Hot and Dense Matter in the RHIC-LHC Era
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Radiative energy loss: problems and some new developments

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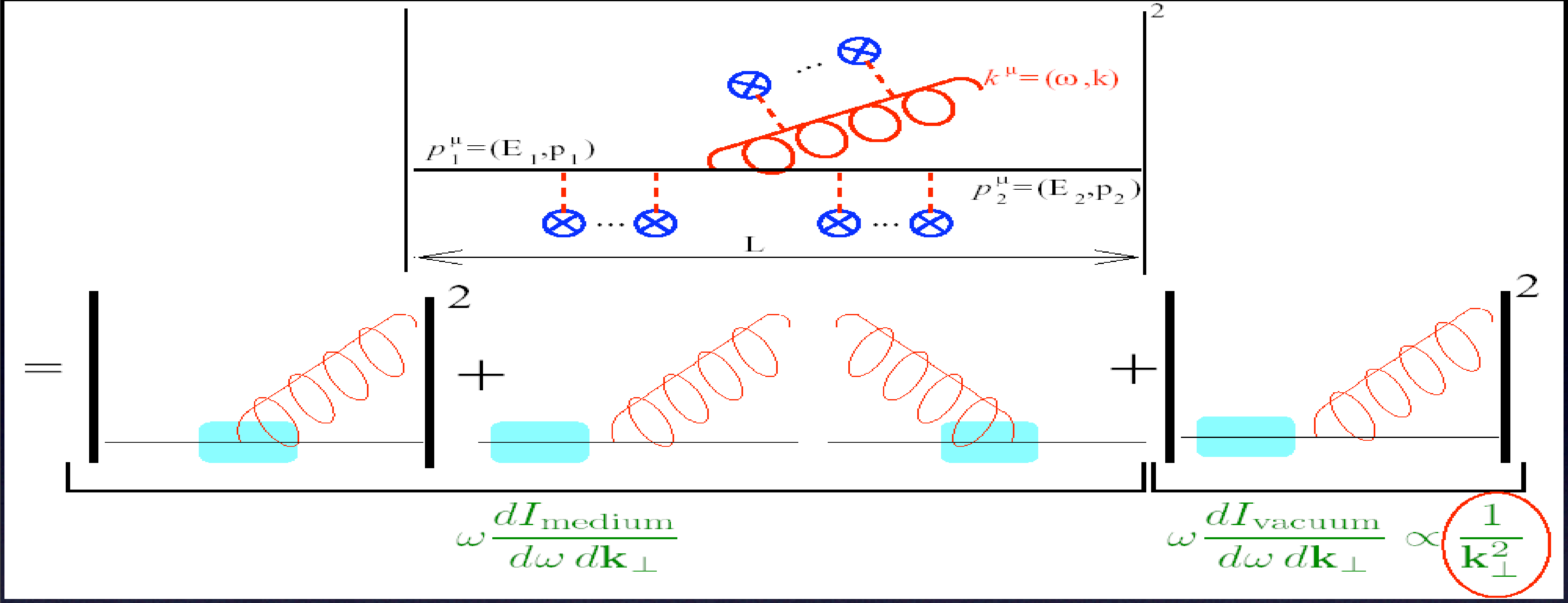
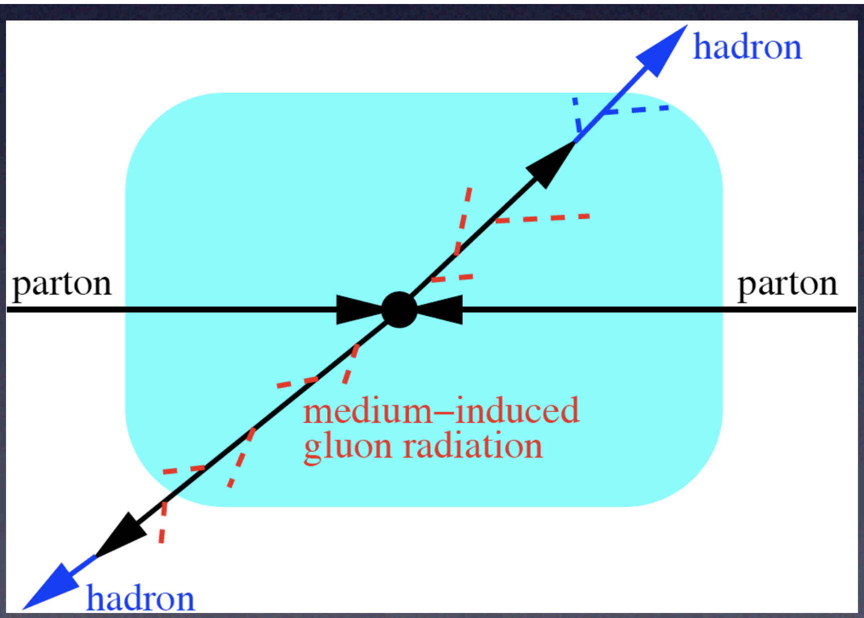
I.1. Theoretical setup:



Medium-modified gluon radiation through interference of production and rescattering.



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

BDMPS

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

Two parameters define the medium: qhat or gluon density plus mean free path, and length (geometry, dynamical expansion).

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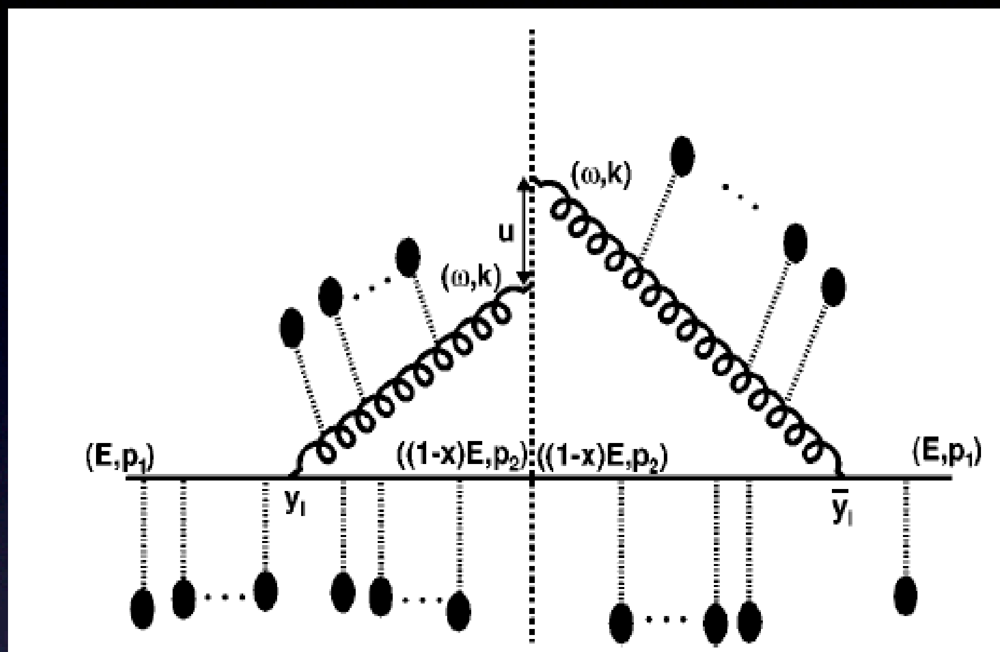
1.2. Models (I) (Majumder, nucl-th/0702066):

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.

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

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

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

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

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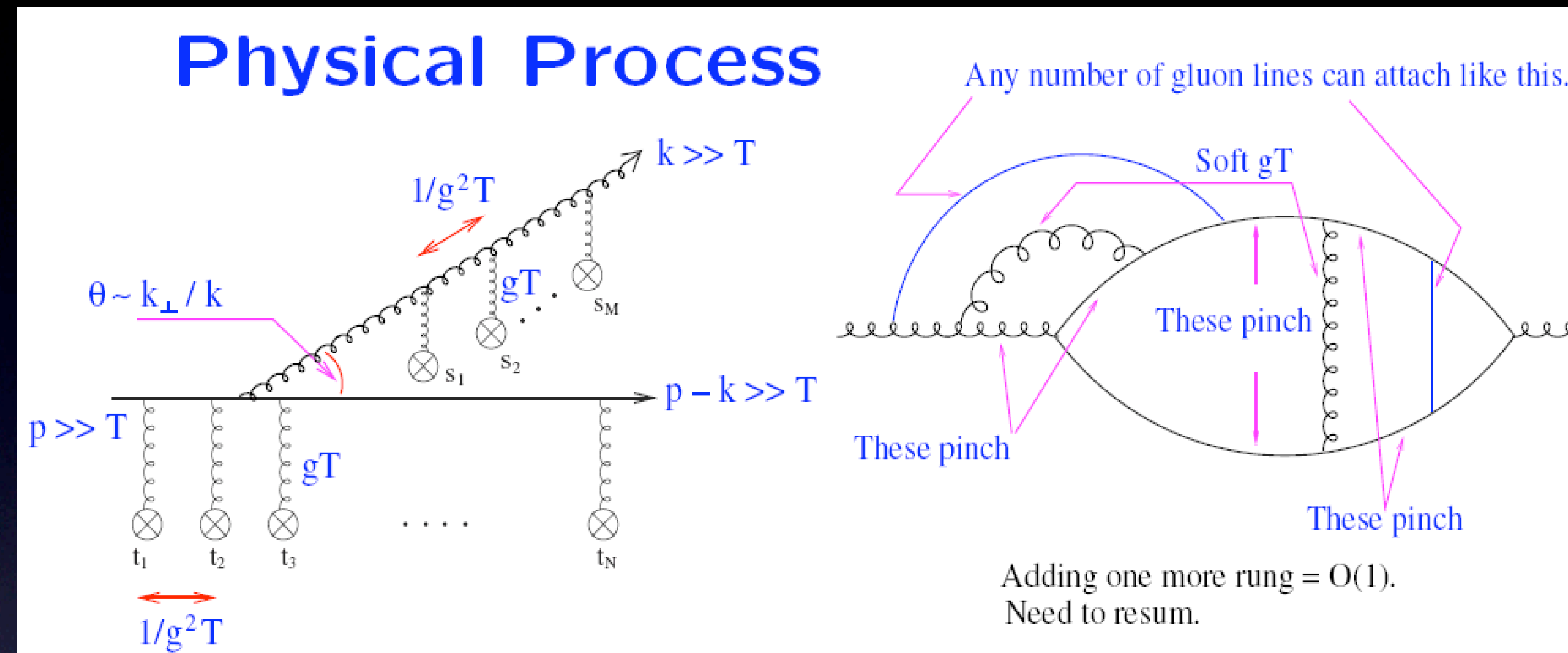
1.2. Models (II):

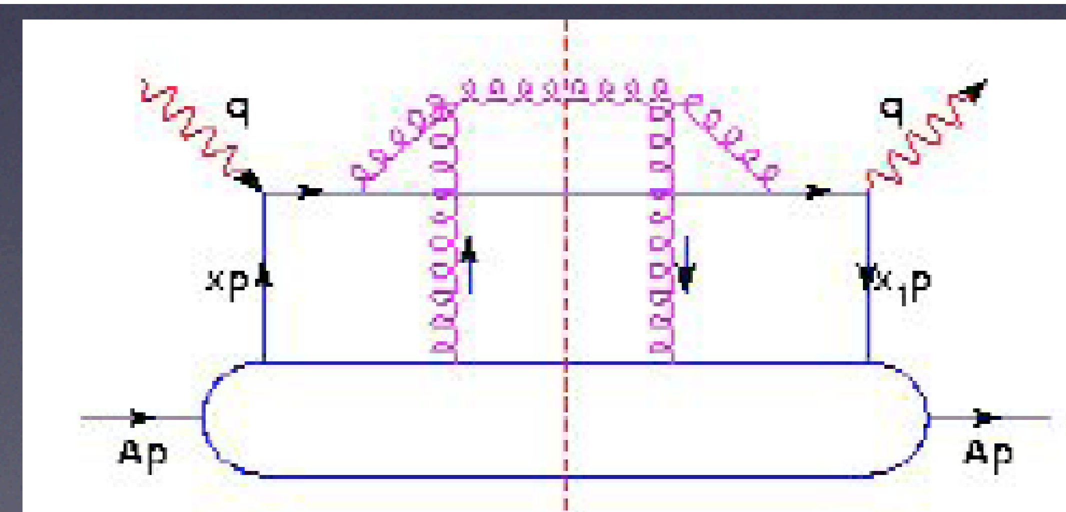
3. AMY: rates order α_s, dynamical medium, no interference of emissions in/out medium, expansion.



4. GW(M): FF in DIS on nuclei, first corrections in L/k_T^2, modification of DGLAP splitting functions, virtuality (see also Majumder et al. '07).

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

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



2. Successes and problems:

2.1. Light hadrons: R_{AA} and back-to-back suppression. :-)

2.2. Non-photonic electrons and more differential observables. :-(

2.3. qhat: dependence on medium modeling :-(

2.4. Limitations of the formalism. :-(

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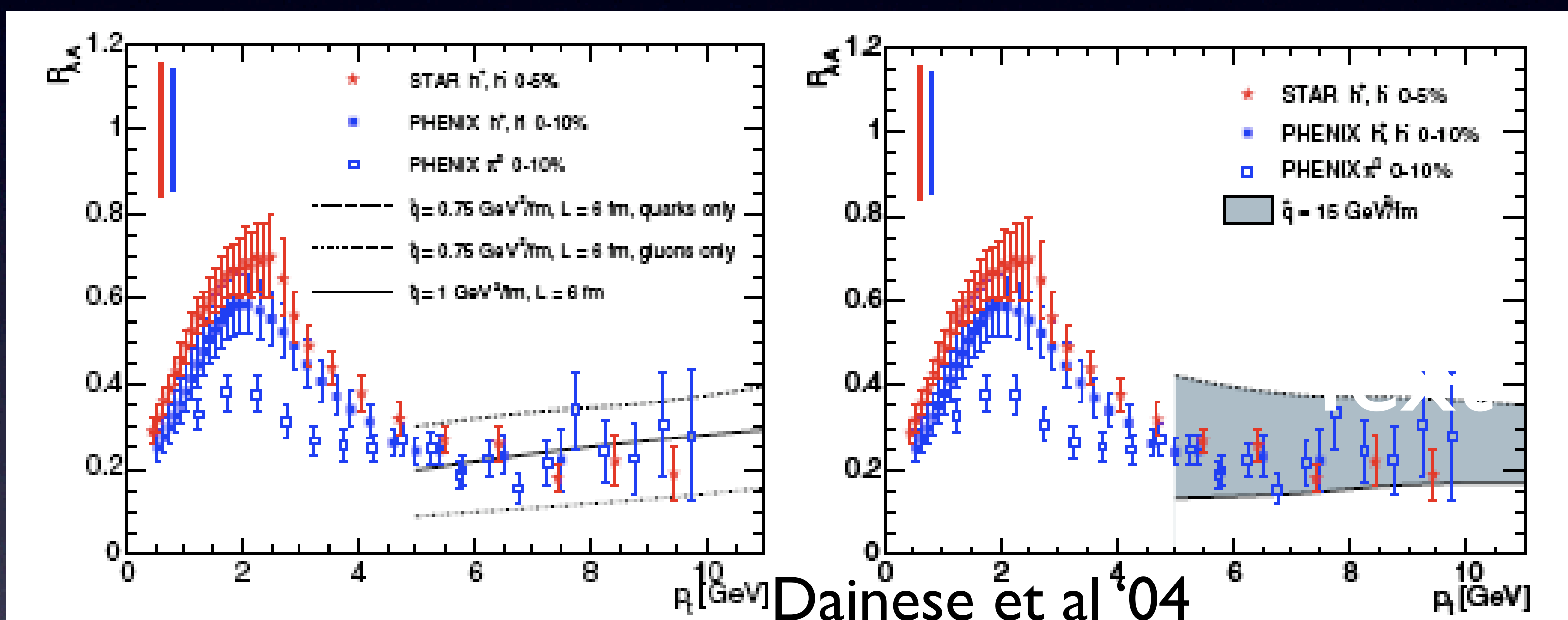
2.1. R_{AA} and btb for light:

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

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

BDMS '01; Wang et al '96

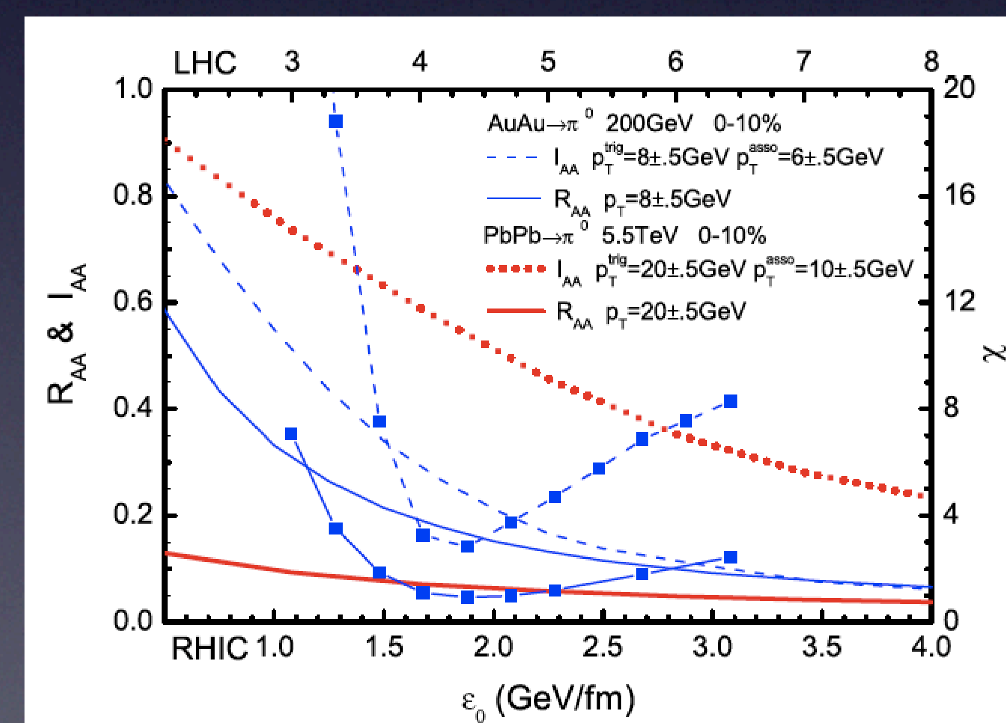
Medium modeling → $<\tau_0 \mathrm{qhat}>$=1-15GeV^2

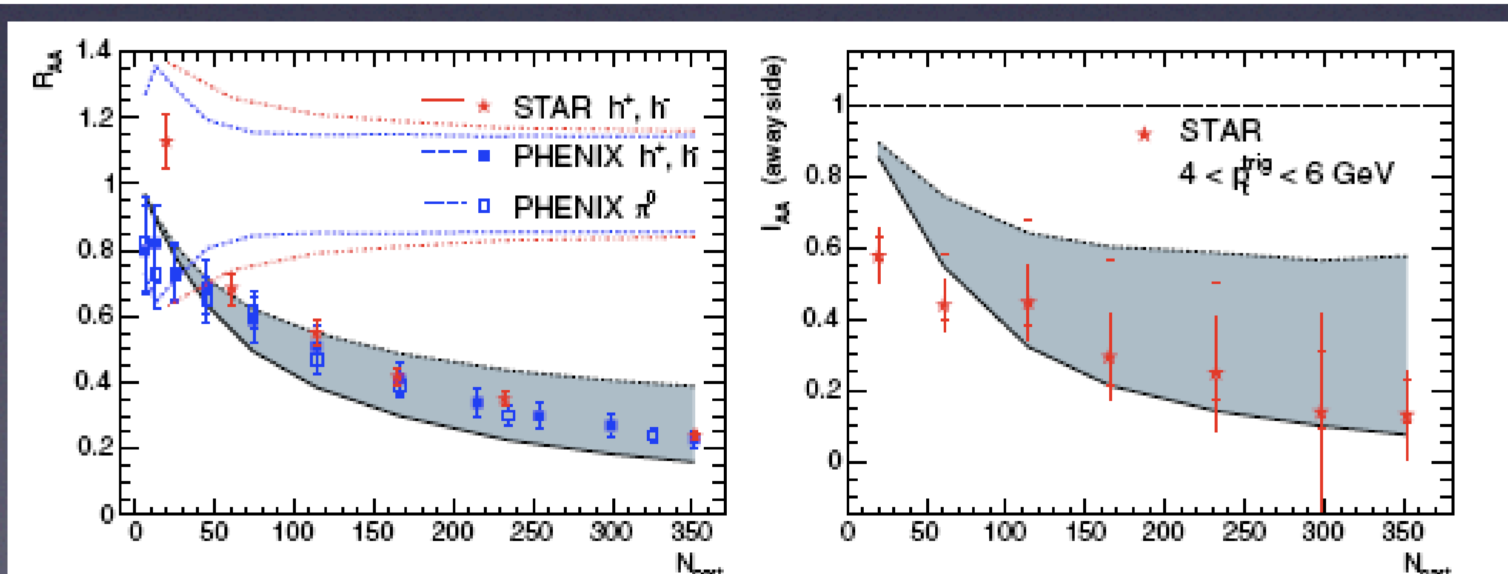


Dainese et al '04

Zhang et al '07

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





2.1. R_{AA} and btb for light:

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

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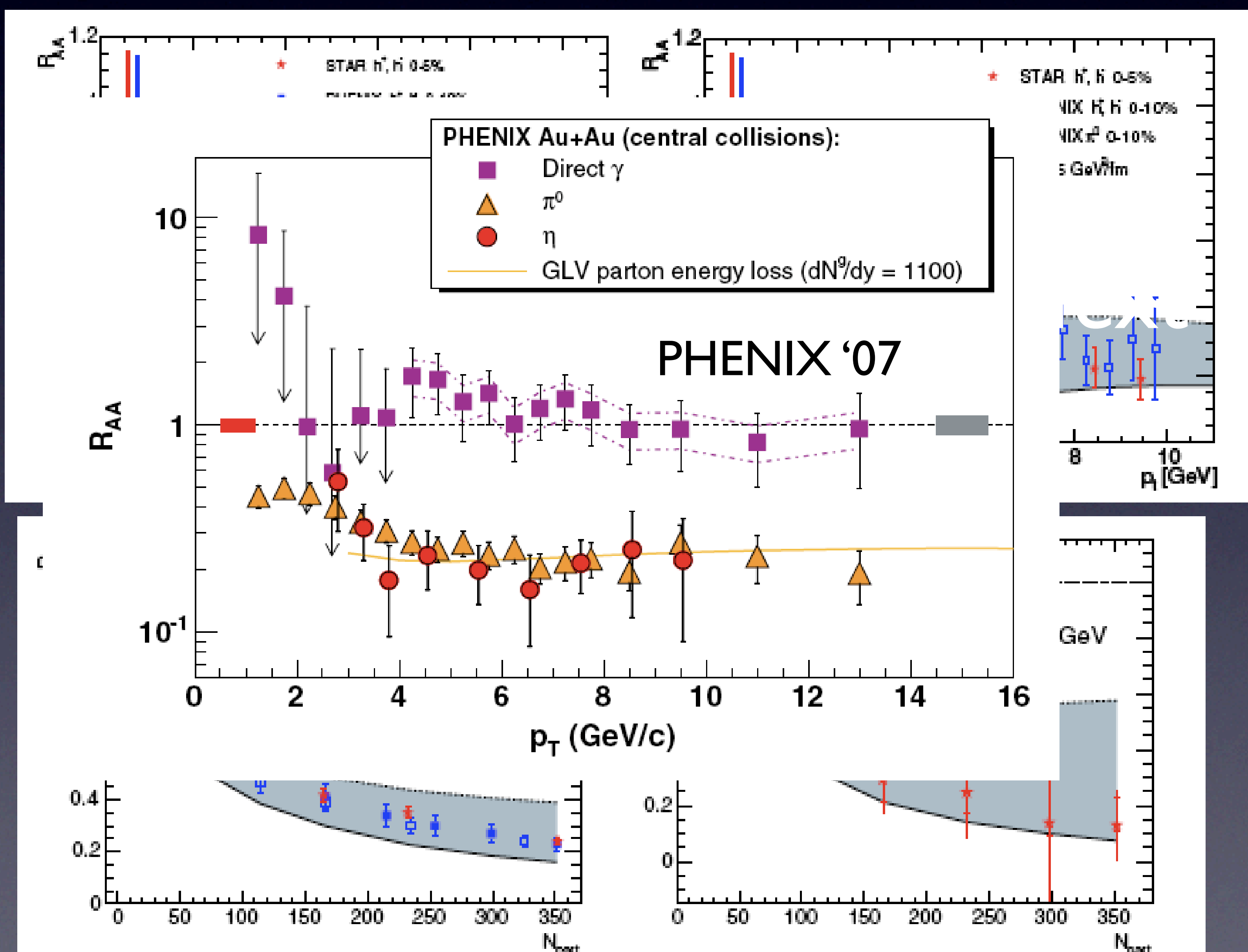
BDMS '01; Wang et al '96

Medium modeling → $<\tau_0\hat{q}>=1-15\,\mathrm{GeV}^2$



Zhang et al '07

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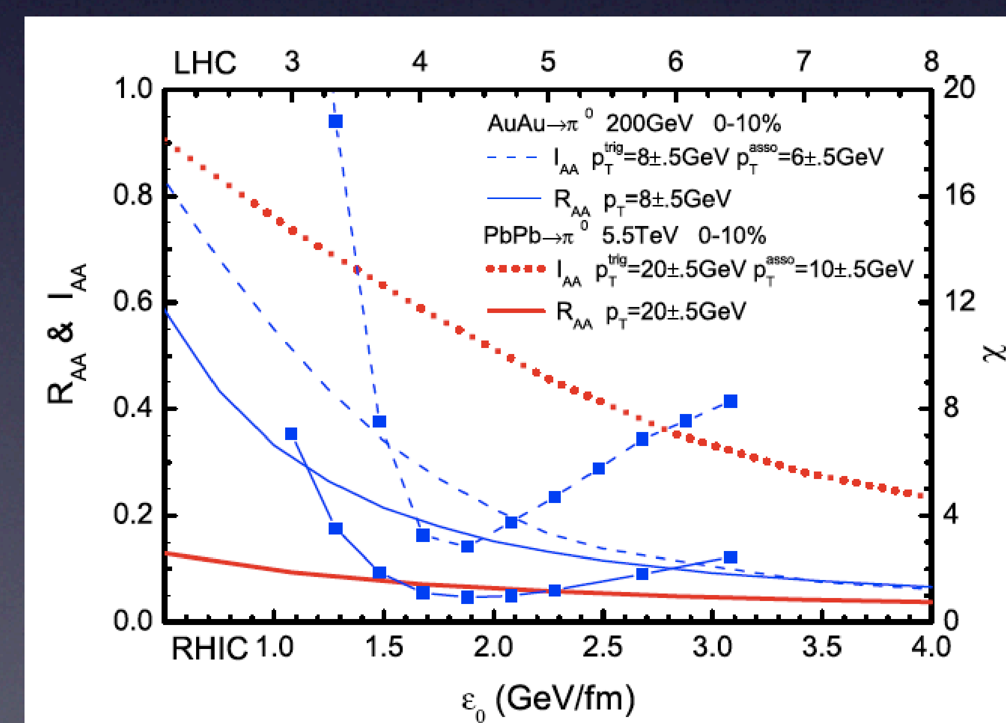

