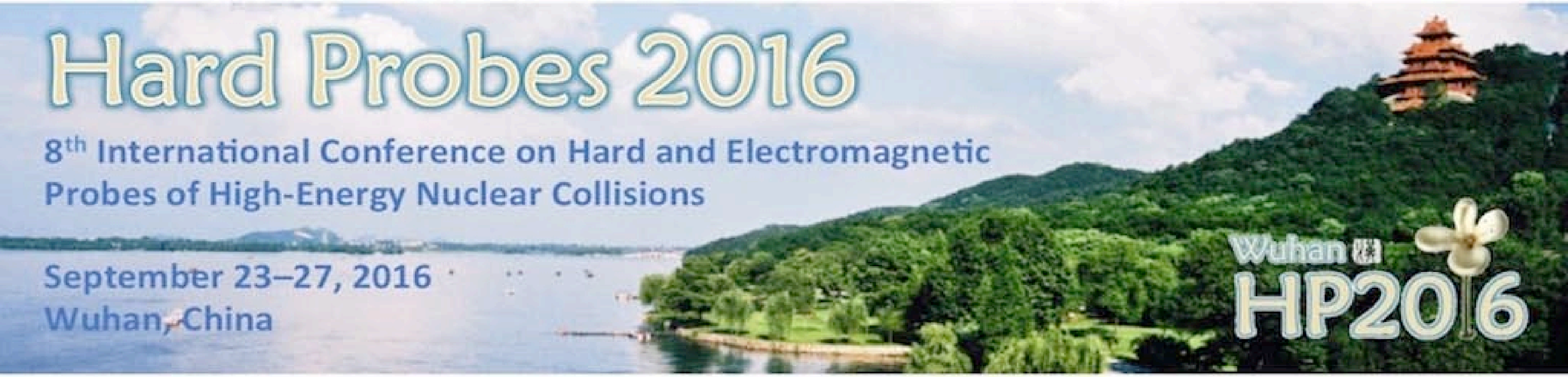


Full jet evolution in quark-gluon plasma and nuclear modification of jet structure in Pb+Pb collisions at the LHC

Ning-Bo Chang
Central China Normal University

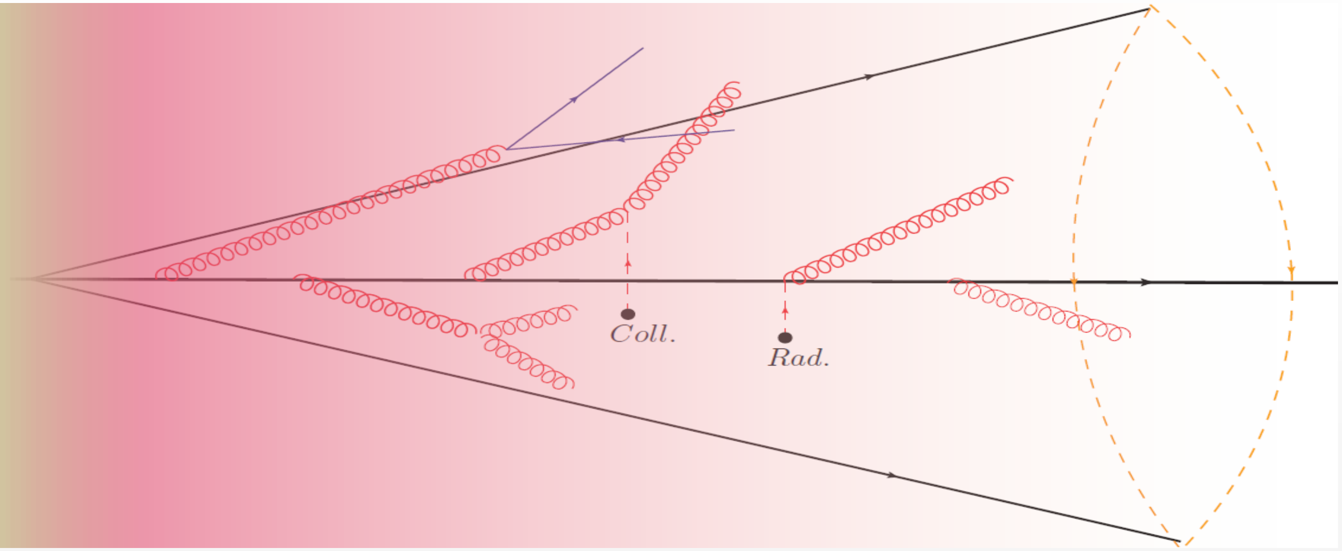
In collaboration with Guang-You Qin
Based on Phys.Rev.C94(2016).024902

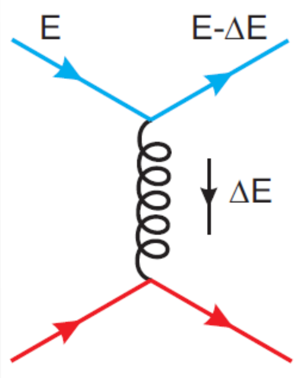
Outline

- Motivation and Framework
- Nuclear modification on jet energy
  - Inclusive jet spectra
  - Di-jet and photon-jet asymmetry
- Nuclear modification on jet structure
- Summary and Outlook

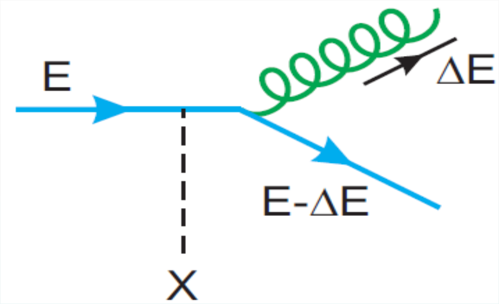
Analysis of various jet-medium interaction mechanisms

Motivation: Full jet

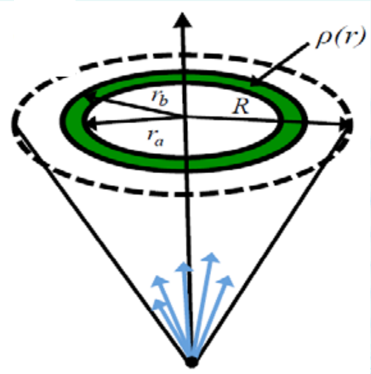




Elastic scattering



Inelastic scattering



- Energy loss of the leading parton due to medium induced radiation may be not the energy loss of the full jet.
- Collisional energy loss may be more important for full jets than single hadrons
- Jet structure and its modification can reveal more detailed information

Framework: Boltzmann transport equation

$$\frac{d}{dt}f_j(\omega_j, k_{j\perp}^2, t) = \hat{e}_j \frac{\partial}{\partial \omega_j} f_j(\omega_j, k_{j\perp}^2, t)$$

Collisional energy loss

$$+ \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t)$$

KT broadening

Radiation

gain

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_i(\omega_i, k_{i\perp}^2, t)$$

loss

$$- \sum_i \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_j(\omega_j, k_{j\perp}^2, t)$$

$$\boxed{f_j(\omega_j, k_{j\perp}^2, t) = \frac{dN_j(\omega_j, k_{j\perp}^2, t)}{d\omega_j dk_{j\perp}^2}}$$

$\hat{e} = dE/dt$ $\quad \hat{q} = d(\Delta p_\perp)^2/dt$ $\quad \hat{q} = 4T\hat{e}$

$$q \begin{cases} g \to q\bar{q},\ q \to qg \\ q \to qg,\ q \to gq \end{cases}$$

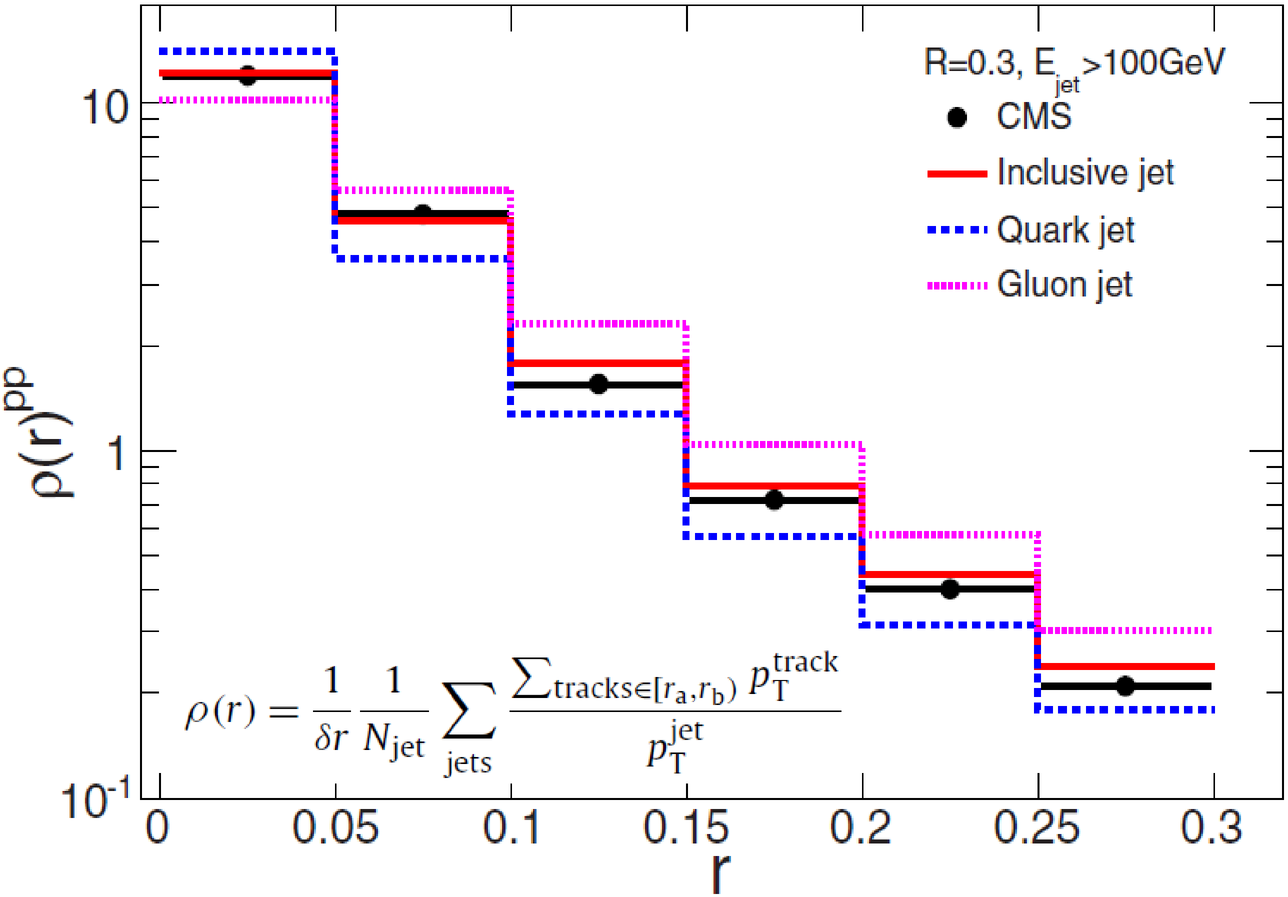
$$g \begin{cases} q \to gq,\ g \to gg \\ g \to gg,\ g \to q\bar{q} \end{cases}$$

$$\Gamma(\omega, k_\perp^2 | E, 0) = \frac{2\alpha_s}{\pi} \frac{xP(x)\hat{q}(t)}{\omega k_\perp^4} \sin^2 \frac{t - t_i}{2\tau_f}$$

$$t_i = \frac{2Ex_i(1-x_i)}{k_{i\perp}^2} \qquad \tau_f = \frac{2\omega_i x_{ij}(1-x_{ij})}{k_{ij\perp}^2} \qquad \omega_{cut} = 2GeV$$

