Jet Fragmentation & Substructure in Nuclear Collisions at the LHC

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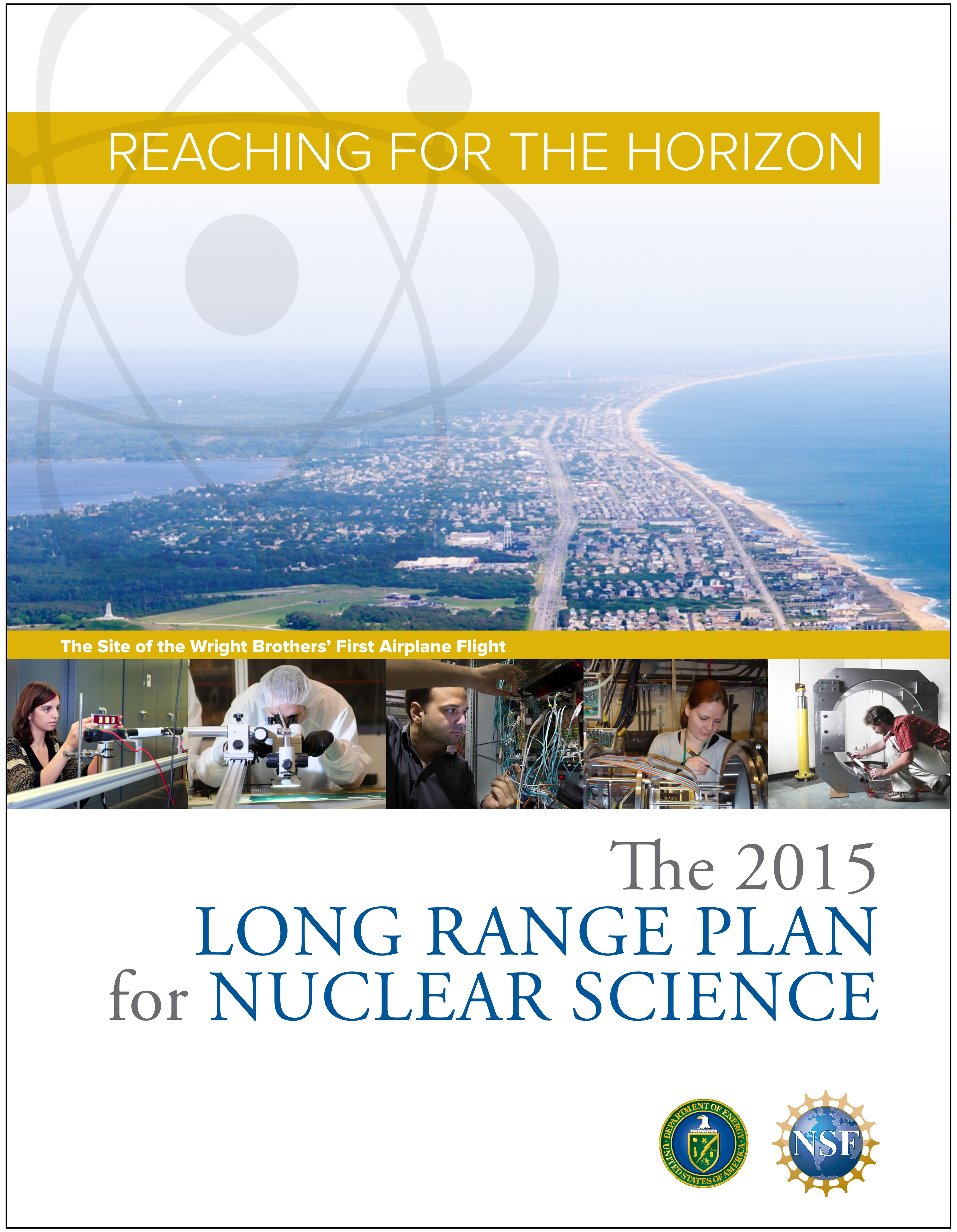
why jets in AA collisions?



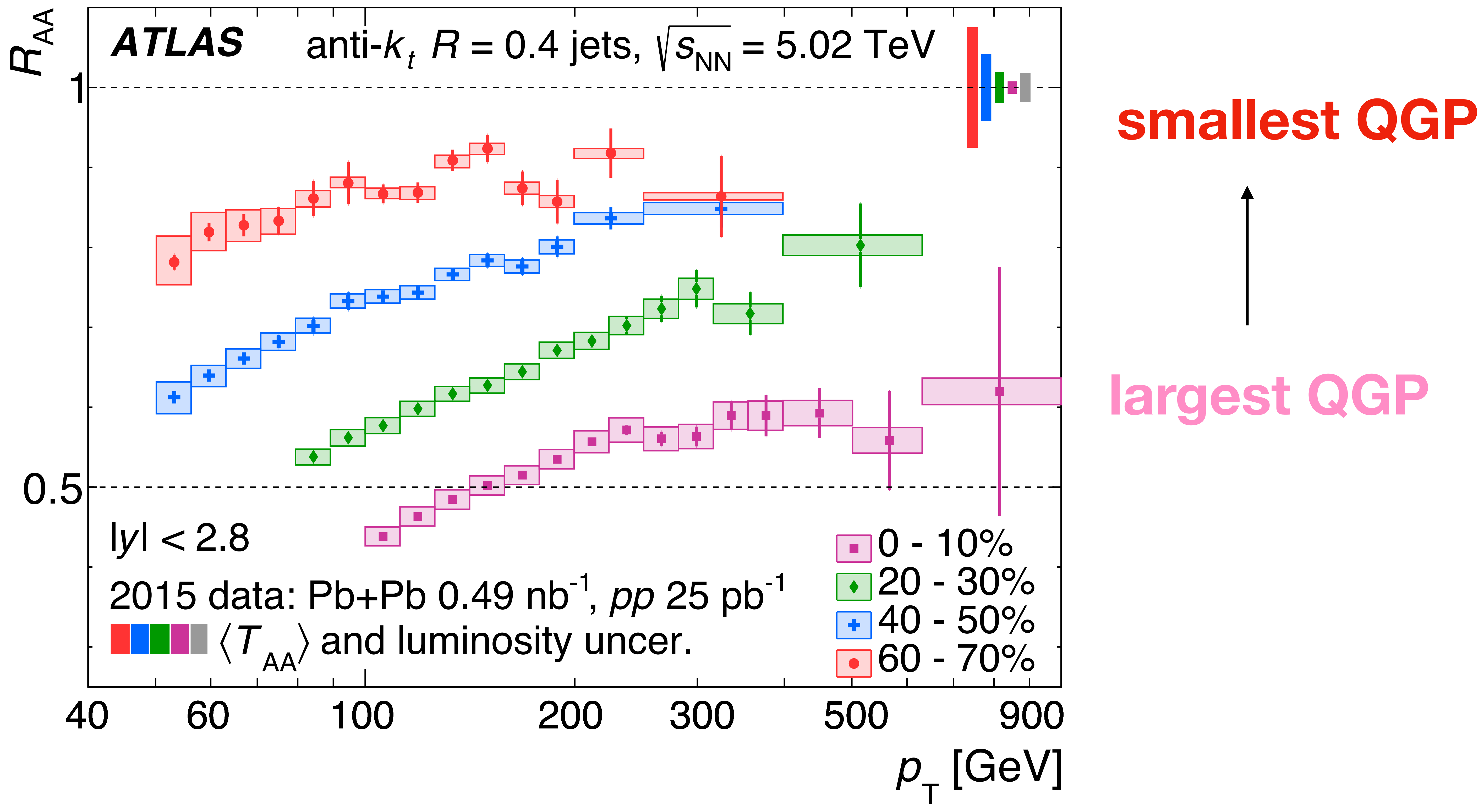
"To understand the workings of the QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see are quarks and gluons interacting only weakly with each other. **The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid.**"

jet *quenching*

- R_{AA} tells us jet quenching is important but it integrates over everything except the jet momentum

- the focus of current measurements is to understand how quenching depends on the:
  - structure of the jet
  - amount of QGP the jet sees

jet rates / expectations



ATLAS:1805.05635

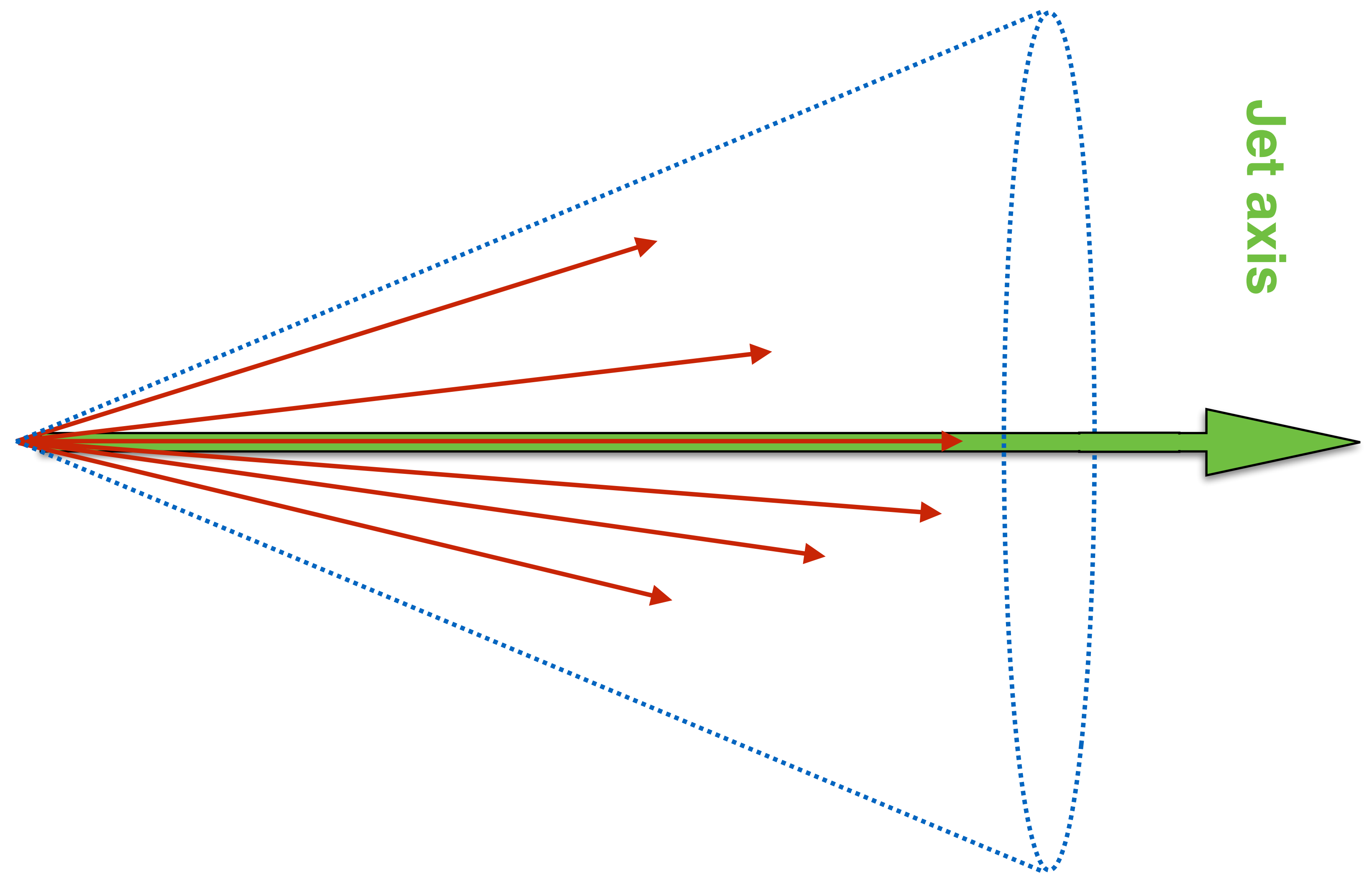
fragmentation functions & substructure

- **fragmentation functions**: single particle distributions inside of jets
  - direct measure of the average jet properties & how they are modified by the QGP interactions
- **substructure**: jet wide correlation measures
  - sorting jets by substructure provides direct information on which jets are suppressed in the QGP

both types of measurements are very necessary to over-constrain the physics of interest

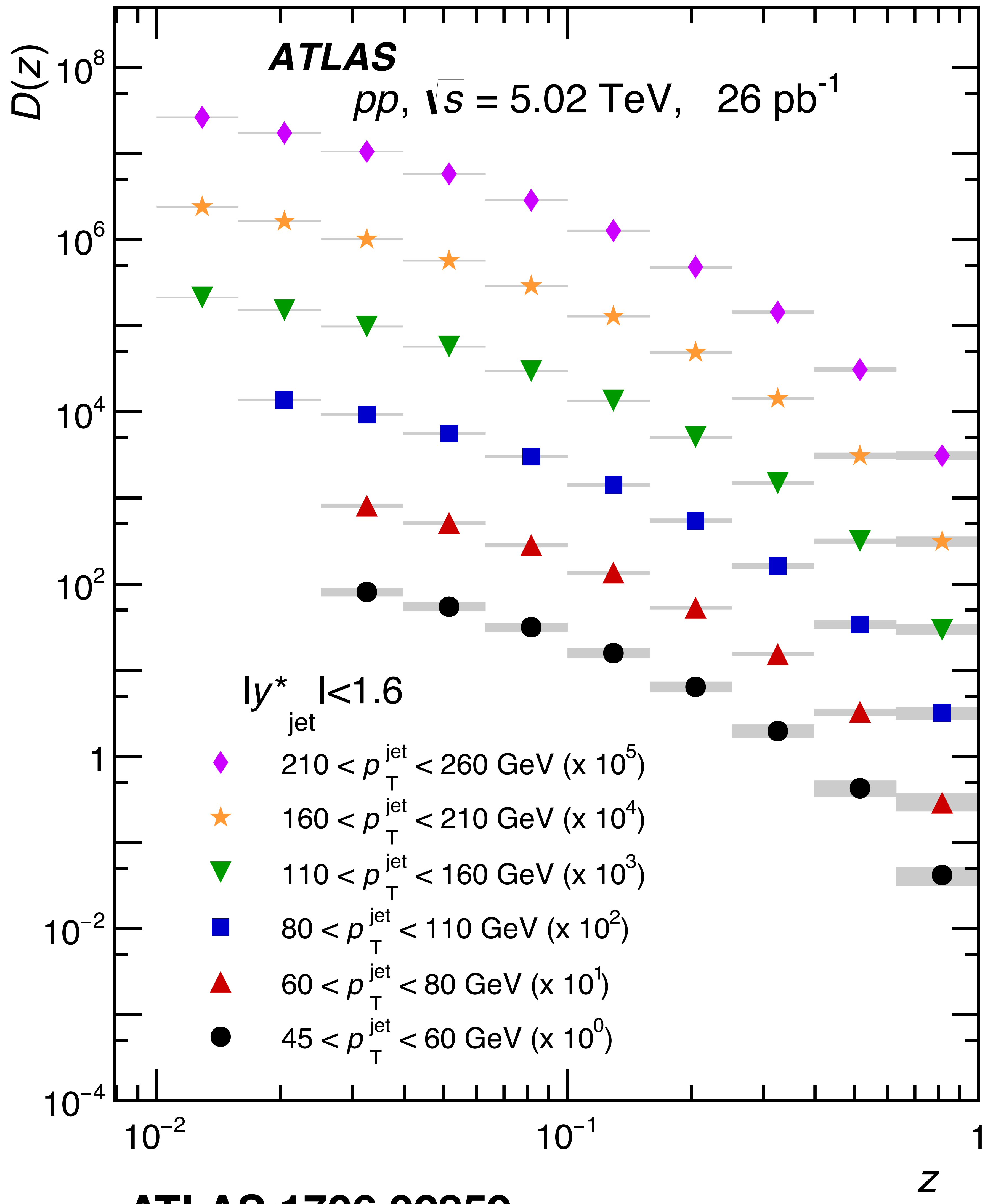
these measurements are very challenging in AA collisions due to the large UE