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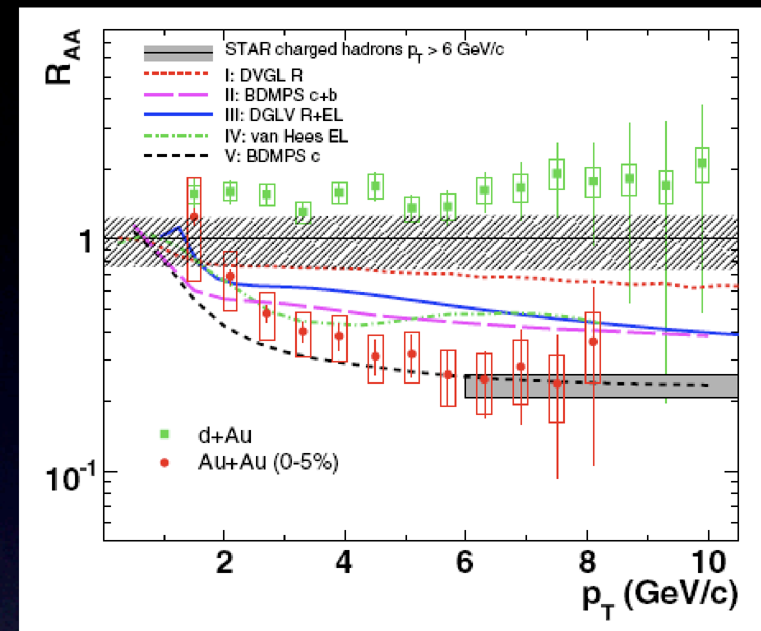
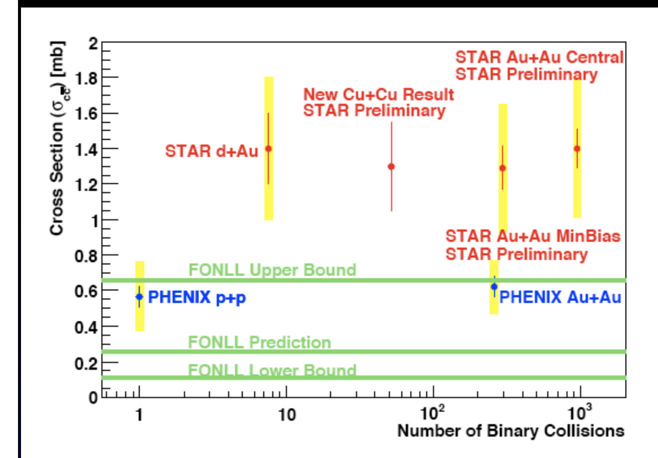
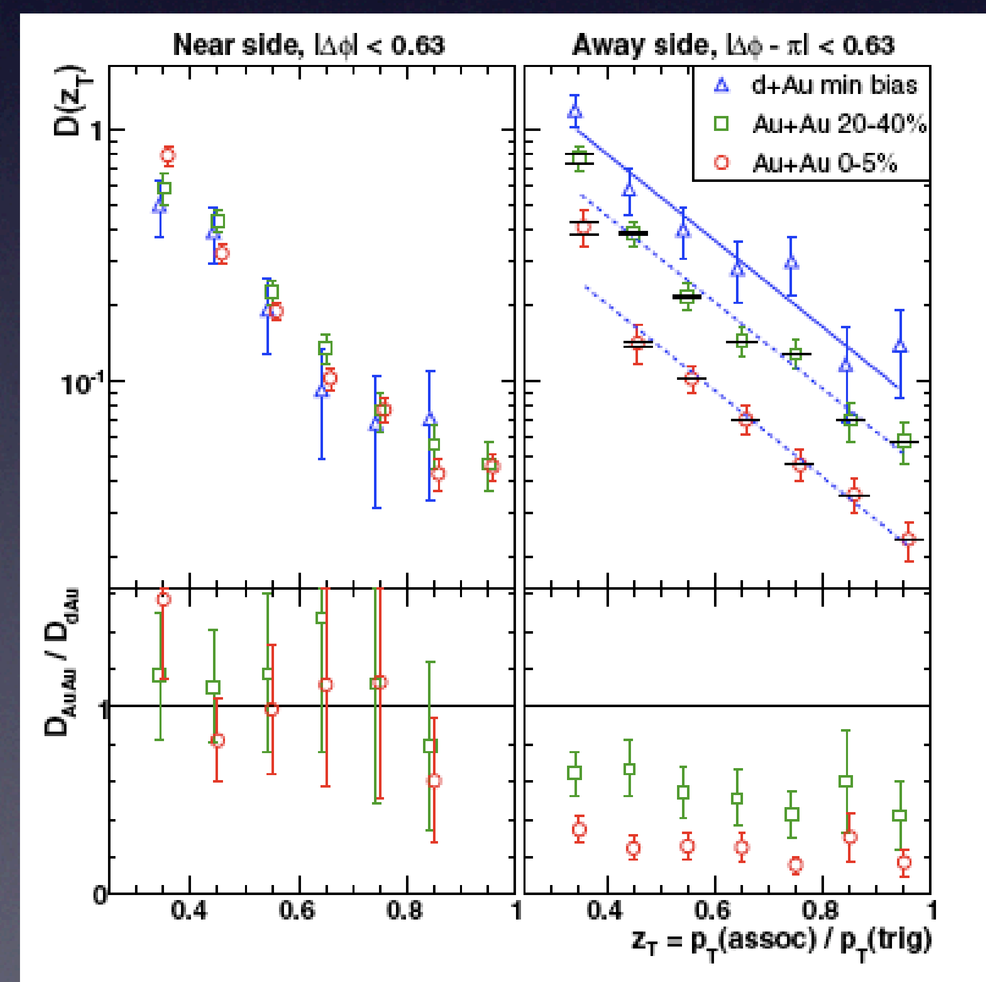
2.2. e's, differential observ.:

- Heavy quarks radiate less: non-photonic electrons not conclusive: benchmark (Armesto et al '05), hadronization (Adil et al '06), collisional (Djordjevic et al '06), resonances (van Hees et al '06), dynamical medium (Djordjevic et al. '08),...
- PseudoFF not well understood: no broadening at high p_t in the near side, trigger bias?





STAR '06, '07



2.3. qhat: medium modeling

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

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

Gyulassy et al. '01, Salgado et al. '02

Phenomenological implementation	qhat (GeV^2/fm)
fixed length	<~1 (average)
Woods-Saxon (PQM)	4-14 (average)
dynamical medium (Djordjevic et al.)	decreases
flow (Armesto et al., Baier et al.)	no effect
dilution	increases, factor 2-5
hydro (Eskola et al., Bass et al.)	K~3-4, late times important

2.4. Limitations of the formalism:

- Calculations done in the high-energy approximation: only soft emissions.
- Energy-momentum conservation imposed a posteriori in the single inclusive spectrum (SGLV; Salgado et al. '03).
- Multiple gluon emission: Quenching Weights (BDMS '01), independent (Poissonian) gluon emission: assumption!

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

- No role of virtuality in medium emissions (but GWM!).
- Medium and vacuum treated differently.

3. Beyond:

Recent attempts to go beyond (arXiv:0710.3073 [hep-ph], JHEP to appear, with L. Cunqueiro, C. A. Salgado, *Santiago* and W.-C. Xiang, *Wuhan and Bielefeld*); also with G. Corcella (*Pisa*).

Motivation: to check radiative eloss, more differential and unbiased observables (particle correlations and jets) have to be studied (others: Borghini et al. '05-..., Wang et al. '01-..., Vitev '05, Polosa et al. '06) → Monte Carlo for in-medium parton branching.

3.1. Medium-modified splitting functions (SF) and Sudakovs.

3.2. Medium-modified DGLAP evolution of frag. funct. (FF).

3.3. Preliminary: PYTHIA with in-medium branching.

3.1. Medium-modified SF and Sudakovs:

In the vacuum, the formalism gives collinear (z→1) SFs:

$$\frac{dI^{\rm vac}}{dz\,d{\bf k}_\perp^2} = \frac{\alpha_s}{2\pi}\frac{1}{{\rm k}_\perp^2}P^{\rm vac}(z), \quad P^{\rm vac}(z) \simeq \frac{2C_R}{1-z}$$

$$\omega = (1-z)E \ \text{and} \ {\bf k}_\perp^2 = z(1-z)t$$

In the medium, we make the analogy (ansatz!!!) (Polosa et al. '06):

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z,t)$$

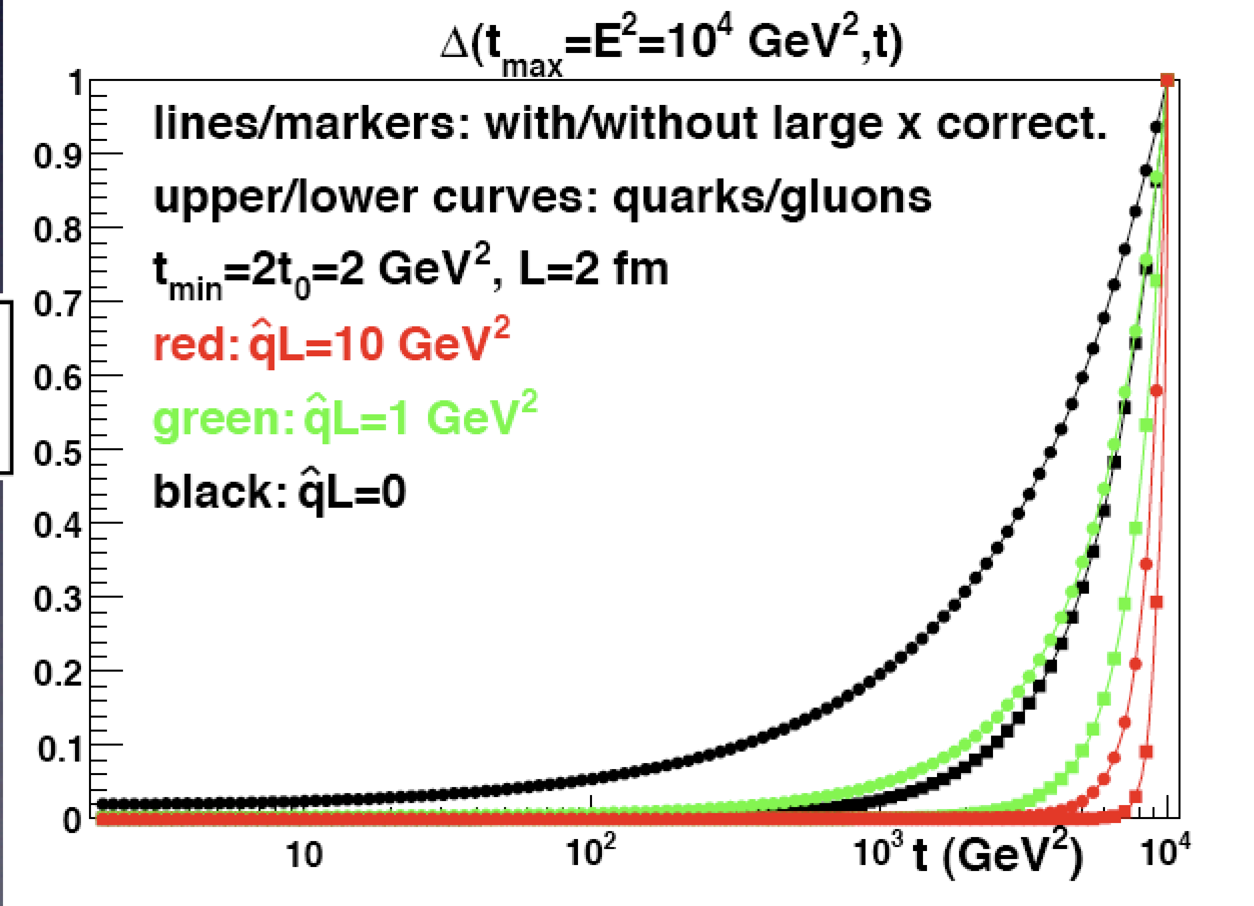
$$\Delta P(z,t) \simeq \frac{2\pi t}{\alpha_s}\frac{dI^{\rm med}}{dzdt}$$

Medium-modified Sudakovs:

$$\Delta_i(t) = \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int_{z_{min}(t')}^{1-z_{min}(t')} dz\frac{\alpha_s(t',z)}{2\pi}\sum_j P_{i\to j}(z,t')\right]$$

$$z_{min}(t) = t_0/t$$

3-flavor coupling with scale k_T^2; different small-z extensions.

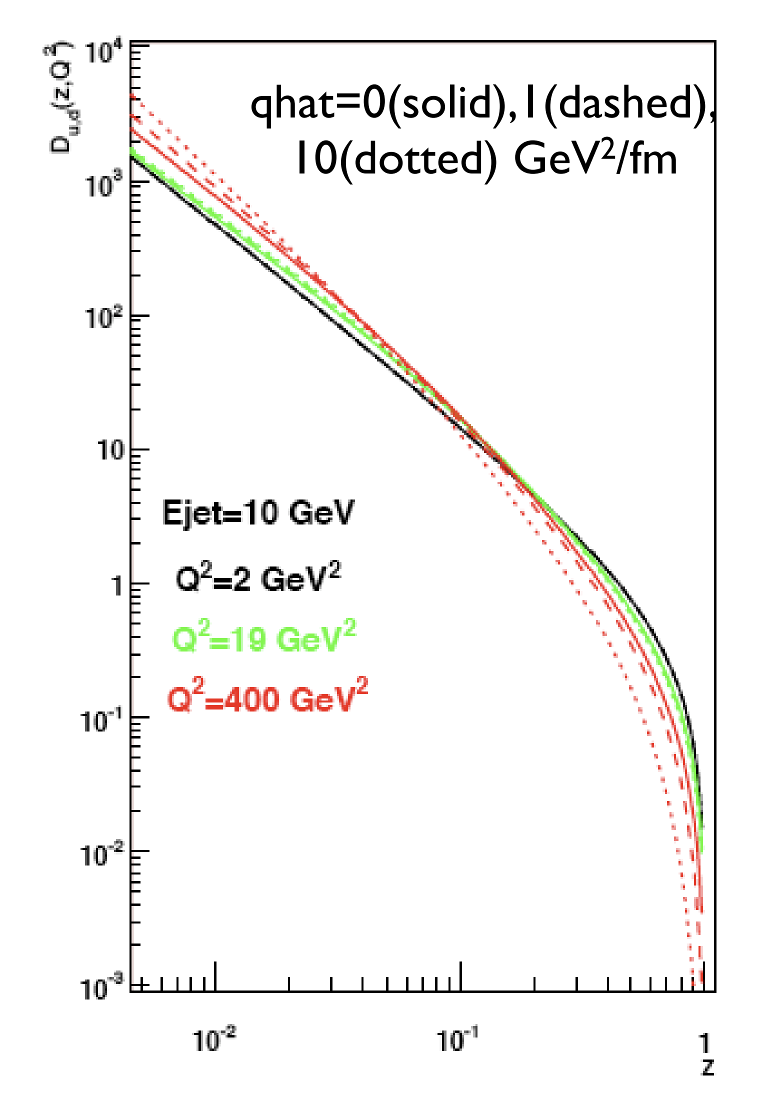


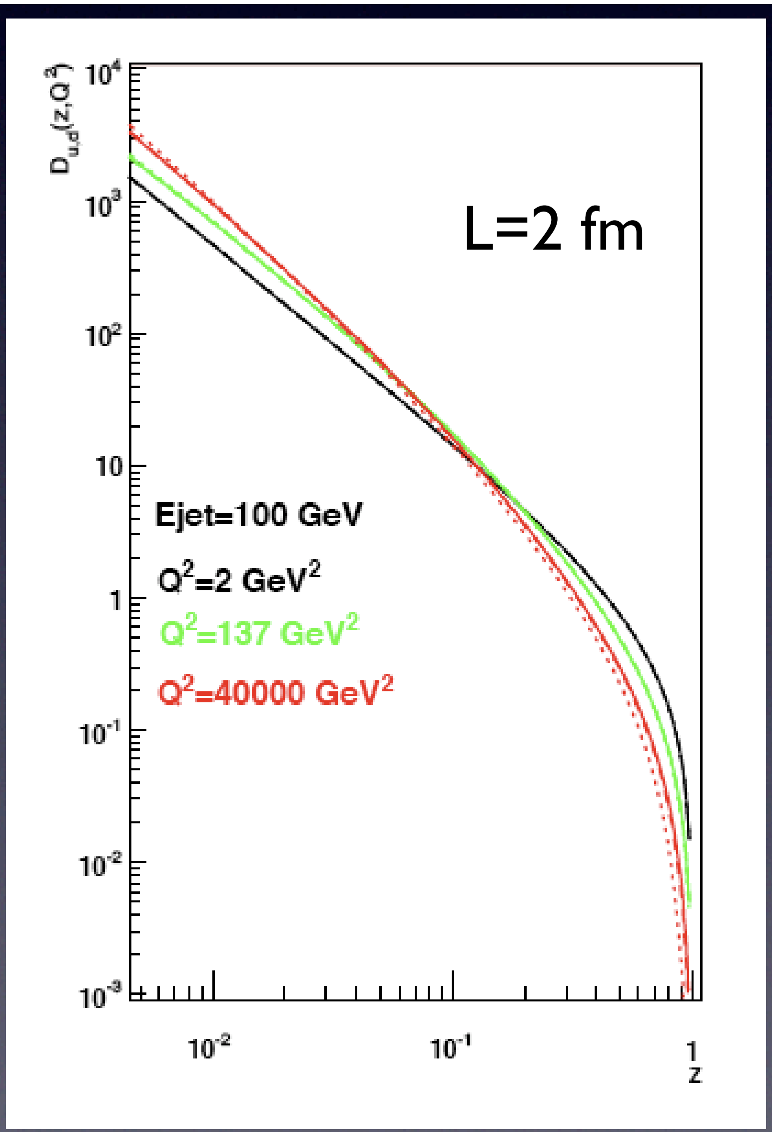
3.2. Medium modified DGLAP evolution of FF (I):

