2023 RHIC/AGS Annual Users' Meeting

# Comparing energy-loss models for jet quenching: medium modification of jets, jet substructures, and photons

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in collaboration with:

Rouzbeh Modarresi Yazdi, Sangyong Jeon, Charles Gale

refs: [Phys.Rev.C, 106 (2022) 064902, 107 (2023) 034908 + work in progress]

# contents

- introduction: heavy-ion collisions and jet energy loss

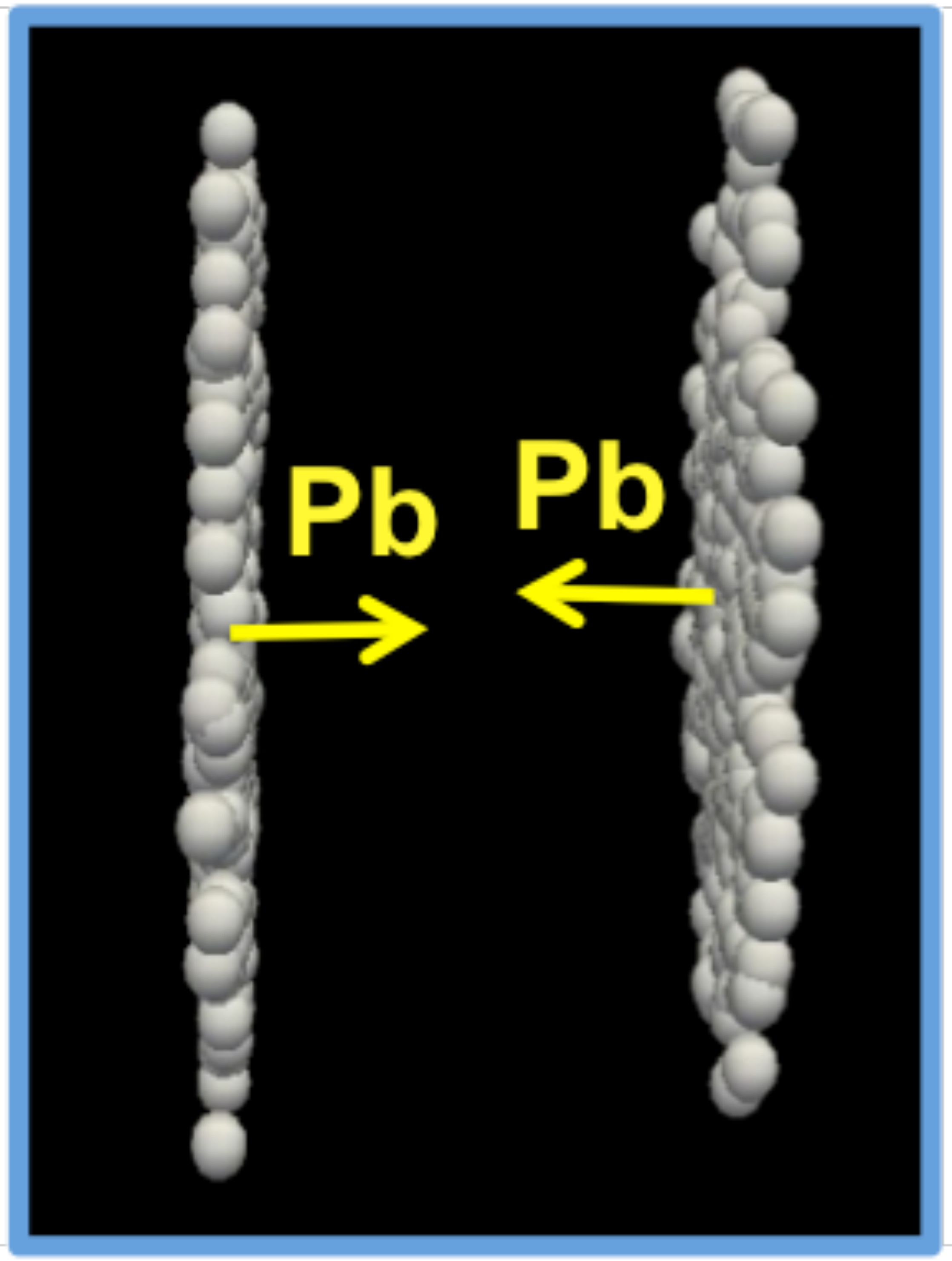
- how do we discriminate different energy-loss models?
  - jet substructure
  - jet-medium photon

- summary and outlook
  - can we observe the effect of non-perturbative collision kernels?

# Heavy-Ion Collisions



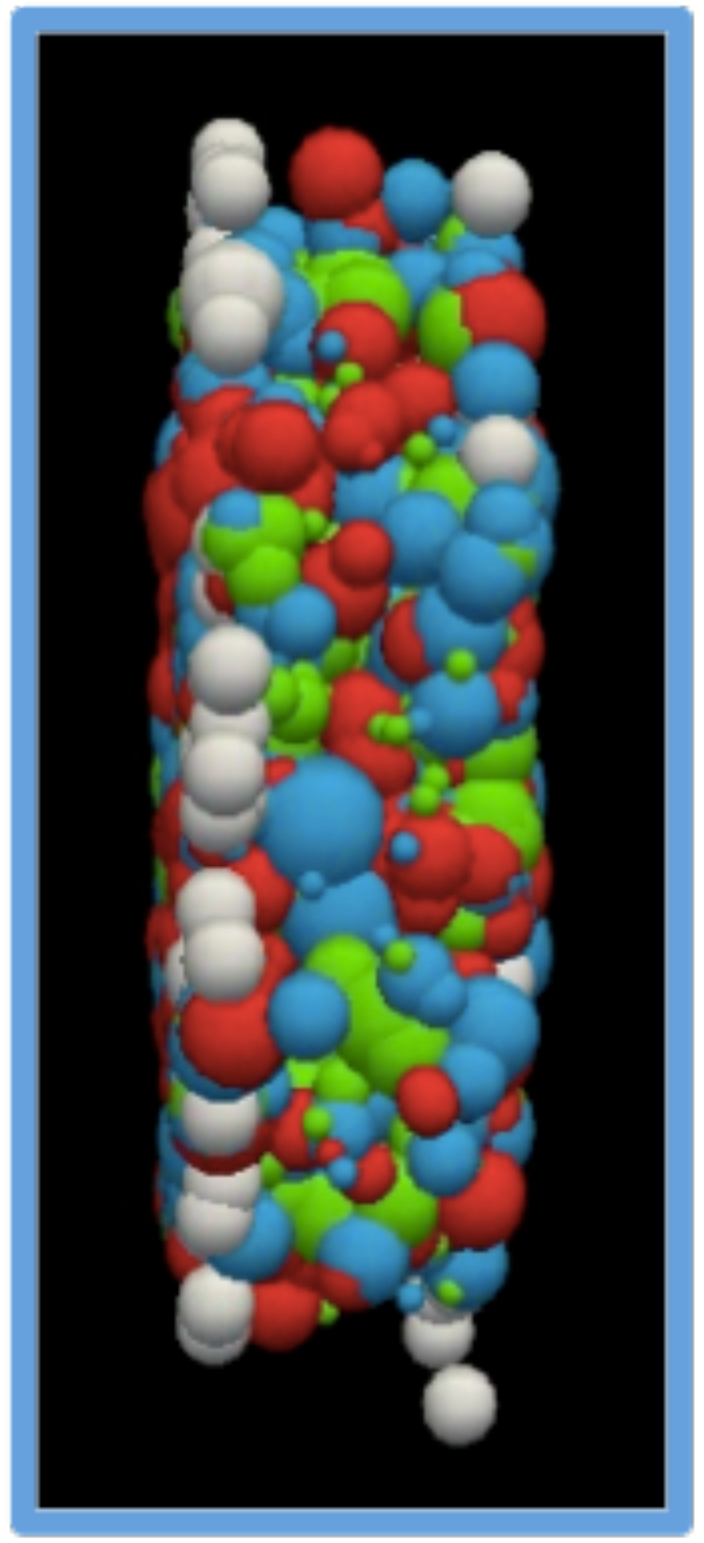
**Pre-reaction**



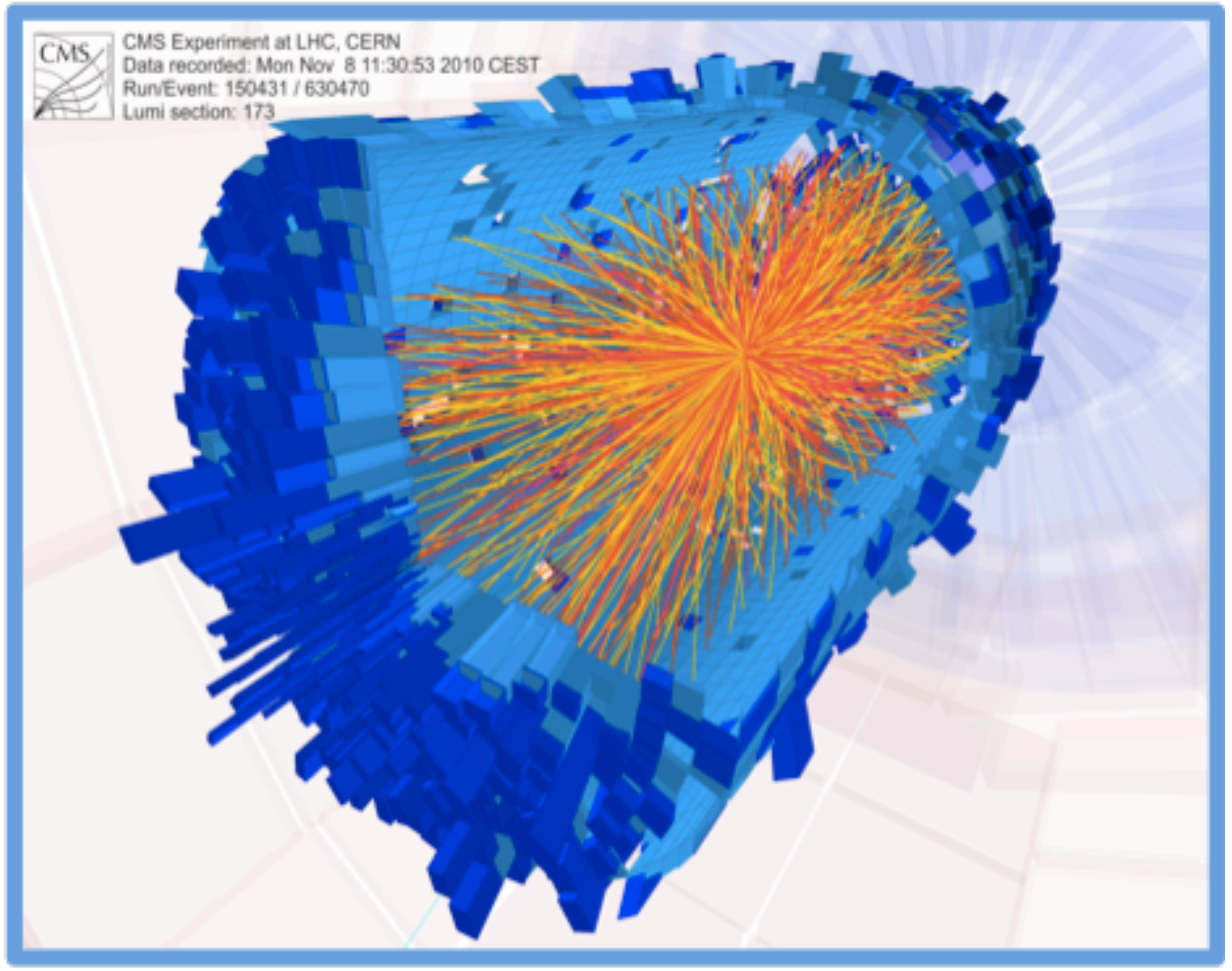

Lorentz contraction

$\gamma \sim 100 - 2000$

**Quark-Gluon Plasma**



**Detection**




final state particles

$N \sim 10^{3-4}$

# Jets -- tomography of QGP

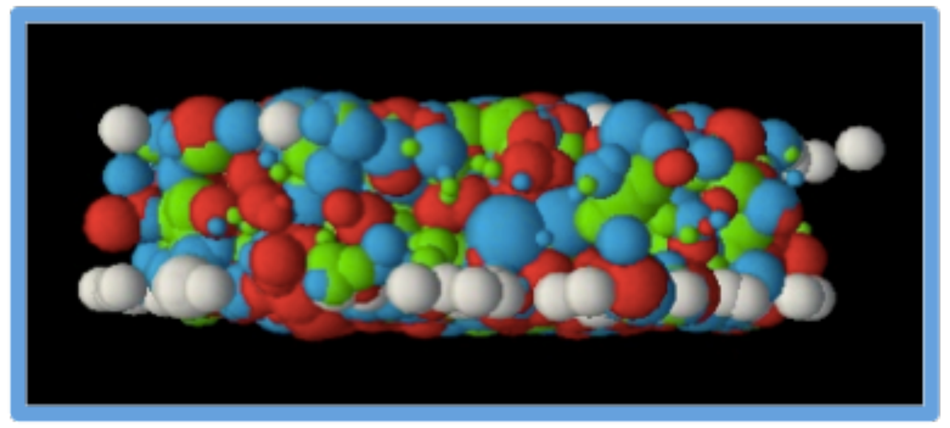


*Jet Quenching:*

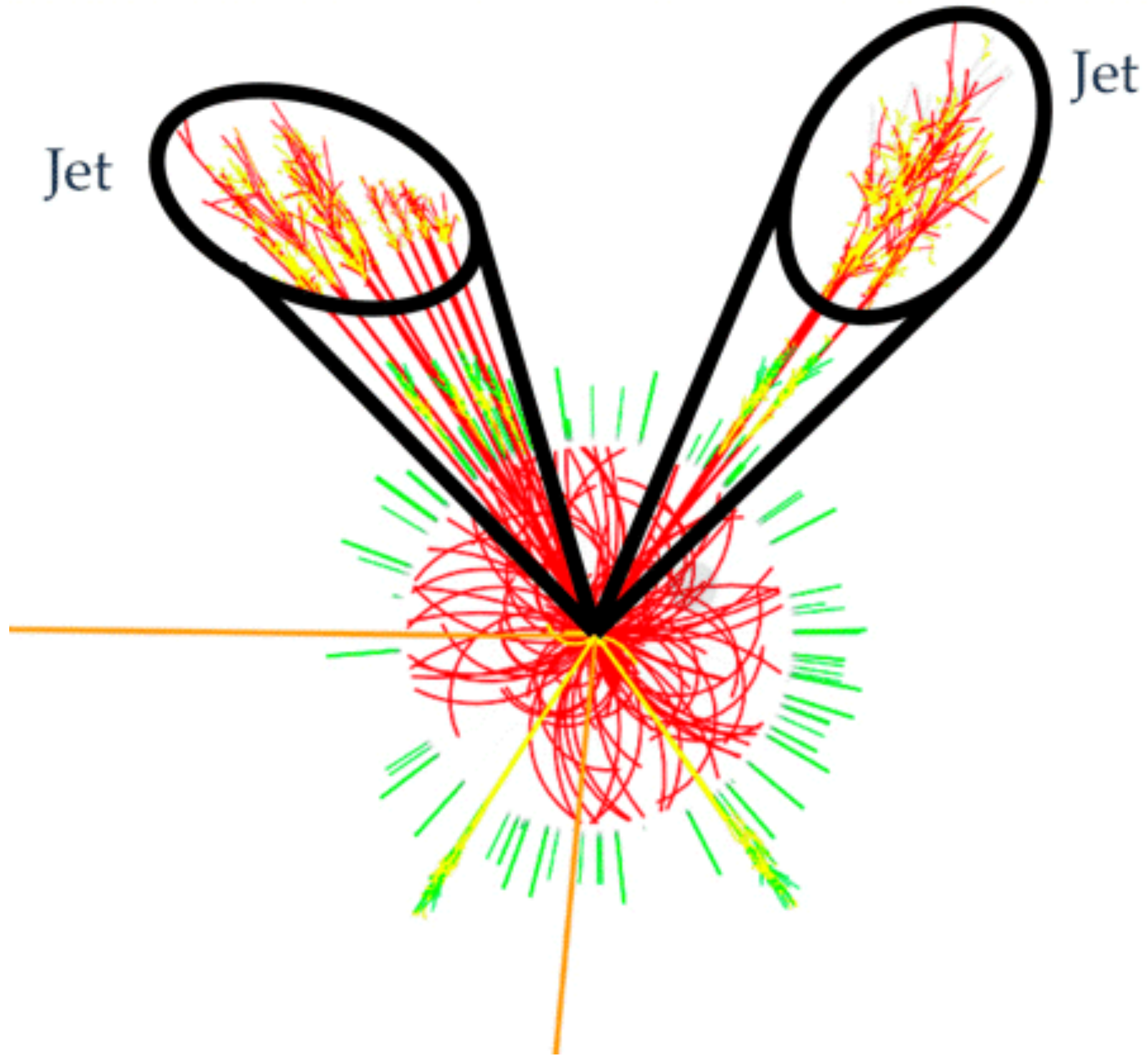
*particles w/ high momentum* $(E > 10\ \mathrm{GeV}) \gg (k_B T \sim 160\ \mathrm{MeV})$

nucl.+nucl. (init.) = p+p

QGP



nucl.+nucl. (fin.)




