Unbiased quantification of jet energy loss

João M. Silva (LIP/IST)

In collaboration with:
Liliana Apolinário (LIP/IST)
Lénea Luís (LIP/IST)
Guilherme Milhano (LIP/IST)

arXiv:2408.XXXXX

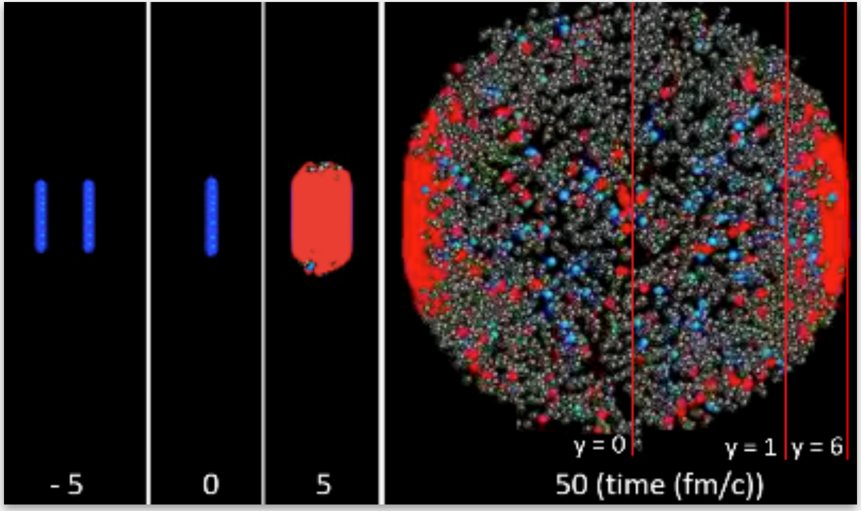
BOOST 2024
Genova, August 2024

TÉCNICO LISBOA
LIP
FCT Fundação para a Ciência e a Tecnologia
CERN/FIS-PAR/0032/2021
erc European Research Council
Established by the European Commission

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 ~ 1 fm/c (10^{-24} s) after the collision, with energy densities well above those inside typical hadrons ($\sim 0.5\ \mathrm{GeV/fm^3}$)
- Its collective properties are **lost on a timescale of ~ 10 fm/c** due to hydrodynamical expansion.

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



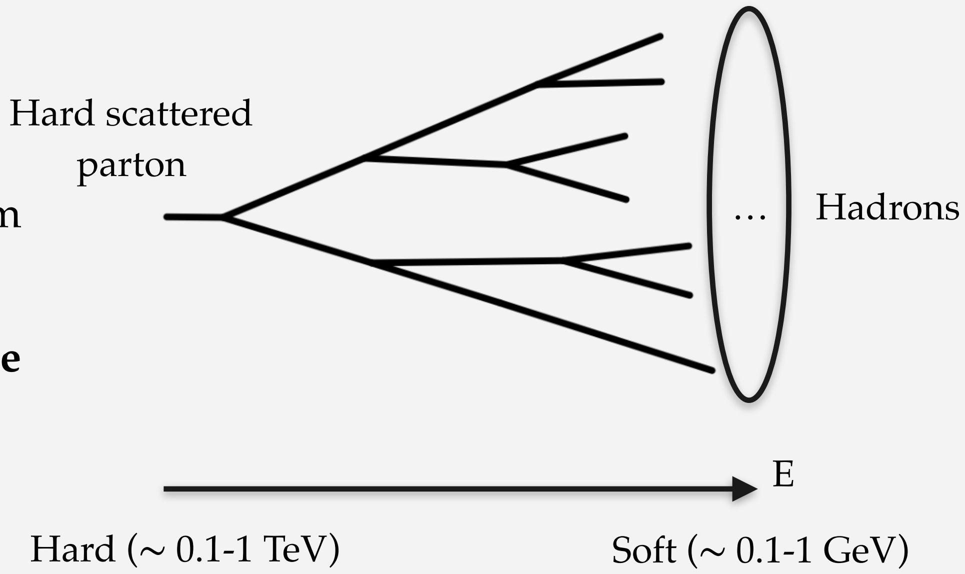
Busza et al, arXiv:1802.04801

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!**

jets - collimated energetic QCD cascades

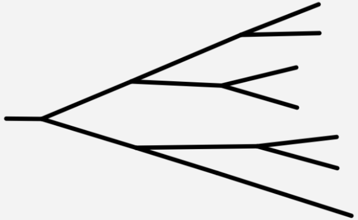


Probing the QGP with jets

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

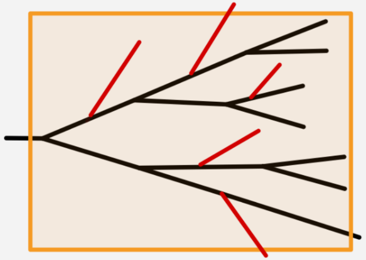
→ imprinted modifications tell a story (**jet quenching**)



[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?

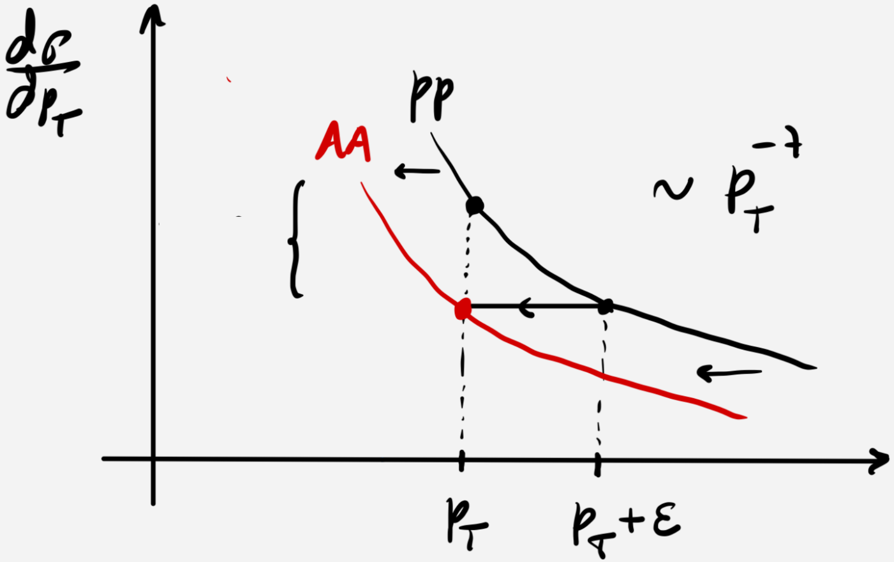
- Common procedure: Choose a window of **reconstructed jet** p_T
- Common problem:
  - AA jets **migrate** to lower reconstructed p_T (jet energy loss)

$\Longrightarrow$ We are comparing jets that **“started out” differently**.

Bin migration in R_{AA}

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

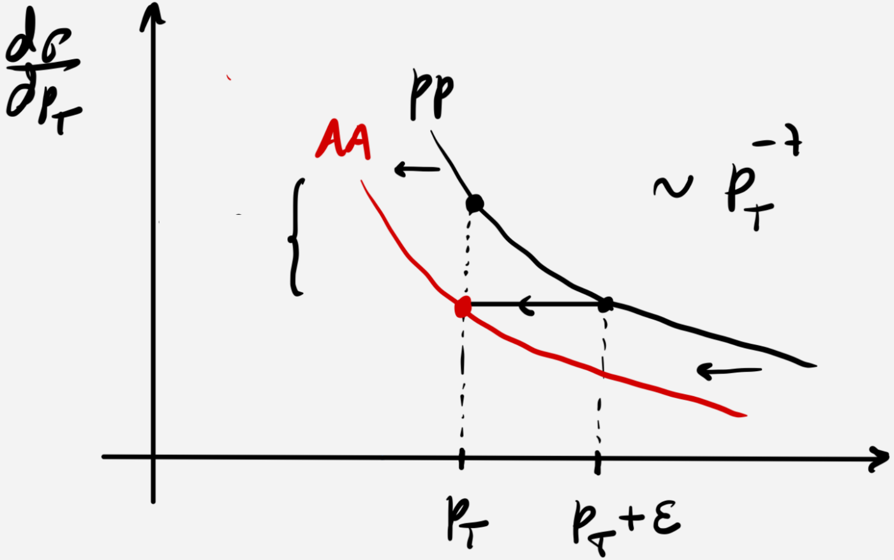
$$p_T \to p_T - \epsilon$$

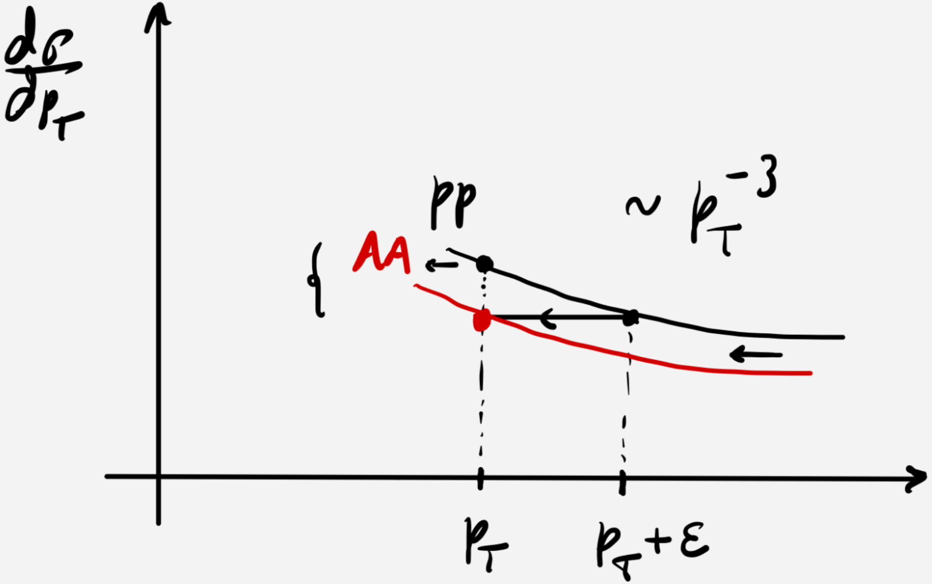


Bin migration in R_{AA}

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

$$p_T \to p_T - \epsilon$$





Same energy loss but **different R_{AA} !**

Biased jet comparison

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

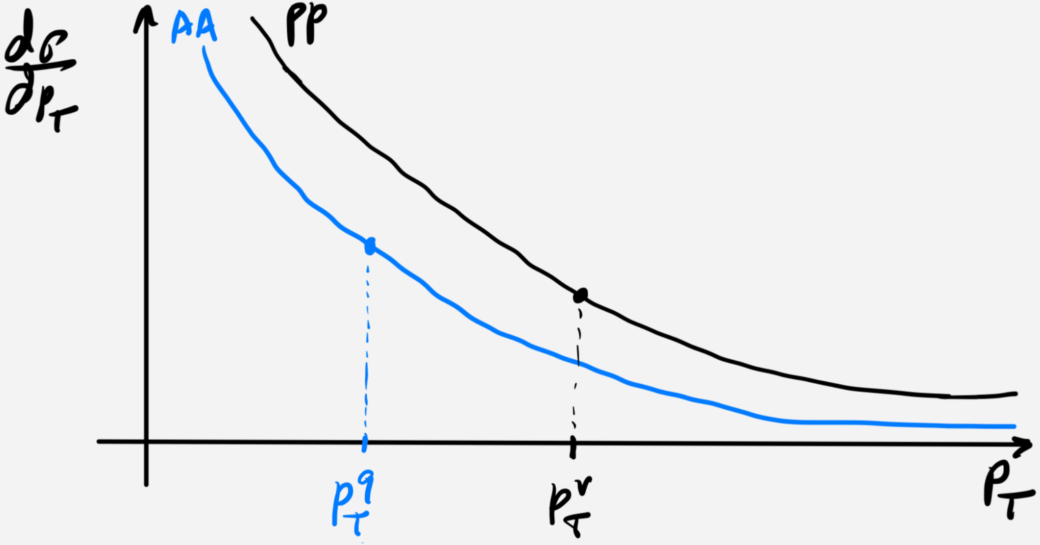
- Common procedure: Choose a window of **reconstructed jet** p_T
- Common problem:
  - AA jets **migrate** to lower reconstructed p_T (jet energy loss)

    ⟹ We are comparing jets that **“started out” differently**.

- Possible solution: **boson + jet events**? ⟹ Statistics not as good as inclusive jet events!

