Hard probes of heavy ion collisions with ATLAS

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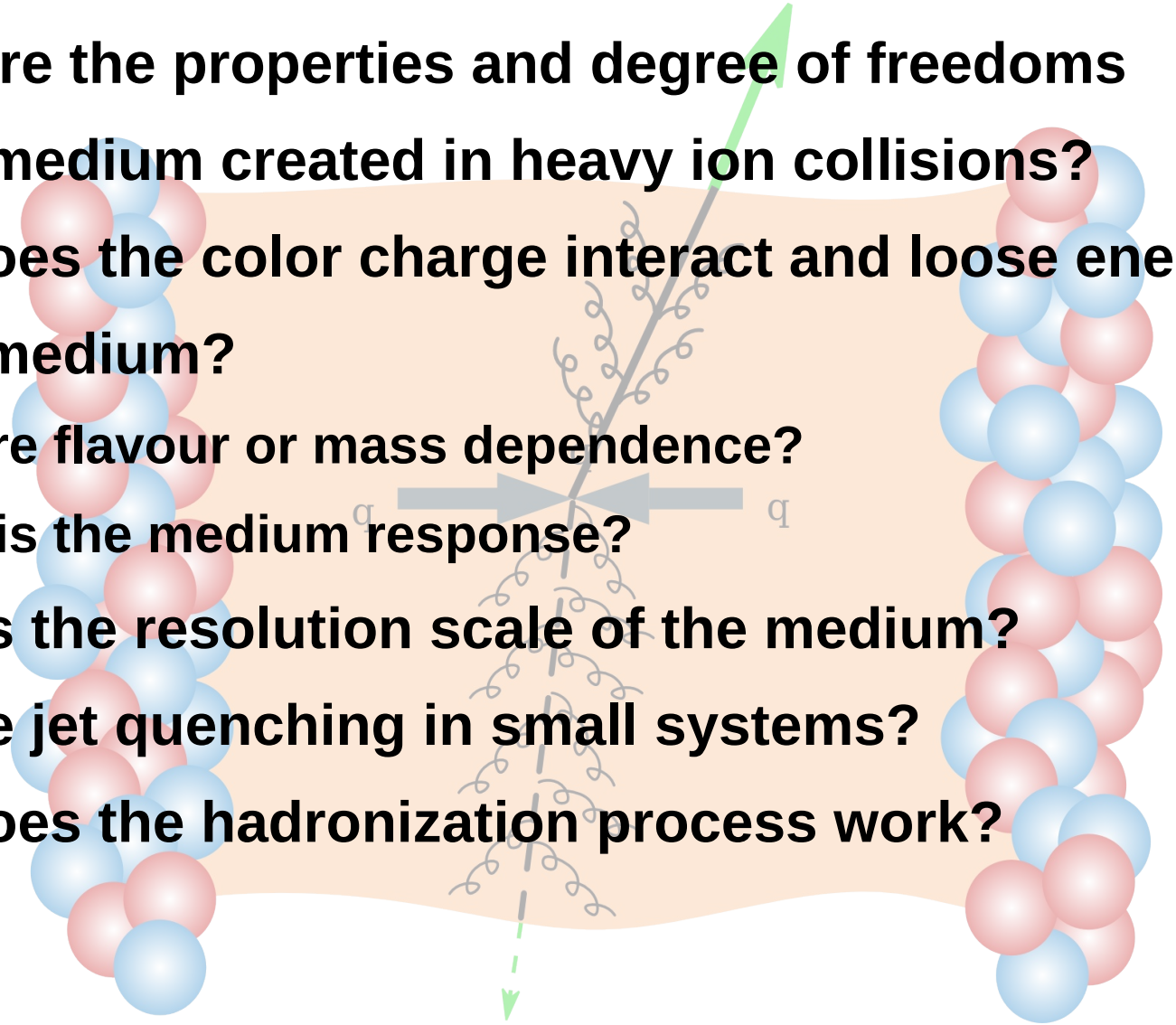
What do we want to know...

- What are the properties and degree of freedoms of the medium created in heavy ion collisions?
- How does the color charge interact and loose energy in the medium?
  - Is there flavour or mass dependence?
  - What is the medium response?
- What is the resolution scale of the medium?
- Is there jet quenching in small systems?
- How does the hadronization process work?



Hard probes of QGP

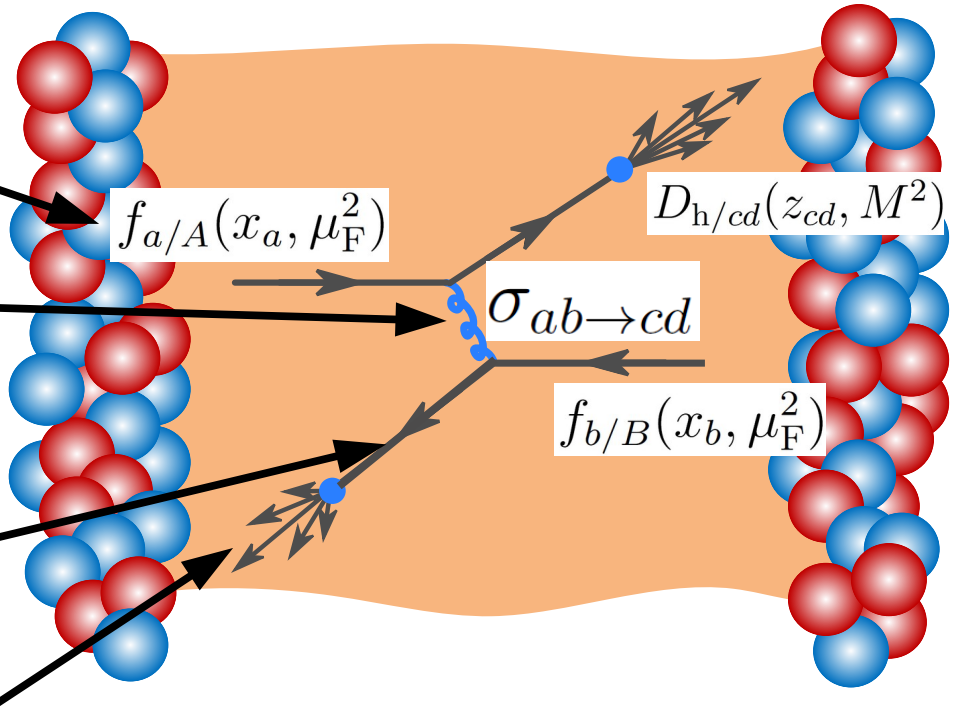
We can use hard probes to answer these questions!

nPDF effects

Hard scattering: high energy, short distance

Emissions of collinear and soft partons, elastic scattering, drag force

Hadronization

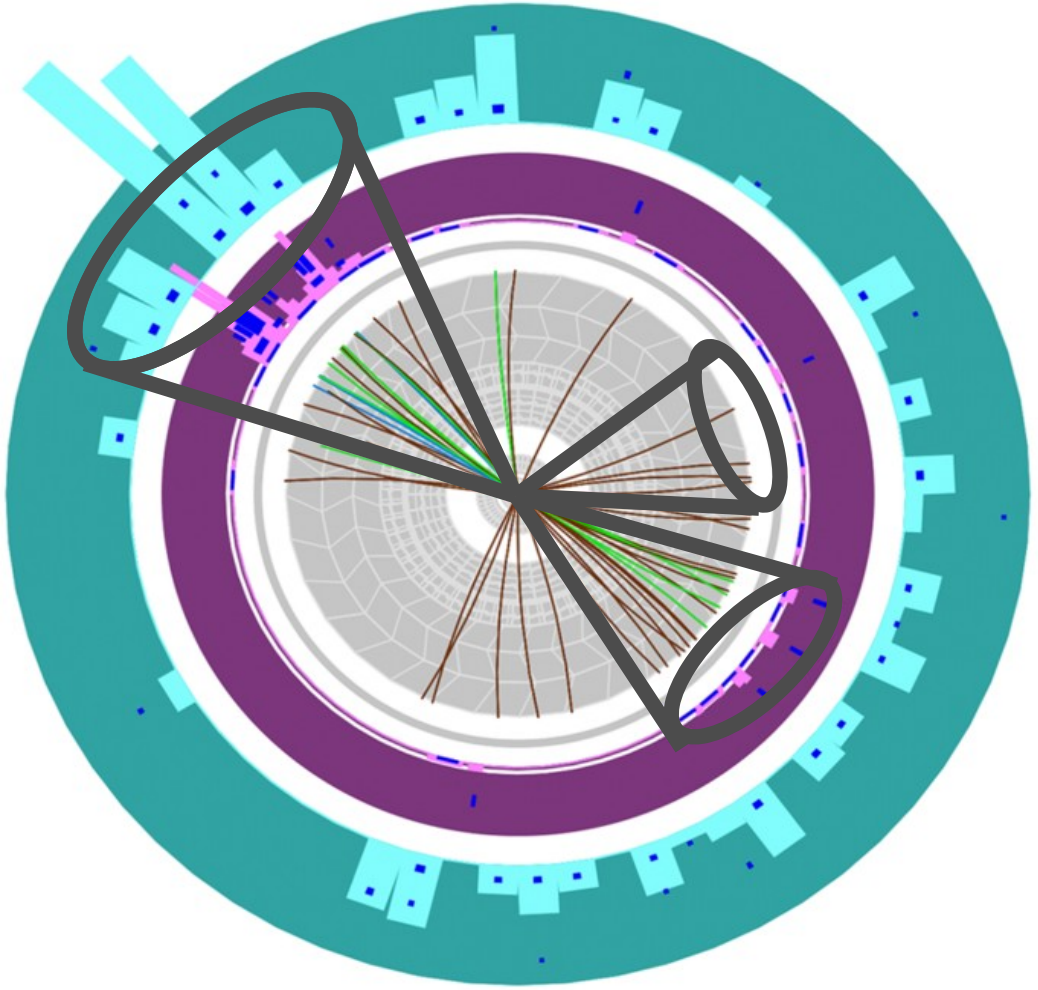


Fast partons lose energy in the medium ➡ jet quenching

➡ **Hard processes probe the QGP at various scales.**

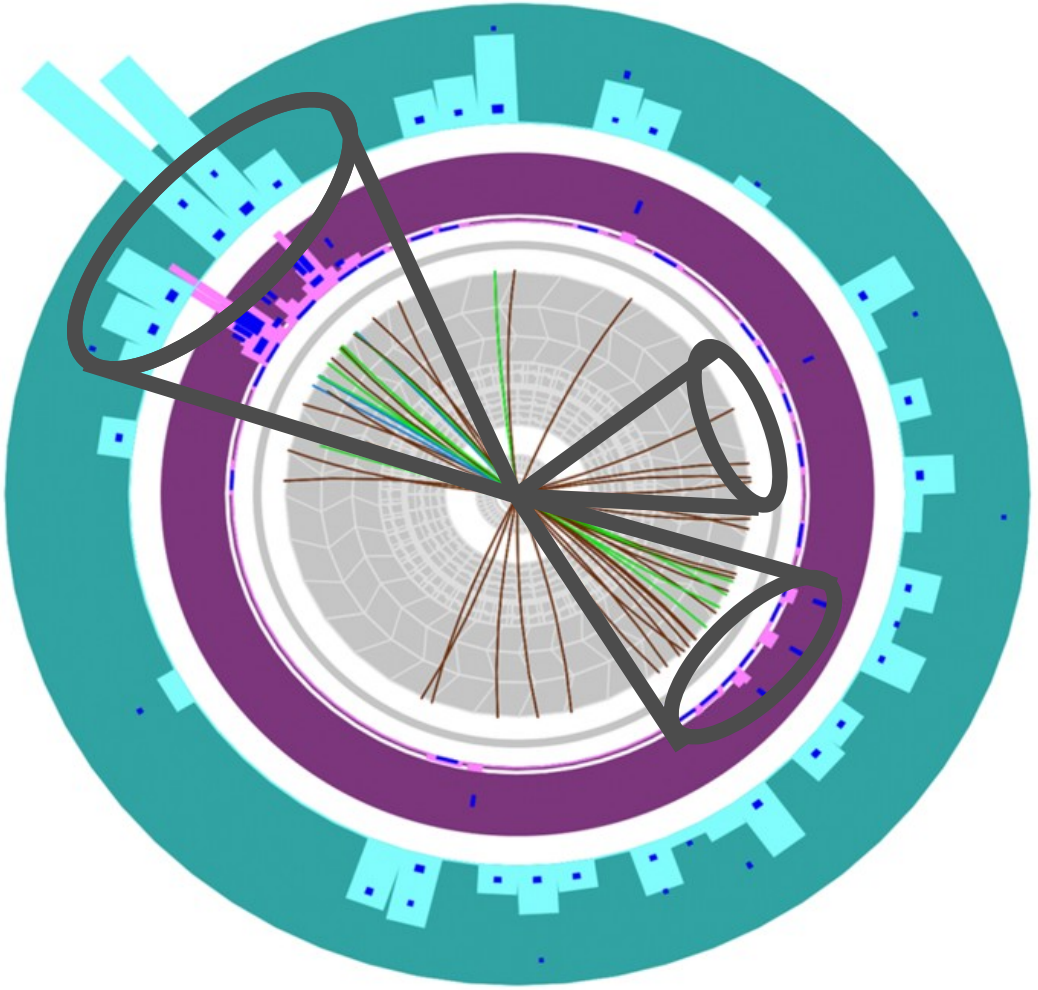
Jet quenching measurements

Many observables: inclusive jets, balance, jet structure...

