High-p_T suppression and surface effects in nucleus-nucleus collisions (within the Parton Quenching Model)

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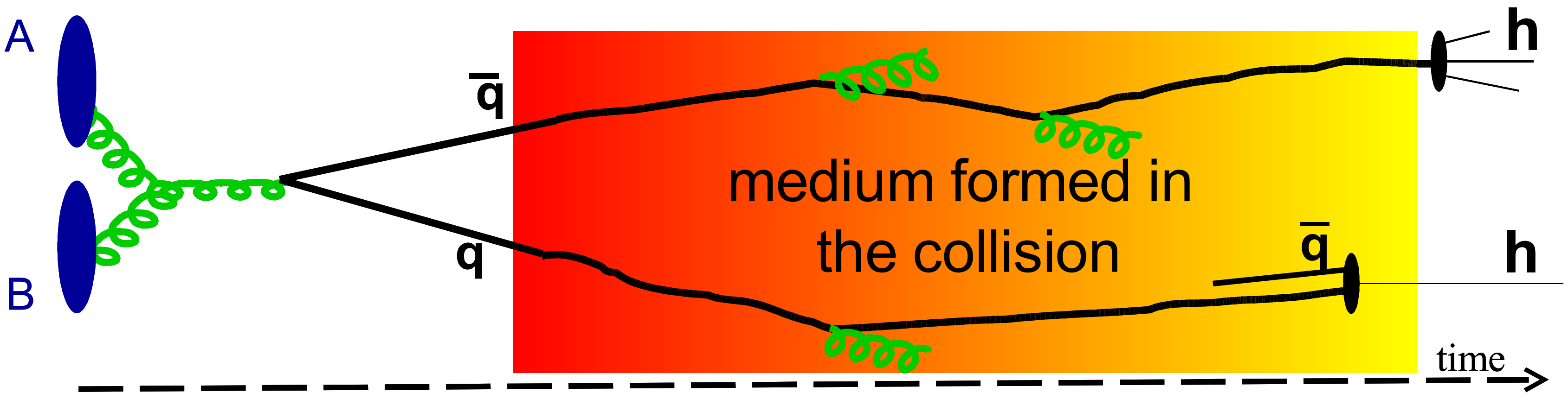
based on work in collaboration with:

A.Dainese and G.Paic

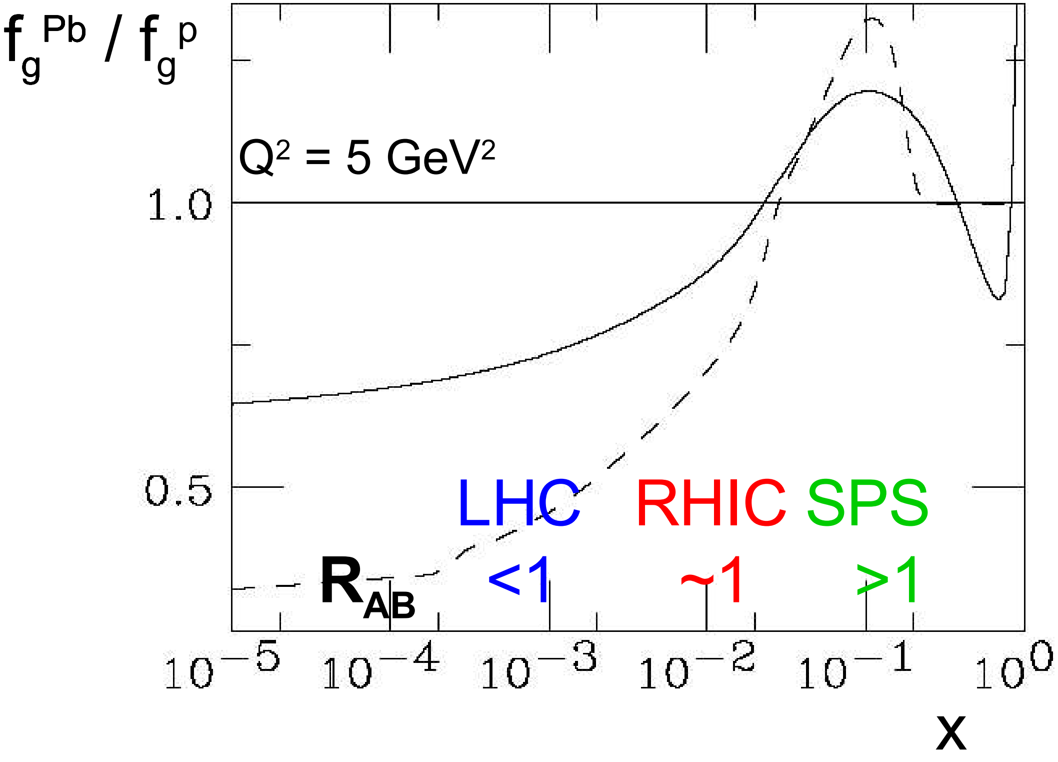
Outline

- High-pt suppression at RHIC (skipped)
- Introduction to PQM (Parton Quenching Model)
  - BDMPS-Z-SW quenching weights
  - Glauber geometry
  - Parton-by-parton approach
- Confrontation with RHIC data
  - Analysis of trigger biases
- Opacity problem (skipped)

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 / fragmentation



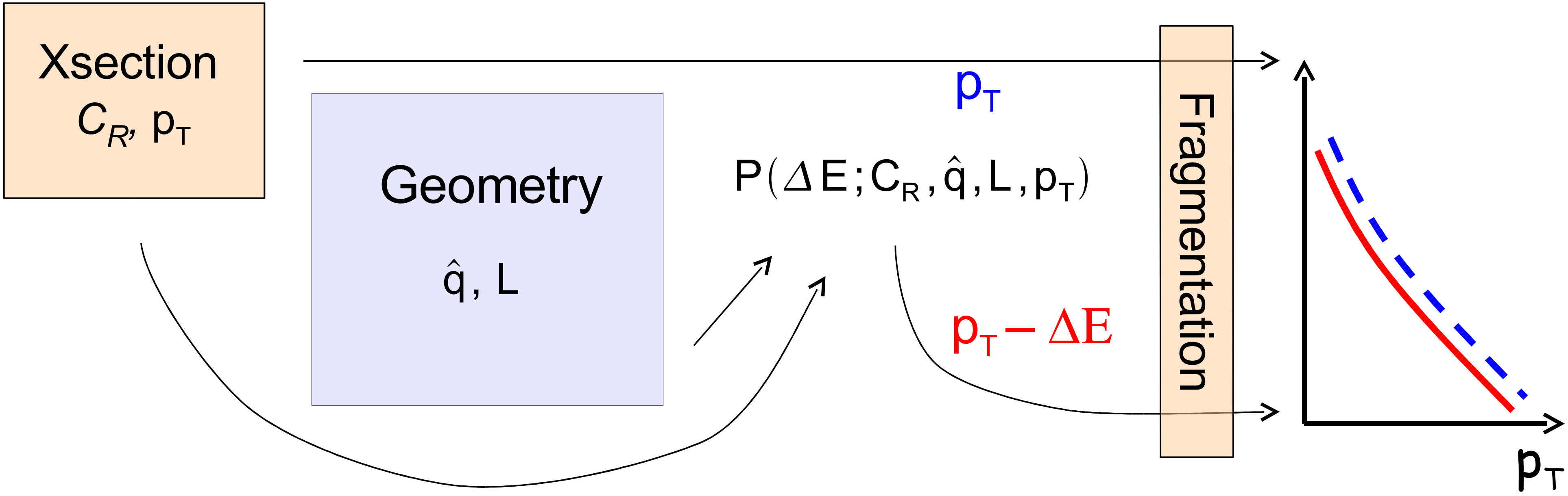
Calculating quenched particle spectra

Factorized pQCD + final state quenching + vacuum fragmentation

$$\left.\frac{d^2\sigma^{h}_{\text{quenched}}}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j}\int dF_{ab}\,d\Delta E_j\,dz_j\,dp^{\text{init}}_{T,j}\left.\frac{d^2\sigma^{ab\to jX}}{dp^{\text{init}}_{T,j}\,dy}\right|_{y\approx 0}\times$$

$$\delta(p^{\text{init}}_{T,j}-p_{T,j}-\Delta E_j)\,P(\Delta E_j;C_j,\hat{q}_j,L_j,p_{T,j})\,\frac{D_{h/j}(z_j)}{z_j^2}$$

Monte Carlo approach:



Xsection

C_R, p_T

Geometry

$\hat{q}$, L

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

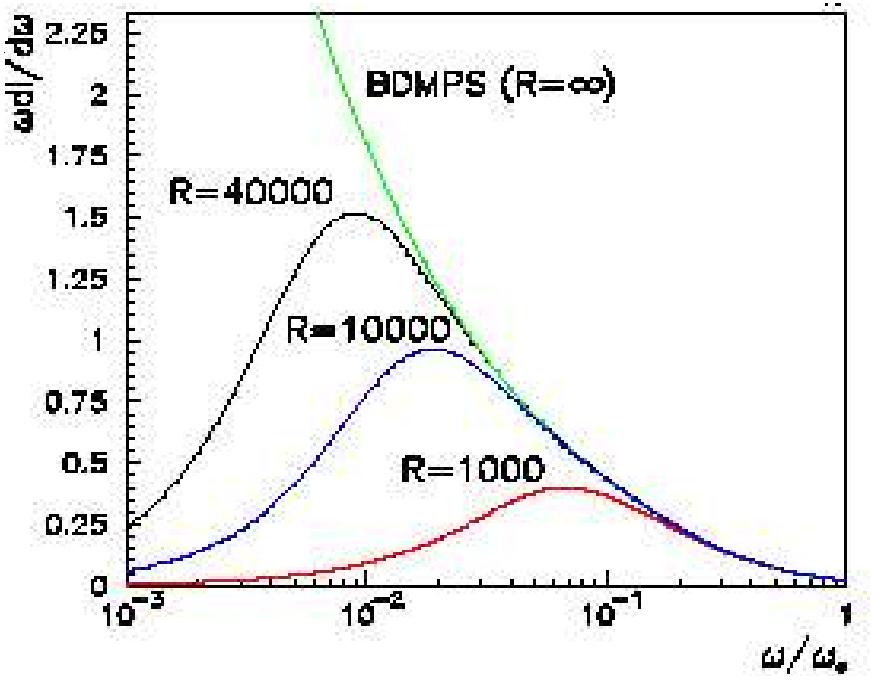
p_T

$p_T-\Delta E$

Fragmentation

p_T

Parton energy loss in BDMPS-Z formalism



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.

Quenching weights

- Compute energy loss probability distributions

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

- Calculated from ω dI/dω in the $E\rightarrow\infty$ approximation (no E dep.)

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

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

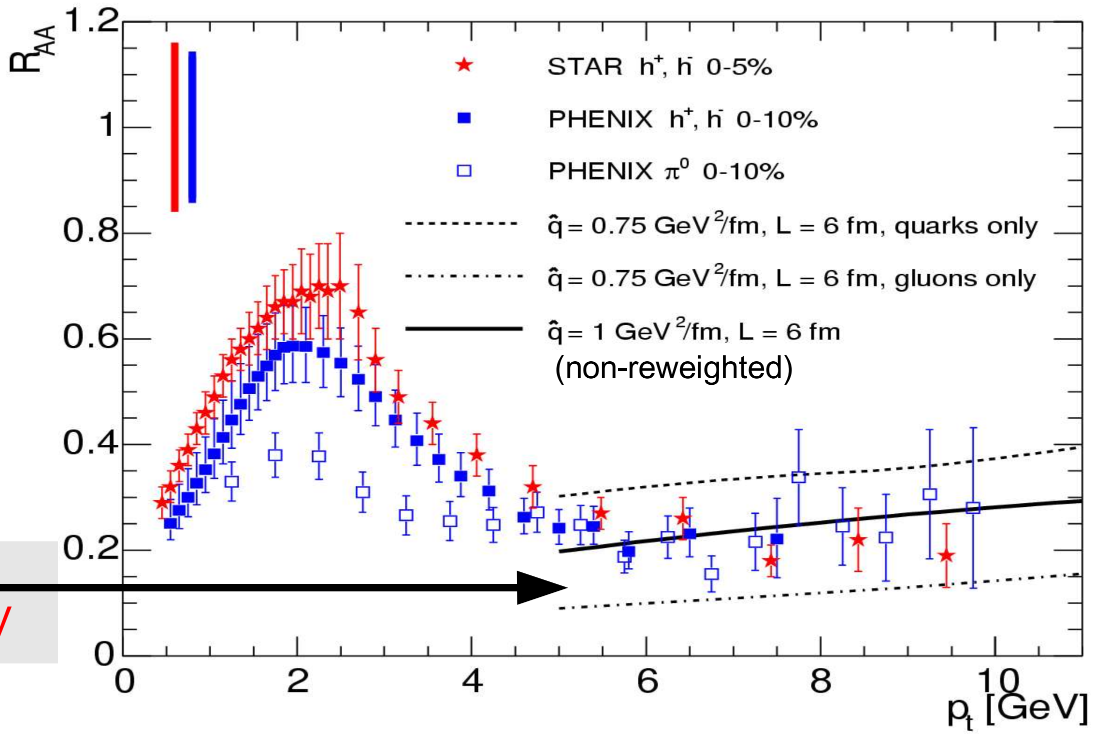
BDMS, JHEP 0109 (2001) 033
Salgado, Wiedemann, PRD 68 (2003) 014008

