Exploring QCD with Jet Substructure Measurements

Workshop of the APS Topical Group on Hadronic Physics 2025

Dhanush Hangal

March 15, 2025

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory
under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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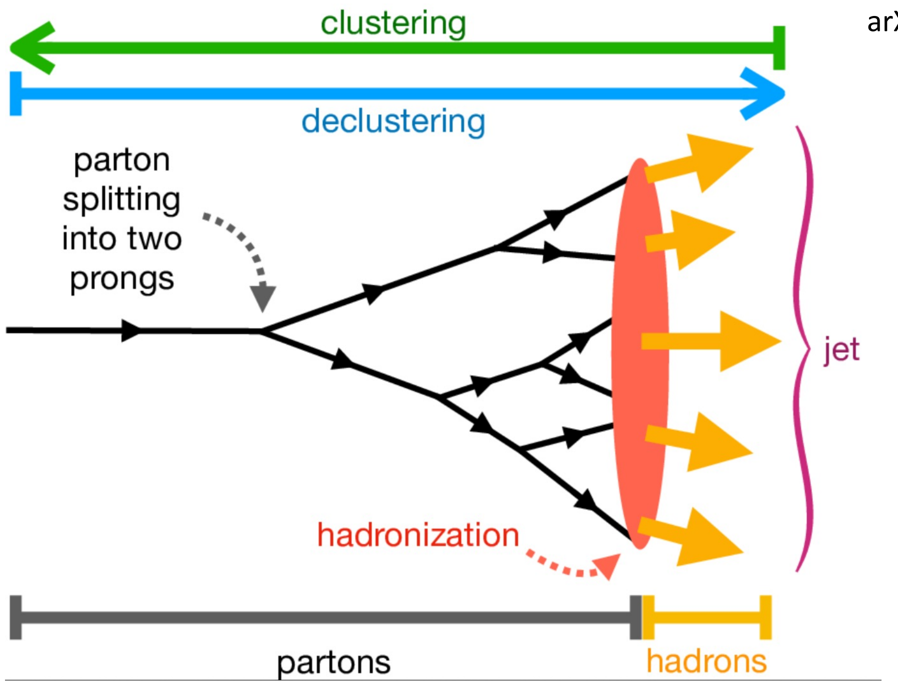
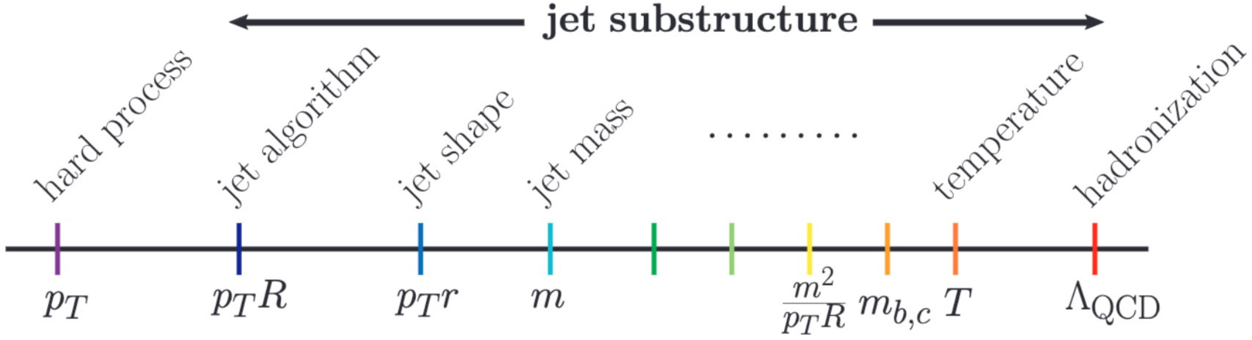
Why Jets?

- Jets are rich objects whose formation involves rich QCD dynamics

arXiv:2303.13347





Yang Ting Chien
QM'19

Jet Substructure: Powerful tools in QCD

- Jets are rich objects whose formation involves rich QCD dynamics
- Jet Substructure first used to tag and differentiate boosted objects from QCD jets

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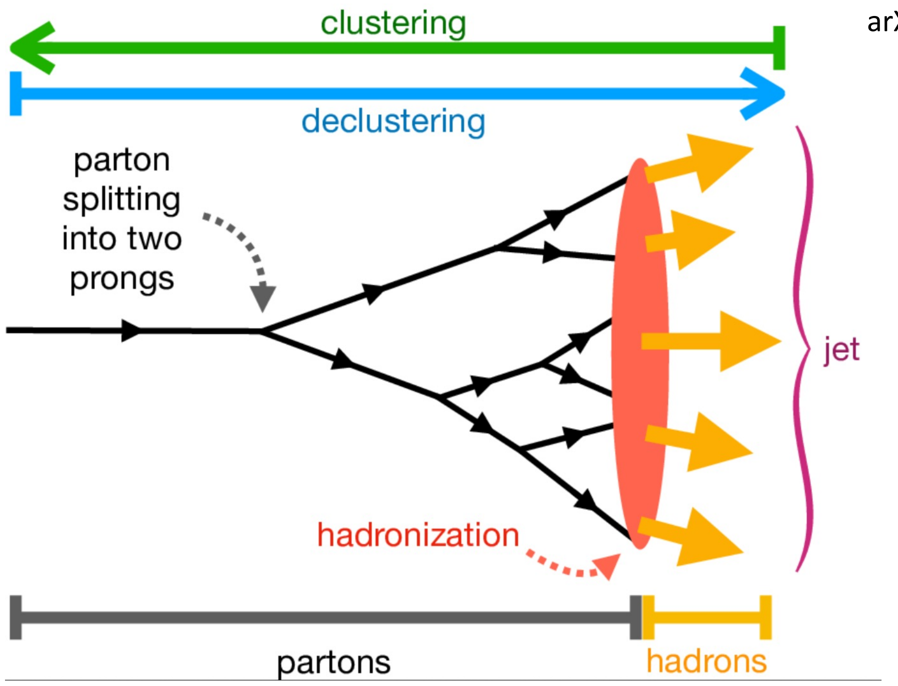
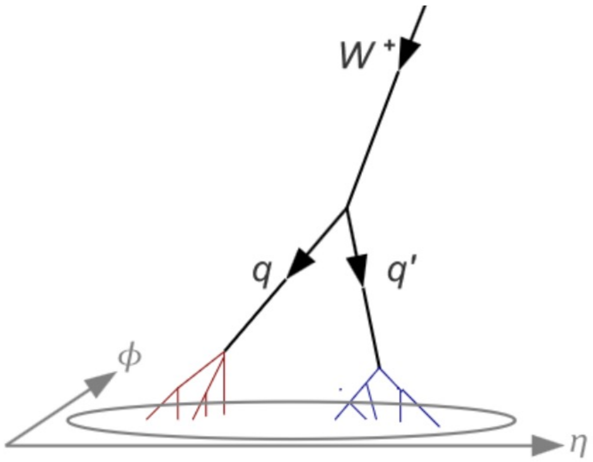
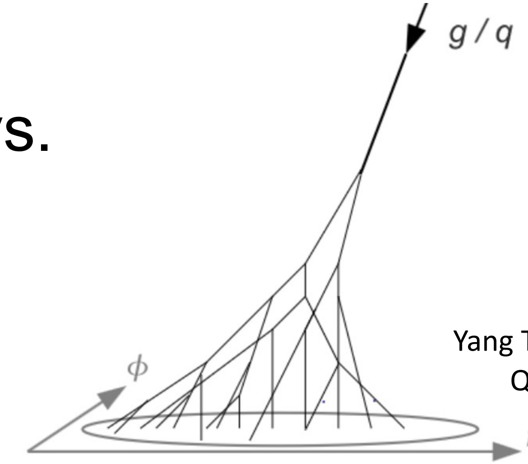


JHEP 1103:015.2011



vs.



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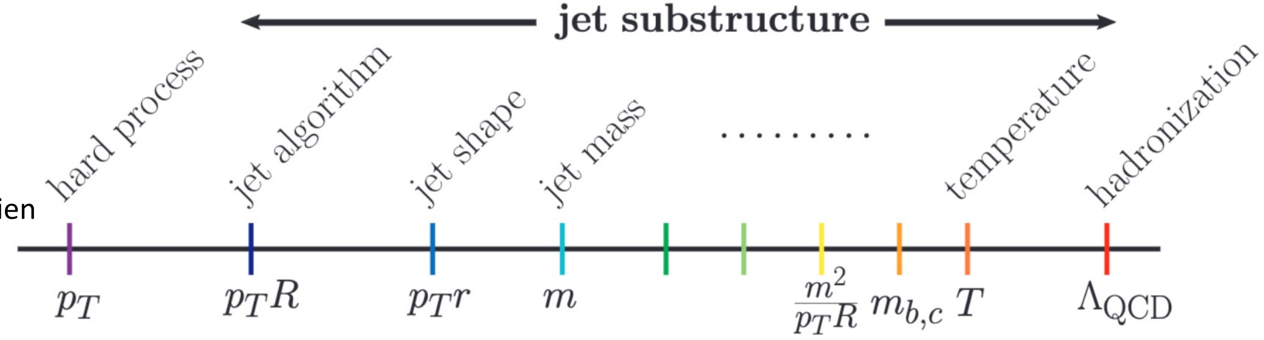
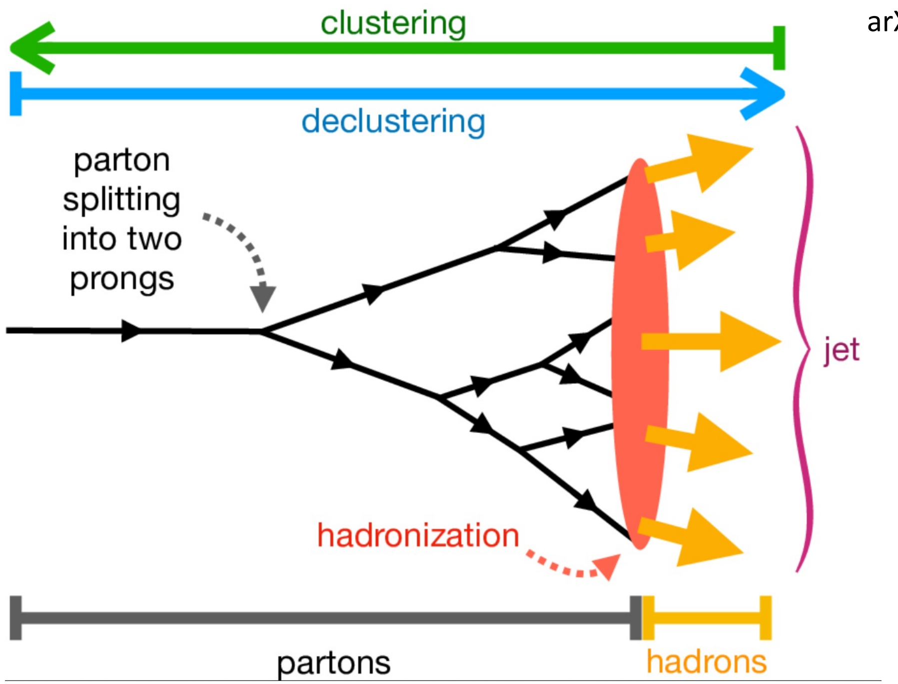
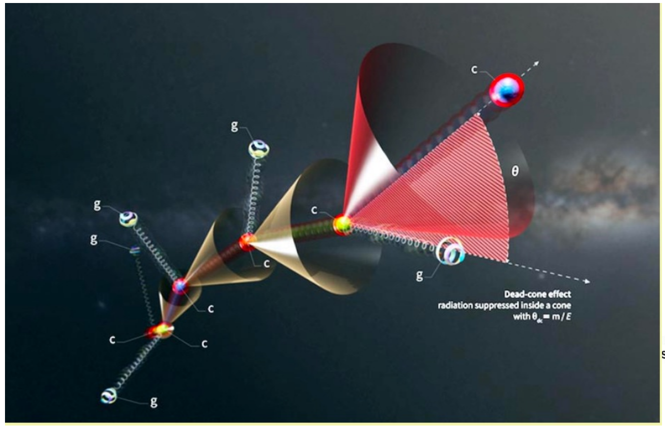


Jet Substructure: Powerful tools in QCD

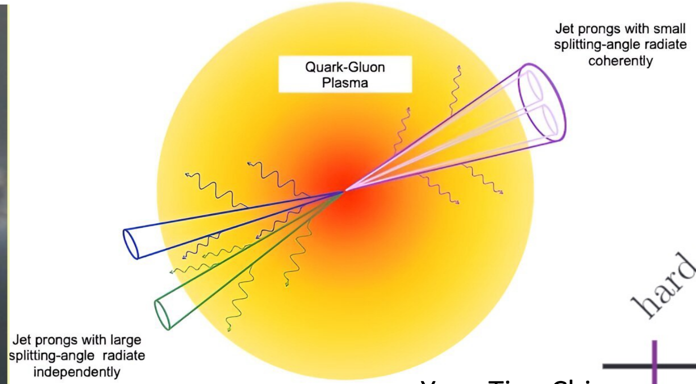
- Jets are rich objects whose formation involves rich QCD dynamics
- Jet Substructure first used to tag and differentiate boosted objects from QCD jets
- Jet substructure has since been critical in analyzing and studying
  - Parton Showers and hadronization processes
  - Heavy flavor physics
  - Quark-Gluon Plasma physics among many others!

arXiv:2303.13347





[ALICE 2022]



