Hard Probes 2018: International Conference on Hard & Electromagnetic Probes of High-Energy Nuclear Collisions

Nuclear modification of full jets and jet structure in relativistic nuclear collisions

Ning-Bo Chang

Xinyang Normal University &
Central China Normal University

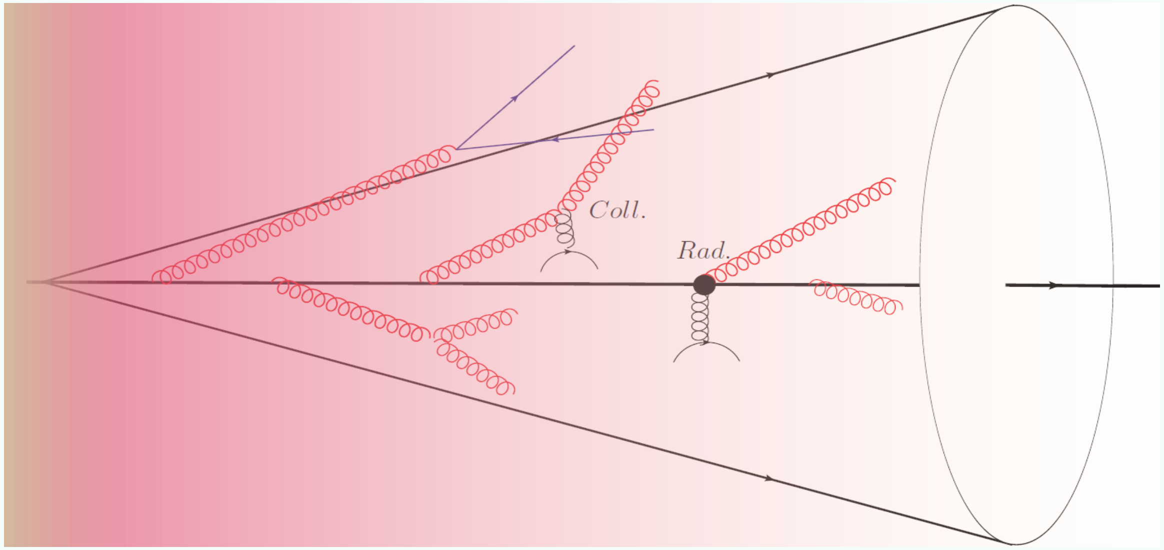
In collaboration with Guang-You Qin and Yasuki Tachibana

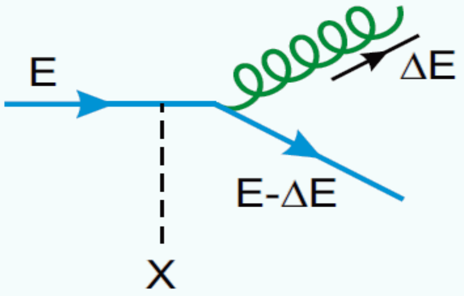
Based on PRC.94.024902, PRC.95.044909 and paper in preparation.

Outline

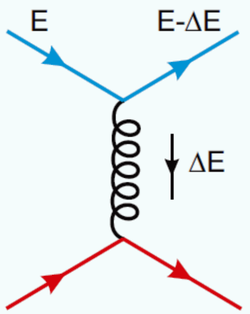
- Motivation and Framework
- Results at 2.76A TeV and analysis
  - Jet energy loss
  - Jet shape modification
- Results at 5.02A TeV
- Medium response
- Summary and Outlook

Full jet evolution in medium

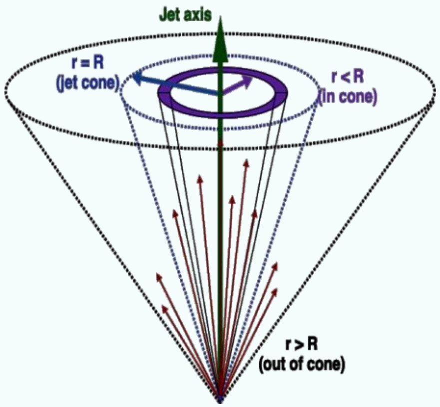




Inelastic scattering



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

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

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

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

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

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

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

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

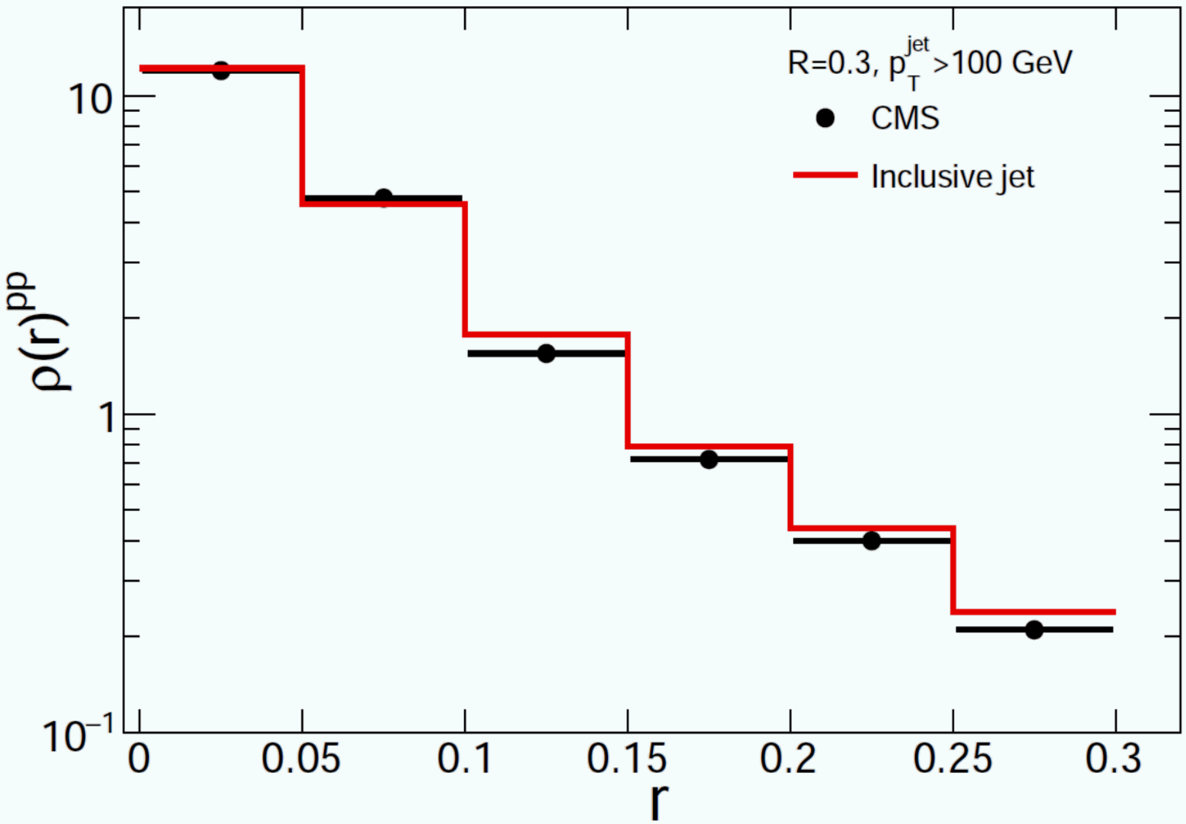
$$t_i = \frac{2Ex_i(1-x_i)}{k_{i\perp}^2} \qquad \tau_f = \frac{2\omega_i x_{ij}(1-x_{ij})}{k_{ij\perp}^2}$$

q	$g \to q\bar{q},\ q \to qg$ $q \to qg,\ q \to gq$
g	$q \to gq,\ g \to gg$ $g \to gg,\ g \to q\bar{q}$

Framework: input and Hydro.

Initial condition from PYTHIA

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



Hydrodynamic simulation from VISH2+1 or Yasuki Tachibana

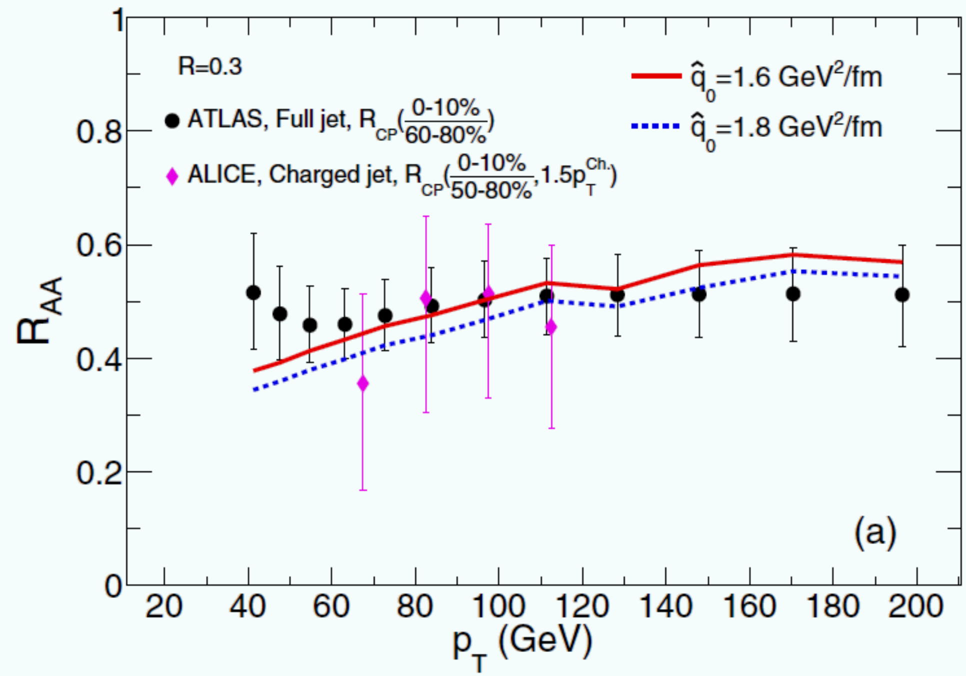
$$\hat{q}(\tau,\vec{r}\,) = \hat{q}_0 \cdot \frac{T^3(\tau,\vec{r}\,)}{T_0^3(\tau_0,\vec{0})} \cdot \frac{p\cdot u(\tau,\vec{r}\,)}{p_0}$$

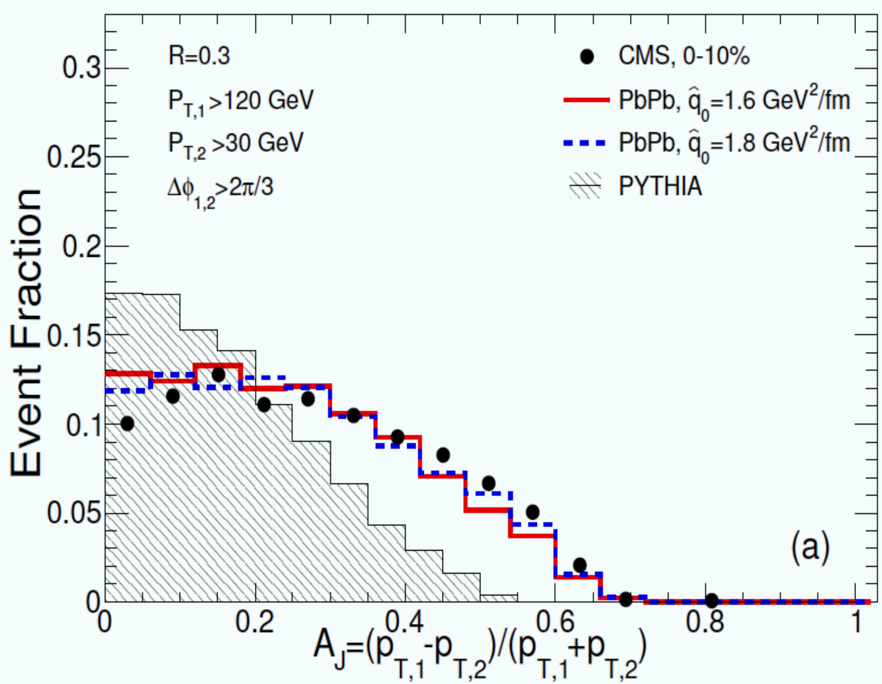
Observables related with full jets energy loss:

