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Characterizing the medium in heavy ion collisions through jets

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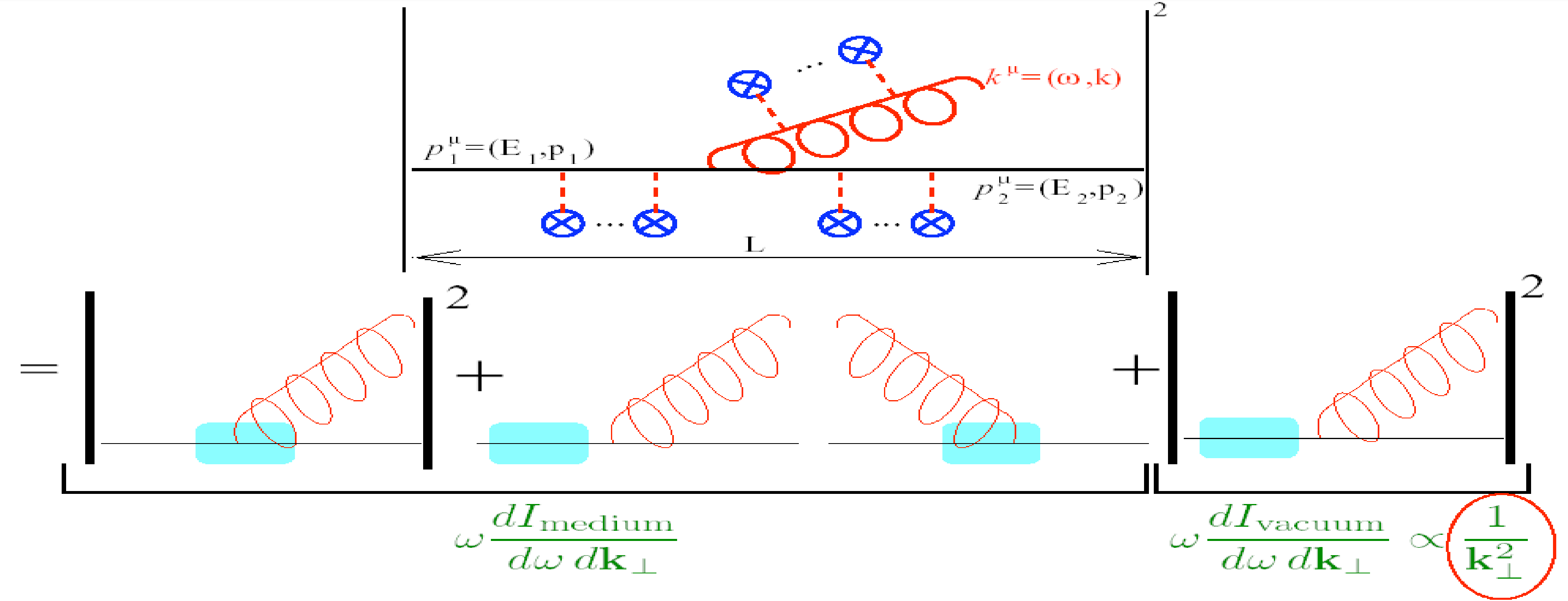
I. Introduction: radiative energy loss

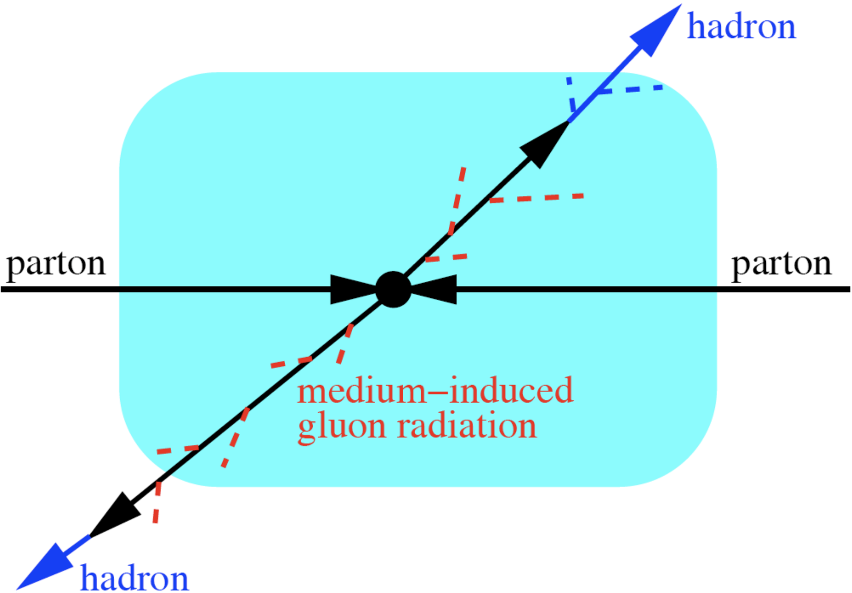
1.1. Theoretical setup.

1.2. Models.

I.1. Theoretical setup:



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



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

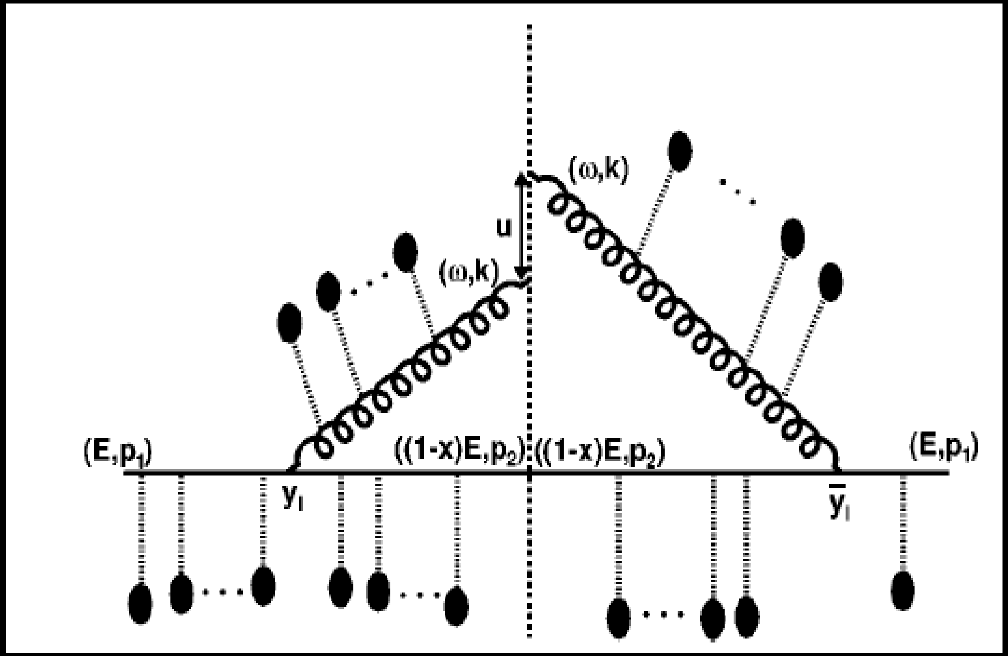
BDMPS

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

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

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

1/2. BDMPS/GLV: static medium.



$$\omega\frac{dI}{d\omega\, d\mathbf{k}_\perp}=\frac{\alpha_s C_F}{(2\pi)^2\omega^2}2\,\mathrm{Re}\int_0^\infty dy_1\int_{y_1}^\infty d\bar{y}_1 e^{i\bar{q}(y_1-\bar{y}_1)}$$
$$\times\int d\mathbf{u}e^{-i\mathbf{k}_\perp\cdot\mathbf{u}}\exp-\left(\frac{1}{2}\int_{\bar{y}_1}^\infty d\xi\, n(\xi)\sigma(\mathbf{u})\right)$$
$$\times\frac{\partial}{\partial\mathbf{y}}\cdot\frac{\partial}{\partial\mathbf{u}}\int_{\mathbf{y}=0=\mathbf{r}(y_1)}^{\mathbf{u}=\mathbf{r}(\bar{y}_1)}\mathcal{D}\mathbf{r}\ \exp\left[i\int_{y_1}^{\bar{y}_1}d\xi\frac{\omega}{2}\left(\dot{\mathbf{r}}^2-\frac{n(\xi)\sigma(\mathbf{r})}{i\omega}\right)\right]$$

Exact solution unknown, two approximations:

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

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

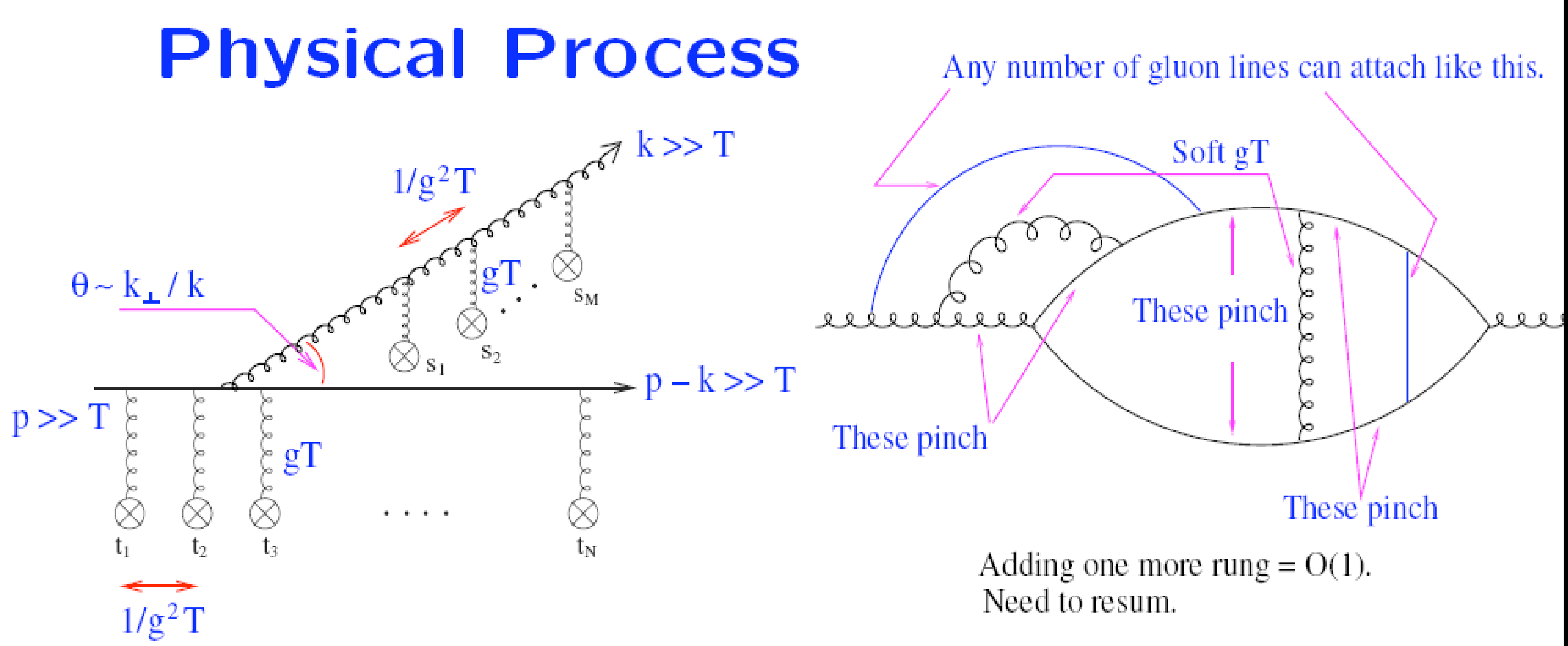
2. Opacity expansion: N=1, single hard scattering, corrects Brownian motion.

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

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

1.2. Models (II):

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



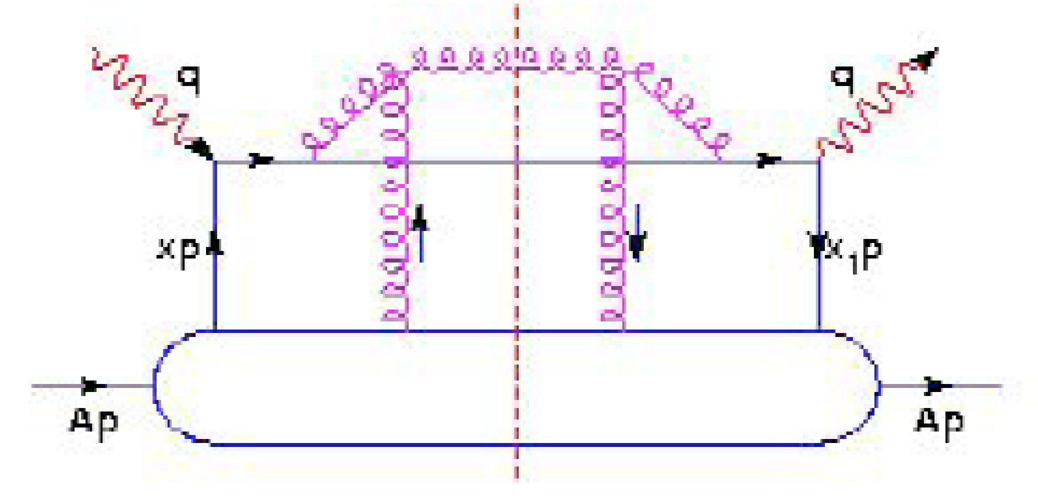
Any number of gluon lines can attach like this.

