Sensitivity of Energy-Energy Correlators to Multiple QCD Regimes in Heavy-Ion Collisions

Speaker: PhD candidate @ IST

Nuno Olavo Madureira (nuno.olavo@tecnico.ulisboa.pt)

Co-authors:

- Liliana Apolinário (PhD supervisor)
- Rithya Kunnawalkam Elayavalli (PhD supervisor)
- Jun-Xing Sheng
- Xin-Nian Wang
- Zhong Yang

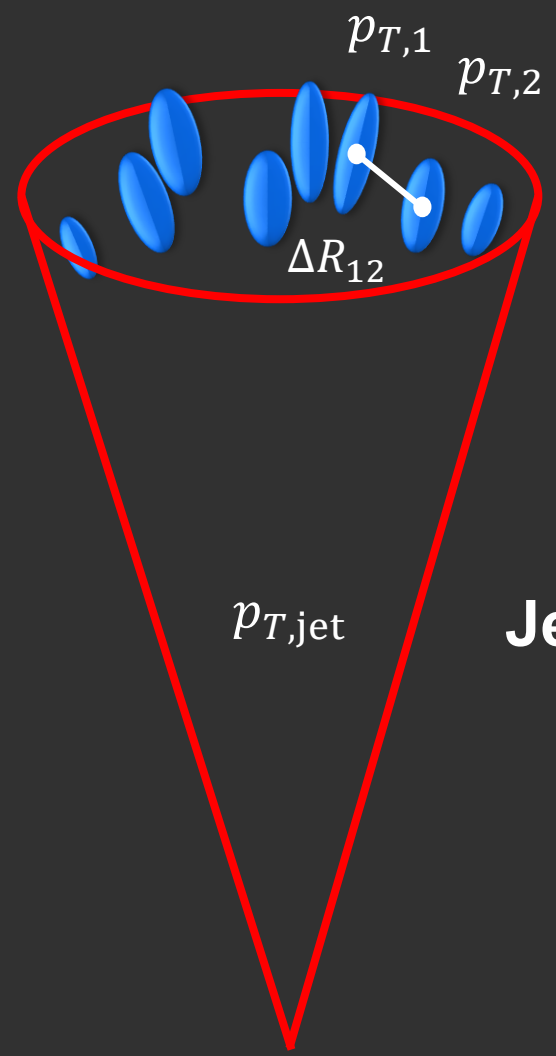
PhD Host Institutions

Energy-Energy Correlators

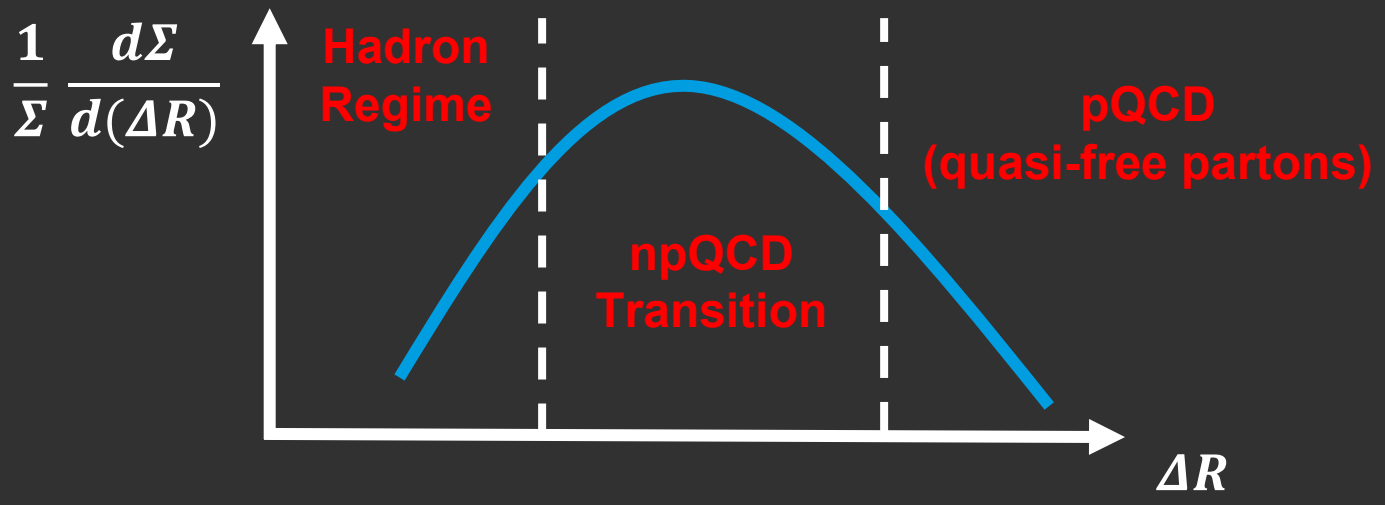
$$\Delta R_{12} = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$$

- Jet energy-energy correlators (EEC) quantify pairwise energy correlations inside jets as a function of angle (ΔR):

$$\frac{1}{\Sigma}\frac{d\Sigma}{d(\Delta R)} = \frac{1}{C_{norm}} \sum_{jets} \sum_{\substack{i,j \in jet \\ \Delta R_{ij} \in bin(\Delta R)}} \frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2}$$



- Multiscale objects proposed to factorize pQCD, npQCD and hadron physics in separate angular regions:

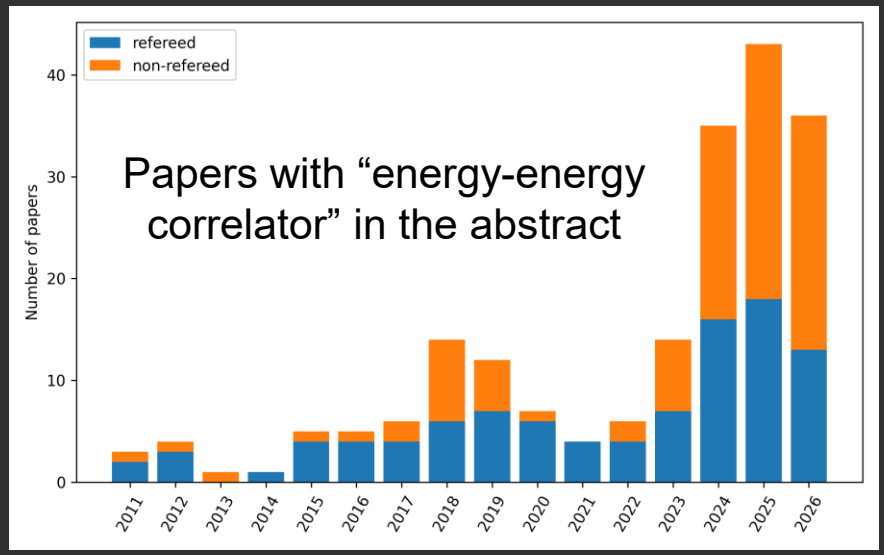


Motivation: EEC Proliferation

- EECs becoming the subject of growing number of theoretical and phenomenological studies;

Ian Moult, Hua Xing Zhu, arXiv:2506.09119
etc.

Extracted from NASA ADS database



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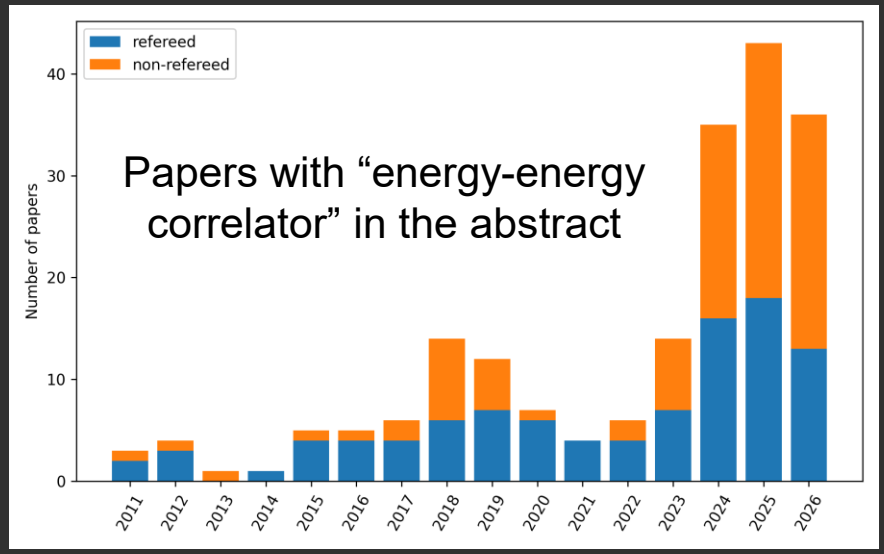
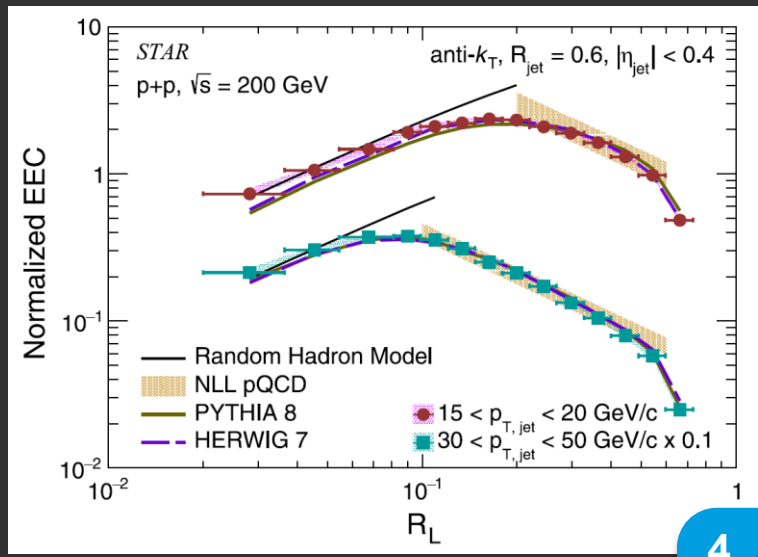


1st EEC measurement at RHIC (pp)



STAR Collaboration, Phys.Rev.Lett. 135 (2025)

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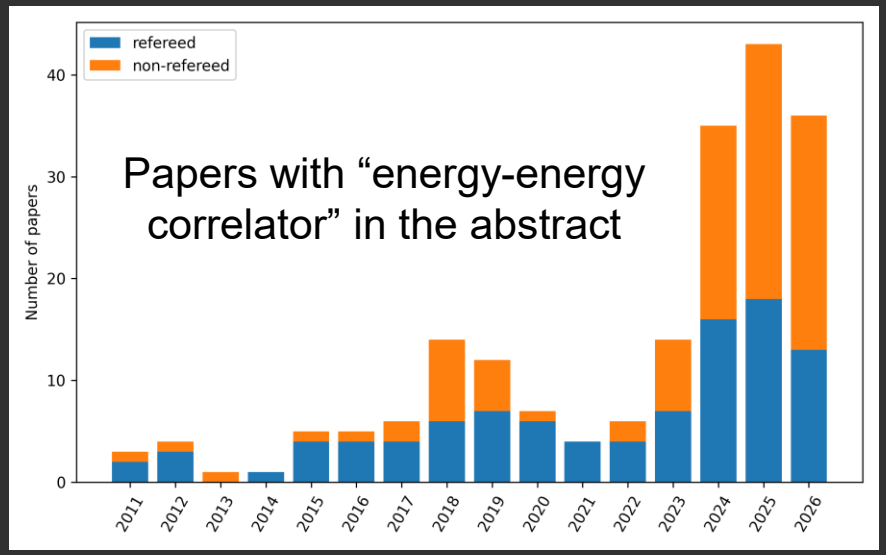
  Ian Moult, Hua Xing Zhu, arXiv:2506.09119 etc.

- Past few years also brought first experimental measurements;

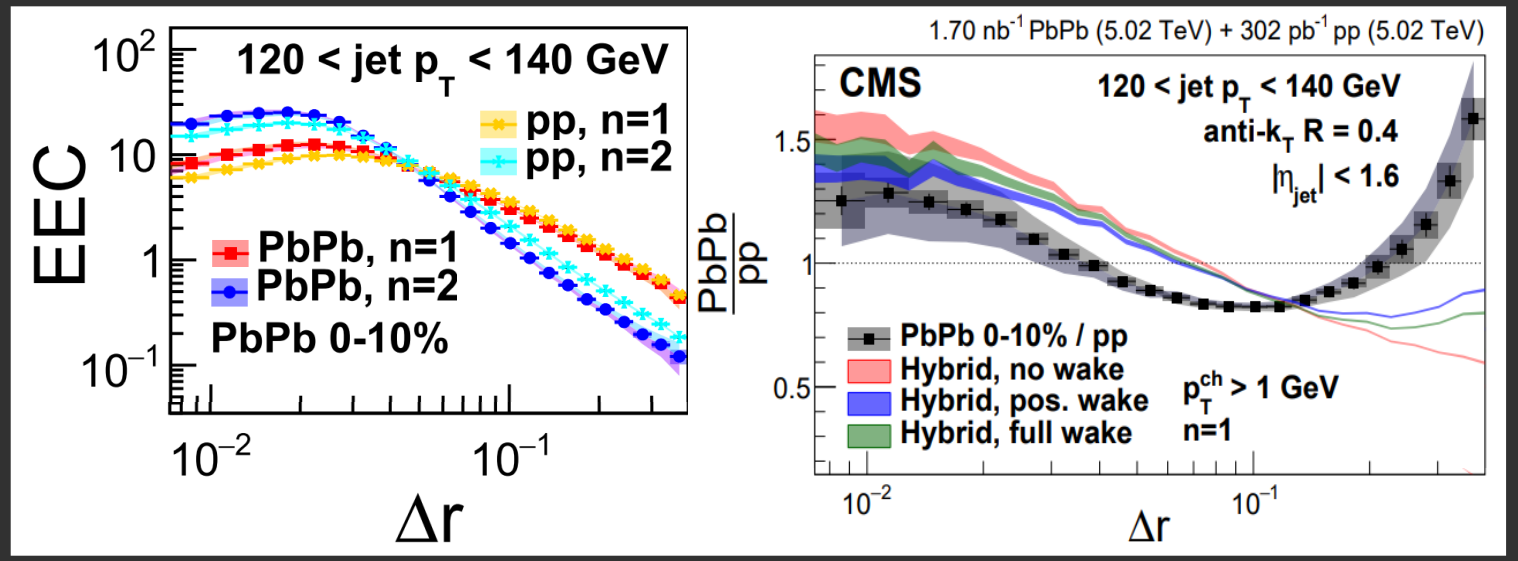
- Important applications in Heavy-Ion Collisions (HICs) to probe the Quark-Gluon Plasma (QGP).