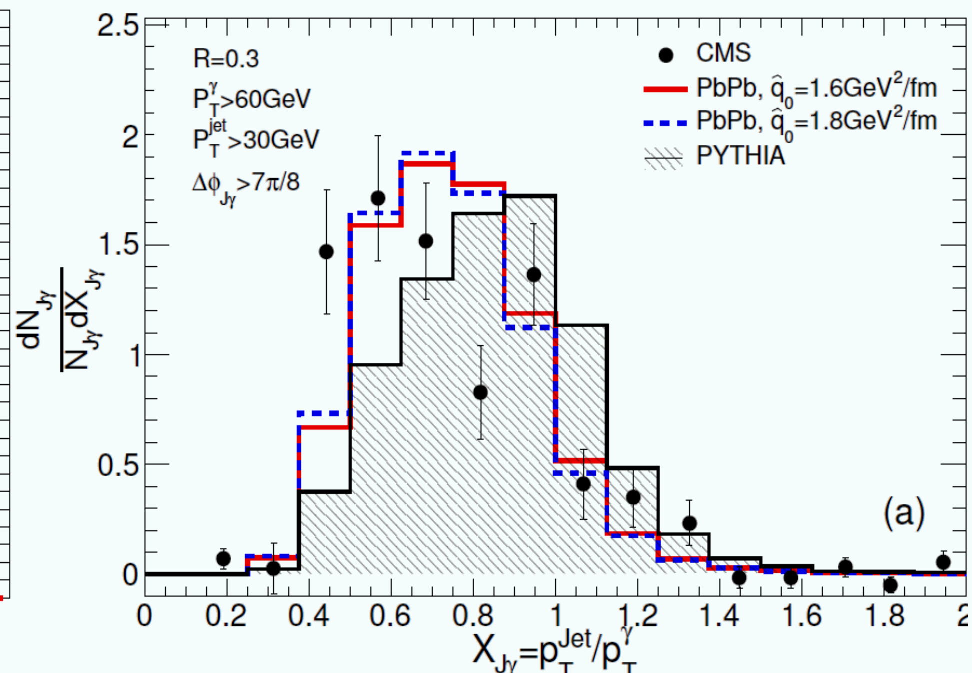
$$E_{\text{jet}}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2$$

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

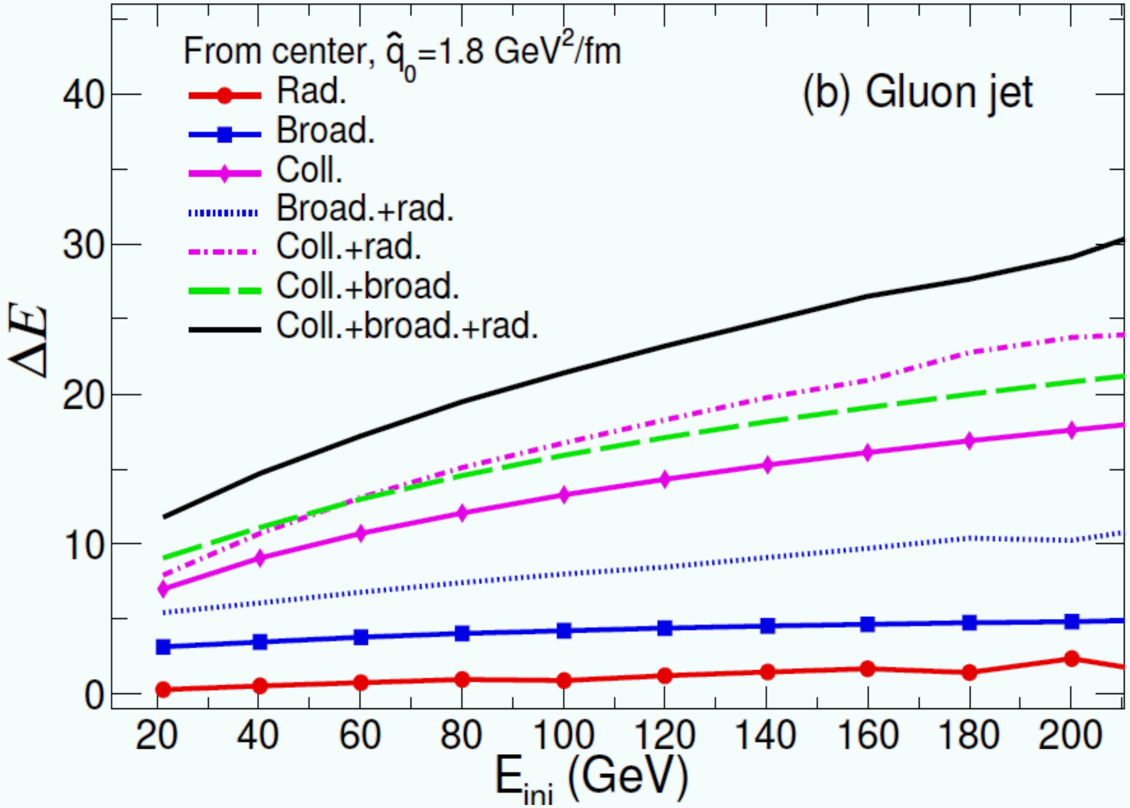
$$A_J = \frac{p_{T,1}-p_{T,2}}{p_{T,1}+p_{T,2}} \qquad X_{J\gamma} = \frac{p_T^{Jet}}{p_T^{\gamma}}$$







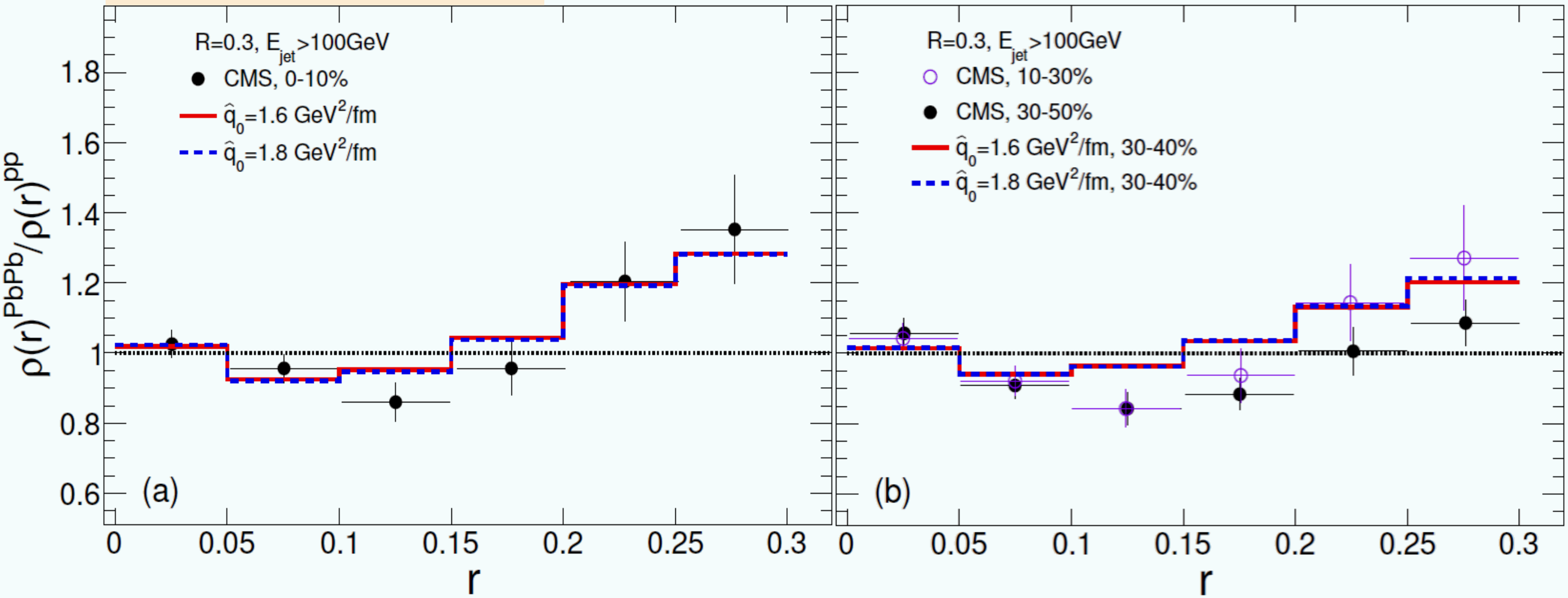
Jet Energy Loss from different mechanisms



