Challenges and opportunities with jets: from small to large system

Yaxian MAO (毛亚显)

Central China Normal University

CENTRAL CHINA NORMAL UNIVERSITY

Opportunities and Ideas at the QCD Frontier

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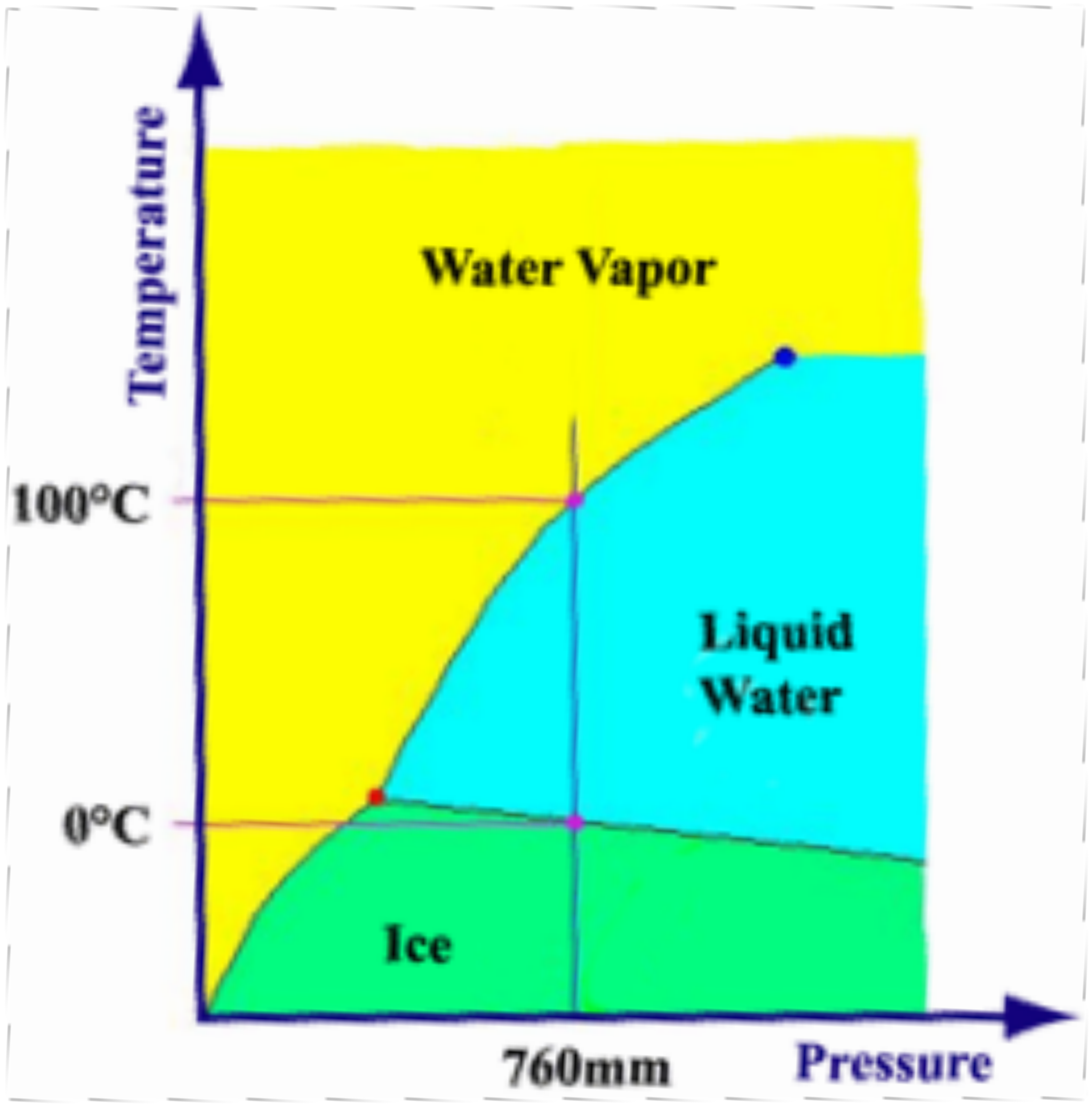
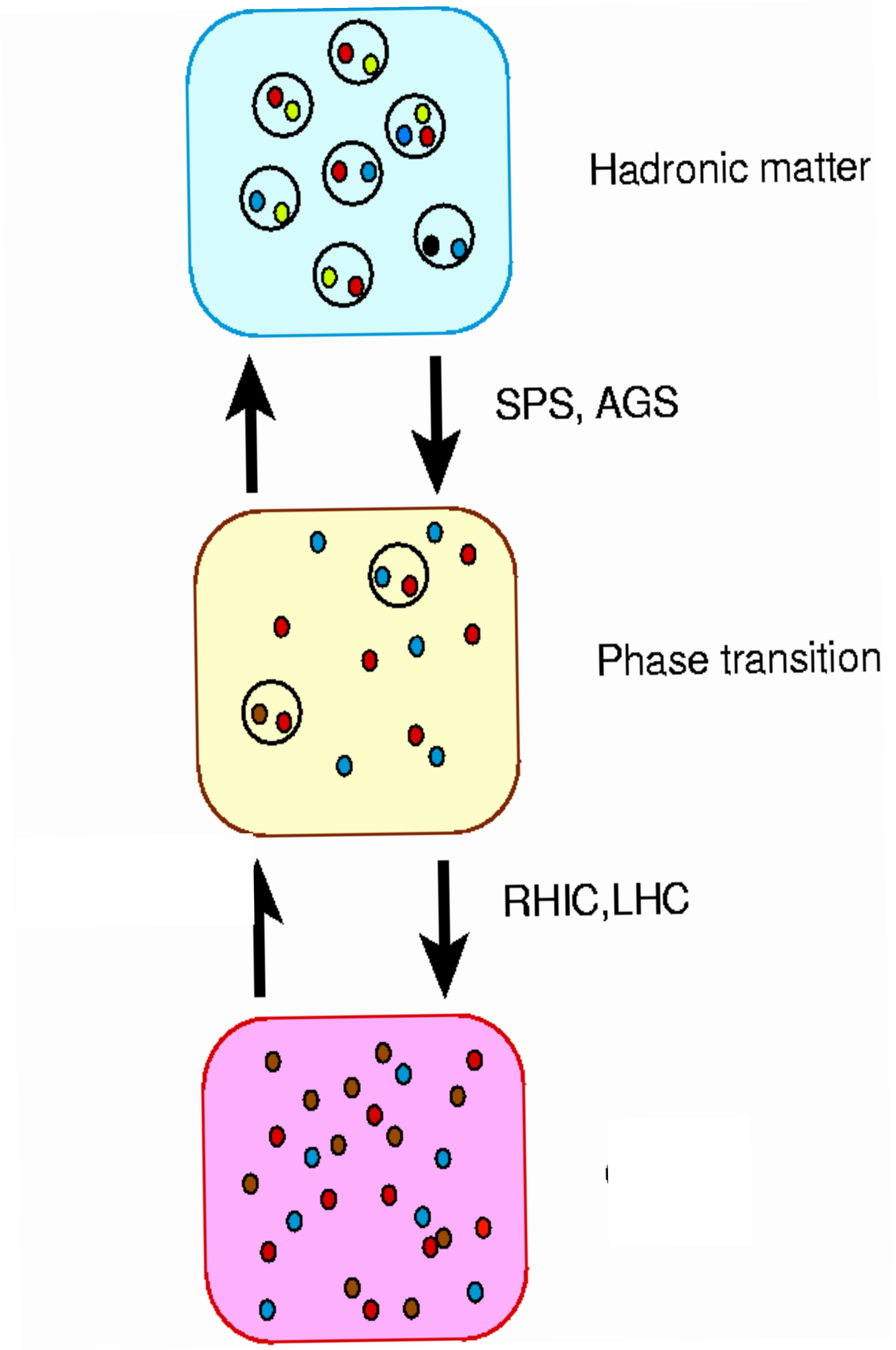
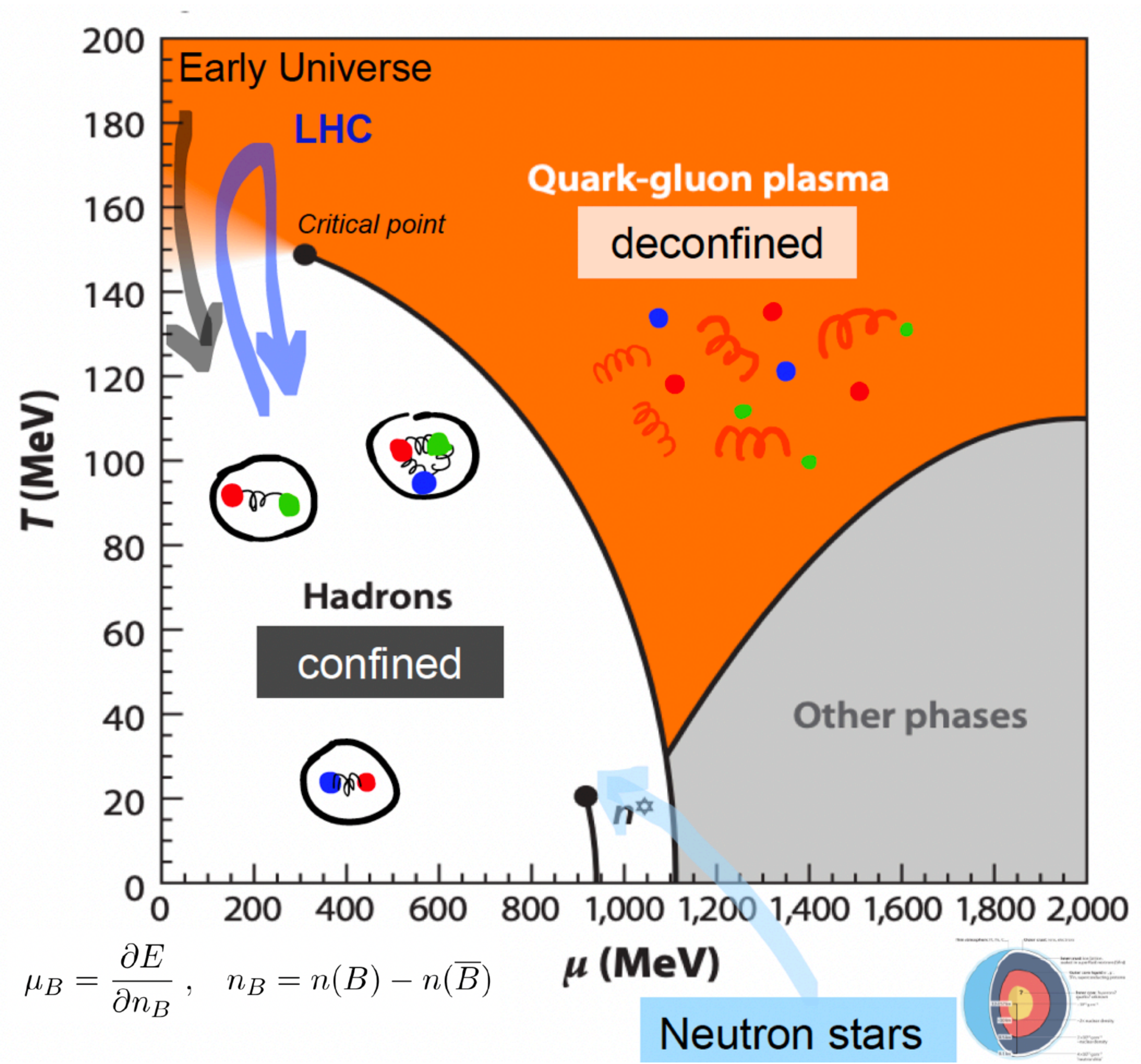
中国高等科学技术中心

Phase transition in nature







QCD (the strong interaction sector of the Standard Model of particles and forces) predicts:

"at sufficient high energy density (provided by HIC) nuclear matter undergoes a transition from ordinary matter to a new state of matter called the Quark Gluon Plasma (**QGP**)"

The Quark-Gluon Plasma (QGP)

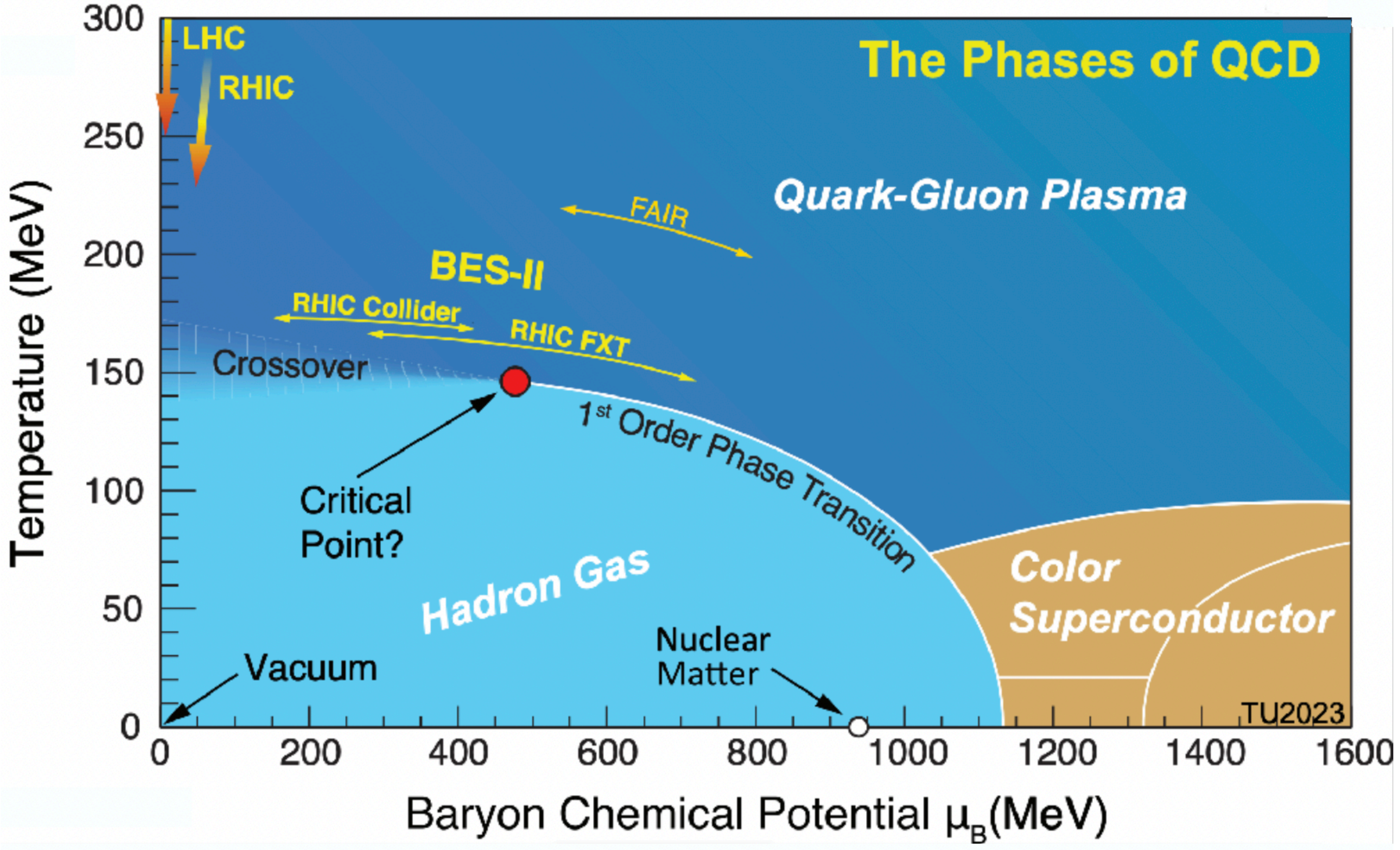
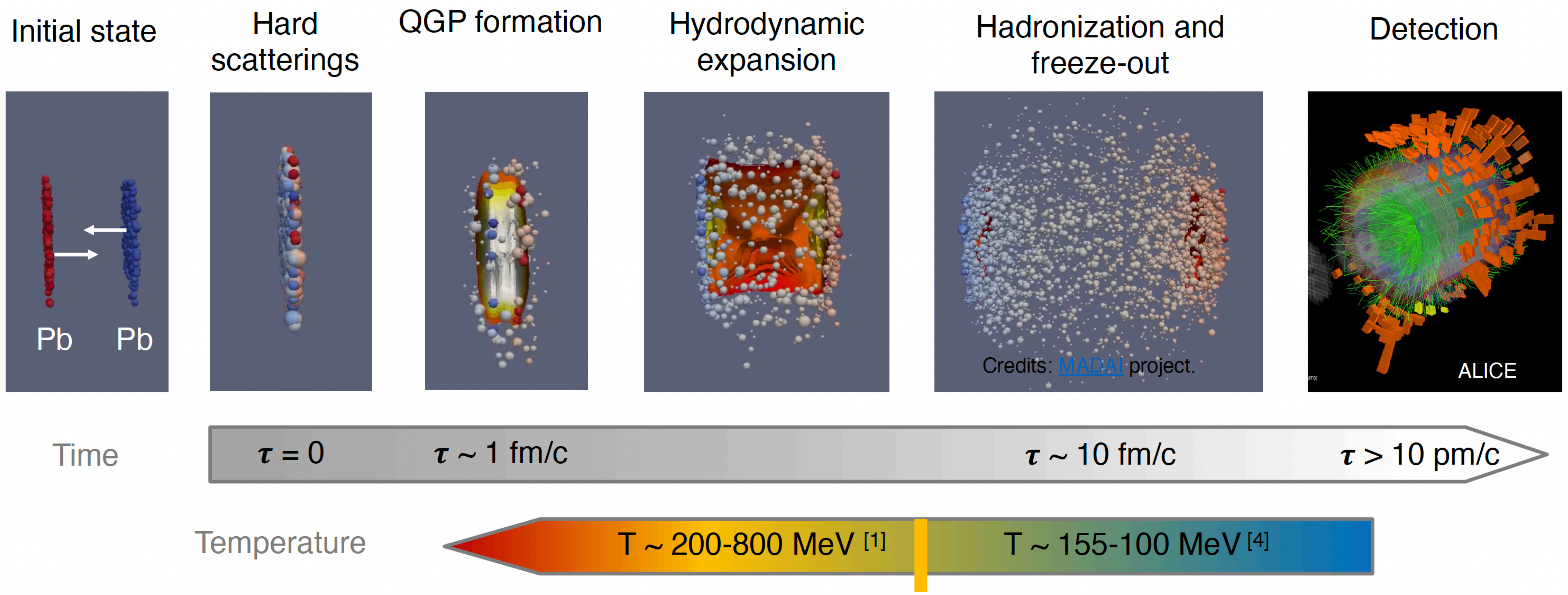


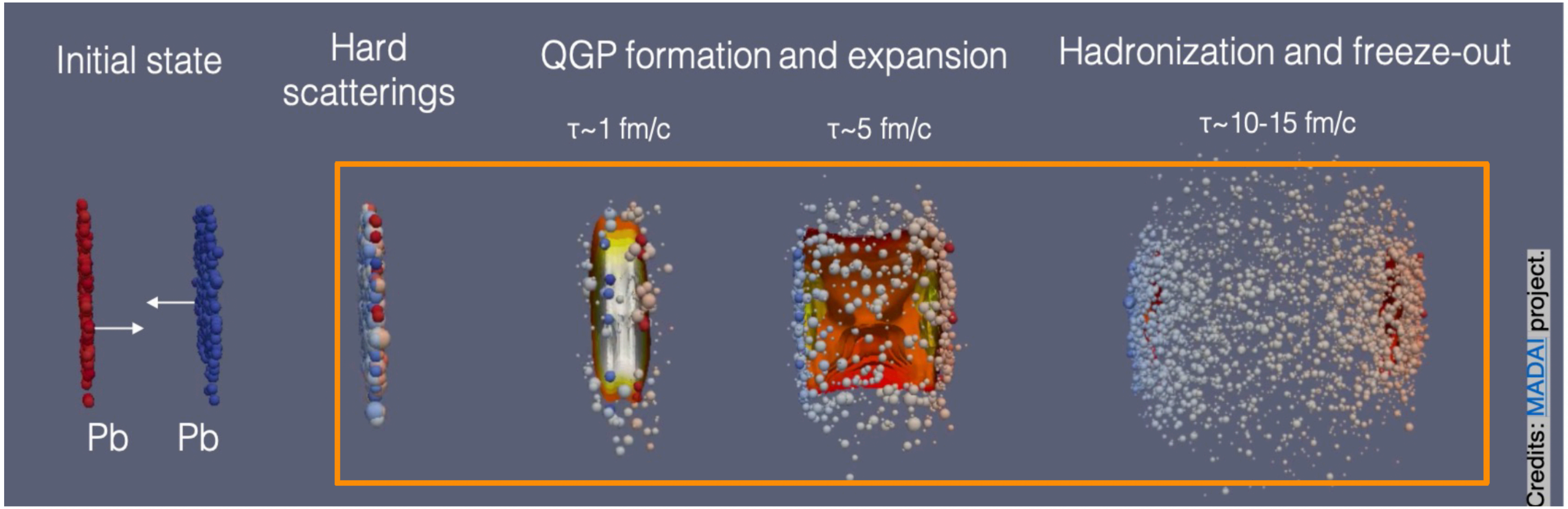
fig. H. Caines



[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

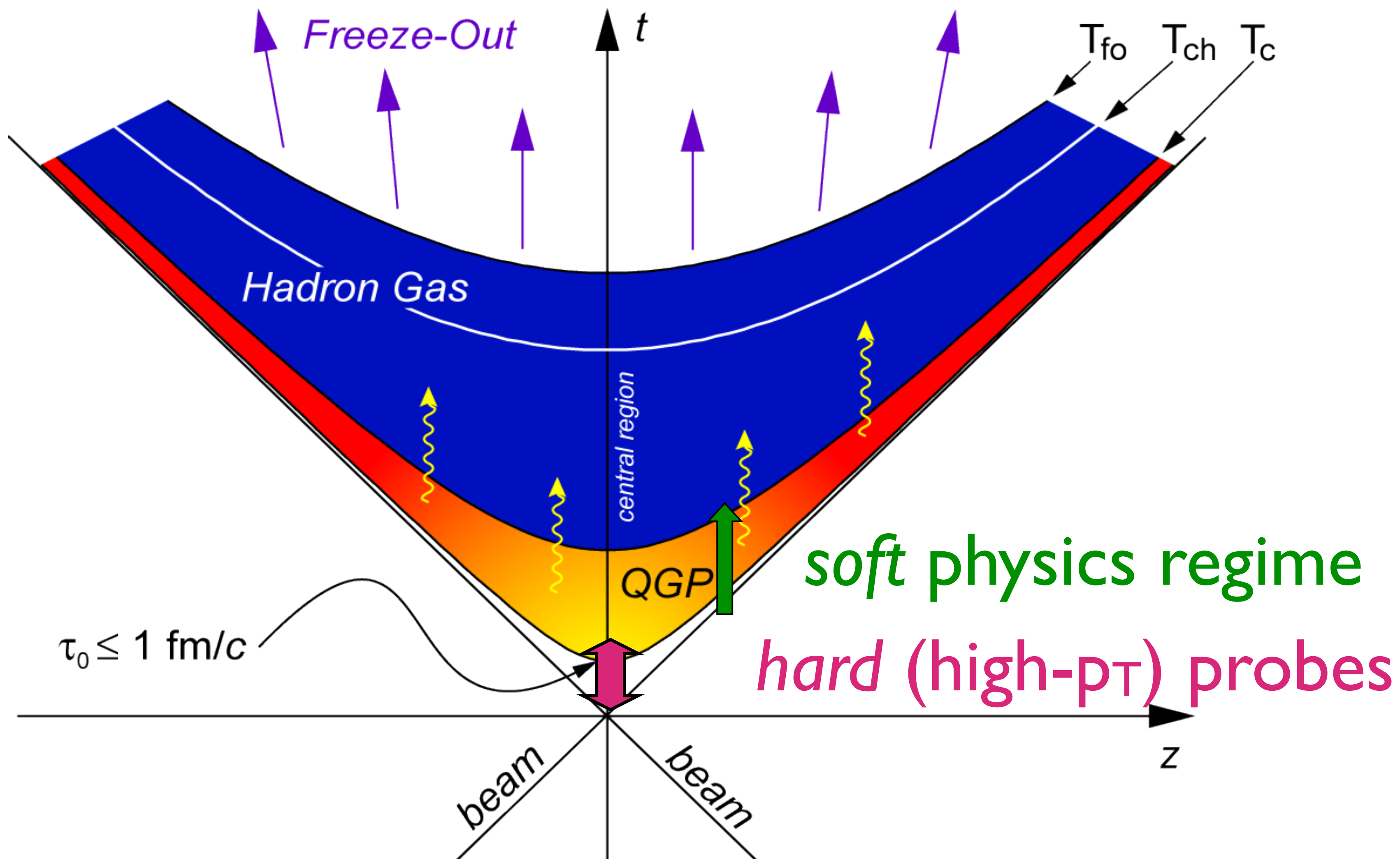
- Phase transition at high temperature or density to deconfined state of quarks and gluons
  - **quark-gluon plasma (QGP)**
- Calculations on the lattice predicts smooth crossover at ~155 MeV at low baryon density
- Created at the LHC at RHIC using **ultra-relativistic heavy-ion collisions**

Probing the QGP

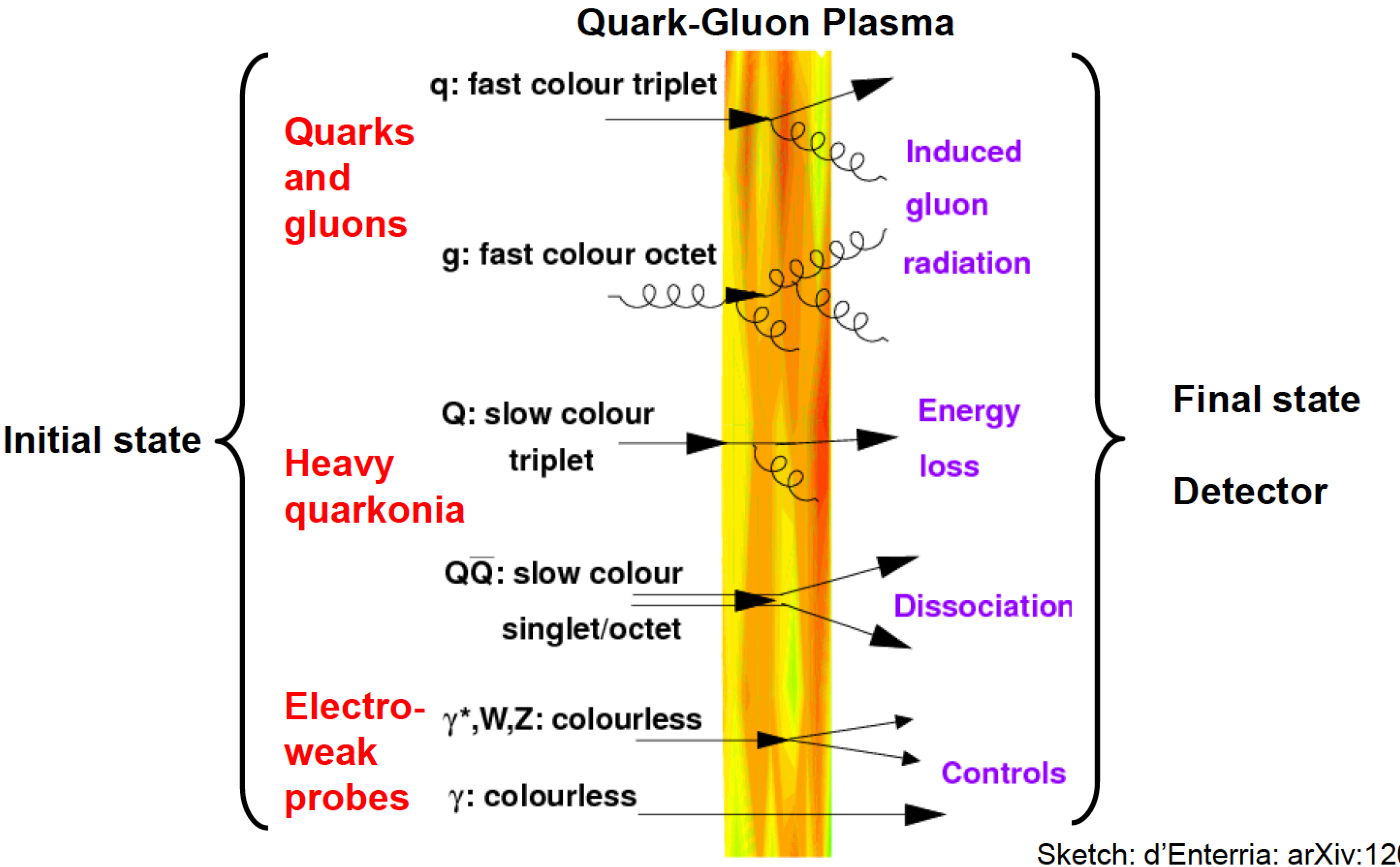


1 fm/c = 3x10^-24 s, 1 MeV ~ 10^10 K

- To probe the QGP, we have many tools in our toolbox
  - hydrodynamic flow
  - hadron chemistry and kinematics
  - electromagnetic radiation from QGP
  - quarkonium disassociation/regeneration
  - partonic interactions with QGP → heavy quarks and jets



Hard probes traverse the QGP



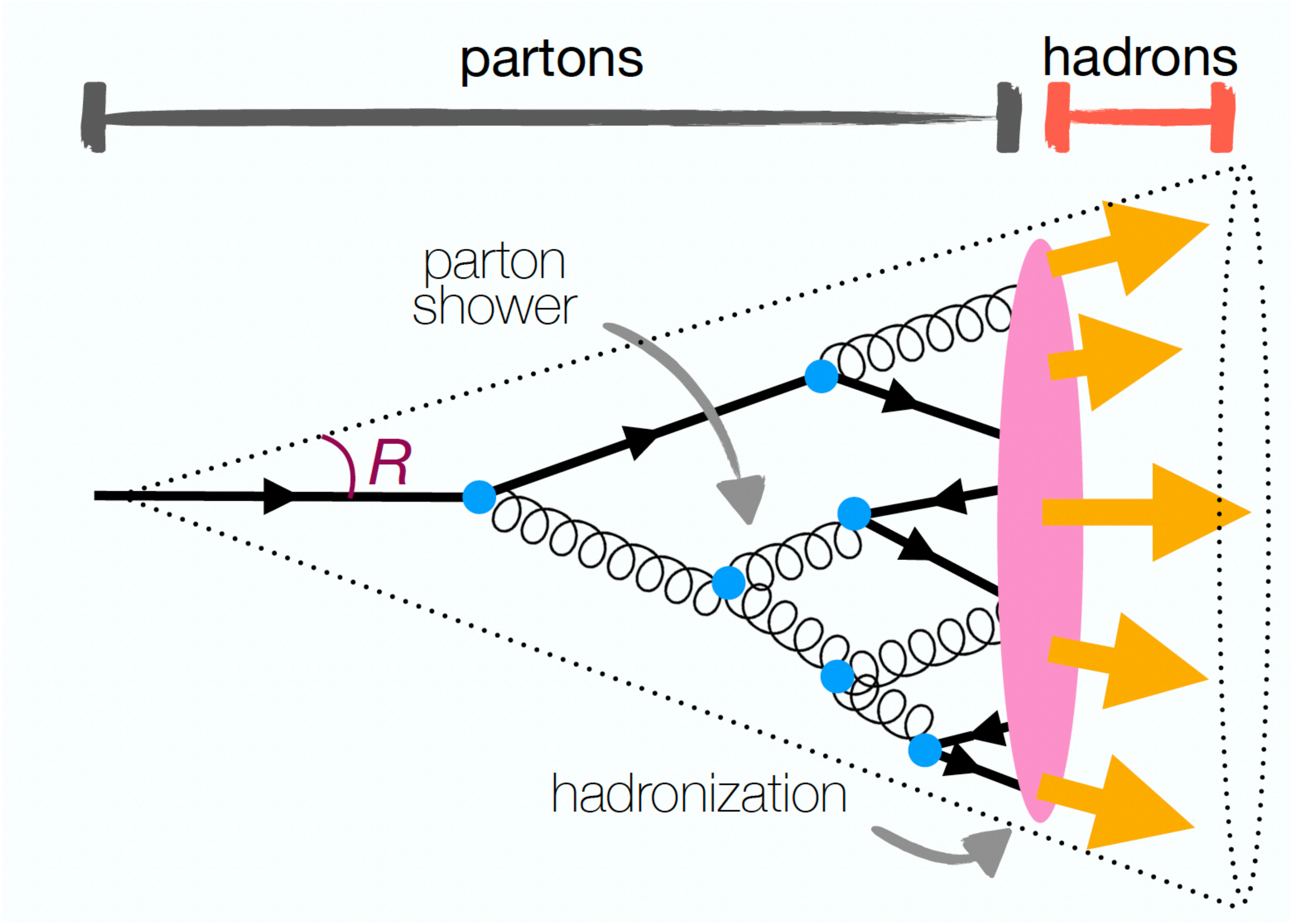
Sketch: d'Enterria: arXiv:1207.4362

The importance of the control measurement(s) cannot be overstated!

Probing QGP with jets

Vacuum fragmentation
(e.g. pp collisions)

Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)



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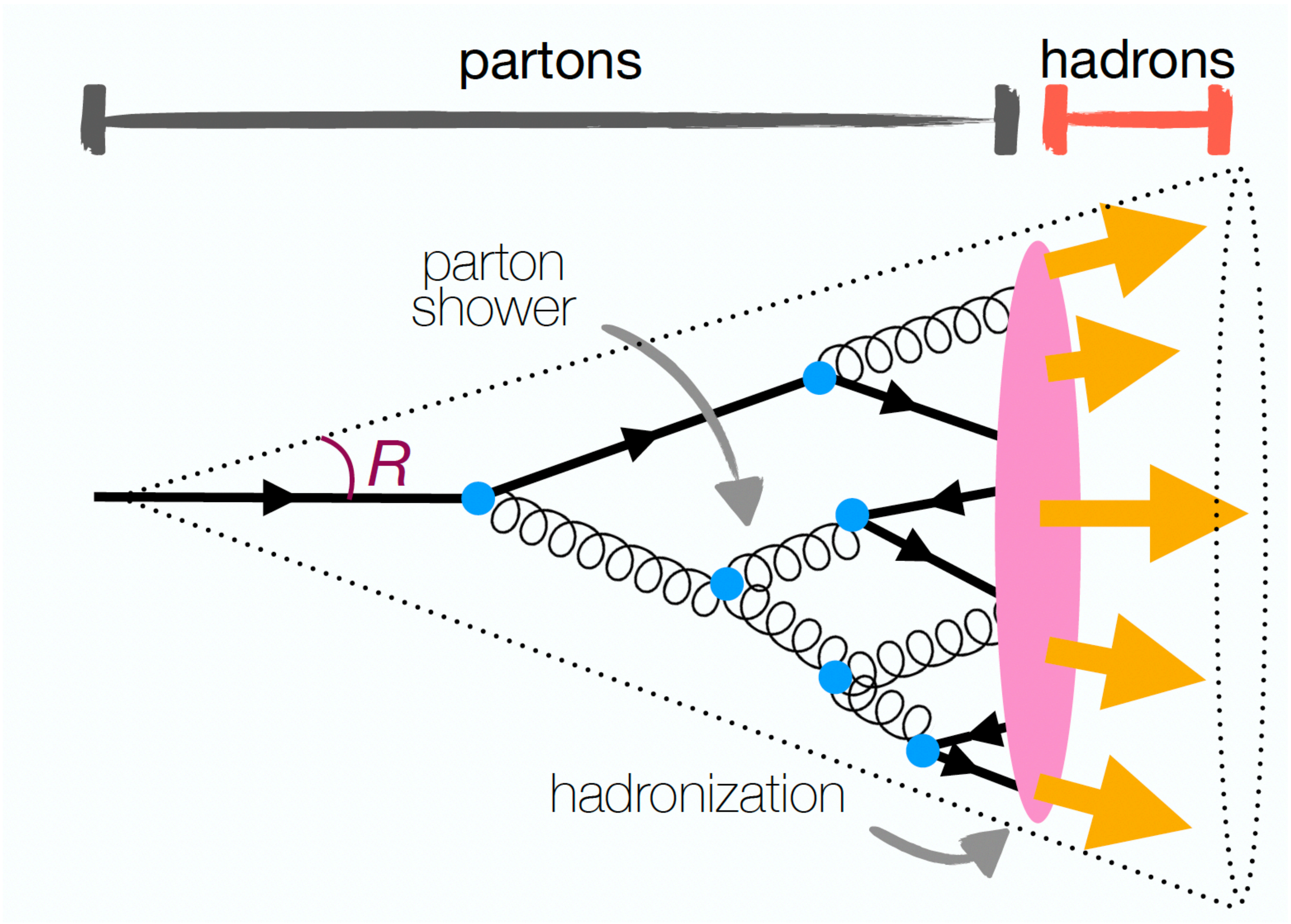
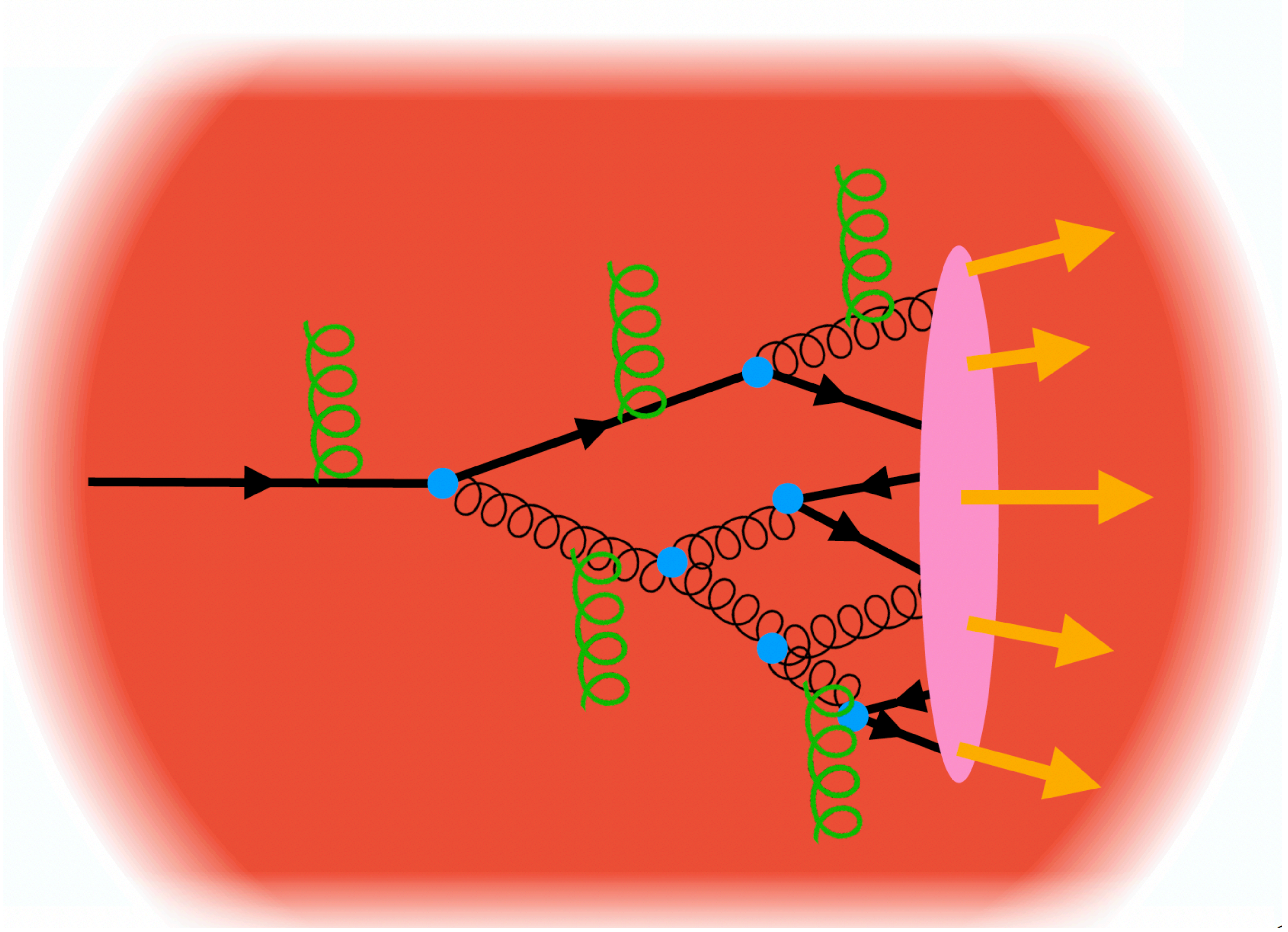


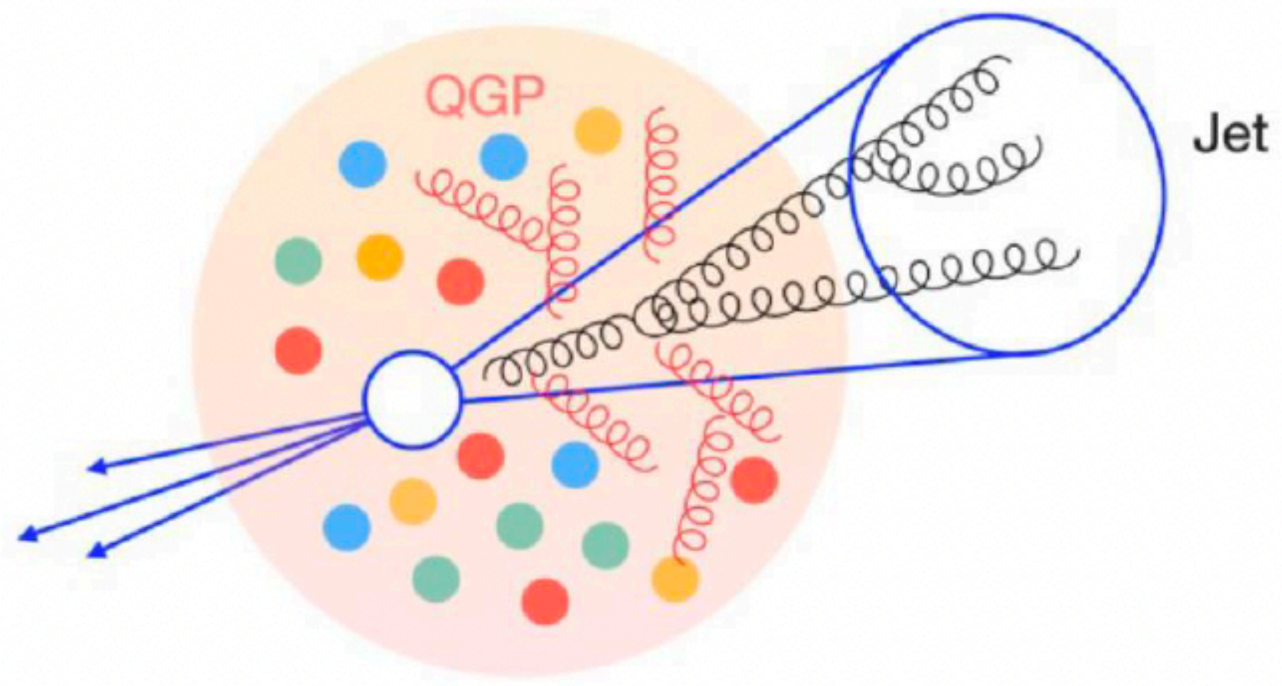
In-medium fragmentation (e.g. Pb-Pb collisions)

Quenching→parton lose energy through medium-induced gluon radiations and collisions with medium constituents



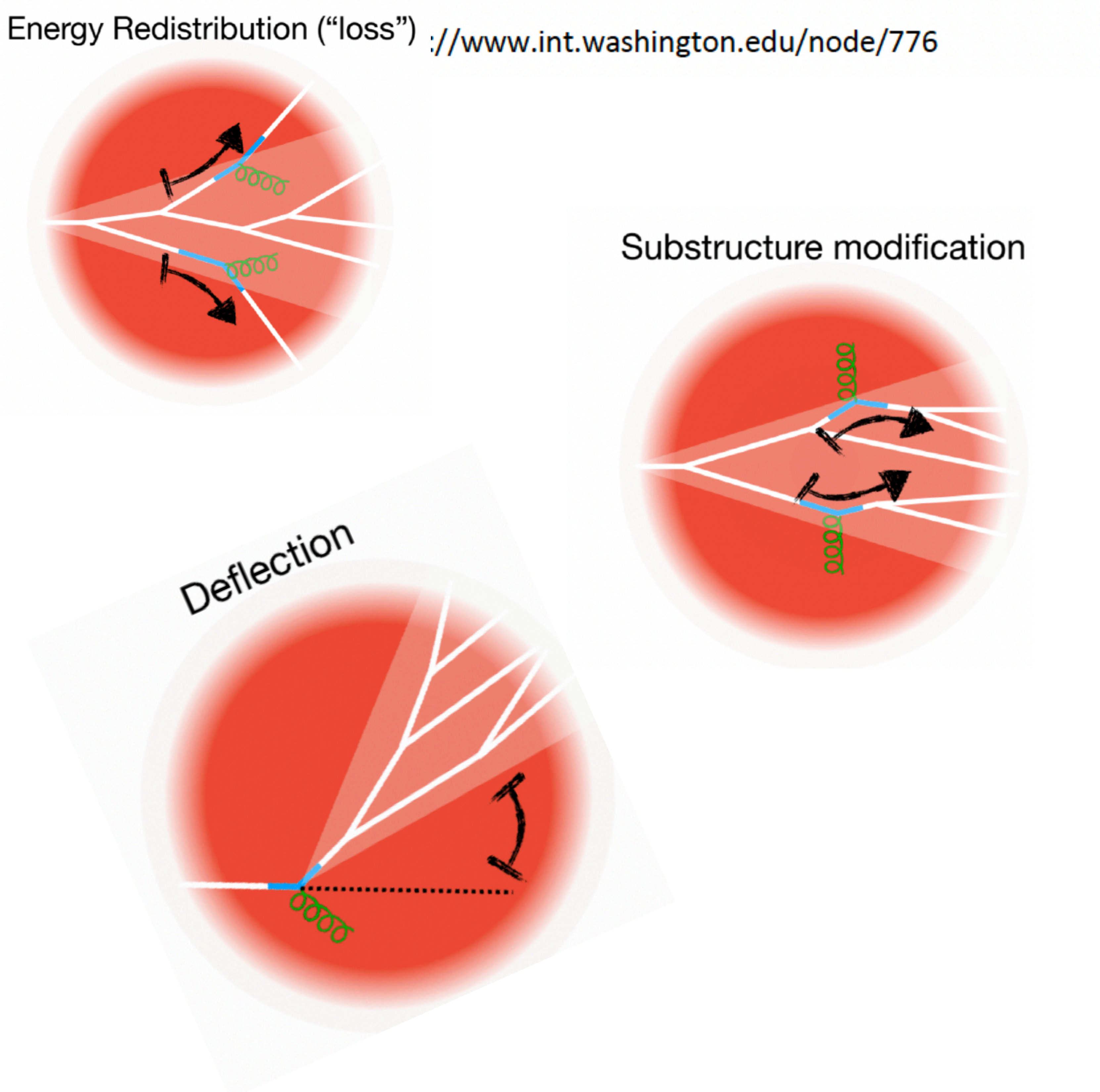
Jets as a probe of the quark-gluon plasma