Adding one more rung = O(1).
Need to resum.

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. :-(

2.5. Jets (see the talk by G. Salam at HP2008). :-))))))))

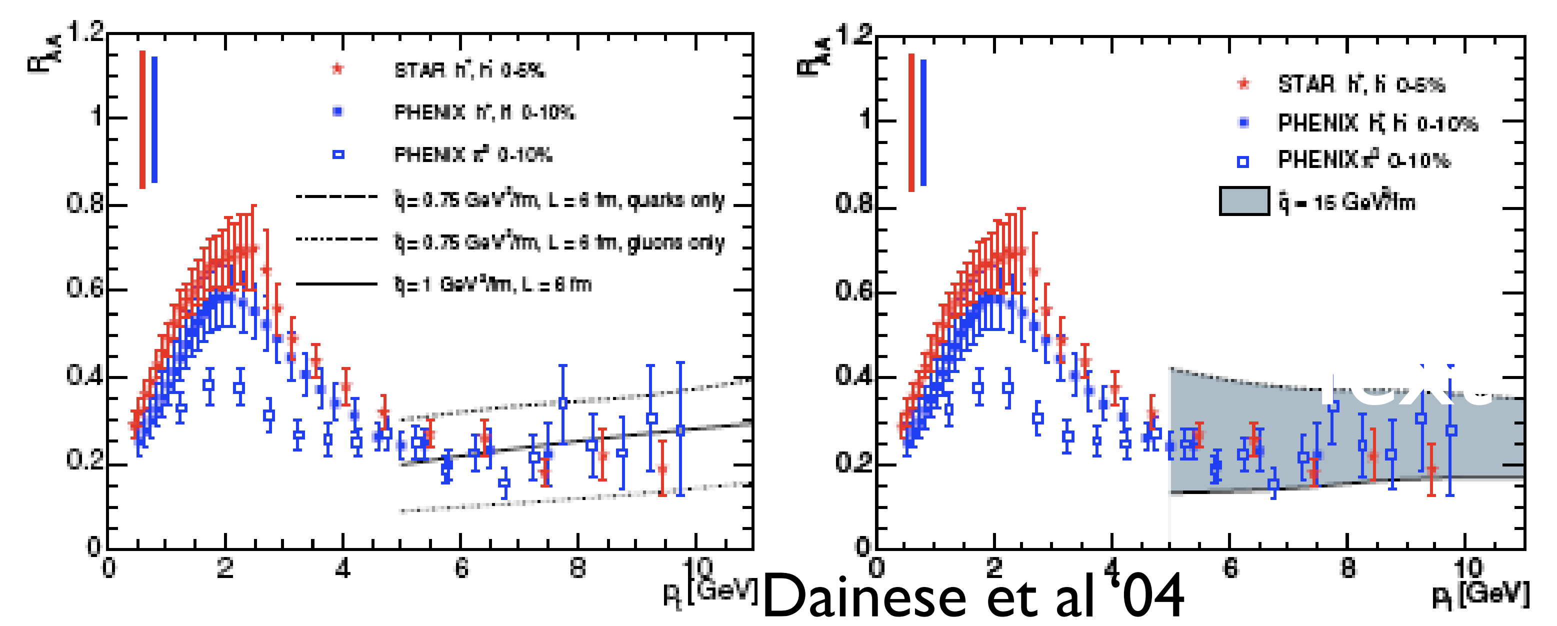
2.1. R_{AA} and back-to-back for light:

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

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

BDMS '01; Wang et al '96

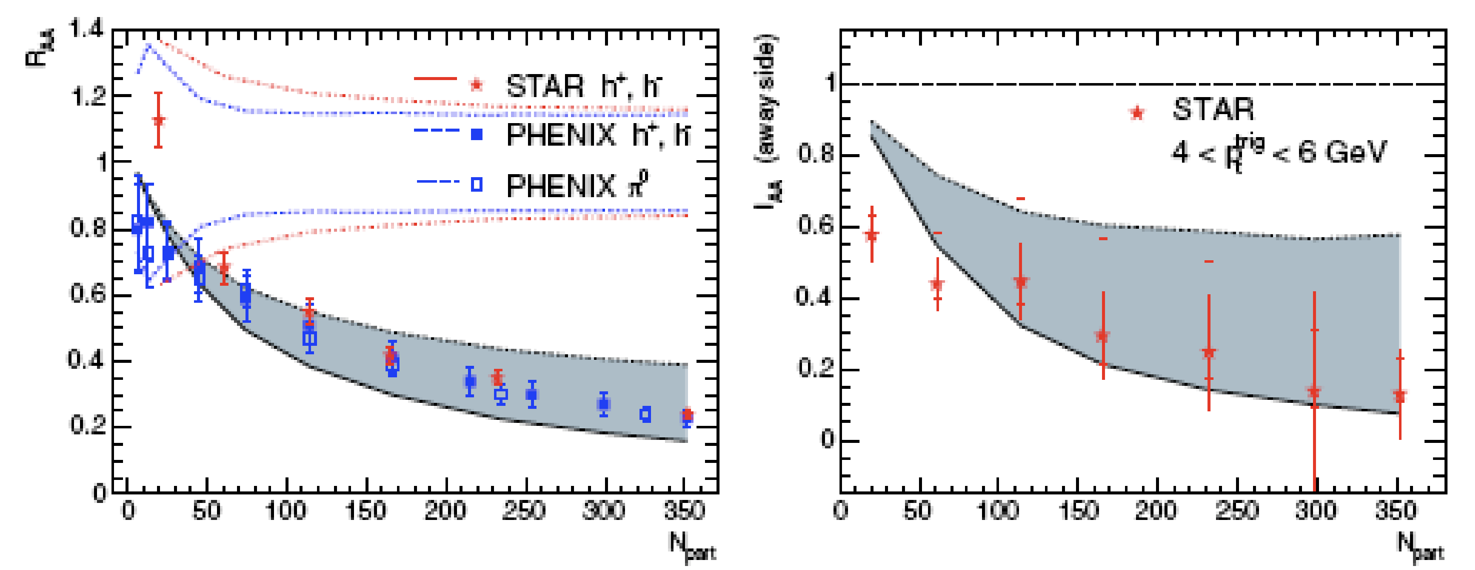
Medium modeling → $<\tau_0\hat{q}>=1\text{-}15\,\mathrm{GeV}^2$

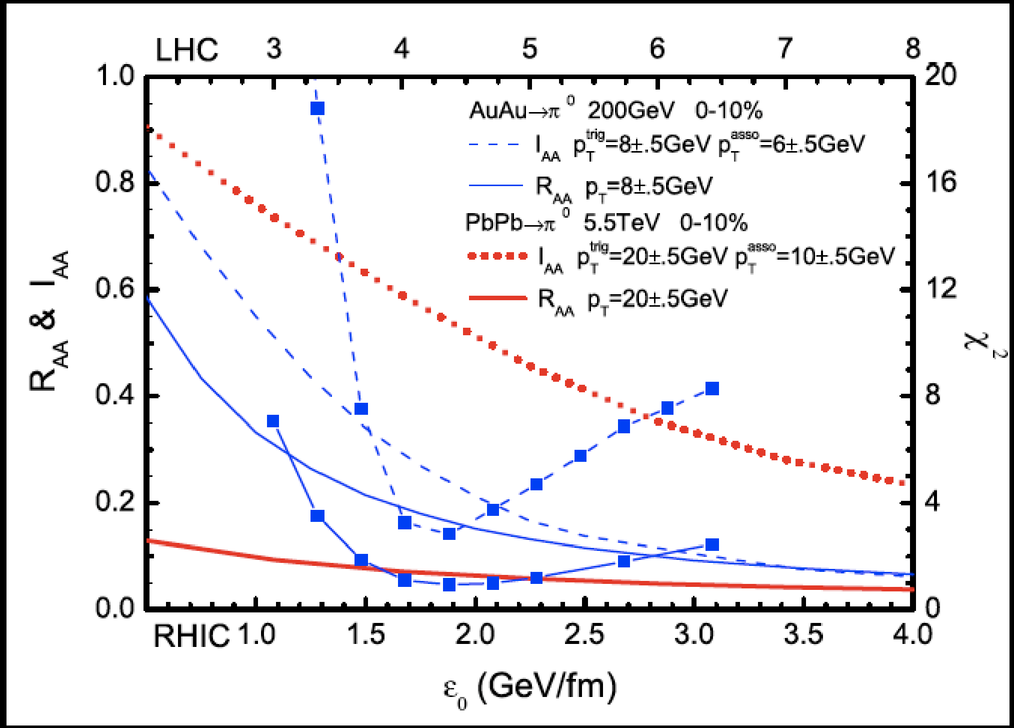


Dainese et al '04

Zhang et al '07

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





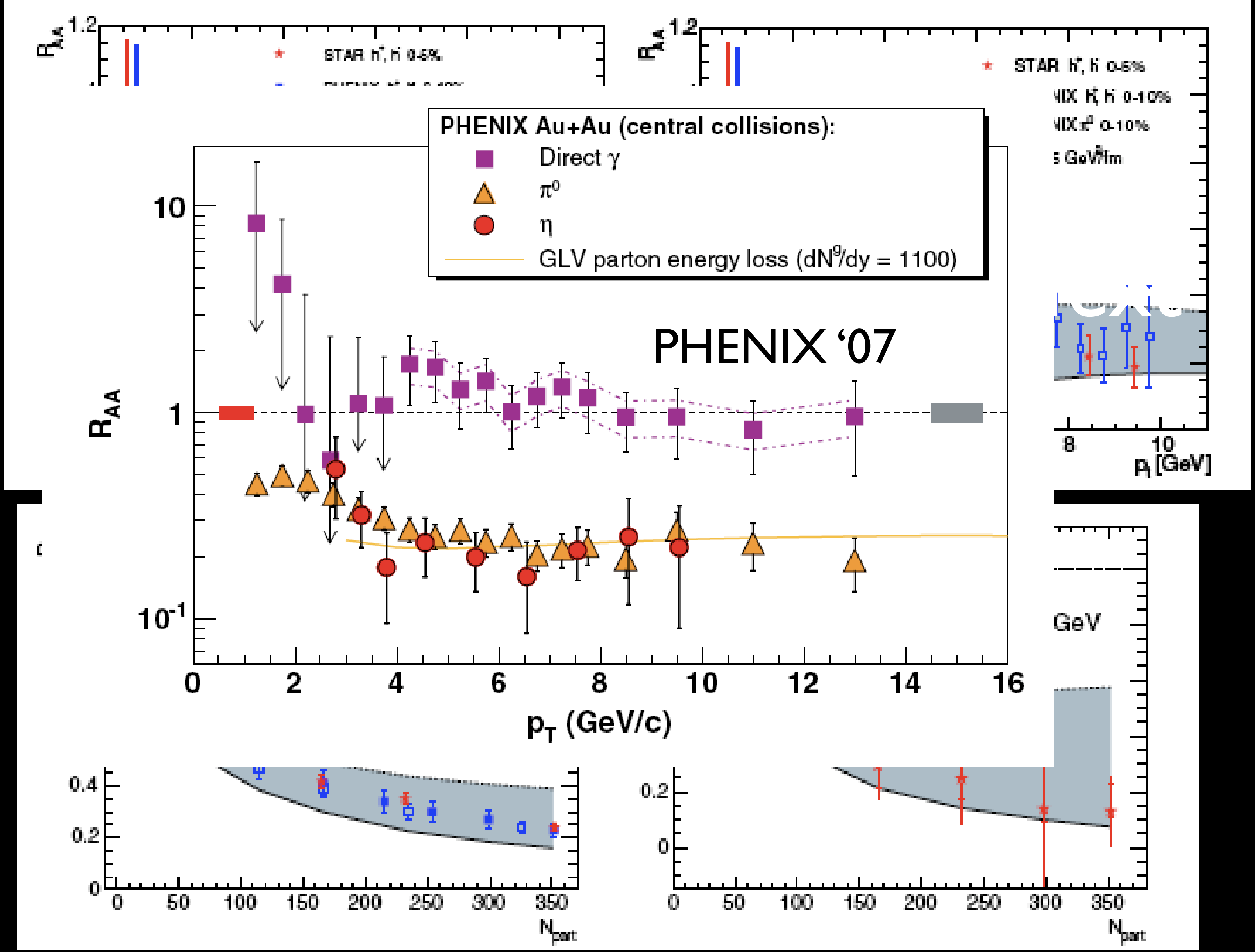
2.1. R_{AA} and back-to-back for light:

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

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

BDMS '01; Wang et al '96

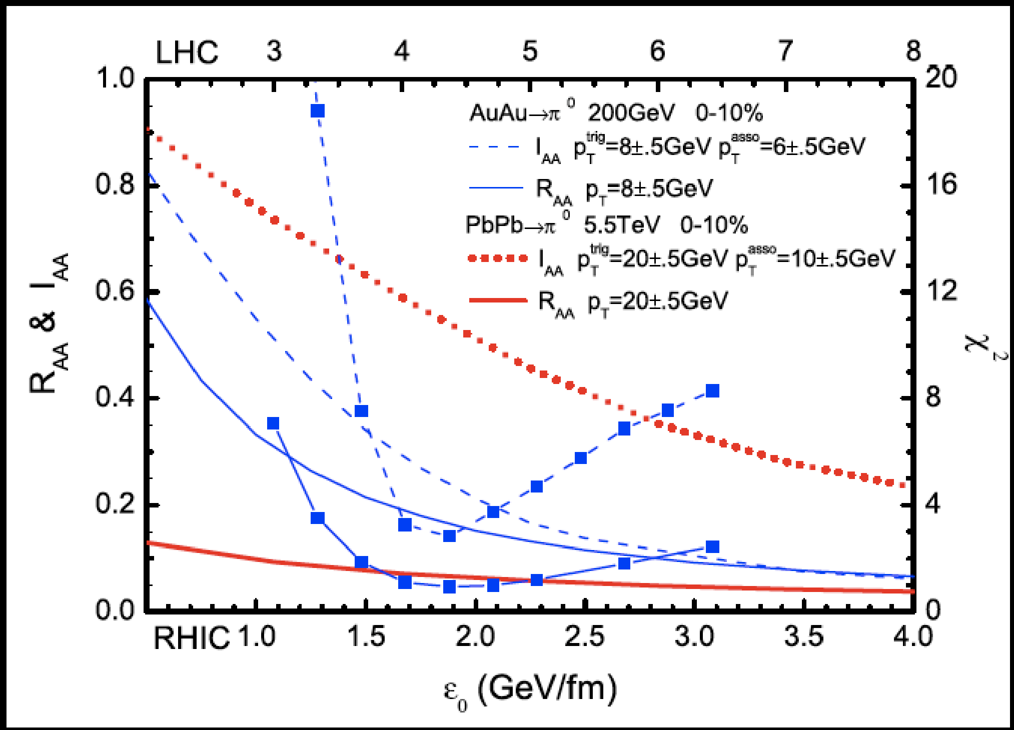
Medium modeling → $\langle\tau_0\hat{q}\rangle$=1-15GeV^2



PHENIX '07

Zhang et al '07

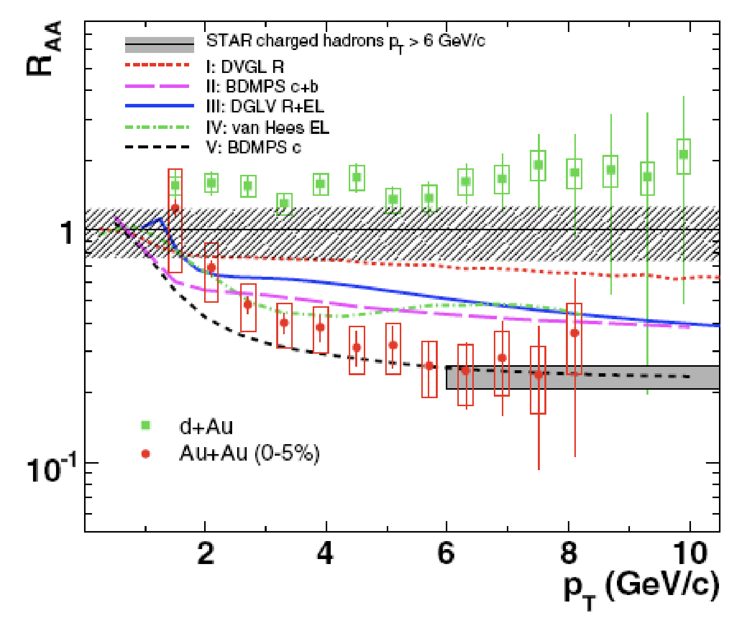
$$\langle\hat{q}_0\tau_0\rangle\approx 2\div 3\ \ {\rm GeV}^2$$

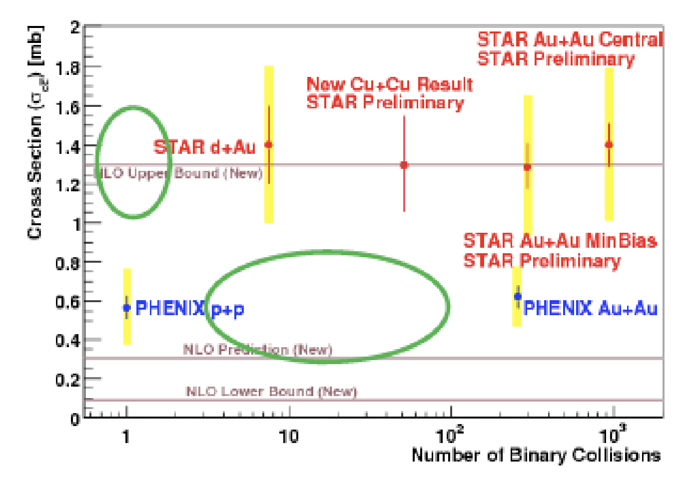


2.2. e's, differential observ.:

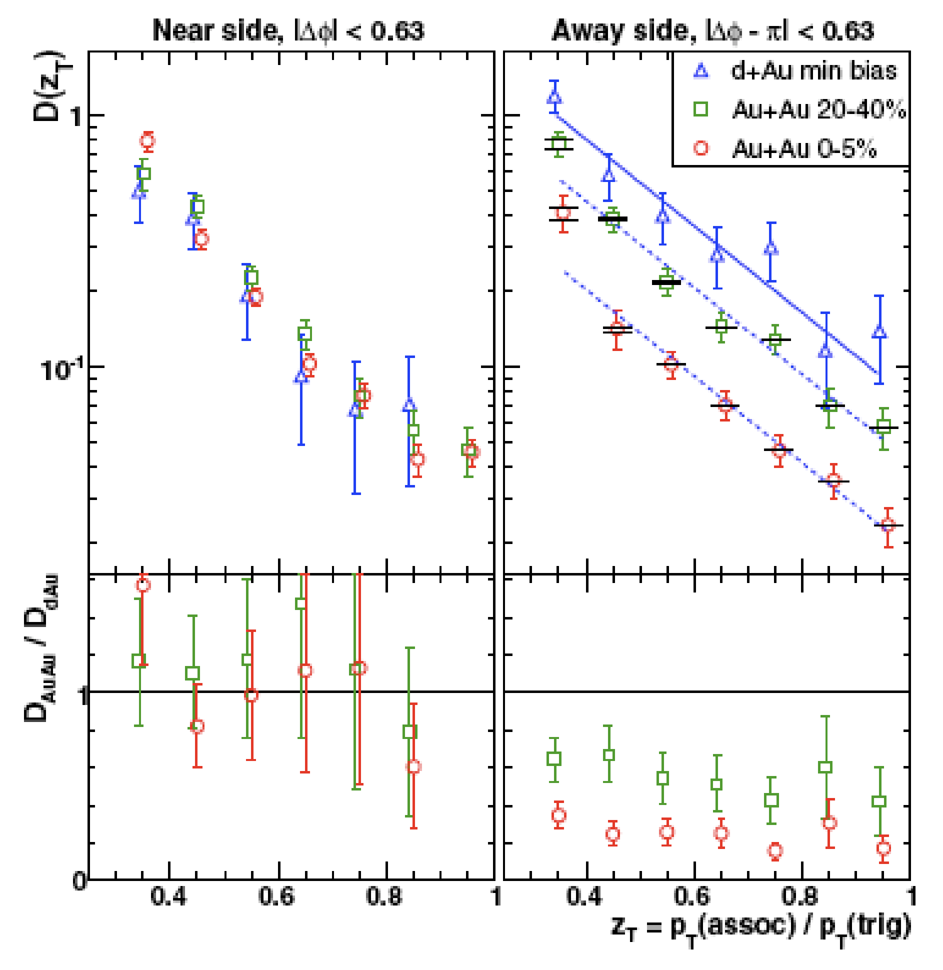
- Heavy quarks radiate less: non-photonic electrons not conclusive: benchmark (Armesto et al '05), hadronization (Adil et al '06), collisional (Djordjevic et al '06, Ayala et al. '07), resonances (van Hees et al '06), dynamical medium (Djordjevic et al. '08),...

- PseudoFF not well understood: no broadening at high p_T in the near side, trigger bias?





STAR '06, '07



Characterizing the medium in HIC through jets: 2. Successes and problems.

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)
dilution	increases, factor 2-5
dynamical medium (Djordjevic et al.)	decreases
flow (Armesto et al., Baier et al.)	no effect
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 (GLV; Salgado et al. '03).
- Multiple gluon emission: Quenching Weights (BDMS '01), independent (Poissonian) gluon emission: assumption!

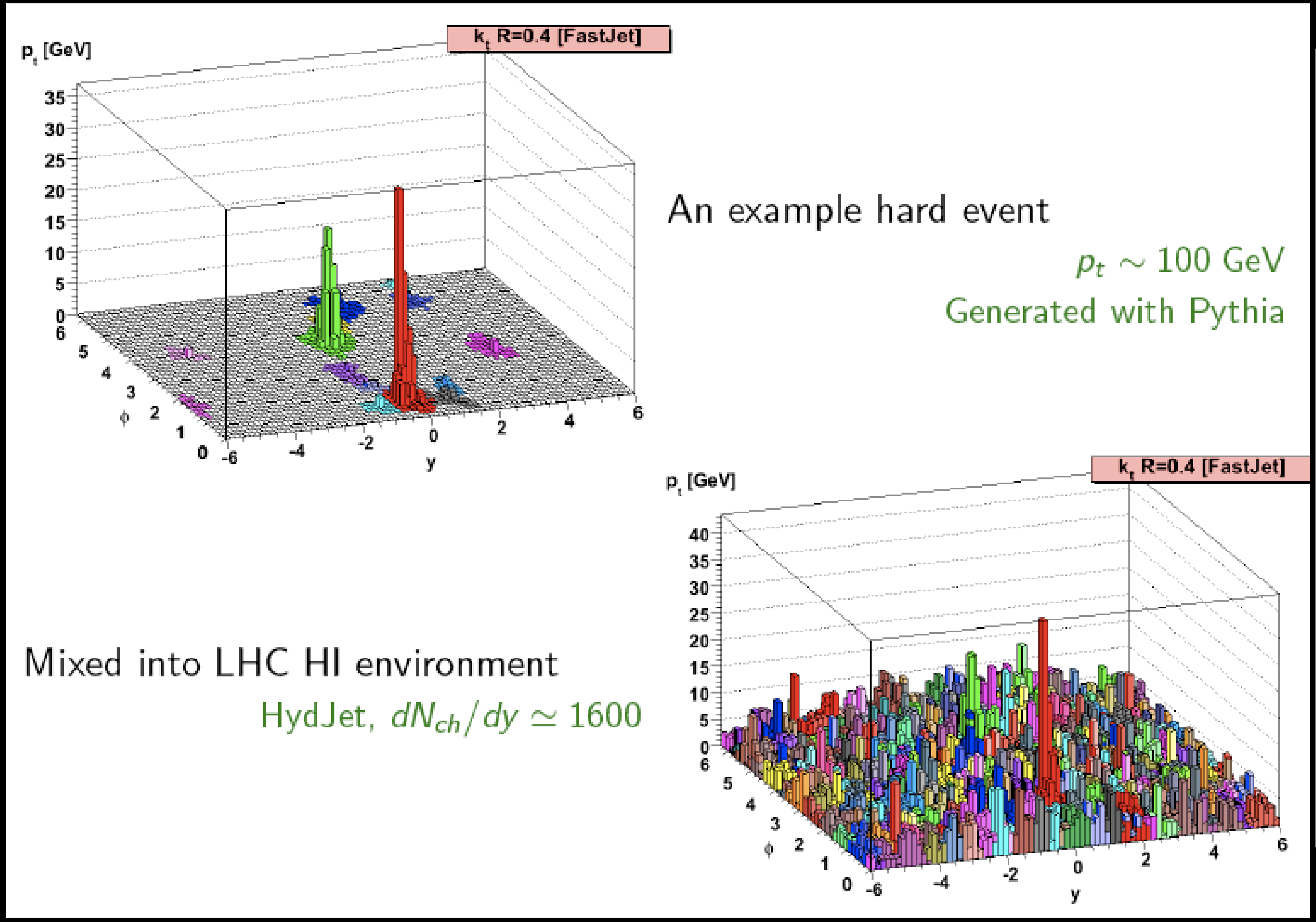
$$P(\Delta E)=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\prod_{i=1}^{n}\int d\omega_i\frac{dI(\omega_i)}{d\omega}\right]\delta\left(\Delta E-\sum_{i=1}^{n}\omega_i\right)\exp\left[-\int_0^{\infty}d\omega\frac{dI}{d\omega}\right]$$

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

2.5. Jets (I):

- Jets are theoretical well-defined objects which are as close to QCD partons as we can achieve. They require a definition (clustering algorithm).

- Difficulty in heavy ion collisions (ALICE, ATLAS, CMS): background with large EBE fluctuations, substraction! (Cacciari-Salam).



