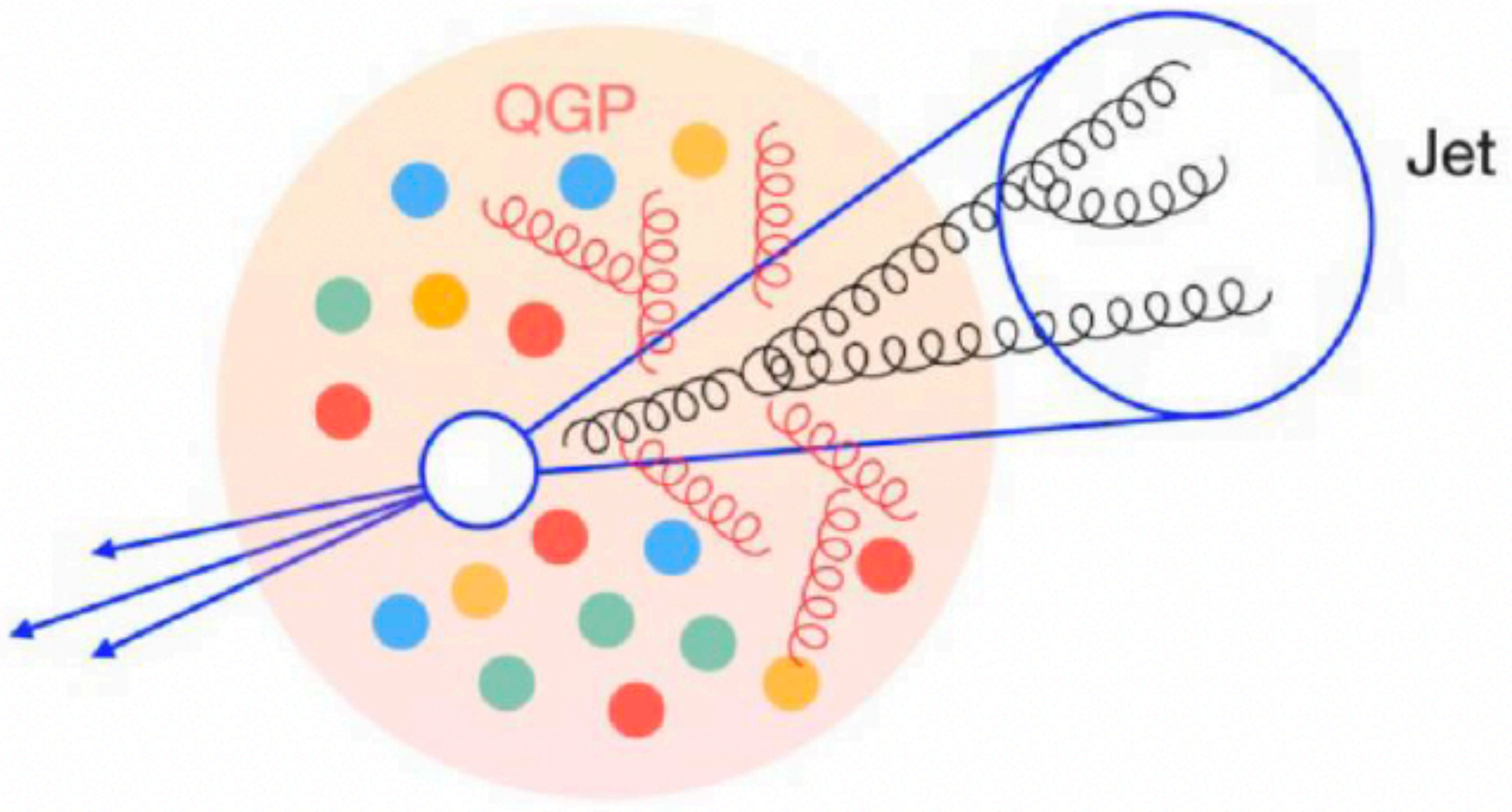
LHC能区喷注物理最新进展及未来展望



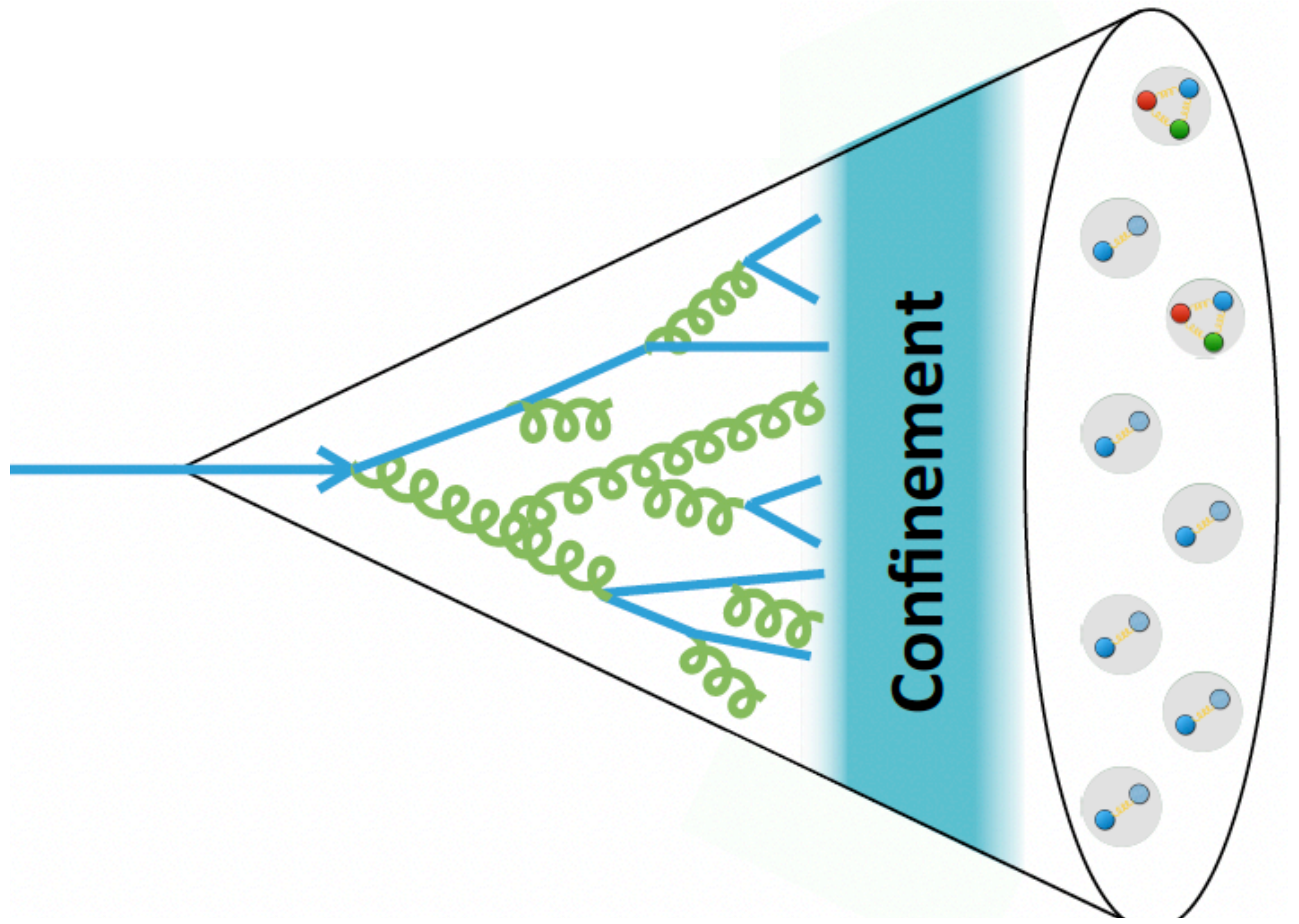
https://www.int.washington.edu/node/776

毛亚显 (Yaxian MAO)

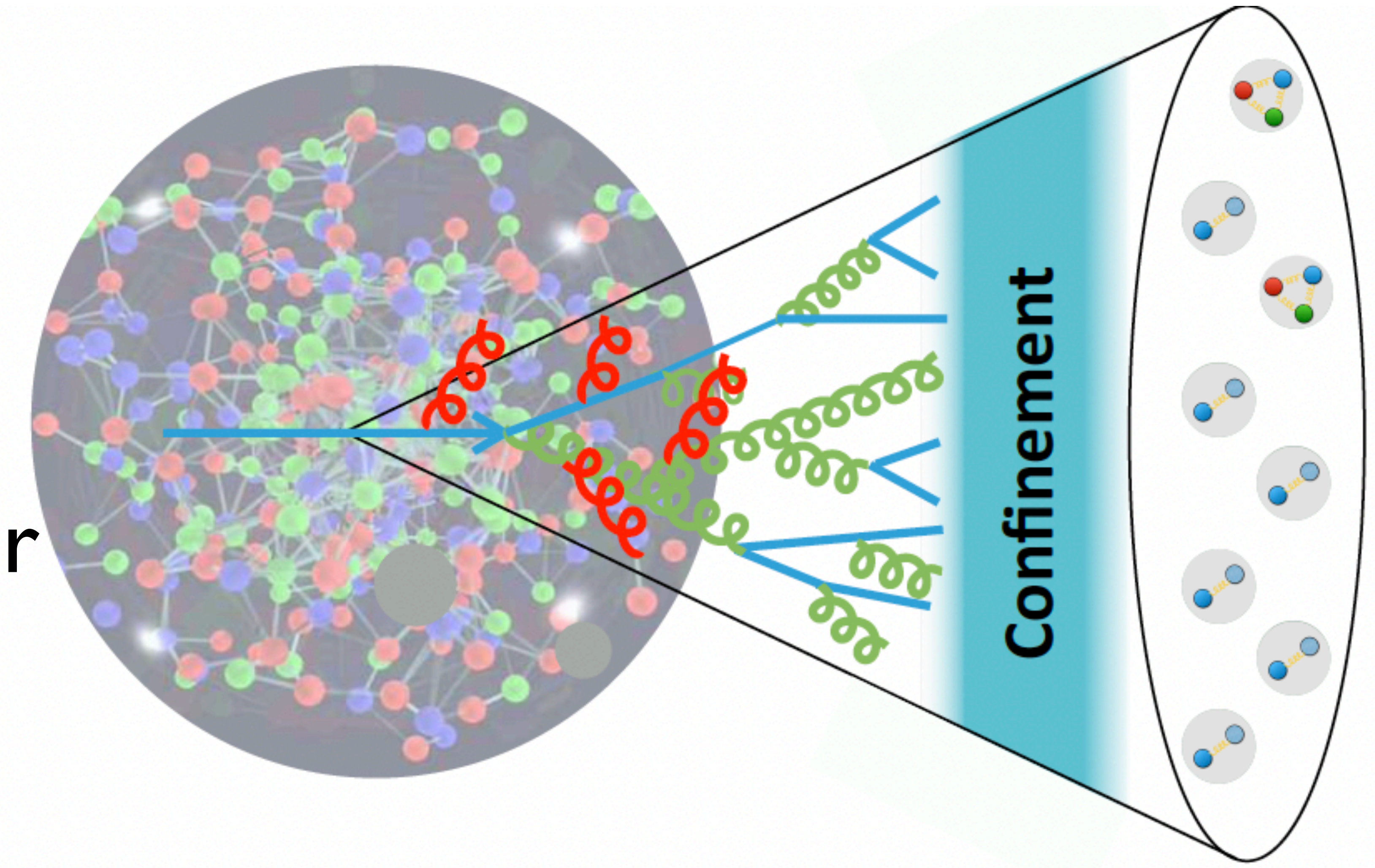
华中师范大学 (Central China Normal University)

Jet as object and probe

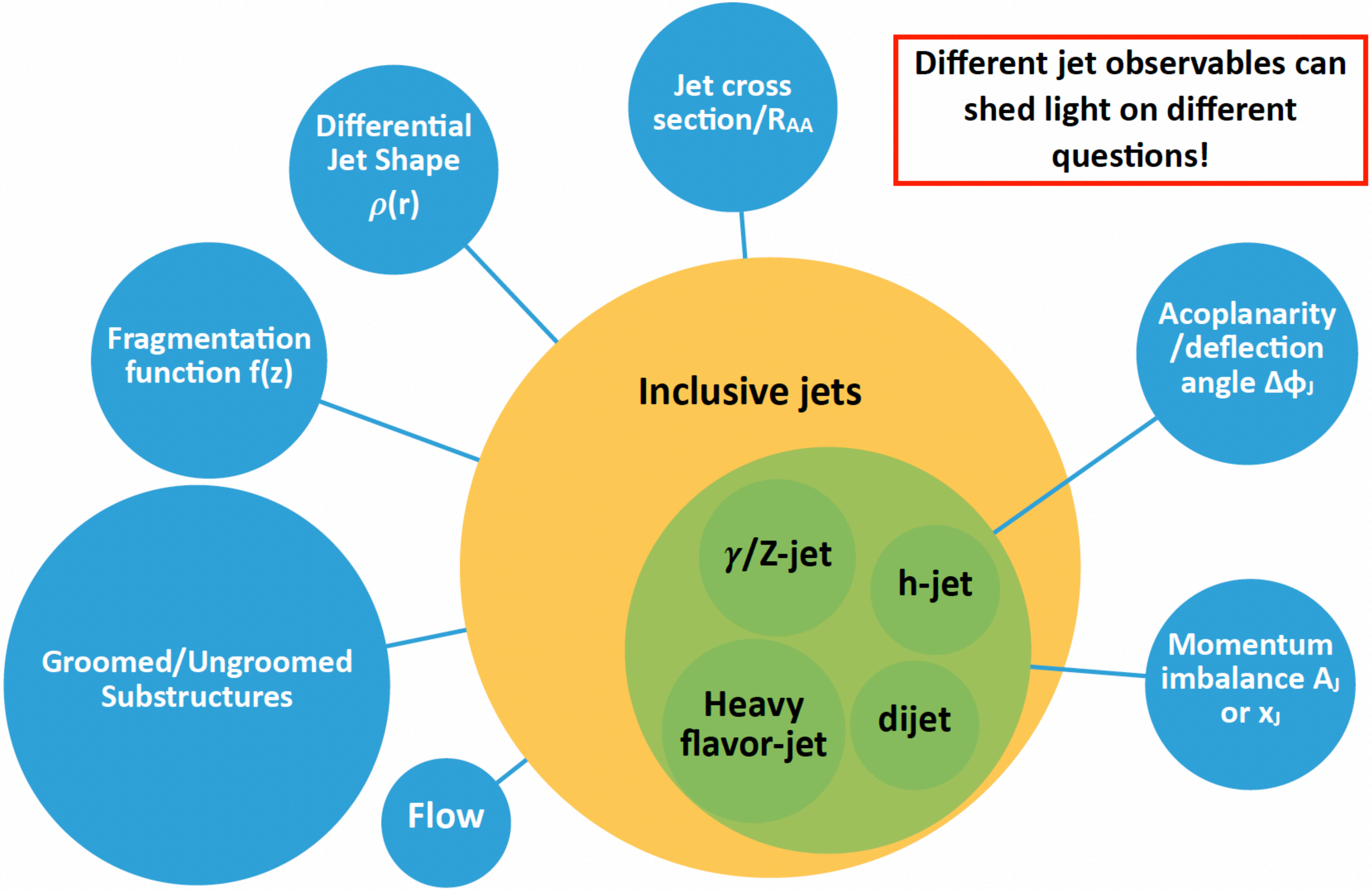
- p+p: precision study of the perturbative and non-perturbative (NP) aspects of QCD in vacuum
  - What can we learn about perturbative interactions between q/g?
  - What can we learn about the NP effects (hadronization)?
  - What is the role of color charge and mass?



- A+A: use the interplay between jet and the medium to probe the properties of QGP
  - How does the medium modifies the jet?
  - What is the path-length dependence? What is the role of parton color charge and mass?
  - properties of QGP: medium size, transport coefficient, coherence length, quasi-particles?

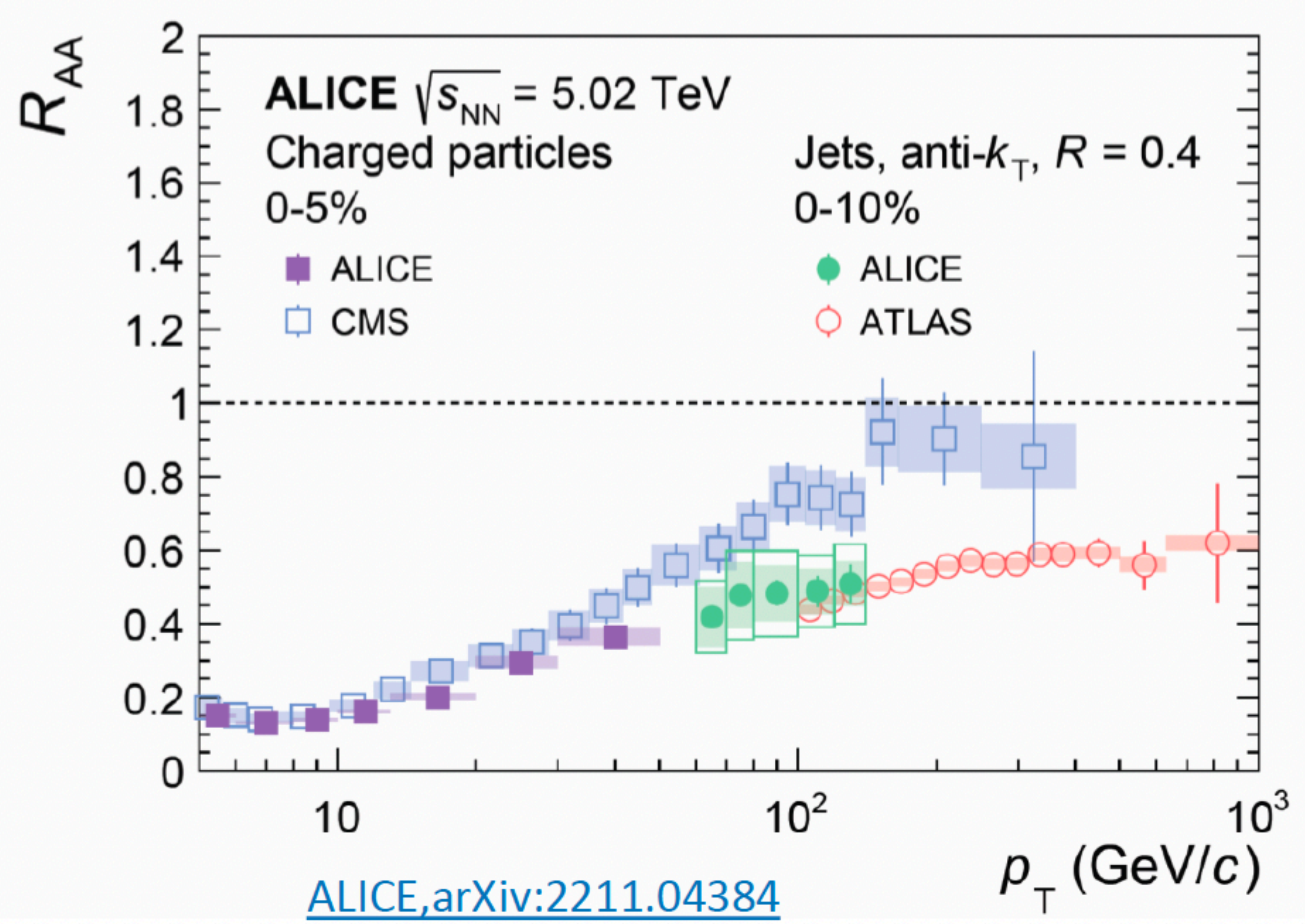


A (incomplete) roadmap of jet measurements

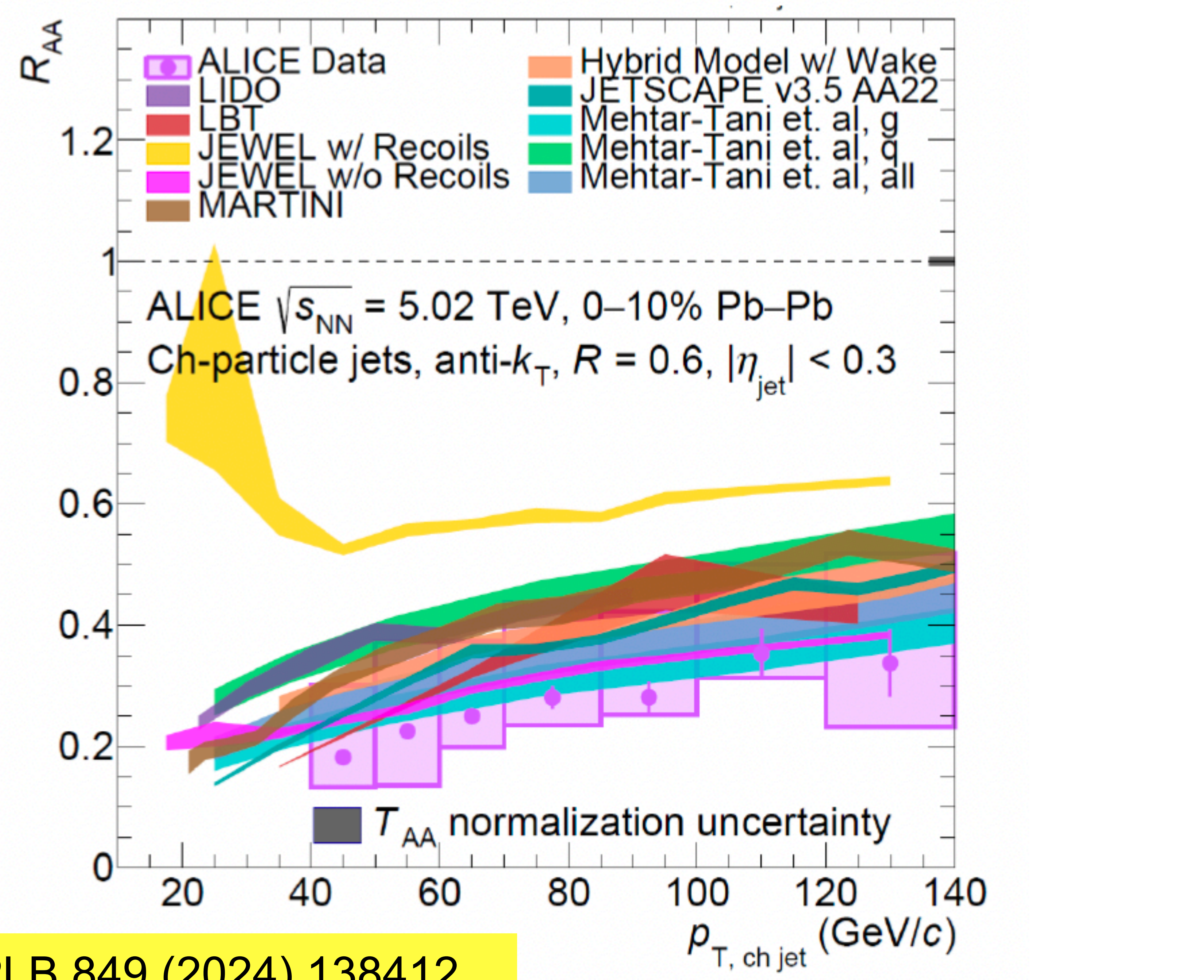


Different jet observables can shed light on different questions!

Jet suppression and energy redistribution



ALICE,arXiv:2211.04384

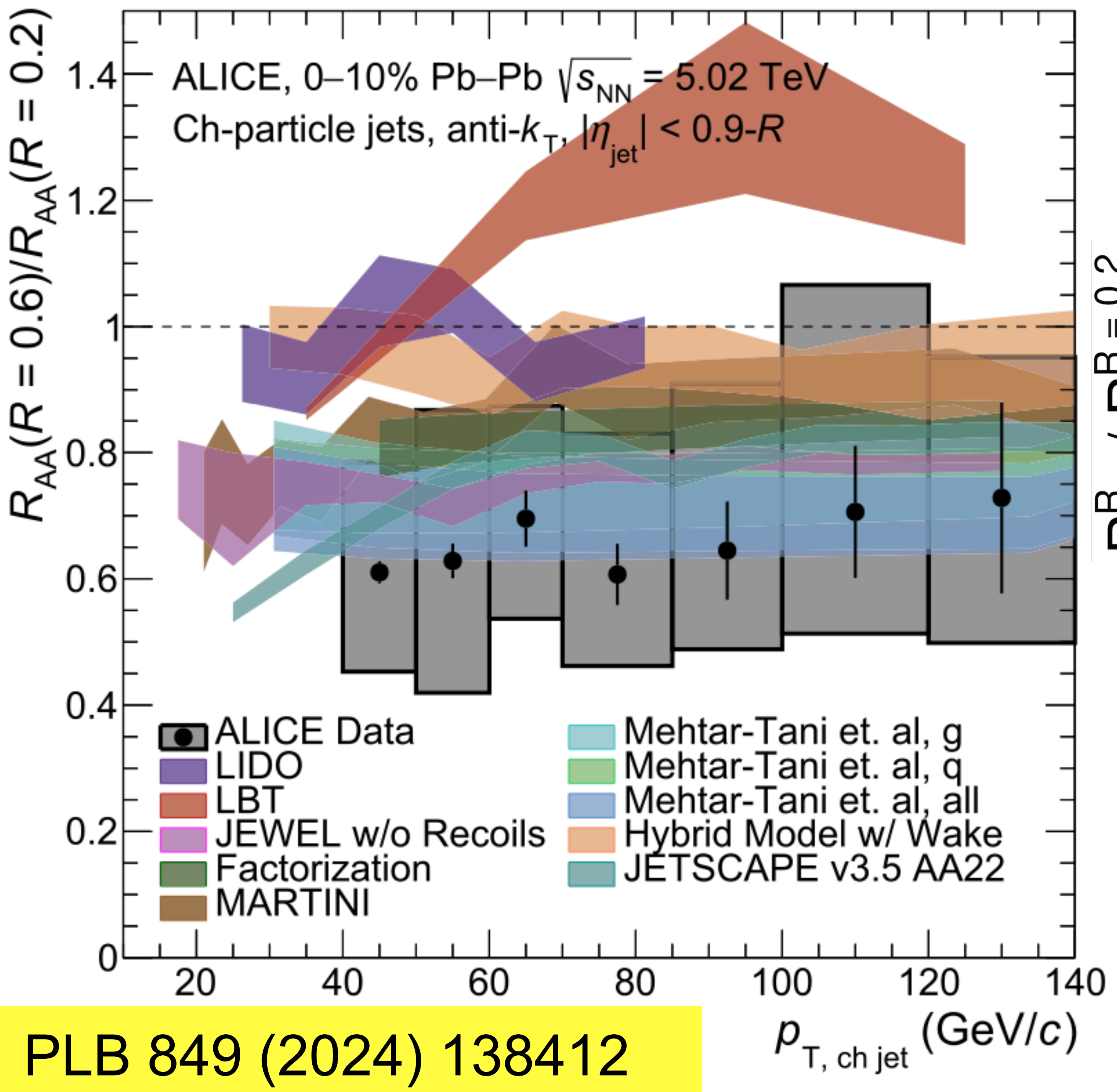


PLB 849 (2024) 138412

- Jet and high p_T hadron suppression observed over extensive range
  - Interplay between high p_T and jet results
- New ML-based techniques allow for the extension to lower jet p_T and large R = 0.6
  - improvements on background subtraction and systematics

R dependence of jet quenching

- R dependence of jet R_{AA} can be sensitive to medium response effect and help to disentangle energy loss mechanisms
  - competing effect between the amount/how energy redistributed and ability to recover it



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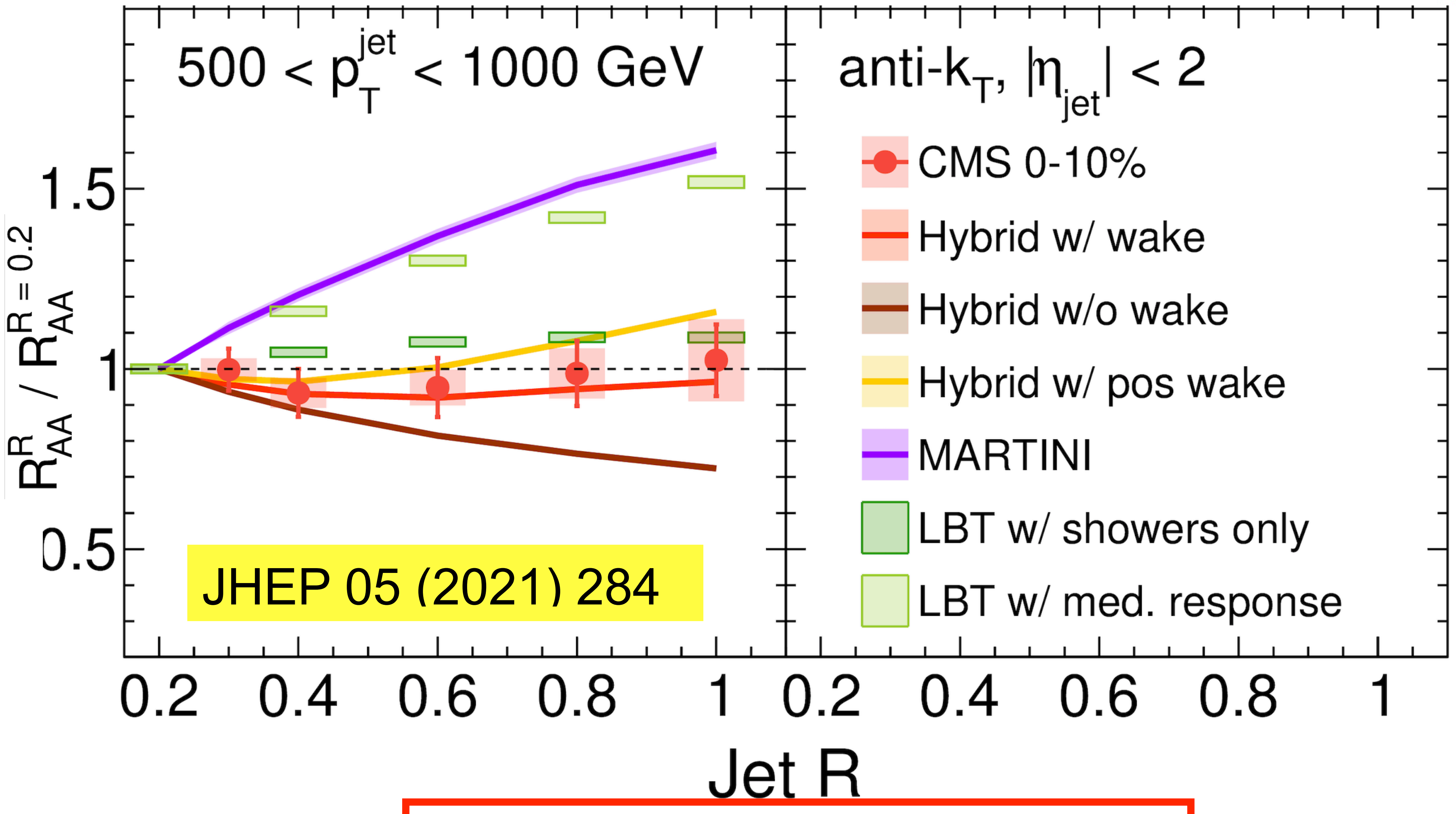
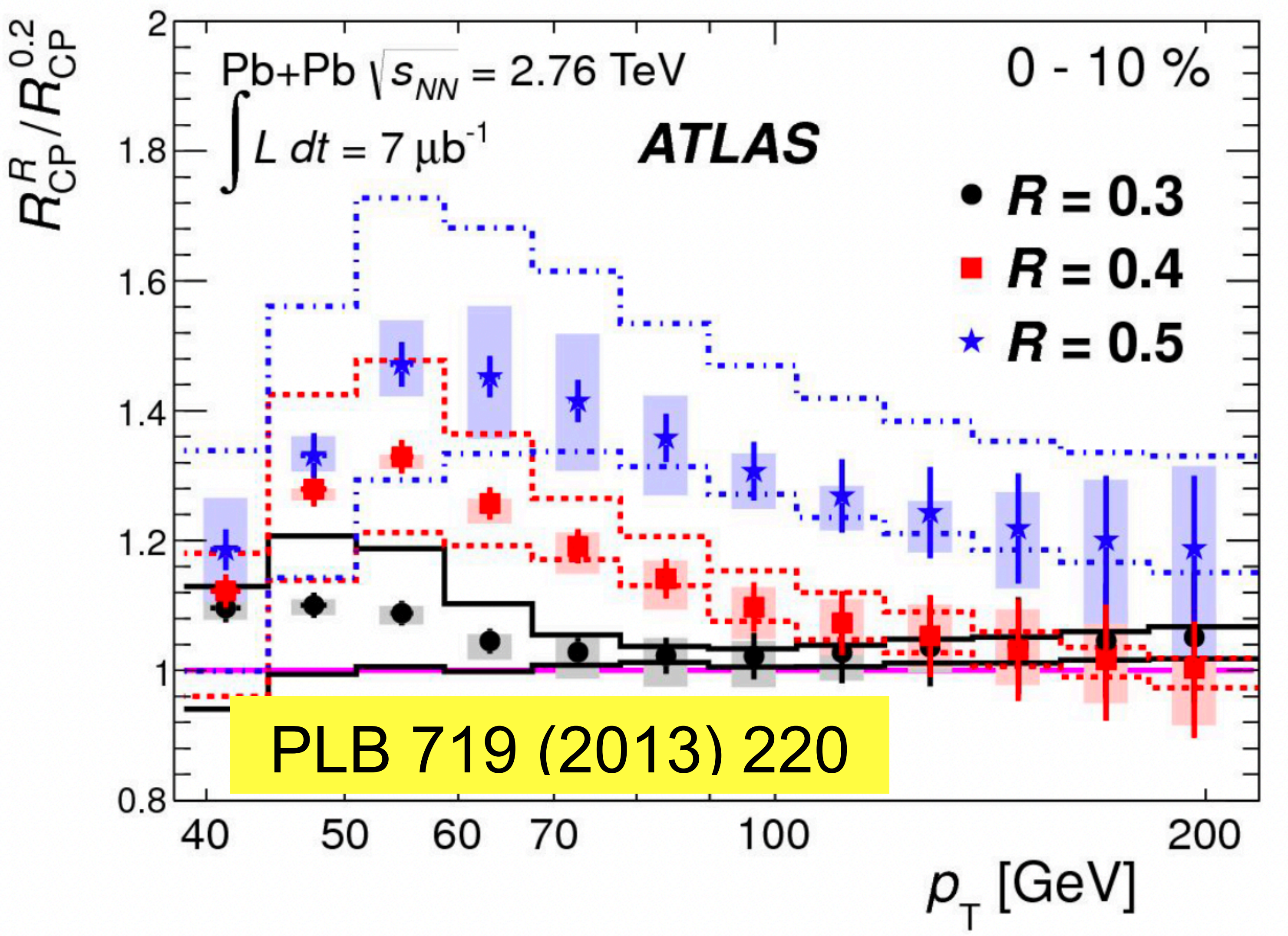
Larger radius **more** suppressed



