Unbiased quantification of jet energy loss

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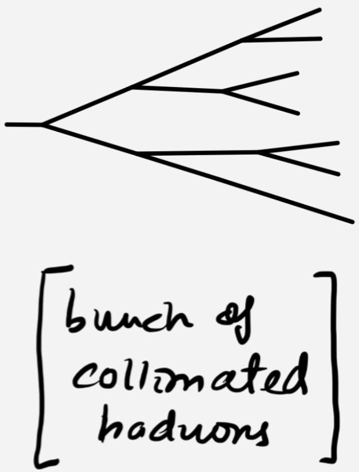
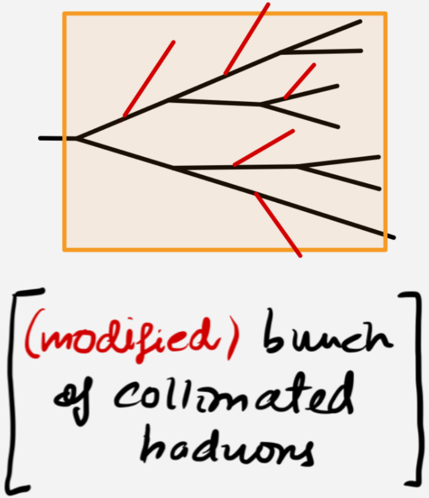
New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions

Trento, February 2024

TÉCNICO LISBOA
LIP
FCT Fundação para a Ciência e a Tecnologia
erc European Research Council Established by the European Commission
STRONG 2020
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

Probing the QGP with jets





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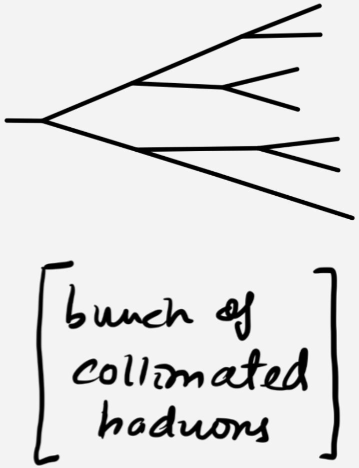
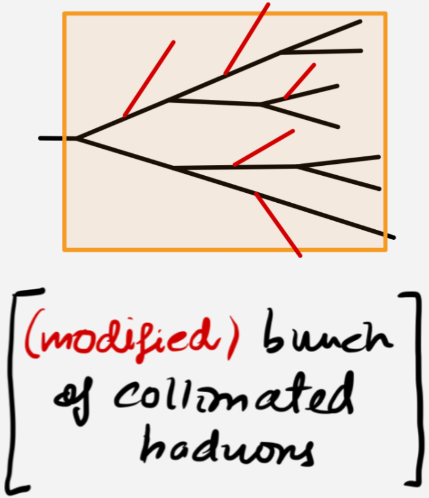


Compare **AA jets** with the well established vacuum baseline of **pp jets**

Infer properties of the QGP



Biased jet comparison

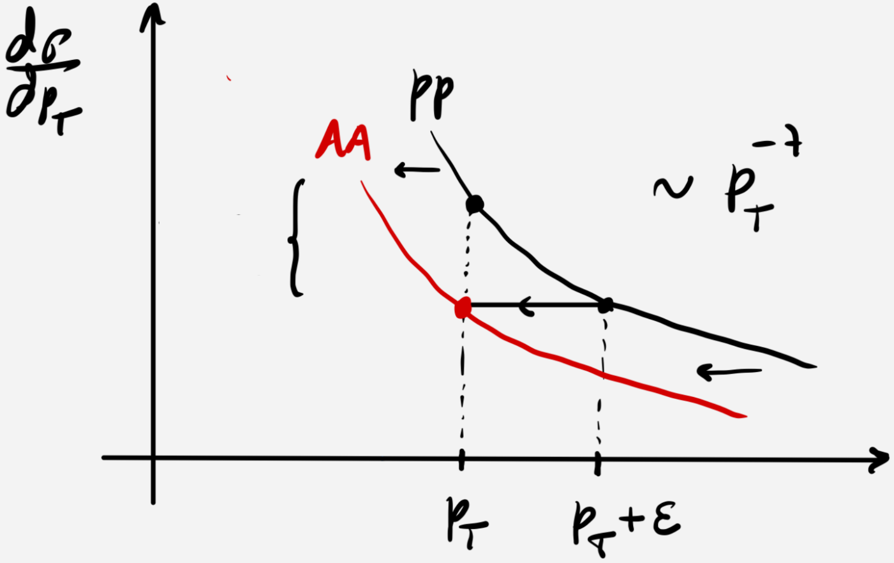
Which AA jets should I compare to a given set of pp jets?

- ➔ Common procedure: Choose a window of **reconstructed jet** p_T
- ➔ Common problems:
  - ◆ AA jets **migrate** to lower reconstructed p_T (wide angle out of cone radiation)

    ⟹ We are comparing jets that **"started out" differently**.

Bin migration in R_{AA}

$$p_T \to p_T - \epsilon$$



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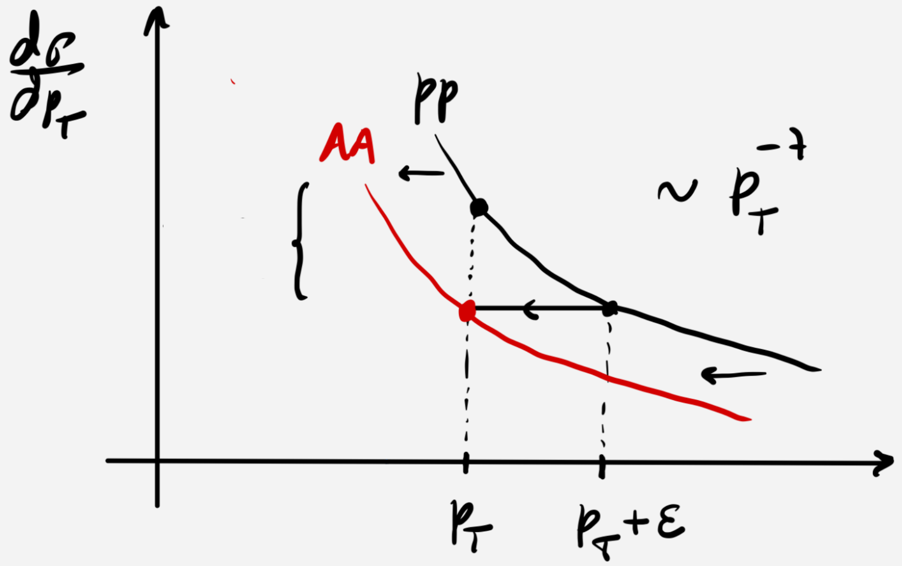

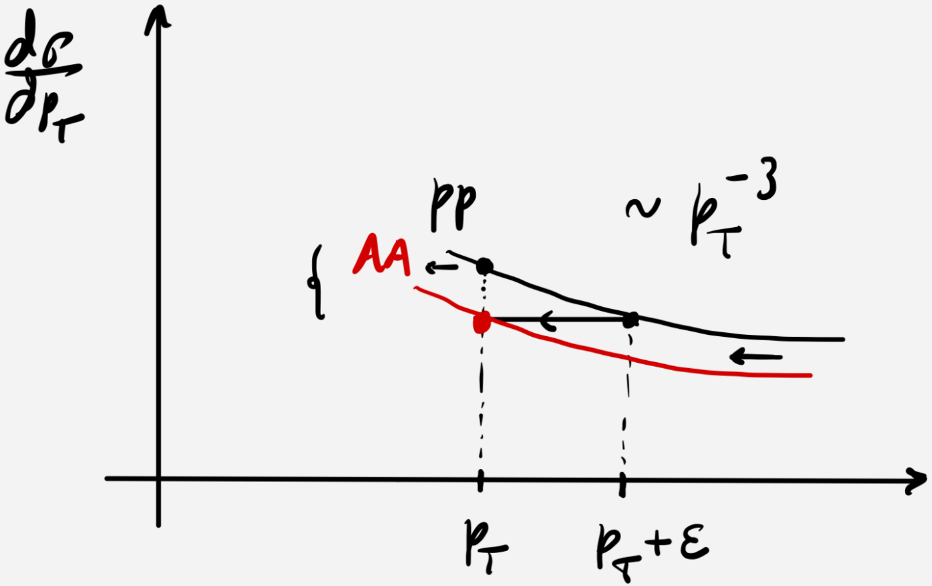

Same energy loss but **different** R_{AA} **!**

Biased jet comparison

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  - **Selection/survivor bias** - in-medium jet samples are biased towards **less modified jets**.

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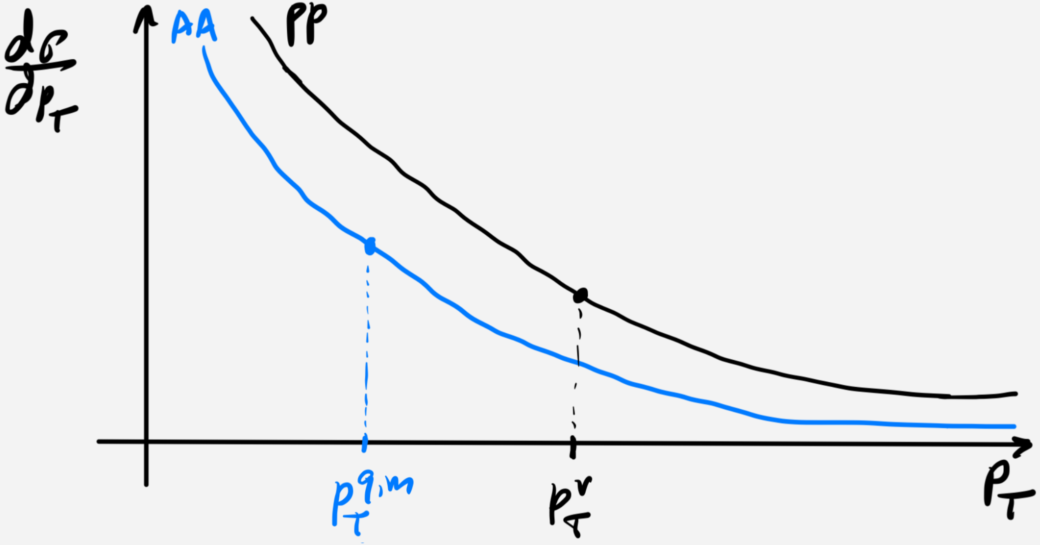
    ⟹ We are comparing jets that **“started out” differently**.
  - ◆ **Selection/survivor bias** - in-medium jet samples are biased towards **less modified jets.**
- → Possible solution: **electroweak boson + jet**? ⟹ Lower statistics

  Brewer et al. Journal of High Energy Physics 2022(2), 1-22
  Apolinário et al. 2401.14229 (Pablo’s talk Thursday 16:00)

Quantiles - a way to estimate p_T migration



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

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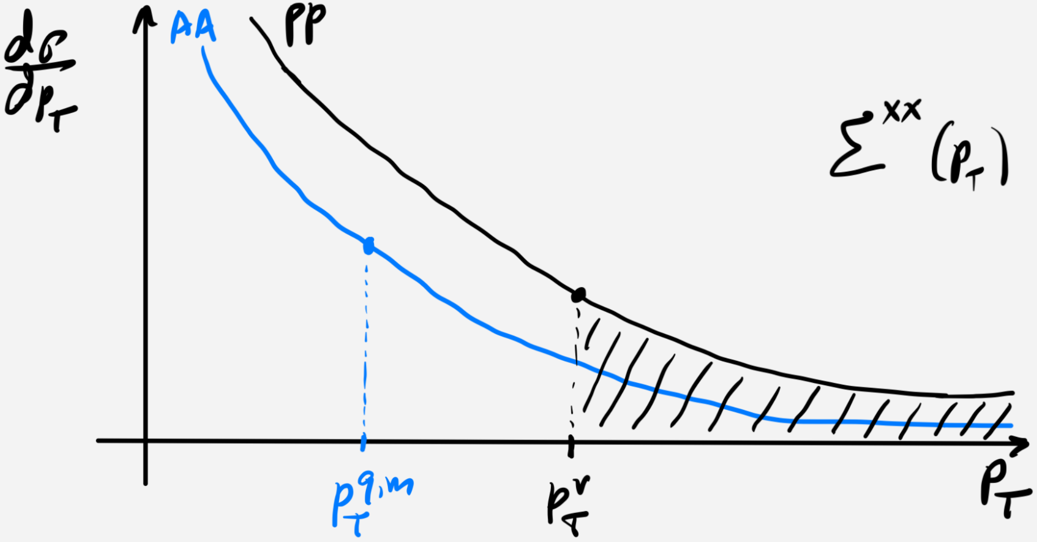

$$\Sigma^{xx}(p_T) \equiv \int_{p_T}^{+\infty} dp'_T \, \frac{d\sigma^{xx}}{dp'_T}$$

