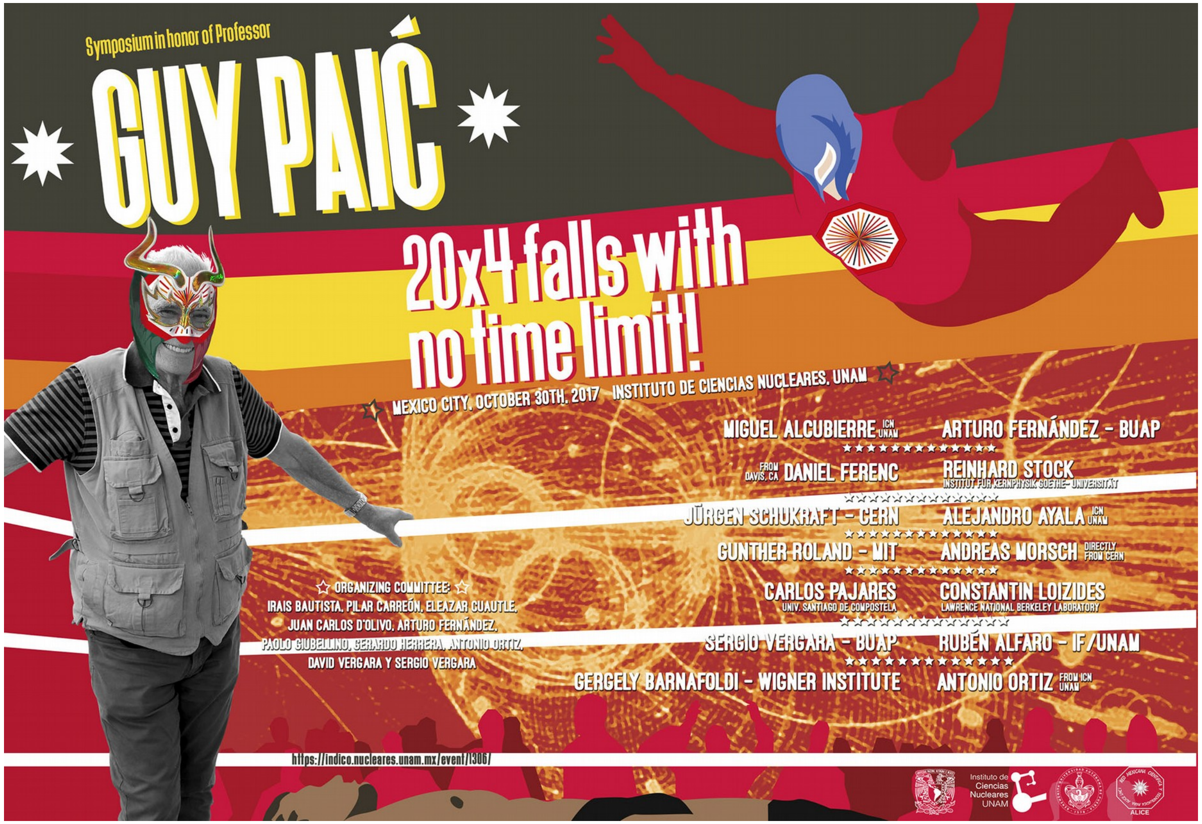

Looking for jet modification with Guy

Symposium in honor of Professor Guy Paic

C.Loizides (ORNL)

30 Oct 2017

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Digital Object Identifier (DOI) 10.1140/epjc/s2004-02077-x

THE EUROPEAN PHYSICAL JOURNAL C

Leading-particle suppression in high energy nucleus–nucleus collisions

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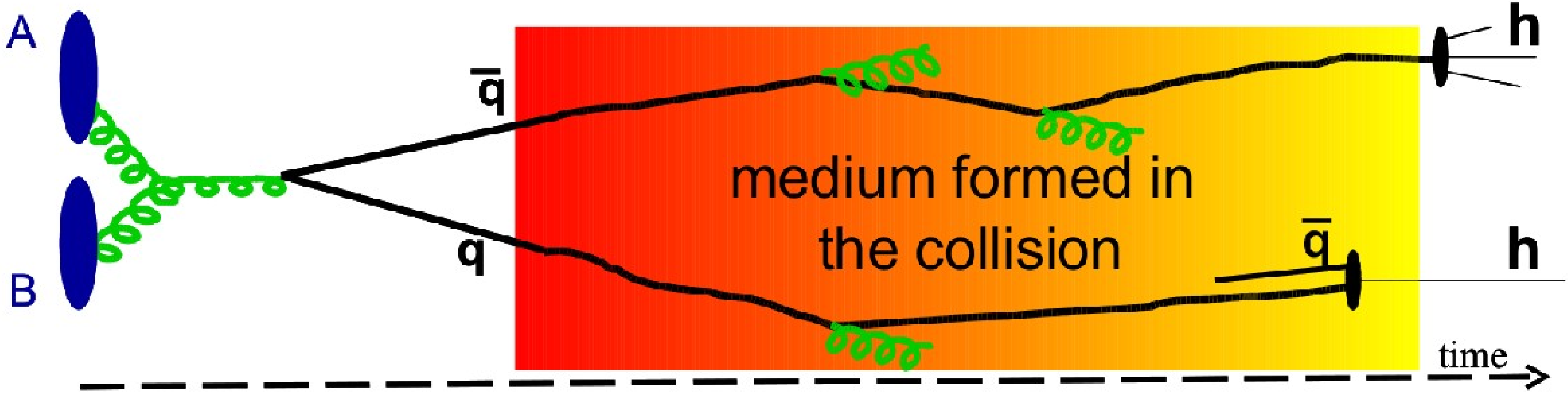
Abstract. Parton energy loss effects in heavy-ion collisions are studied with the Monte Carlo program PQM (Parton Quenching Model) constructed using the BDMPS quenching weights and a realistic collision geometry. The merit of the approach is that it contains only one free parameter that is tuned to the high-p_t nuclear modification factor measured in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Once tuned, the model is consistently applied to all the high-p_t observables at 200 GeV: the centrality evolution of the nuclear modification factor, the suppression of the away-side jet-like correlations, and the azimuthal anisotropies for these observables. Predictions for the leading-particle suppression at nucleon–nucleon centre-of-mass energies of 62.4 and 5500 GeV are presented. The limits of the eikonal approximation in the BDMPS approach, when applied to finite-energy partons, are discussed.

3 Leading particle production in AA collisions



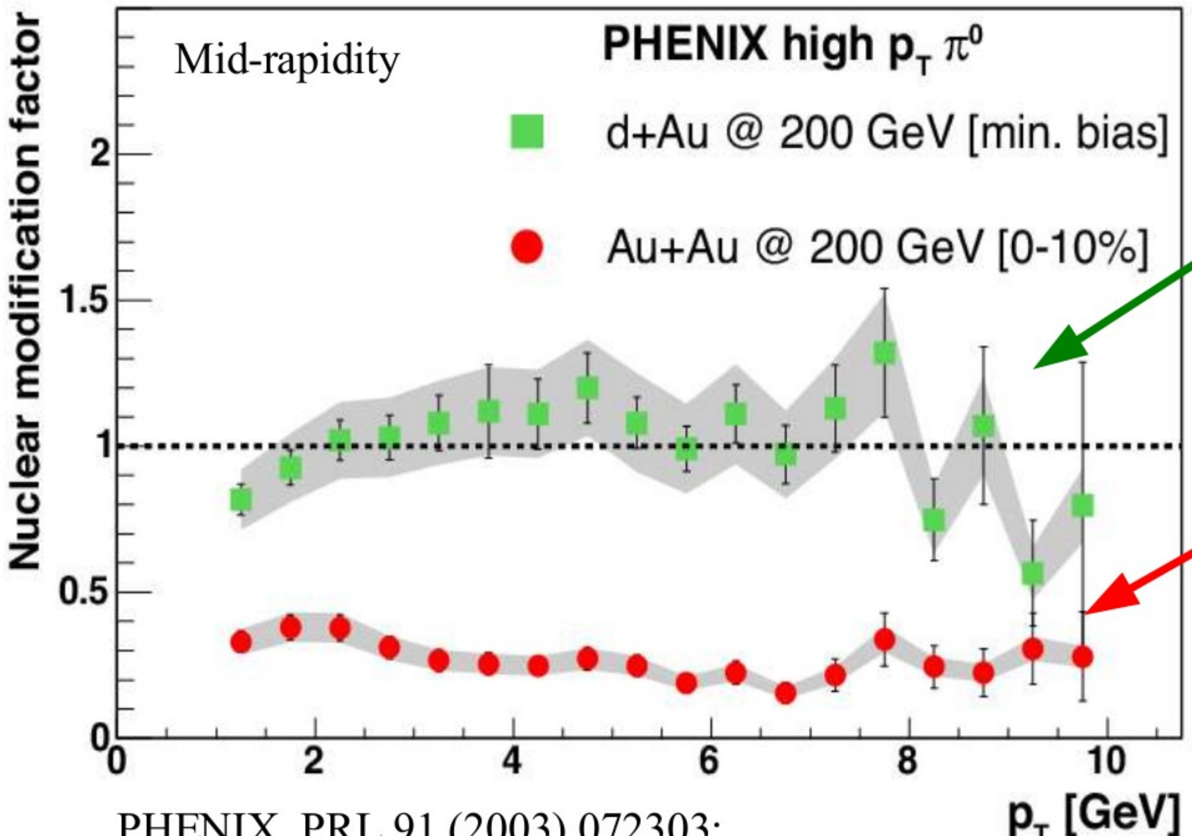
- Large virtuality Q leads to
  small “formation time” $\Delta t \sim 1/Q$ and small α_s
- Initial yields and p_T distributions in A+B are predicted by pp measurements + pQCD + collision geometry (Glauber) + additional “known” nuclear (initial state) effects (e.g. nPDFs)
- Observed deviations are attributed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

Leading particle suppression ~2003

Comparison of p_T distributions at high p_T measured in pp, dAu and AA (for different centralities)

Quantification via the Nuclear Modification Factor

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



PHENIX, PRL 91 (2003) 072303;
STAR, PRL 91 (2003) 072304;
many more (see eg. RHIC white papers).

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

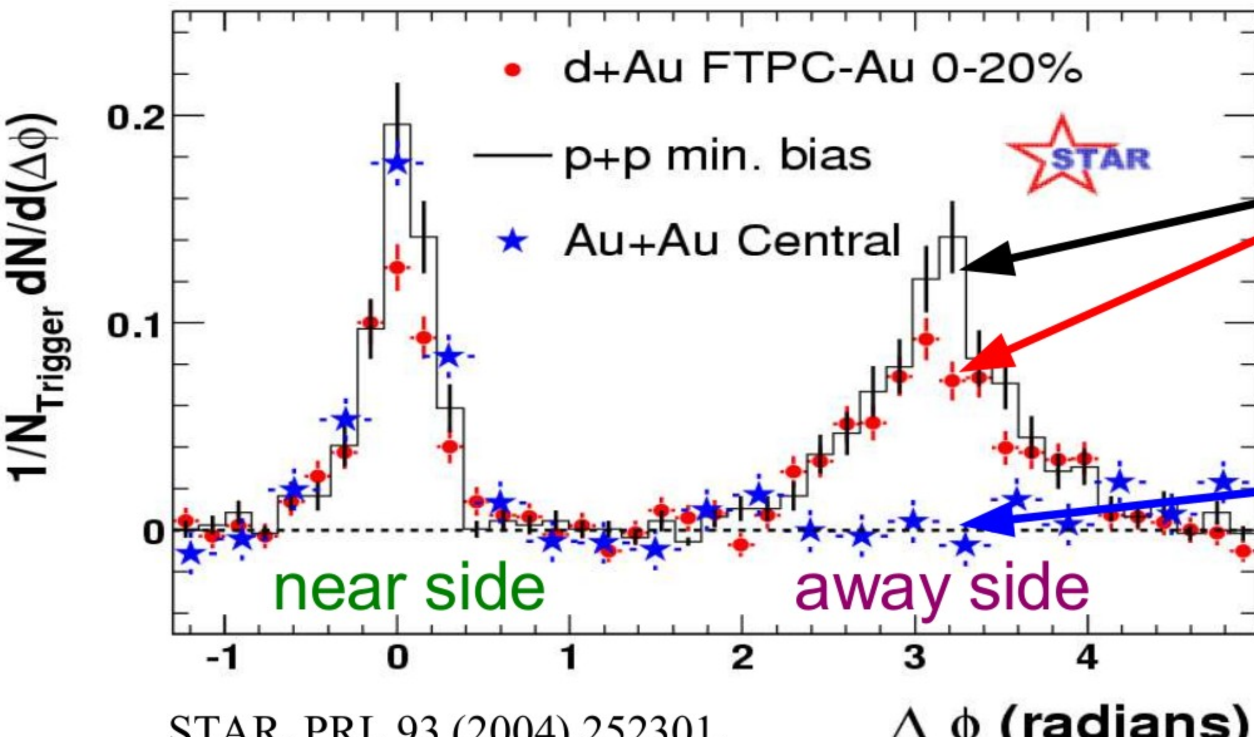
Suppression of away-side ~2003

Comparison of azimuthal distributions rel. to high p_T trigger particle measured in pp, dAu and AA (for different centralities)

- Trigger: highest p_T track with p_T>4 GeV
- Associated particles: 2 GeV < p_T < $p_T^{trigger}$

Away-side suppression quantified via

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



STAR, PRL 93 (2004) 252301.

