中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA

HENPIC

Jets and heavy flavor

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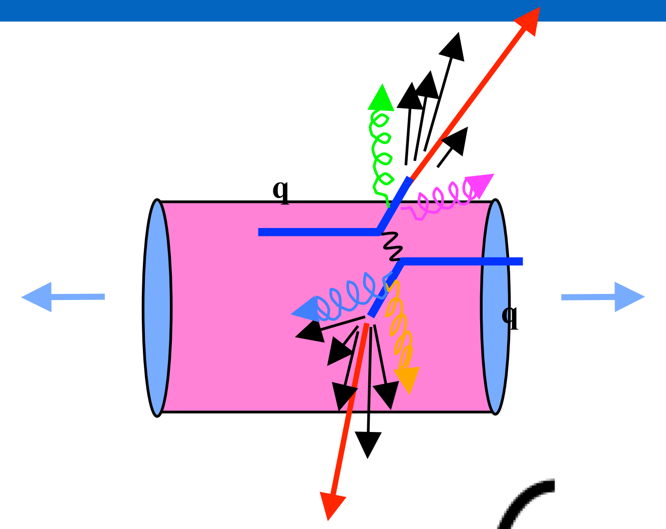
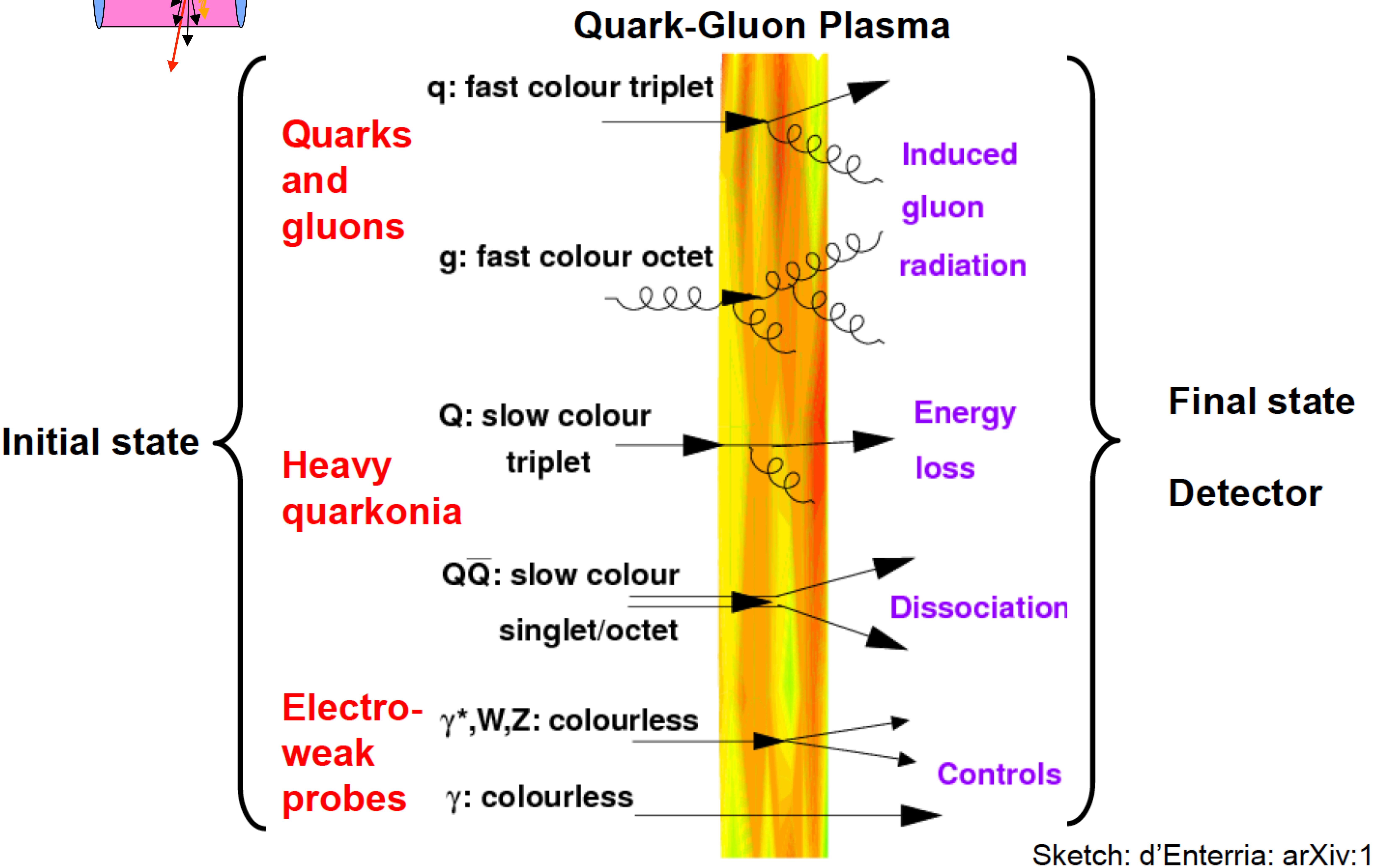
Hard Probes: jets and heavy flavor





Sketch: d'Enterria: arXiv:1207.4362

- Many observables can be studied in the HP sector
- So far there are many many exciting and interesting results
- but …

➡ we must keep in mind that the study of different effects in a complementary way must yield consistent picture

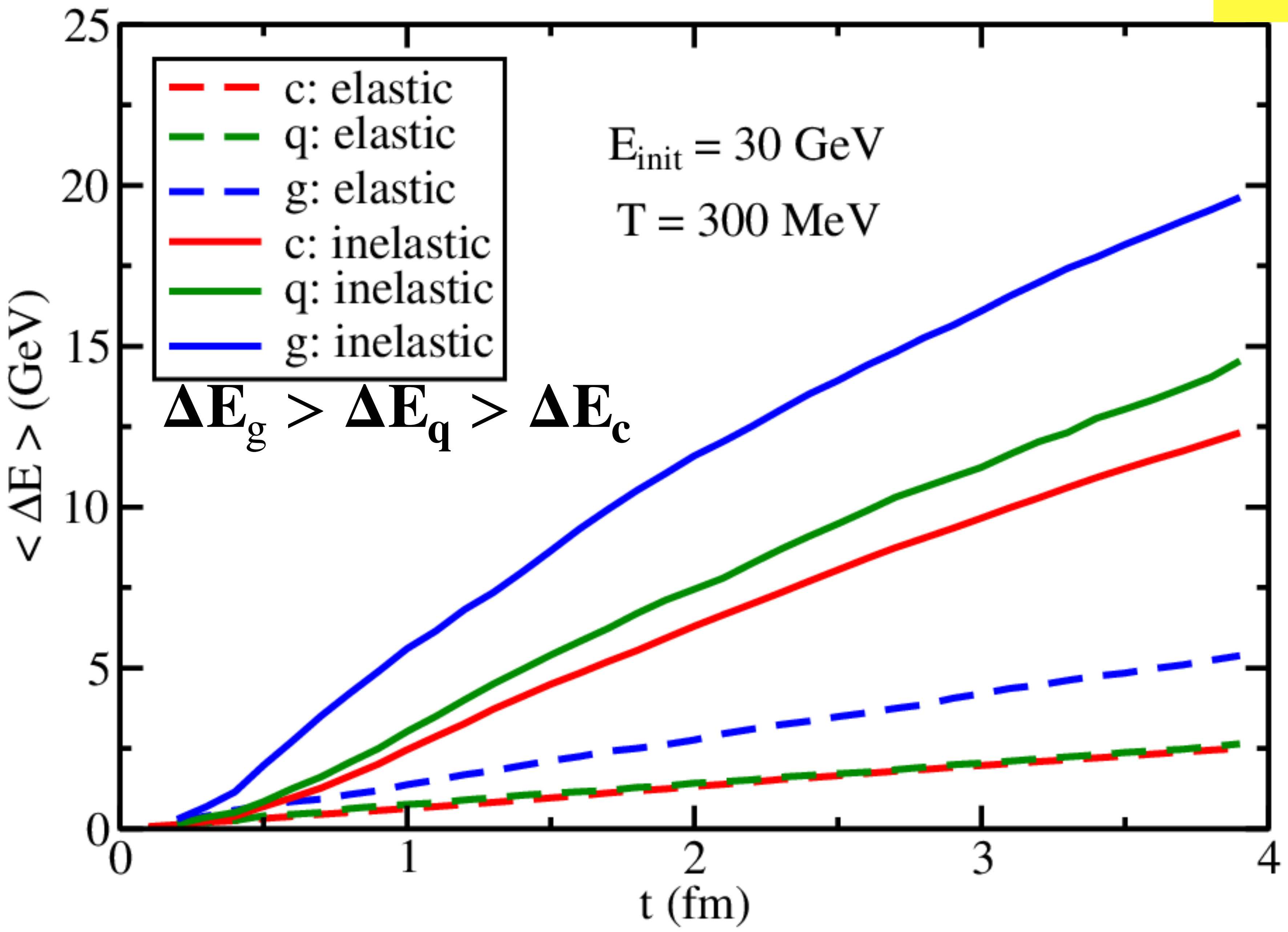
➡ focus in this talk: discuss existing experimental and theoretical results which not so consistency or need further improvements/thoughts

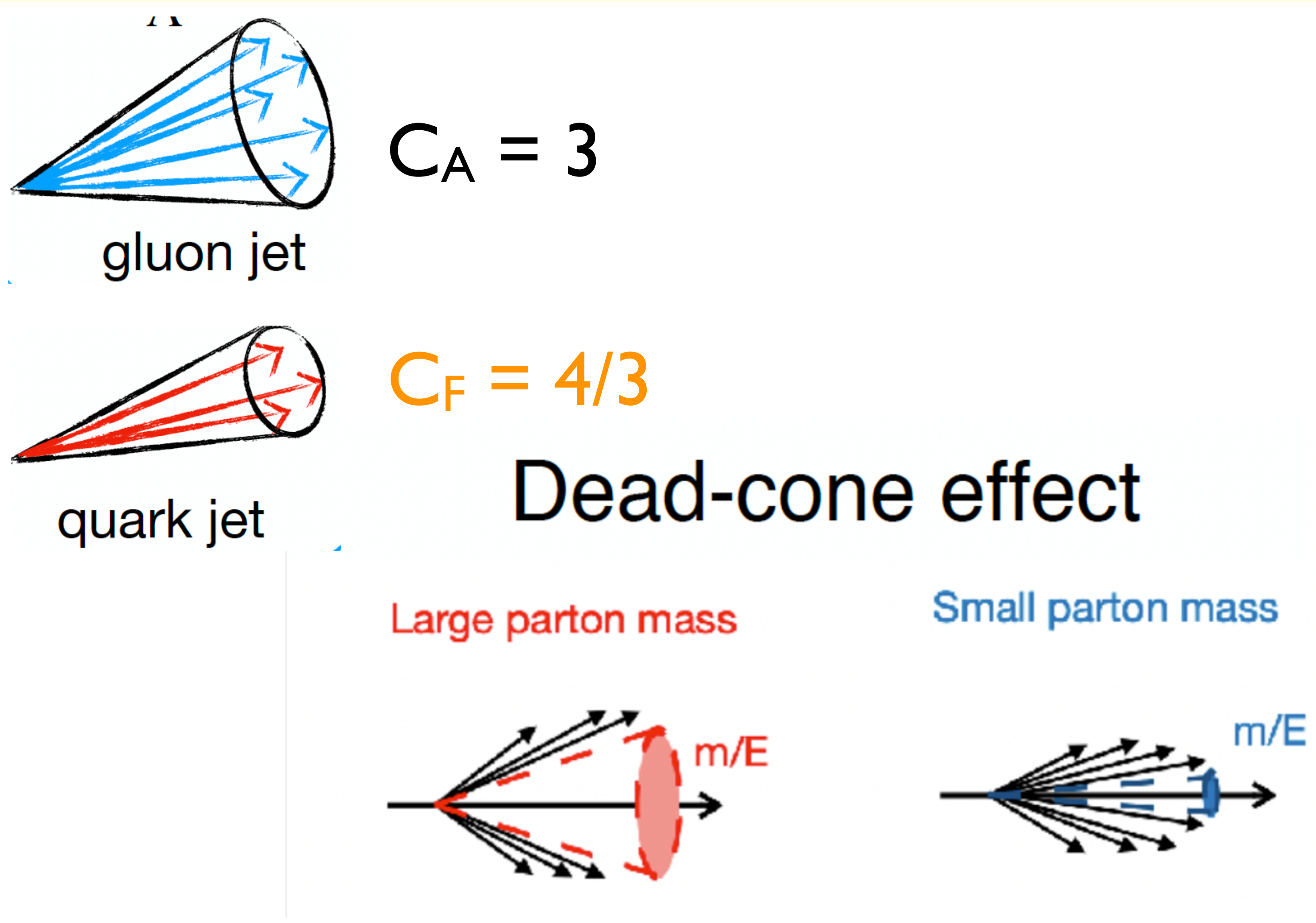
Outline

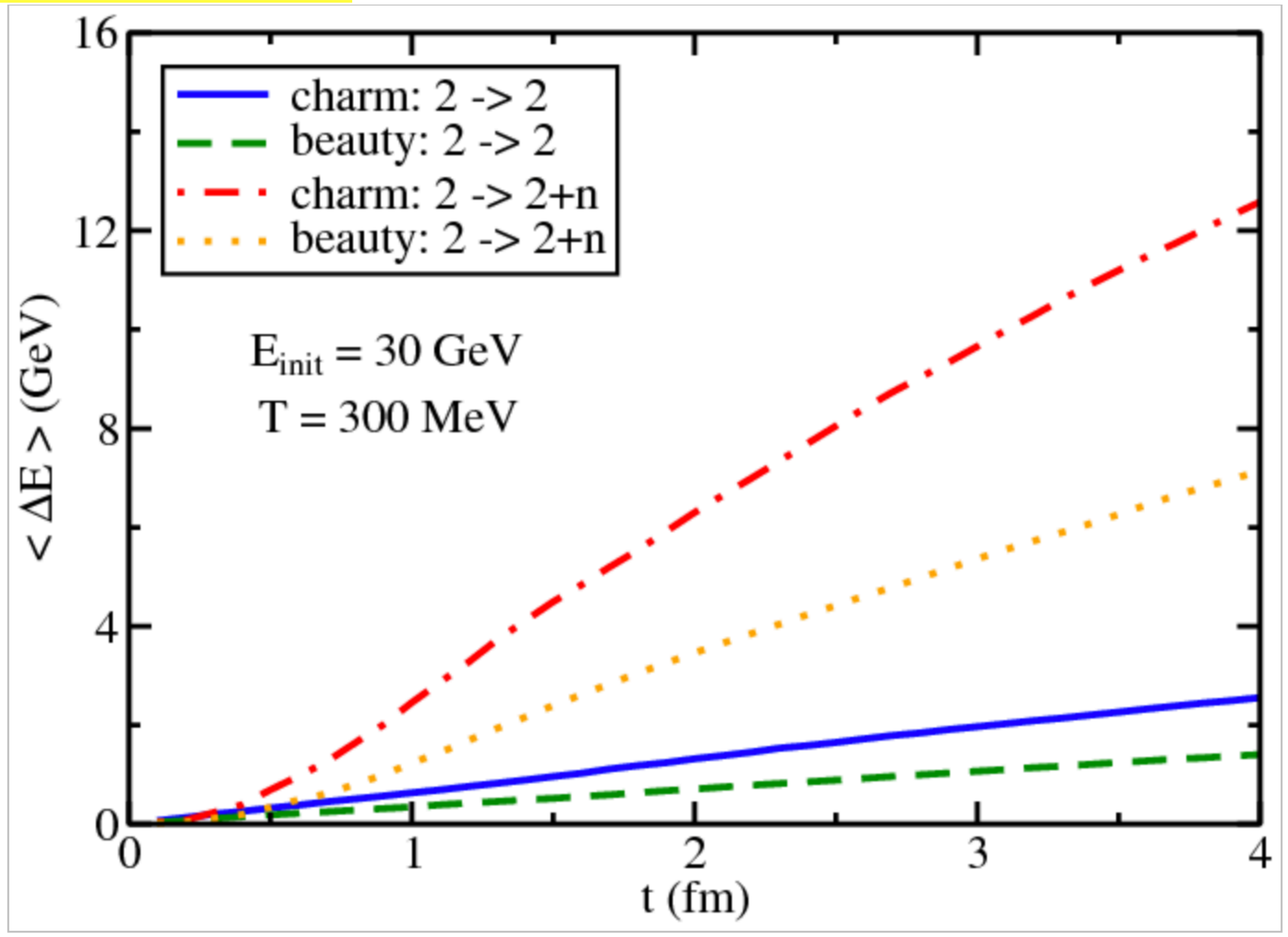
- Flavor dependence of jet quenching
- Medium response
- R-dependence of jet quenching
- Full jet and jet substructure
- Hadron chemistry & hadronization
- Extract medium properties
- Jet quenching in small systems

Flavor dependence of parton energy loss

PRC 91 (2015) 054908; PRC 94 (2016) 014909; PLB 805 (2020) 135424



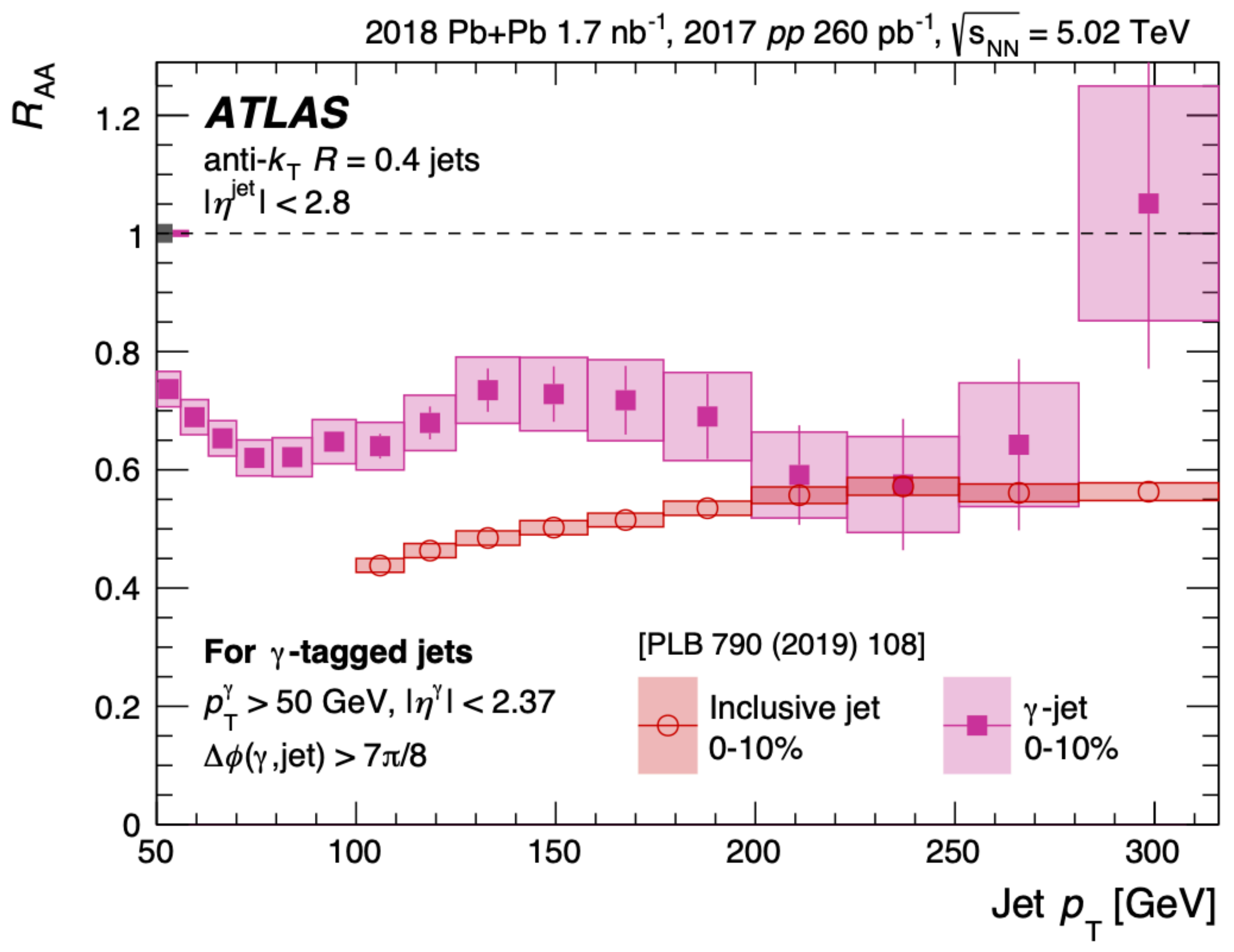




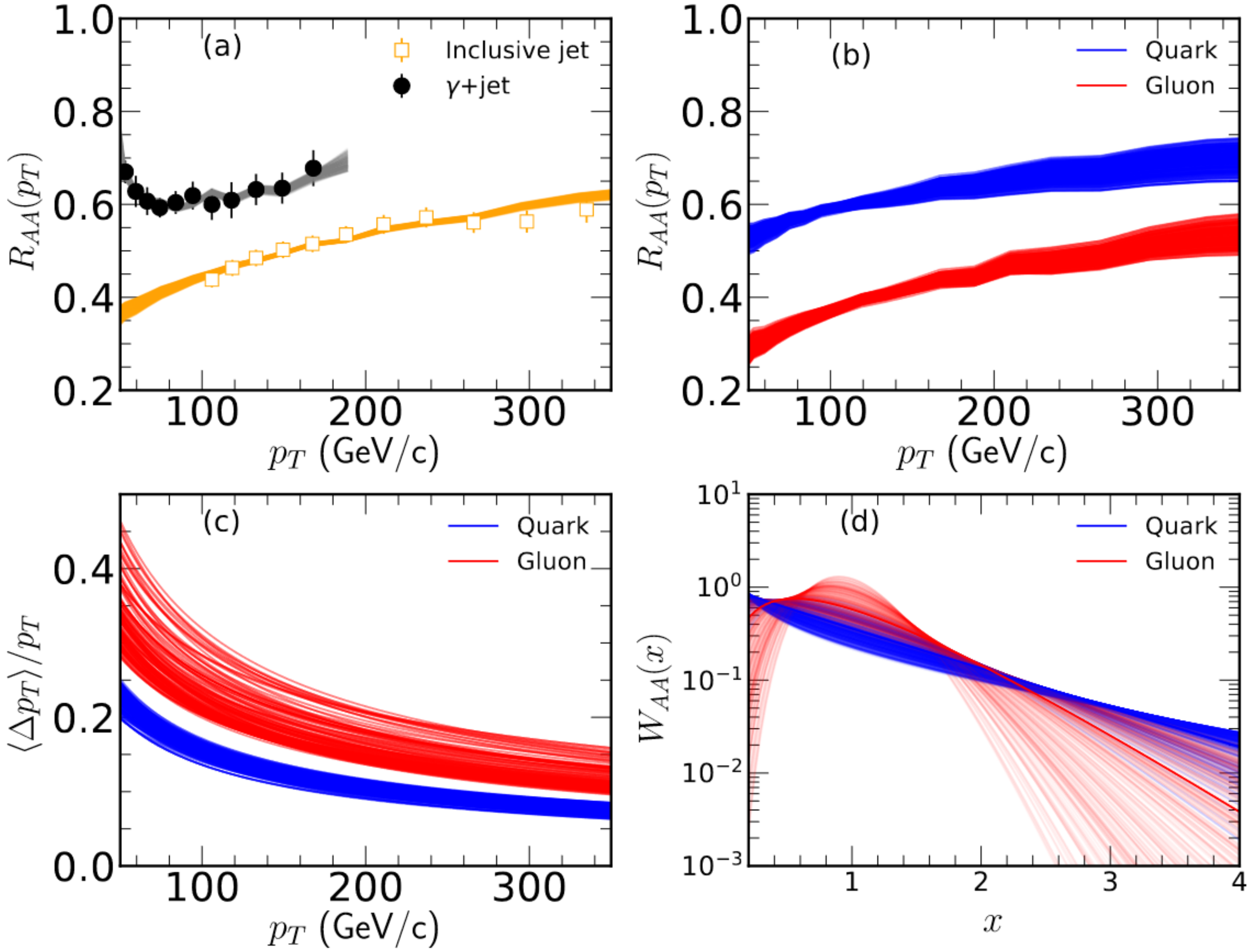
- Flavor dependence involves: a) color charge differences; b) mass dependence
- Flavor dependence of energy loss: $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{light-quark}} > E_{\text{loss}}^{c} > E_{\text{loss}}^{b}$

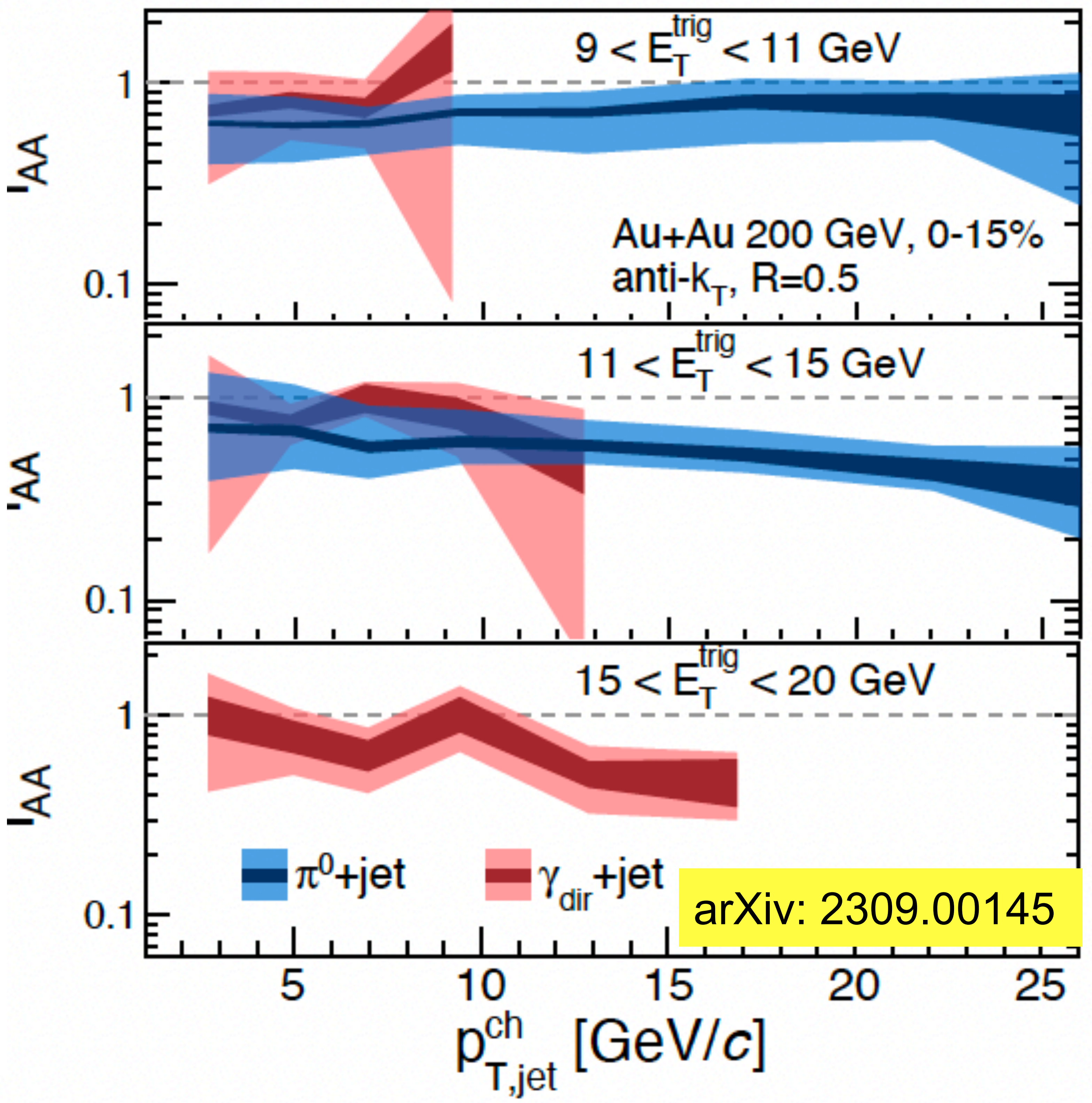
Color charge dependence of jet energy loss

arXiv: 2303.10090



arXiv:2303.14881





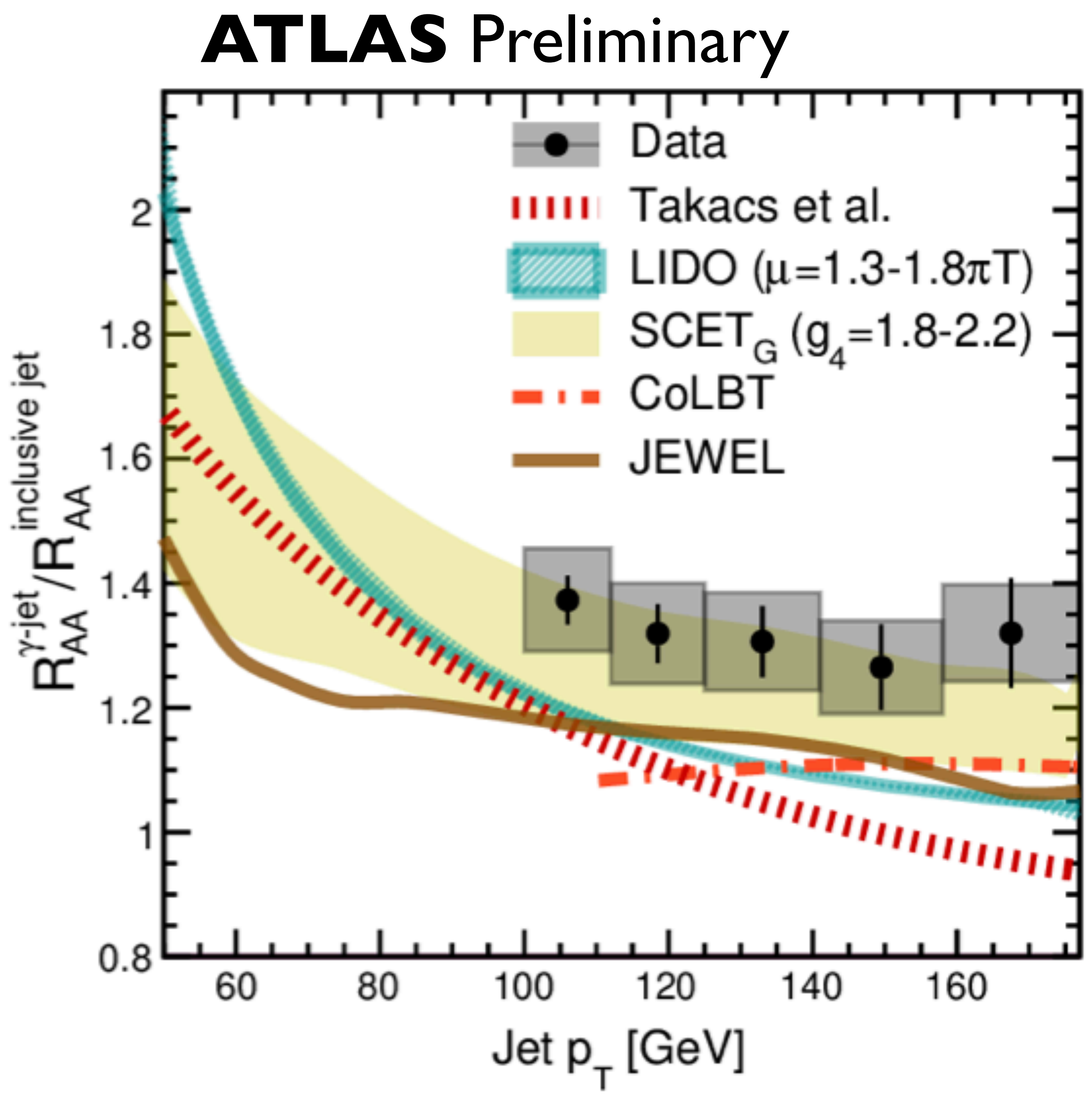
arXiv: 2309.00145

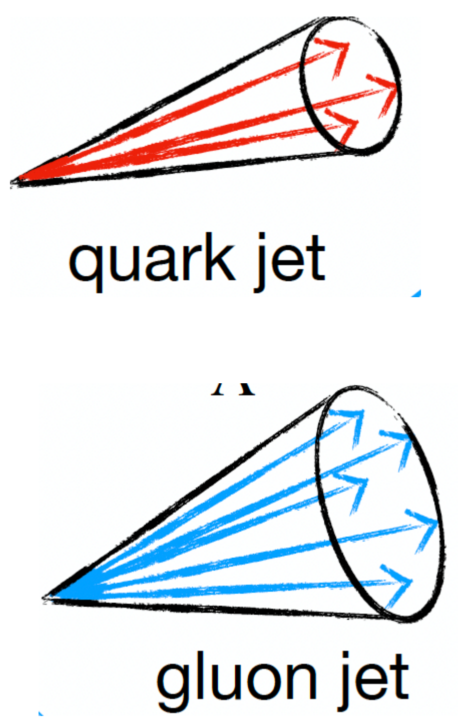
- Quark-initiated jets lose less energy and shows weaker dependence on the jet p_T compared to gluon-initiated jets
- Photon-tagged (quark) jets being significantly less suppressed than inclusive jets → color factor dependence of parton-medium interaction (only true below p_T < 200 GeV, why?)
- Very small differences between photon and π^0-tagged jets modifications at RHIC energy

Color charge dependence of energy loss

Flavor dependence of radiation:

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

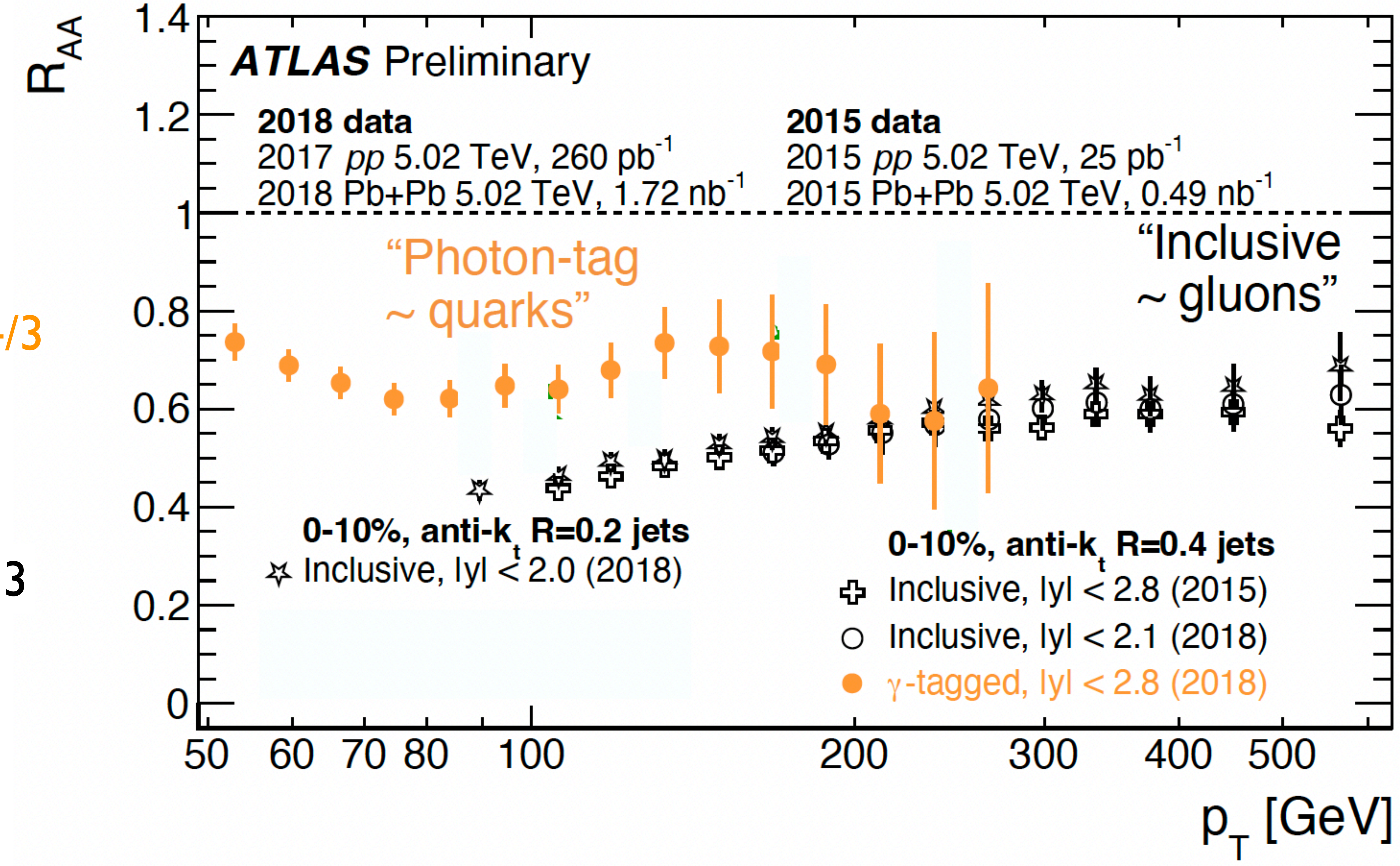




$C_F = 4/3$

$C_A = 3$

Caveat: "spectra steepness" plays a role!



- Energy loss depends on color charge

Flavor/Mass dependence of energy loss

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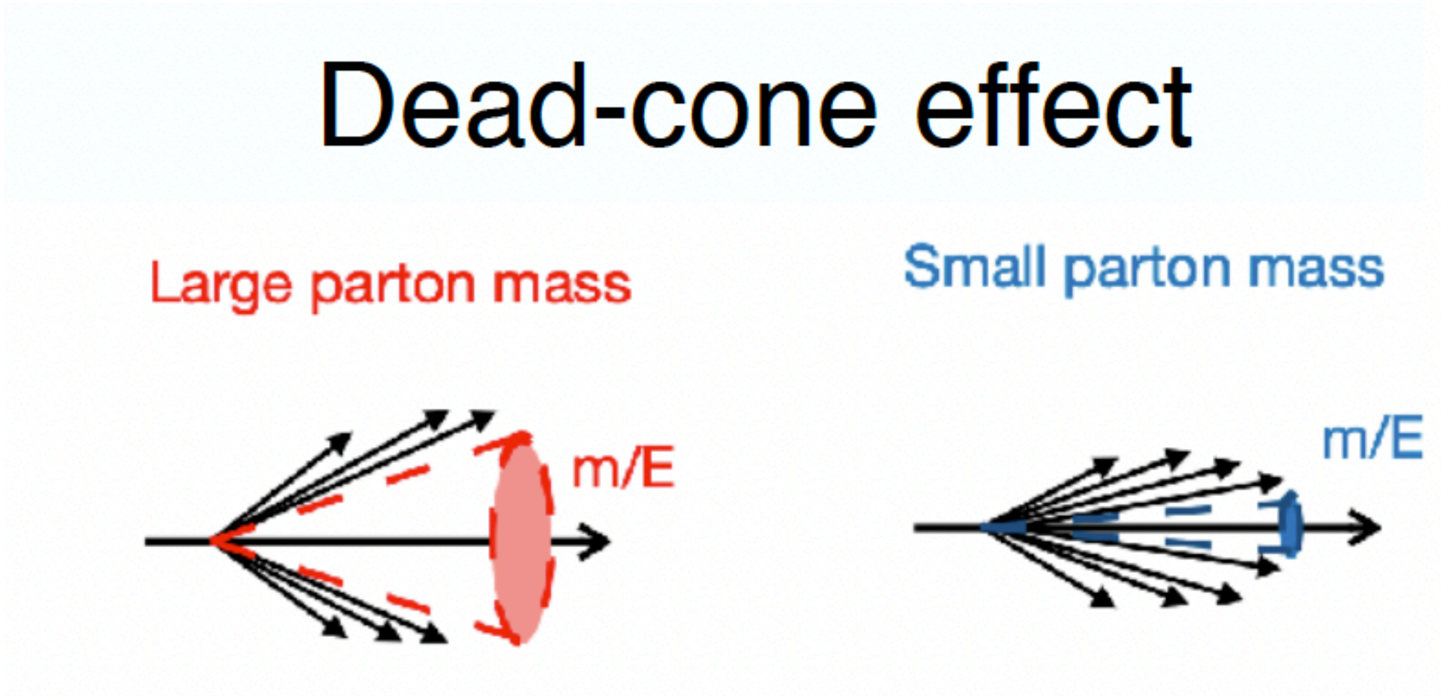

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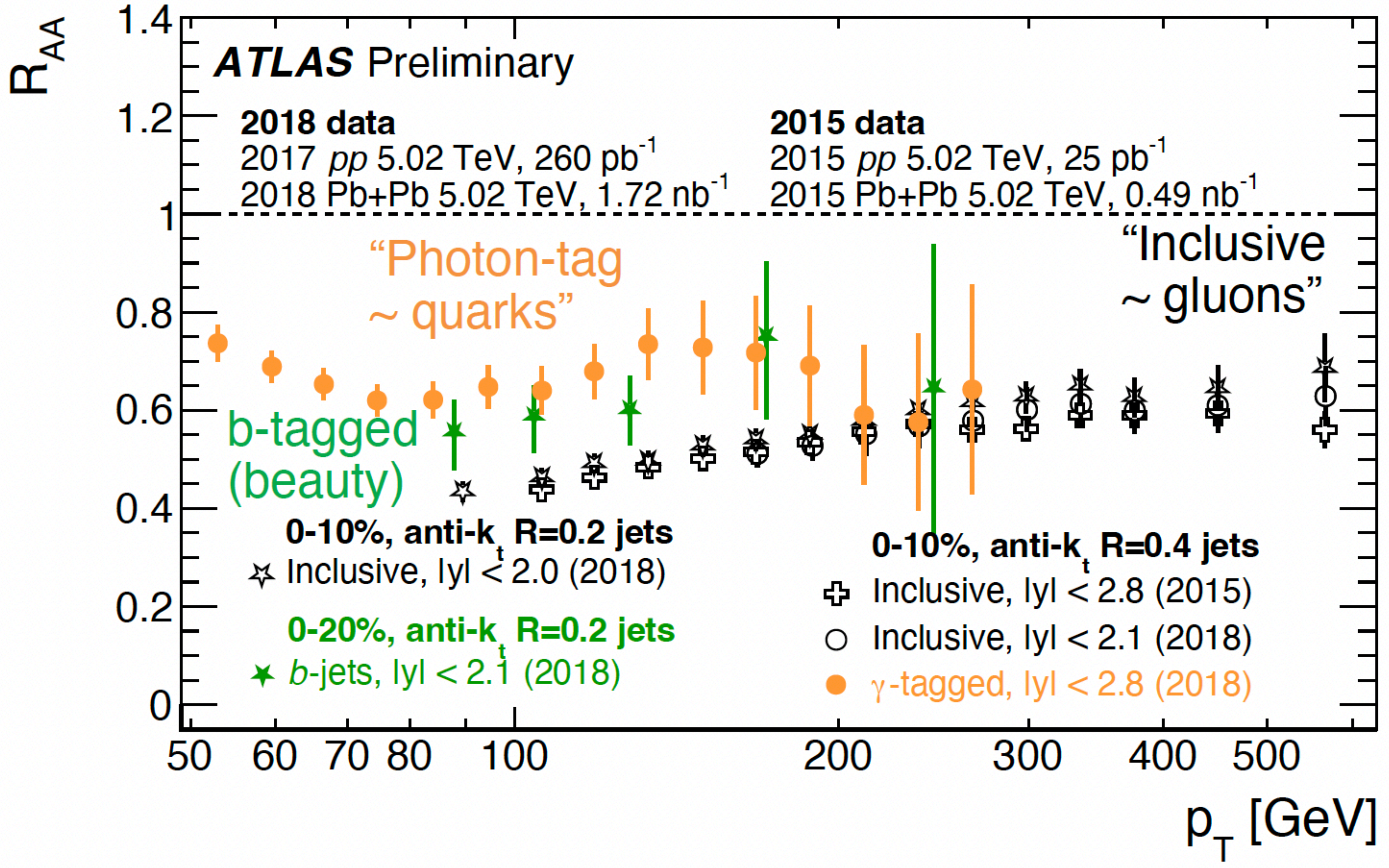

- Energy loss depends on color charge (and mass of parton?)