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

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

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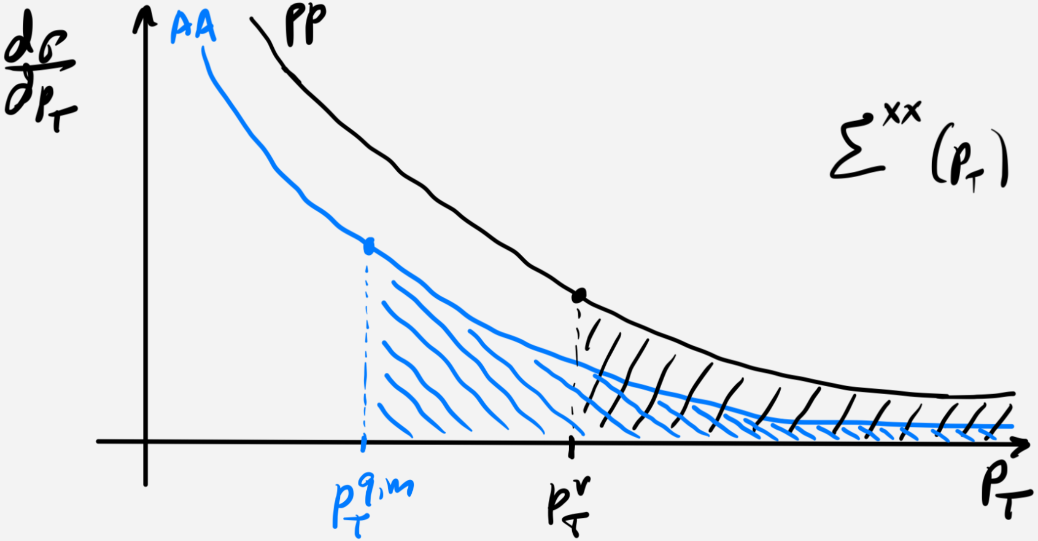

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$$\Sigma^{pp}(p_T^{v}) = \Sigma^{AA}(p_T^{q,m}) \rightarrow \boxed{p_T^{q,m} = p_T^{q,m}(p_T^{v})}$$

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!

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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 nucleon-nucleon collisions including nuclear PDFs
  - ↳ Differences between vacuum and medium samples are in principle **dominated by quenching effects**

Vacuum jet spectrum

$$\frac{d\sigma^{vac}}{dp_T} = \left.\frac{d\sigma^{NN+nPDFs}}{dp_T}\right|_{NN=\{pp,pn,np,nn\}}$$

In-medium jet spectrum

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

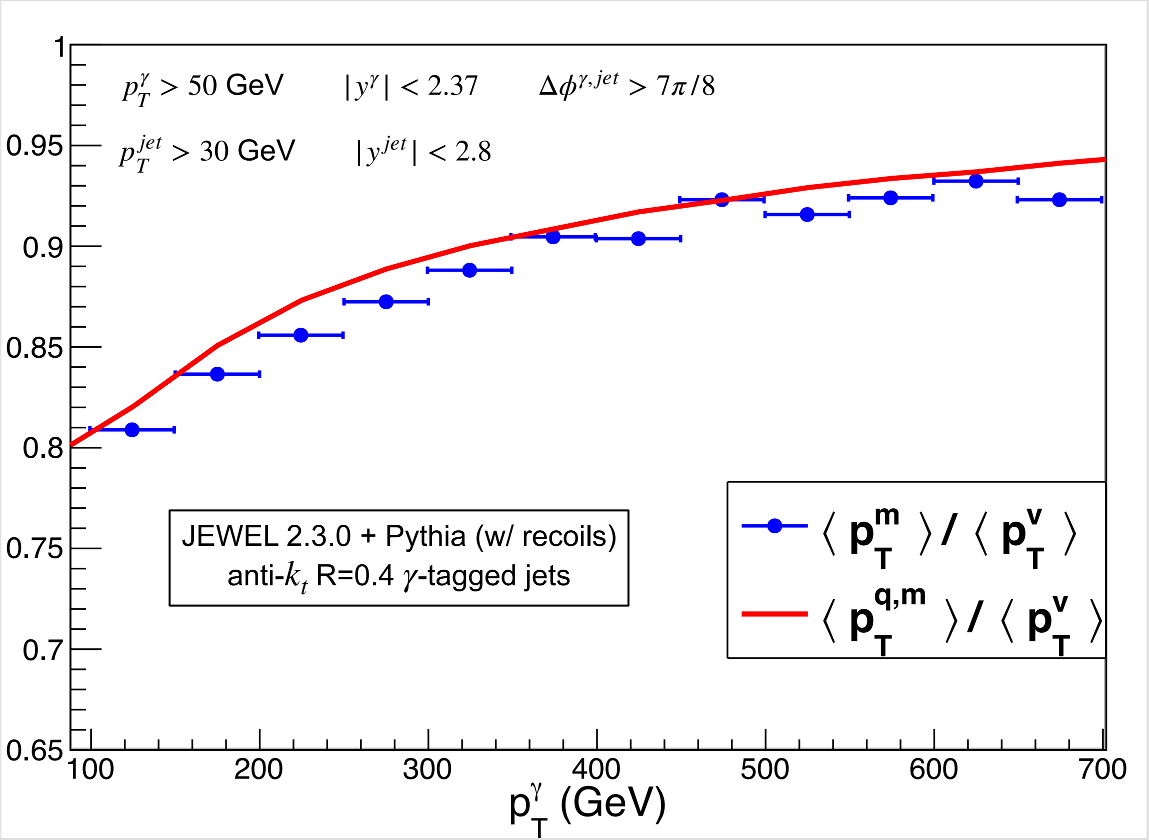
Quantile procedure validation

Average jet p_T for a given photon p_T

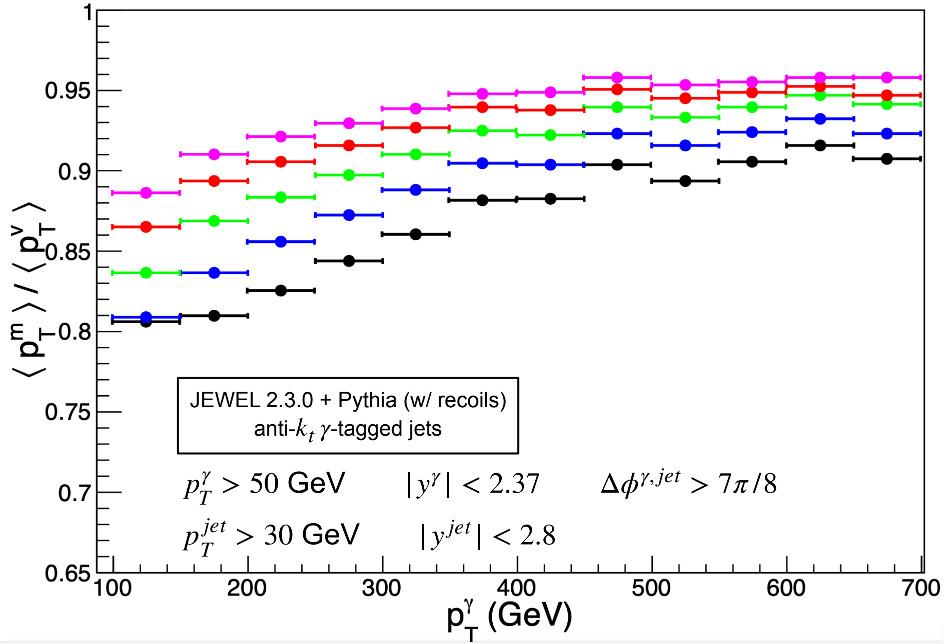
$$\langle p_T^{v/m} \rangle = \int dp_T \frac{dN^{v/m}}{dp_T}[p_T^{\gamma}] \cdot p_T$$

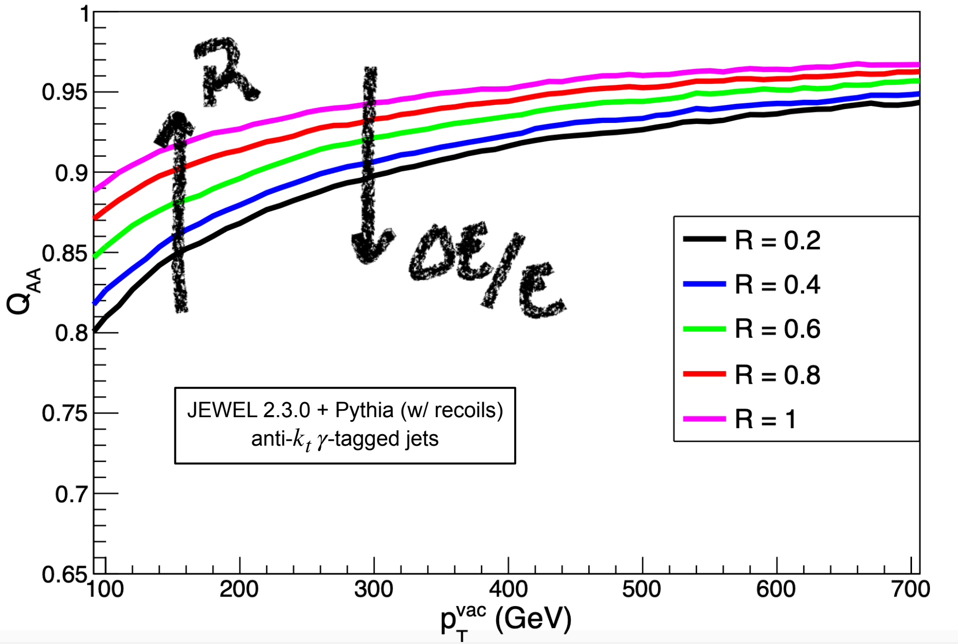
Average quantile p_T for a given photon p_T

$$\langle p_T^{q,m} \rangle = \int dp_T \frac{dN^{v}}{dp_T}[p_T^{\gamma}] \cdot p_T^{q,m}(p_T^{v})$$



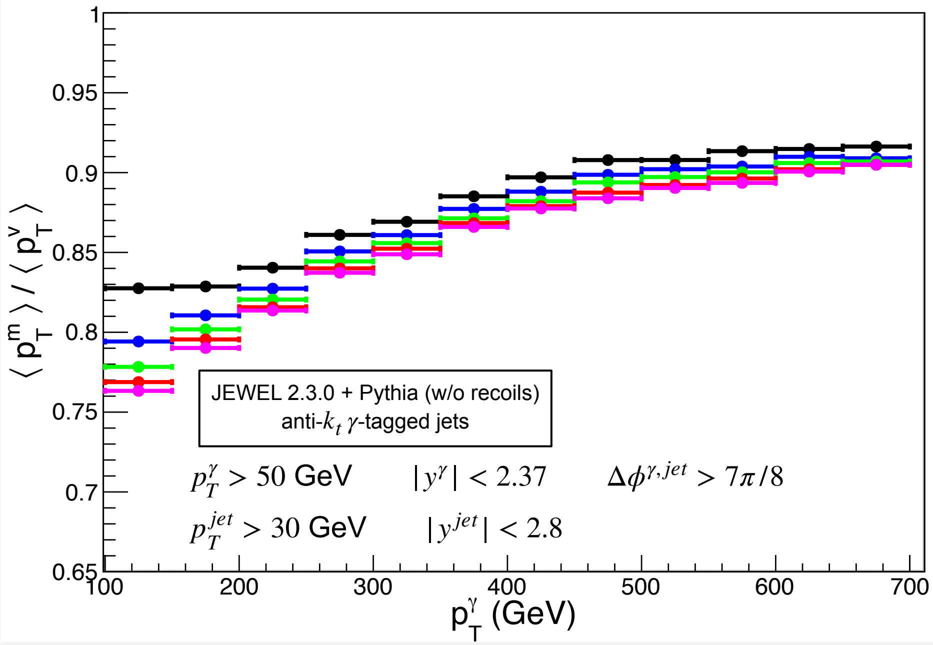
Energy loss as a function of jet radius (w/ recoils)

