Jet modifications in nuclear collisions with ATLAS

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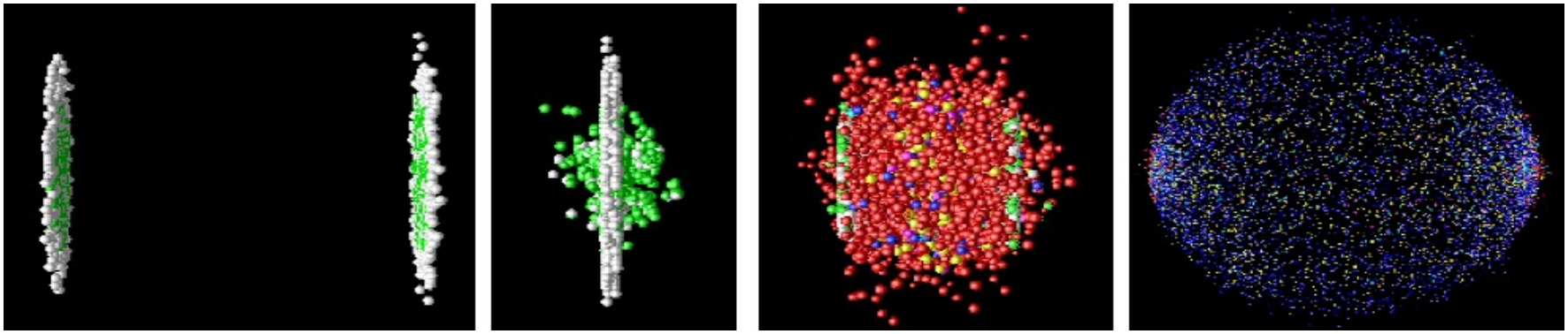
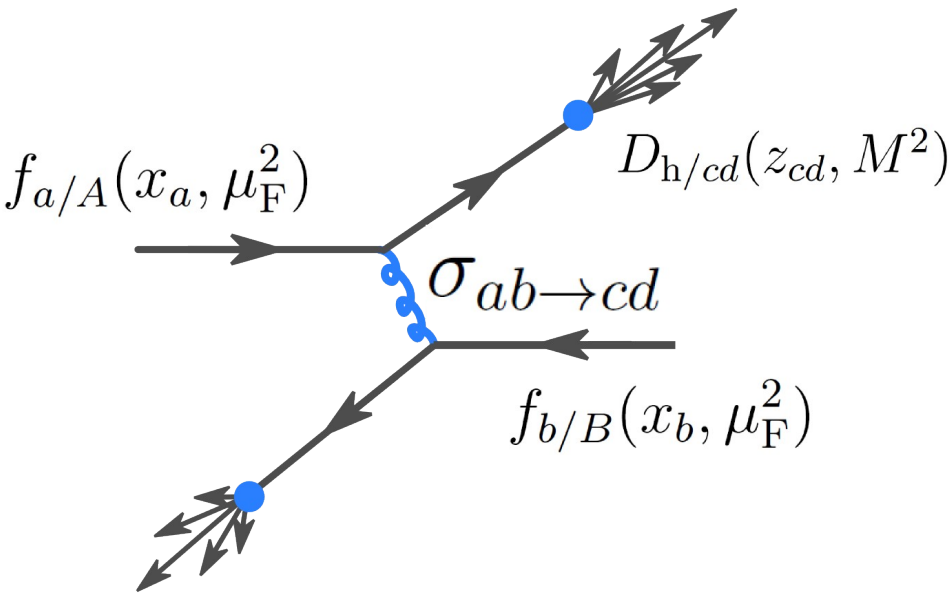
QCD matter at high temperatures

- In HI collisions we want to:
  - Study parton dynamics underlying QGP properties.
  - Characterize macroscopic long-wavelength QGP properties.
  - Understand particle production mechanism both in small and larger systems.
  - Understand the initial state effects and study nPDF effects
- We can achieve that **by using (hard) probes of different scales...**

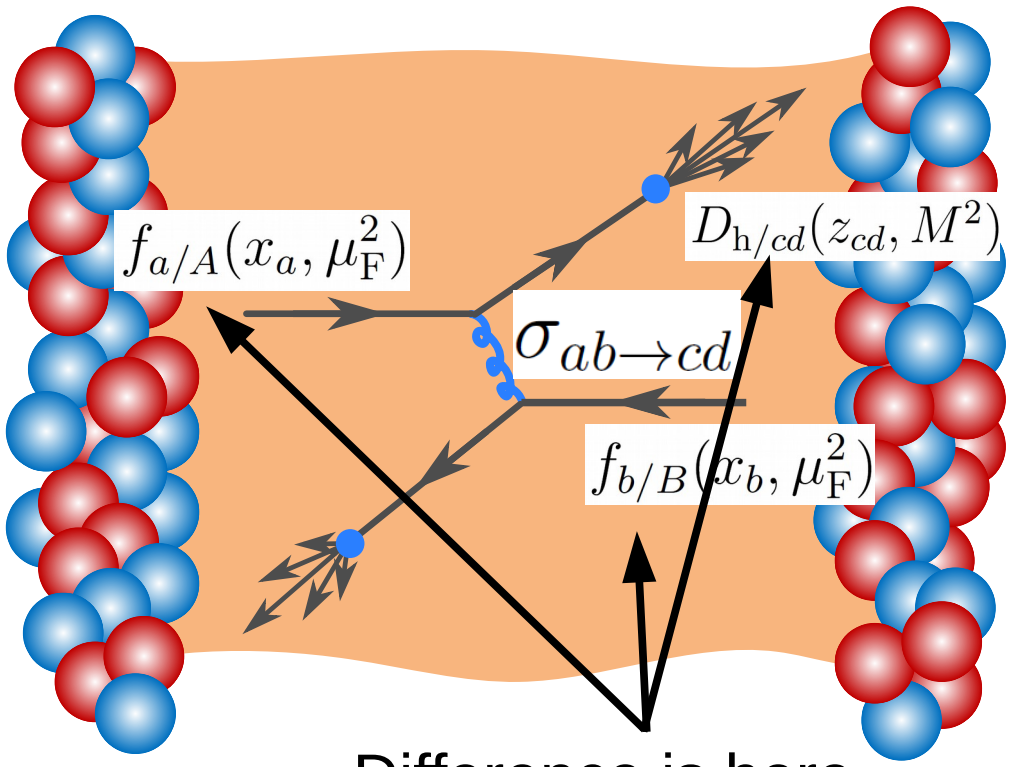


Jets in quark-gluon plasma

hadron-hadron



nucleus-nuclus

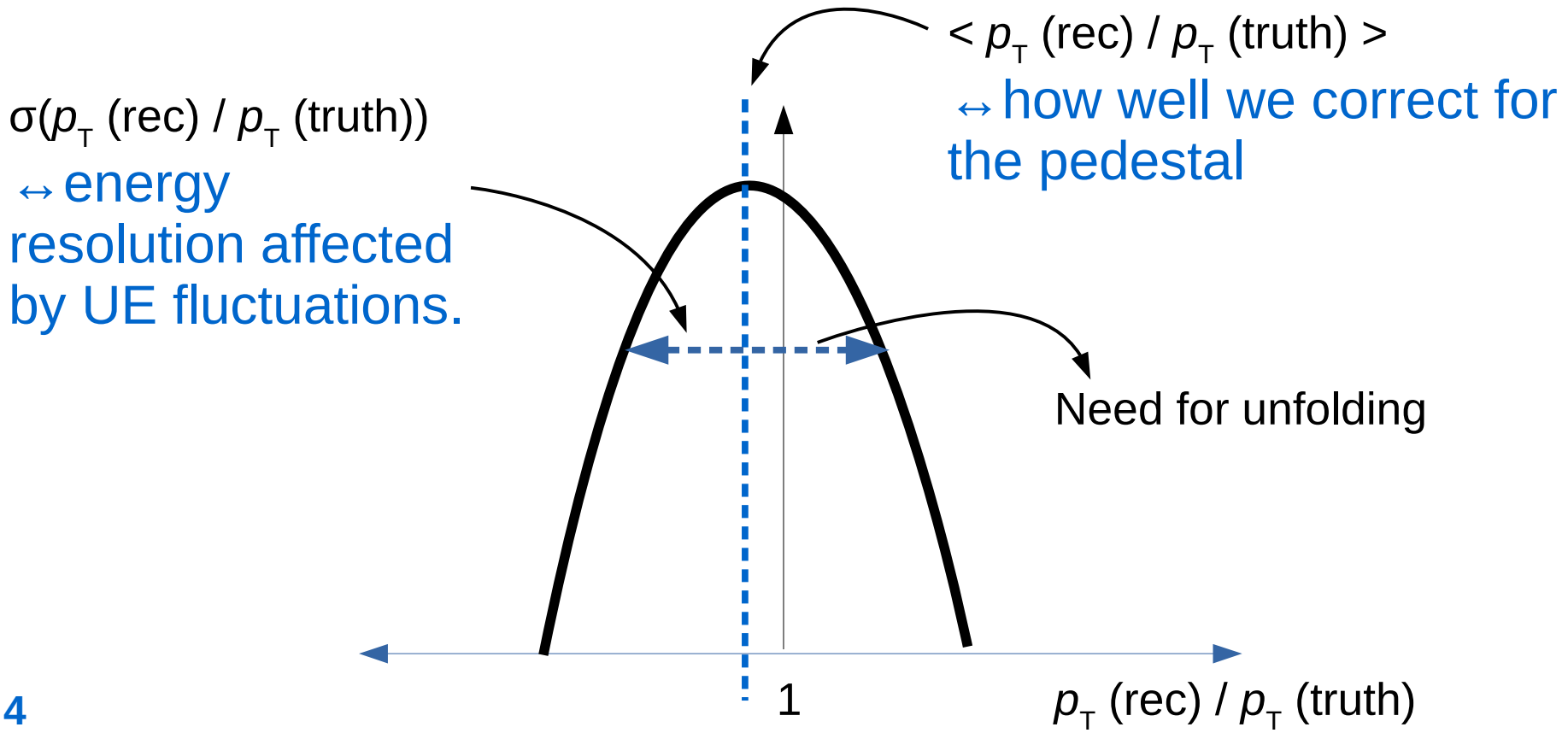


Difference is here

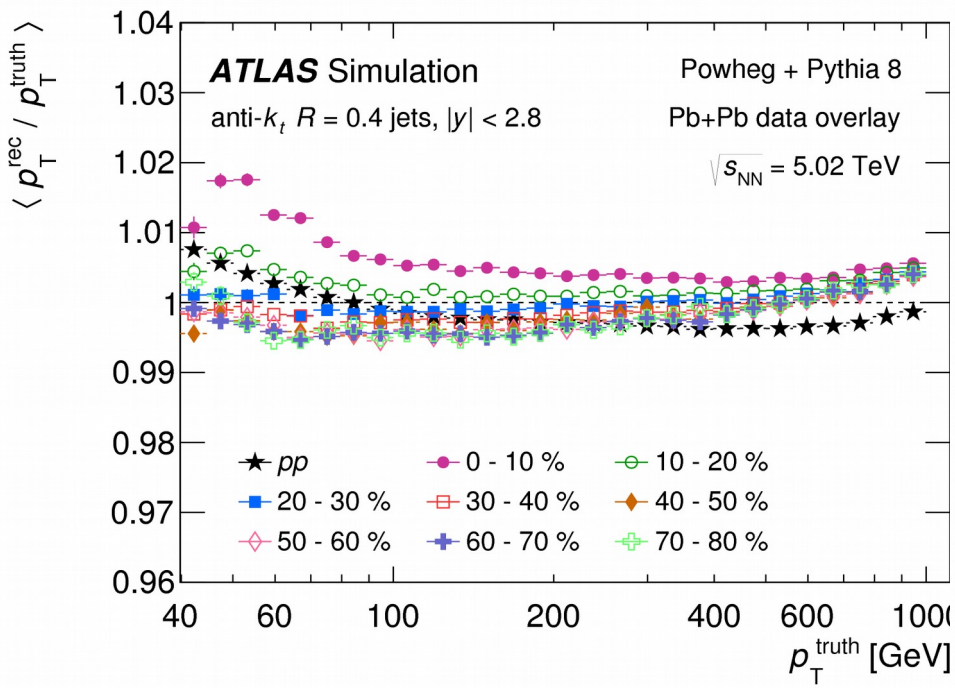
- How much modification is from different initial state like nPDFs?
- Parton shower is affected by the medium.

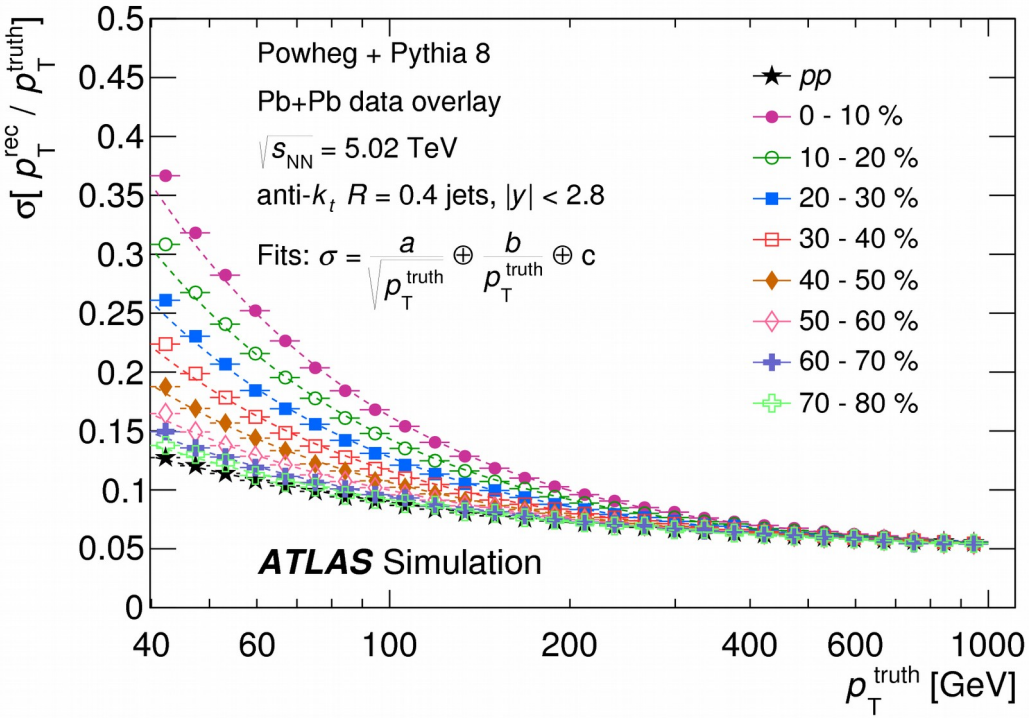
Jet reconstruction

- Jets reconstructed with Anti-k_t with R=0.4 and underlying event (UE) subtraction.
- Mean UE, up to 150 GeV for 0.4 jet, estimated event-by-event as a function of pseudorapidity and corrected for v_n modulation.



