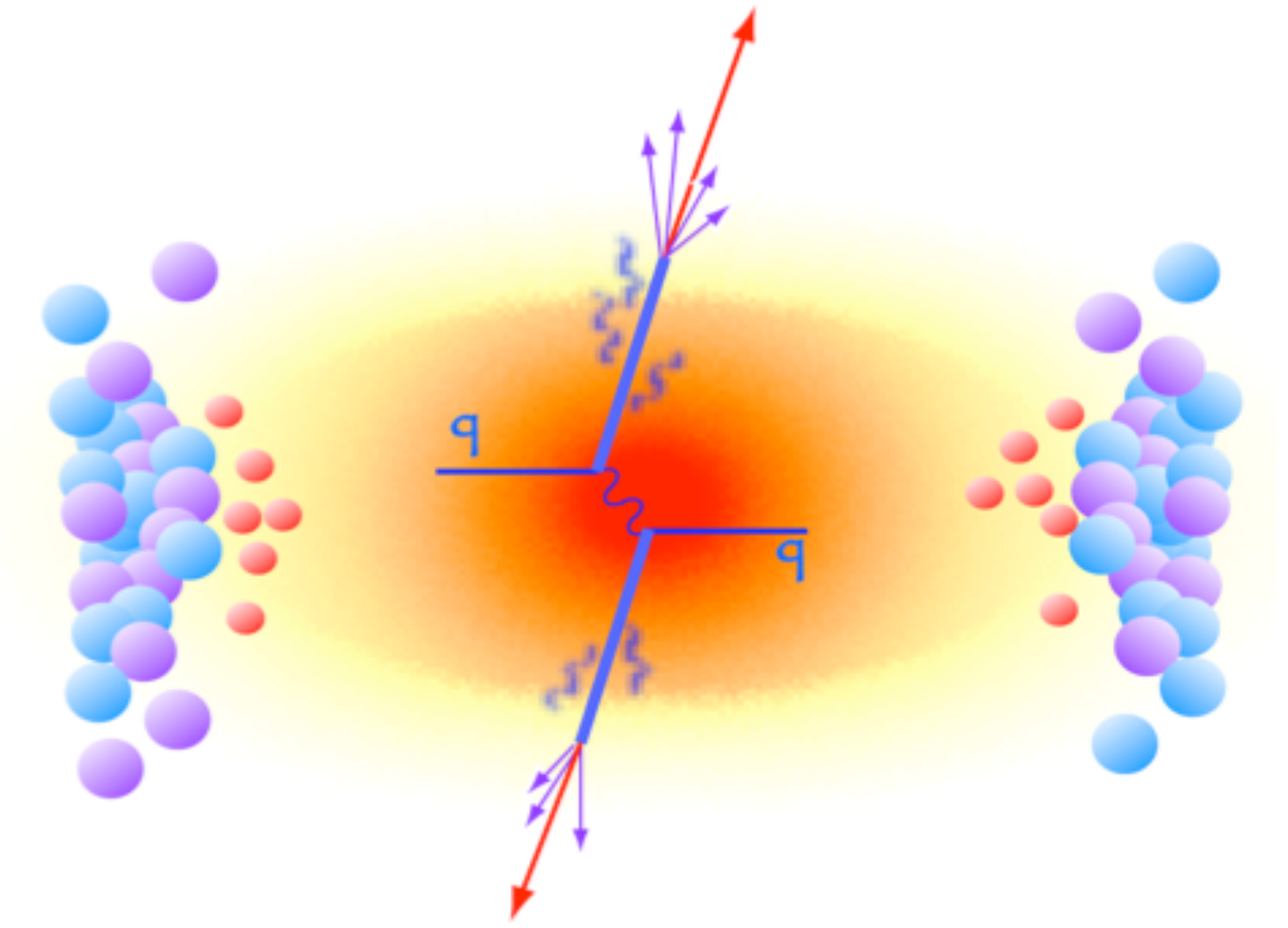
Jet physics with ALICE



毛亚显 (Yaxian MAO)

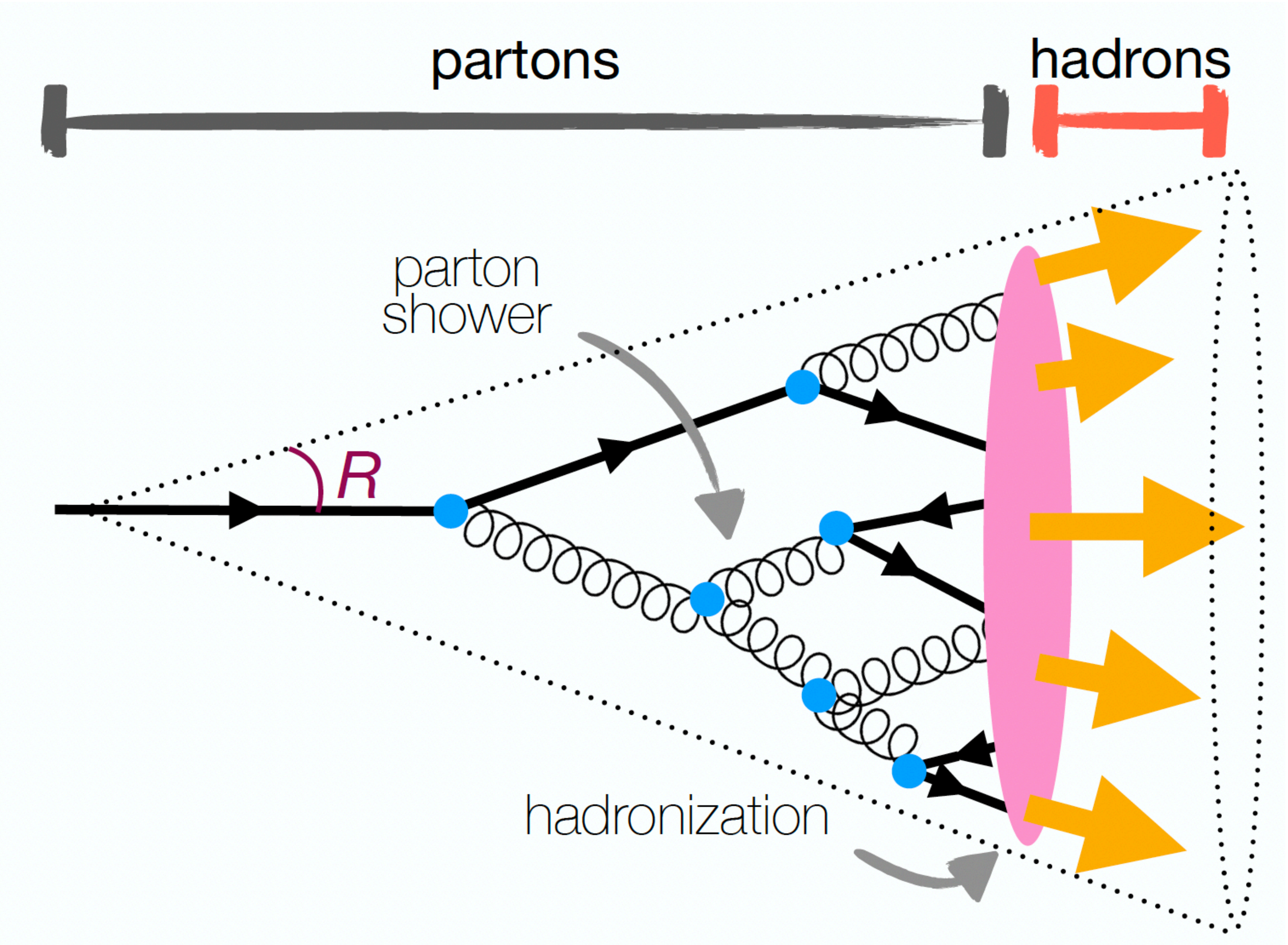
华中师范大学 (Central China Normal University)

CLHCP2022, 南京, 2022/11/26

Probing QGP with jets

Vacuum fragmentation (e.g. pp collisions)

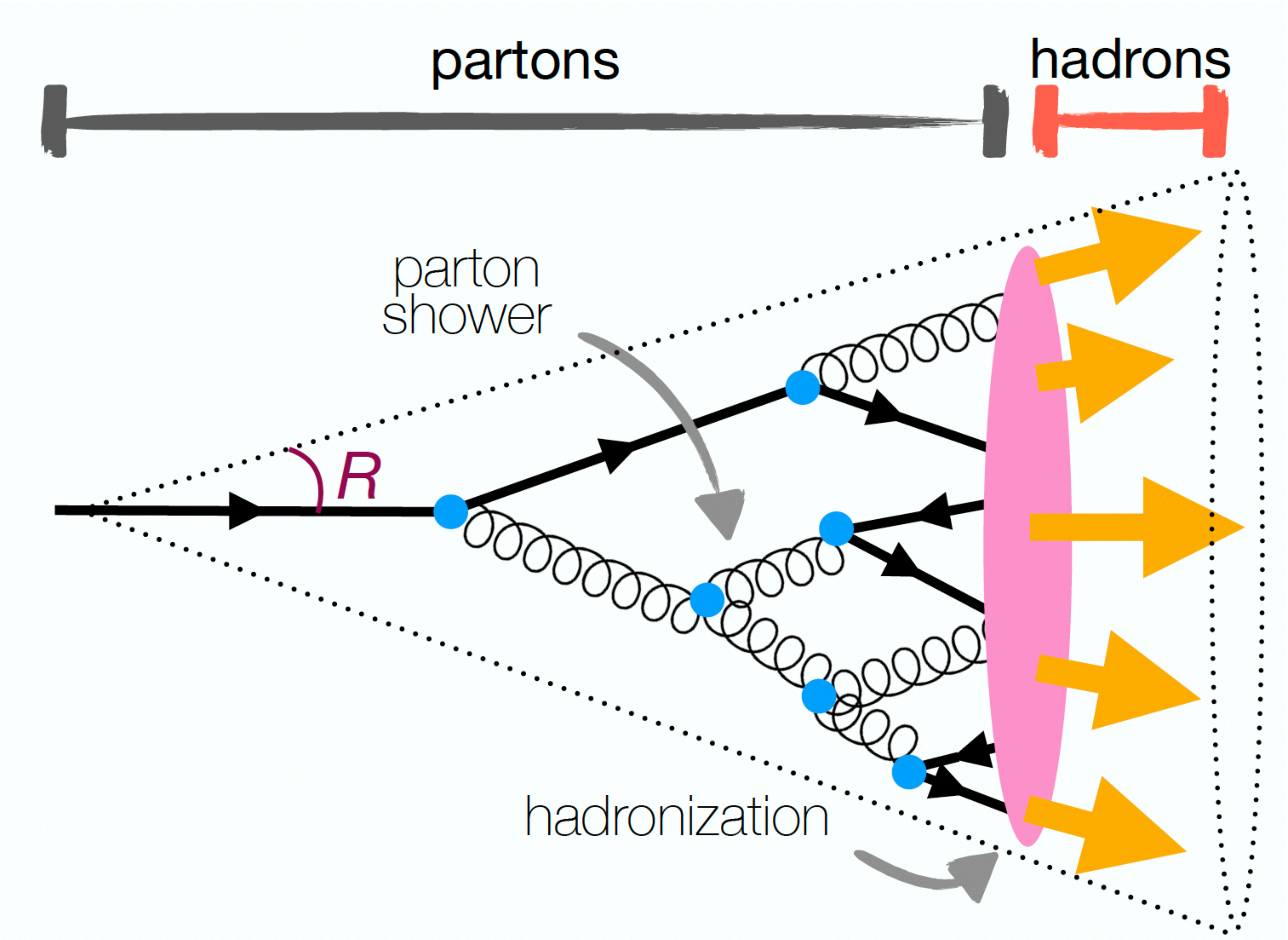
Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)