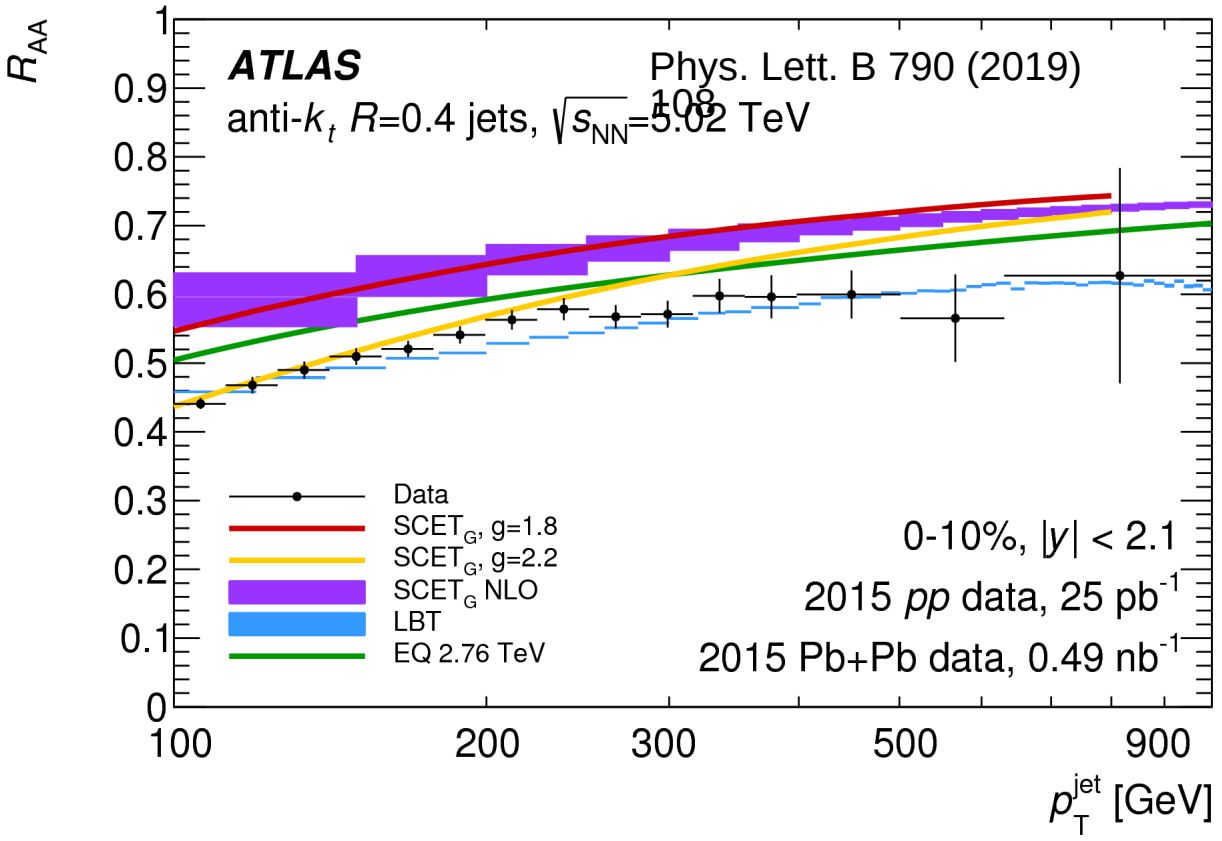


…each observable is sensitive to different aspects of energy loss.

Let’s start with jet counting….



Measure of modifications: Nuclear modification factor



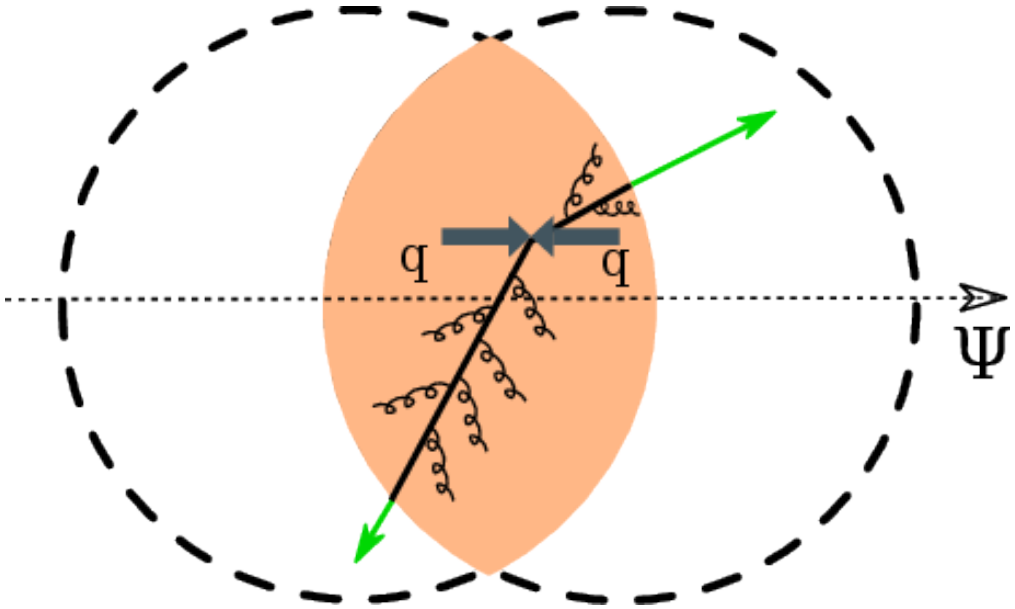
$$R_{AA} = \frac{1}{N_{\text{coll}}} \frac{\text{QCD in medium}}{\text{QCD in vacuum}} = \frac{\frac{1}{N_{\text{coll}}} \frac{dN_{AA}}{dp_T}}{\frac{dN_{pp}}{dp_T}}$$

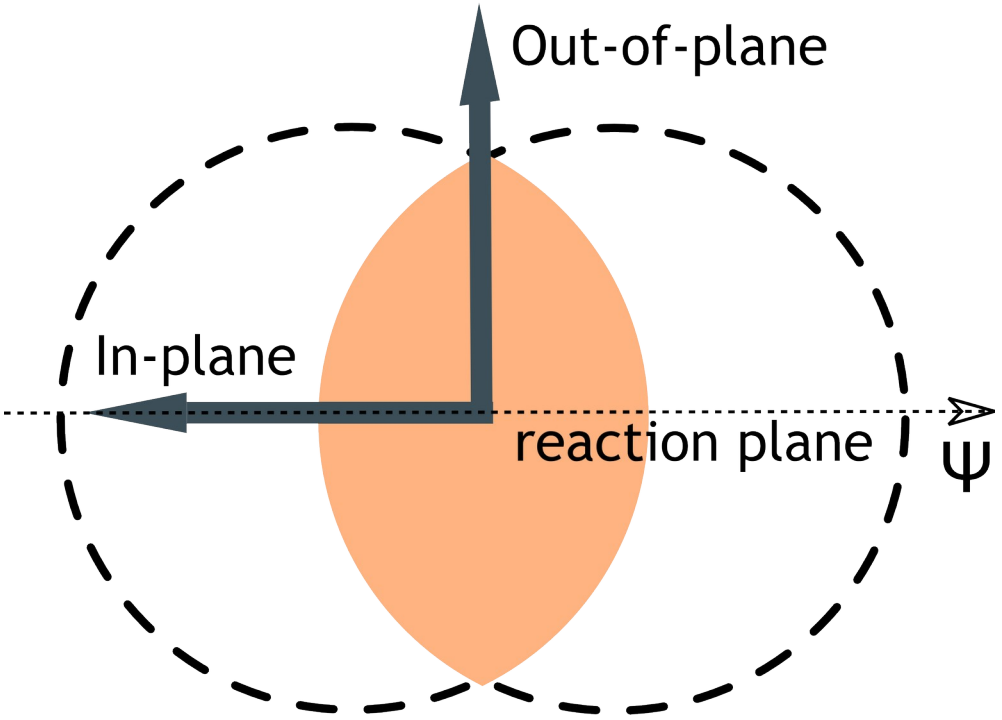
Caveat on R_{AA}:
Sensitive to shapes of p_T spectra

Lorentz Boltzmann Transport (LBT) model (arXiv:1503.03313)
Soft Collinear Effective Field Theory (SCETg) (arXiv:1509.02936)
Effective Quenching (EQ) model (arXiv:1504.05169)

Jet anisotropies

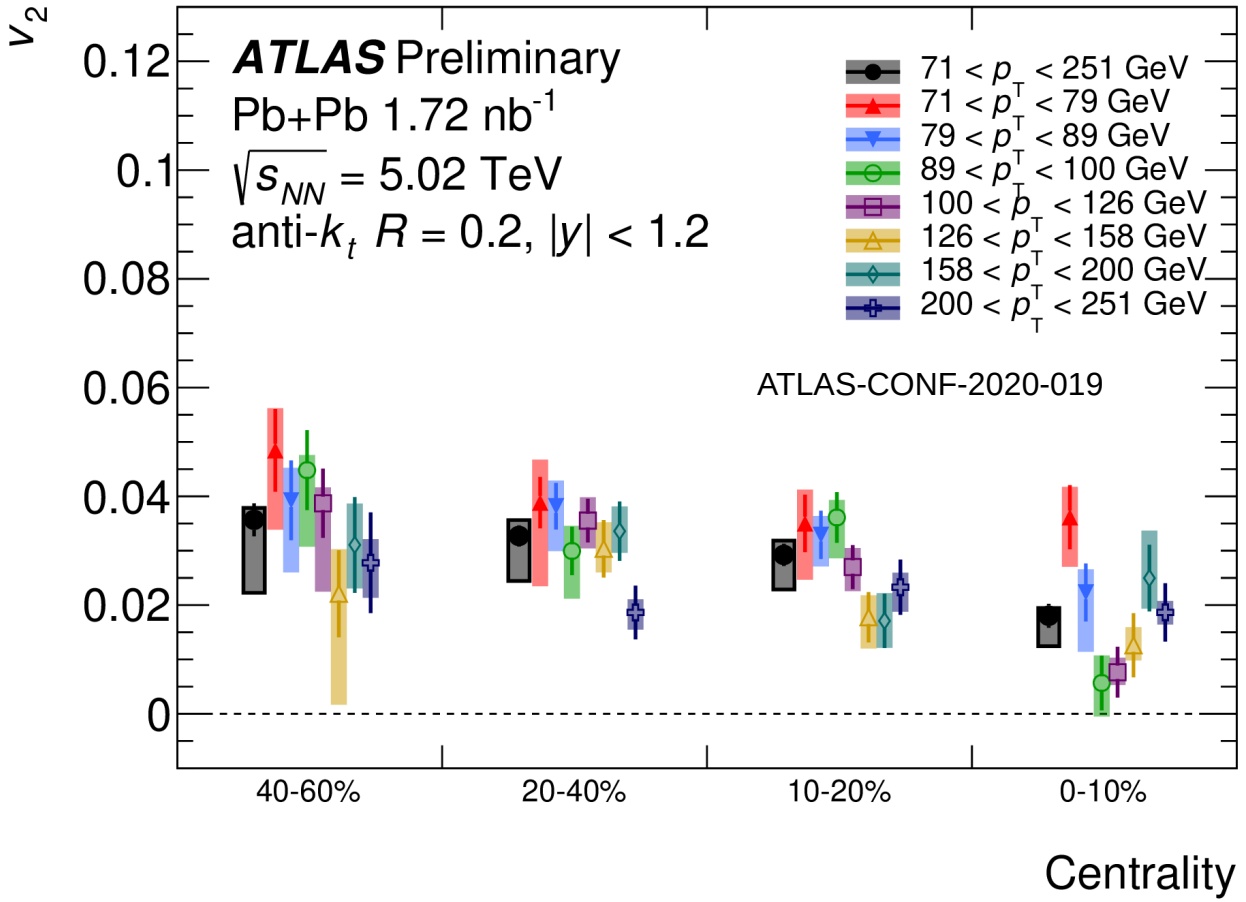
- Measuring jet yields deferentially w.r.t. reaction plane.





The angular distribution of jets is described via a Fourier expansion: $$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{n} v_n \cos(n(\phi - \Psi_n))$$

Path-length dependence: jet v_2



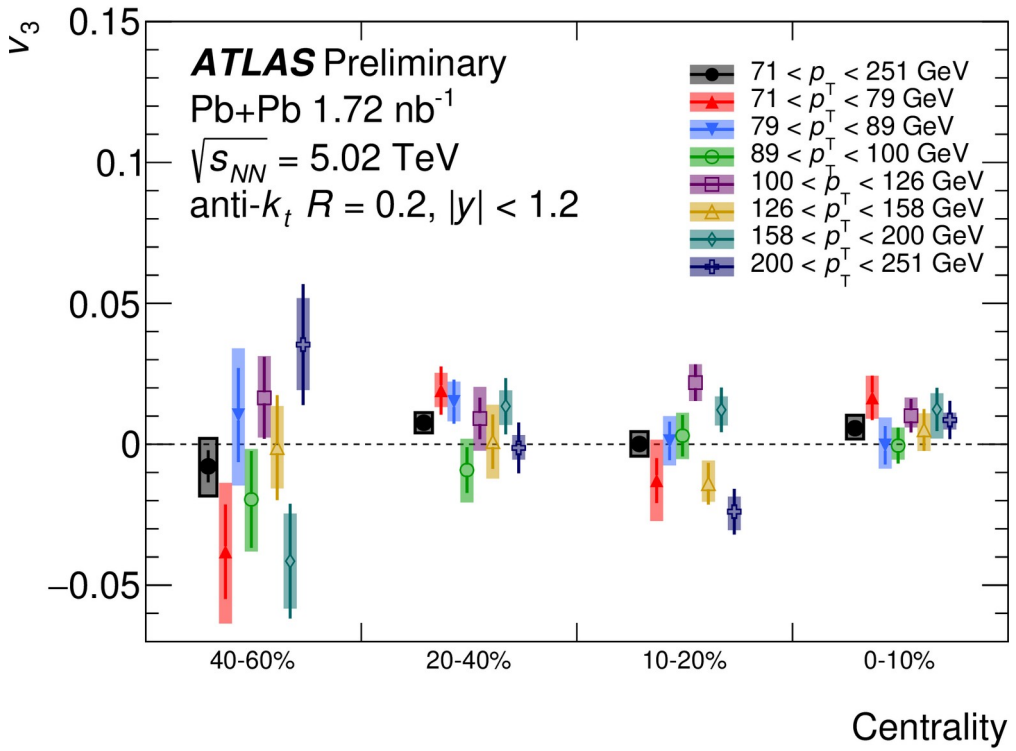
In-plane: shorter path length in the medium ➡ less suppression

