Early Time Dynamics in Heavy Ion Collisions
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On the determination of the transport coefficient $\hat{q}$ in radiative energy loss formalisms

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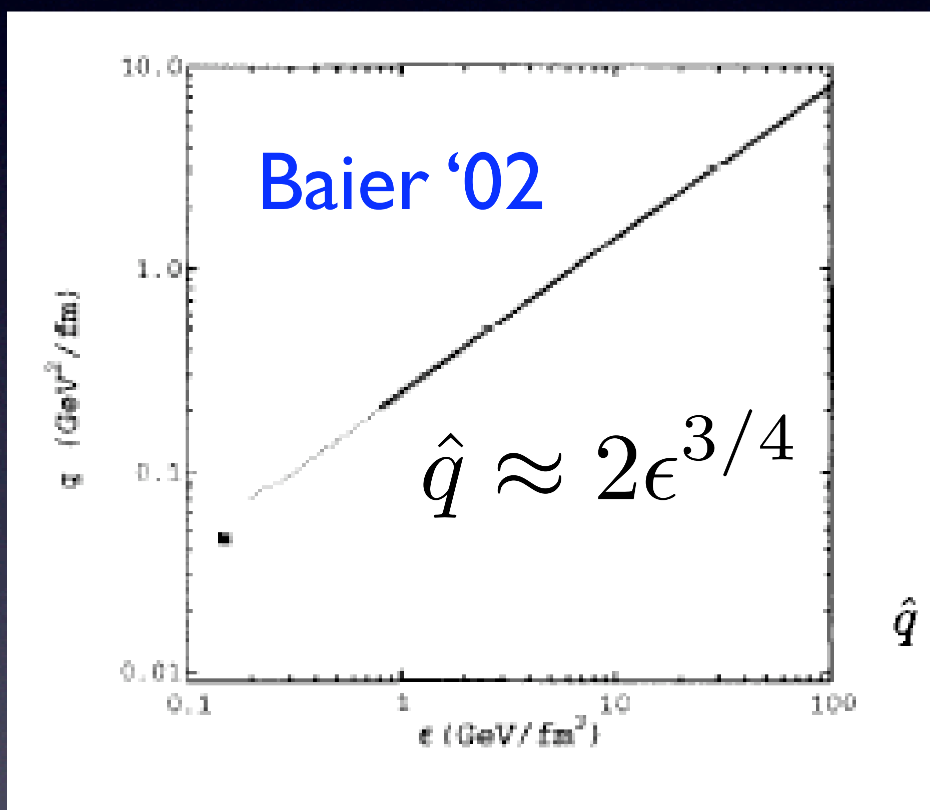
Related theory talks: Baier, Djordjevic, Majumder, Ruppert.

1. Introduction (I):

- Radiative energy loss has become the baseline for explanations of both single particle and back-to-back suppression measured at RHIC.
- Four formalisms available: BDMPS/GLV, MW and AMY. They consider the same physical process under different approximations.
- In all of them, medium defined by two ingredients: geometry/dynamics (soft), and medium density (initial conditions, soft) times parton-medium cross section (hard?, soft?). Thus, radiative eloss explores the medium.

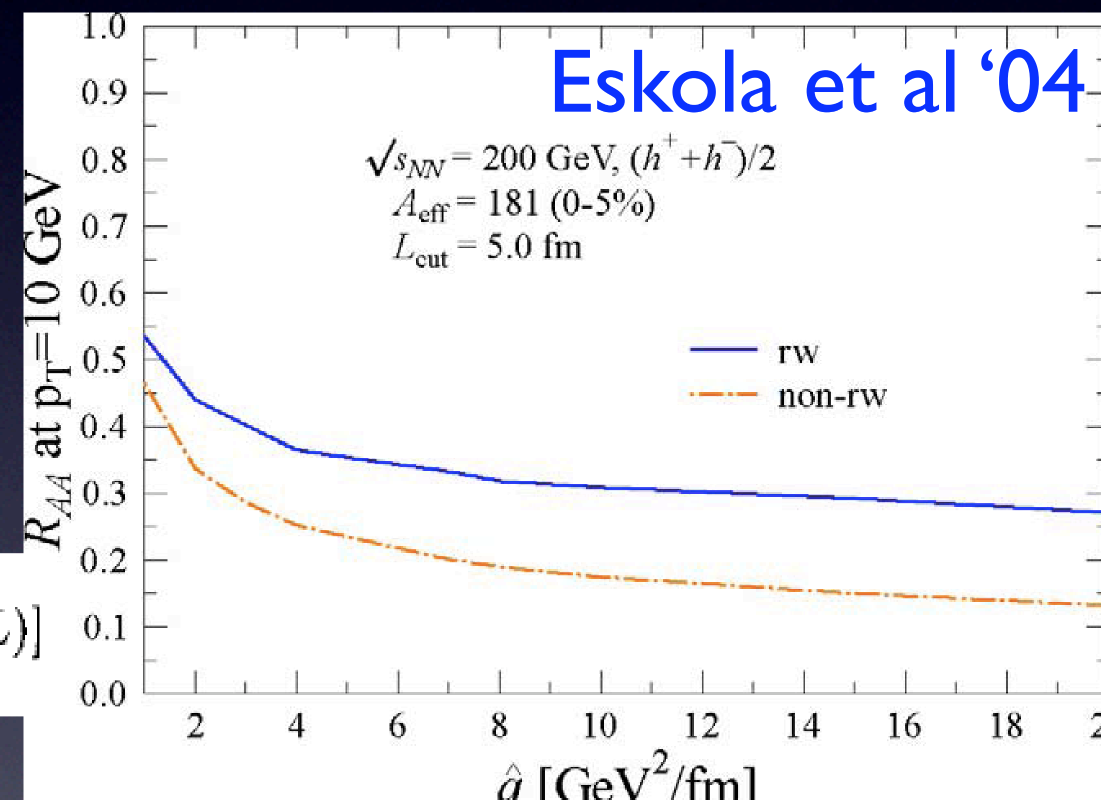
I. Introduction (II):

- Medium density times parton-medium cross section now standardly discussed in terms of the transport coefficient:



$$\hat{q} = \frac{\mu^2}{\lambda}$$

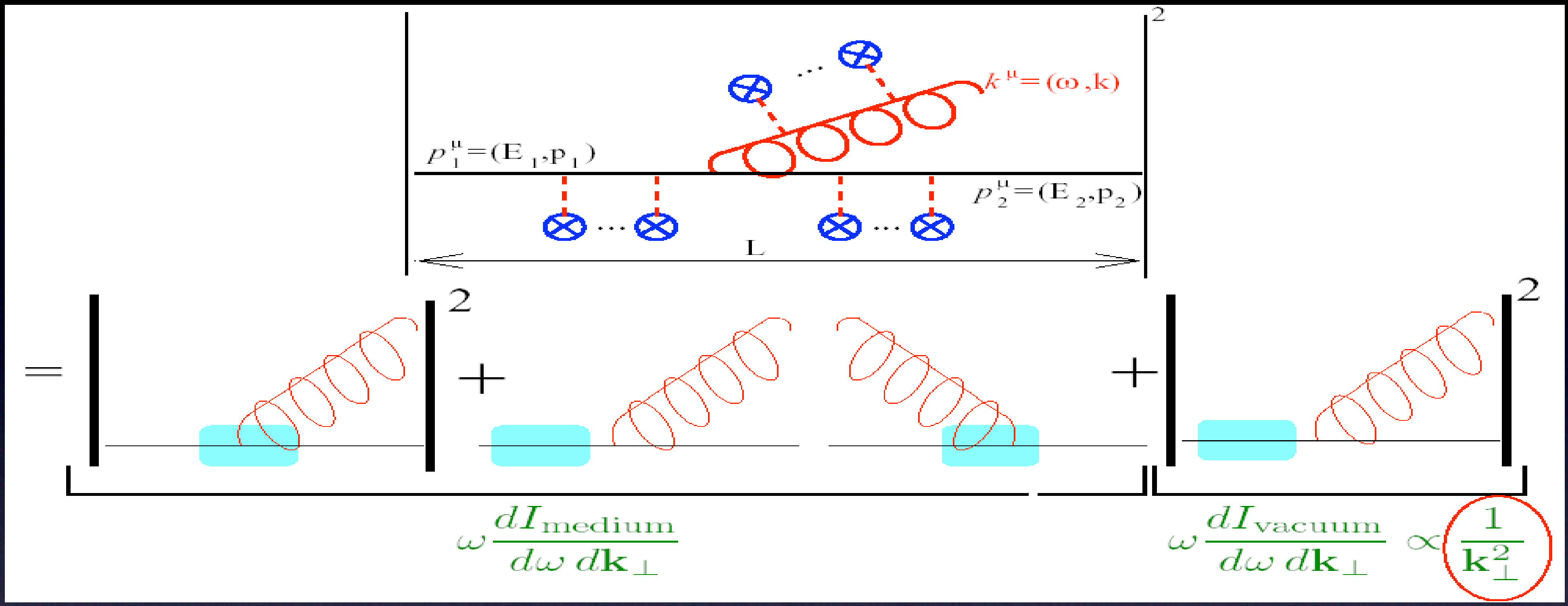
$$\hat{q} = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} \rho \, [xG(x, \hat{q}L)]$$