Probing QGP with jets

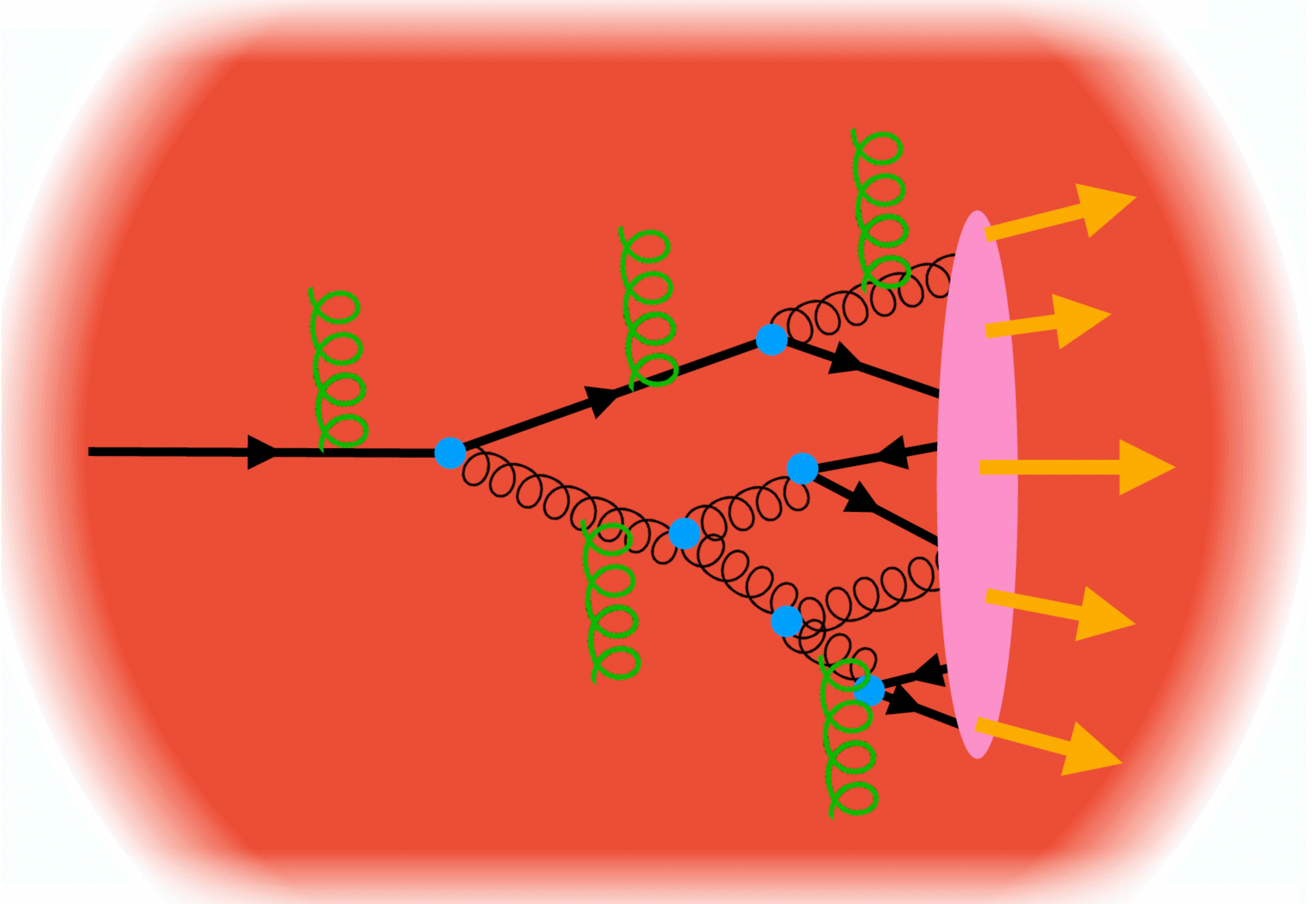
Vacuum fragmentation (e.g. pp collisions)

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



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

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



Jet quenching: an opportunity to study QGP

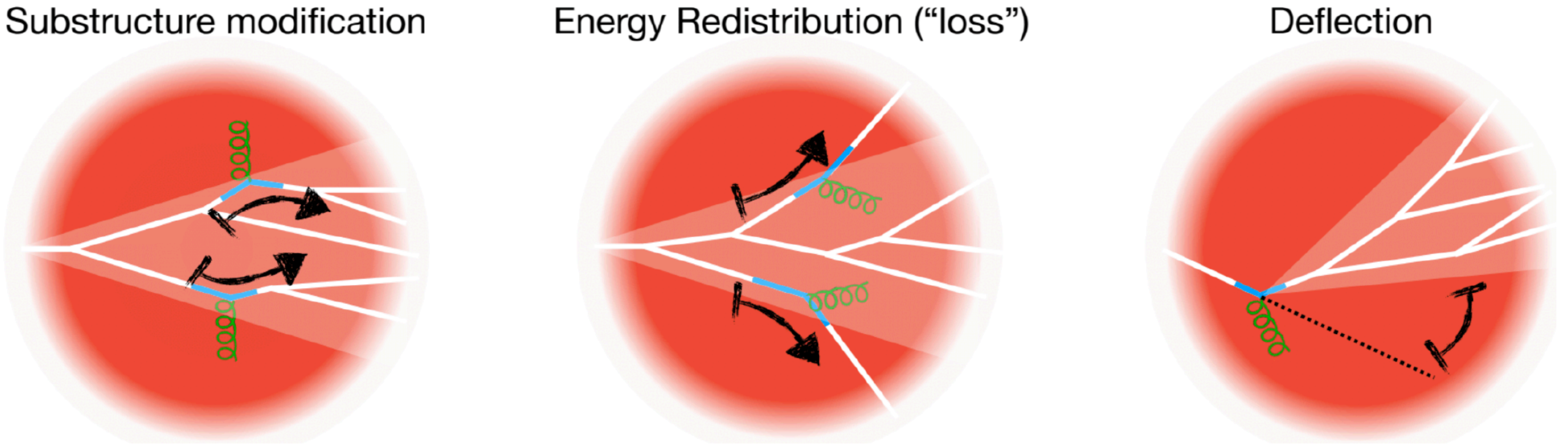
- Study structure of QGP by understanding jet modification from medium interaction (quenching)

- Several types of jet observables

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

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

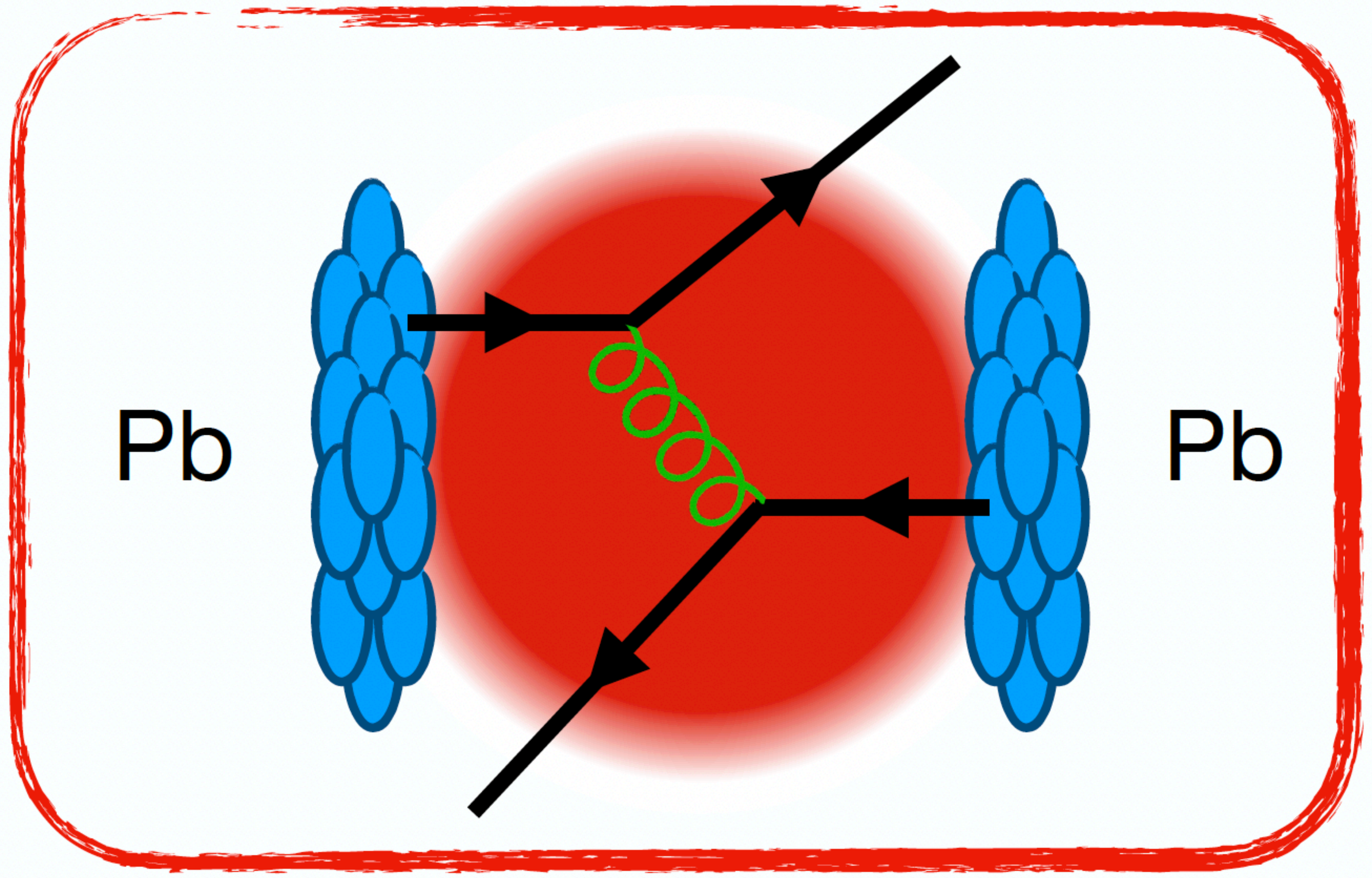
  - Angular correlation → jet deflection ($\Delta\varphi$)