- Study structure of QGP by understanding jet modification from medium interaction (jet quenching)



- Several types of jet observables
  - Jet yields and constituents → suppression and energy redistribution
  - Jet reconstruction and declustering → jet substructure modification
  - Jet correlations and tagging → angular deflection and asymmetry

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



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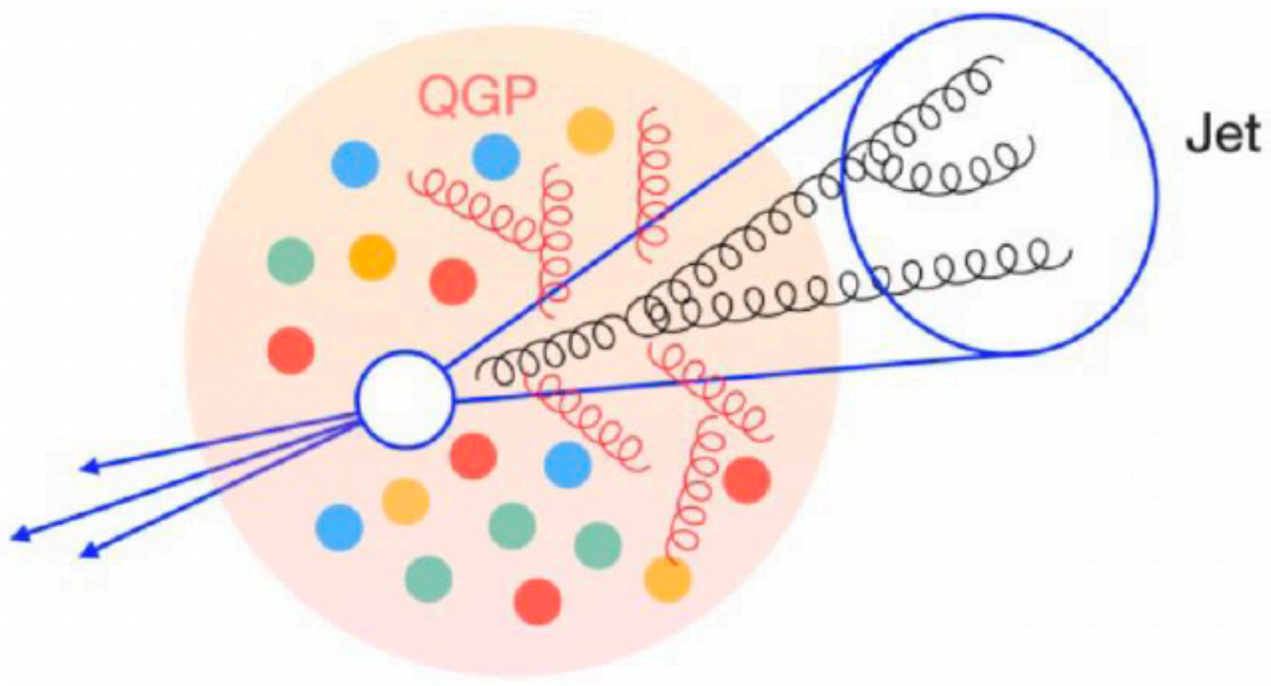

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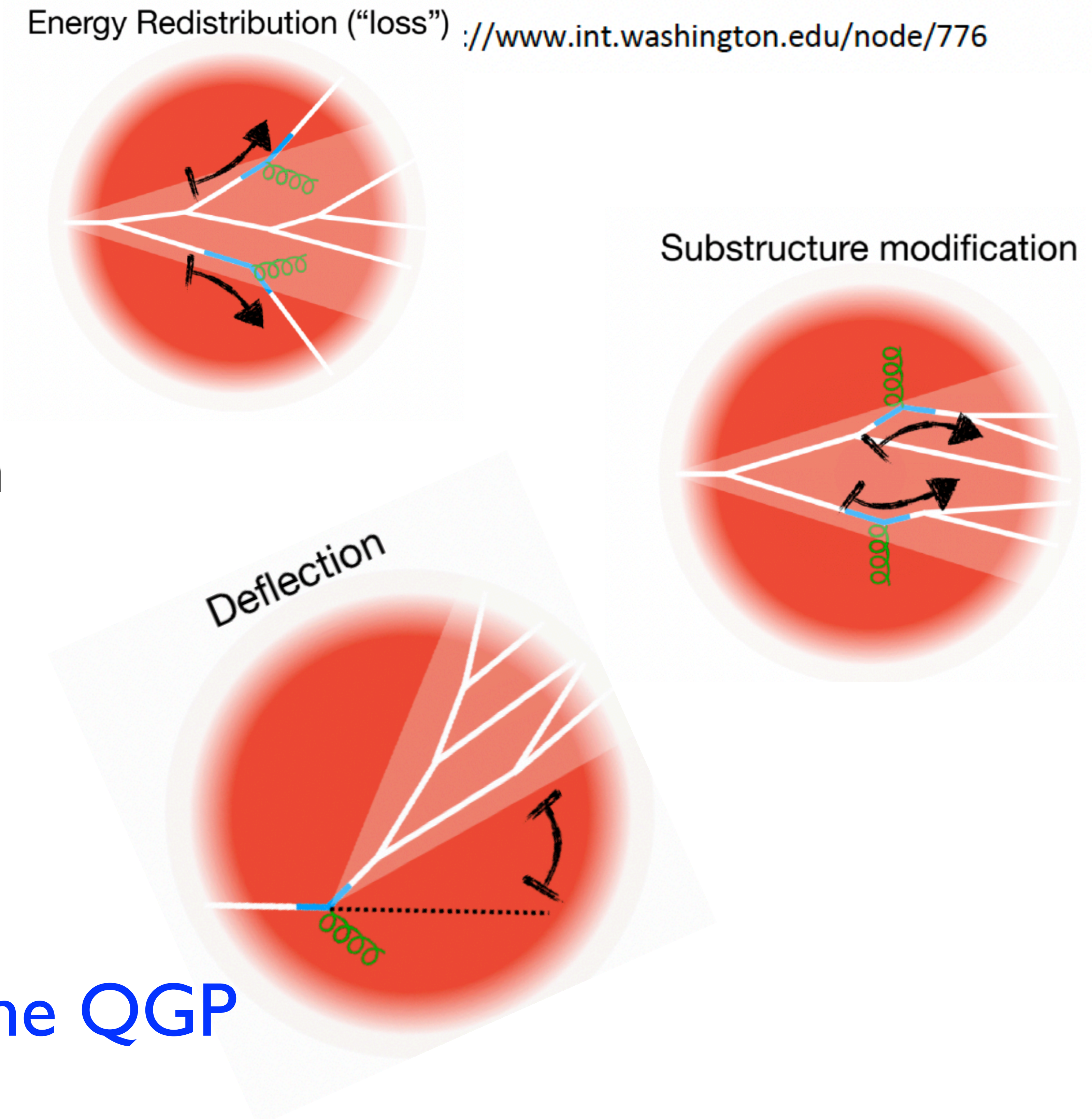
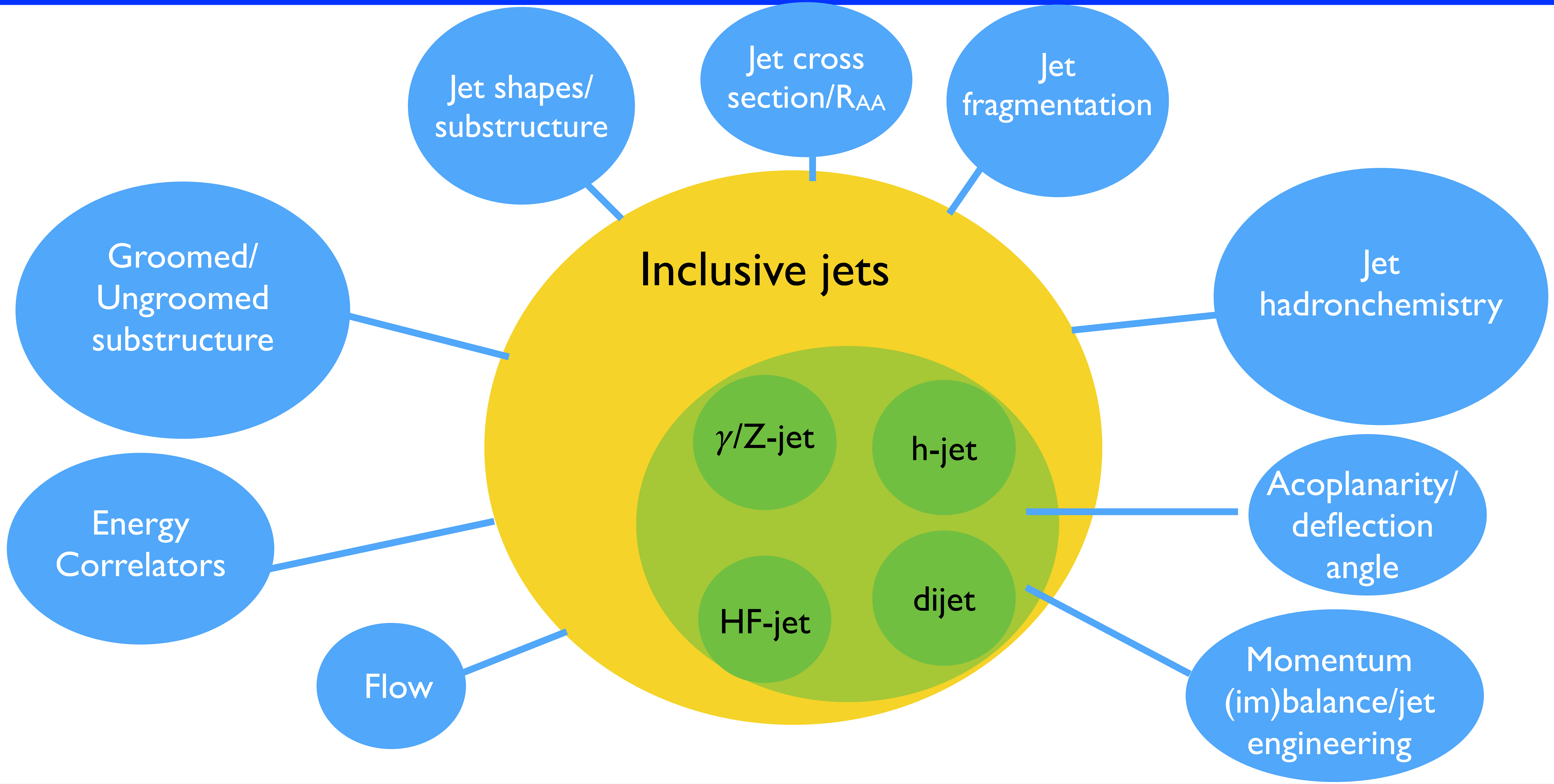


Goal: design observables to disentangle effects and extract properties of the QGP

A (incomplete) roadmap of jet measurements



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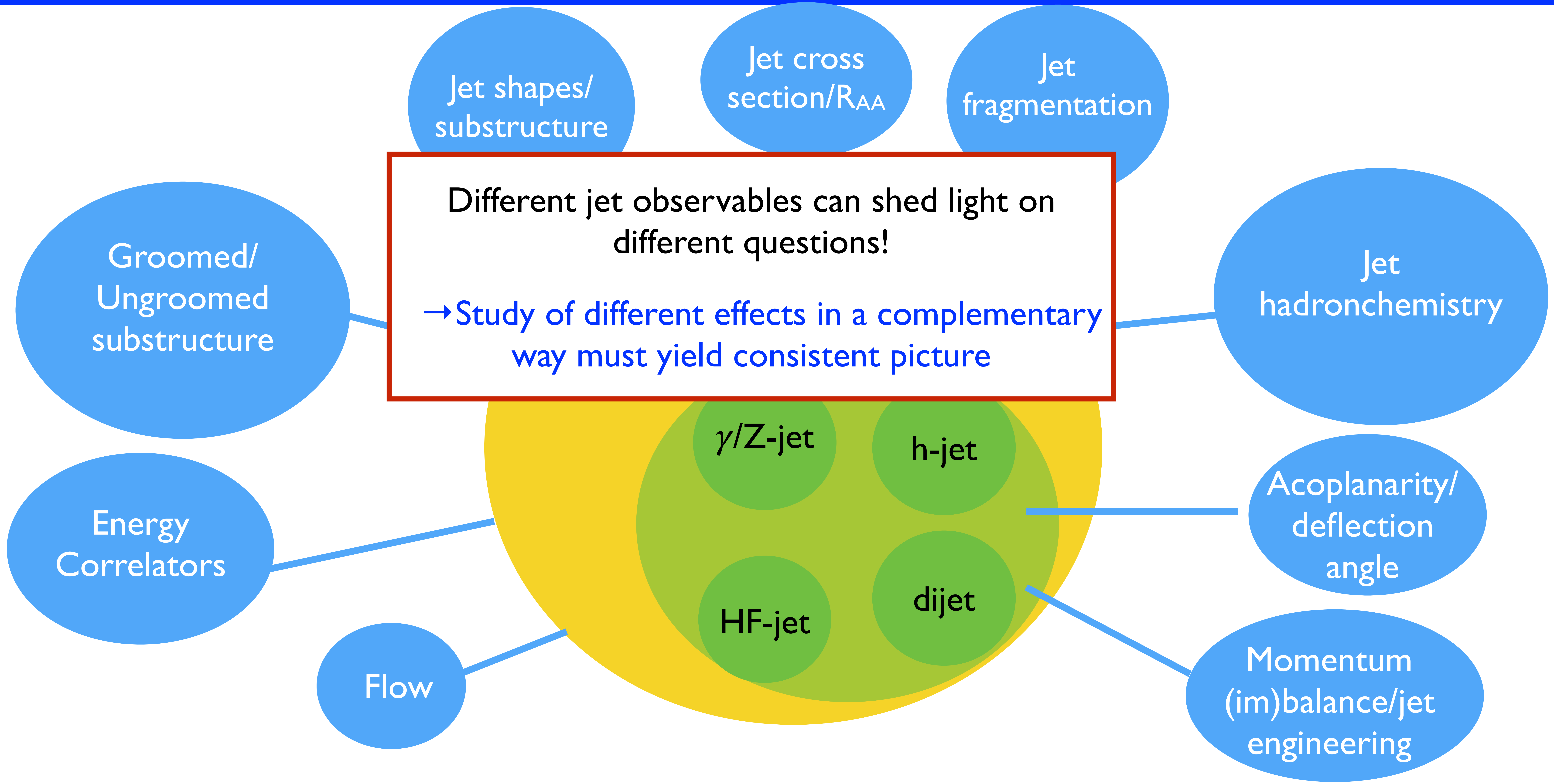
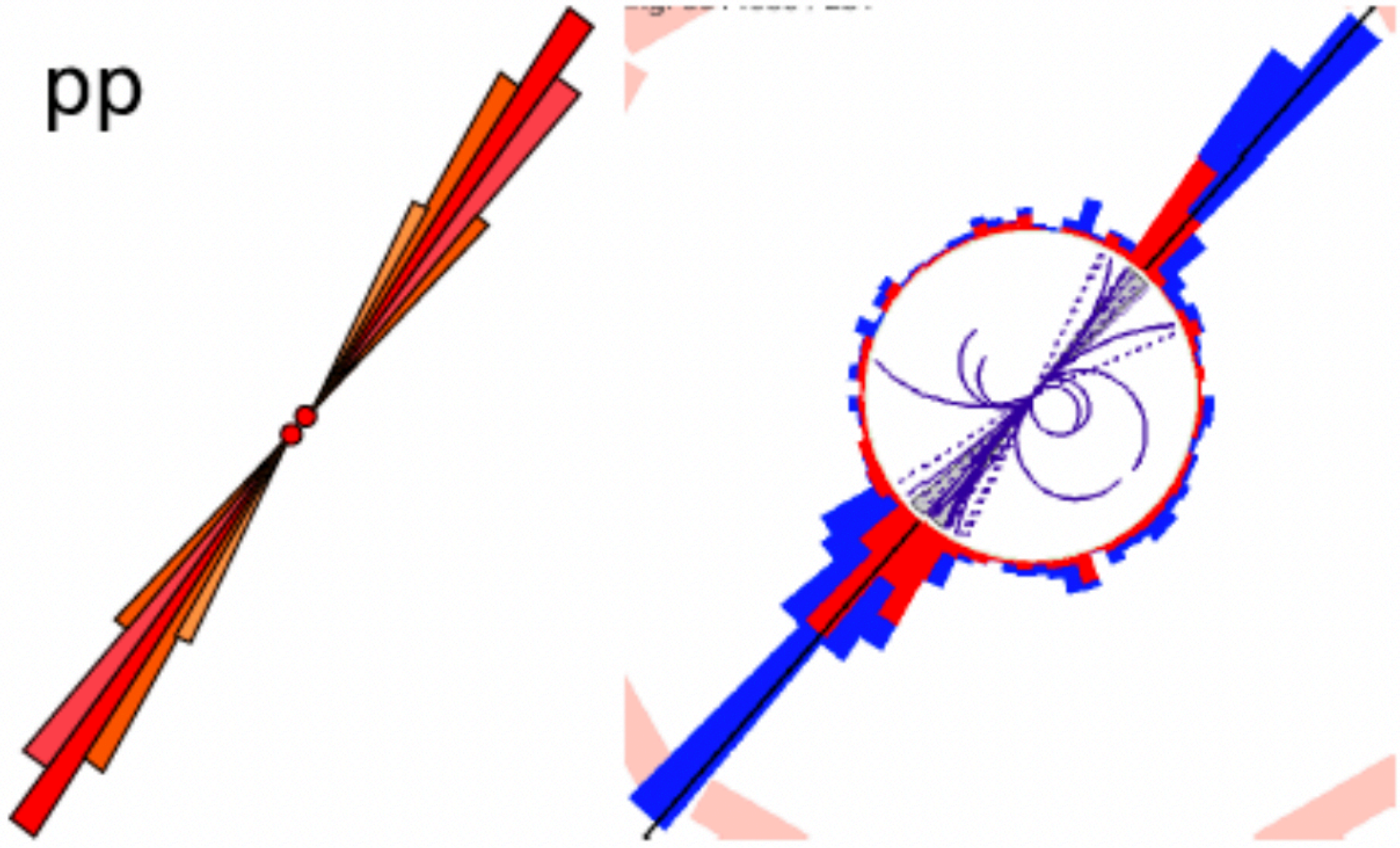


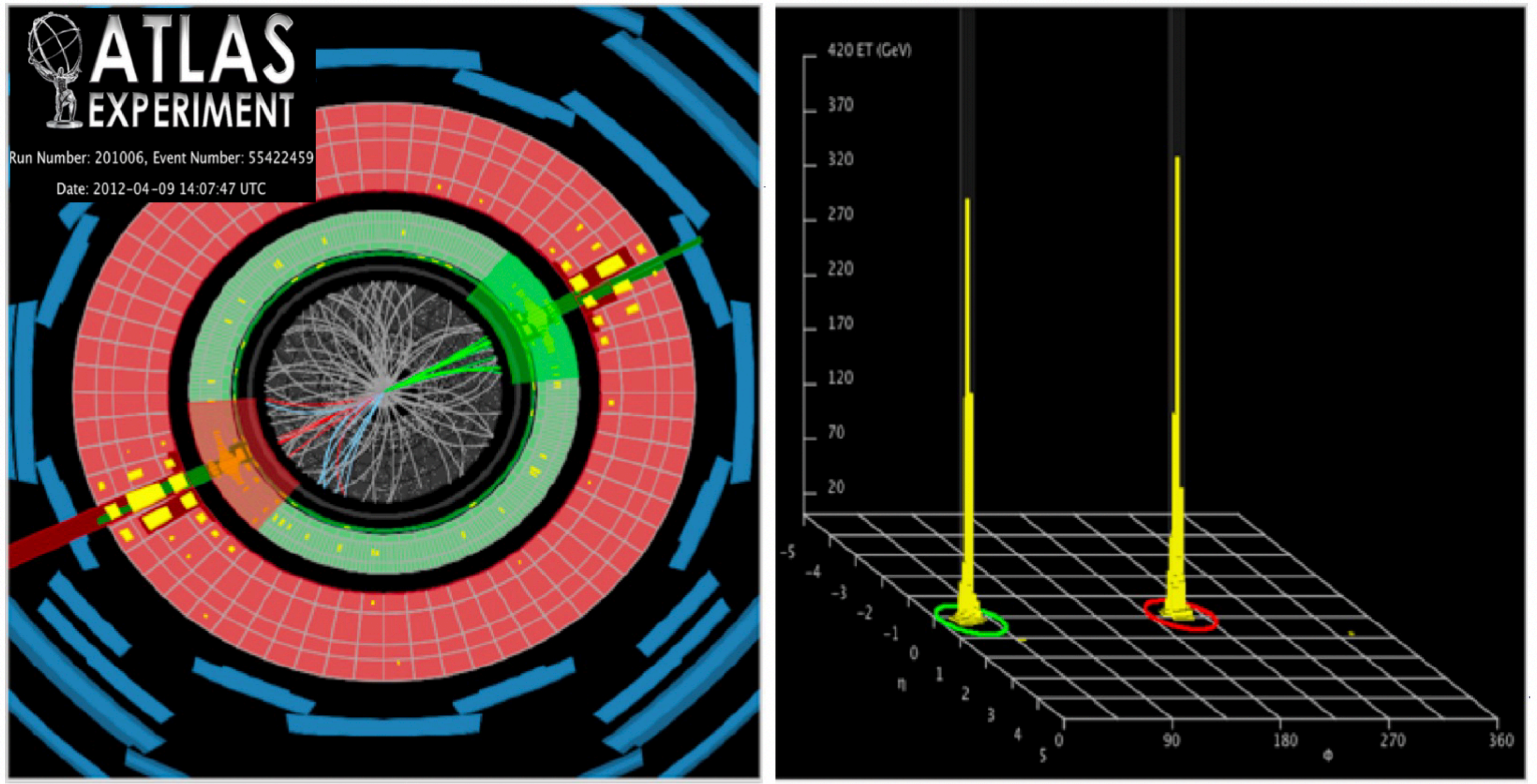
Different jet observables can shed light on different questions!

→Study of different effects in a complementary way must yield consistent picture

In the early stage of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated "sprays" of hadrons

➡ in-vacuum fragmentation



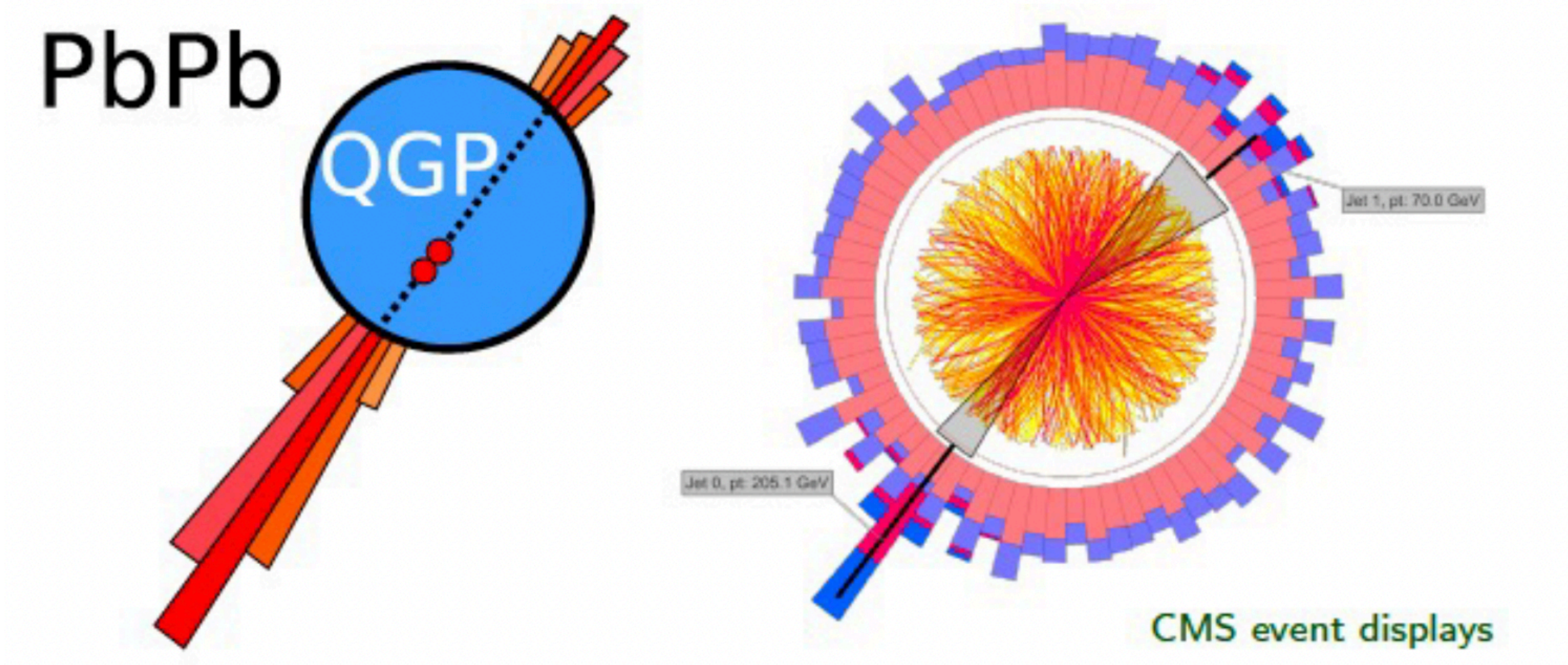


ATLAS, pp collision event display

Jets (in medium)

In the early stage of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated "sprays" of hadrons

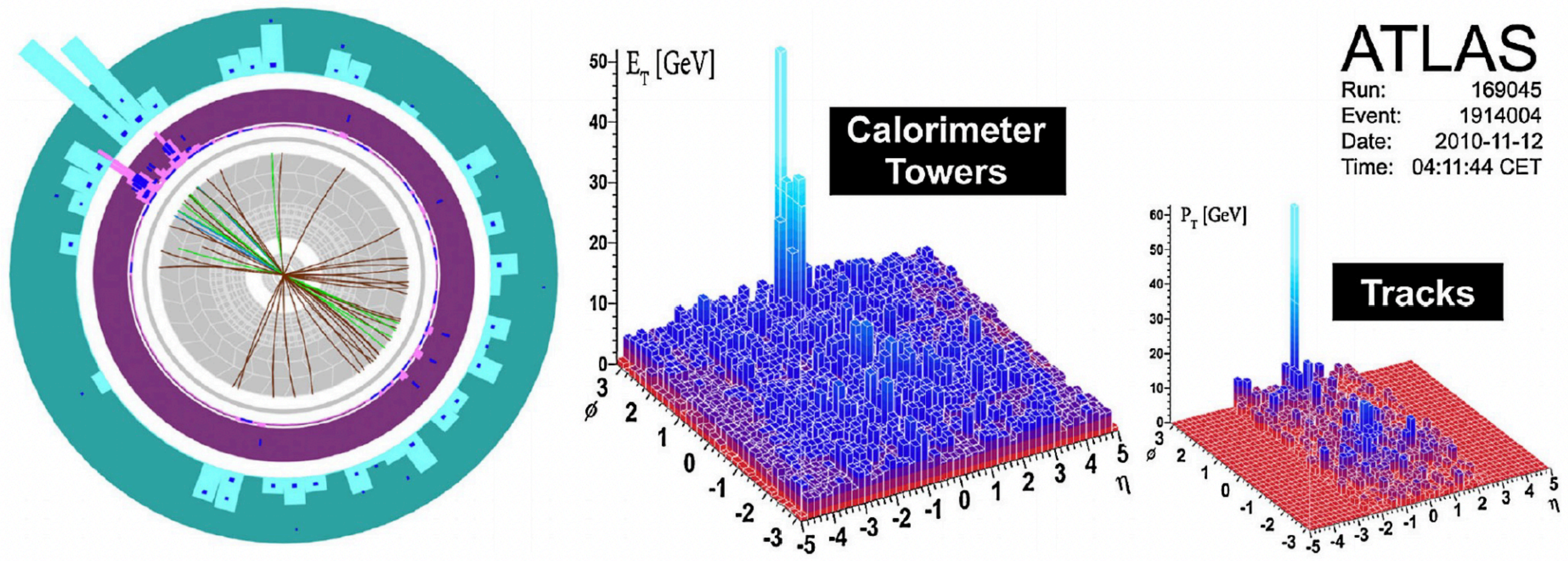
➡ in-vacuum fragmentation



When a QGP is formed, the colored partons traverse and interact with a colored medium

➡ in-medium fragmentation

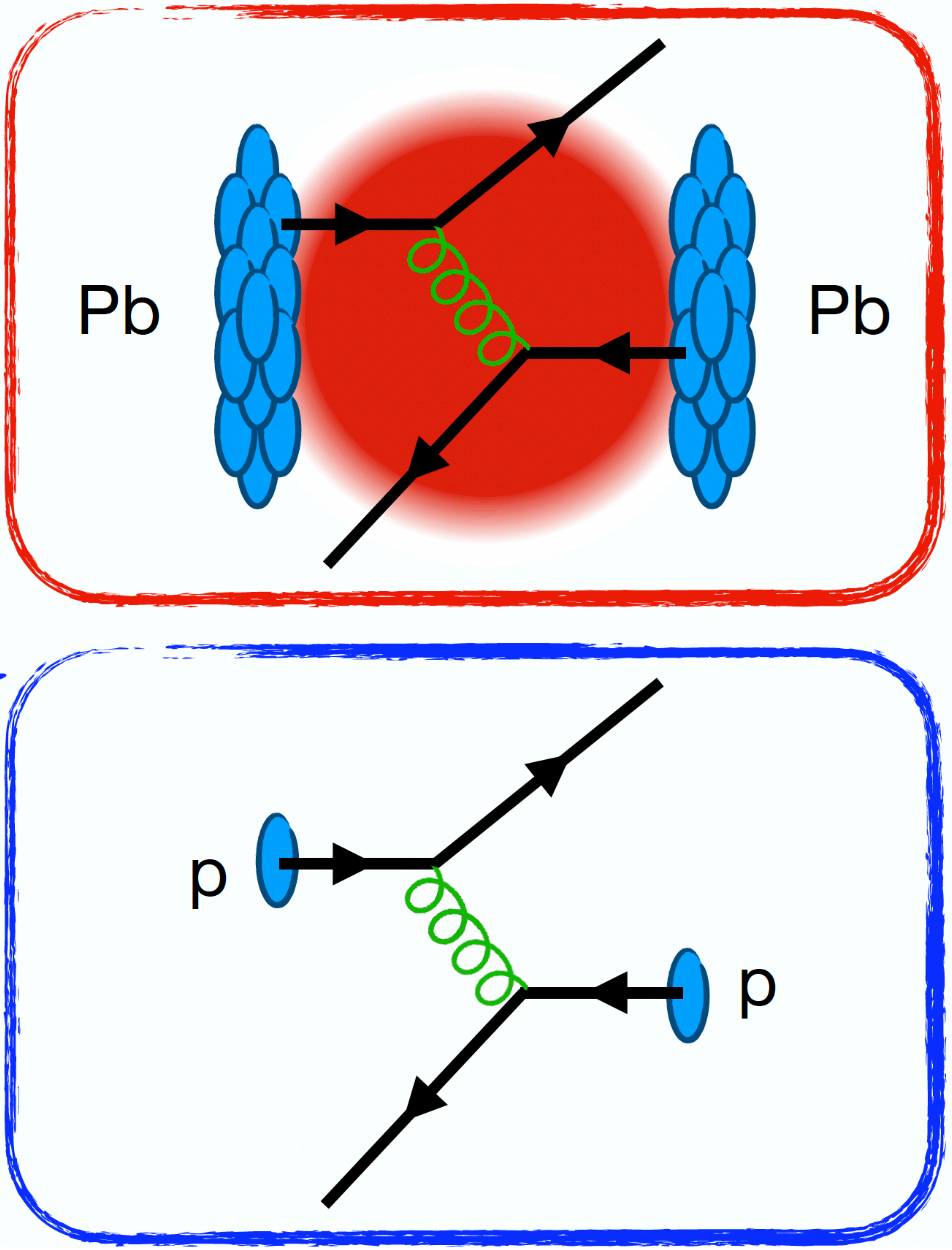
➡ jet "quenching" (energy loss)



Goal: understand the nature of this energy loss to characterize the strongly-interacting QGP

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

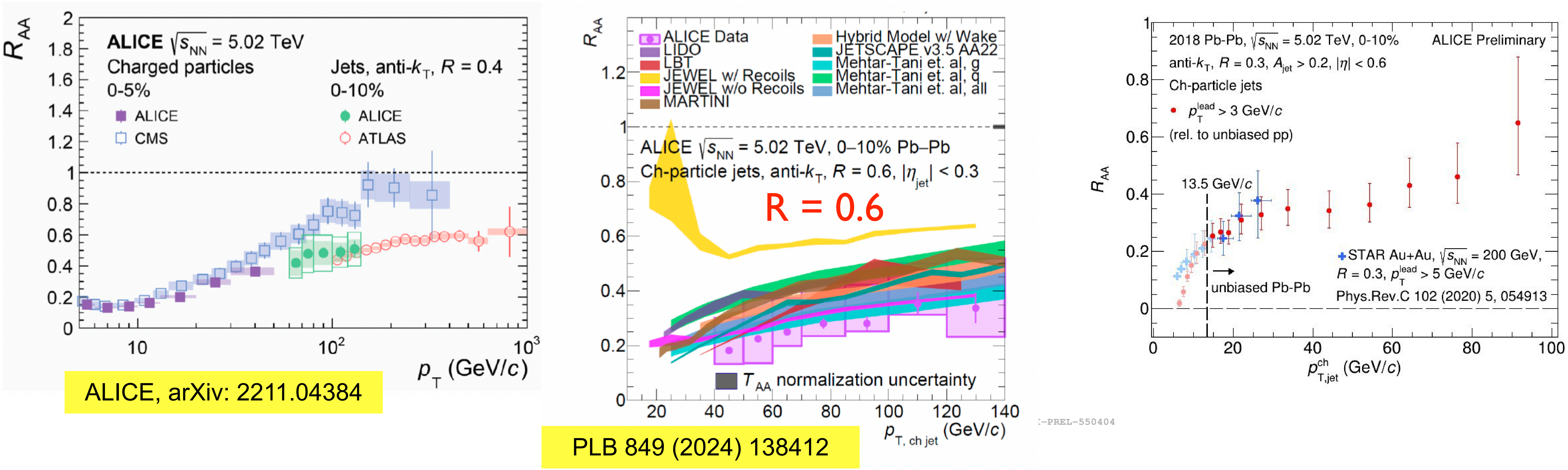


$R_{\mathrm{AA}} > 1$ → enhancement

$R_{\mathrm{AA}} = 1$ → no medium modification

$R_{\mathrm{AA}} < 1$ → supression

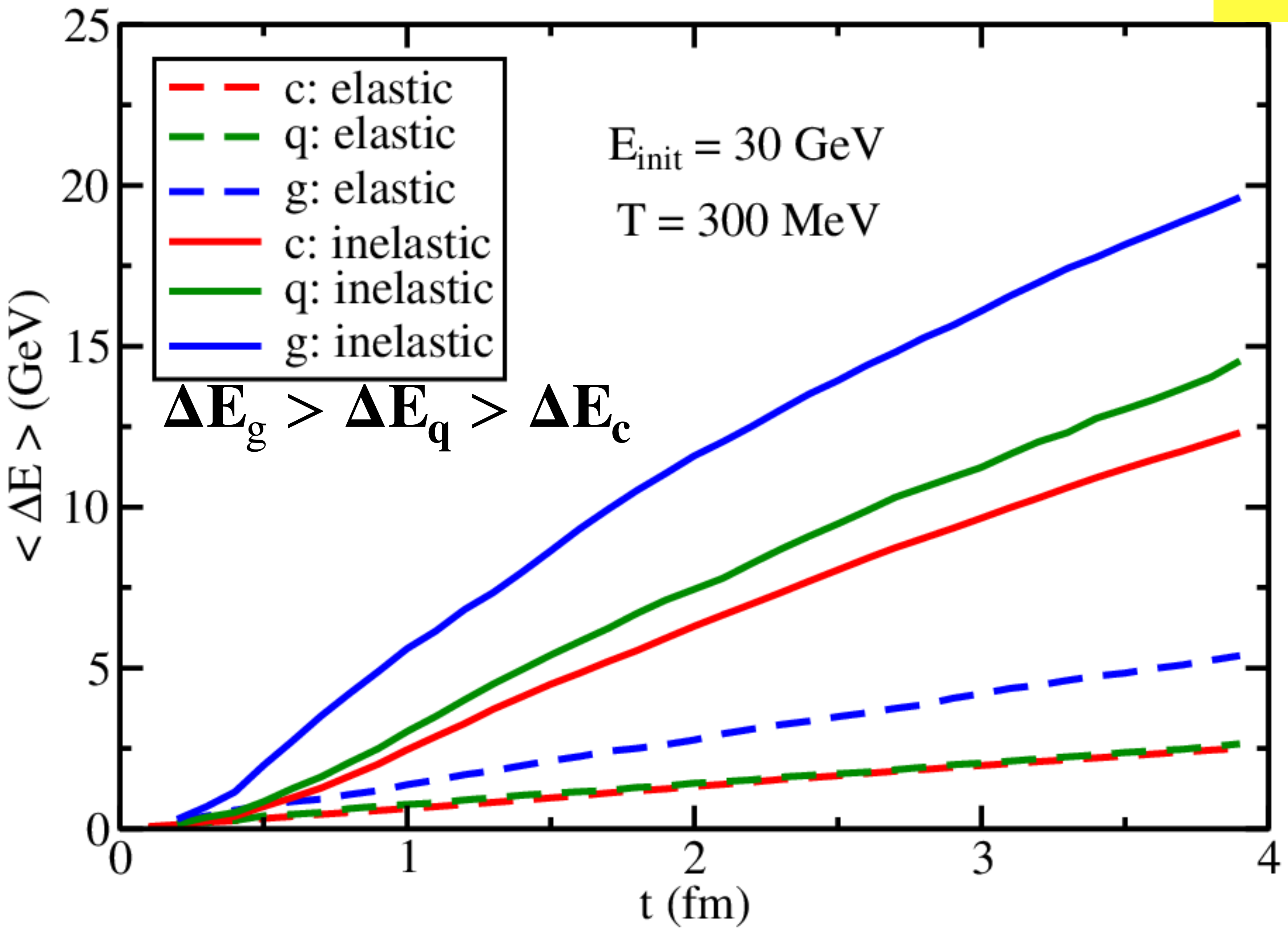
Jet suppression and energy redistribution

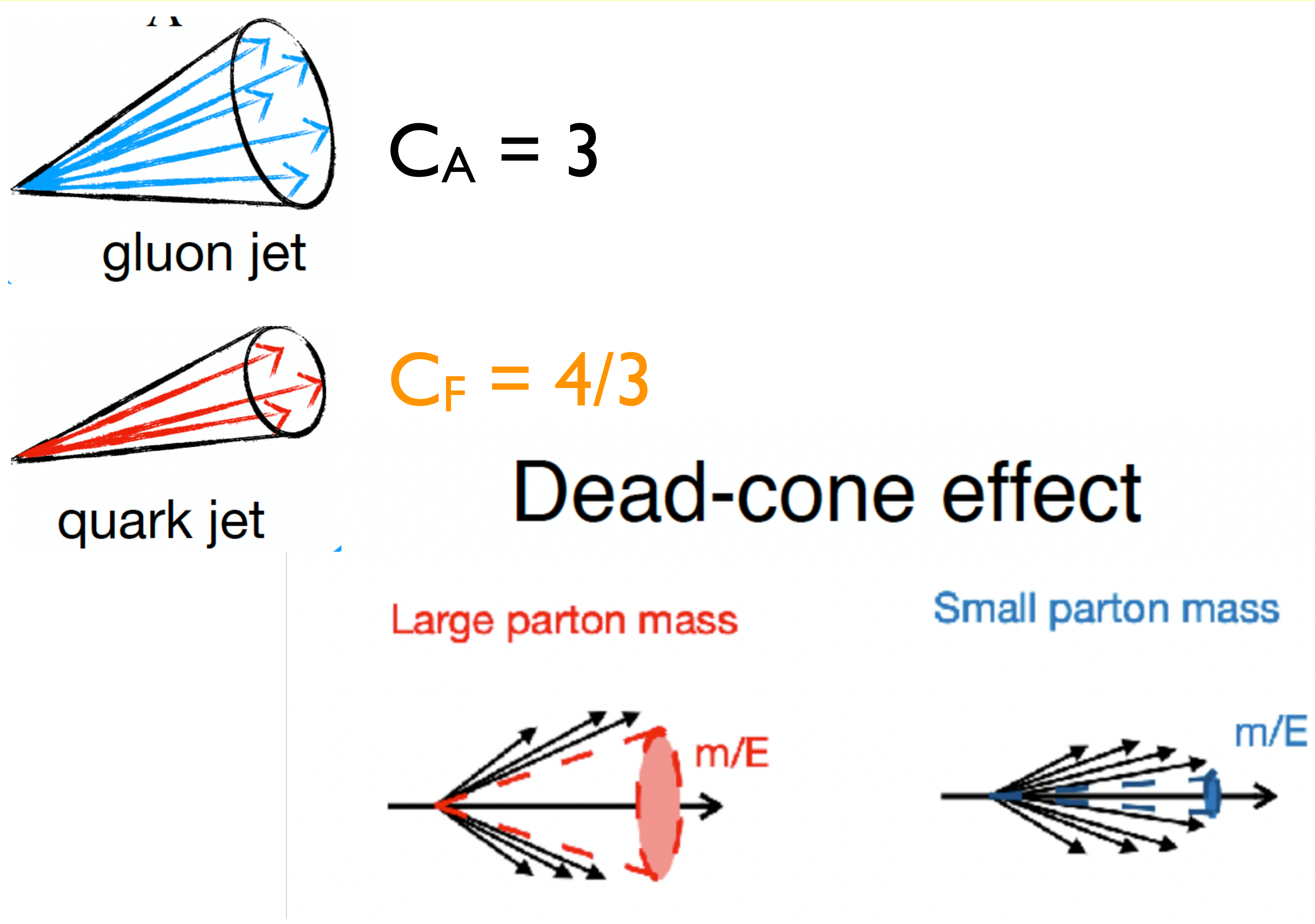


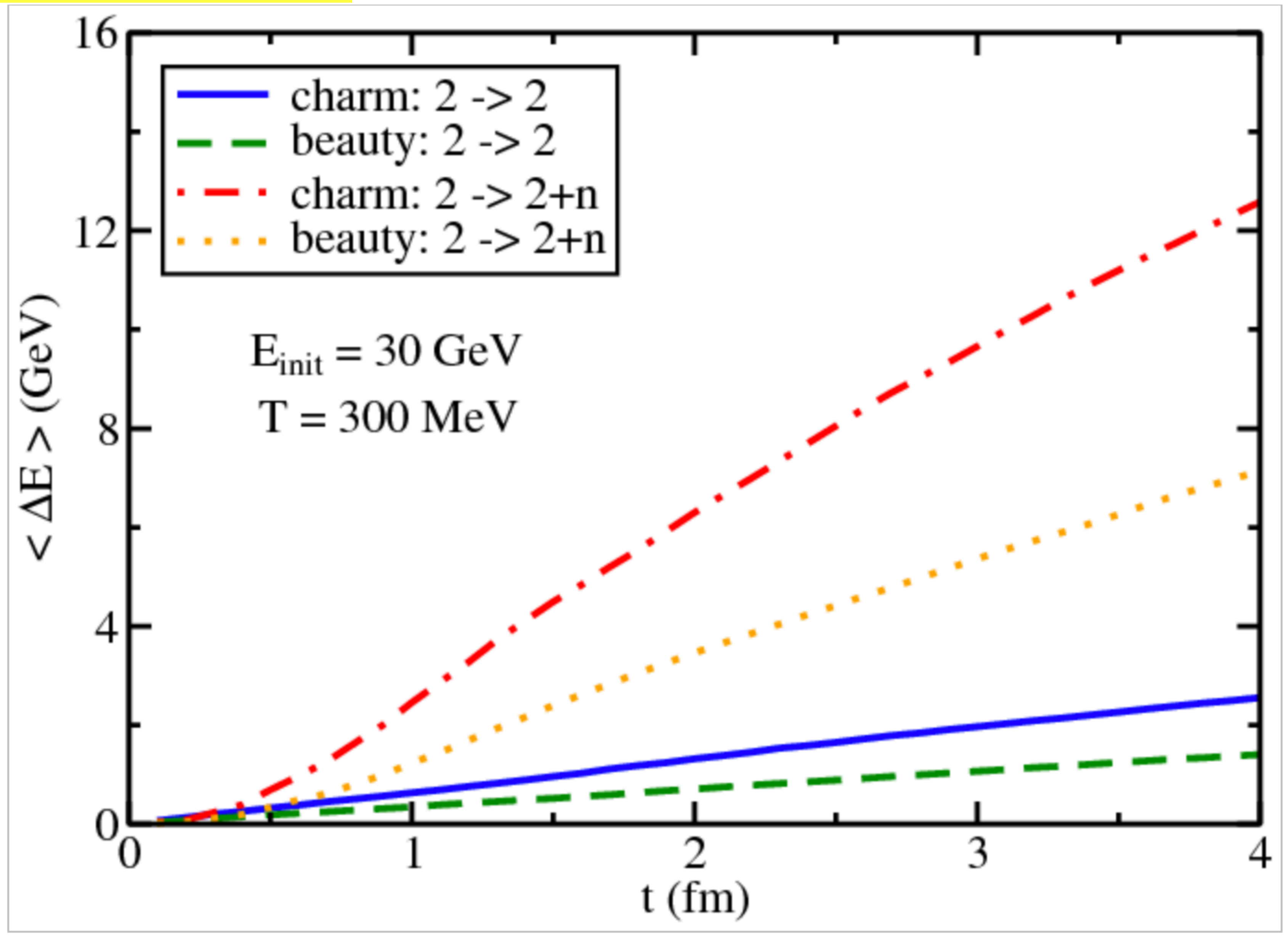
- Jet and high p_T hadron suppression observed over extensive range
  - Interplay between high p_T and jet results
- New ML&ME techniques allow for the extension to lower jet p_T and large R
  - Allows for an overlapping regime between RHIC and LHC

