: For fixed geometry R_{AA} rises as expected

Dainese, Loizides, Paic, EPJC38 (2005), 461.

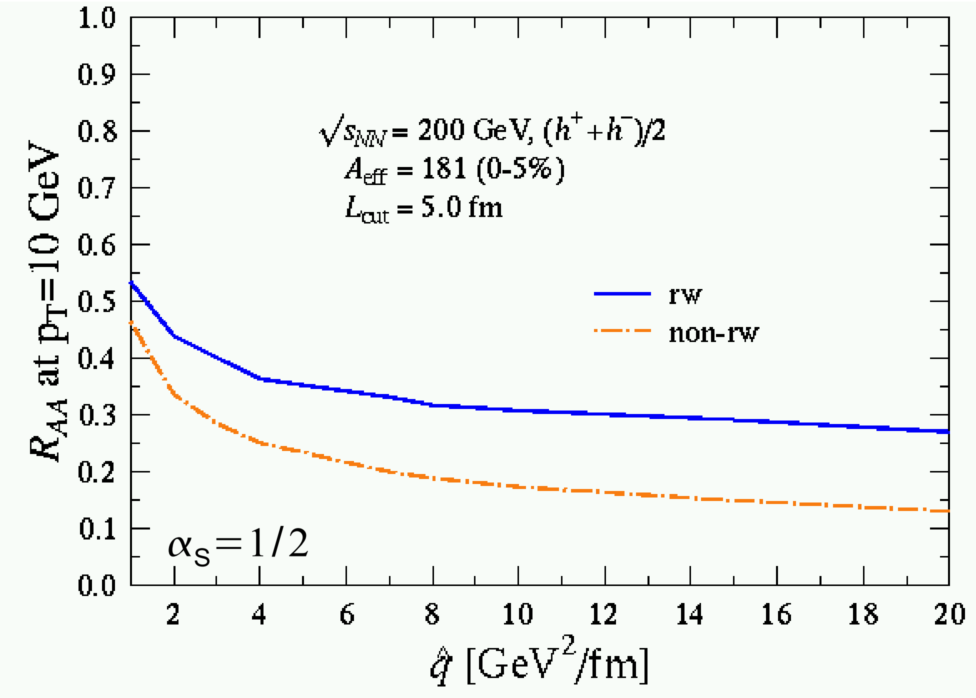
Why is R_{AA} flat? (2)



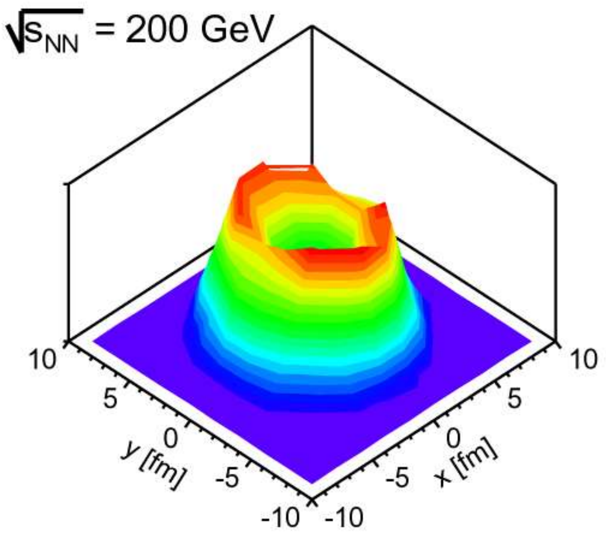
$$R_{AA}(p_T) = \int d\Delta E\, dH\; P(\Delta E, p_T+\Delta E; H)\, \frac{dN/dp_T(p}{dN/dp}$$

$$R_{AA}(p_T) = \int d\Delta E\, dH\; P(\Delta E, p_T+\Delta E; H)\, \exp(\Delta E) = \mathrm{const}$$

Limited sensitivity of R_{AA}



"Leading-particle probes are fragile!"



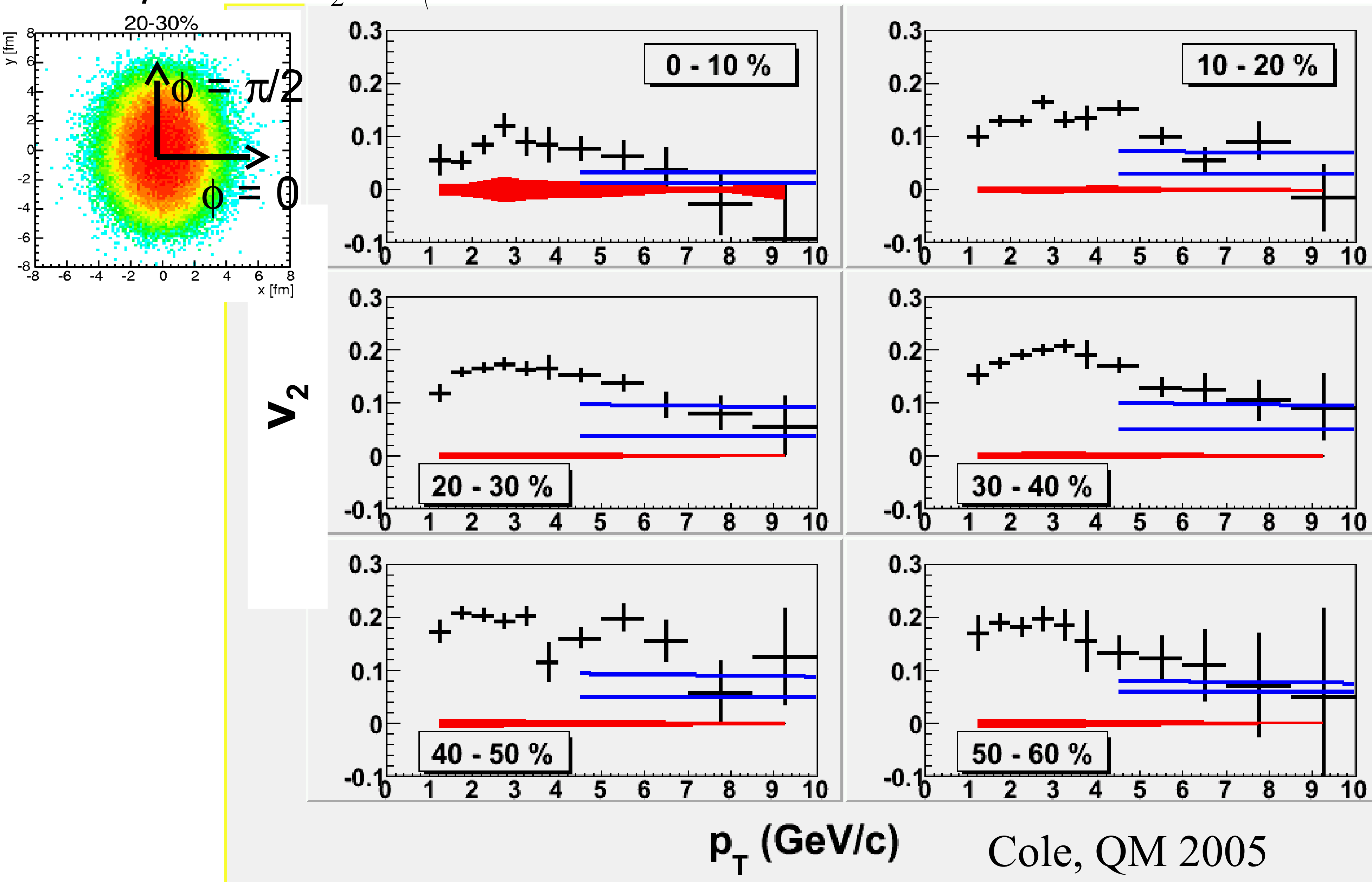
- Strong suppression requires very large densities
- Opaque medium leeds to surface emission
- R_{AA} determined by geometry rather than by density

→ **More differential observables?**

Müller, PRC67 (2003) 061901.
Escola, Honkanen, Salgado, Wiedemann, NPA747 (2005) 511.