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

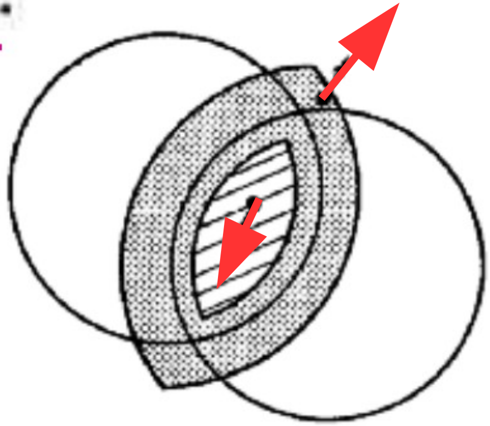
Parton energy loss: Early ideas

- Partons travel a few (~4) fm in the high color-density medium
- Bjorken (`82): energy loss due to elastic (collisional) scattering

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma.

...

An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



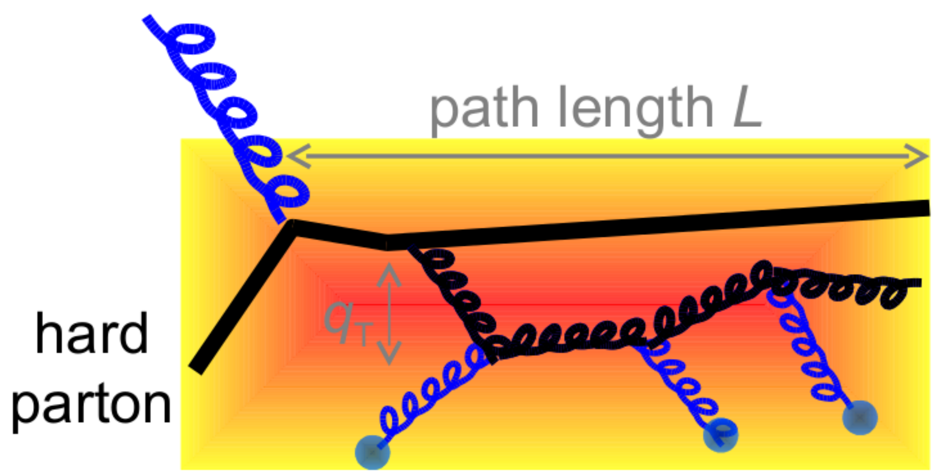
Bjorken, FERMILAB-Pub-82/59-THY (1982).

Parton energy loss from pQCD

- Successive calculations (`92++) revealed that medium-induced gluon radiation (QCD bremsstrahlung) dominates:

$$\omega \frac{dI}{d\omega\, dk} = \alpha_S C_R / \omega^2 \, F\left(\eta(\xi)\sigma(r)\right) \quad \begin{cases} \frac{1}{2}\hat{q}(\xi) r & \text{(BDMPS)} \\ \left(n(\xi)\sigma(r)\right)^N & \text{(opacity expansion)} \end{cases}$$

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, ...

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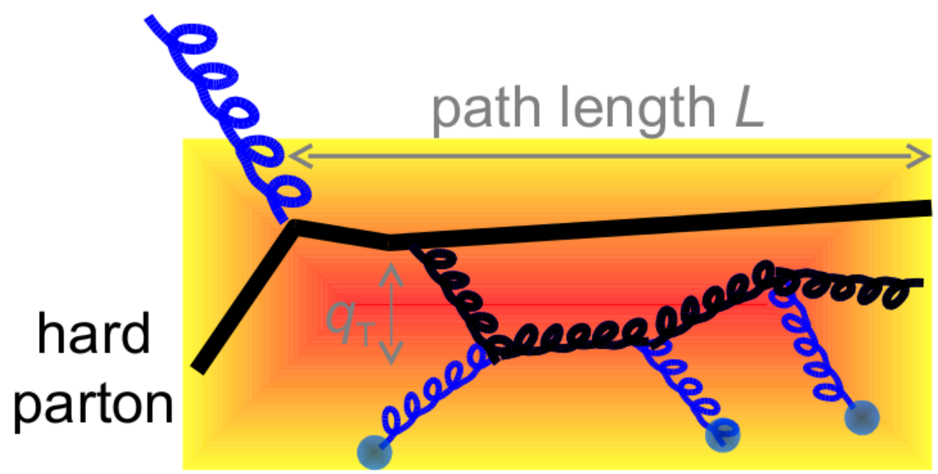
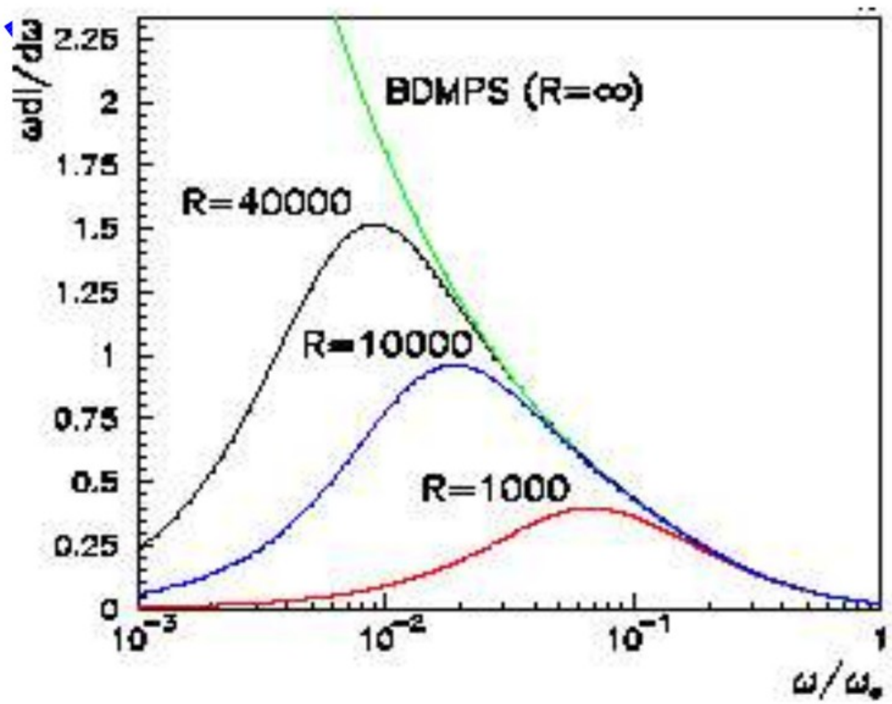


Transport coefficient

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

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

BDMPS-Z radiated energy spectrum



STATIC MEDIUM

BDMPS-Z formalism

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

Radiated-gluon energy distrib.:

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

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.

Average energy loss in BDMPS-Z

Average energy loss (in eikonal limit)

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

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

(gluons volume-density and interaction cross section)

Probe the medium

Average energy loss in BDMPS-Z

Average energy loss (in eikonal limit)

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

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(gluons volume-density and interaction cross section)

Probe the medium

Finite parton energy (qualitatively)

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

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

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

12 Calculating leading particle spectra

Factorized pQCD + final state quenching + vacuum fragmentation

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

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

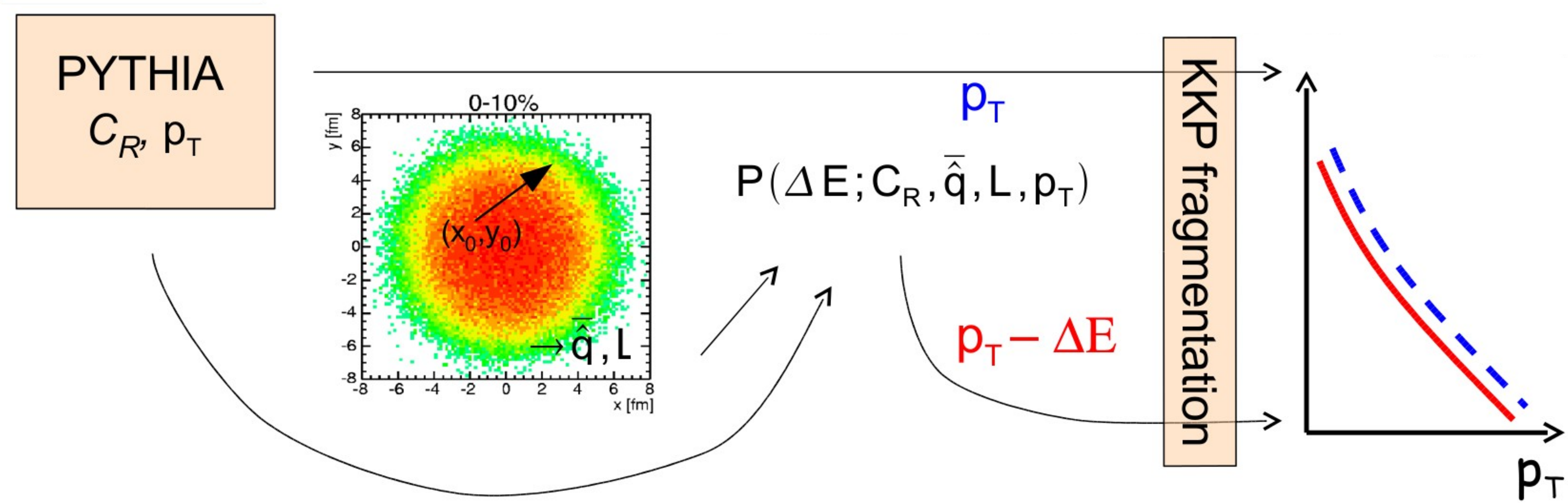
13 Calculating leading particle spectra

Factorized pQCD + final state quenching + vacuum fragmentation

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

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

Monte Carlo approach:



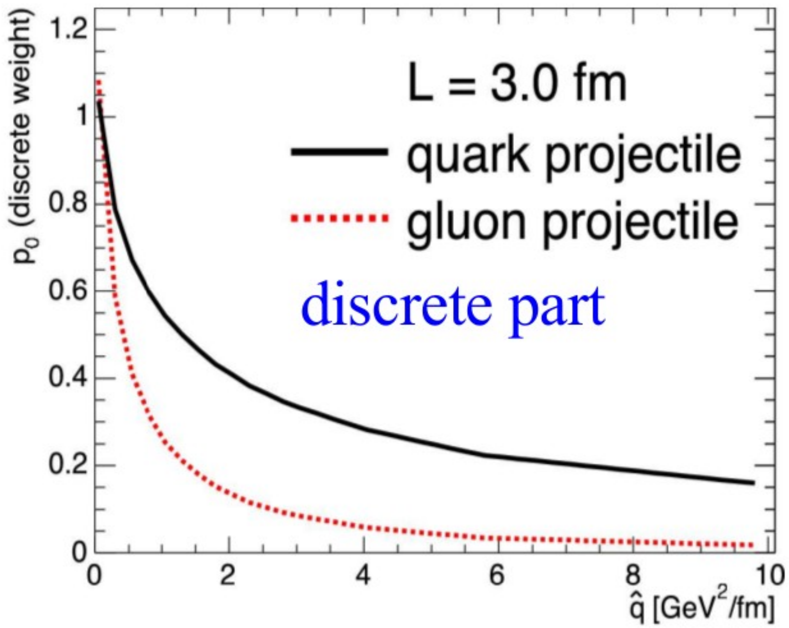
14 Quenching weights

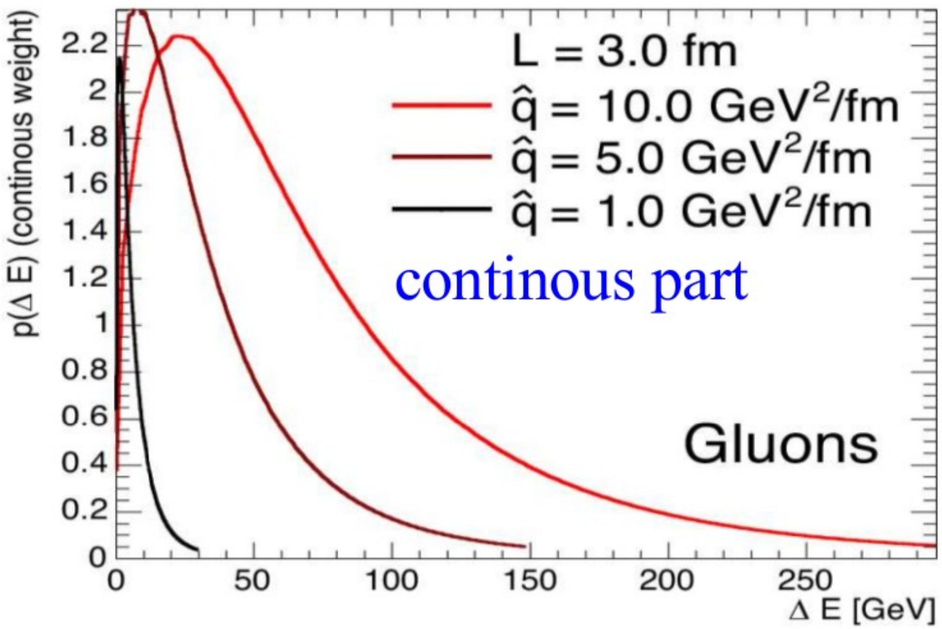
- Compute energy loss probability distributions

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

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

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





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

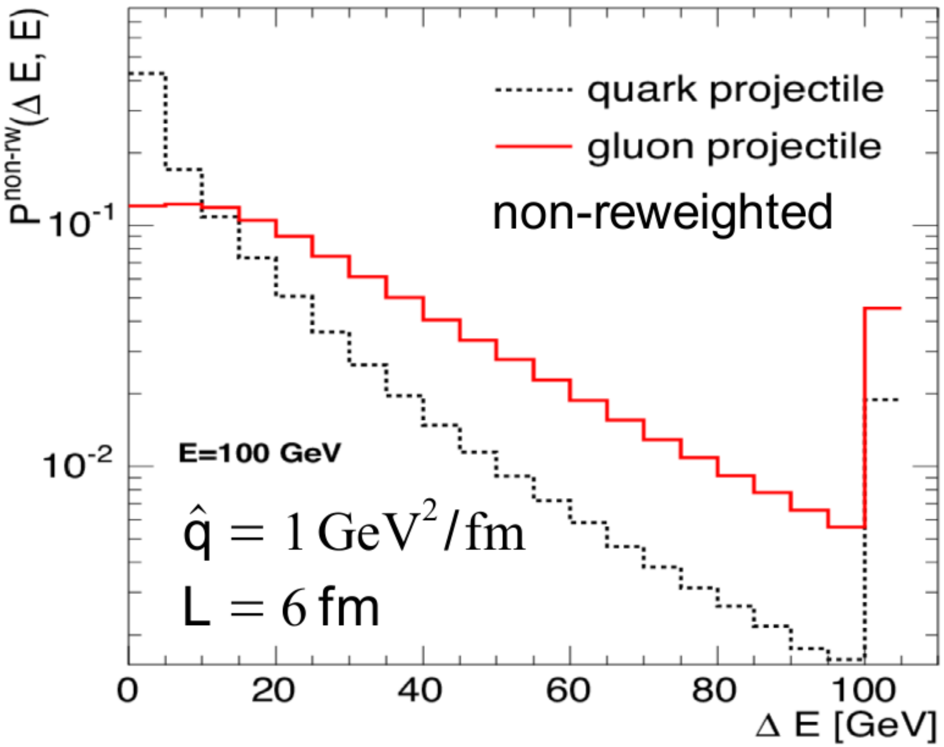
Constrained weights

15 Constrained quenching weights

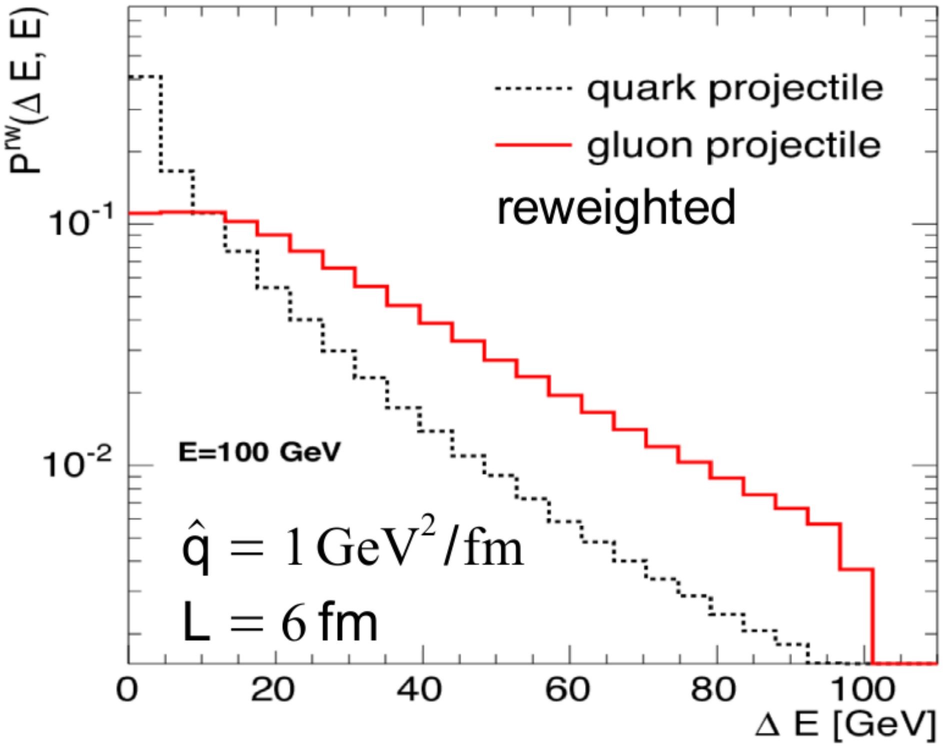
Construct constrained weights from quenching weights

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

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

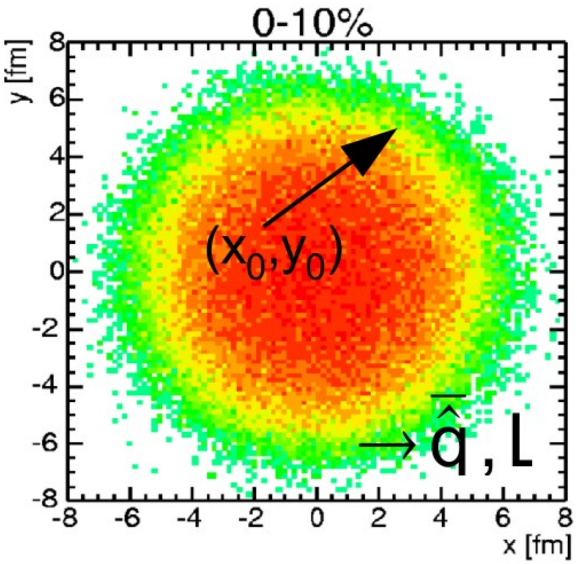


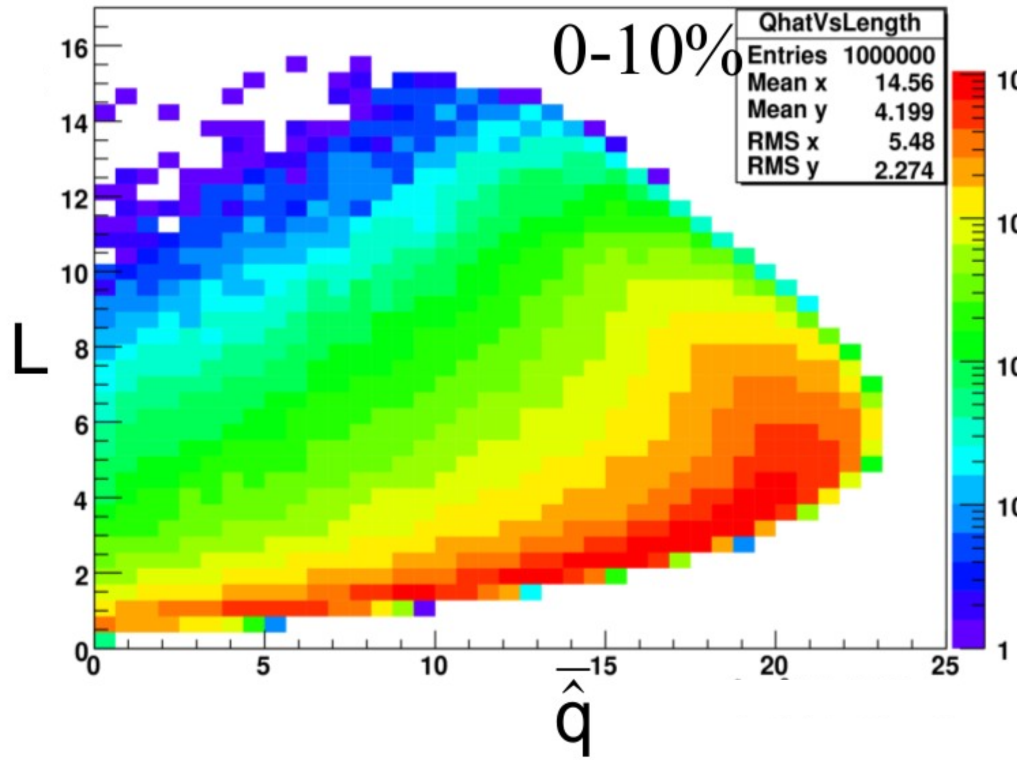
b) reweighted weight
(truncate + renormalize at ΔE=E)



Two ways to construct constrained weights treated as systematic uncertainty on final results (later abandoned reweighted approach as it is non-physical)

