Wayne State University, August 20-23, 2012

Jet Modification in Medium

Xin-Nian Wang

CCNU & LBNL

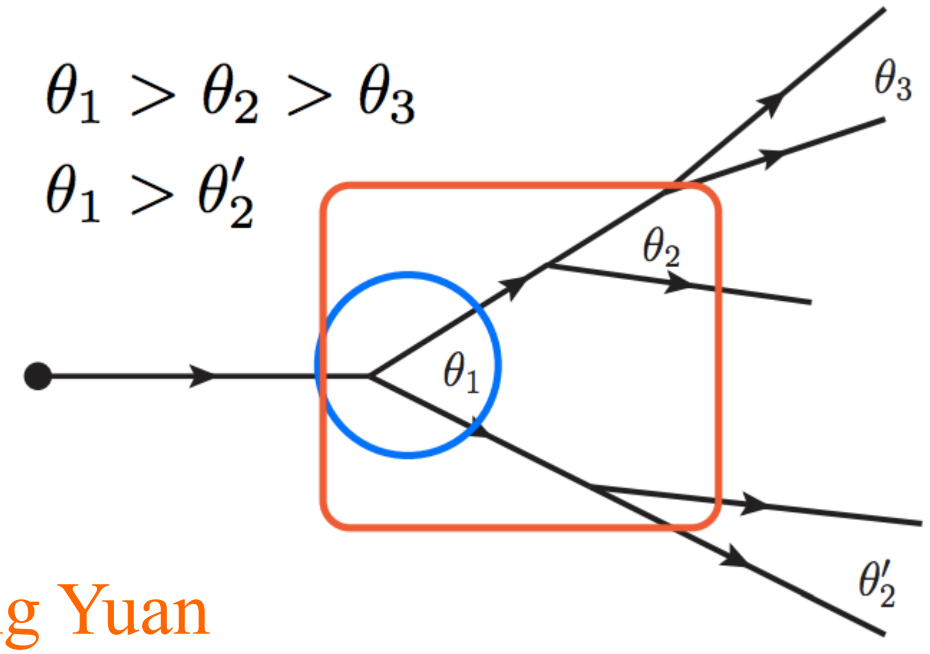
New developments

- Angular (anti-angular) ordering:

  Yacine Mehtar-Tani, K. Tywoniuk

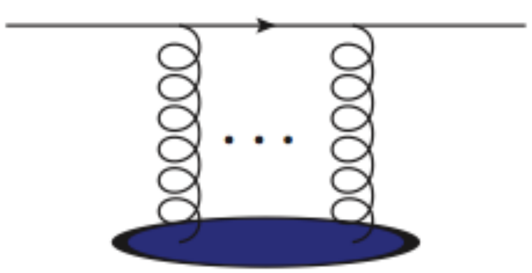
$\theta_1 > \theta_2 > \theta_3$

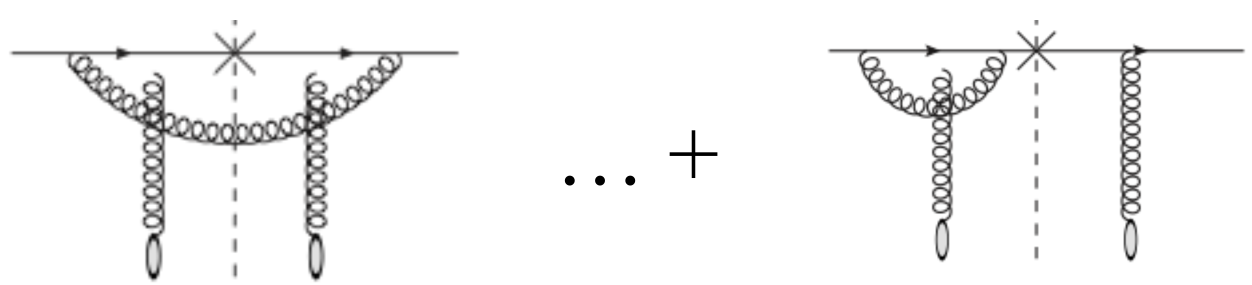
$\theta_1 > \theta_2'$



- NLO calculation: Bowen Xiao and Feng Yuan

$$\frac{d\sigma_{\rm LO}^{pA\to hX}}{d^2p_\perp dy_h} = \int_\tau^1 \frac{dz}{z^2}\left[\sum_f x_p q_f(x_p)\mathcal{F}(k_\perp)D_{h/q}(z) + x_p g(x_p)\tilde{\mathcal{F}}(k_\perp)D_{h/g}(z)\right]$$

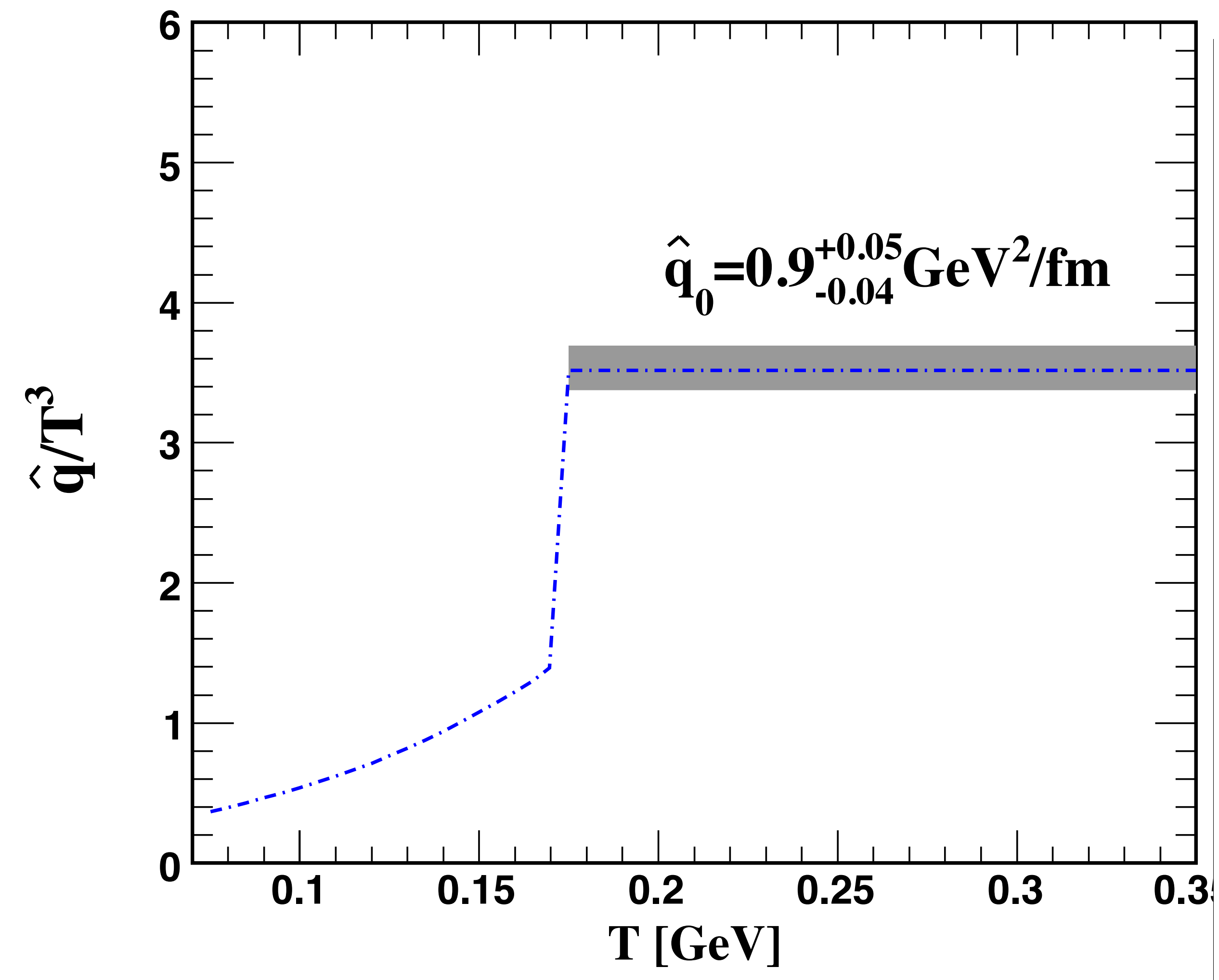


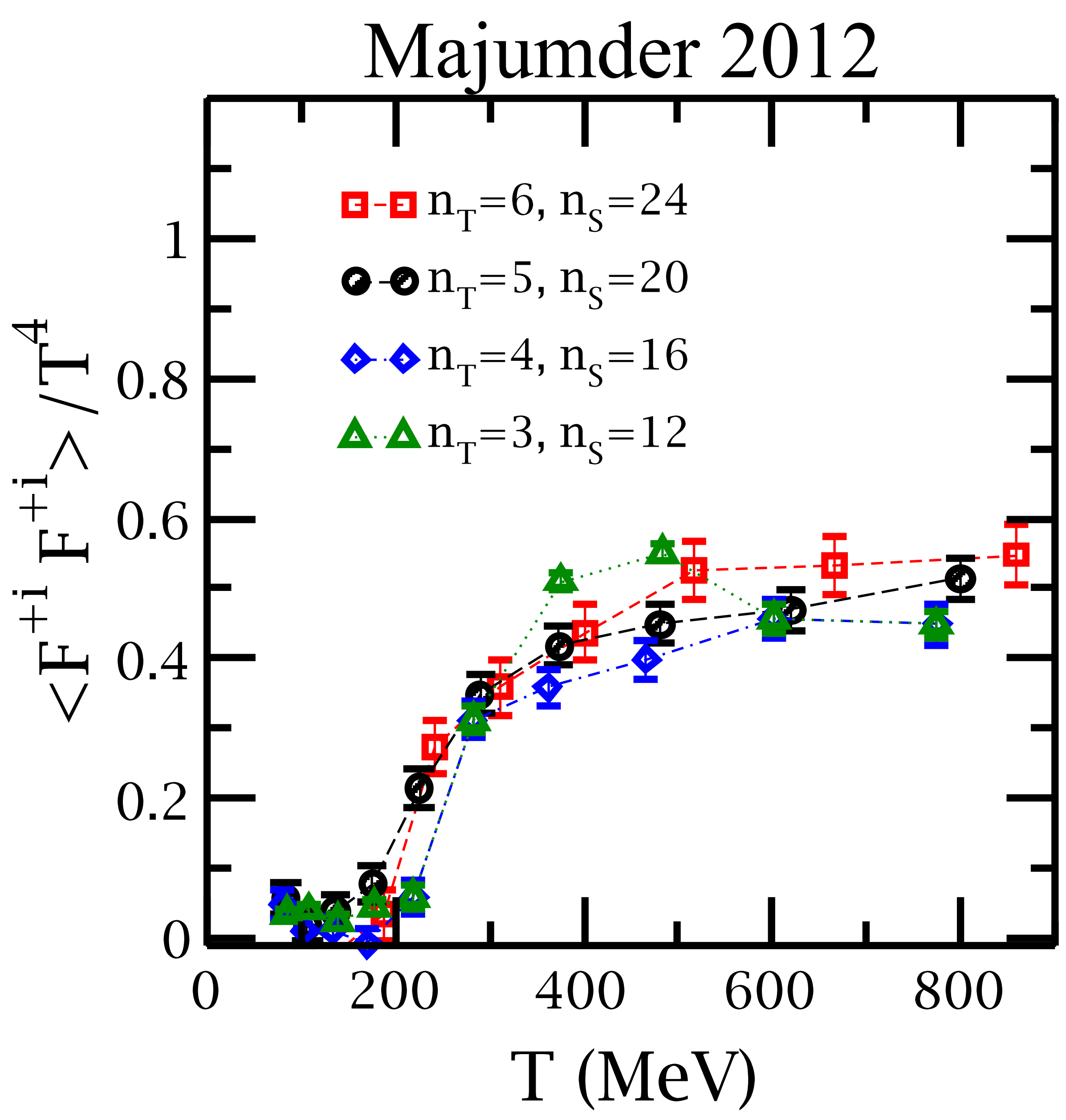


$$\frac{d^3\sigma^{p+A\to h+X}}{dyd^2p_\perp} = \int \frac{dz}{z^2}\frac{dx}{x}\xi xq(x,\mu)D_{h/q}(z,\mu)\int\frac{d^2x_\perp d^2y_\perp}{(2\pi)^2}\left\{S_Y^{(2)}(x_\perp,y_\perp)\left[\mathcal{H}_{2qq}^{(0)}+\frac{\alpha_s}{2\pi}\mathcal{H}_{2qq}^{(1)}\right]\right.$$
$$\left.+\int\frac{d^2b_\perp}{(2\pi)^2}S_Y^{(4)}(x_\perp,b_\perp,y_\perp)\frac{\alpha_s}{2\pi}\mathcal{H}_{4qq}^{(1)}\right\}$$

