# Nuclear modification of full jets and jet structure in PbPb collisions at the LHC

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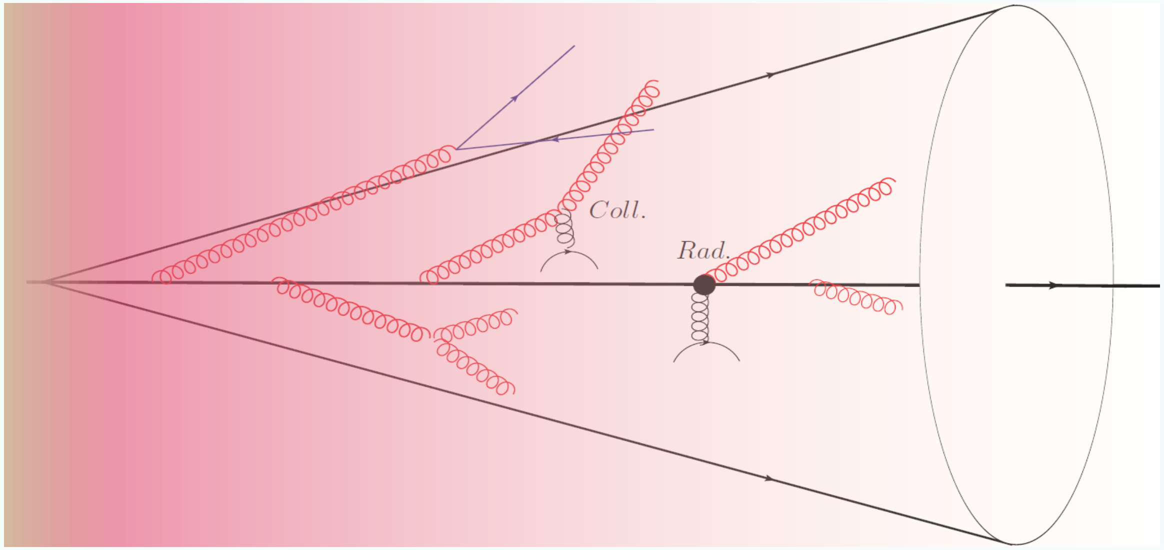
In collaboration with Guang-You Qin and Yasuki Tachibana

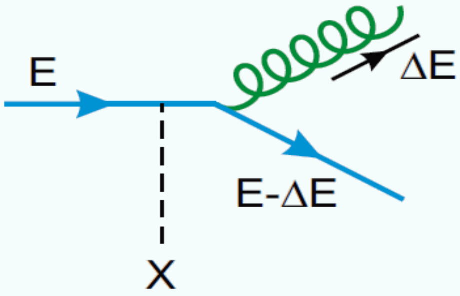
Based on PRC.94.024902, PRC.95.044909 and paper in preparation.

# Outline

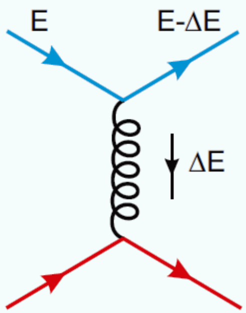
- Motivation and Framework
- Jet energy loss
- Jet shape modification
- Medium response
- Summary and Outlook

# Full jet evolution in medium

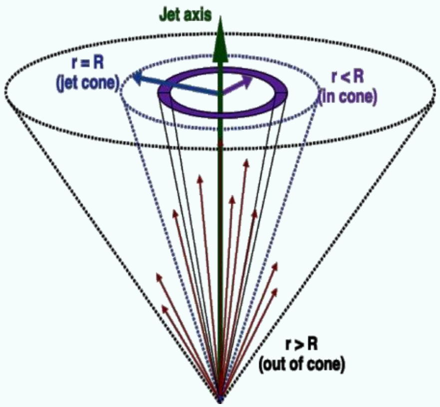



Inelastic scattering




Elastic scattering




- Radiative energy loss for full jet may be not so important as it for leading parton.
- Collisional energy loss may be more important for full jets than single hadrons.
- Jet structure and its modification provides more observables, can reveal more detailed information.

# Framework: Boltzmann transport equation

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

$$\begin{aligned}
\frac{d}{dt} f_j(\omega_j, k_{j\perp}^2, t) \quad = \quad & \hat{e}_j \frac{\partial}{\partial \omega_j} f_j(\omega_j, k_{j\perp}^2, t) \\
+ \quad & \frac{1}{4}\hat{q}_j \nabla_{k_\perp}^2 f_j(\omega_j, k_{j\perp}^2, t) \\
+ \quad & \sum_i \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_i(\omega_i, k_{i\perp}^2, t) \\
- \quad & \sum_i \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_j(\omega_j, k_{j\perp}^2, t)
\end{aligned}$$

Collisional energy loss

$K_T$ broadening

Radiation: gain, loss

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

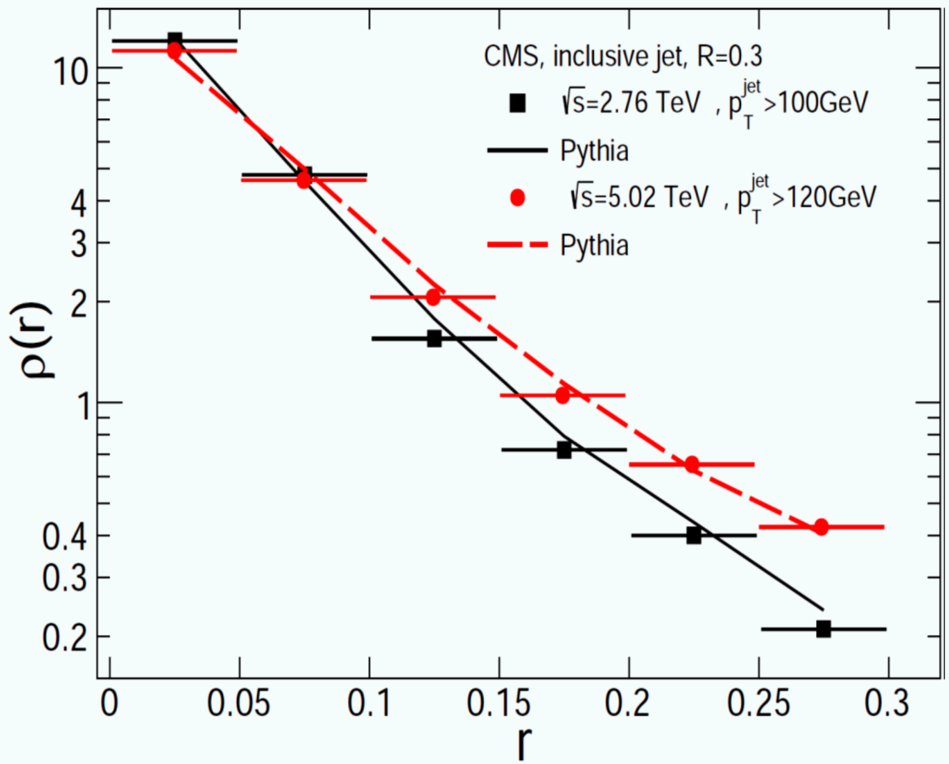
| | |
|---|---|
| $q$ | $g \to q\bar{q}$, $q \to qg$<br>$q \to qg$, $q \to gq$ |
| $g$ | $q \to gq$, $g \to gg$<br>$g \to gg$, $g \to q\bar{q}$ |

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

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

# Framework: input from Pythia and Hydro.

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jets}\frac{\sum_{{\rm tracks}\in[r_a,r_b)} p_T^{\rm track}}{p_T^{\rm jet}}$$




Parameters in Pythia differ from 2.76A TeV to 5.02A TeV.

At same jet energy, jets at 2.76A TeV are steeper.

## Hydrodynamic simulation from VISH2+1 or Yasuki Tachibana

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

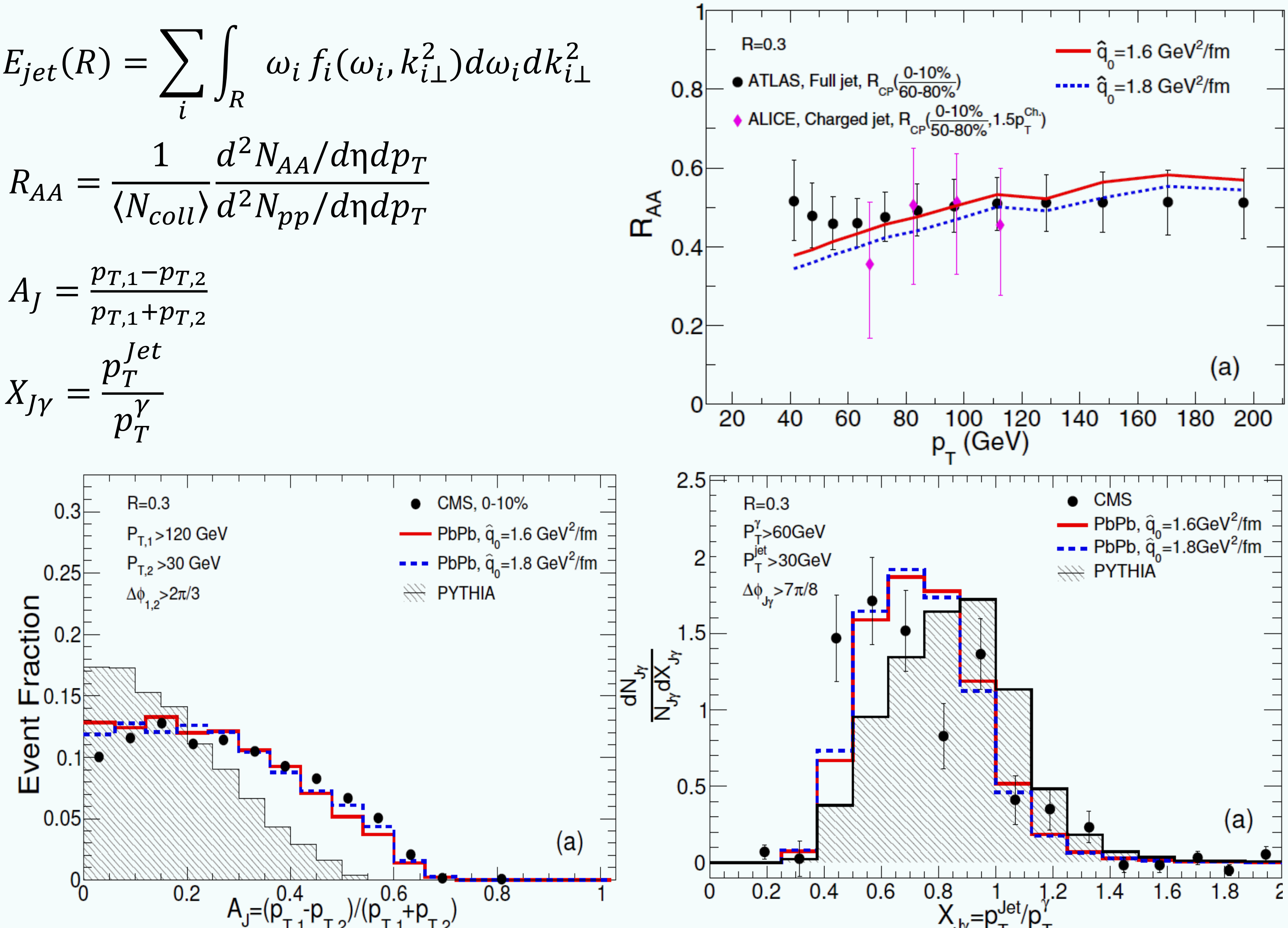
# Observables of Jet energy loss @ 2.76A TeV