- 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

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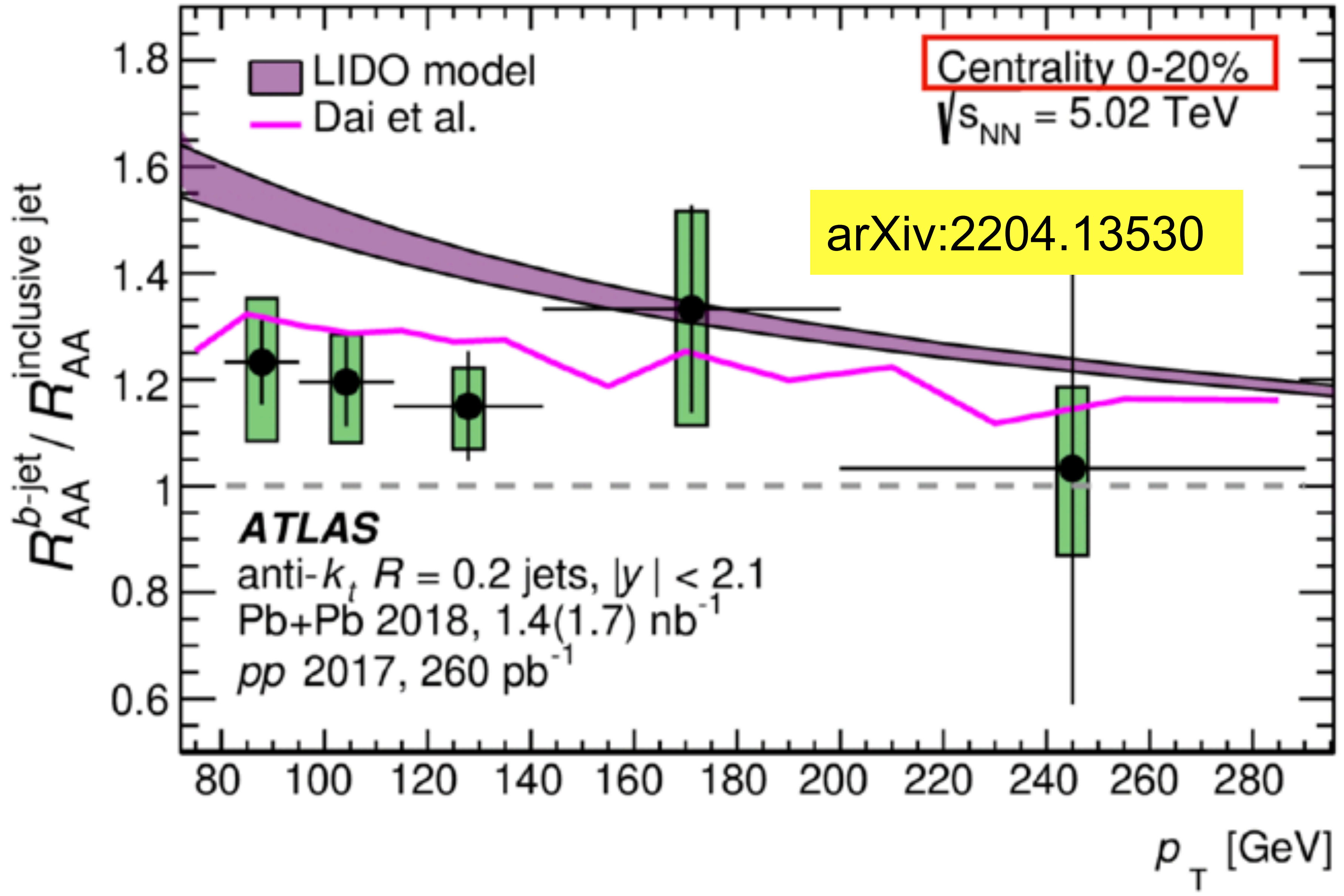

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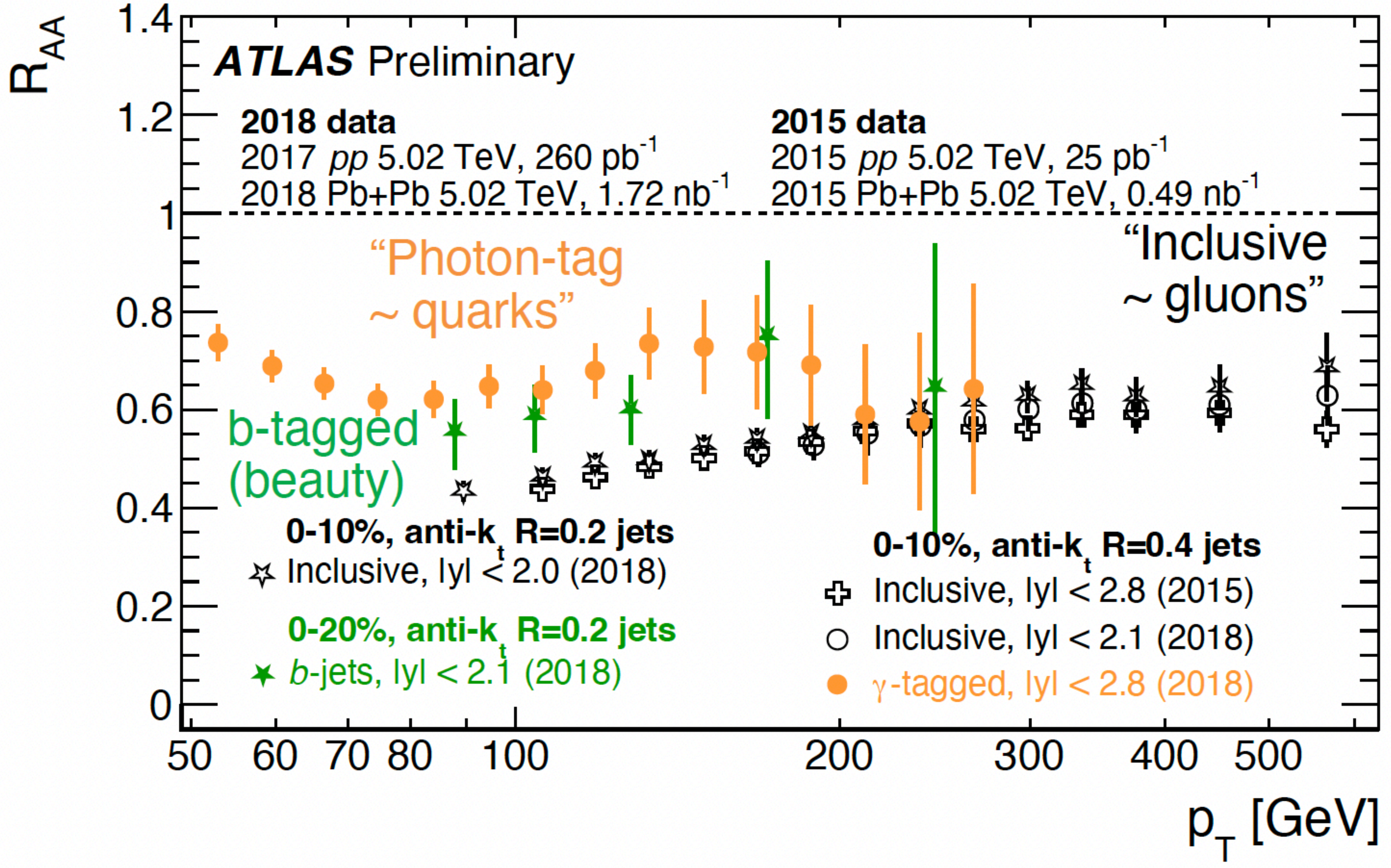
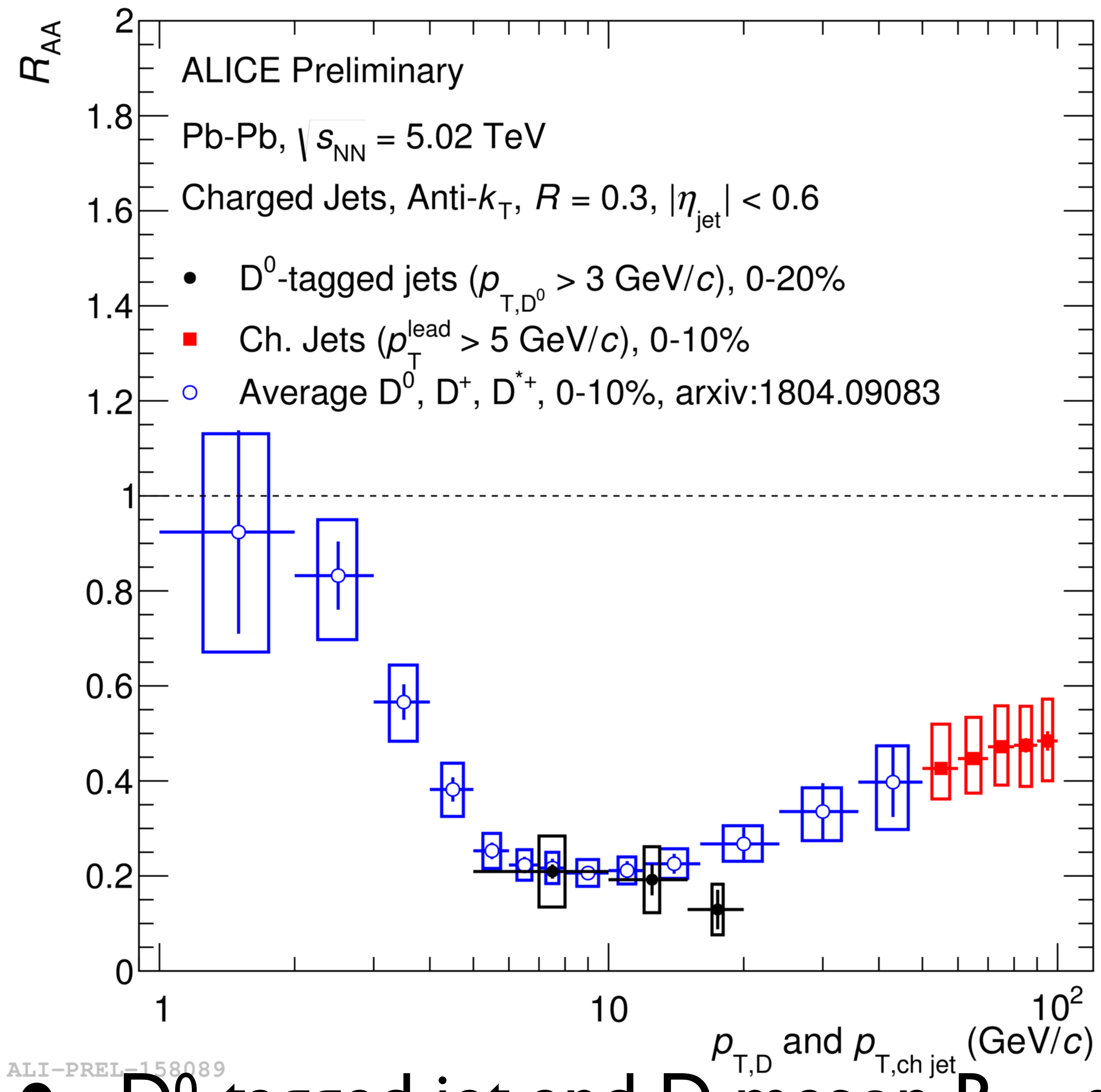


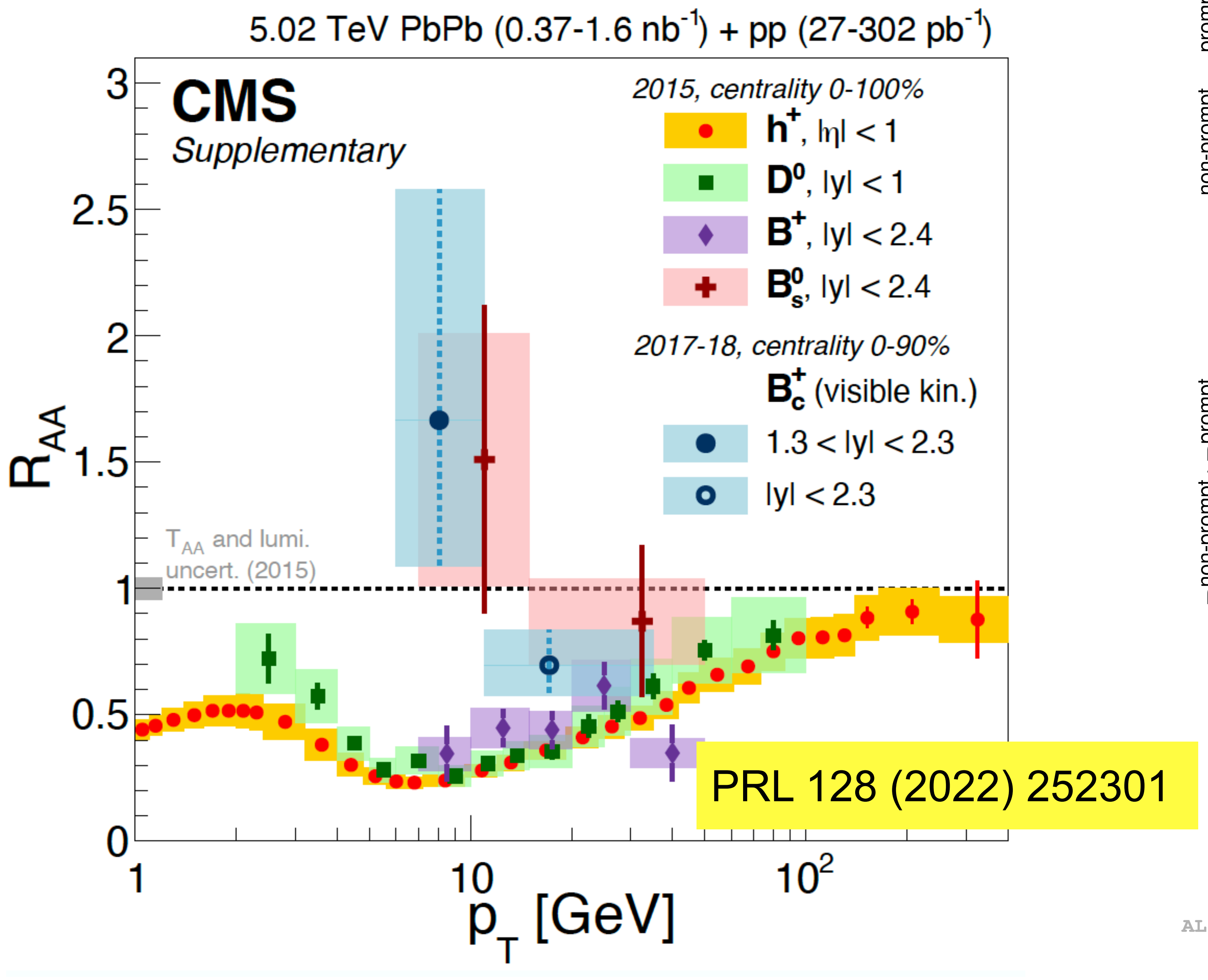
- Energy loss depends on color charge (and mass of parton?)

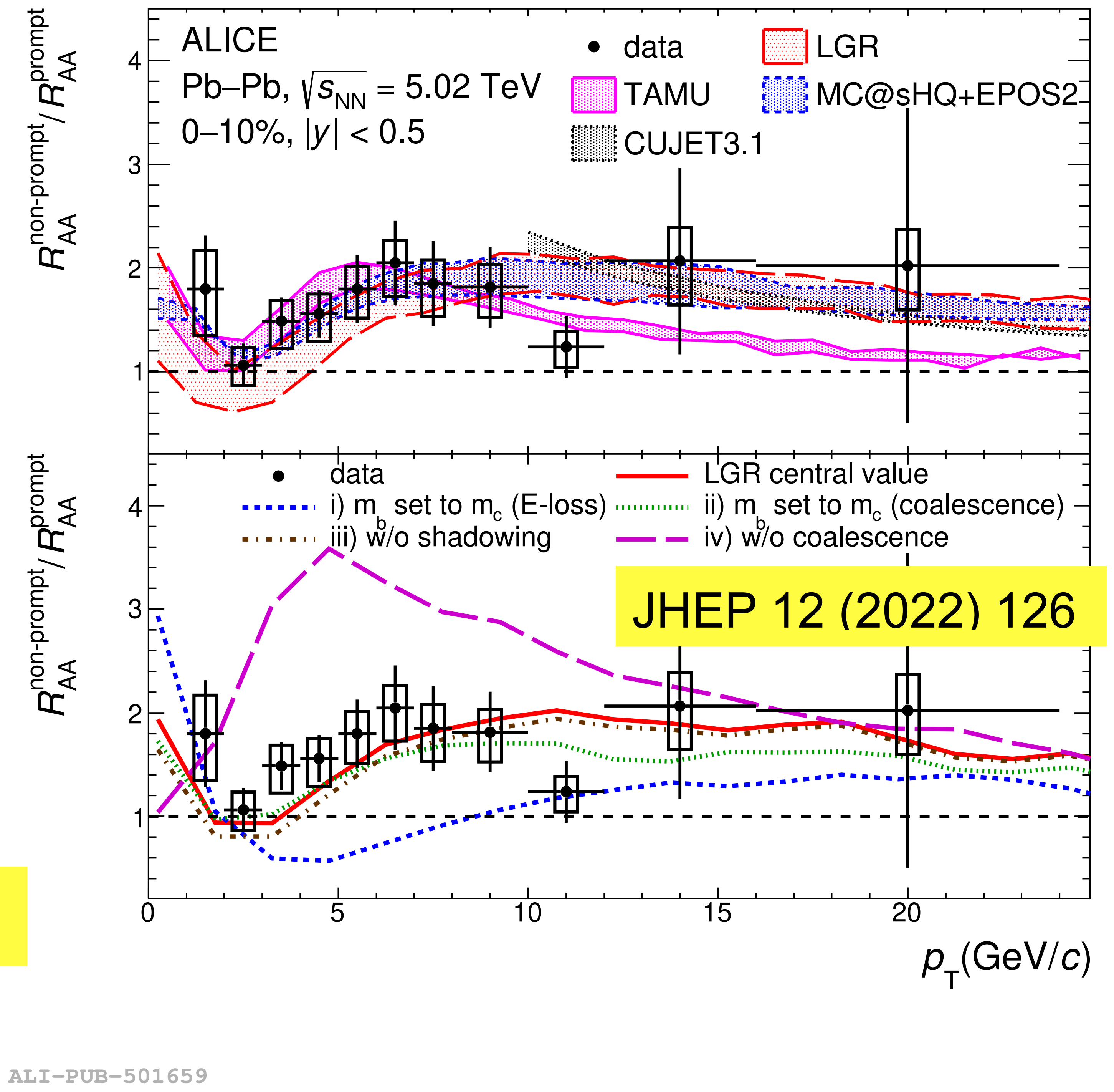
- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect

- Less suppression of b-jets than inclusive jets in most central collisions

Flavor/Mass dependence of energy loss

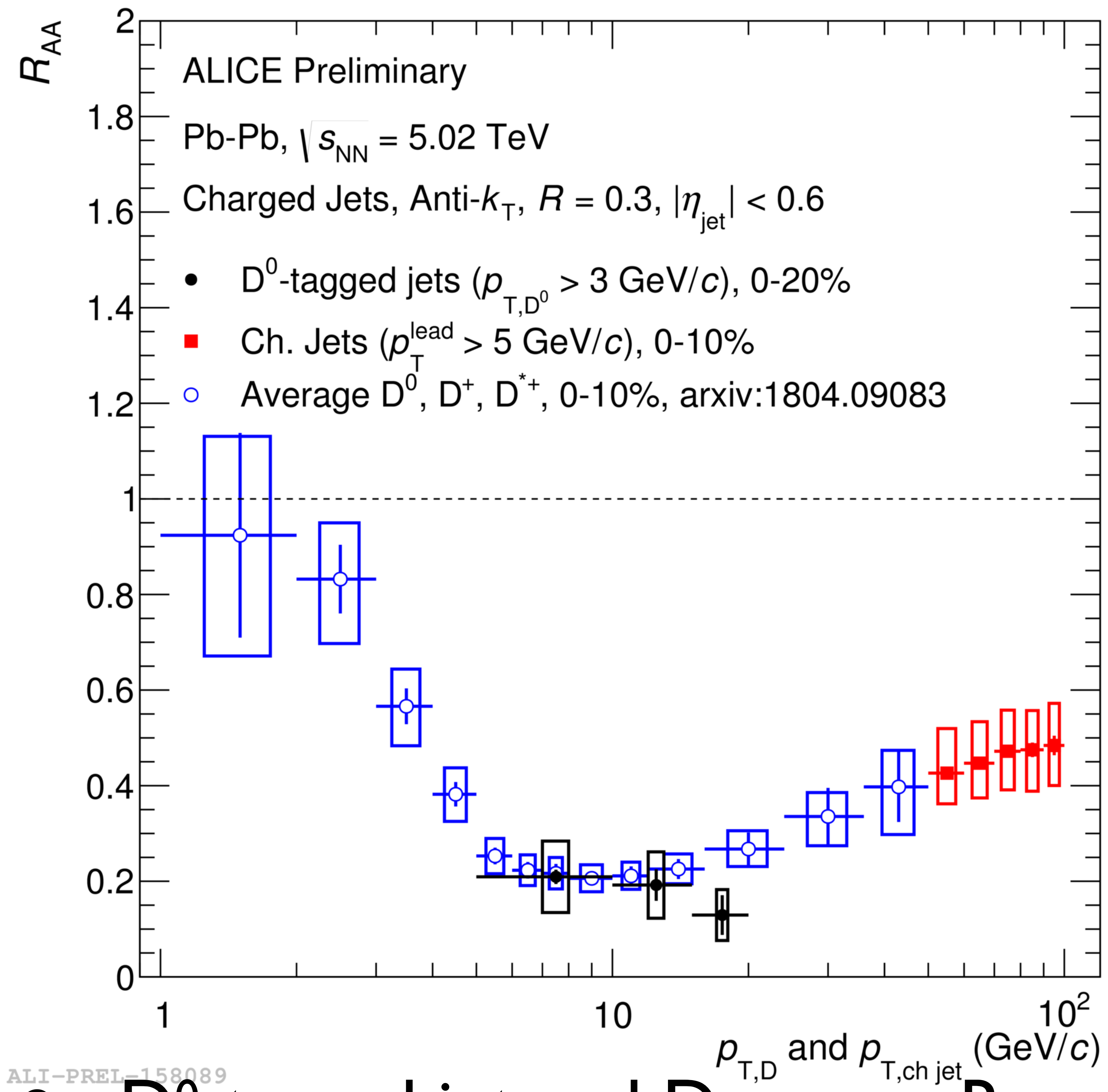


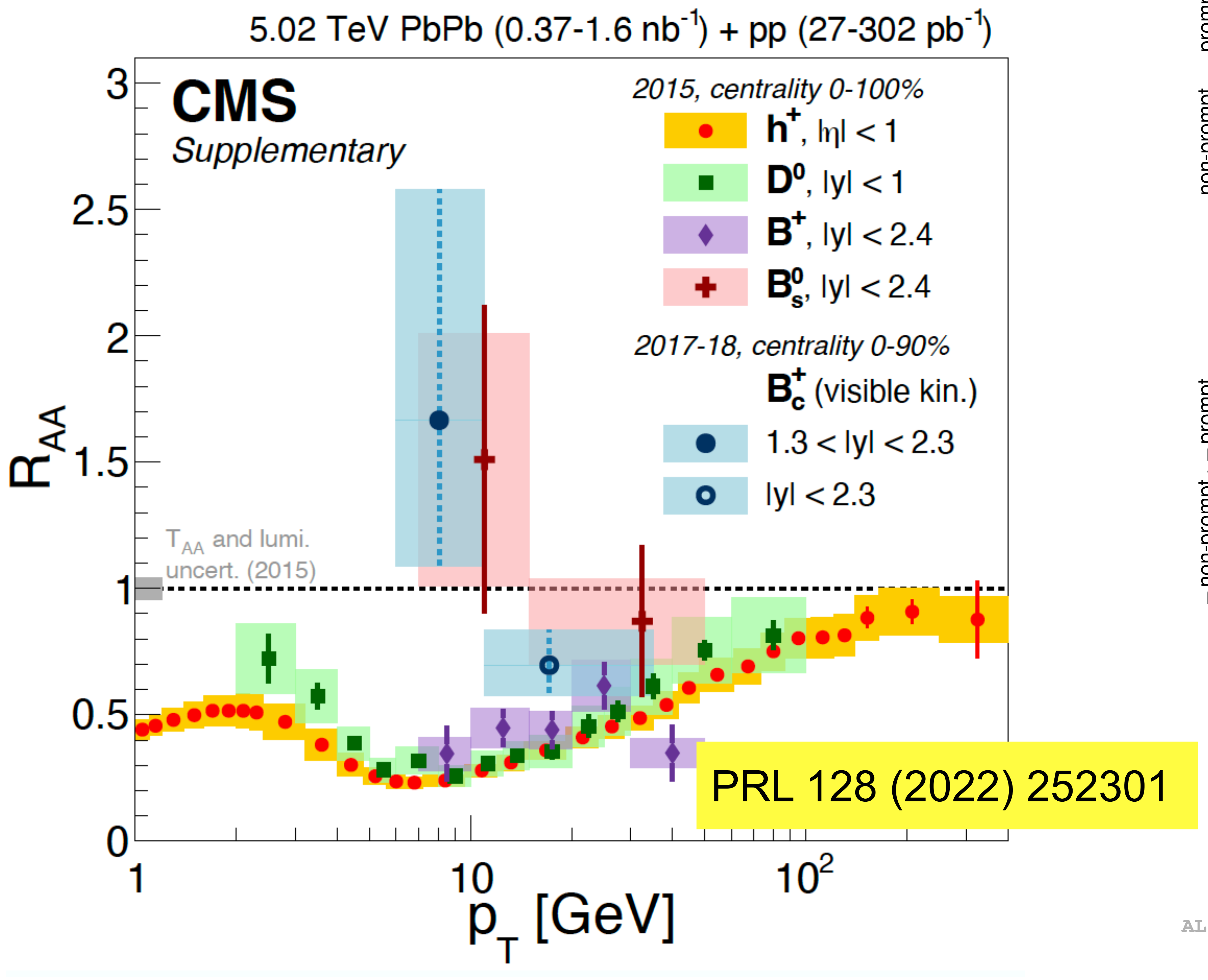


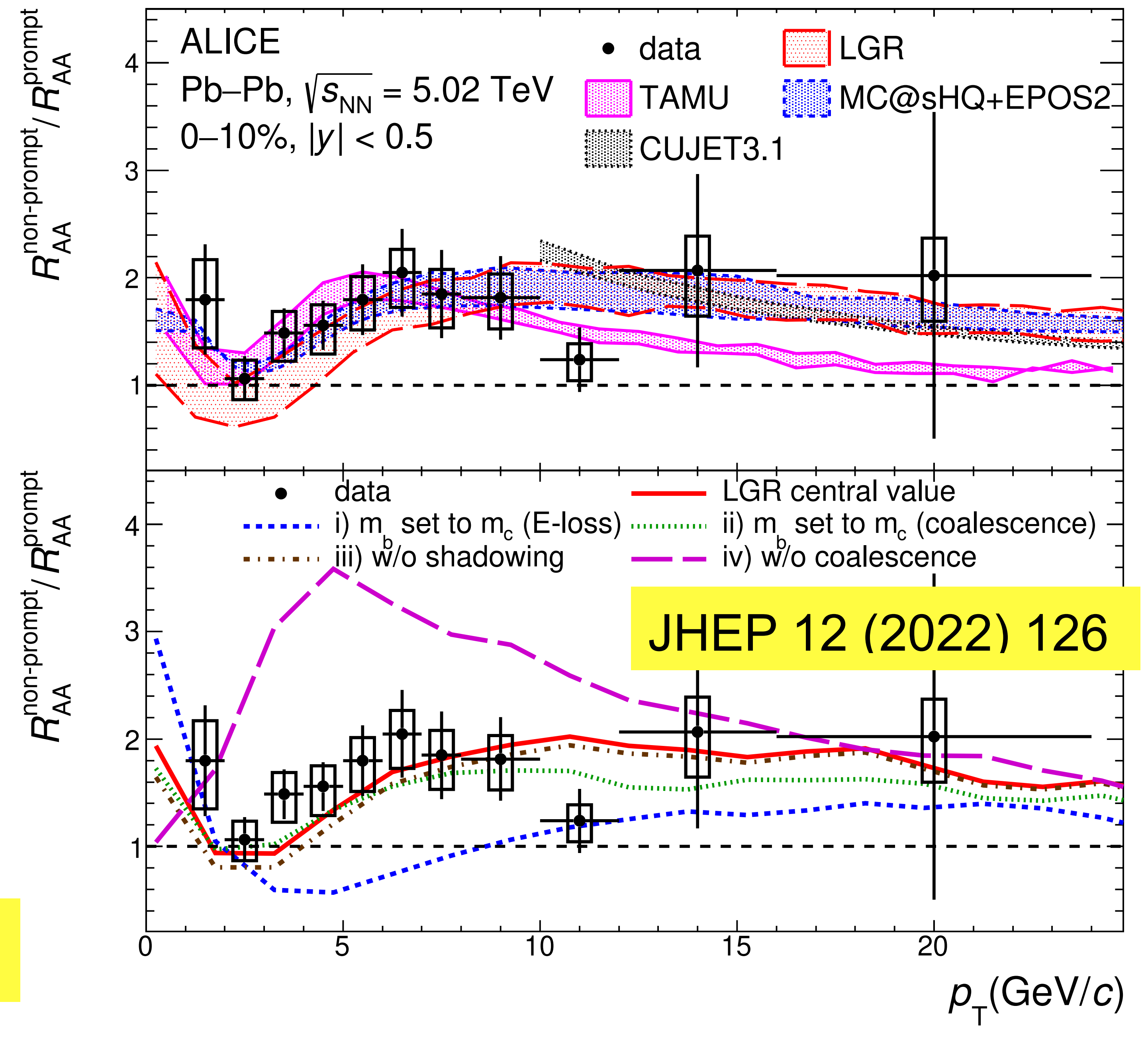


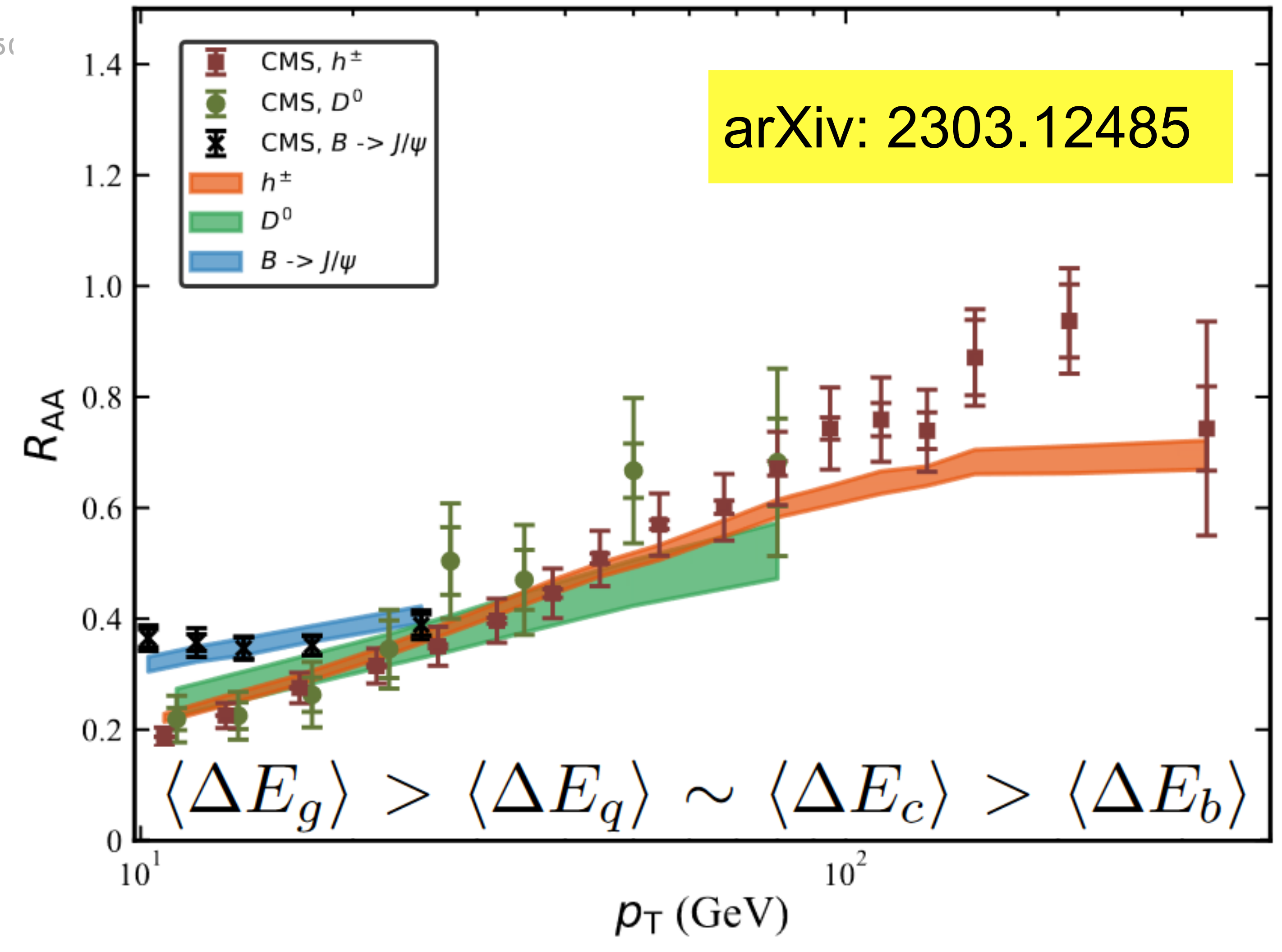
- D^0-tagged jet and D meson R_{AA} similar to inclusive jets/hadrons
- Mass dependence of energy loss is found between B and inclusive hadrons/ jets, but not charm and light flavors

Flavor/Mass dependence of energy loss







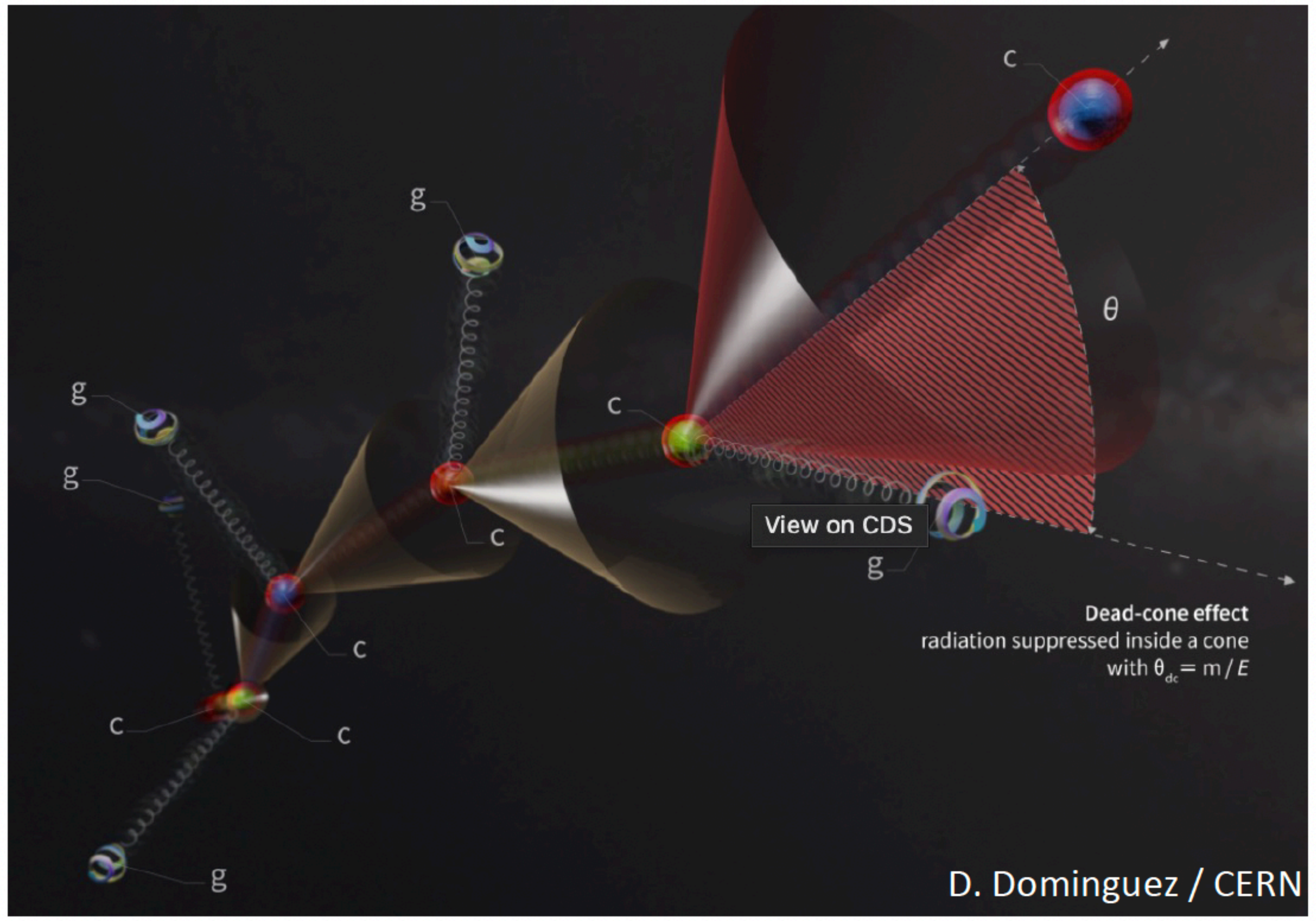


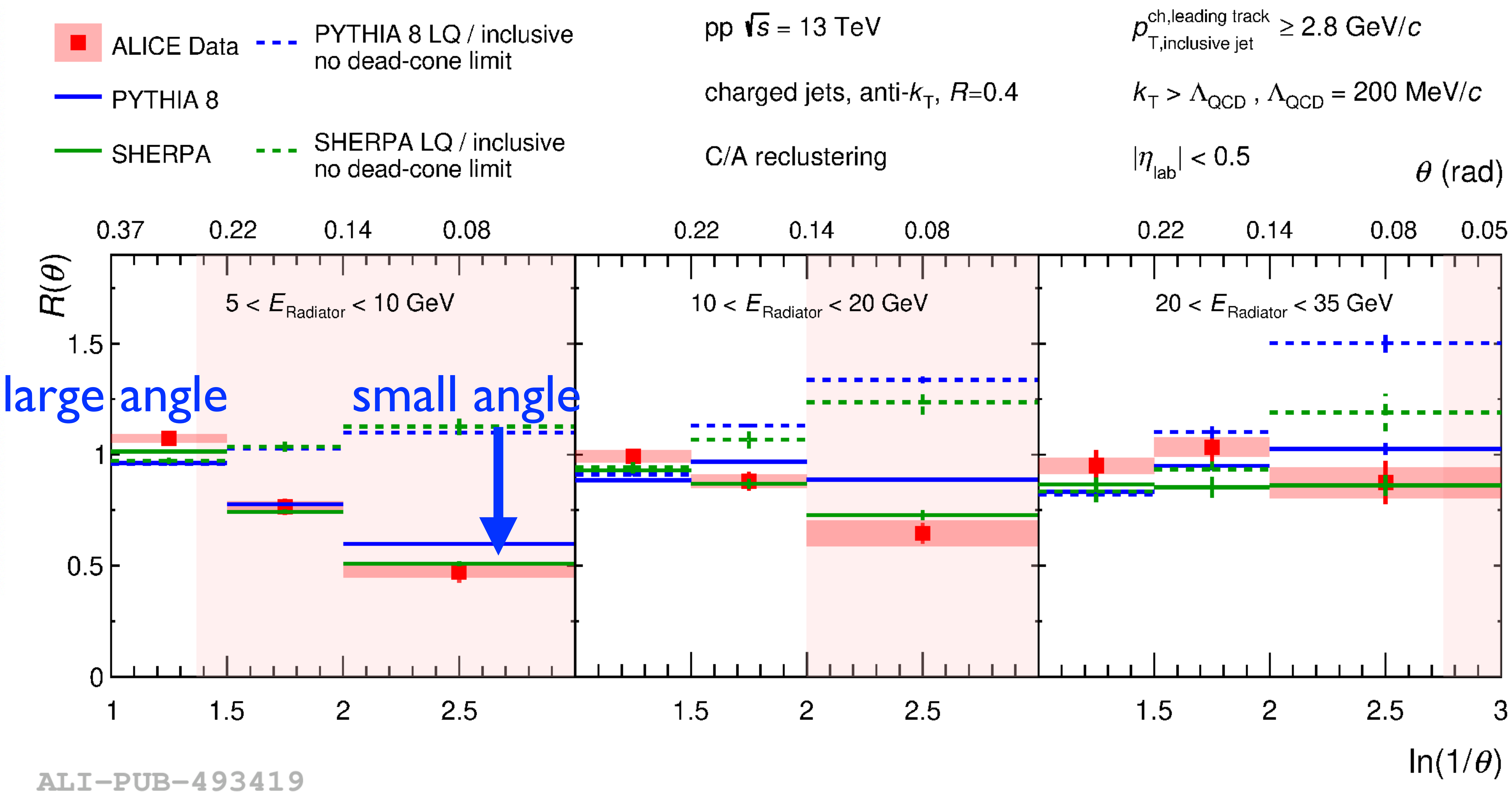
- D^0-tagged jet and D meson R_{AA} similar to inclusive jets/hadrons
- Mass dependence of energy loss is found between B and inclusive hadrons/jets, but not charm and light flavors
- Model that includes both quark and gluon fragmentation to light and heavy flavor hadrons can explain the flavor dependence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

In pp: dead cone effect exposed by ALICE

- Reduction of gluon radiation from heavy quarks at small angles

Nature 605 (2022) 7910





- First direct observation of dead-cone effect in pp using jet iterative declustering and Lund plane analysis of jets that contain a soft D^0 meson.
- D-tagged jets in pp does show the dead-cone effect! where is it in AA?

