Predictions for sPHENIX workshop 2022, RIKEN BNL Research Center, July 20-22, 2022

MATTER+LBT (JETSCAPE) based predictions for sPHENIX jet measurements

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McGill University

(On behalf of JETSCAPE collaboration)

Outline

❑ Jet evolution in quark-gluon plasma

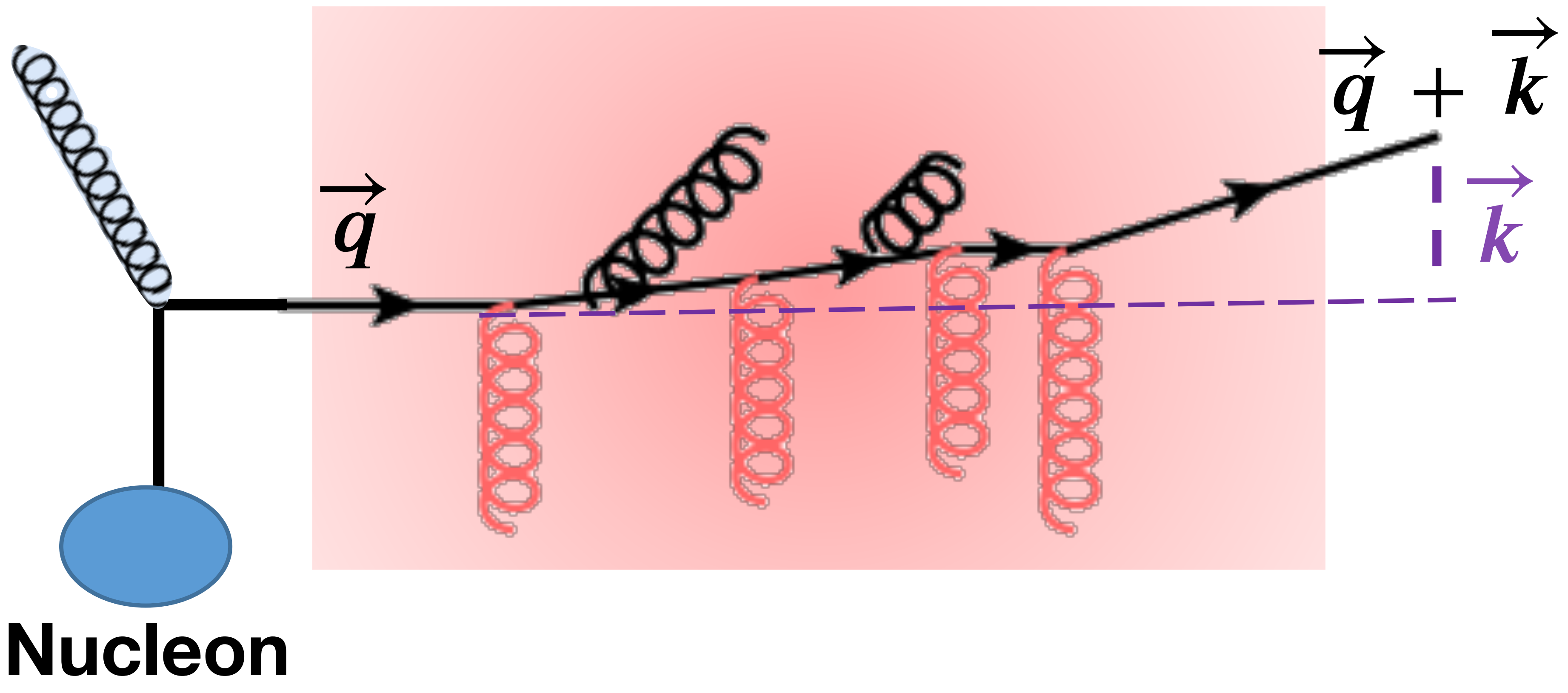
❑ JETSCAPE framework overview
✦ Multi-stage jet energy loss (Ex: MATTER+LBT)
✦ Coherence effect and reduction of jet-quenching strength
✦ Jet-medium response through recoils

❑ Jet and leading hadron suppression at RHIC and LHC

❑ Predictions for inclusive jets, groomed jet observables, photon-triggered jet at $\sqrt{s_{NN}} = 200$ GeV

Jet transport coefficients in hot/cold nuclear medium

❑ **Factorized approach to jet evolution**



Higher-twist formalism: (collinear expansion)

$$\frac{dN}{dy d\mu^2} = \frac{\alpha_s}{2\pi}\frac{P_{qg}(y)}{\mu^2}\left[1+\int_{\xi_o^+}^{\xi_o^+ + \tau^+} d\xi^+ K(\xi^+,\xi_o^+,y,q^+,\mu^2)\right];$$

$$K(\xi^+,\xi_o^+,y,q^+,\mu^2) = \frac{1}{y(1-y)\mu^2(1+\chi)^2}\left\{2-2\cos\left(\frac{\xi^+-\xi_o^+}{\tau^+}\right)\right\} \times \left\{C_{qg}^{\hat{q}^-}\hat{q} + C_{qg}^{\hat{e}^-}\hat{e} + C_{qg}^{\hat{e}_2^-}\hat{e}_2\right\}$$

❑ **Transport coefficient $\hat{q}$:**

Average transverse momentum squared per unit length

$$\hat{q}(\vec{r},t) = \frac{\langle \vec{k}_\perp^2 \rangle}{L} \propto \langle M | F_\perp^+(y^-,y_\perp) F^{+\perp}(0) | M \rangle$$

❑ **Transport coefficient $\hat{e}$:**

$$\hat{e}(\vec{r},t) = \frac{\langle k_z \rangle}{L} \propto \langle M | \partial^- A^+(y^-,y_\perp) A^+(0) | M \rangle$$

❑ **Transport coefficient $\hat{e}_2$:**

$$\hat{e}_2(\vec{r},t) = \frac{\langle k_z^2 \rangle}{L} \propto \langle M | F^{+-}(y^-,y_\perp) F^{+-}(0) | M \rangle$$

Complementary studies between RHIC and LHC plasma

- ❑ **Transport coefficient $\hat{q}$:**

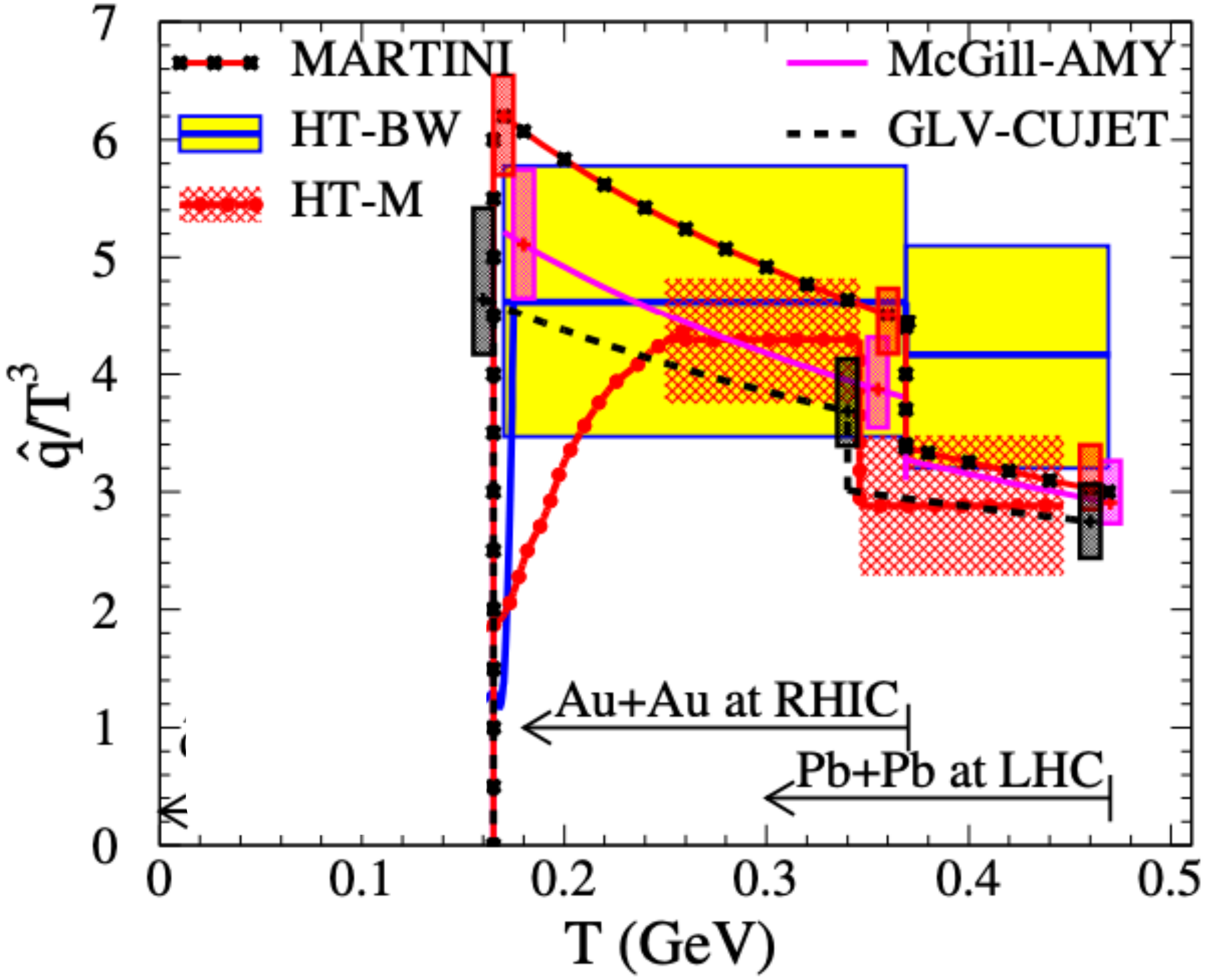
  Average transverse momentum squared per unit length

$$\hat{q}(\vec{r},t) = \frac{\langle \vec{k}_{\perp}^{2} \rangle}{L} \propto \langle M | F_{\perp}^{+}(y^{-}, y_{\perp}) F^{+\perp}(0) | M \rangle$$

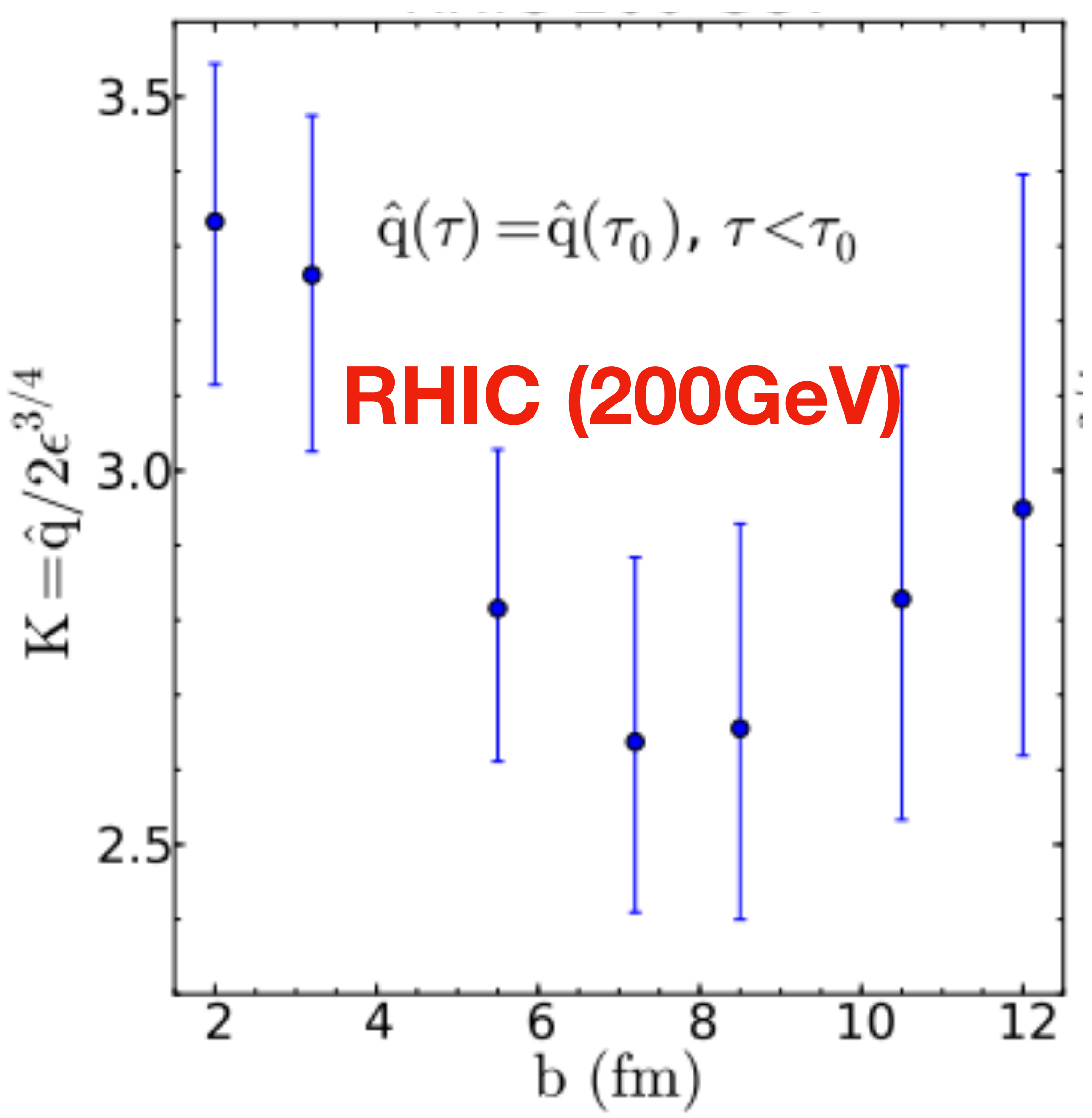
- ❑ **Based on fit to single hadron R_{AA} at RHIC and LHC**

- ❑ **$\hat{q}/T^3$ is higher at RHIC collision energy compared to LHC energy**

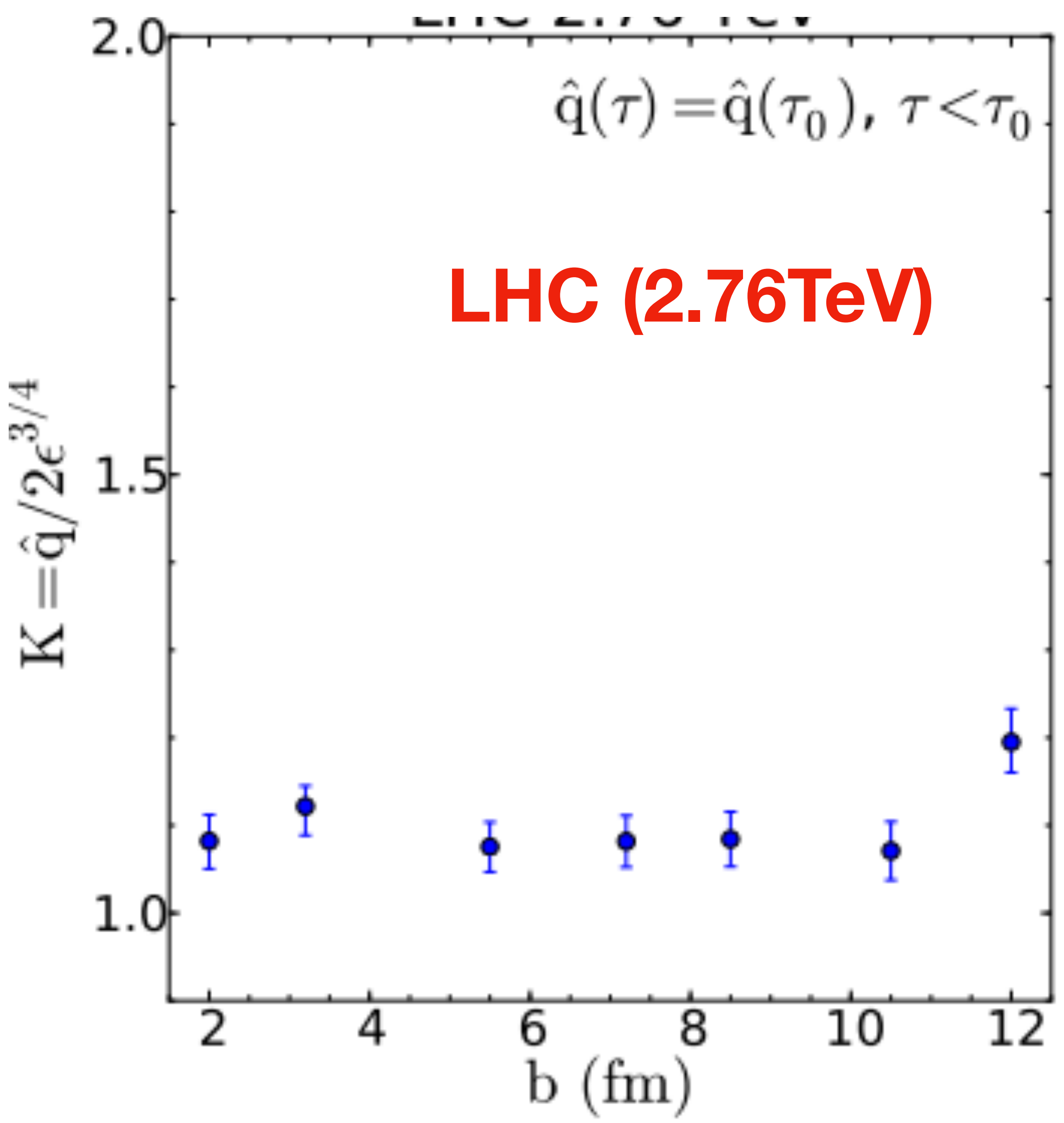
JET collaboration



PRC 90 (2014) 1, 014909



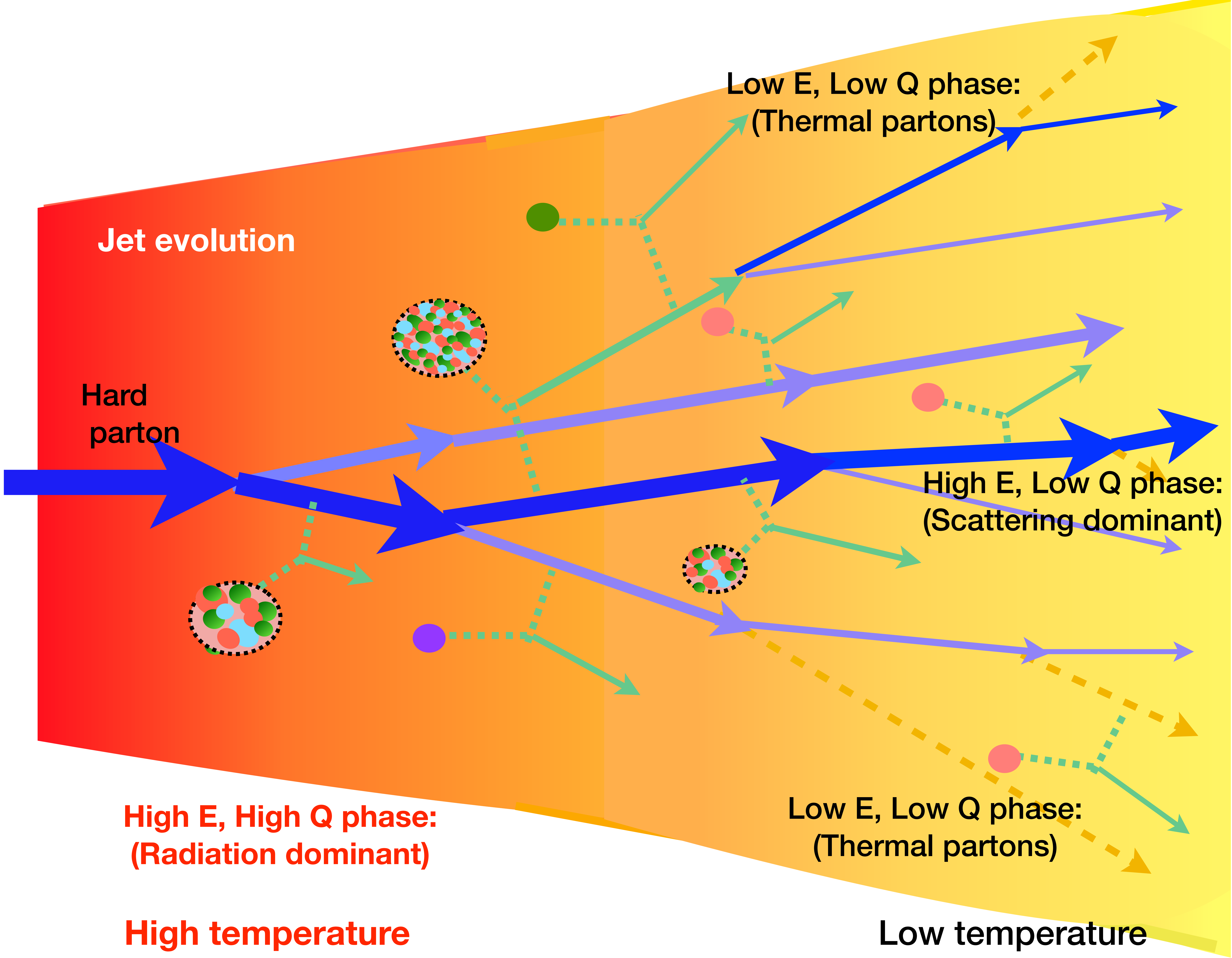
RHIC (200GeV)



LHC (2.76TeV)

Nucl.Part.Phys.Proc. 289-290 (2017)

Multi-scale dynamics of jets in evolving plasma



(1) How to extract short-distance structure of QGP in terms of PDF?

(2) Extract jet energy loss transport coefficient for transverse broadening and longitudinal broadening $\hat{q}, \hat{e}, \hat{e}_2$ etc?