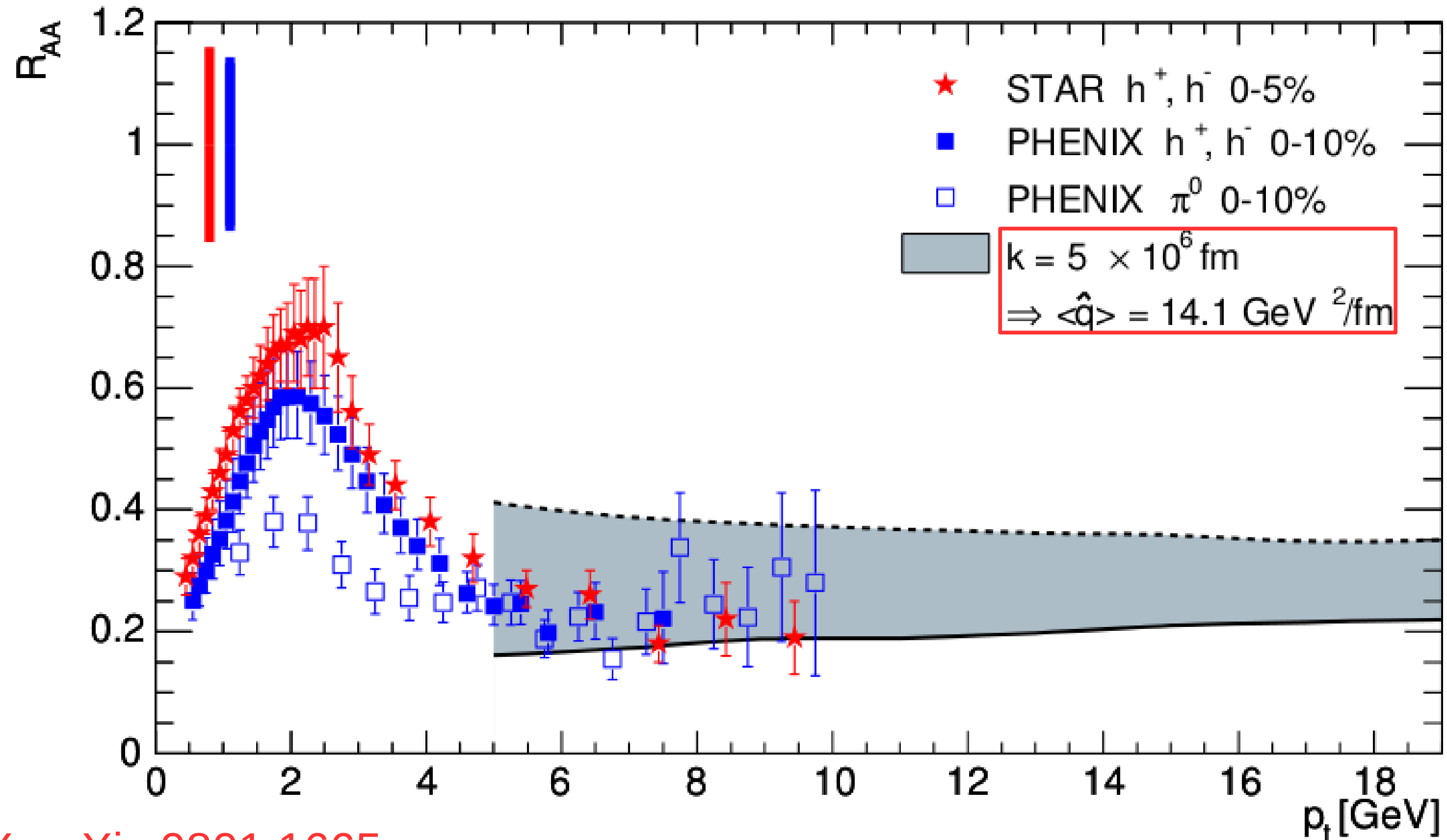
16 Geometry



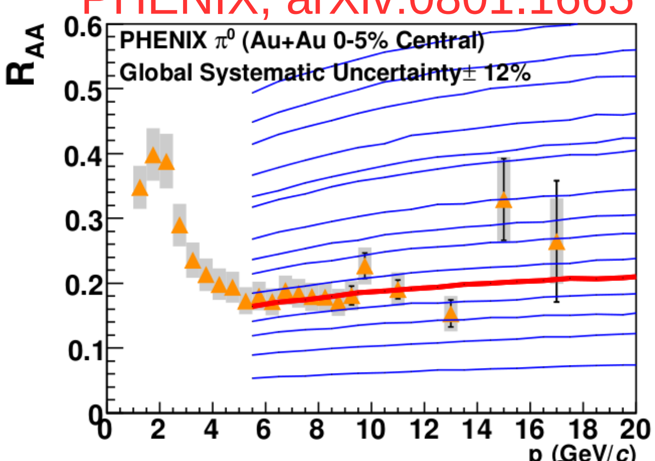


- Optical Glauber with Wood-Saxon density distribution
- Parton production in transverse plane according to $\rho_{\mathrm{coll}} \propto T_A T_B$
  - Determine (x_0, y_0) and uniform emission direction φ_0
- Matter density according to $\rho \propto k T_A T_B(x_0 + \xi\cos\phi_0, y_0 + \xi\sin\phi_0)$
- Calculate parton-by-parton $I_i = \int \mathrm{d}\xi\, \rho(\xi)\xi^i$
  - Obtain $L = 2I_1/I_0$ and $\hat{q} = 0.5 I_0^2/I_1$

17 Result for central Au+Au collisions



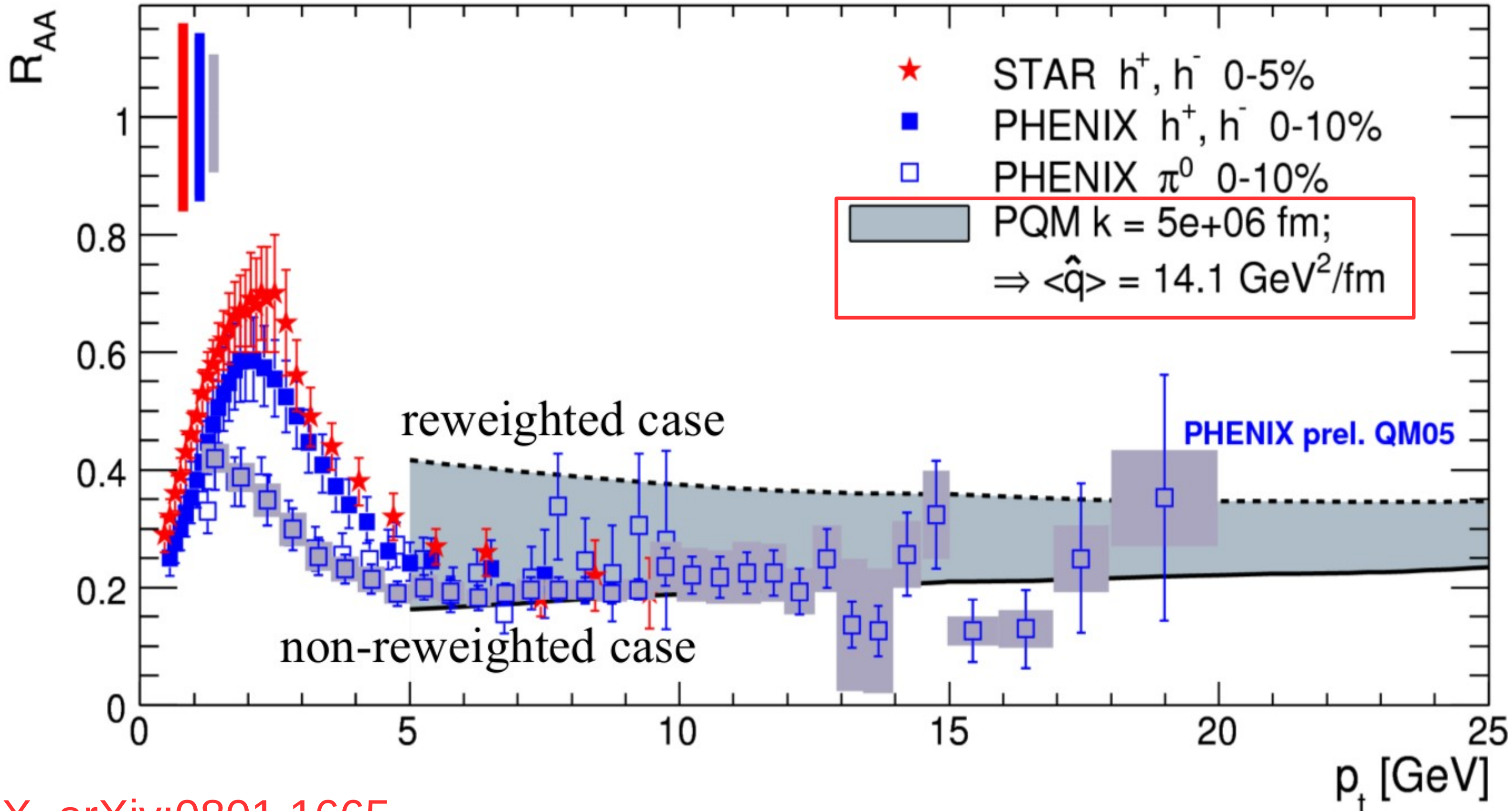
PHENIX, arXiv:0801.1665



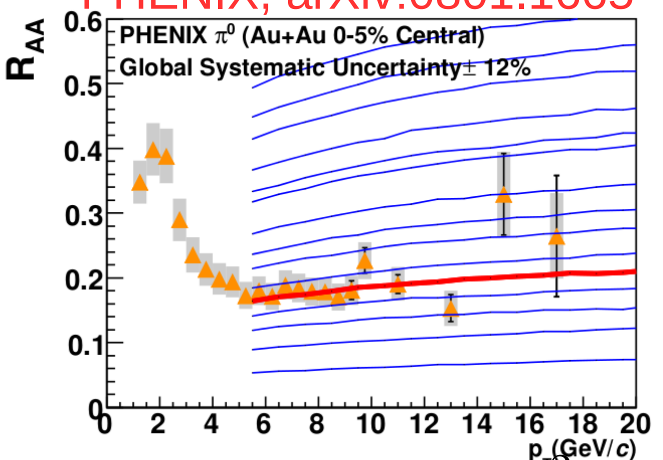
$$\langle \hat{q} \rangle = 13.2 \pm 2.7\,\mathrm{GeV}^2/\mathrm{fm}$$

- Large values for transport coefficient
  - Few times larger than expected from pQCD
- However, similar scale as first
  - AdS/CFT calculation: PRL 97 (2006) 182301
  - Lattice QCD calculations: PRL 112 (2014) 162001

18 Result for central Au+Au collisions



PHENIX, arXiv:0801.1665



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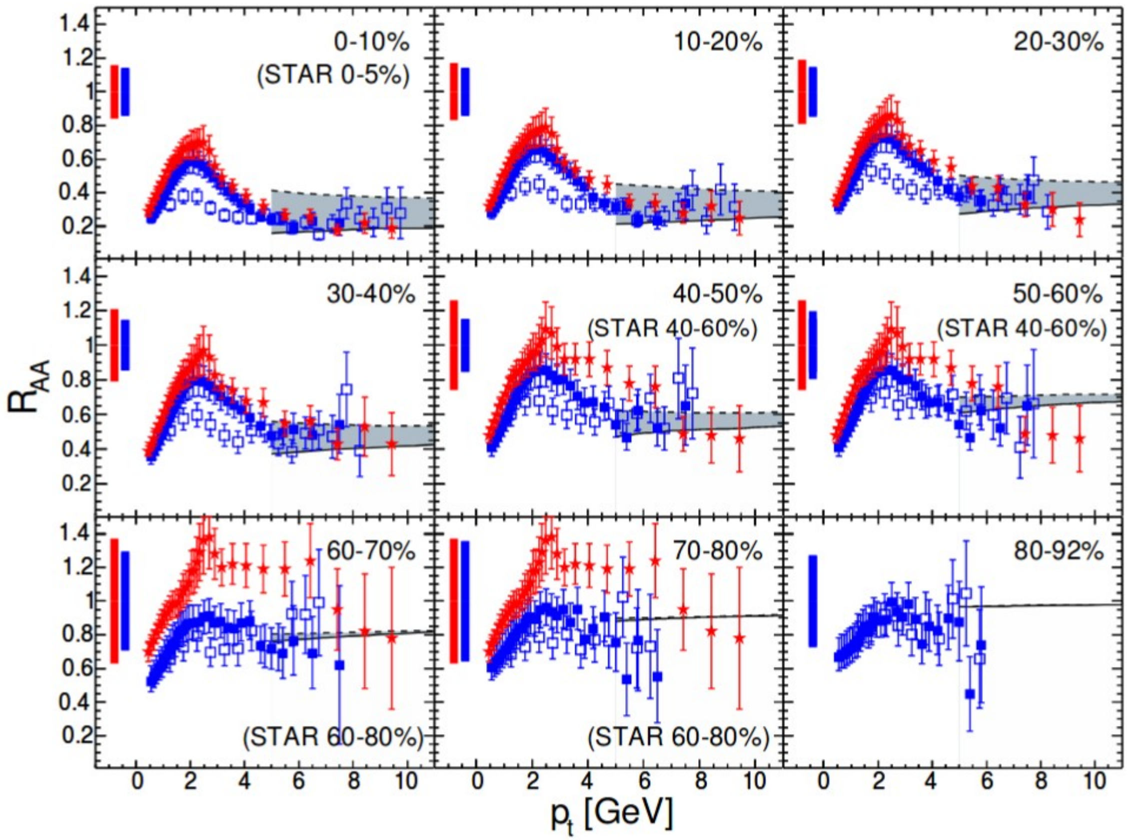
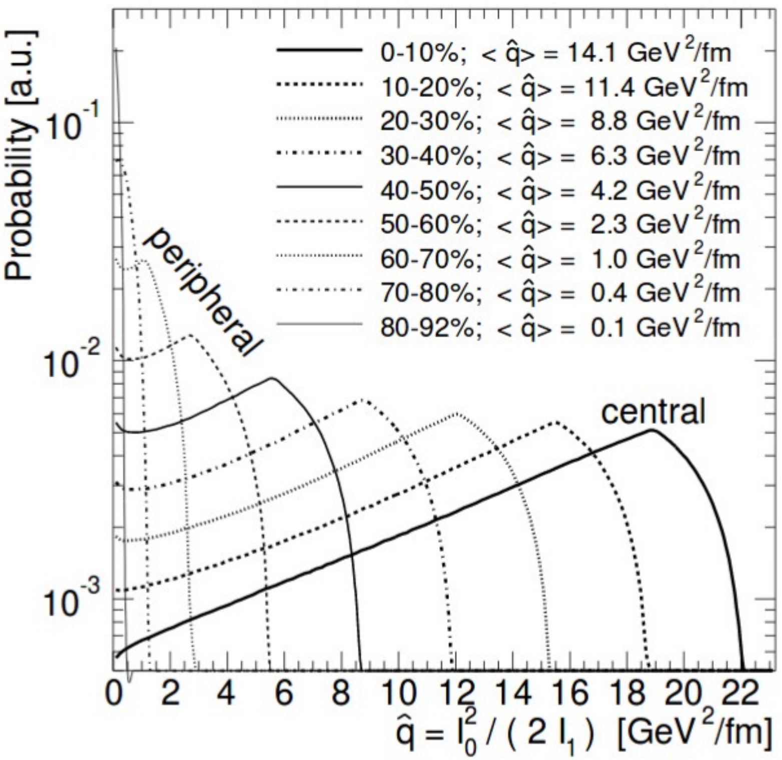
19 Centrality evolution