  Carlota Andres et al., Phys.Rev.Lett. 130 (2023) 26, 262301, etc.

Extracted from NASA ADS database



1st ever HIC EEC measurement (@LHC)



CMS Collaboration, Phys.Lett.B 866 (2025)

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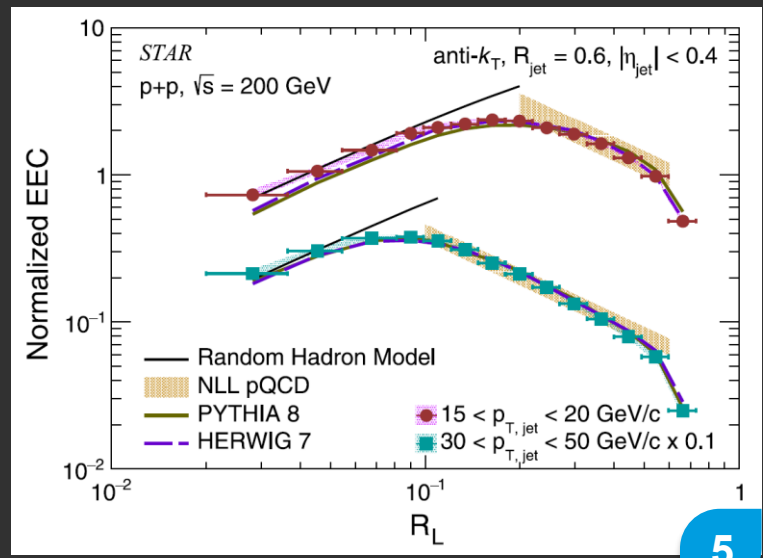


STAR Collaboration, Phys.Rev.Lett. 135 (2025)

EECs in Heavy-Ions

- EEC challenges:
  - In kind to most other jet substructure observables, energy correlators have a challenging physical interpretation in heavy-ions;
  - QGP introduces jet selection biases & survival biases that are at times difficult to disentangle from the effects of jet-medium interactions;
- Our goal:
  - Contribute to a more quantitative description of the multiscale dependencies of the energy correlator;
- Our approach: phenomenology
  - Monte Carlo tools to estimate the impact of multiple QCD processes and scales:
    → PYTHIA;
    → HERWIG;
    → CoLBT-hydro.

PYTHIA 8
Christian Bierlich et al.,
arXiv.2203.11601

HERWIG 7
Gavin Bewick et al.,
Eur.Phys.J.C 84 (2024) 10, 1053

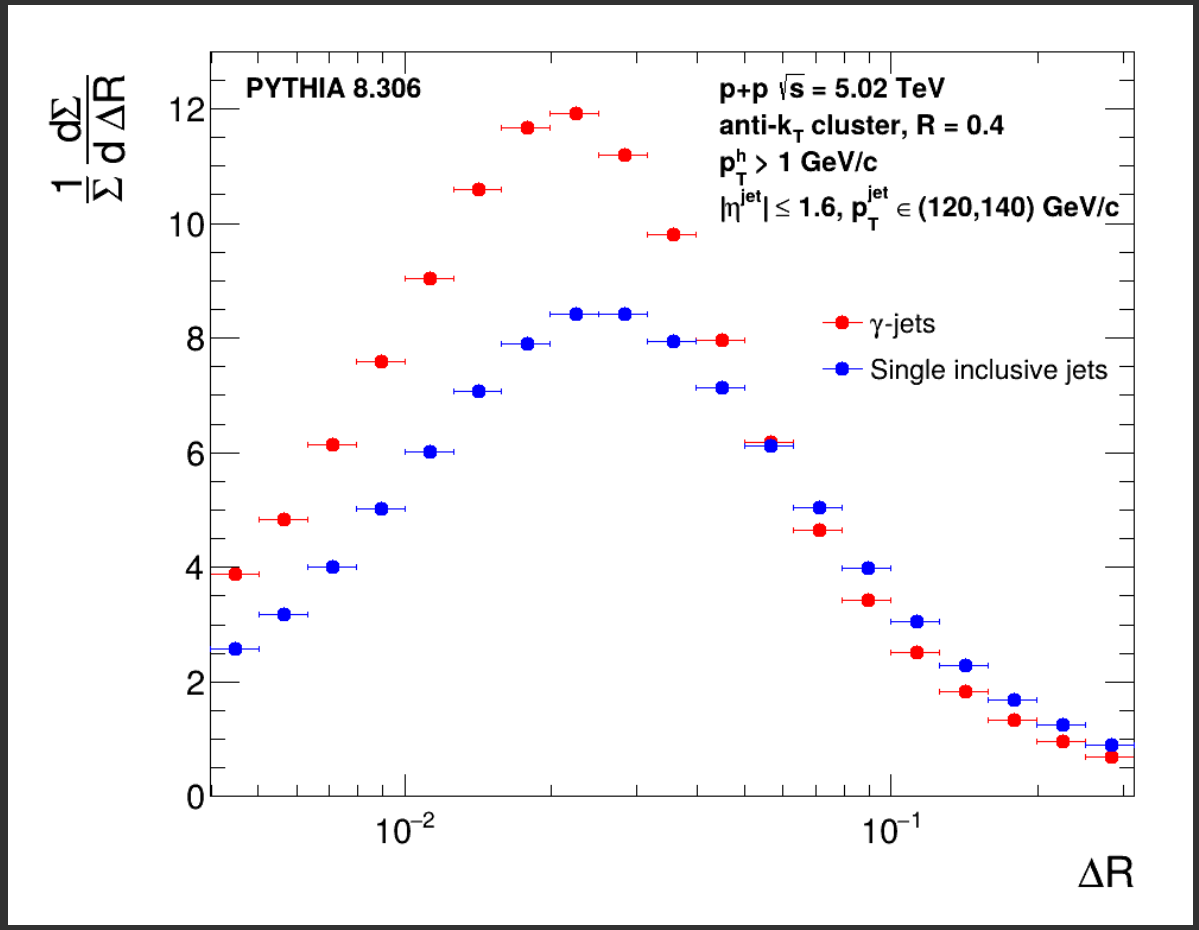
CoLBT-hydro

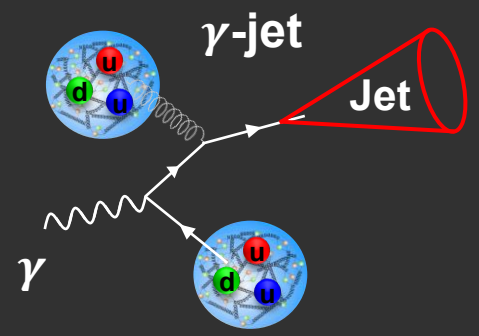
Xin-Nian Wang et al.,
Phys.Lett.B 777 (2018) 86-90

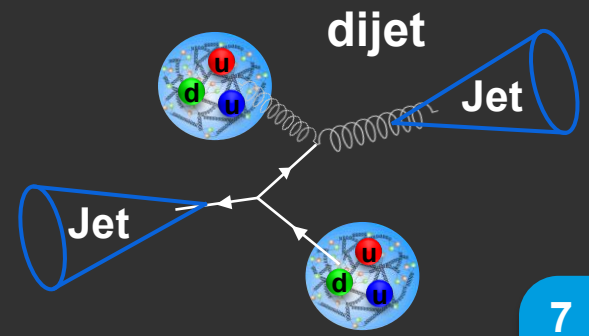
Sensitivity to Jet Flavor

- EEC for $pp \longrightarrow \gamma + jet$ events in 🔴 ;
- EEC for $pp \longrightarrow dijet$ events in 🔵 ;

N.O. Madureira et al., Phys. Rev. D 112, 054018





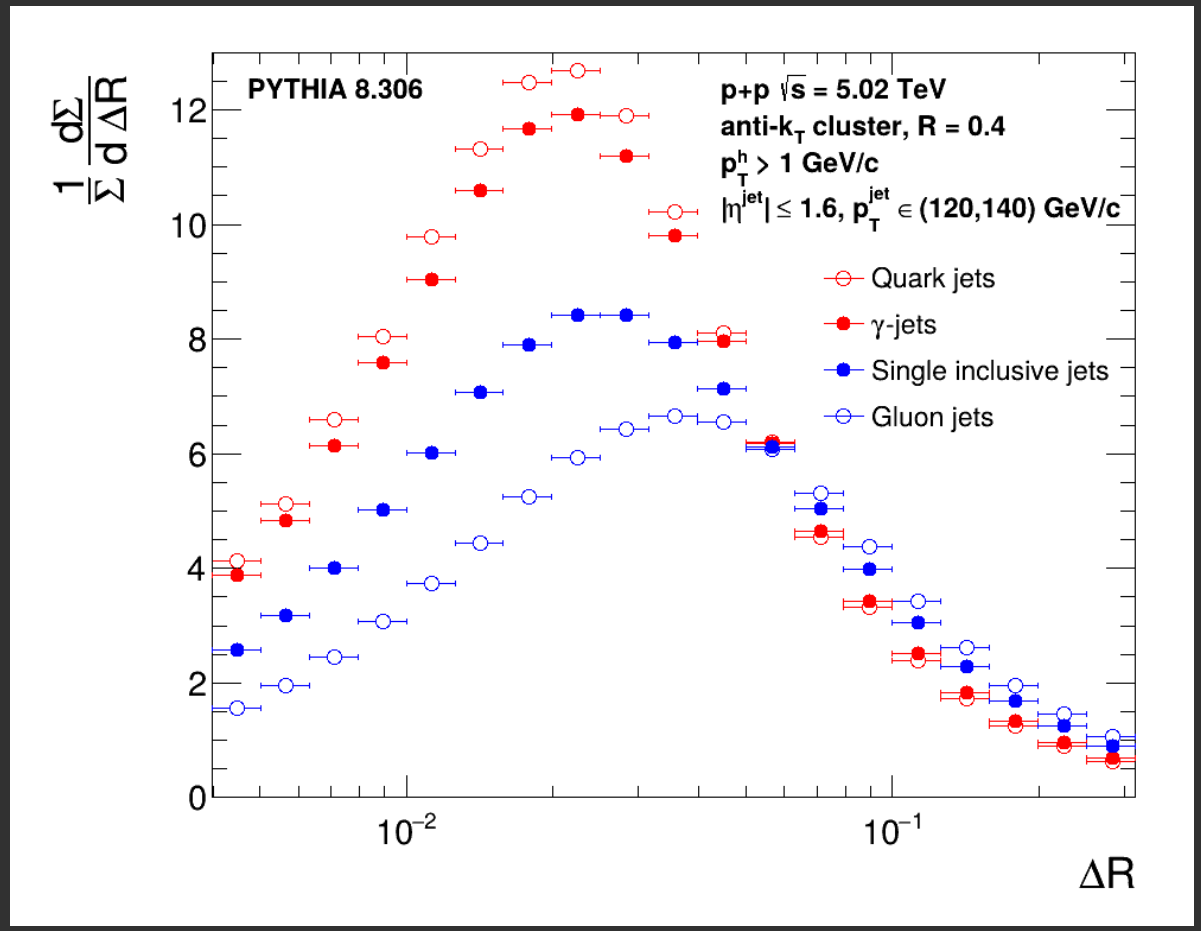


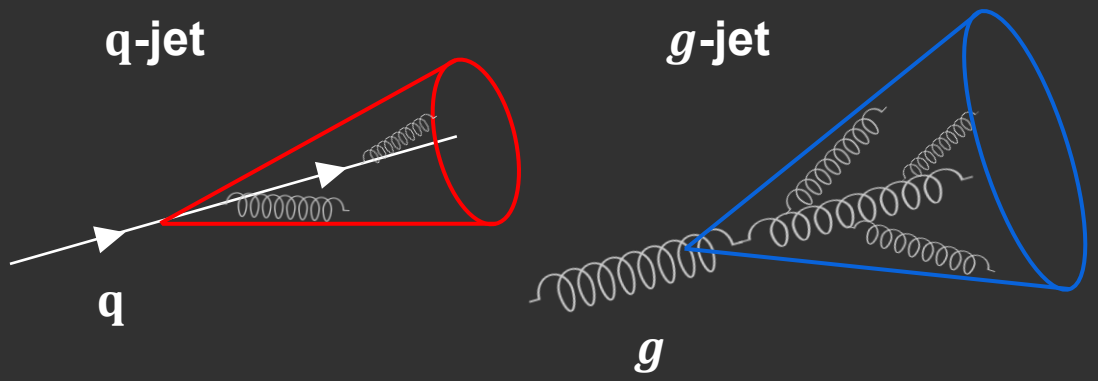
Sensitivity to Jet Flavor

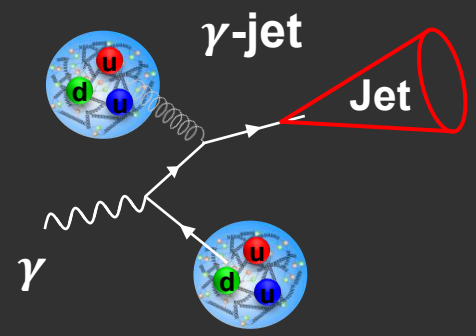
- EEC for $pp \longrightarrow \gamma + jet$ events in ● ;
- EEC for $pp \longrightarrow dijet$ events in ● ;
- EEC for **quark**-initiated jets in ○ ;
- EEC for **gluon**-initiated jets in ○ ;

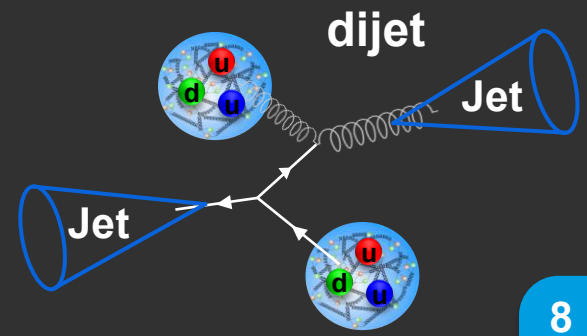
Differences in **γ-jet** vs **single inclusive jet** EECs amount to their different flavor composition!