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

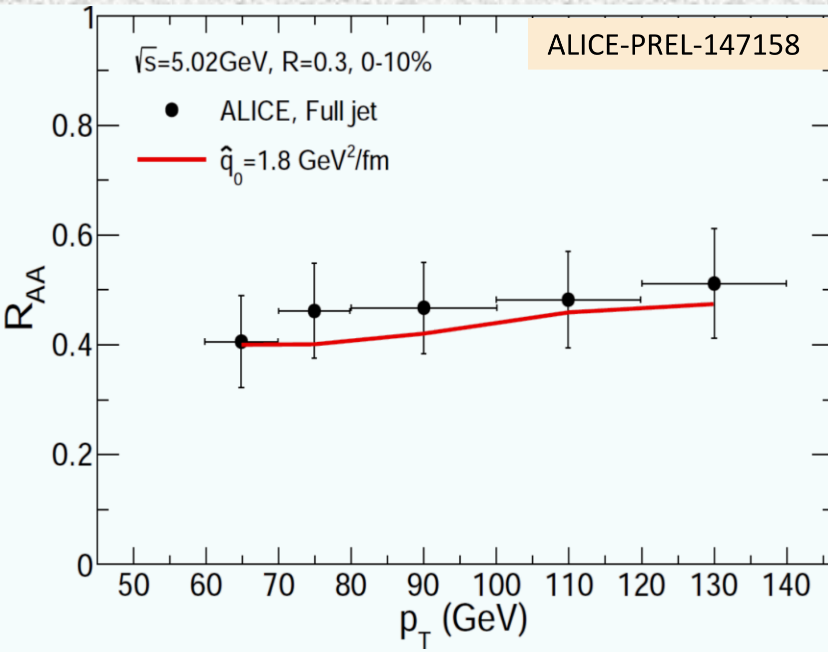
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/d\eta dp_T}{d^2N_{pp}/d\eta dp_T}$$

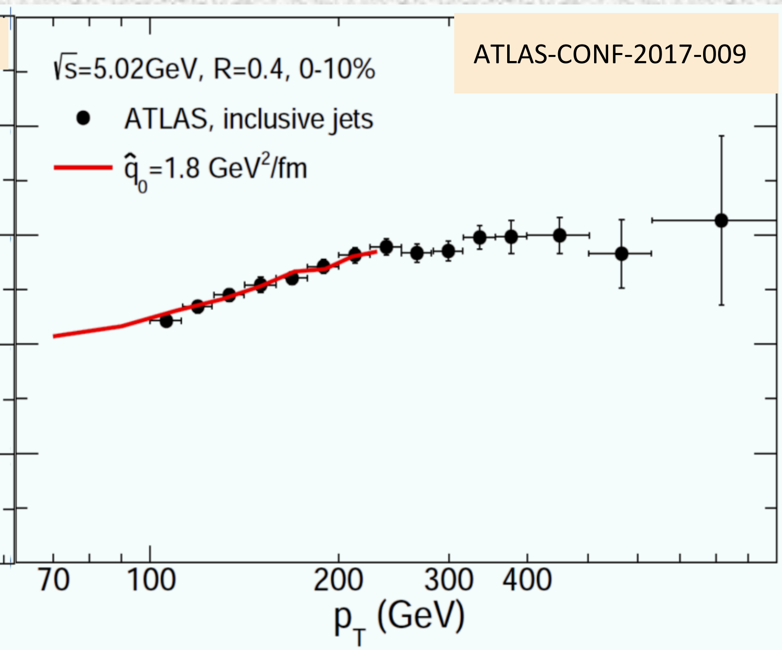
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

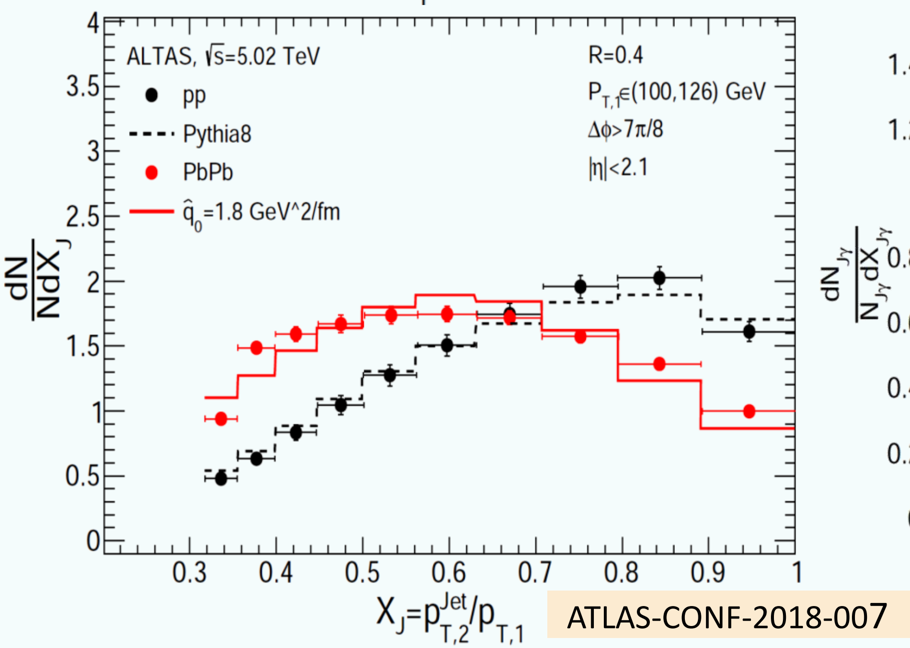
$$X_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$