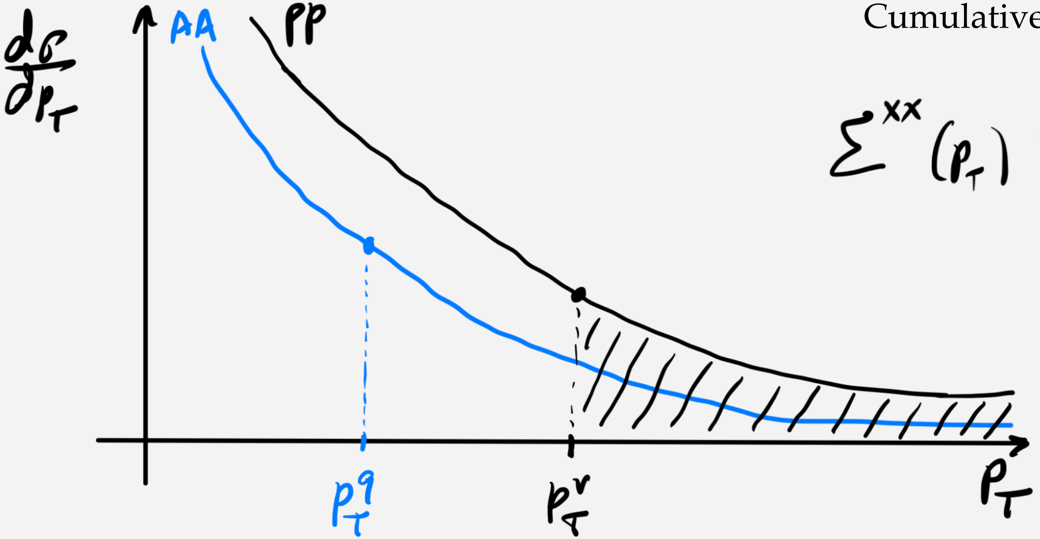
Brewer et al. Journal of High Energy Physics 2022(2), 1-22, Apolinário et al. arXiv:2401.14229

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



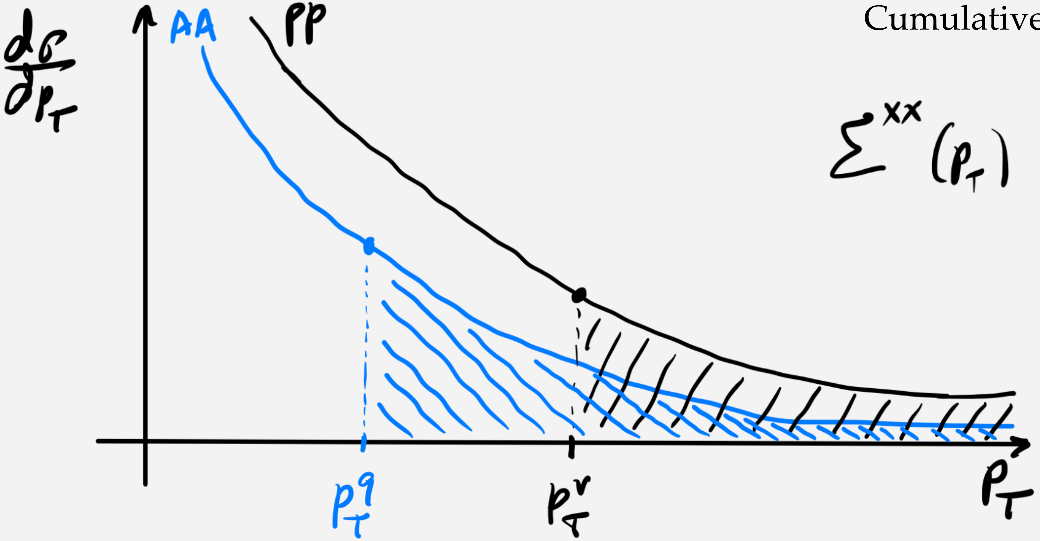
Cumulative jet p_T cross section

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

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

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

Quantiles - a way to estimate p_T migration

$$p_T \to p_T - \epsilon(p_T), \qquad \frac{d\epsilon}{dp_T} < 1$$

N most energetic pp jets
=
N most energetic AA jets

$$\implies p_T^v - p_T^q(p_T^v) = \epsilon(p_T^v)$$

It is exact in the case of zero dispersion!

Quantiles - a way to estimate p_T migration

$$p_T \to p_T - \epsilon(p_T), \qquad \frac{d\epsilon}{dp_T} < 1$$

N most energetic pp jets
=
N most energetic AA jets

$$\Longrightarrow \; p_T^v - p_T^q(p_T^v) = \epsilon(p_T^v)$$

It is exact in the case of zero dispersion!

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

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

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

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

Medium jet spectrum

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

Quantile procedure validation

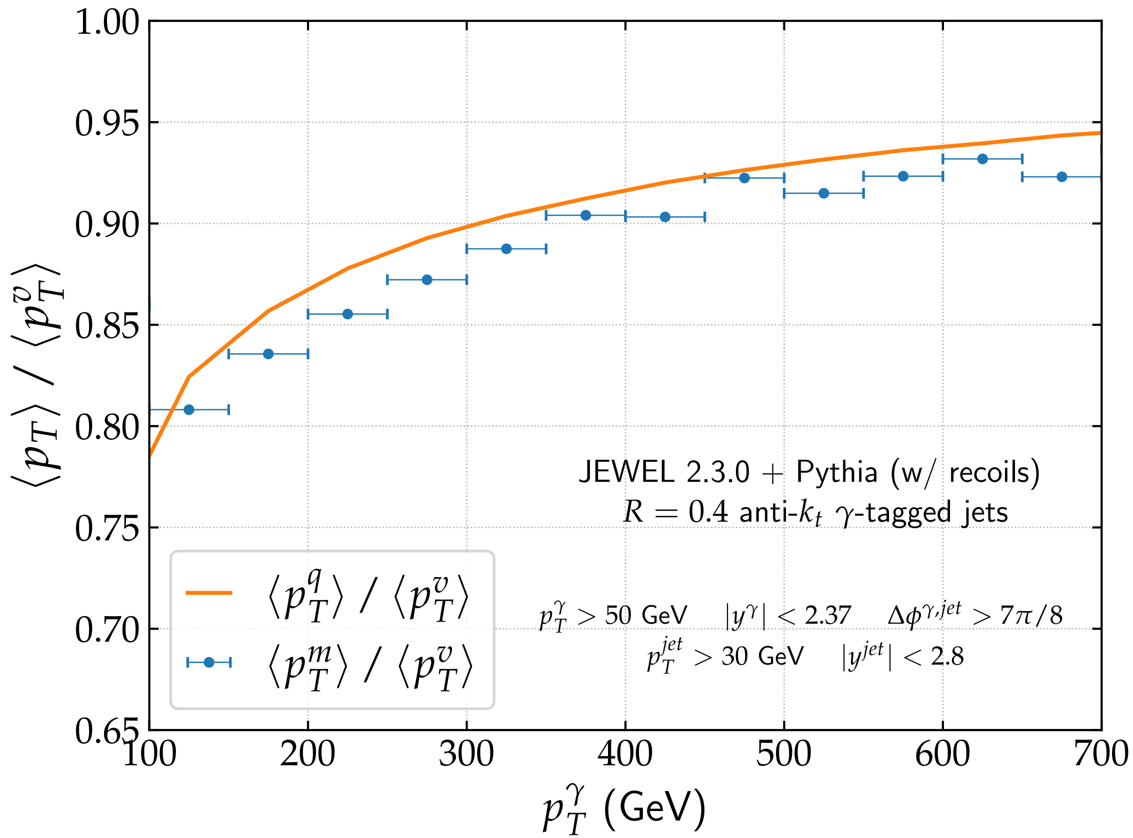
Two different **energy loss proxies**:

Average jet p_T for a given photon p_T

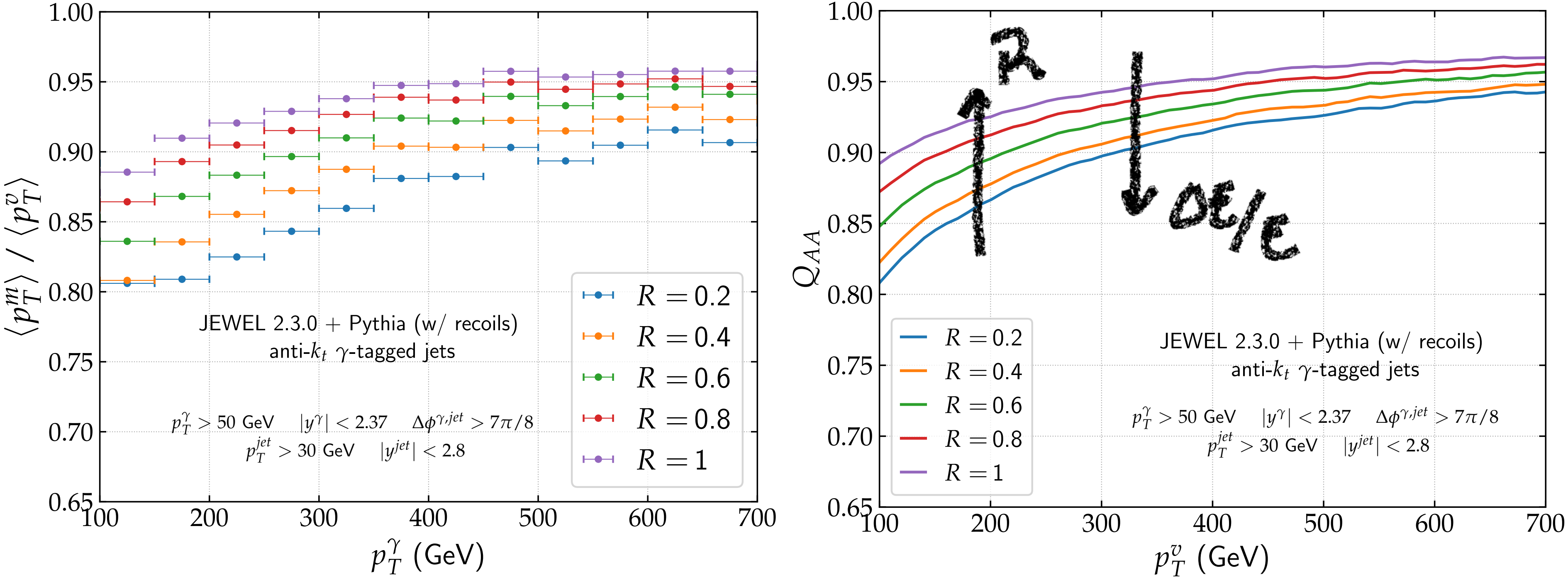
$$\langle p_T^{v/m} \rangle \Big|_{p_T^\gamma} = \int dp_T \, \frac{dN^{v/m}}{dp_T}\Bigg|_{p_T^\gamma} p_T$$

Average quantile p_T for a given photon p_T

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

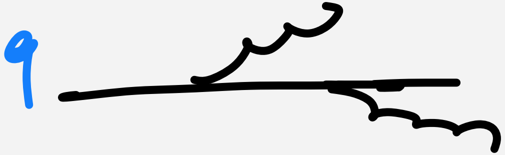


Energy loss as a function of jet radius (w/ recoils)