(3) Typical scale for parton energy loss to switch from radiation dominant to scattering dominant phase

(4) Mechanism of Jet-medium response

JETSCAPE instrument: a unified framework for heavy-ion collisions

- ✦ **Modular, extensible and task-based event generator**
- ✦ **Framework is modular to “multi-stage”, “energy-loss” models**
- ✦ **Statistical package to perform Bayesian analysis**

✦ **JETSCAPE framework (arXiv:1903.07706)**

JETSCAPE pp19 tune (arXiv:1910.05481)

JETSCAPE AA (arXiv:2204.01163)

→ **See talk by Raymond (Fri 9AM)**

GitHub JETSCAPE 3.0 is available: **github.com/JETSCAPE**

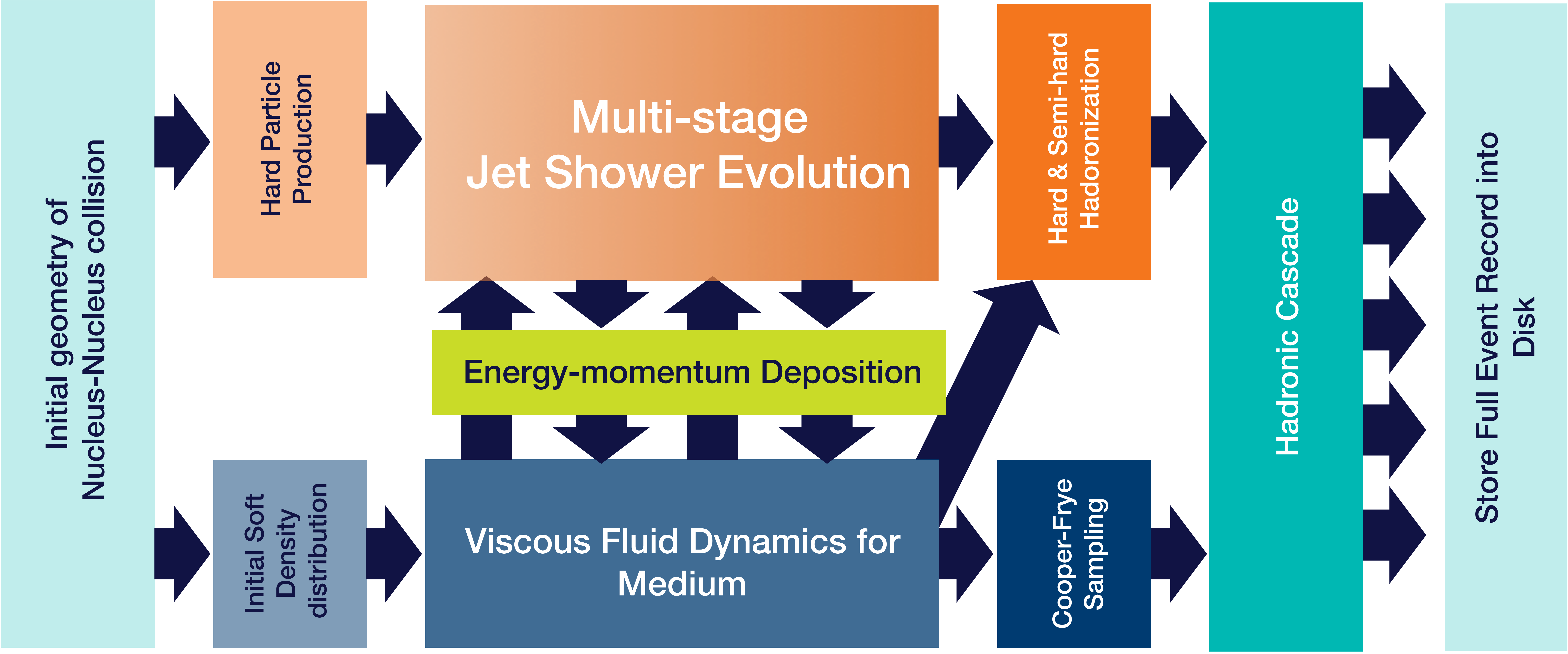
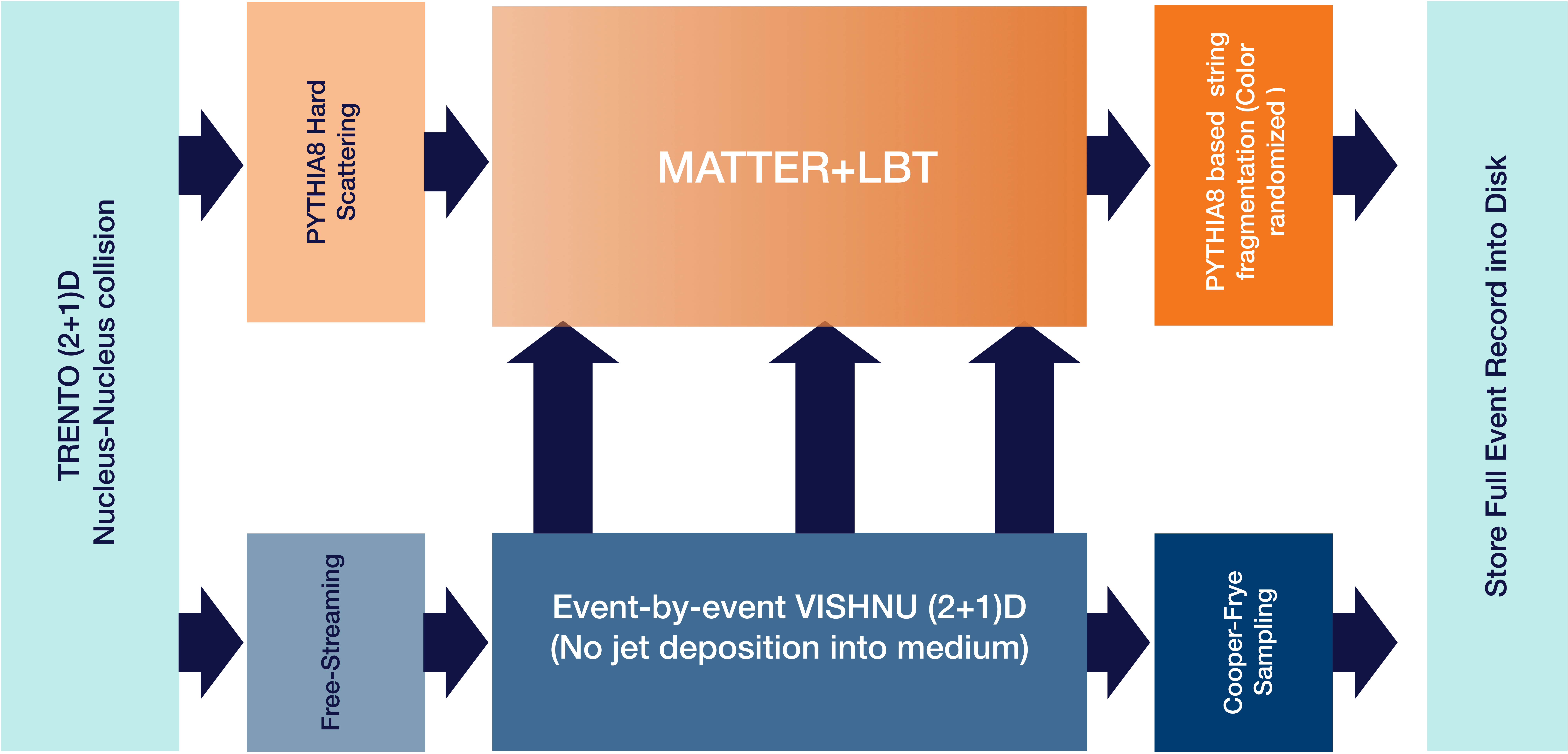


Diagram by:
Y. Tachibana

AA collisions within JETSCAPE framework

A possible choice of models to generate AA collisions

JETSCAPE AA (arXiv:2204.01163)



Jet evolution in high virtuality and low virtuality phase

- **MATTER: In-medium DGLAP evolution equation**

In limit: $< k_\perp^2 > \sim \hat{q}\tau^- << l_\perp^2 \sim Q^2$

Formation time: $\tau^- \sim q^-/Q^2$

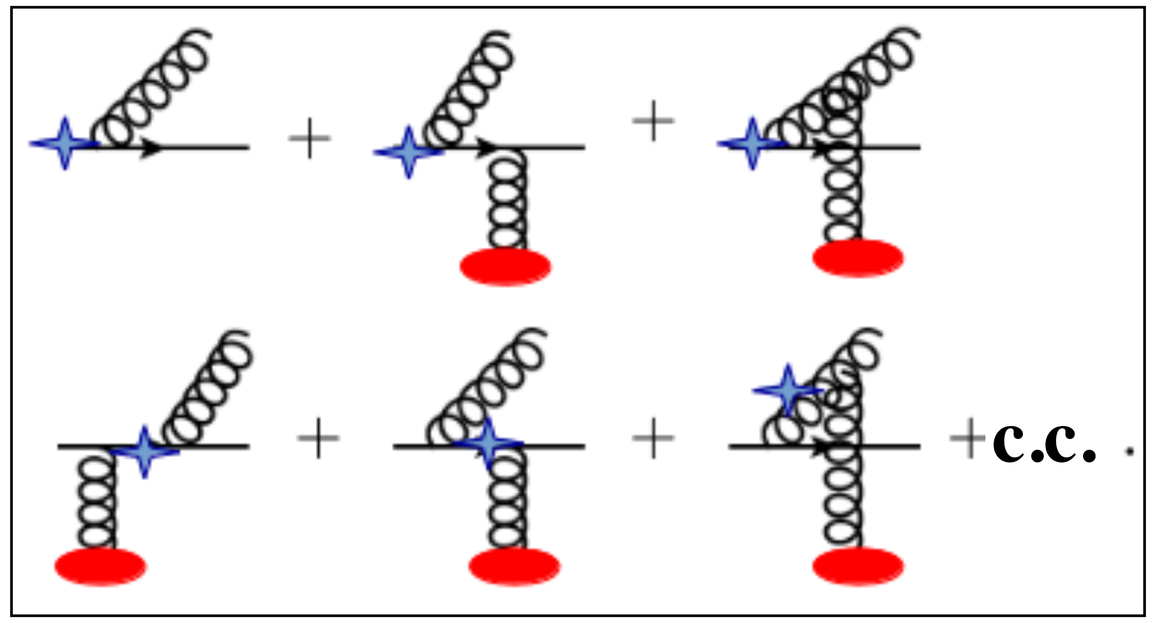
$$\frac{\partial D\left(z, Q^2, \zeta_i^-\right)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int_z^1 \frac{dy}{y}\left[P_+\left(y\right) D\left(\frac{z}{y}, Q^2, \zeta_i^-\right) + \right.$$

Vacuum term

$$\left. + \left(\frac{P(y)}{y\left(1-y\right)}\right)_+ D\left(\frac{z}{y}, Q^2, \zeta_i^- + \tau^-\right) \times \int_{\zeta_i^-}^{\zeta_i^- + \tau^-} d\zeta^- \frac{\hat{q}\left(\zeta^-\right)}{Q^2}\left\{2 - 2\cos\left(\frac{\zeta^- - \zeta_i^-}{\tau^-}\right)\right\}\right]$$

Medium term

Repeating single emission single scattering kernel



Virtuality ordered emission approximation

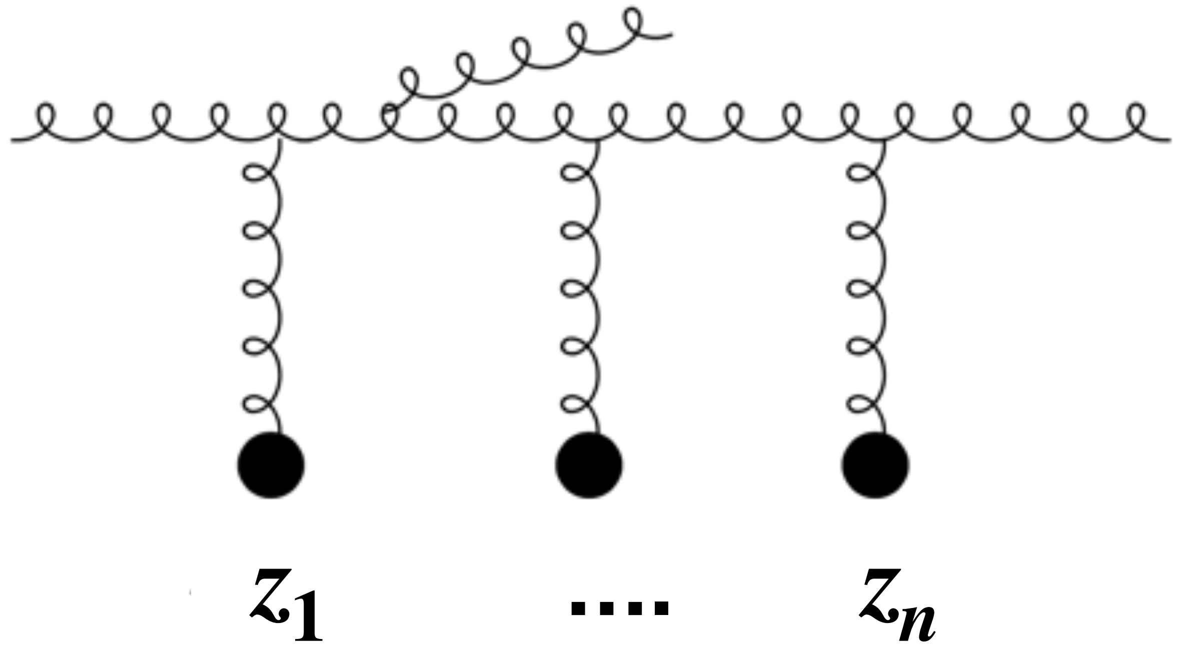
- **LBT: Based on linear Boltzmann transport equation**

Evolution of phase-space distribution

$$p_i \cdot \partial f_i(x_i, p_i) = E_i(\mathscr{R}_{el} + \mathscr{R}_{inel})$$

Elastic scattering: LO 2 ↔ 2 proccess

Inelastic scattering: Single gluon emission rate using Higher Twist (depends on $\hat{q}$)



Multiple scattering and single emission

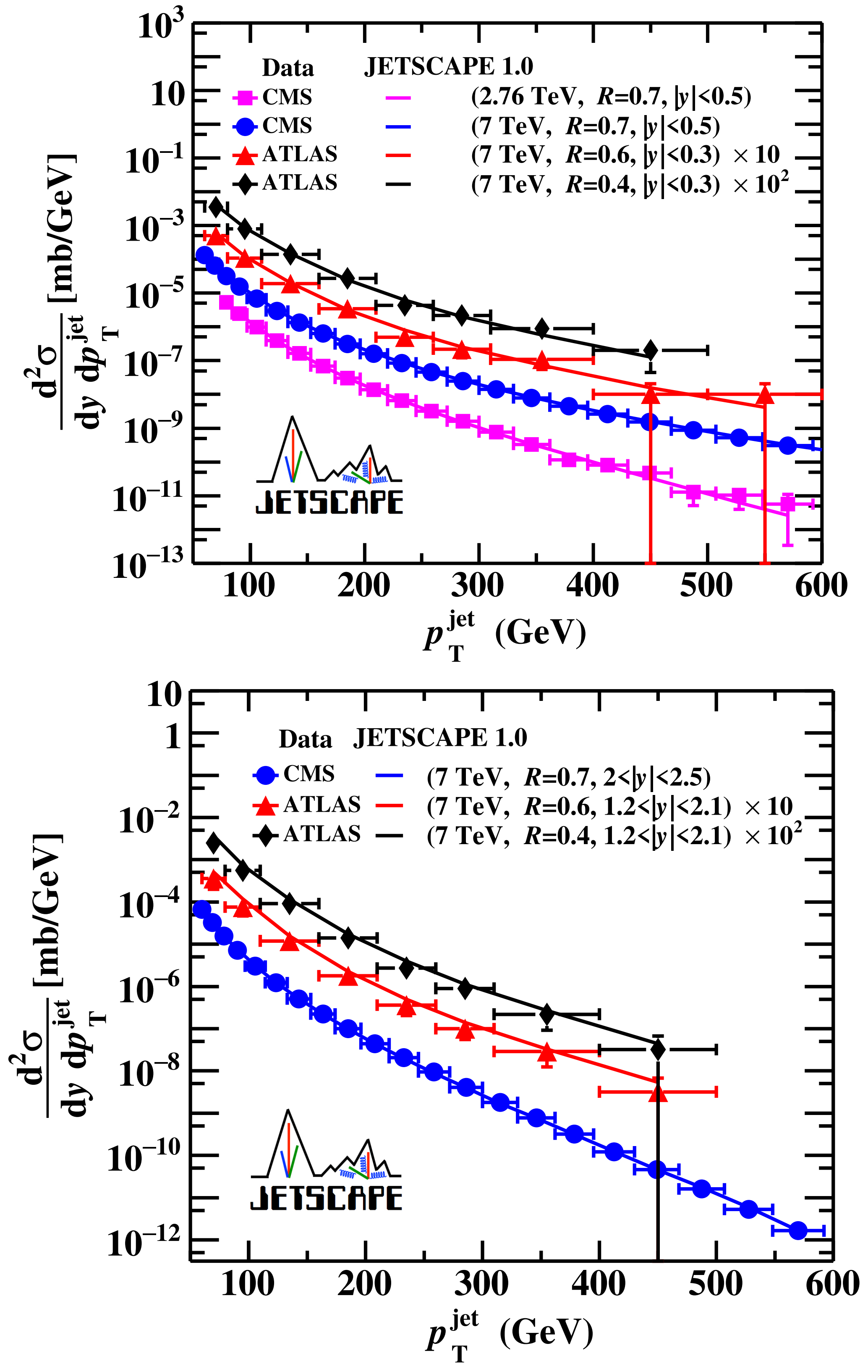
JETSCAPE pp19 tune

Optimized value of parameters:

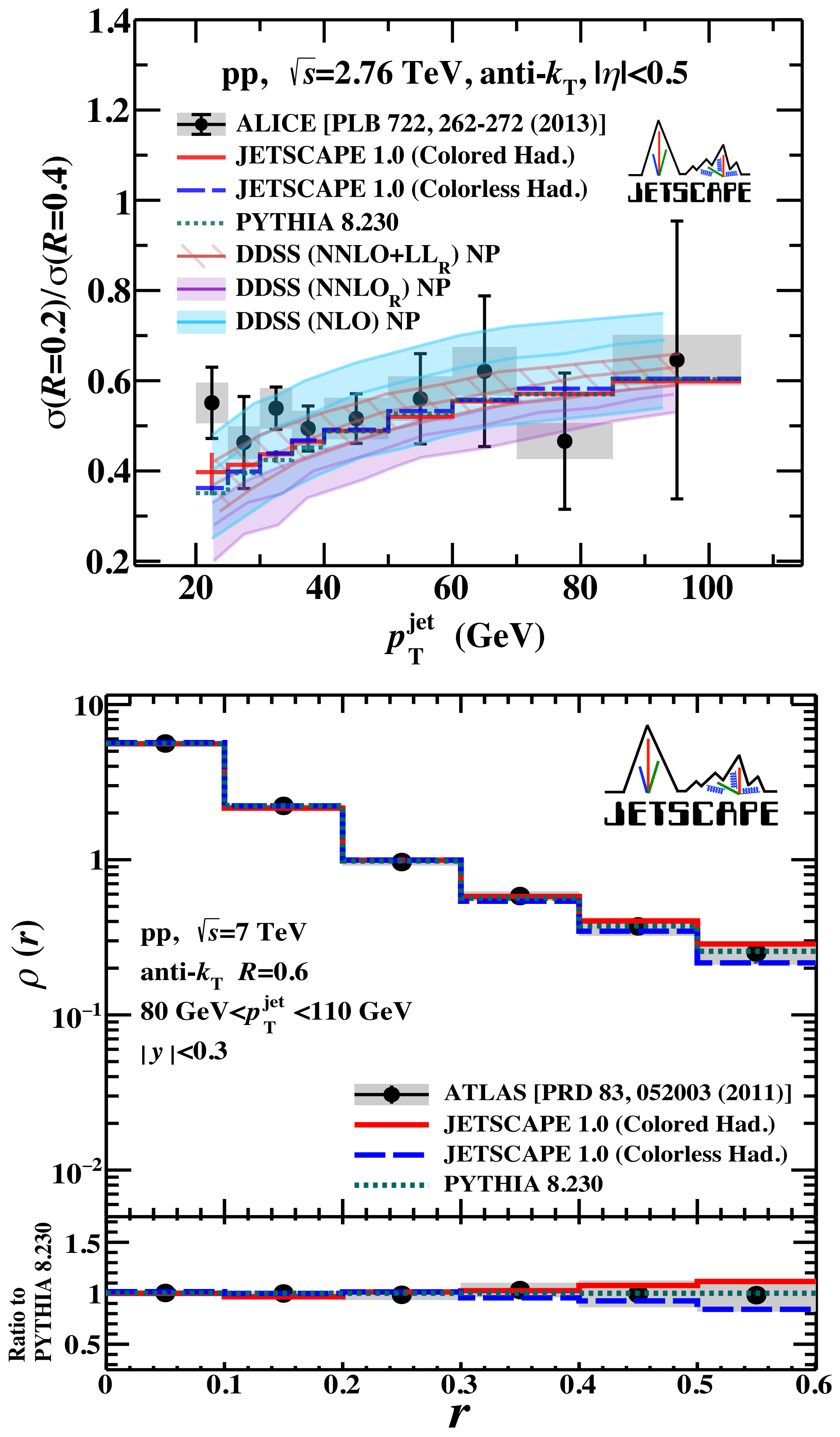
- Lambda QCD: $\Lambda_{\mathrm{QCD}} = 200\mathrm{MeV}$
- Initial virtuality (off-shellness) of the parton after hard scattering: $Q_{\mathrm{in}} = \dfrac{p_{\mathrm{T}}}{2}$

pp19 tune (arXiv:1910.05481)