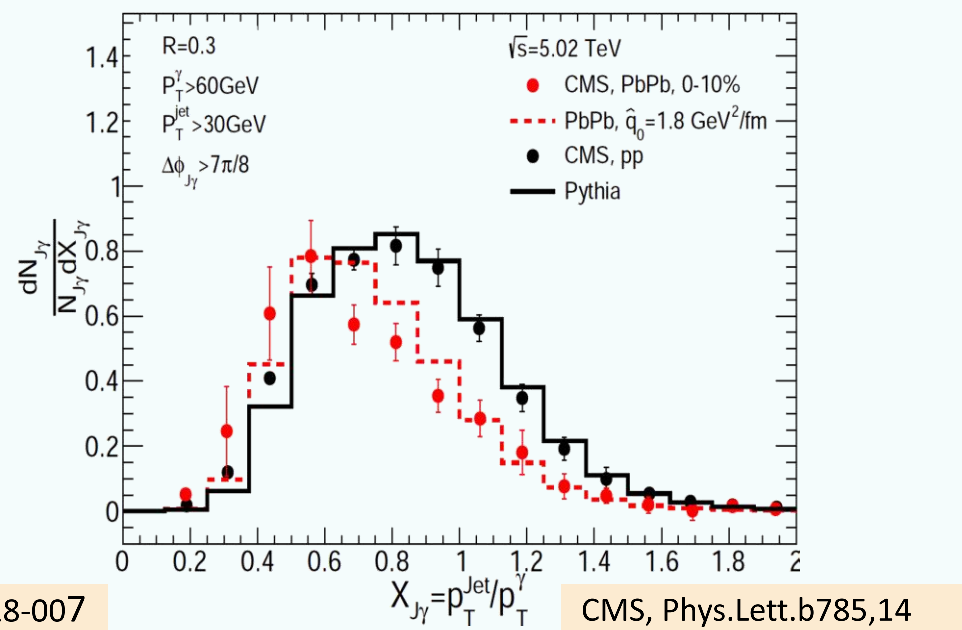


# Observables of Jet energy loss @ 5.02A TeV



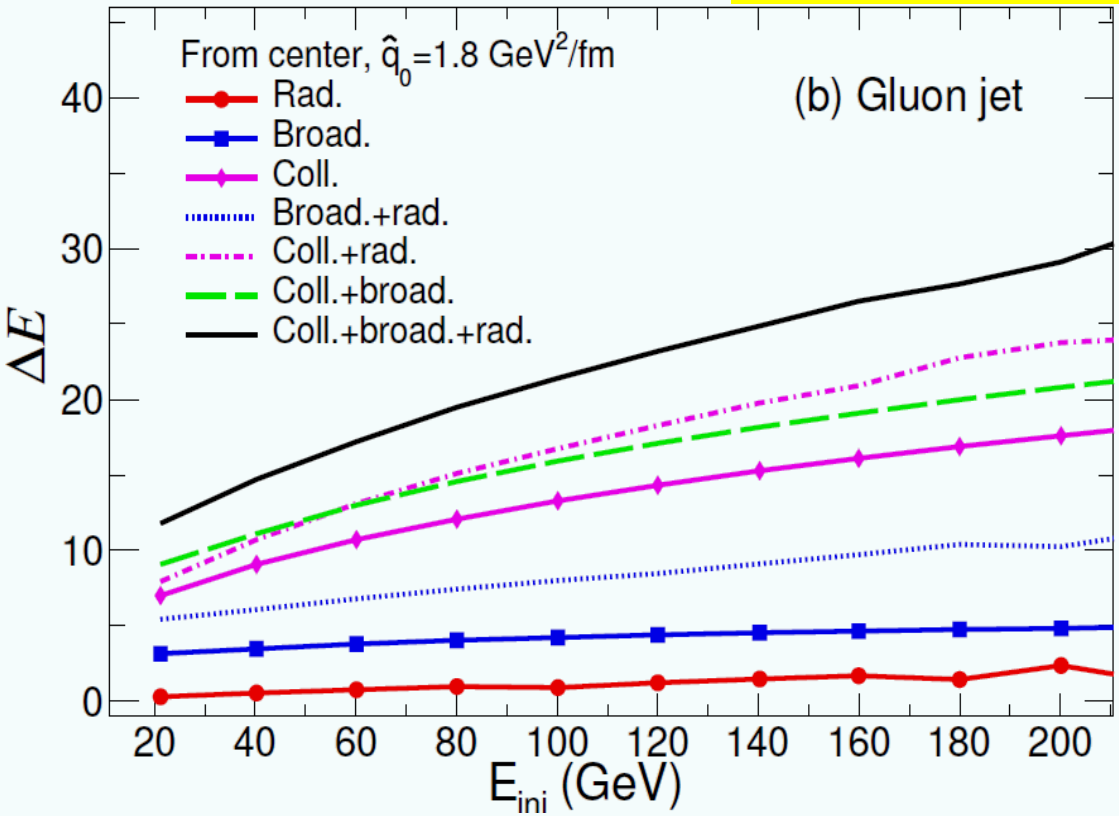



# Jet Energy Loss from different mechanisms

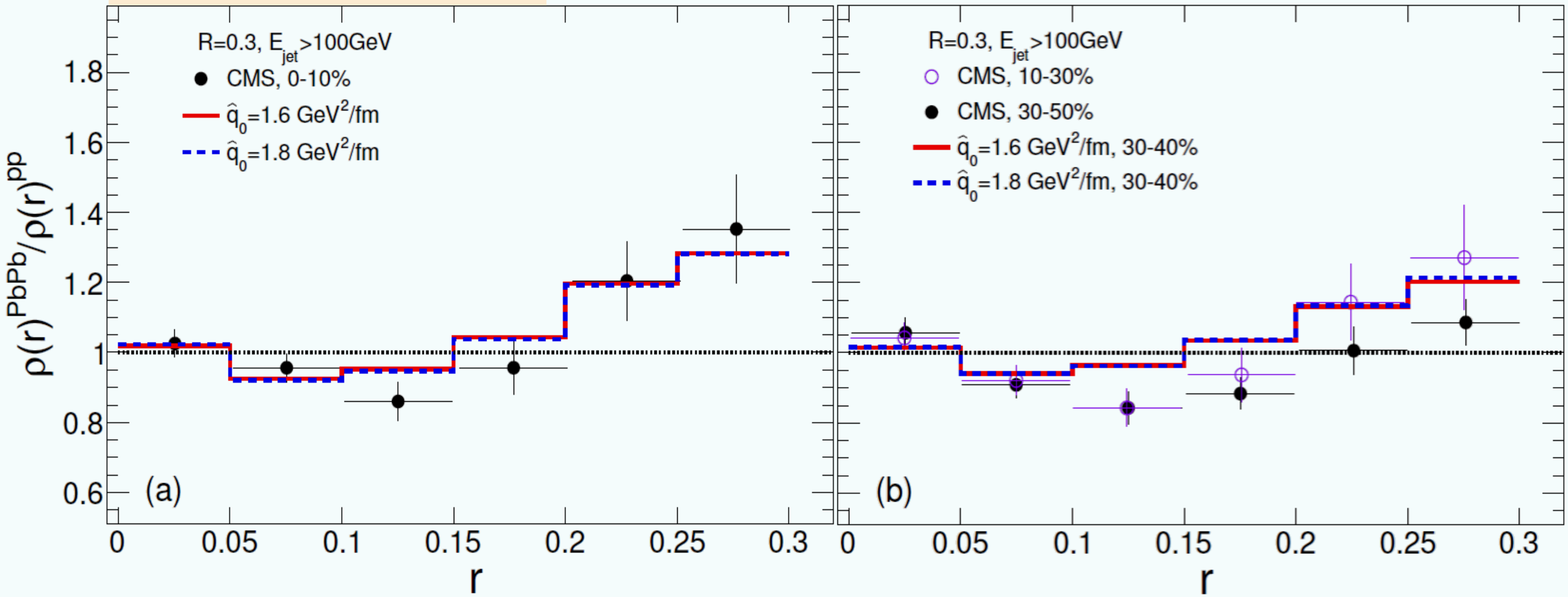
@ 2.76A TeV




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

# Nuclear modification of Jet shape @ 2.76A TeV

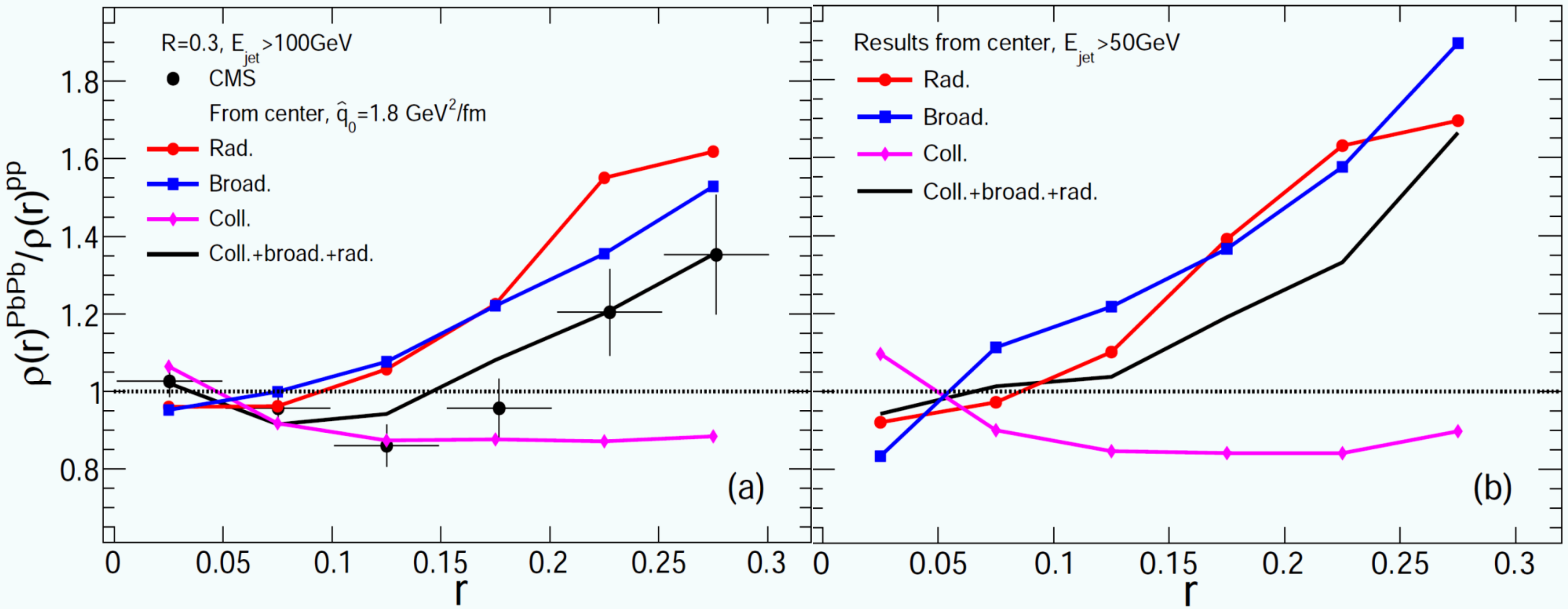
CMS, Phys.Let.B730(2014),243




Jet shape is modified little at small r, suppressed at middle r and enhanced at large r.