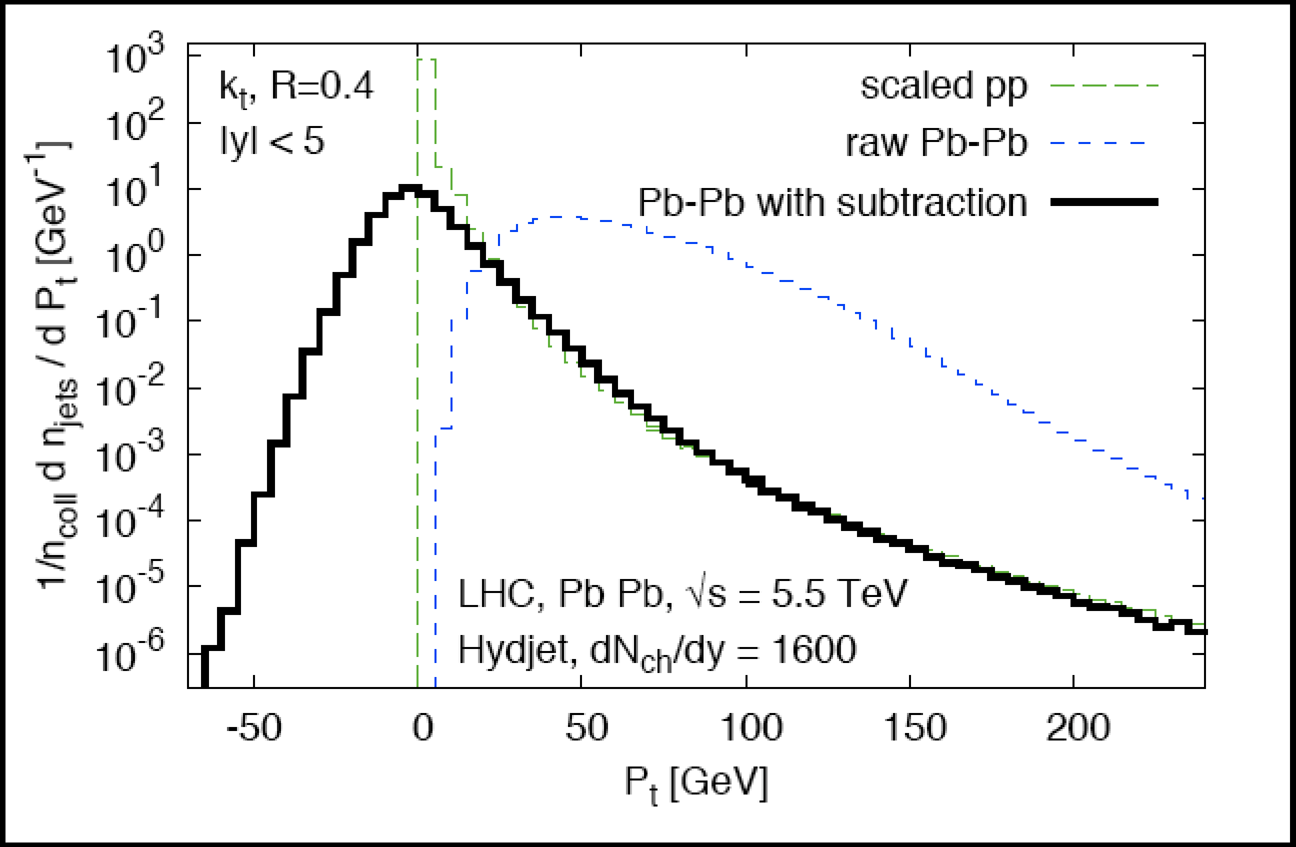
An example hard event

$p_t \sim 100$ GeV

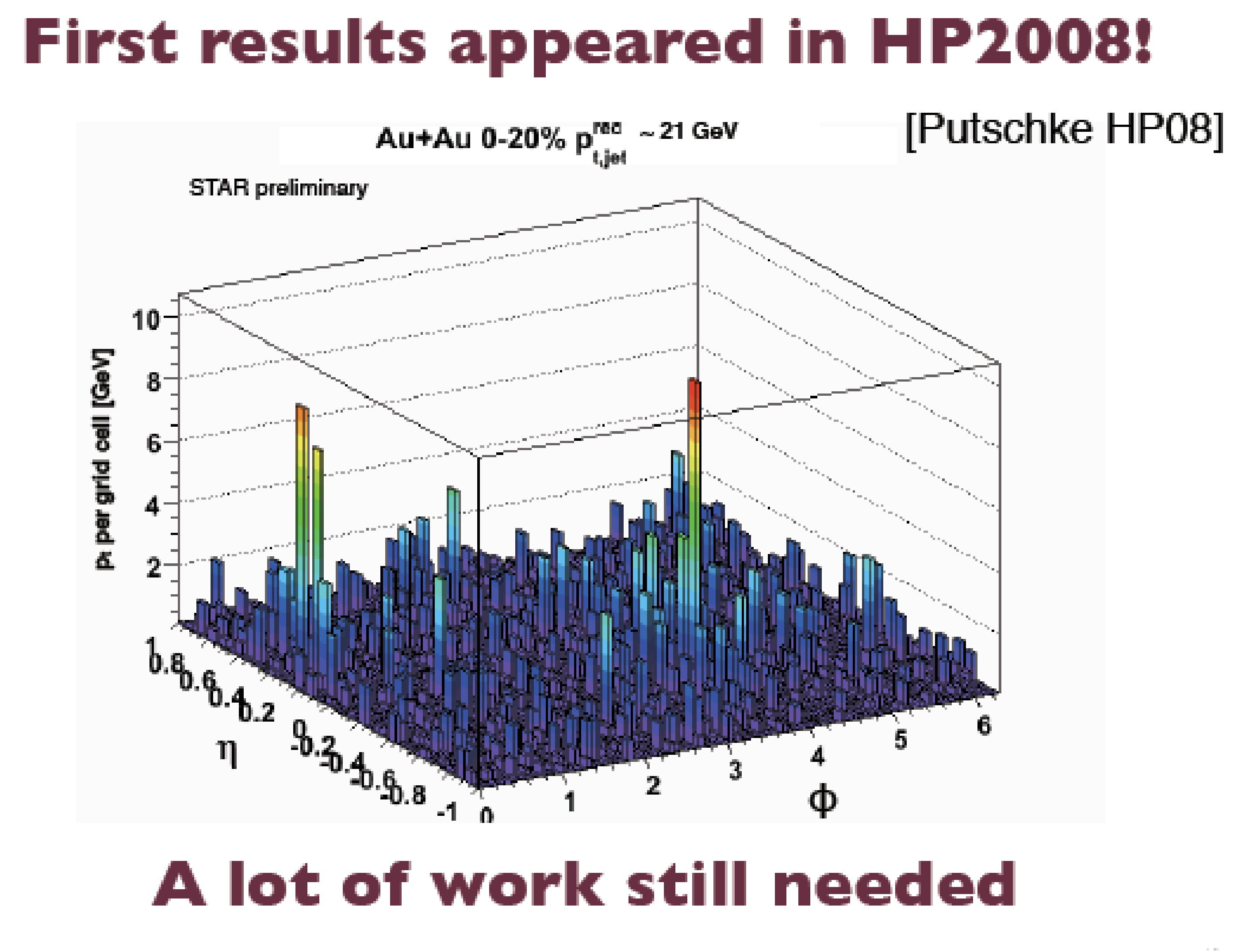
Generated with Pythia

Mixed into LHC HI environment

HydJet, $dN_{ch}/dy \simeq 1600$



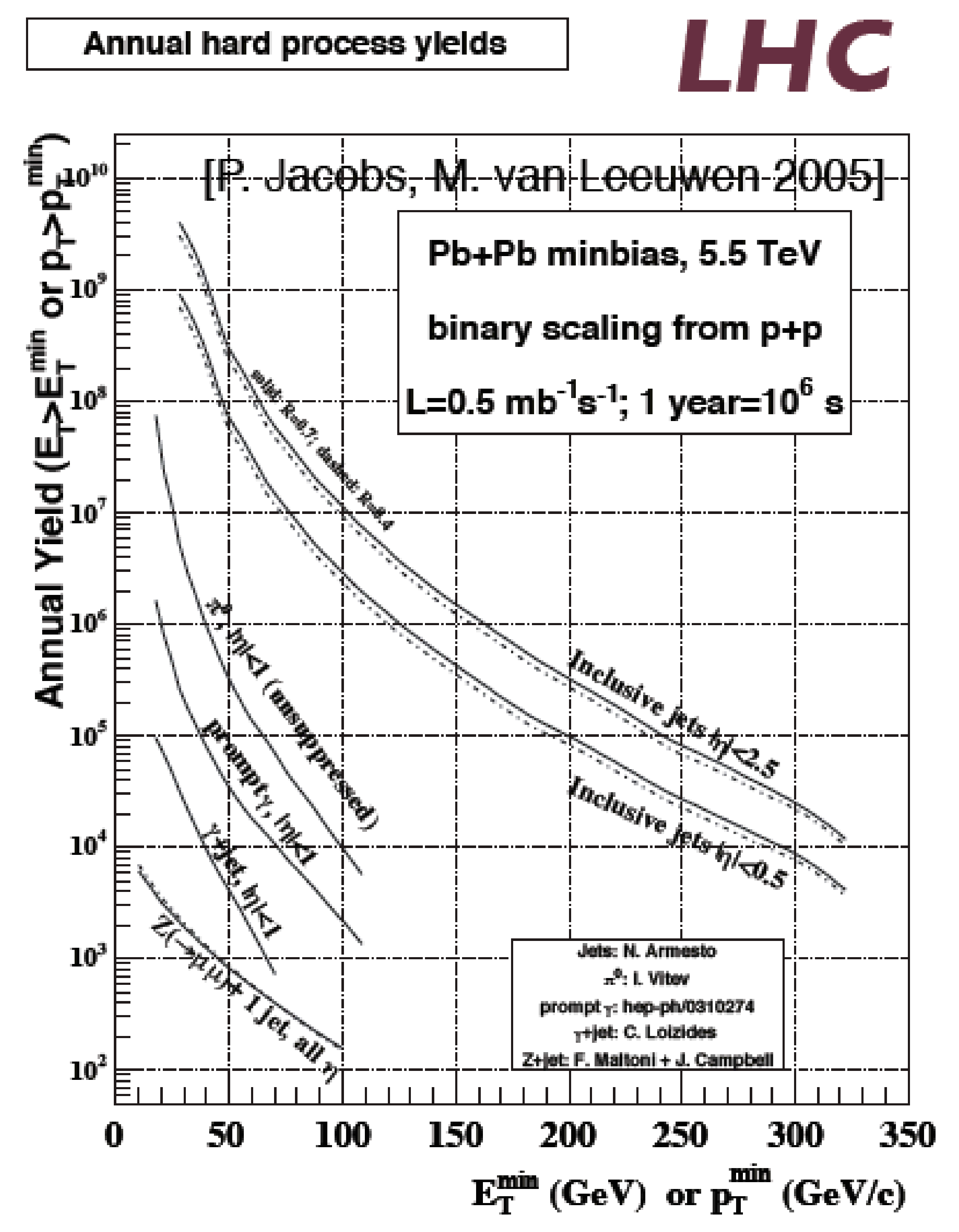
2.5. Jets (II):



First results appeared in HP2008!

[Putschke HP08]

A lot of work still needed



At RHIC, the measurement is still biased (a high-p_T particle required); only at the LHC (RHIC-II?) truly unbiased measurements will be available (e.g. ff. for $z<0.7$ or $\xi<5$).

3. Going beyond:

Recent attempts to go beyond (JHEP0802 (2008) 048, with L. Cunqueiro, C. A. Salgado, *Santiago* and W.-C. Xiang, *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 DGLAP evolution of frag. funct. (FF).