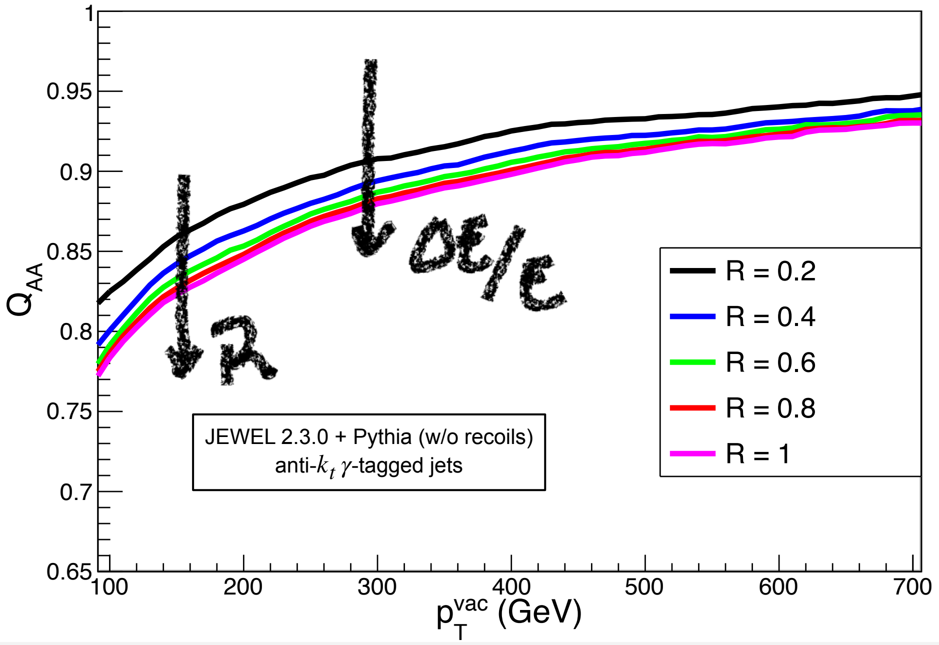




Larger jets lose a **smaller** fraction of their energy

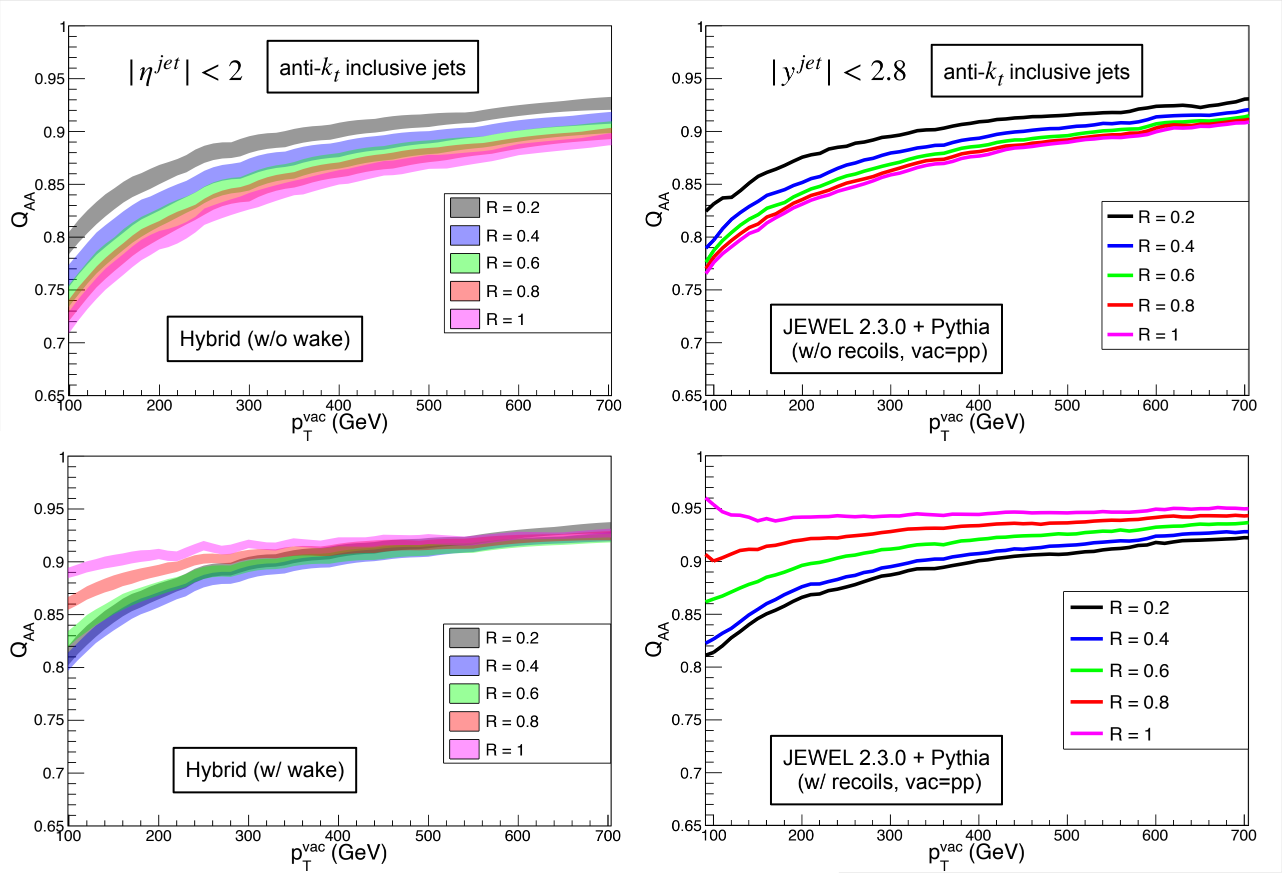
Energy loss as a function of jet radius (w/o recoils)



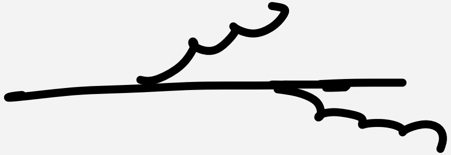


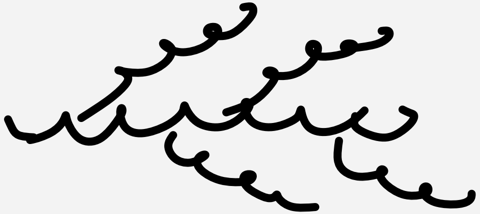
Larger jets lose a **larger** fraction of their energy

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



Energy loss dependence on color charge

q  ~ C_F

g  ~ C_A

γ+jet ~ q init. jets

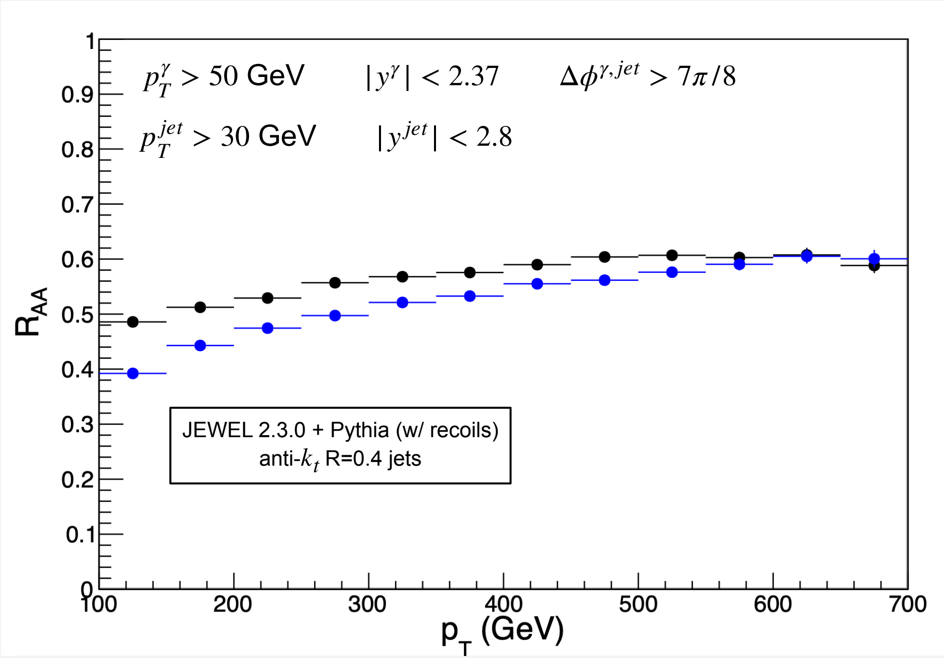
dijet ~ mixture of q and g init. jets

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

=

Casimir scaling in jets ?

Energy loss dependence on color charge



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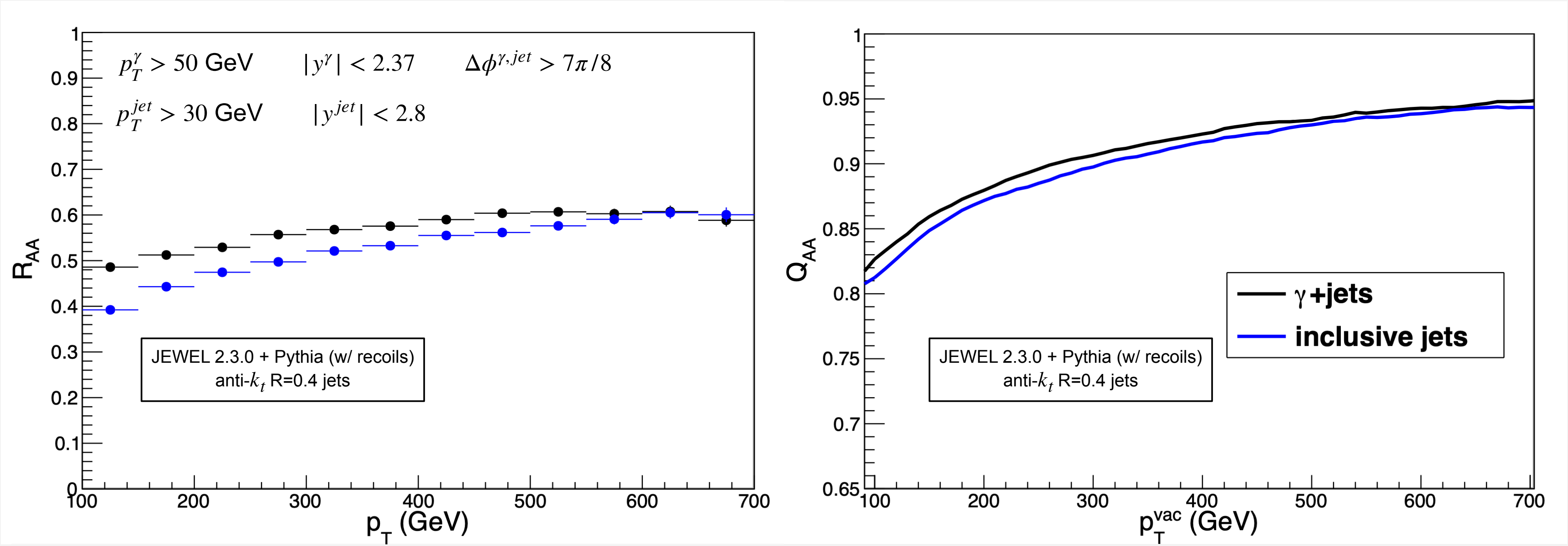

Color charge dependence of jet energy loss is not as strong as suggested by the R_{AA}