R_{AA} in Au+Au at 200 GeV

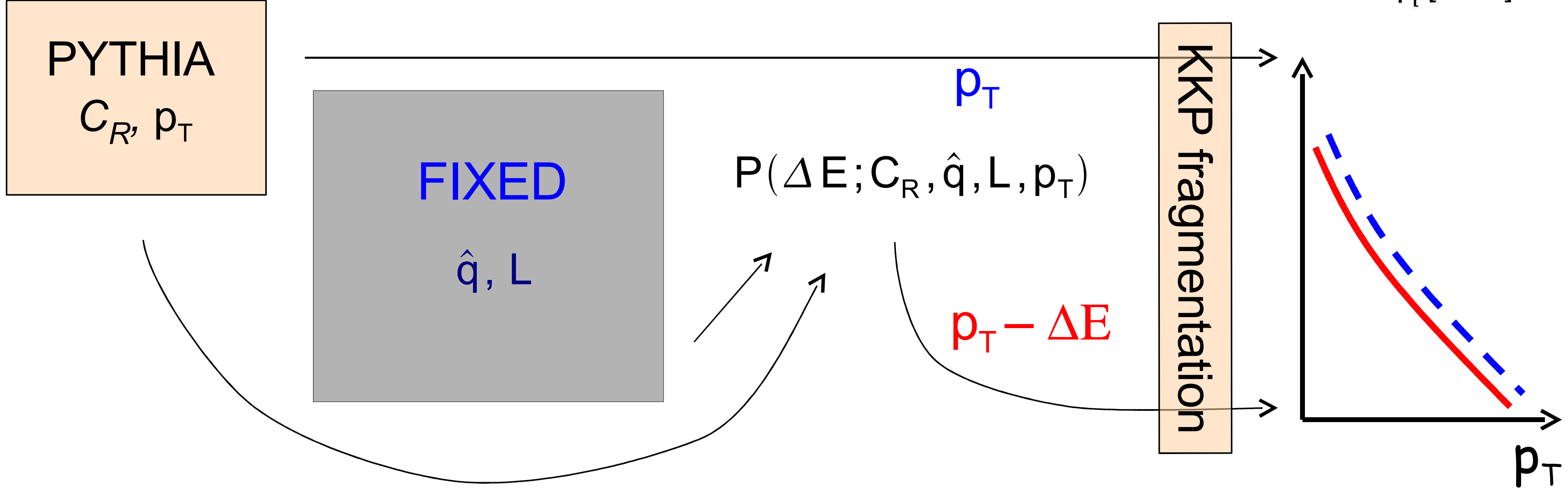
Need

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

to describe the measured suppression in 0-10% Au+Au for fixed length 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_T

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

$p_T - \Delta E$

KKP fragmentation

p_T

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

EQUIVALENT STATIC SCENARIO

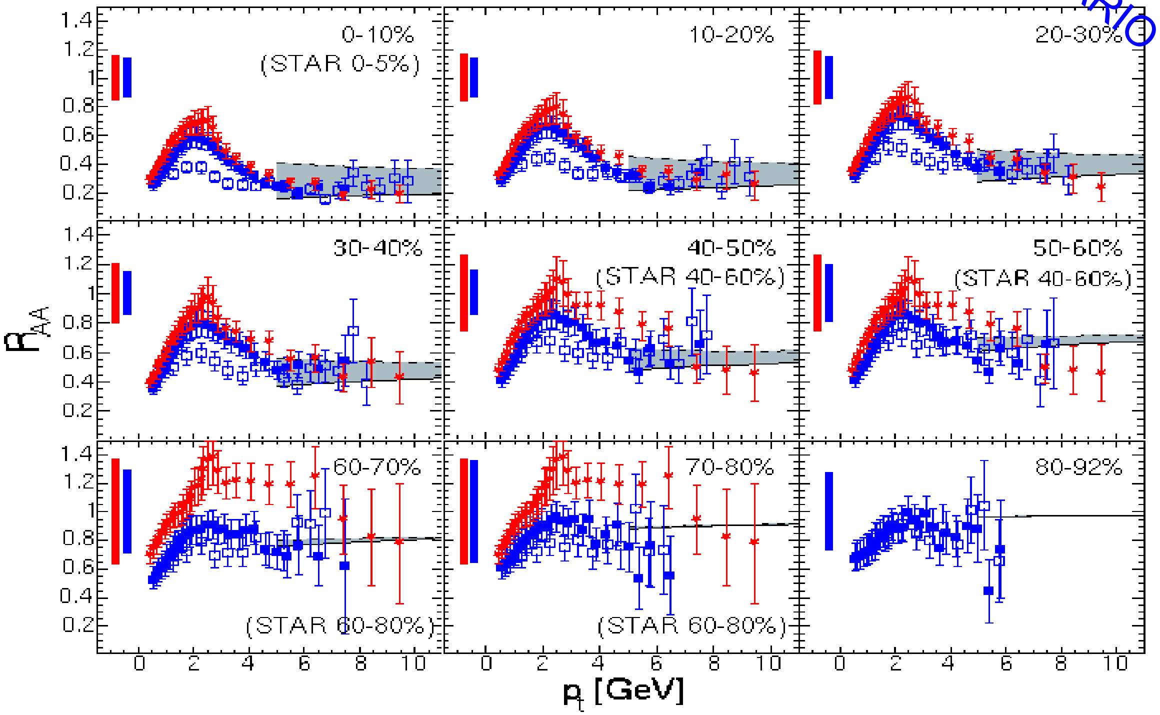
Need

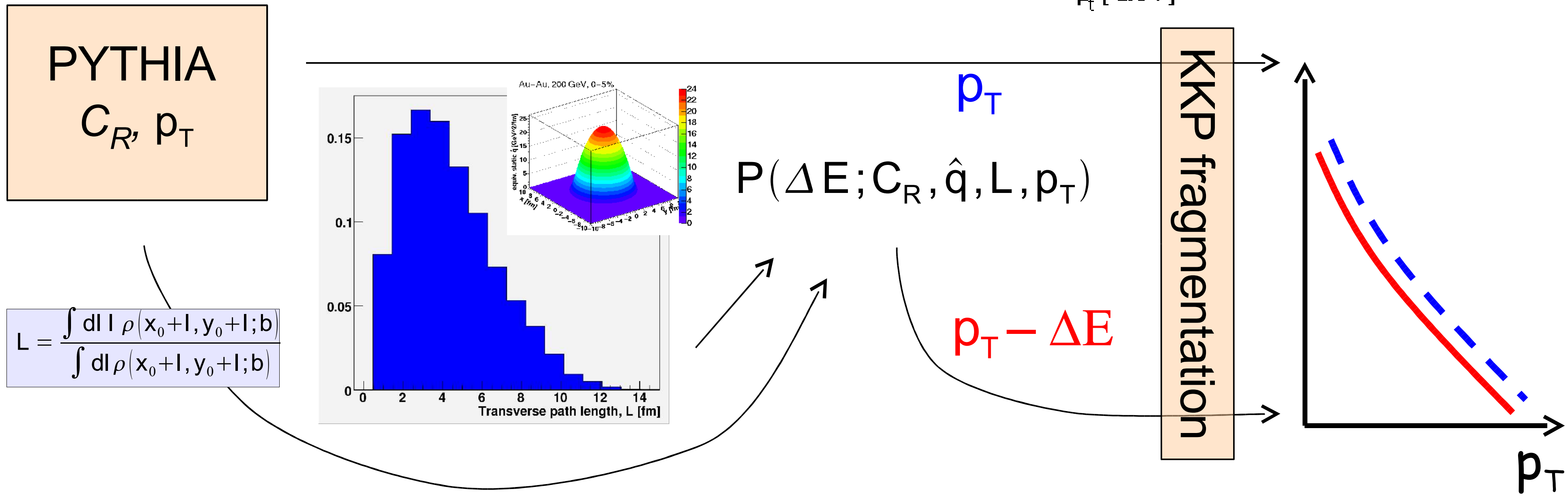
$$\langle \hat{q} \rangle = 4 - 14\,\mathrm{GeV}^2/\mathrm{fm}$$

