

Unbiased quantification of jet energy loss

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arXiv:2408.XXXXX

BOOST 2024

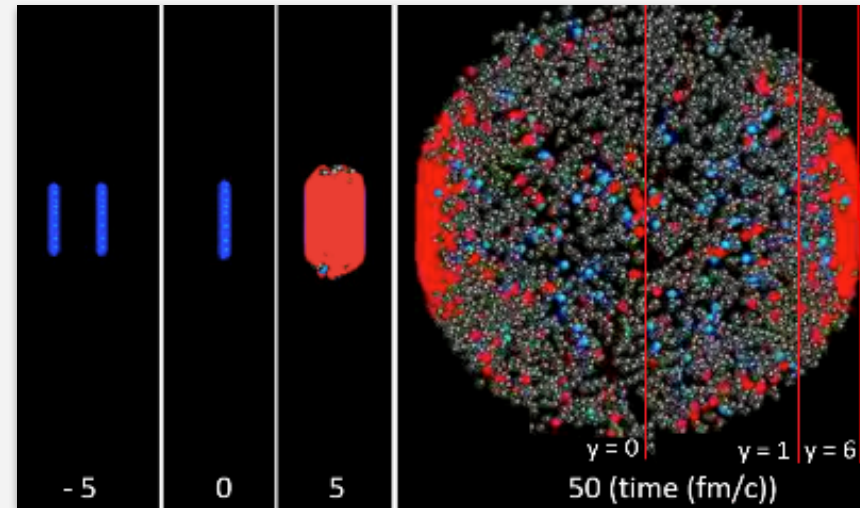
Genova, August 2024



Quark-gluon plasma

- ◆ Created in **ultra-relativistic heavy-ion collisions** (HICs), e.g., Pb-Pb or Au-Au, conducted at the LHC and at RHIC
- ◆ Signaled by an **abrupt increase in energy and particle densities** about $\sim 1 \text{ fm}/c$ (10^{-24} s) after the collision, with energy densities well above those inside typical hadrons ($\sim 0.5 \text{ GeV}/\text{fm}^3$)
- ◆ Its collective properties are **lost on a timescale of $\sim 10 \text{ fm}/c$** due to hydrodynamical expansion.

Hot and dense \sim perfect liquid ($\eta/s \sim 1/4\pi$) of deconfined quarks and gluons!

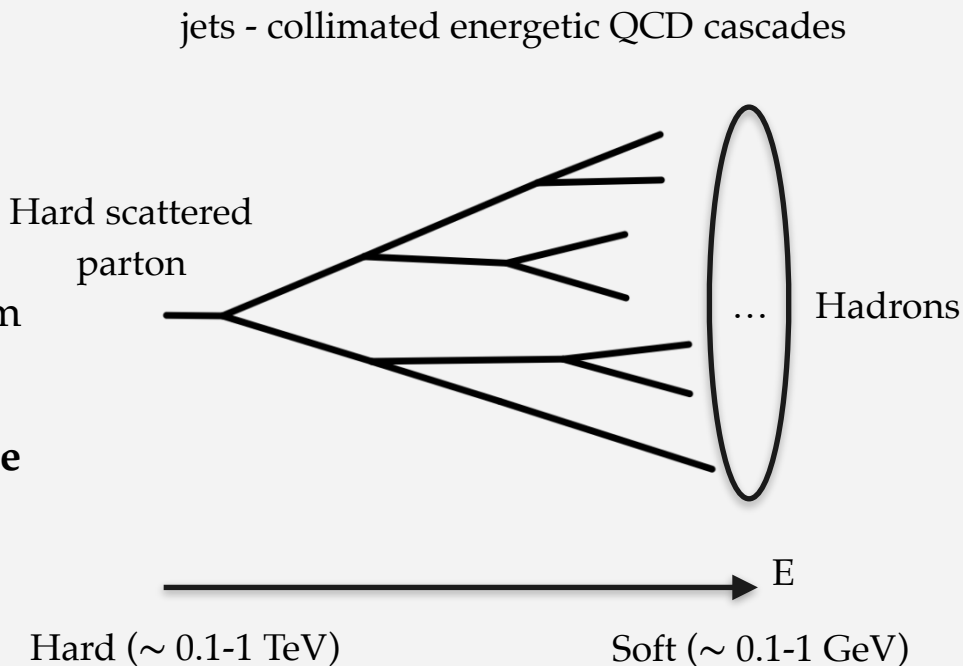


Busza et al, arXiv:1802.04801

Probing the QGP with jets

- ◆ We need a probe:
 - ❖ sensitive to multiple scales
 - ❖ concurrently produced with the medium

◆ **Jets are extended in space-time and evolve simultaneously with the QGP!**

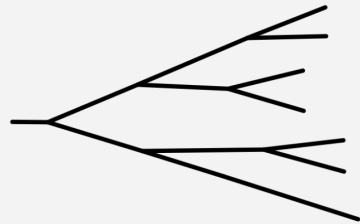


Probing the QGP with jets

Reviews: Mehtar-Tani et al, arXiv:1302.2579, Qin et al, arXiv:1511.00790, Cunqueiro et al, arXiv:2110.14490, Apolinário et al, arXiv:2203.16352

Jets in **heavy-ion** collisions have to **propagate through a medium and interact with it**

→ imprinted modifications tell a story (**jet quenching**)

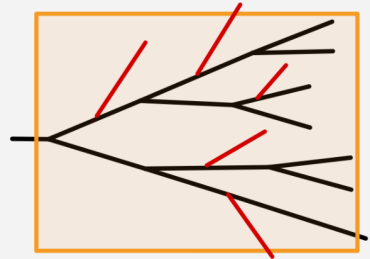


[bunch of collimated hadrons]

Compare **heavy-ion jets** with the well established vacuum baseline of **pp jets**



Infer the properties of the medium



[(modified) bunch of collimated hadrons]

Biased jet comparison

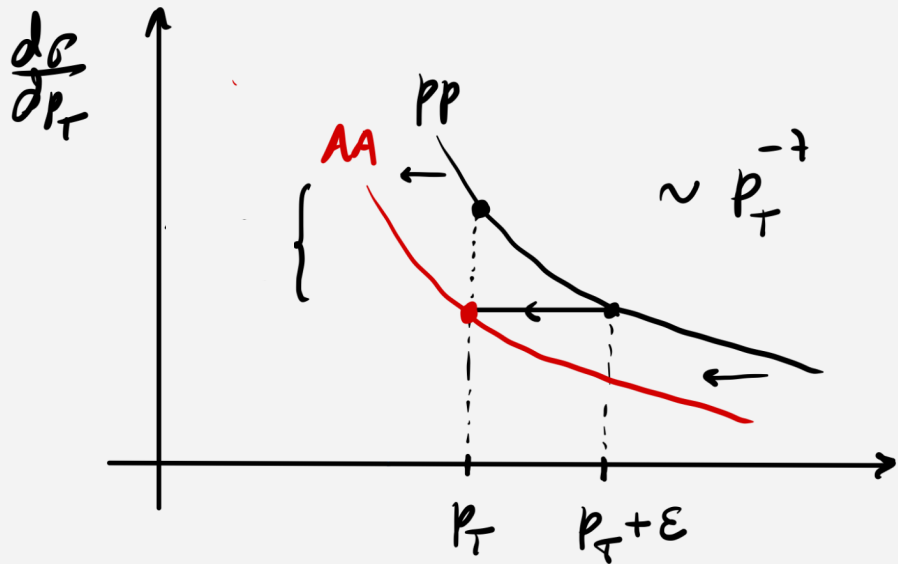
Which AA jets should I compare to a given set of pp jets?

- ◆ Common procedure: Choose a window of **reconstructed jet** p_T
- ◆ Common problem:
 - ❖ AA jets **migrate** to lower reconstructed p_T (jet energy loss)
 - ⇒ We are comparing jets that “**started out**” differently.

Bin migration in R_{AA}

$$R_{AA} = \frac{d\sigma^{AA}/dp_T}{d\sigma^{PP}/dp_T}$$

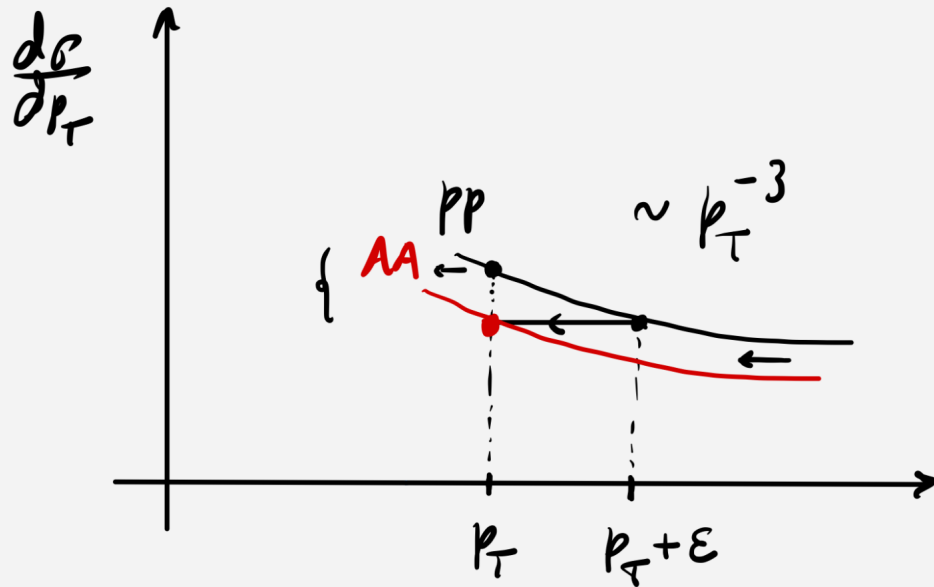
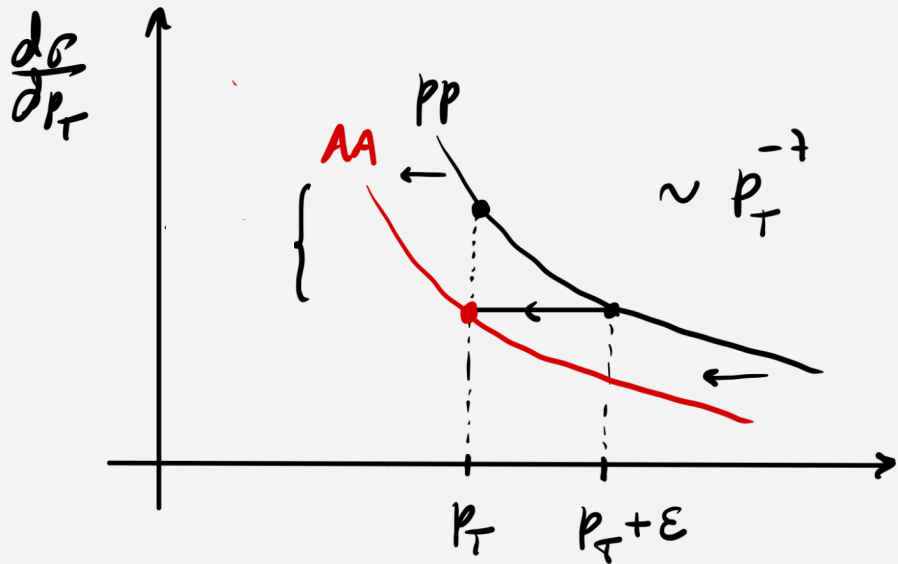
$$p_T \rightarrow p_T - \epsilon$$



Bin migration in R_{AA}

$$R_{AA} = \frac{d\sigma^{AA}/dp_T}{d\sigma^{PP}/dp_T}$$

$$p_T \rightarrow p_T - \epsilon$$



Same energy loss but different R_{AA} !

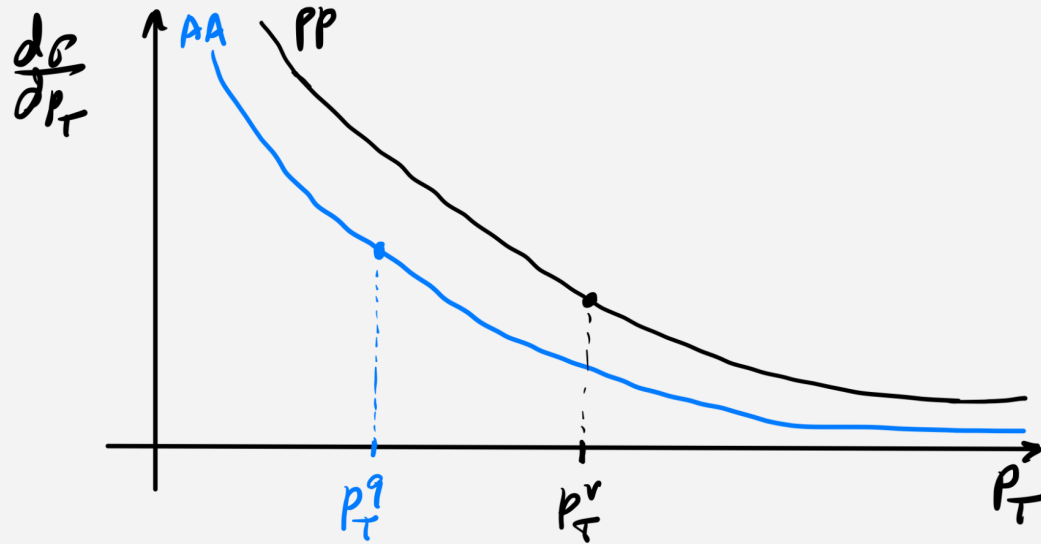
Biased jet comparison

Which AA jets should I compare to a given set of pp jets?