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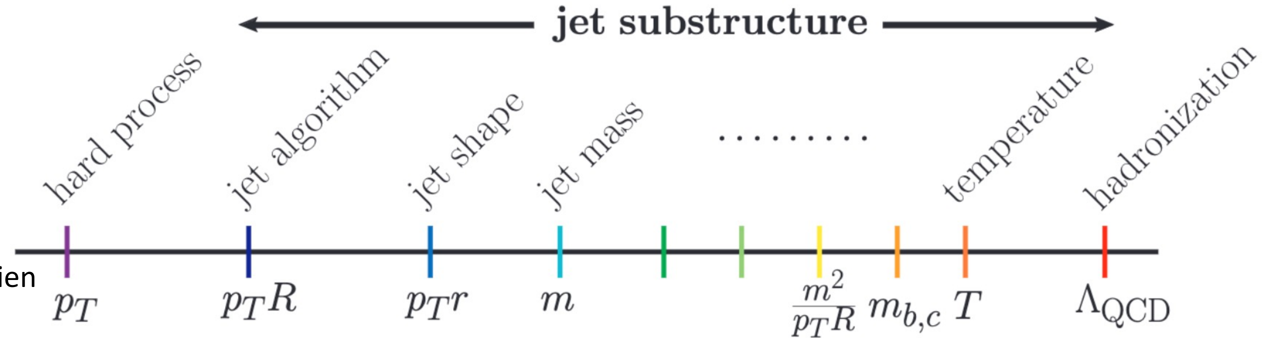
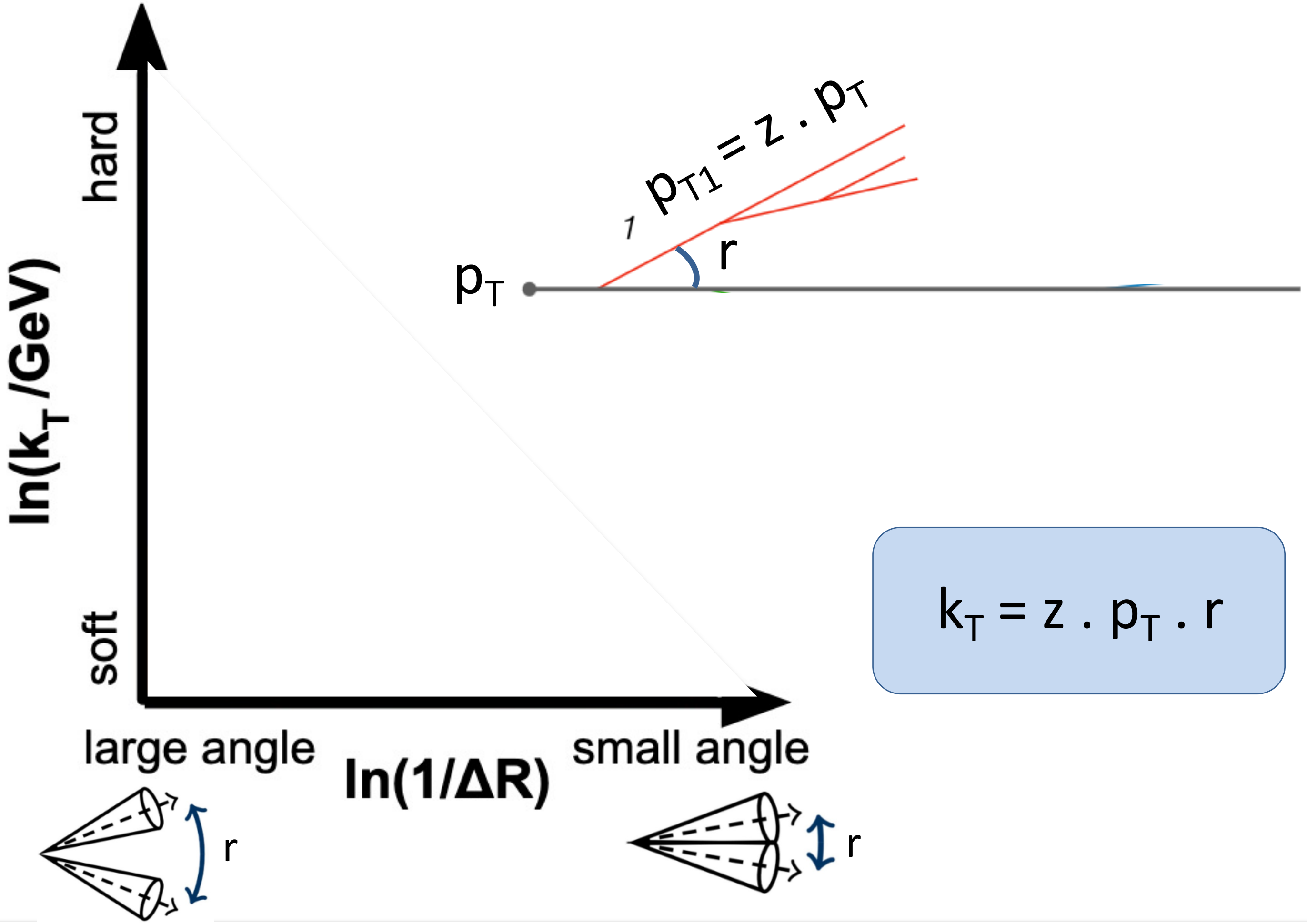


Mapping the Evolution of a Jet

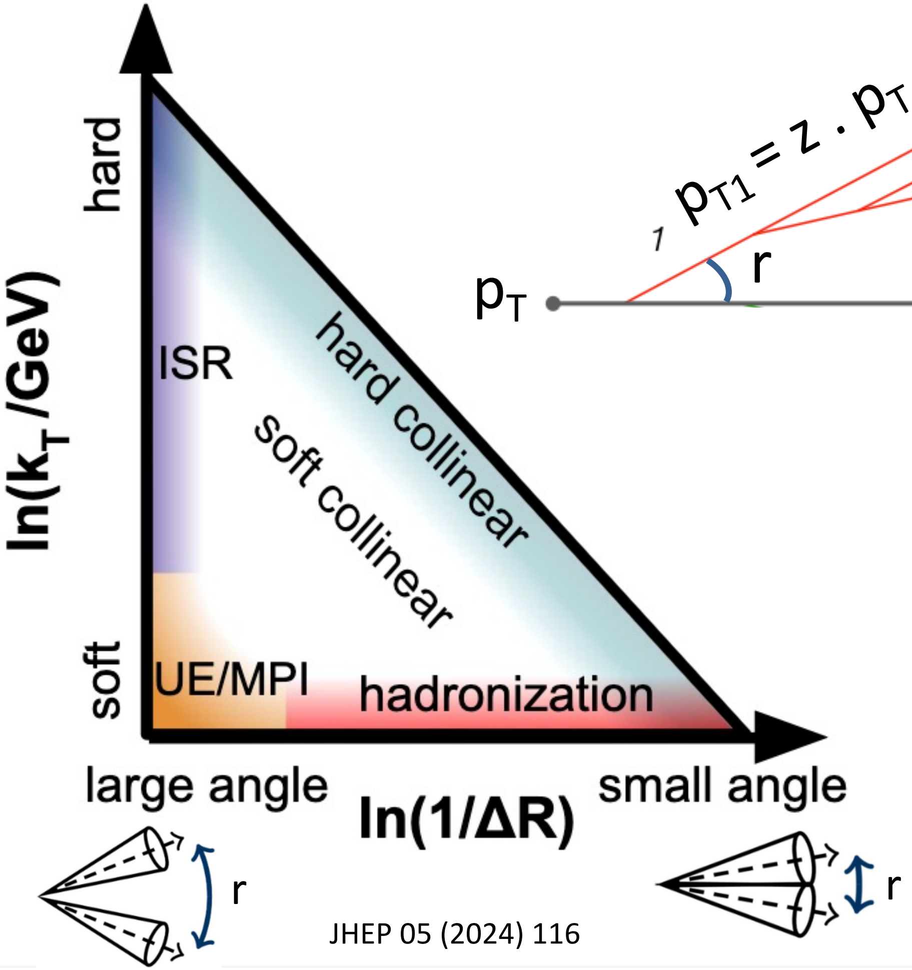
JHEP12(2018)064



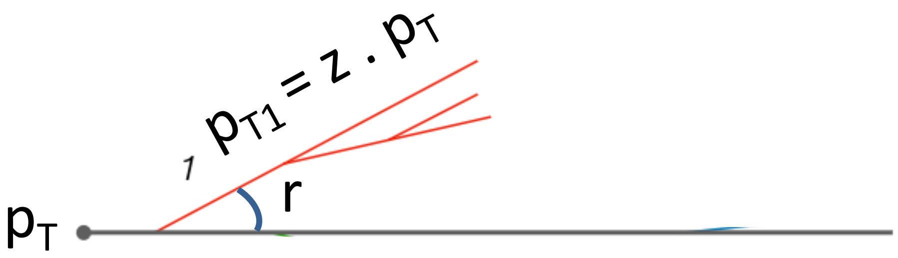
$k_T = z \cdot p_T \cdot r$

The (Primary) Lund Jet Plane

JHEP12(2018)064

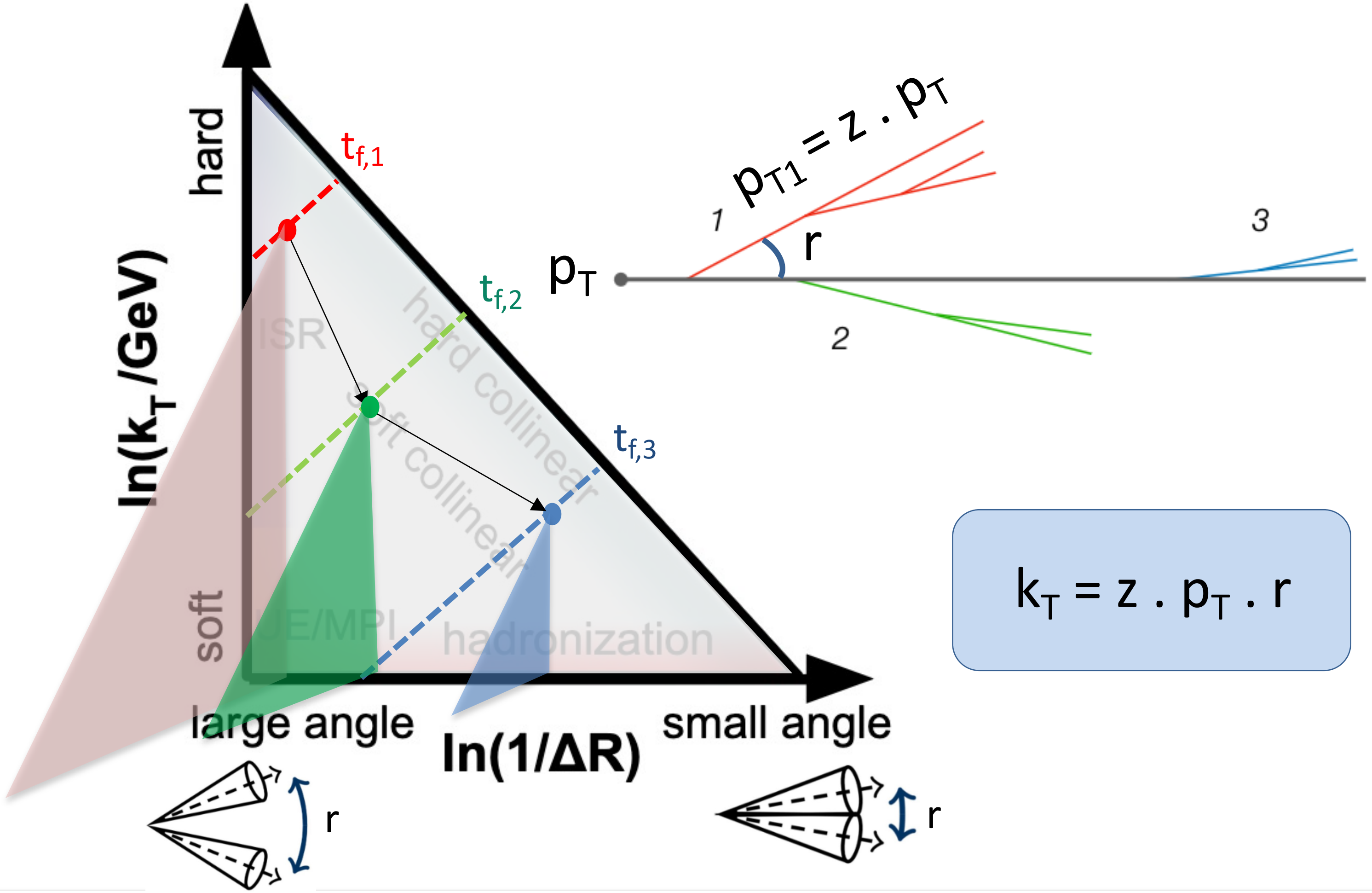


JHEP 05 (2024) 116



$k_T = z \cdot p_T \cdot r$

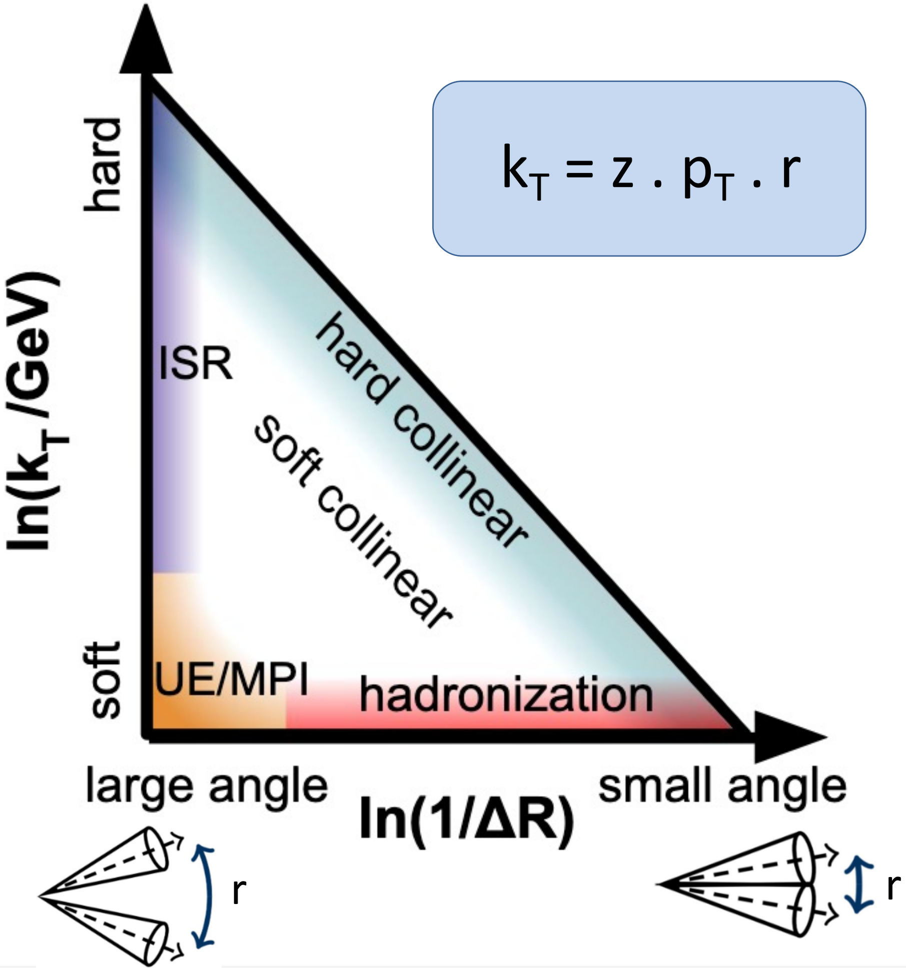
The Lund Jet Plane



Each given emission creates new phase space (a triangular leaf) for further emissions.