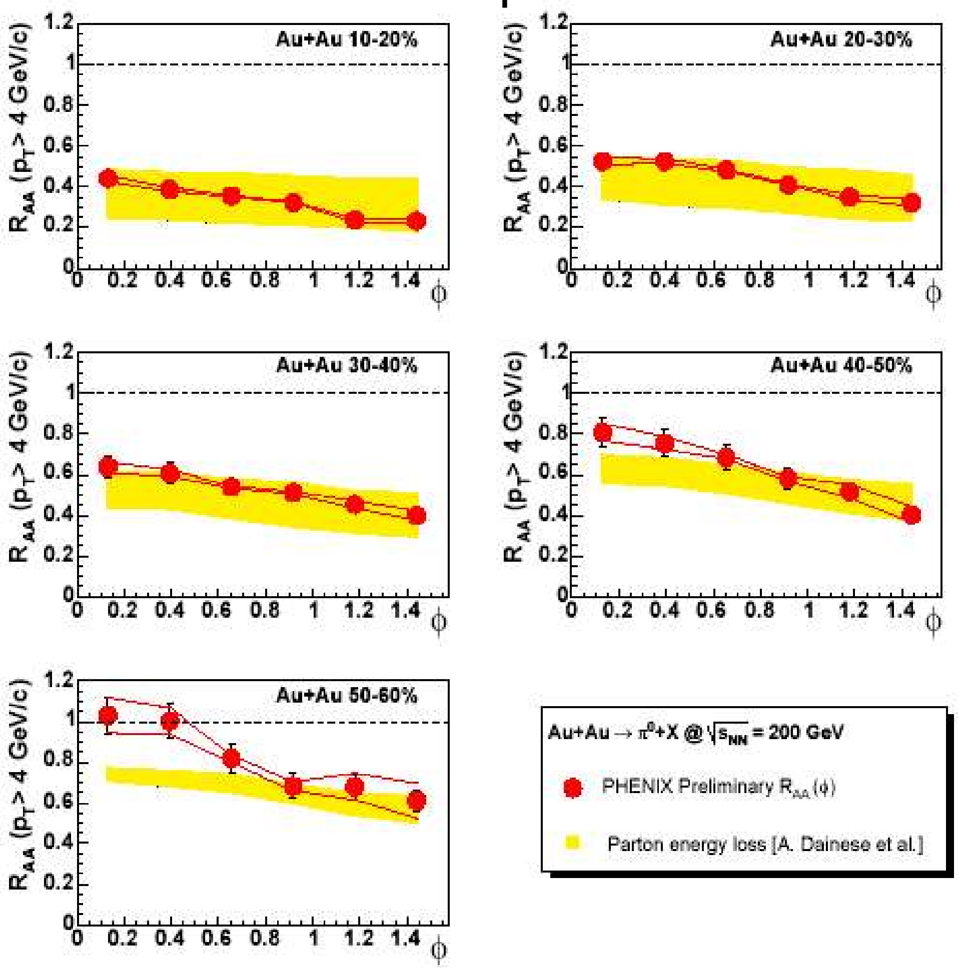
Azimuthal asymmetry

$dN/d\phi \propto 1 + 2\,v_2 \cos($

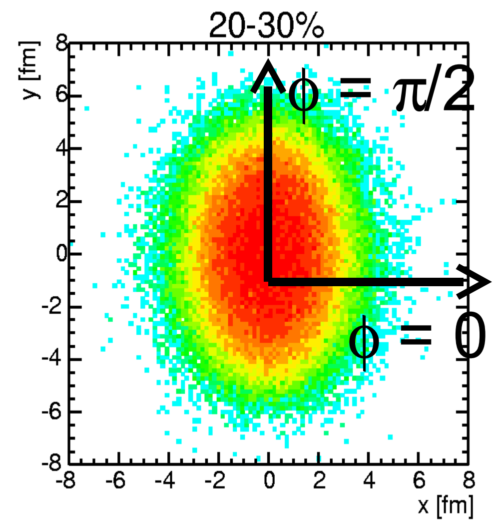


→ Further handle on *L*-dependence*

PHENIX π^0 prel. vs PQM



D. d'Enterria (nucl-ex/0504001)



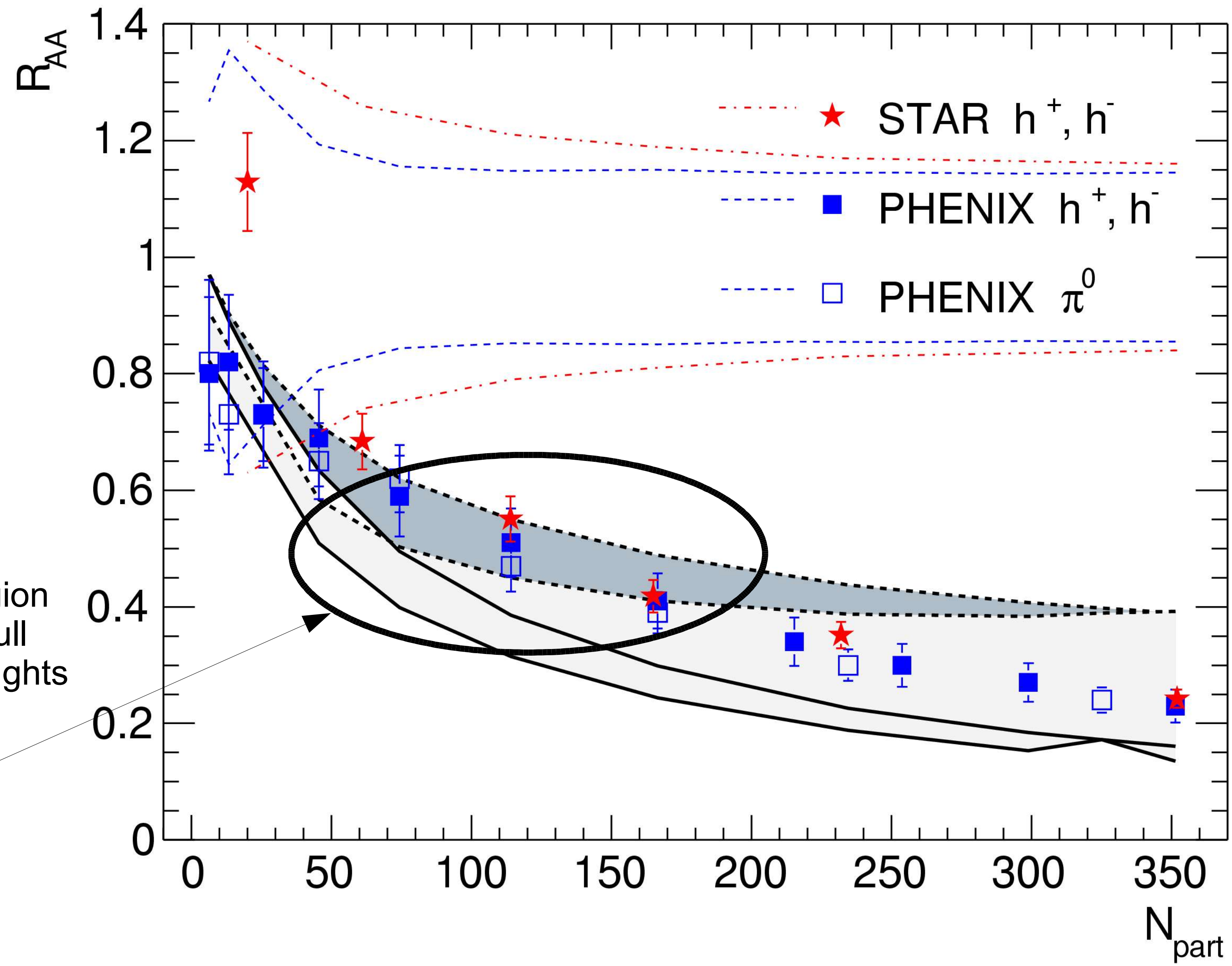
Data show stronger ϕ dep. than PQM model

Note: model is not $\Delta E \propto L^2$, rather $\Delta E \propto L$

* ***Beware:*** effect of collective flow on R_{AA} vs ϕ !?!

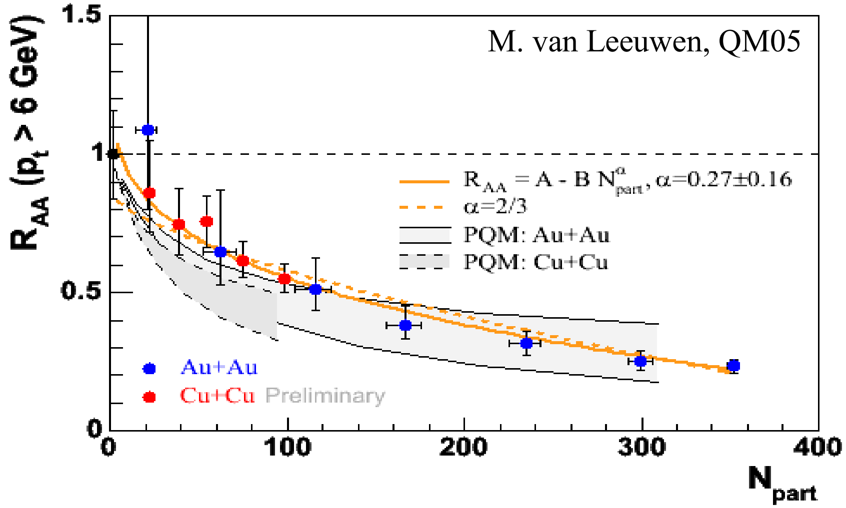
Construct the extreme case of absorption

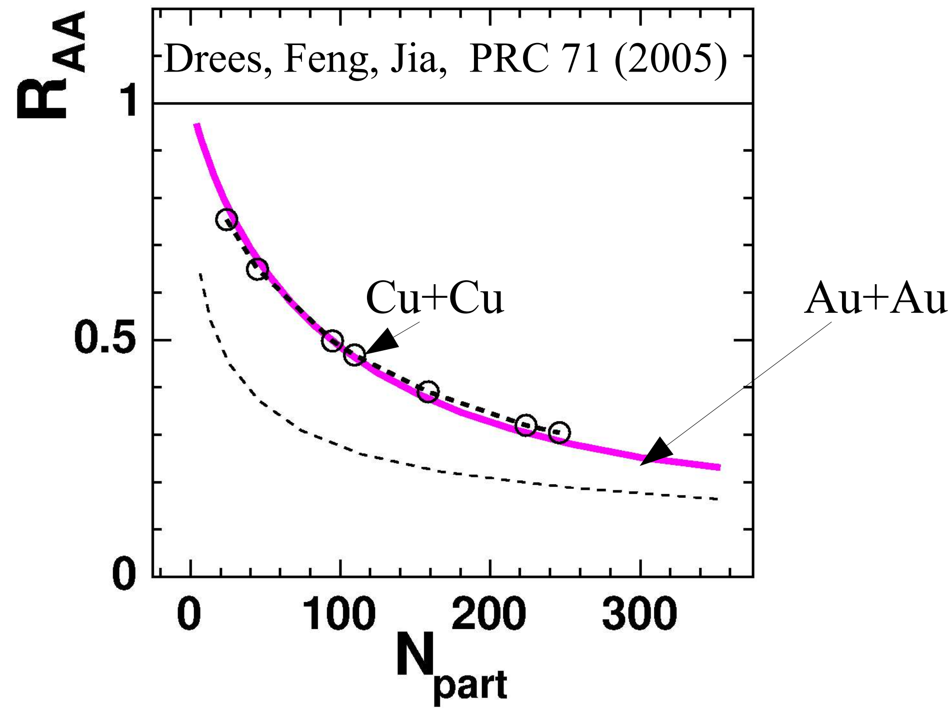
$$P(\Delta E, E; H) \approx p_0(E,H)\,\delta(\Delta E) + (1 - p_0(E,H))\,\delta(E - \Delta E)$$



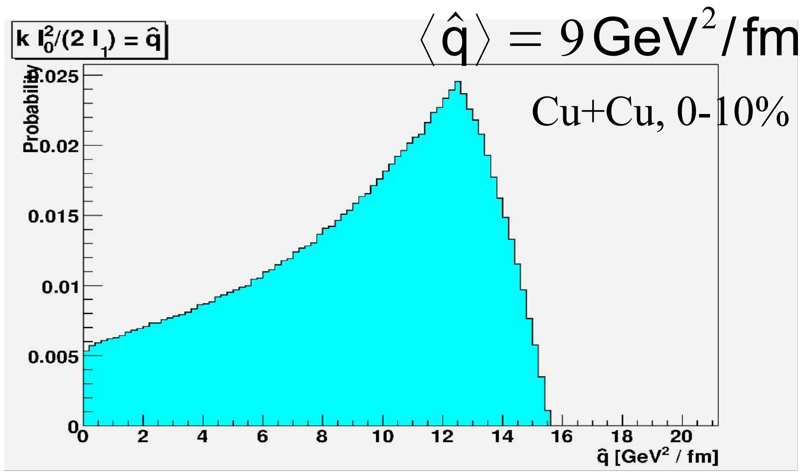
Interesting region which needs full quenching weights

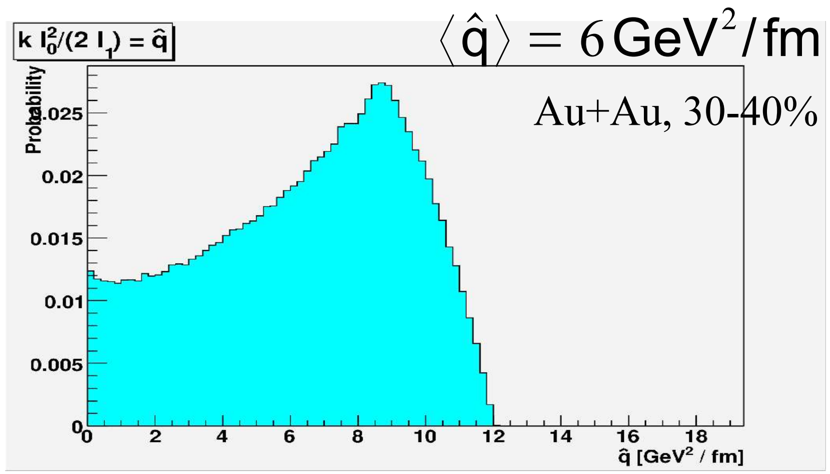
Simple(r) models challenge!!!