Jet reconstruction



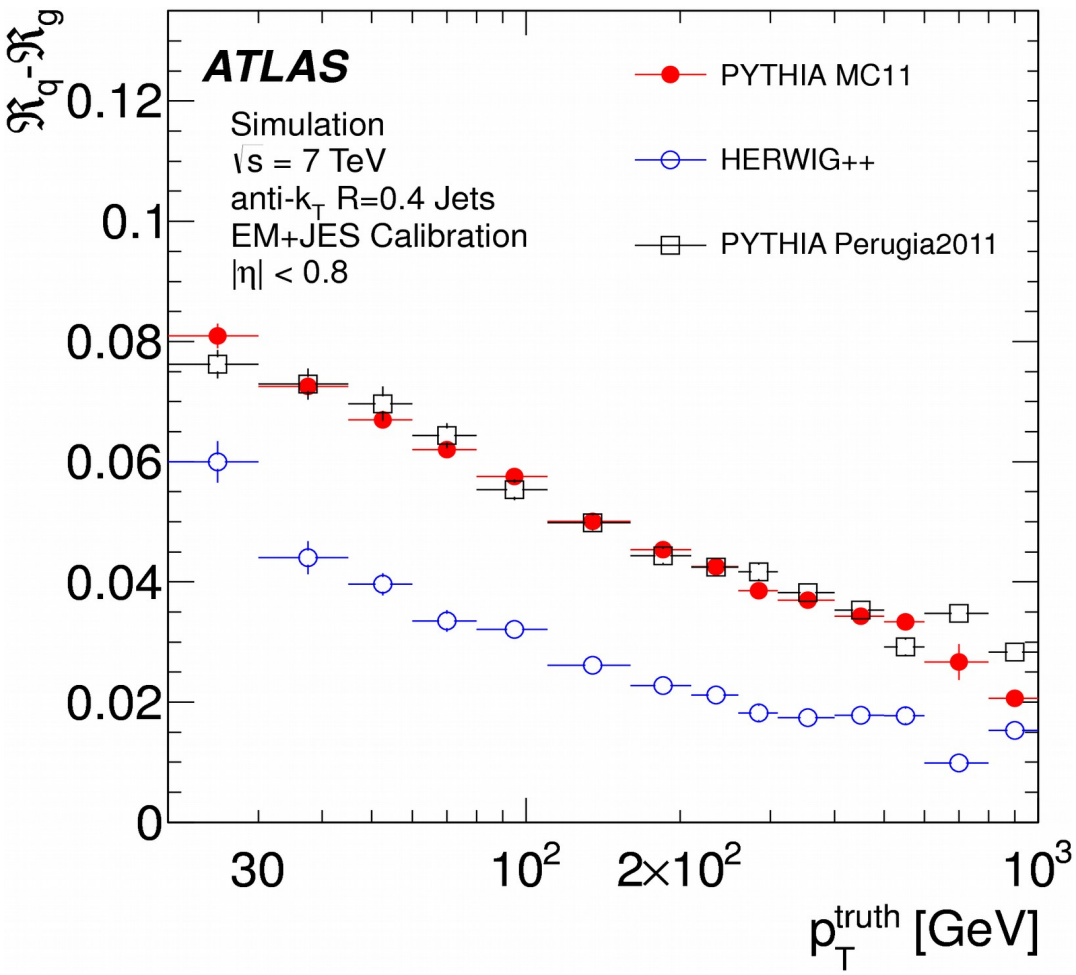


Average responses within 1% from unity almost independent of centrality.

Jet energy resolution dominated by UE fluctuations.

arXiv:1805.05635

Jet response vs observable



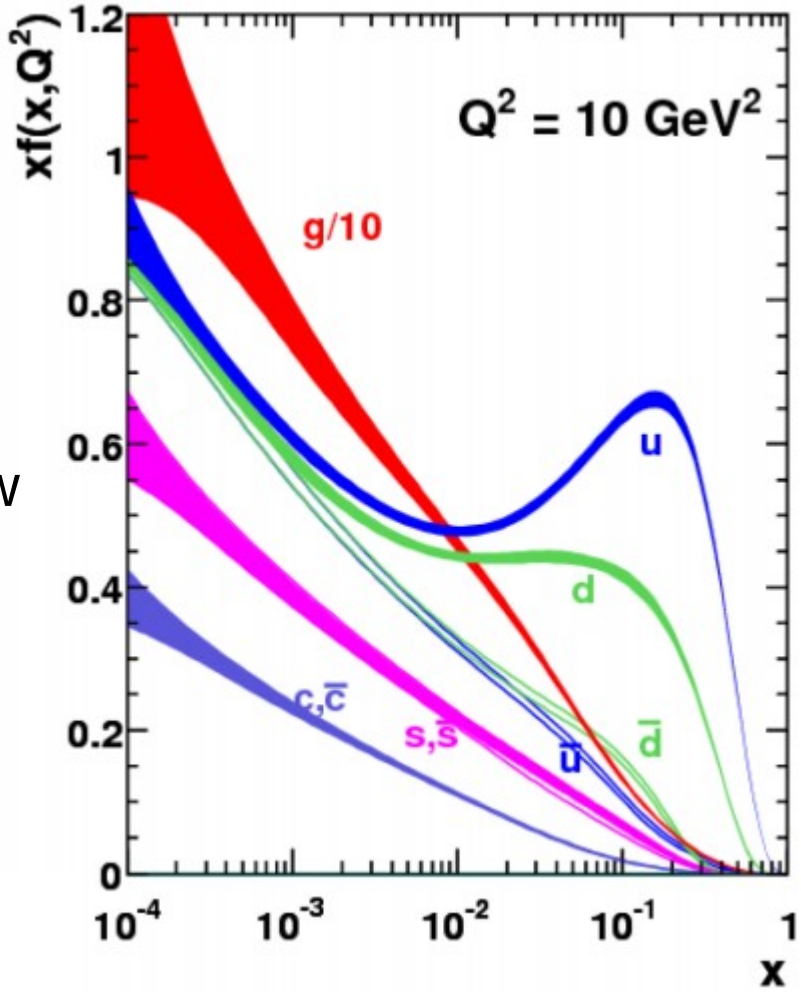
Difference in response between quark and gluon jets in 7 TeV pp data.

Response (and resolution) depends on the jet appearance.

Probing low-x with di-jets

- Steep rise of gluon PDFs at low-x versus unitary.
- Saturation can bring expected change of trend at low x.
- Di-jets sensitive to saturation effects.

➡ measurement to be performed with as low p_T and as forward direction as possible.



Probing low-x with di-jets

- Steep rise of gluon PDFs at low-x versus unitary.
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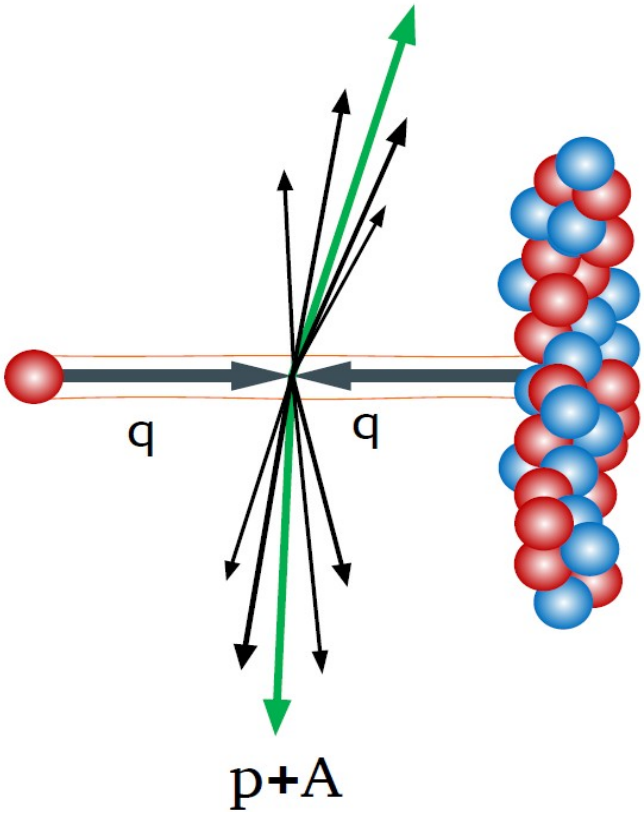
- ➡ measurement to be performed with as low p_T and as forward direction as possible.
- Gluon density increased in nuclear collisions → increased sensitivity.
- Sensitive also to the onset of non-linear QCD.



Observables

Angular correlations

$$C_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{1,2}}{\mathrm{d}\Delta\phi}$$

$$W_{12} = \mathrm{RMS}(C_{12})$$

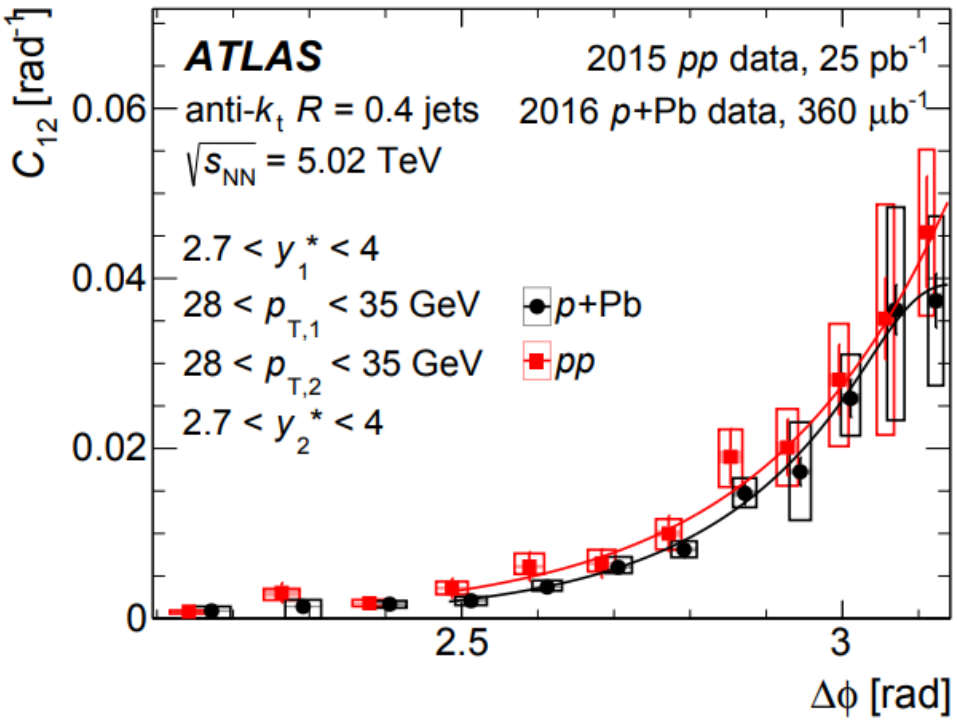
$$\rho_W^{\mathrm{pPb}} = \frac{W_{12}^{p+\mathrm{Pb}}}{W_{12}^{pp}}$$

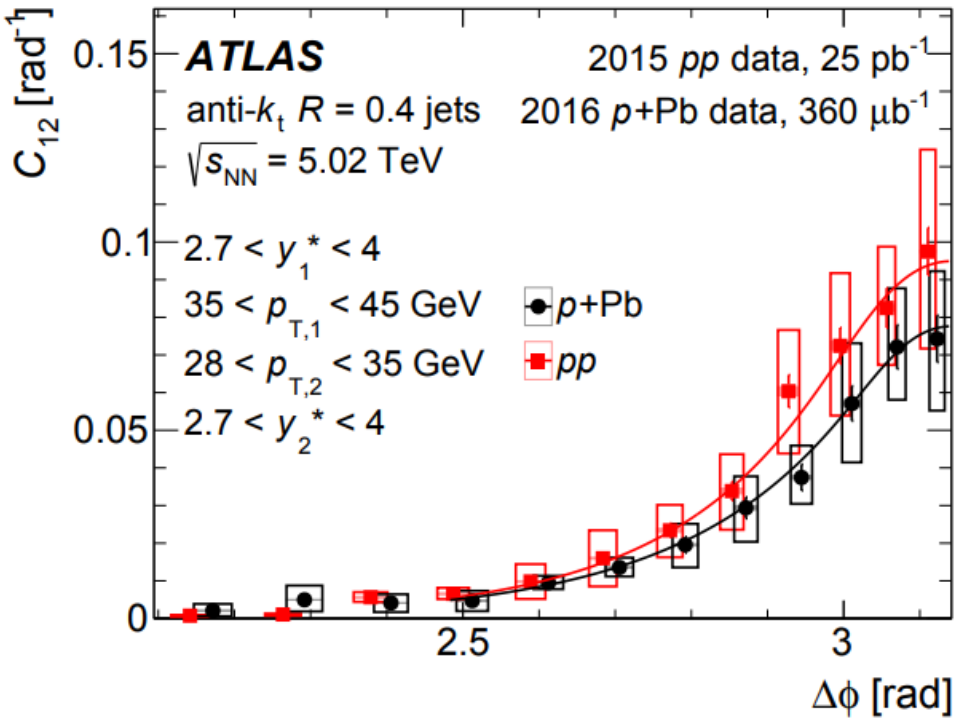
Di-jet conditional yields

$$I_{12} = \frac{1}{N_1}\frac{\mathrm{d}N_{1,2}}{\mathrm{d}y_1^*\mathrm{d}y_2^*\mathrm{d}p_{\mathrm{T},1}\mathrm{d}p_{\mathrm{T},2}}$$