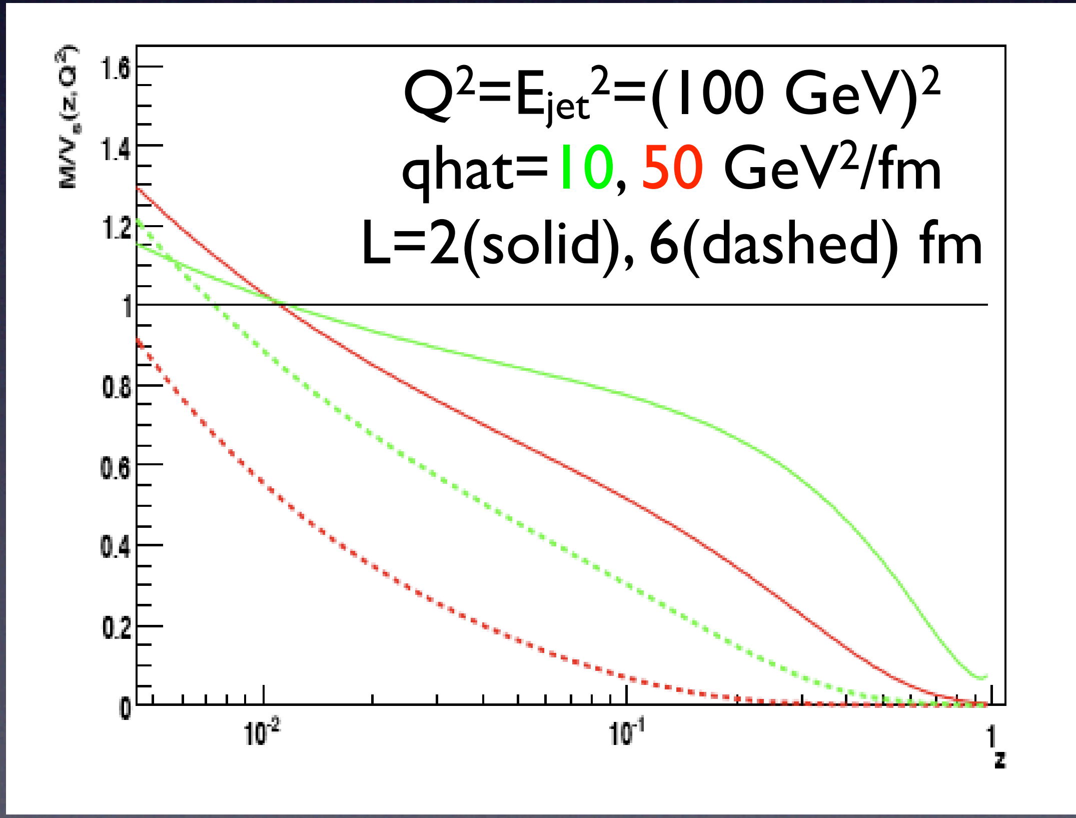
- Medium-modified DGLAP evolution of FF (from KKP IC):

$$D(x,t) = \Delta(t)D(x,t_0) + \Delta(t)\int_{t_0}^{t}\frac{dt_1}{t_1}\frac{1}{\Delta(t_1)}\int\frac{dz}{z}P(z)D\left(\frac{x}{z},t_1\right)$$

$$D^{\rm med}(x,t_0) = D^{\rm vac}(x,t_0)$$

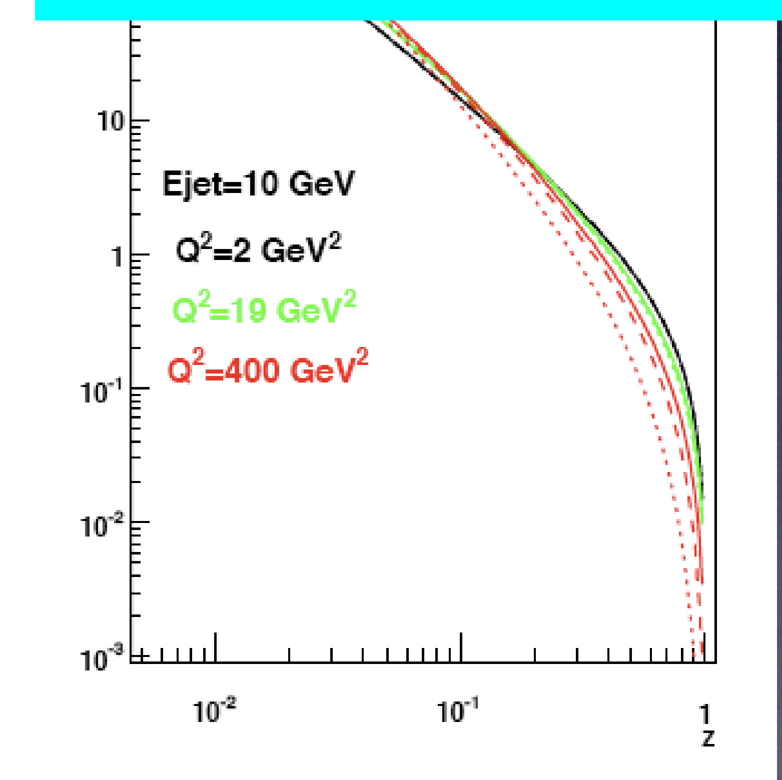


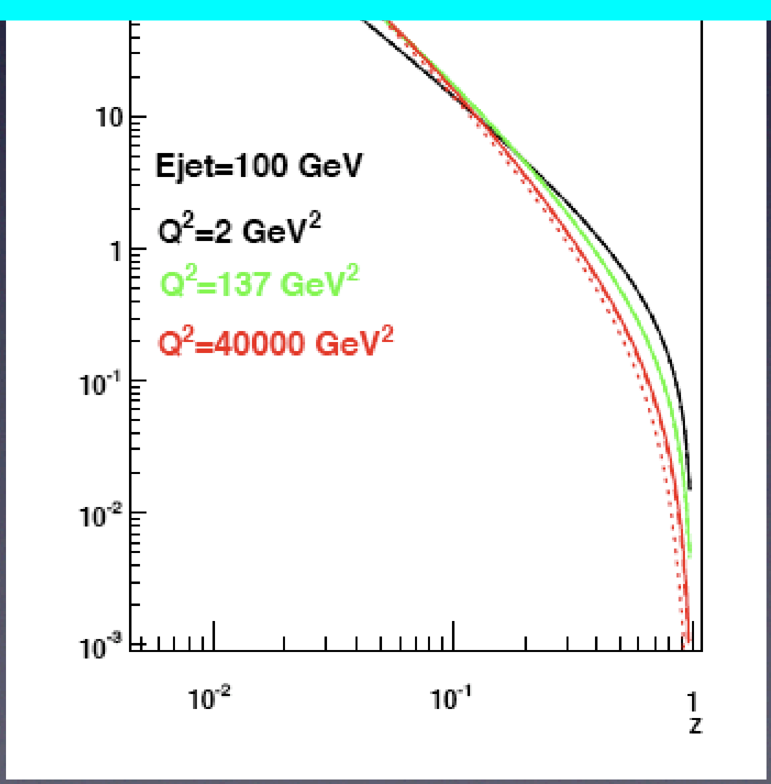


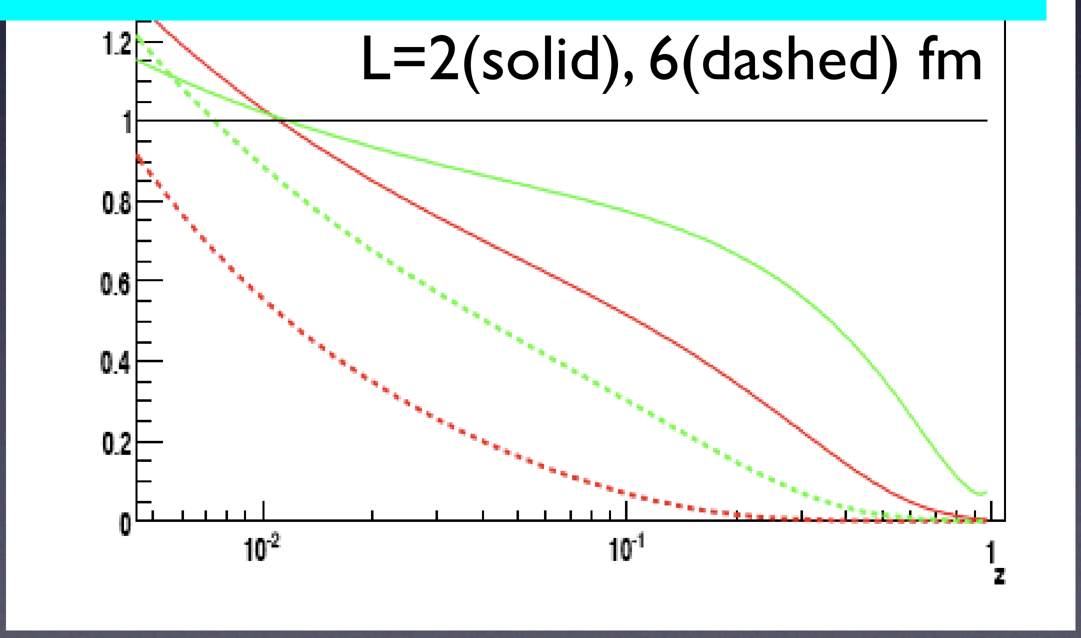


3.2. Medium modified DGLAP evolution of FF (I):

- ➪ Improvements: virtuality in medium emissions, medium and vacuum treated on the same footing, energy momentum conservation.
- ➪ Drawbacks: formation time of the gluons does not affect the medium length seen by the radiating partons; no elastic scattering, no conversions included.

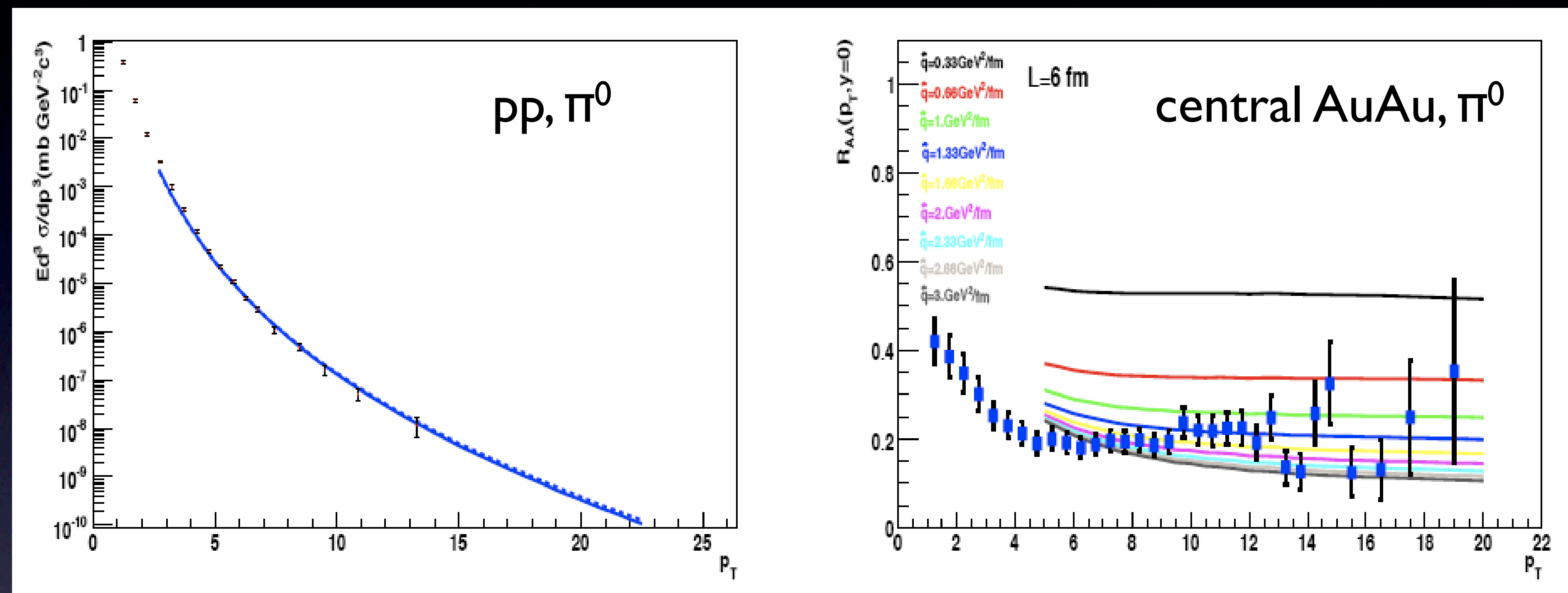




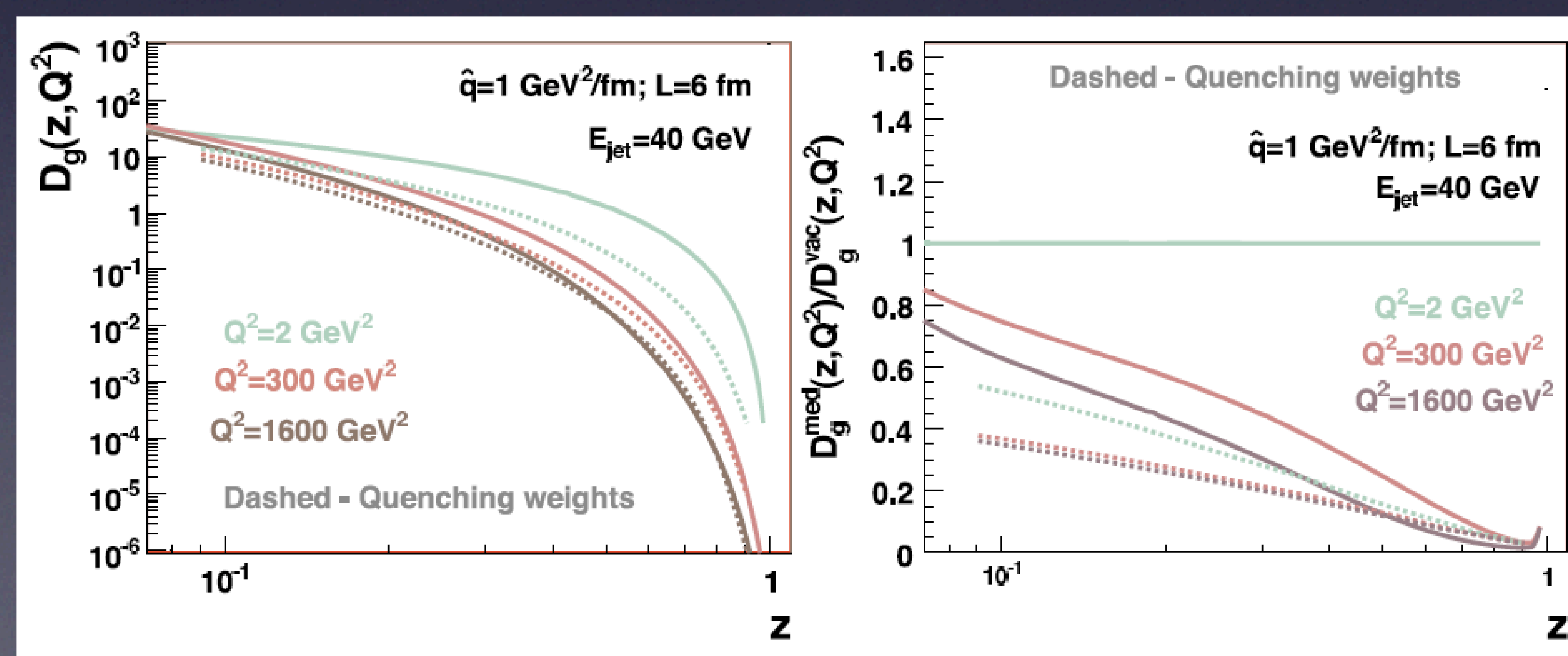


3.2. Medium modified DGLAP evolution of FF (II):

Comparison with experimental data gives qhat~1 GeV²/fm (as with QW for fixed L) or qhat~10 GeV²/fm (for cylinder or sphere).