- ◆ Common procedure: Choose a window of **reconstructed jet** p_T
- ◆ Common problem:
 - ❖ AA jets **migrate** to lower reconstructed p_T (jet energy loss)
 - ⟹ We are comparing jets that “**started out**” differently.
- ◆ Possible solution: **boson + jet events?** ⟹ Statistics not as good as inclusive jet events!

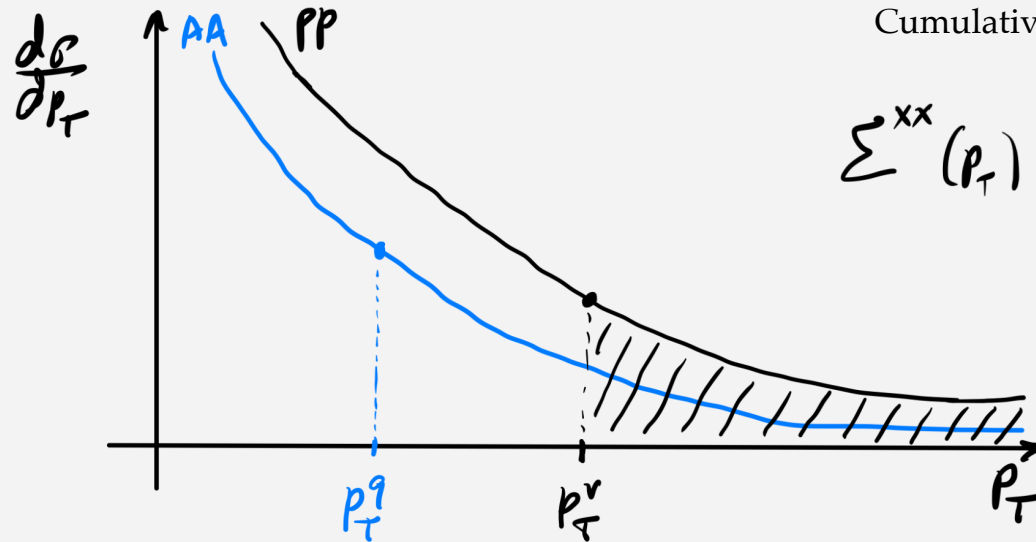
Brewer et al. [Journal of High Energy Physics 2022\(2\), 1-22](#), Apolinário et al. [arXiv:2401.14229](#)

Quantiles - a way to estimate p_T migration



J. Brewer, J. Milhano, J. Thaler; Phys. Rev. Lett. 122 (2019) 22, 222301

Quantiles - a way to estimate p_T migration



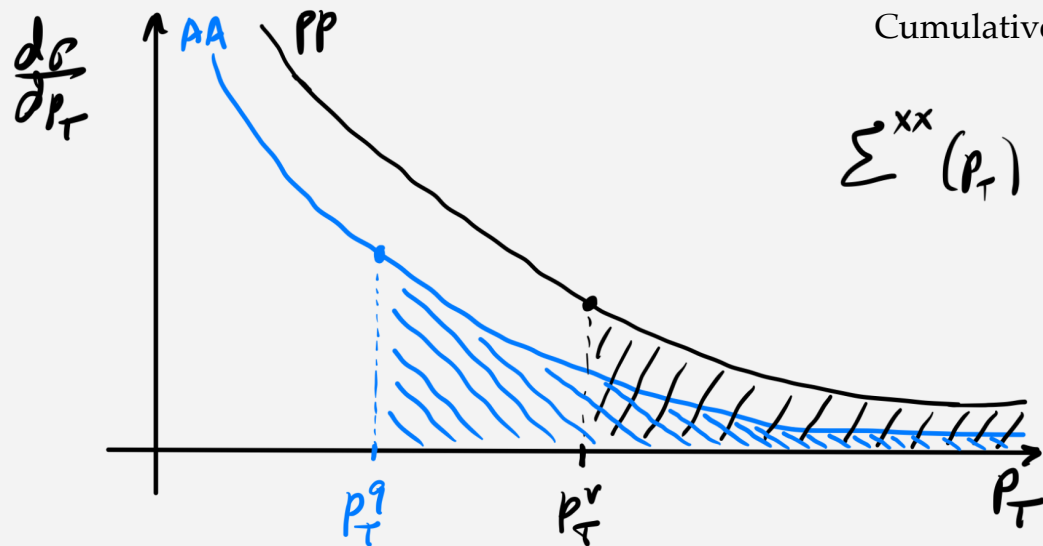
Cumulative jet p_T cross section

$$\Sigma^{xx}(p_T) \equiv \int_{p_T}^{+\infty} dp_T' \frac{d\sigma^{xx}}{dp_T'}$$

J. Brewer, J. Milhano, J. Thaler; Phys. Rev. Lett. 122 (2019) 22, 222301

$$\Sigma^{PP}(p_T^v) =$$

Quantiles - a way to estimate p_T migration



Cumulative jet p_T cross section

$$\Sigma^{xx}(p_T) \equiv \int_{p_T}^{+\infty} dp_T' \frac{d\sigma^{xx}}{dp_T'}$$

J. Brewer, J. Milhano, J. Thaler; Phys. Rev. Lett. 122 (2019) 22, 222301

Quantile function

$$\Sigma^{PP}(p_T^v) = \Sigma^{AA}(p_T^q) \rightarrow$$

$$p_T^q = p_T^q(p_T^v)$$

Quantiles - a way to estimate p_T migration

$$p_T \rightarrow p_T - \epsilon(p_T), \quad \frac{d\epsilon}{dp_T} < 1$$

$$\implies p_T^v - p_T^q(p_T^v) = \epsilon(p_T^v) \quad \text{It is exact in the case of zero dispersion!}$$

N most energetic pp jets
=
N most energetic AA jets

Quantiles - a way to estimate p_T migration

$$p_T \rightarrow p_T - \epsilon(p_T), \quad \frac{d\epsilon}{dp_T} < 1$$

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N most energetic pp jets
=
N most energetic AA jets

In the case of a non-zero dispersion it should hold for the average:

$$p_T^v - p_T^q(p_T^v) \approx \langle \epsilon \rangle(p_T^v) \implies Q_{AA}(p_T^v) \equiv \frac{p_T^q(p_T^v)}{p_T^v} \approx 1 - \frac{\langle \epsilon \rangle(p_T^v)}{p_T^v}$$

J. Brewer, J. Milhano, J.
Thaler; Phys. Rev. Lett.
122 (2019) 22, 222301

→ “ $1 - Q_{AA}$ is a proxy for the **average fractional jet energy loss**”

Event generation and analysis details

- 10^6 medium and vacuum samples generated with **JEWEL w/ and w/o recoils** (γ + jet and dijet events at $\sqrt{s_{NN}} = 5.02$ TeV and [0 – 10] % centrality)
 - ↳ Constituent event-wise background subtraction (J. Milhano, K. Zapp, Eur.Phys.J.C 82 (2022) 11, 1010)
- Vacuum samples are generated as pp collisions weighted by isospin averaged nuclear PDFs
 - ↳ Differences between vacuum and medium samples are in principle **dominated by quenching effects**

Vacuum jet spectrum

$$\frac{d\sigma^{vac}}{dp_T} = \frac{d\sigma^{pp+nPDFs}}{dp_T}$$

Medium jet spectrum

$$\frac{d\sigma^{med}}{dp_T} = \frac{1}{\langle N_{coll} \rangle} \frac{d\sigma^{PbPb}}{dp_T}$$

Quantile procedure validation

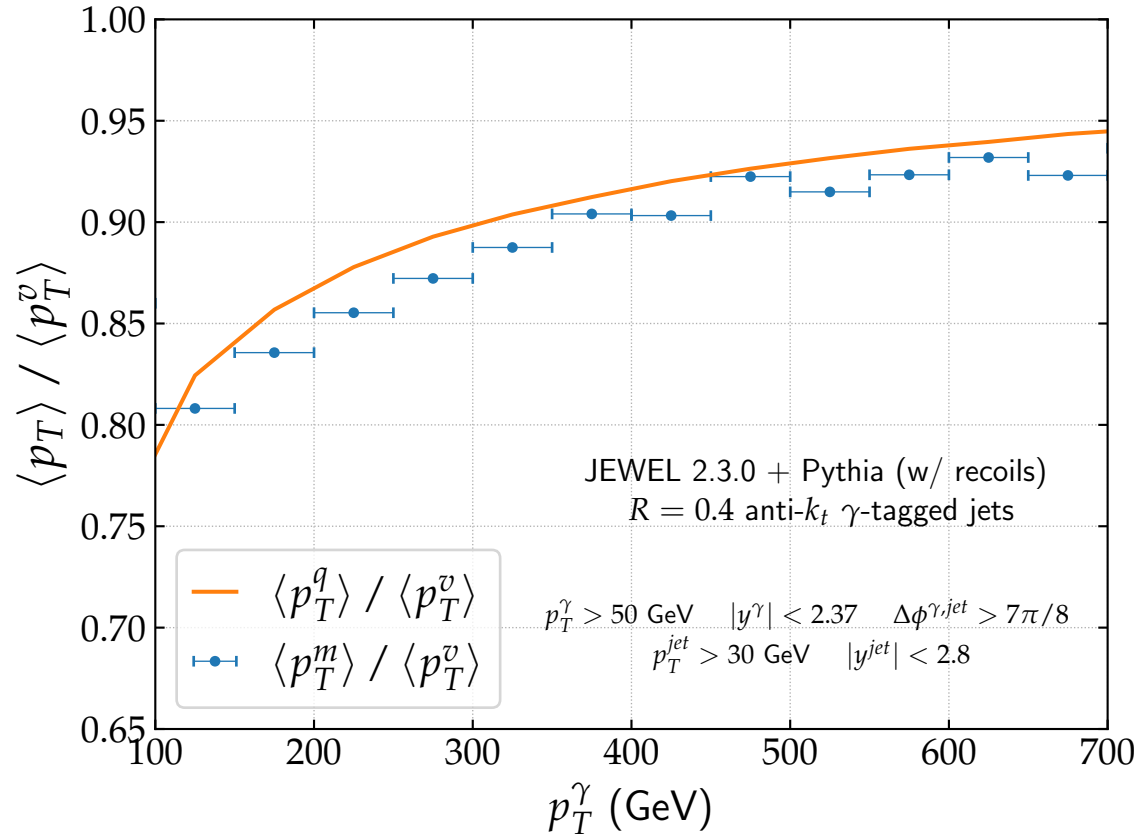
Two different **energy loss proxies**:

Average jet p_T for a given photon p_T

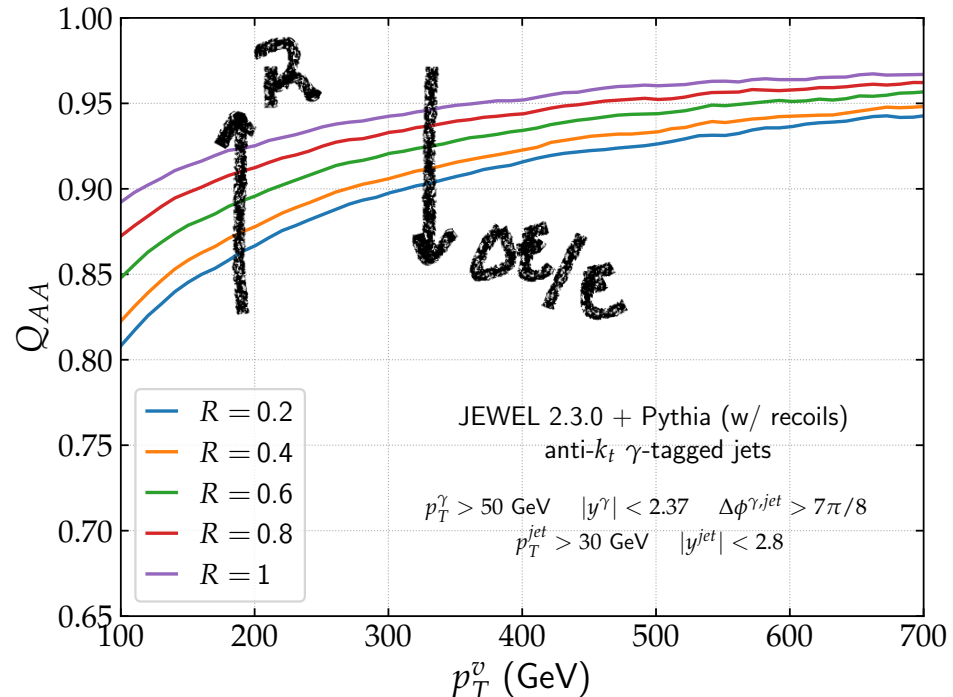
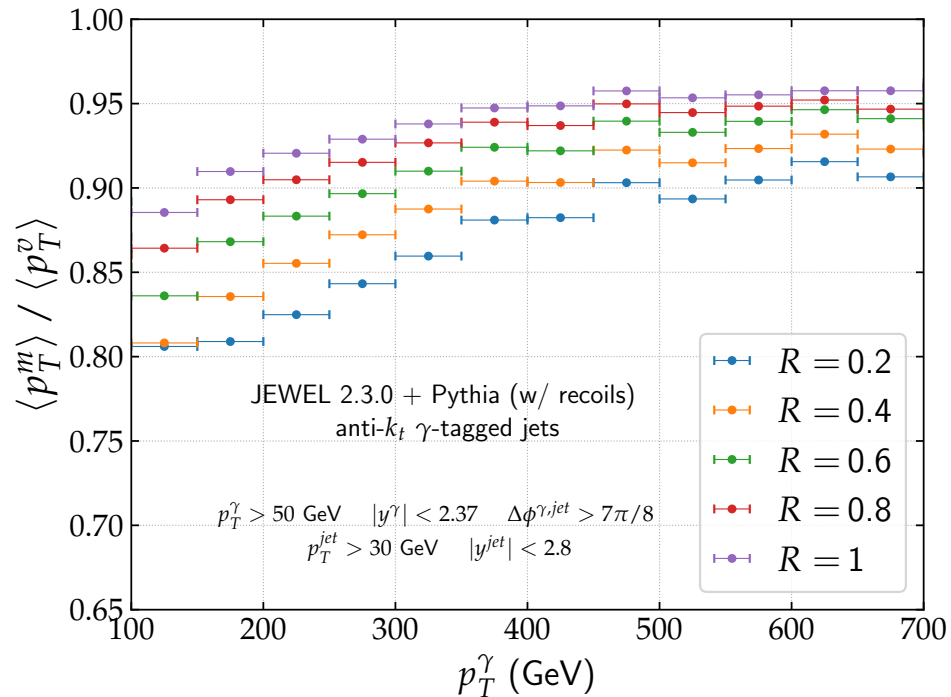
$$\langle p_T^{v/m} \rangle \Big|_{p_T^\gamma} = \int dp_T \frac{dN^{v/m}}{dp_T} \Big|_{p_T^\gamma} p_T$$