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

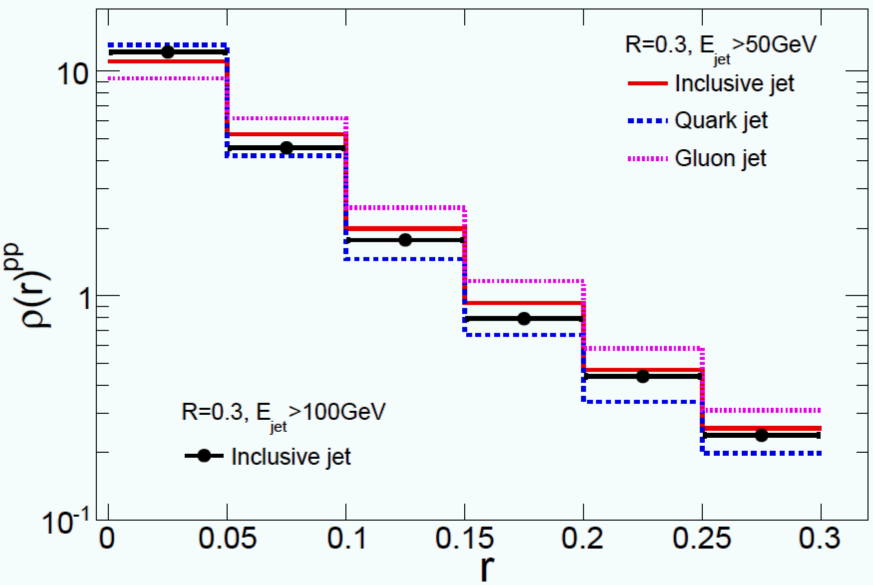
Nuclear modification of Jet shape

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

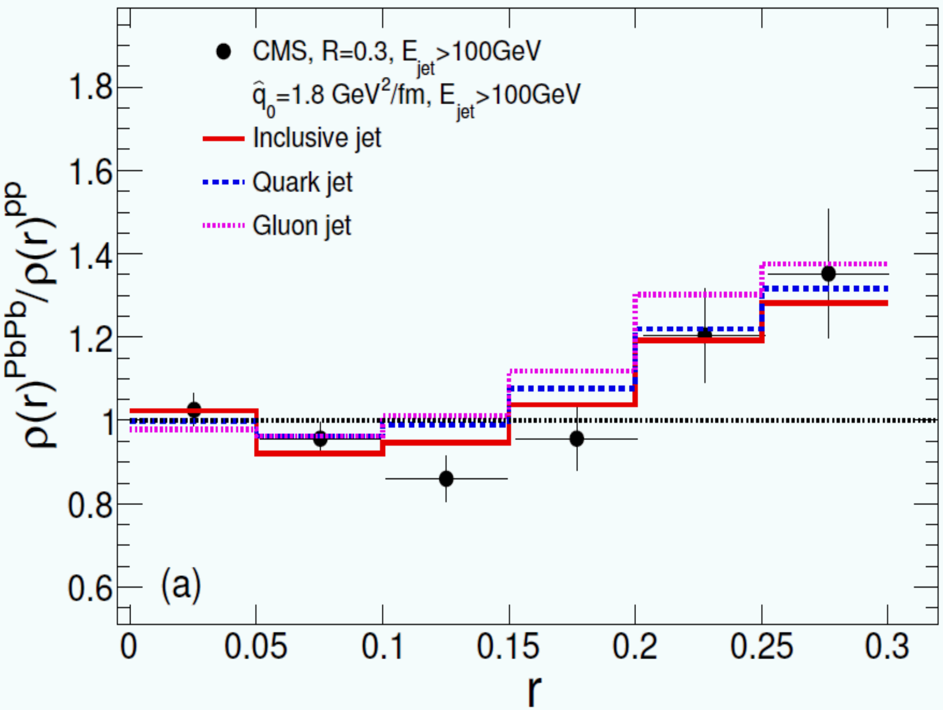


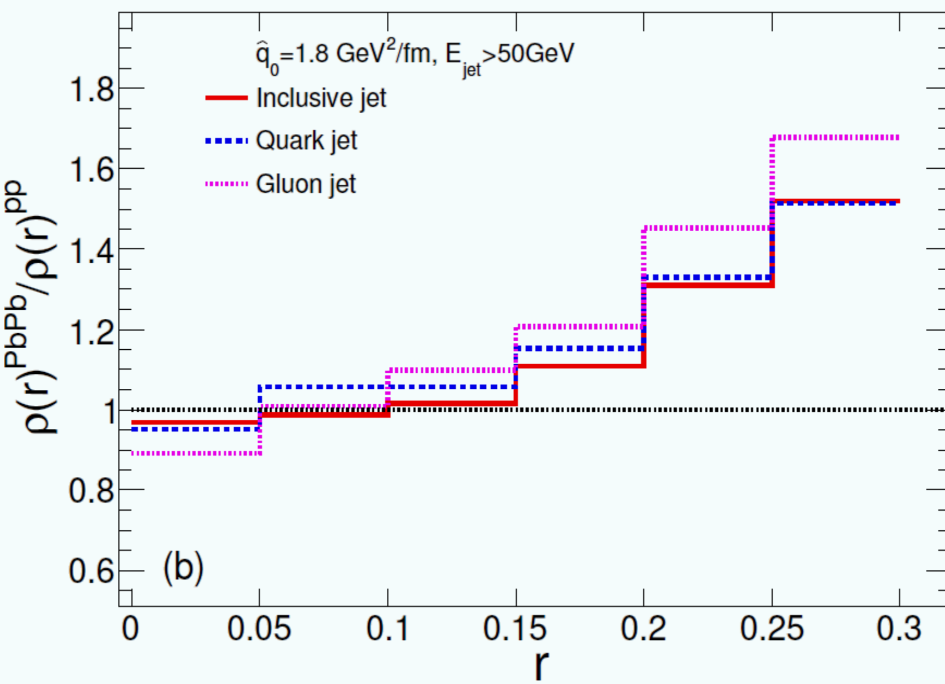
Jet shape is modified little at small r, suppressed at middle r and enhanced at large r.

Energy and flavor dependence

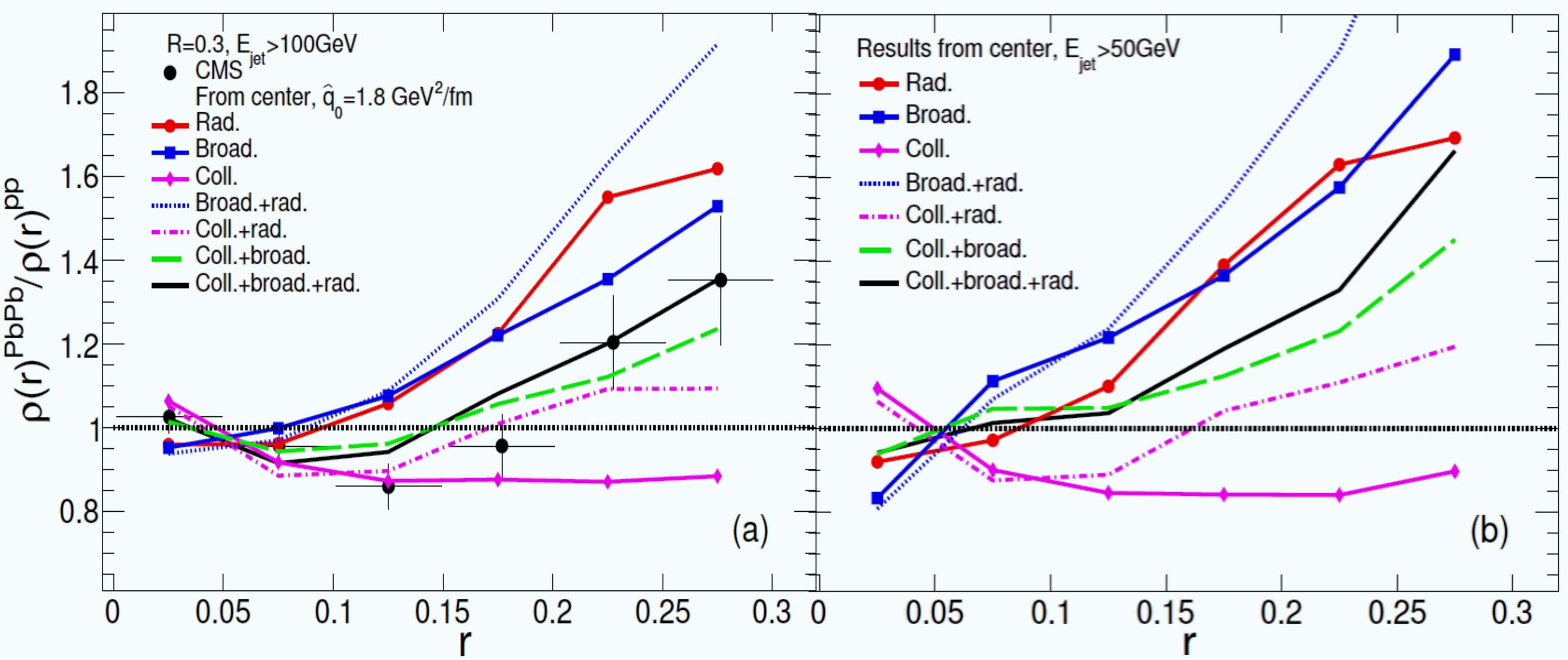


Sensitive to jet energy, less to flavor.





Effects of different mechanisms on **Jet shape**



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

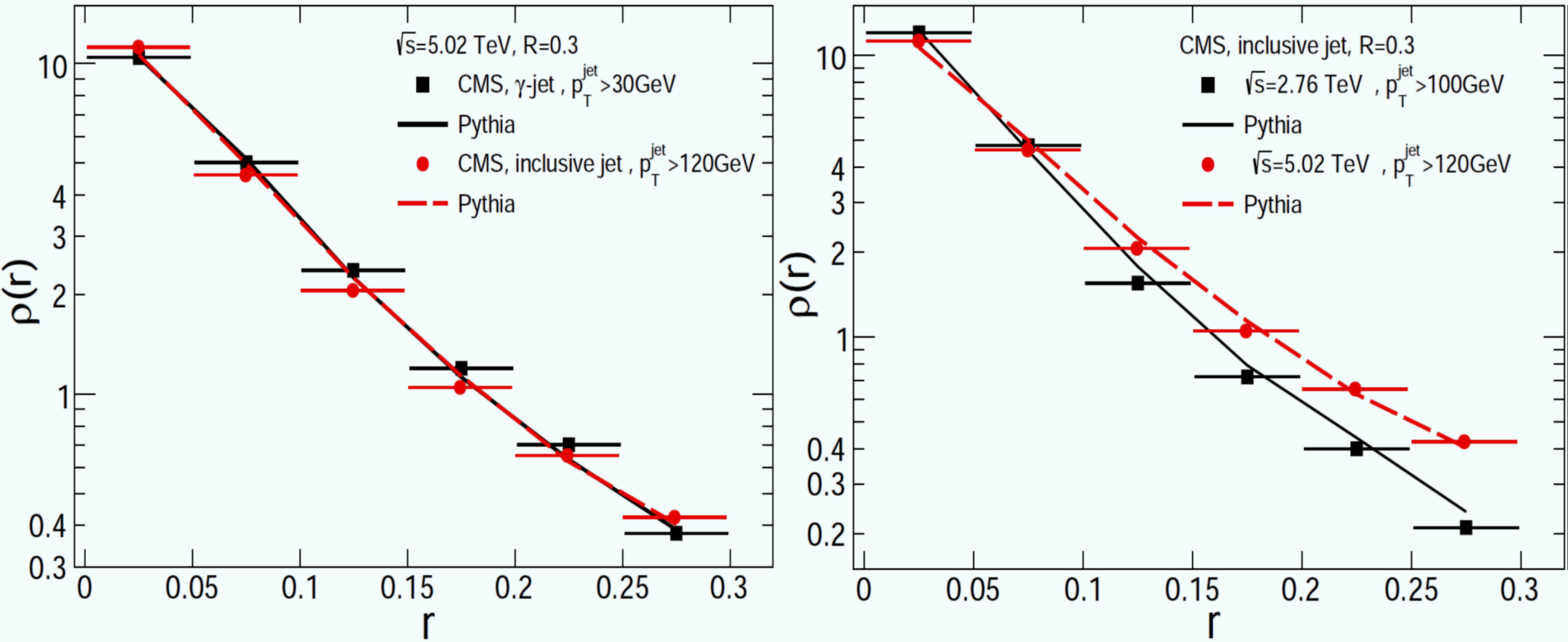
Coll. leads inner core losing less fraction of energy than outer part.

For lower energy jet, its inner core is changed more.