pp collisions



$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{dn_{\rm ch}}{dz}$$

$$z \equiv p_{\rm T} \cos \Delta R \,/\, p_{\rm T}^{\rm jet}$$

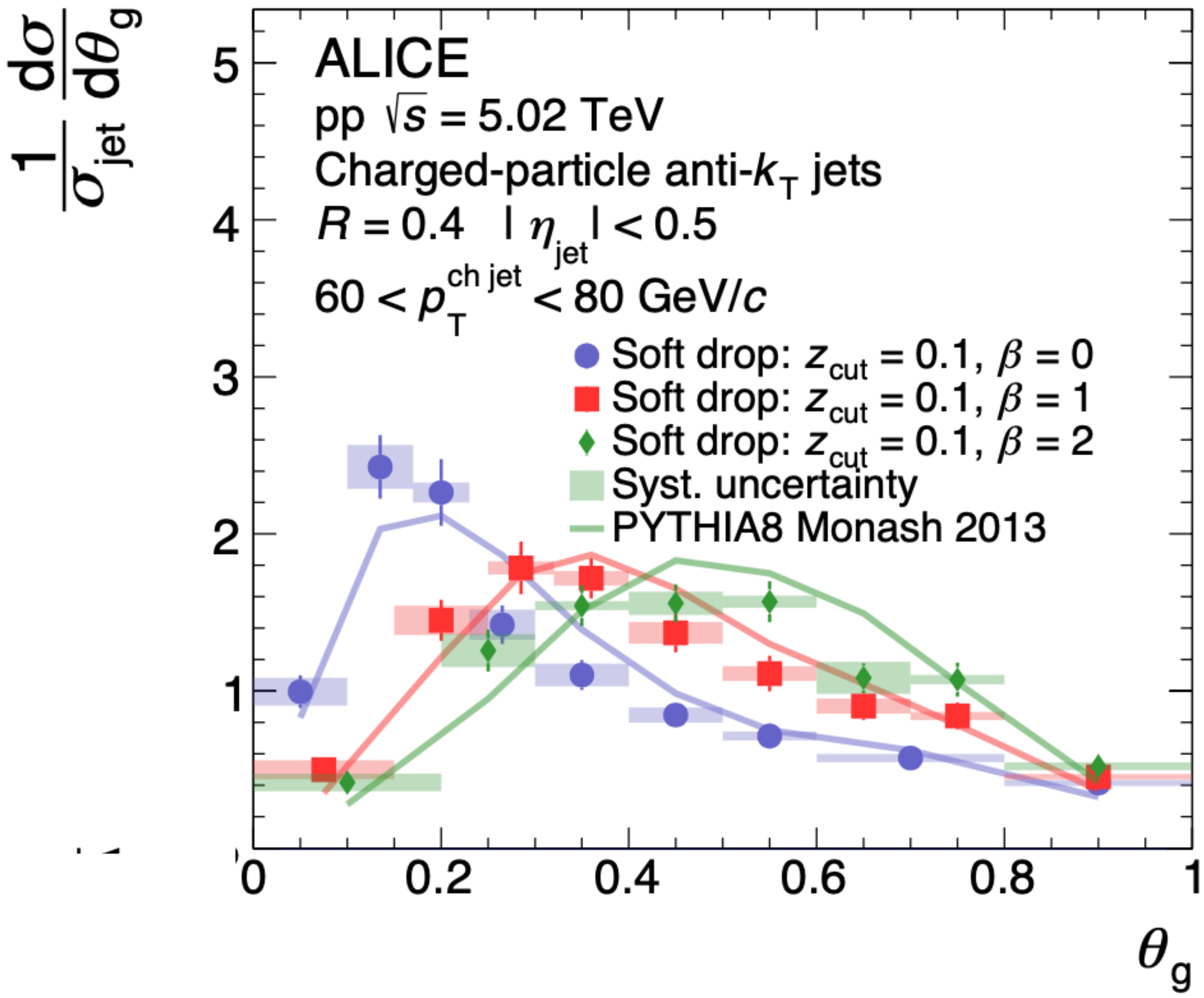


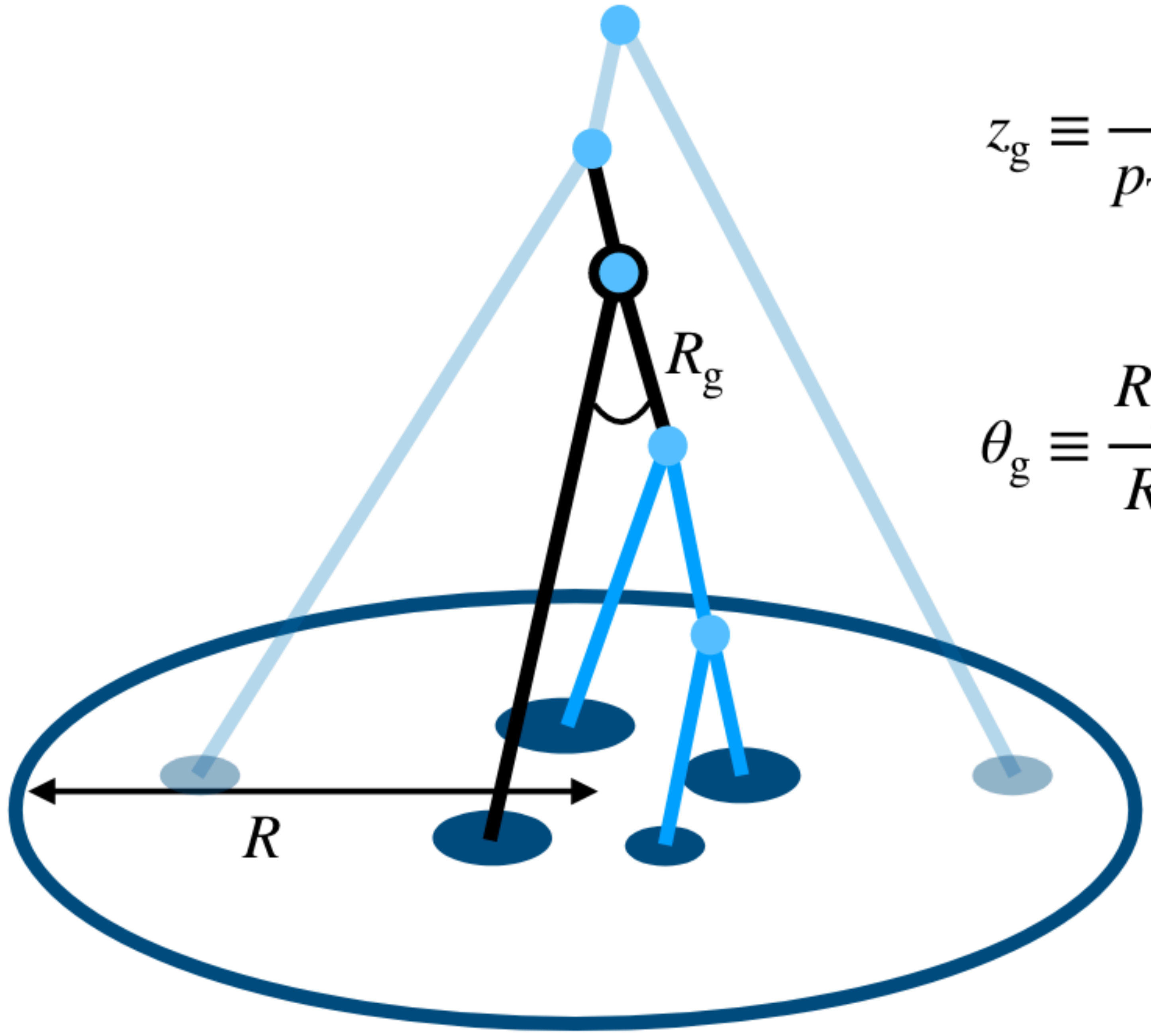
ATLAS:1706.02859

2D unfolding in $p_{\rm Tjet}$ & z
corrects for jet energy resolution & fragmentation dependence of the calorimeter response

pp collisions

ALICE: 2204.10246



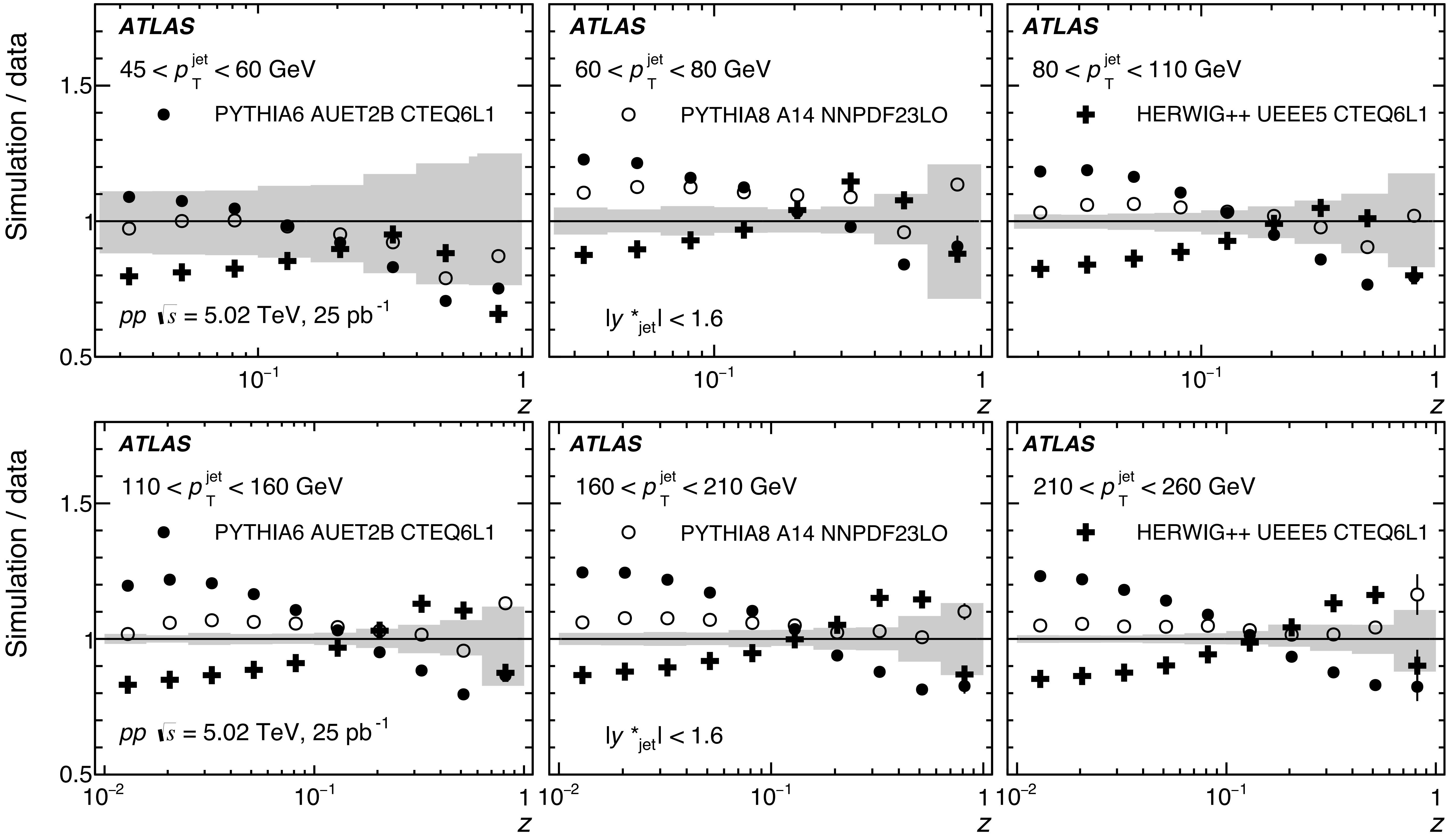


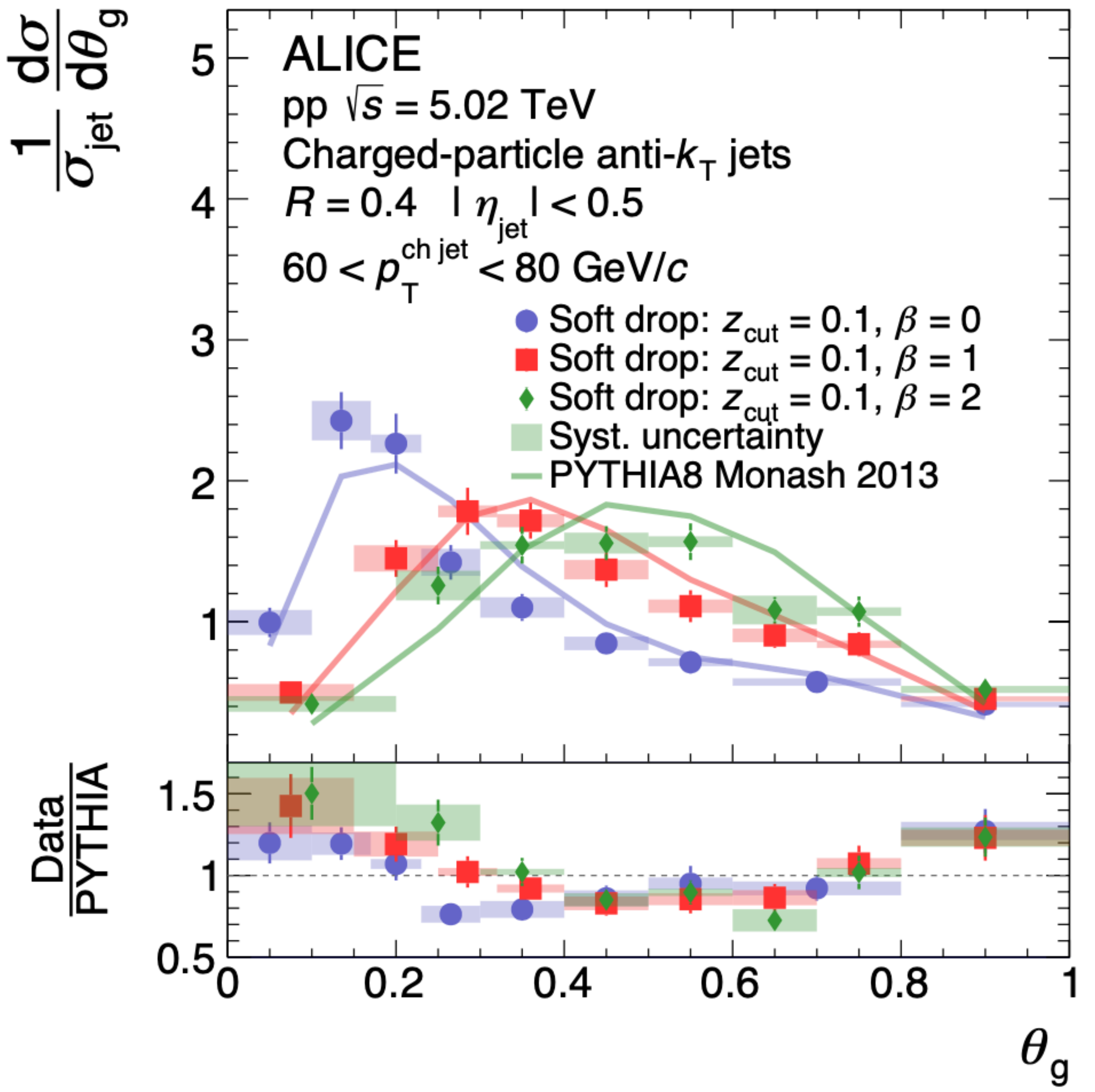
$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

2D unfolding in p_{Tjet} & θ_g

pp measurements compared to generators

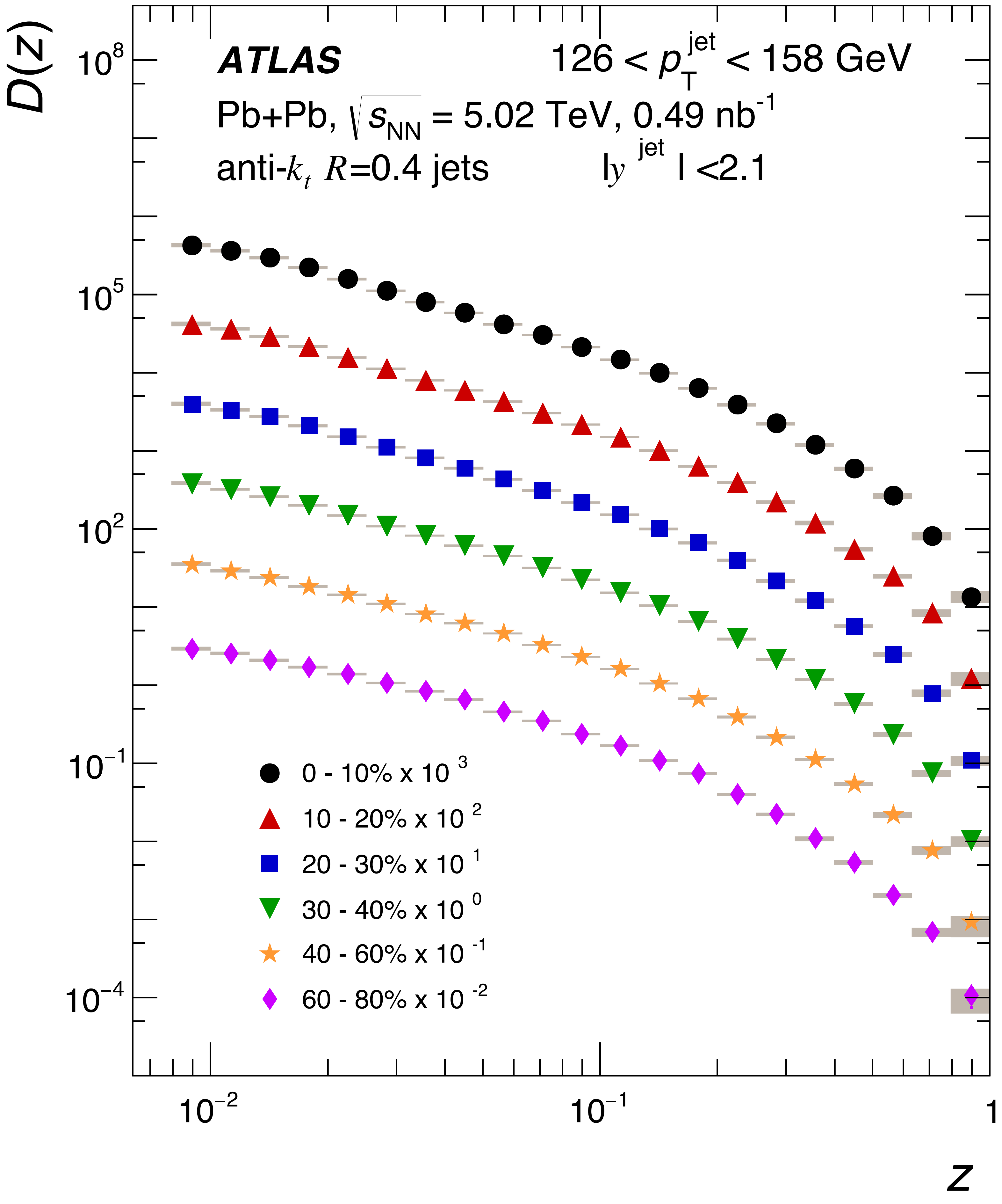




ALICE: 2204.10246

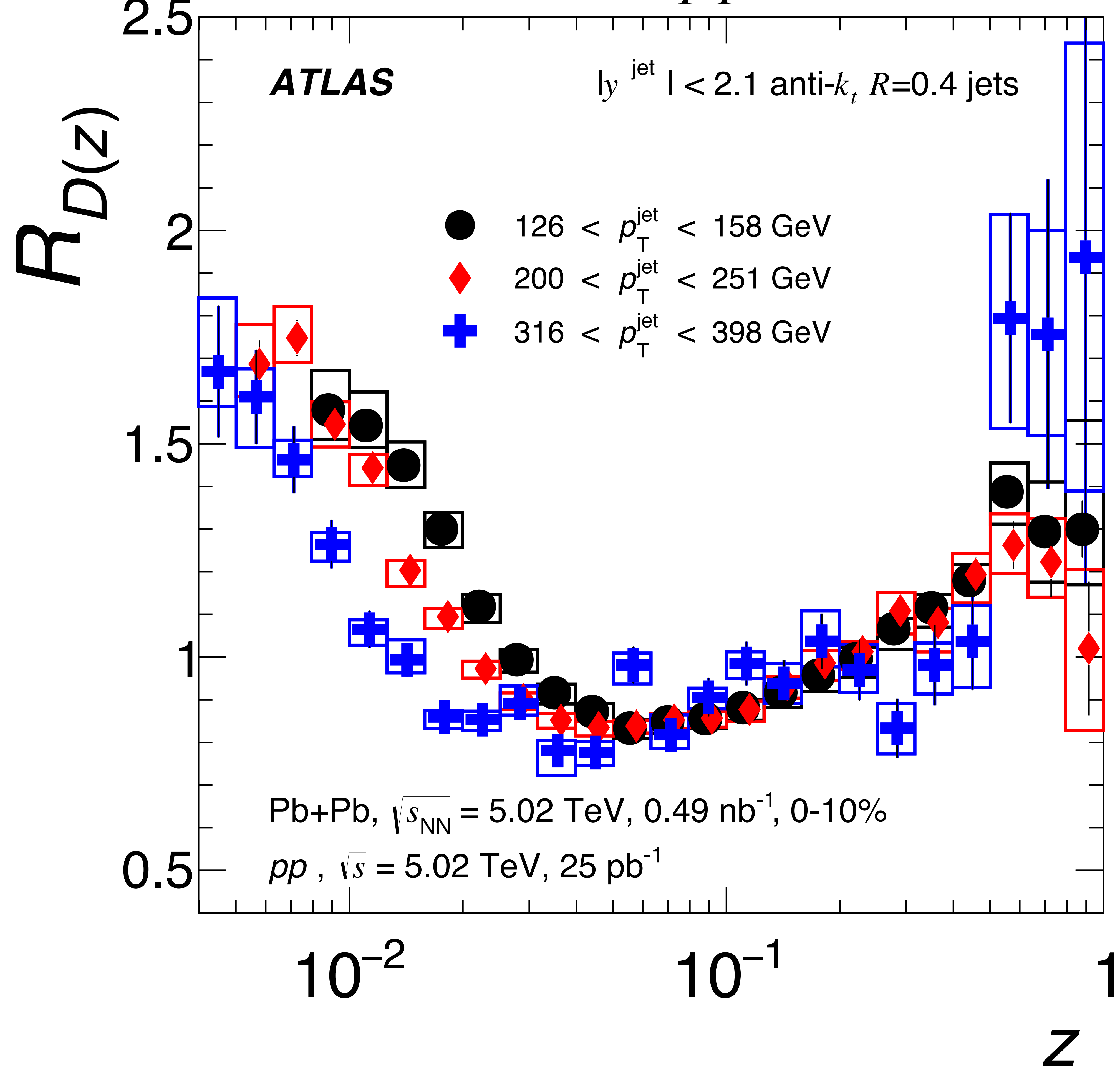
differences between pp & generators require pp data as a reference for AA/ pA collisions