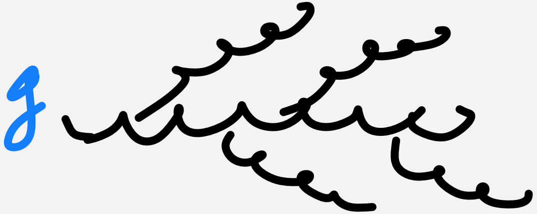


Larger jets lose a **smaller** fraction of their energy

Energy loss dependence on color charge



$\sim C_F$



$\sim C_A$

γ+jet ~ q init. jets

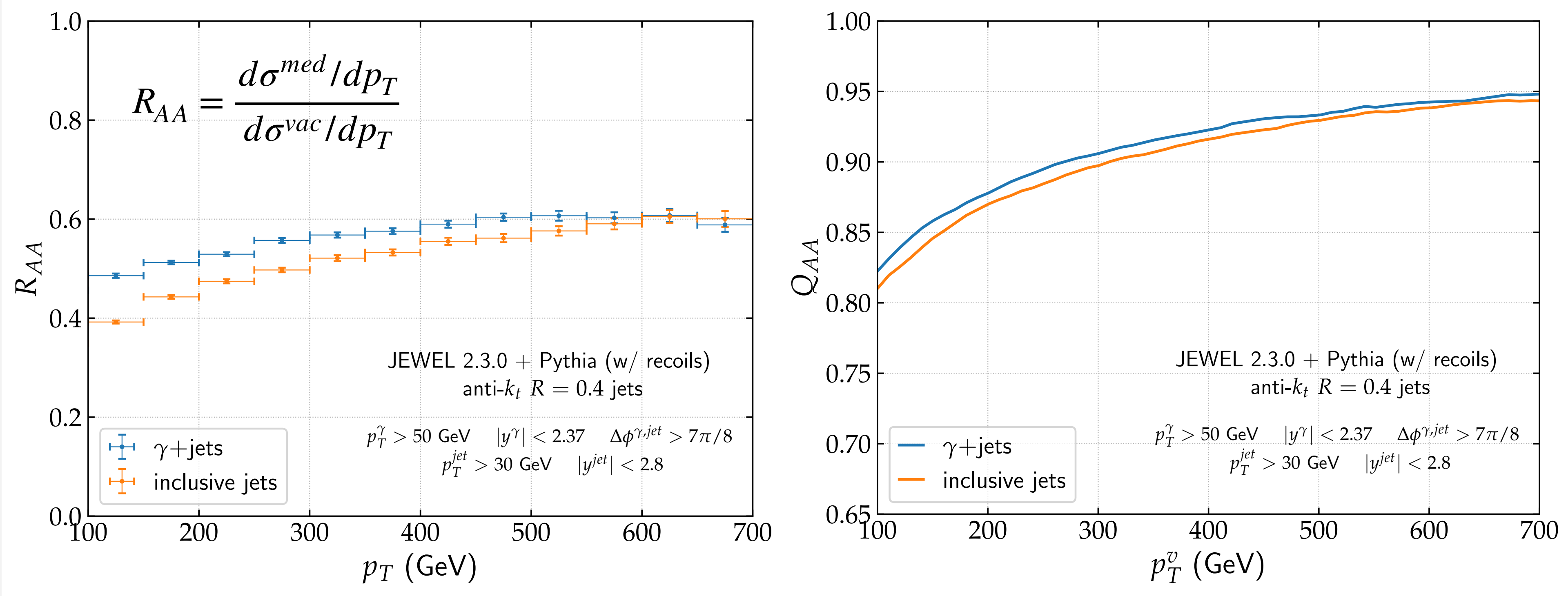
dijet ~ mixture of q and g init. jets

$$\Rightarrow R_{AA}^{\gamma j} > R_{AA}^{jj}$$

=

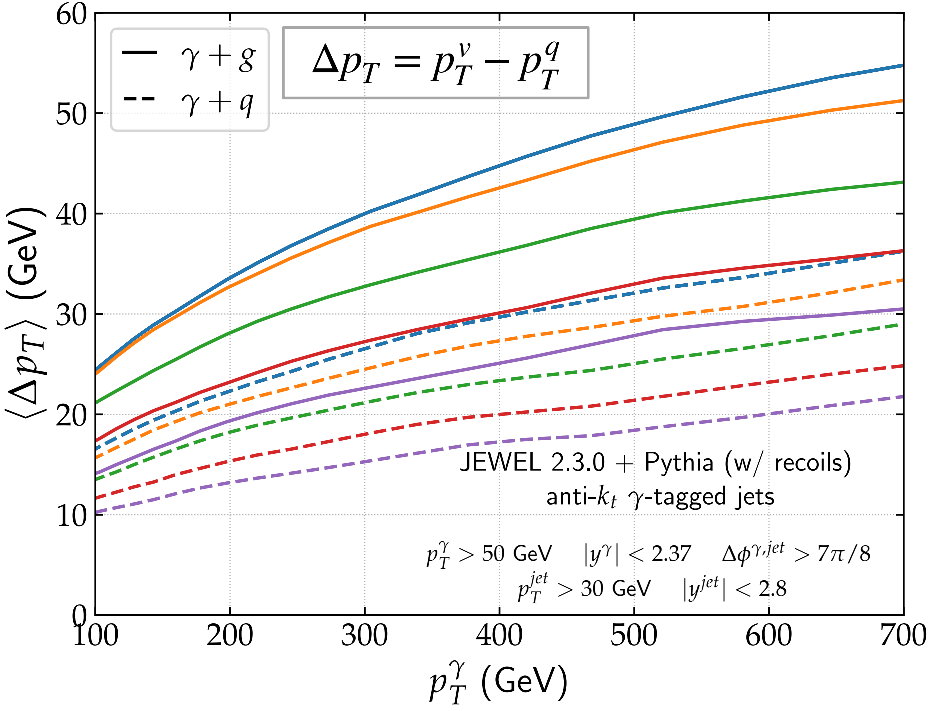
Casimir scaling in jets ?

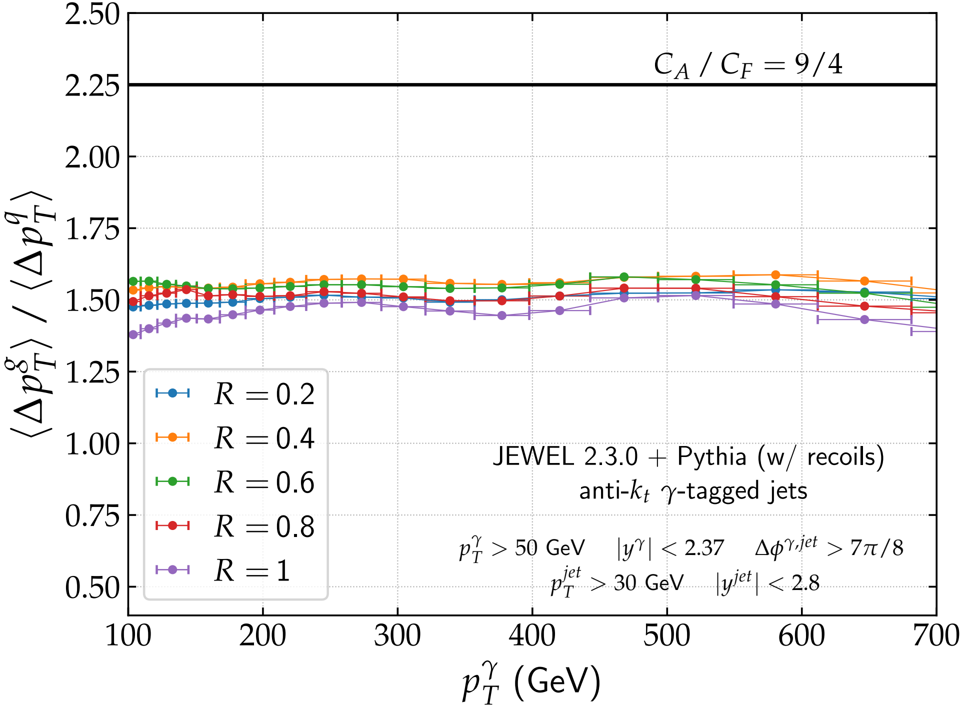
Energy loss dependence on color charge



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

Energy loss dependence on color charge



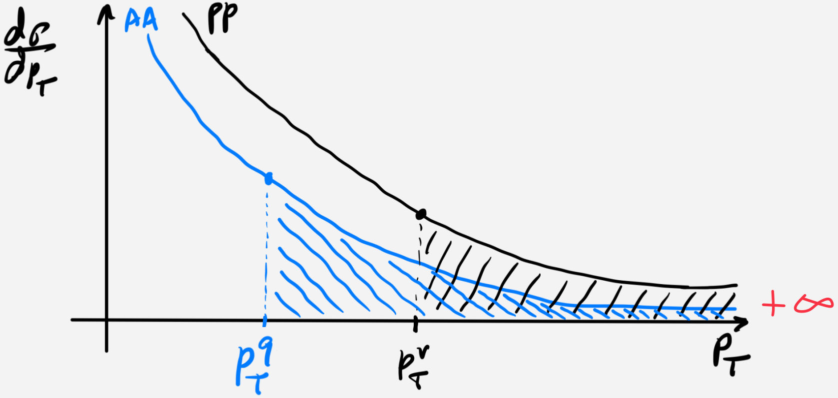


Casimir scaling is significantly reduced with respect to naive single parton scaling

The cutoff problem

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

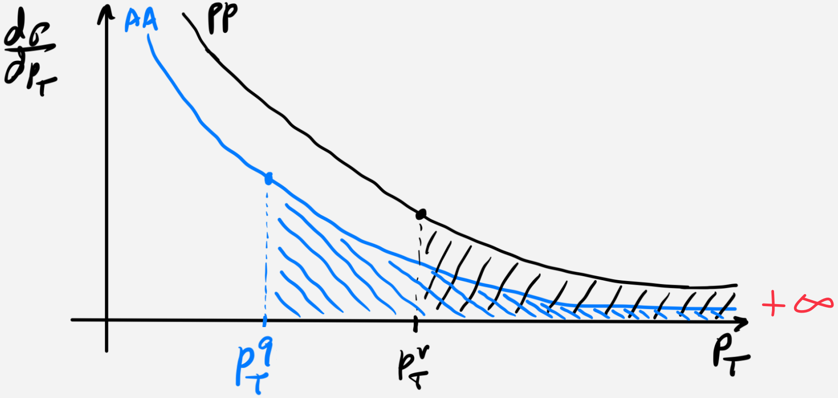
$$\int_{p_T^v}^{+\infty} dp_T \, \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{+\infty} dp_T \, \frac{d\sigma^m}{dp_T}$$



The cutoff problem

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

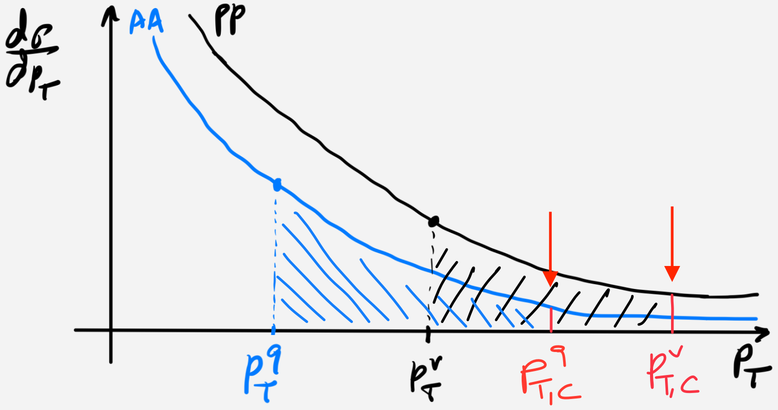
$$\int_{p_T^v}^{+\infty} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{+\infty} dp_T \frac{d\sigma^m}{dp_T}$$