Spectrum p_T cutoff effect

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

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

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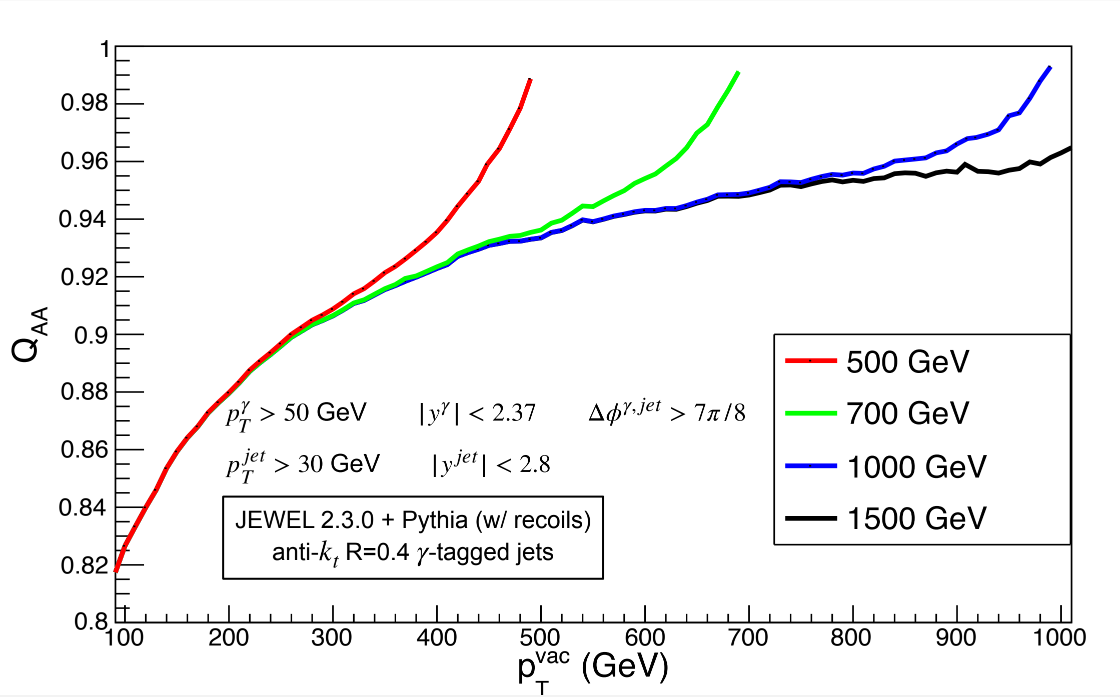
Underdetermined problem

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

Equal p_T cutoff for both spectra

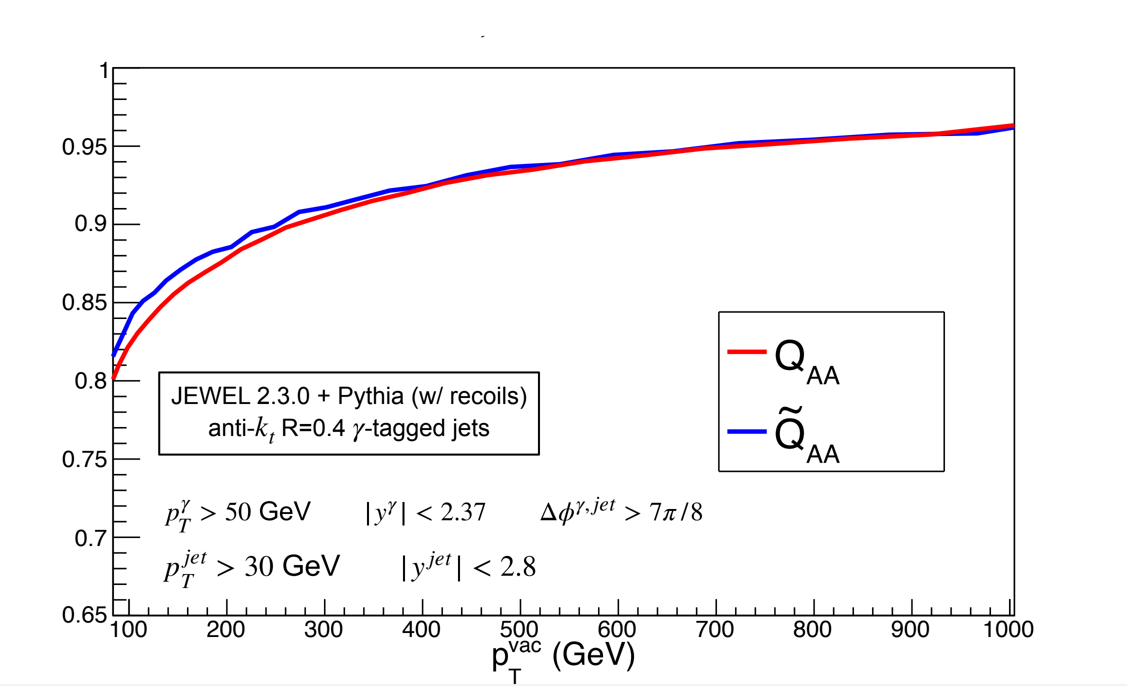
$$\int_{p_T^{v}}^{p_T^{c}} dp_T \frac{d\sigma^{v}}{dp_T} \simeq \int_{p_T^{\gamma}(p_T^{v})}^{p_T^{c}} dp_T \frac{d\sigma^{m}}{dp_T}$$



Using $\tilde{Q}_{AA}$ to solve the cutoff problem

$$\int_{p_T^v}^{p_T^c} dp_T \frac{d\sigma^v}{dp_T} \simeq \int_{p_T^q(p_T^v)}^{\tilde{p}_T^q(p_T^c)} dp_T \frac{d\sigma^w}{dp_T}$$

$$\left[\frac{d\sigma^v}{dp_T}(p_T^v) = \frac{d\sigma^w}{dp_T}\left(\tilde{p}_T^q(p_T^v)\right) \right]$$



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

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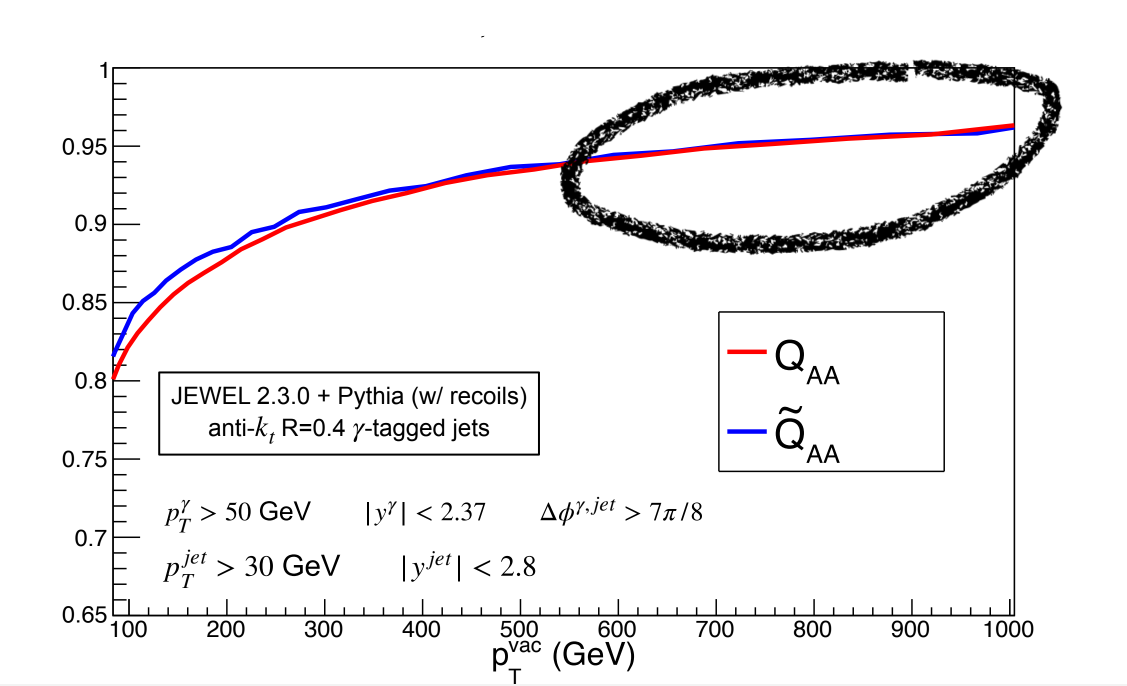

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Effect of suppressing p_T migration

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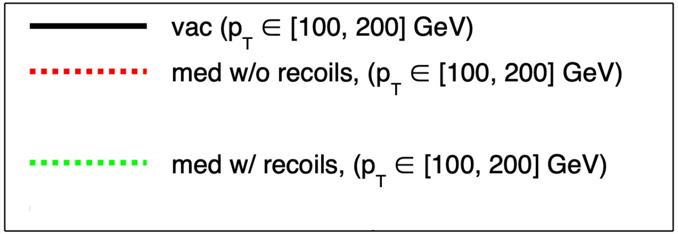


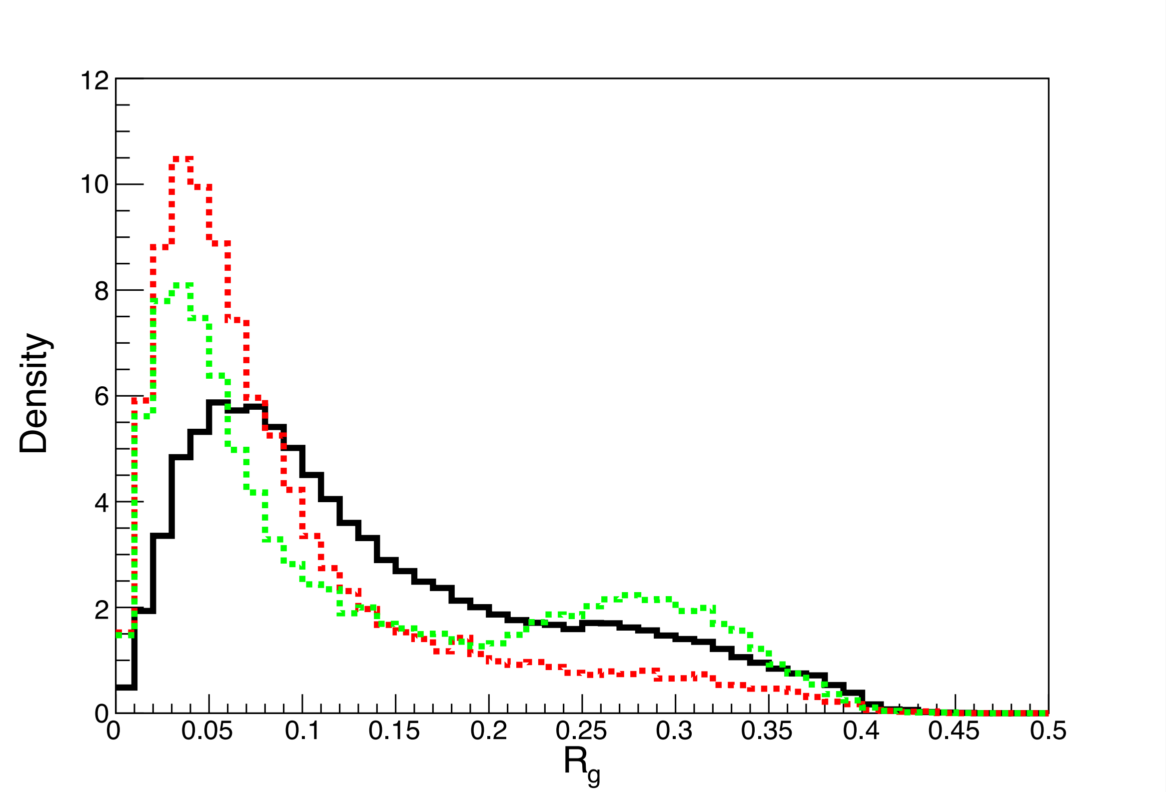
R_g :

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

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

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

Observables calculated from code in Romão et al. 2304.07196



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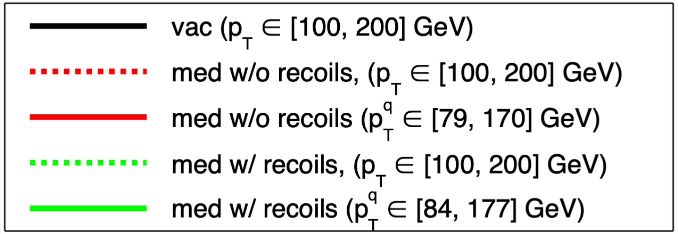