fragmentation functions in PbPb collisions

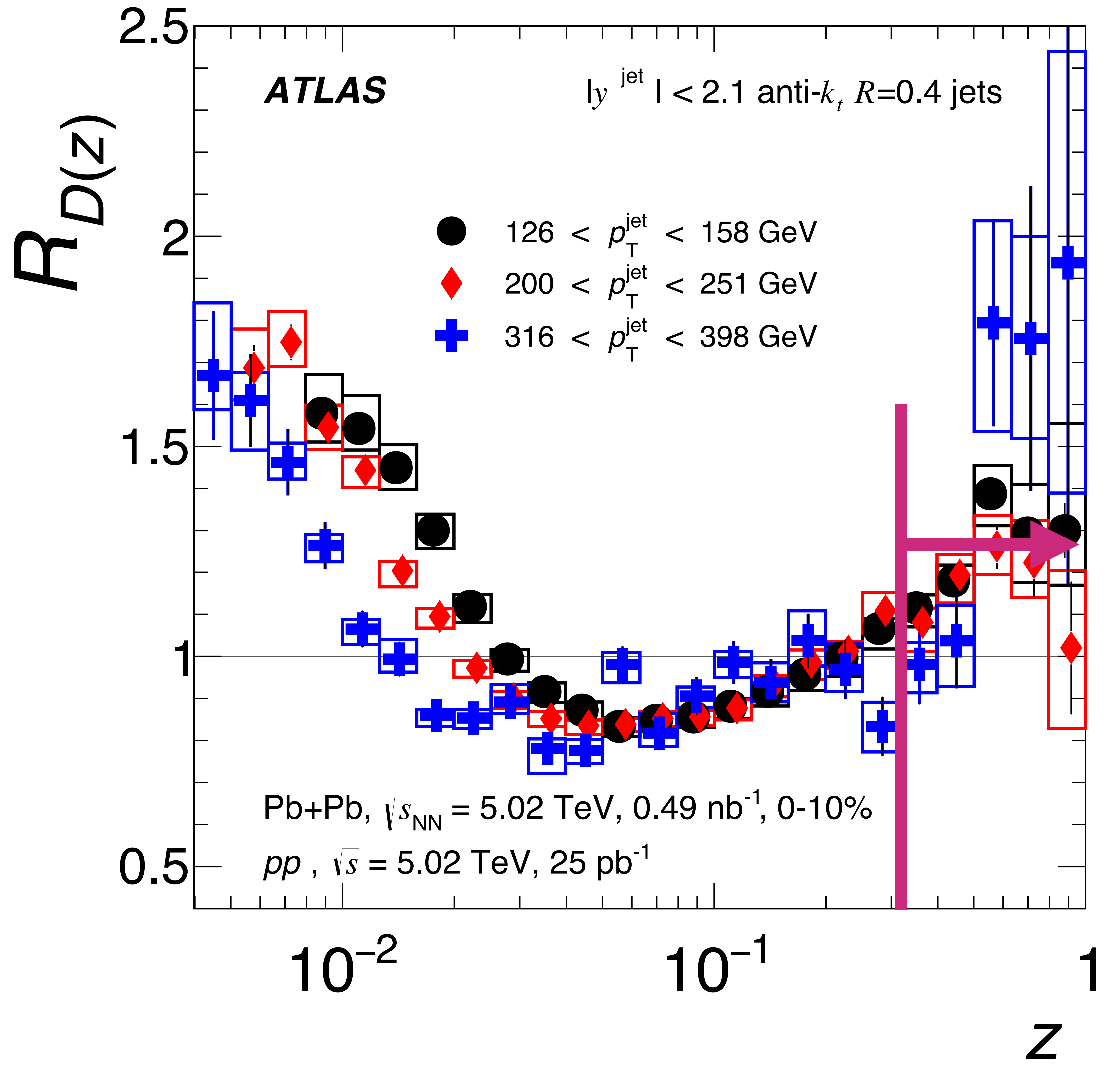


PRC98 (2018) 024908

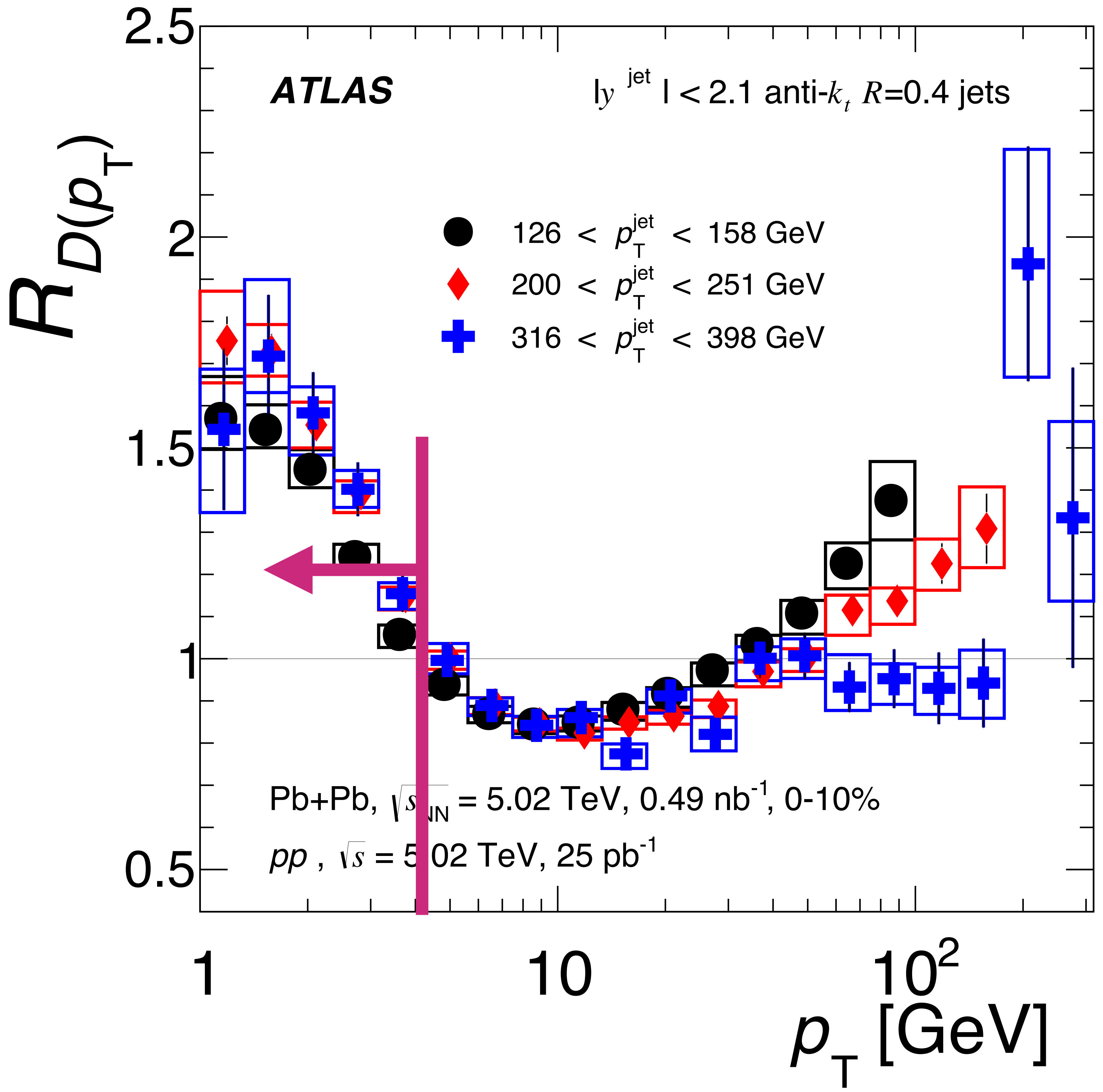
$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}}$$



fragmentation functions in z & p_T



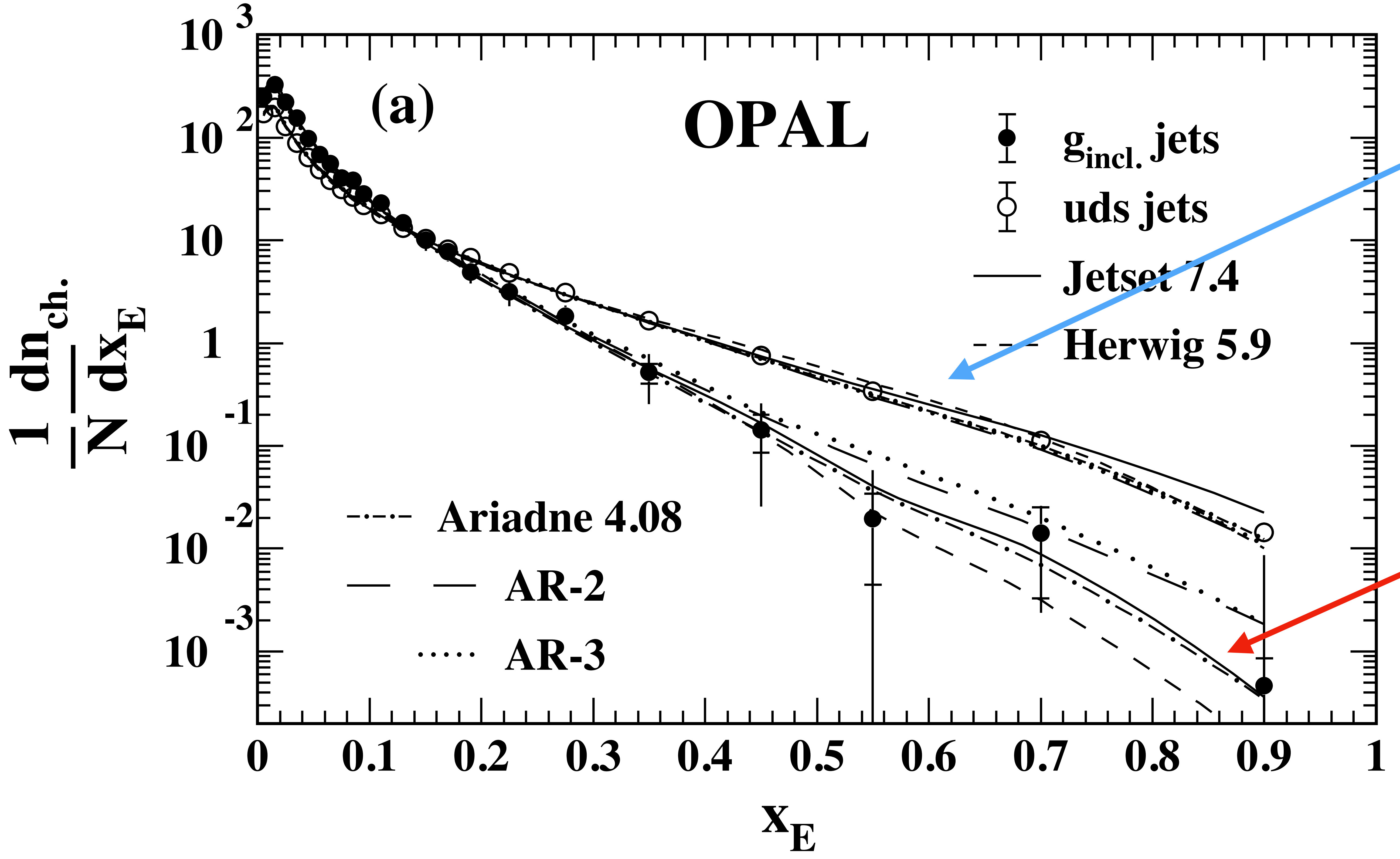
high z scaling:
related to fragmentation?



low p_T scaling:
QGP scale?

PRC98 (2018) 024908

quark & gluon fragmentation



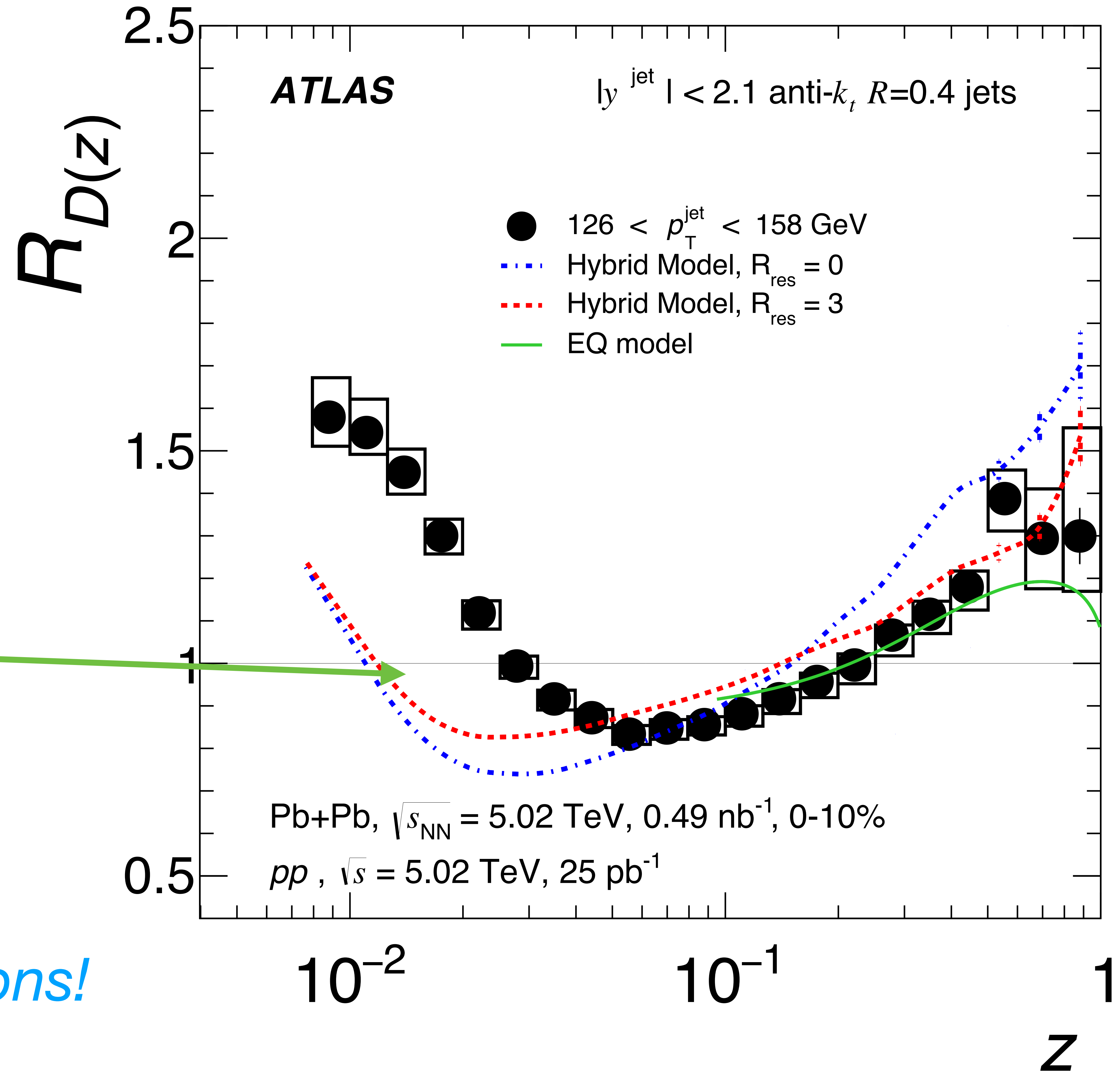
quark jets have more high z particles than **gluon** jets

if gluons lose more energy than quarks, then there will be an enhanced fraction of quarks in PbPb compared to pp at a given jet p_T

high z excess

Interpreting Single Jet Measurements in Pb+Pb Collisions at the LHC

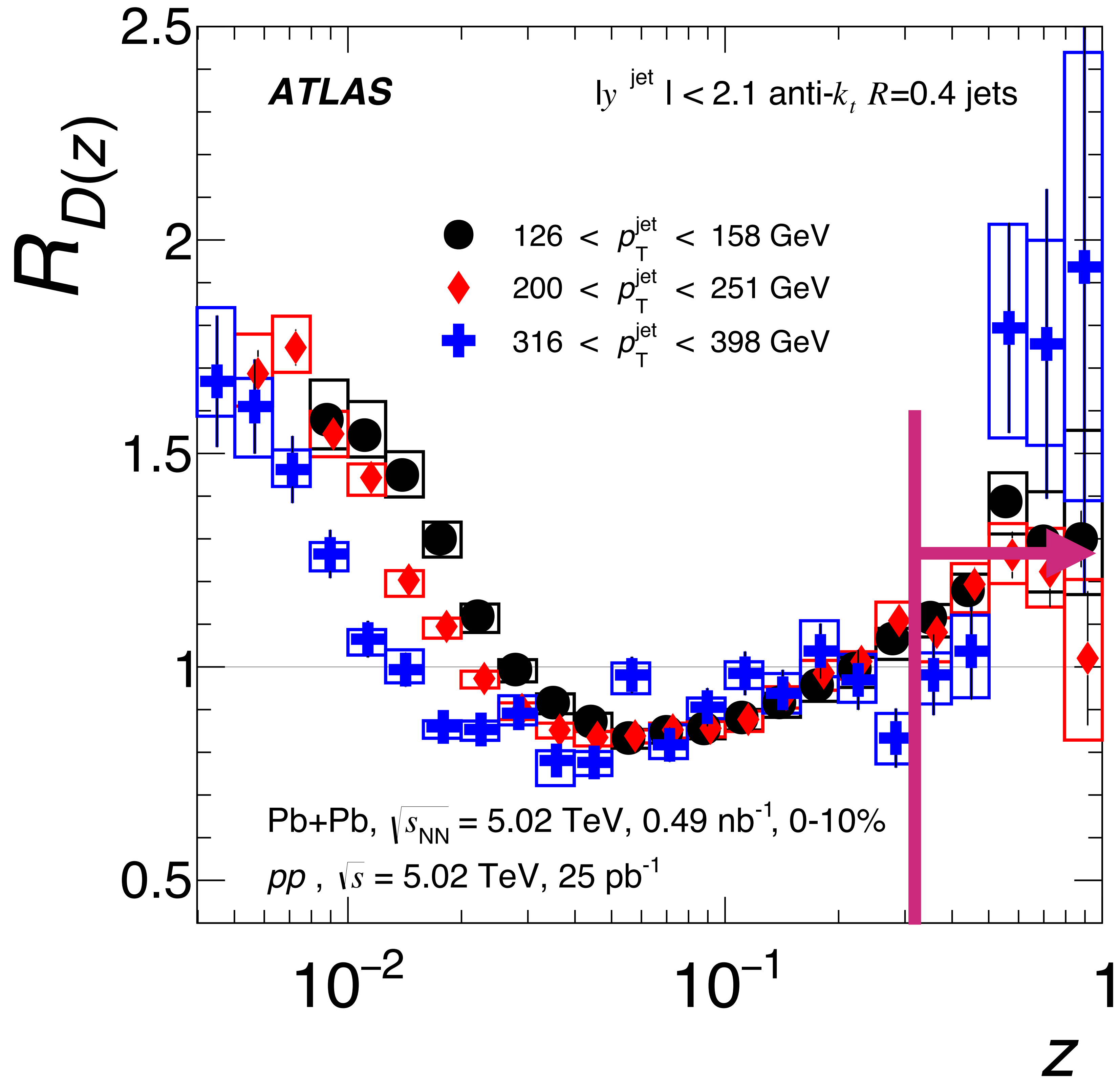
Martin Spousta[a], Brian Cole[b] 1504.05169