JHEP 05 (2021) 284

No radius **dependence**



PLB 719 (2013) 220

Larger radius **less** suppressed

R dependence of jet quenching

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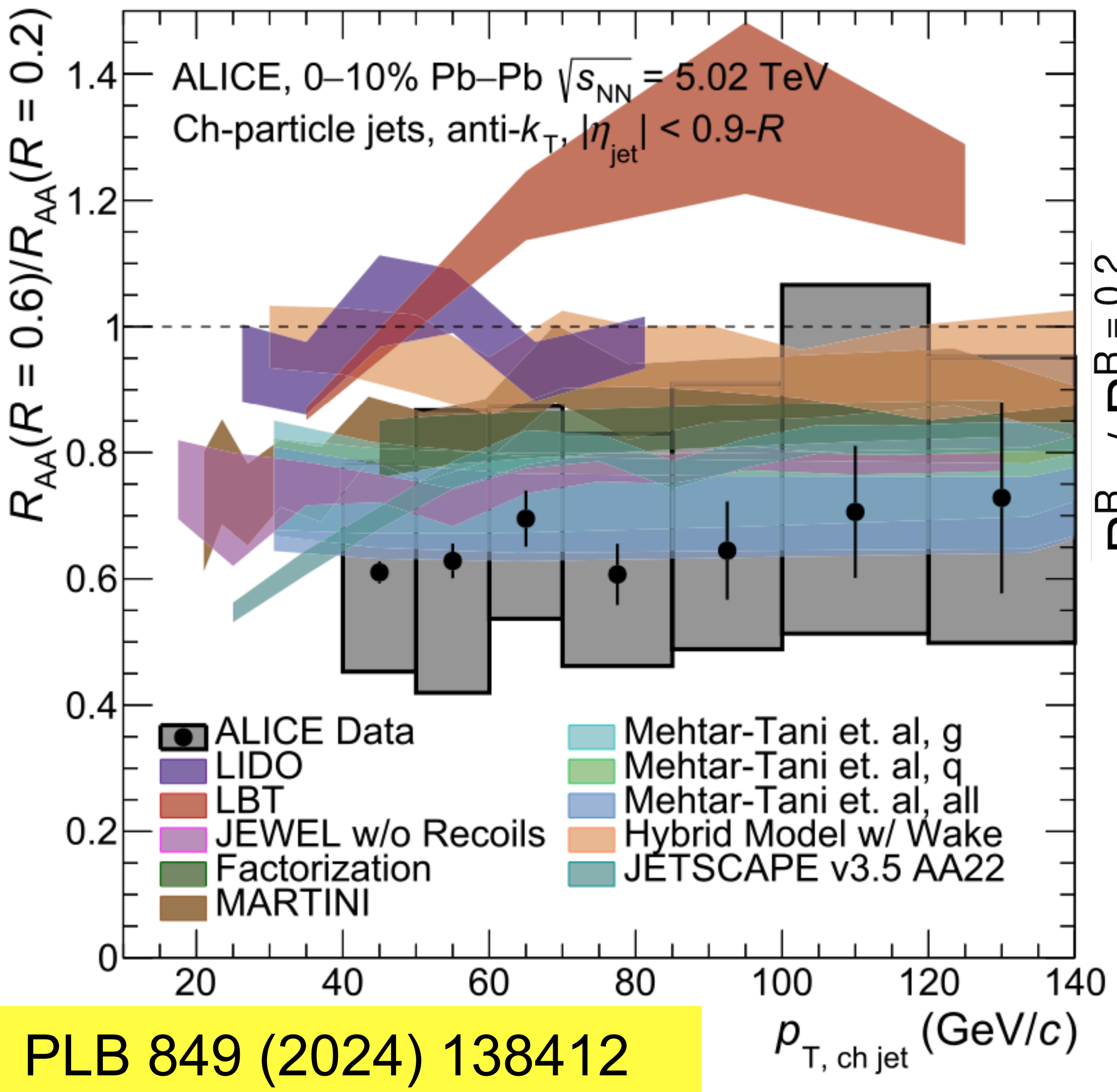

PLB 849 (2024) 138412

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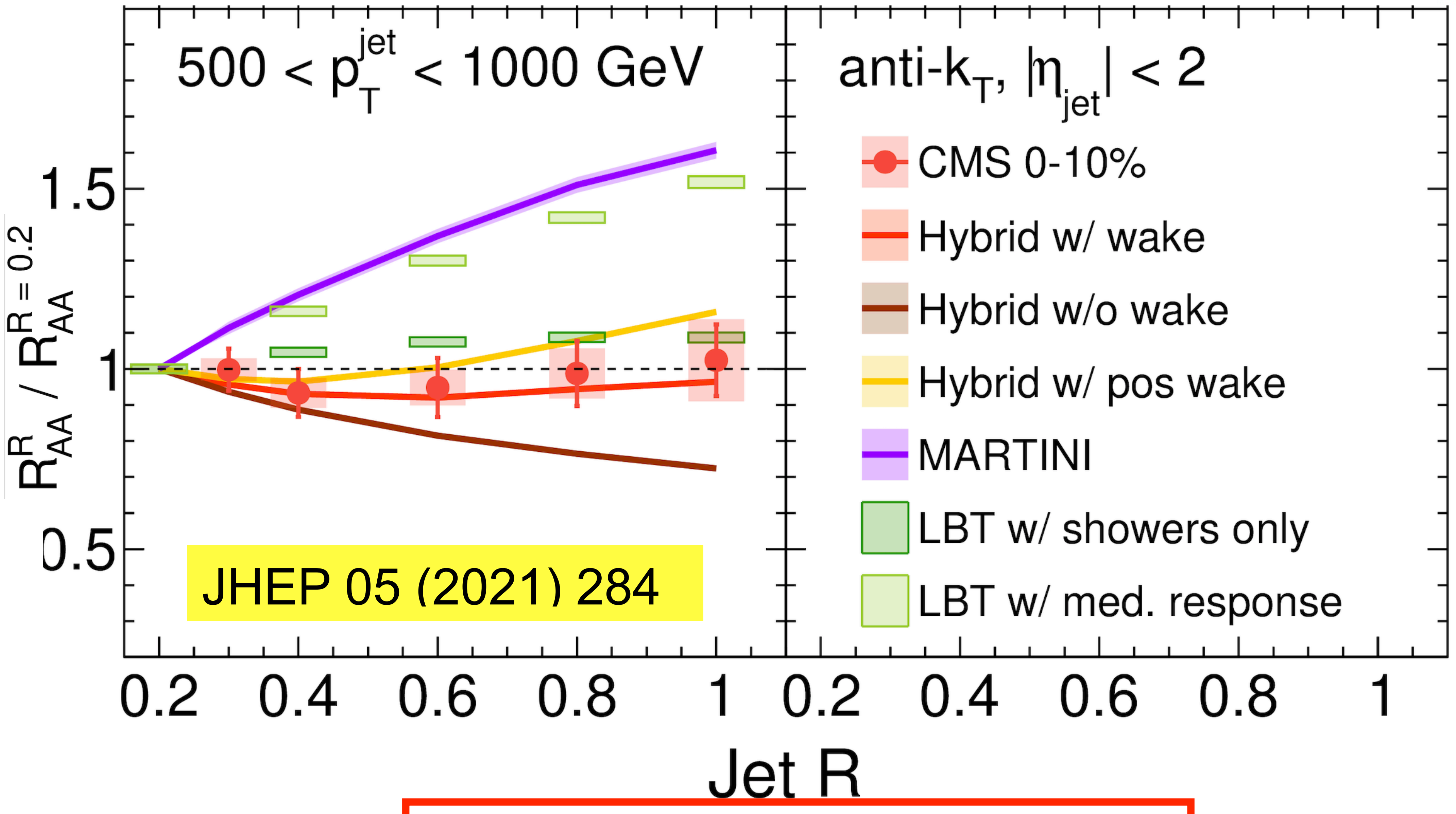

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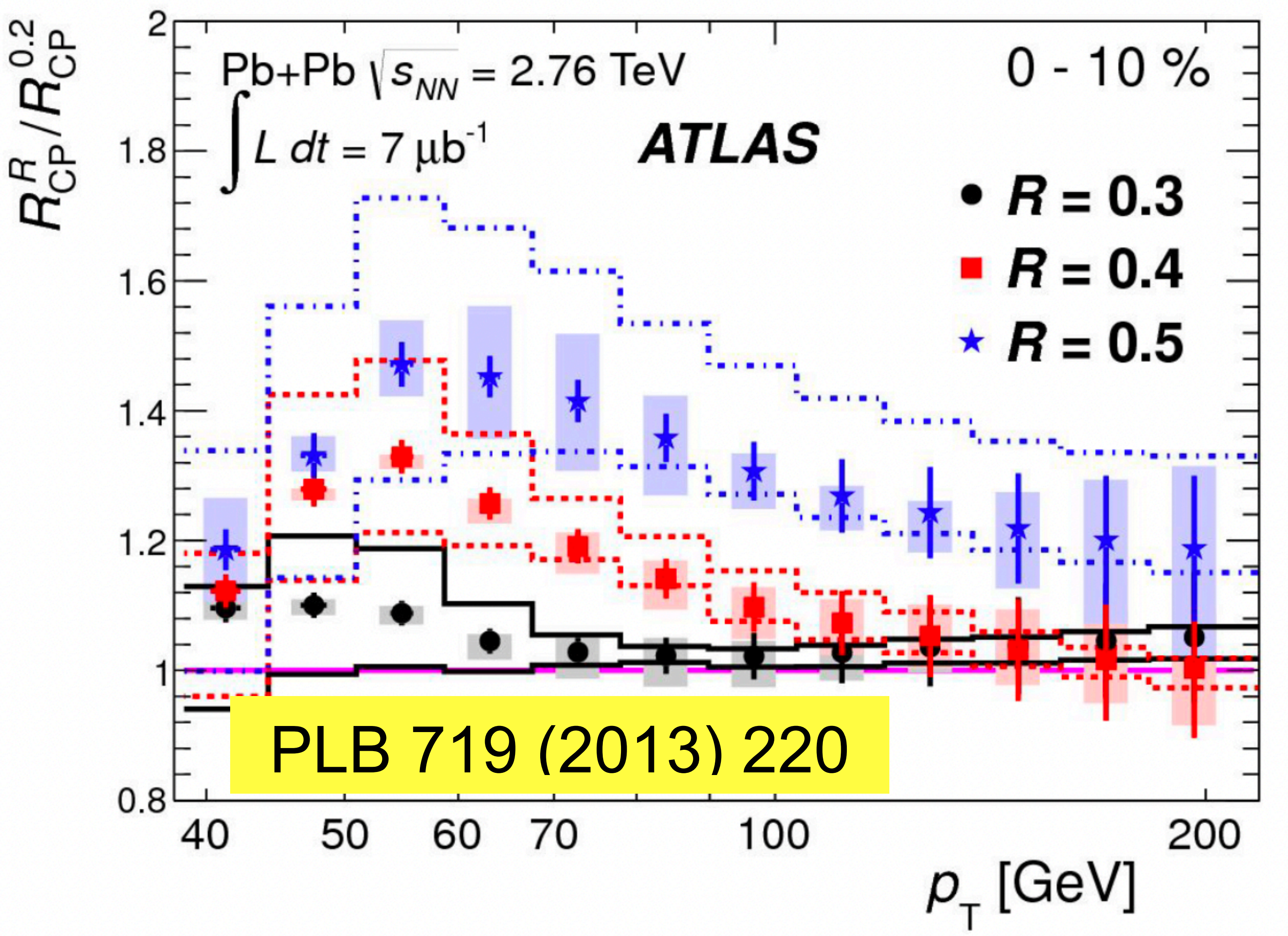


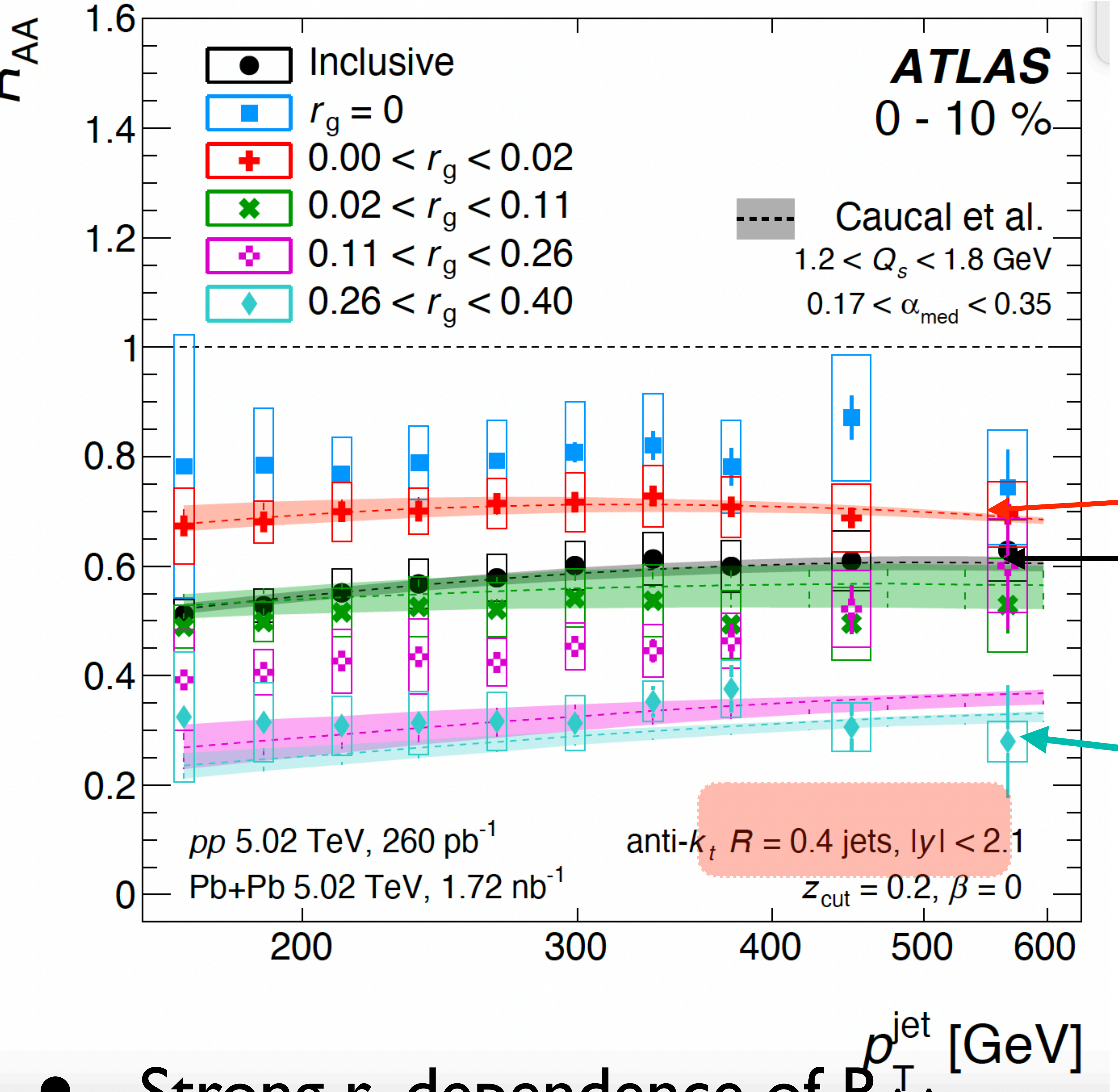
Larger radius less suppressed

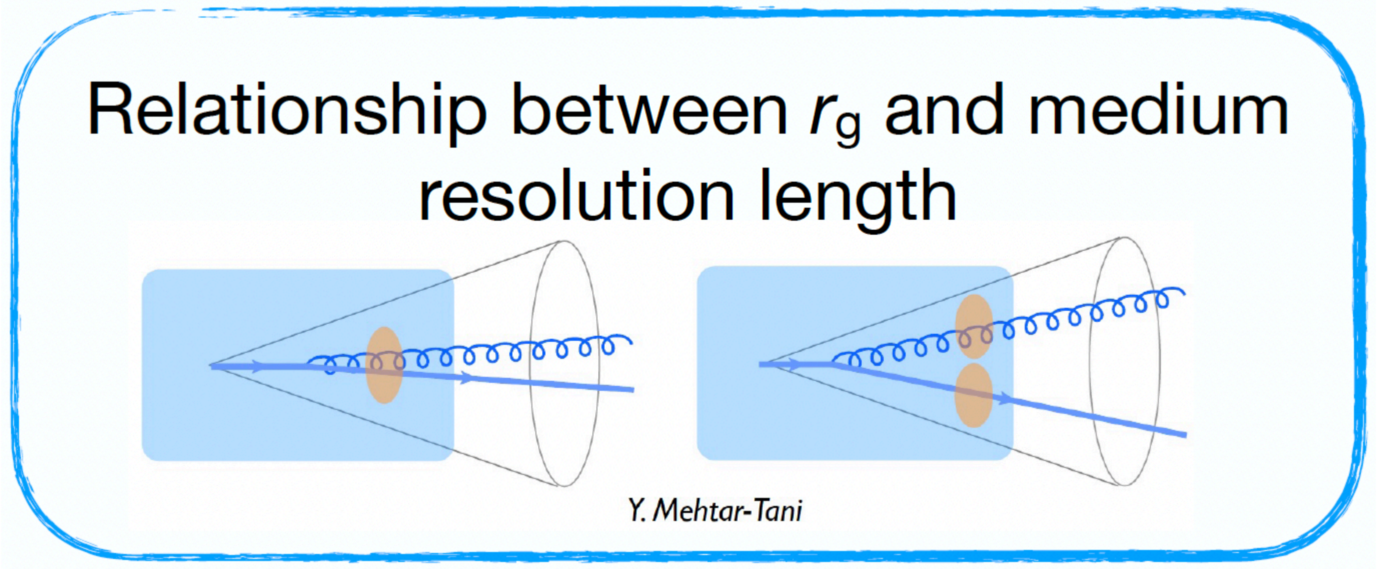
- Not exactly the same observables: R_{cp} vs. R_{AA}
- Different types of jets: full vs. charge
- Different centre-of-mass energy and phase-space

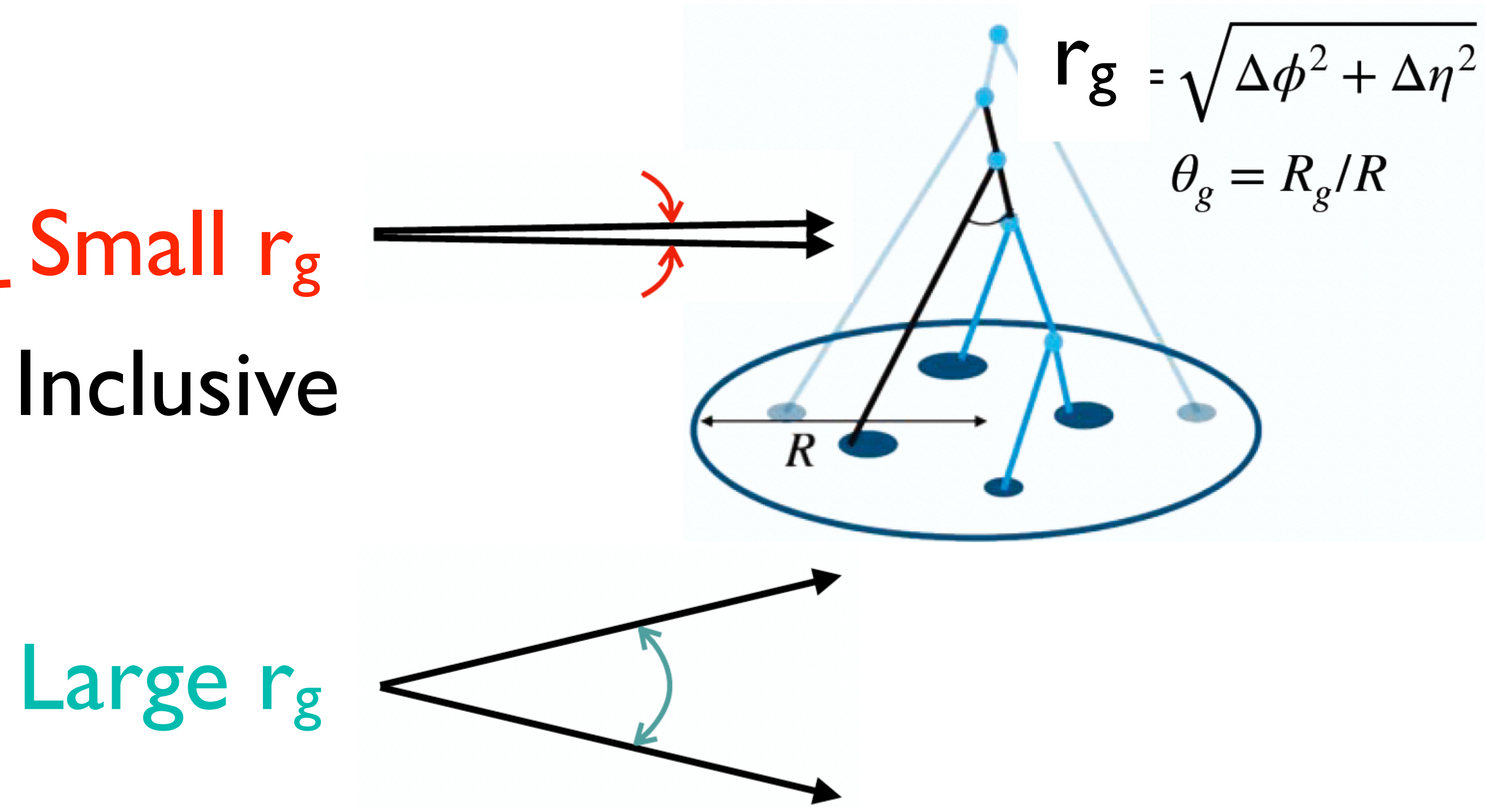
→More detailed comparison and future studies are needed

