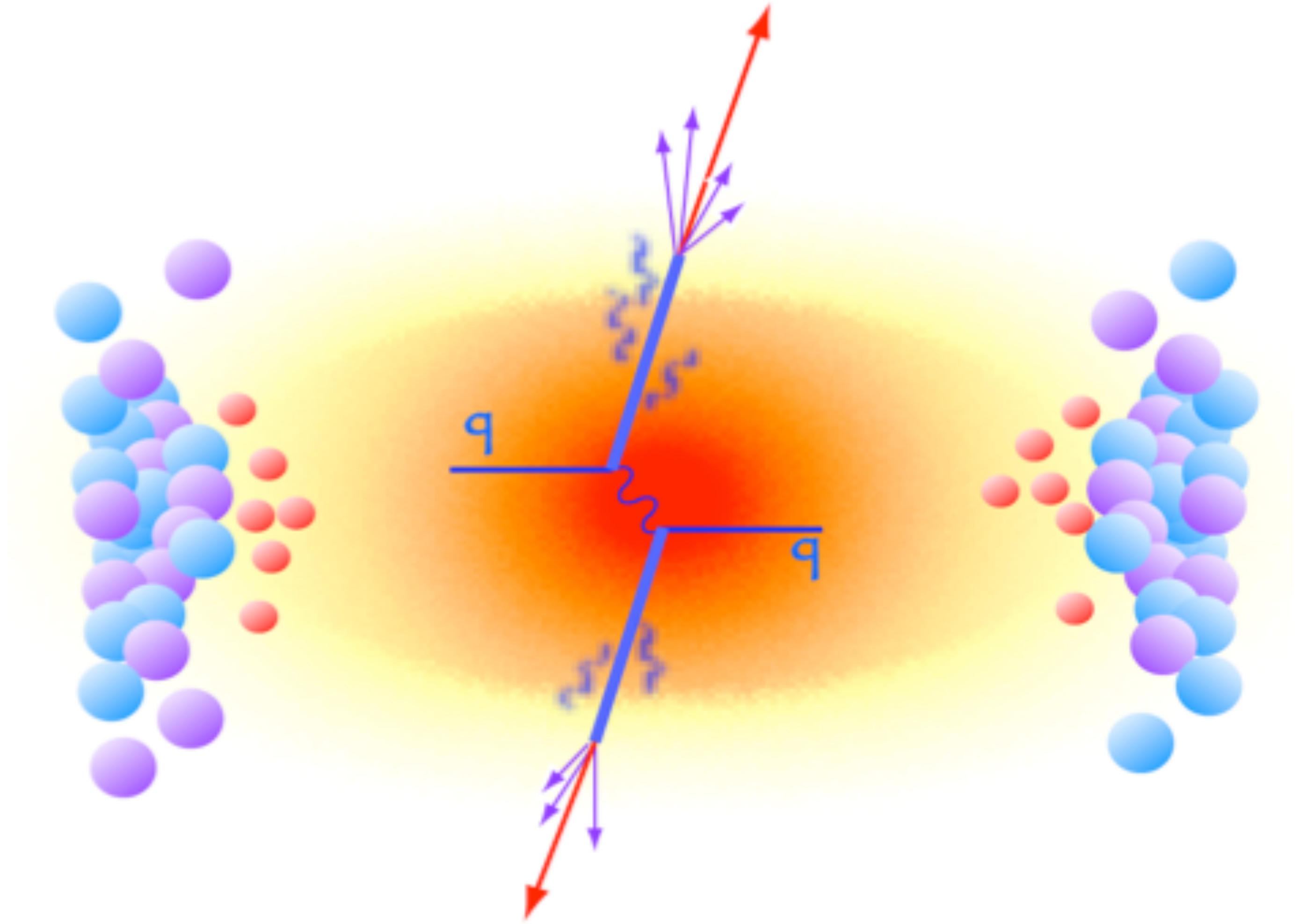
Inclusive jet suppression (multi-experiment)

Yaxian MAO

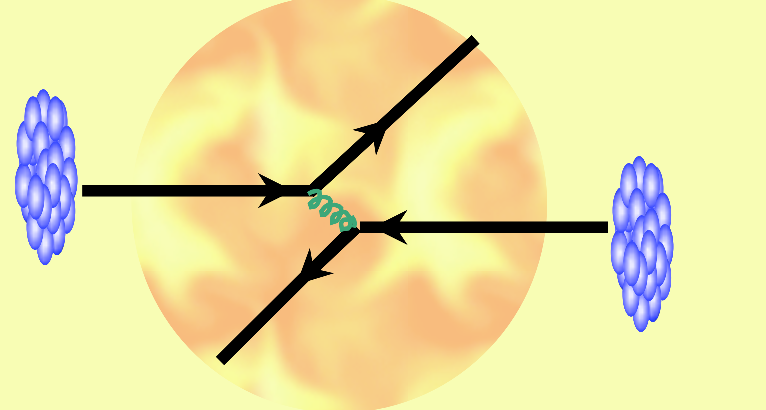
Central China Normal University

Probing QGP medium with jets

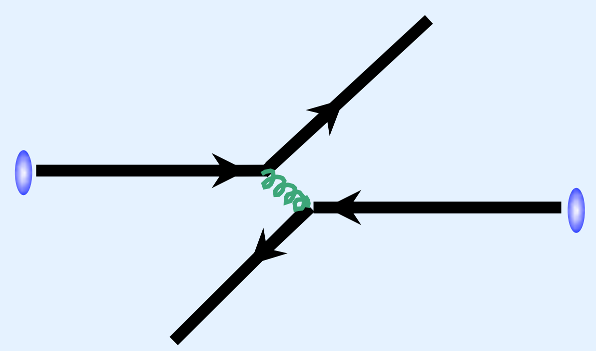


- Jets serve as calibrated probe (pQCD)
- Jets traverse through the medium and interact strongly with QGP medium
- Suppression pattern provides density measurements
- General picture: parton energy loss through medium-induced gluon radiation and collisions with medium constituents
- Quantify the medium effects with nuclear modification factor

PbPb measurements



pp reference

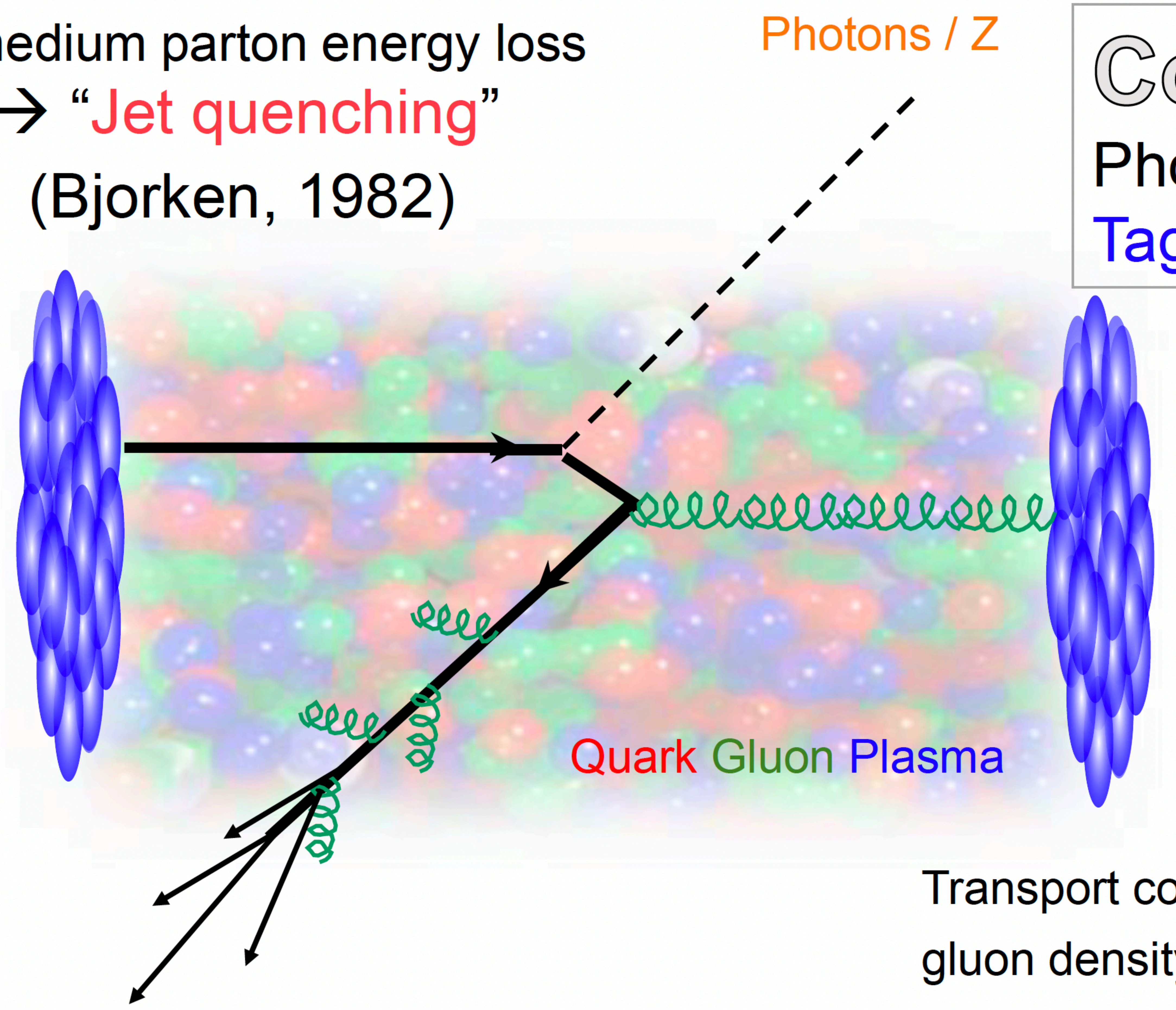


$$= R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

Jets: a tomographic probe of the medium

In medium parton energy loss
→ "Jet quenching"
(Bjorken, 1982)

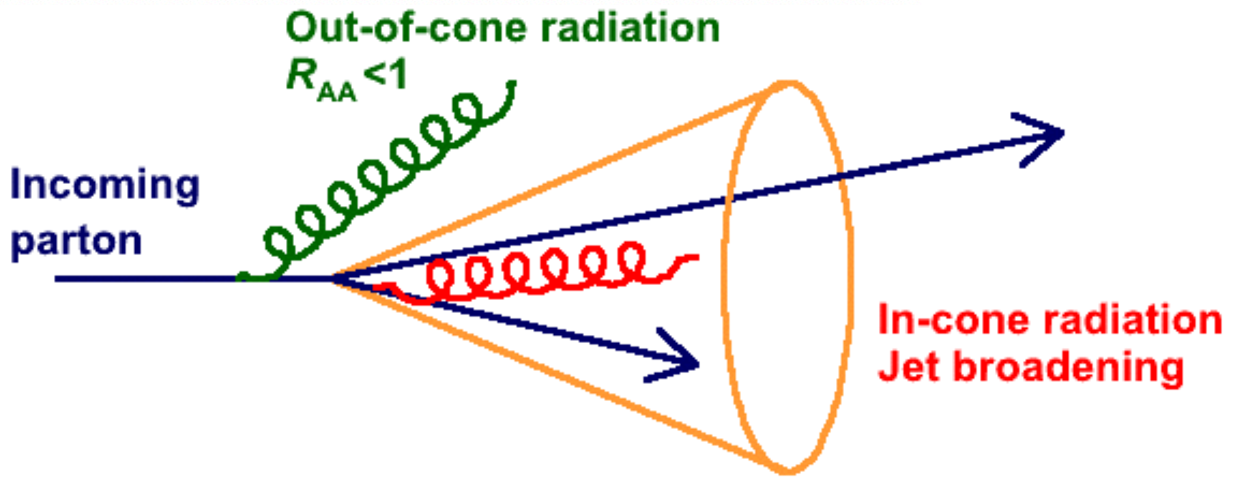


Colorless Probes

Photons, electroweak bosons

Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…



Colored Probes:

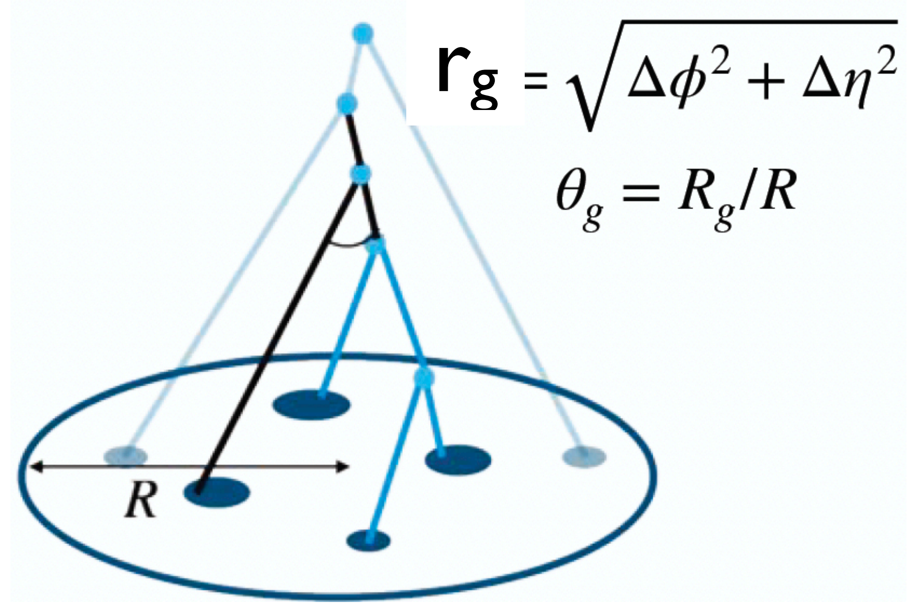
high energy quarks and gluons, heavy quarks

Studies of the medium properties

Types of jet observables

"Jet tomography" via

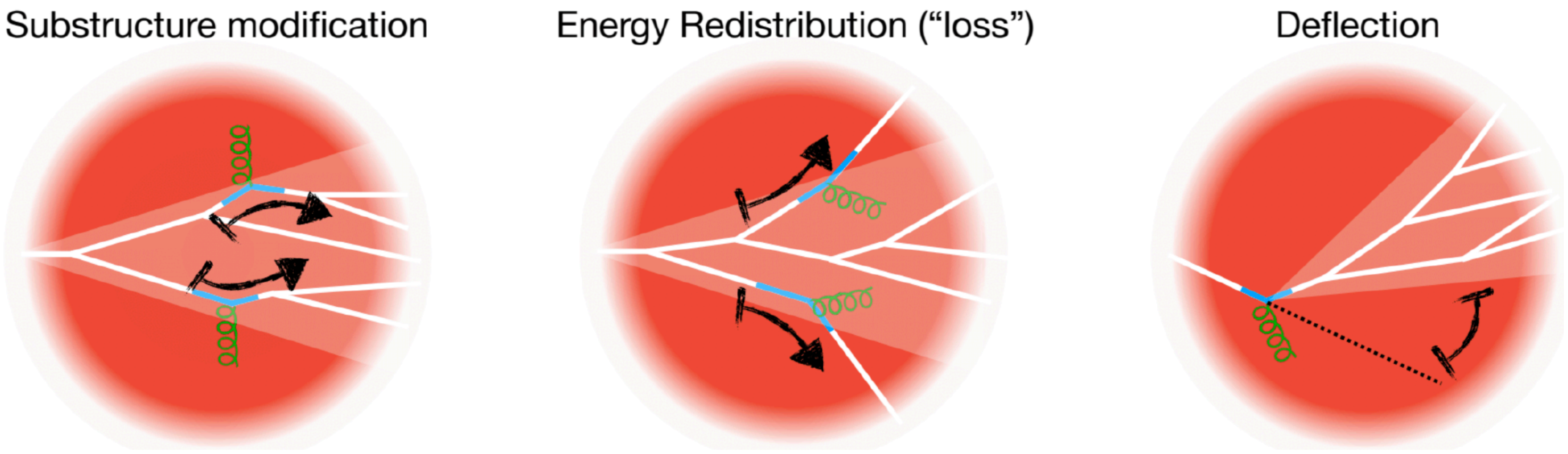
- Jet reconstruction and declustering → jet substructure (r_g, θ_g) modification



- Jet yields and constituents → jet suppression and energy redistribution (R_{AA}, I_{AA})

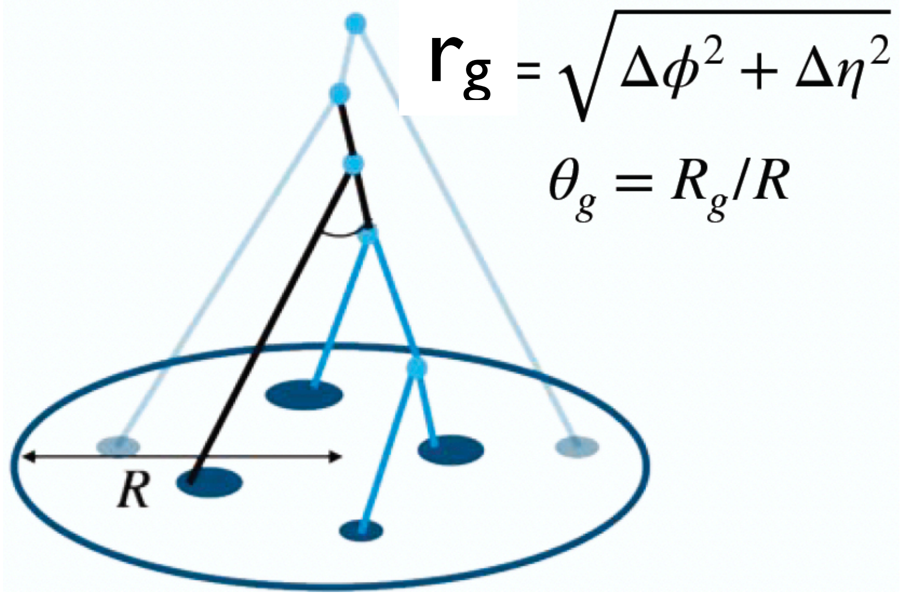
$$I_{AA} = \frac{\text{per-trigger yield in Pb-Pb}}{\text{per-trigger yield in pp}}$$

- Angular correlation → jet deflection ($\Delta\varphi$)



Types of jet observables

"Jet tomography" via



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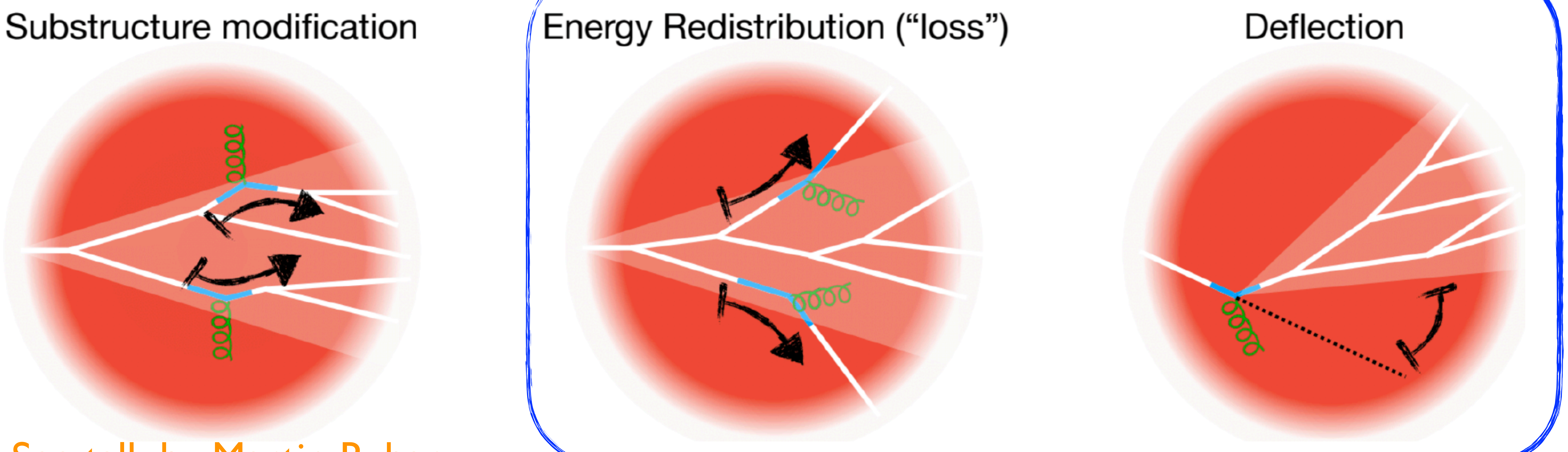
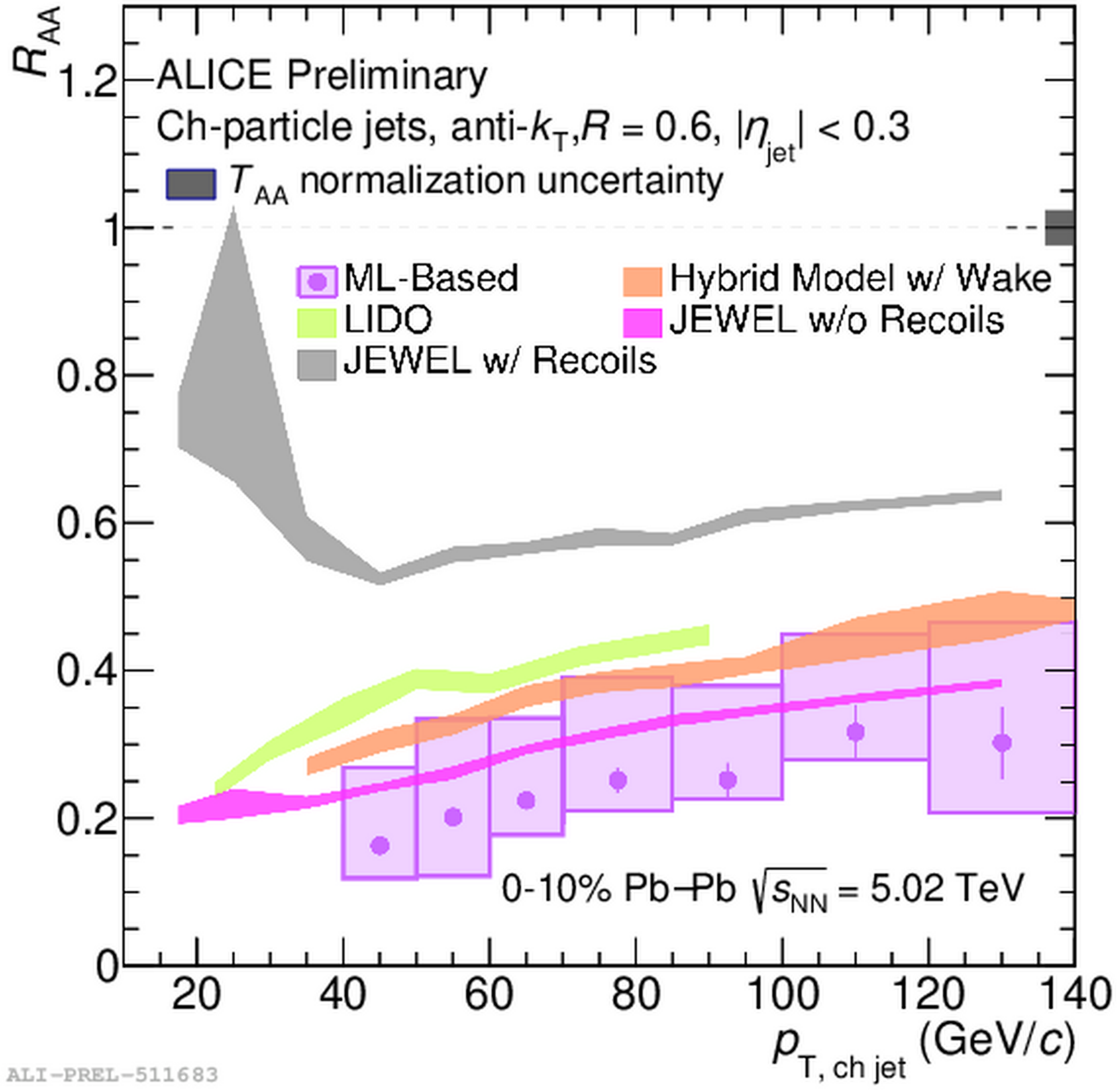
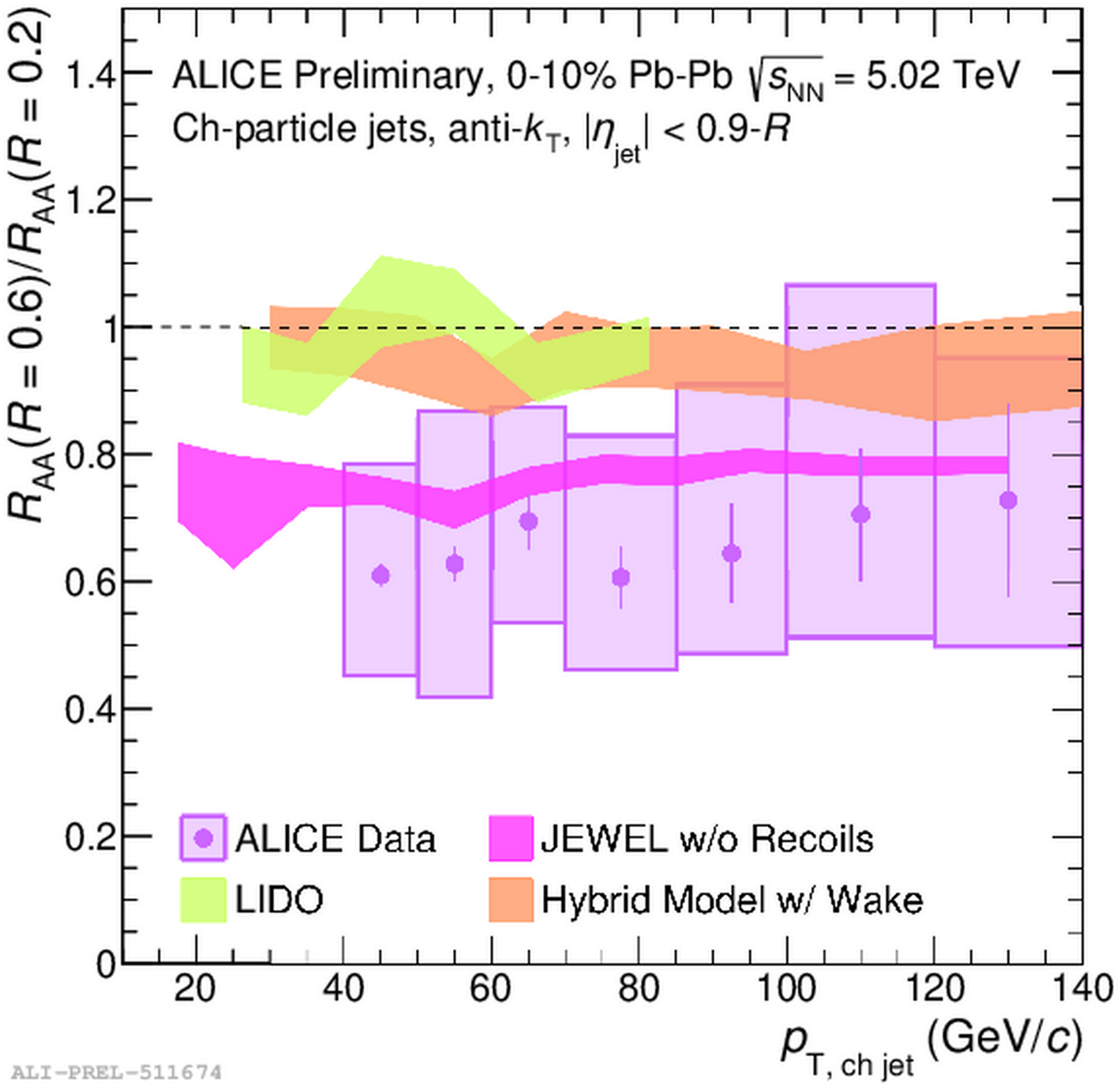