The Big Picture:
What we want to learn from JET

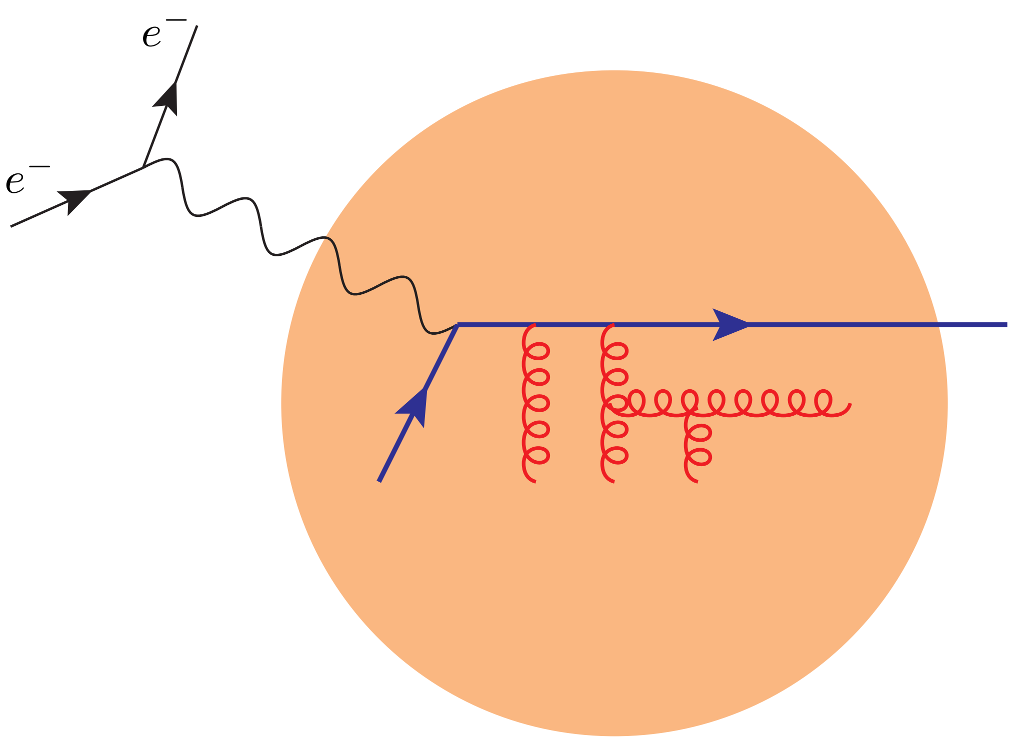
Chen, Greiner, Wang, XNW, Xu （2010）



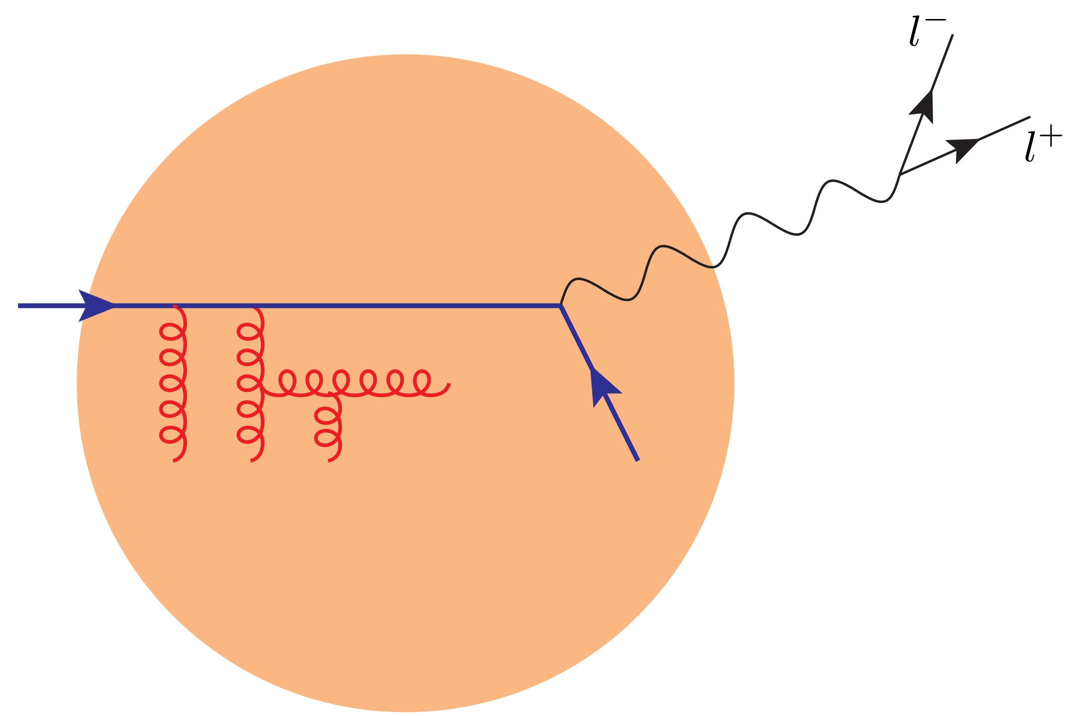


Parton energy loss in cold nuclear matter

DIS of large nuclei

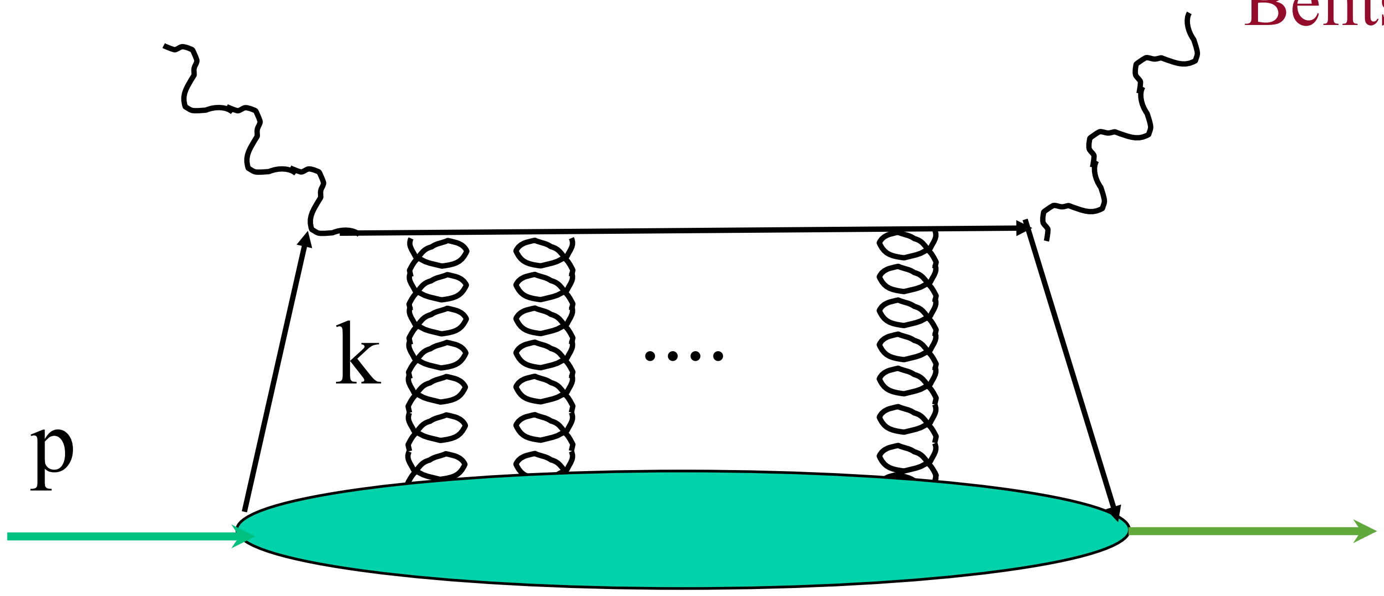


DY production in pA



Leading-twist parton distribution in DIS

Belitsky, Ji and Yuan (2002)

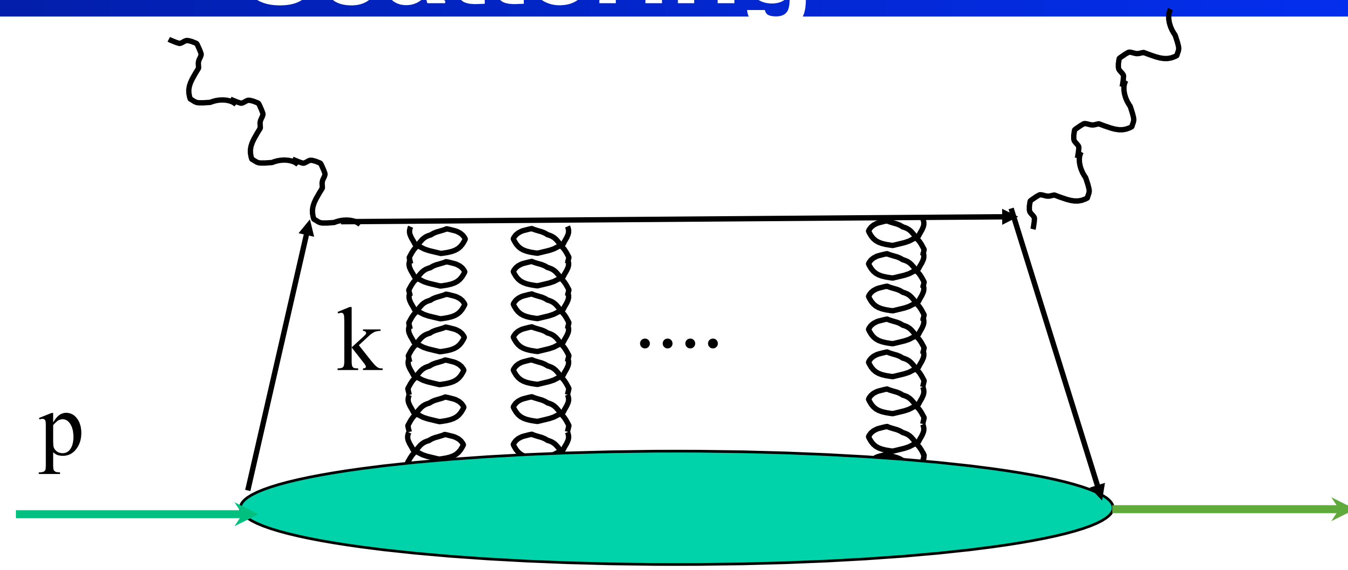


$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp}\langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$

$$\mathcal{L}(0,y) = \mathcal{L}_{\|}^{\dagger}(\infty,0;\vec{0}_\perp)\ \mathcal{L}_{\perp}^{\dagger}(\infty;\vec{y}_\perp,\vec{0}_\perp)\ \mathcal{L}_{\|}(\infty,y^-;\vec{y}_\perp)$$

$$\mathcal{L}_{\|}(0,y^-;\vec{0}_\perp) = \mathcal{P}\exp\left[ig\int_0^{y^-} d\xi^- A_+(\xi^-,\vec{0}_\perp)\right] \quad \mathcal{L}_{\perp}(\infty;\vec{y}_\perp,\vec{0}) = \mathcal{P}\exp\left[-ig\int_{\vec{0}_\perp}^{\vec{y}_\perp} d\vec{\xi}_\perp\cdot\vec{A}_\perp(\infty,\vec{\xi}_\perp)\right]$$

Higher Twist Contributions in Multiple Scattering



$$H(x_i, \vec{k}_{Ti}) = H(x_i, \vec{k}_{Ti} = 0) + \vec{k}_{Ti} \cdot \vec{\partial}_{k_T} H(x_i, \vec{k}_{Ti} = 0) + \cdots$$

$$\vec{k}_T \rightarrow -i\vec{\partial}_T$$

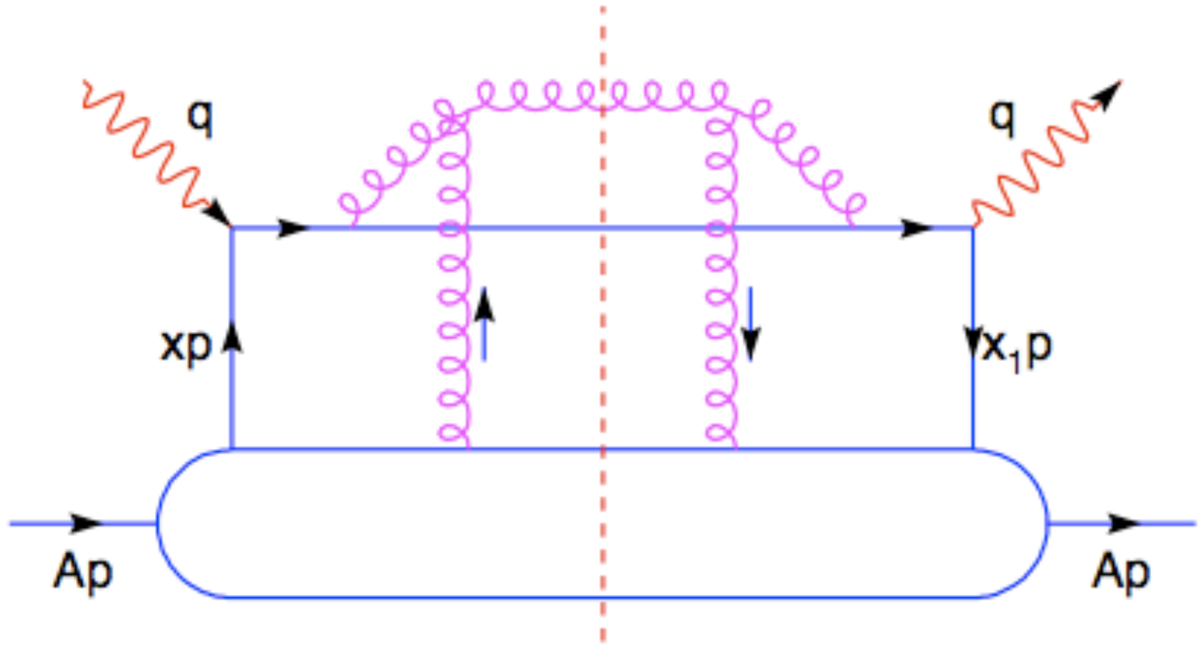
$$gA(y) = gA^+ + g\vec{A}_T(y)$$

$$\vec{D}_T = \vec{\partial}_T + ig\vec{A}_T(y)$$

Jet Transport $\vec{W}_\perp(y^-, \vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g\int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp)$

Liang, XNW & Zhou （2008）

Modified fragmentation function in DIS



Guo, XNW 2000

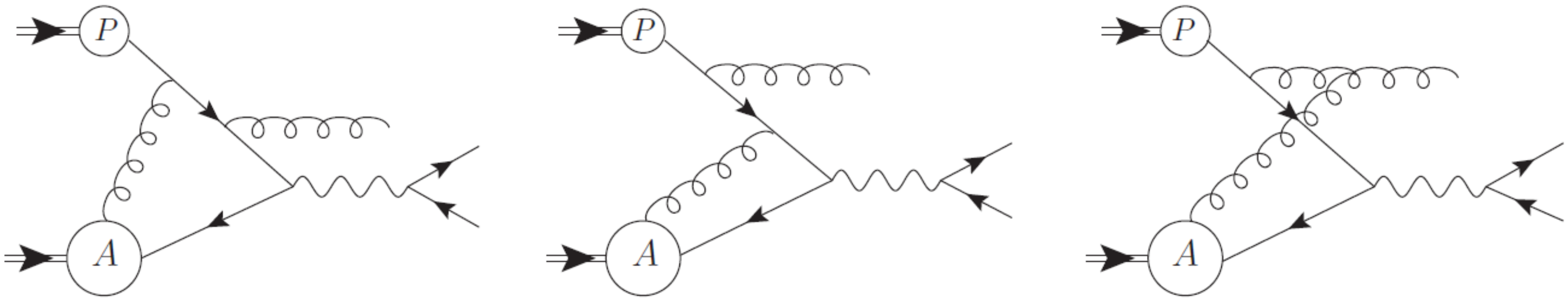
$$\Delta D_{q\to h}(z_h, Q^2) = \frac{\alpha_s}{2\pi}\int_0^{Q^2}\frac{d\ell_\perp^2}{\ell_\perp^2}\int_{z_h}^1\frac{dz}{z}\left[\Delta\gamma(z,\ell_\perp^2)D_{q\to h}(\frac{z_h}{z}) + \cdots\right]$$

$$\Delta\gamma(z,\ell_\perp^2) = C_A\frac{1+z^2}{(1-z)_+}\frac{2}{\ell_\perp^2}\int d\xi_N\hat{q}(\xi_N)[1-\cos(x_L p^+\xi_N^-)]$$

$$R = \frac{D(z_h) + \Delta D(z_h)}{D(z_h)}$$

Double scattering in DY

- Annihilation-like:



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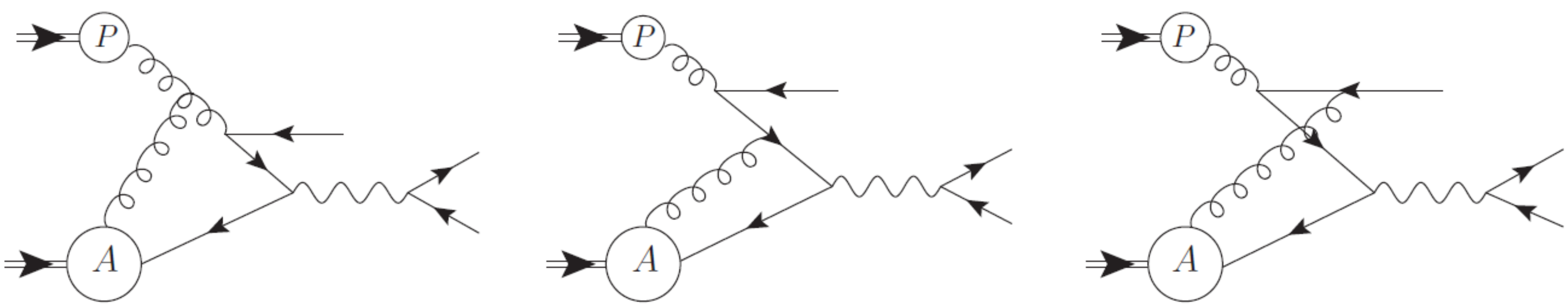
- Compton-like:



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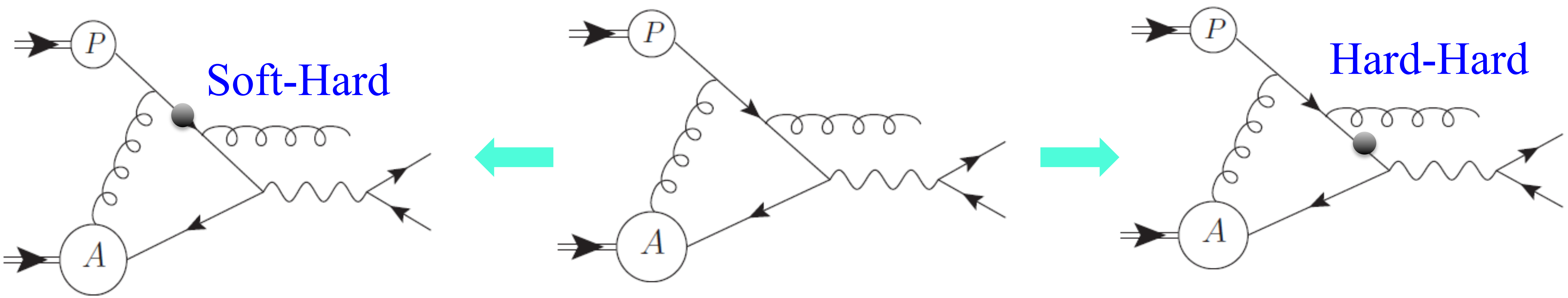
LPM interference in DY

$$-\frac{1}{4}g^{\alpha\beta}\frac{\overline{H}_{A11}}{\partial k_T^\alpha \partial k_T^\beta}\Big|_{k_T=0} = \alpha_{em}e_q^2\alpha_s^2\frac{C_F}{N_c^2}8(2\pi)^2\frac{1+z^2}{1-z}\frac{z^2}{q_T^4}\theta(-y_2^-)\theta(y^- - y_1^-)e^{i(x_B+x_t)p^+y^-}$$
$$\times \left[1-e^{-ix_tp^+(y^- - y_1^-)}\right]\left[1-e^{-ix_tp^+y_2^-}\right],$$



Role of interference between soft-hard and hard-hard double scattering

Formation time of the radiated gluon: $\tau_f \equiv 1/x_t p^+ \propto 1/q_T^2$

- Short formation time, the interference can be neglected;
- Long formation time, Collinear radiation suppressed, LPM effect.