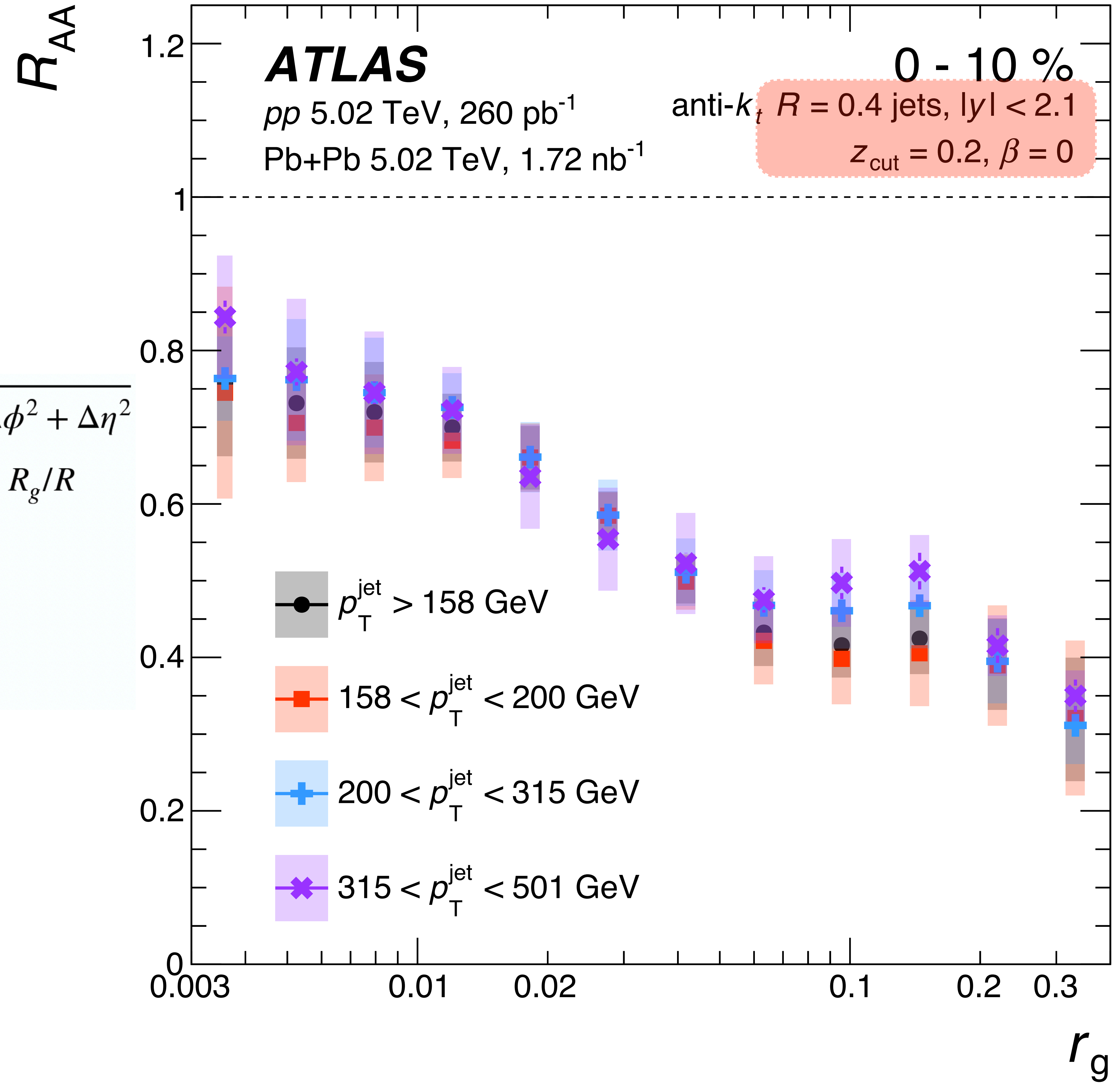
R_{AA} - substructure interplay

PRC 107 (2023) 054909





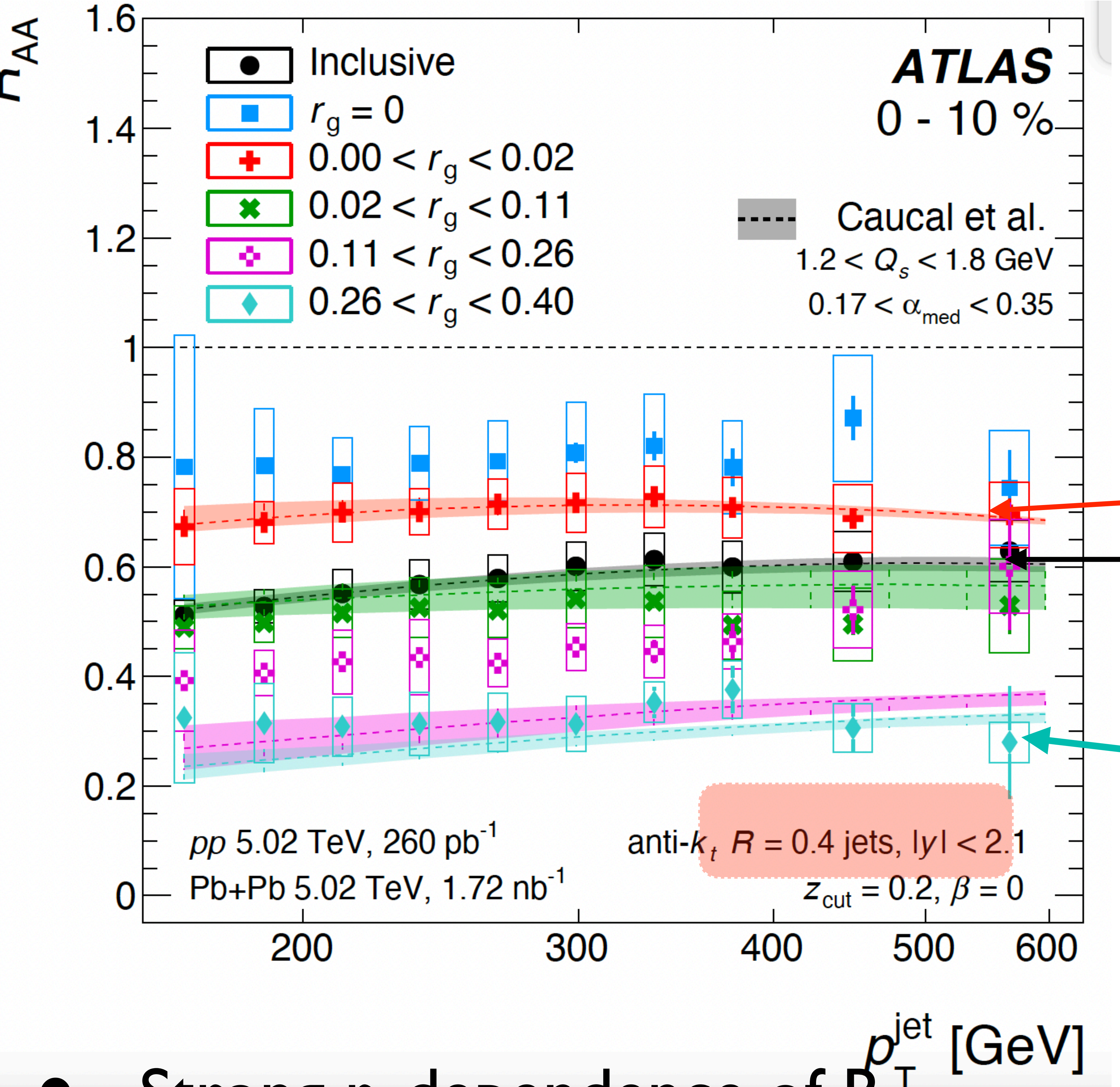


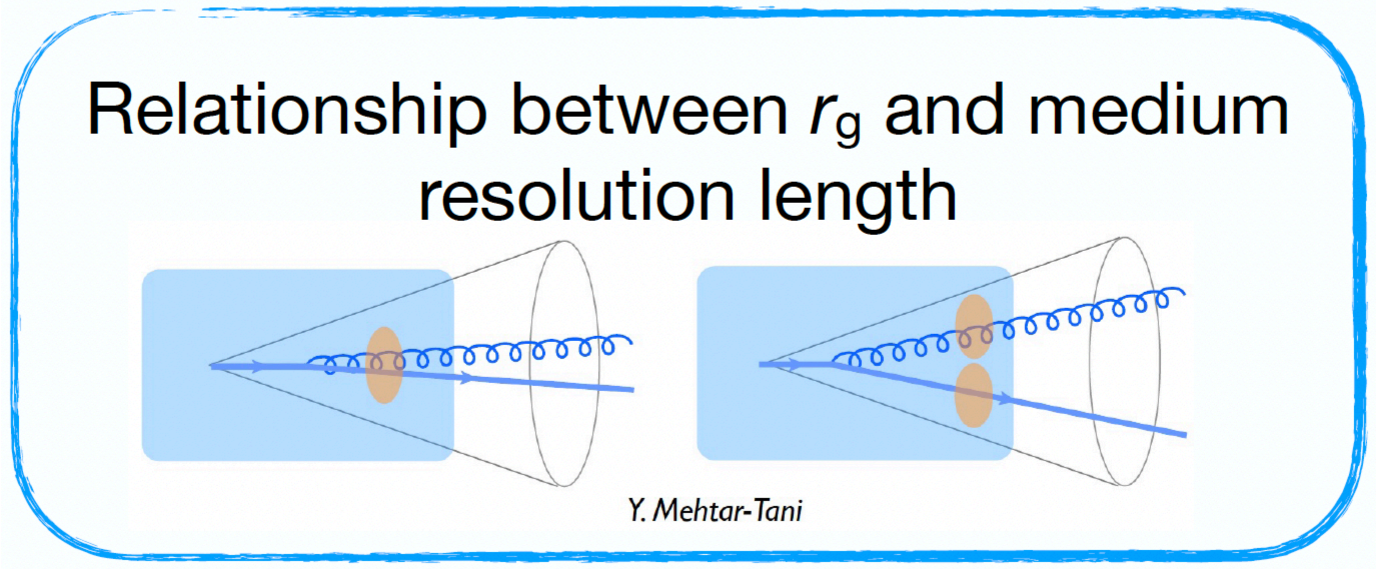


- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splitting

R_{AA} - substructure interplay

PRC 107 (2023) 054909

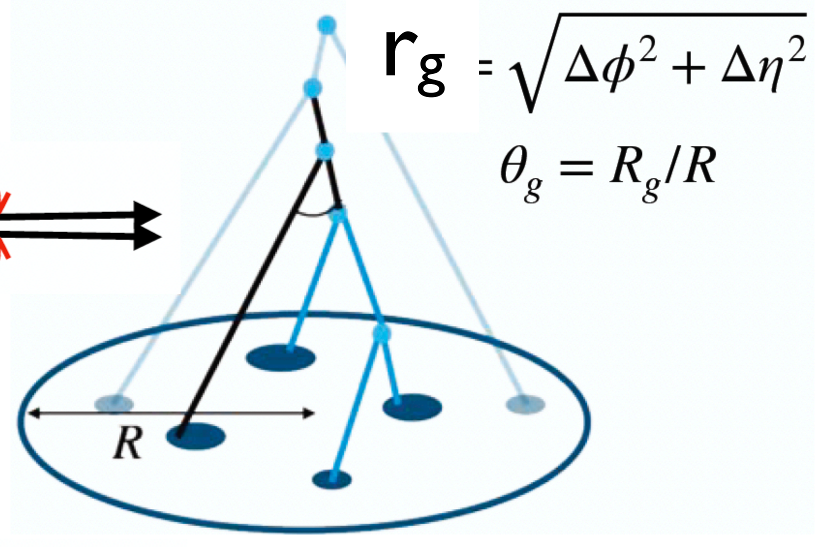


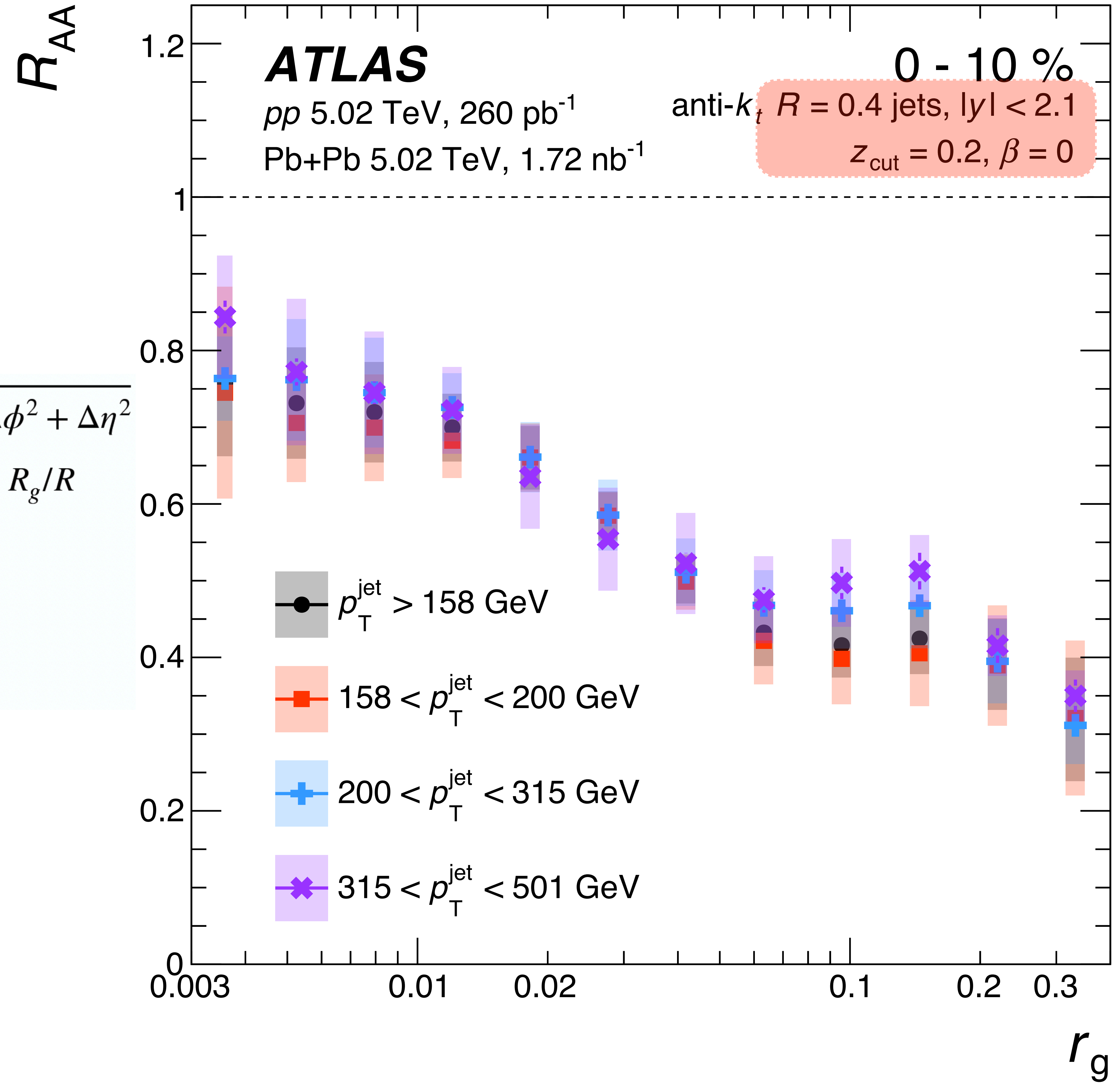


Small r_g

Inclusive

Large r_g



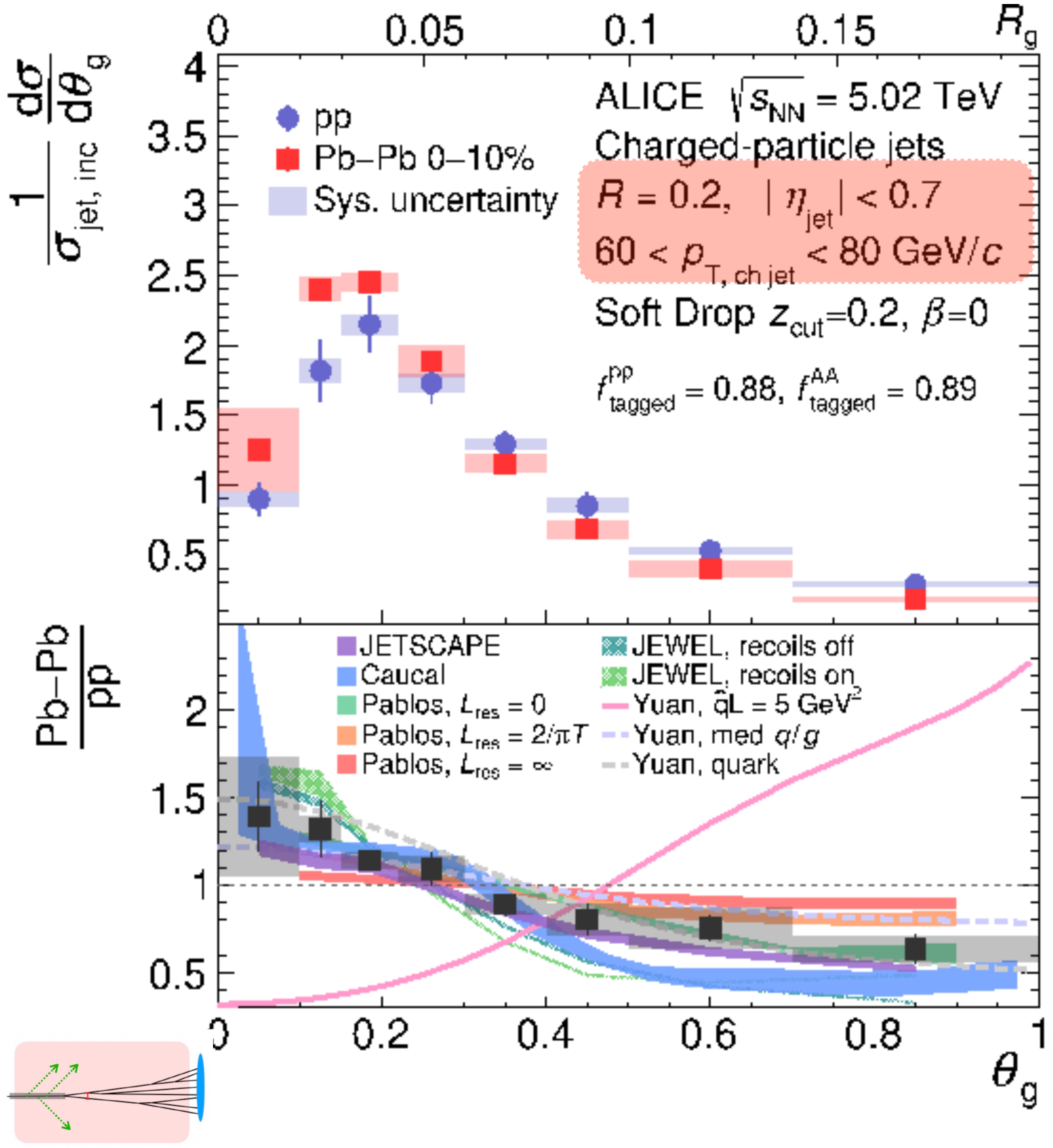


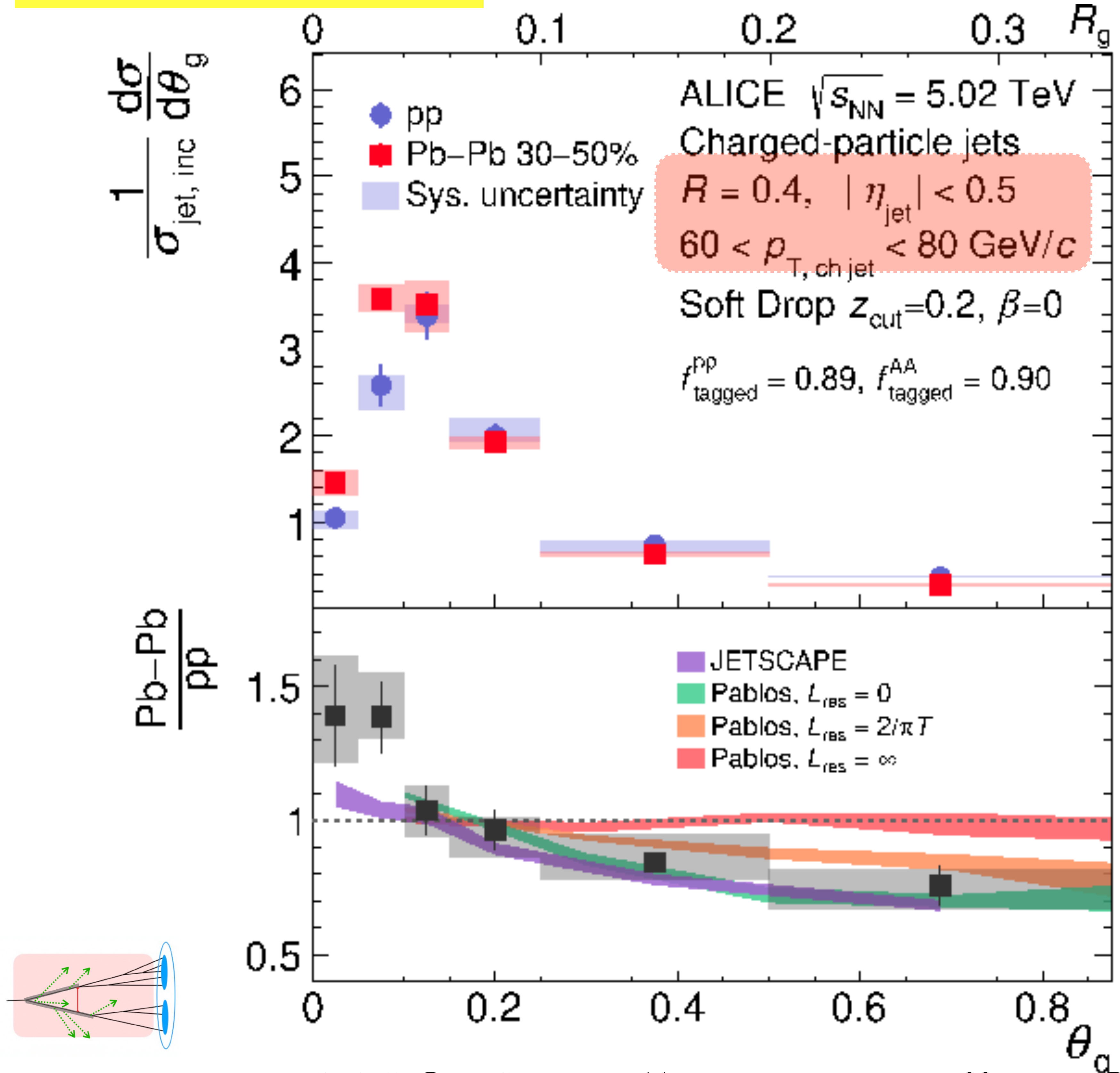
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splitting

→important to study the r_g dependent R_{AA} with different R

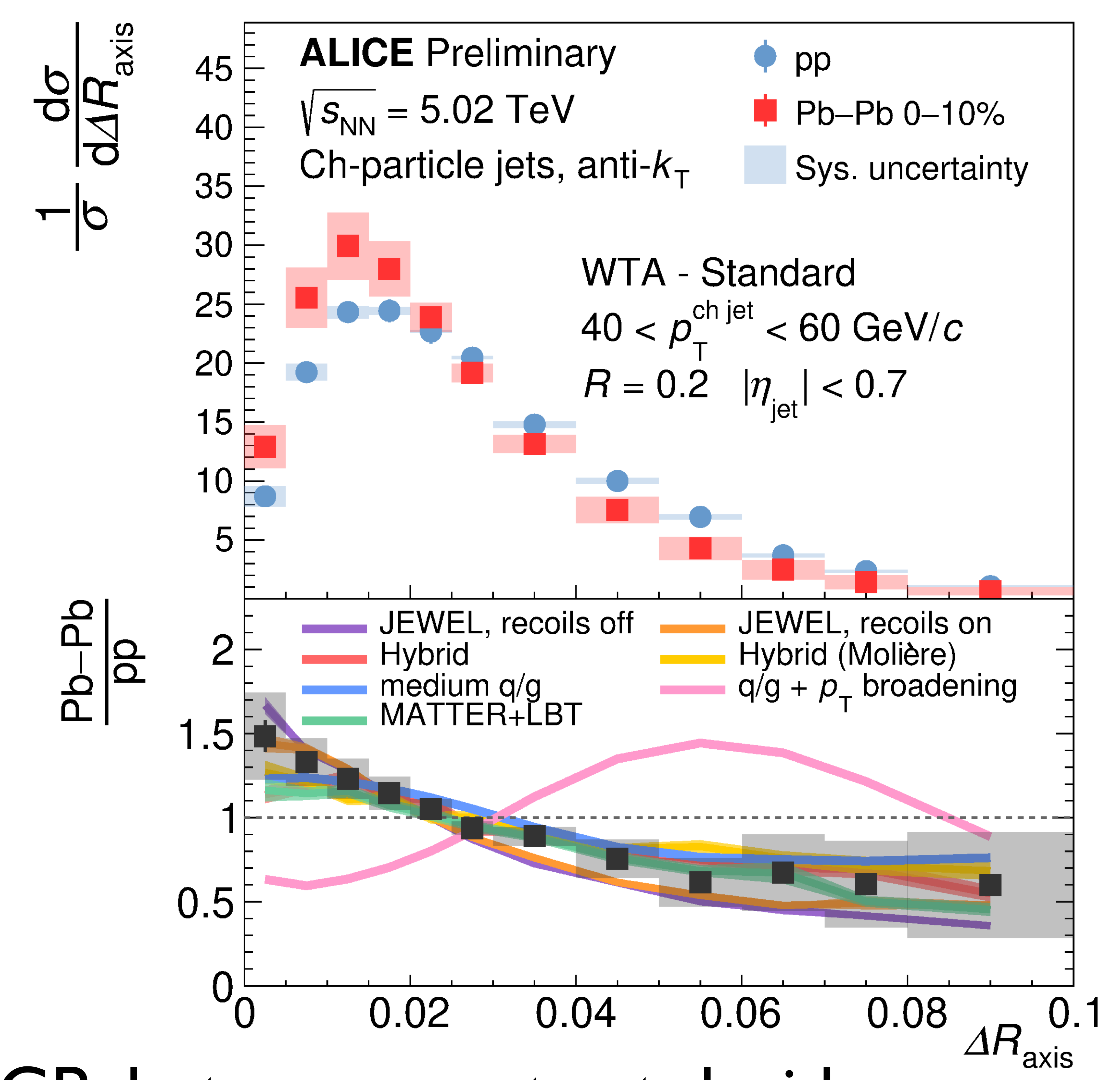
Jet substructure modifications

PRL 128 (2022) 102001





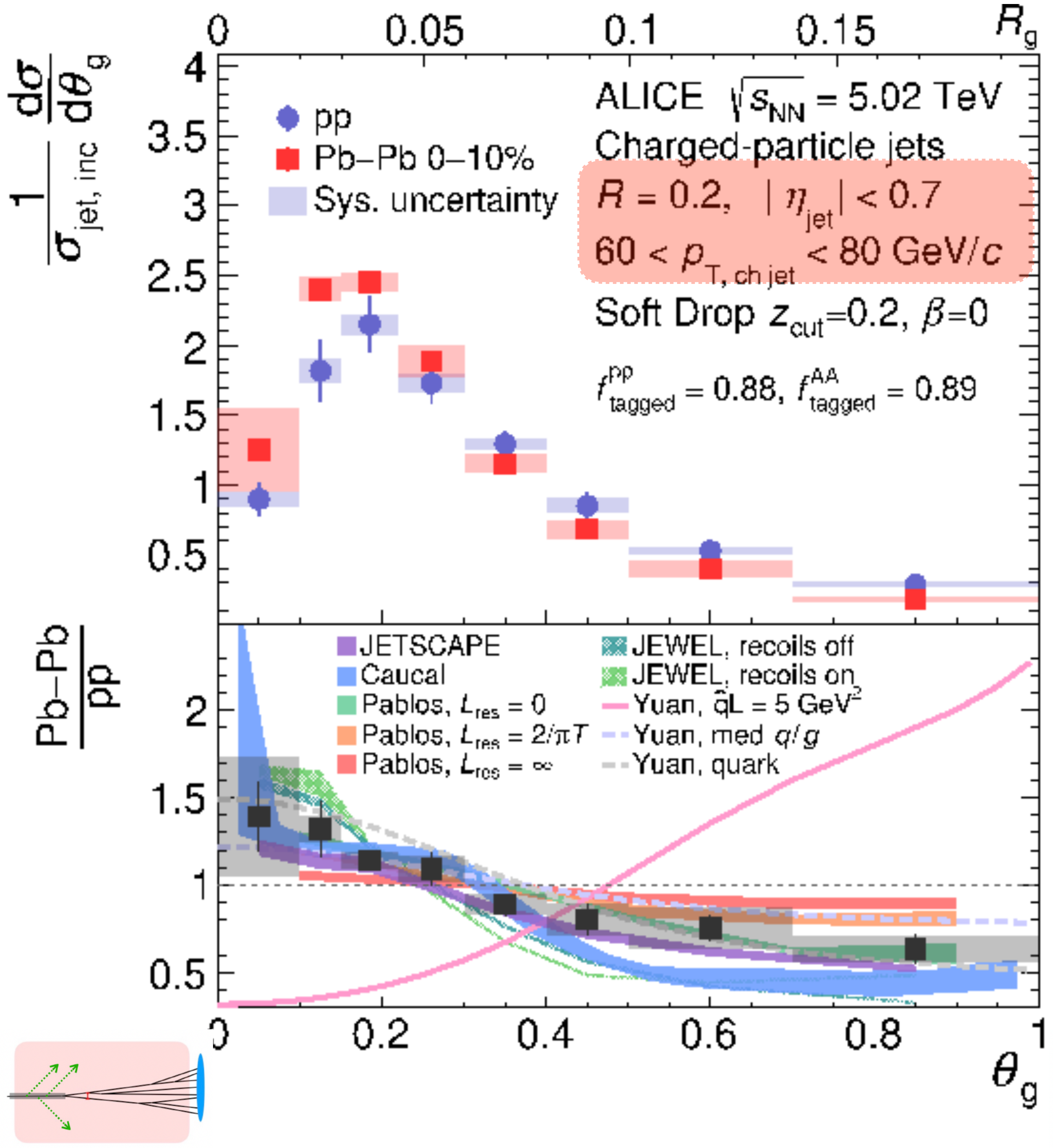
Angle between standard and WTA jet axes

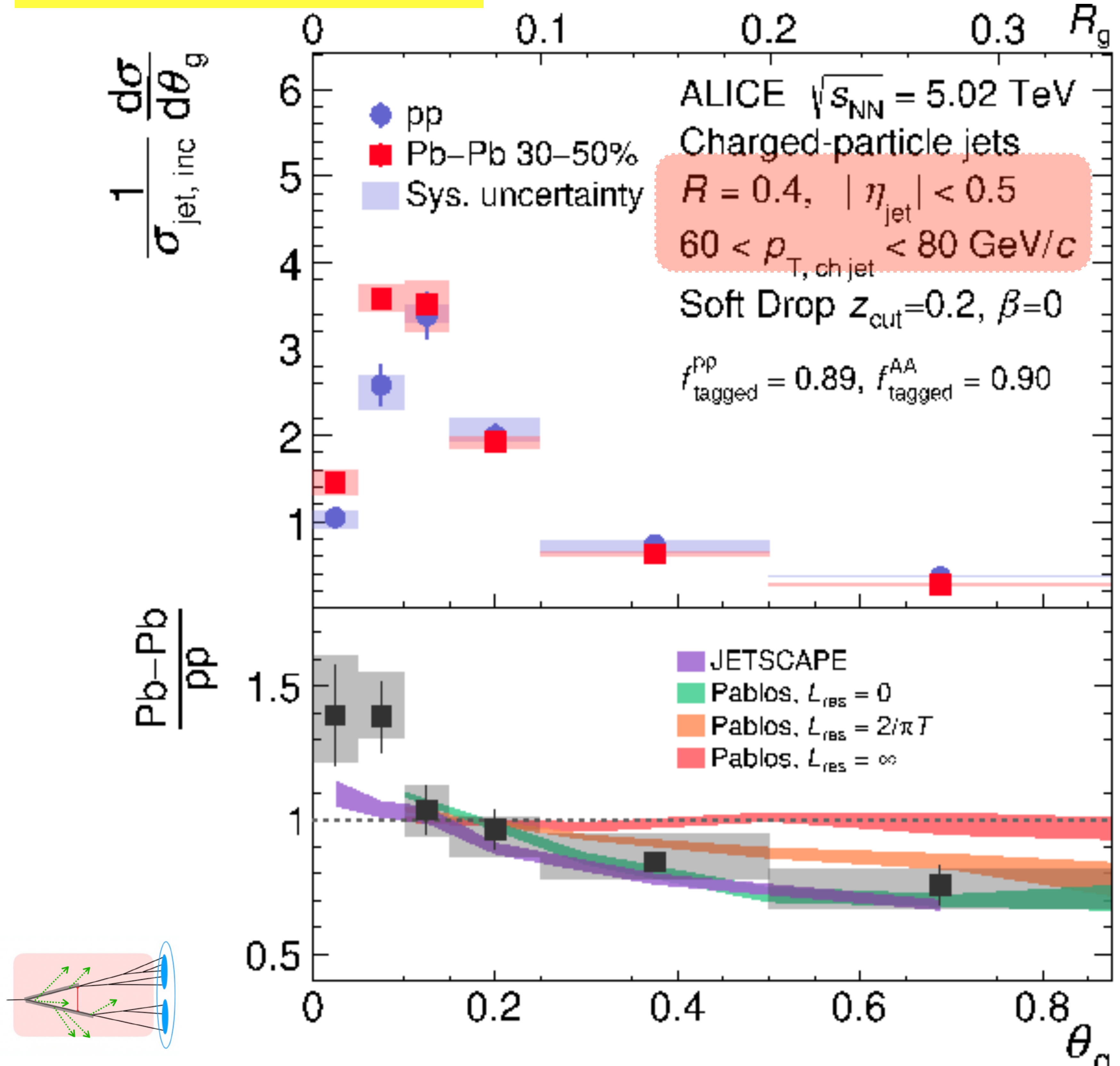


- Many jet substructure measurements at LHC show "narrowing" in QGP, but we cannot yet decide:
  - Energy loss makes the jets narrower?
  - selection bias
  - q/g-fraction changes

Jet substructure modifications

PRL 128 (2022) 102001





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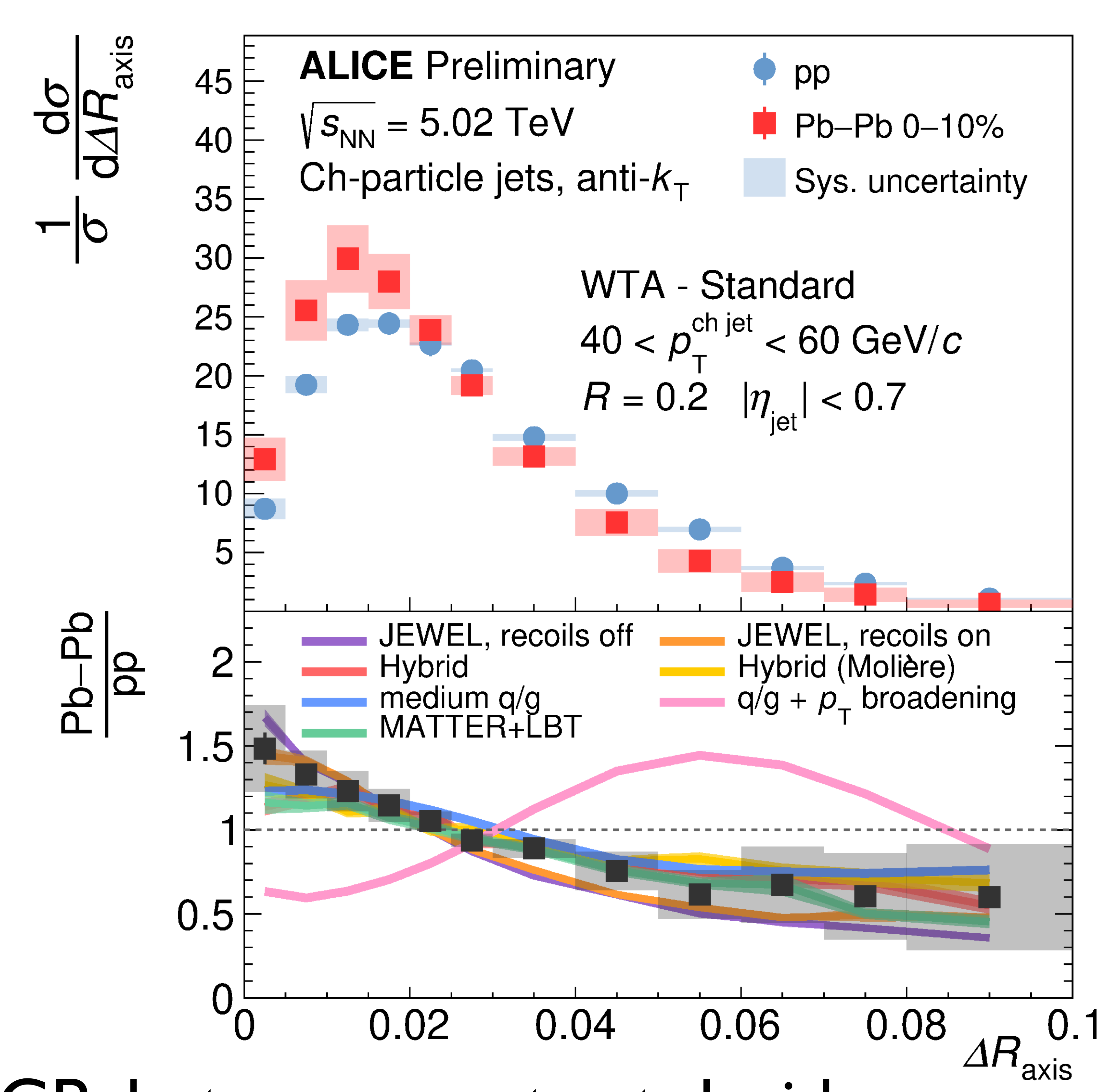
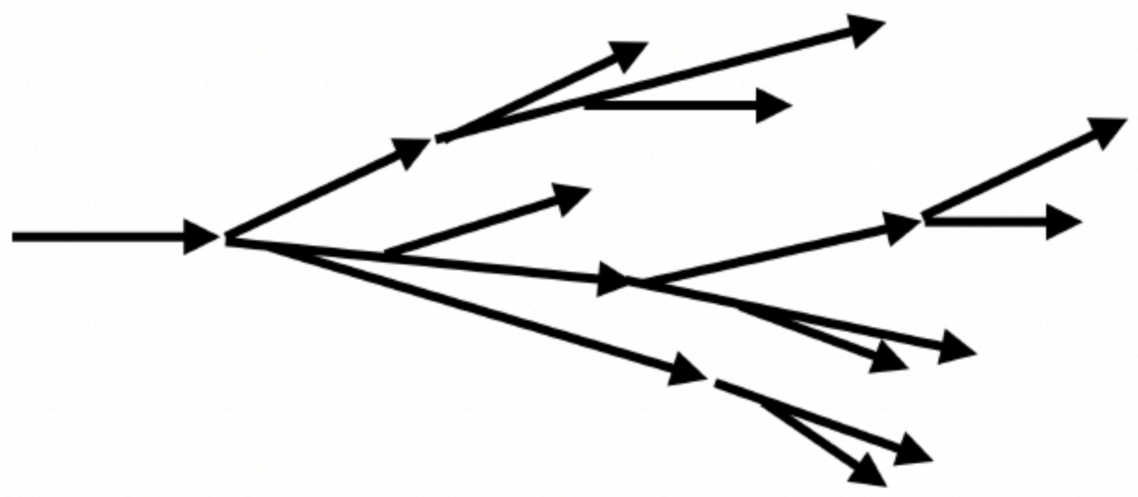


- Many jet substructure measurements at LHC show "narrowing" in QGP, but we cannot yet decide:
  - Energy loss makes the jets narrower?
  - selection bias
  - q/g-fraction changes

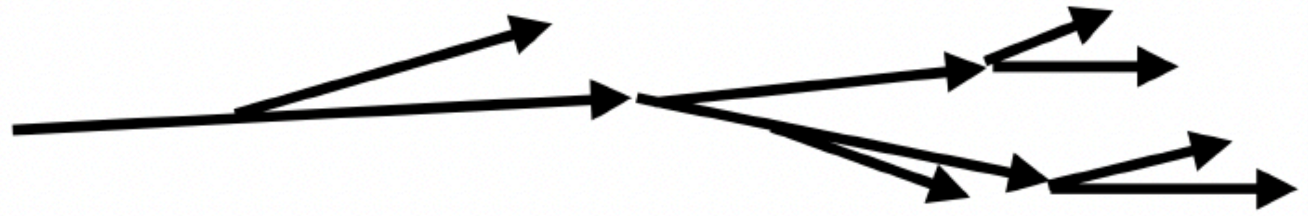
→Z/γ-jet substructure can avoid selection bias and q/g fraction differences

Flavour/Color dependence of parton energy loss

Gluon-initiated shower



Quark-initiated shower



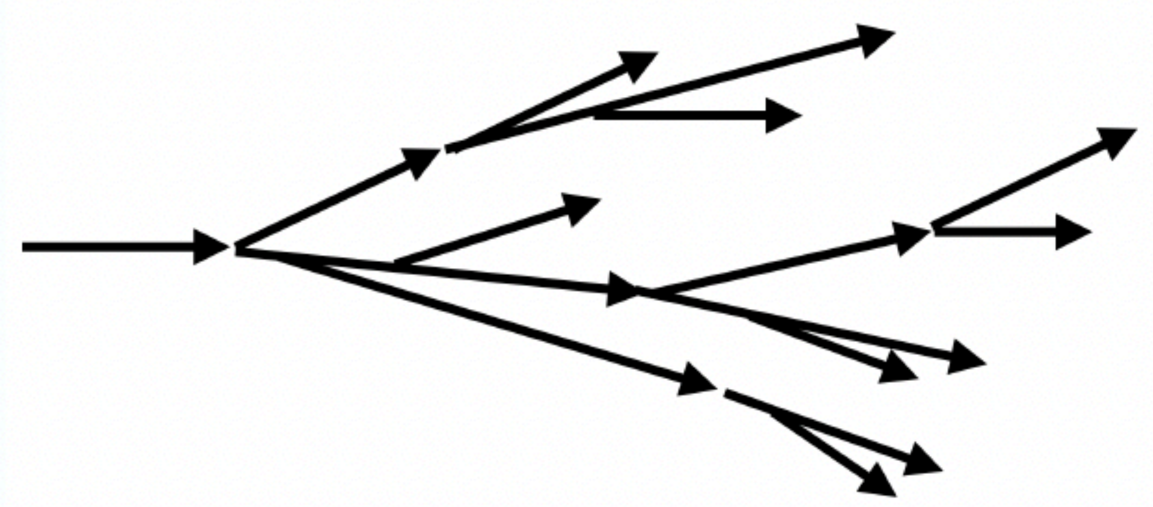
$$\frac{C_A}{C_F} = \frac{9}{4}$$

Casimir color factors

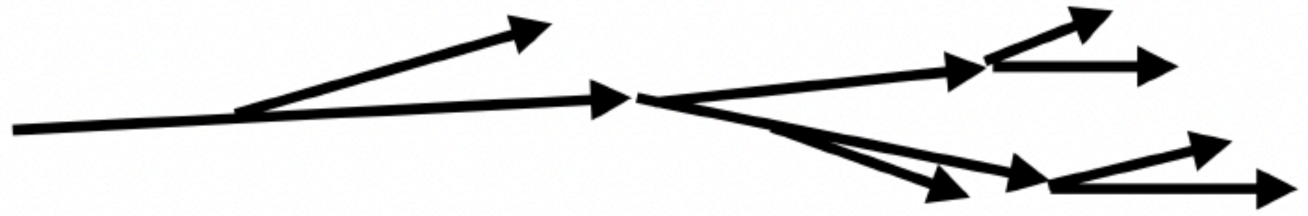
Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Flavour/Color dependence of parton energy loss

Gluon-initiated shower

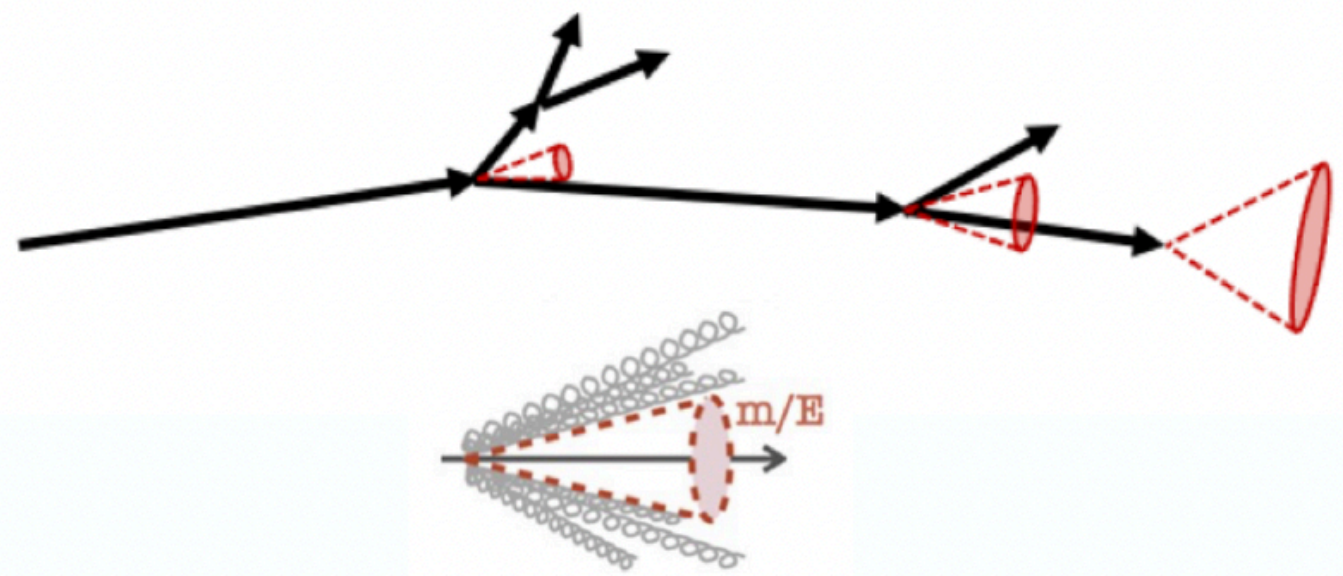


Quark-initiated shower



$$\frac{C_A}{C_F} = \frac{9}{4}$$

Heavy-quark-initiated shower



Casimir color factors

Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Mass effects

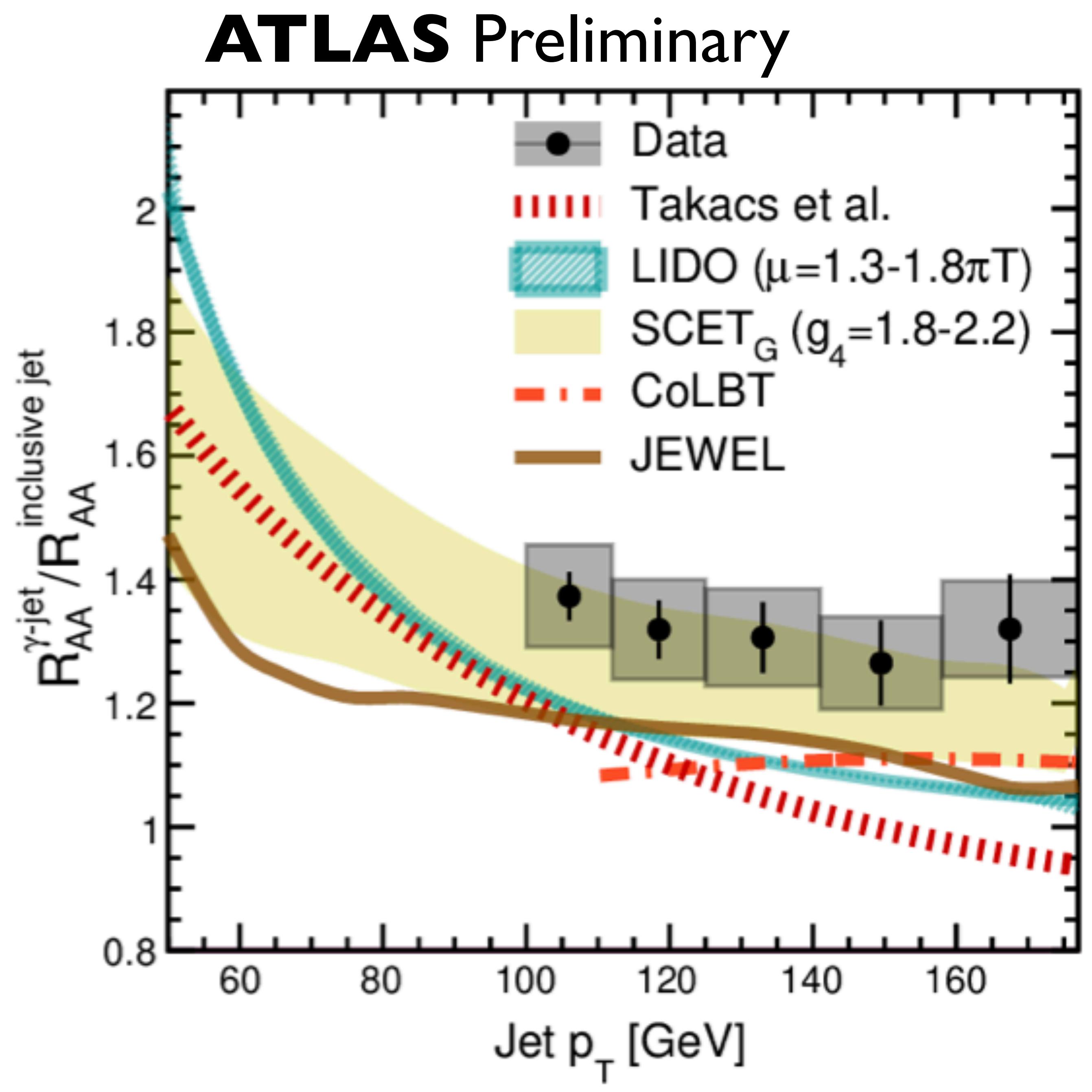
A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of a dead cone which suppresses radiation close to the heavy-quark

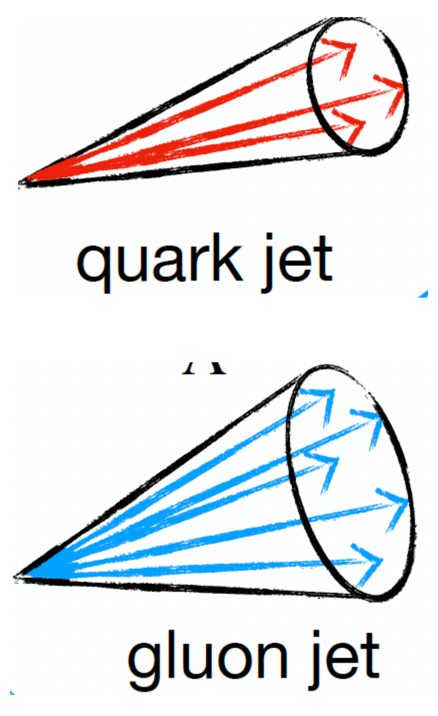
- Flavor dependence involves: a) color charge differences; b) mass dependence (dominant at low p_T)
- Flavor dependence of energy loss: $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{light-quark}} > E_{\text{loss}}^{c} > E_{\text{loss}}^{b}$

Color charge dependence of energy loss

Flavor dependence of radiation:

$$E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{light-quark}} > E_{\text{loss}}^{c} > E_{\text{loss}}^{b}$$

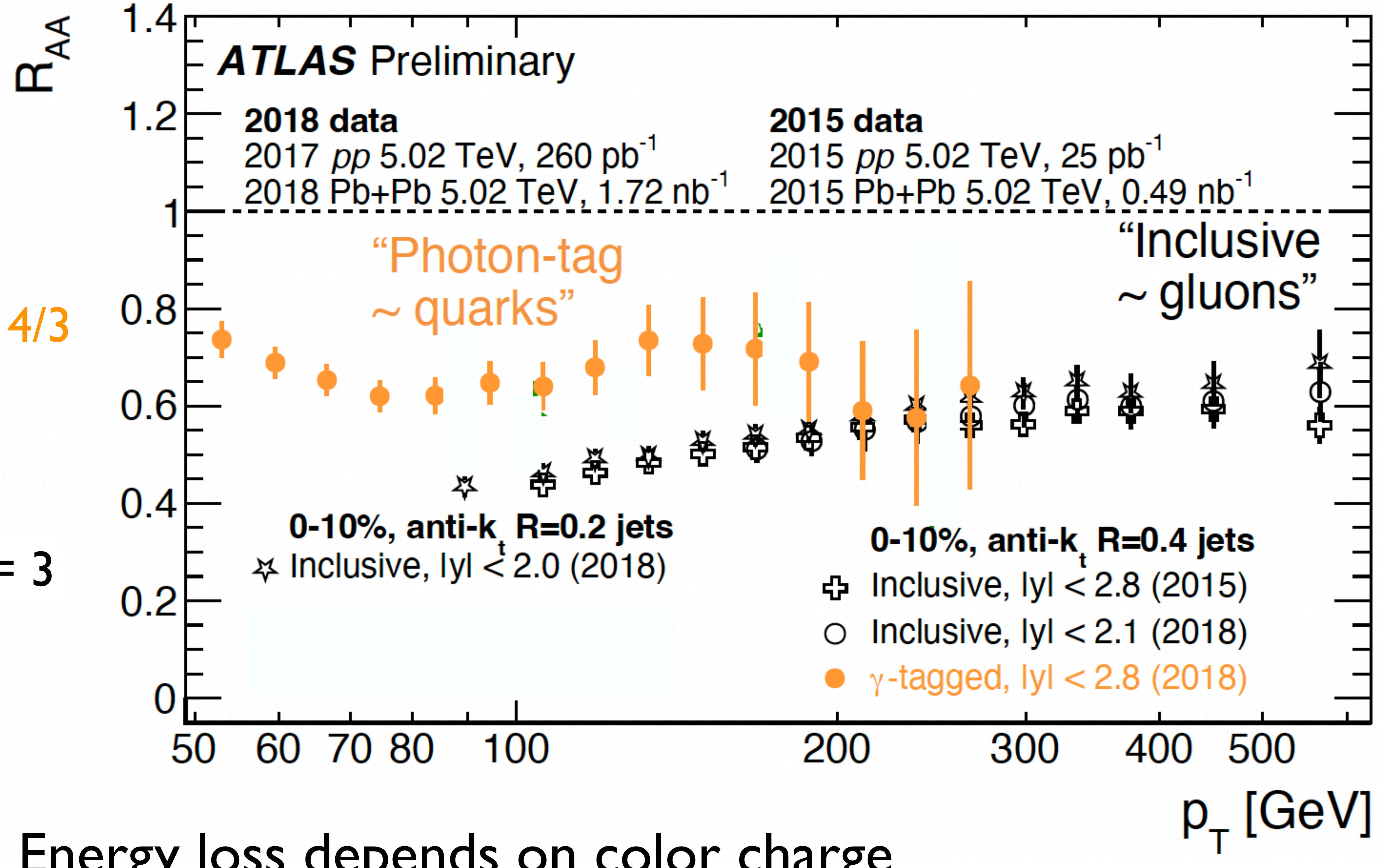




$C_F = 4/3$

$C_A = 3$

Caveat: "spectra steepness" plays a role!