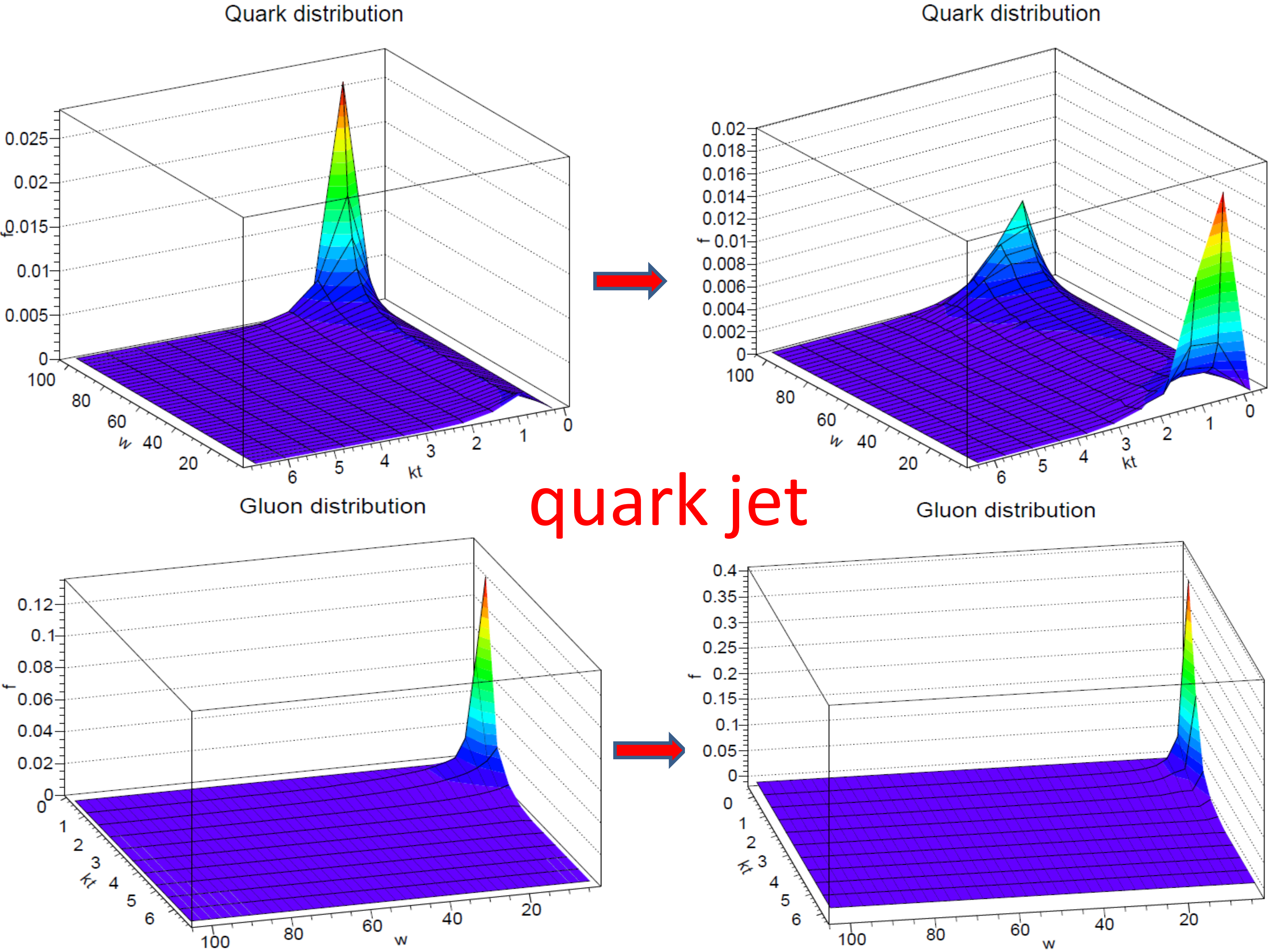
Framework

Initial condition from PYTHIA

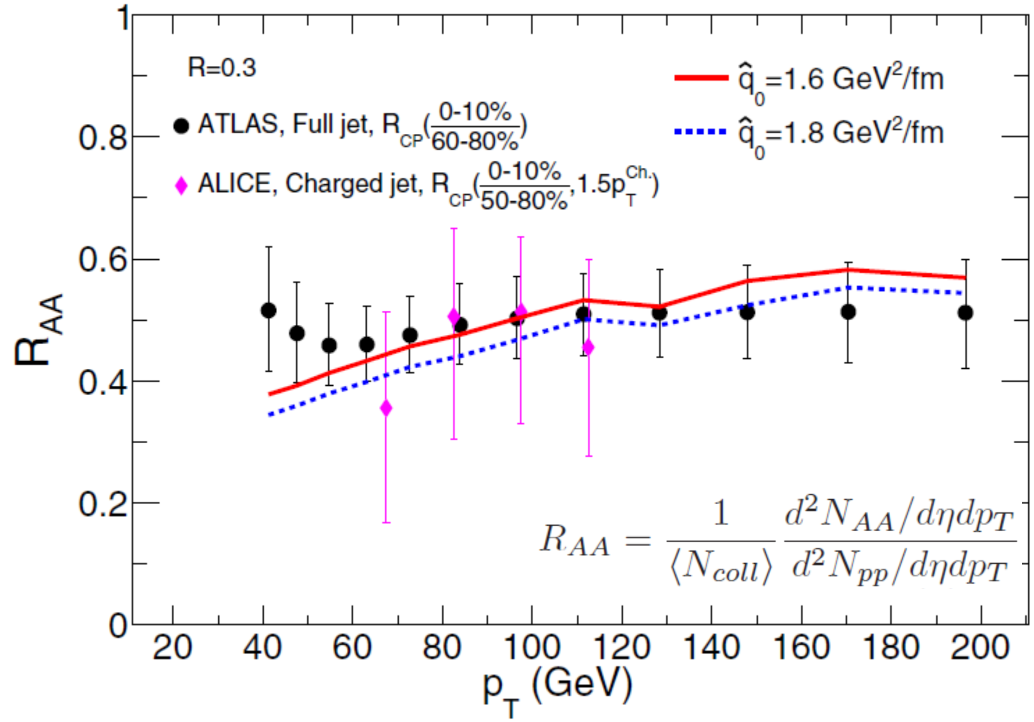


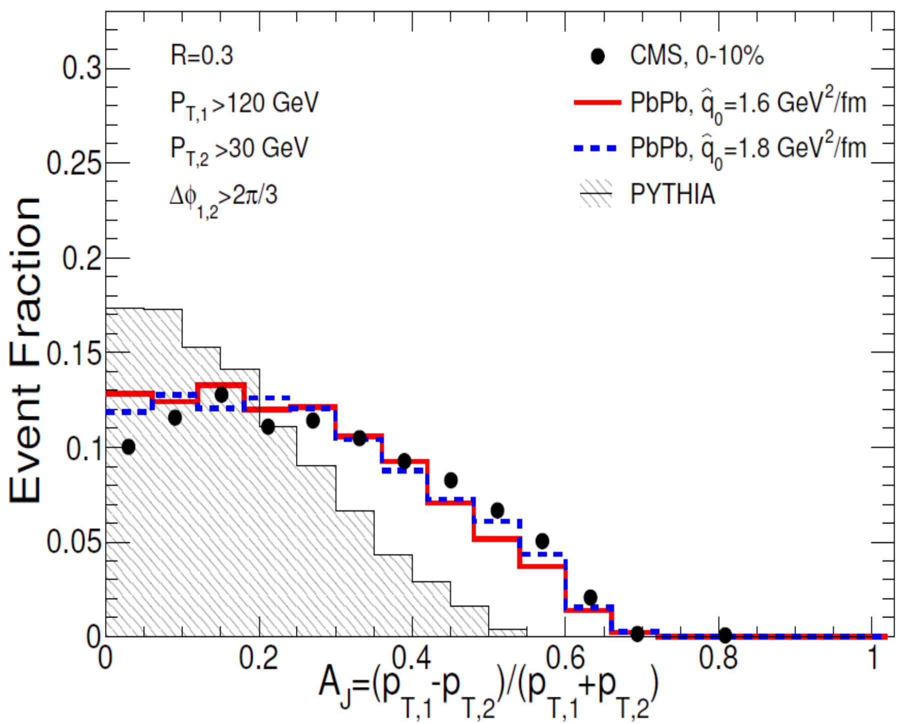
Hydrodynamic Simulation using VISH2+1

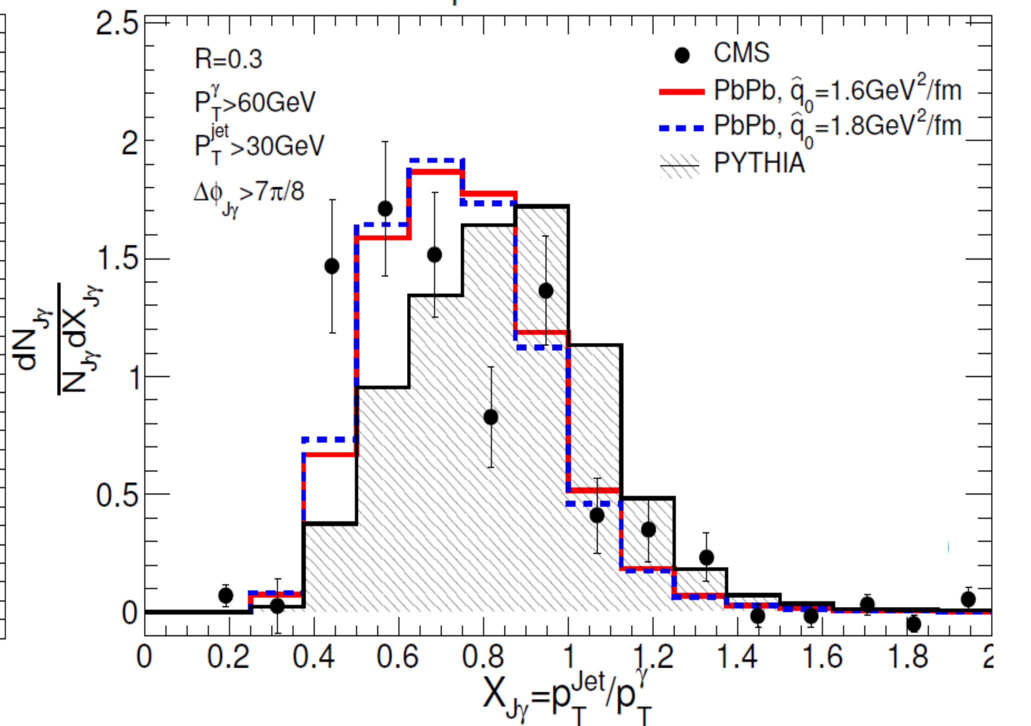
$$\hat{q}(\tau,\vec{r}\,) = \hat{q}_0 \cdot \frac{T^3(\tau,\vec{r}\,)}{T_0^3(\tau_0,\vec{0})} \cdot \frac{p \cdot u(\tau,\vec{r}\,)}{p_0}$$


Quark distribution
f
0.025
0.02
0.015
0.01
0.005
0
w
100
80
60
40
20
kt
6
5
4
3
2
1
0
Quark distribution
f
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
w
100
80
60
40
20
kt
6
5
4
3
2
1
0
quark jet
Gluon distribution
f
0.12
0.1
0.08
0.06
0.04
0.02
0
kt
0
1
2
3
4
5
6
w
100
80
60
40
20
Gluon distribution
f
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
kt
0
1
2
3
4
5
6
w
100
80
60
40
20