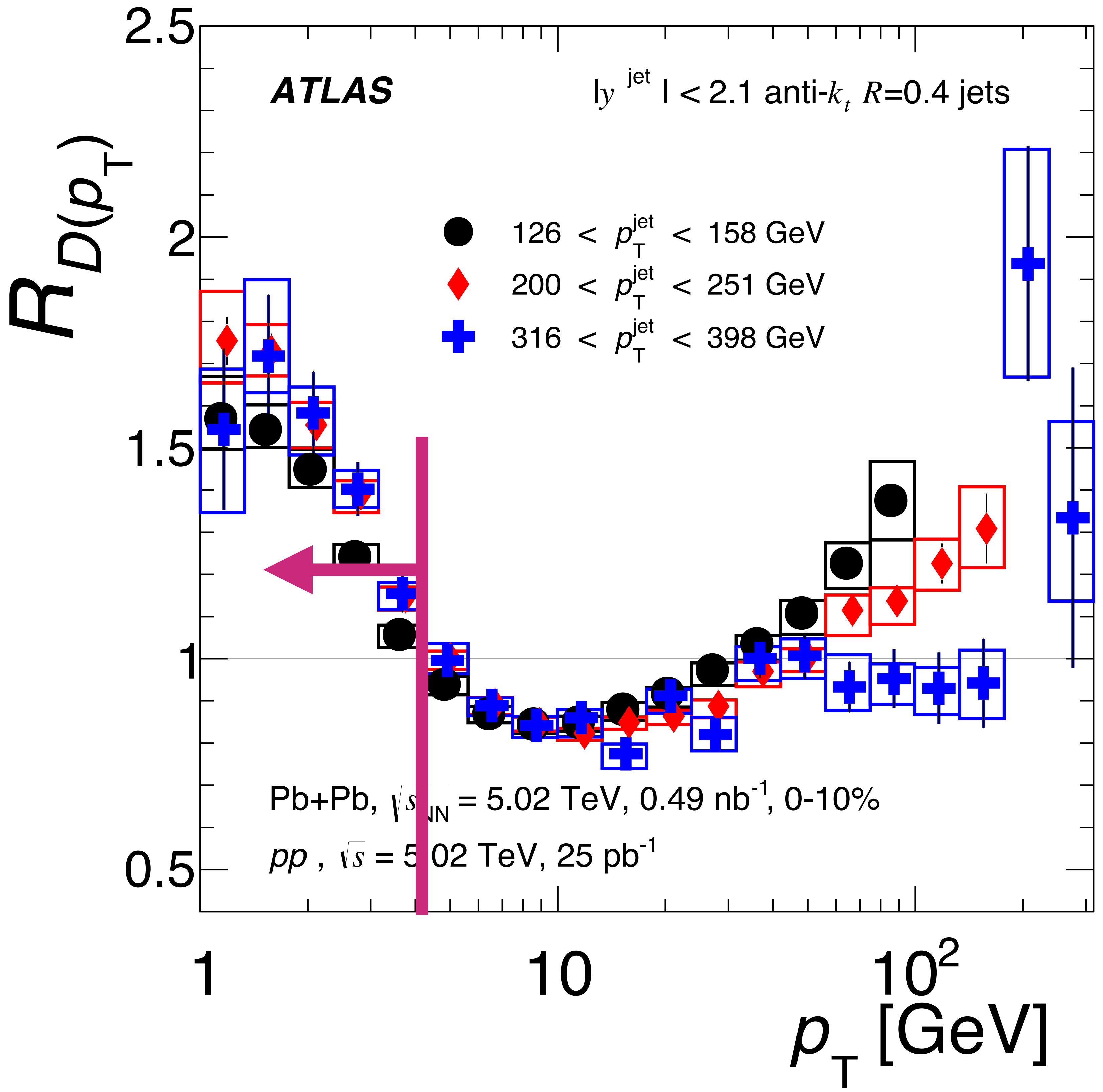
larger energy loss for gluons than quarks followed by pythia fragmentation

illustrative model not a substitute for theoretical calculations!

fragmentation functions in z & p_T



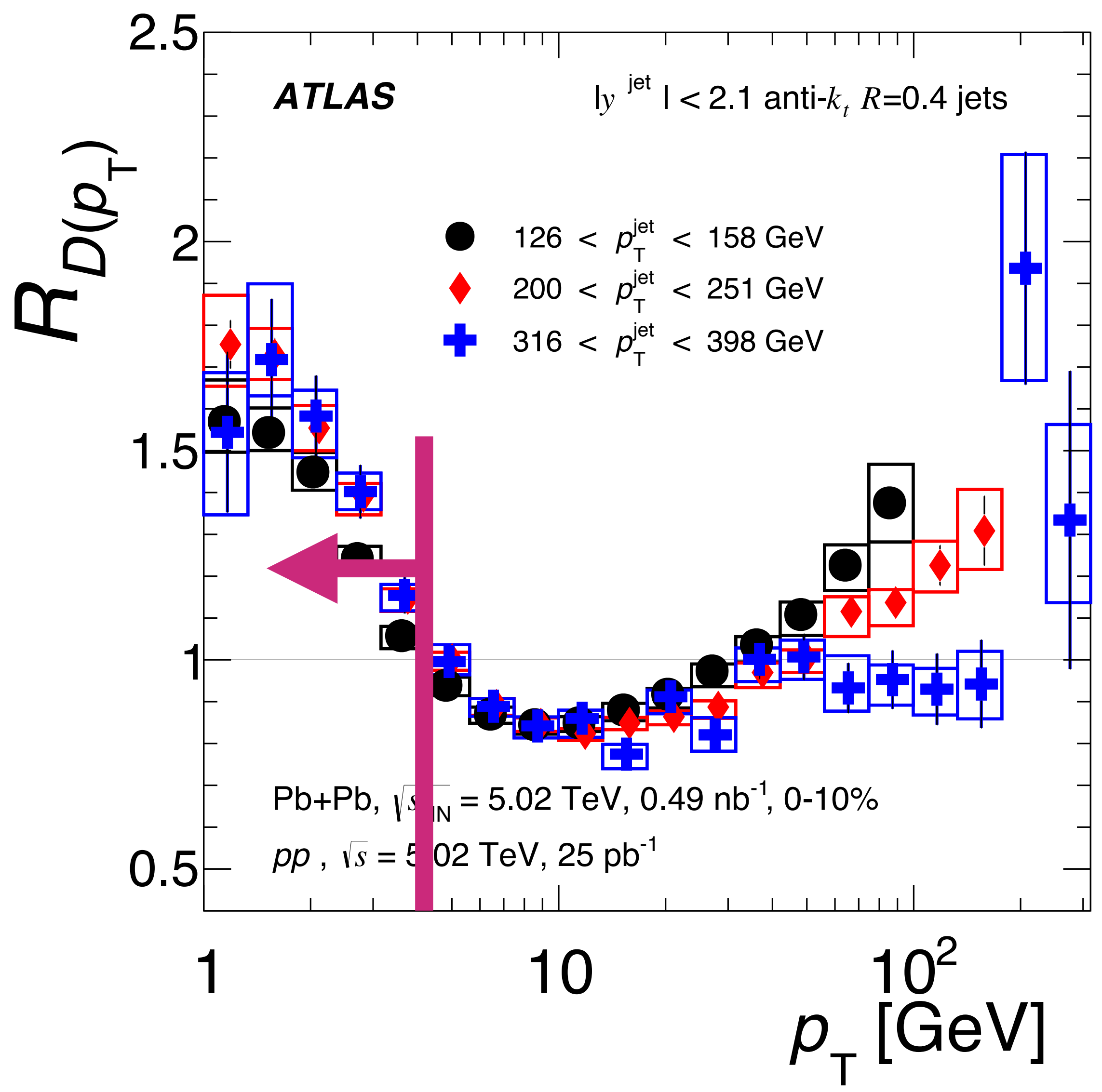
high z scaling:
related to fragmentation?



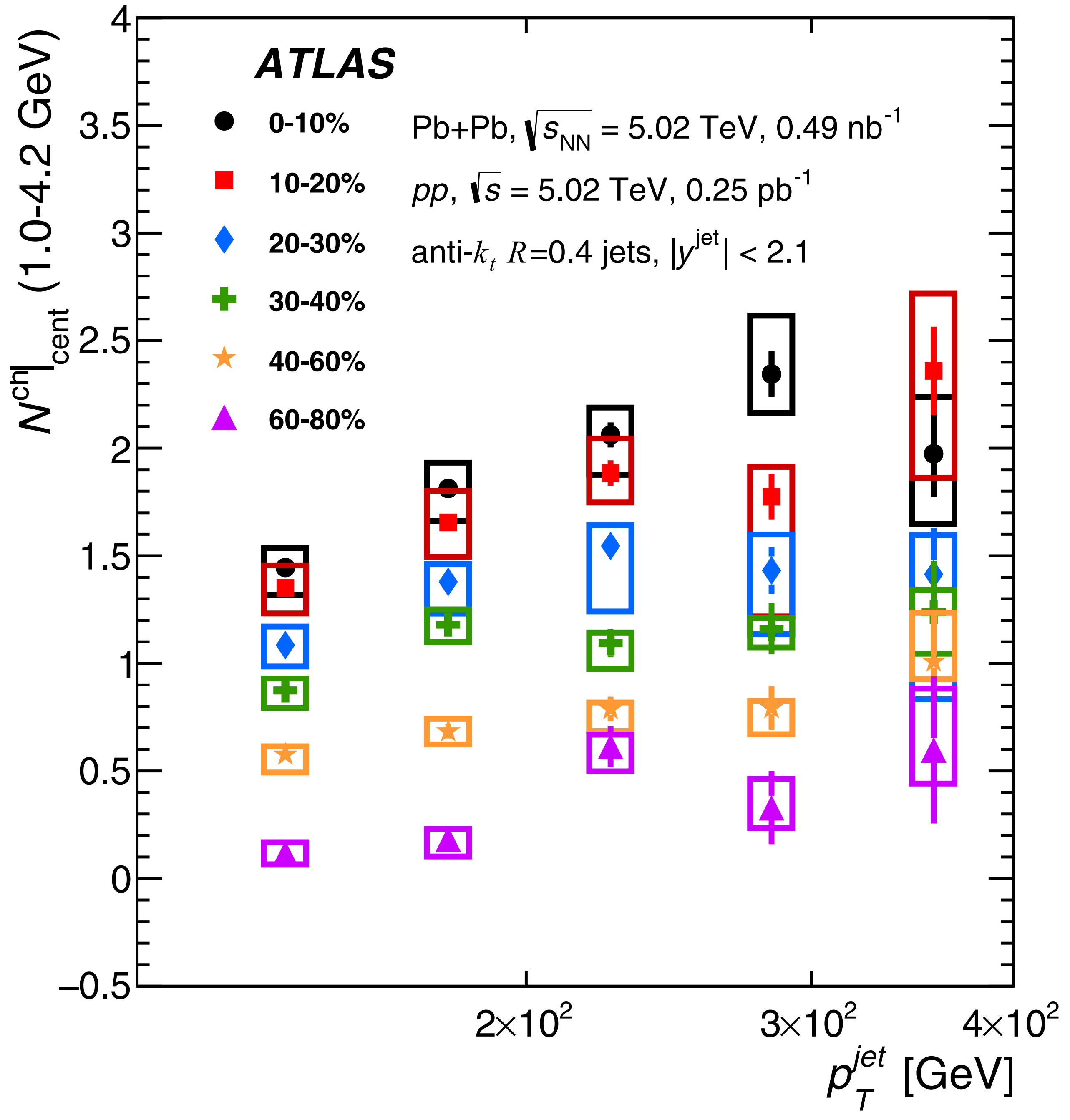
low p_T scaling:
QGP scale?

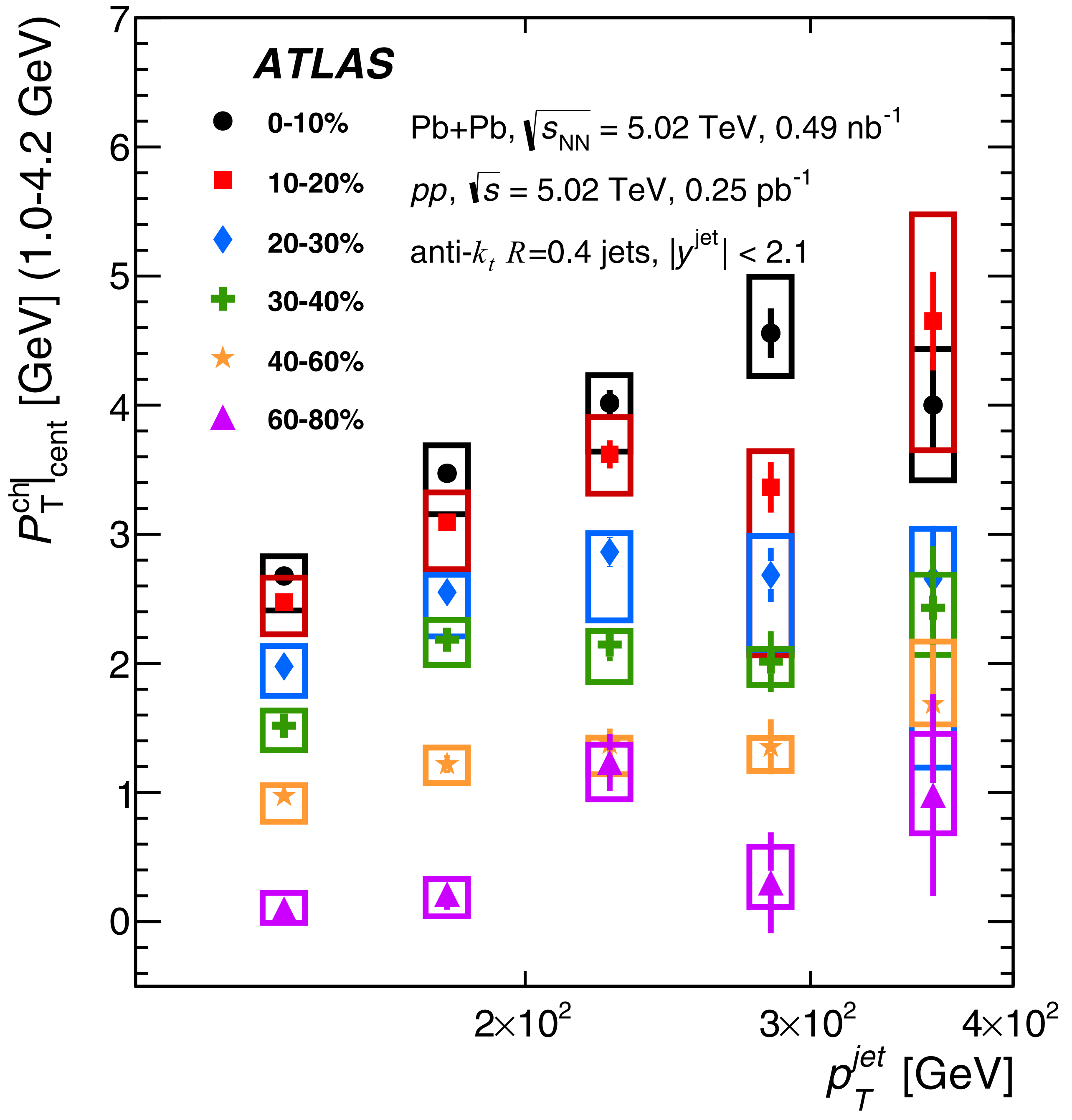
PRC98 (2018) 024908

how much energy is there in these soft fragments?



inside an R = 0.4 jet ~2 extra particles carrying a total of ~4 GeV with 1 < p_T < 4 GeV