Medium modified projectile PDF

- Modified quark distribution - Vacuum + Medium

$$\tilde{f}_{q/h}(x',\mu^2) = f_{q/h}(x',\mu^2) + \frac{\alpha_s}{2\pi}\int_0^{\mu^2}\frac{dq_T^2}{q_T^2}\int_{x'}^1\frac{d\xi}{\xi}\left[f_{q/h}(\xi)\Delta\gamma_{q\to qg}(x'/\xi,q_T^2) + f_{g/h}(\xi)\Delta\gamma_{g\to q\bar{q}}(x'/\xi,q_T^2)\right]$$

Modified splitting function

$$\Delta\gamma_{q\to qg}(z,q_T^2) = \left[\frac{1+z^2}{(1-z)_+}T^A_{gq} + \delta(1-z)\Delta T^A_{gq}\right]\frac{C_F 2\pi\alpha_s}{q_T^2 N_C f_{\bar{q}/A}(x)}$$

$$\Delta\gamma_{g\to q\bar{q}}(z,q_T^2) = \left[(1-z)^2+z^2\right]T^C_{gq}\frac{2\pi\alpha_s C_A}{q_T^2(N_C^2-1)f_{\bar{q}/A}(x)}$$

- Modified DGLAP evolution

$$\frac{\partial\tilde{f}_{q/h}(x',\mu^2,A)}{\partial\ln\mu^2} = \frac{\alpha_s}{2\pi}\int_{x'}^1\frac{d\xi}{\xi}\left[\tilde{f}_{q/h}(\xi,\mu^2,A)\tilde{\gamma}_{q\to qg}(x'/\xi,\mu^2) + \tilde{f}_{g/h}(\xi,\mu^2,A)\tilde{\gamma}_{g\to q\bar{q}}(x'/\xi,\mu^2)\right]$$

- "factorized" gluon-quark correlation function

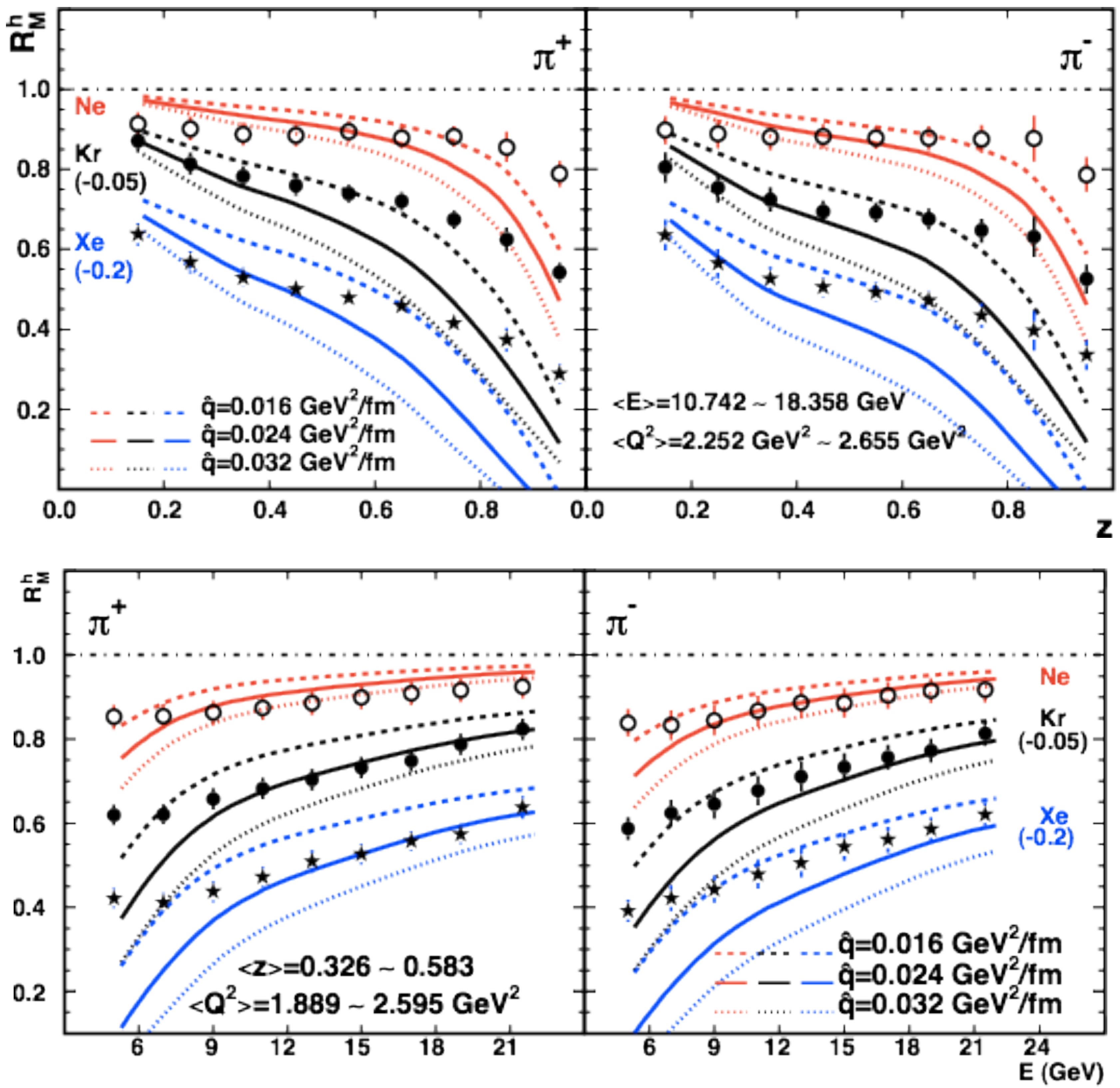
$$T_{gq}(x,x_t) = \int \frac{dy^-}{2\pi} dy_1^- dy_2^- e^{i(x+x_t)p^+y^-} \left(1-e^{-ix_tp^+(y^- - y_1^-)}\right)\left(1-e^{-ix_tp^+y_2^-}\right)$$
$$\times \frac{1}{2} < A|F_\alpha^+(y_2^-)\overline{\psi}_q(0)\gamma^+\psi_q(y^-)F^{+\alpha}(y_1^-)|A > \theta(-y_2^-)\theta(y^- - y_1^-)$$

$$= \frac{6}{\pi\alpha_s} f_{\bar{q}/A}(x_B) \int dy_1^- \sin^2\frac{x_tp^+y_1^-}{2}\hat{q}(y_1)$$

- Jet transport parameter

$$\hat{q}(x_t, y^-, \vec{b}) \equiv \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho_A(y^-,\vec{b})\frac{1}{2}\left[xf_{g/N}^A(x,\vec{b})|_{x\approx 0} + x_t f_{g/N}^A(x_t,\vec{b})\right]$$
$$\approx \hat{q}_0\frac{\rho_A(y^-,\vec{b})}{\rho_A(0,\vec{0}_\perp)},$$

DIS of large nuclei



$$R = \frac{N_h^{eA}}{N_h^{eD}}$$

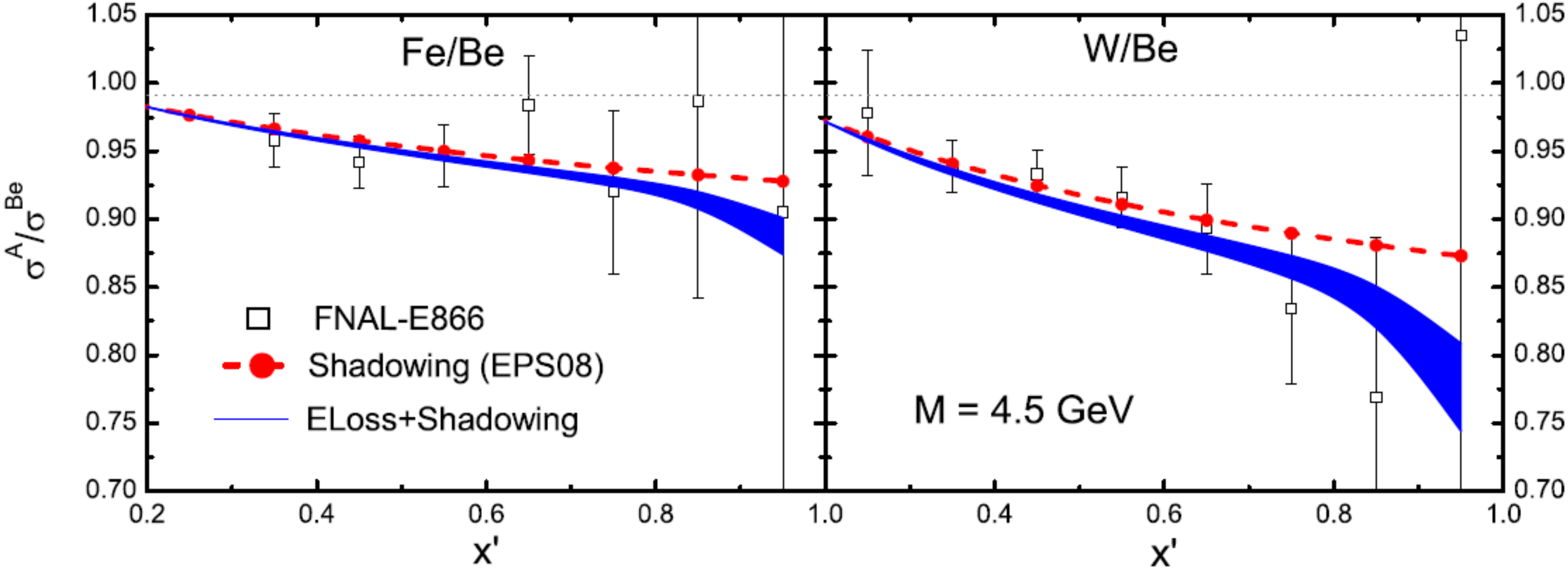
Deng & XNW (**2010**)

$$\hat{q}_N \approx 0.02\ \mathrm{GeV}^2/\mathrm{fm}$$

Nuclear effects in Drell-Yan

$$\frac{B\sigma^A}{A\sigma^B} = \frac{\sum_q \int dx\, f_{\bar{q}/A}(x,\mu^2)\tilde{f}_{q/p}(x',\mu^2,A)H_0(x,p,q)}{A\sum_q \int dx\, f_{\bar{q}/N}(x,\mu^2)f_{q/p}(x',\mu^2)H_0(x,p,q)}$$

Energy loss VS. Shadowing (FNAL-E866 ELab = 800 GeV)