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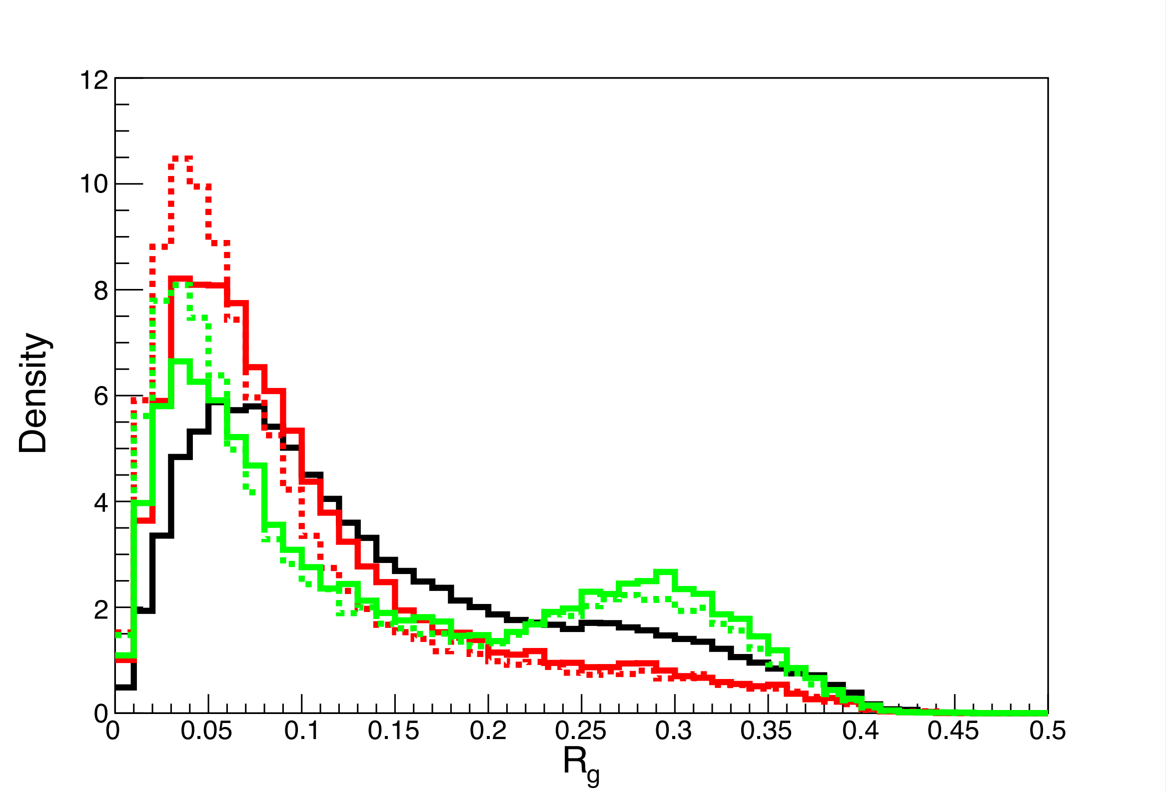

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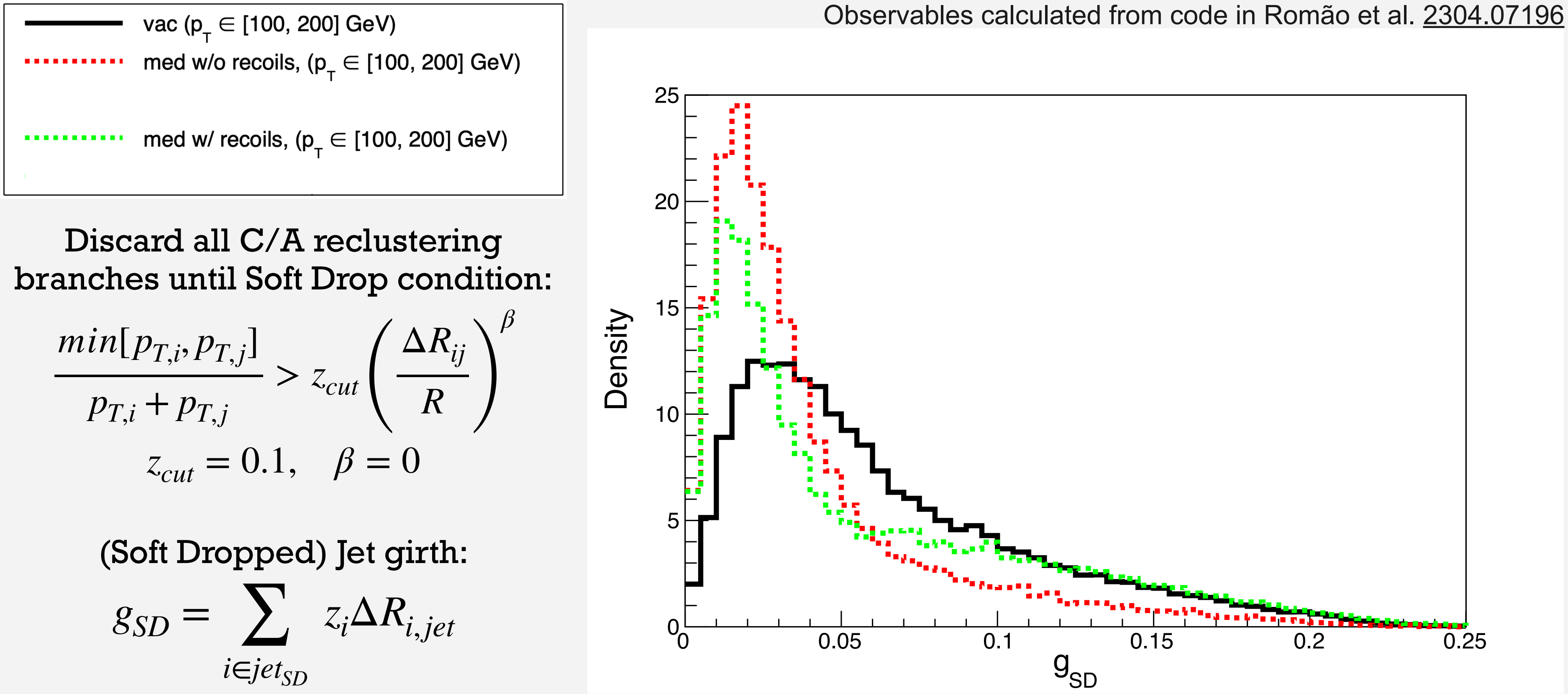

Discard all C/A reclustering branches until Soft Drop condition:

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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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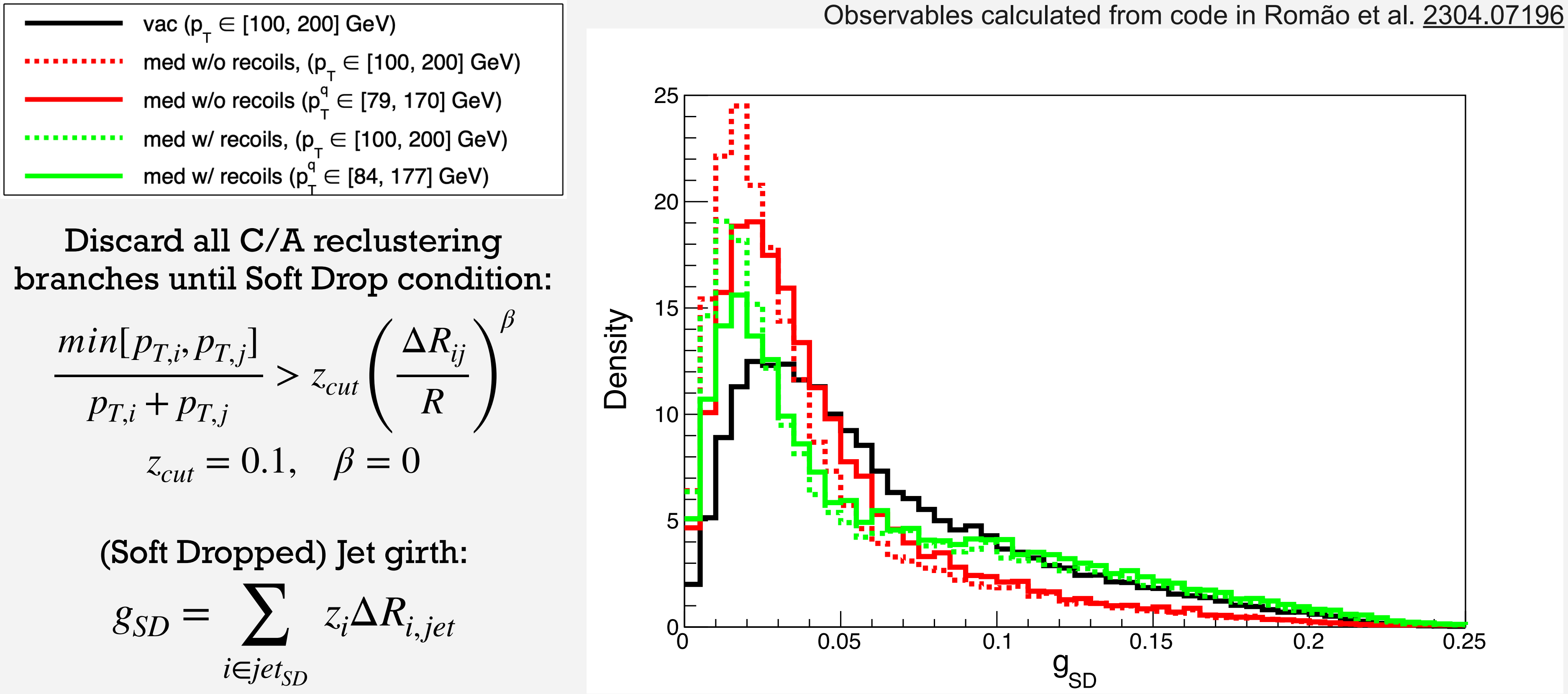

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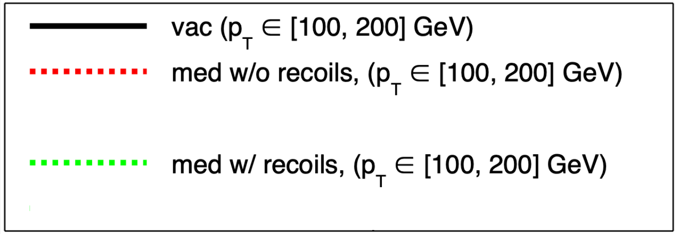

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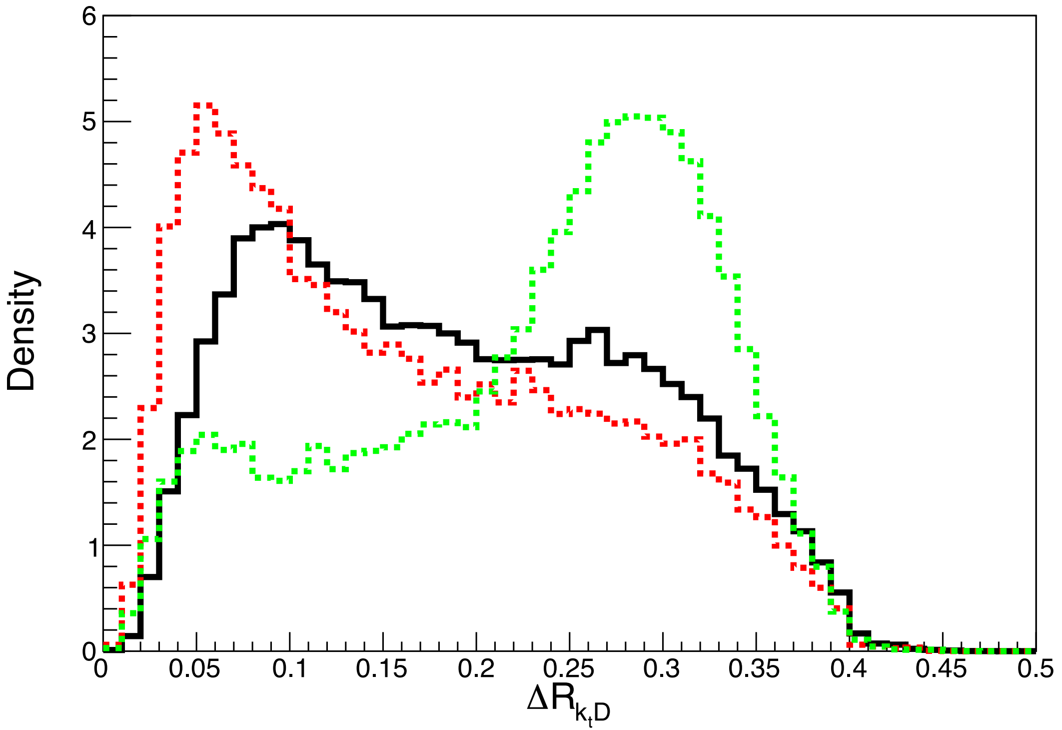