- Problem: different implementations/observables give different values: $\hat{q} = 1 \div 15 \ \mathrm{GeV}^2/\mathrm{fm}$

2. Models for radiative eloss (I):

(Majumder, nucl-th/0702066)



All models treat the medium modification of gluon radiation through the interference of production and rescattering.

$$\Delta E \sim \int d\omega \omega \frac{dI}{d\omega} \sim \alpha_s C_R \omega_c = \frac{1}{2}\alpha_s C_R \hat{q} L^2$$

$$n(z)\sigma(r) \propto \hat{q} r^2, \quad \hat{q} = \frac{\mu^2}{\lambda}$$

Fragmentation (assumed outside the medium) modified due to the difference in radiation to get rid of virtuality.

2. Models for radiative eloss (II):

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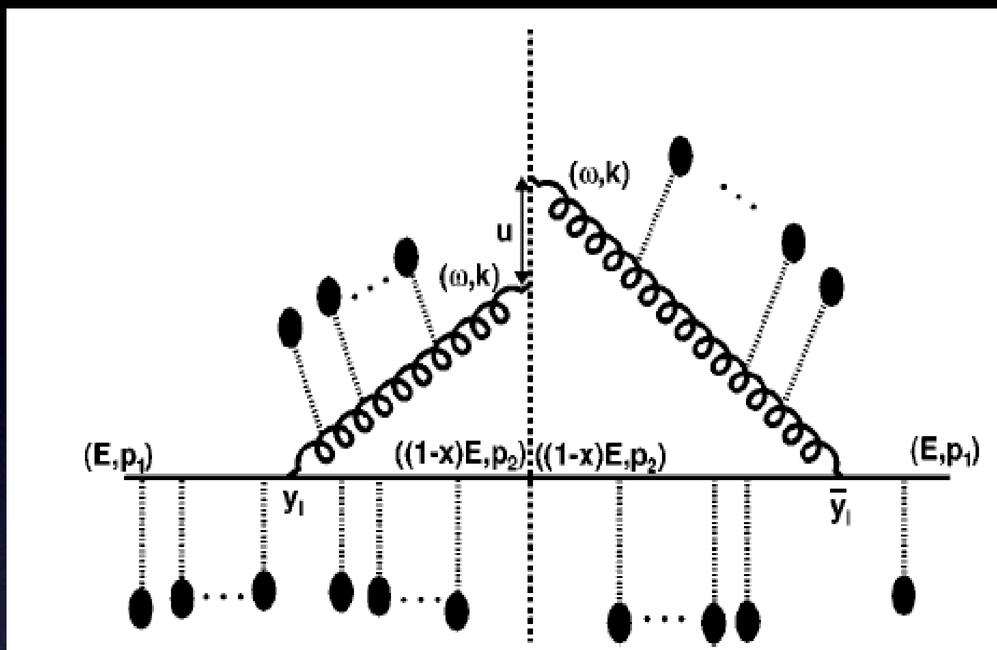
1/2. BDMPS/GLV: static medium.



$$\omega \frac{dI}{d\omega\, d\mathbf{k}_\perp} = \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} 2\,\mathrm{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l e^{i\bar{q}(y_l-\bar{y}_l)} \times \int d\mathbf{u}\, e^{-i\mathbf{k}_\perp\cdot\mathbf{u}} \exp-\left(\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\sigma(\mathbf{u})\right)$$

$$\times \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \int_{\mathbf{y}=0=\mathbf{r}(y_l)}^{\mathbf{u}=\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r}\, \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2}\left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\sigma(\mathbf{r})}{i\omega}\right)\right]$$

Exact solution unknown, two approximations:

1. Harmonic oscillator (Brownian motion): multiple soft scatterings.

$$n(\xi)\sigma(\mathbf{r}) \simeq \frac{1}{2}\hat{q}(\xi)\mathbf{r}^2$$

2. Opacity expansion: N=1, single hard scattering, corrects Brownian motion.

$$[n(\xi)\sigma(\mathbf{r})]^N$$

Comparison for massless and massive: SW '03, ASW '04.

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2. Models for radiative eloss (III):

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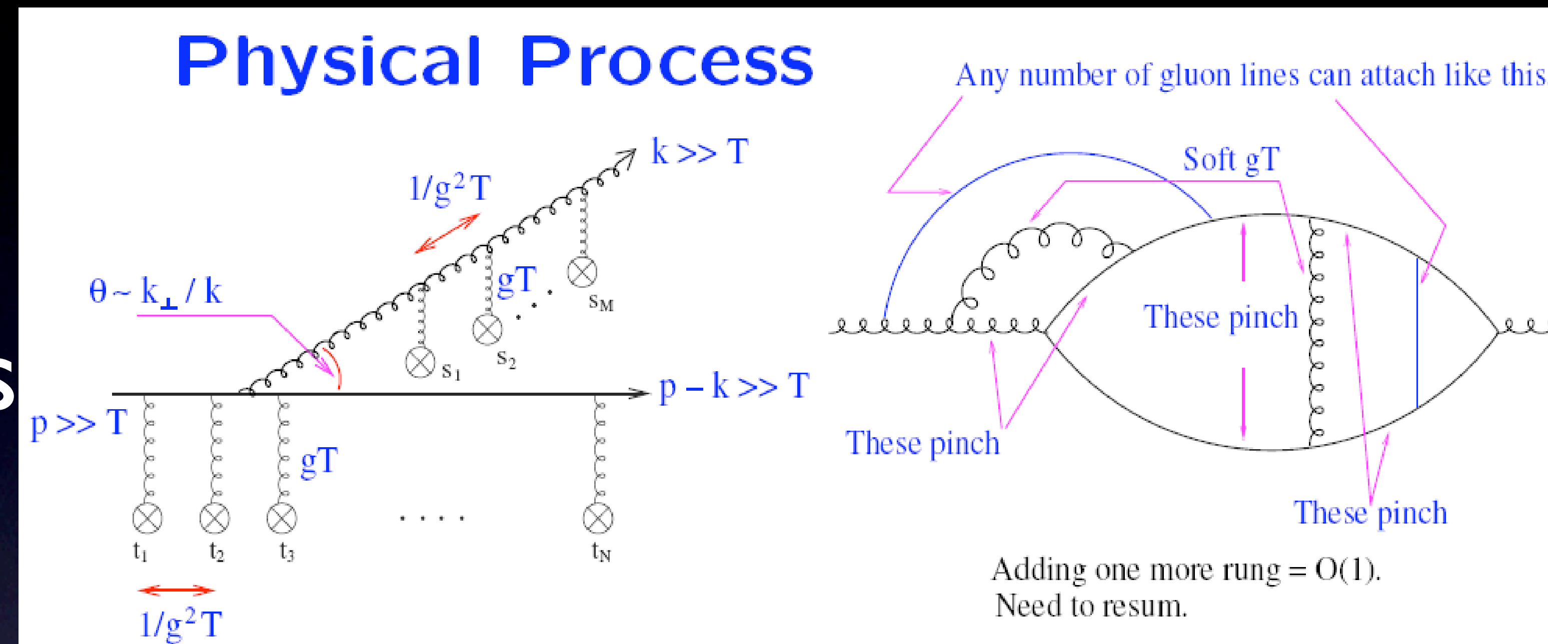
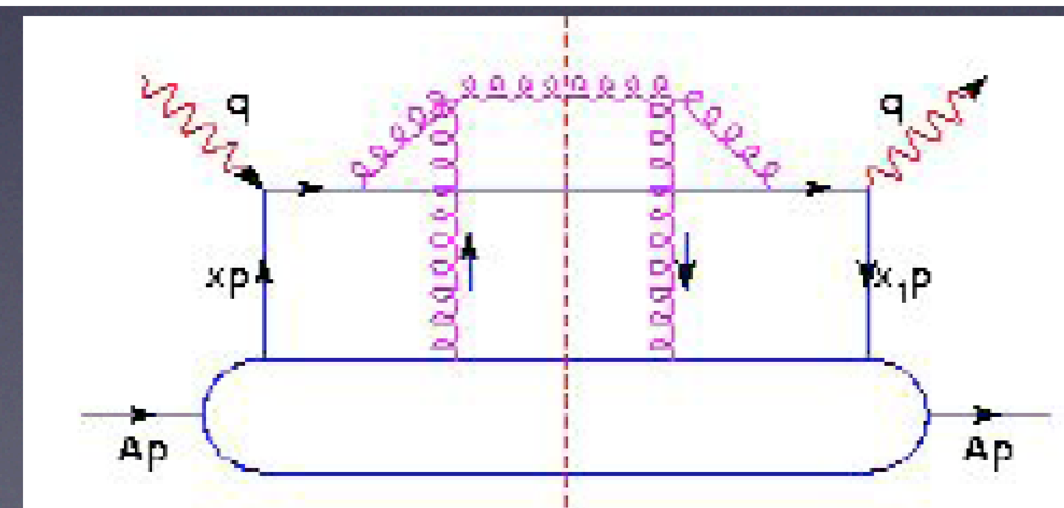
3. AMY: rates order α_s , dynamical medium, no interference of emissions in/out medium, expansion.