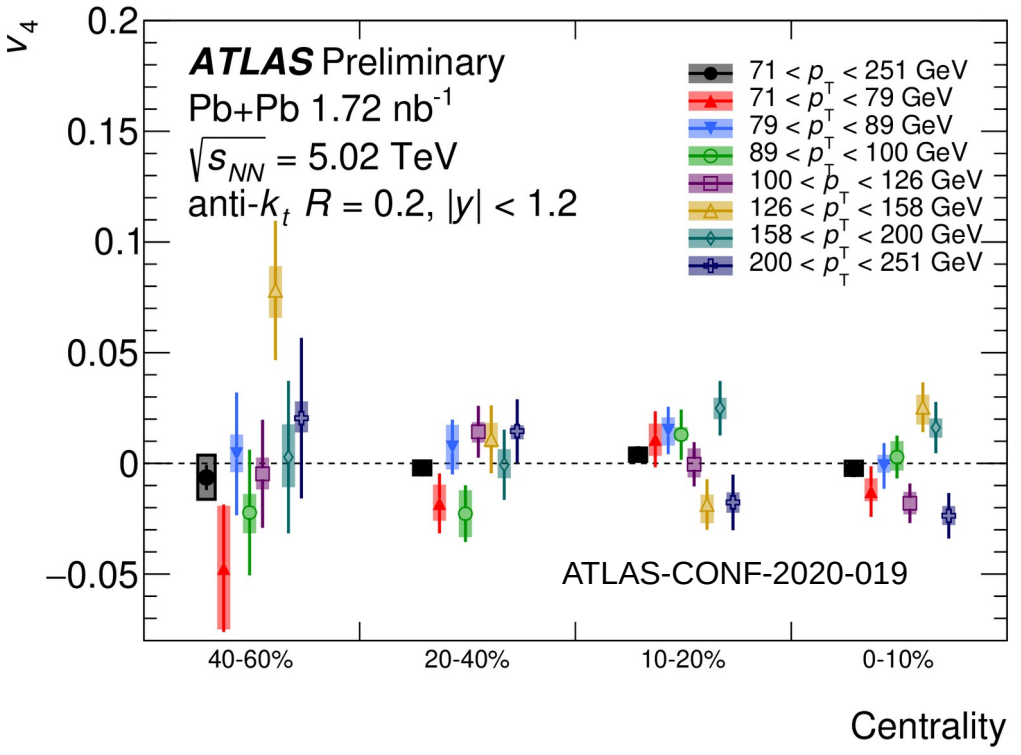
Out-of-plane: longer path length in the medium ➡ more suppression

➡ **positive v_2.**

Fluctuations: Jet $v_{n;n>2}$

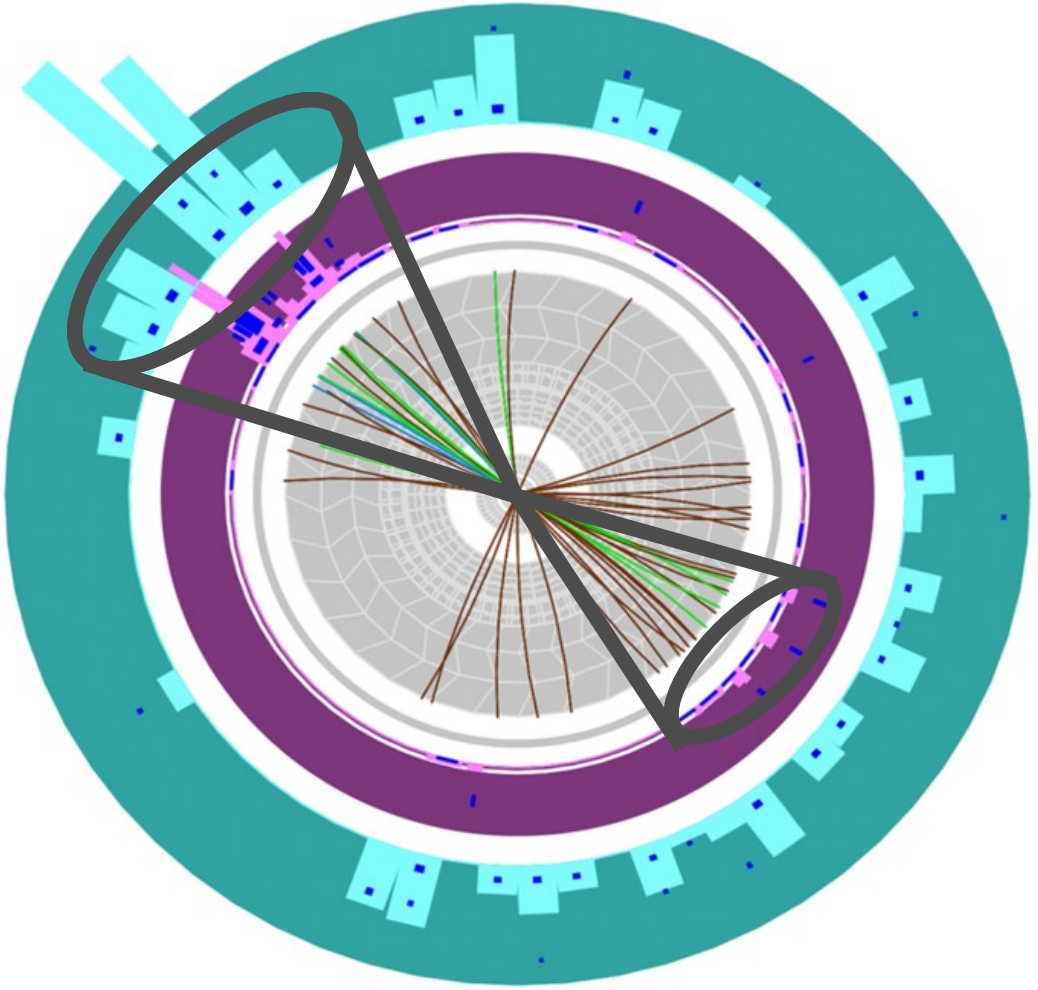
Can give insight into the role of fluctuations in the initial state.





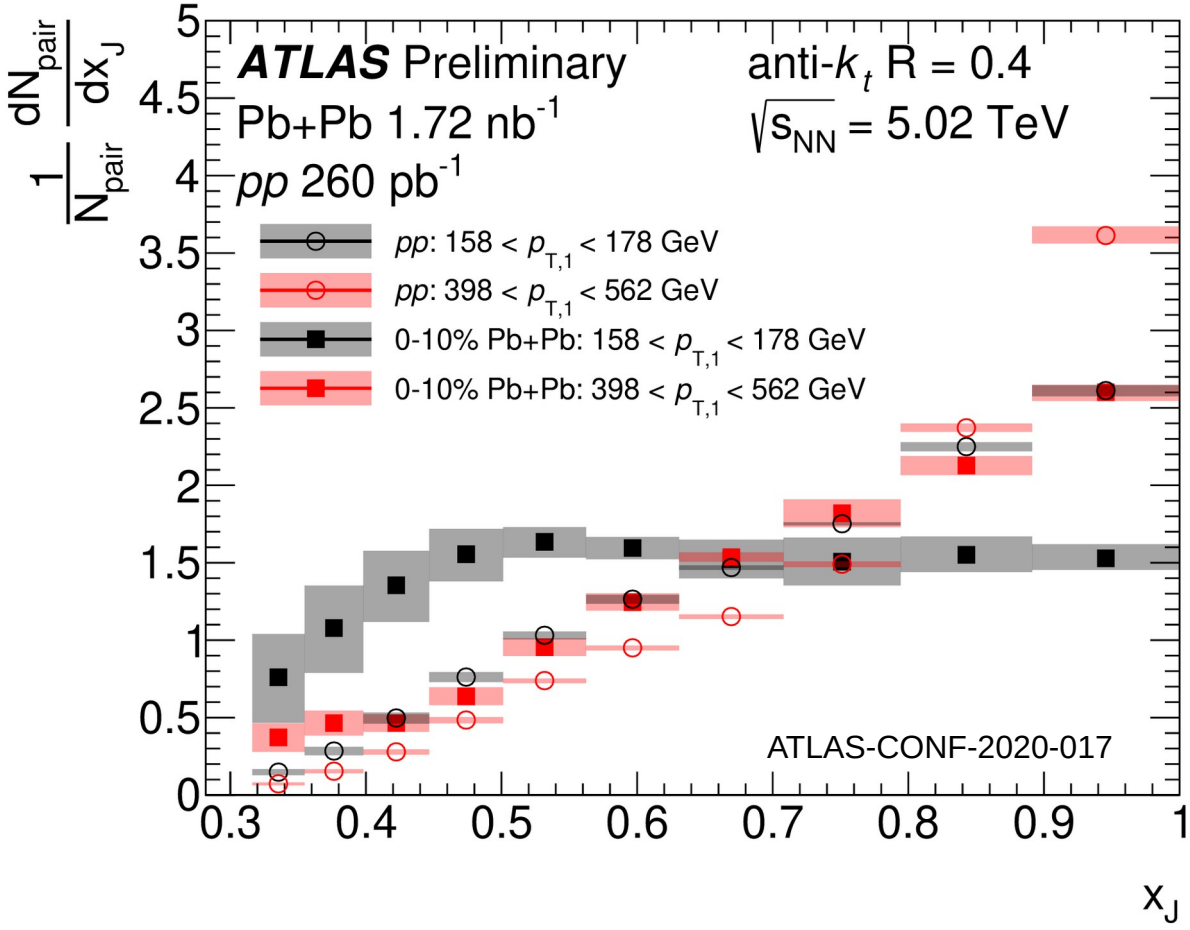
- Jet v_3 and v_4 compatible with zero with current precision.

Balance & angular correlation measurements



Di-jet balance

Probes path-length dependence and per-jet fluctuations of the jet quenching.

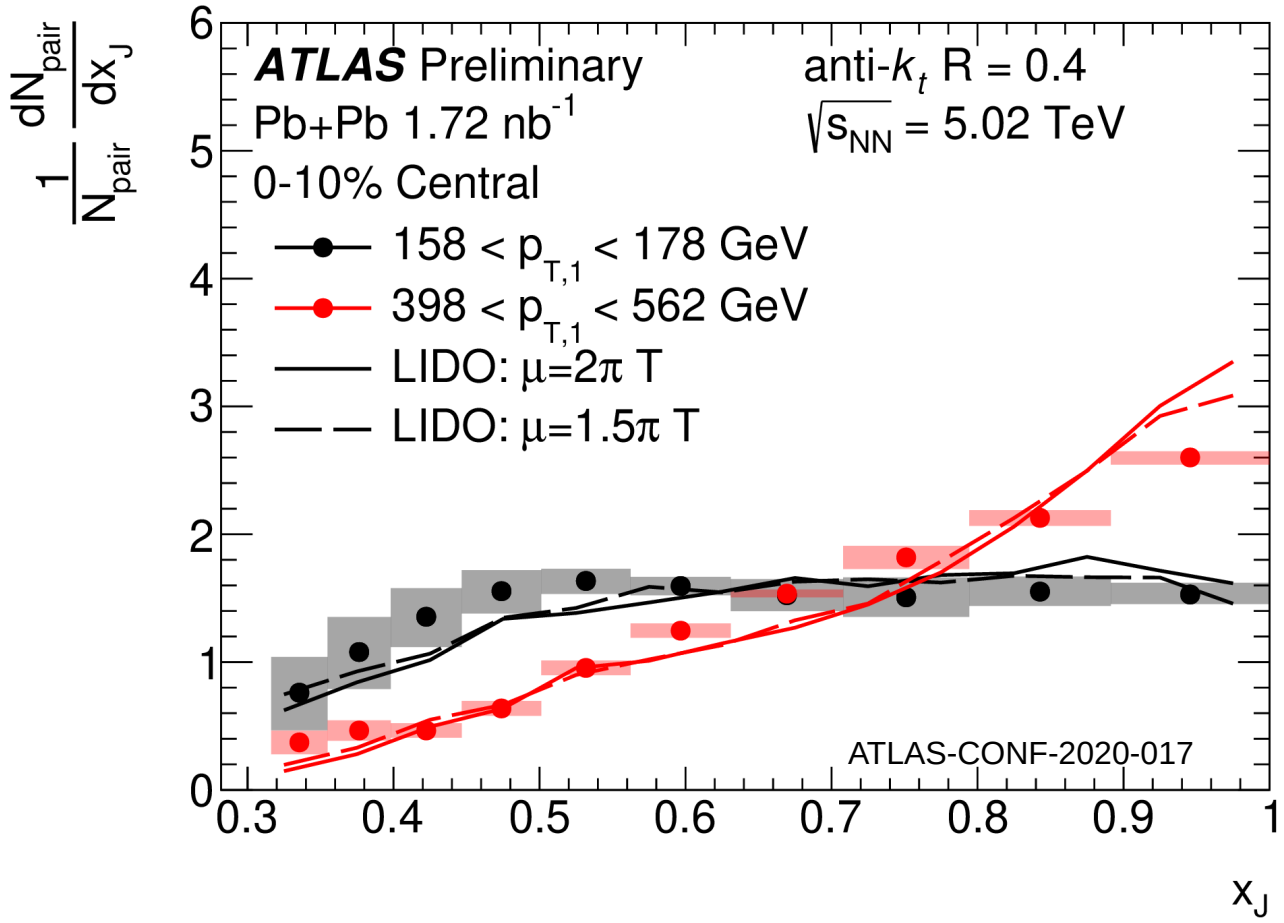


$$x_{\mathrm{J}} \equiv p_{\mathrm{T}_2}/p_{\mathrm{T}_1}$$

- Flattening of the x_{J} distributions in central Pb+Pb at lower p_{T}.
- Still some, but smaller, modification between Pb+Pb and *pp* for jets $p_{\mathrm{T}} > 400$ GeV.