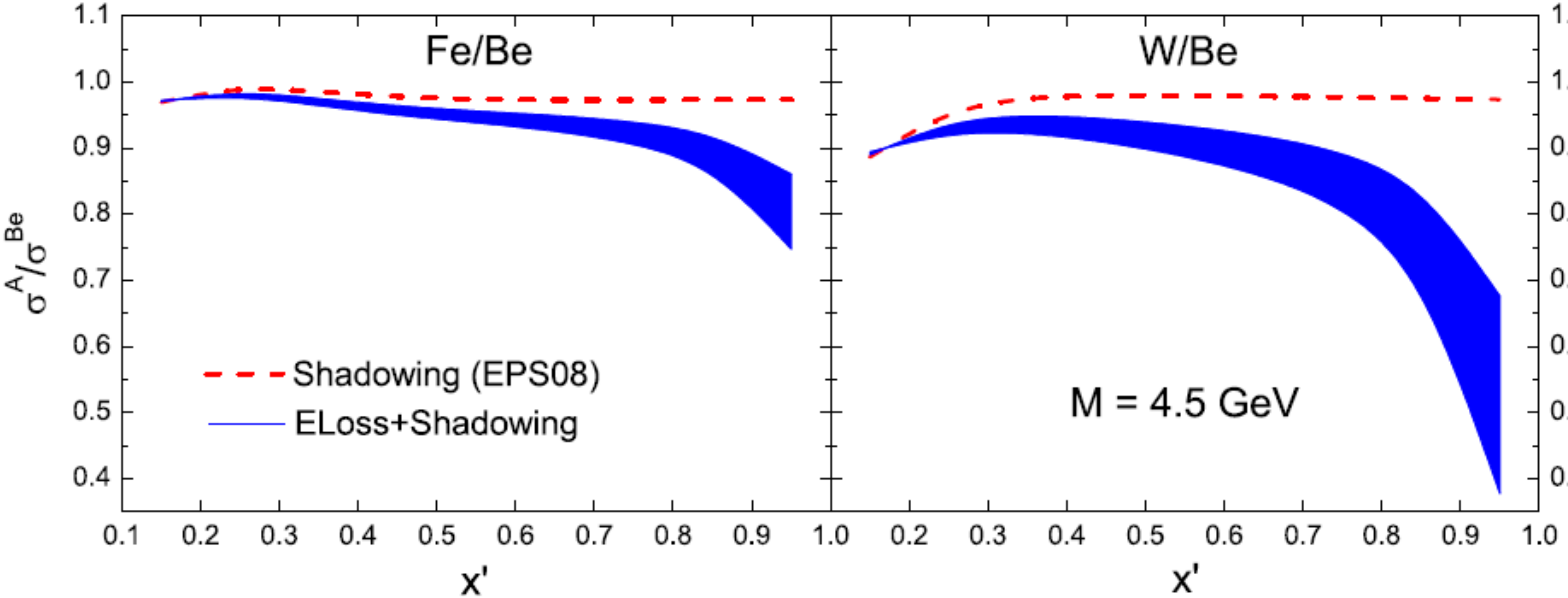


H. Xing, Y. Guo. E. Wang & XNW, 2012

$\hat{q}_N \approx 0.02\ \mathrm{GeV}^2/\mathrm{fm}$

Parton energy loss in Drell-Yan

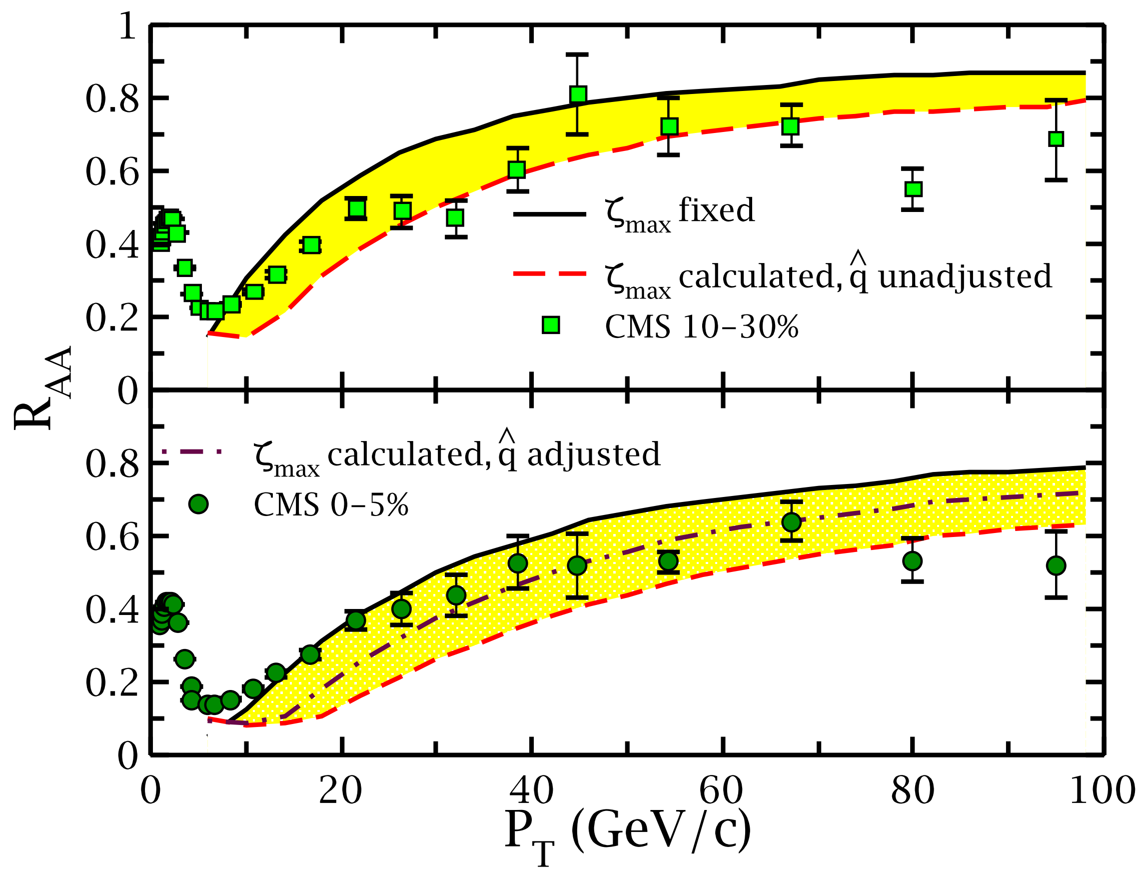
Energy loss VS. Shadowing (FNAL-E906 ELab = 120 GeV)

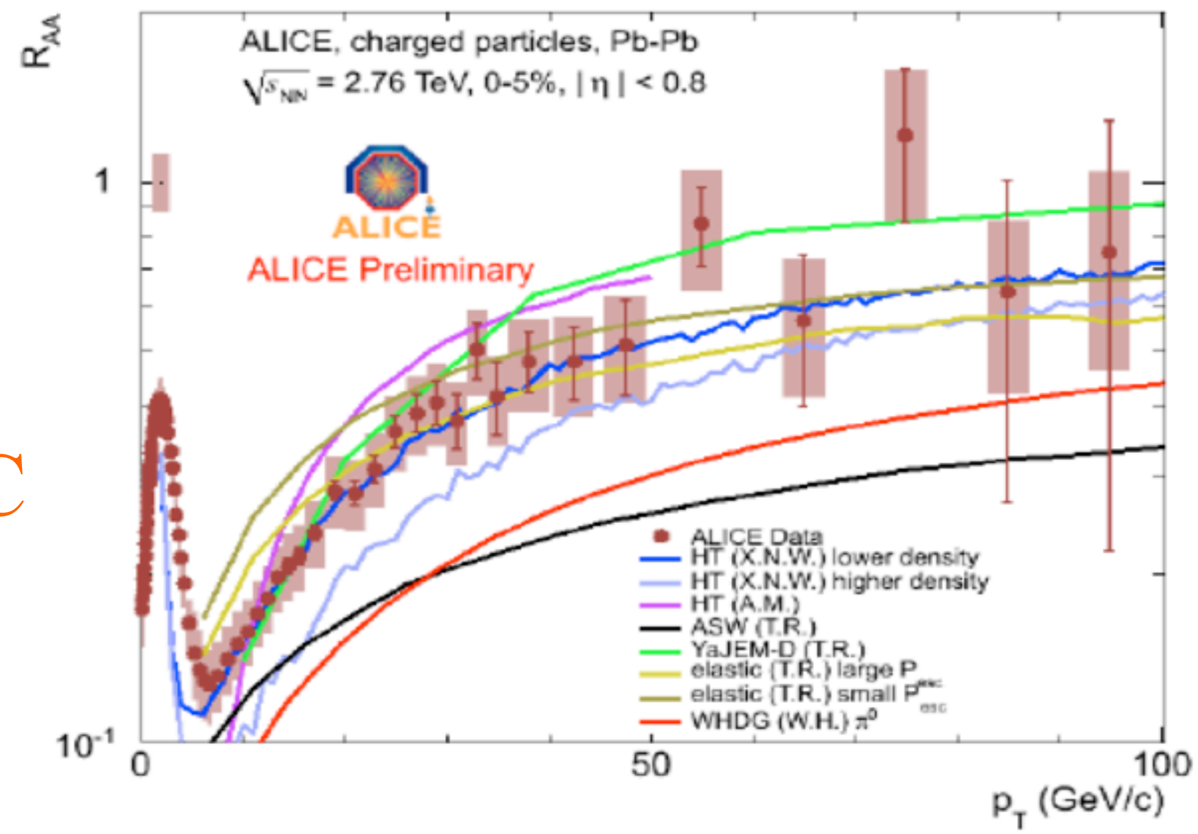


FNAL-E906 provide unambiguous measurement of initial state energy loss

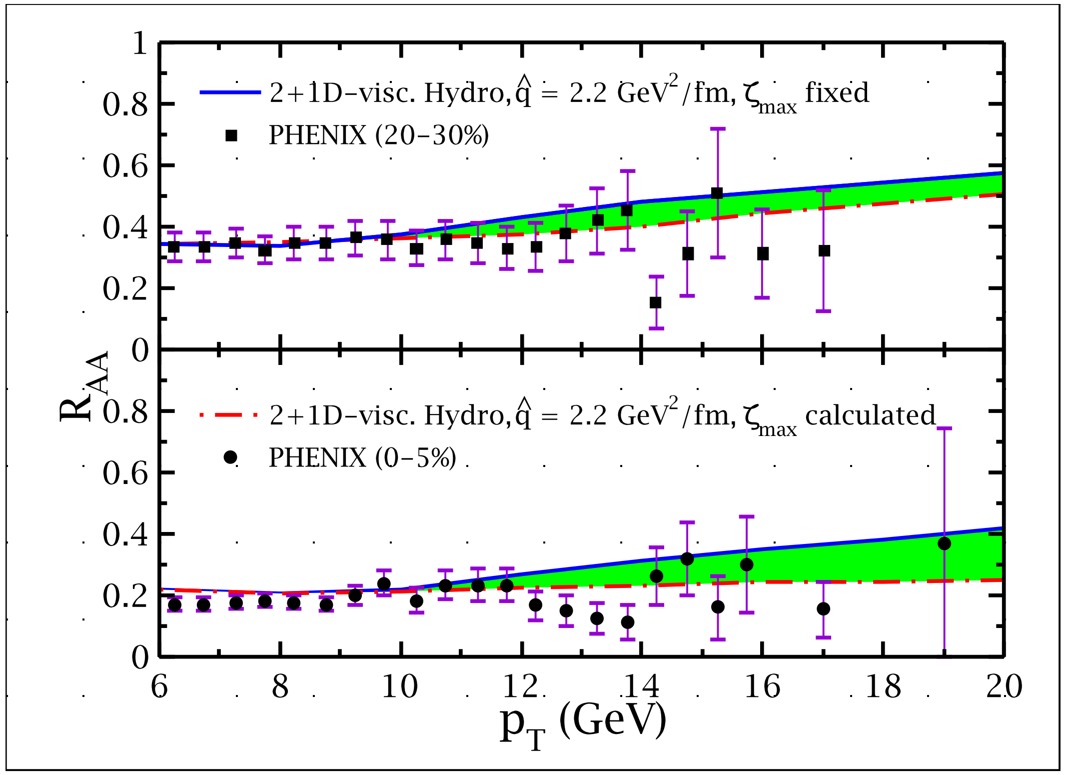
H. Xing, Y. Guo. E. Wang & XNW, 2012

Jet quenching in AA collisions

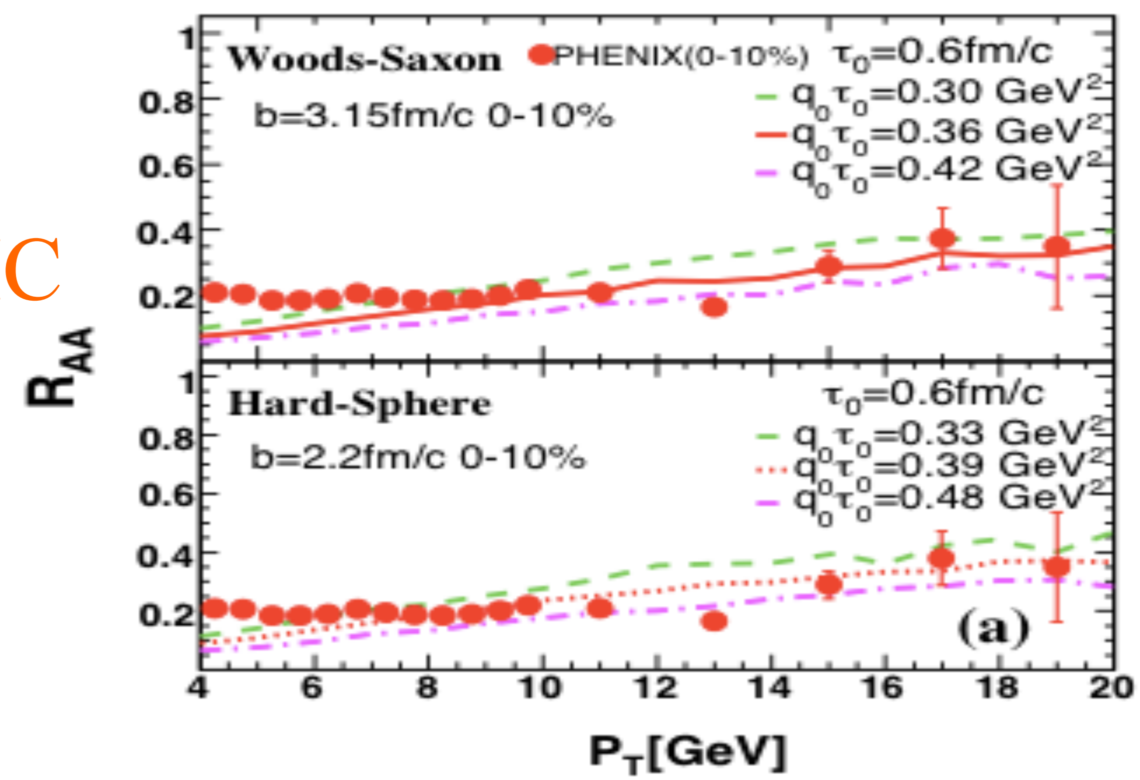




LHC



RHIC



Modified DGLAP Equations

$$\frac{\partial \tilde{D}_q^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\left[\tilde{\gamma}_{q\to qg}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{q\to gq}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\right]$$

$$\frac{\partial \tilde{D}_g^h(z_h,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\int_{z_h}^1 \frac{dz}{z}\left[\sum_{q=1}^{2n_f}\tilde{\gamma}_{g\to q\bar{q}}(z,\mu^2)\tilde{D}_q^h(\frac{z_h}{z},\mu^2) + \tilde{\gamma}_{g\to gg}(z,\mu^2)\tilde{D}_g^h(\frac{z_h}{z},\mu^2)\right]$$

Modified splitting functions

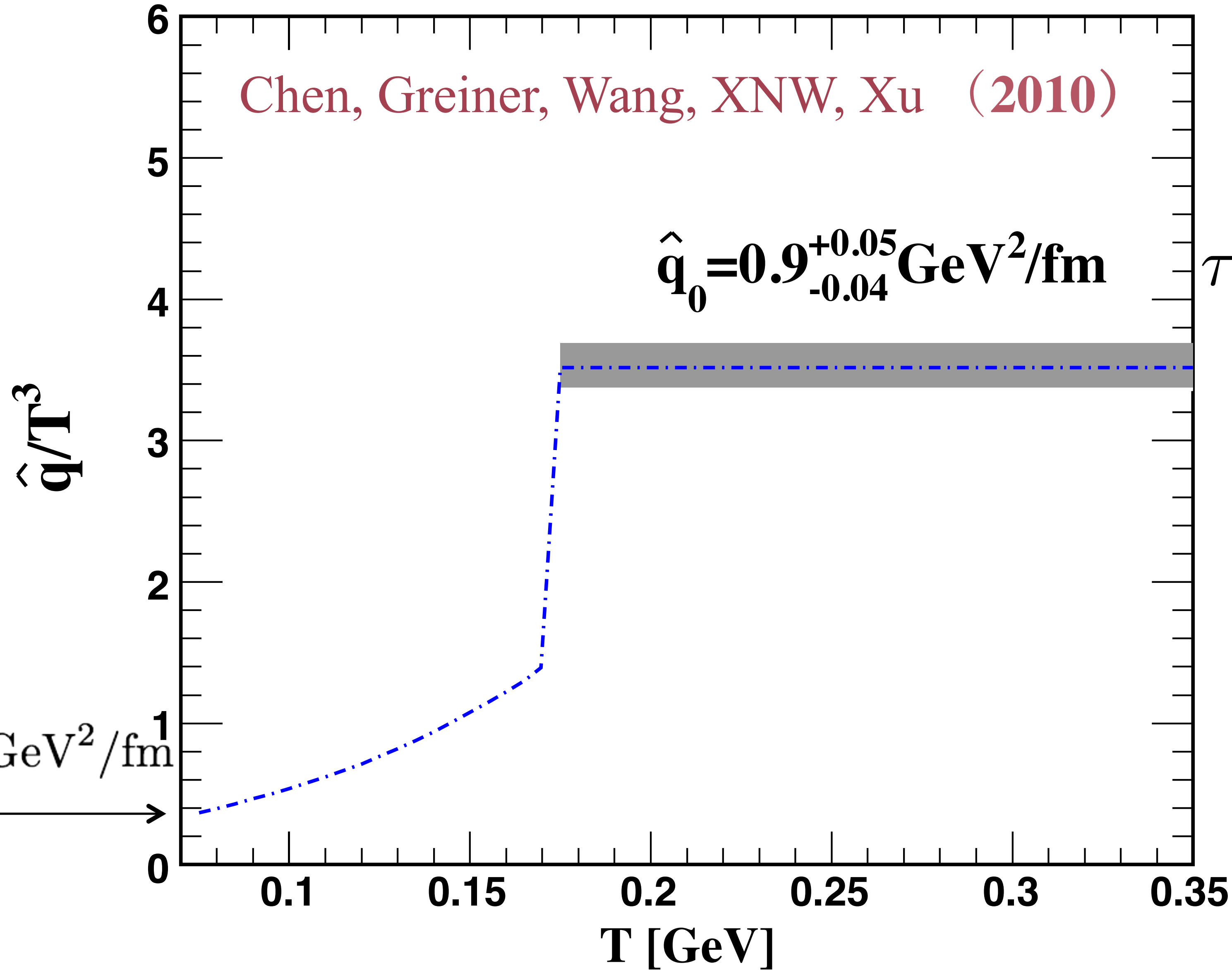
$$\tilde{\gamma}_{a\to bc}(z,l_T^2) = \gamma_{a\to bc}(z) + \Delta\gamma_{a\to bc}(z,l_T^2)$$

- Correlation between Q^2 and space-time
- Initial FF's at Q_0^2 –still determined by pQCD?