Need to refine our scaling with EKRT?

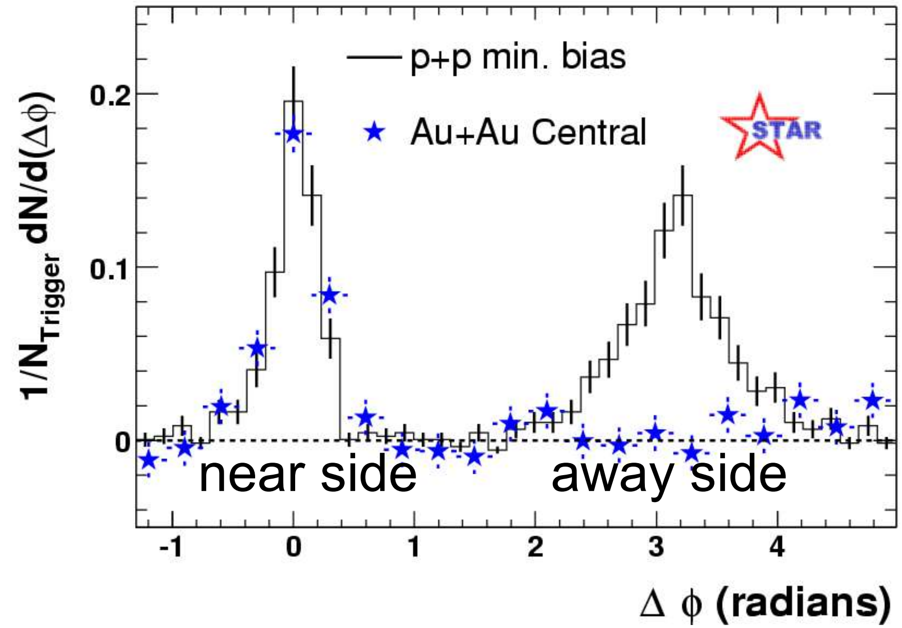


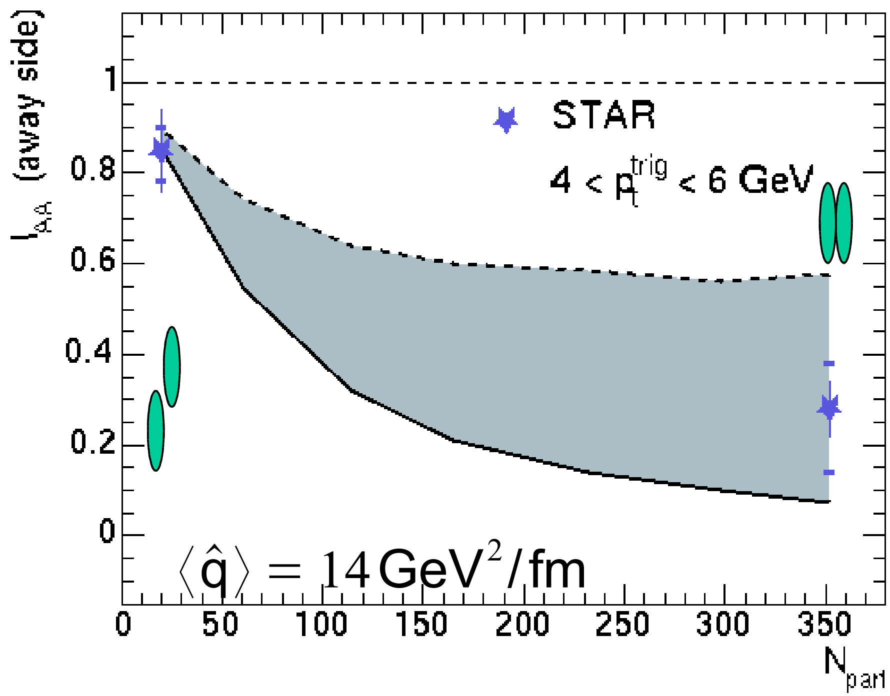


$$I_{AB}^{away} = \int_{away} dN_{AB} / \int_{away} dN_{pp}$$

Trigger $4 < p_T^{trigger} < 6$ GeV

$\Delta\phi$ distribution: 2 GeV $< p_T < p_T^{trigger}$





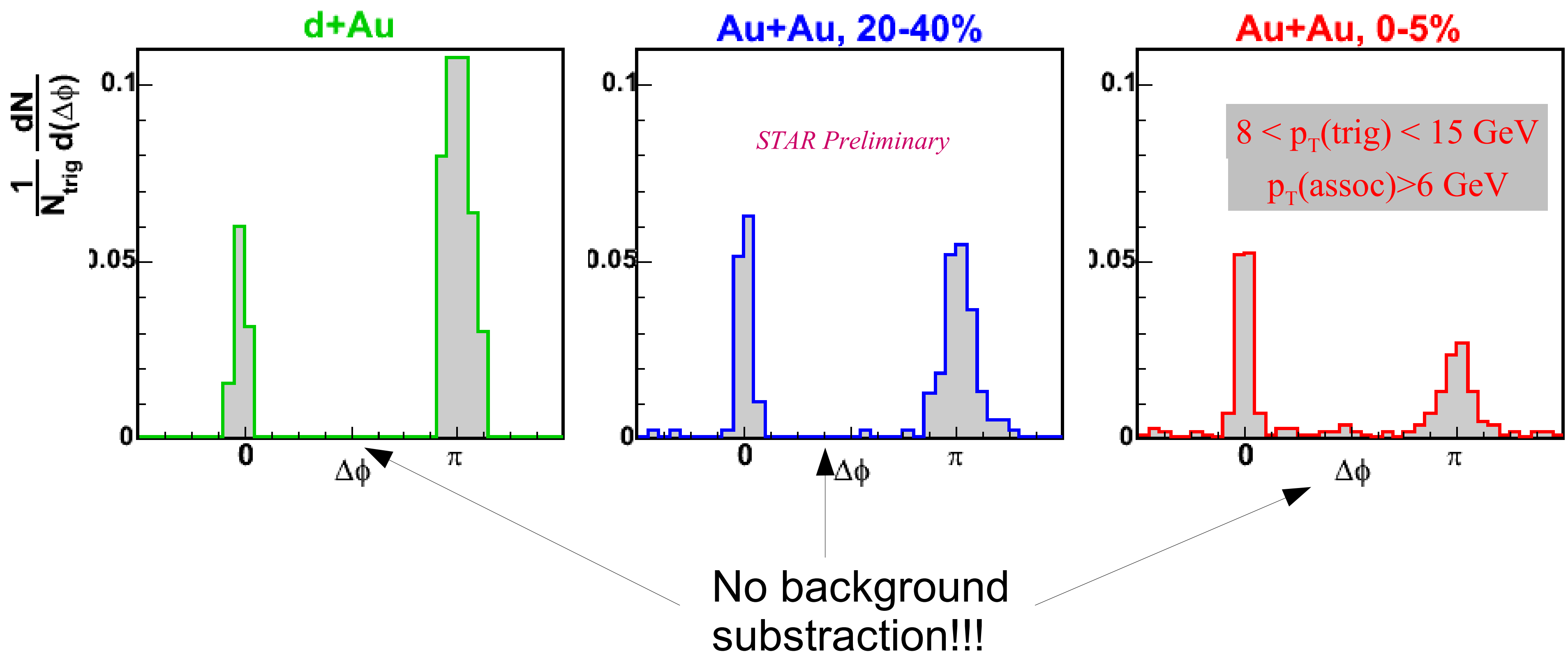
STAR Coll., PRL 90 (2003) 082302

STAR Coll., nucl-ex/0501016

Emergence of true Di-jets in AuAu

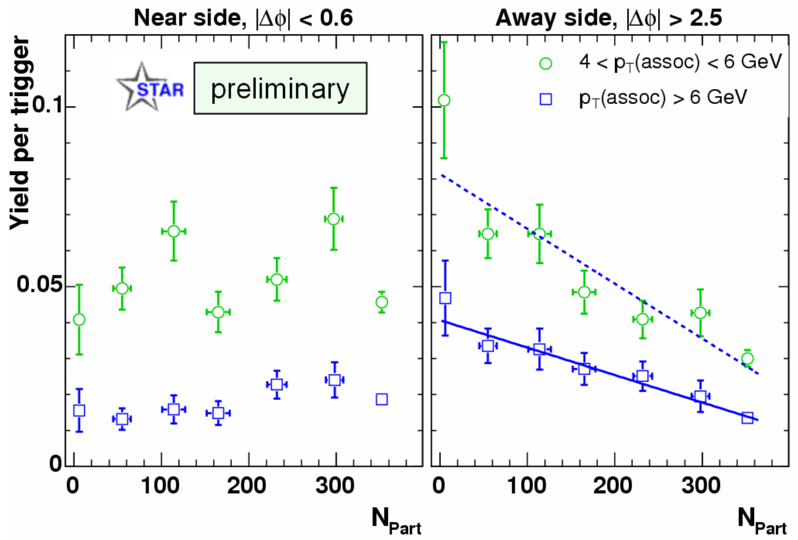
Au+Au Run4 allows jet-like two-particle correlations with much higher statistics

QM 2005, Dan Magestro

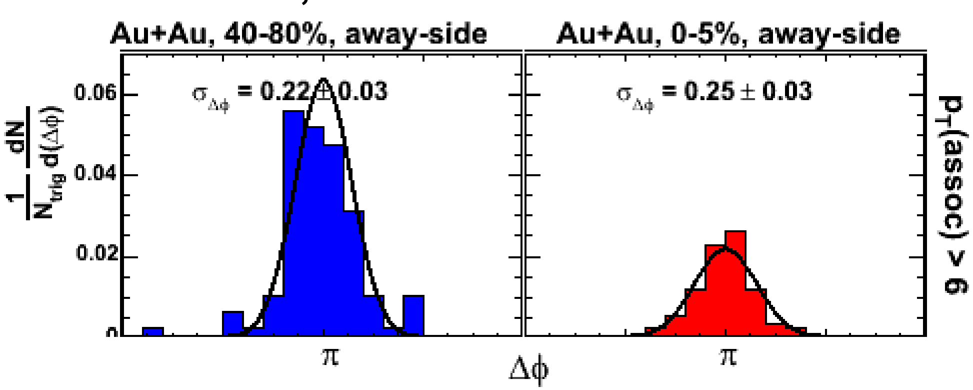


For the first time clear jet-like peaks seen on near + away-side in central Au+Au collisions