Di-jet balance

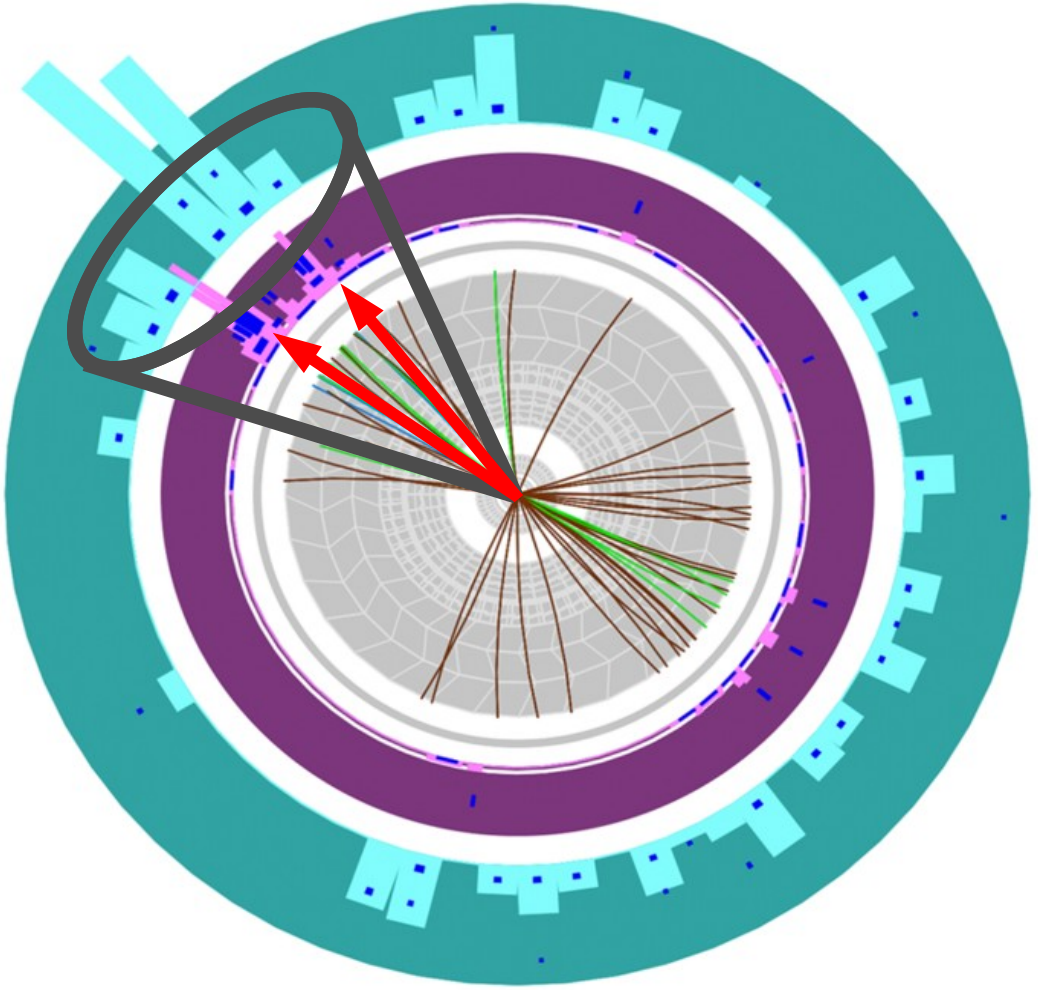
Probes path-length dependence and per-jet fluctuations of the jet quenching.



$$x_J \equiv p_{T_2}/p_{T_1}$$

- Linearized transport model with a jet-induced hydrodynamic response (LIDO) is consistent with the centrality and $p_{T,1}$ seen in the data.

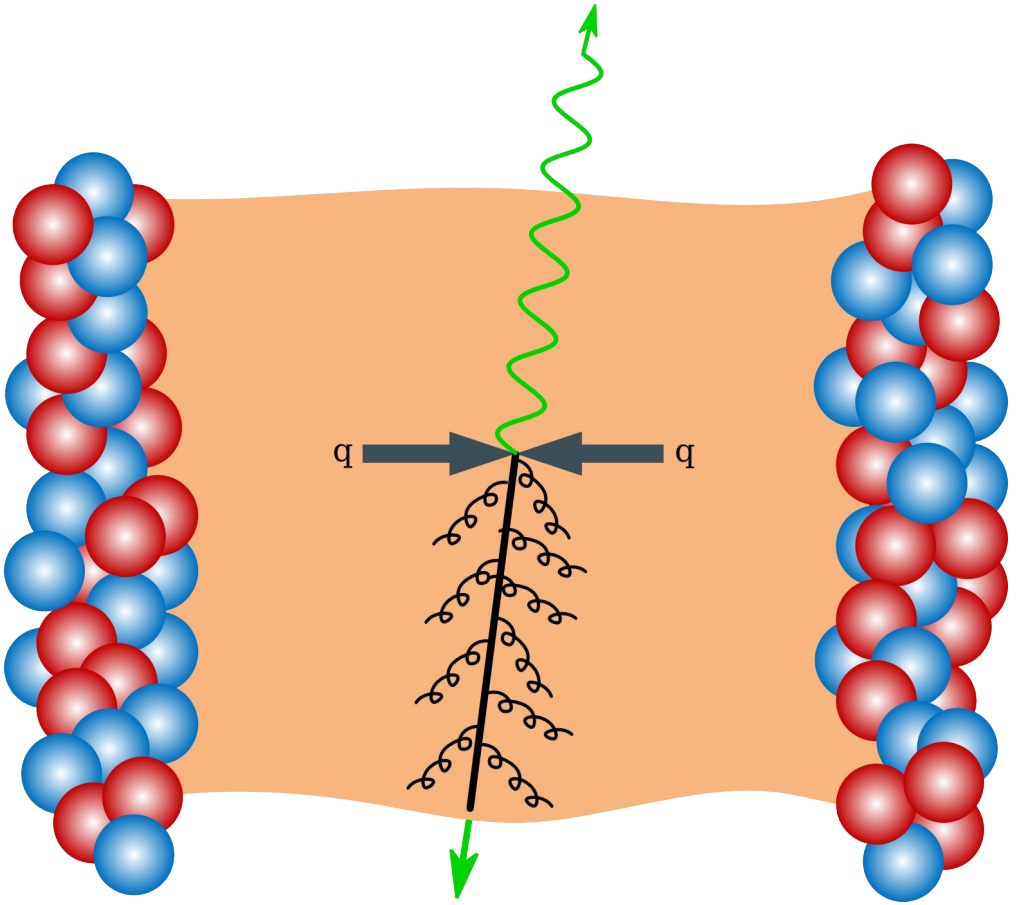
Jet structure and substructure



Moving forward with measurements of hadrons in jets

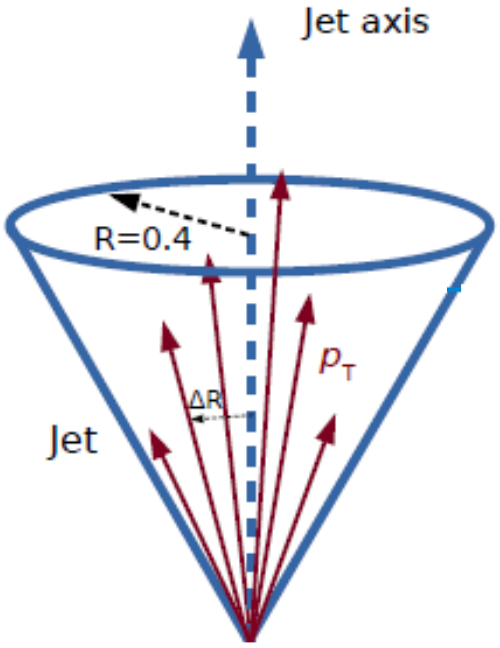
- Expanding existing measurements of inclusive jet fragmentation measurements and jet shapes (including large angles) measurements:

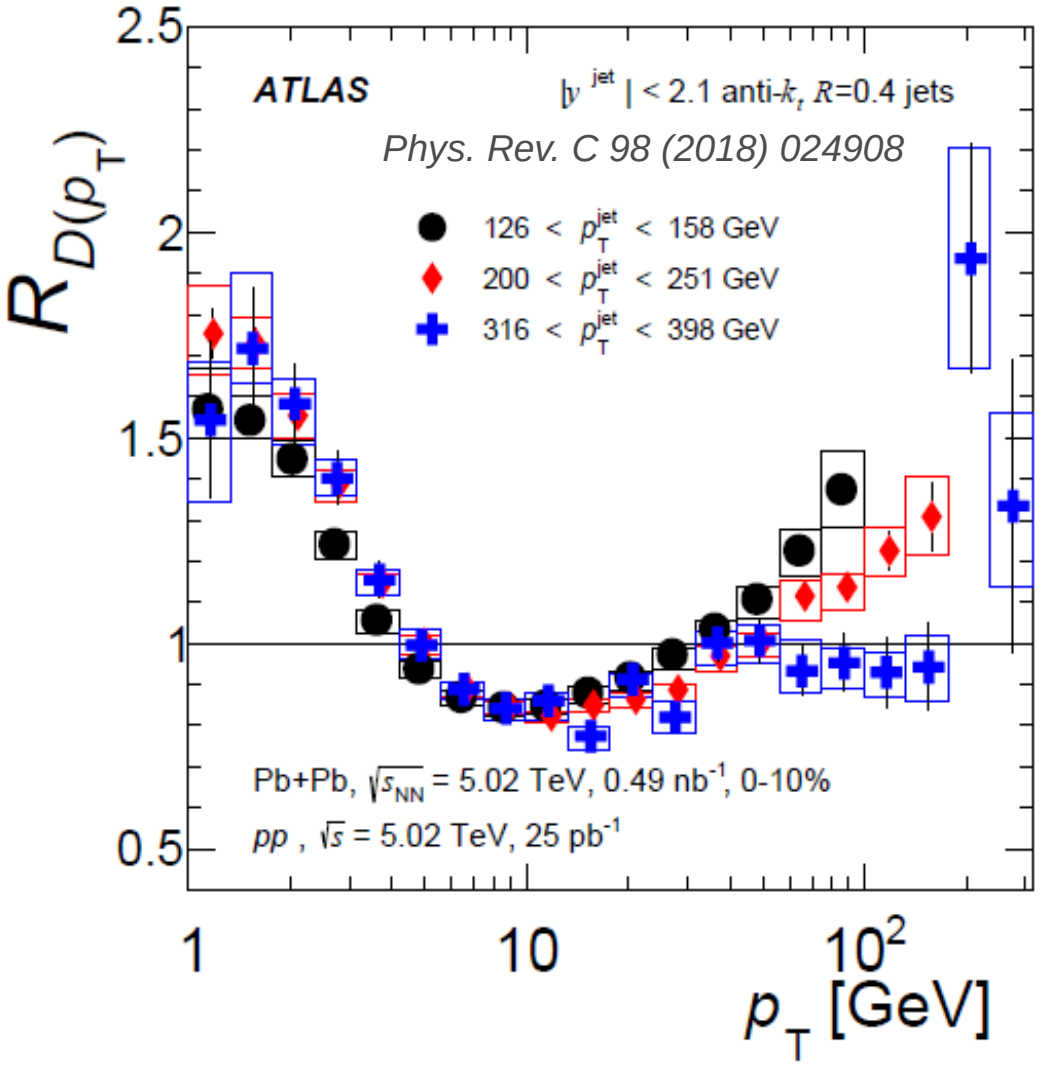
  Tagged jets and identified hadrons...



Towards Z-tagged measurements: inclusive fragmentation

What is the new information compared to the inclusive measurement?





Ratio of inclusive jet fragmentation functions in Pb+Pb and pp.