T-dependence of jet transport coefficient

$$\hat{q}(\tau,r)=\hat{q}_0\frac{\rho^{QGP}(\tau,r)}{\rho^{QGP}(\tau_0,0)}(1-f)+\hat{q}_h(\tau,r)f$$

$$\hat{q}_h=\frac{\hat{q}_N}{\rho_N}\left[\frac{2}{3}\sum_M\rho_M(T)+\sum_B\rho_B(T)\right]$$

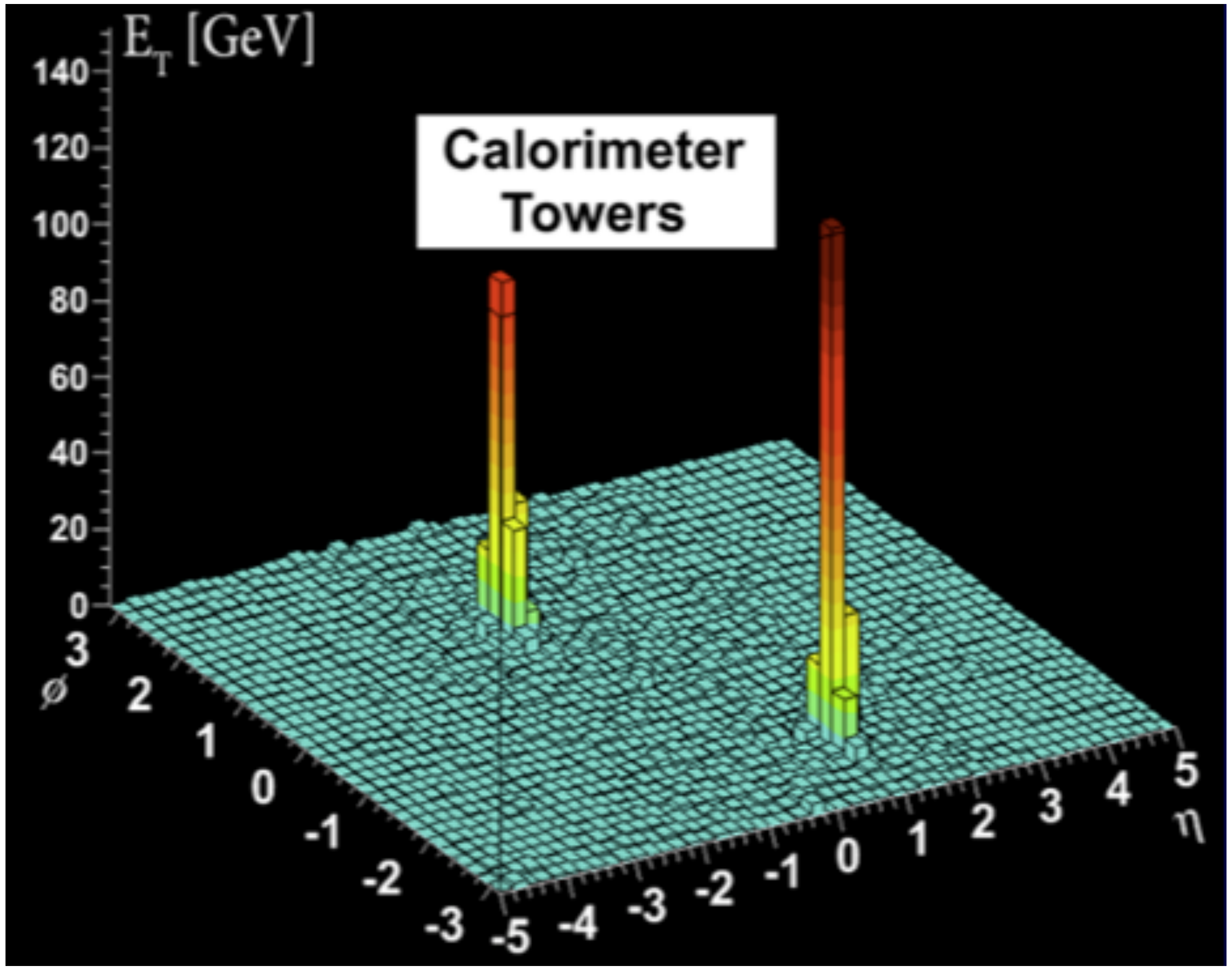


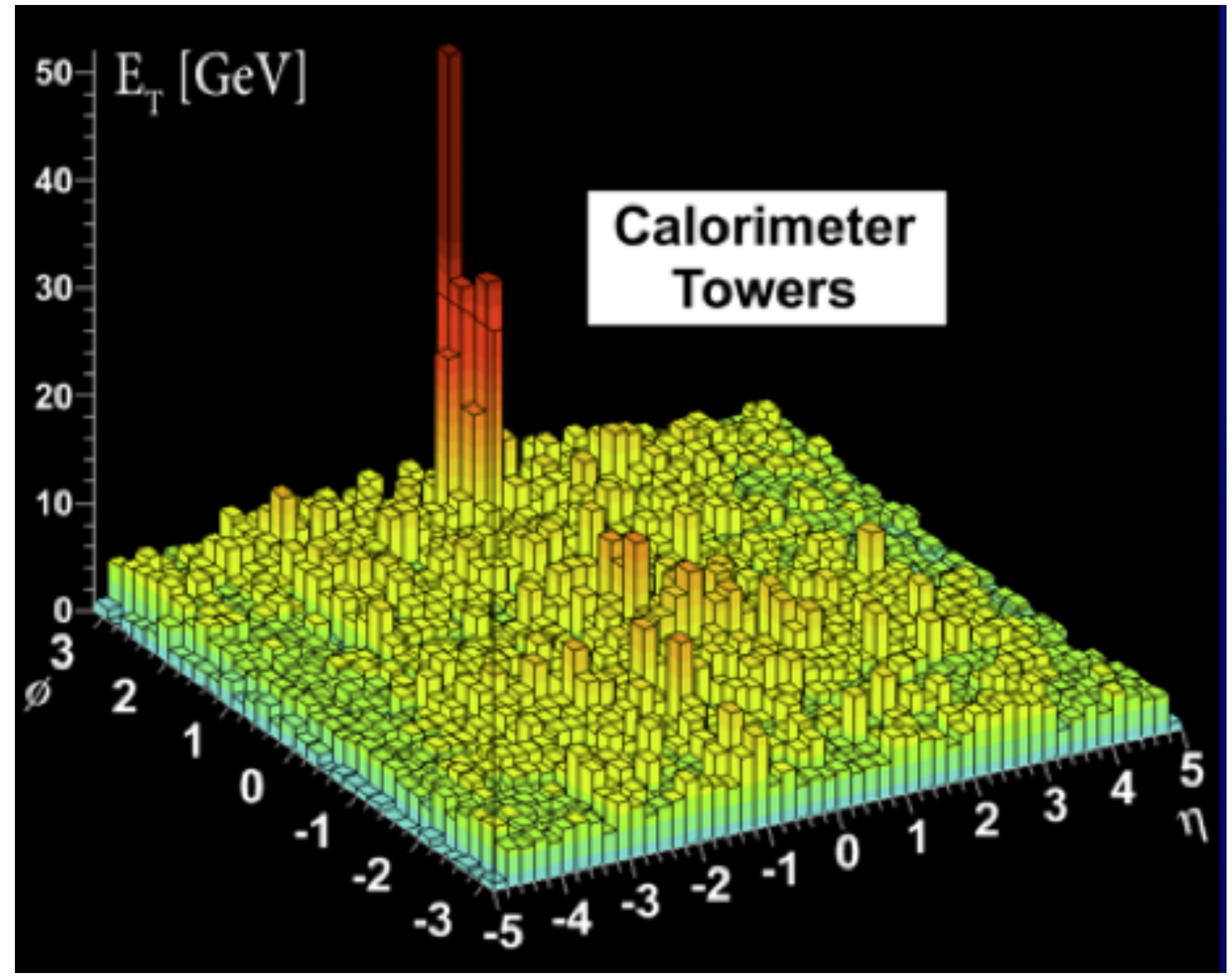
$\hat{q}_N = 0.02\ \ \mathrm{GeV}^2/\mathrm{fm}$

$\tau_0 = 0.6\ \ fm/c$

30% quenching from hadronic phase

Full jet tomography





- Development of jet parton shower in medium (angular ordering?)
- Response of the medium – when medium becomes part of a jet?
- Jet profile
- Parton or hadron distribution inside a re-constructed jet

Linear Jet Boltzmann Transport

$$p_1 \cdot \partial f_1(p_1) \quad = \quad -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left|M_{12\to 34}\right|^2 (2\pi)^4 \delta^4 (\sum_i p_i),$$

$$\frac{d\sigma}{dt} = |M_{12\to 34}|/16\pi^2 s^2$$

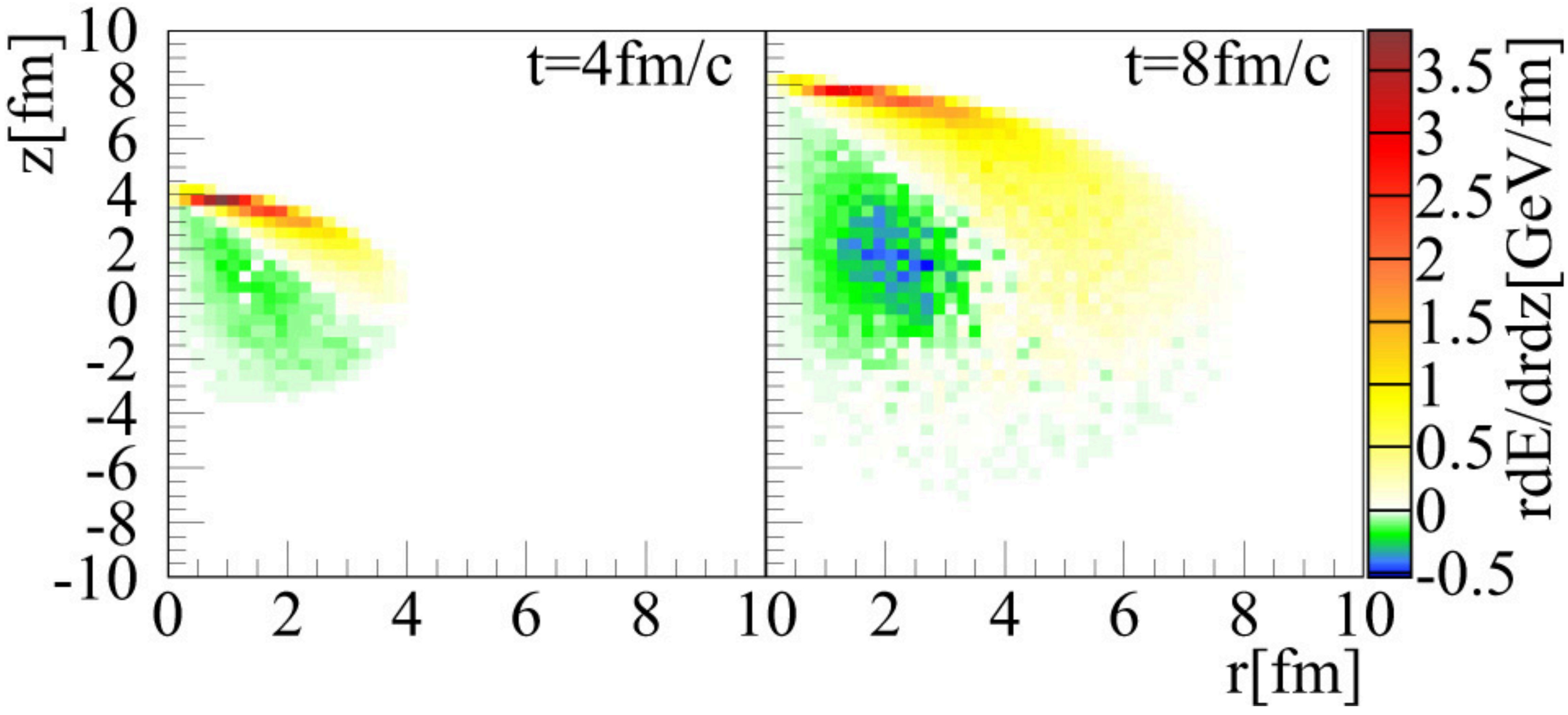
$$f_i(p) = (2\pi)^3 \delta^3(\vec{p}_i - \vec{p}_0)\delta^3(\vec{x} - \vec{x}_0 - t\vec{v}_i)[i = 1, 3]$$

$$f_i(p_i) = \frac{1}{e^{p_i \cdot u/T} \pm 1}(i = 2, 4)$$

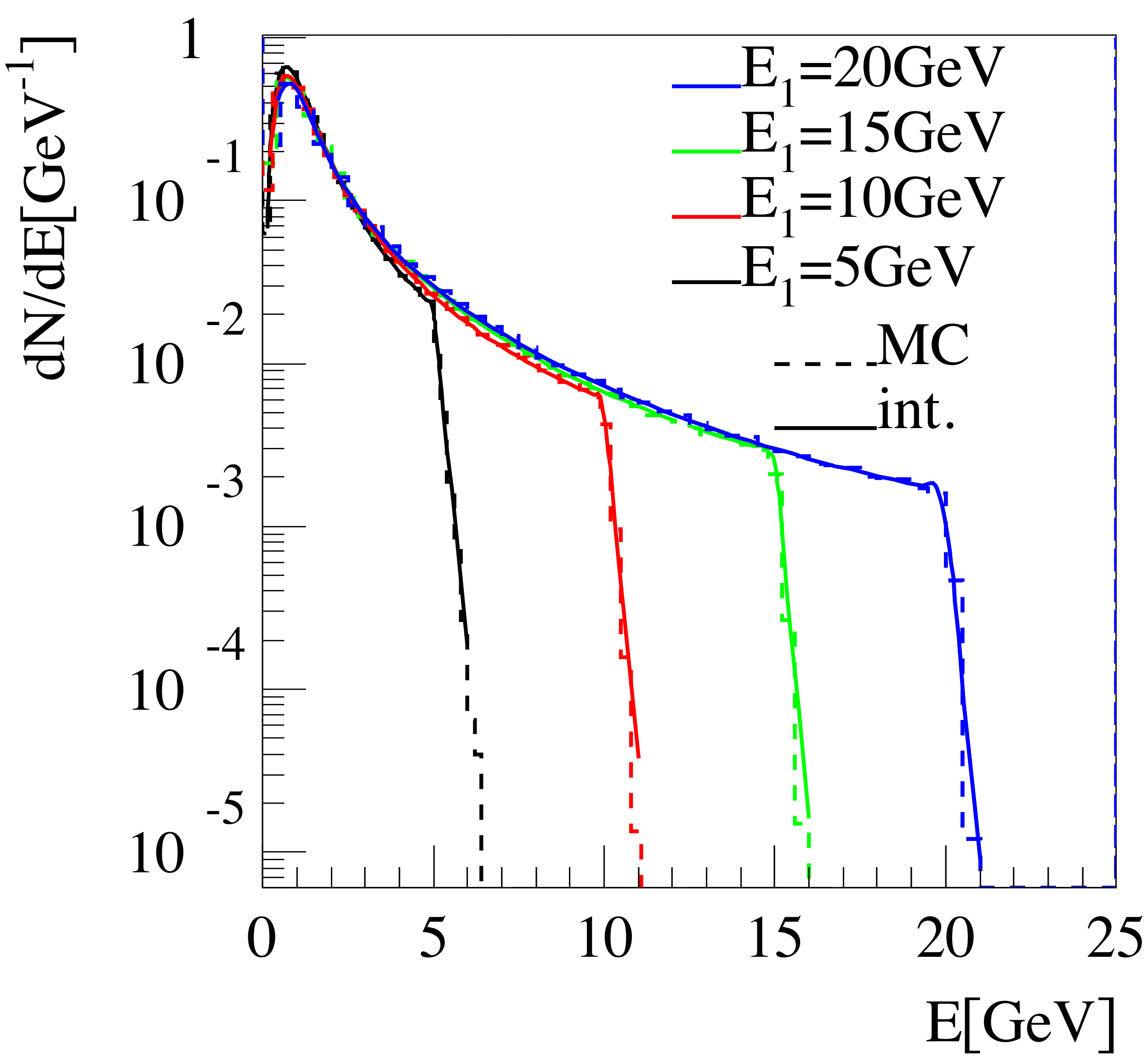
$$\frac{dN_g}{dz d\ell_\perp^2 dL} = \frac{C_A \alpha_s}{\pi} P(z) \frac{1}{\ell_\perp^4} \hat{q}(L)(1 - \cos(L/\tau_f))$$