Flavor dependence of parton energy loss

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

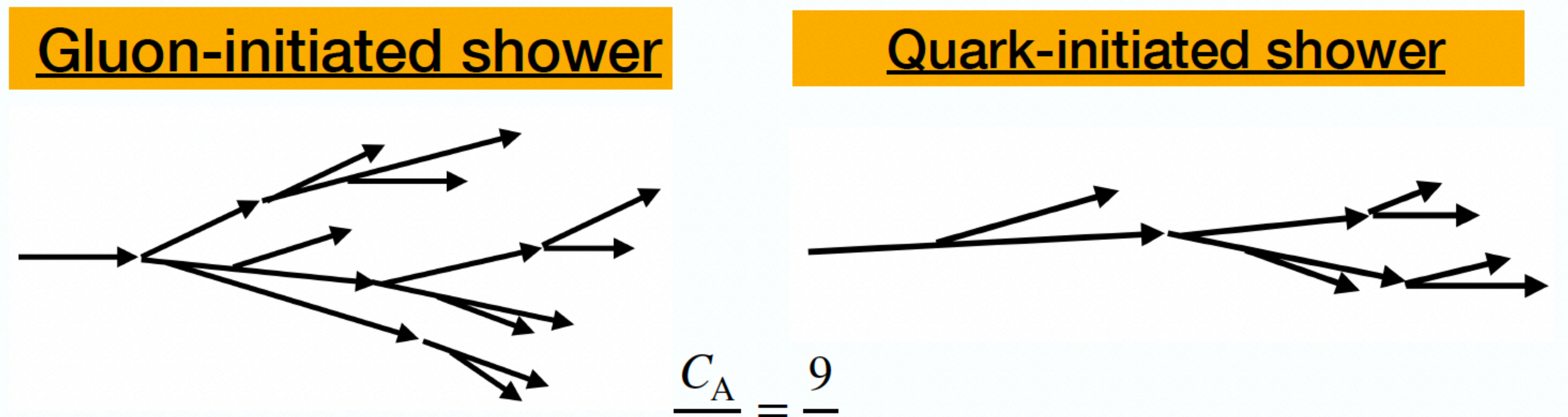






- Flavor dependence involves: a) color charge differences; b) mass dependence
- Flavor dependence of energy loss: $E_{\rm loss}^{\rm gluon} > E_{\rm loss}^{\rm light-quark} > E_{\rm loss}^{c} > E_{\rm loss}^{b}$

Energy loss dependence on parton flavor/mass



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

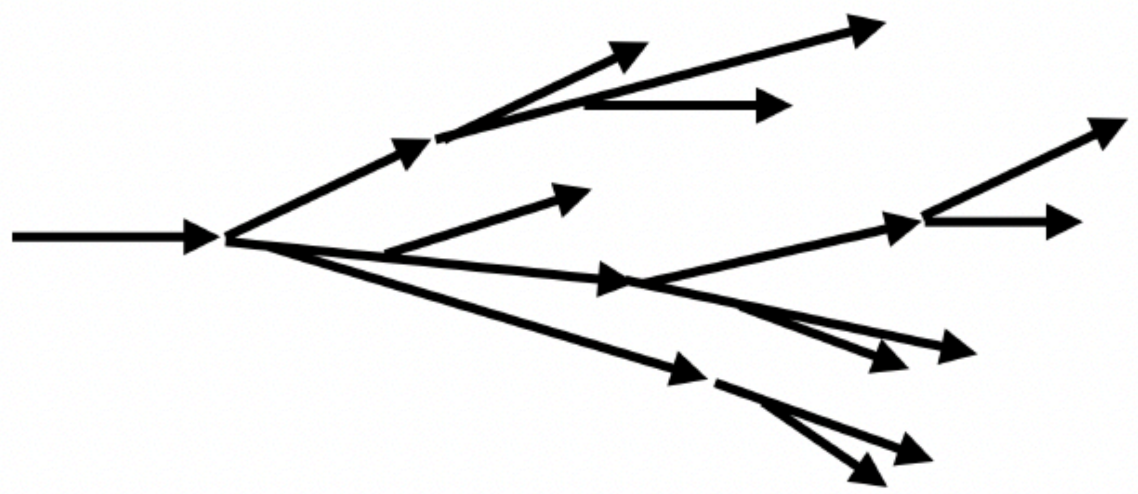
Casimir color factors

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

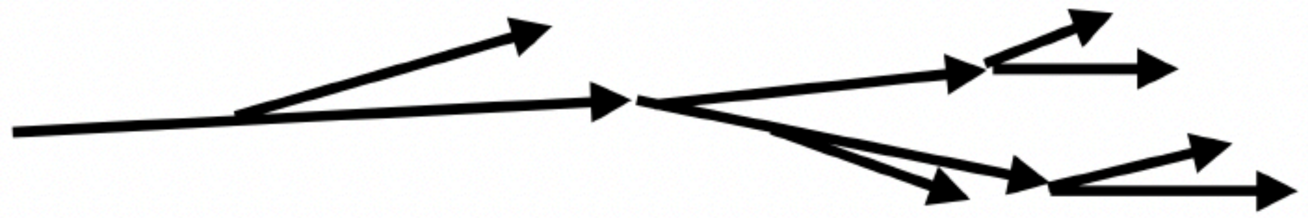
- Color charge dependence of energy loss: $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{quark}}$

Energy loss dependence on parton flavor/mass

Gluon-initiated shower



Quark-initiated shower



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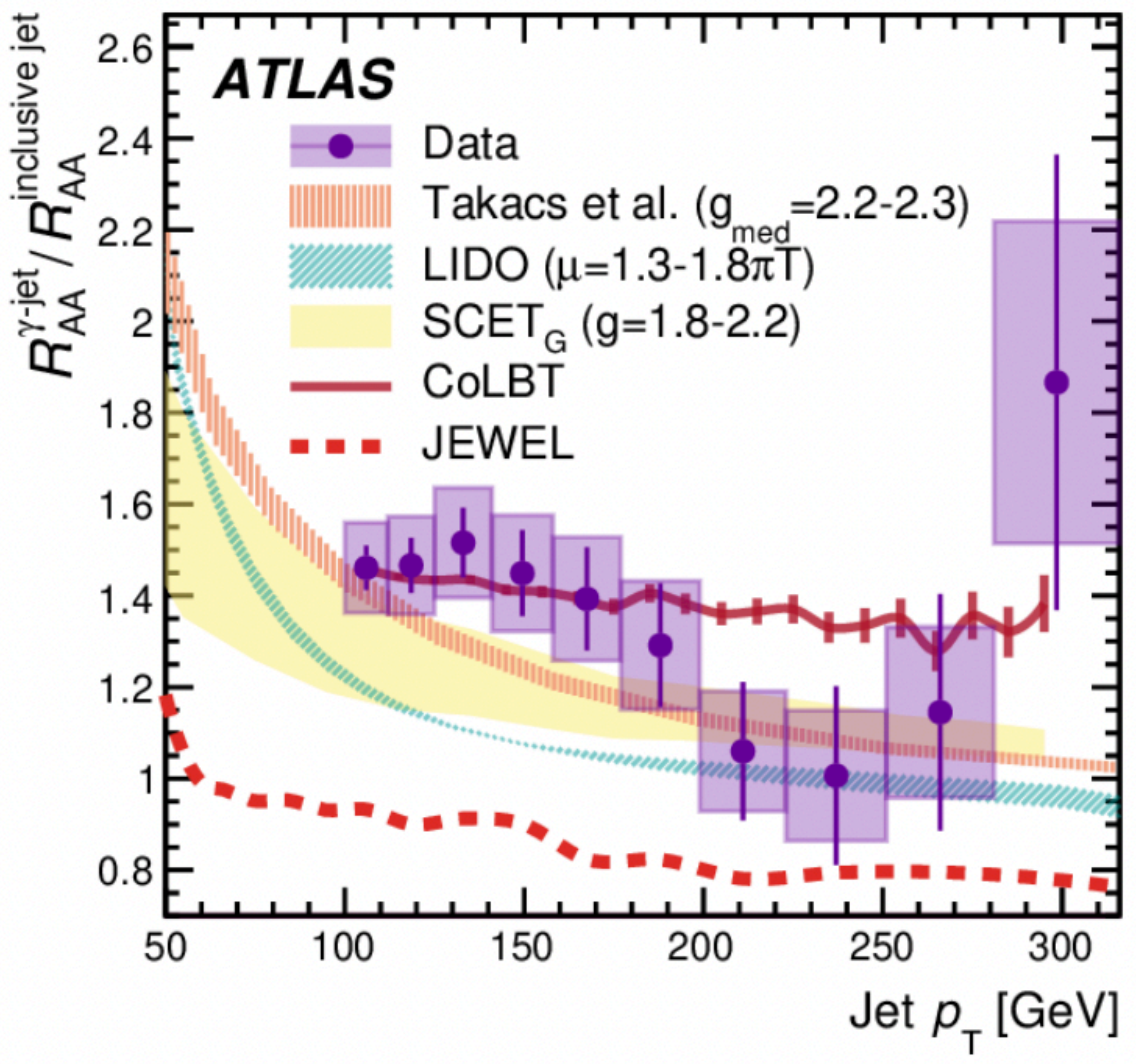
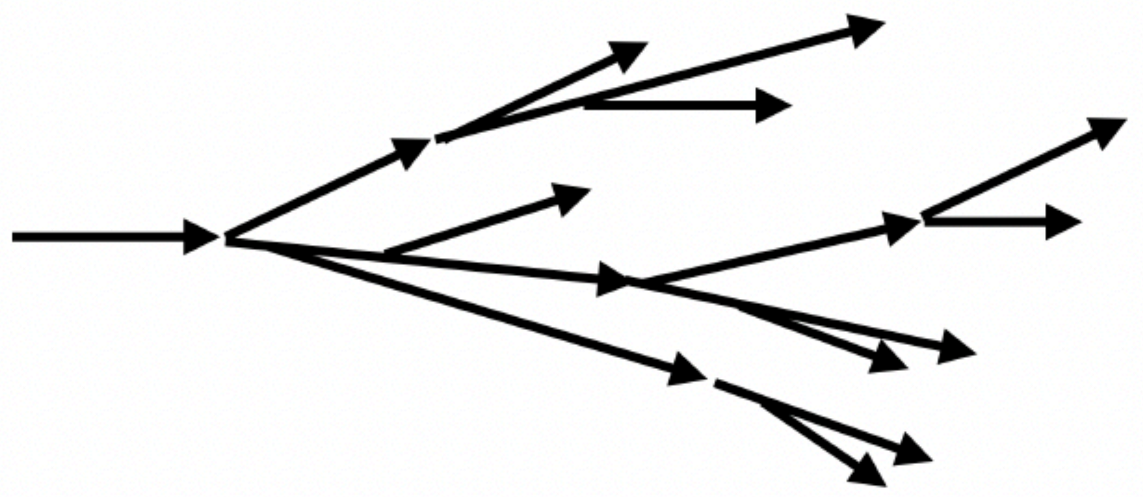
Phys. Lett. B 846 (2023) 138154



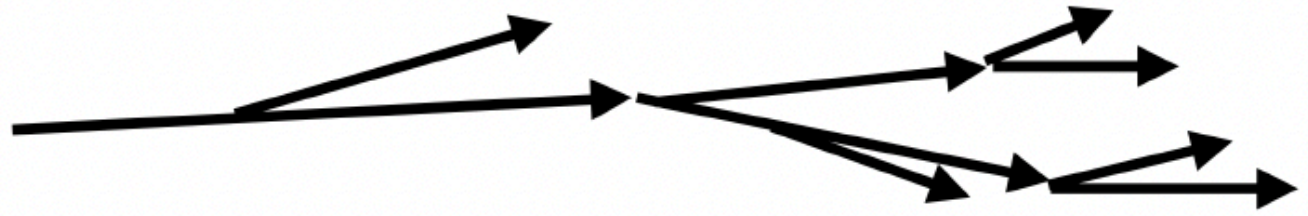
- Color charge dependence of energy loss: $E_{\text{loss}}^{\text{gluon}} > E_{\text{loss}}^{\text{quark}}$
- γ-tagged (quark enriched) jets are less suppressed than inclusive (gluon dominated) jets

Energy loss dependence on parton flavor/mass

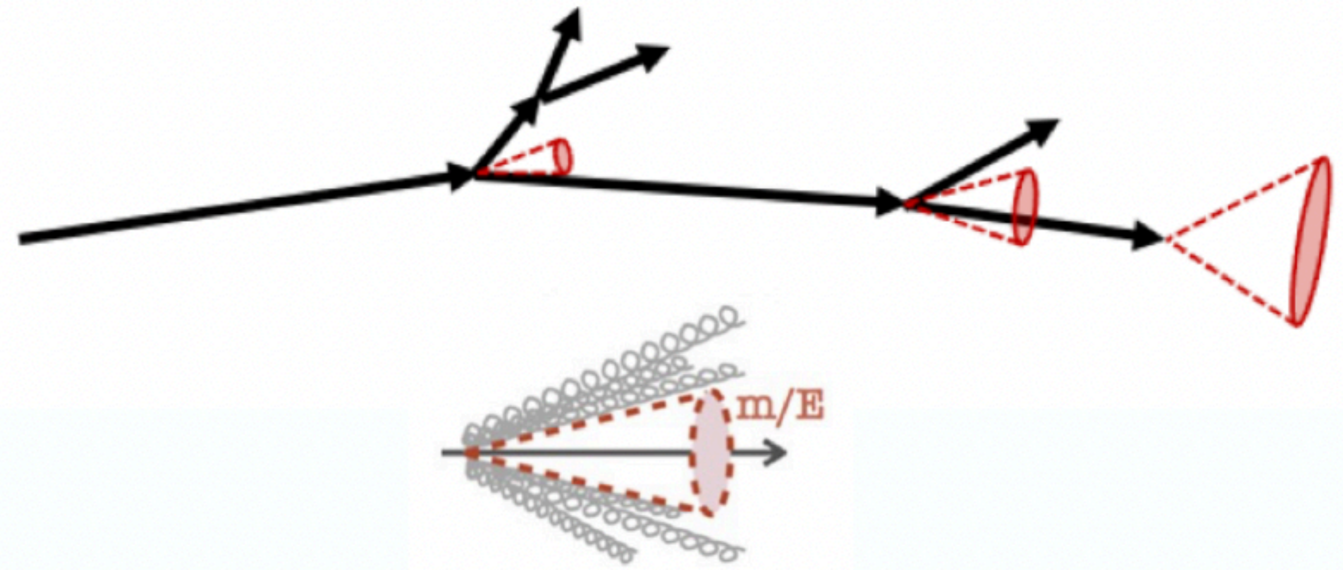
Gluon-initiated shower



Quark-initiated shower



Heavy-quark-initiated shower



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

Casimir color factors

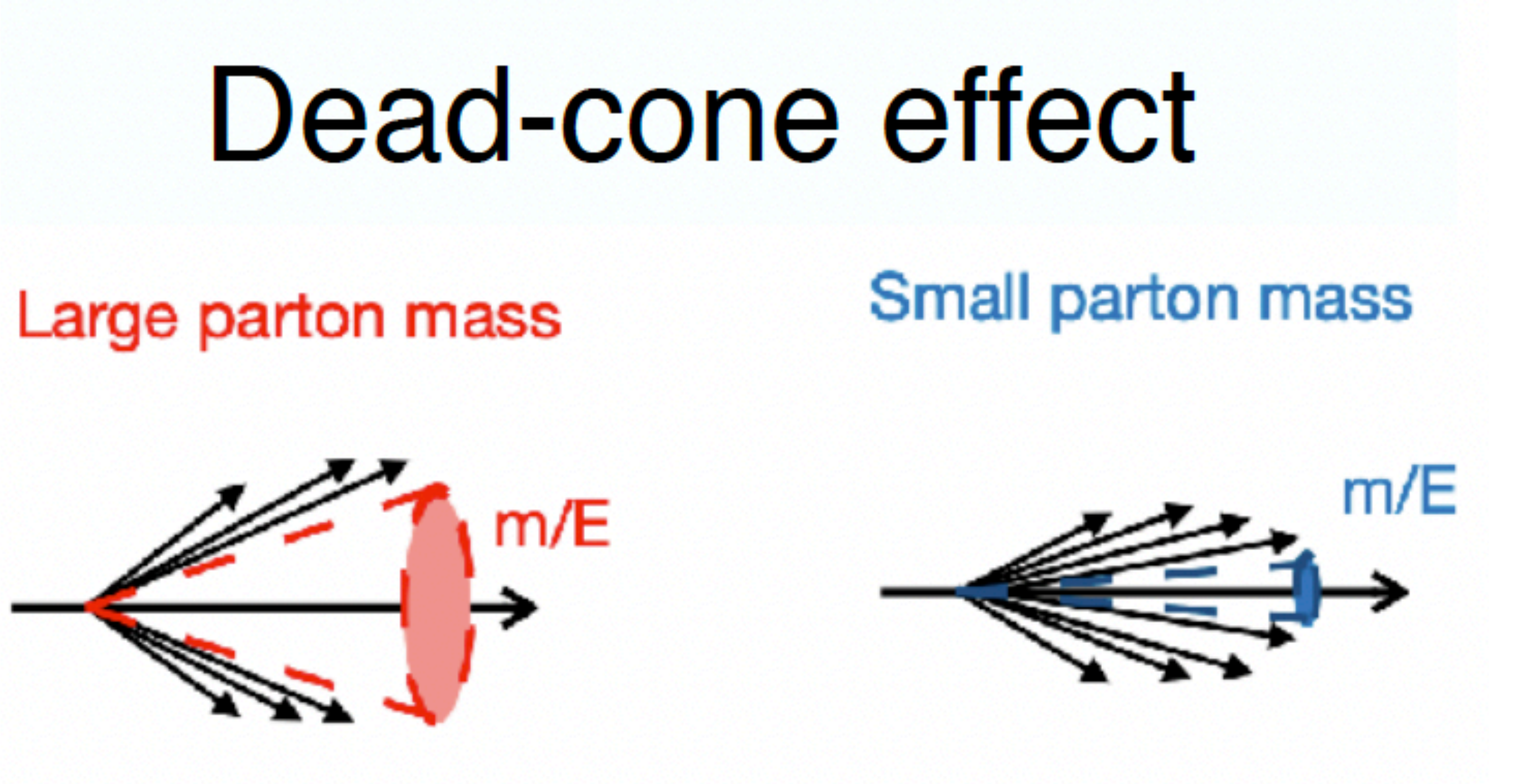
Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

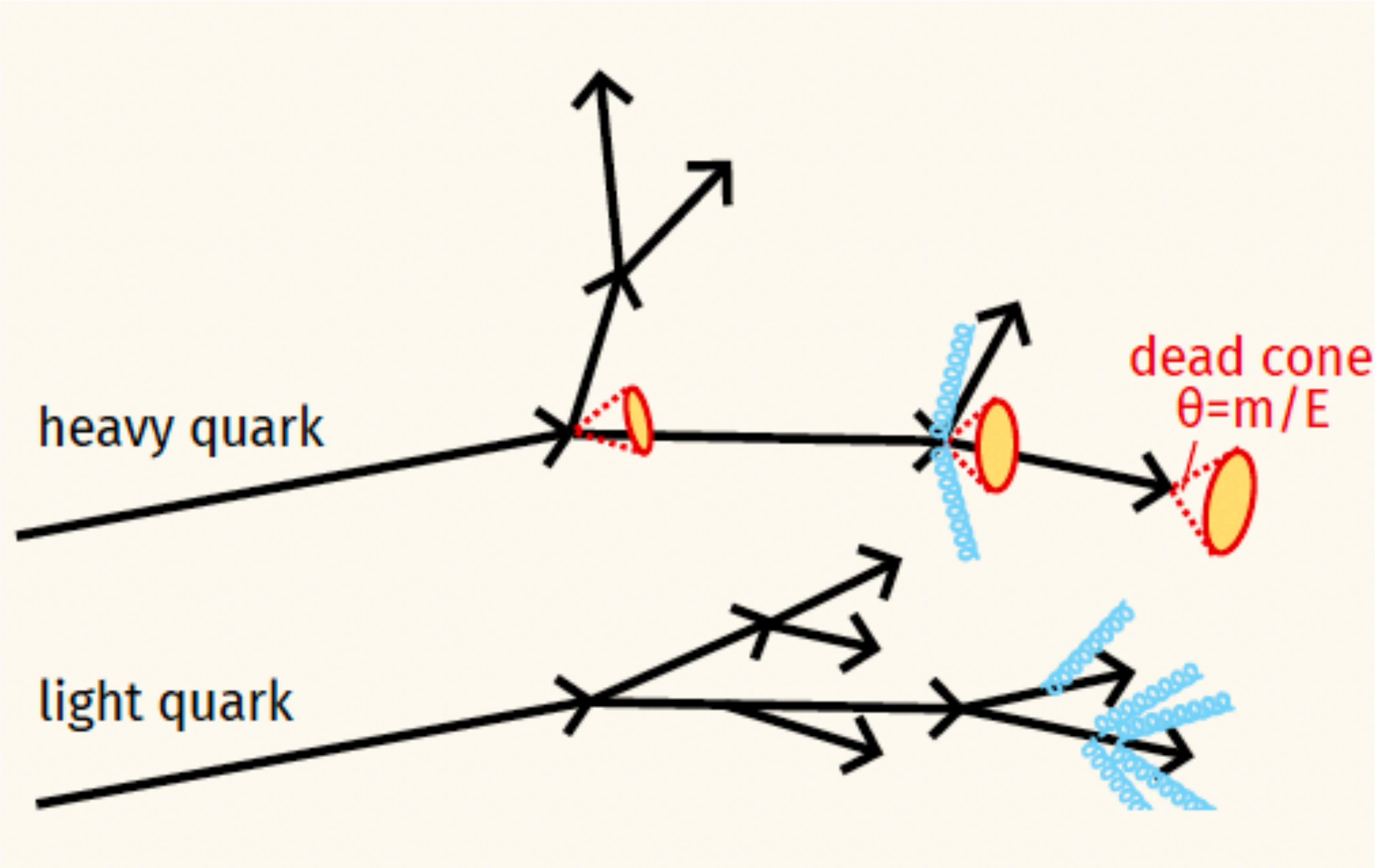
Mass effects

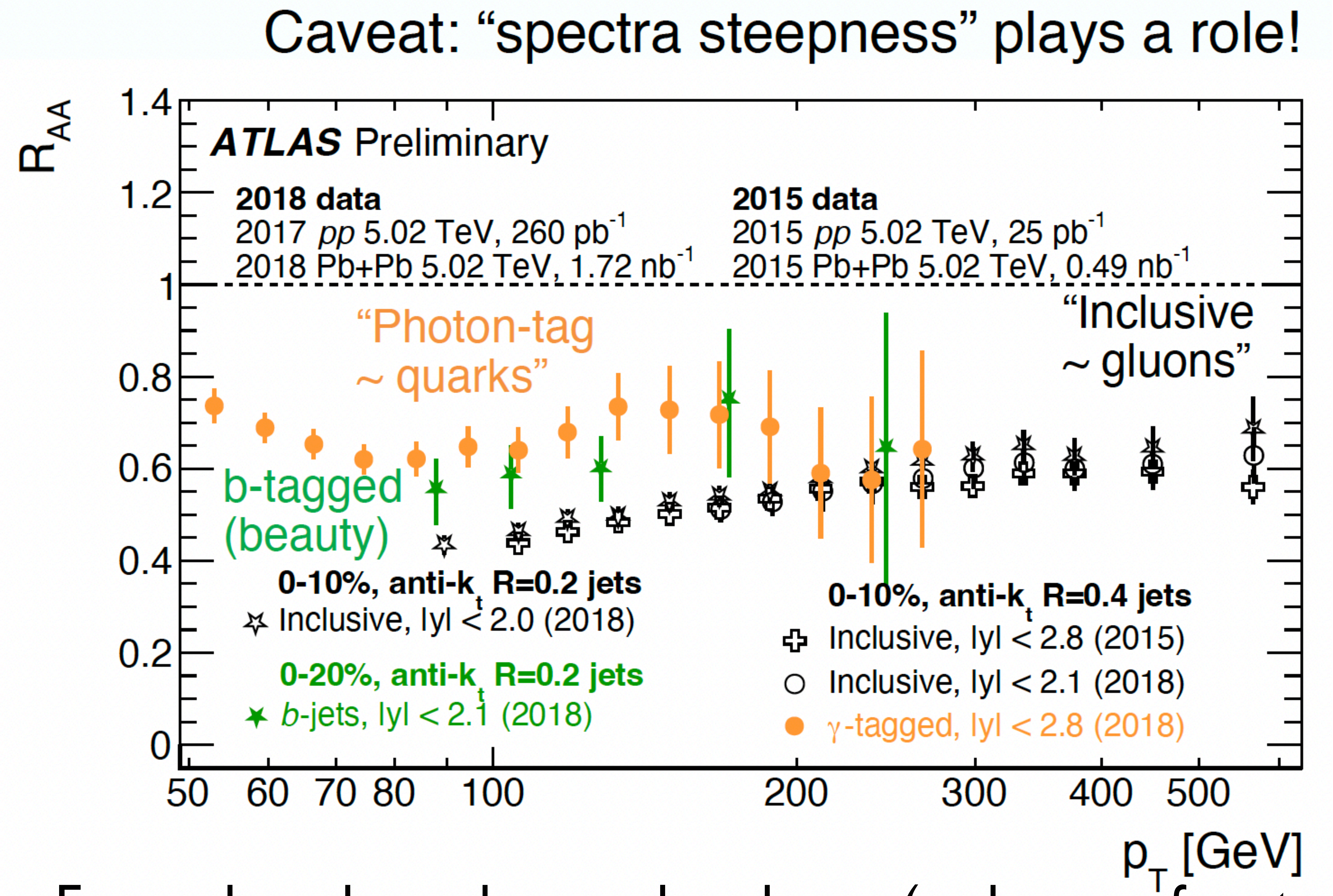
A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of a dead cone which suppresses radiation close to the heavy-quark

- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect
- Flavor dependence of energy loss: $E_{\rm loss}^{\rm gluon} > E_{\rm loss}^{\rm light-quark} > E_{\rm loss}^{c} > E_{\rm loss}^{b}$

Flavor/Mass dependence of energy loss







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

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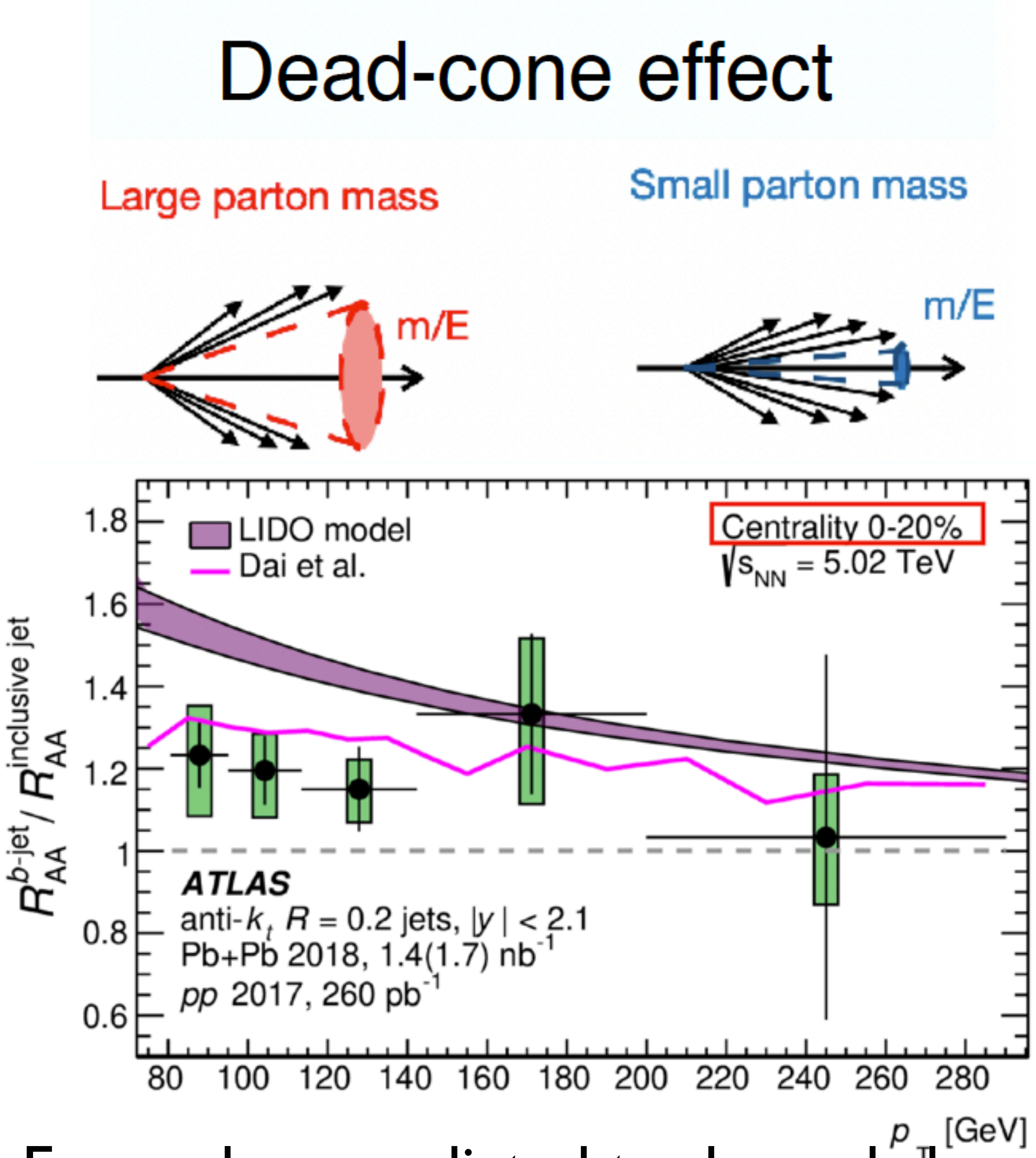
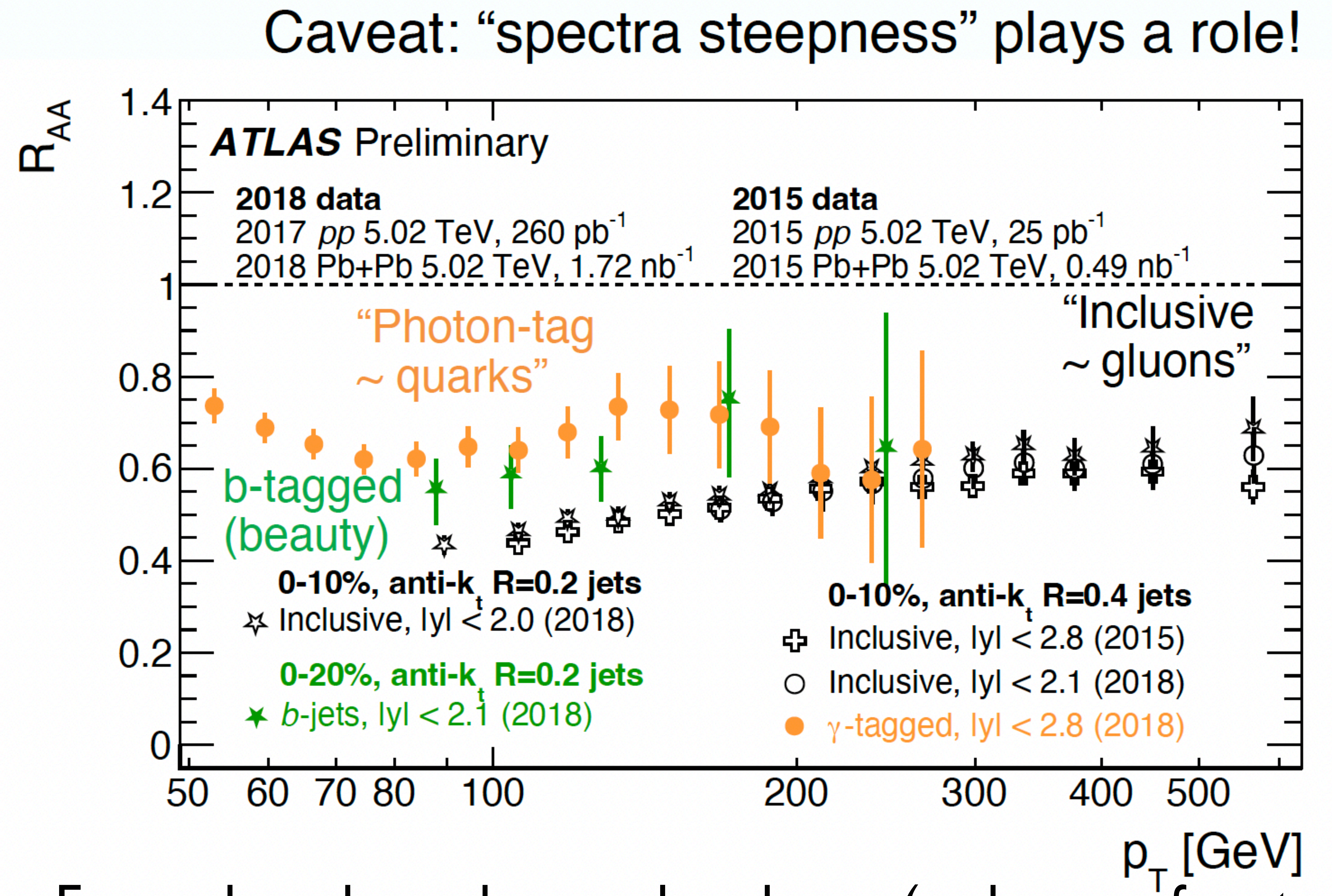
Flavor/Mass dependence of energy loss





- 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

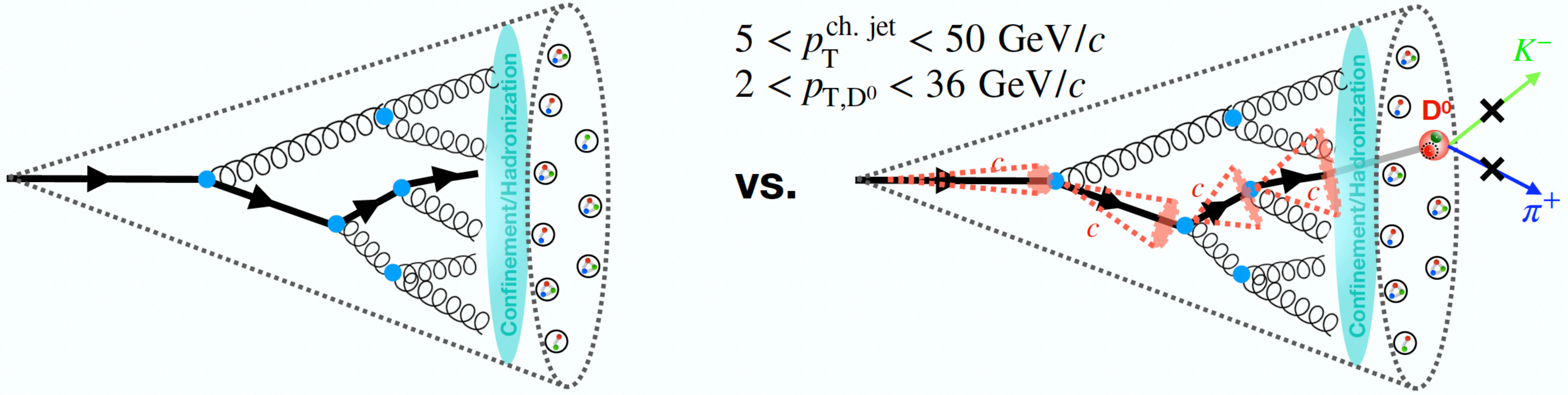
Test QCD flavor effects experimentally

Flavor-untagged (q or g) jets

Inclusive jets (gluon dominated)

Charm-tagged jets (c)

D^0-tagged jets (charm dominated)



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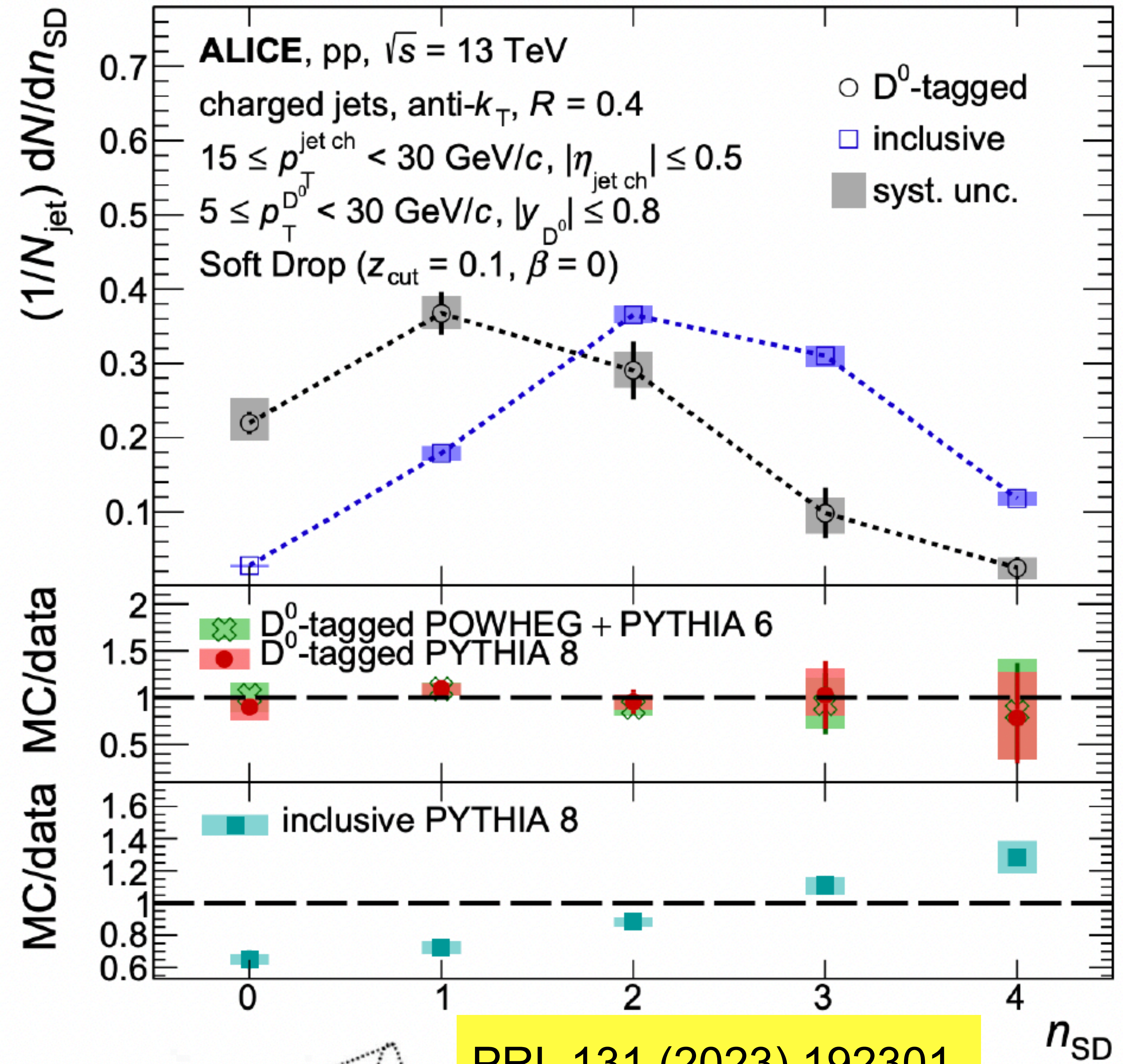
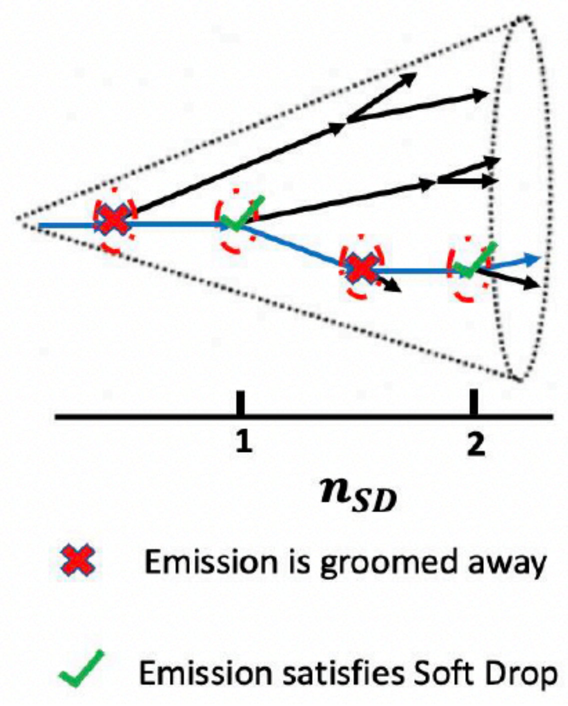