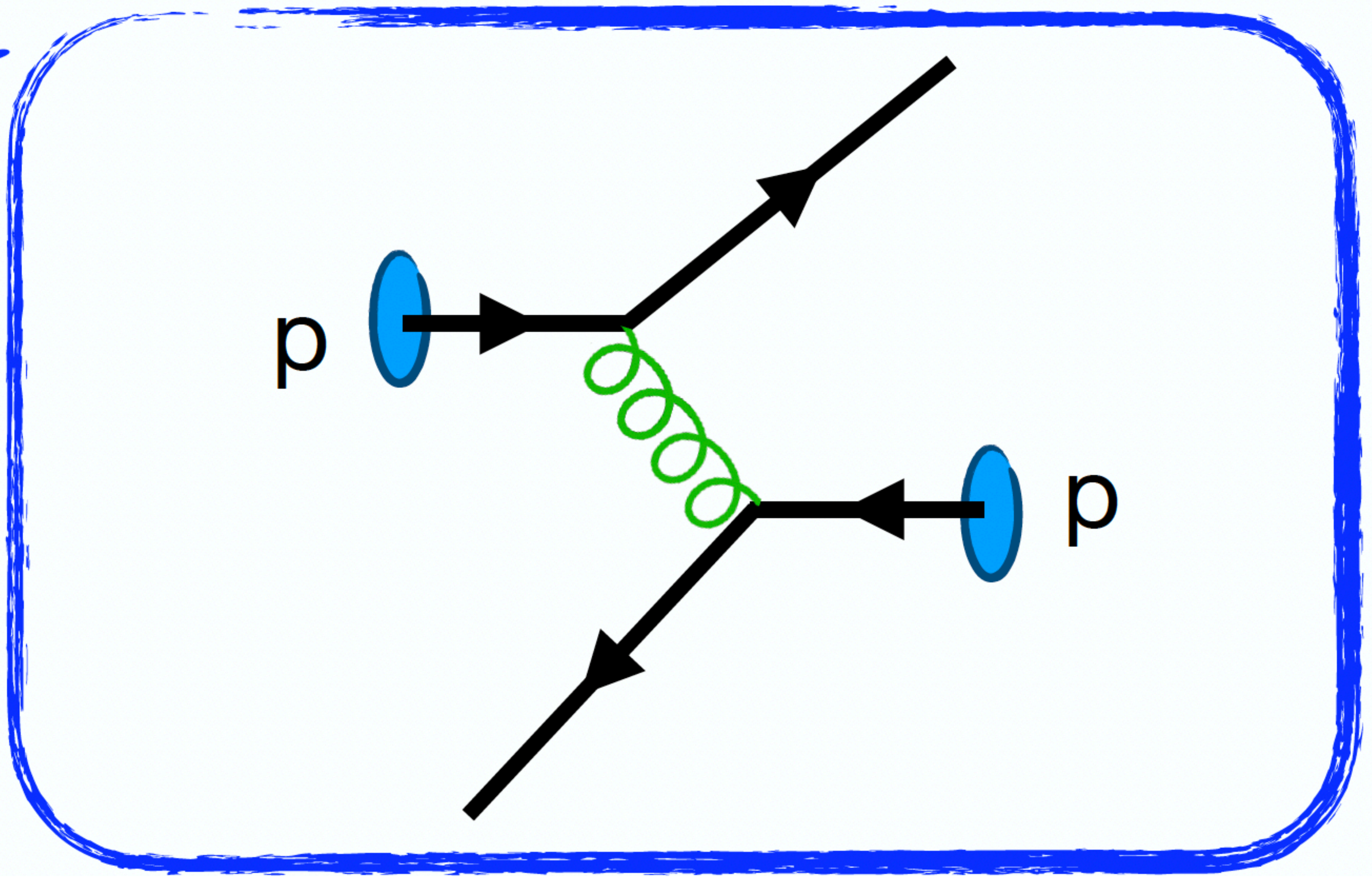


Study of different effects in a complementary way must yield consistent picture

Nuclear modification factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



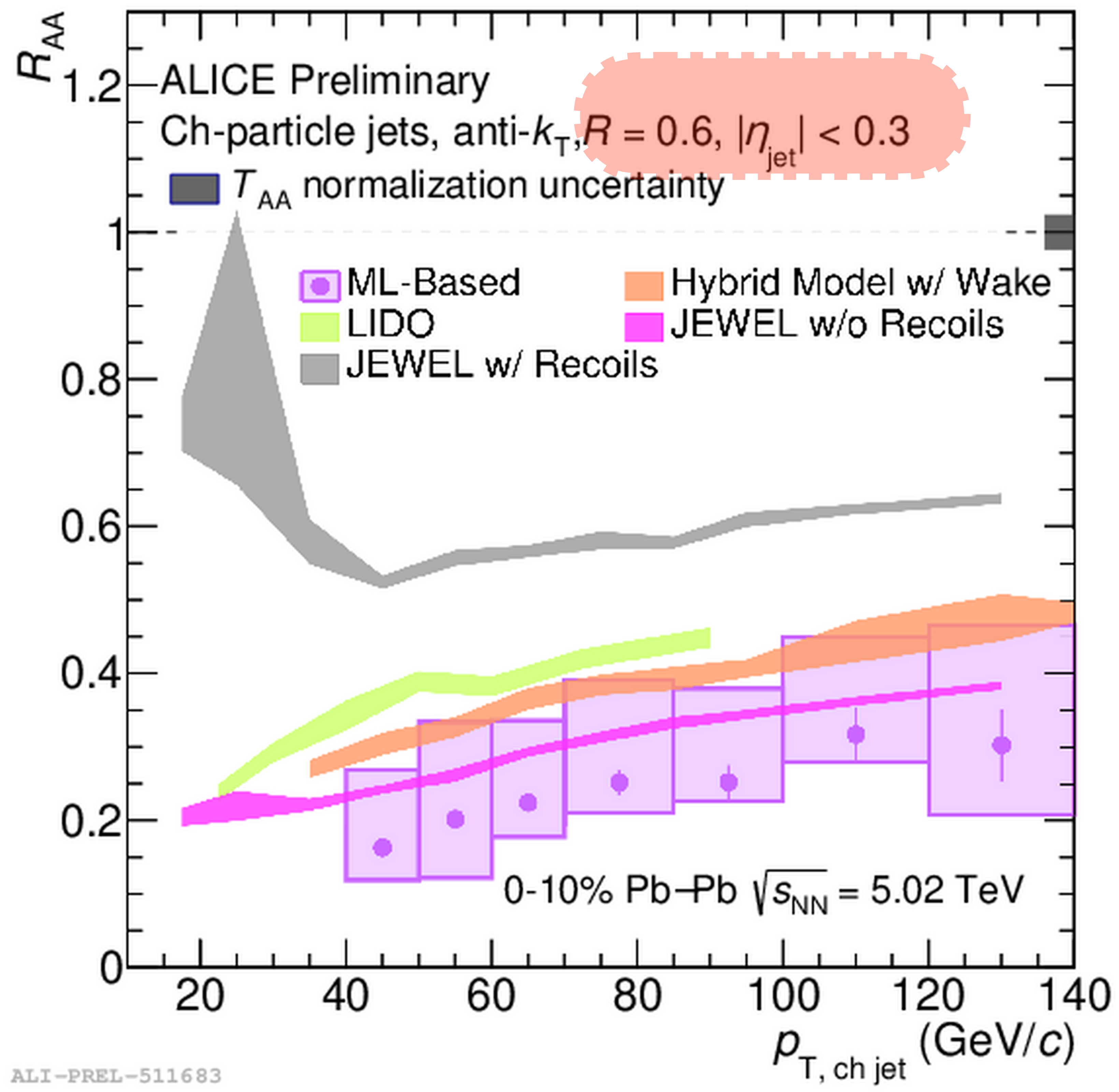


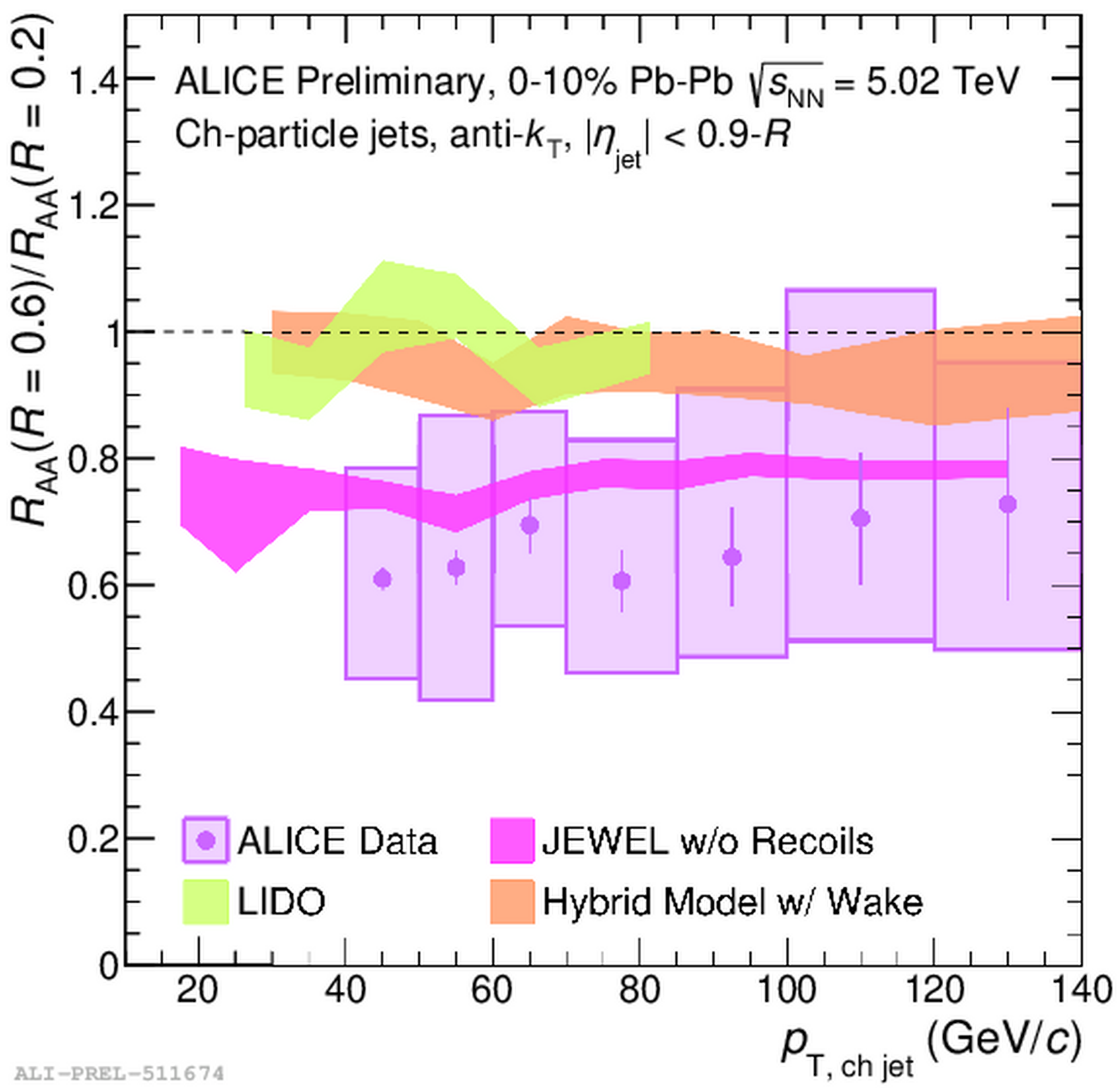
$R_{AA} > 1$ → enhancement

$R_{AA} = 1$ → no medium modification

$R_{AA} < 1$ → supression

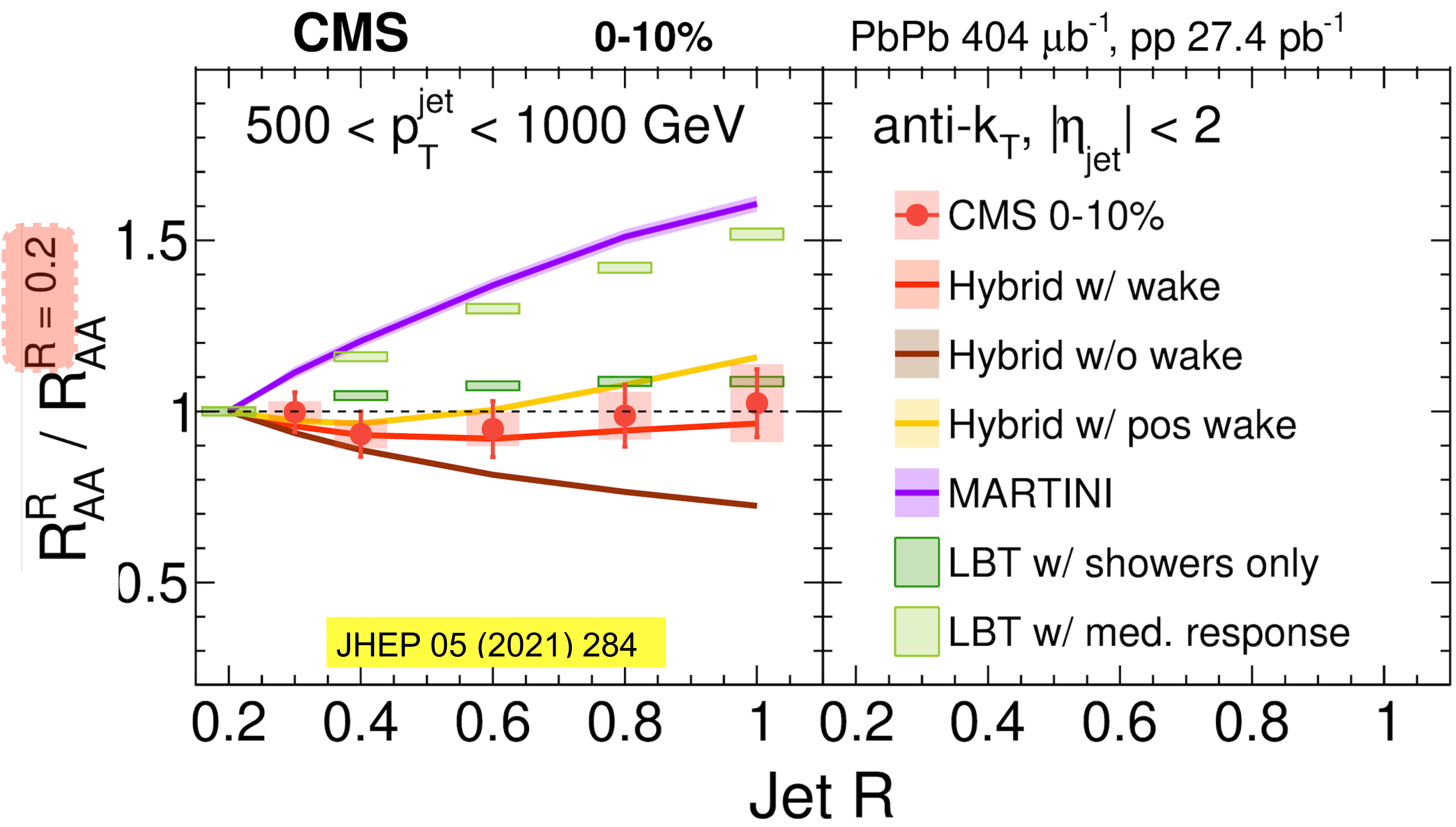
Jet suppression and energy redistribution