See talk by Martin Rybar

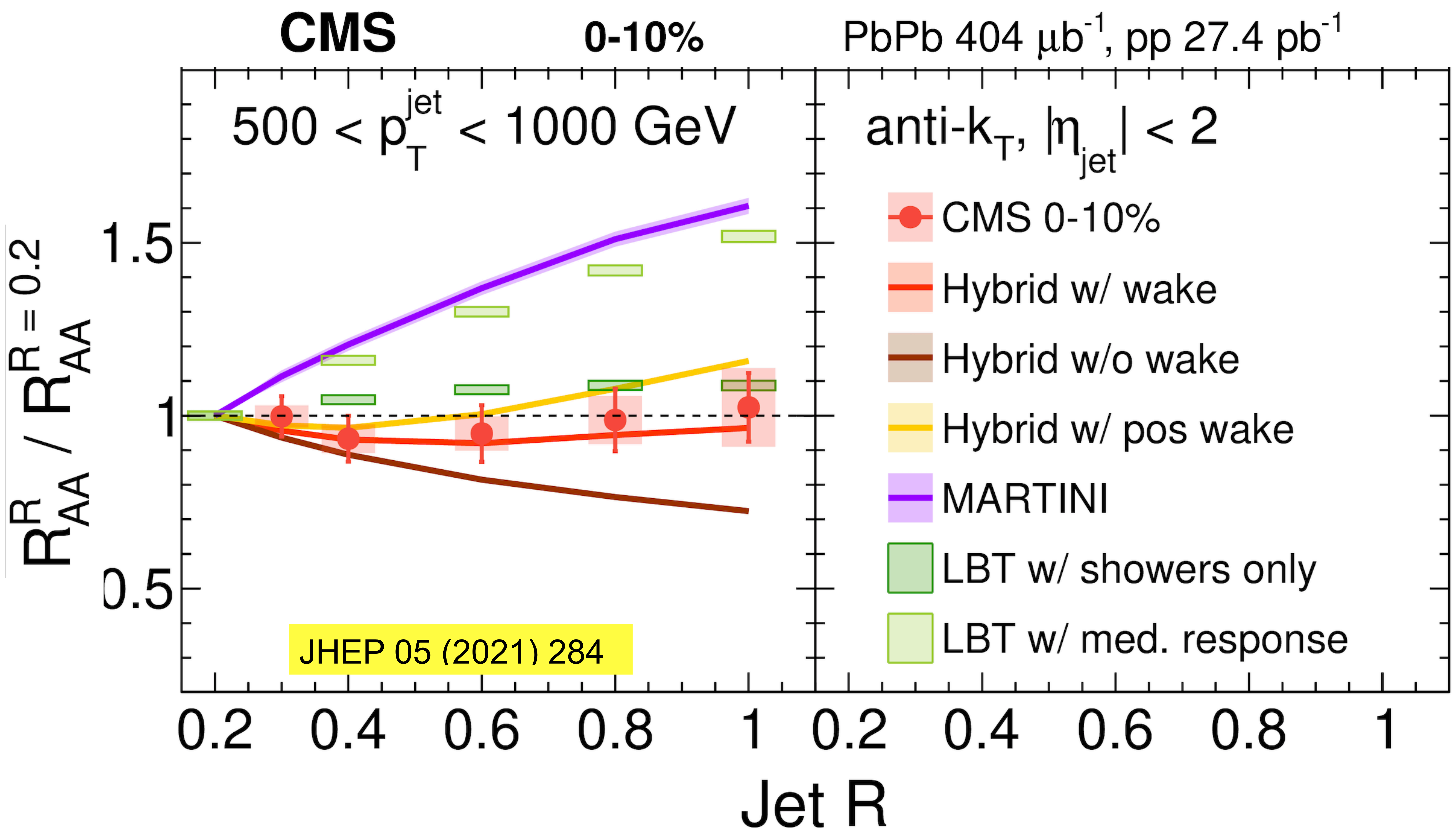
Jet suppression and energy redistribution





- Jet measurements extended to lower jet p_T and large R using machine learning (ML)
  - improvements on background subtraction and systematics
- Large R (= 0.6) jets indicate a stronger suppression than smaller R (= 0.2) jets
  - suggesting R-dependence of jet energy loss

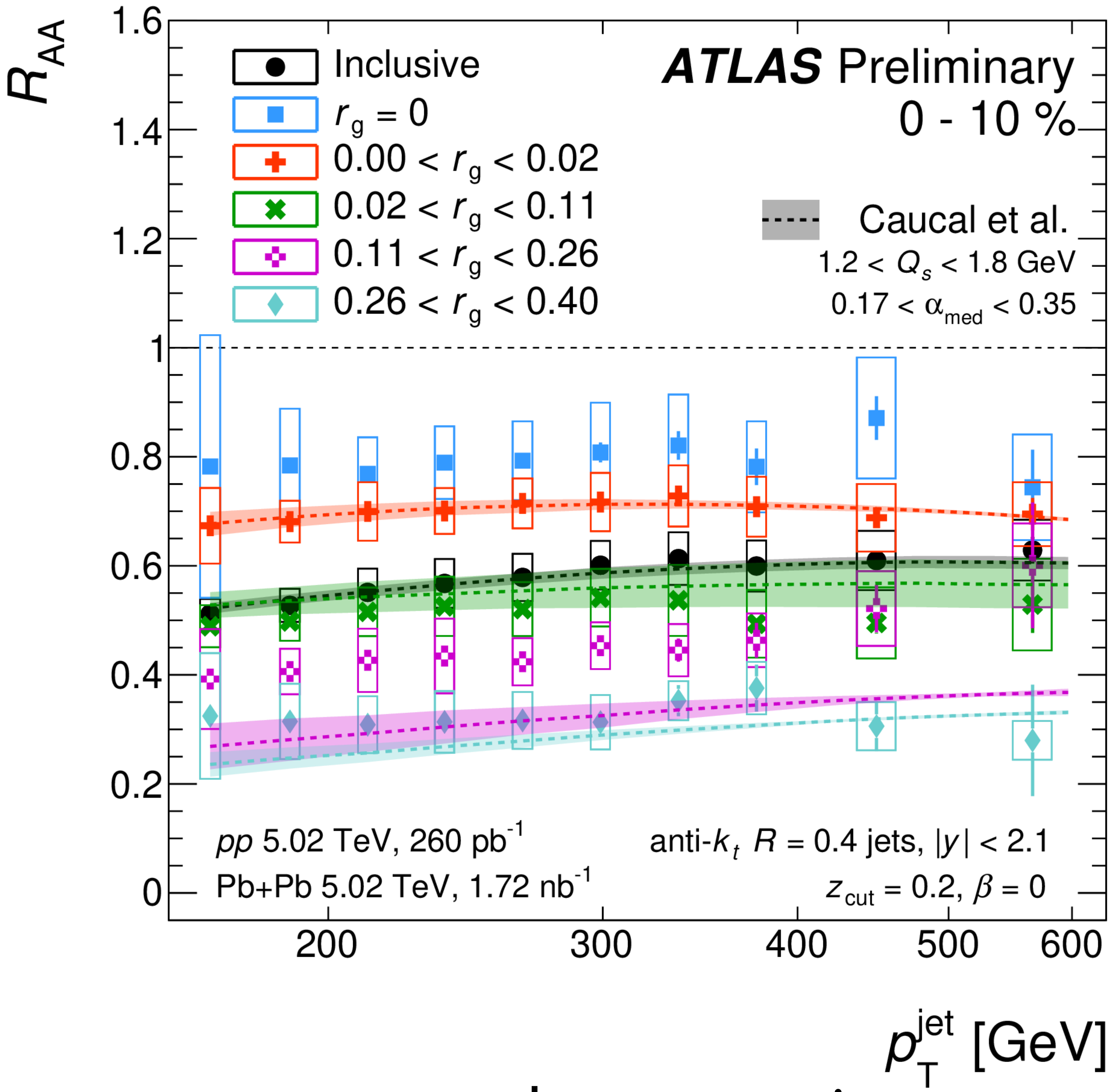
R dependence of jet suppression

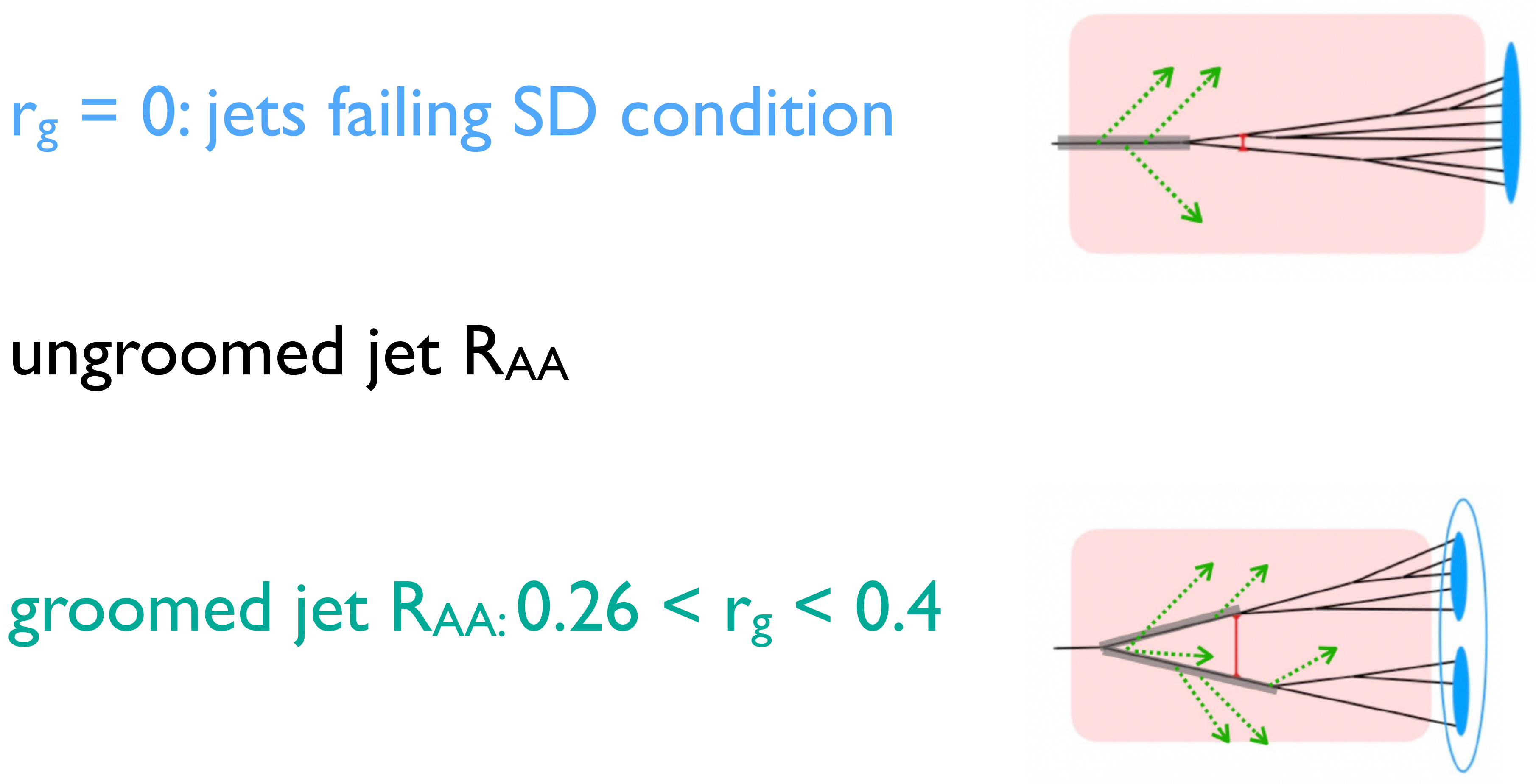


- No strong R dependence of jet R_{AA} for very high p_T jets observed by CMS
- R dependence of jet R_{AA} can help to disentangle energy loss mechanisms
  - competing effect between the amount/how energy redistributed and ability to recover it

Understanding R dependence of jet R_{AA}

ATLAS-CONF-2022-026

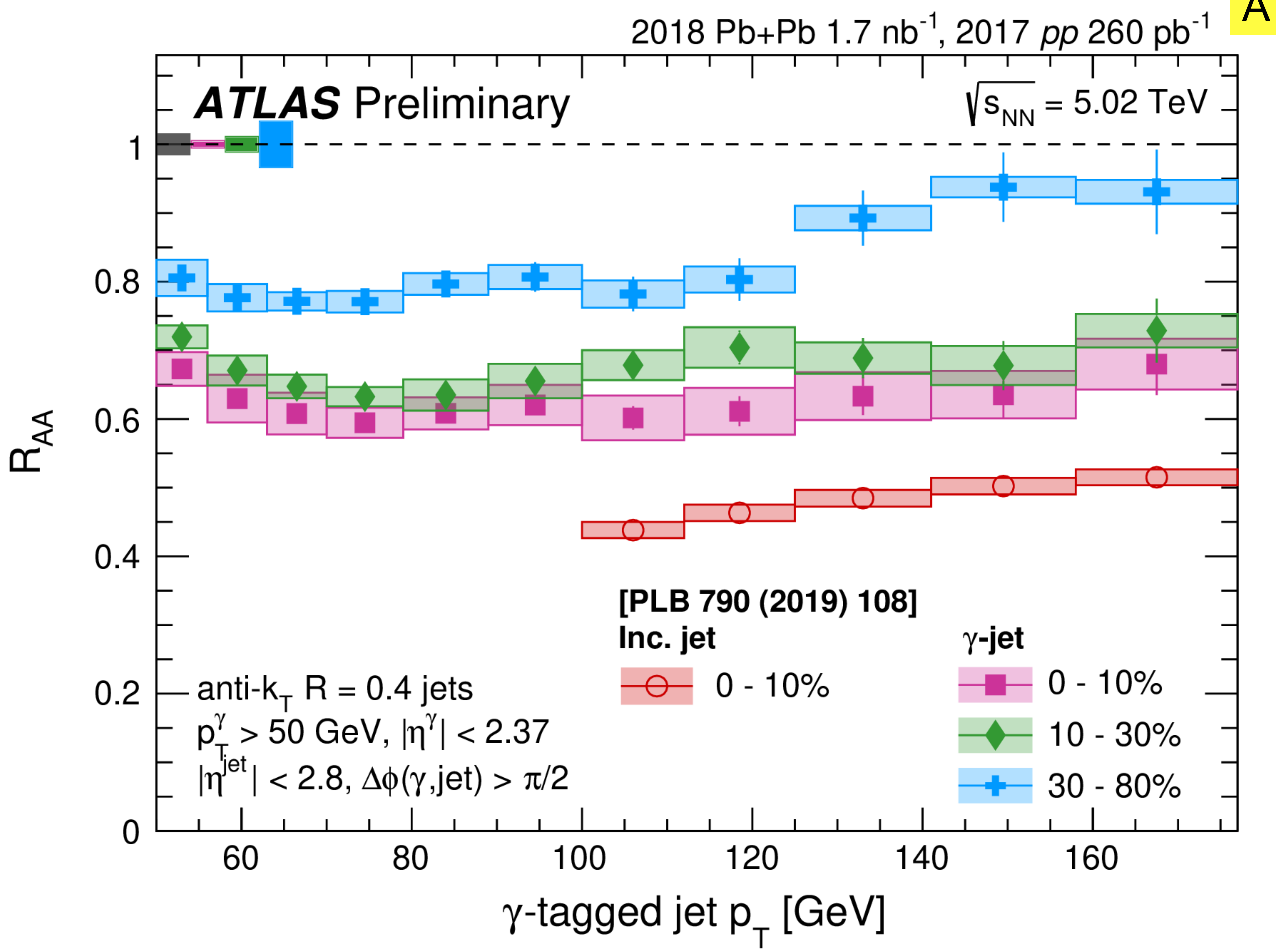


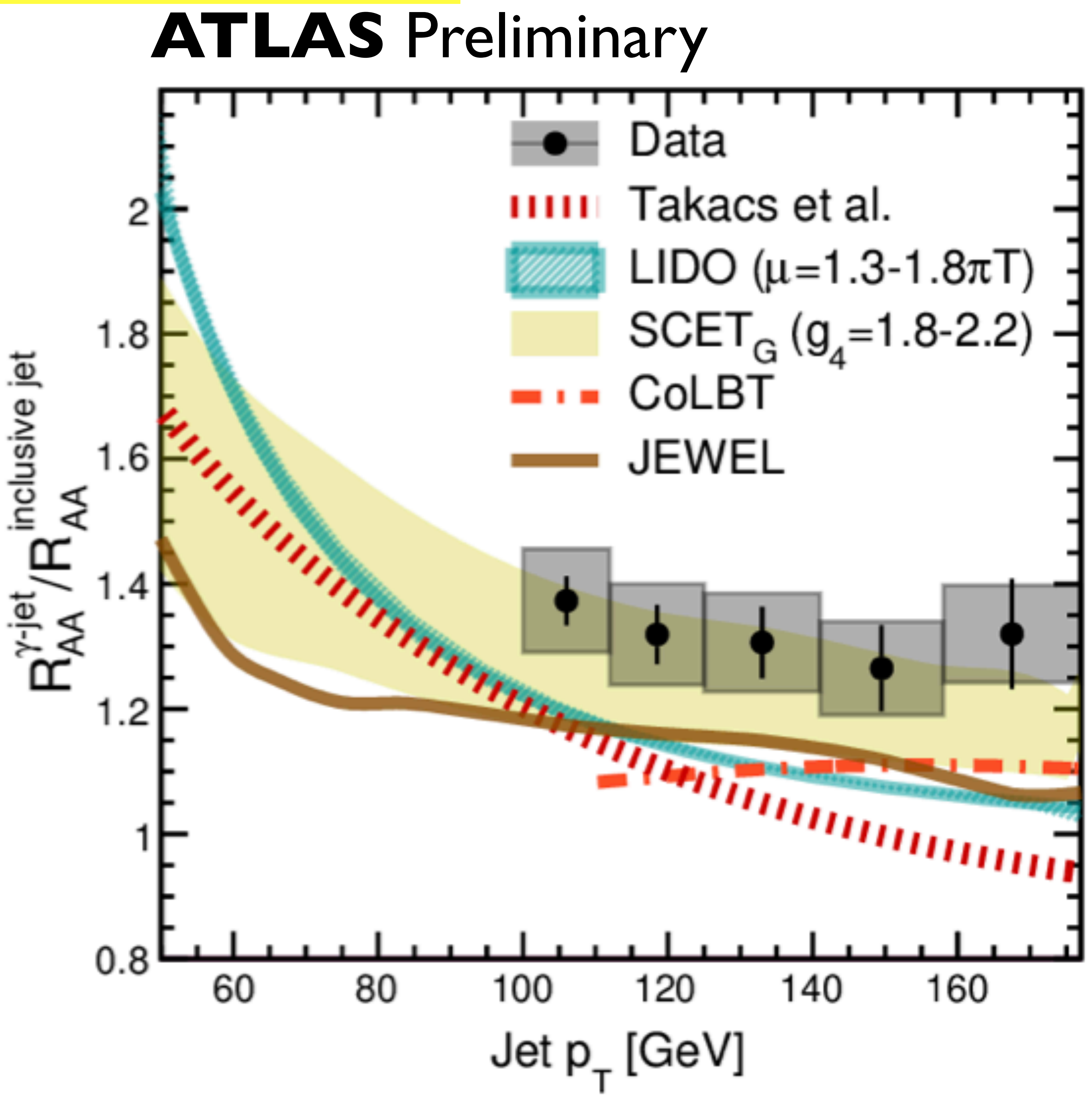


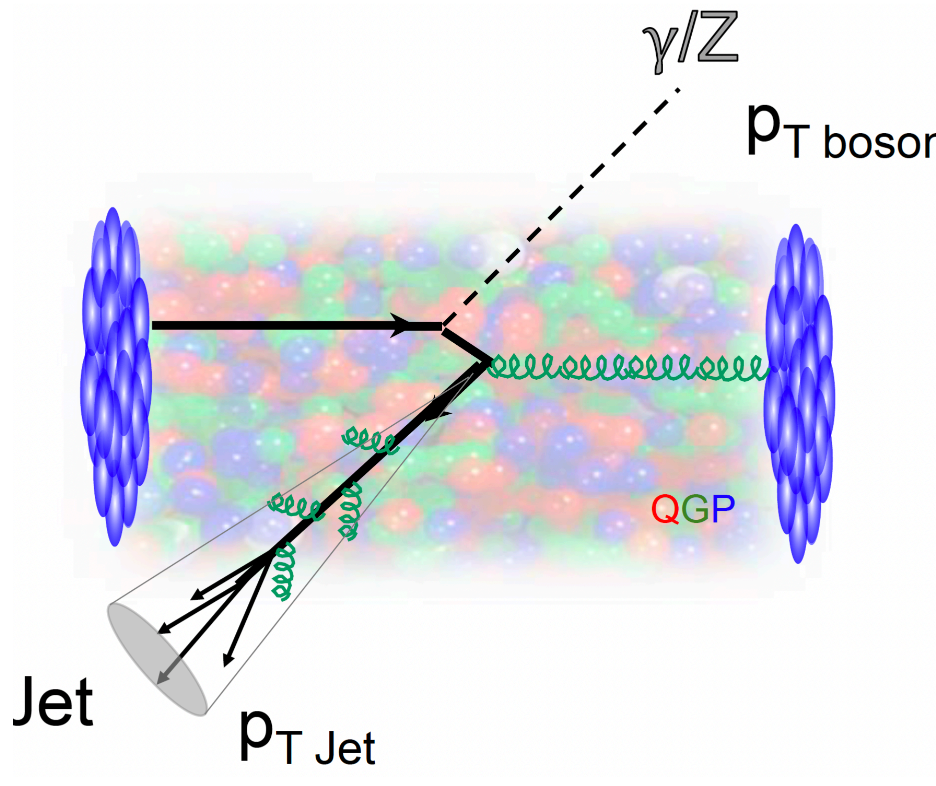
- Large r_g jets are more suppressed → suggesting strong r_g dependence of R_{AA}
- Large r_g jets potentially select more active vacuum shower or with more independent prongs that are more quenched in medium → large R-jet has higher probability for large r_g splittings at fixed jet p_T

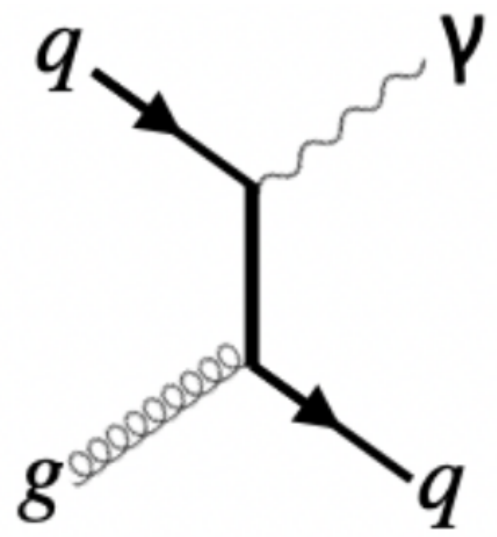
Color charge dependence of jet energy loss

ATLAS-CONF-2022-019





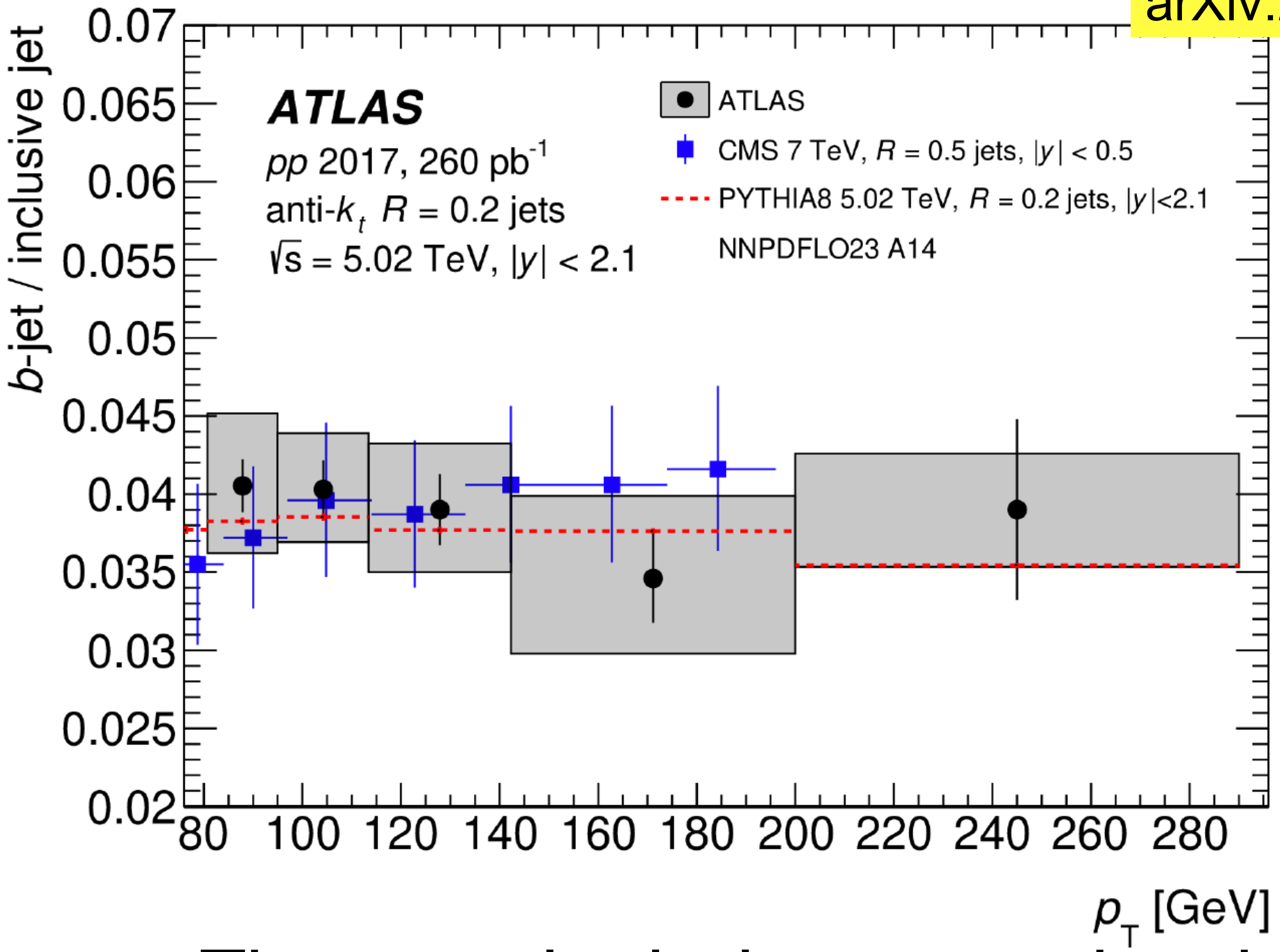


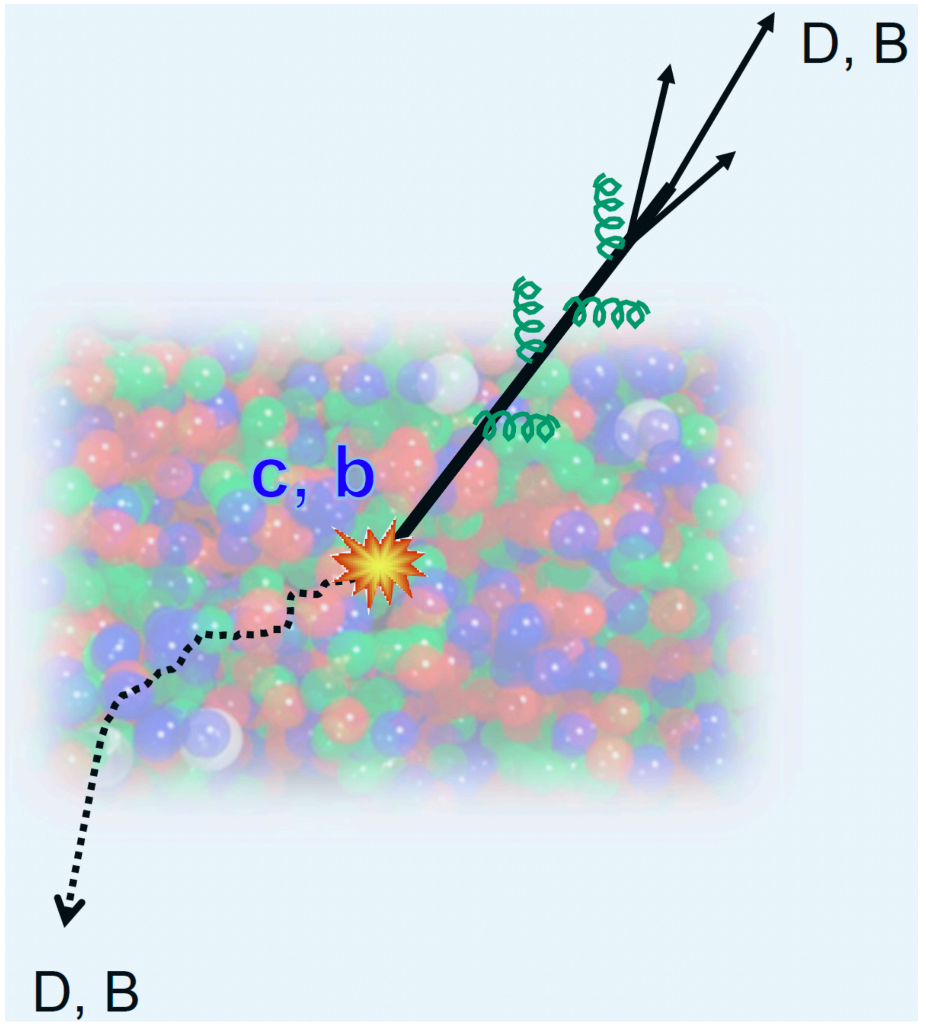


- Quark fraction can be enhanced by selecting jets recoiling from a prompt photon
- Photon-tagged (quark) jets being significantly less suppressed than inclusive jets
  - quark jets less active in medium, fewer radiating prongs → color factor dependence of parton-medium interaction