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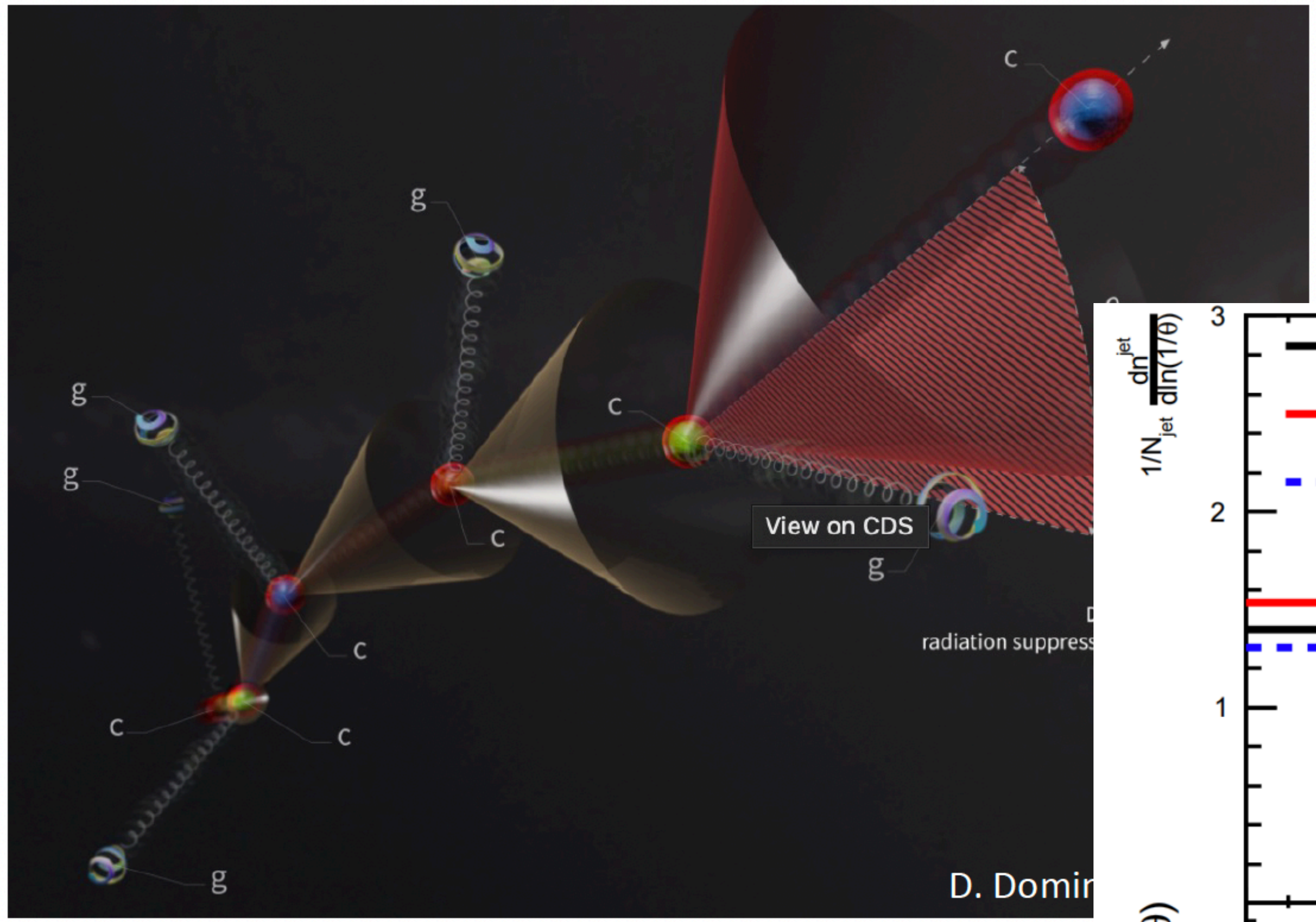

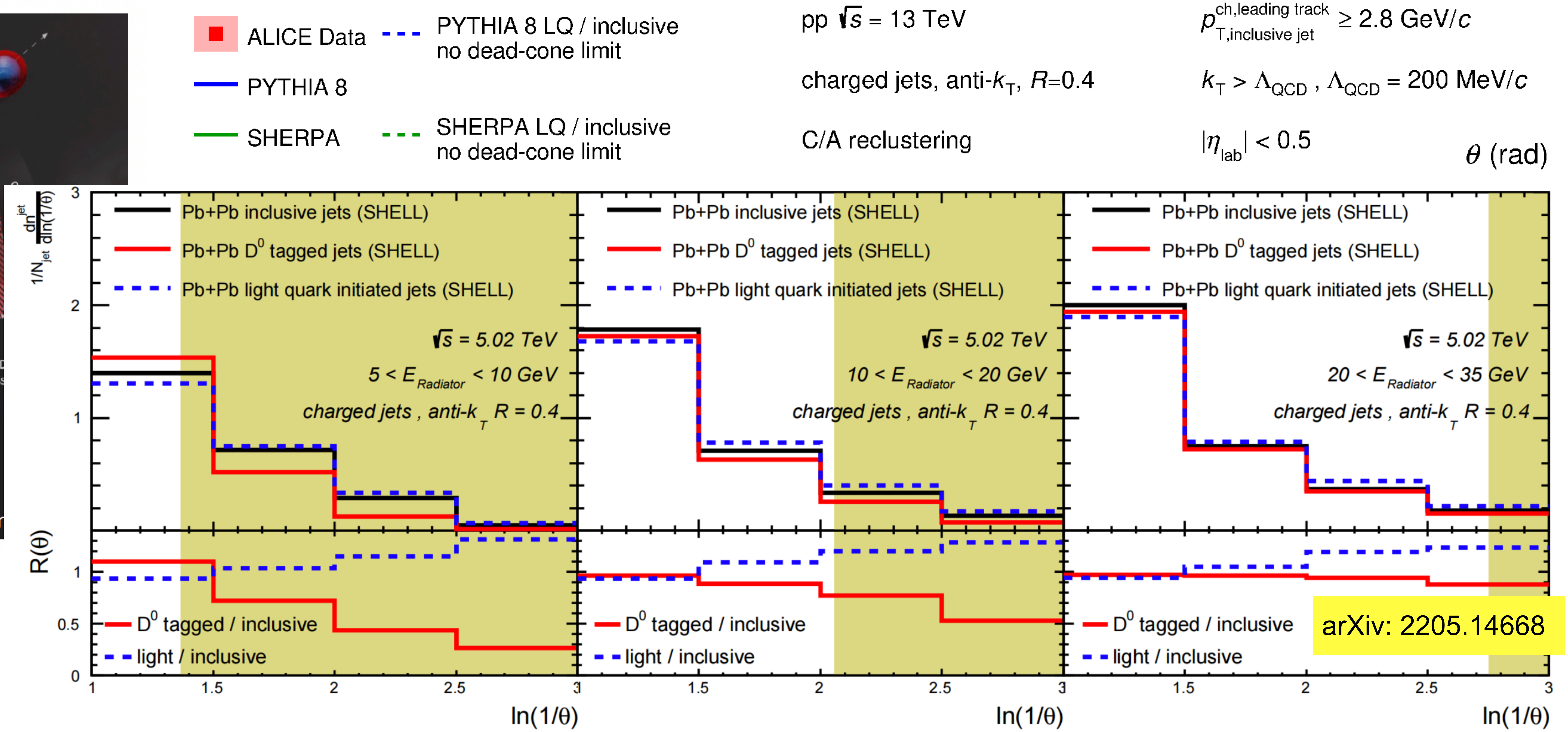

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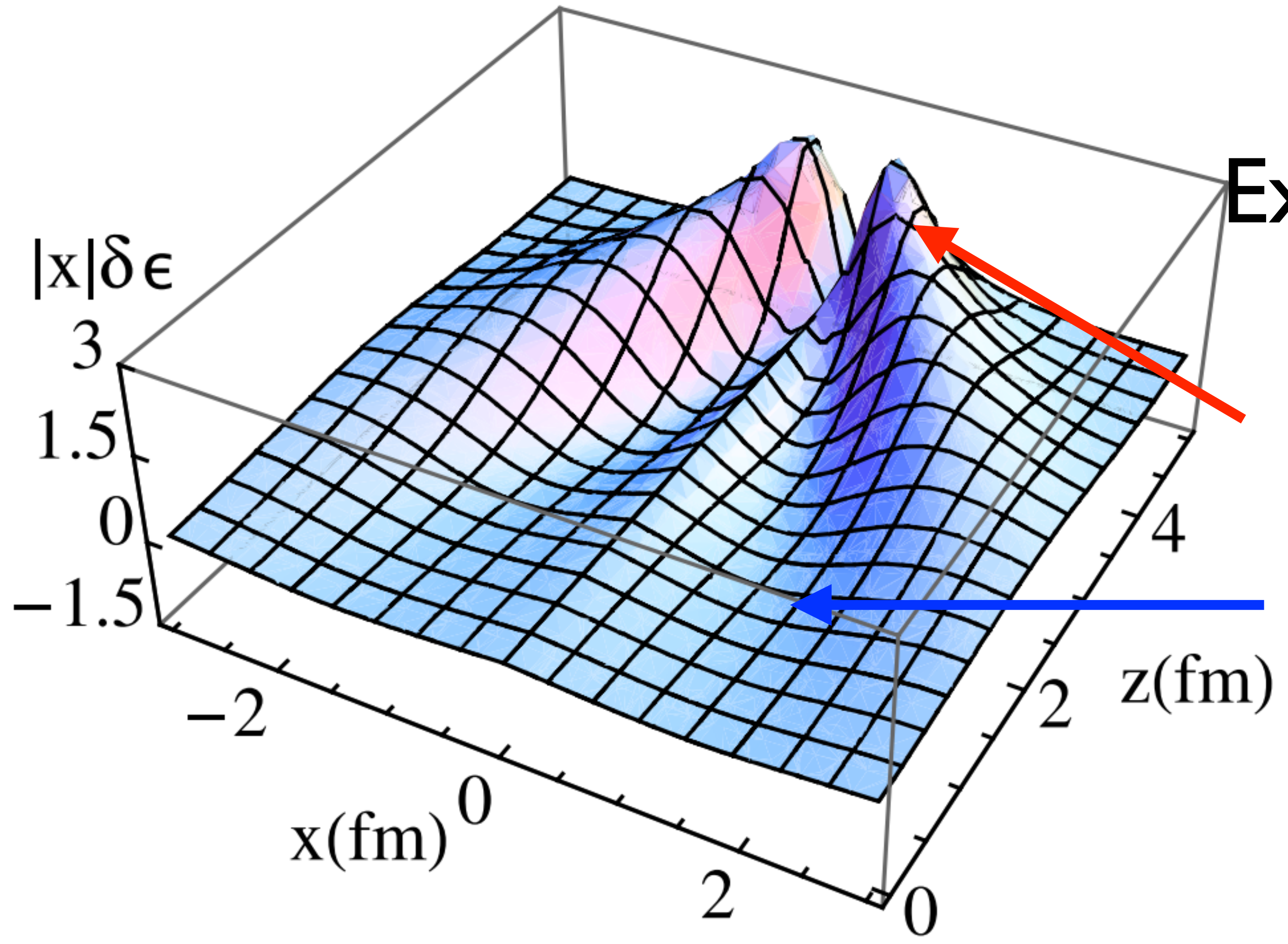
Medium response to propagating parton

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

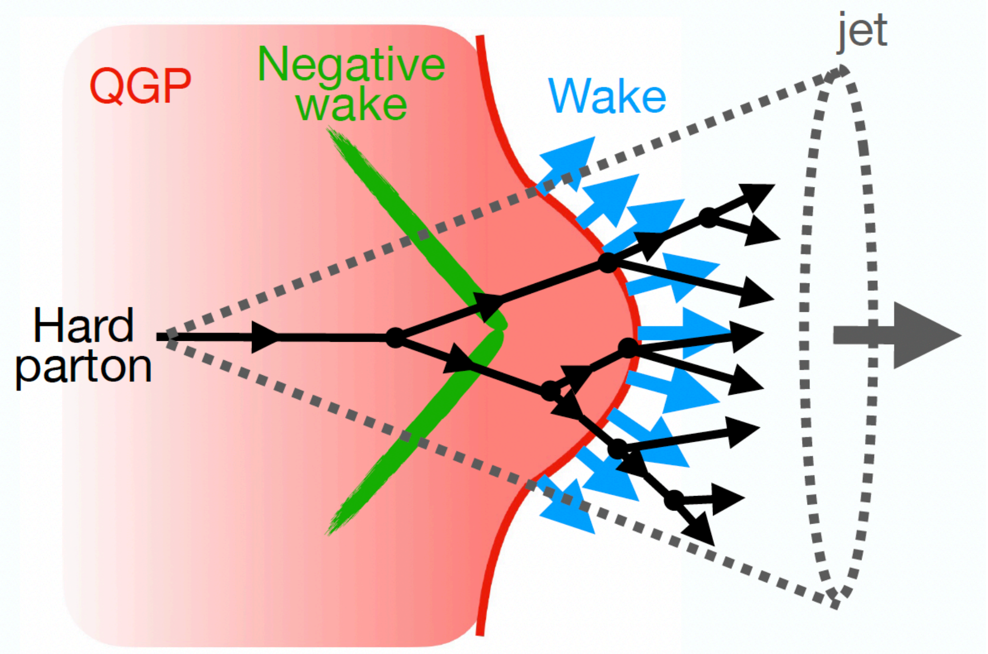


Expectations: "wake effects"

Enhancement around jet

Depletion opposite jet

PRL 103 (2009) 152303



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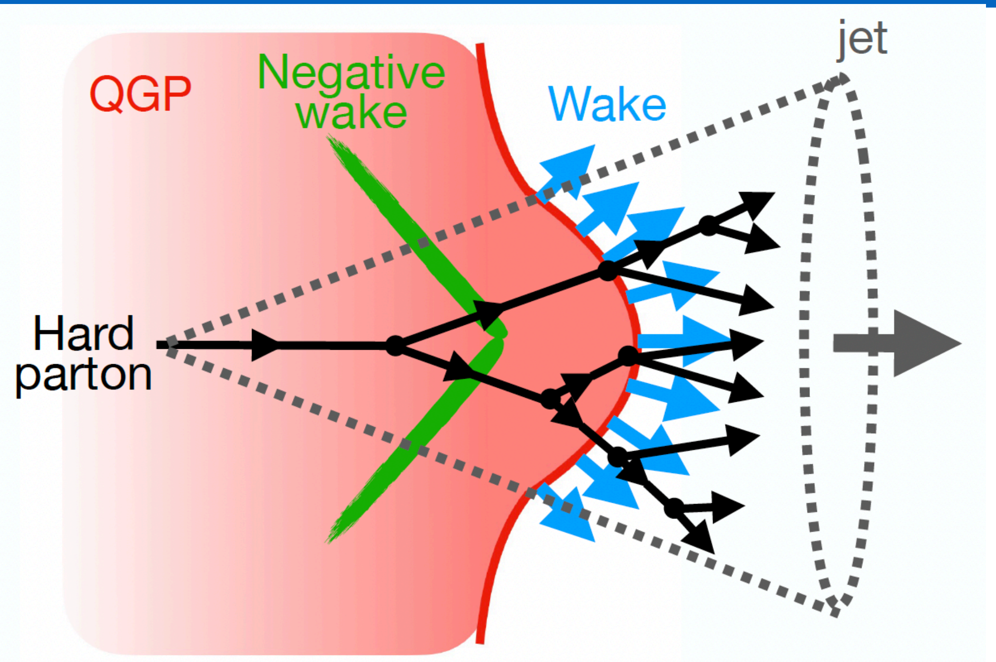

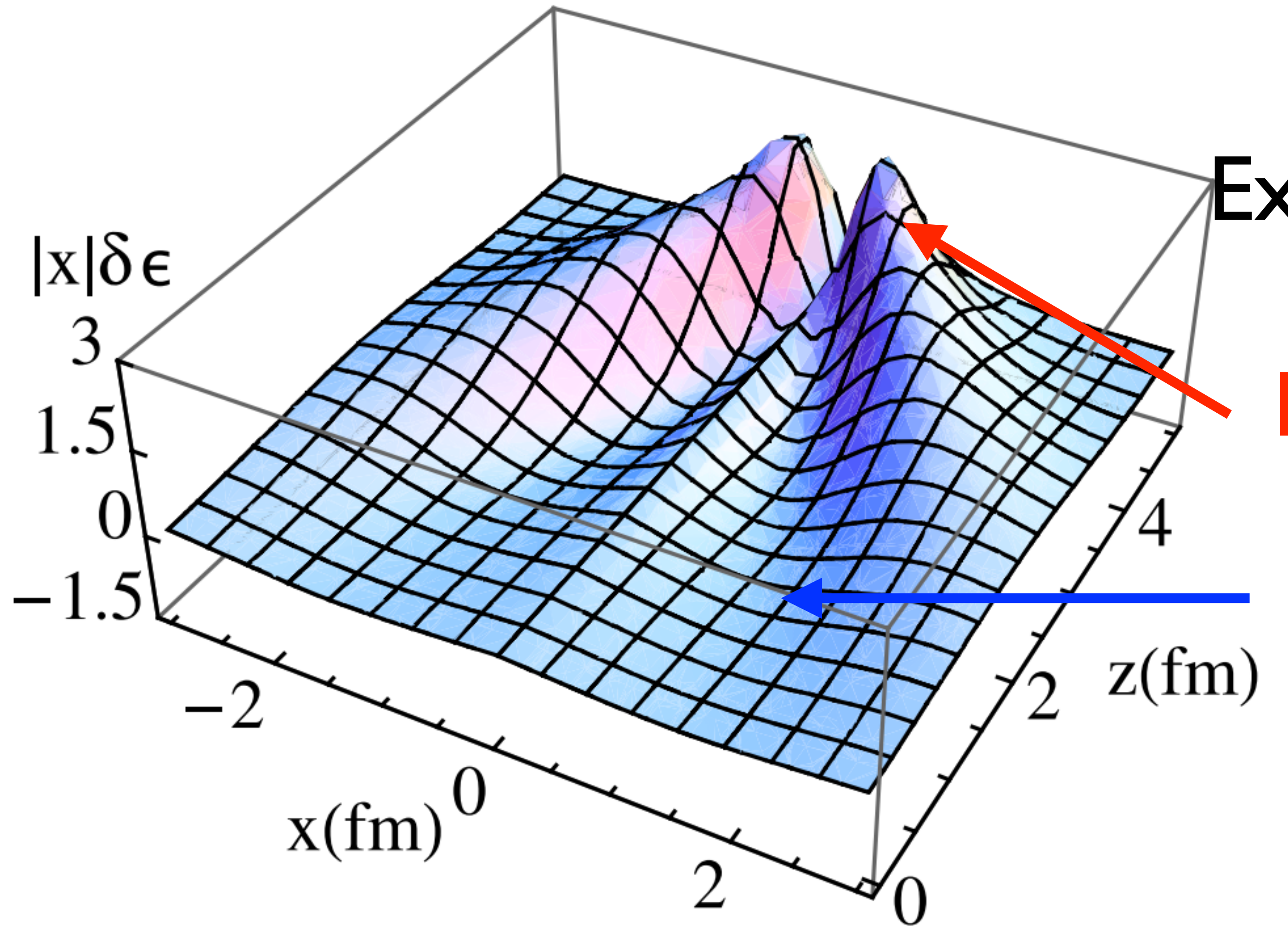

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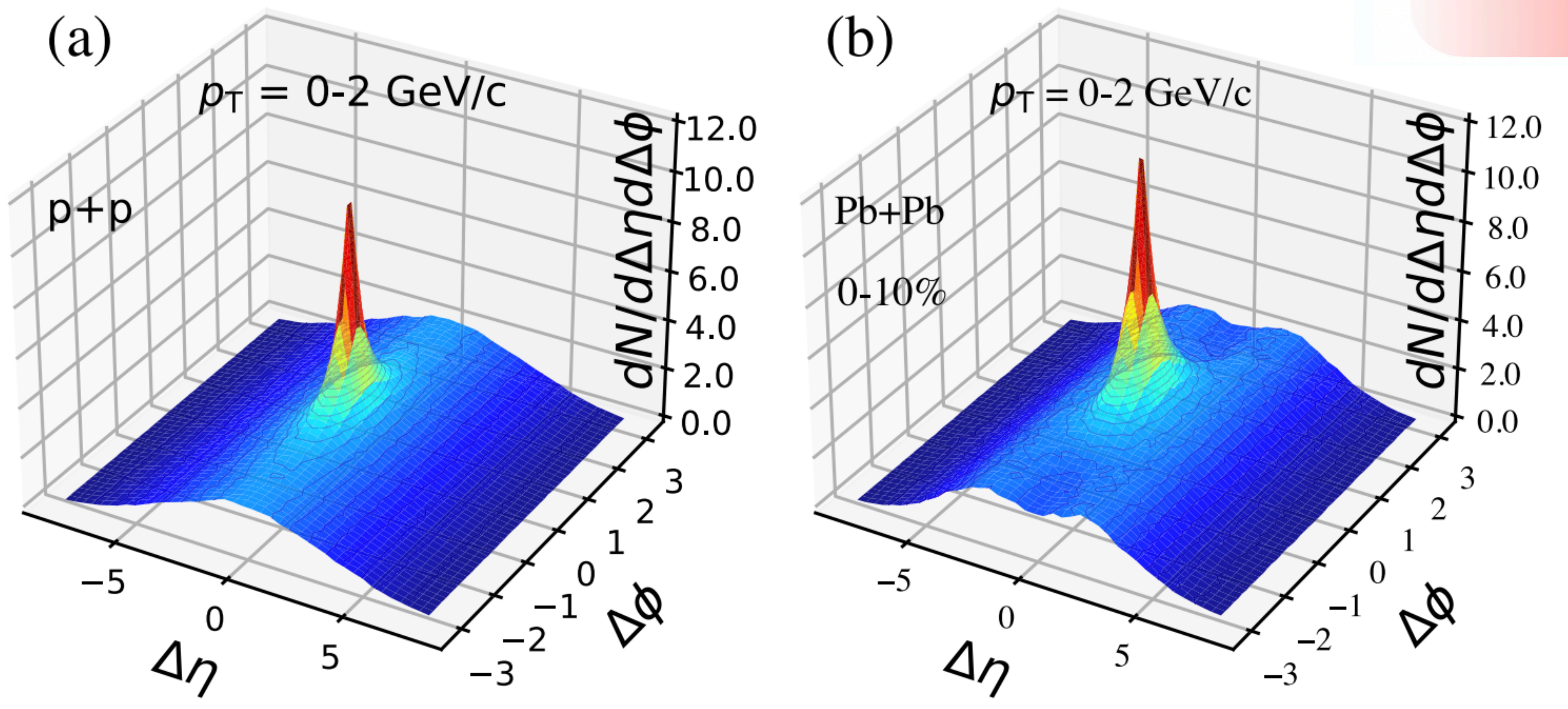
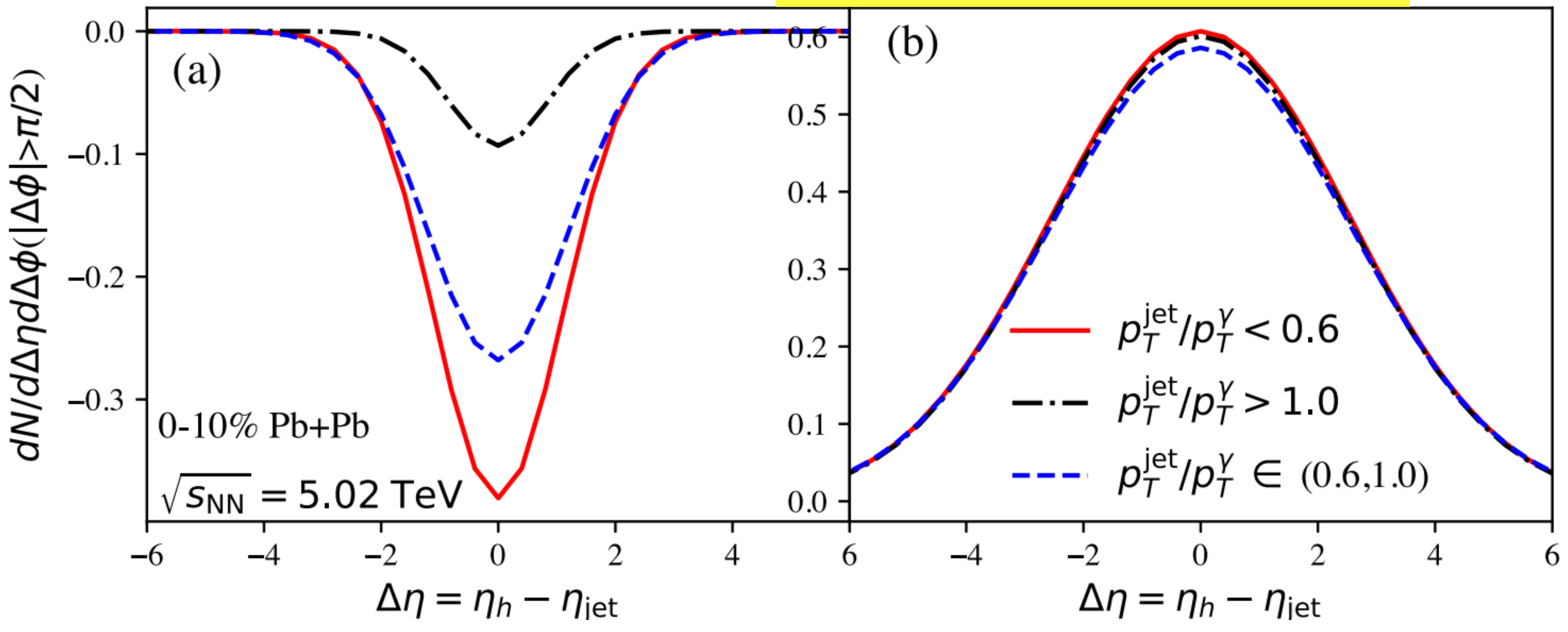


PRL 130 (2023) 052301

- 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



Medium response to propagating parton

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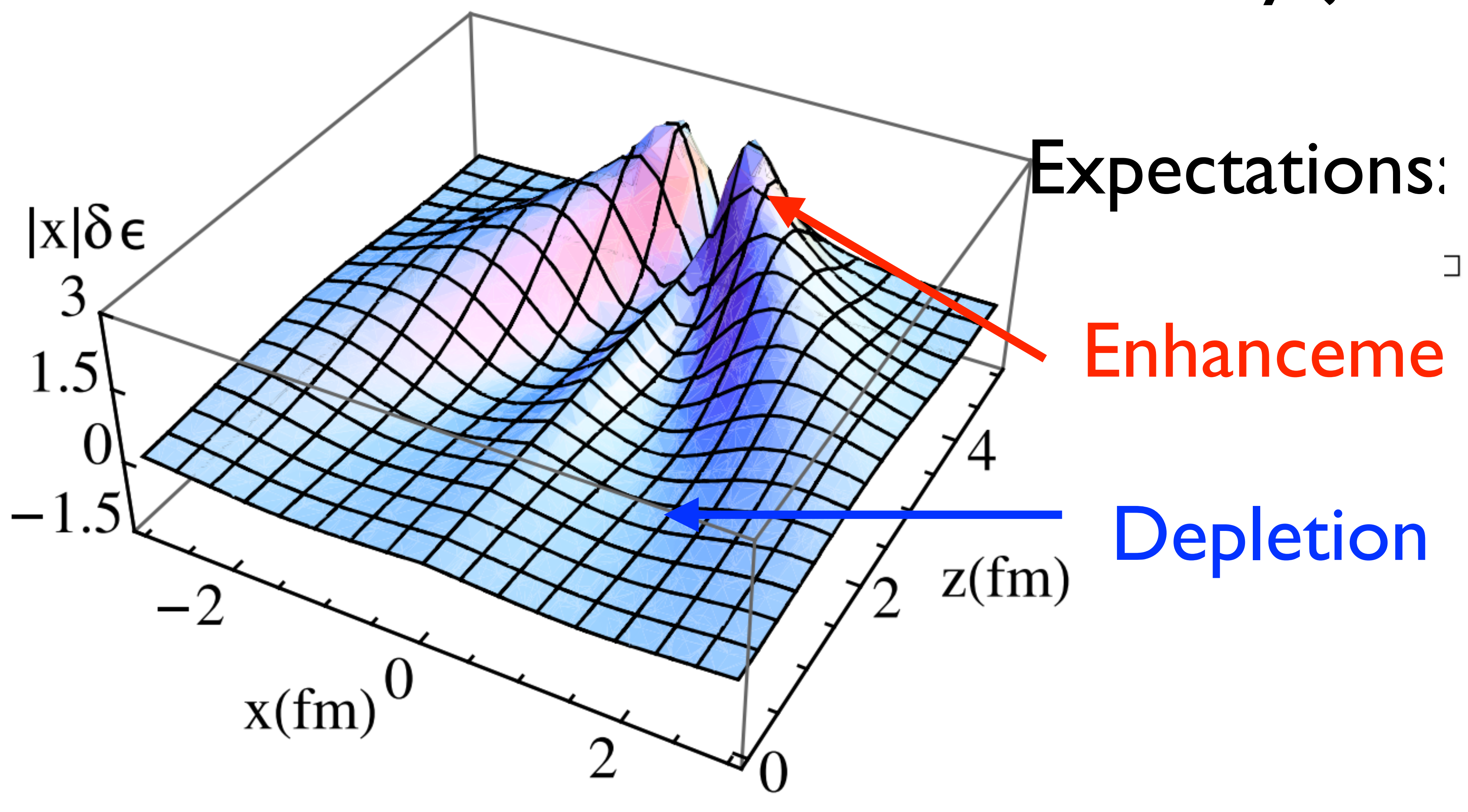
Expectations:



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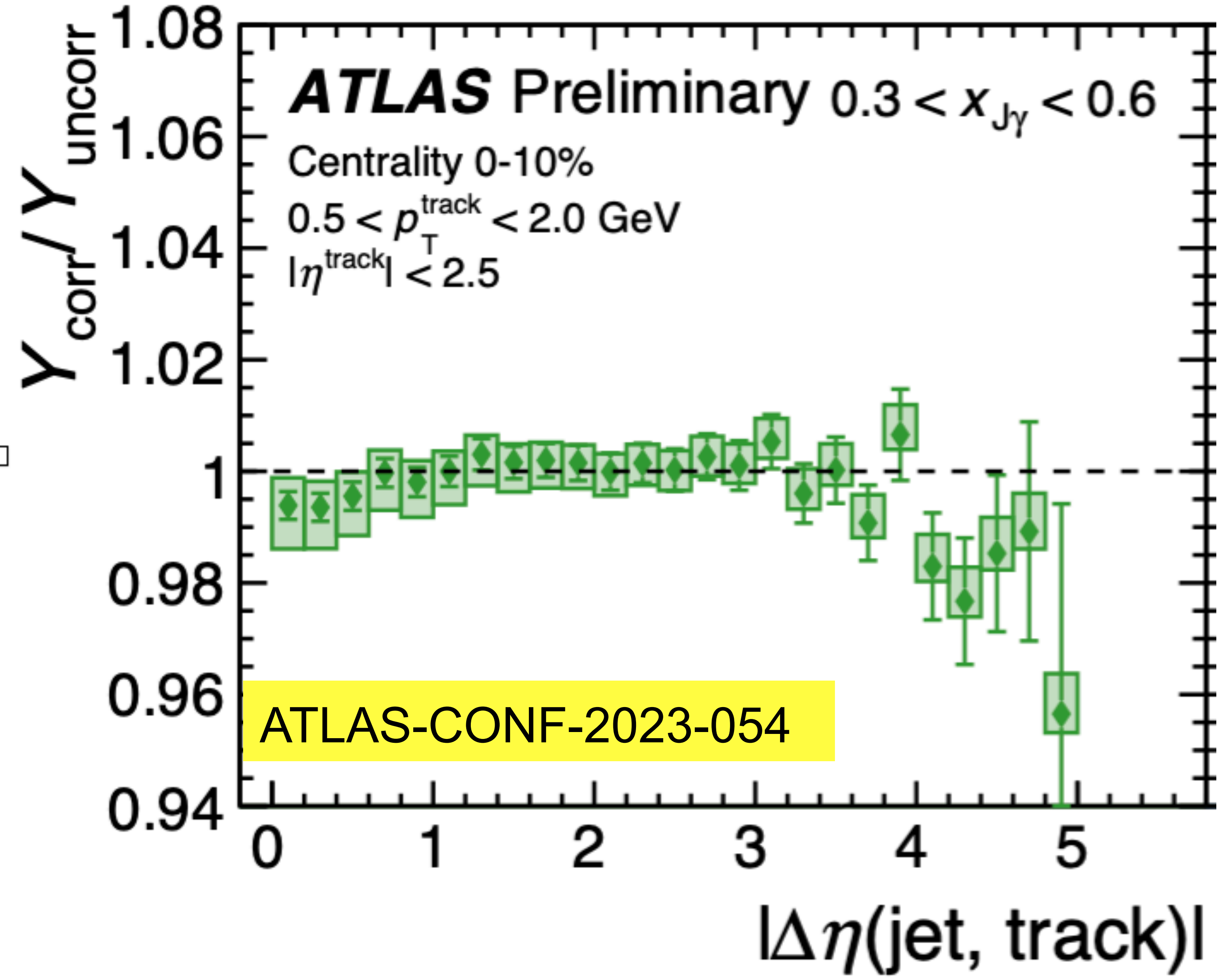
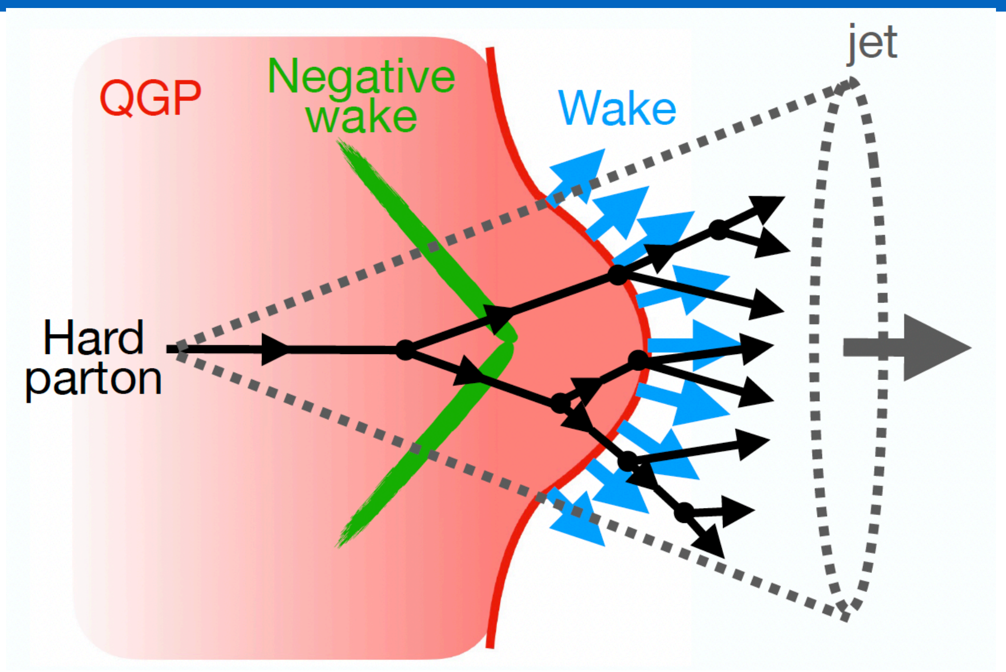
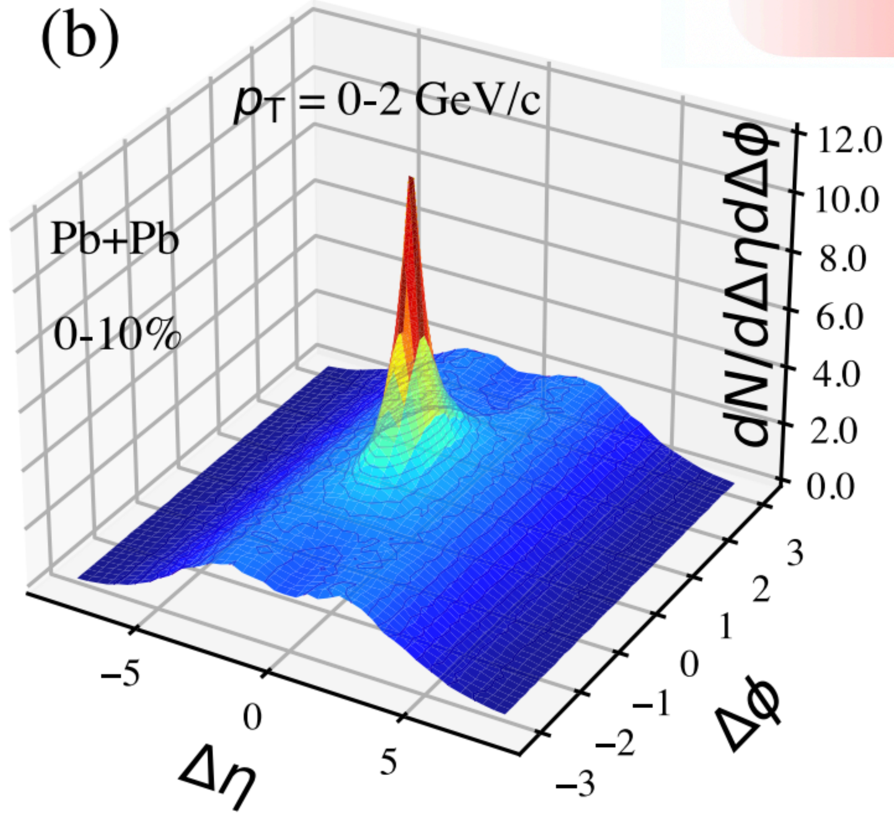
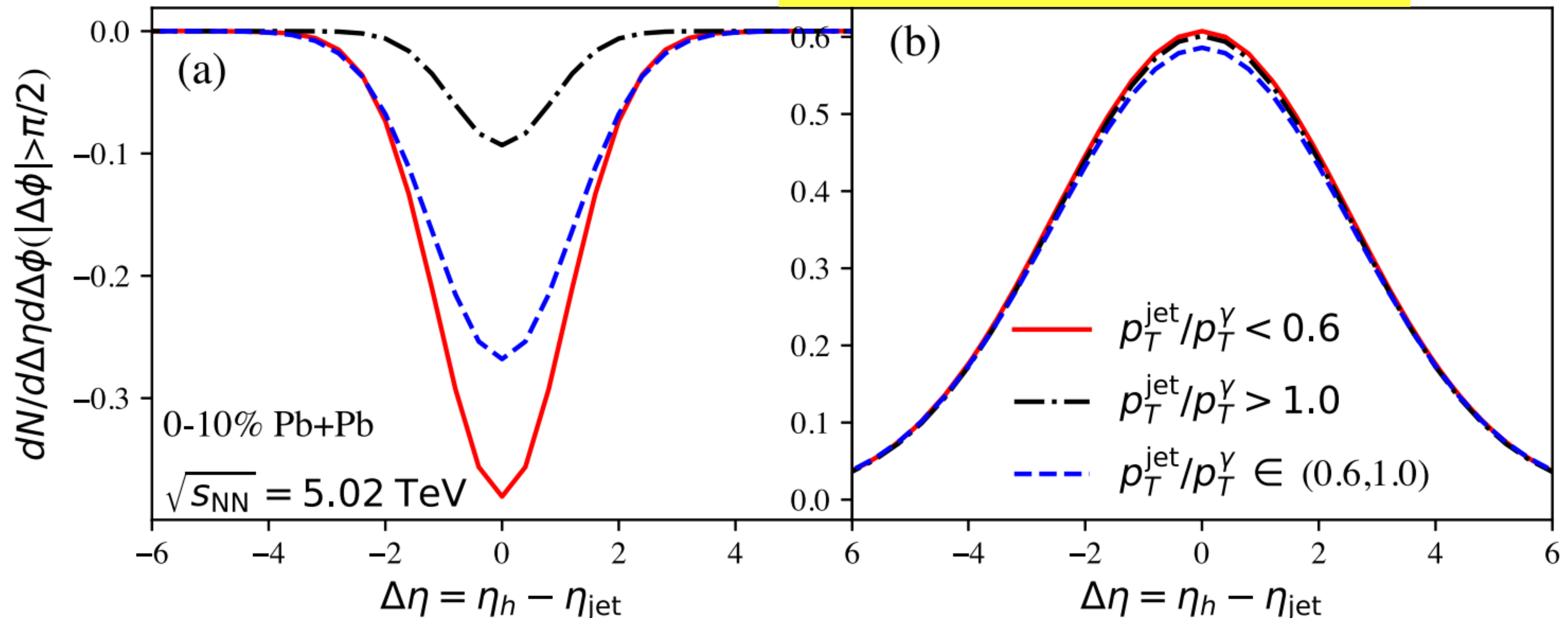






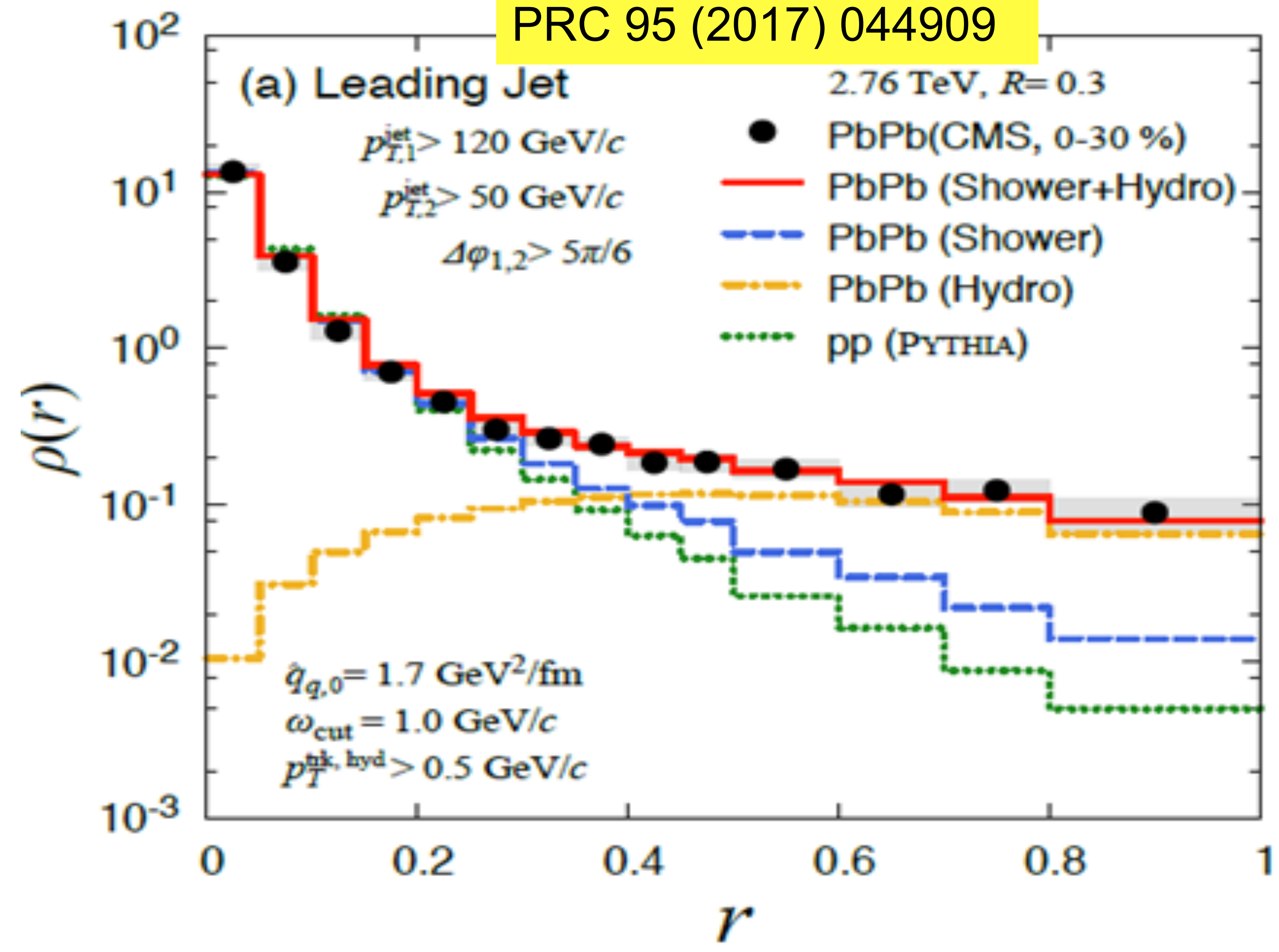
PRL 130 (2023) 052301



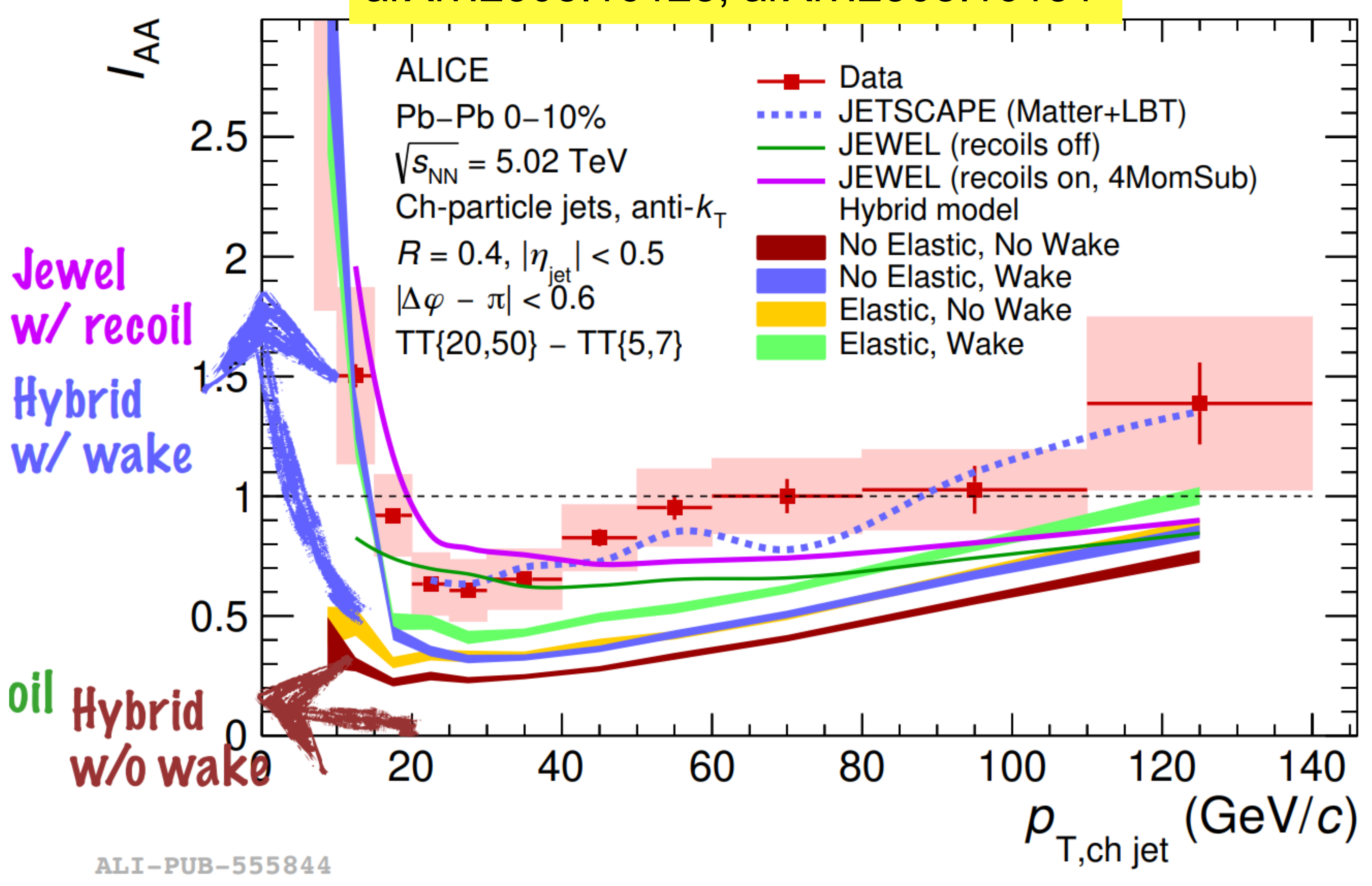
- CoLBT-Hydro predicts double peak structure in γ-hadron correlations as a function of rapidity and azimuth (valley from diffusion wake, ridge from MPI)
- Depth of the diffusion wake valley increases with increasing jet energy loss as characterized by γ-jet asymmetry