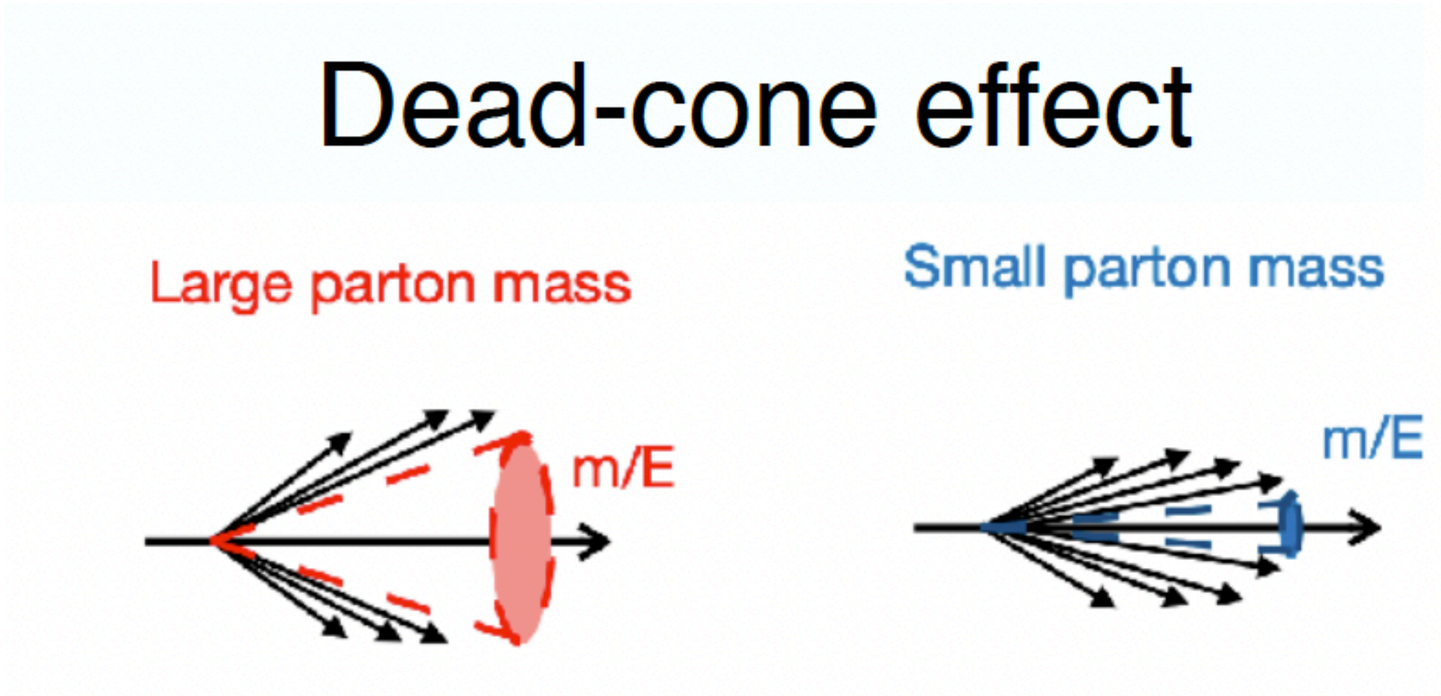


- Energy loss depends on color charge

Flavor/Mass dependence of energy loss

Flavor dependence of radiation:

$$E_{\rm loss}^{\rm gluon} > E_{\rm loss}^{\rm light-quark} > E_{\rm loss}^{c} > E_{\rm loss}^{b}$$



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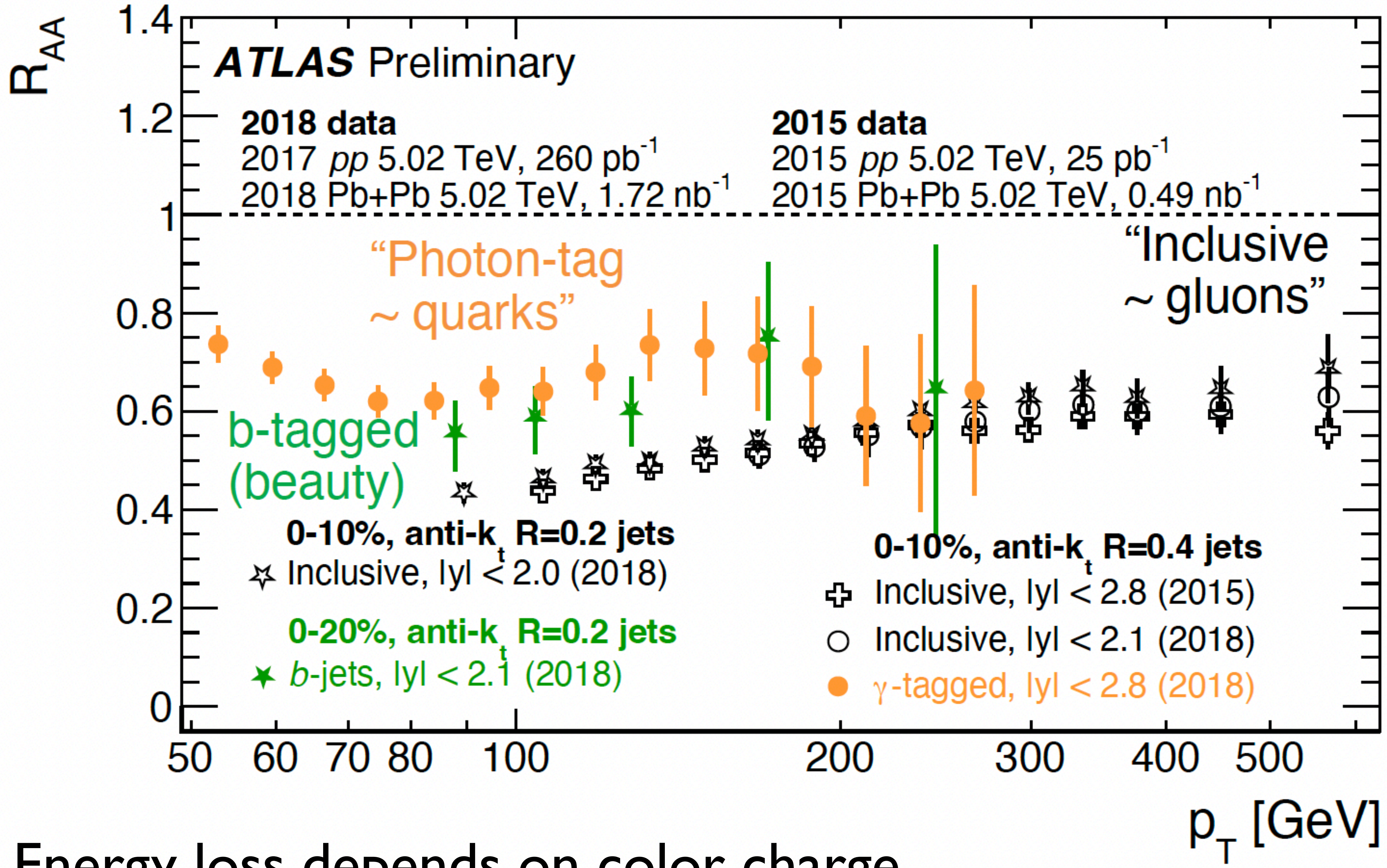


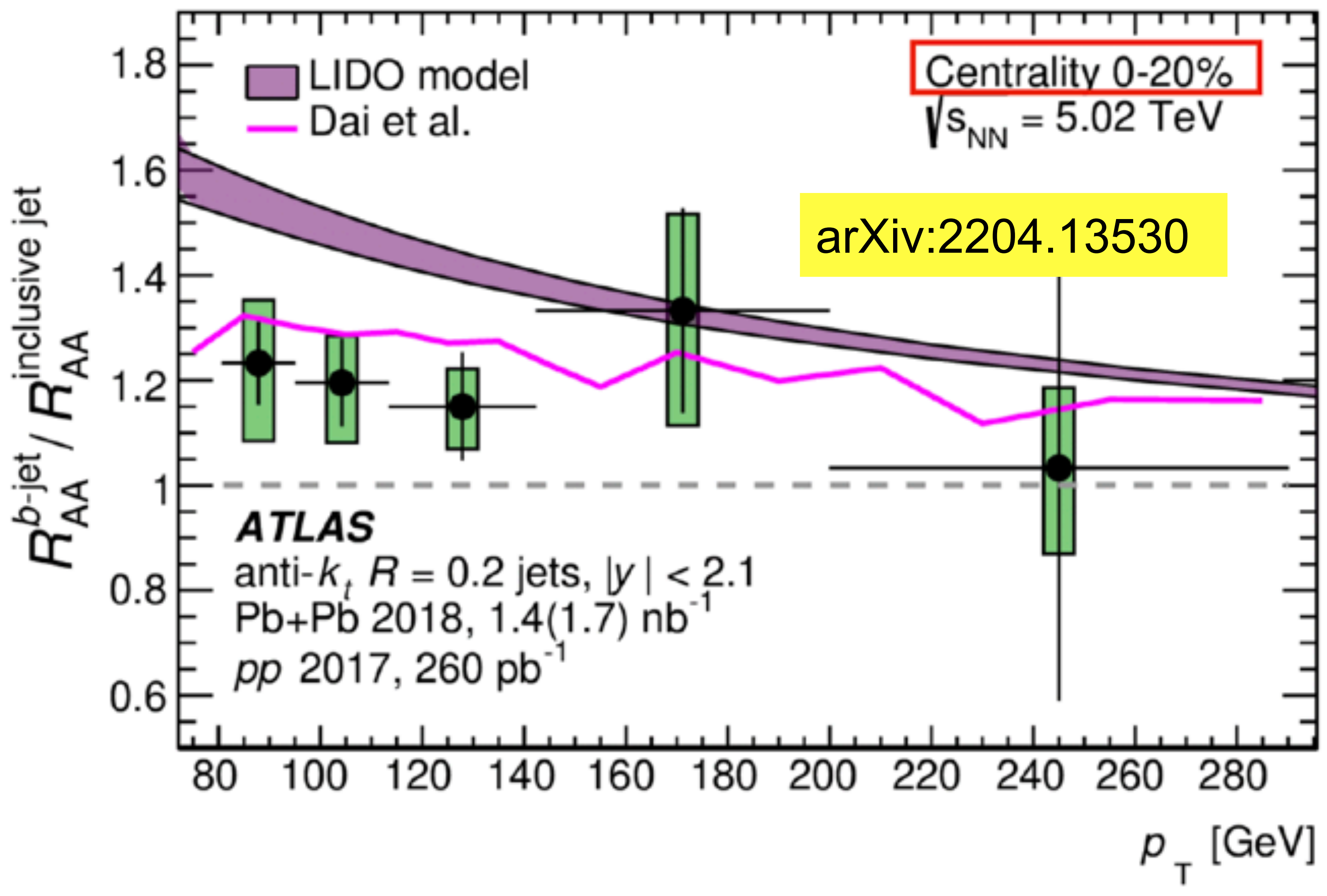
- Energy loss depends on color charge

- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect

Flavor/Mass dependence of energy loss

Flavor dependence of radiation:

$$E^{\text{gluon}}_{\text{loss}} > E^{\text{light-quark}}_{\text{loss}} > E^{c}_{\text{loss}} > E^{b}_{\text{loss}}$$



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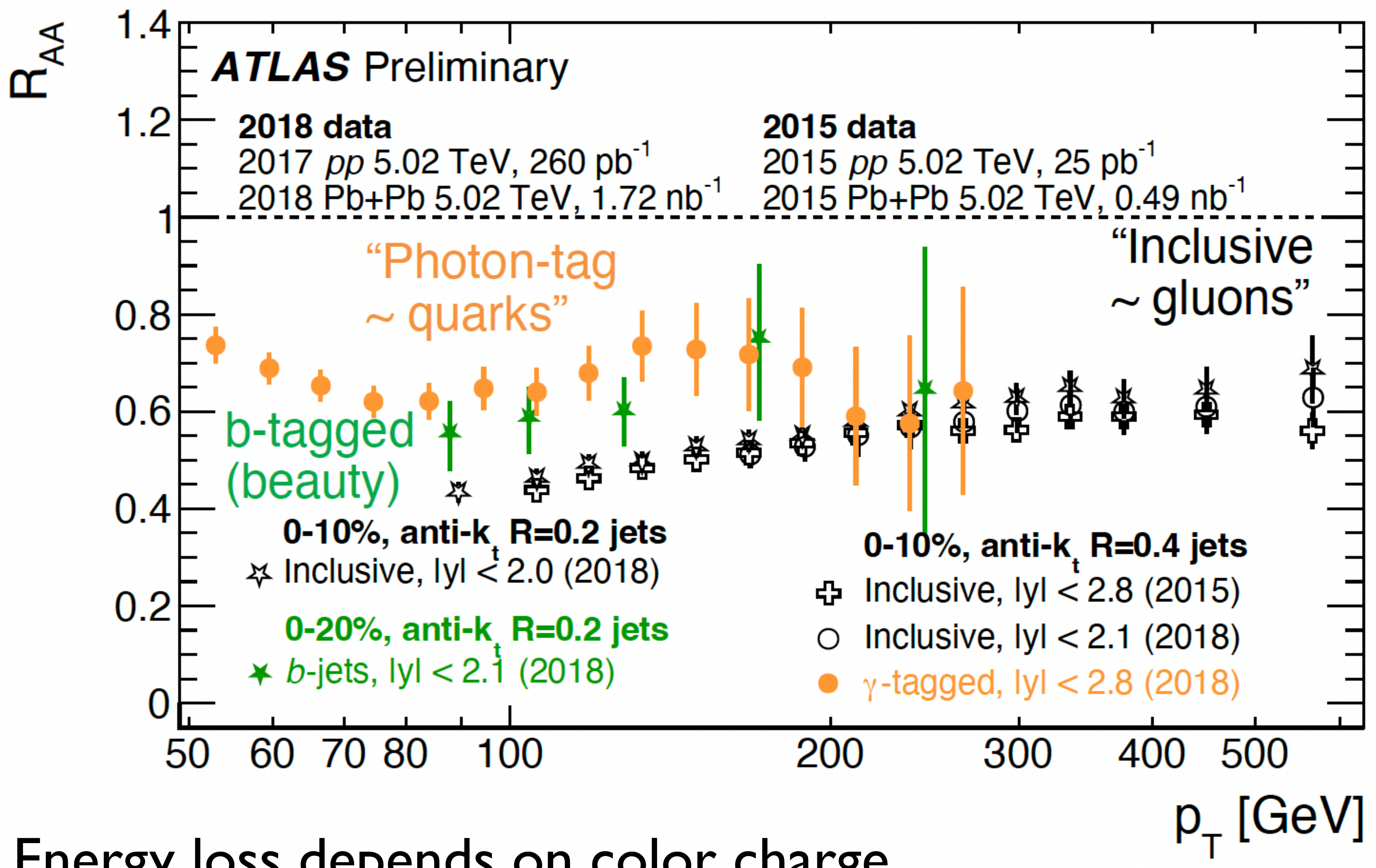
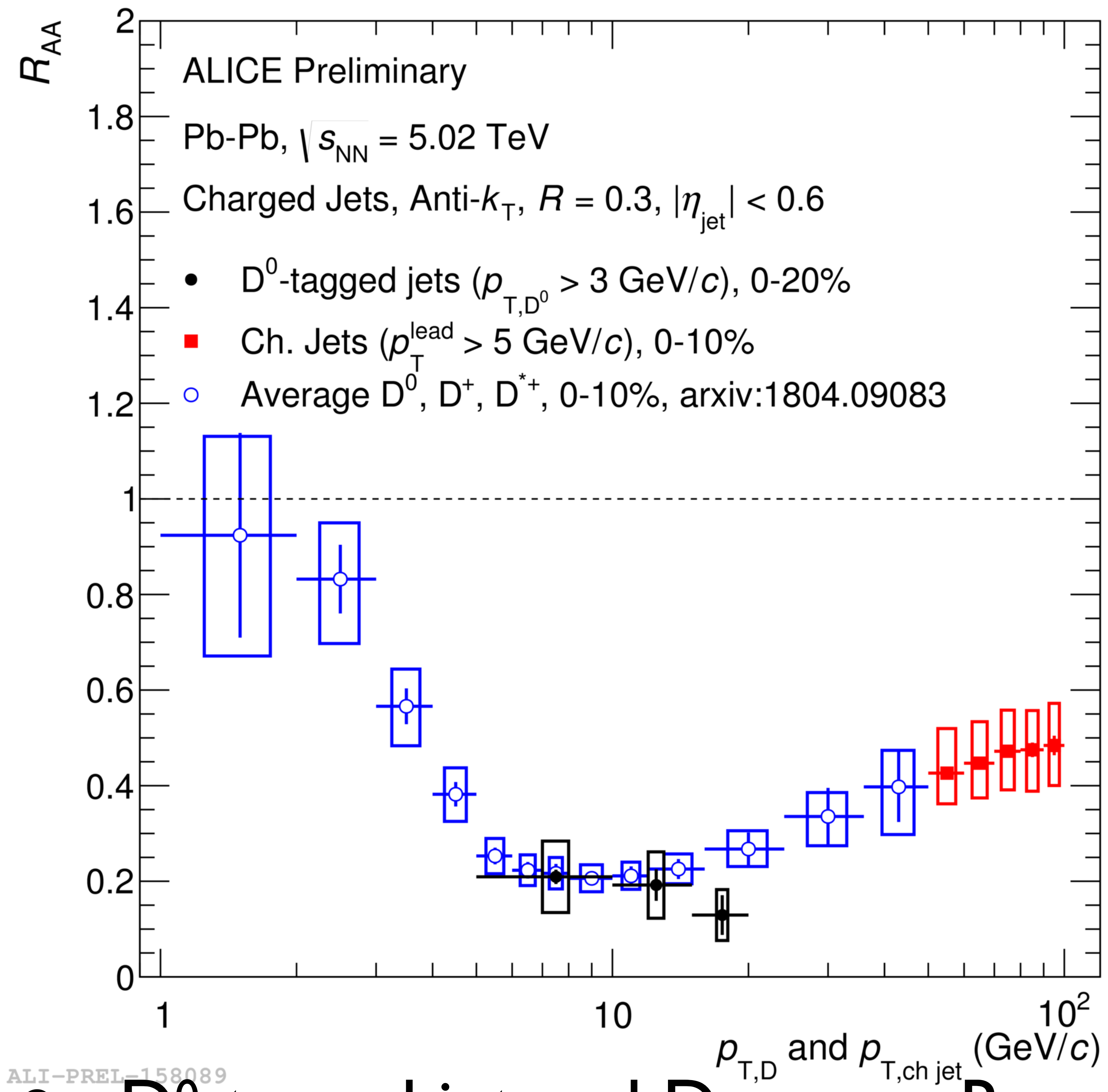
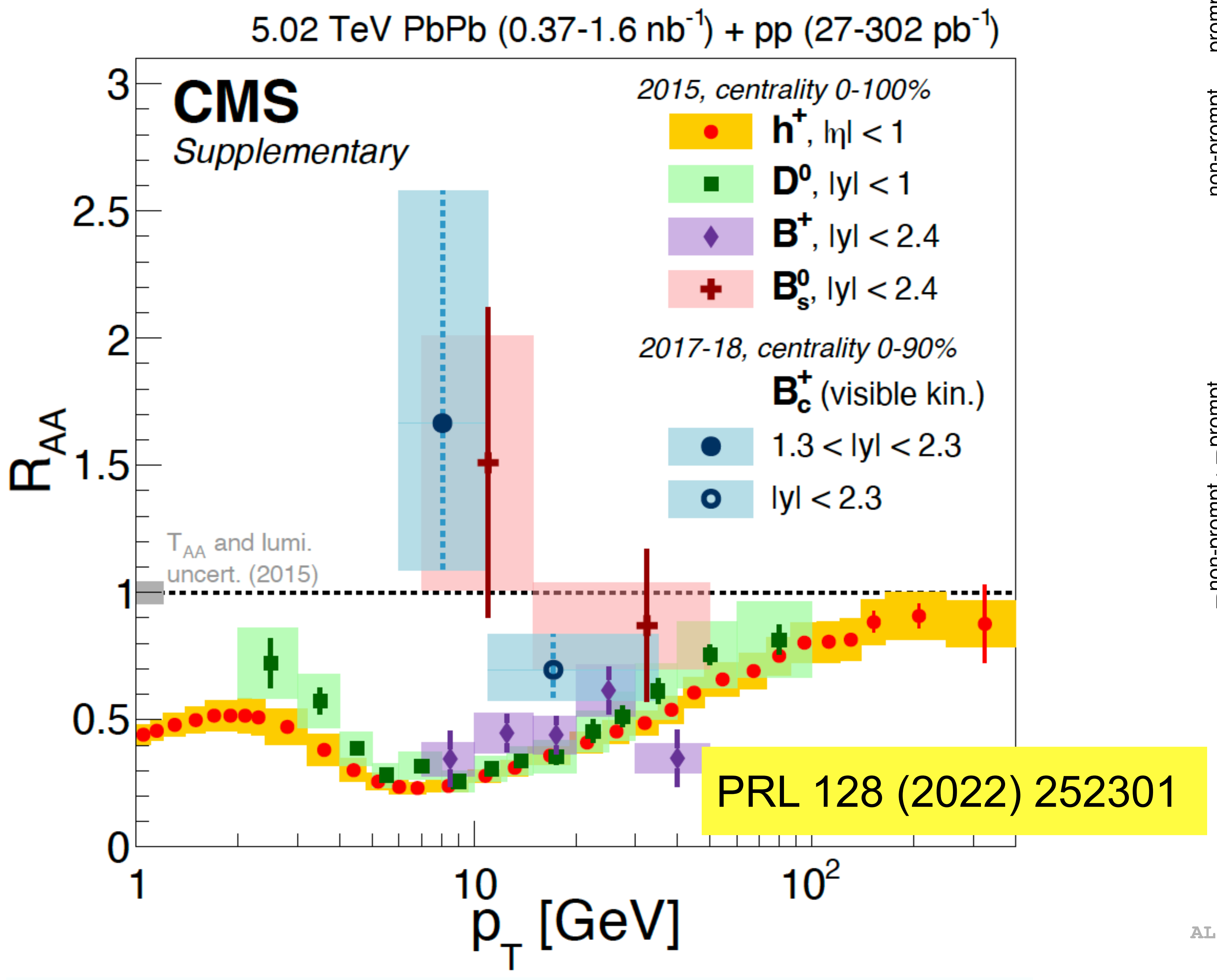


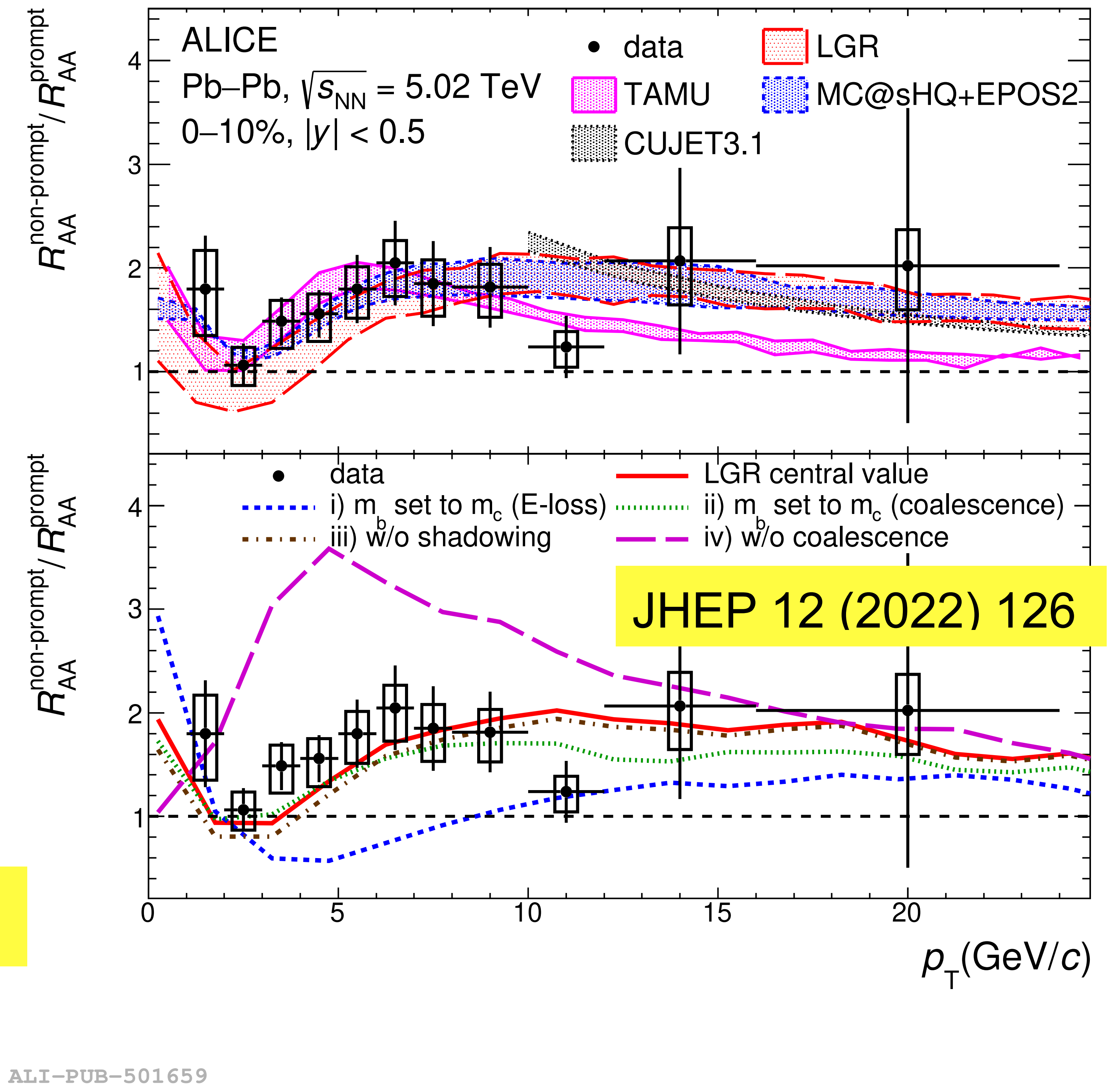
- Energy loss depends on color charge

- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect
- Less suppression of b-jets than inclusive jets in most central collisions