N.O. Madureira et al., Phys. Rev. D 112, 054018









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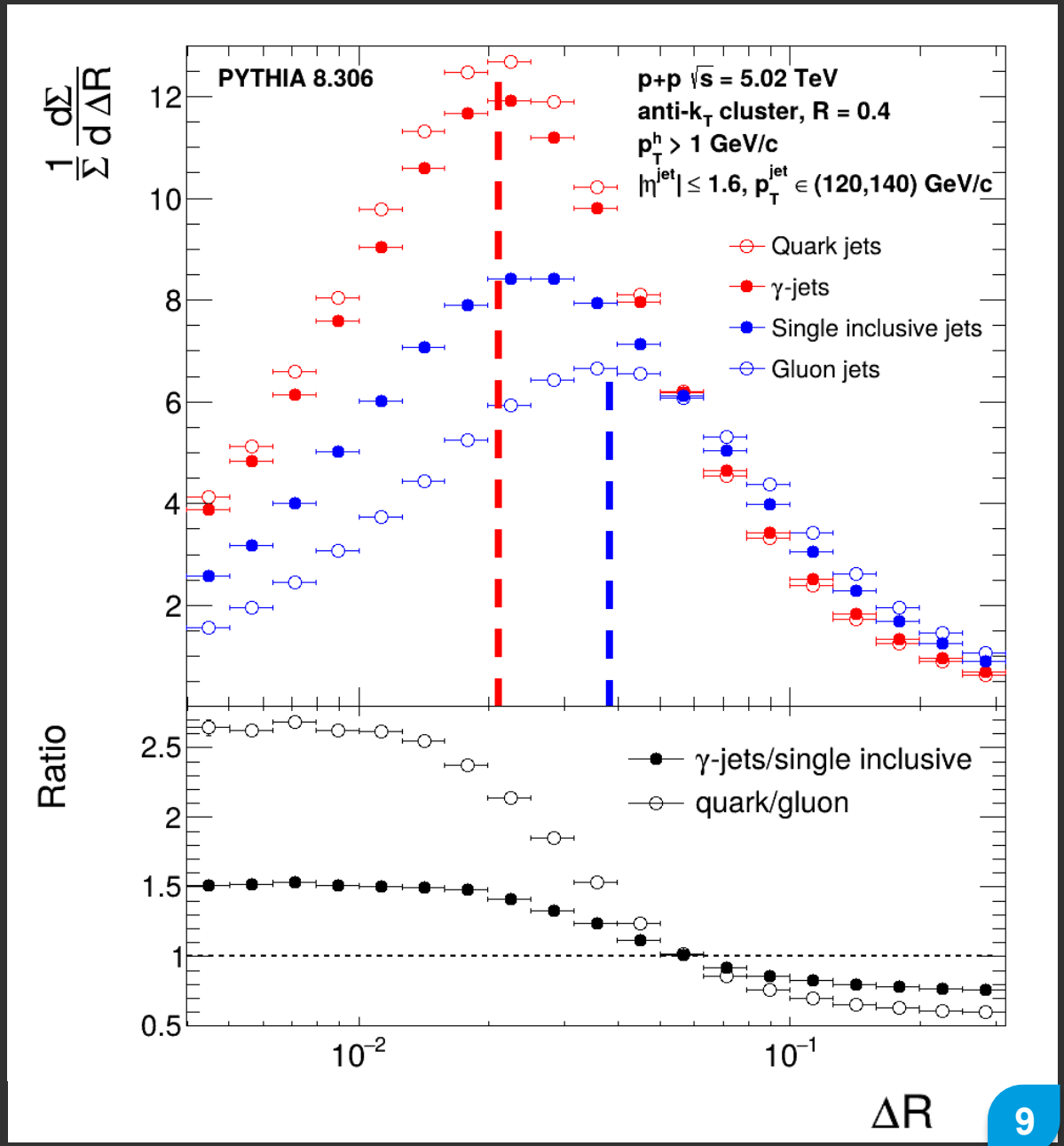
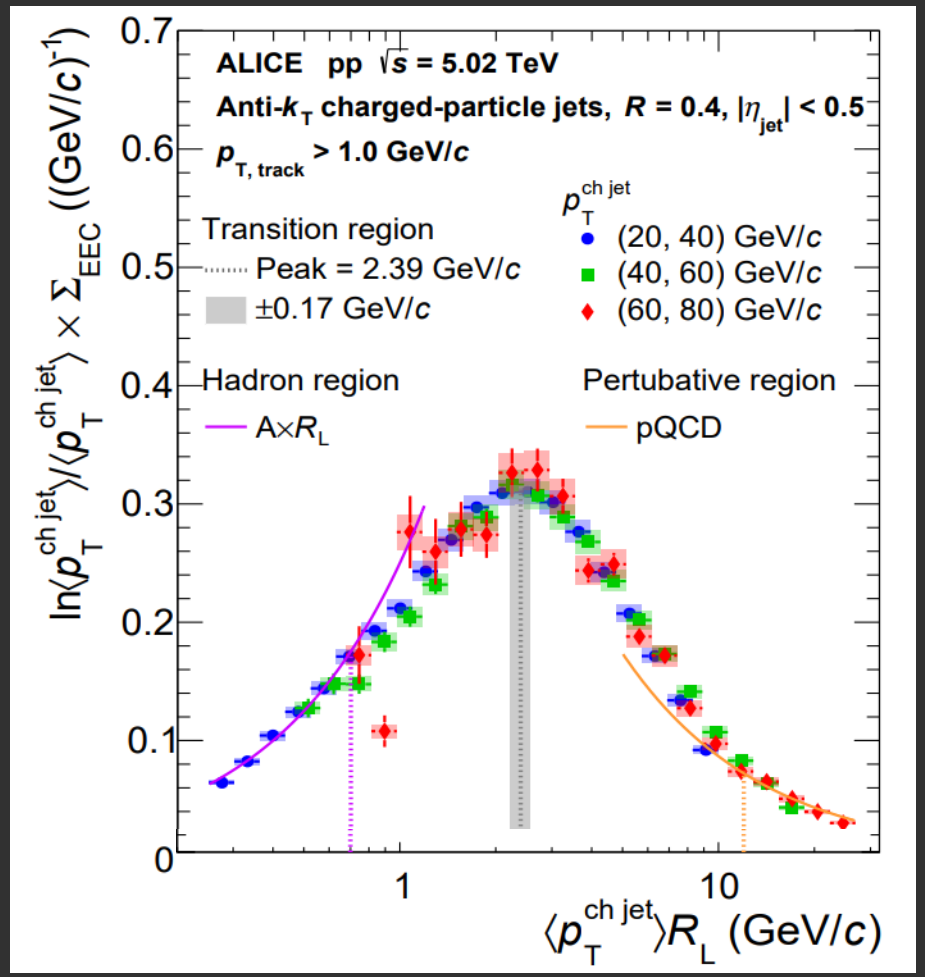
EEC transition is highly-sensitive to jet flavor variations!

N.O. Madureira et al., Phys. Rev. D 112, 054018



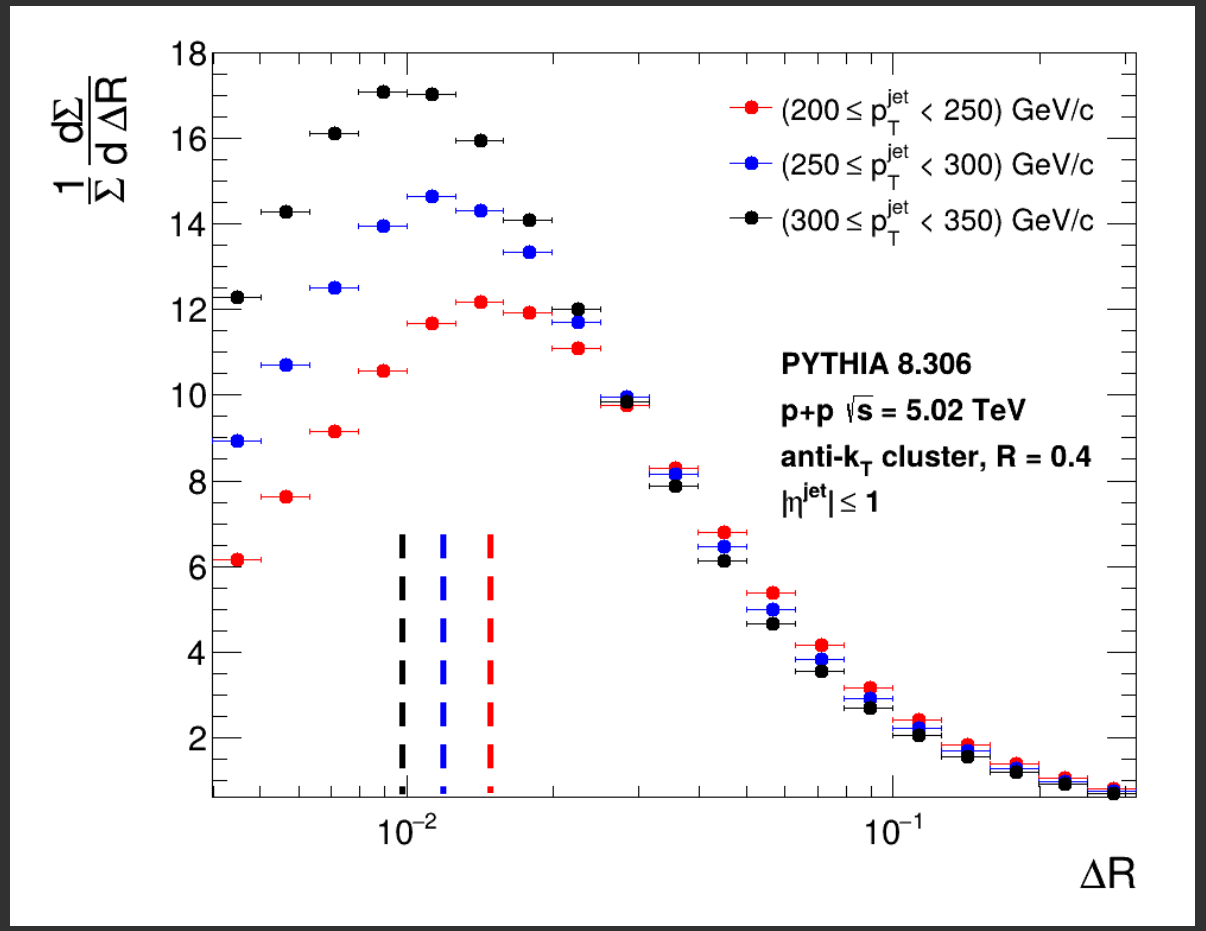
Sensitivity to Jet p_T

- Jet p_T dependence is a well-established property of EECs, characterized by a shift to small ΔR when jet p_T increases!

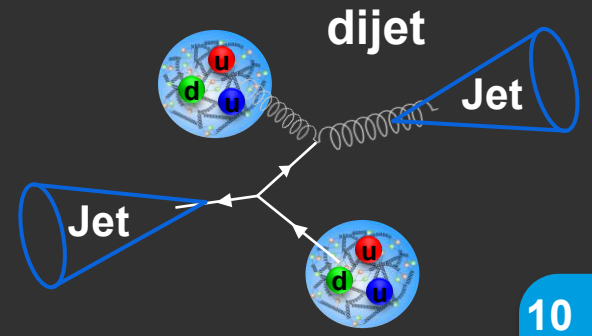


ALICE Collaboration, arXiv.2409.12687

N.O. Madureira et al., Phys. Rev. D 112, 054018



$$\Delta R_{peak} \sim \frac{\Lambda_{QCD}}{p_T^{jet}}$$

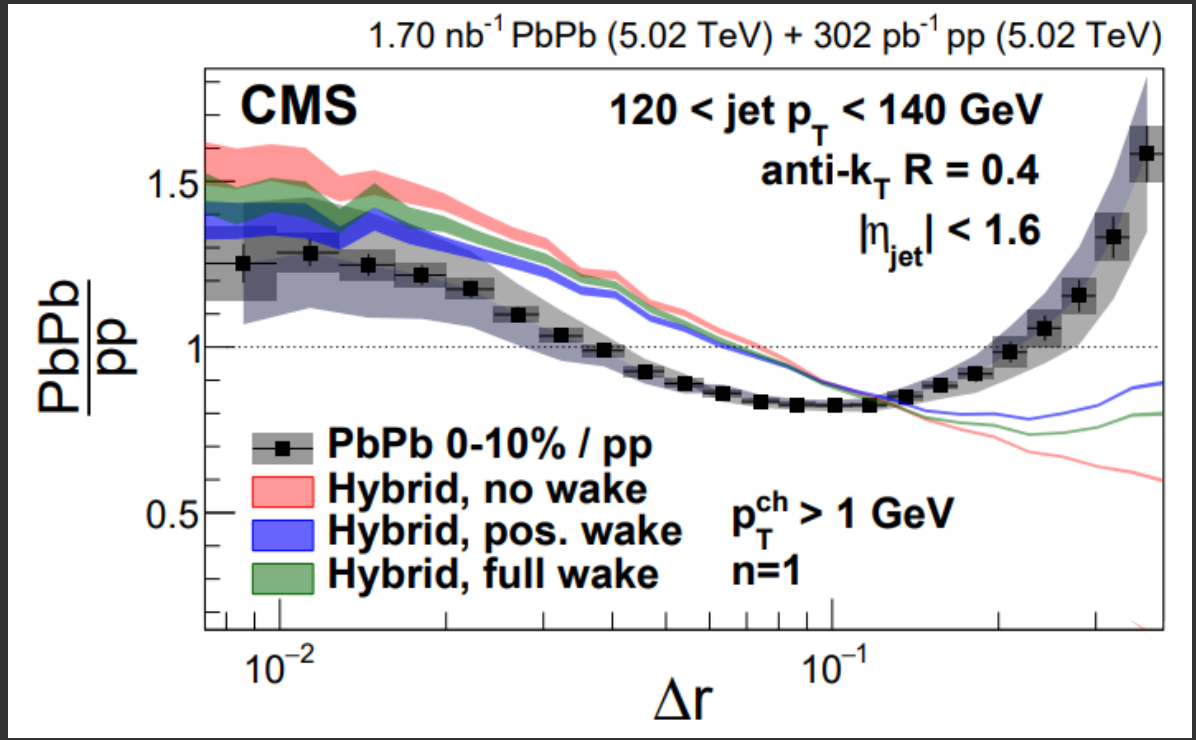


See also:
STAR Collaboration, Phys.Rev.Lett. 135 (2025)

Small ΔR Enhancement

- **Jet p_T Selection Bias**: PbPb jets with same reconstructed p_T as pp jets come on average from harder processes!