Towards Z-tagged measurements: inclusive fragmentation

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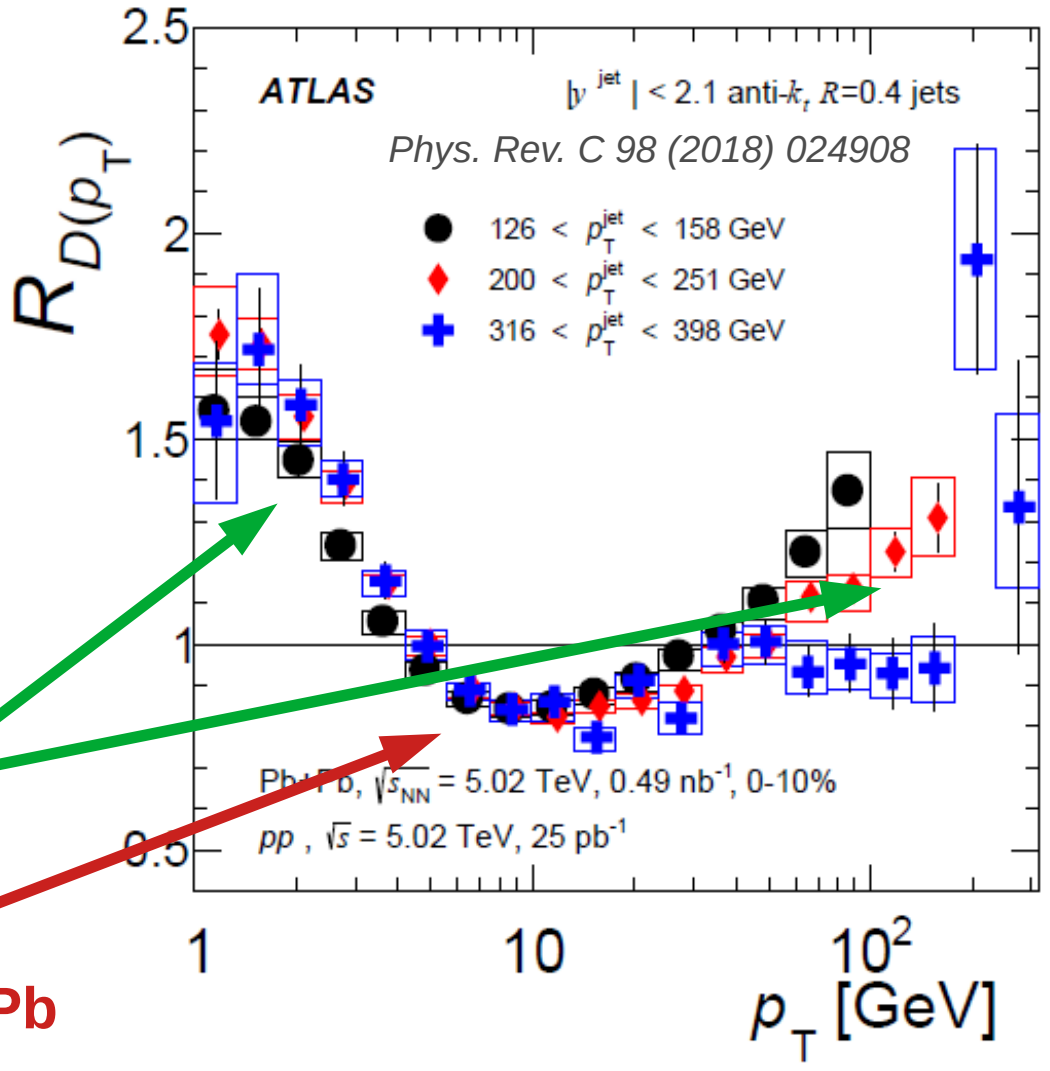


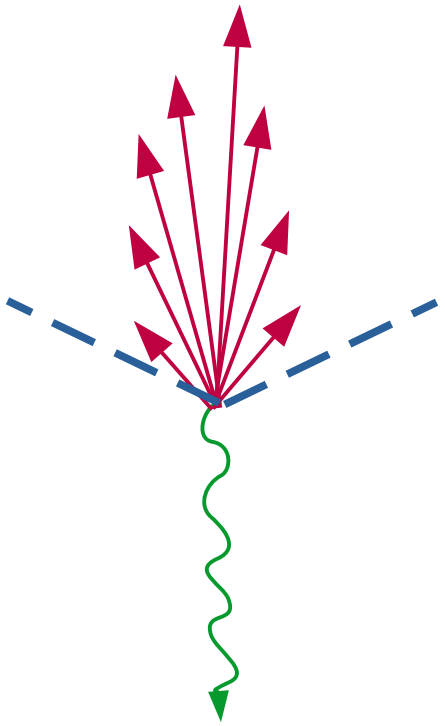
More soft and hard particles in Pb+Pb

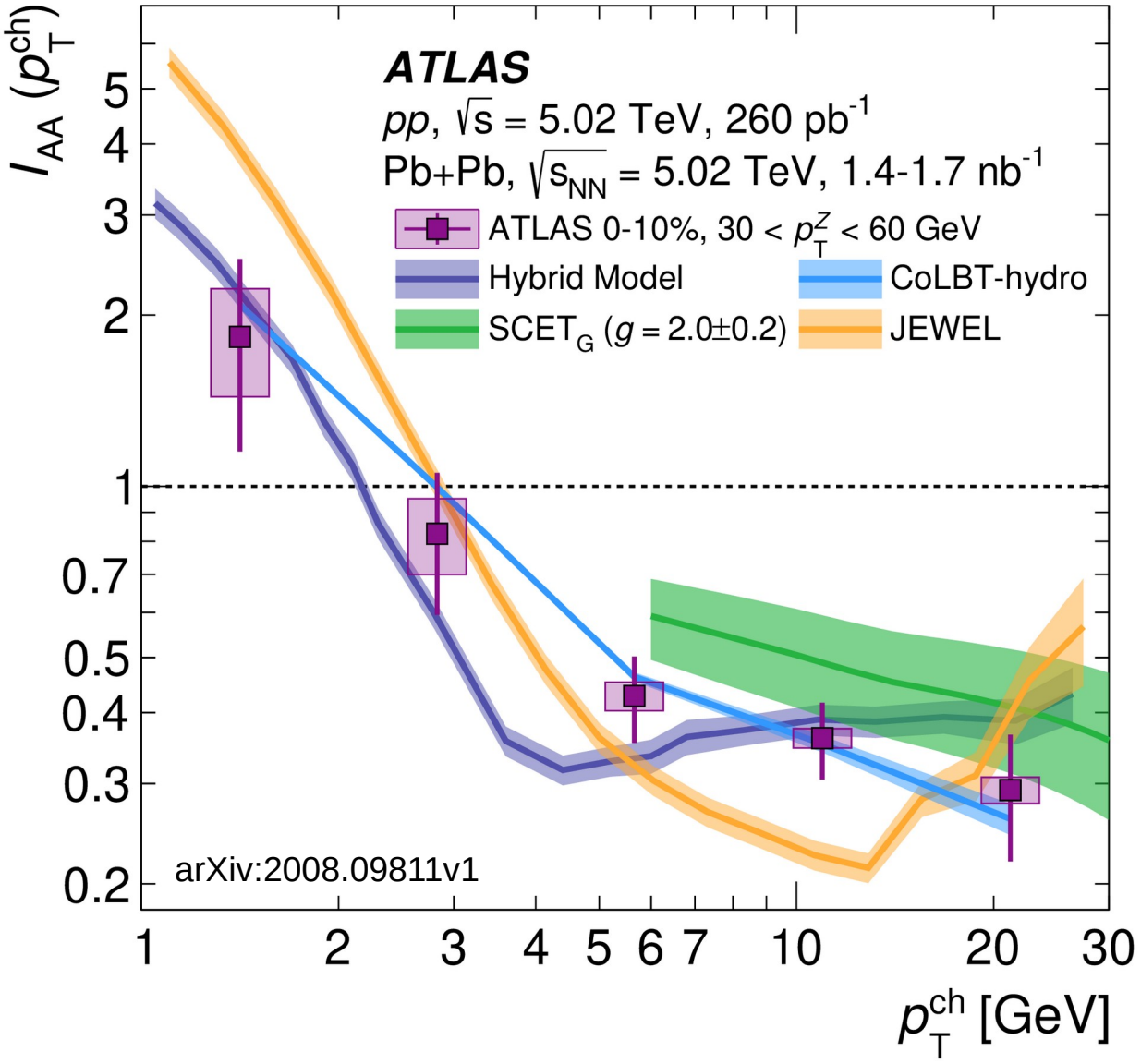
Less mid-p_T particles in Pb+Pb

Ratio of inclusive jet fragmentation functions in Pb+Pb and pp.

Z-tagged measurements

What is the new information compared to the inclusive measurement?

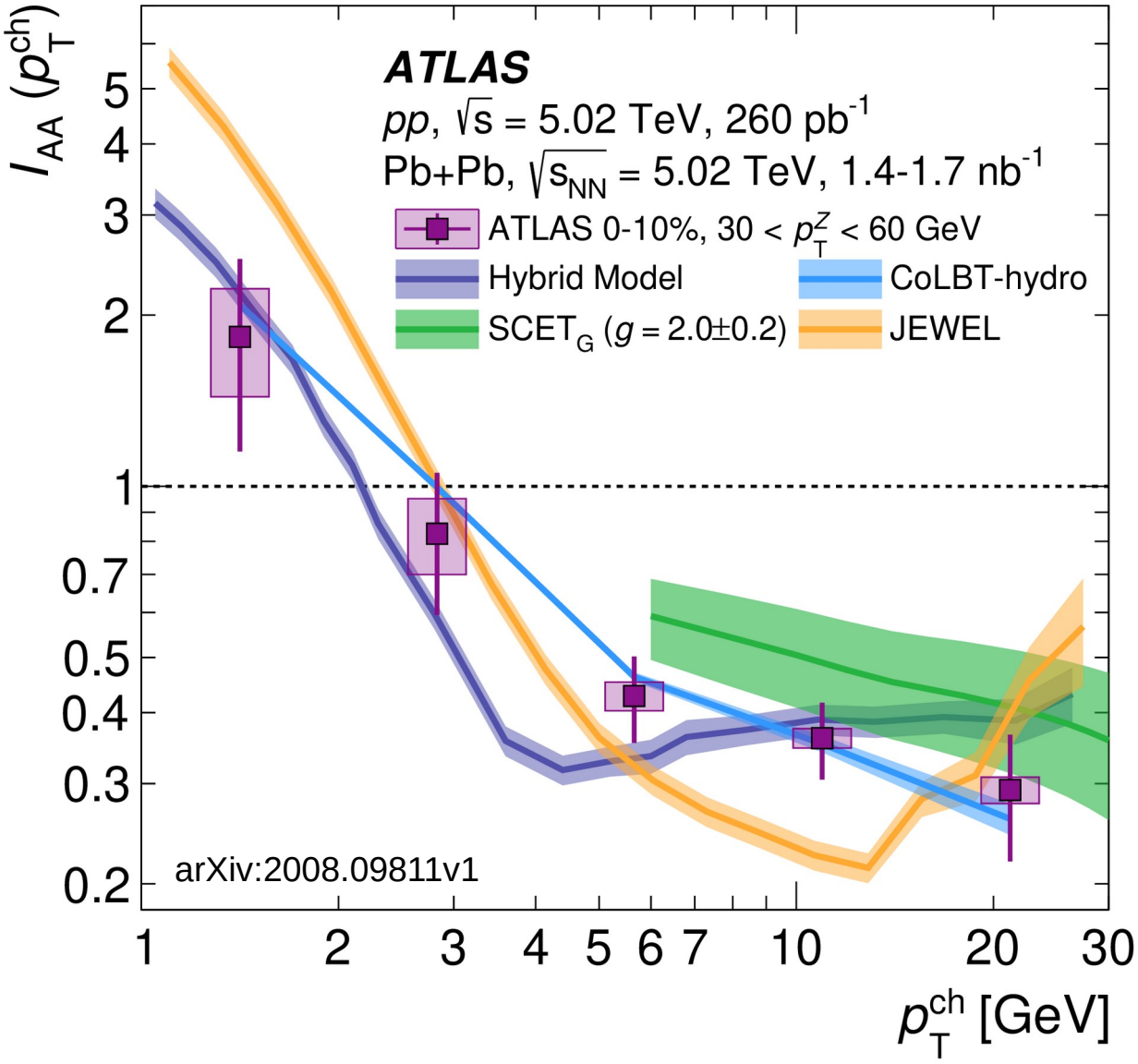




Z-tagged measurements

What is the new information compared to the inclusive measurement?

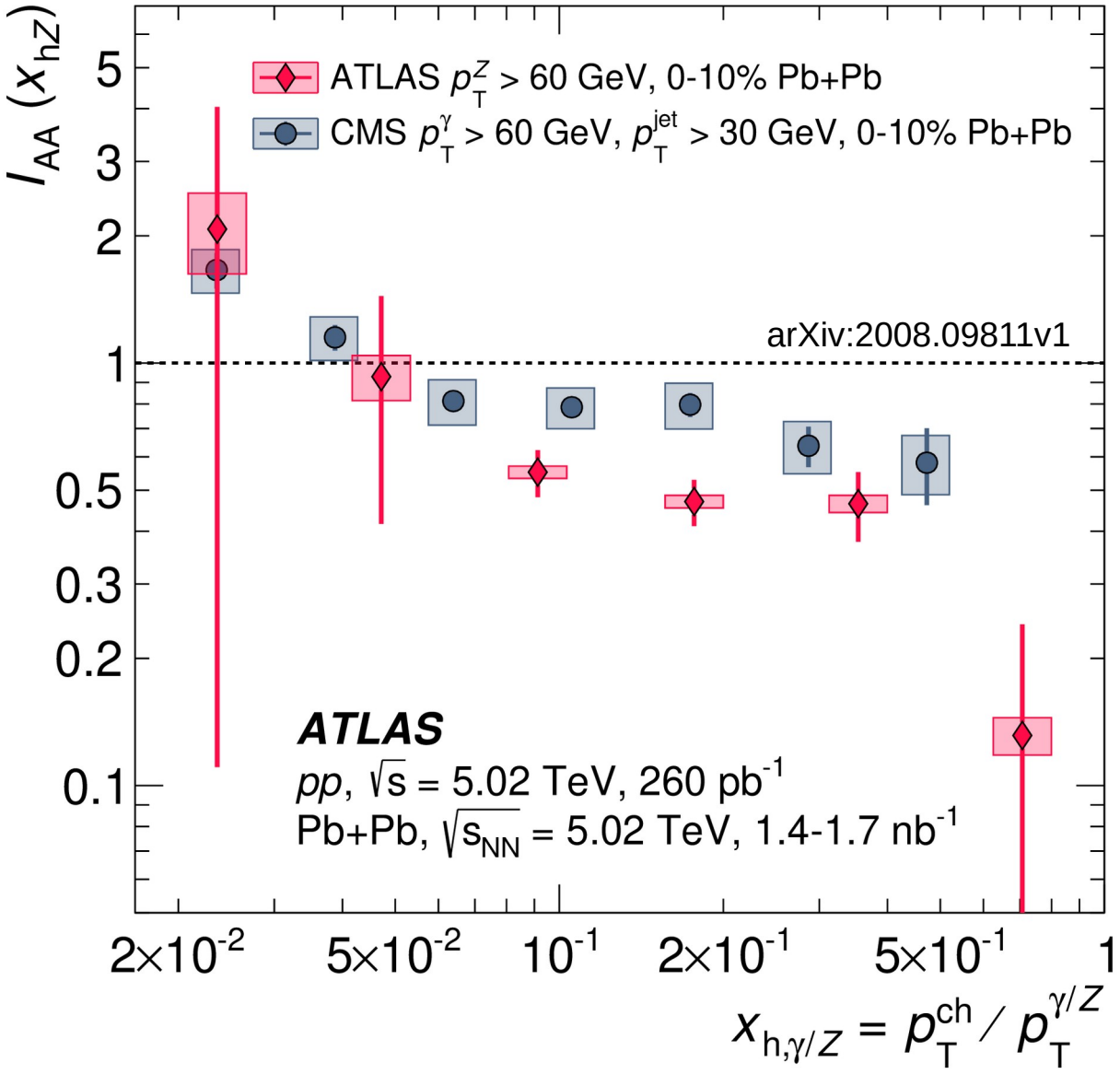
- Quark dominated jet sample
- Access to low p_T (jet) region.
- Comparable features as in other measurements of jet fragmentation.