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

Local density

$q(\xi; x_0, y_0, \phi_0; b) = \Big(\frac{}{\tau_0}$





PYTHIA

C_R, p_T

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

p_T

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

$p_T - \Delta E$

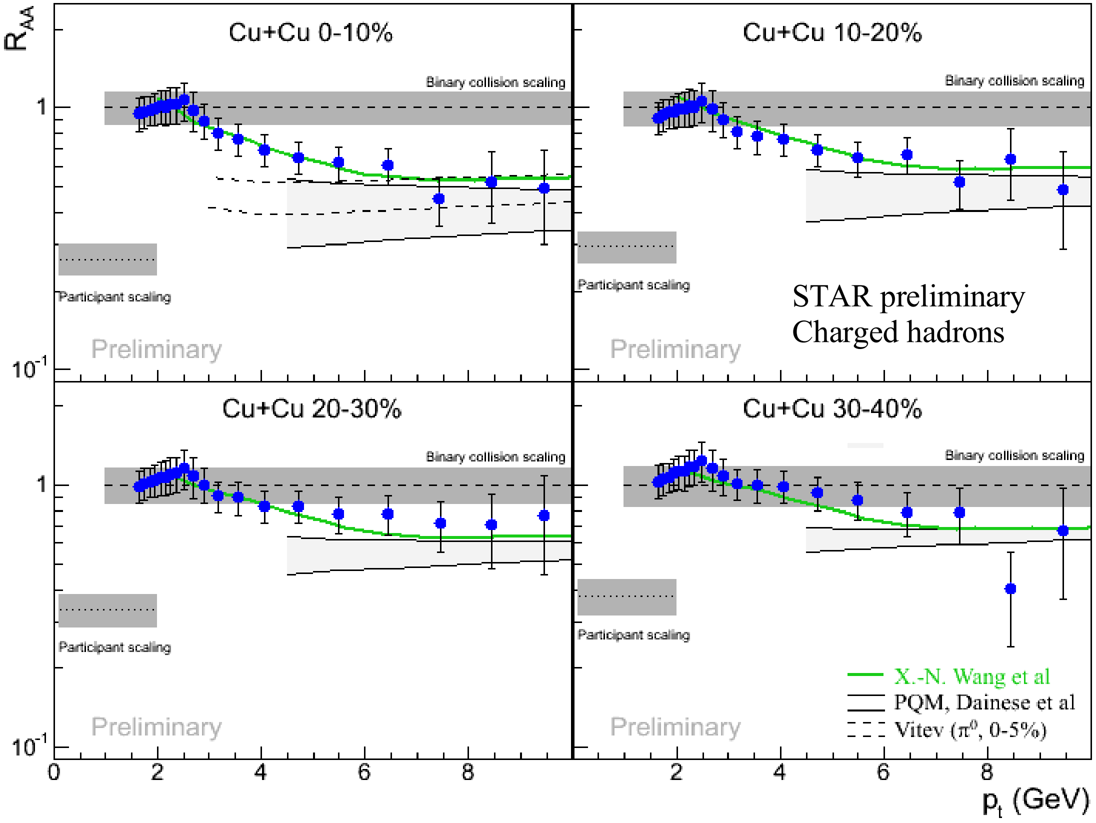
KKP fragmentation

p_T

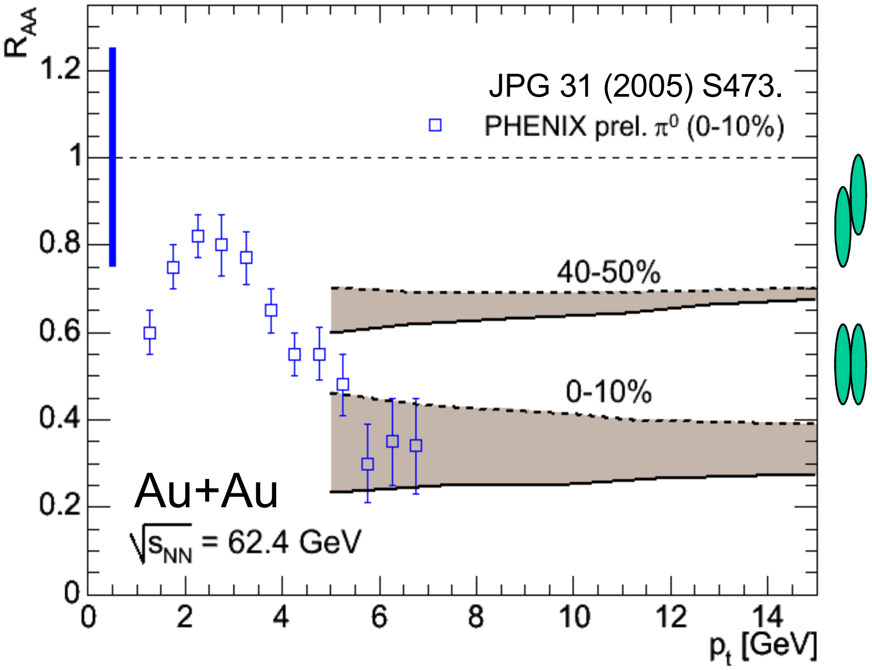
Extrapolation to other systems

EQUIVALENT STATIC SCENARIO

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



$$\langle \hat{q}^{62.4,\mathrm{AuAu}} \rangle = 7\,\mathrm{GeV}^2/\mathrm{fm}$$



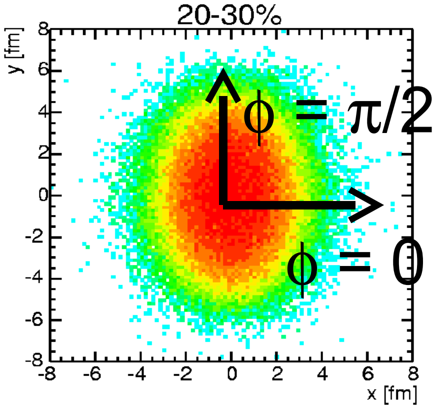
Using EKRT saturation model, we scale

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

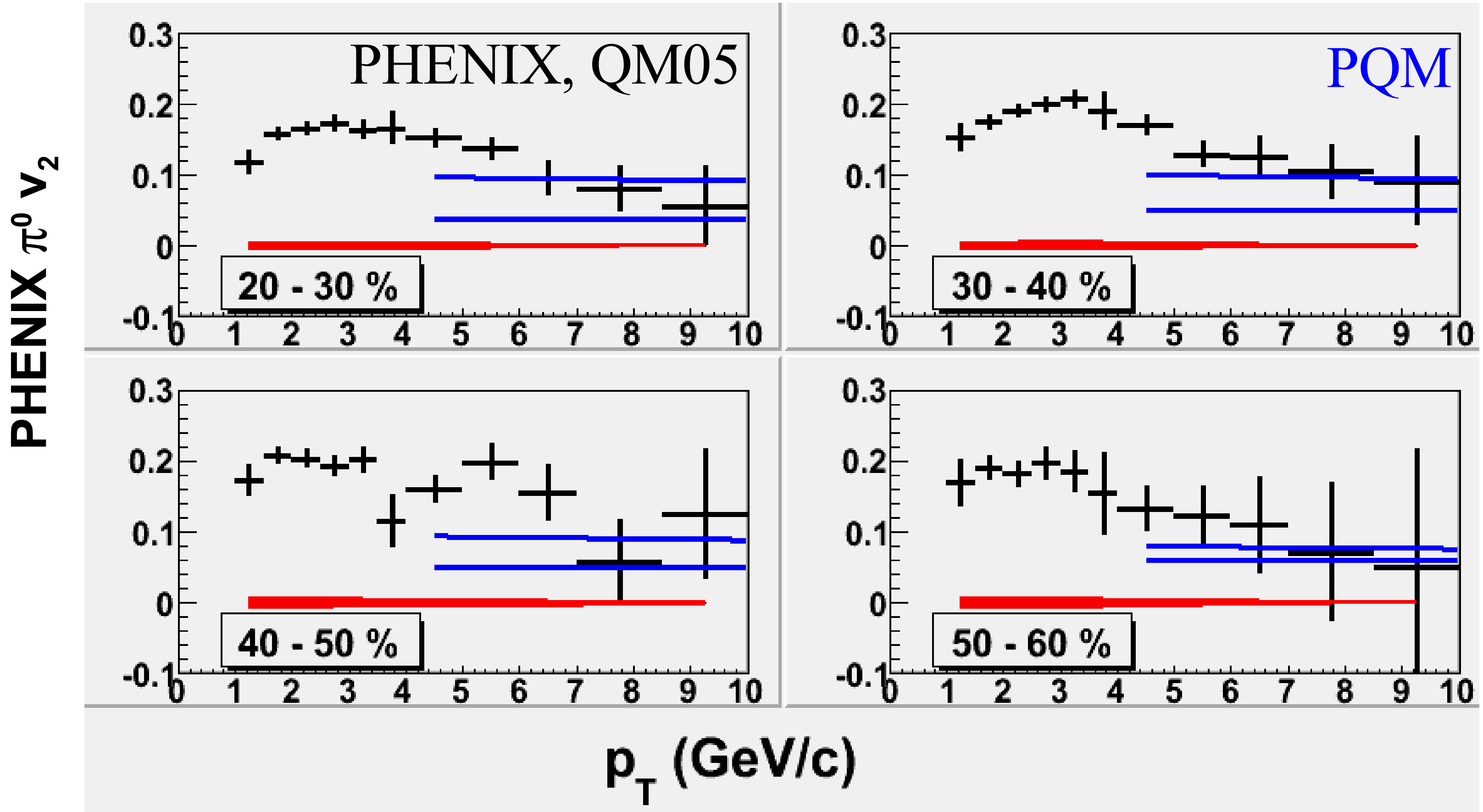
Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000) 379.

Testing dependence on path-length?

EQUIVALENT STATIC SCENARIO



- The azimuthal asymmetry --v_2 or $R_{AA}(\phi)$-- of high-p_T particle yields in *non-central* collisions tests the path-length dependence of E loss (almond-shaped medium)
- Note that new data is comparable with Shuryaks estimate for complete absorption (from ~2001).

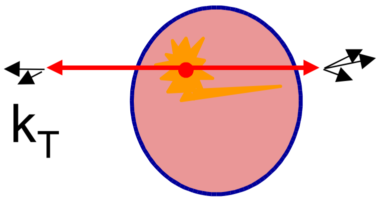


v_2 from energy loss: Dainese, Loizides, Paic, EPJC 38 (2005) 461

Away-side suppression within PQM

EQUIVALENT STATIC SCENARIO

Back-to-back partons in PQM: no k_T

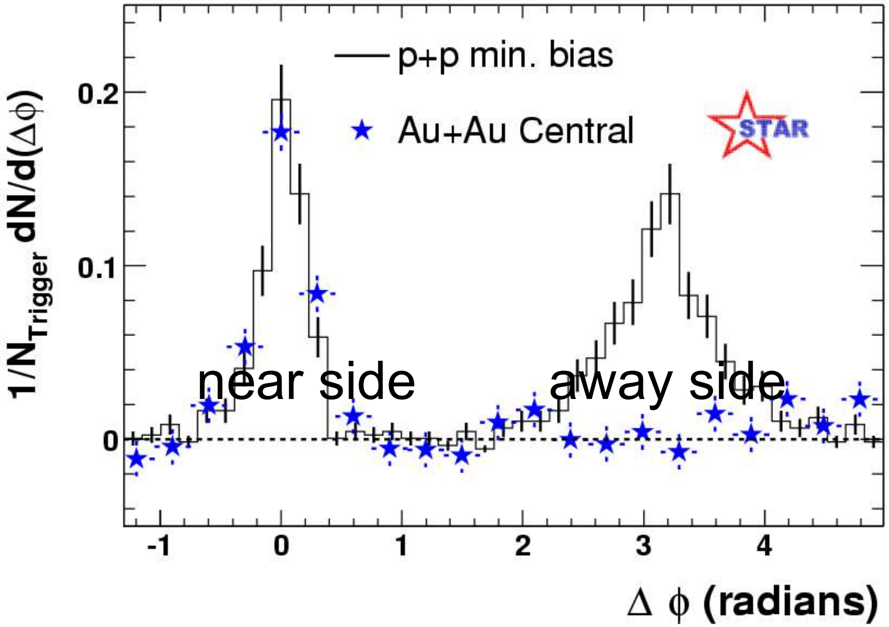


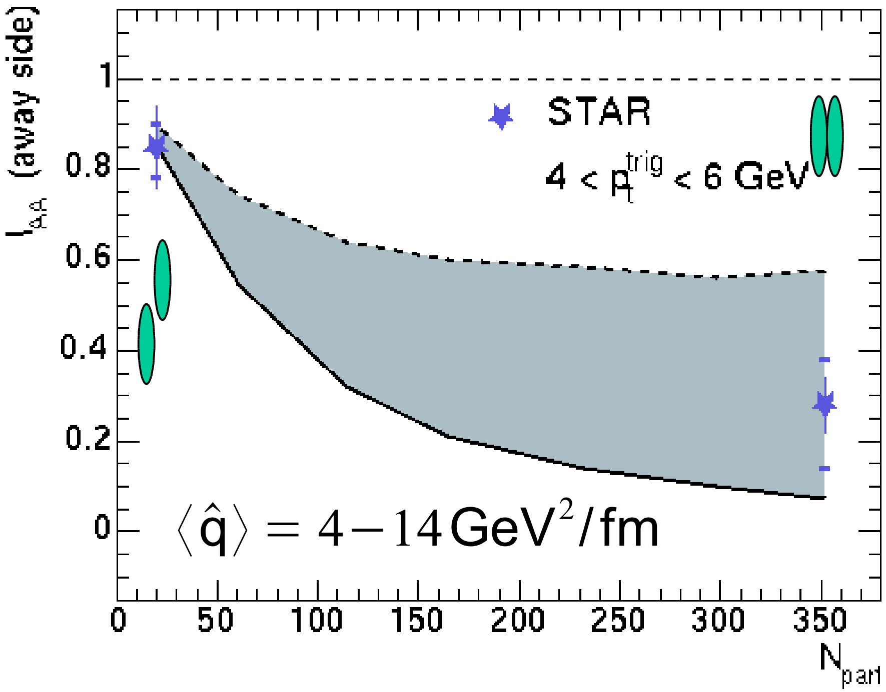
transverse plane

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

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

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





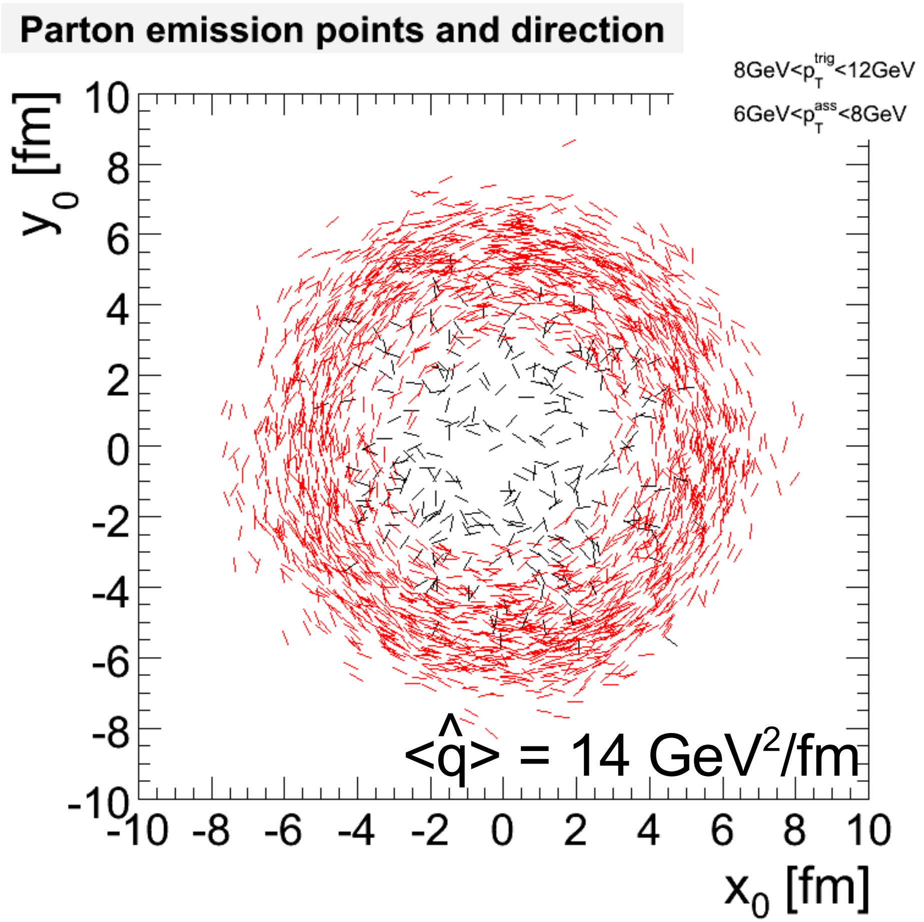
STAR Coll., PRL 90 (2003) 082302

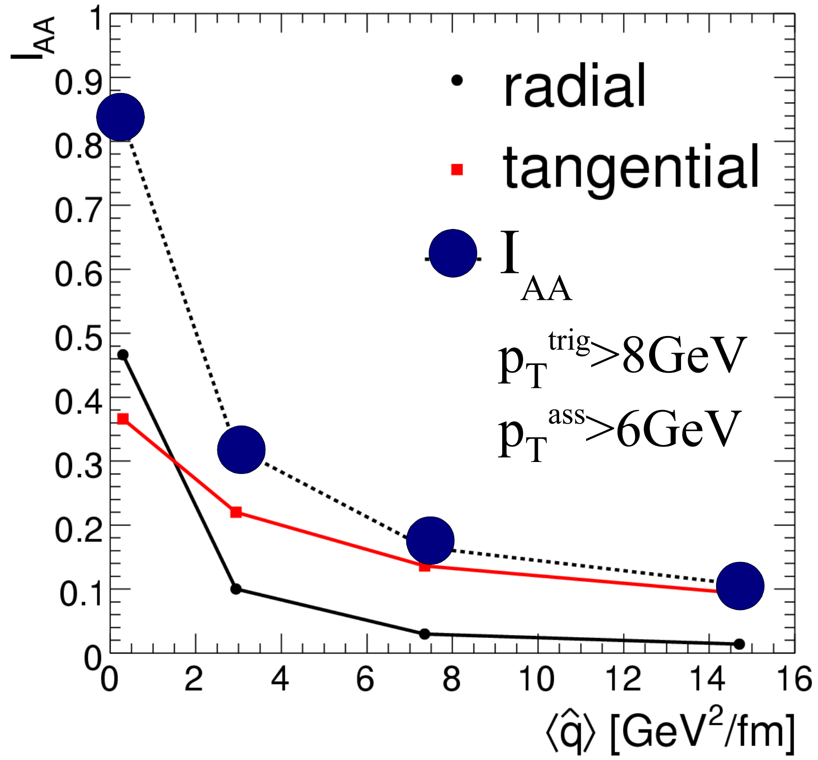
STAR Coll., nucl-ex/0501016

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

PQM: Tangential di-jet emission?