Observables on full jets energy loss

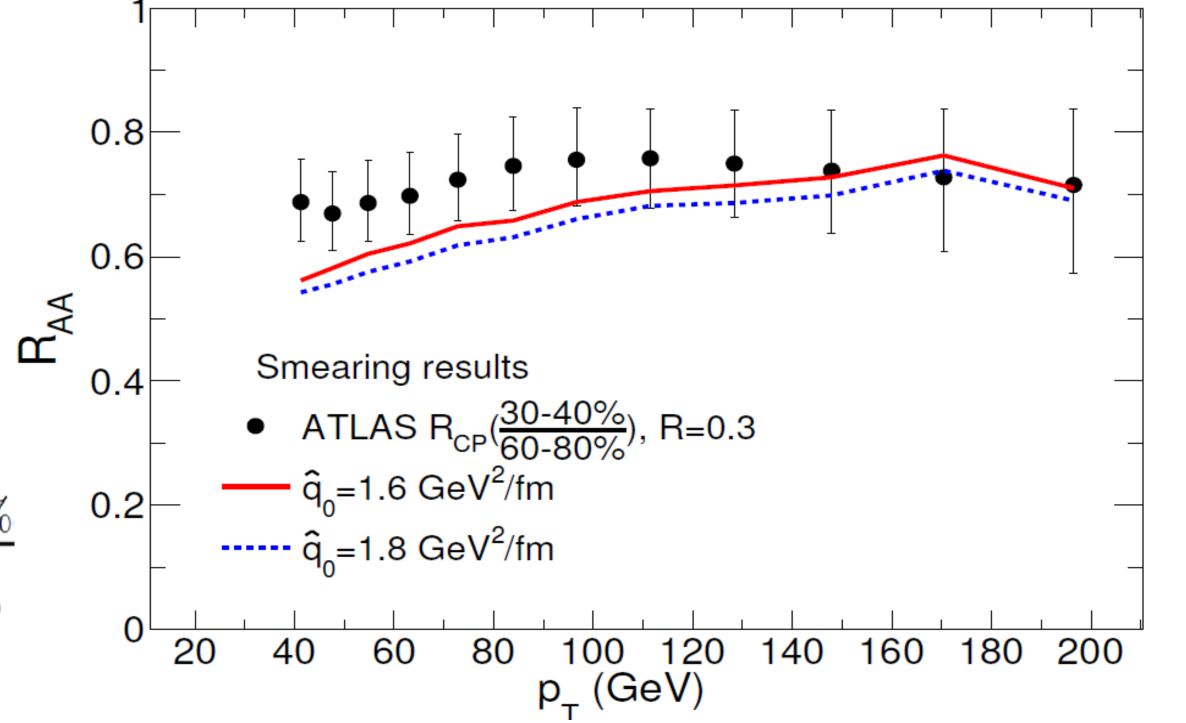


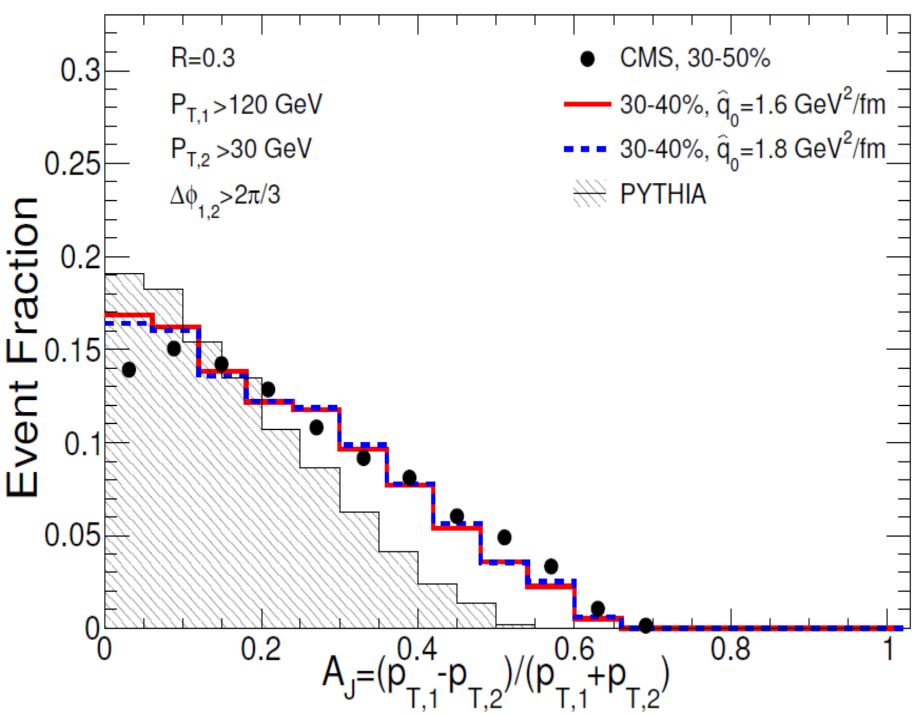


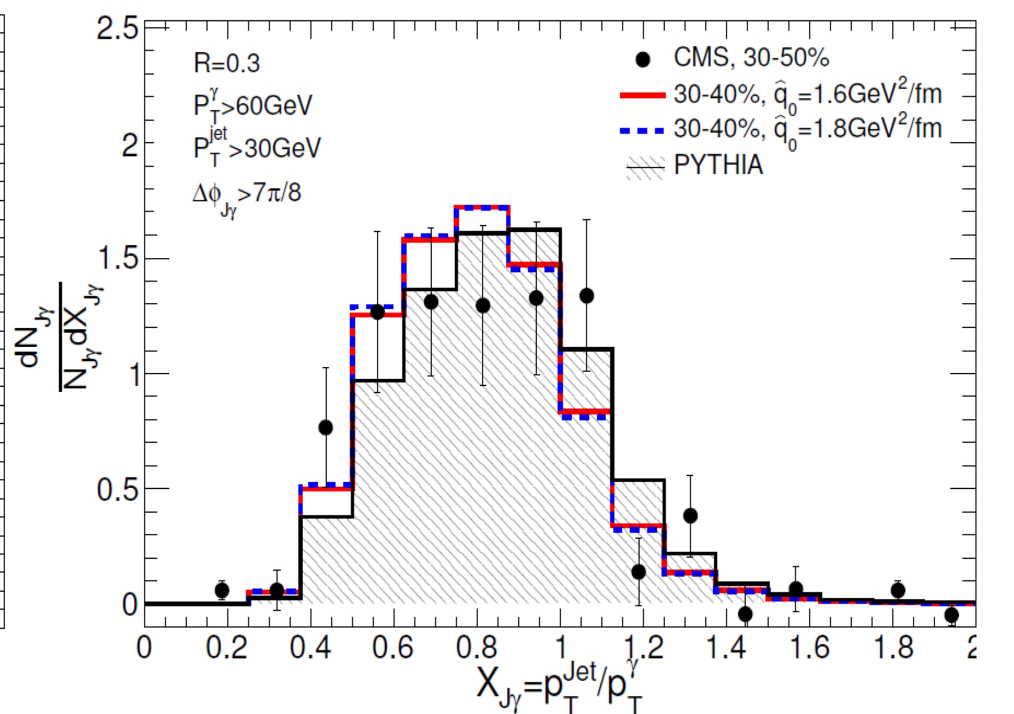


Centrality dependence

$$\hat{q}_0^{30\text{-}40\%} = \hat{q}_0^{0\text{-}10\%} \frac{T^3(\tau_0,0)_{30\text{-}40\%}}{T^3(\tau_0,0)_{0\text{-}10\%}}$$

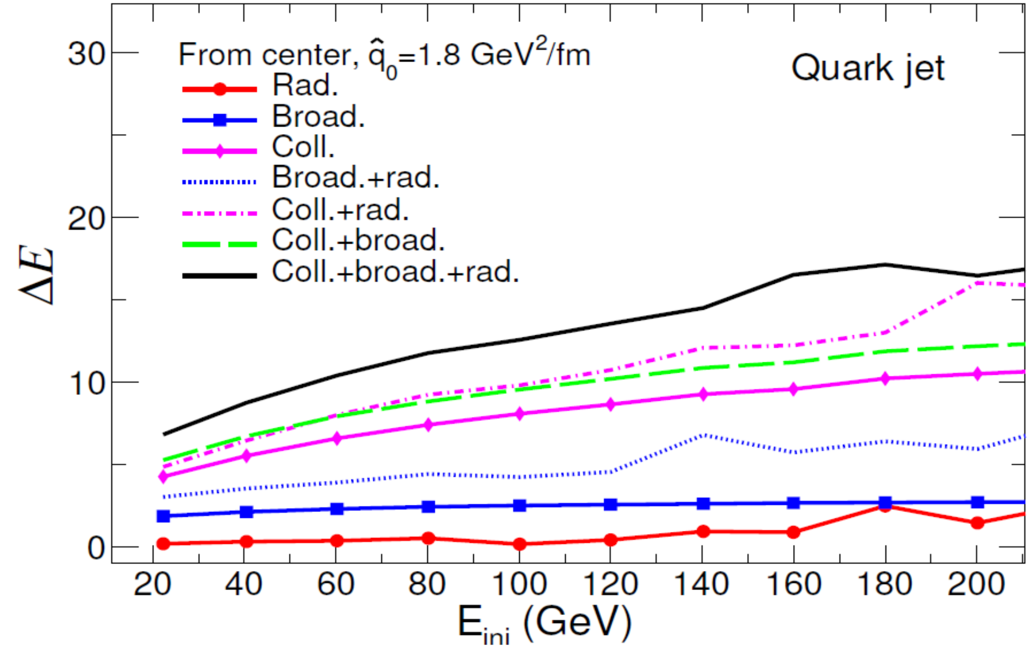


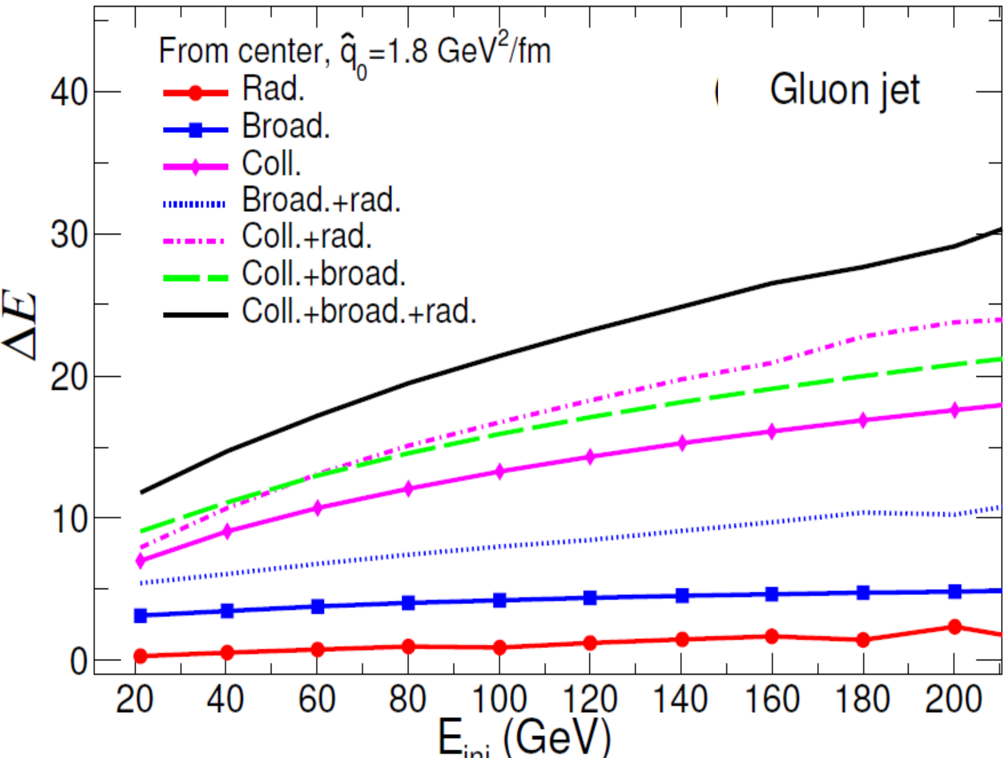




Effects of diff. interaction mechanisms on Jet Energy Loss

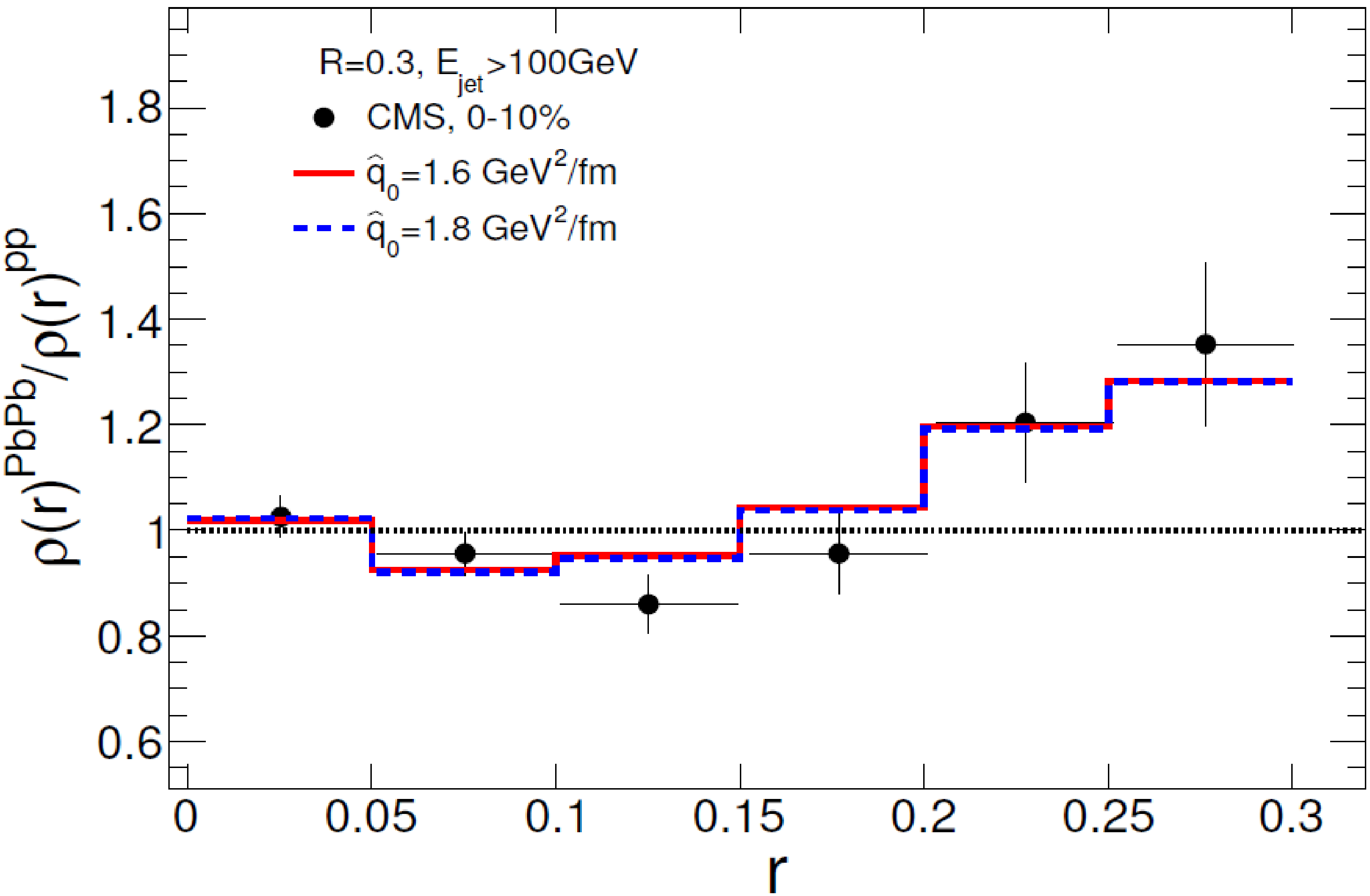
R=0.3





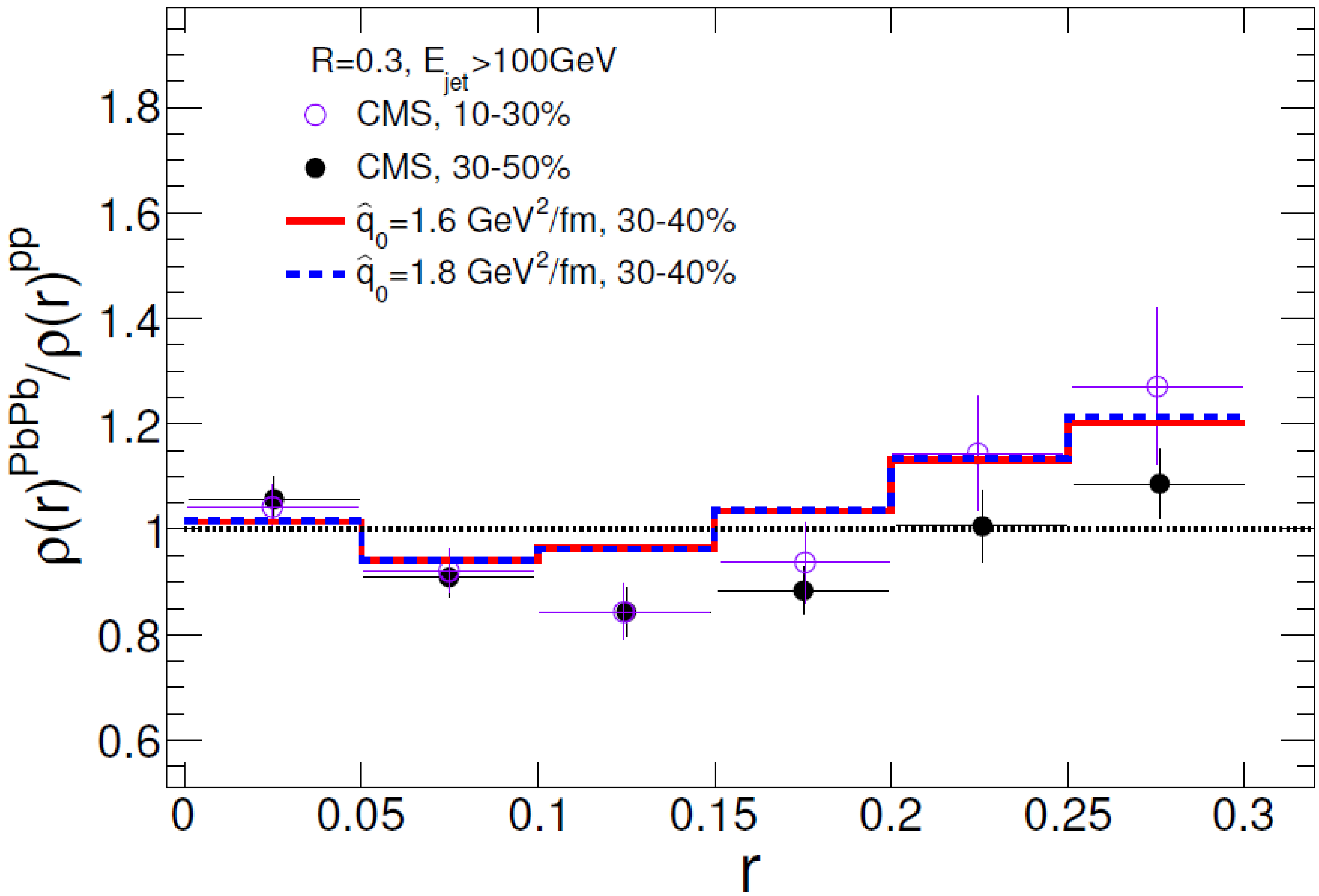
Collisional energy loss contribute the most, medium induced radiation contribute least but can enhance other mechanism.