4. GW(M): ff in DIS on nuclei, first corrections in L/k_T^2 , modification of DGLAP splitting functions, virtuality.

$$\tilde{D}(z_1,\mu^2)=D(z_1,\mu^2)+\frac{\alpha_s}{2\pi}\int_0^{\mu^2}\frac{dl_\perp^2}{l_\perp^2}\int\frac{dy}{y}\left[\frac{1+y^2}{1-y}f(x,y,Q^2,l_\perp)+V.C.\right]D(z_1/y,\mu^2)$$

$$f=\frac{C_A\,2\pi\,\alpha}{l_T^2+k_T^2}\,\frac{\int dy\,dy_1\,dy_2\langle A|\bar{\psi}(y)\,F(y_1)\,F(y_2)\,\psi(0)|A\rangle\, e^{i\ factors}}{N_c\,f^A(x)}$$



3. Determinations of $\hat{q}$ (I):

- qhat is a natural parameter only in BDMPS.
- Extraction from a comparison with R_{AA}.
- Phenomenological implementations are key: mean eloss rudimentary, distribution of energy losses better: quenching weights (BDMS, GLV '01).
- Fixed length (GLV; Arleo '02; SW '03) gives ~< 1 GeV^2/fm.

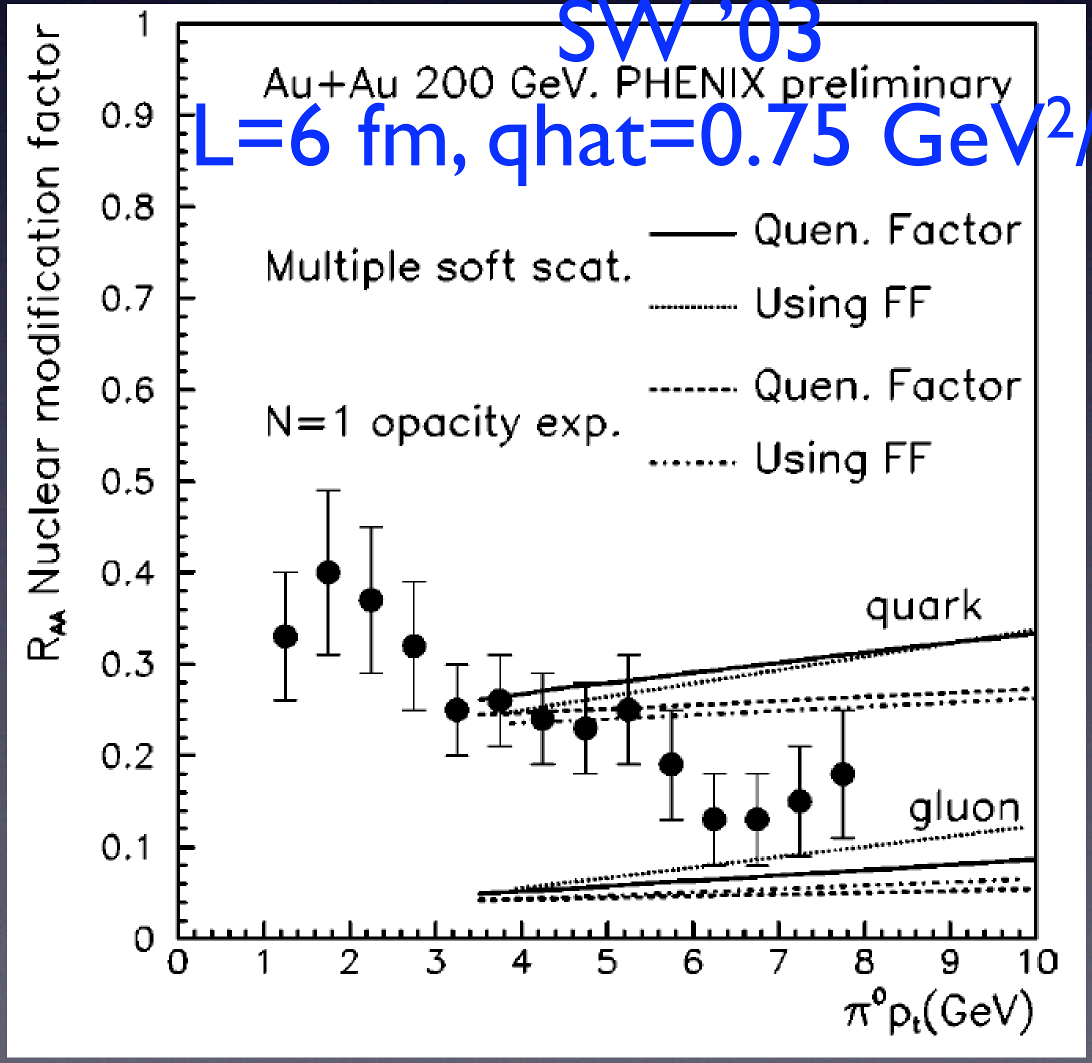
$$Q(p_\perp) = \frac{d\sigma^{med}(p_\perp)/dp_\perp^2}{d\sigma^{vac}(p_\perp)/dp_\perp^2} = \int d\Delta E\, P(\Delta E) \left(\frac{d\sigma^{vac}(p_\perp+\Delta E)/dp_\perp^2}{d\sigma^{vac}(p_\perp)/dp_\perp^2}\right)$$

BDMS '01; Wang et al '96

$$D_{h/q}^{(med)}(x,Q^2) = \int_0^1 d\epsilon\, P(\epsilon) \frac{1}{1-\epsilon} D_{h/q}\left(\frac{x}{1-\epsilon}, Q^2\right)$$