EQUIVALENT STATIC SCENARIO





Radial (black) lines: one jet of the dijet crosses inner core of R=3 fm. Tangential (red) lines: none of the jets crosses inner core.

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

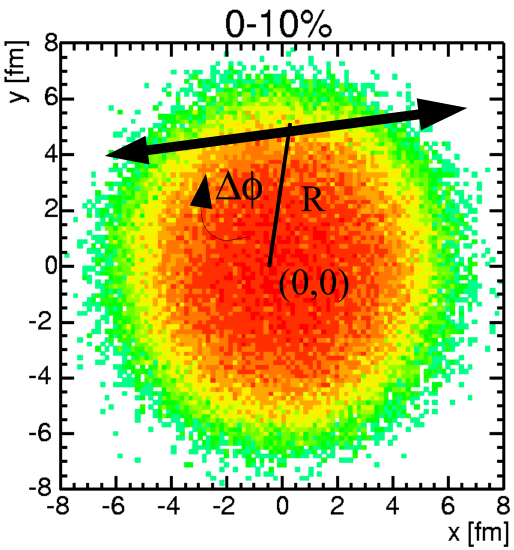
Müller, PRC67 (2003) 061901.
Dainese, Loizides, Paic, QM 2005 Poster.

Static scenario vs. Bjorken expansion

- Define time-depende oefficient

$$\hat{q}(\xi; x_{0,} y_{0,} \phi_0; b) = \Big(\frac{\tau}{\tau_0}\quad \cos\phi_{0,} y_0 + \xi \sin\phi_0; b)$$

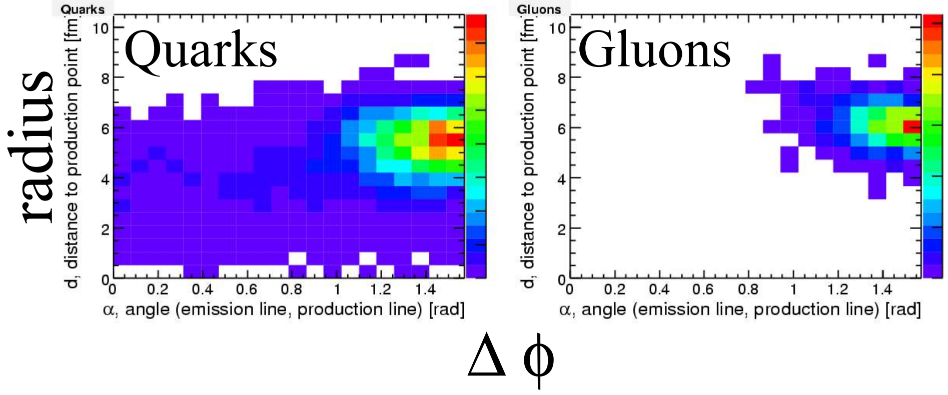
- Compare static (α =0) th τ_0 = 0.15-0.2fm



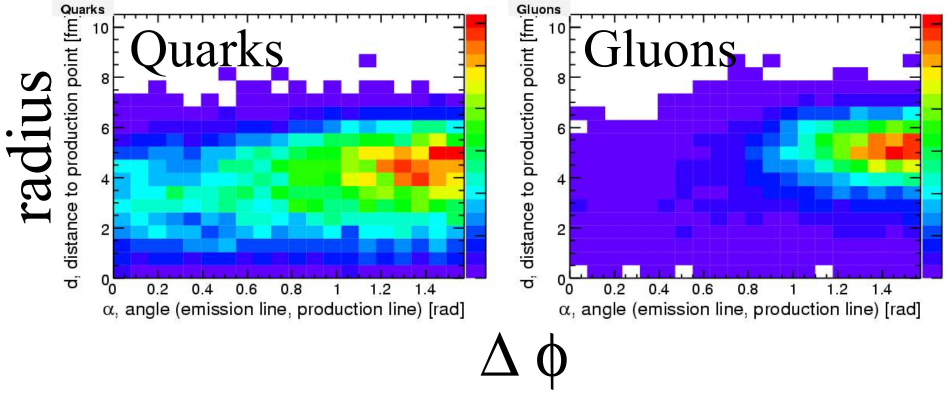
EQUIVALENT
STATIC

DYNAMICAL
SCENARIO

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



$\langle\hat{q}\rangle = 58\,\mathrm{GeV}^2/\mathrm{fm}$



No qualitative but quantitative change

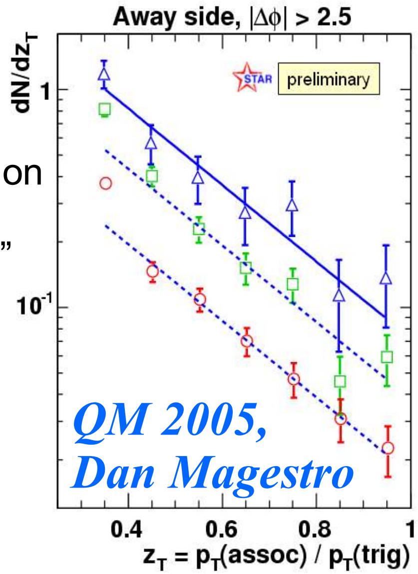
Static scenario vs. Bjorken expansion (2)

	Static	**1-dim Bjorken α =1**
Medium	7 (63*) GeV^2/fm	58* GeV^2/fm
R_{AA} (10GeV)	0.25	0.25
IAA (highest cuts)	0.13	0.16
dE/dx (all partons)	2 GeV/fm	4-5 GeV/fm
dE/dx (all survivors)	200-300 MeV/fm	200-300 MeV/fm
dE/dx (away jet)	~300 MeV/fm	~200 MeV/fm

* at initial time

Due to the trigger bias, the energy loss the surving partons suffered is similar to the order of cold nuclear matter. Surviving jets and dijets propagate through low(est)-density region.

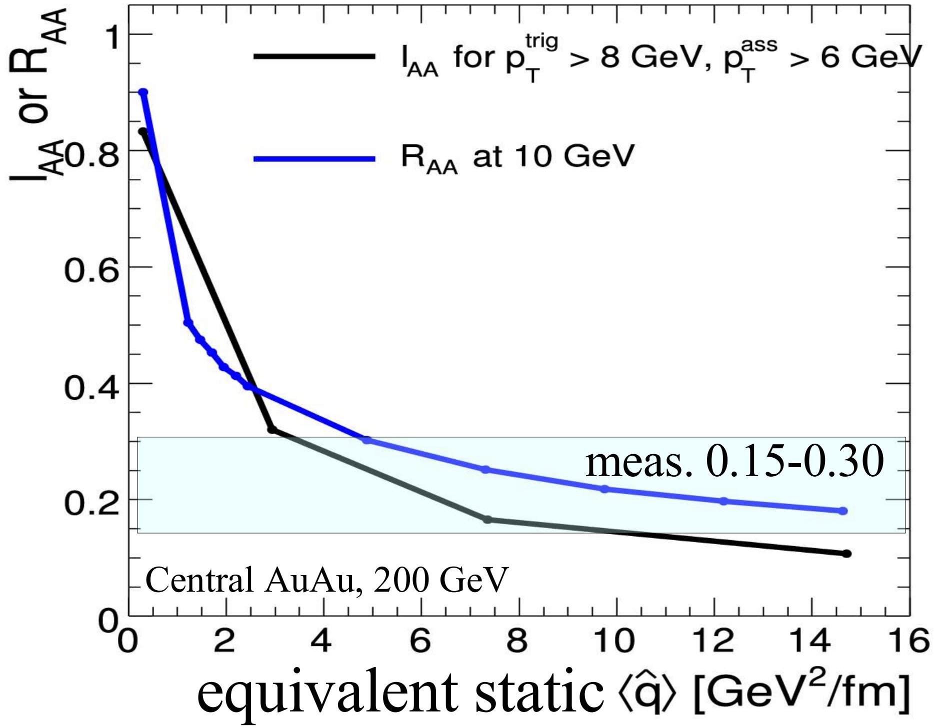
Dainese, Loizides, Paic, nucl-ex/0511045



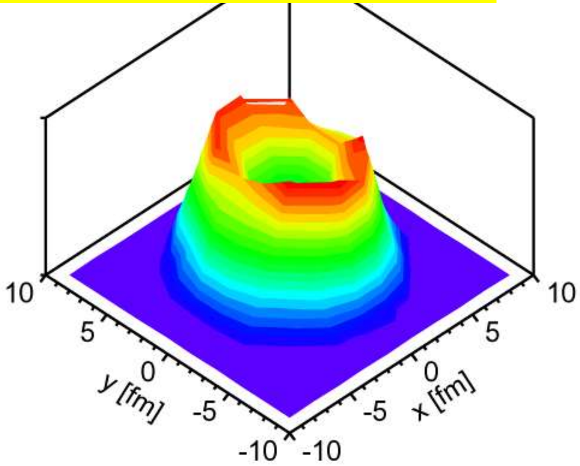
"Away-side fragmentation pattern unchanged"

QM 2005, Dan Magestro

Sensitivity of probes



"Leading-particle probes are fragile"



- Strong suppression described by very large densities
- Opaque medium leeds to strong trigger biases
- R_{AA} and I_{AA} pre-dominantly determined by geometry

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

Summary

- Parton Quenching Model
  - BDMPS framework married with Glauber geometry (plus long. exp)
  - Simple model with one single parameter
  - Rather consistently describes most high-p_T RHIC data
  - Reveals trigger biases in R_{AA} and I_{AA}
    - Surface effects for single-inclusive and di-jet probes
- RHIC Data (including data shown at QM 2005) constrains

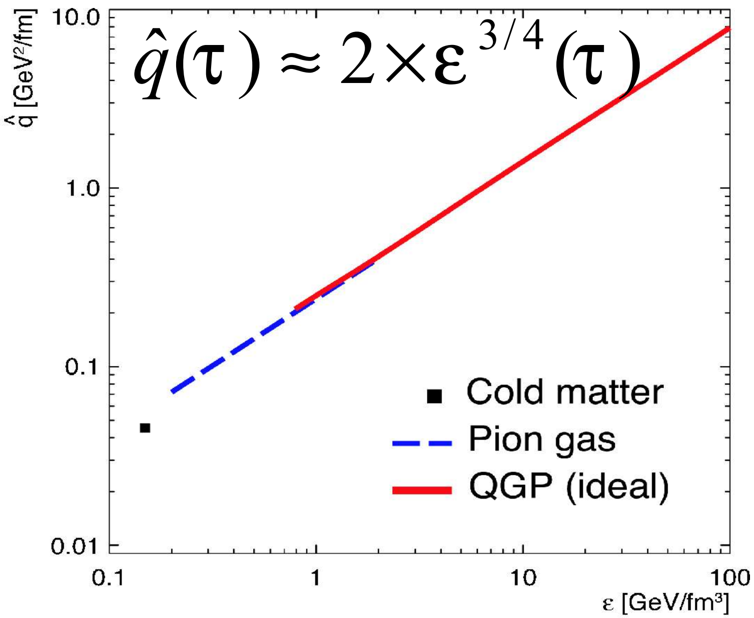
$$\langle \hat{q} \rangle = 4 - 14\,\mathrm{GeV}^2/\mathrm{fm}$$