# Effects of different mechanisms on Jet shape

@ 2.76A TeV

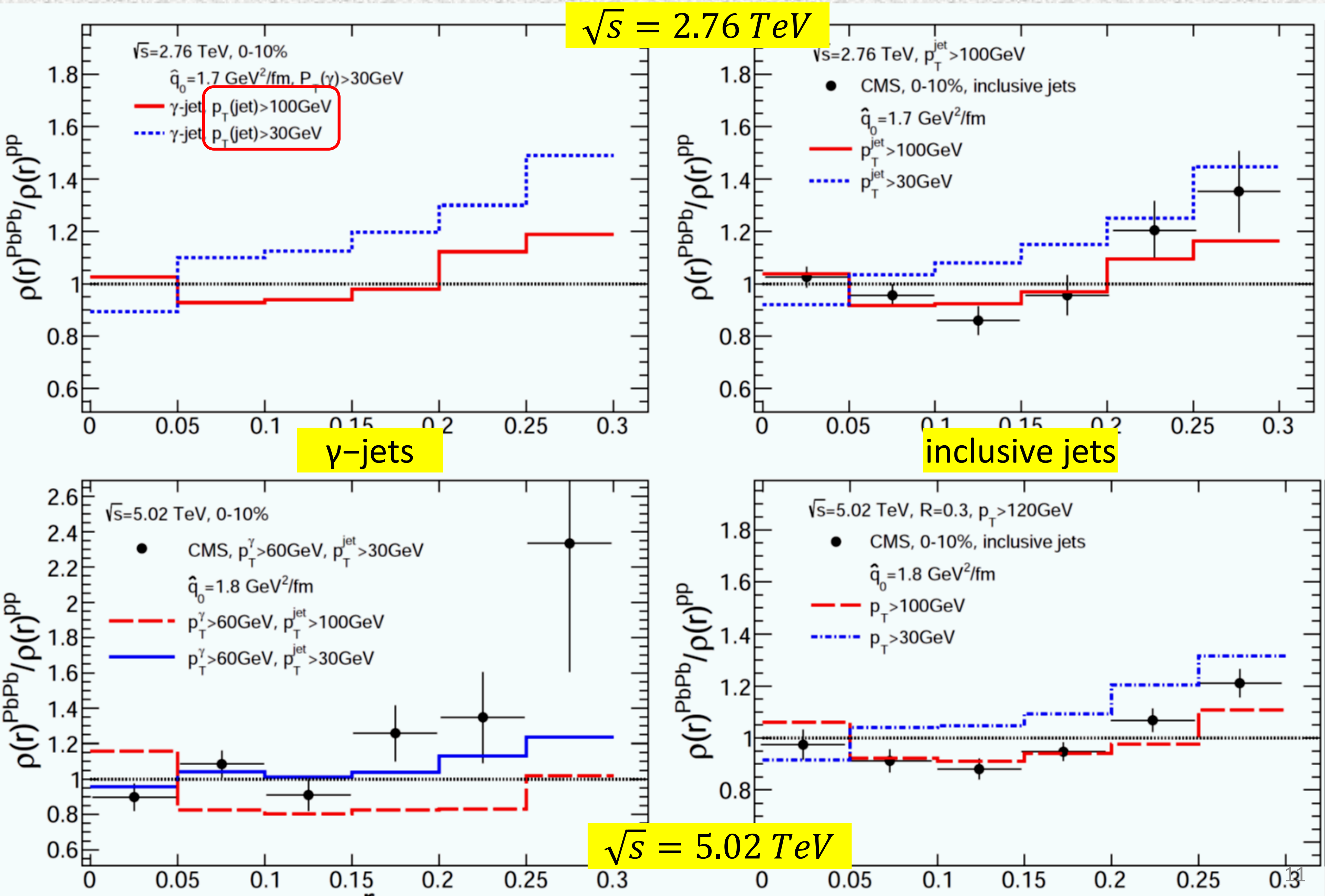



Rad. and Broad. transport energy from center to periphery,

Coll. leads inner core losing less fraction of energy than outer part.

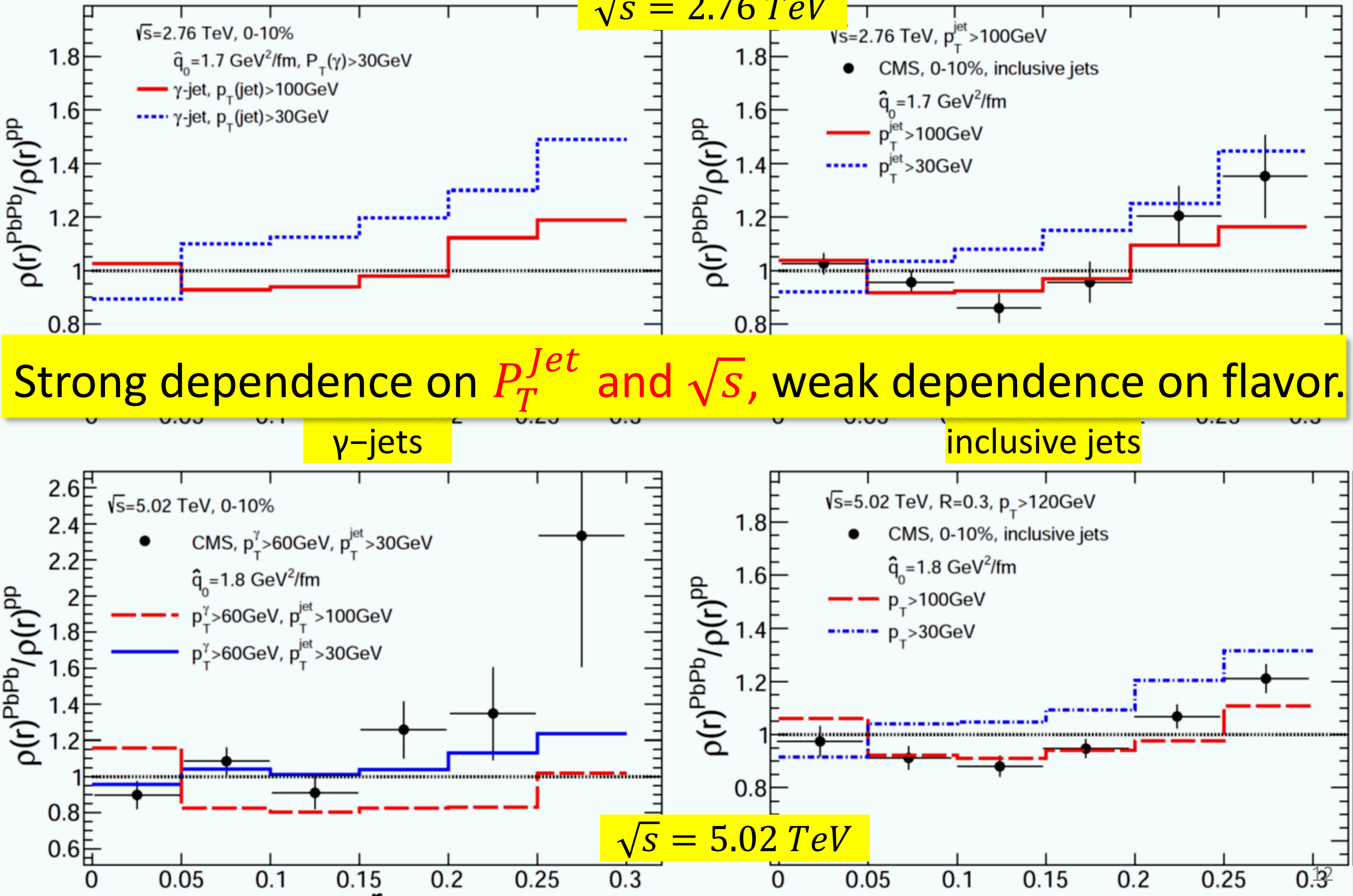
For lower energy jet, its inner core is easier to be modified.

# $P_T^{Jet}$, $\sqrt{s}$ and Jet flavor dependence



# $P_T^{Jet}$, $\sqrt{s}$ and flavor dependence

$\sqrt{s} = 2.76\ TeV$




Strong dependence on $P_T^{Jet}$ and $\sqrt{s}$, weak dependence on flavor.

γ−jets

inclusive jets

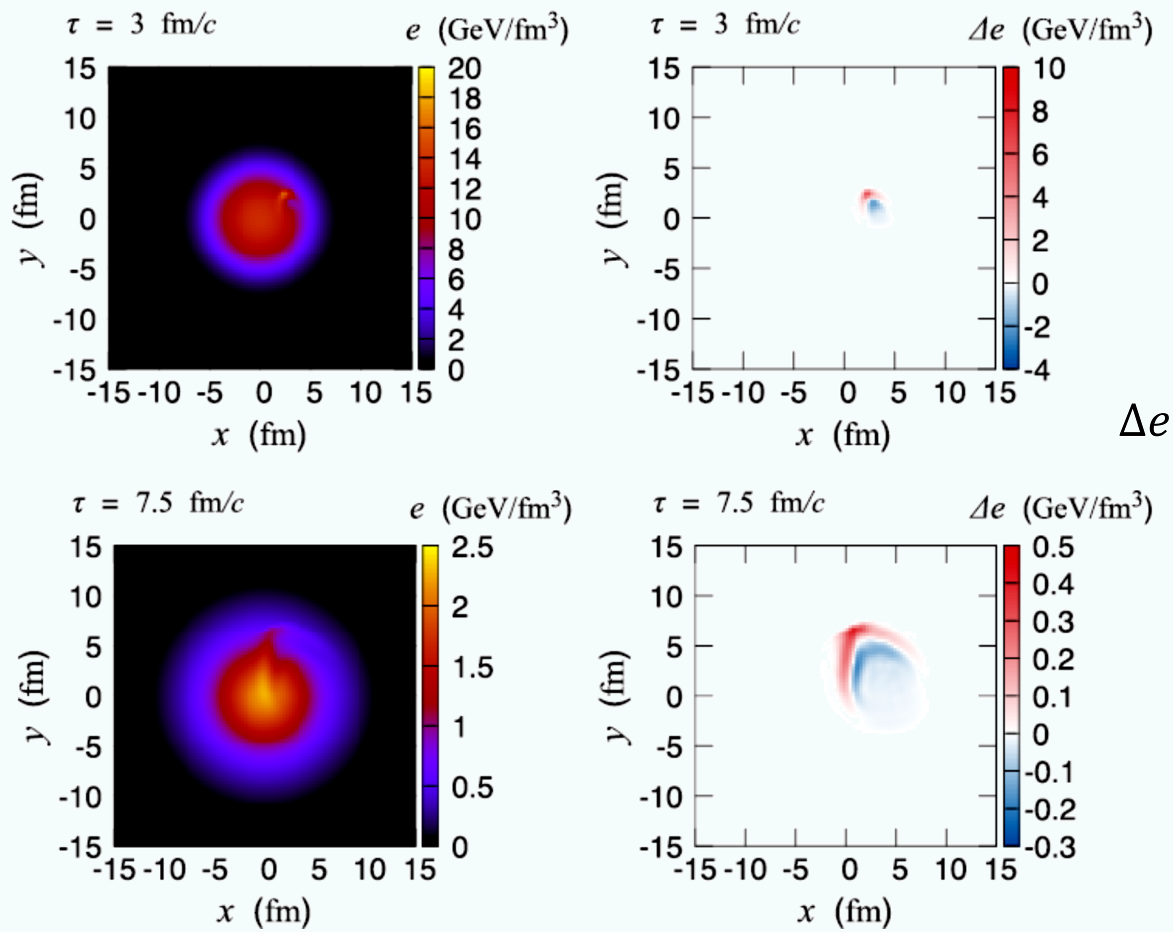
$\sqrt{s} = 5.02\ TeV$

# Medium response

$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}} = 0 \Rightarrow \partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x)$$