3.2. PYTHIA with in-medium branching: **Q-PYTHIA**.

3.1. Medium-modified SF and Sudakovs:

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

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

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

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

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

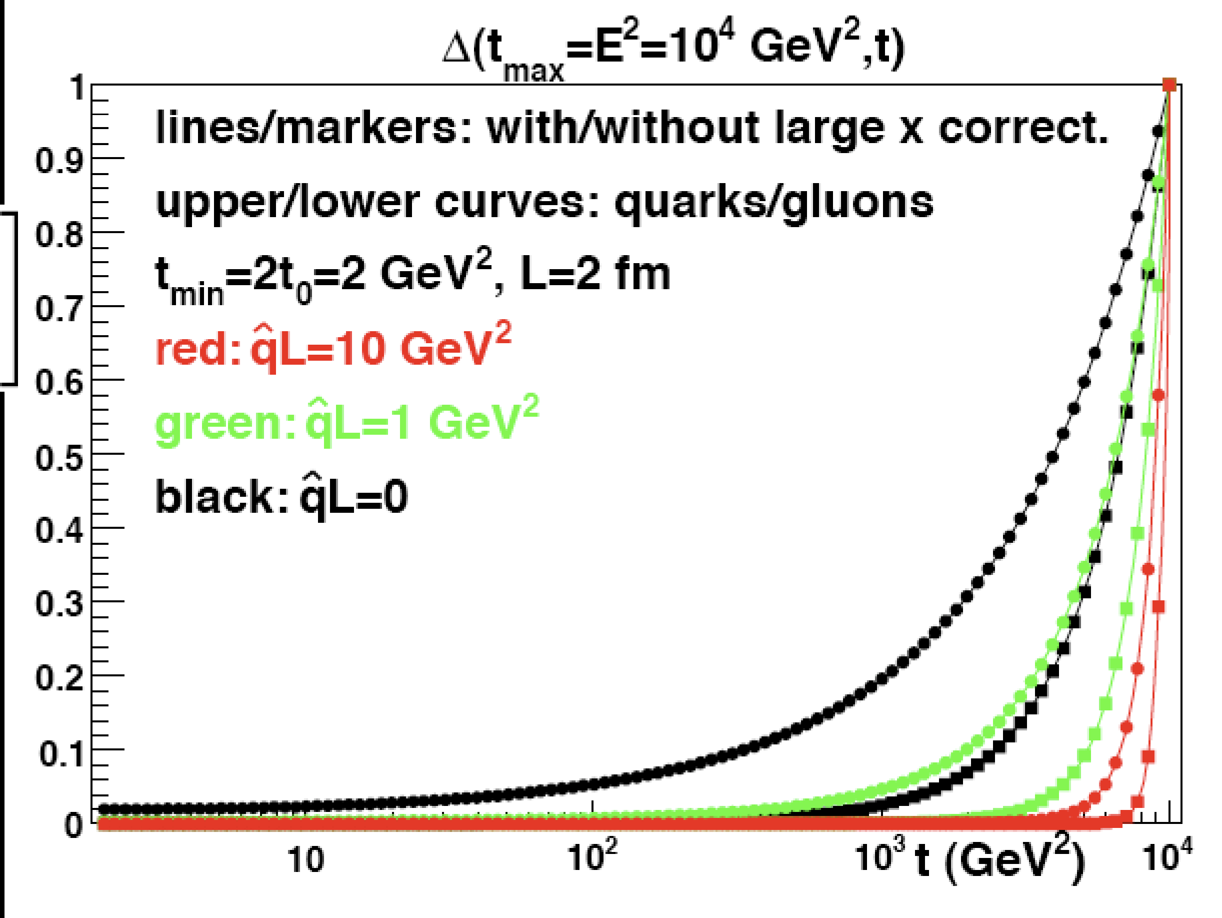
$$\Delta P(z,t) \simeq \frac{2\pi t}{\alpha_s}\frac{dI^{\rm med}}{dzdt}$$

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.

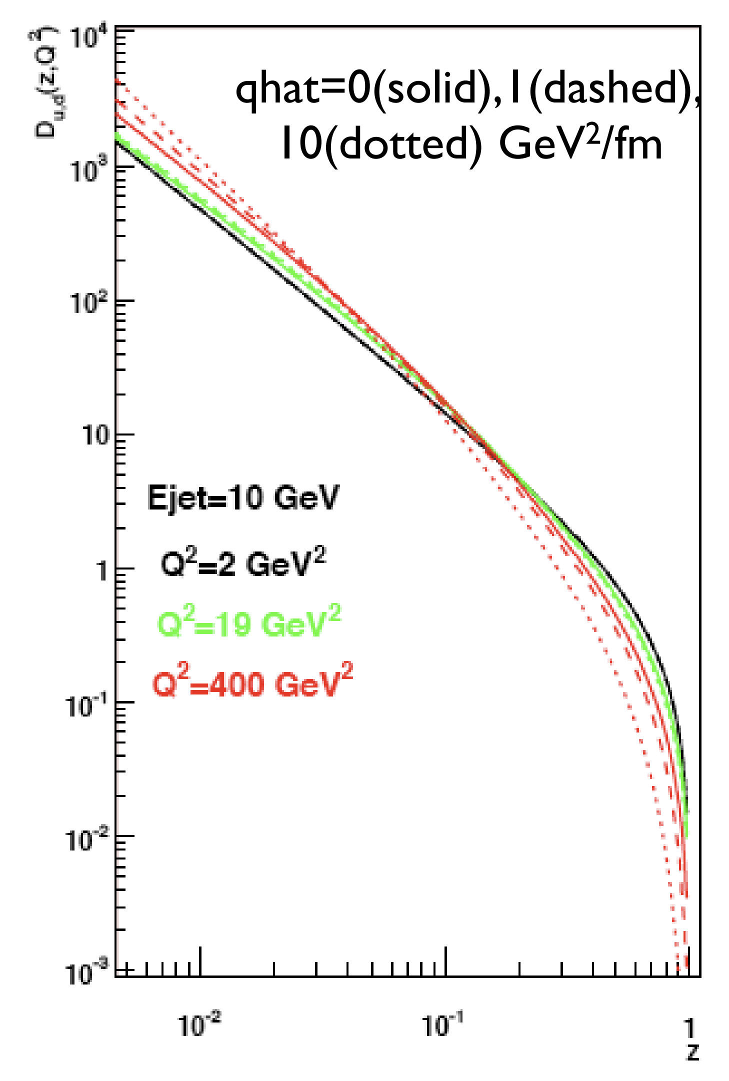


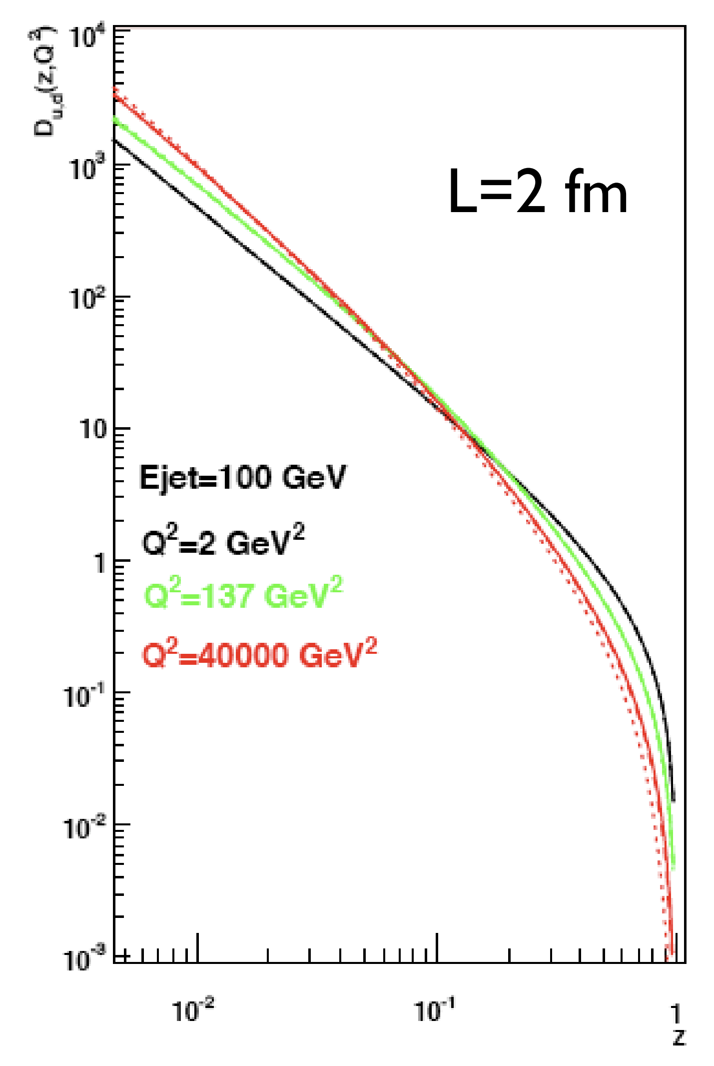
3.1. Medium modified DGLAP evolution of FF (I):

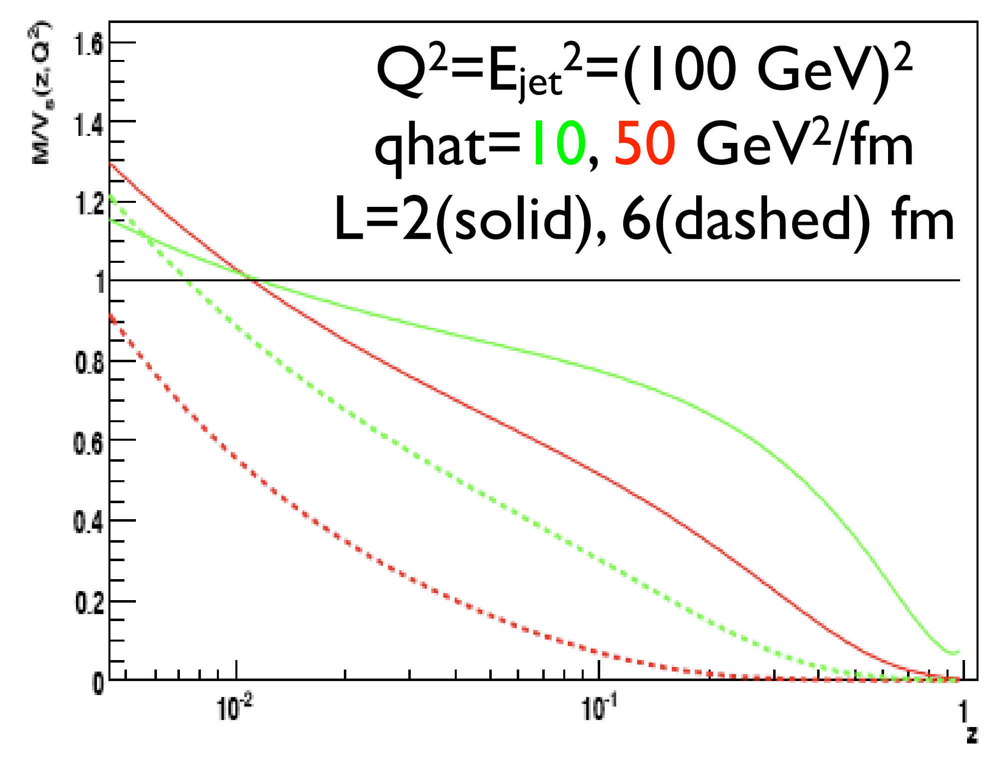
- Medium-modified DGLAP evolution of FF (from KKP i. c.):