SW '03

L=6 fm, qhat=0.75 GeV^2/fm



3. Determinations of $\hat{q}$ (II):

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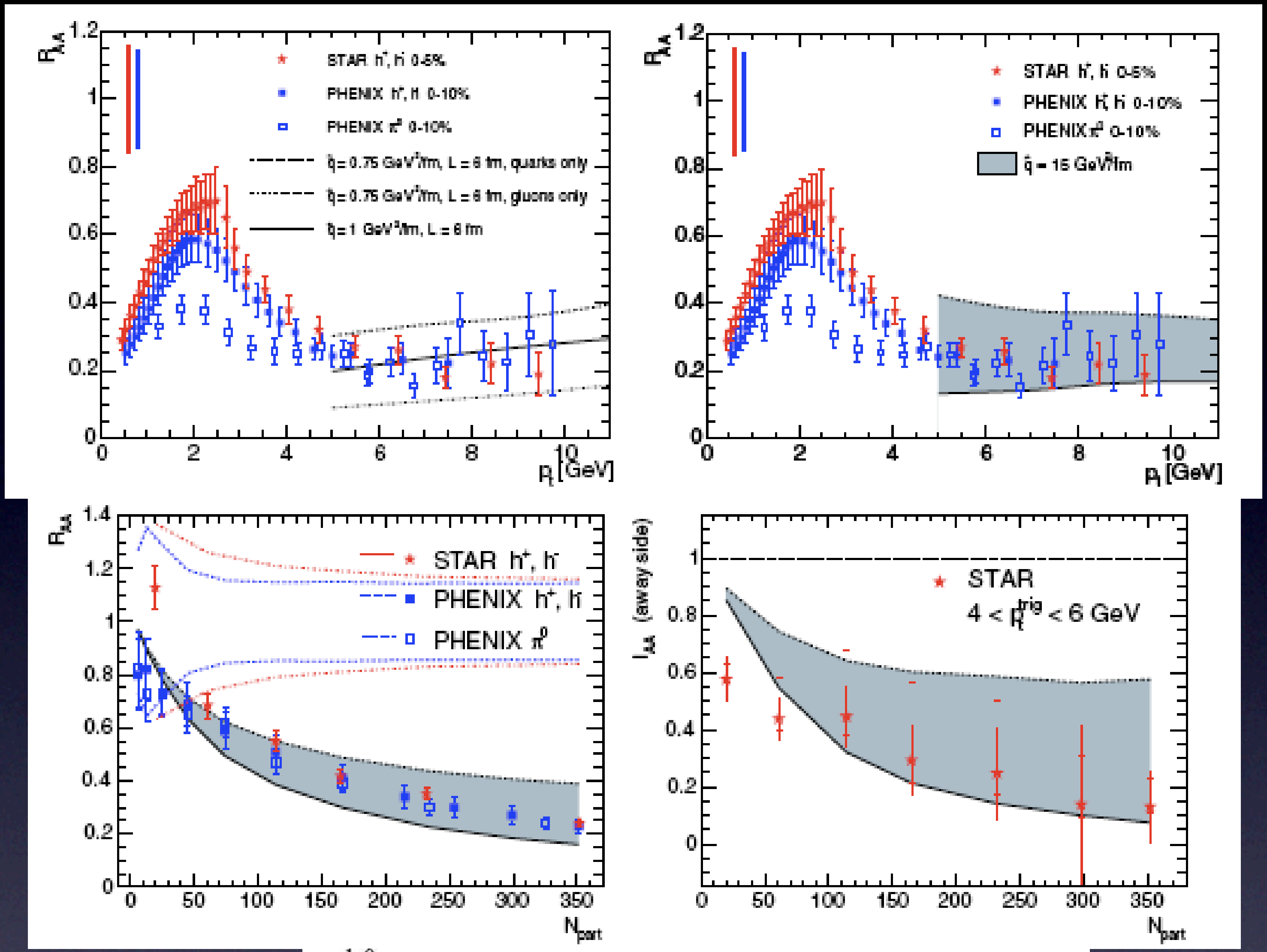
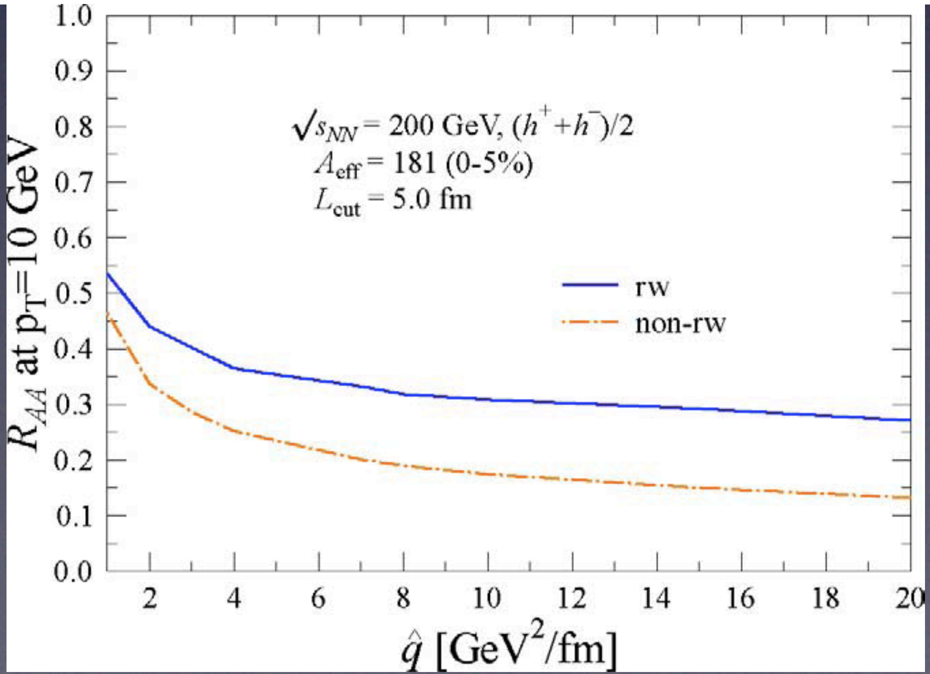
- A Woods-Saxon geometry (production plus 'medium') gives larger values and leads to saturation: fragility (Dainese et al, Eskola et al '04).
- Surface bias (Muller '03).
- <qhat>=4-14 GeV^2/fm.
- Energy constraints (Baier et al '06); energy dependence (Casalderrey et al '07).





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3. Determinations of $\hat{q}$ (III):

- Hard probes '06: AMY gives 2, GLV gives <1, MW give 3-4 GeV^2/fm: all at initial time.
- Dilution: introduced effectively (GLVW '01, SW '02)

$$\langle \hat{q} \rangle = \frac{2}{L^2 - \tau_0^2} \int_{\tau_0}^{L} d\tau \tau \hat{q}_0 \frac{\tau_0}{\tau} \simeq \frac{2\tau_0 \hat{q}_0}{L} \approx \frac{\hat{q}_0}{2 \div 5}$$

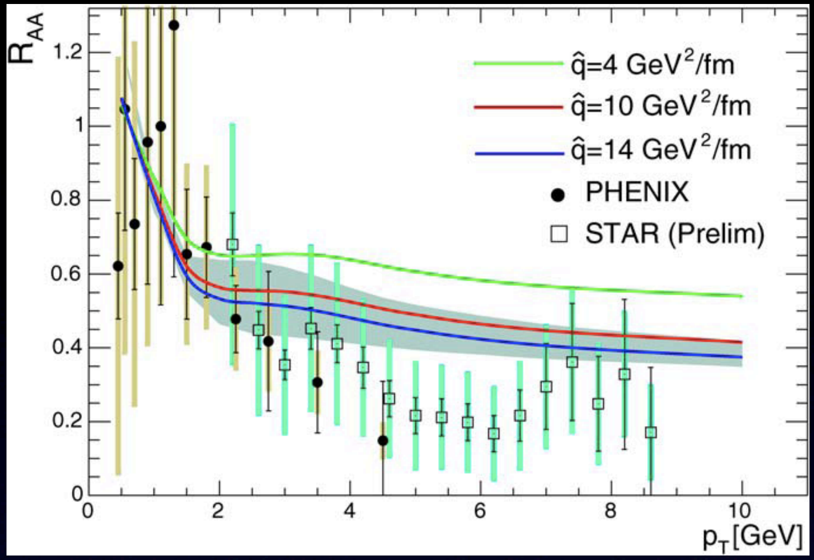
- Flow (Armesto et al '04) doesn't lower qhat (Baier et al '06).
- A dynamical medium decreases qhat (AMY?, Djordjevic et al '07).