# two different models



## AMY-MARTINI

$$\frac{d\Gamma^{\text{AMY}}_{i\to jk}}{dz}(P,z) = \frac{\alpha_s P_{i\to jk}(z)}{[2Pz(1-z)]^2} f_j(zP) f_k((1-z)P) \times \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} \,\text{Re}\left[2\mathbf{p}_\perp \cdot \mathbf{g}_{(z,P)}(\mathbf{p}_\perp)\right] ,$$

$$2\mathbf{p}_\perp = i\delta E(z,P,\mathbf{p}_\perp)\mathbf{g}_{(z,P)}(\mathbf{p}_\perp) + \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2}\, \bar{C}(q_\perp) \times \Big\{ C_1[\mathbf{g}_{(z,P)}(\mathbf{p}_\perp) - \mathbf{g}_{(z,P)}(\mathbf{p}_\perp - \mathbf{q}_\perp)] + C_z[\mathbf{g}_{(z,P)}(\mathbf{p}_\perp) - \mathbf{g}_{(z,P)}(\mathbf{p}_\perp - z\mathbf{q}_\perp)] + C_{1-z}[\mathbf{g}_{(z,P)}(\mathbf{p}_\perp) - \mathbf{g}_{(z,P)}(\mathbf{p}_\perp - (1-z)\mathbf{q}_\perp)] \Big\} .$$

- full expansion in opacity
- no explicit time dependence (if no formation time effect)

Arnold-Moore-Yaffe:
JHEP: 11(2001)057, 12(2001)009, 06(2002)030

## DGLV-CUJET

Djordjevic-Gyulassy-Levai-Vitev:
Nucl.Phys.B: 571(2000)197, 594(2001)371,
Nucl.Phys.A: 733(2004) 265

# two different models



## AMY-MARTINI

$$\frac{d\Gamma^{AMY}_{i\to jk}}{dz}(P,z) = \frac{\alpha_s P_{i\to jk}(z)}{[2Pz(1-z)]^2} f_j(zP) f_k((1-z)P) \times \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} \,\mathrm{Re}\left[2\mathbf{p}_\perp \cdot \mathbf{g}_{(z,P)}(\mathbf{p}_\perp)\right] ,$$

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## DGLV-CUJET

$$\frac{d\Gamma^{DGLV}_{i\to gi}}{dz}(P,z,\tau) = \frac{18 C_i^R}{\pi^2} \frac{4+N_f}{16+9N_f} \rho(T) \times \int d^2\mathbf{k}_\perp \Bigg\{ \frac{1}{z_+} \left|\frac{dz_+}{dz}\right| \alpha_s\!\left(\frac{\mathbf{k}_\perp^2}{z_+ - z_+^2}\right) \times \int \frac{d^2\mathbf{q}_\perp}{\mathbf{q}_\perp^2} \Bigg[ \frac{\alpha_s^2(\mathbf{q}_\perp^2)}{\mathbf{q}_\perp^2 + \mu^2} \frac{-2}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2} \times \left( \frac{\mathbf{k}_\perp \cdot (\mathbf{k}_\perp - \mathbf{q}_\perp)}{\mathbf{k}_\perp^2 + \chi^2} - \frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2} \right) \times \left( 1 - \cos\left( \frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2}{2z_+ P} \tau \right) \right) \Bigg] \Bigg\} ,$$

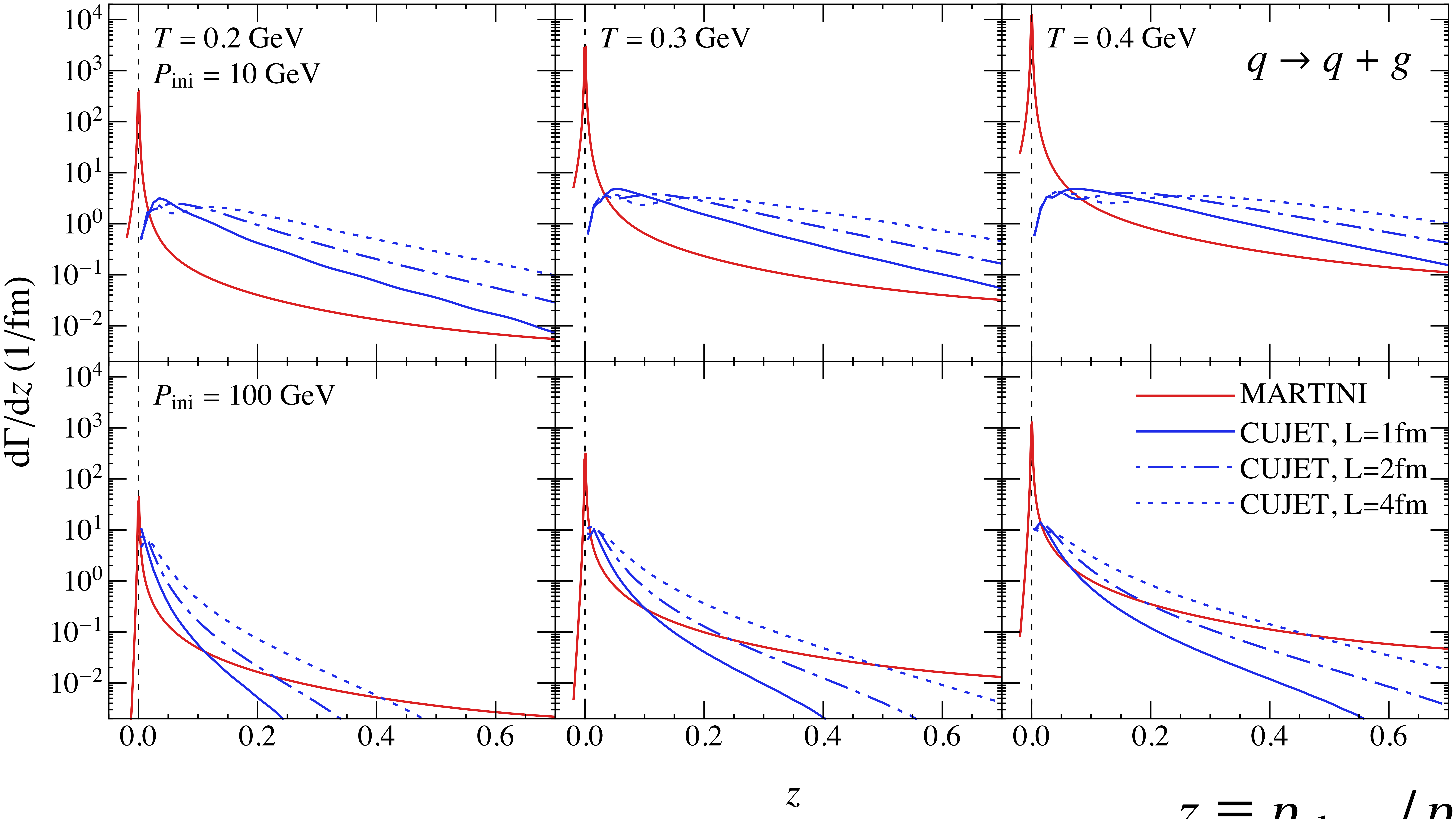
- first order in opacity expansion
- explicit time dependence

Djordjevic-Gyulassy-Levai-Vitev:
Nucl.Phys.B: 571(2000)197, 594(2001)371,
Nucl.Phys.A: 733(2004) 265

# comparison



radiation rates

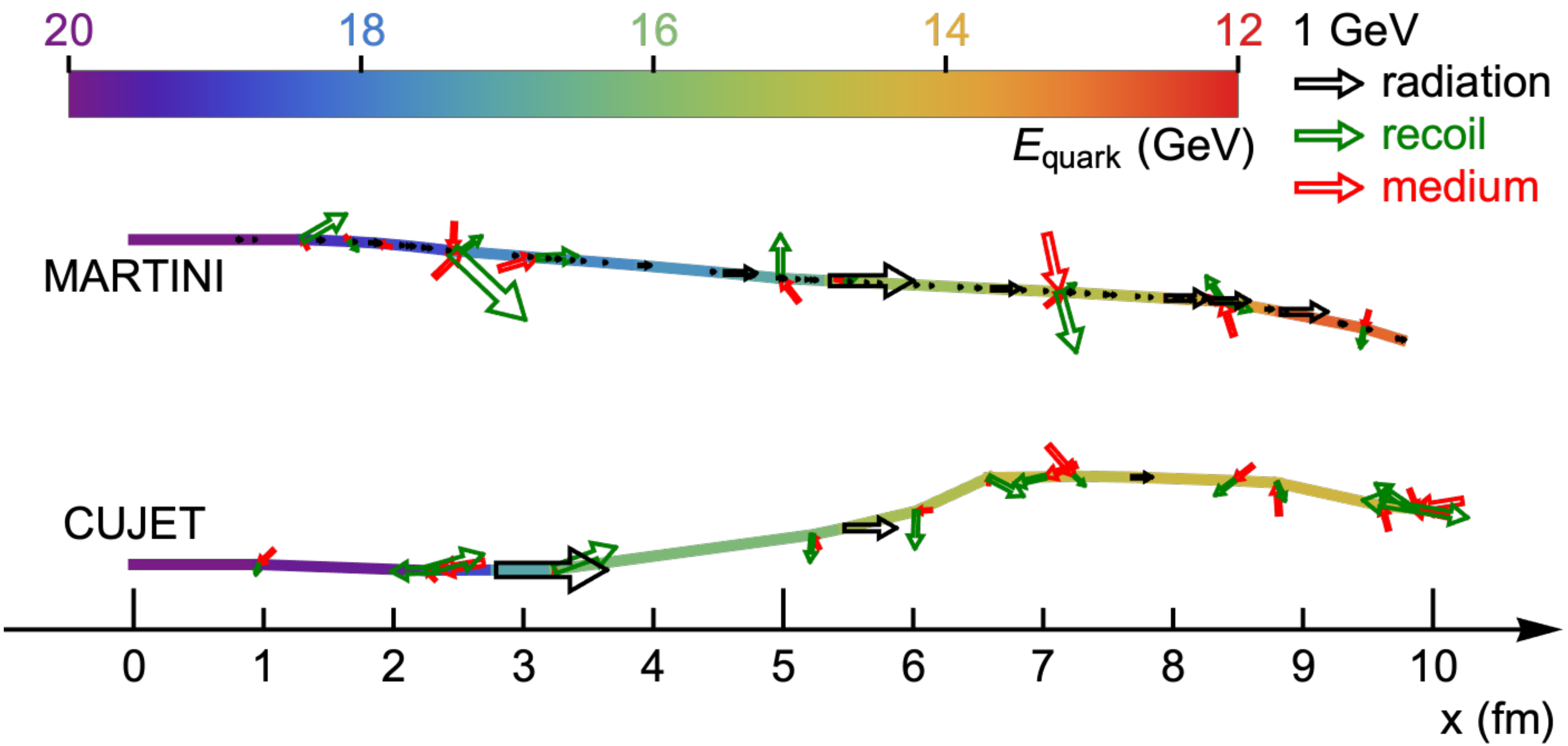



$z \equiv p_{\rm gluon} / p_{\rm jet}$

# comparison



hard quark trajectories in a QGP brick



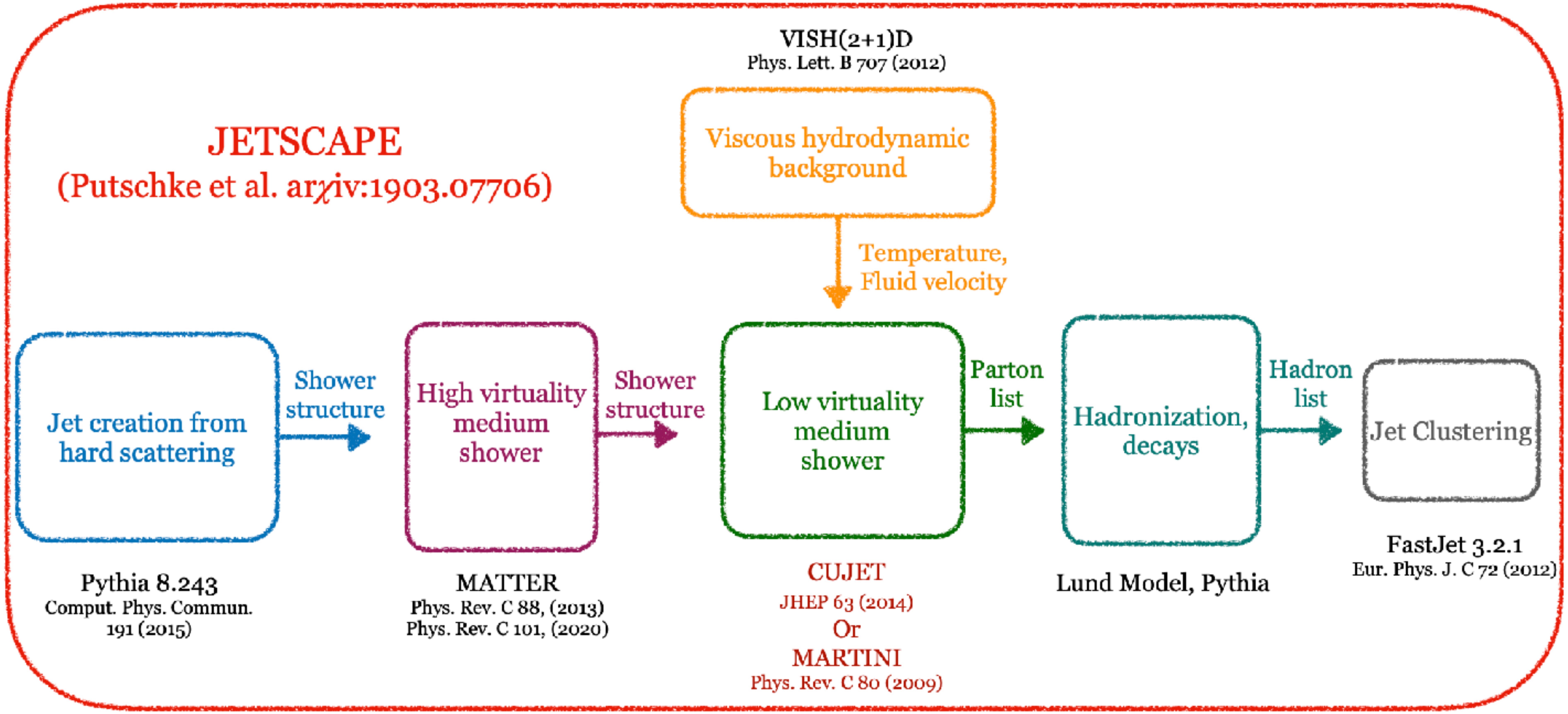

[select random MARTINI/CUJET events with similar final state energy]

# fair comparison in phenomenological simulations?

# fair comparison in phenomenological simulations?

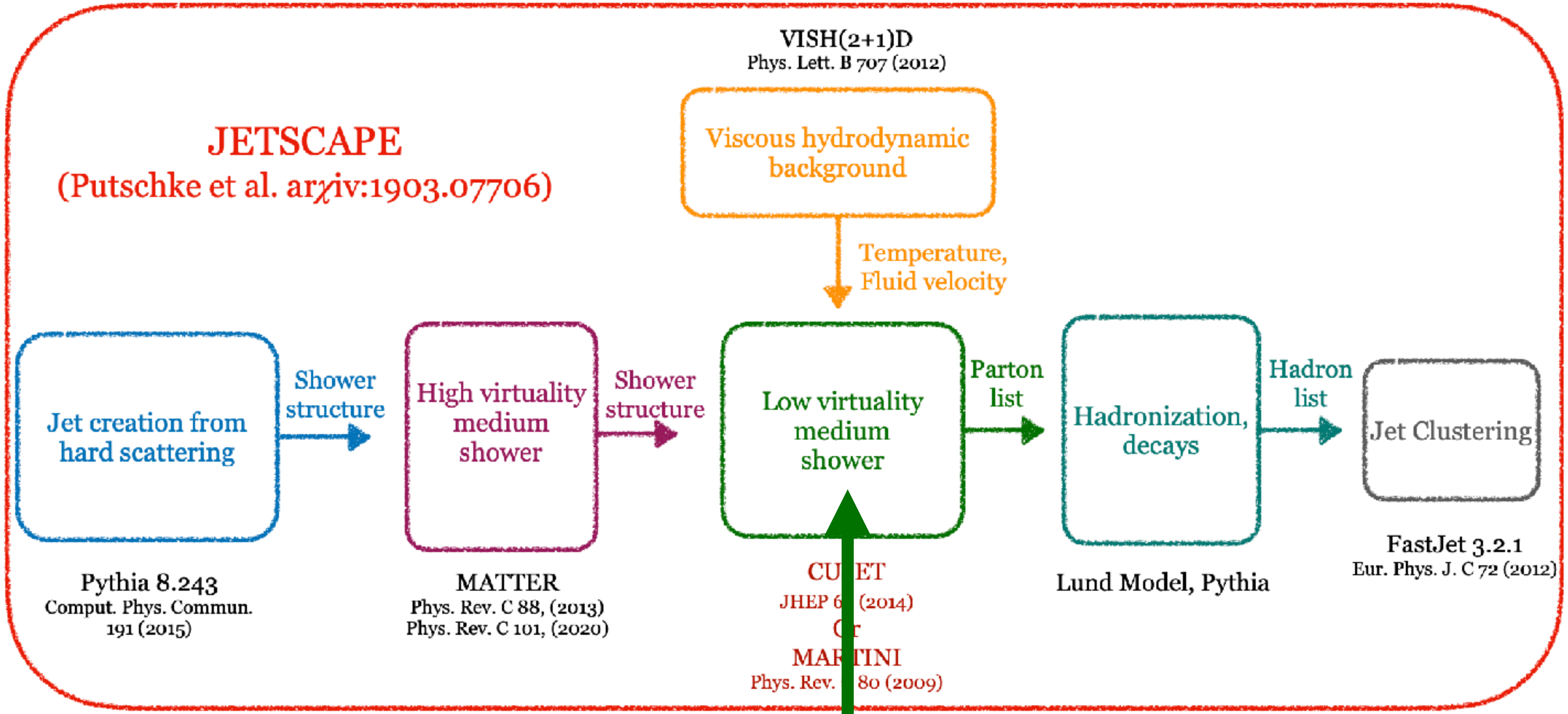


JETSCAPE: a framework that allows apple-to-apple comparison of energy-loss models



# fair comparison in phenomenological simulations?

JETSCAPE: a framework that allows apple-to-apple comparison of energy-loss models



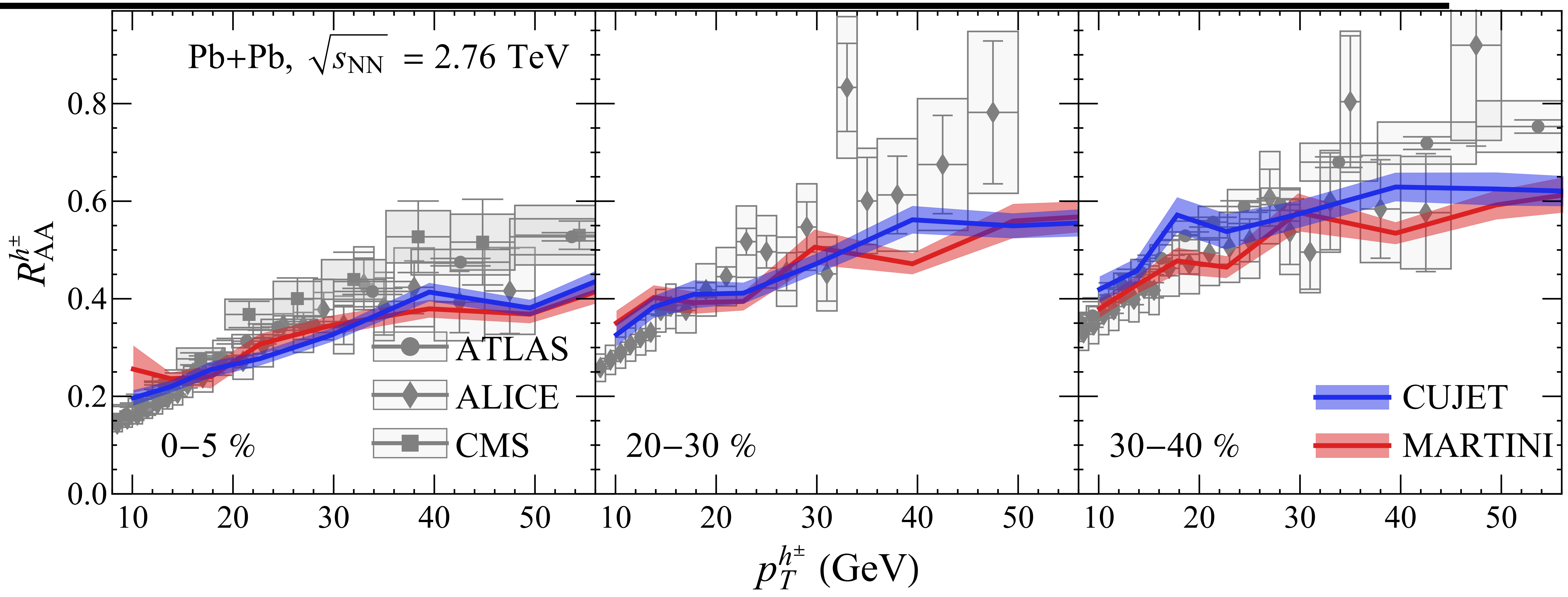

AMY-MARTINI / DGLV-CUJET
implemented here!