$$\rho(b) \propto k^{\mathrm{Au+Au}}_{\mathrm{central}} T_A T_B(b)$$

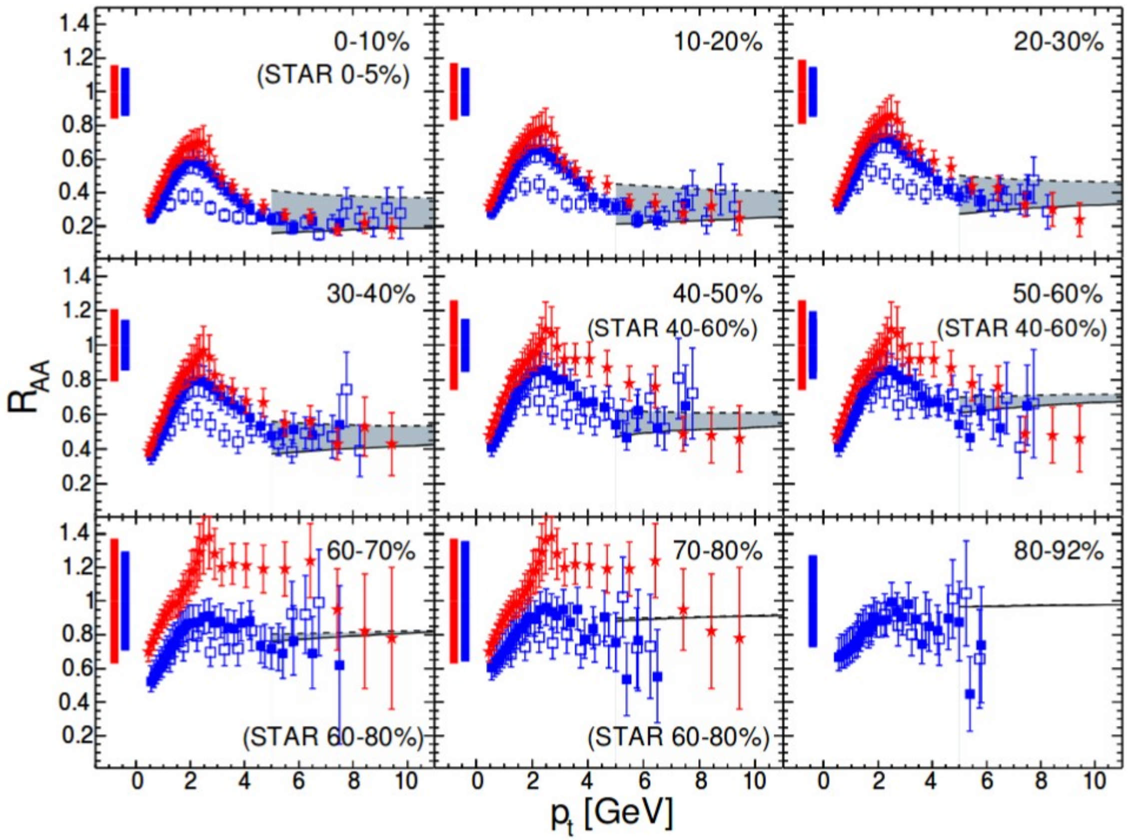


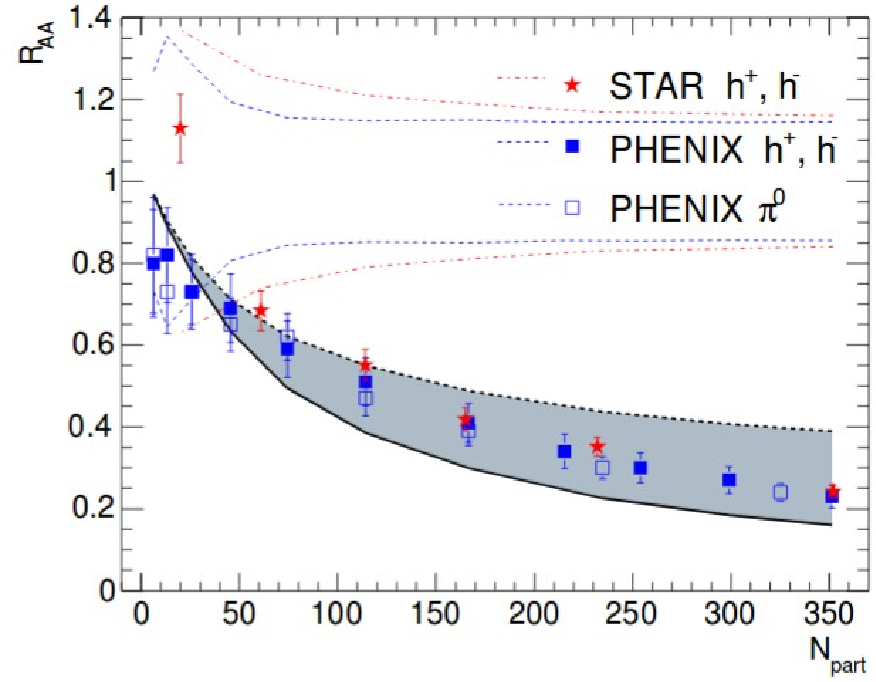


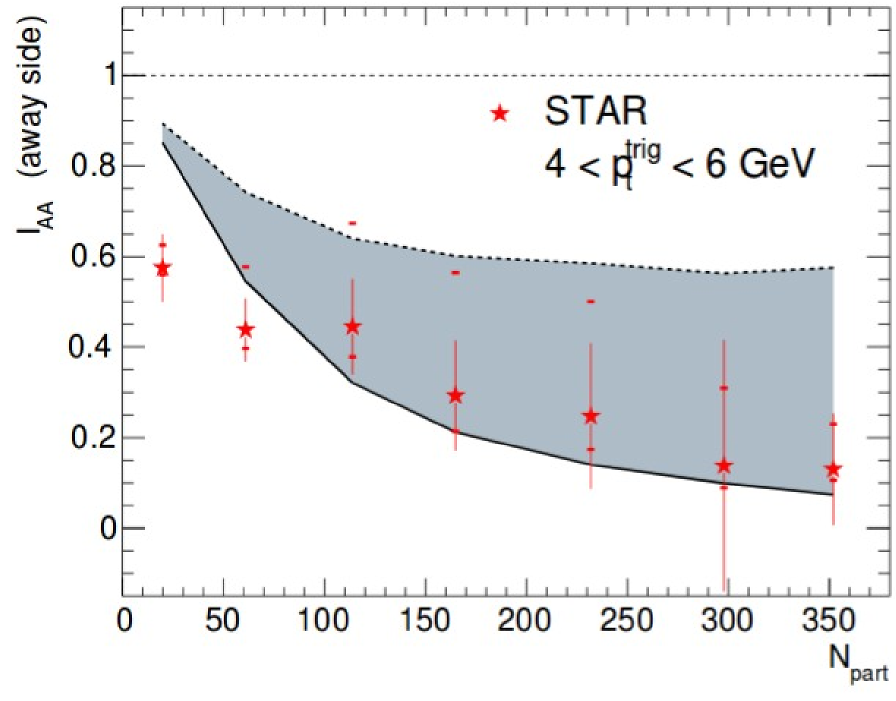
Very good description of centrality dependent suppression observables