Average quantile p_T for a given photon p_T

$$\langle p_T^q \rangle \Big|_{p_T^\gamma} = \int dp_T \frac{dN^v}{dp_T} \Big|_{p_T^\gamma} p_T^q(p_T)$$



Energy loss as a function of jet radius (w/ recoils)



Larger jets lose a smaller fraction of their energy

Energy loss dependence on color charge

$$q \sim C_F$$

$$g \sim C_A$$

$$\delta + \text{jet} \sim q \text{ mit. jets}$$

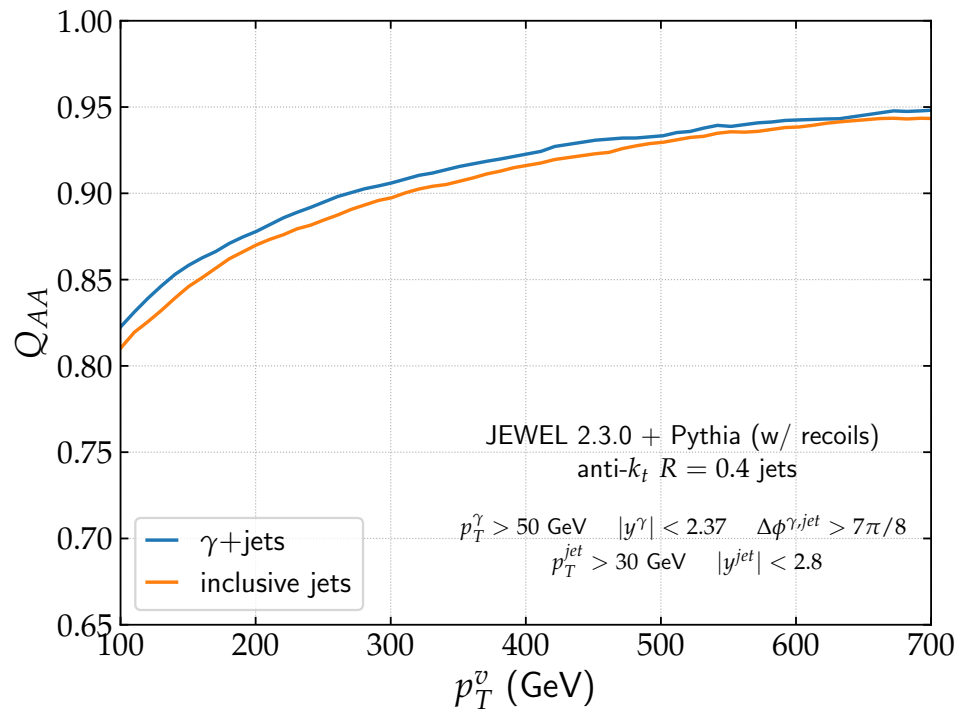
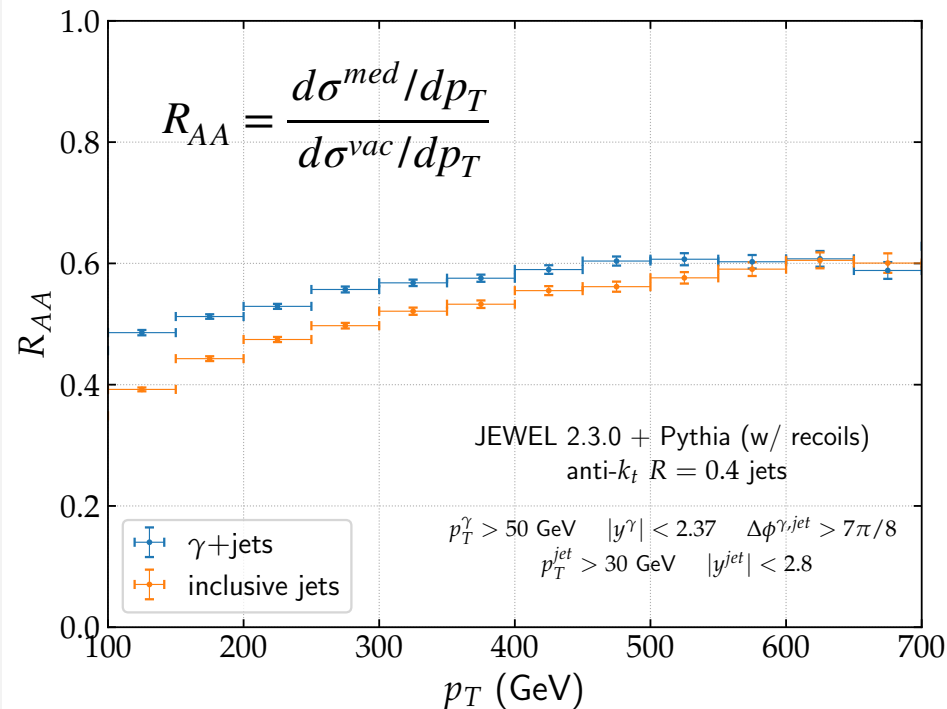
$$R_{AA}^{\delta j} > R_{AA}^{j j}$$

\Rightarrow

dijet \sim mixture of
 q and g mit. jets

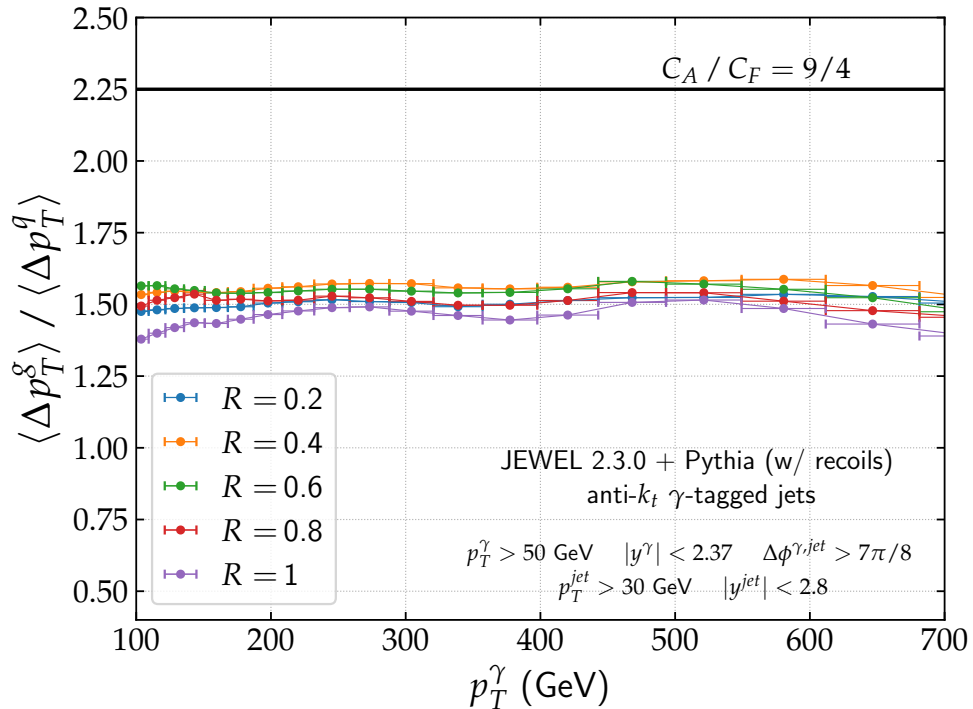
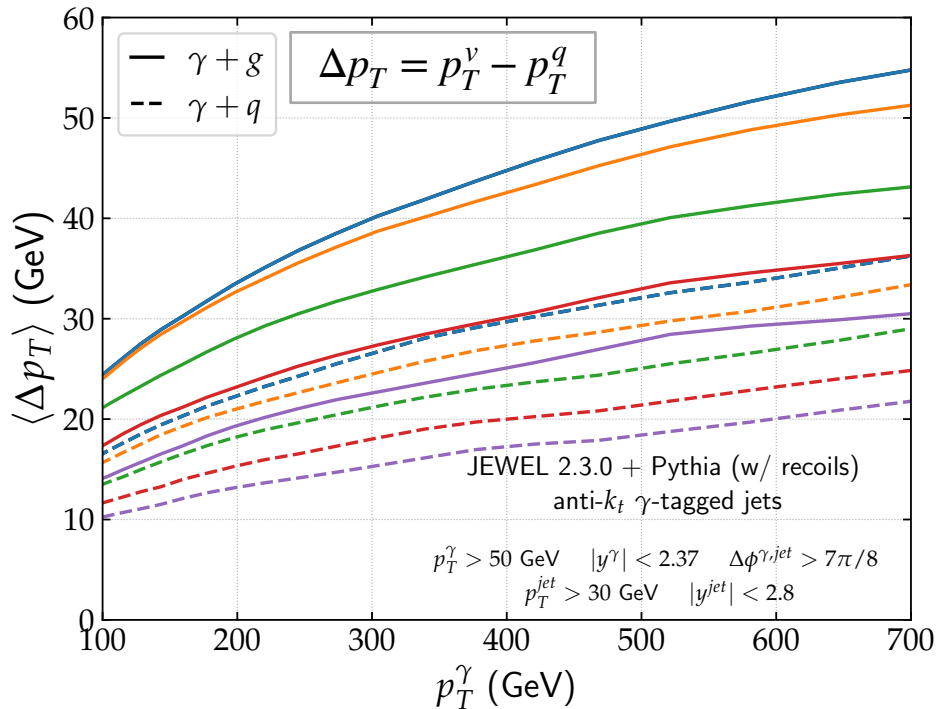
$=$
Casimir scaling
in jets ?

Energy loss dependence on color charge



Color charge dependence of jet energy loss is **not as strong**
as suggested by the R_{AA}

Energy loss dependence on color charge

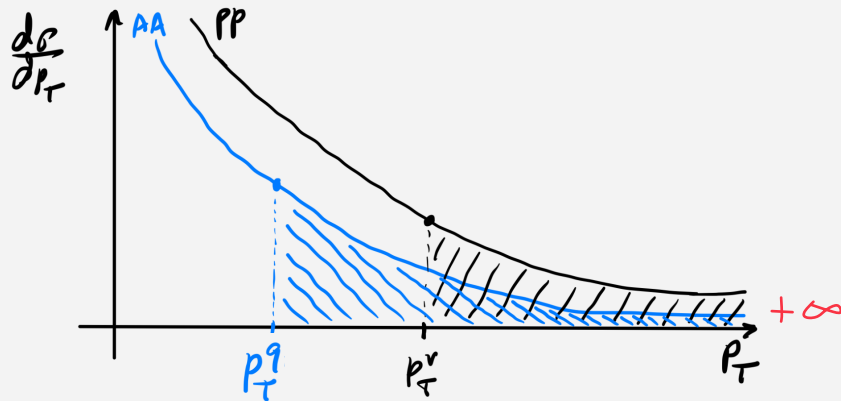


Casimir scaling is significantly reduced with respect to naive single parton scaling

The cutoff problem

Not feasible experimentally -
jets are not measured with arbitrarily large p_T

$$\int_{p_T^v}^{+\infty} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{+\infty} dp_T \frac{d\sigma^m}{dp_T}$$