Flavour dependence of jet suppression

arXiv:2204.13530





- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation

Flavour dependence of jet suppression

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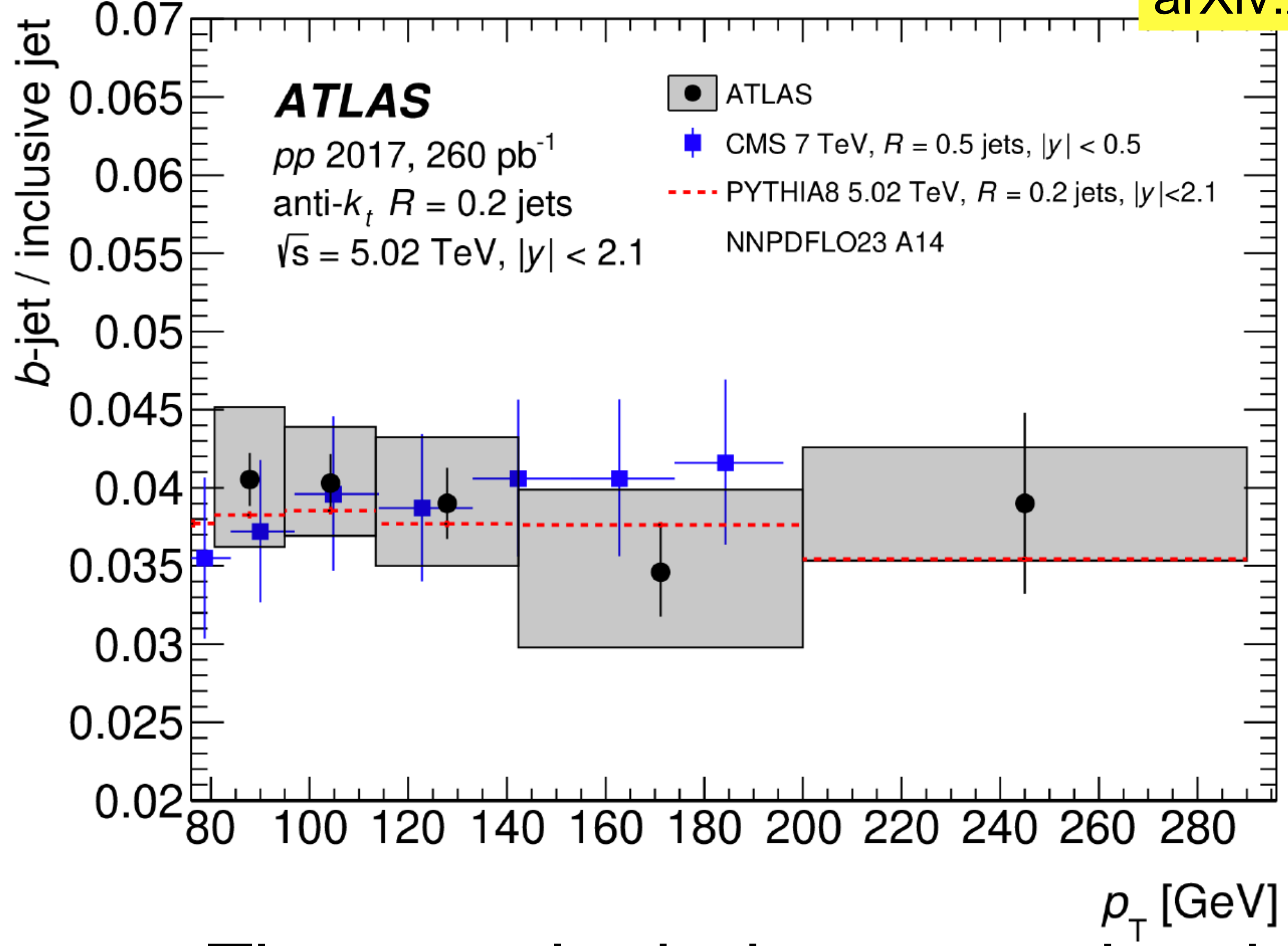
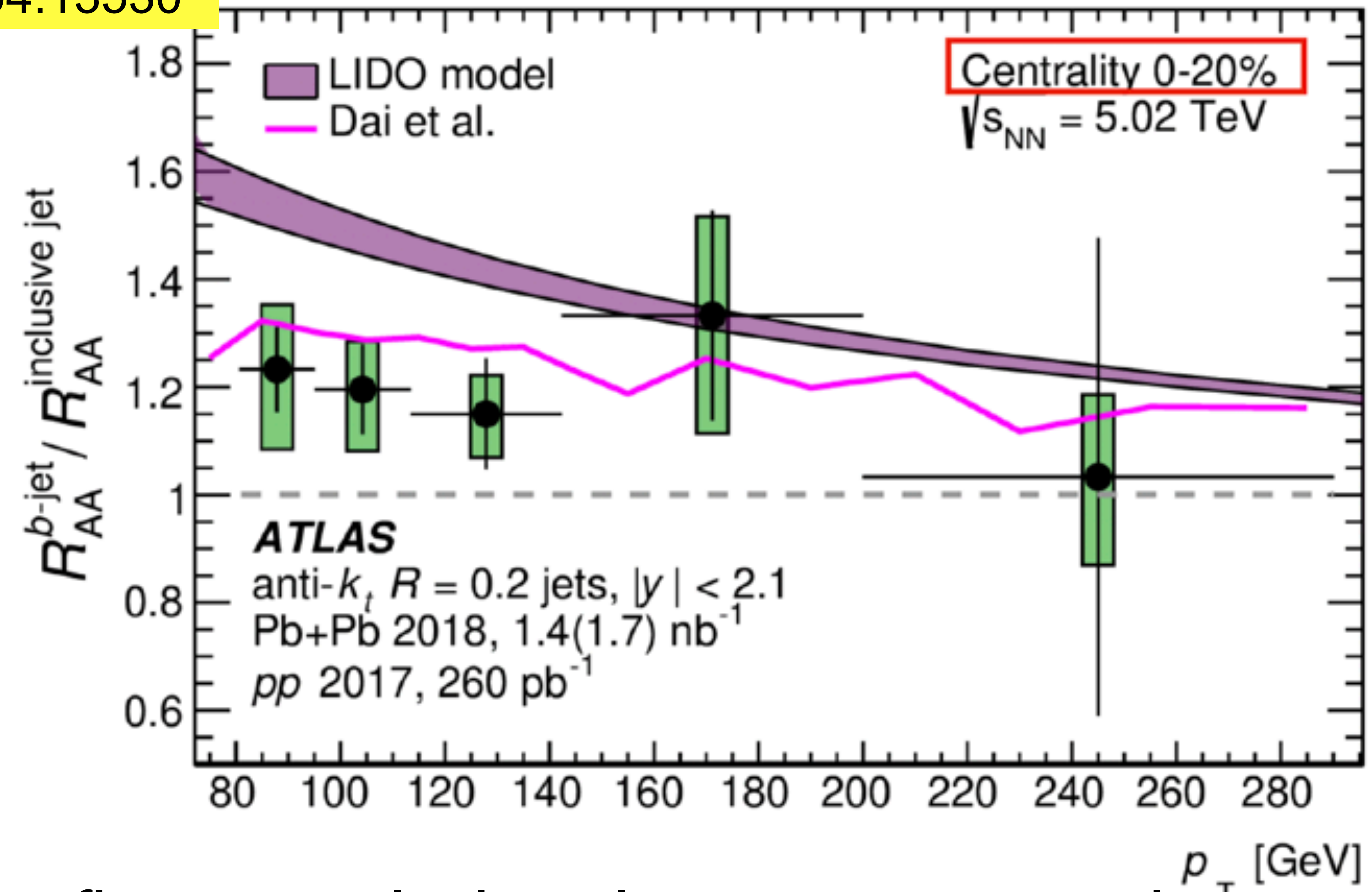
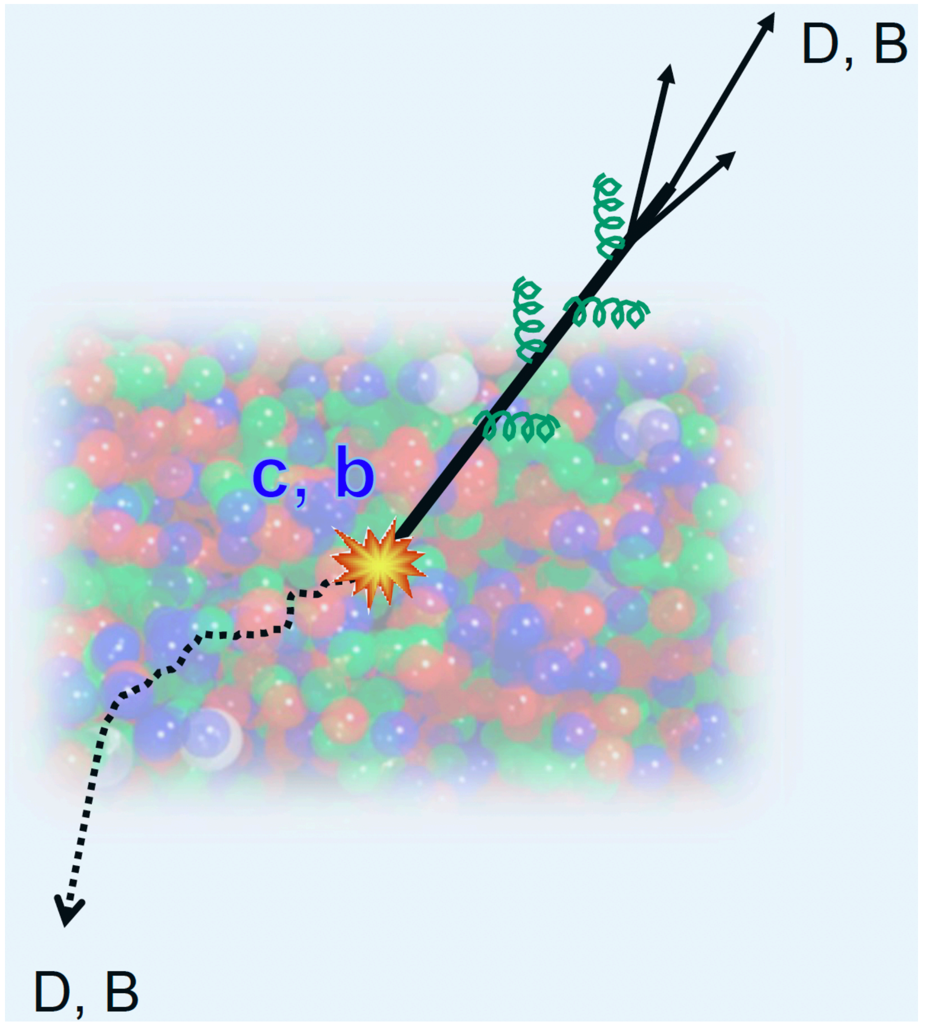
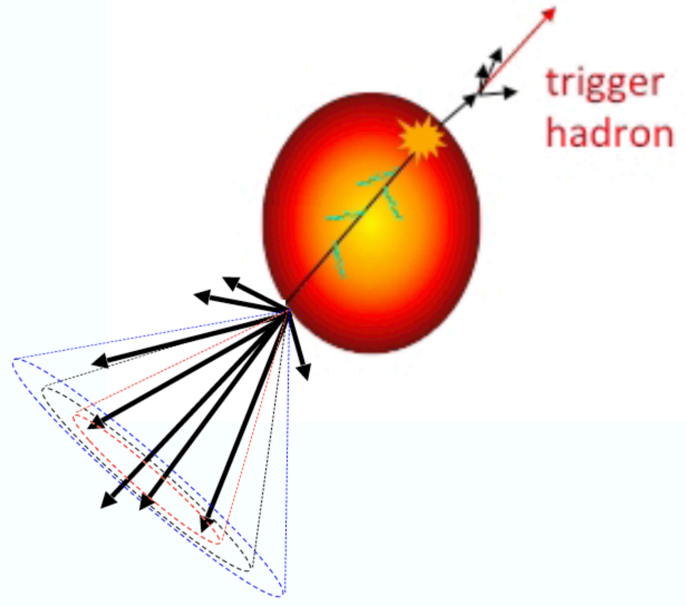


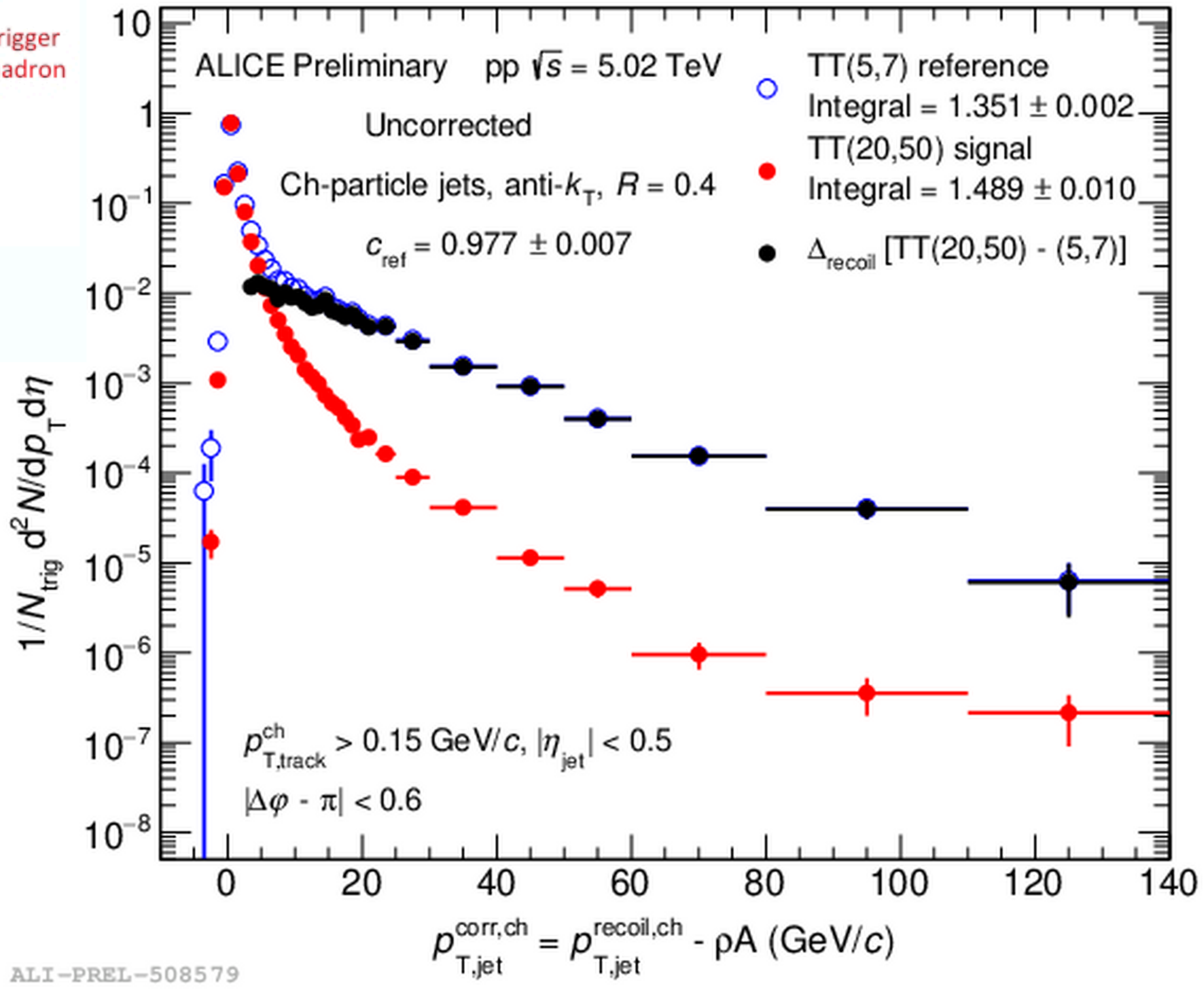




- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation
- Less suppression of b-jets than inclusive jets in most central collisions
  - color charge and mass dependence of energy loss

Coincidence measurements down to low p_T using recoil jets

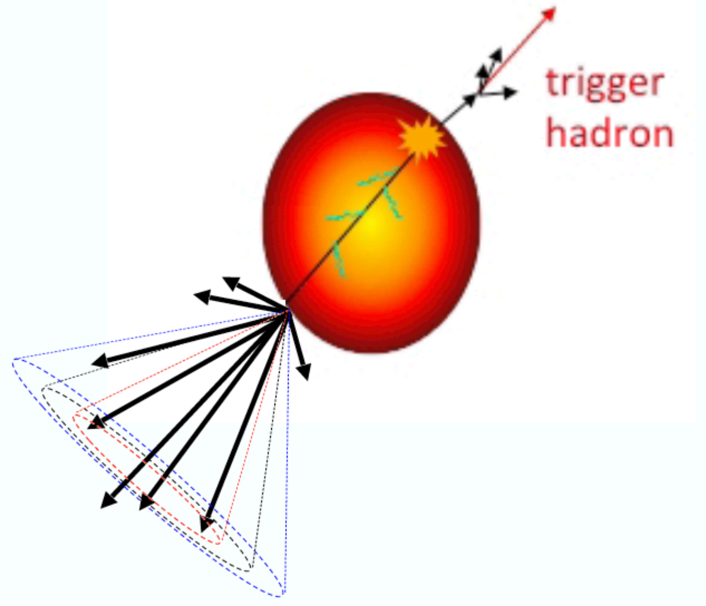


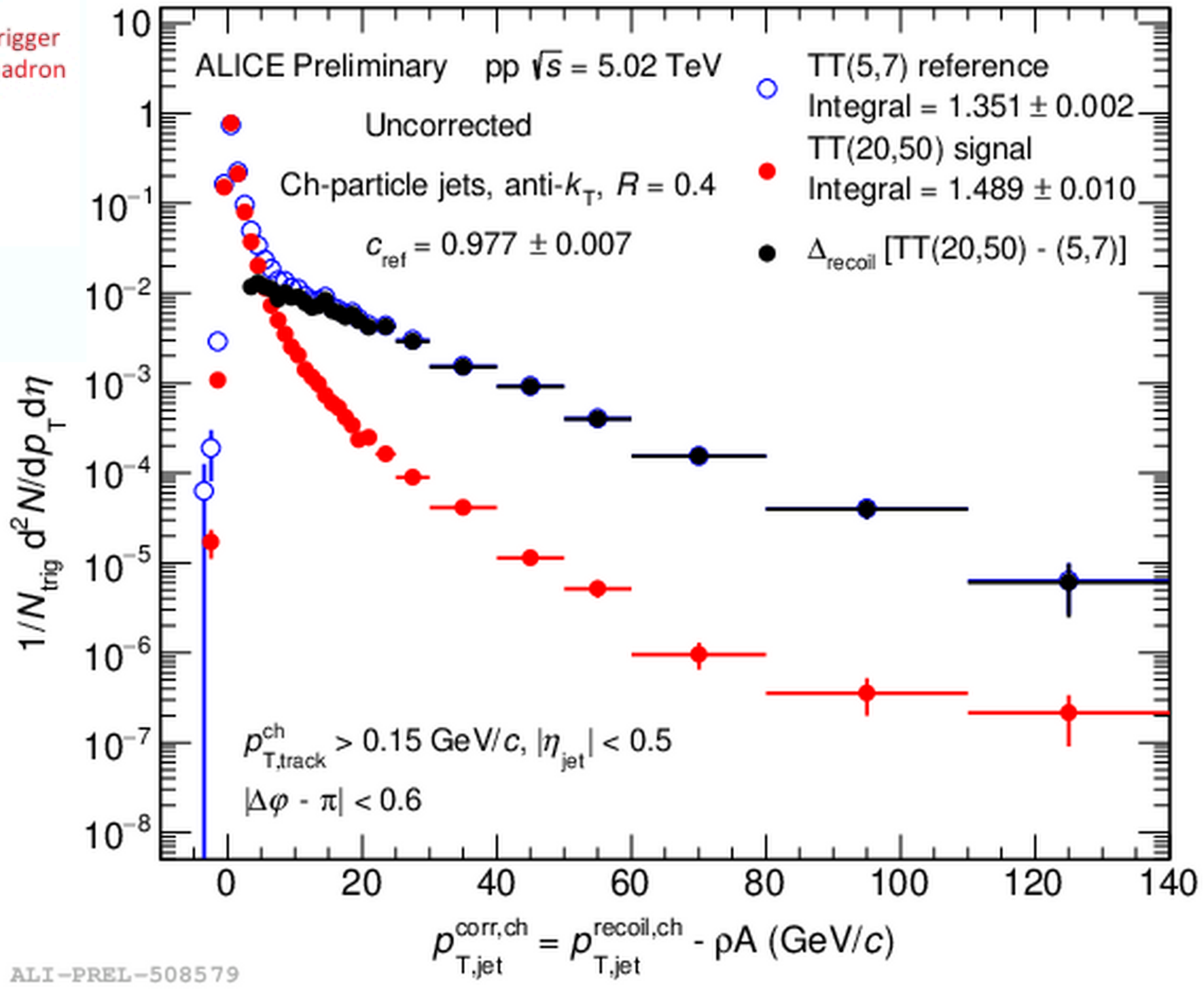


$$\Delta_{\rm recoil} = \frac{1}{N^{AA}_{\rm trig}} \frac{d^2N^{AA}_{\rm jet}}{dp^{\rm ch}_{\rm T,jet} d\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT_{Sig}}} - c_{\rm Ref}\cdot \frac{1}{N^{AA}_{\rm trig}} \frac{d^2N^{AA}_{\rm jet}}{dp^{\rm ch}_{\rm T,jet} d\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT_{Ref}}}$$

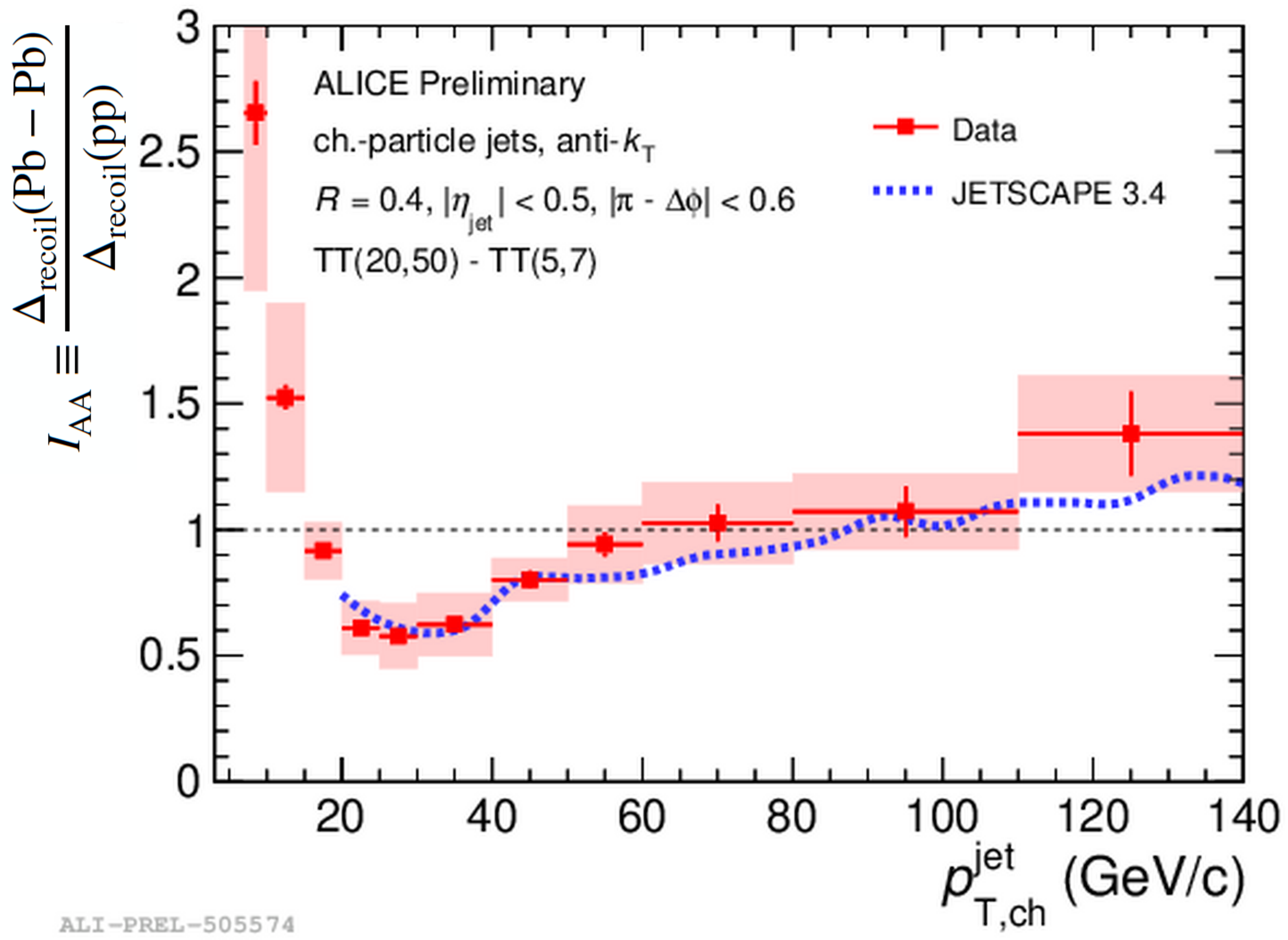
- Measurements of semi-inclusive yields of jets recoiling from a high p_T trigger hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening

Coincidence measurements down to low p_T using recoil jets



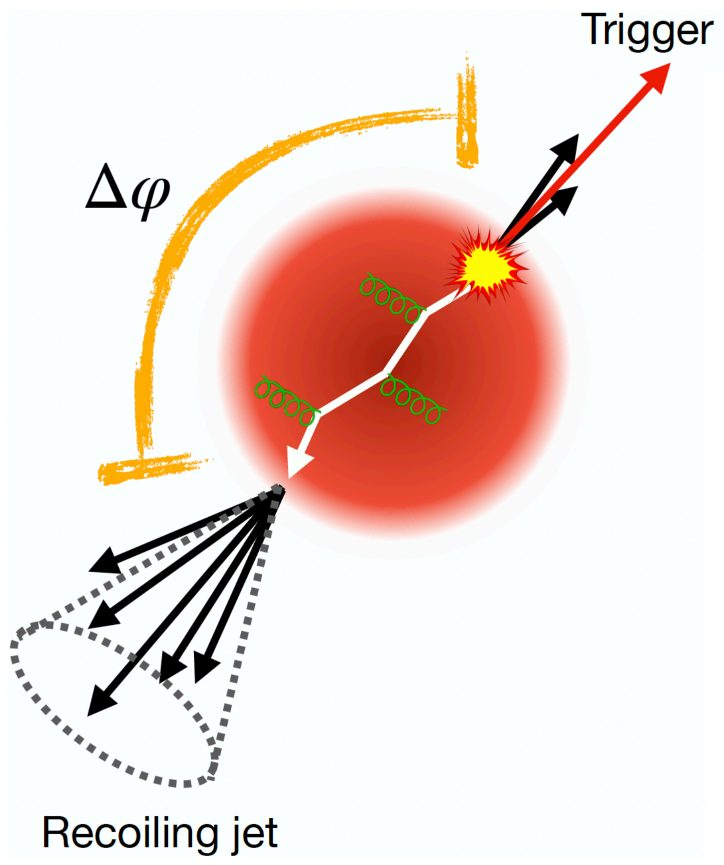


$$\Delta_{recoil} = \frac{1}{N^{AA}_{trig}} \frac{d^2N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N^{AA}_{trig}} \frac{d^2N^{AA}_{jet}}{dp^{ch}_{T,jet}\, d\eta_{jet}}\bigg|_{p_{T,trig}\in TT_{Ref}}$$

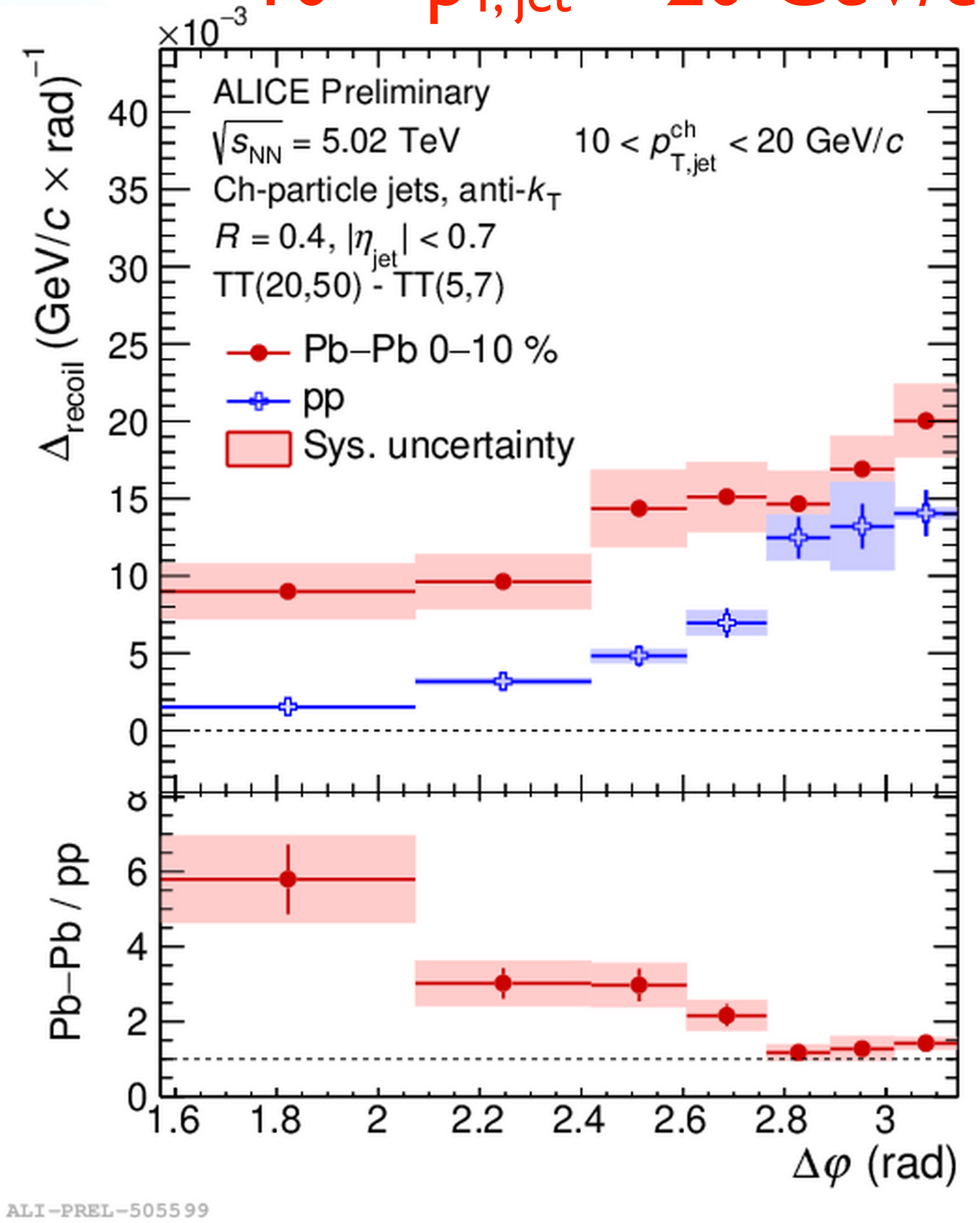


- Measurements of semi-inclusive yields of jets recoiling from a high p_T trigger hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening
- Increase of low p_T yields →hints of energy recovery for very low p_T jets

Angular deflection observed by h-jet correlations



10 < $p_{T,\,jet}$ < 20 GeV/c



- Azimuthal distribution of recoil jets provides additional insight into QGP properties
  - broadening of away side jet peak gives direct access to transport coefficient

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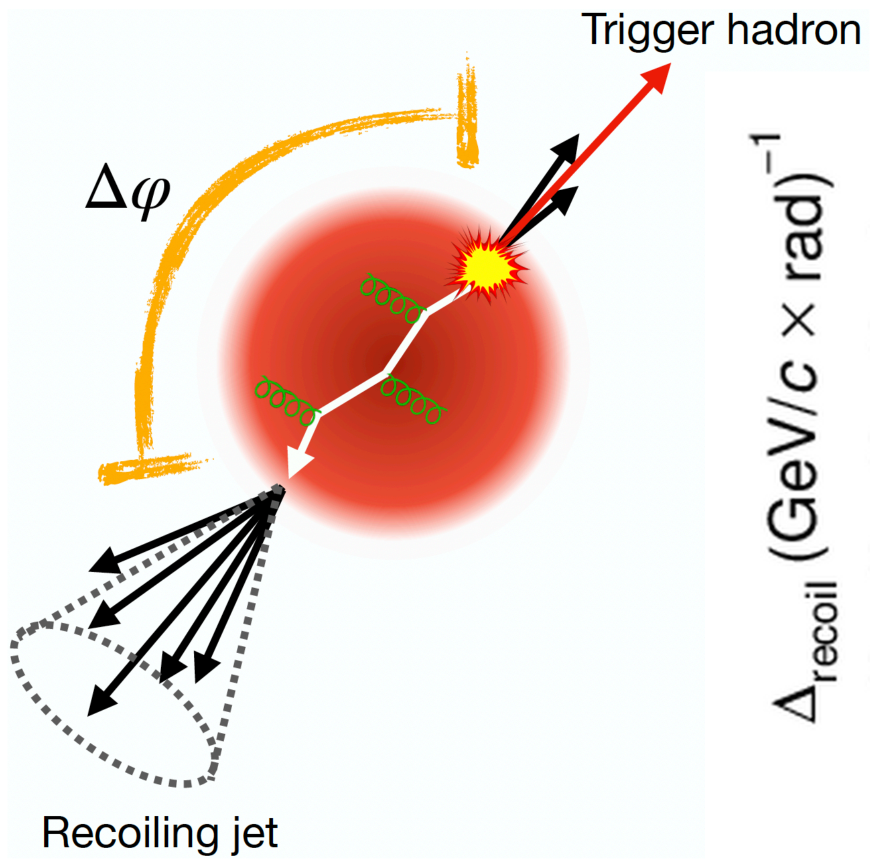
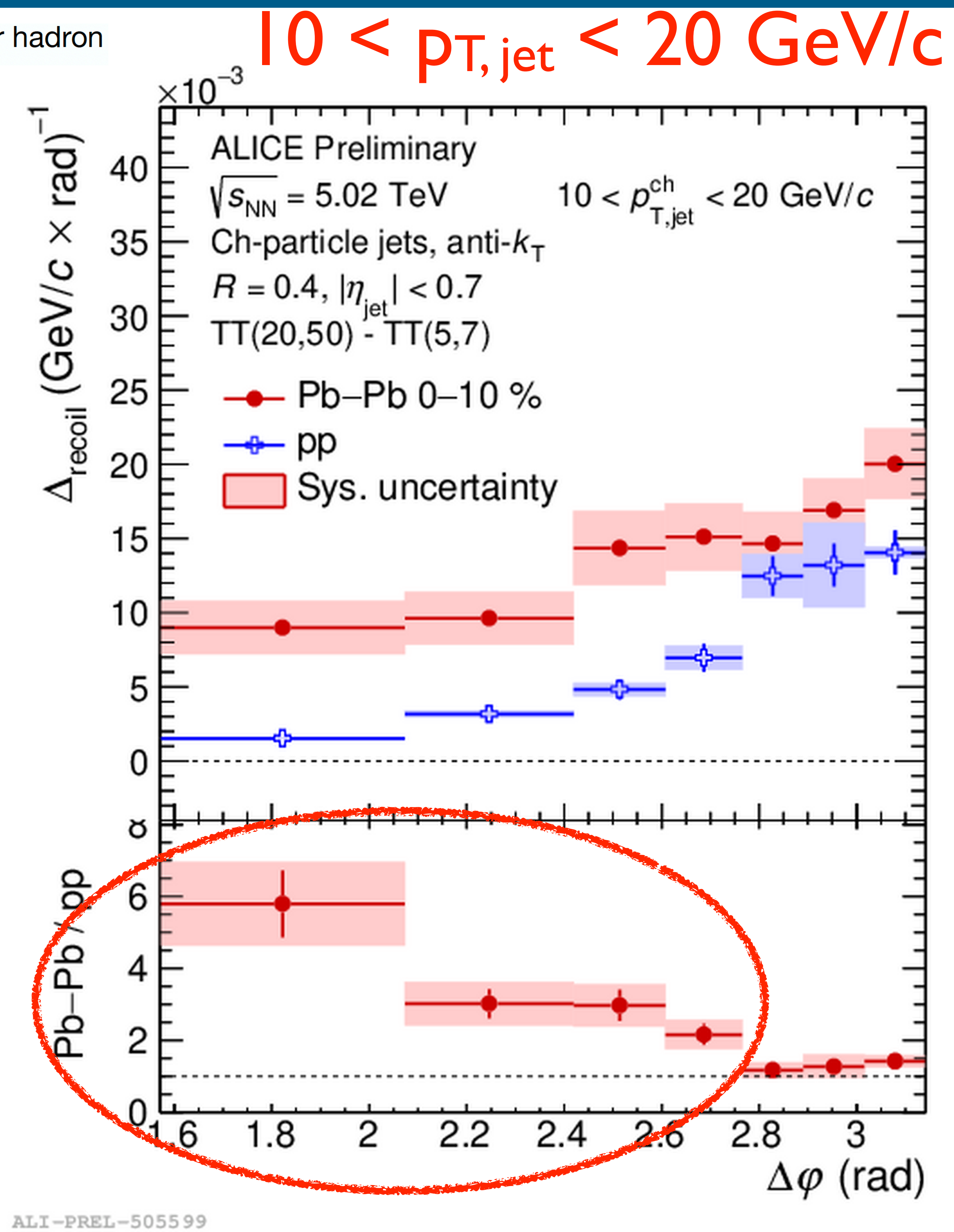
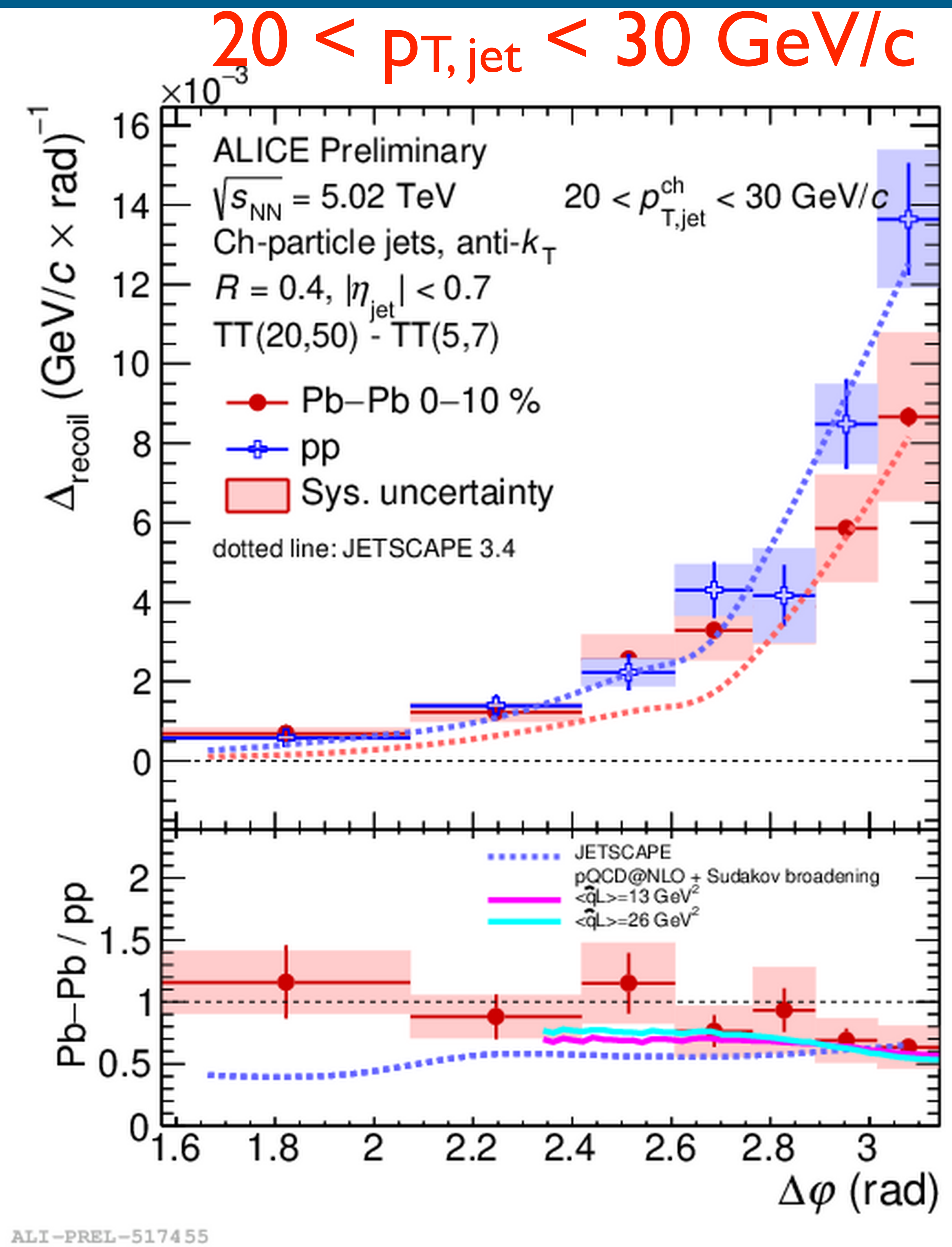
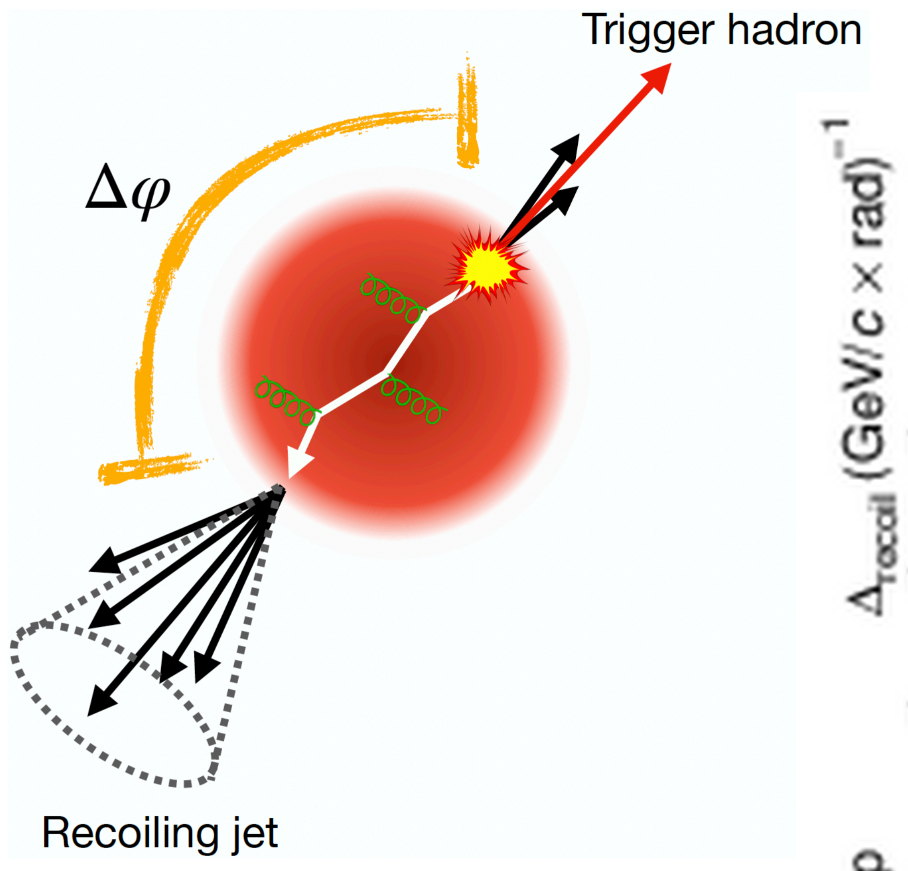


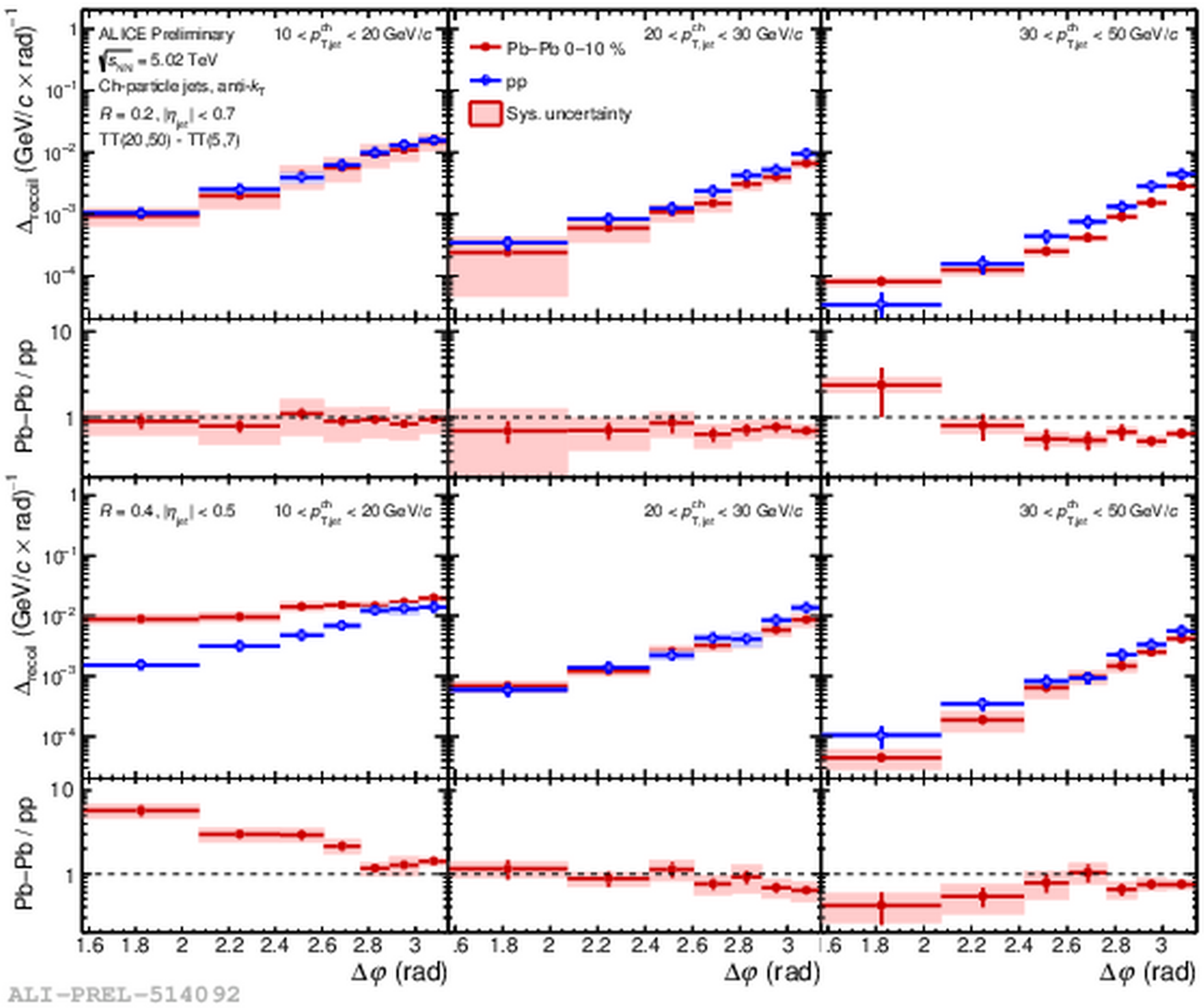




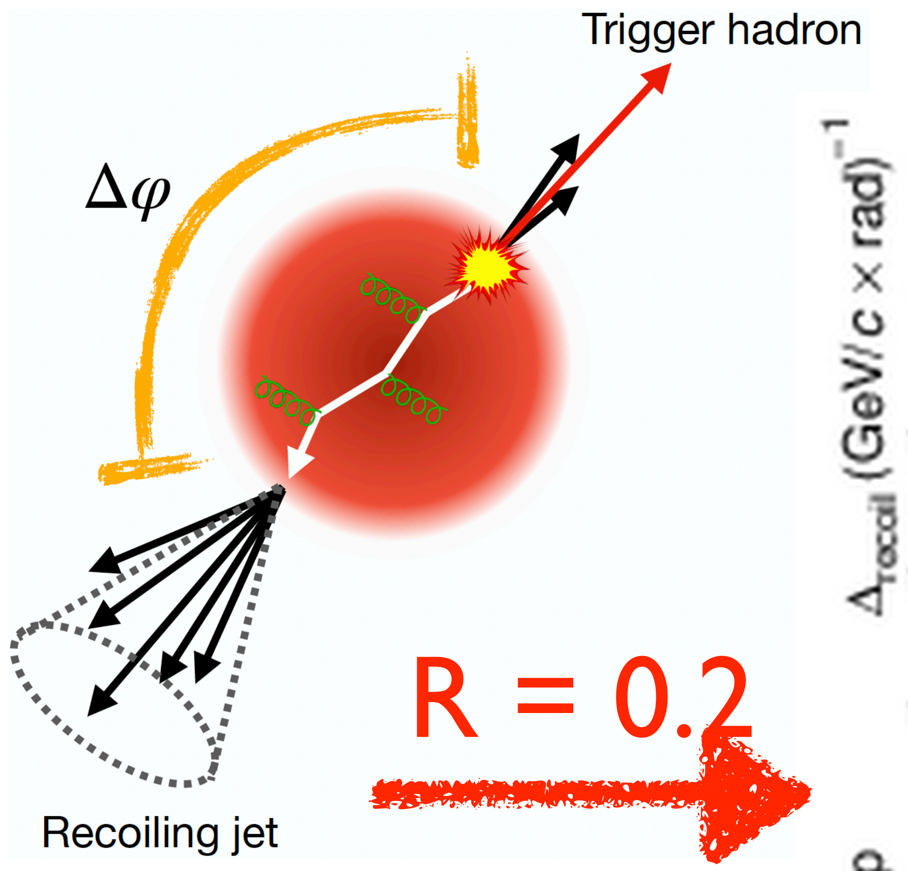
- Azimuthal distribution of recoil jets provides additional insight into QGP properties
  - broadening of away side jet peak gives direct access to transport coefficient
- Clear signature of azimuthal decorrelation of soft jets with R = 0.4, vanished for high p_T jets

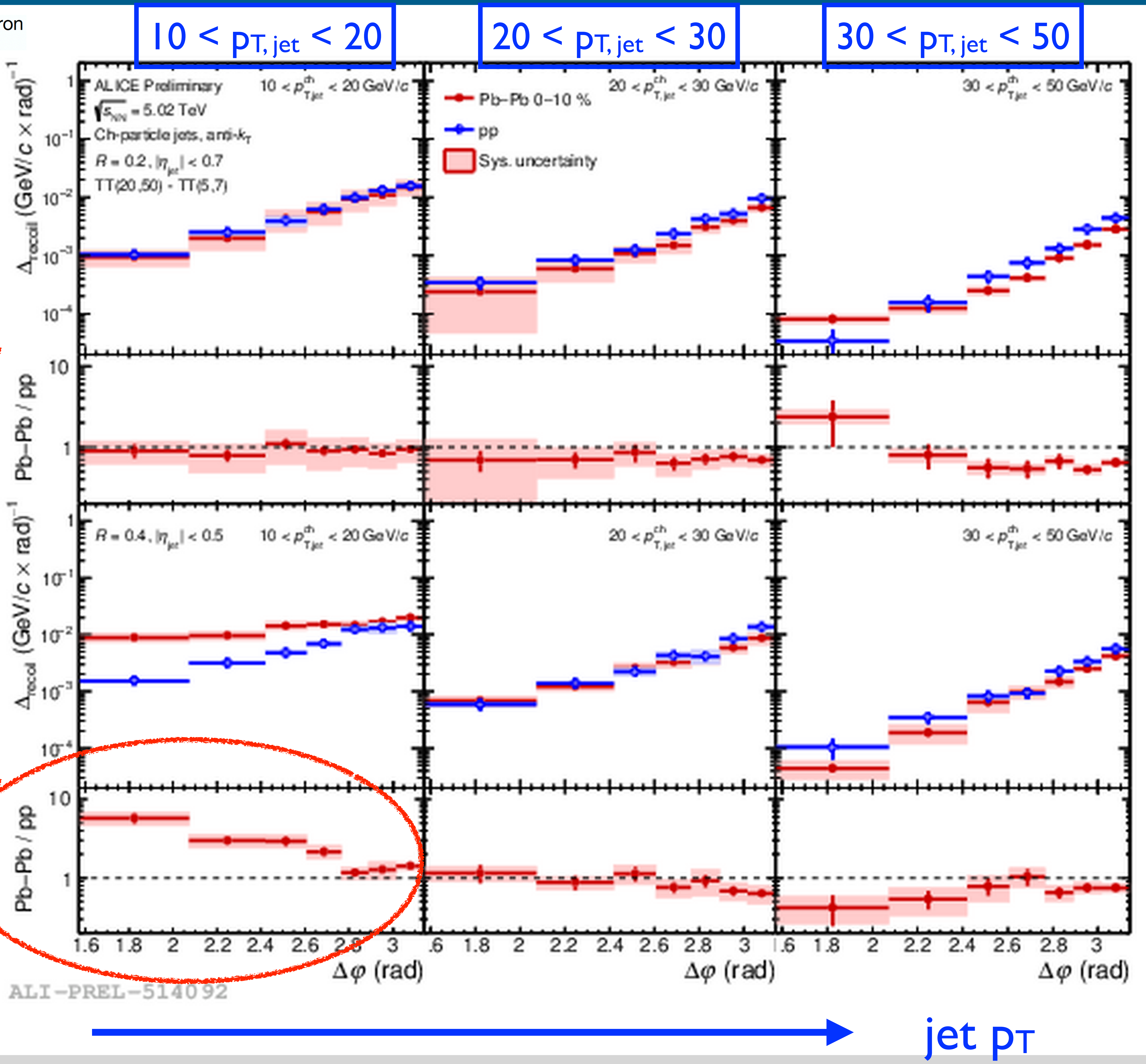
Angular deflection observed by h-jet correlations