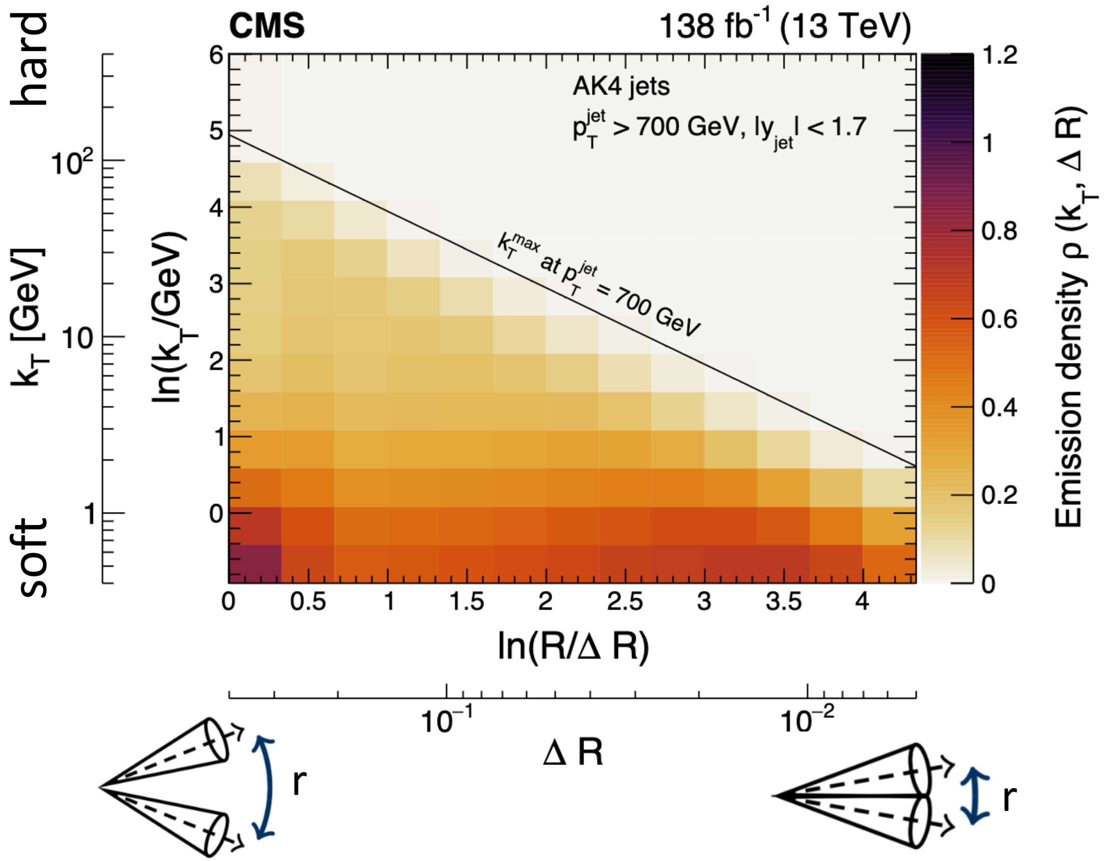
$k_T = z \, . \, p_T \, . \, r$

The Lund Jet Plane



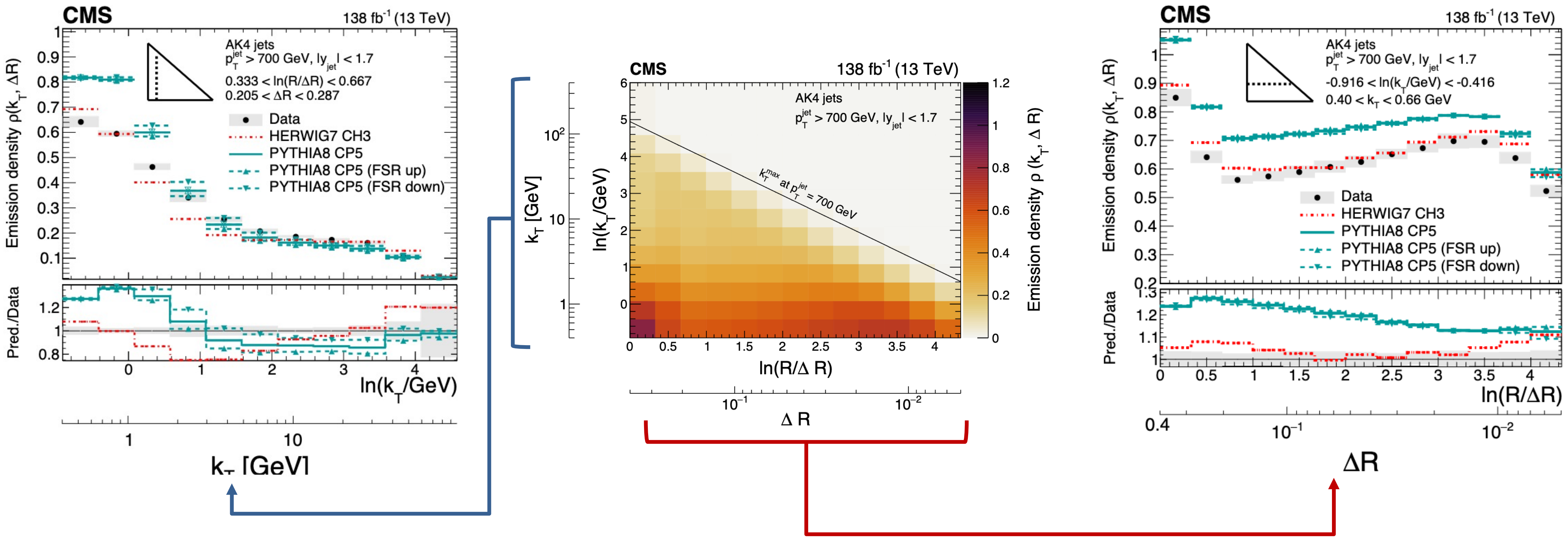
$k_T = z \cdot p_T \cdot r$

Unfolded measurements of the Primary Lund Jet plane in pp collisions



The Lund Jet Plane Projections

Unfolded measurements of the Primary Lund Jet plane in pp collisions



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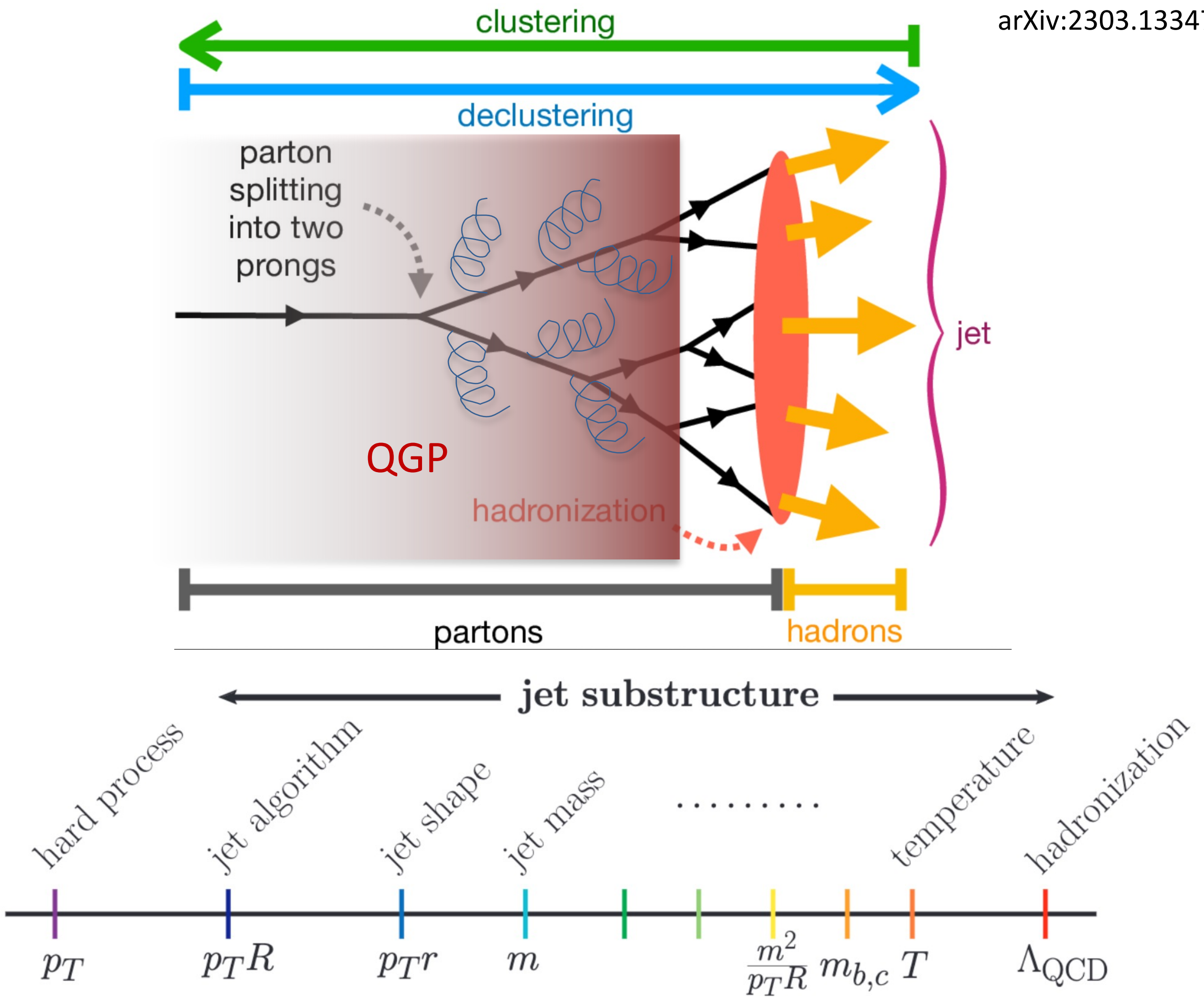
Jets in Heavy-Ion Collisions

- Collide nuclei at the LHC and RHIC to produce droplets of **hot, dense quark-gluon plasma**
- **Use jets as probes to study the properties of the QGP**

arXiv:2303.13347



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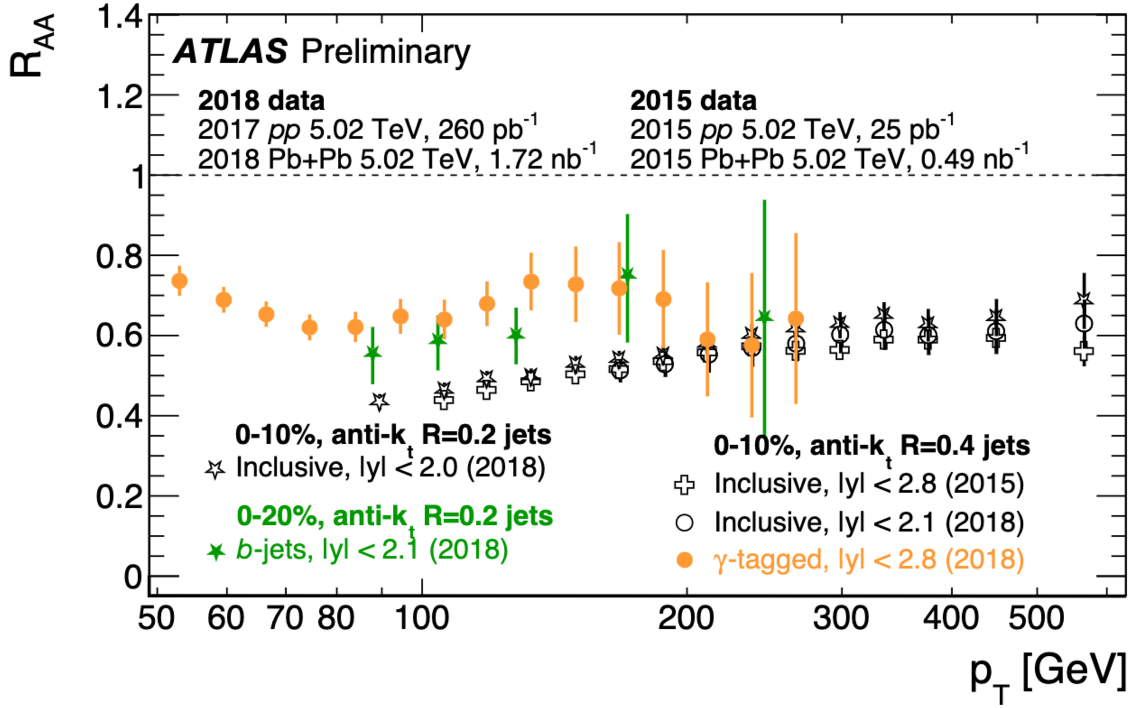