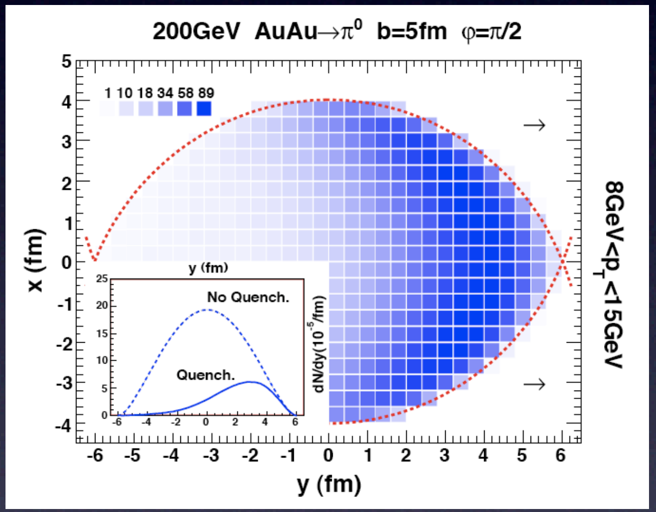
$$\hat{q}(\xi) = K \cdot 2 \cdot \epsilon^{3/4}(\xi)$$

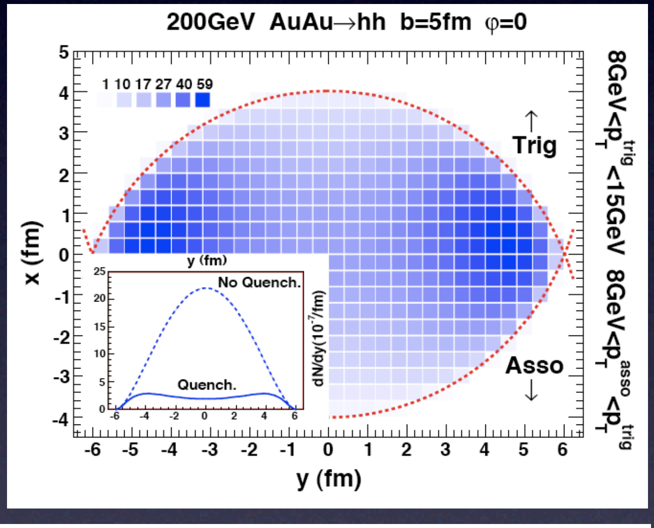
- A dynamical expansion (Hirano-Nara '03; Ruppert-Renk '05, '06; Majumder et al '07; Qin et al '07) lowers qhat with respect to a static medium; still K>1; late time effect?

3. Determinations of $\hat{q}$ (IV):

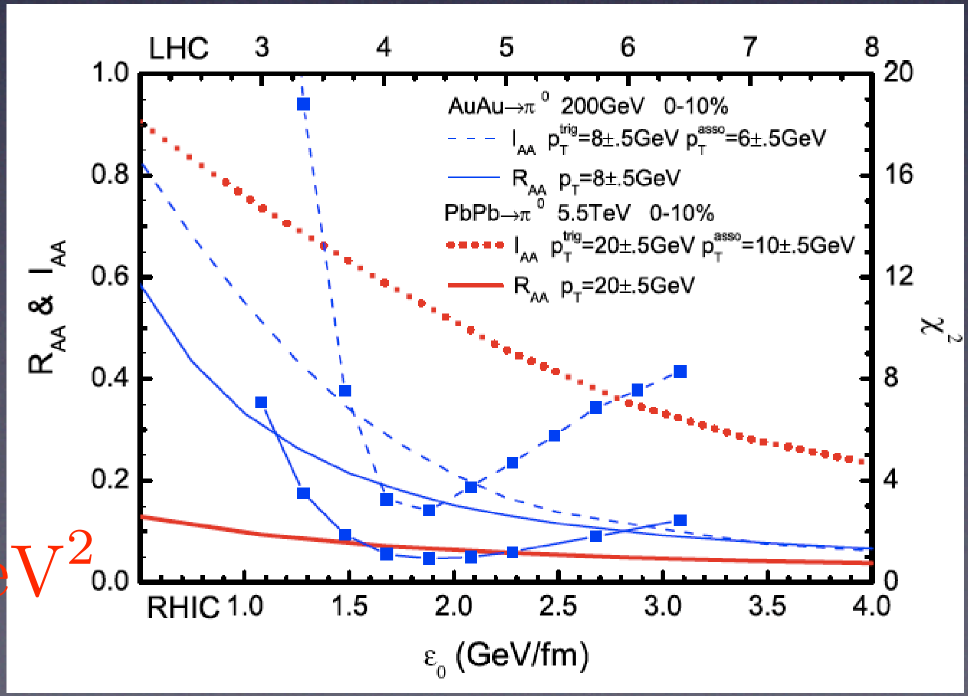
- **Non-photonic electrons** not conclusive: benchmark (Armesto et al '05), hadronization inside (Adil et al '06), collisional (Djordjevic et al '06)...







- **I_{AA} or away side pseudoframentation function** (Wang '03) tend to favor low values of qhat (Renk '06; Loizides '06; Zhang et al '07): punch-through.



$$\langle \hat{q}_0 \tau_0 \rangle \approx 2 \div 3 \;\; \mathrm{GeV}^2$$

4. An exercise (I):

(with Carlos A. Salgado, *Rome La Sapienza*)

Quantification of the effect on qhat of some of the phenomenological ingredients, based on R_{AA} for central, using a pQCD spectrum and QW.

$$Q(p_\perp) = \frac{d\sigma^{\rm med}(p_\perp)/dp_\perp^2}{d\sigma^{\rm vac}(p_\perp)/dp_\perp^2}$$

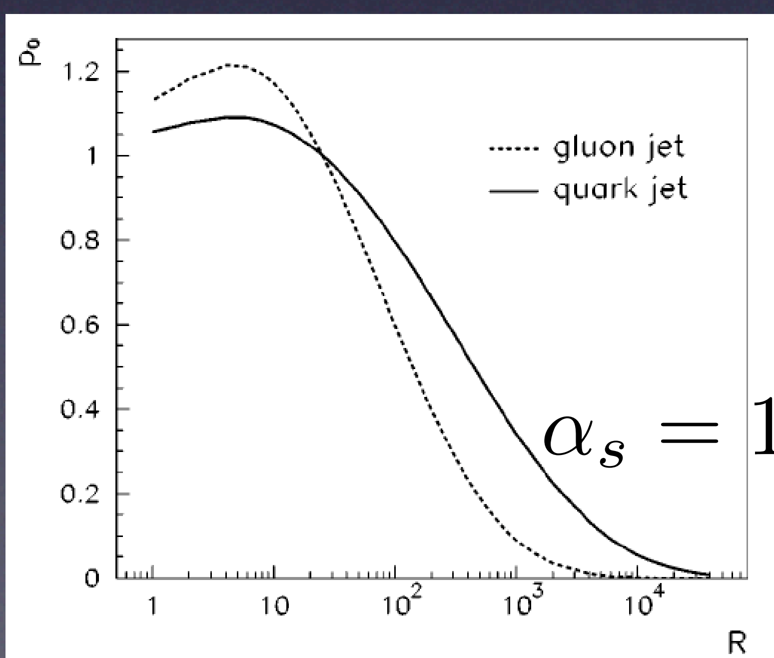
$$= \int d\Delta E\, P(\Delta E) \left(\frac{d\sigma^{\rm vac}(p_\perp + \Delta E)/dp_\perp^2}{d\sigma^{\rm vac}(p_\perp)/dp_\perp^2} \right)$$

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int_0^\infty d\omega \frac{dI}{d\omega} \right]$$