Z-tagged measurements

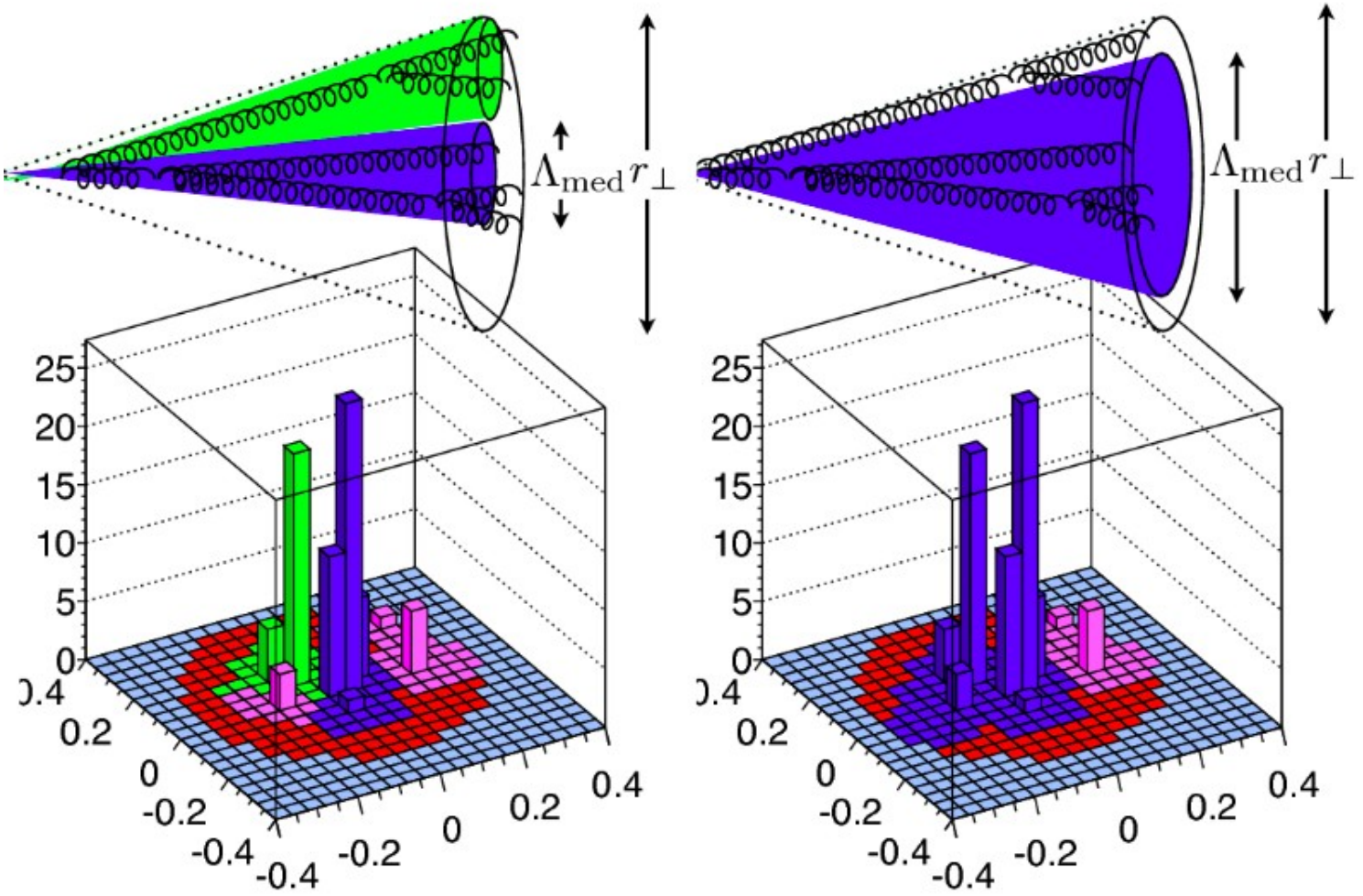
What is the new information compared to the inclusive measurement?

- Quark dominated jet sample.
- Testing role of parton virtuality when comparing Z- and γ-tagged measurements.
- Access to low p_T (jet) region
- γ-tagged measurements differs in kinematic region → large quenched jets not included.



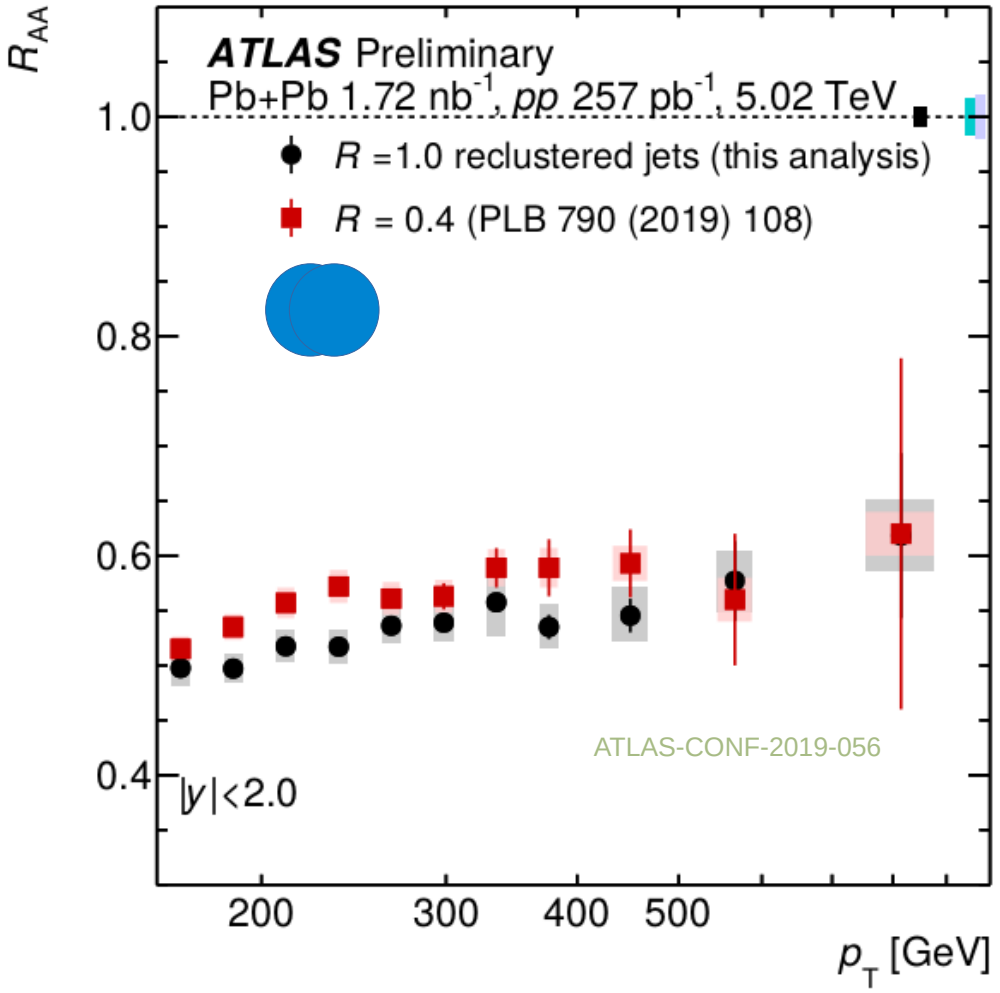
Jet substructure

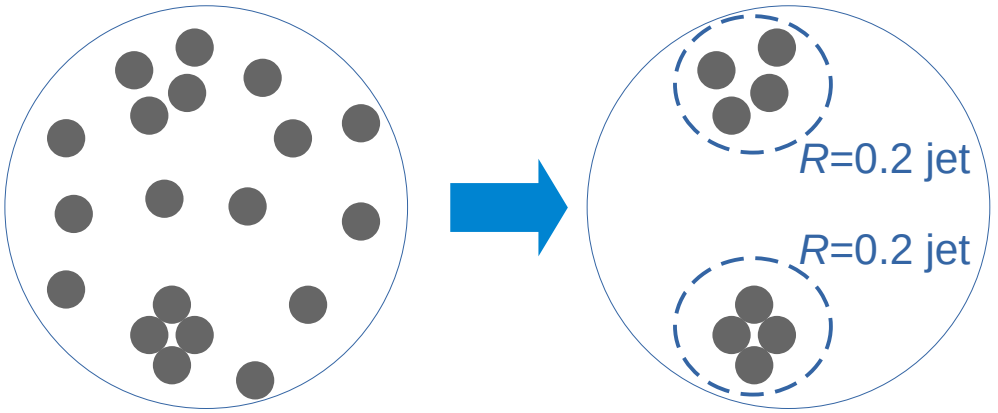
Does the jet suppression depend on jet structure?