Centrality evolution

$$\rho(b) \propto k^{\mathrm{Au+Au}}_{\mathrm{central}} T_A T_B(b)$$



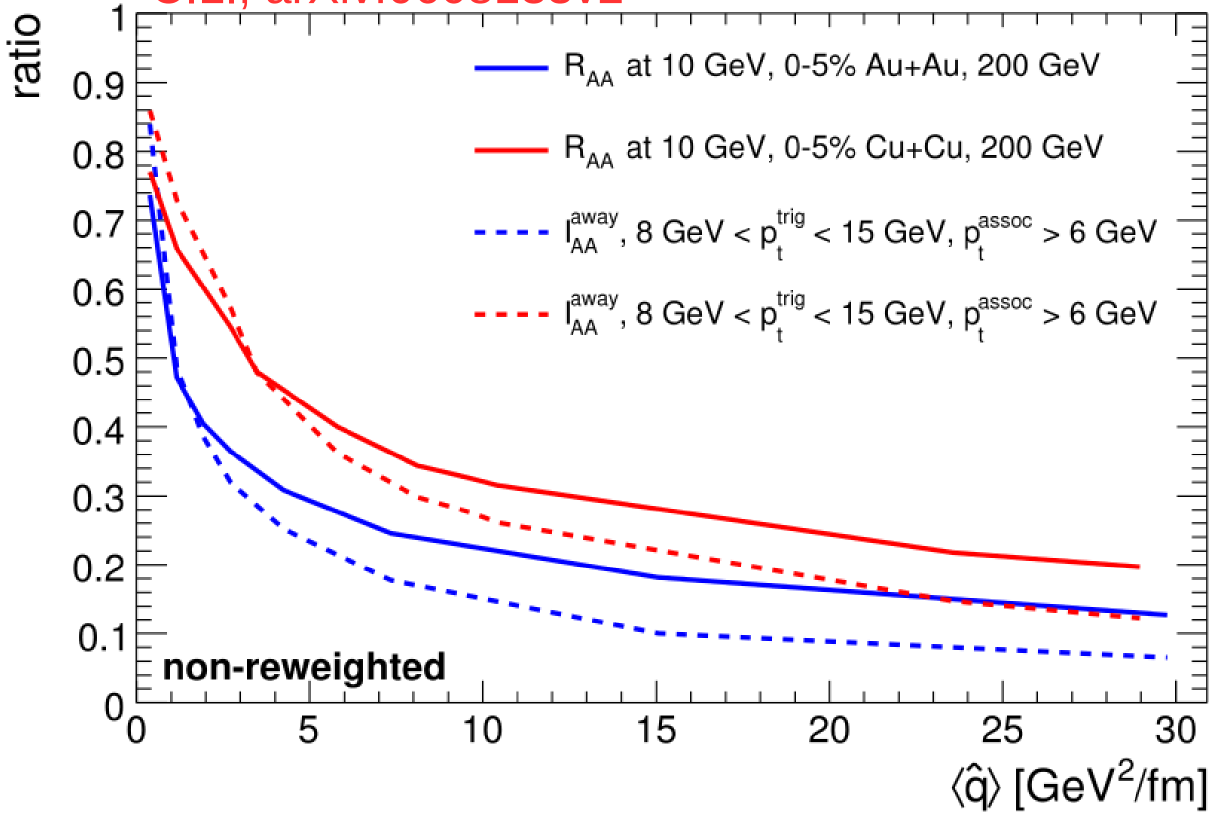


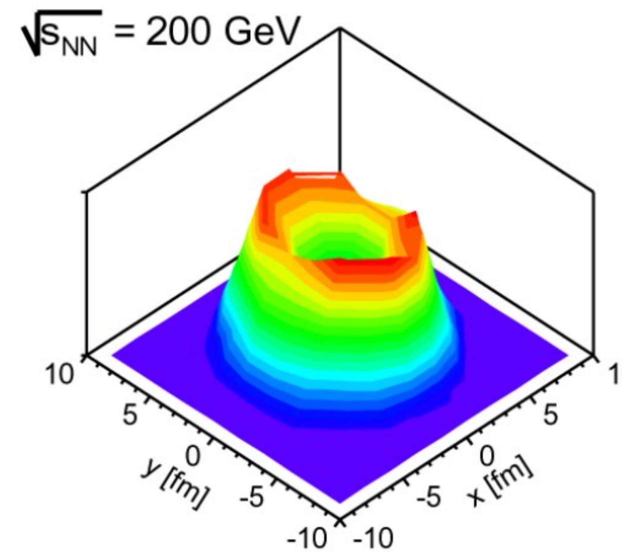


Very good description of centrality dependent suppression observables

21 Surface emission and trigger bias

C.L., arXiv:0608133v2

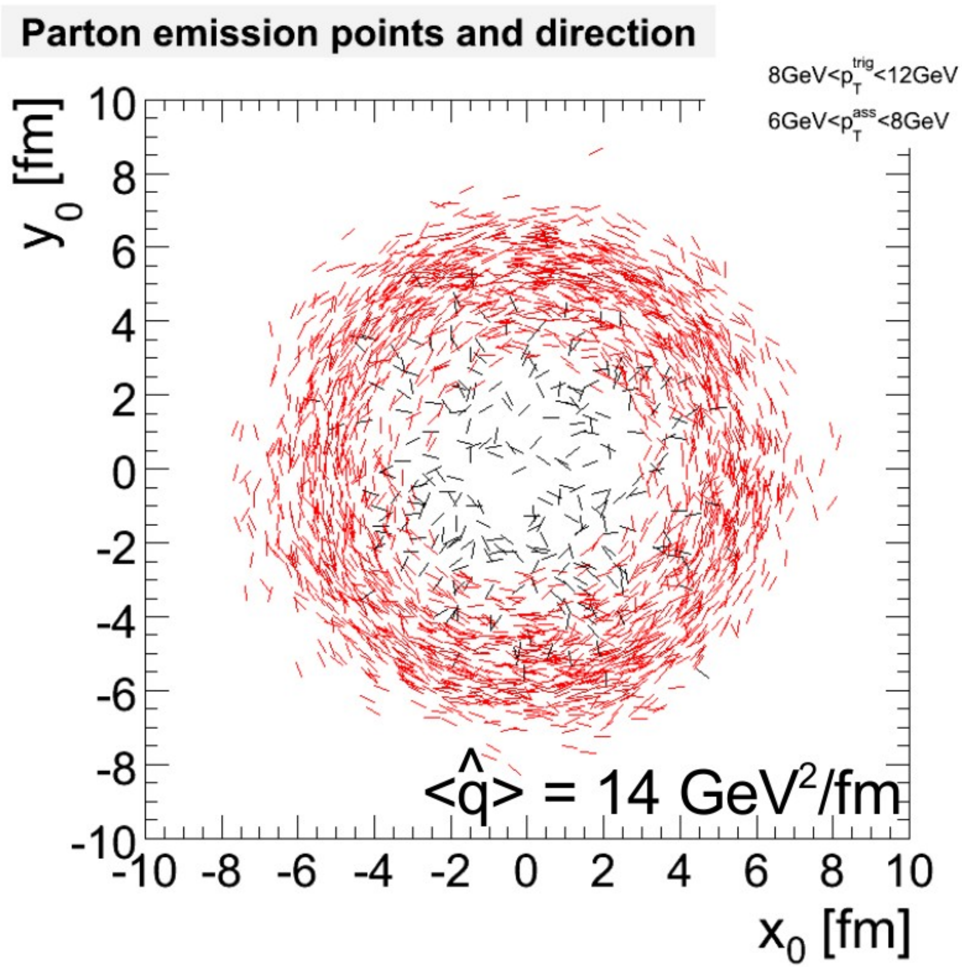


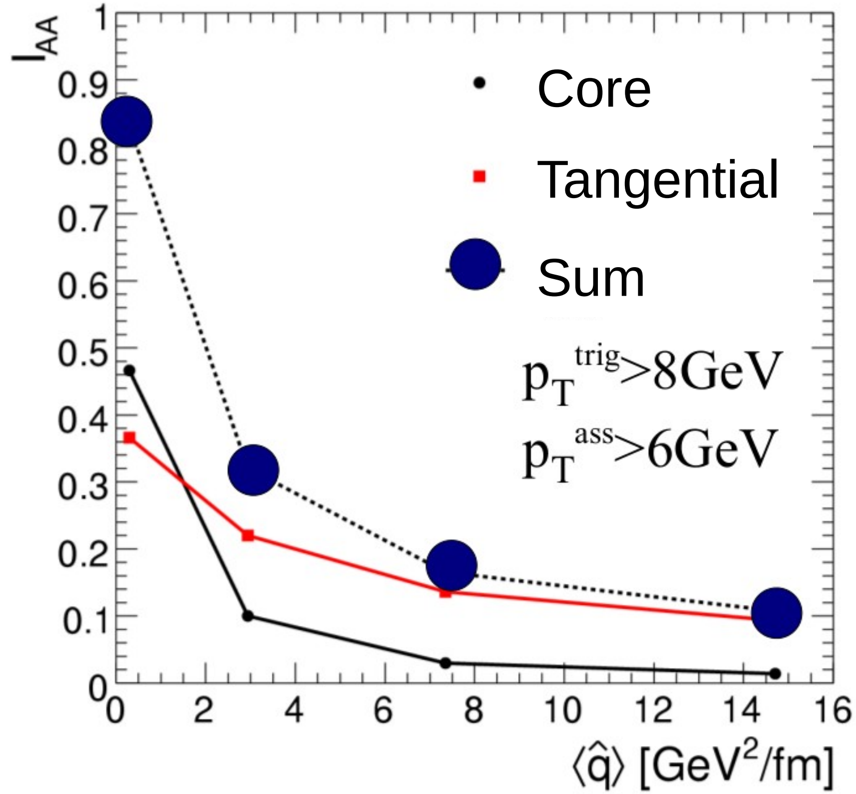


- Strong observed suppression implies large densities
- Opaque medium leeds to strong trigger biases
- R_{AA} and I_{AA} pre-dominantly determined by geometry

Müller, PRC67 (2003) 061901.
Drees, Feng, Jia, PRC 71 (2005).
Escola, Honkanen, Salgado, Wiedemann, NPA747 (2005) 511.

22 Tangential emission





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

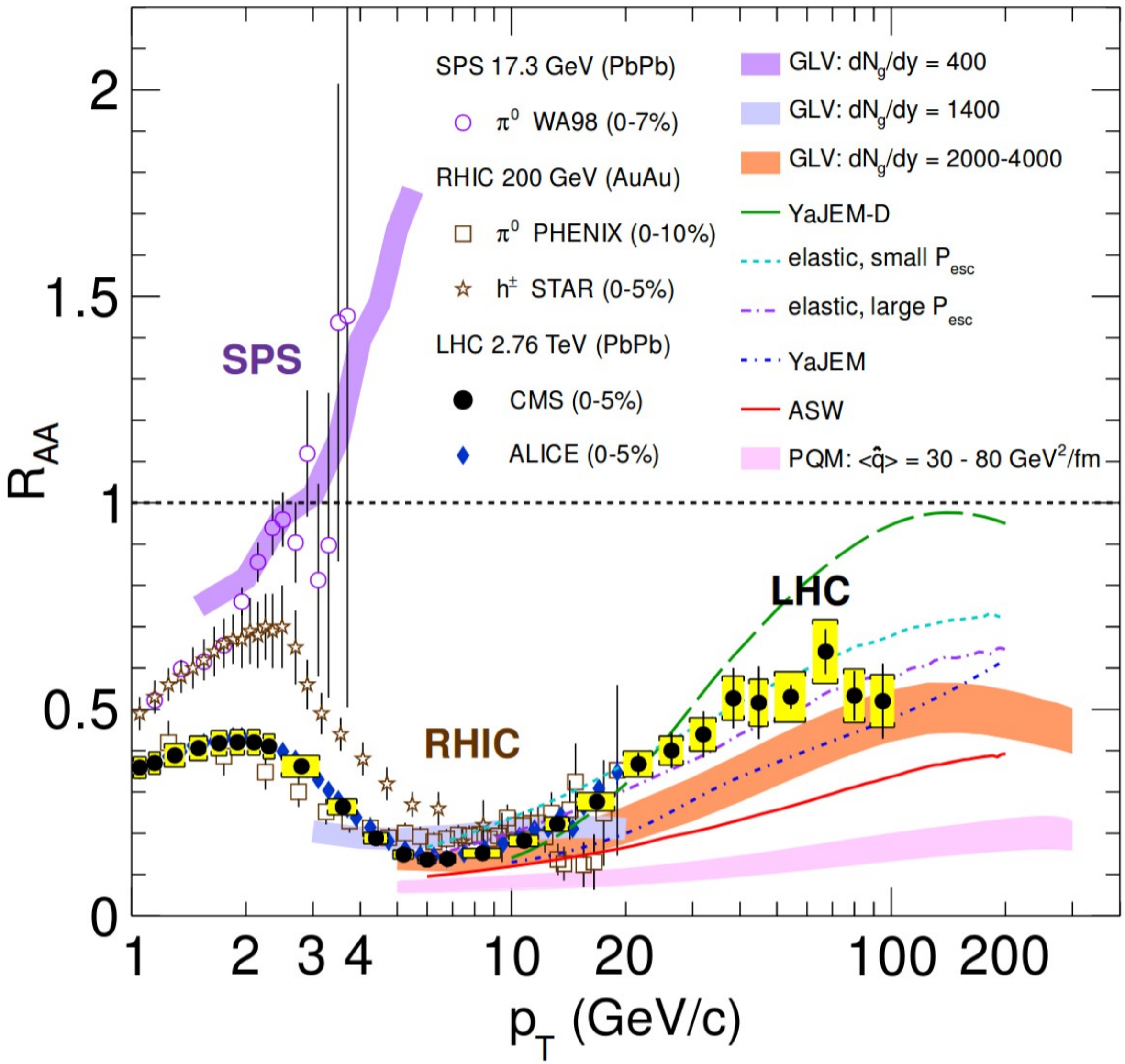
Large medium density biases dijets towards edges of surface ("tangential emission")

(highly debated in the literature, but qualitatively the effect is there)