Modification of Jet shape

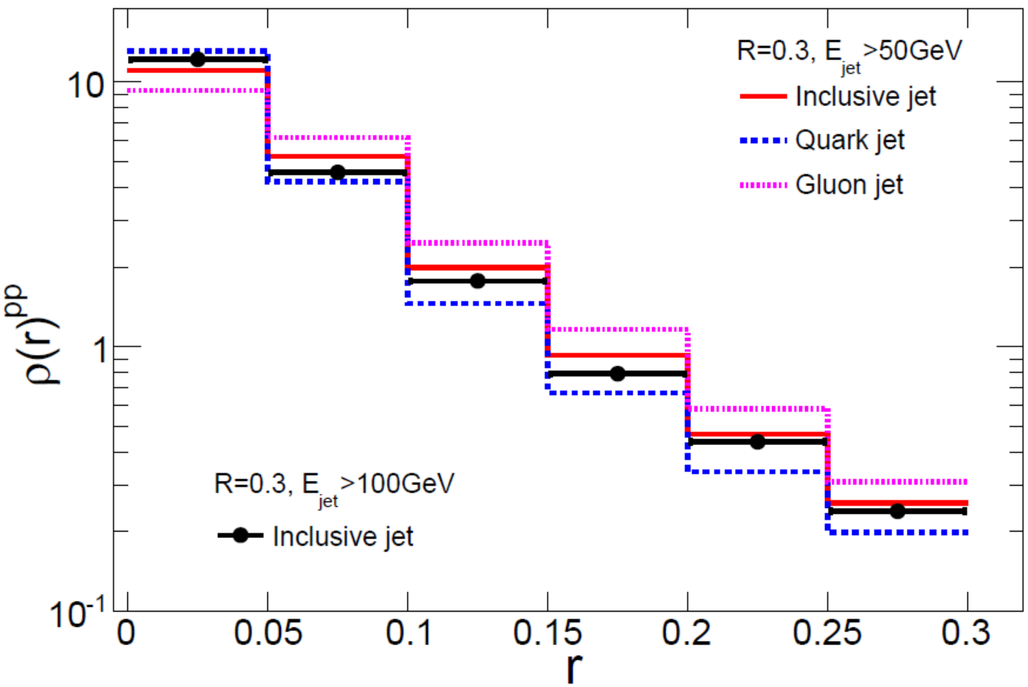


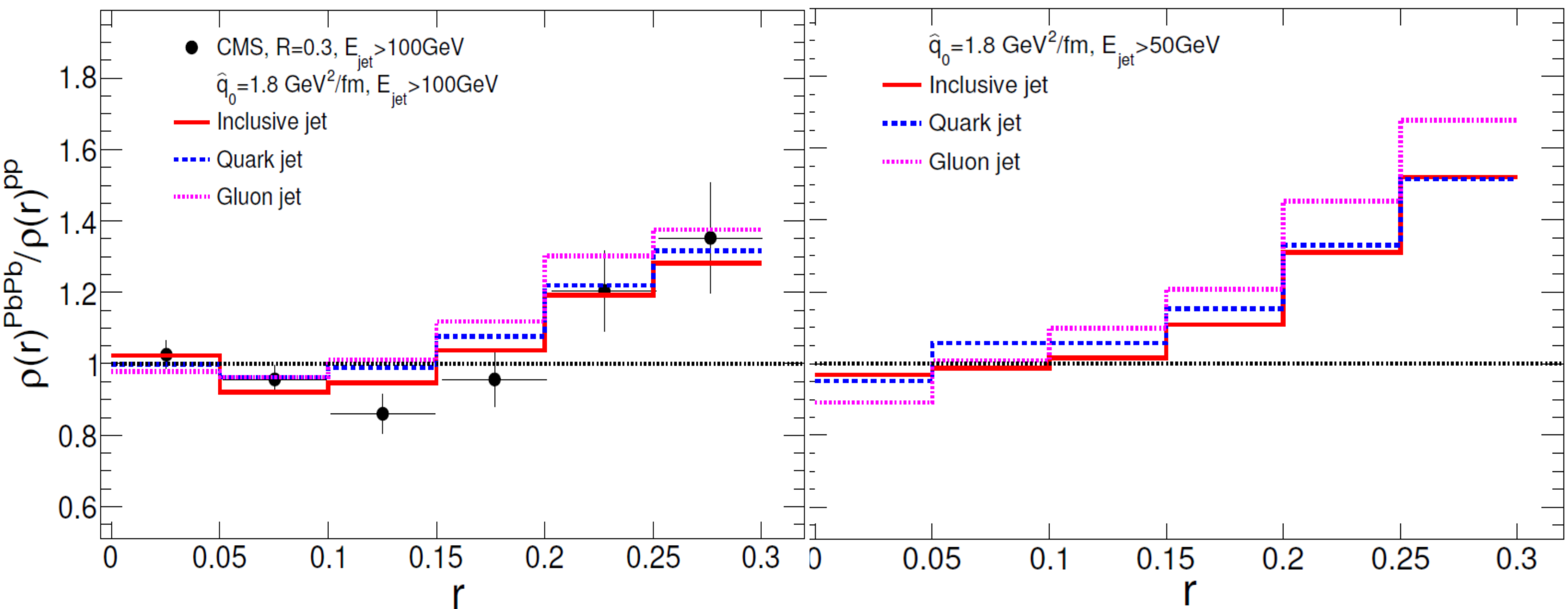
Jet shape function is normalized and deep-falling, exact fit on each data point is difficult.