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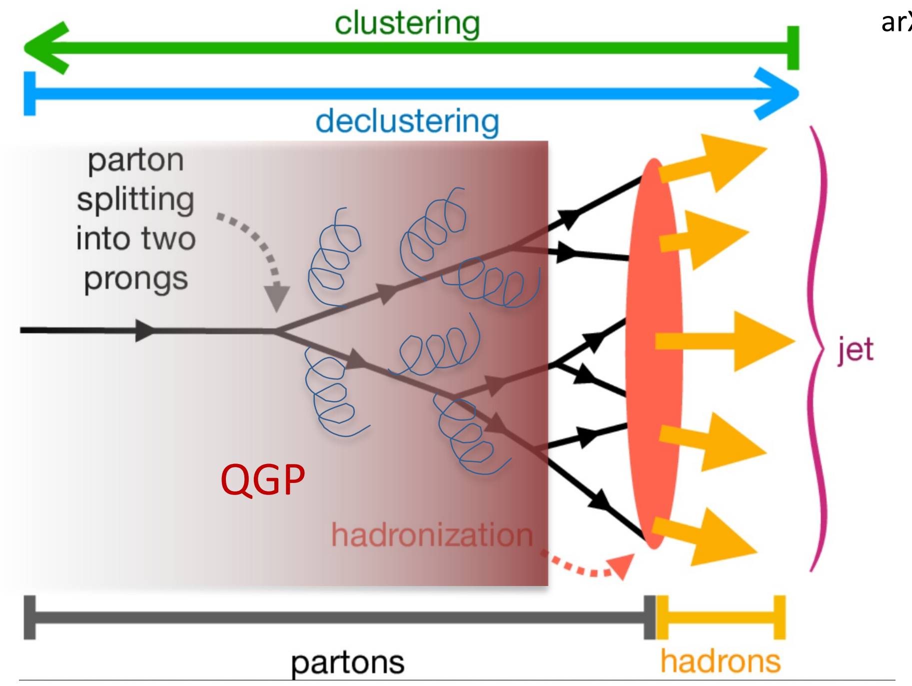
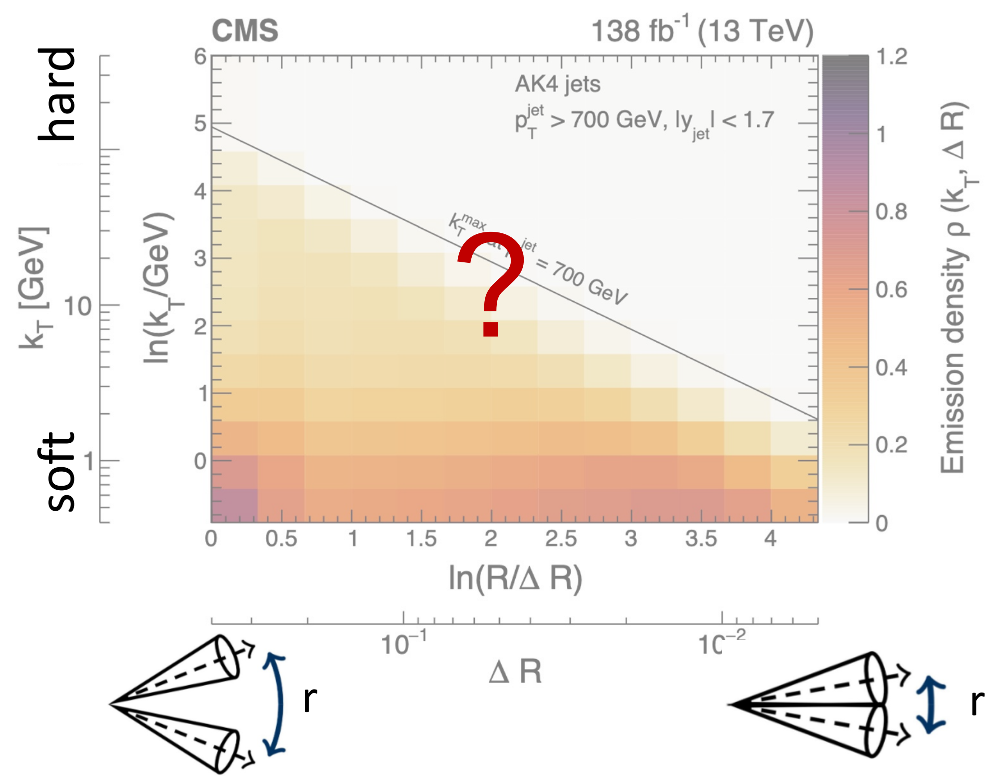
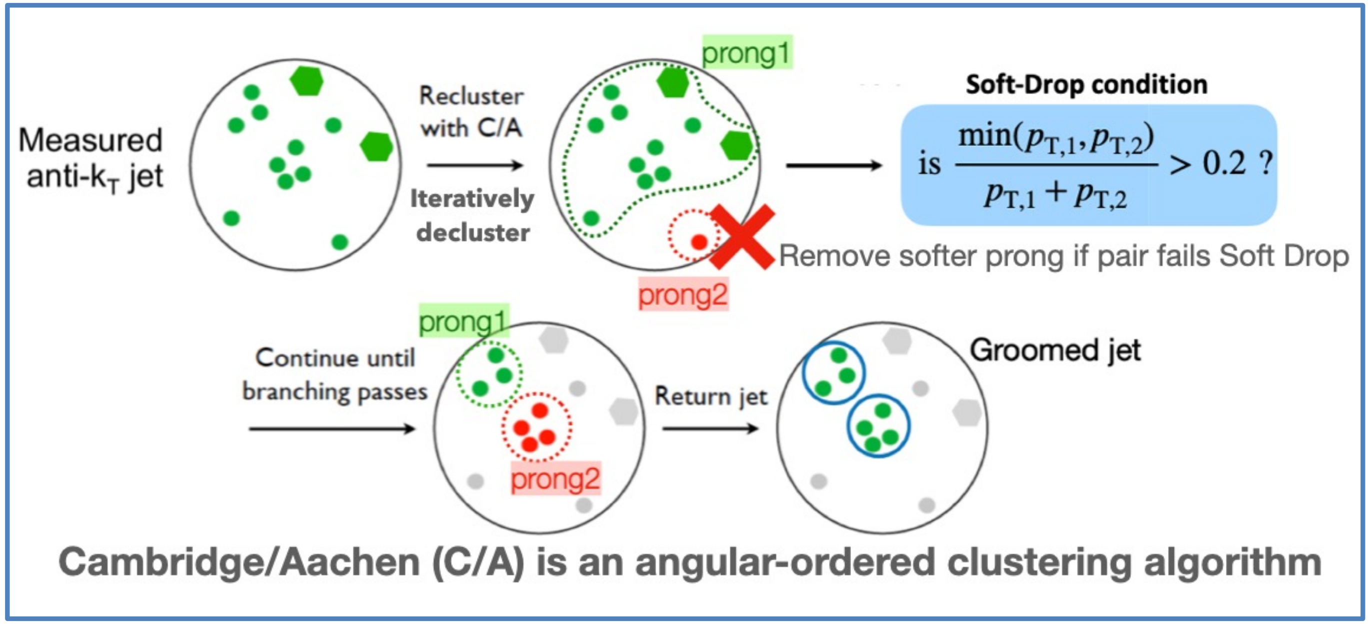


$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

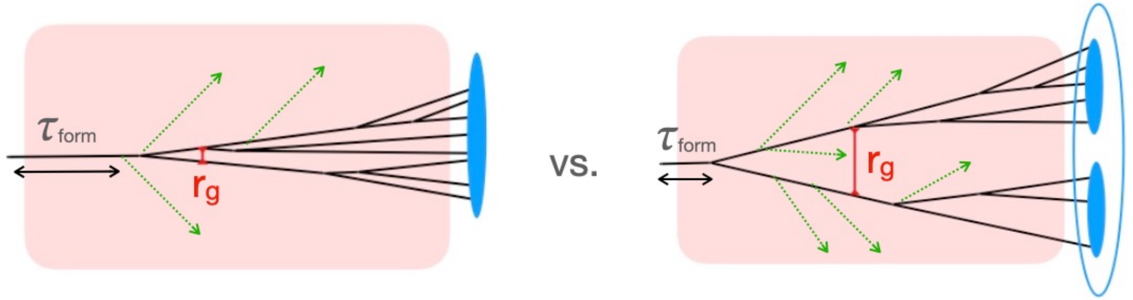
Jet Substructure in Heavy-Ion Collisions

What does the multiscale evolution of jets look like in presence of the QGP?



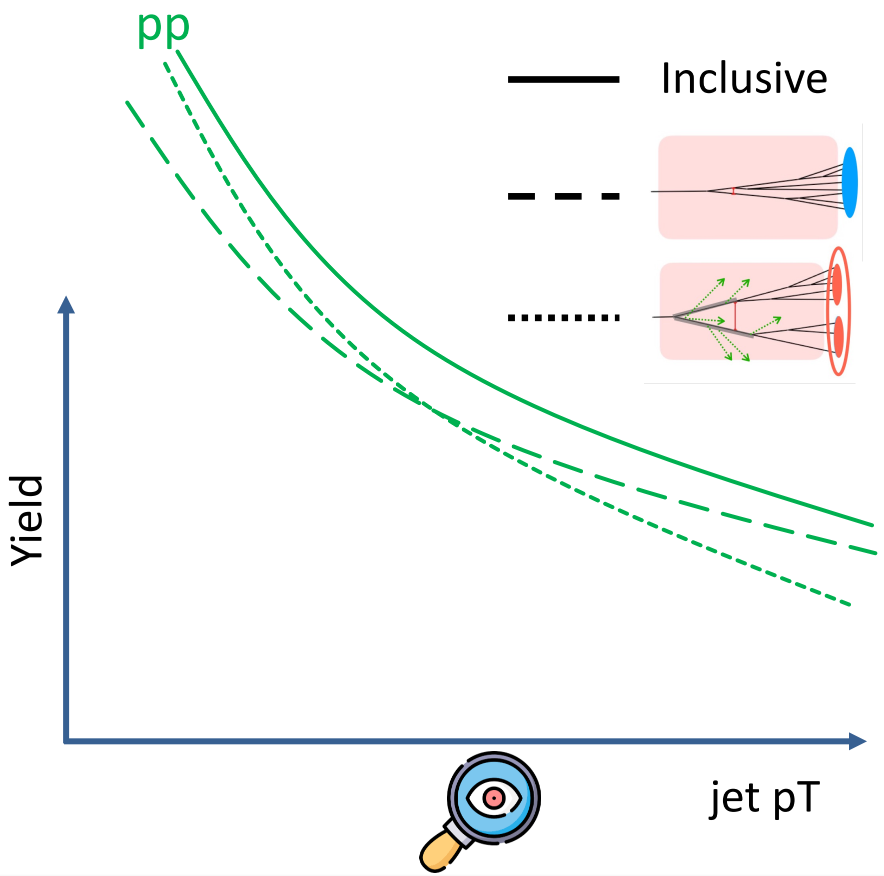


Can the medium resolve splittings below a threshold angle?

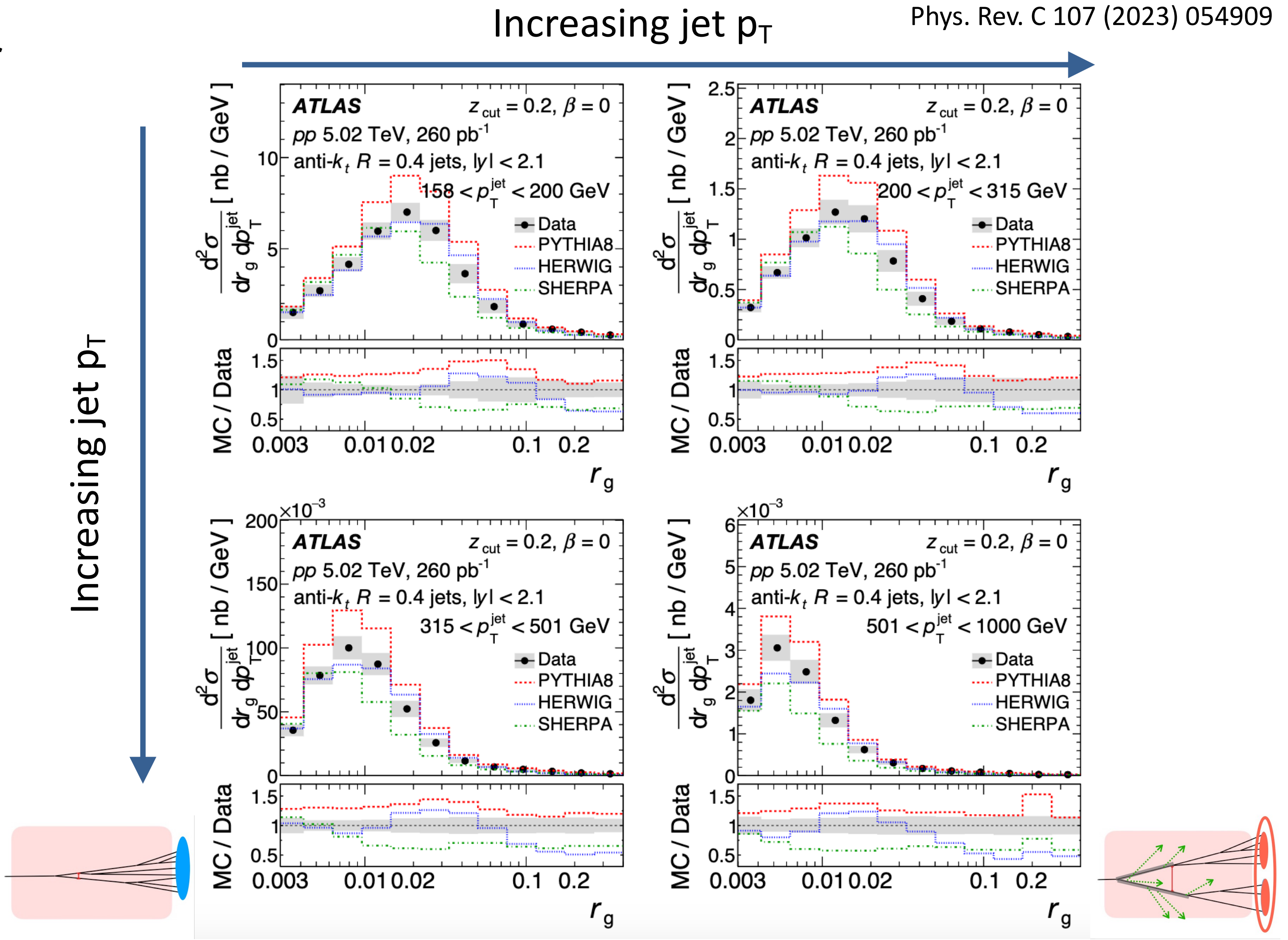


ATLAS : r_g yield in pp

The r_g distributions are observed to peak at lower values of r_g with increasing jet p_T