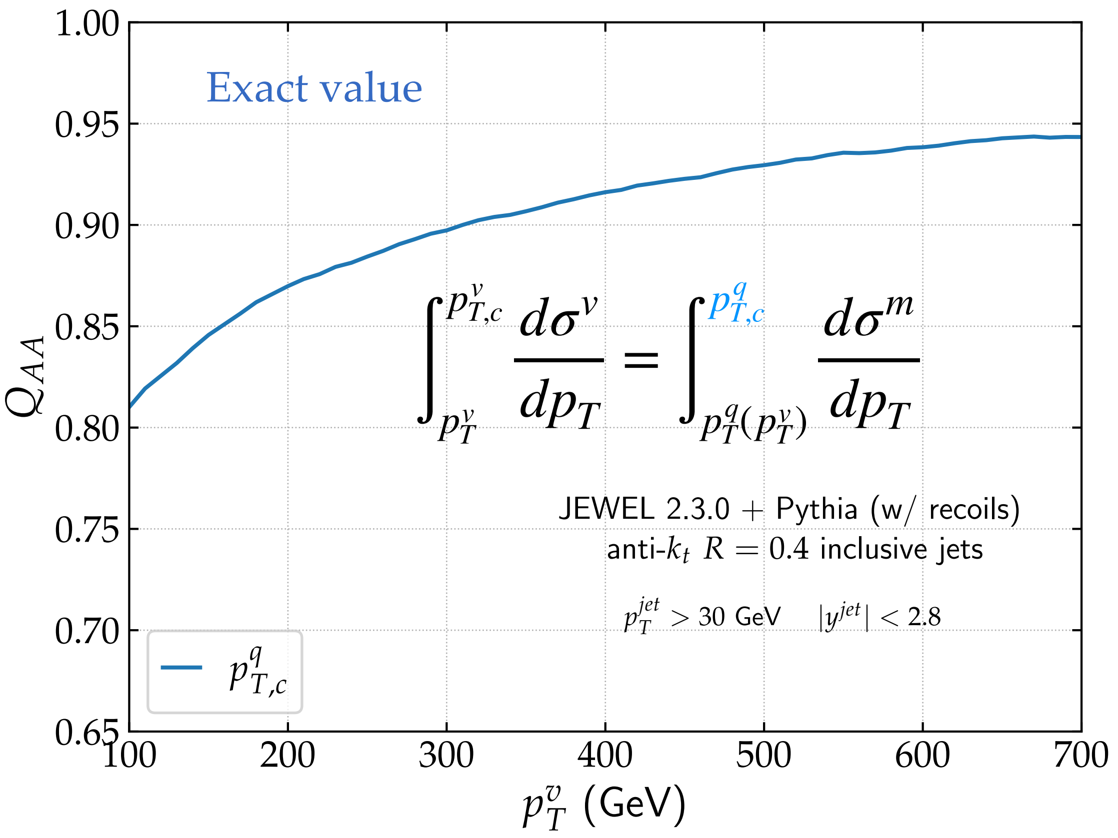
$$\Leftrightarrow$$

Needs an **initial condition** to be set

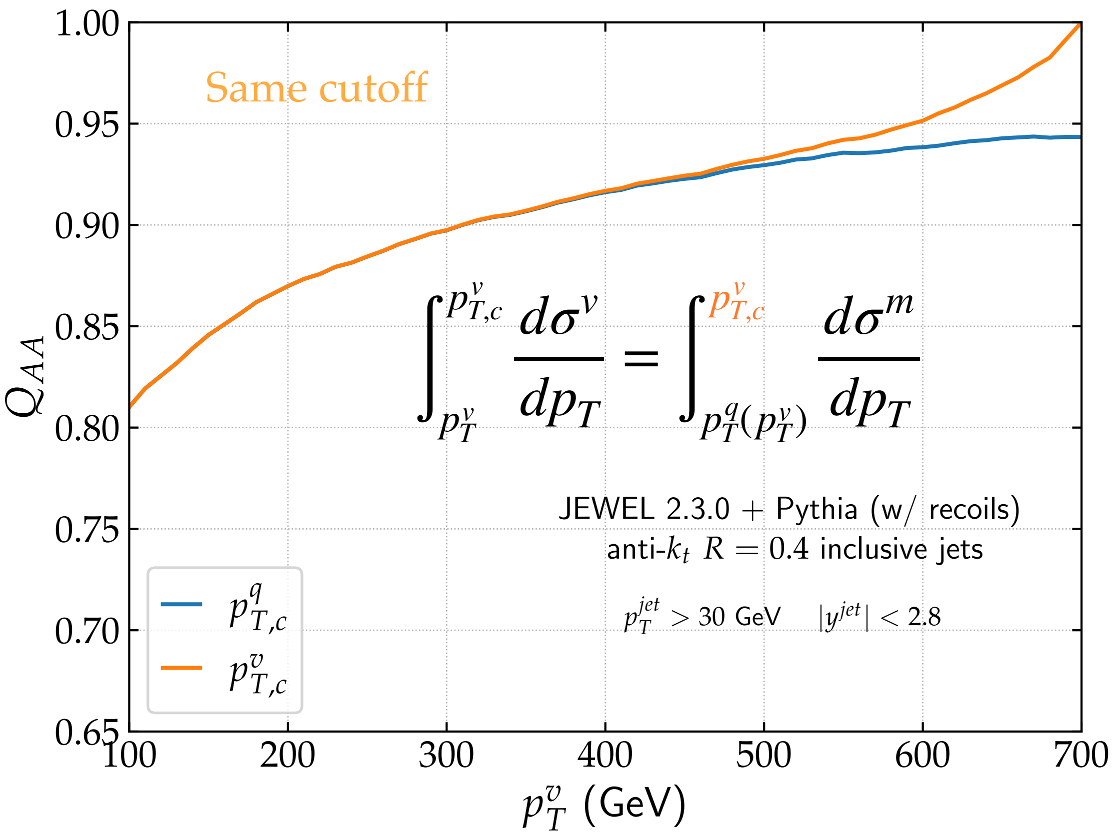
$$\int_{p_T^v}^{p_{T,c}^v} dp_T \frac{d\sigma^v}{dp_T} = \int_{p_T^q(p_T^v)}^{p_{T,c}^q = p_T^q(p_{T,c}^v)} dp_T \frac{d\sigma^m}{dp_T}$$



The cutoff problem



The cutoff problem



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

JEWEL 2.3.0 + Pythia (w/ recoils)
anti-k_t $R = 0.4$ inclusive jets

$p_T^{jet} > 30$ GeV $|y^{jet}| < 2.8$

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

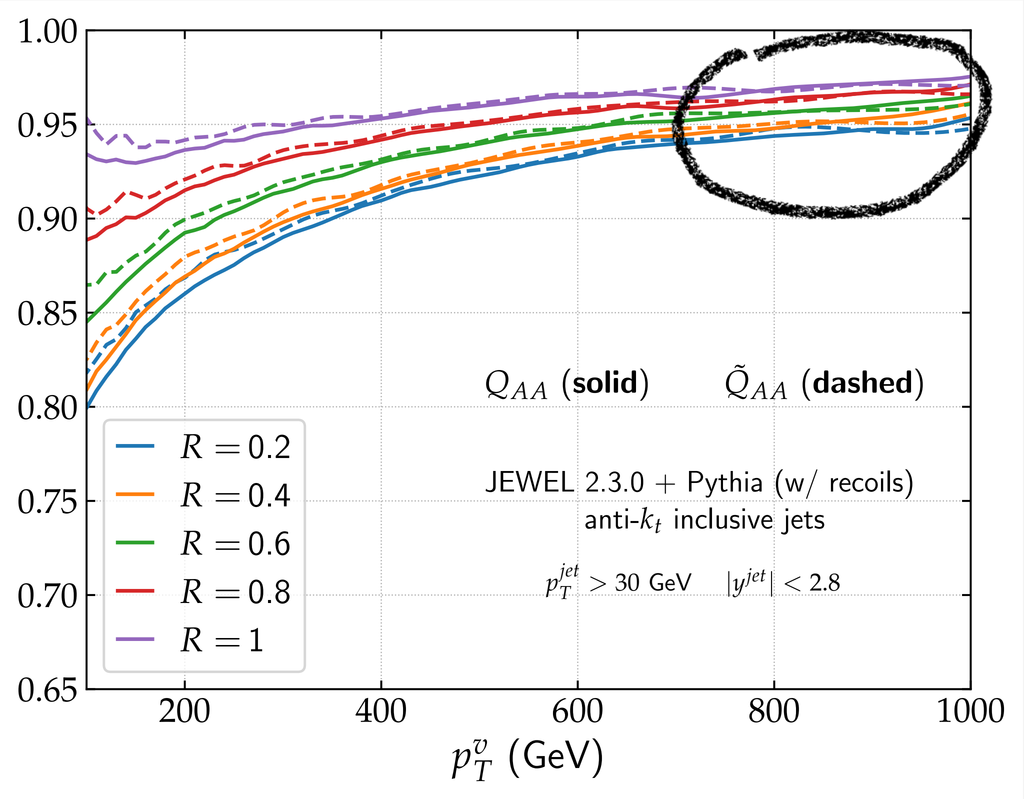
J. Brewer, J. Milhano, J. Thaler; Phys. Rev. Lett. 122 (2019) 22, 222301

Pseudo-quantile ($\tilde{p}_T^q$)

(equate cross sections rather than cumulative cross sections)

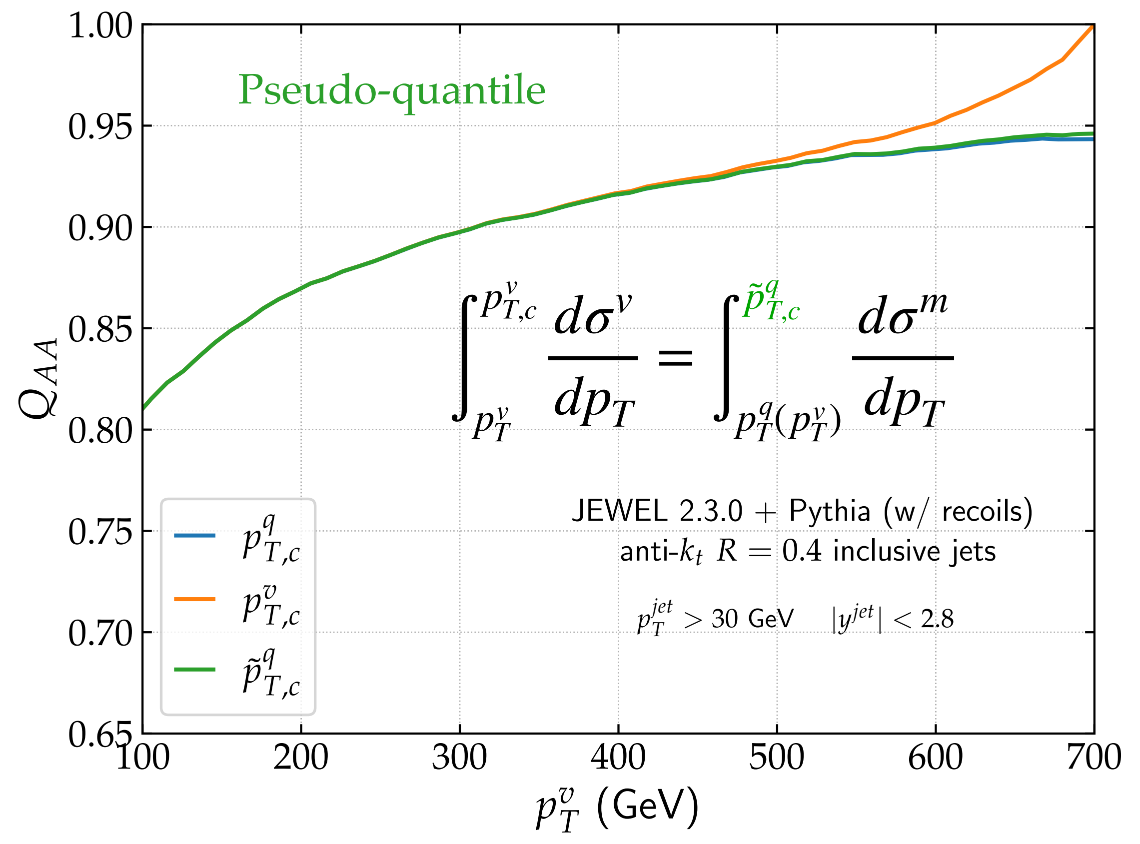
$$\frac{d\sigma^v}{dp_T^v}(p_T^v) = \frac{d\sigma^m}{d\tilde{p}_T^q}(\tilde{p}_T^q(p_T^v))$$

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



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

$\tilde{p}^q_{T,c} = \tilde{p}^q_T(p^v_{T,c})$



$$\int_{p^v_T}^{p^v_{T,c}} \frac{d\sigma^v}{dp_T} = \int_{p^q_T(p^v_T)}^{\tilde{p}^q_{T,c}} \frac{d\sigma^m}{dp_T}$$