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

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

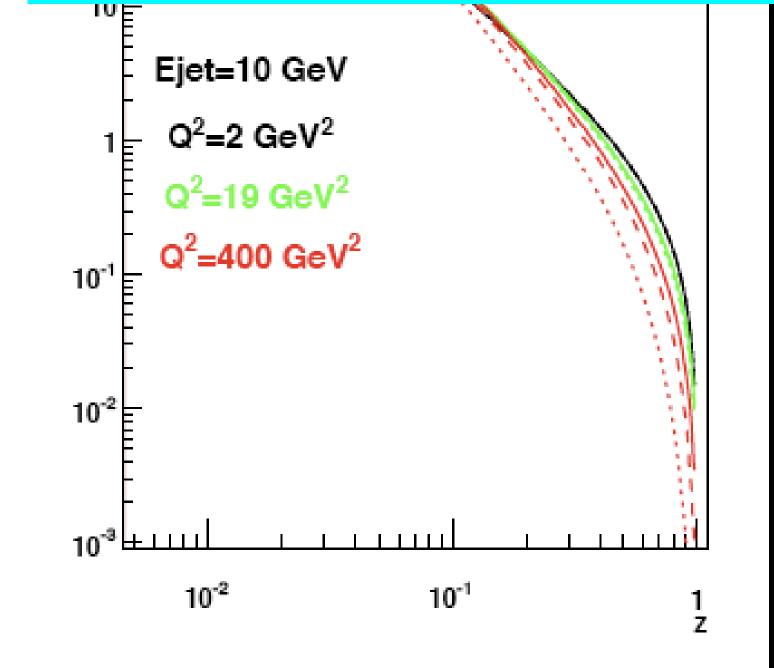


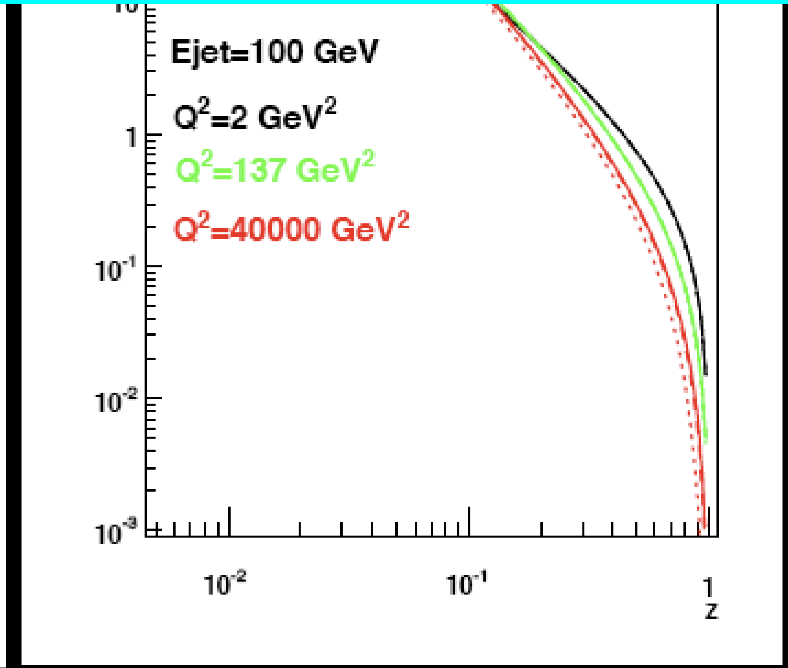


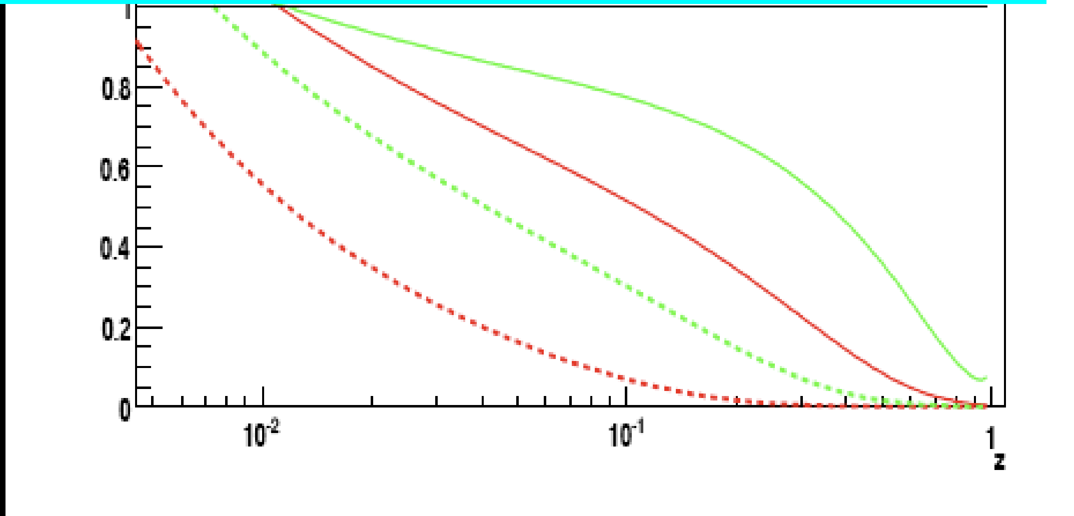


3.1. Medium modified DGLAP evolution of FF (I):

- 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; energy degradation of the parent not considered; no elastic scattering, no conversions, no color reconnections with the medium included.

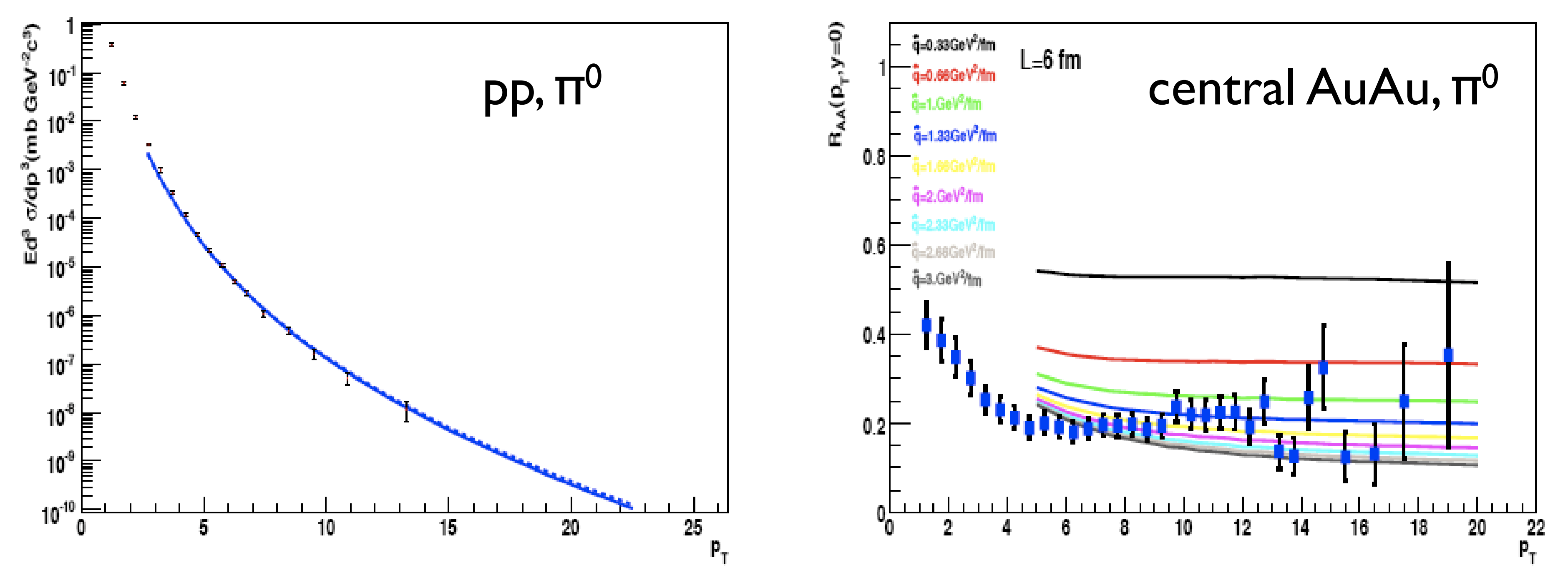


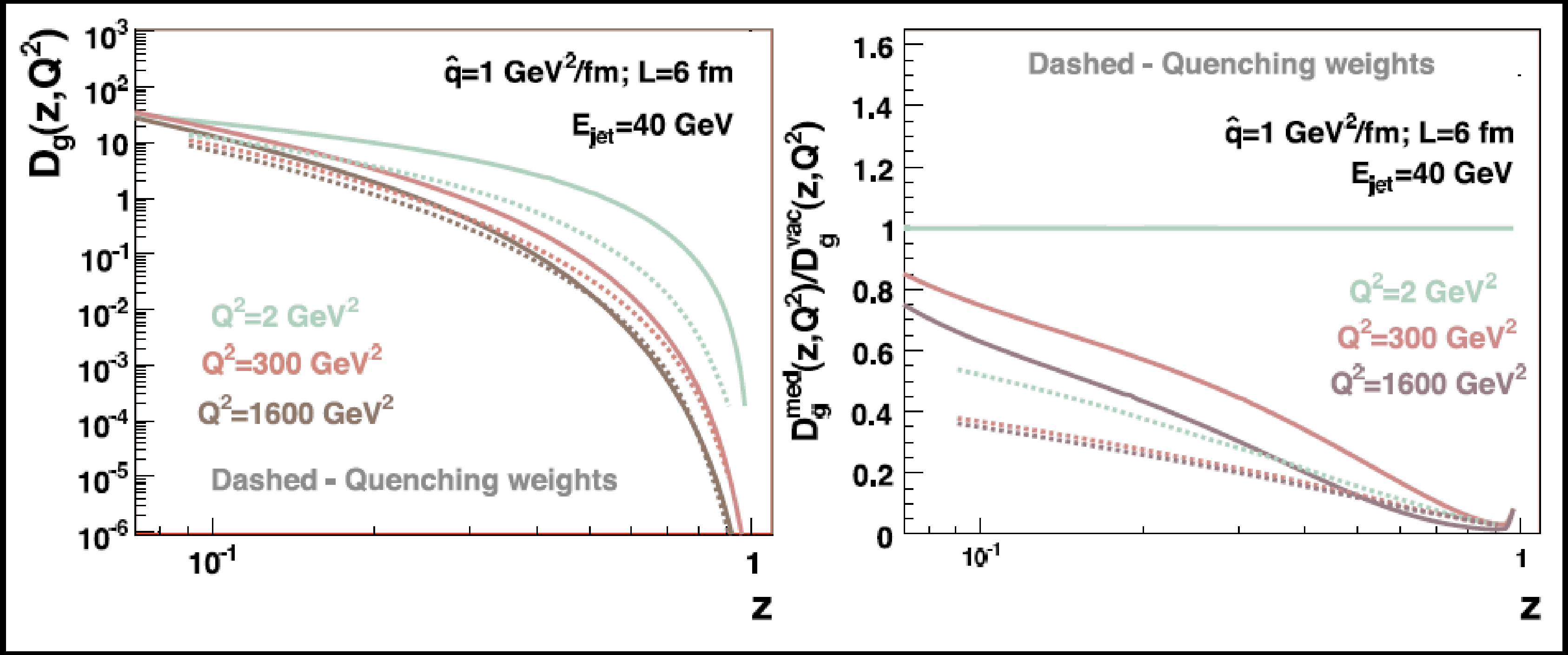




3.1. Medium modified DGLAP evolution of FF (II):

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.

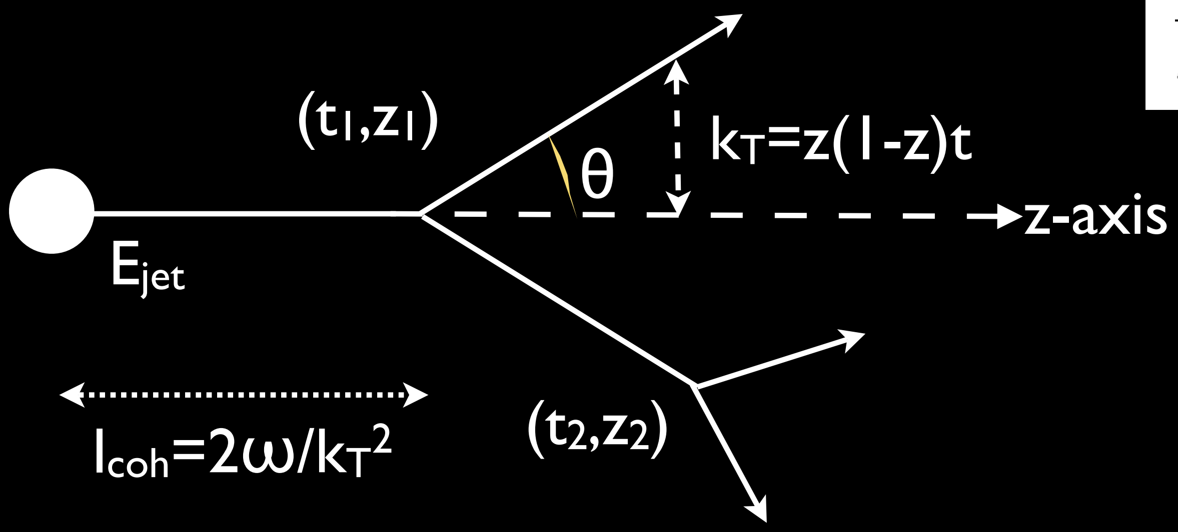
3.2. Q-PYTHIA: implementation

- We modify PYTHIA FSR routine PYSHOW, for t-ordered branching, introducing the medium-modified splittings into the dicing of both t and z.

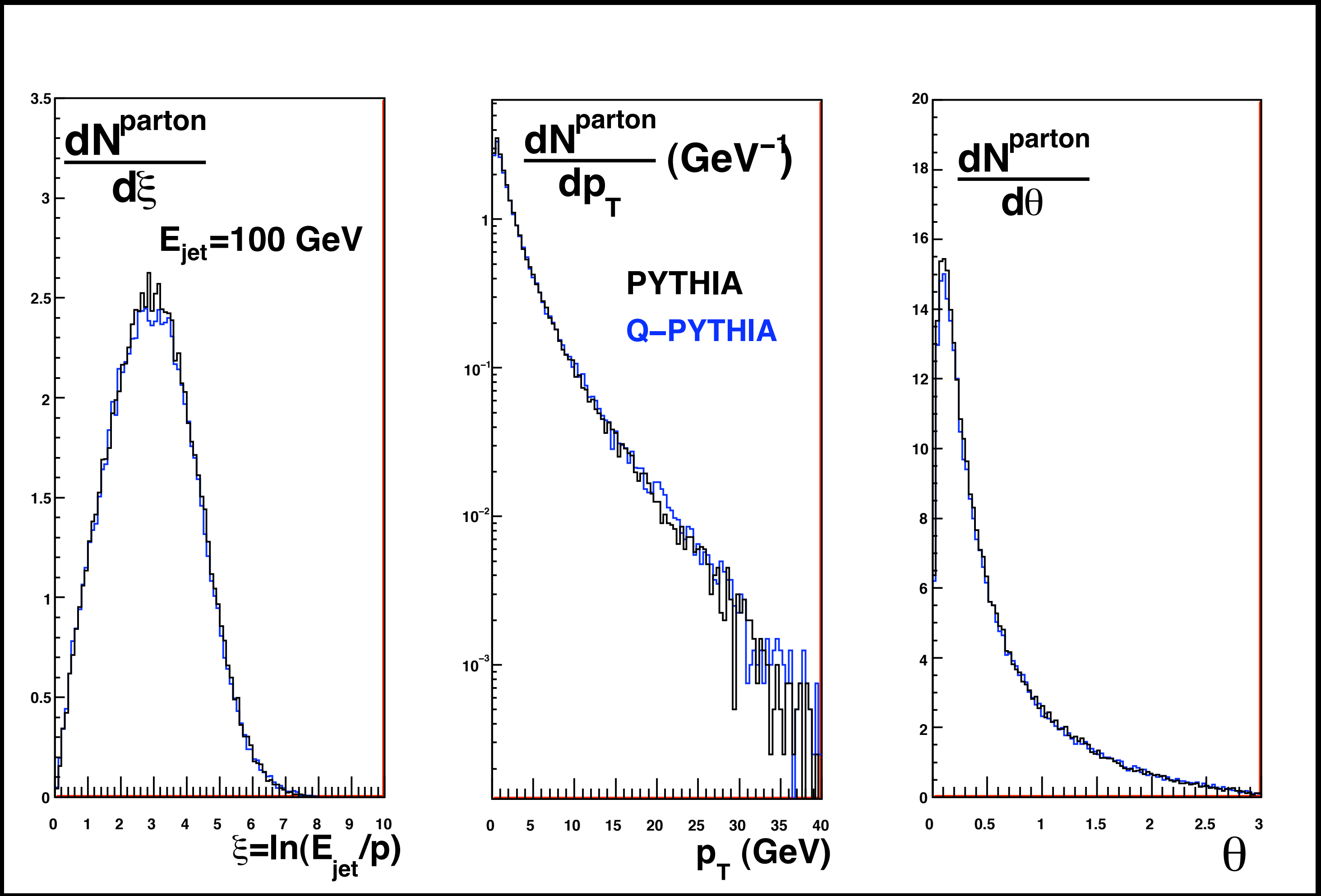
$$P_{\rm tot}(z) = P_{\rm vac}(z) \rightarrow P_{\rm tot}(z) = P_{\rm vac}(z) + \Delta P(z,t,\hat{q},L,E)$$

$$\frac{\Delta(t_2)}{\Delta(t_1)} = R,$$

$$\int_{z_-}^{z_2} dz \frac{\alpha_S}{2\pi} P(z) = R' \int_{z_-}^{z_+} dz \frac{\alpha_S}{2\pi} P(z)$$



- Energy degradation and formation time considered.
- Rejections undone: agreement between vacuum and default as a check.