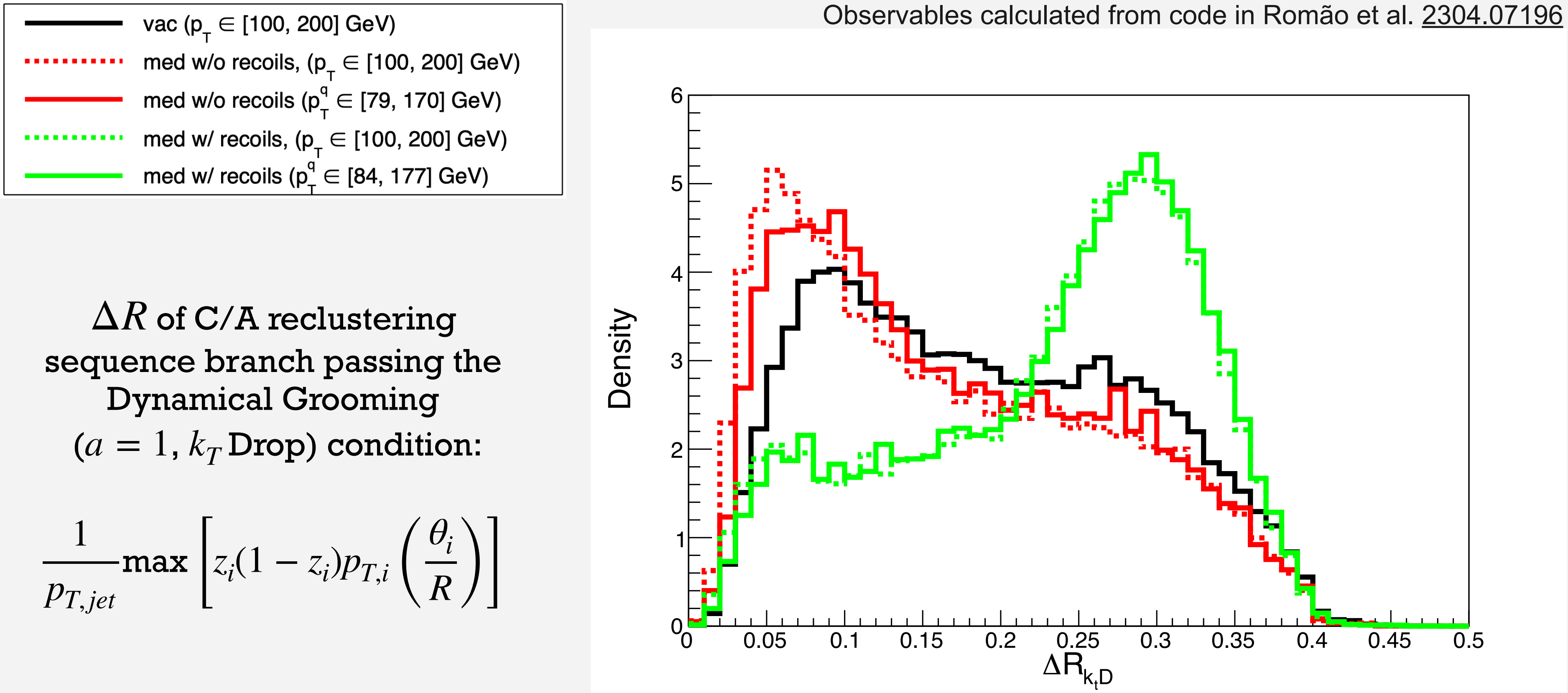
ΔR of C/A reclustering sequence branch passing the Dynamical Grooming ($a = 1$, k_T Drop) condition:

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

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



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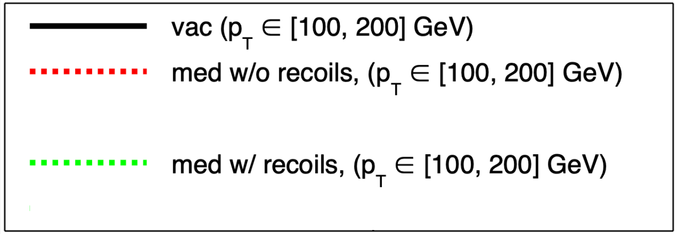

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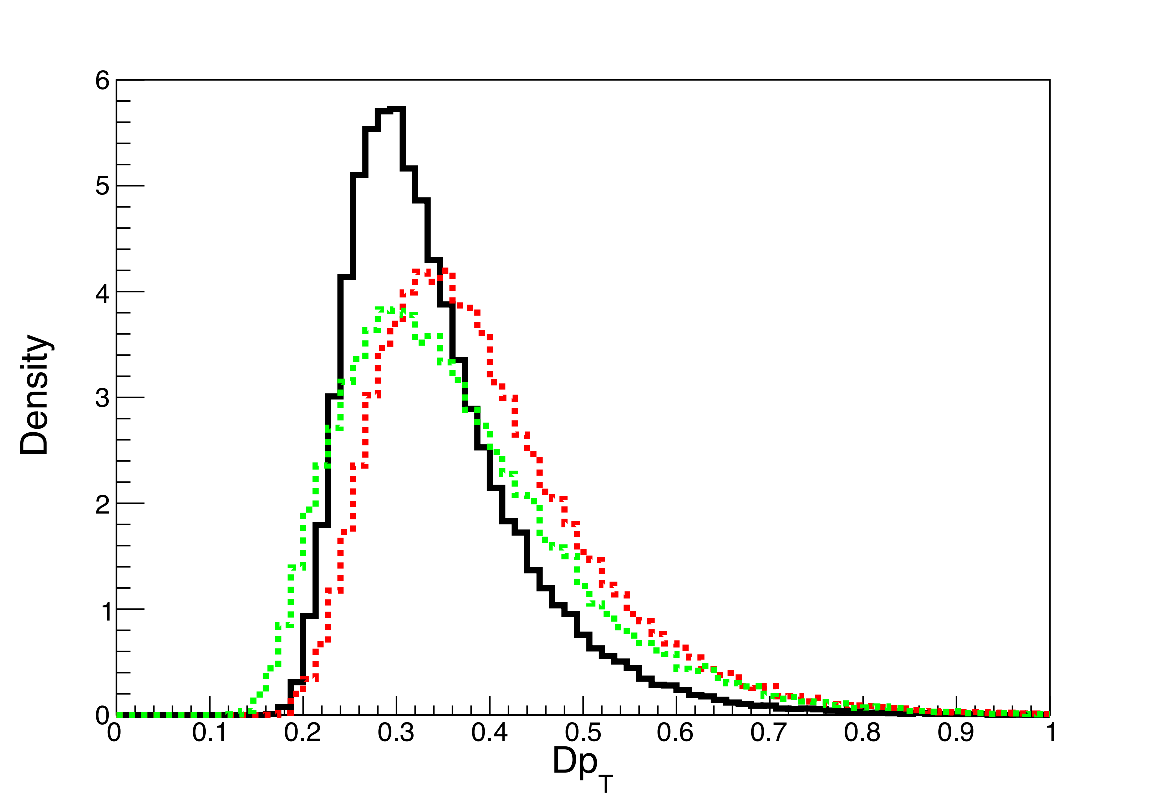

Momentum dispersion:

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

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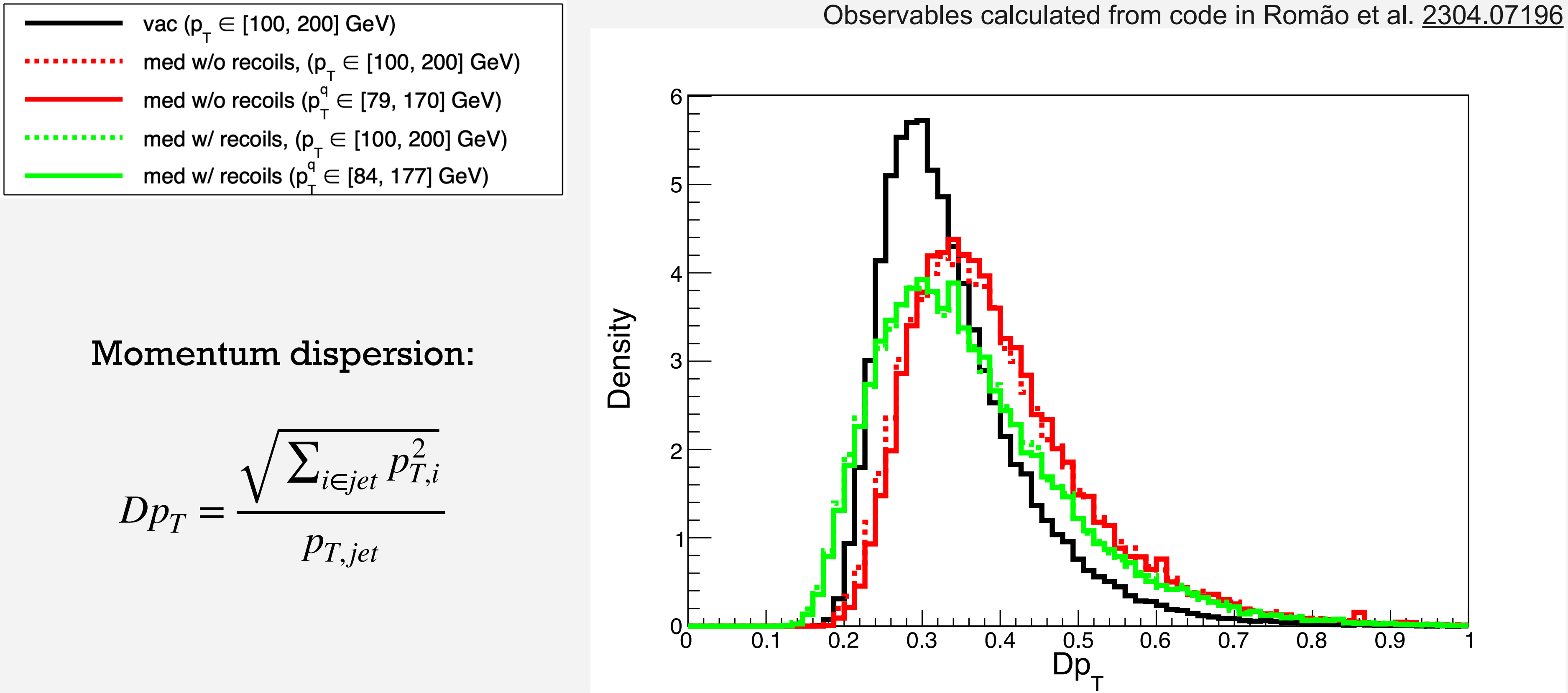

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Energy loss dependence on substructure

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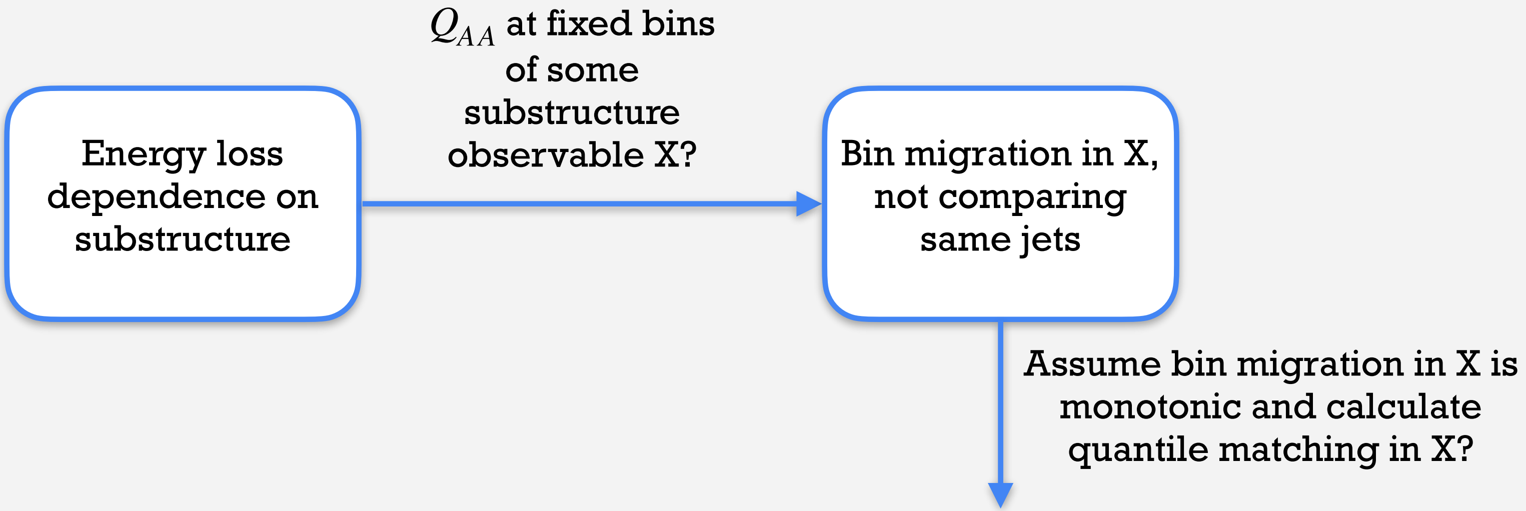
Q_{AA} at fixed bins of some substructure observable X?