CMS Collaboration, Phys.Lett.B 866 (2025)



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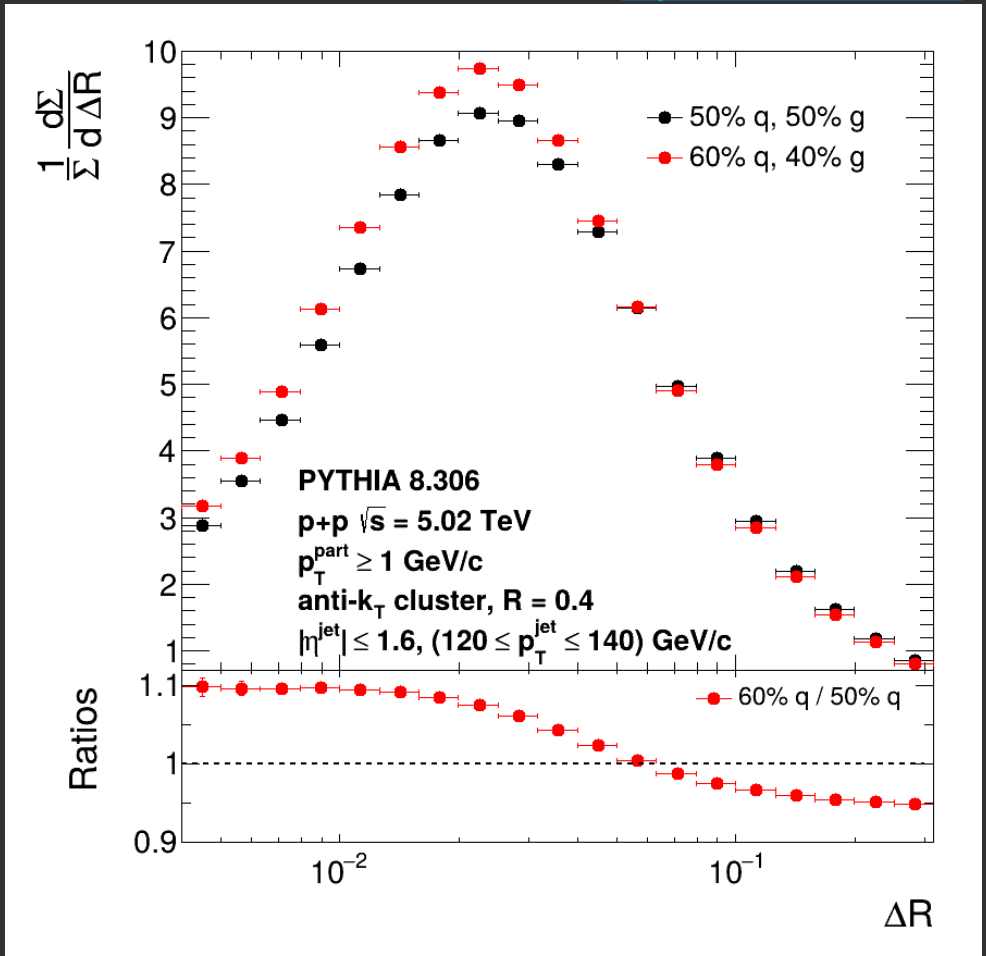

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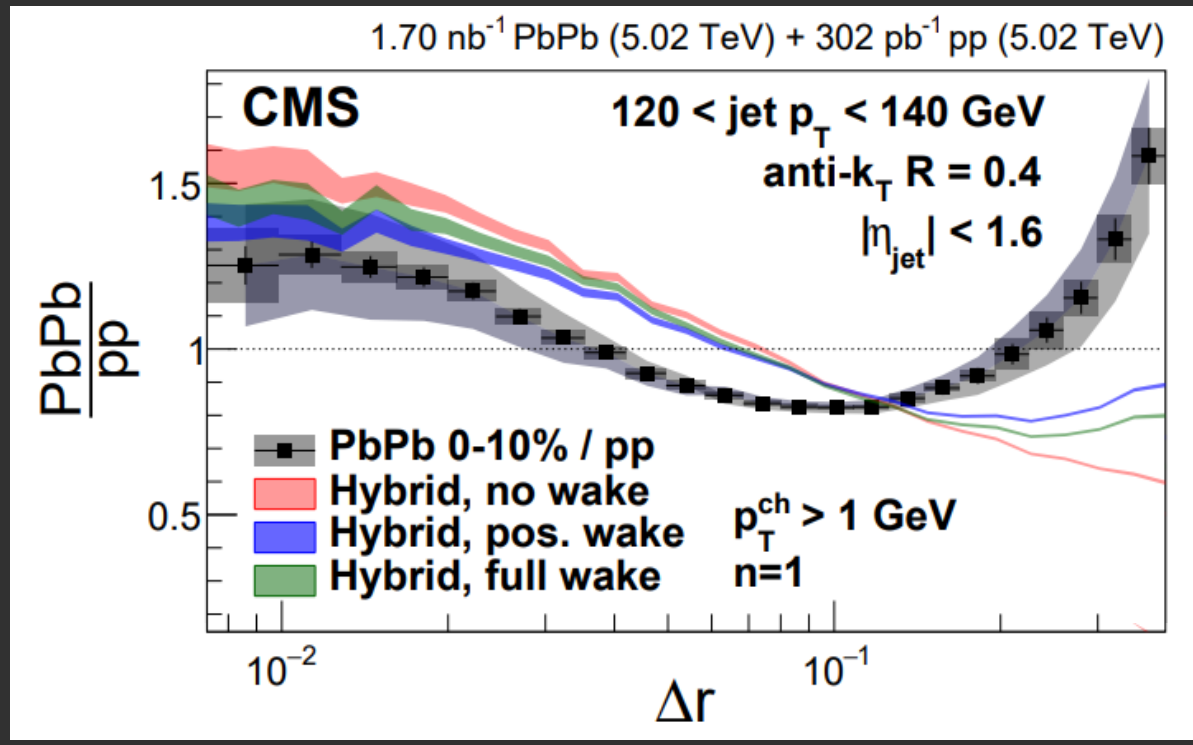


- **Quark Jet Survivor Bias**: gluon jets loose on average more energy to the QGP medium, meaning fewer gluon jets in final PbPb sample!

10% increase in quark jet fraction

⇓

10% EEC enhancement at small ΔR

Sensitivity to pQCD effects

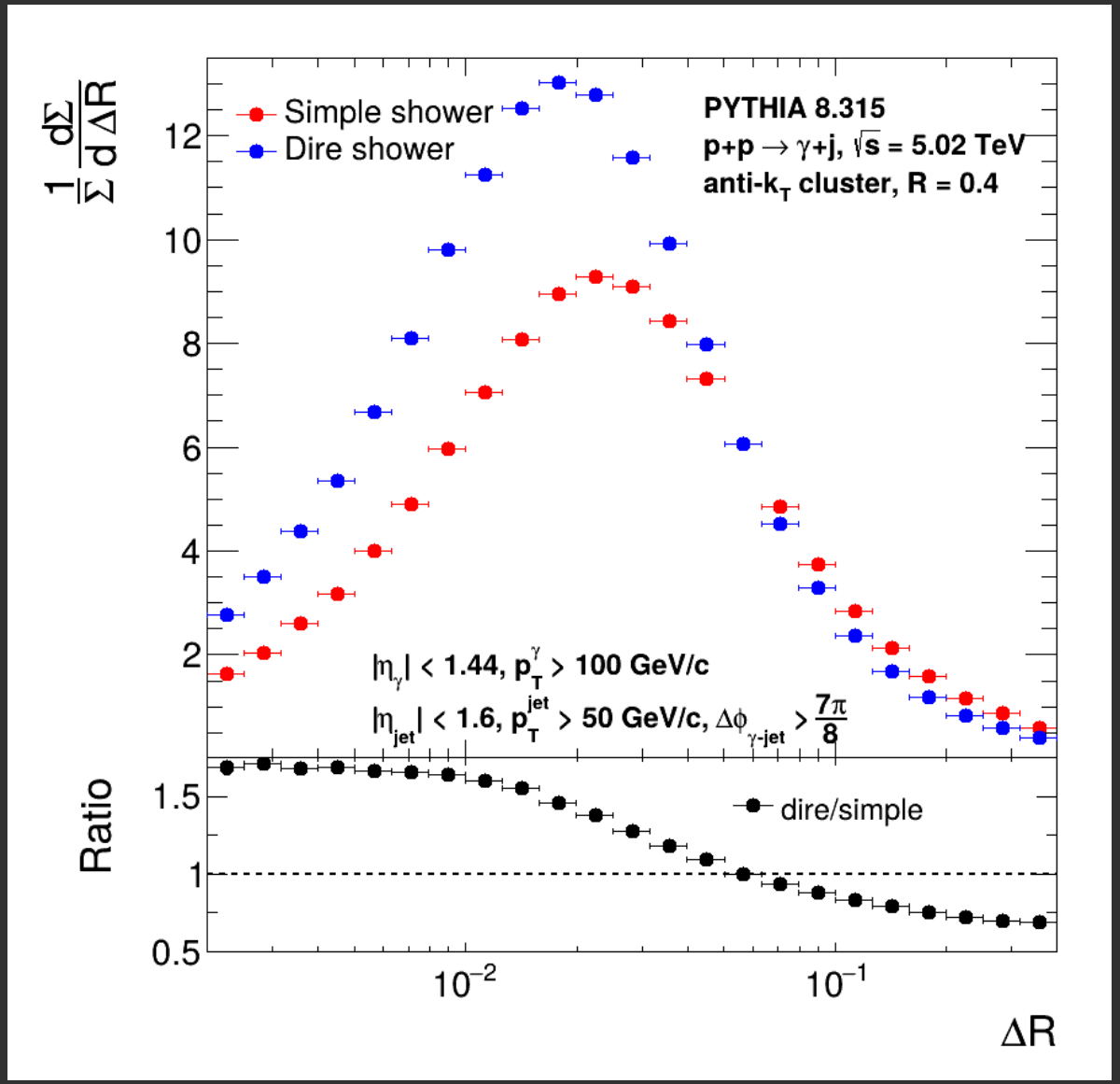
- PYTHIA8 offers two parton shower descriptions:
  - **Simple**;
  - **DIRE**;

S. Höche, S. Prestel,
Eur.Phys.J.C 75 (2015) 9, 461

DIpole **RE**summation kernel

$$\frac{1-z}{(1-z)^2+k^2}$$

N.O. Madureira et al., preliminary results from soon-to-be published paper



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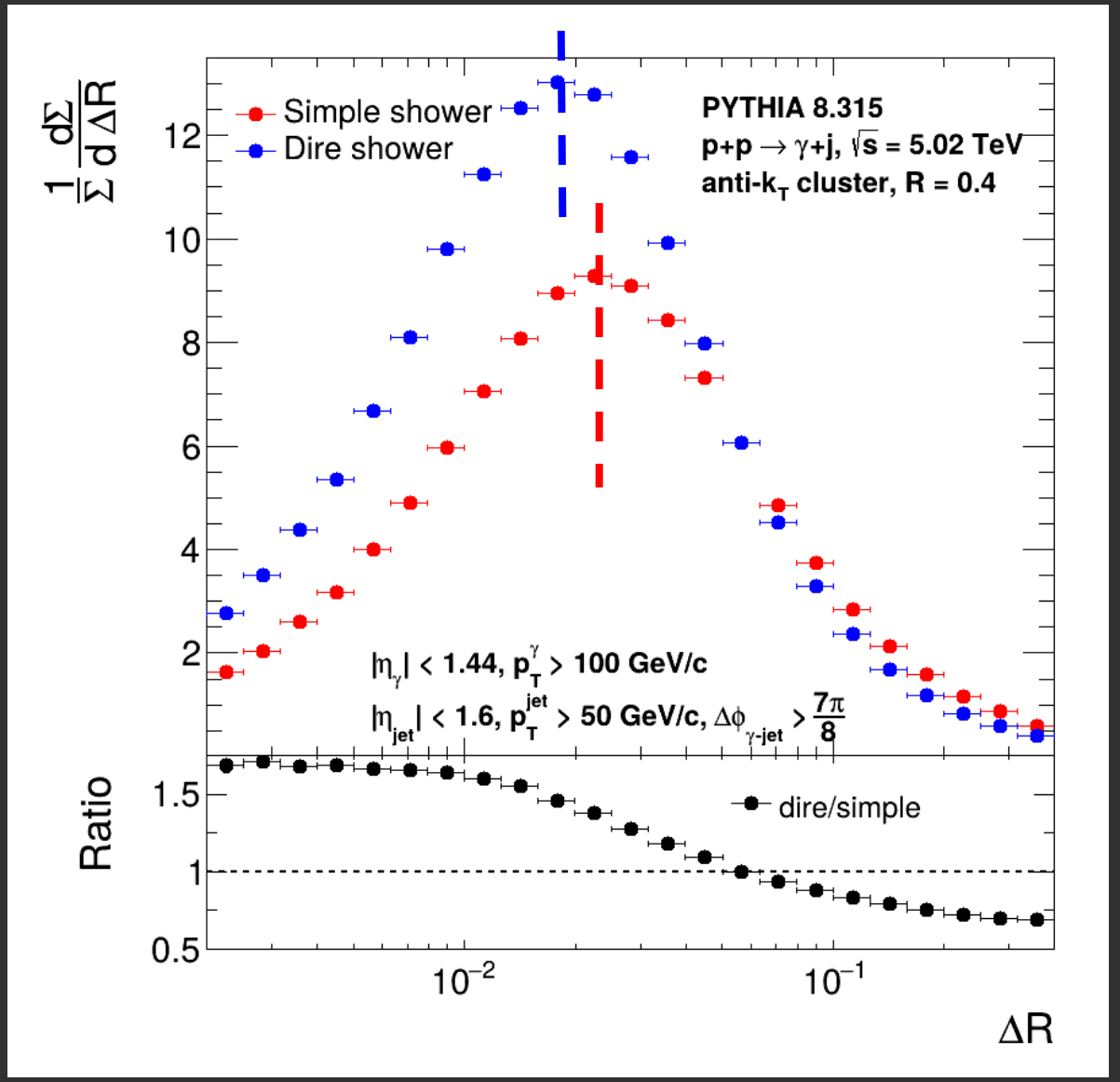