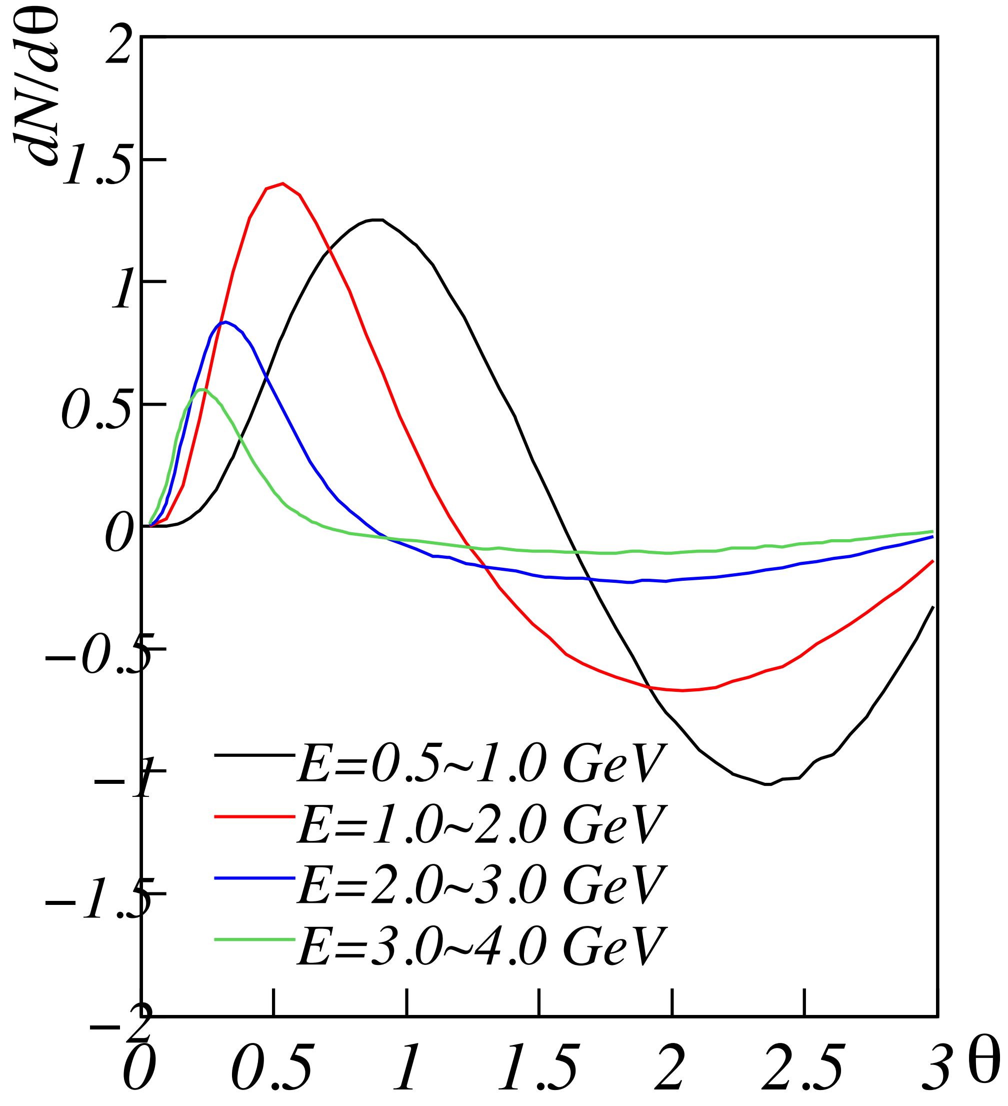
Medium response to jet propagation

Jet excited wake-front



Medium response to jet propagation

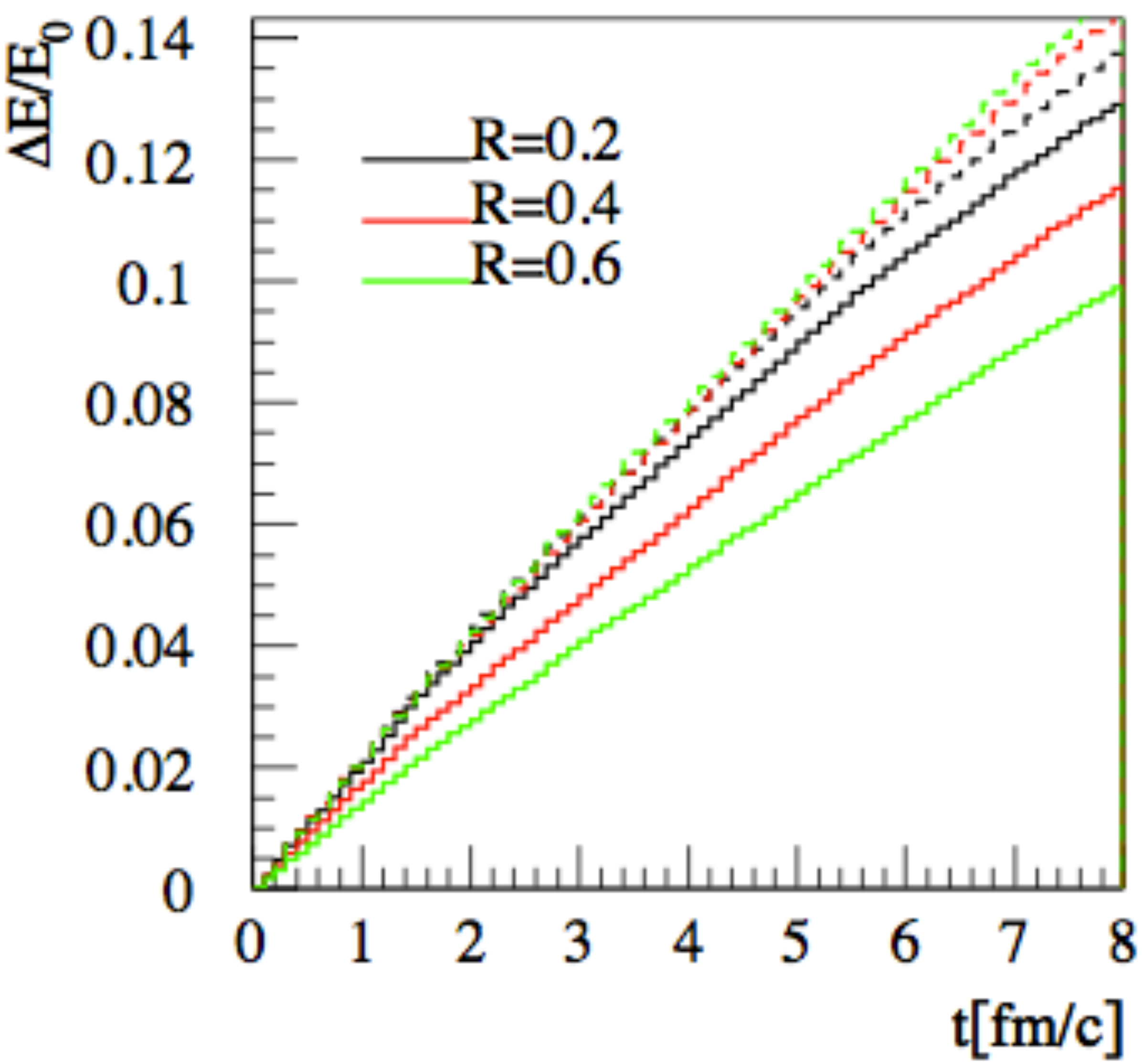




Jet-energy loss

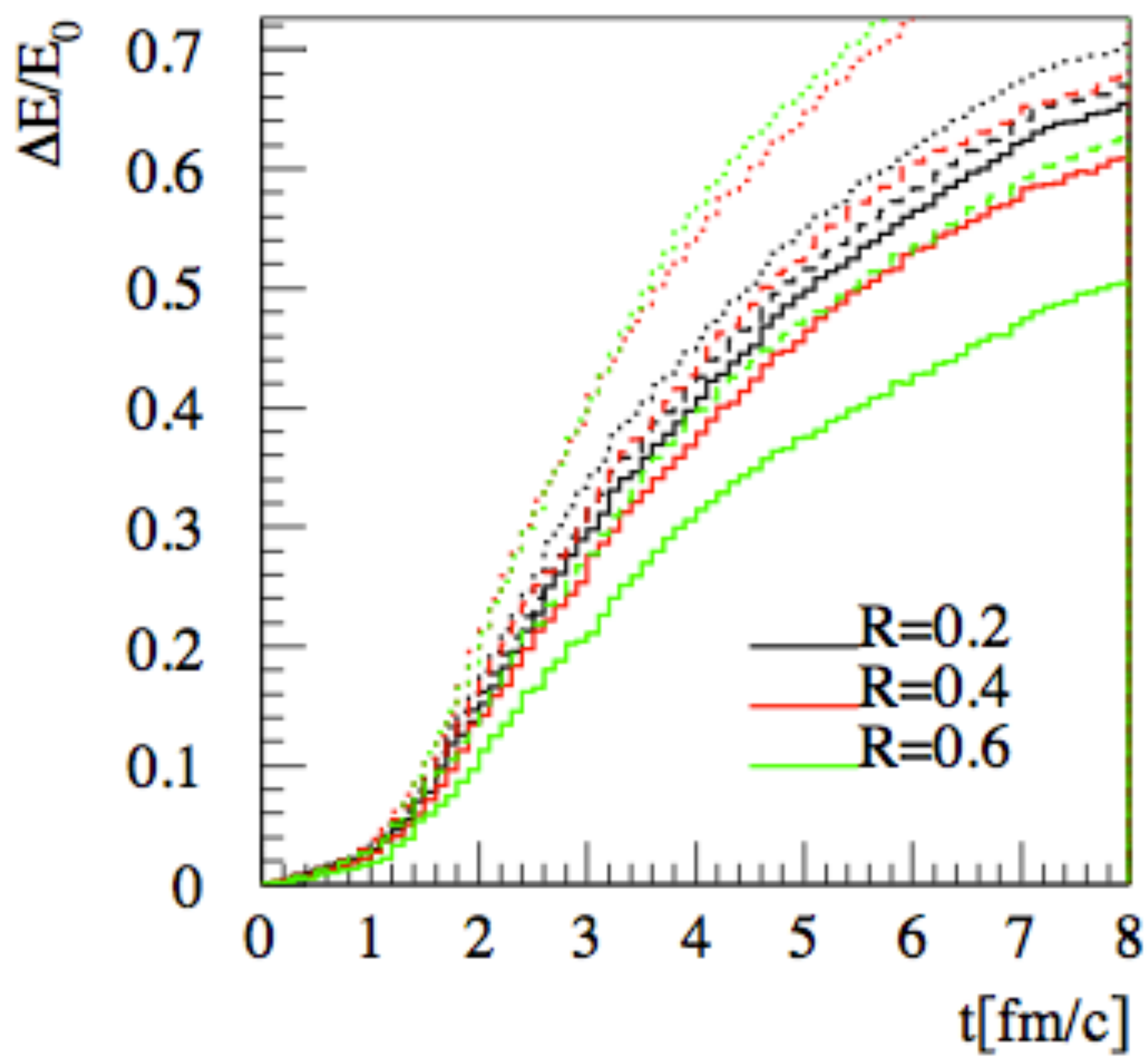
Gamma-jet: E_γ=60 GeV in uniform medium at T=300 MeV

Elastic



Solid: jet+medium
Dashed: jet

Elastic+radiative



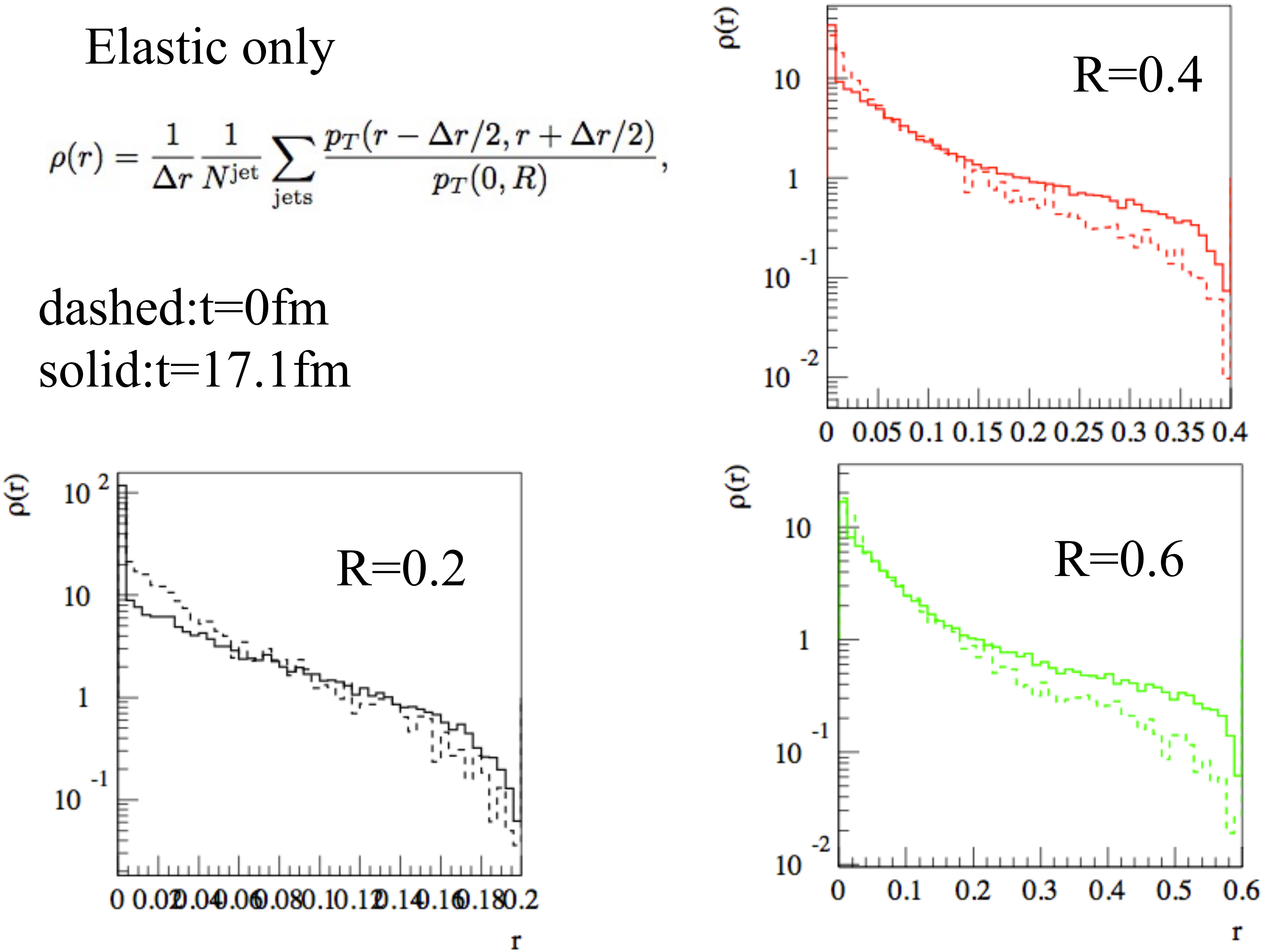
Solid: jet+radiatied+medium
Dashed: jet+radiated
Dotted: jet