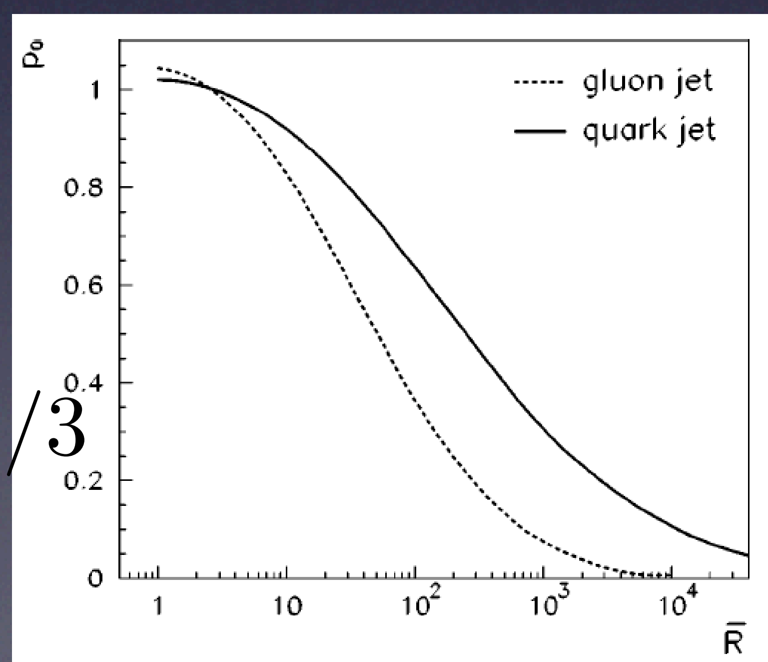
$$\omega_c = \frac{1}{2}\hat{q}L^2, \quad R = \omega_c L, \quad L/\lambda = 1$$

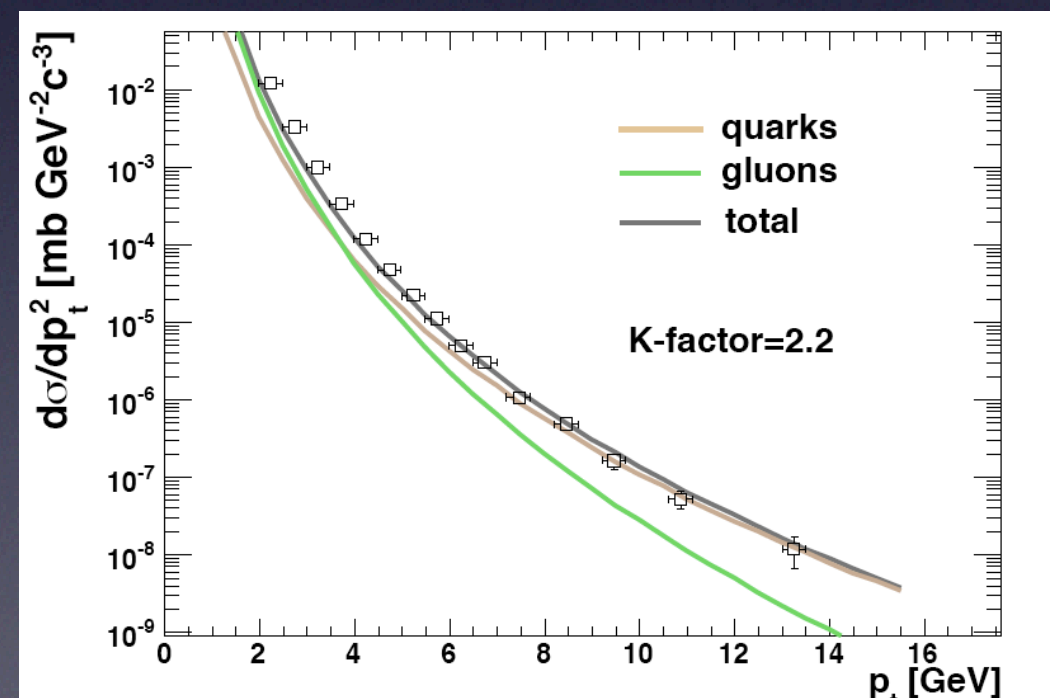
multiple soft

single hard



$\alpha_s = 1/3$





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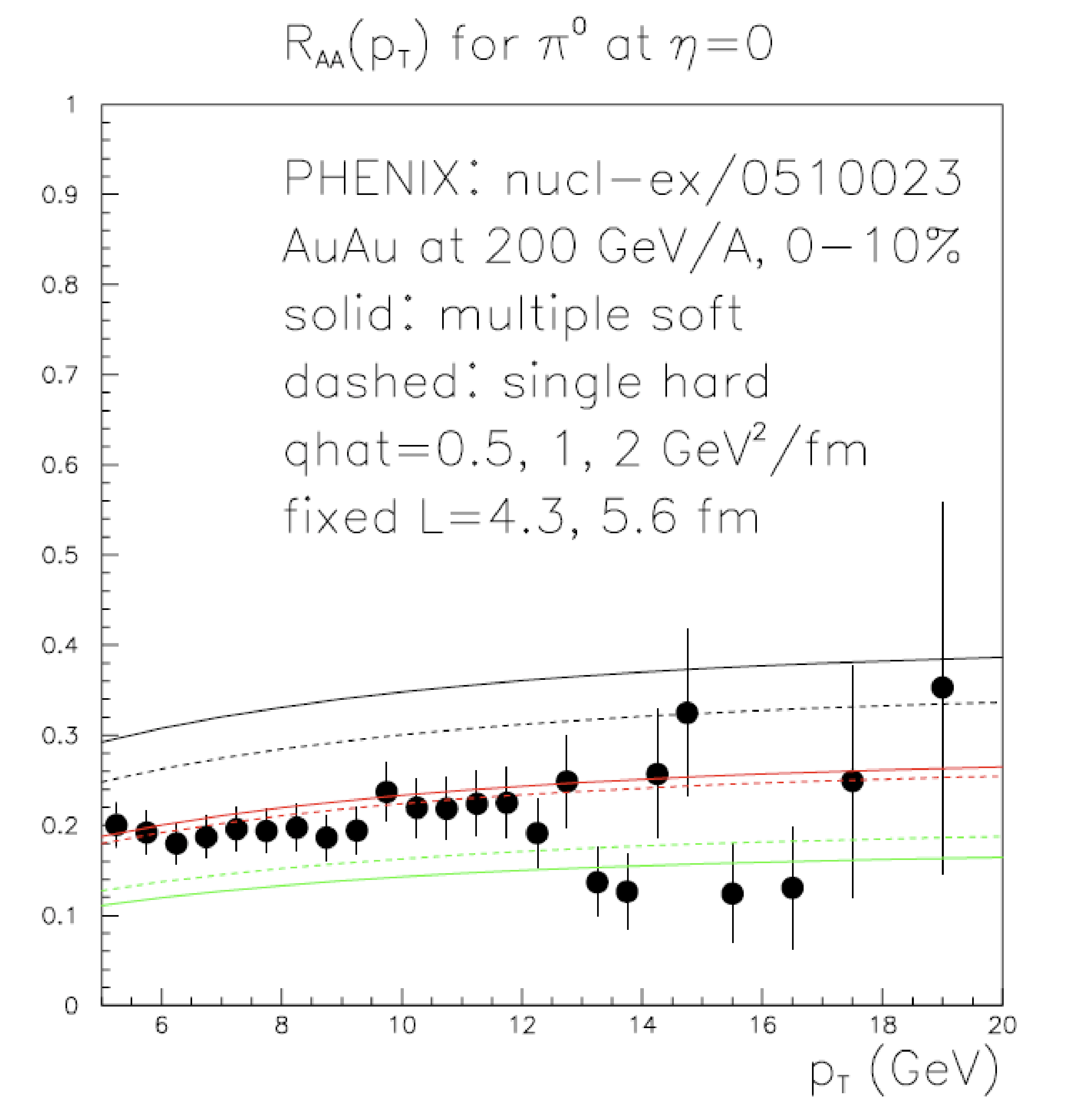
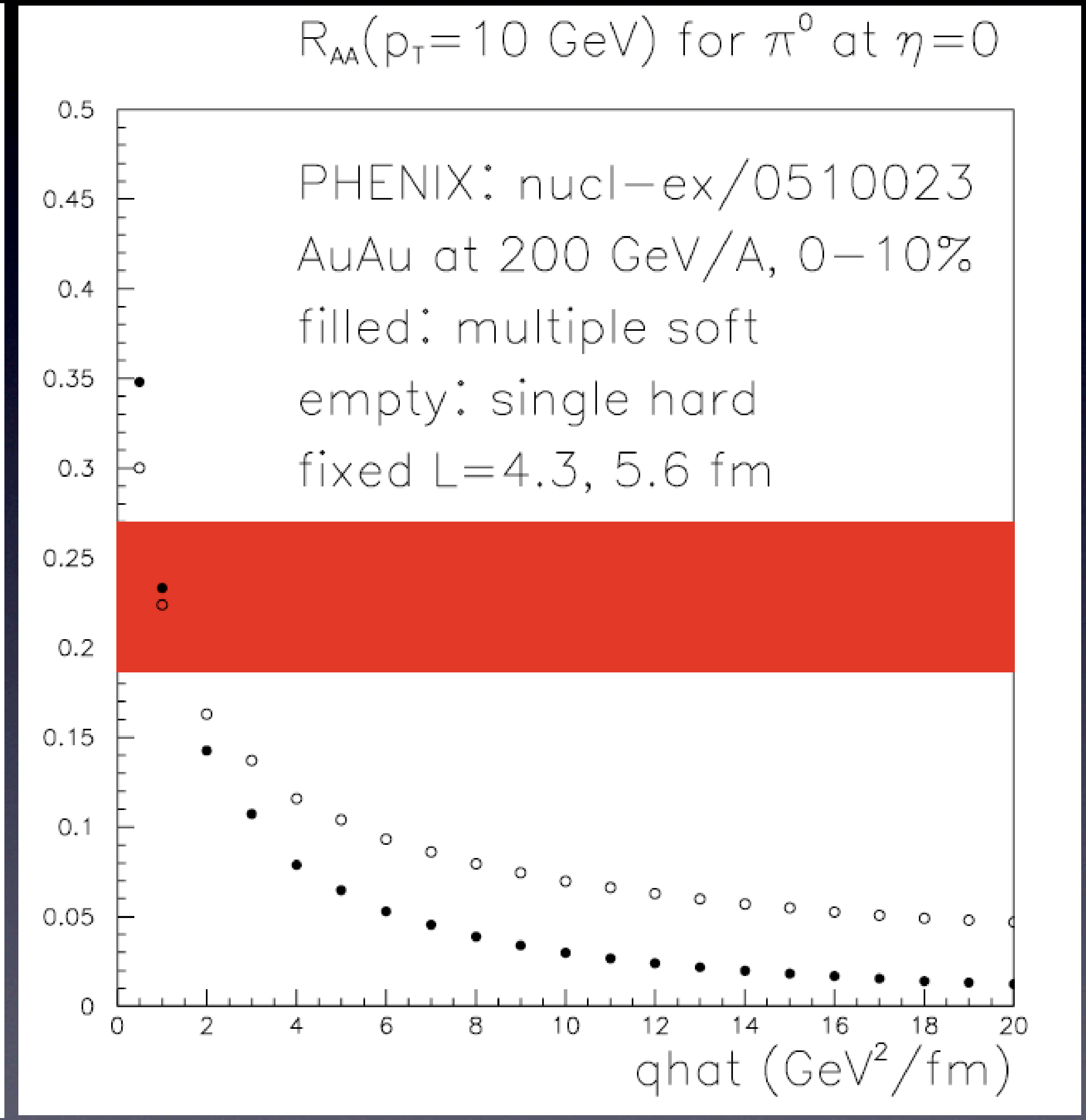
4. An exercise (II): fixed length