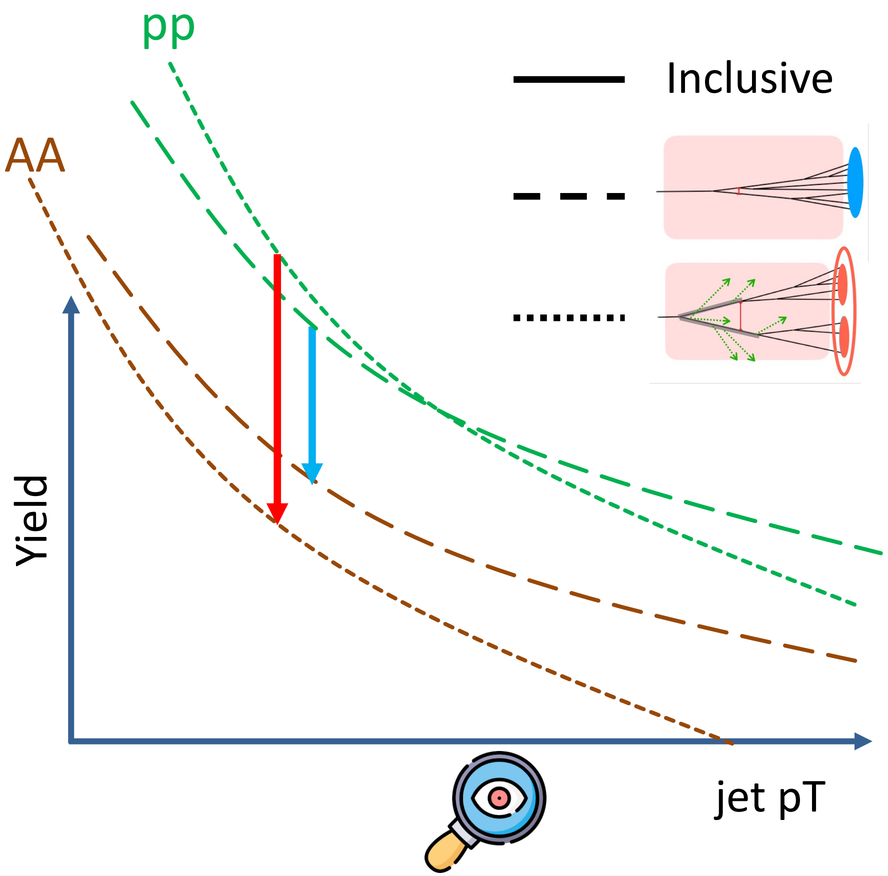
Phys. Rev. C 107 (2023) 054909

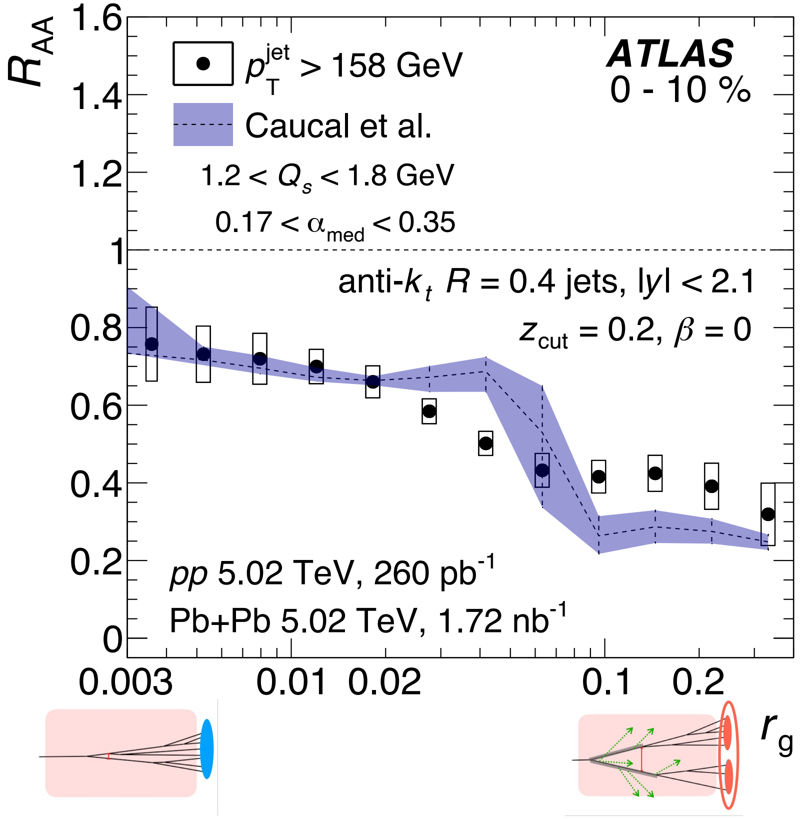


ATLAS : R_{AA} vs. r_g

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

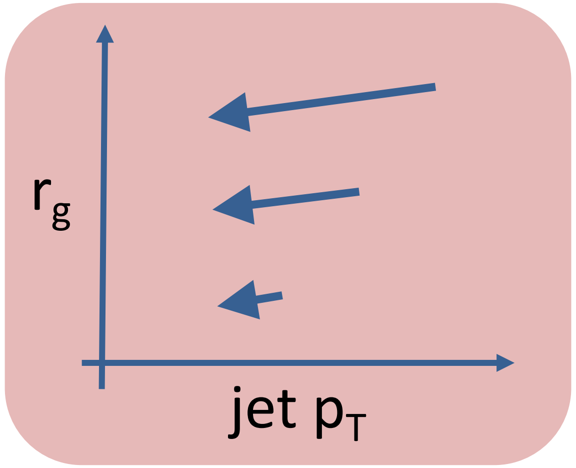
- The R_{AA} value is observed to depend significantly on jet r_g
- Jets with largest r_g are twice as suppressed as those with the smallest r_g in central Pb+Pb collisions





Soft-Drop condition

$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$



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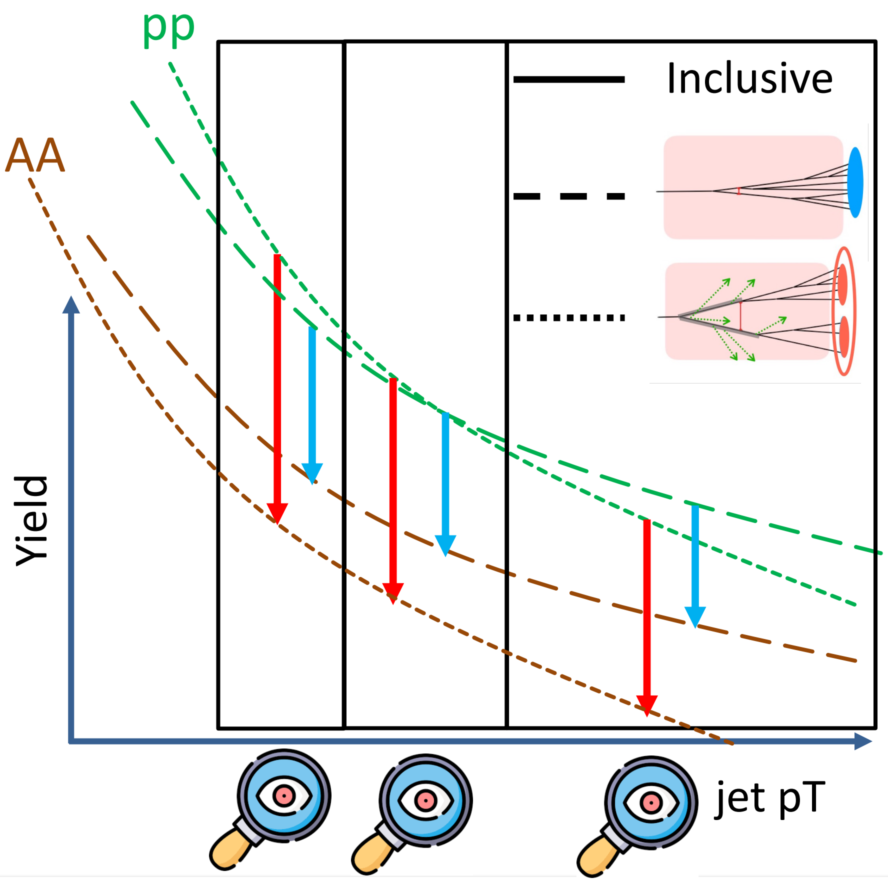
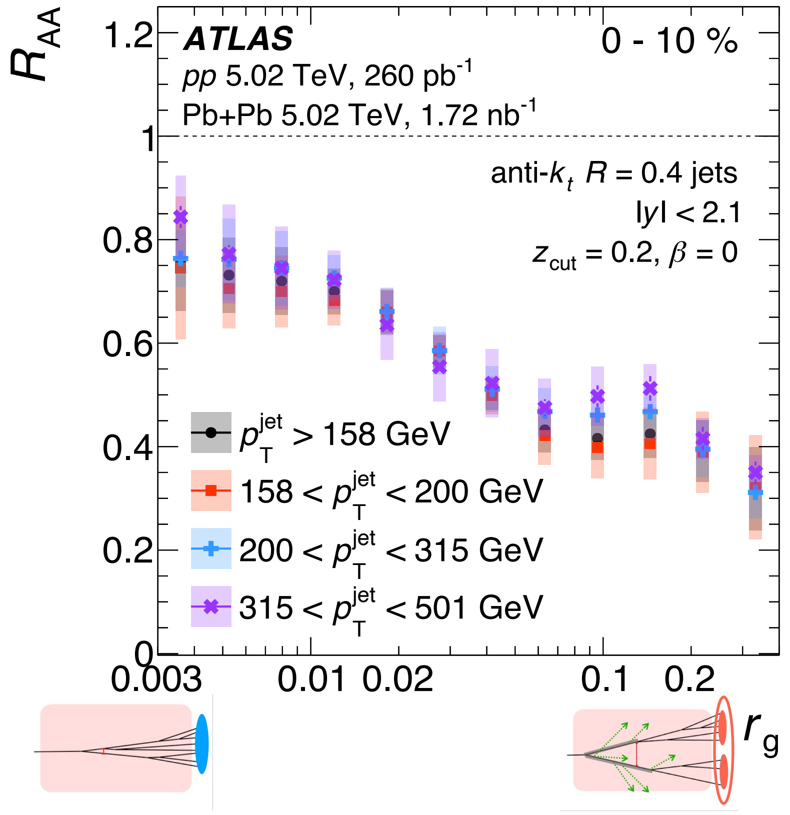
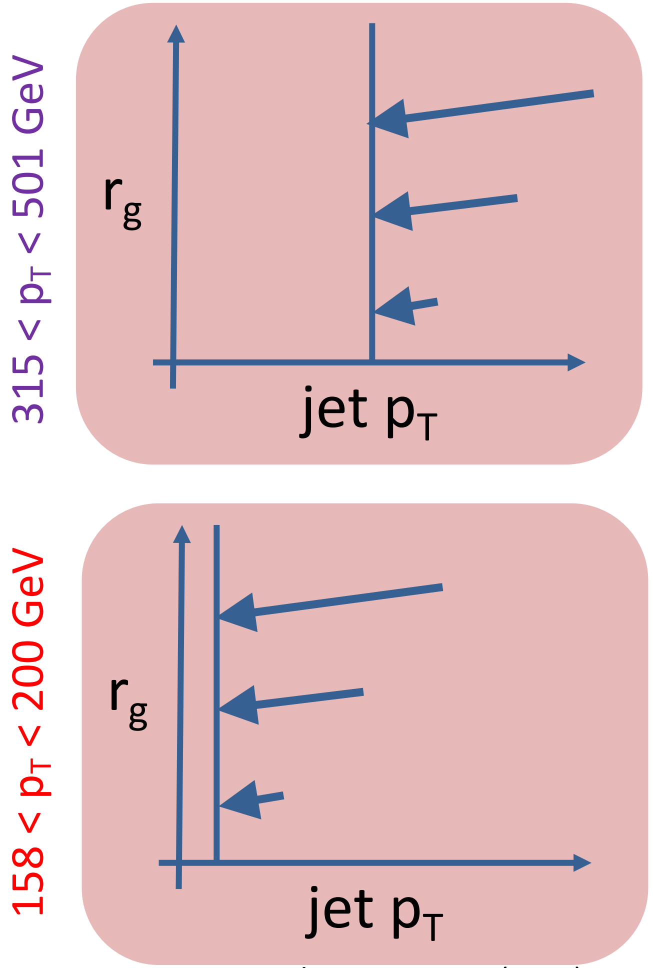
ATLAS : R_{AA} vs. (r_g and jet p_T)

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

The R_{AA} values do not exhibit a strong variation with jet p_T in any of the r_g intervals







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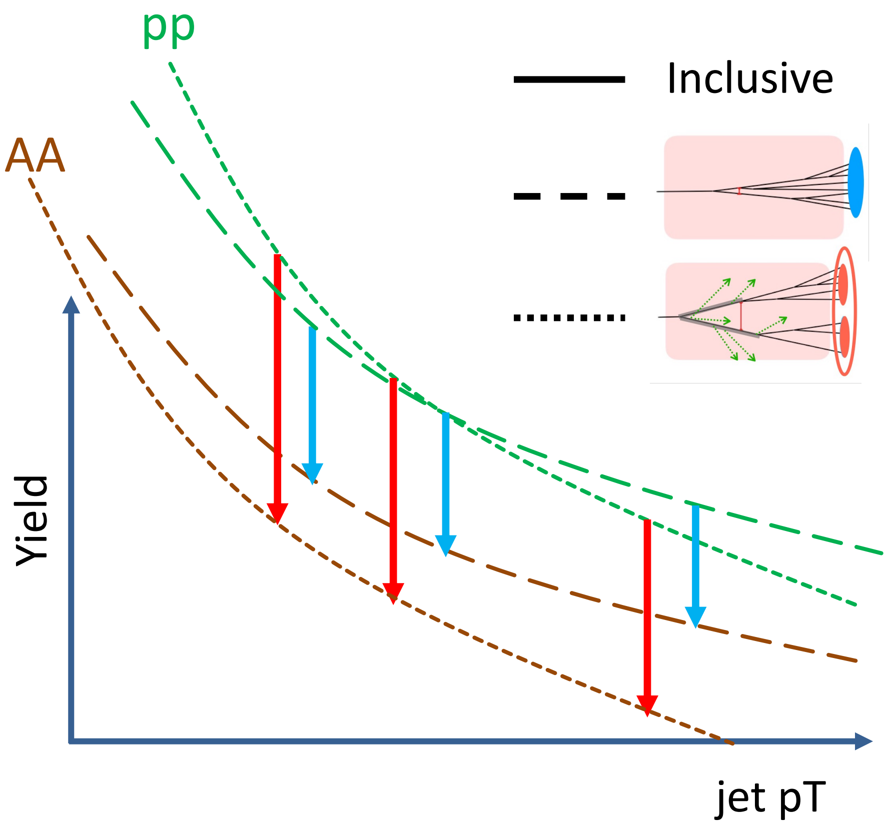
ATLAS : R_{AA} vs. (r_g and jet p_T)