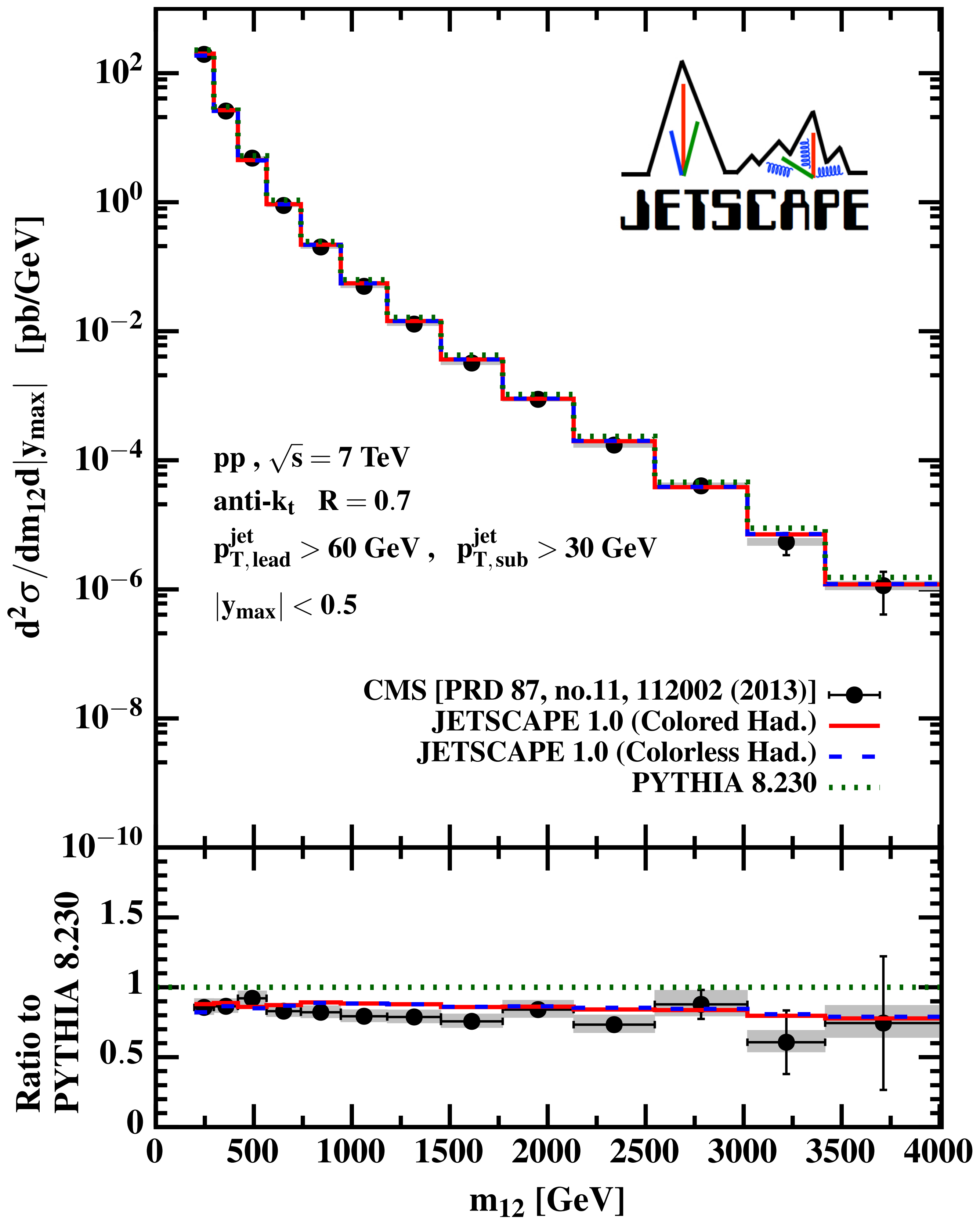
Inclusive jet cross section



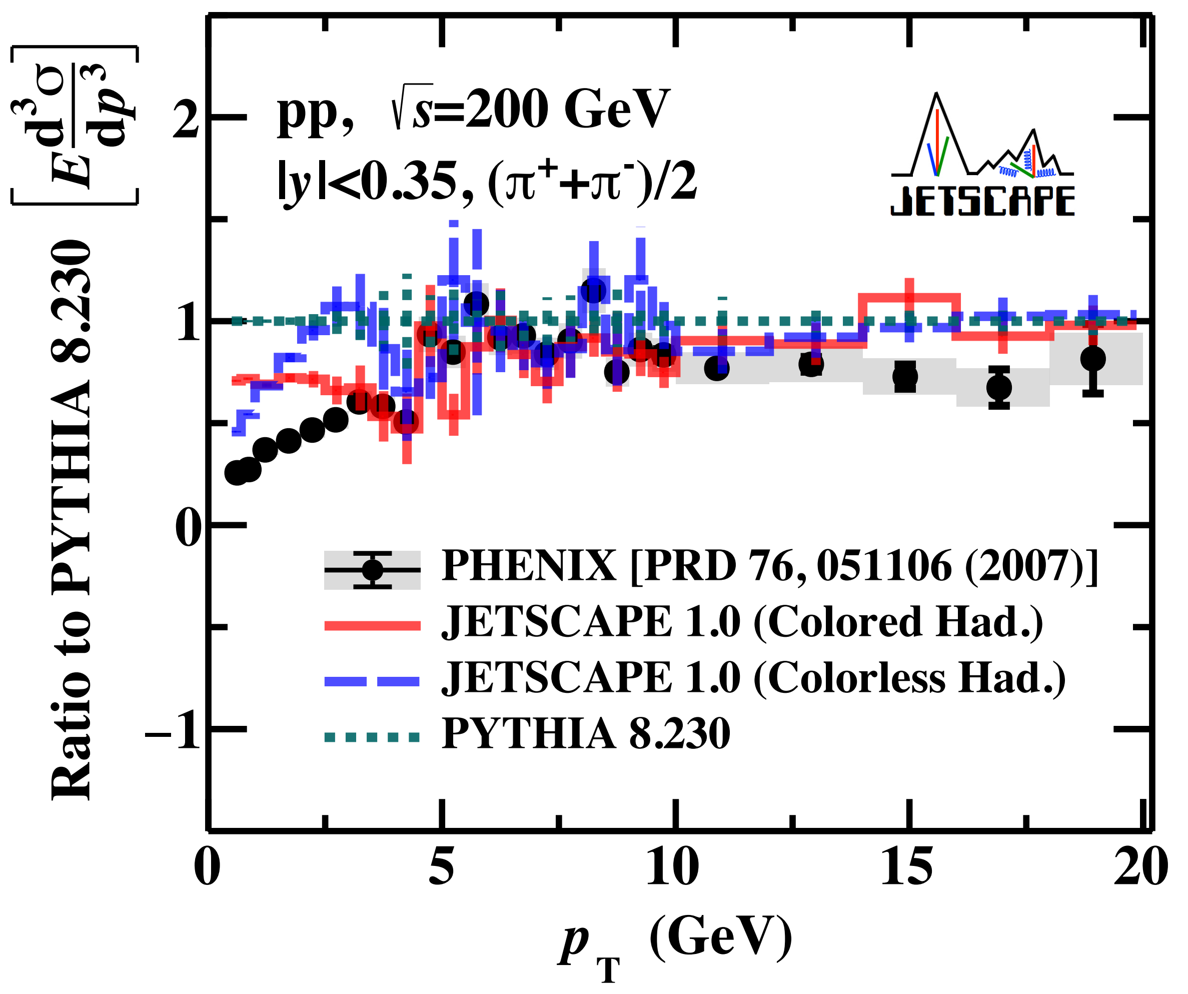
Jet shape



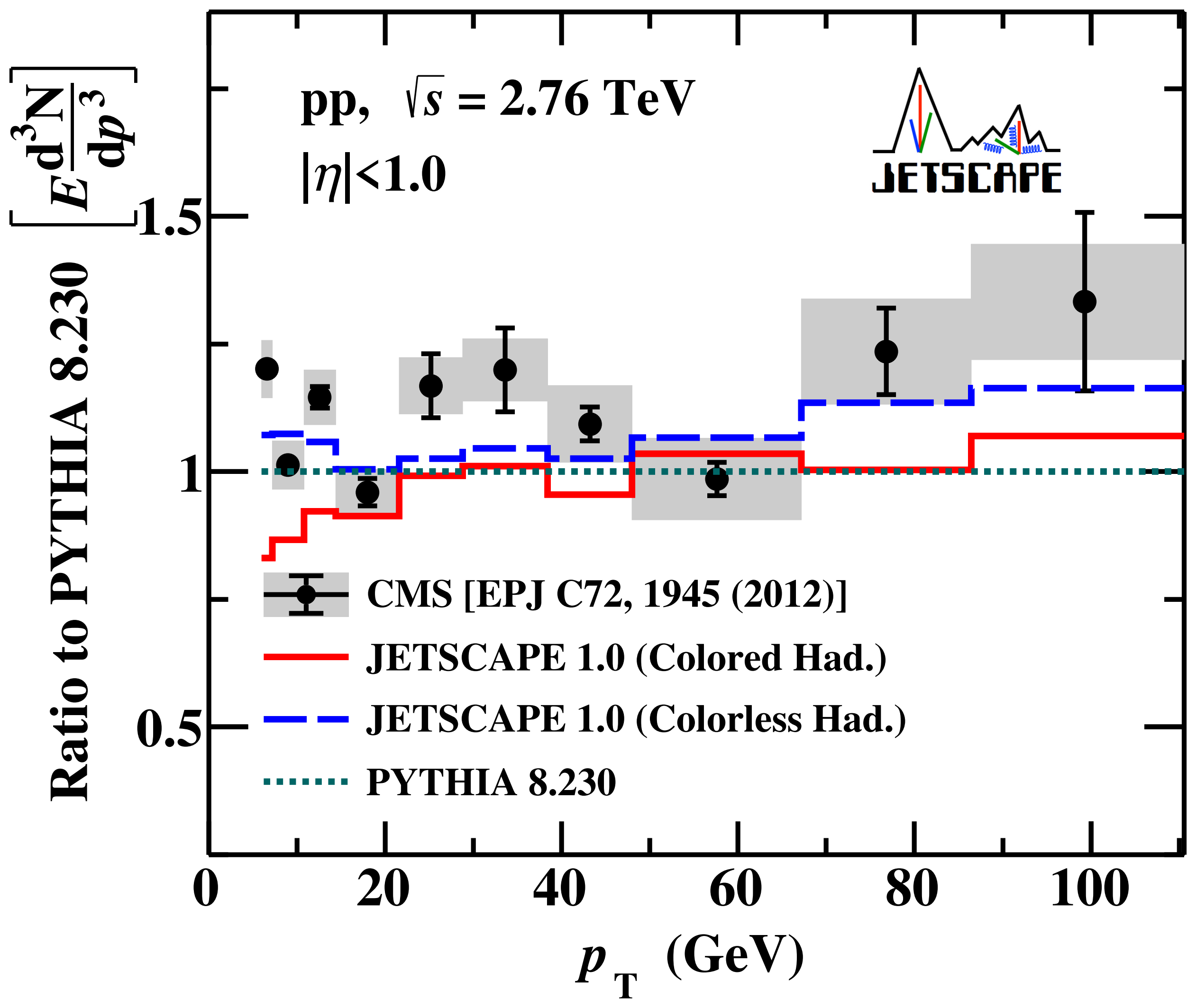
Jet Mass



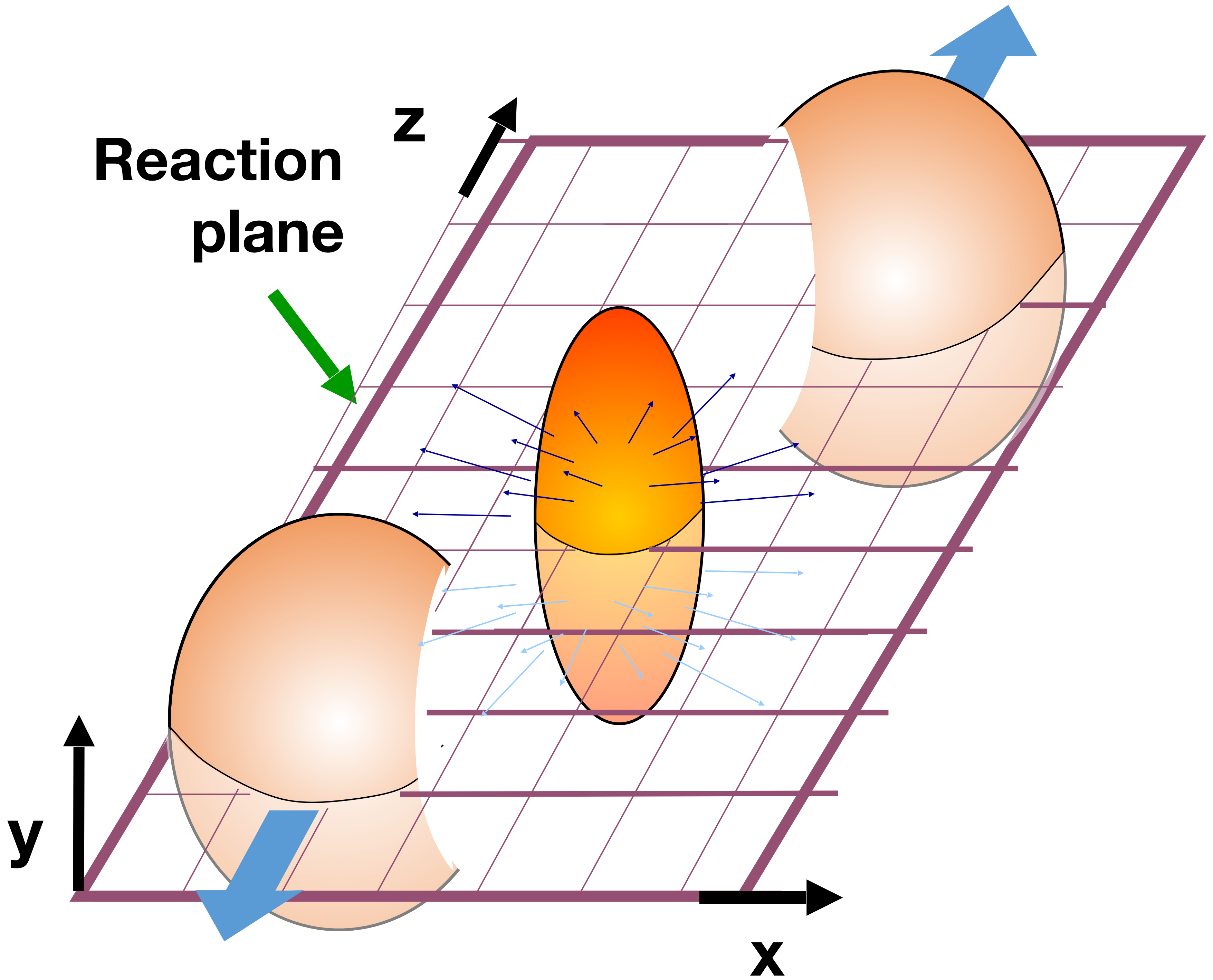
Charged hadron yield

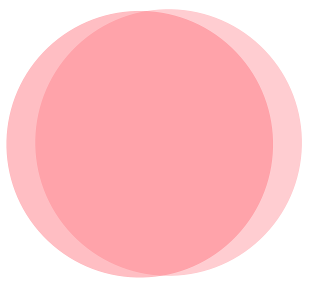


Charged hadron yield

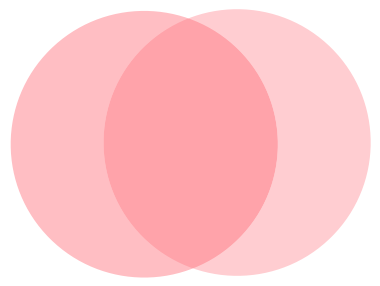


Soft sector calibration

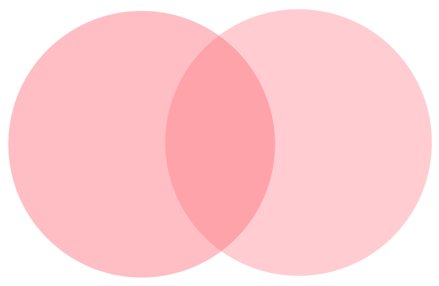




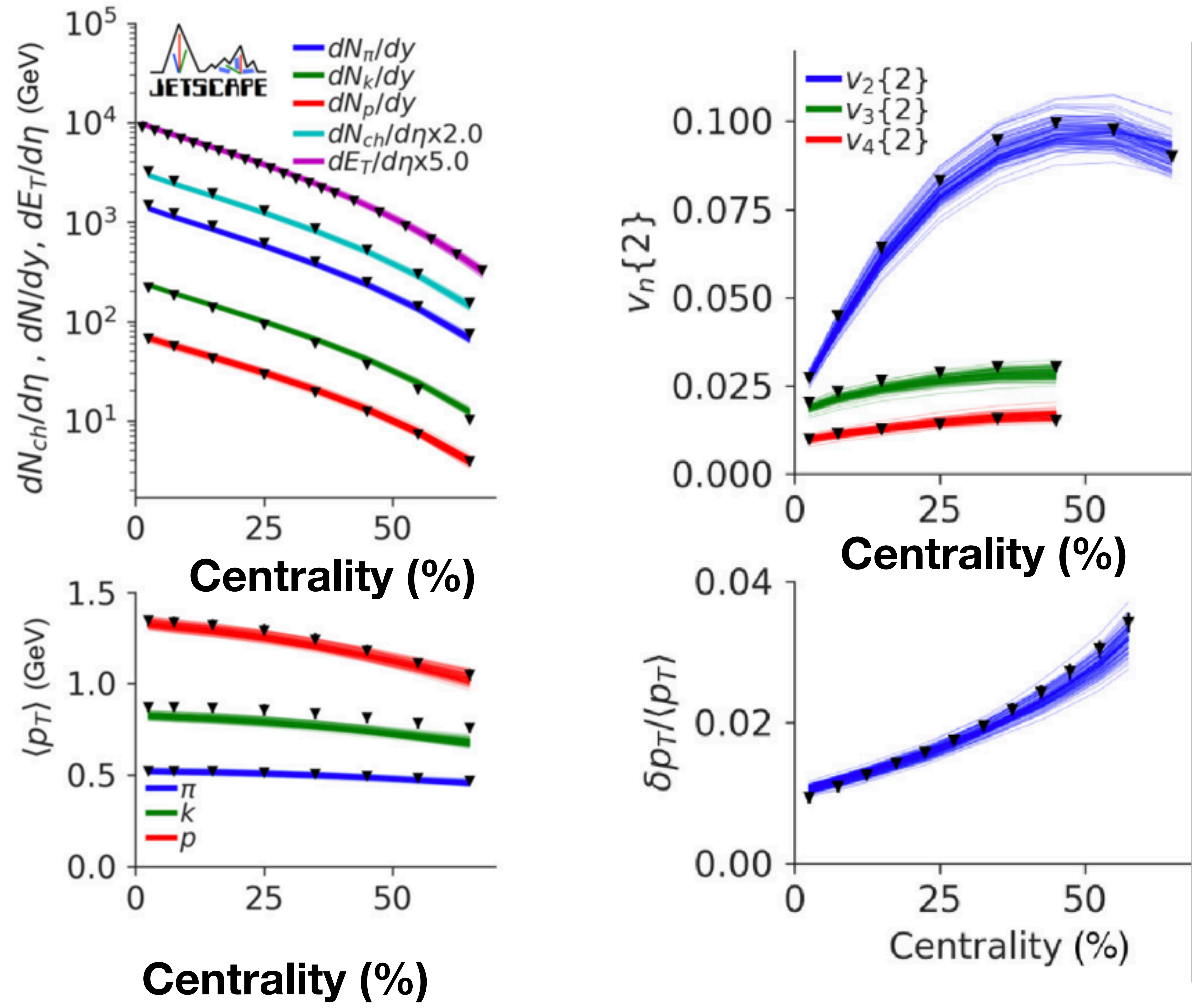
Central



Semi-peripheral



peripheral

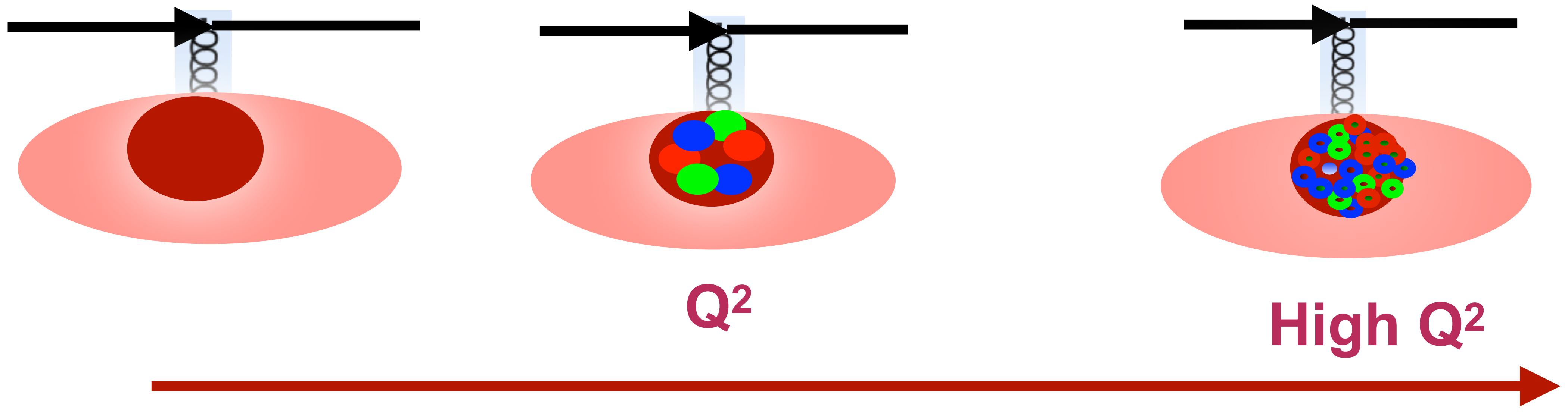


TRENTO+ Free-streaming + VISHNU+UrQMD Bayesian calibration [Nature Physics vol15, 1113–1117 (2019)]

Scale-resolution dependence of jet-medium interaction

Coherence effects

Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, PLB707, 156-159 (2012)
J. Casalderrey-Solana, E. Iancu, JHEP08, 015 (2011)

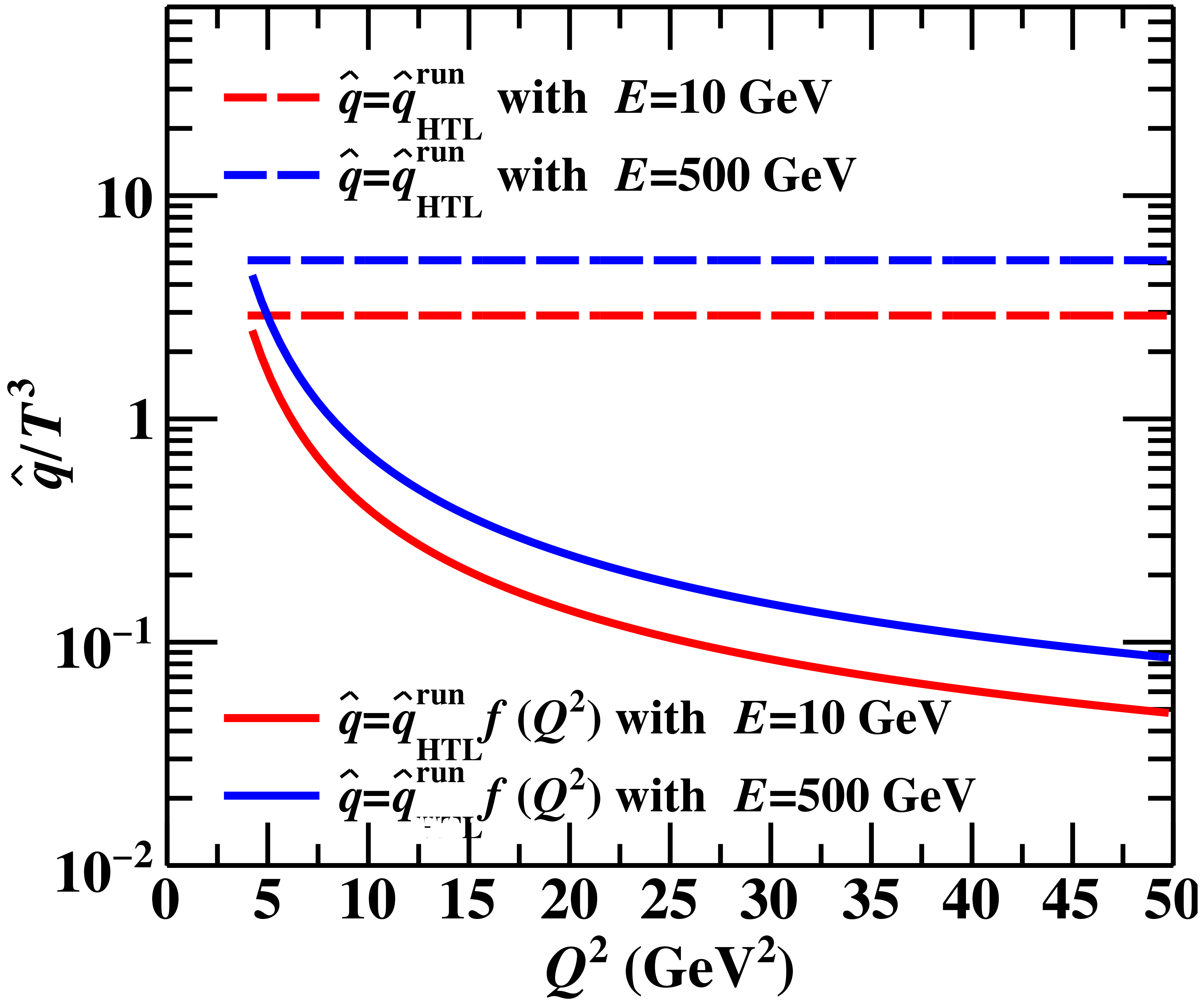


- Scale evolution of QGP constituent distribution
  Kumar, Majumder, Shen, PRC101, 034908 (2020)
- Less interaction for large-Q^2 partons
  → Implemented in MATTER

Effective jet-quenching strength $\Longrightarrow \hat{q}_{\rm HTL} \cdot f(Q^2)$

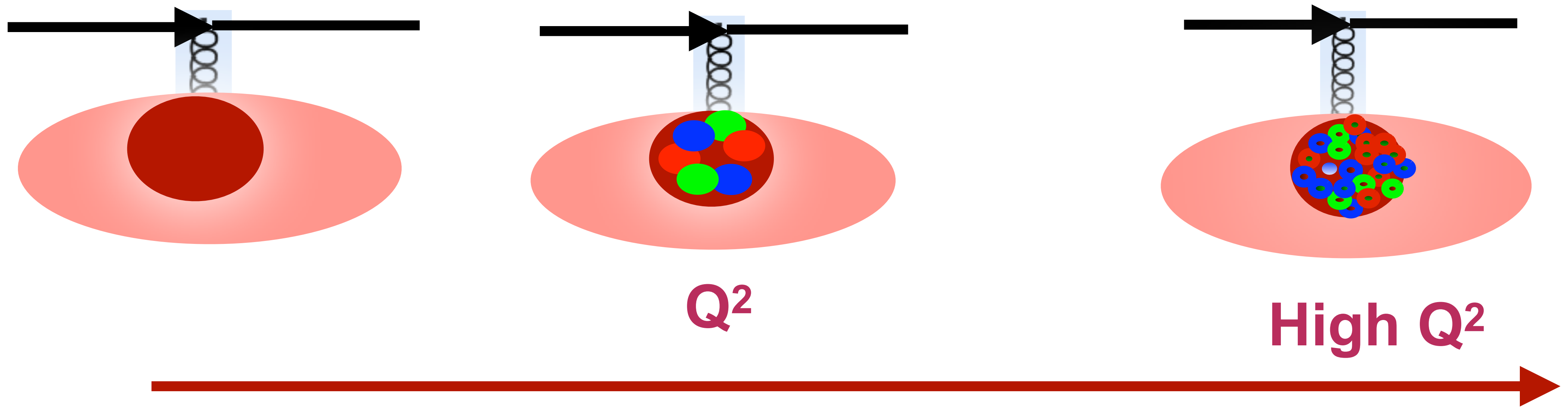
$$\hat{q}_{\rm HTL} = C_a \frac{42\zeta(3)}{\pi} \alpha_s^{\rm run} \alpha_s^{\rm fix} T^3 \ln \left[\frac{2ET}{6\pi T^2 \alpha_s^{\rm fix}} \right]$$