Jet Profile

Elastic only

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\rm jet}}\sum_{\rm jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},$$

dashed:t=0fm
solid:t=17.1fm

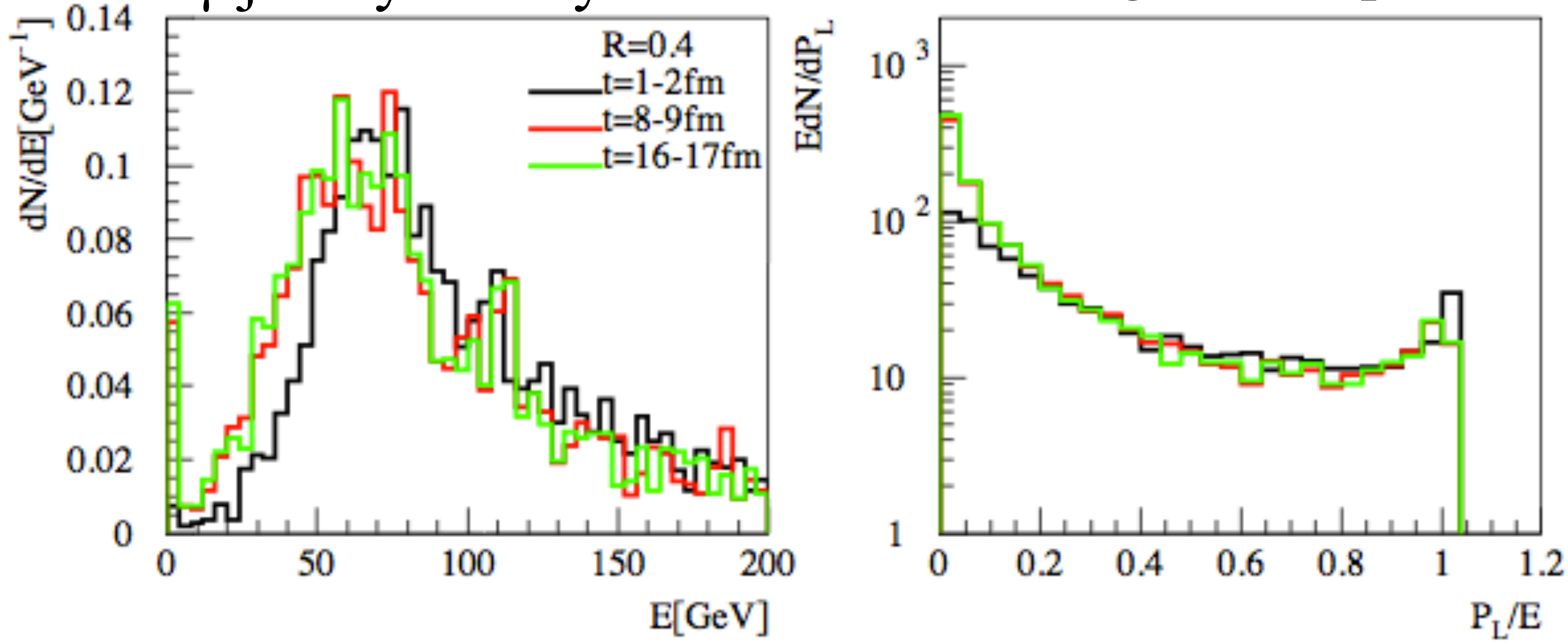


Hydro medium: γ-jet asymmetry and FF

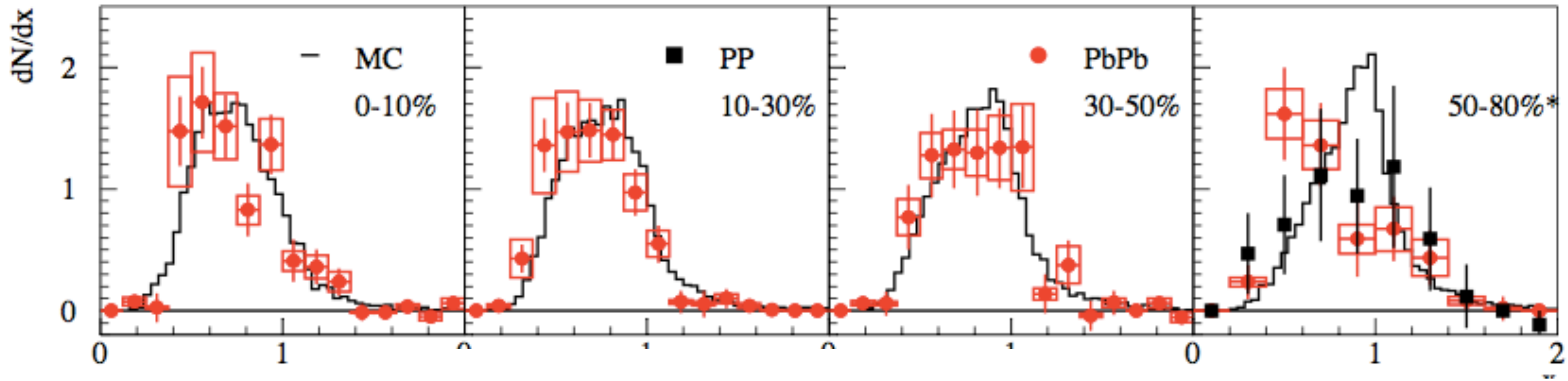
Pb+Pb 0-10% 3+1D hydro medium, E_γ=60 GeV, α_s=0.4

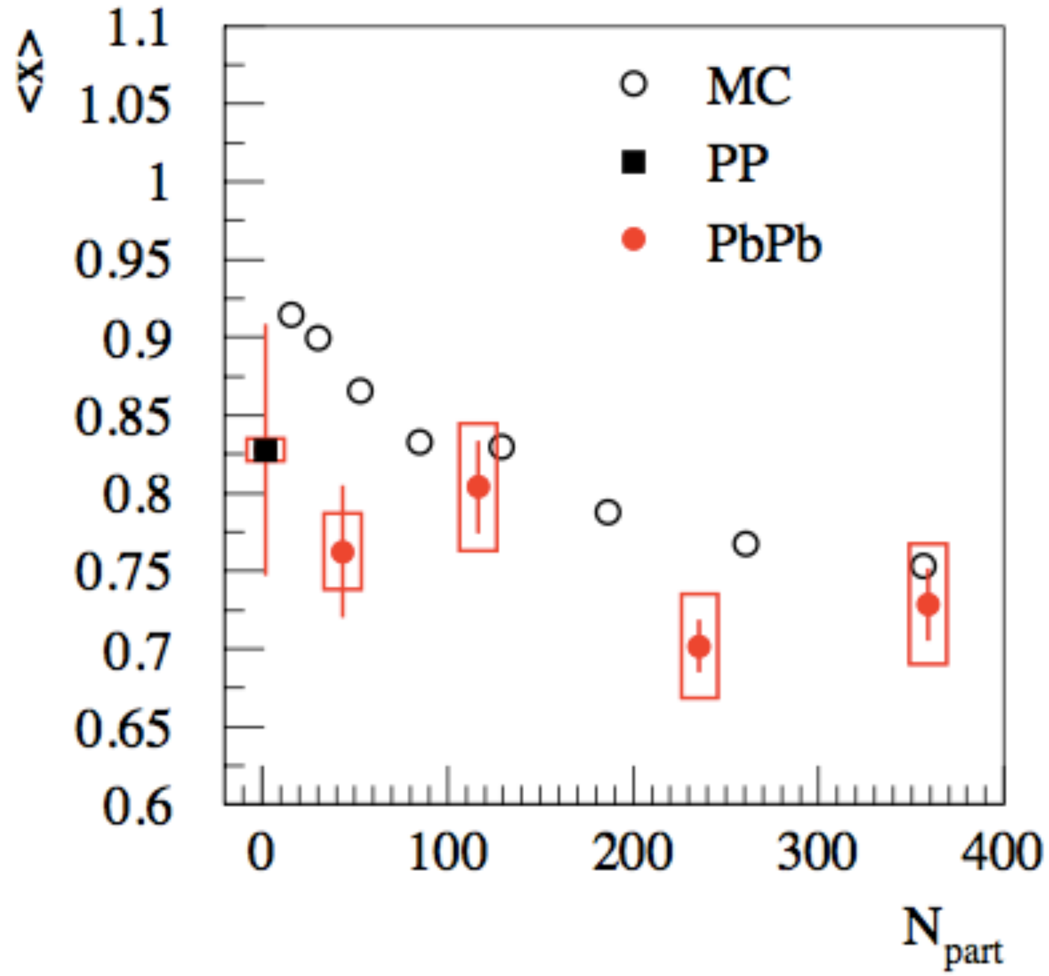
γ-jet asymmetry

Jet longitudinal profile function



Gamma-jet asymmetry



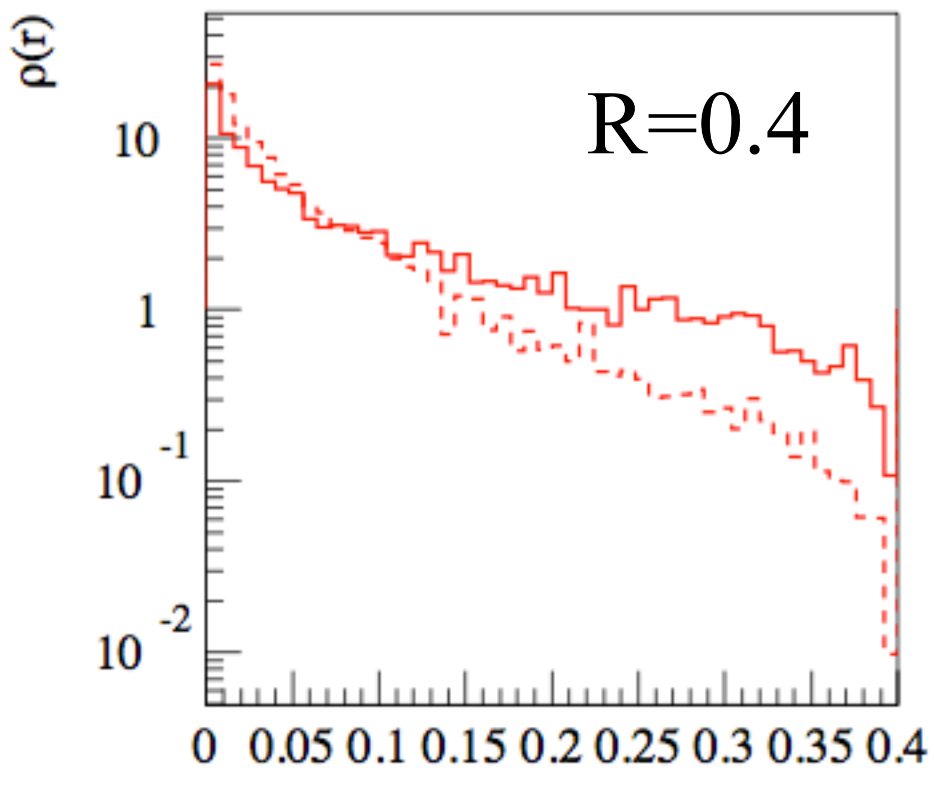


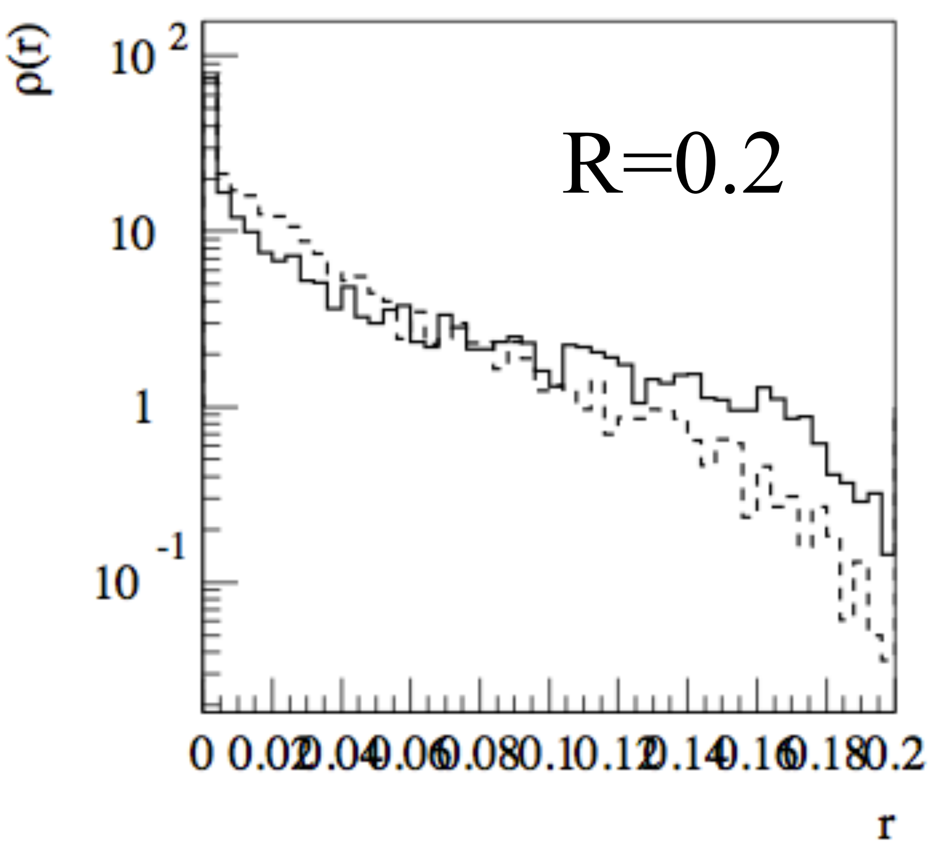
R=0.3

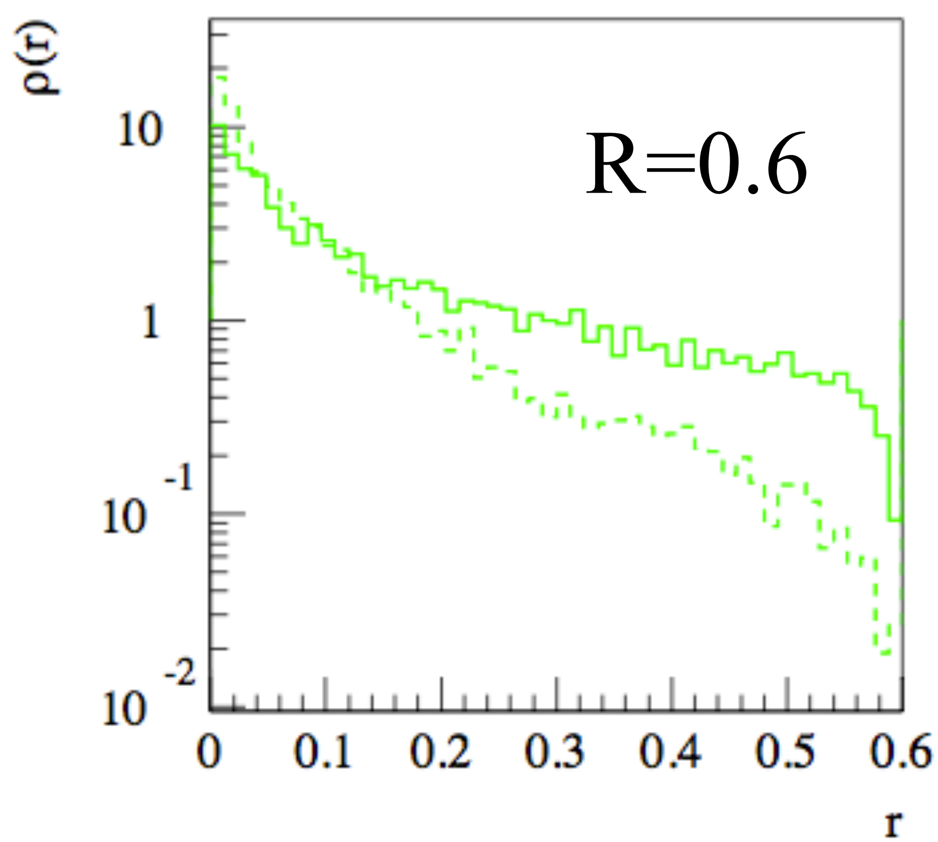
Jet transverse profile modification

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\rm jet}} \sum_{\rm jets} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)},$$