$$\rho_I^{\mathrm{pPb}} = \frac{I_{12}^{p+\mathrm{Pb}}}{I_{12}^{pp}}$$

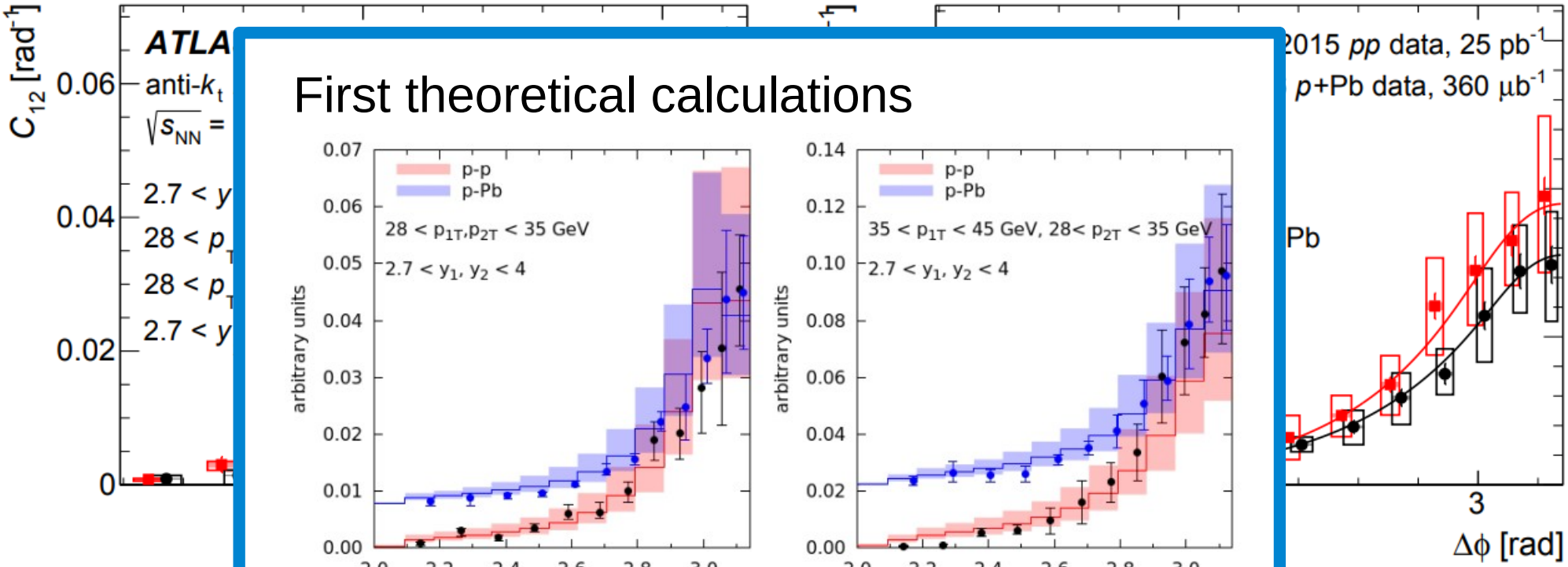
Angular correlations





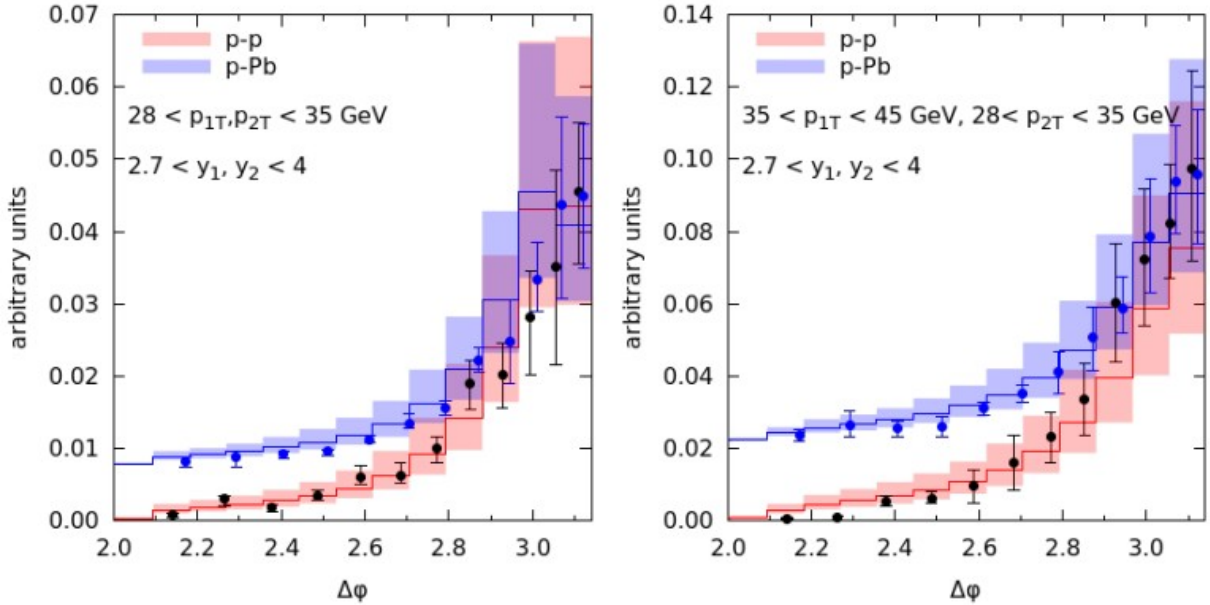
- The forward-forward configuration at lowest p_T probes x down to 1.5×10^{-4}.

Angular correlations



- The for … x down to 1.5 x 1 …

First theoretical calculations

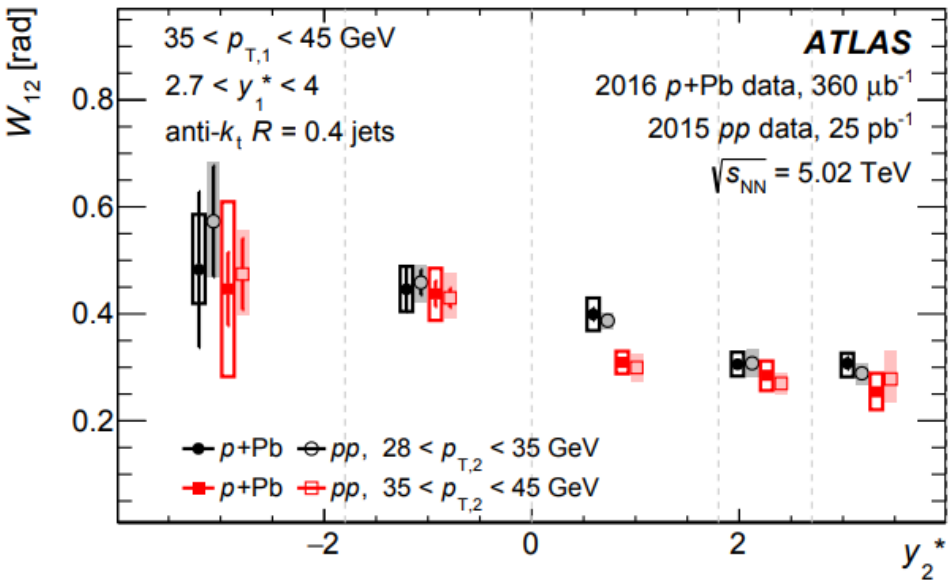


arXiv:1903.01361

effects due to gluon saturation and the resummation of large logarithms of the hard scale included.

Di-jets in *p*+Pb and *pp*

Widths of angular correlations



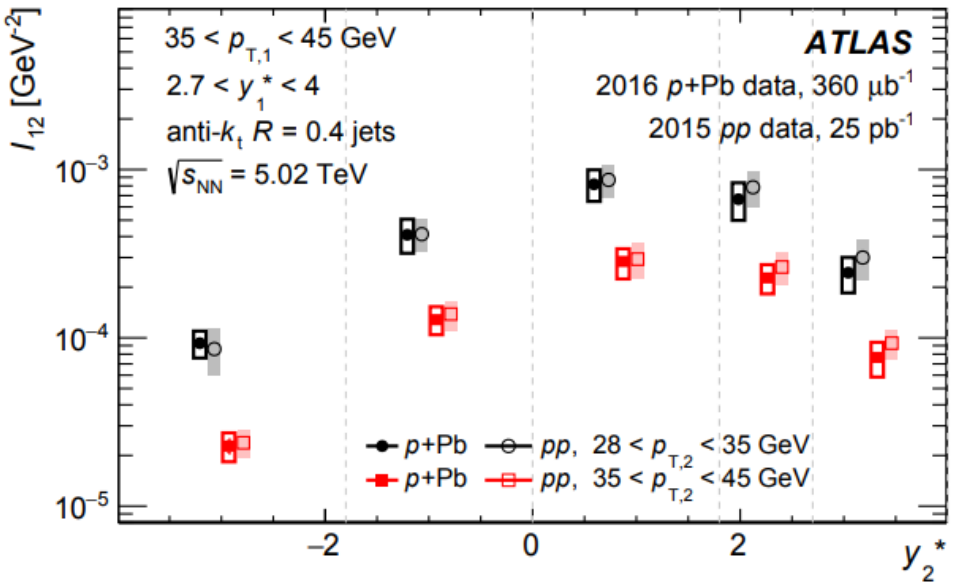
Di-jet conditional yields

- Widths of azimuthal correlations increase with increasing rapidity separation and p_T imbalance between jets.

Di-jets in *p*+Pb and *pp*

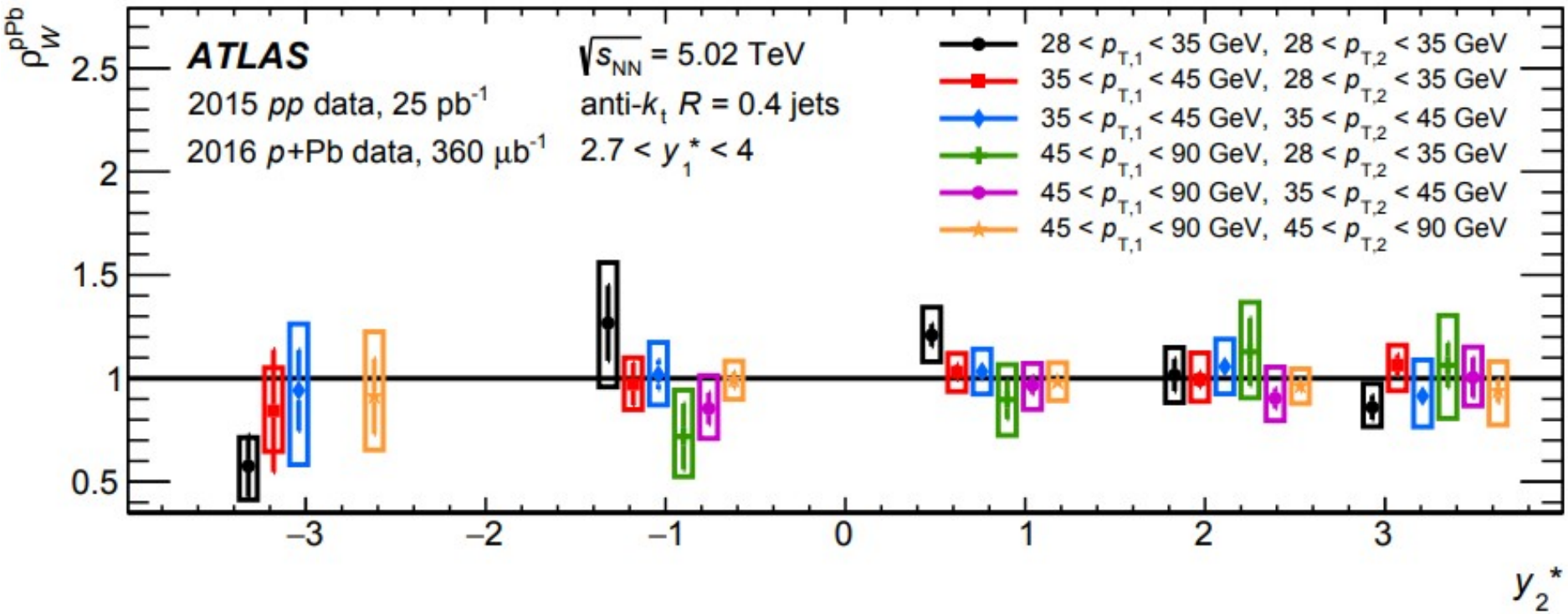
Widths of angular correlations

Di-jet conditional yields



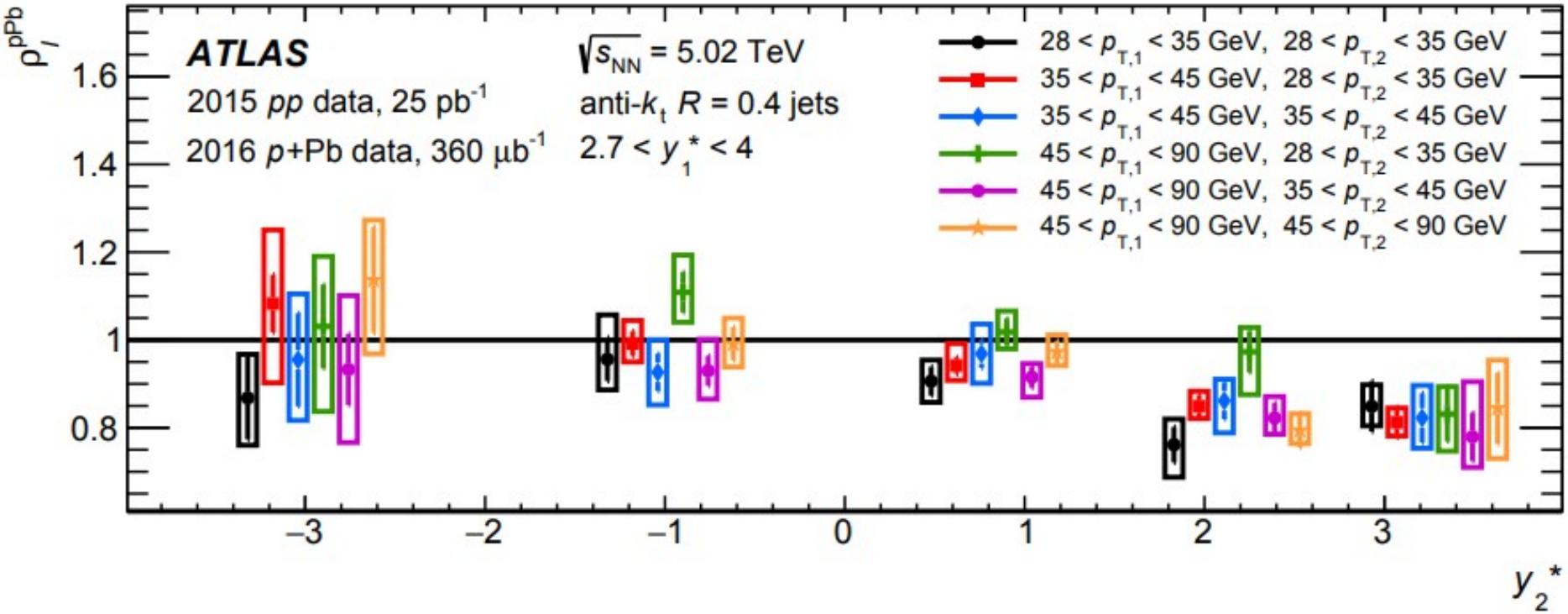
- Dependence of yield given by faster decrease of the di-jet cross-section at large rapidity compared to inclusive jet cross-section.