PRL 131 (2023) 192301

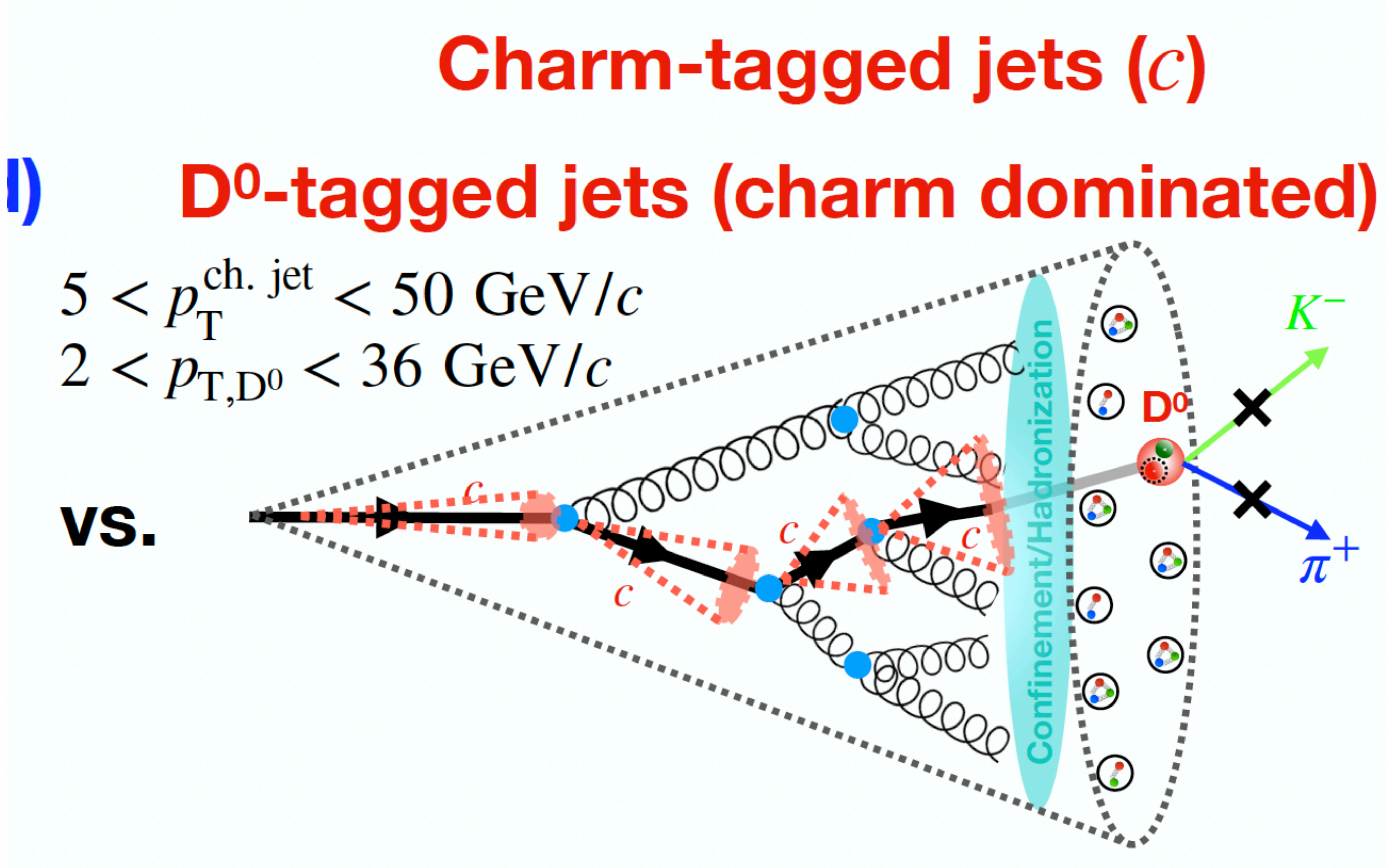


Soft Drop grooming condition

$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}$$

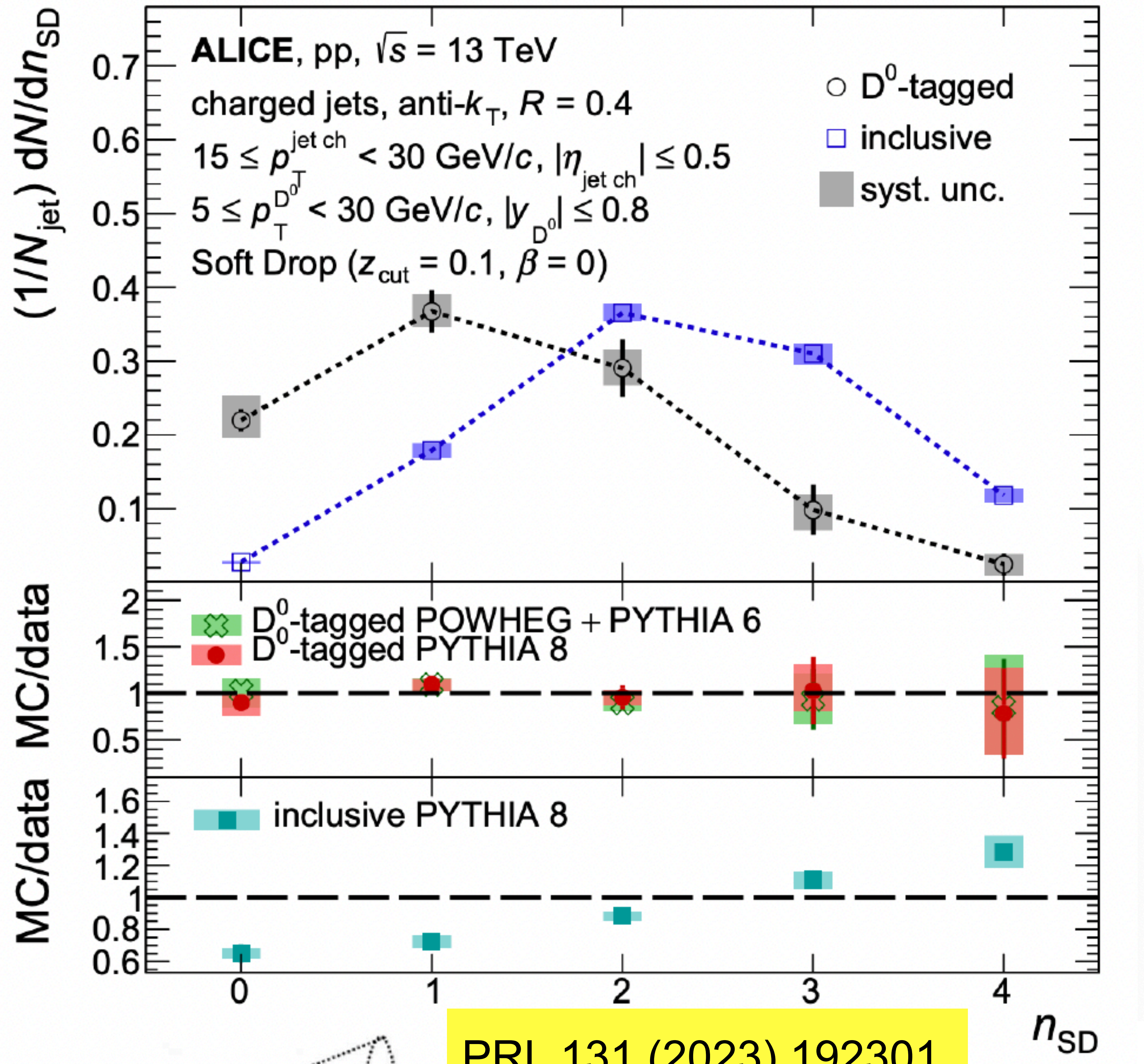
$$z_{cut} = 0.1, \beta = 0$$

A. J. Larkoski et al. , JHEP 1405 (2014) 146



- More differential study on HF(c tagged)-jet substructure →Clear flavor(mass) hierarchy observed

Test QCD flavor effects experimentally



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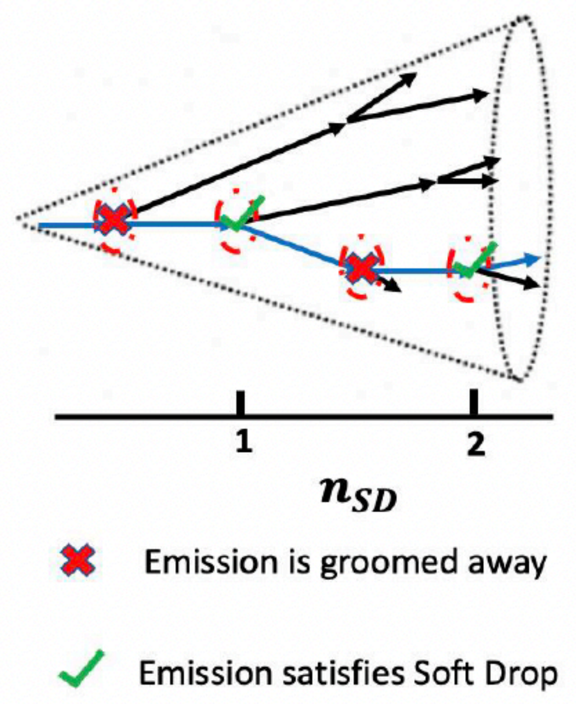

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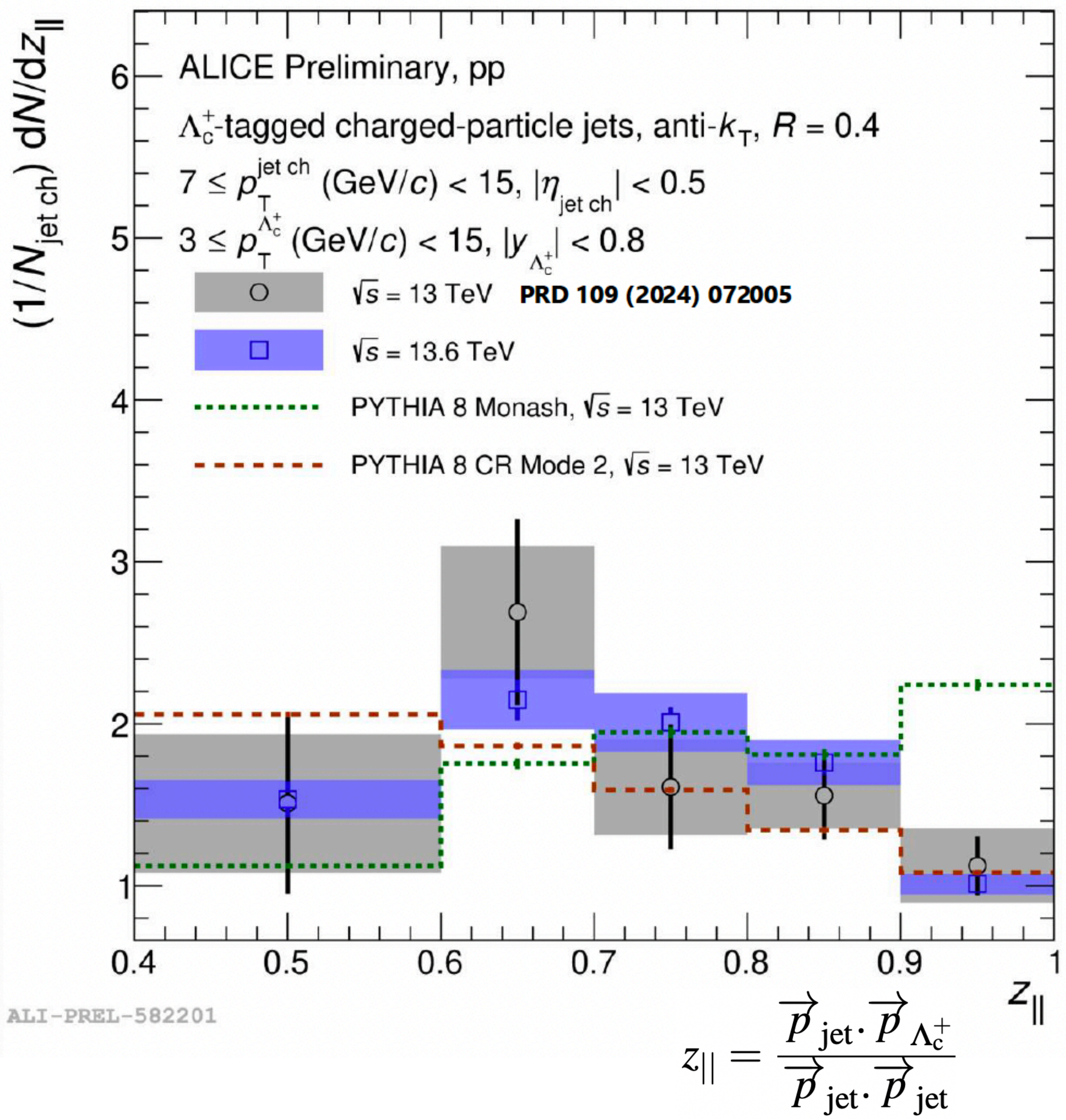
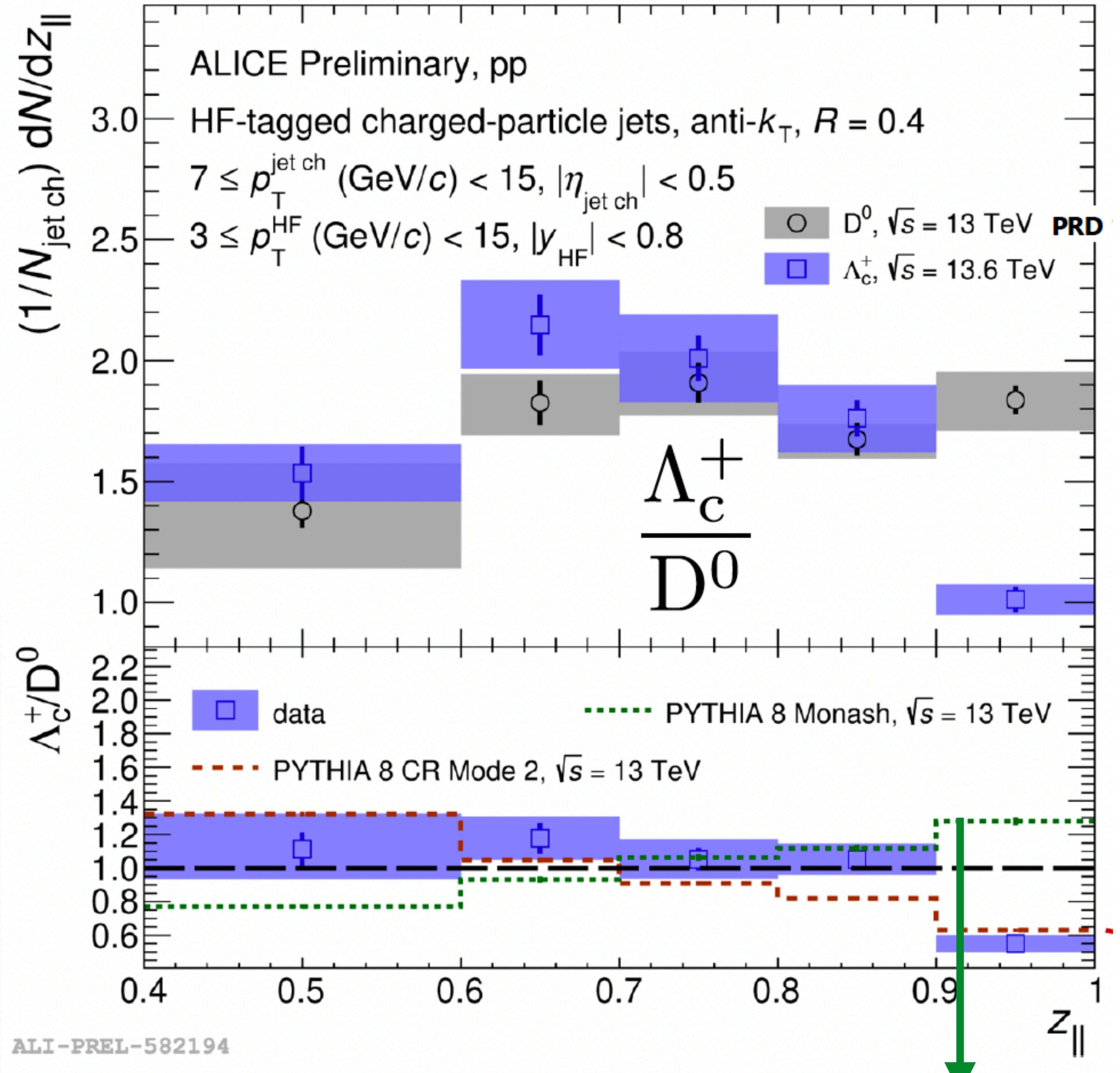




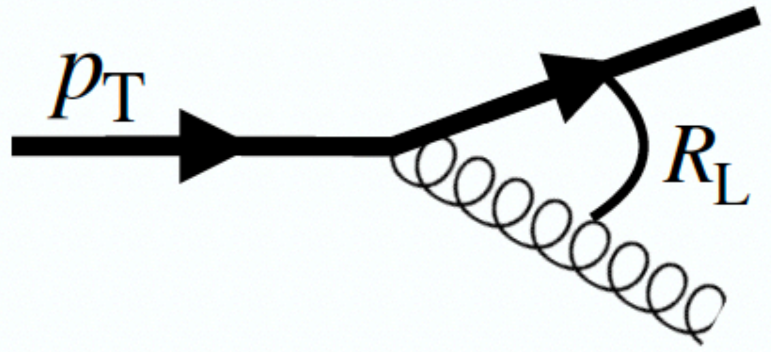
Model tuned on e+e-

- More differential study on HF(c tagged)-jet substructure →Clear flavor(mass) hierarchy observed
- Softer fragmentation for baryons compared to mesons

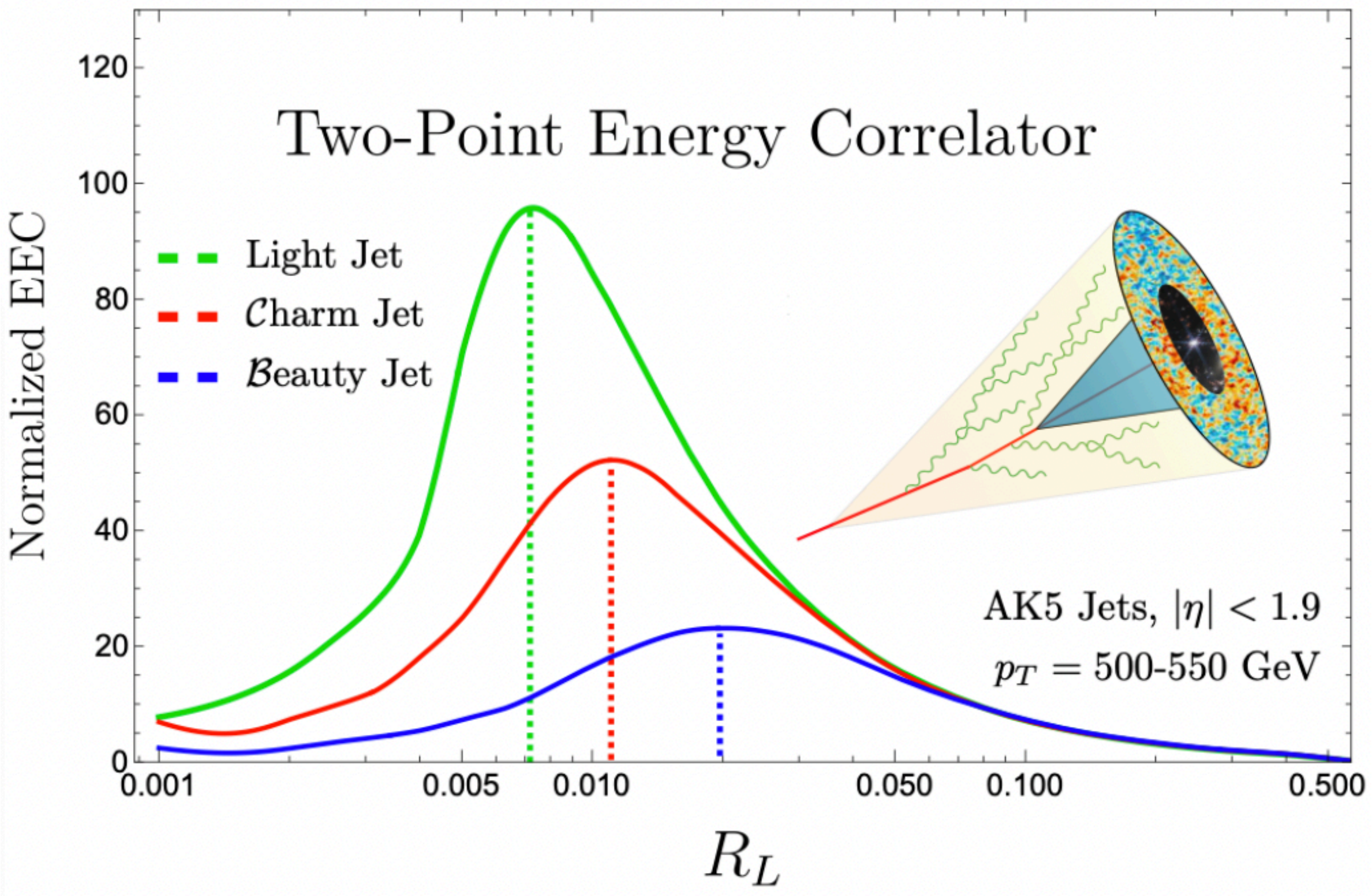
Mass/Flavor dependent EECs in jets

Scaling behavior identical to massless case for larger $R_{\rm L}$

$$\text{virtuality} \sim p_{\rm T}R_{\rm L} + m$$



A turn-over for $R_{\rm L} \rightarrow m_{\rm Q}/p_{\rm T}$



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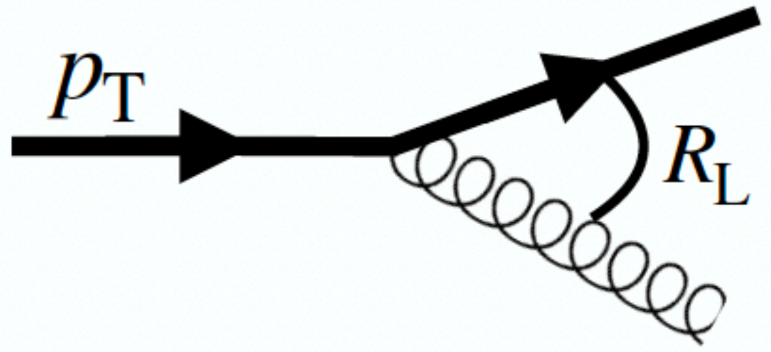

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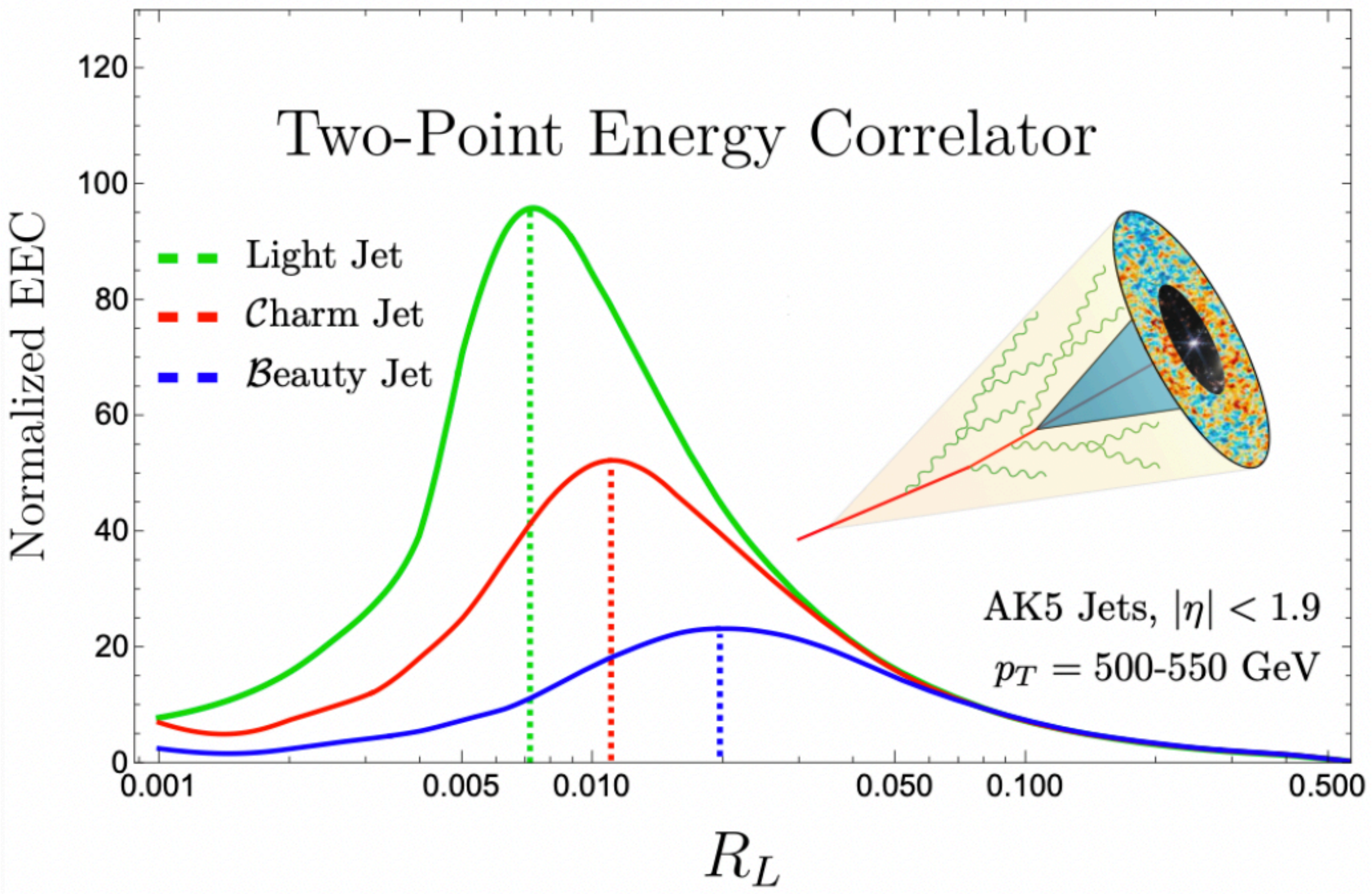
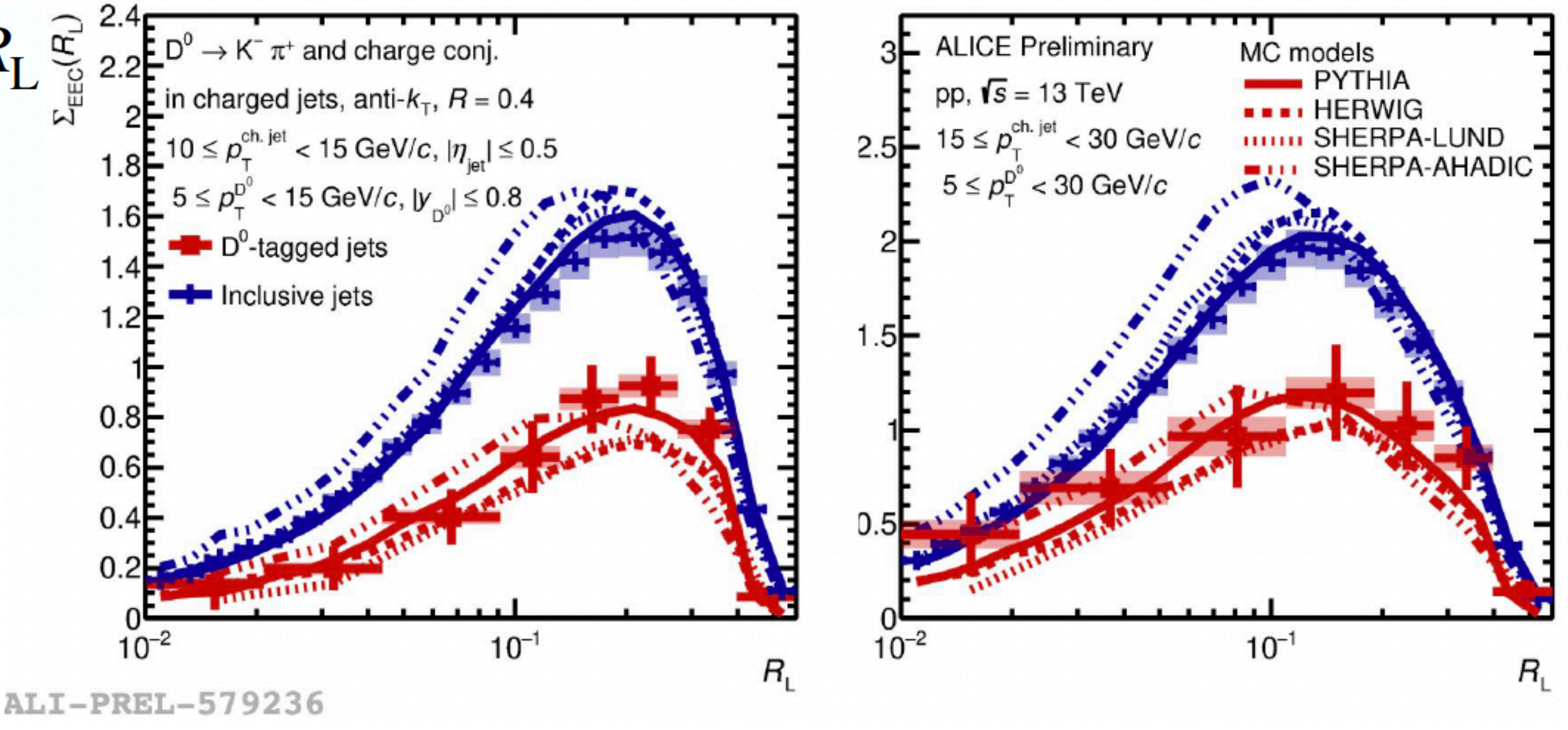


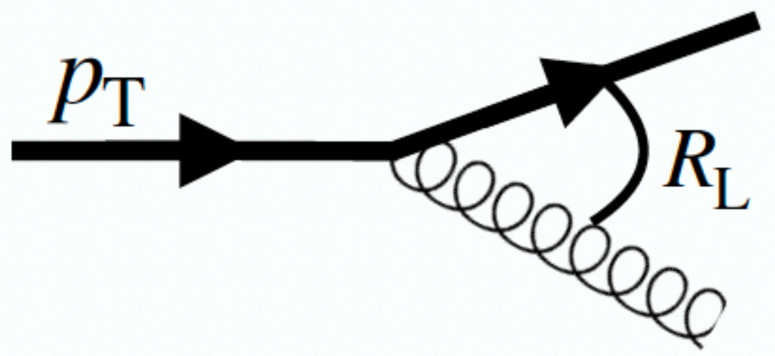


- Clear flavor(mass) hierarchy observed in jet EEC measurements

Mass/Flavor dependent EECs in jets

Scaling behavior identical to massless case for larger R_L

virtuality $\sim p_T R_L + m$



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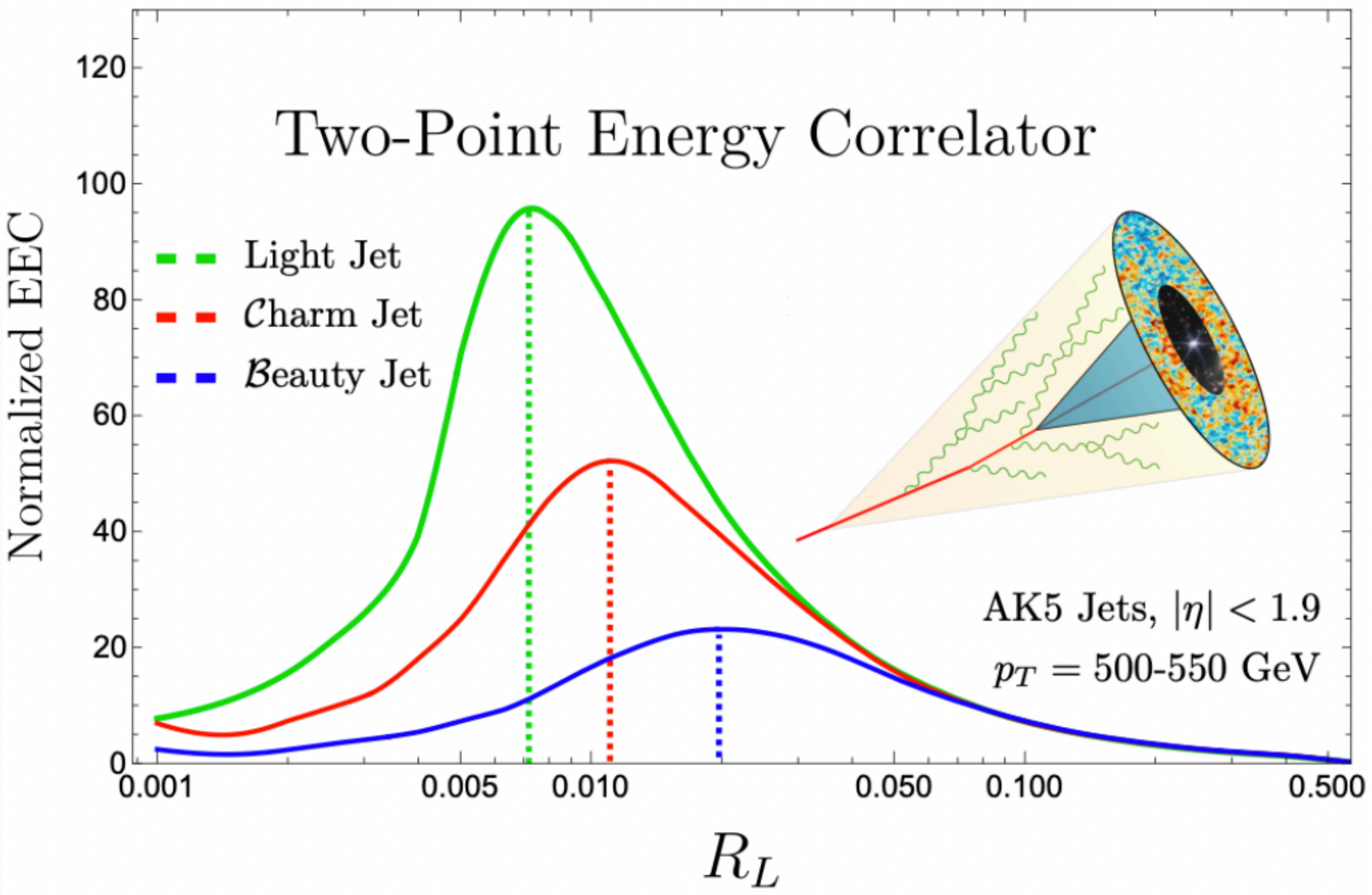
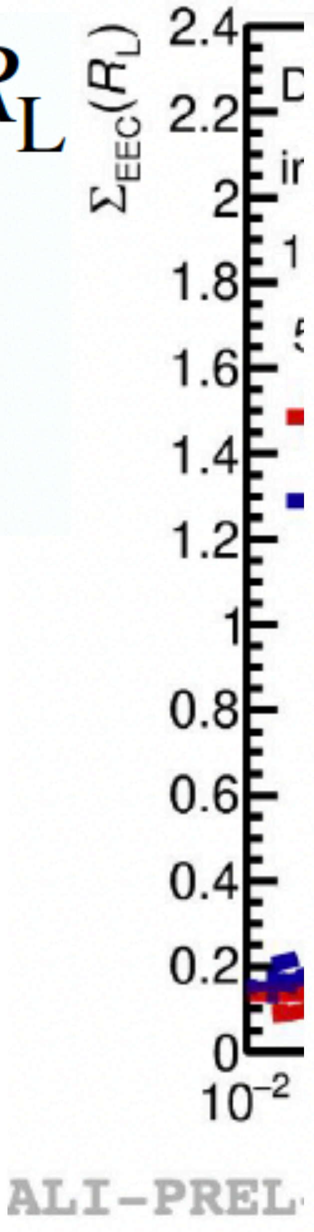
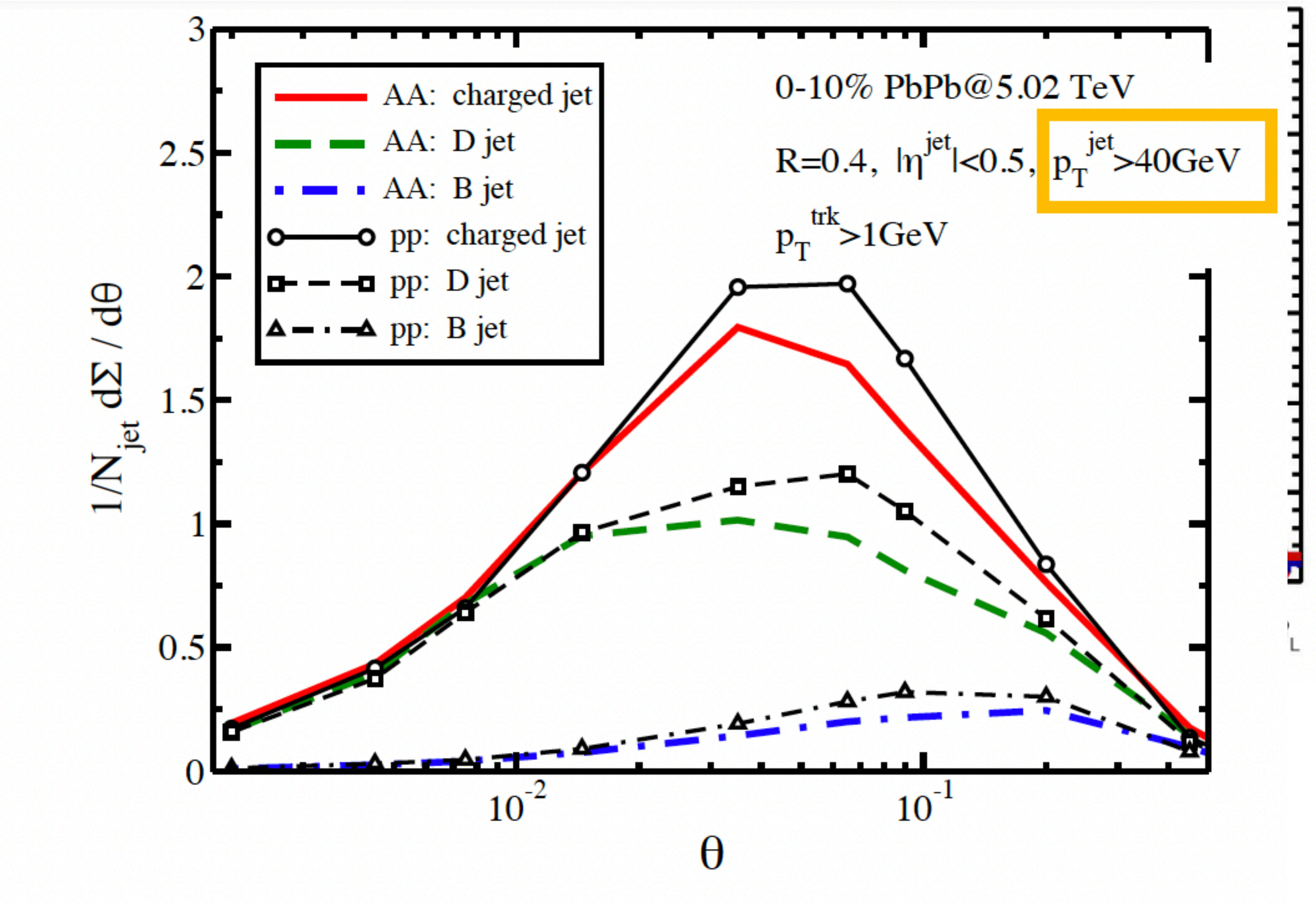




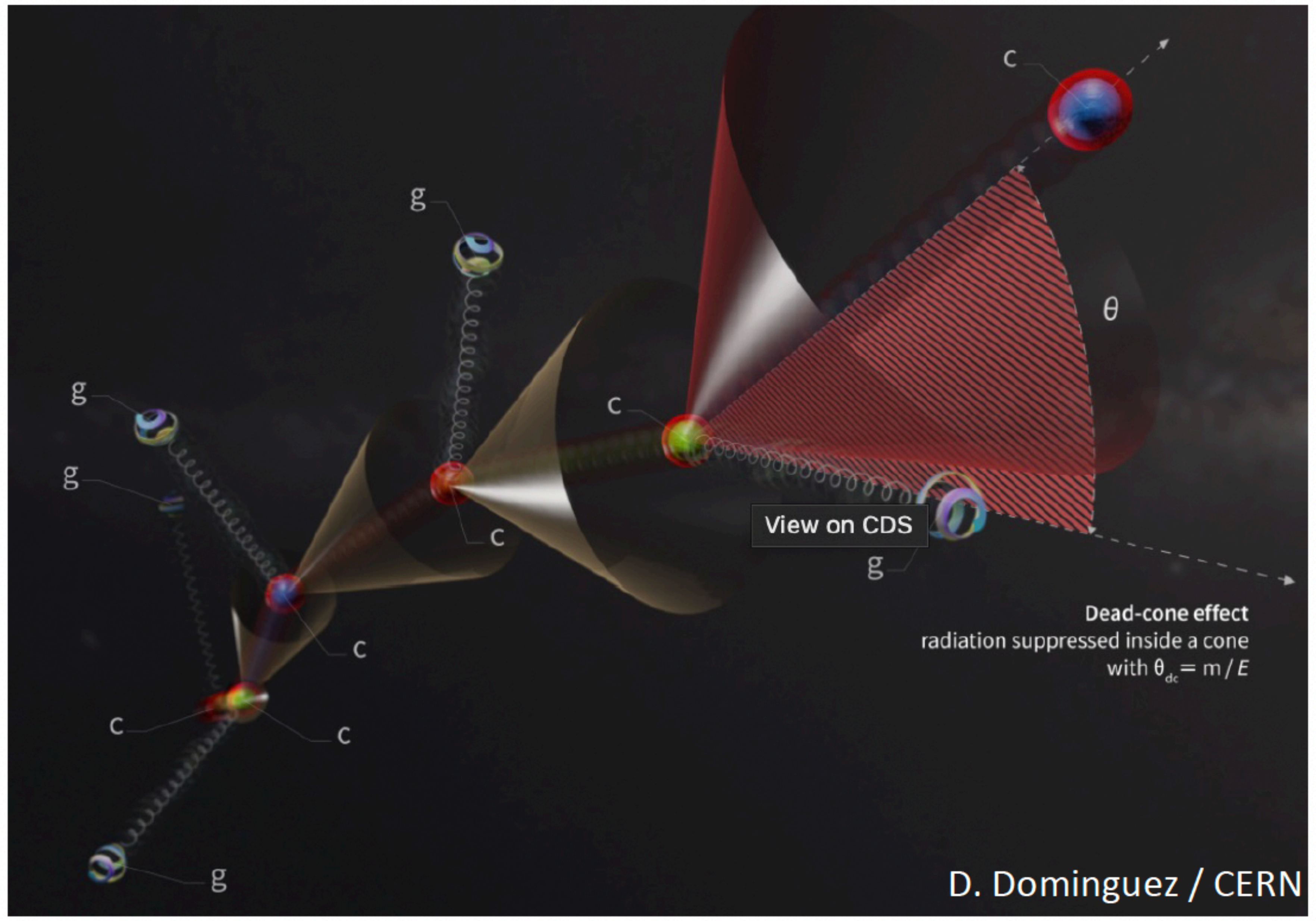


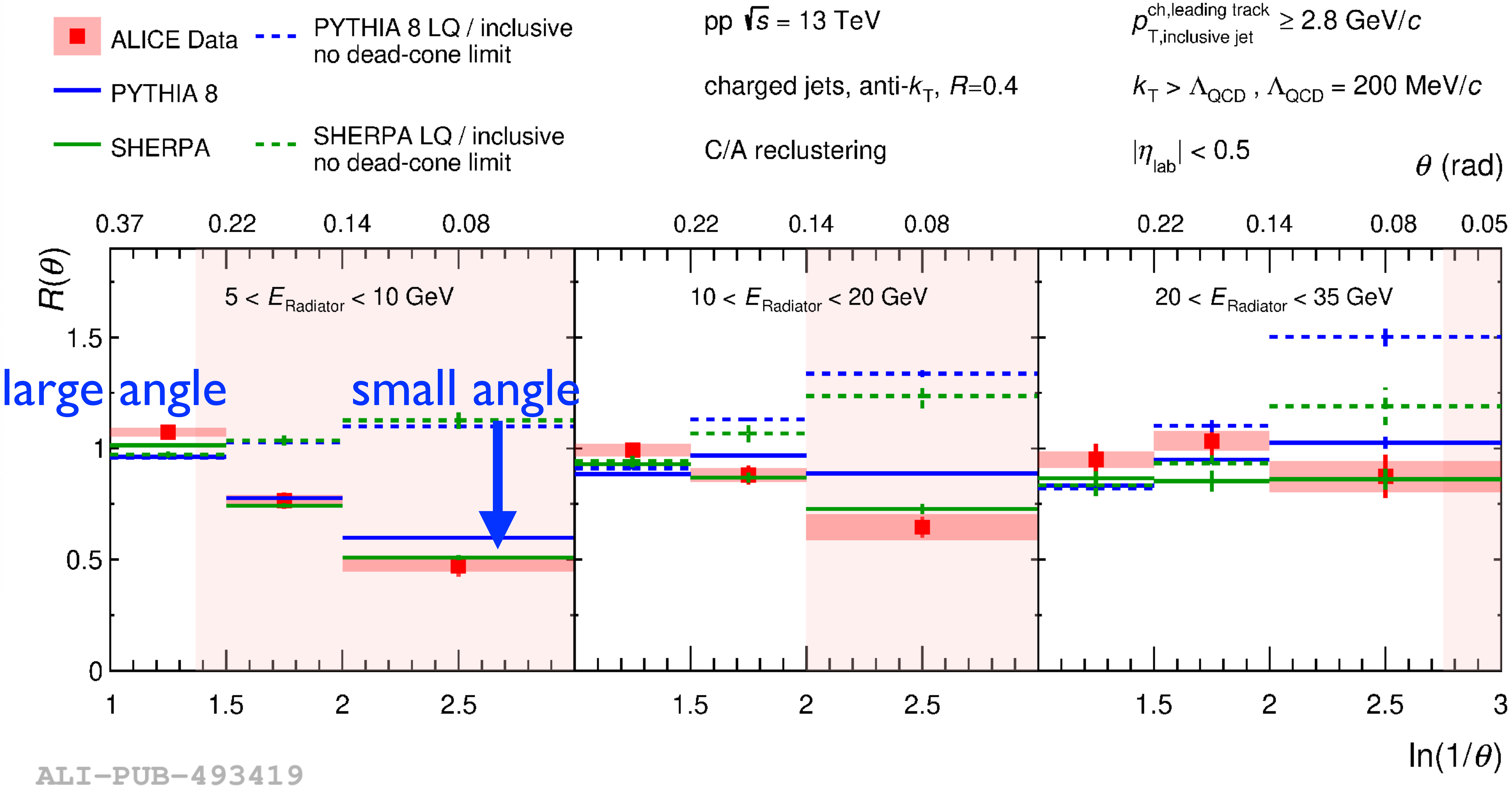
- Clear flavor(mass) hierarchy observed in jet EEC measurements
- Theory already predicted the modifications in HI case →experimental measurements ongoing

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 D⁰ meson.
- D-tagged jets in pp does show the dead-cone effect! where is it in AA?