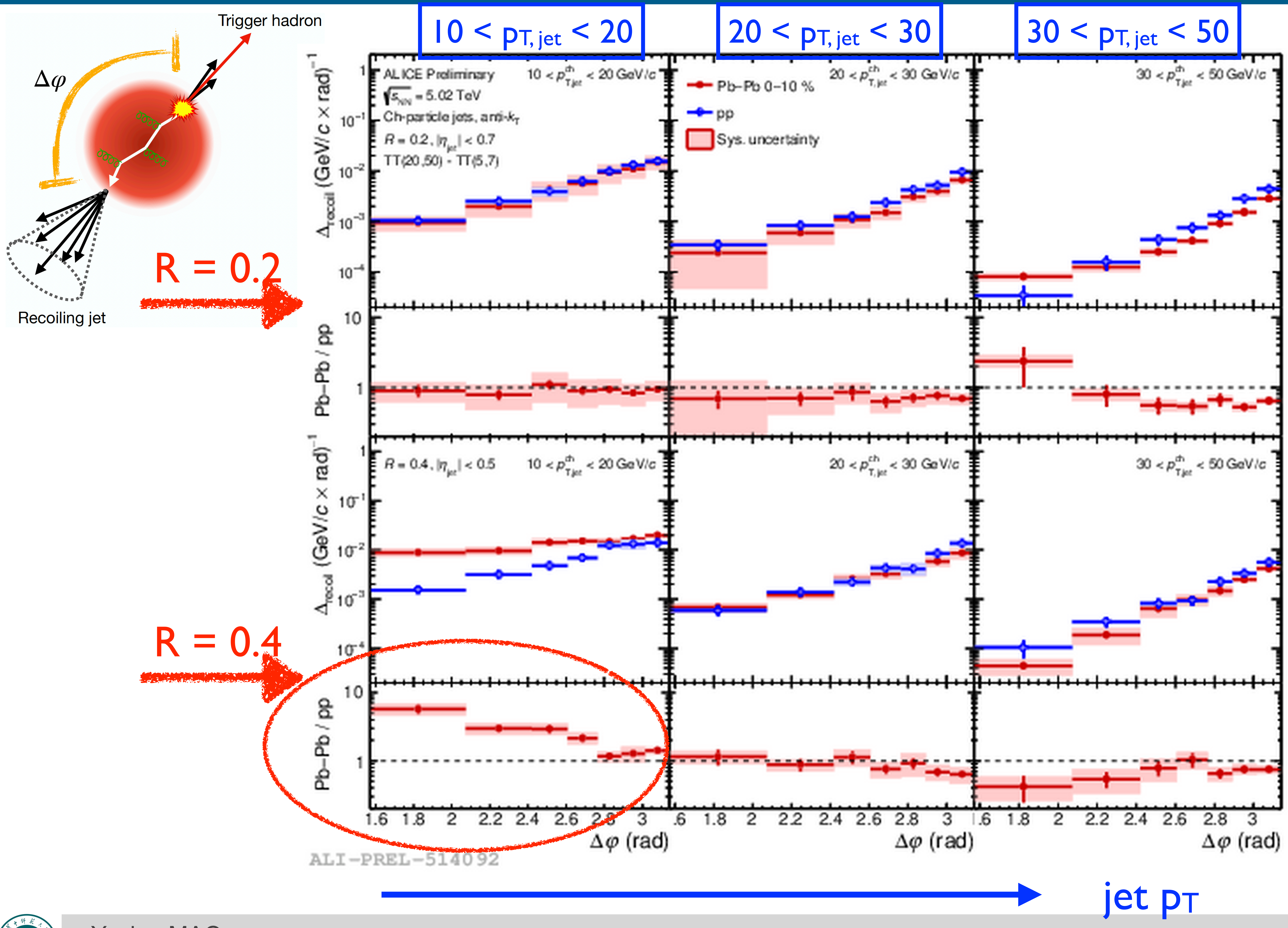
Angular deflection observed by h-jet correlations

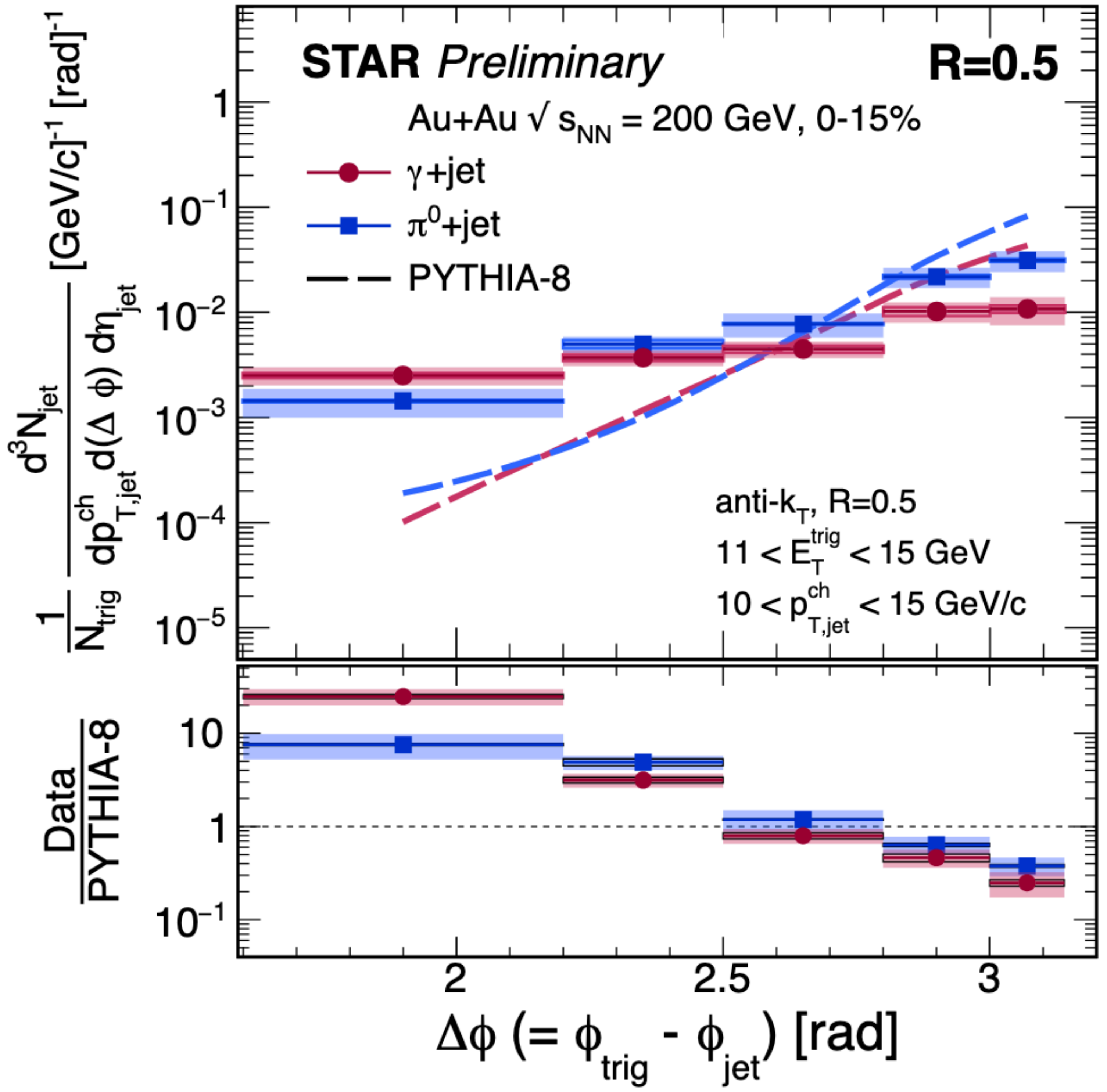




- Scan of azimuthal deflection study for different jet R and jet p_T
  - broadening of away side jet peak observed for very soft jets with R = 0.4

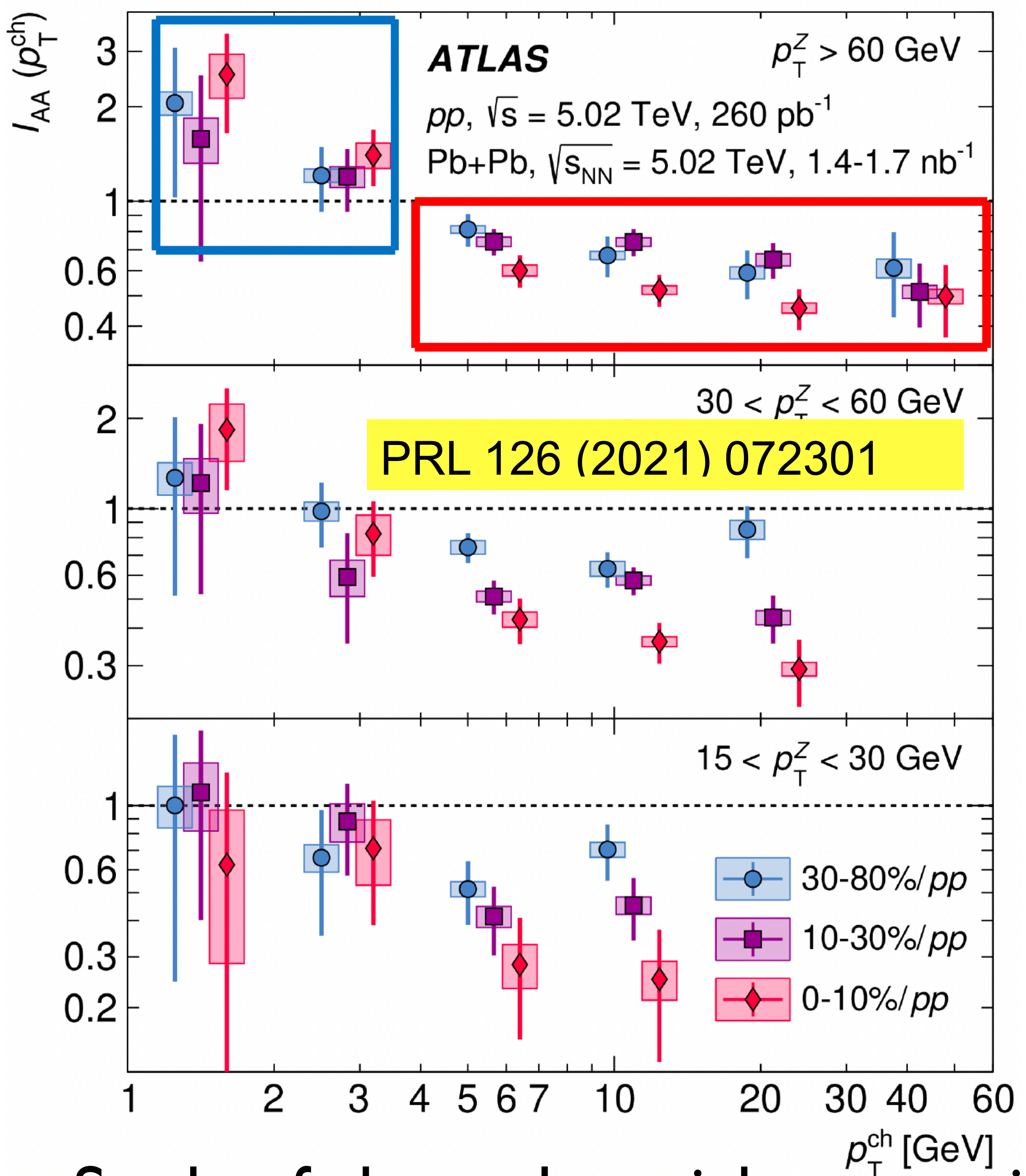
Angular deflection observed by h-jet correlations

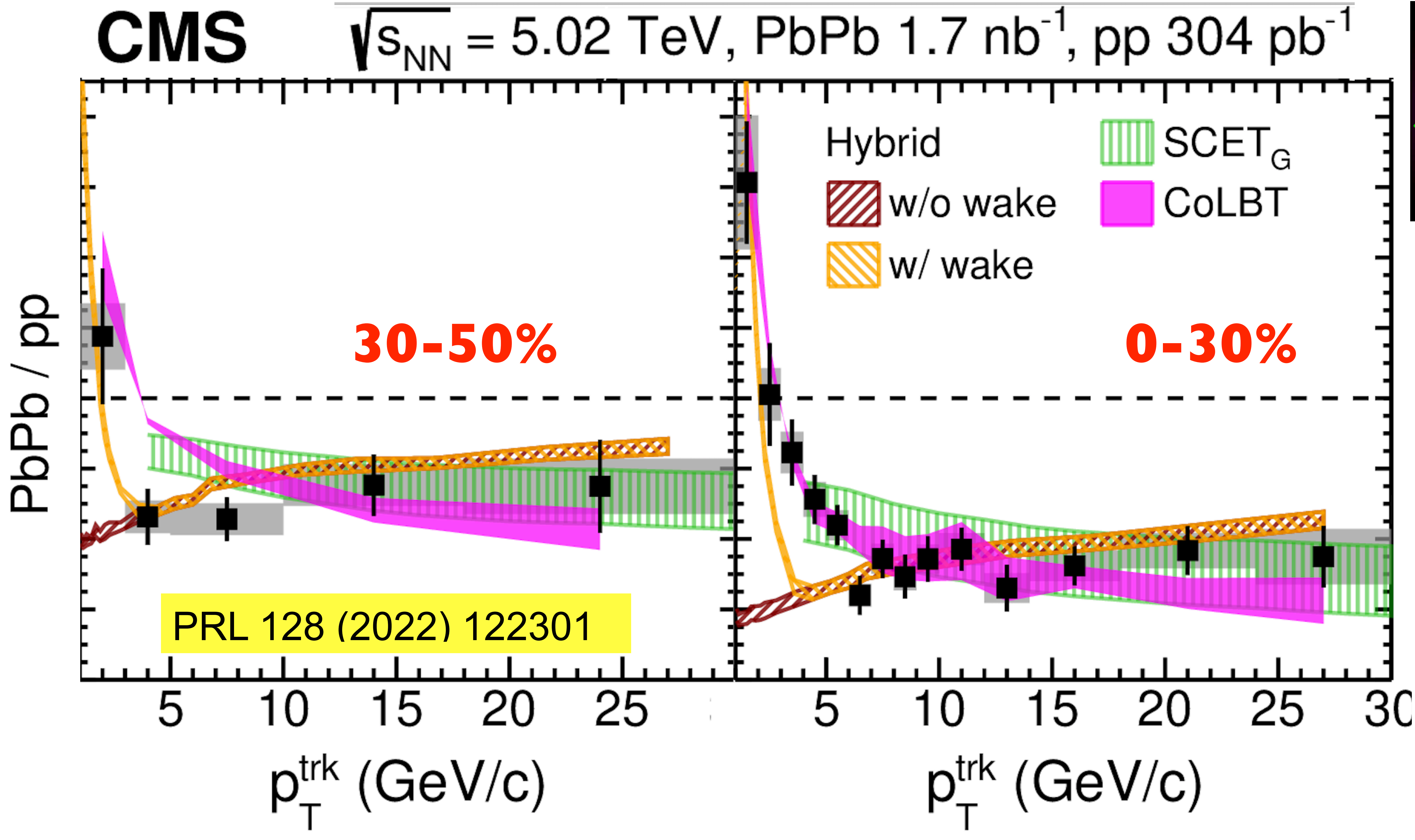


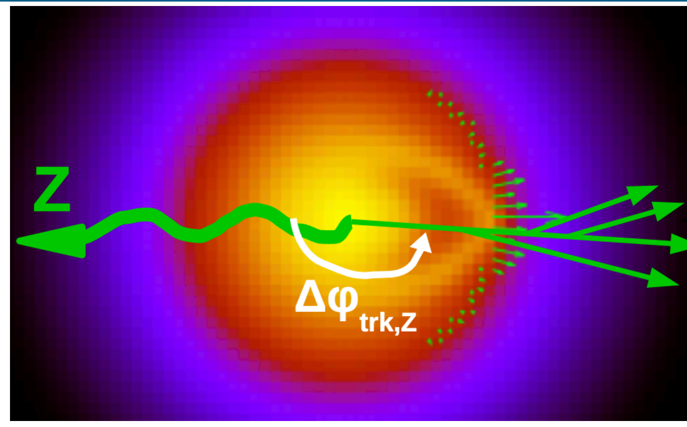


- Similar observation also found by STAR

Coincidence measurements from Z -hadron correlations

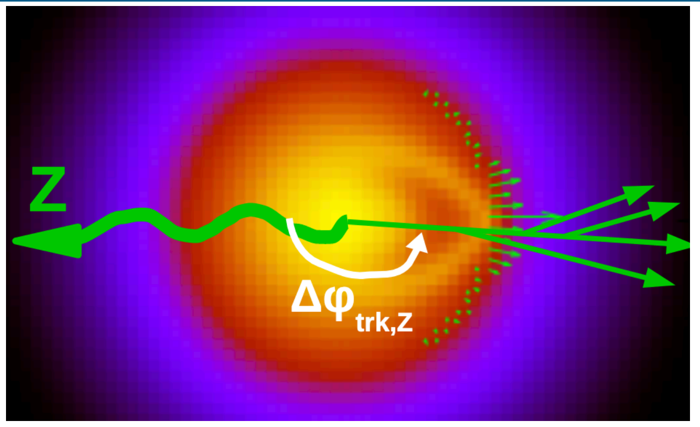


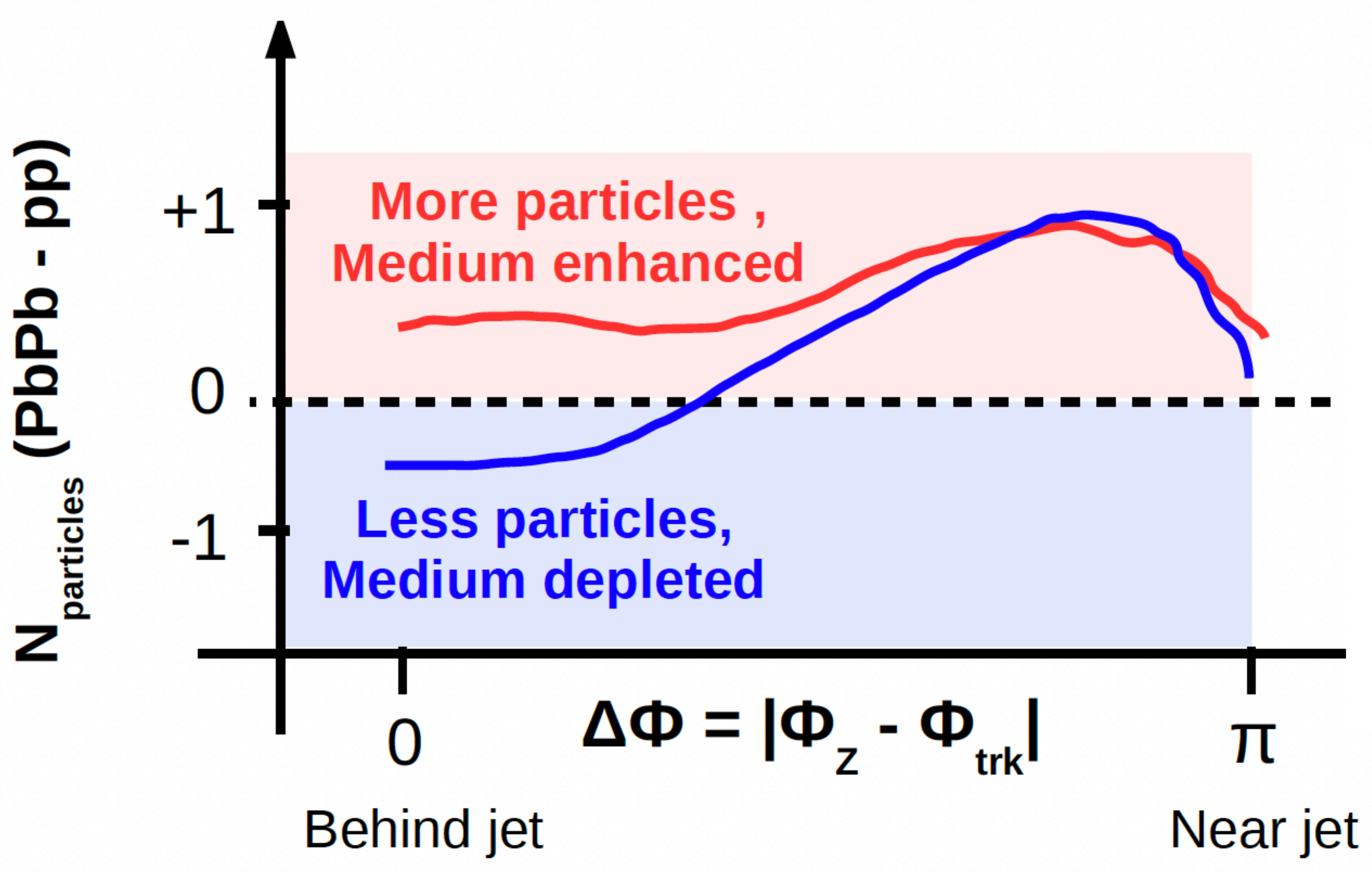


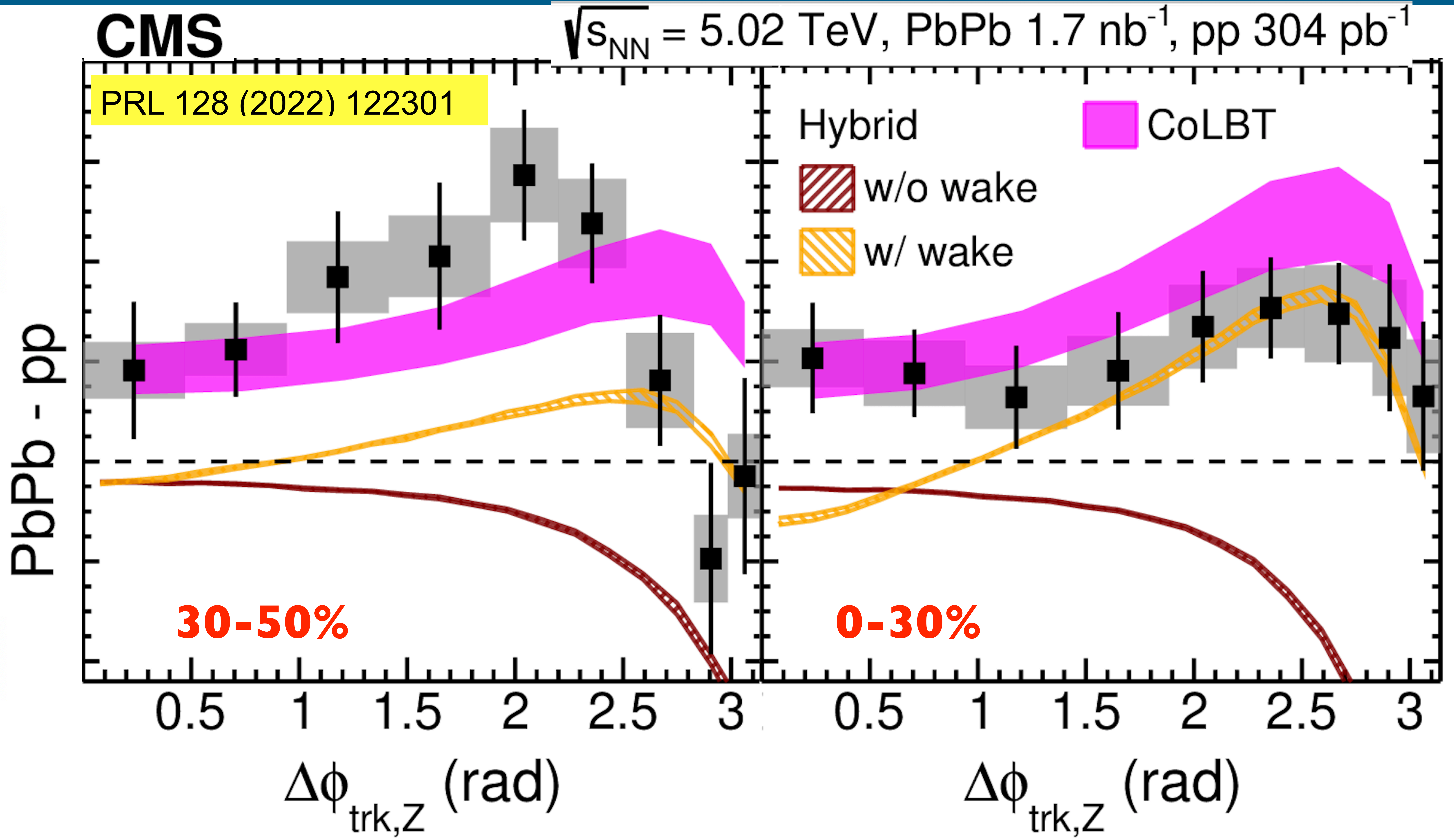


- Study of charged particles opposite to Z without jet reconstruction allows to understand the modification of jet constituents and jet fragmentation functions
  - Colorless Z sets initial scattering proxy, allows probing low p_T range
- Low p_T excess and high p_T suppression → energy redistribution due to quenching