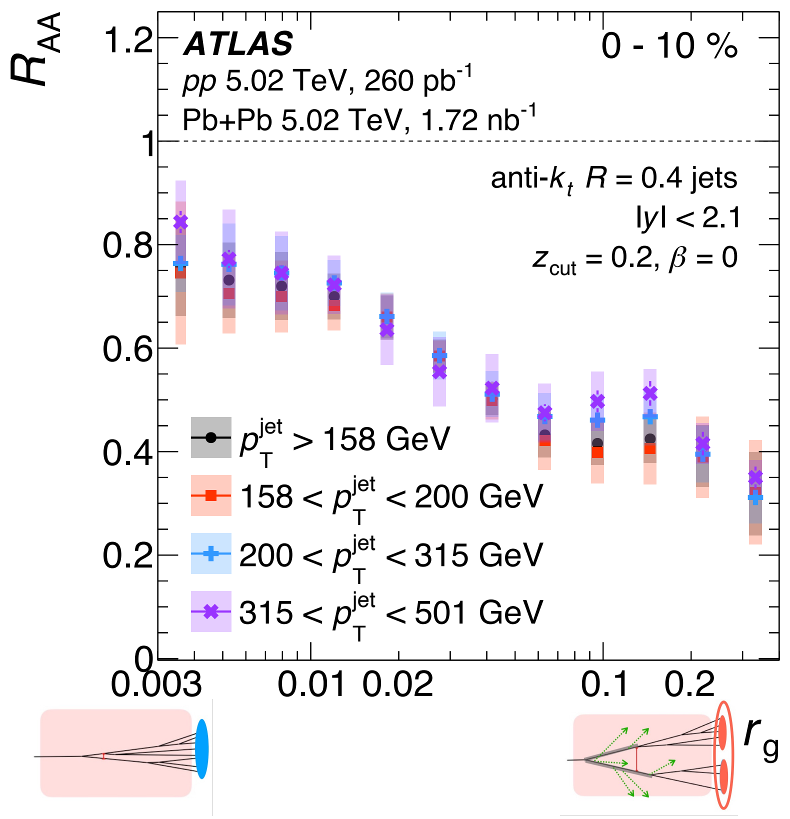
$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

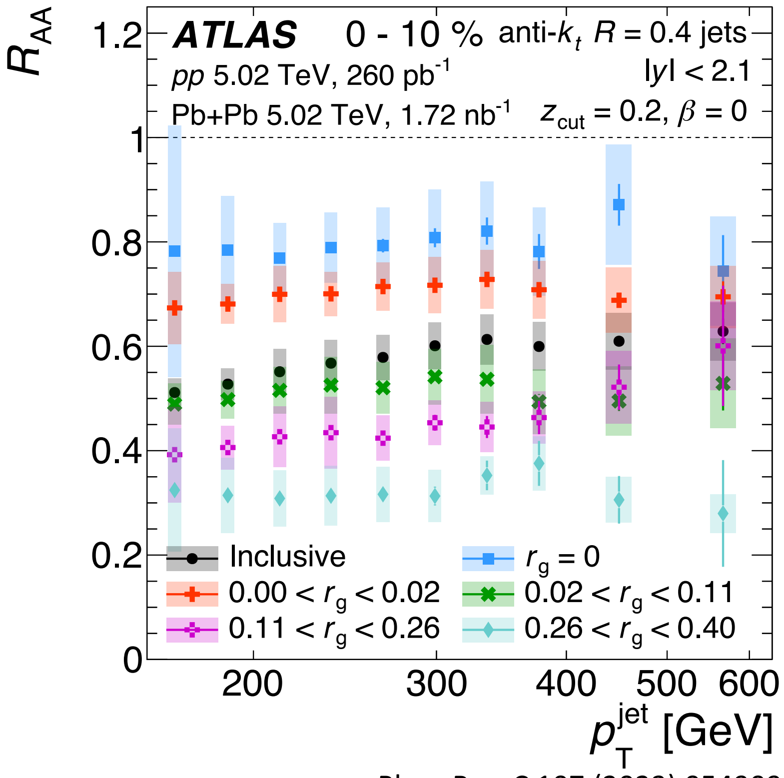
The R_{AA} is observed to have a clear ordering with respect to the splitting angle r_g

Soft-Drop condition

$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$







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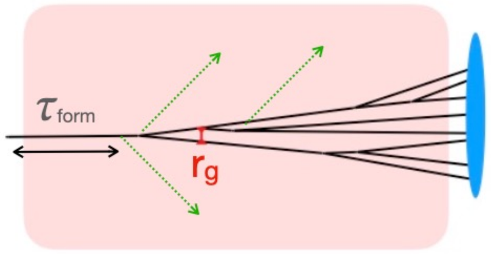
Formation time

$$R_{AA} = \frac{\text{per-NN yields in PbPb}}{\text{yields in } pp}$$

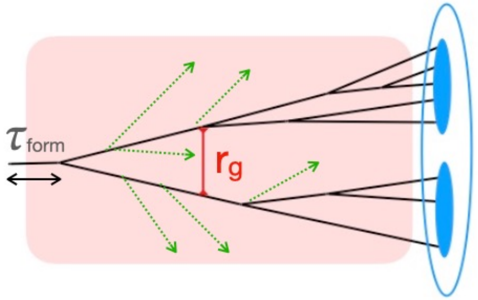
Look at formation time (τ) to select jets with different degrees of quenching without biasing their initial pT

Formation time

$$\tau_{\text{form}} \simeq \frac{1}{2Ez_1z_2(1-\cos\theta_{12})}$$



vs.



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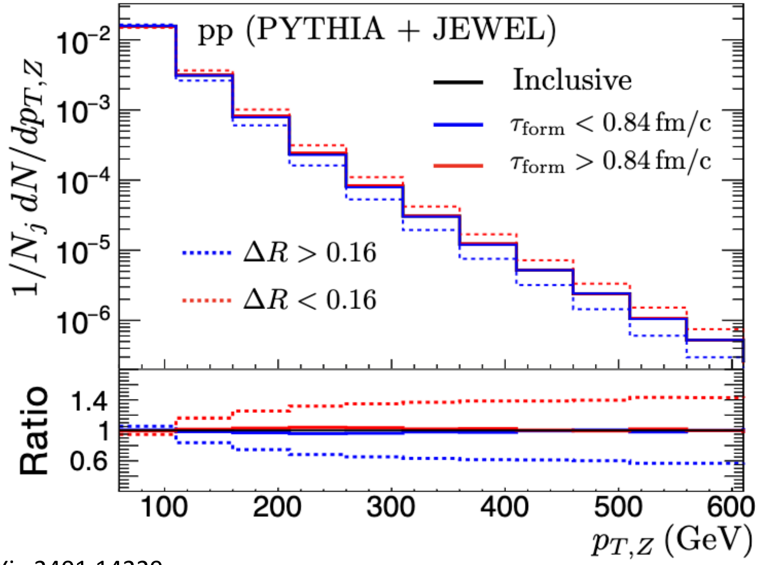
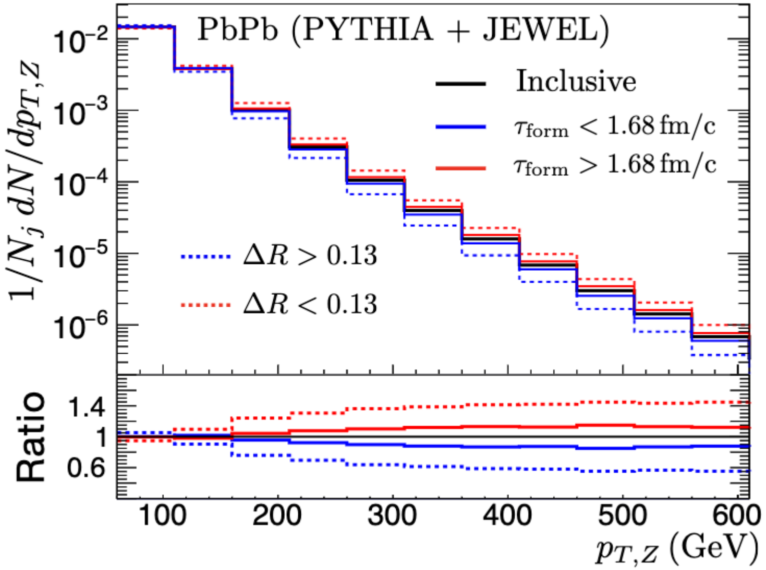
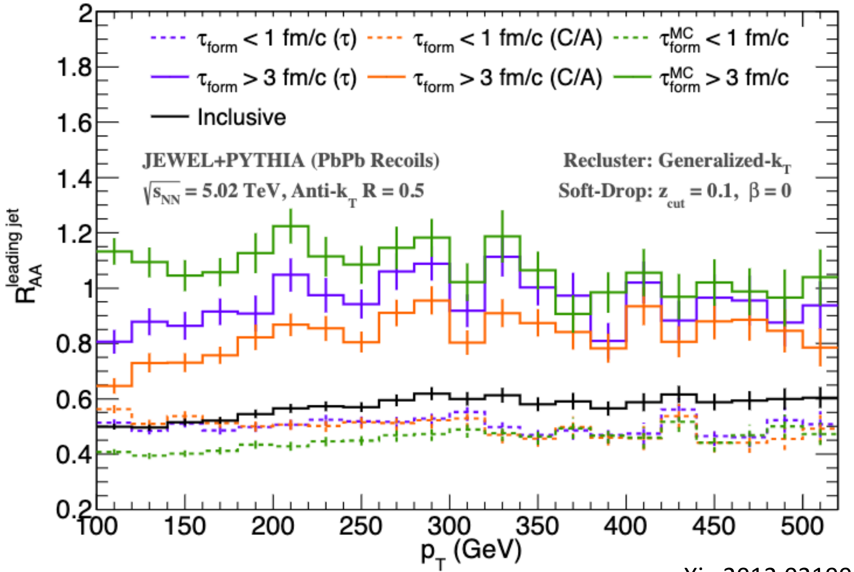




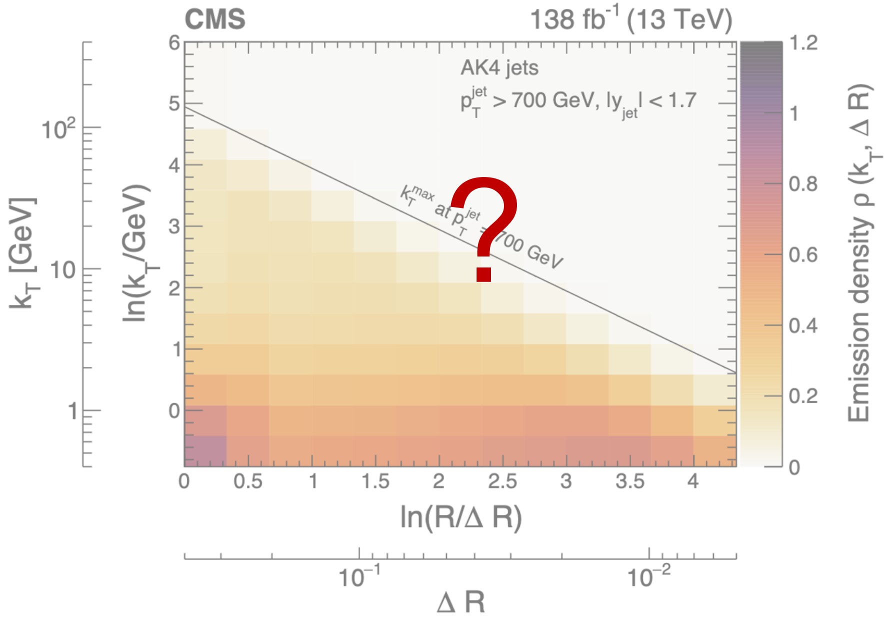


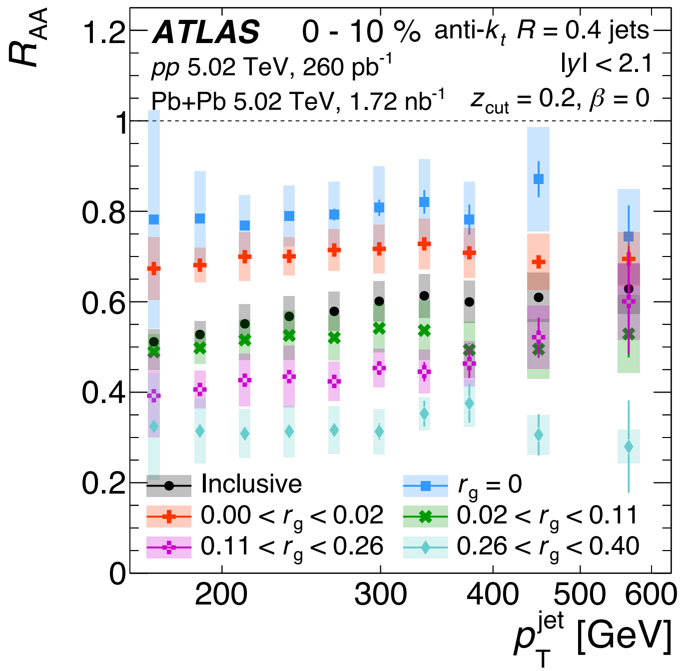
arXiv:2401.14229

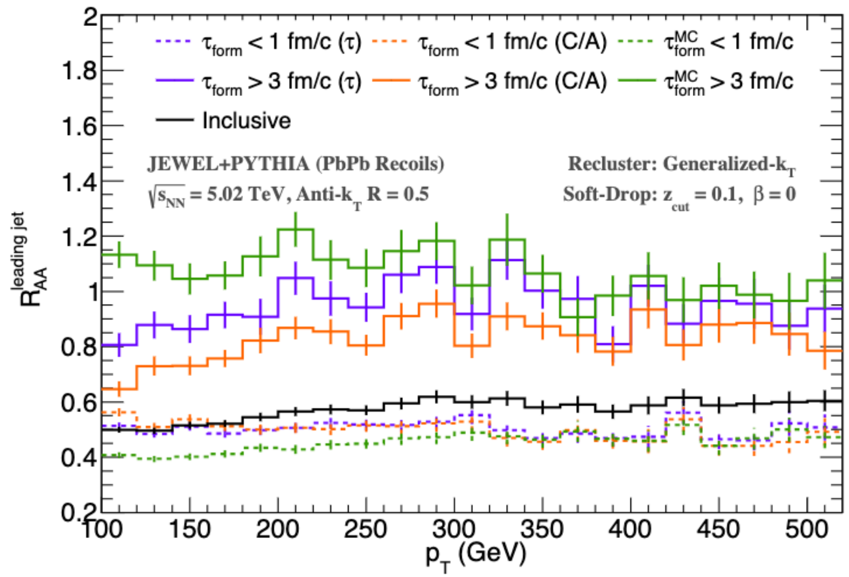
arXiv:2012.02199

Jet Substructure : Long Journey Ahead

- Jet evolution in a hot and dense QCD medium is a multiscale problem and requires a comprehensive characterization
- Need to better understand what we're measuring with the novel observables and analysis methods in the field