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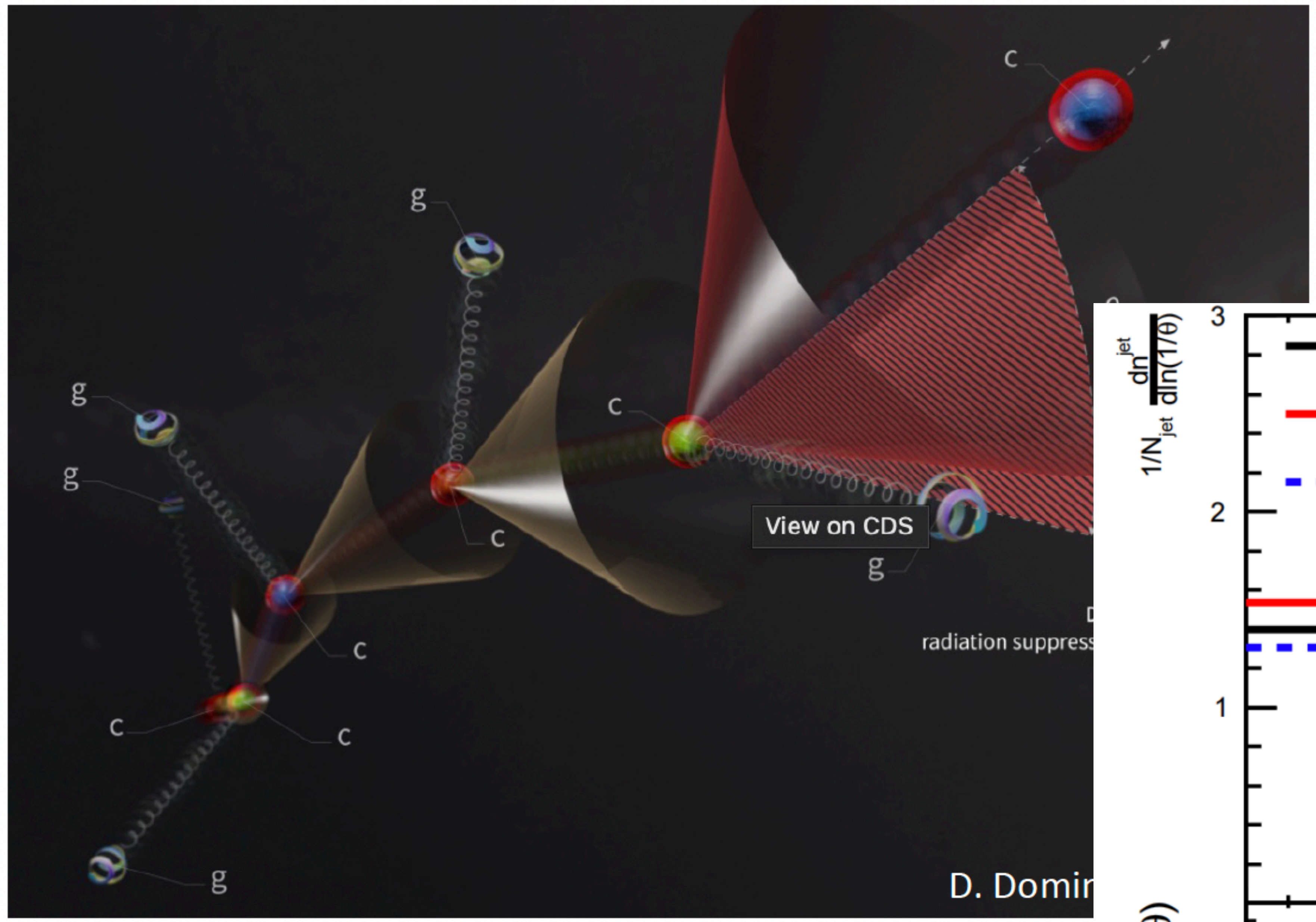

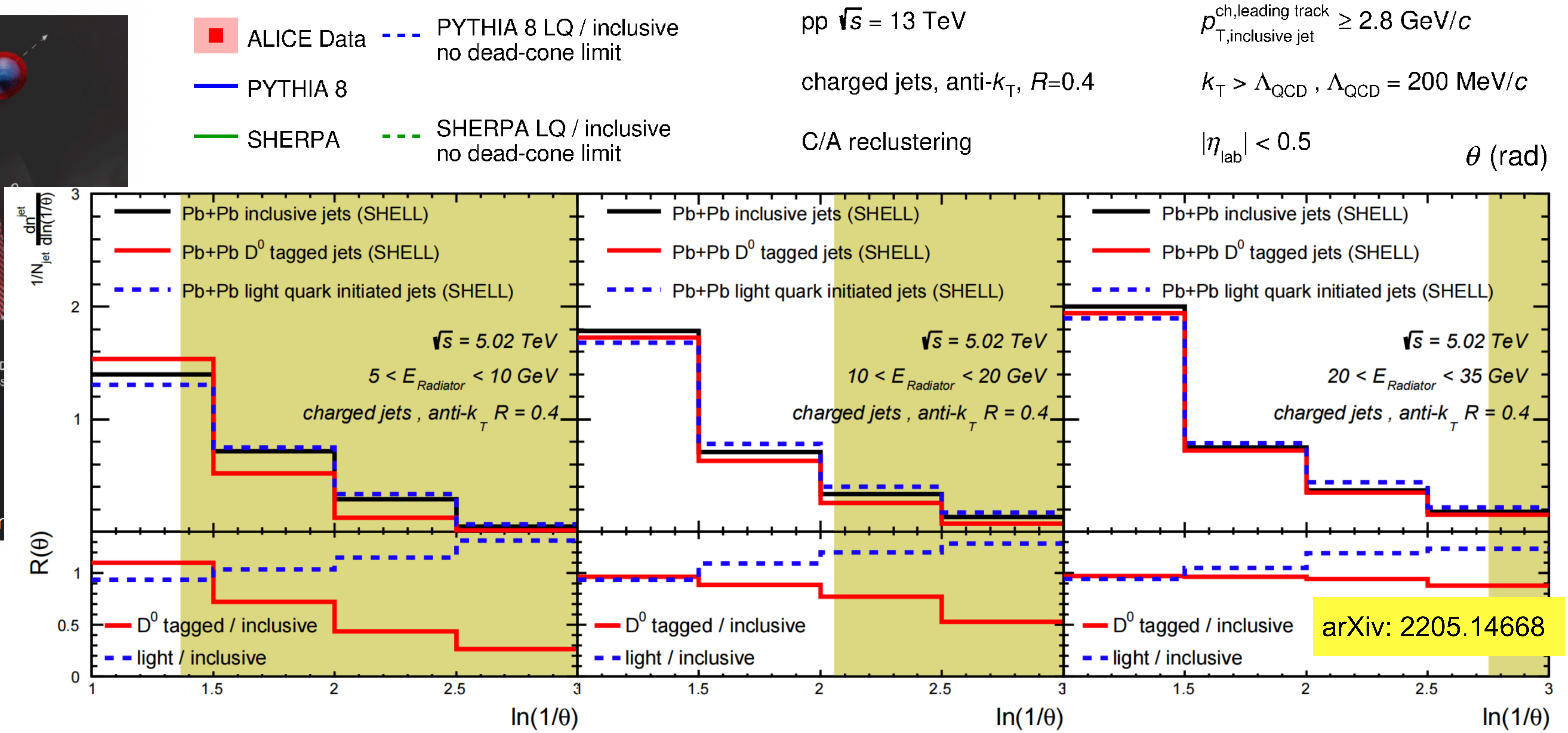

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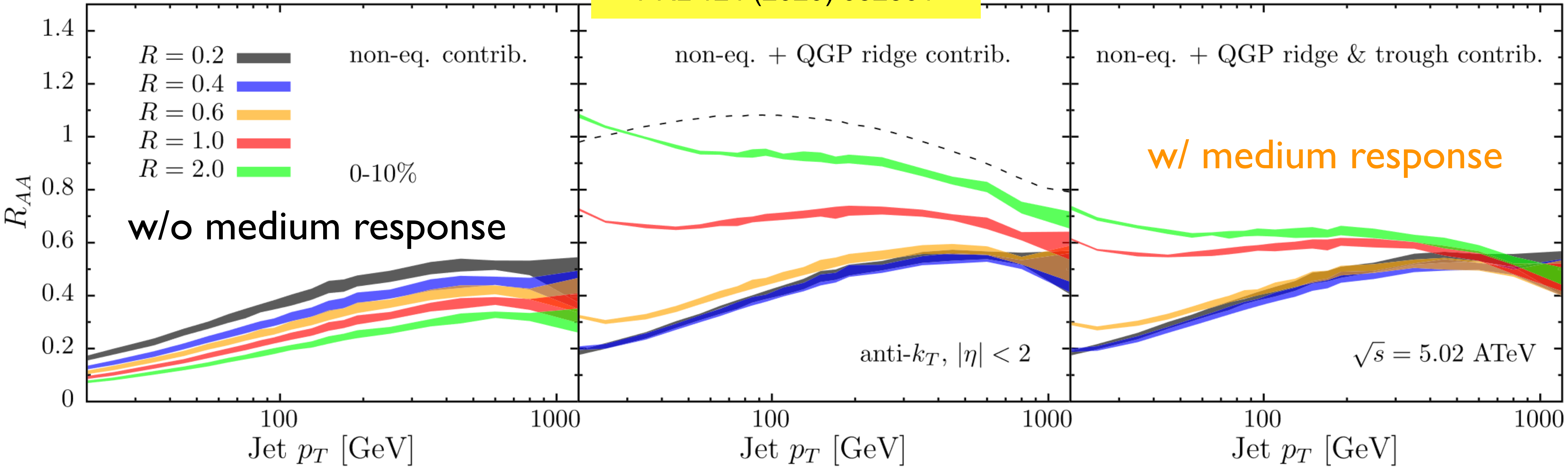
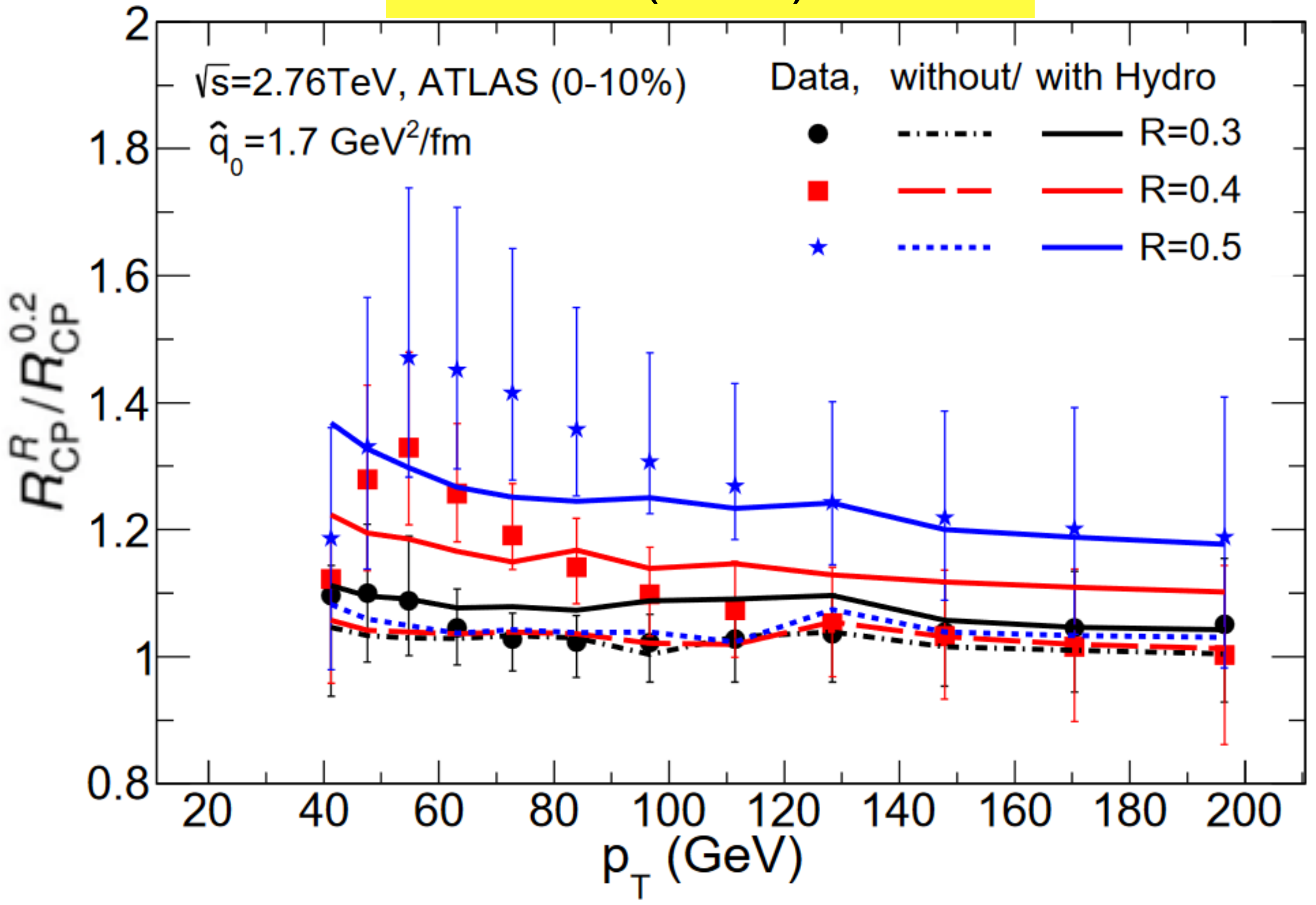
R dependence of jet quenching

- 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

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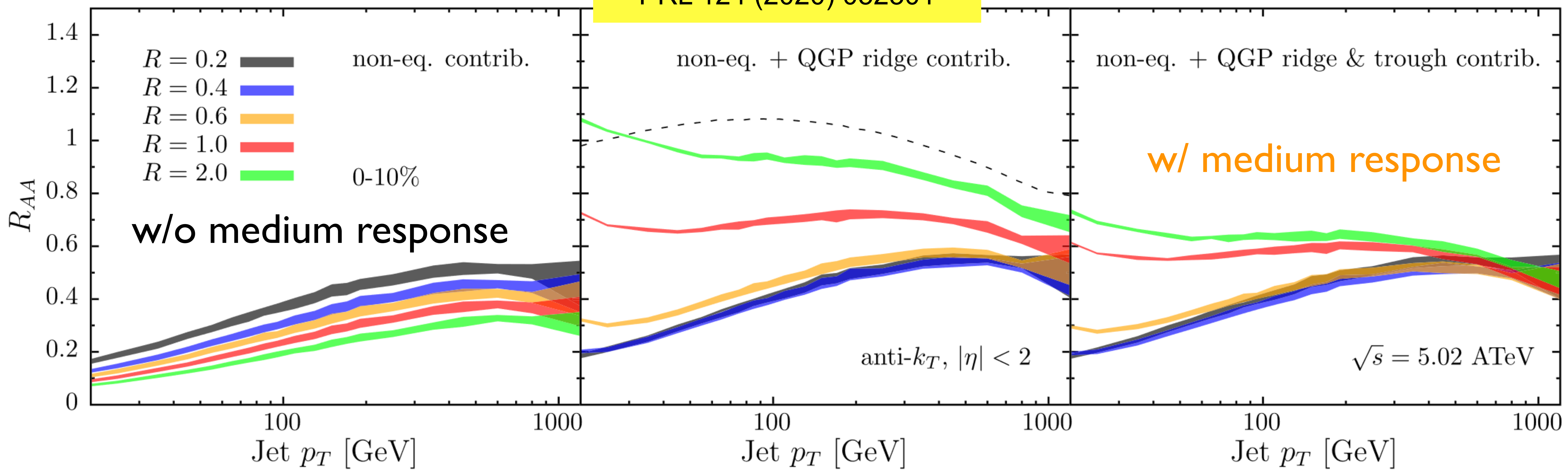
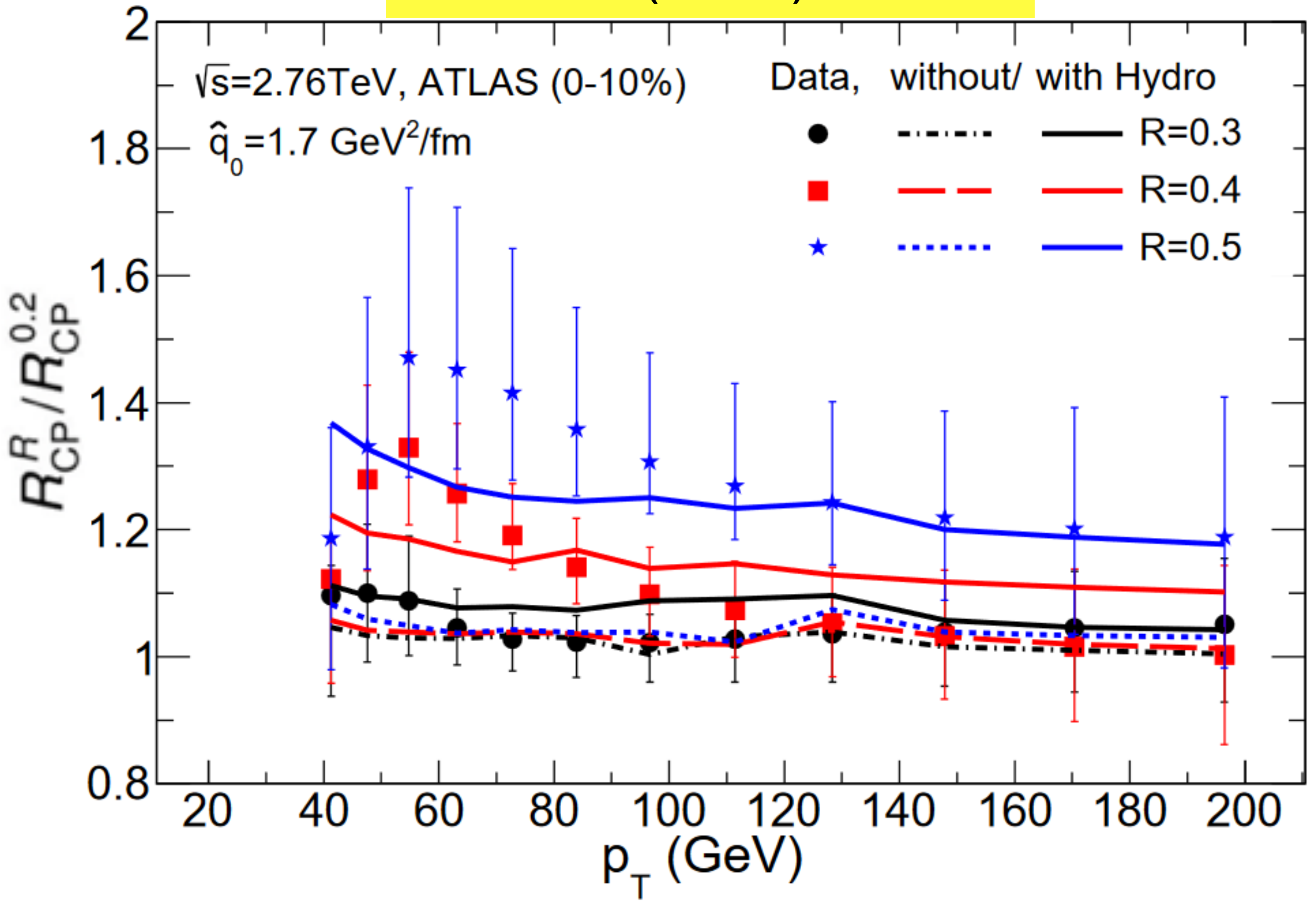
PRL 124 (2020) 052301



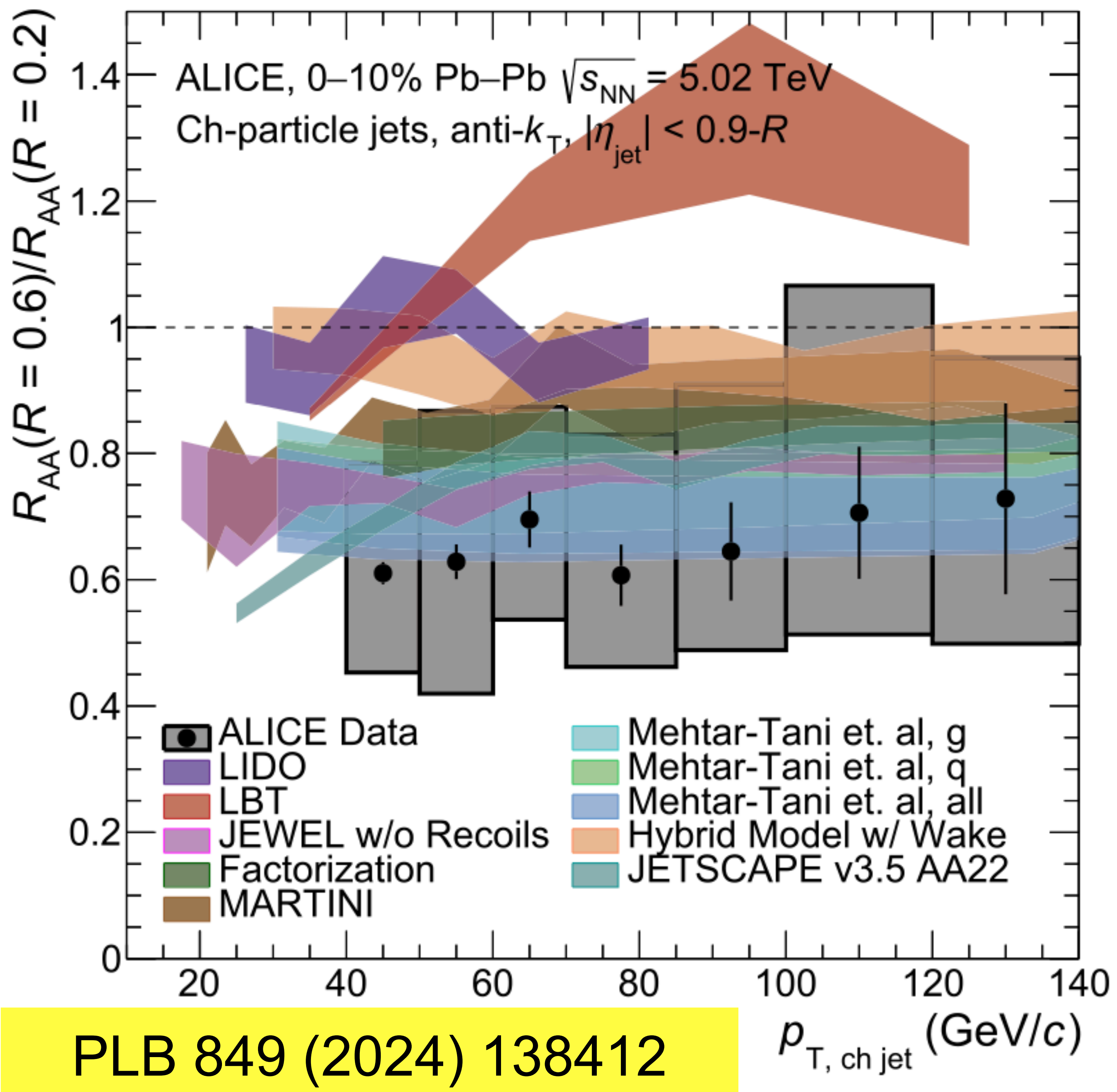
PLB 801 (2020) 135181



- 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

→More differential and uniform analyses comparison and future studies are needed

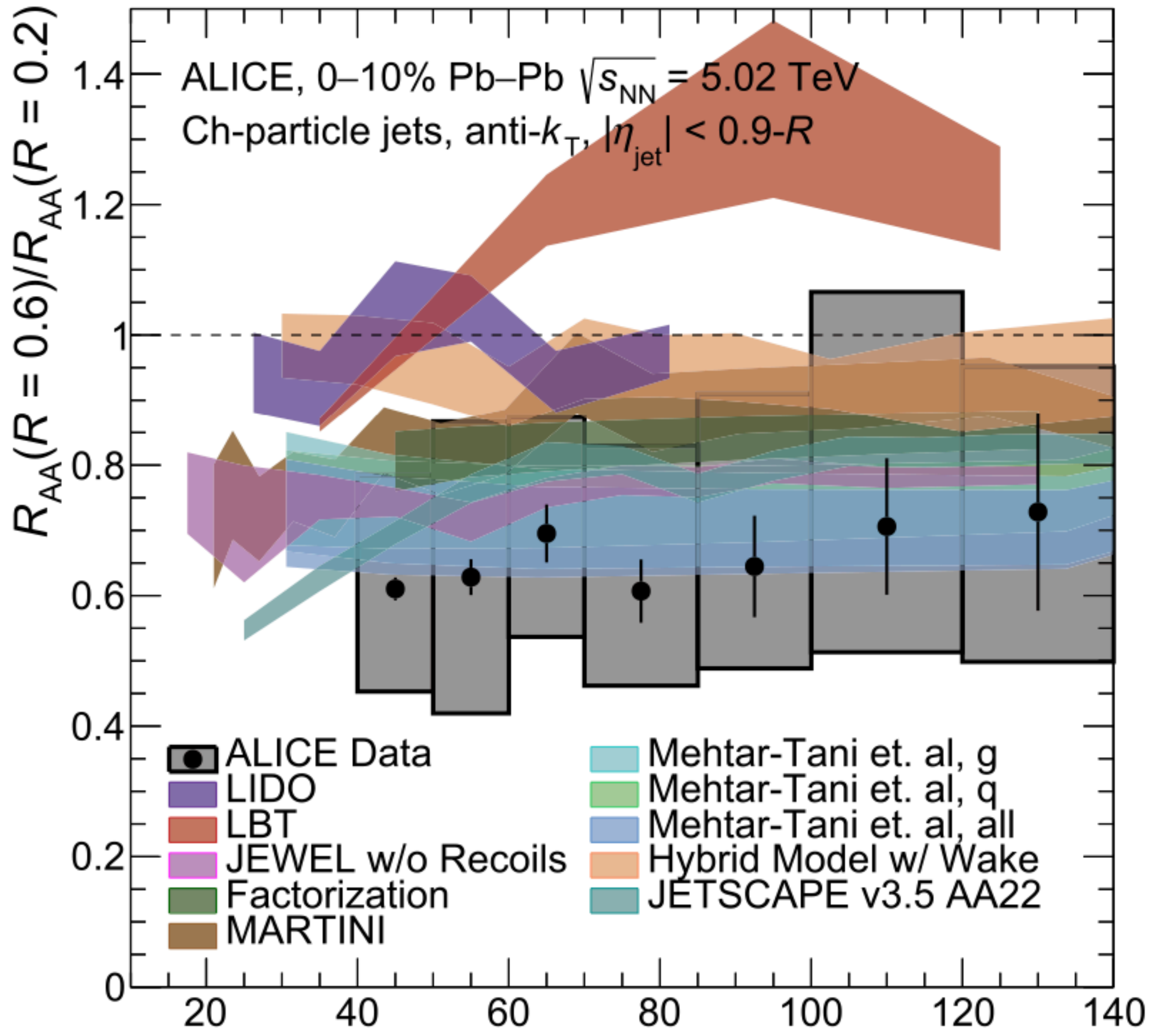
R dependence of jet quenching



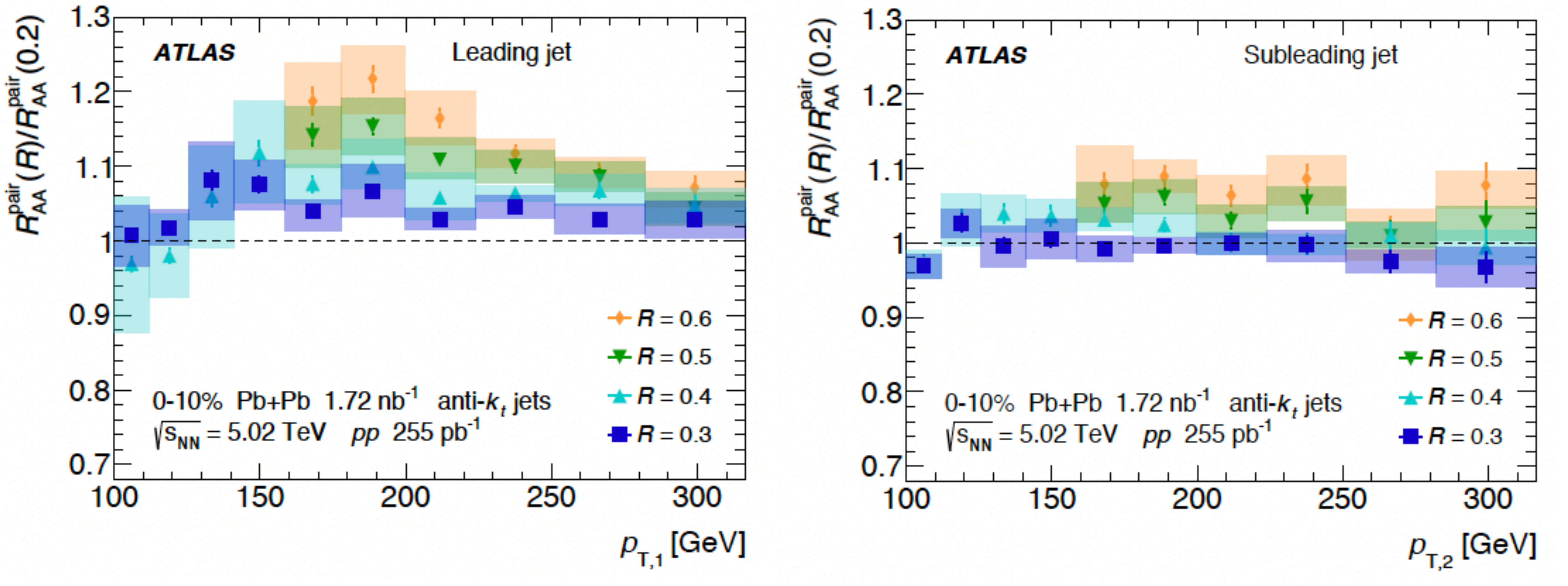
PLB 849 (2024) 138412

- Inclusive jets R_{AA} ratio from ALICE: larger radius jets more suppressed

R dependence of jet quenching



PLB 849 (2024) 138412



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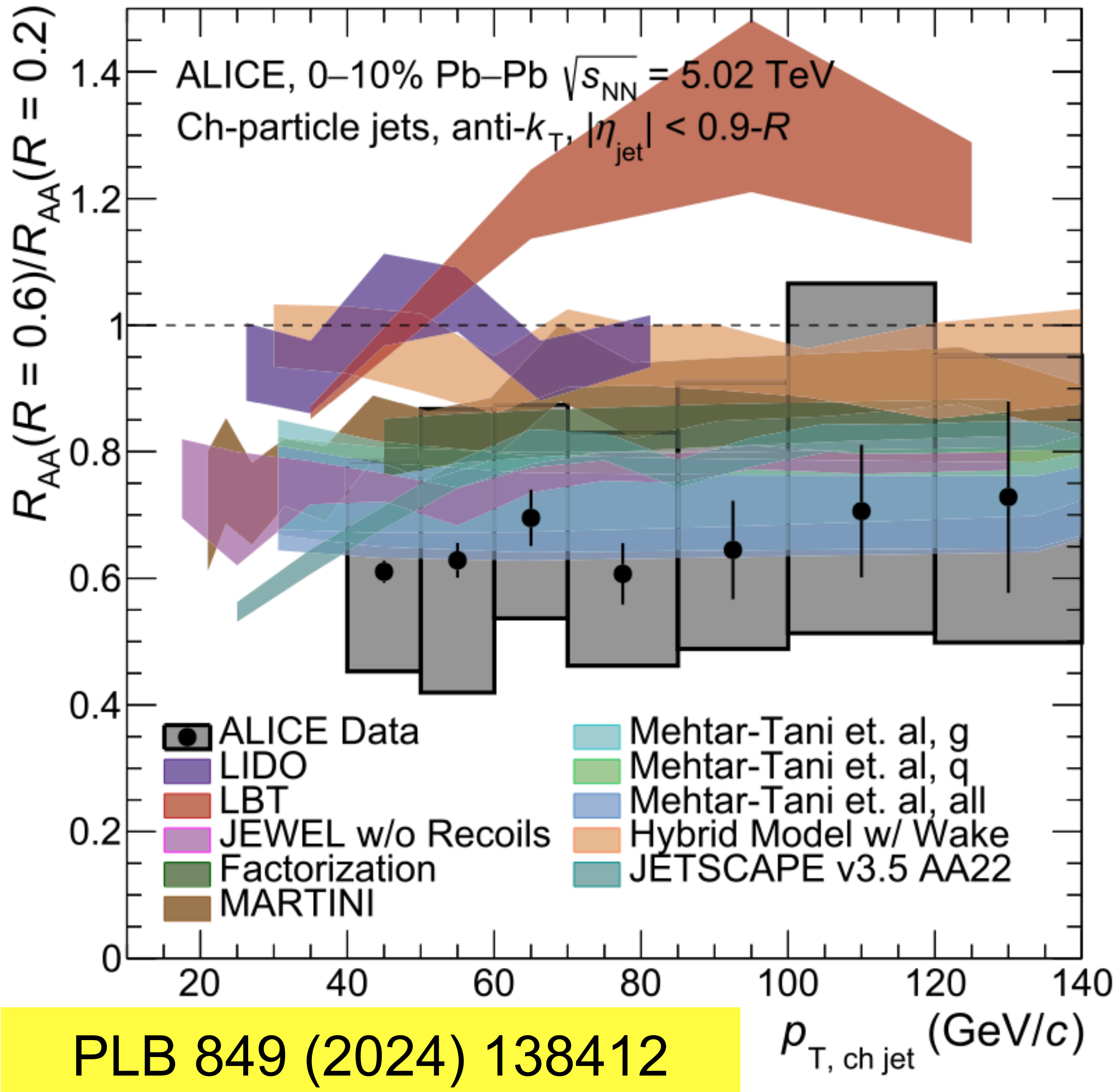
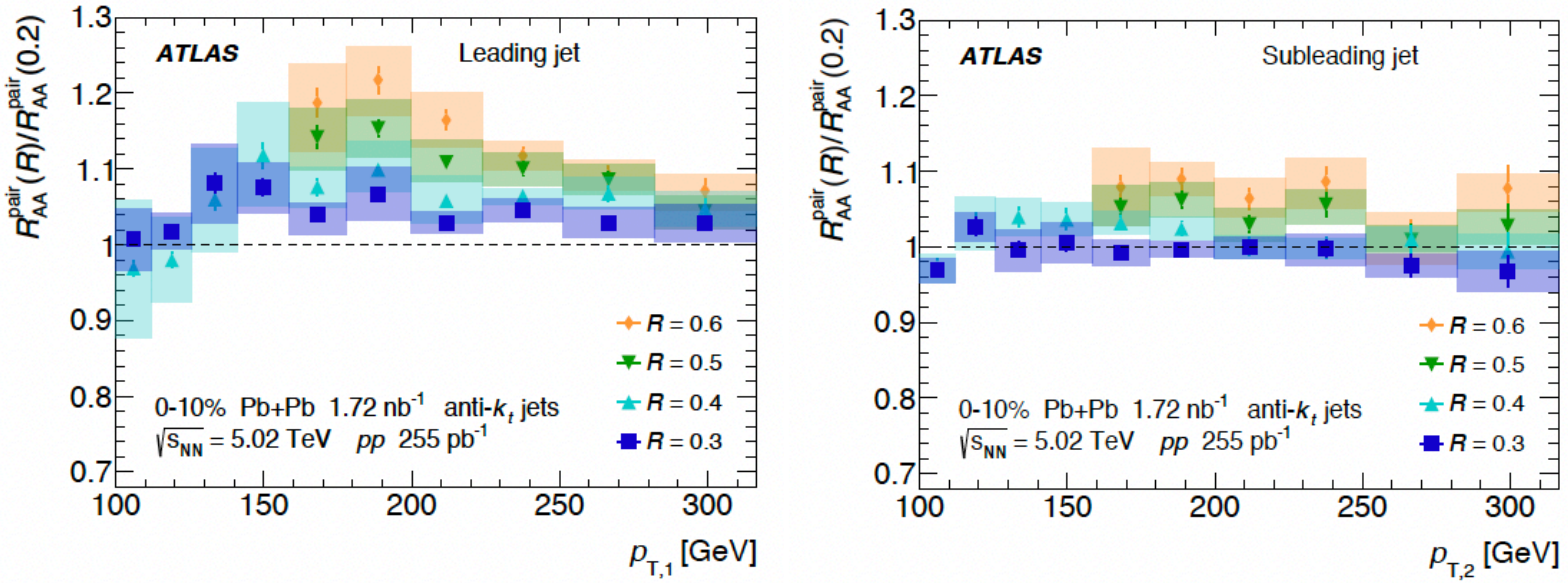
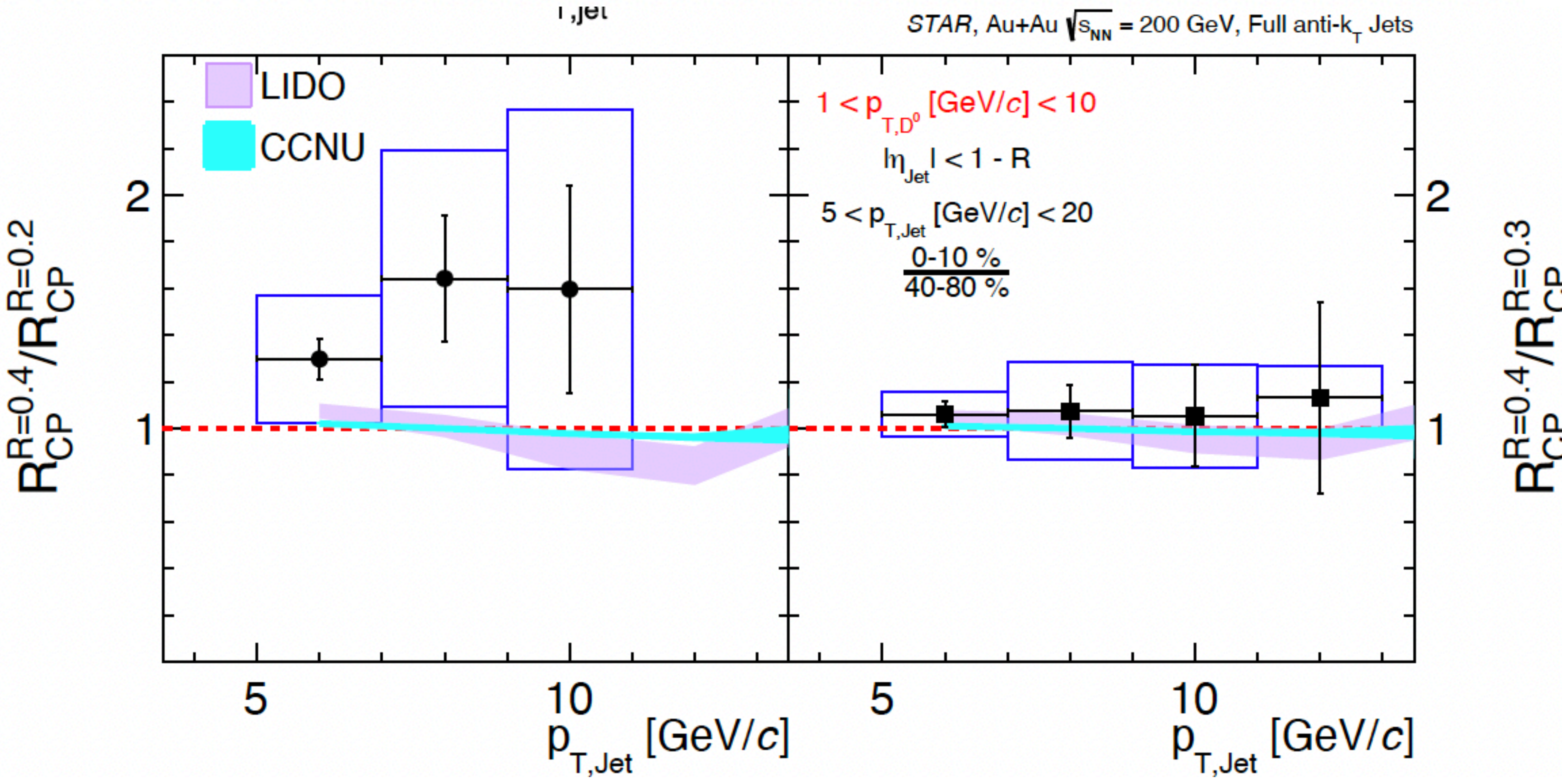
R dependence of jet quenching