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

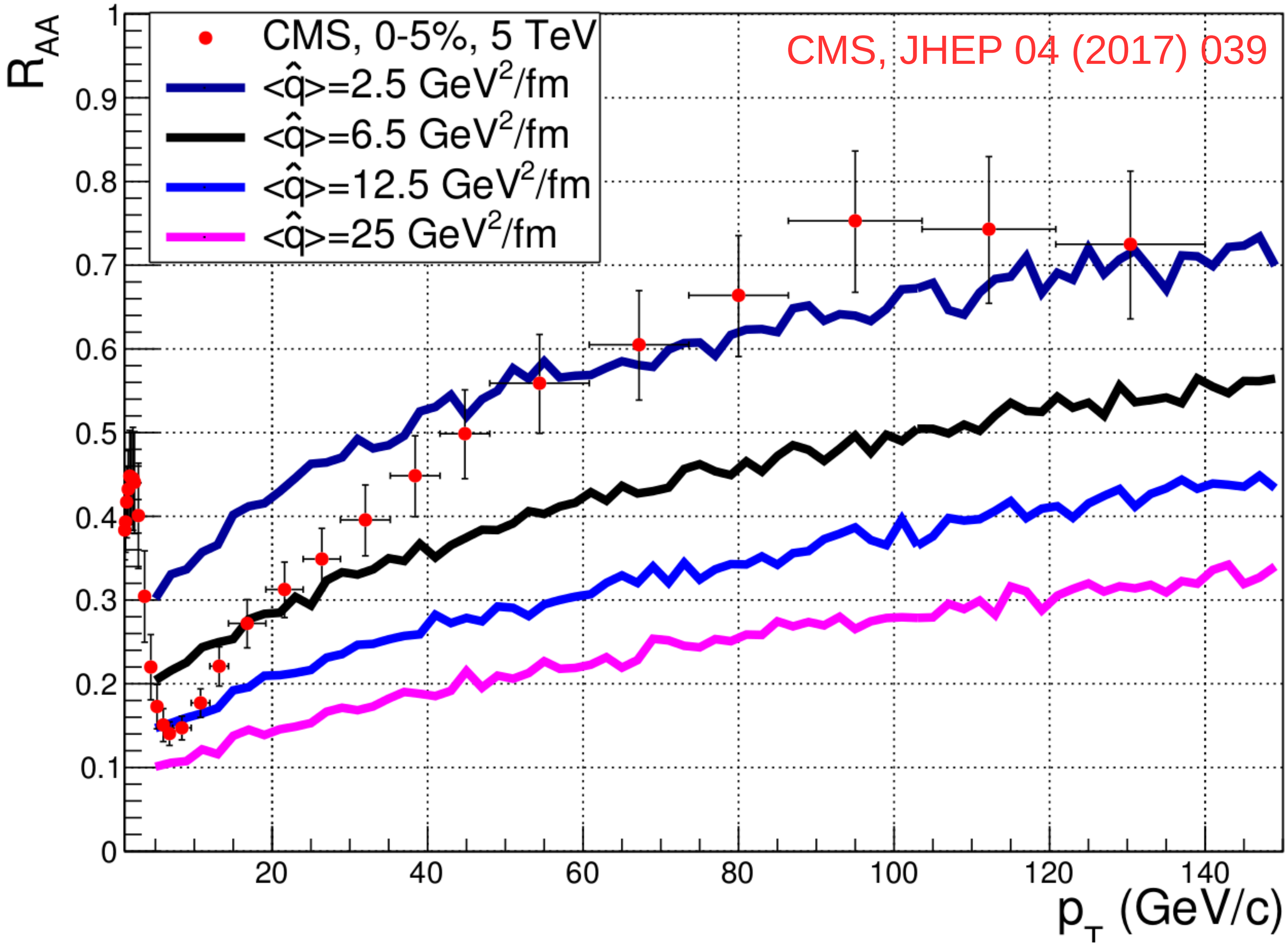
Comparison with LHC R_{AA} (predictions)

EPJC 72 (2012) 1945



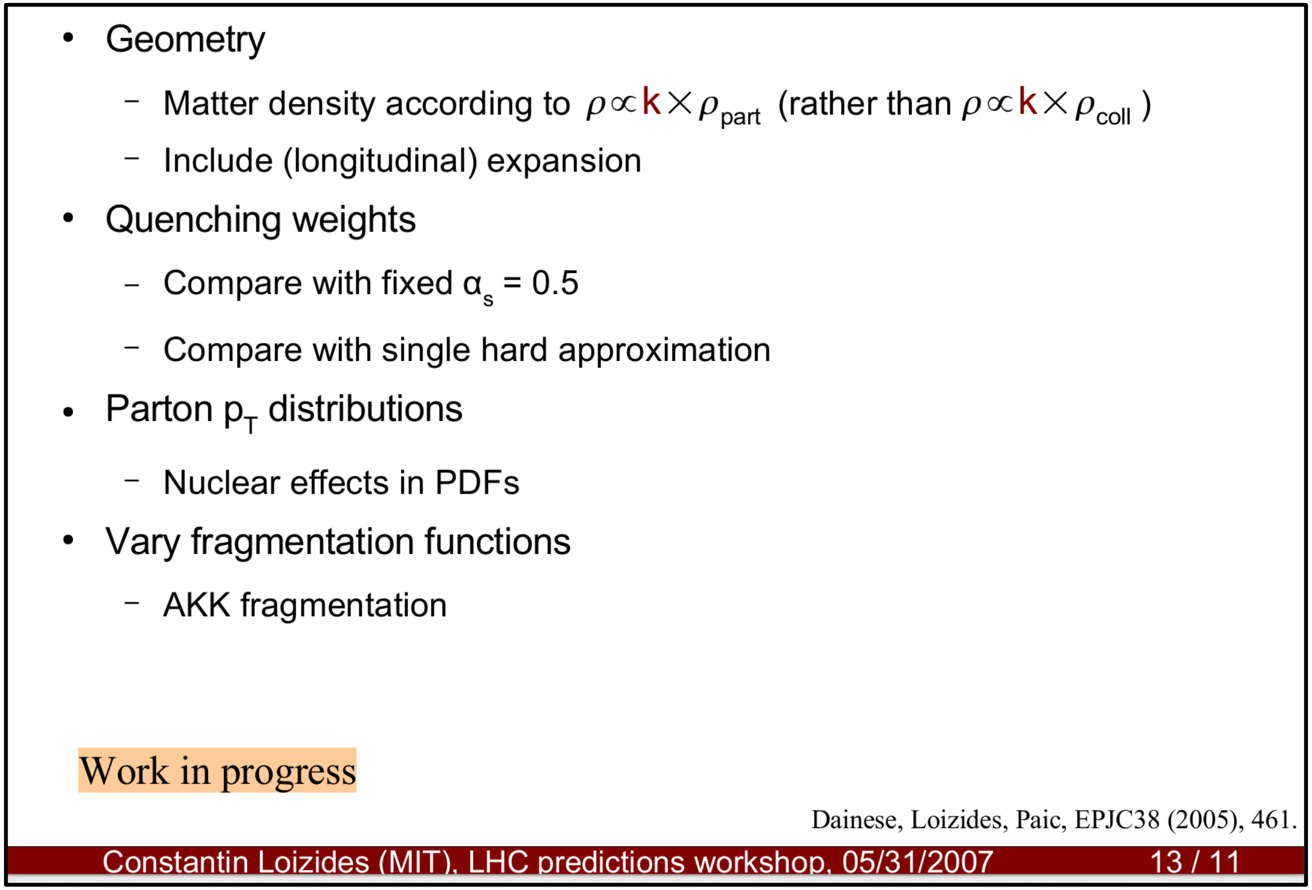
All (RHIC) models have difficulties with the apparent transparency at LHC
(In part due to the much smaller increase in multiplicity than anticipated)

Comparison with LHC R_{AA} (PQM)



LHC central R_{AA} indicate surprisingly low value for qhat.
However, shape of data and PQM clearly different

25 Further studies



- Geometry
  - Matter density according to $\rho \propto k \times \rho_{\mathrm{part}}$ (rather than $\rho \propto k \times \rho_{\mathrm{coll}}$)
  - Include (longitudinal) expansion
- Quenching weights
  - Compare with fixed $\alpha_s = 0.5$
  - Compare with single hard approximation
- Parton p_T distributions
  - Nuclear effects in PDFs
- Vary fragmentation functions
  - AKK fragmentation

Work in progress

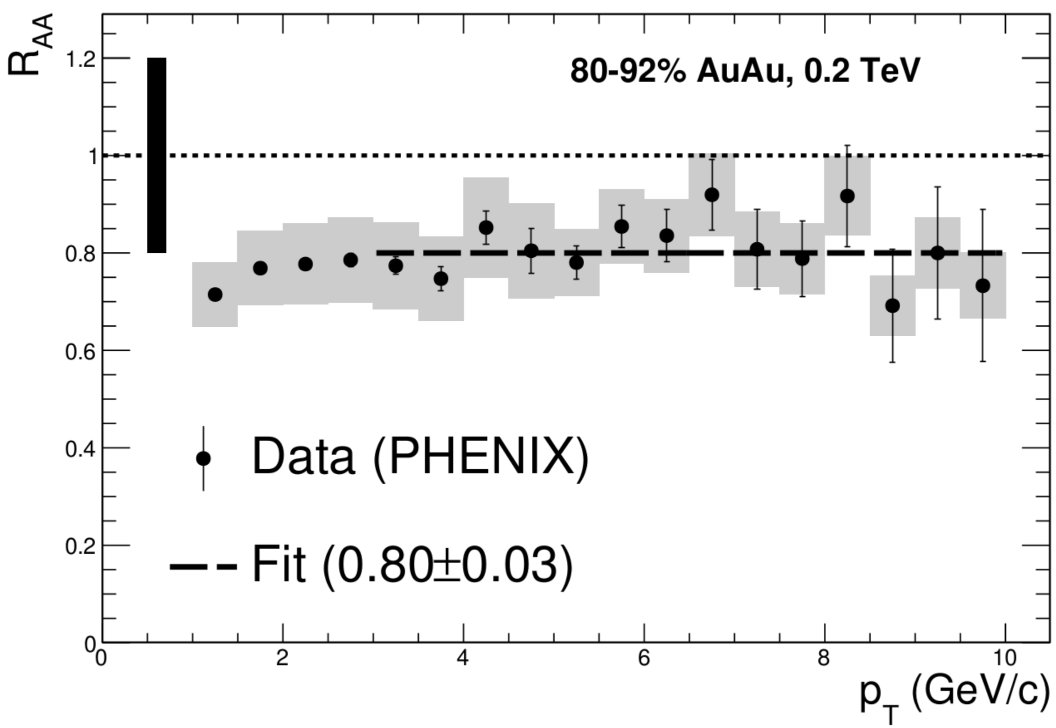
Dainese, Loizides, Paic, EPJC38 (2005), 461.

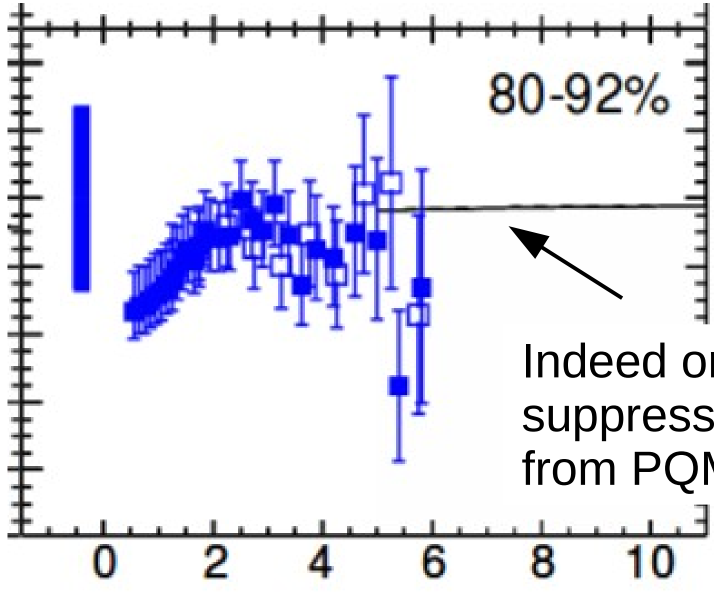
Constantin Loizides (MIT), LHC predictions workshop, 05/31/2007 13 / 11

"Something for you to tackle in the next years?"

- And more could be done
  - Adapt calculation for LHC energies
    (eg. to measured multiplicity, check pp case)
  - Embed calculation in hydrodynamics
  - Check implementation in Q-Pythia (arXiv:0907.1014)
  - …