Angular deflection from Z -hadron correlations



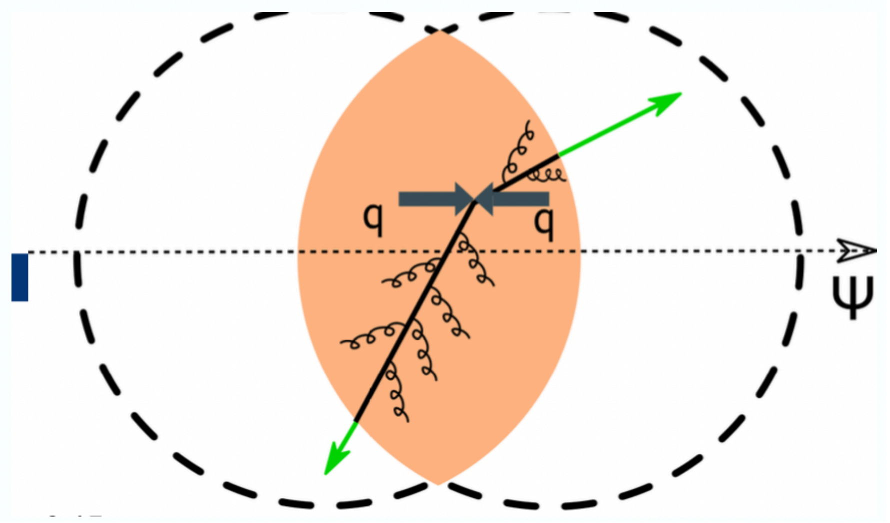


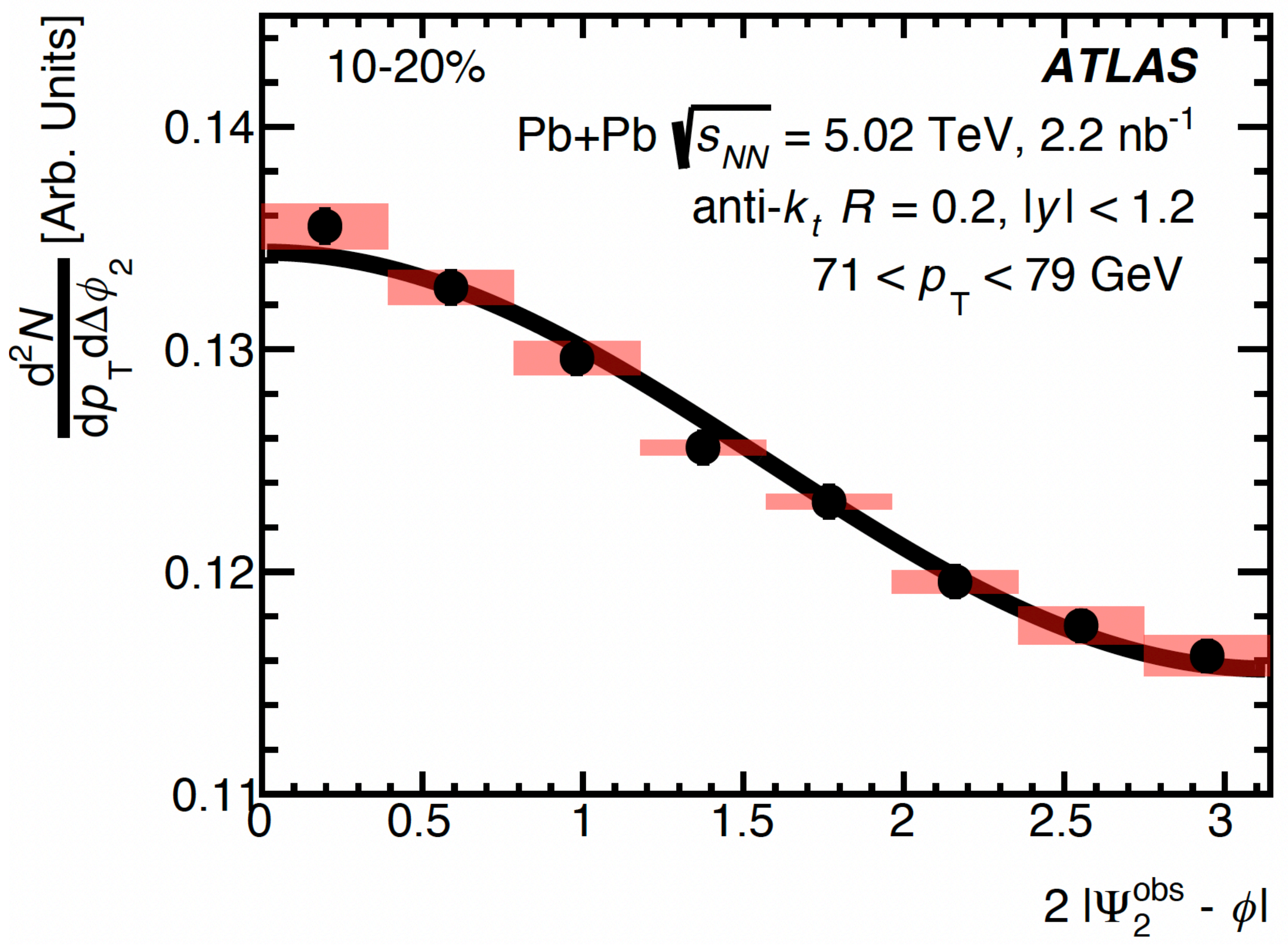


- Momentum of initial parton determined by Z, allowing precise measurements of angular correlations
- Excess of particle yields in central PbPb collisions →CoLBT (quenching + hydro) reproduces data results
  - Provides constrains for modeling medium-parton interaction

Path length dependence of jet energy loss

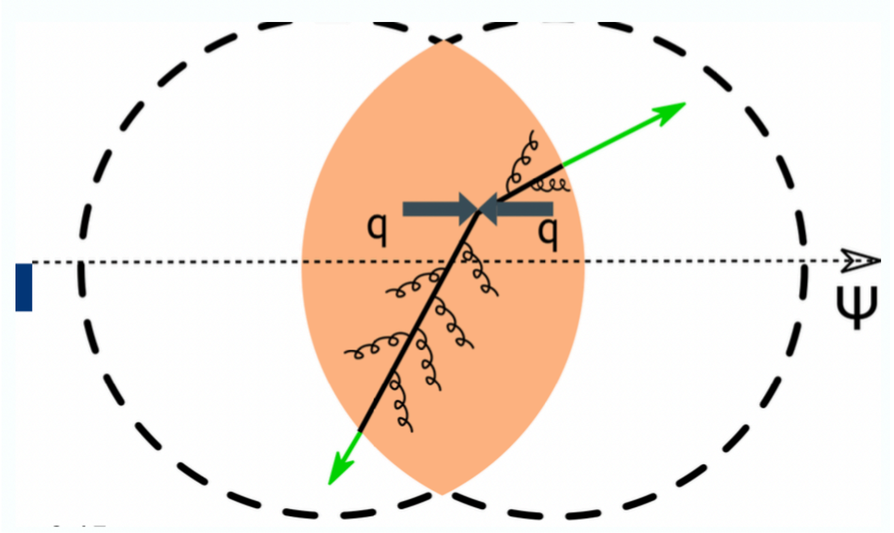
arXiv:2111.06606





- Measuring jet rates as a function of event plane is sensitive to path length dependence of jet energy loss

Path length dependence of jet energy loss



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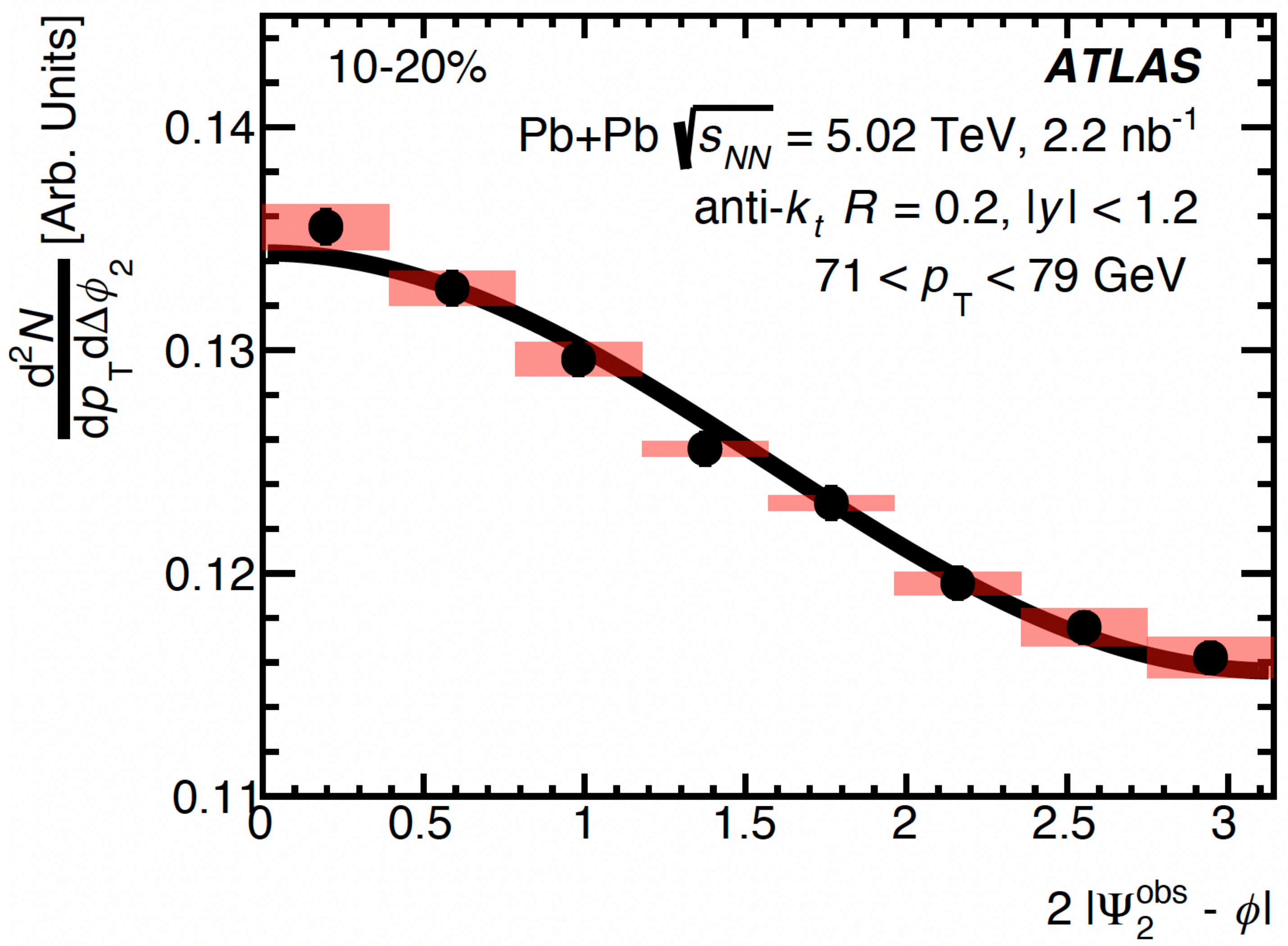
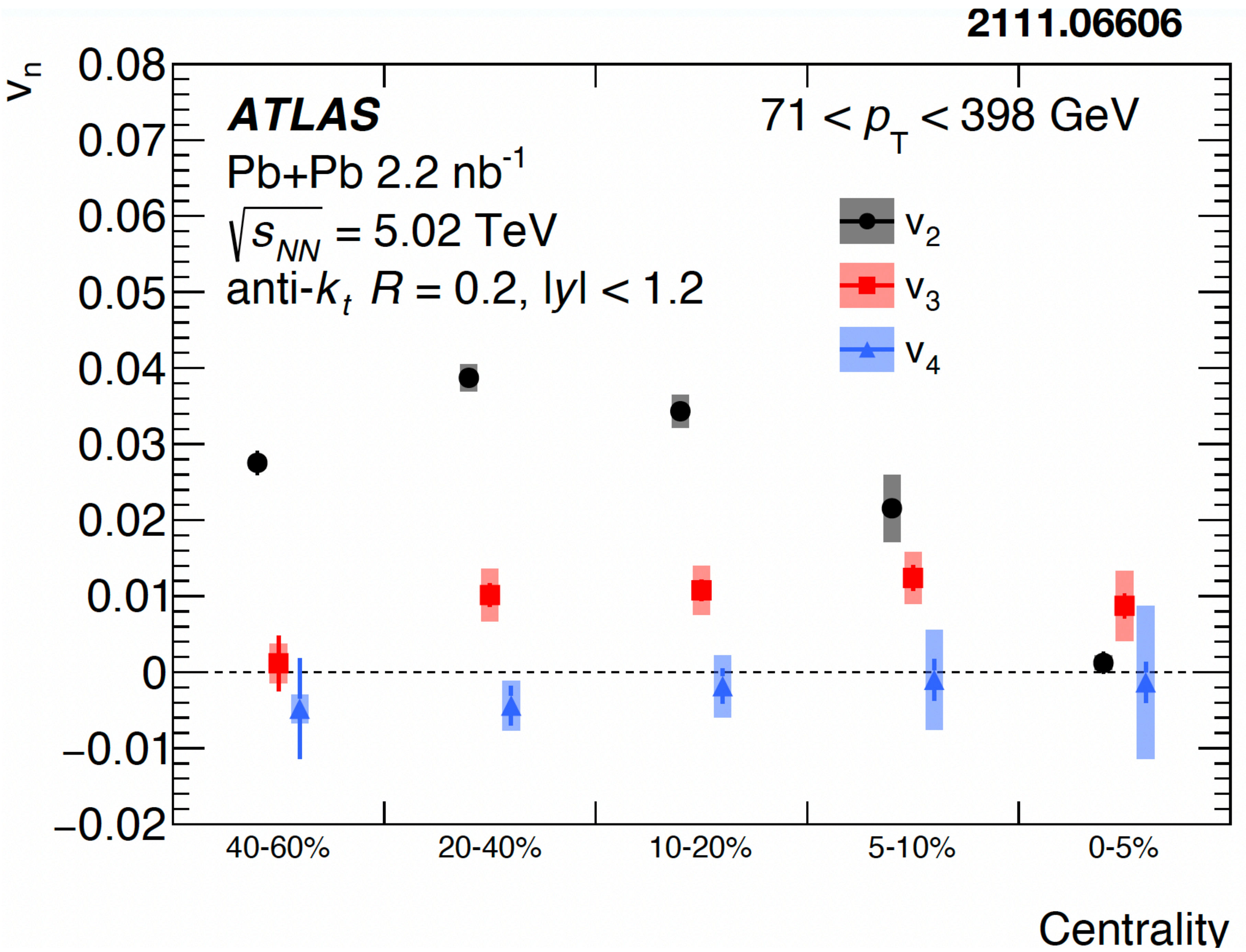
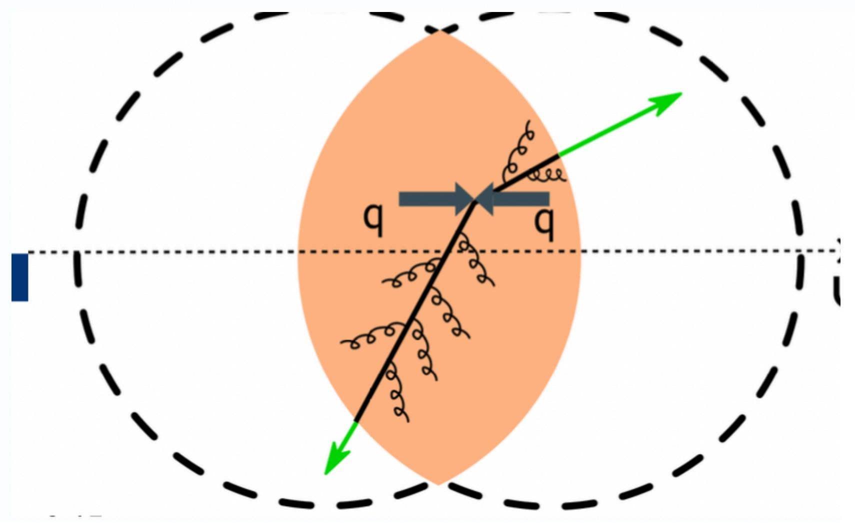


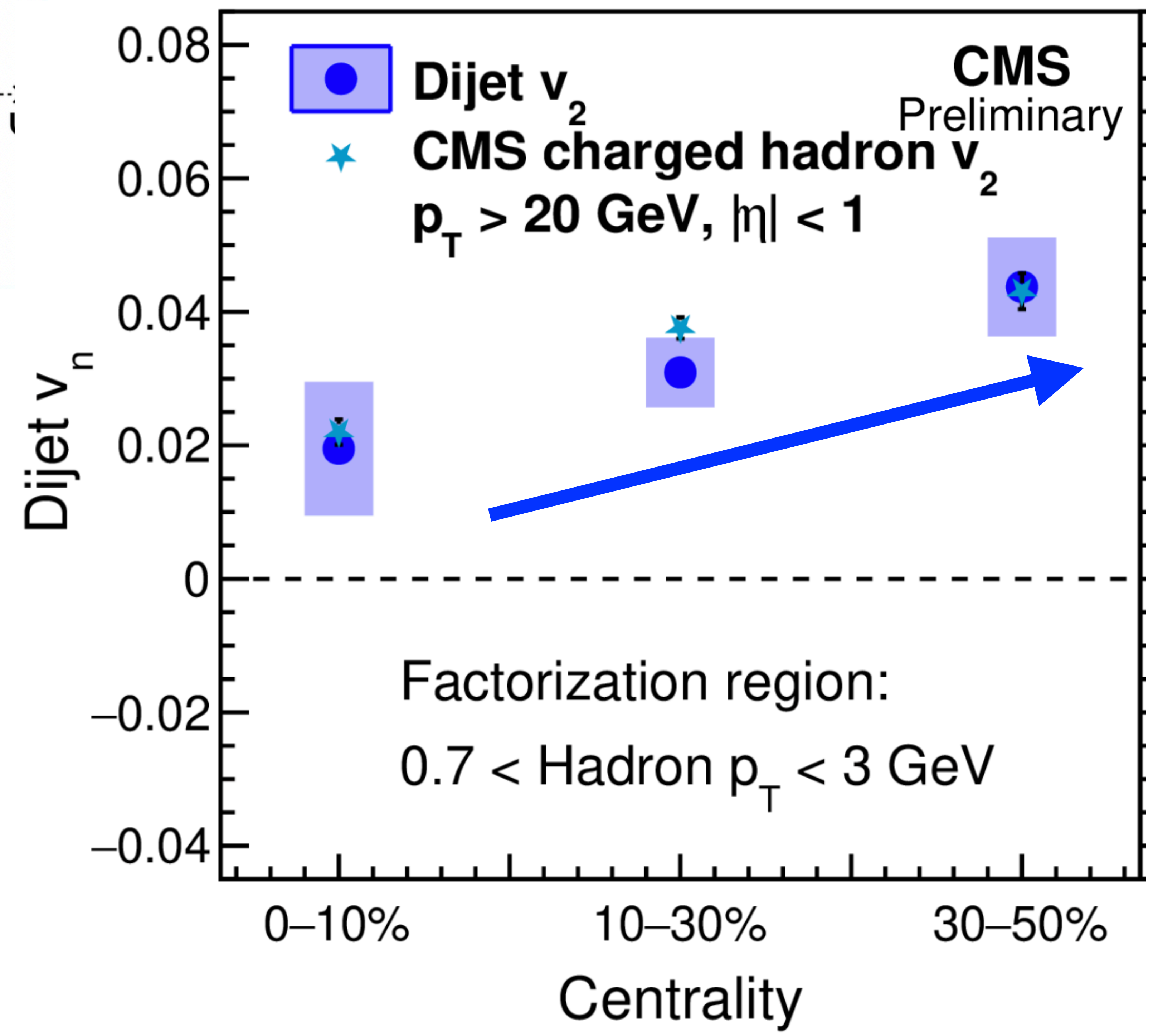


- Measuring jet rates as a function of event plane is sensitive to path length dependence of jet energy loss
- Centrality dependence of positive inclusive jet v_2 & v_3 is observed, similar to hydrodynamic v_n which is driven by initial geometry
  - suggesting same geometry plays significant role in jet quenching

Path length dependence of jet energy loss



CMS-HIN-21-002



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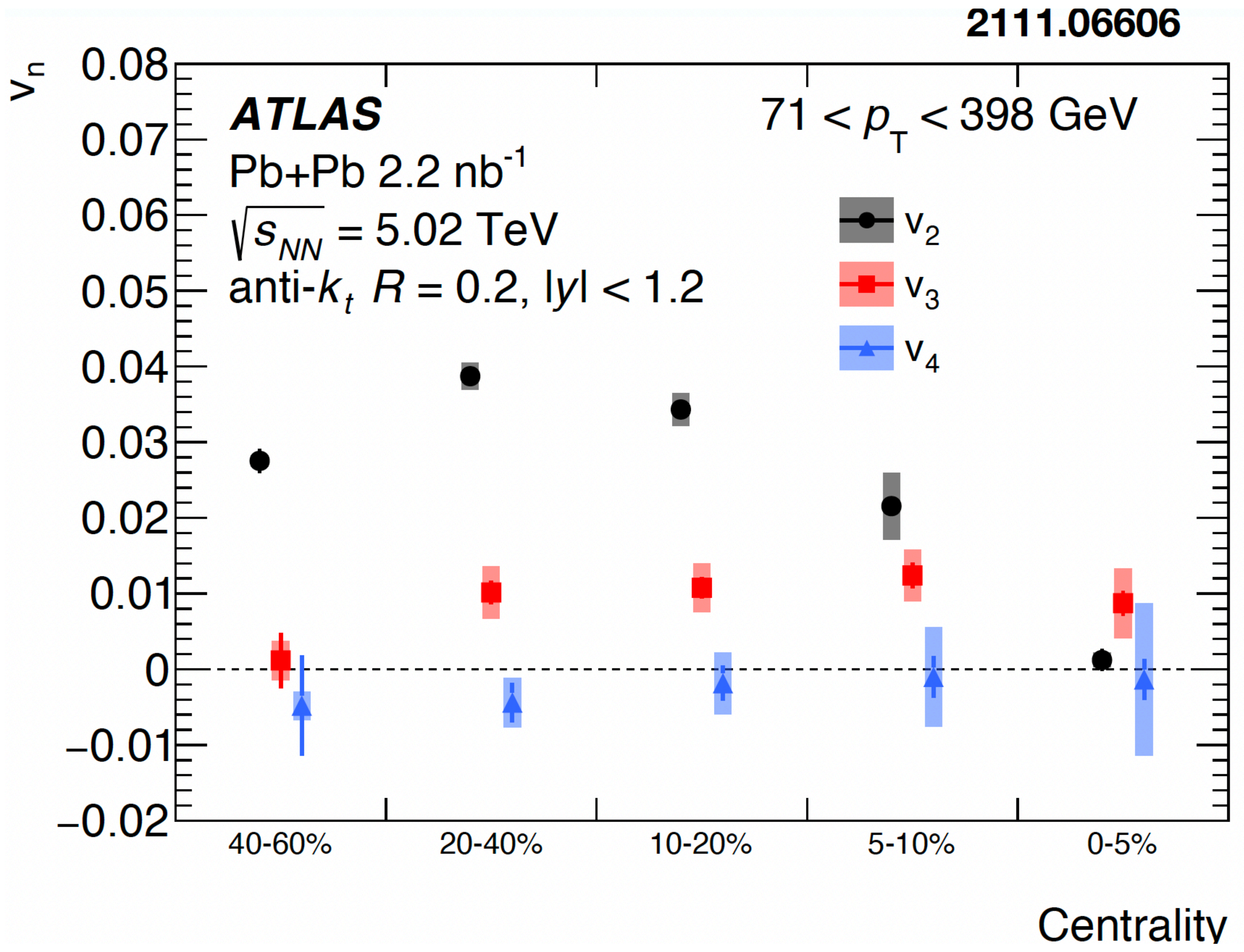

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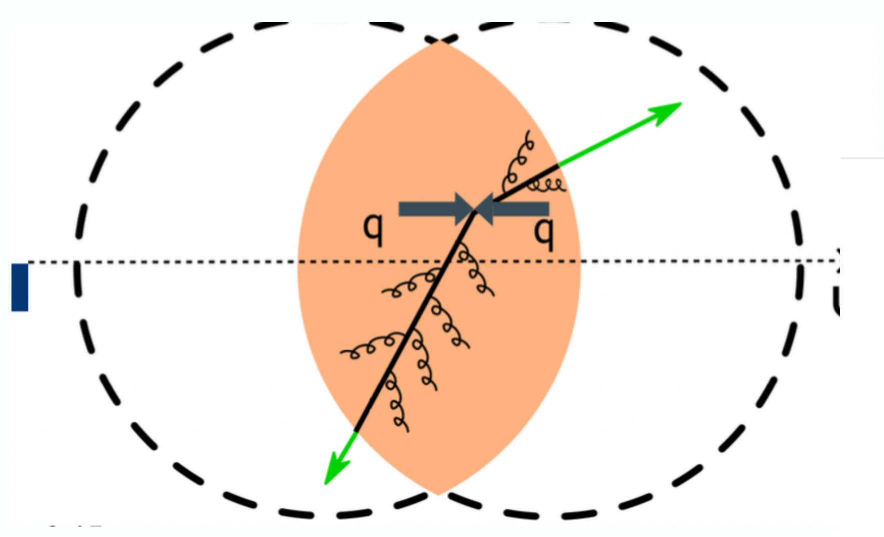
- Centrality dependence of positive inclusive jet v_2 & v_3 is observed, similar to hydrodynamic v_n which is driven by initial geometry
  - suggesting same geometry plays significant role in jet quenching
- CMS dijet v_2 is consistent with ATLAS inclusive jet v_2, compatible with high p_T charged particles v_2

Path length dependence of jet energy loss



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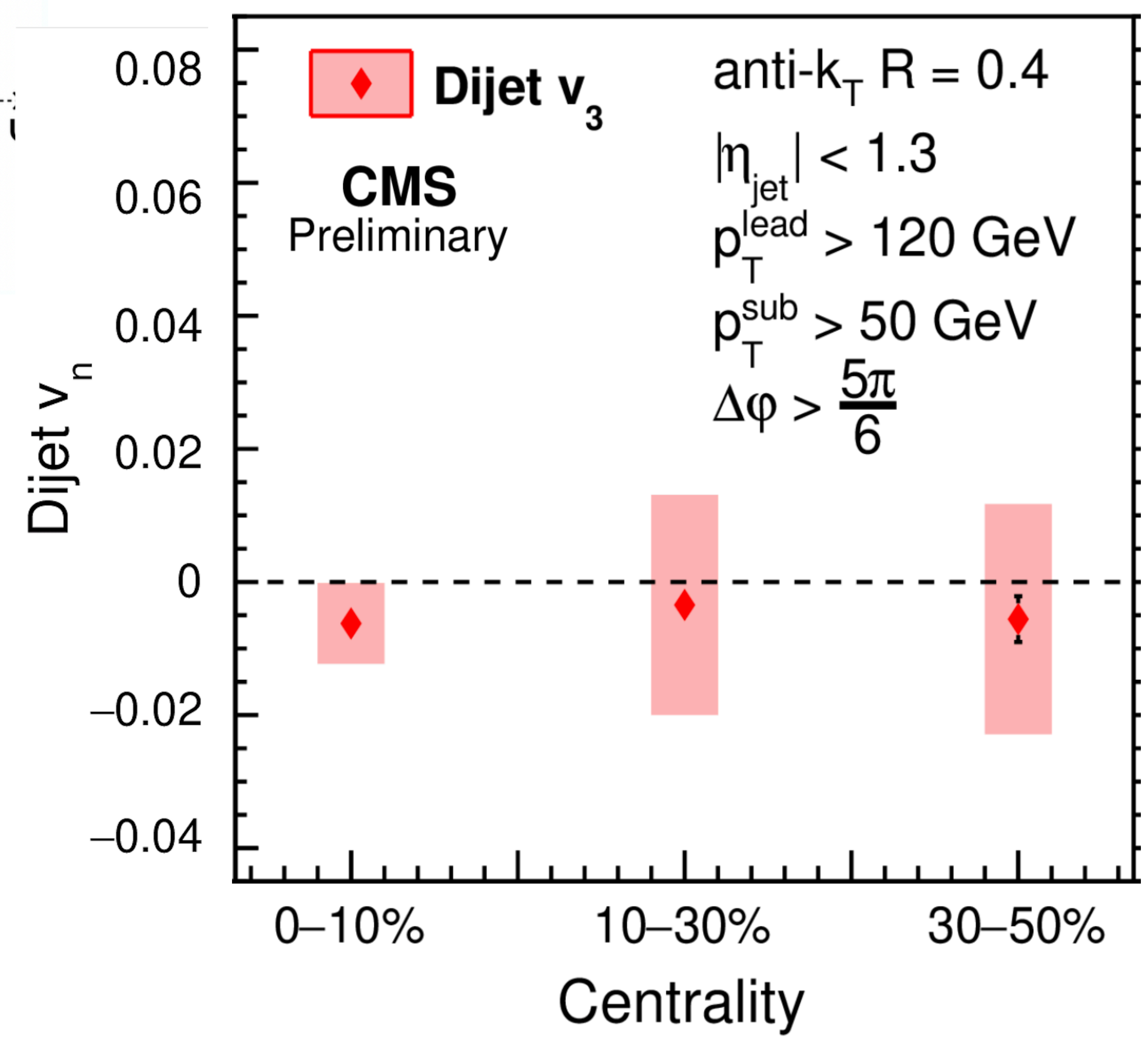