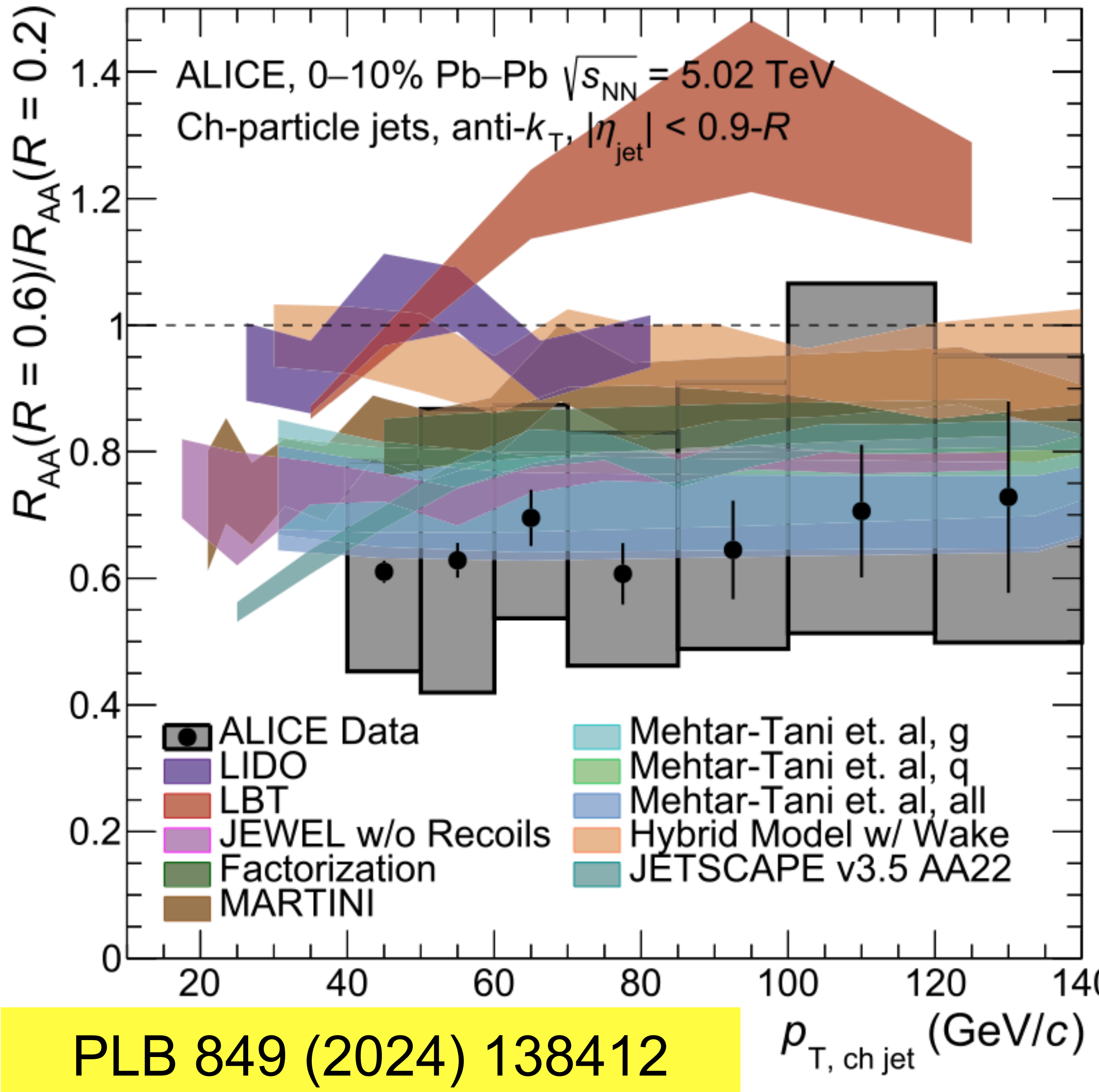
PLB 849 (2024) 138412



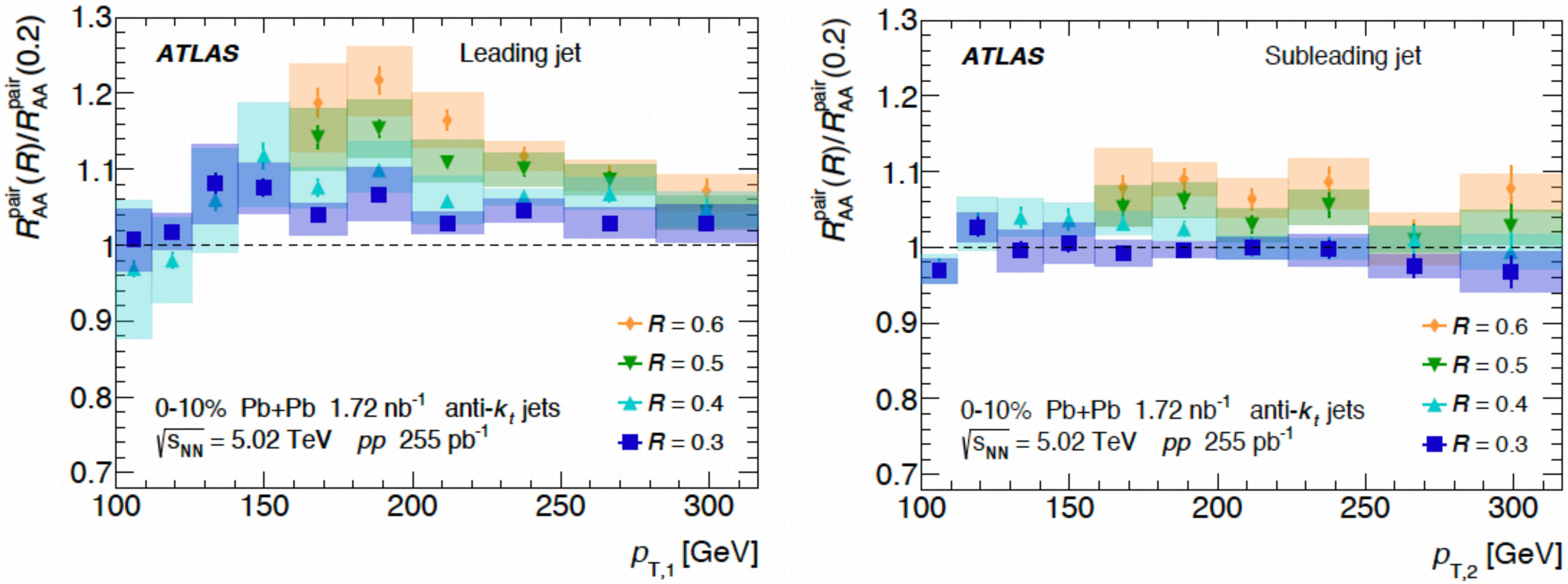


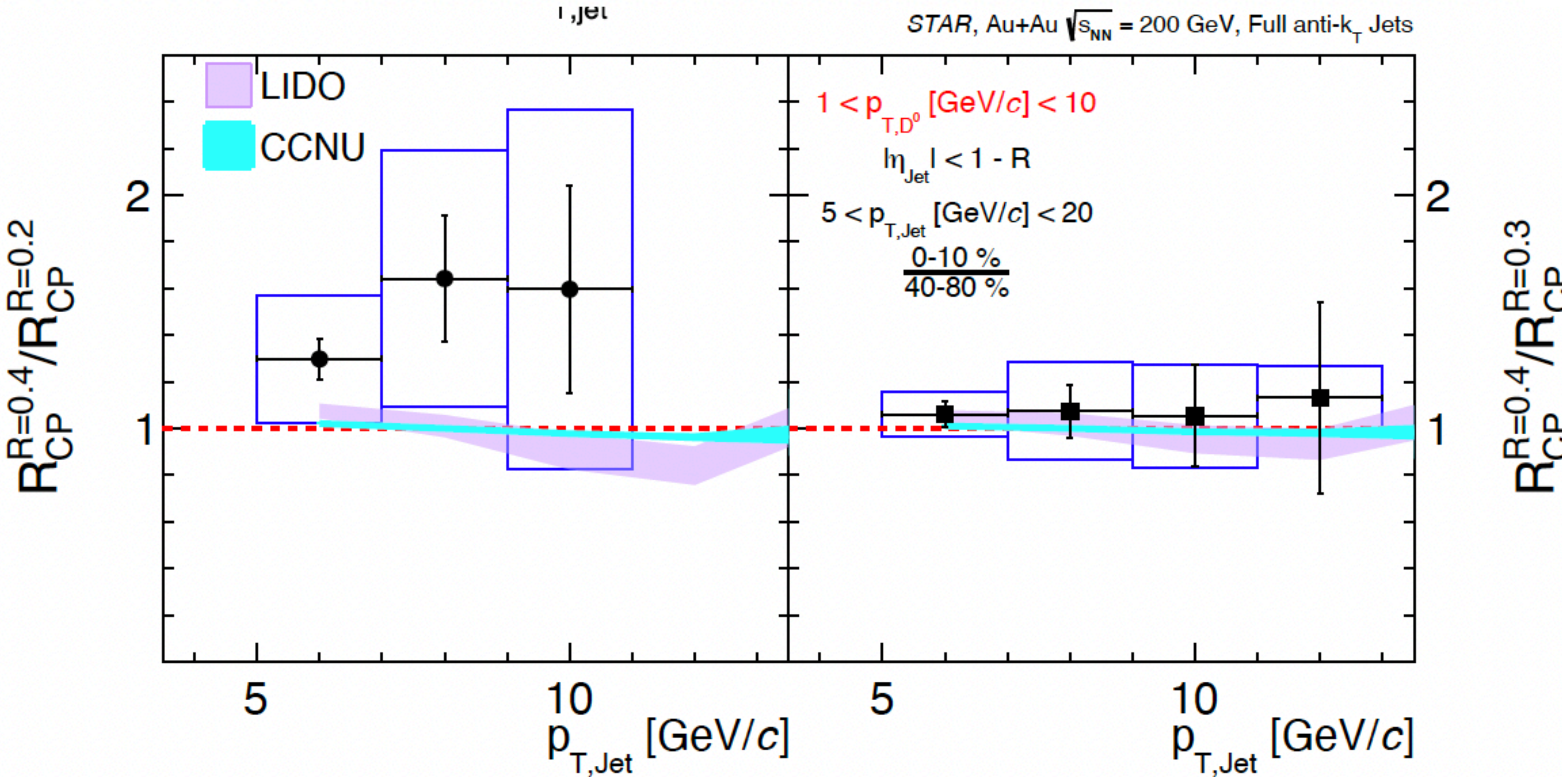
- Inclusive jets R_{AA} ratio from ALICE: larger radius jets more suppressed
- Dijet pair R_{AA} ratio from ATLAS: larger radius jets less suppressed
- B-jet R_{cp} ratio from STAR: no strong radius dependence

R dependence of jet quenching



PLB 849 (2024) 138412

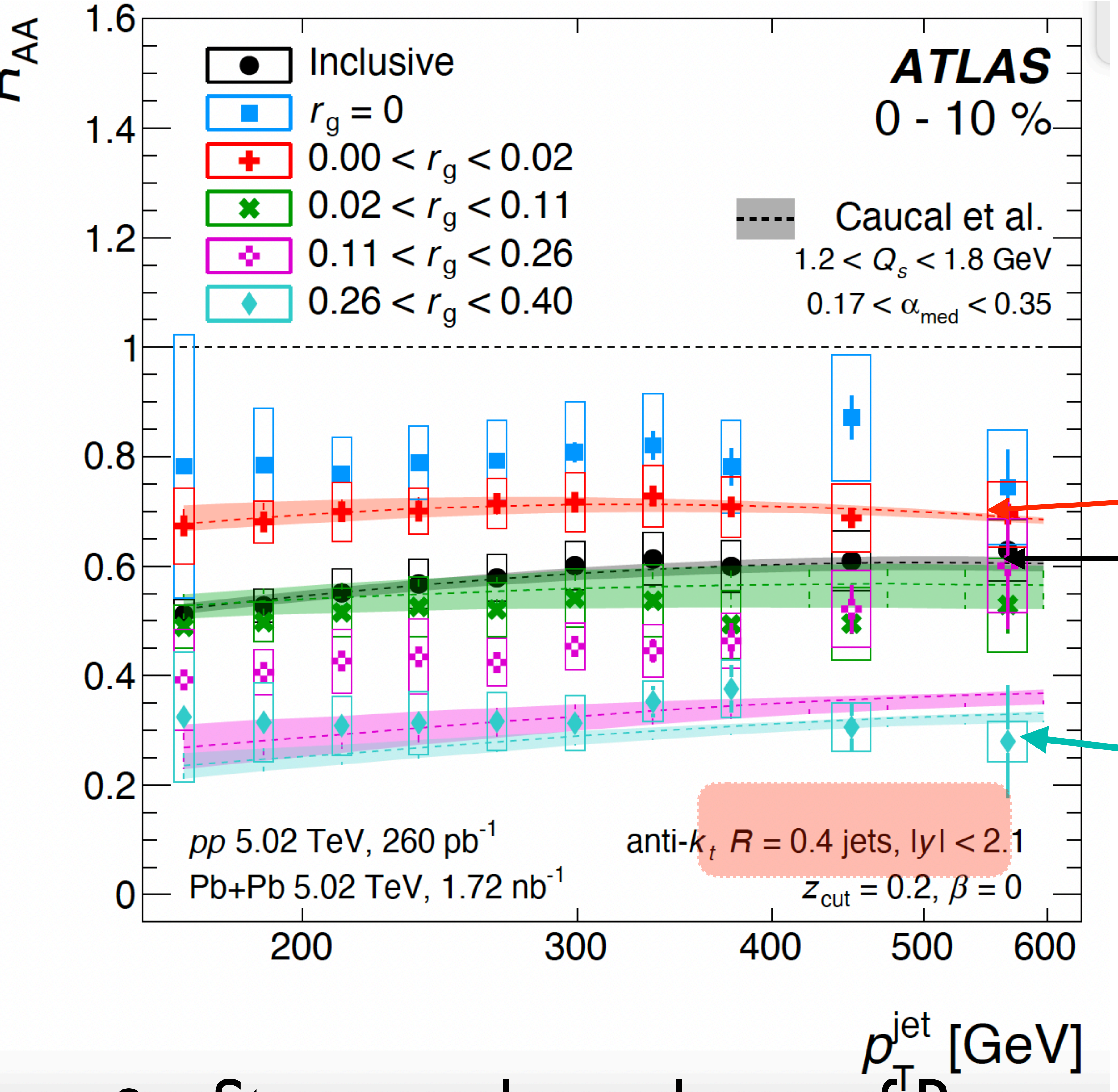


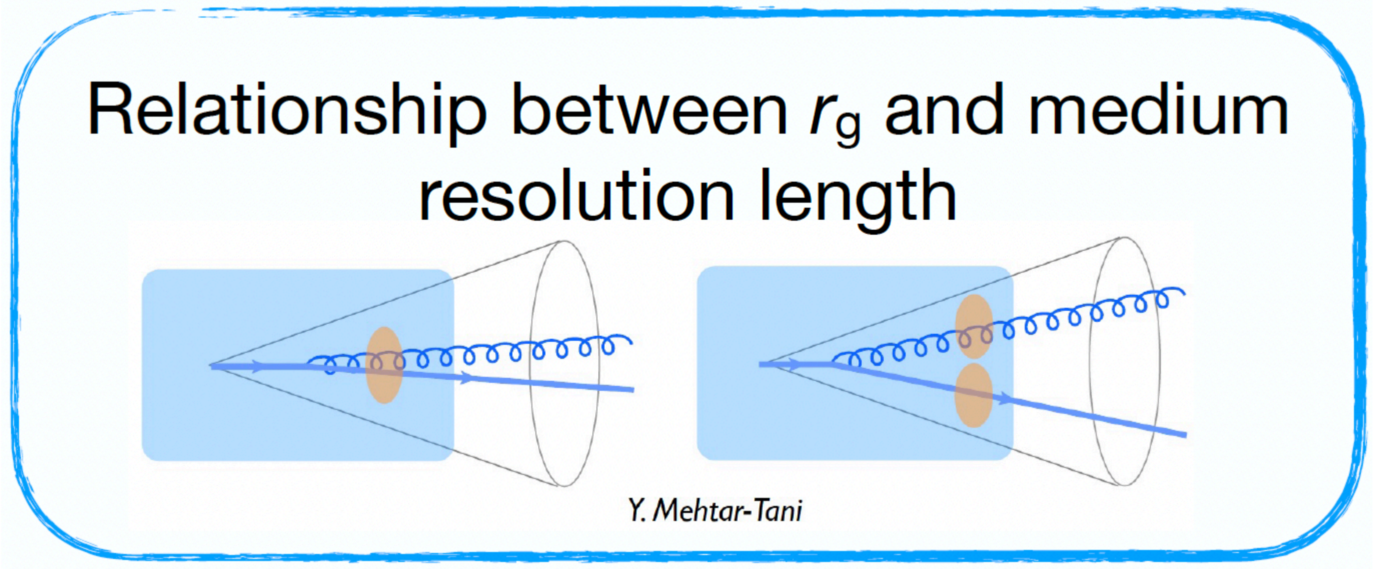


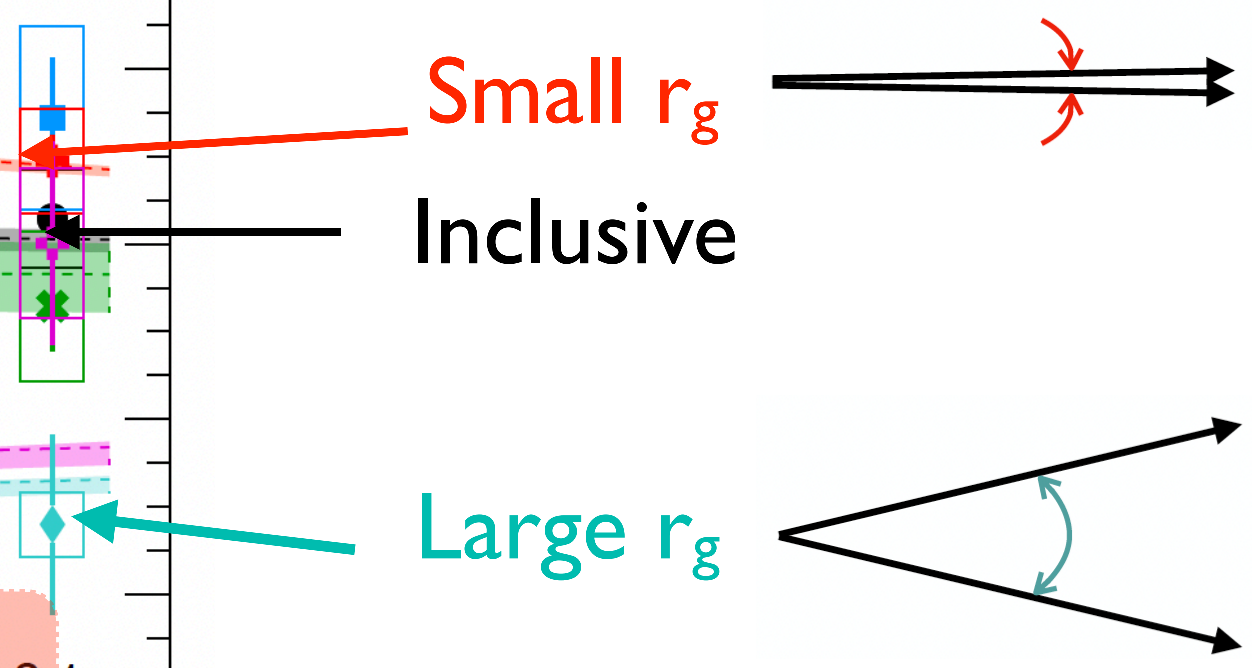
- Not the same jet type (inclusive vs. dijet vs. b-jet)
- Not the same kinematics (q/g fraction and jet structure can be different)
- p_T dependence of energy loss are quite different (no matching for different R jets)

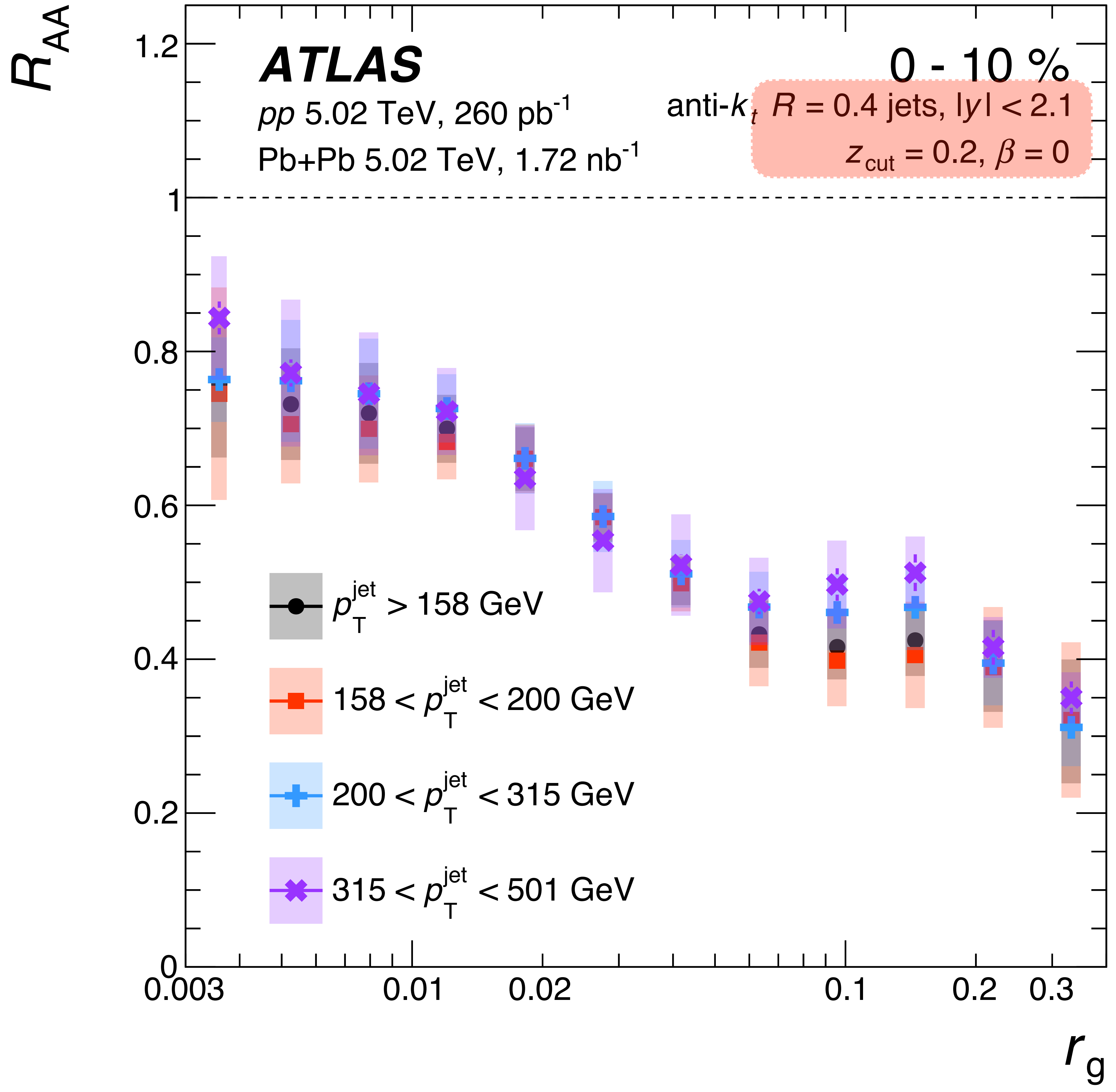
R_{AA} - substructure interplay

PRC 107 (2023) 054909





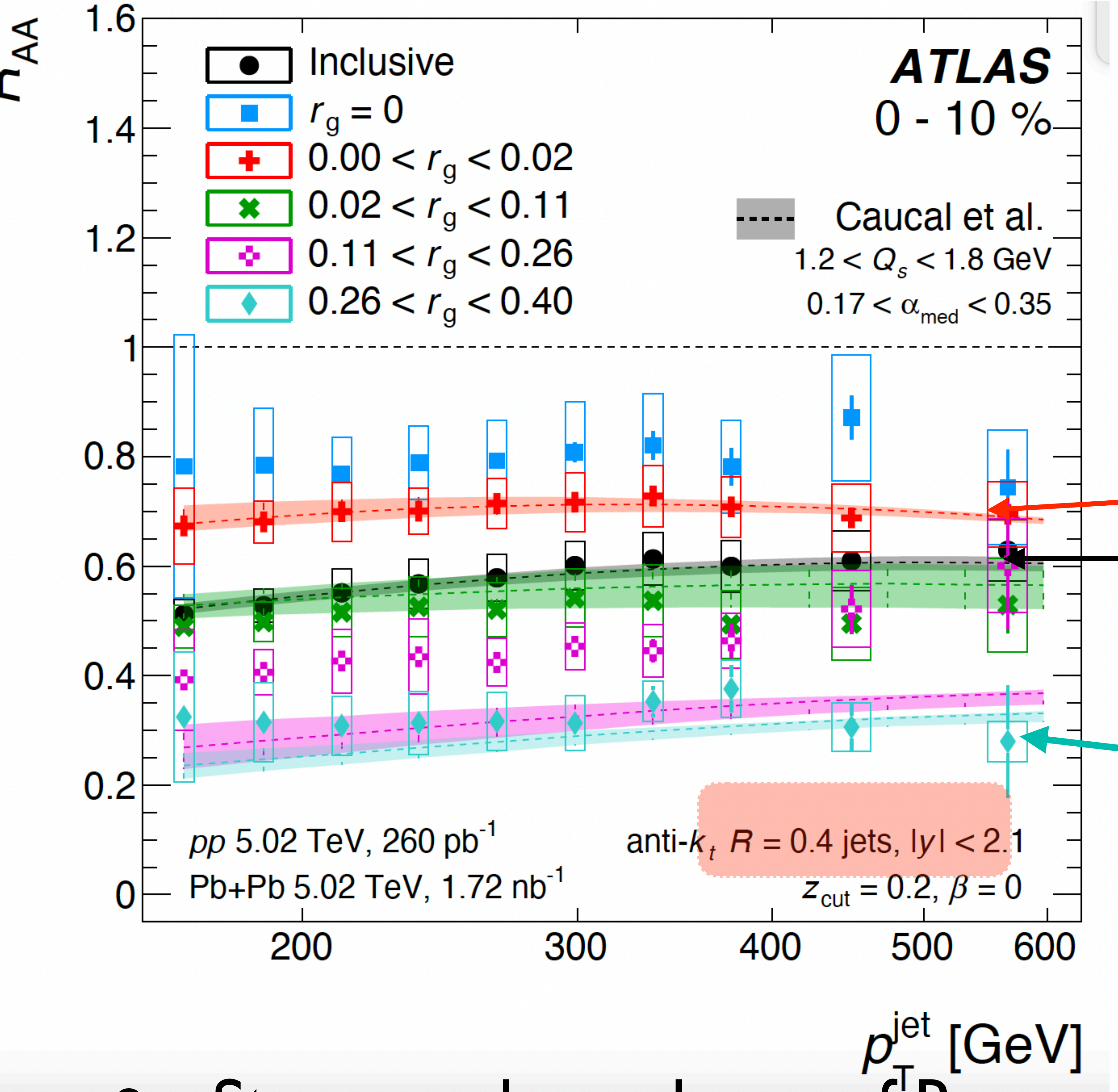


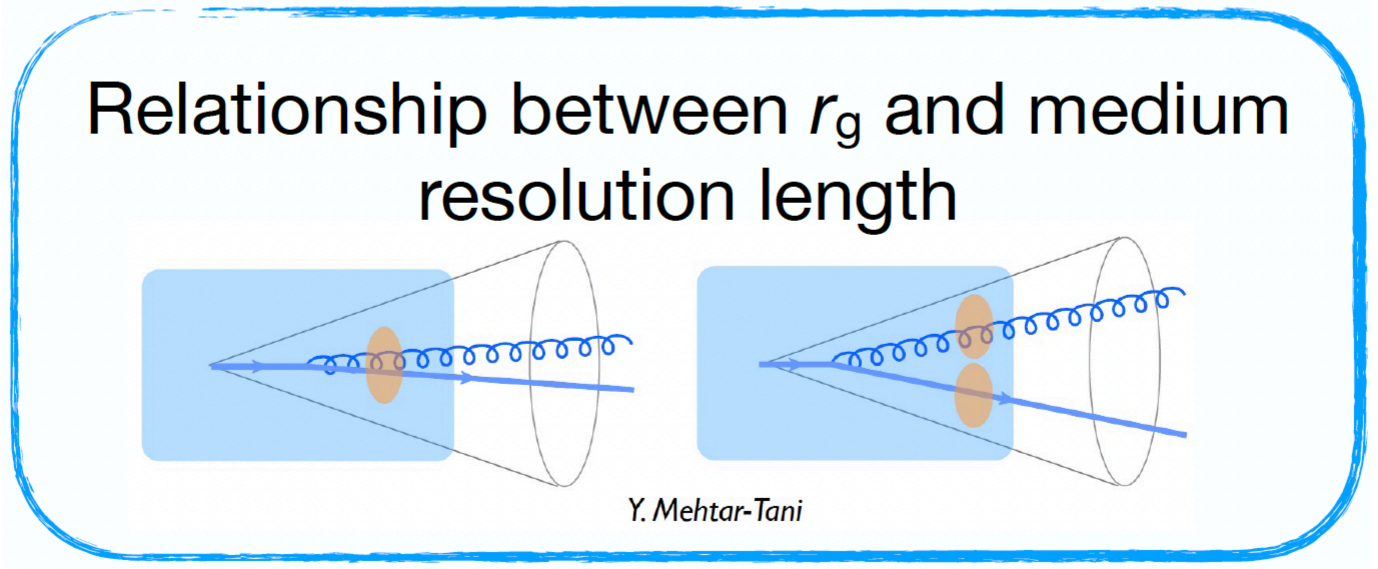


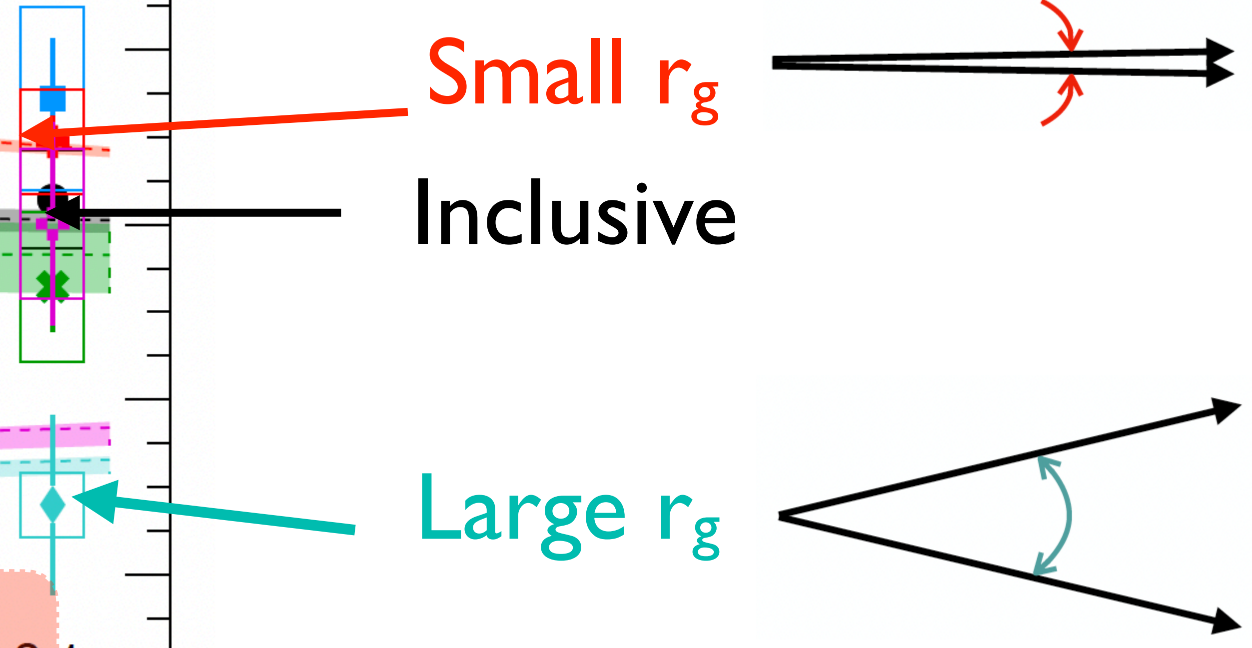
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

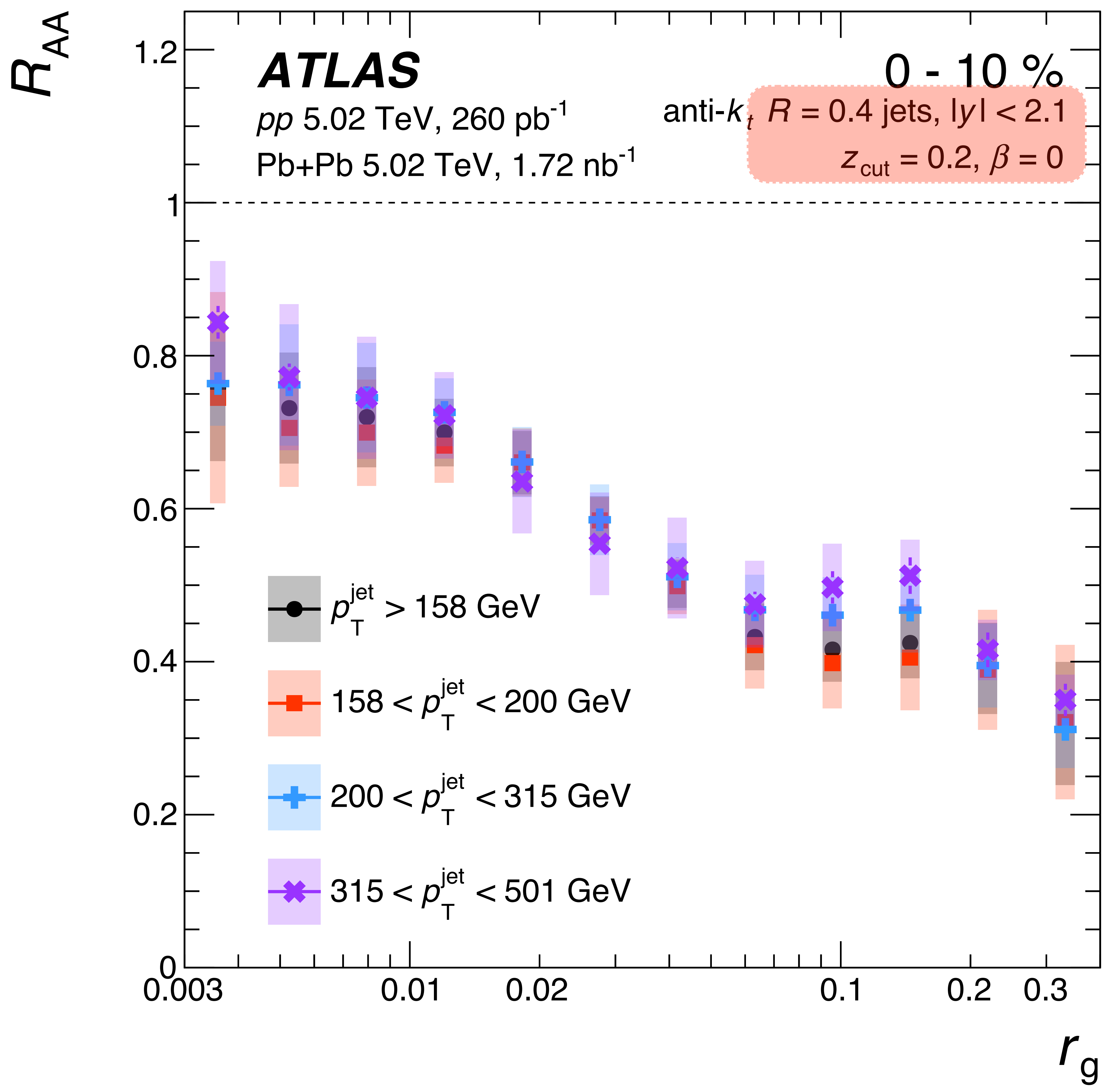
R_{AA} - substructure interplay

PRC 107 (2023) 054909







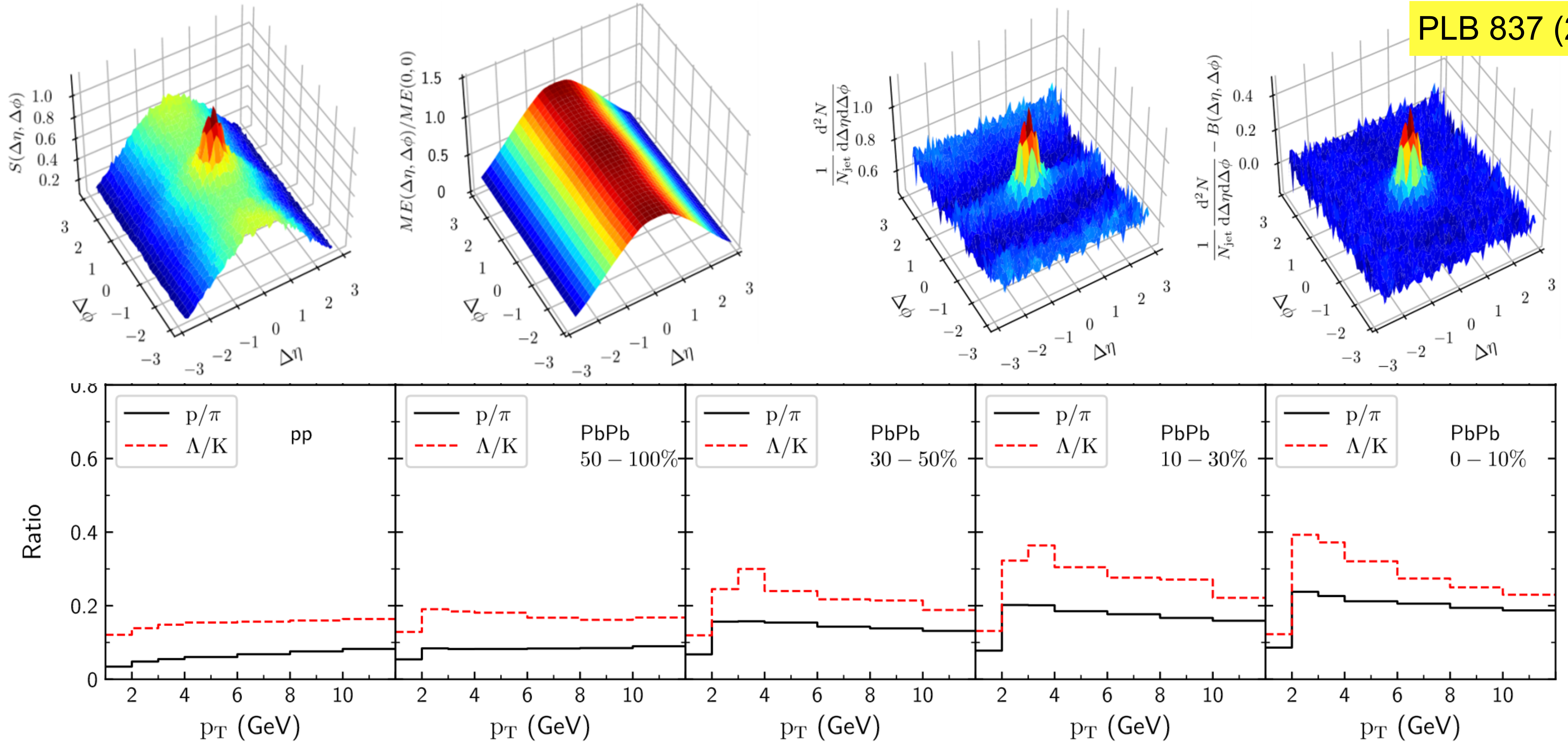


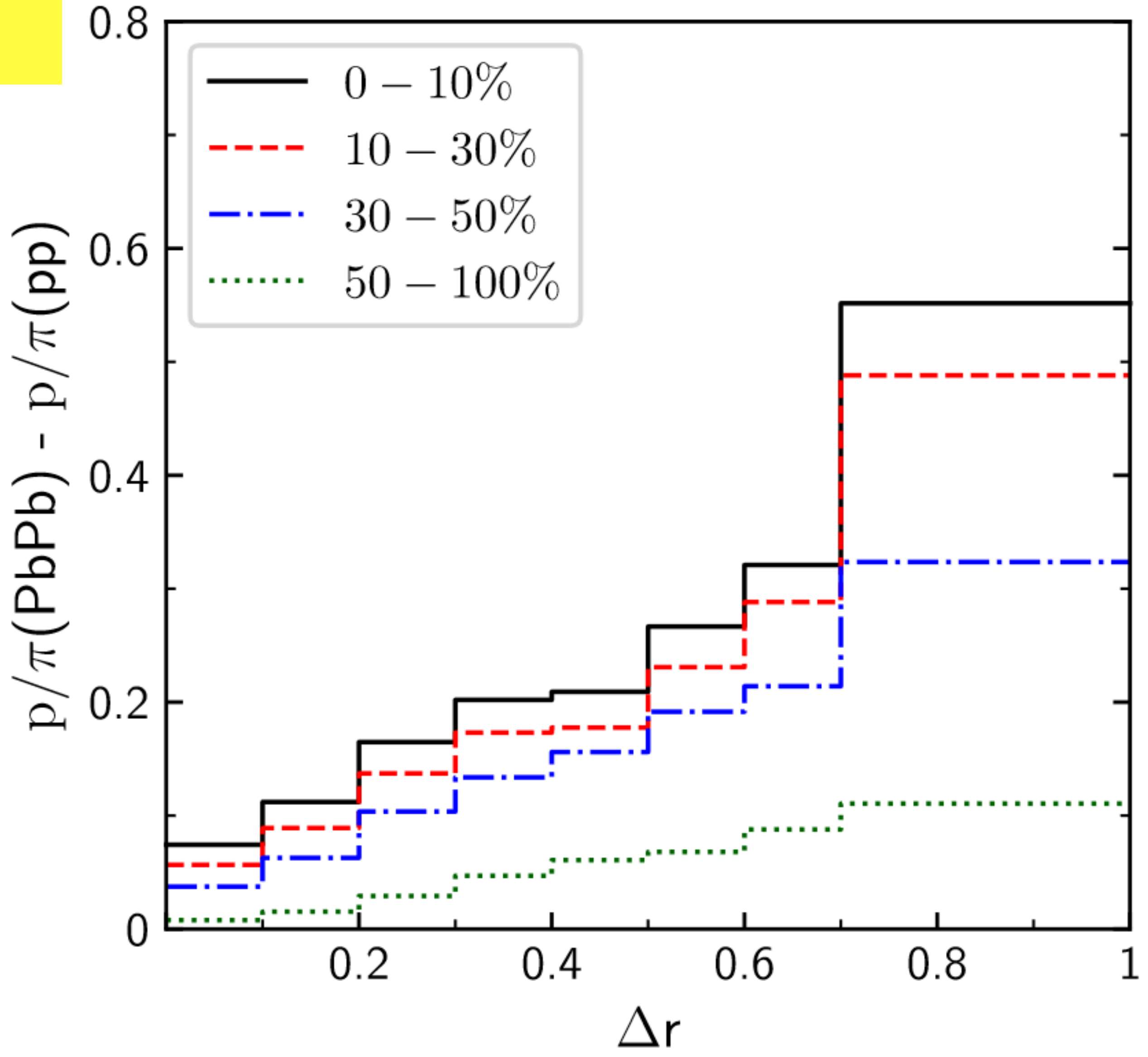
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

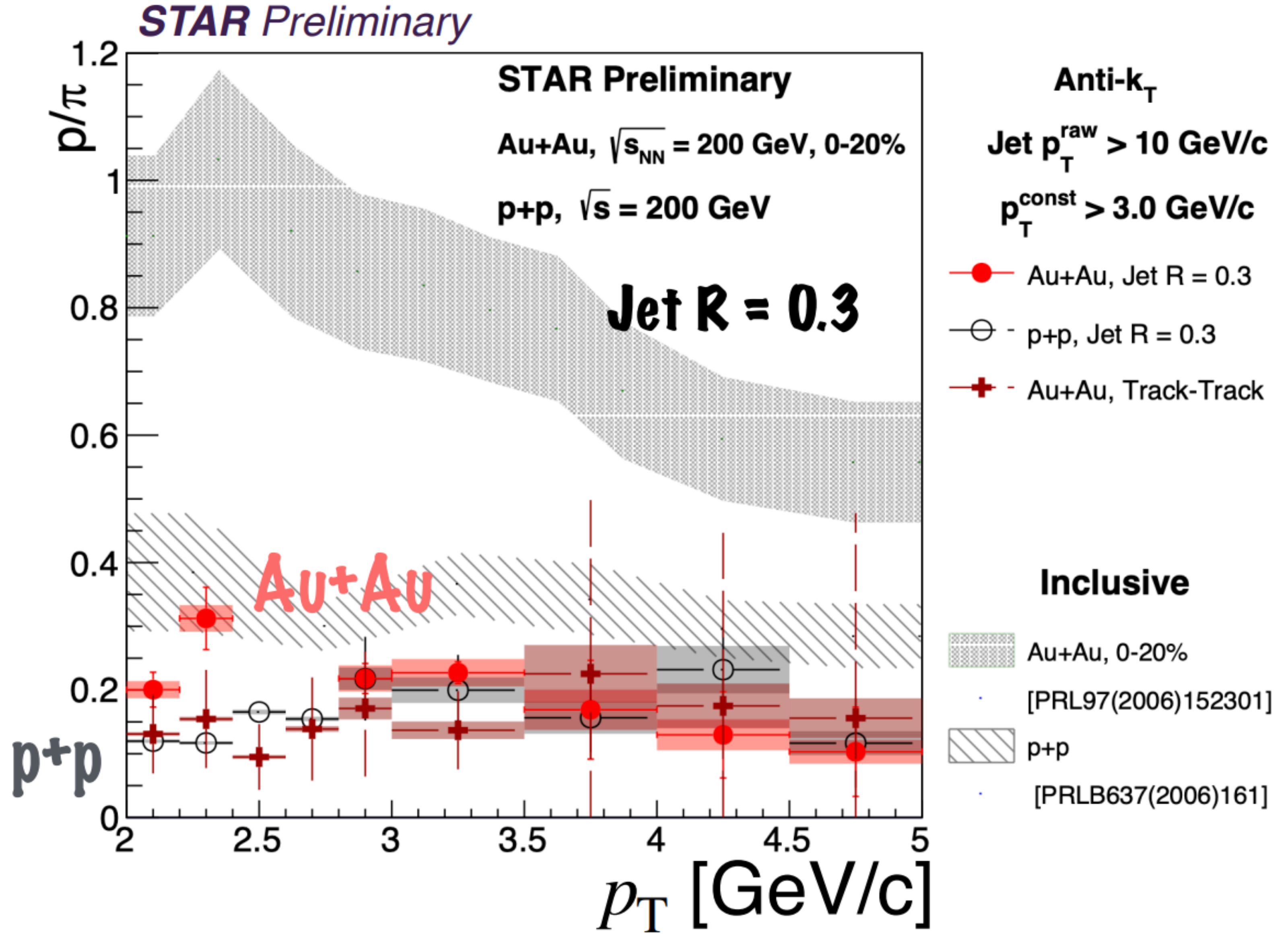
→important to study the r_g dependent R_{AA} with different R