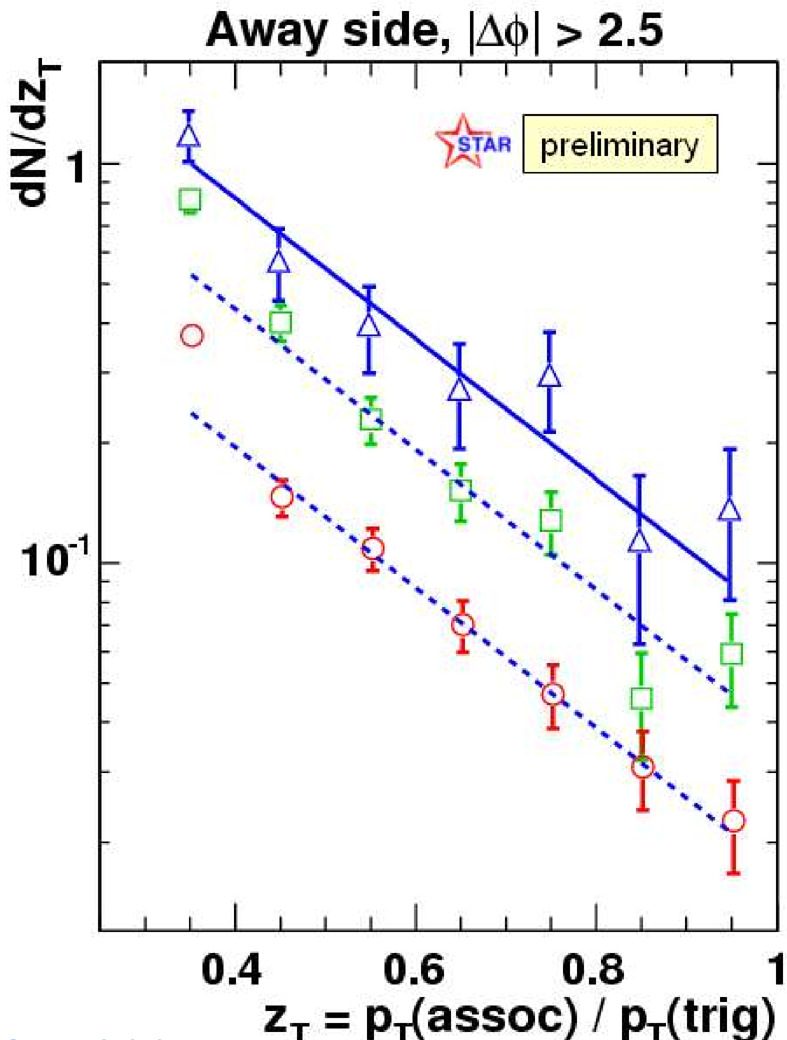
Dijets more suppressed from d+Au to central collisions



Away-side widths similar for central, noncentral



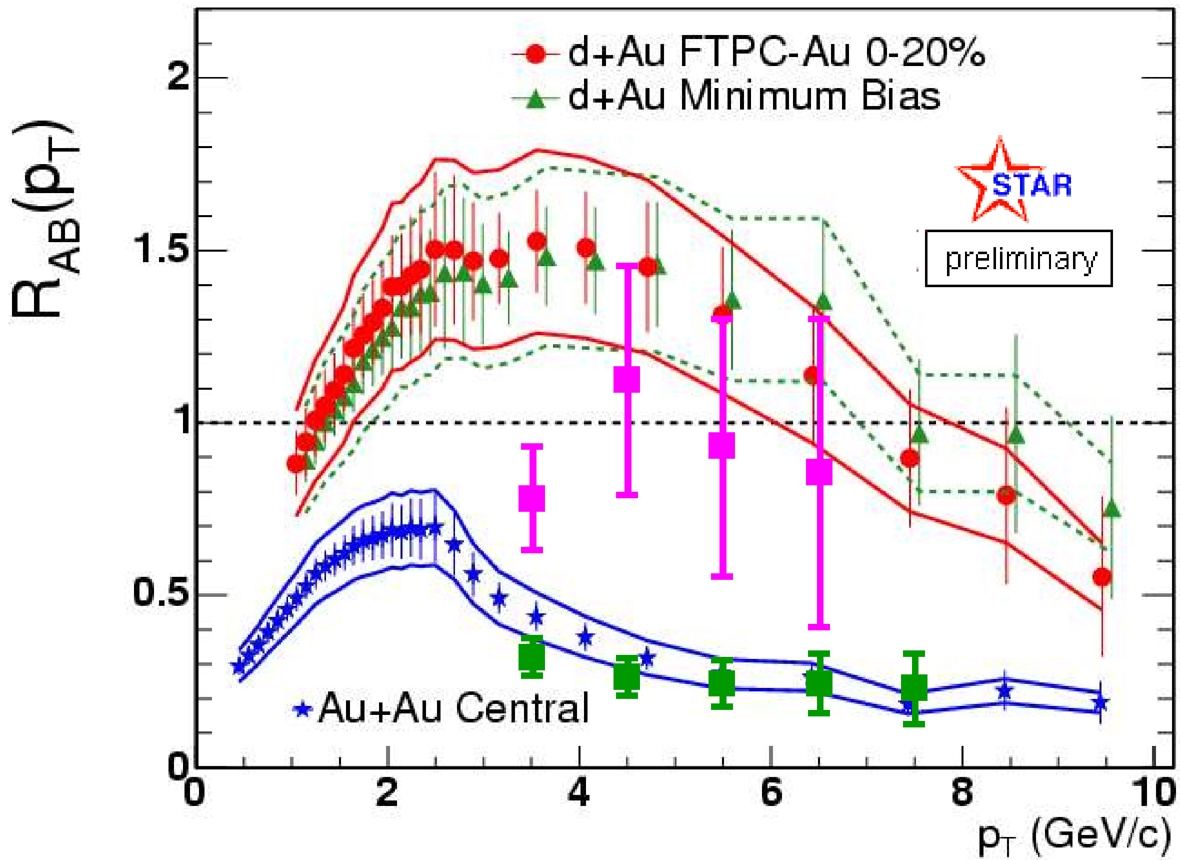
Away-side fragmentation pattern unchanged



QM 2005,
courtesy Dan Magestro

Dijet assoc. yields (I_{AA}) vs. R_{AA}

STAR, Phys. Rev. Lett. 91 (2003) 072304



QM 2005, courtesy Dan Magestro

8 < p_T(trig) < 15 GeV/c

= Near-side I_{AA}

= Away-side I_{AA}

- Near-side yields consistent with unity
- Away-side associated yields similar to R_{AA} values

$$I_{AA} = \frac{\text{Yield(0-5\% Au+Au)}}{\text{Yield(d+Au)}}$$

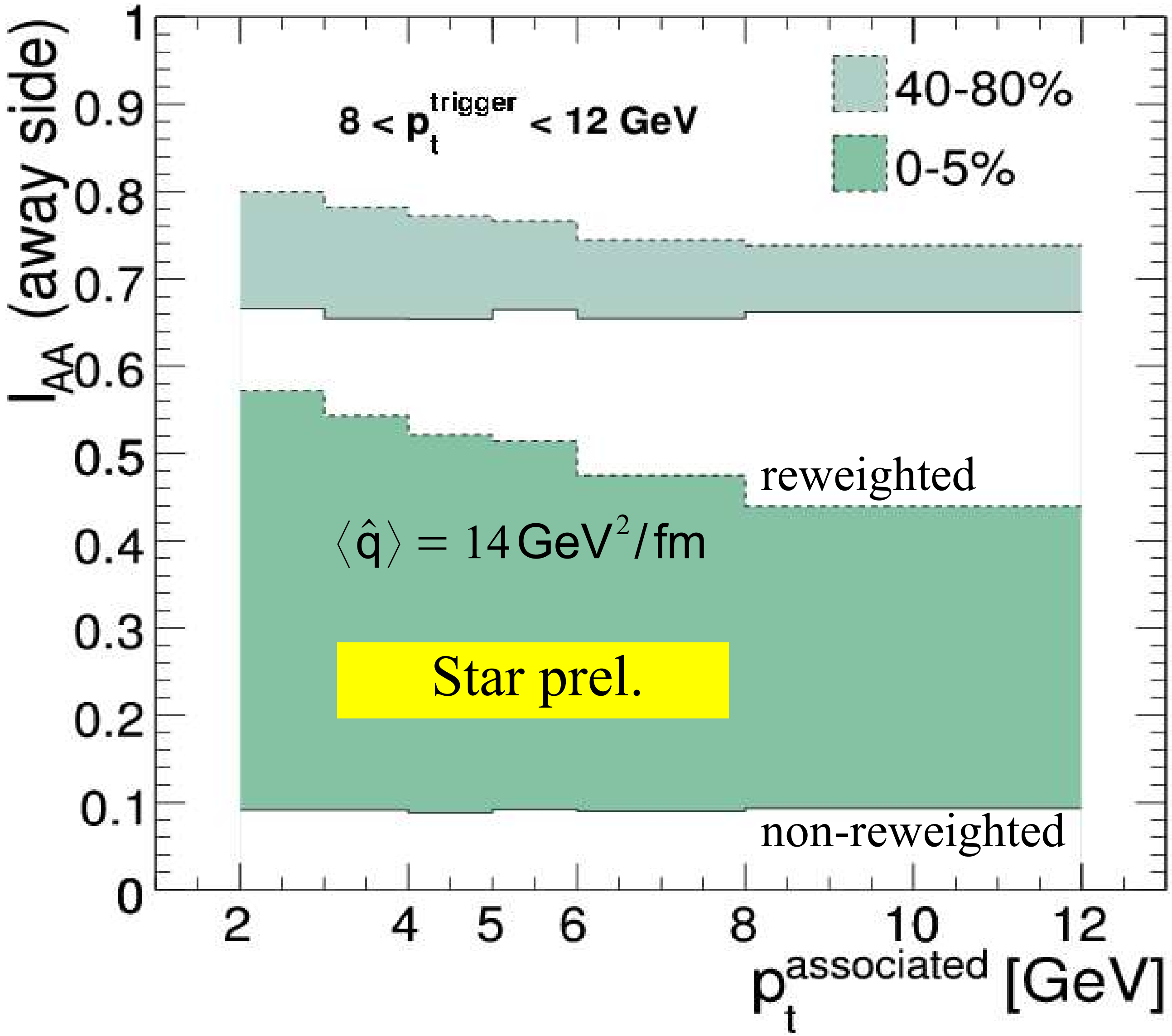
Note: Very different quantities are being compared