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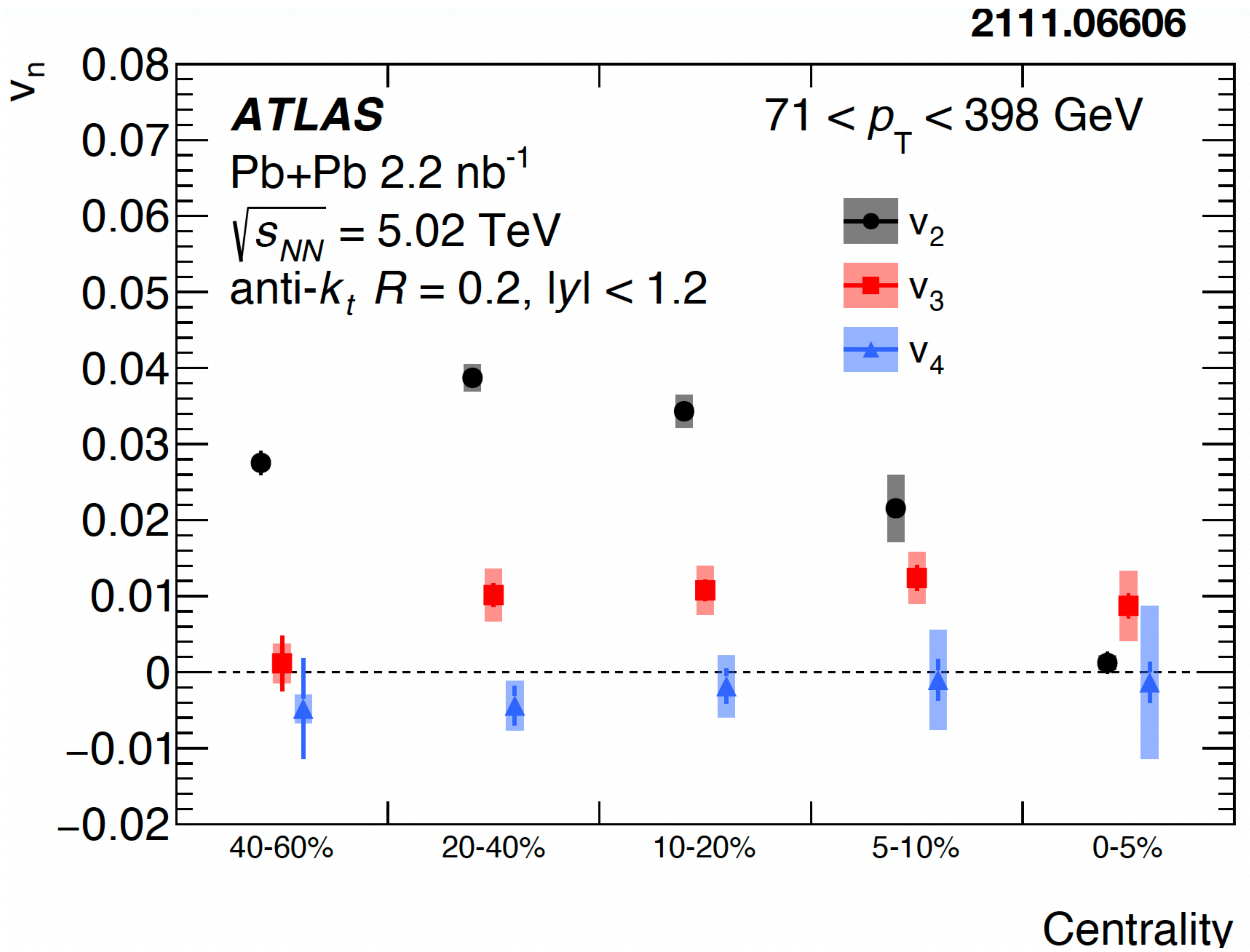
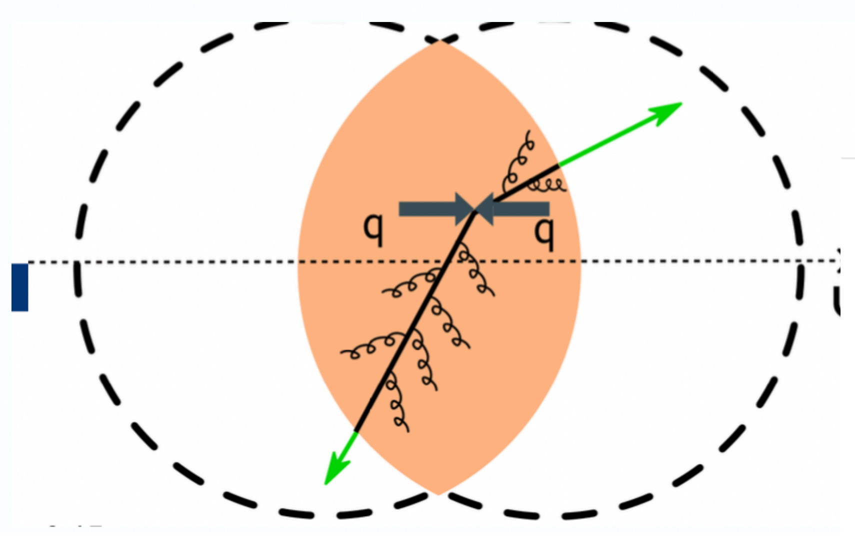
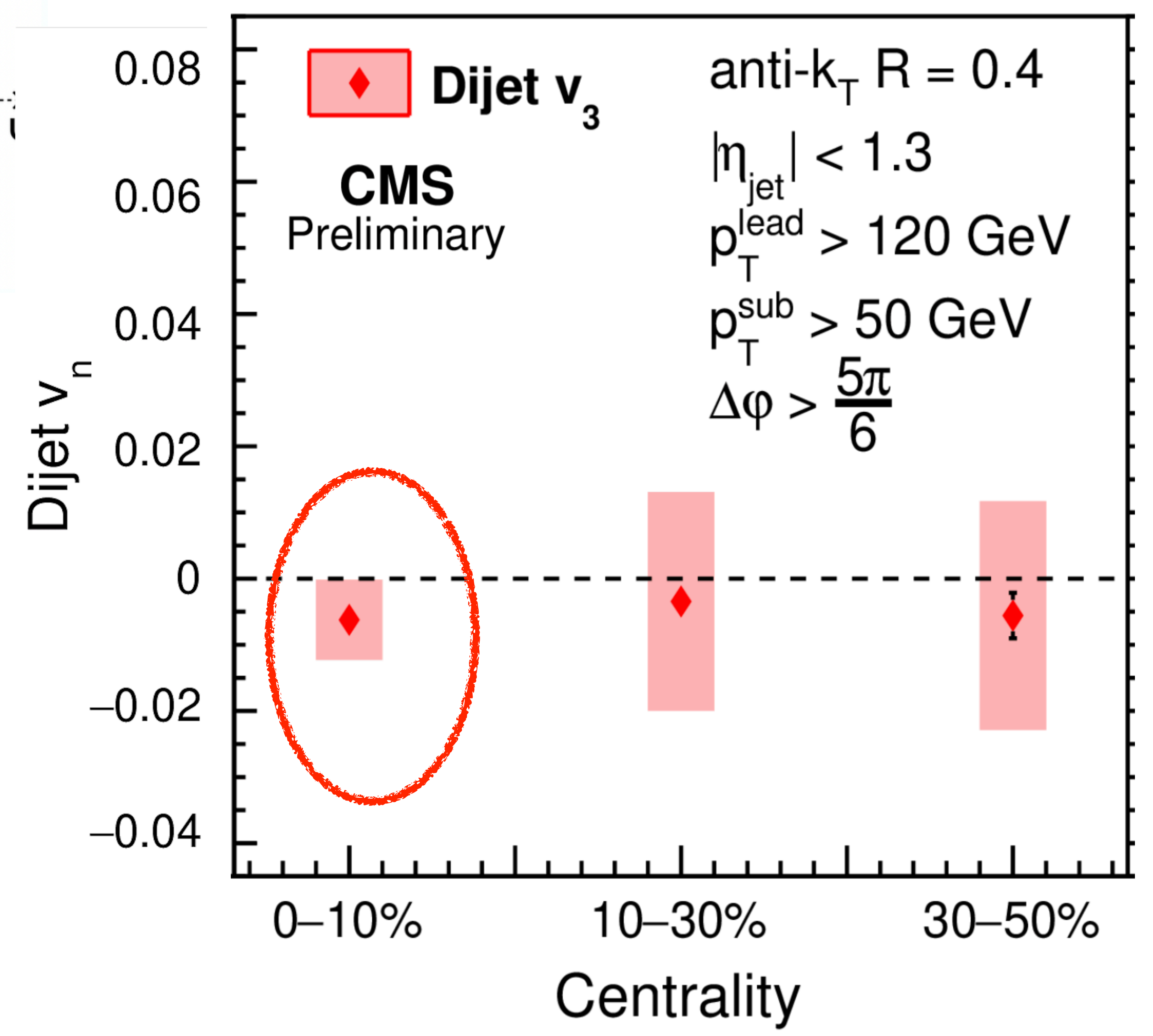


- Measuring jet rates as a function of event plane is sensitive to path length dependence of jet energy loss
- CMS dijet v_3 is consistent with zero, different from ATLAS inclusive jet v_3

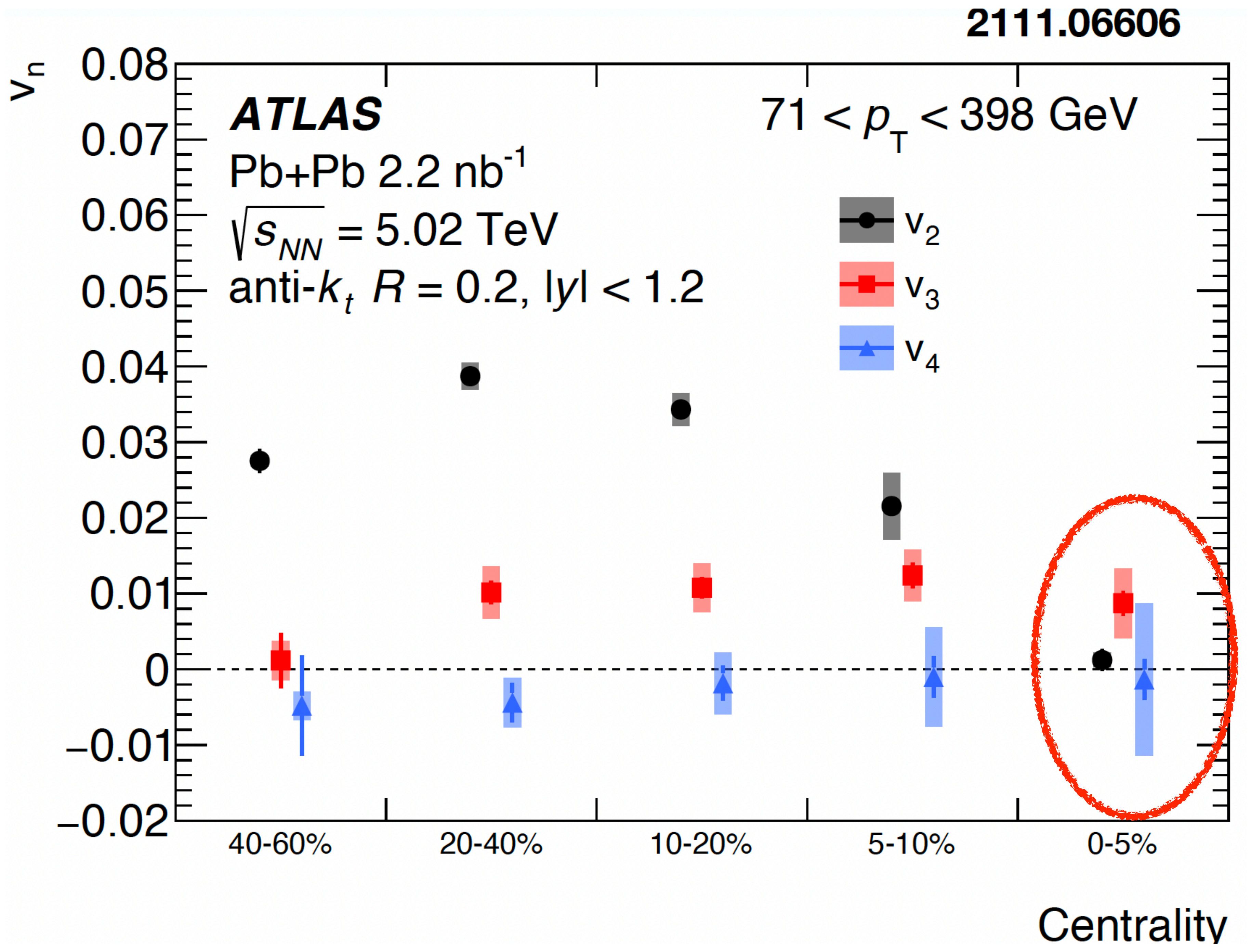
Path length dependence of jet energy loss



CMS-HIN-21-002

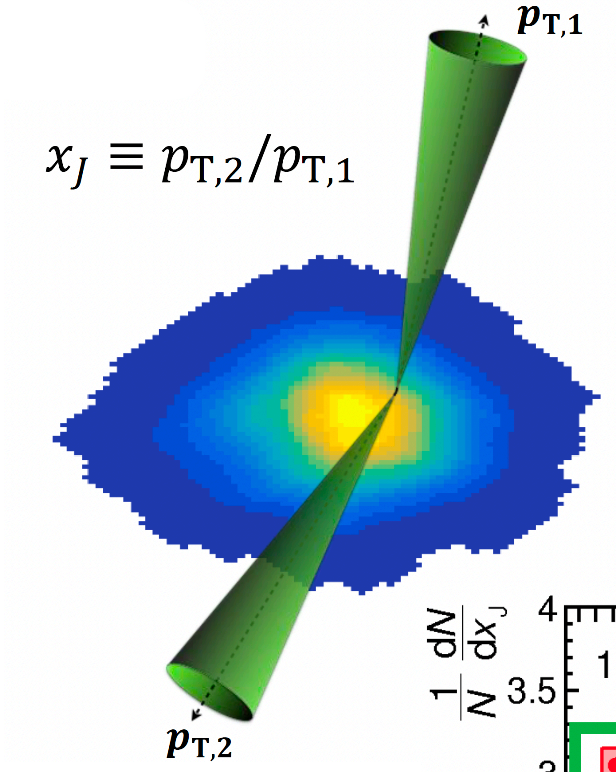


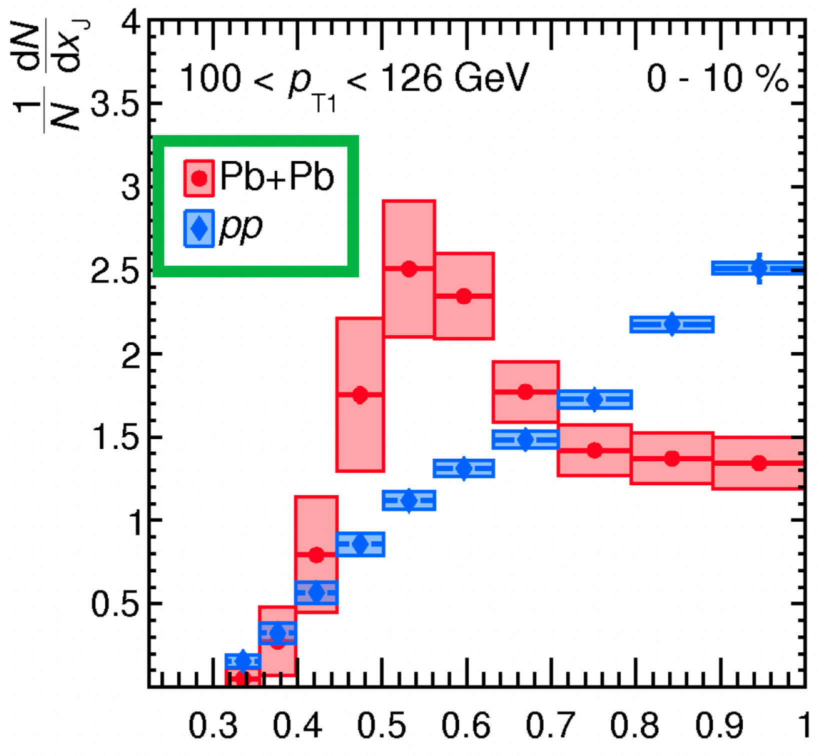
arXiv:2111.06606



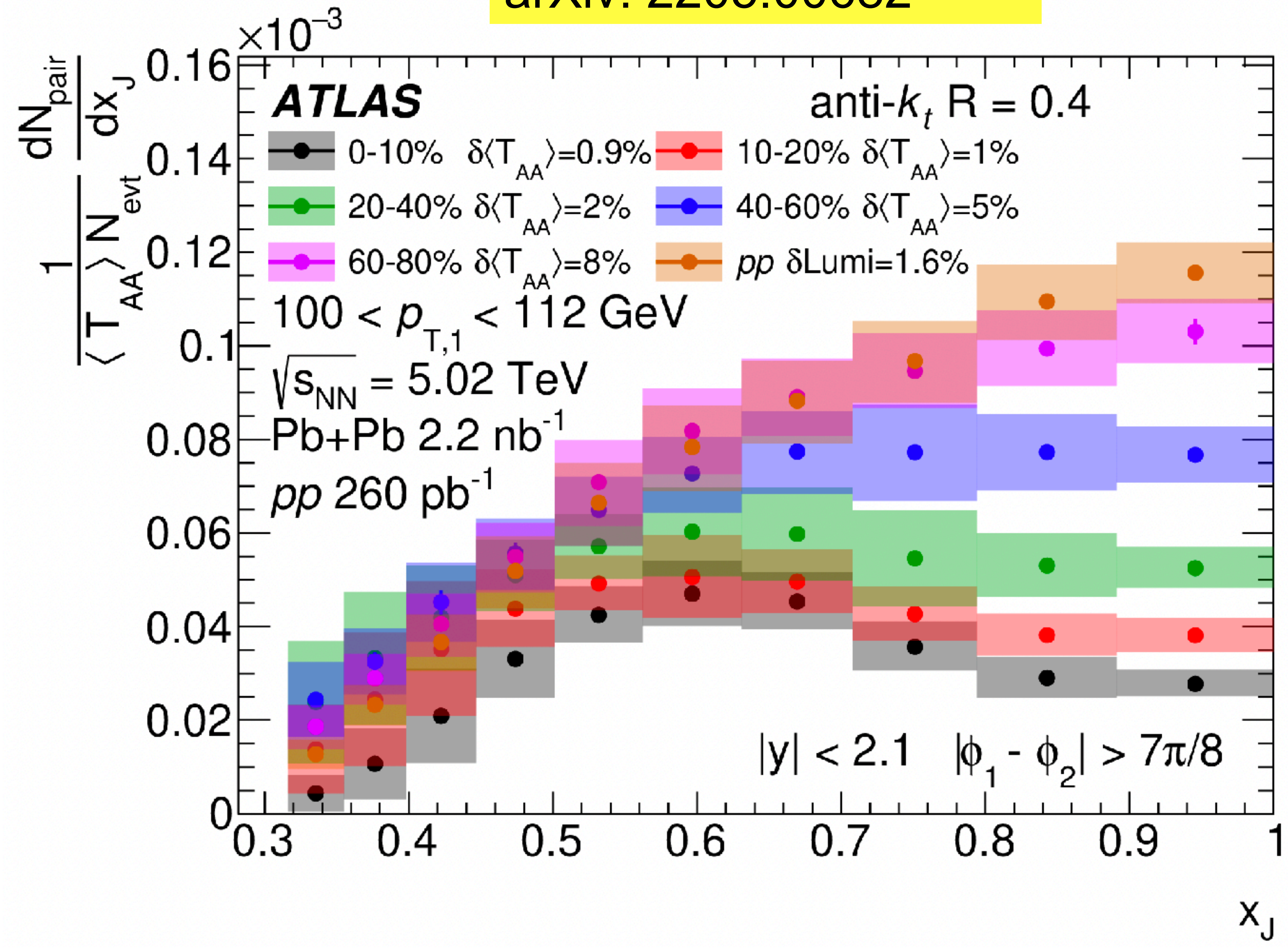
- Measuring jet rates as a function of event plane is sensitive to path length dependence of jet energy loss
- CMS dijet v_3 is consistent with zero, different from ATLAS inclusive jet v_3
  - suggesting different sensitivity to medium density fluctuations?

Path length dependence of jet energy loss



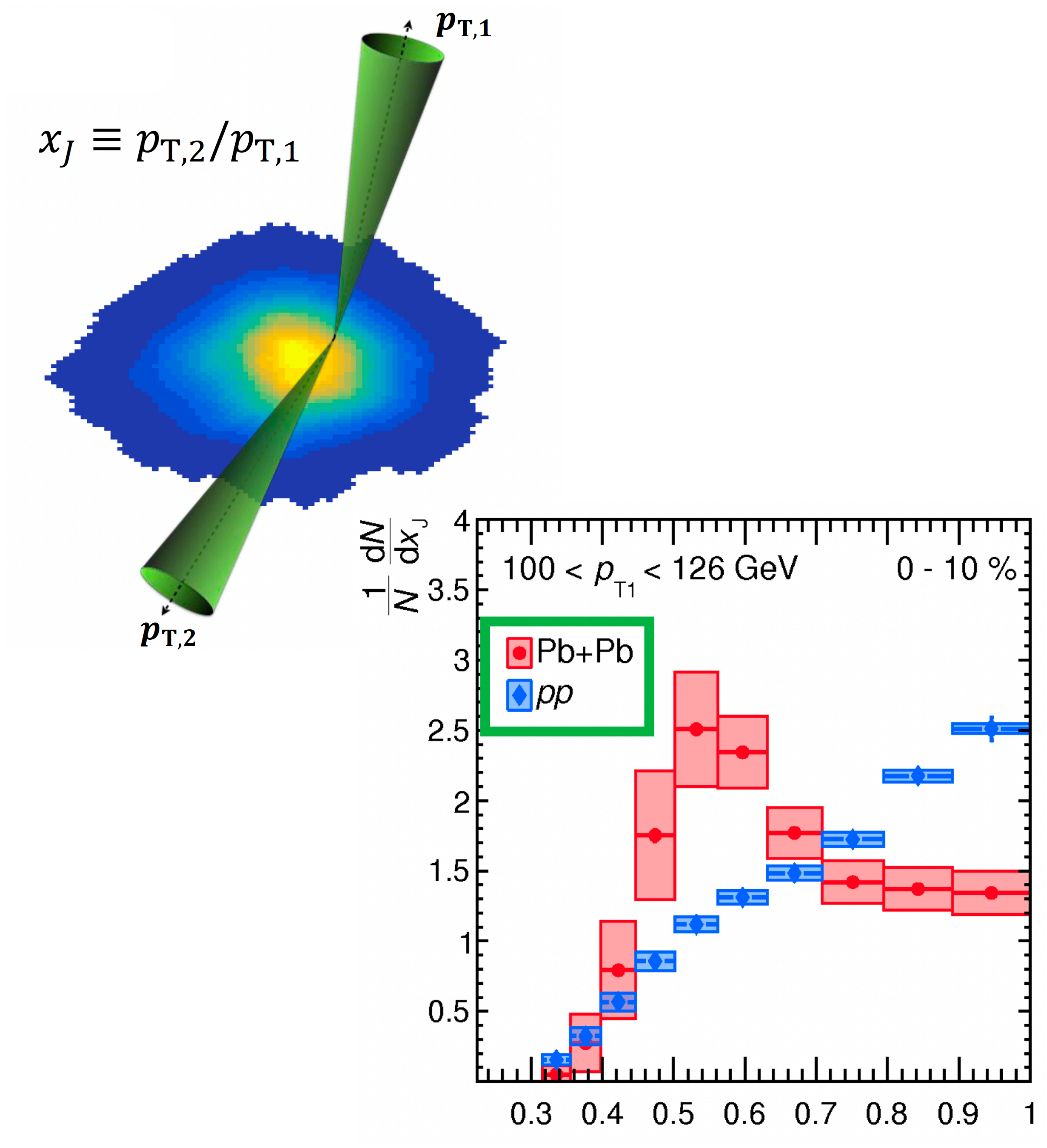


arXiv: 2205.00682

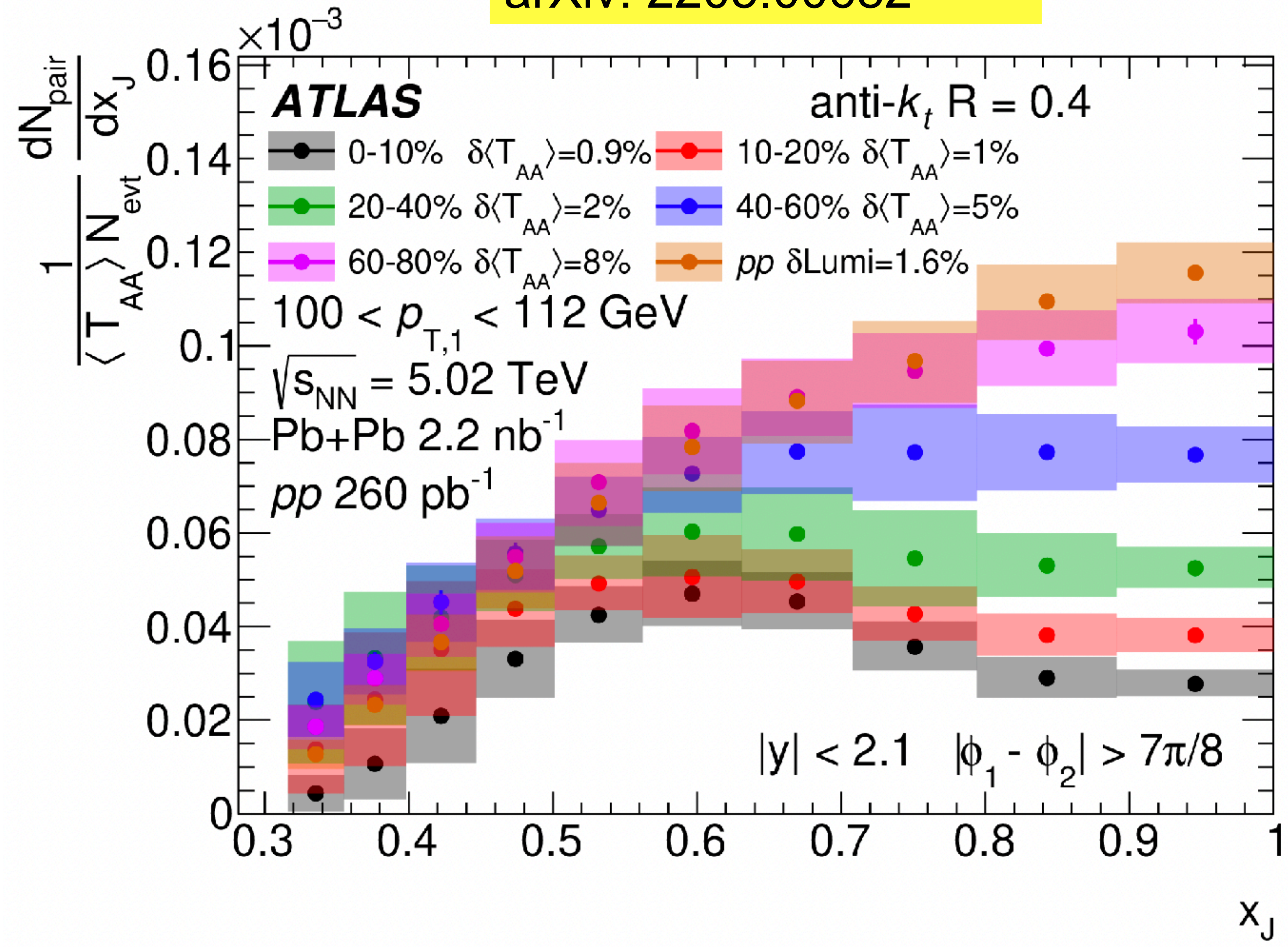


- Back-to-back jet pairs provide access to asymmetric energy loss due to unequal path lengths in QGP
- A peak structure observed at intermediate x_J indicates the suppression of symmetric dijets