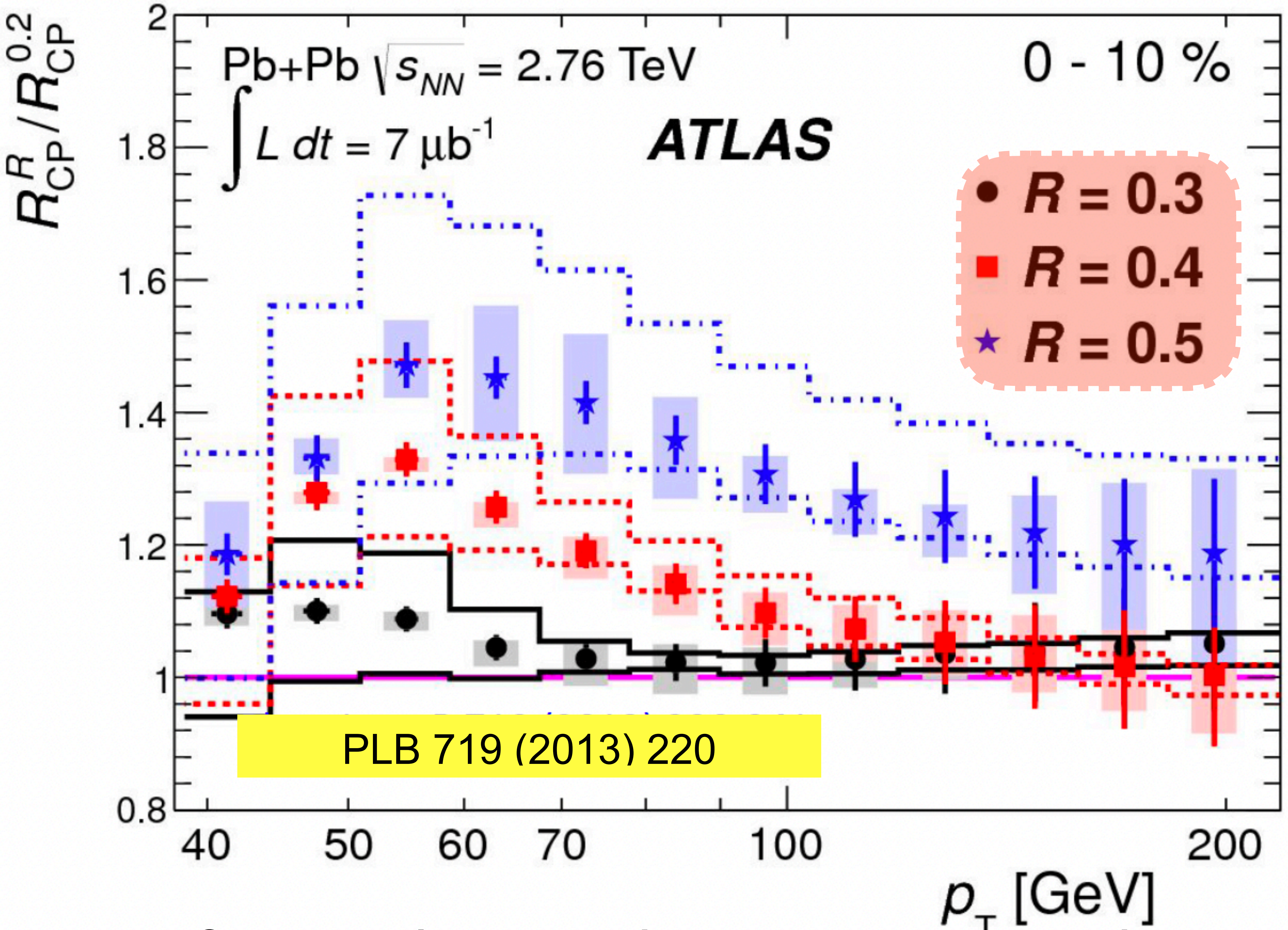
- Jet measurements extended to lower jet p_T and large R using machine learning (ML)
  - improvements on background subtraction and systematics
- Large R (= 0.6) jets indicate a stronger suppression than smaller R (= 0.2) jets
  - suggesting R-dependence of jet energy loss

R dependence of jet R_{AA}

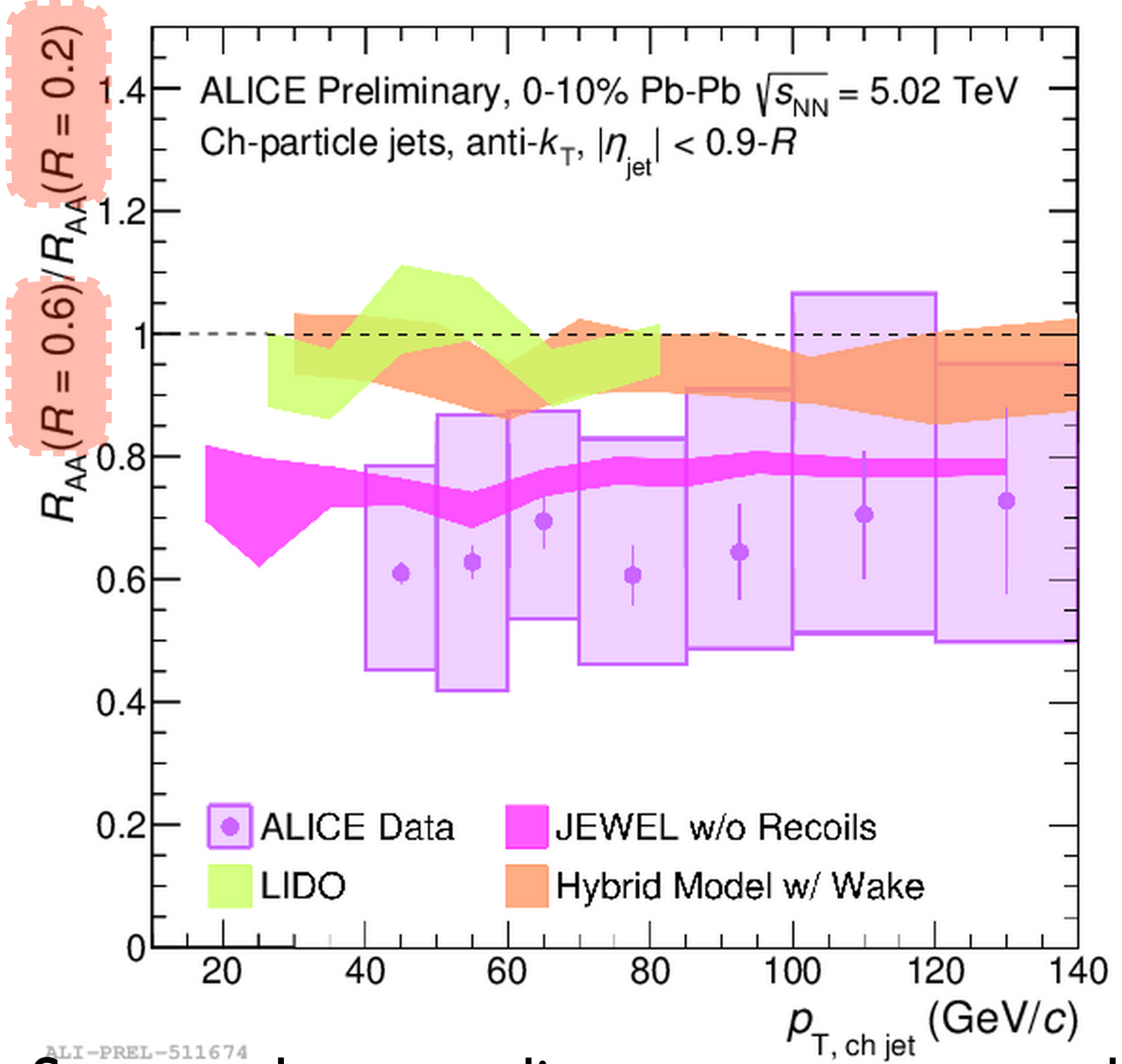


- No strong R dependence of jet R_{AA} for very high p_T jets observed by CMS
- R dependence of jet R_{AA} can help to disentangle energy loss mechanisms
  - competing effect between the amount/how energy redistributed and ability to recover it