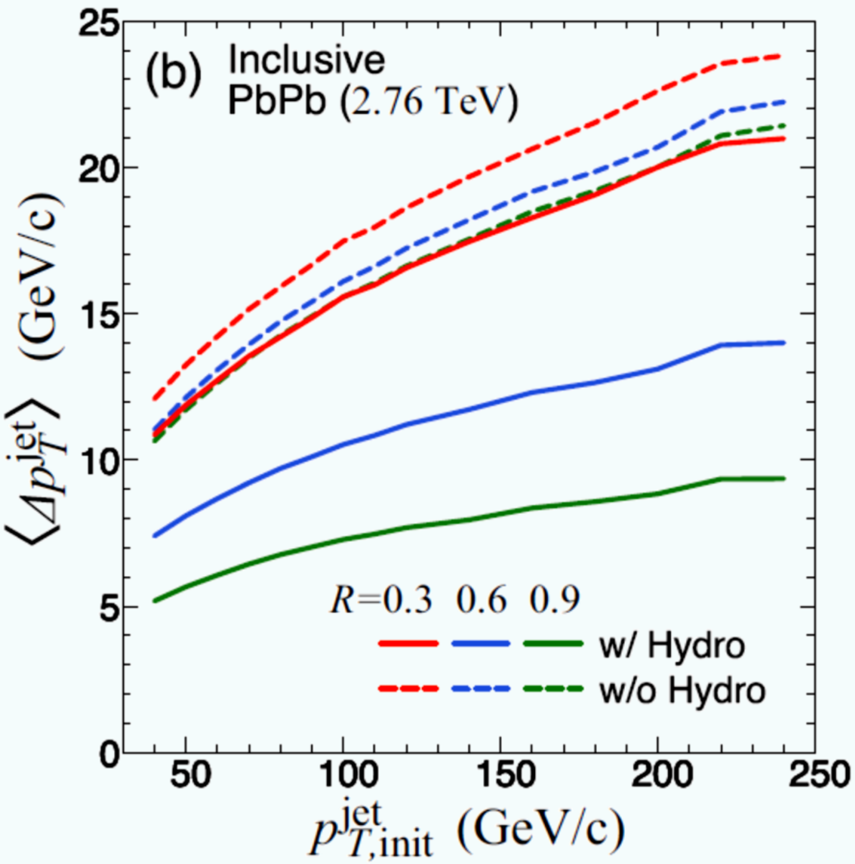
Yasuki Tachibana, Ning-Bo Chang and Guang-You Qin, PRC.95.044909

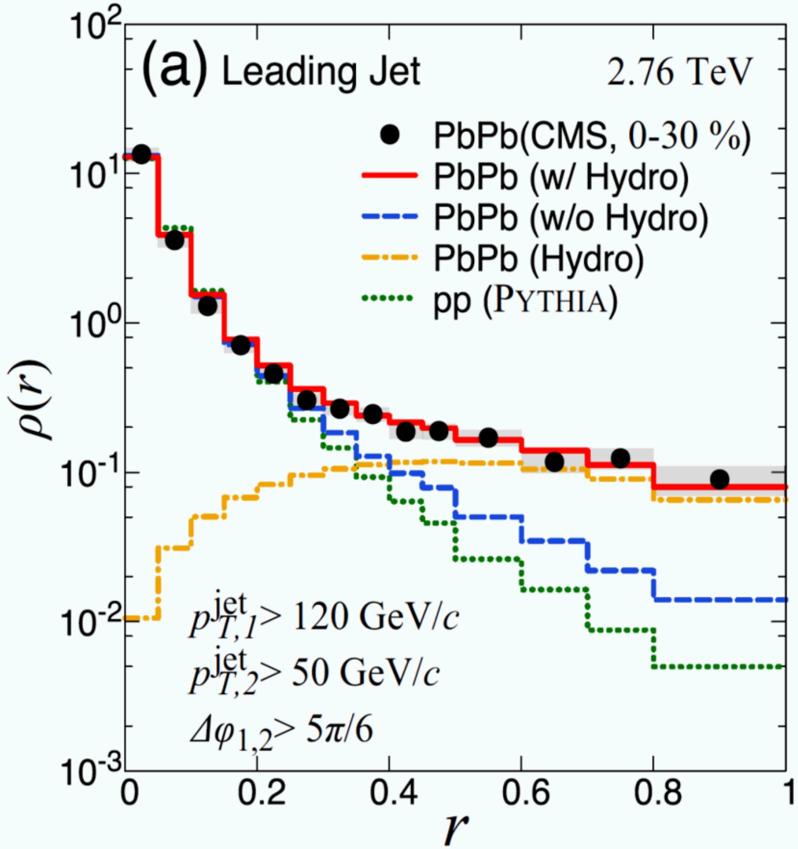
$$J^\nu(x) = -\sum_j \int d^3k_j k_j^\nu \left.\frac{df_j(\boldsymbol{k}_j,t)}{dt}\right|_{\mathrm{col.}} \delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_0^{\mathrm{jet}} - \frac{\boldsymbol{k}_j}{\omega_j}t\right)$$




$$\Delta e = e|_{w/jet} - e|_{w/ojet}$$

# Effect of medium response



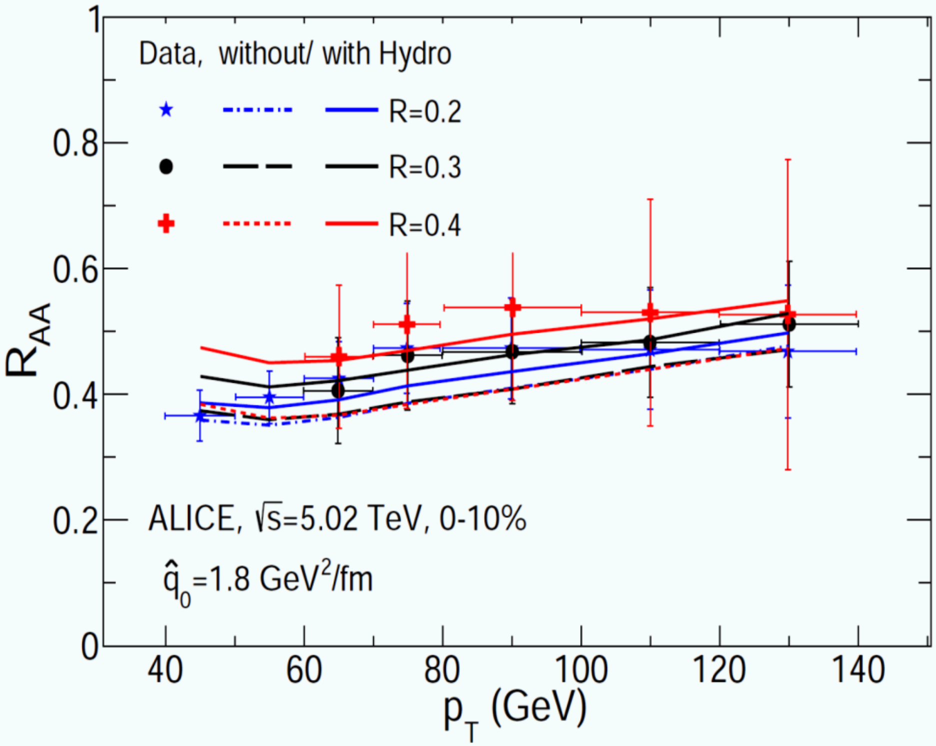



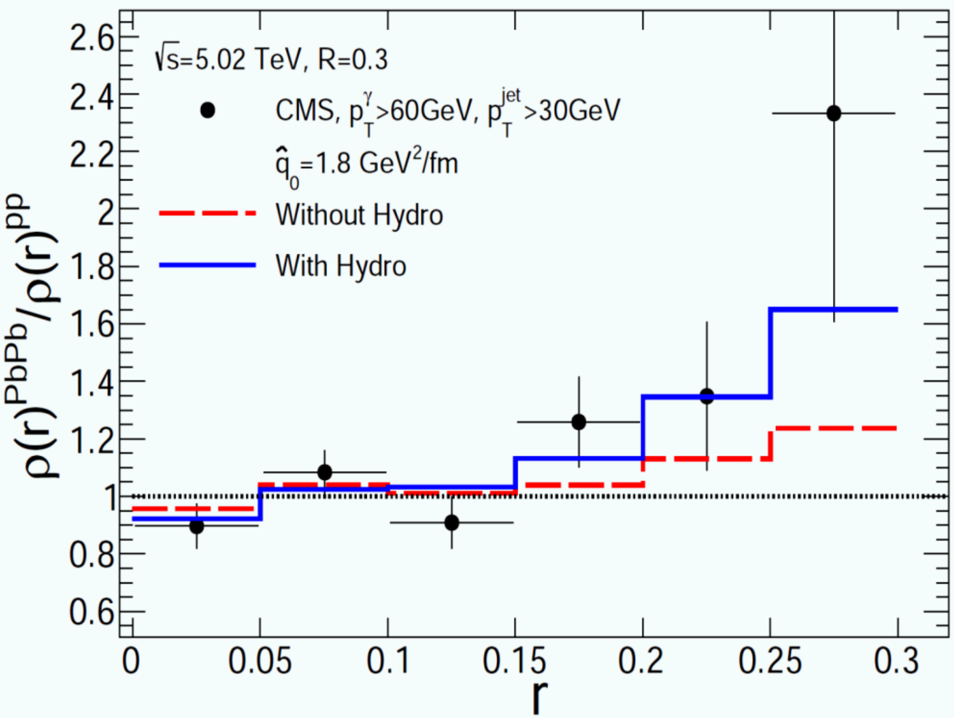

Medium response can feed back some energy to the jet cone.