J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

Dependence of jet suppression on substructure



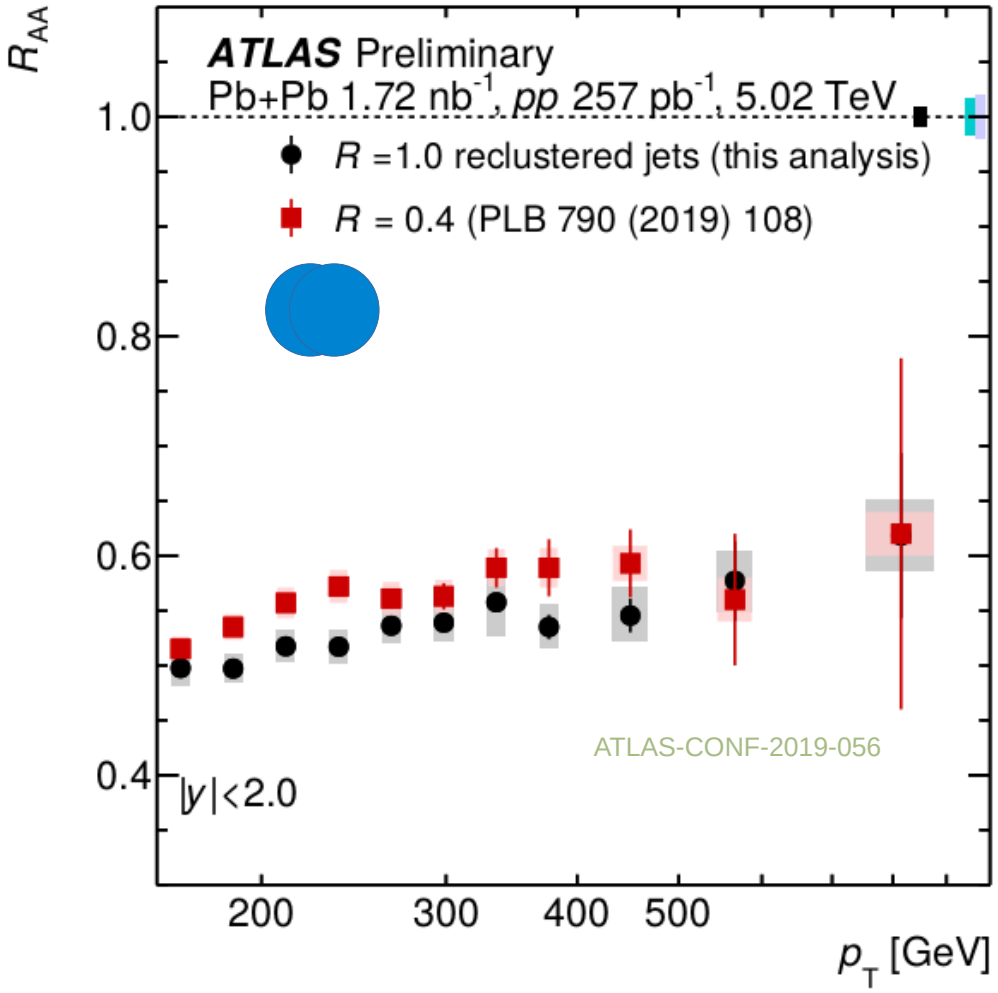


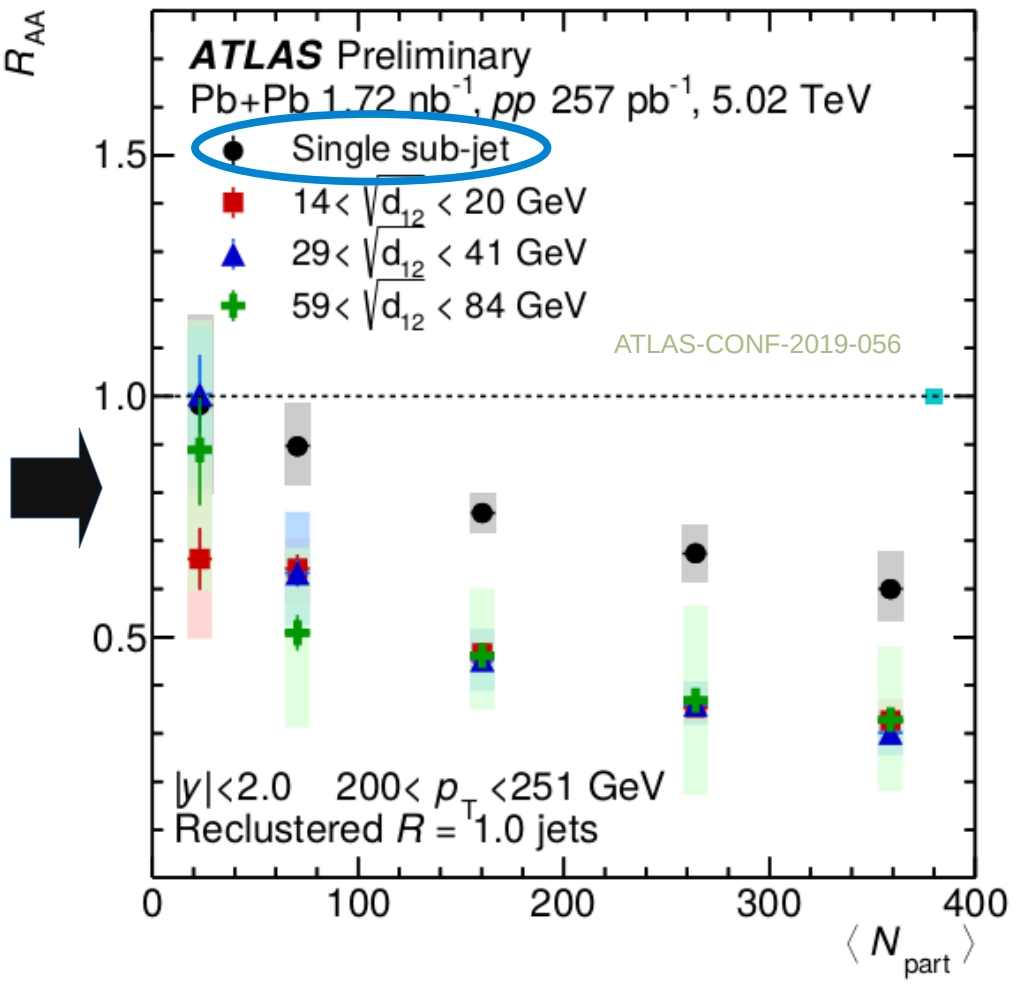
"Conventional" large-*R* jet

Re-clustered large-*R* jet with 0.2 jets as constituents

- Soft contribution is removed from *R*=1.0 re-clustered jets.
  → Larger suppression compared to ordinary small-*R* jets.
  → Focus on hard splittings.

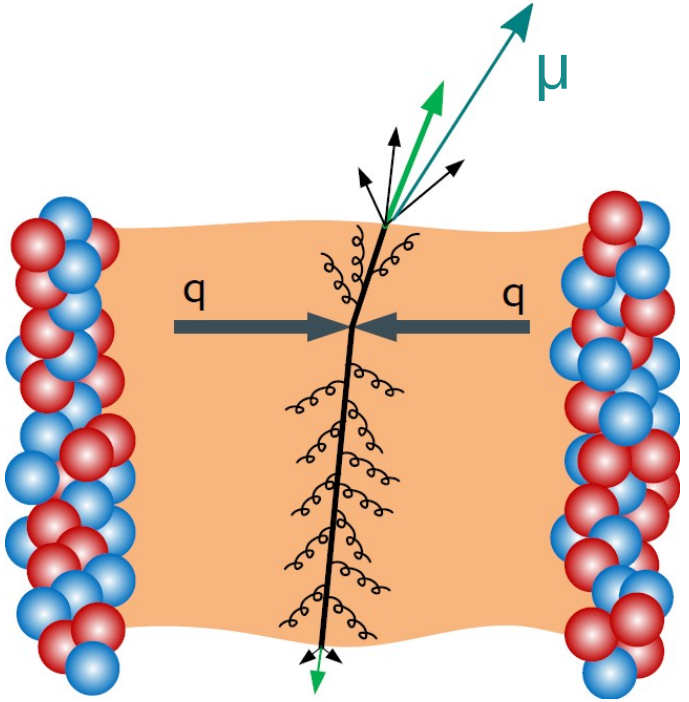
Dependence of jet suppression on substructure





- A continuous increase of the suppression with increasing centrality.
- The jets with single sub-jet are less suppressed with respect to those with higher sub-jet multiplicity → color decoherence.

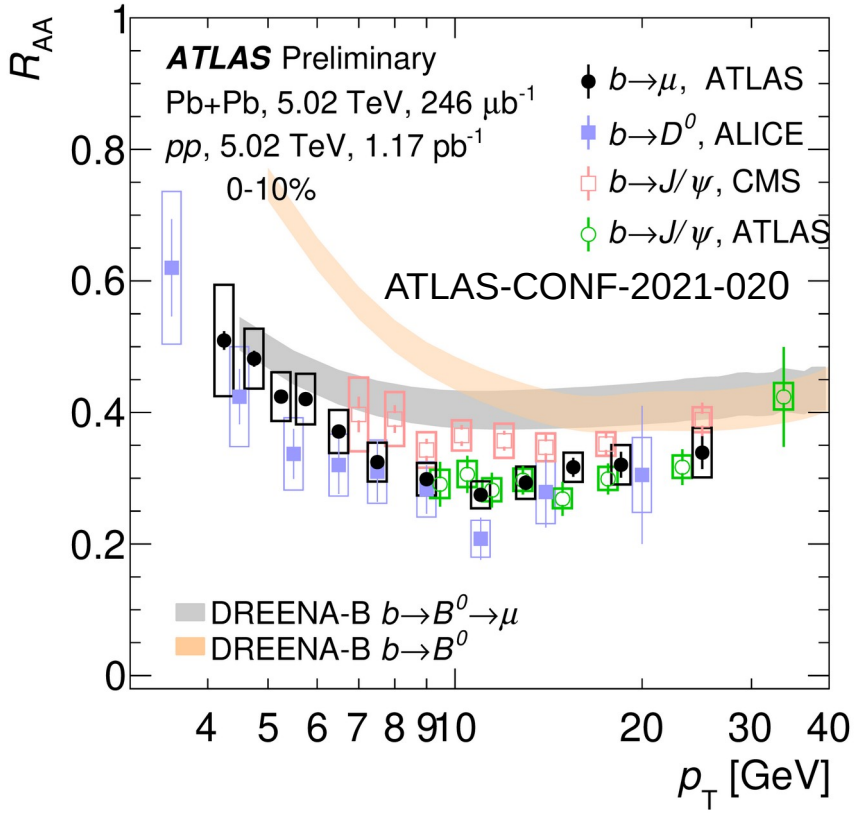
Open heavy flavor



- Mass of heavy quarks as additional relevant scale.
- Short formation time & small thermal production rate.
- pQCD calculable.
- Energy loss depends on:
  - Color charge $\Delta E_g > \Delta E_{u,d,s}$
  - Parton mass $\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Open heavy flavor

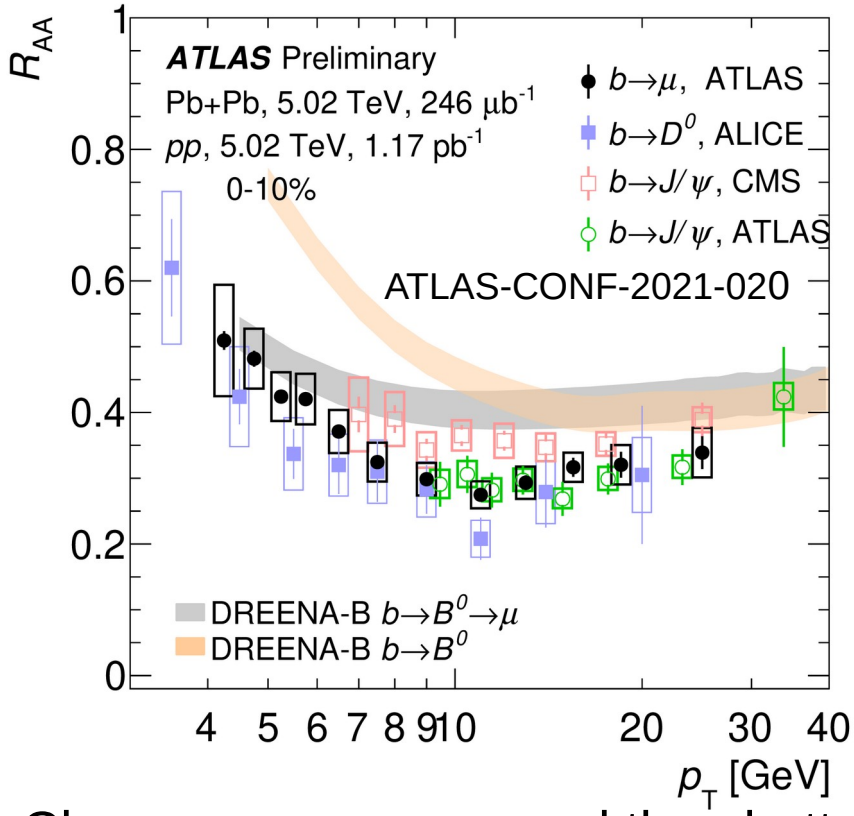
- B-quark production measured in various channels and compared to charm production ⟷ decay kinematics.

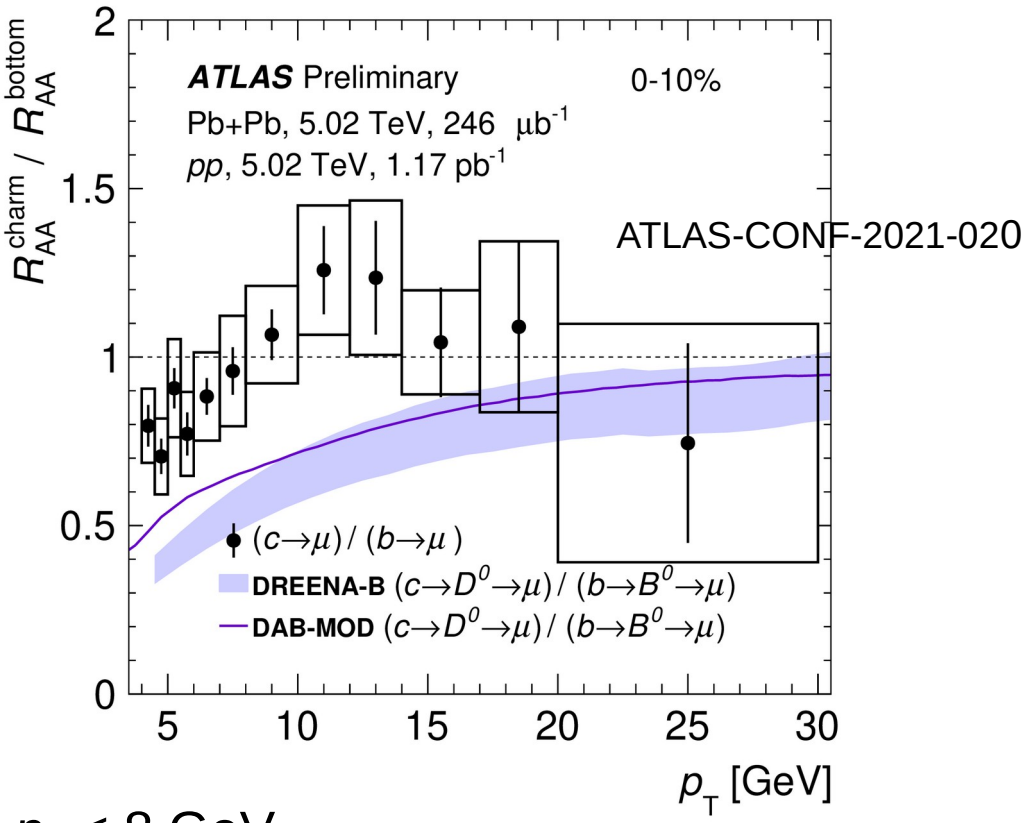


DREENA-B (arXiv:1805.04786)
Dynamic energy loss in 1+1D expanding QCD medium.

Open heavy flavor

- B-quark production measured in various channels and compared to charm production ⟷ decay kinematics.





- Charm more suppressed than bottom p_T < 8 GeV.
  - Radiative energy loss reduced by “dead-cone” effect.
  - The mass splitting in R_{AA} quantitatively described by theory.
  - The p_T dependence of mass splitting → relative contribution or energy loss mechanisms.
- No conclusion can be made for higher p_T.

Summary

- Hard probes provide access into various QCD phenomena.
- Jet (sub)structure is a fast developing field and still growing.
  → New jet substructure and differential measurements come along with new techniques and performance improvement.
- Charm and beauty R_{AA} measured in a wide range of p_T and in many channels.
  → $R_{AA}^{beauty} > R_{AA}^{strange} > R_{AA}^{charm} \sim R_{AA}^{light}$
- Using high statistics LHC data and new techniques bring us to era of precise measurements HI collisions.
  → Strong constraints on theoretical models.
- But there are opened questions…
  → Resolution scale of the QGP, role of medium response, quenching in small systems…

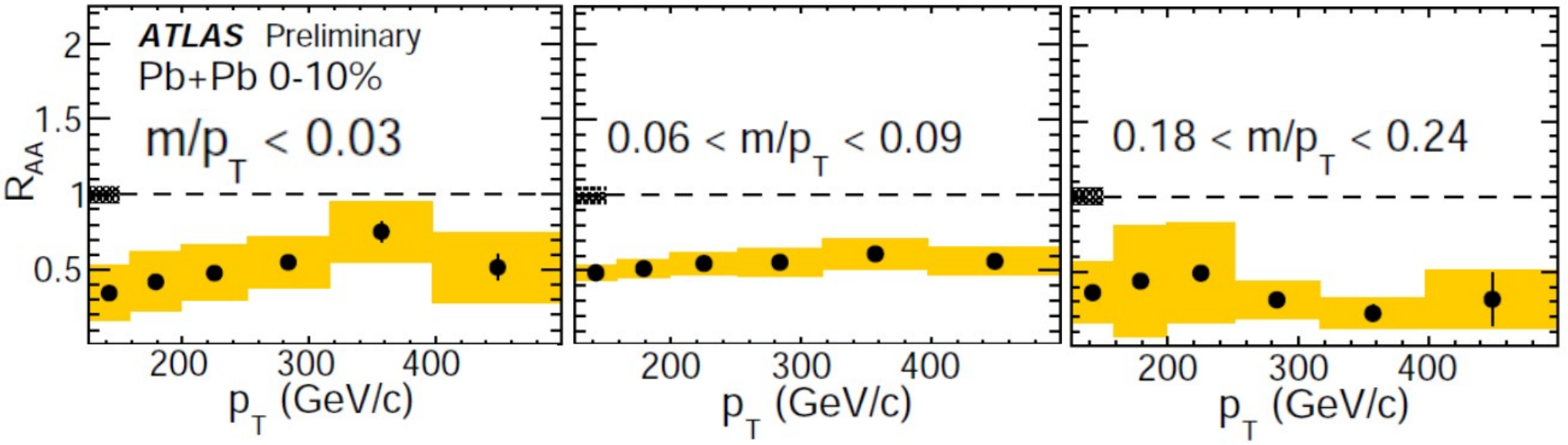
Looking forward to results using HI data from Run3.