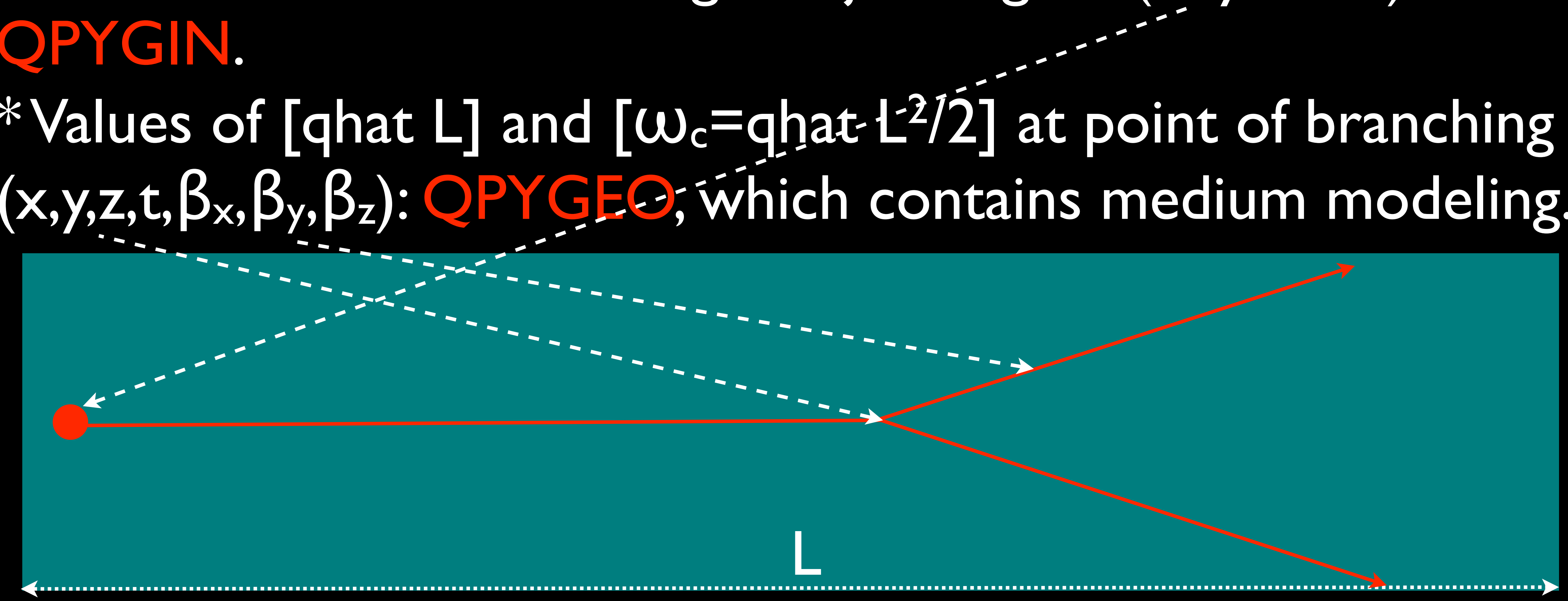


3.2. Q-PYTHIA: program

- Fortran program, uses PYTHIA-6.4.18 defaults (arXiv:0809.4433 [hep-ph]).

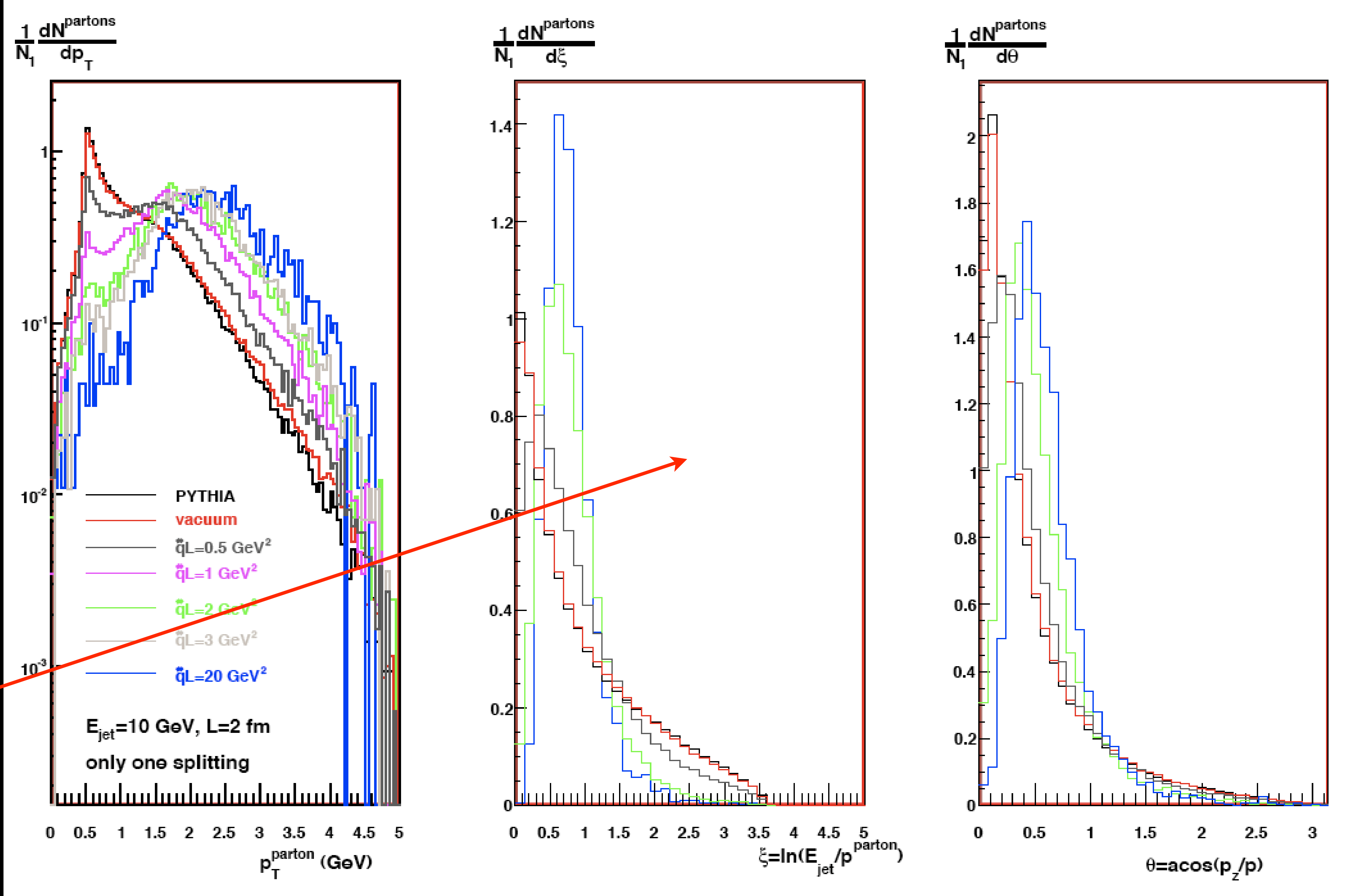
- We modify *only* PYSHOW, providing additional auxiliary routines: black box for the user.

- User-defined:
  - * Position of hard scattering - of jet origin - (x_0,y_0,z_0,t_0): QPYGIN.
  - * Values of [qhat L] and [ω_c=qhat $L^2/2$] at point of branching $(x,y,z,t,\beta_x,\beta_y,\beta_z)$: QPYGEO, which contains medium modeling.



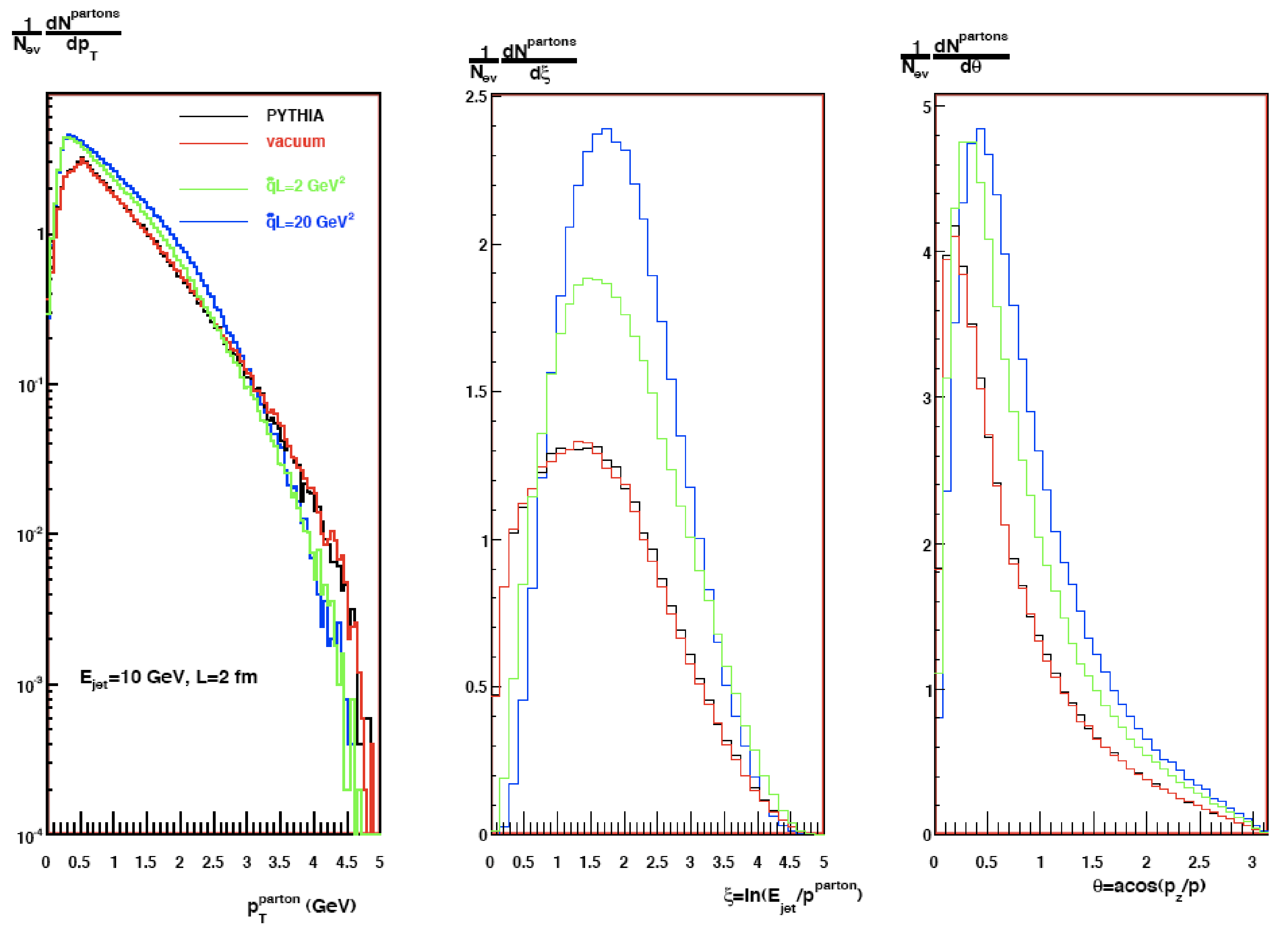
3.3. Q-PYTHIA: results (I)