p+Pb vs *pp*: widths



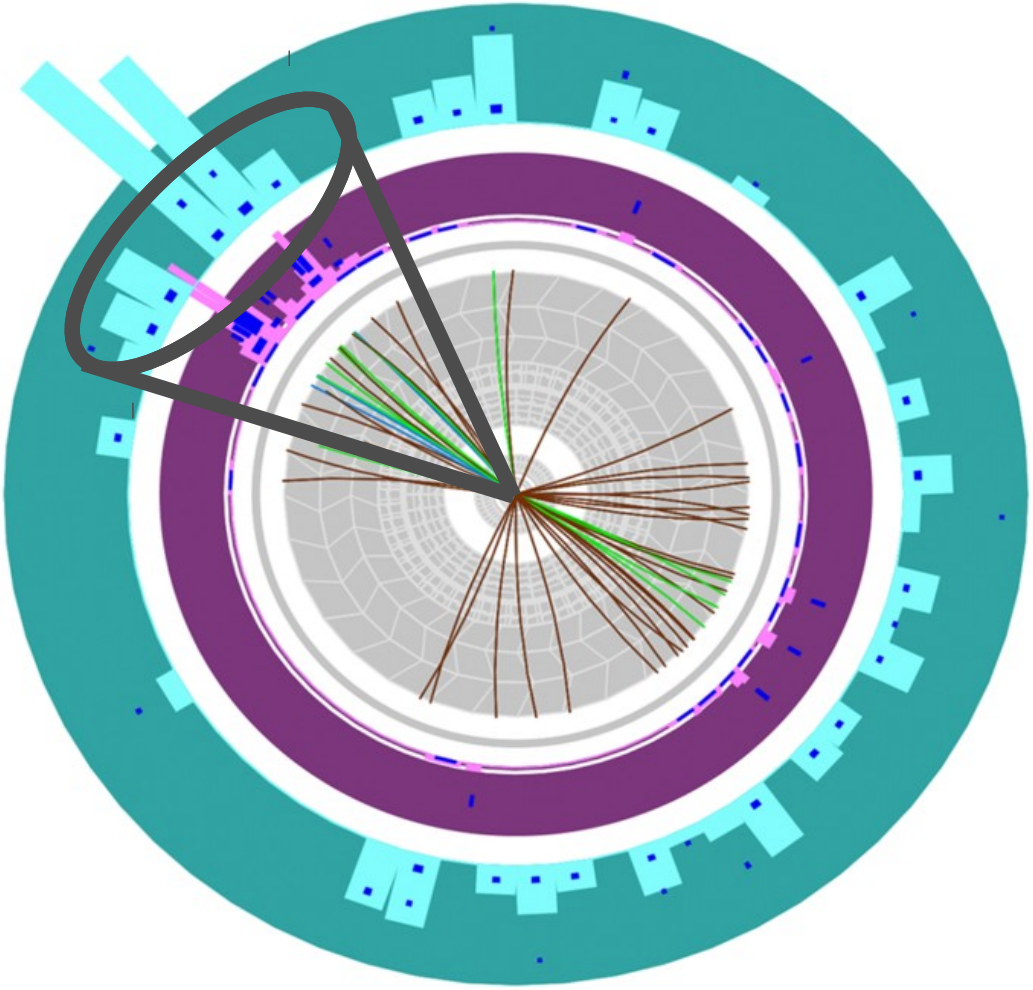
- No significant broadening of azimuthal correlations in *p*+Pb compared to *pp*.

p+Pb vs *pp*: yields



- Up to 20% suppression of conditional yields for forward-forward configuration in *p*+Pb compared to *pp*.

Jet structure in Pb+Pb collisions



How much is the jet structure modified in Pb+Pb?

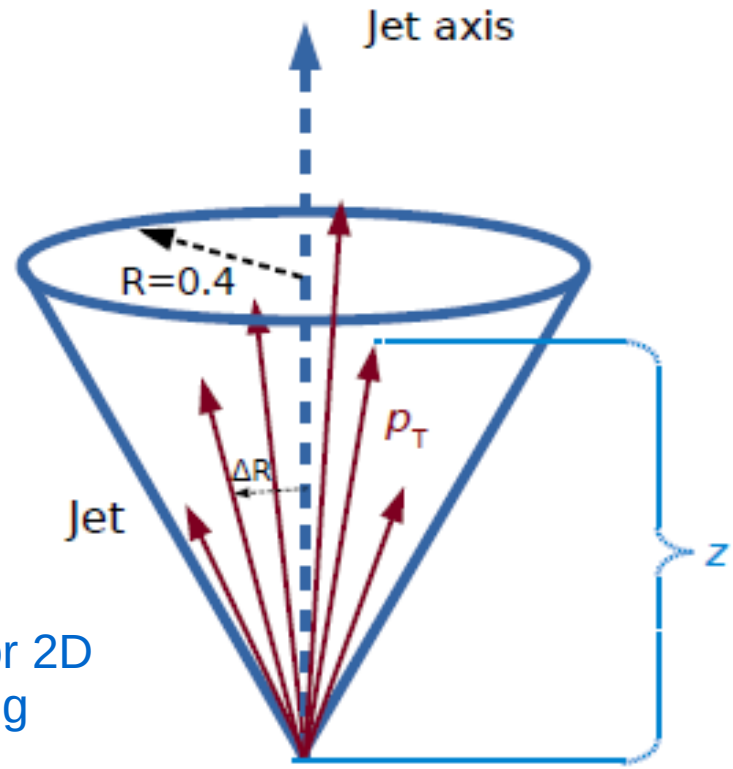
- Measurement of fragmentation functions

$$D(p_T) \equiv \frac{1}{N_{jet}} \frac{dn_{ch}}{dp_T} \qquad D(z) \equiv \frac{1}{N_{jet}} \frac{dn_{ch}}{dz}$$, where $z \equiv p_T \cos \Delta R \,/\, p_T^{jet}$

Shower in medium

$$R_{D(z)} \equiv \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

Shower in vacuum



- Jet response depends on parton flavour.
- Steeper FF when approaching the z~1.
- Worsening of track momentum resolution at high p_T.
- Difference in the jet energy resolution in pp and Pb+Pb at lower p_T.

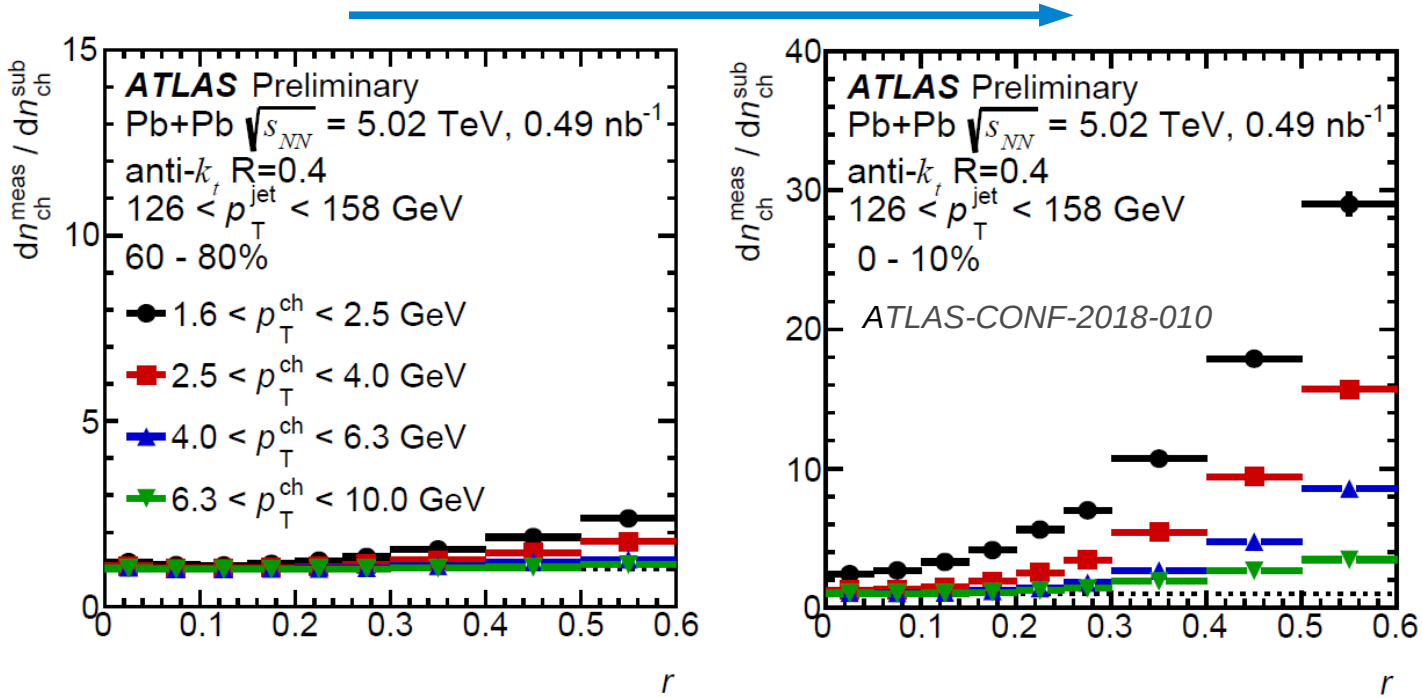
Need for 2D unfolding

Aspects of measurement @ low-p_T

- Significant contribution of background from underlying event (UE).

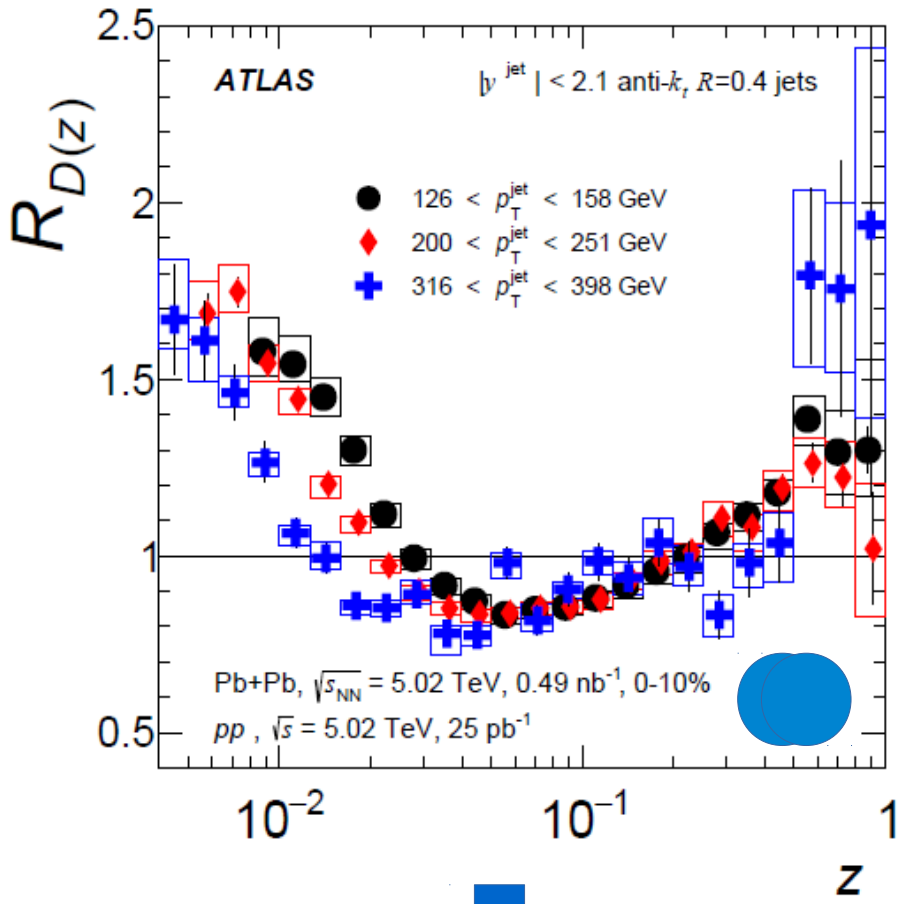
more central collisions

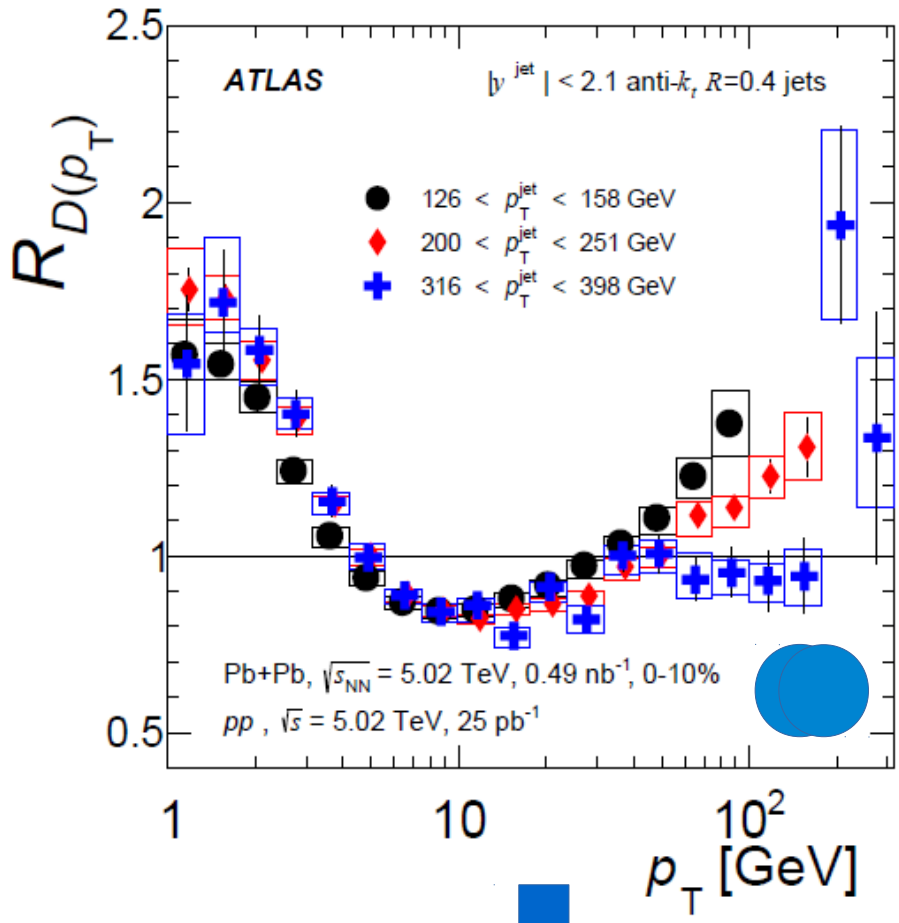
$$\frac{\text{Signal + Background}}{\text{Signal}} :$$



- Signal-to-background ratio decreasing with increasing centrality, increasing *r*, and decreasing p_T.
- Various properties of UE are taking into account in subtraction method: η-dependence, flow variation, correlation of UE and jet energy resolution.