Medium response: redistribution of lost energy

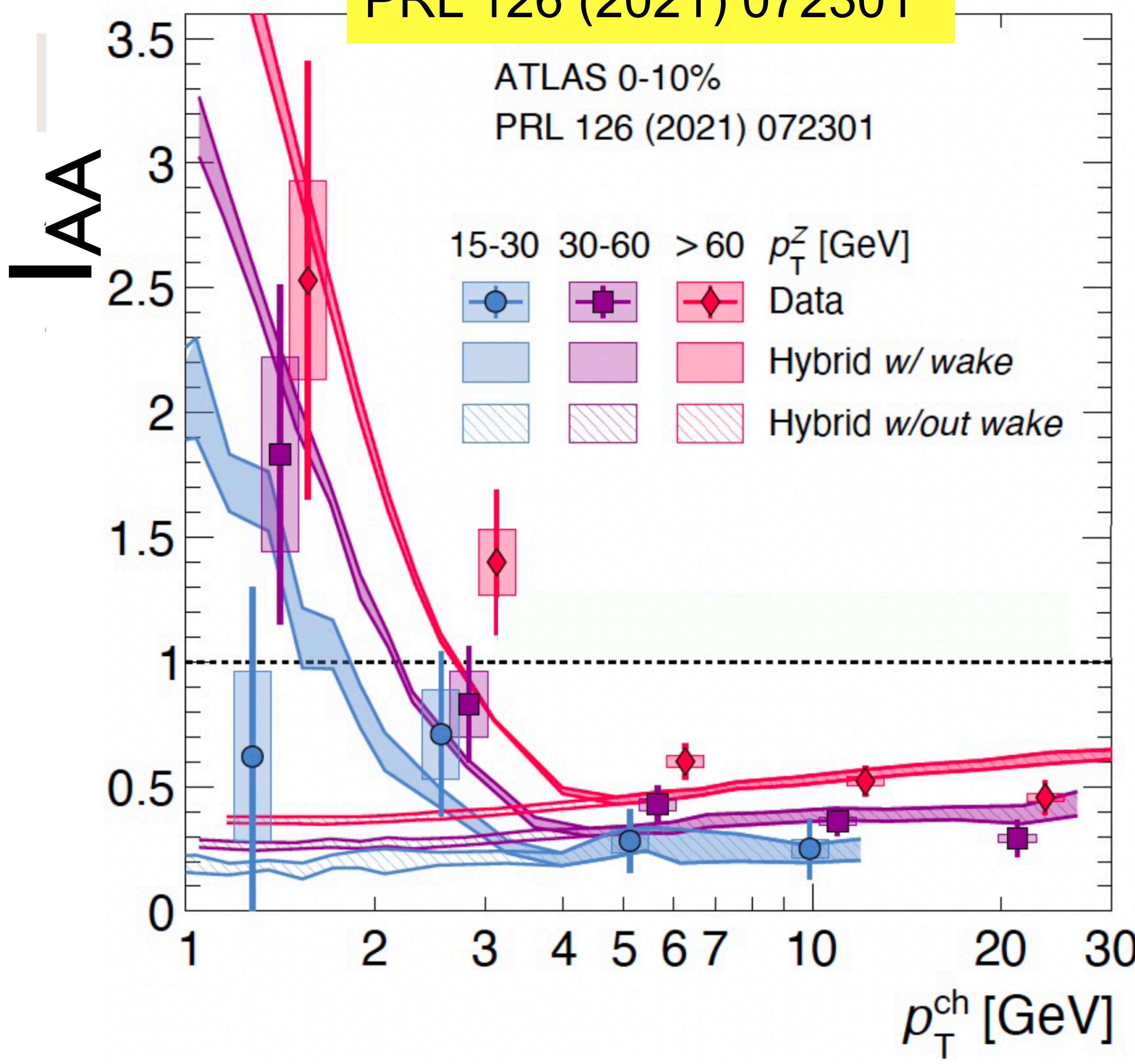
PRC 95 (2017) 044909

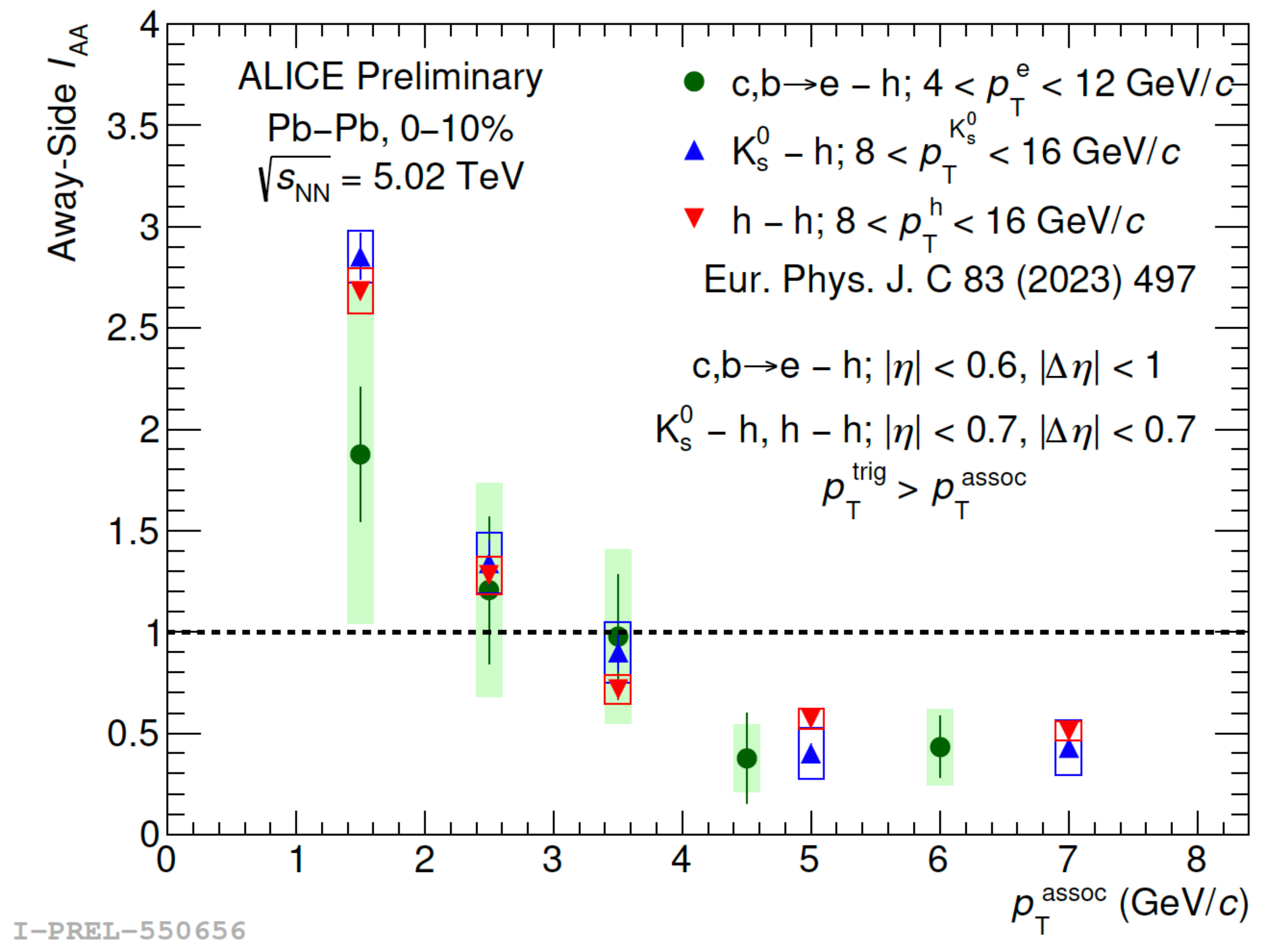


arXiv:2308.16128, arXiv:2308.16131



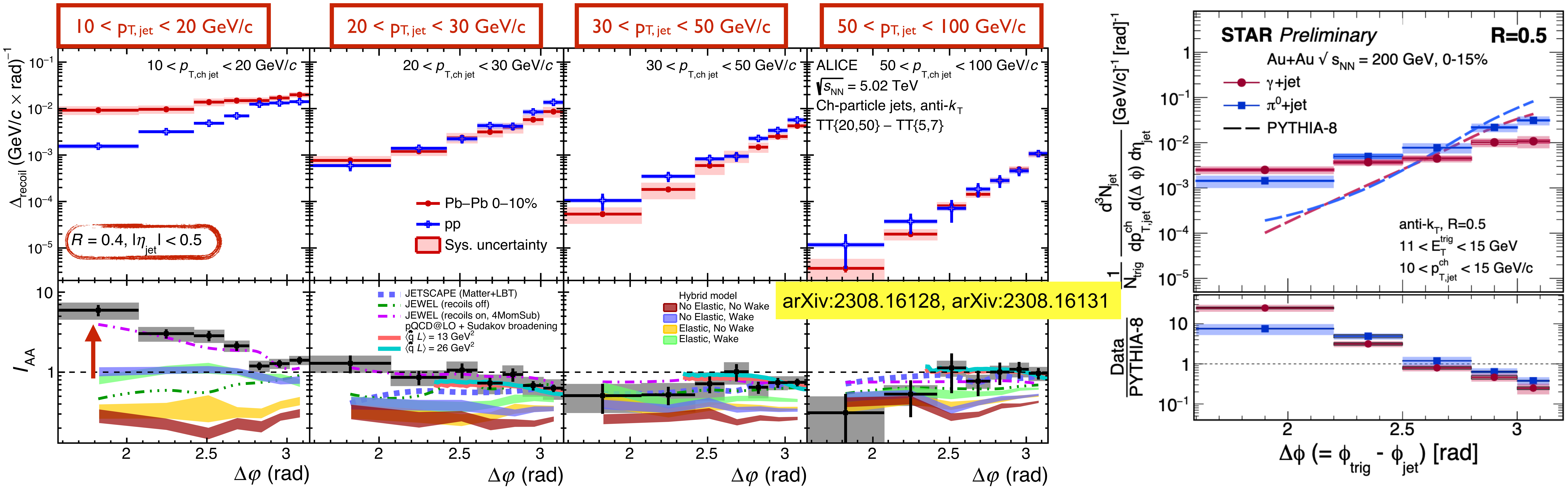
PRL 126 (2021) 072301





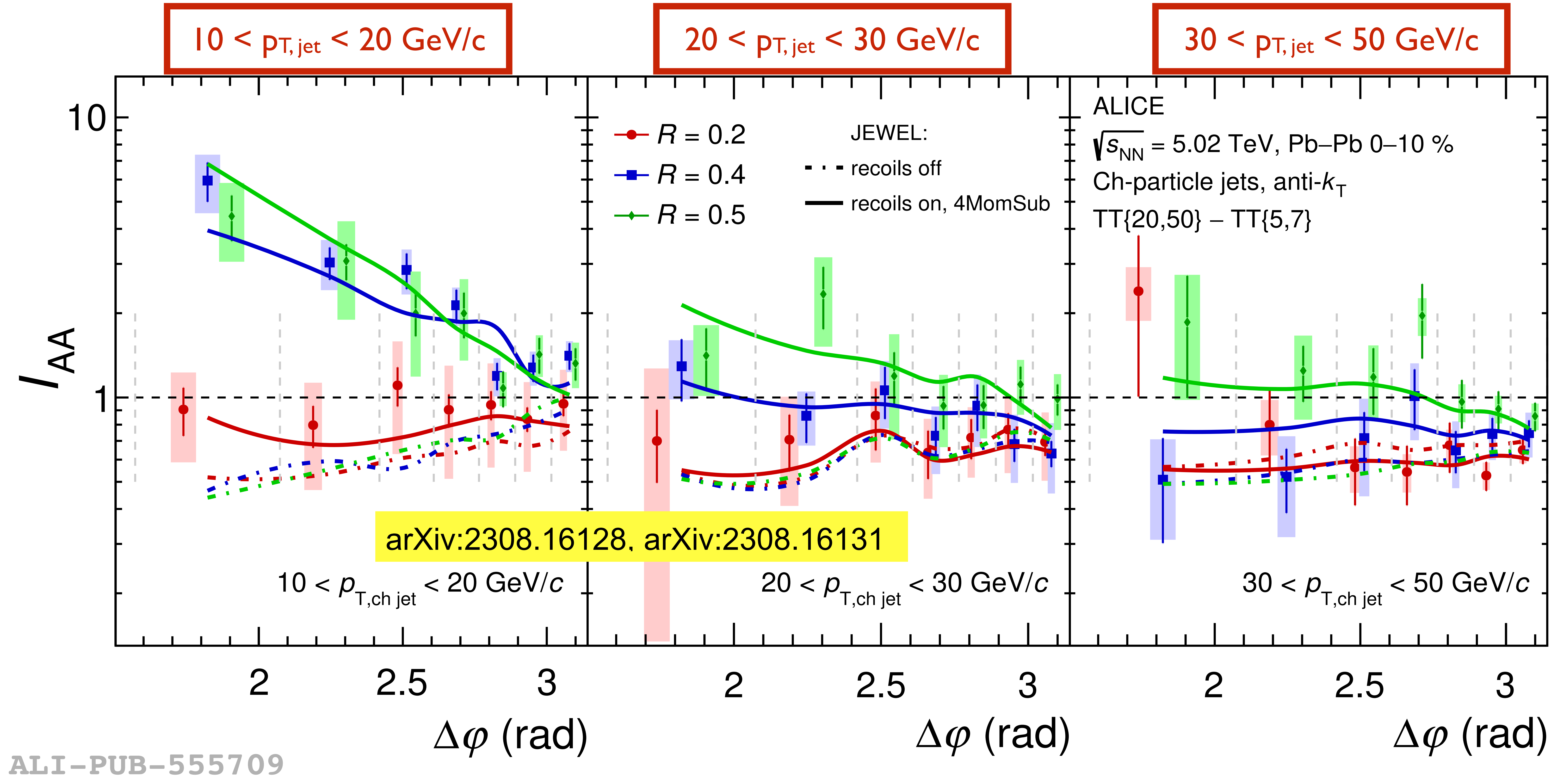
- Low p_T and large r excess →energy redistribution due to jet quenching
  - ➡ Jet-fluid model can describe the enhancement of jet shape at large r
  - ➡ Hybrid and JEWEL w/ wake (recoil on) can capture the enhancement for low p_T jet
  - ➡ JETSCAPE captures the enhancement for high p_T jet

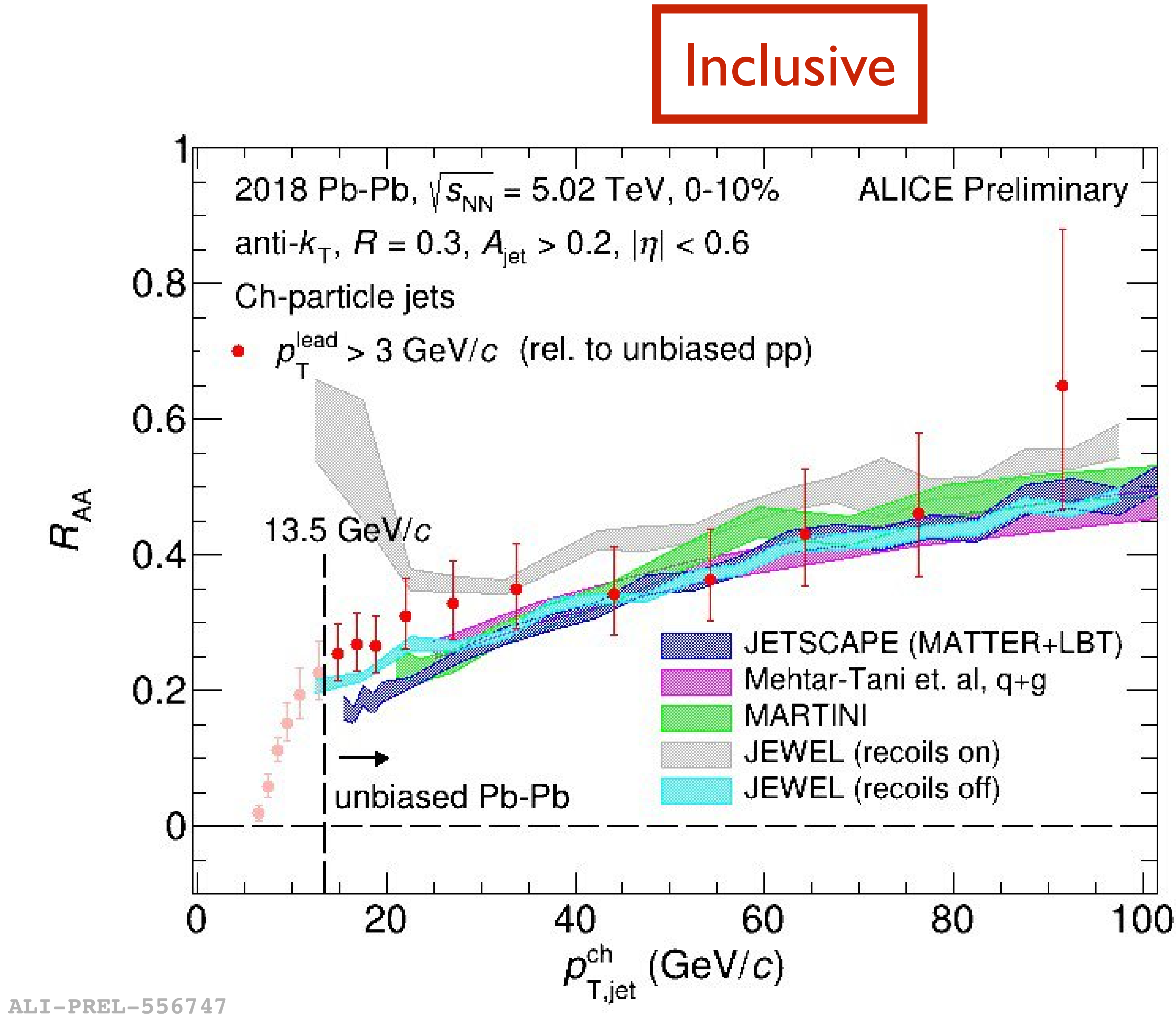
Recoil jet $\Delta\varphi$ modifications: angular broadening



- 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

Recoil jet and inclusive jet modification: JEWEL comparison



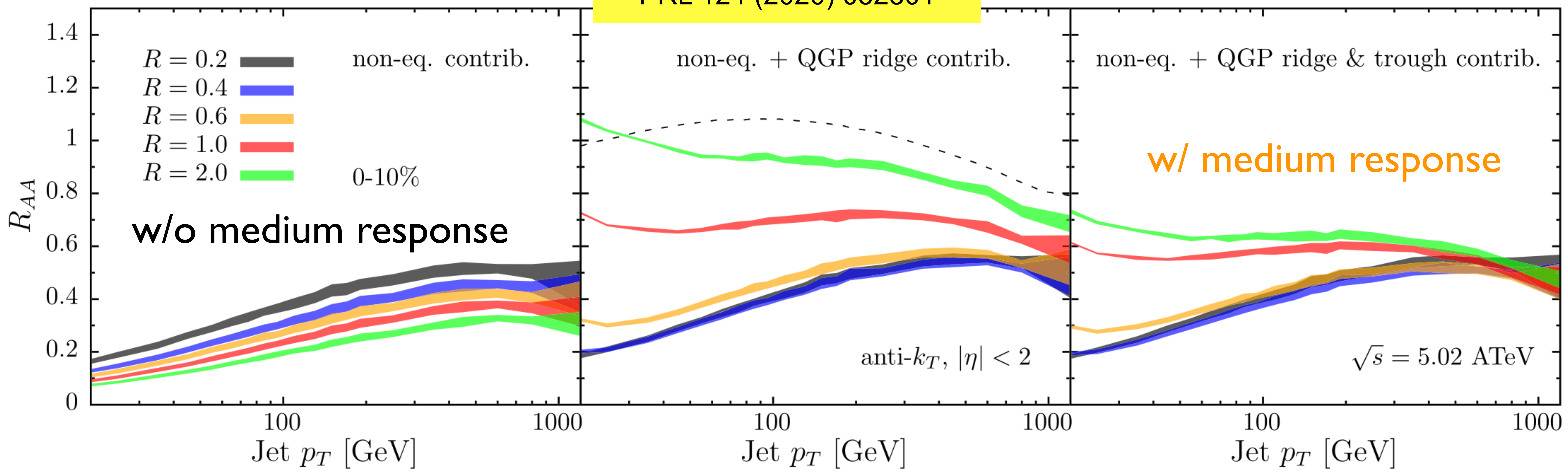


- JEWEL with recoil on can describe I_{AA} but not R_{AA}
- No model (with/without medium response) can describe all measured observables

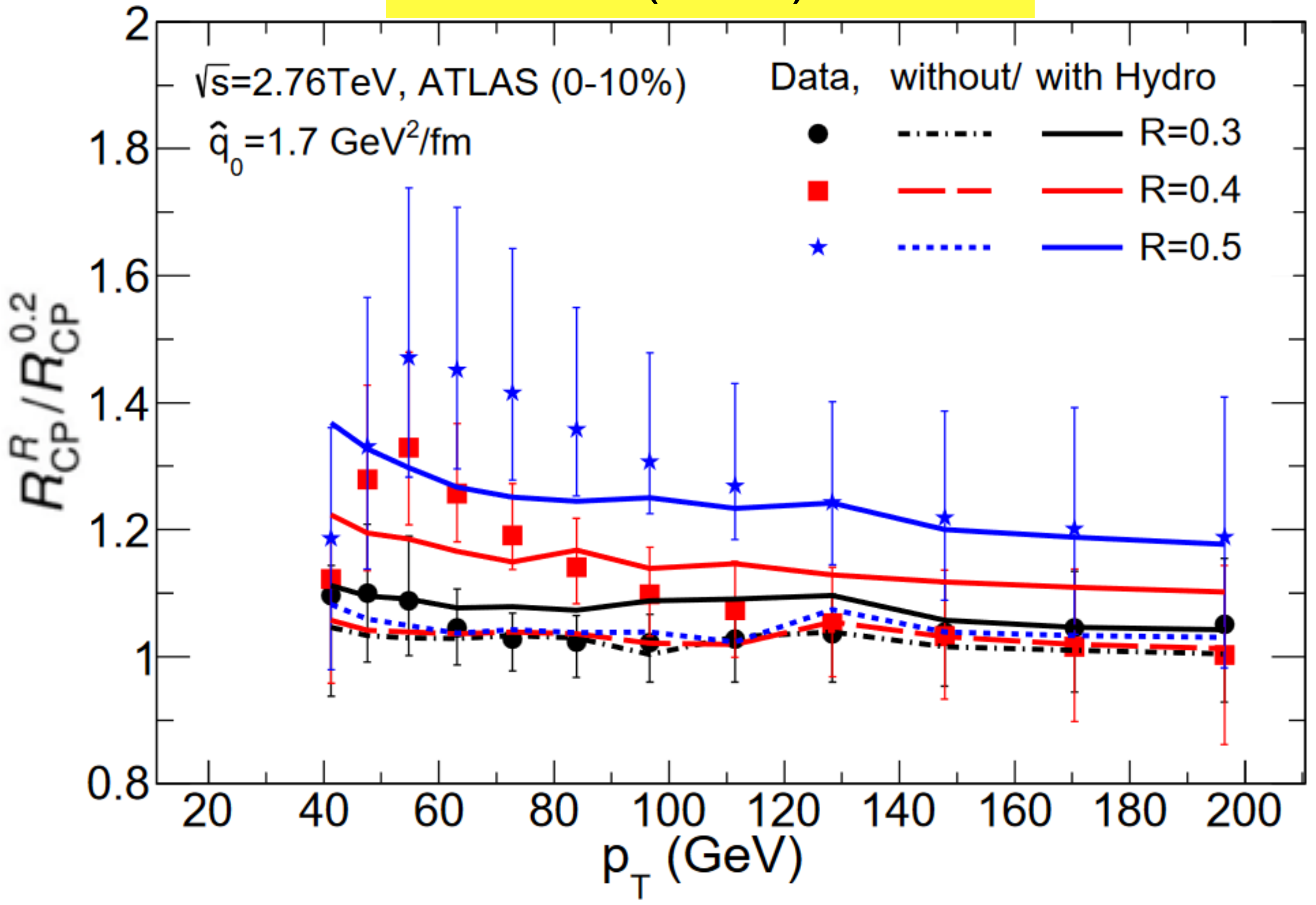
R dependence of jet quenching

- 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

PRL 124 (2020) 052301



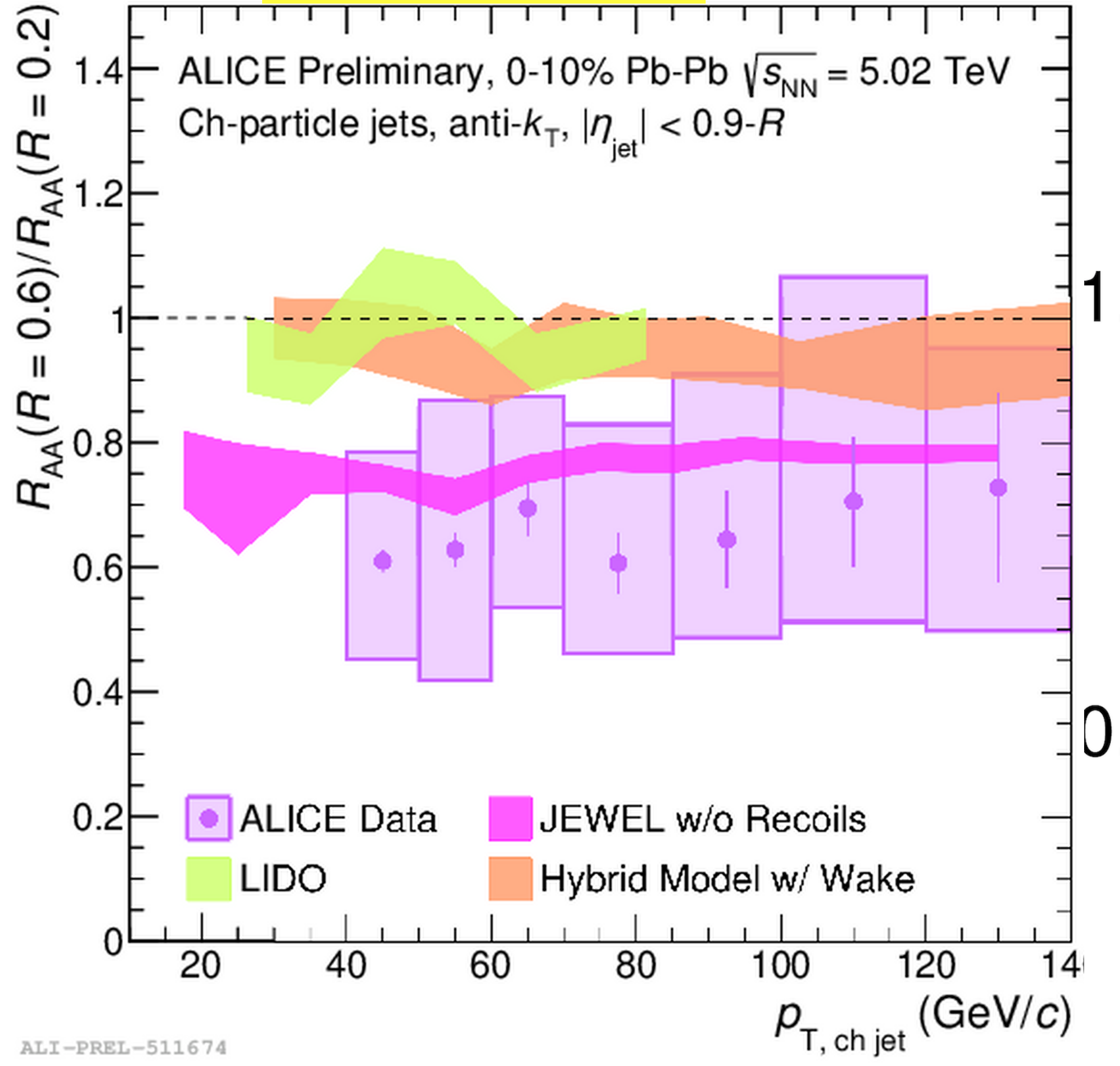
PLB 801 (2020) 135181



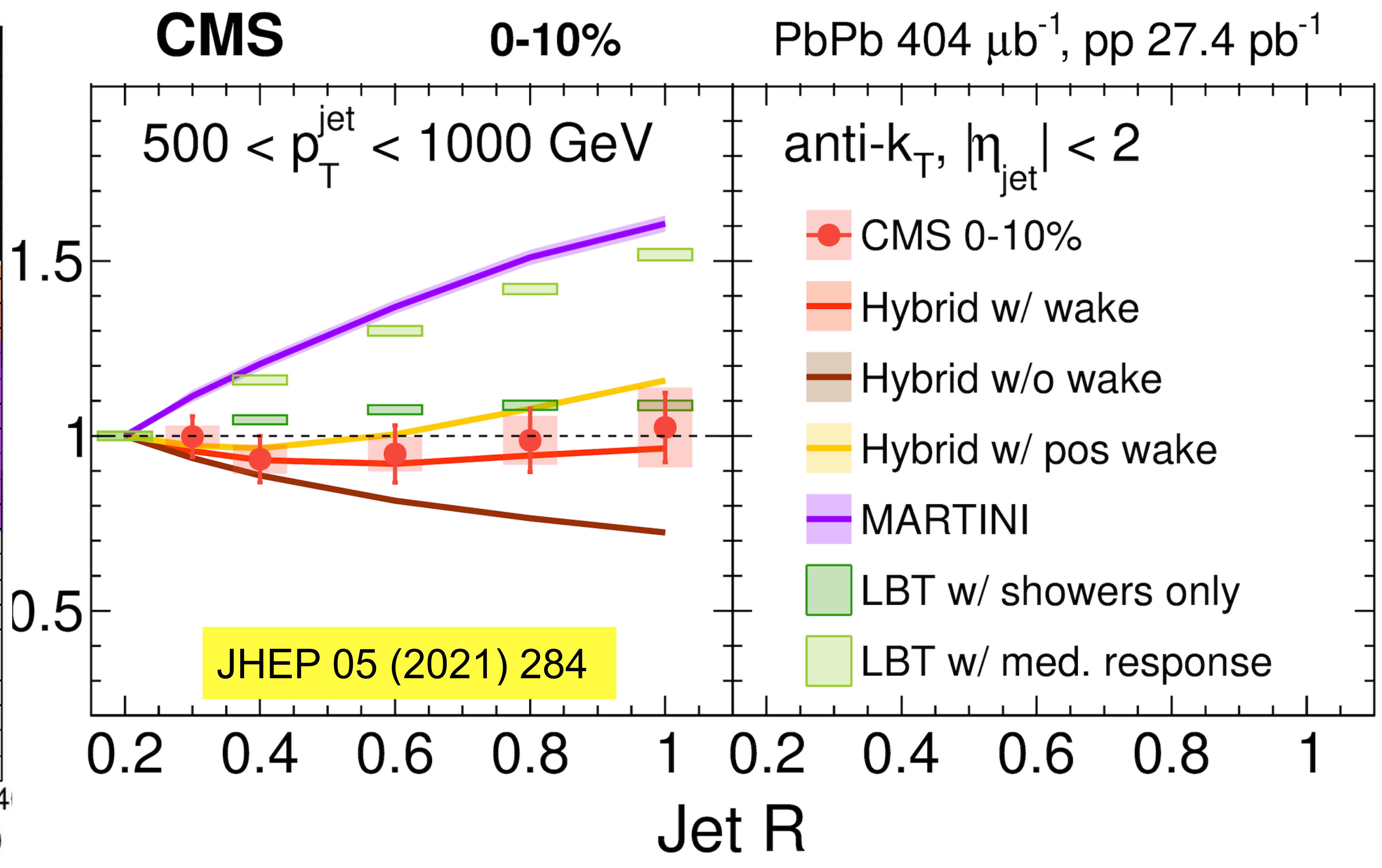
- Hybrid model predicts different (even reversed) R-dependence of jet R_{AA} due to medium response
- Jet-fluid model w/ hydrodynamic wake can reproduce the R-dependence of experimental Run1 ATLAS results

R dependence of jet R_{AA}: experimental data

arXiv:2303.00592

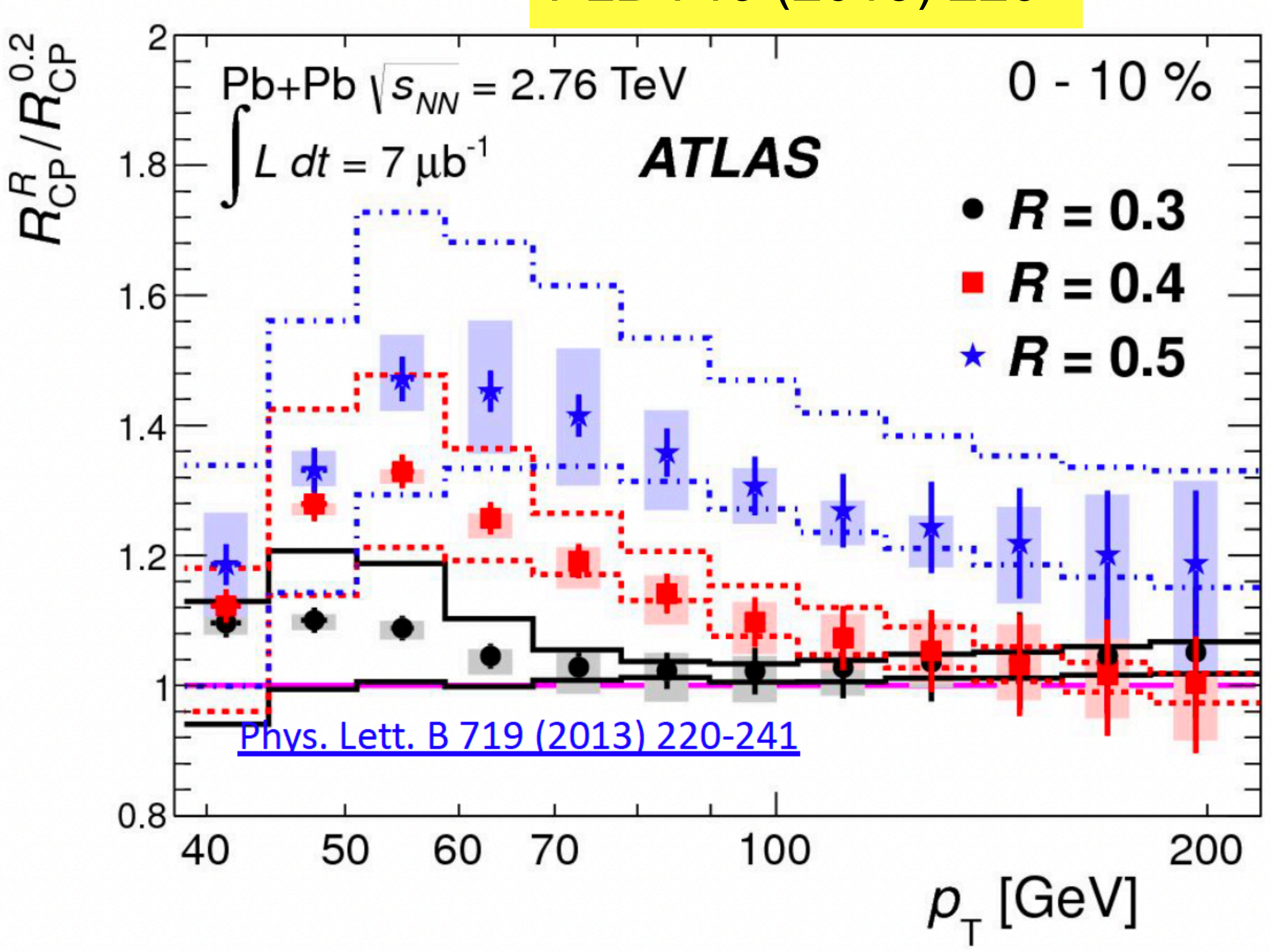


larger radius **more** suppressed



No strong R dependence for **very high p_T jets**

PLB 719 (2013) 220



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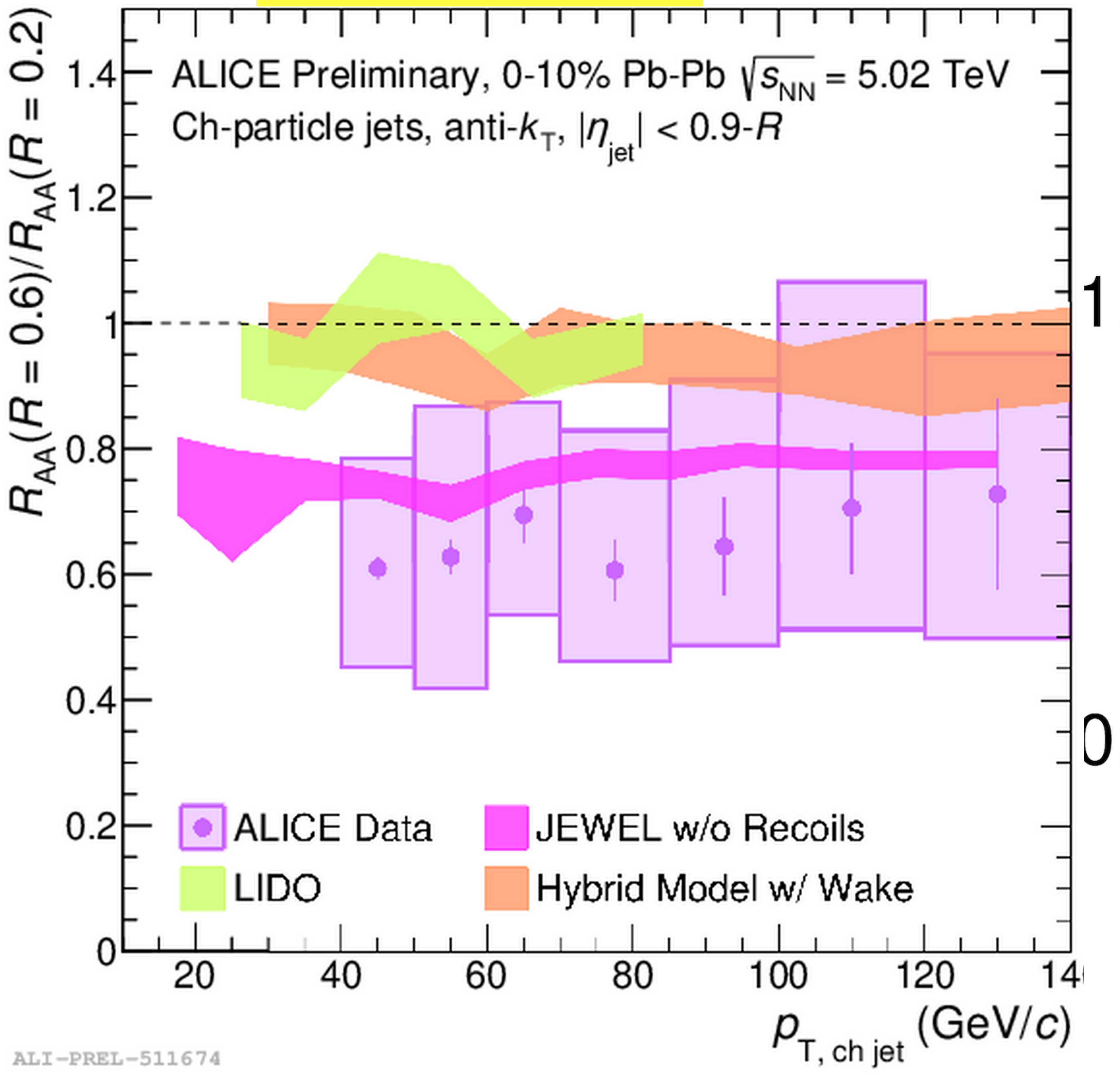