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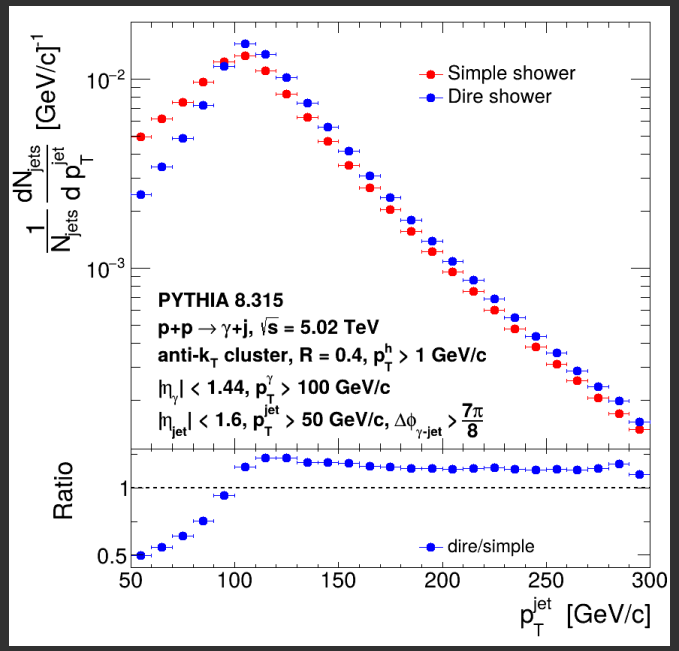

Simple vs **DIRE**

jet $\mathbf{p_T}$ spectra have large differences!

N.O. Madureira et al., preliminary results from soon-to-be published paper

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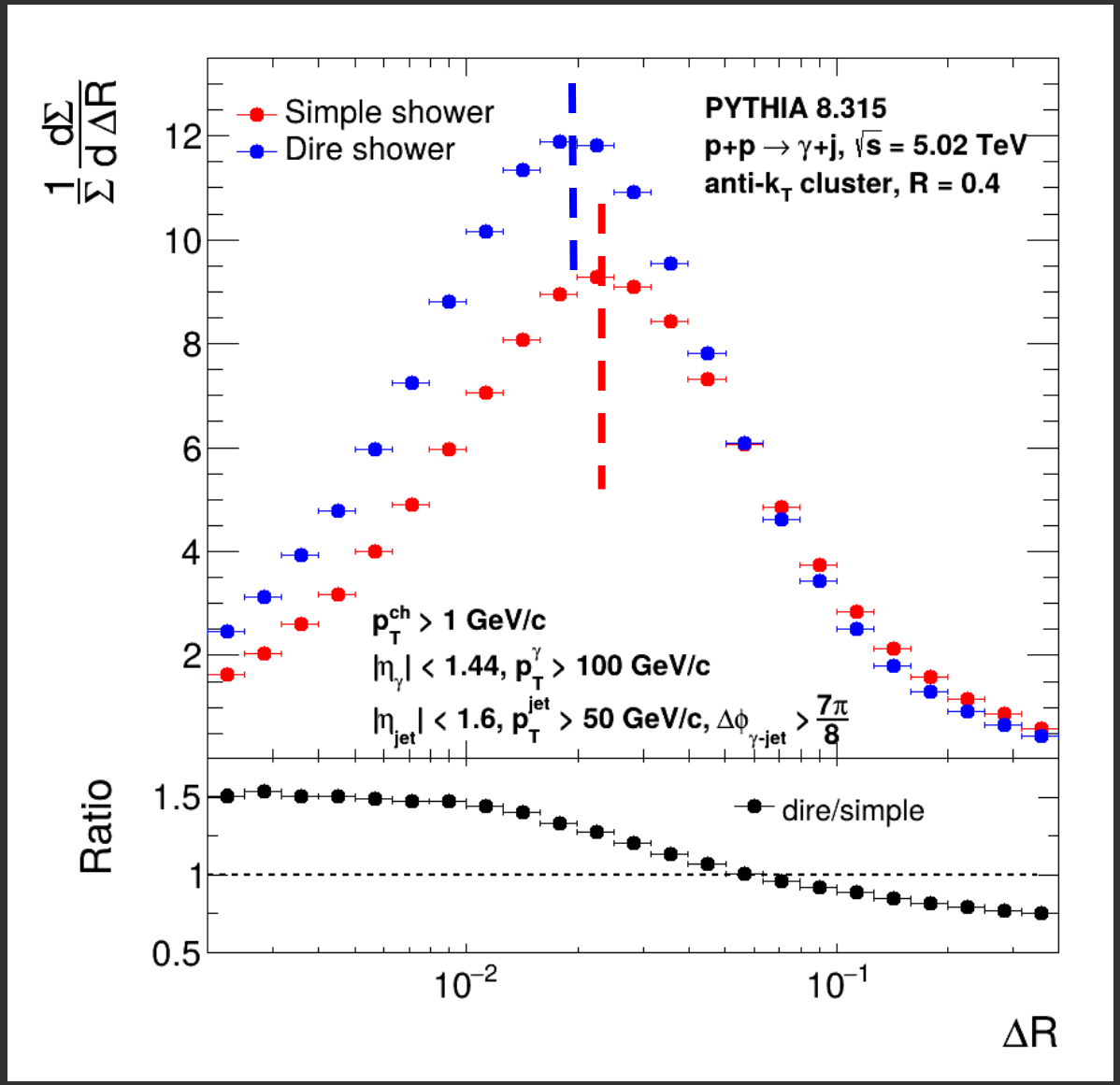
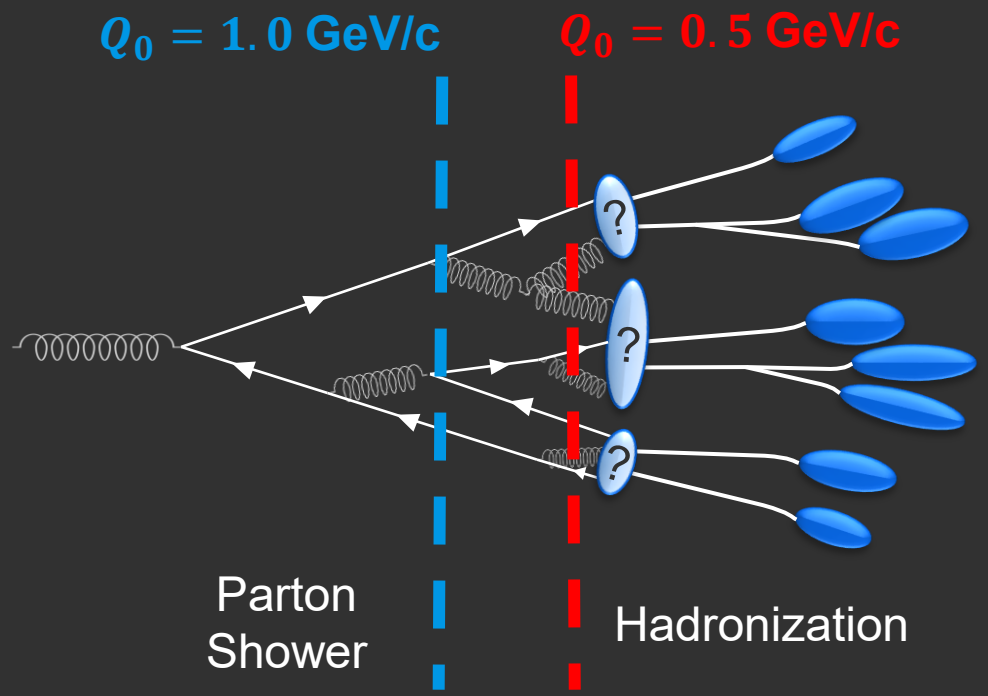


Sensitivity to pQCD effects even with jet spectra corrections!

Sensitivity to Hadronization Scale

- $\mathbf{Q_0}$ is the scale at which a Monte Carlo transitions from its pQCD to its npQCD description;
- Larger $\mathbf{Q_0}$ makes for less extended parton showers, affecting the transition region!



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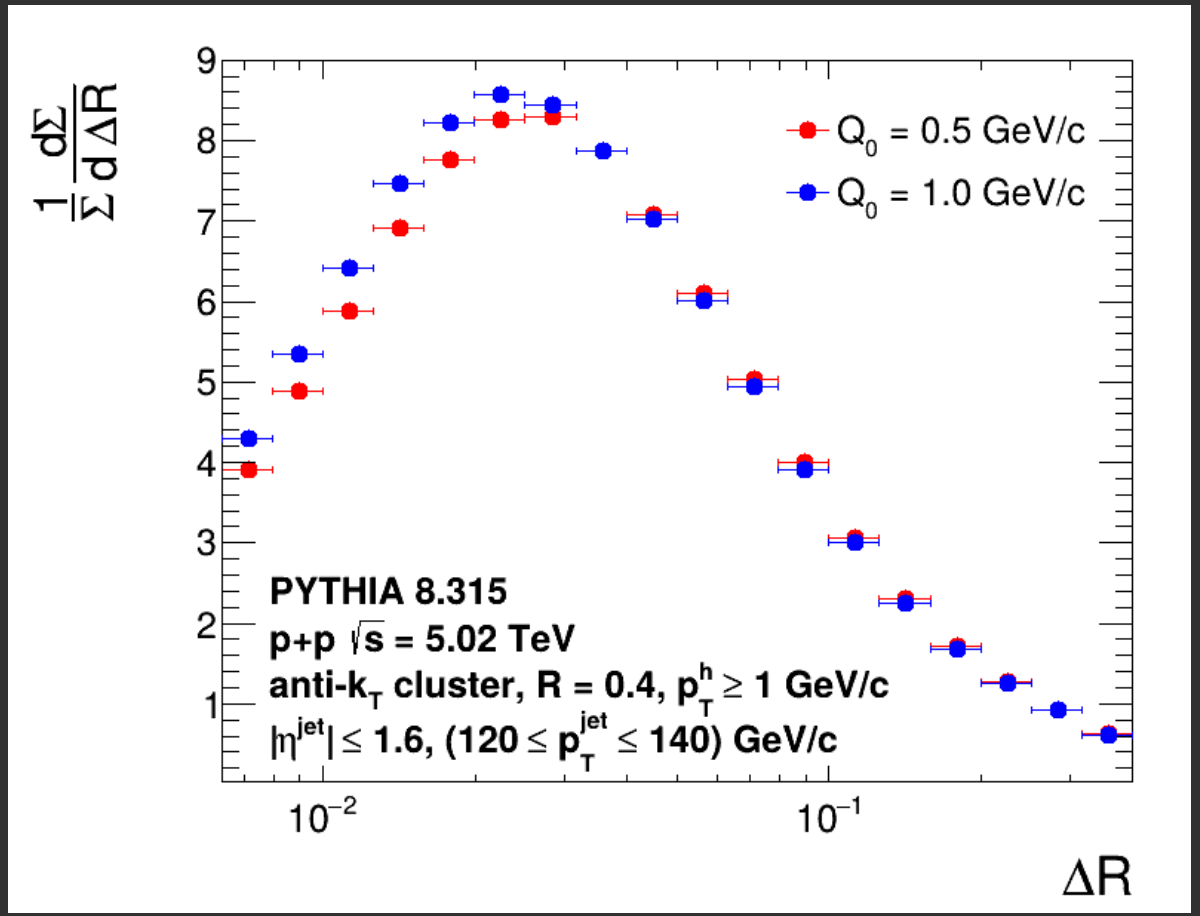