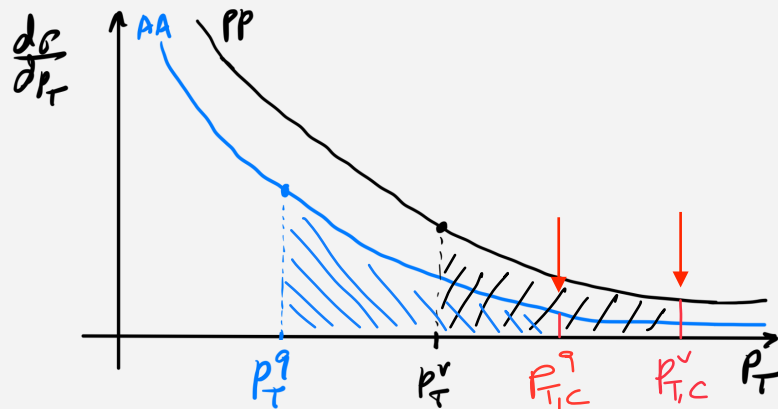
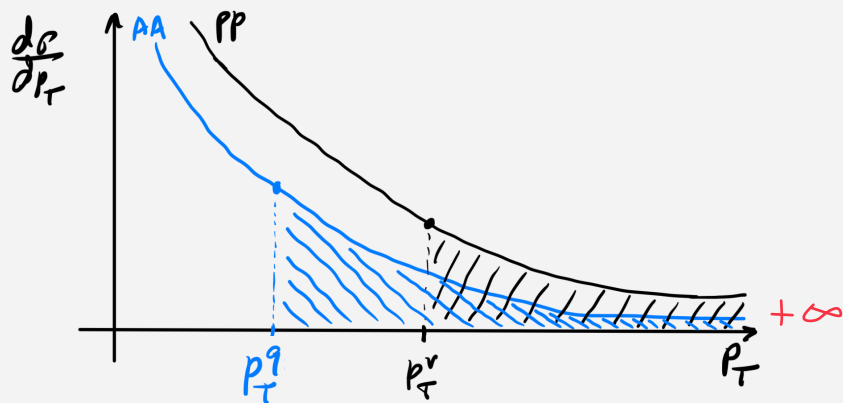
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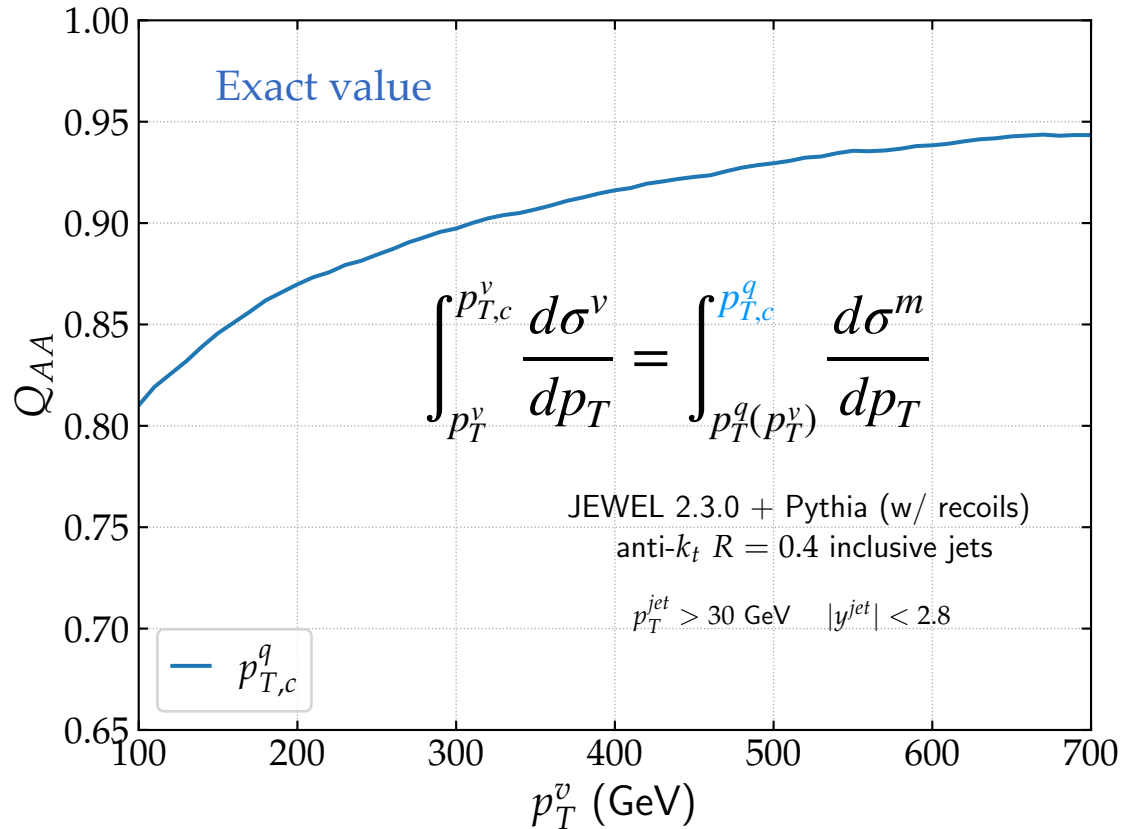
Needs an **initial condition** to be set

$$\int_{p_T^v}^{+\infty} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{+\infty} dp_T \frac{d\sigma^m}{dp_T} \iff$$

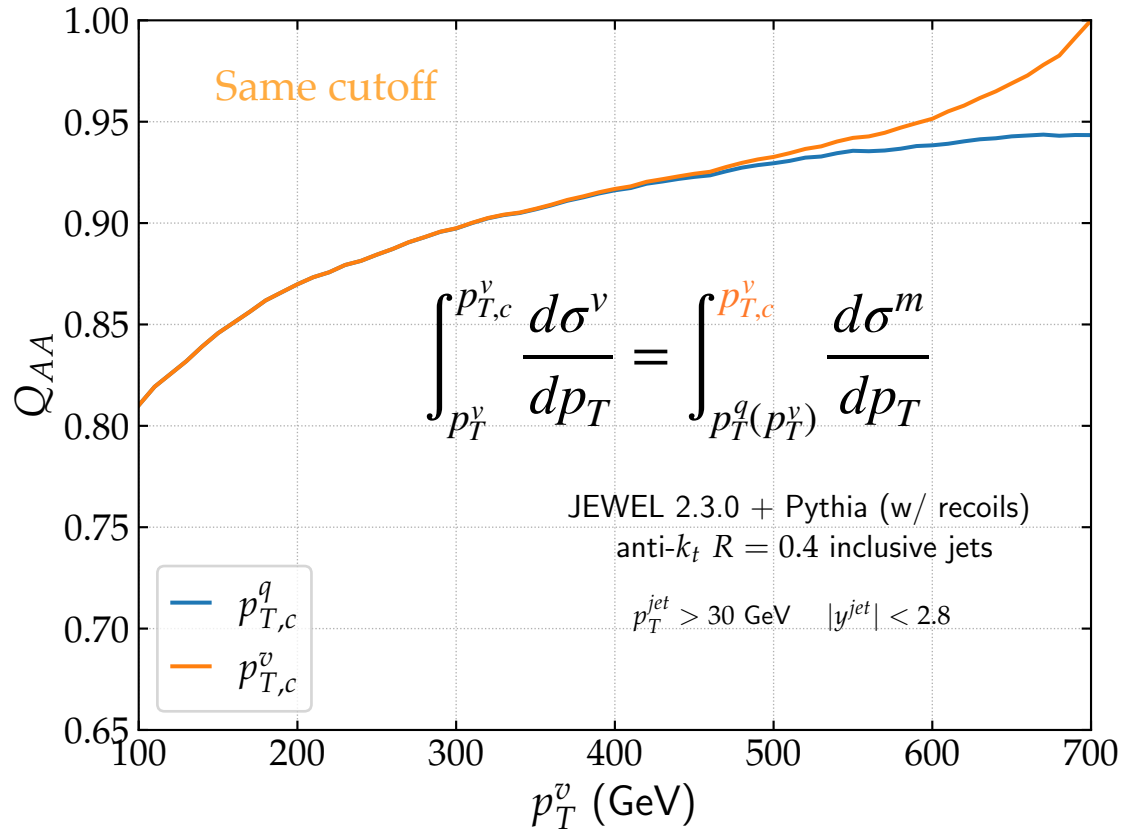
$$\int_{p_T^v}^{p_{T,c}^v} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{p_{T,c}^q = p_{T,c}^q(p_T^v, c)} dp_T \frac{d\sigma^m}{dp_T}$$



The cutoff problem



The cutoff problem



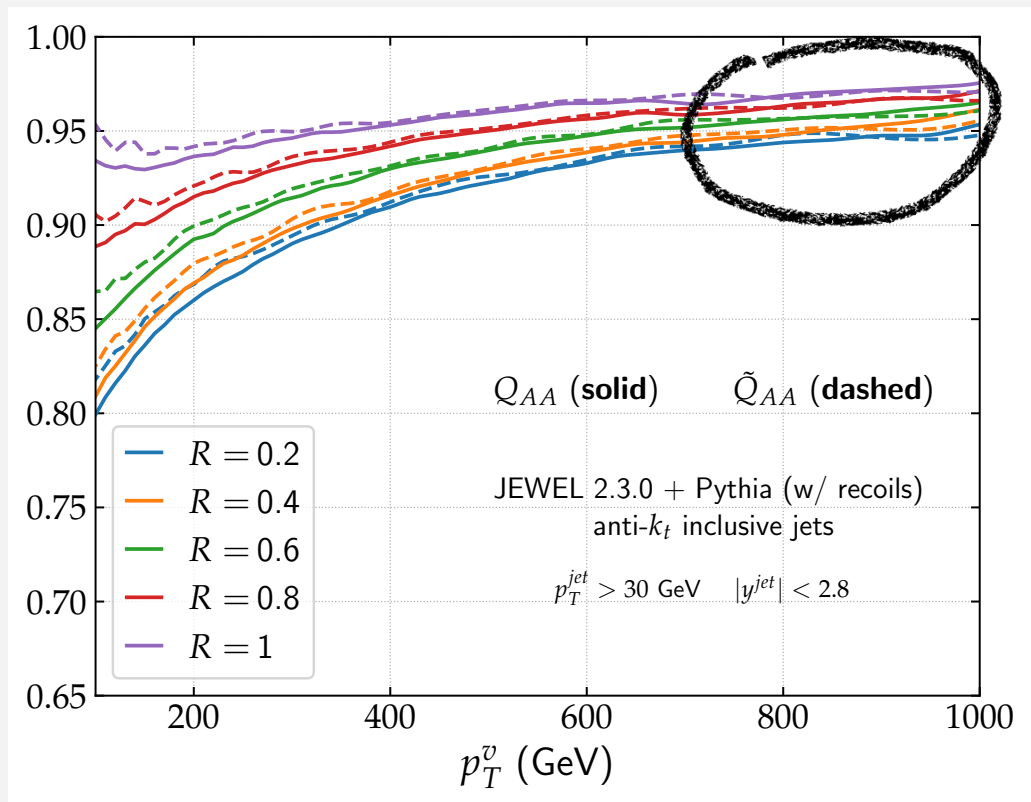
The cutoff problem: using \tilde{Q}_{AA} as a solution

J. Brewer, J. Milhano, J. Thaler; Phys. Rev. Lett. 122 (2019) 22, 222301

Pseudo-quantile (\tilde{p}_T^q)
 (equate cross sections rather than cumulative cross sections)

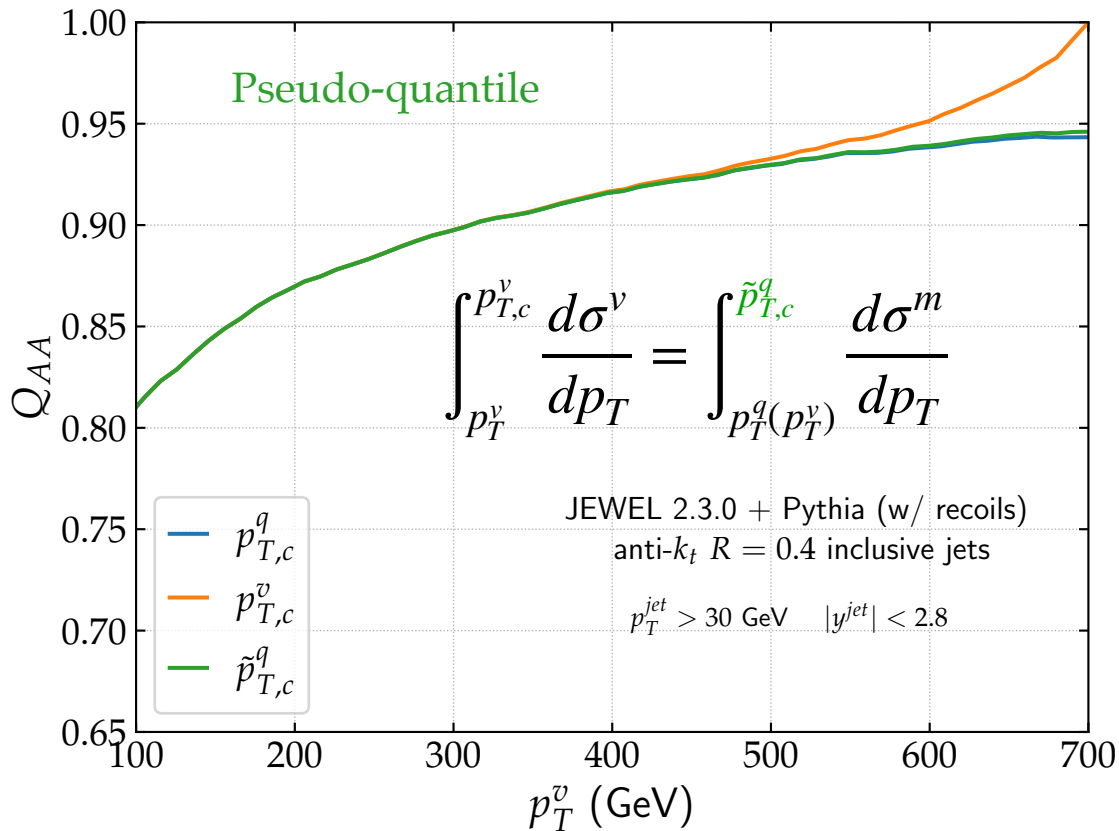
$$\frac{d\sigma^v}{dp_T^v}(p_T^v) = \frac{d\sigma^m}{d\tilde{p}_T^q}(\tilde{p}_T^q(p_T^v))$$