Flavor/Mass dependence of energy loss

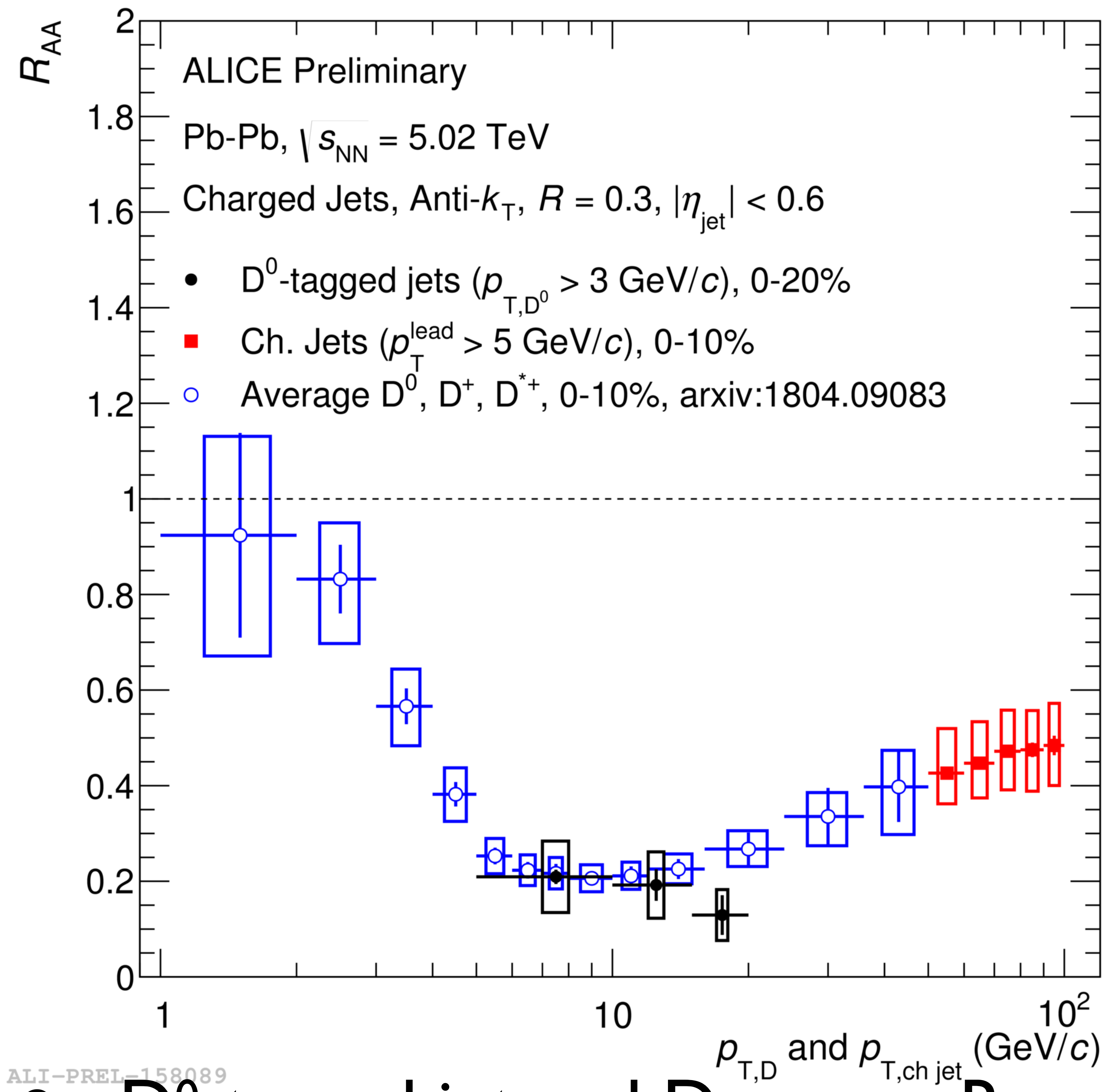


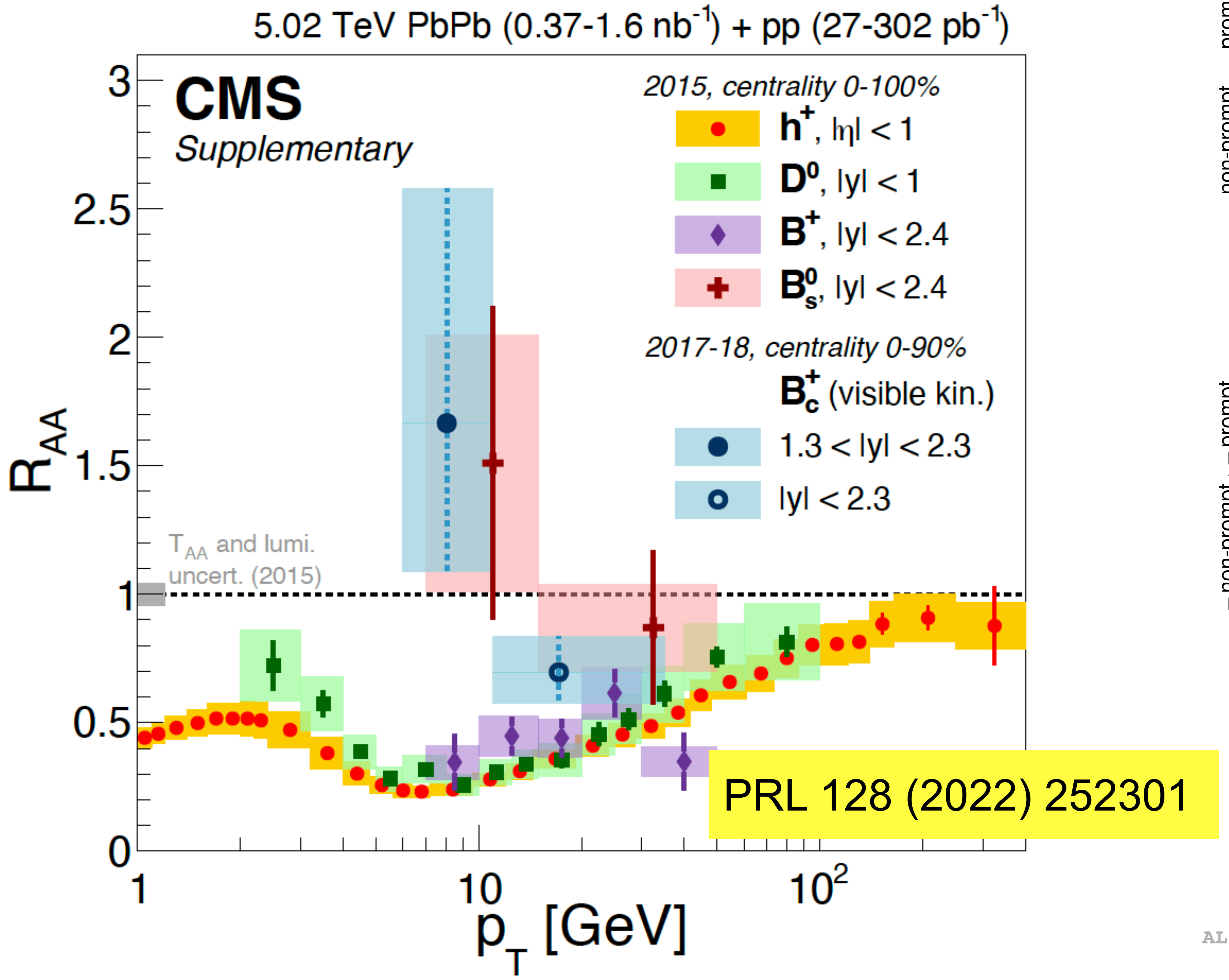


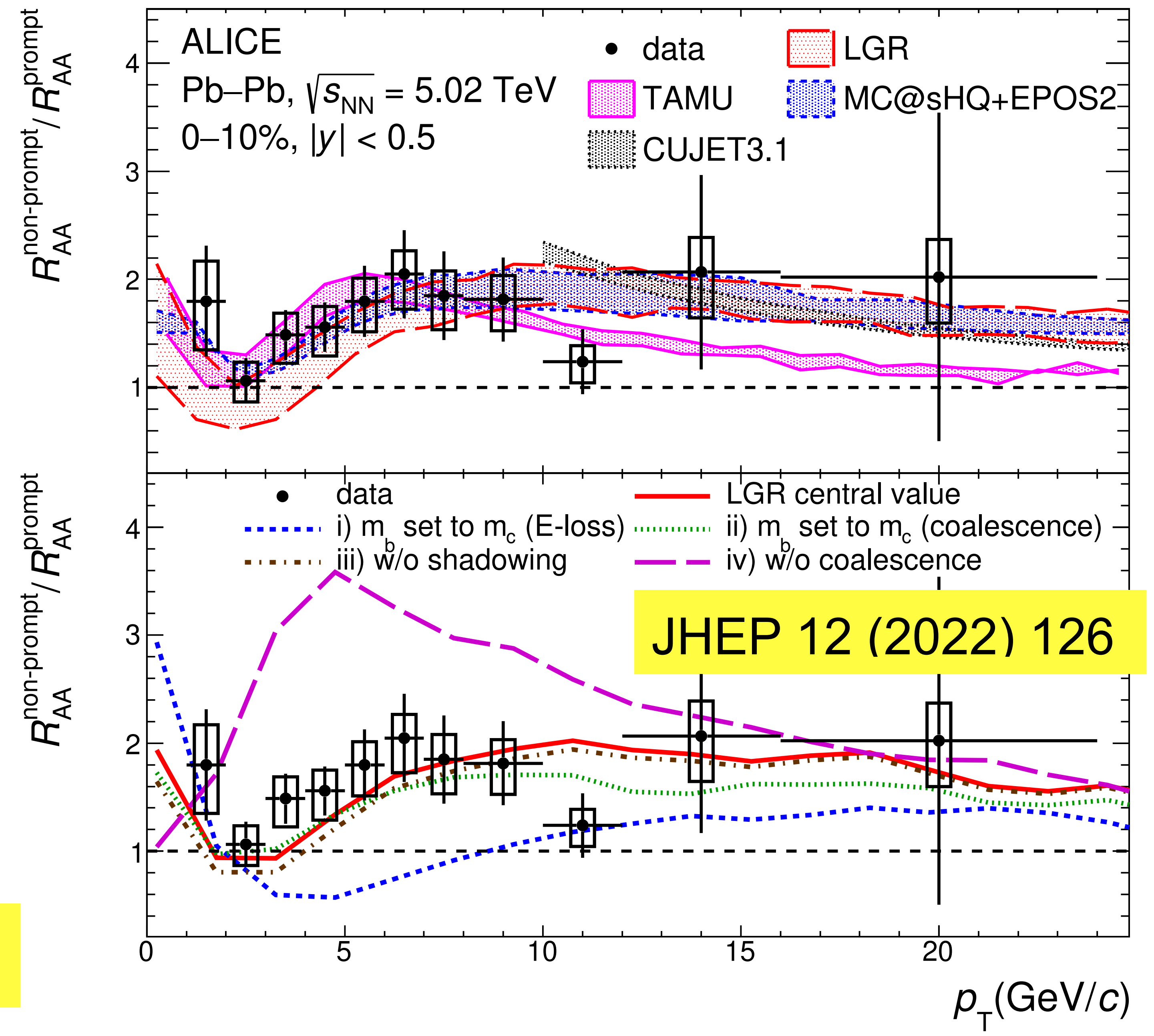


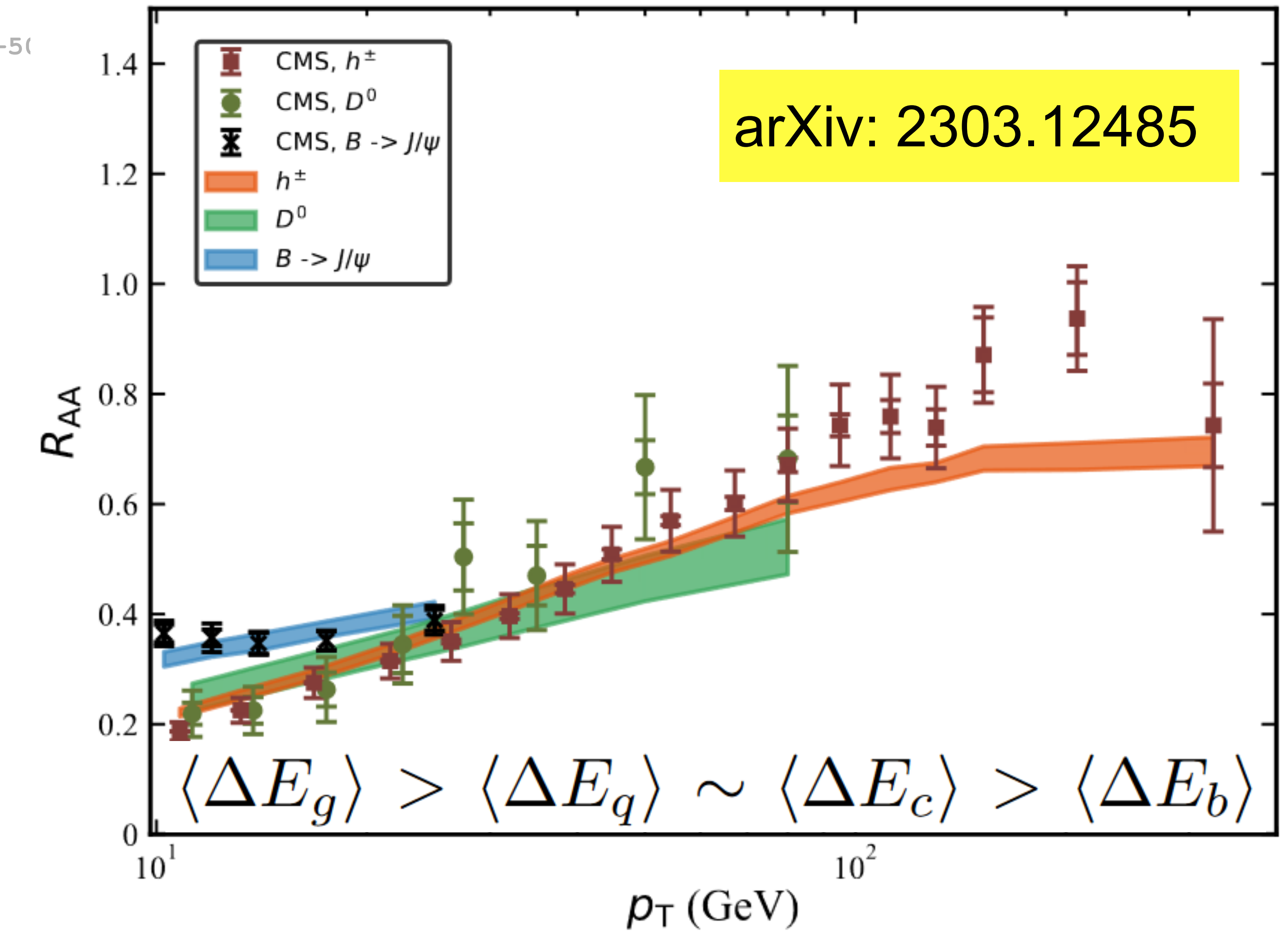
- D^0-tagged jet and D meson R_{AA} similar to inclusive jets/hadrons
- Mass dependence of energy loss is found between B and inclusive hadrons/ jets, but not charm and light flavors

Flavor/Mass dependence of energy loss



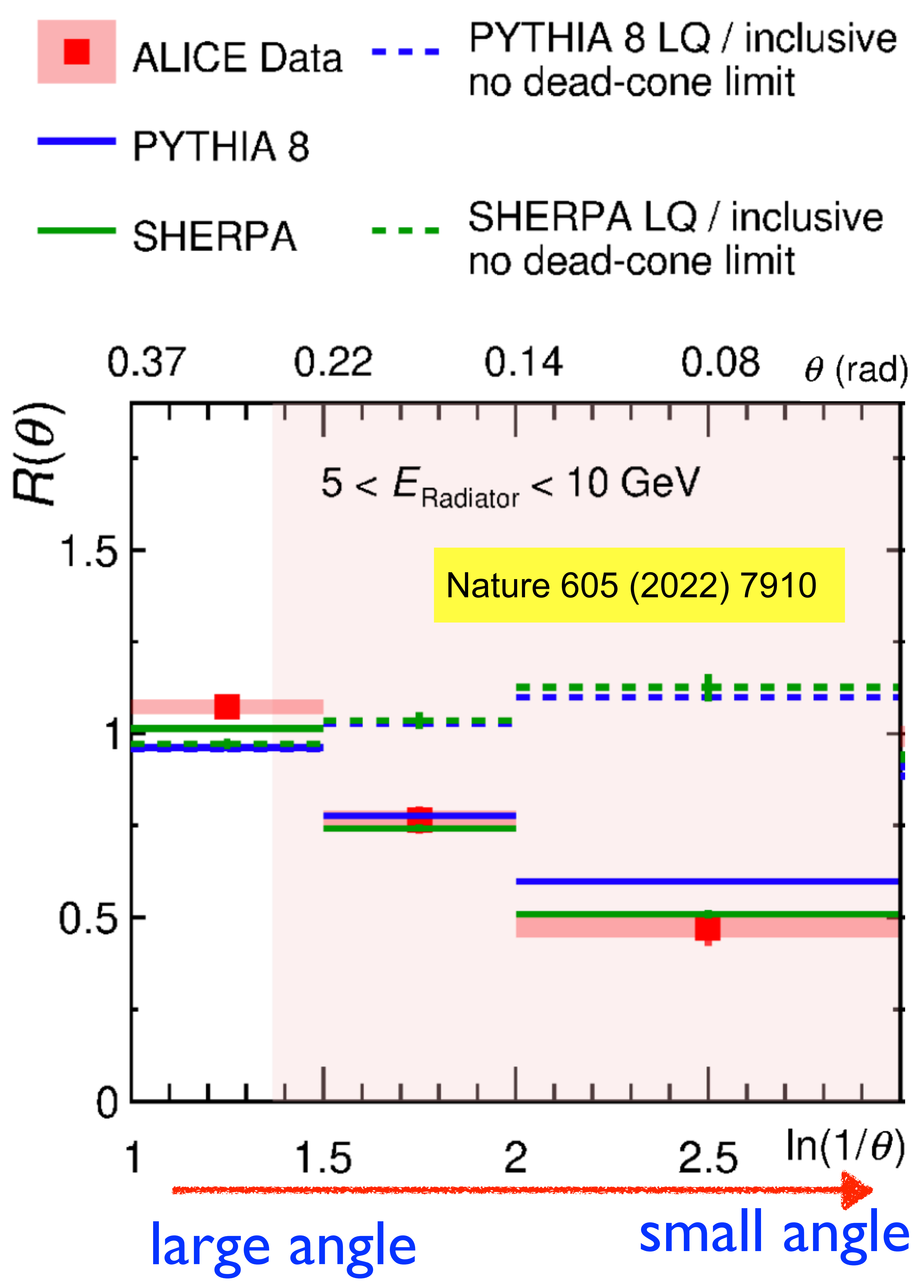


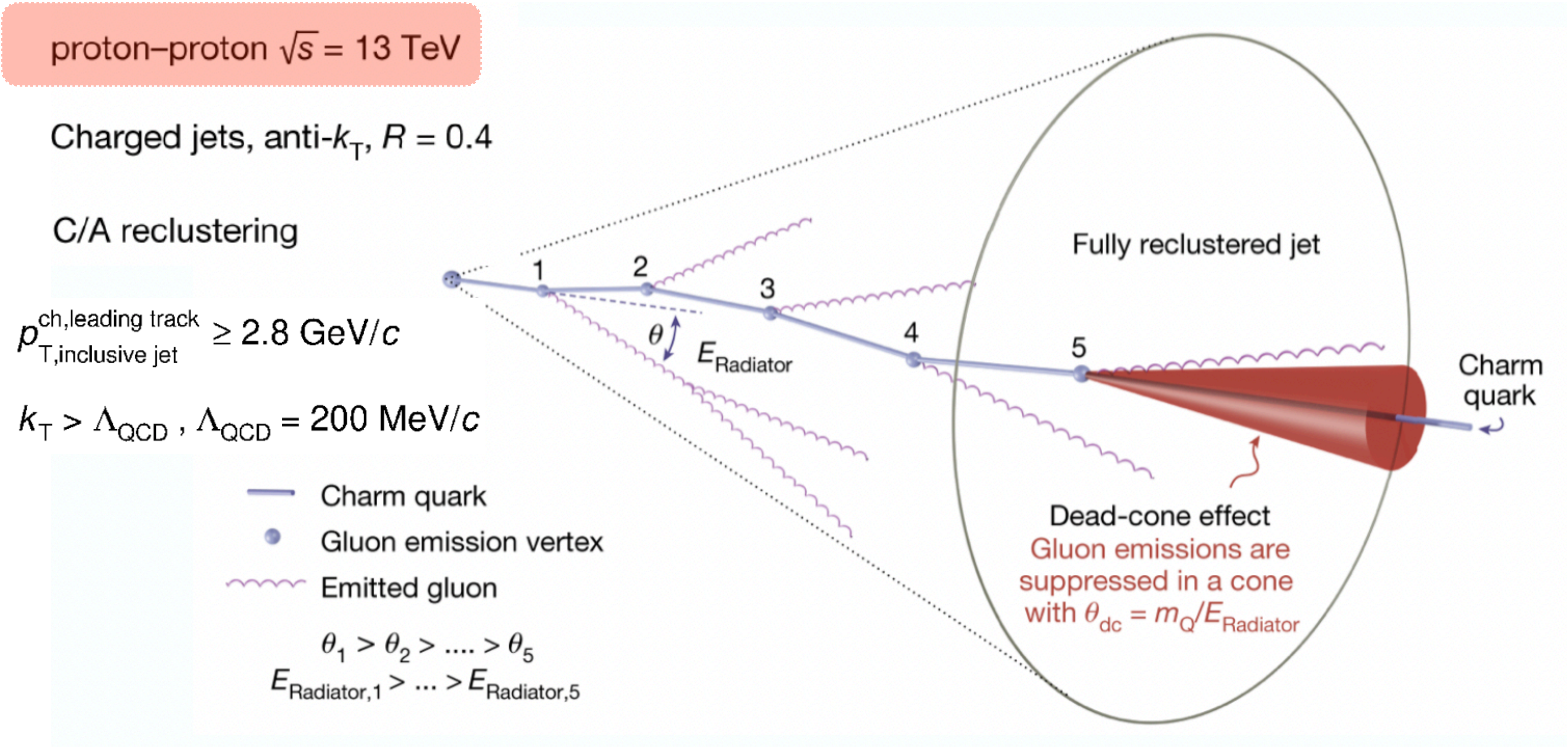




- D^0-tagged jet and D meson R_{AA} similar to inclusive jets/hadrons
- Mass dependence of energy loss is found between B and inclusive hadrons/jets, but not charm and light flavors
- Model that includes both quark and gluon fragmentation to light and heavy flavor hadrons can explain the flavor dependence of hadrons

First observation of dead-cone effect in pp





$$R(\theta) = \frac{1}{N^{\mathrm{D^0 jets}}} \frac{\mathrm{d}n^{\mathrm{D^0 jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\ jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\ jets}}}{\mathrm{d}\ln(1/\theta)} \Big|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

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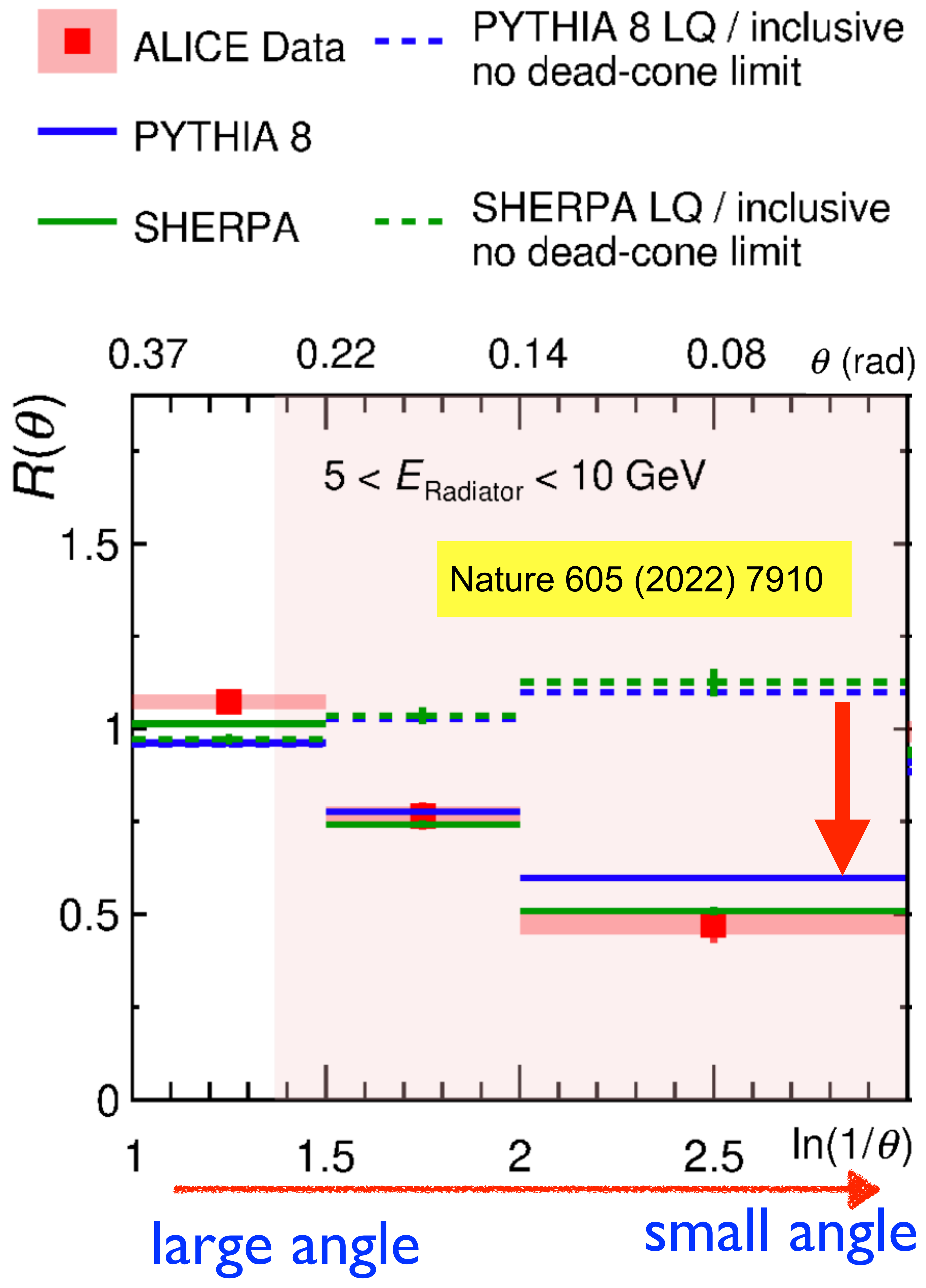

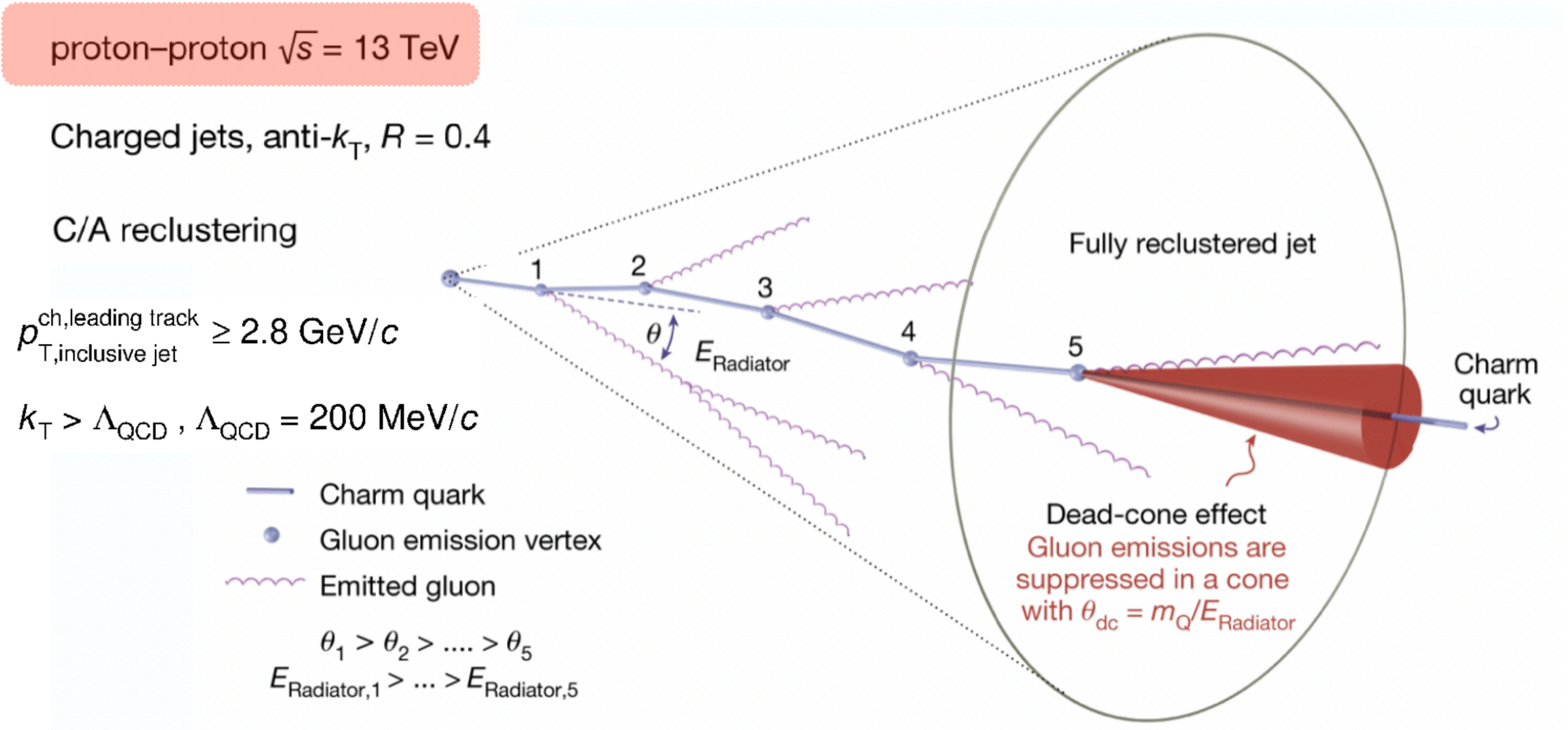

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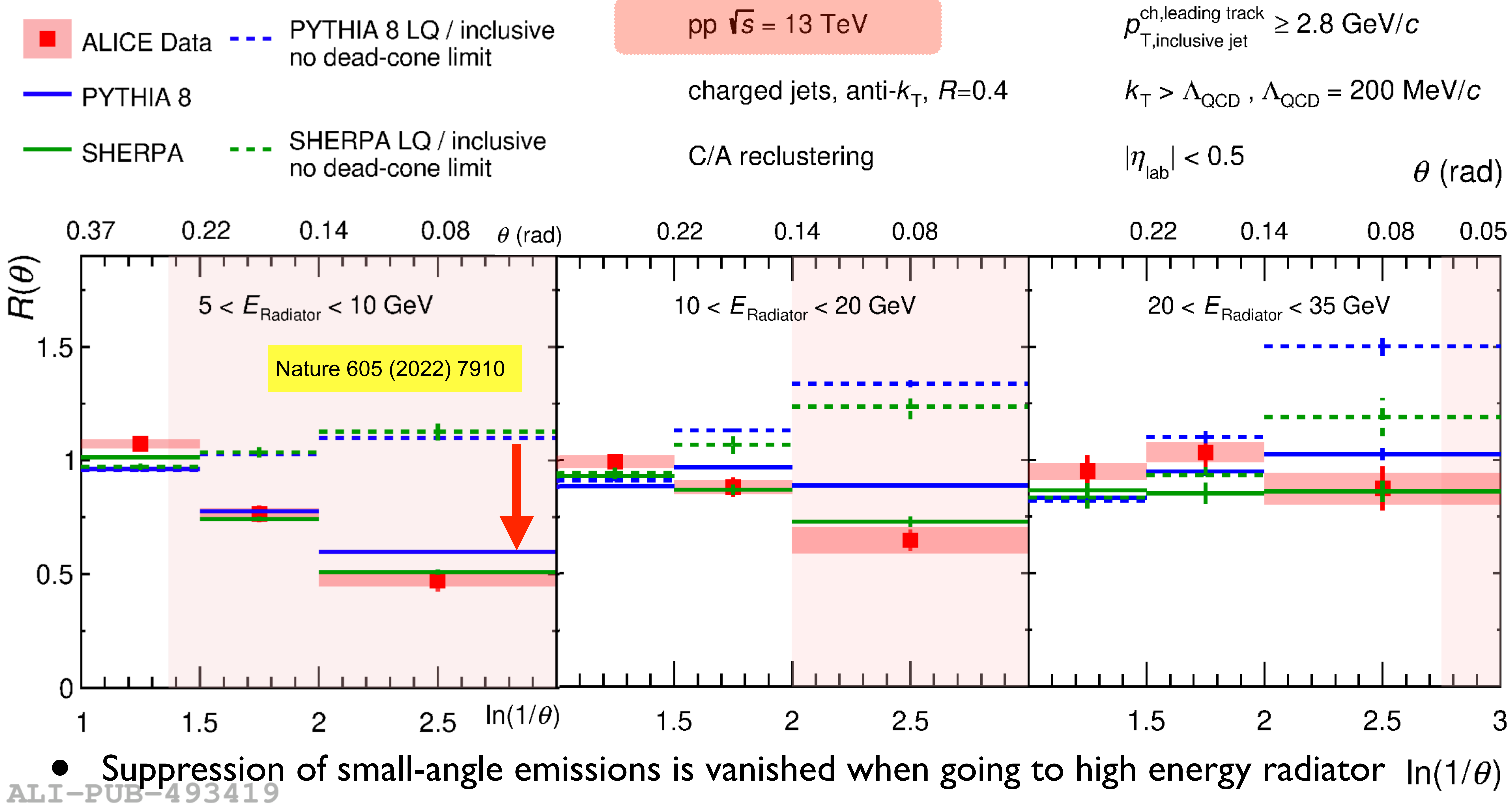
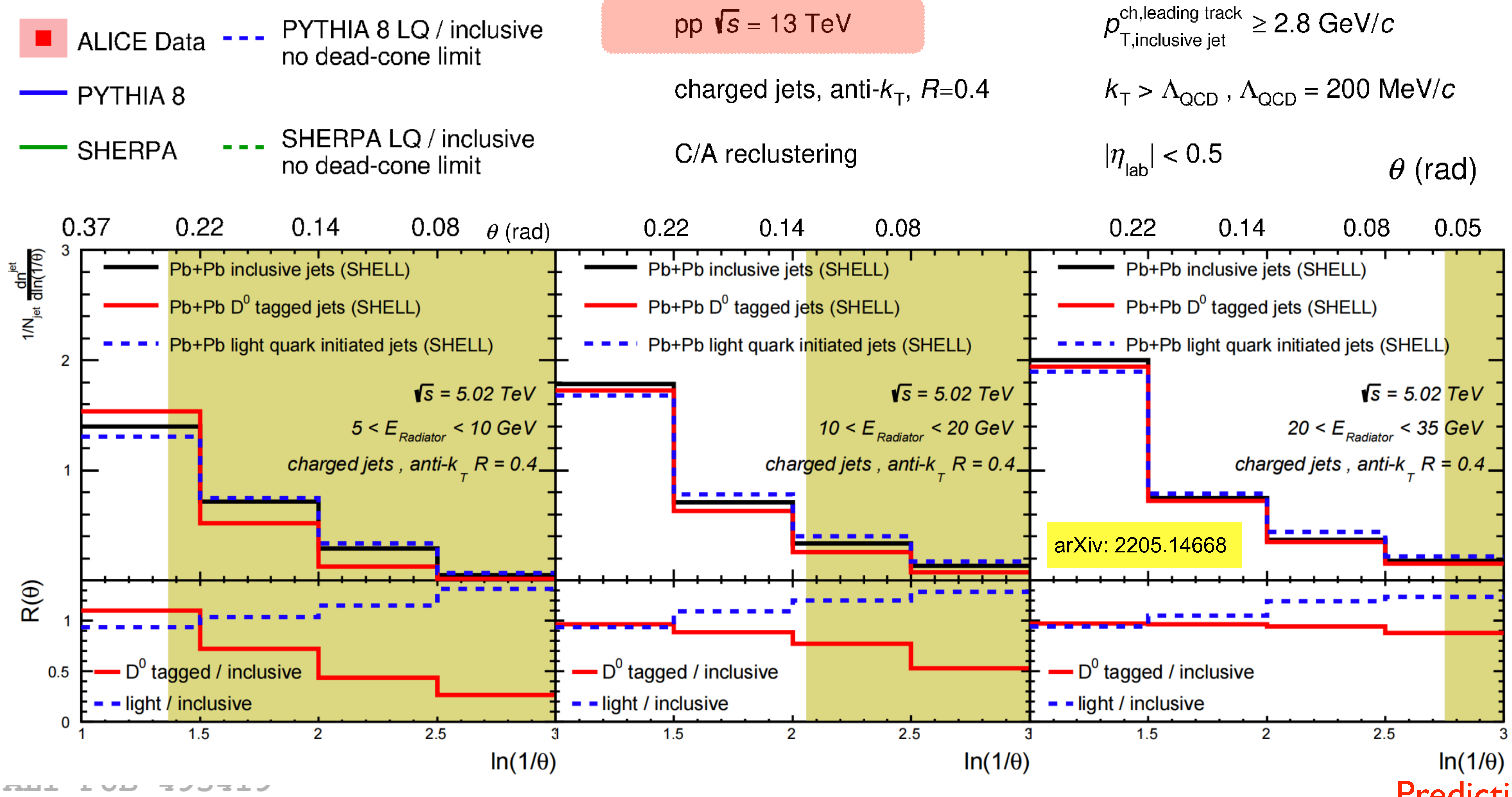
- Significant suppression of small-angle emissions using Lund plane analysis of jets that contain a soft D^0 meson

Dead-cone effects for charm quark



- Suppression of small-angle emissions is vanished when going to high energy radiator

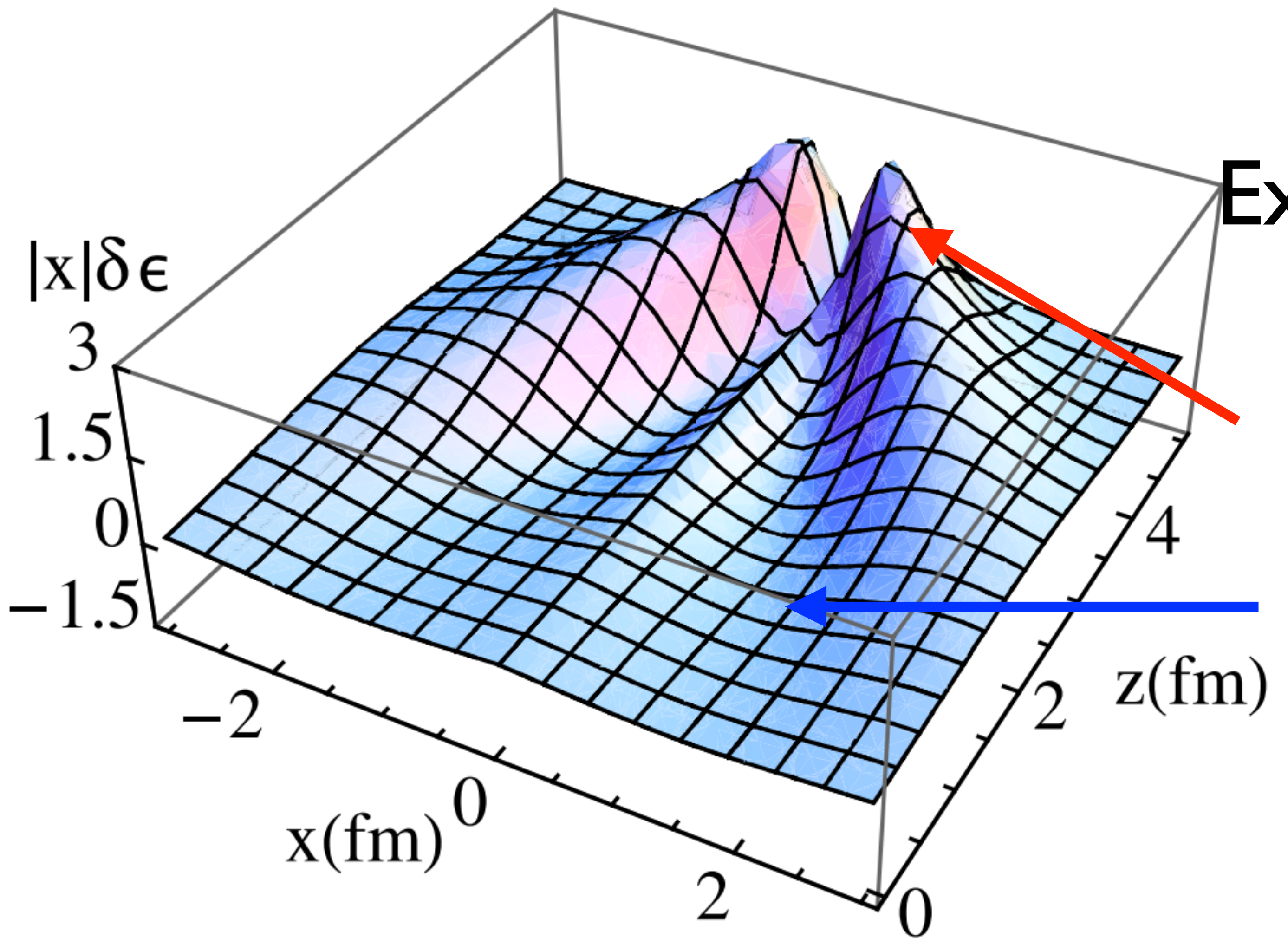
Dead-cone effects for charm quark



Predictions in AA!