Baryon to meson enhancement around jets

PLB 837 (2023) 137638

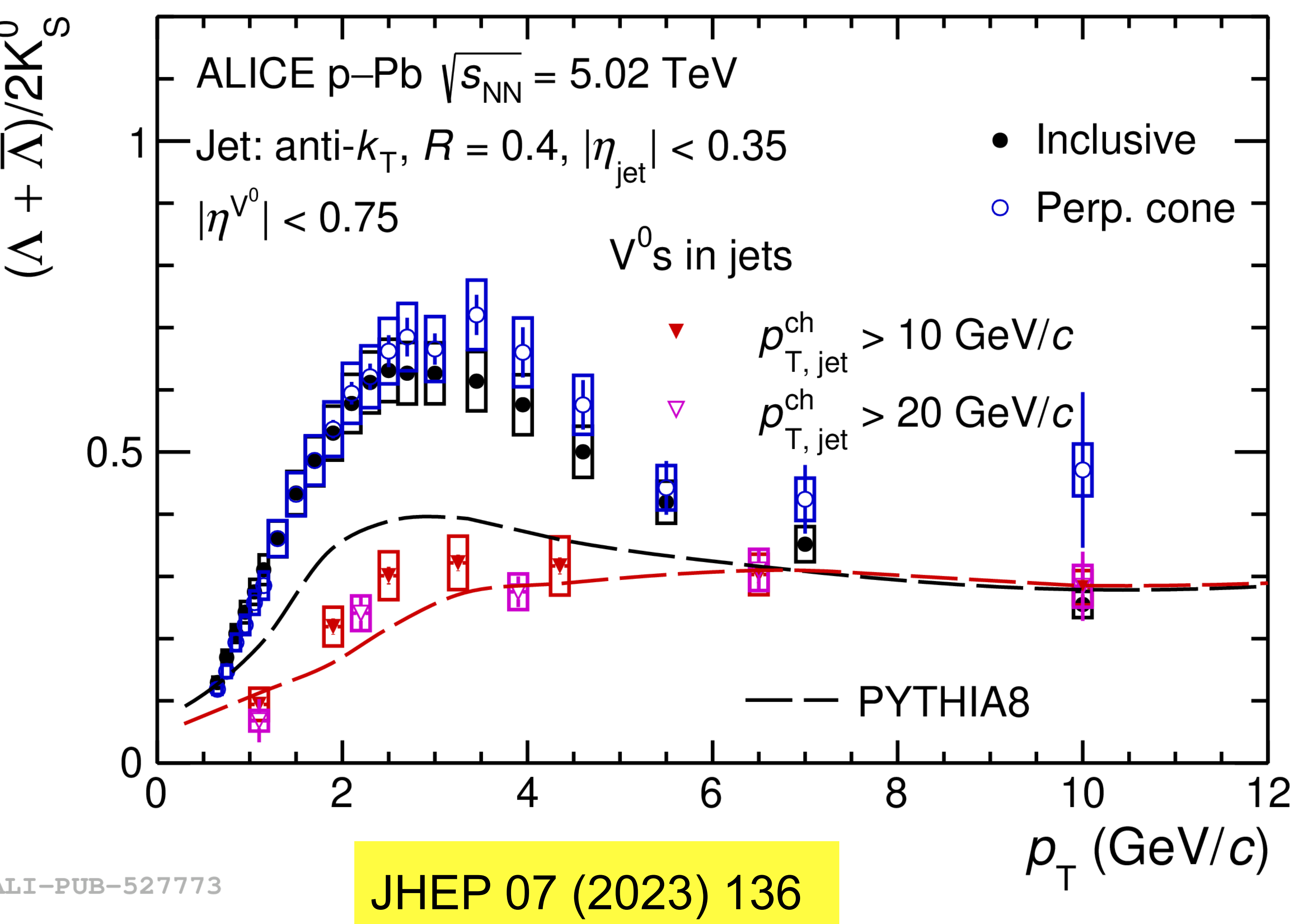




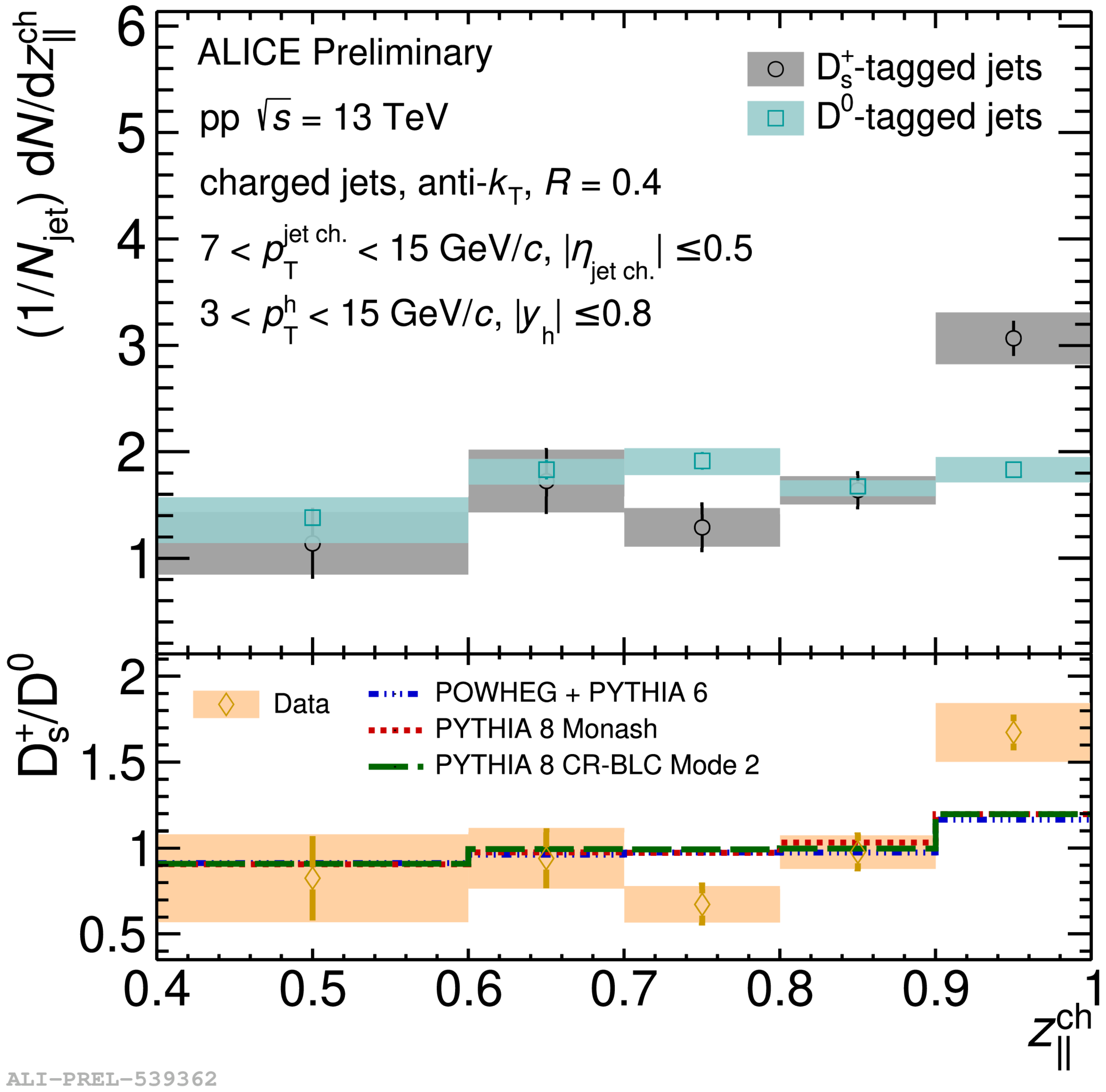


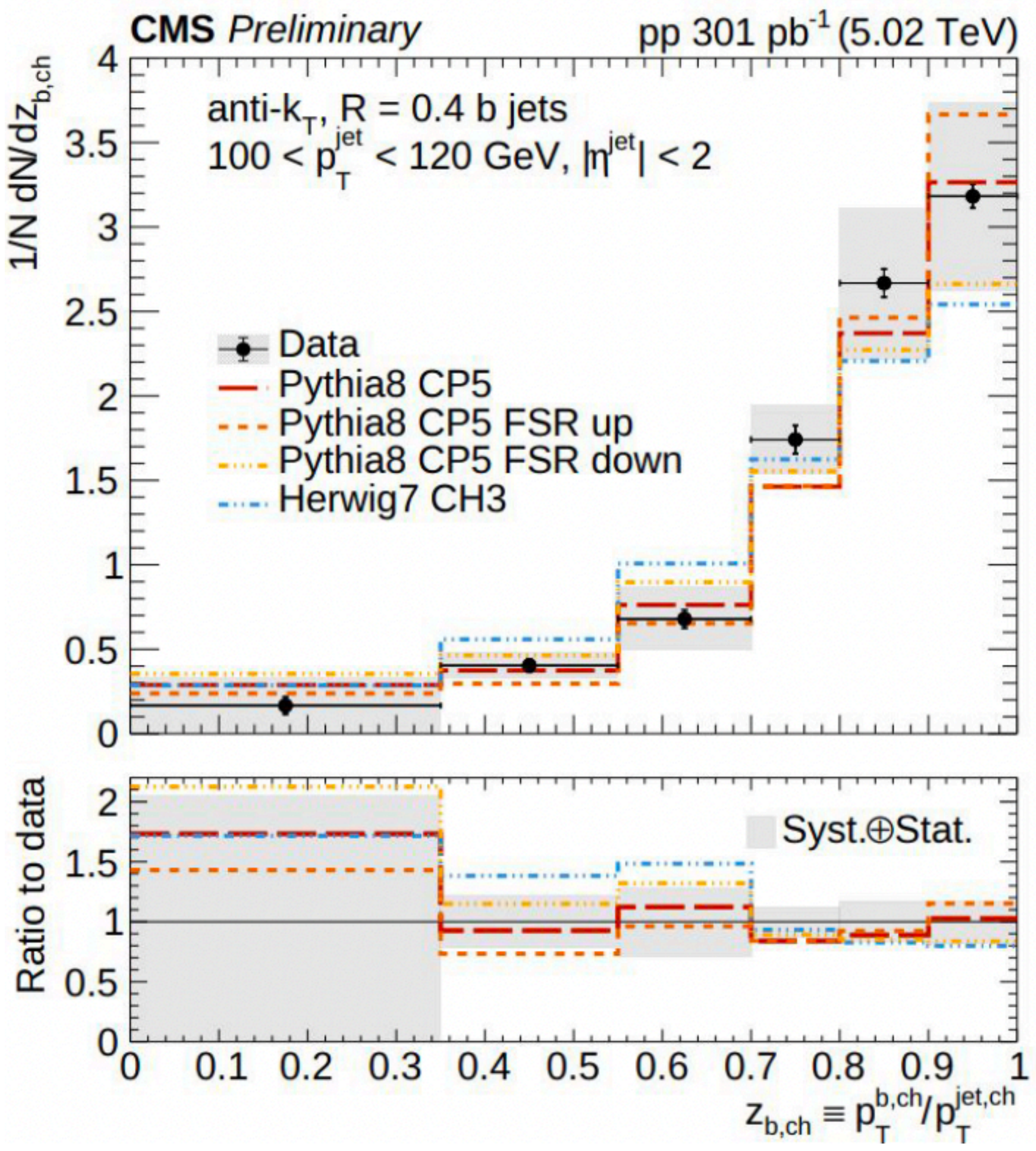
- Strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons
- Enhancement of jet-induced B/M ratios is stronger at intermediate p_T (2-6 GeV/c)for larger distance because the lost energy from quenched jets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

Jet fragmentation into HF particles



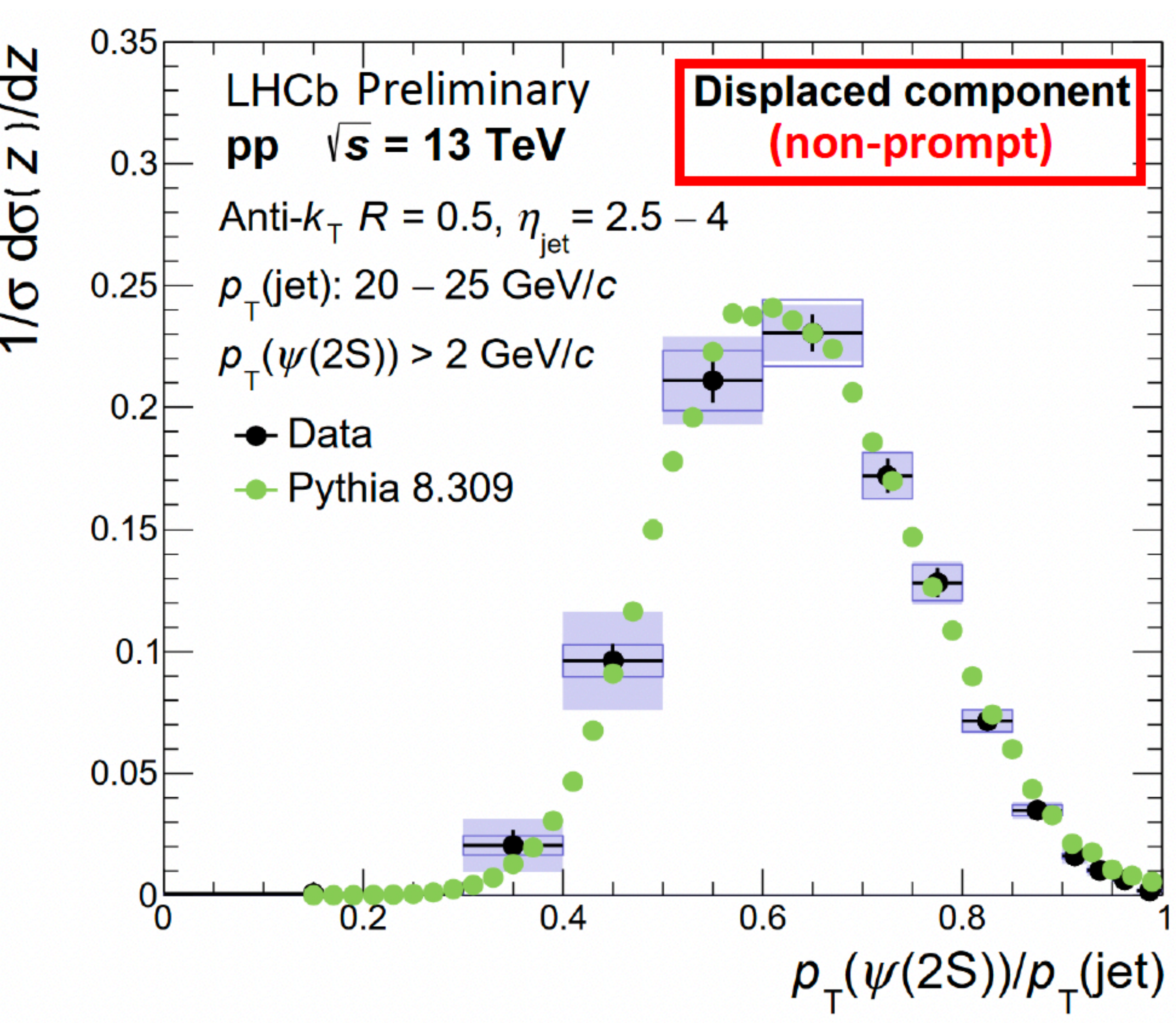
JHEP 07 (2023) 136

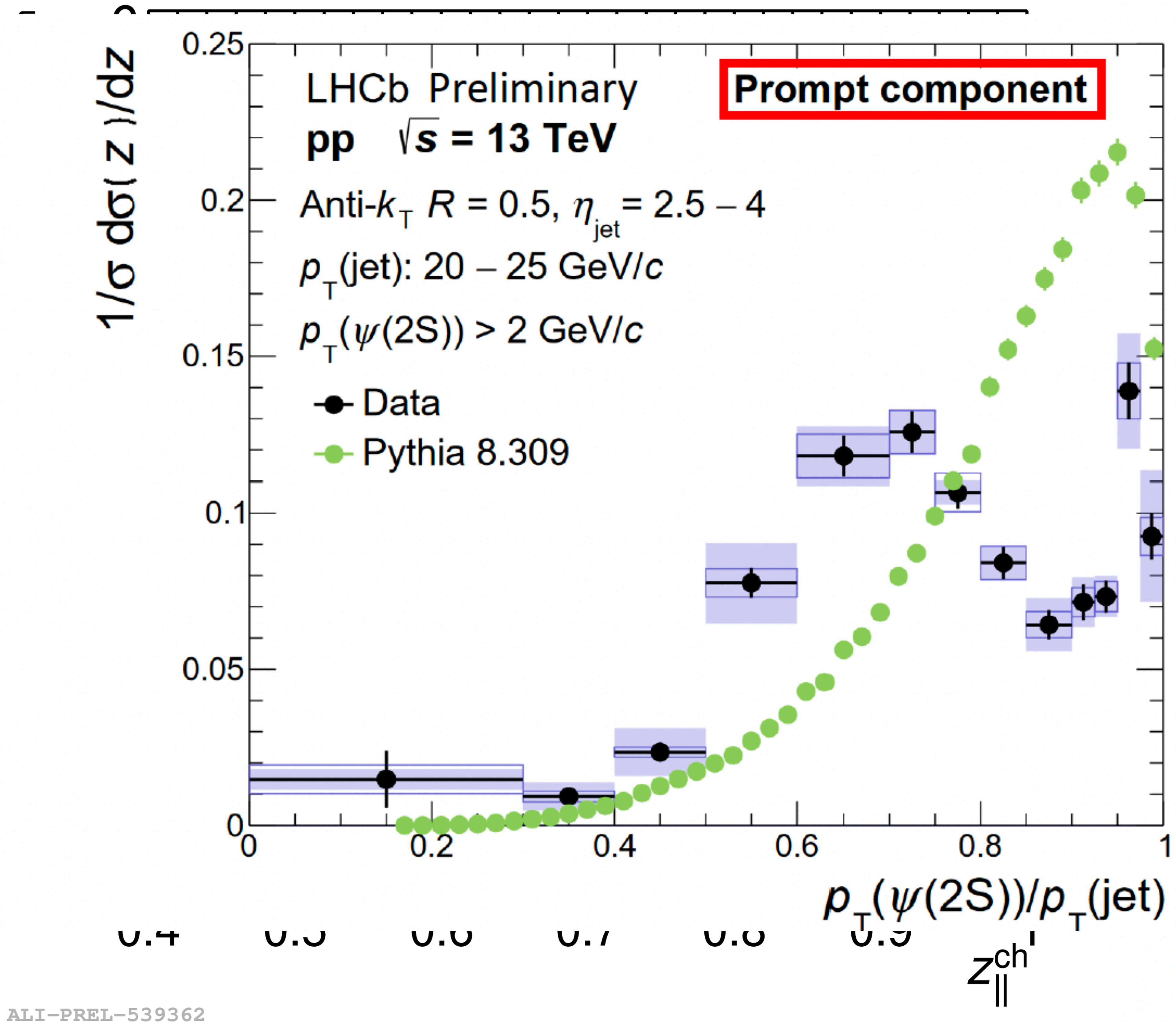


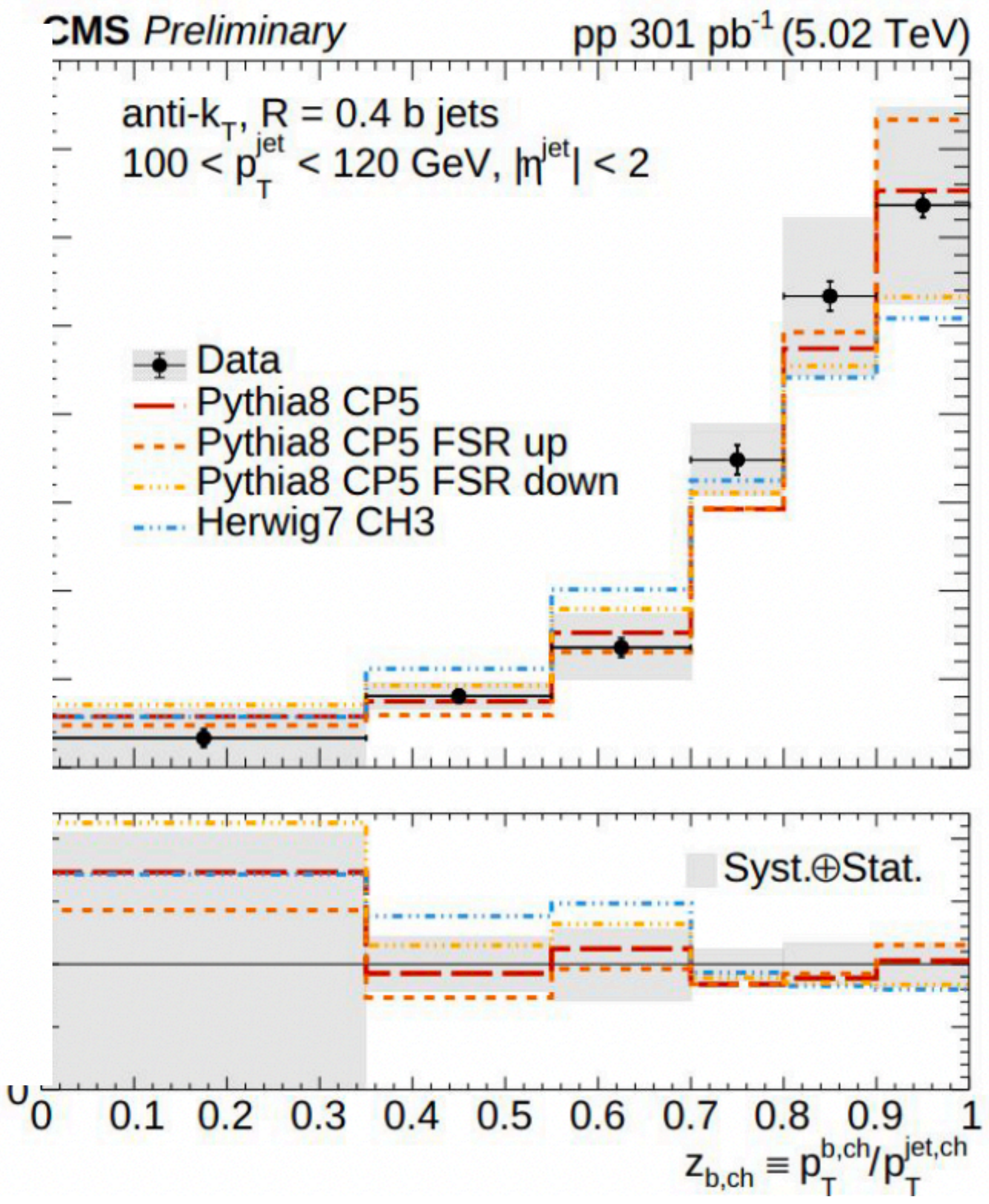


- B/M ratio inside jet cone doesn't show a peak as inclusive case at intermediate p_T
- Charmed-jet fragmentation is slightly different when containing a strangeness quark hadrons

Jet fragmentation into HF particles

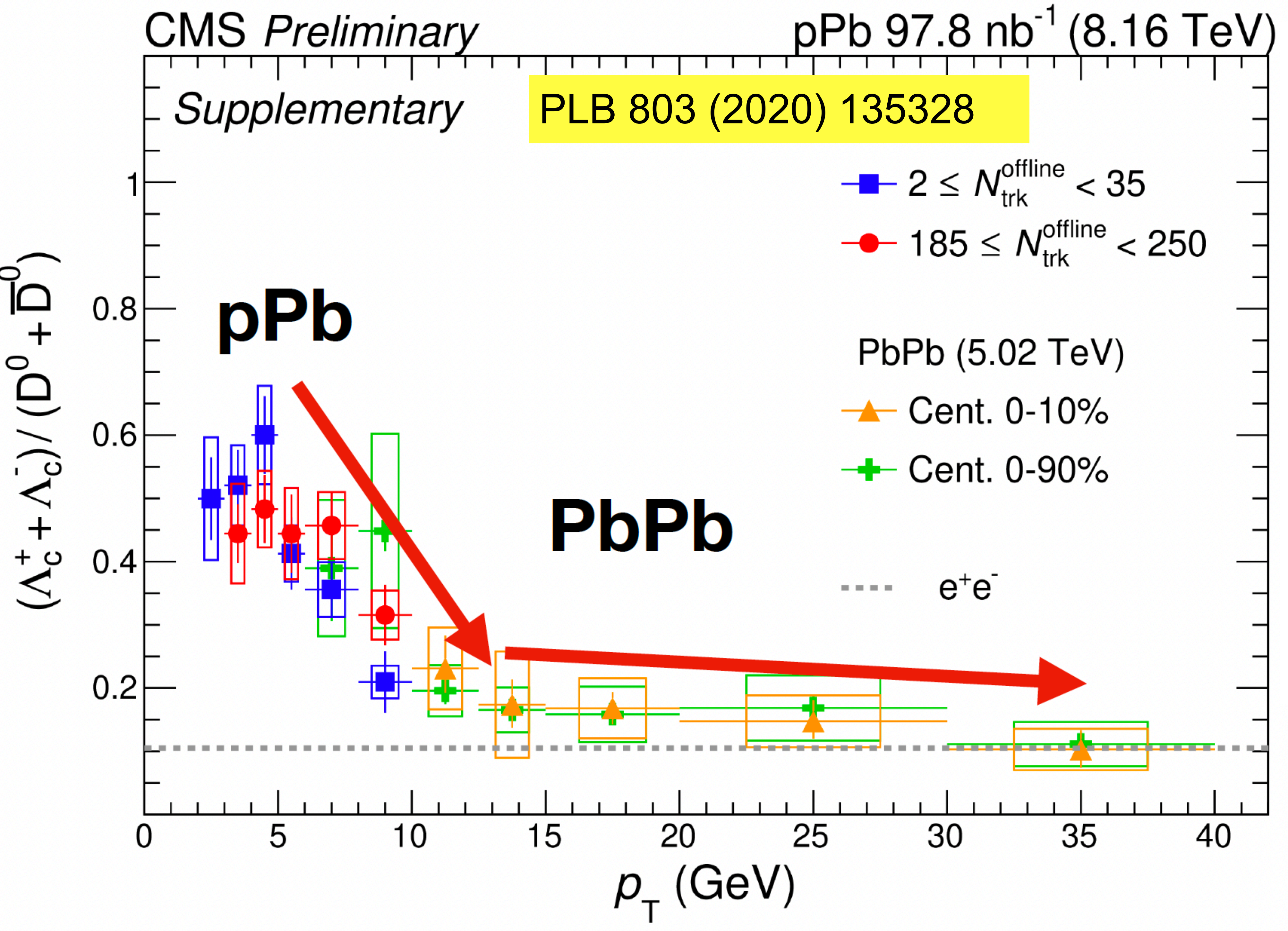


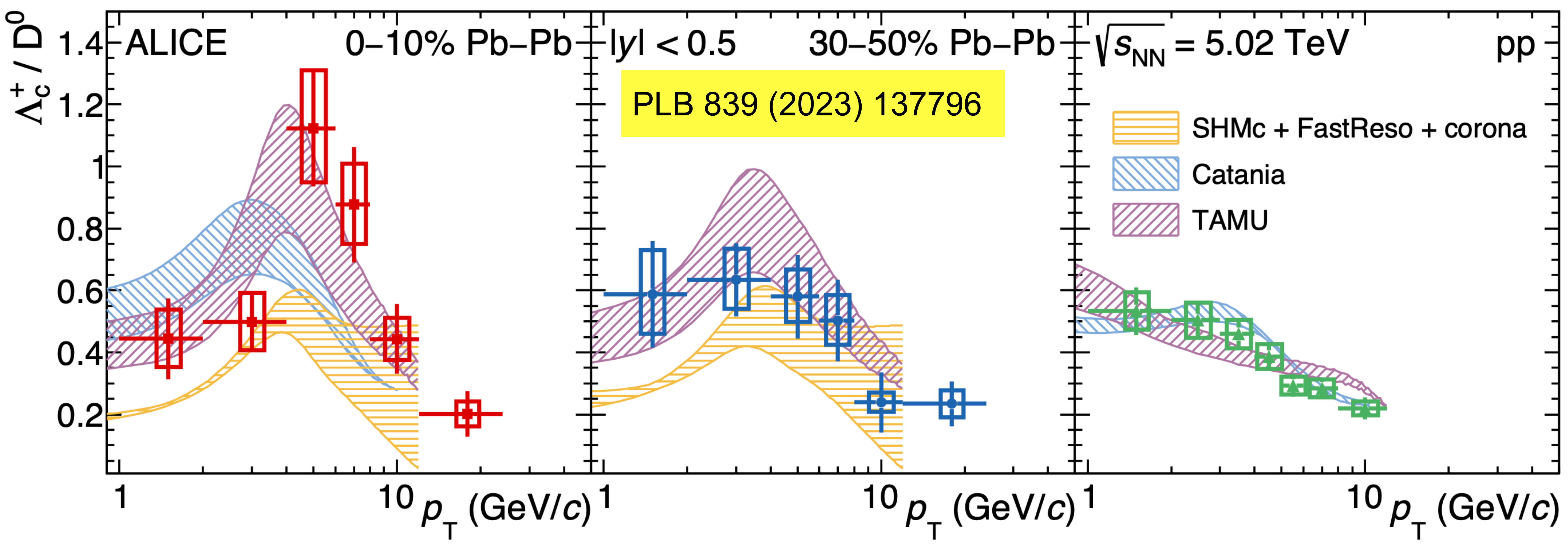




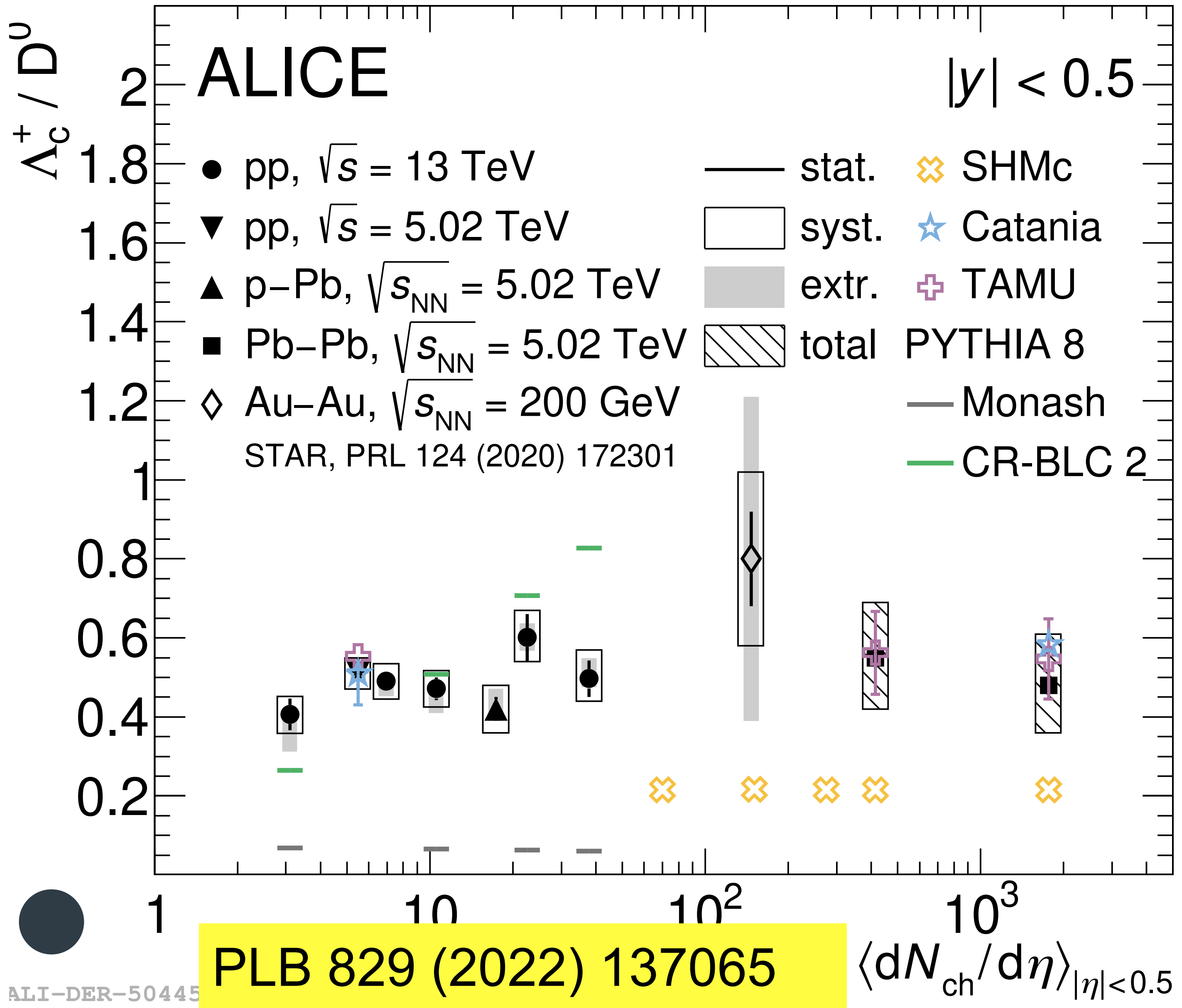
- B/M ratio inside jet cone doesn't show a peak as inclusive case at intermediate p_T
- Charmed-jet fragmentation is slightly different when containing a strangeness quark hadrons
- PYTHIA can't produce quarkonium jet fragmentation ψ(2S) →further development of theoretical models are needed

Heavy flavor hadronization: B/M ratio

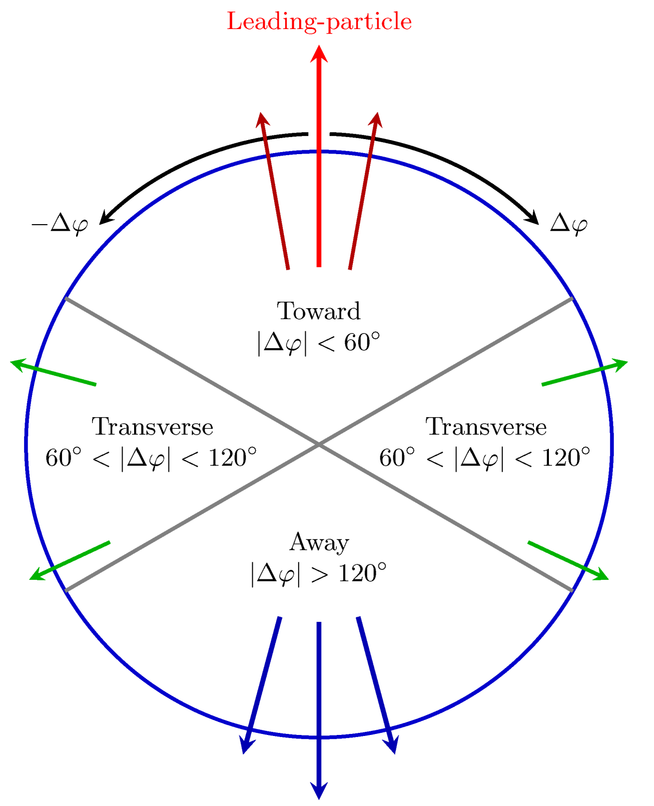




- Enhanced baryon to meson ratio (Λ_c^+/D^0) compared to e+e- collisions at low p_T, regardless of centrality or multiplicity
- Higher p_T behavior close to e+e- baseline
- TAMU model can reproduce the Λ_c^+/D^0 ratio in both pp and Pb-Pb collisions



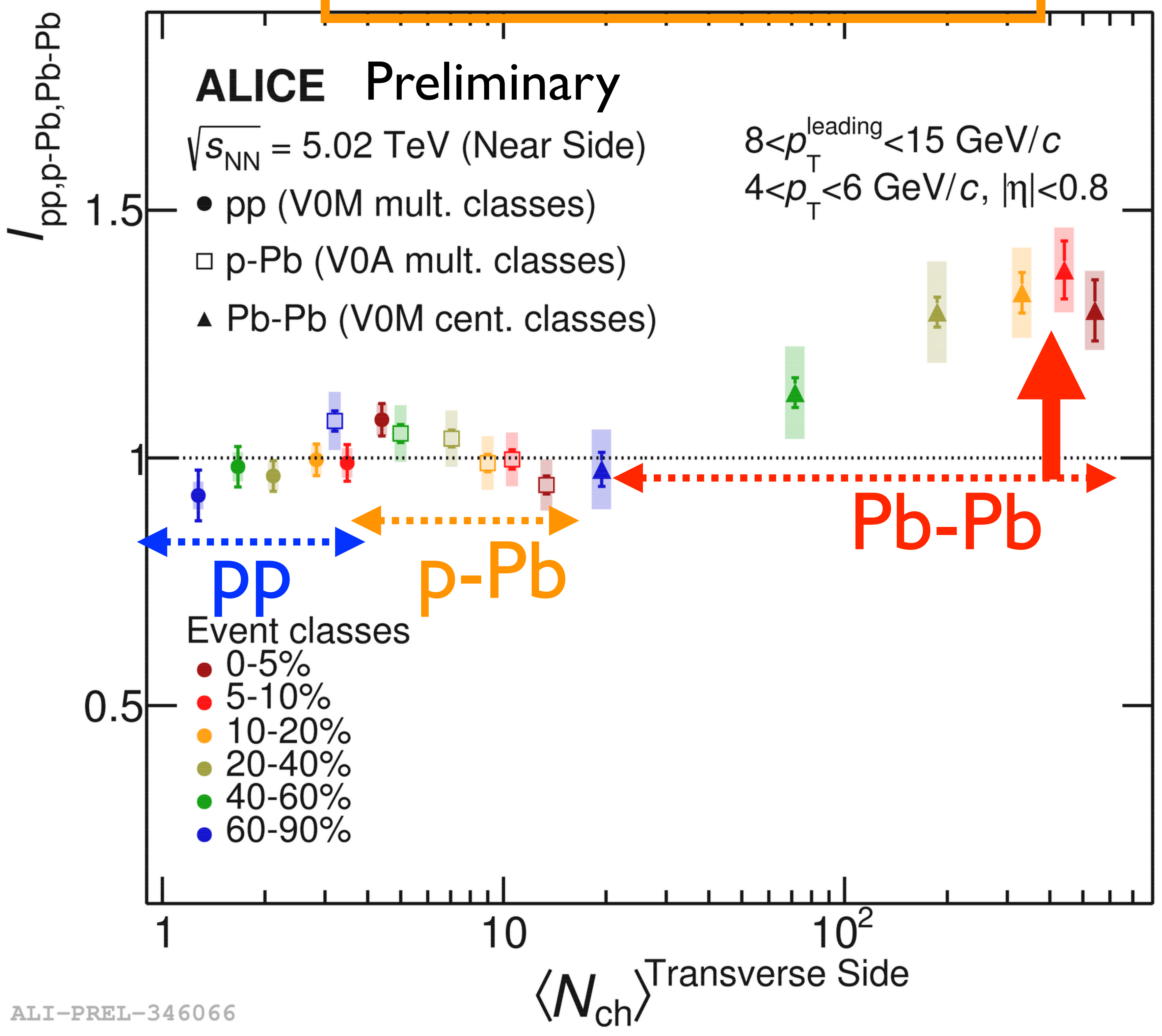
Search for jet quenching in small systems



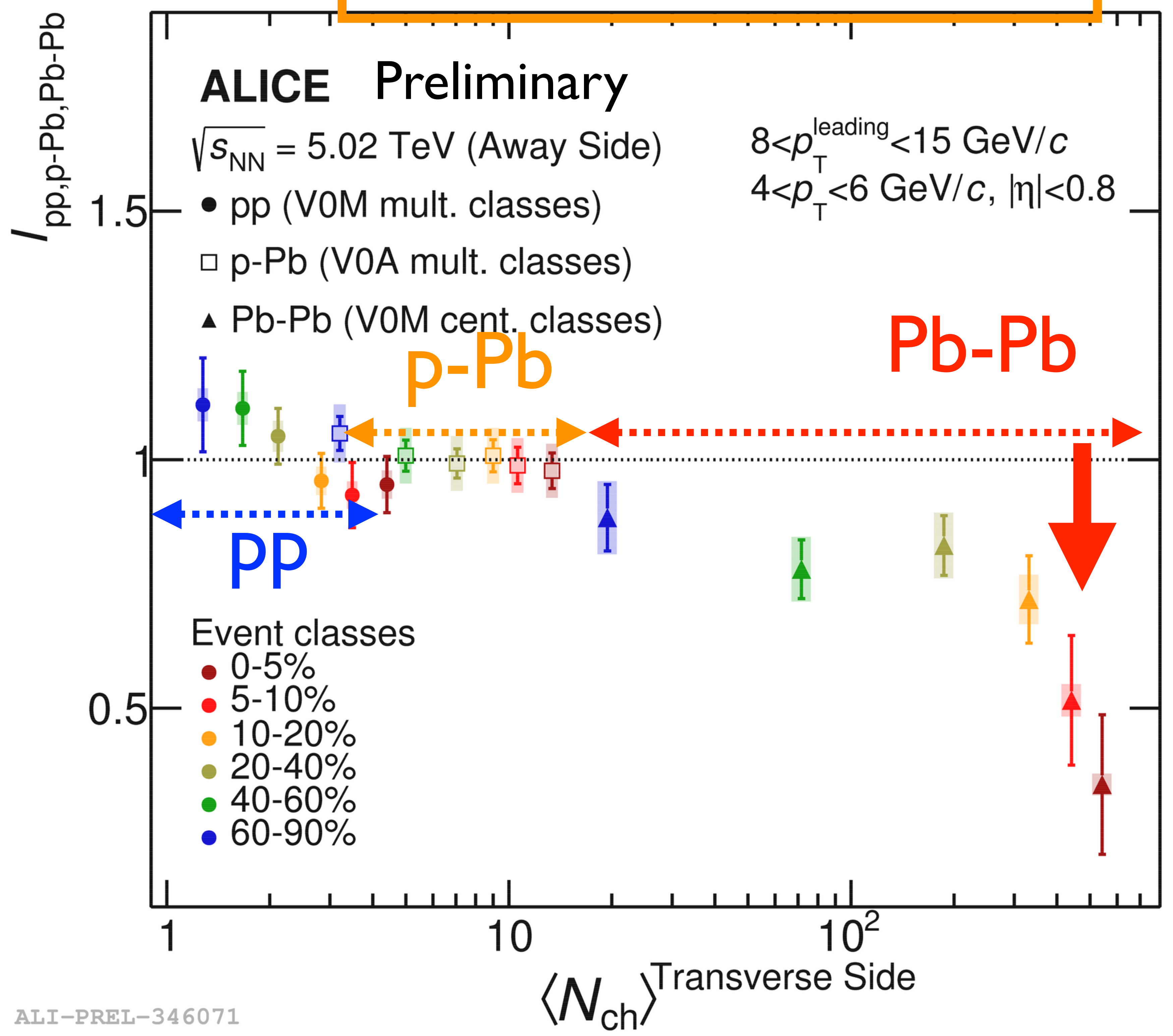
$\Delta\phi = |\phi_{\text{leading}} - \phi_{\text{associate}}|$

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

Near side: $|\Delta\phi| < 60^{\circ}$

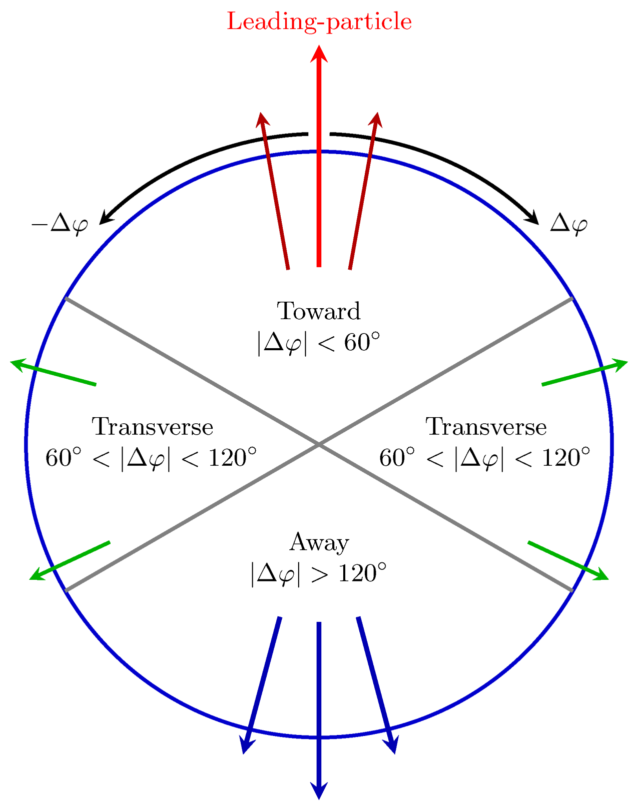


Away side: $|\Delta\phi| > 120^{\circ}$



- 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

Search for jet quenching in small systems



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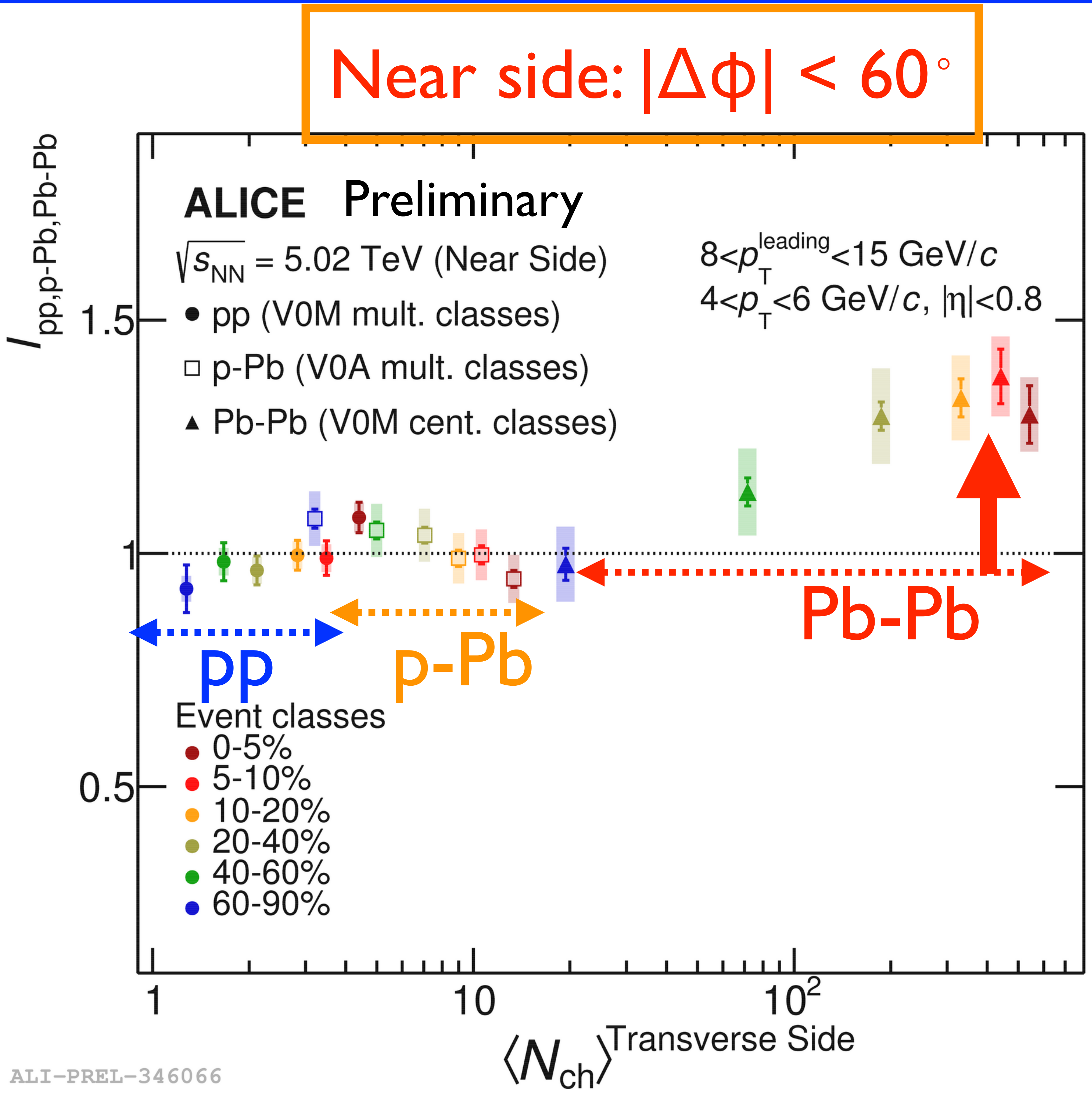
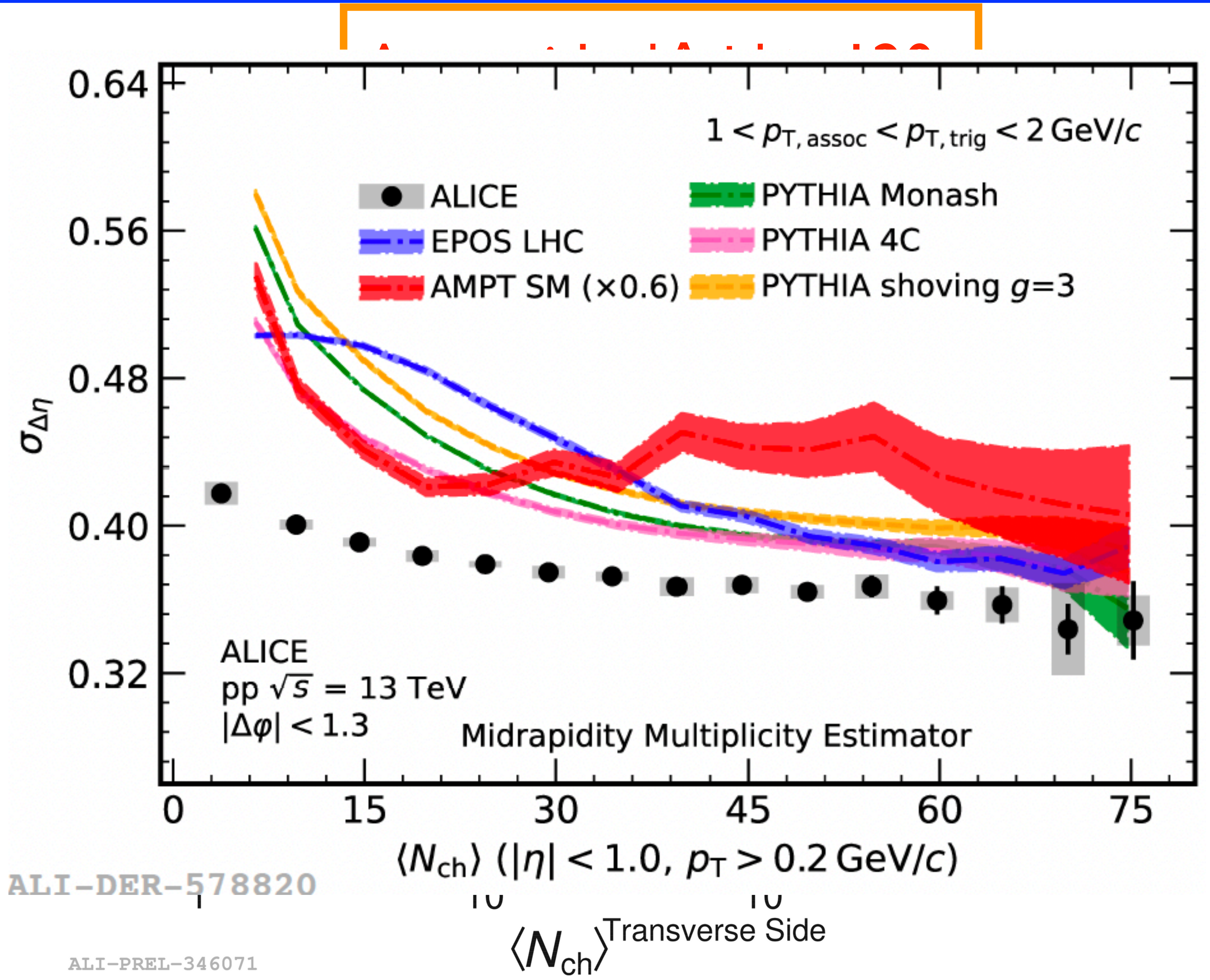
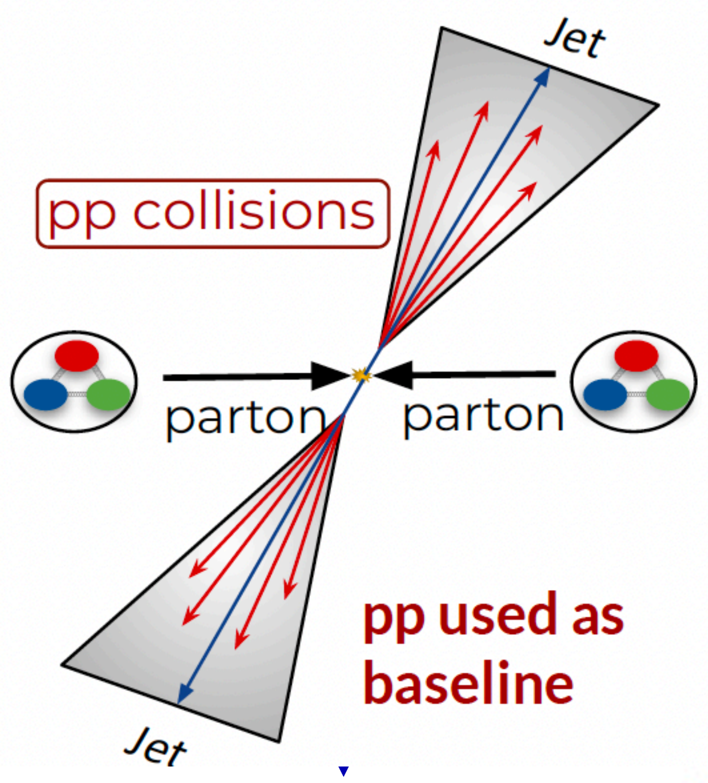
$$I_{pp/pA/AA} = \frac{Yield^{pp/pA/AA}_{NS/AS}}{(Yield^{pp/pA/AA}_{NS/AS})_{min.bias}}$$