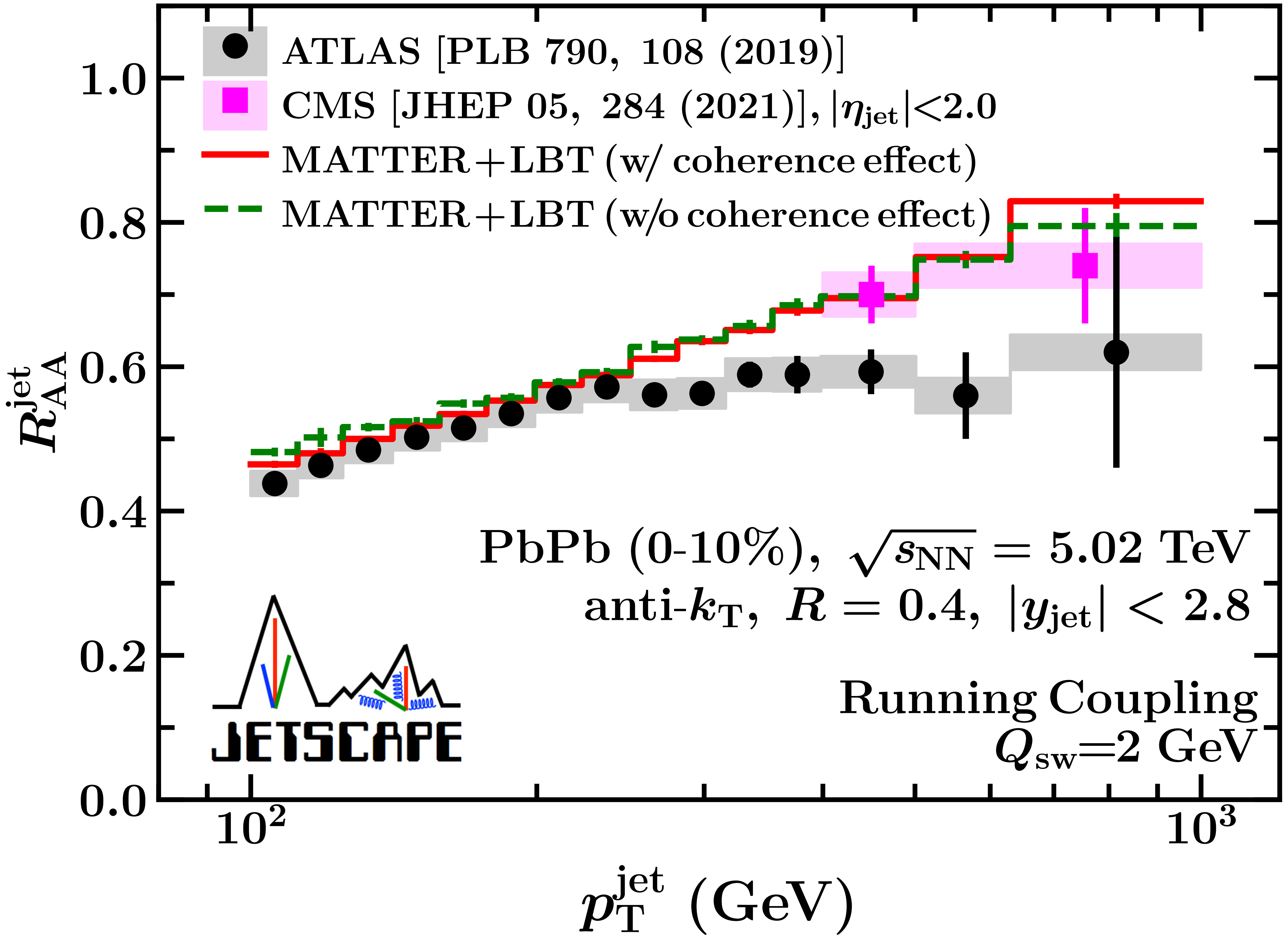
$$f(Q^2) = \frac{1 + c_1 \ln^2(Q^2_{\rm sw}) + c_2 \ln^4(Q^2_{\rm sw})}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$

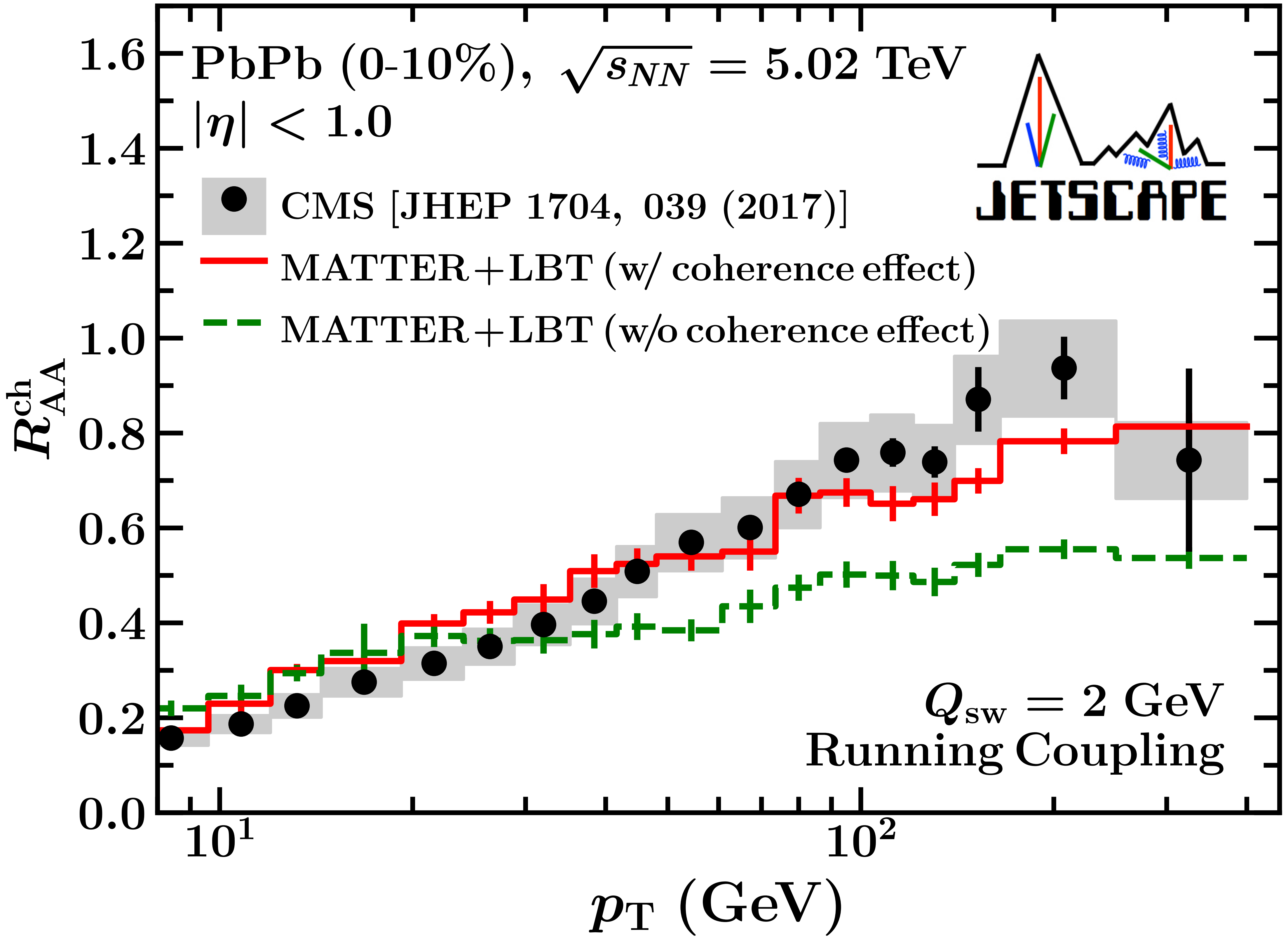


Jets and Leading hadron suppression at $\sqrt{s}_{NN} = 5.02$ TeV

Effective jet-quenching strength $\Longrightarrow \hat{q}_{\rm HTL} \cdot f(Q^2)$





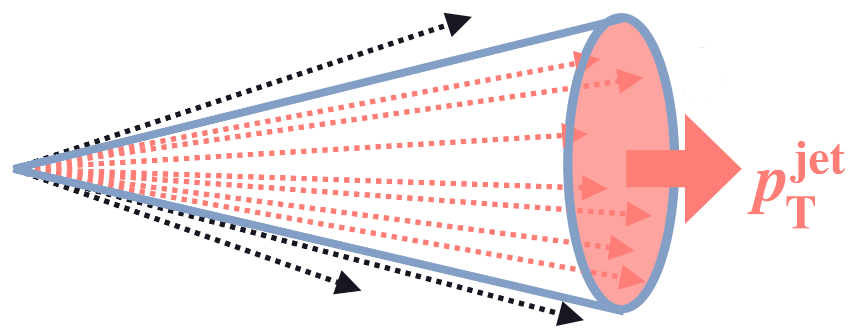


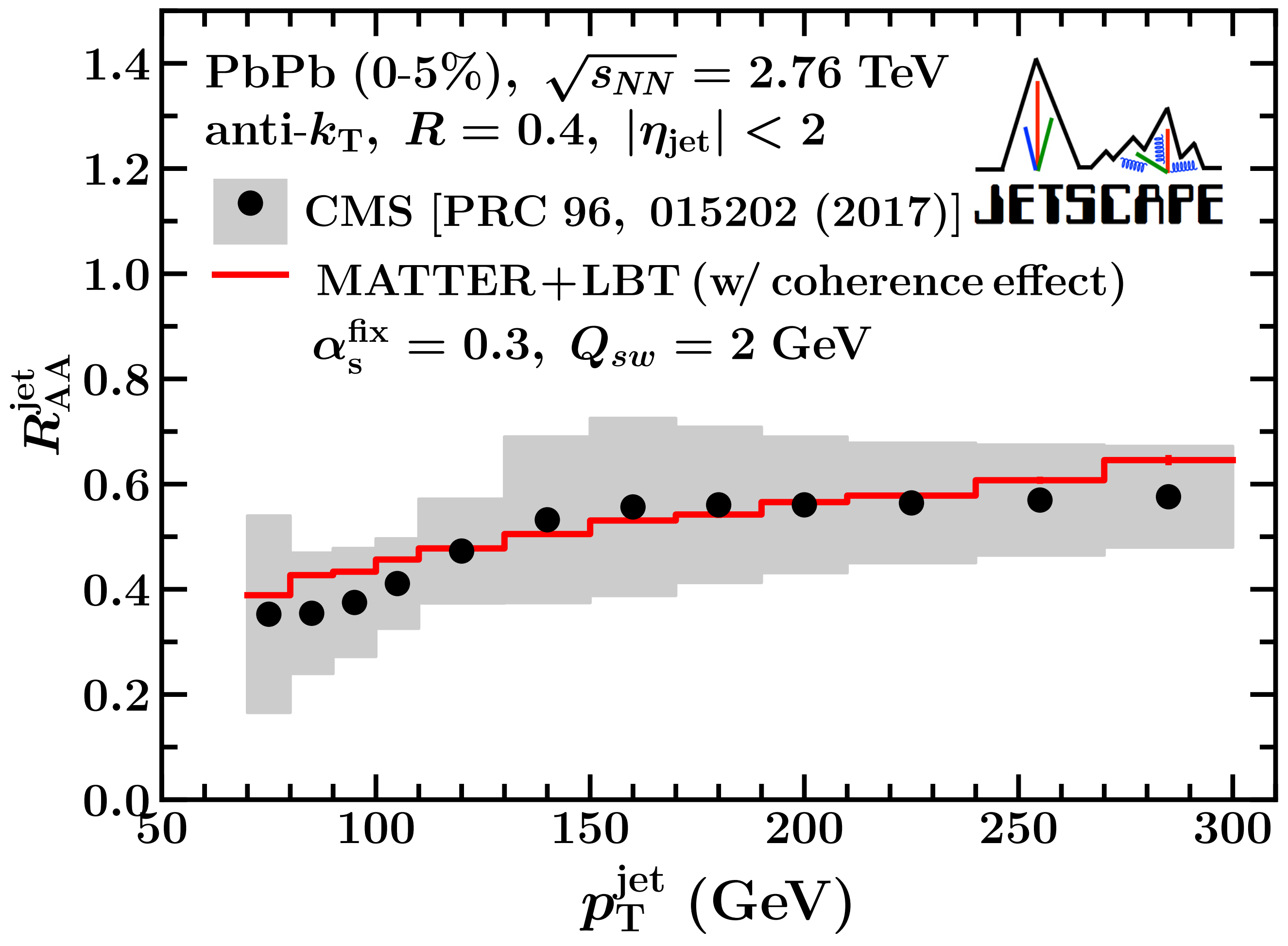
Strong coherence effects are observed for high-p_T hadrons

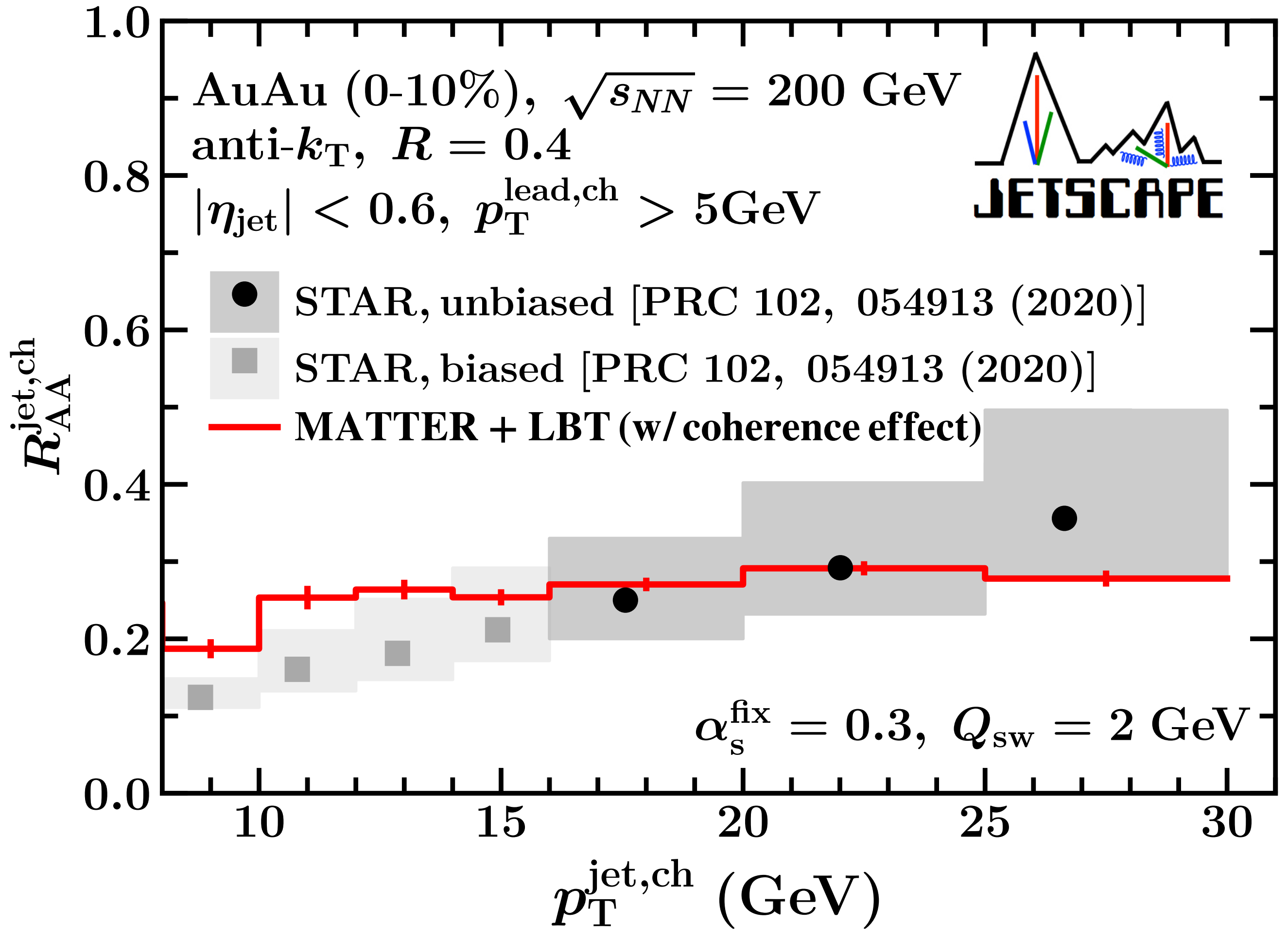
Collision energy dependence of Jet and Hadron R_{AA}