PQM: prediction before PQM

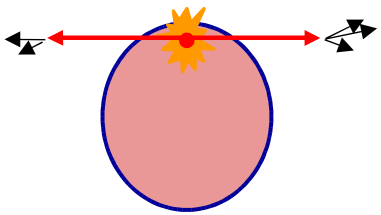
Density ($\hat{q}$) still "tuned" to match R_{AA}

in central Au+Au at 200 GeV

$$I_{AB}^{away} = \int_{away} dN_{AB} / \int_{away} dN_{pp}$$

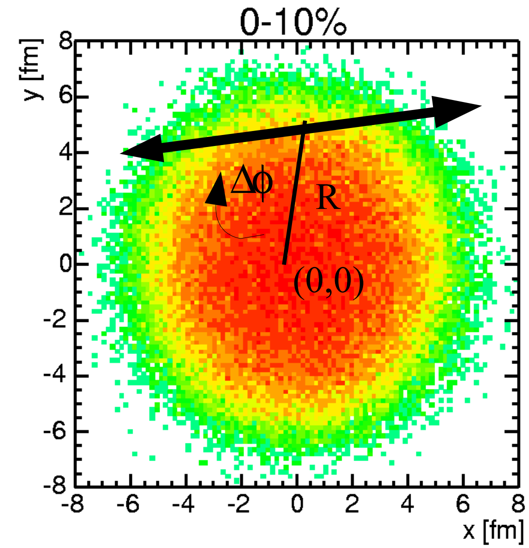


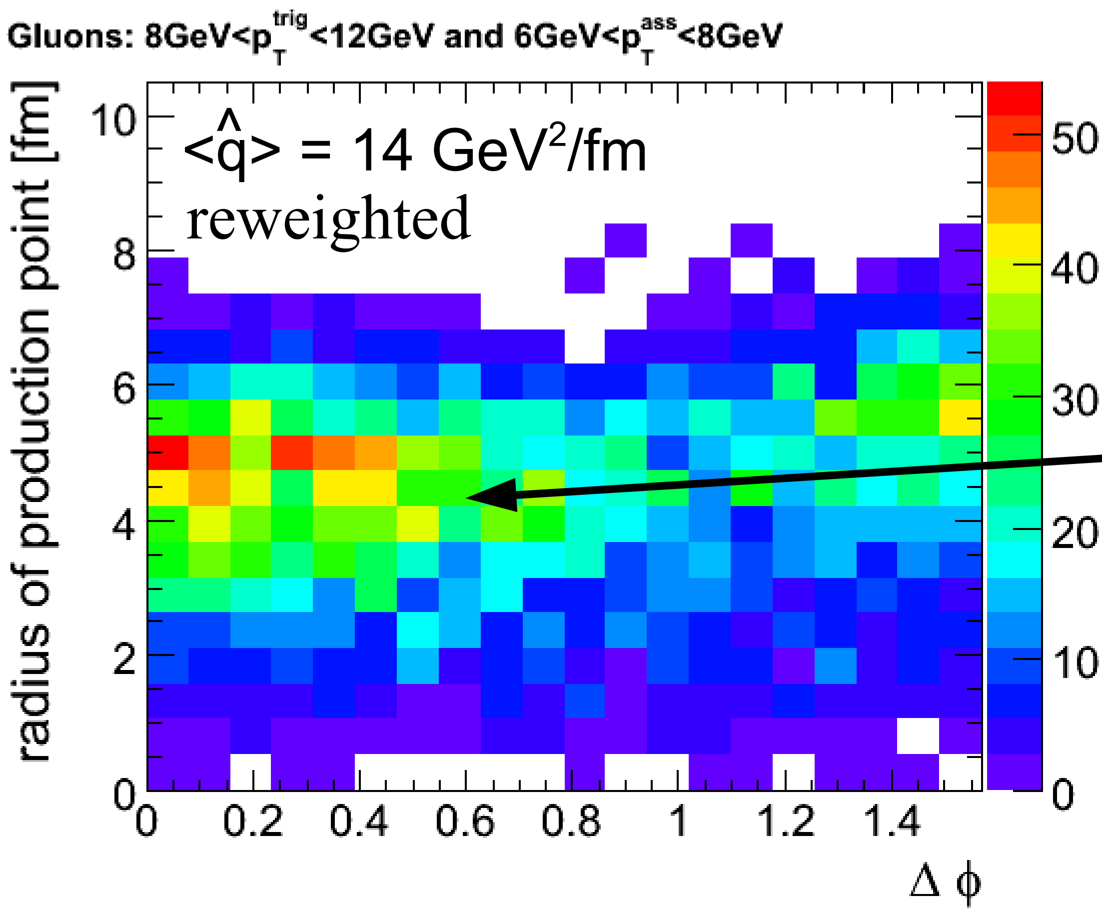
PQM: Tangential di-jet emission?



transverse plane

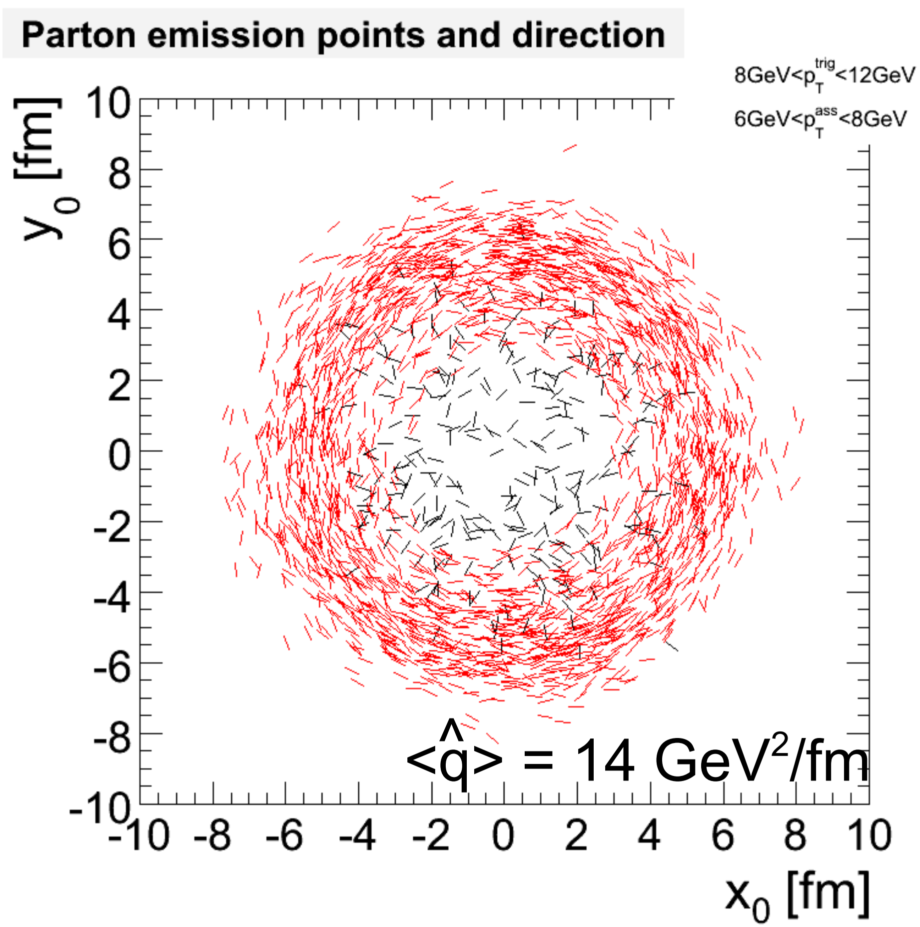
What is the phase space of parton pairs which yield hadrons that contribute to the away-side I_{AA}?

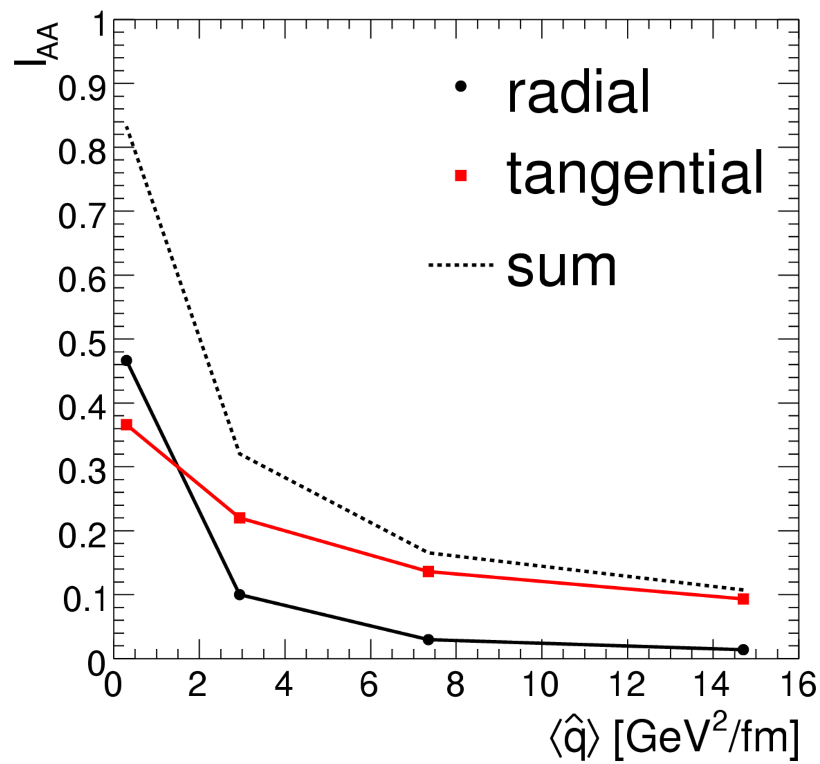




Unphysical behaviour of reweighting!!!

PQM: Tangential di-jet emission?