Results at 5.02A TeV

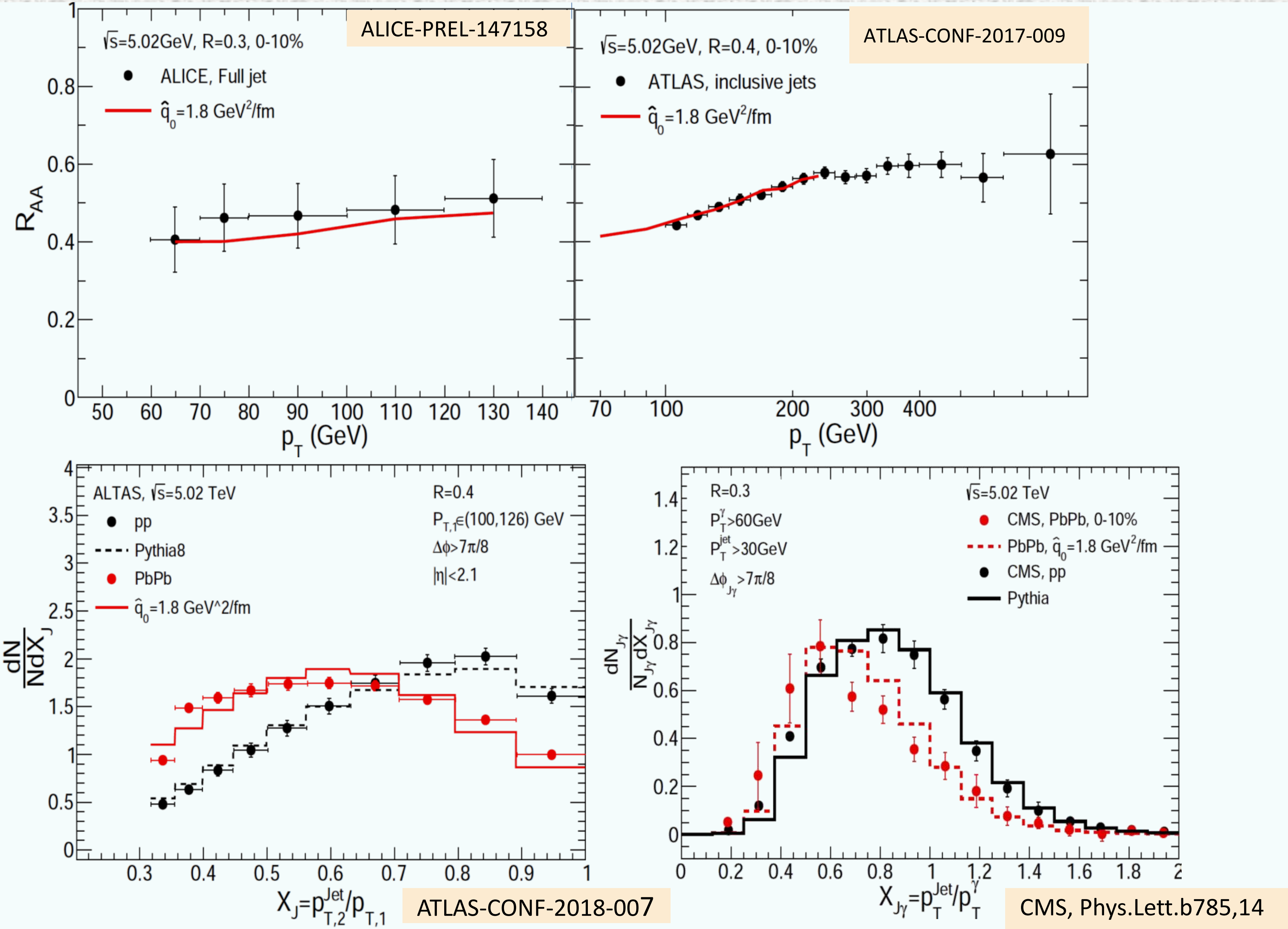
Initial condition: tuning in Pythia

CMS, PAS HIN-18-006; CMS, JHEP.1805(2018),006; CMS, Phys.Let.B730(2014),243



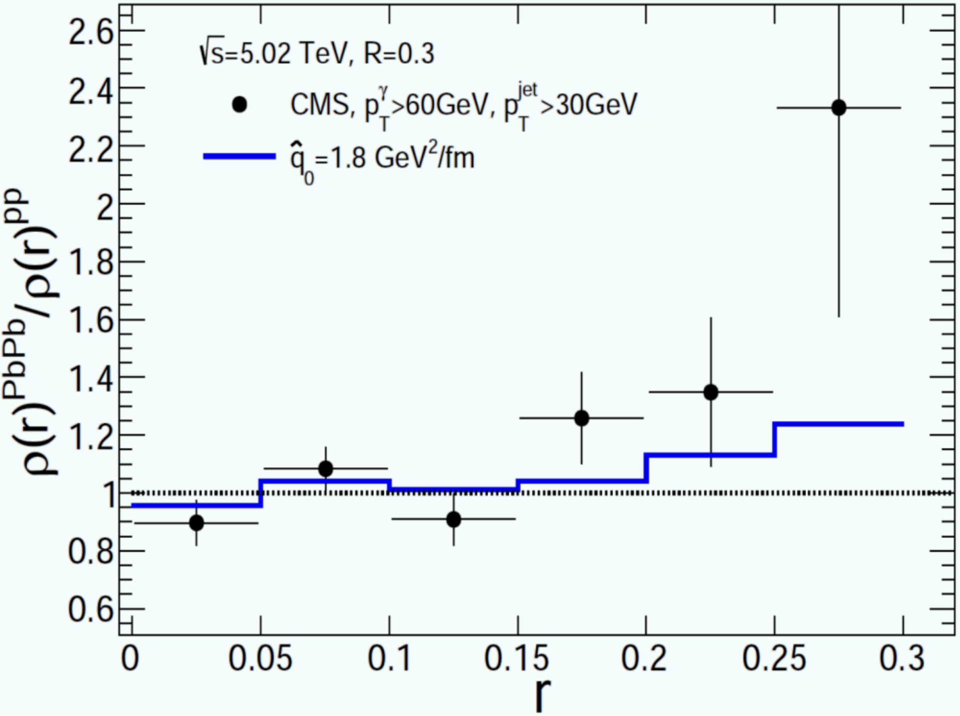
From 2.76A TeV to 5.02A TeV, need tuning in Pythia.
At same jet energy, jets at 2.76A TeV are steeper.

Jet R_{AA} and modification of Dijet asymmetry

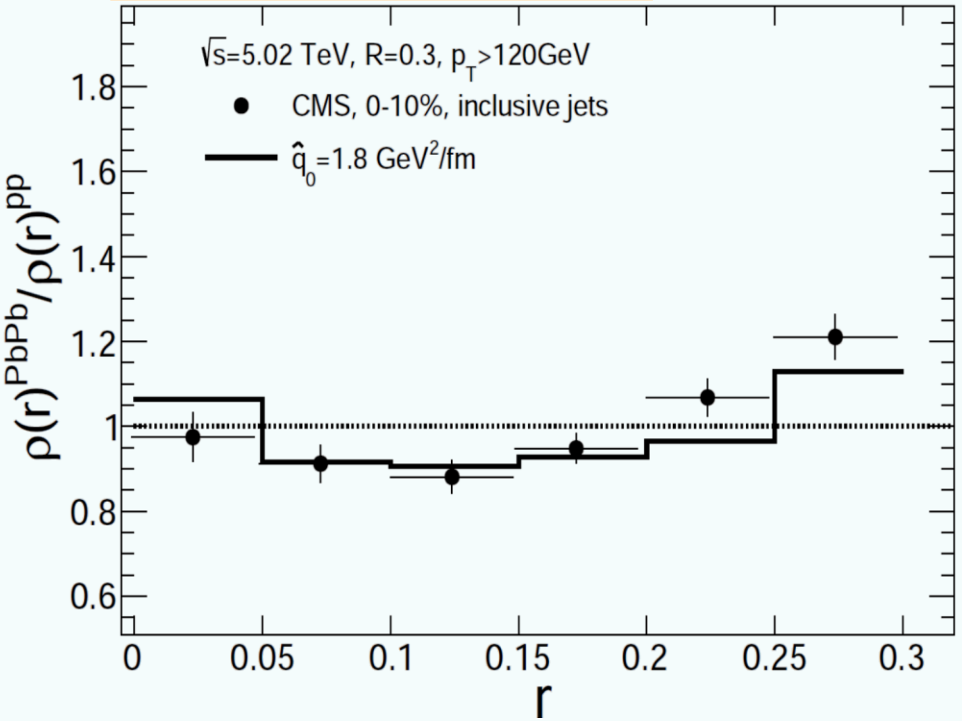


Jet shape modification in γ-jets and inclusive jets

CMS, PAS HIN-18-006



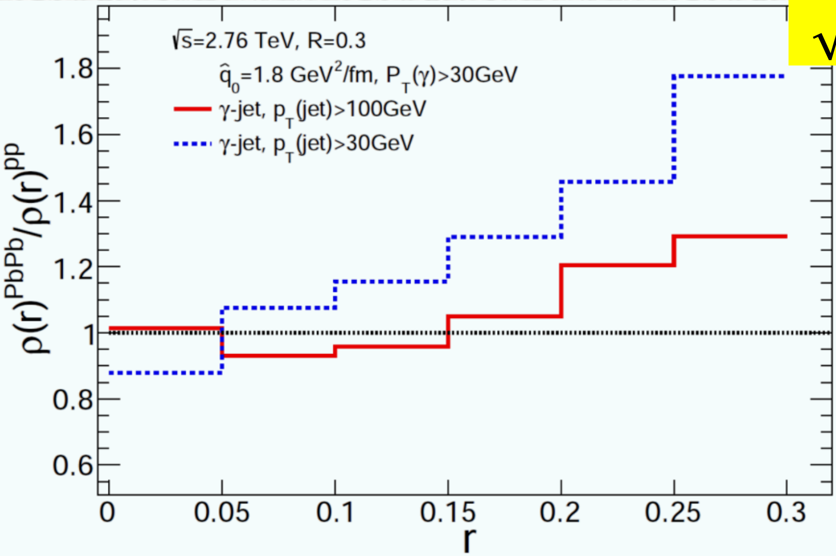
CMS, JHEP.1805(2018),006

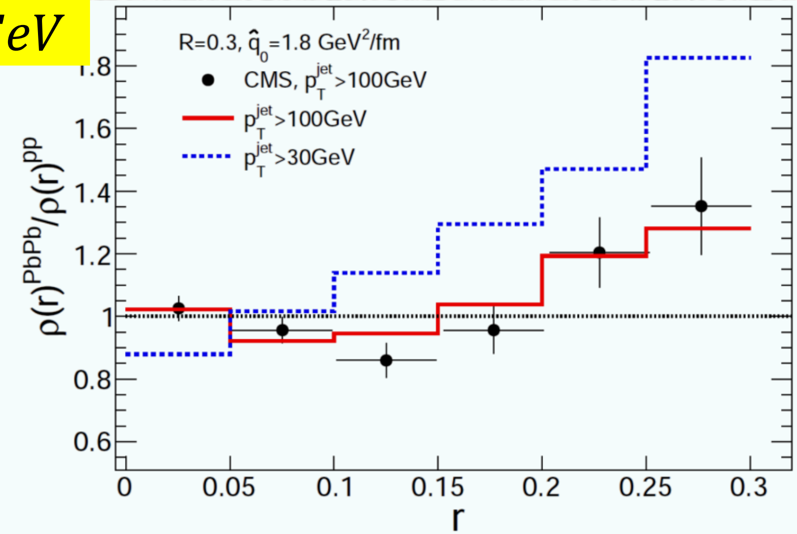


Describe the jet shape modification in two p_T ranges.

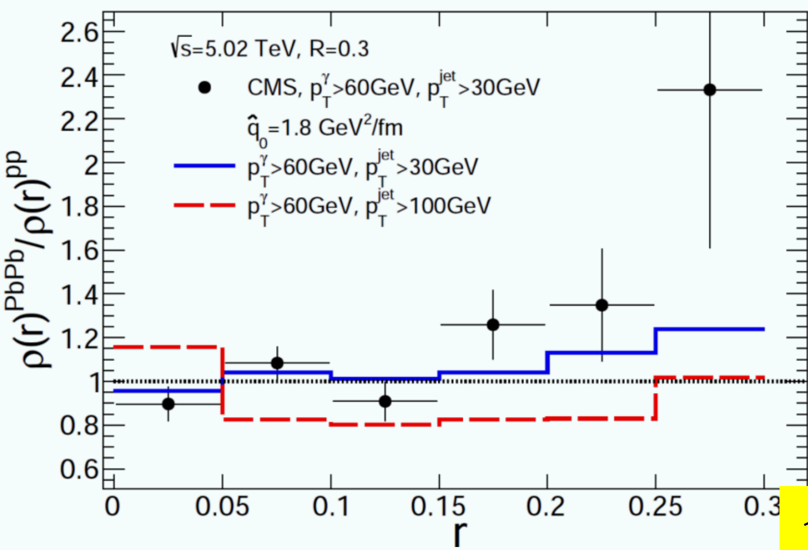
P_T^{Jet}, $\sqrt{s}$ and flavor dependence

$\sqrt{s} = 2.76\ TeV$

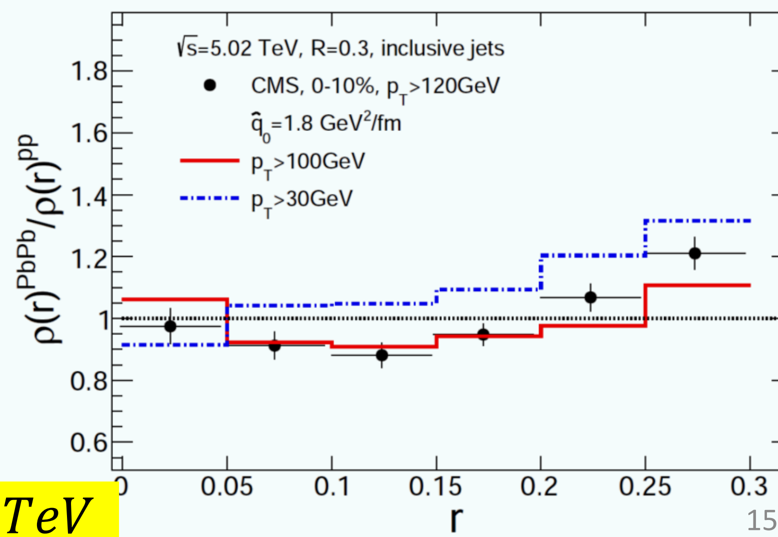




Modification of $\rho(r)$ is sensitive to P_T^{Jet} and $\sqrt{s}$, less to flavor.