Path length dependence of jet energy loss



arXiv: 2205.00682



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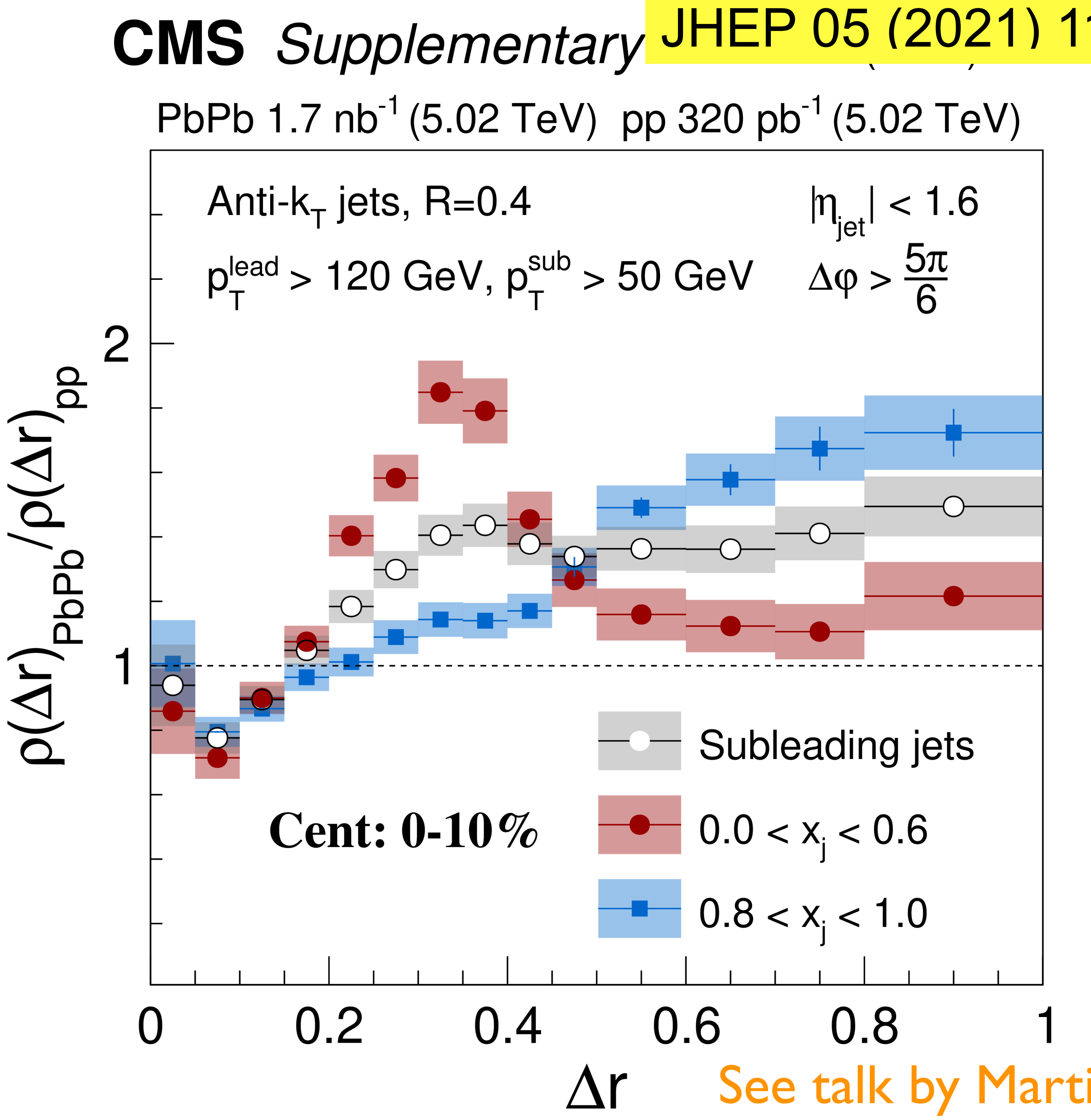
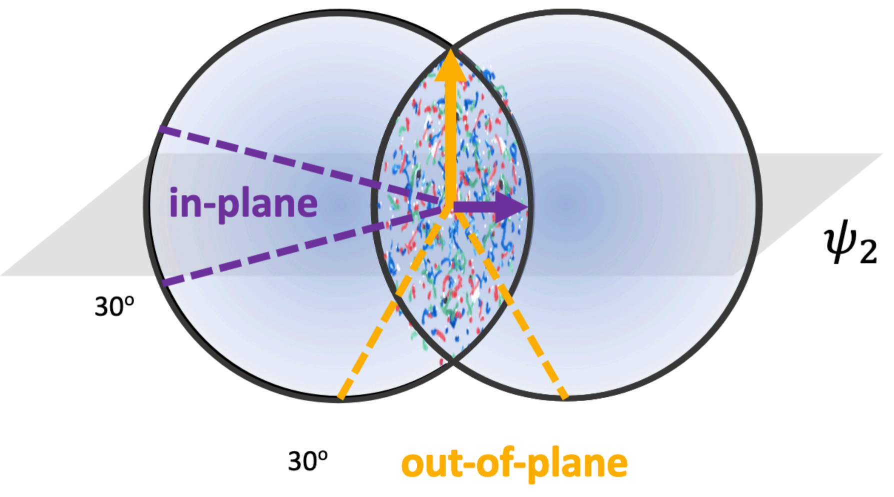


See talk by Martin Rybar

- Back-to-back jet pairs provide access to asymmetric energy loss due to unequal path lengths in QGP
- A peak structure observed at intermediate x_J indicates the suppression of symmetric dijets
- Similar observation for jet shapes measurements in CMS using dijets events
  - subleading jets from asymmetric dijet selection (larger traversing path in QGP) are more quenched

Path length dependence of jet energy loss

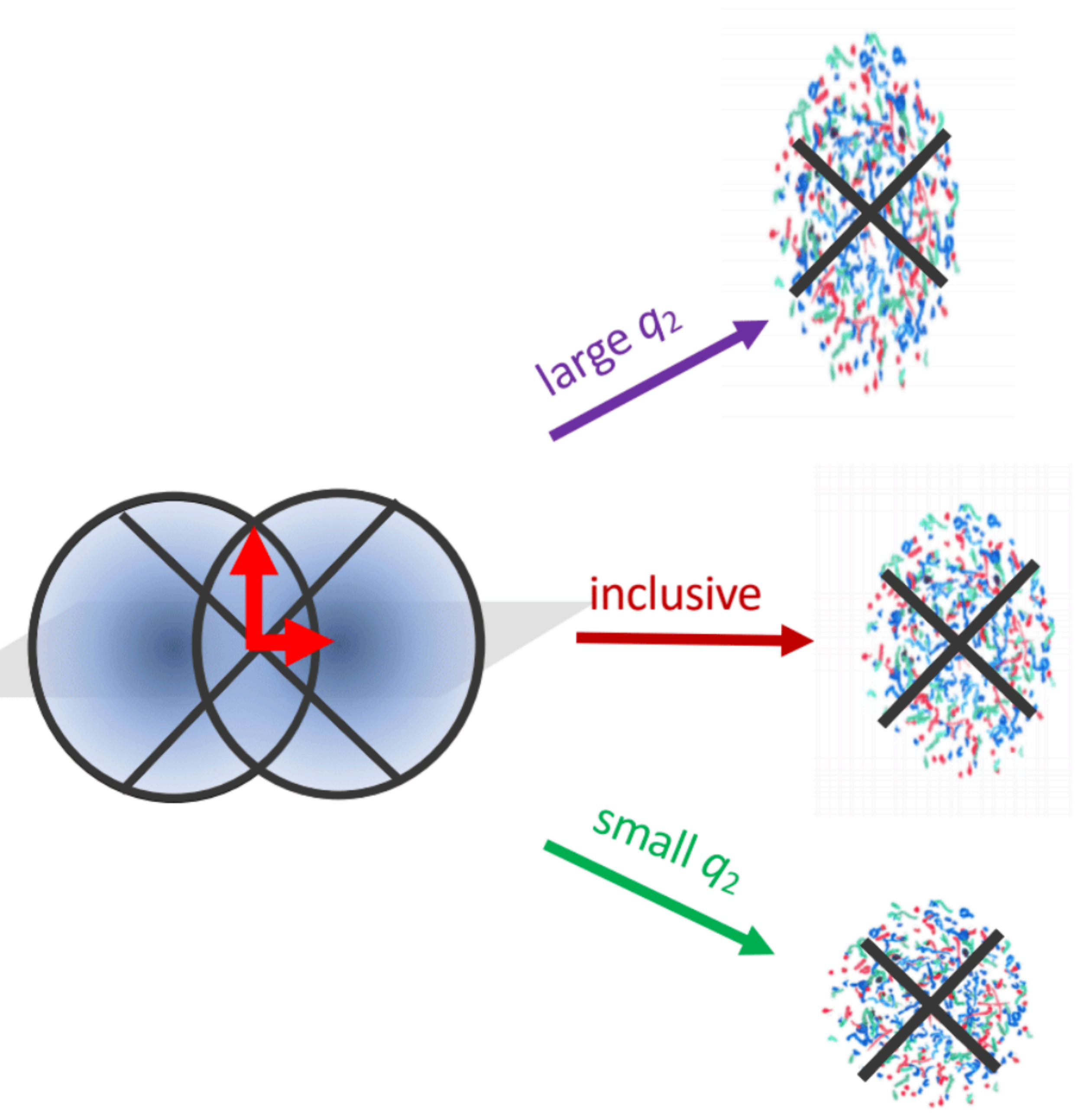


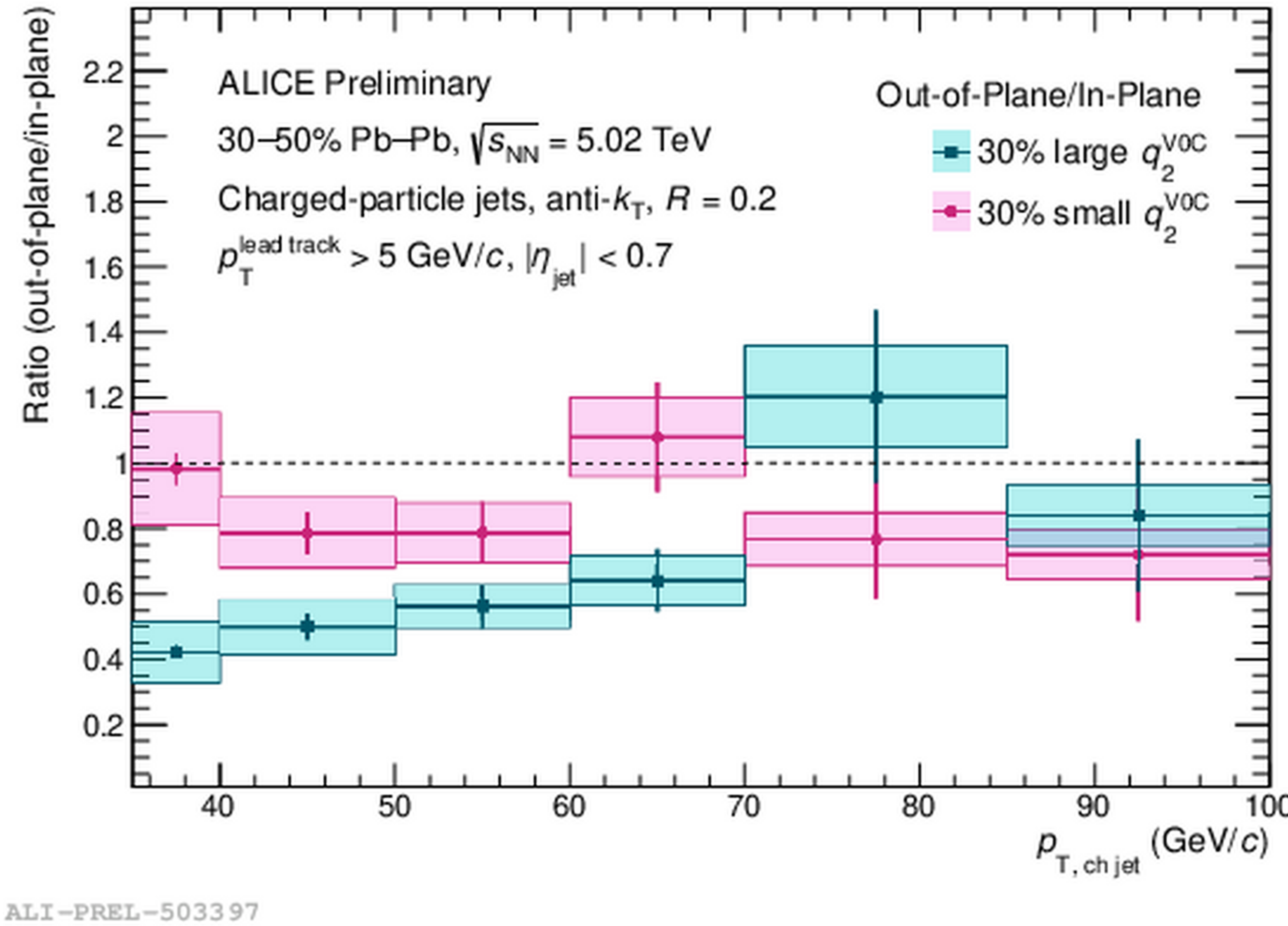
M = multiplicity

$$q_2 = |\mathbf{Q}_2|/\sqrt{M}$$

$$\mathbf{Q}_2 = \left(\sum_{i=1}^{M}\cos(2\varphi_i), \sum_{i=1}^{M}\sin(2\varphi_i)\right)$$

φ_i = azimuthal angle of i[th] particle





- Selecting specific event shapes according to their anisotropy (q_2) allows to maximize in plane and out of plane path length differences
- More suppressed jet yield ratio of out-of-plane relative to in-plane for larger q_2 events
  - consistent with stronger suppression along the out-of-plane axis

Summary

- Large number of jet results based on full Run 2 LHC data sample
  - More precision, extending to low p_{T}/large R, more differential, new analysis
- Detailed insights on the QGP properties
  - Color and mass dependent jet energy loss observation
  - Path length dependent jet quenching
  - First evidence of the broadening of the γ-jet and h-jet azimuthal correlations for very soft jets
- Plenty of encouraging and interesting new theoretical/experimental developments with nice results

Enjoy the conference and talks!

Thanks for your attention!

The 10th annual Large Hadron Collider Physics conference

R-dependence of the R_{AA}

→ *R*-dependence of the R_{AA} is another way to disentangle energy loss mechanisms.

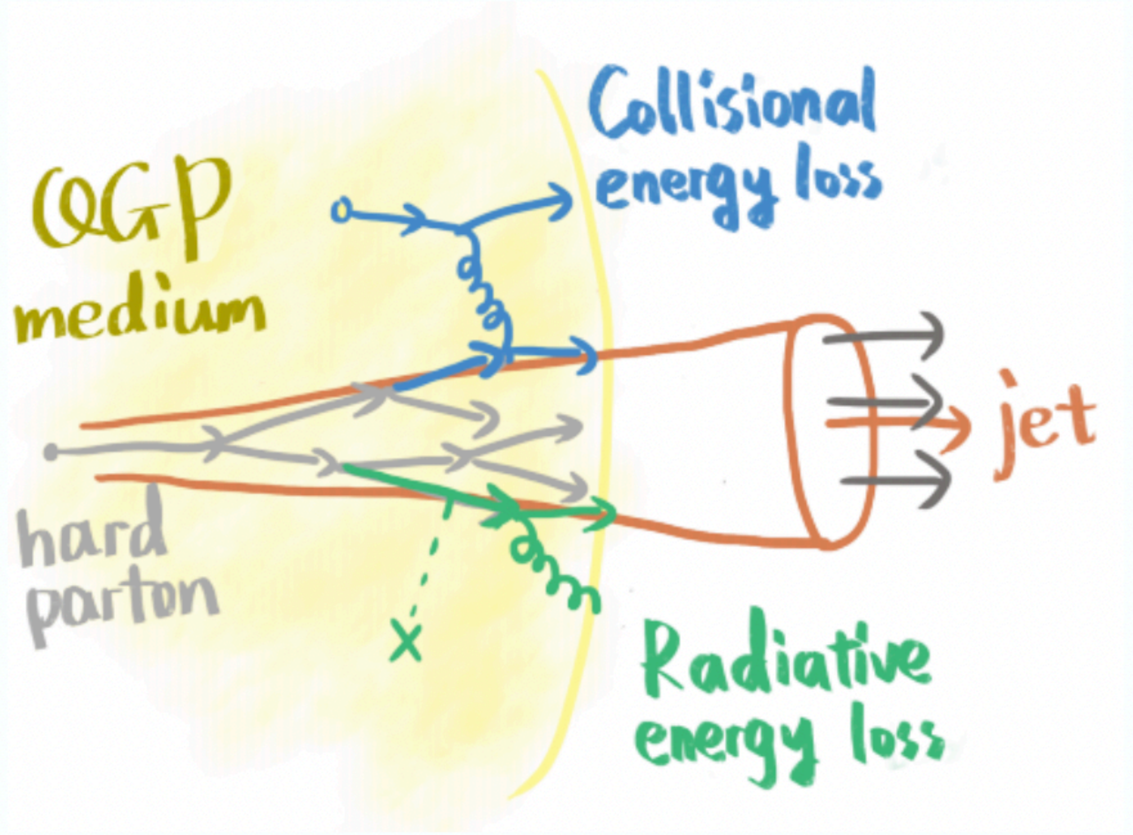
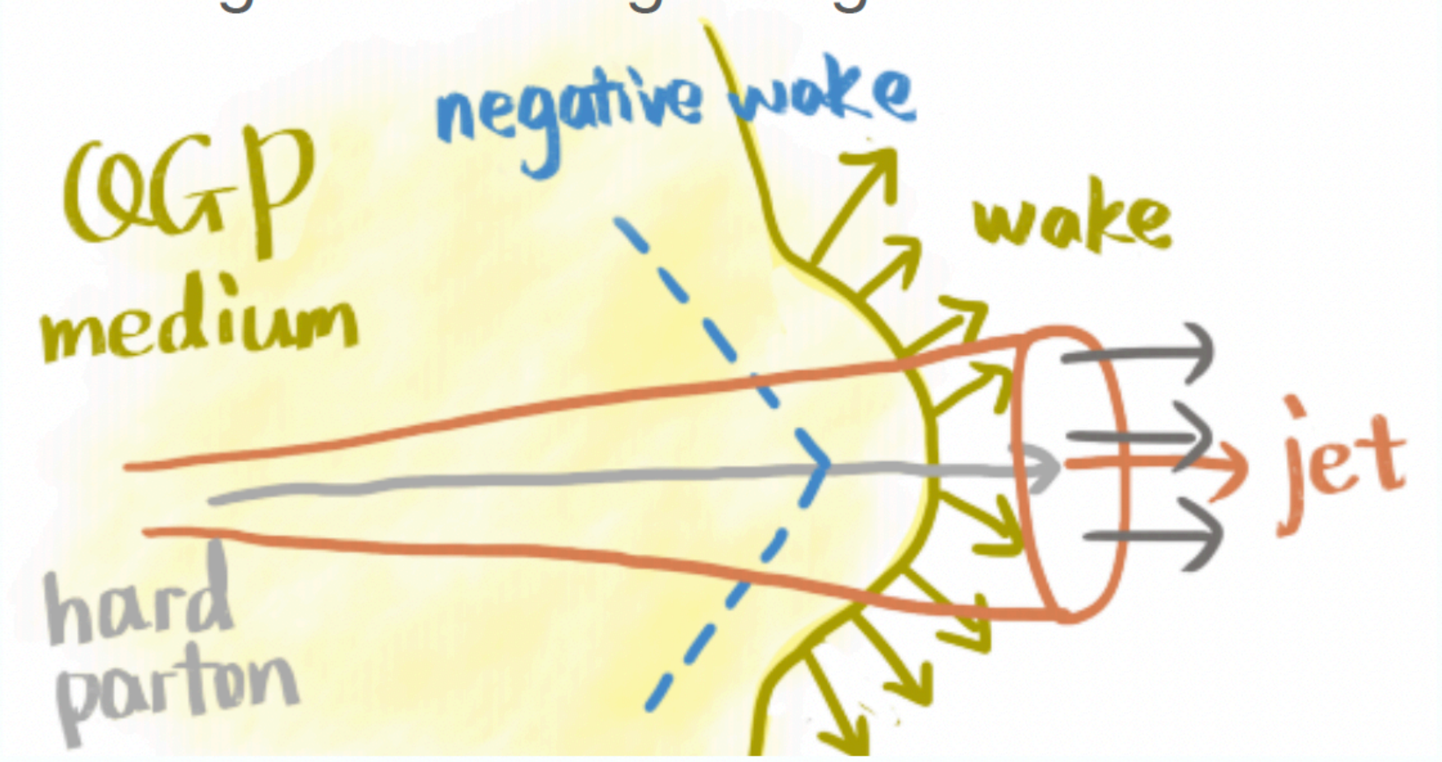


Image Credit:Jing Wang



→ Recovery of wide angle radiation $R_{AA} \nearrow$

→ Medium response adds energy to the jet cone $R_{AA} \nearrow$

→ Large *R* jets have more effective energy loss sources, therefore could experience more quenching. $R_{AA} \searrow$

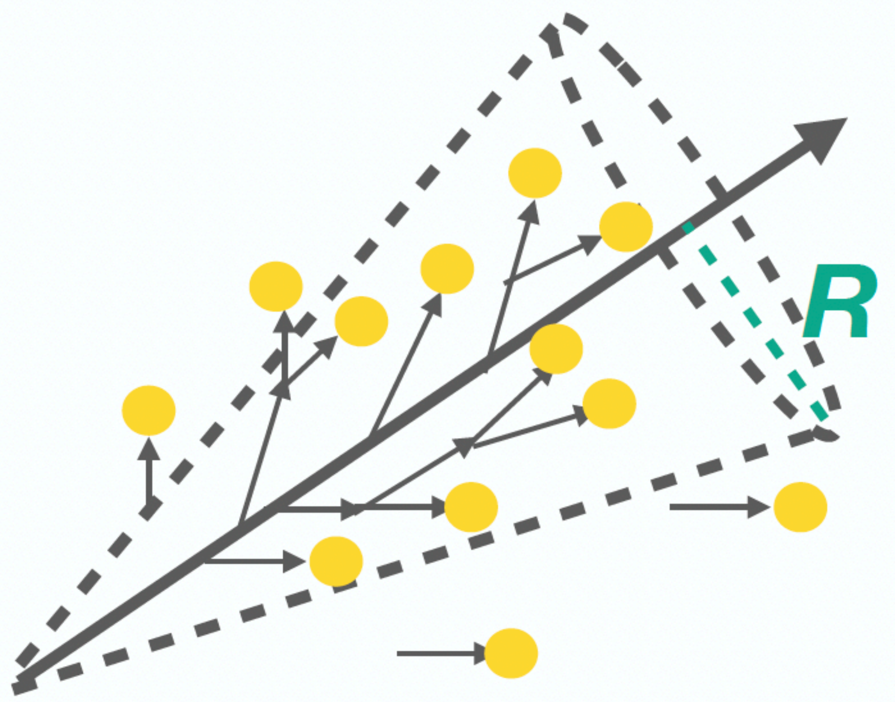
→ Increase gluon to quark ratio at fixed p_T, gluons lose more energy $R_{AA} \searrow$

→ Inclusive jet measurements at large *R* and low p_T difficult due to the large fluctuating underlying event ($\propto R^2$)

ML-based background estimator

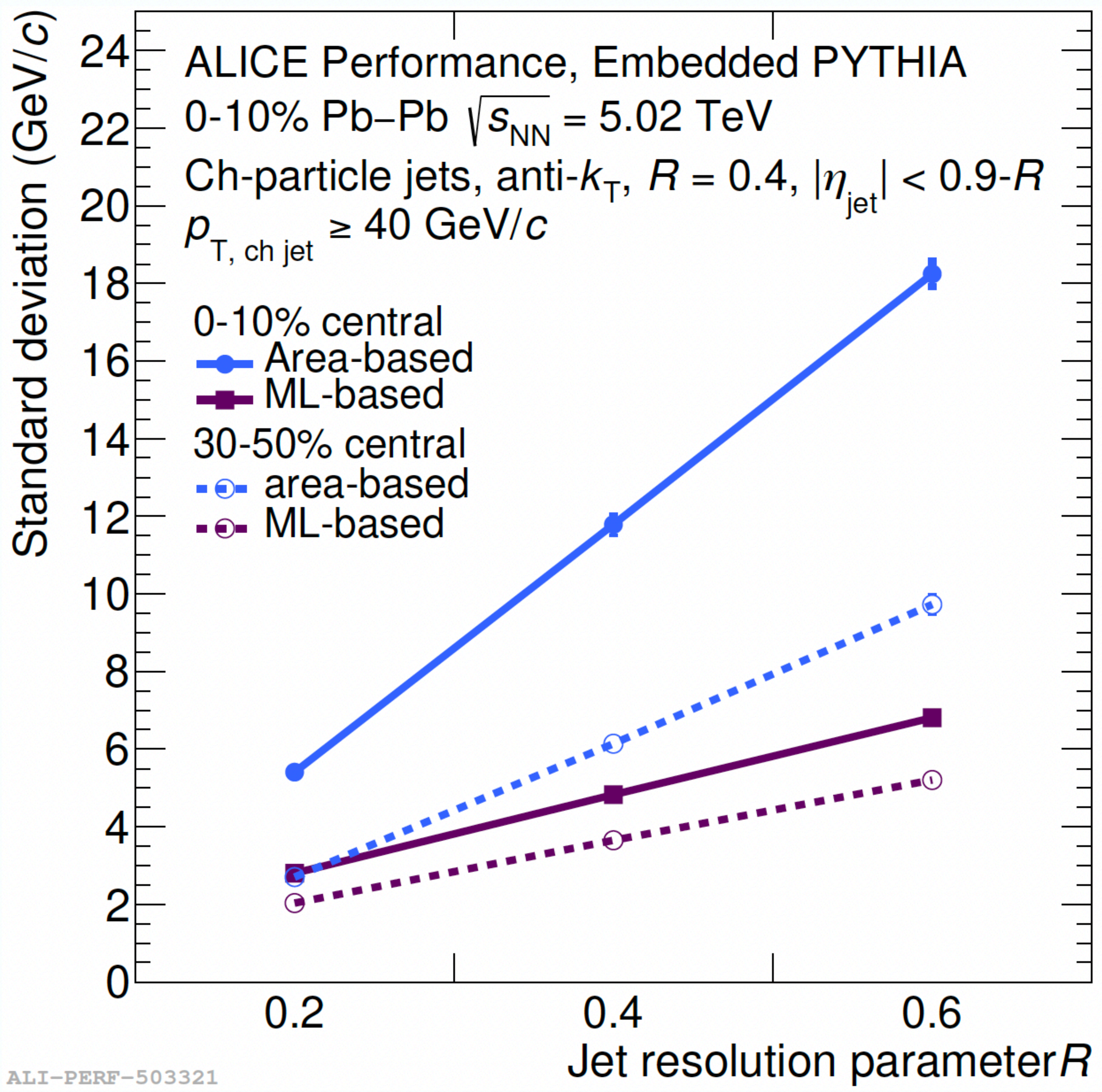
ALICE area-based approach: Correct the jet for the background with a pedestal subtraction. Apply a minimum p_T requirement on the leading track of the jet.

ML approach: Use ML to construct the mapping between measured and corrected jet without a leading track bias.



Fragmentation dependence introduced by learning on constituent information included as a systematic.

$$\delta p_T = p_{T,rec} - p_{T,true}$$



R.Haake, C. Loizides Phys. Rev. C 99, 064904 (2019)