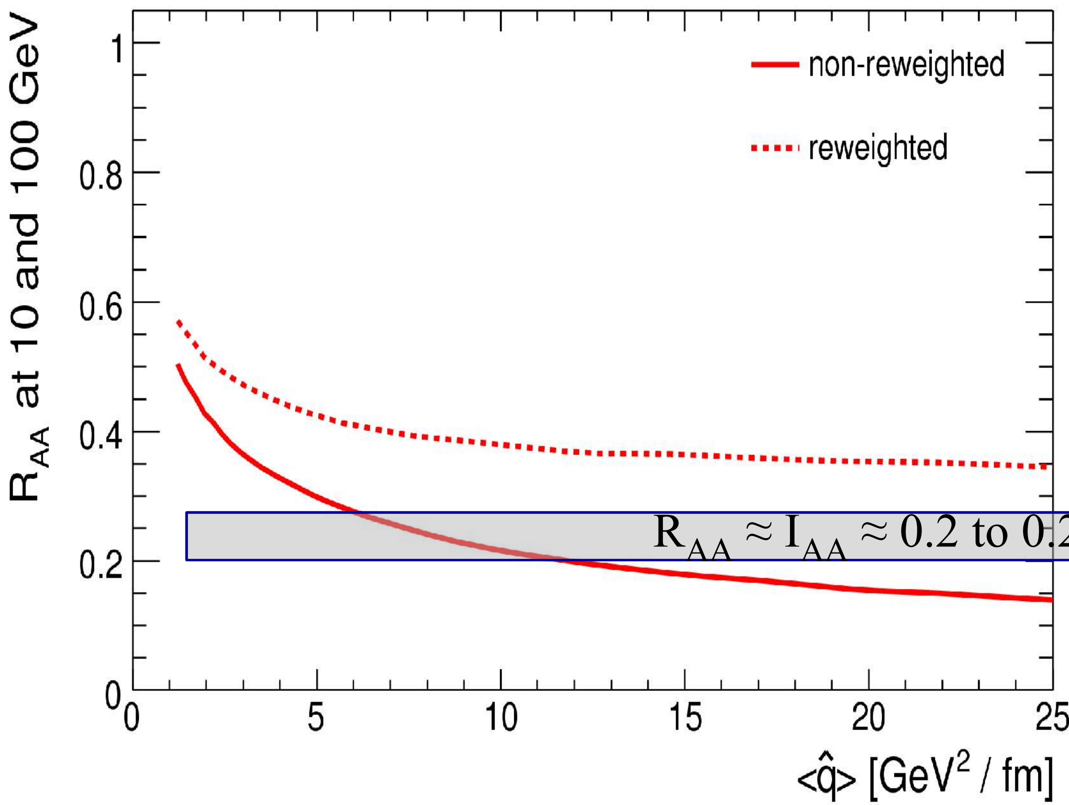


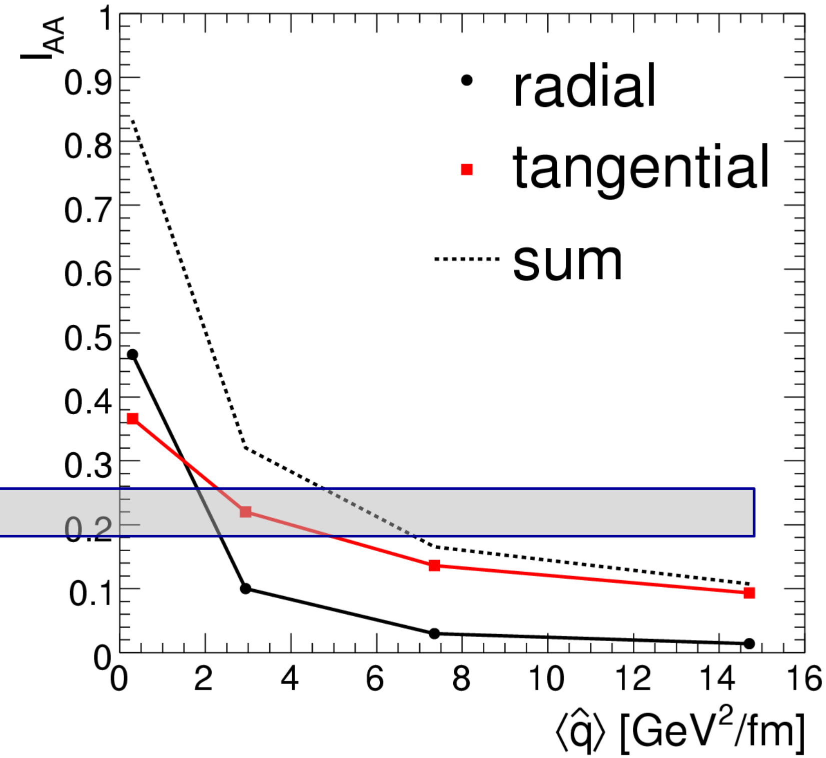


Large medium density biases dijets towards edges of surface ("tangential emission")

Müller, PRC67 (2003) 061901.
Dainese, Loizides, Paic, QM 2005 Poster.

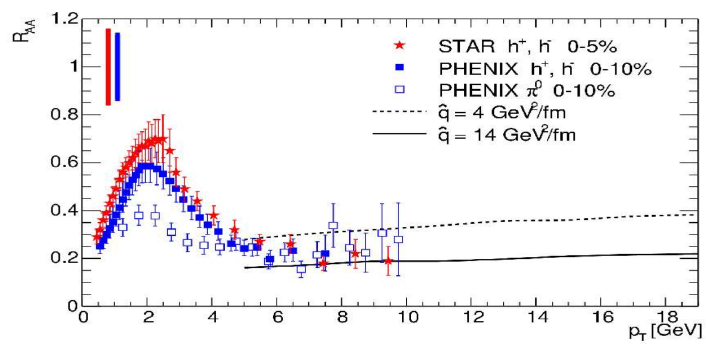
PQM: Putting pieces together



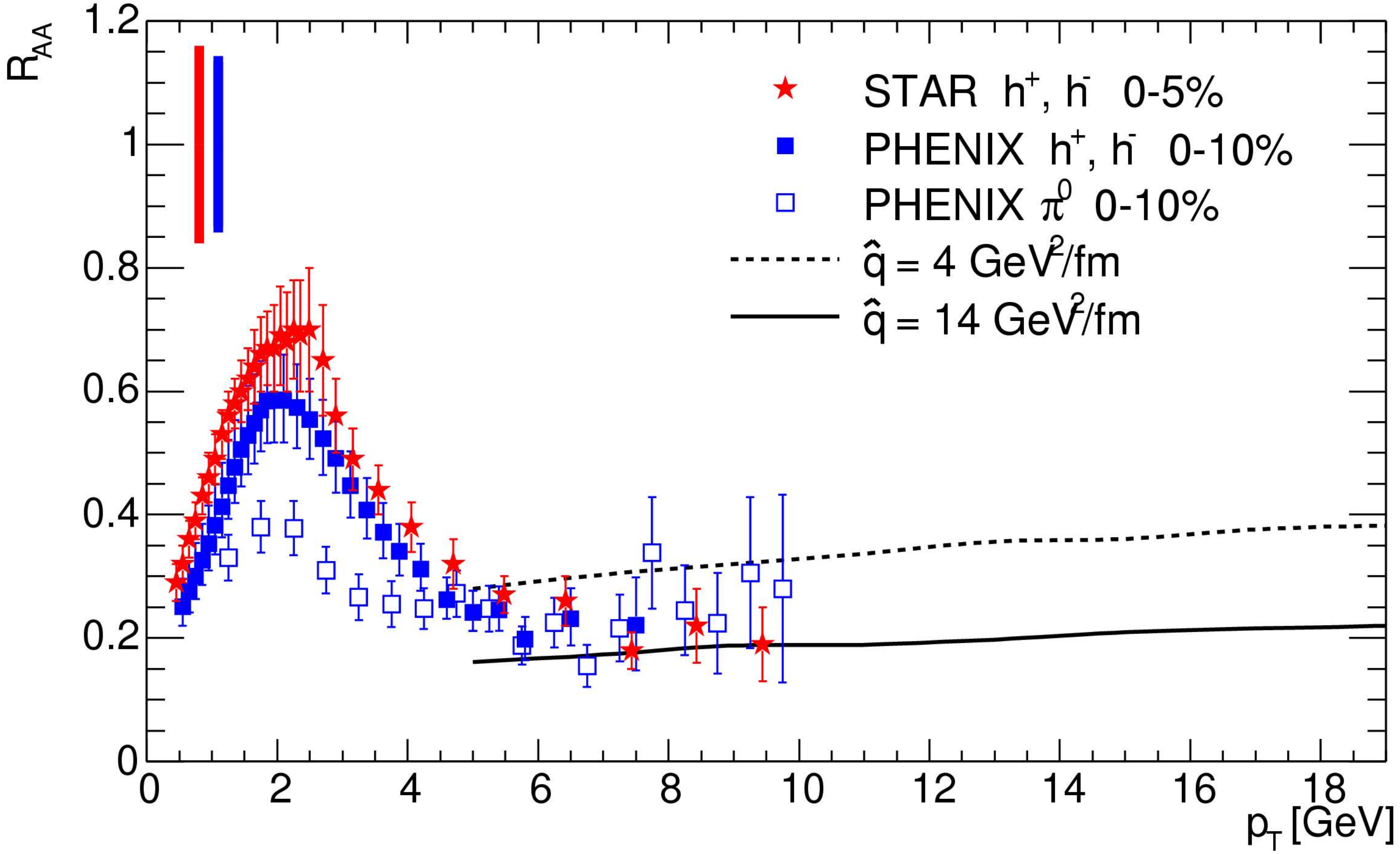


$R_{AA} \approx I_{AA} \approx 0.2$ to 0.25

$$\langle \hat{q} \rangle = 6 - 7\,\mathrm{GeV}^2/\mathrm{fm}$$



R_{AA} for non-reweighted band

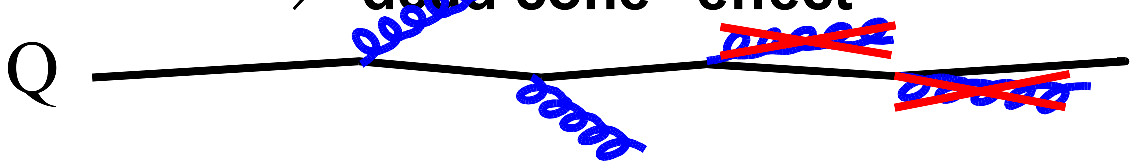


Lower E loss for heavy quarks ?

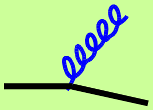
Courtesy by A.Dainese

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

→ **“dead cone” effect**



Gluonsstrahlung probability

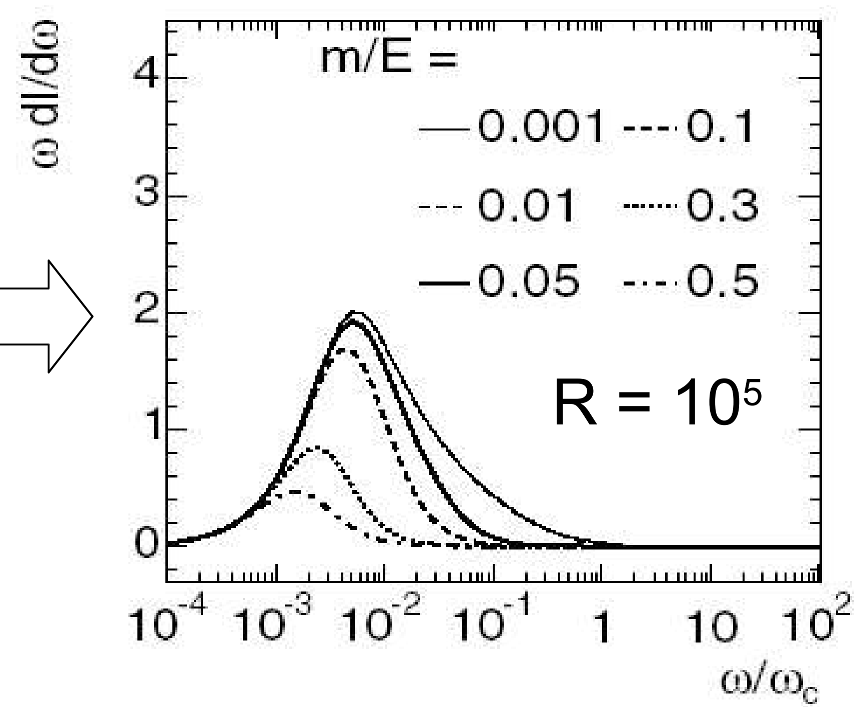


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppress high-ω tail

Detailed massive calculation confirms this qualitative feature

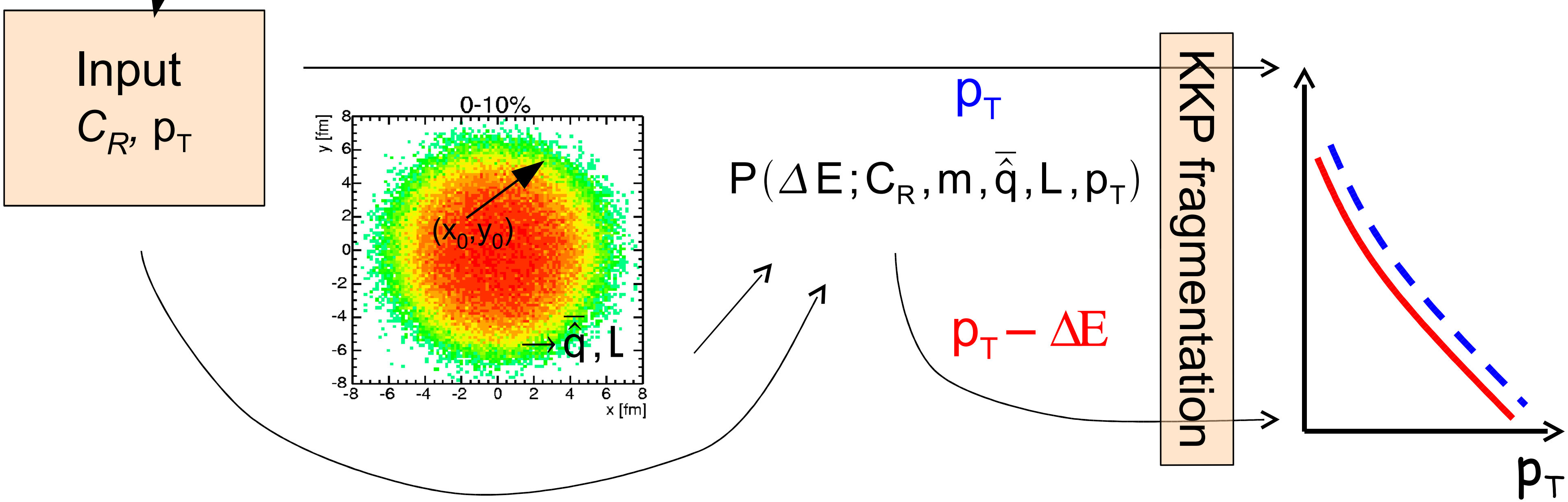
(Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003)



Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Implementation in PQM

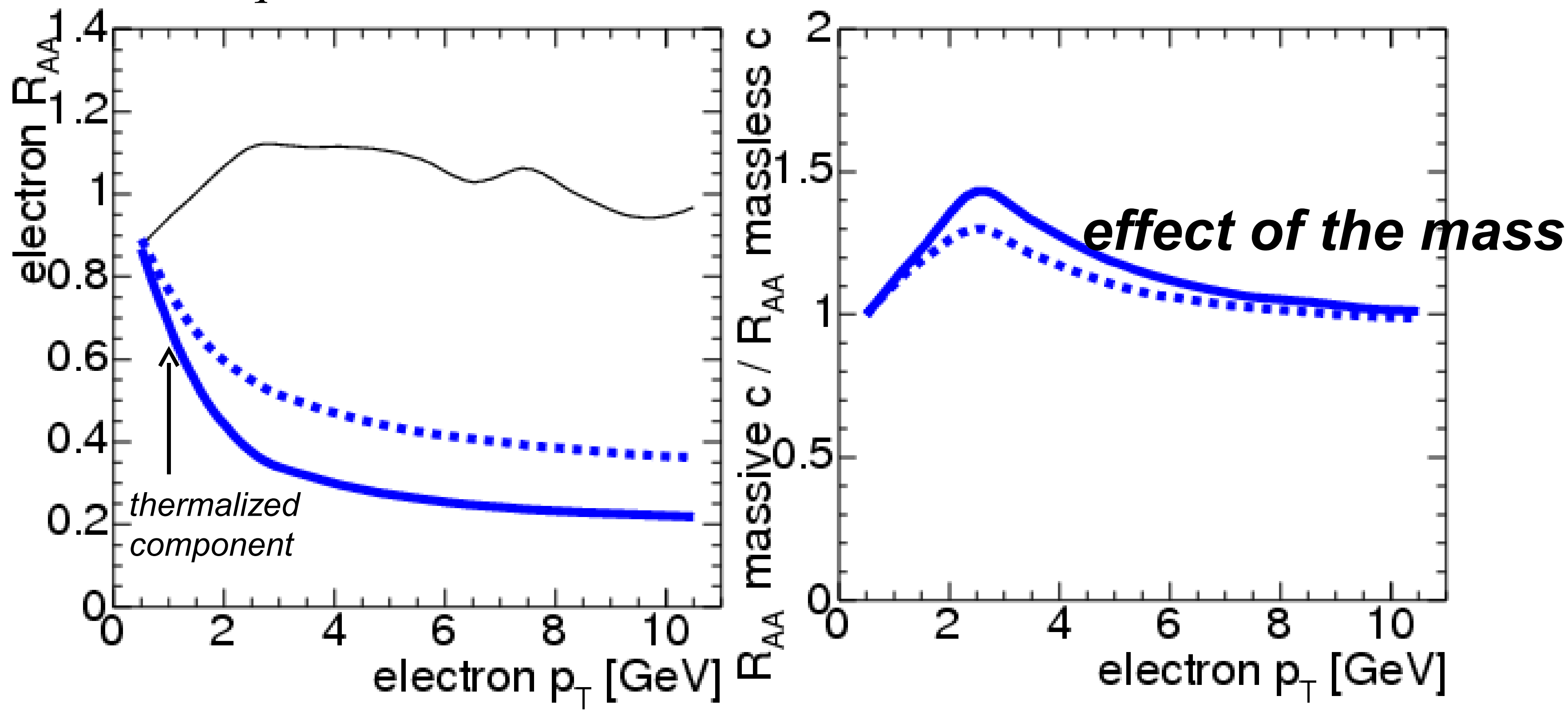
Tuned pythia, CTEQ4L, EKS98
or FNLLO, CTEQ6L



Charm R_{AA} at RHIC

Courtesy by A.Dainese

$\hat{q} = 4 \div 14\,\mathrm{GeV}^2/\mathrm{fm}$ (extracted from light-hadron data)



Small effect of mass for charm (~50% for D, ~30% for e) at low p_T [large uncertainties!]

Basically no effect in "safe" p_T-region

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.

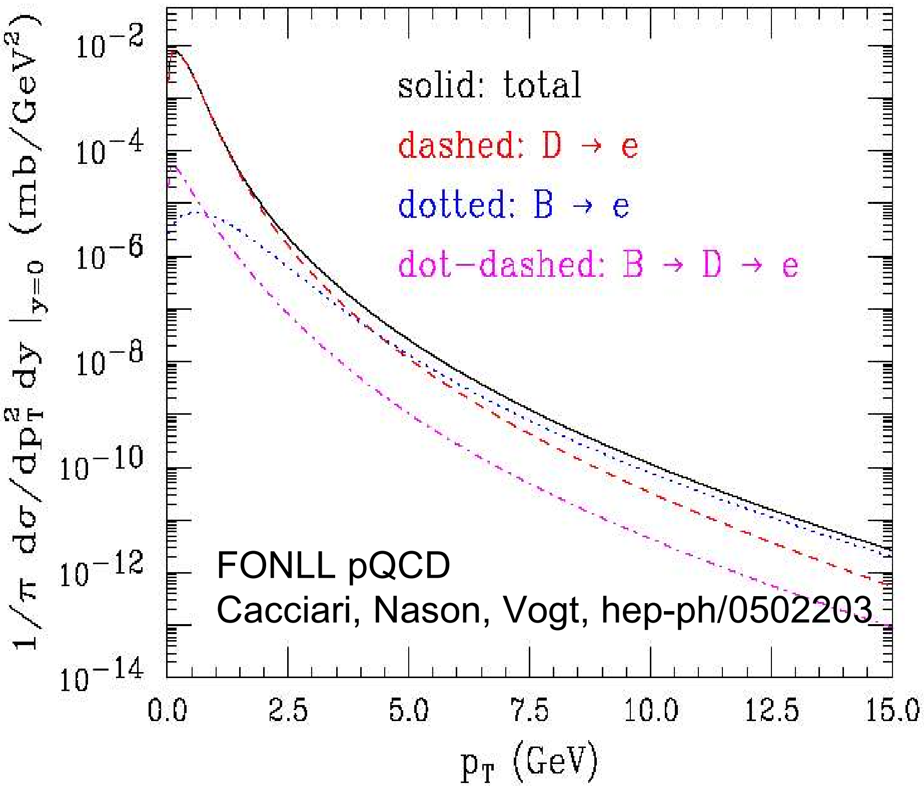
Role of beauty at RHIC?

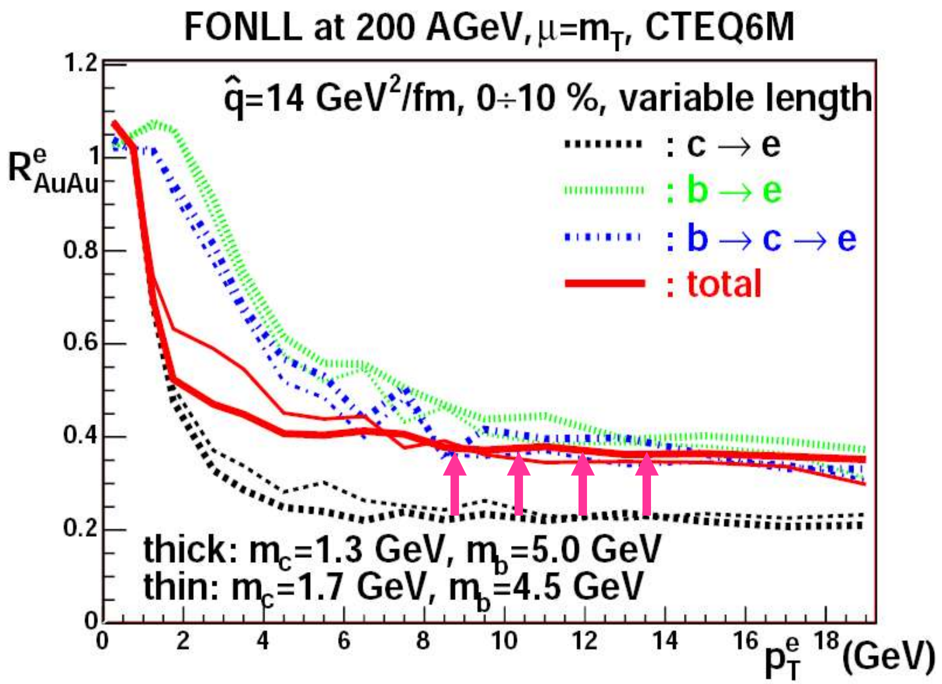
c + b (?) decay $e^{\pm}$ R_{AA} at RHIC

Courtesy by A.Dainese

FONLL:
Electron spectrum may be ~50% charm + ~50% beauty for $3 < p_T < 8$ GeV

Due to larger mass of b quark electron R_{AA} incresed by ×2 (mass uncertainty also studied)