$$\Delta r/2 \le r \le R - \Delta r/2$$

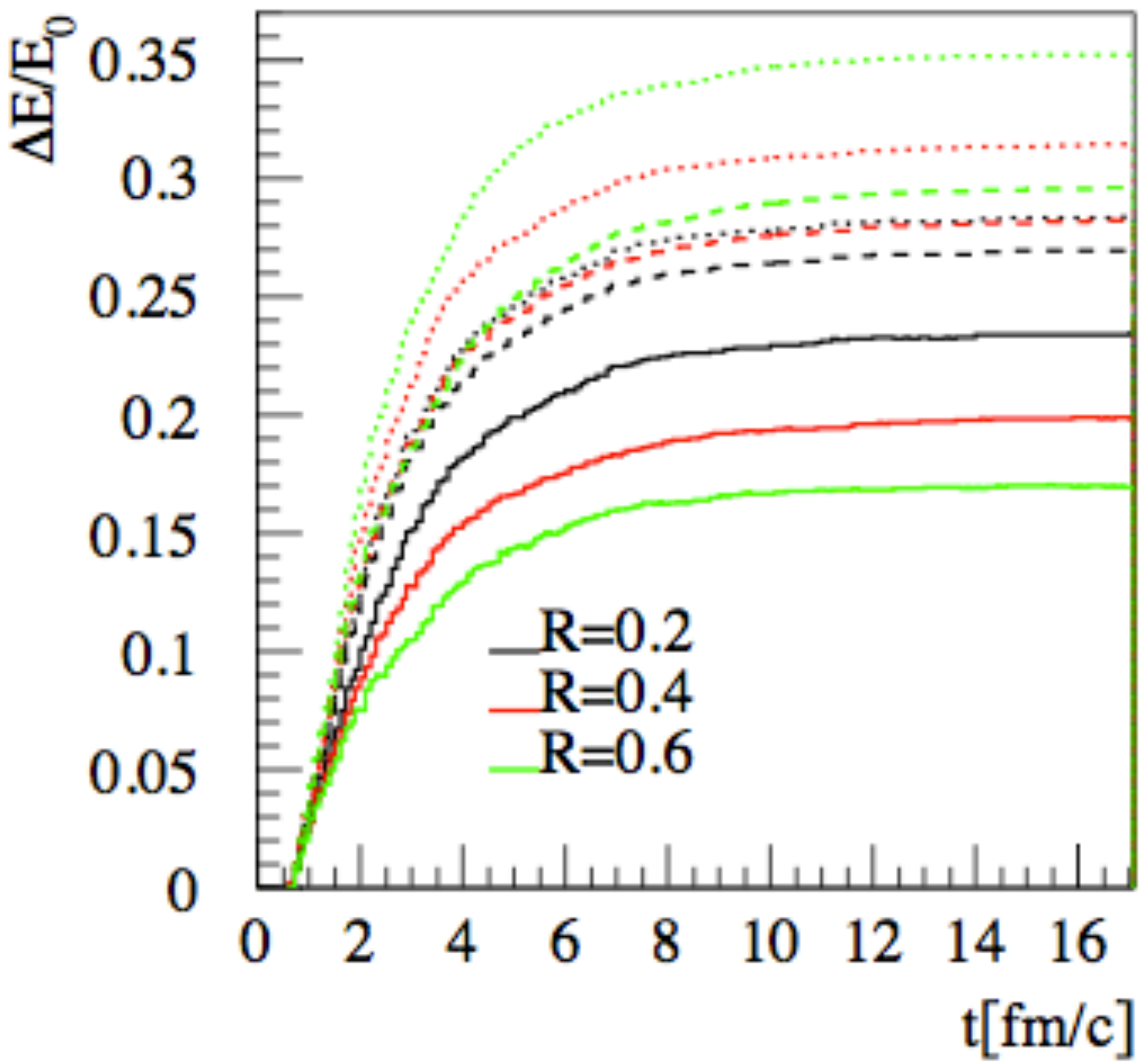






Jet energy loss in Pb+Pb at LHC

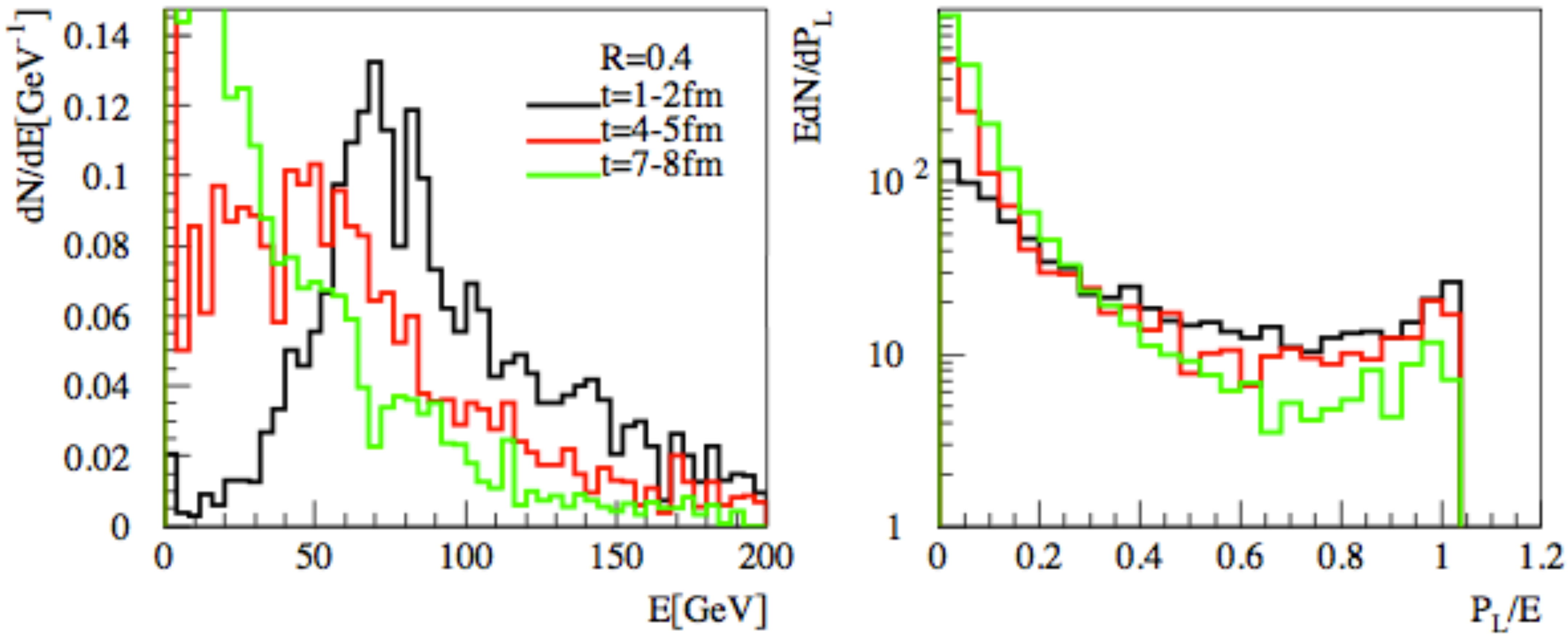
Pb+Pb 0-10% 3+1D hydro medium, E_γ=60 GeV, α_s=0.4



Solid: jet+radiatied+medium
Dashed: jet+radiated
Dotted: jet

Toward Jet tomography

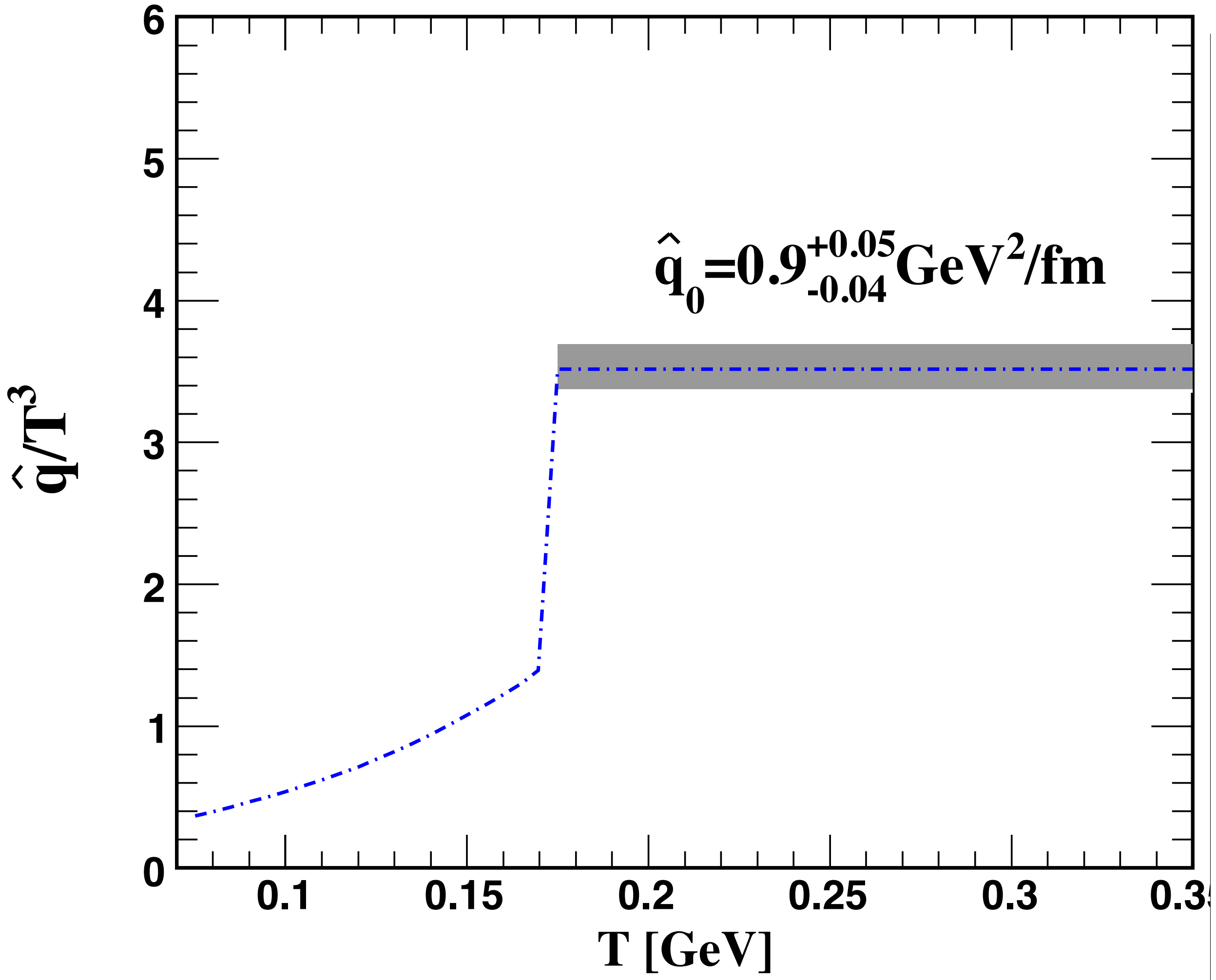
Jet shower in a uniform medium with T=300 MeV

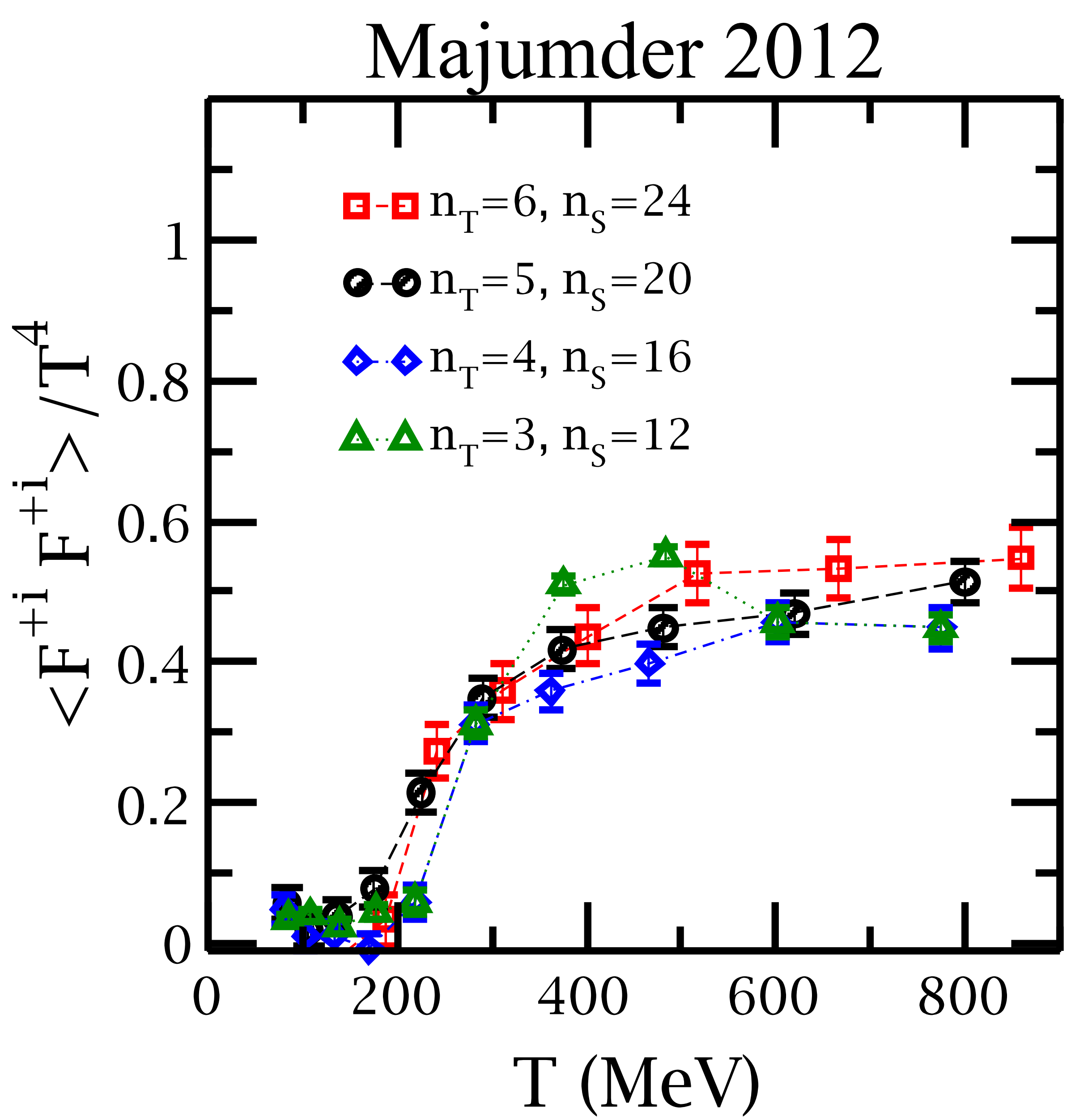


Select jet with different value of E_{jet}/E_{γ}: study FF, Jet profile

T-dep of qhat

Chen, Greiner, Wang, XNW, Xu （2010）





Summary

- Medium modification of jet FF determined by the jet transport coefficient
- Medium modification of FF in DIS and beam parton distribution in DY same mechanism.
- Medium response to jet propagation important for full jet measurement
- Toward jet tomography in gamma-jet study