$$\Rightarrow \tilde{Q}_{AA} = \frac{\tilde{p}_T^q}{p_T^v}$$



The cutoff problem: using \tilde{Q}_{AA} as a solution

$$\tilde{p}_{T,c}^q = \tilde{p}_T^q(p_{T,c}^v)$$



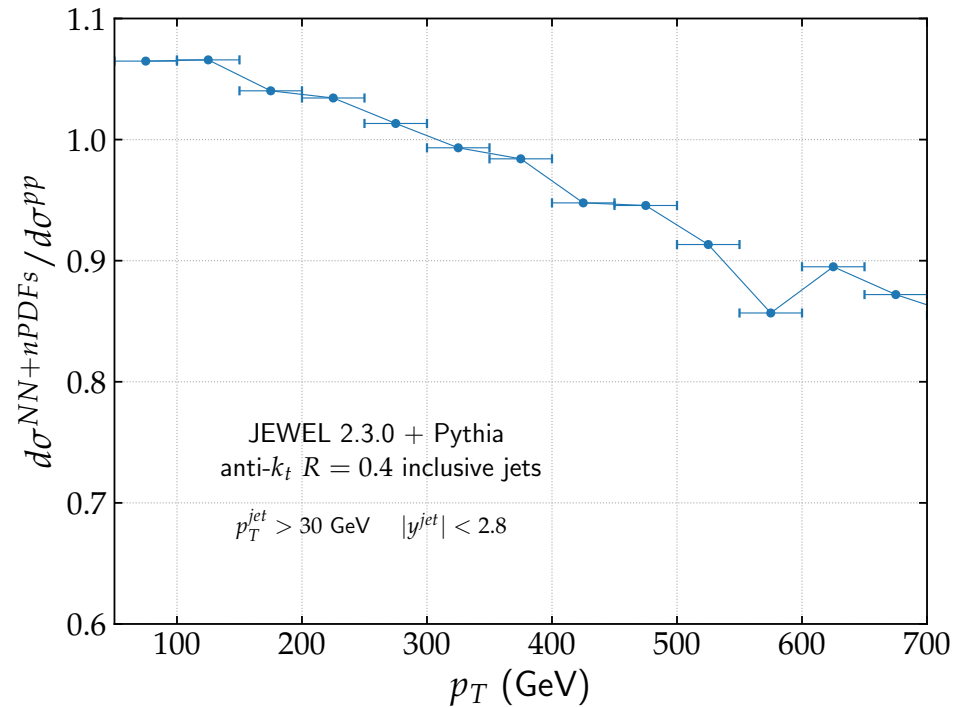
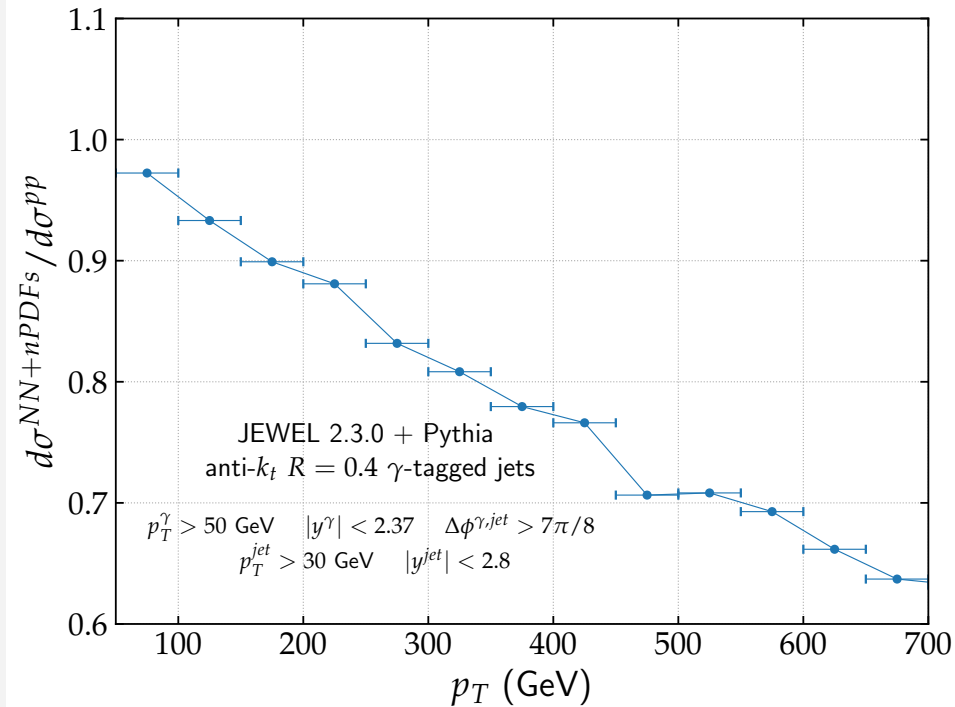
Summary

- ◆ The Q_{AA} provides a **proxy for jets that started out similarly** that can be used in inclusive jet events and possibly a model-independent way of quantifying jet energy loss;
- ◆ The color charge of the initiating parton does not play as important a role in jet energy loss as one would have thought by looking into R_{AA} - **the difference in spectrum steepness is quite impactful**;
- ◆ Experimental challenge to the measurement of the Q_{AA} presented by a **momentum cutoff** on the spectrum is easily circumvented using \tilde{Q}_{AA} .

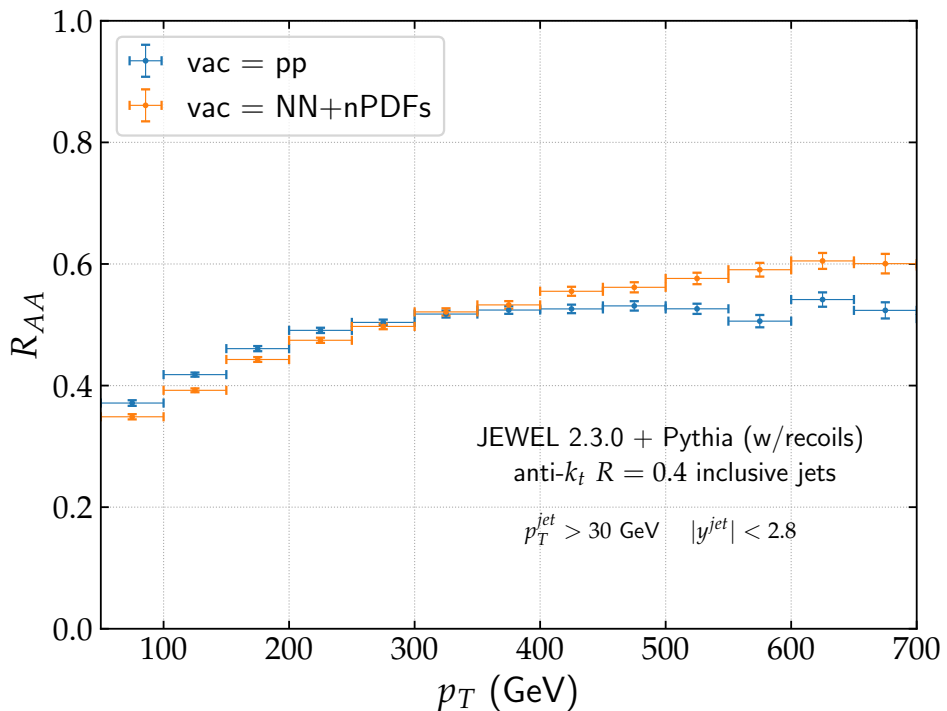
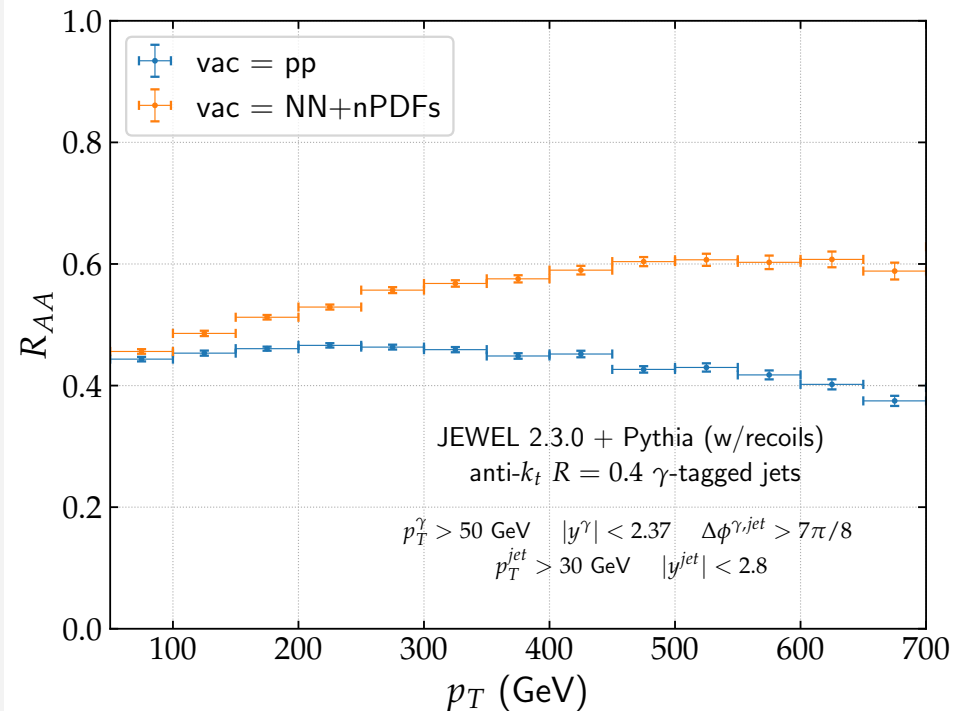
THANKS!

Back-up

Nuclear effects on the jet p_T spectrum



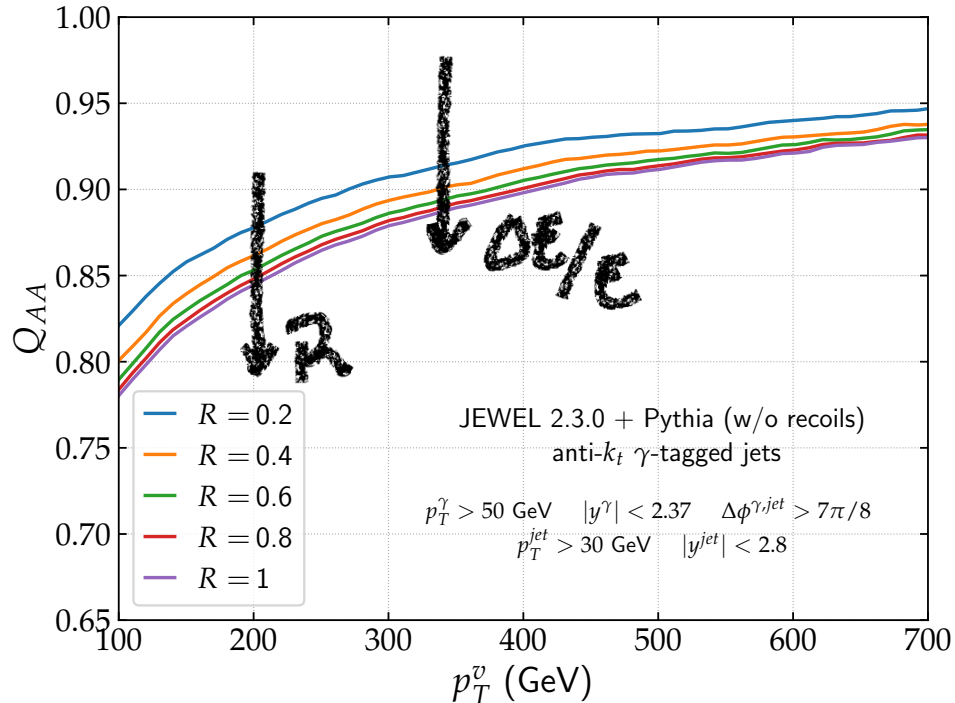
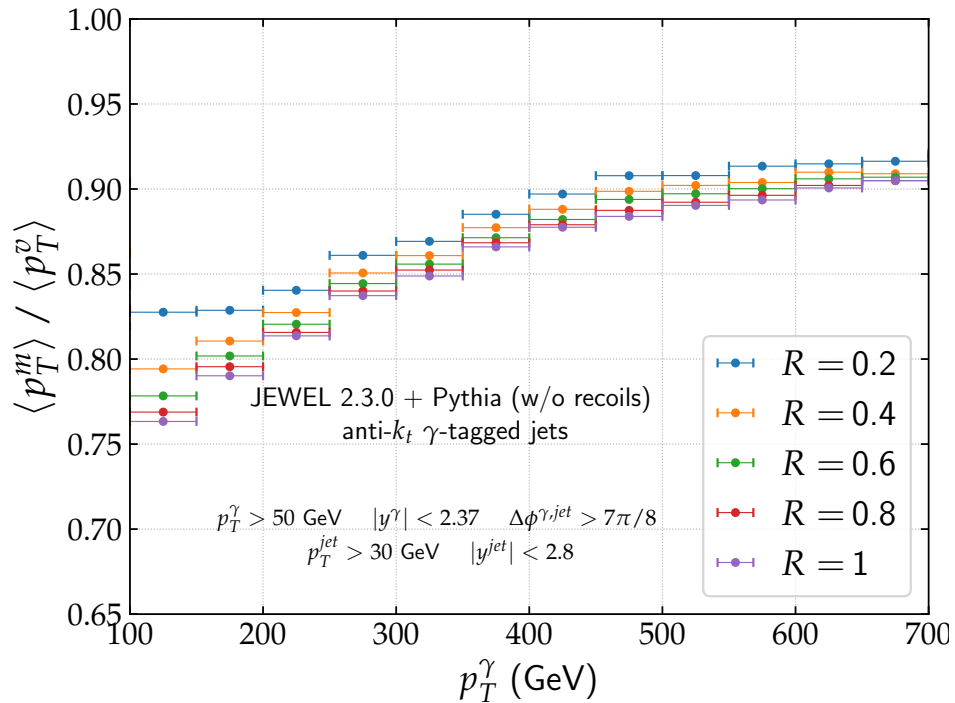
Nuclear effects on the R_{AA}