Energy loss dependence on substructure



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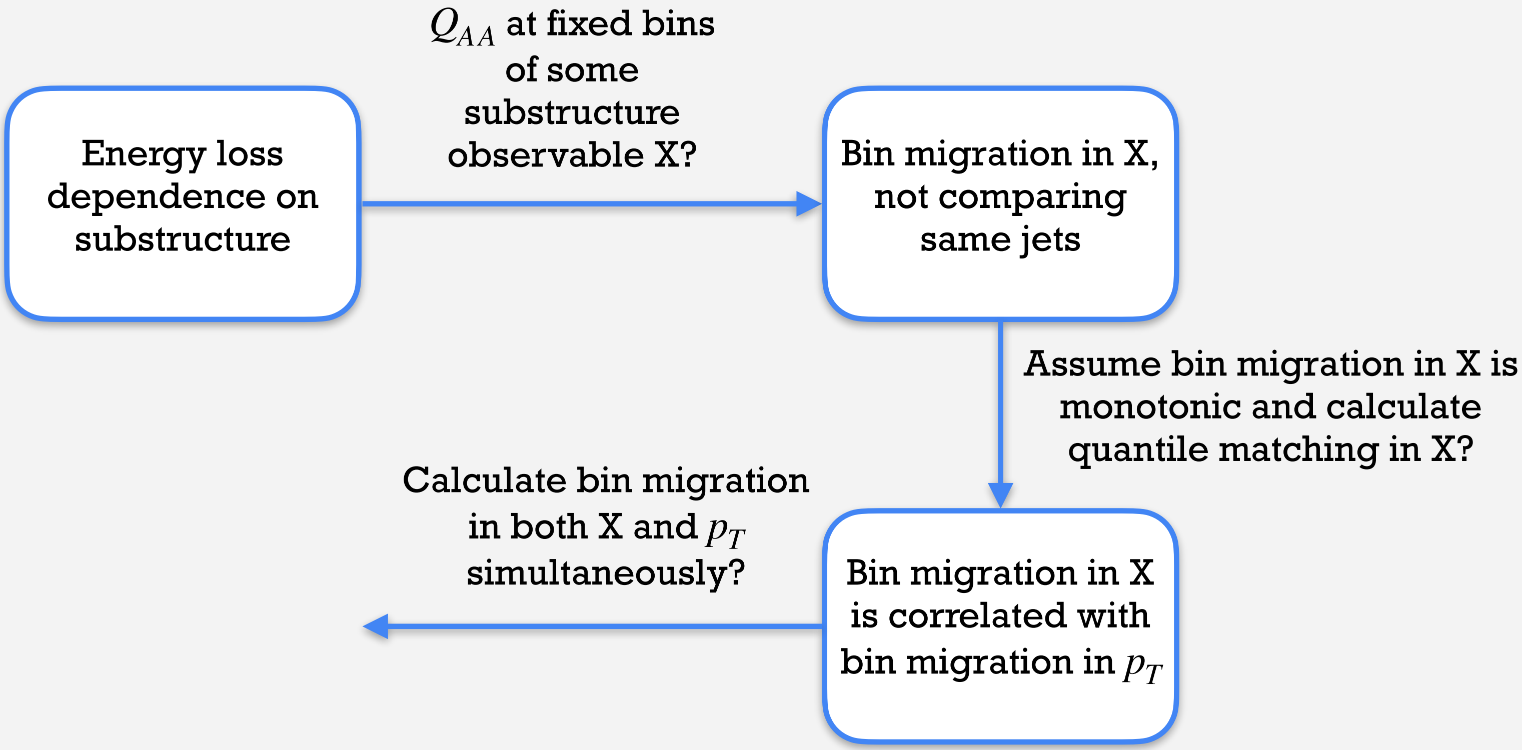

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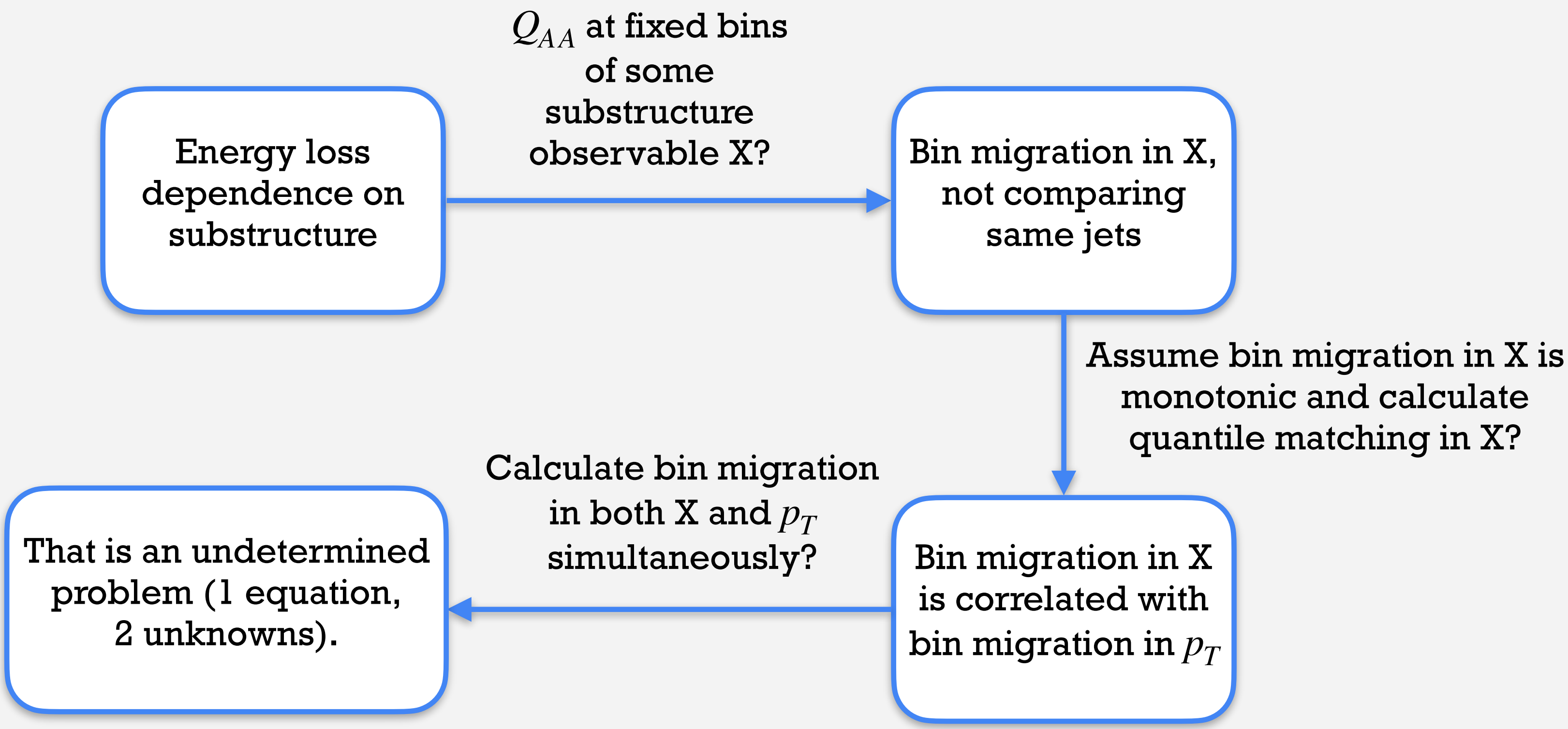

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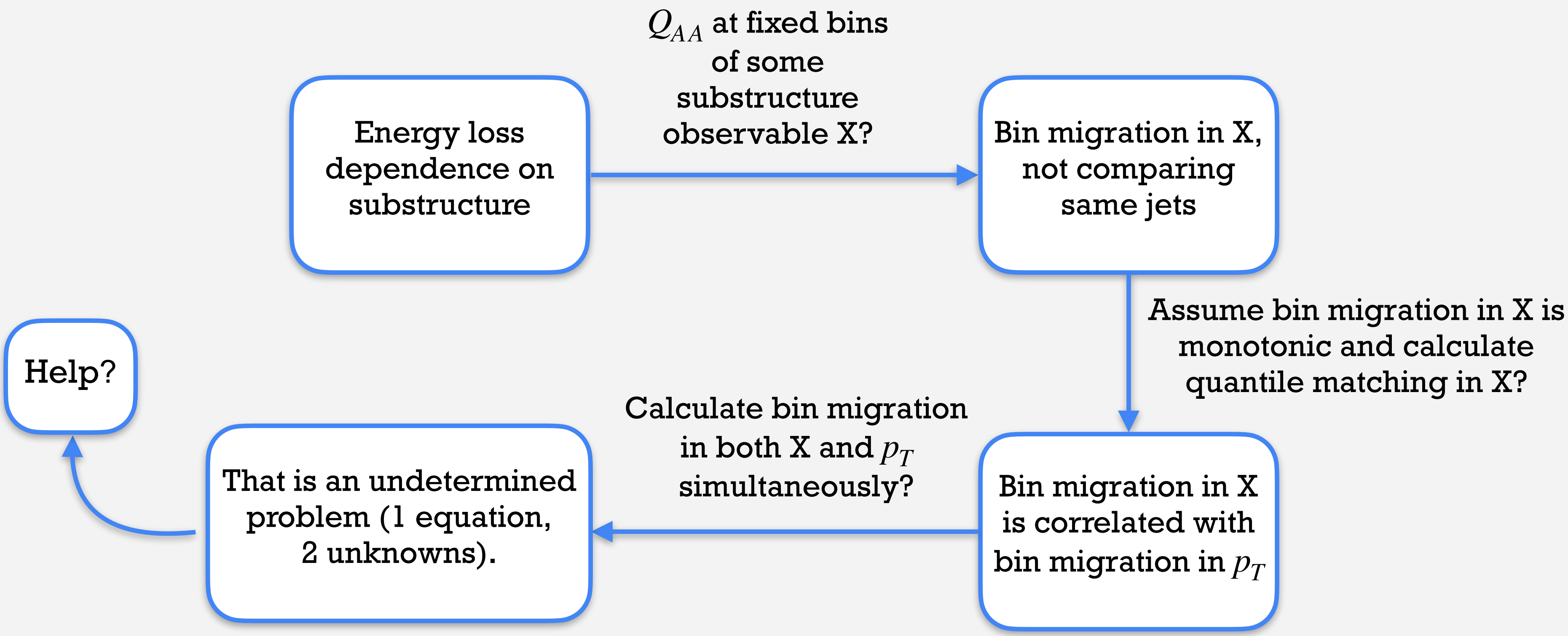
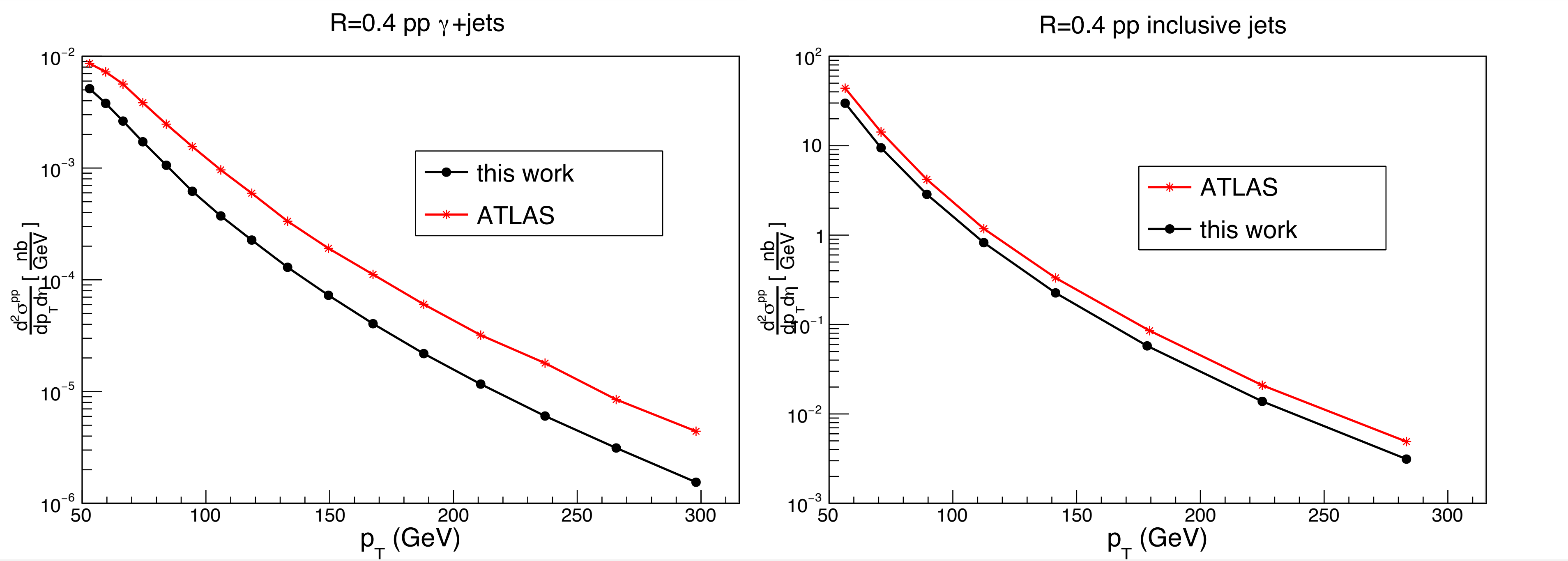