- **Pb+Pb at 2.76 TeV**
- **Au+Au at 200 GeV**

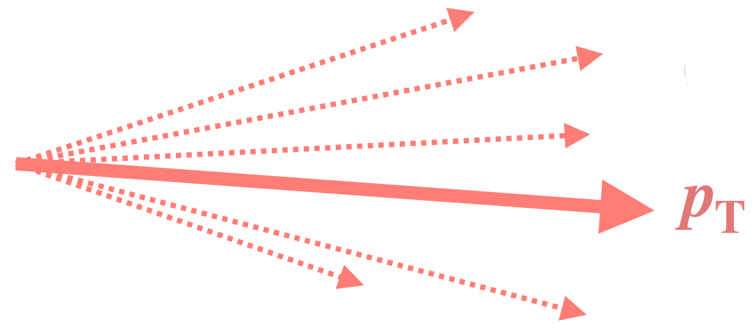
Jet R_{AA}

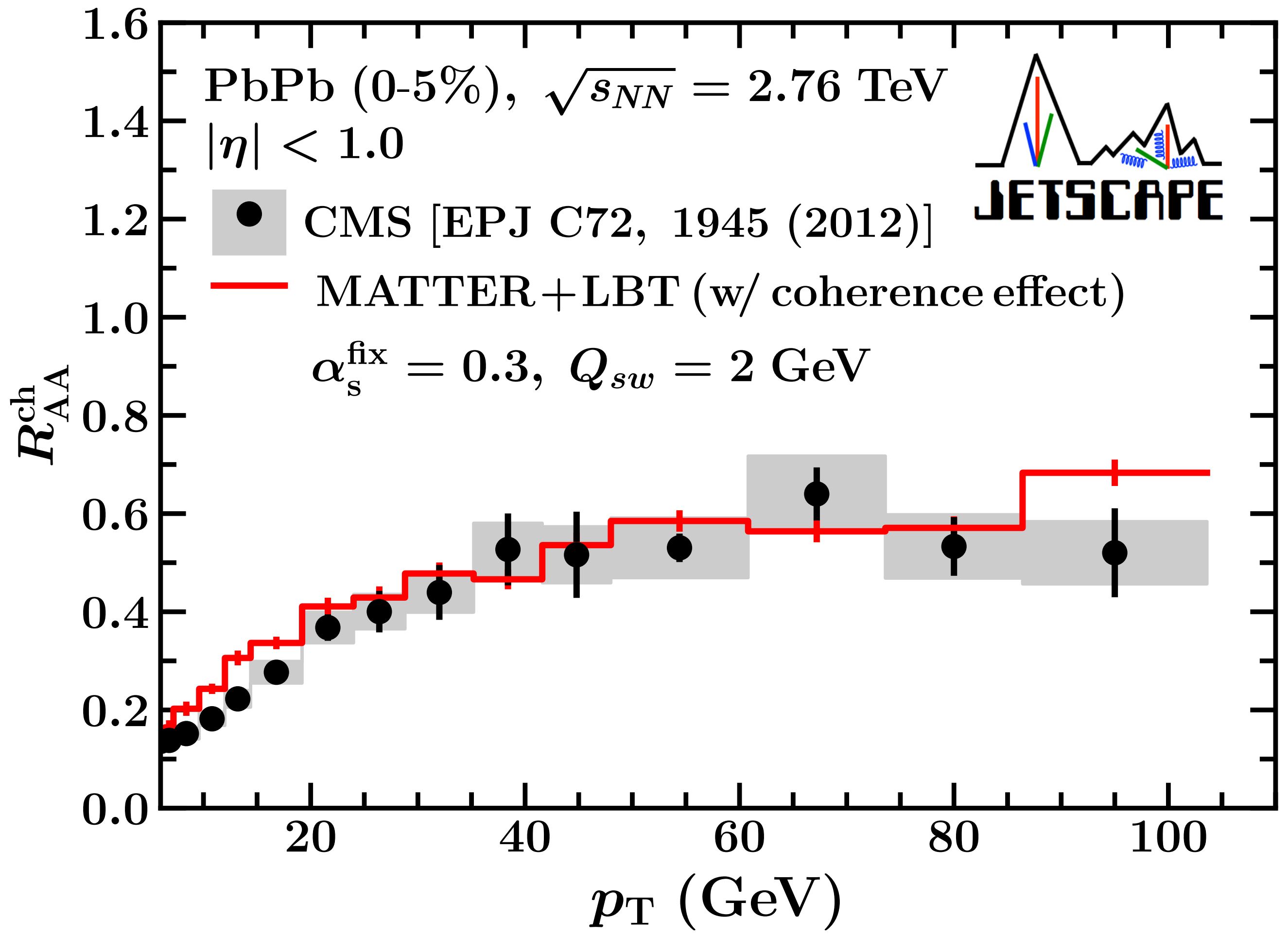


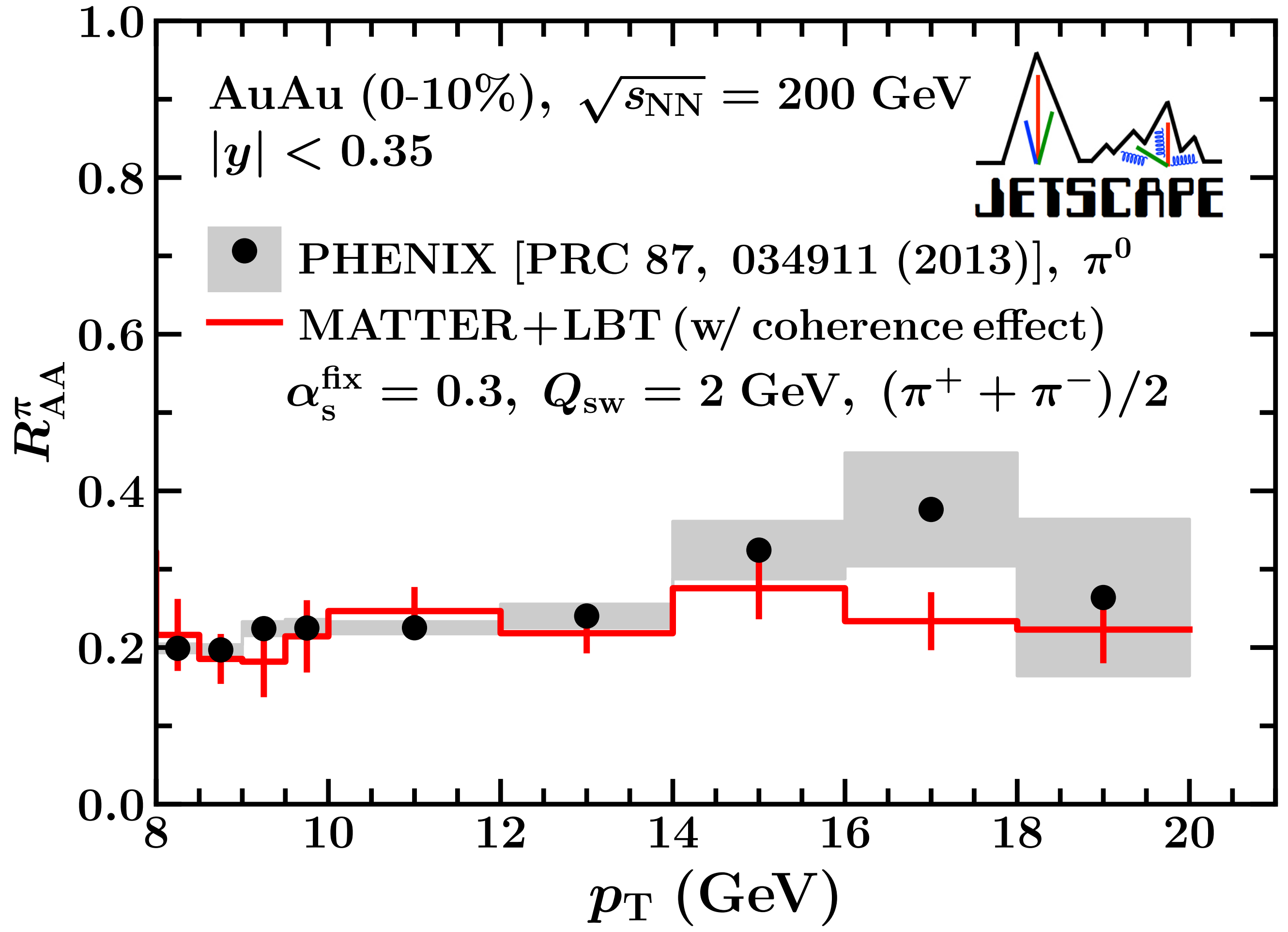




Particle R_{AA}



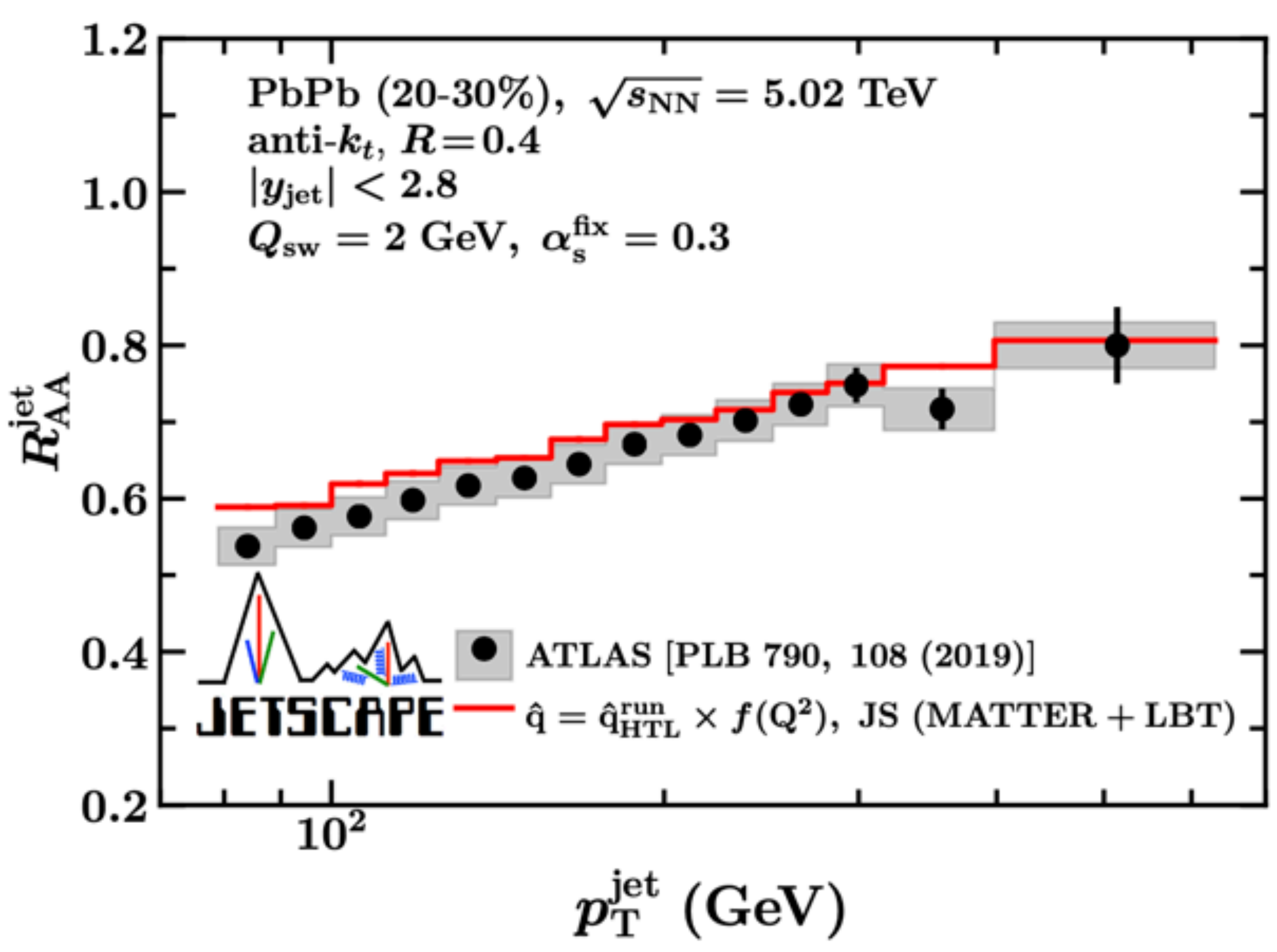




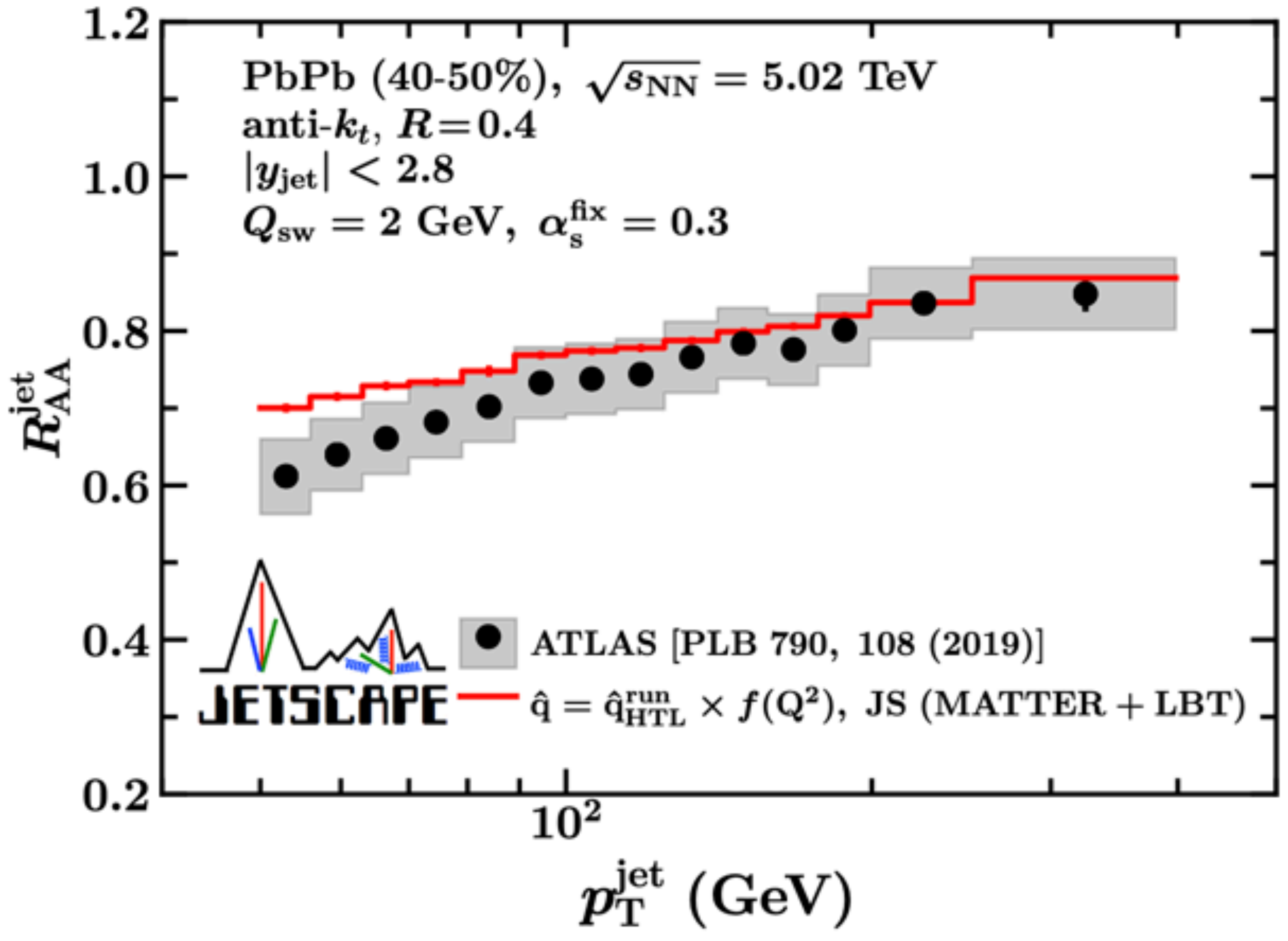
No further retuning of parameters done

Centrality dependence of Jet and hadron R_{AA}

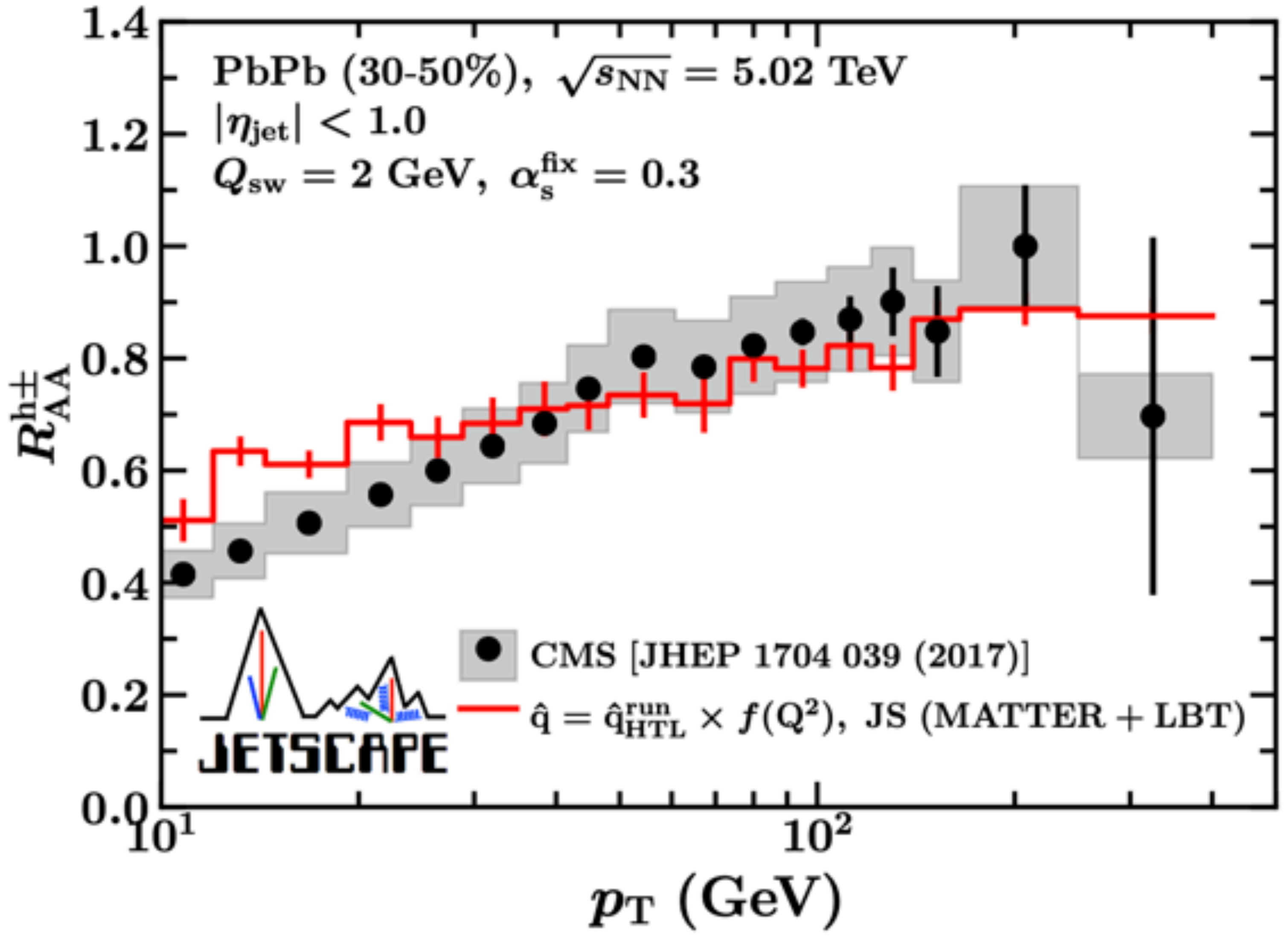
Jet R_{AA} (20-30%)



Jet R_{AA} (40-50%)



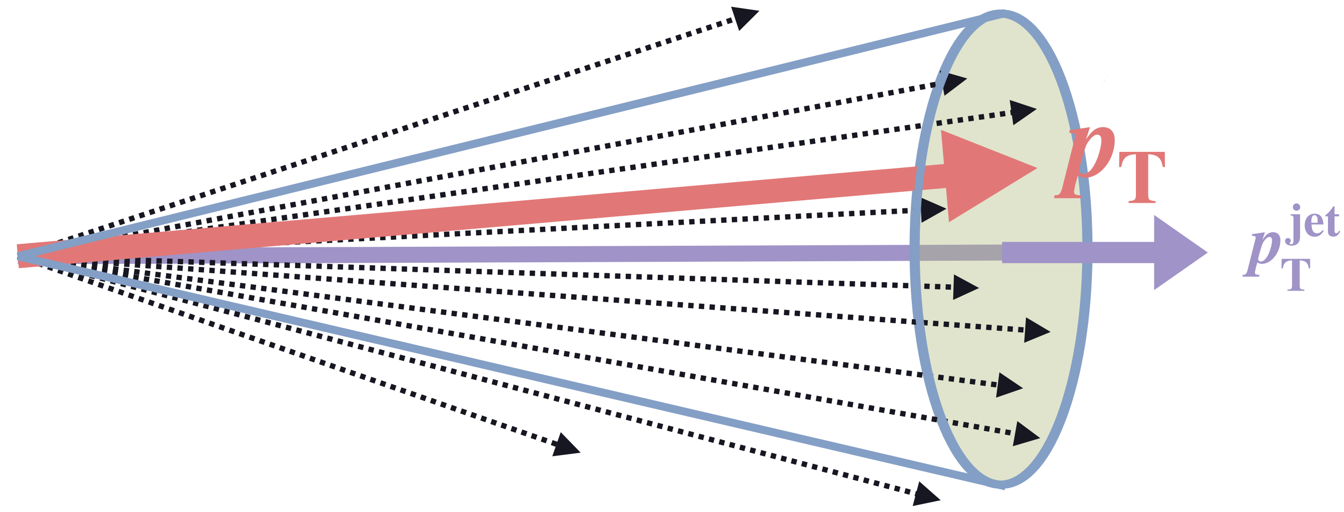
Hadron R_{AA} (30-50%)



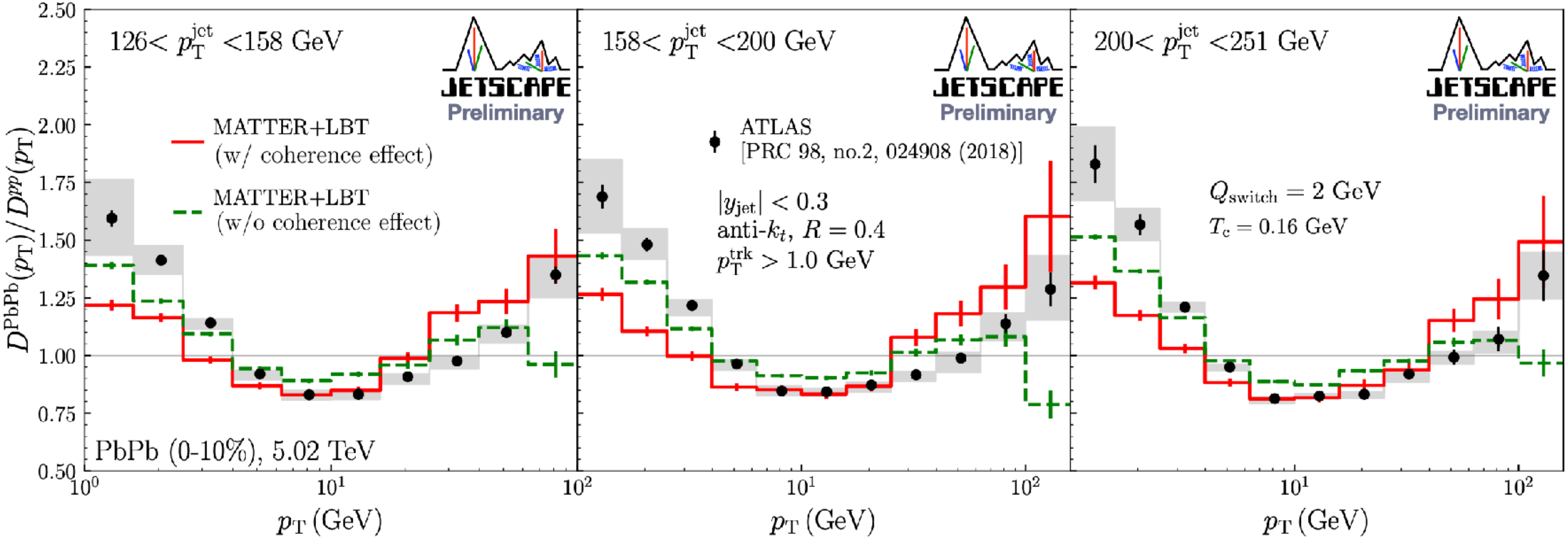
Quenching in hadronic phase is not included. Jet energy loss turns off when $T < 160$ MeV
No further retuning of parameters done.

Jet Fragmentation function

$$D(p_T) = \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{dN_{trk}}{dp_T^{ch}}$$



Shows sensitivity to coherence effects

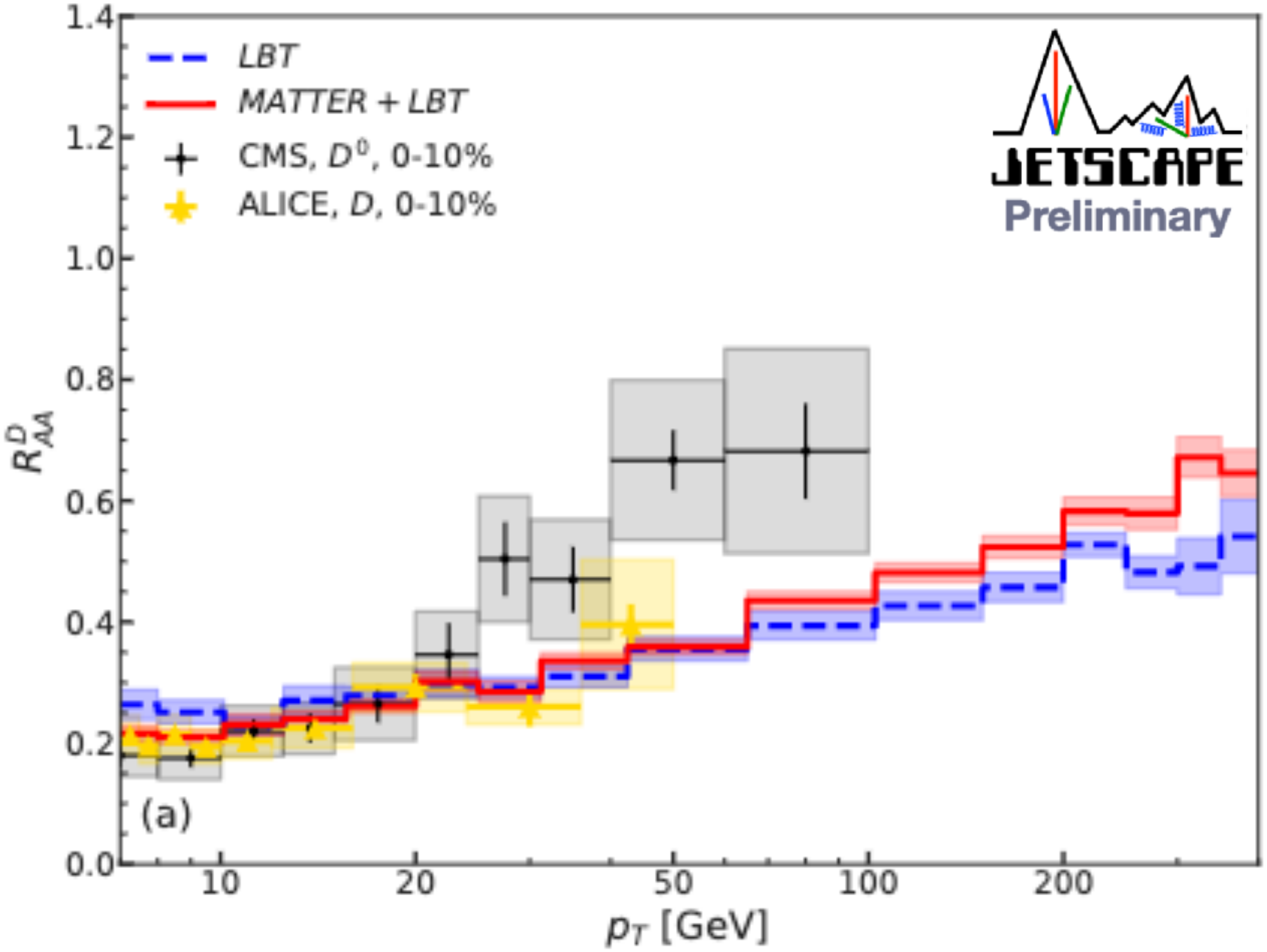


Inclusion of heavy-quarks in MATTER and LBT

Allows to explore
(1) parton flavor energy loss dependence
(2) the mass and momentum dependence

Flavor dependence is comparable with Experimental measurements

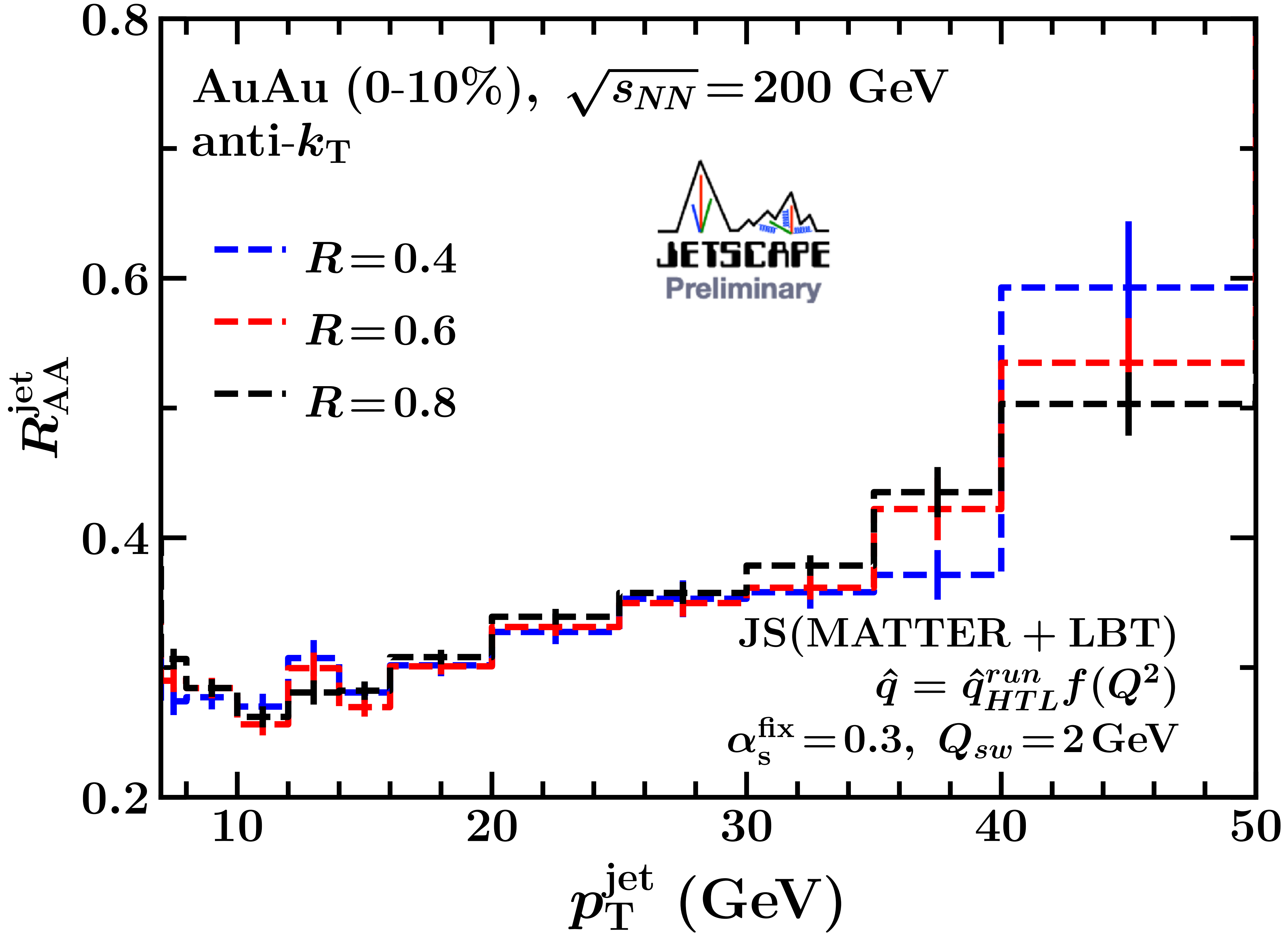
No further retuning of parameters done.