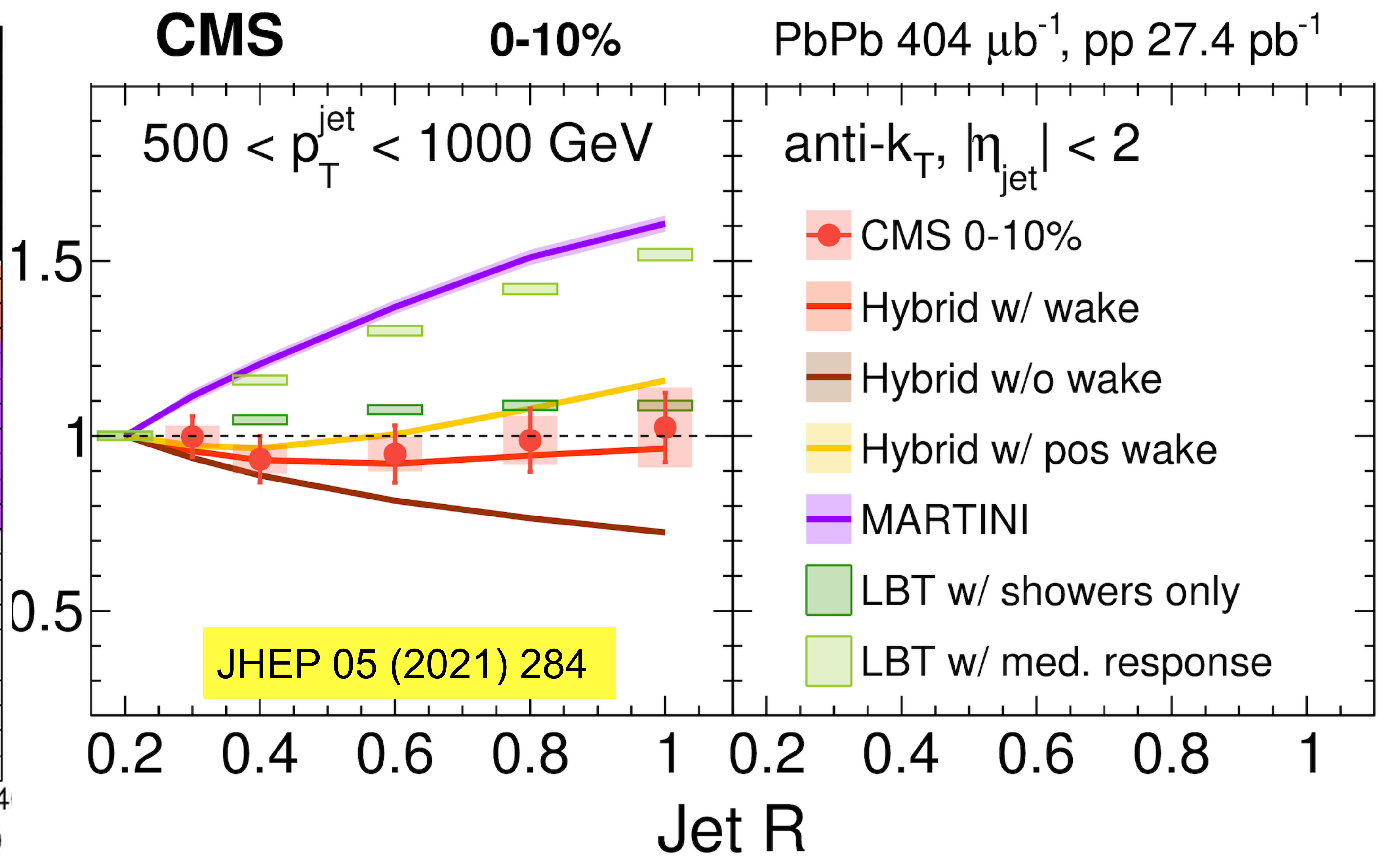

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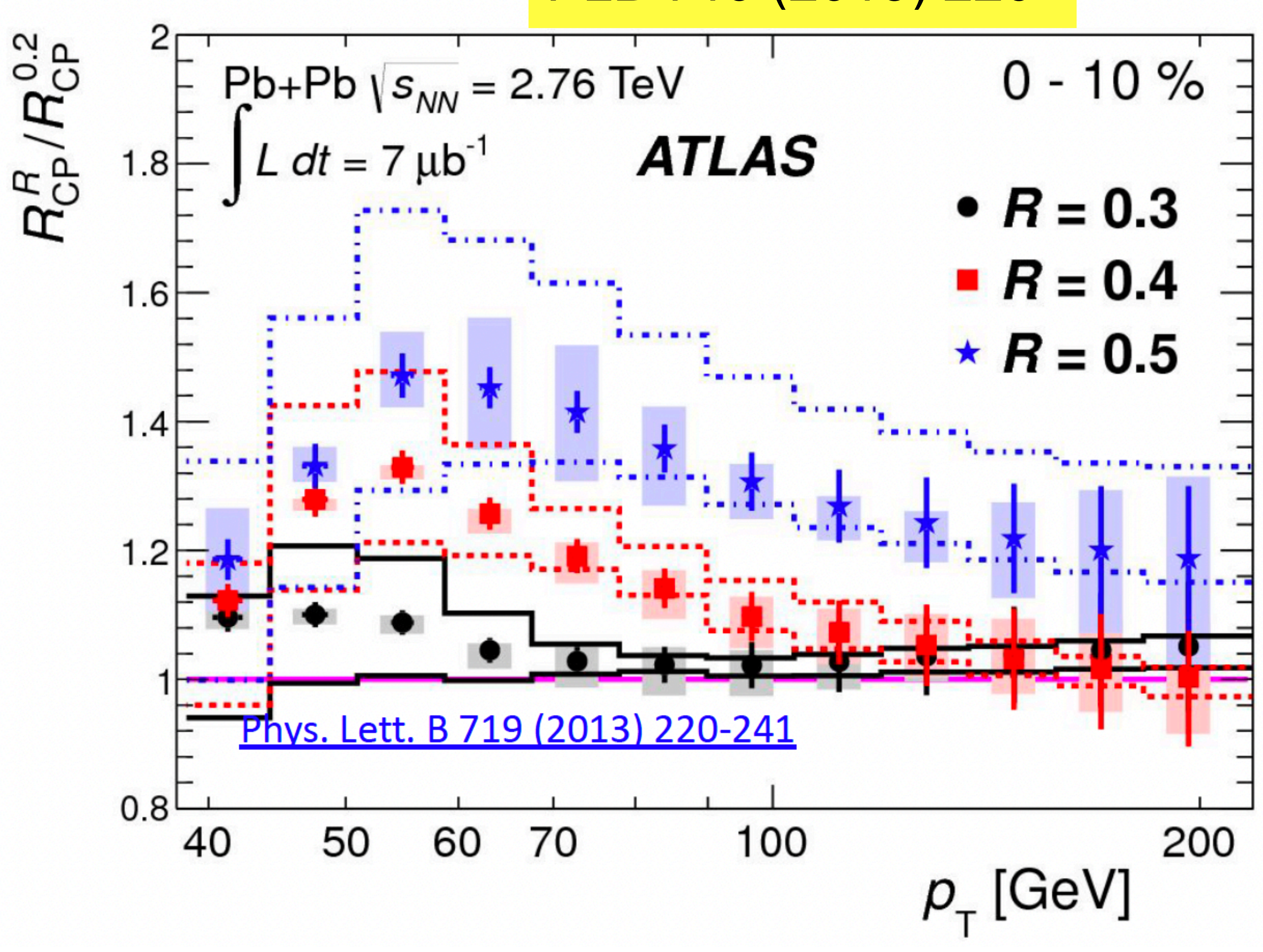


larger radius **more** suppressed

No strong R dependence for very high p_T jets

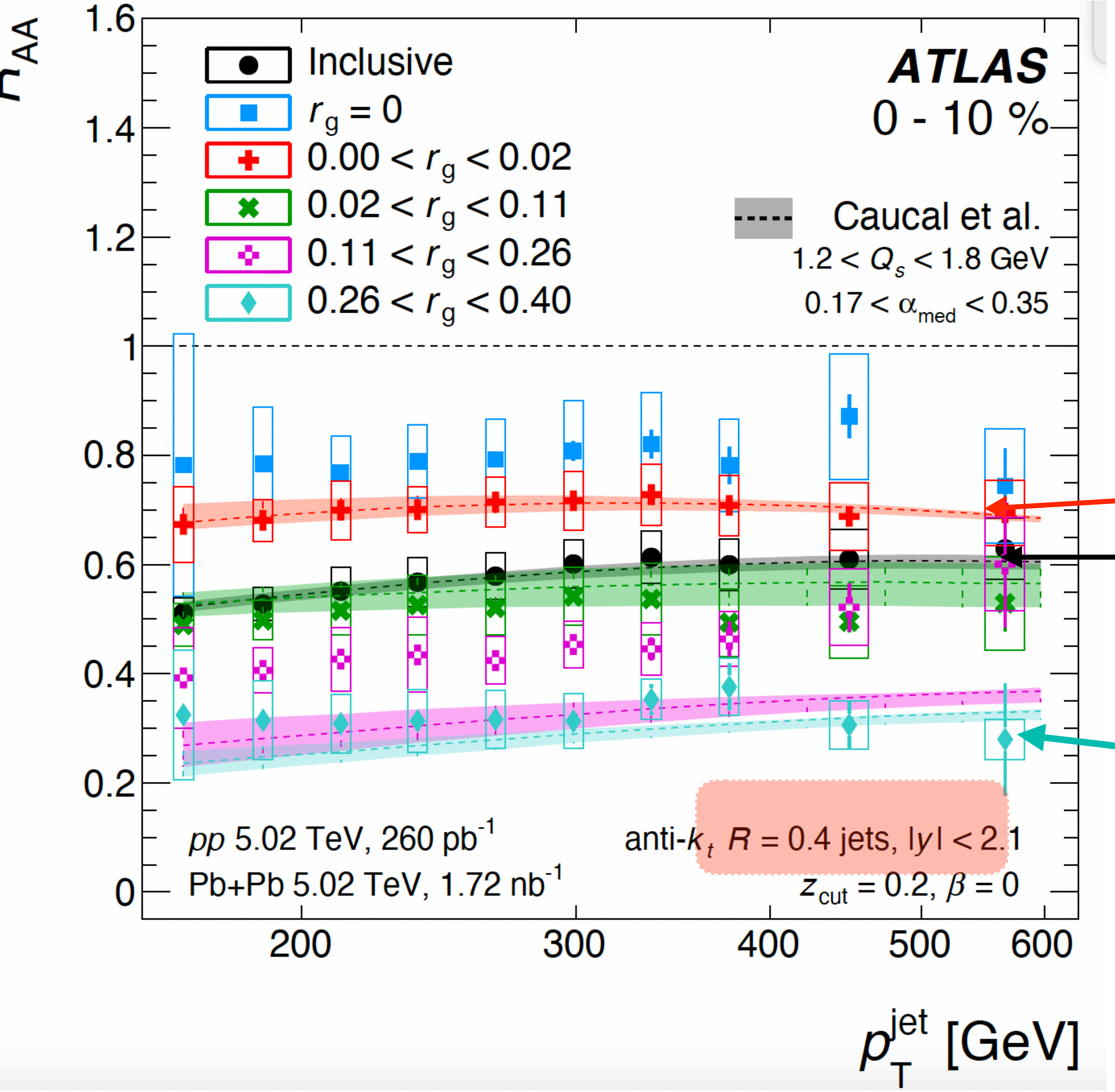
larger radius **less** suppressed

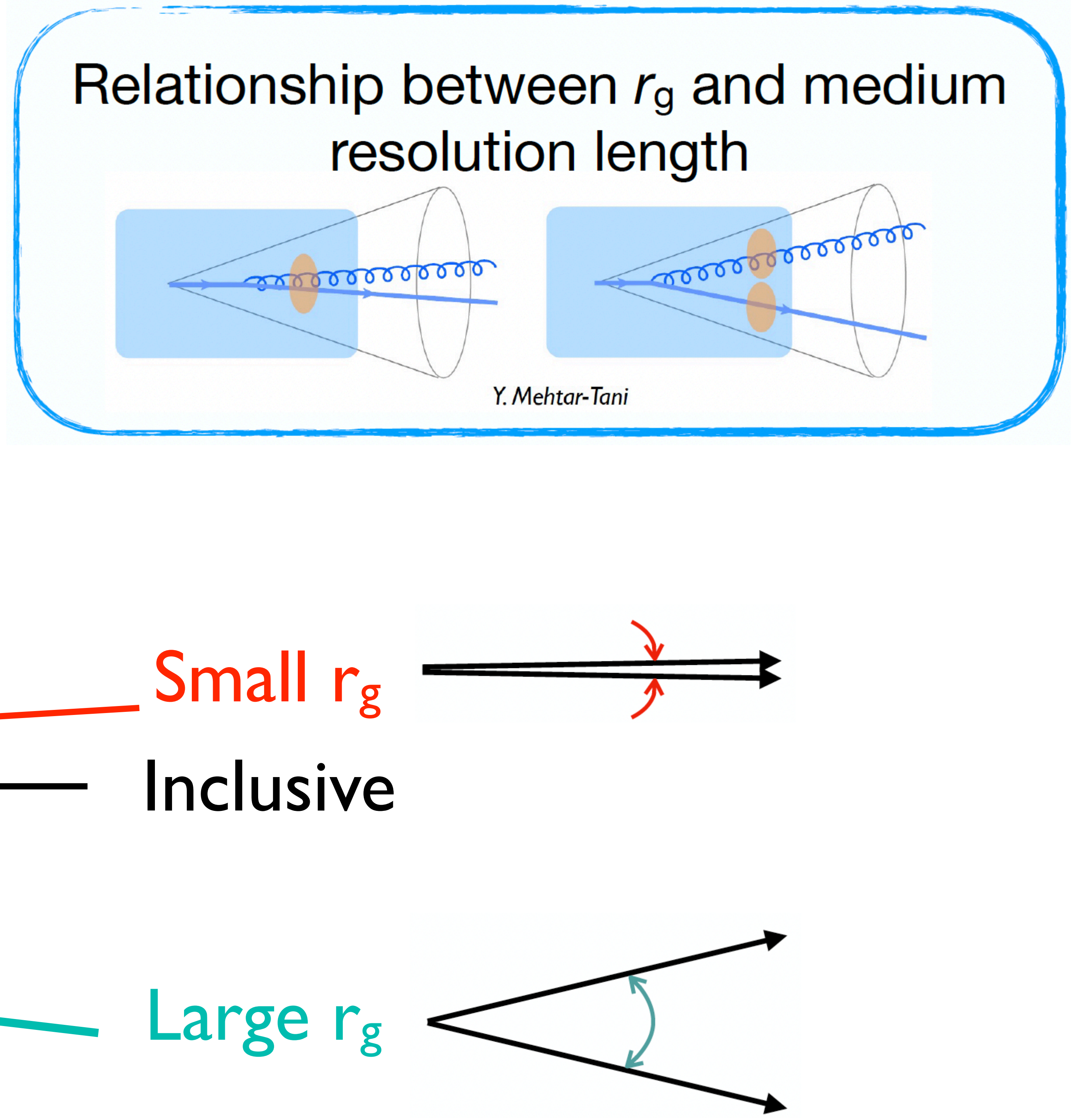
- Not exactly the same observables: R_{AA} vs. R_{cp}
- Different types of jets: full vs. charge
- Different centre-of-mass energy and phase-space
- Larger systematics in ALICE

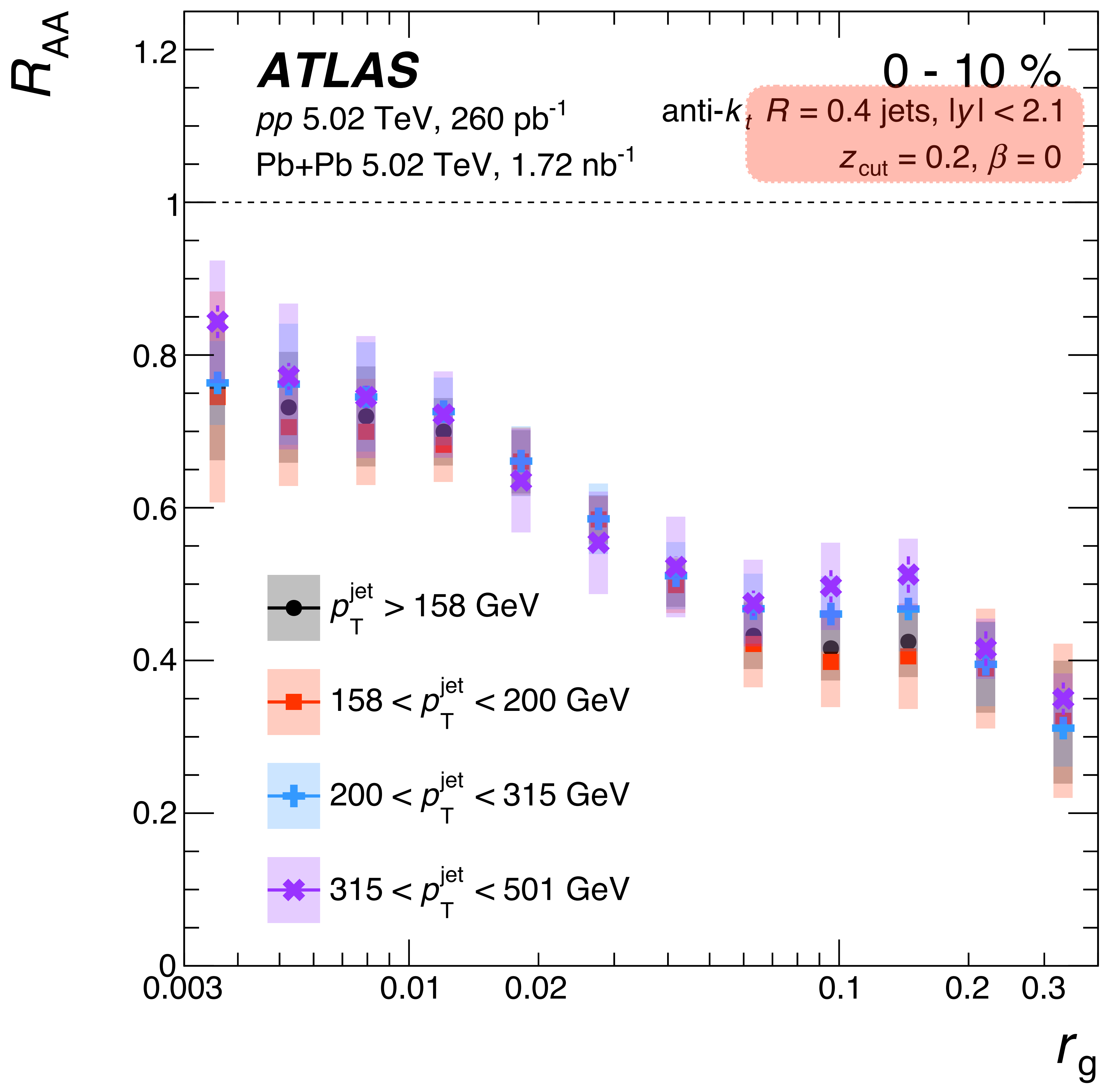
→More detailed comparison and future studies are needed

RAA - substructure interplay

PRC 107 (2023) 054909



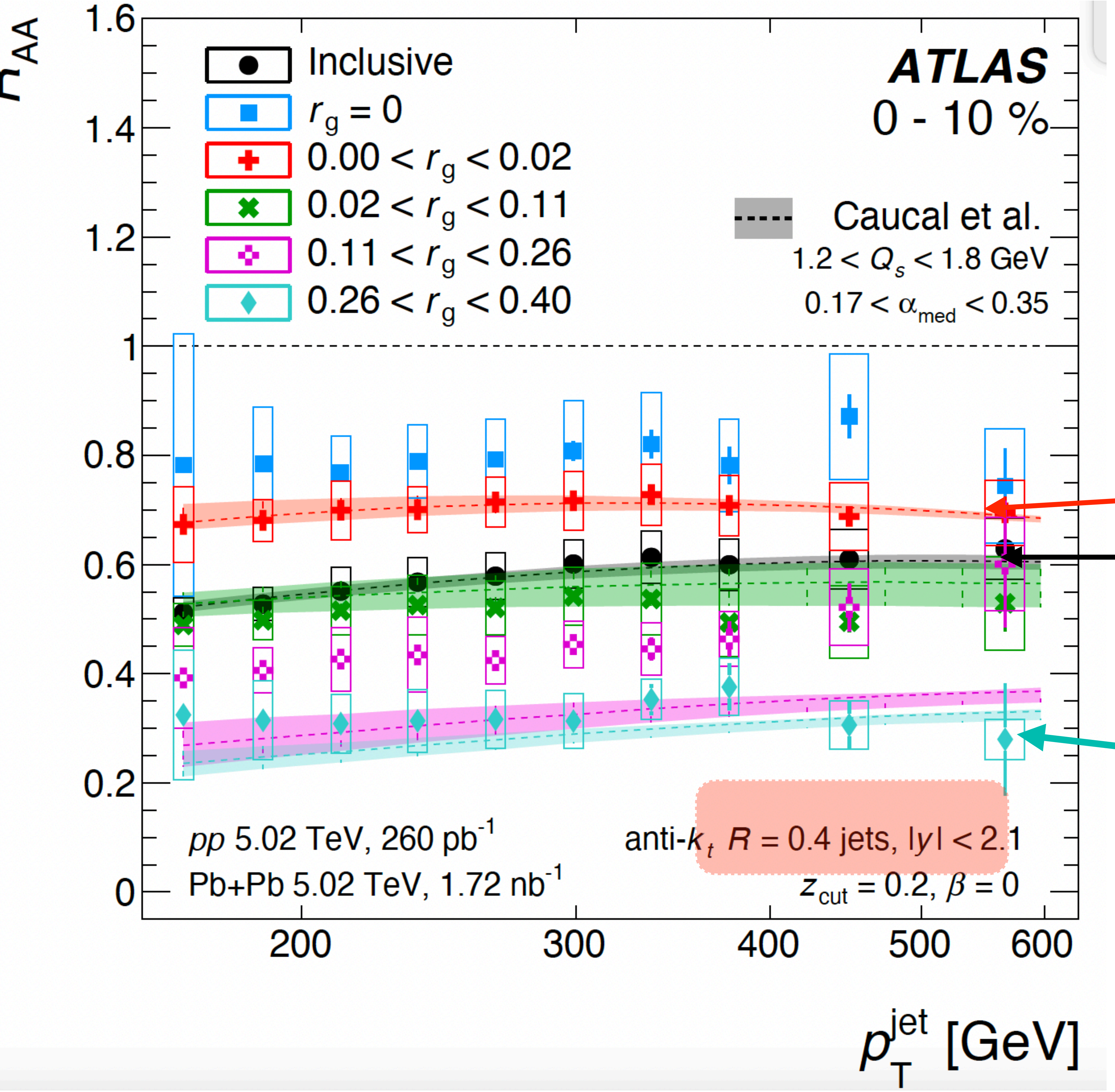


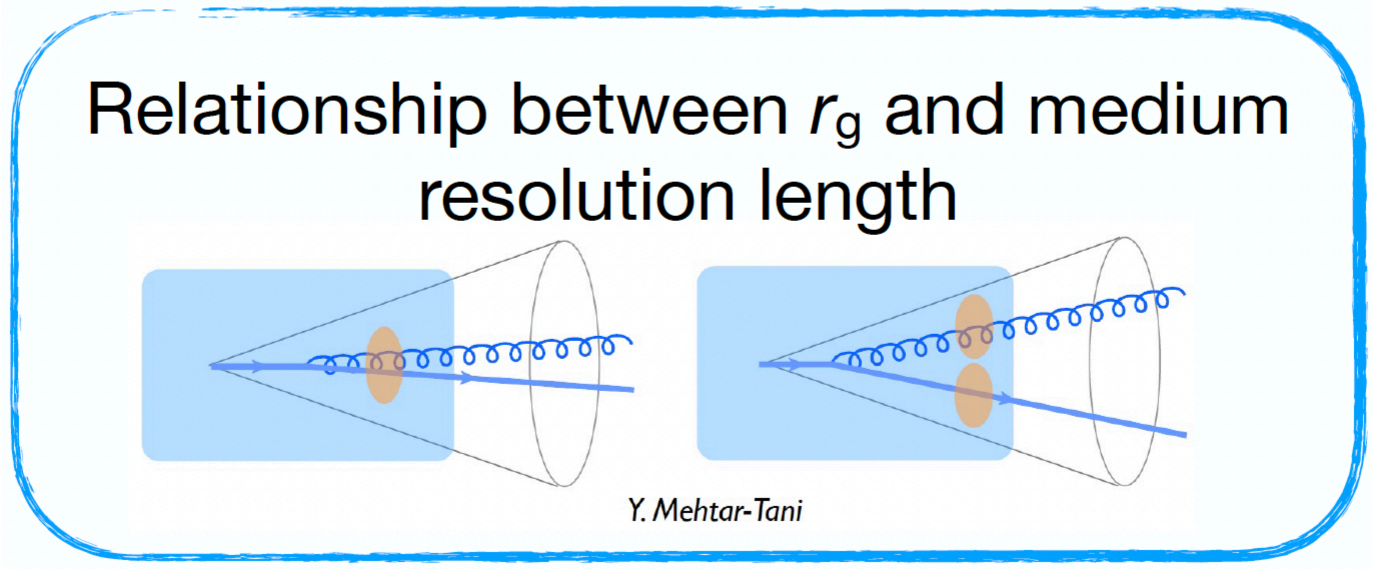


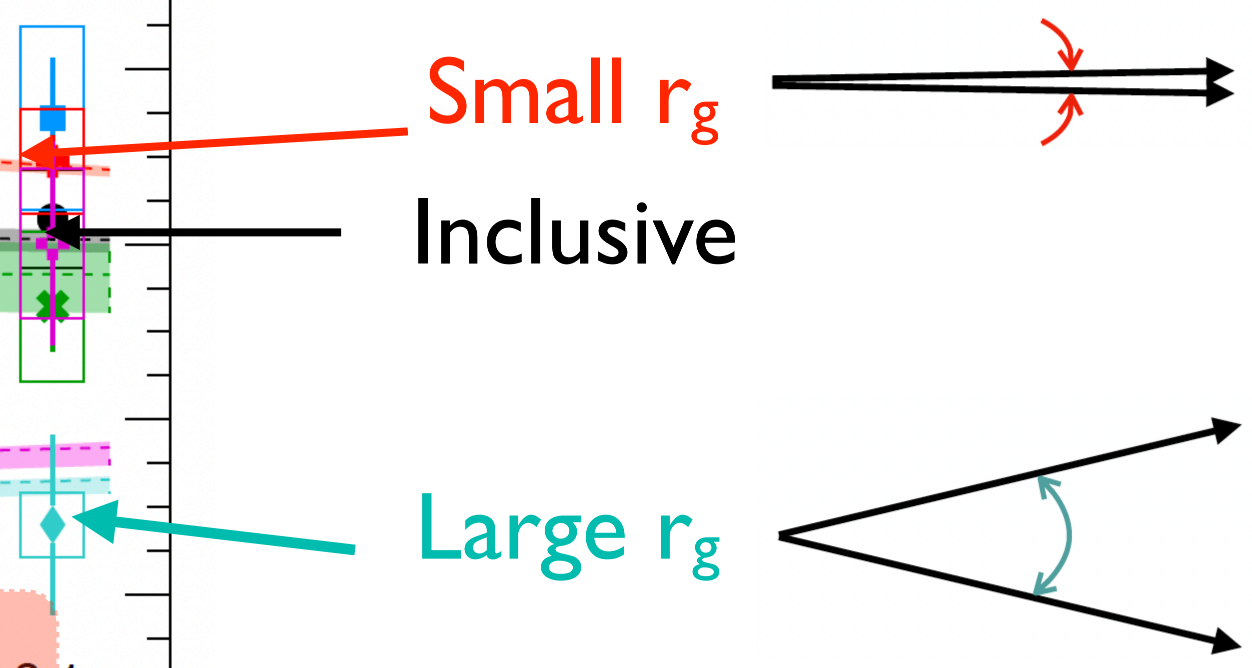
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

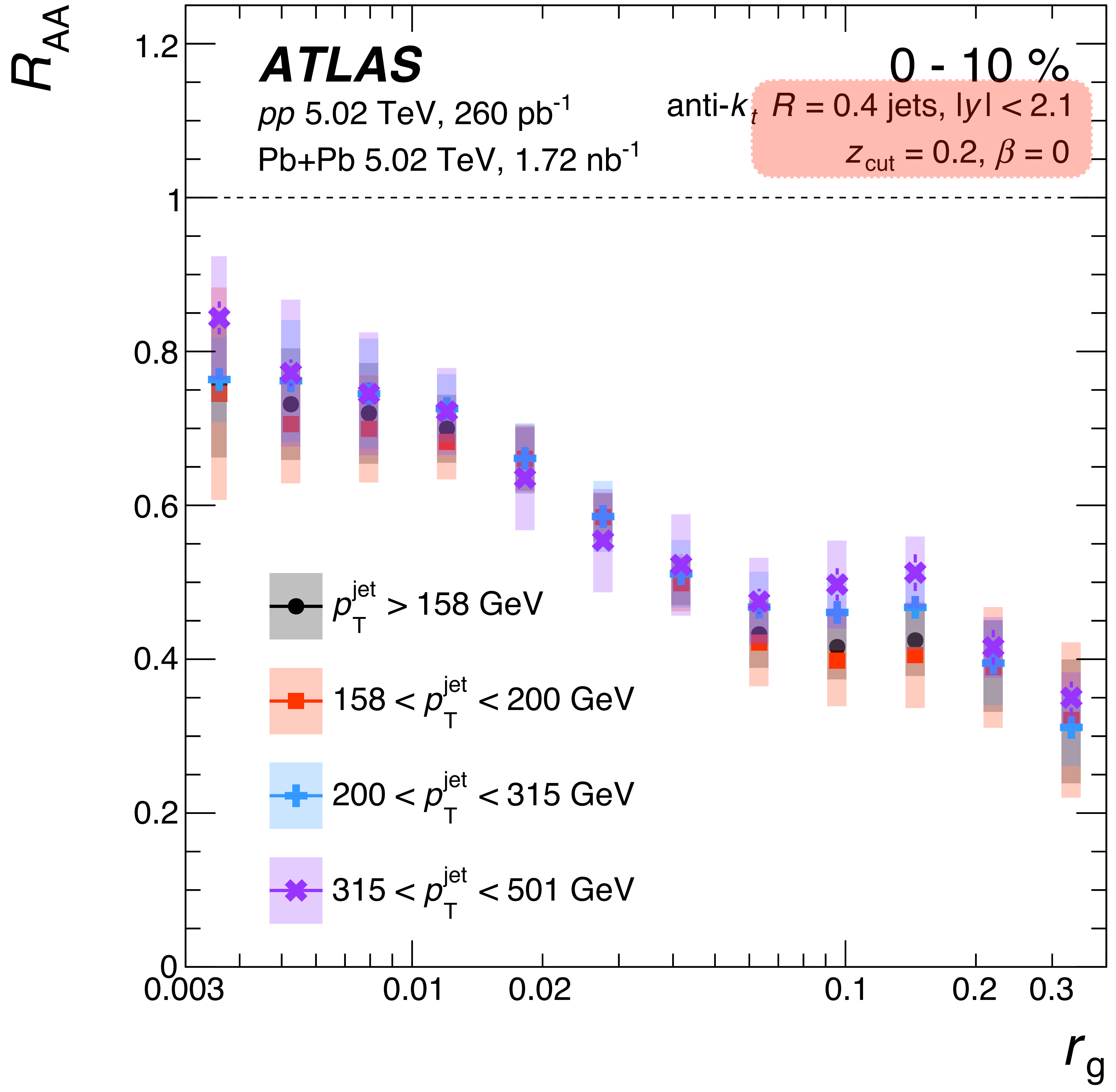
R_{AA} - substructure interplay

PRC 107 (2023) 054909







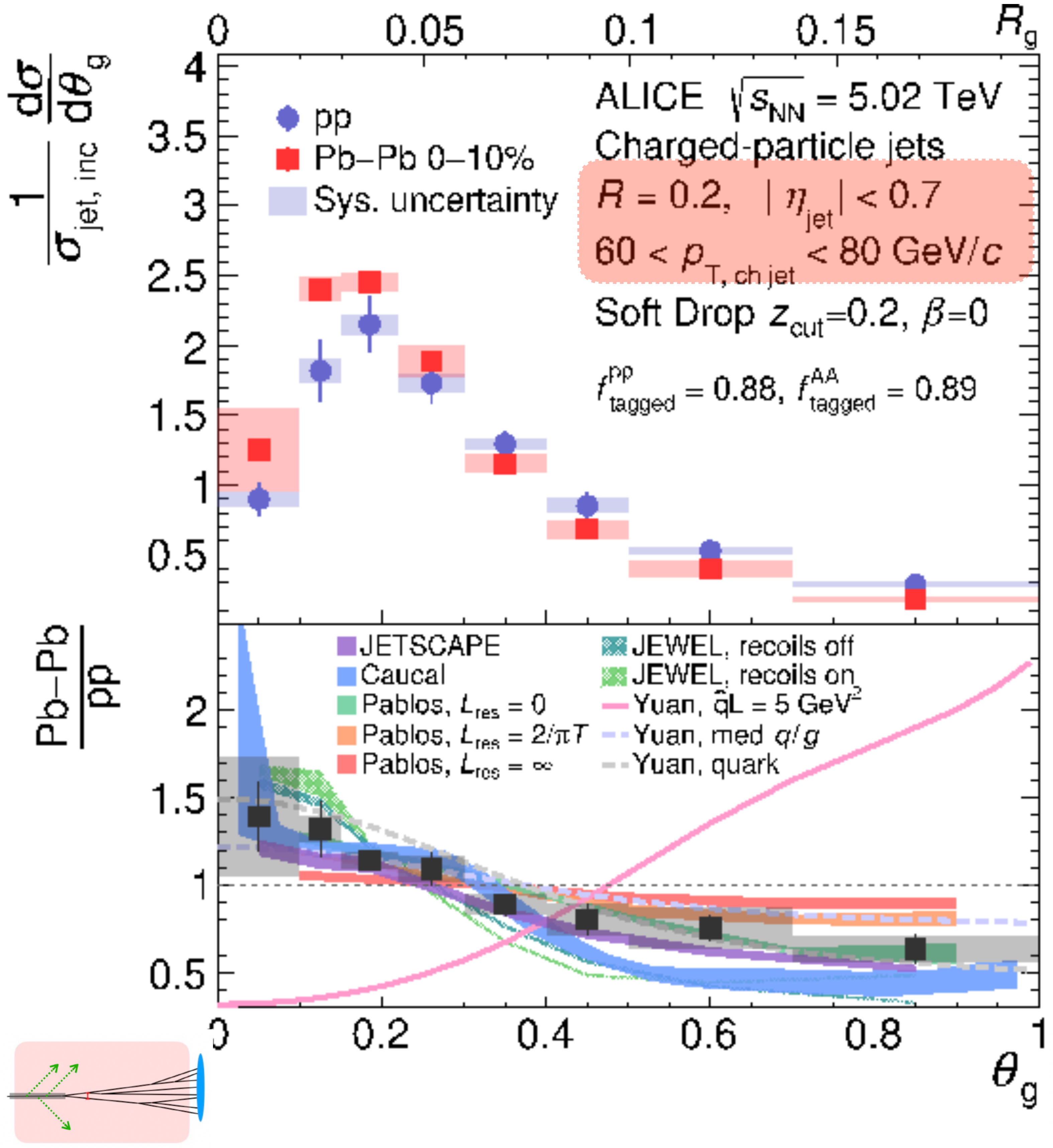


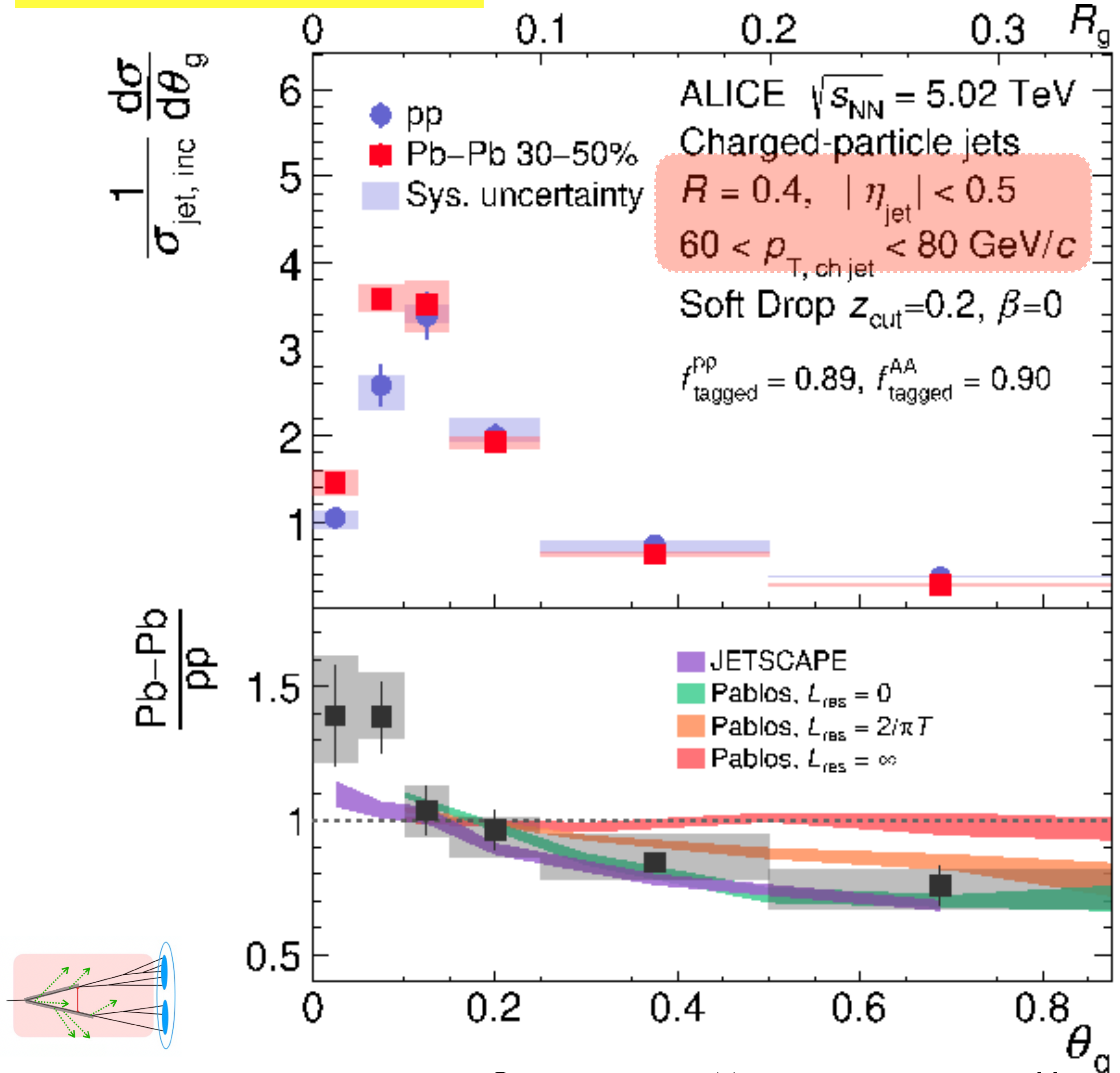
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

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

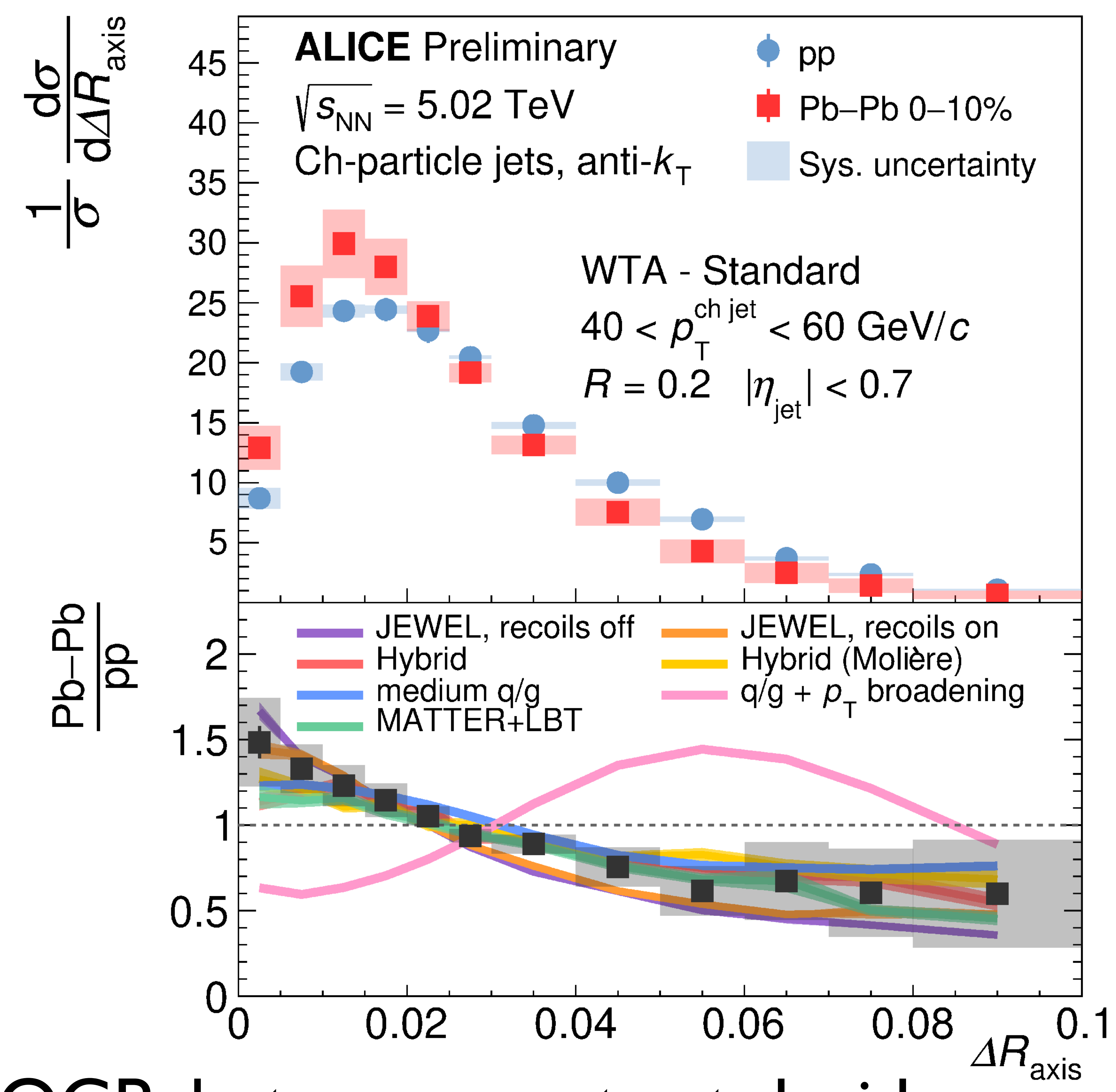
Jet substructure modifications

PRL 128 (2022) 102001





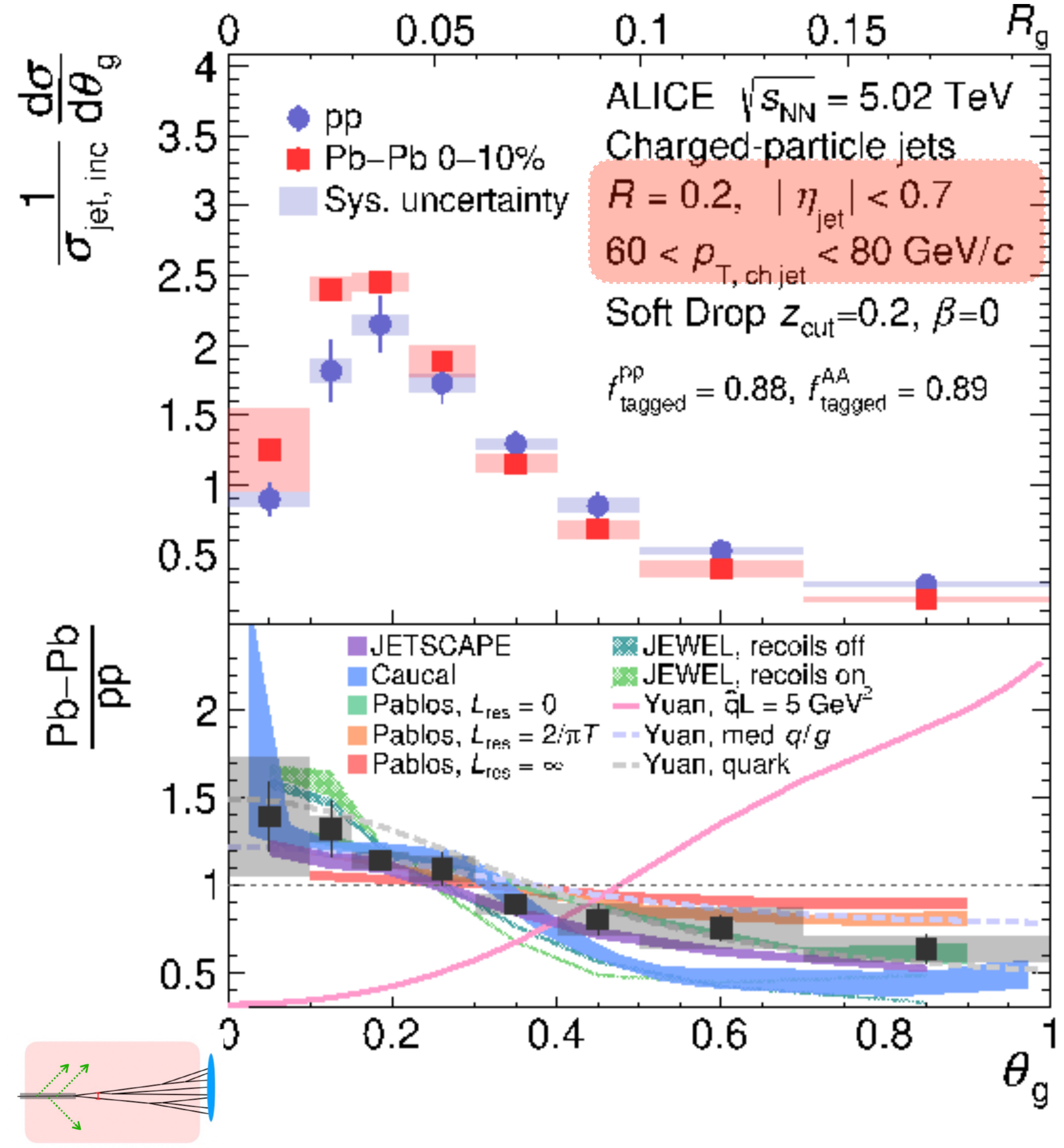
Angle between standard and WTA jet axes

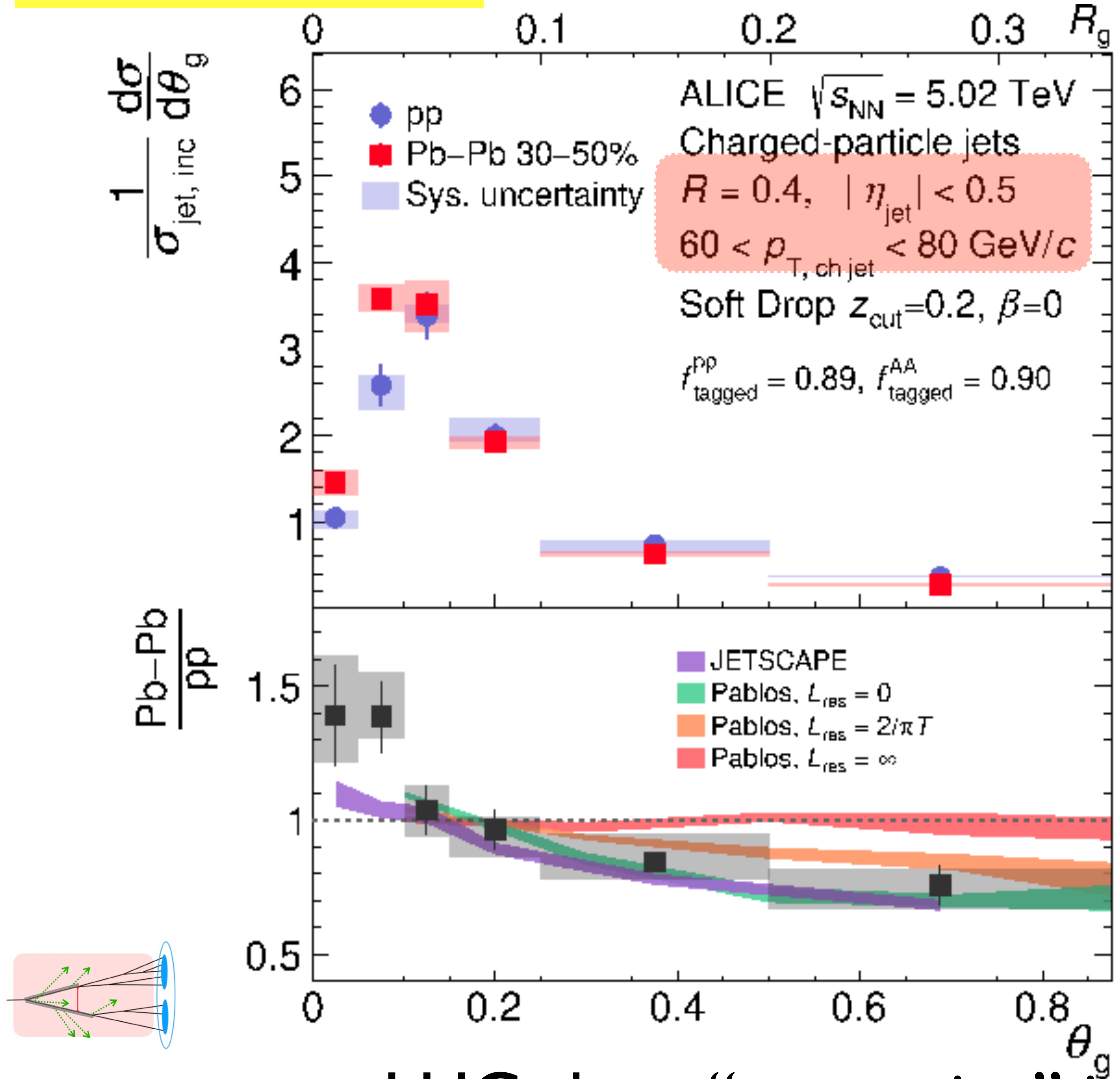


- Many jet substructure measurements at LHC show "narrowing" in QGP, but we cannot yet decide:
  - Energy loss makes the jets narrower?
  - selection bias
  - q/g-fraction changes