# comparison of observables



$$R_{AA}(p_T) \equiv \frac{\text{spectrum[AA]}}{\text{spectrum[pp]}}$$

hadrons:



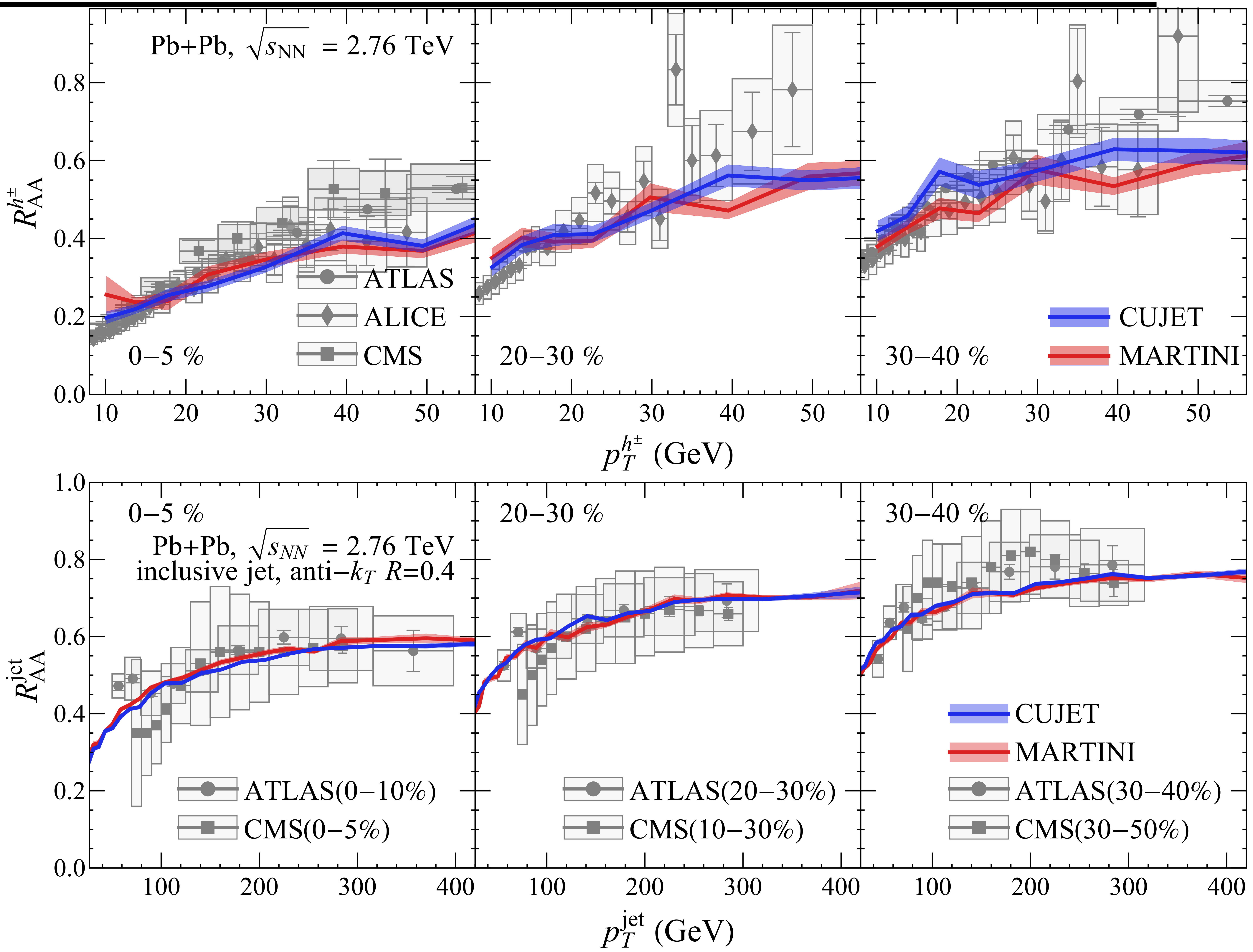

strong couplings tuned, separately for two models, to fit charged hadron RAA @ 0-5%

# comparison of observables

$$R_{AA}(p_T) \equiv \frac{\text{spectrum[AA]}}{\text{spectrum[pp]}}$$

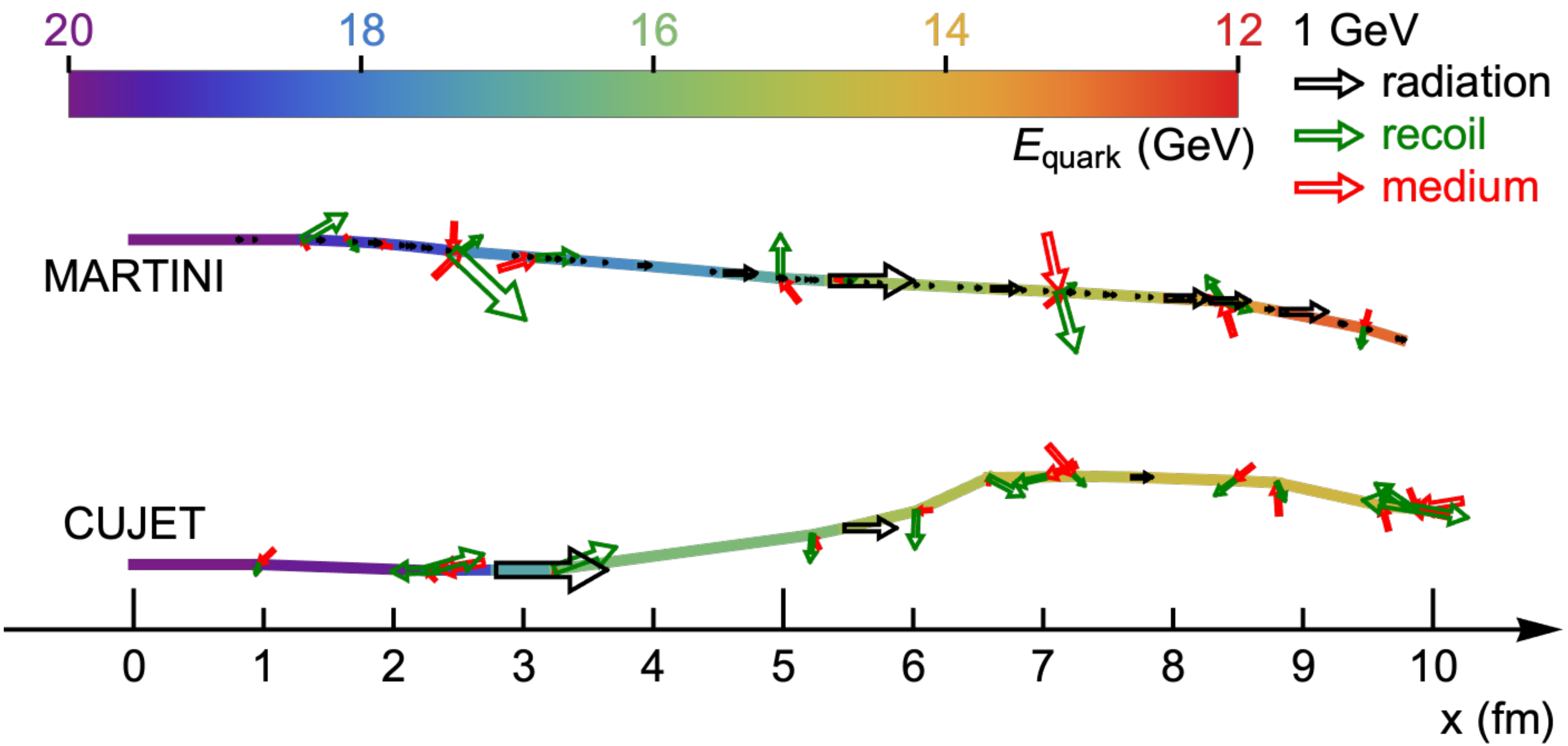
hadrons:

jets:



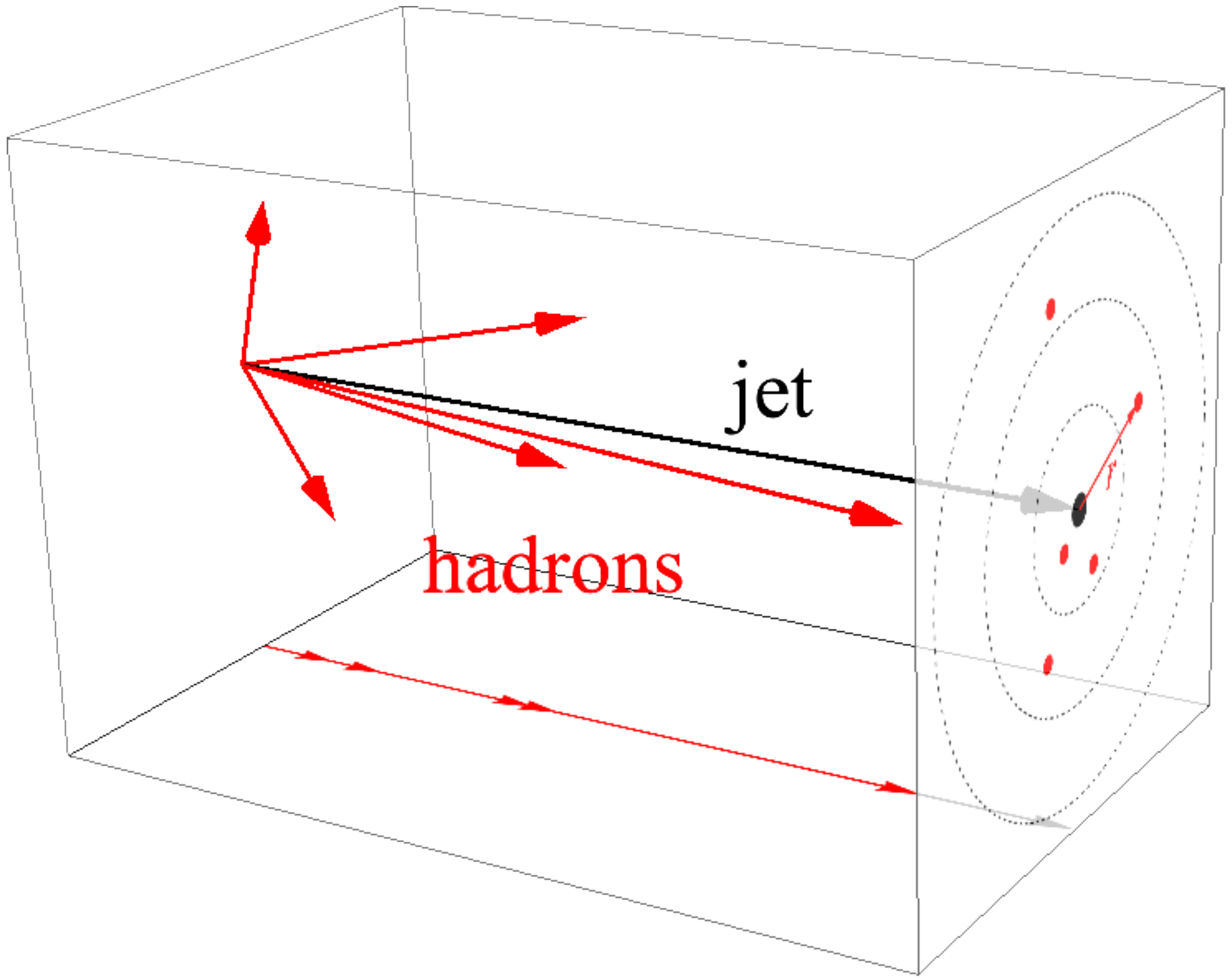
# how can we see the difference?