- Opacity problem: Include
  - collisional energy loss? (see A.Peshier)
  - transverse flow? (see T.Renk and J.Ruppert)
  - In-medium fragmentation / hadronic rescattering? (see A.Accardi)

Backup Slides

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: $c^{pQCD} = 2$



$$\hat{q}(\tau) \approx 2 \times \varepsilon^{3/4}(\tau)$$

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

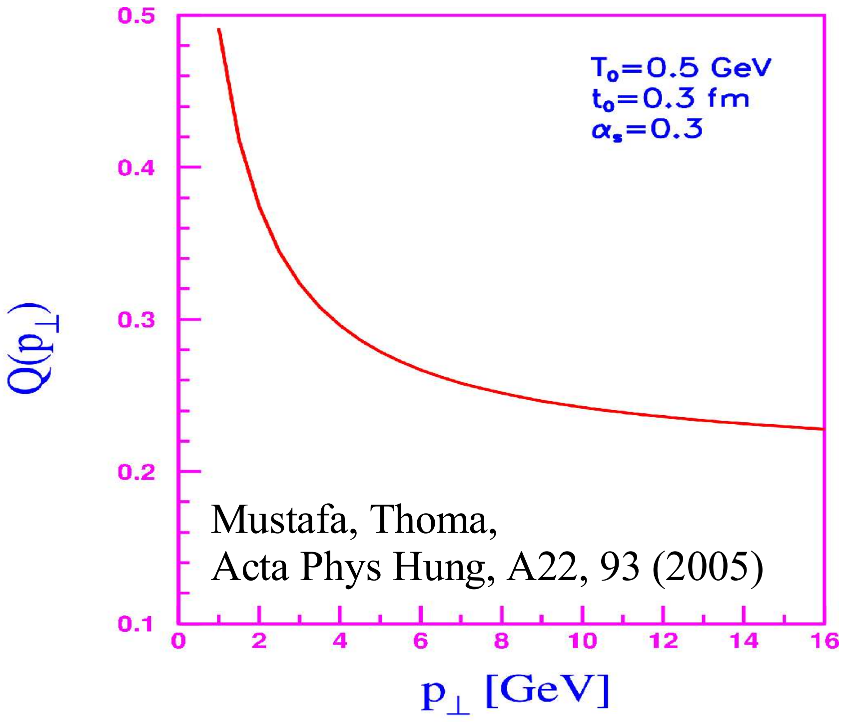
  and $0.75 < \alpha < 1$

→ $c = 8 \ldots 20$

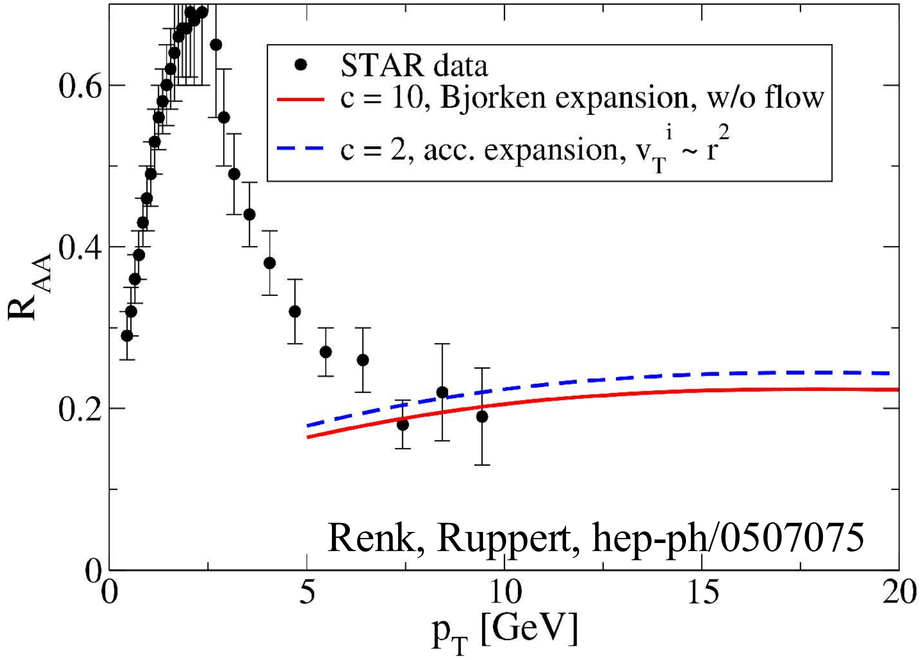
The interaction of the hard parton with the medium is much stronger than (perturbatively) expected

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

The opacity problem (2)



Mustafa, Thoma,
Acta Phys Hung, A22, 93 (2005)



Renk, Ruppert, hep-ph/0507075

- Collisional energy
  - Boltzmann Transport
  - Bjorken Expansion
- Cylinder geometry used
  - Realistic geometry ?

- Local transport coefficient

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

- Transverse flow
- Fireball model for transverse and longitudinal expansion

Calculating unquenched particle spectra

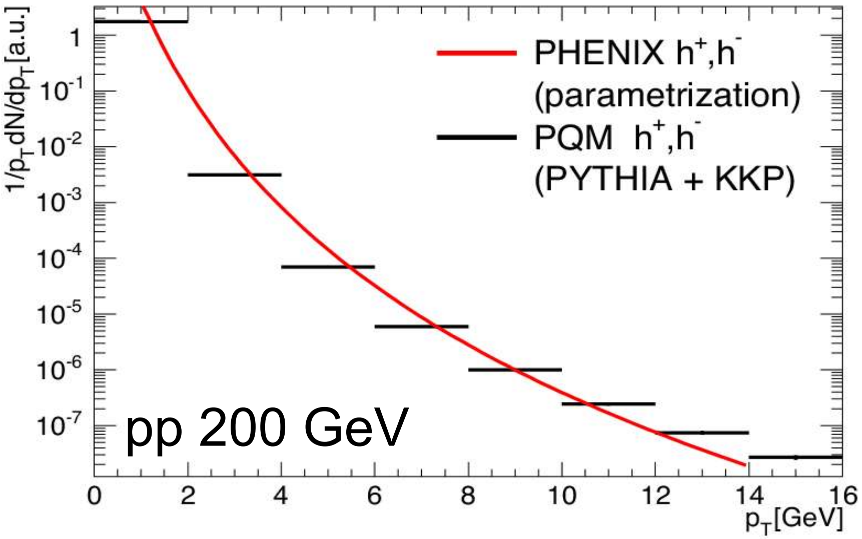
Standard pQCD + collinear factorization + vacuum fragmentation

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

Monte Carlo approach:

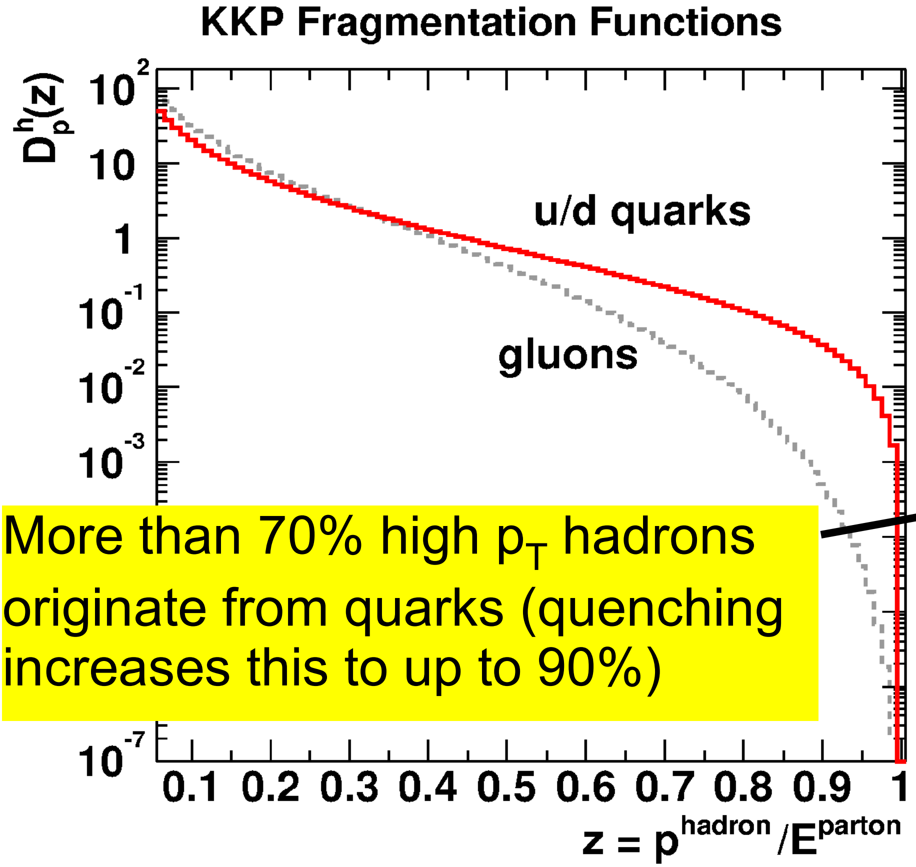
Verify shape with PHENIX parametrization for pp

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

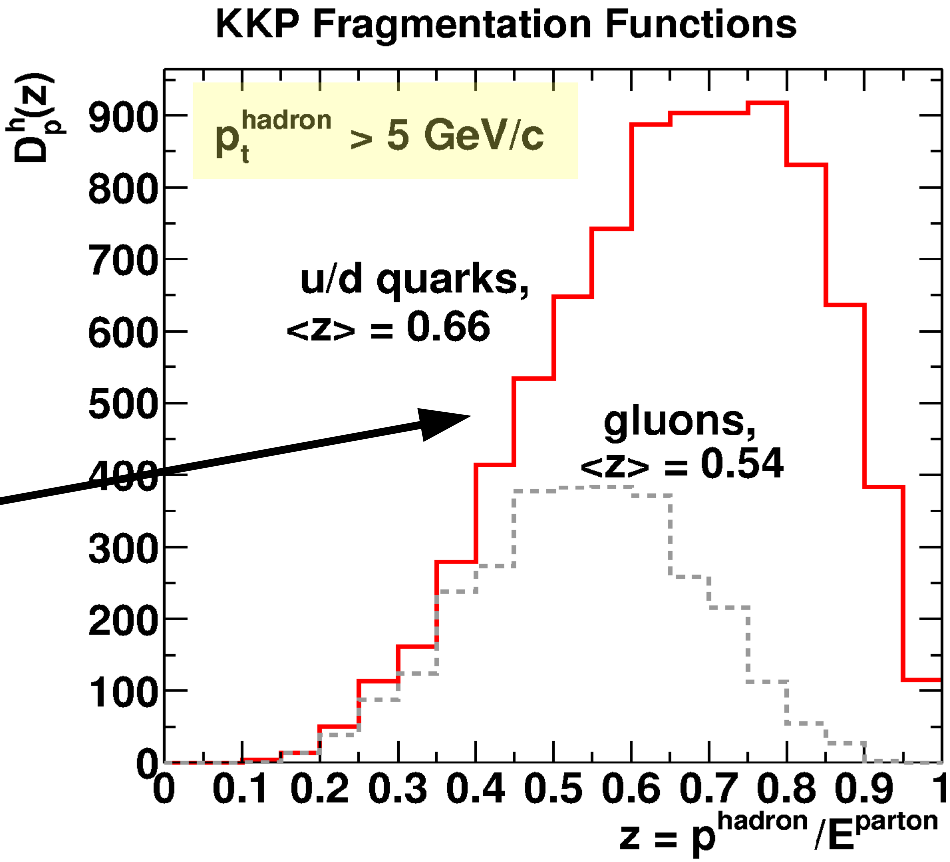


PYTHIA + KKP fragmentation

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%)



Parton energy loss inspired by pQCD

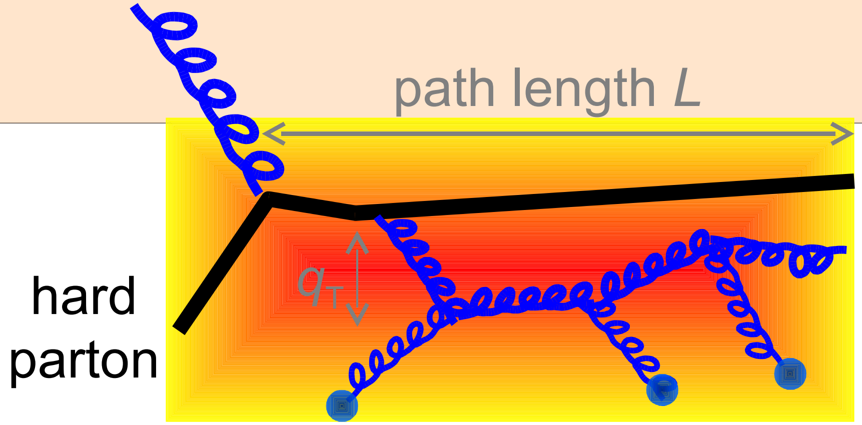
- Partons travel a few (~4) fm in the high color-density medium
- Bjorken (`82): energy loss due to elastic (collisional) scattering
- Successive calculations (`92++) revealed(???) that medium-induced gluon radiation (QCD bremsstrahlung) dominates:

$$\omega \frac{dI}{d\omega\, dk} = \alpha_S C_R / \omega^2\, F\left(\eta(\xi)\sigma(r)\right)$$