Differential version of the quantile procedure

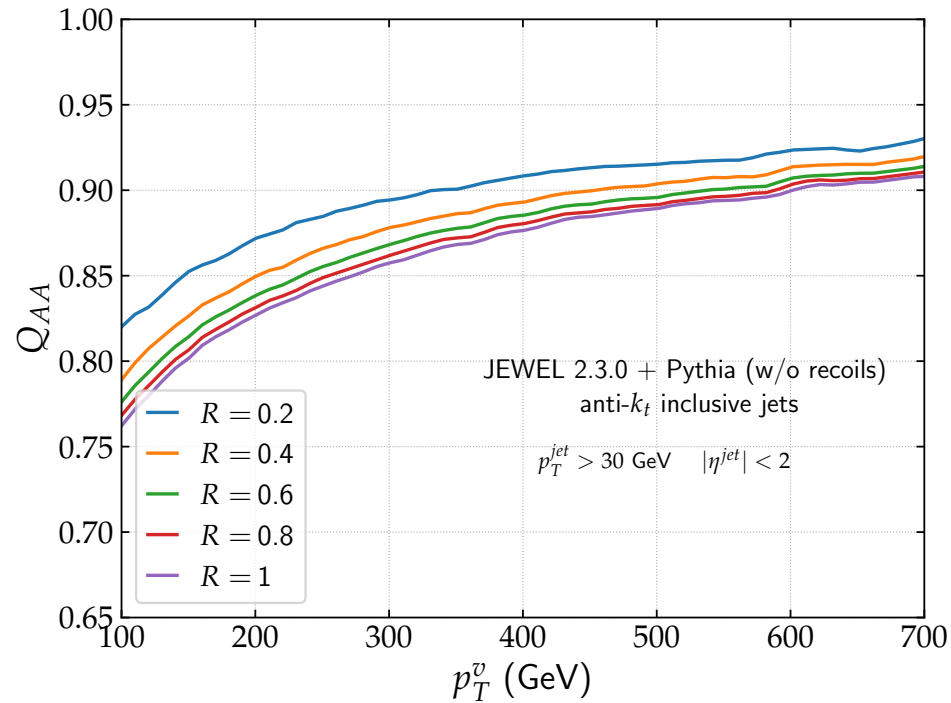
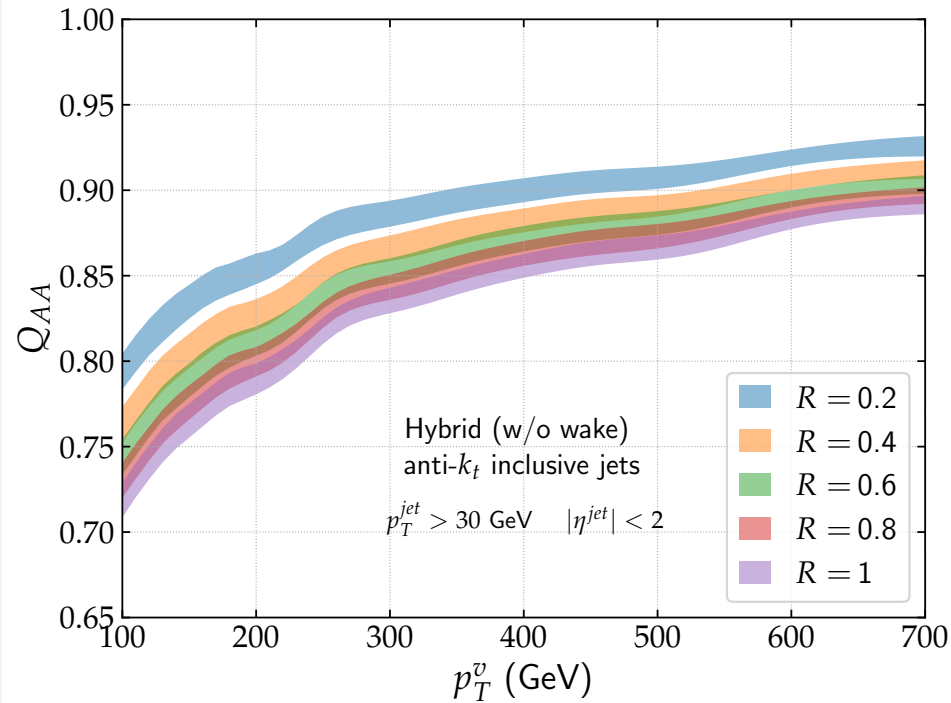
$$\frac{d}{dp_T^v} \left(\int_{p_T^v}^{+\infty} dp_T \frac{d\sigma^{pp}}{dp_T} \right) = \frac{d}{dp_T^v} \left(\int_{p_T^q(p_T^v)}^{+\infty} dp_T \frac{d\sigma^{AA}}{dp_T} \right)$$
$$\implies \frac{d\sigma^{pp}}{dp_T}(p_T^v) = \frac{dp_T^q}{dp_T^v} \frac{d\sigma^{AA}}{dp_T}(p_T^q(p_T^v))$$

Energy loss as a function of jet radius (w/o recoils)

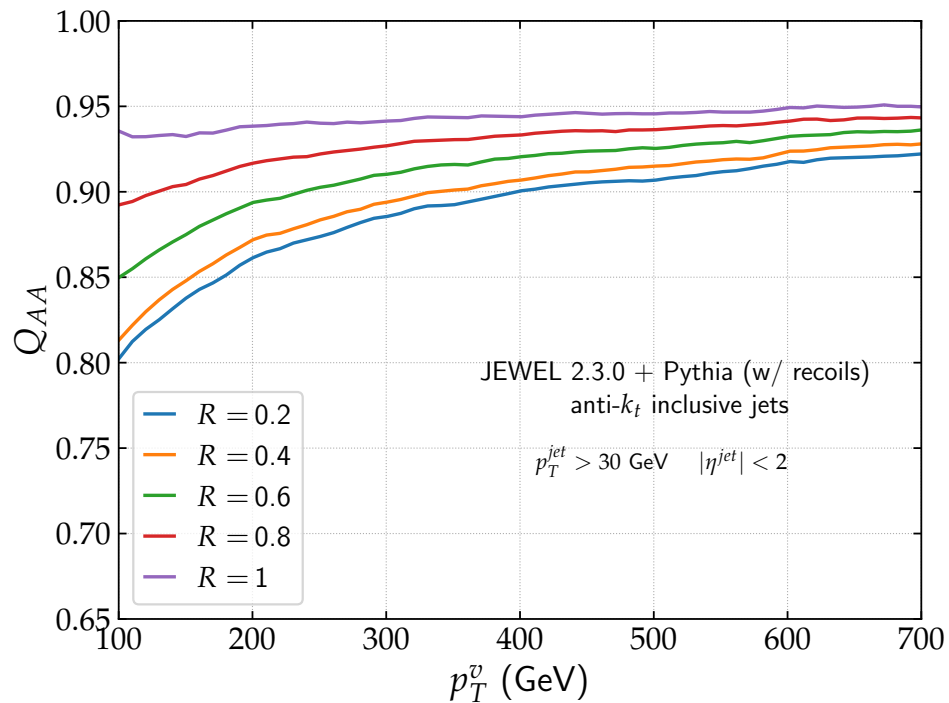
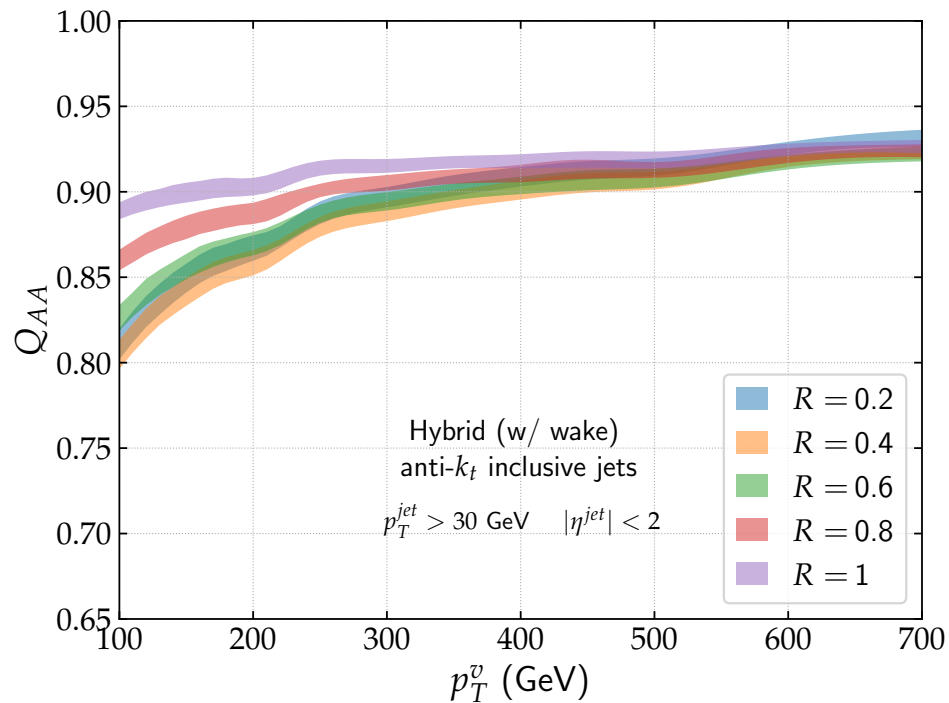


Larger jets lose a larger fraction of their energy

Energy loss as a function of jet radius (model comp.)



Energy loss as a function of jet radius (model comp.)



Effect of suppressing p_T migration

Observables calculated from code in Romão et al. [2304.07196](#)

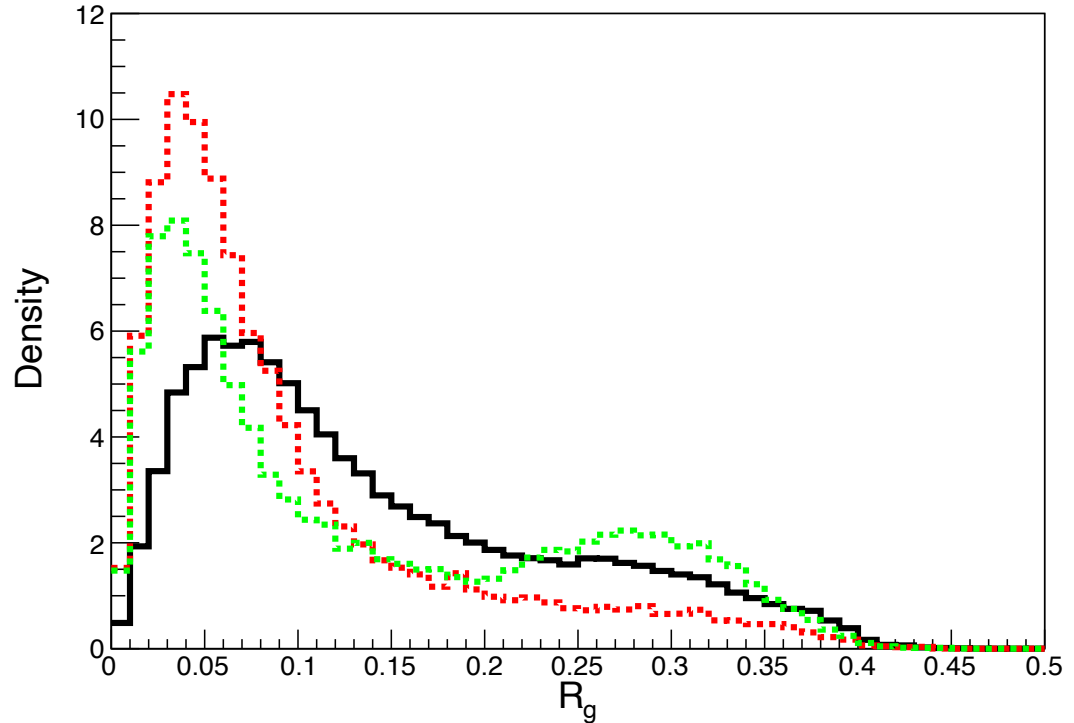
- vac ($p_T \in [100, 200]$ GeV)
- ⋯ med w/o recoils, ($p_T \in [100, 200]$ GeV)
- ⋯ med w/ recoils, ($p_T \in [100, 200]$ GeV)