Medium response to propagating parton

- Jet lose energy due to interaction with medium
  - ➡ medium modified by jets

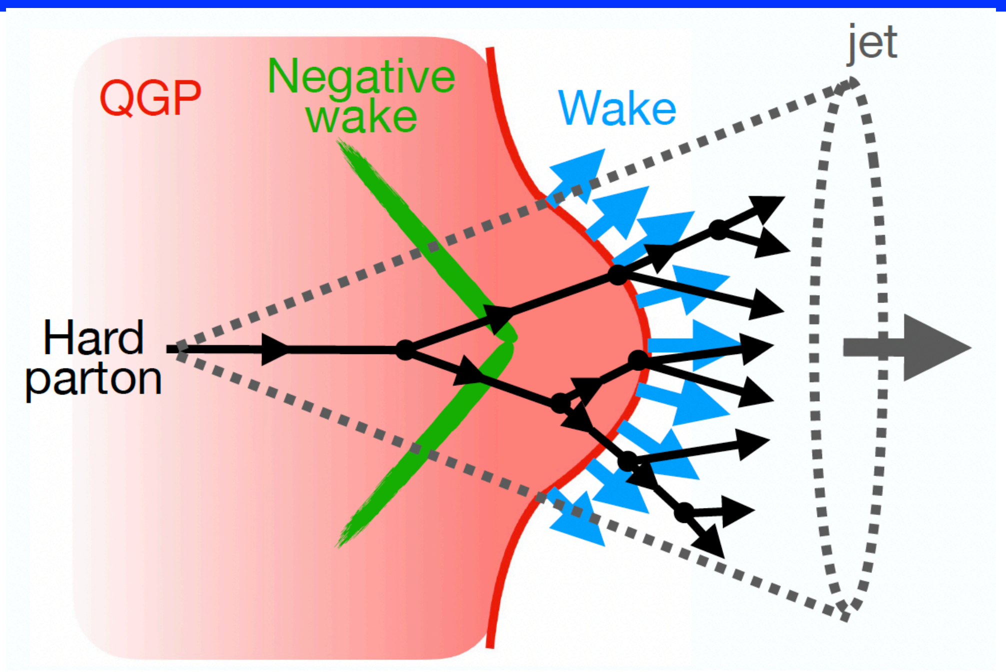


Expectations: "wake effects"

Enhancement around jet

Depletion opposite jet

PRL 103 (2009) 152303



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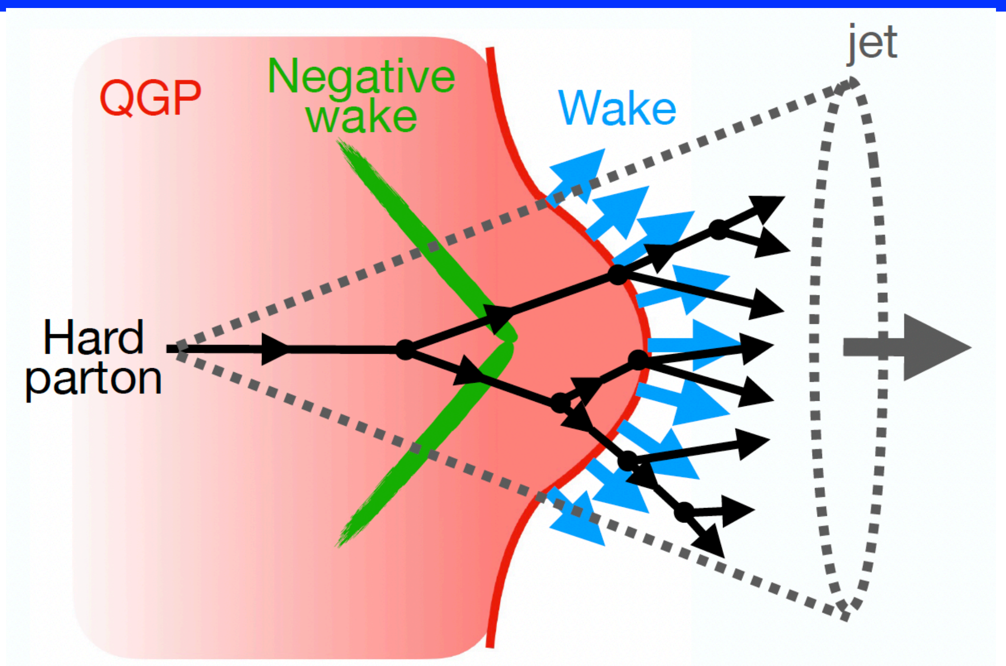
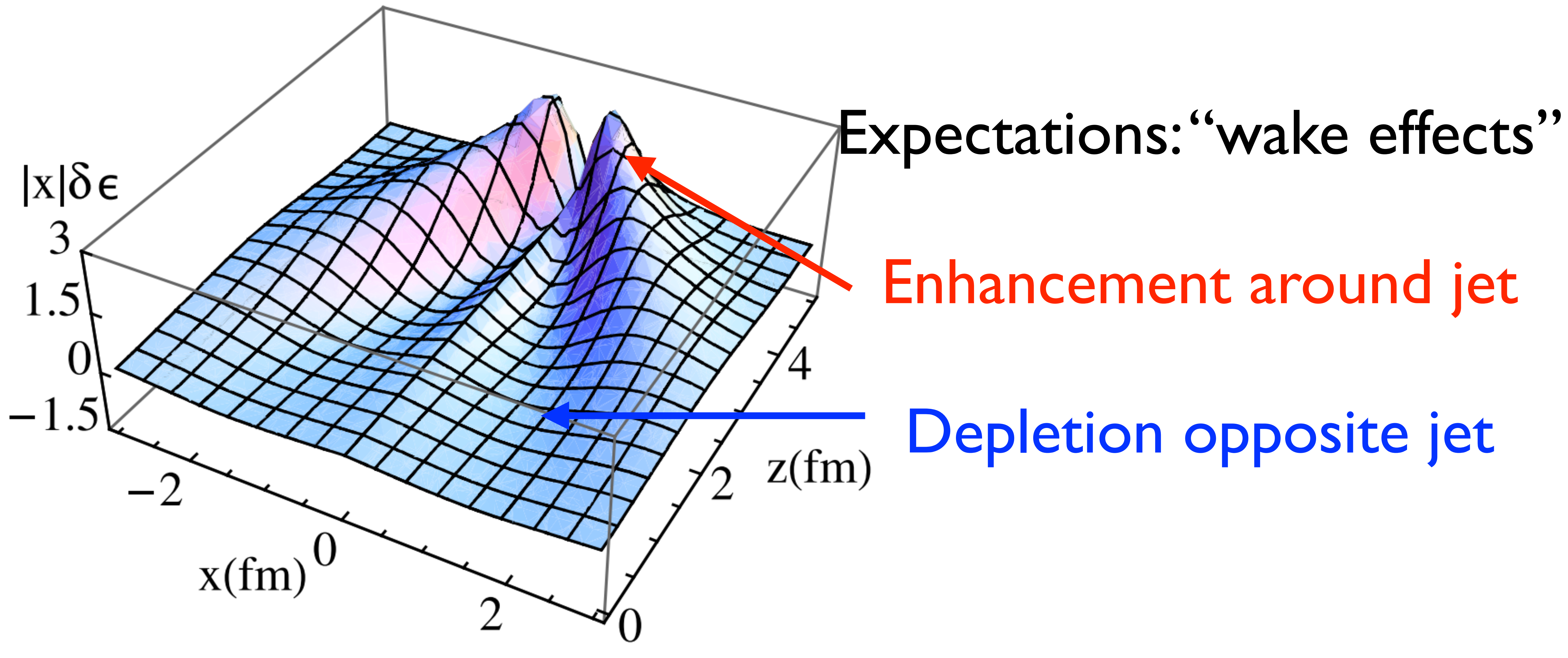
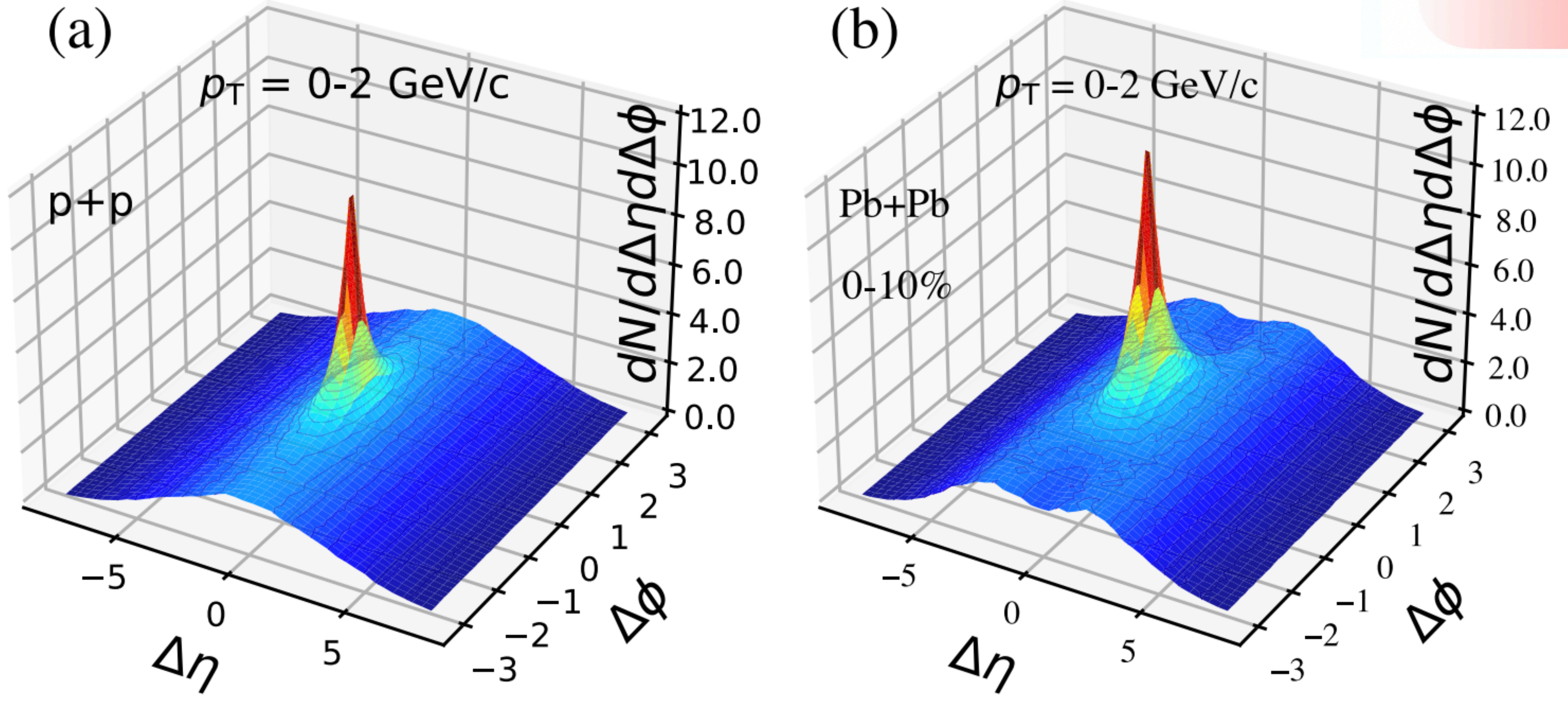


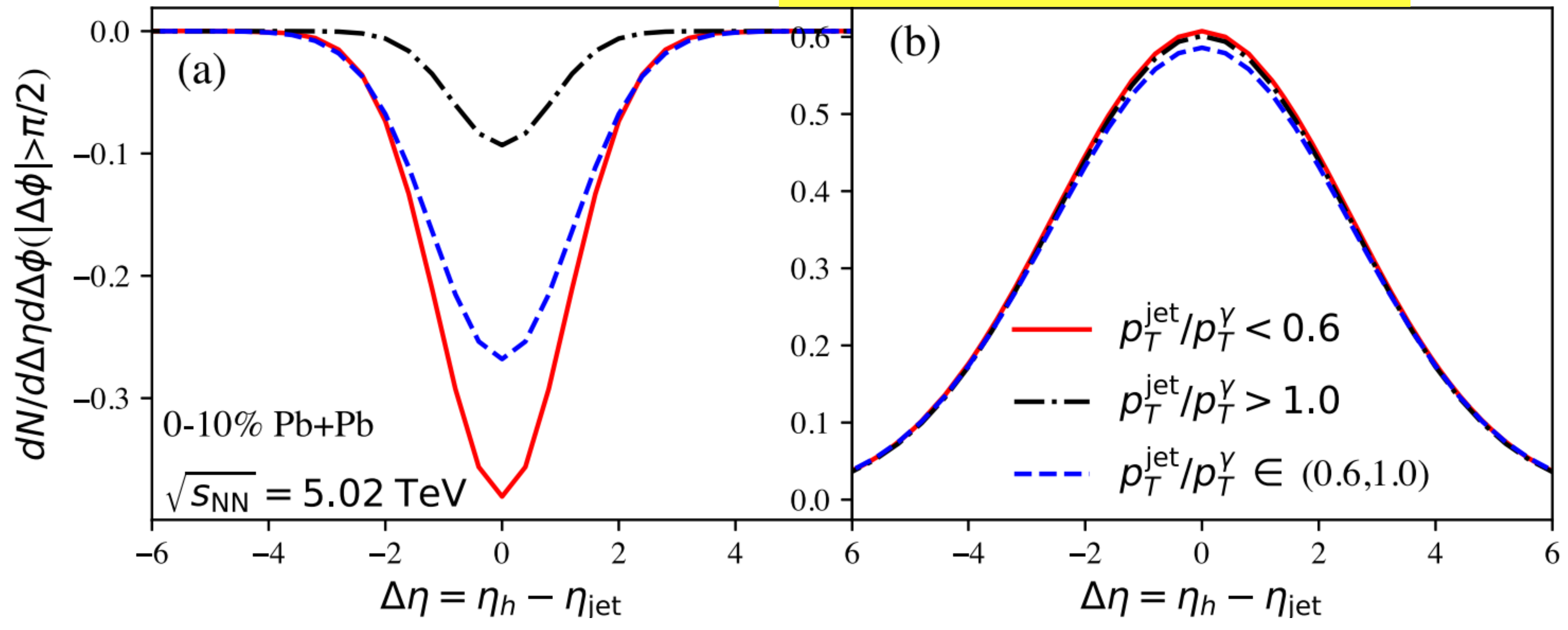


PRL 103 (2009) 152303



PRL 130 (2023) 052301

- CoLBT-Hydro predicts double peak structure in γ-hadron correlations as a function of rapidity and azimuth (valley from diffusion wake, ridge from MPI)
- Depth of the diffusion wake valley increases with increasing jet energy loss as characterized by γ-jet asymmetry



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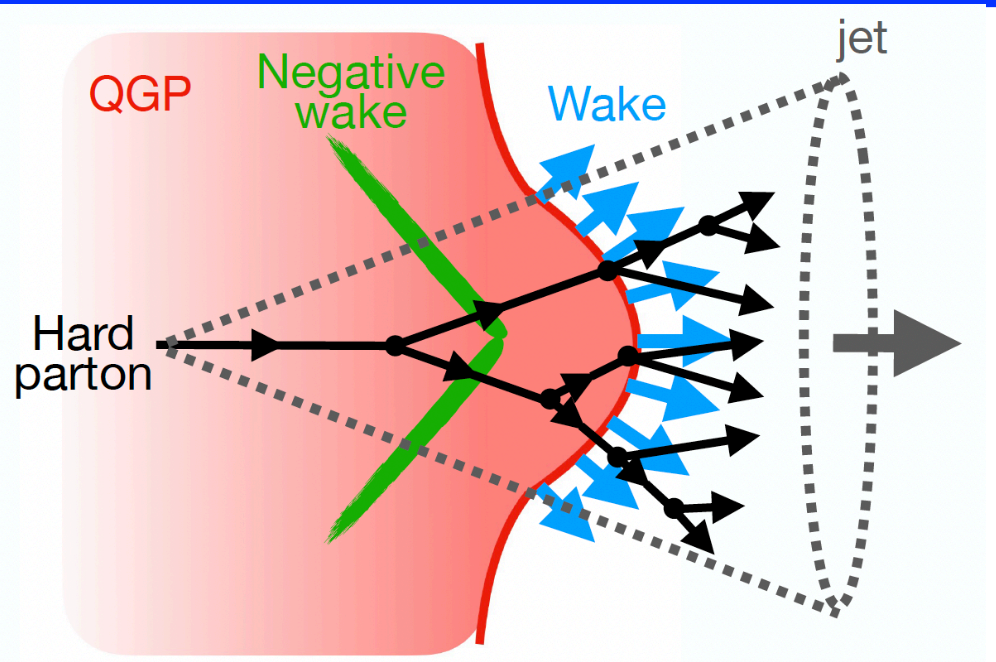
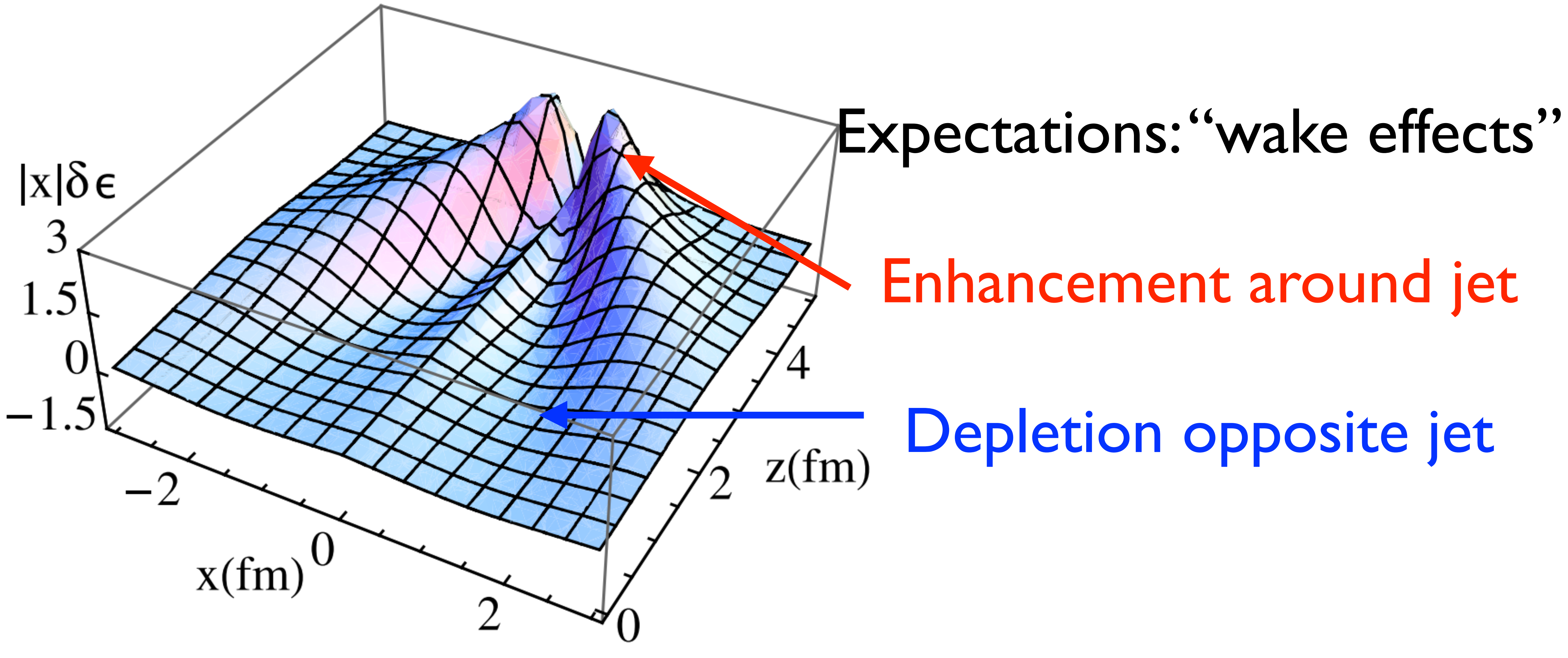
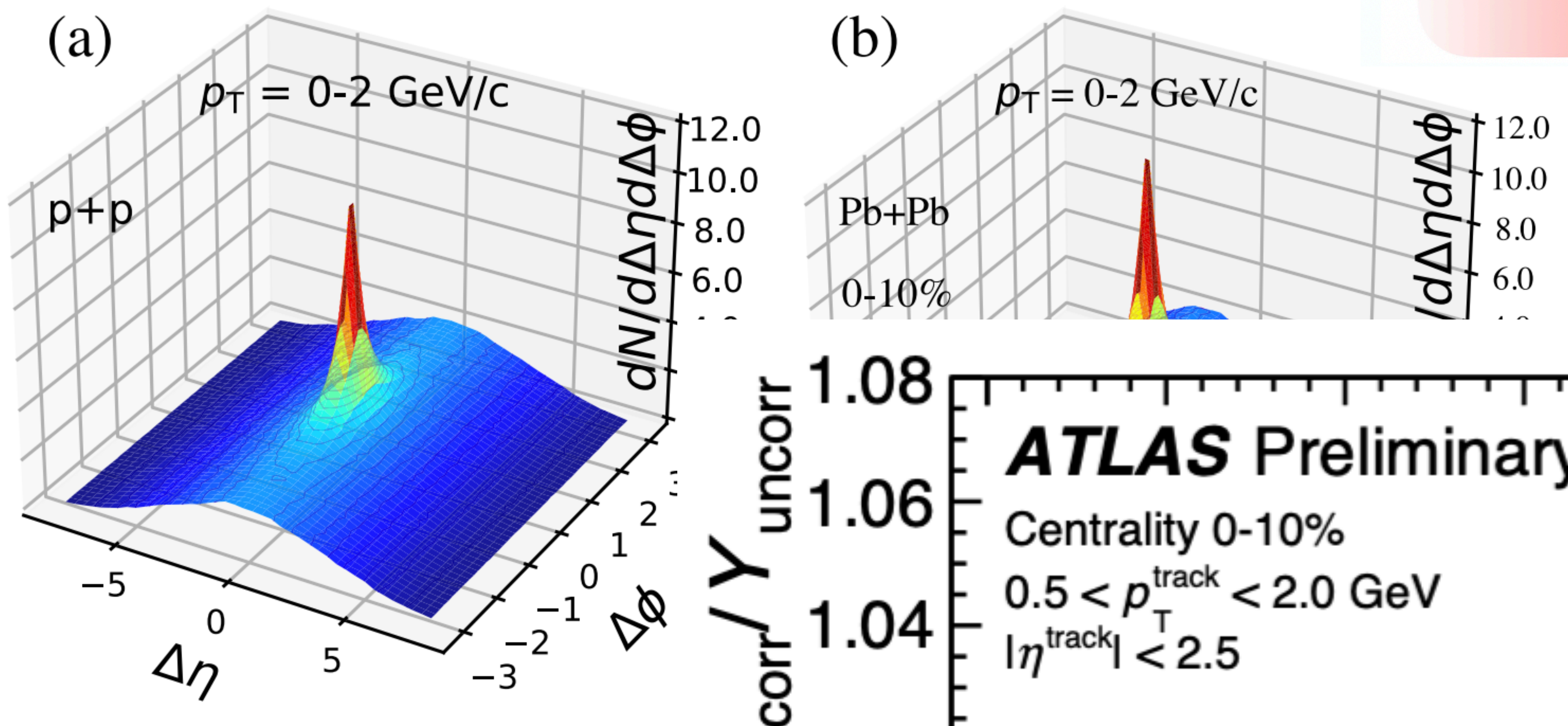
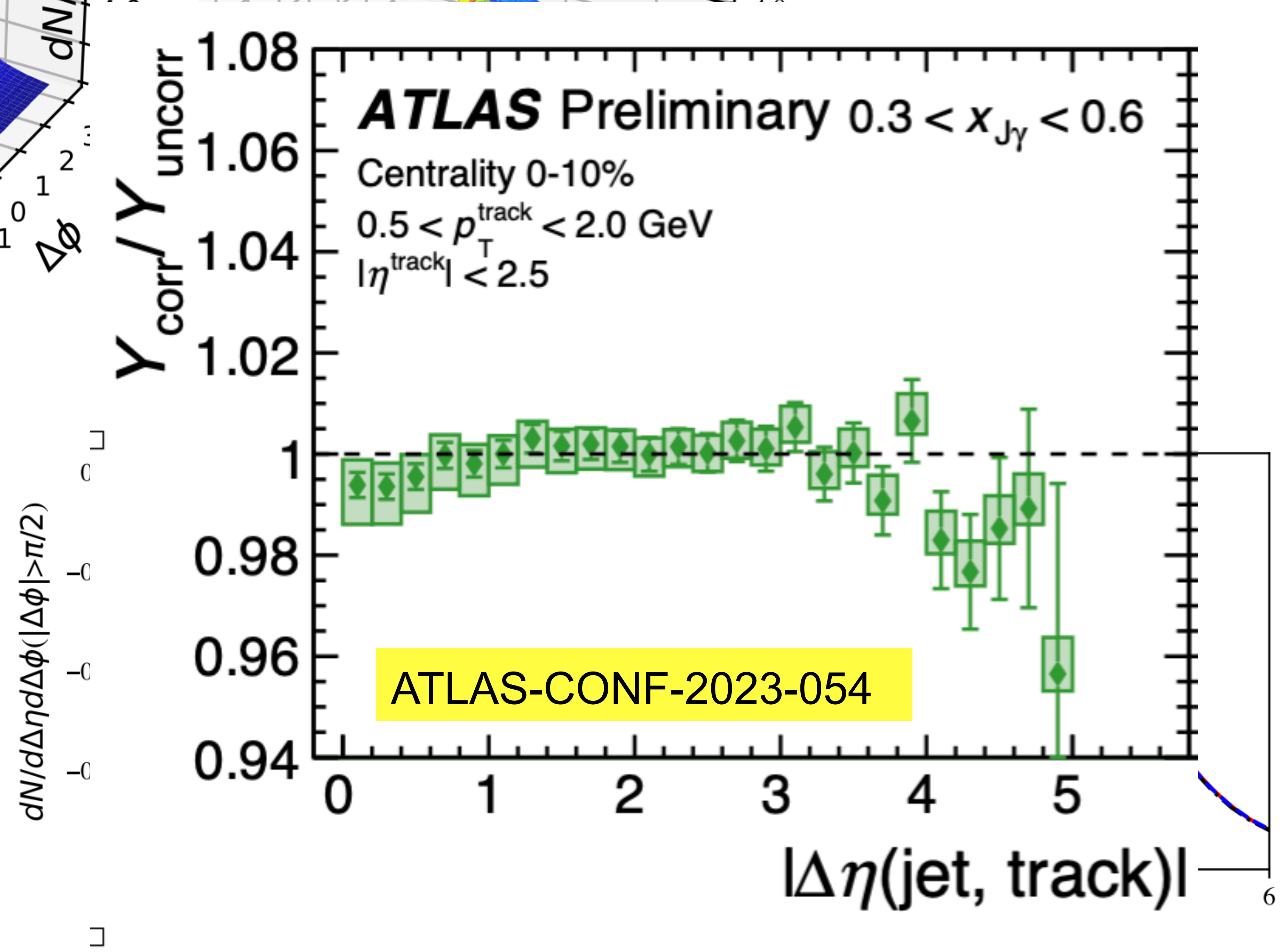
- Jet lose energy due to interaction with medium
  - ➡ medium modified by jets





PRL 103 (2009) 152303

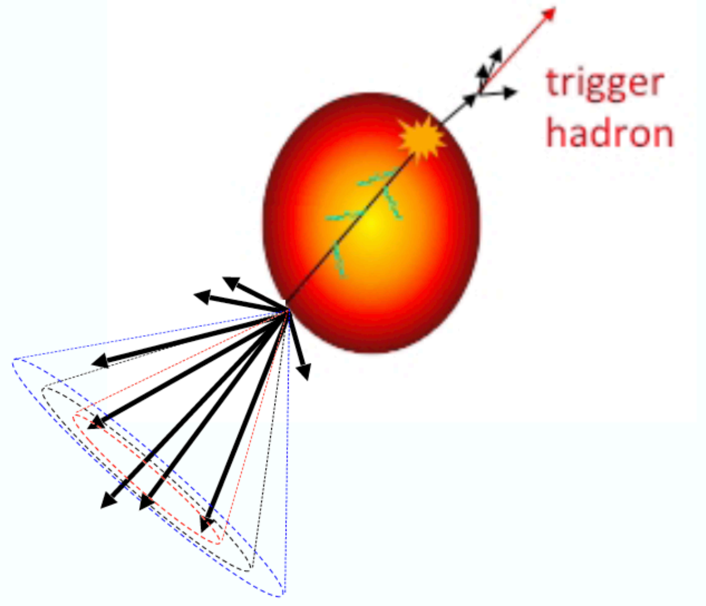


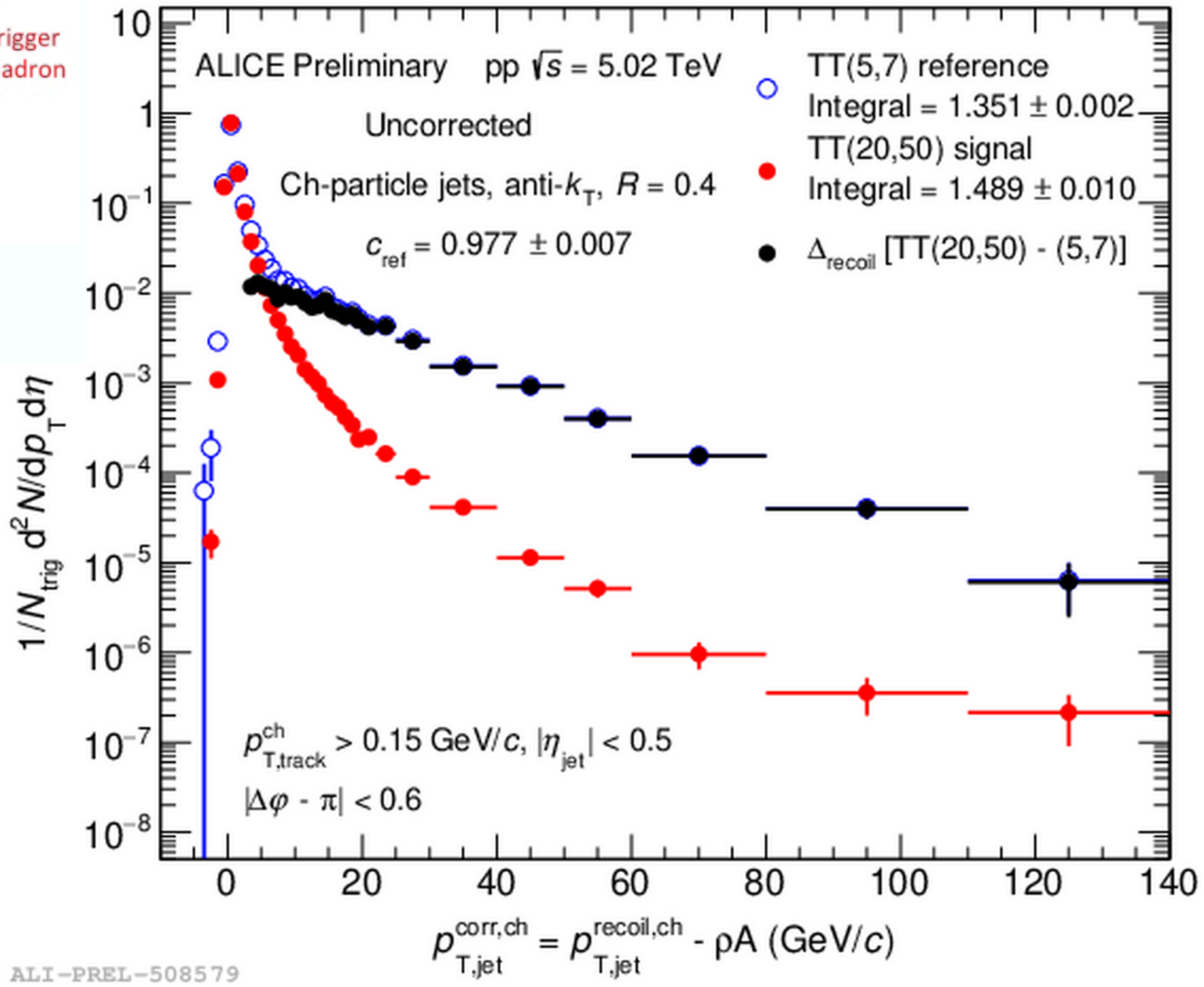


ATLAS-CONF-2023-054

- CoLBT-Hydro predicts double peak structure in γ-hadron correlations as a function of rapidity and azimuth (valley from diffusion wake, ridge from MPI)
- Depth of the diffusion wake valley increases with increasing jet energy loss as characterized by γ-jet asymmetry

Semi-inclusive yield of jets recoiling from high-p_T hadron

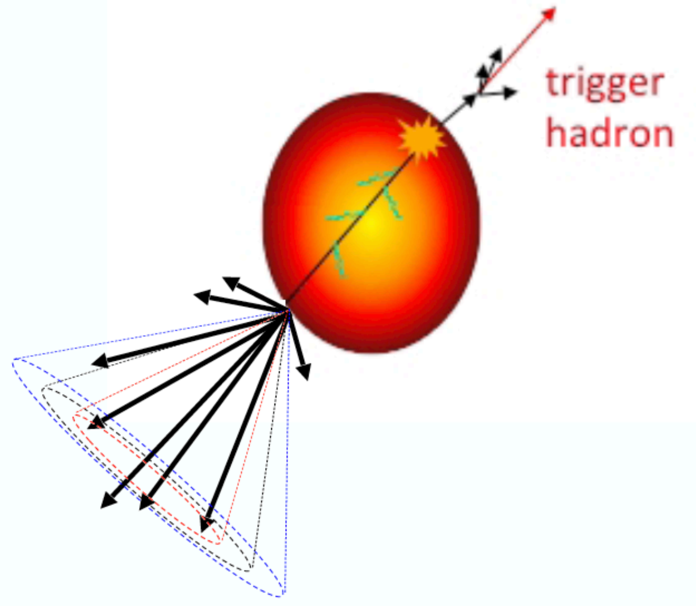


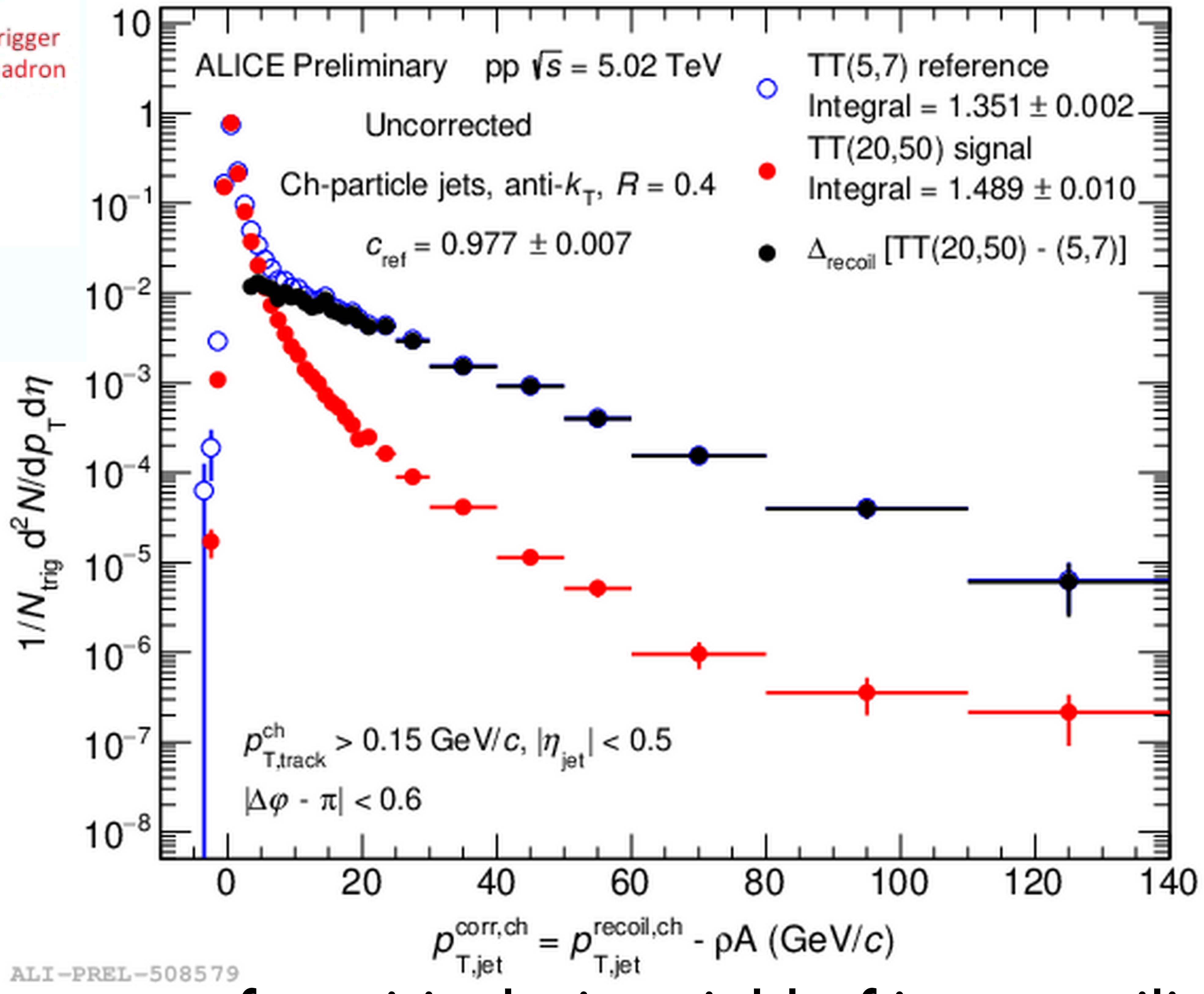


$$\Delta_{\mathrm{recoil}} = \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}}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