For lager cone size, more energy is recovered.

Medium response dominates jet shape at large r.

# Effect of medium response



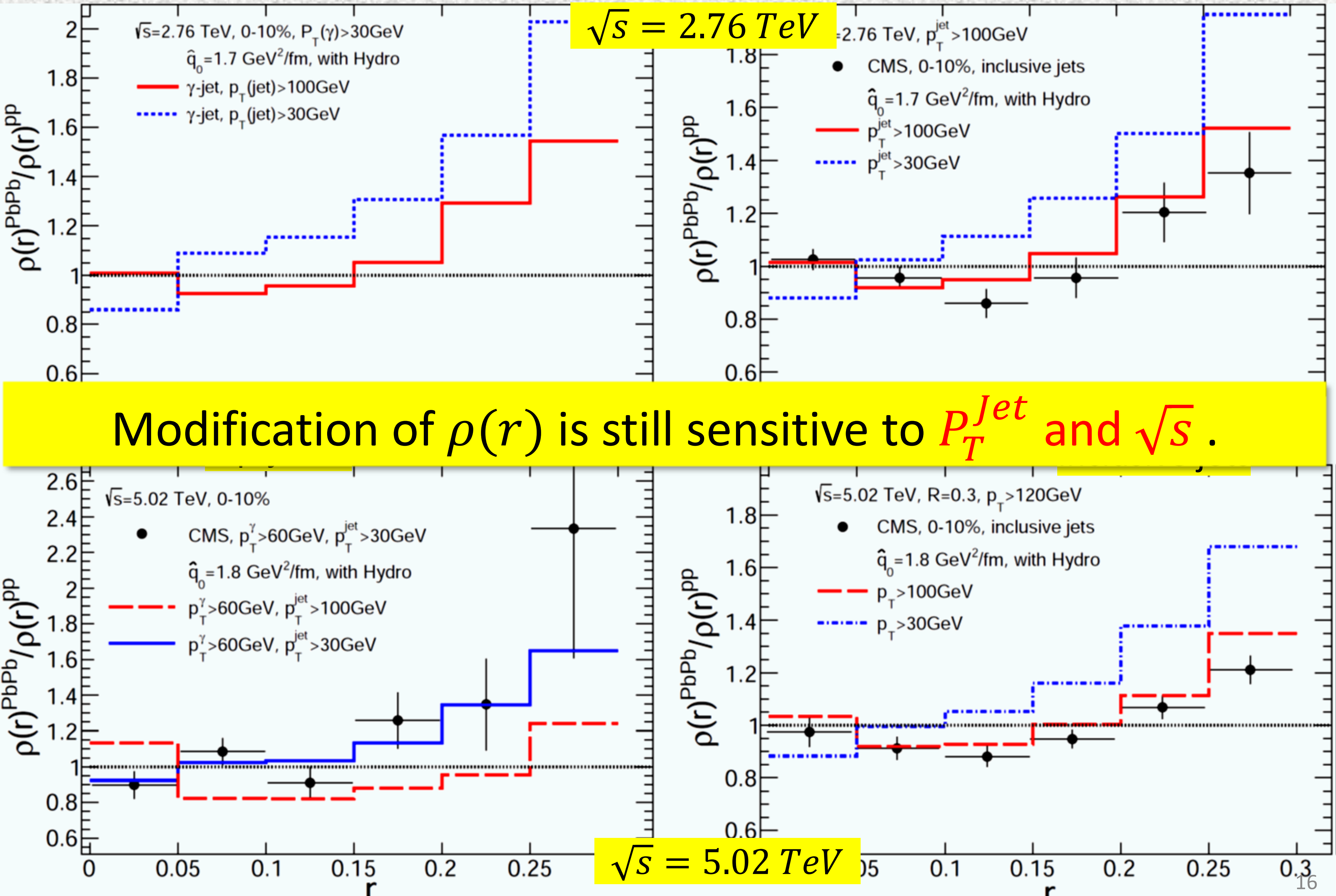




Rises $R_{AA}$ value.

Important to cone size dependence of jet $R_{AA}$ .

Rises $\rho(r)^{PbPb}$/ $\rho(r)^{pp}$ at large r.

# Effect of medium response




**Modification of $\rho(r)$ is still sensitive to $P_T^{Jet}$ and $\sqrt{s}$ .**

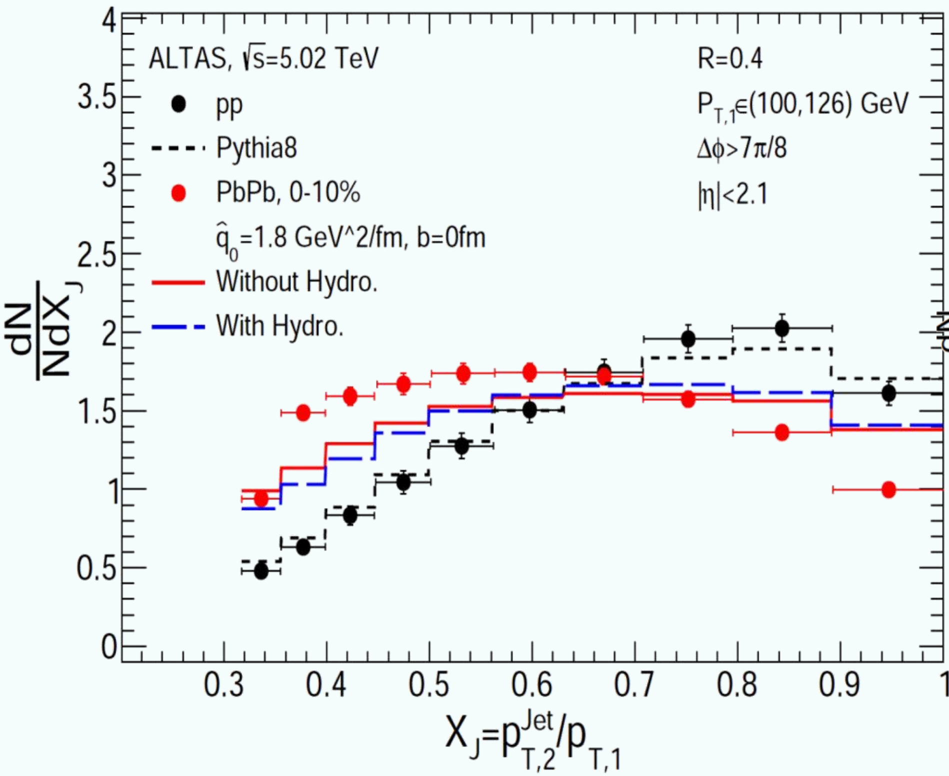
# Summary

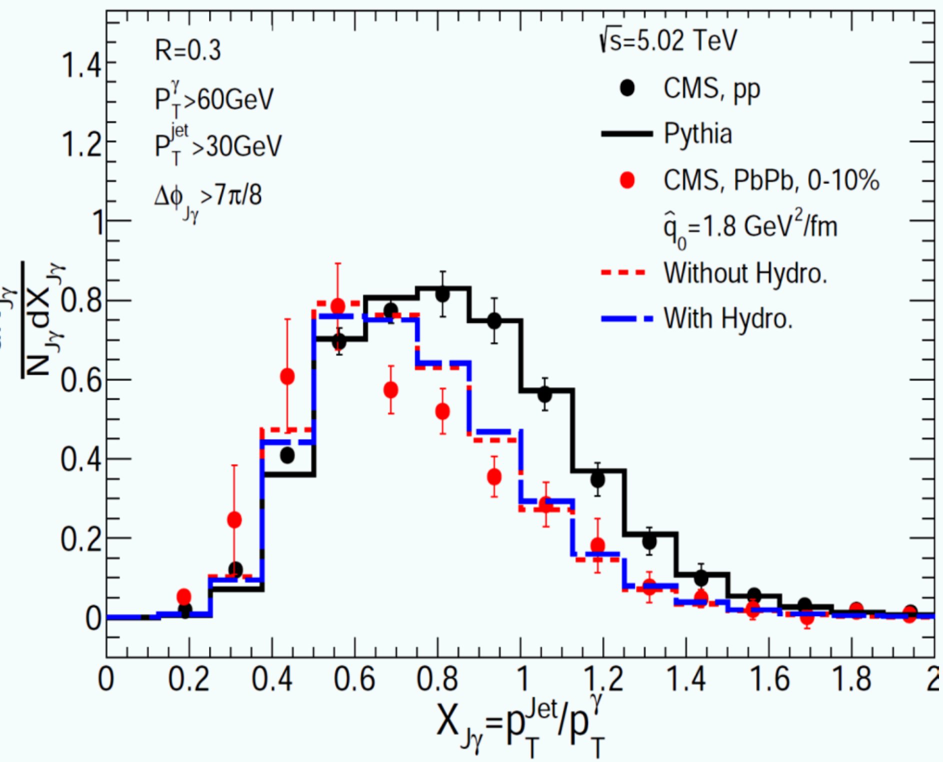
- Coupled differential transport equations are constructed to study the evolution of the partonic jet shower in the QGP medium, can describe the nuclear modification of the full jet energy and jet structure at both 2.76A TeV and 5.02A TeV.
- Collisional energy loss contributes most to full jet energy loss, and must be combined with other mechanisms to explain the modification of jet shape function.
- Modification of jet shape is sensitive to jet energy and collision energy, and not much to jet flavor. Need more measurements.
- Medium response feeds back some energy, and is important to jet shape at large r and cone size dependence of jet $R_{AA}$.