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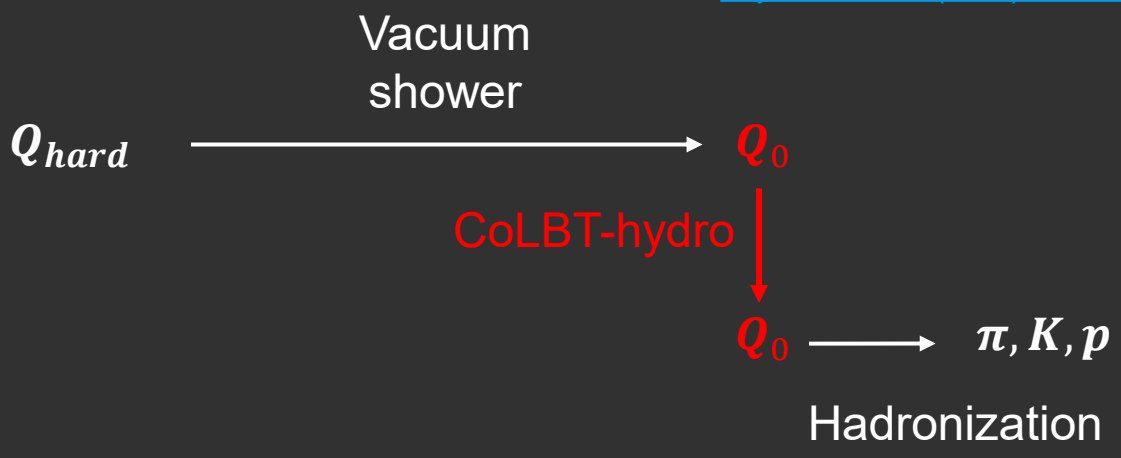
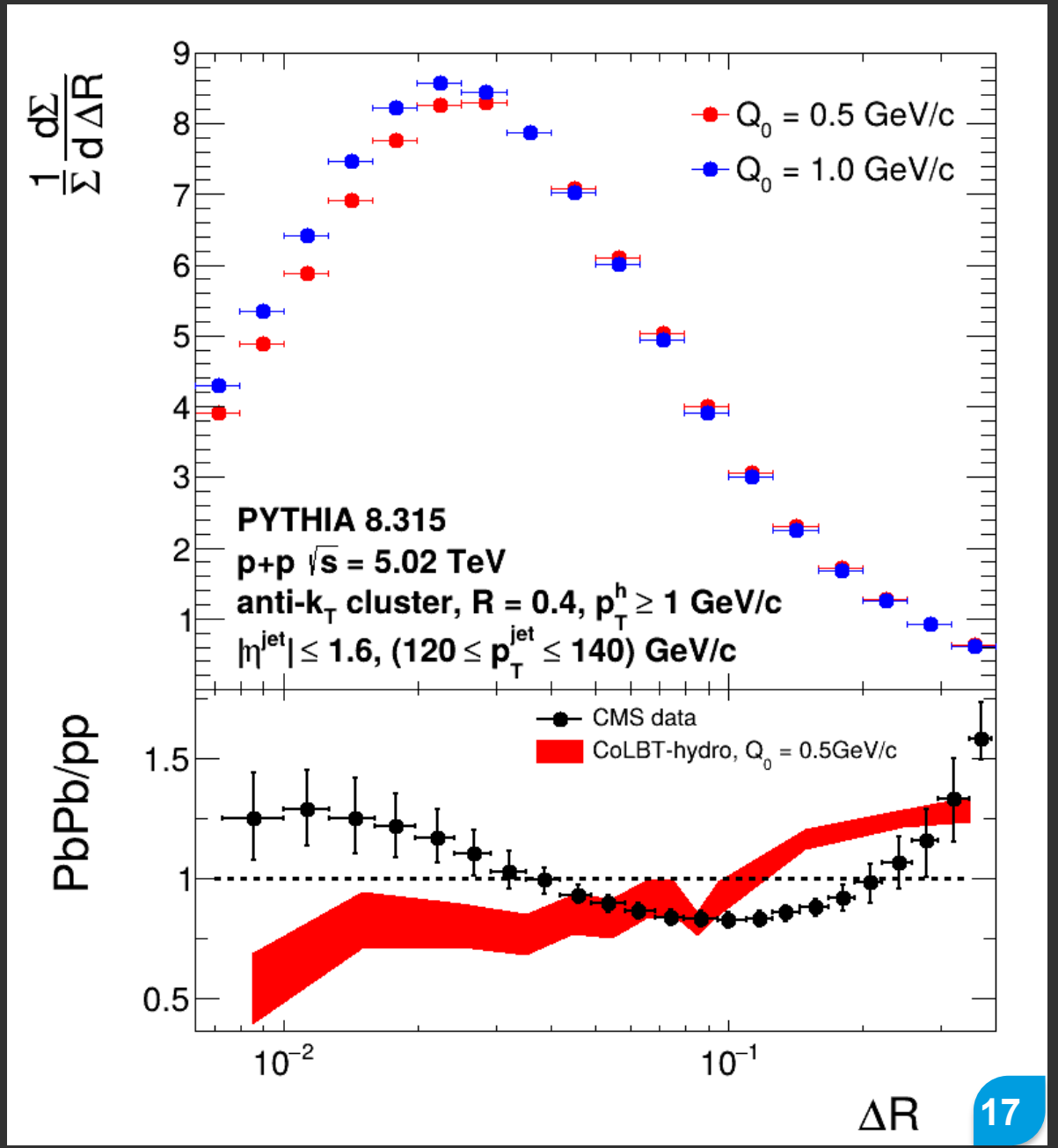
- CoLBT-hydro model has accurately reproduced PbPb data before;

Xin-Nian Wang et al., Phys.Lett.B 810 (2020) 135783



CMS Collaboration, CMS-PAS-HIN-23-004
N.O. Madureira et al., preliminary results from soon-to-be published paper



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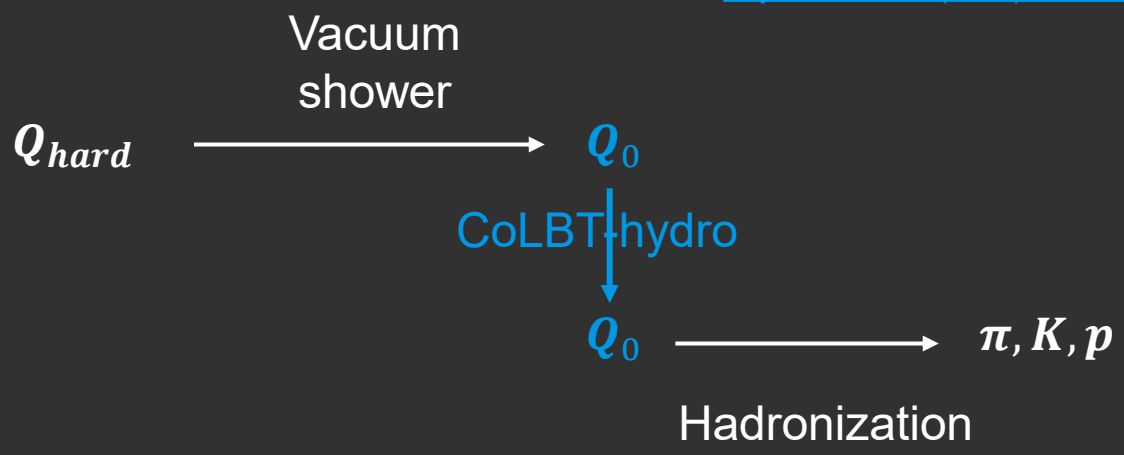

CMS Collaboration, CMS-PAS-HIN-23-004
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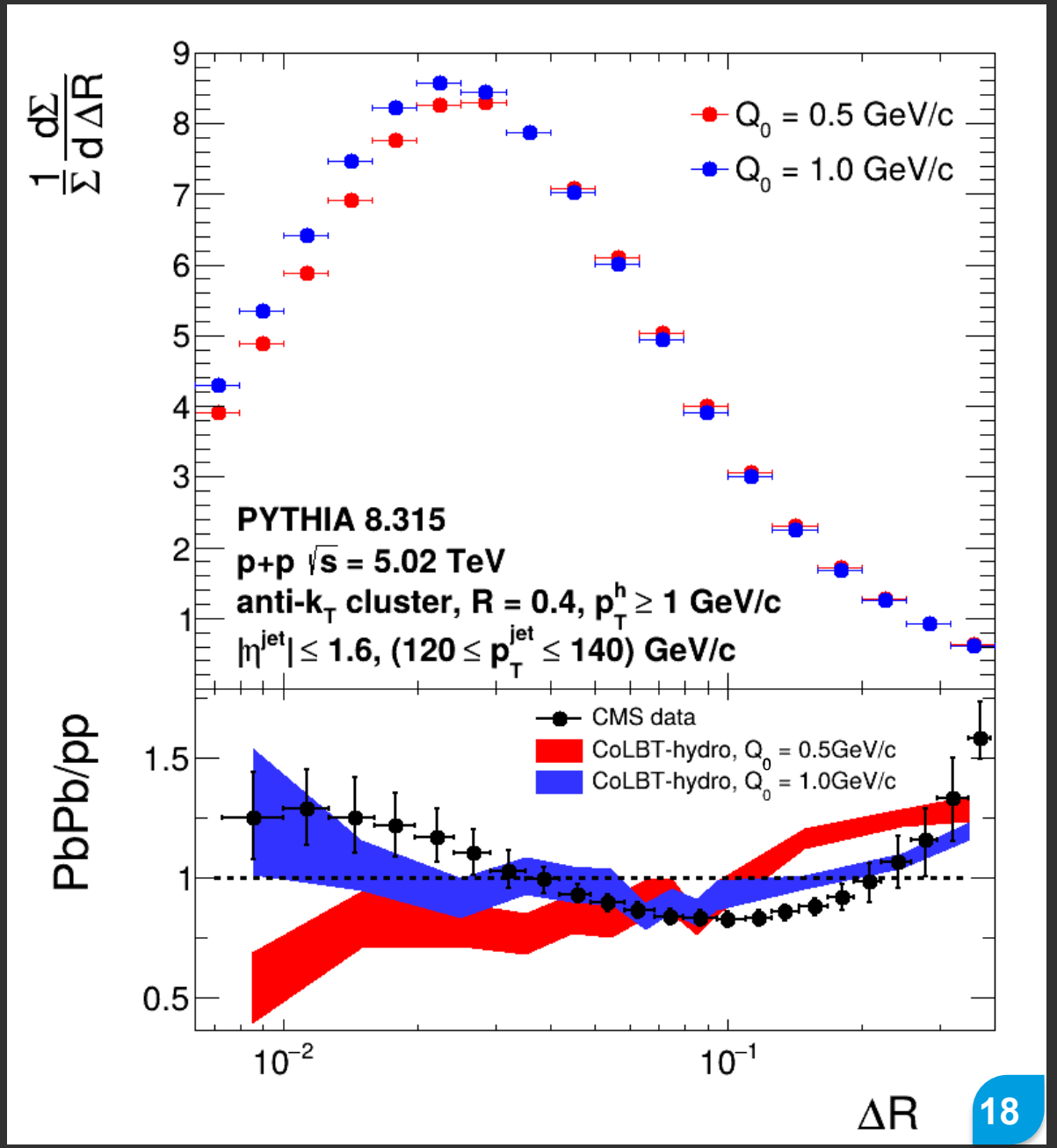

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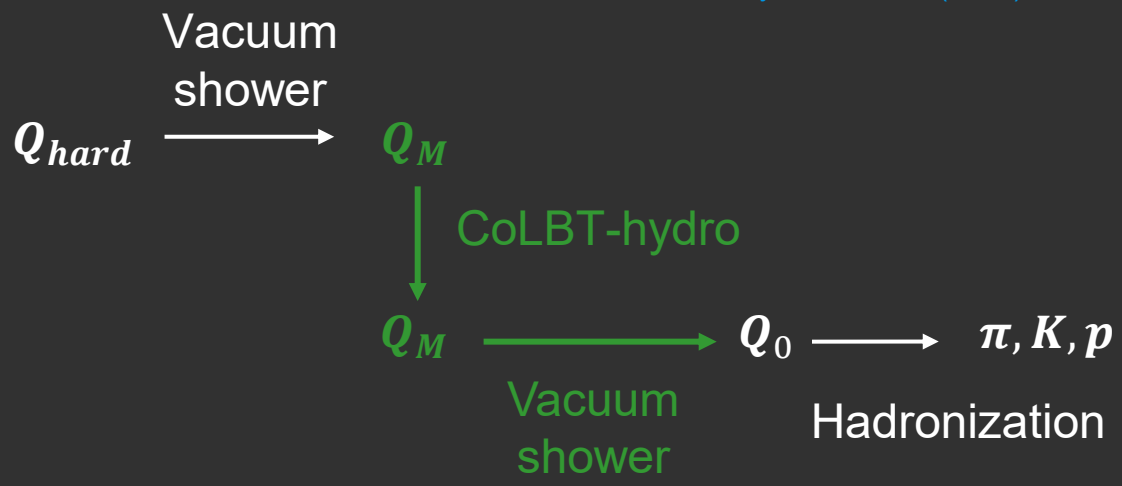
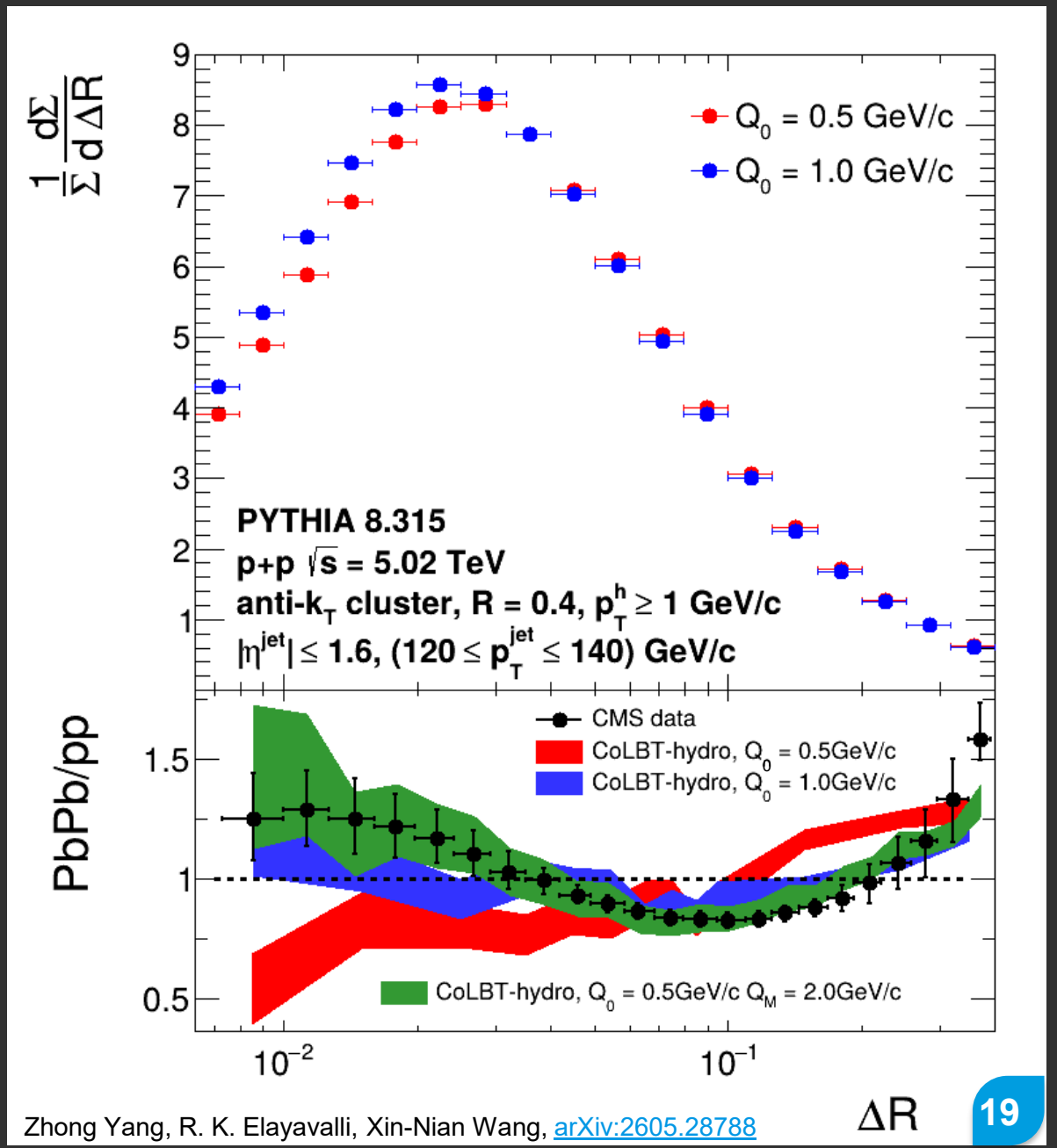