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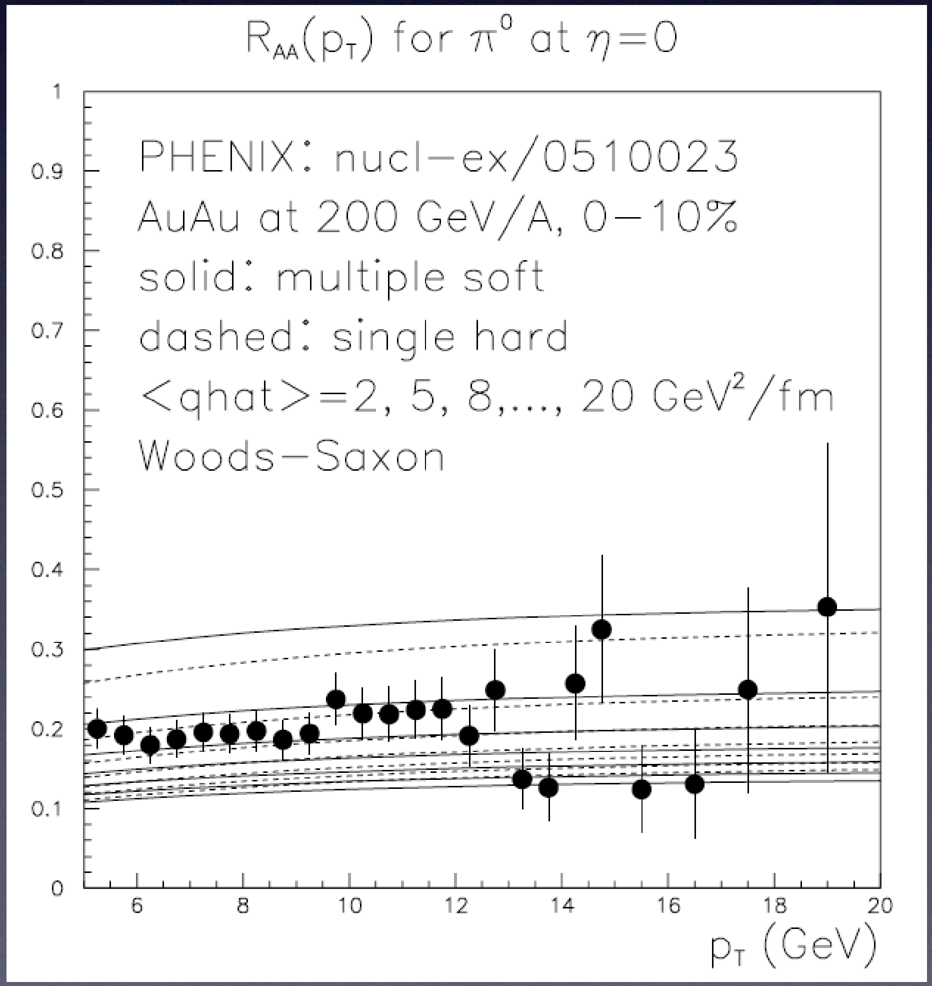
4. An exercise (III): Woods-Saxon