Modification in central collisions





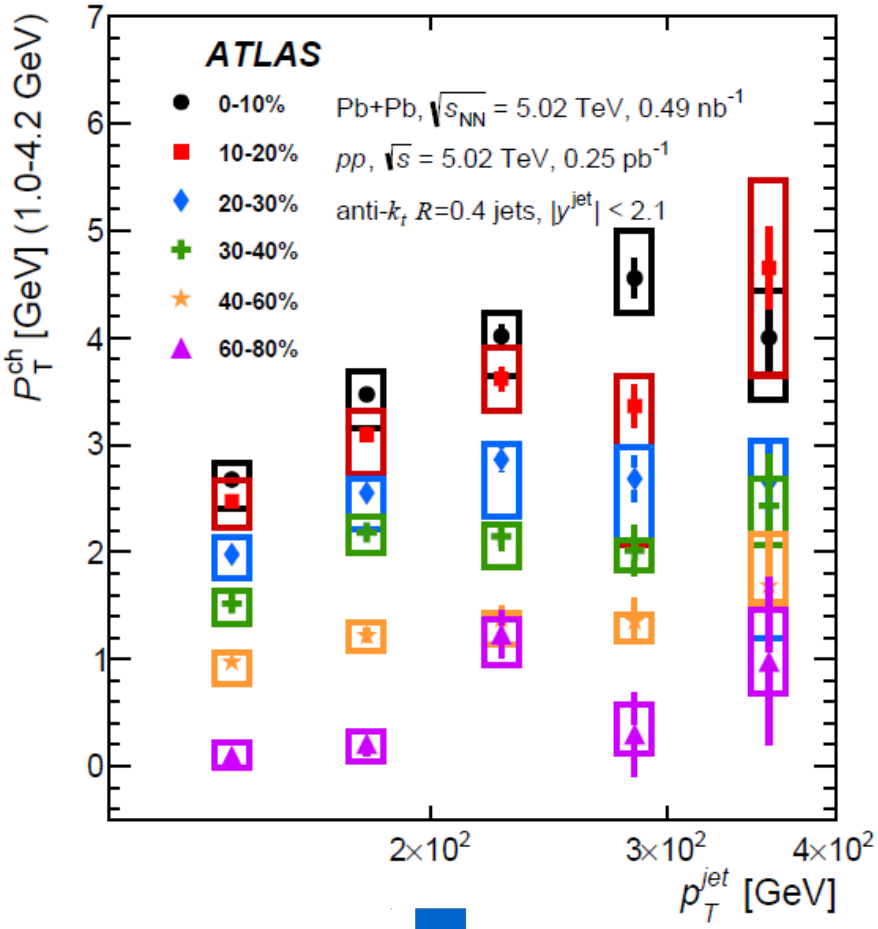
Enhancement of hard fragments.

Enhancement of soft fragments.

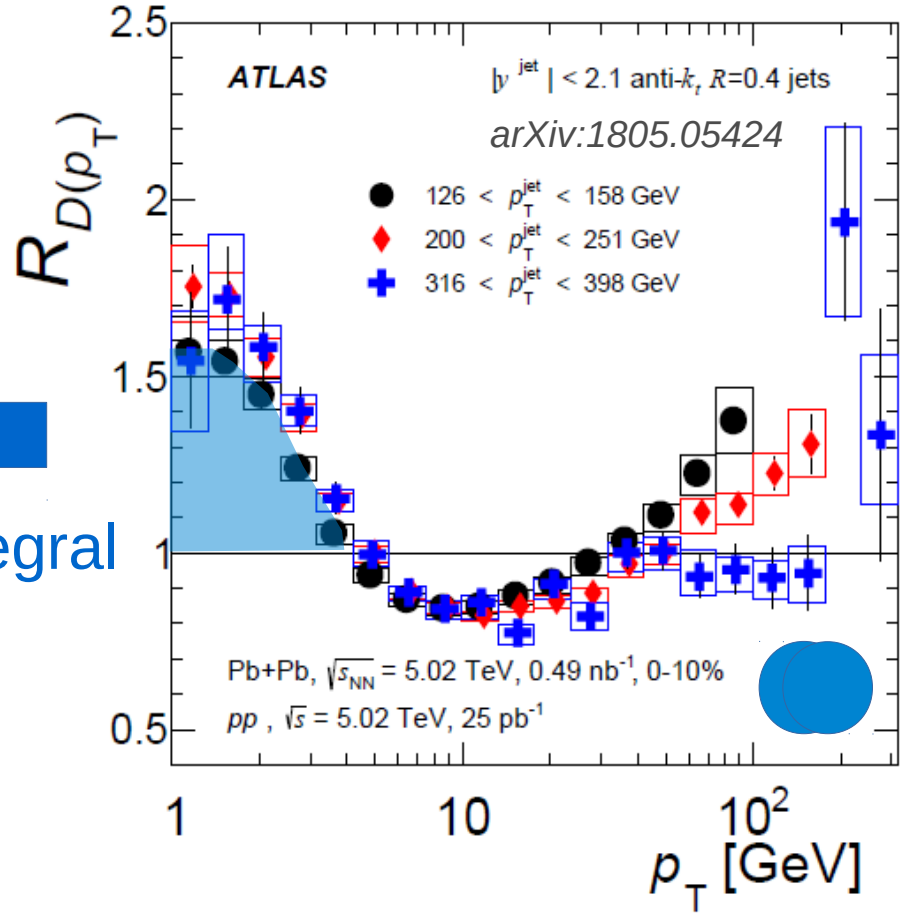
No dependence on jet p_T observed at high z for jets up to 400 GeV.

Phys. Rev. C 98 (2018) 024908

Modification in central collisions



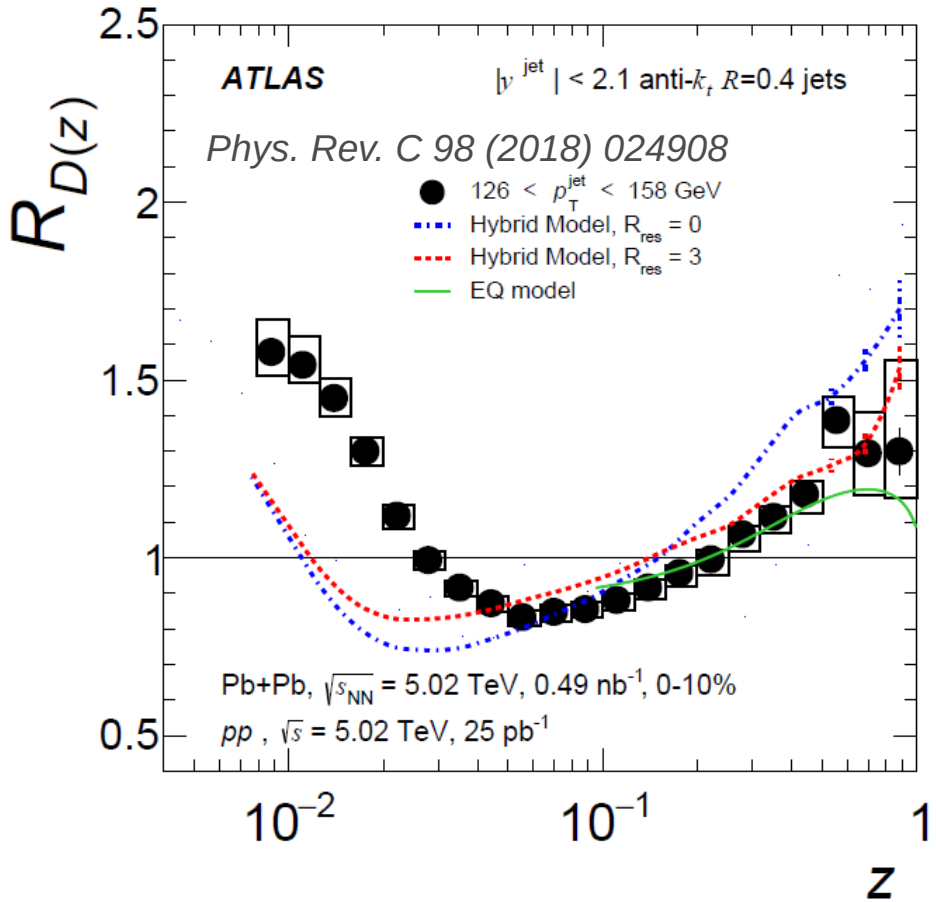
Integral

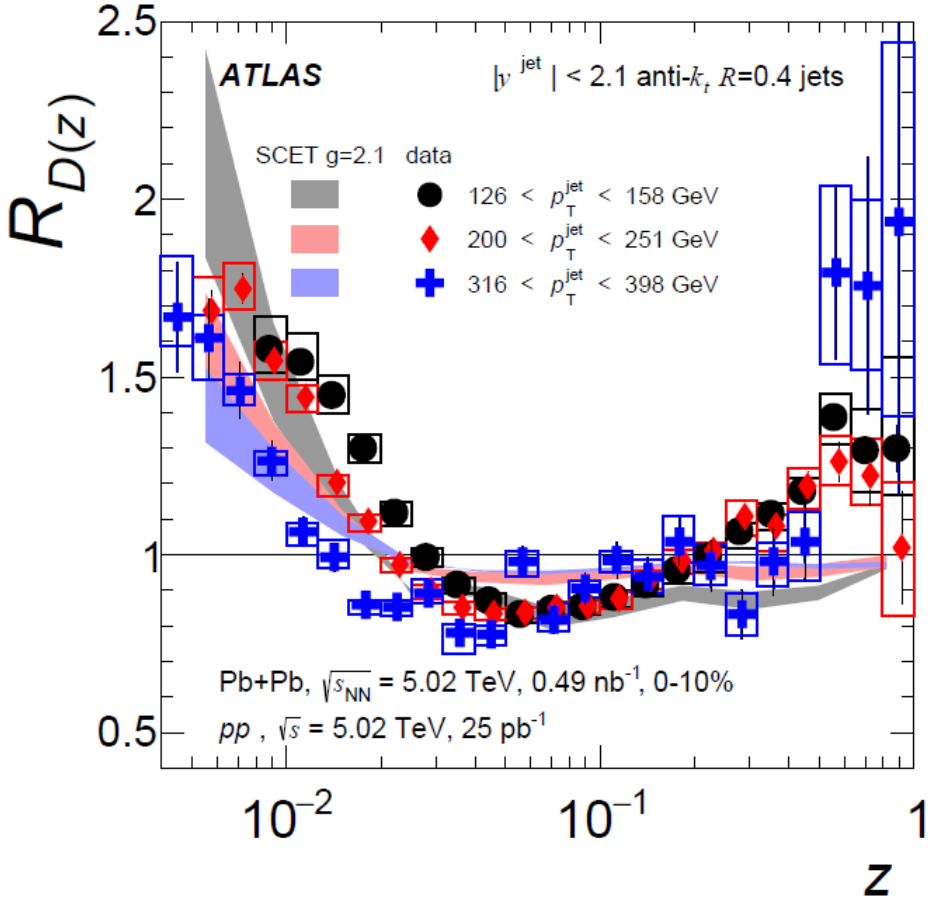


- Jet p_T dependence to the enhancement.
- Response of the medium to the high-p_T parton?

Phys. Rev. C 98 (2018) 024908

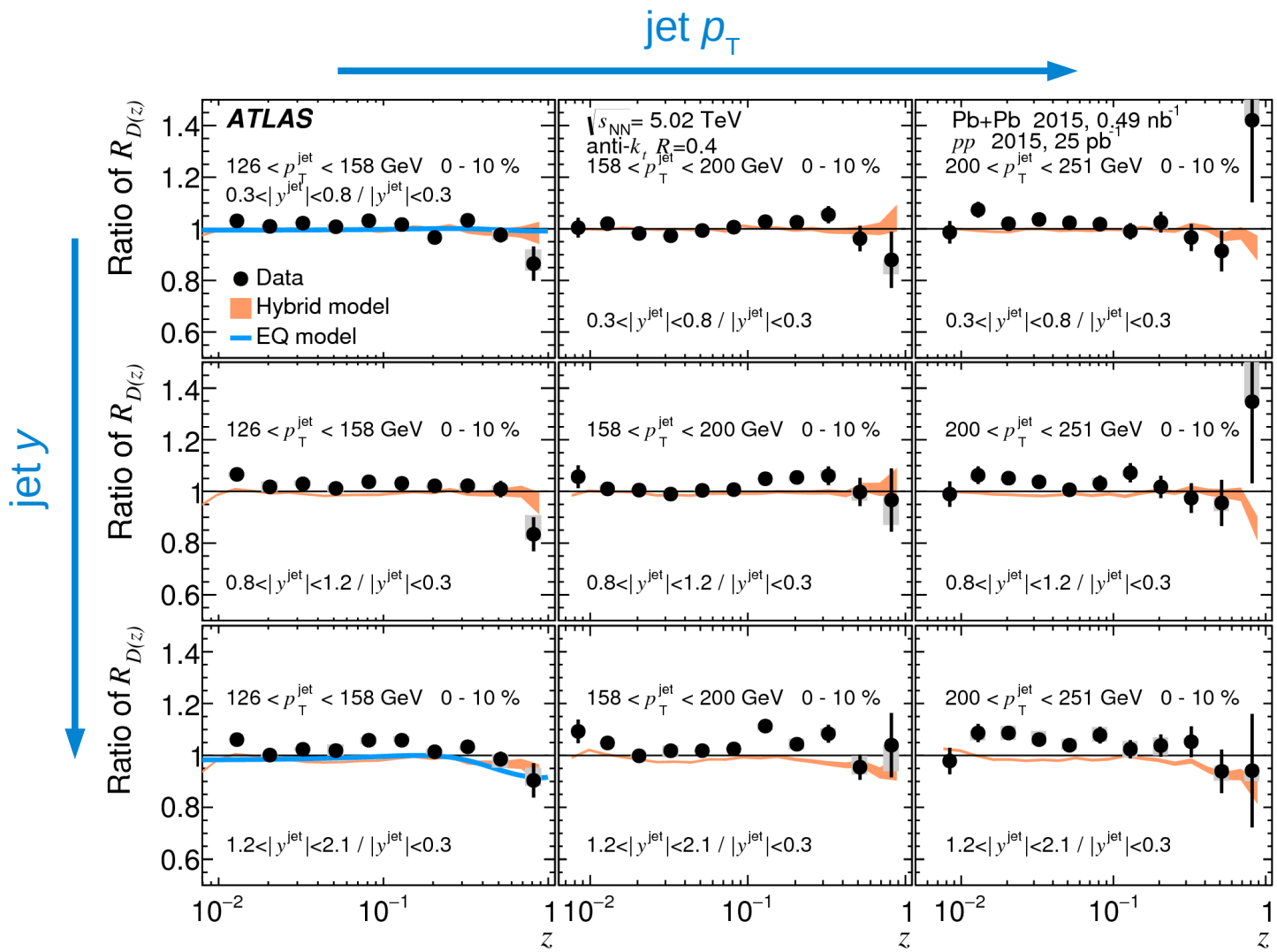
Can theory describe measurement?