Modification of Jet shape: mid-centrality

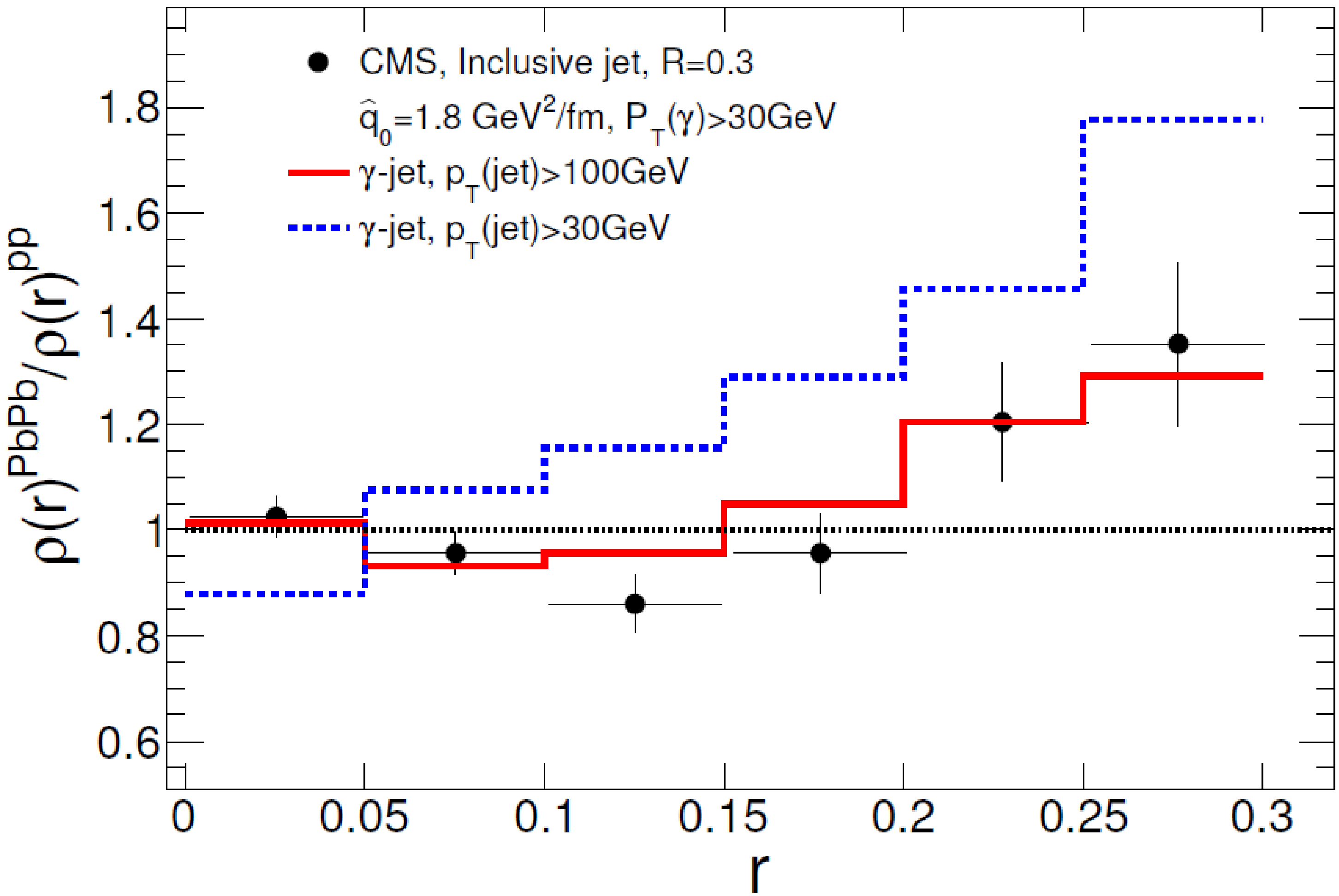


Modification of jet shape: Energy and flavor dependence



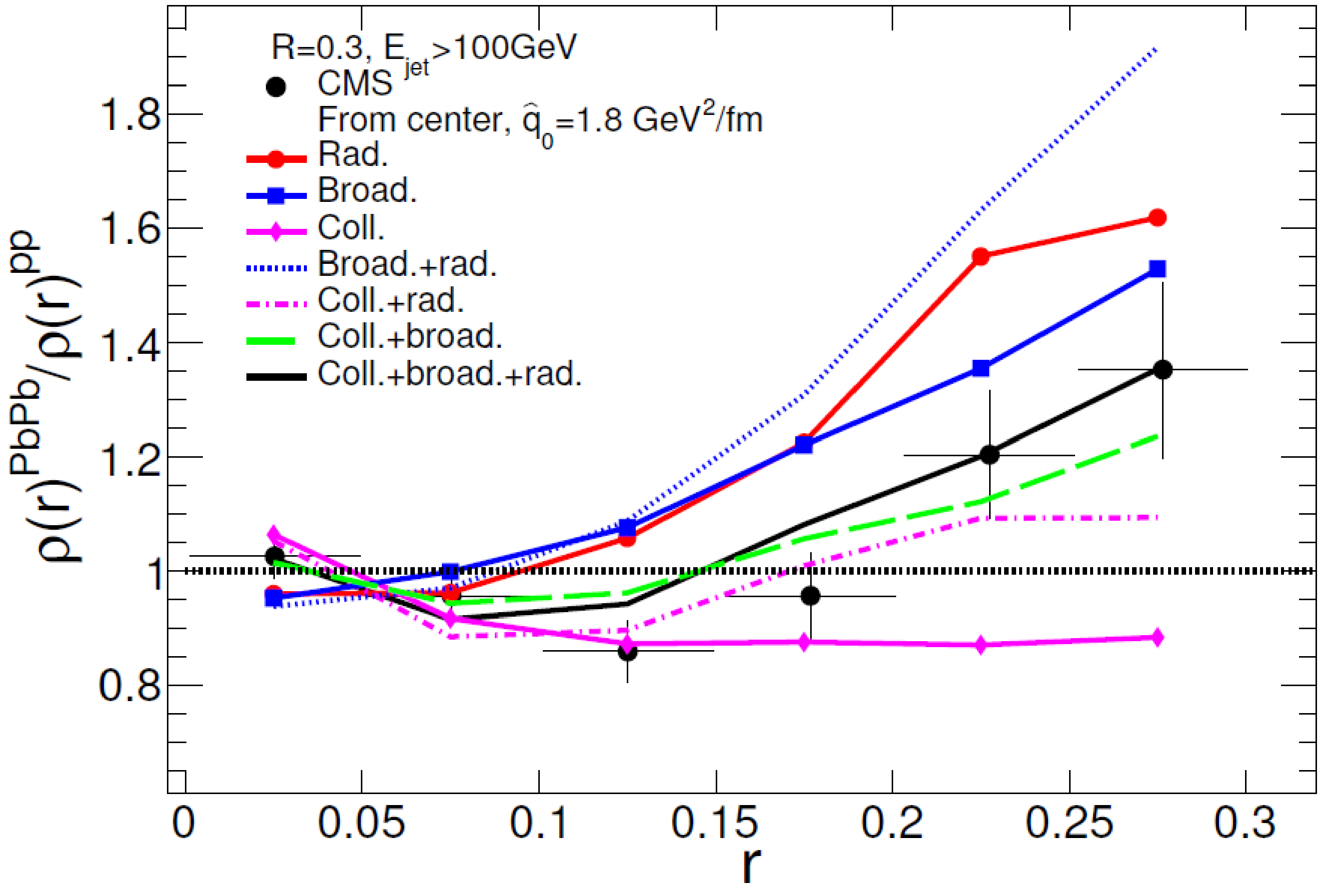


Jet shape: gamma-jet



Same energy dependence in gamma-jet

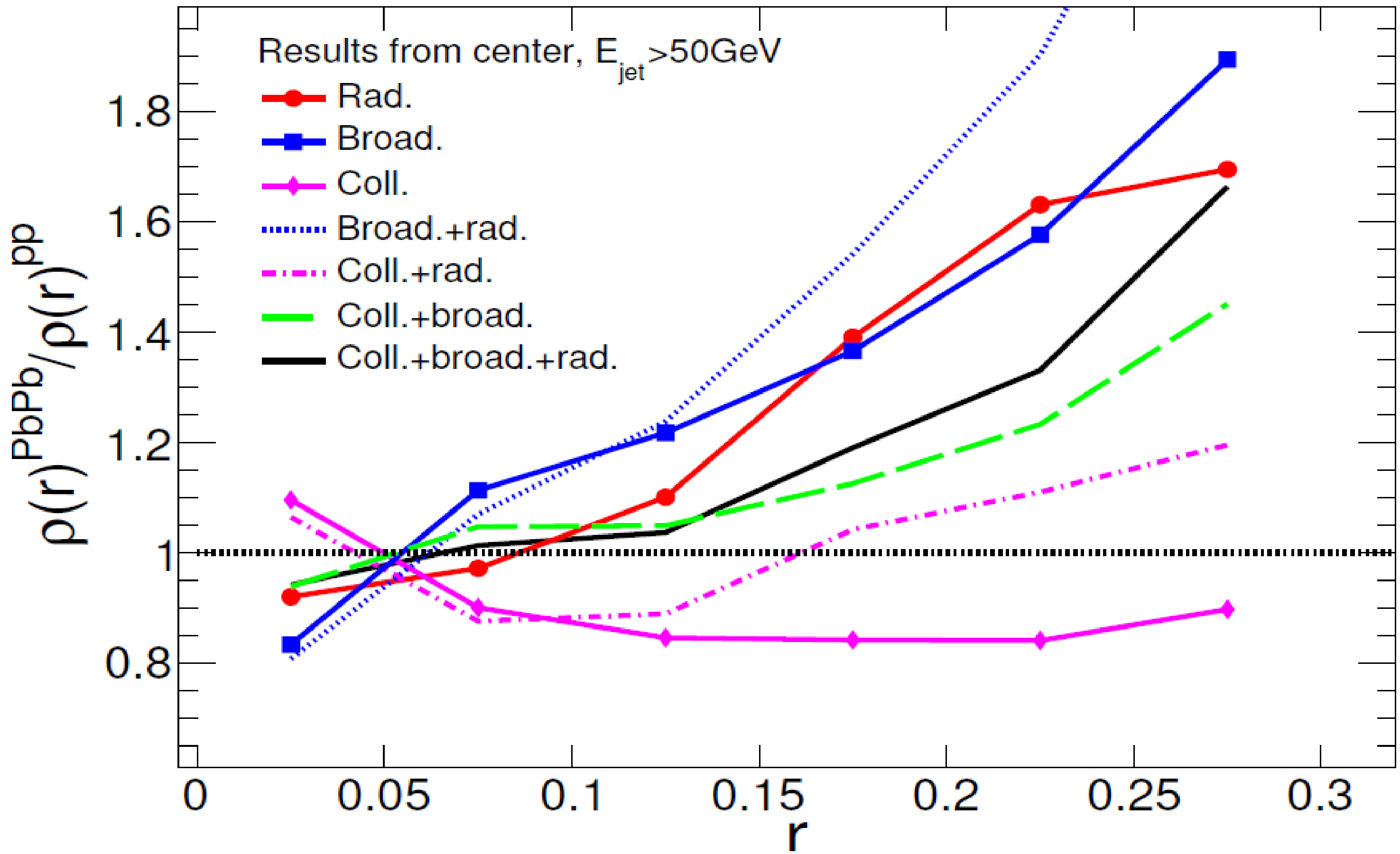
Effects of different mechanisms on Modification of Jet shape



Rad. and Broad. transport energy from center to periphery

Coll. lead inner core lose less fraction of energy than outer part

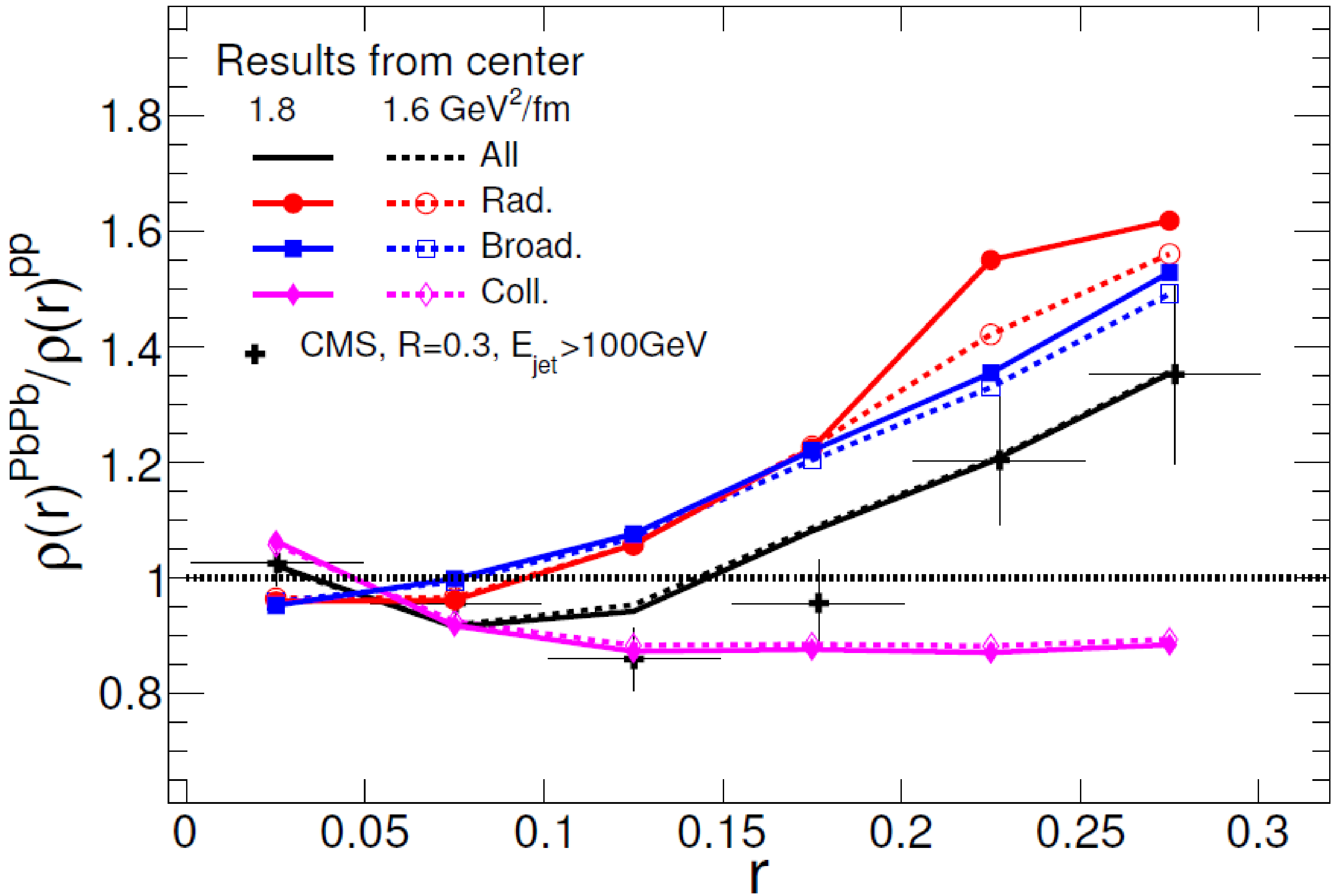
Effects of different mechanisms on Modification of Jet shape: lower energy jet



Rad. and Broad. become stronger,

the inner core can be affected more easily.

Sensitivity to the value of qhat



Every mechanism has sensitivity to qhat,

but the sensitivity become modest when all of them exist

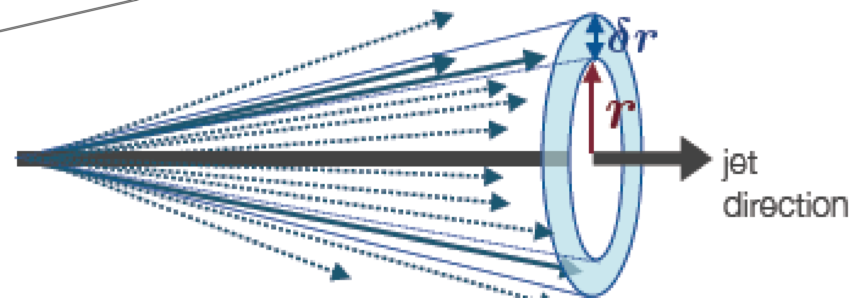
Jet shape modification

Last talk by Yasuki Tachibana

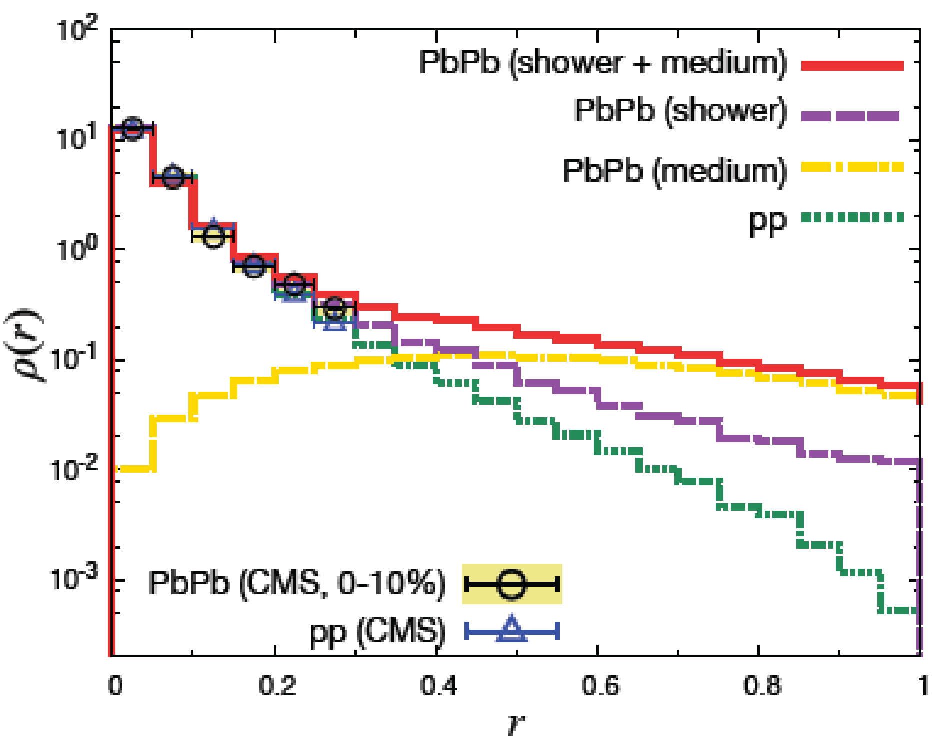
- Jet shape function

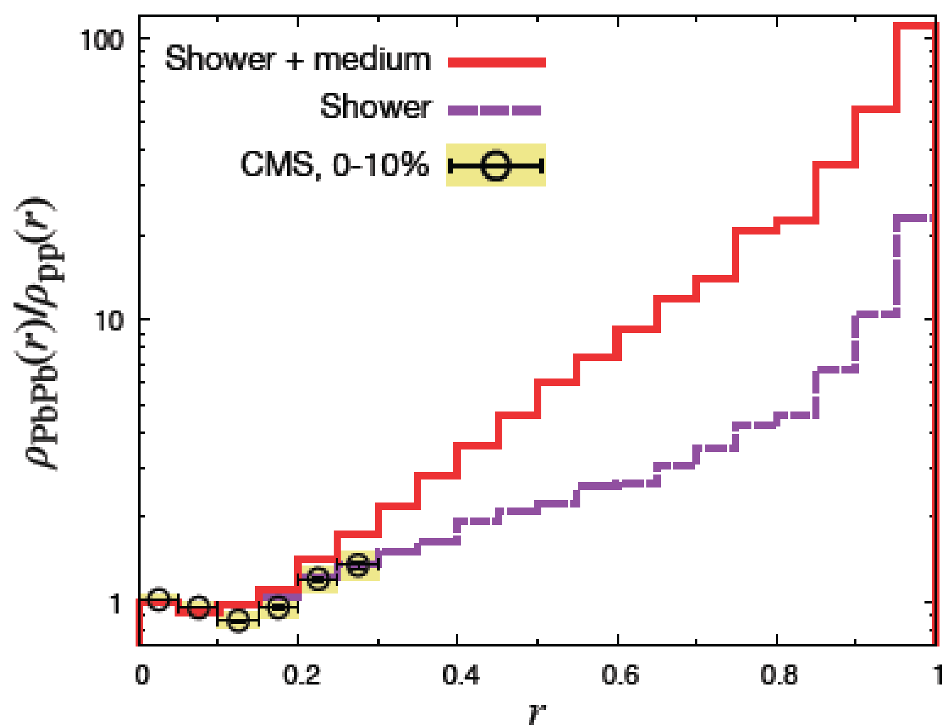
$$r = \sqrt{(\phi_p - \phi_{\rm jet})^2 + (\eta_p - \eta_{\rm jet})^2}$$

$$\rho(r) = \sum_i \frac{p_T^i}{p_T^{\rm jet}} \frac{\theta[r_i - (r - \frac{1}{2}\delta r)]\theta[(r + \frac{1}{2}\delta r) - r_i]}{\delta r}$$



- Inclusive, $E_{\rm jet} \geq 100\,{\rm GeV}$ $(\Delta R = 0.3)$





Summary

- *Coupled differential transport equations are constructed to study the evolution of the partonic jet shower in the QGP medium, can describe the nuclear modification of the full jet energy and jet structure at LHC simultaneously.*
- *The special effects of different jet-medium interaction mechanisms are analyzed, showing us that different mechanisms must be considered together to explain all the experimental data.*