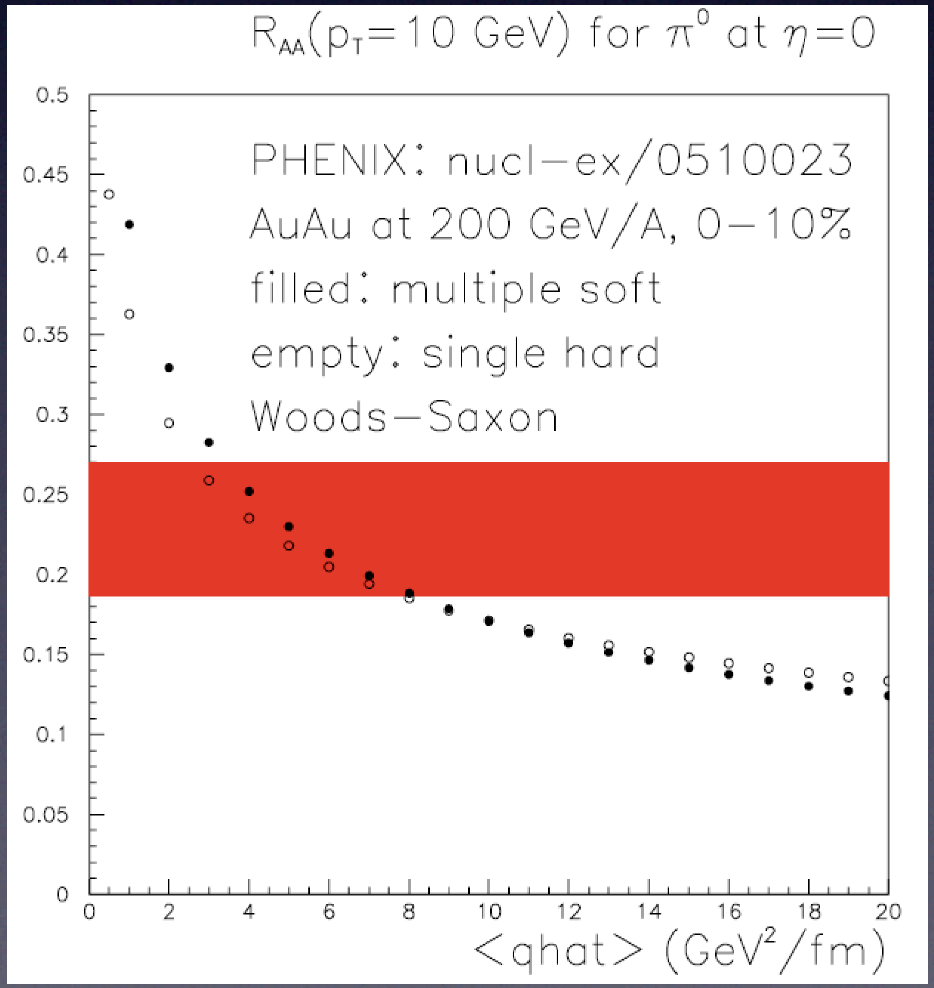
$$\omega_c(\mathbf{r}_0,\phi) = \int_0^\infty d\xi\, \xi\, \hat{q}(\xi)$$

$$\langle \hat{q} L\rangle(\mathbf{r}_0,\phi) = \int_0^\infty d\xi\, \hat{q}(\xi)$$

$$\hat{q} \propto T_A T_B(x_0 + \xi\cos\phi, y_0 + \xi\sin\phi)$$

$$R(\mathbf{r}_0,\phi) = 2\omega_c^2(\mathbf{r}_0,\phi)/\langle \hat{q} L\rangle(\mathbf{r}_0,\phi), \quad L = R/\omega_c, \quad \langle \hat{q}\rangle = 2\omega_c^2/(LR)$$





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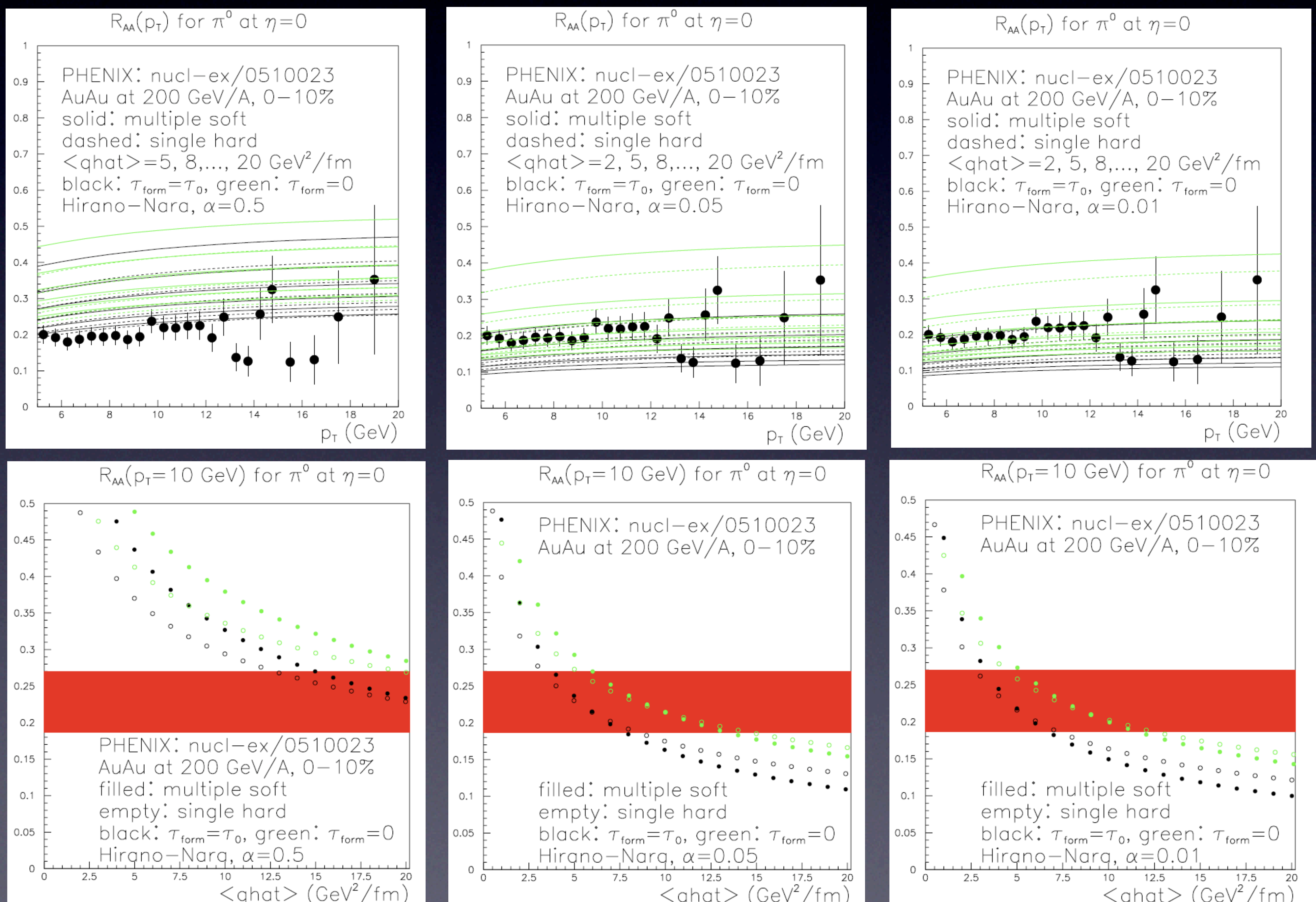
4. An exercise (IV): hydro

Hirano-Nara: 3+1 ideal hydro, for AuAu@200, b=3.1 fm, ideal EOS with N_f=3, $B^{1/4}$=247 MeV.

$$\langle \epsilon \rangle (\tau_0) \simeq 27(36)\ \mathrm{GeV/fm^3}$$
$$\langle \epsilon^{3/4} \rangle (\tau_0) \simeq 1.5(2.2)\ \mathrm{GeV^2/fm}$$
$$\tau_0 = 0.6\ \mathrm{fm},\ \tau_{max} = 10.2\ \mathrm{fm}$$



$$\hat{q}(\xi) = c\epsilon^{3/4}(\xi)$$

We explore:

$$\tau_{form} = 0 \div \tau_0$$

$$0.5 < \alpha < 0.01$$

$$\langle \hat{q} \rangle = 4\ \mathrm{GeV^2/fm}$$
$$\Rightarrow \quad K \sim 3$$

$$\langle \hat{q}_0 \tau_0 \rangle \sim 5\ \mathrm{GeV^2/fm}$$

5. Summary:

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		qhat (GeV^2/fm)
Phenomenological implementation	fixed length	<=1 (average)
	Woods-Saxon	4-14 (average)
	dynamical medium	decreases
	flow	no effect
	dilution	increases, factor 2-5
	hydro	K~3-4, late times
Observables	I_{AA}/pff	favors low values
	non-photonic electrons	unconclusive
Models	AMY	2 (initial)
	MW	2-3 (initial)
	multiple soft/single hard	small decrease
	GLV	<1 (initial)

Future: heavy flavor ID, more differential observables, LHC.