- Hybrid model (arXiv:1707.05245) consistent at high *z*, disagreement at low z due to simplistic medium response modeling.
- EQ model is able to describe the high-*z* excess.
- SCETg model is able to qualitatively described the low-*z* excess.

Rapidity dependence

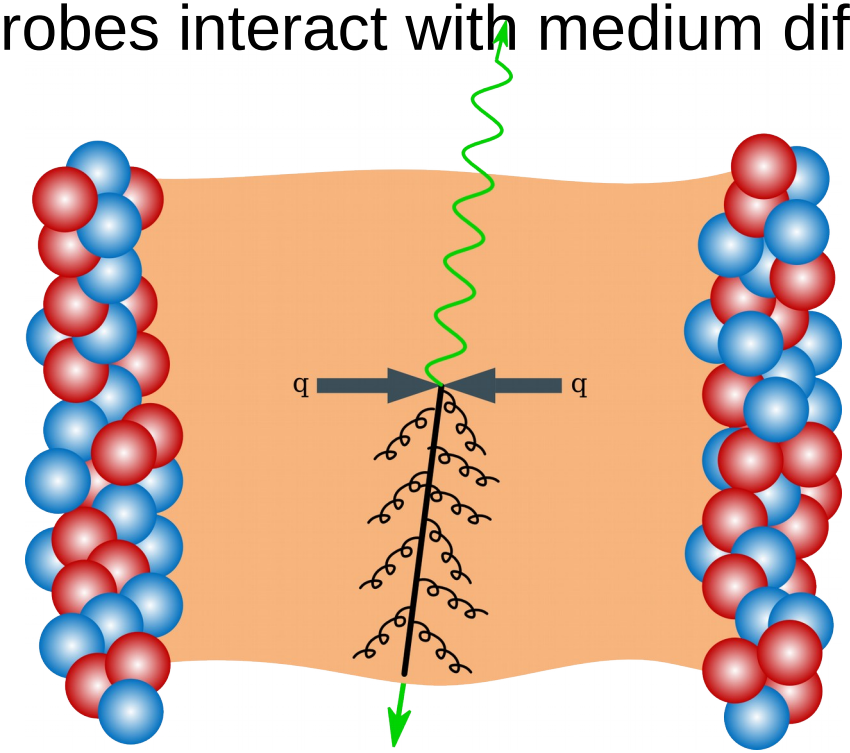


- $R_{D(z)}$ in central region is compared to that in forward.
- No significant rapidity dependence to the modification.
- Sign of depletion at high *z*.
- Comparison to EQ and Hybrid model.

➡ Both models are able to describe the rapidity dependence in data.

Jets + vector bosons

- Different hard probes interact with medium differently.

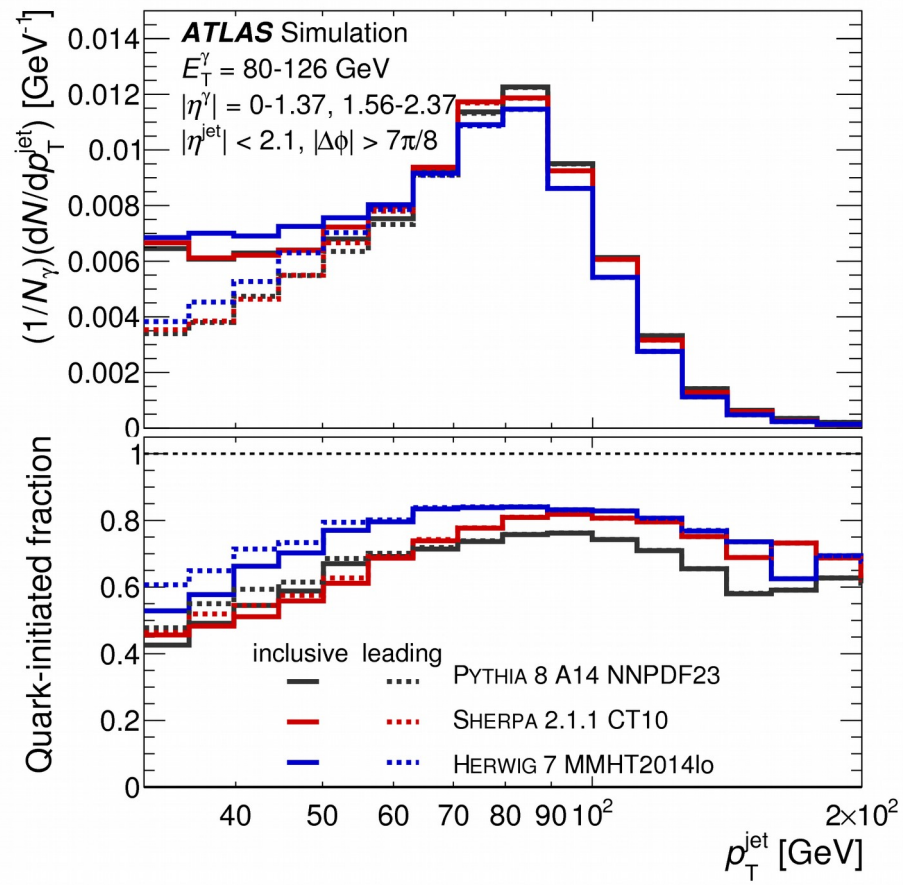


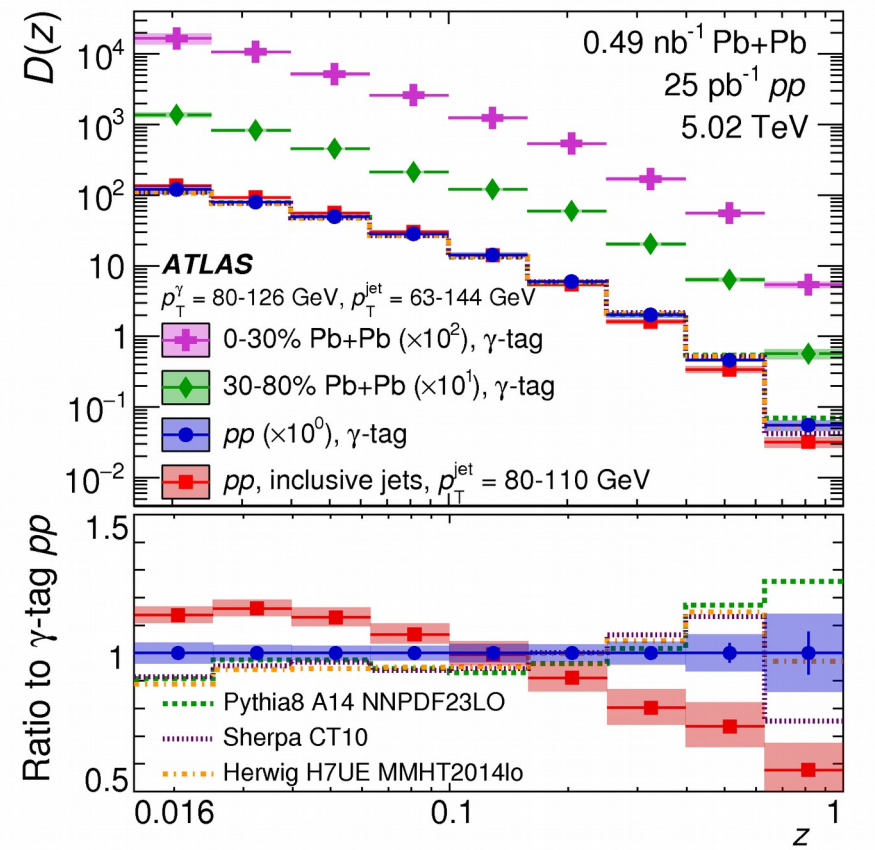
- Photons and Z's calibrate the parton energy.
- Flavor fraction differs compared to di-jets.

Photon-tagged jet fragmentation

- Enhanced quark jet contribution compared to inclusive jets.

➡ flavor dependence of quenching.

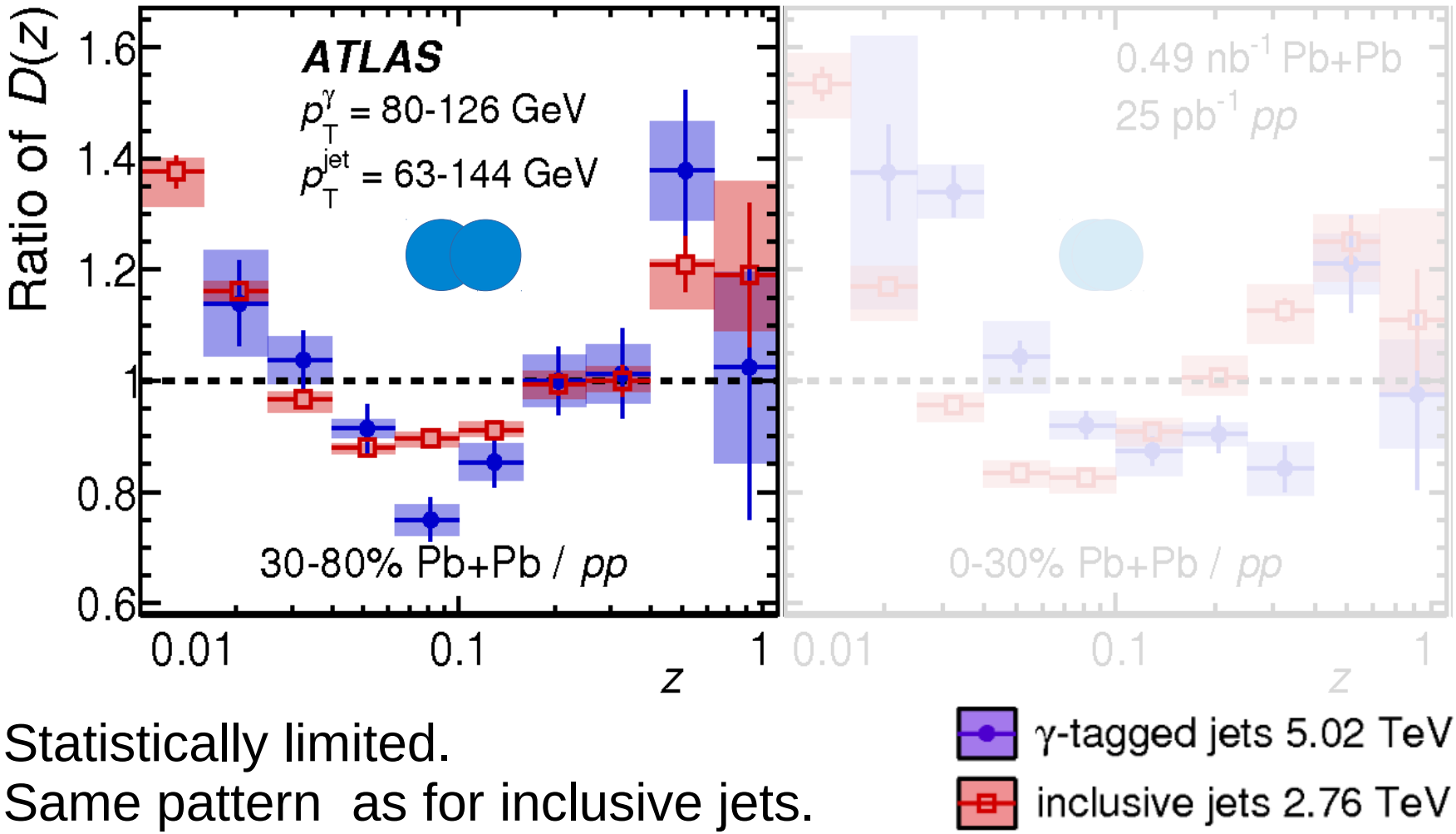




➡ Steeper FF in photon-tagged jets.

arXiv:1903.02209

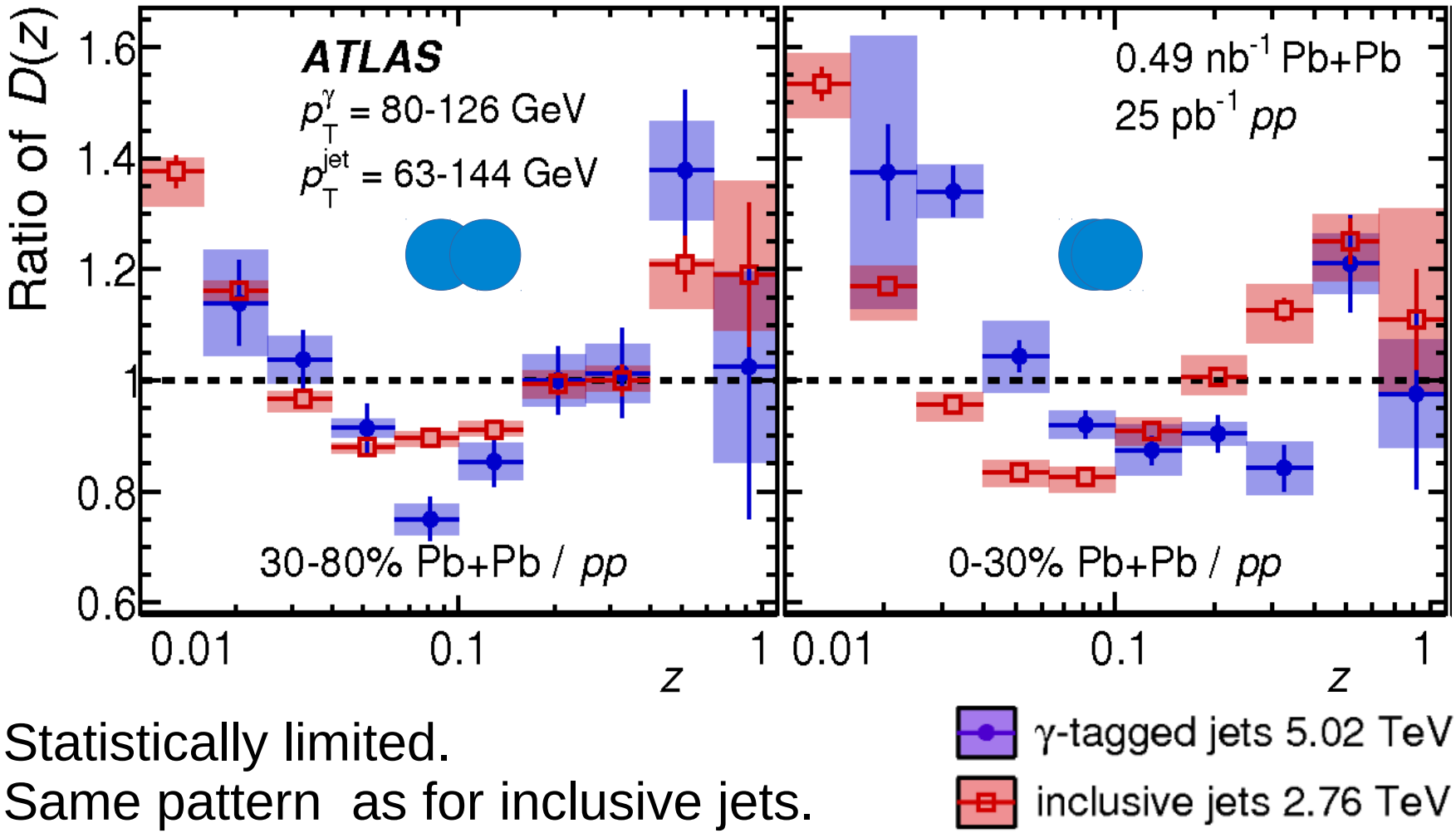
Photon-tagged jet fragmentation



- Statistically limited.
- Same pattern as for inclusive jets.
- Ratios similar in peripheral collisions.