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



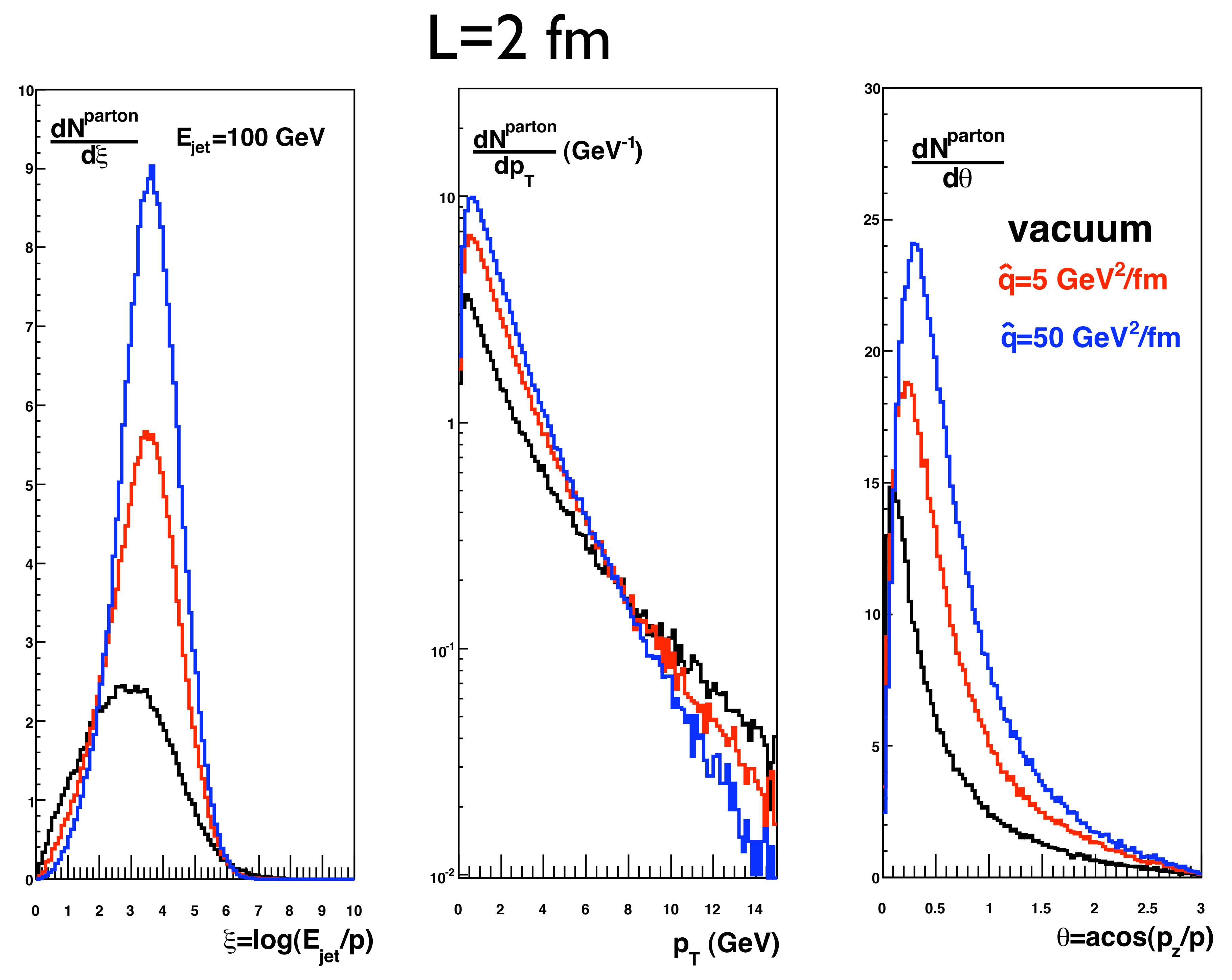
3.3. Q-PYTHIA: results (II)

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



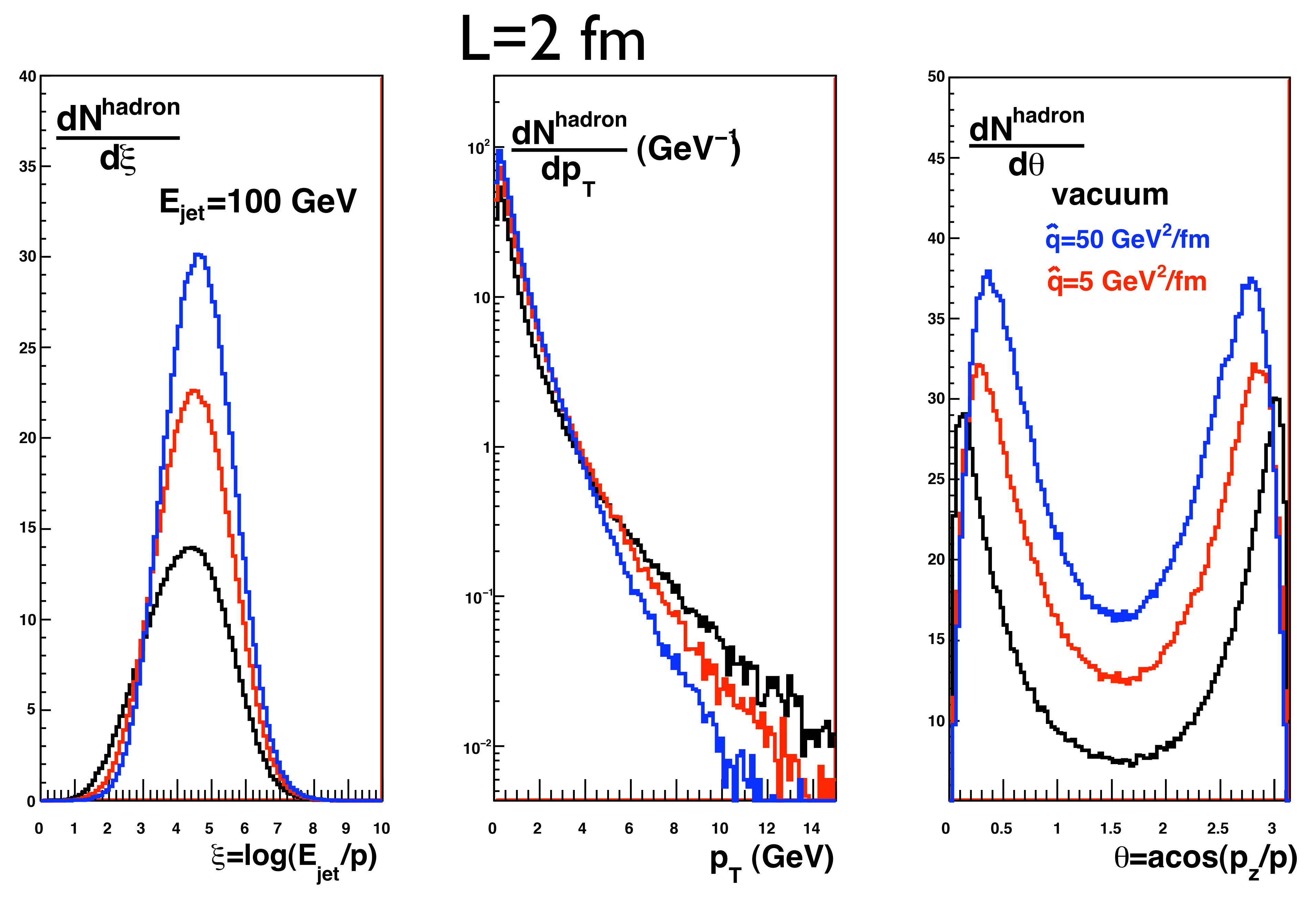
3.3. Q-PYTHIA: results (III)

At parton level and for high energy, high multiplicity enhancement and modest broadening. Energy constraints and multiple splitting very important.

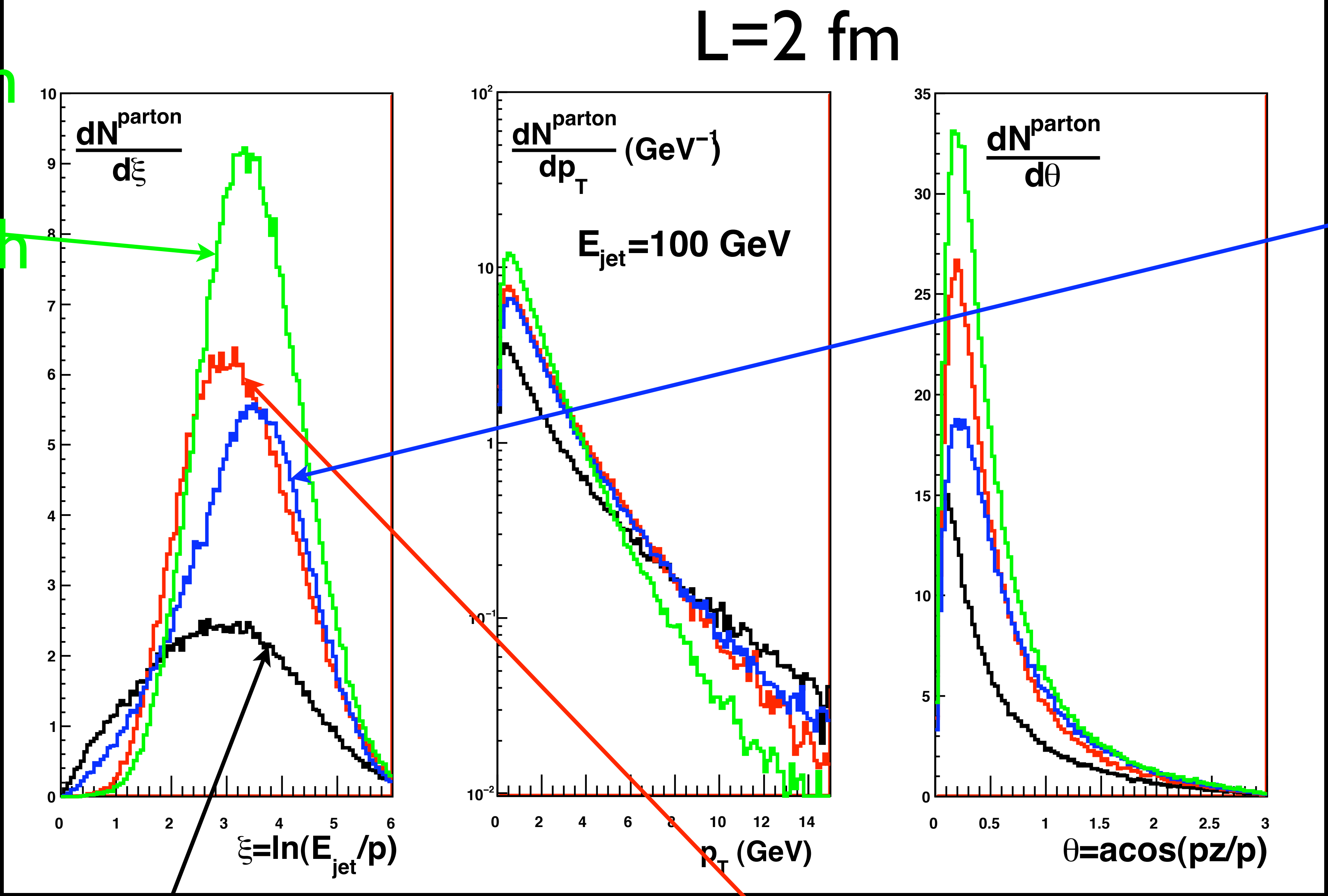


3.3. Q-PYTHIA: results (IV)

Two back-to-back gluons in singlet: an extreme example of hadronization. It kills most of the multiplicity enhancement, medium effects (soft stuff) less evident.



3.3. Q-PYTHIA: results (V)



Evolution in energy, not in length (qhat=10 GeV^2/fm)

Evolution in length and energy (qhat=10 GeV^2/fm)

vacuum (qhat=0)

No evolution in length nor energy (qhat=10 GeV^2/fm)

3.3. Q-PYTHIA: others

- **PQM** (Dainese-Loizides-Paic): PYTHIA with radiative eloss via QW.

- **PYQUEN** (Lokhtin-Snigirev): elastic scattering on top of radiative energy loss à la BDMPS with additional included gluons (path length considerations).

- **JEWEL** (Zapp-Ingelman-Rathsman-Stachel-Wiedemann): elastic scattering in DGLAP evolution plus radiative energy loss through a multiplicative constant in the collinear part of the splitting functions (Borghini-Wiedemann).

- **YaJEM** (Renk): increase of virtuality (i.e. of the length of the evolution) through qhatL computed at every point.

4. Summary and outlook:

- 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: virtuality, energy conservation, vacuum and medium treated on the same footing. A modified DGLAP evolution for fragmentation functions has been performed, its compatibility with QW for high virtualities showed.

- A publicly available (http://igfae.usc.es/qatmc/) medium-modified Monte Carlo parton shower: **Q-PYTHIA.1.0** has been shown (Q-HERWIG to follow), required for correlations and jet shape studies. Future: jet reconstruction, color reconnections, energy flow from/to the medium, theoretical basis.