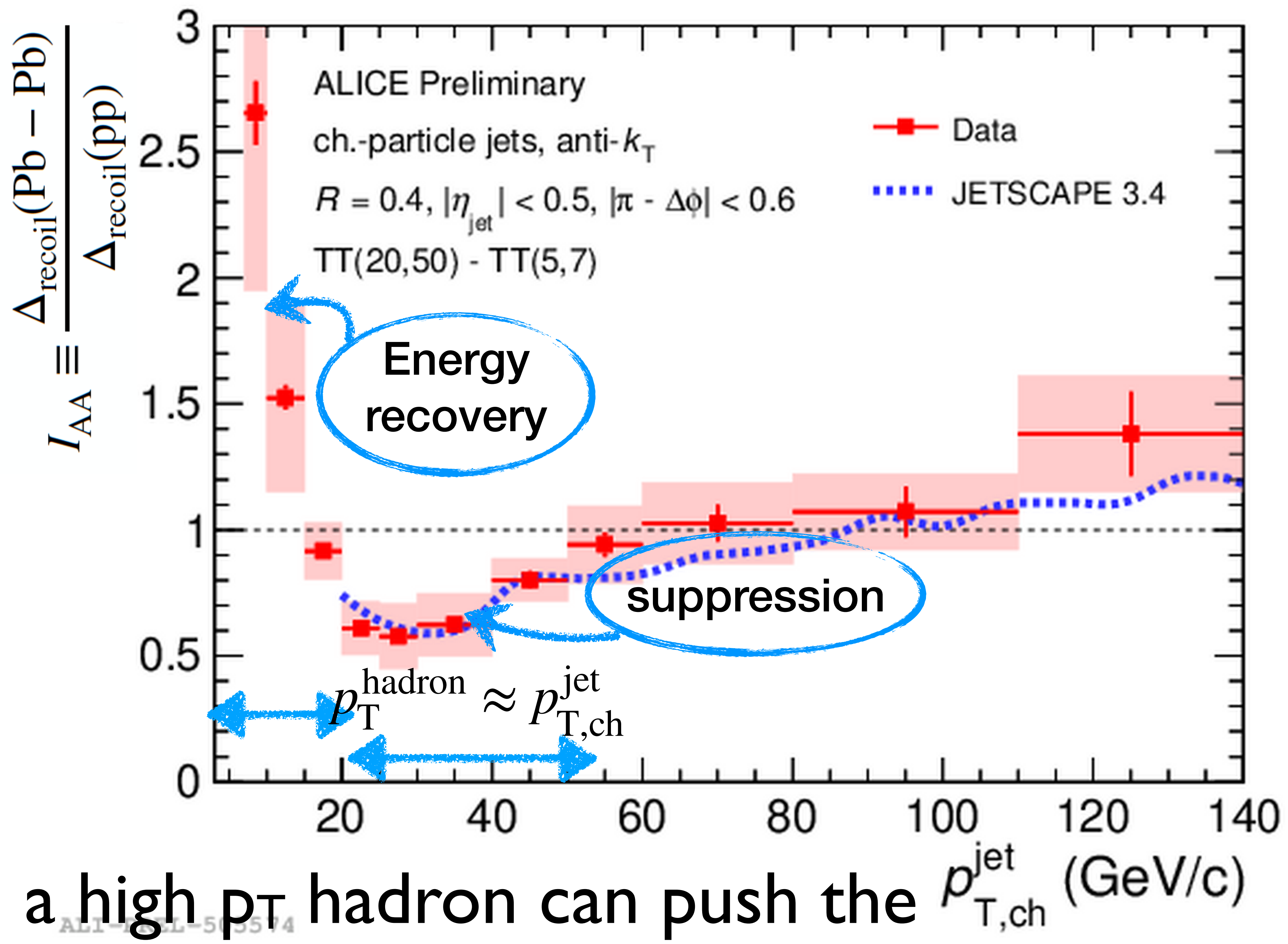
- Measurements of semi-inclusive yield of jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening

Semi-inclusive yield of jets recoiling from high-p_T hadron





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



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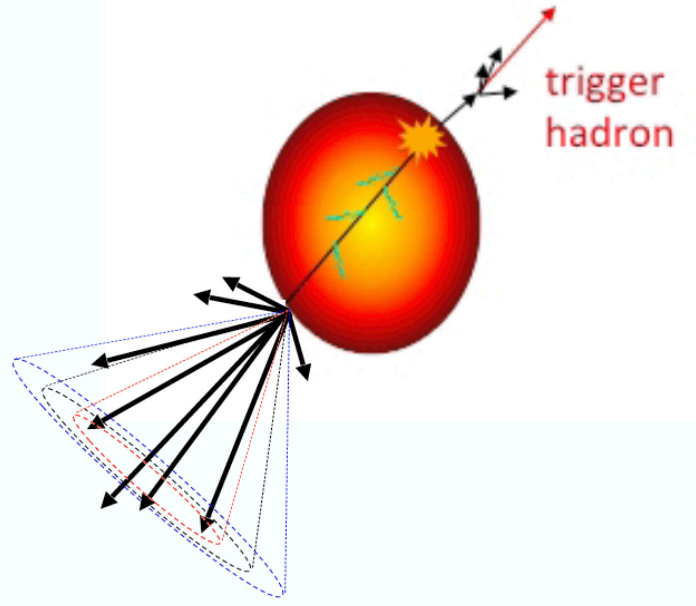
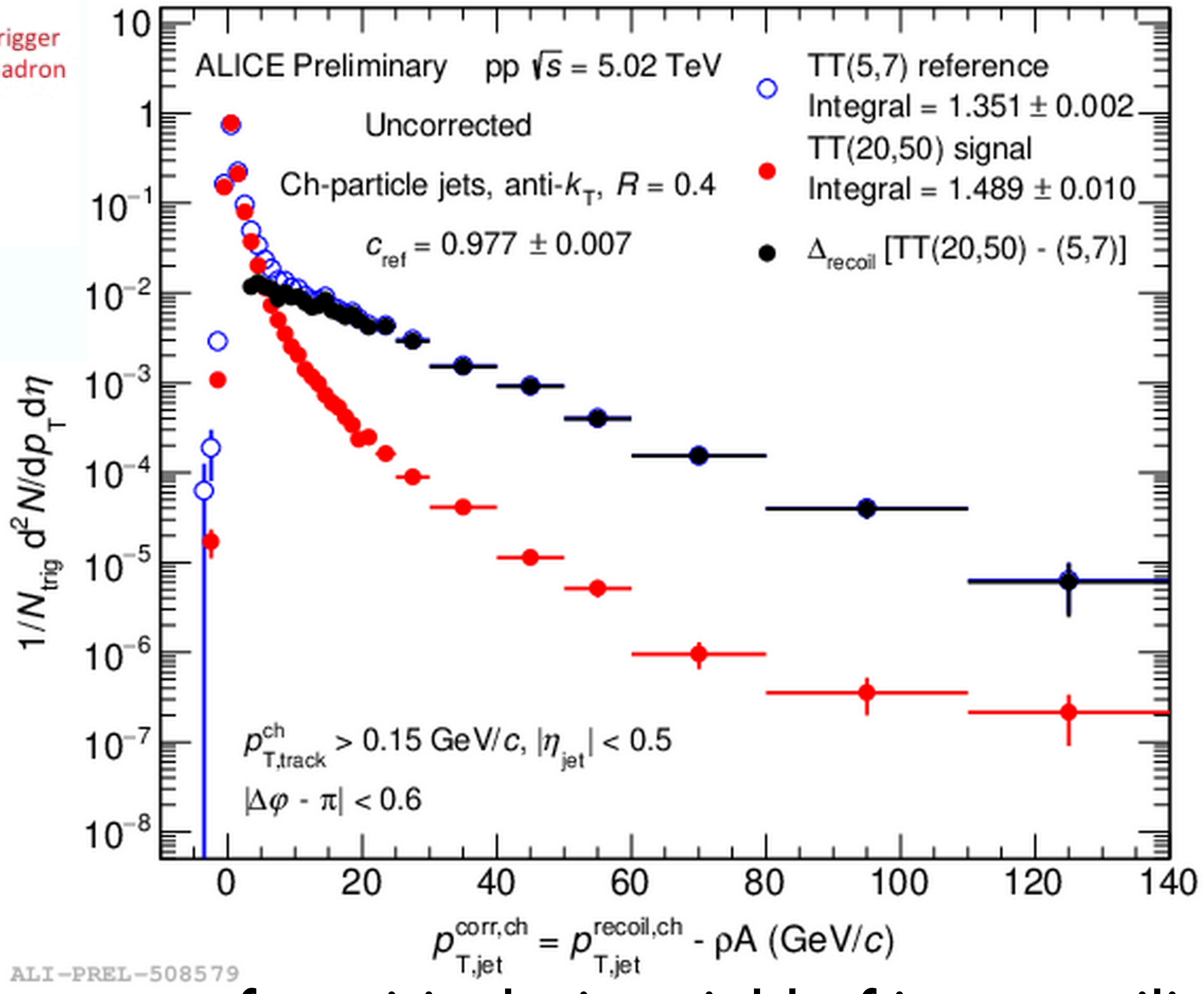
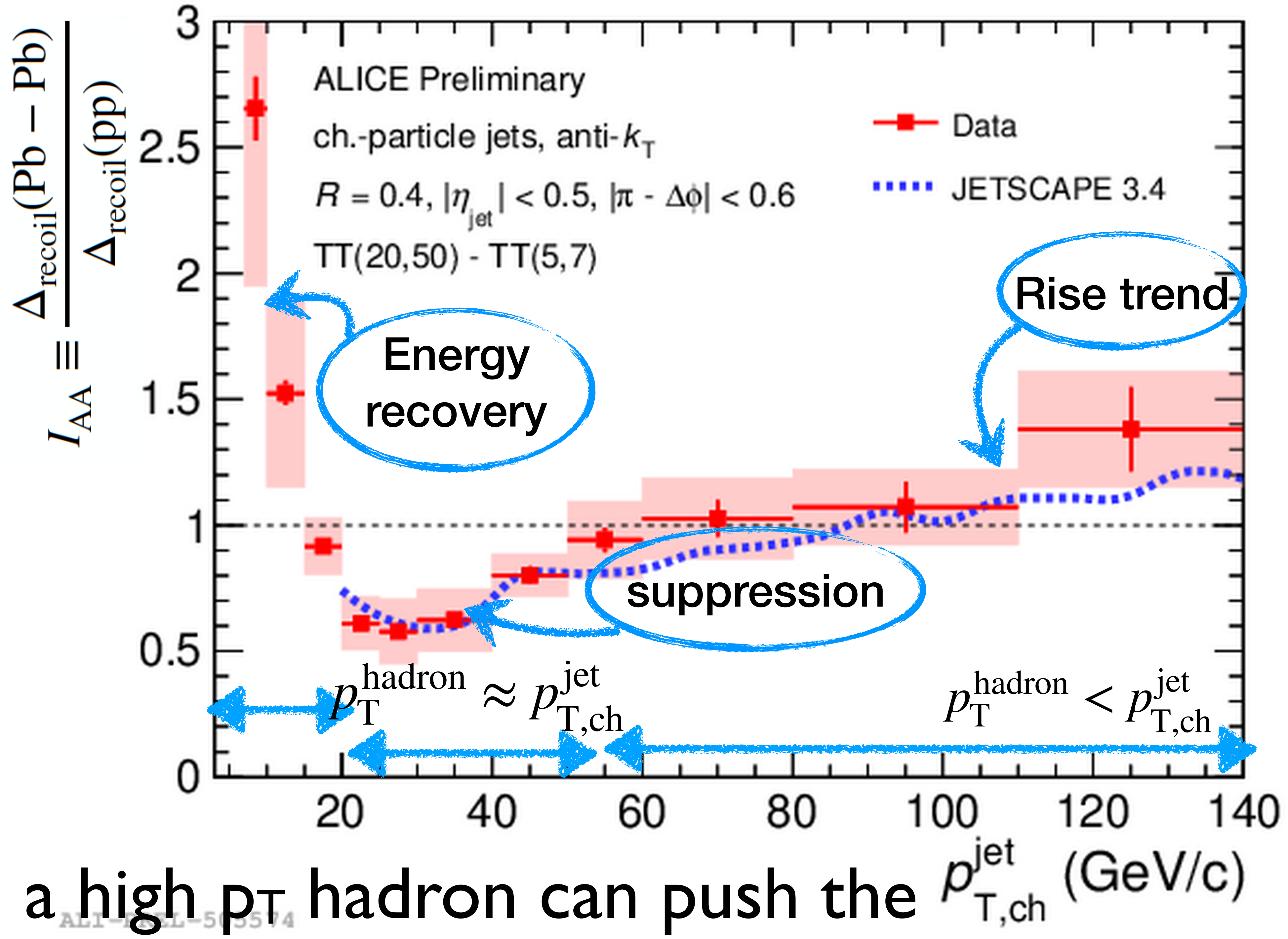
- Increase of low p_T yields →hints of energy recovery for very low p_T jets

Semi-inclusive yield of jets recoiling from high-p_T hadron





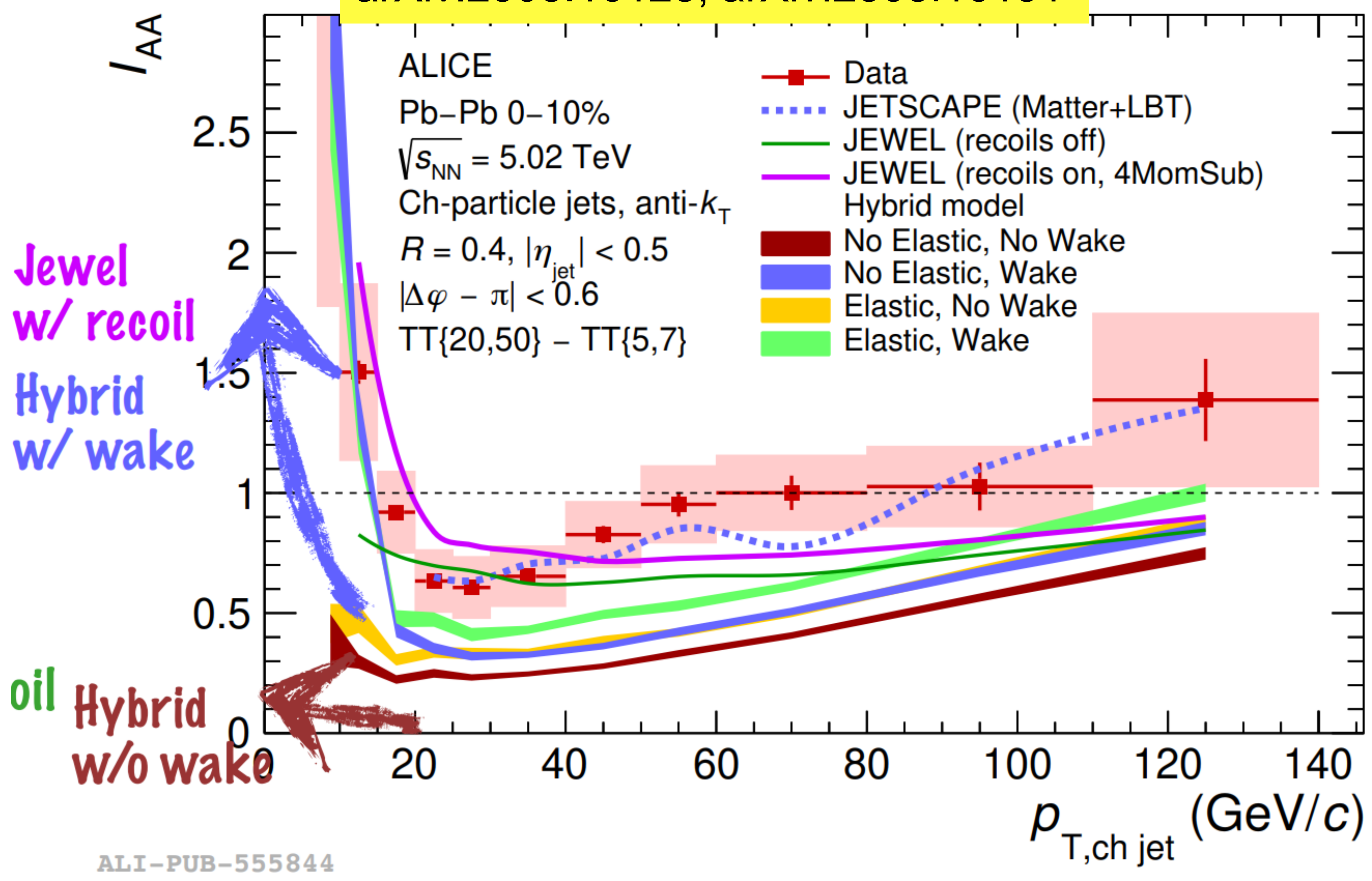
$$\Delta_{recoil} = \frac{1}{N^{AA}_{trig}} \frac{d^2N^{AA}_{jet}}{dp^{ch}_{T,jet}d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N^{AA}_{trig}} \frac{d^2N^{AA}_{jet}}{dp^{ch}_{T,jet}d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Ref}}$$

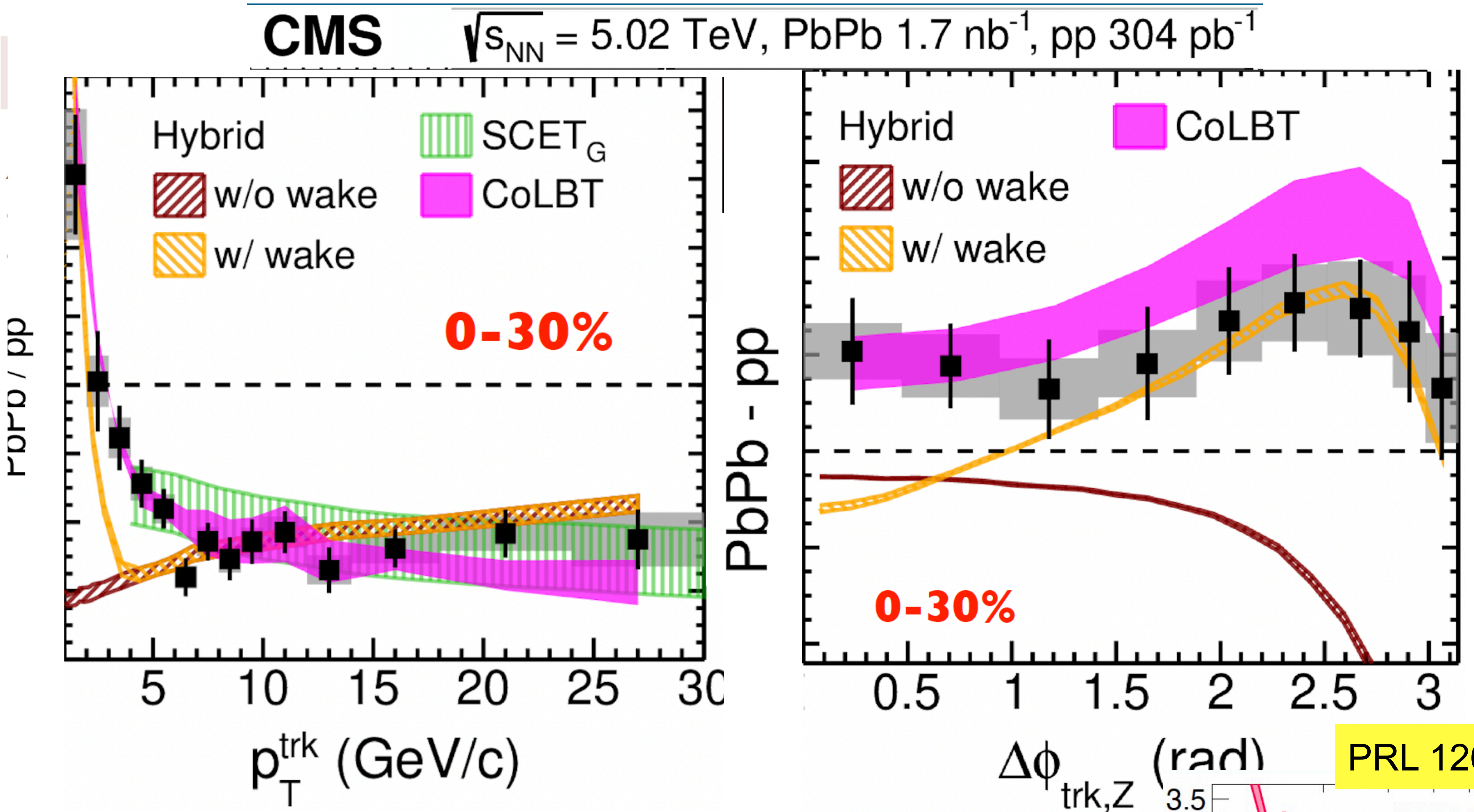


- Measurements of semi-inclusive yield of jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening
- Increase of low p_T yields →hints of energy recovery for very low p_T jets
- Rising trend: interplay of jet quenching effects on hadron and jet production?

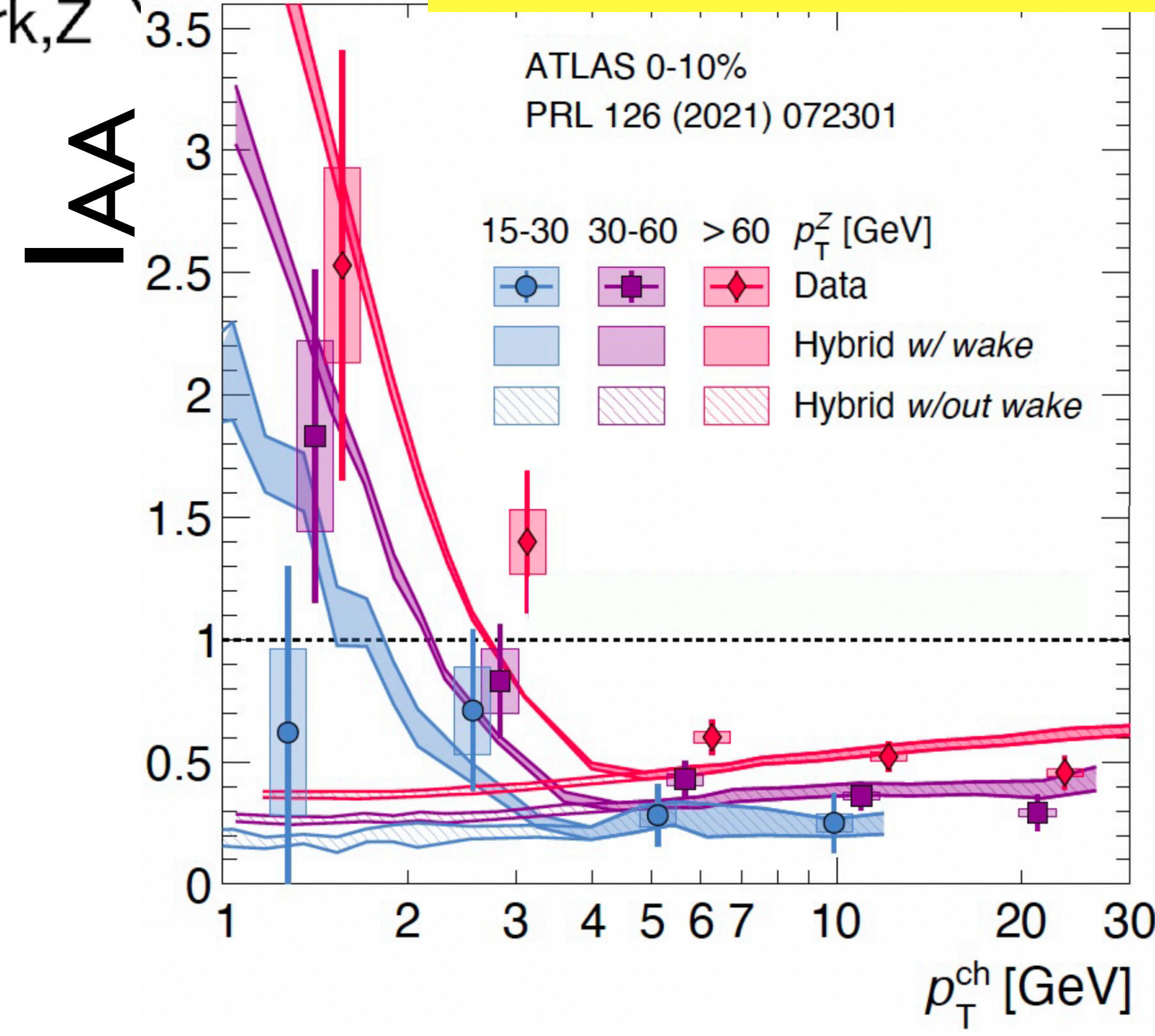
Medium response: redistribution of lost energy

arXiv:2308.16128, arXiv:2308.16131



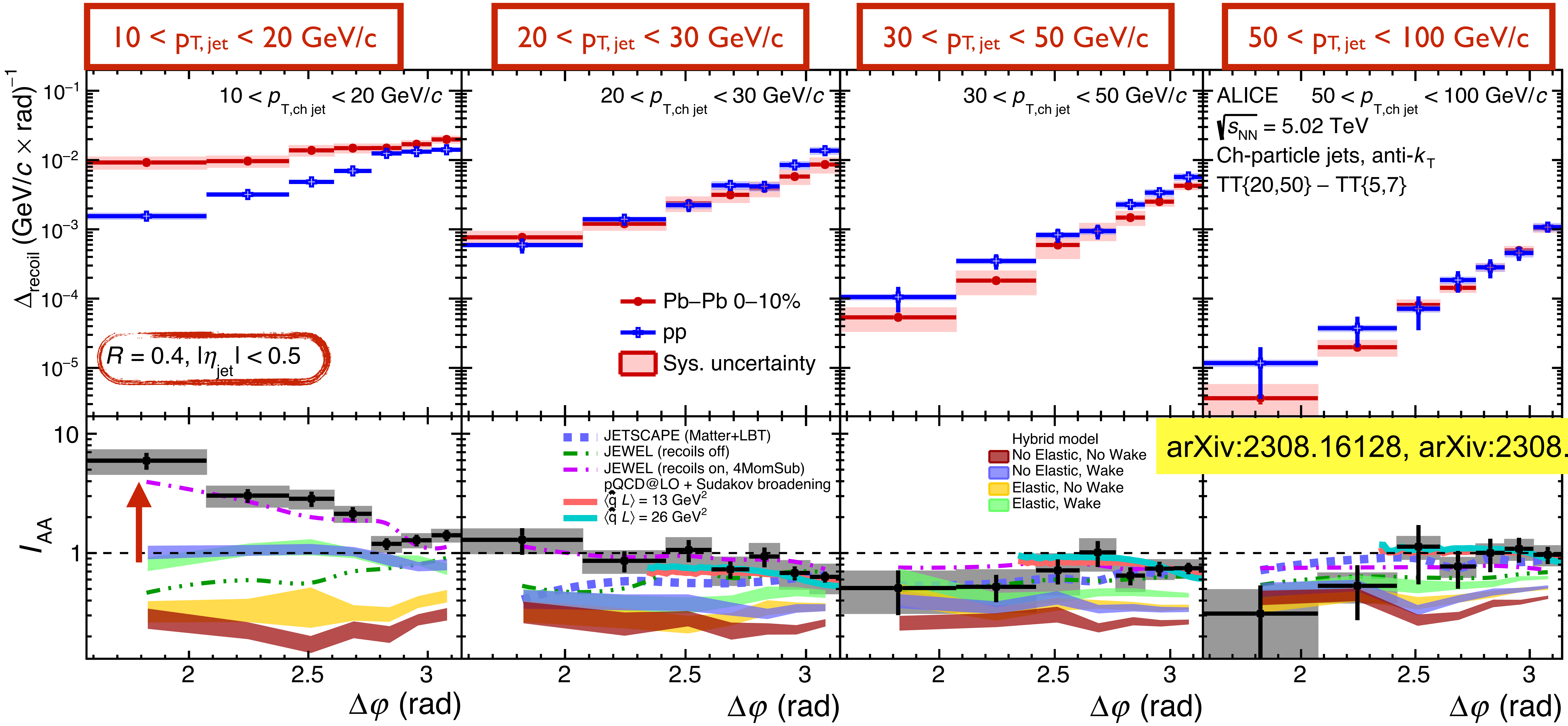


PRL 126 (2021) 072301

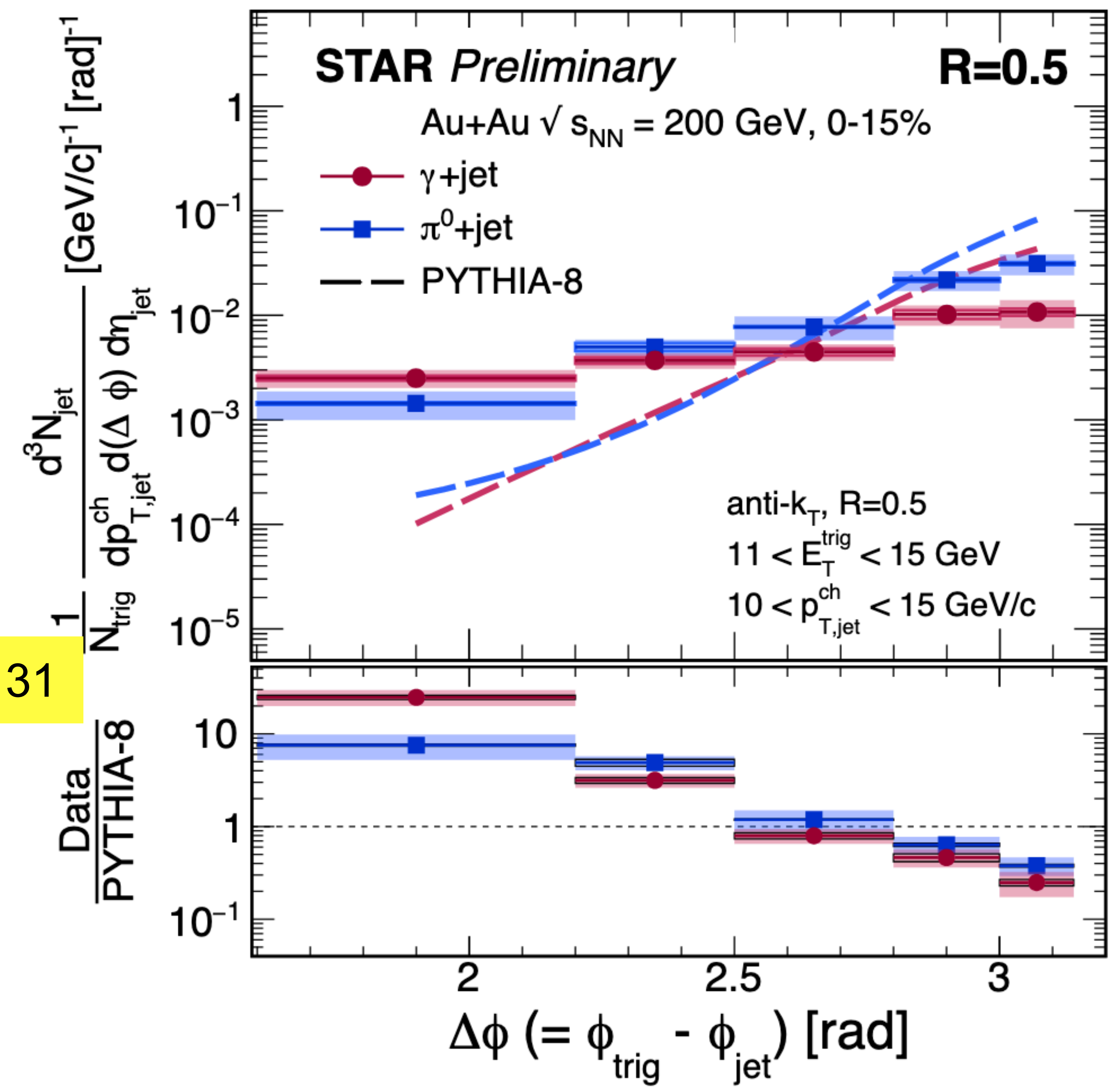


- Low p_T excess and high p_T suppression → energy redistribution due to jet quenching
  - ➡ Jet-fluid model can describe the enhancement of jet shape at large r
  - ➡ Hybrid and JEWEL w/ wake (recoil on) can capture the enhancement for low p_T jet
  - ➡ JETSCAPE captures the rising trend of high p_T jets