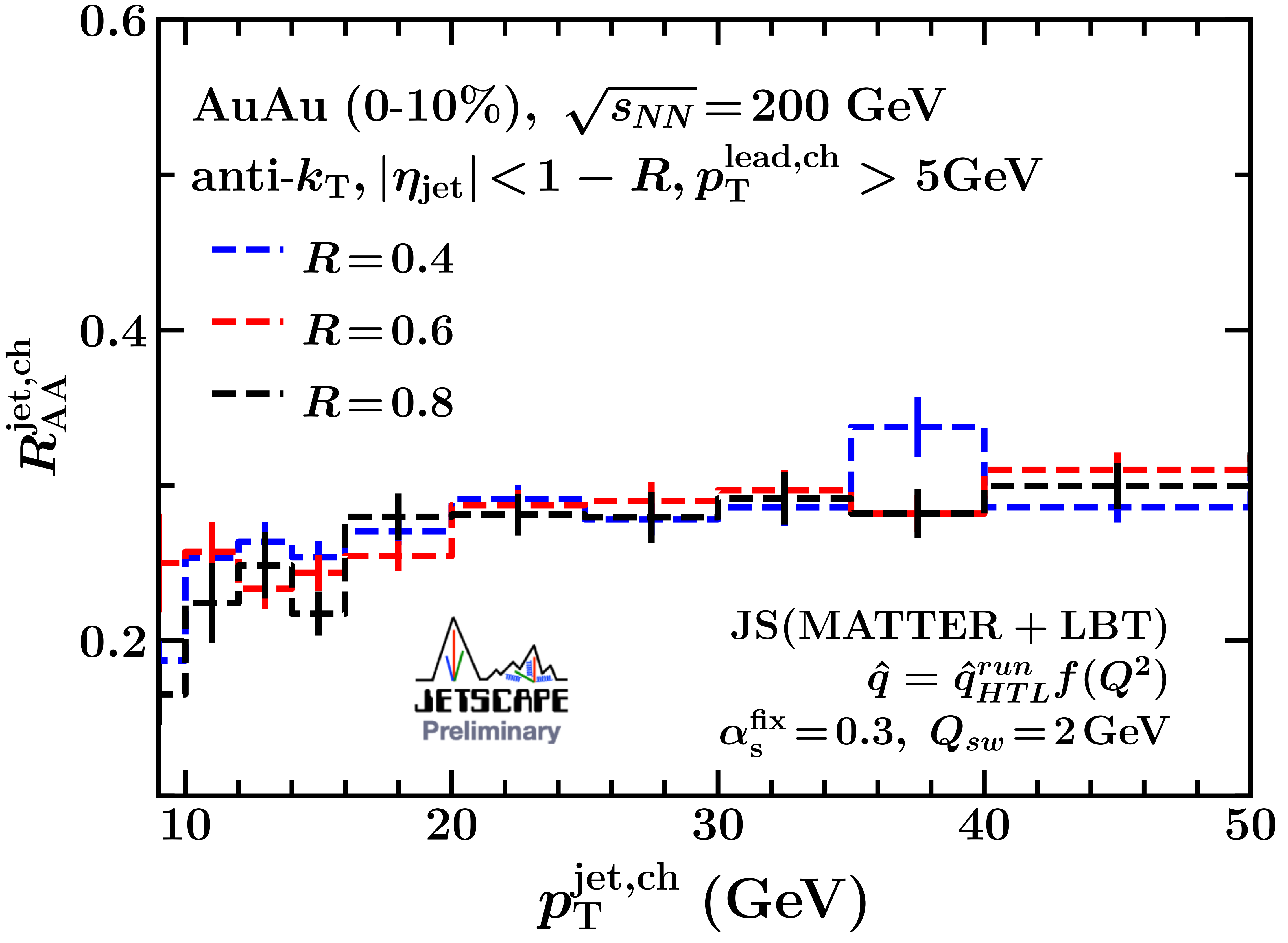
Predictions at $\sqrt{s_{NN}} = 200\mathrm{GeV}, 0-10\,\%$ (MATTER+LBT@JETSCAPE)

Jet R-dependence of Inclusive jets and charged jets

Inclusive Jet R_{AA}



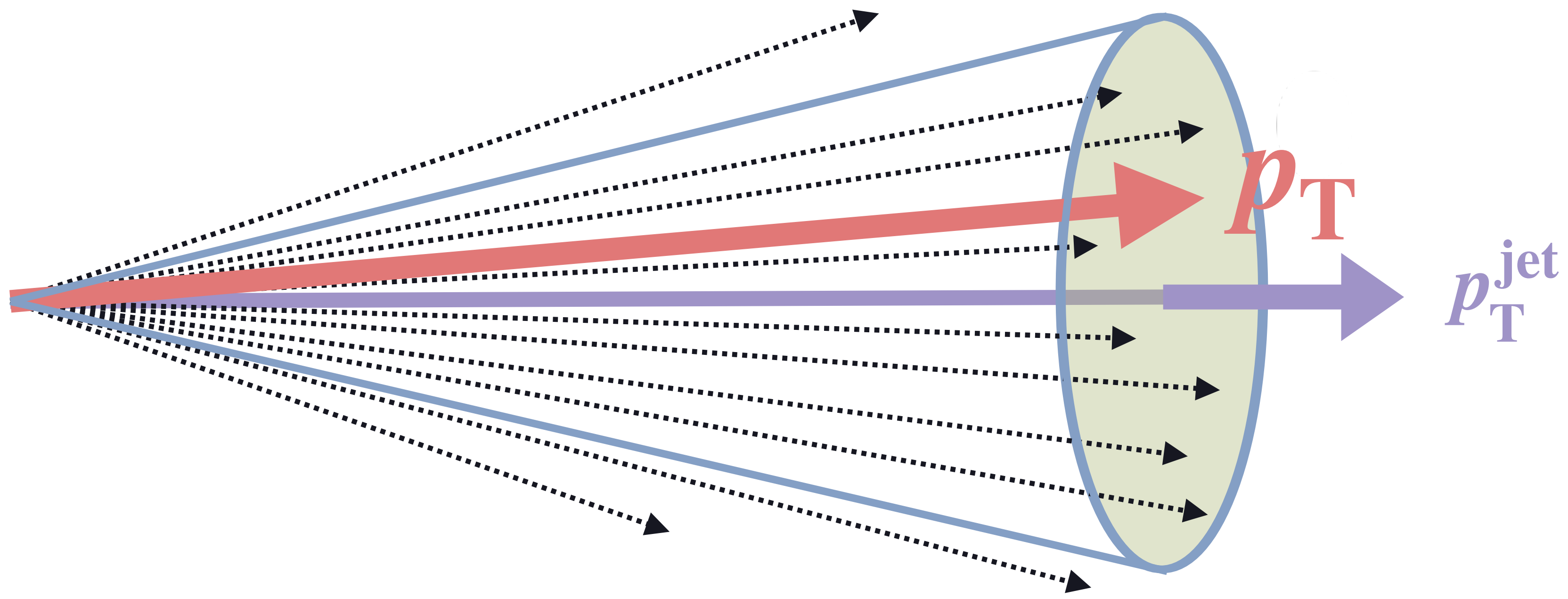
Charged Jet R_{AA}



No strong jet cone size dependence is observed

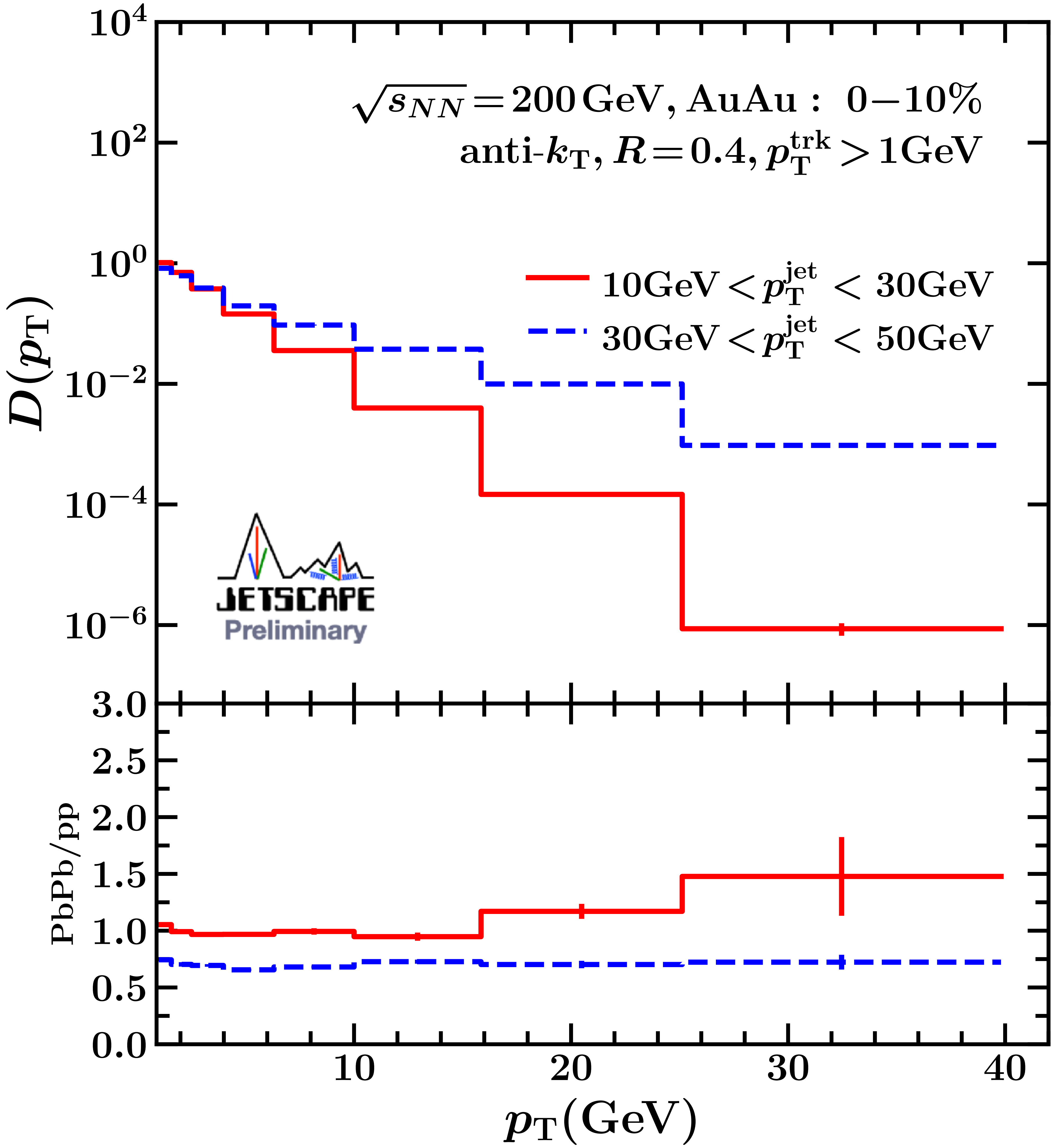
Prediction for Jet fragmentation function

Jet fragmentation function



$$D(p_T) = \frac{1}{N_{jet}} \sum_{jets} \frac{dN_{trk}}{dp_T^{ch}}$$

$D(p_T)$ for higher jet p_T^{jet} is strongly modified



Jet grooming and soft drop condition

Take a jet clustered with e.g. anti-kt algorithm

↓

Re-cluster it using Cambridge-Aachen (C/A) algorithm

↓

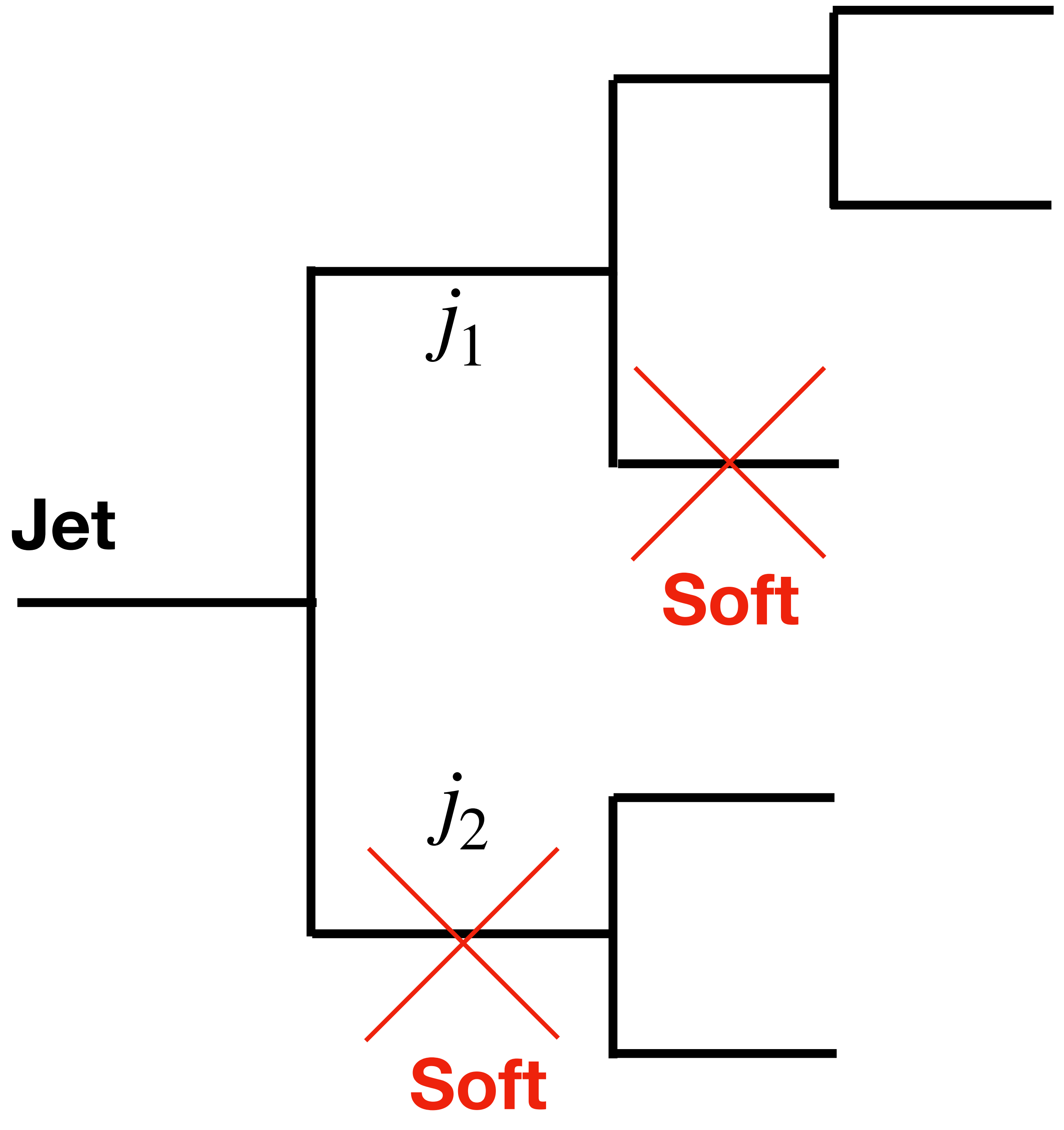
Traverse the clustering tree backwards

↓

If a branch point satisfies the soft drop condition, stop

↓

Otherwise remove the softer branch and continue down the harder branch



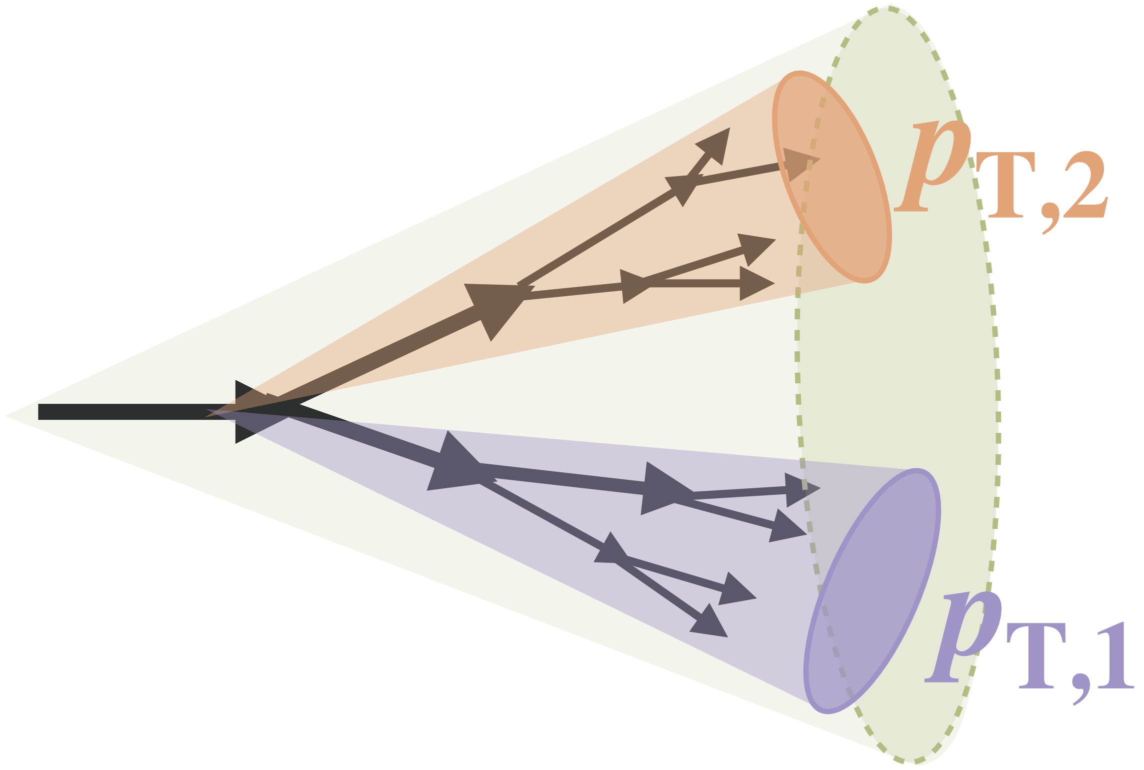
$$\frac{\min(p_{T,j_1},p_{T,j_2})}{p_{T,j_1}+p_{T,j_2}} > z_{cut}\left(\frac{\Delta R(j_1,j_2)}{R}\right)^{\beta}; \qquad z_{cut}=0.2 \quad \beta=0$$

By construction the condition fails for wide-angle soft radiation

Prediction for Jet splitting function (z_g)

- **Momentum fraction in the hardest splitting of jet (z_g)**

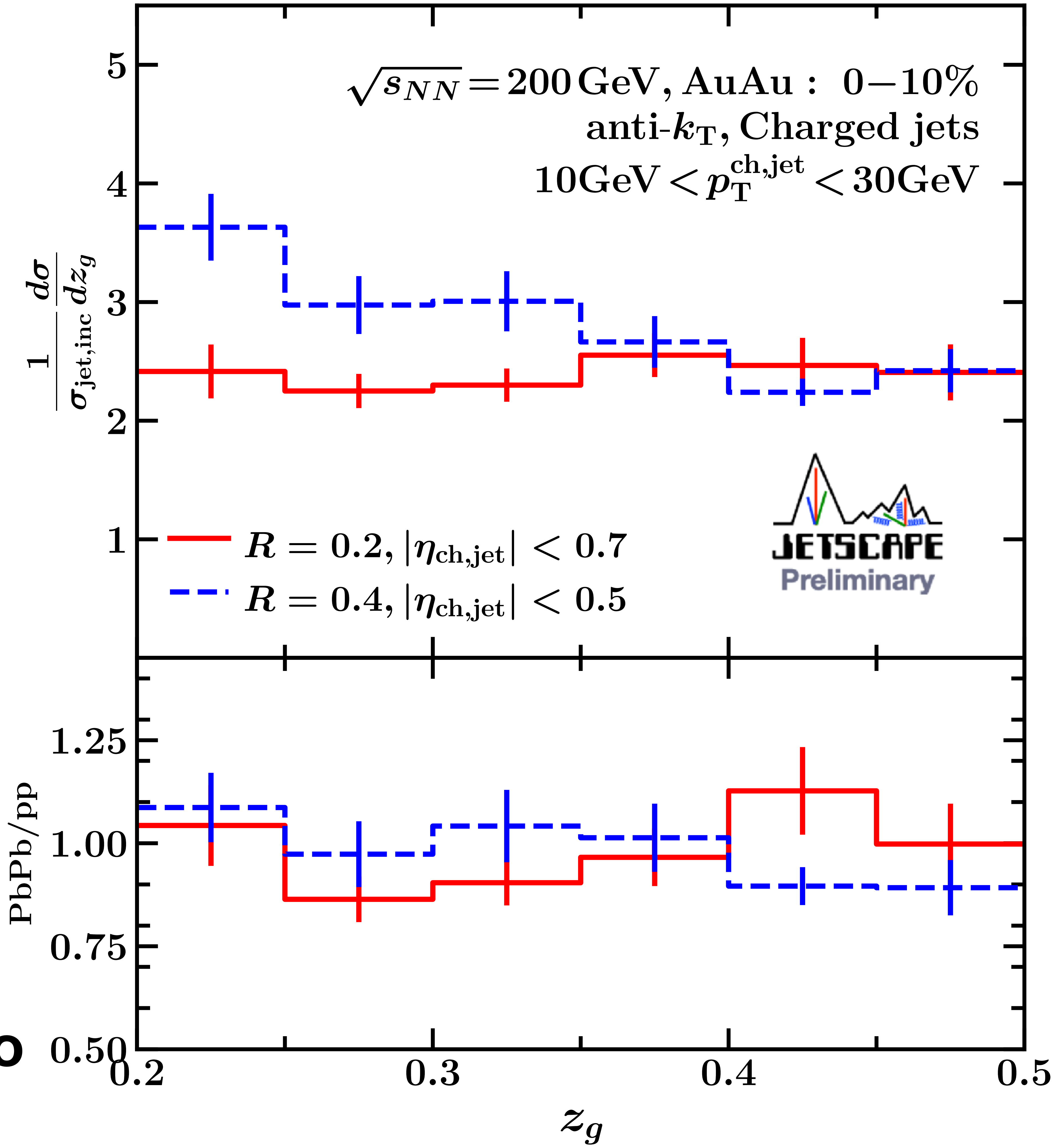
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