R_g :

ΔR of first C/A reclustering
sequence branch passing the Soft
Drop condition:

$$\frac{\min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R} \right)^\beta$$

$$z_{cut} = 0.1, \quad \beta = 0$$



Effect of suppressing p_T migration

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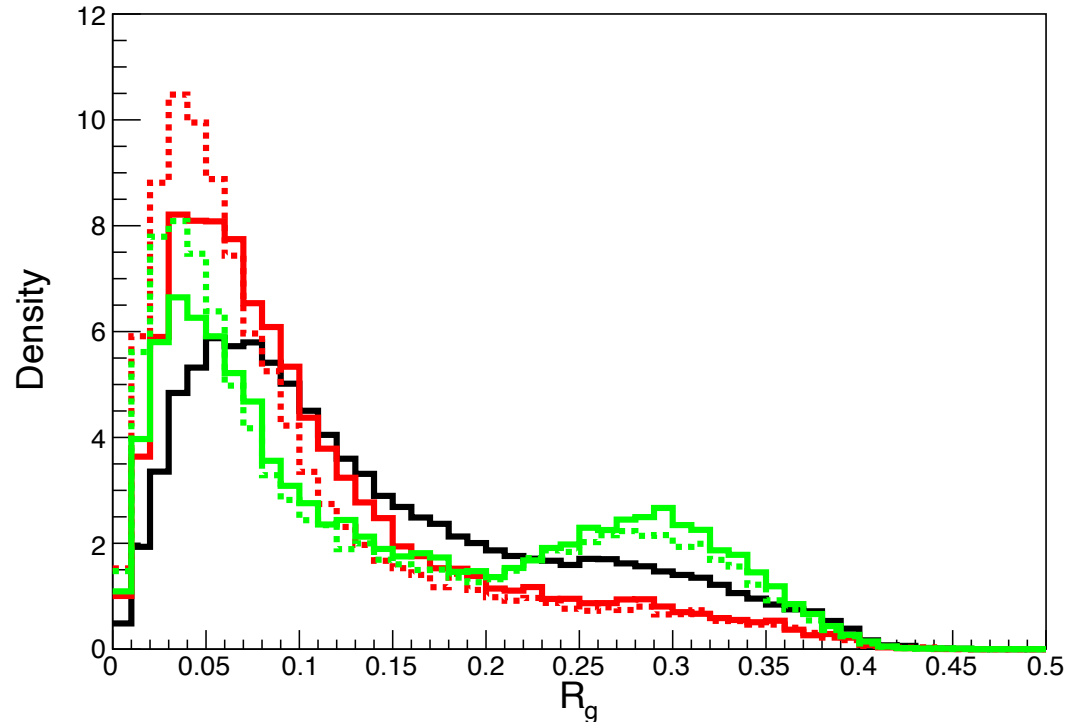
- vac ($p_T \in [100, 200]$ GeV)
- ⋯ med w/o recoils, ($p_T \in [100, 200]$ GeV)
- med w/o recoils ($p_T^q \in [79, 170]$ GeV)
- ⋯ med w/ recoils, ($p_T \in [100, 200]$ GeV)
- med w/ recoils ($p_T^q \in [84, 177]$ GeV)

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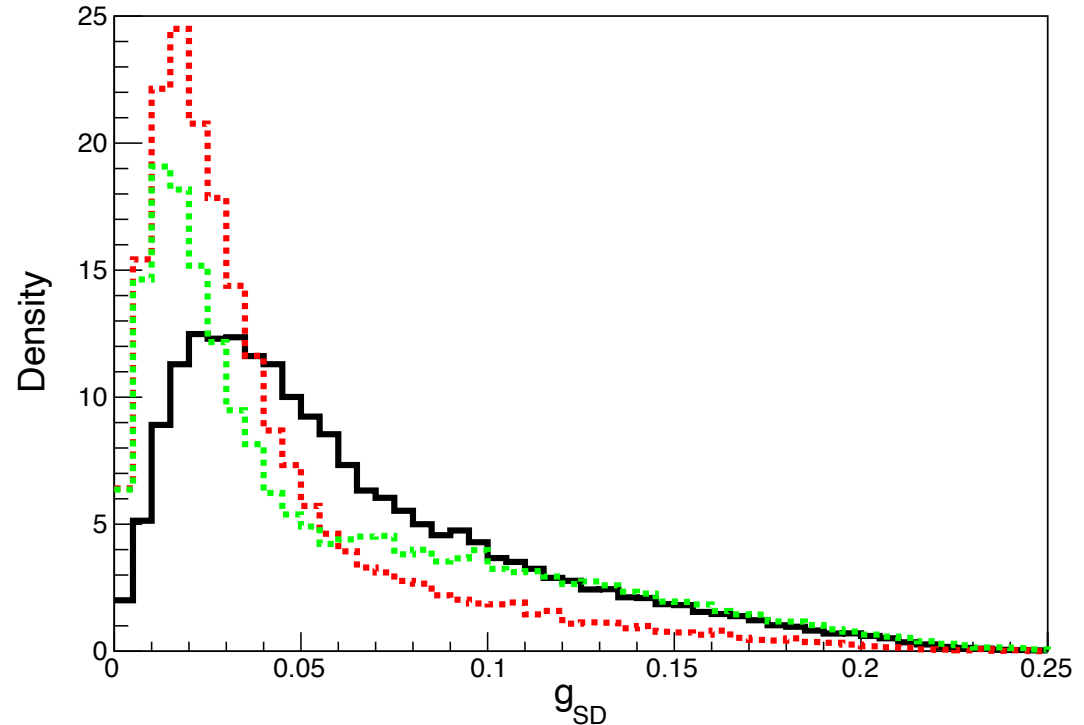
Discard all C/A reclustering branches until Soft Drop condition:

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(Soft Dropped) Jet girth:

$$g_{SD} = \sum_{i \in jet_{SD}} z_i \Delta R_{i,jet}$$

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Effect of suppressing p_T migration

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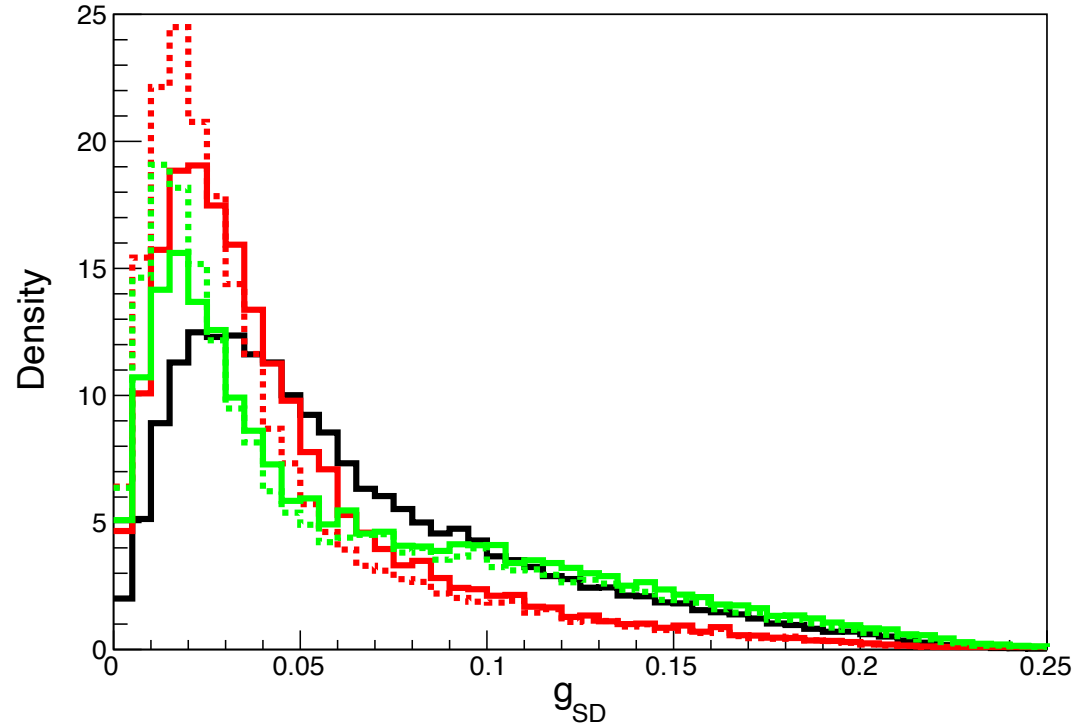
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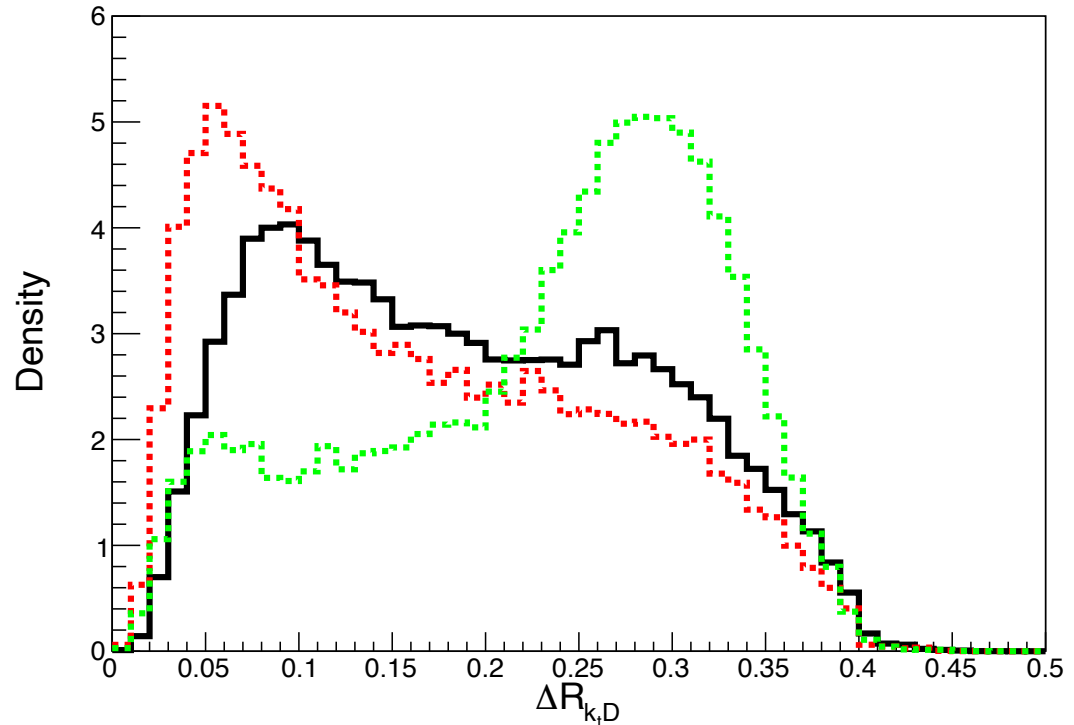
Effect of suppressing p_T migration

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- ⋯ med w/ recoils, ($p_T \in [100, 200]$ GeV)

ΔR of C/A reclustering sequence
branch passing the Dynamical
Grooming
($a = 1, k_T$ Drop) condition:

$$\frac{1}{p_{T,jet}} \max \left[z_i(1 - z_i)p_{T,i} \left(\frac{\theta_i}{R} \right) \right]$$



Y. Mehtar-Tani, A. Soto-Ontoso and K. Tywoniuk, [Phys. Rev. D 101\(3\), 034004 \(2020\)](#)

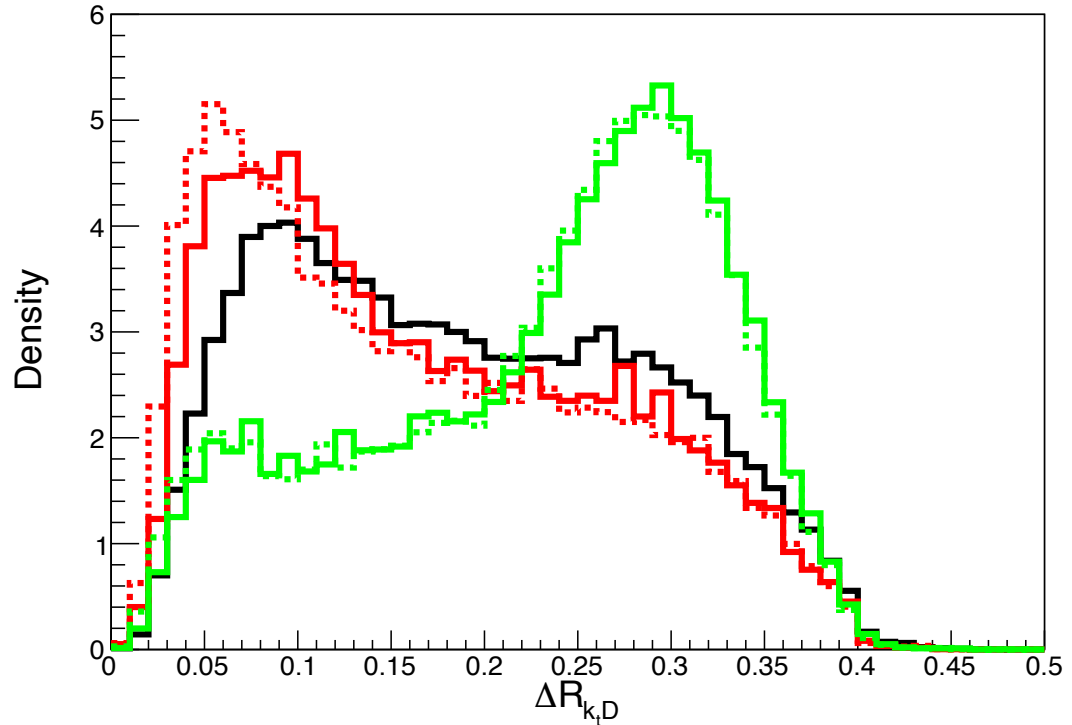
Effect of suppressing p_T migration

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Y. Mehtar-Tani, A. Soto-Ontoso and K. Tywoniuk, [Phys. Rev. D 101\(3\), 034004 \(2020\)](#)