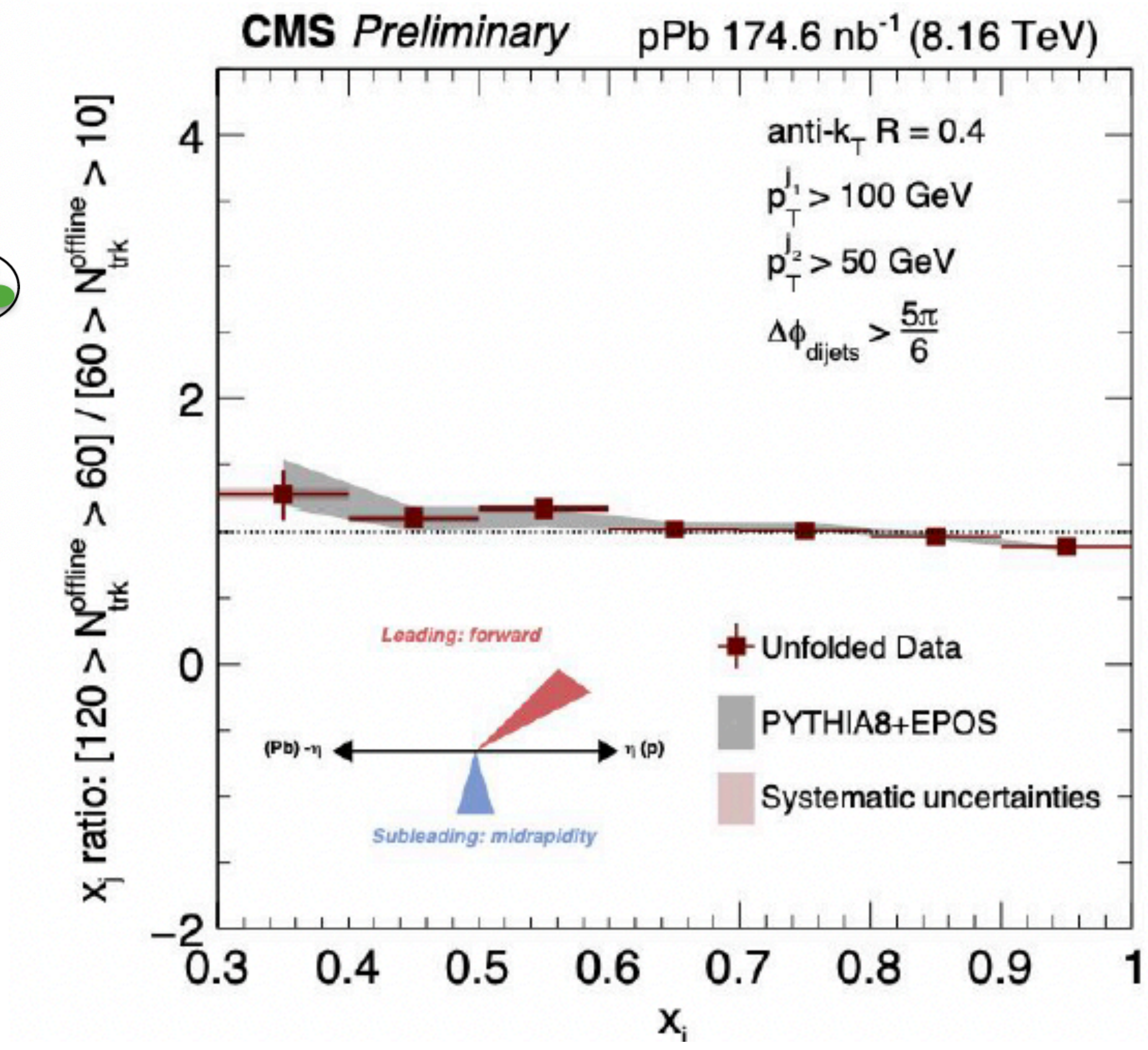


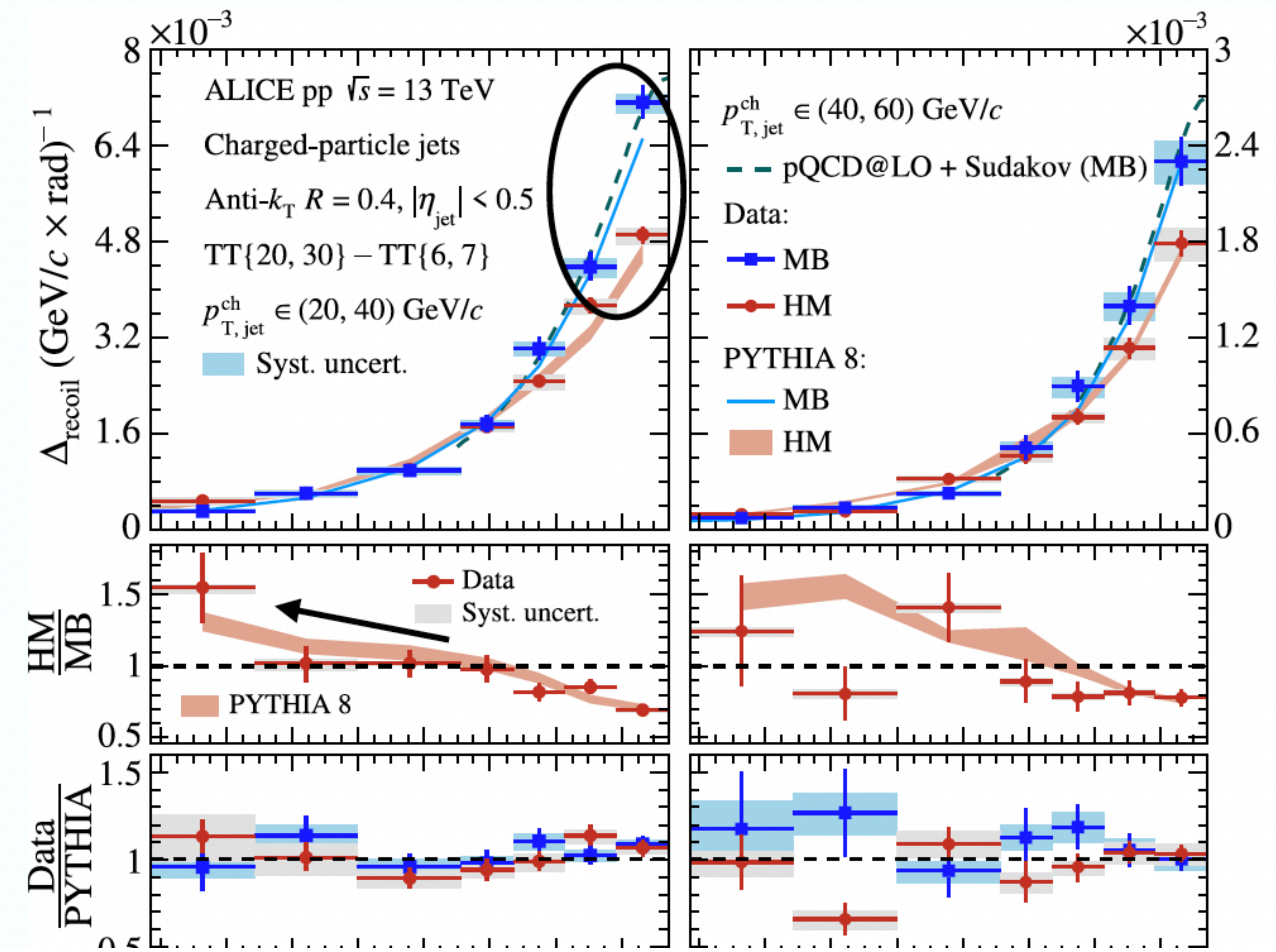


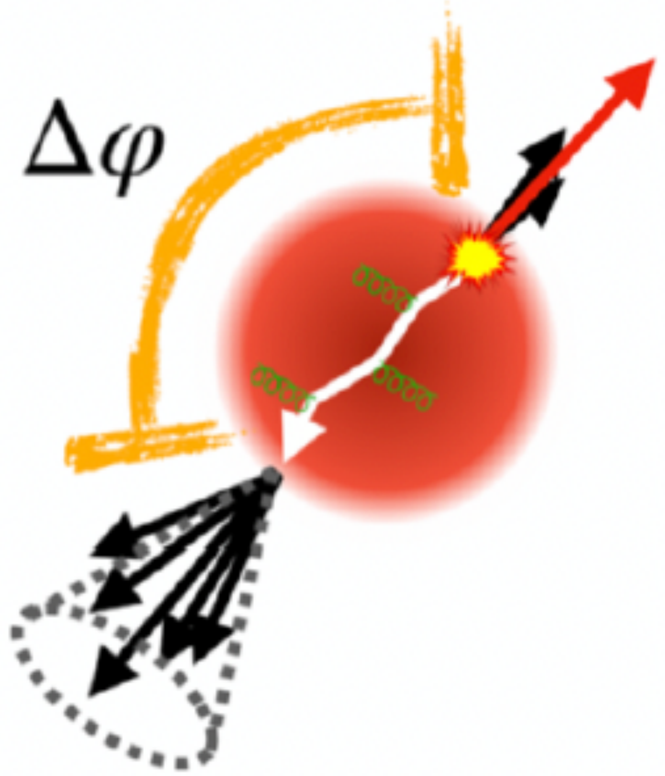
- Using multiplicity in transverse region as event activity classifier to better separate soft and hard processes
  - No enhancement (suppression) observed for Near (Away) side in pp and p-Pb collisions
  - Peak width become narrower in HM events for low p_T associated particles

Search for jet quenching in small systems



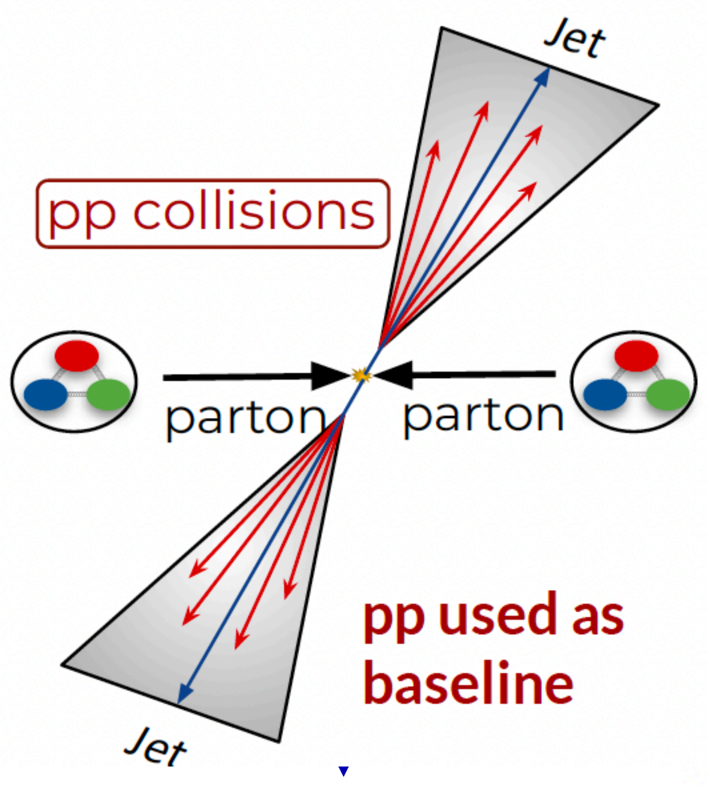


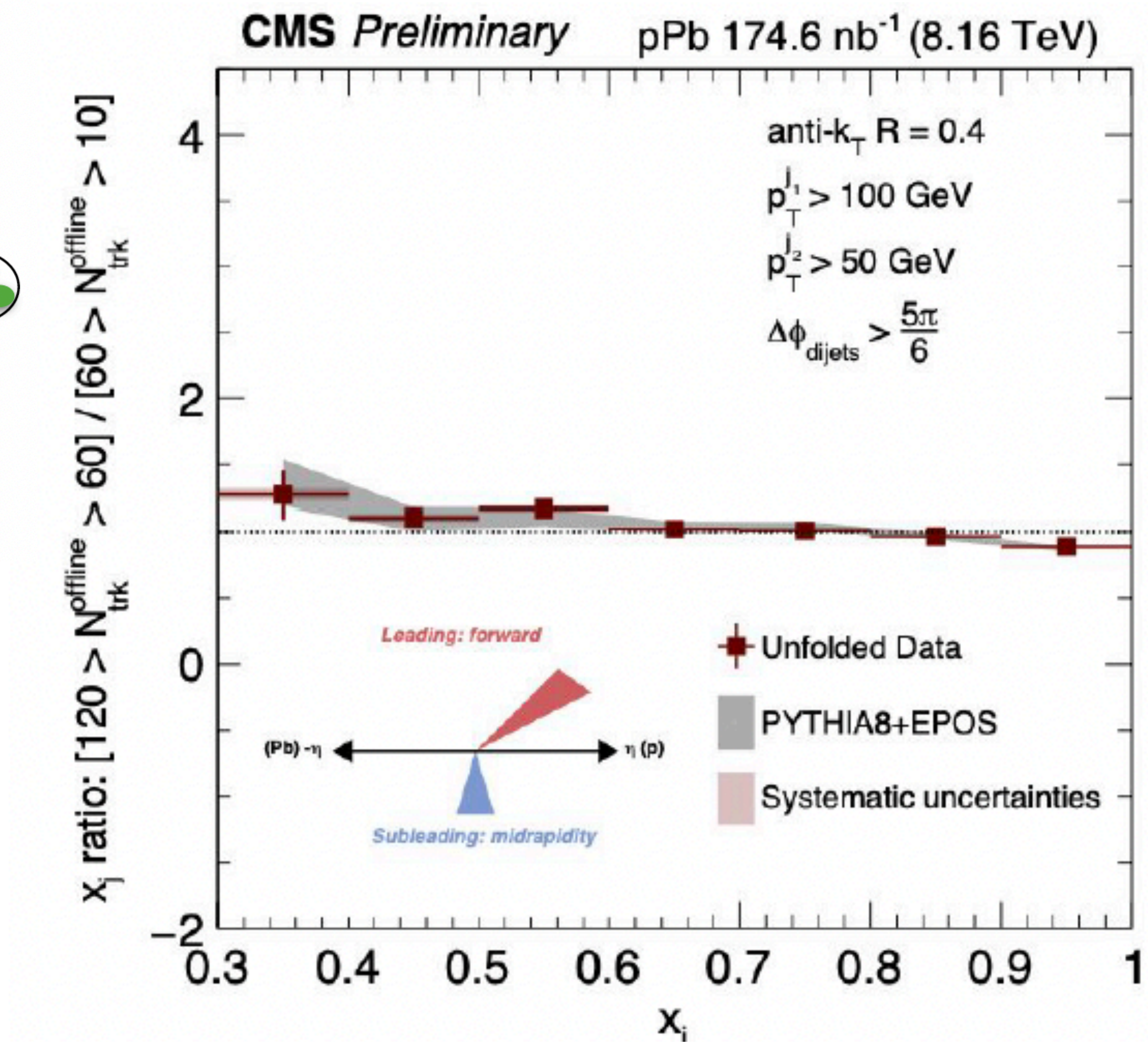


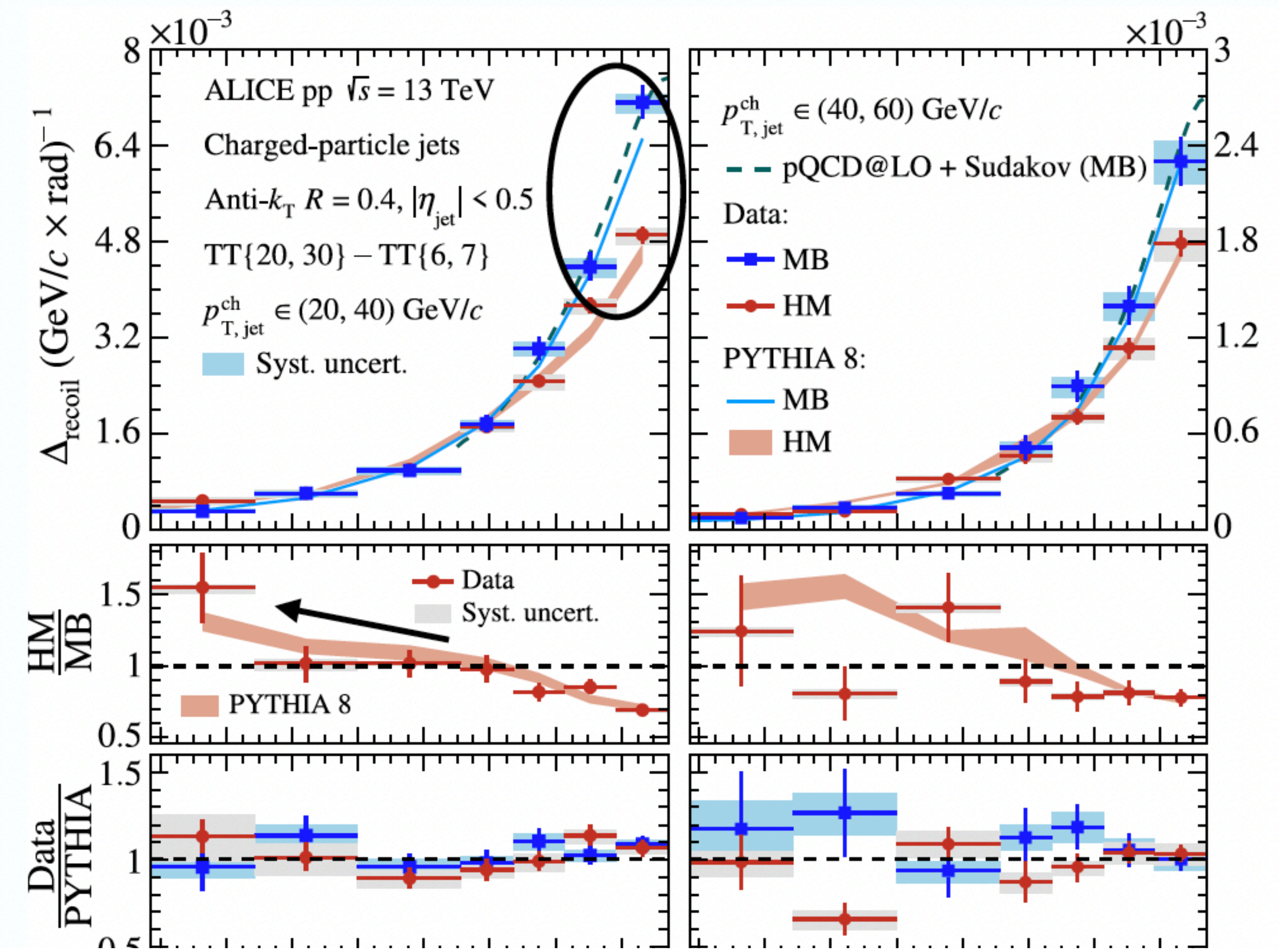


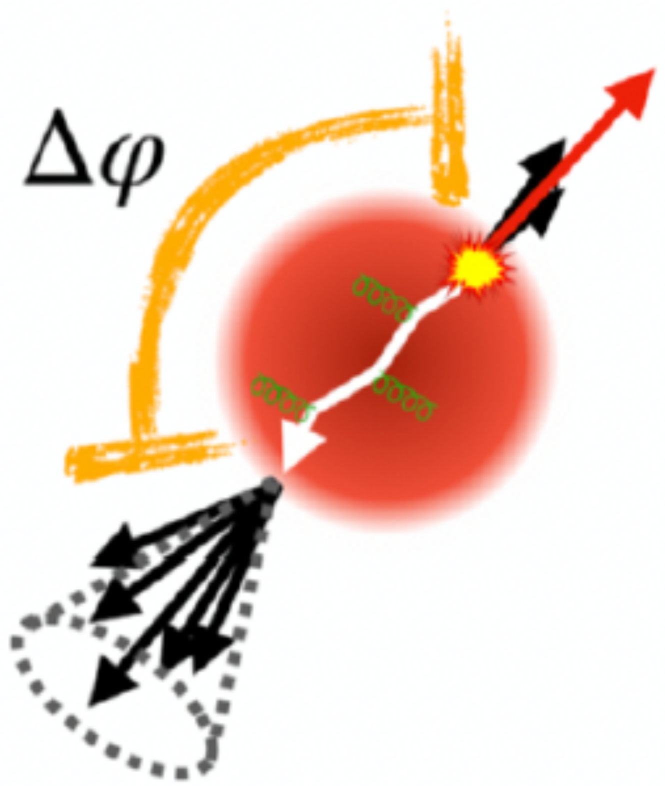
- With full jet reconstruction, study the dijet balance or h-jet azimuthal correlations
  - No modification observed at HM of jet-jet geometry
  - Azimuthal broadening in HM events observed for recoiling jets with high p_T trigger particles

Search for jet quenching in small systems









- With full jet reconstruction, study the dijet balance or h-jet azimuthal correlations
  - No modification observed at HM of jet-jet geometry
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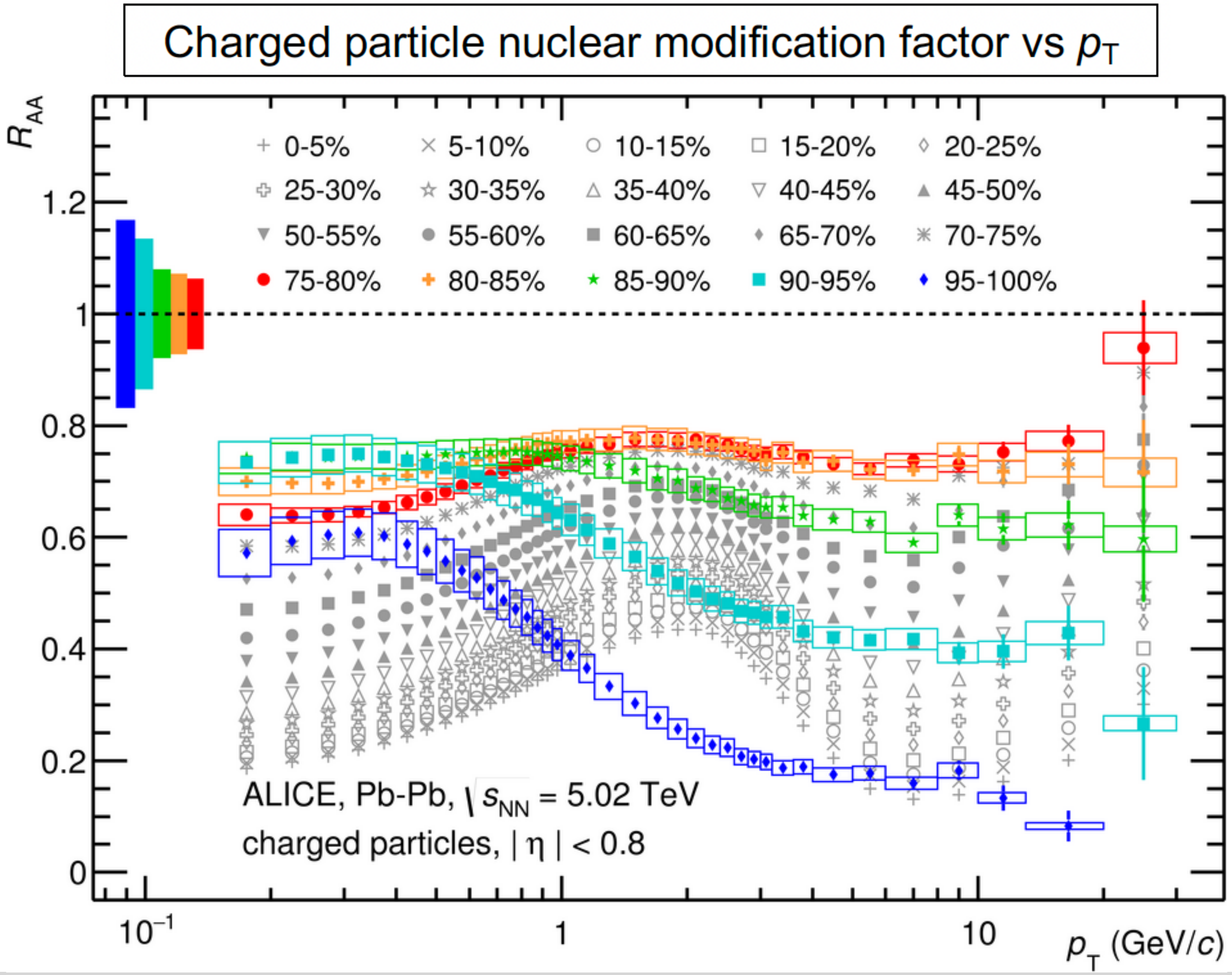
➡ Consistency study between particle and jet correlations?

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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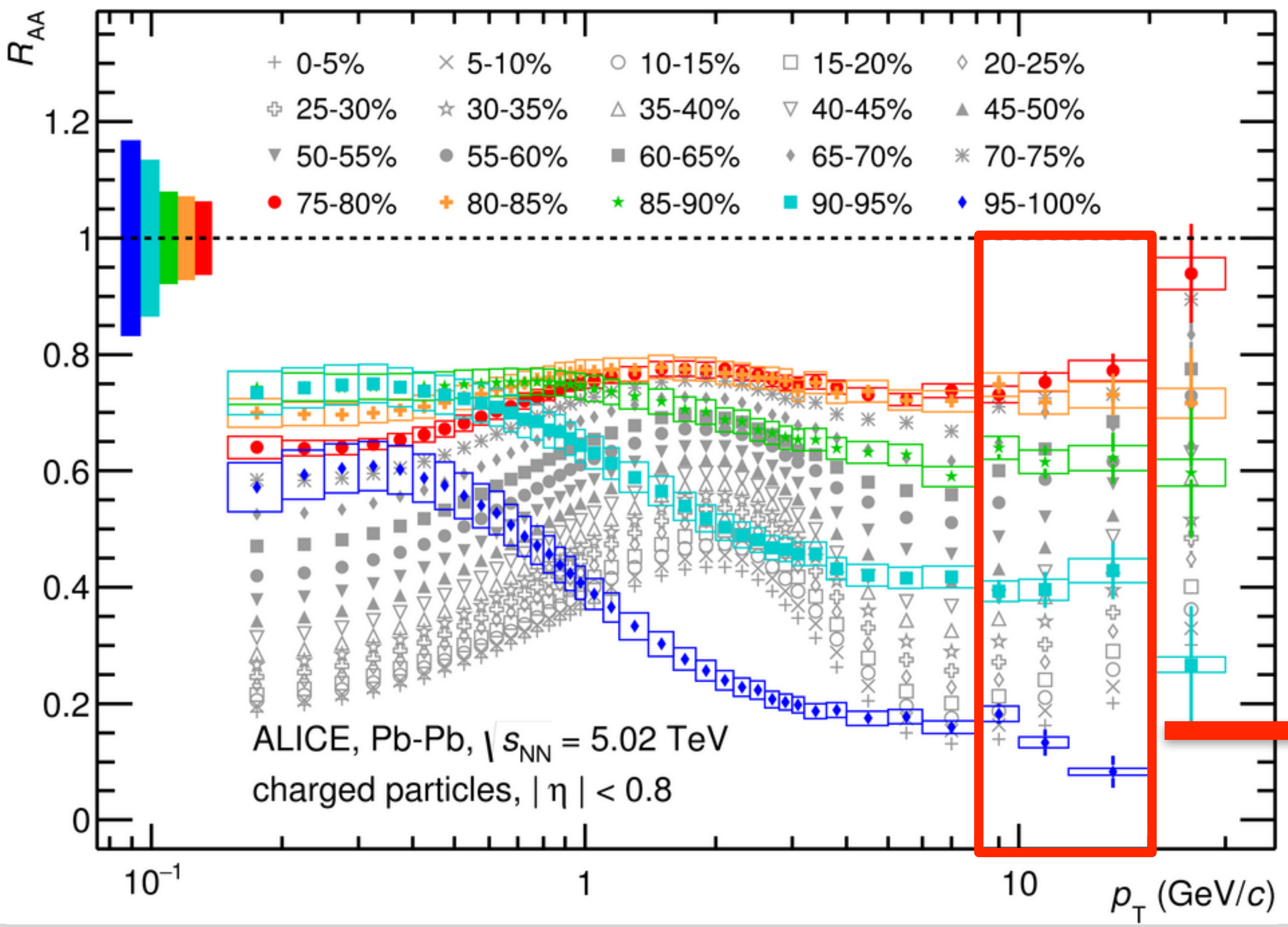
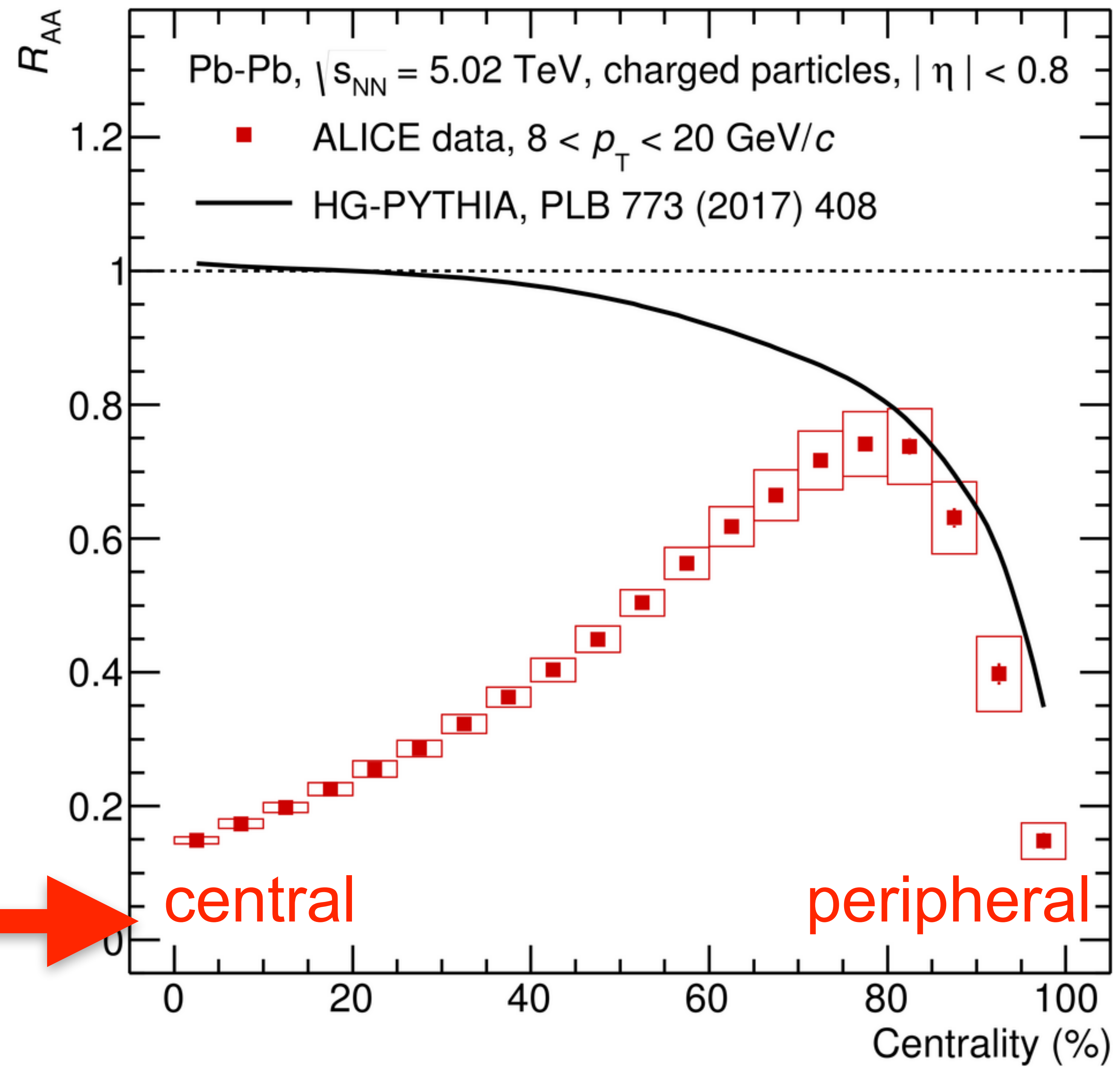
Charged particle nuclear modification factor vs p_T



High pT, centrality dependence



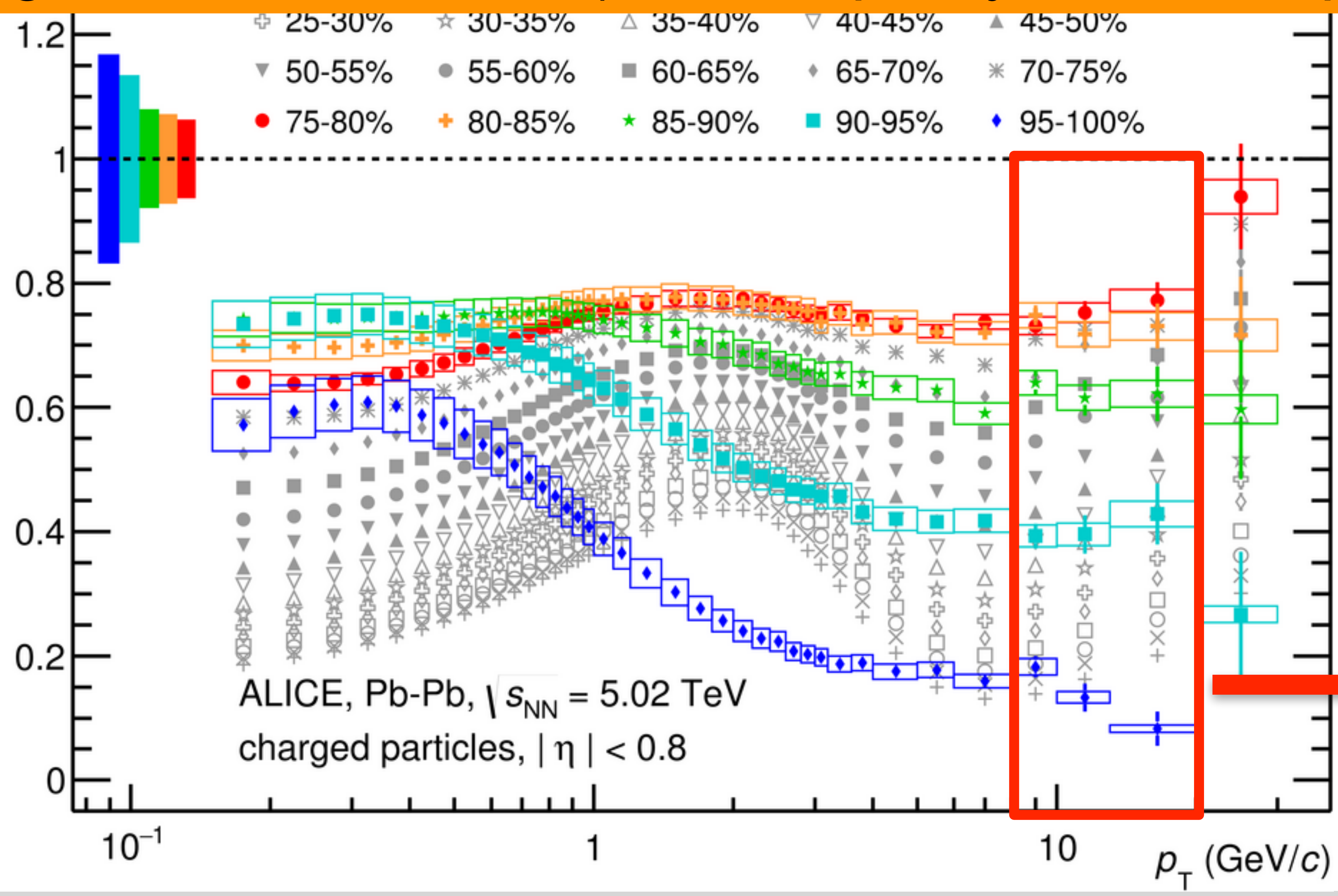
Jet quenching not observed in small systems

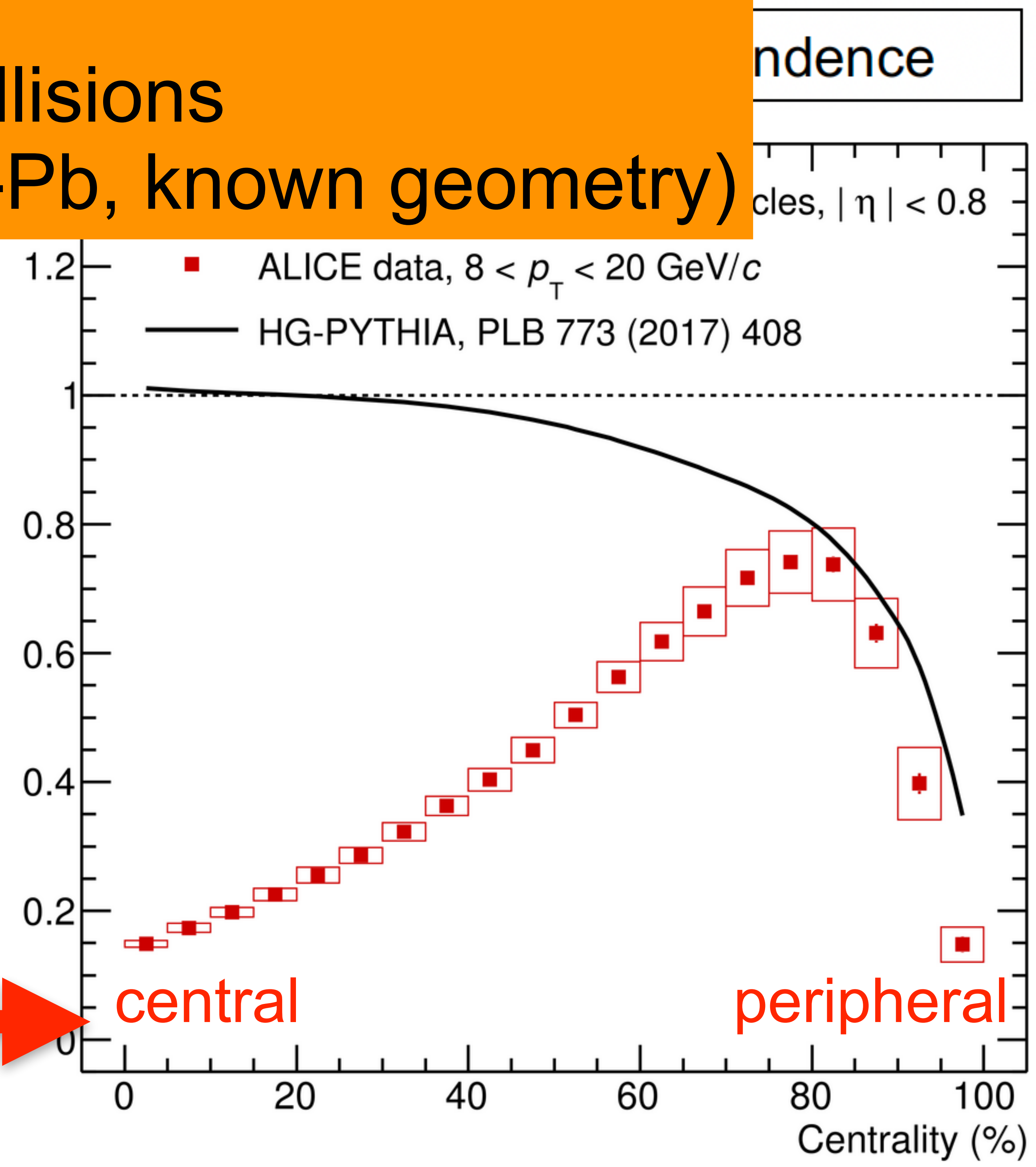
No significant energy loss observed so far

- 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!

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

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 discussion

- Instead of a summary, a short list for discussion (only based on what I have presented):
  - Flavor/Mass dependence: can we decouple the flavor and mass effects for jet quenching study?
  - R-dependence of jet quenching: how do jet substructure and medium response interplay in different R jets?
  - Jet fragmentations: do we really understand vacuum jets?
  - Jet hadronchemistry: do we fully understand coalescence with different quark contents?
  - Jet quenching in small systems: what is the boundary to create QGP? what part of the jet is most sensitive to jet-medium interaction?

Thank you for your attention!