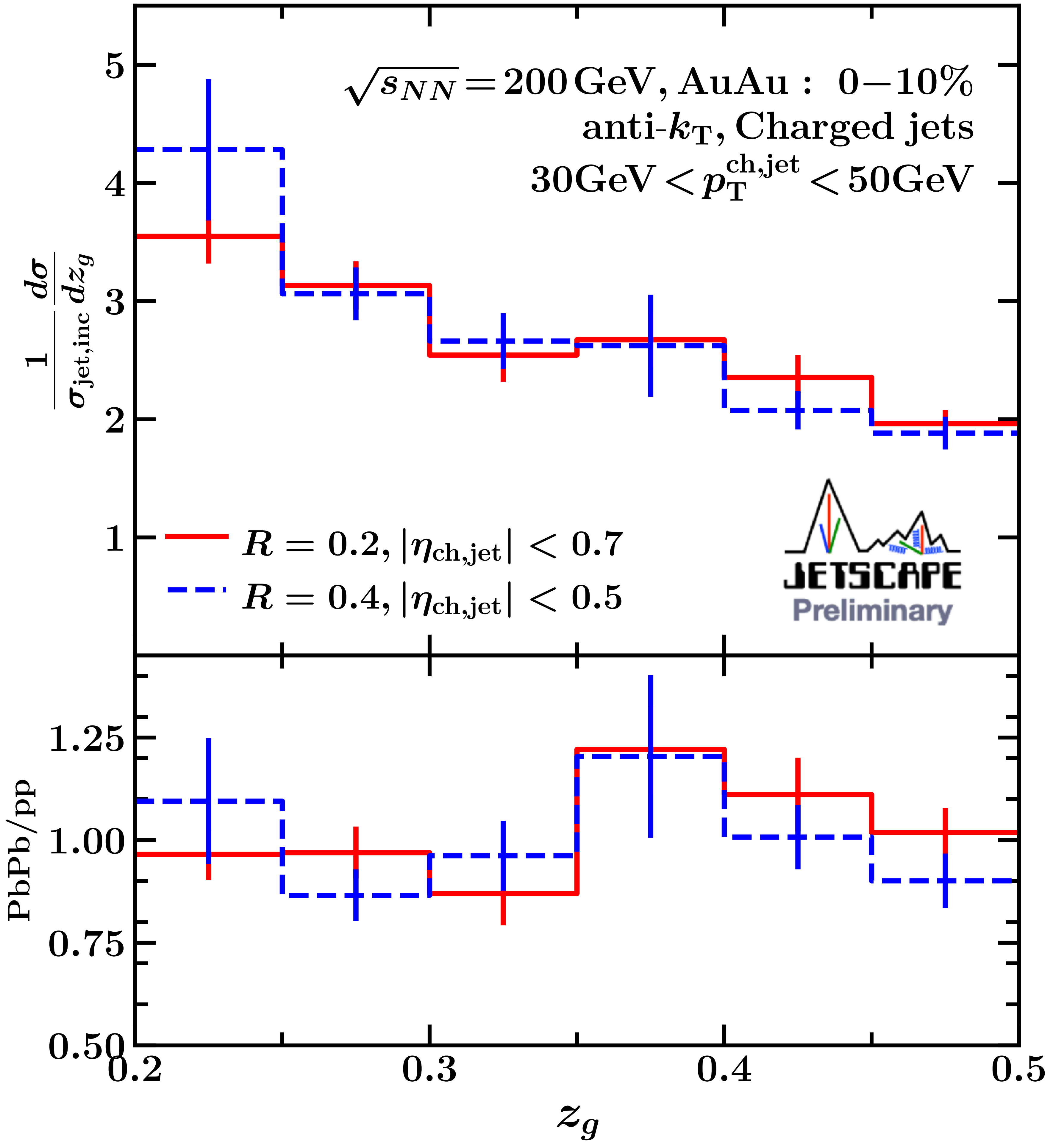


$z_{cut} = 0.2, \beta = 0$

The nuclear modification are not significant within the statistical uncertainty

The trend is very similar to ALICE measurement at @5.02TeV

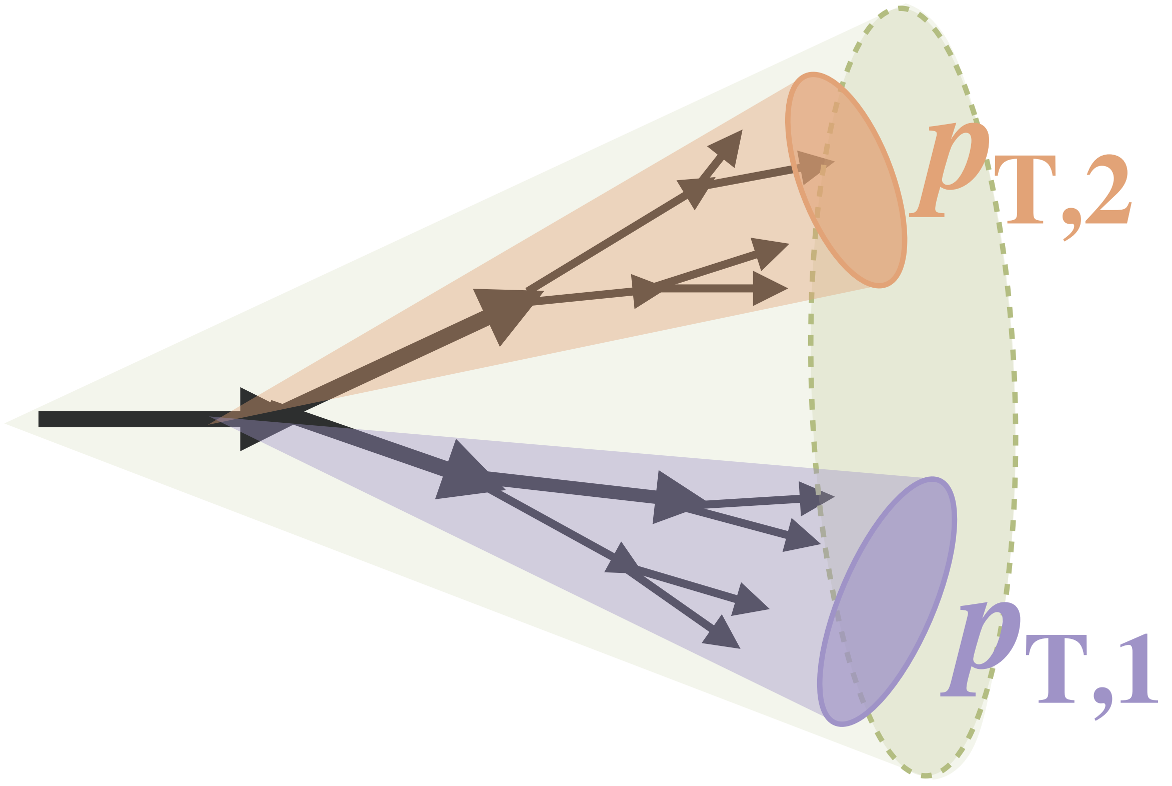




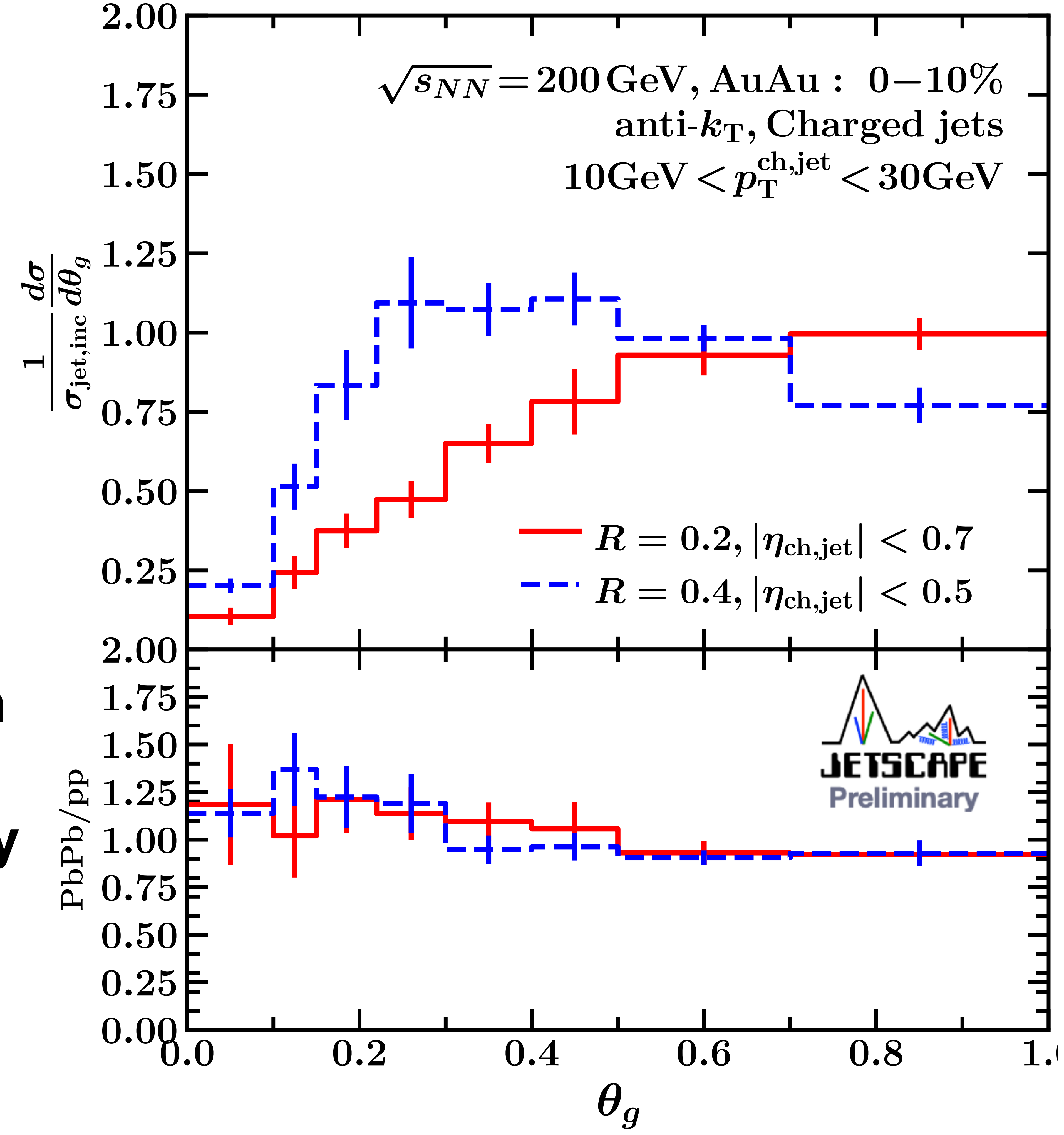
Prediction for Jet splitting angle (θ_g)

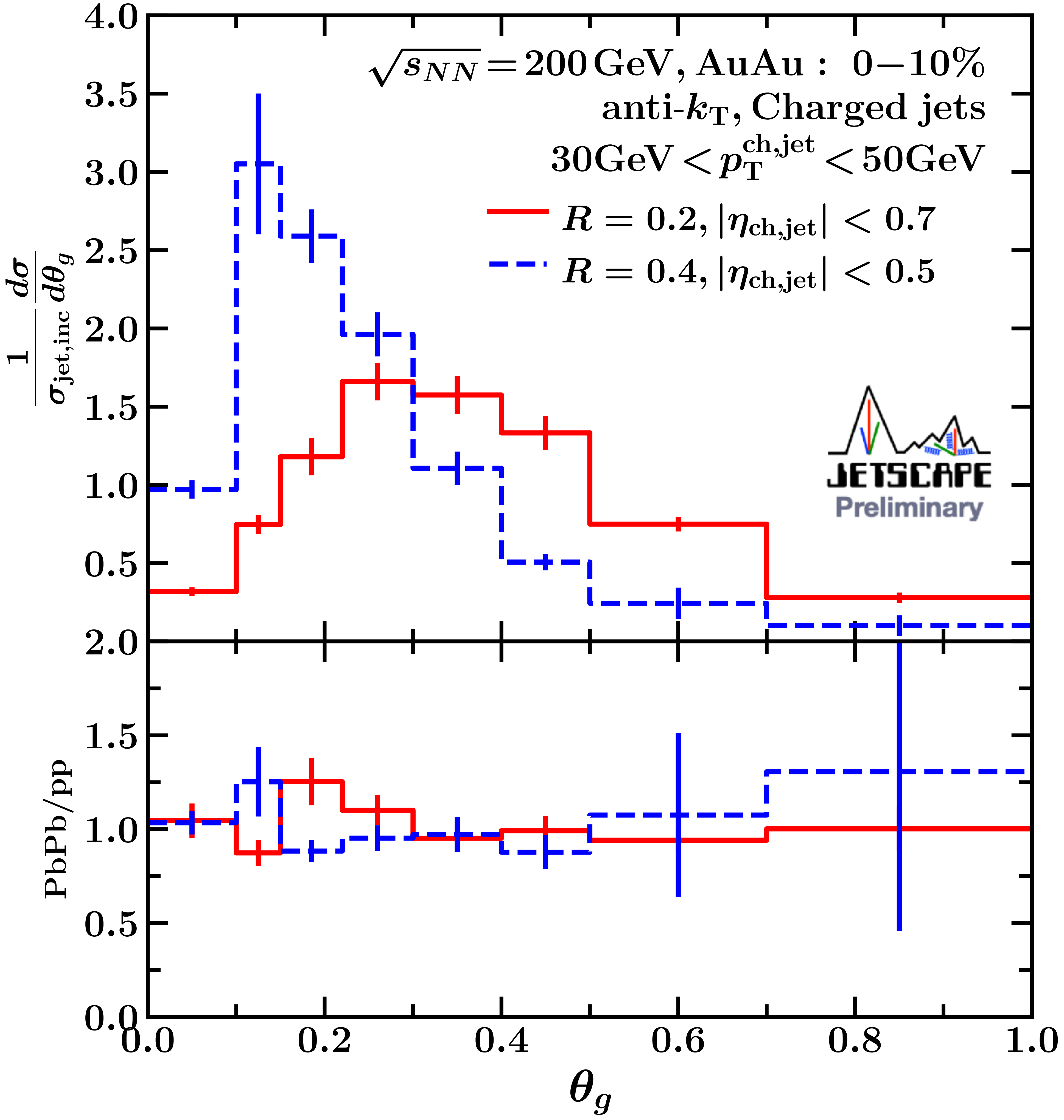
Groomed jet $\theta_g = r_g/R$

r_g**= Opening angle between two prongs**



$z_{cut} = 0.2, \beta = 0$





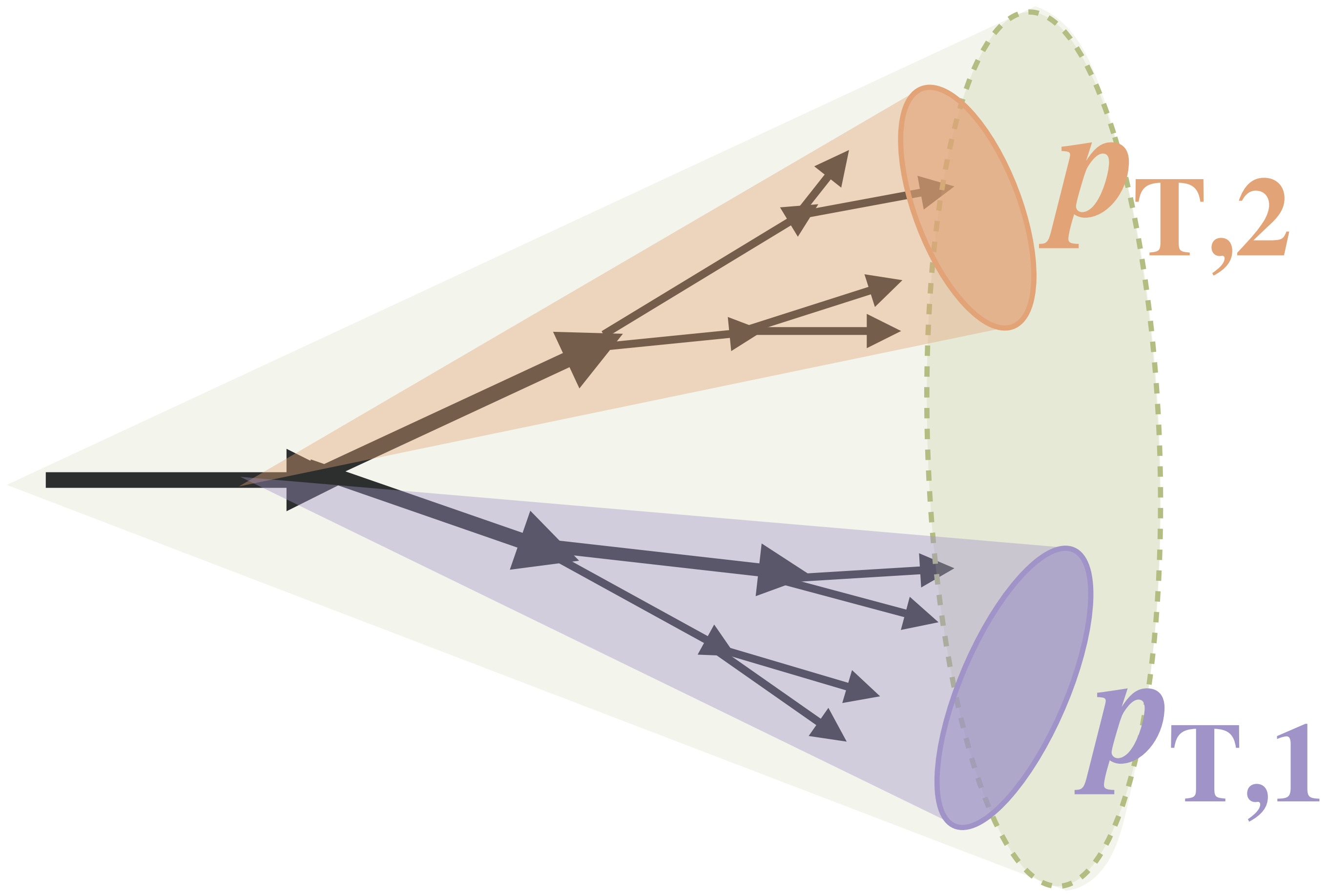
The nuclear modification are not significant within the statistical uncertainty

The trend is different compared LHC collision energies

Prediction for groomed jet mass (m_g)

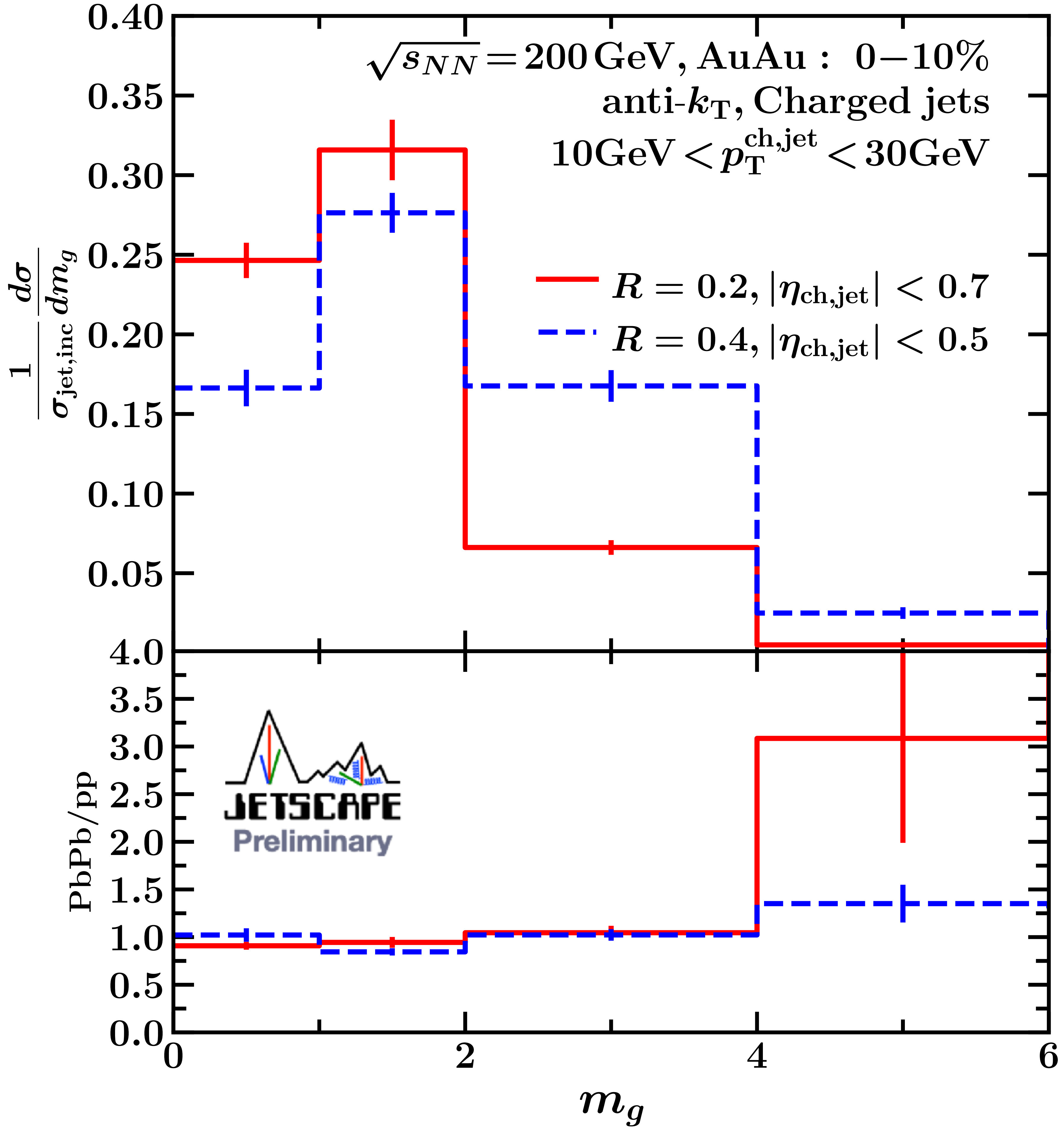
Groomed jet m_g

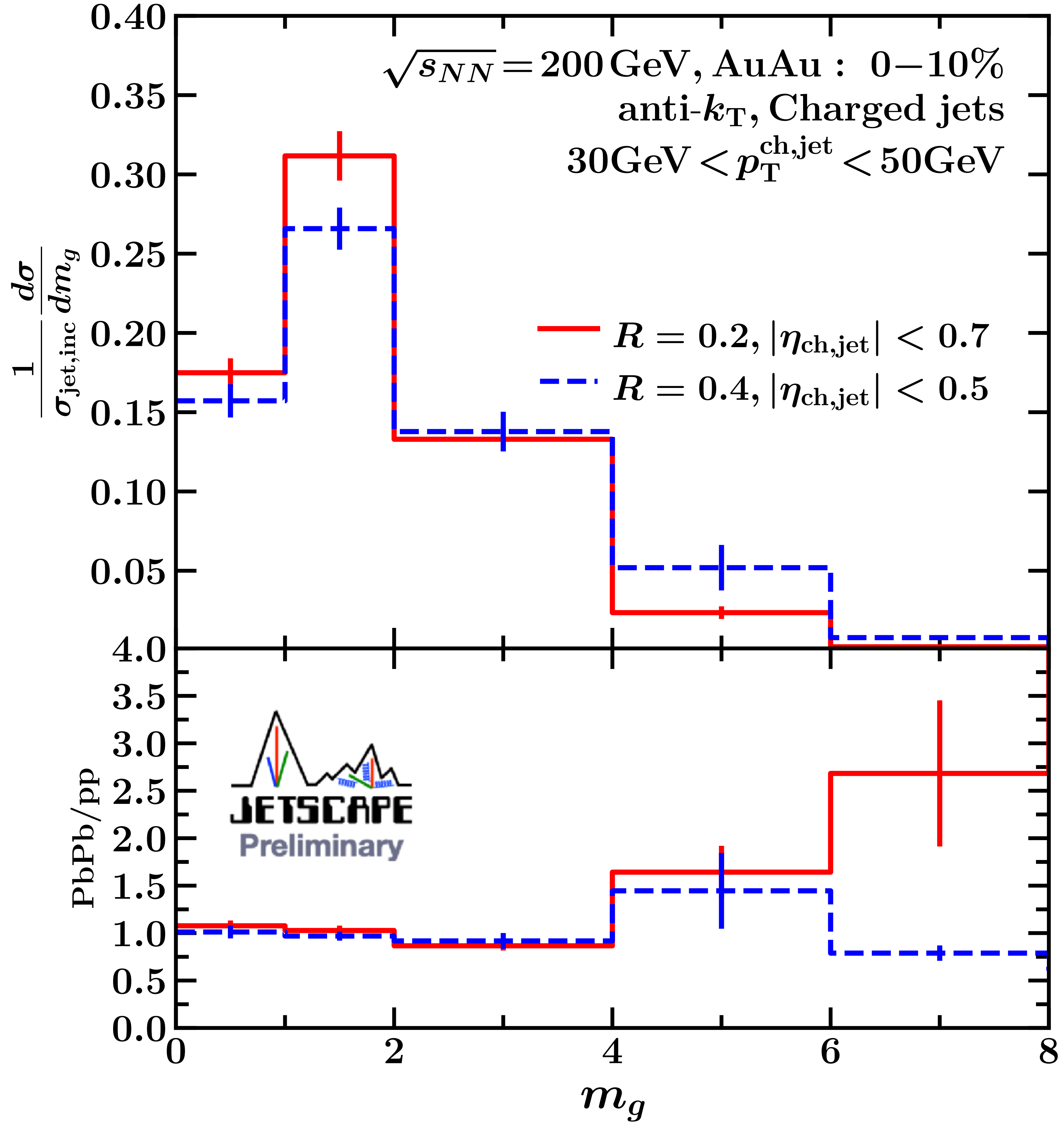
Without any smearing



$z_{cut} = 0.2, \beta = 0$

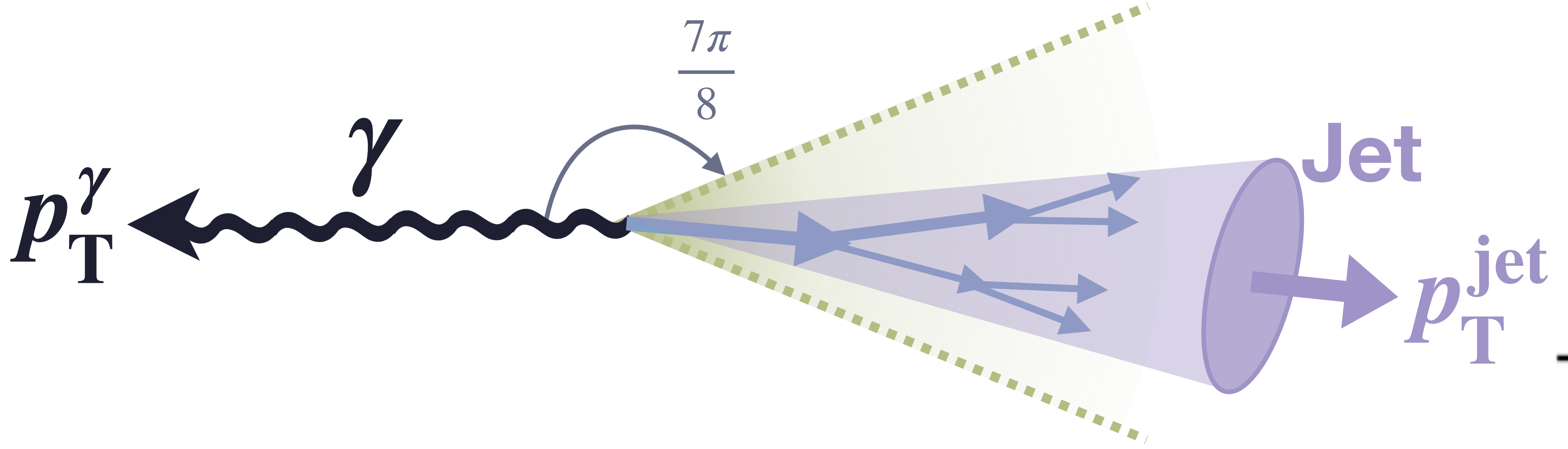
Nuclear modifications are not significant in low groomed jet mass region