**Outlook：** $R_{AA}$ at very high $p_T$, Energy dependent transport coefficients, hadronization, jet FF…

Thanks for your attention!

# Effect of medium response

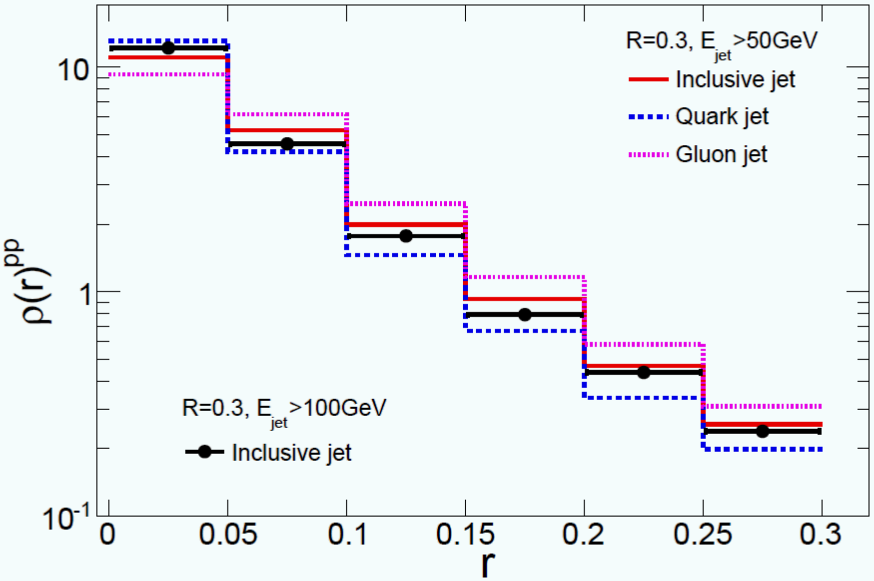


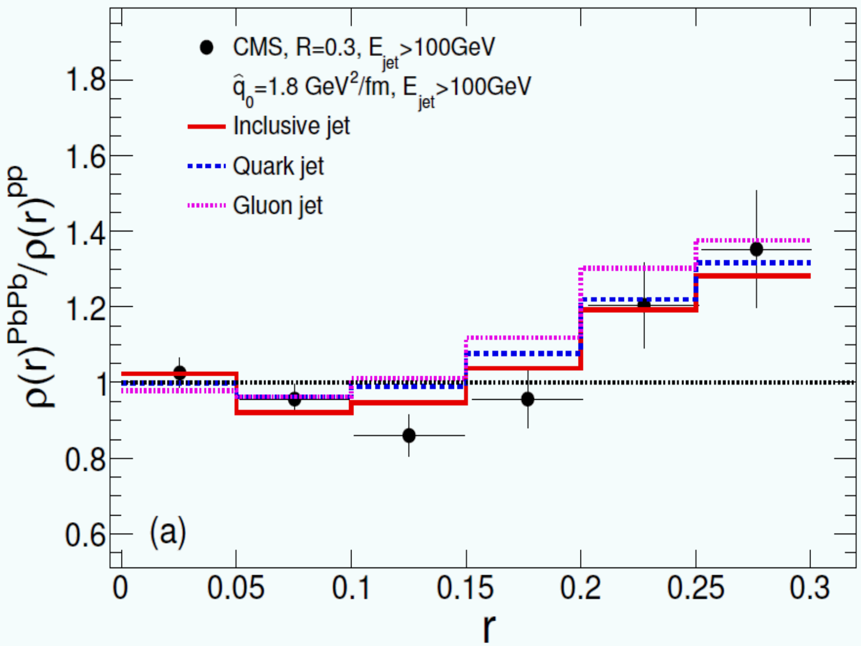



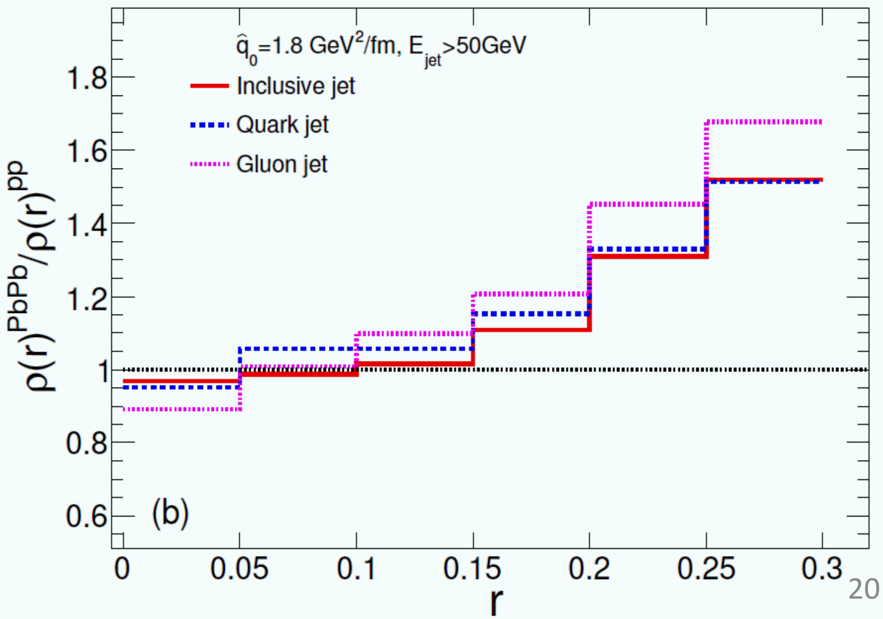

**Medium response moves the $X_J$ distribution to larger values.**

# Jet energy and flavor dependence

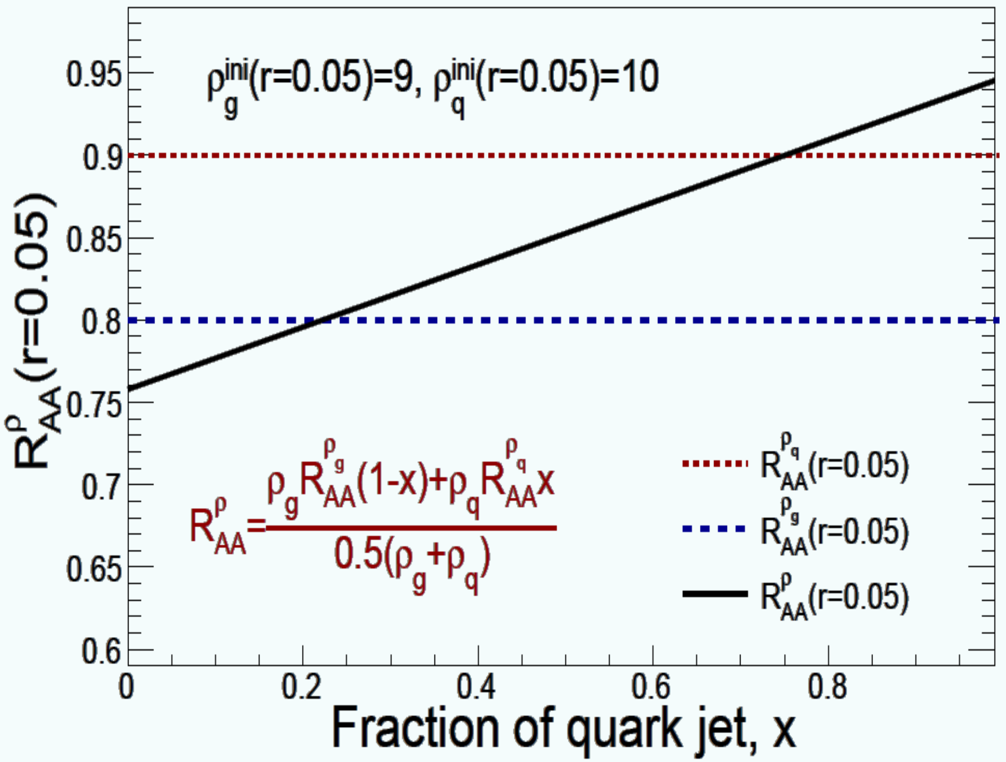
Lower energy jet is broader,
gluon jet is broader.



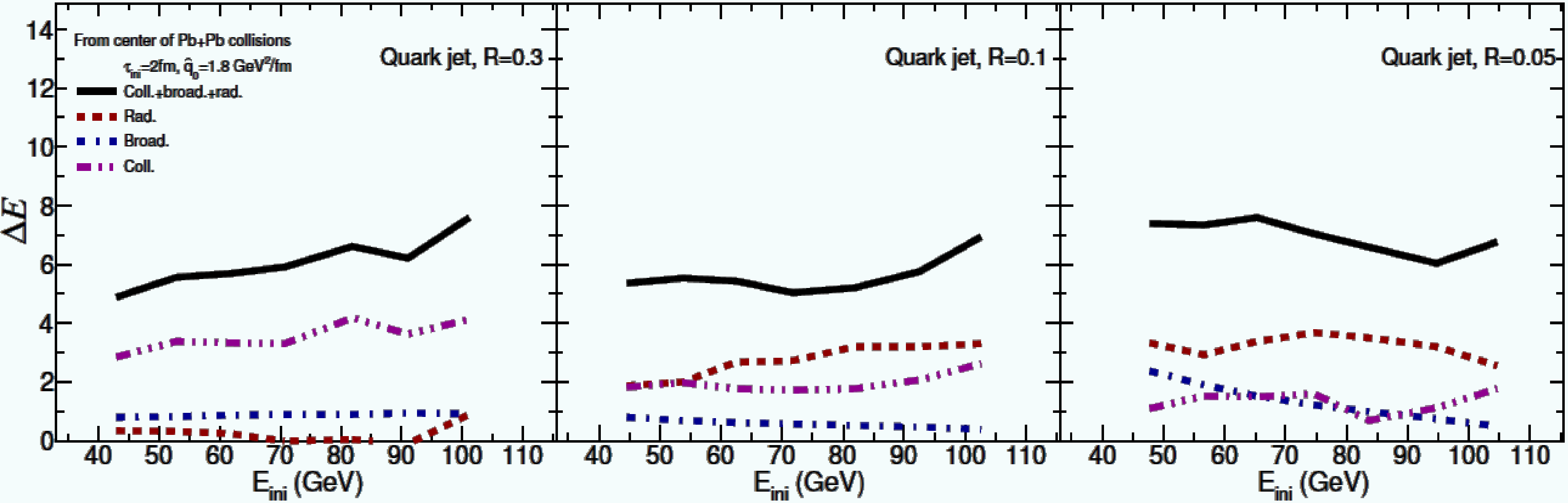

Modification of jet shape function is
sensitive to jet energy, less to flavor.