$\rightarrow \frac{1}{2}\hat{q}(\xi) r$ (BDMPS)

$\rightarrow \left(n(\xi)\sigma(r)\right)^N$ (opacity expansion)

- 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 BDMPS-Z formalism

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

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

(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
an equivalent
transport coe

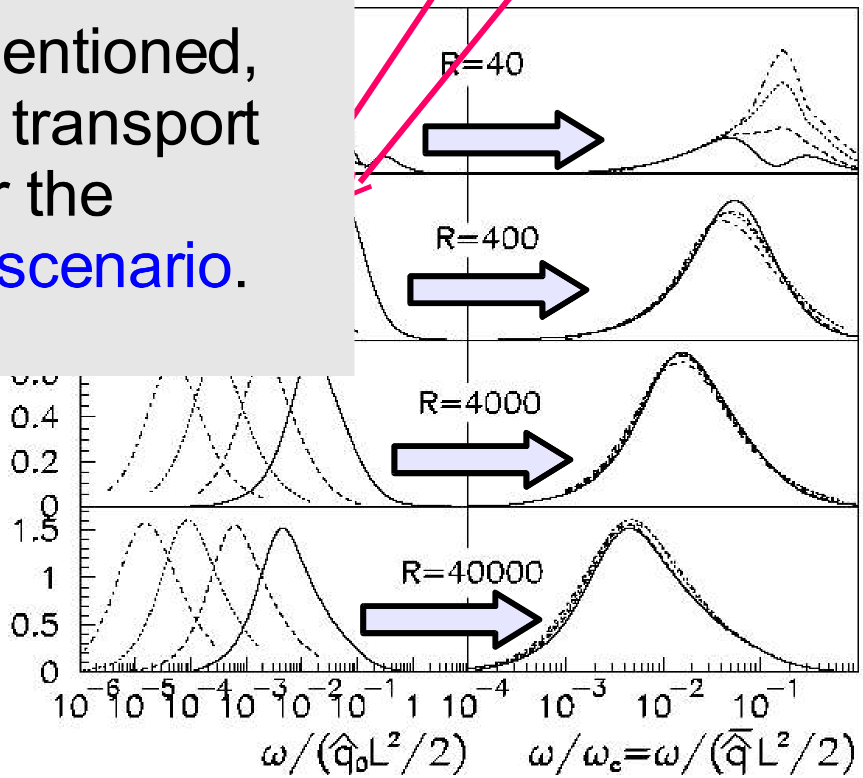
$$\bar{\hat{q}} = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau \left(\tau - \tau_0\right) \hat{q}(\tau)$$

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

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

α = 1.5, 1.0, 0.5, 0

EQUIVALENT STATIC SCENARIO



Salgado, Wiedemann, PRL 89 (2002) 092303.

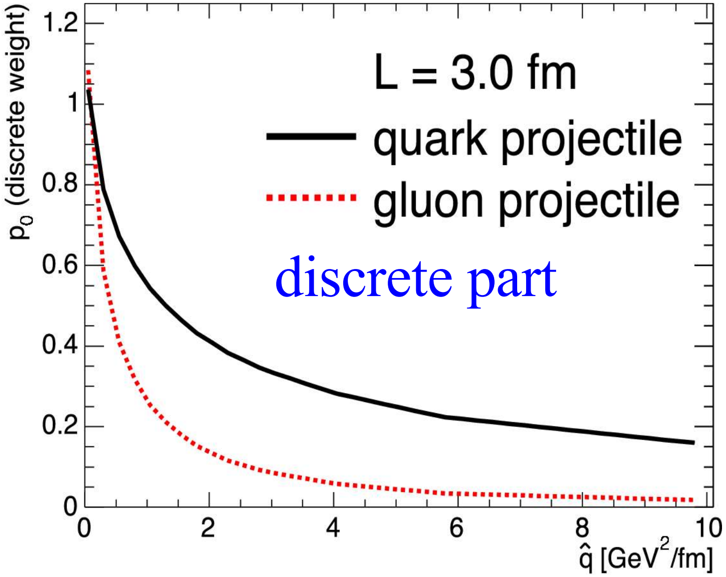
Quenching weights

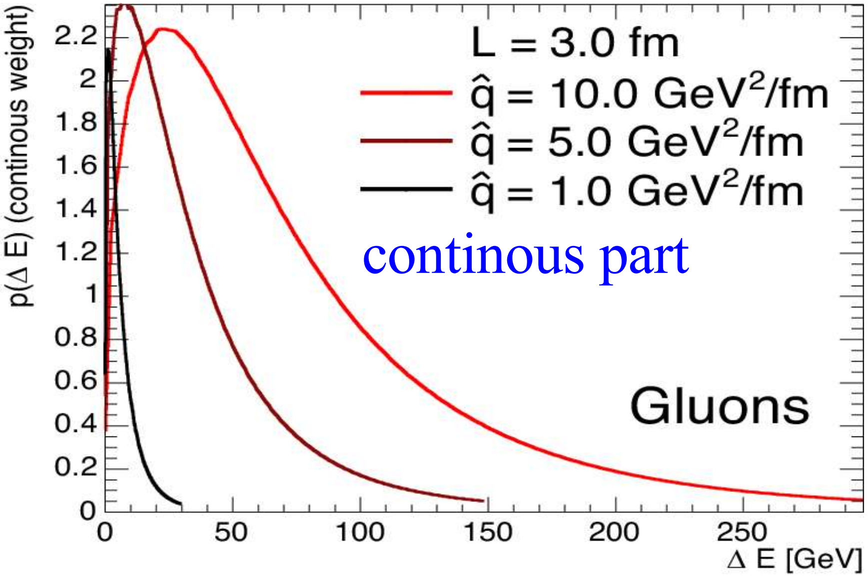
- Compute energy loss probability distributions

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

- Calculated from ω dI/dω 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

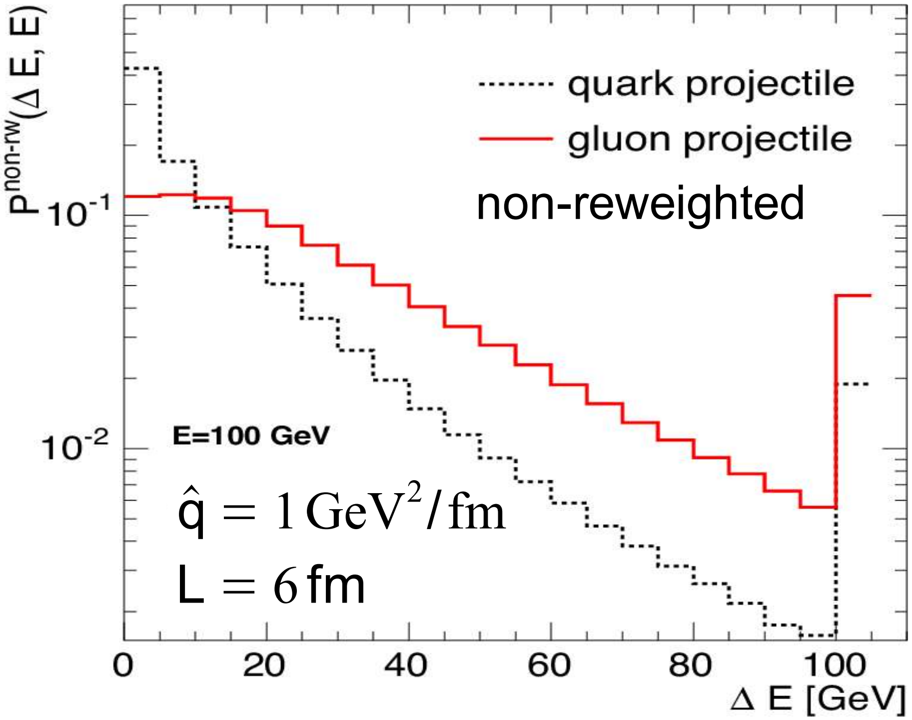
→ **Constrained weights**

Constrained quenching weights

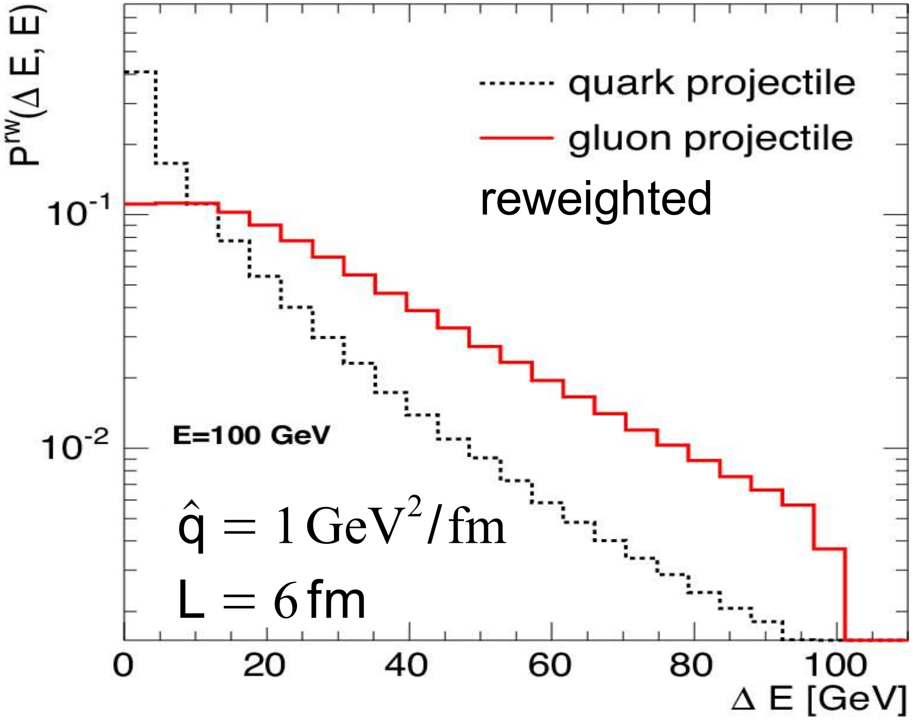
Construct constrained weights from quenching weights