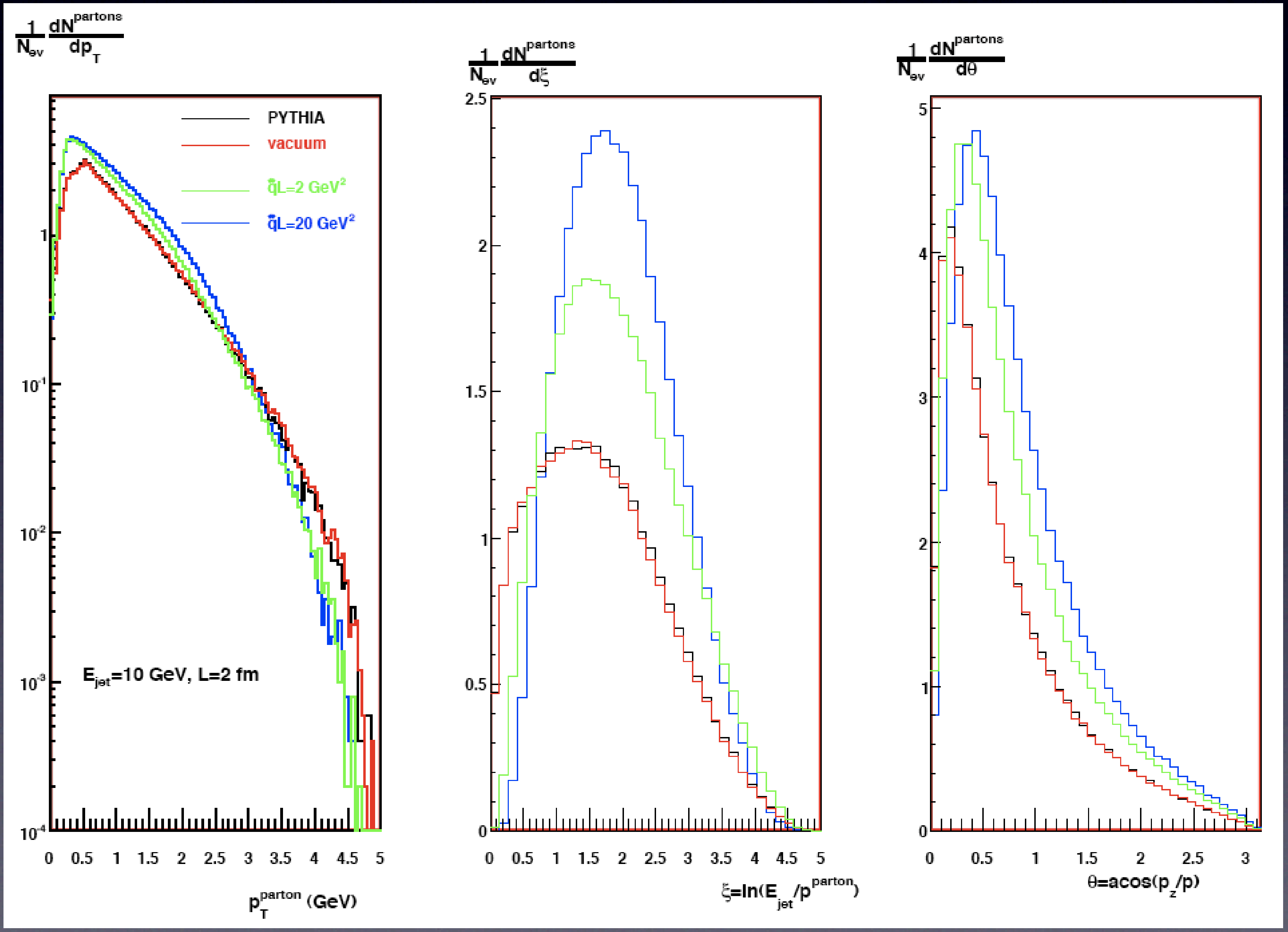
QW reproduced (numerically and analytically) for high energies and virtualities.



3.3. Medium-mod. PYTHIA (I):

- We modify PYTHIA FSR (pyshow) routine introducing the medium-modified splittings and Sudakovs.

Good agreement between default and vacuum; medium enhancement at intermediate, decrease at large p_T.



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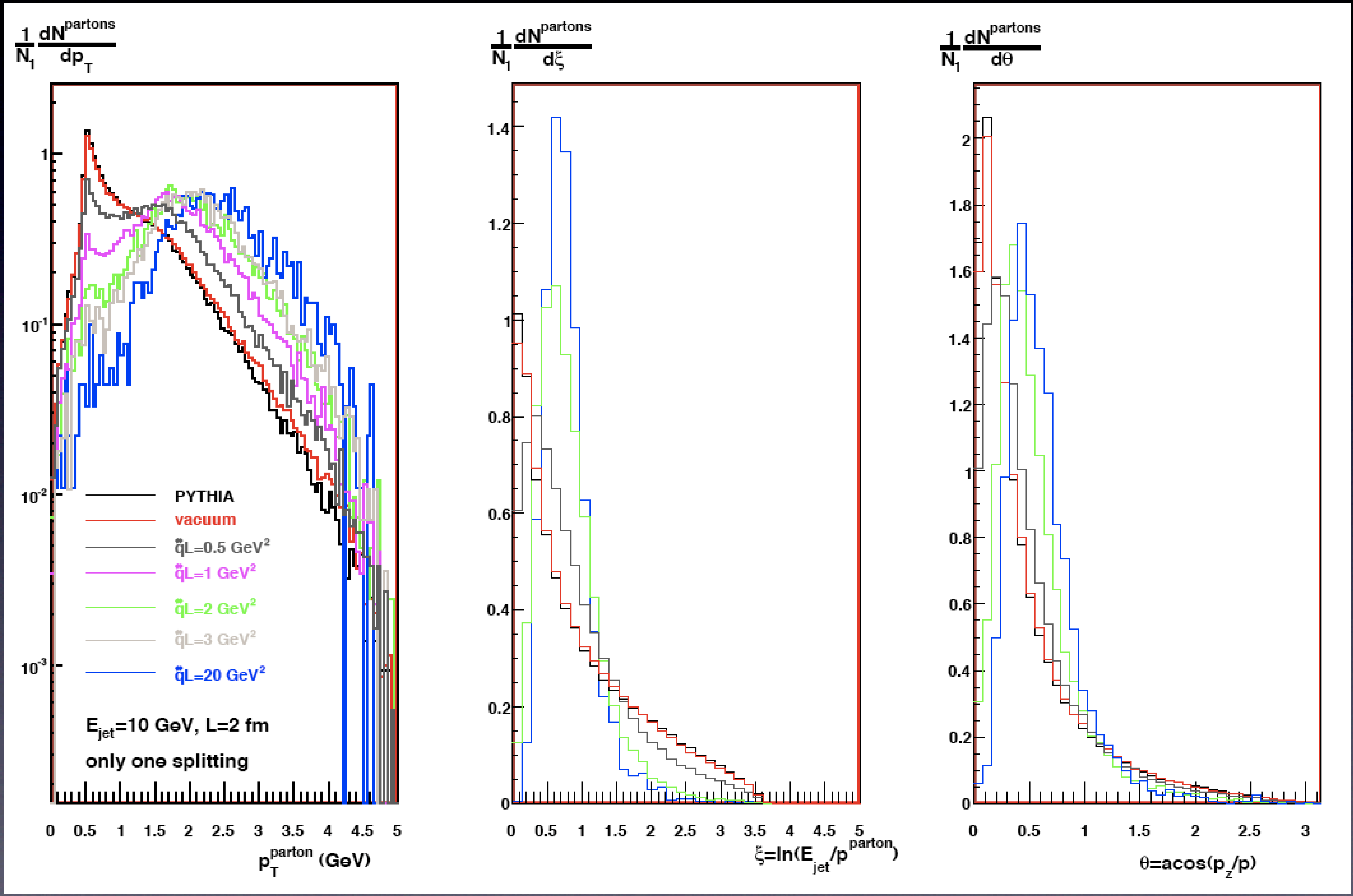
3.3. Medium-mod. PYTHIA (II):

For just one splitting, clear p_T and angular broadening (Vitev '06, Salgado-Polosa '06): importance of multiple splitting.



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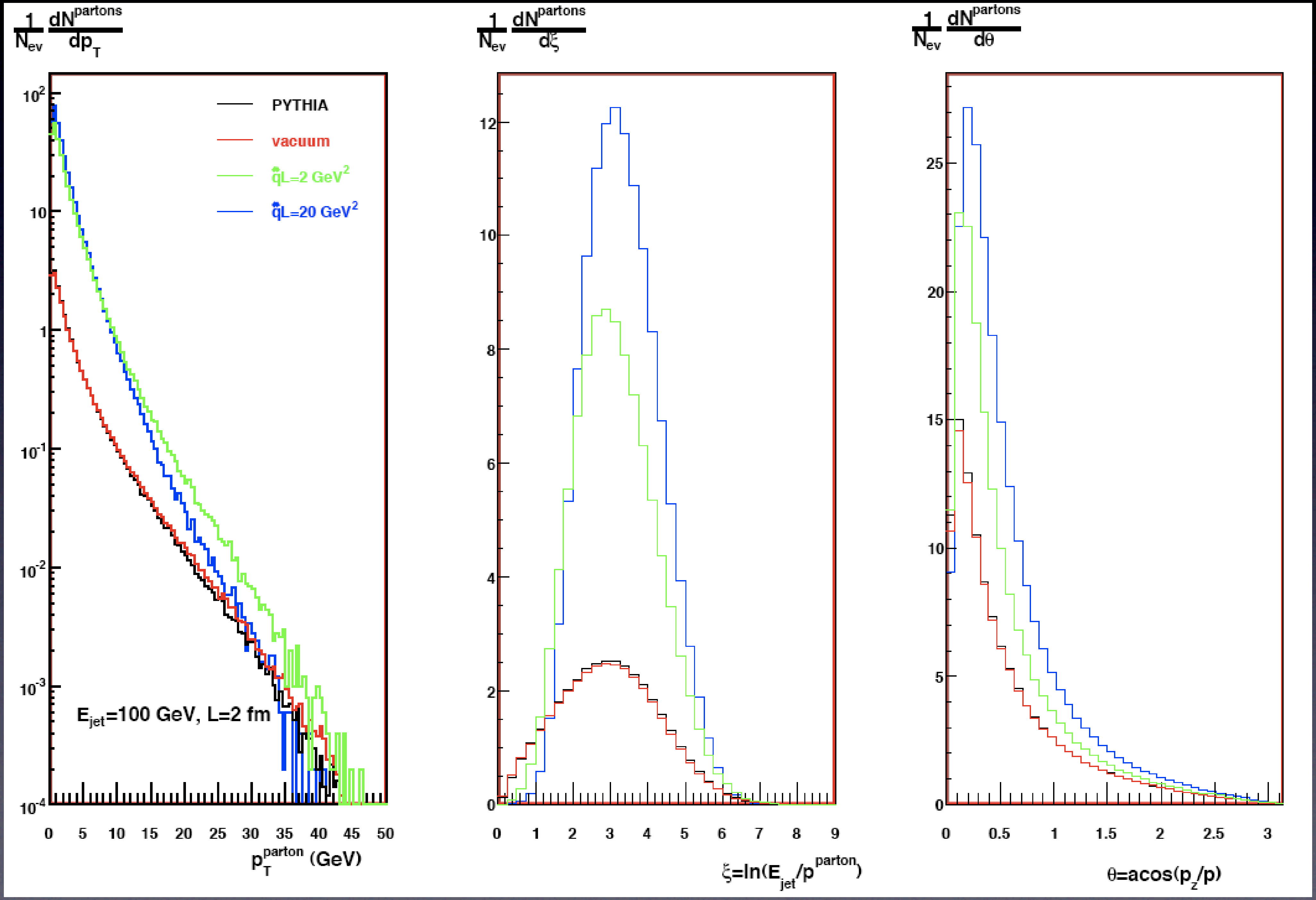
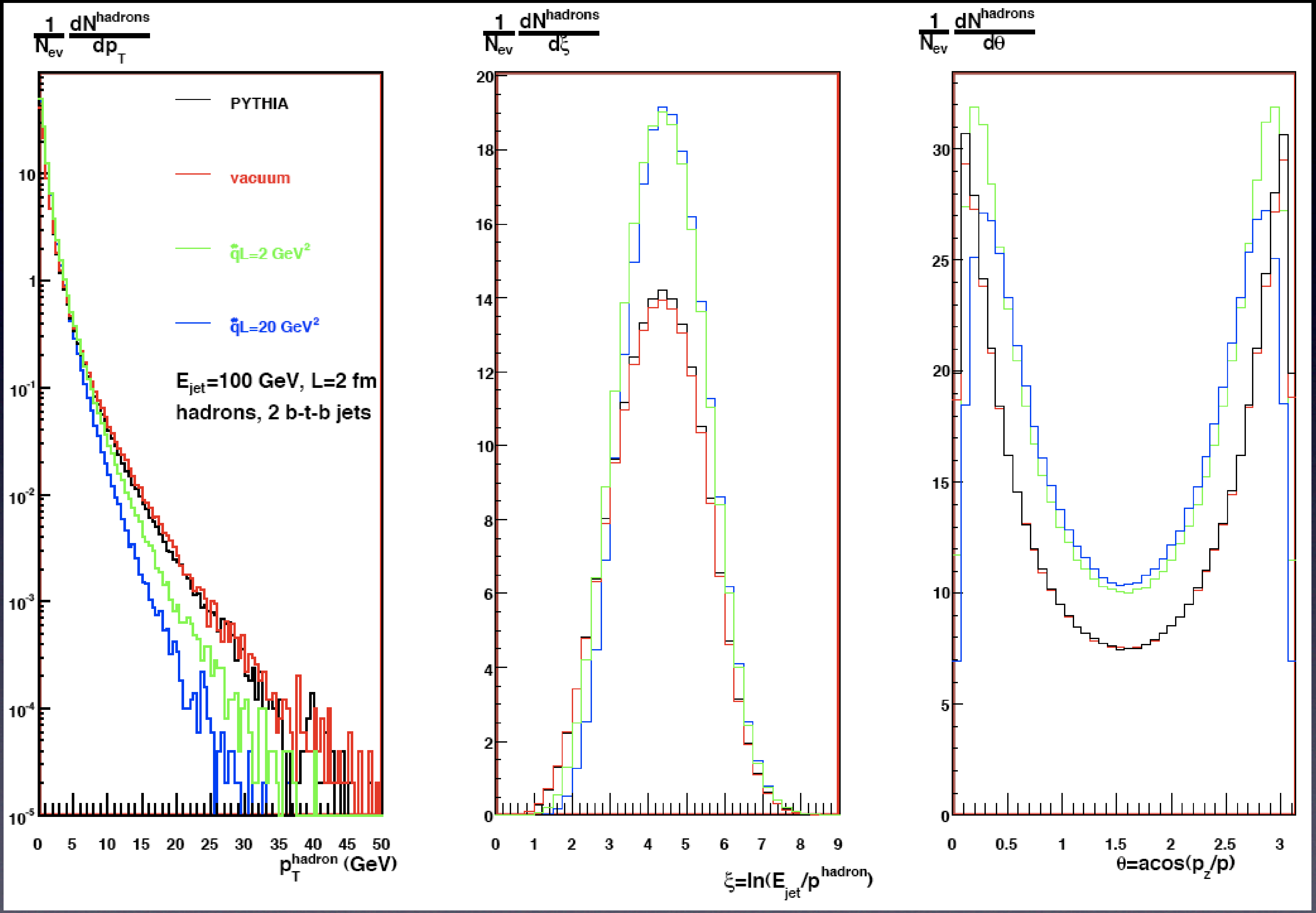
3.3. Medium-mod. PYTHIA (III):