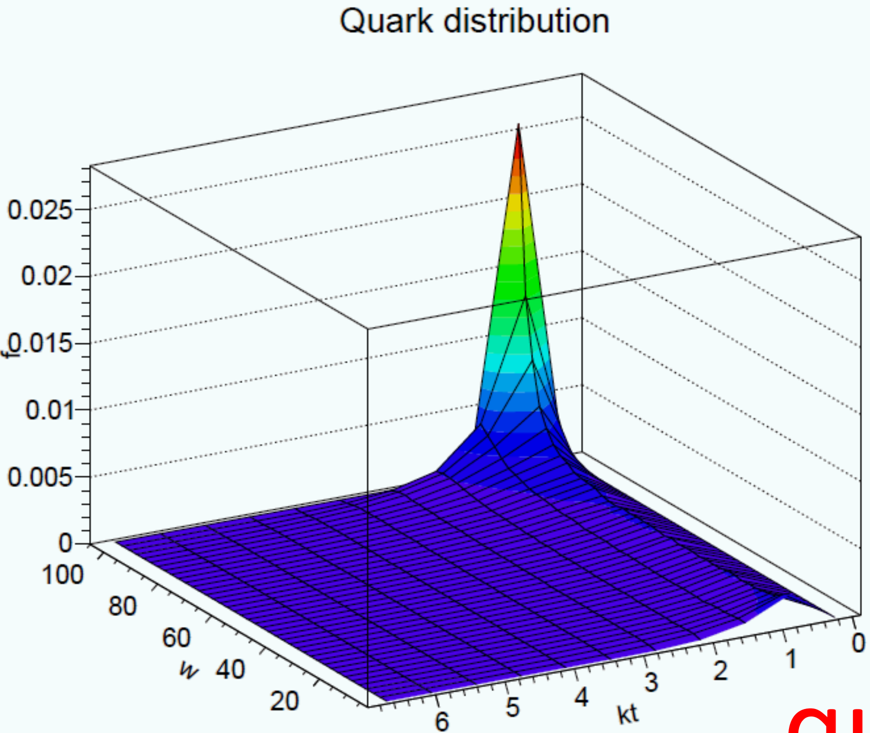
$\rho_g^{ini}(r=0.05)=9,\ \rho_q^{ini}(r=0.05)=10$
$R_{AA}^{\rho}(r=0.05)$
Fraction of quark jet, x
$R_{AA}^{\rho}=\frac{\rho_g R_{AA}^{\rho_g}(1-x)+\rho_q R_{AA}^{\rho_q}x}{0.5(\rho_g+\rho_q)}$
$R_{AA}^{\rho_q}(r=0.05)$
$R_{AA}^{\rho_g}(r=0.05)$
$R_{AA}^{\rho}(r=0.05)$

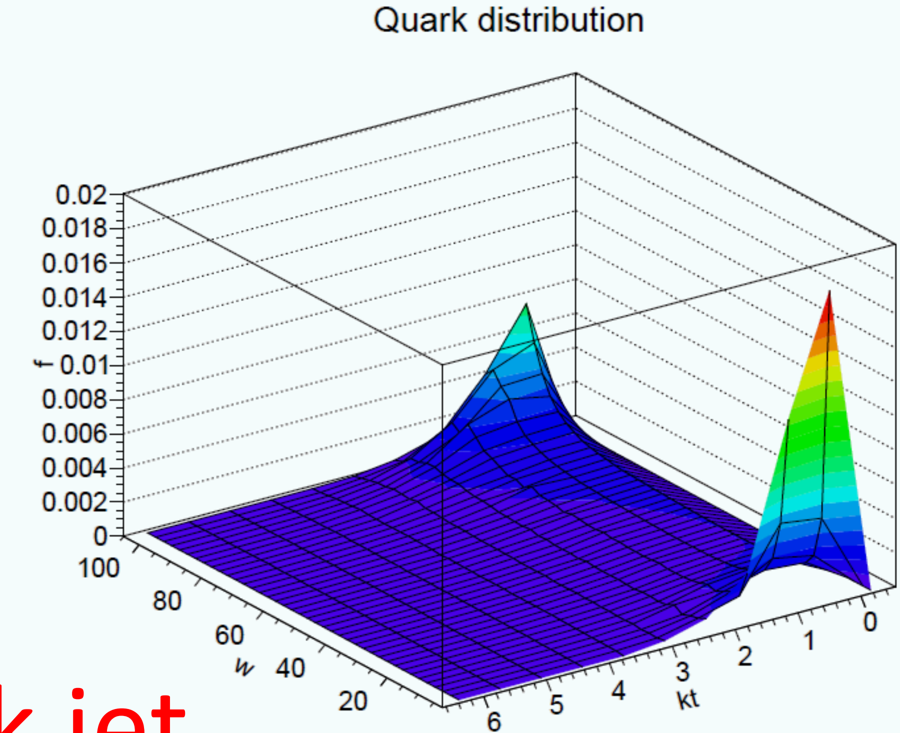
# Jet cone size dependence

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

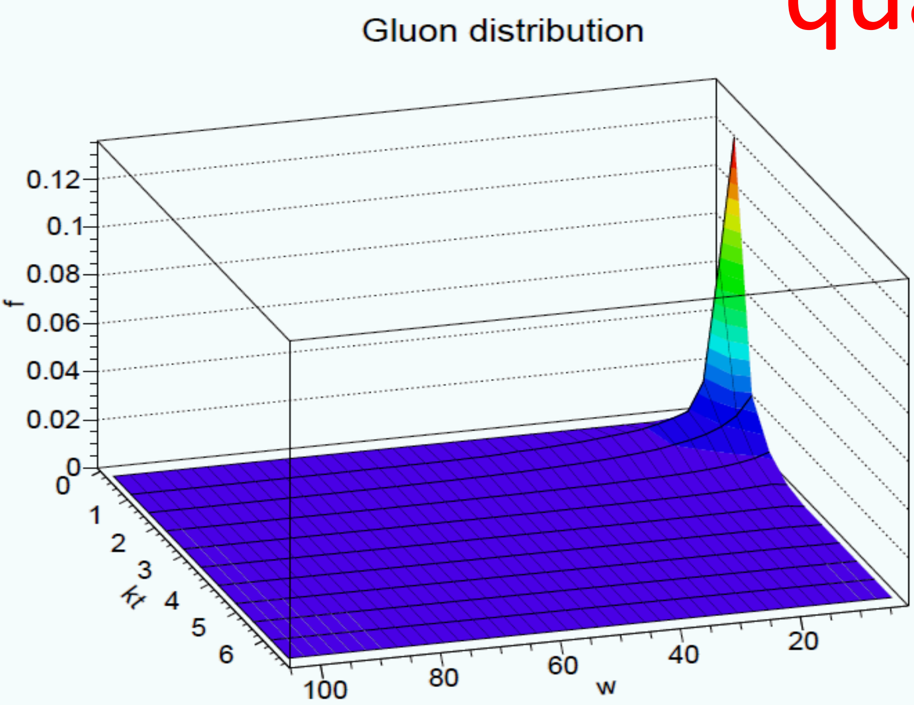


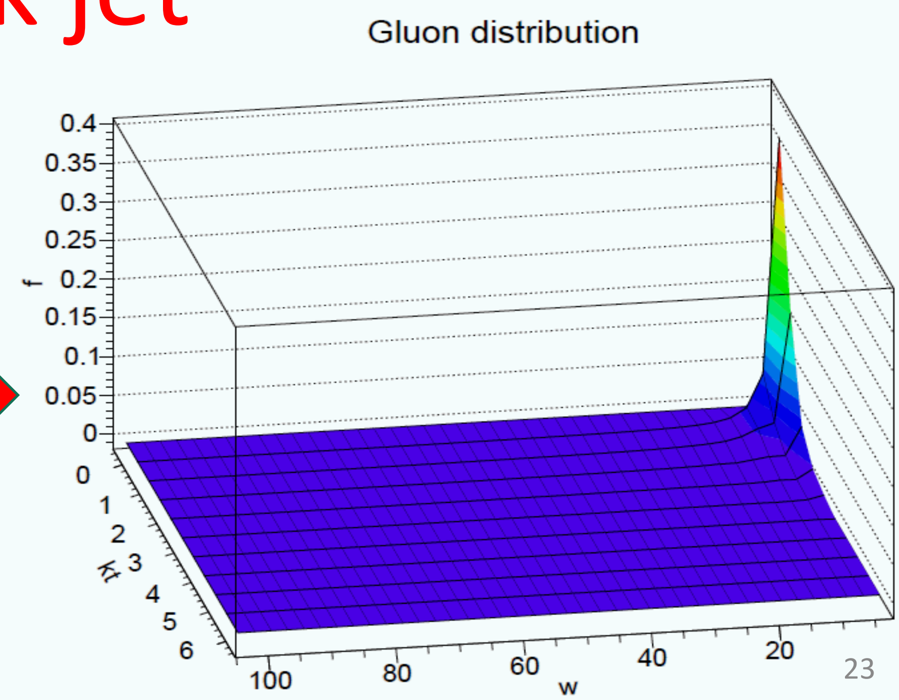

When jet cone size decreases, radiative energy loss increases, collisional energy loss decreases.


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