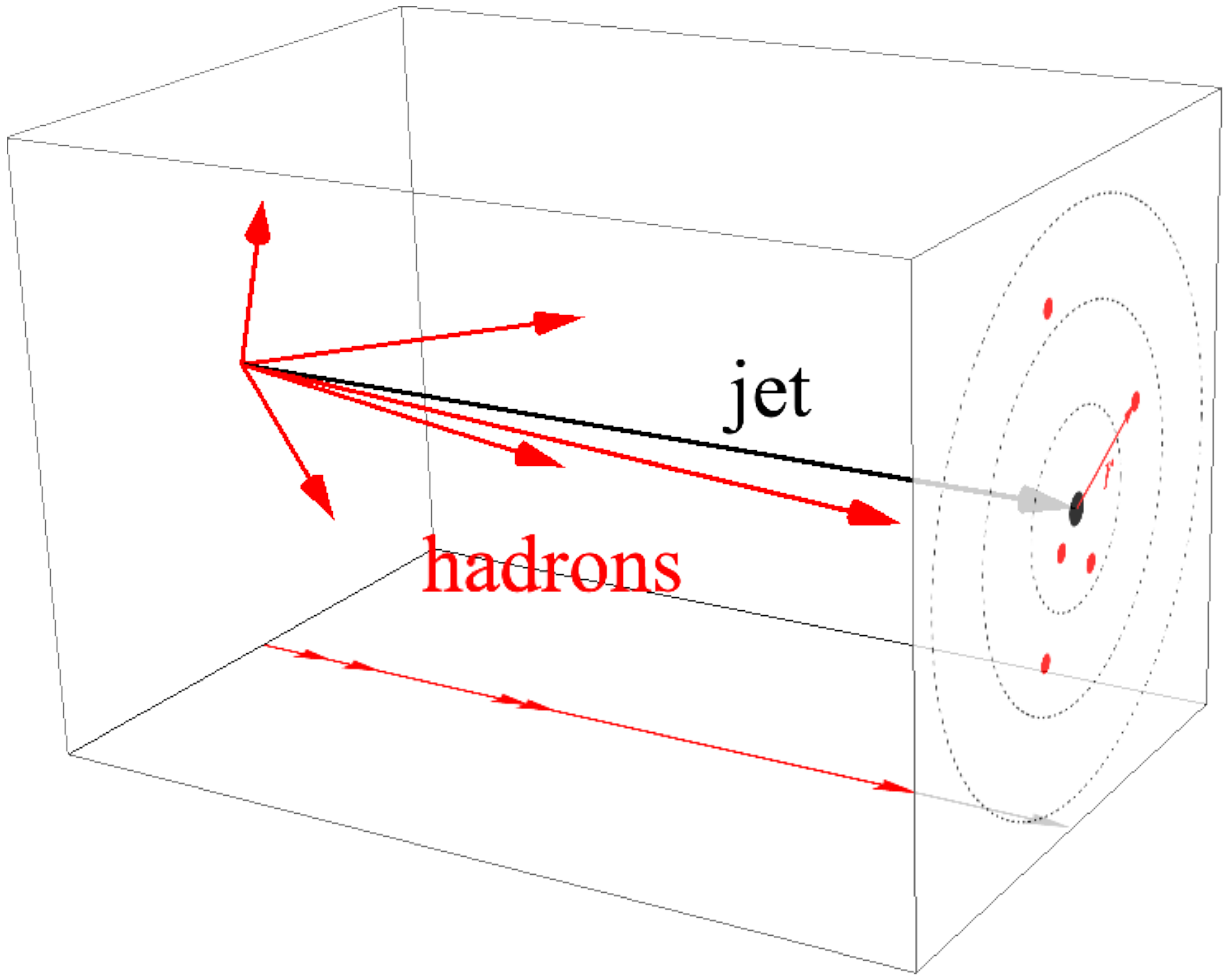
# jet sub-structures

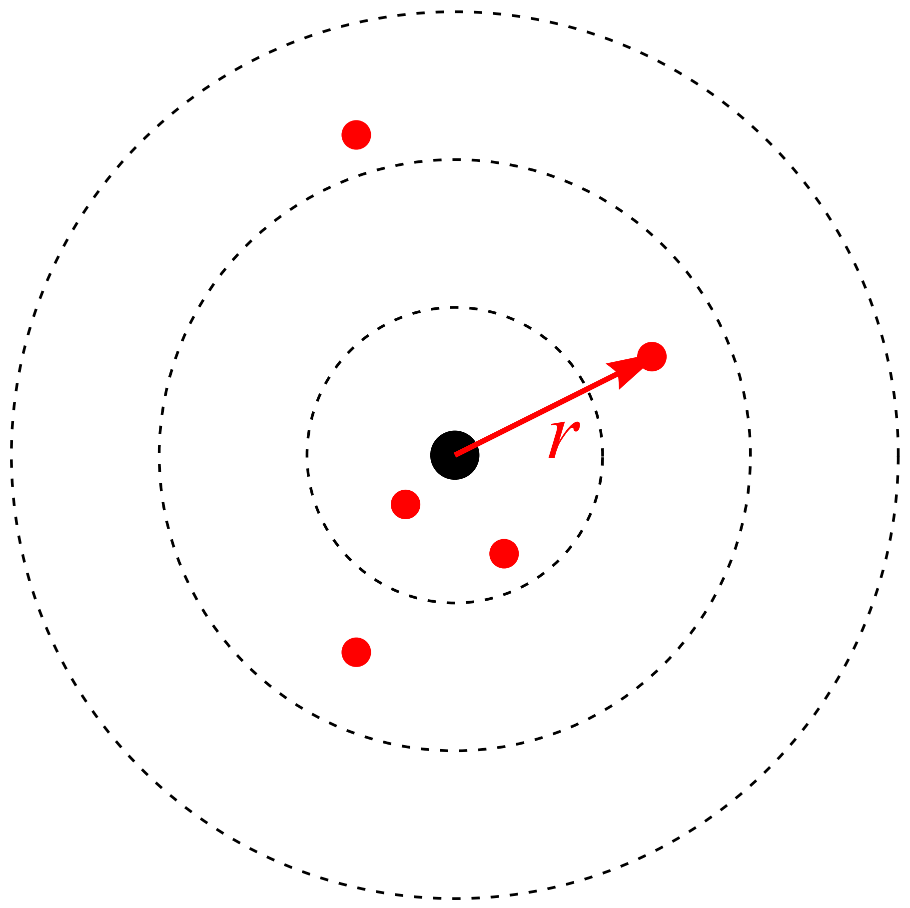




# jet sub-structures



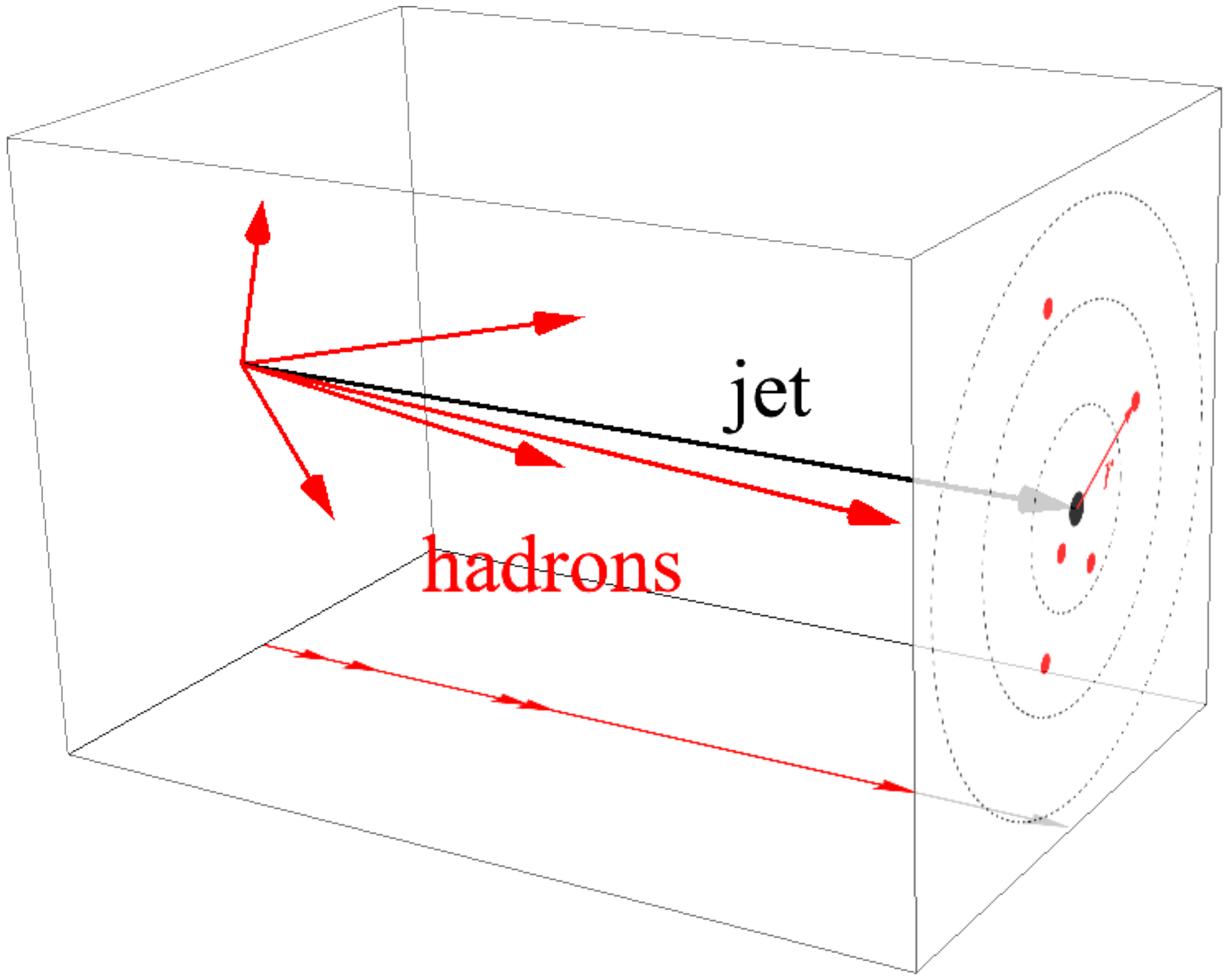


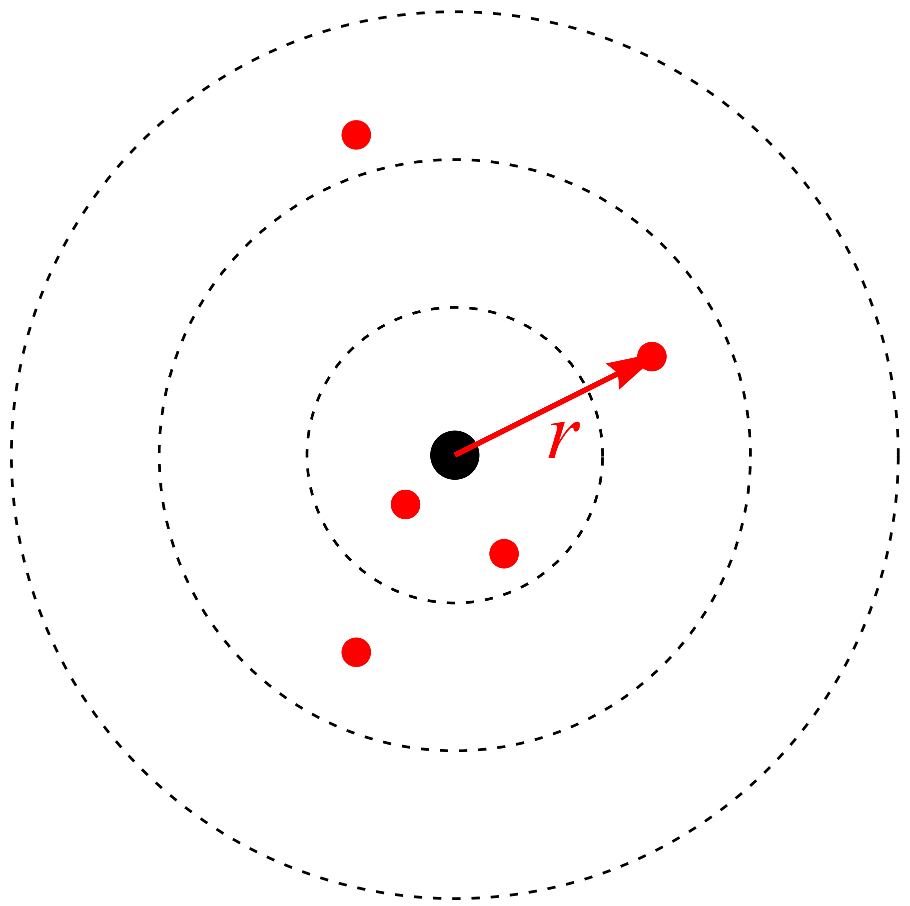




jet shape:
energy distribution in the transverse plane

# jet sub-structures






jet shape:
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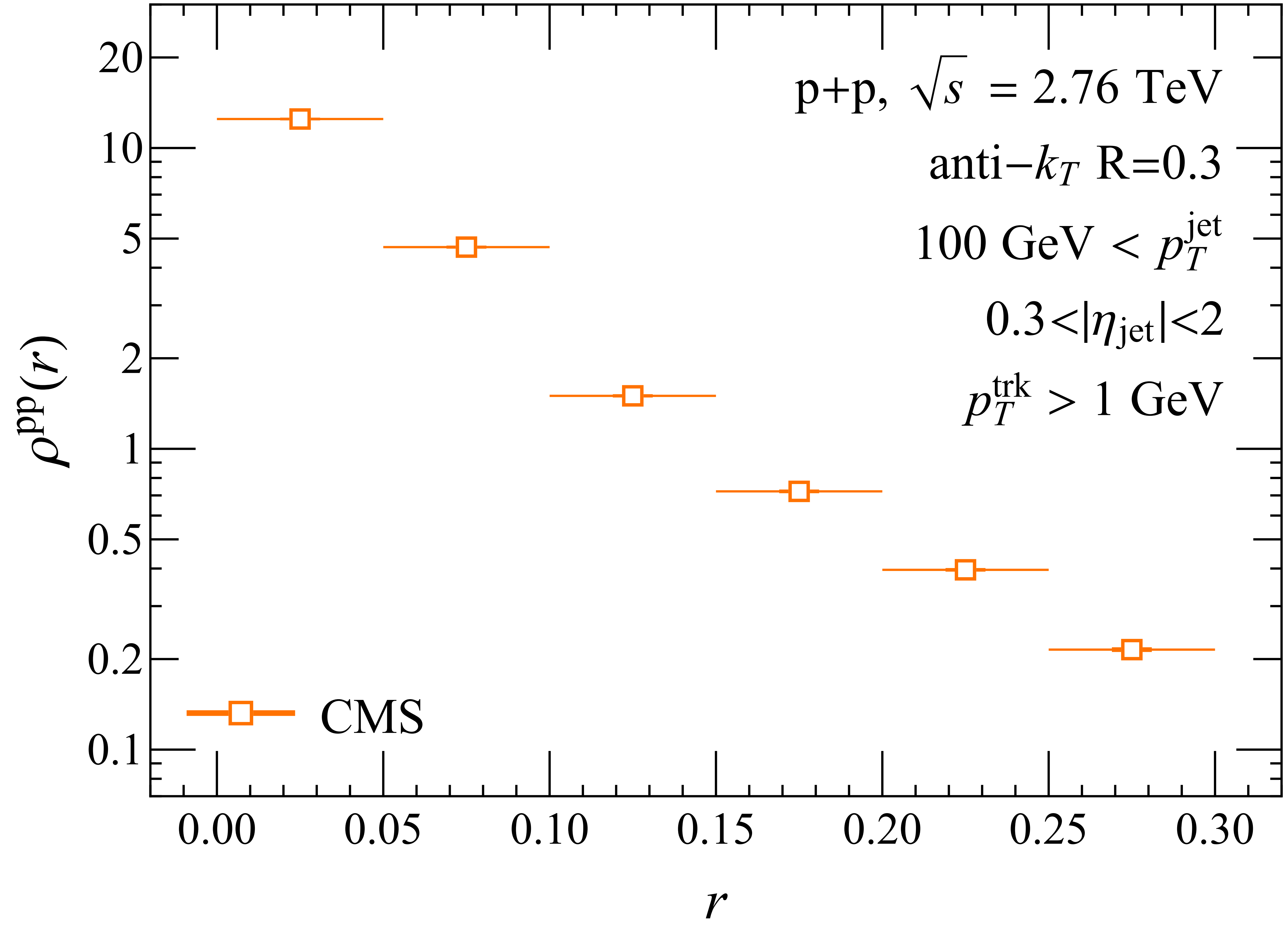
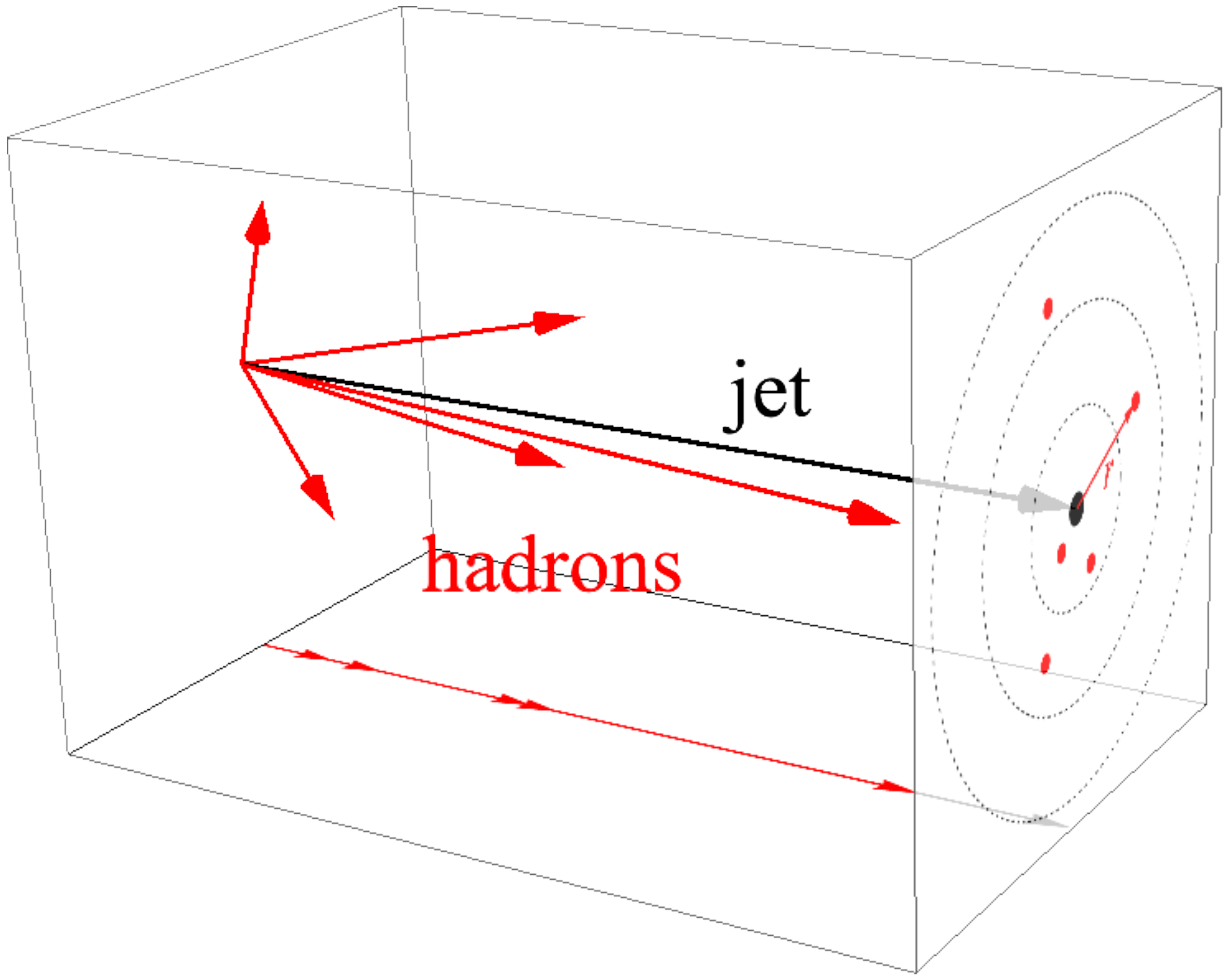



CMS, Phys.Lett.B 730, 243 (2014)