$\sqrt{s} = 5.02\ TeV$

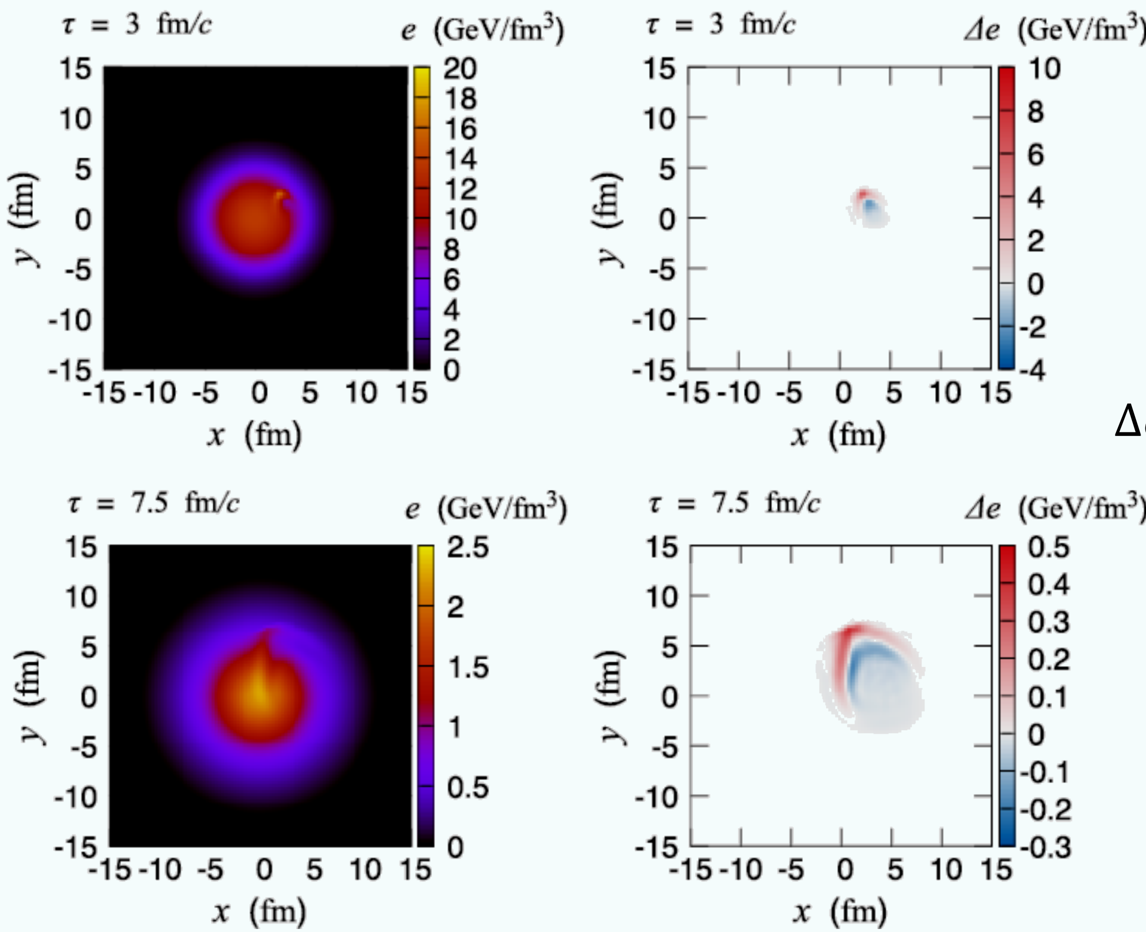


Medium response

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

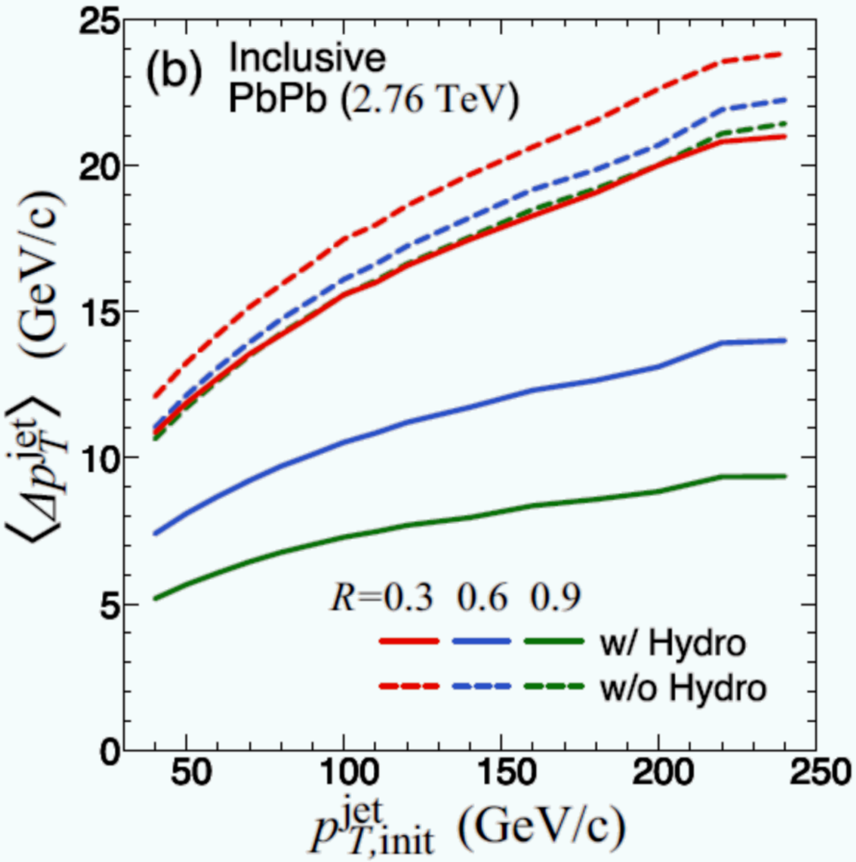
$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}} = 0 \Rightarrow \partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x)$$

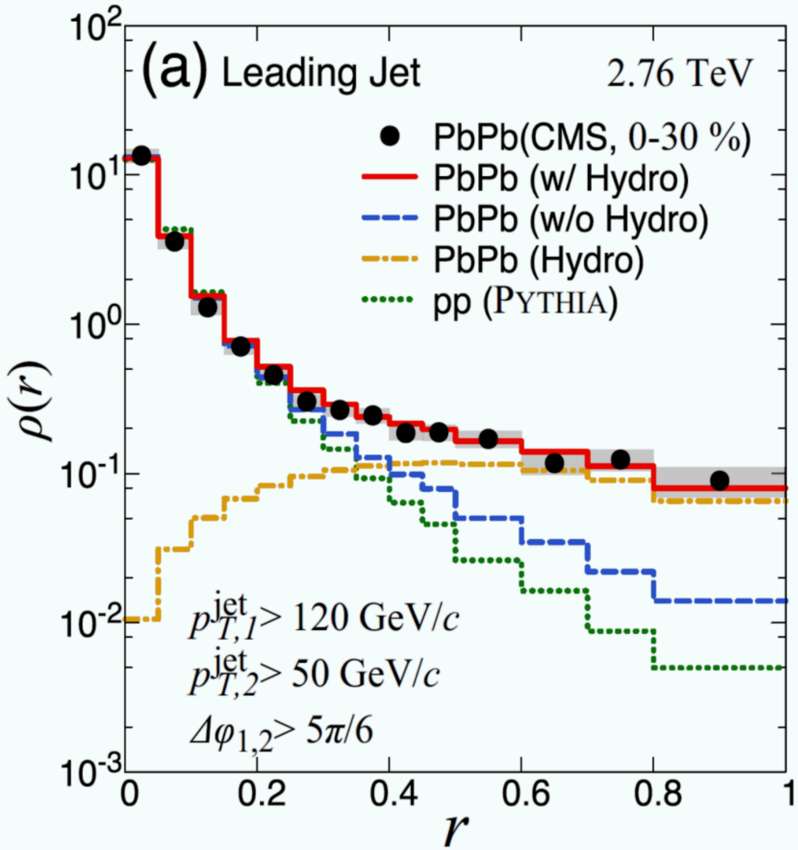
$$J^\nu(x) = -\sum_j \int d^3k_j k_j^\nu \left.\frac{df_j(\boldsymbol{k}_j,t)}{dt}\right|_{\mathrm{col.}} \delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_0^{\mathrm{jet}} - \frac{\boldsymbol{k}_j}{\omega_j}t\right)$$