Summary

- 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 $\tilde{Q}_{AA}$.
- Energy loss dependence on substructure is an ongoing work.

THANKS!

Back-up


R=0.4 pp γ+jets
this work
ATLAS
$\frac{d^2\sigma^{pp}}{dp_T d\eta}$ [$\frac{nb}{GeV}$]
p_T (GeV)
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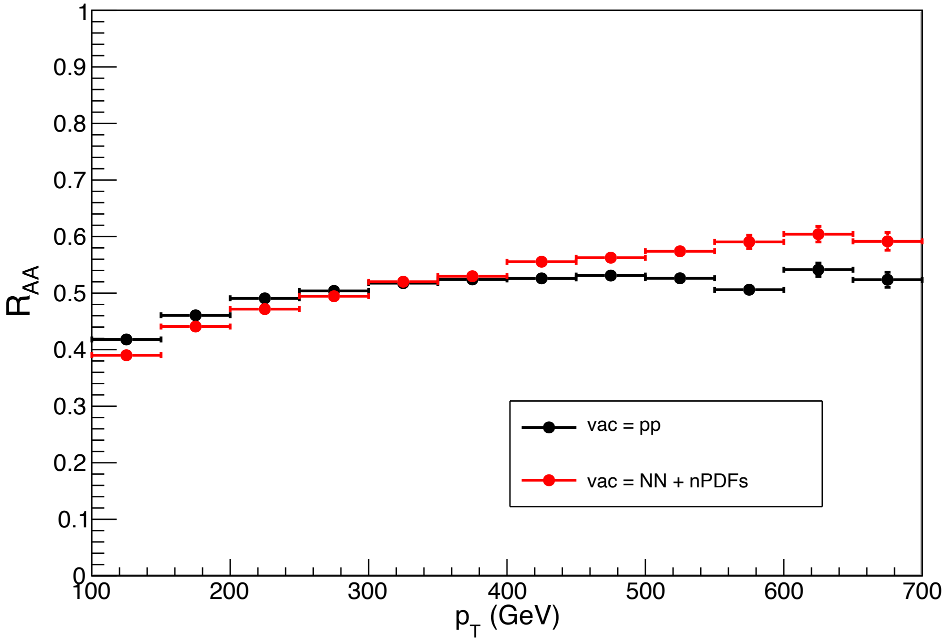
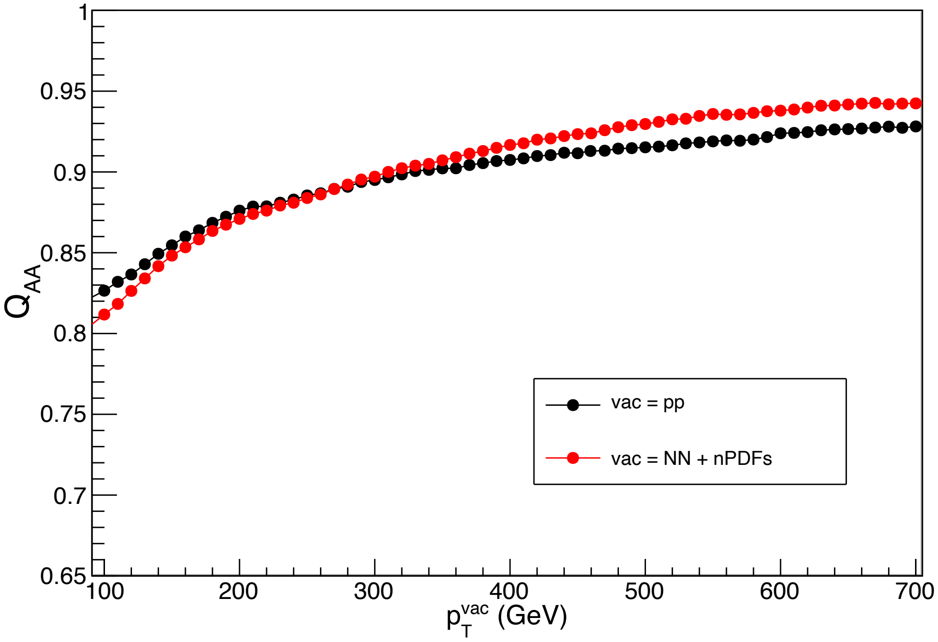
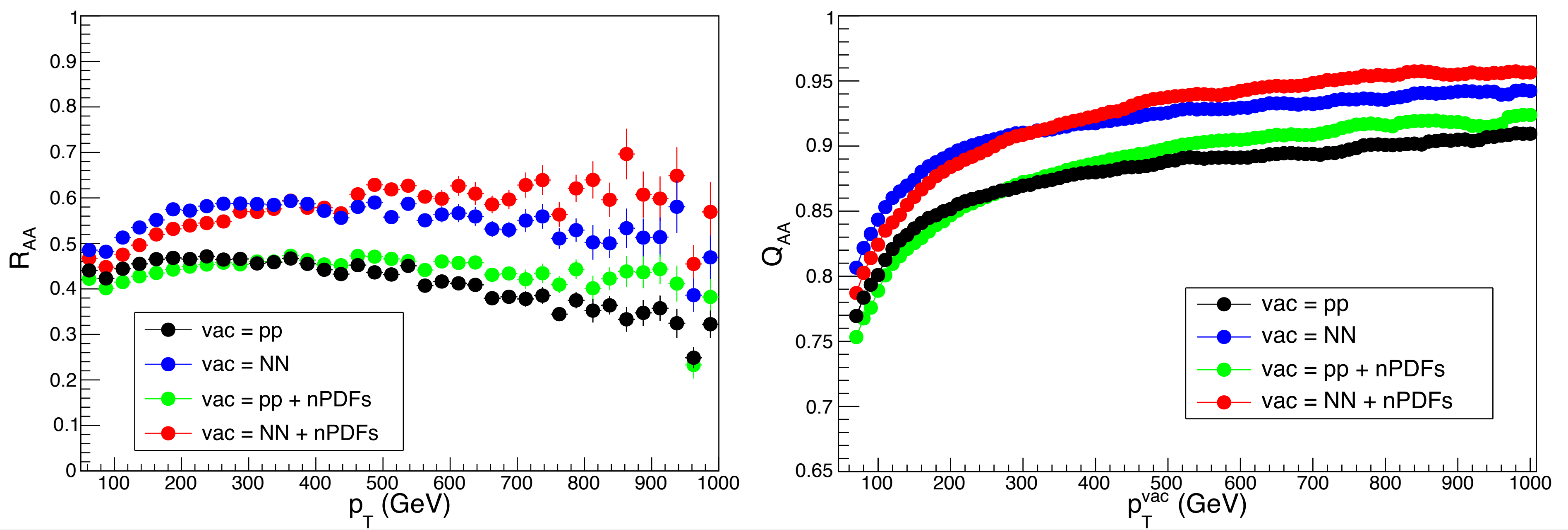
this work
$\frac{d^2\sigma^{pp}}{dp_T d\eta}$ [$\frac{nb}{GeV}$]
p_T (GeV)

Isospin and nuclear PDF effects in inclusive jets

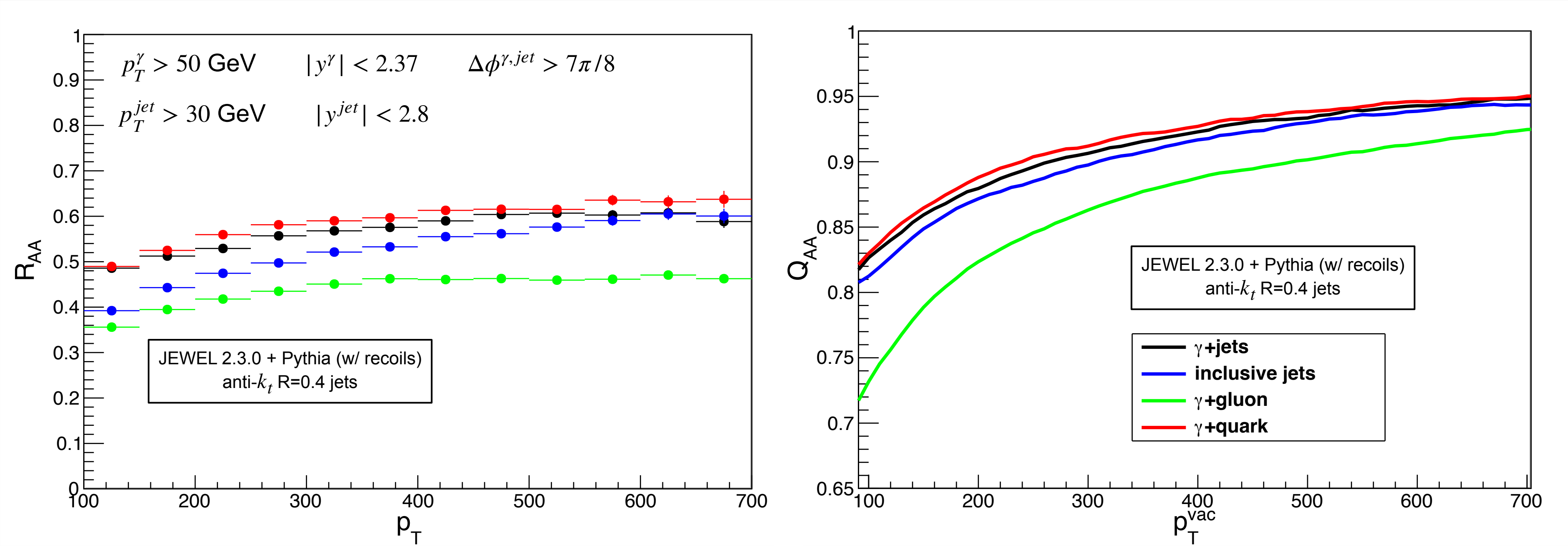




Isospin and nuclear PDF effects in γ+jets



Energy loss dependence on color charge



Equivalence between integral (Q_{AA}) and differential (S_{loss}) quantile calculation

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

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

$$\implies \frac{d\sigma^{pp}}{dp_T}(p_T^v) = \left(1 - \frac{d\Delta p_T}{dp_T^v}\right)\frac{d\sigma^{AA}}{dp_T}(1 - \Delta p_T(p_T^v))$$

$$\Delta p_T(p_T^v) = p_T^v - p_T^q(p_T^v)$$

Q_{AA} sensitivity to binning of the spectrum