arXiv:1902.10007

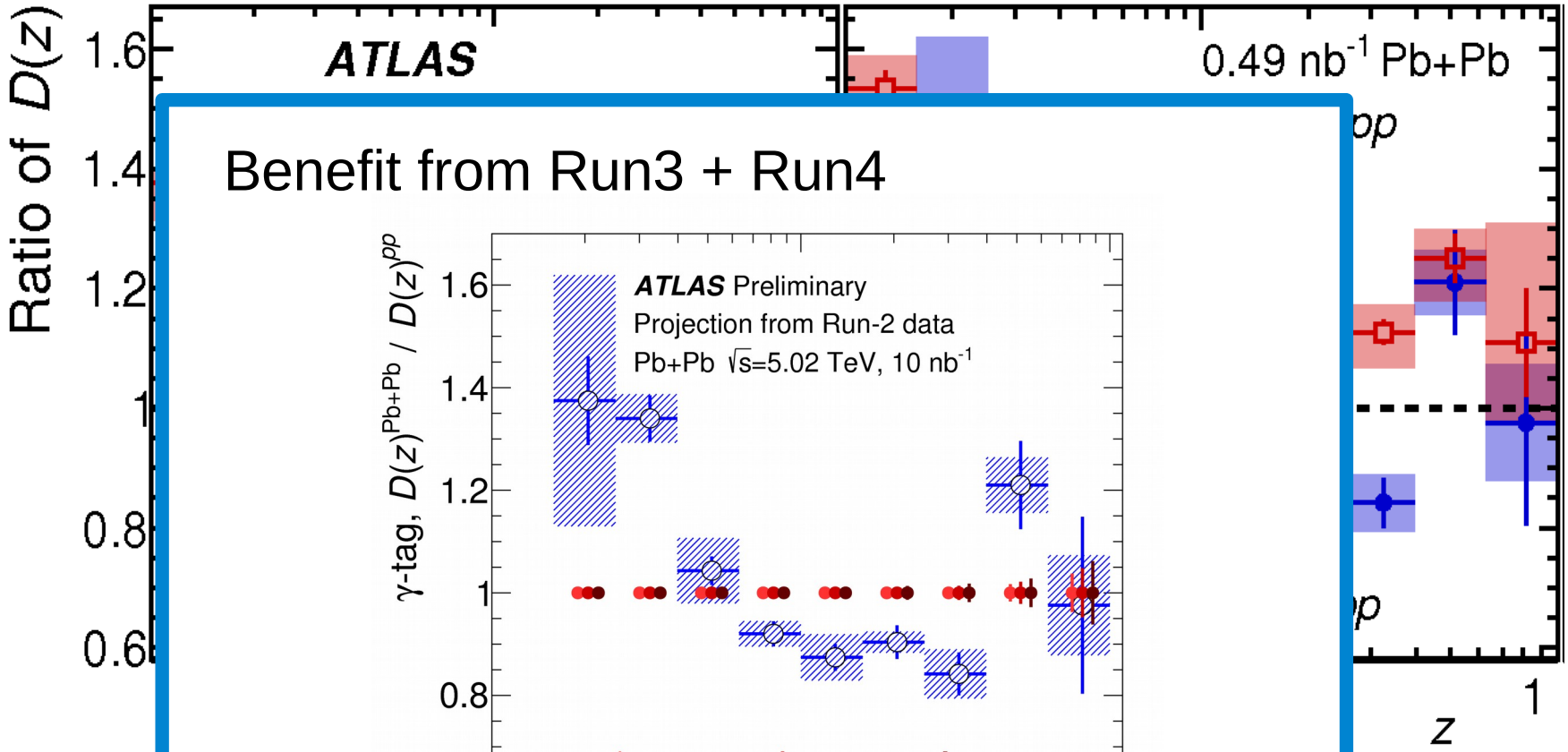
Photon-tagged jet fragmentation



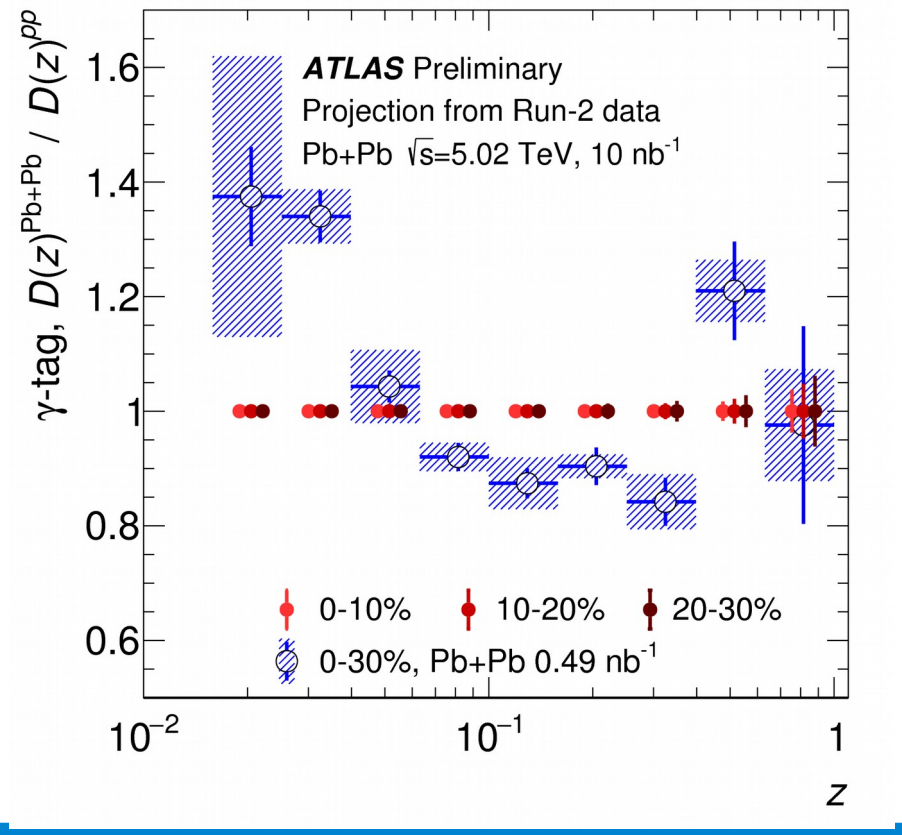
- Statistically limited.
- Same pattern as for inclusive jets.
- Ratios similar in peripheral collisions.
- Extra enhancement/suppression seen in photon-tagged FF in central collisions.

arXiv:1902.10007

Photon-tagged jet fragmentation



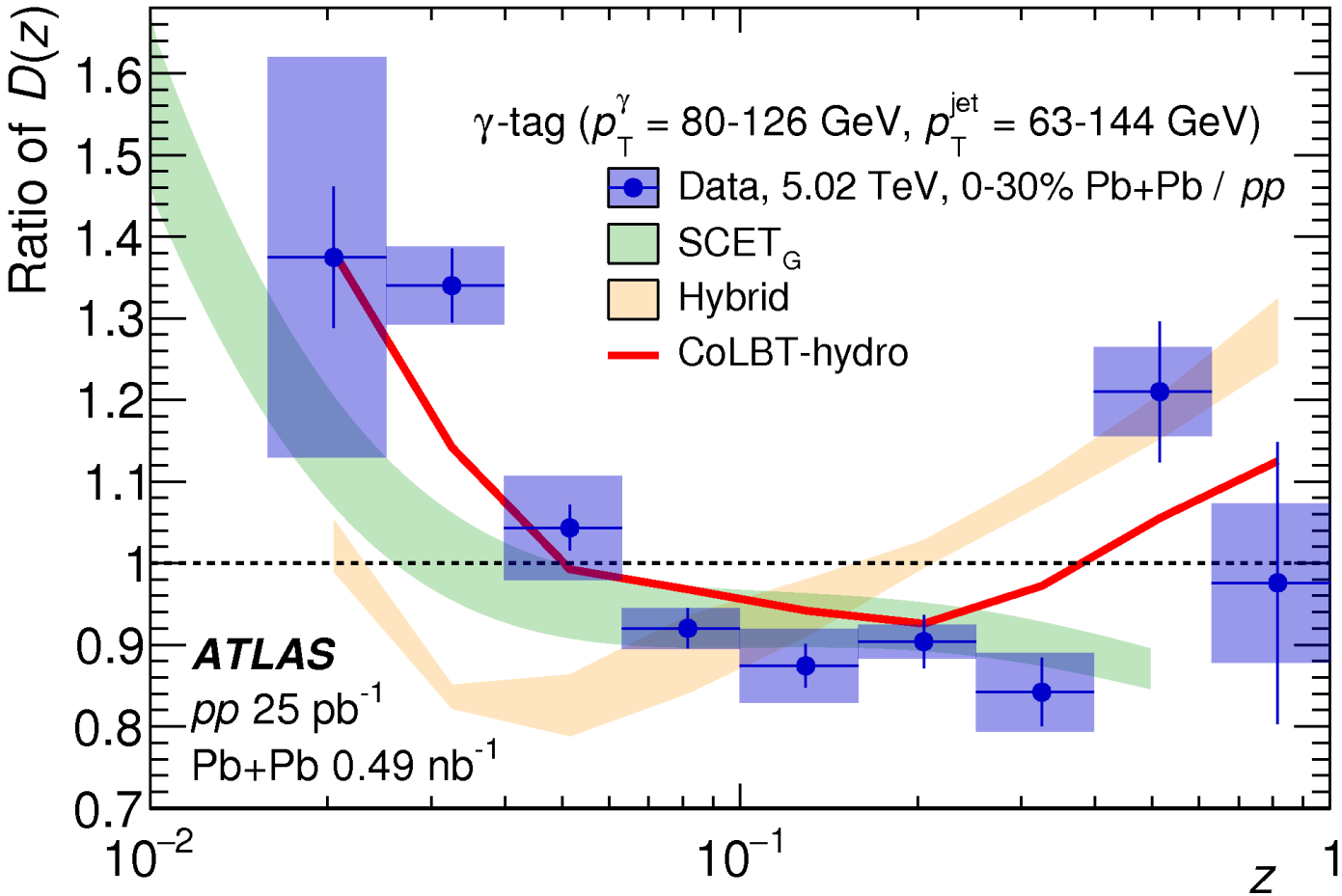
Benefit from Run3 + Run4



- Statist
- Same
- Ratios
- Extra enhancement/suppression seen in photon-tagged FF in central collisions.

arXiv:1902.10007

Photon-tagged jet fragmentation vs theory

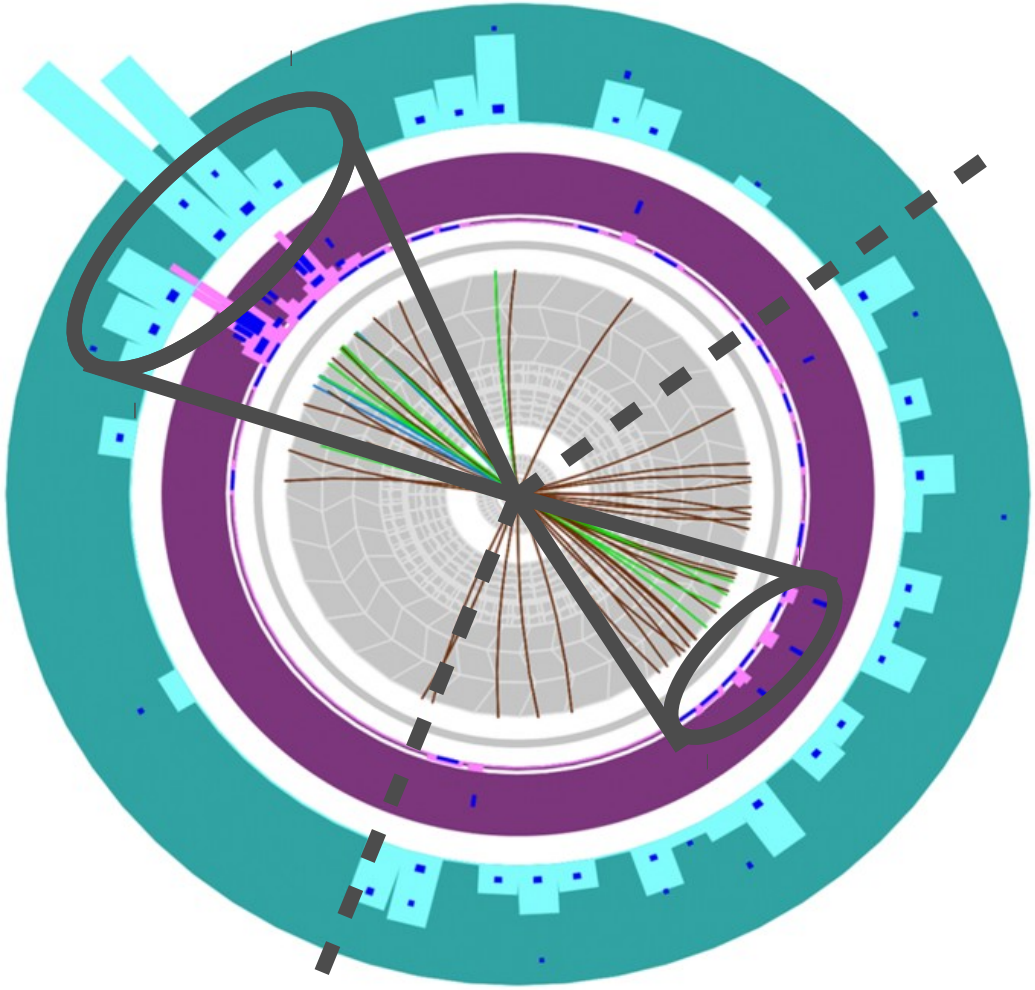


- The SCETg calculation and the CoLBT-hydro model is able to describe the key features of the data.