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

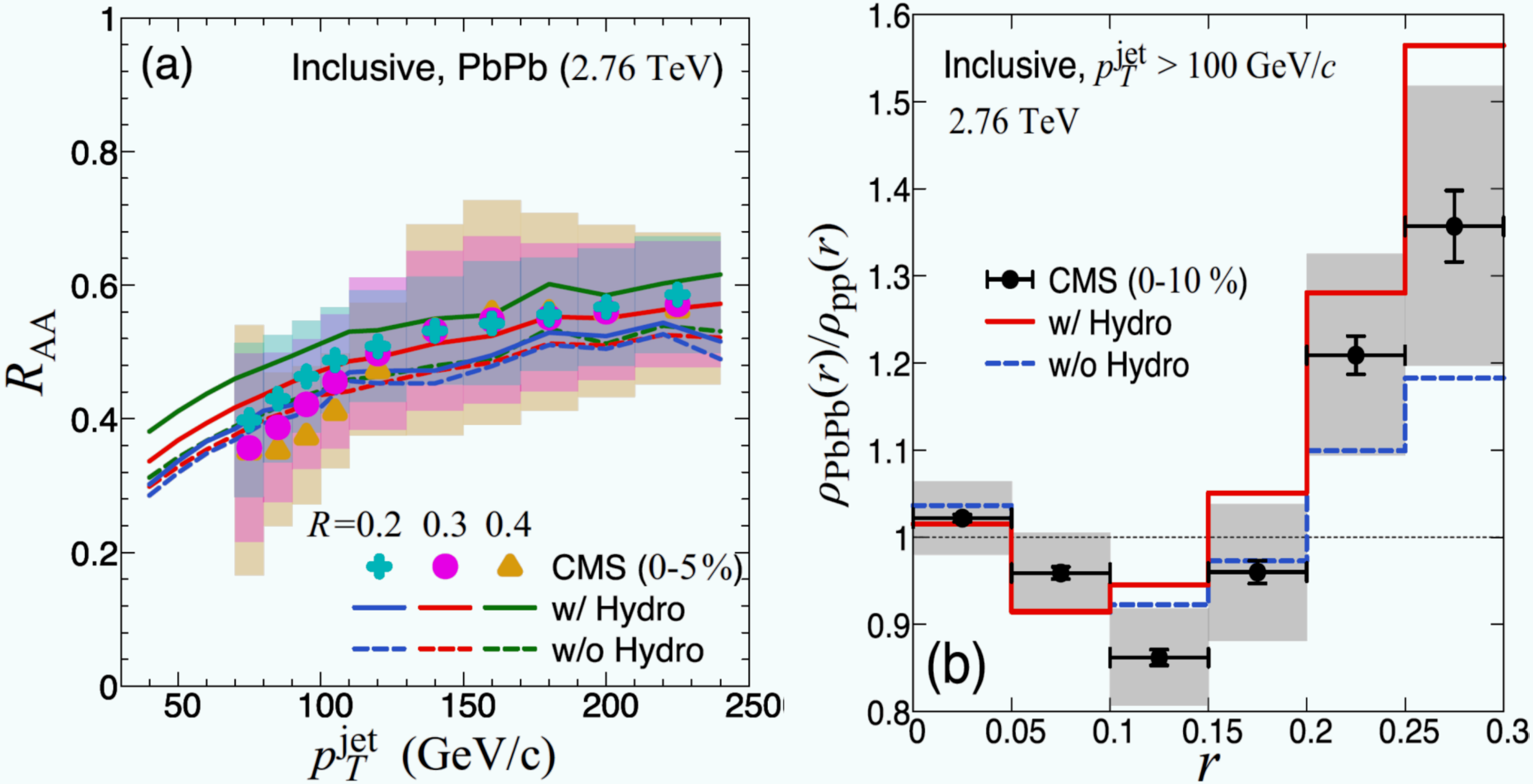
Effect of medium response





Lost energy is transported to medium at large r,
Medium response dominates jet shape at large r.

Effect of medium response



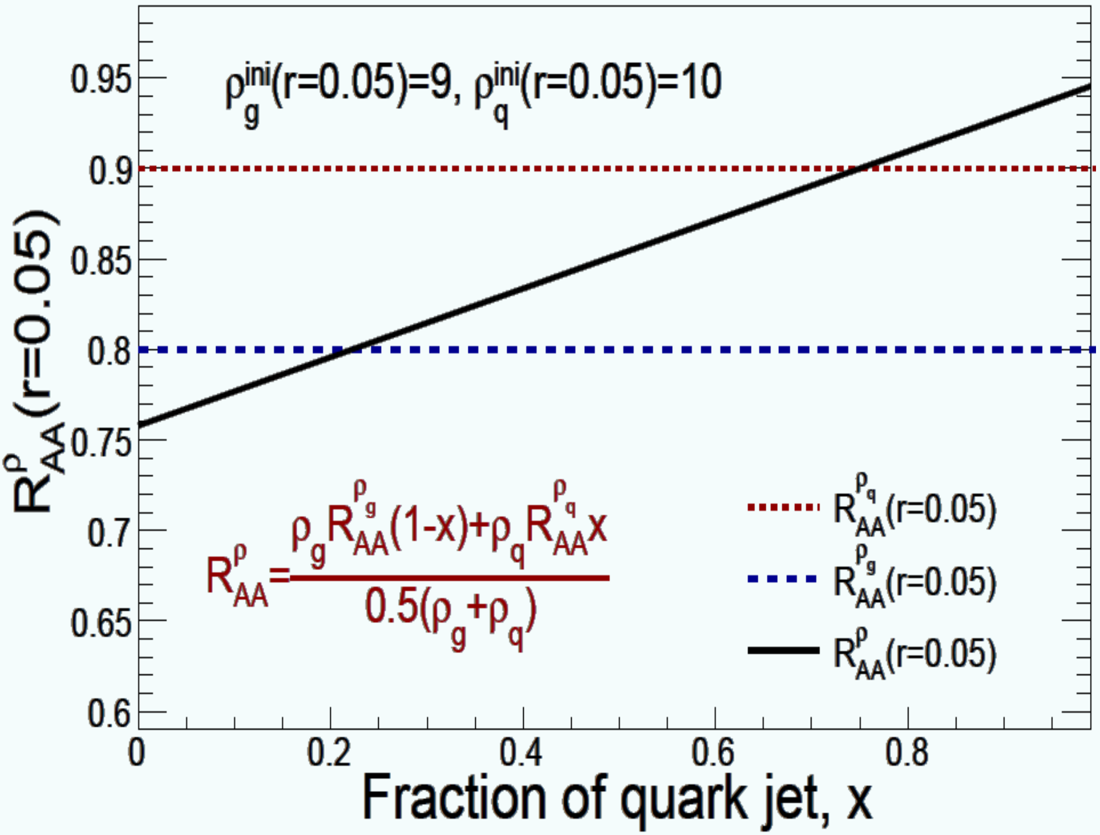
Rise R_{AA} value, and jet shape at large r.

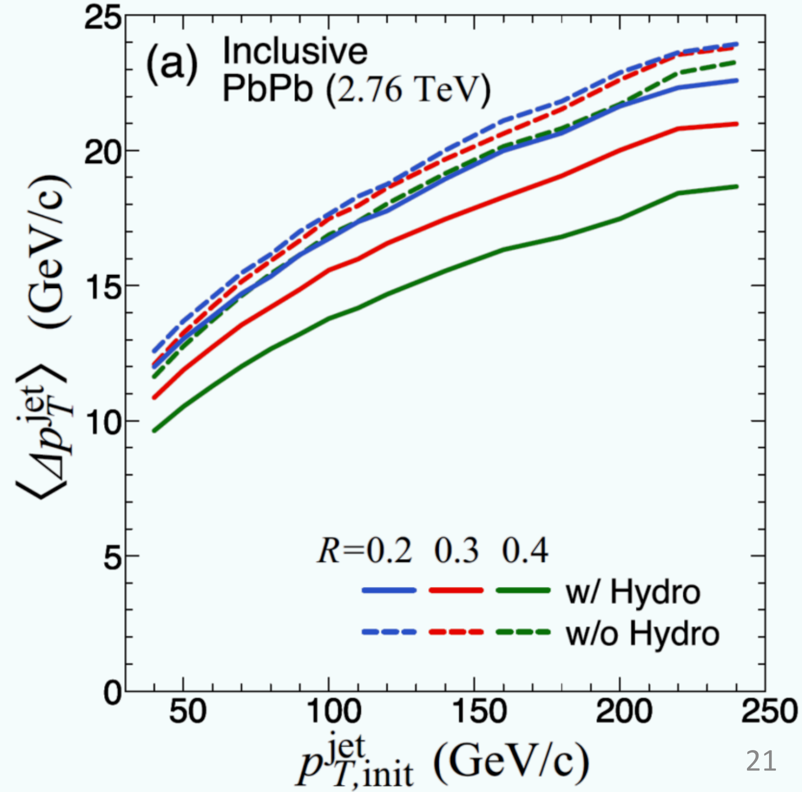
Summary

- 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.
- 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.
- 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 becomes important to jet shape at large r.

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

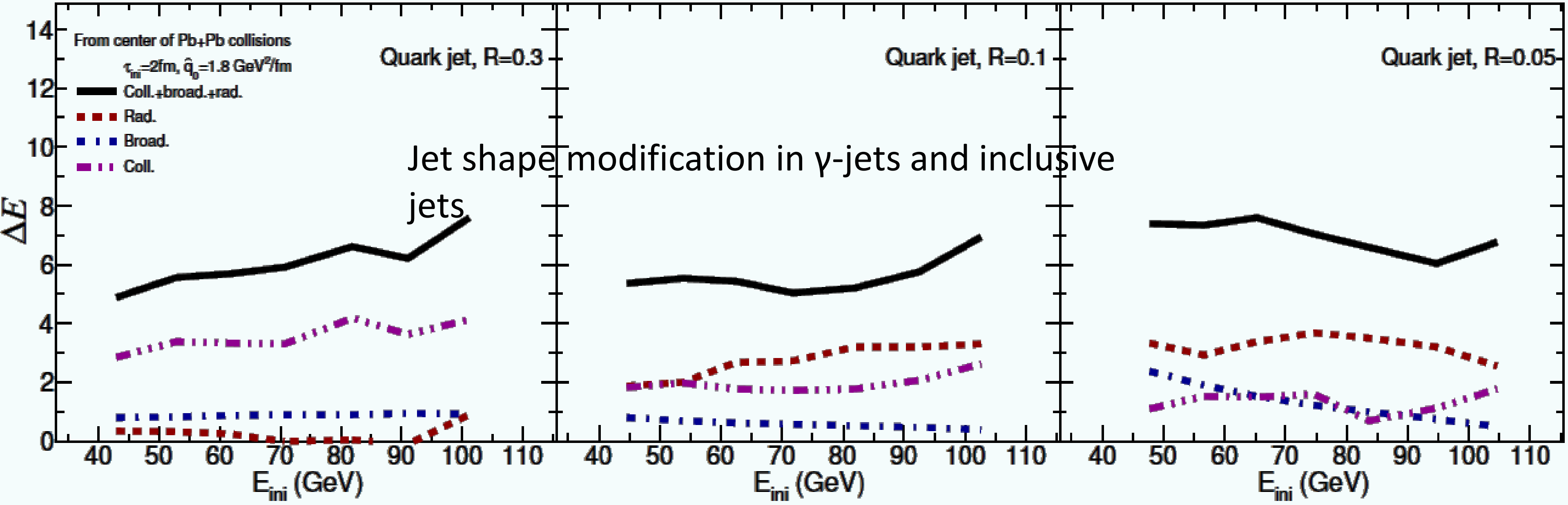
Thanks for your attention!