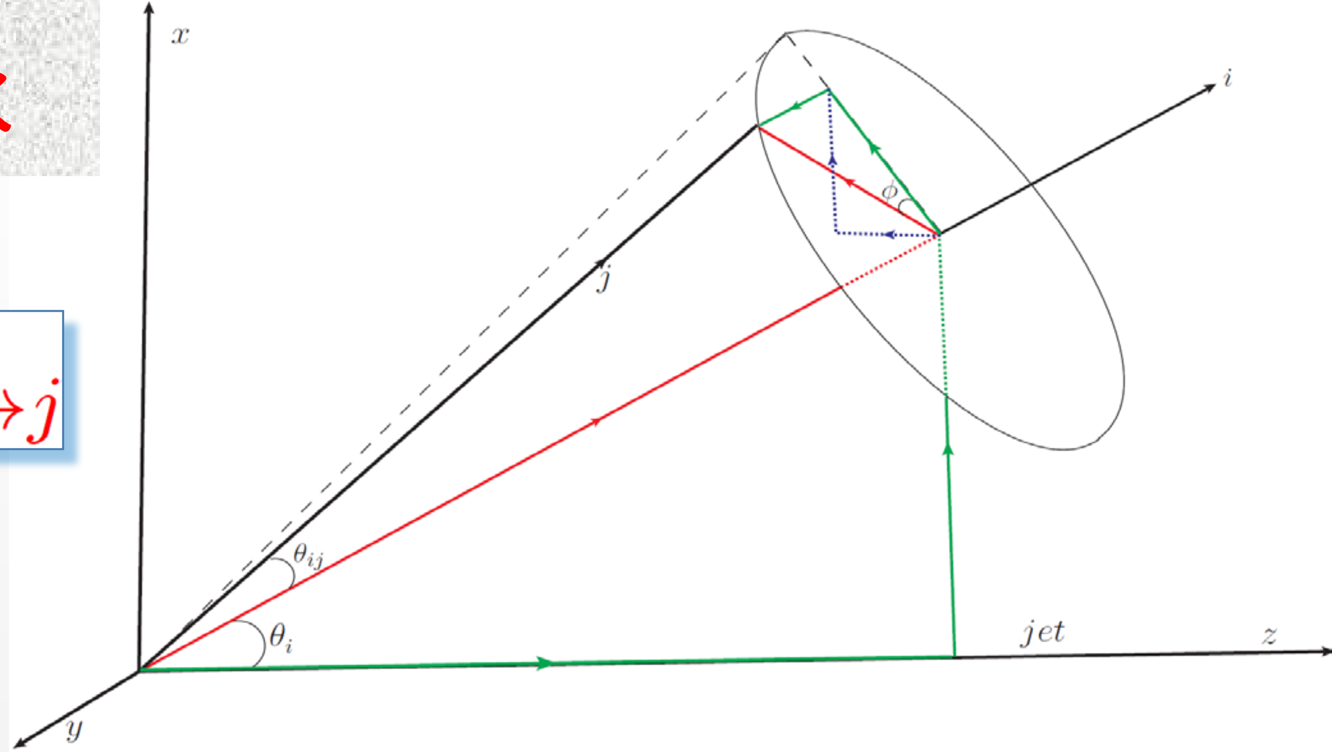
Outlook

Energy *et al* dependent transport coefficients, hadronization, jet FF…

Thanks for your attention!

Framework

$$\Gamma_{i\to j} \to \tilde{\Gamma}_{i\to j}$$



$$\frac{dN_g^{\mathrm{med}}}{d\omega dk_\perp^2 dt} = \Gamma(\omega, k_\perp^2|E,0) = \frac{2\alpha_s}{\pi}\frac{xP(x)\hat{q}(t)}{\omega k_\perp^4}\sin^2\frac{t-t_i}{2\tau_f}$$

$$k_{j\perp}^2 = k_x^2 + k_y^2 = \omega_j^2[(\cos\theta_{ij}\sin\theta_i + \sin\theta_{ij}\cos\phi_{ij}\cos\theta_i)^2 + (\sin\theta_{ij}\sin\phi_{ij})^2]$$

Small angle approximation: $\langle(\frac{k_{j\perp}}{\omega_j})^2\rangle \approx \theta_i^2 + \theta_{ij}^2 \approx (\frac{k_{i\perp}}{\omega_i})^2 + (\frac{k_{ij\perp}}{\omega_j})^2$

$t_i = \frac{2Ex_i(1-x_i)}{k_{i\perp}^2}$ $\tau_f = \frac{2\omega_i x_{ij}(1-x_{ij})}{k_{ij\perp}^2}$ $\omega_{cut} = 2GeV$

Framework: Coupled differential Equations

Quark in the jet

$$q \begin{cases} \underset{\sim\sim\sim}{g} \rightarrow q\bar{q},\ \underline{q \rightarrow qg} & +term \\ \underline{q \rightarrow qg},\ q \rightarrow \underset{\sim\sim\sim}{gq} & -term \end{cases}$$

$$\frac{d}{dt} f_q(\omega_j, k_{j\perp}^2, t) = \hat{e}\frac{\partial f_q}{\partial \omega_j} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_q$$

$$+ \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to qg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_q(\omega_i, k_{i\perp}^2, t) + 2n_f \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to q\bar{q}}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_g(\omega_i, k_{i\perp}^2, t)$$

$$- \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to qg}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_q(\omega_j, k_{j\perp}^2, t)$$

Gluon in the jet

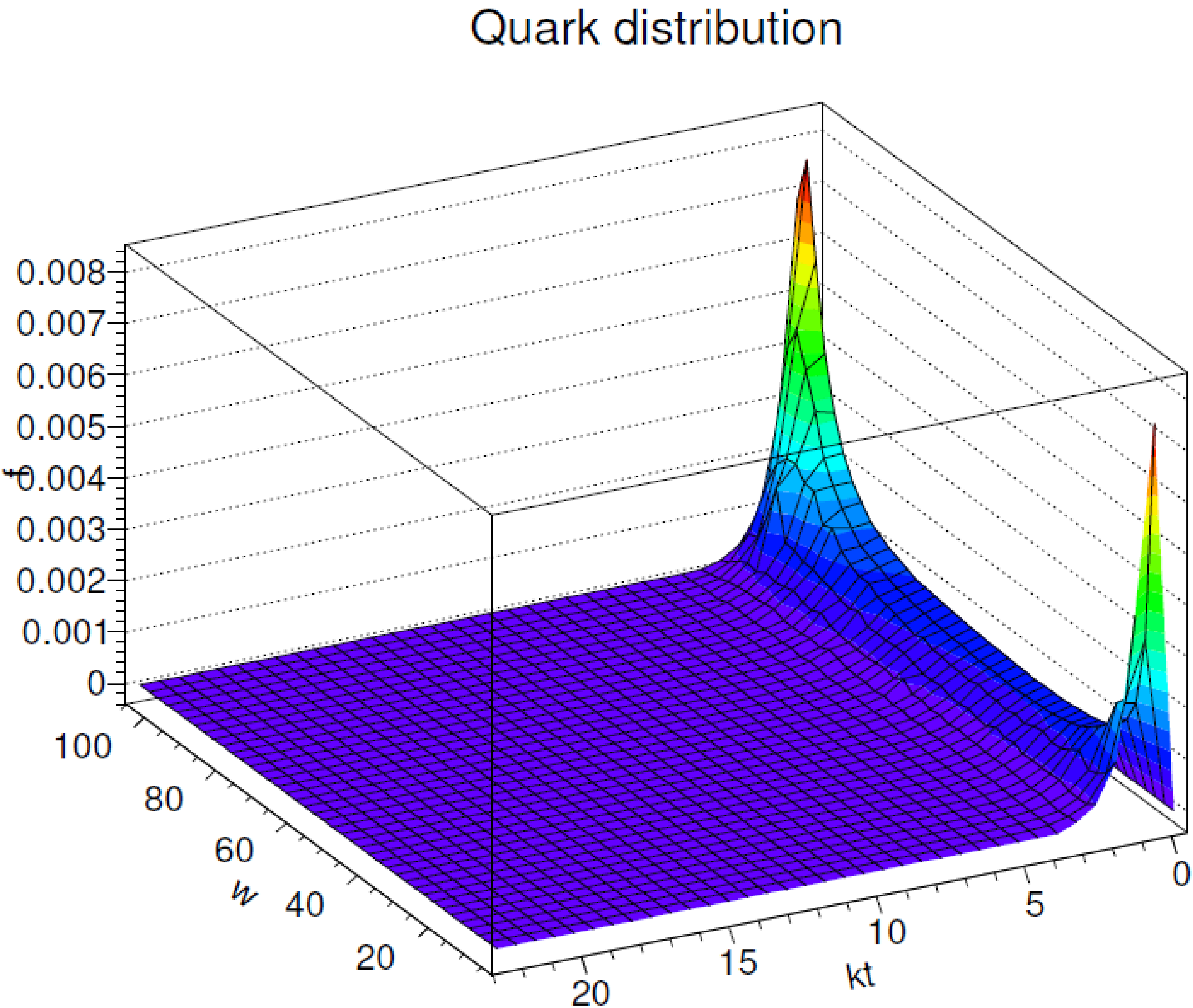
$$g \begin{cases} q \rightarrow \underset{\sim\sim\sim}{gq},\ \underline{g \rightarrow gg} & +term \\ \underline{g \rightarrow gg},\ \underset{\sim\sim\sim}{g \rightarrow q\bar{q}} & -term \end{cases}$$

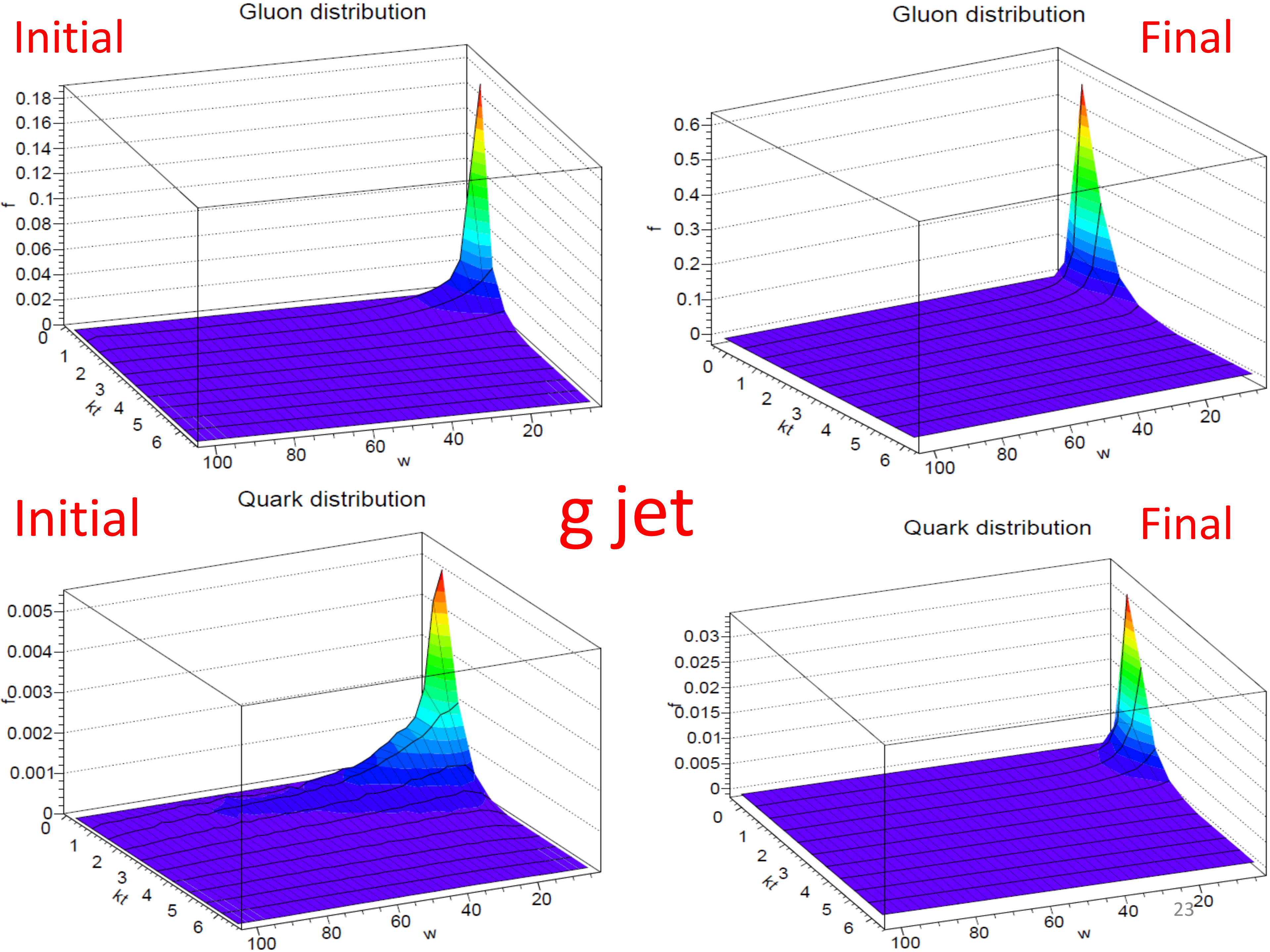
$$\frac{d}{dt} f_g(\omega_j, k_{j\perp}^2, t) = \hat{e}\frac{\partial f_g}{\partial \omega_j} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g$$

$$+2 \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to gg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_g(\omega_i, k_{i\perp}^2, t) + \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to gq}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_q(\omega_i, k_{i\perp}^2, t)$$

$$- \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to gg}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_g(\omega_j, k_{j\perp}^2, t) - n_f \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to q\bar{q}}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_g(\omega_j, k_{j\perp}^2, t)$$

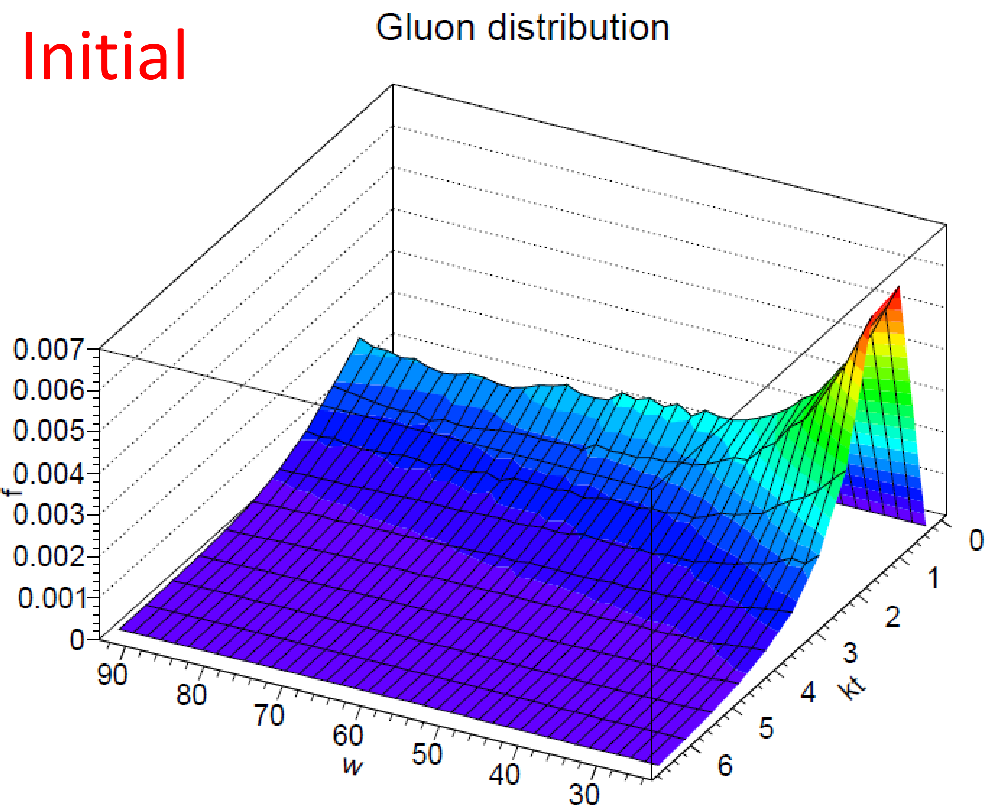
Final distribution without $g \to q\bar{q}$