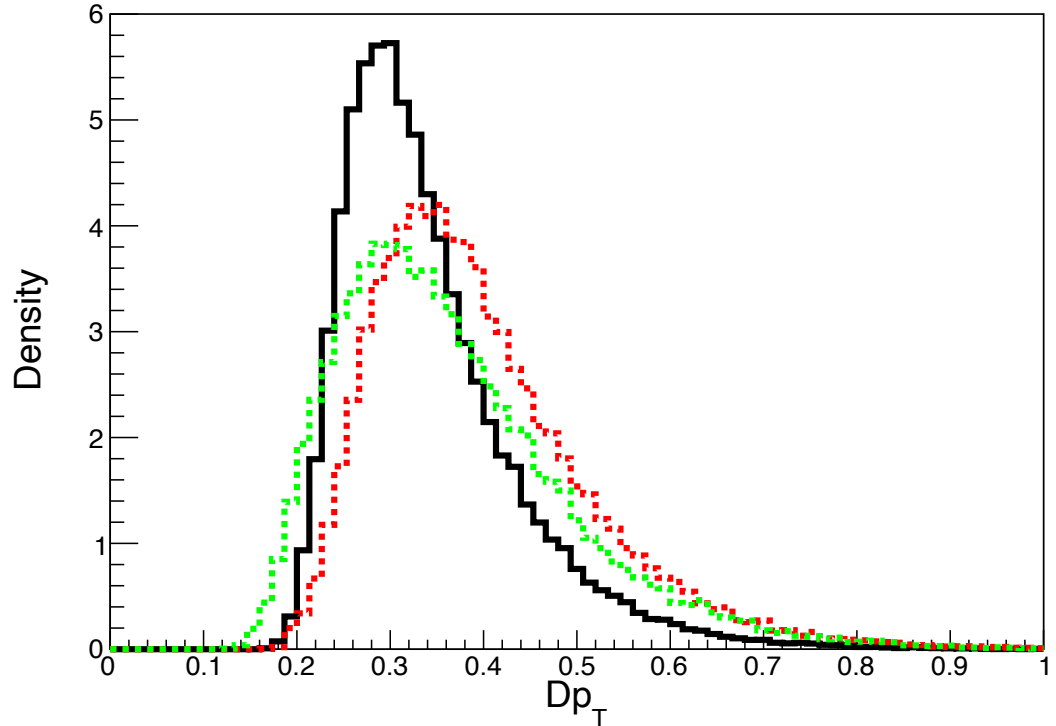
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- ⋯ med w/ recoils, ($p_T \in [100, 200]$ GeV)

Momentum dispersion:

$$Dp_T = \frac{\sqrt{\sum_{i \in \text{jet}} p_{T,i}^2}}{p_{T,\text{jet}}}$$

Observables calculated from code in Romão et al. [2304.07196](#)



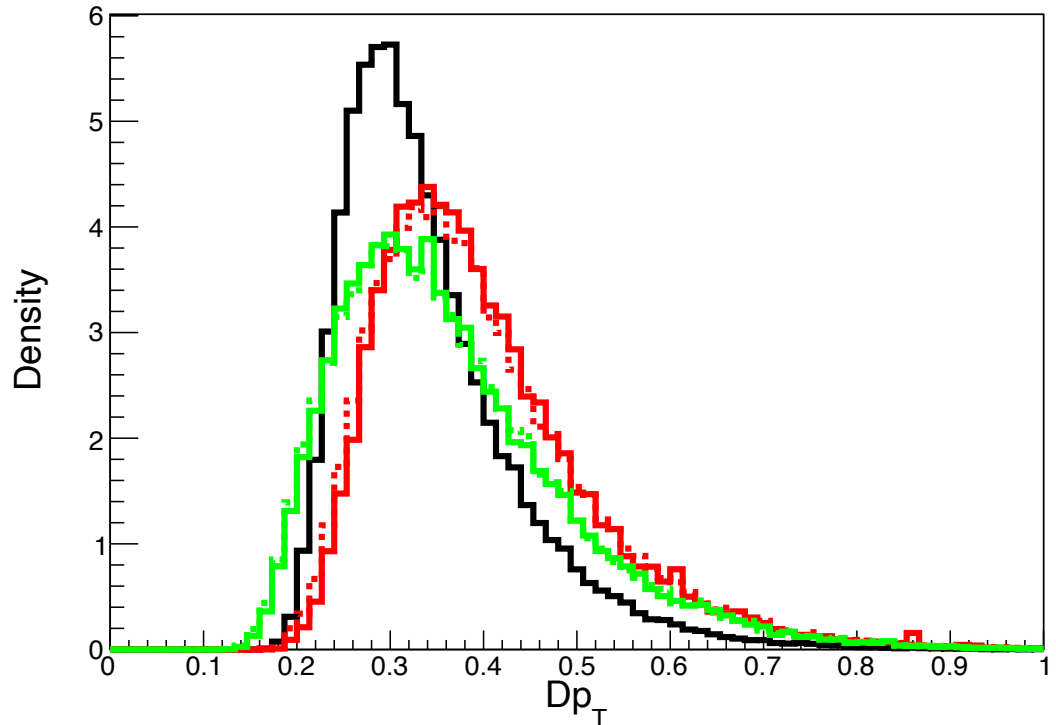
Effect of suppressing p_T migration

- vac ($p_T \in [100, 200]$ GeV)
- ⋯ med w/o recoils, ($p_T \in [100, 200]$ GeV)
- med w/o recoils ($p_T^q \in [79, 170]$ GeV)
- ⋯ med w/ recoils, ($p_T \in [100, 200]$ GeV)
- med w/ recoils ($p_T^q \in [84, 177]$ GeV)

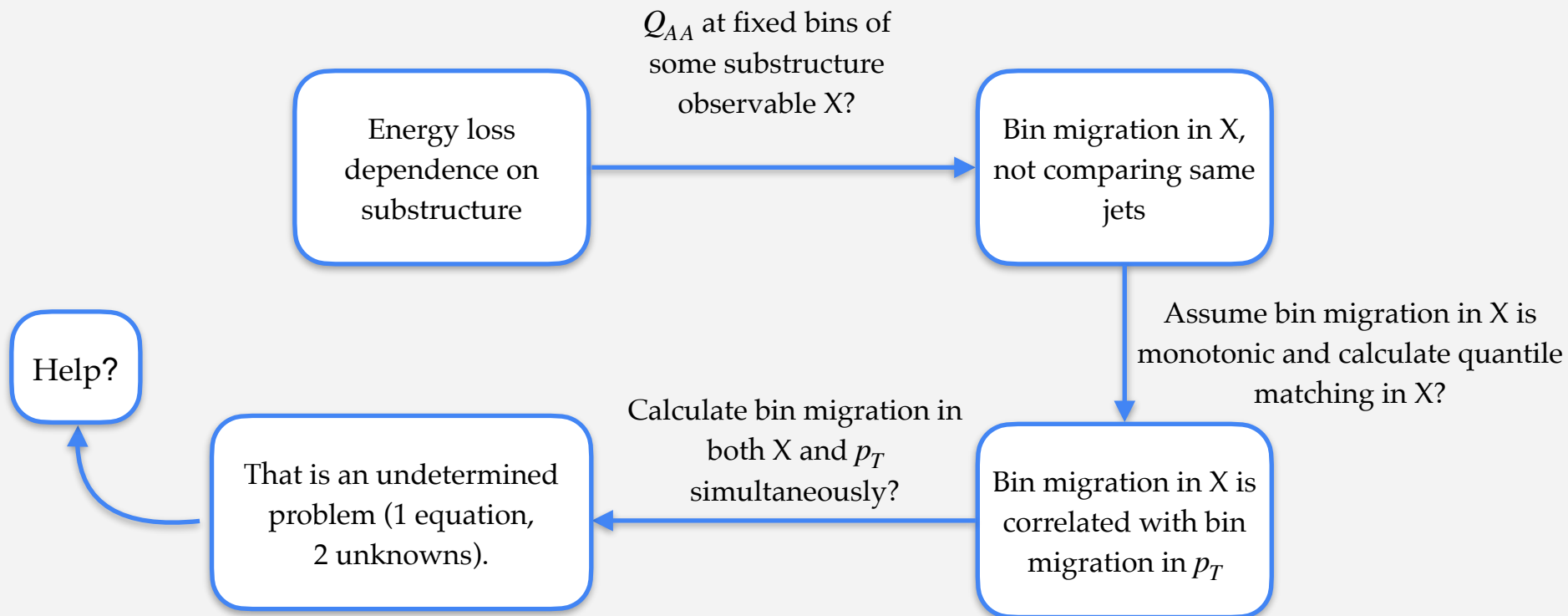
Momentum dispersion:

$$Dp_T = \frac{\sqrt{\sum_{i \in \text{jet}} p_{T,i}^2}}{p_{T,\text{jet}}}$$

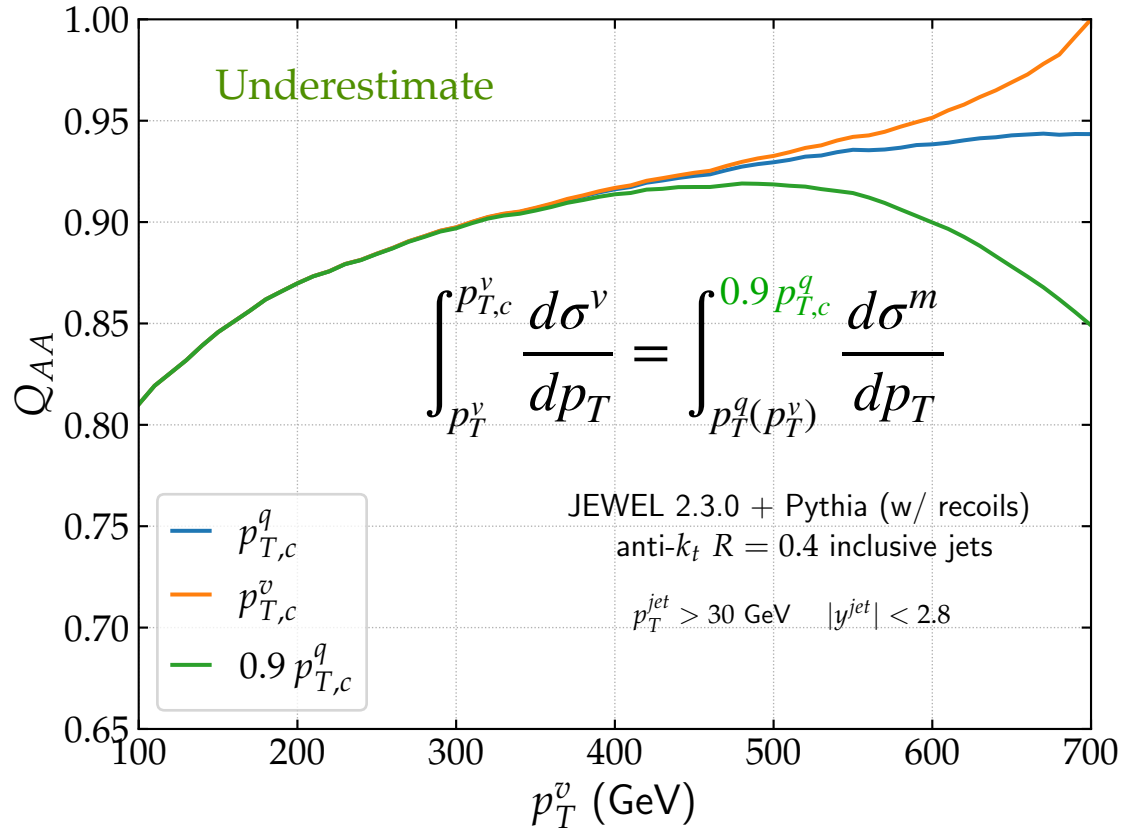
Observables calculated from code in Romão et al. [2304.07196](#)



Energy loss dependence on substructure



The cutoff problem



Q_{AA} sensitivity to spectrum binning