At parton level and for high energy, high multiplicity enhancement and modest broadening.



3.3. Medium-mod. PYTHIA (IV):

A extreme example of hadronization kills most of the multiplicity enhancement, medium effects (soft stuff) less evident.



4. Summary:

- To check radiative energy loss as the explanation for jet quenching, differential probes needed: relation energy degradation / radiation enhancement / p_T broadening.
- We have supplemented vacuum splitting functions with medium terms, based on an analogy with radiation spectra: virtuality, energy conservation, and vacuum and medium treated on the same footing.
- A modified DGLAP evolution for fragmentation functions has been performed (proof of principle), and its compatibility with QWs for high virtualities showed.
- A medium-modified parton shower is under development, required for correlations and jet shape studies: LHC.

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 GeV²/fm.

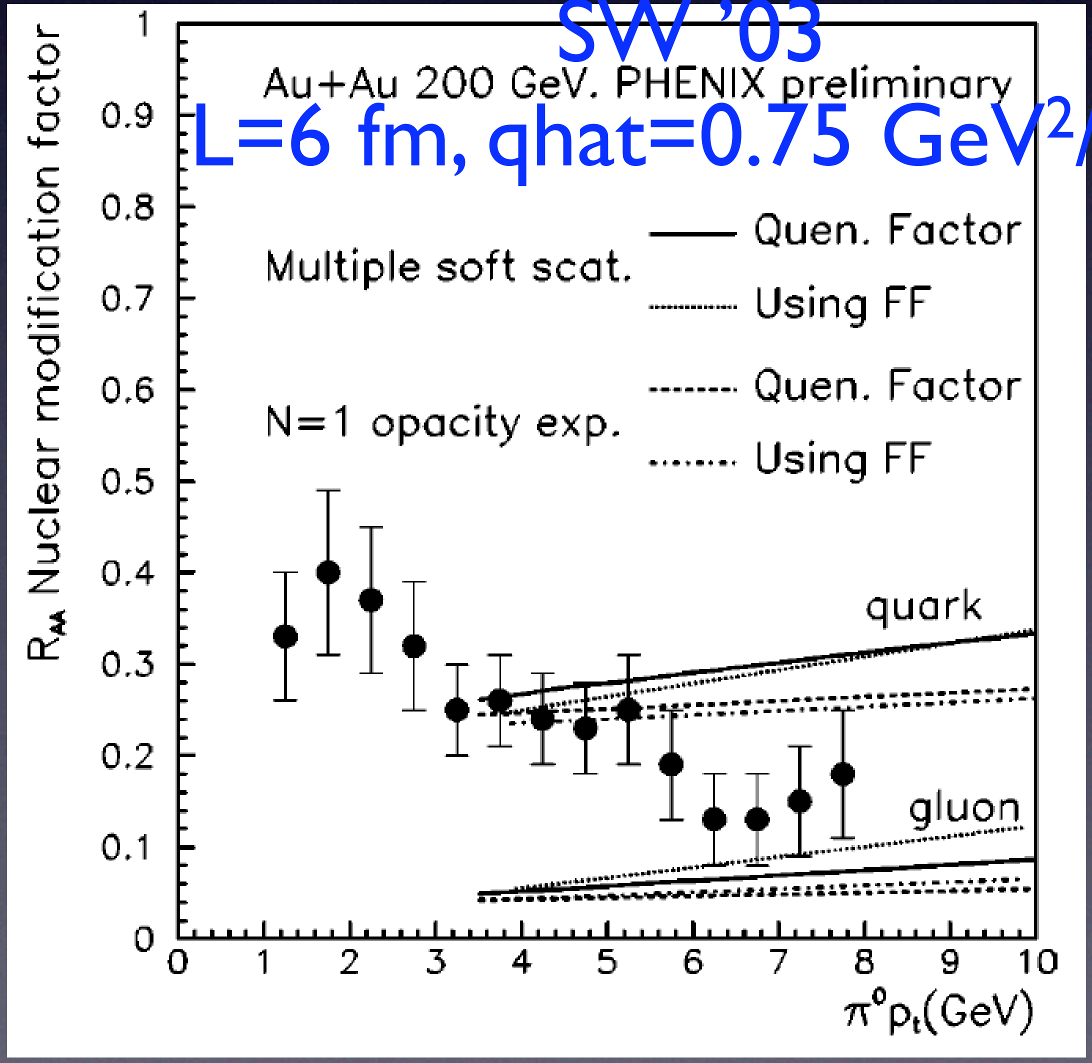
$$Q(p_\perp) = \frac{d\sigma^{\rm med}(p_\perp)/dp_\perp^2}{d\sigma^{\rm vac}(p_\perp)/dp_\perp^2} = \int d\Delta E\, P(\Delta E) \left(\frac{d\sigma^{\rm vac}(p_\perp + \Delta E)/dp_\perp^2}{d\sigma^{\rm vac}(p_\perp)/dp_\perp^2} \right)$$

BDMS '01; Wang et al '96

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

SW '03

L=6 fm, qhat=0.75 GeV²/fm



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

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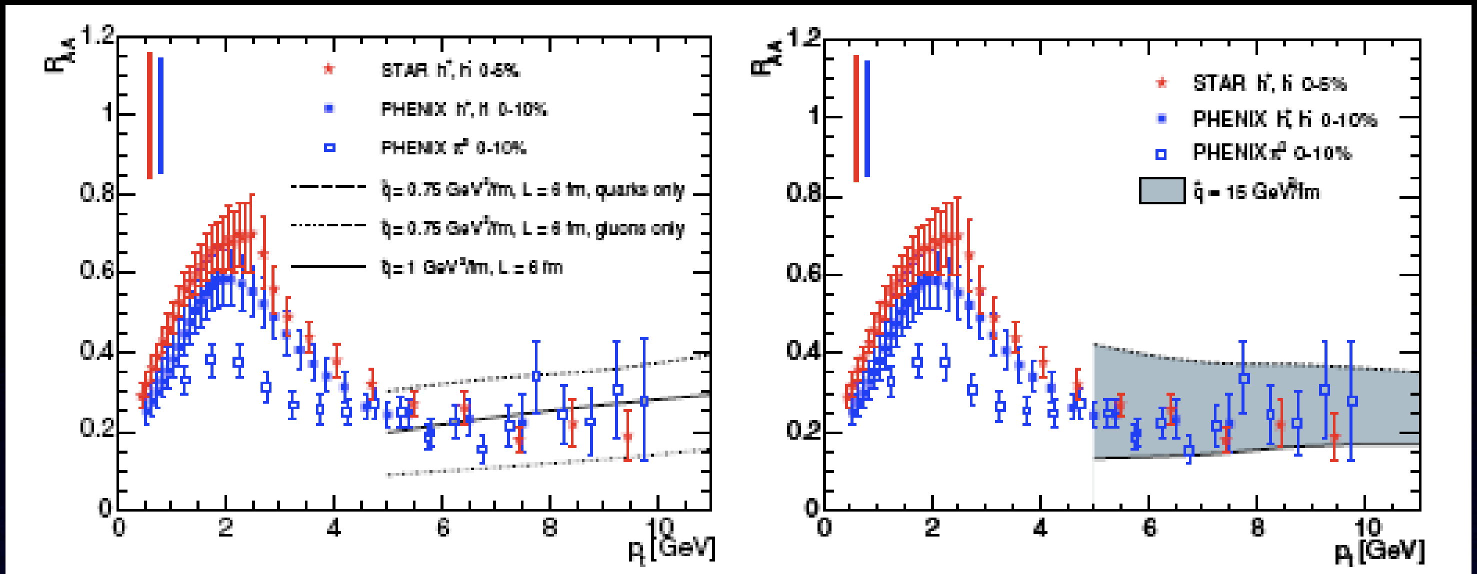
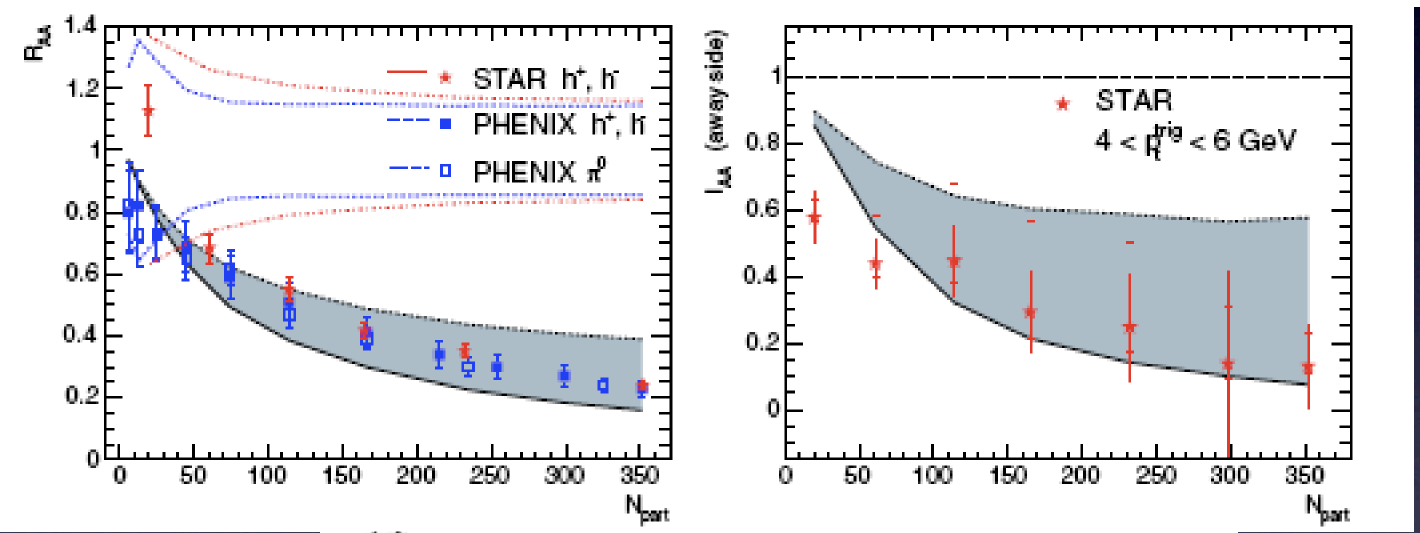
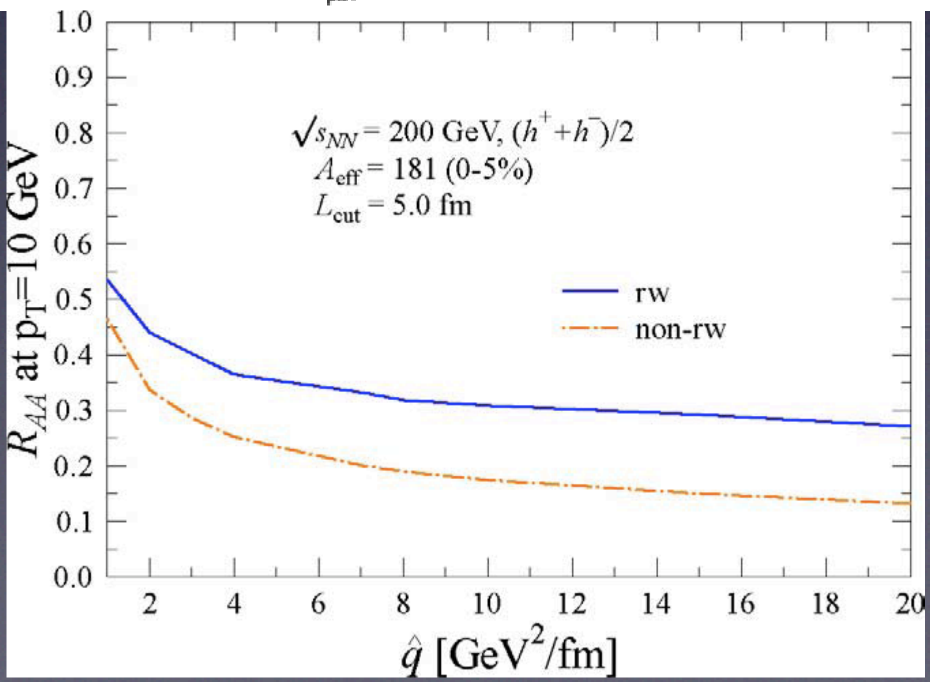
- A Woods-Saxon geometry (production plus ‘medium’) gives larger values and leads to saturation: fragility (Dainese et al, Eskola et al ‘04).
- Surface bias (Muller ‘03).
- <qhat>=4-14 GeV^2/fm.
- Energy constraints (Baier et al ‘06); energy dependence (Casalderrey et al ‘07).