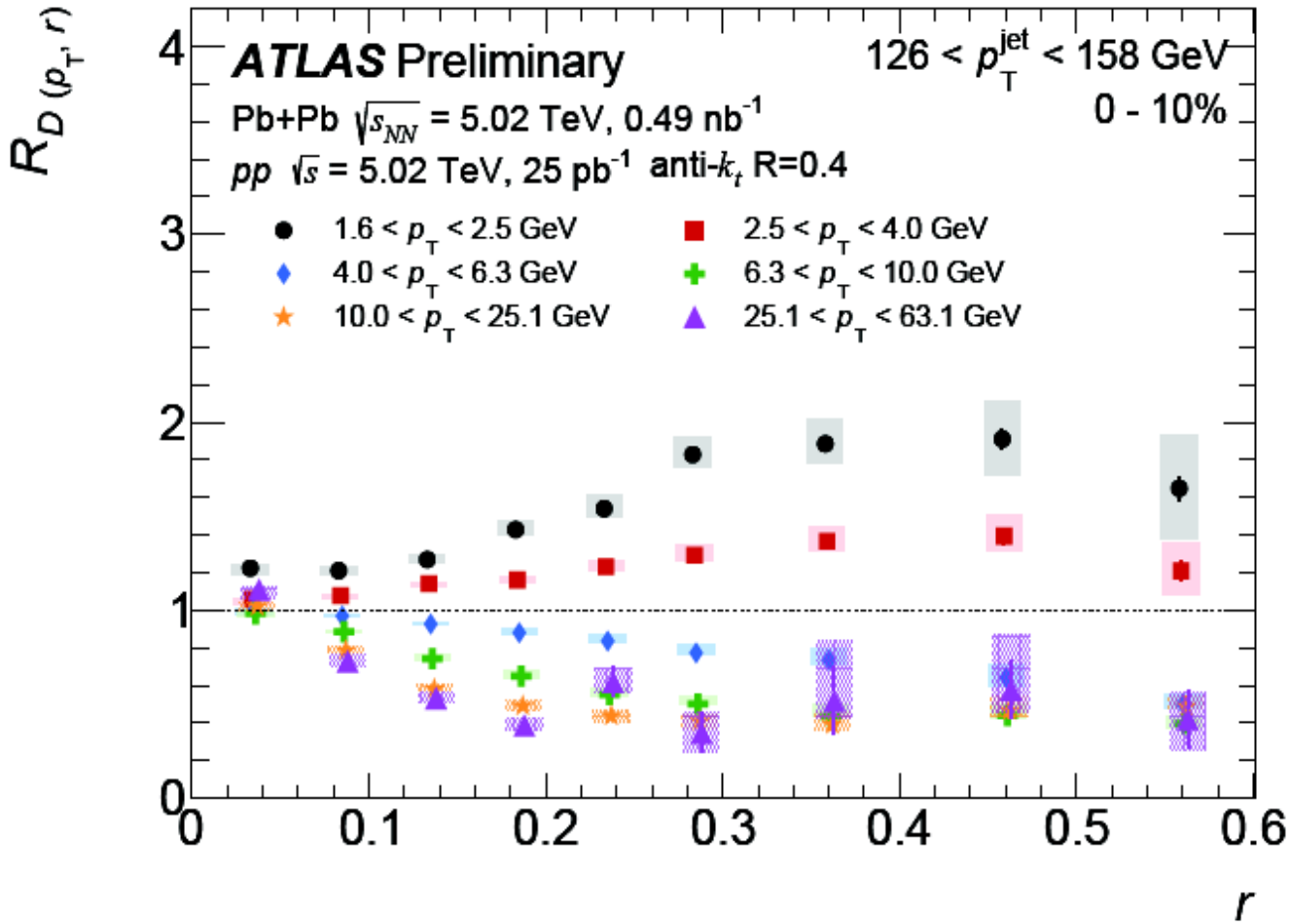
arXiv:1902.10007

Jet quenching measurement

Track-jet correlations at large angles

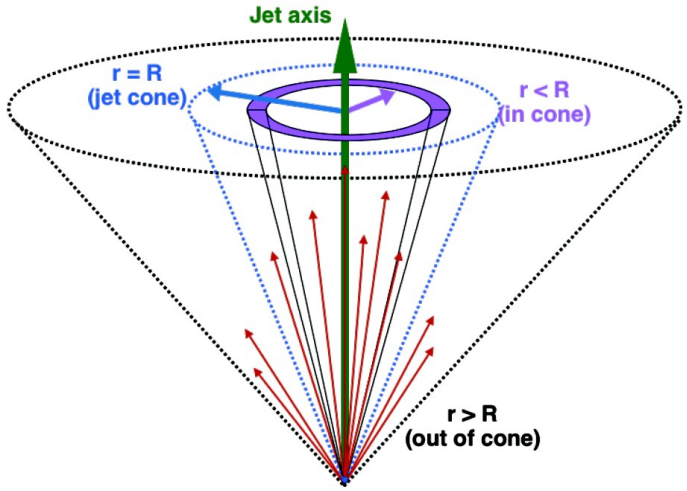


Let's look around jet….



$$D(p_T, r) = \frac{1}{N_{jet}} \frac{1}{2\pi r} \frac{d^2 n_{ch}(r)}{dr\, dp_T}$$

where $r < 0.6$



- Jets are broader in central collisions compared to *pp*.
  - But decrease of yields of intermediate p_T particles with *r*.
- Smallest modification seen in the jet core.

ATLAS-CONF-2018-010

Summary

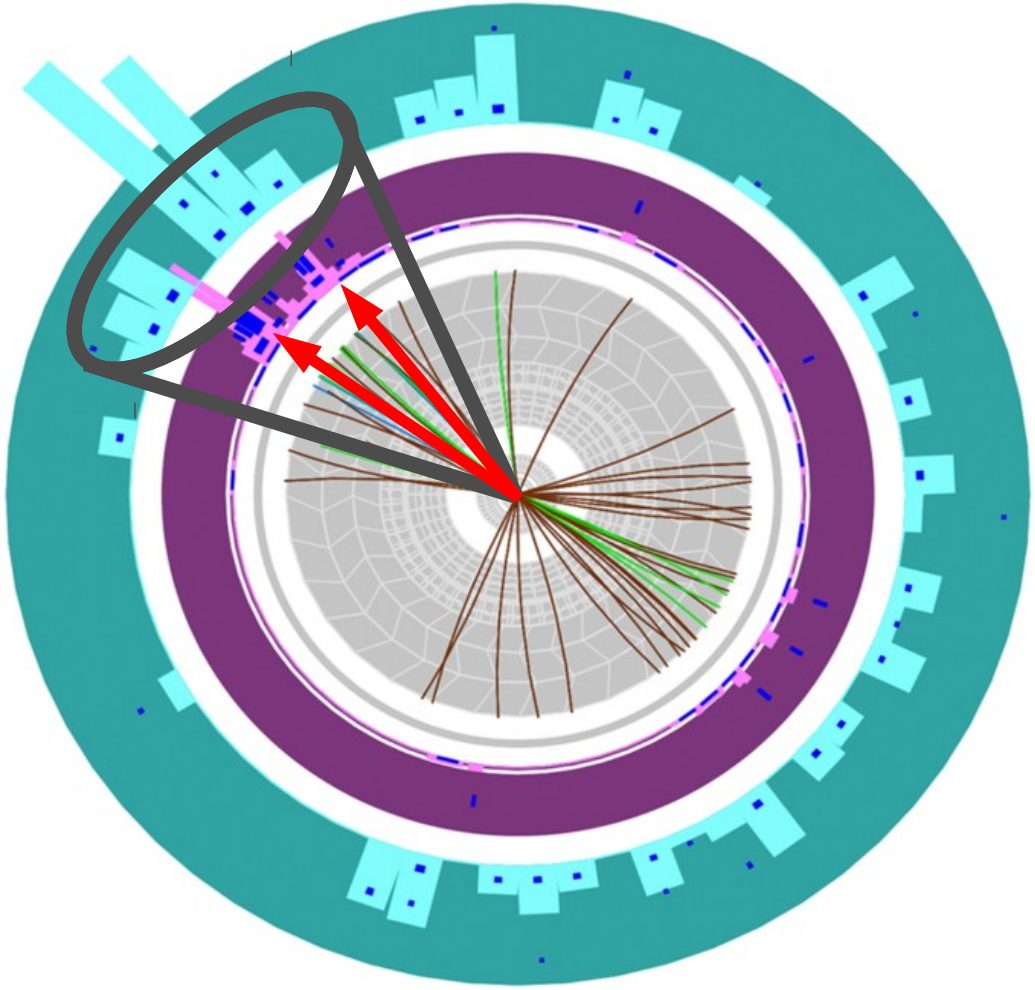
- Using high statistics LHC data and new techniques bring us to era of precise measurements in heavy-ion collisions
  - New dijet measurement in p+Pb and pp collisions should provide new input for saturation models.
  - Different jet structure observables sensitive to different aspect of probing the QGP.
  - Complementary measurements of jet structure put strong constraints on theoretical models.

All ATLAS Heavy Ion public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Backup

Jet quenching measurement

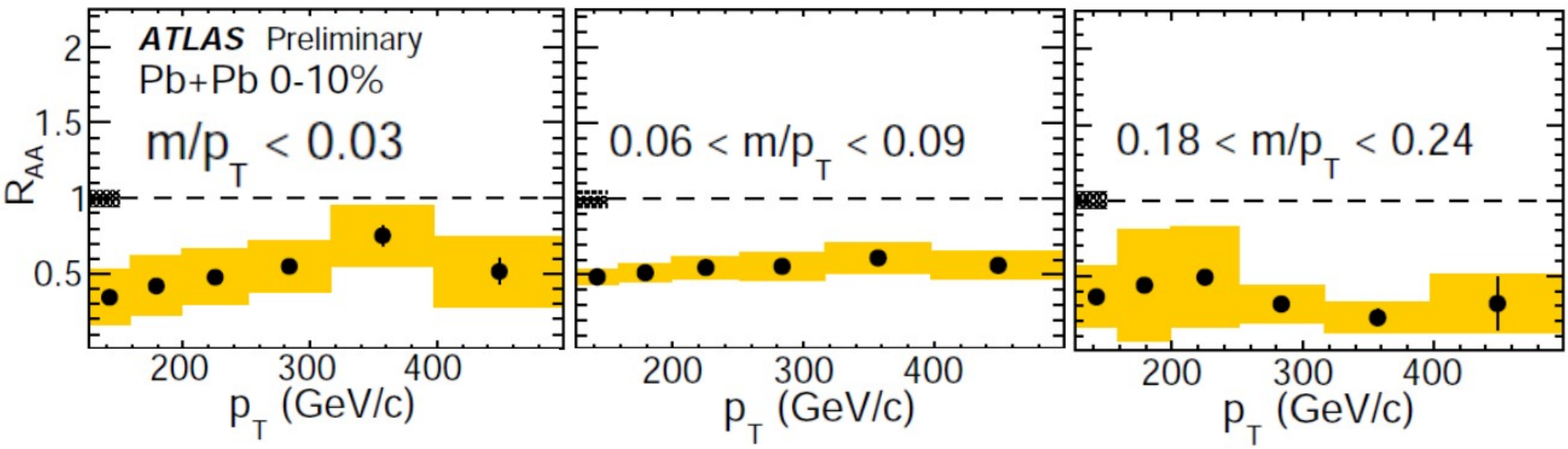
Jet substructure



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.

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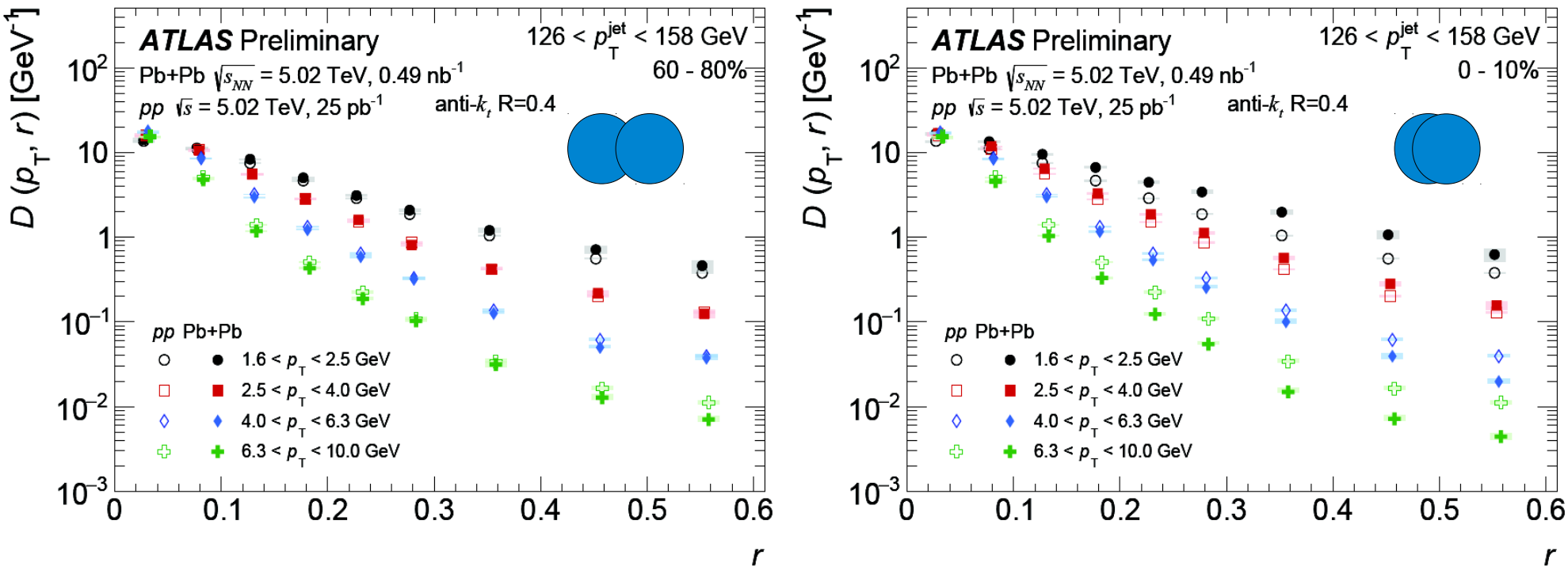
Radial Profile



Change of shapes in central Pb+Pb collisions compared to *pp* reference.

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