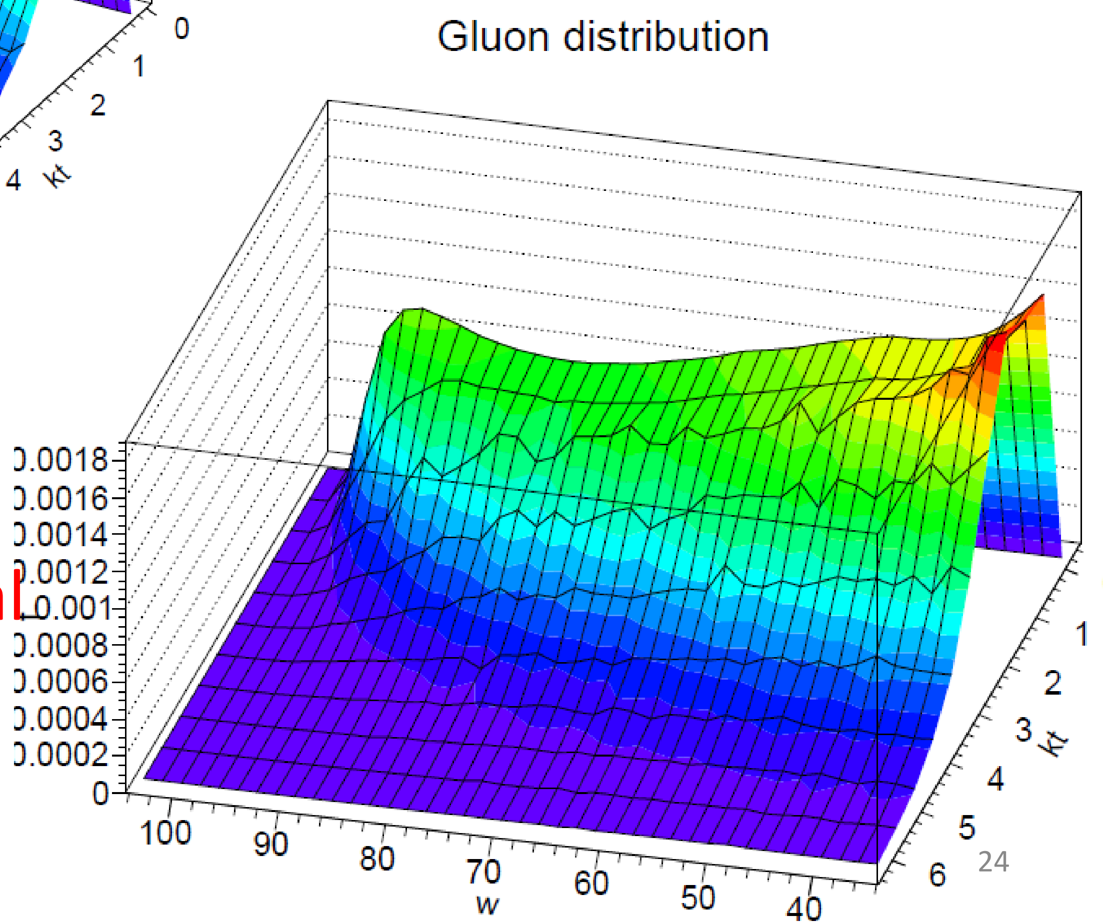
Initial
Gluon distribution
f
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
kt
0 1 2 3 4 5 6
w
100 80 60 40 20
Gluon distribution
Final
f
0.6
0.5
0.4
0.3
0.2
0.1
0
kt
0 1 2 3 4 5 6
w
100 80 60 40 20
g jet
Initial
Quark distribution
f
0.005
0.004
0.003
0.002
0.001
0
kt
0 1 2 3 4 5 6
w
100 80 60 40 20
Quark distribution
Final
f
0.03
0.025
0.02
0.015
0.01
0.005
0
kt
0 1 2 3 4 5 6
w
100 80 60 40 20

Initial



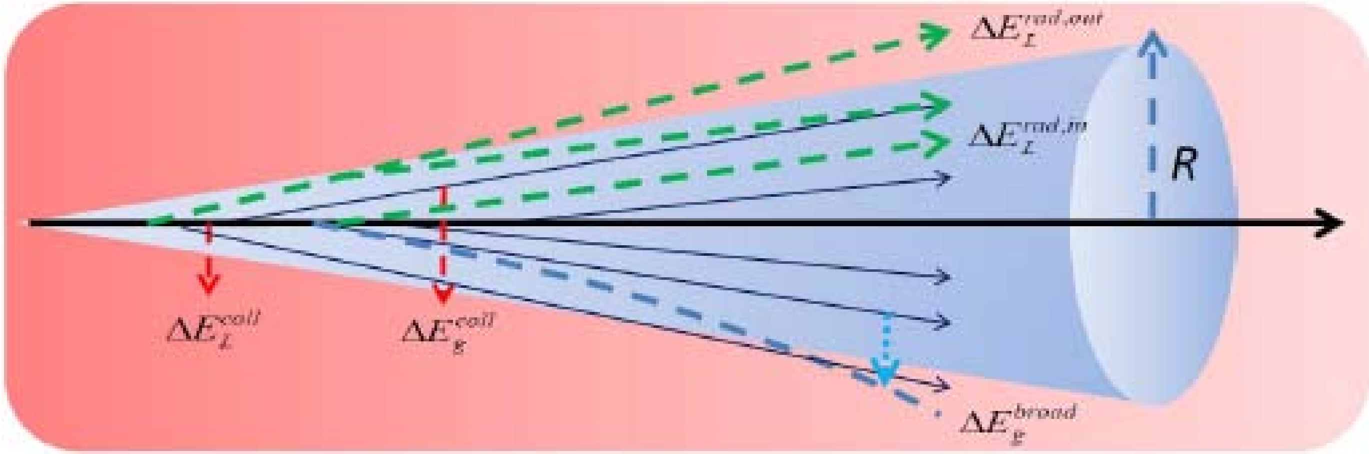
g jet

Final



Framework

Guang-You Qin and Berndt Muller, PRL,106,162302



$$\boxed{f_g(\omega, k_\perp^2, t) = \frac{dN_g(\omega, k_\perp^2, t)}{d\omega dk_\perp^2}}$$

$$\hat{e} = dE/dt$$

$$\hat{q} = d(\Delta p_\perp)^2/dt$$

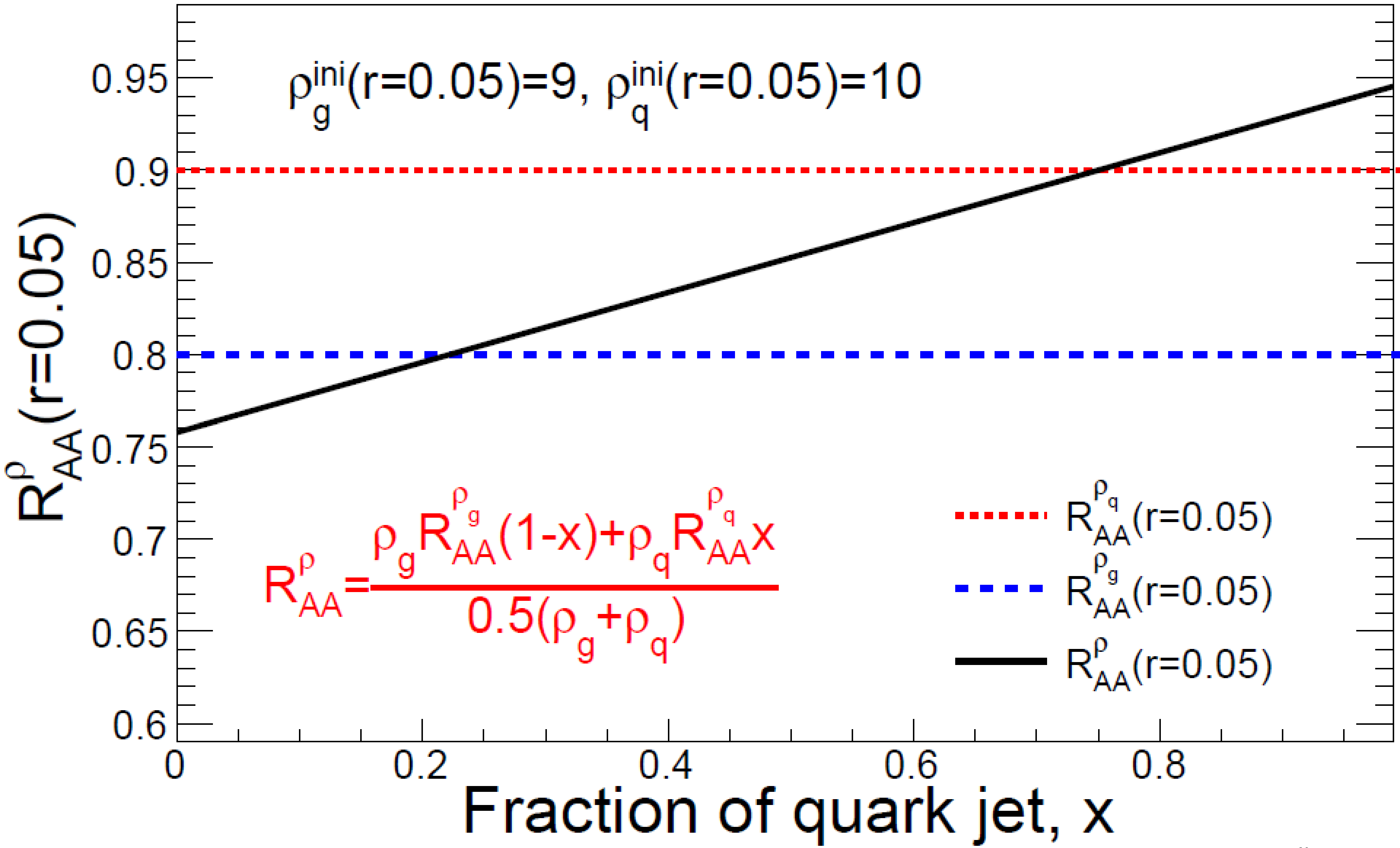
$$\hat{q} \ = \ 4T\hat{e}$$

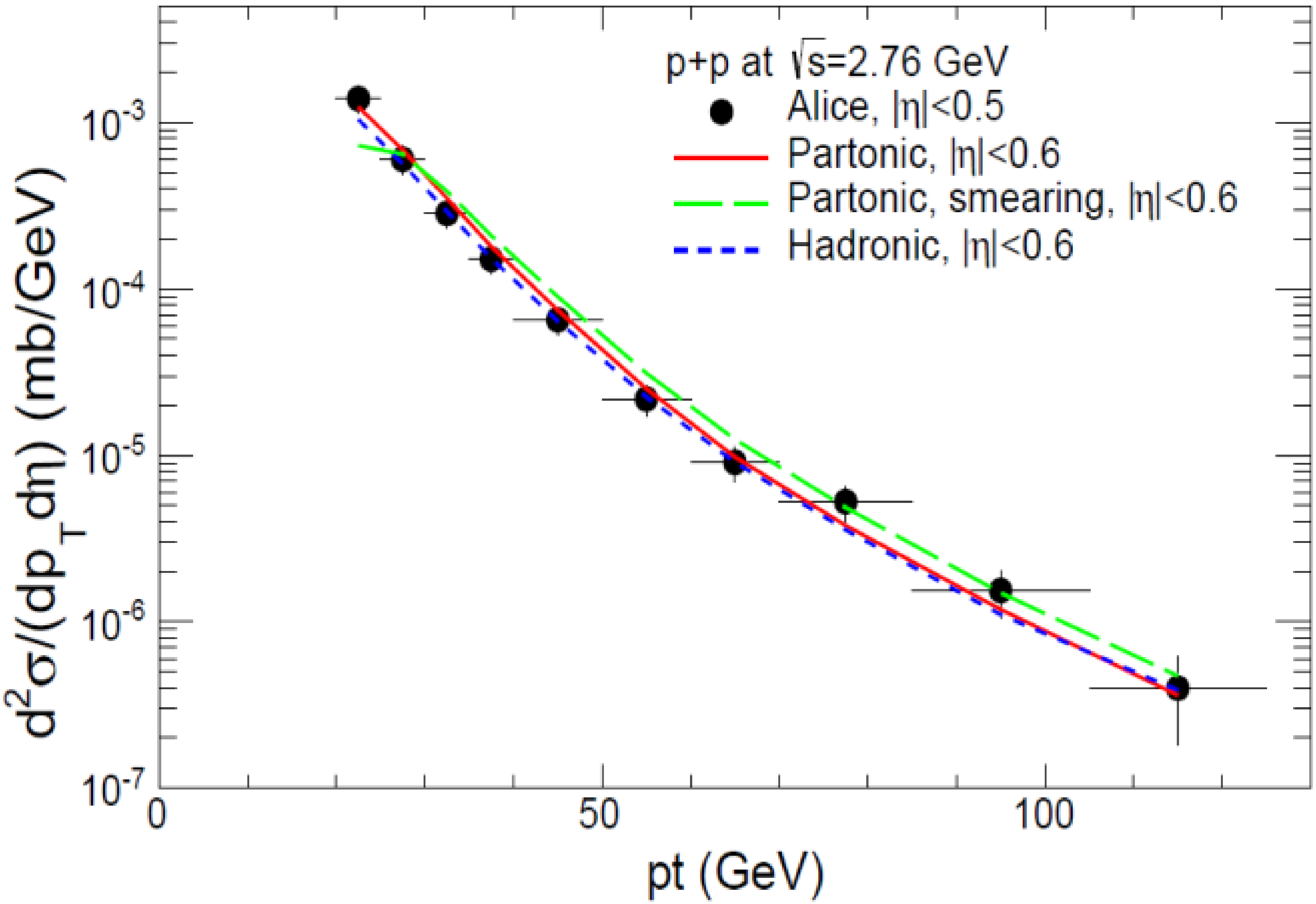
$$\frac{d}{dt} f_g(\omega, k_\perp^2, t) = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{\rm med}}{d\omega dk_\perp^2 dt}$$