Vacuum showering after CoLBT-hydro improves model

CMS Collaboration, CMS-PAS-HIN-23-004
N.O. Madureira et al., preliminary results from soon-to-be published paper



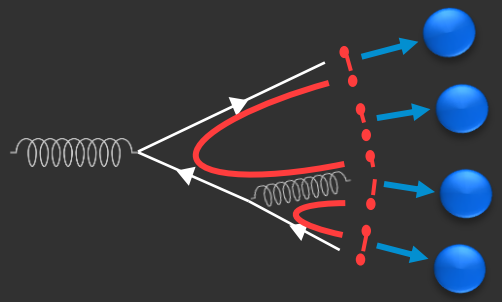
Zhong Yang, R. K. Elayavalli, Xin-Nian Wang, arXiv:2605.28788

Sensitivity to npQCD effects

- Monte Carlo tools employ two widely used phenomelogical descriptions of hadronization:

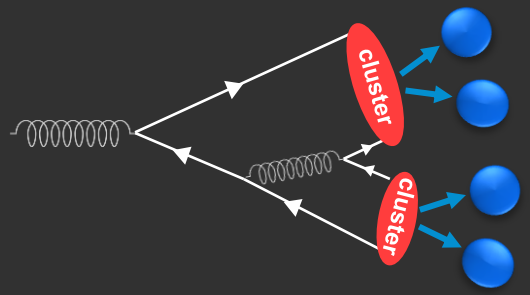
Lund String

B. Andersson et al.,
Z.Phys.C 20 (1983) 317



Cluster Fragmentation

D. Amati and G. Veneziano,
Phys. Lett. B 83 (1979) 87-92



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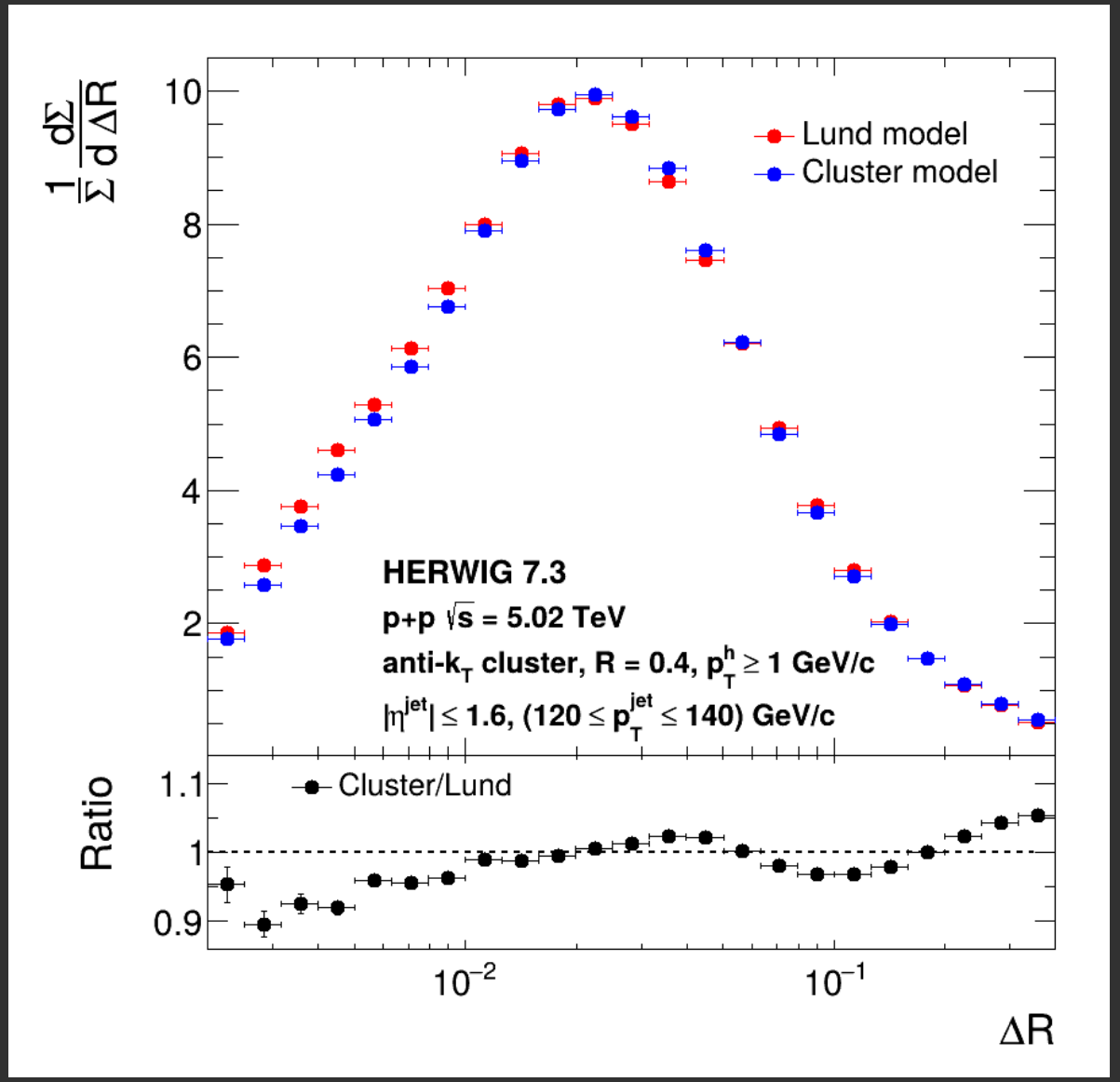


EECs more sensitive to the hadronization scale than to the hadronization mechanism!

Conclusions

- Energy-Energy Correlators display large & non-trivial sensitivity to multiple QCD processes and scales – challenging observable!
- Energy-Energy Correlators can be used as benchmarks for the quality and robustness of our current and future descriptions of the multiscale evolutions of jets!
- Understanding flavor, pQCD and npQCD effects in medium is crucial to unlock the full potential of energy correlators as probes of the Quark-Gluon Plasma!

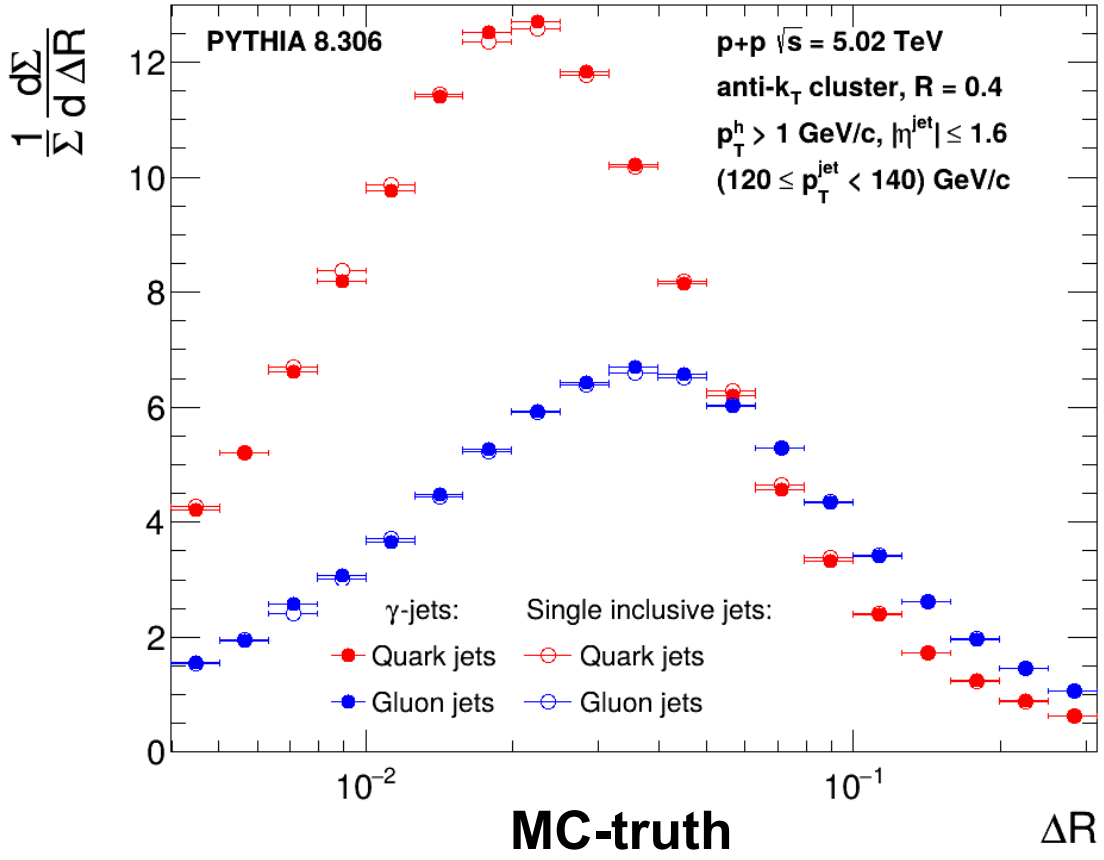
Thank you for your attention!

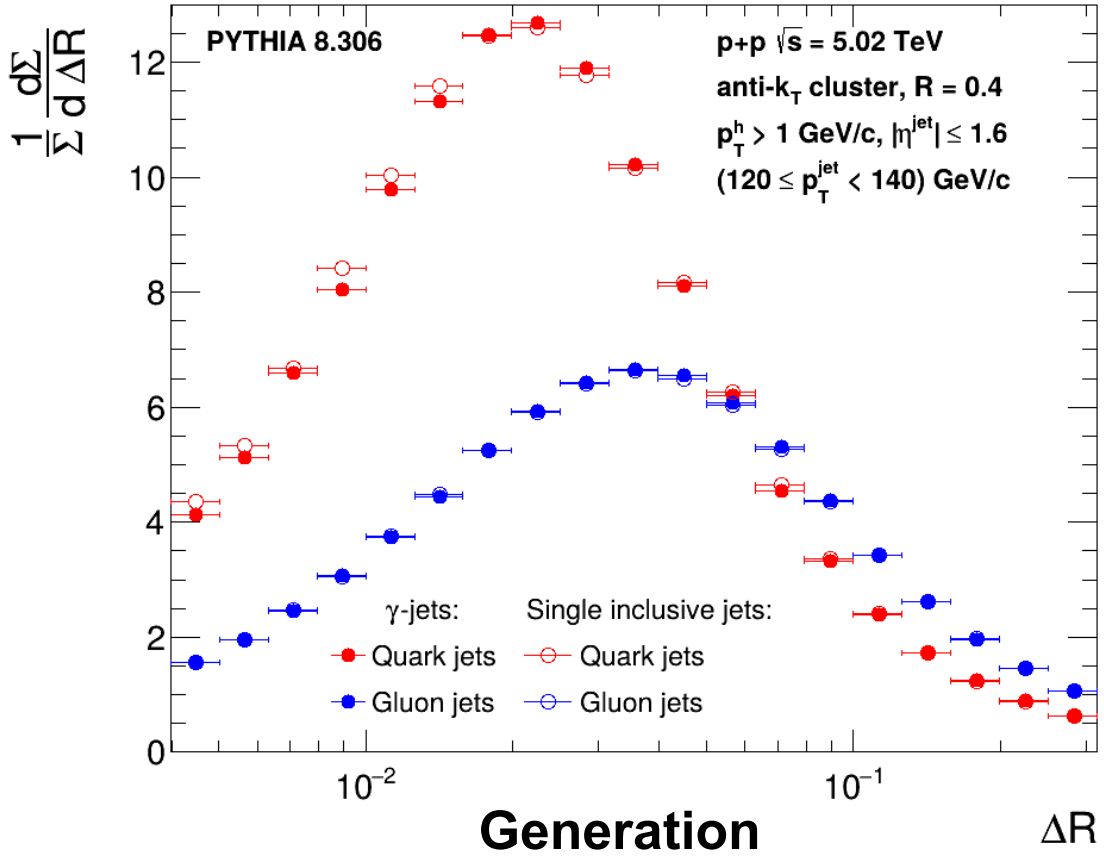
Questions?