Tension with previous ATLAS results

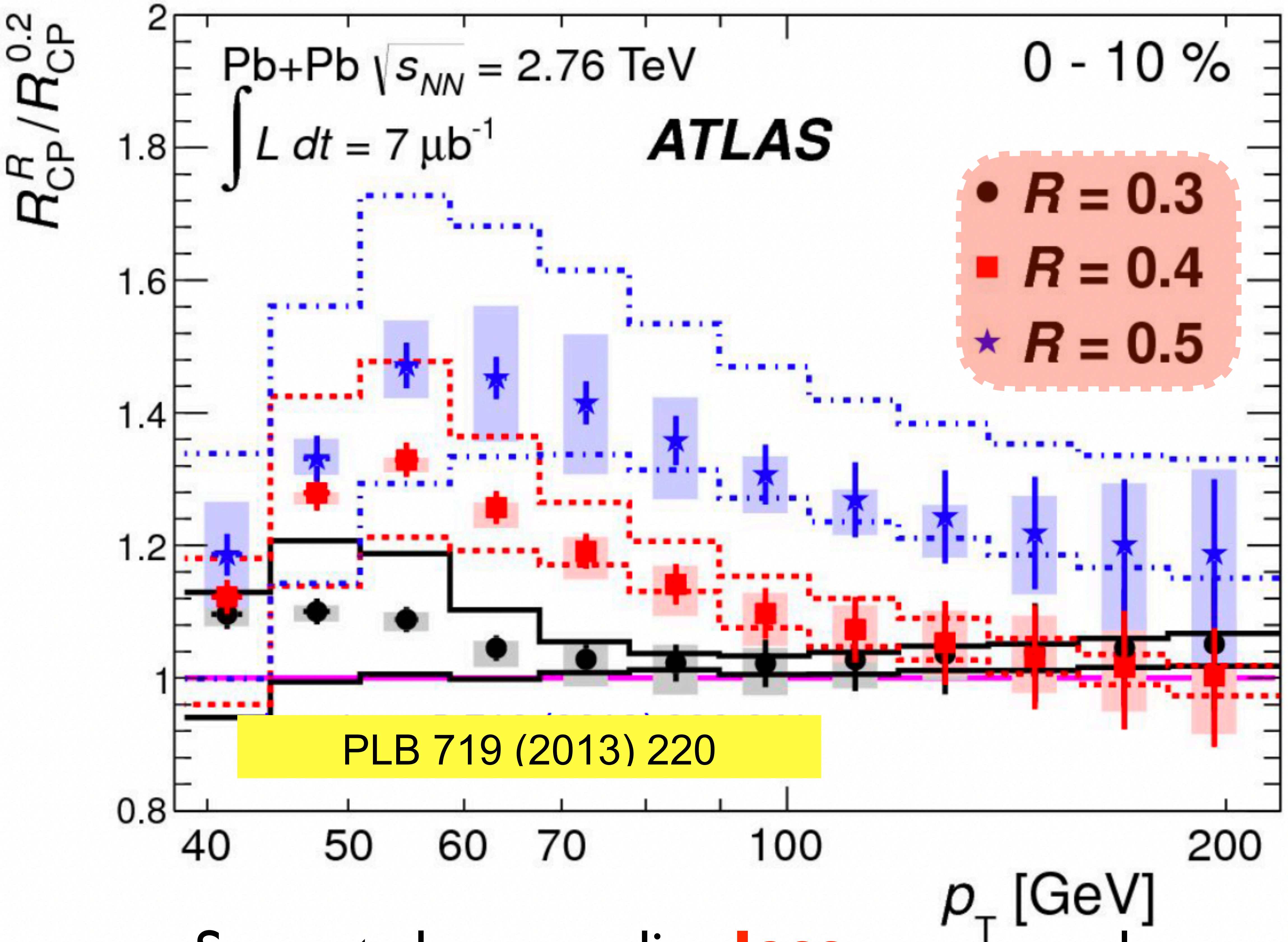


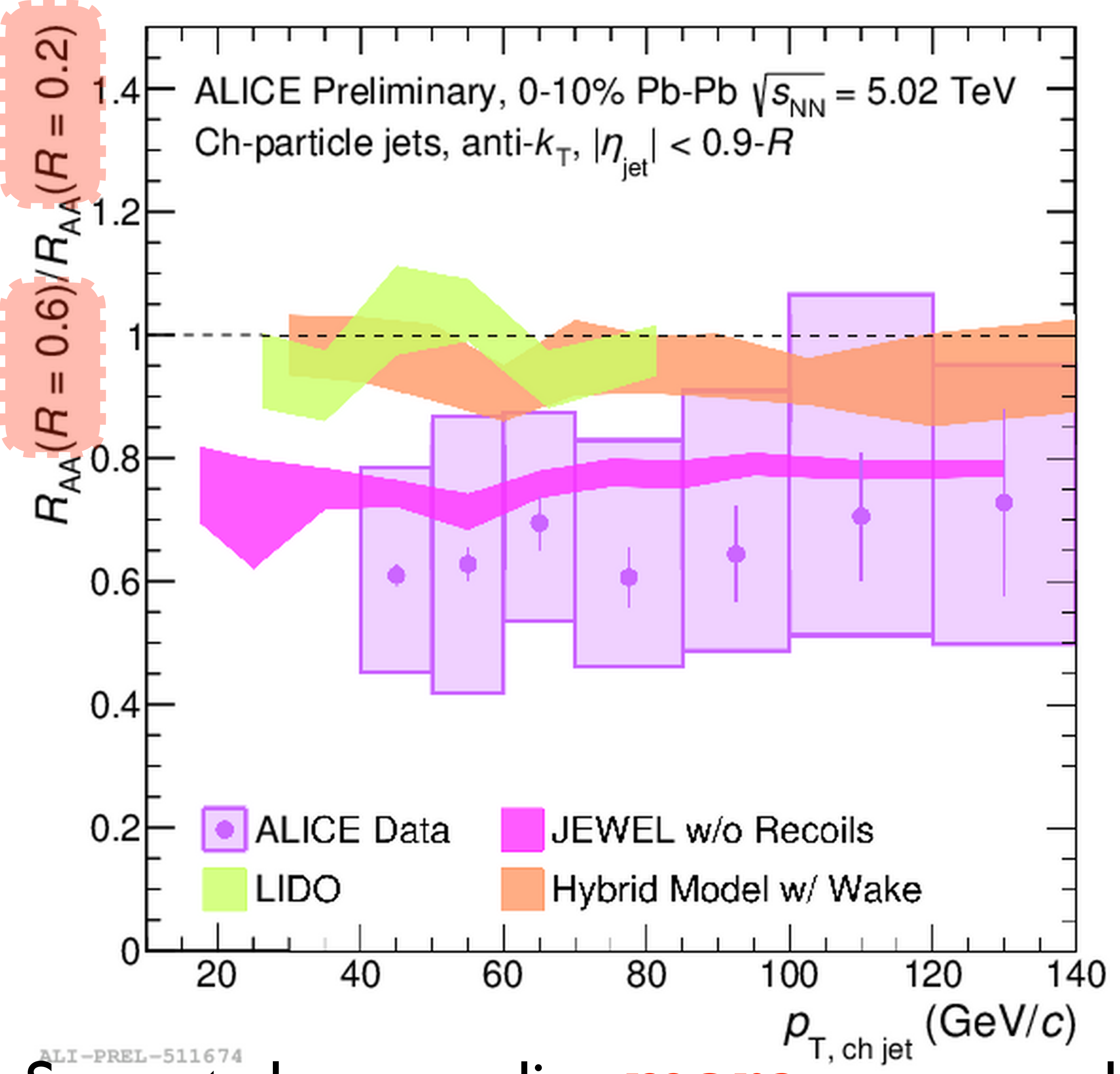
Suggests larger radius **less** suppressed



Suggests larger radius **more** suppressed

Tension with previous ATLAS results





Suggests larger radius **less** suppressed

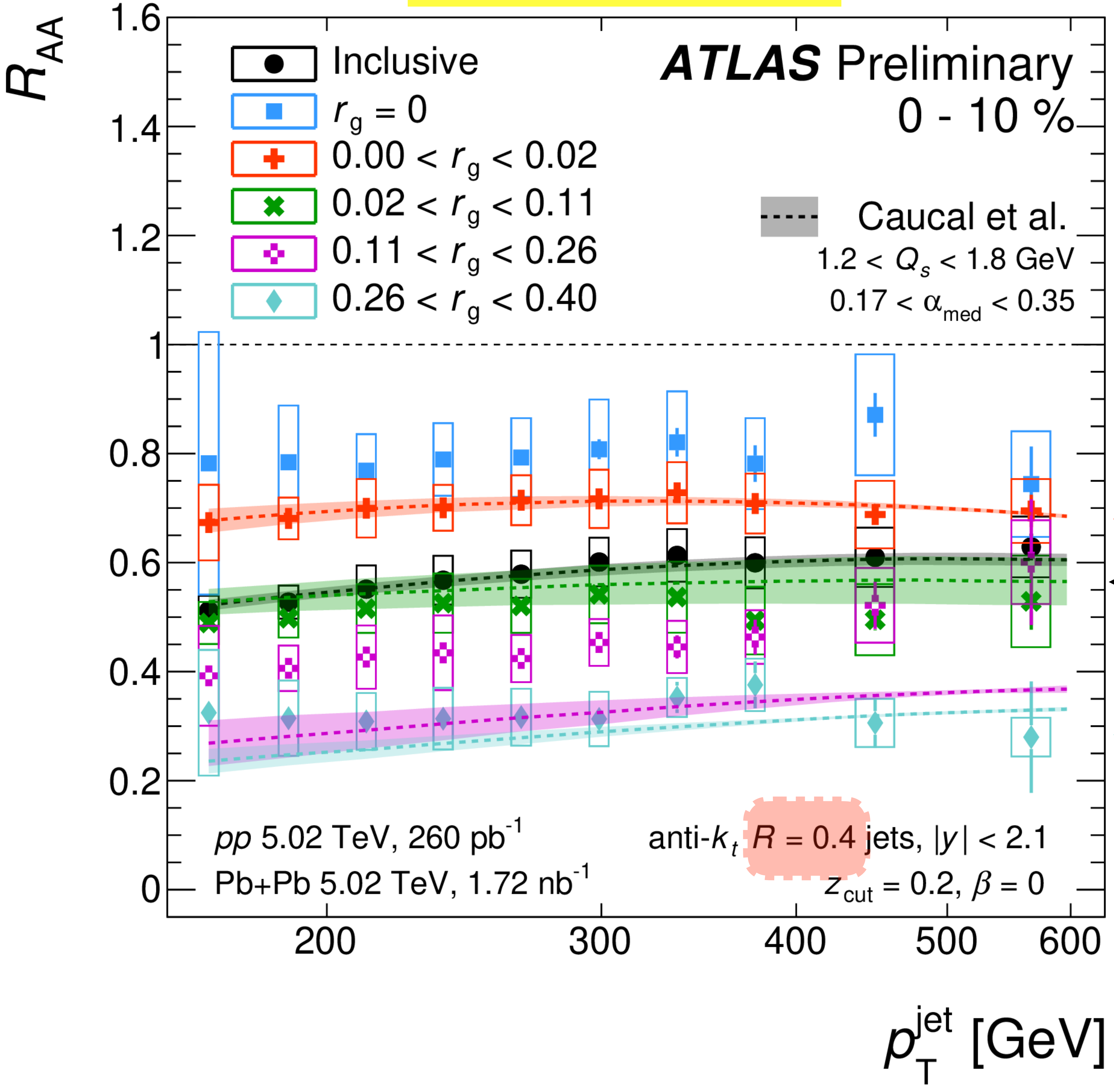
Suggests larger radius **more** suppressed

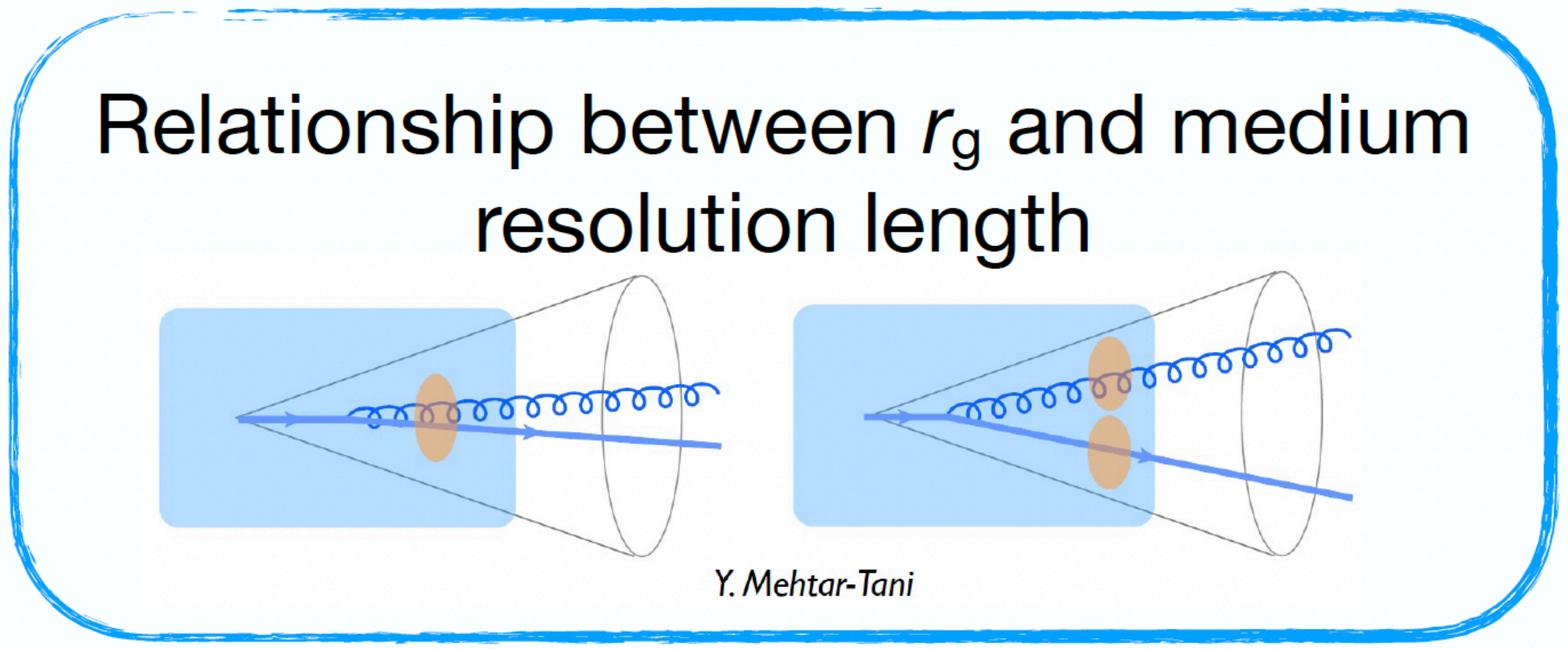
- Not exactly the same observables: R_{cp} vs. R_{AA}
- Different types of jets: full vs. charge
- Different centre-of-mass energy and phase-space
- Larger systematics in ALICE