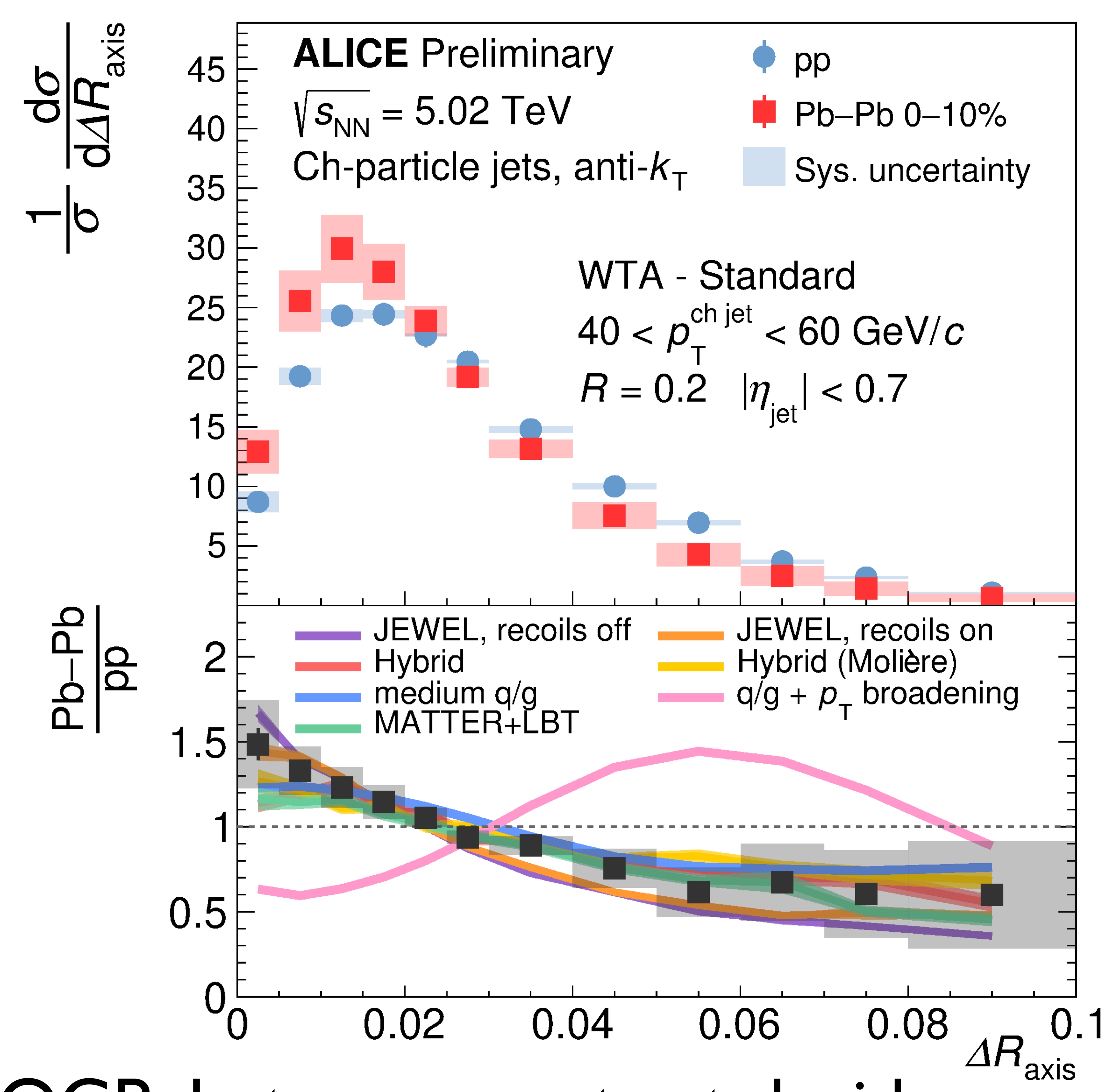
Jet substructure modifications

PRL 128 (2022) 102001





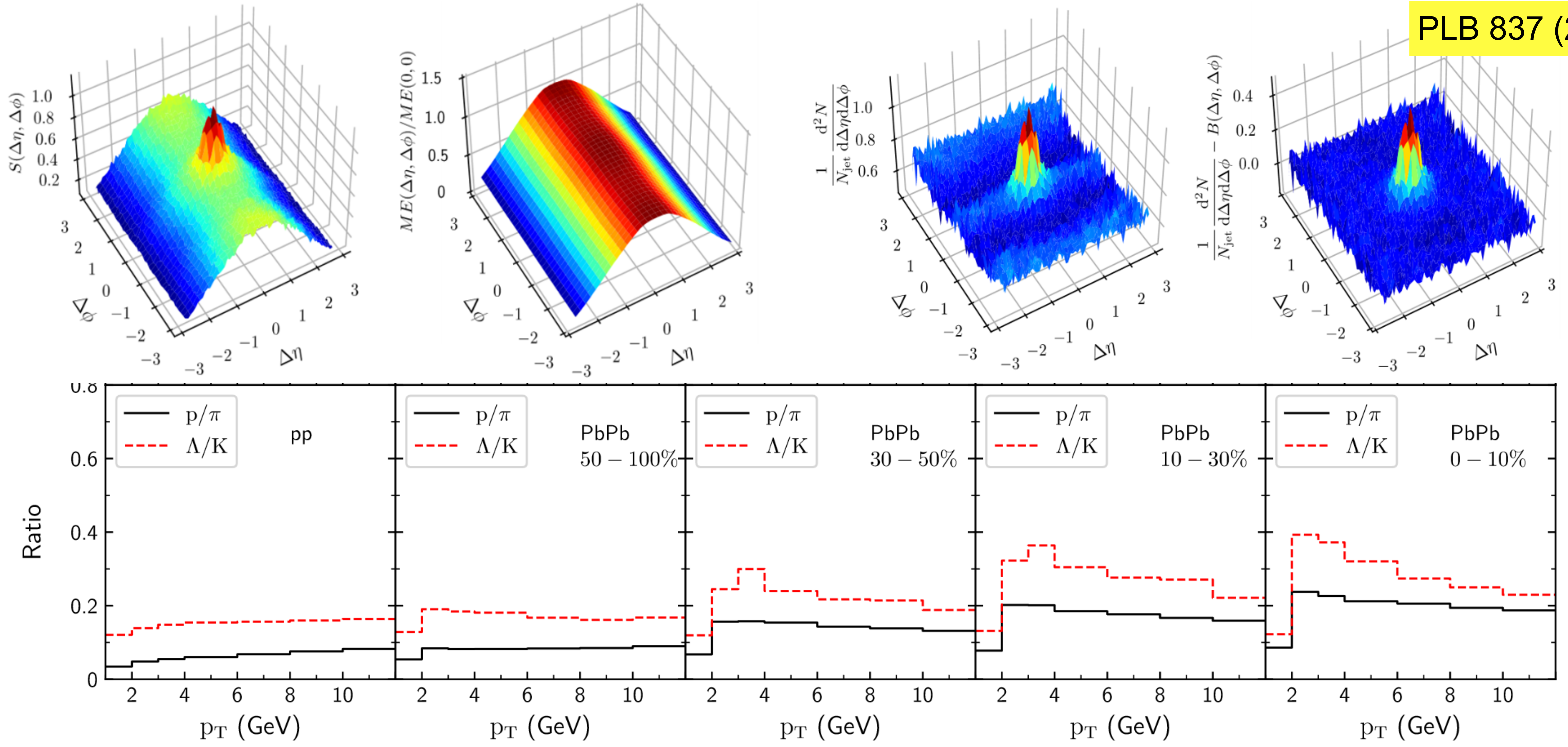
Angle between standard and WTA jet axes

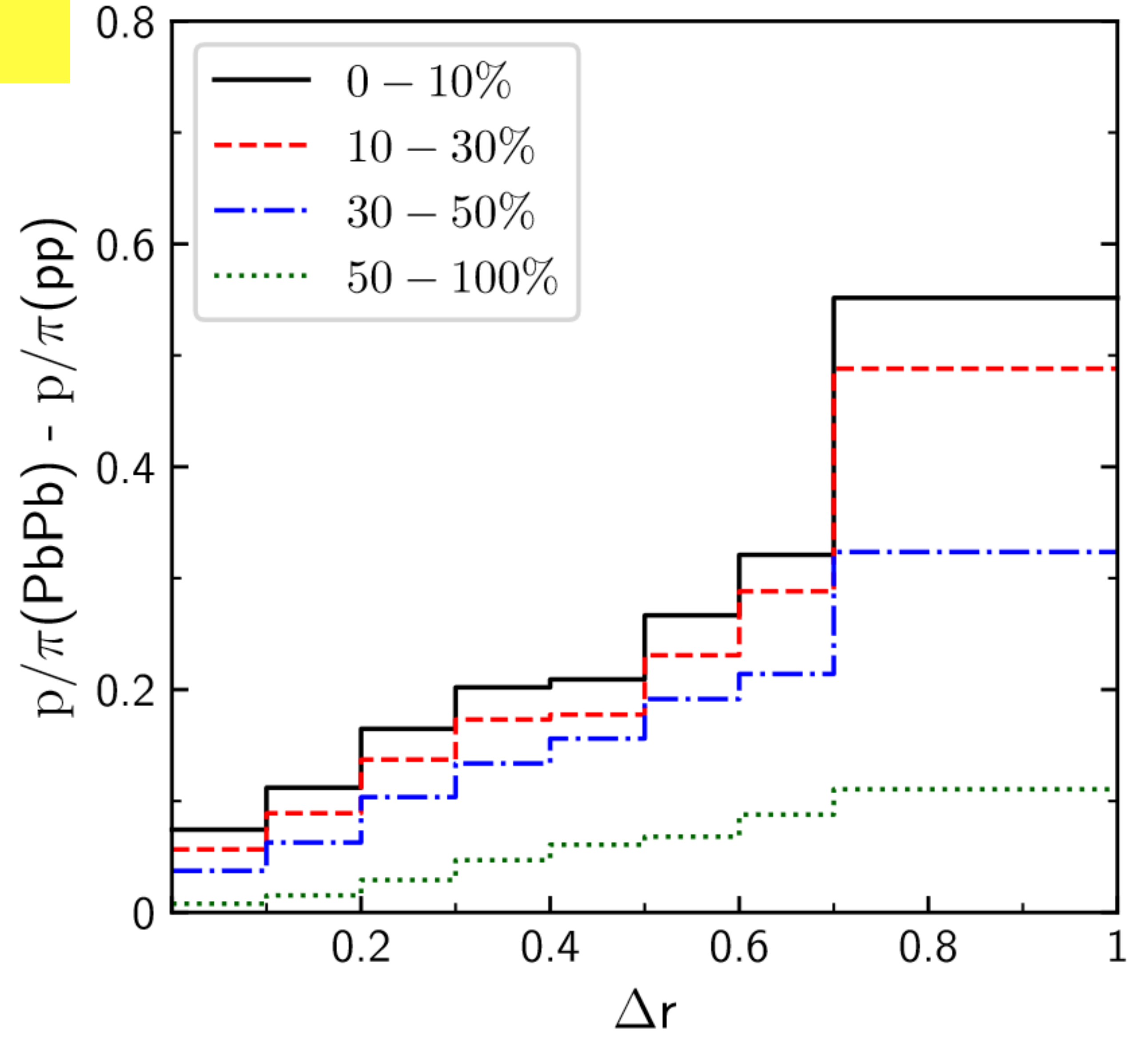


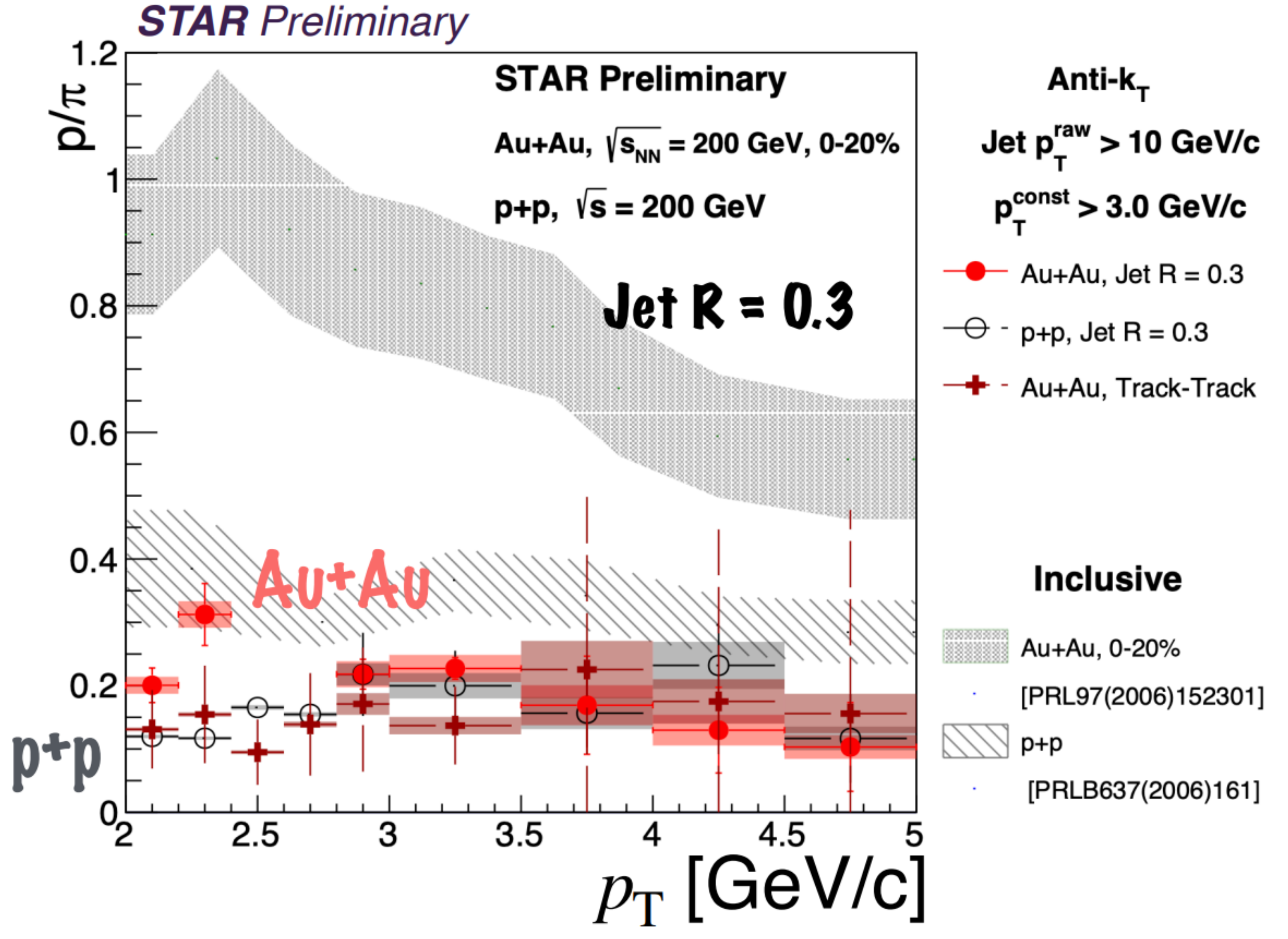
- Many jet substructure measurements at LHC show "narrowing" in QGP, but we cannot yet decide:
  - Energy loss makes the jets narrower?
  - selection bias
  - q/g-fraction changes

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

Baryon to meson enhancement around jets

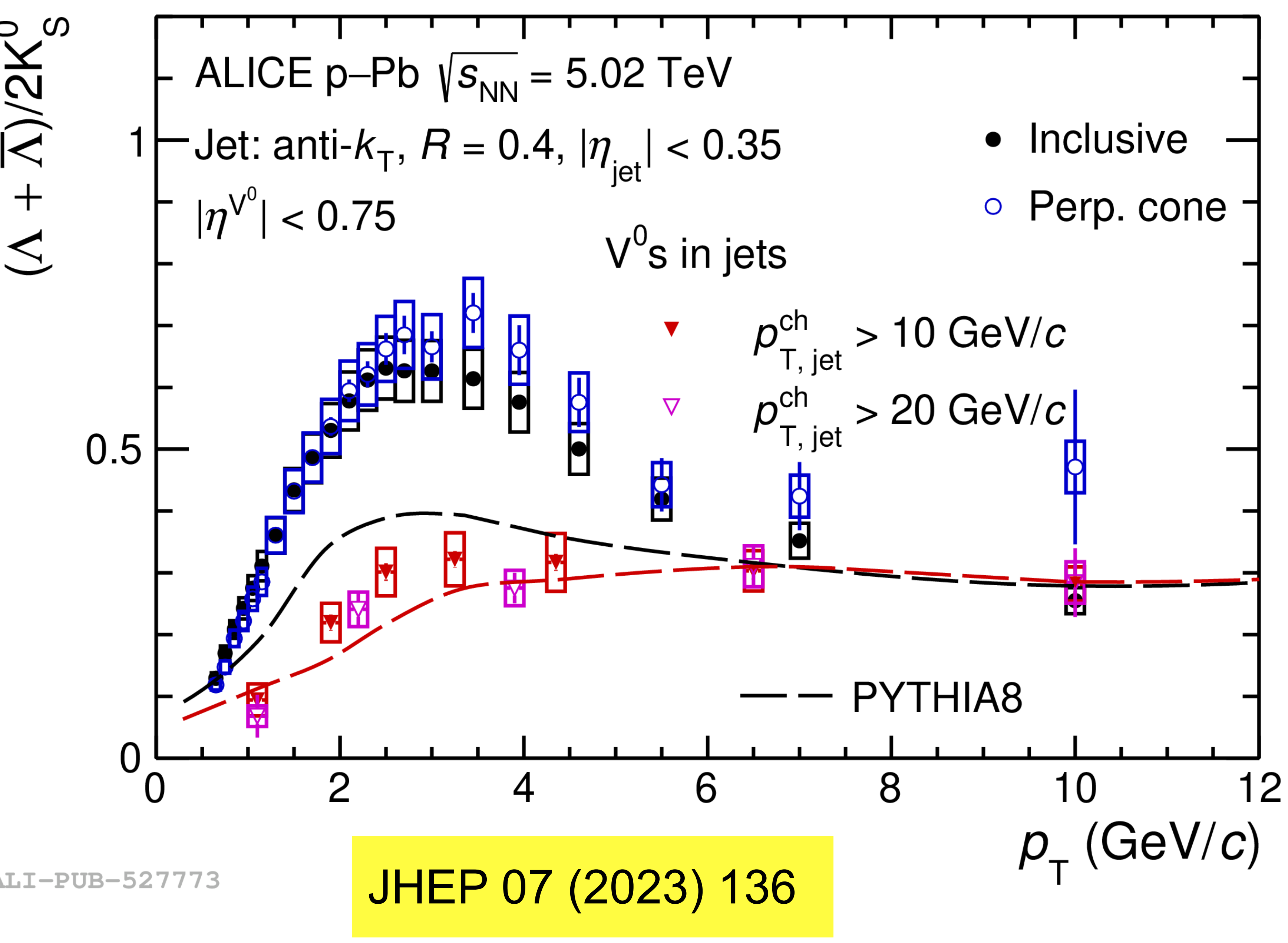


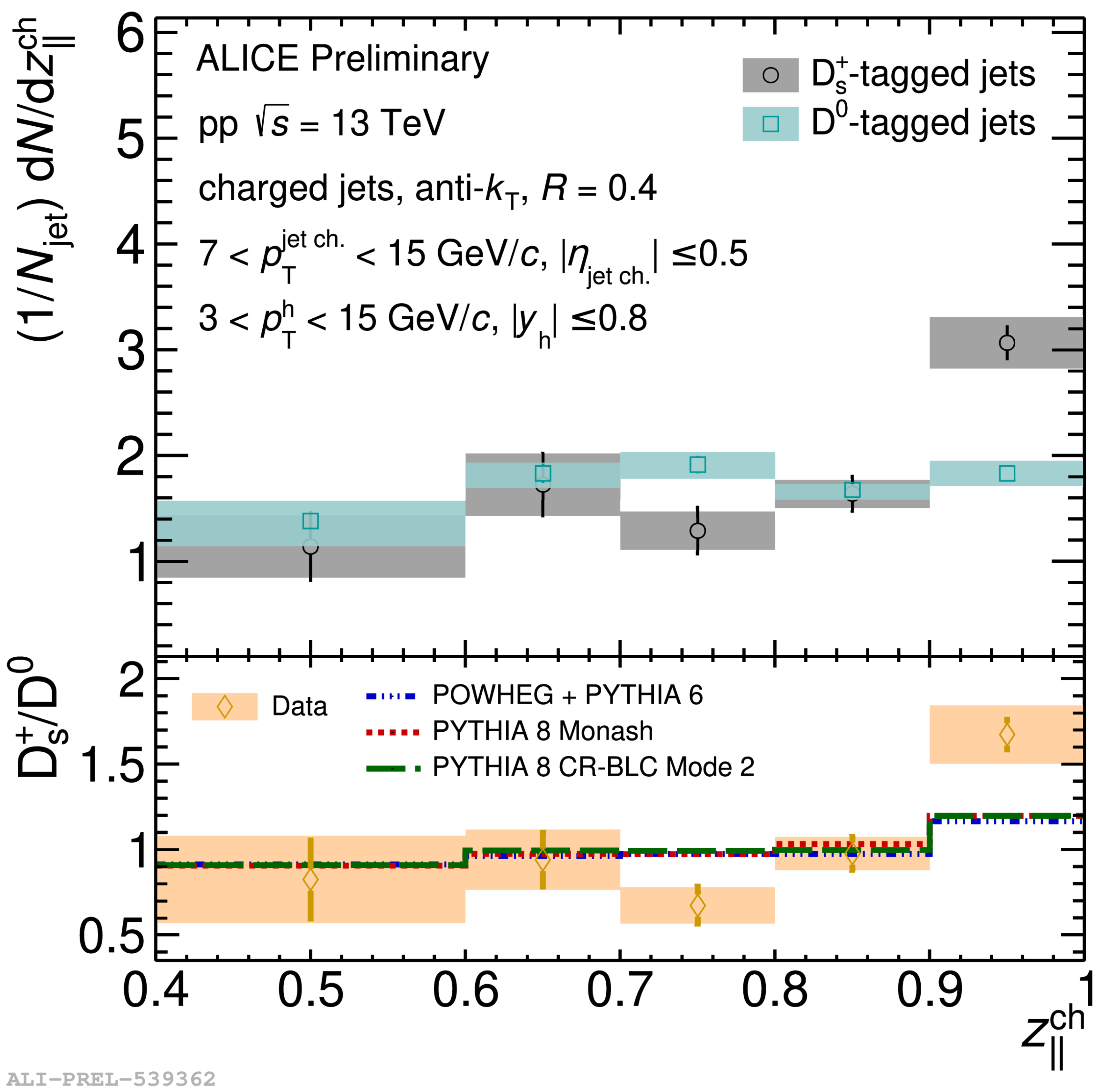


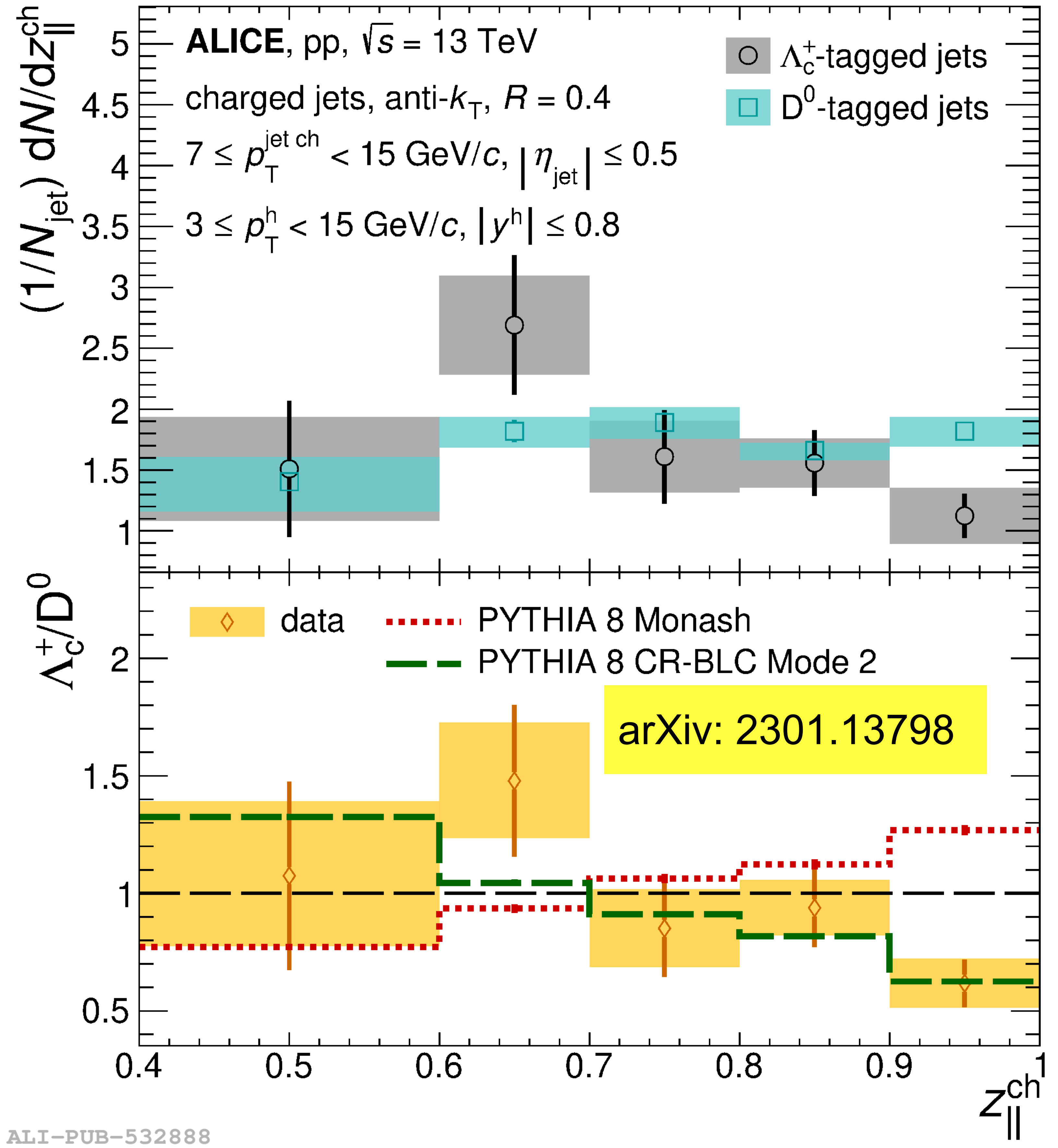


- Strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons
- Enhancement of jet-induced B/M ratios is stronger at intermediate p_T (2-6 GeV/c)for larger distance because the lost energy from quenched jets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

Hadron chemistry and charm quark fragmentation

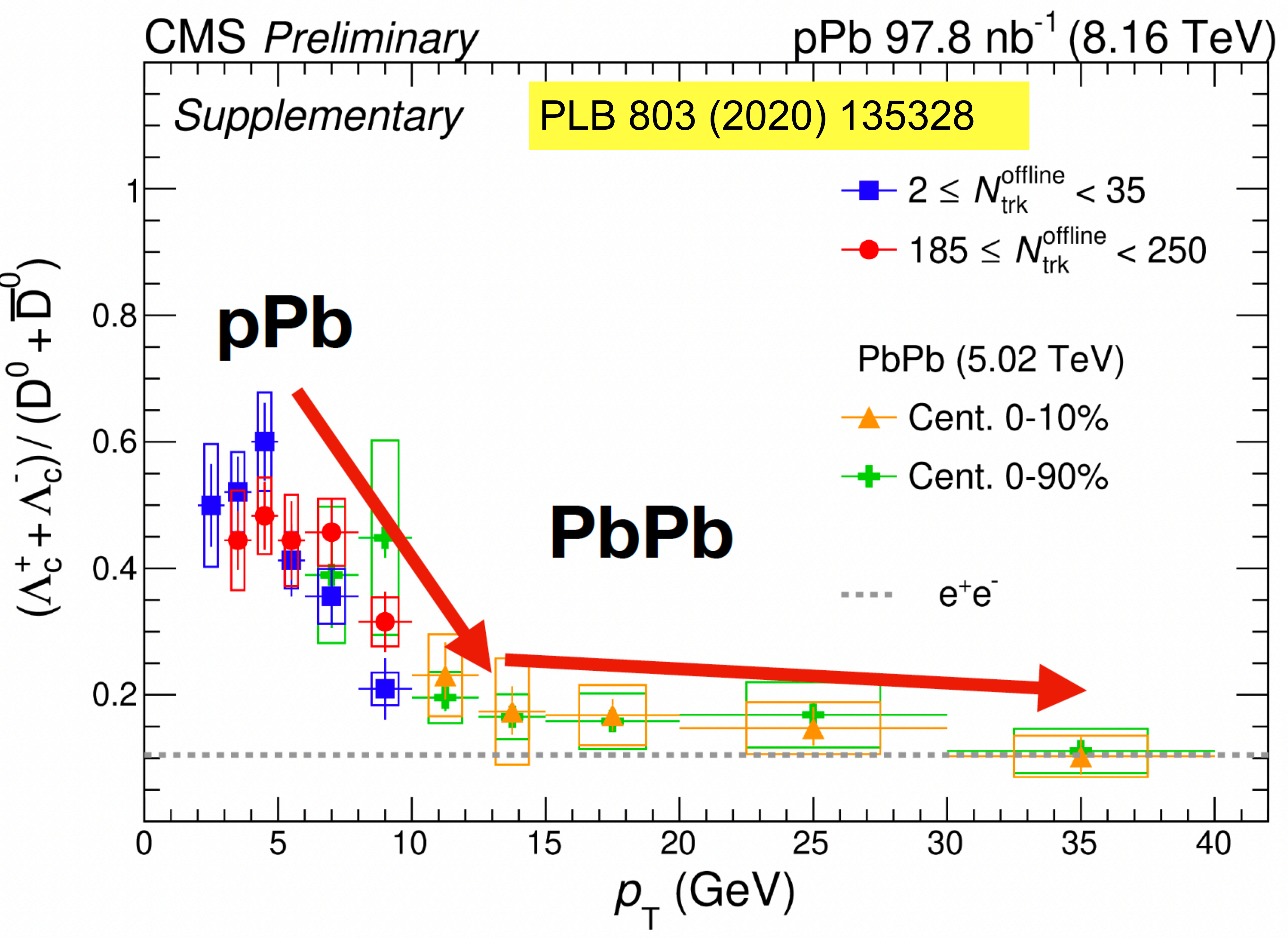


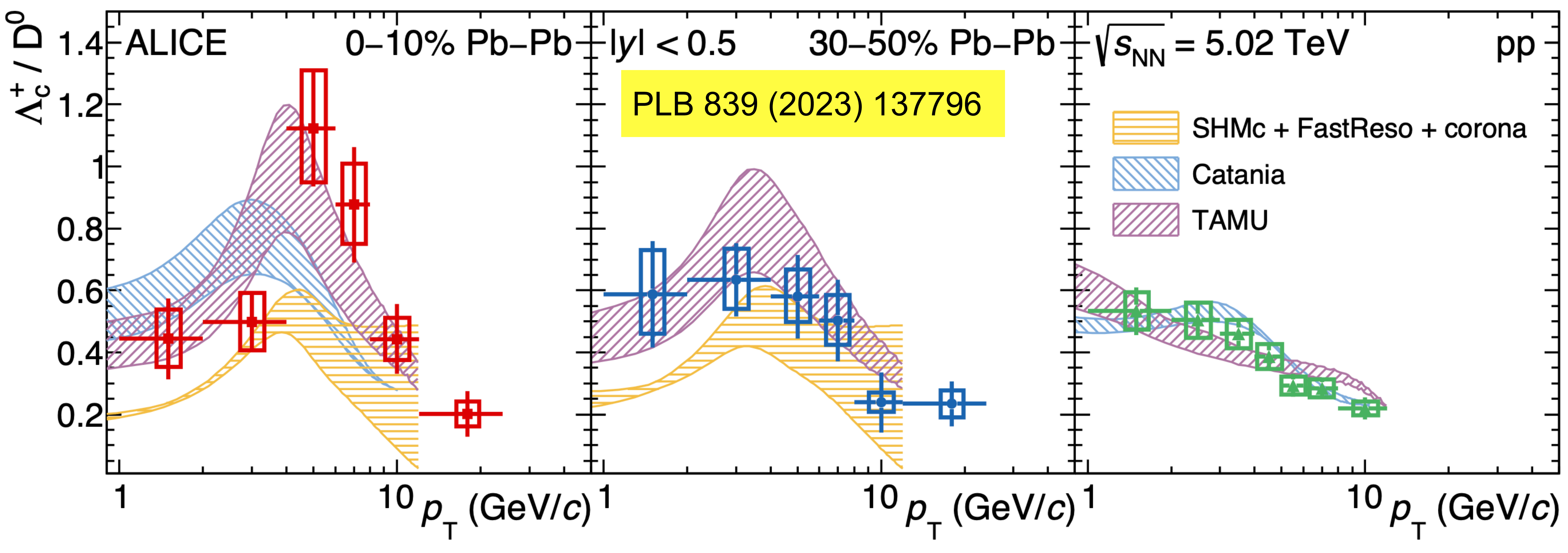


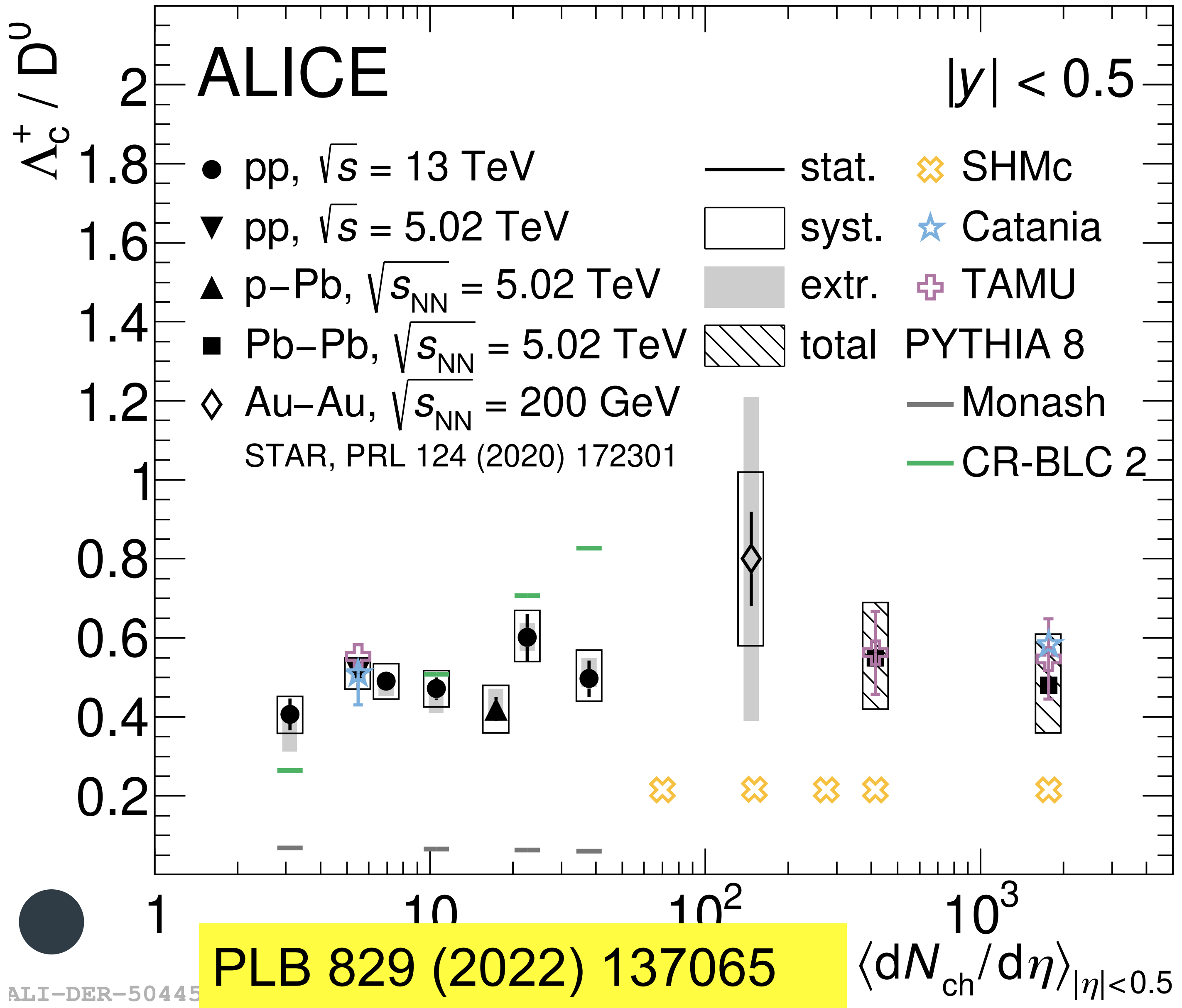


- B/M ratio inside jet cone doesn't show a peak as inclusive case at intermediate p_T
- Charmed-jet fragmentation is slightly different when containing a strangeness quark hadrons
- Charm quarks have a softer fragmentation into Λ_c^+ baryons compared to D^0 mesons