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

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



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



PQM parton-by-parton approach

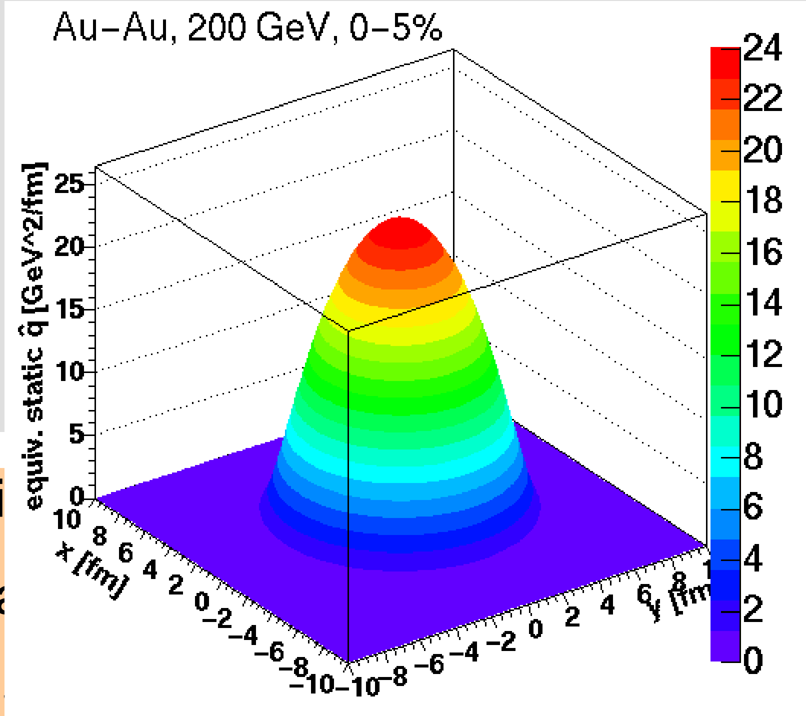
- Define "local" transport coefficient

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

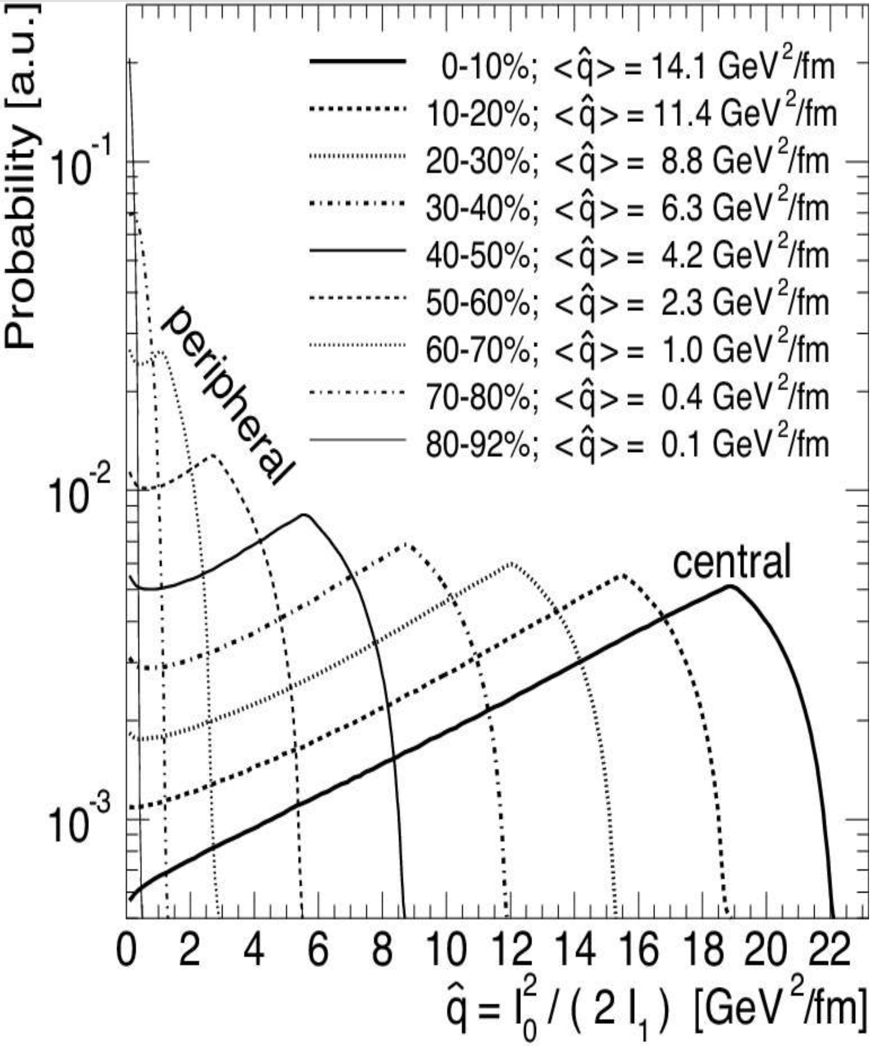
(note

ts

t $\bar{\hat{q}}$

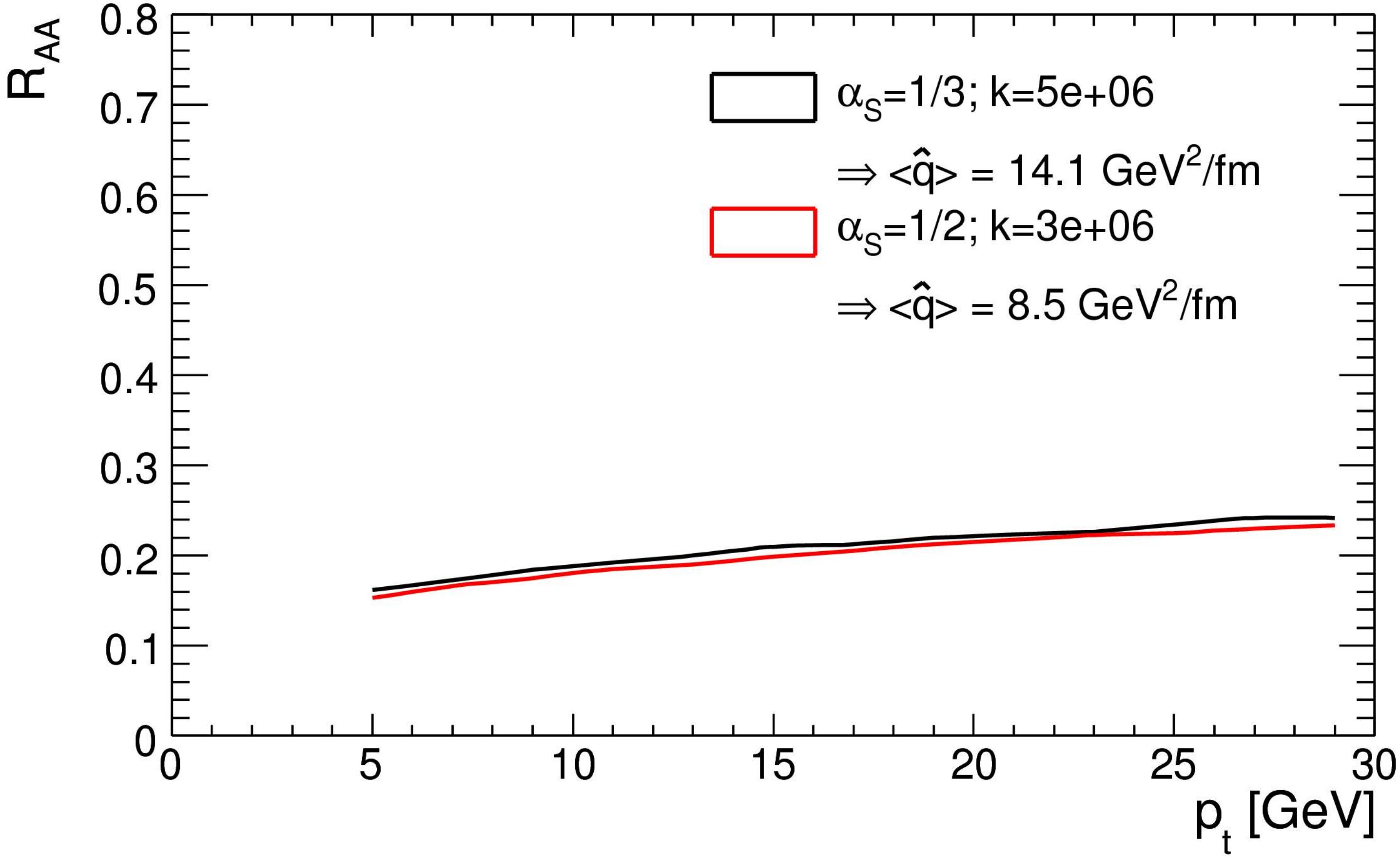


- Defi
- Para nce)
  - –
  - Implicitly depends on systems and energy (see later)
  - Use Glauber to scale to other centralities
  - Report $\langle\hat{q}\rangle\propto k$ for a given centrality range



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

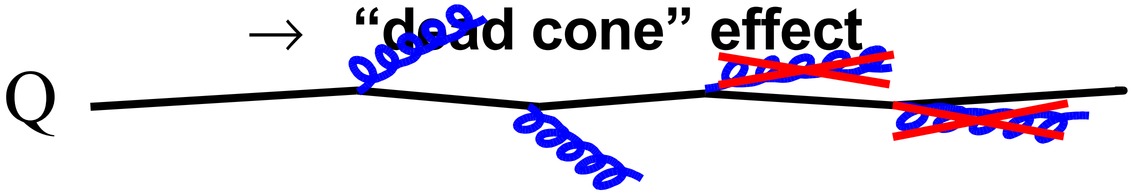
Change to larger α_S



Lower E loss for heavy quarks ?

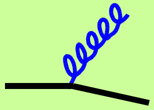
Courtesy by
A.Dainese

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



→ “dead cone” effect

Gluonsstrahlung probability

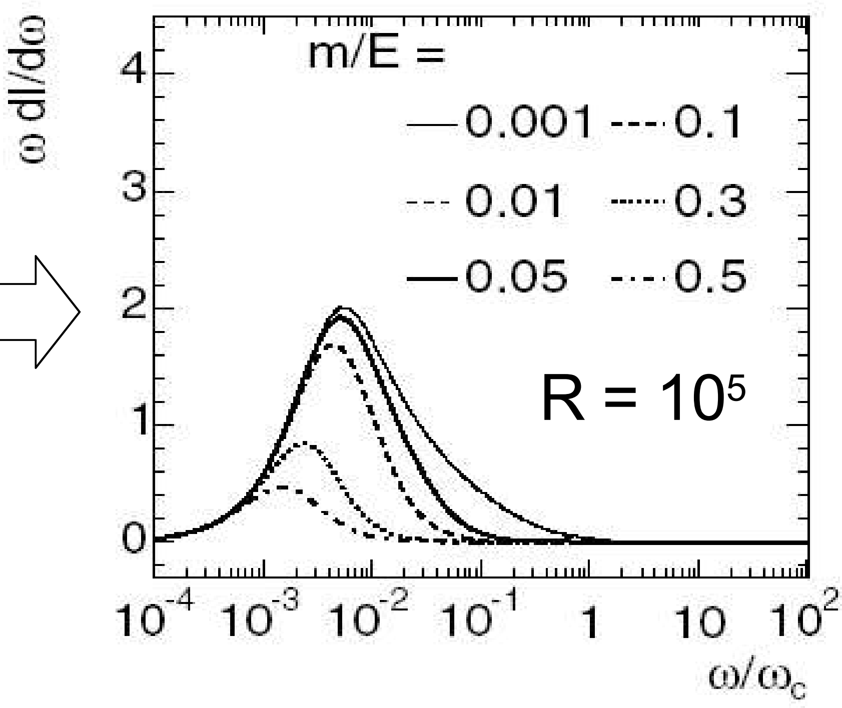


$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

- *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

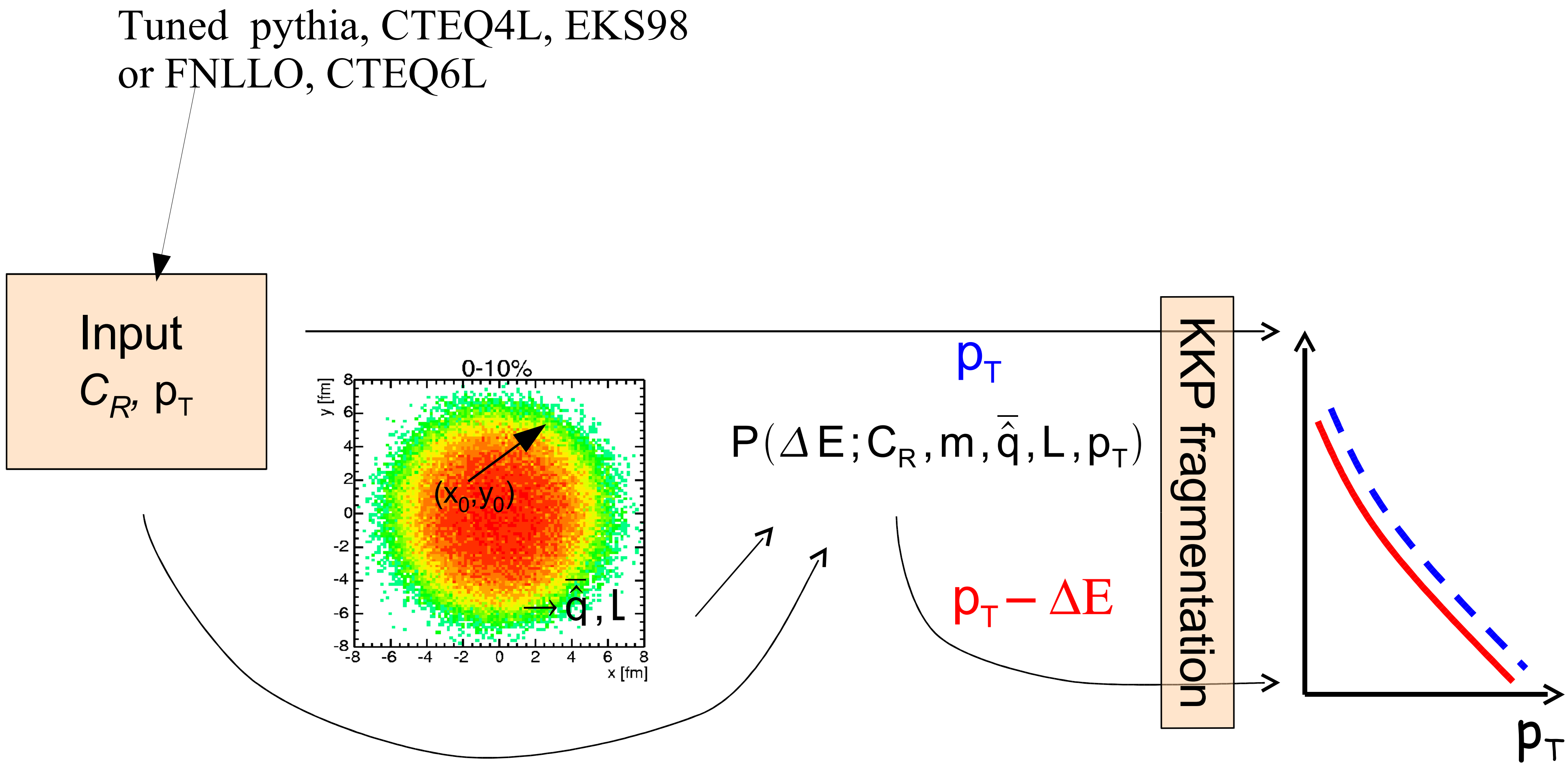
Detailed massive calculation confirms this qualitative feature