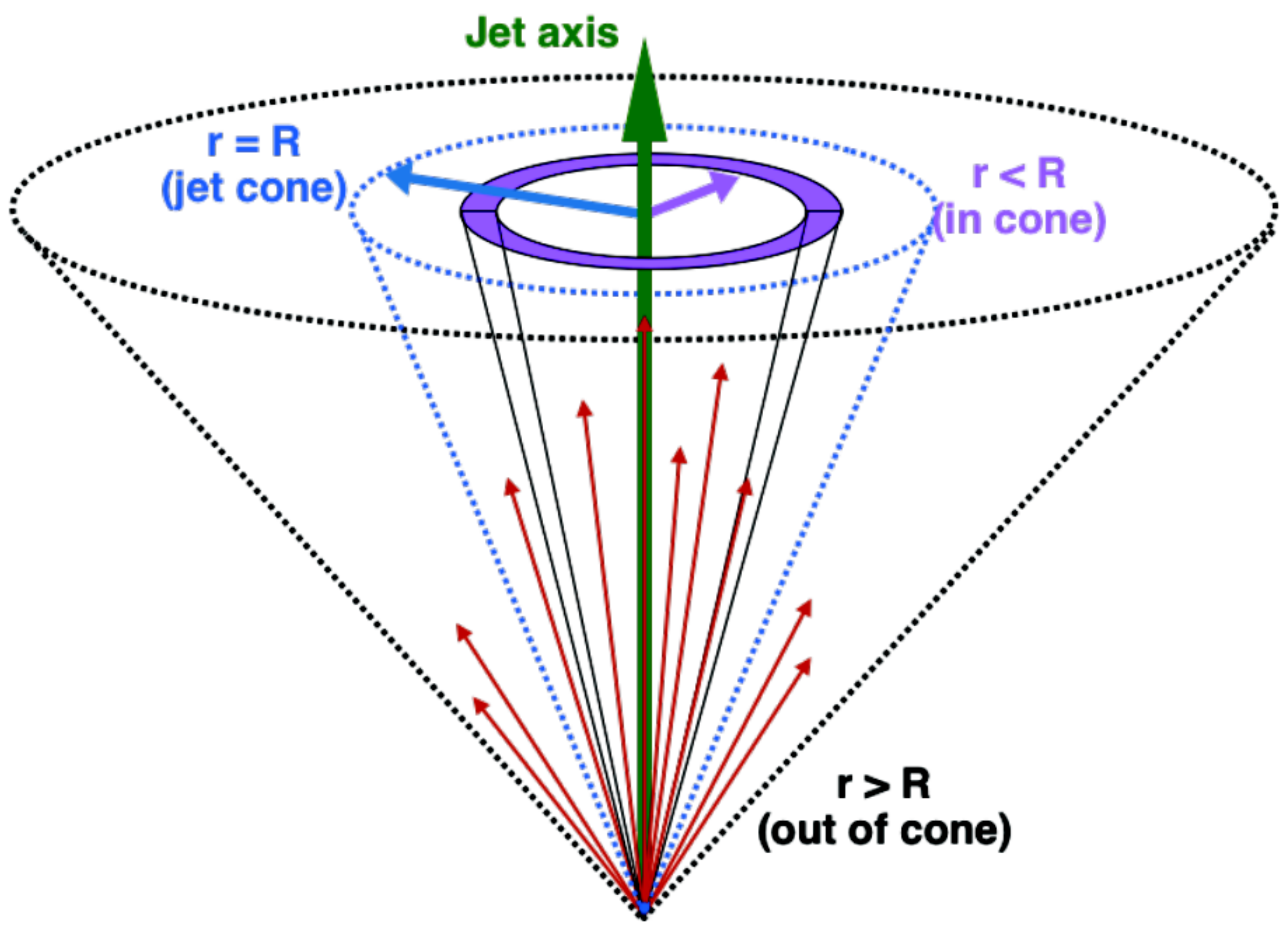


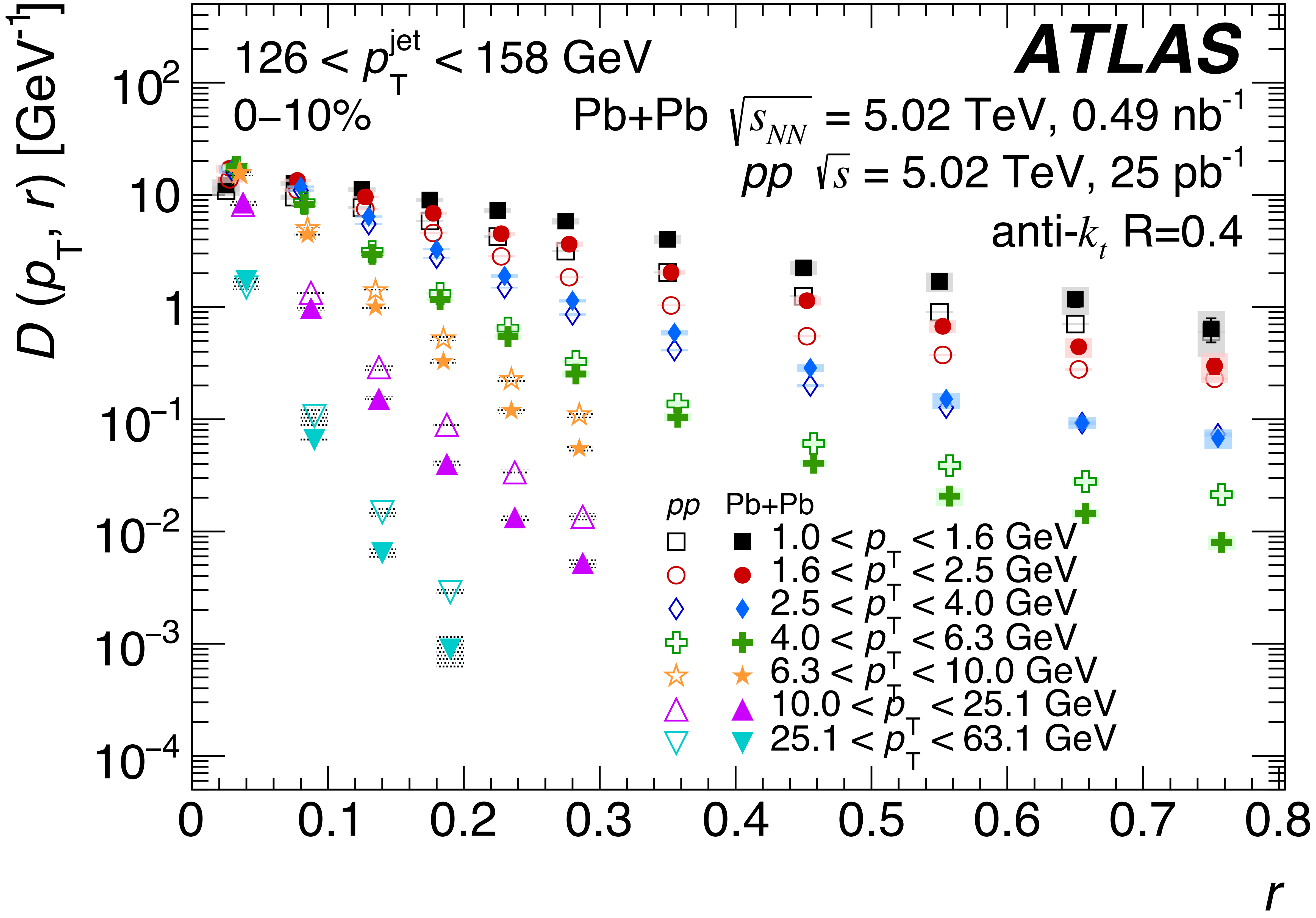


PRC98 (2018) 024908

angular and momentum dependence of jet particles

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



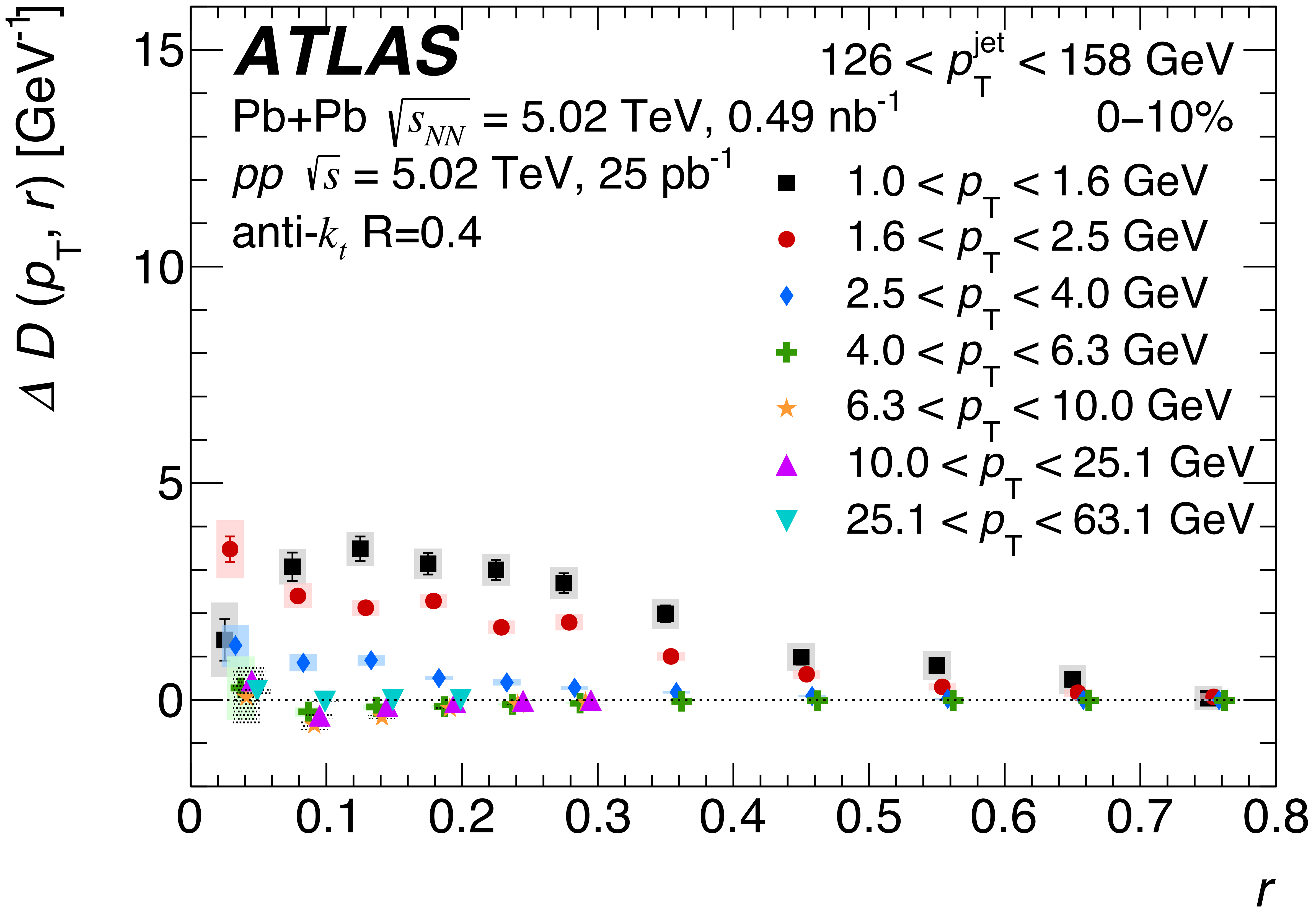


provides the most detailed map of how jets are modified at low p_T
this kind of information is crucial to constraining models of energy loss & medium response

PRC100 (2019) 064901

PbPb modifications versus r

in pp collisions most particles are near the jet axis so looking (PbPb - pp) can be useful in addition to the ratio



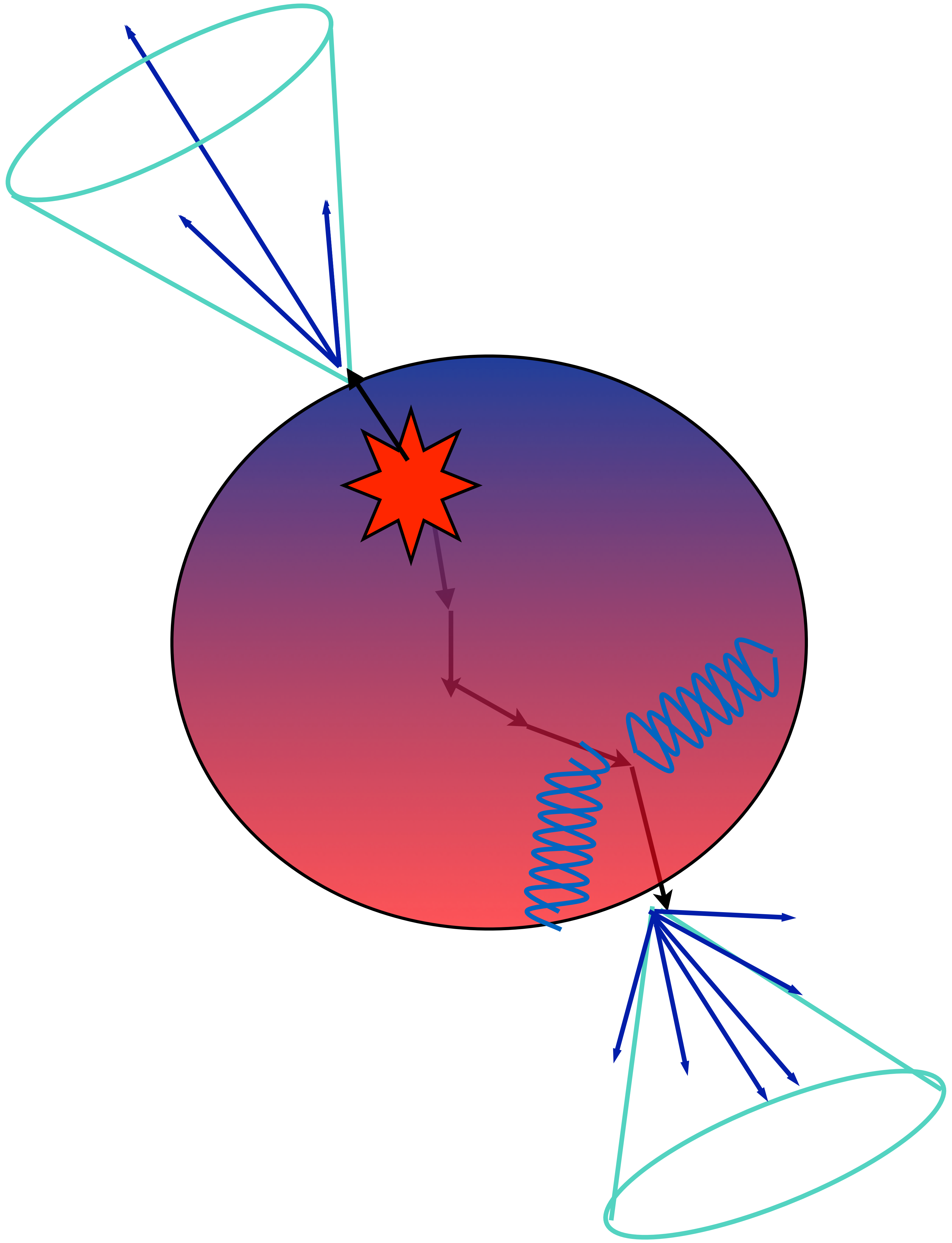
$$\Delta D(p_{\rm T}, r) = D(p_{\rm T}, r)_{\rm Pb+Pb} - D(p_{\rm T}, r)_{pp}$$

in PbPb collisions: large excess of soft particles, in & near the jet cone resulting from interactions between QGP & jet: both gluon radiation & response of the QGP

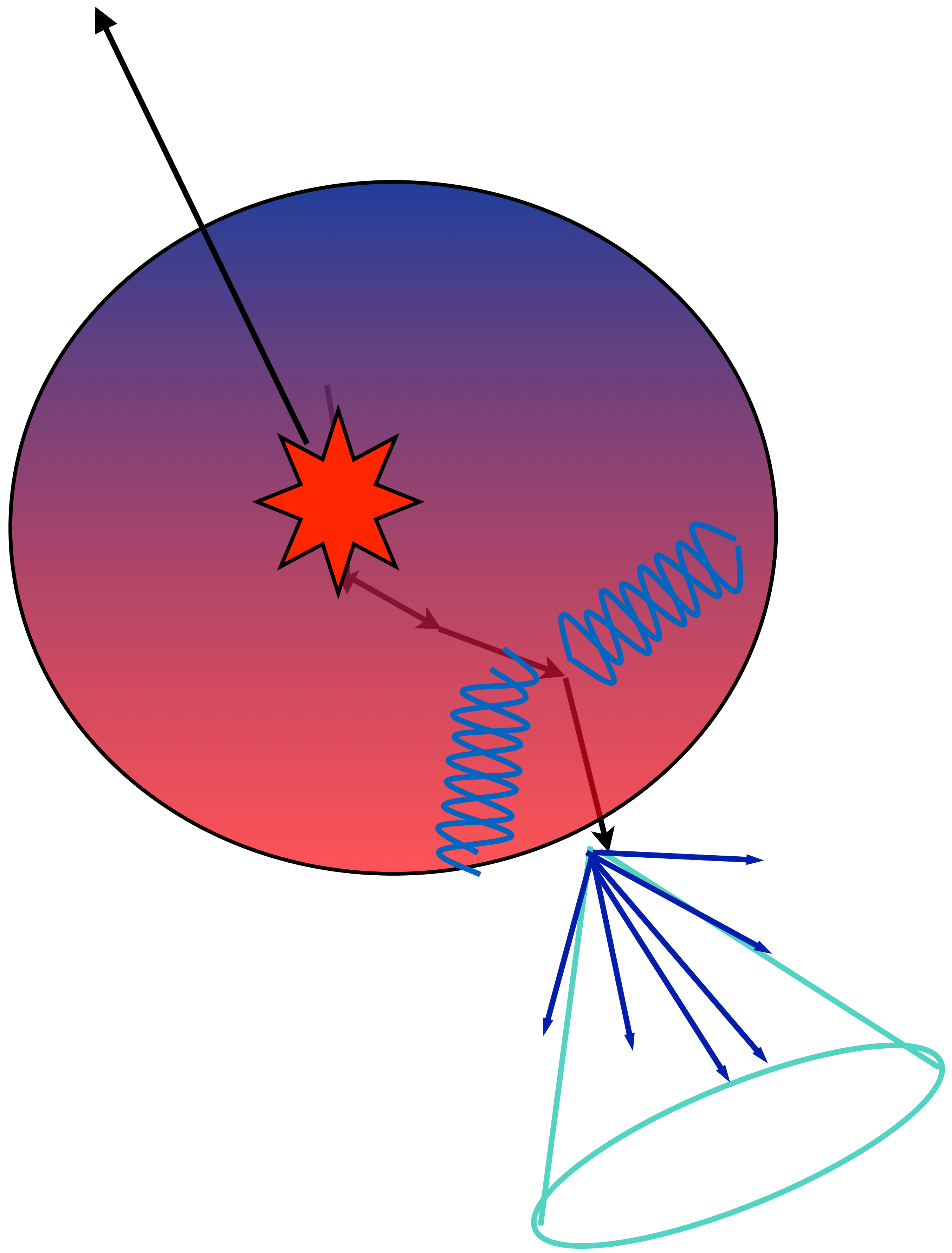
PRC100 (2019) 064901

EW boson tagged-jets

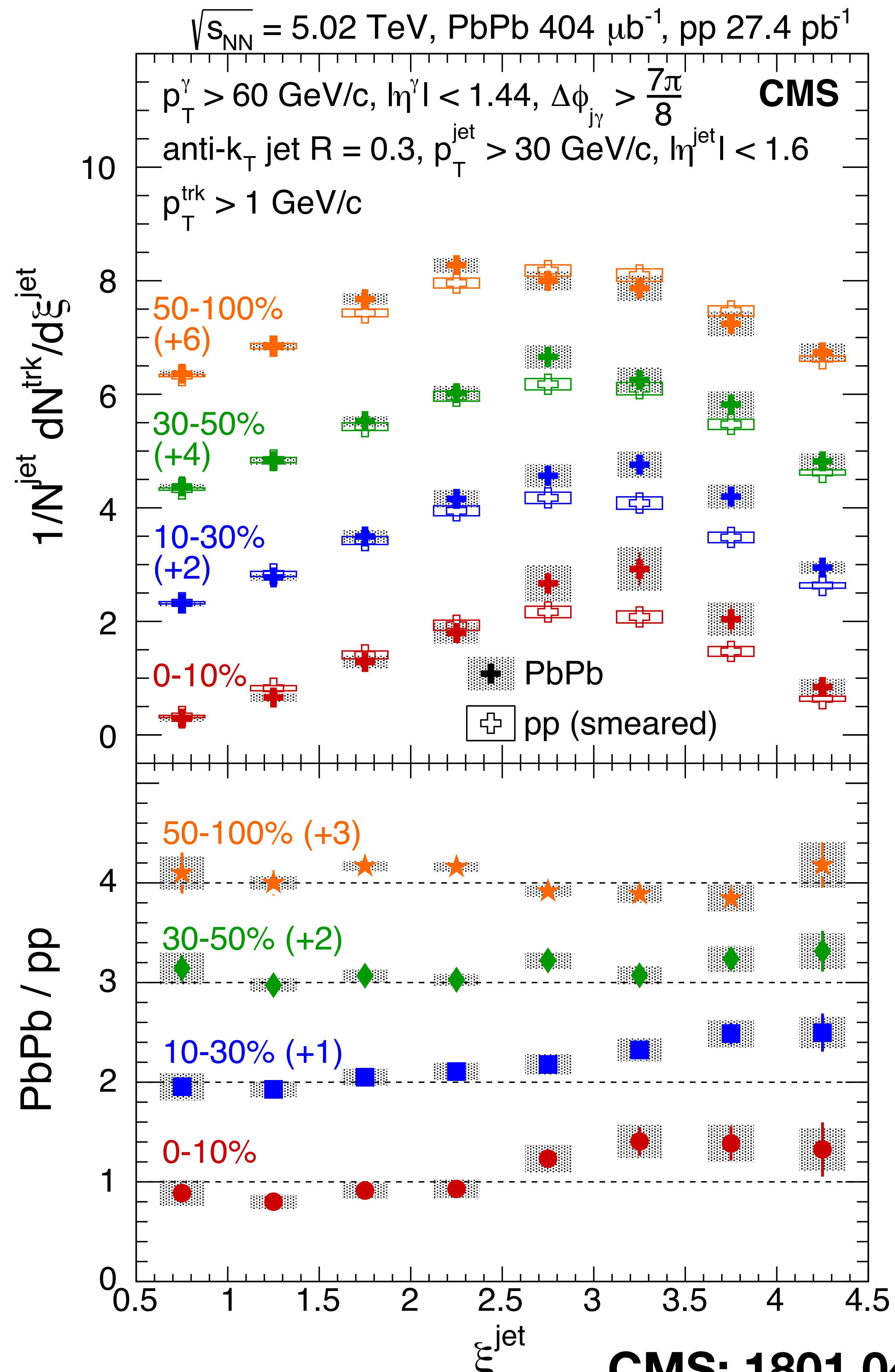
inclusive jets dominated by dijet production