# jet sub-structures



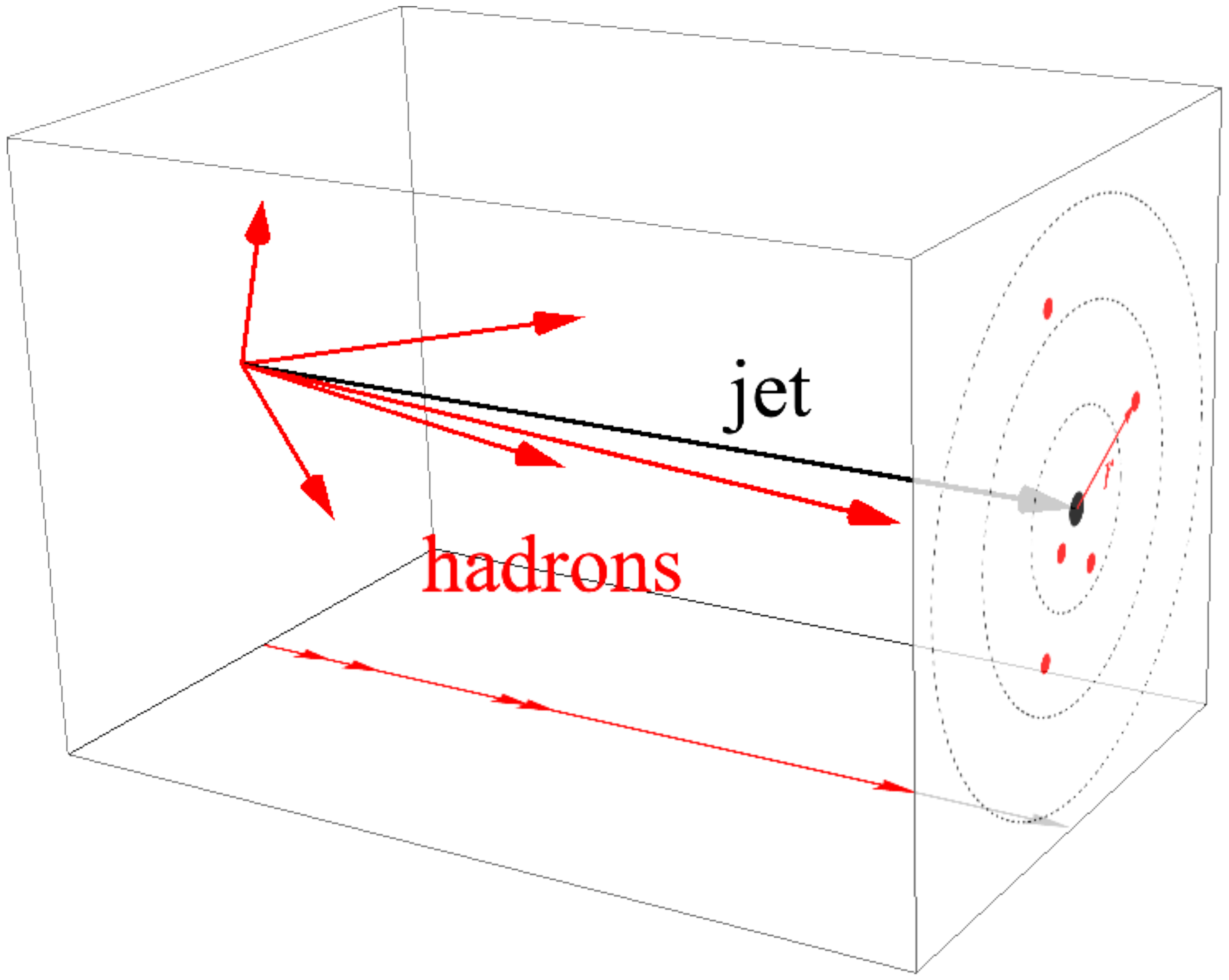



fragmentation function:
particle distribution in the longitudinal direction

$$z_h \equiv \frac{p_h \cdot p_{\rm jet}}{p_{\rm jet}^2}$$

# jet sub-structures



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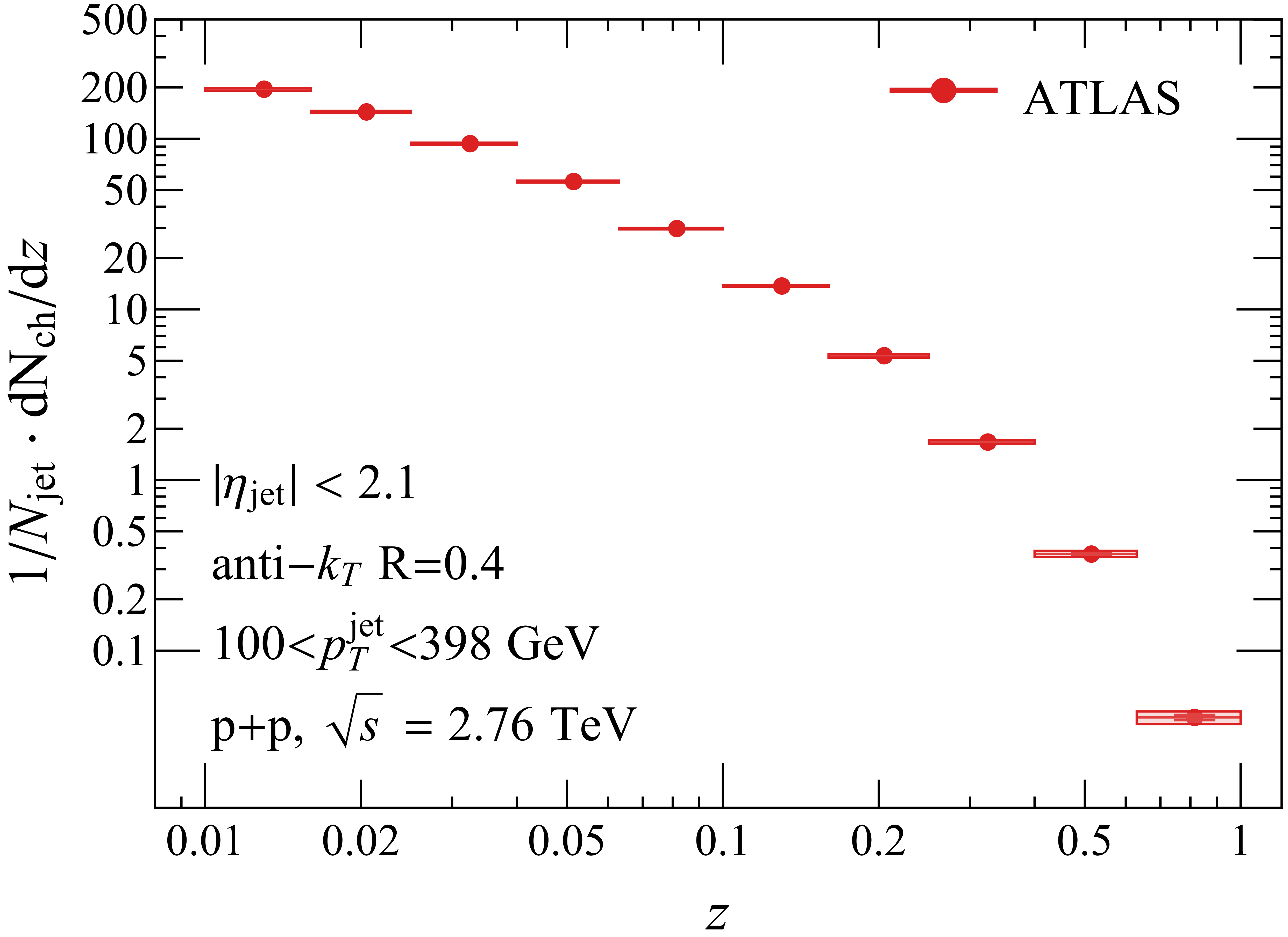


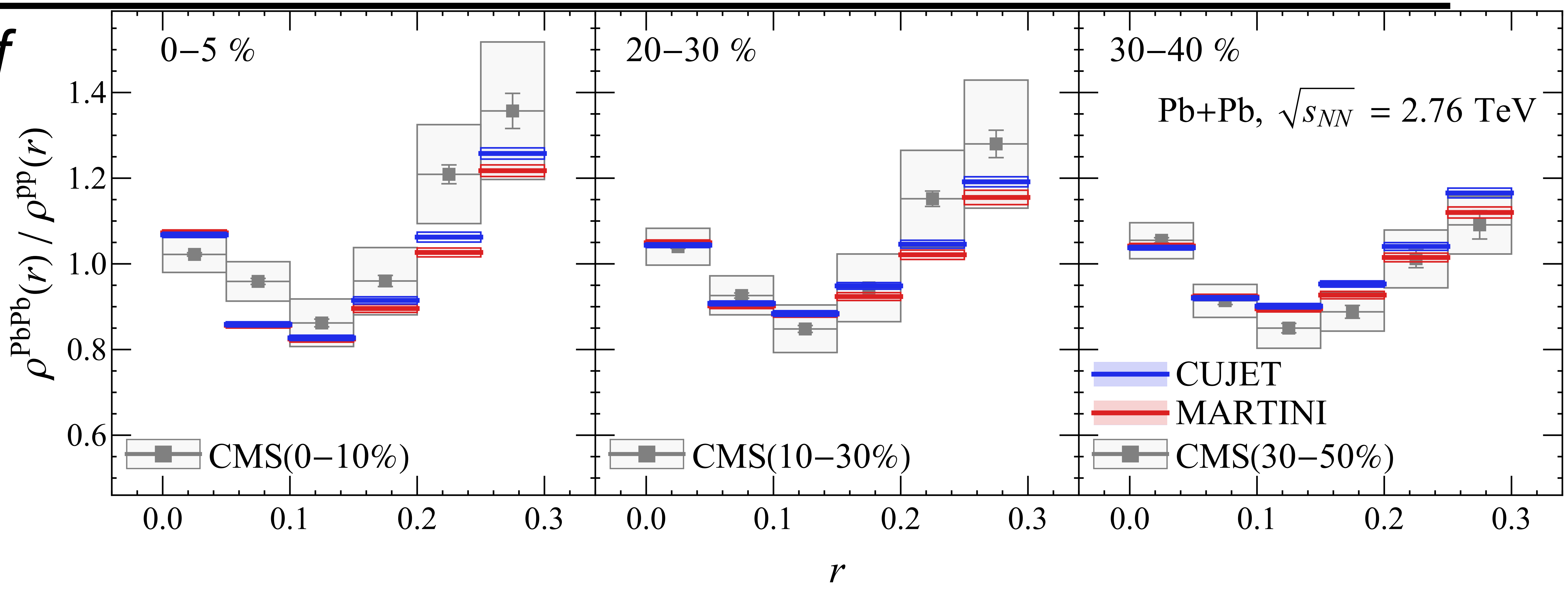

ATLAS, EPJC 77, 379 (2017)