Backup Slides

Sensitivity to Jet Flavor

- Quark-initiated jet and gluon-initiated jet EECs have less than ~1% variations when they come from dijet or γ-jet production levels, both at the Monte Carlo truth level and at the generation level!





N.O. Madureira et al., Phys. Rev. D 112, 054018

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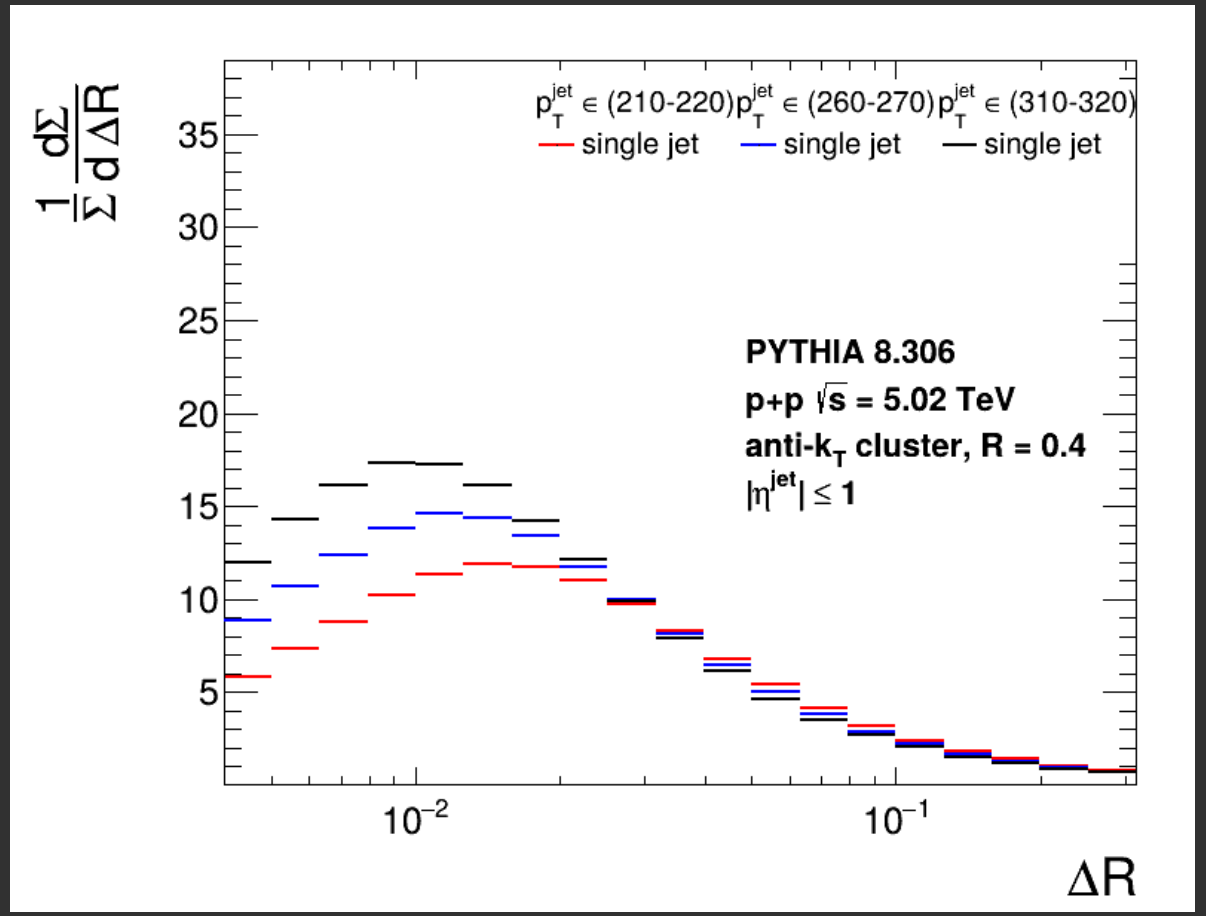
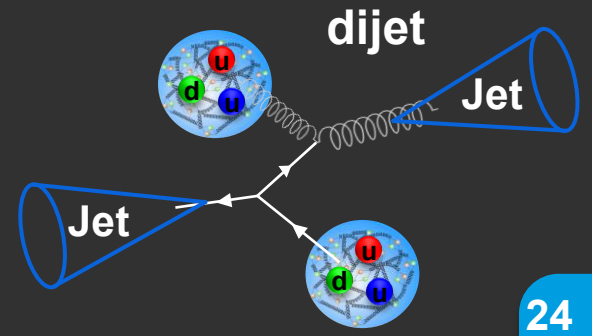
$$\Delta R_{\text{had. peak}} \sim \frac{\Lambda_{QCD}}{p_T^{jet}}$$

N.O. Madureira et al., Phys. Rev. D 112, 054018





Sensitivity to Jet Flavor

- Well-established EEC property is its so-called jet p_T dependence, characterized by a shift to small ΔR when jet p_T increases:

$$\Delta R_{\text{had. peak}} \sim \frac{\Lambda_{QCD}}{p_T^{jet}}$$

- This dependence is convoluted with a jet flavor variation effect;

Quark jet EECs ● Gluon jet EECs ○

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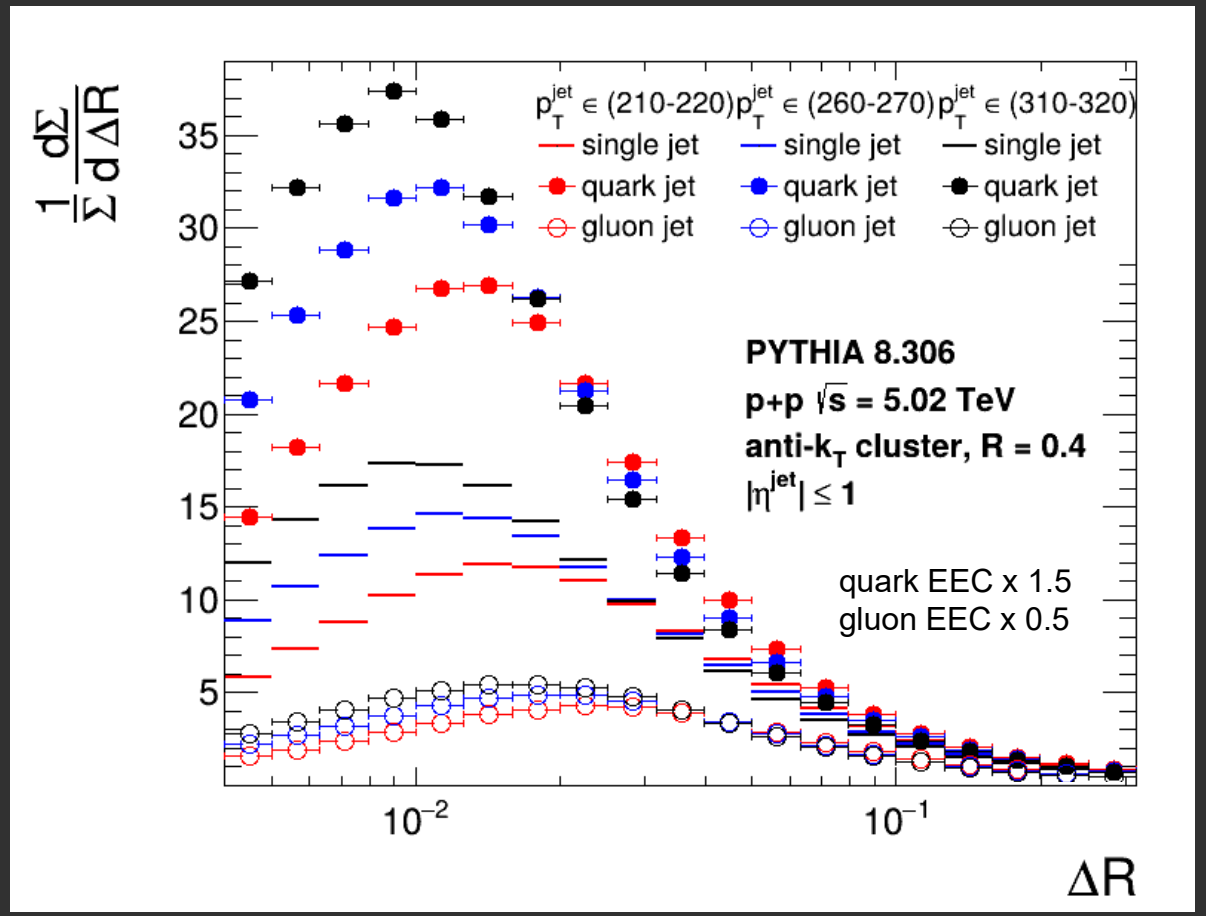

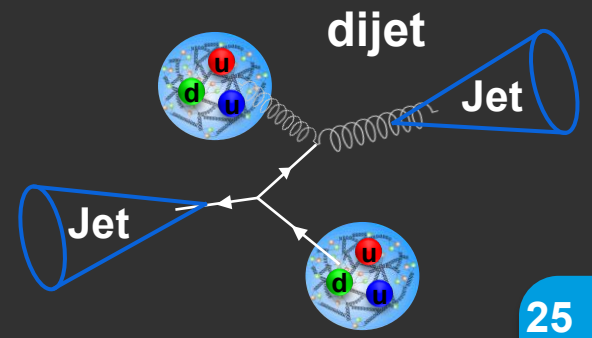

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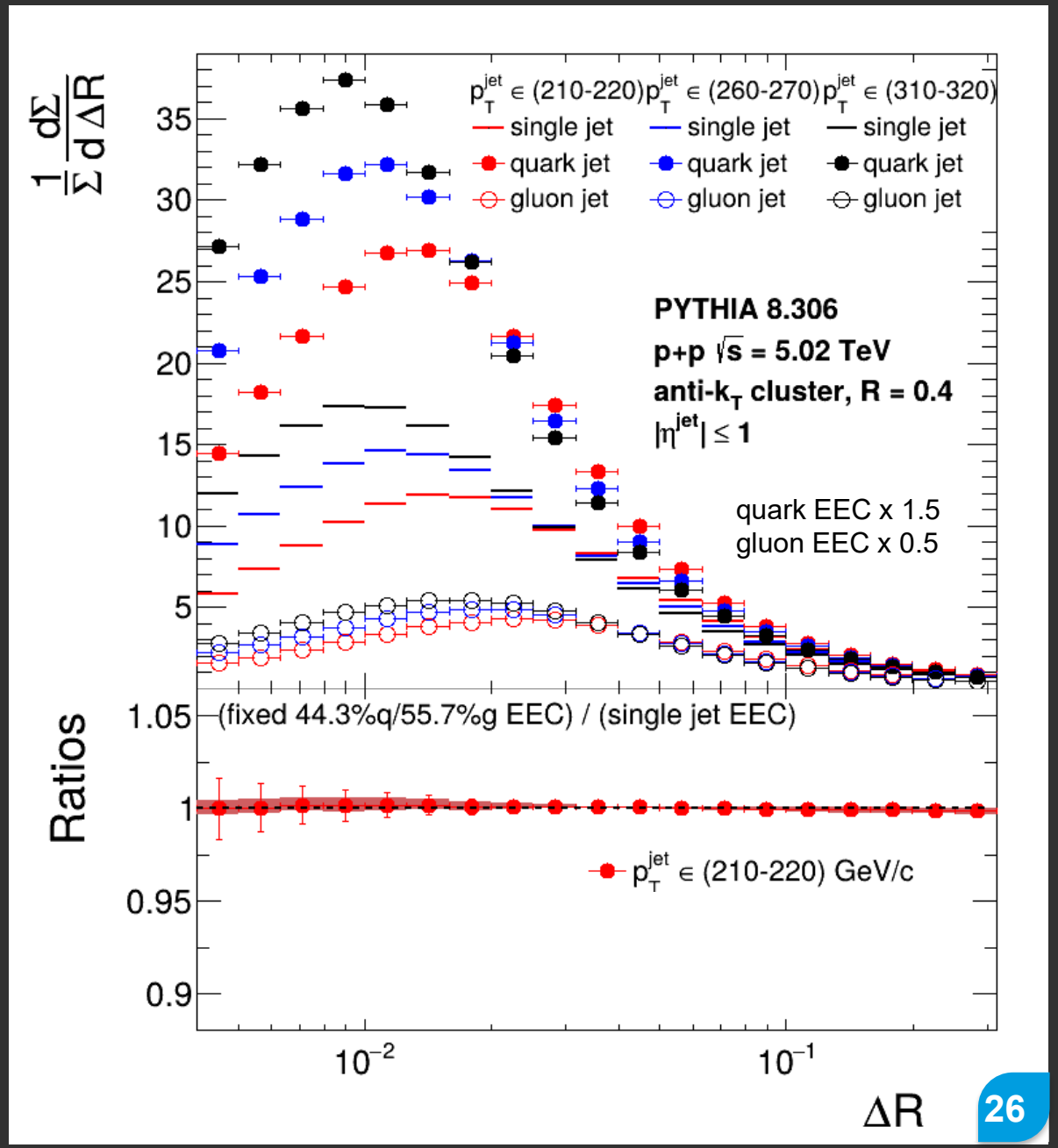

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EEC jet p_T dependence for single inclusive jets is amplified by quark jet enrichment at higher pT!

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