Heavy flavor hadronization: B/M ratio

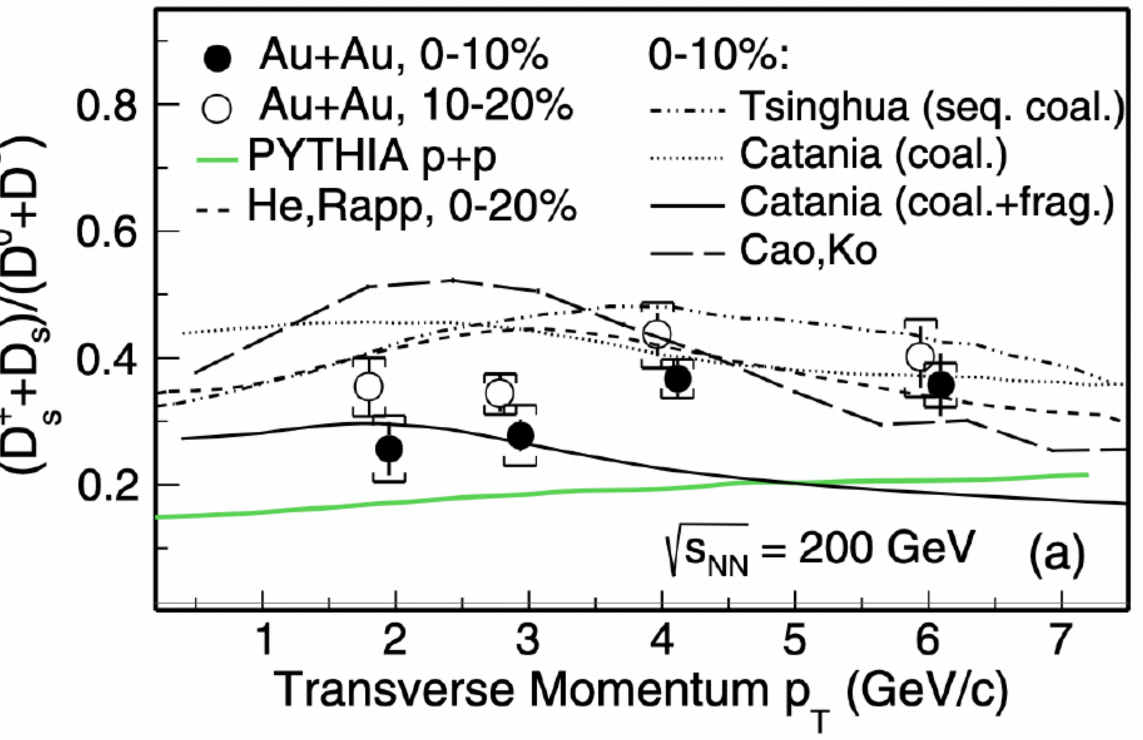




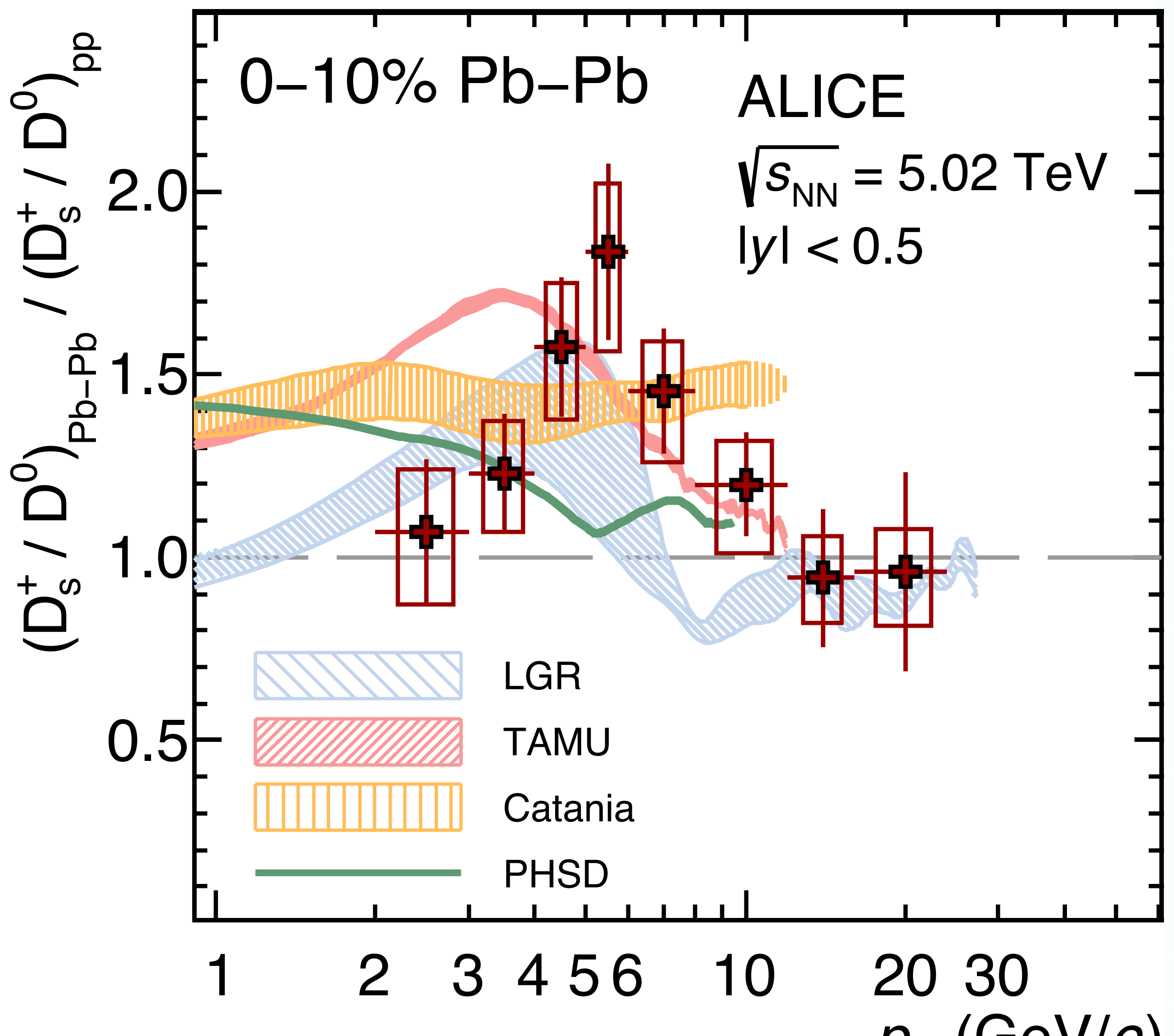


- Enhanced baryon to meson ratio (Λ_c^+/D^0) compared to e+e- collisions at low p_T, regardless of centrality or multiplicity
- Higher p_T behavior close to e+e- baseline
- TAMU model can reproduce the Λ_c^+/D^0 ratio in both pp and Pb-Pb collisions

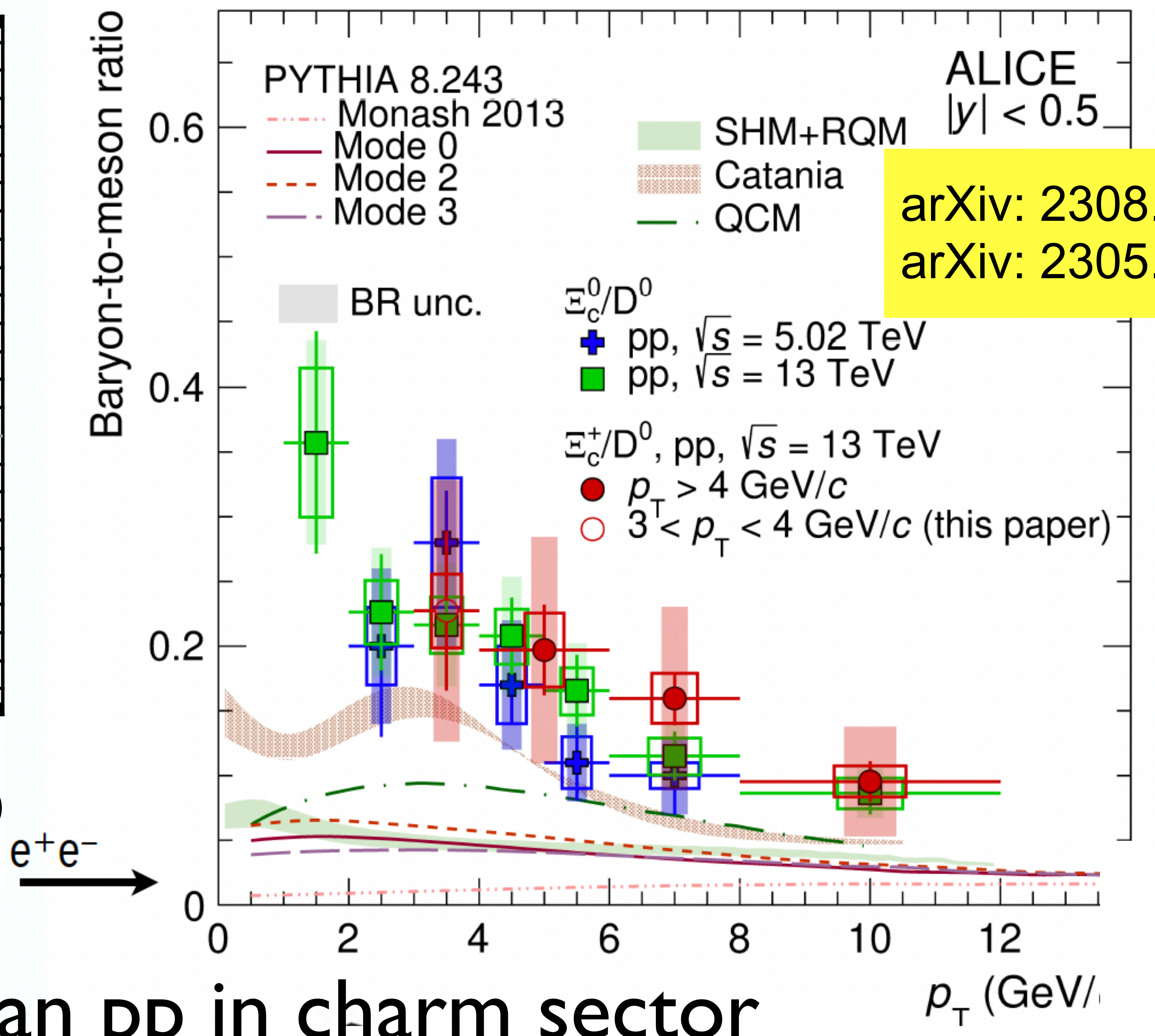
HF hadronization with strange-quark content



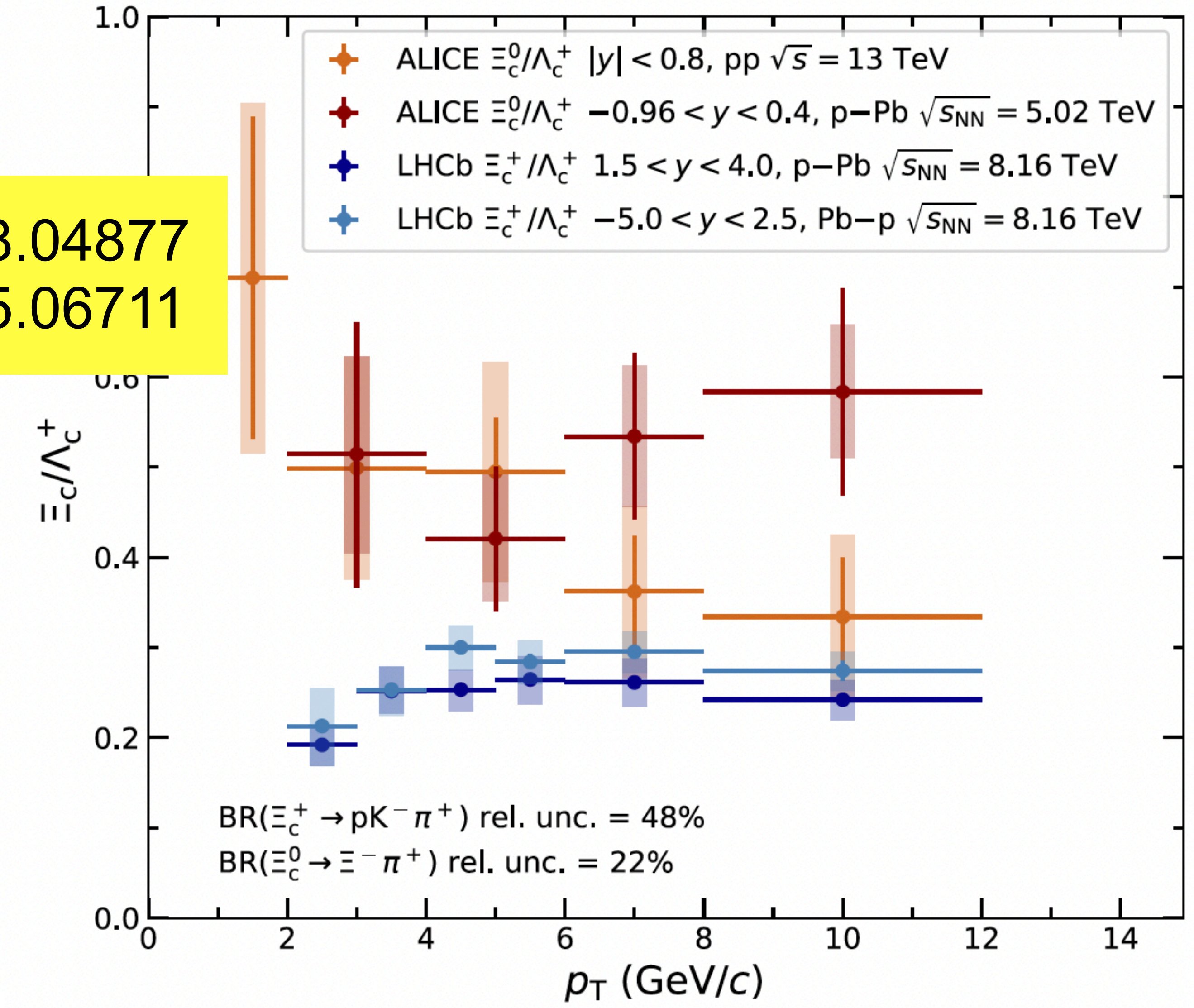
PRL 127 (2021) 092301

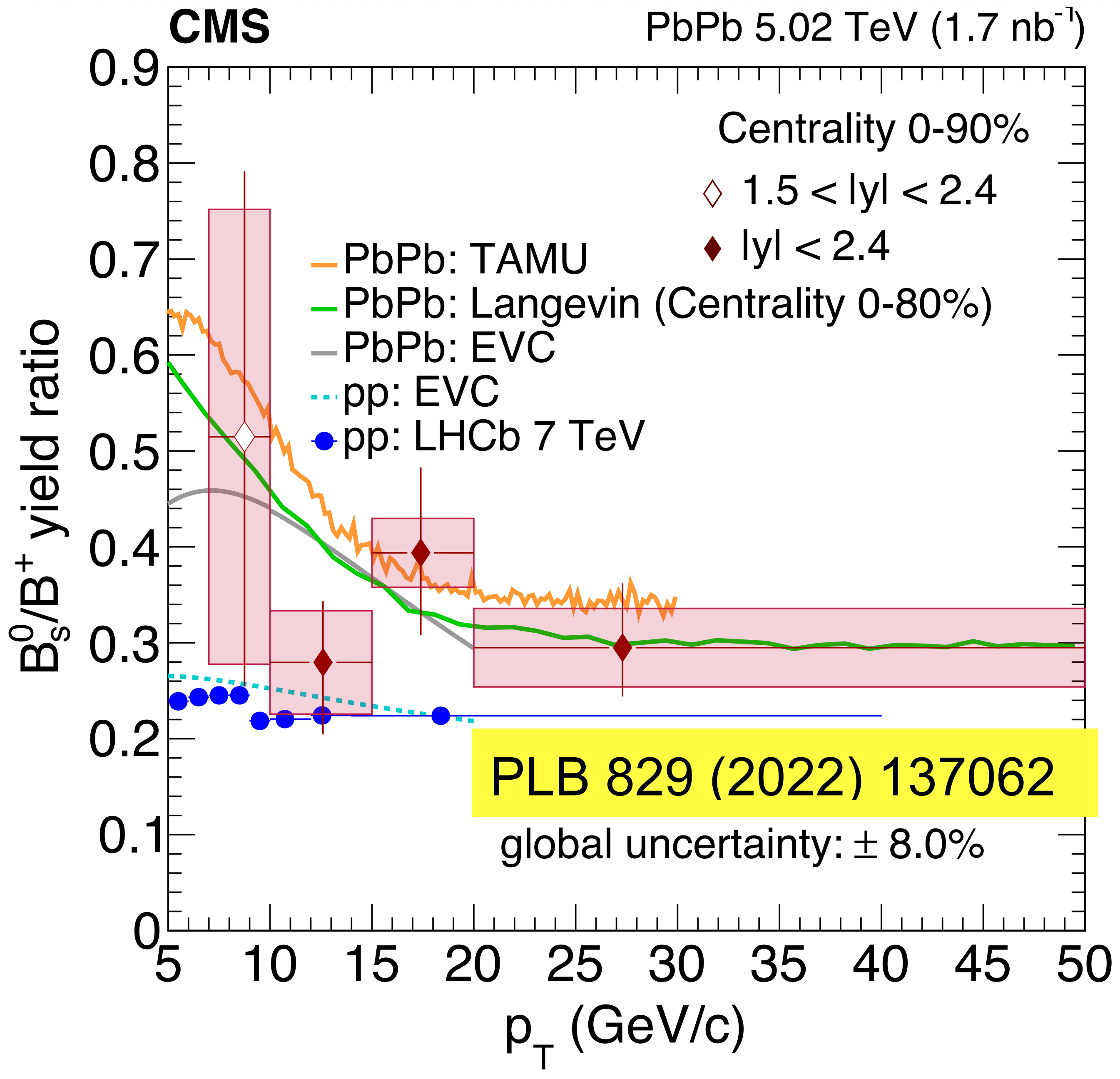


PLB 827 (2022) 136986



arXiv: 2308.04877
arXiv: 2305.06711

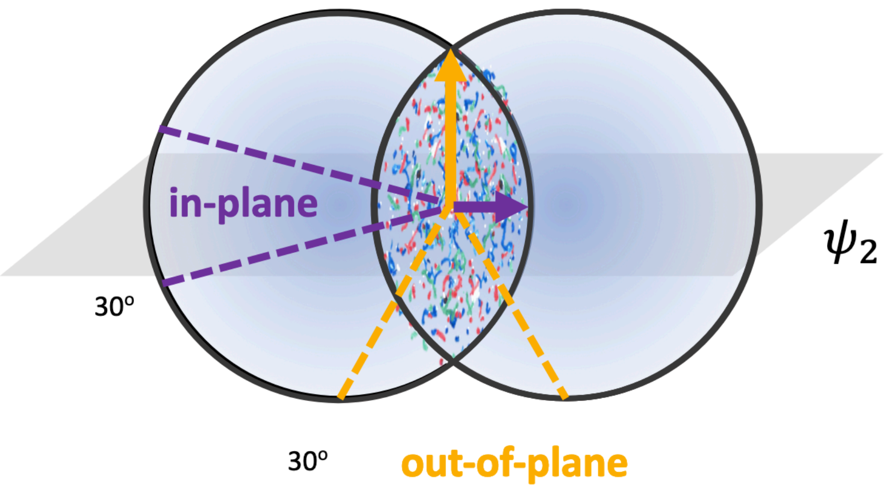




PLB 829 (2022) 137062

- Strange-to-nonstrange ratio is higher in HI than pp in charm sector
- Enhanced production of Ξ_c relative to D^0 in pp collisions compared to e+e- collisions → due to large strangeness content?
- Hints of lower Ξ_c/Λ_c at forward rapidity compared to midrapidity
- Hint of B_s^0 enhancement wrt. B^+ in (central) Pb+Pb collisions at low p_T, described by model predictions

Path length dependence of jet energy loss

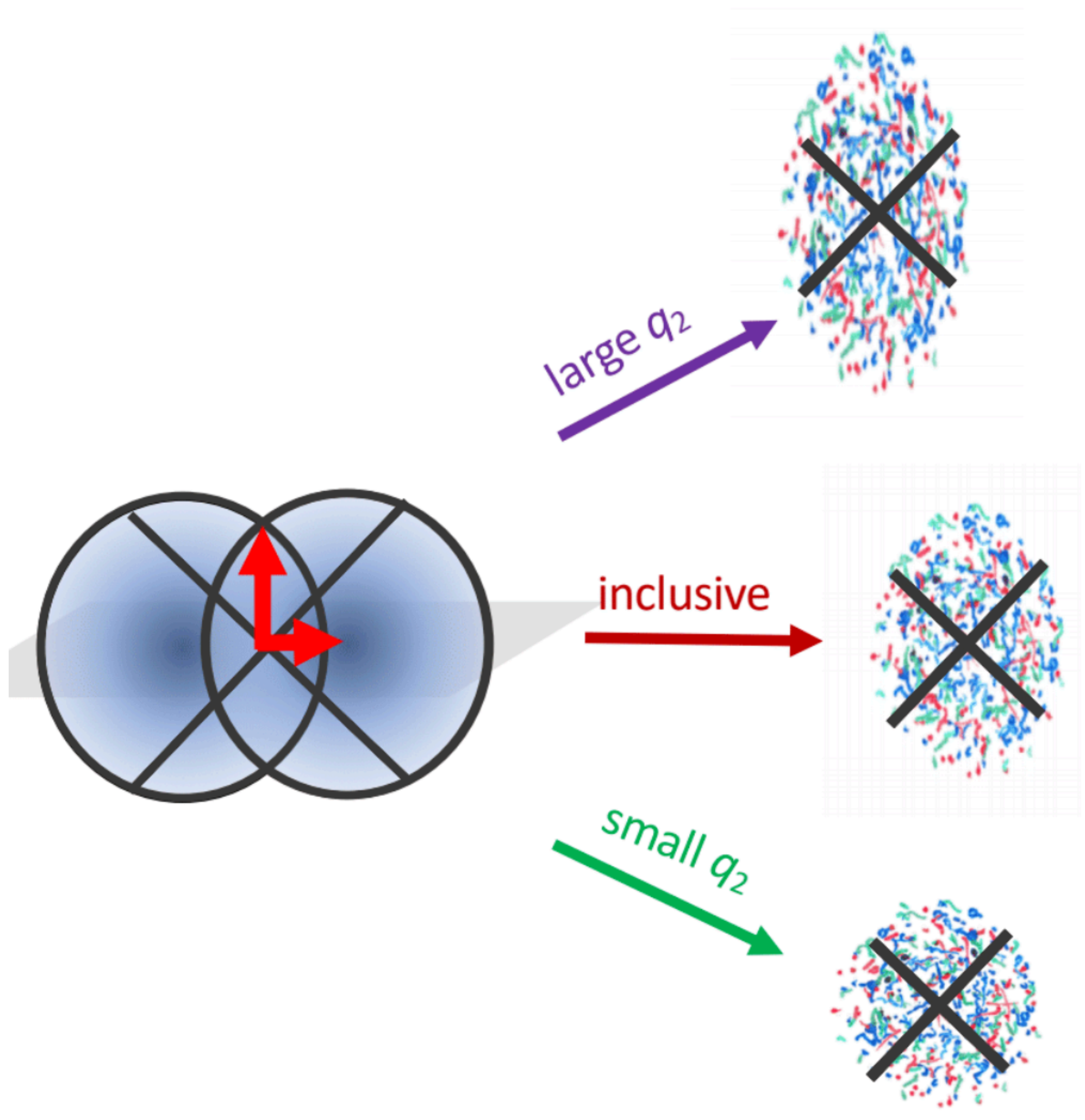


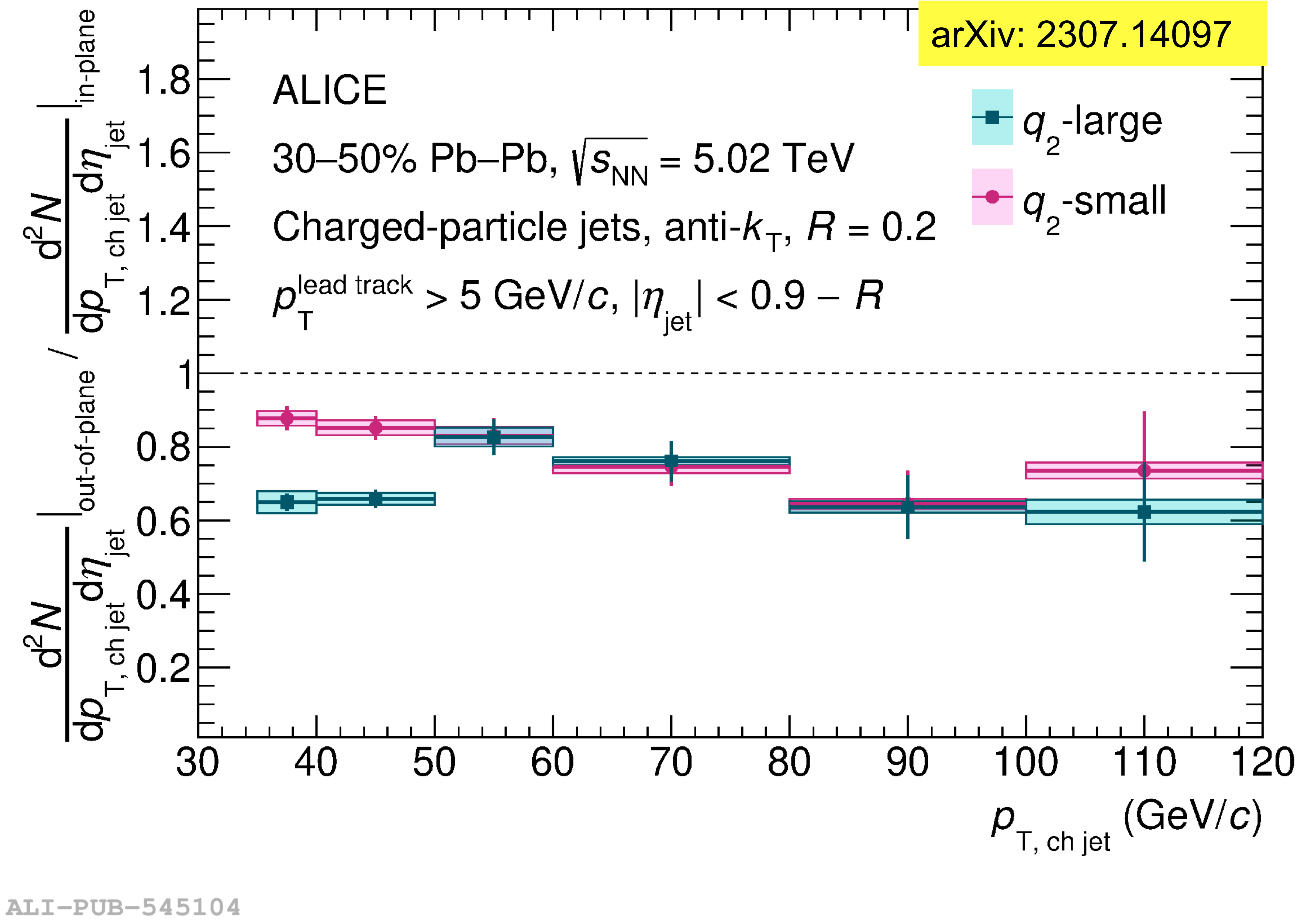
M = multiplicity

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

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

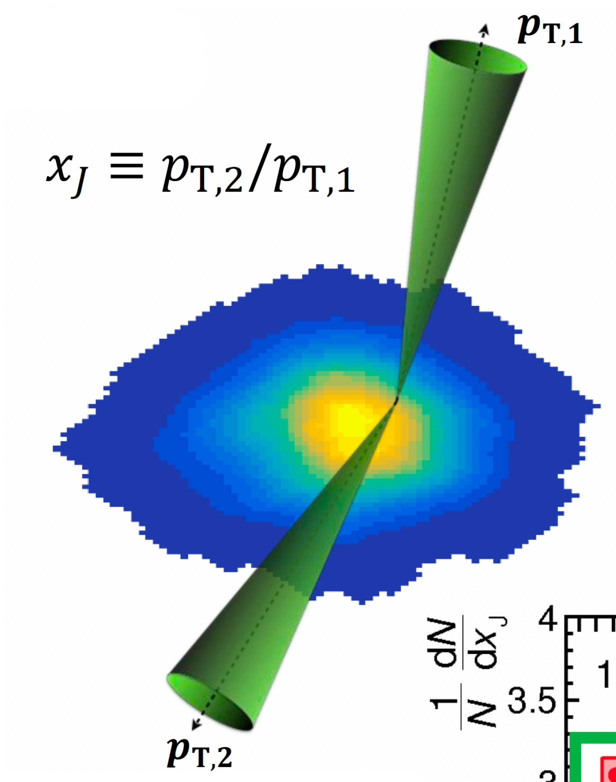
φ_i = azimuthal angle of ith particle

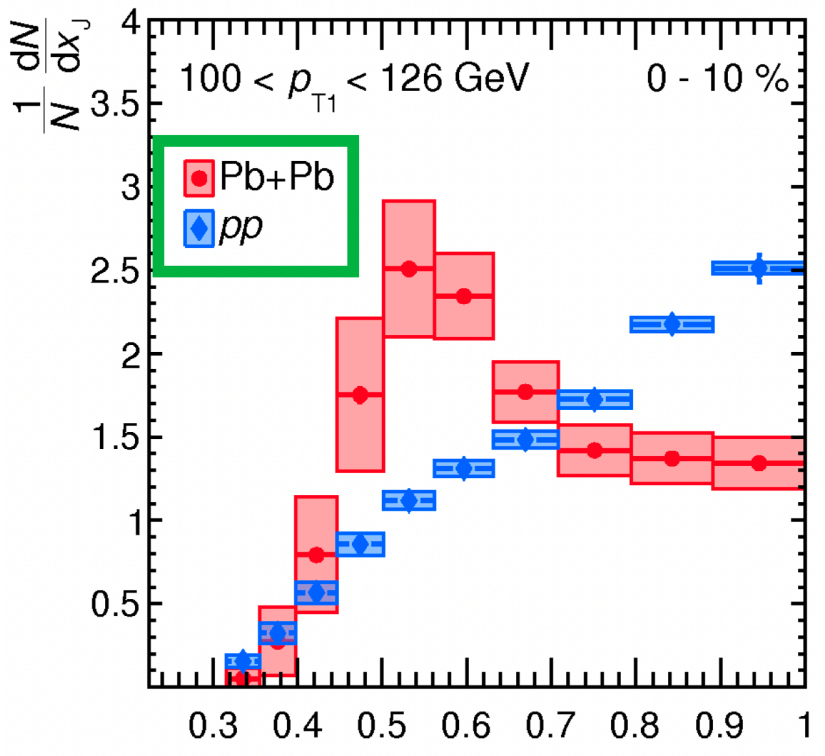




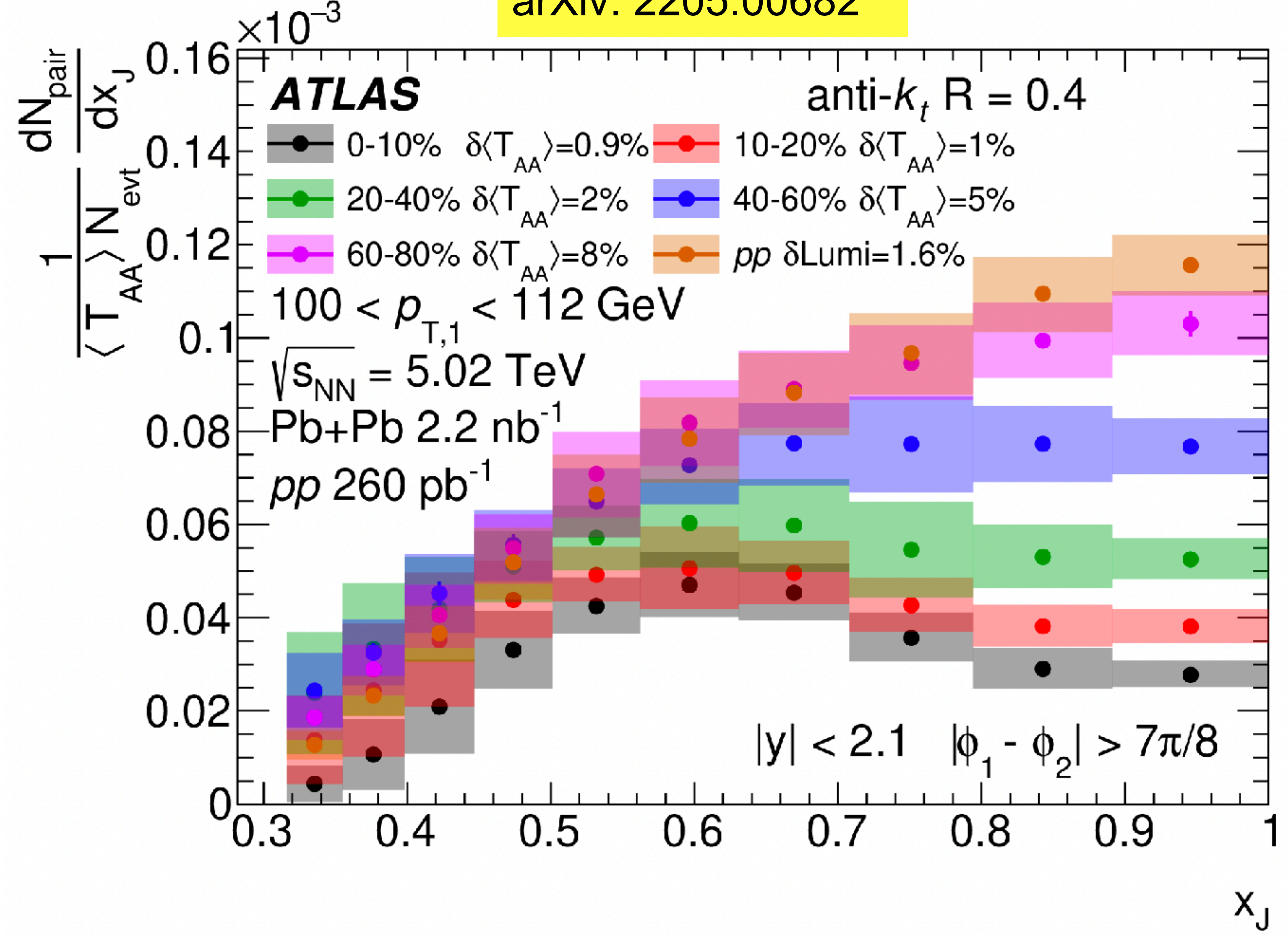
- Selecting specific event shapes according to their anisotropy (q_2) allows to maximize in plane and out of plane path length differences
- More suppressed jet yield ratio of out-of-plane relative to in-plane for larger q_2 events for low p_T jets
  - consistent with stronger suppression along the out-of-plane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

Path length dependence of jet energy loss



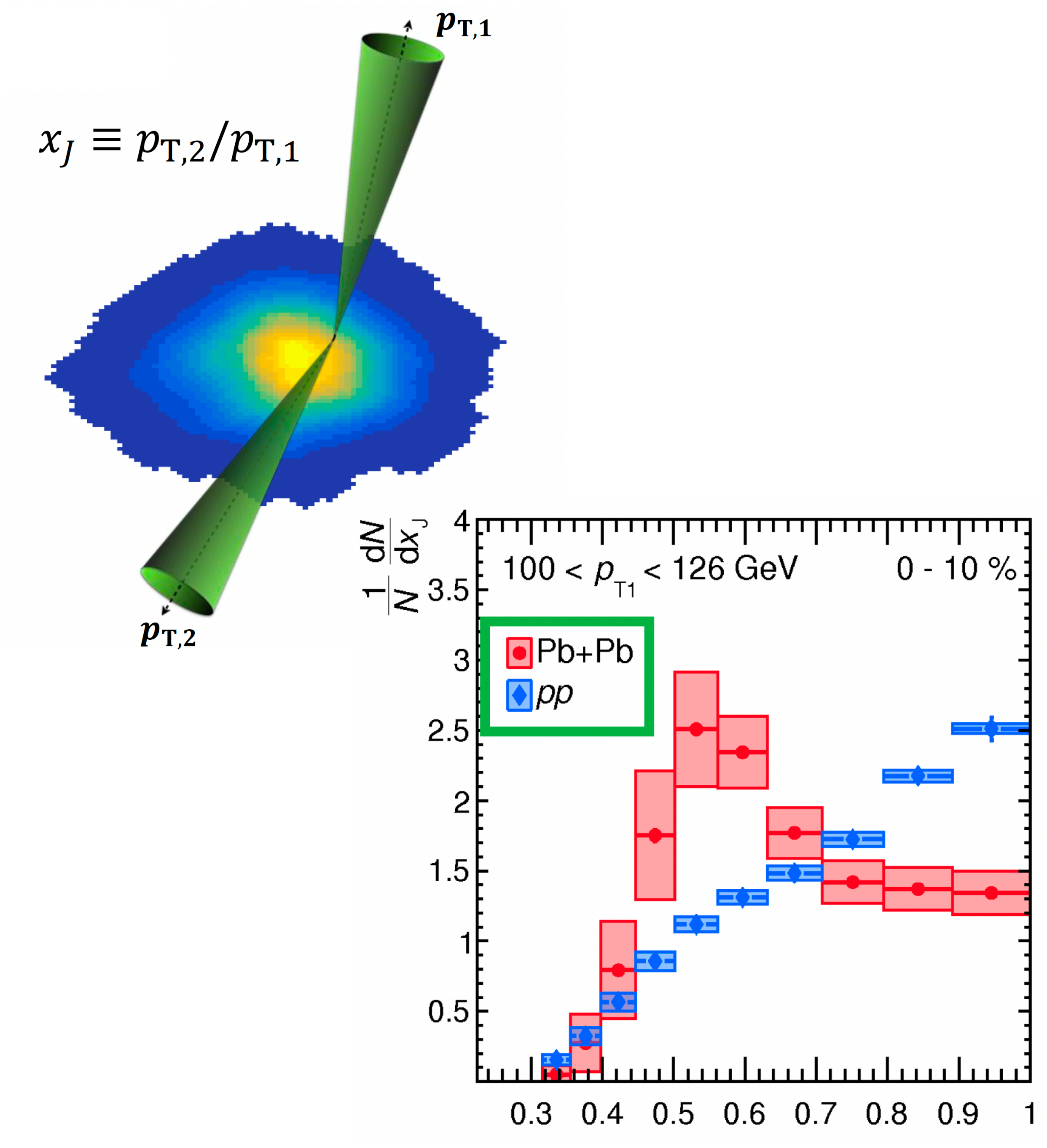


arXiv: 2205.00682



- 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



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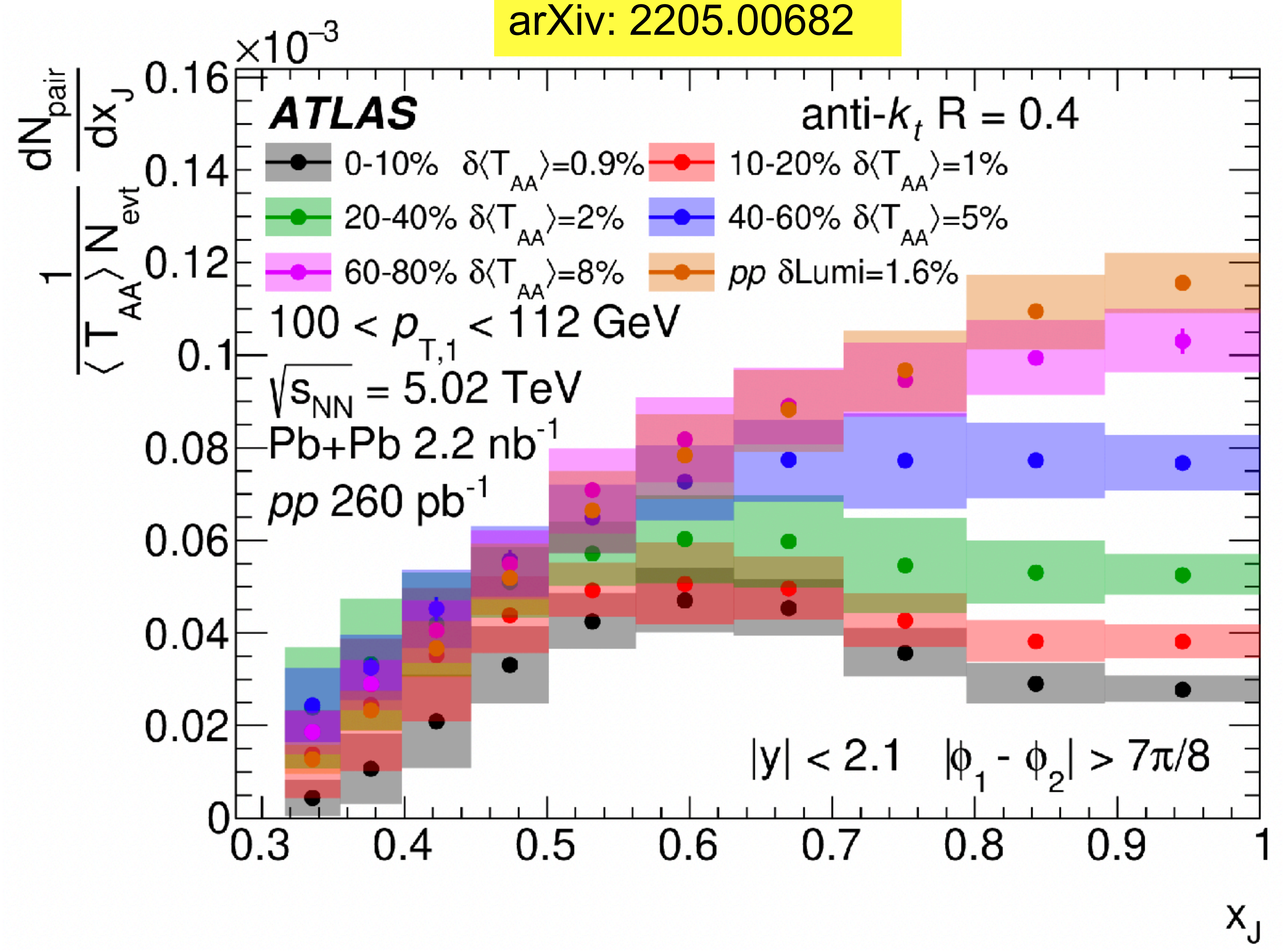
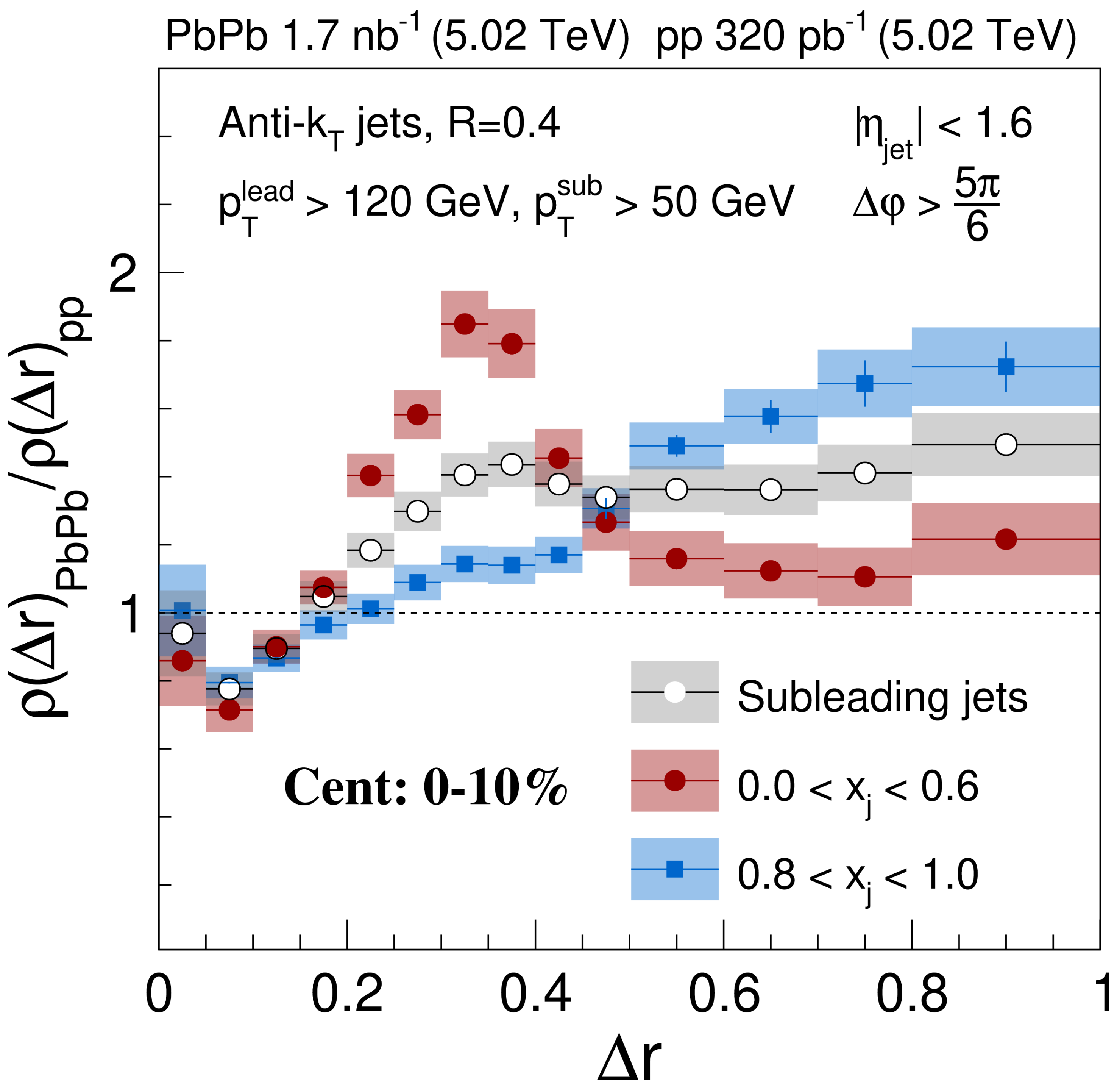