# comparison of jet sub-structures



*medium modification of*

jet shape

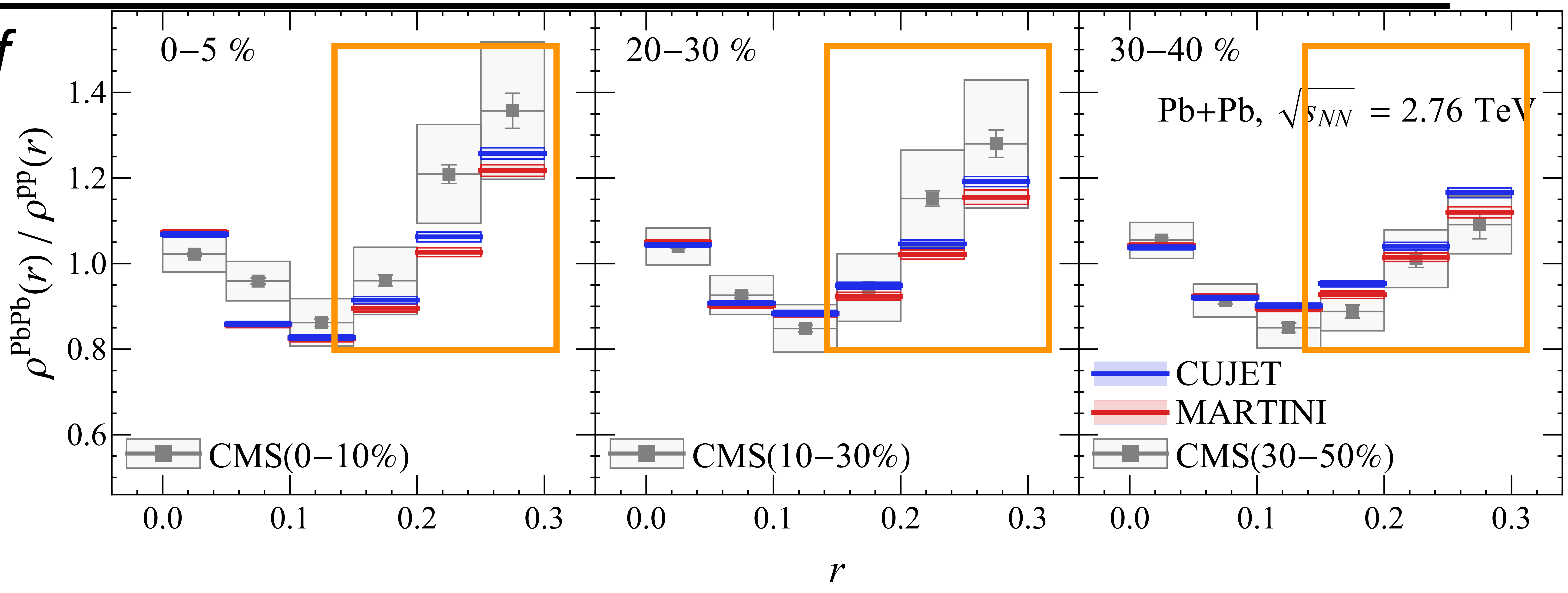


# comparison of jet sub-structures



*medium modification of*

jet shape

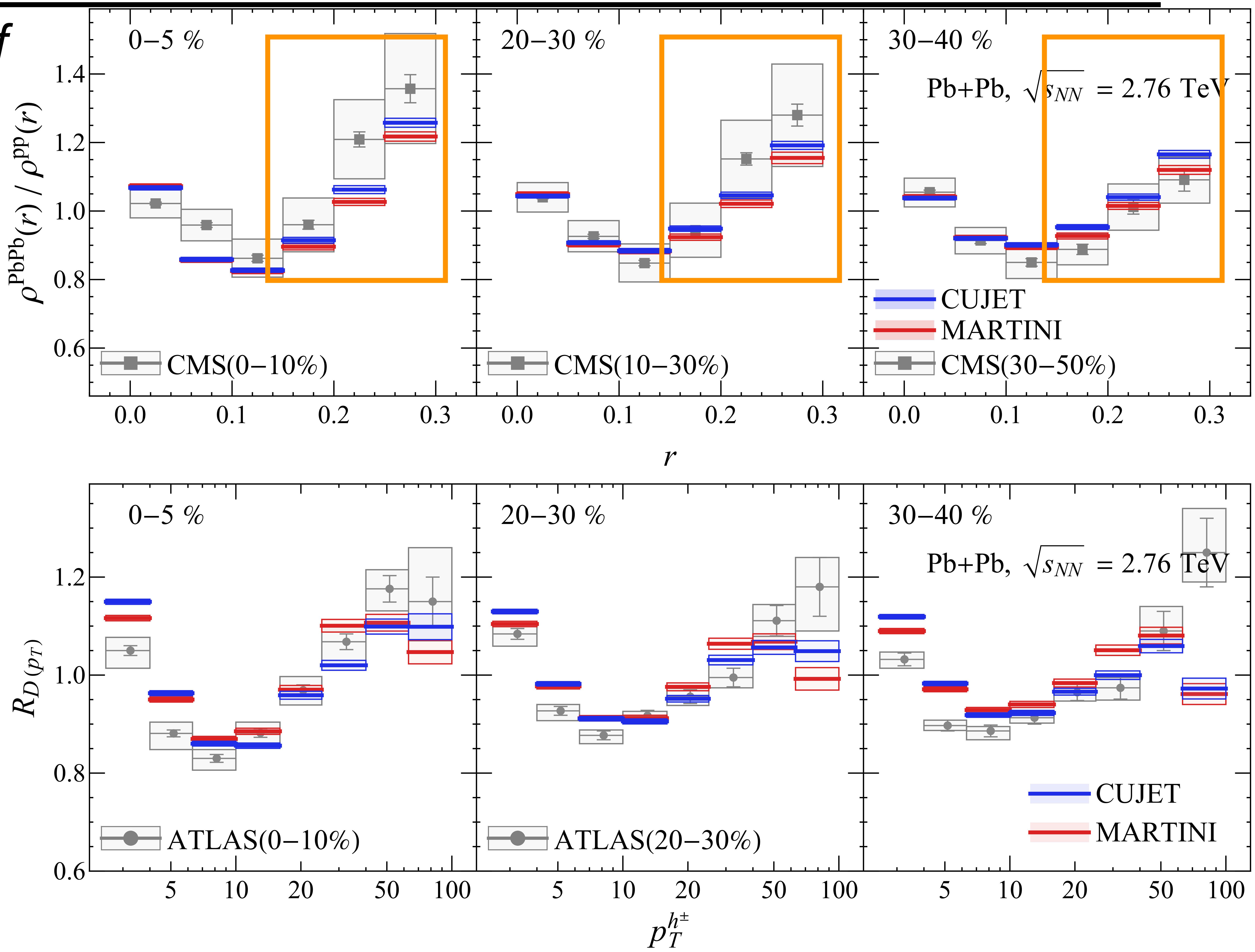


# comparison of jet sub-structures

*medium modification of*

jet shape

fragmentation function



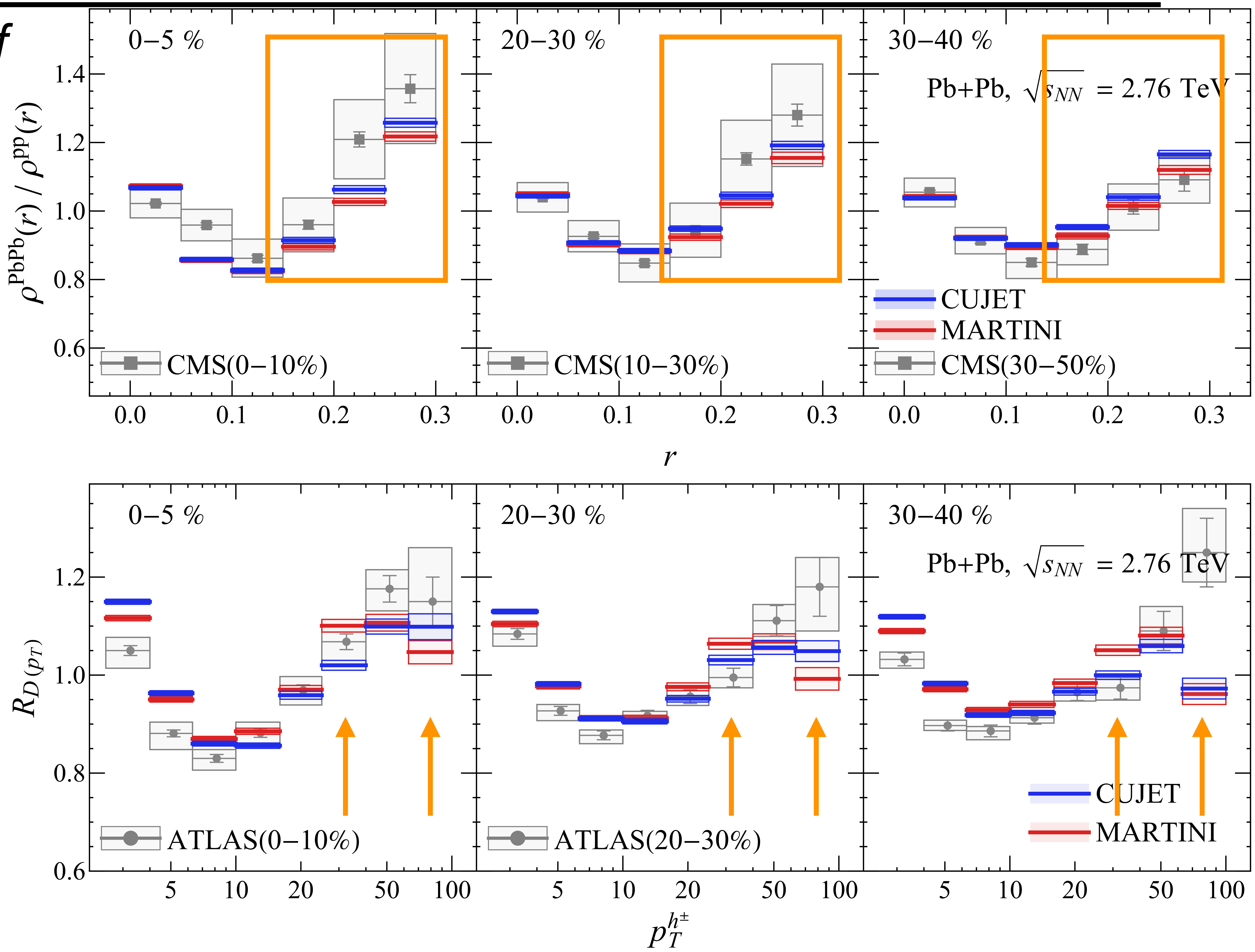
# comparison of jet sub-structures



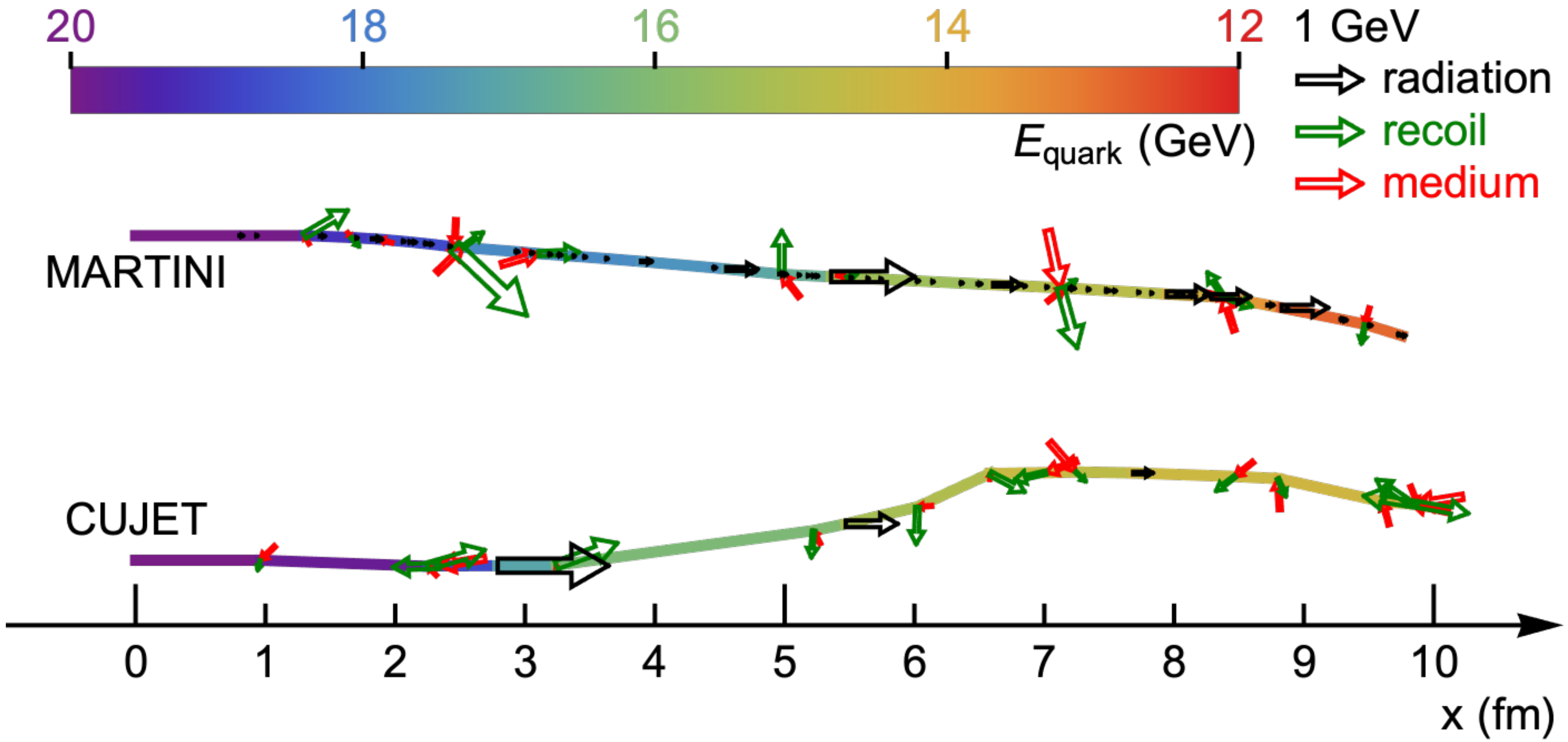
*medium modification of*

jet shape

fragmentation function



# more direct comparison?



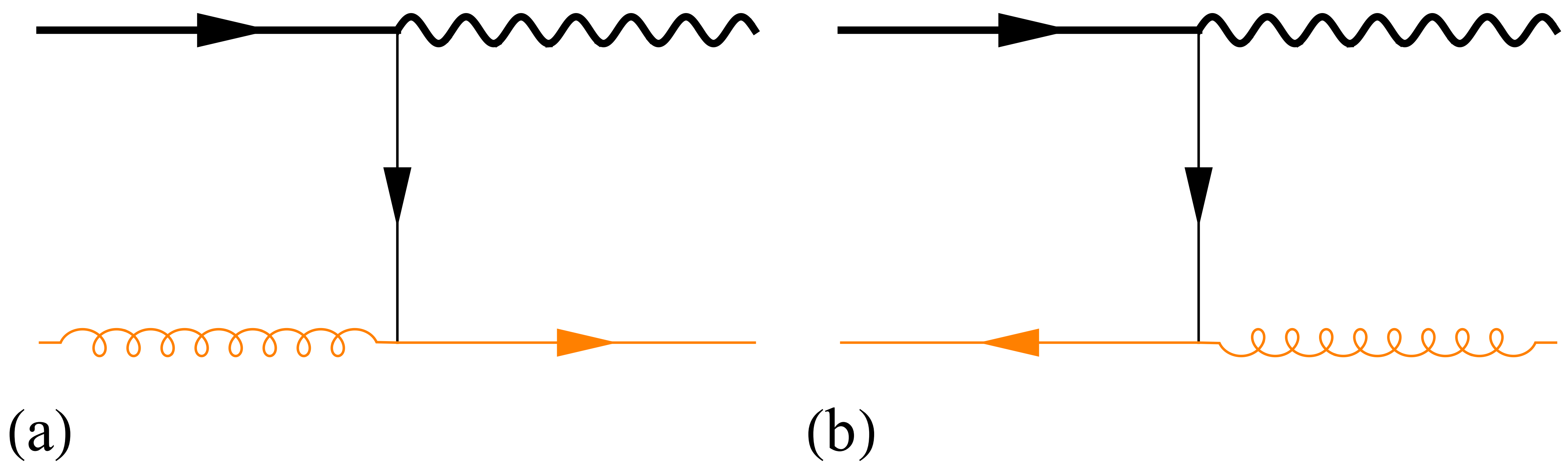

We cannot observe the brem. gluons directly, but we can observe the brem. photons.

# sources of jet-medium photons



conversion:

[jet → (hard) photon]



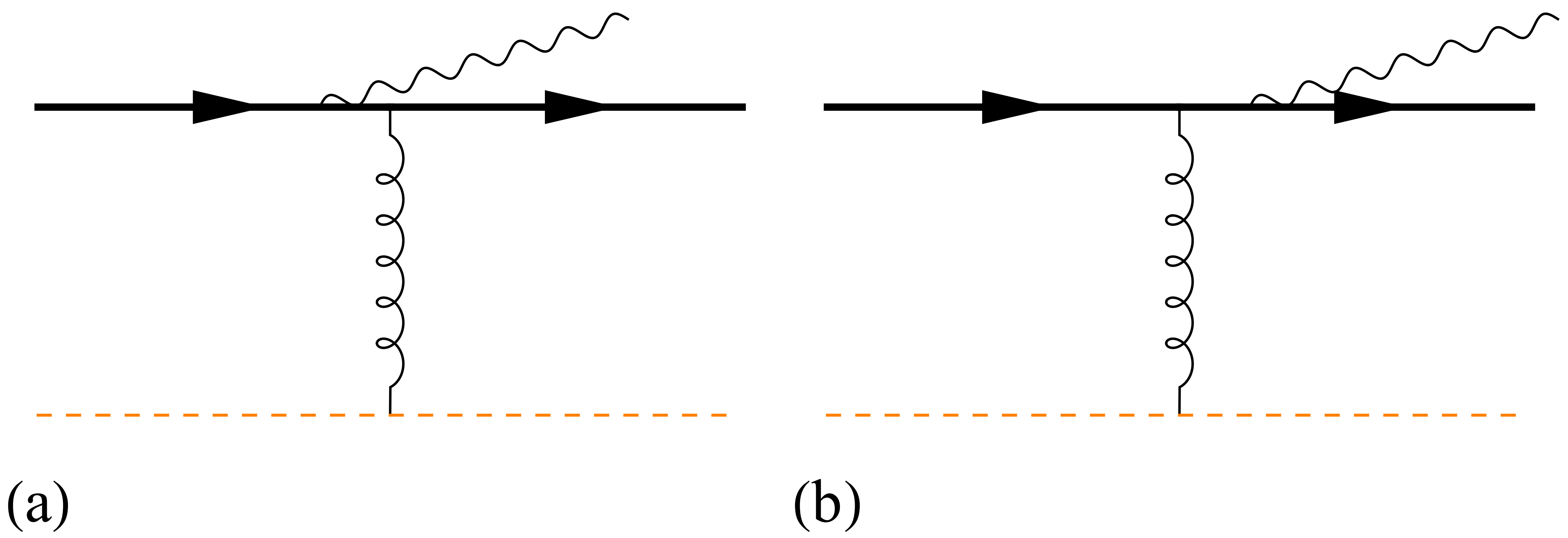

*elastic collision, same for MARTINI and CUJET*

# sources of jet-medium photons



bremsstrahlung:

[jet → jet + (soft) photon]

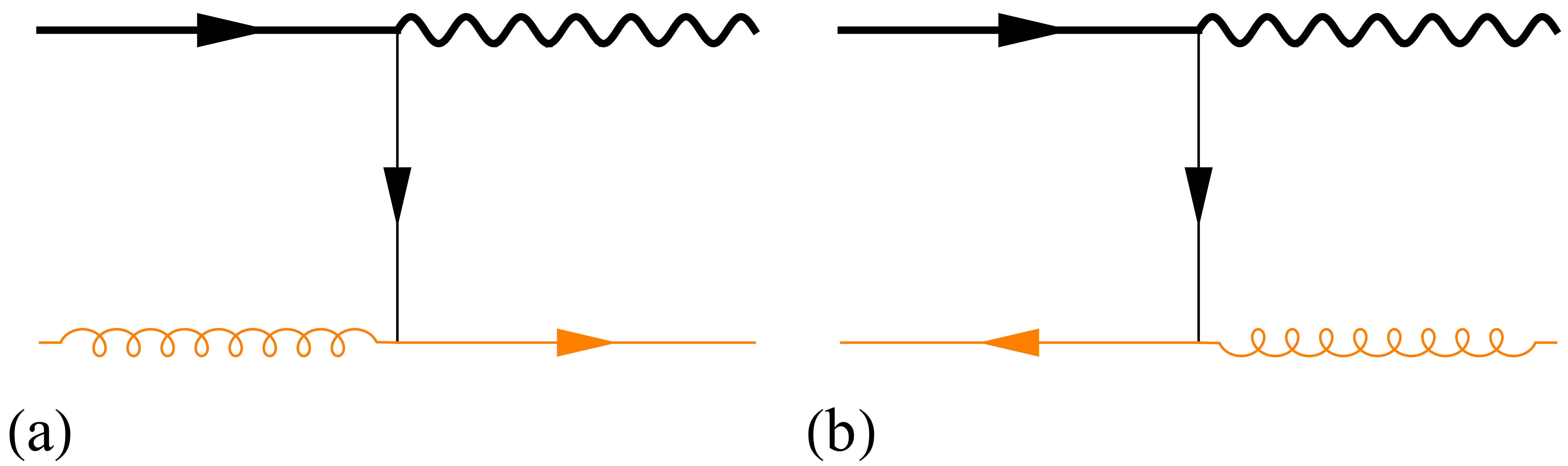



*inelastic interaction, different in MARTINI and CUJET*

*in CUJET, we use Zhang-Kang-Zhang-Wang, EPJC 67, 445 (2010)*

conversion:

[jet → (hard) photon]