Backup

Jet substructure in HI collisions

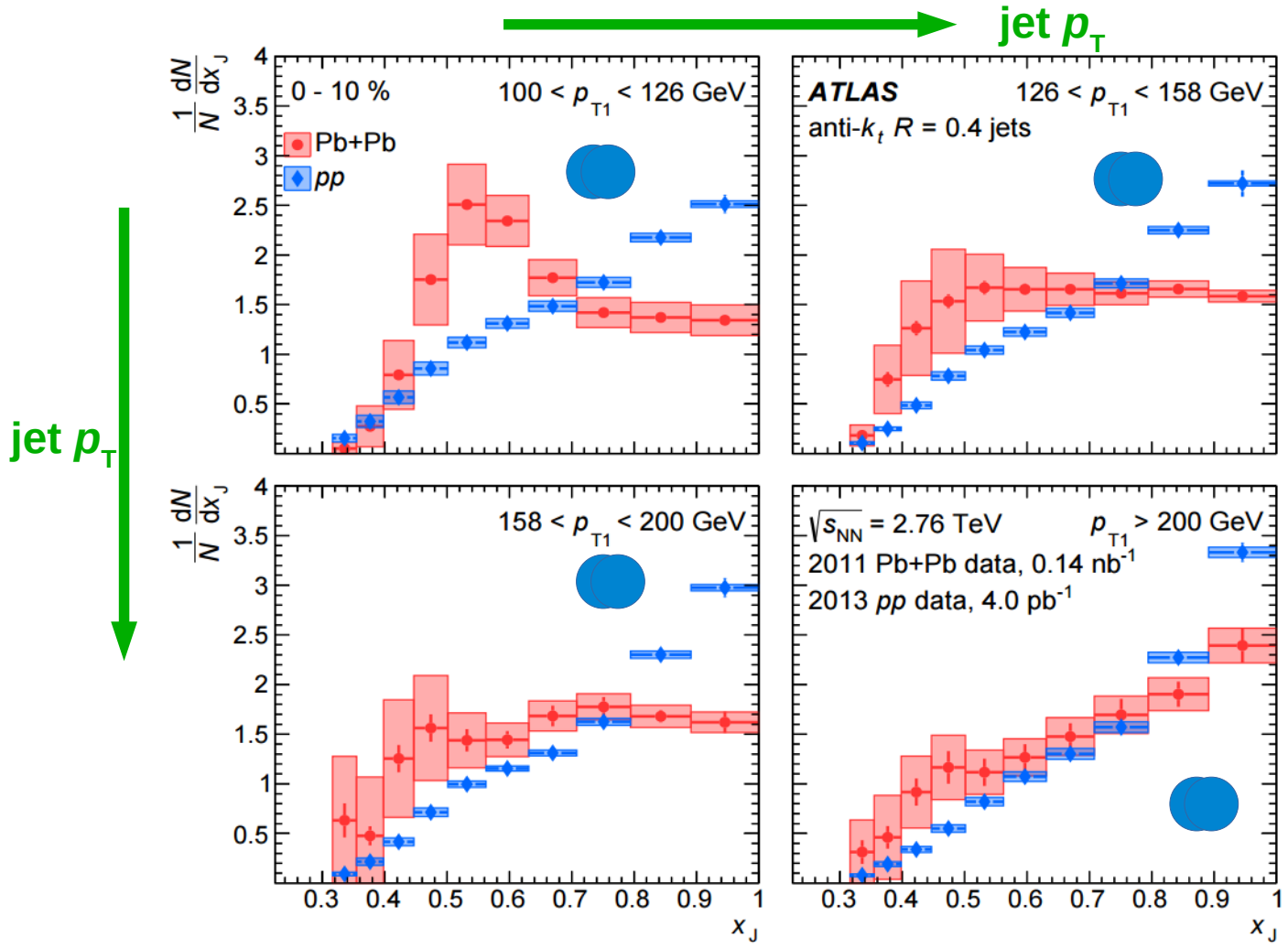
- Does the jet suppression depend on jet structure?
- Jet mass carries information about transverse structure of jet.
  - connection to virtuality of initial parton.

Increasing m/p_T



- No significant change of R_{AA} with mass
  → consistent with inclusive jet R_{AA}.

Di-jet asymmetry

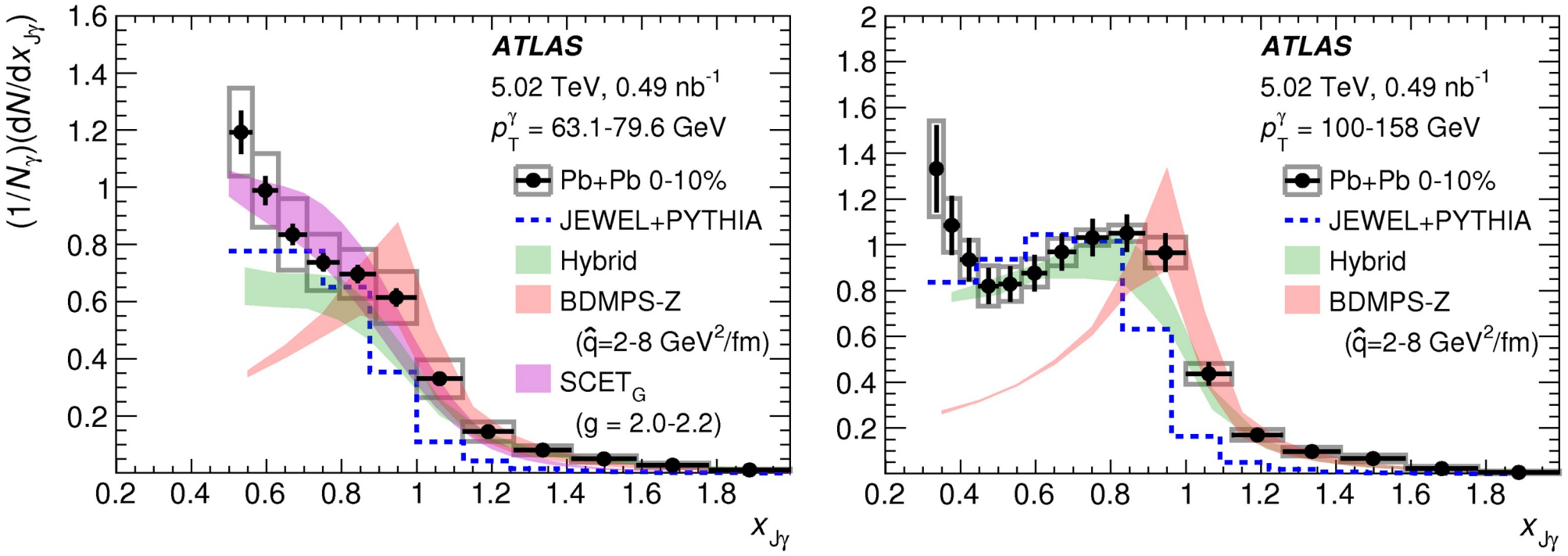


- Much less modification at high p_T.

arXiv:1706.09363

Gamma-jet balance

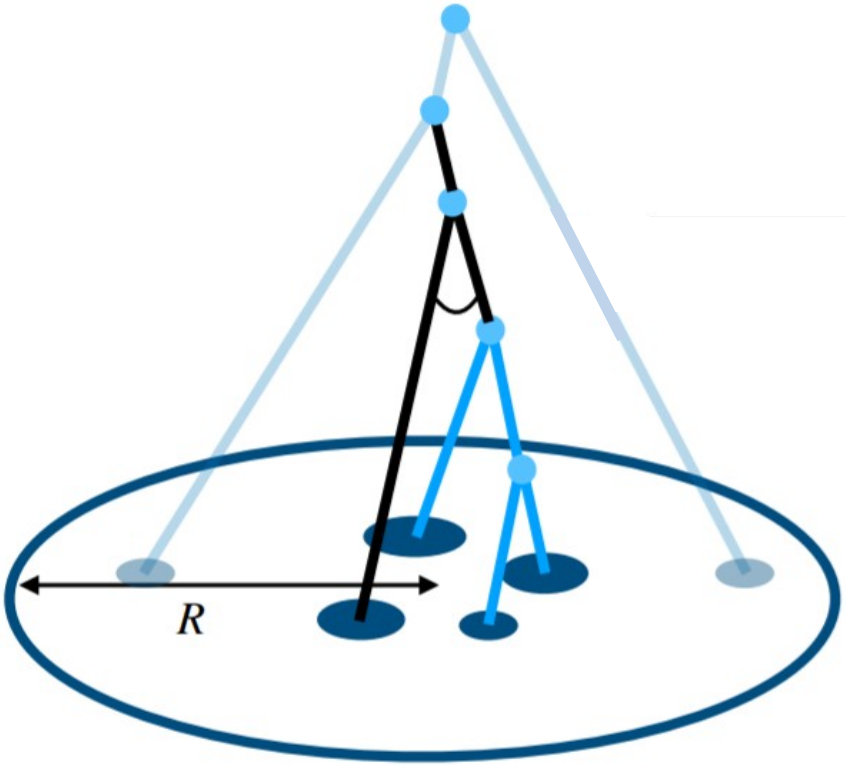
Increasing photon p_T

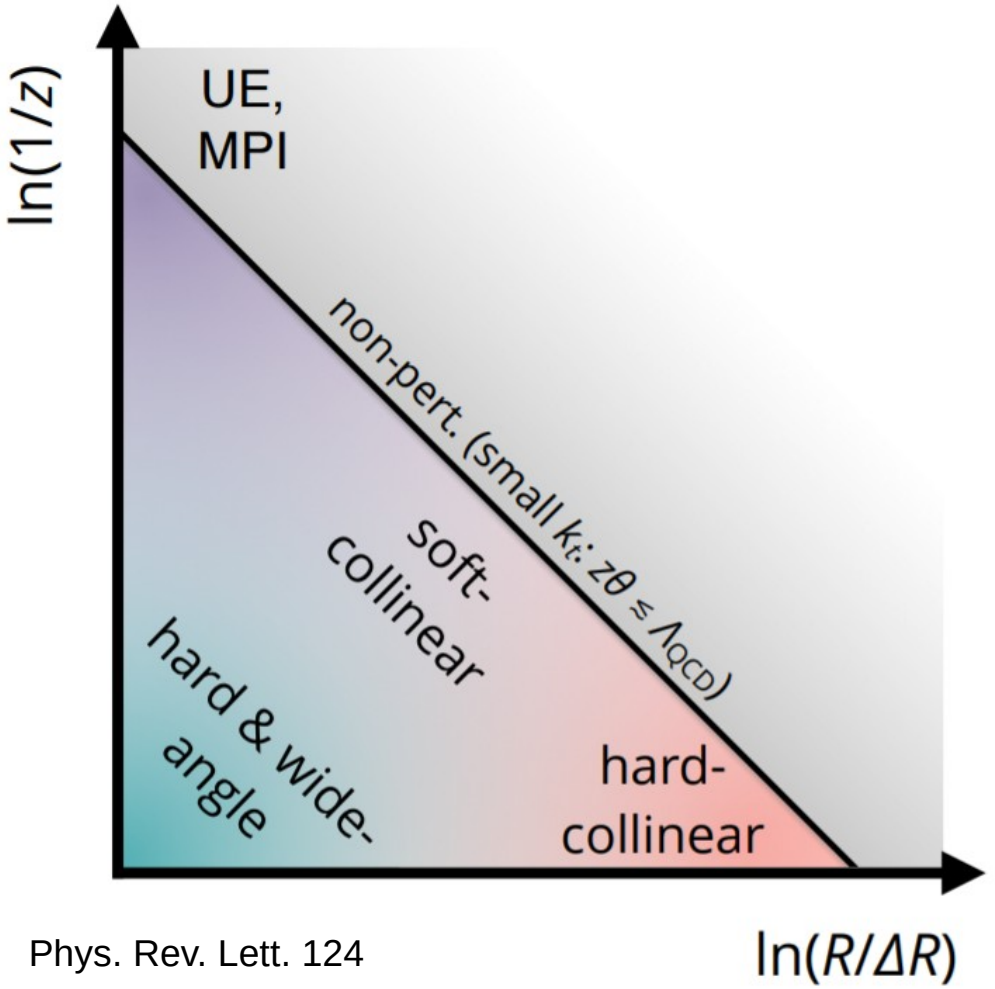


- Some models able to describe basis features.
- Difficult to describe detail behavior of the distribution.

Jet substructure

Classifying parton splittings using spiting scale, opening angle, momentum fraction *z*, sub-jet multiplicity,...





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