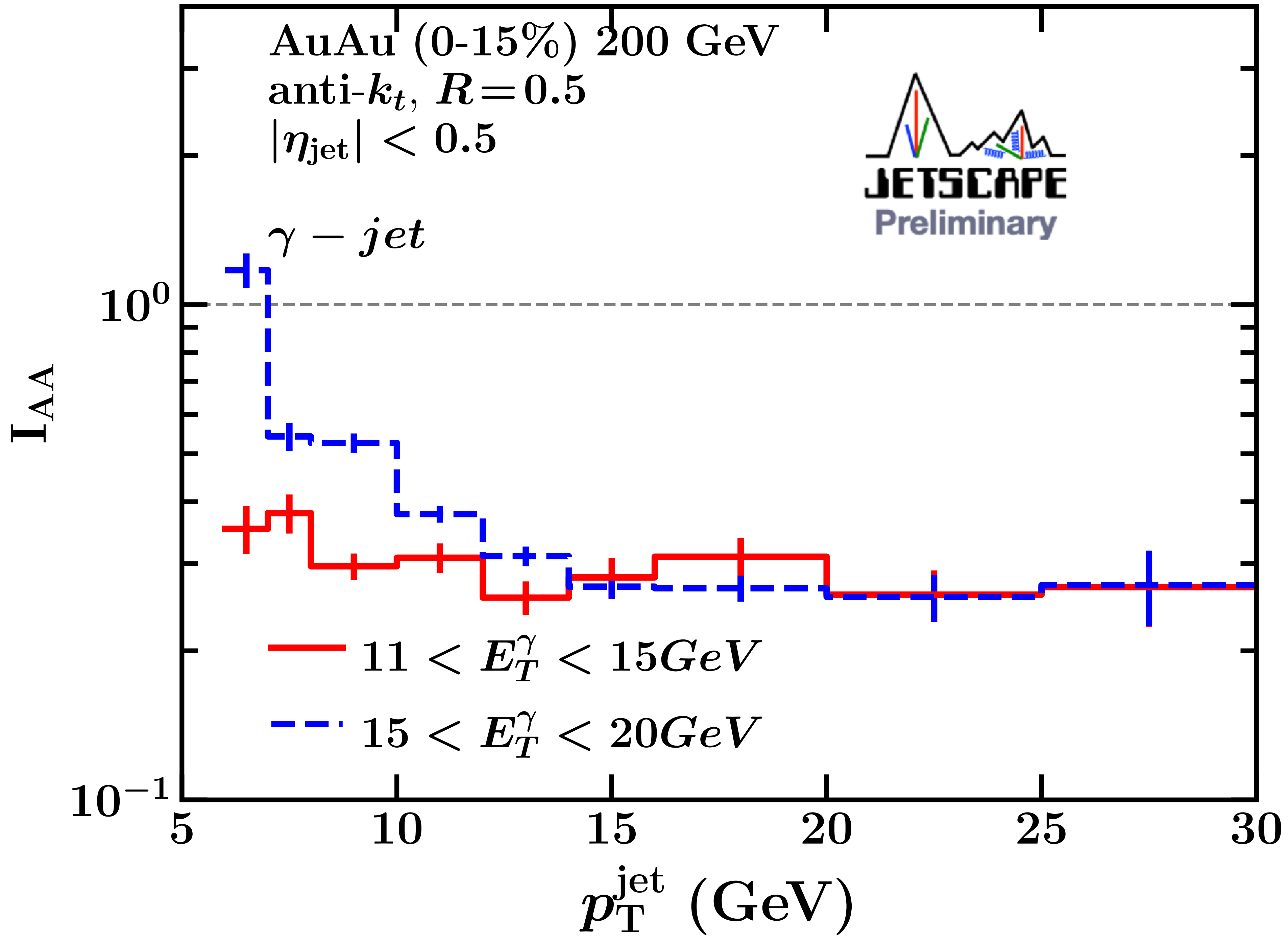


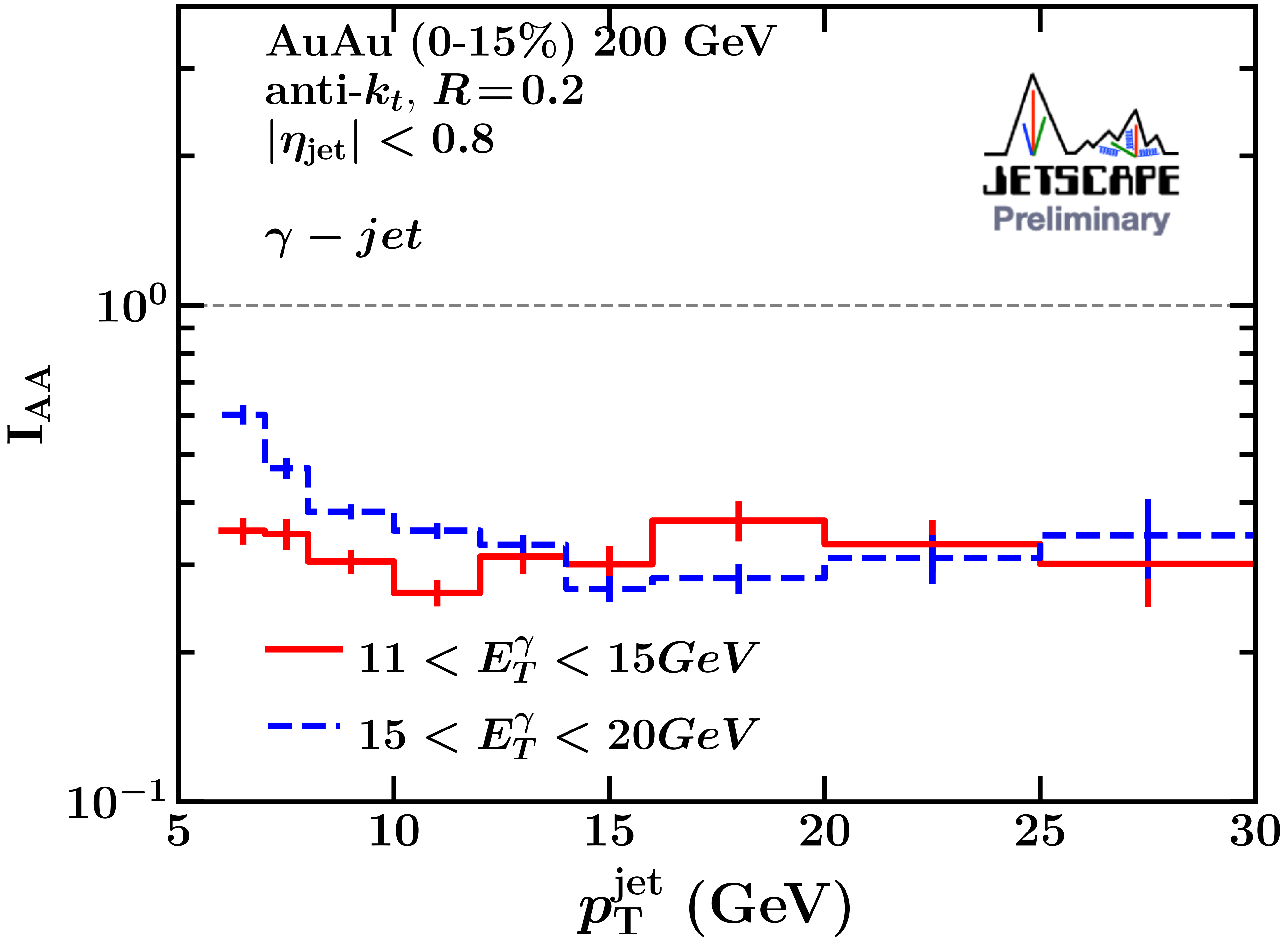


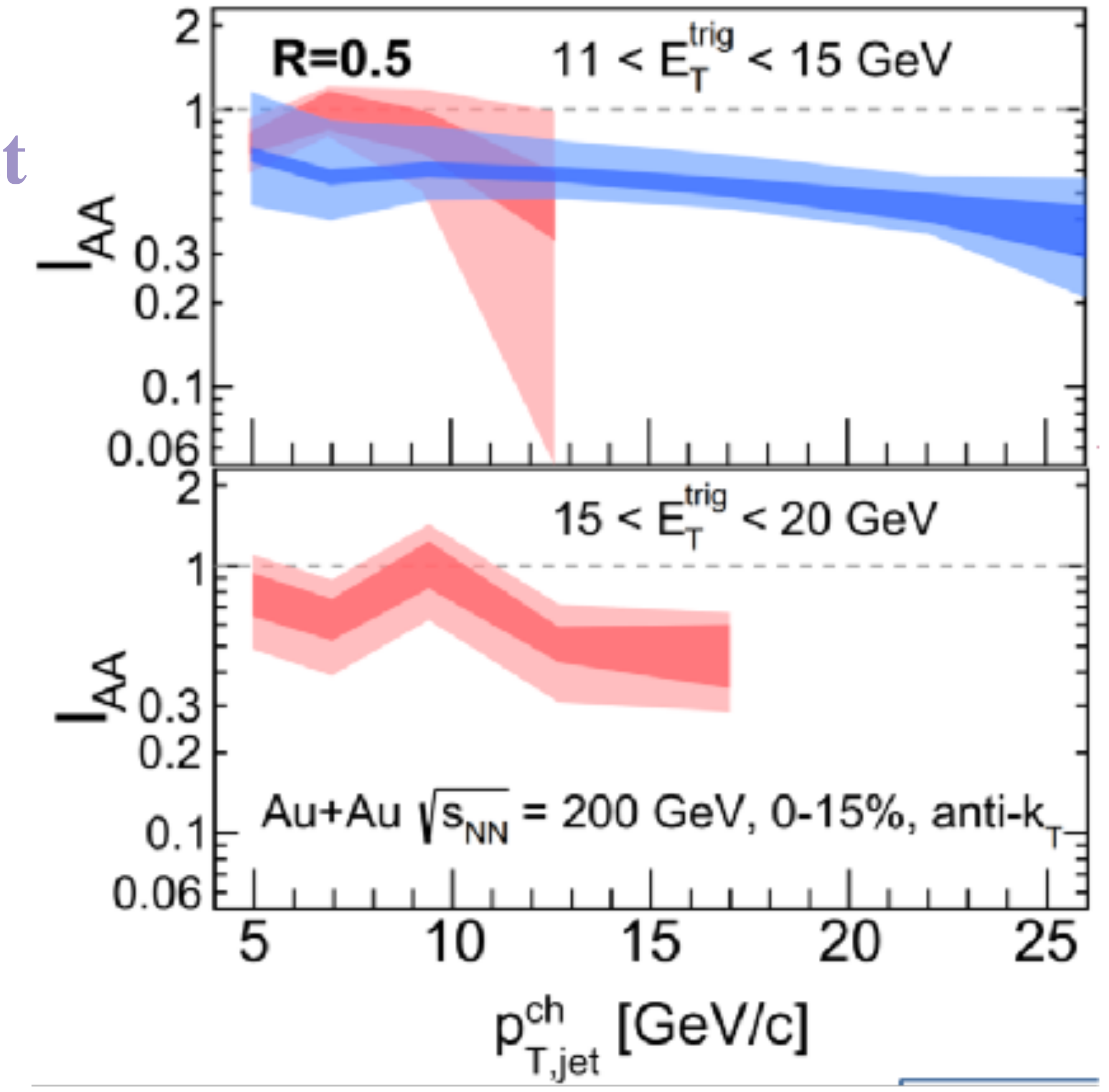
Prediction for γ-triggered jet results

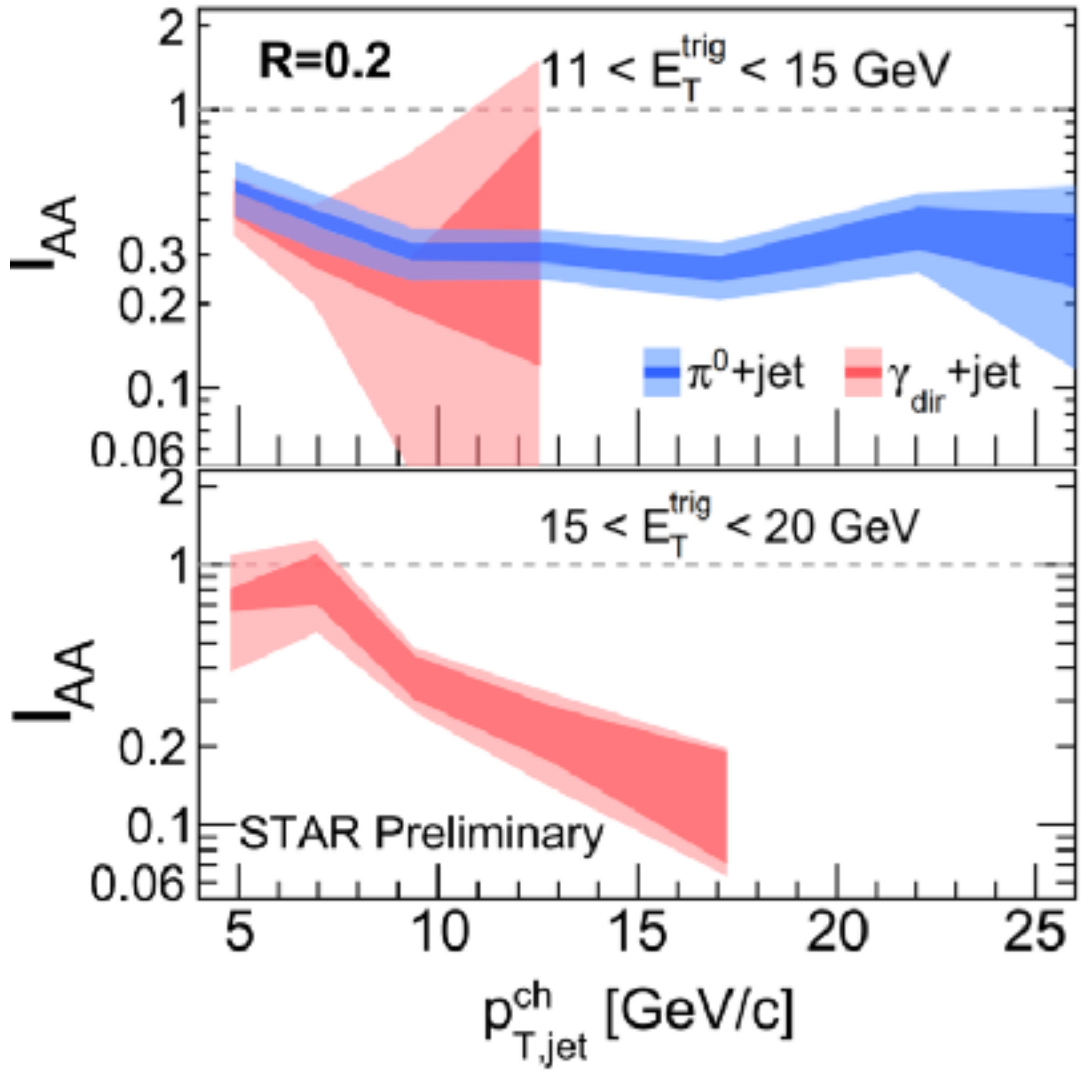
No isolation cut
Photons produced from hard scattering











Summary

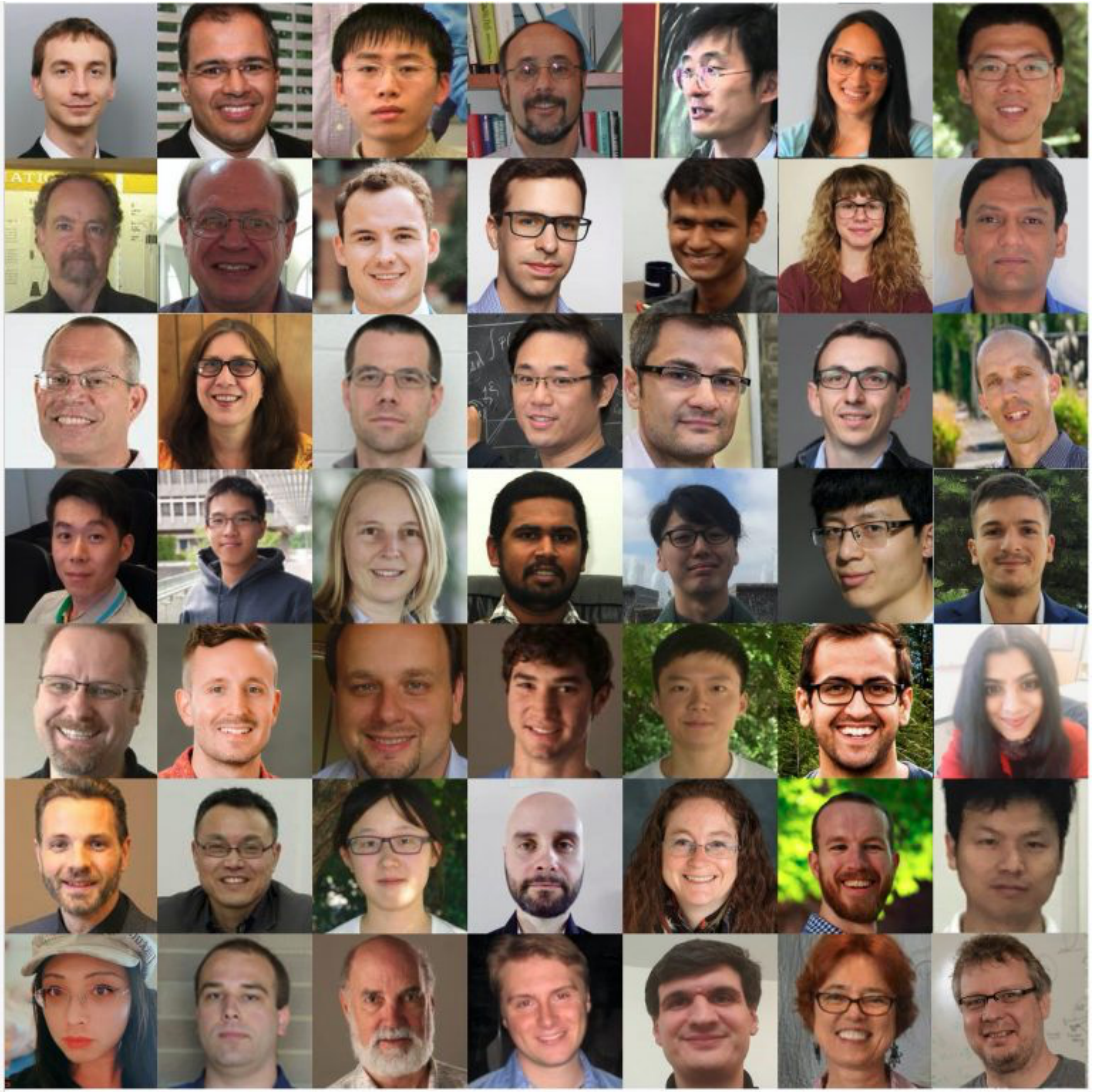
- JETSCAPE— a unified framework for the heavy-ion community— successfully demonstrate that a unified approach effectively captures the physics of multi-scale jet quenching in QCD plasma.

- Simultaneous description of inclusive jets, high-pT hadrons, jet substructure observables
  - ✦ pp19 tune give results consistent to the experimental data and PYTHIA
  - ✦ Jet R_{AA} and charged hadron R_{AA}
    - Constrain Jet R_{AA} and charged-hadron R_{AA} at 0-10% (5.02TeV)
    - Fit parameters provide a consistent description at two collision energies and different centrality

- Predictions at $\sqrt{s_{NN}} = 200$ GeV most central collisions
  - ✦ Jet cone size R dependence of Jet R_{AA} and charged jet R_{AA}
  - ✦ p_T dependence of Jet fragmentation function
  - ✦ Groomed jet observables
  - ✦ Photon-triggered jets

Thanks to

JETSCAPE **Collaboration**



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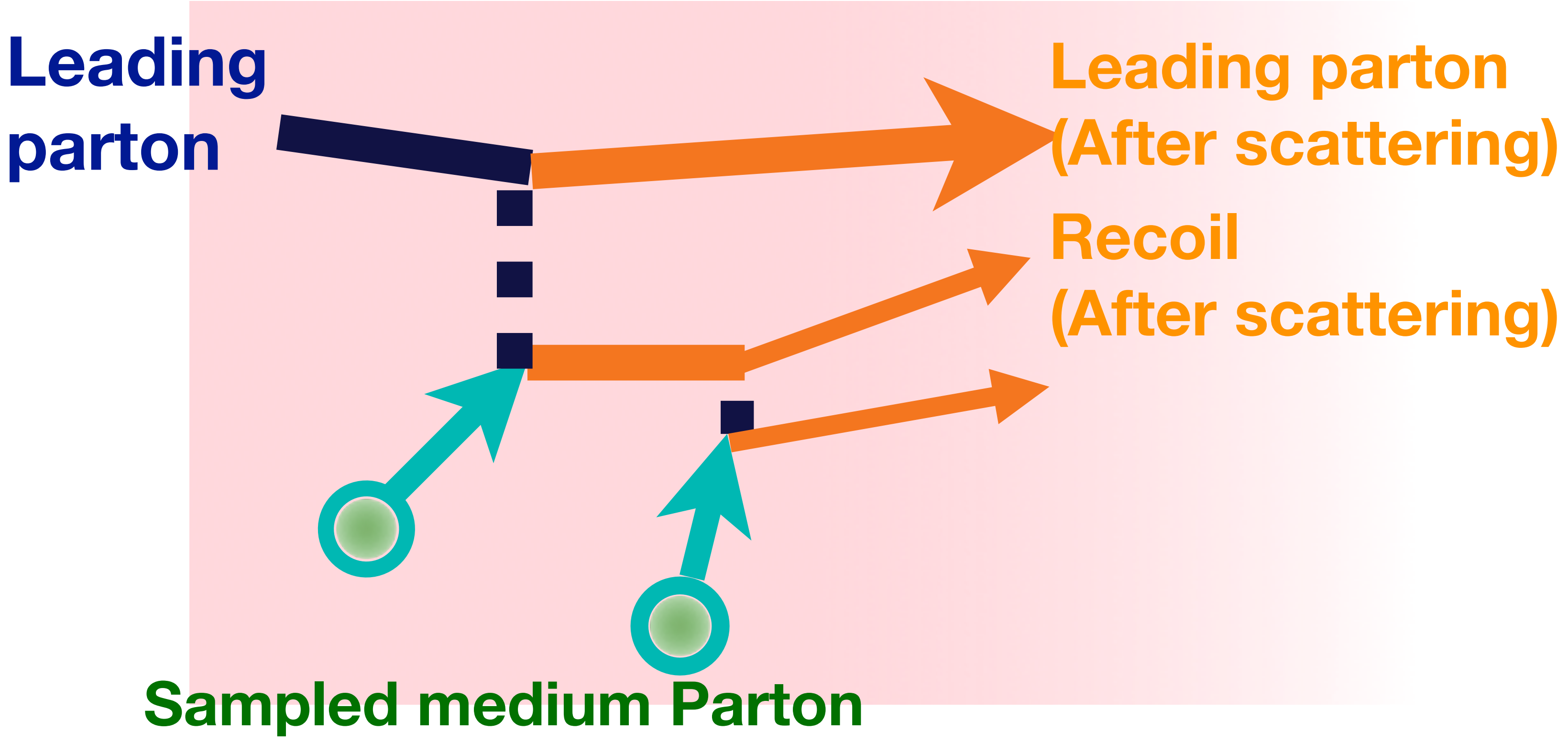
Sensitivity of inclusive jets from recoils



$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{jet shower}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{picked-up}} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{signal}}$$