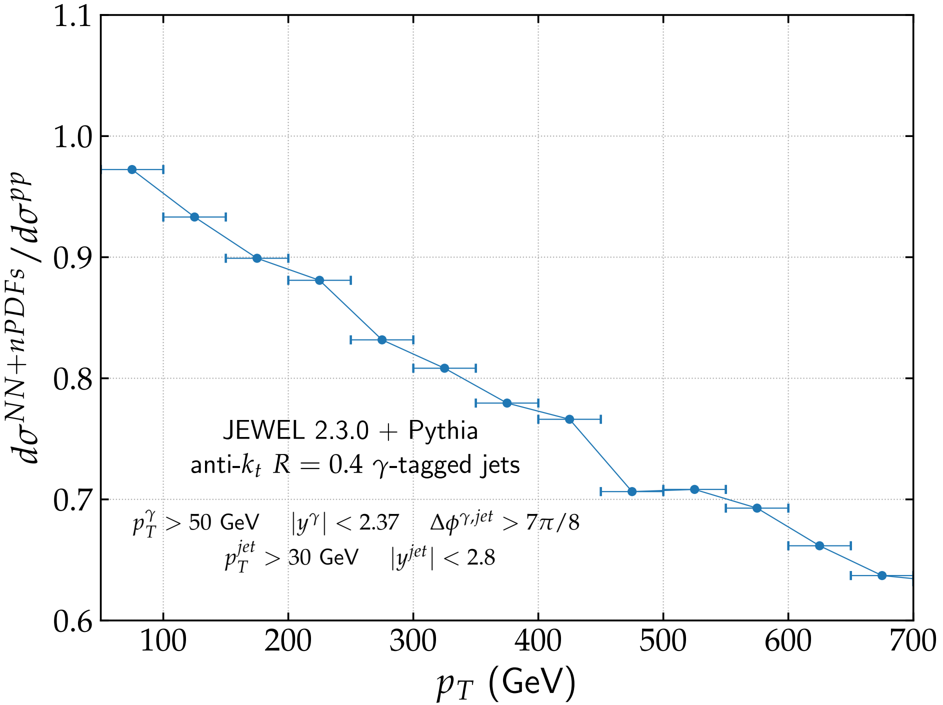
Summary

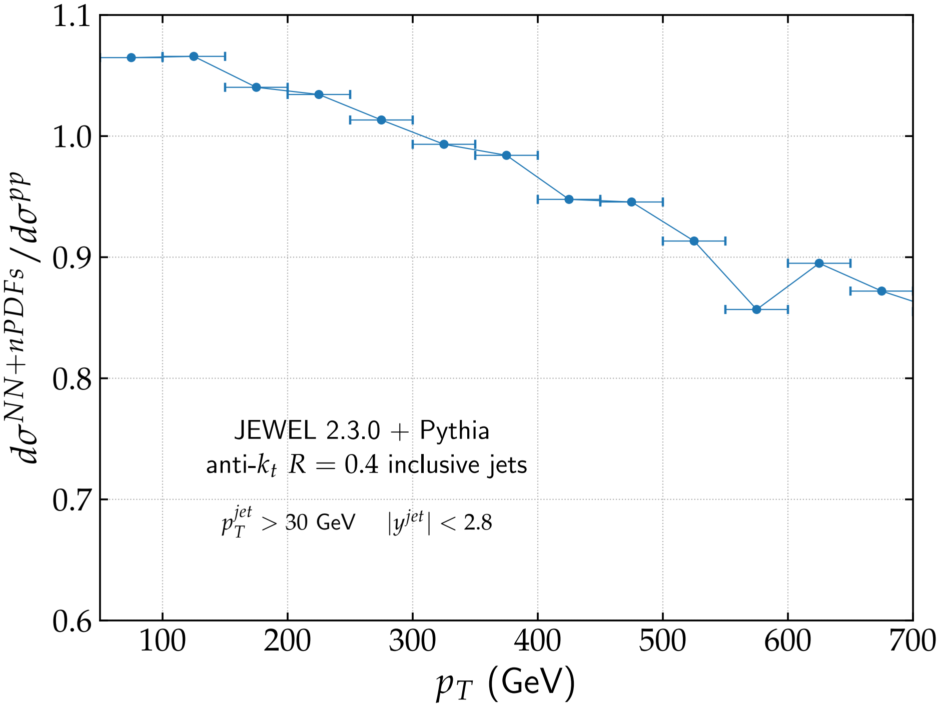
- The Q_{AA} provides **a proxy for jets that started out similarly** that can be used in inclusive jet events and possibly a model-independent way of quantifying jet energy loss;
- The color charge of the initiating parton does not play as important a role in jet energy loss as one would have thought 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!

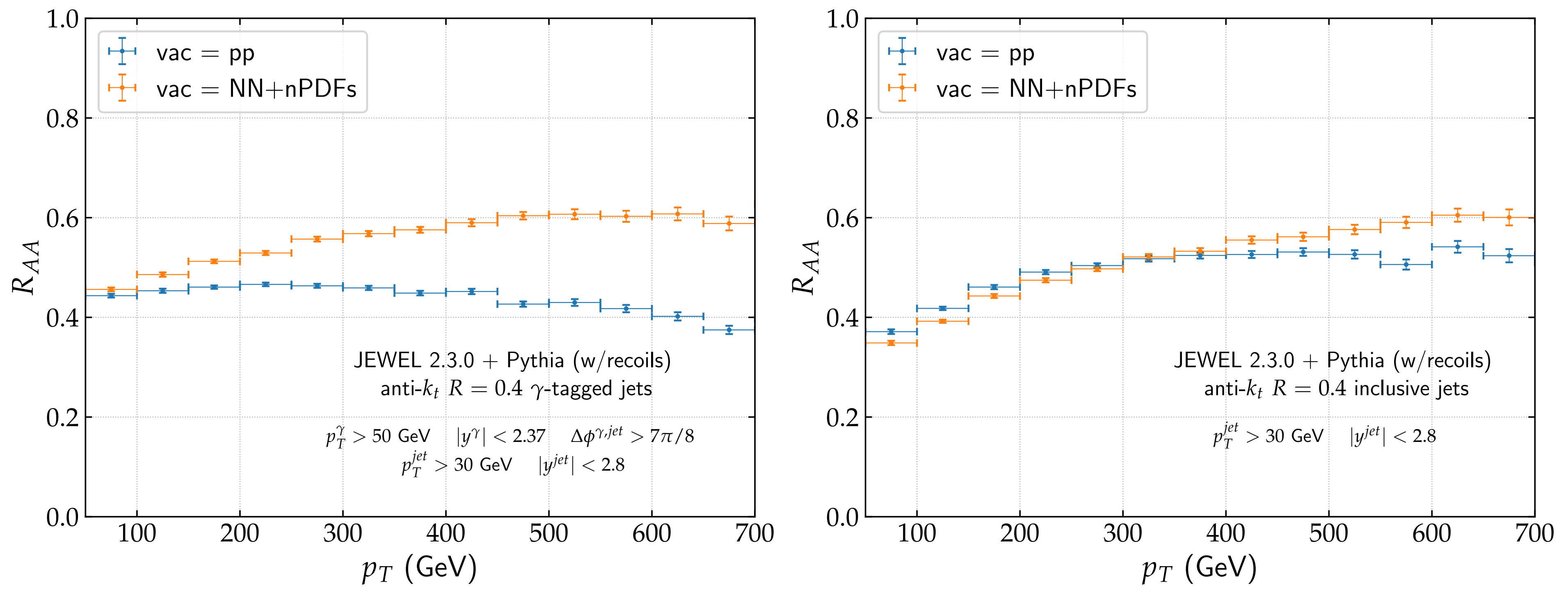
Back-up

Nuclear effects on the jet p_T spectrum





Nuclear effects on the R_{AA}

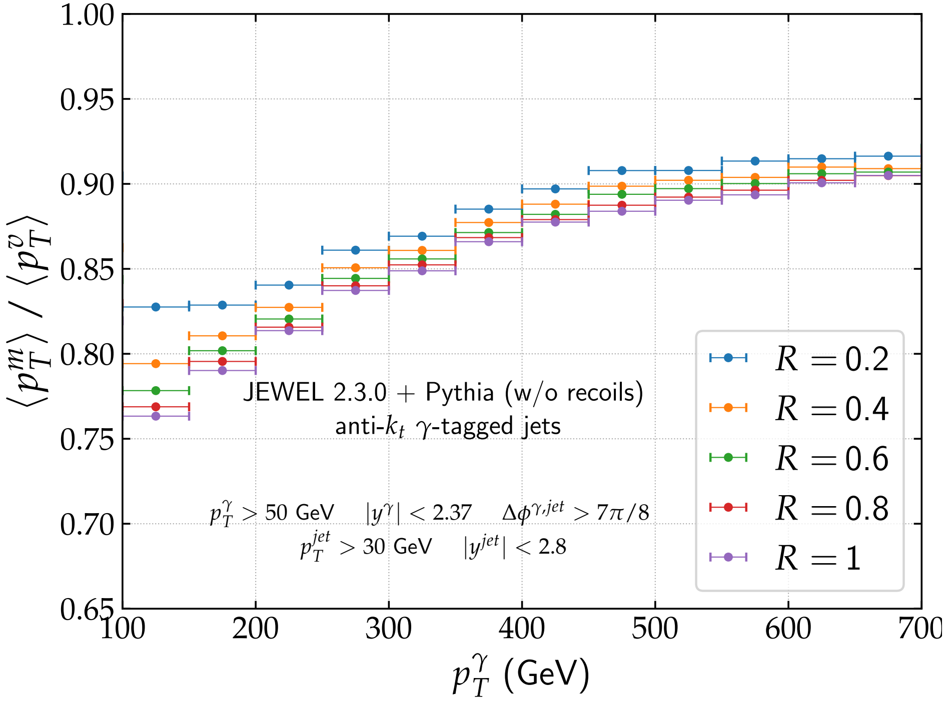


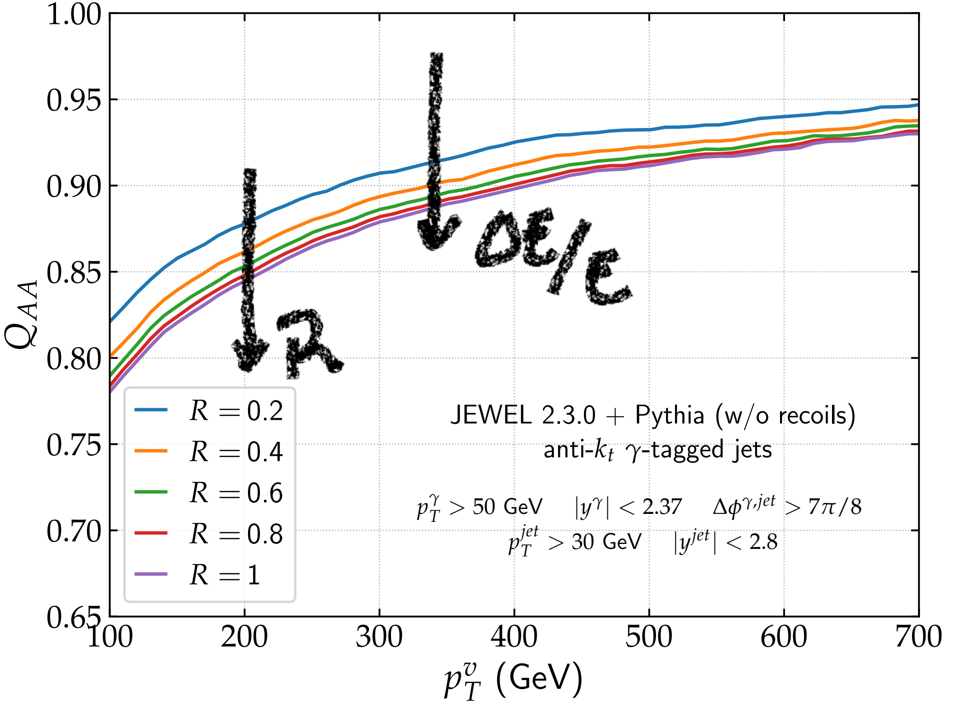
Differential version of the quantile procedure

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

$$\Longrightarrow \frac{d\sigma^{pp}}{dp_T}(p_T^{v}) = \frac{dp_T^{q}}{dp_T^{v}} \frac{d\sigma^{AA}}{dp_T}(p_T^{q}(p_T^{v}))$$

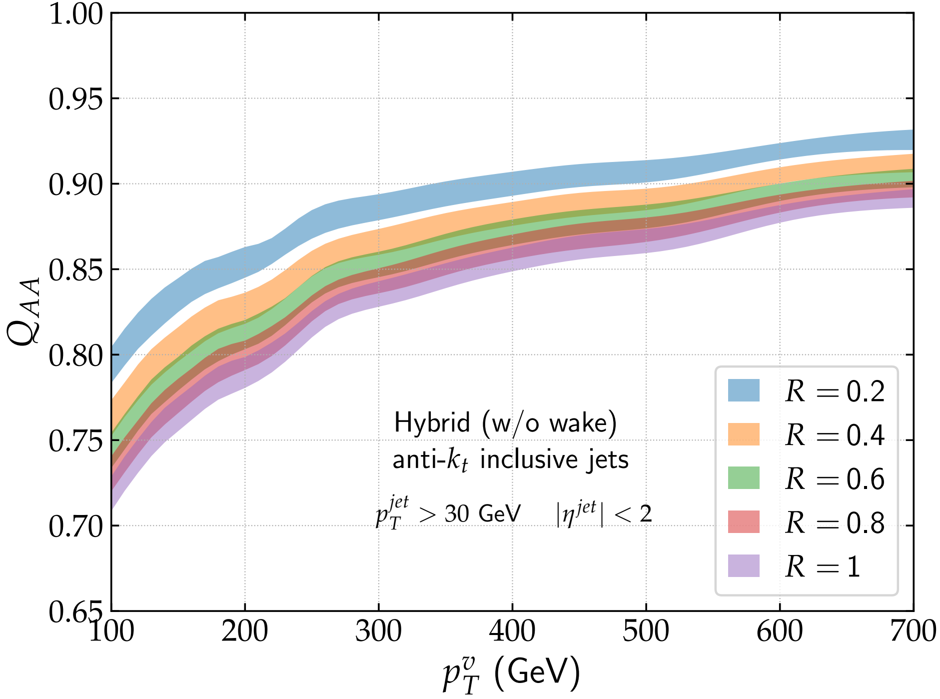
Energy loss as a function of jet radius (w/o recoils)