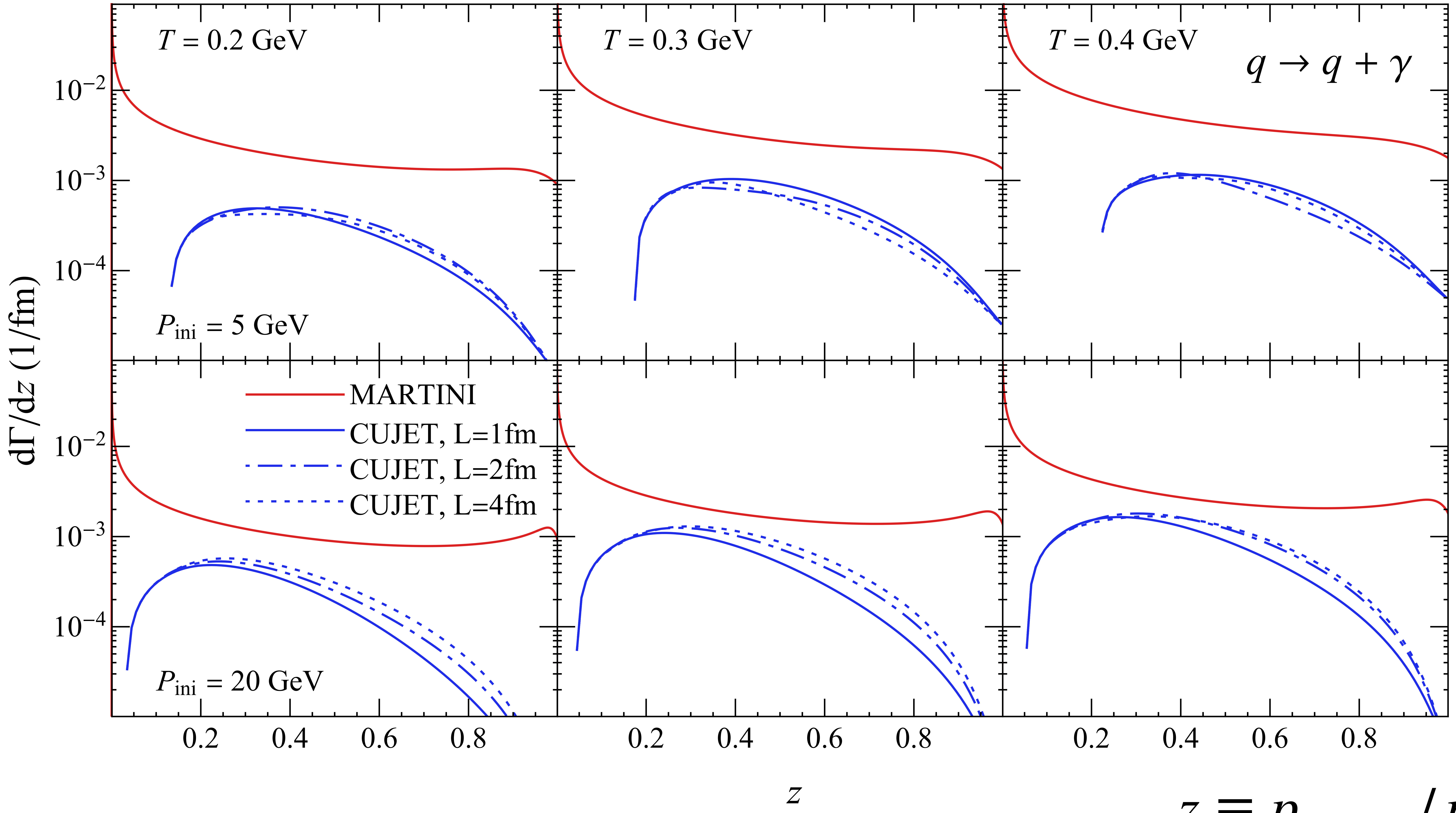



*elastic collision, same for MARTINI and CUJET*

# comparison of jet-medium photons

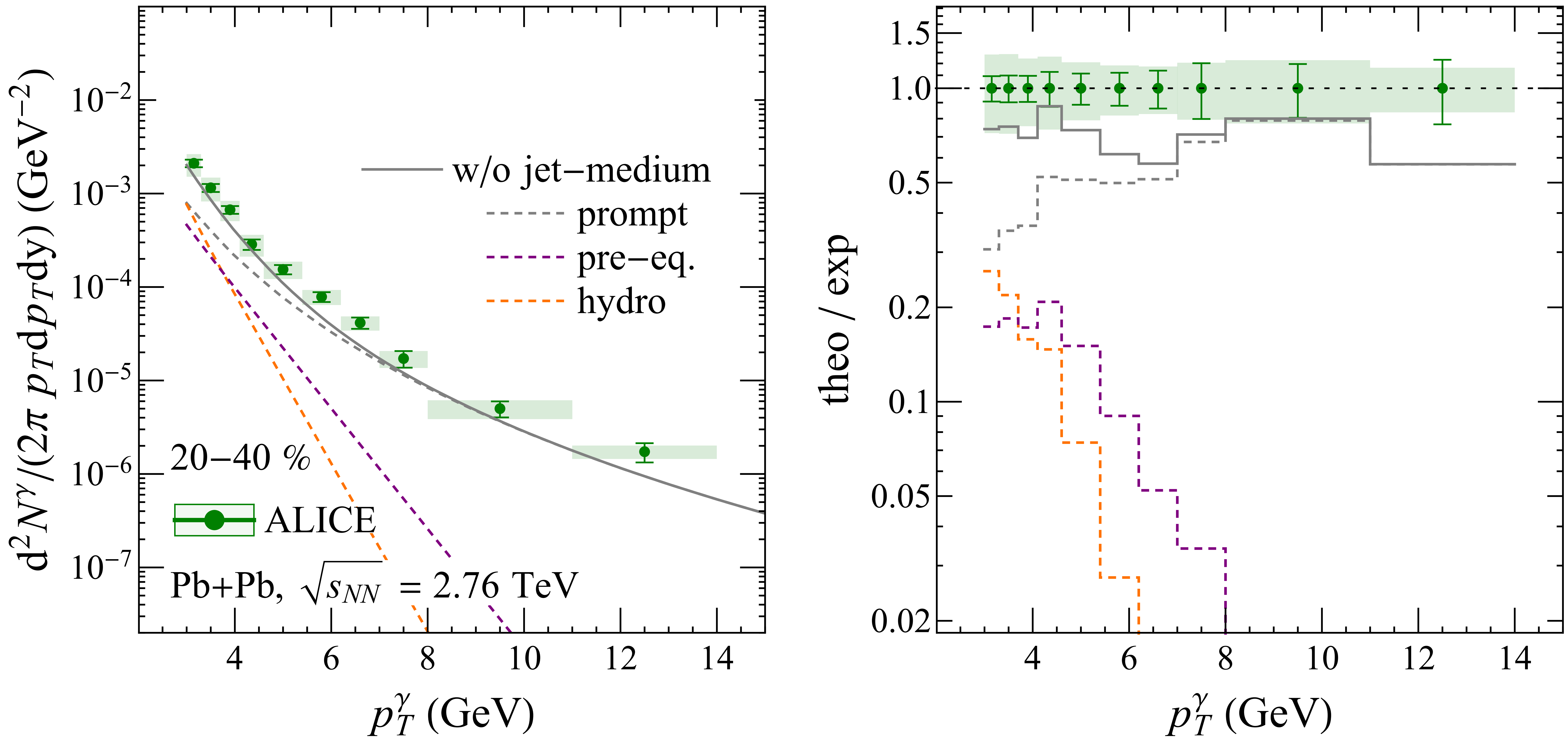


emission rates




$z \equiv p_{\mathrm{photon}} / p_{\mathrm{jet}}$

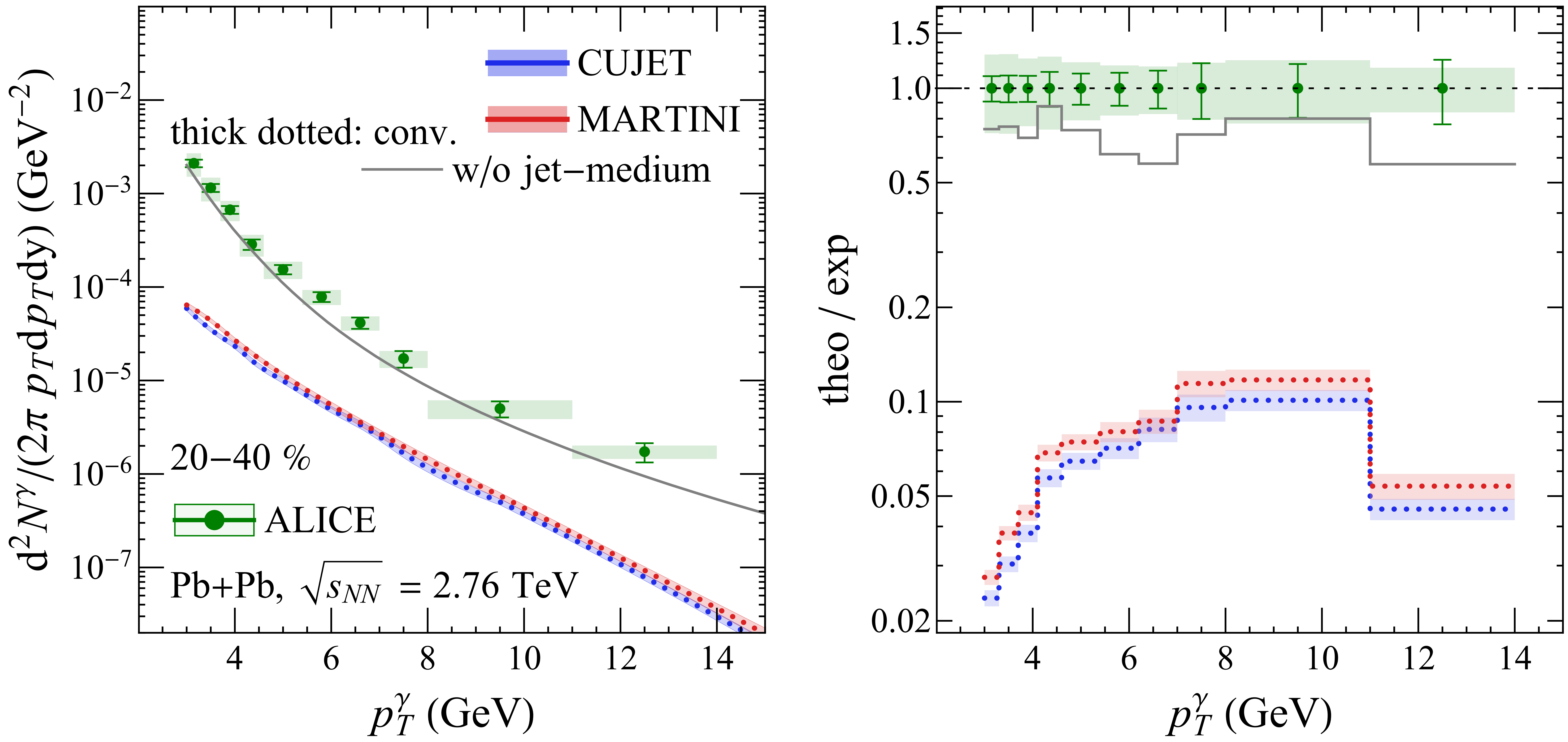
# comparison of jet-medium photons




*baseline w/o jet-medium photons*

# comparison of jet-medium photons

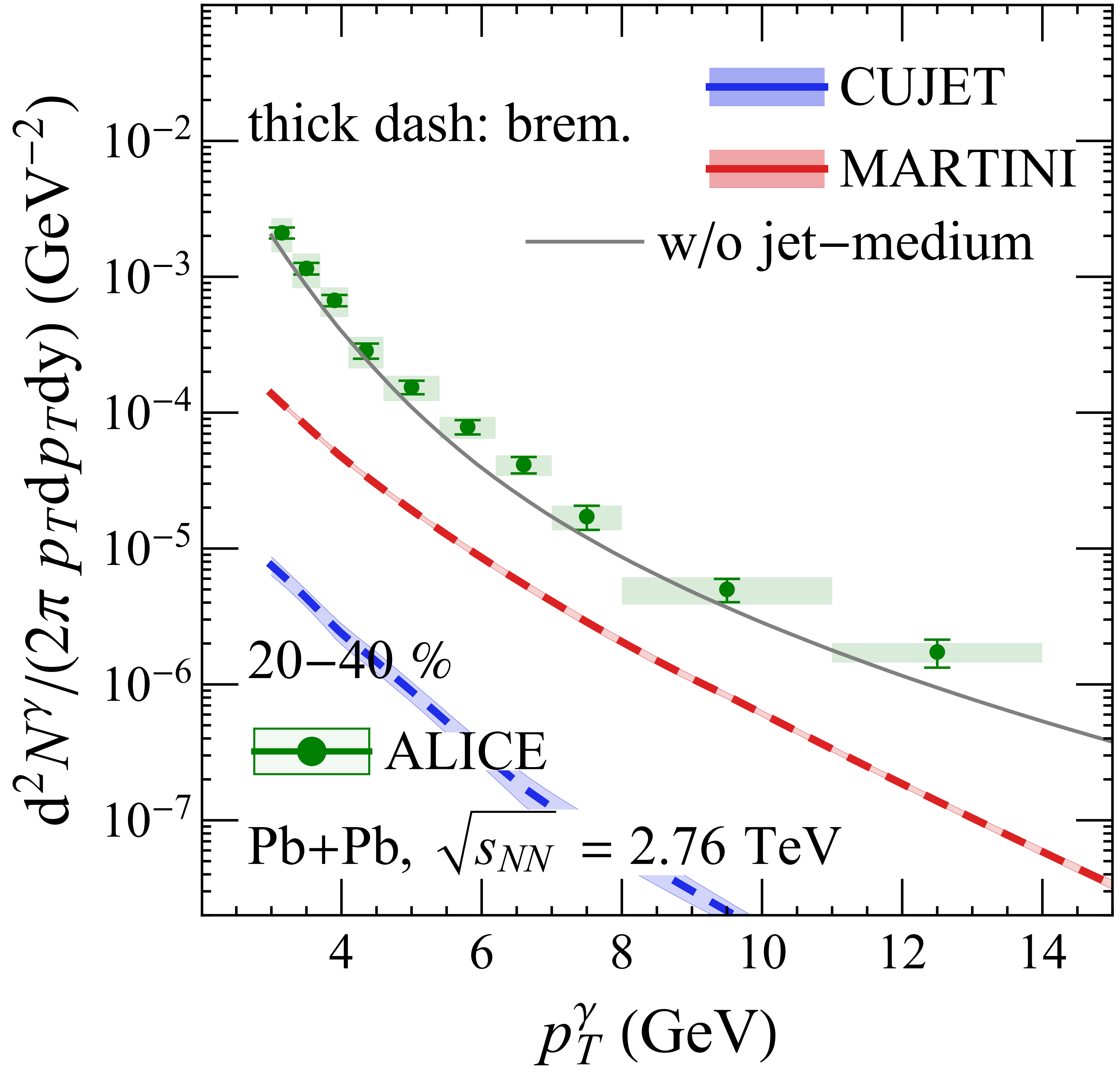


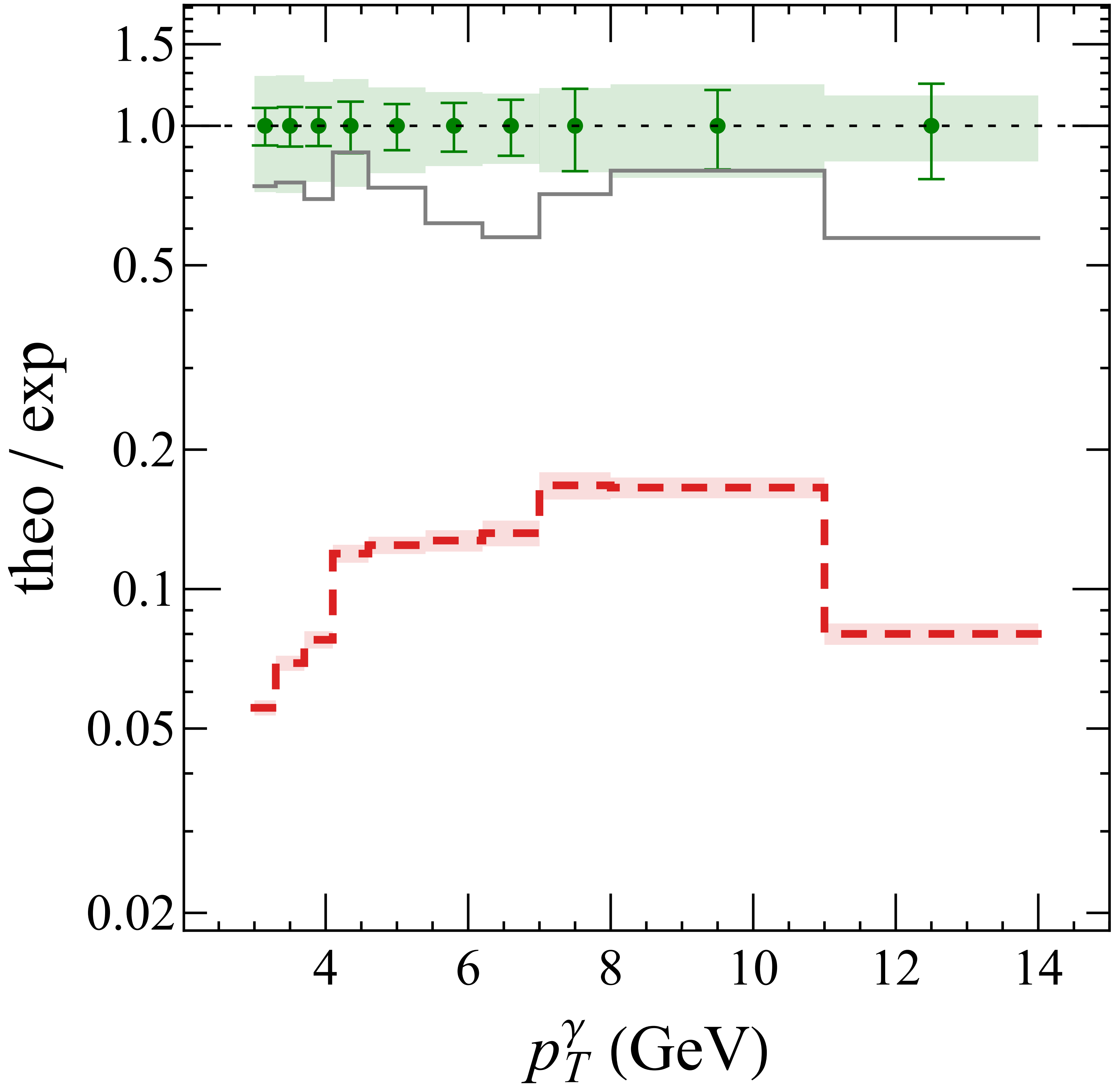



*conversion photons*

# comparison of jet-medium photons

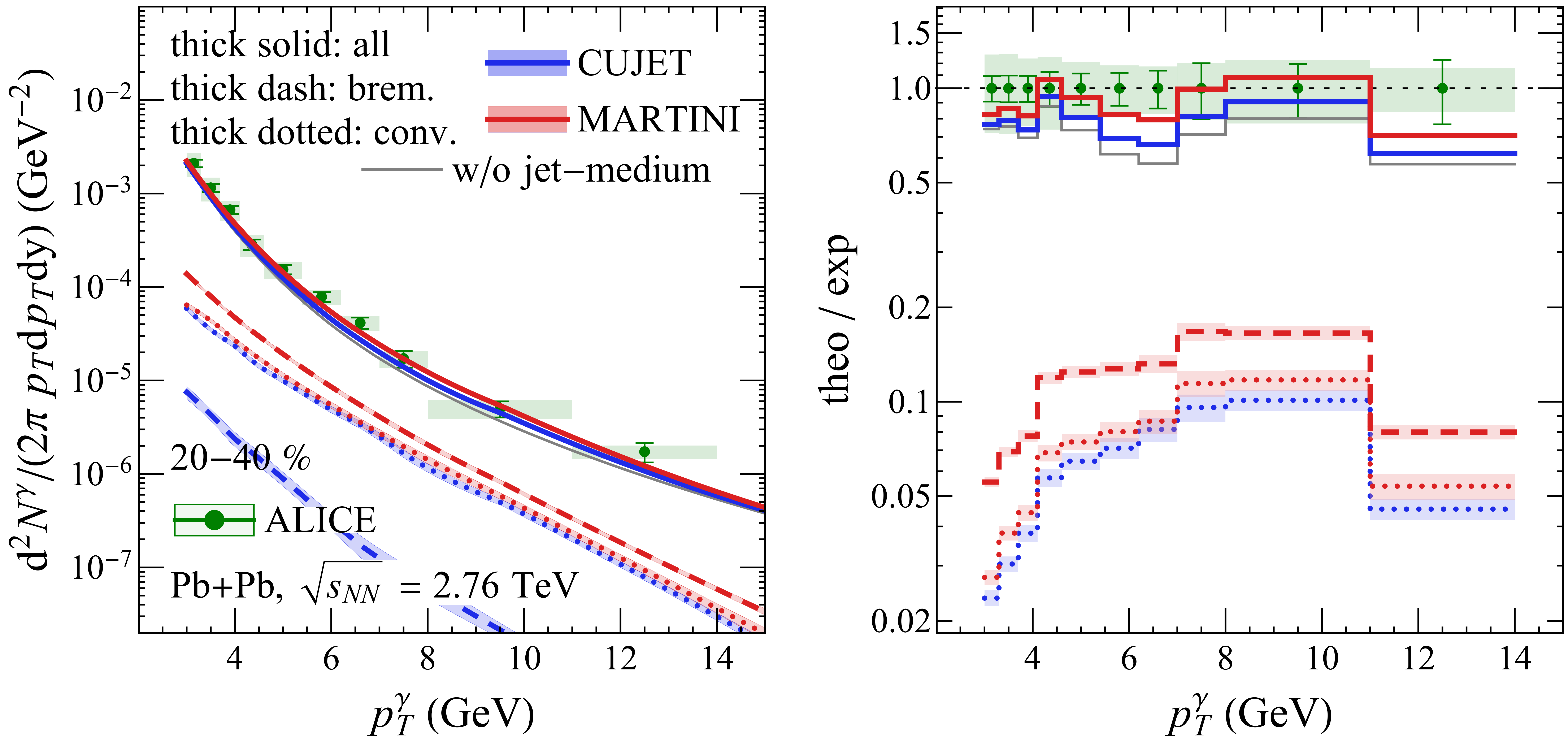




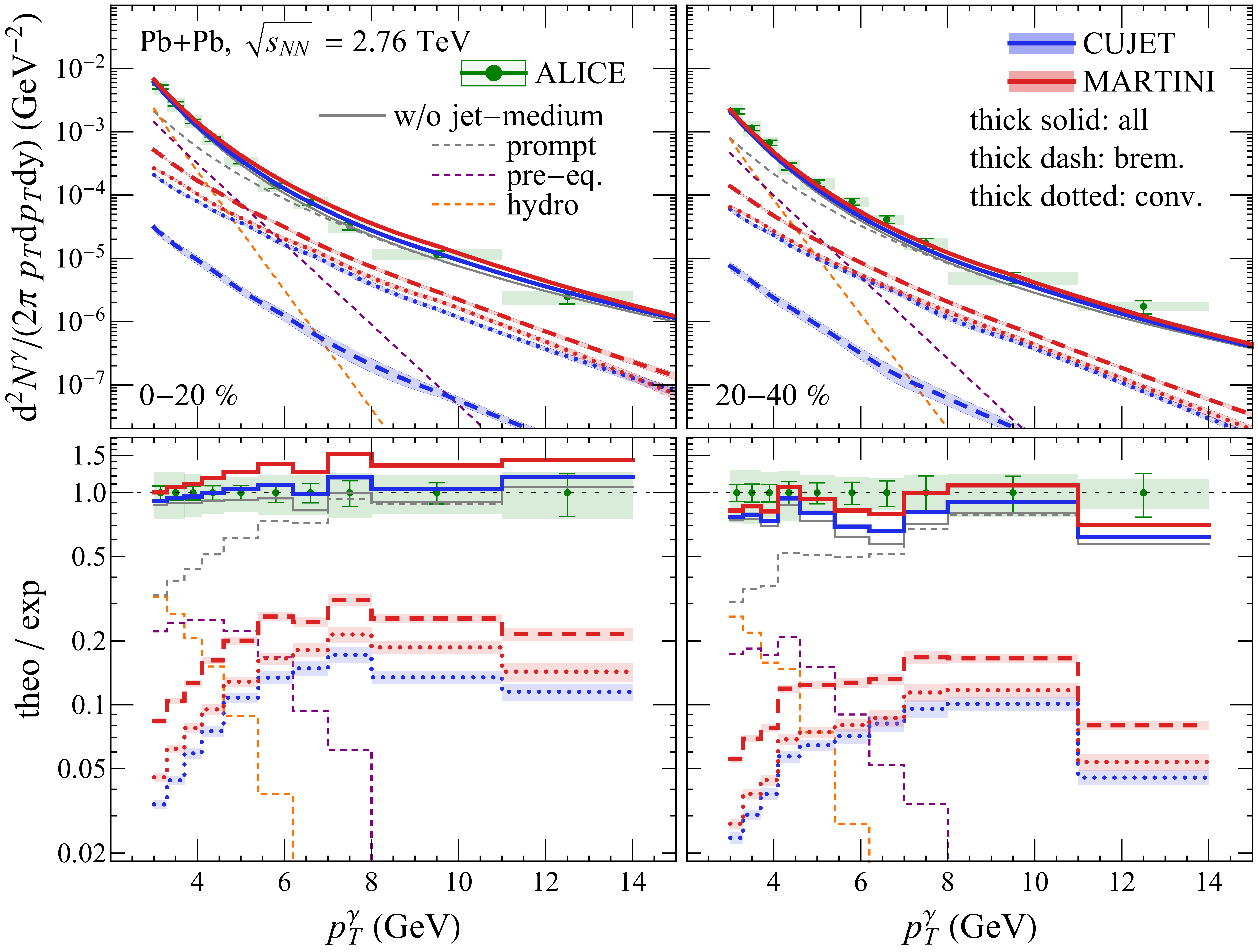

*bremsstrahlung photons*

# comparison of jet-medium photons




*all photons*

# comparison of jet-medium photons



# summary



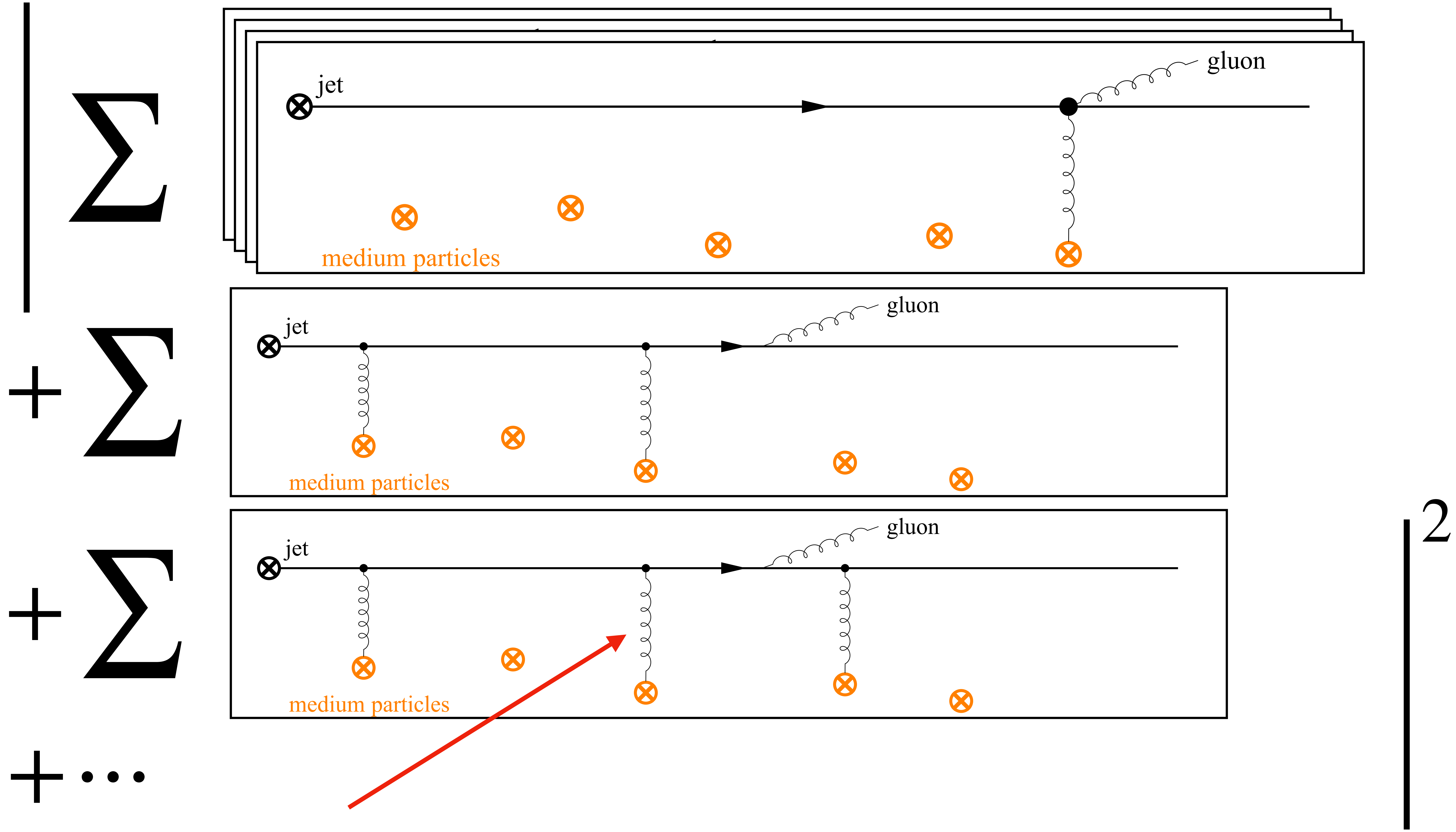
- studied full-jet observables using two different jet energy loss models: AMY-MARTINI and DGLV-CUJET

- we can discriminate different energy-loss models, if better precision in experimental data
  - jet substructure
  - jet-medium photon

[Phys.Rev.C, 107 (2023) 034908 + work in progress]