EW boson (photon, Z) tag changes the jet flavor, geometry and reduces the effect of the background, at the cost of reduced rate

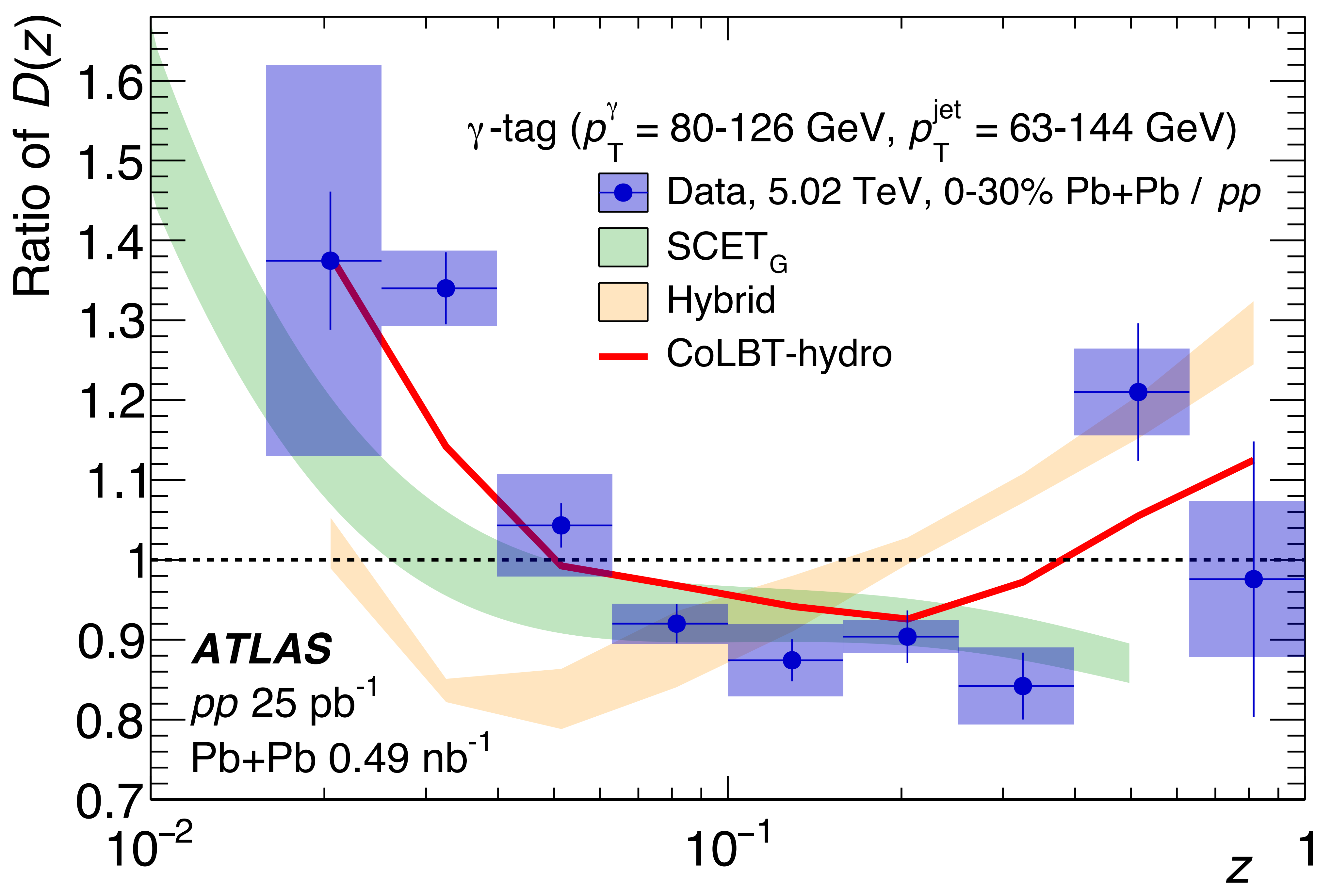


photon-tagged jets



CMS: 1801.04895

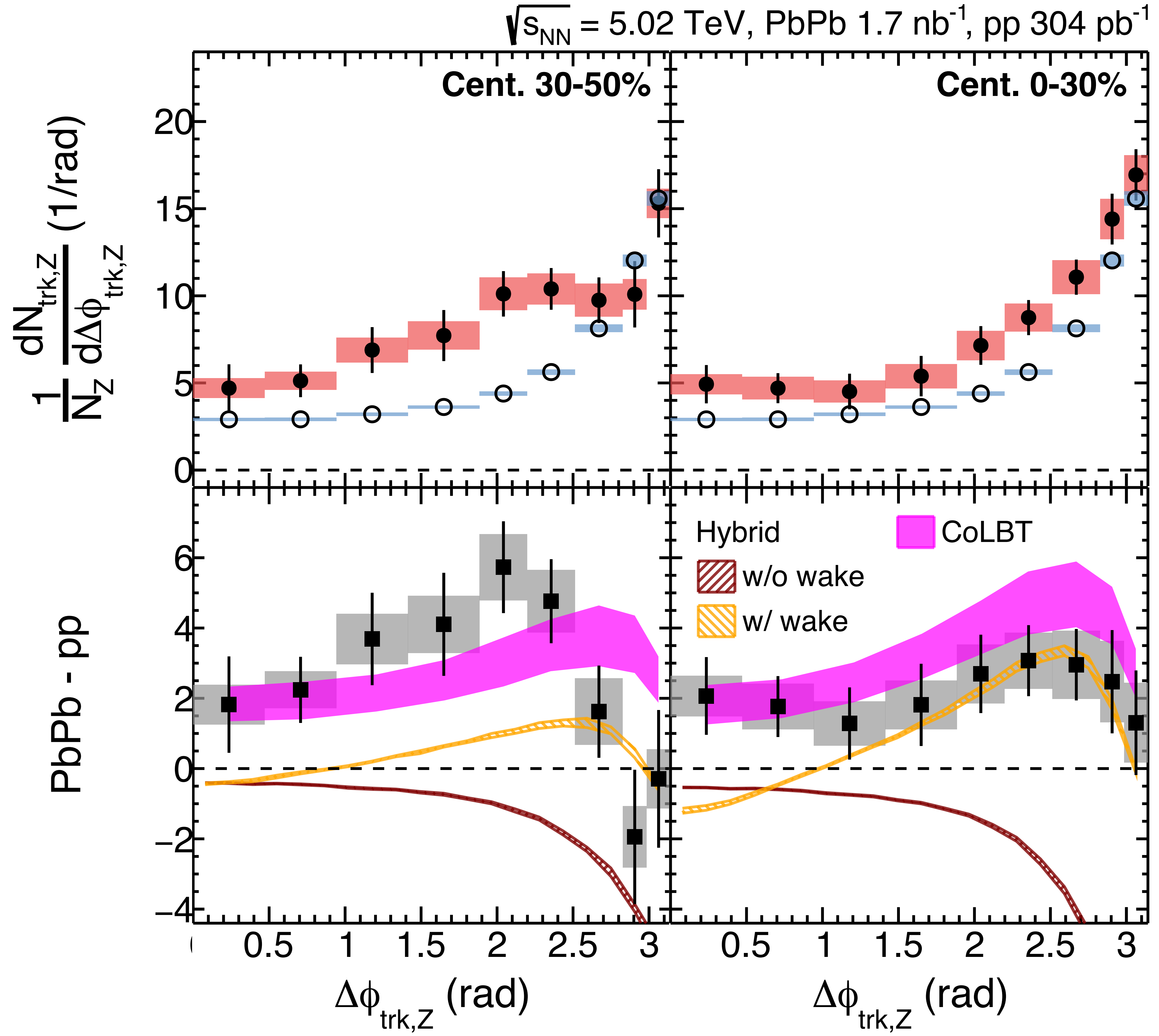
ATLAS: 1902.10007



jets opposite a photon: dominantly from q+g → γ+g process
also allow lower jet p_T because the γ tag suppresses fakes
same qualitative behavior low z (high ξ) behavior as inclusive jets

describing both inclusive and photon-tagged jets necessary in theoretical models

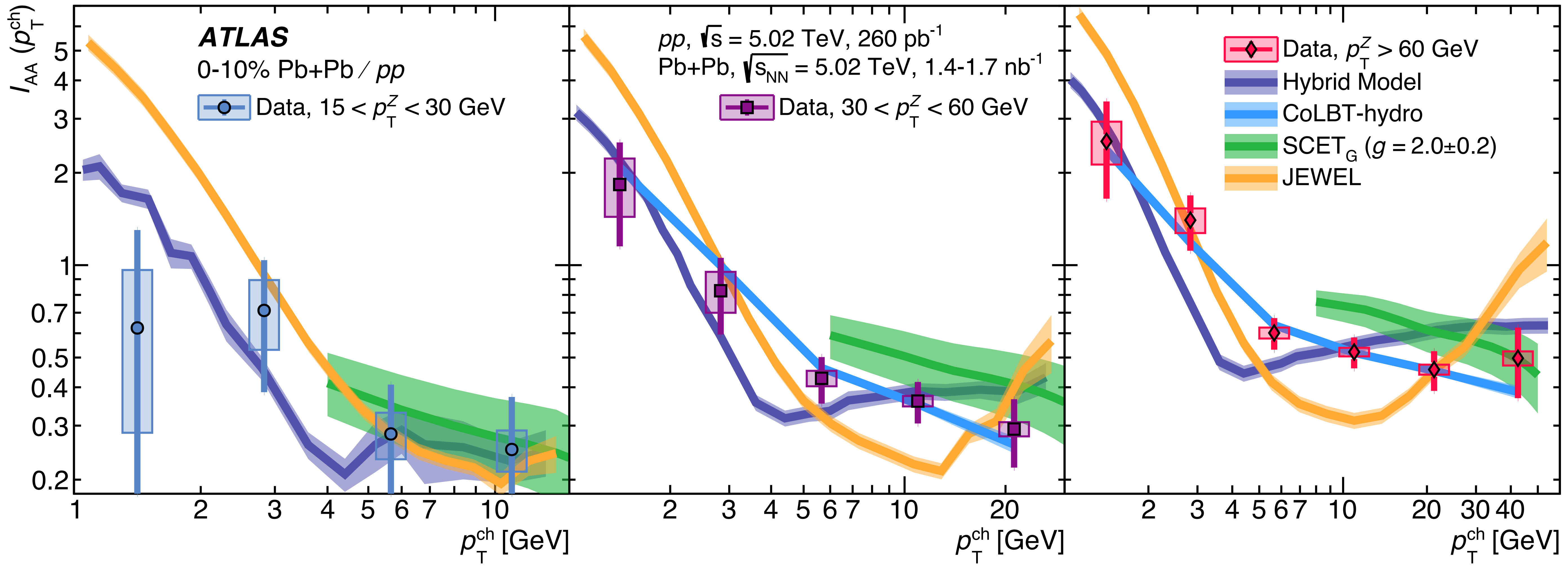
Z - hadron correlations



CMS:2103.04677

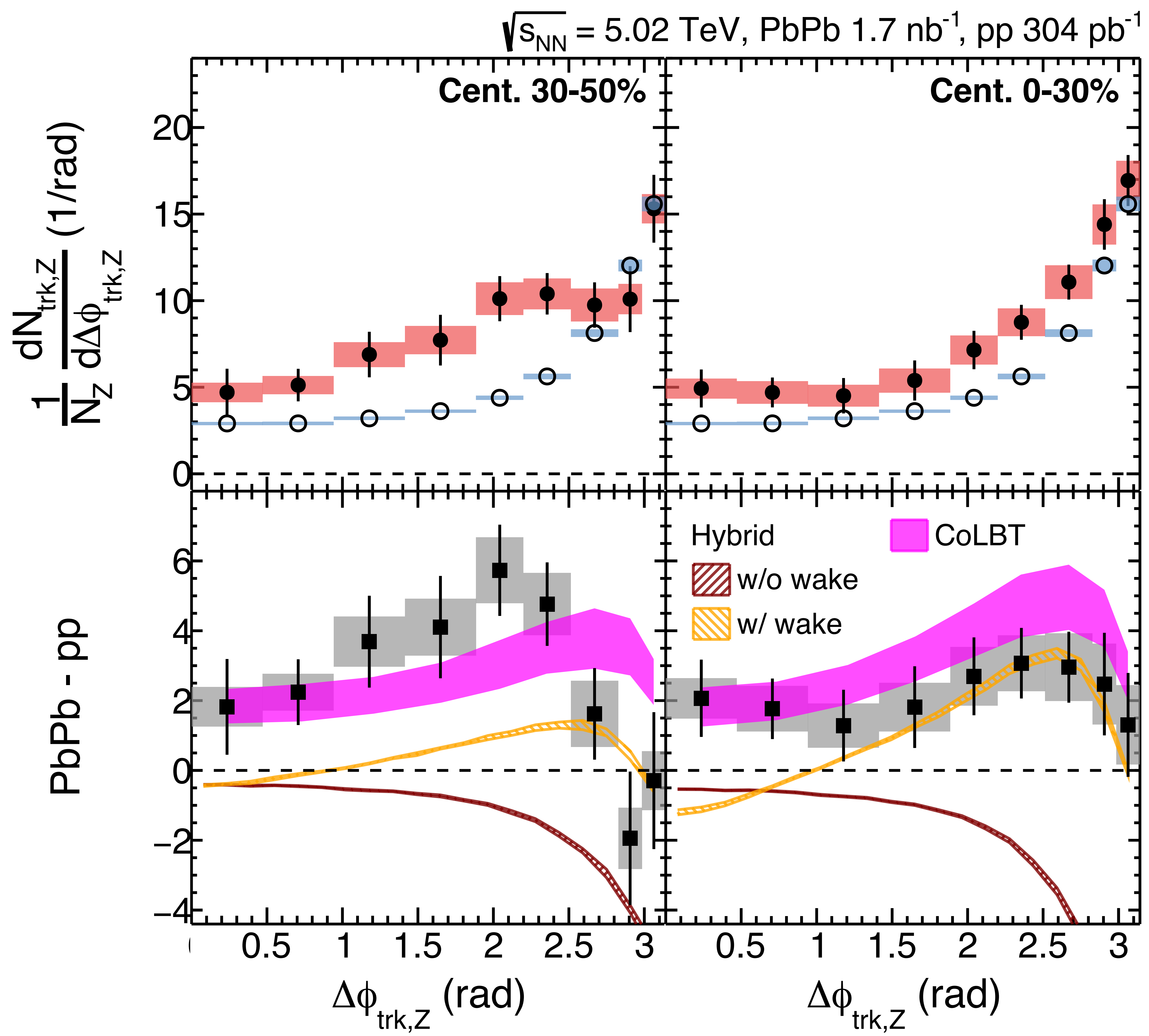
tagging the Z-boson and forgoing jet reconstruction allows push to very low p_T & large angle

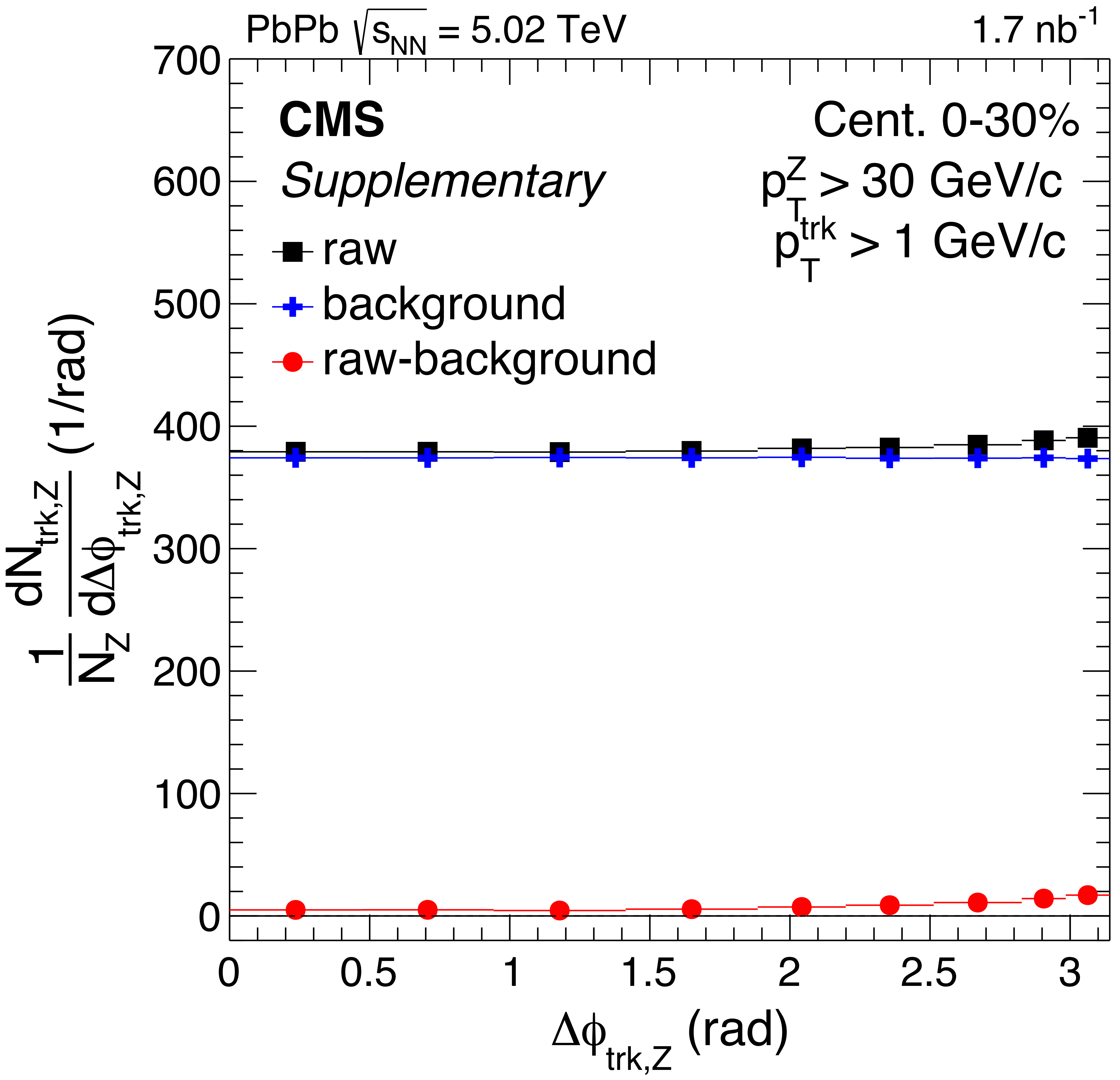
ATLAS: 2008.09811



EW boson tagged jet measurements will benefit greatly from increased LHC luminosity in Run 3