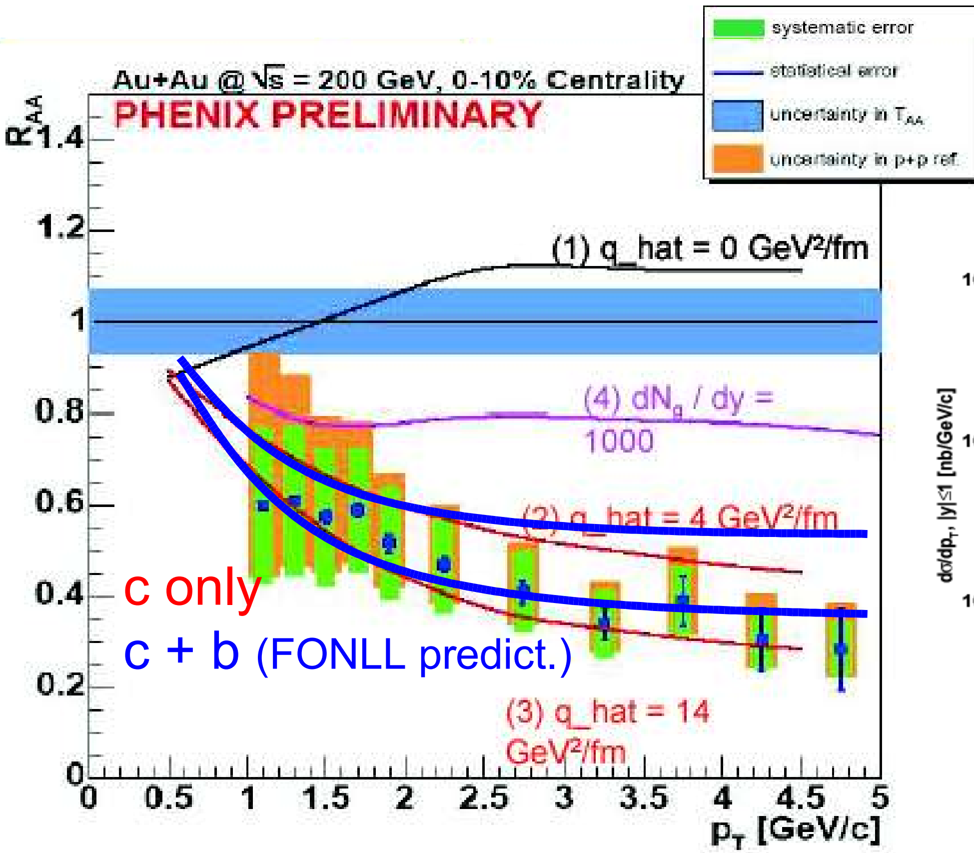




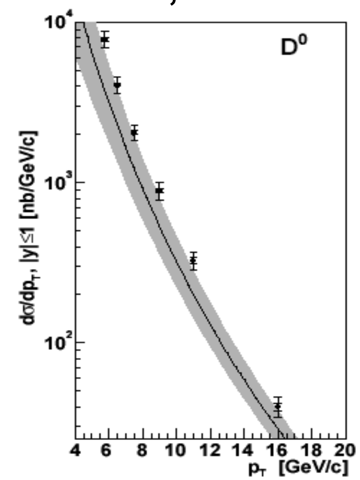
Armesto, Cacciari, Dainese, Salgado, Wiedemann, in preparation,
Armesto @ Quark Matter 05

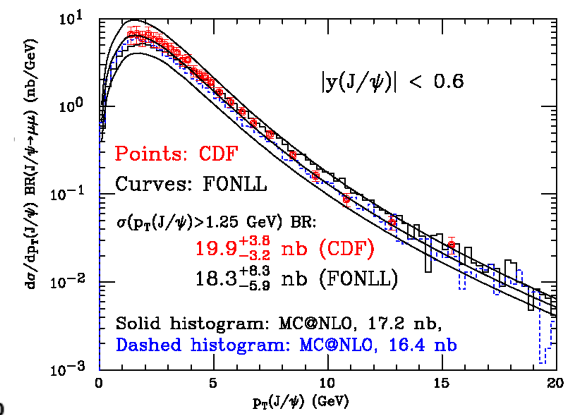
Heavy-flavour data in Au-Au 200 GeV

Courtesy by A.Dainese



Reminder: FONLL@Tevatron:
D production underpredicted
B, instead, is OK





***R_{AA}* down to 0.3 for *p_T* > 4 GeV/c! Heavy-quark quenching.**

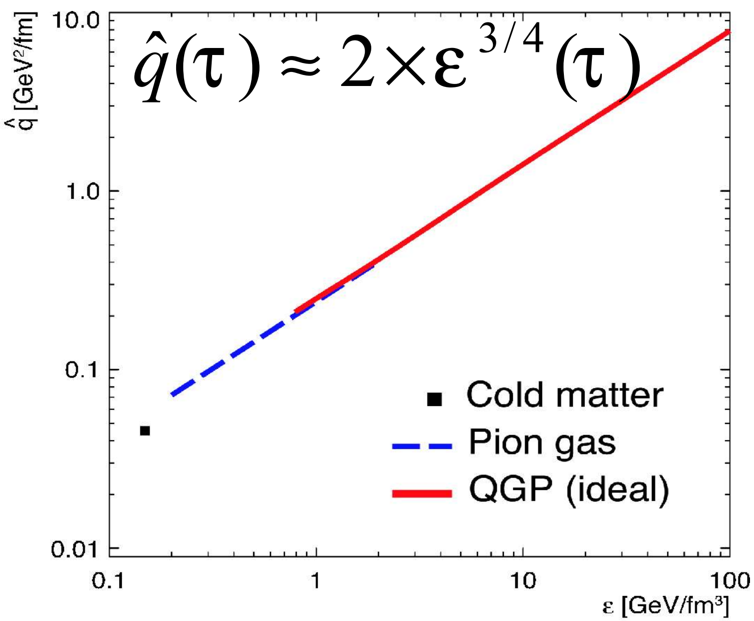
Similar to that of light! Small room for mass effect …

Comparison to predictions: compatible, provided the charm fraction is higher than predicted by FONLL

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027 + w/Cacciari, in preparation

The opacity problem

- To what extent do we probe the medium?
  And to what extent do we control the probe?
- Need to relate extracted $\hat{q}$ to energy density ε
- QCD estimate for ideal QGP: $c^{pQCD} = 2$



- Estimate $c = \frac{q(\tau_0)}{\epsilon(\tau_0)^{4/3}}$
- using $\hat{q}(\tau) = \hat{q}_0 \times \left(\frac{\tau_0}{\tau}\right)^{\alpha}$

  and $\bar{\hat{q}} = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau (\tau - \tau_0)\, \hat{q}(\tau)$
- For $\epsilon(\tau_0) \leq 100\,\mathrm{GeV/fm^3}$

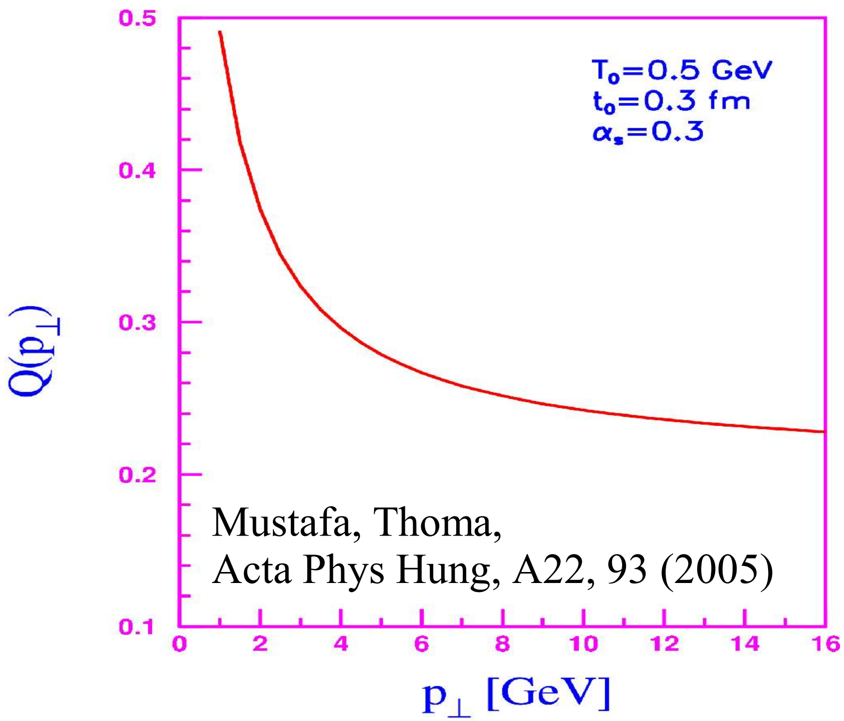
  and $0.75 < \alpha < 1$

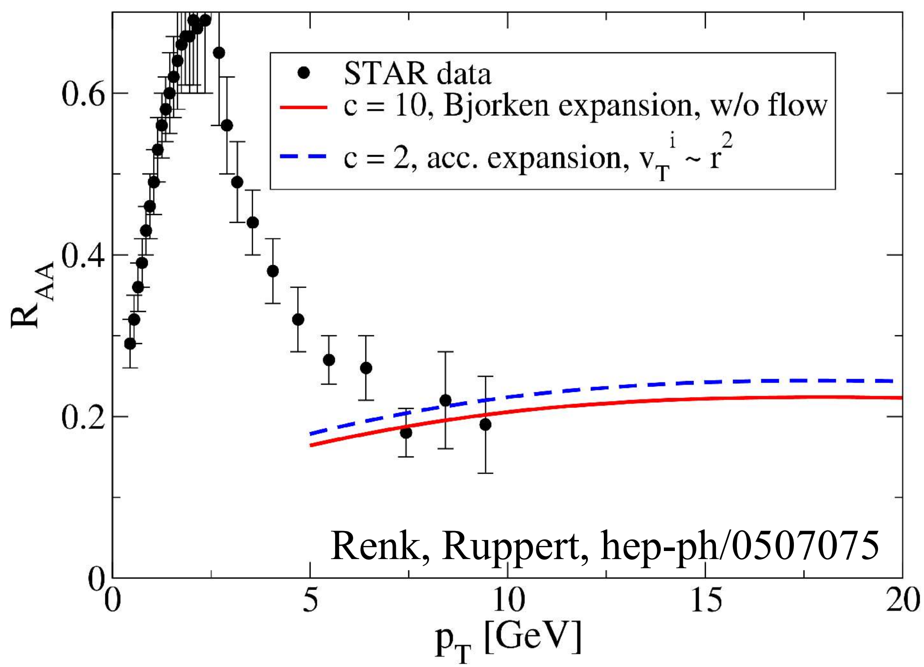
⇒ $c = 8 \ldots 20$

The interaction of the hard parton with the medium is much stronger than (perturbatively) expected

R.Baier, Nucl. Phys. A715 (2003) 209
Escola, Honkanen, Salgado, Wiedemann, NPA747 (2005) 511.

The opacity problem (2)





- Collisional energy
  - Boltzmann Transport
  - Bjorken Expansion
- Cylinder geometry used
  - Path lengths ?

- Transverse flow
- Local transport coefficient

$$\langle \hat{q} \rangle = c\ \epsilon^{3/4} \left(T^{n_T} T^{n-T} \right)$$

- Fireball model for expansion (transverse and longitudinal)

Summary

- PQM combines the BDMPS framework with Glauber geometry for calculation of high-p_T suppression phenomena in nucleus-nucleus collisions
- With a single parameter adjusted to central Au+Au, 200 GeV to we consistently describe most RHIC data at high-p_T
- Recent data shown at QM 2005 constrains
  - 6-7 GeV2/fm
  - 4-14 GeV2/fm
- Opacity problem:
  - Need to include collisional energy loss?
  - Need to include transverse flow?
  - Need to include hadronic rescattering?

Backup Slides

Change to larger α_S