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


(a) Inclusive
PbPb (2.76 TeV)
R=0.2 0.3 0.4
w/ Hydro
w/o Hydro
$\langle \Delta p_T^{jet} \rangle$ (GeV/c)
$p_{T,init}^{jet}$ (GeV/c)

Jet cone size dependence

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

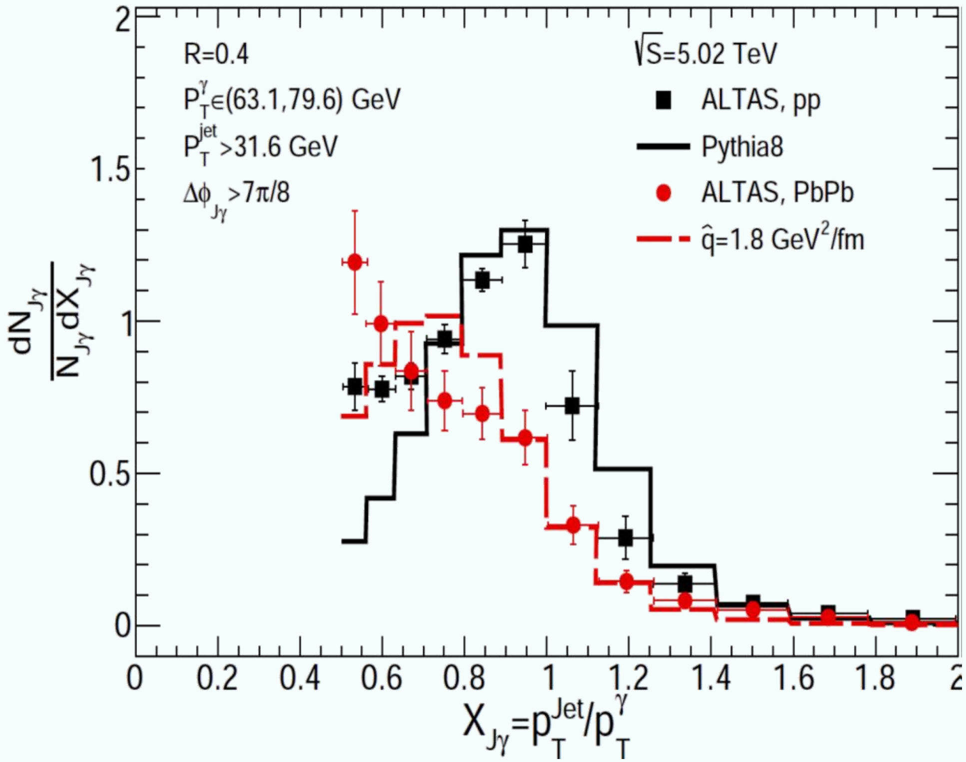


Jet shape modification in γ-jets and inclusive jets

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

Nuclear modification of γ-jet asymmetry with R=0.3/0.4

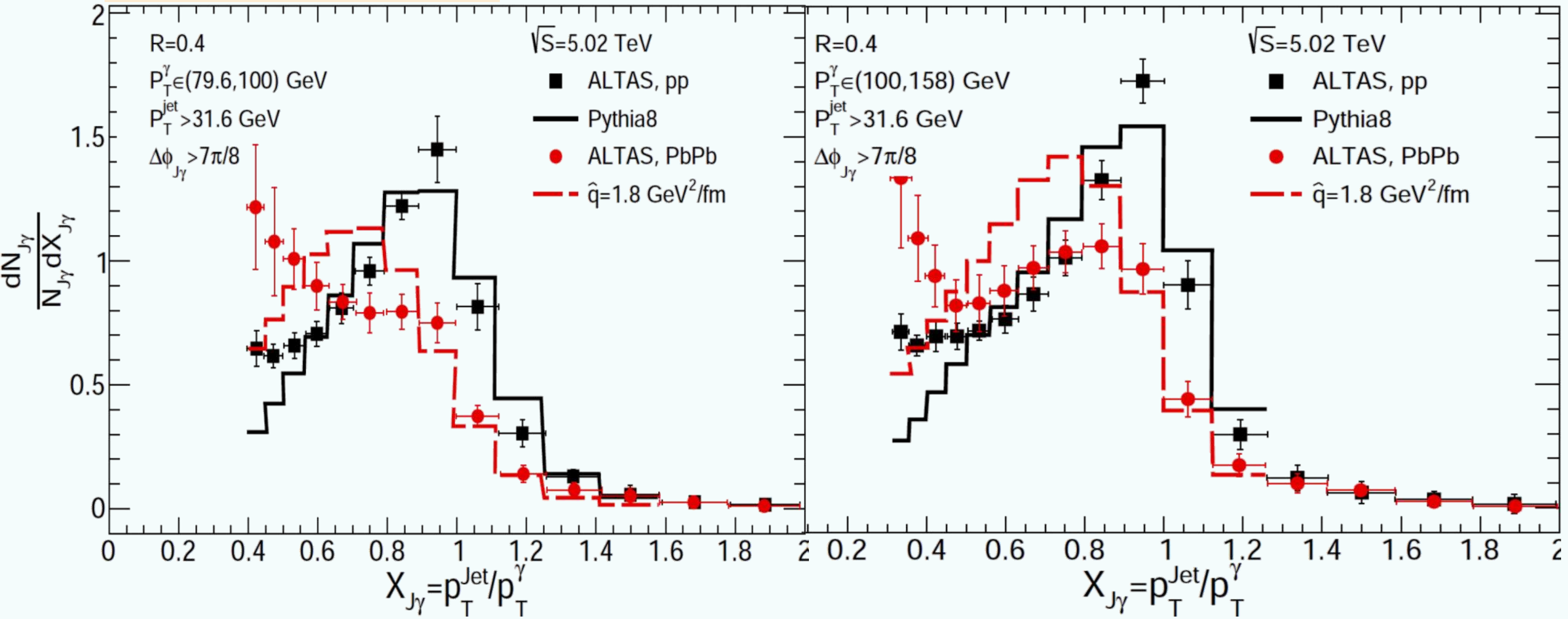
ATLAS-CONF-2018-009



Fail to fit γ-jet asymmetry data in pp by ATLAS at small $X_{J\gamma}$, same modification pattern as data.