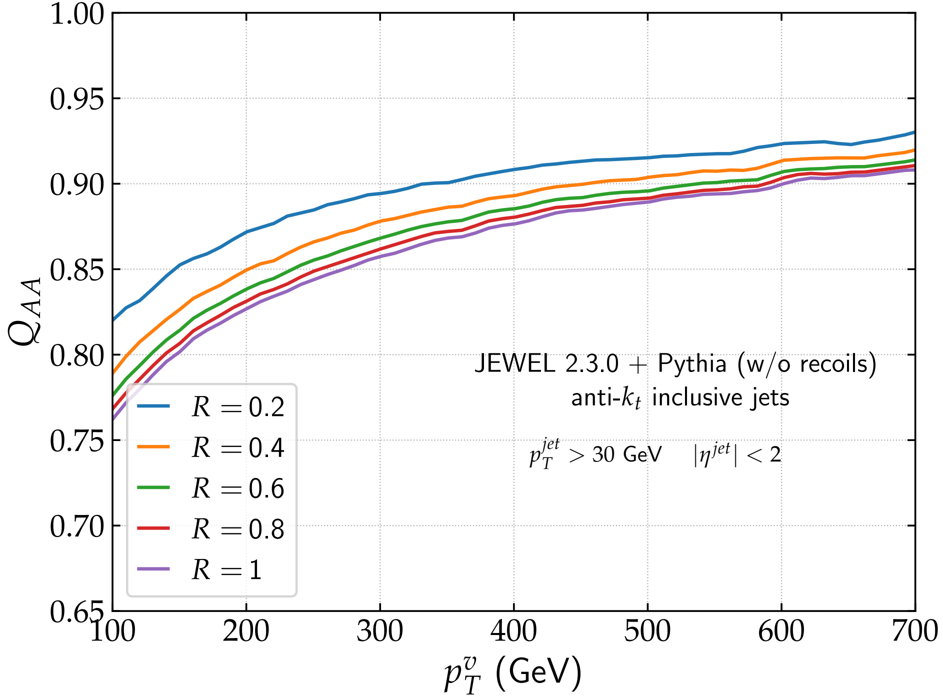




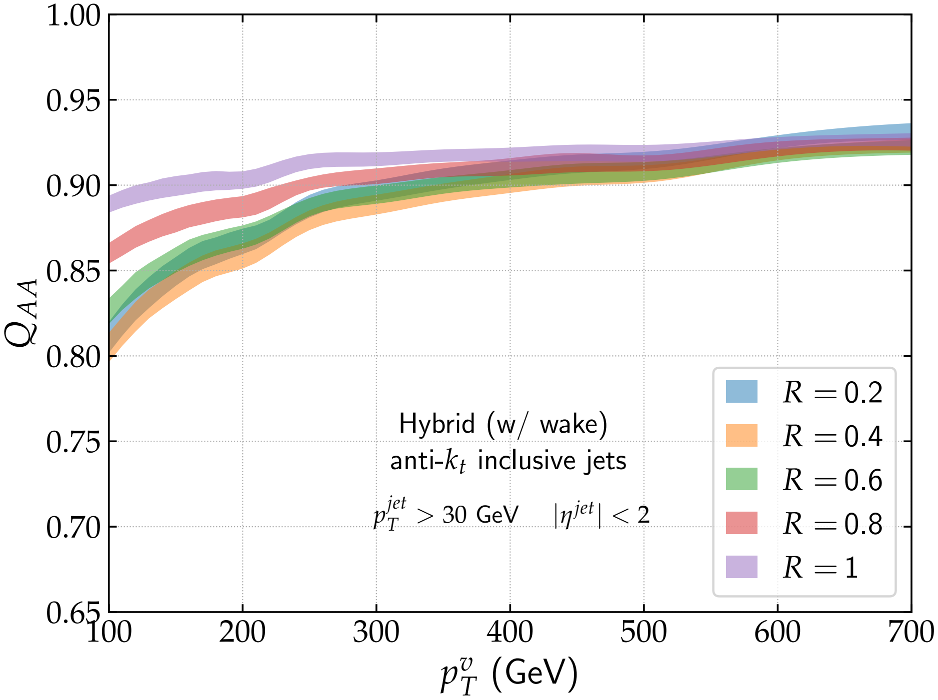
Larger jets lose a **larger** fraction of their energy

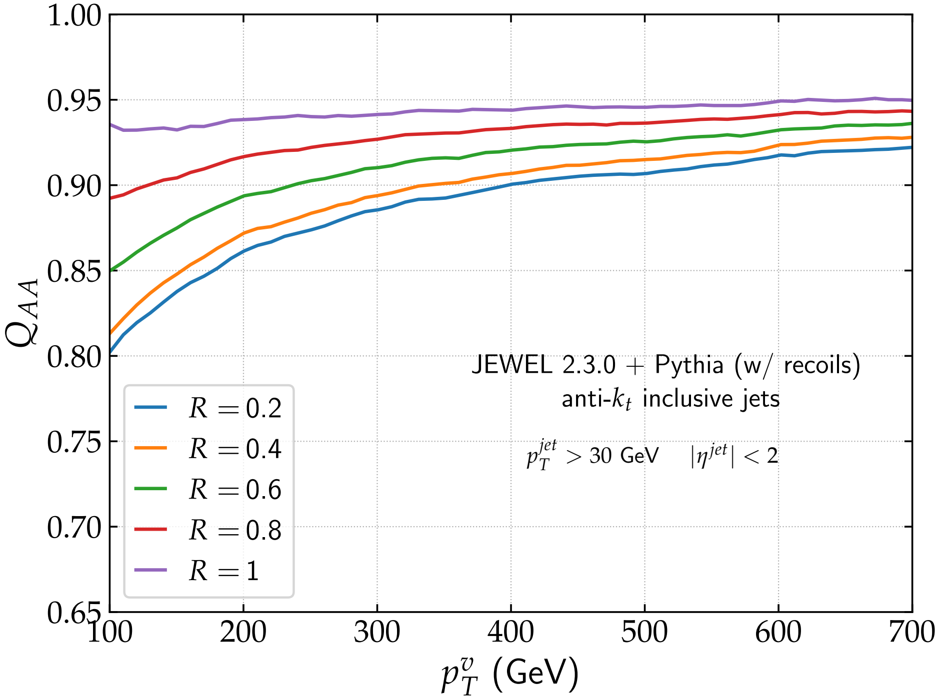
Energy loss as a function of jet radius (model comp.)





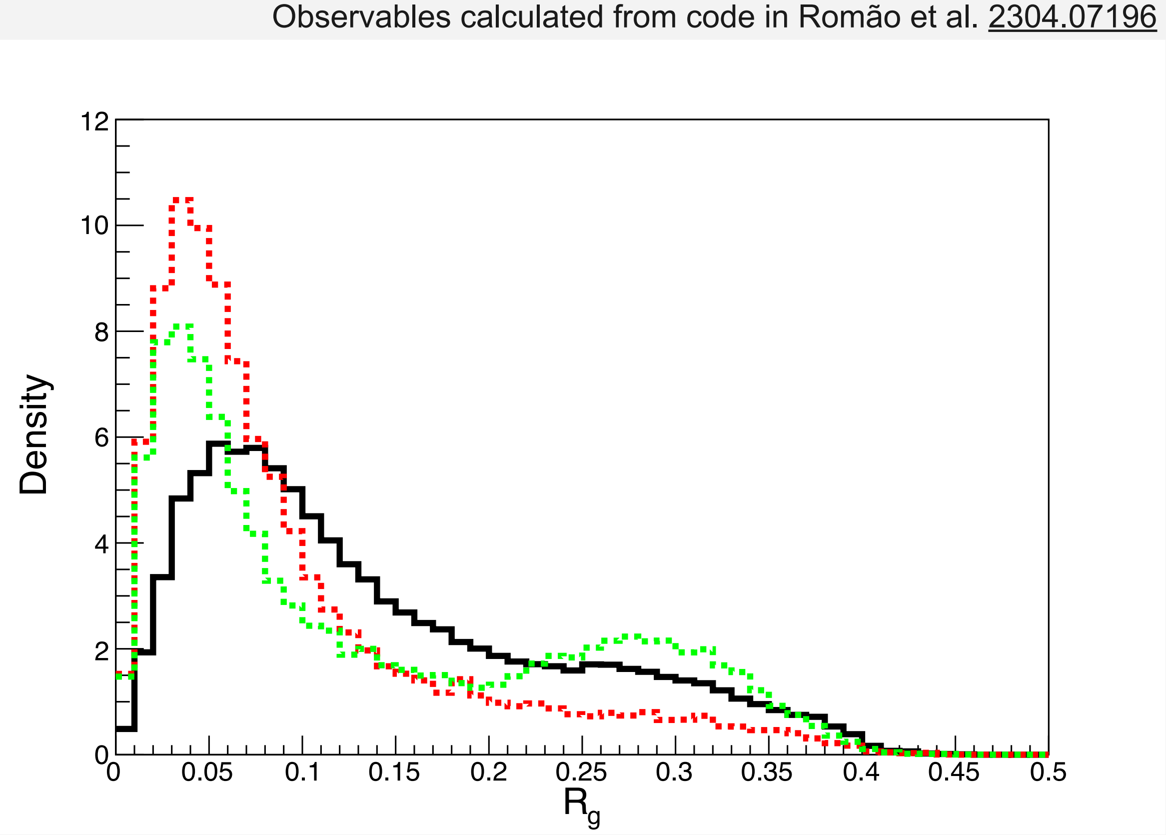
Energy loss as a function of jet radius (model comp.)





Effect of suppressing p_T migration

Observables calculated from code in Romão et al. 2304.07196



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

vac ($p_T \in [100, 200]$ GeV)

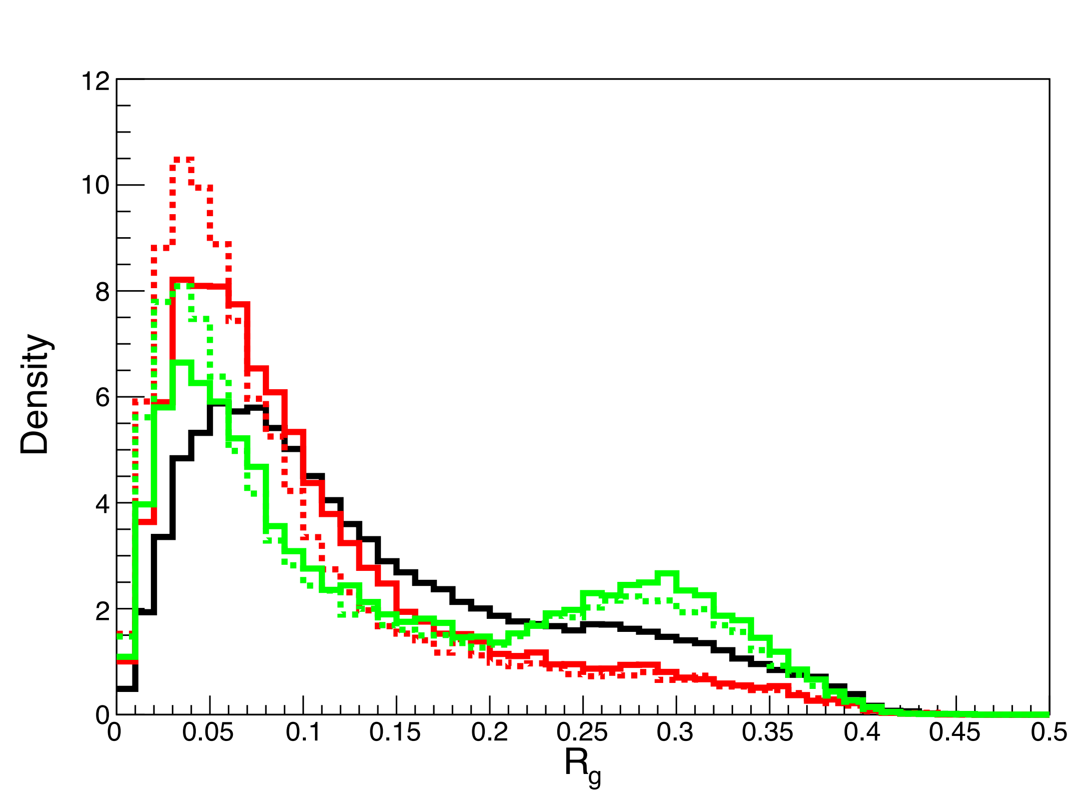
med w/o recoils, ($p_T \in [100, 200]$ GeV)

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)