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

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- 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?

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

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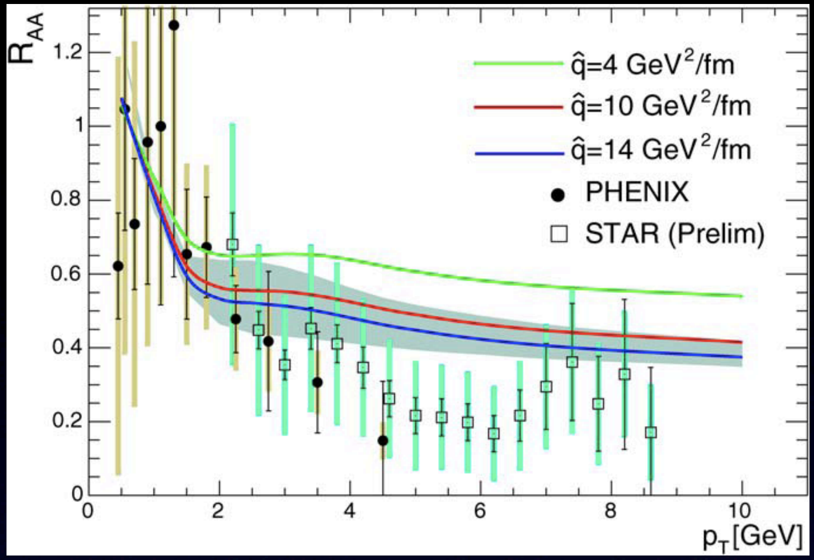
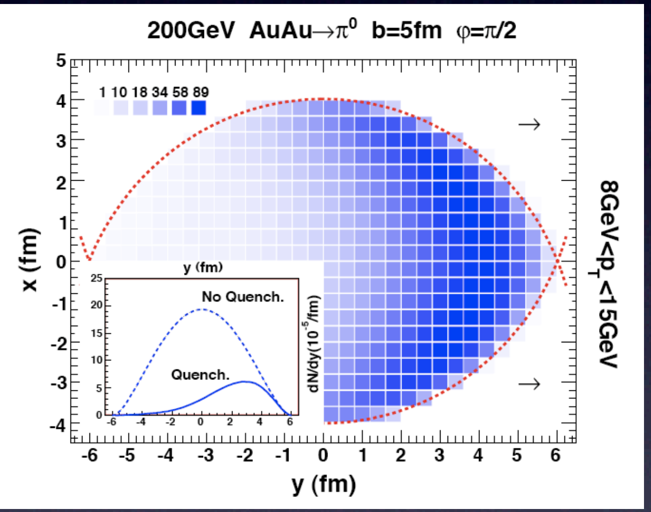
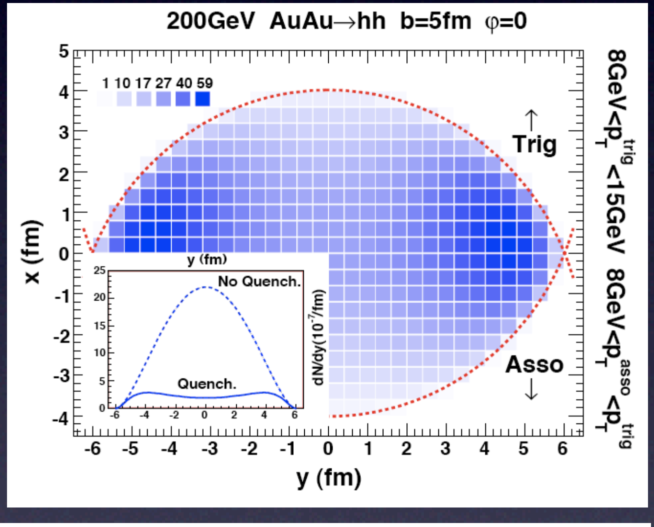
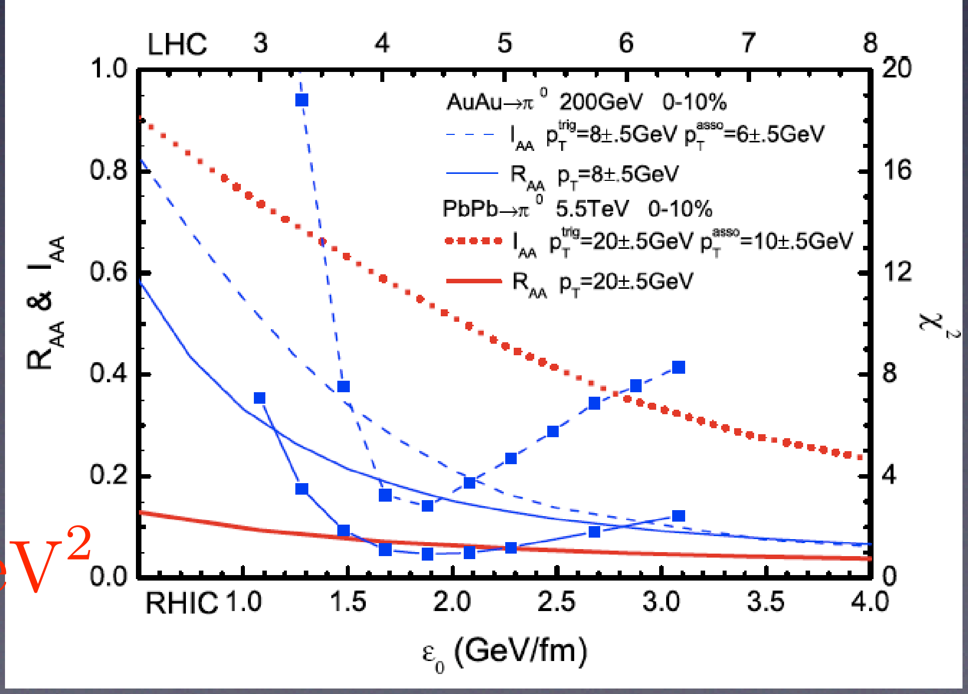
- **Non-photonic electrons** not conclusive: benchmark (Armesto et al '05), hadronization inside (Adil et al '06), collisional (Djordjevic et al '06)...







- **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.



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

On the determination of the transport coefficient.

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.

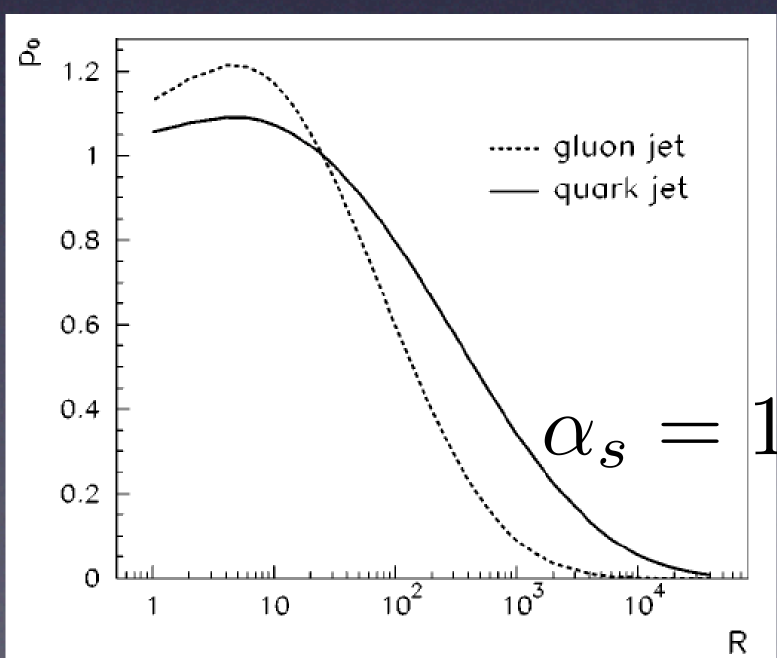
$$Q(p_\perp) = \frac{d\sigma^{med}(p_\perp)/dp_\perp^2}{d\sigma^{vac}(p_\perp)/dp_\perp^2}$$

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

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

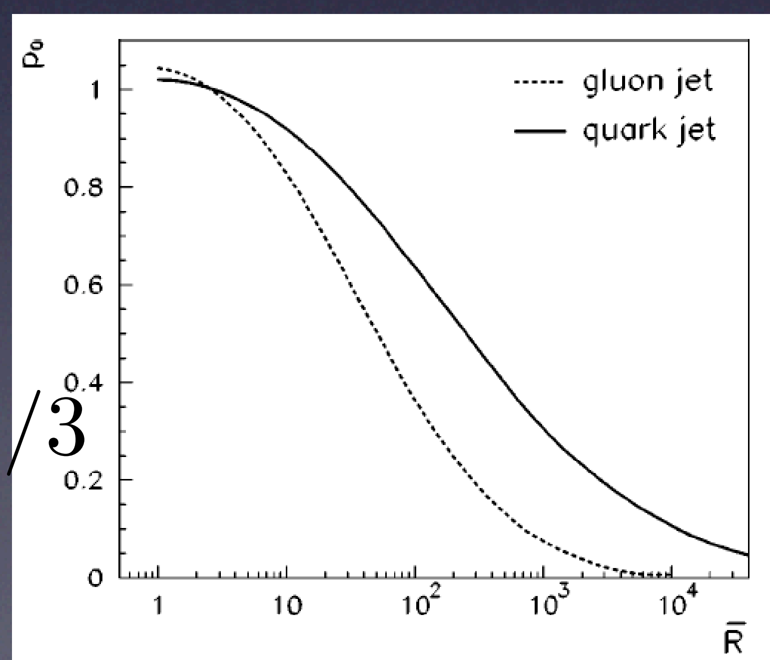
$$\omega_c = \frac{1}{2}\hat{q}L^2, \quad R = \omega_c L, \quad L/\lambda = 1$$