→ More detailed comparison and future studies are needed

R_{AA} - substructure interplay

ATLAS-CONF-2022-026

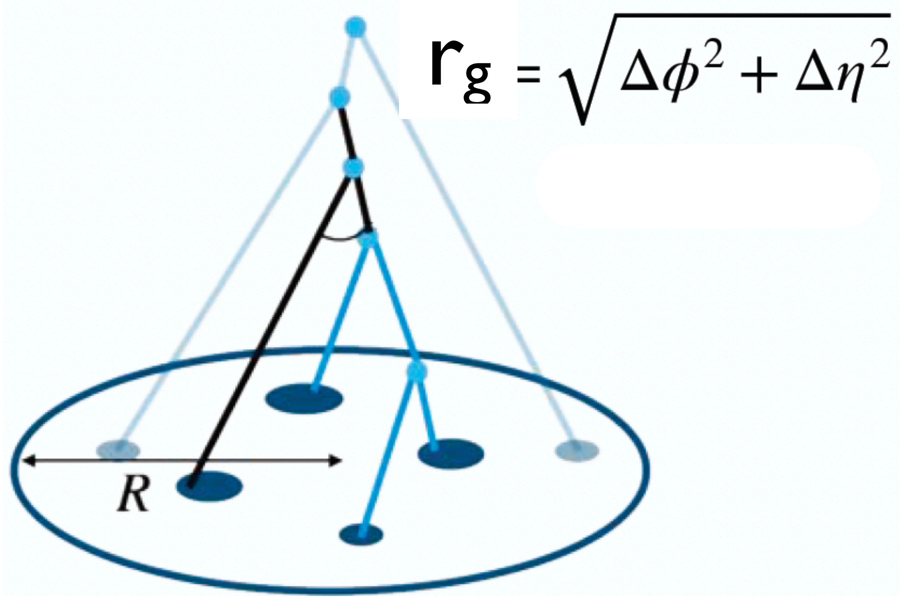




Small r_g

Inclusive

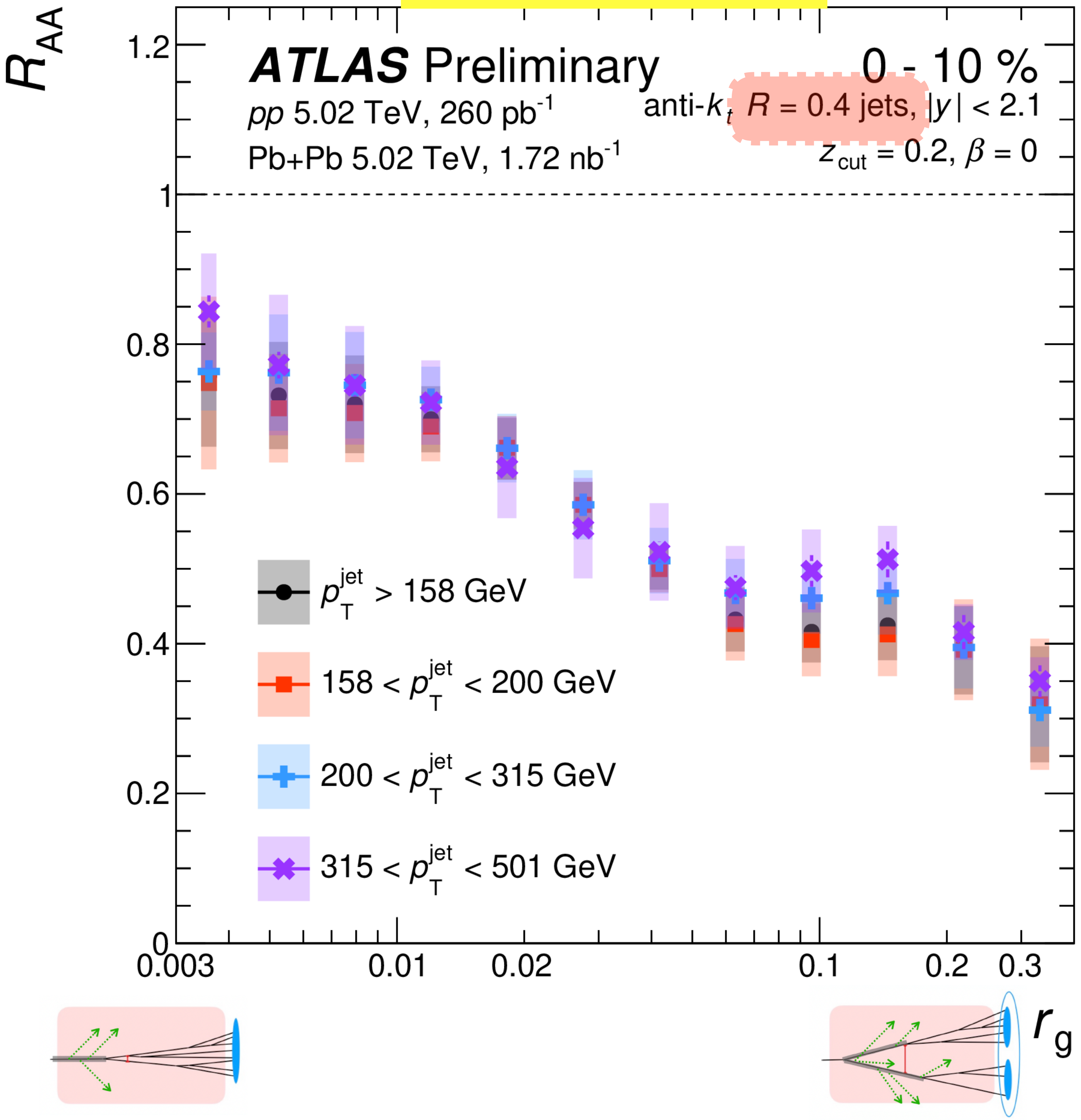
Large r_g



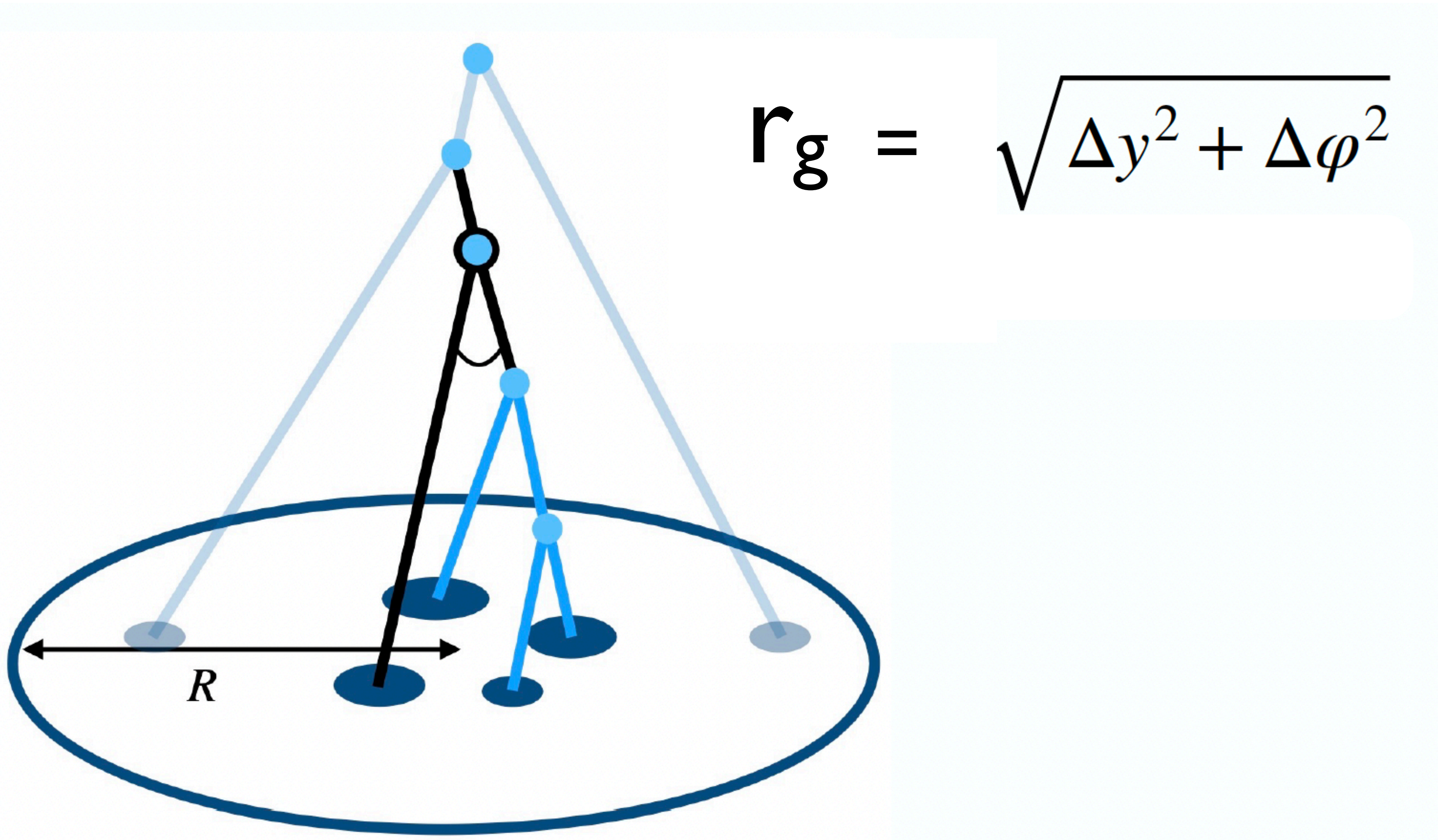
- Strong r_g dependence of R_{AA}
- Large r_g jets are more suppressed

R_{AA} vs groomed jet radius

ATLAS-CONF-2022-026



Absolutely-normalized results



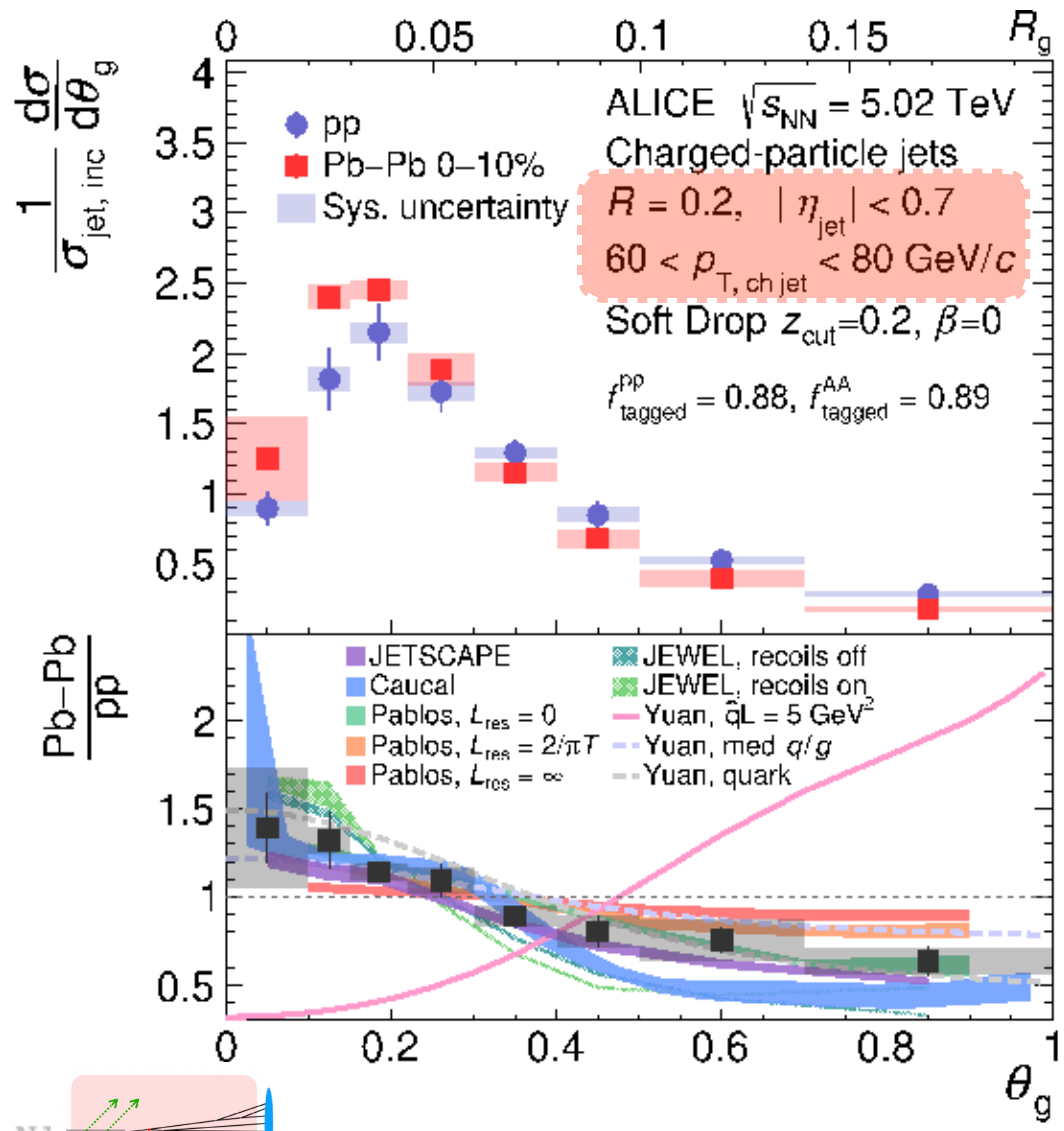
$$r_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