Recoil jet Δφ modifications: angular broadening

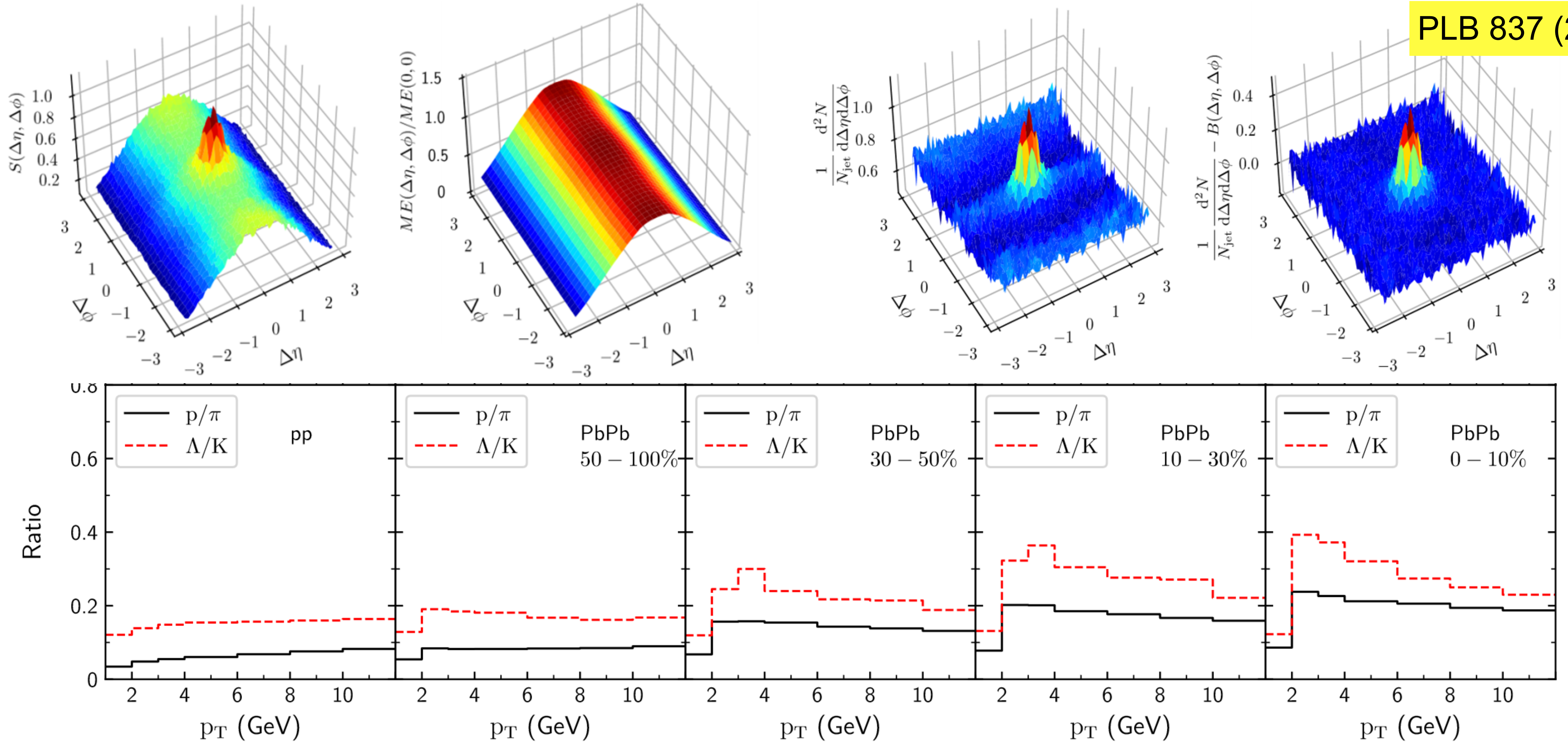


arXiv:2308.16128, arXiv:2308.16131

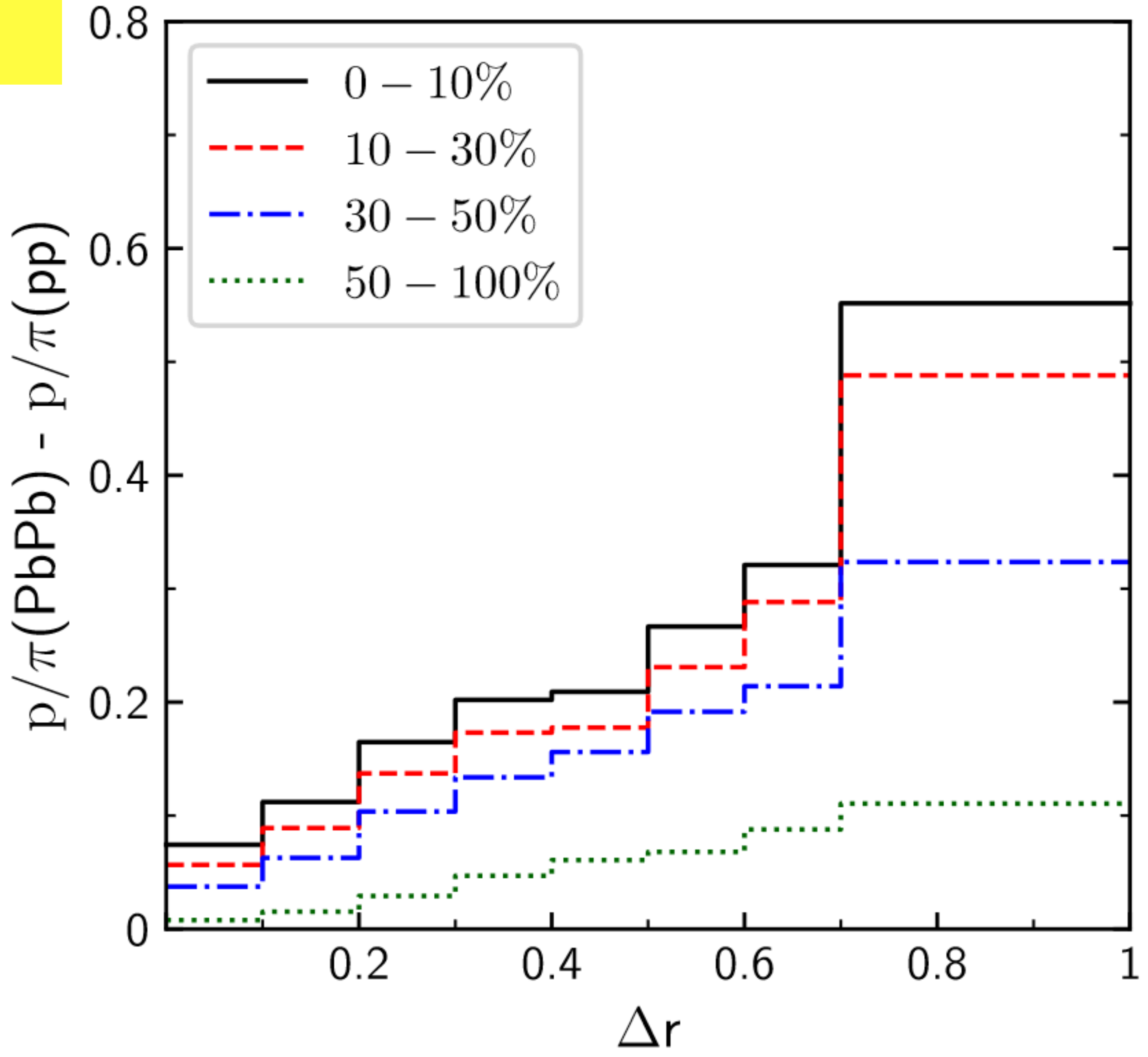


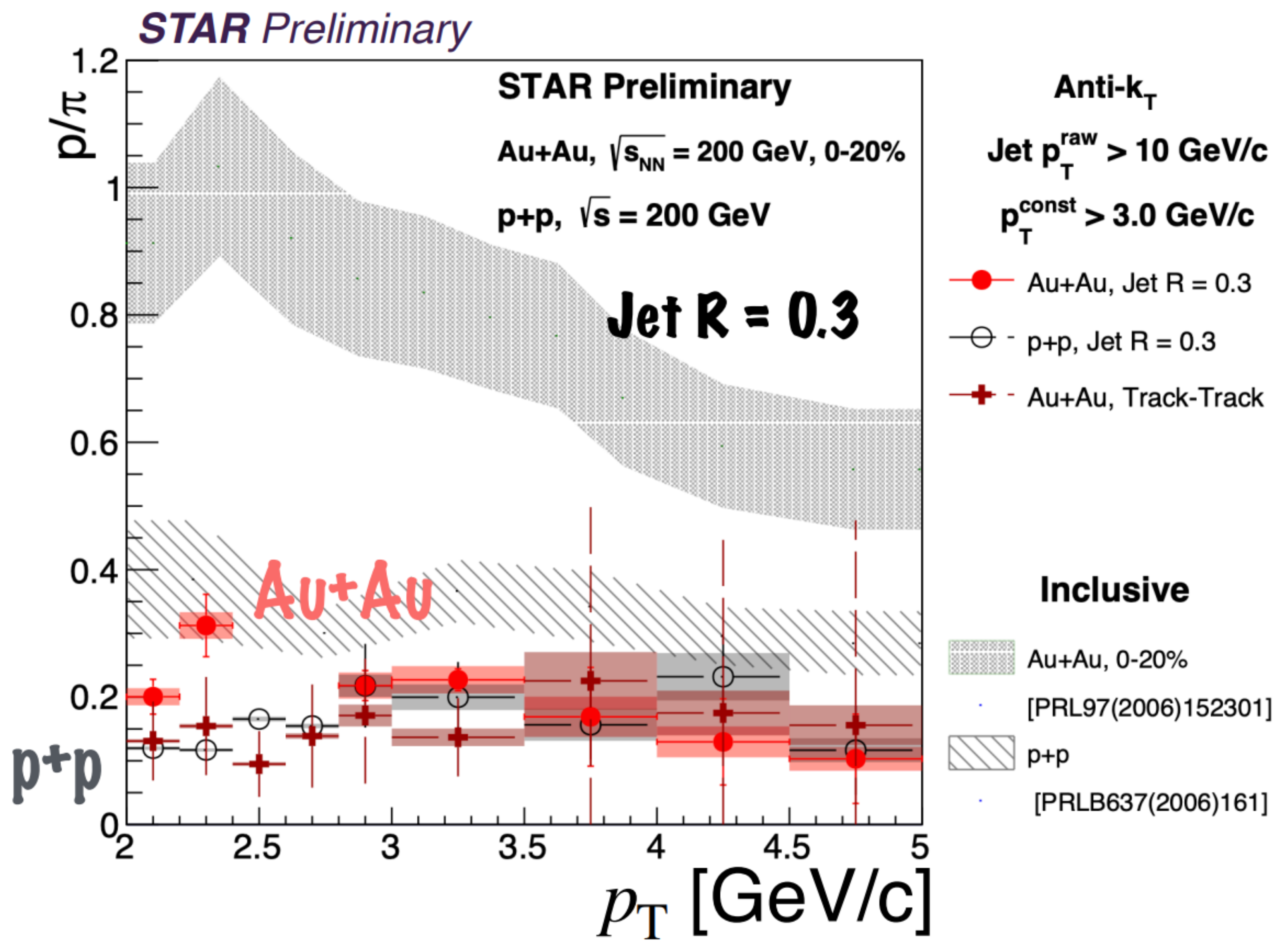
- Broadening of h-jet azimuthal correlations for soft jets
- Similar observation was also found by STAR for γ/π^0- triggered recoil jets
- Hybrid model w/ wake captures the yield enhancement at low p_T but not broadening
- JEWEL with recoil on captures both features

Baryon to meson enhancement around jets



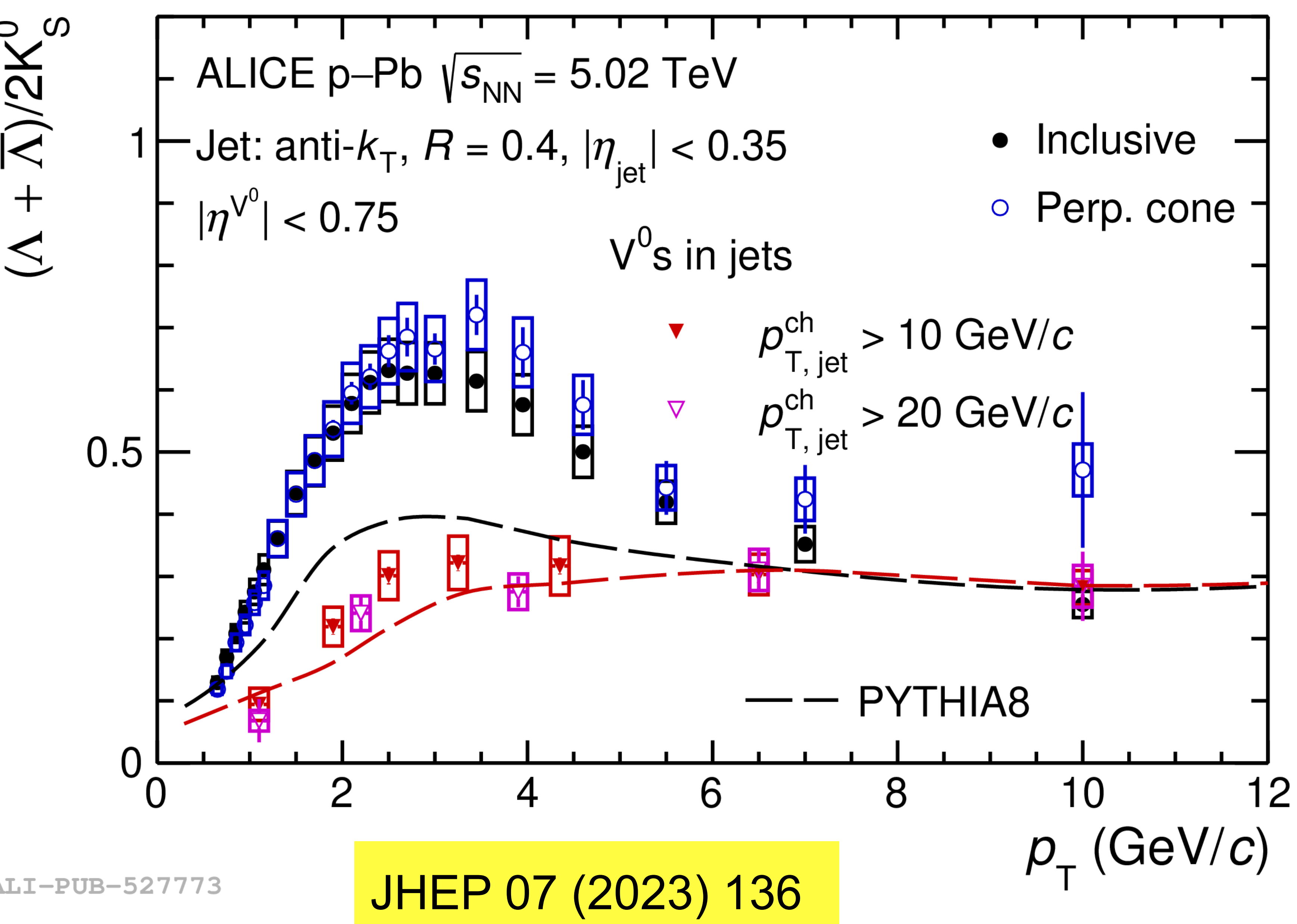
PLB 837 (2023) 137638



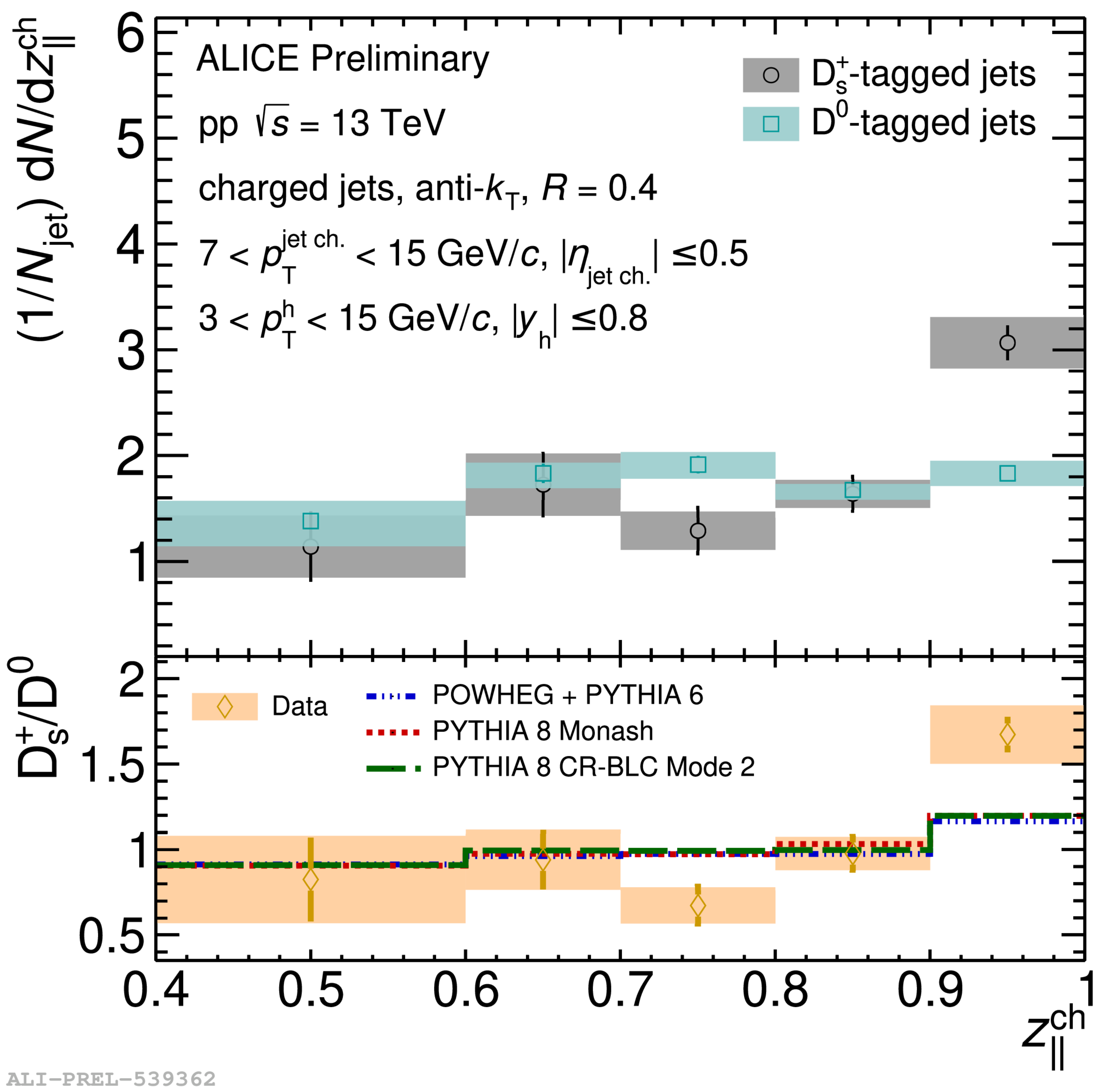


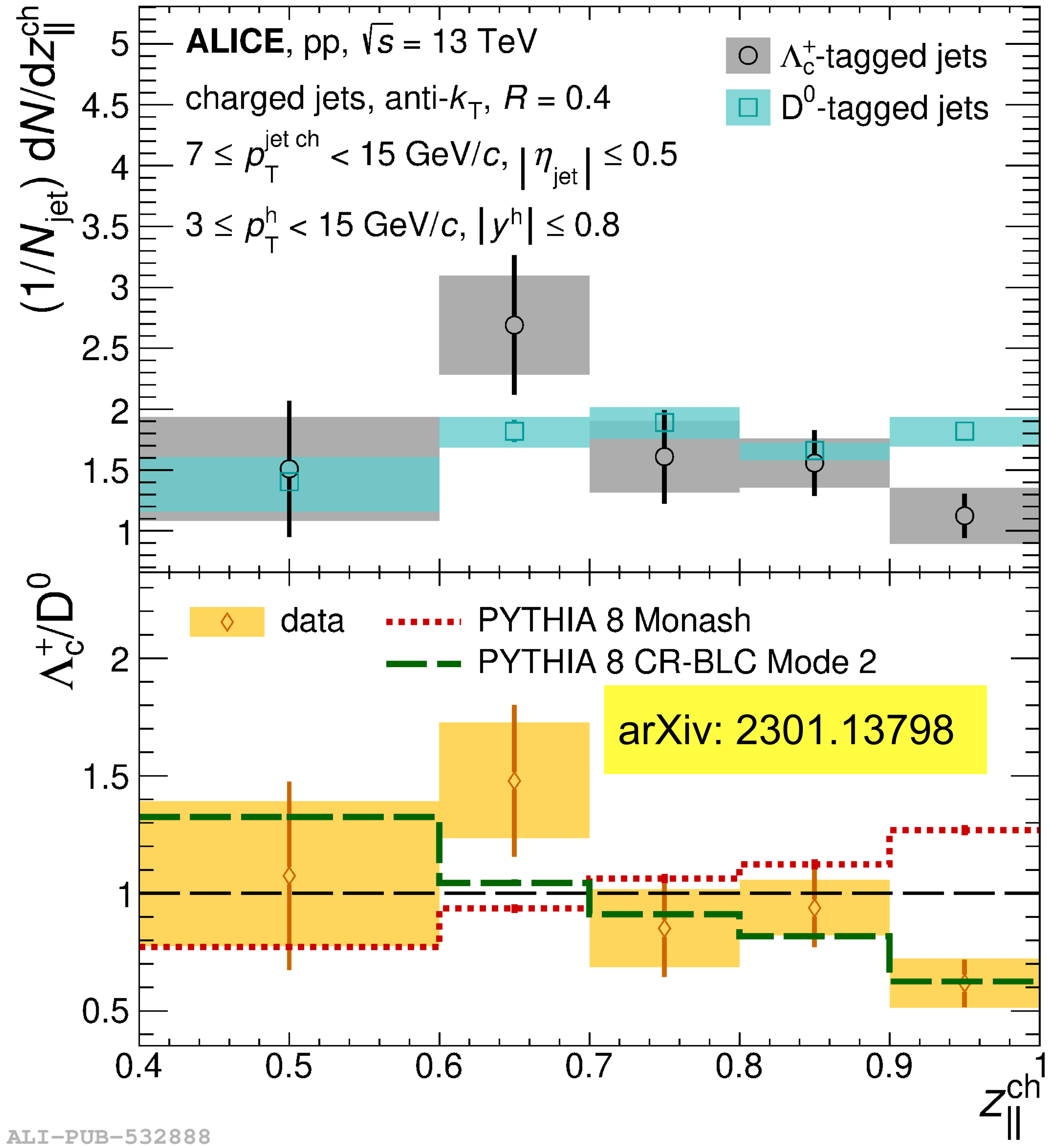
- Strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons
- Enhancement of jet-induced B/M ratios is stronger at intermediate p_T (2-6 GeV/c)for larger distance because the lost energy from quenched jets can diffuse to large angle.

Hadron chemistry and charm quark fragmentation



JHEP 07 (2023) 136

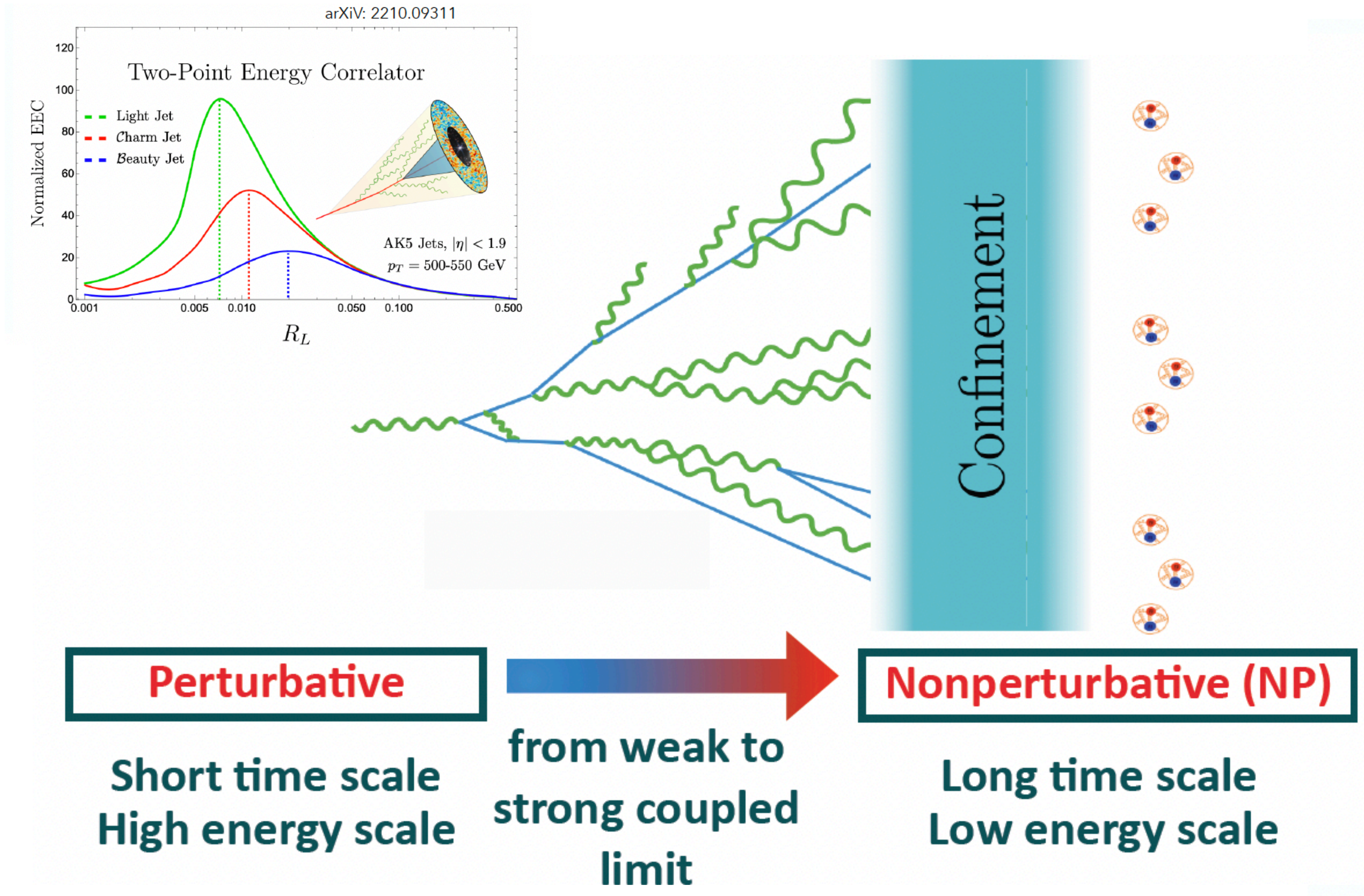


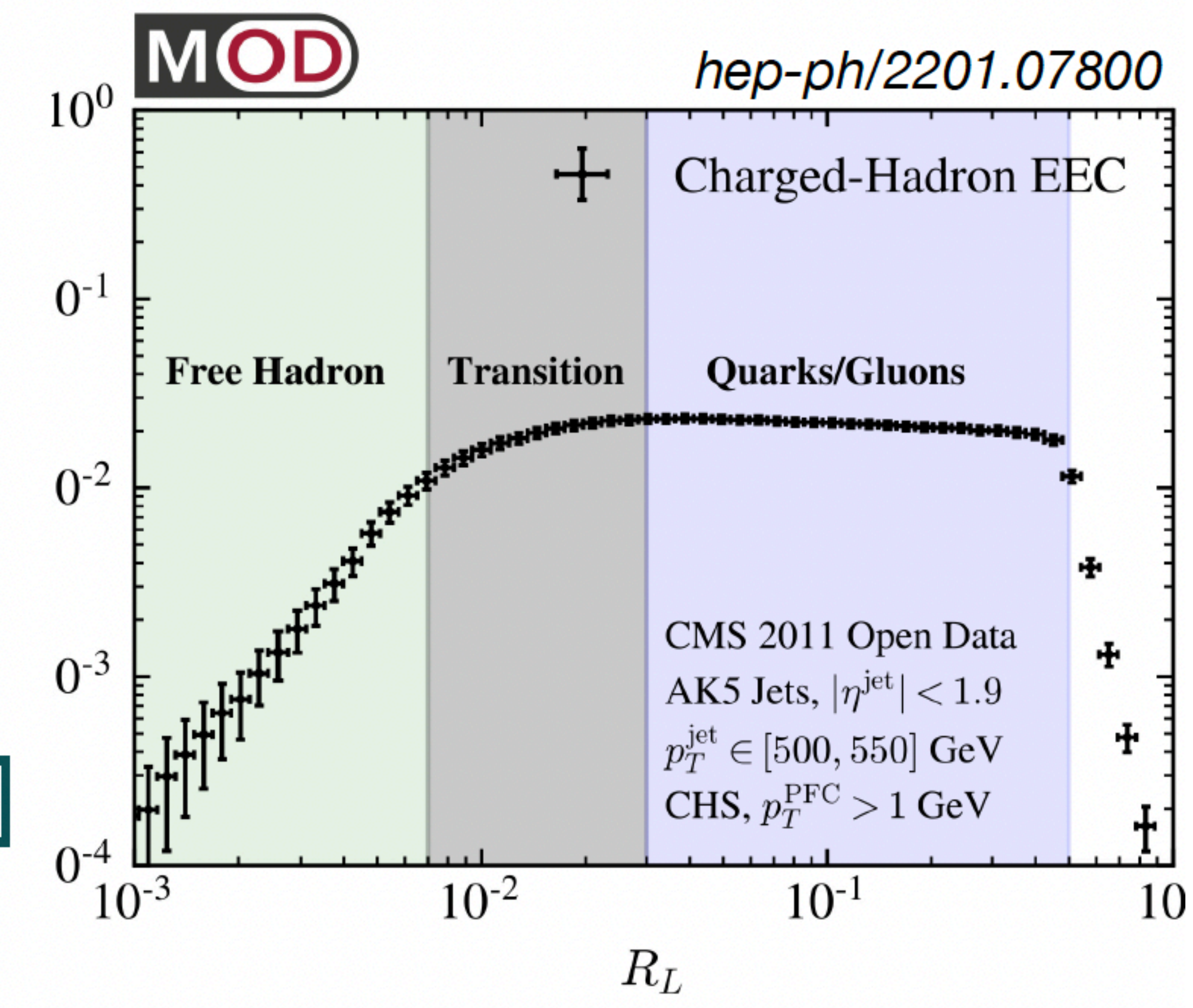


arXiv: 2301.13798

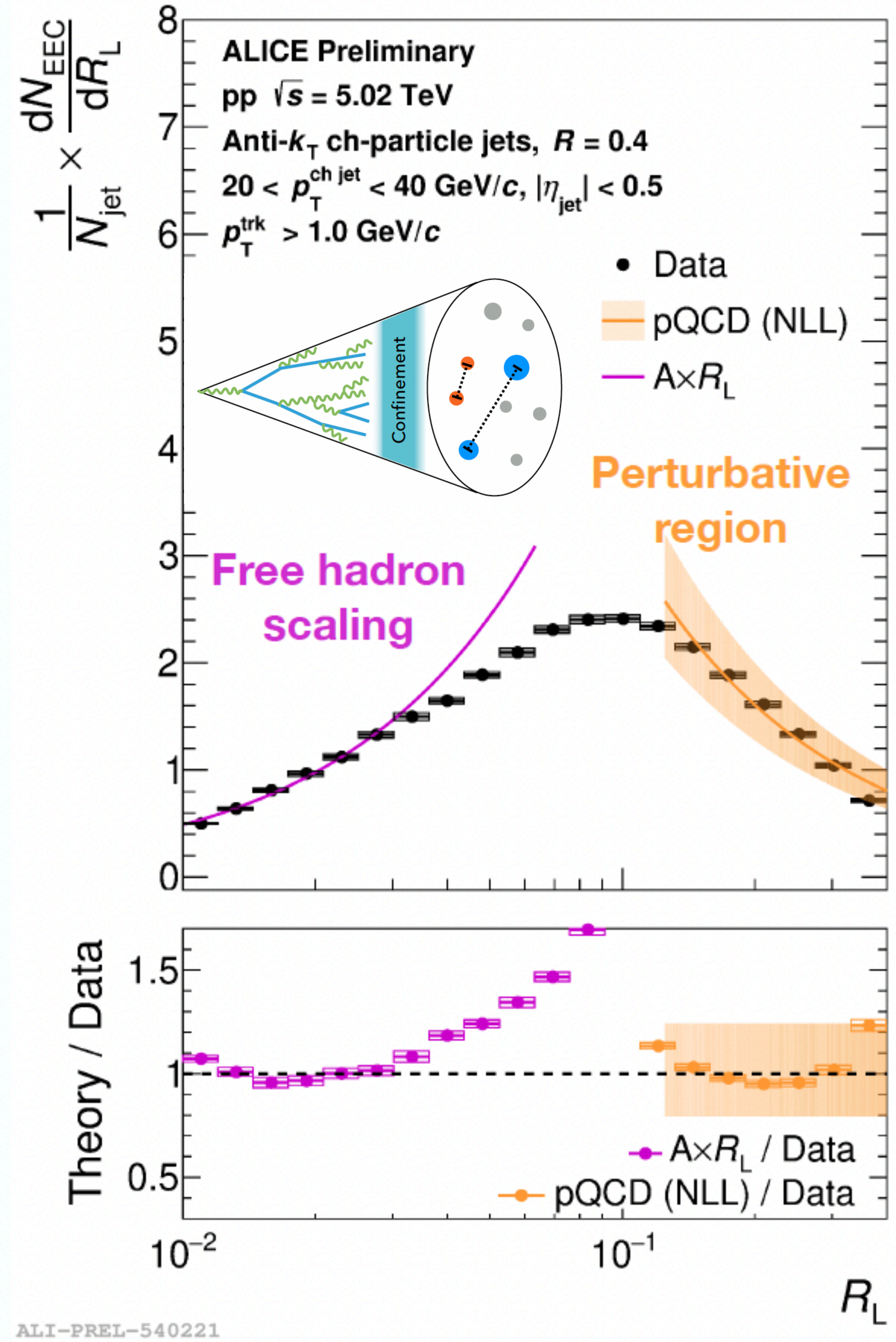
- B/M ratio inside jet cone doesn't show a peak as inclusive case at intermediate p_T
- Charmed-jet fragmentation is slightly different when containing a strangeness quark hadrons
- Charm quarks have a softer fragmentation into Λ_c^+ baryons compared to D^0 mesons

Jet physics at EIC: one example





N-point energy correlators inside jets as a way to probe parton → hadron transition

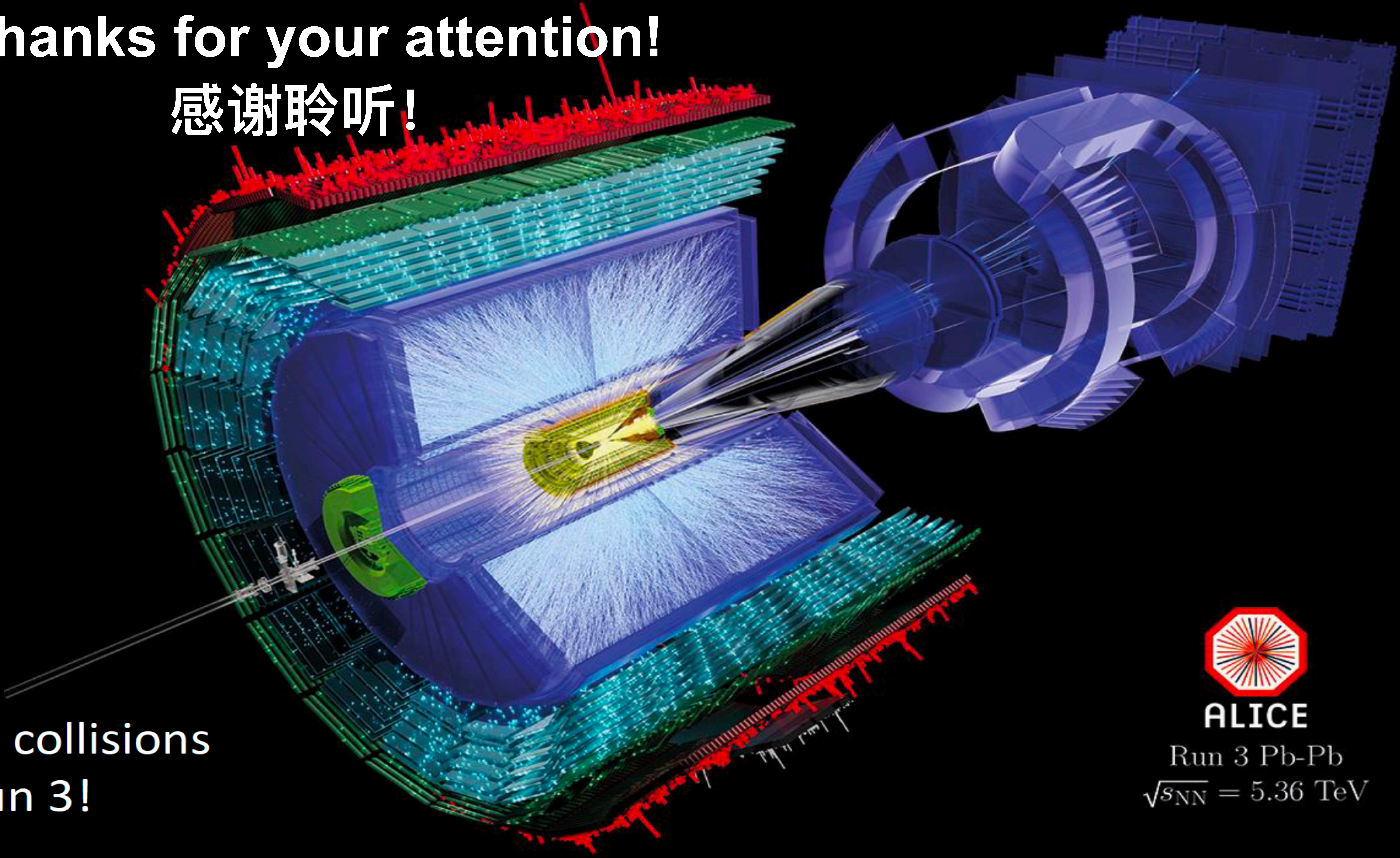


- N-point energy correlators can used to explore the transition between perturbative and non-perturbative dynamics inside jet
- EIC will provide a cleaner environment and energy scale selection leading to discovery physics about non-perturbative effects and hadronization within jets

Summary

- Large number of jet results based on full Run 2 LHC data sample (many more not covered here)
  - More precision, extending to low p_{T}/large R, more differential, new analysis
- Understanding the transition from perturbative to non-perturbative QCD is crucial in order to interpret jet measurements
  - Understanding jet quenching effects in HI collisions
  - Test accuracy of high-order perturbative calculations
- Recent LHC jet measurements explore the expected breakdown of perturbative calculations in the non-perturbative regime
  - Provide guidance or future measurements → ongoing LHC + sPHENIX&EIC !

Thanks for your attention!
感谢聆听！



First Pb-Pb collisions in Run 3!