Only leading parton radiate

$$\frac{dN_g^{\rm med}}{d\omega dk_\perp^2 dt} = \frac{2\alpha_s}{\pi}\frac{xP(x)\hat{q}(t)}{\omega k_\perp^4}\sin^2\frac{t-t_i}{2\tau_f}$$

HT formula


$\rho_g^{ini}(r=0.05)=9,\ \rho_q^{ini}(r=0.05)=10$
$R_{AA}^{\rho}=\frac{\rho_g R_{AA}^{\rho_g}(1-x)+\rho_q R_{AA}^{\rho_q}x}{0.5(\rho_g+\rho_q)}$
$R_{AA}^{\rho_q}(r=0.05)$
$R_{AA}^{\rho_g}(r=0.05)$
$R_{AA}^{\rho}(r=0.05)$
$R_{AA}^{\rho}(r=0.05)$
Fraction of quark jet, x
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
0
0.2
0.4
0.6
0.8

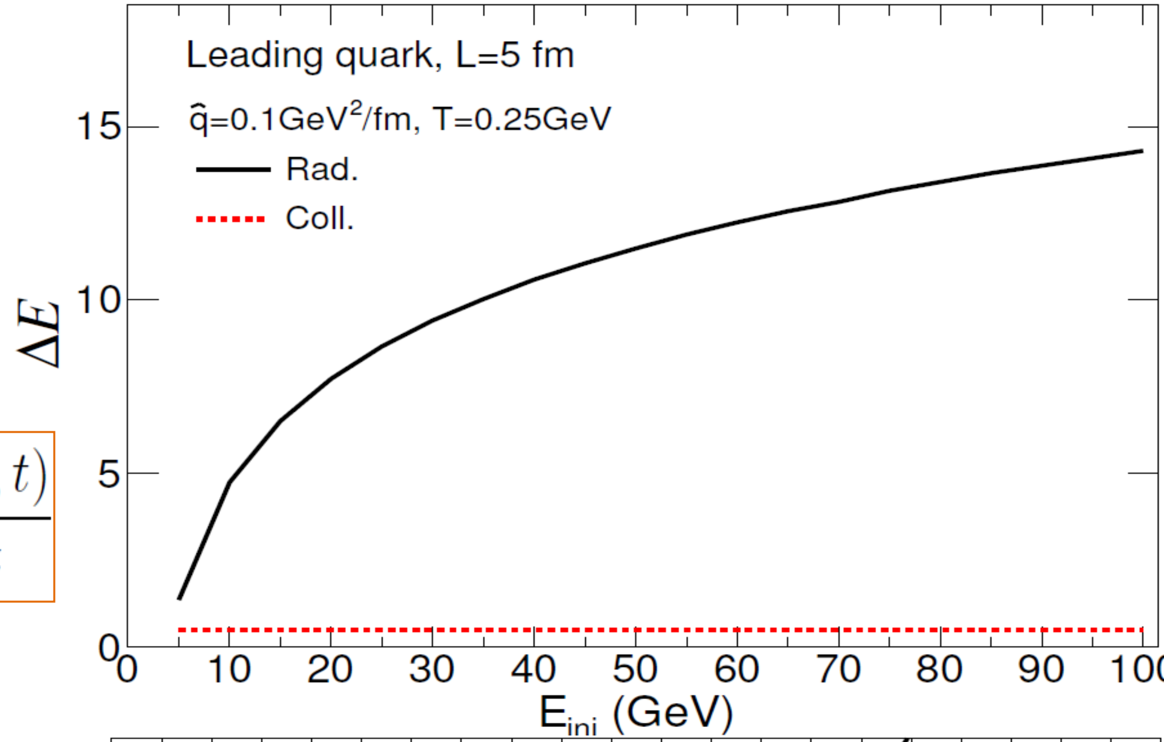

p+p at √s=2.76 GeV
Alice, |η|<0.5
Partonic, |η|<0.6
Partonic, smearing, |η|<0.6
Hadronic, |η|<0.6
$d^2\sigma/(dp_T d\eta)$ (mb/GeV)
pt (GeV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
50
100

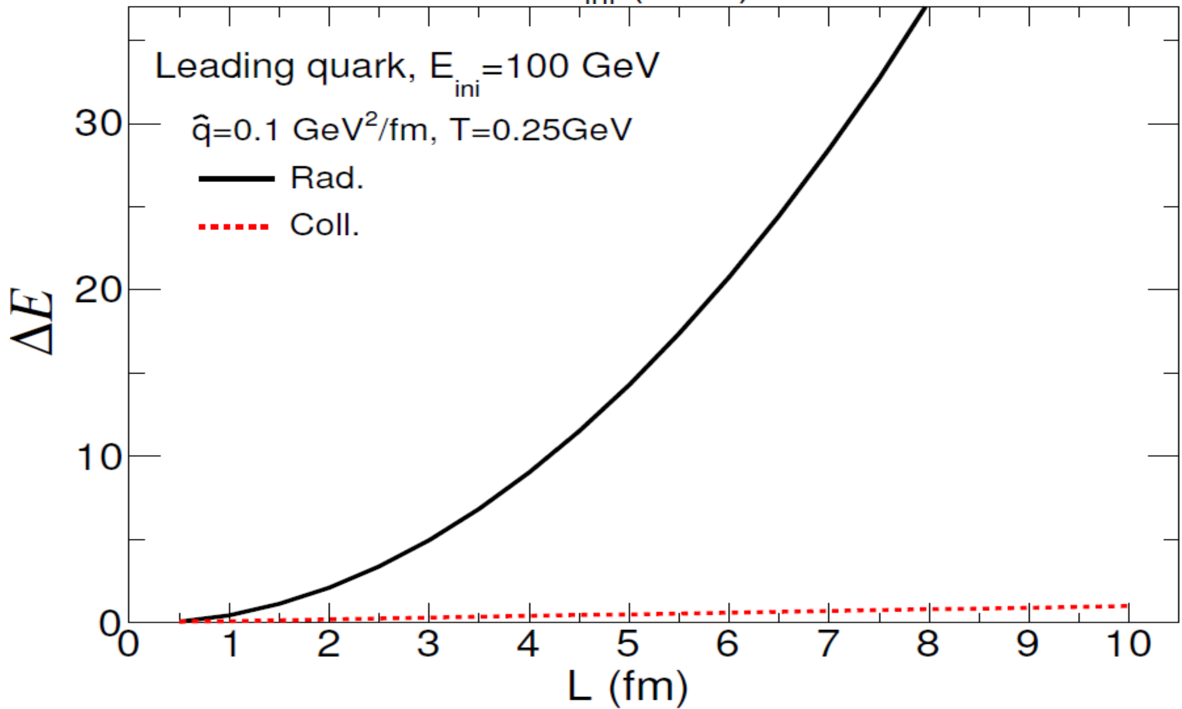
Leading parton Energy Loss

$$\boxed{\Delta E_{Rad} = \int \omega d\omega dk_\perp^2 dt \frac{dN_g(\omega, k_\perp^2, t)}{d\omega dk_\perp^2 dt}}$$

$$\hat{e} = \frac{\hat{q}}{4T}$$

$$\boxed{\Delta E_{Coll} = \int \hat{e}(t) dt}$$





Leading parton Energy Loss

From David d'Enterria, arXiv:0902.2011

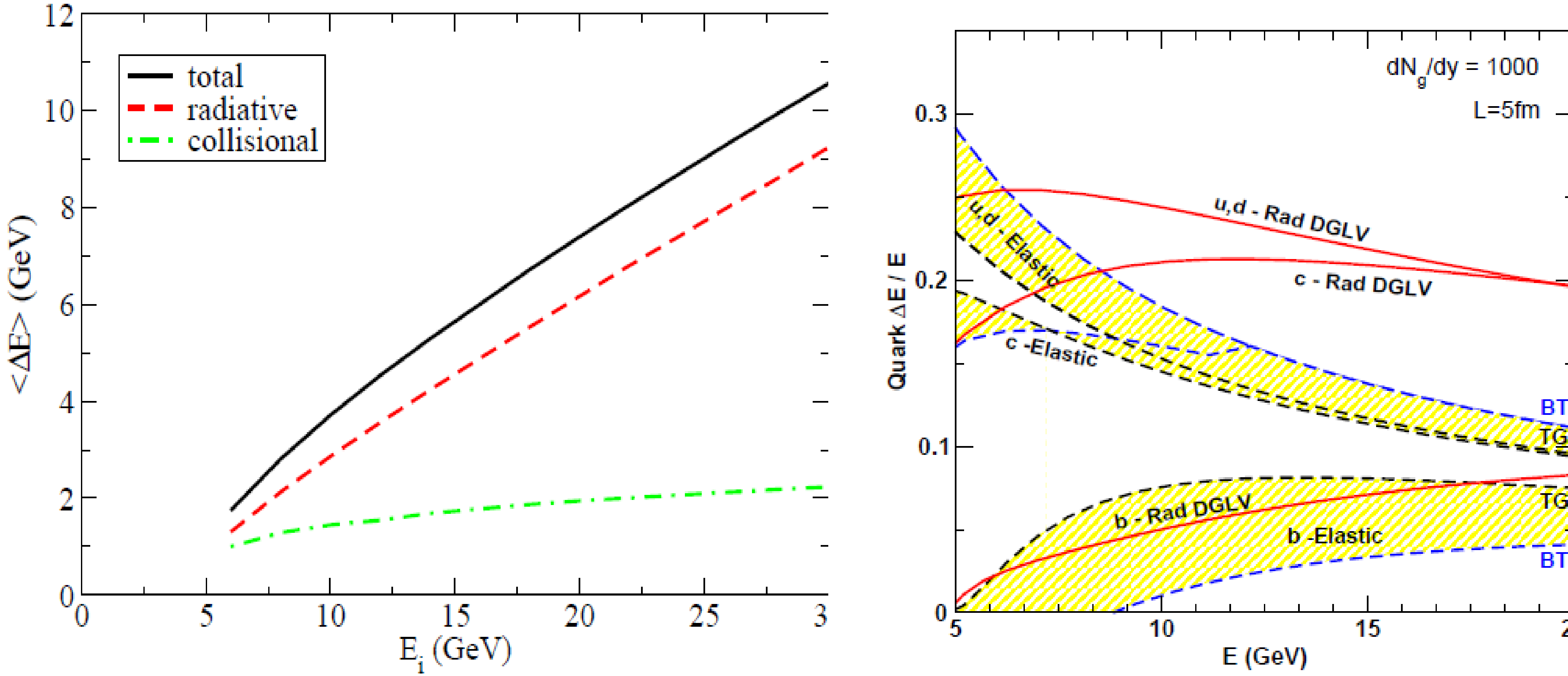
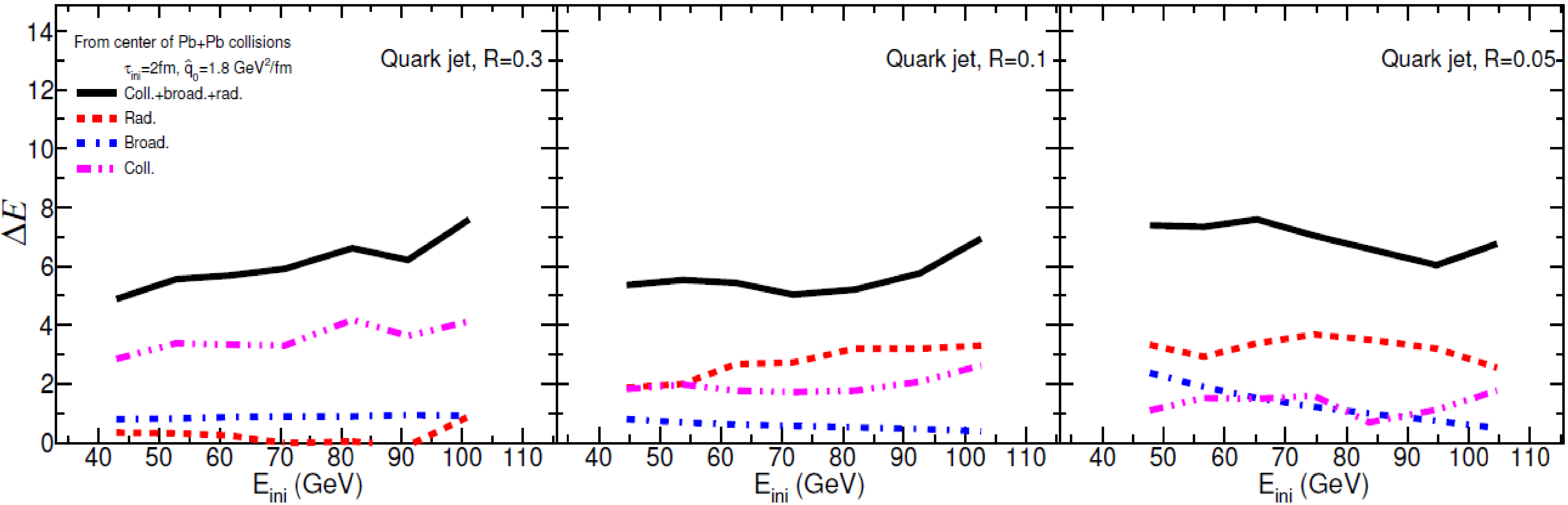


Fig. 5. Comparison of the average radiative and elastic energy losses of light-quarks (left) and light- and heavy-quarks (right) passing through the medium produced in central *AuAu* collisions at RHIC energies as obtained by the AMY [24] and DGLV [25] models (see later).

Cone size dependence

$$E_{\text{jet}}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2$$



w_cut dependence