Observables calculated from code in Romão et al. 2304.07196



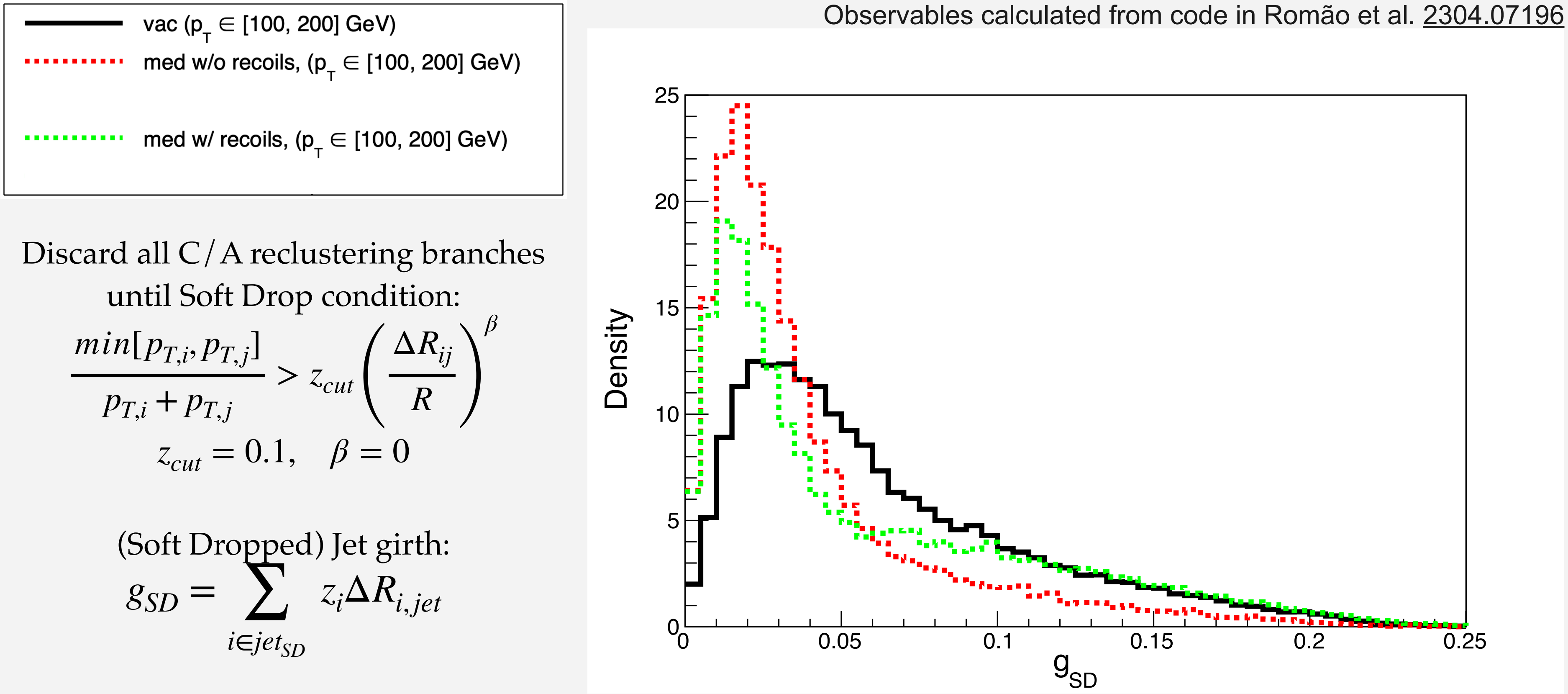
R_g :

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



Observables calculated from code in Romão et al. 2304.07196

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

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

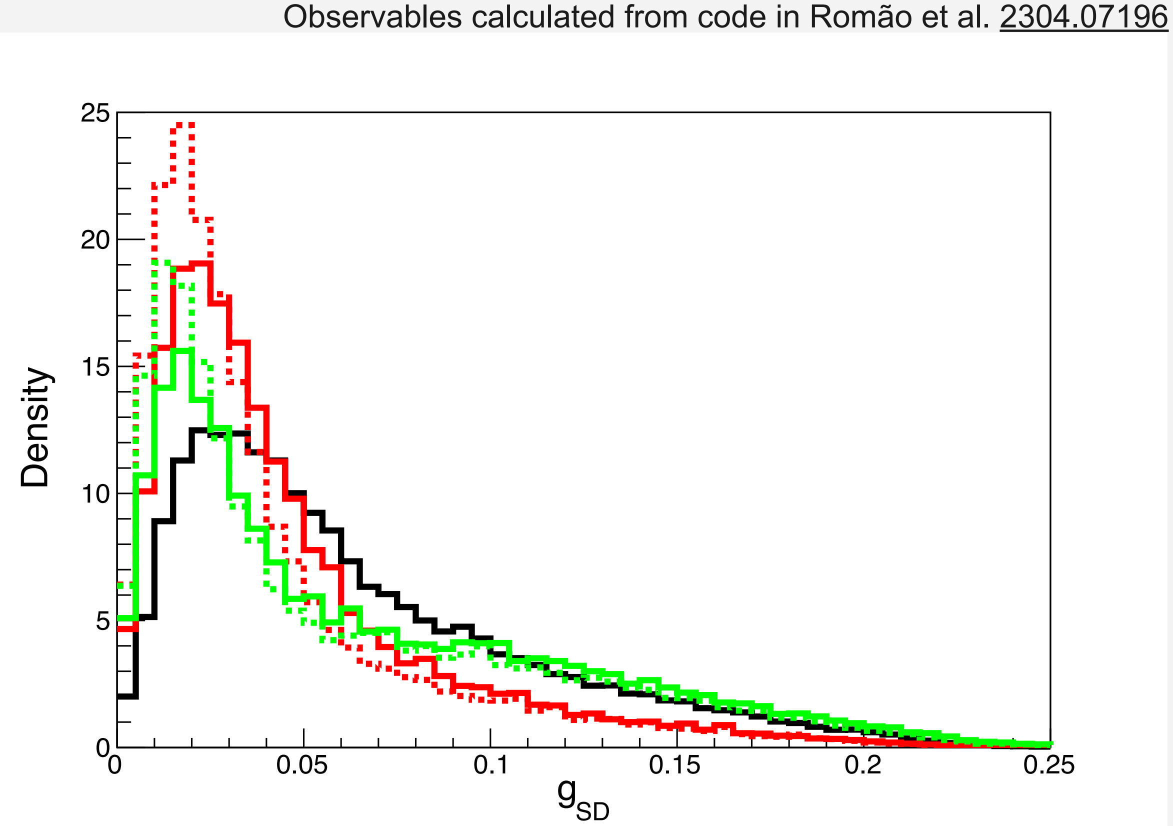
$$z_{cut} = 0.1, \quad \beta = 0$$

(Soft Dropped) Jet girth:

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

Effect of suppressing p_T migration

Observables calculated from code in Romão et al. 2304.07196



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

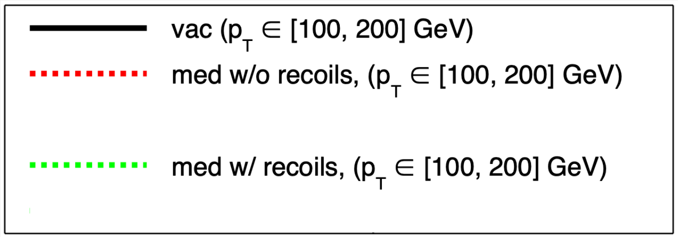
$$\frac{min[p_{T,i}, p_{T,j}]}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R} \right)^{\beta}$$

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

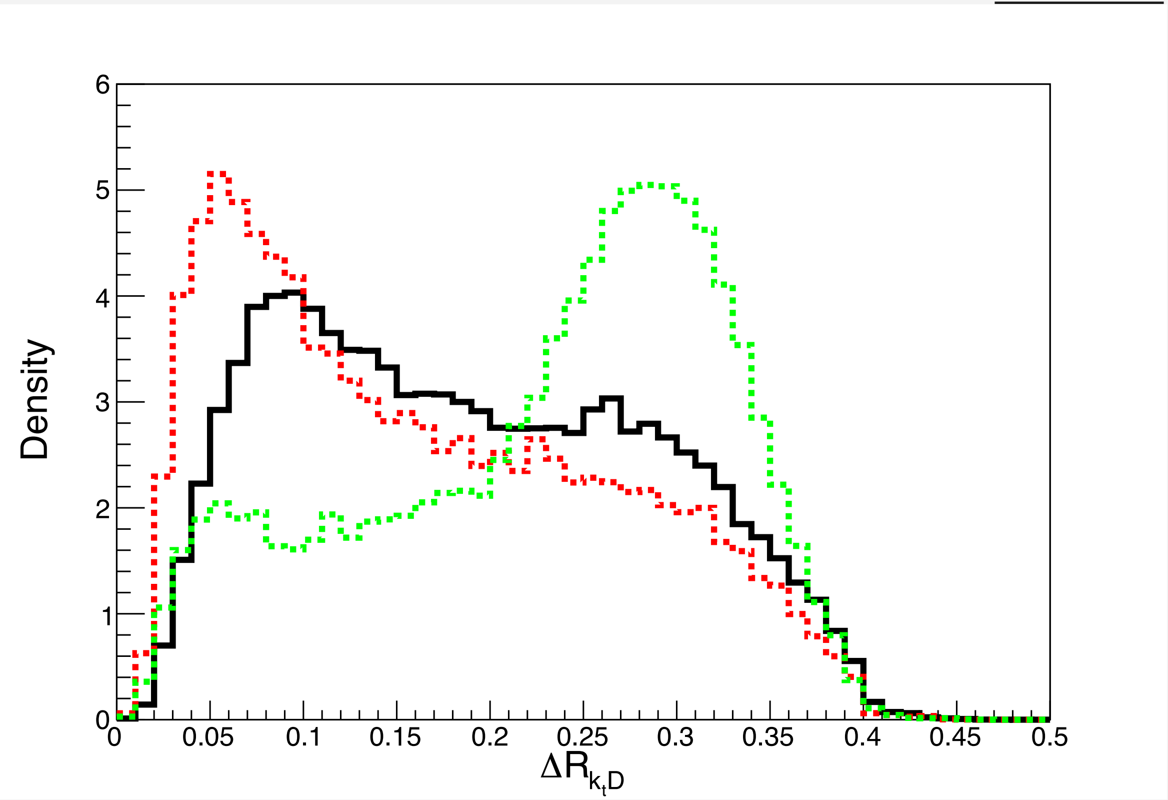
(Soft Dropped) Jet girth:

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

Effect of suppressing p_T migration



Observables calculated from code in Romão et al. 2304.07196



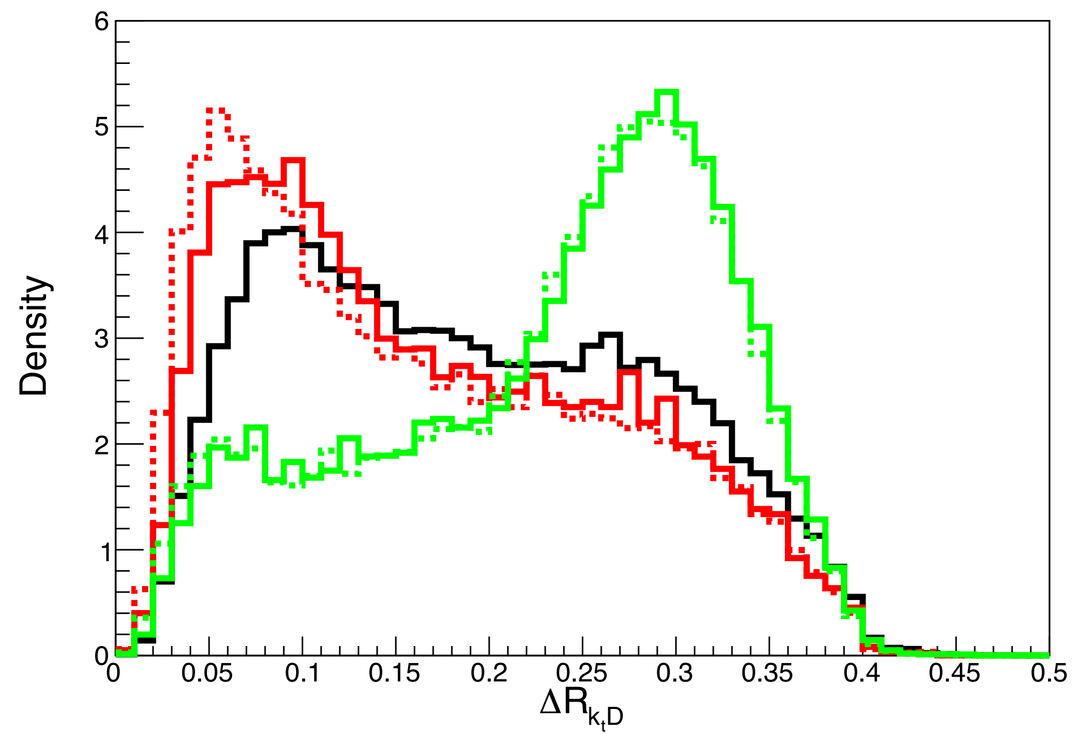
ΔR of C/A reclustering sequence branch passing the Dynamical Grooming ($a = 1$, k_T Drop) condition:

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

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

Effect of suppressing p_T migration

Observables calculated from code in Romão et al. 2304.07196



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

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

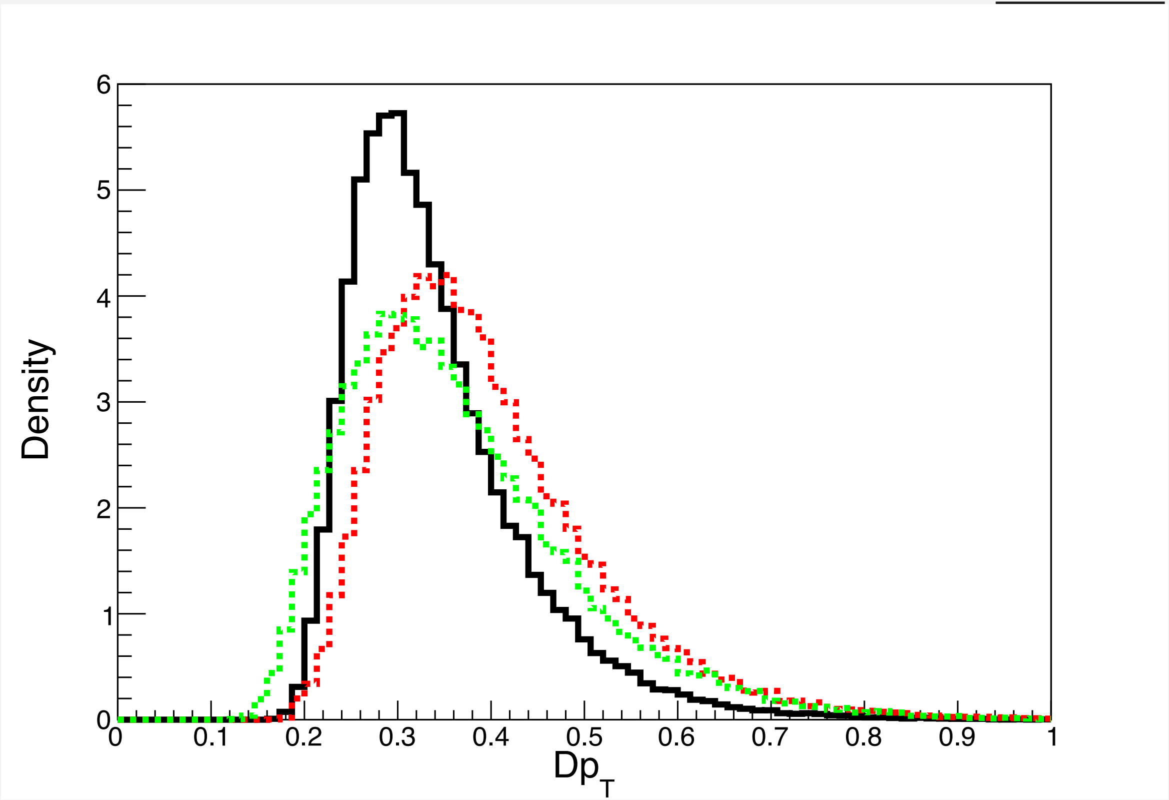
Y. Mehtar-Tani, A. Soto-Ontoso and K. Tywoniuk, Phys. Rev. D 101(3), 034004 (2020)

Effect of suppressing p_T migration

Observables calculated from code in Romão et al. 2304.07196

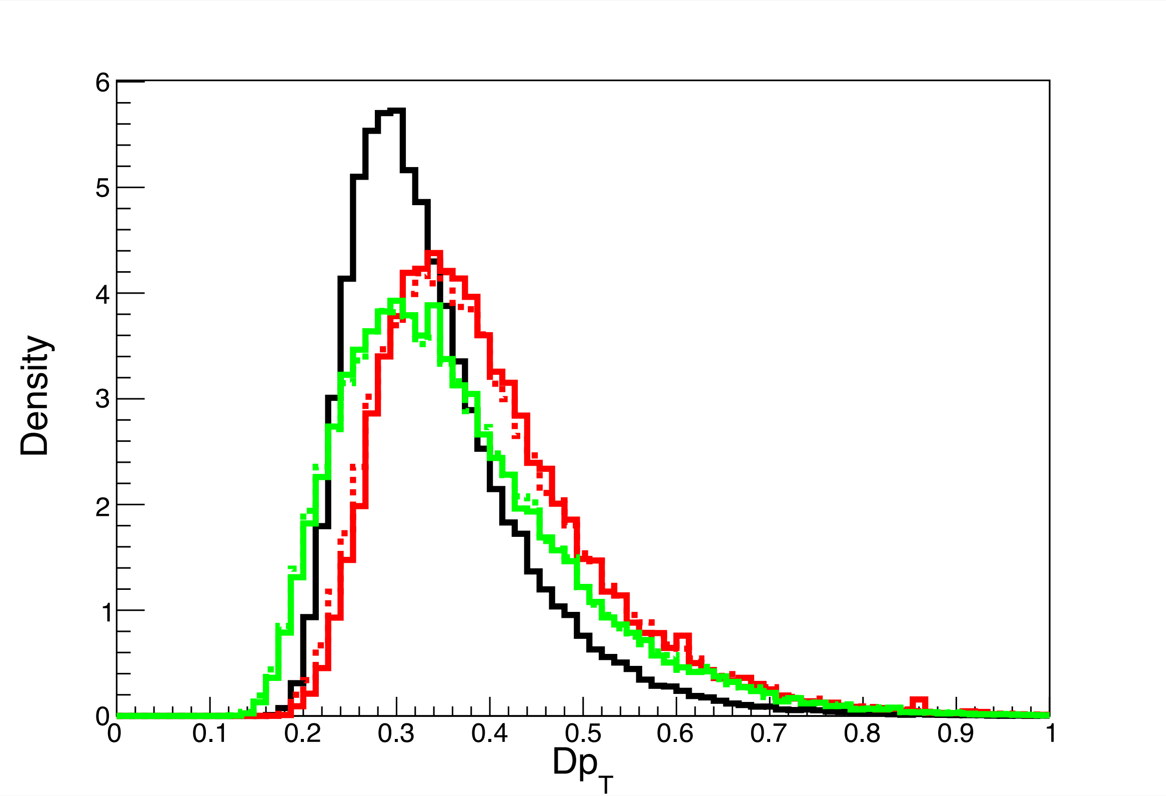
Momentum dispersion:

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



Effect of suppressing p_T migration

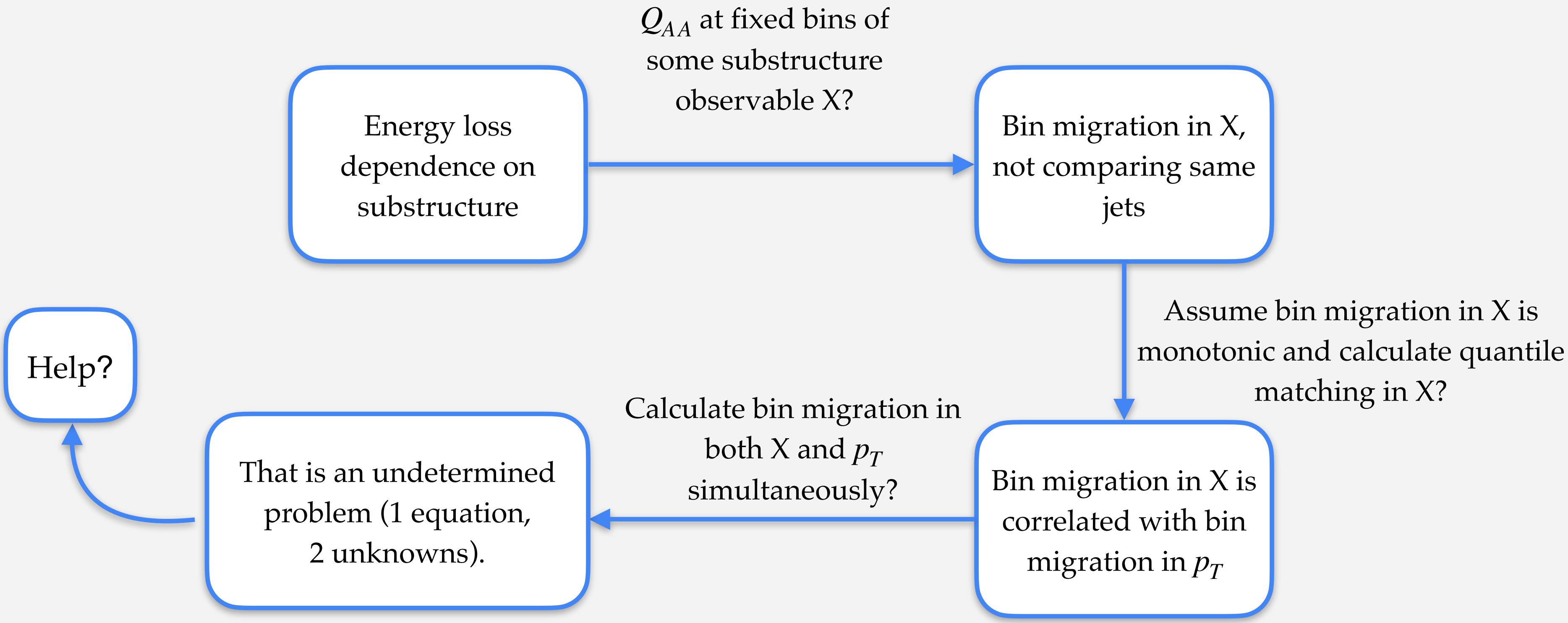
Observables calculated from code in Romão et al. 2304.07196



Momentum dispersion:

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

Energy loss dependence on substructure



Energy loss dependence on substructure

Q_{AA} at fixed bins of some substructure observable X?

Bin migration in X, not comparing same jets

Assume bin migration in X is monotonic and calculate quantile matching in X?

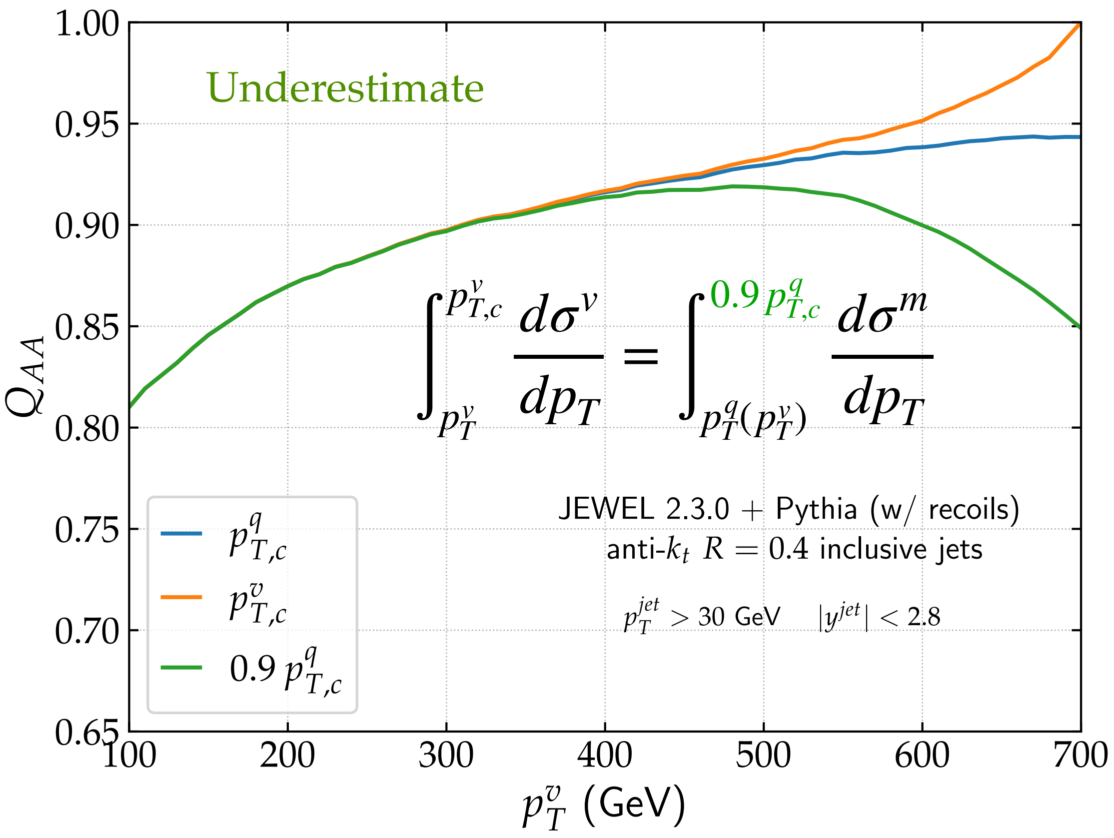
Bin migration in X is correlated with bin migration in p_T

Calculate bin migration in both X and p_T simultaneously?

That is an undetermined problem (1 equation, 2 unknowns).

Help?

The cutoff problem



Q_{AA} sensitivity to spectrum binning