- No significant p_T dependence
- Strong r_g dependence of R_{AA}

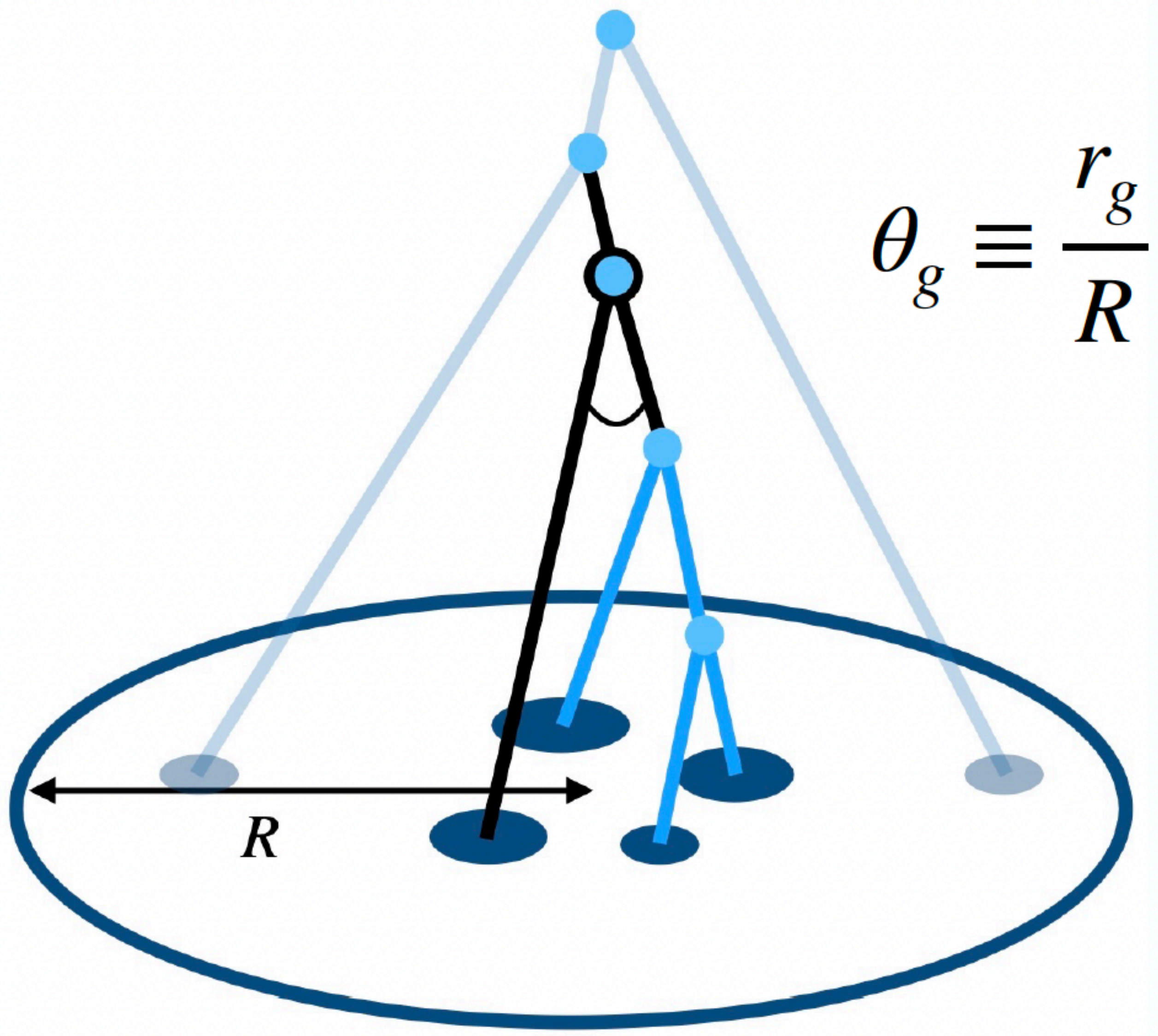
➡ Large r_g jets potentially select more active vacuum shower or with more independent prongs that are more quenched in medium

Groomed jet radius

PRL 128 (2022) 102001

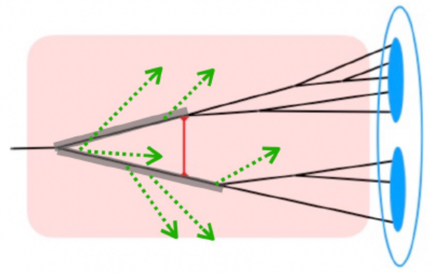


Self-normalized results → shapes!

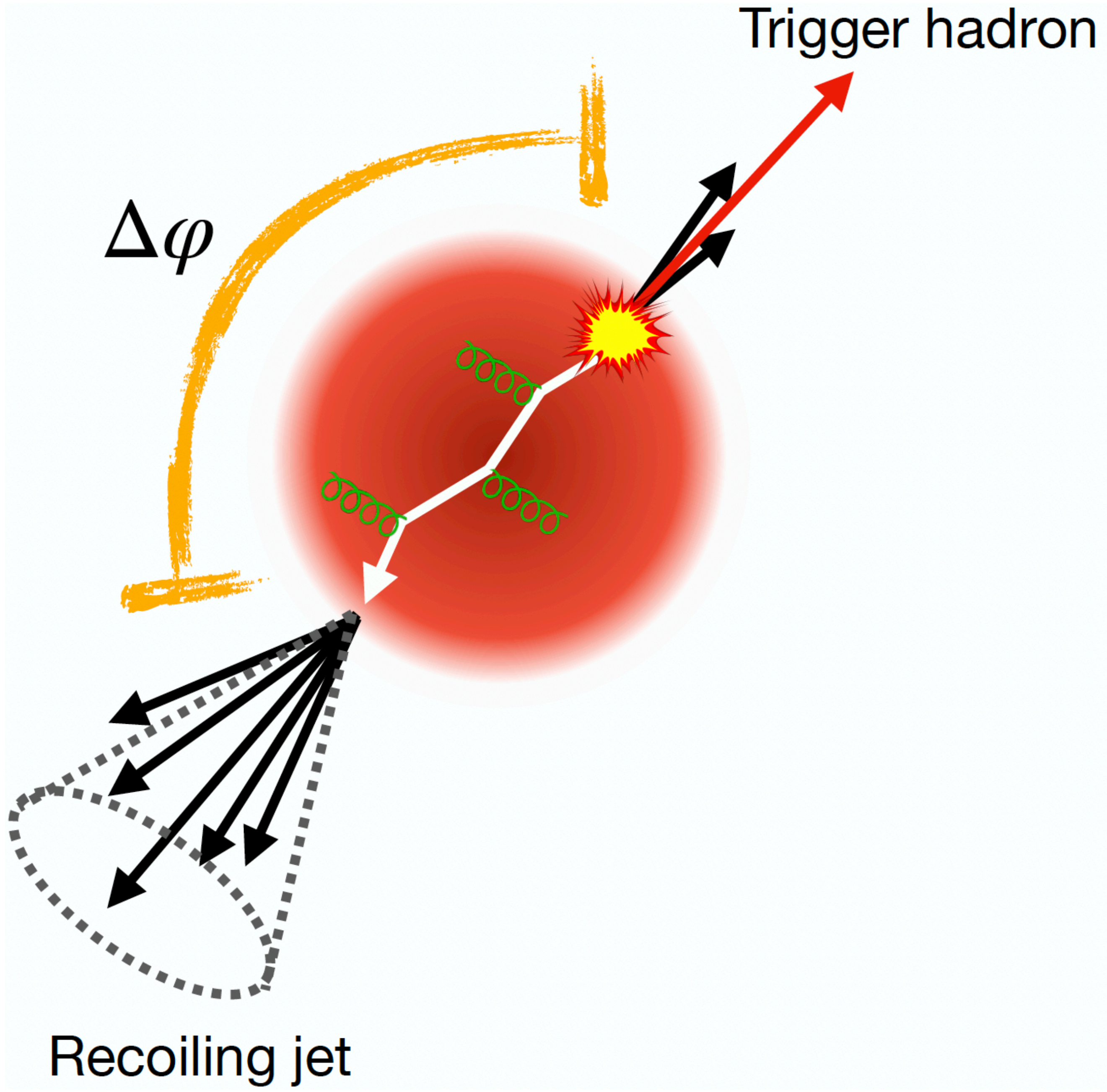


$$\theta_g \equiv \frac{r_g}{R} = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

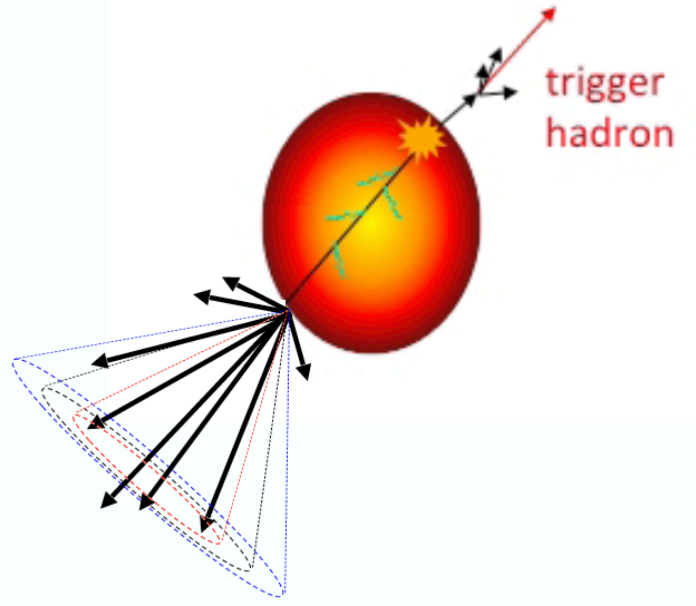
- Large θ_g jets are more suppressed → narrowing of the Pb-Pb distributions
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