Z - hadron correlations





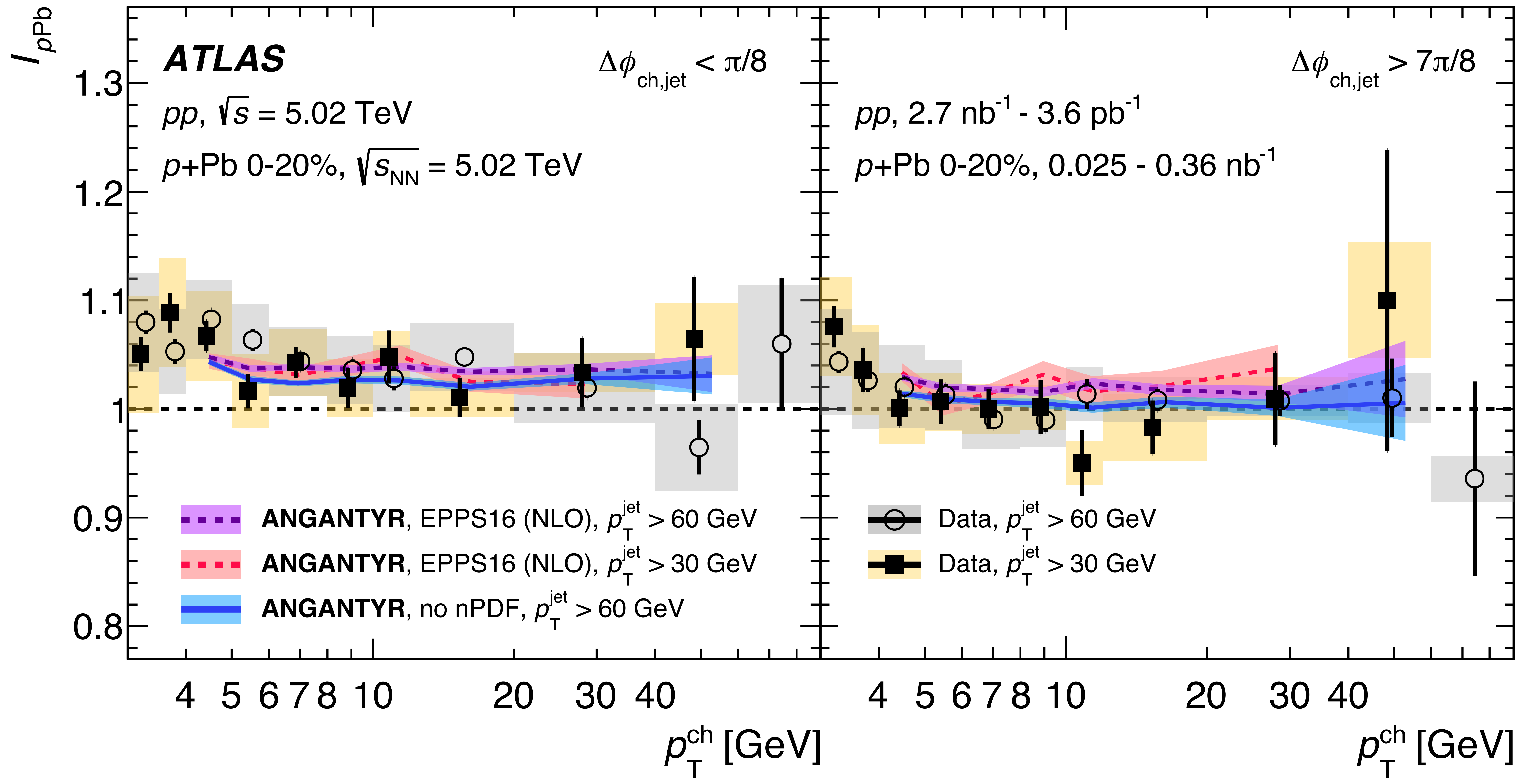
experimental challenge: huge UE event at low p_T

CMS:2103.04677

what is the small size limit of jet quenching?

2206.01138

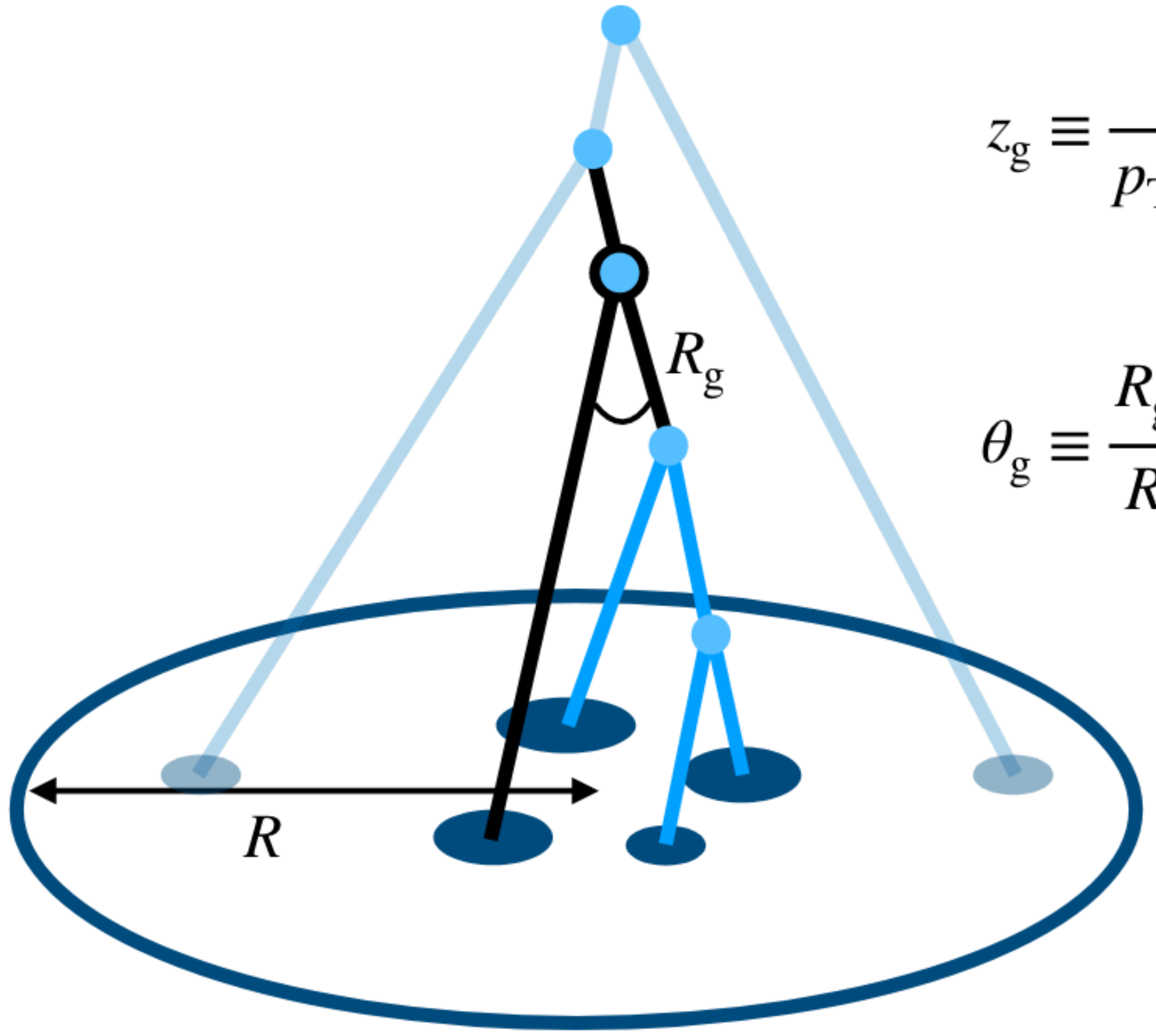
new ATLAS paper looking at jet-hadron correlations in pPb collisions;
still no evidence of jet quenching in pPb collisions



this lack of suppression highlights the importance of the OO data at STAR & upcoming LHC data (2024) in understanding the small path length limit of jet quenching

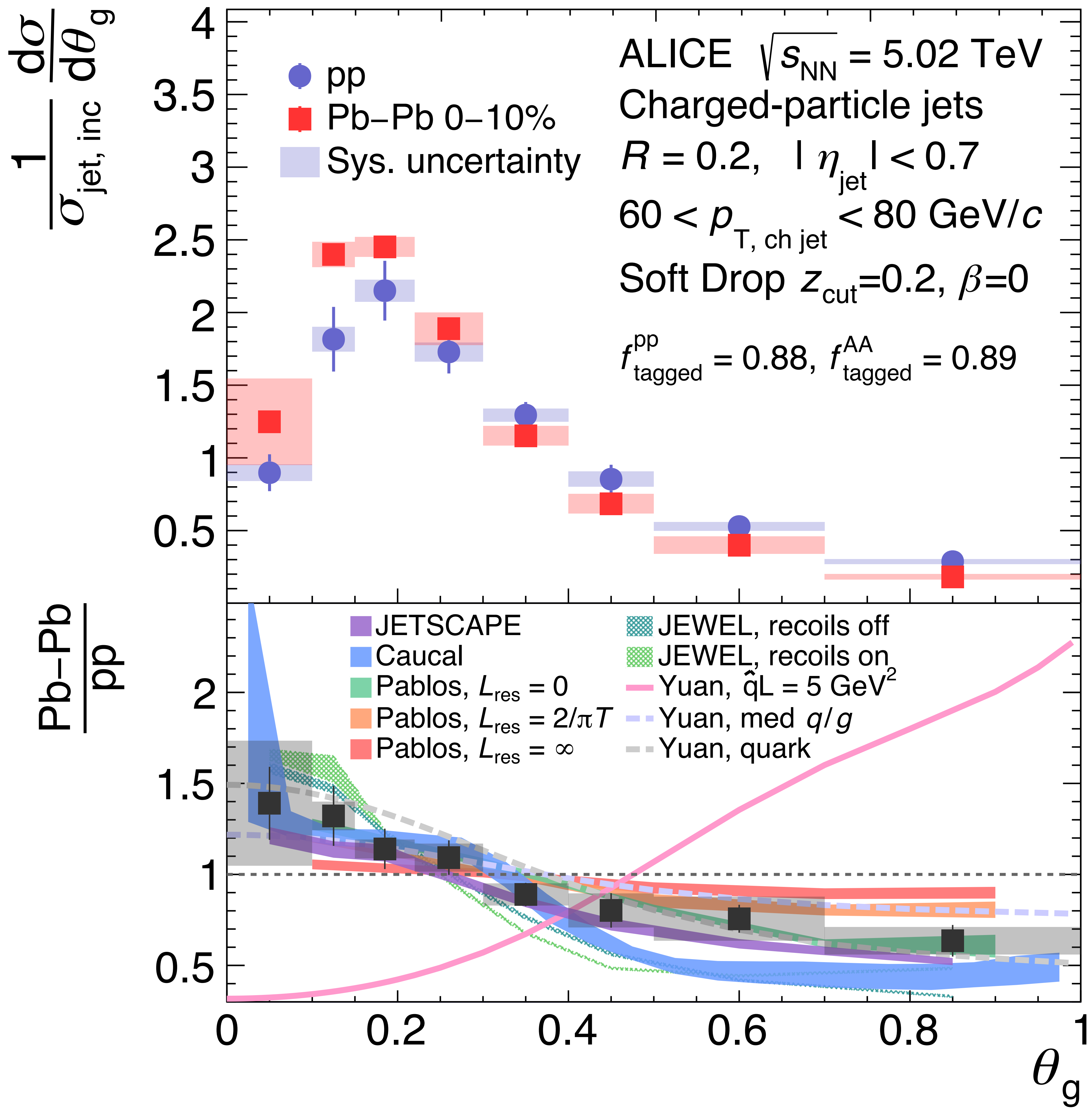
θ_g in PbPb collisions

- increase in the fraction of small θ_g jets in PbPb collisions as opposed to pp collisions



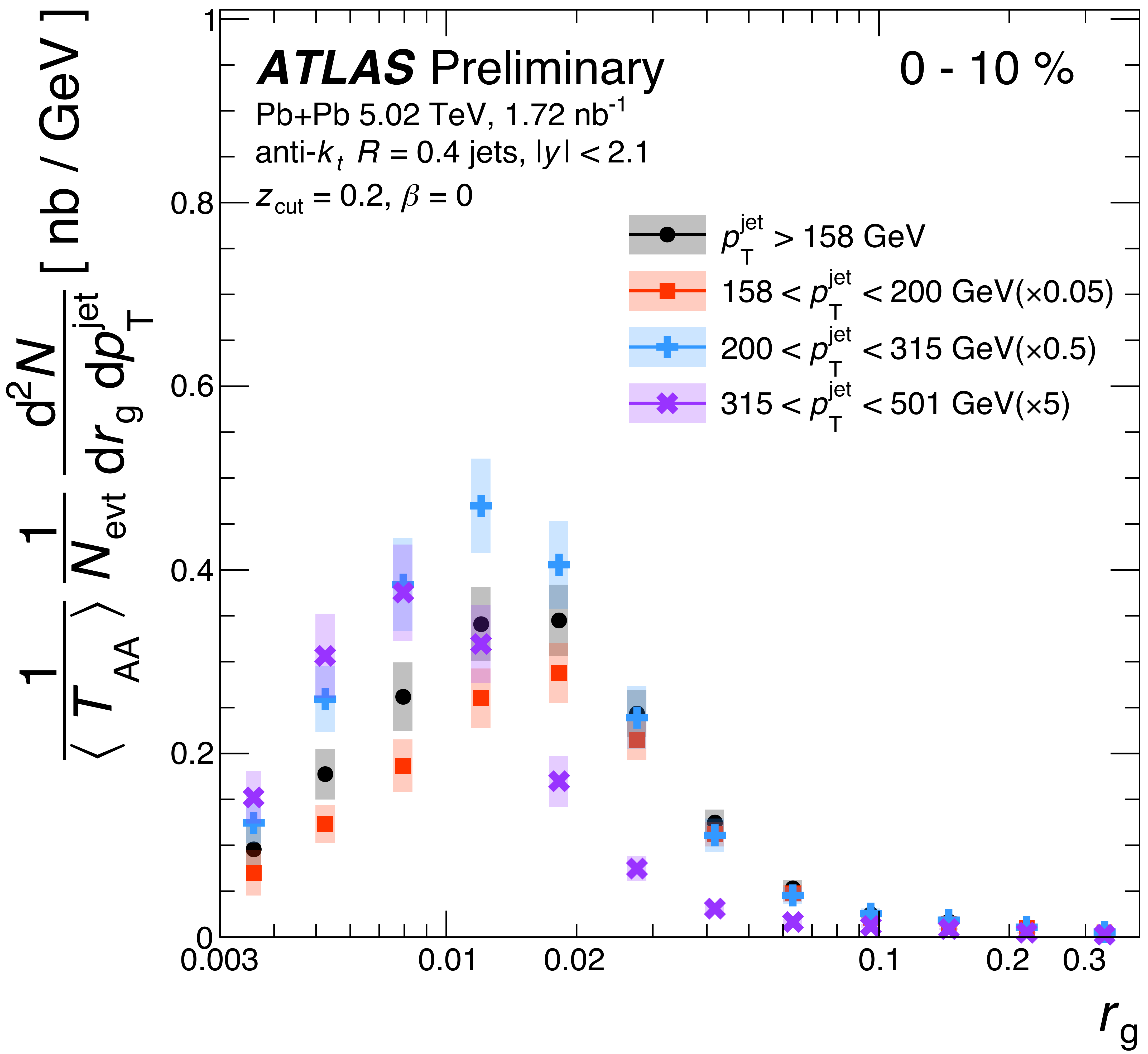
$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$