# outlook: AMY rates w/ NLO and Non-Pert. kernels

AMY-MARTINI cross-section ∝



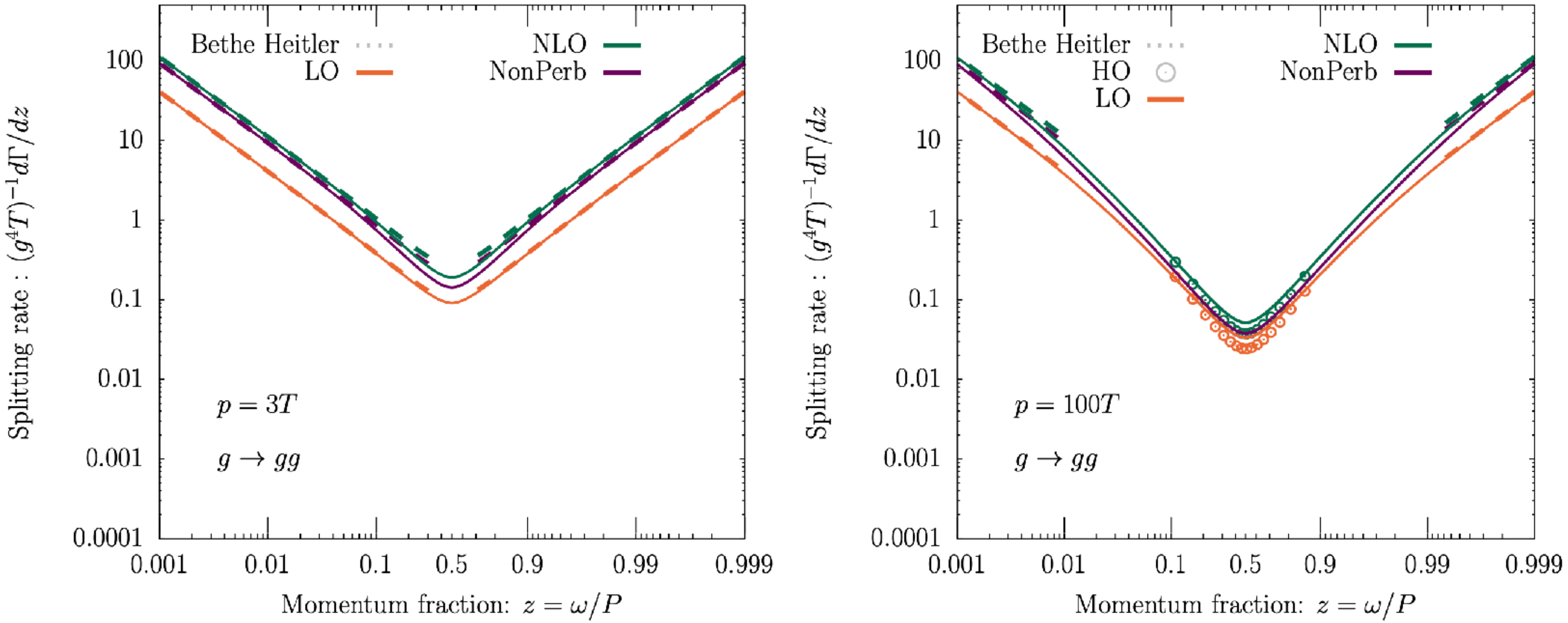

*LO scattering kernel was in use*

# outlook: AMY rates w/ NLO and Non-Pert. kernels



AMY rates w/ LO, NLO and non-perturbative kernels are calculated and compared in [*Moore, Schlichting, Schlusser,* and *Soudi*, JHEP 10(2021)059]

splitting rates

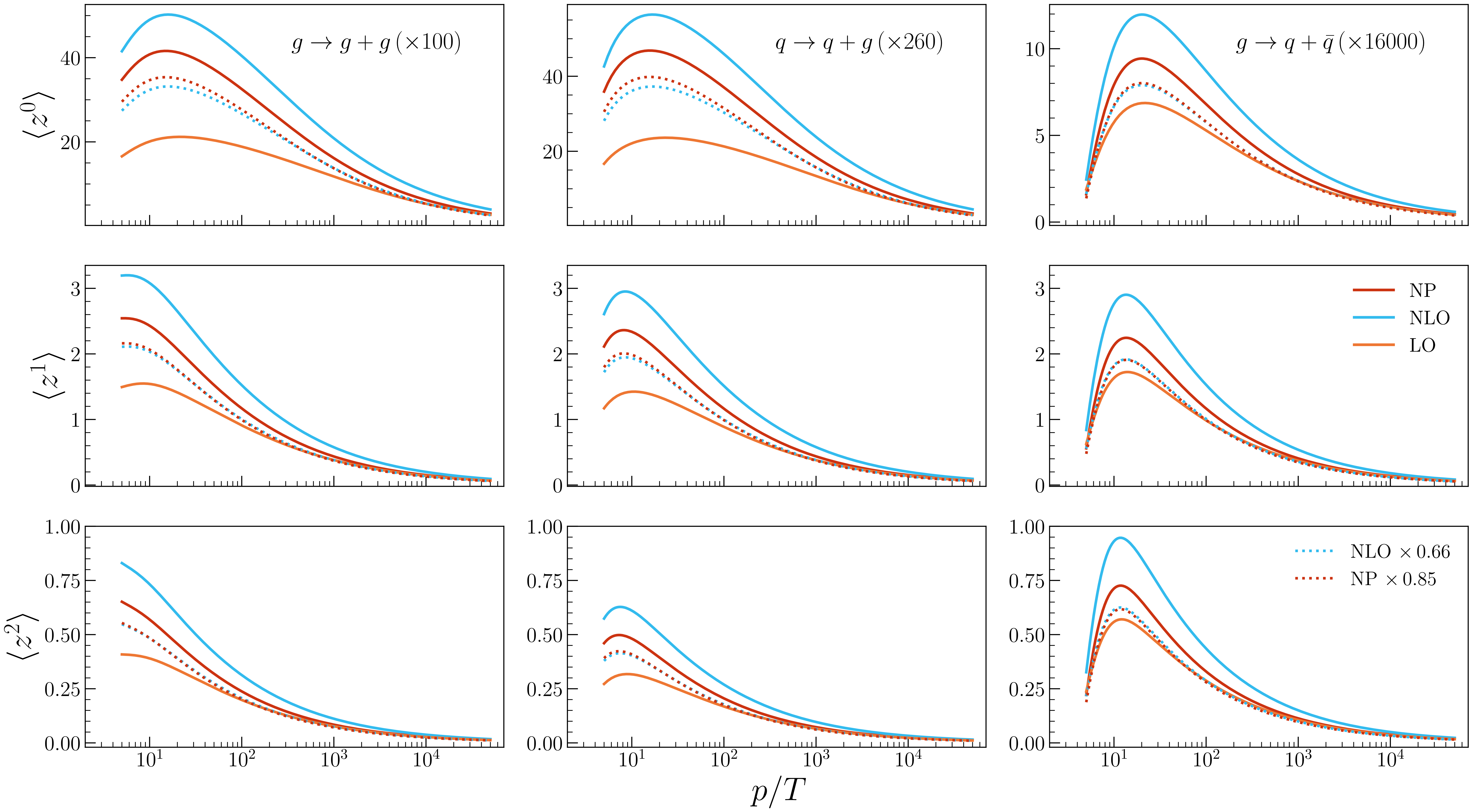


# outlook: AMY rates w/ NLO and Non-Pert. kernels



in [*Modarresi-Yazdi*, ***SS***, *Gale*, and *Jeon*, Phys.Rev.C 106, 064902], we find that the differences can be absorbed by rescaling of $\alpha_s$

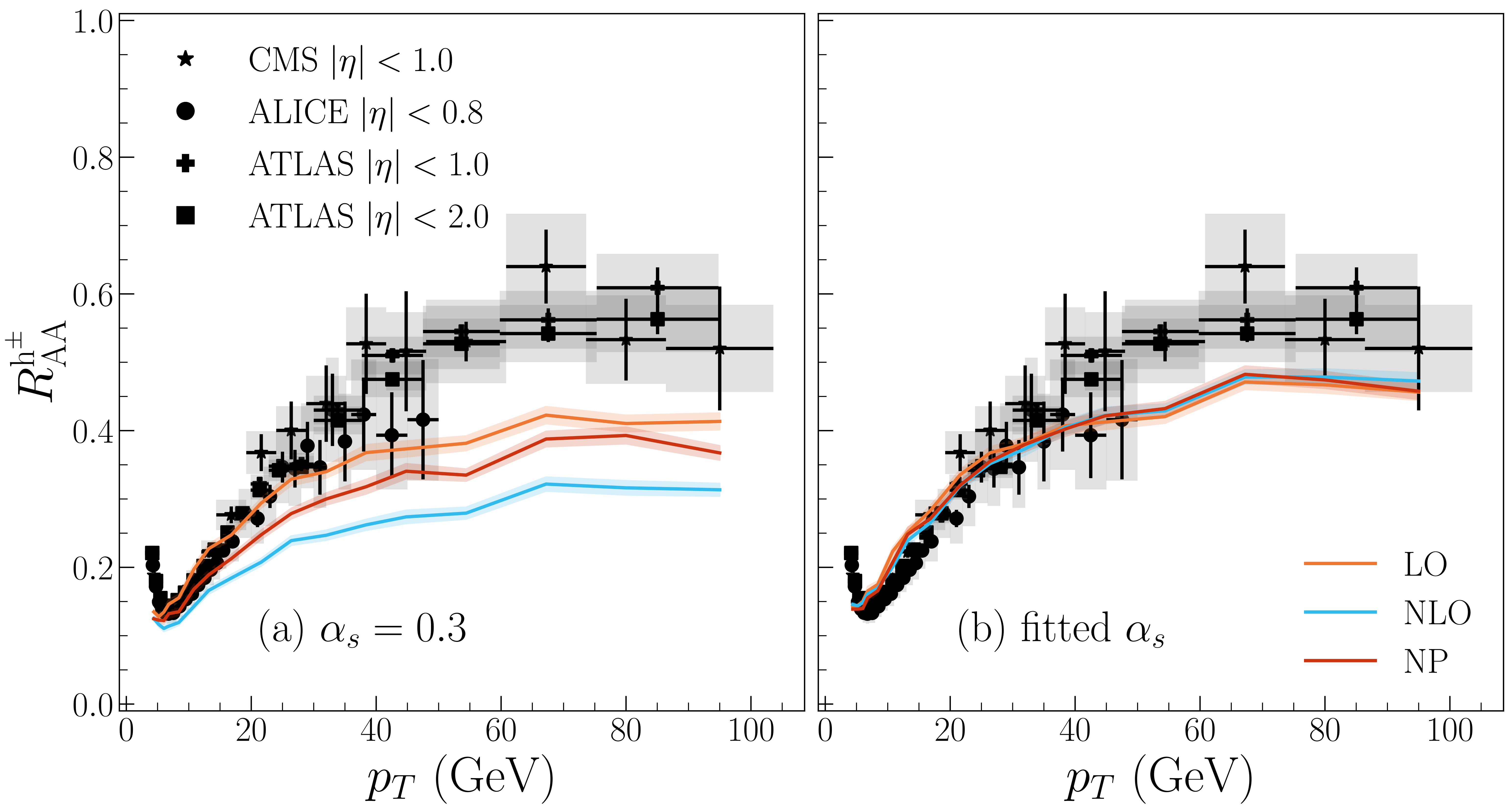
moments of splitting rates



# outlook: AMY rates w/ NLO and Non-Pert. kernels



in [*Modarresi-Yazdi*, ***SS***, *Gale*, and *Jeon*, Phys.Rev.C 106, 064902], we find that no observable difference with separately rescaled $\alpha_s$



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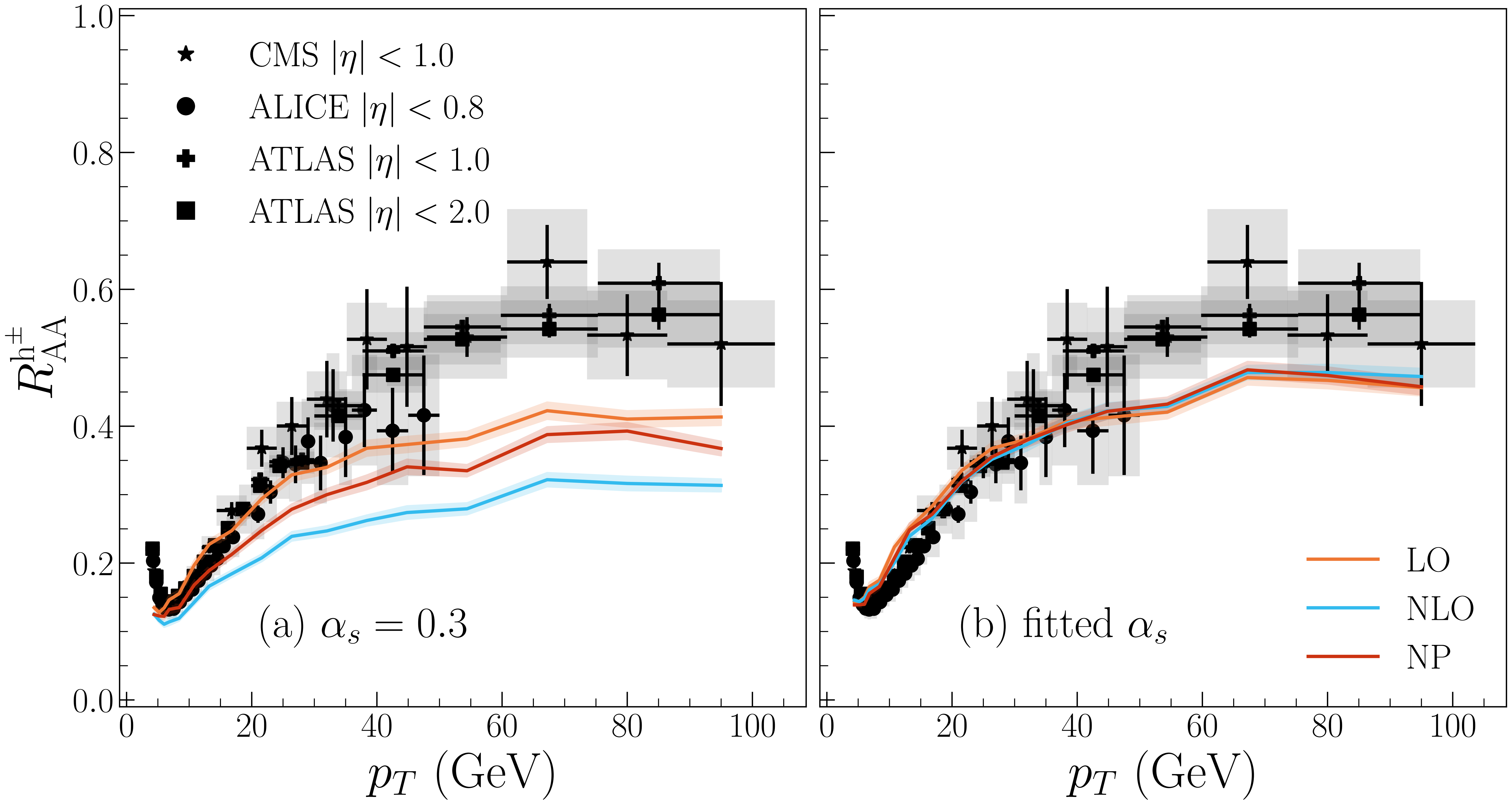


work in progress: full substructure and photons?