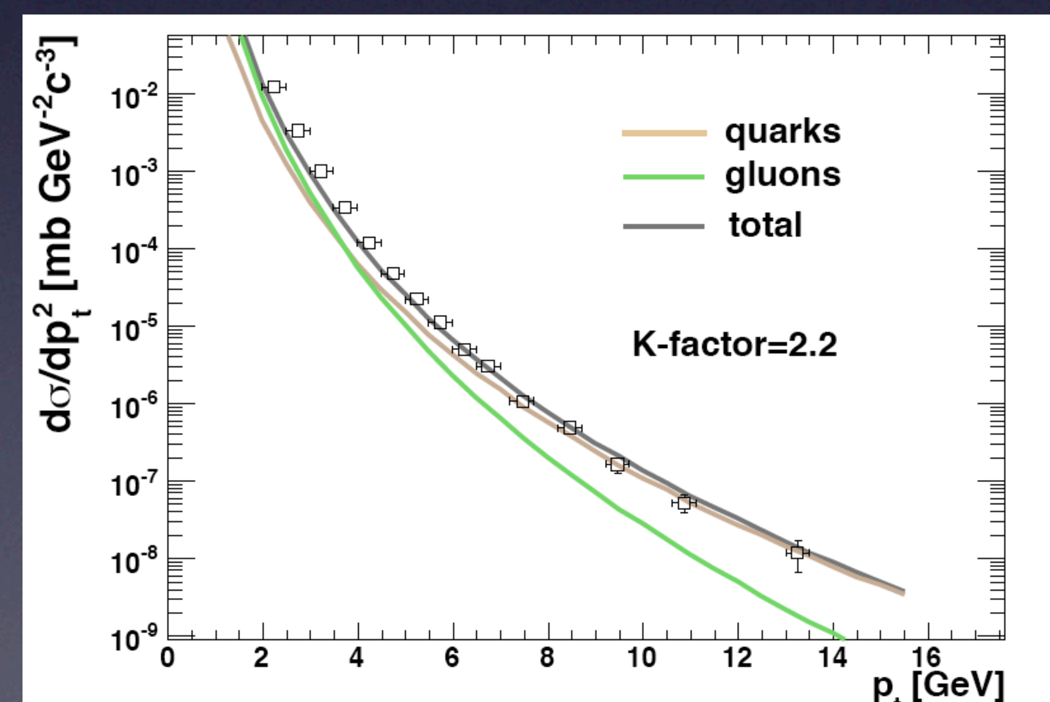
multiple soft



$\alpha_s = 1/3$

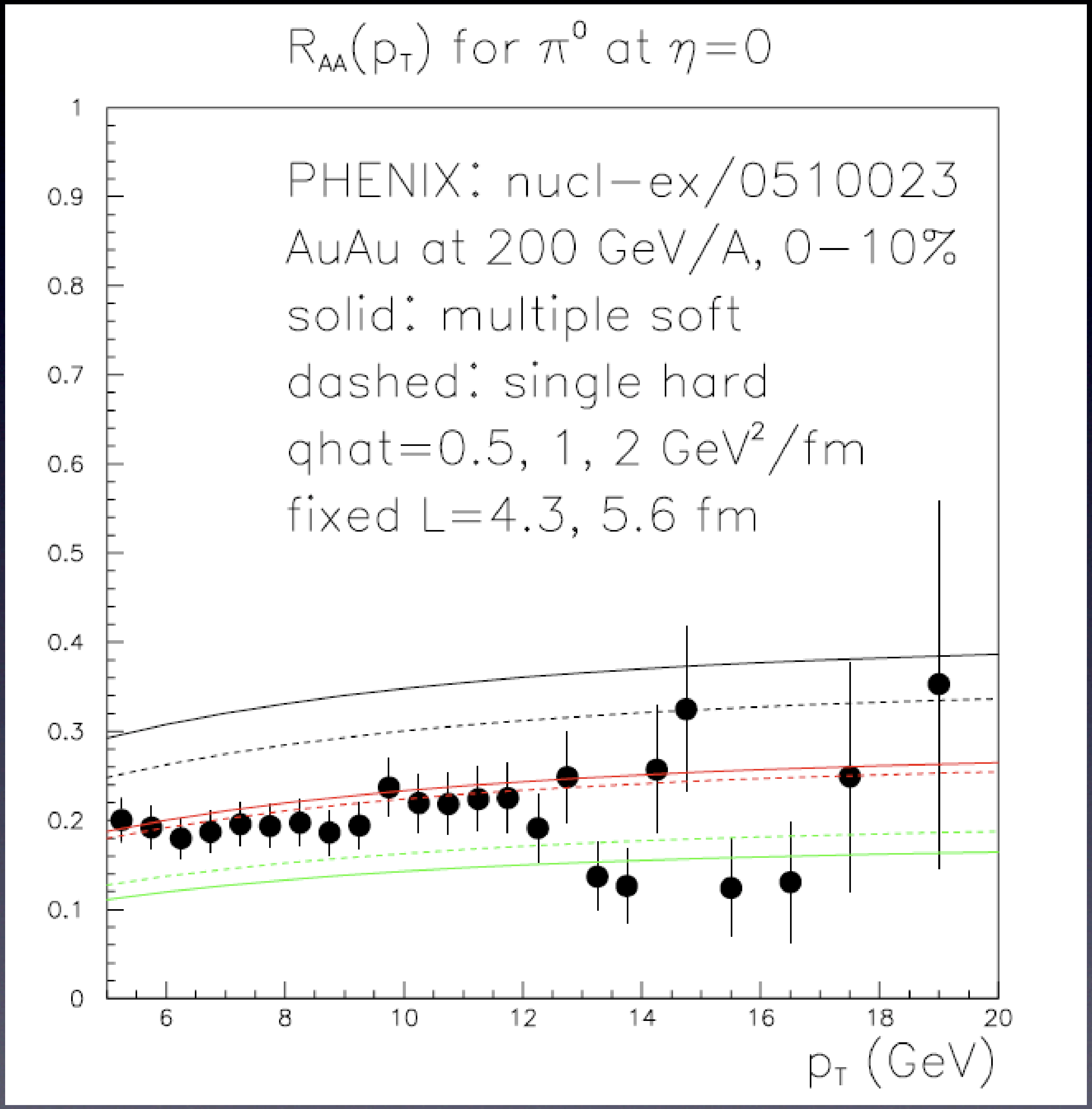
single hard

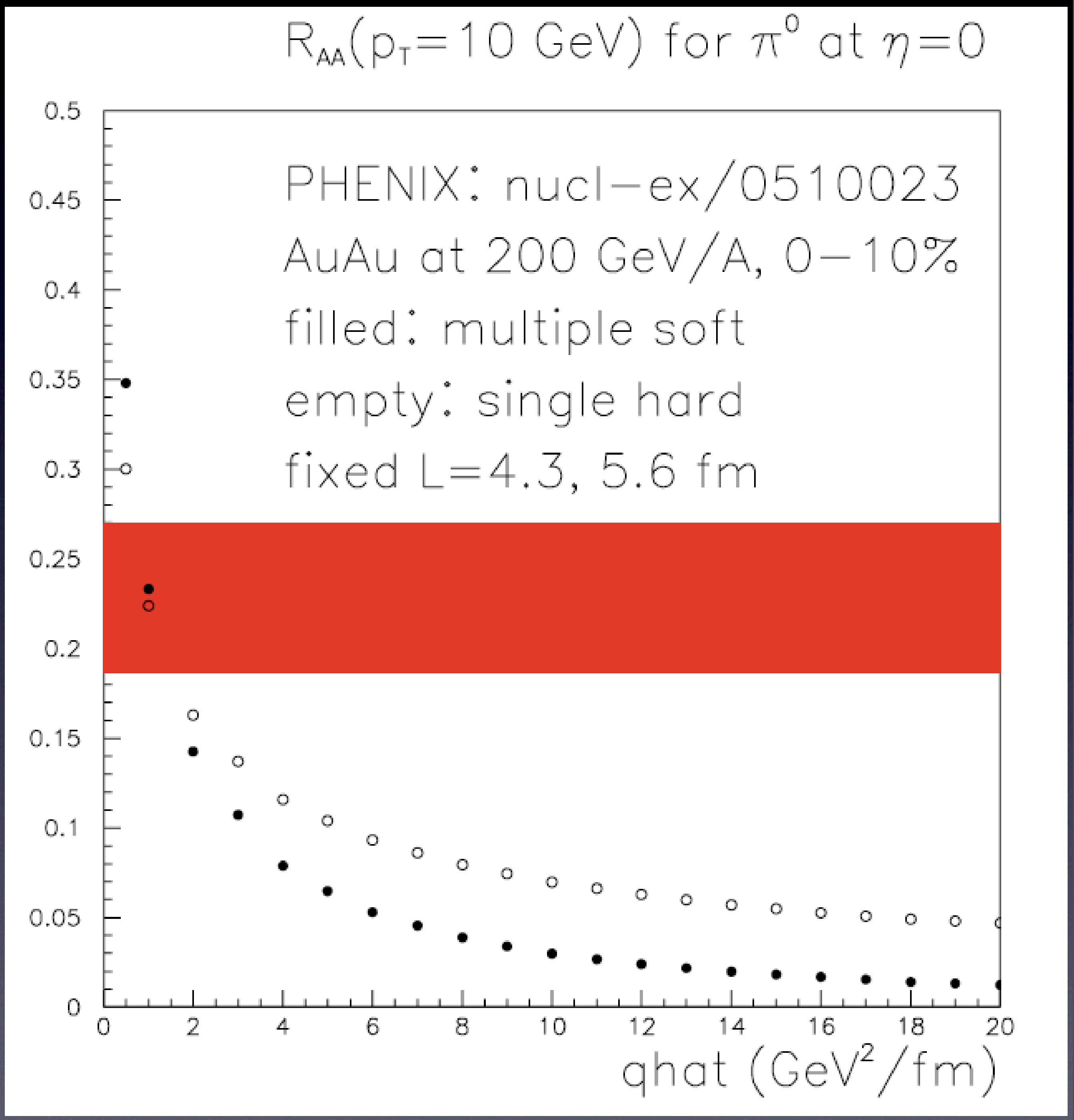




pp@200, PHENIX pi0

4. An exercise (II): fixed length





On the determination of the transport coefficient.

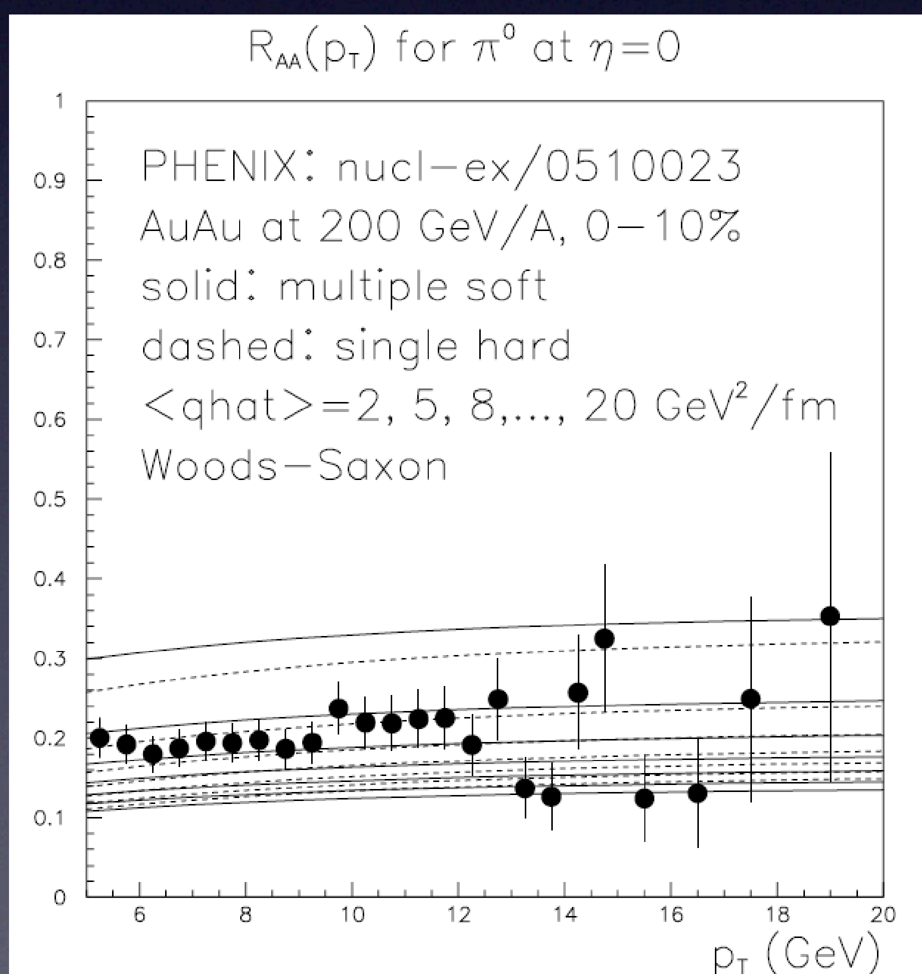
4. An exercise (III): Woods-Saxon

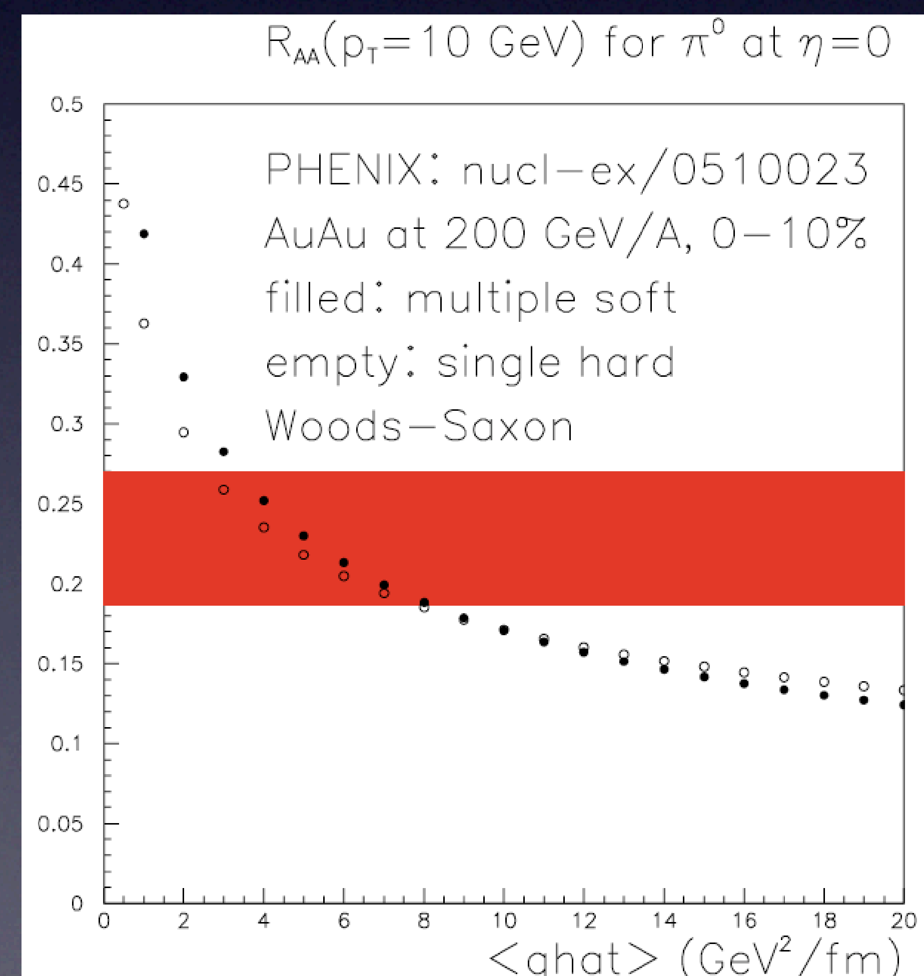
$$\omega_c(\mathbf{r}_0,\phi) = \int_0^\infty d\xi\,\xi\,\hat{q}(\xi)$$

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

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

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





On the determination of the transport coefficient.

4. An exercise (IV): hydro

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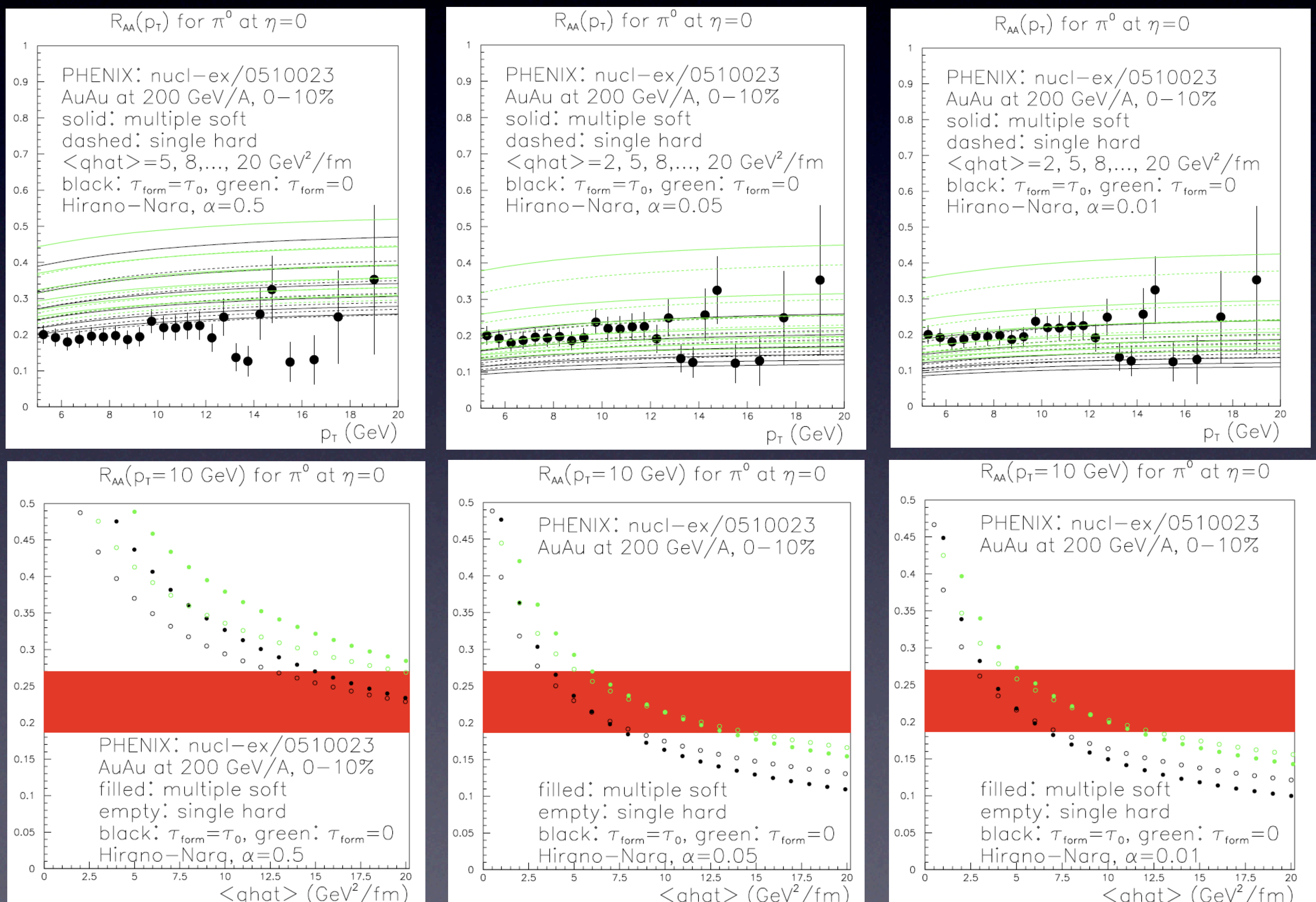
Hirano-Nara: 3+1 ideal hydro, for AuAu@200, b=3.1 fm, ideal EOS with N_f=3, $B^{1/4}$=247 MeV.

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



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

We explore:

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

$$0.5 < \alpha < 0.01$$

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

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

2.3. qhat: medium modeling

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

		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)