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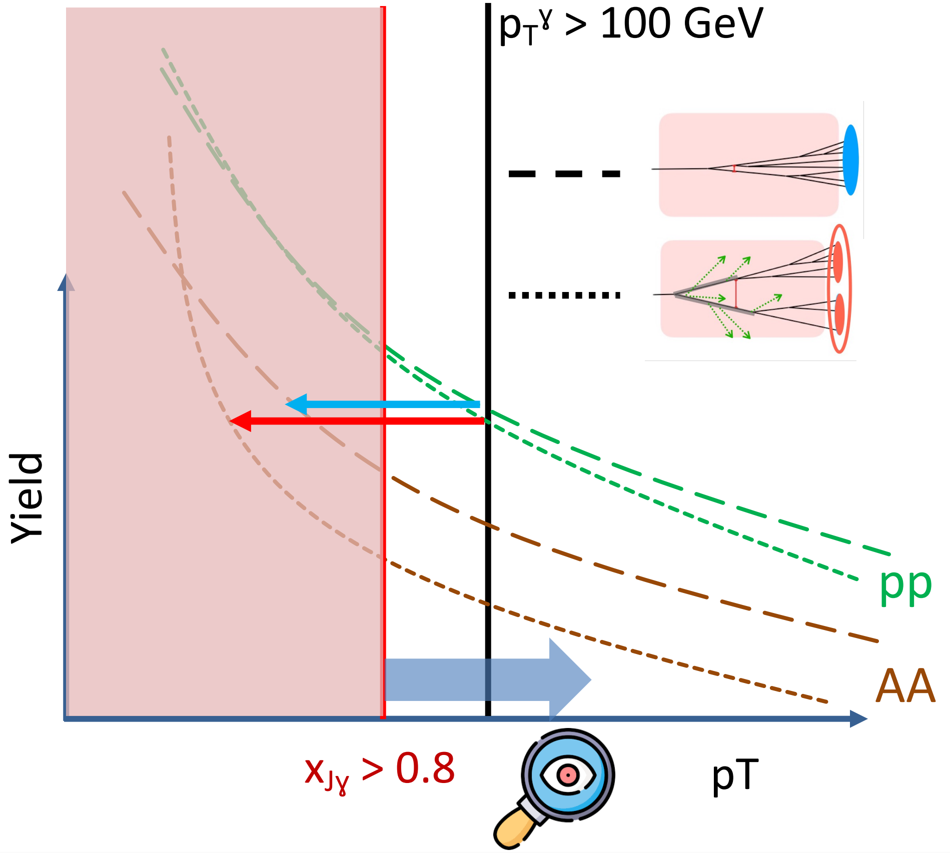
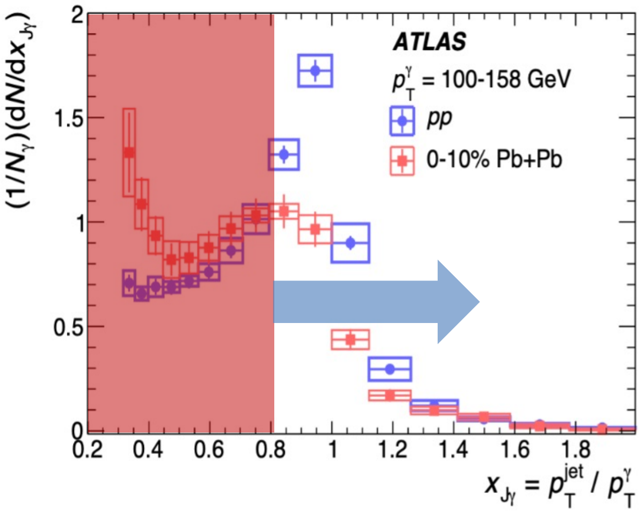
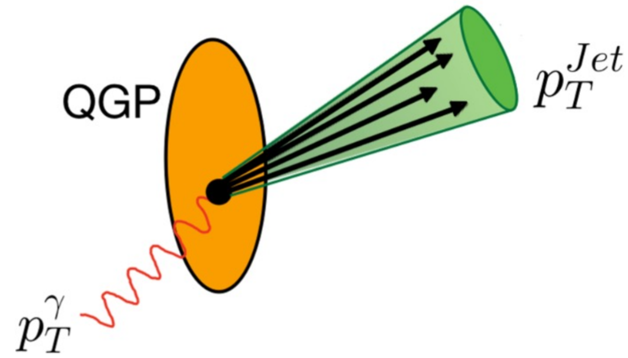
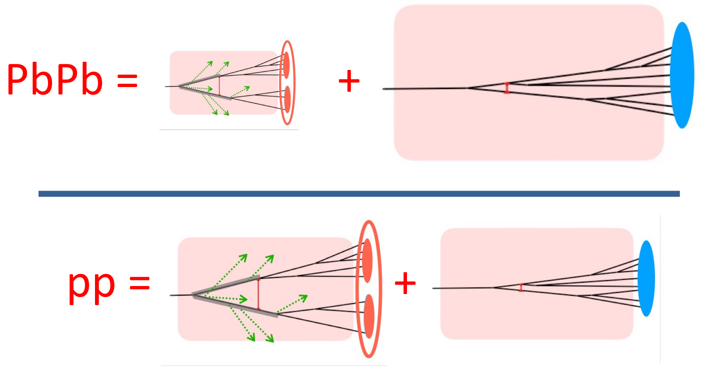
CMS : Photon-tagged jet r_g for $x_{J\gamma} > 0.8$

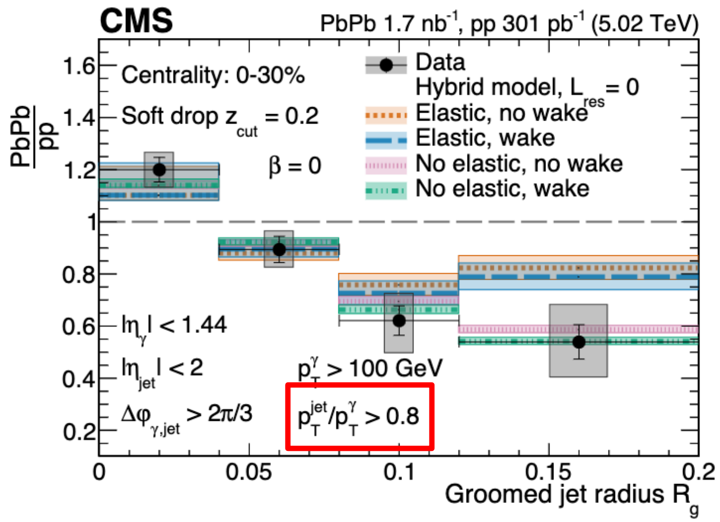
"It is found that jets with $p^{jet}_T / p^{\gamma}_T > 0.8$, i.e., those that closely balance the photon p^{γ}_T , are narrower in PbPb than in pp collisions."







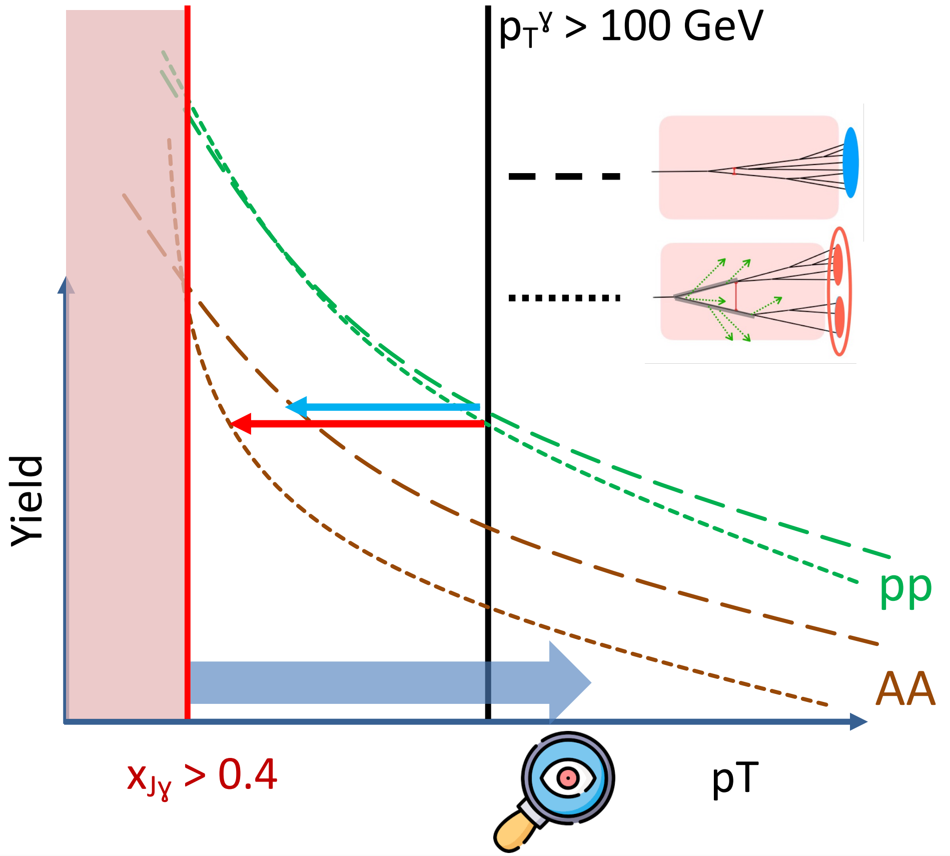


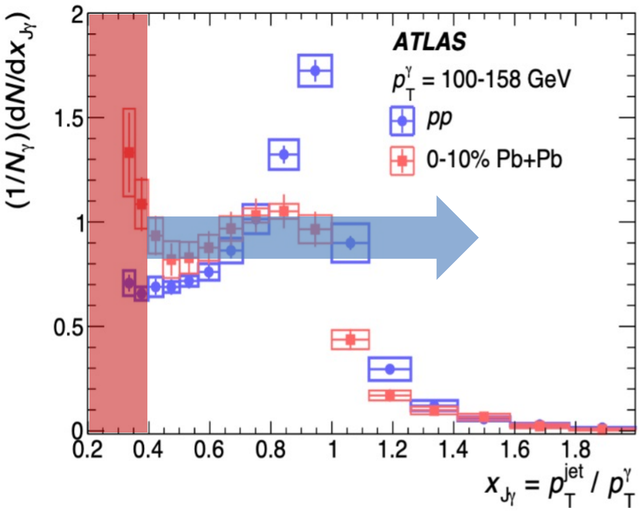


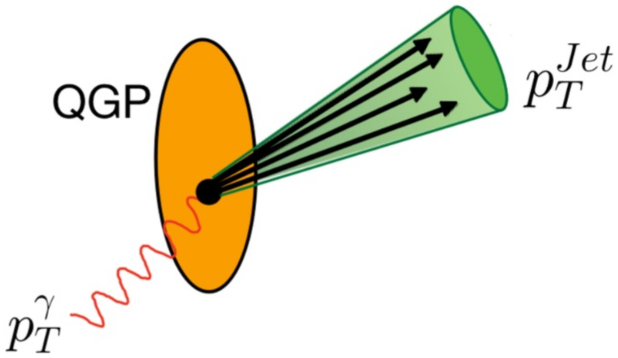
arXiv:2405.02737

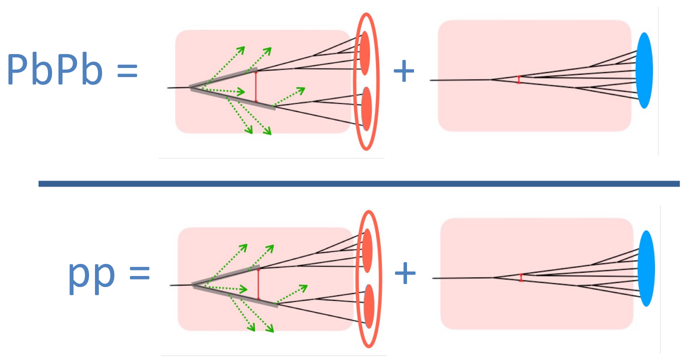
CMS : Photon-tagged jet r_g for $x_{J\gamma} > 0.4$

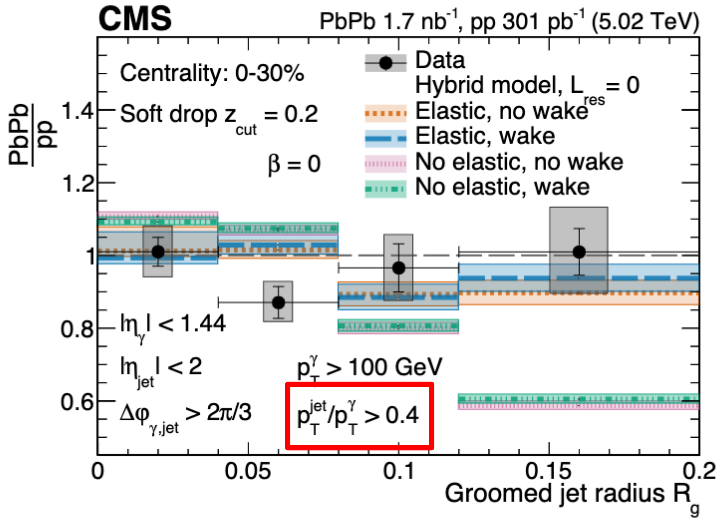
"Relaxing the selection to include jets with $p^{jet}_T / p^{\gamma}_T > 0.4$ reduces the narrowing of the angular structure of jets in PbPb relative to the pp reference."