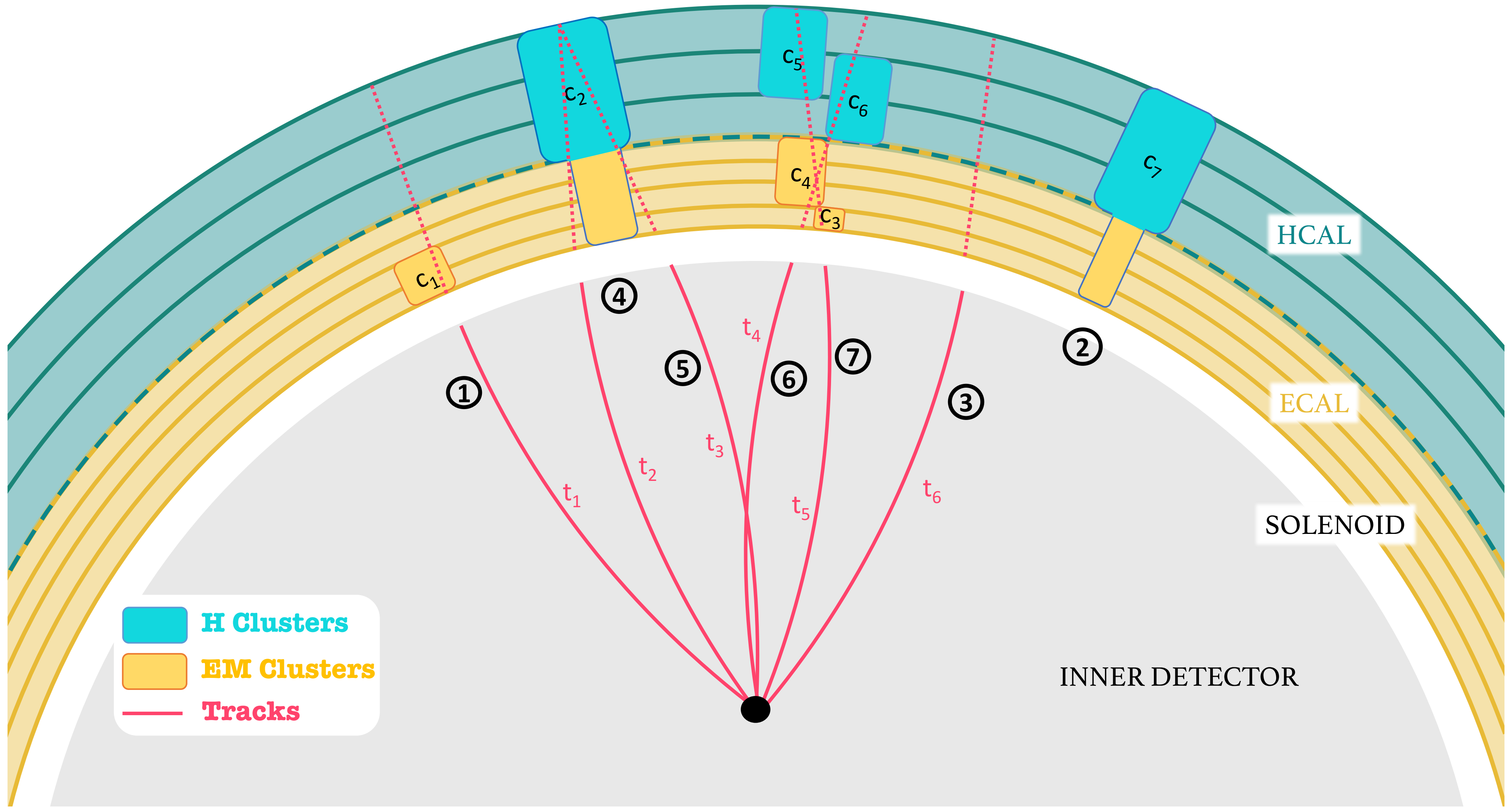
ALICE:2107.12984

r_g distributions vs jet p_T



$$r_g = \Delta R_{i,j}$$ **between the subjets satisfying the SD condition**

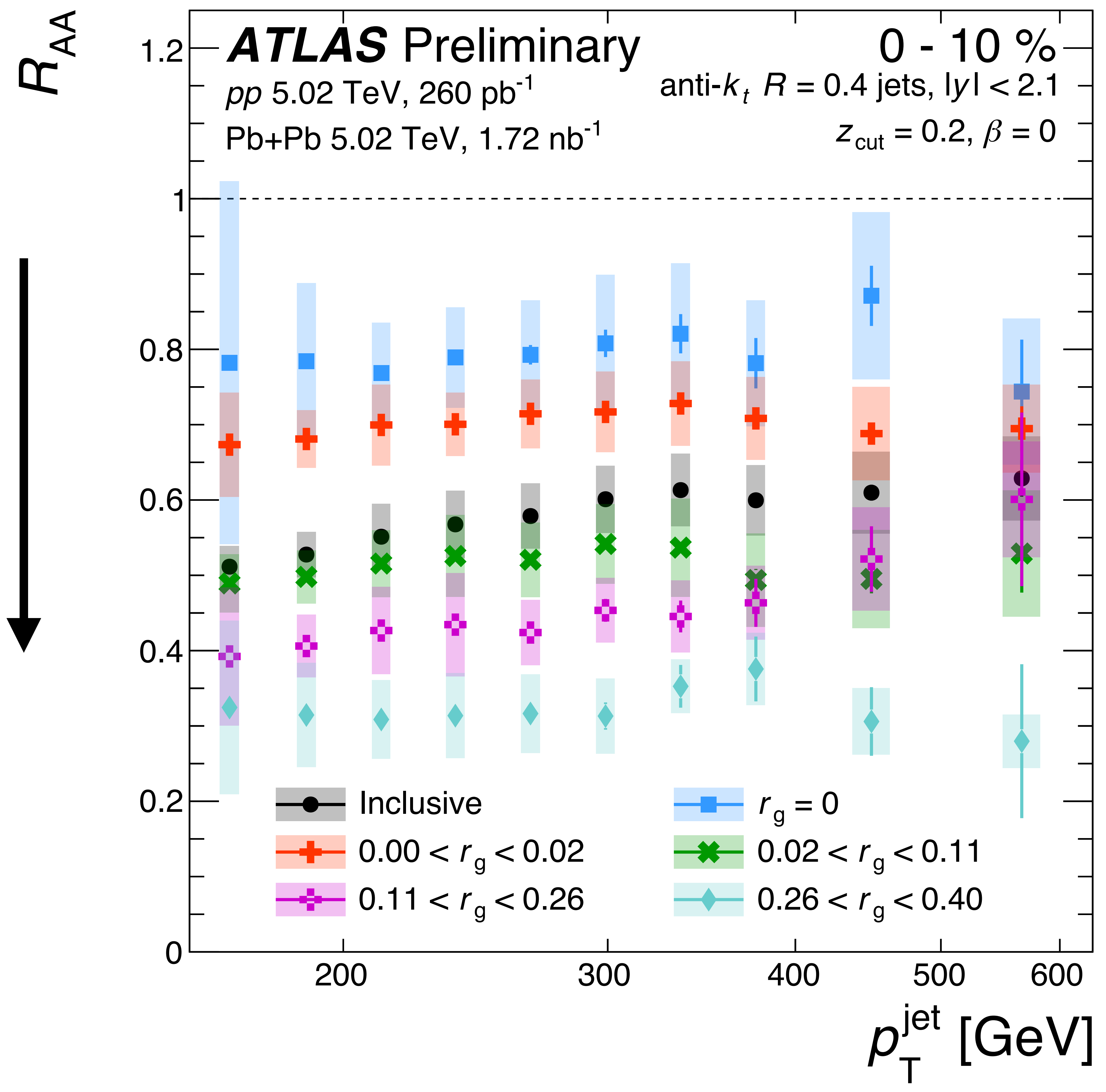
jet constituents are track-calo clusters unfolded for jet p_T and r_g

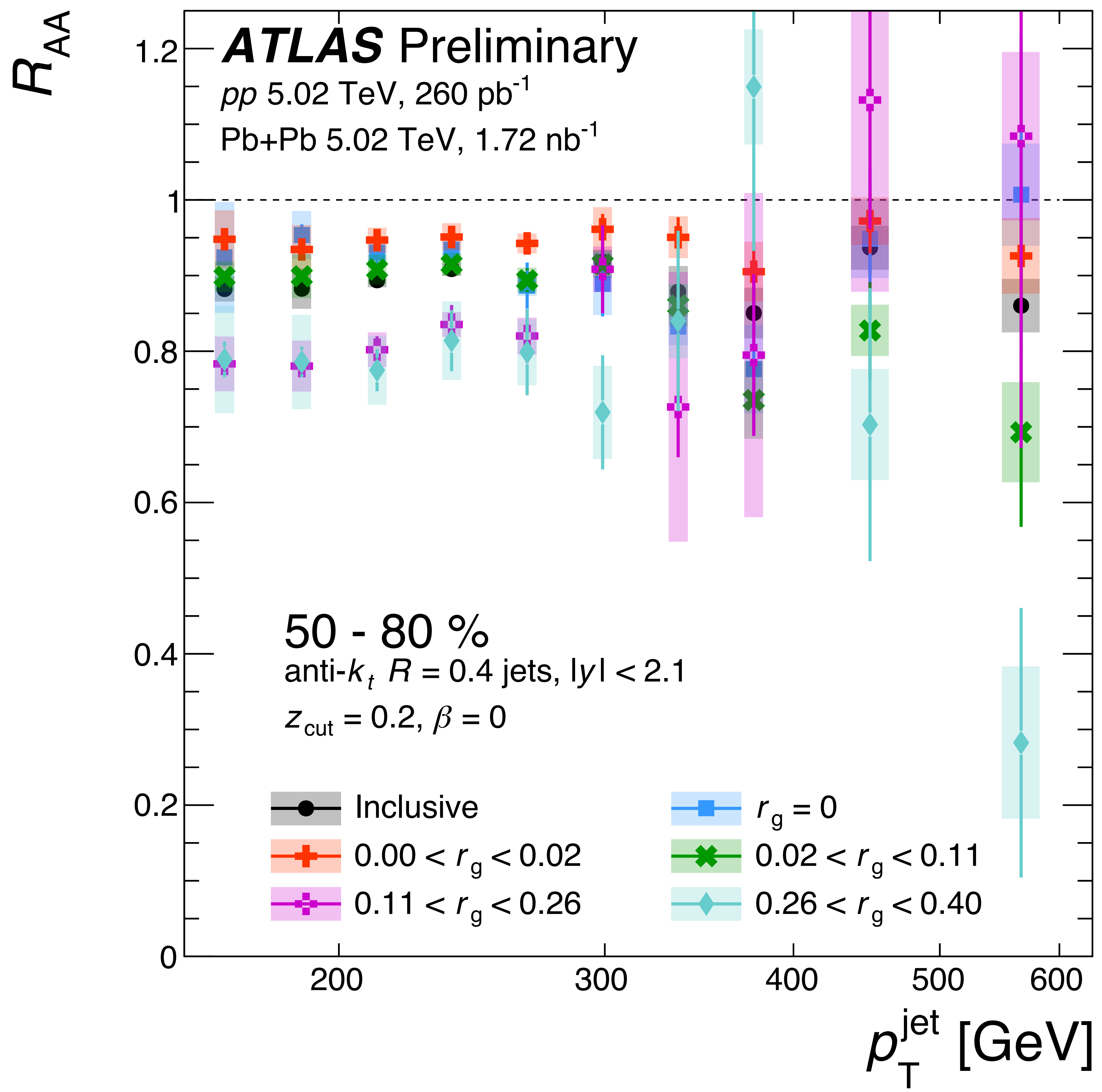


ATLAS-CONF-2022-026

r_g dependence of suppression

large r_g jets more suppressed

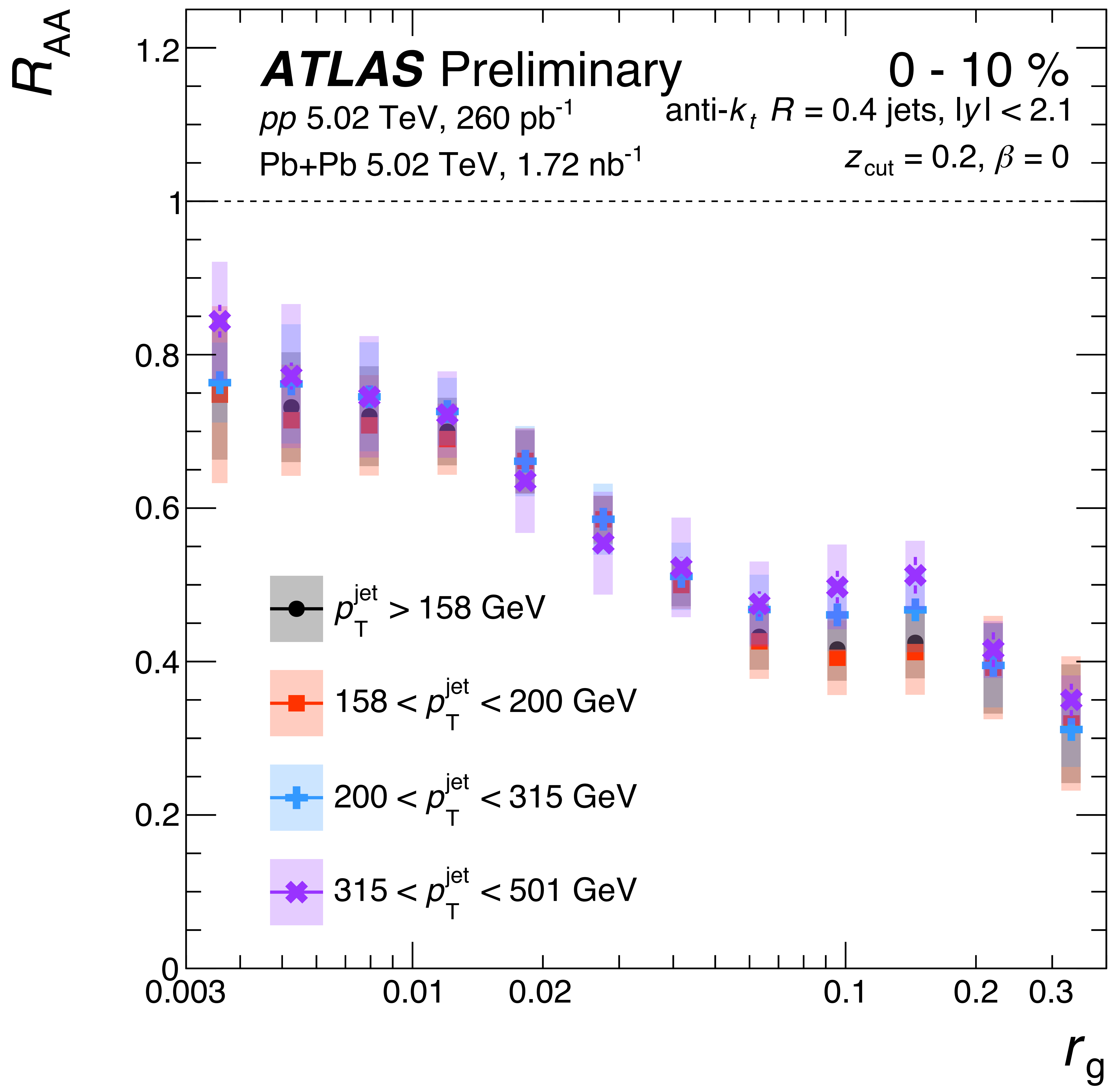




similar trends with r_g for all centralities

ATLAS-CONF-2022-026

r_g dependence of suppression



- clear r_g dependence to R_{AA}
- r_g, not jet p_T, determines the R_{AA}

ATLAS-CONF-2022-026

sPHENIX

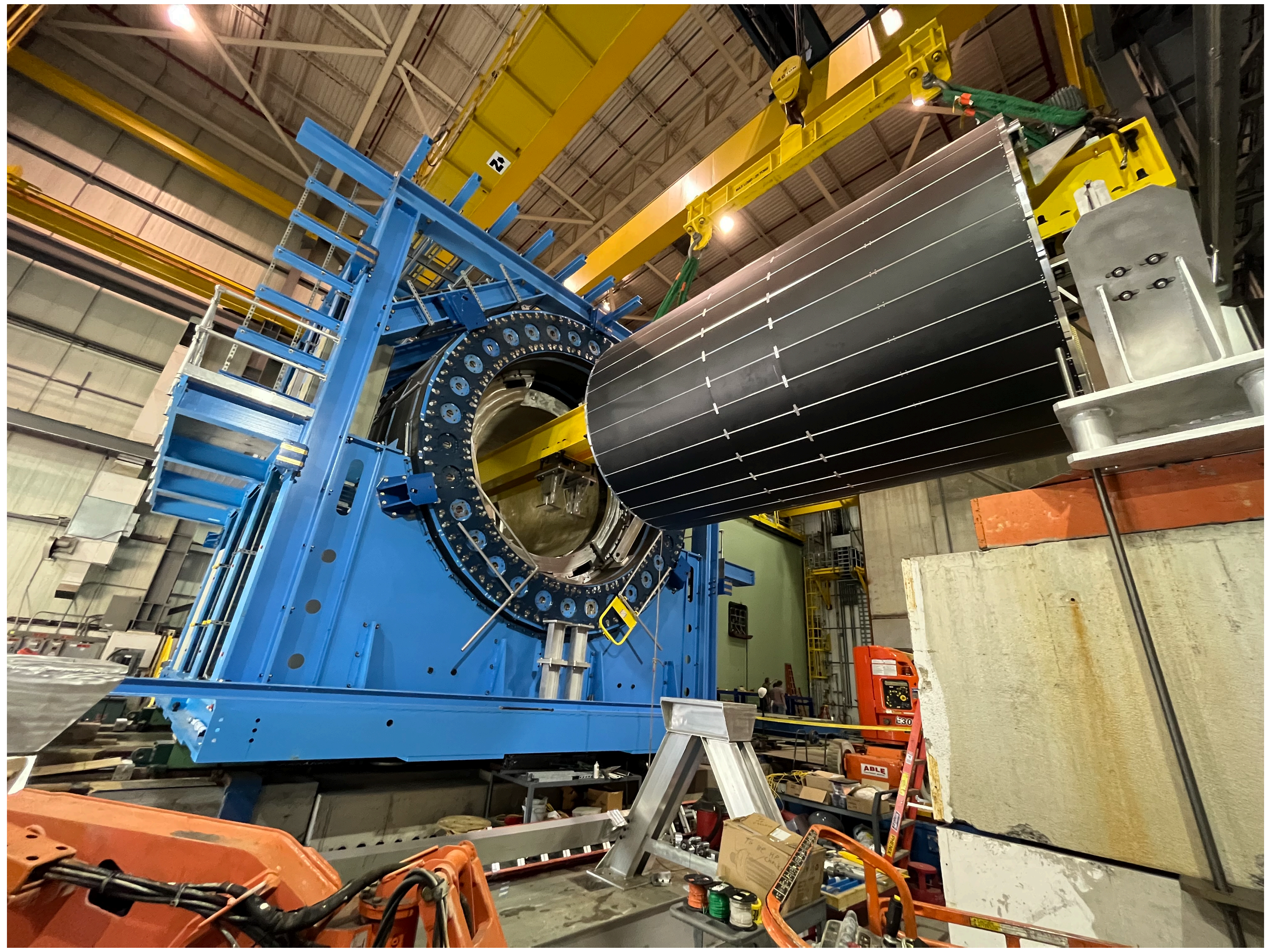
- the kinematic reach of the LHC measurements has been key to extracting the physics

- with sPHENIX we will be able to fully exploit the RHIC luminosity and have large samples of jets in pp & AuAu collisions over most the available kinematic range

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z \rvert < 10$ cm	Samp. Lum. $\lvert z \rvert < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

both sPHENIX & the LHC jet measurements are necessary to constrain the physics of jet quenching

inner HCal insertion June 2022



https://www.bnl.gov/sphenix2022/

summary

- jet structure & substructure measurements are a sensitive tool to measure to understanding the phenomenon of jet quenching
  - wider jets are suppressed more than narrow jets, single suppression pattern as a function of r_g
  - jet fragmentation is softened in PbPb collisions, but no evidence for modification in pPb collisions
  - these measurements are hard—rely on detailed understanding of tracking & calorimetry, large fluctuating backgrounds in AA, …
    - *experimentalists and theorists should pay attention to how the measurements are done & what drives the uncertainties*
- measurements in pp collisions are an essential reference to measurements in AA & pA collisions—key to measure at both RHIC & the LHC
- LHC Run 3 starting in November: much more luminosity & OO collisions (2024)
- excited to use sPHENIX to harvest the full potential of RHIC

measurements at the LHC, RHIC and soon the EIC will bring forth a precision era of using jets to understand QCD