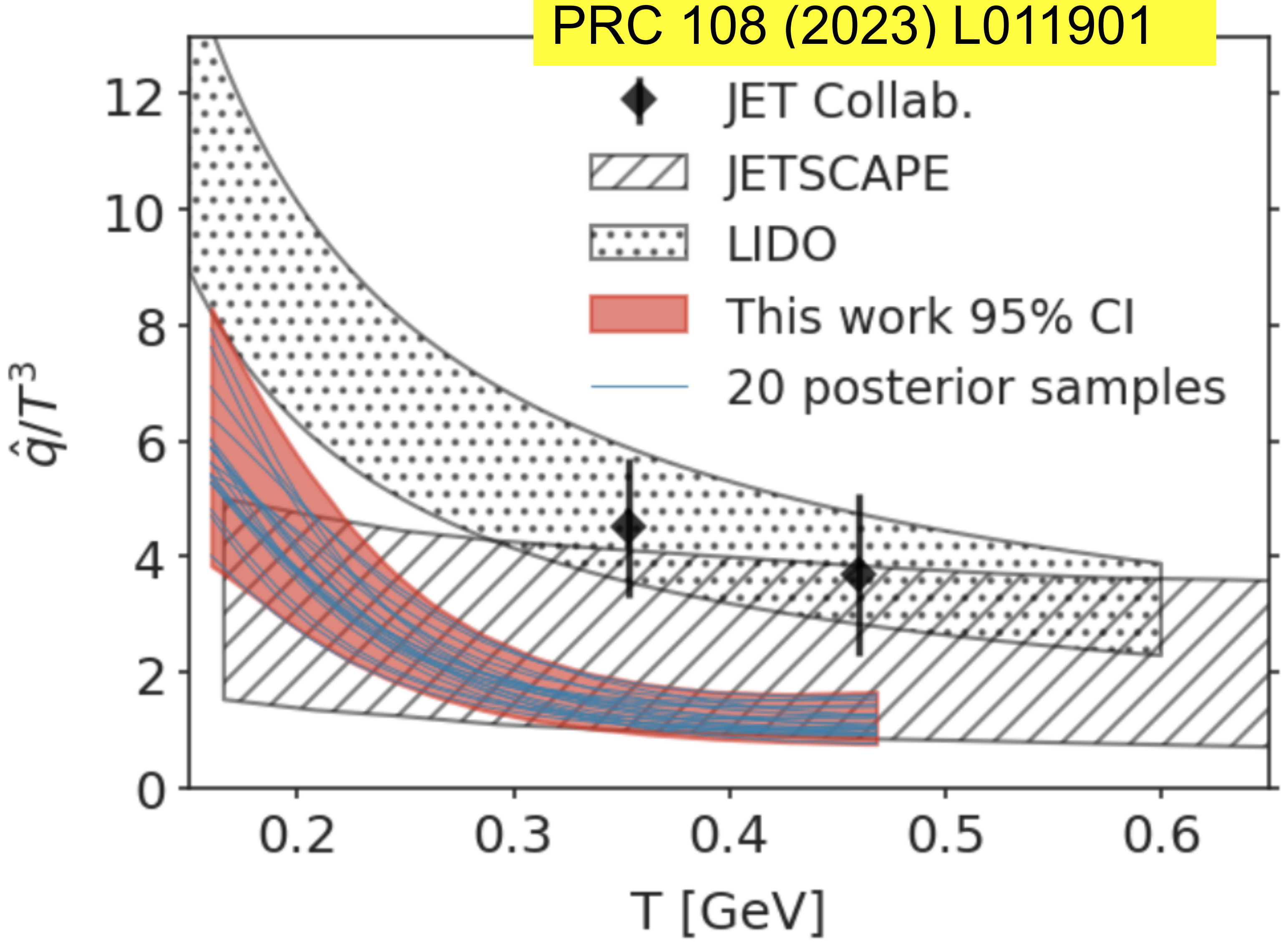
CMS *Supplementary* JHEP 05 (2021) 116



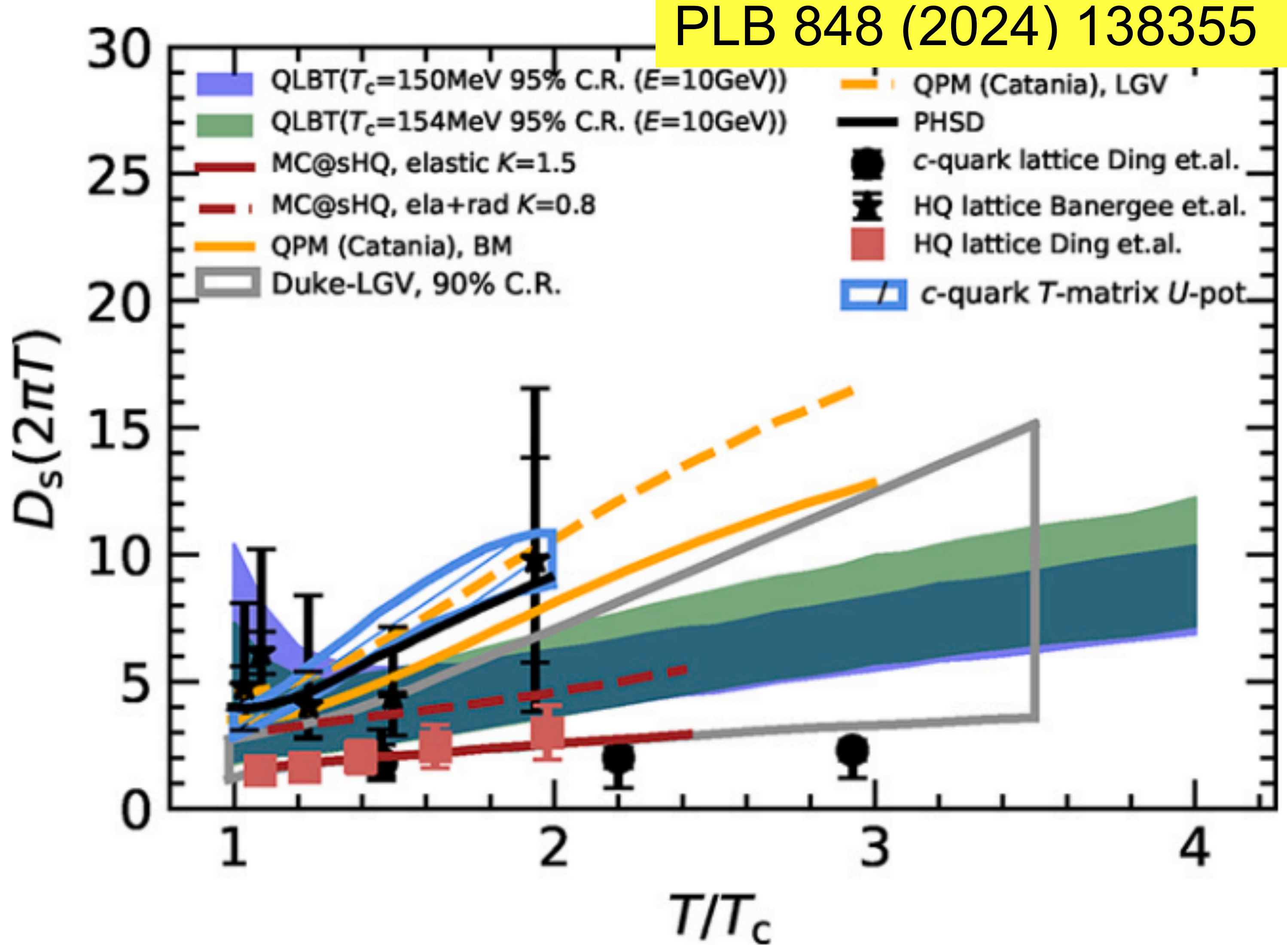
- Back-to-back jet pairs provide access to asymmetric energy loss due to unequal path lengths in QGP
- A peak structure observed at intermediate x_J indicates the suppression of symmetric dijets
- Similar observation for jet shapes measurements in CMS using dijets events
  - subleading jets from asymmetric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

Extract medium properties from hard probes

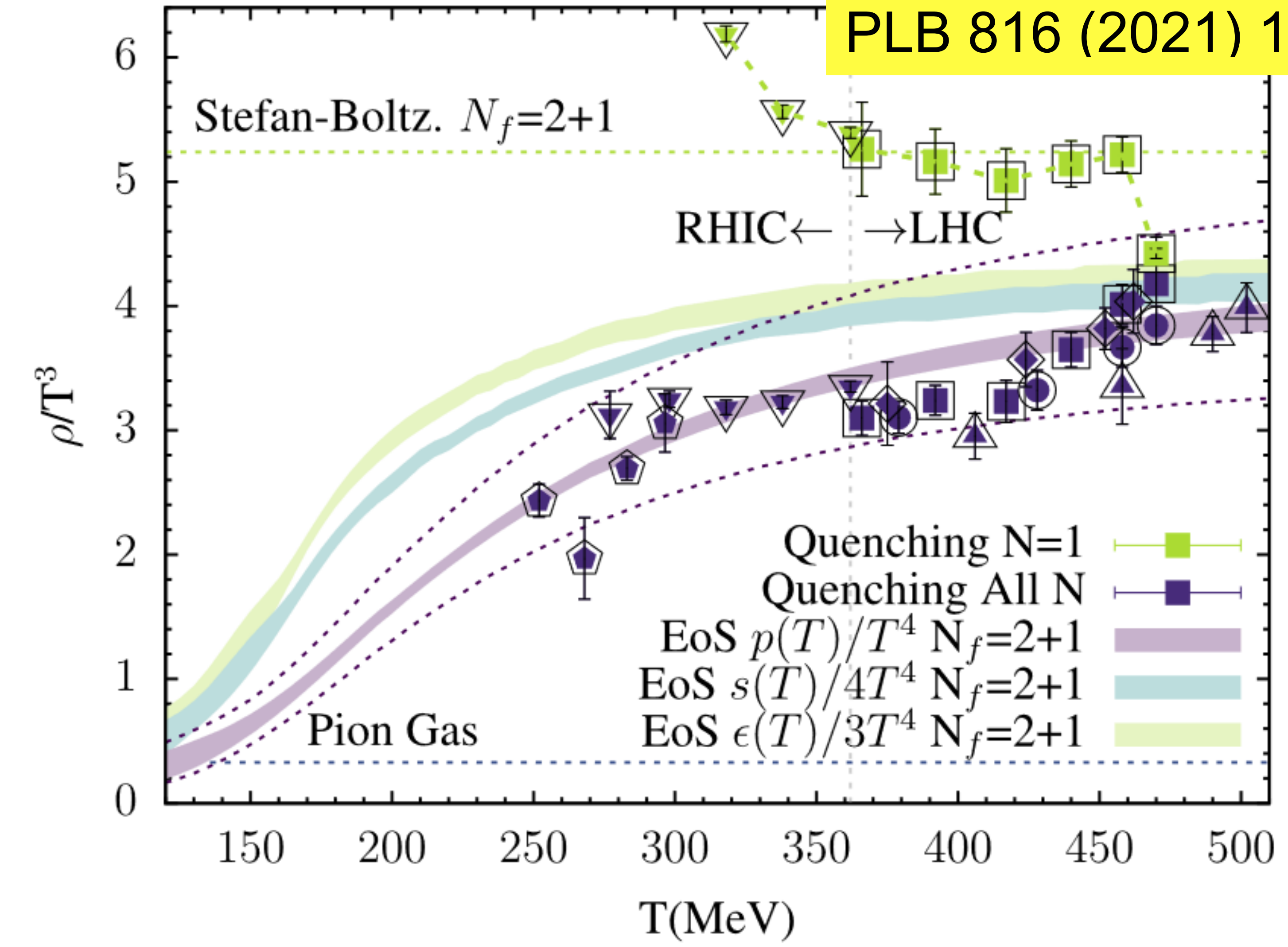
PRC 108 (2023) L011901



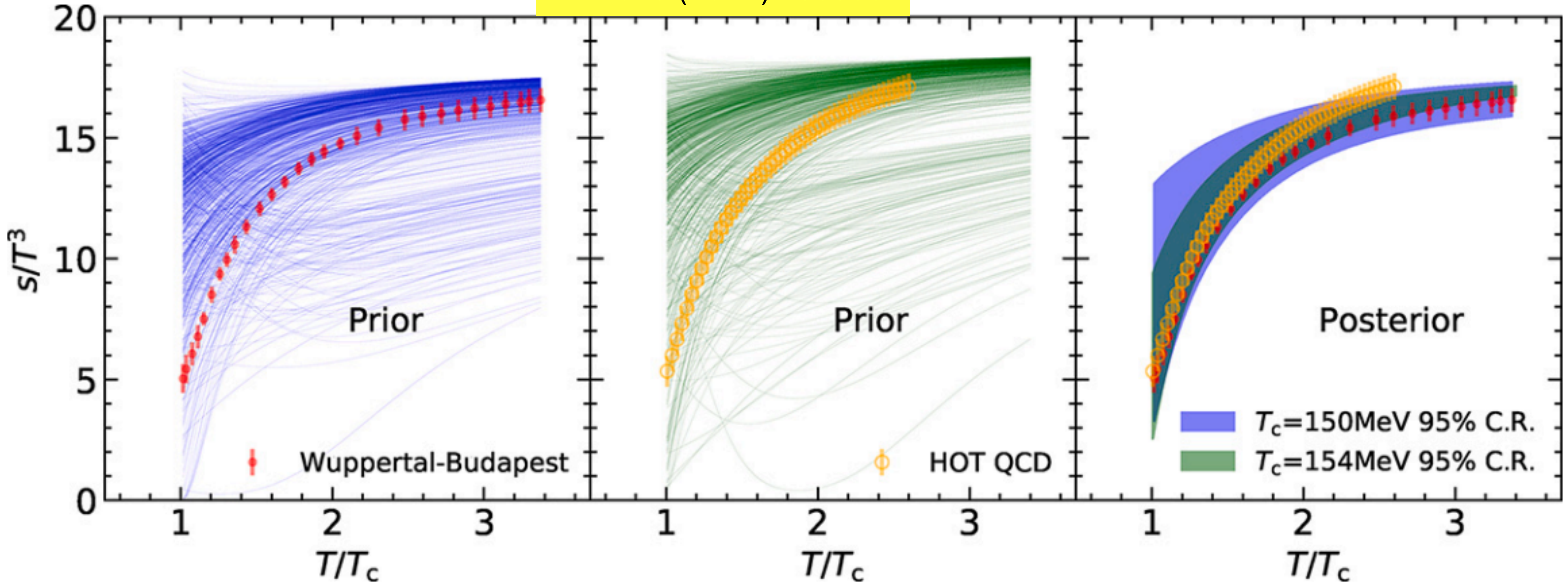
PLB 848 (2024) 138355



PLB 816 (2021) 136251



PLB 848 (2024) 138355



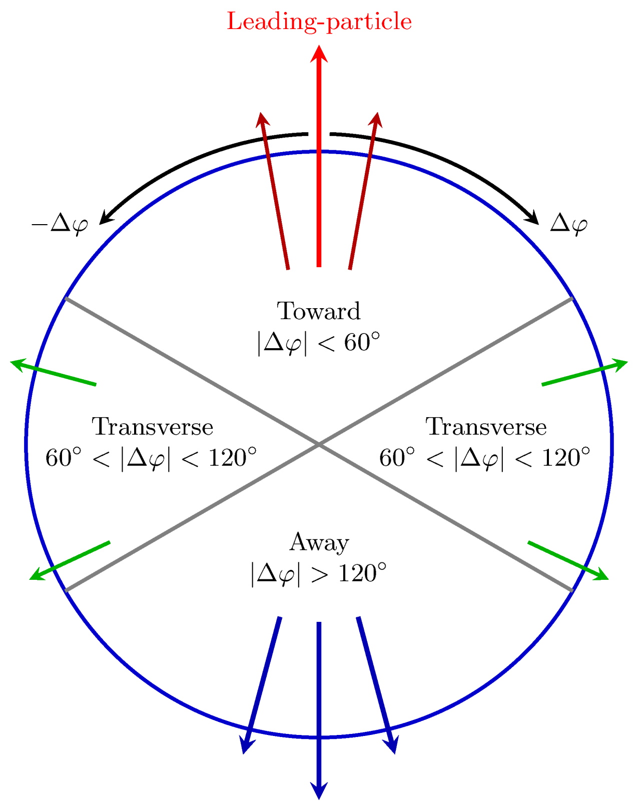
Hard probes can tell:

1. Jet quenching parameter $\hat{q}$
2. Heavy quark diffusion coefficient D_s
3. QGP EoS and η/s

What else important information?

How to narrow down error bars?

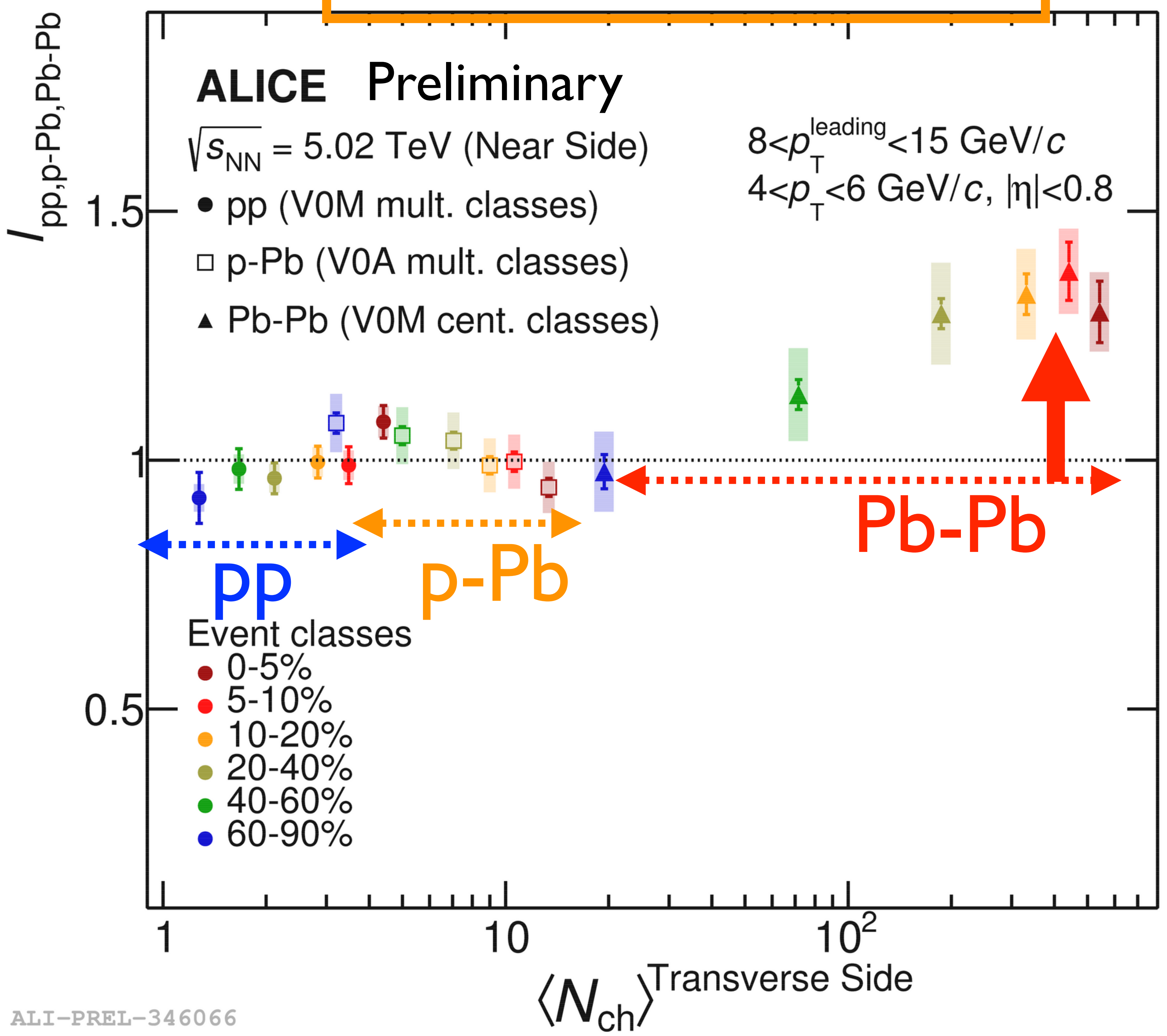
Jet quenching in small collision systems?



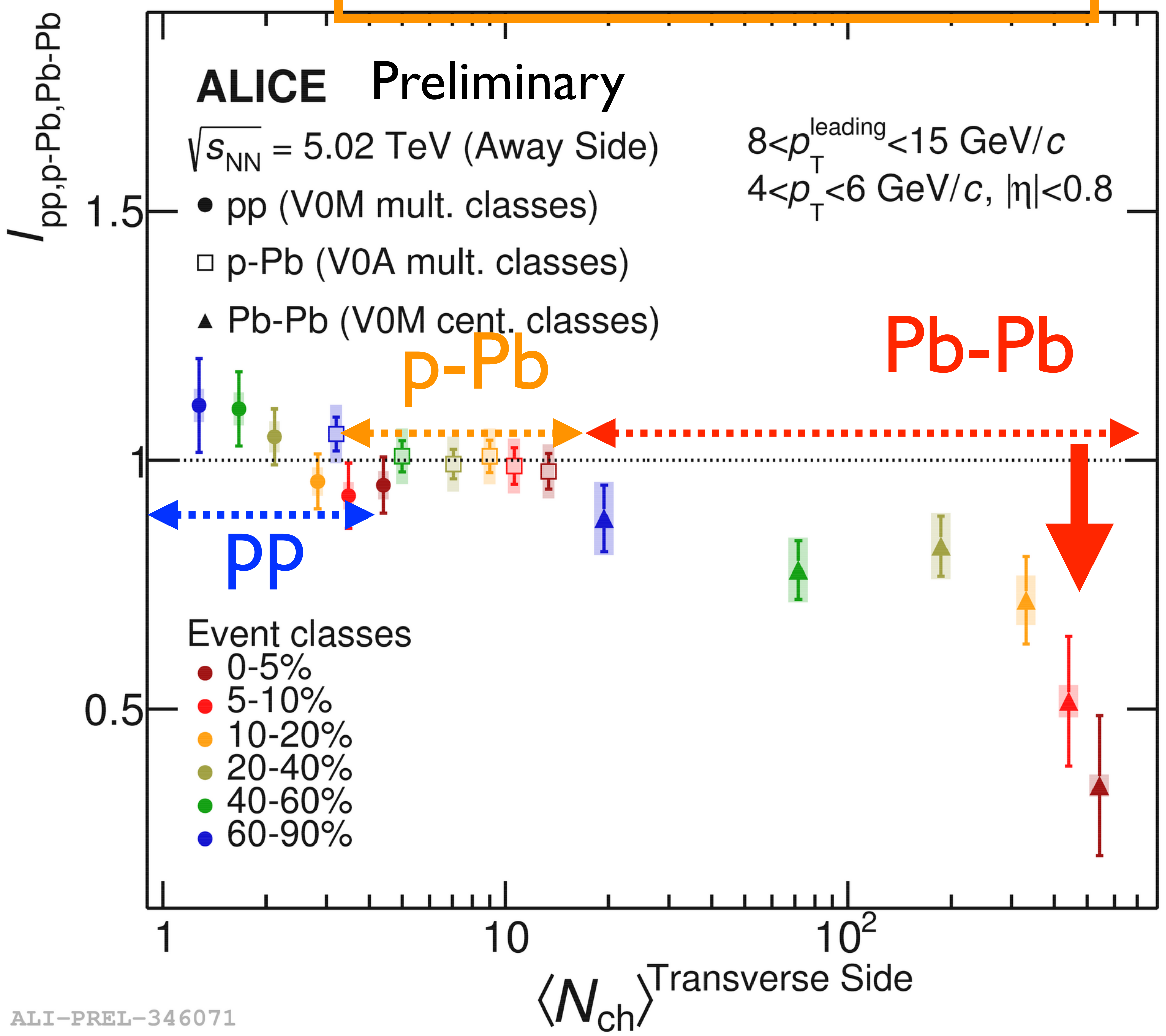
Δϕ=|ϕleading - ϕassociate|

$$I_{\mathrm{pp/pA/AA}} = \frac{Yield^{\mathrm{pp/pA/AA}}_{\mathrm{NS/AS}}}{(Yield^{\mathrm{pp/pA/AA}}_{\mathrm{NS/AS}})_{\mathrm{min.bias}}}$$

Near side: |Δϕ| < 60°



Away side: |Δϕ| > 120°



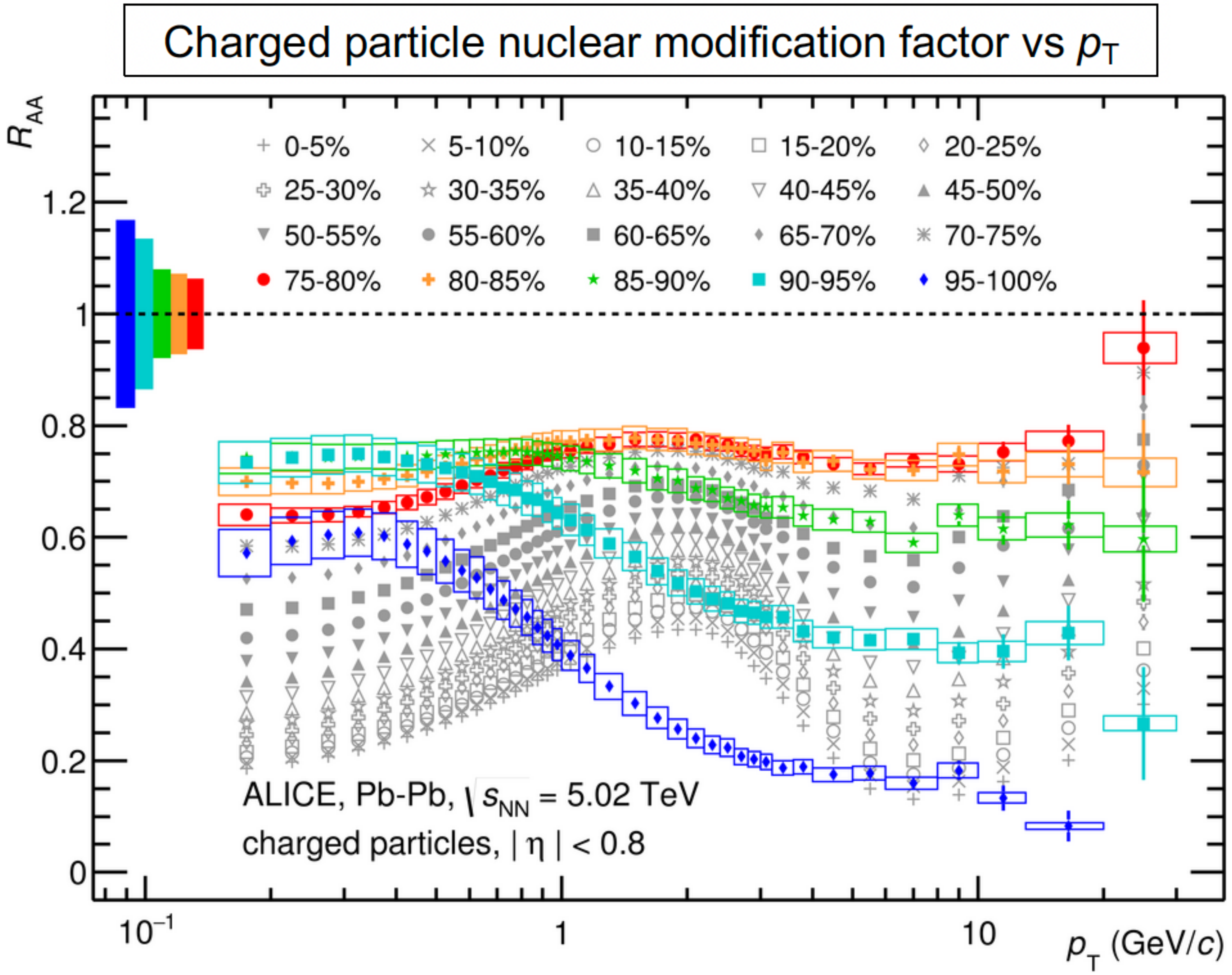
- Using multiplicity in transverse region as event activity classifier to better separate soft and hard processes
- No enhancement (suppression) observed for Near (Away) side in pp and p-Pb collisions

➡ No indication of jet quenching in small collision systems

Jet quenching not observed in small systems

No significant energy loss observed so far

- Strong change of behavior of R_{AA} beyond 80% centrality is reproduced considering biases in event selection and collision geometry, and o nuclear modification → not a medium effect!



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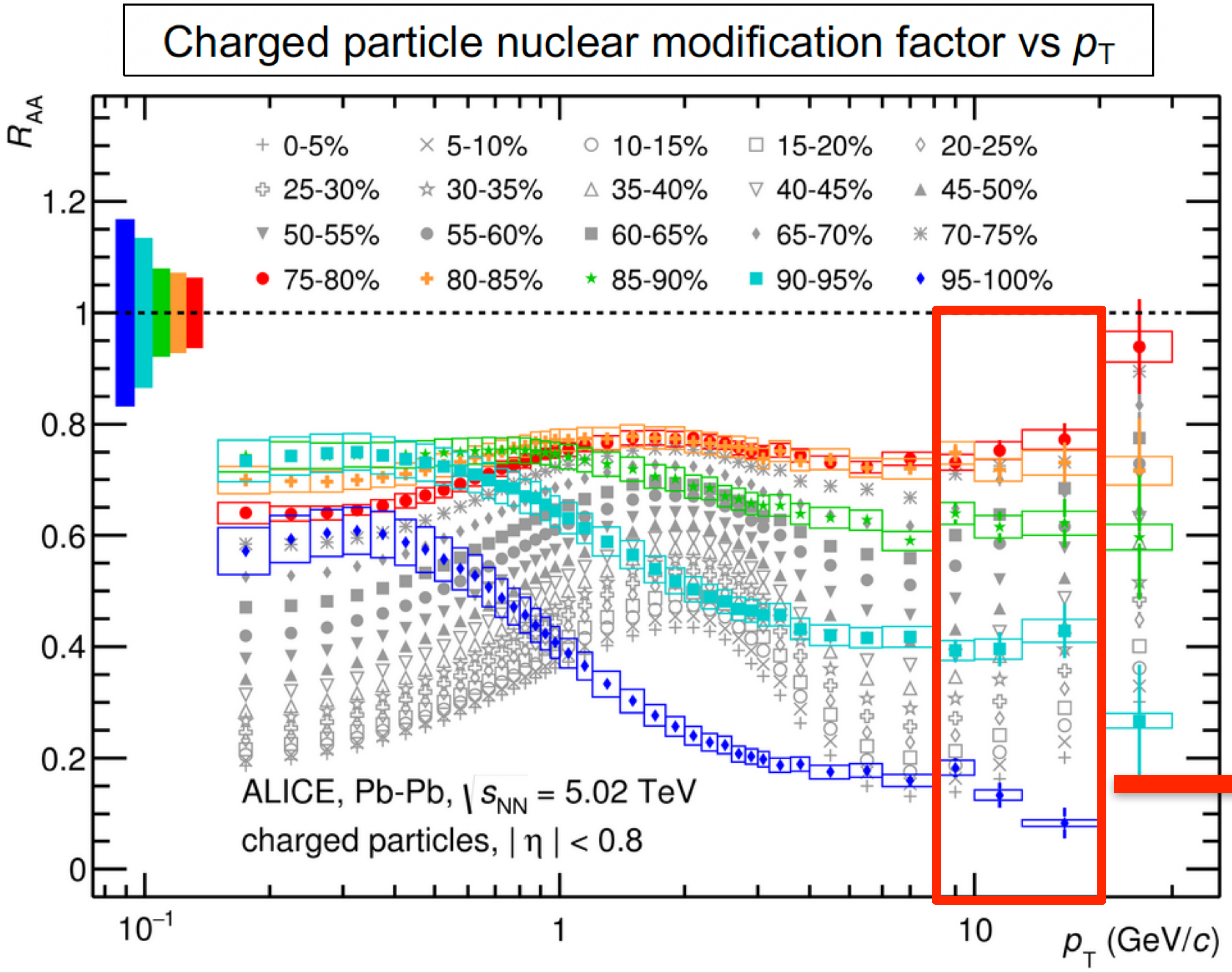

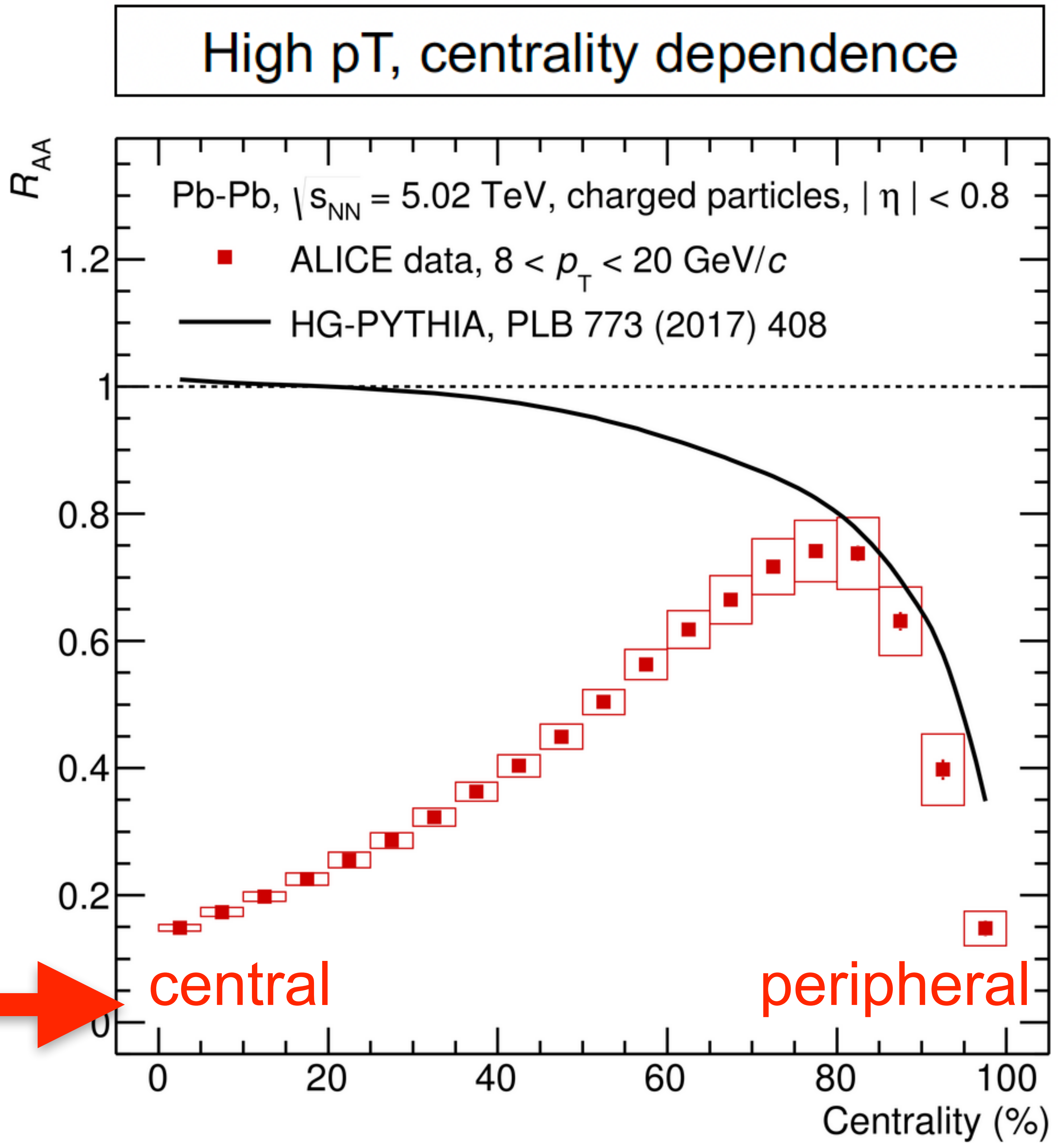

Jet quenching not observed in small systems

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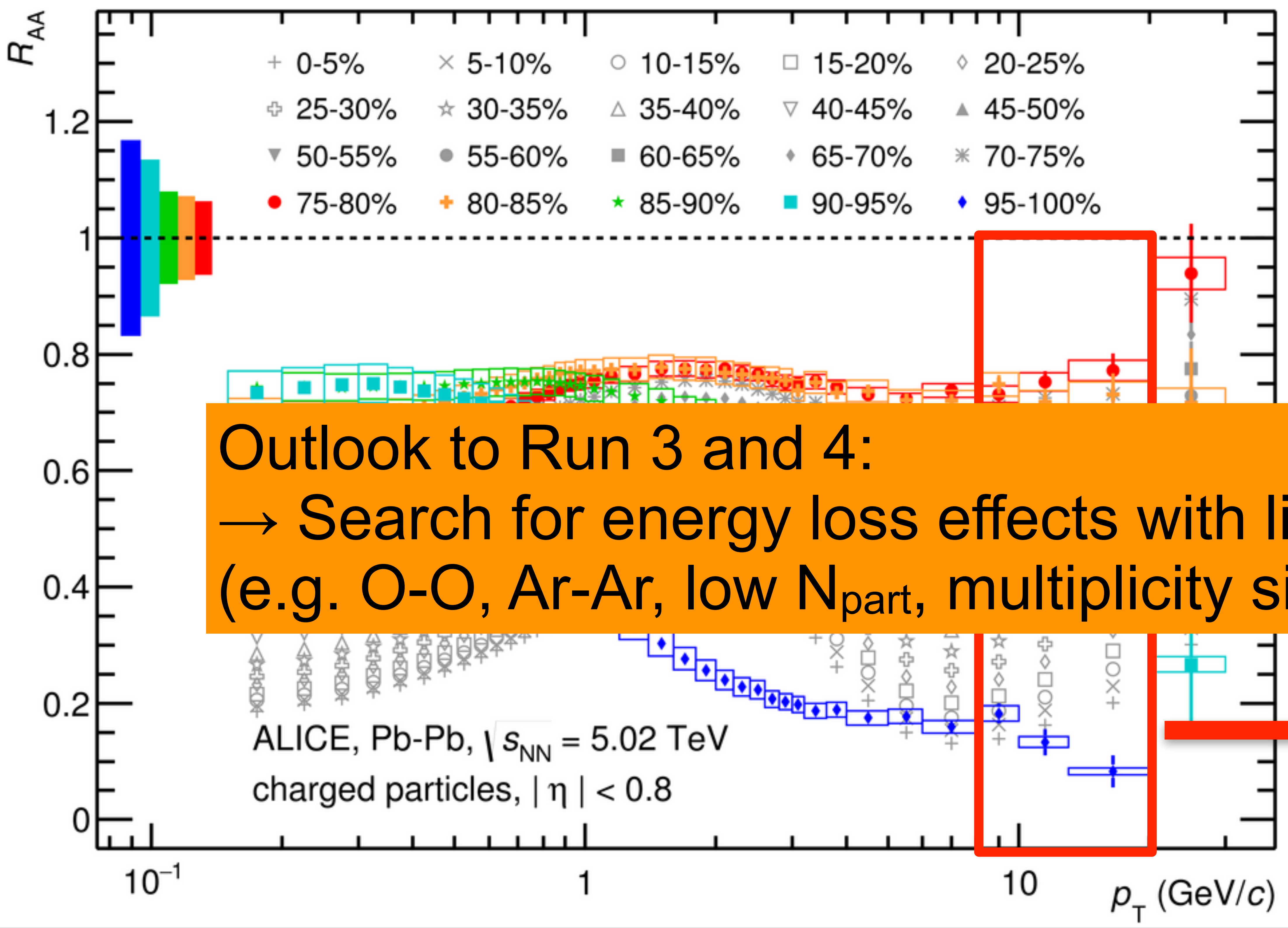
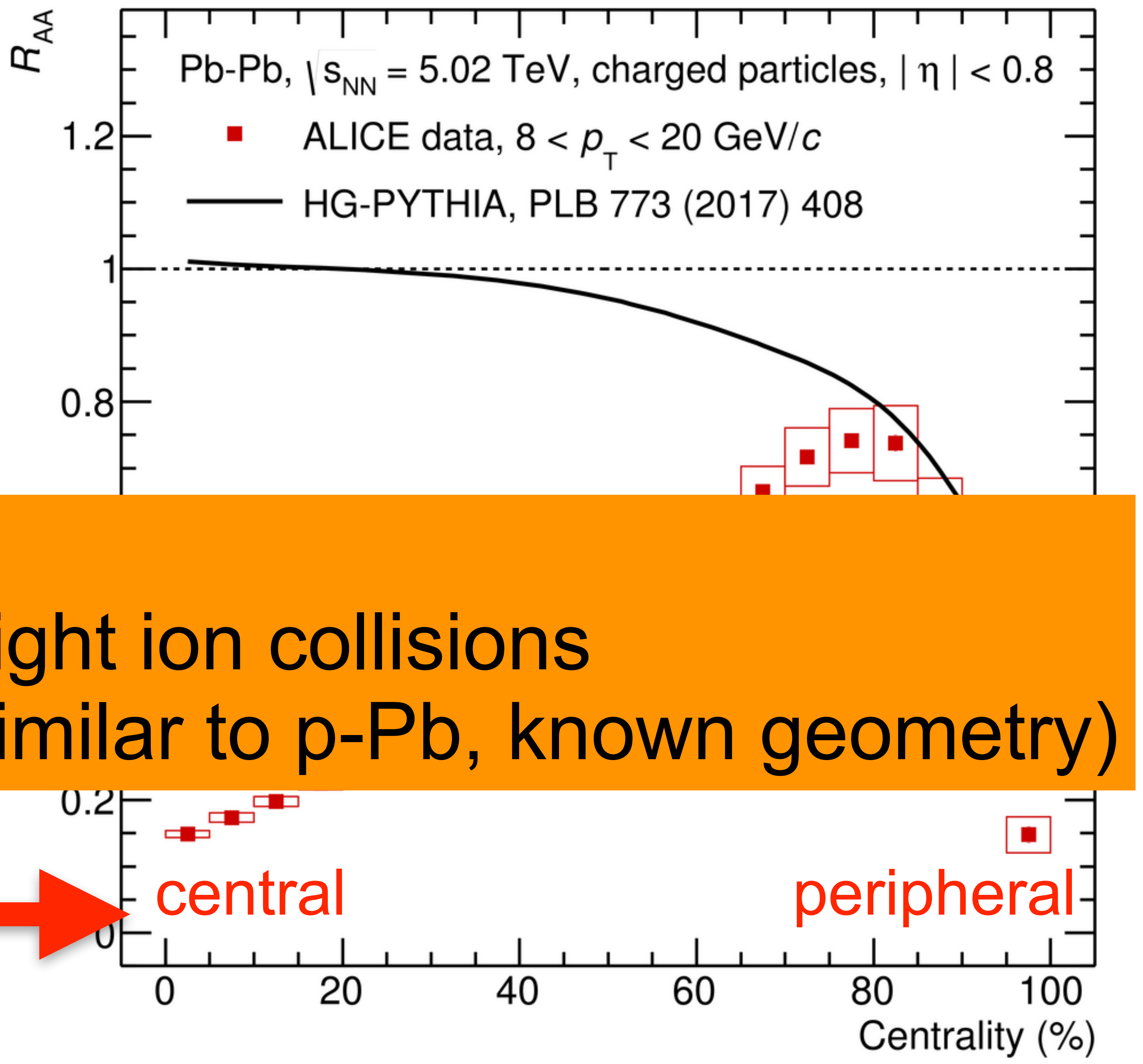
Open question: when (which system size) does energy loss sets in?

Charged particle nuclear modification factor vs p_T



High pT, centrality dependence



Outlook to Run 3 and 4:
→ Search for energy loss effects with light ion collisions
(e.g. O-O, Ar-Ar, low N_{part}, multiplicity similar to p-Pb, known geometry)

Summary and discussions

- Instead of a summary, a short list for discussions (not complete of course):
  - Flavor/Mass dependence: can quenching of jets and hadrons with different flavors/masses be explained by one single model?
  - Medium response: how to distinguish medium response and medium-induced (soft) radiation? what are the decisive (and sensitive) signals?
  - Jet broadening or narrowing: why broadening is observed in correlation analyses, but not in jet substructure measurements? can this be understood consistently?
  - R-dependence of jet quenching: the tension among ALICE/ATLAS/CMS has been solved? how do jet substructure and medium response interplay in large R jets?
  - Heavy flavor chemistry and hadronization: do we fully understand coalescence with different quark content?
  - Jet quenching in small systems: what part of the jet is most sensitive to jet-medium interaction? can event-engineering technique help?

Backup