Nuclear modification of γ-jet asymmetry: γ energy dependence

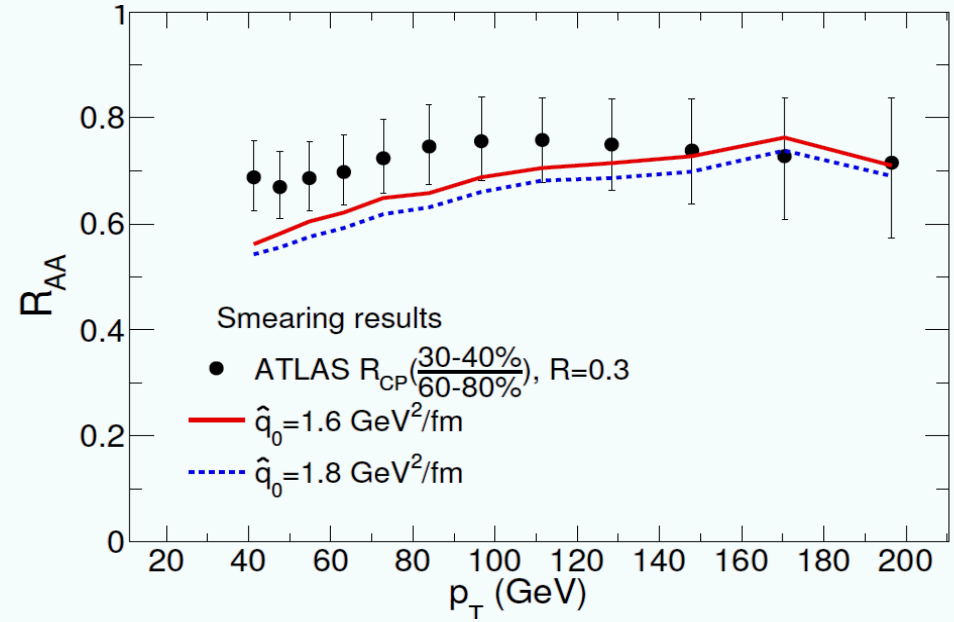
ATLAS-CONF-2018-009

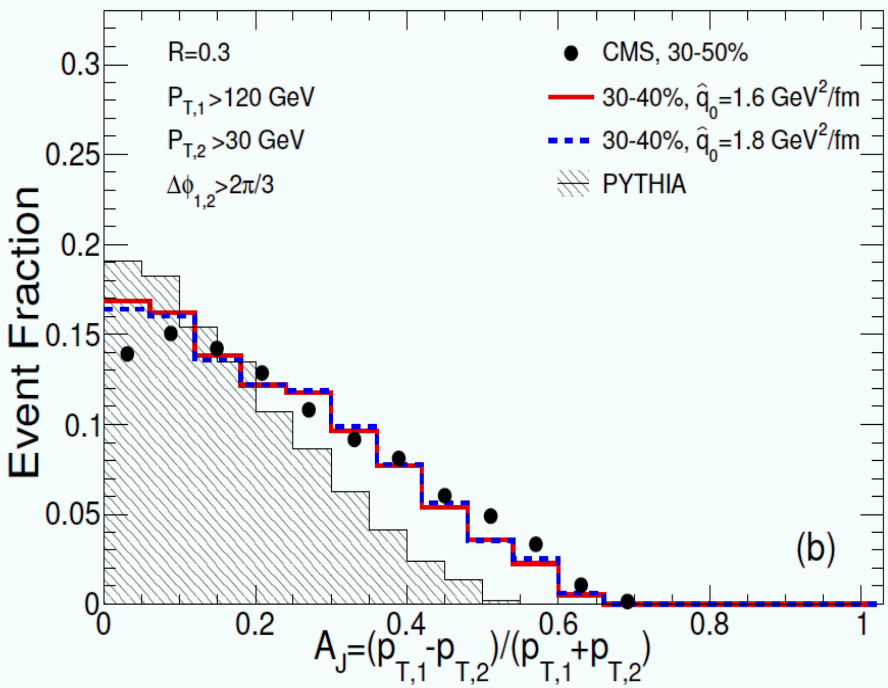


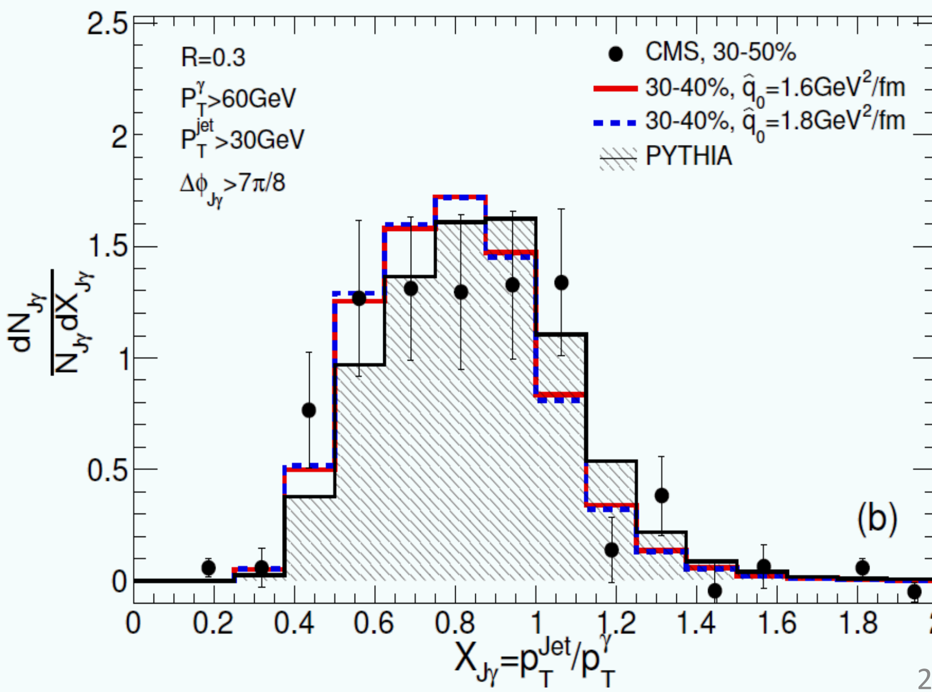
Same for higher P_T^γ

Middle Centrality

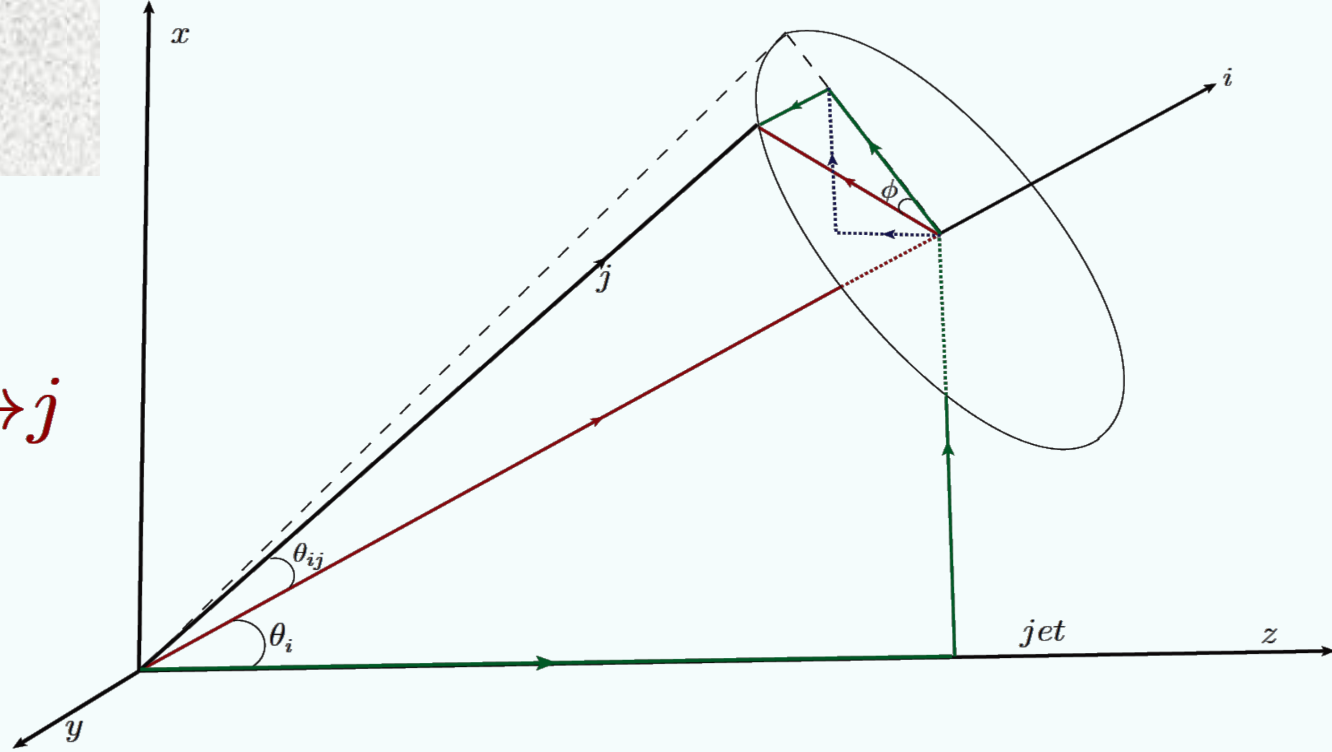
$$\hat{q}_0^{30\text{-}40\%} = \hat{q}_0^{0\text{-}10\%} \frac{T^3(\tau_0, 0)_{30\text{-}40\%}}{T^3(\tau_0, 0)_{0\text{-}10\%}}$$







Framework



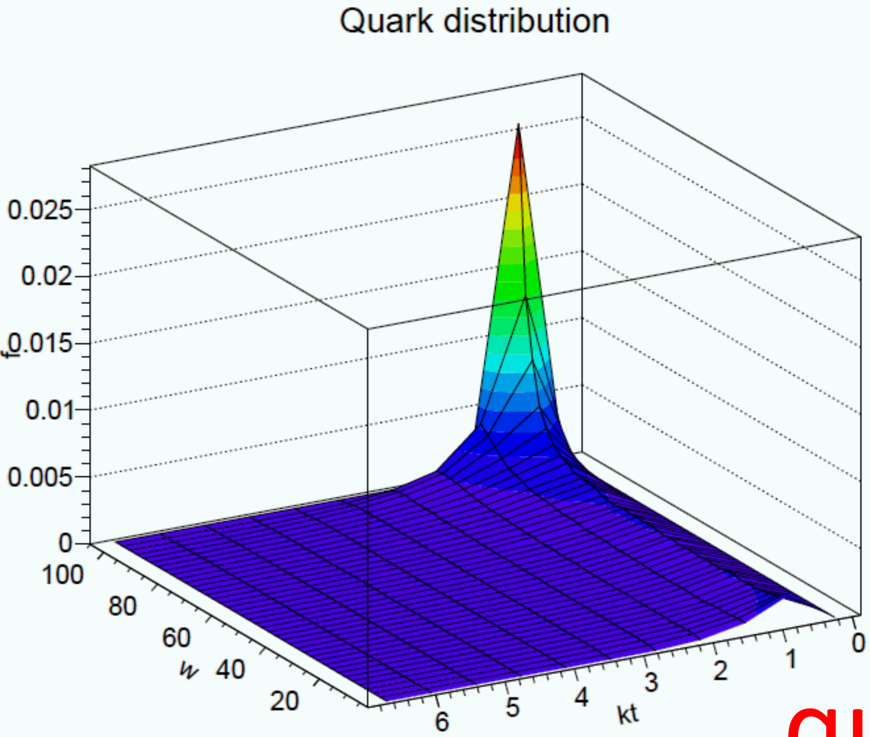
$$\Gamma_{i\to j} \to \tilde{\Gamma}_{i\to j}$$

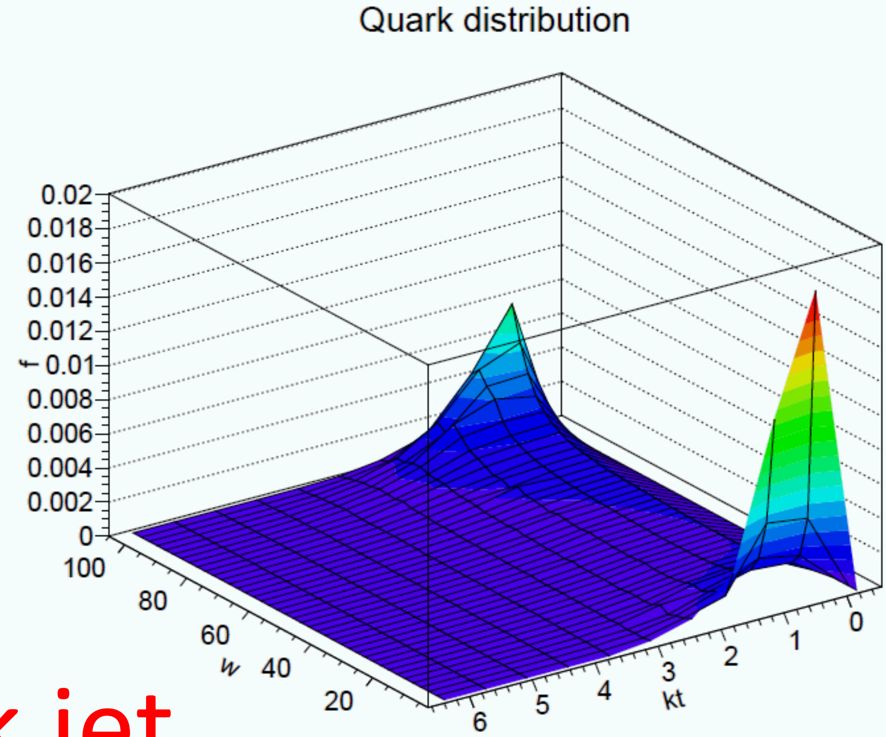
$$\frac{dN_g^{\rm med}}{d\omega dk_\perp^2 dt} = \Gamma(\omega, k_\perp^2|E,0) = \frac{2\alpha_s}{\pi}\frac{xP(x)\hat{q}(t)}{\omega k_\perp^4}\sin^2\frac{t-t_i}{2\tau_f}$$

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

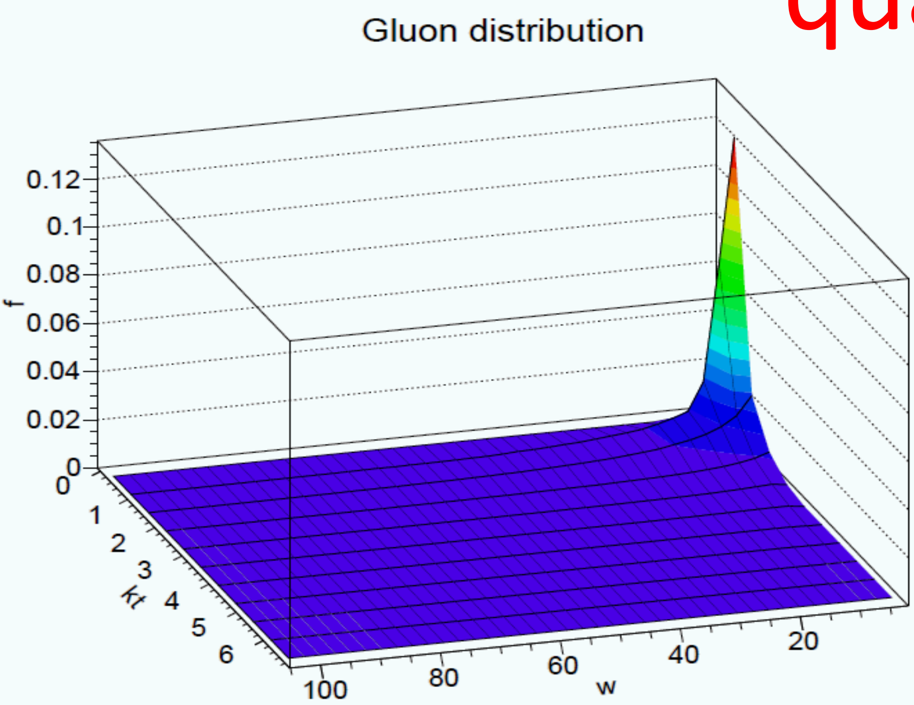
Small angle approximation: $\langle(\frac{k_{j\perp}}{\omega_j})^2\rangle \approx \theta_i^2 + \theta_{ij}^2 \approx (\frac{k_{i\perp}}{\omega_i})^2 + (\frac{k_{ij\perp}}{\omega_j})^2$

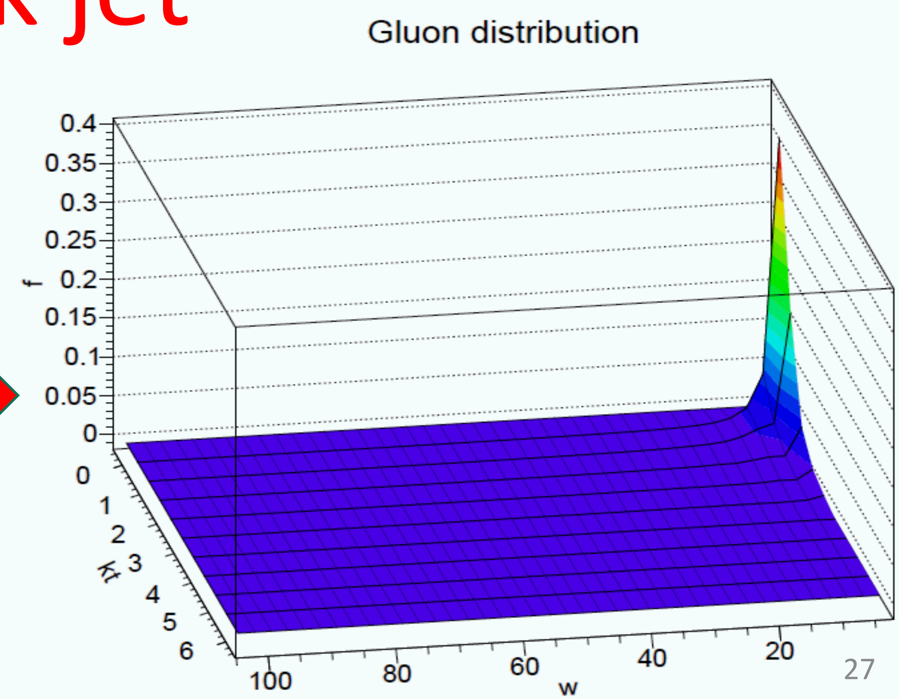
$$t_i = \frac{2Ex_i(1-x_i)}{k_{i\perp}^2} \quad \tau_f = \frac{2\omega_i x_{ij}(1-x_{ij})}{k_{ij\perp}^2}$$


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