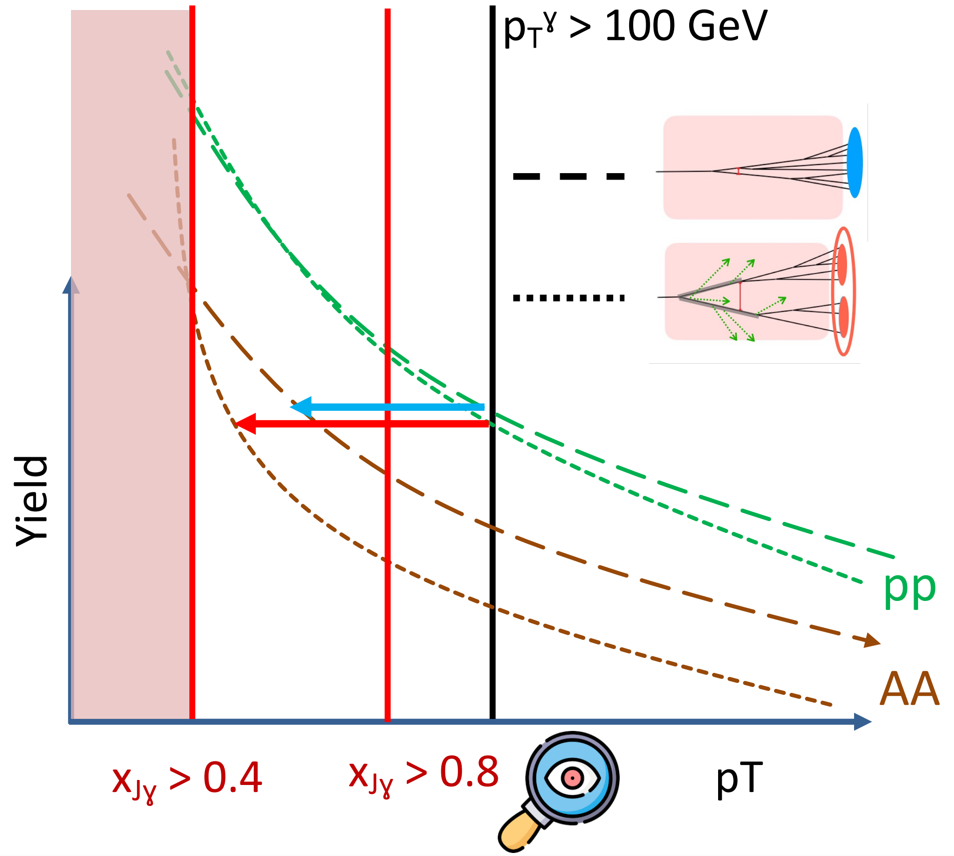


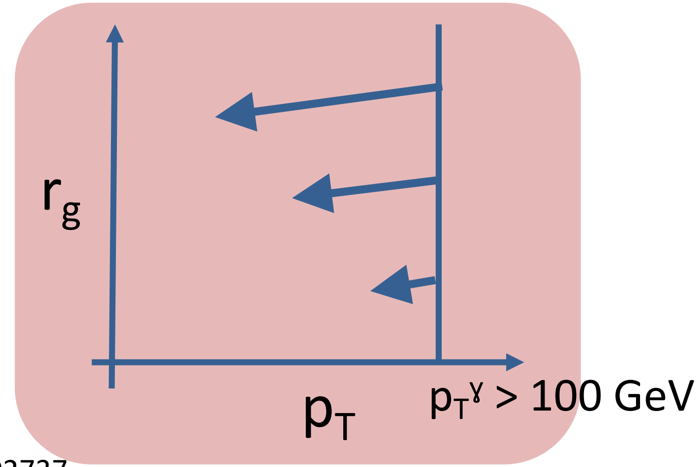


arXiv:2405.02737

CMS : Photon-tagged jet r_g for ($x_{J\gamma}$ > 0.8 vs. $x_{J\gamma}$ > 0.4)

"In contrast to the trends observed by the ALICE and ATLAS Collaborations for R_g in inclusive jet events, we do not observe a narrowing of the substructure of jets in R_g within the experimental uncertainties when selecting jets with $x_{\gamma j}$ > 0.4 and $p_{\gamma T}$ > 100 GeV."





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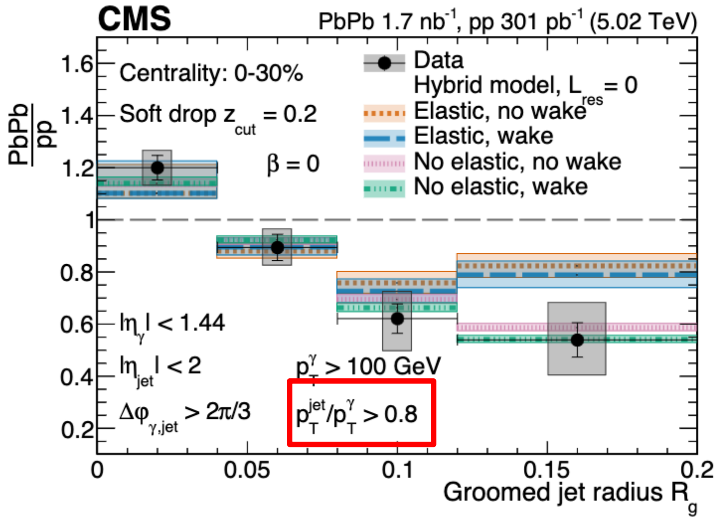
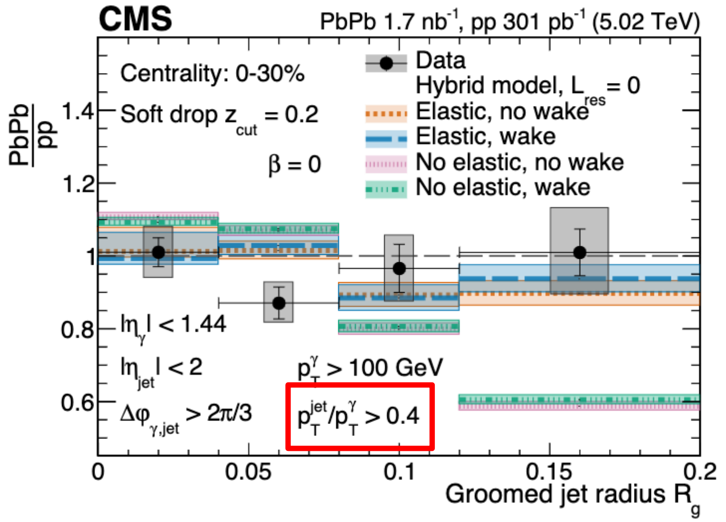
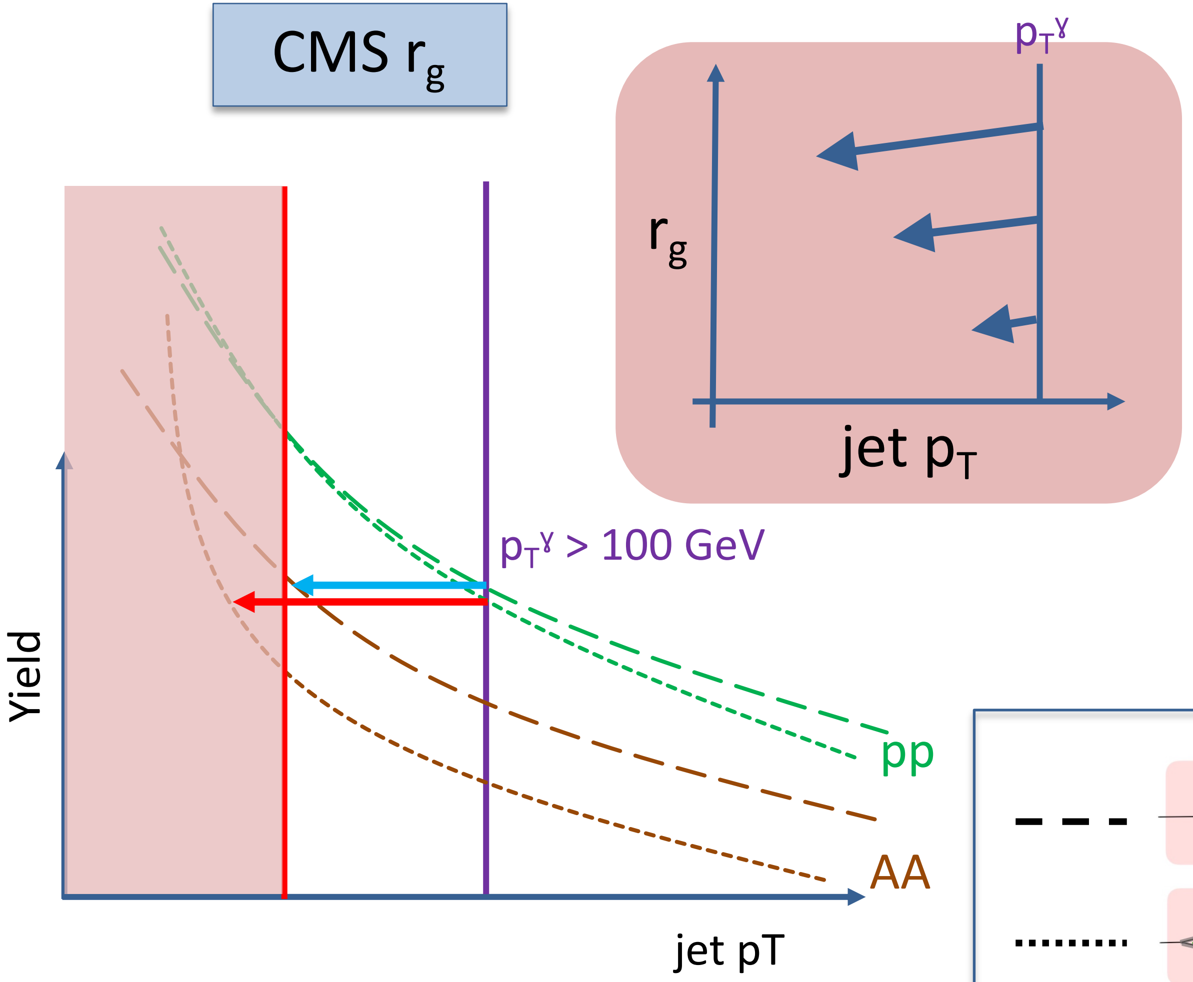




CMS vs. ATLAS measurement interpretations

CMS r_g



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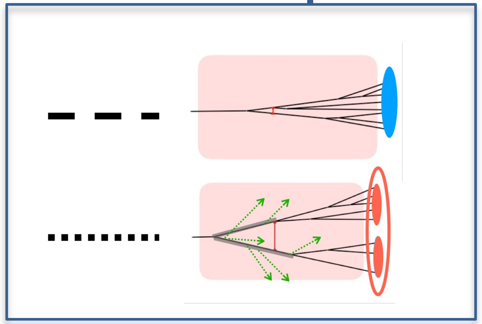
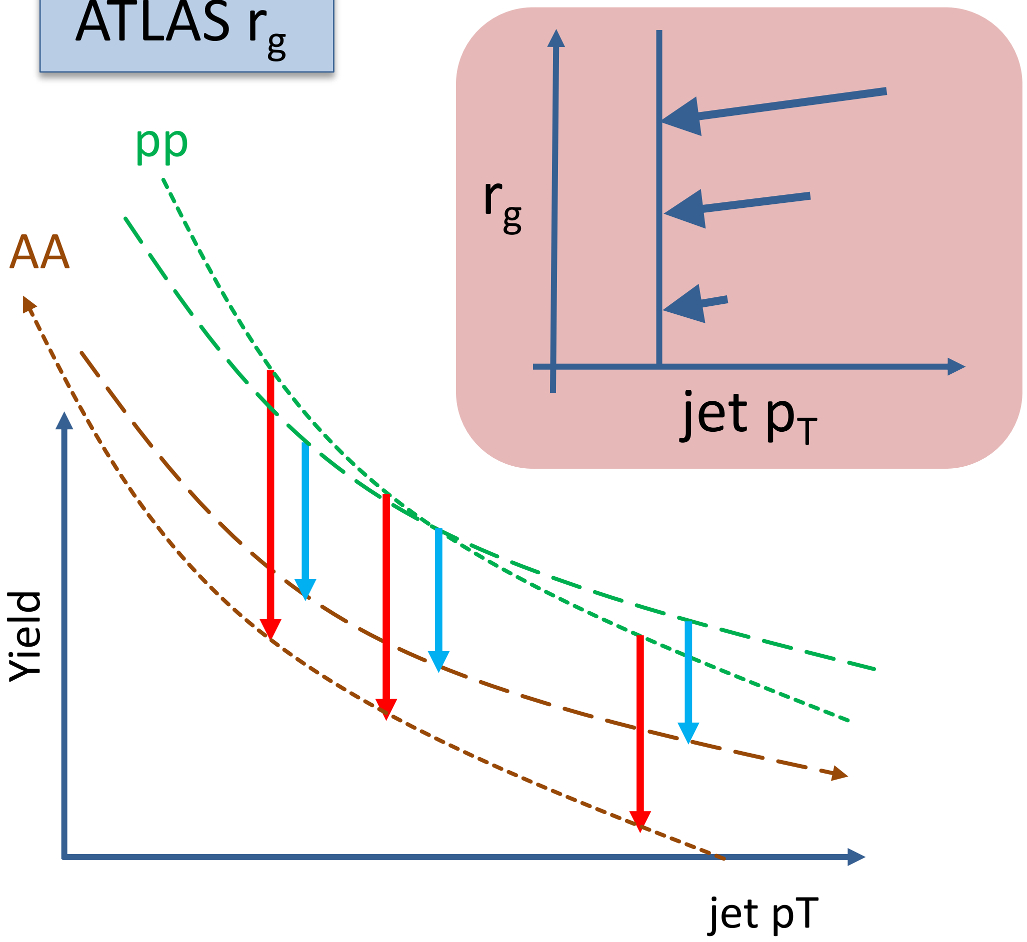


ATLAS r_g



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