26 RAA in very peripheral collisions

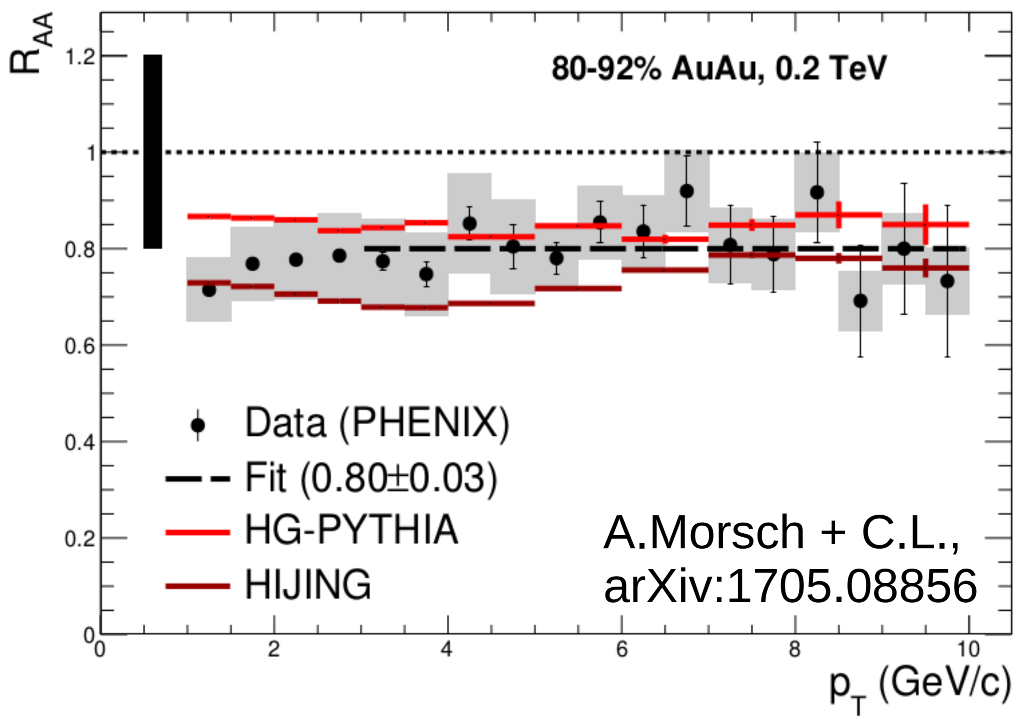


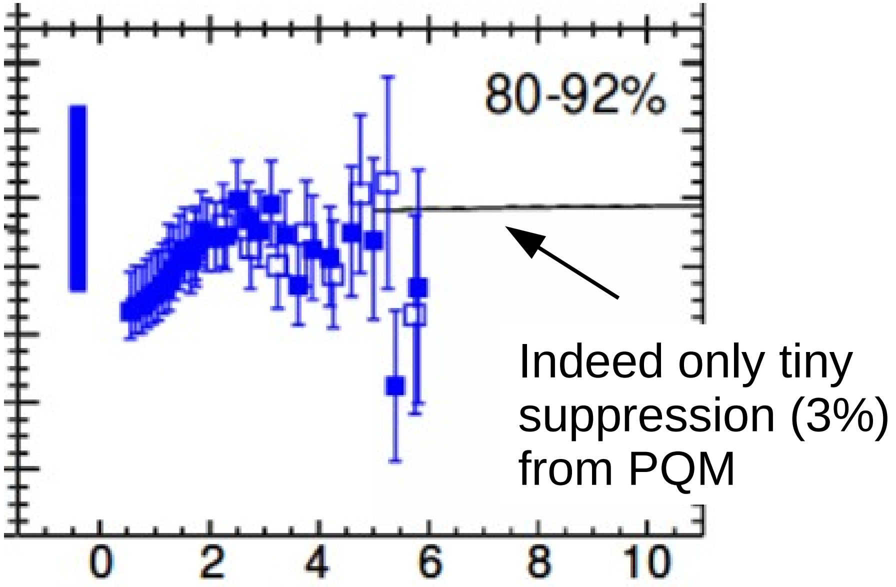


Indeed only tiny suppression (3%) from PQM

- Peripheral R_{AA} clearly below 1
  - PQM does not predict significant suppression
- Model studies
  - HIJING w/o quenching
  - Pythia with HIJING MPI model
- Treating MC just like data (ie ordering events according to multiplicity) shows that multiplicity bias can cause the apparent suppression
  - Effect even stronger for LHC

RAA in very peripheral collisions





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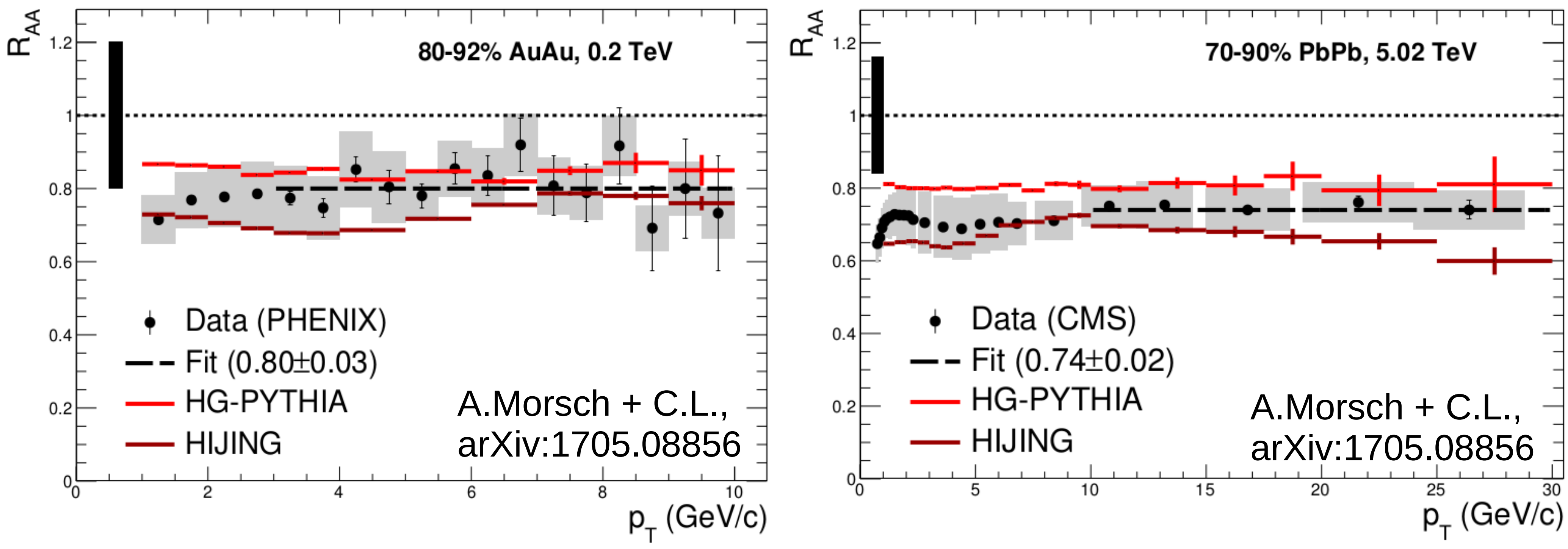

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  - HIJING w/o quenching
  - Pythia with HIJING MPI model
- Treating MC just like data (ie ordering events according to multiplicity) shows that multiplicity bias can cause the apparent suppression
  - Effect even stronger for LHC

Jet R_{AA} up to very high energies

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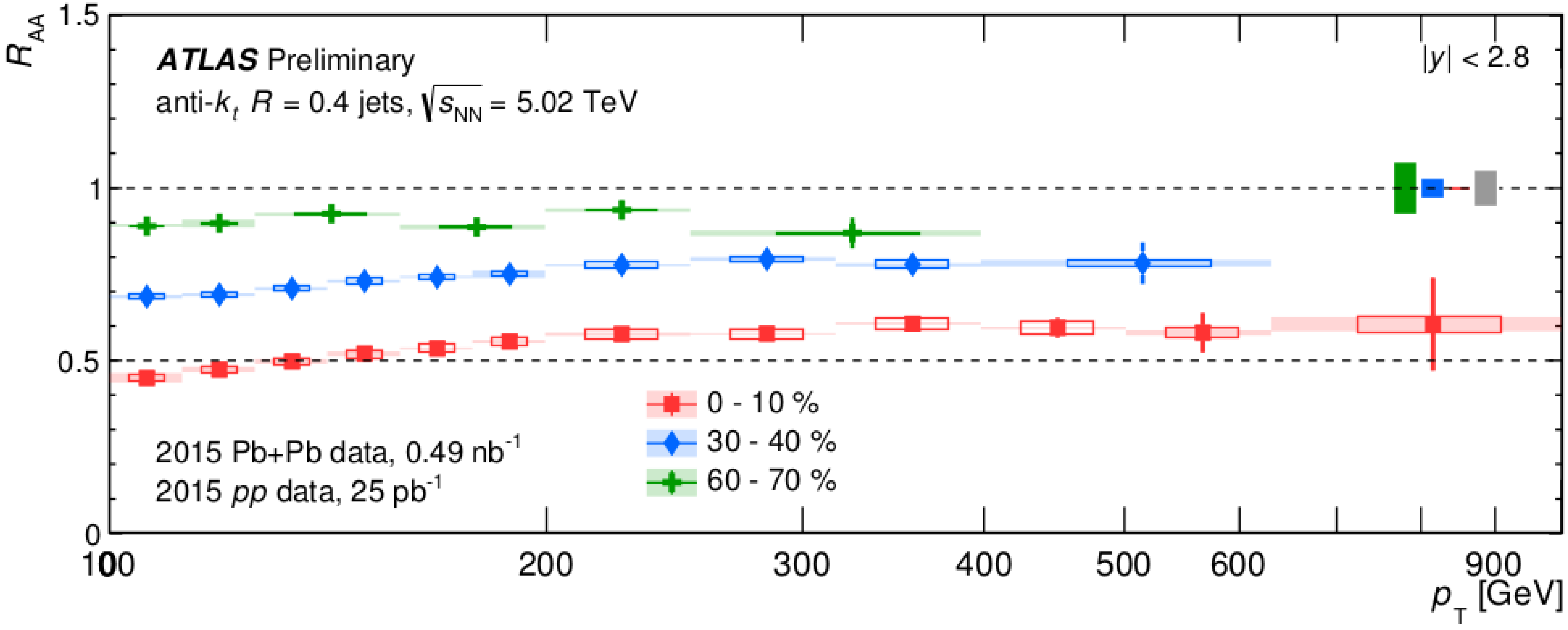
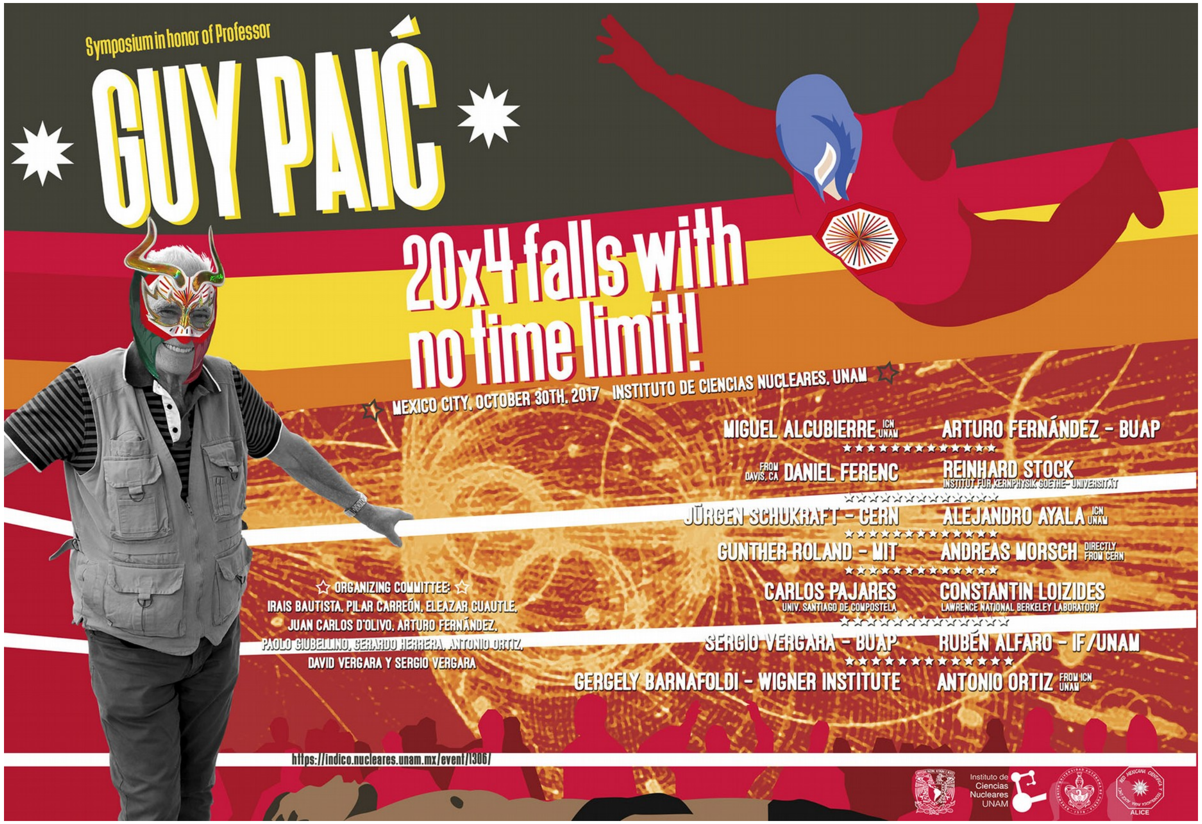


Jet R_{AA} in 0-10% central collisions at ~ 0.5-0.7 at up to 1 TeV;
Really only from energy loss, or another effect / bias?



Happy belated birthday, Guy, and onto the next 20 years!