(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

Input
C_R, p_T

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

p_T

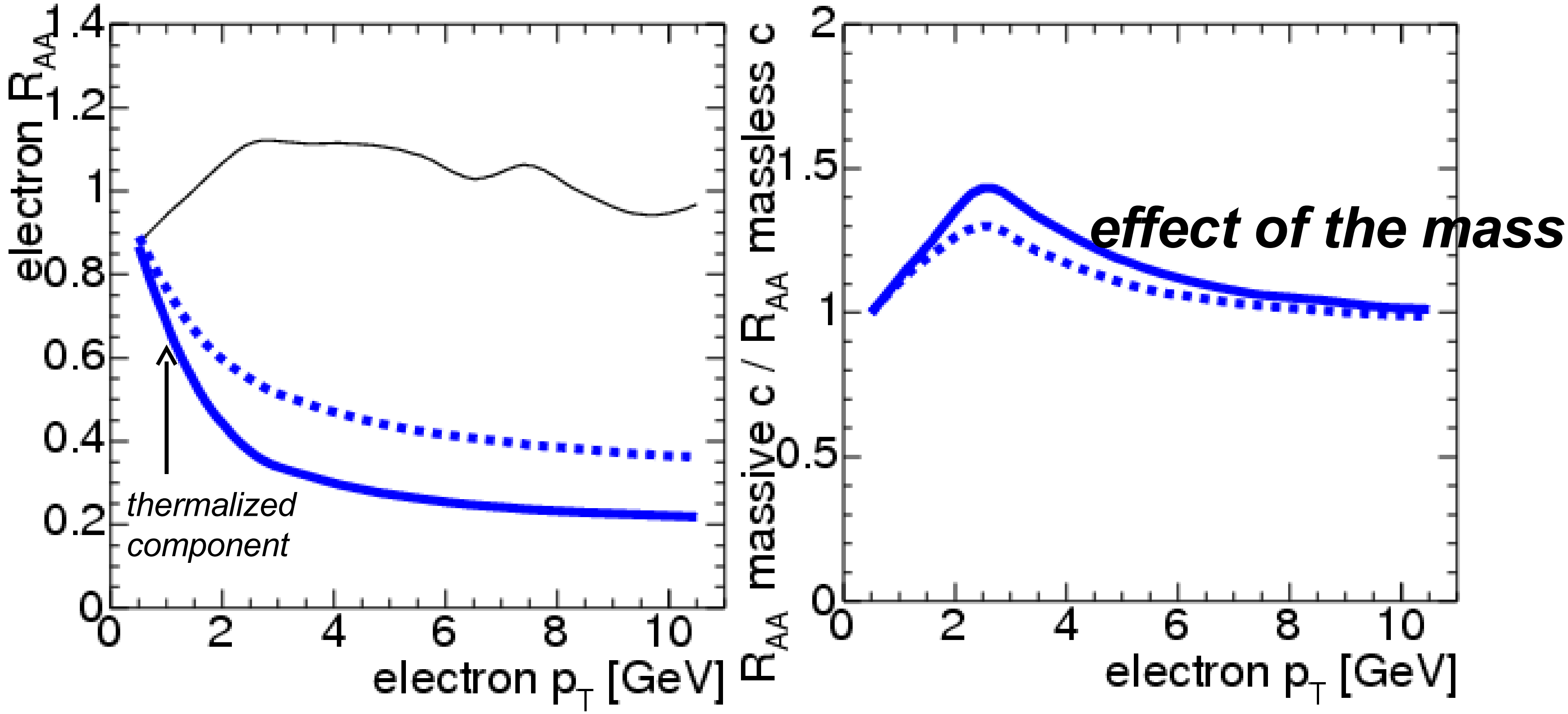
$p_T - \Delta E$

KKP fragmentation

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.

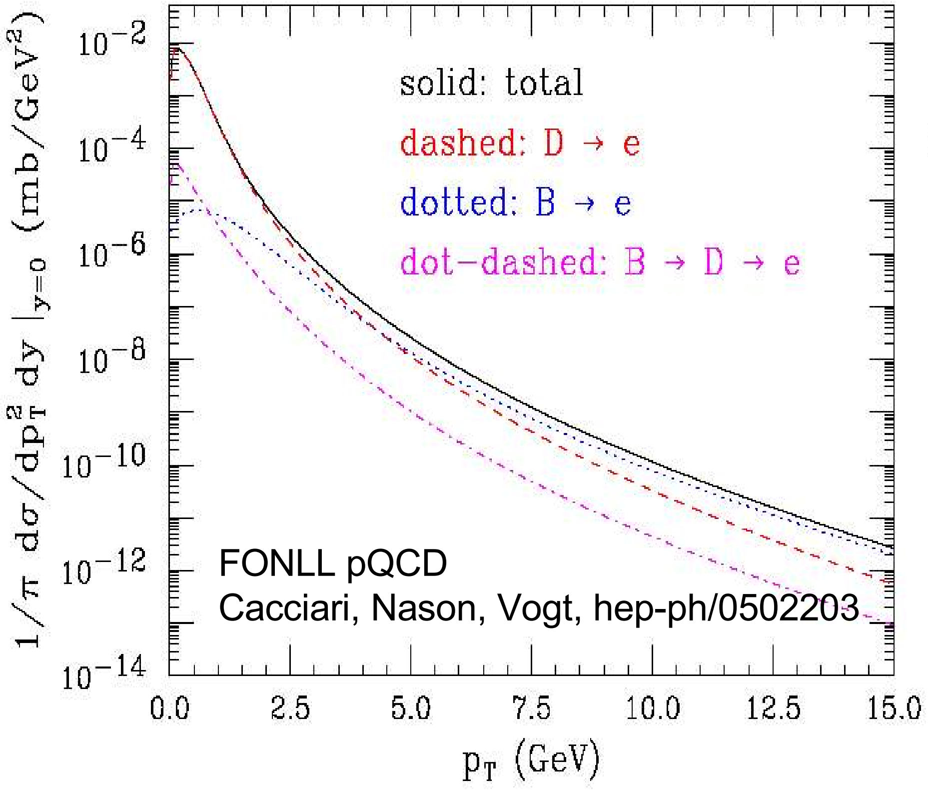
Role of beauty at RHIC?

c + b (?) decay e± R_{AA} at RHIC

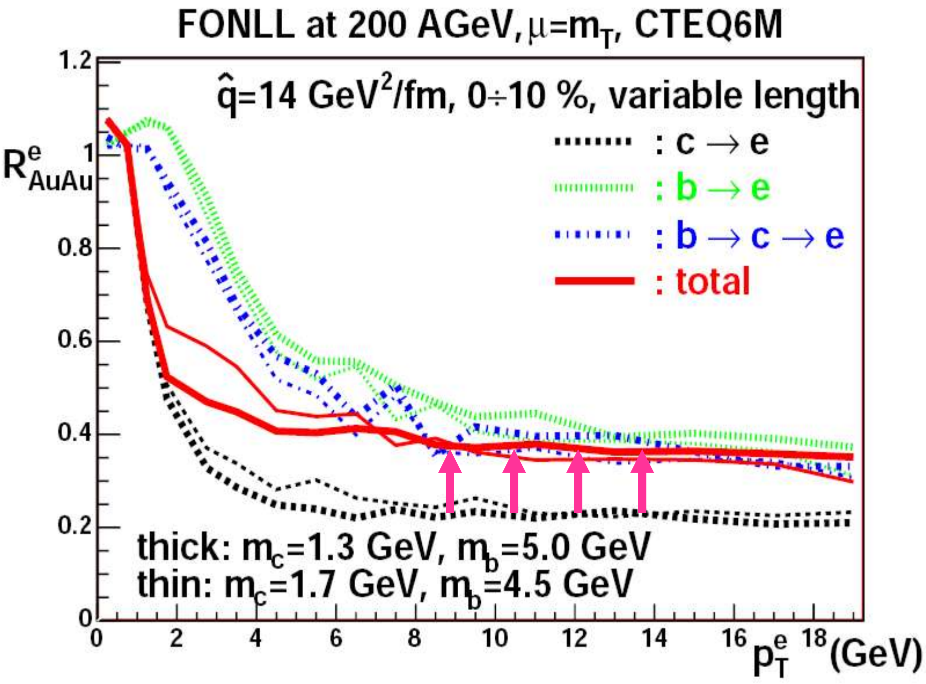
Courtesy by
A.Dainese

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)



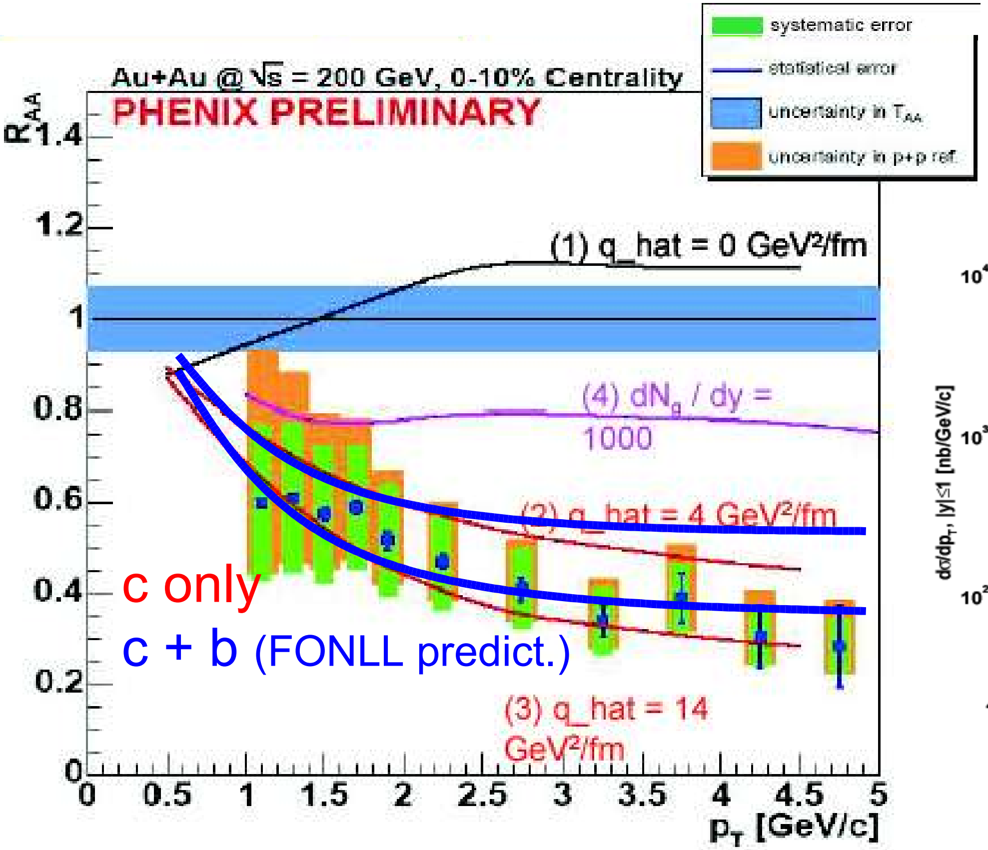
FONLL pQCD
Cacciari, Nason, Vogt, hep-ph/0502203



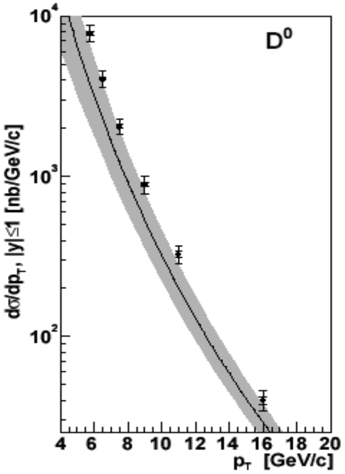
Armesto, Cacciari, Dainese, Salgado, Wiedemann,
in preparation,
Armesto @ Quark Matter 05

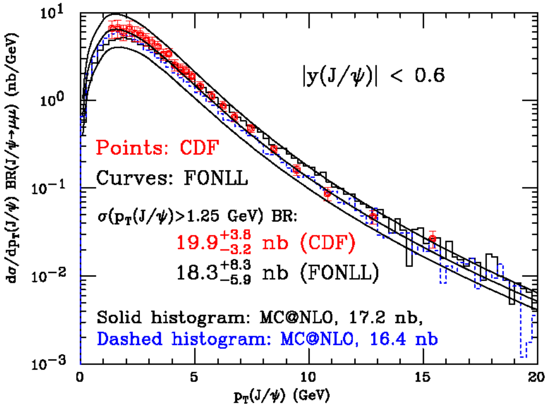
Heavy-flavour data in Au-Au 200 GeV

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