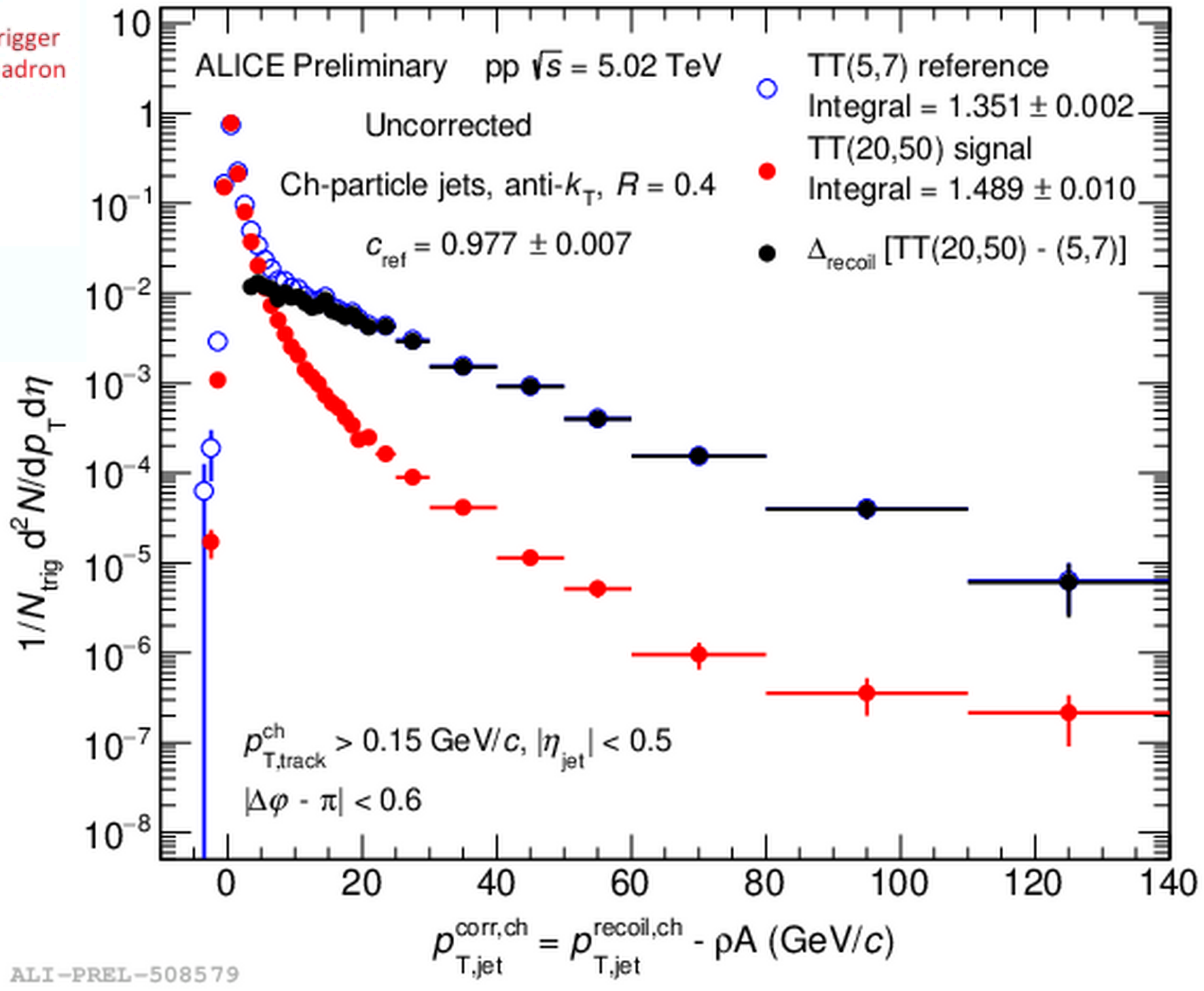


Correlations with high-p_T hadrons



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

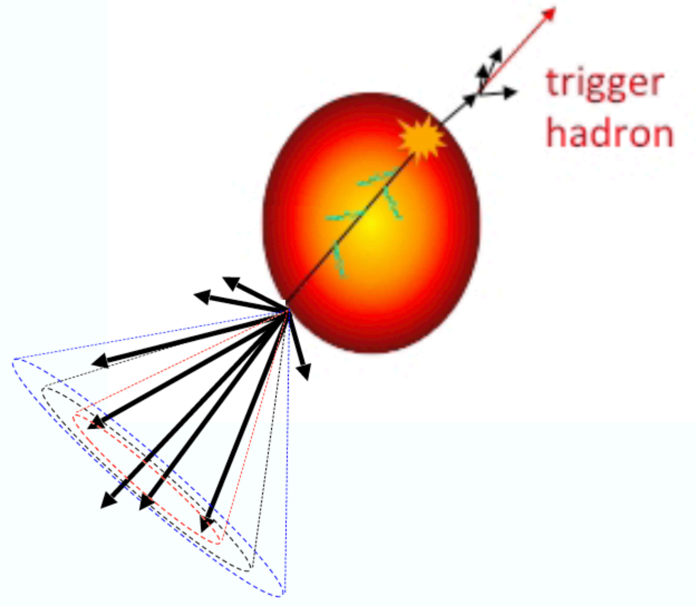


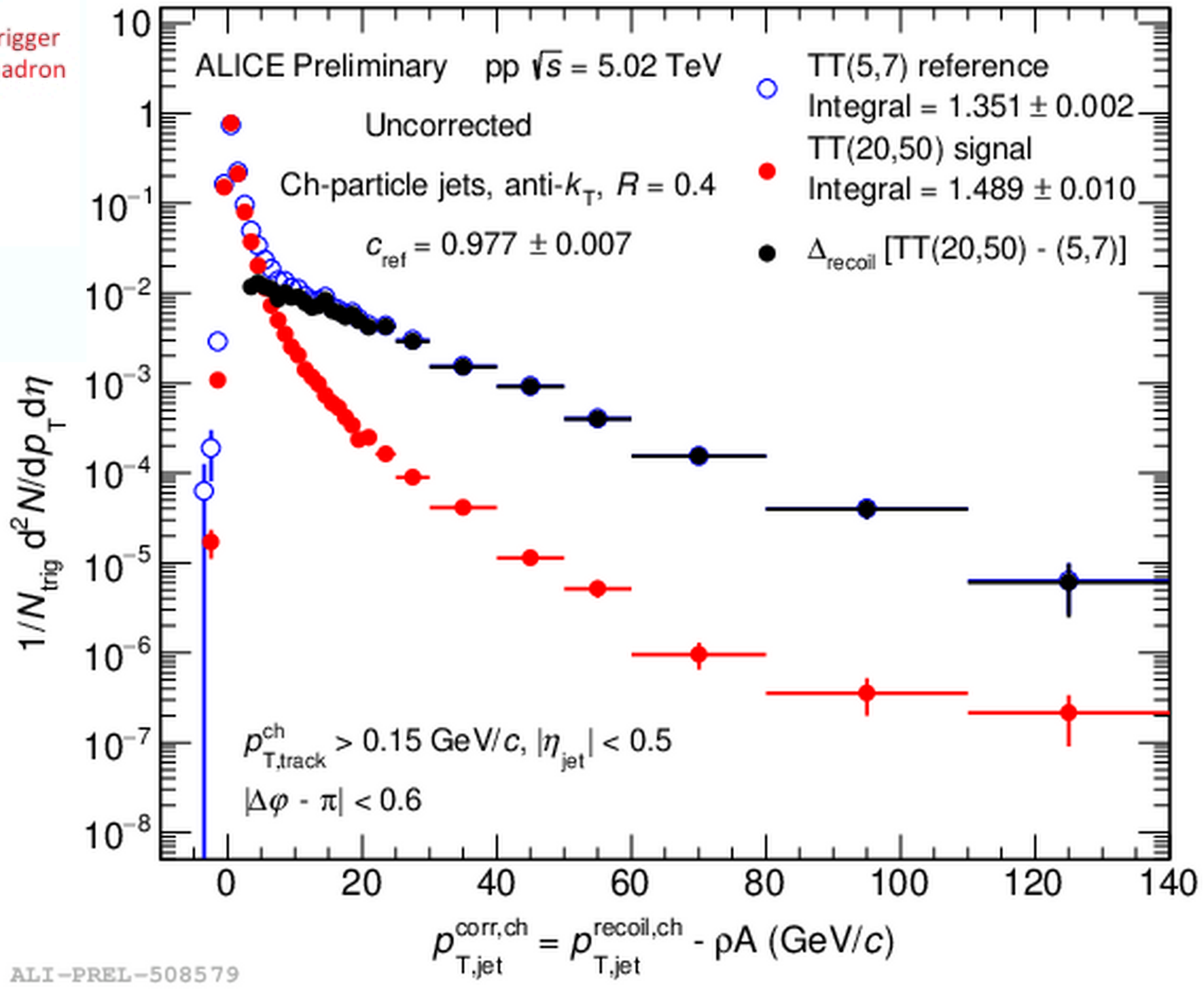


$$\Delta_{\mathrm{recoil}} = \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}} \frac{\mathrm{d}^2\mathrm{N}^{\mathrm{AA}}_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{\mathrm{N}^{\mathrm{AA}}_{\mathrm{trig}}}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

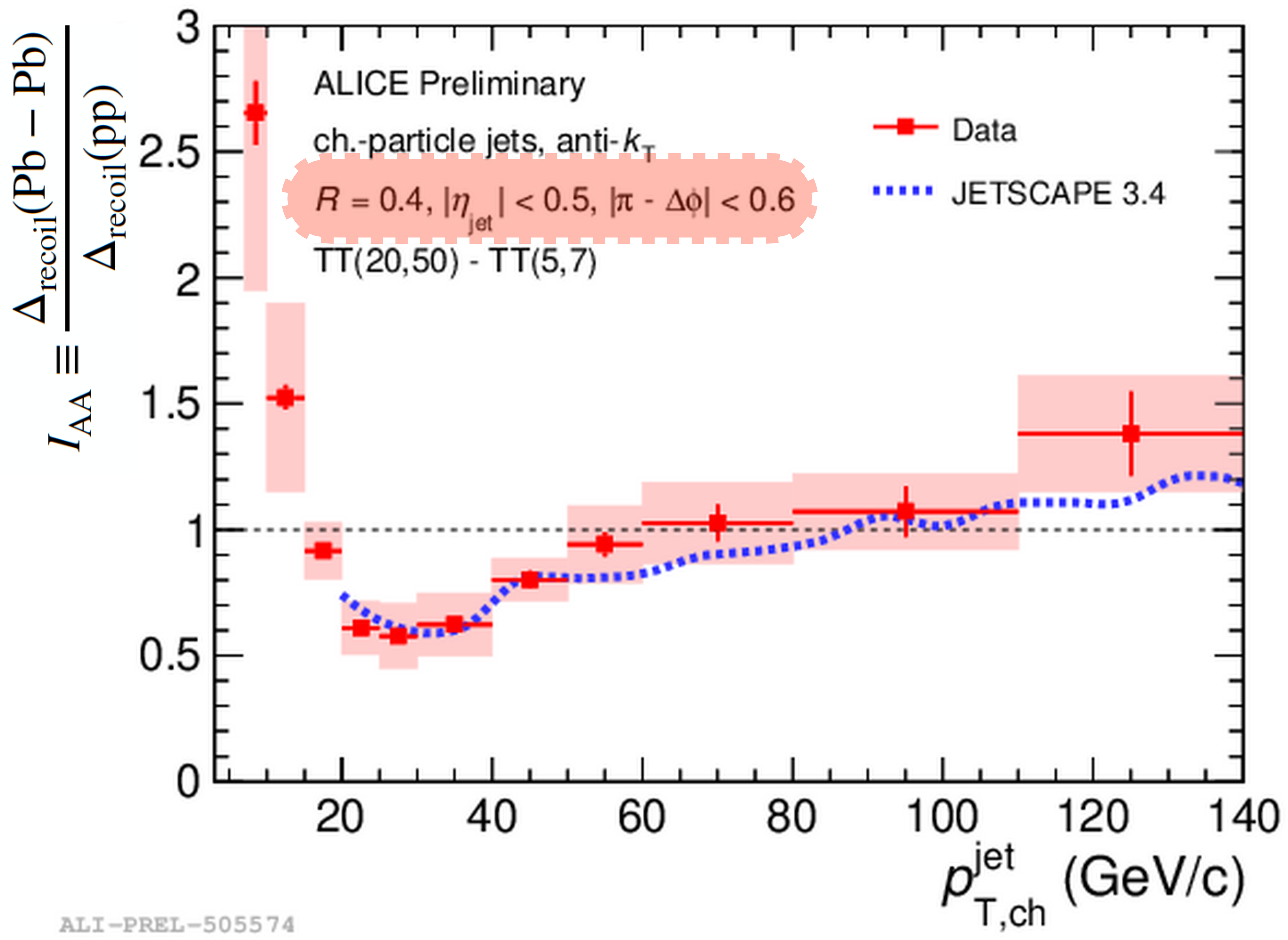
- Measurements of semi-inclusive yield of jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening

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



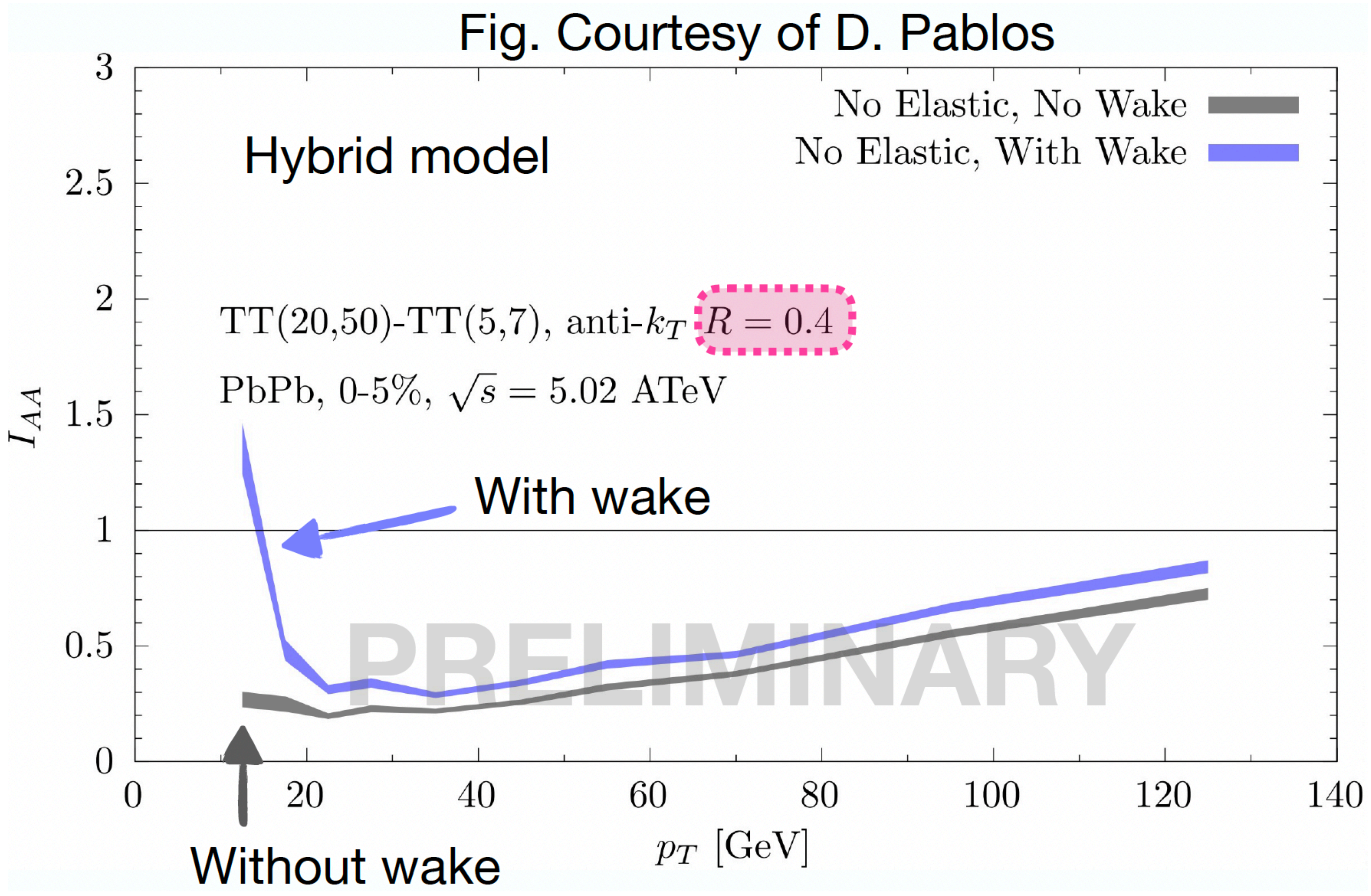


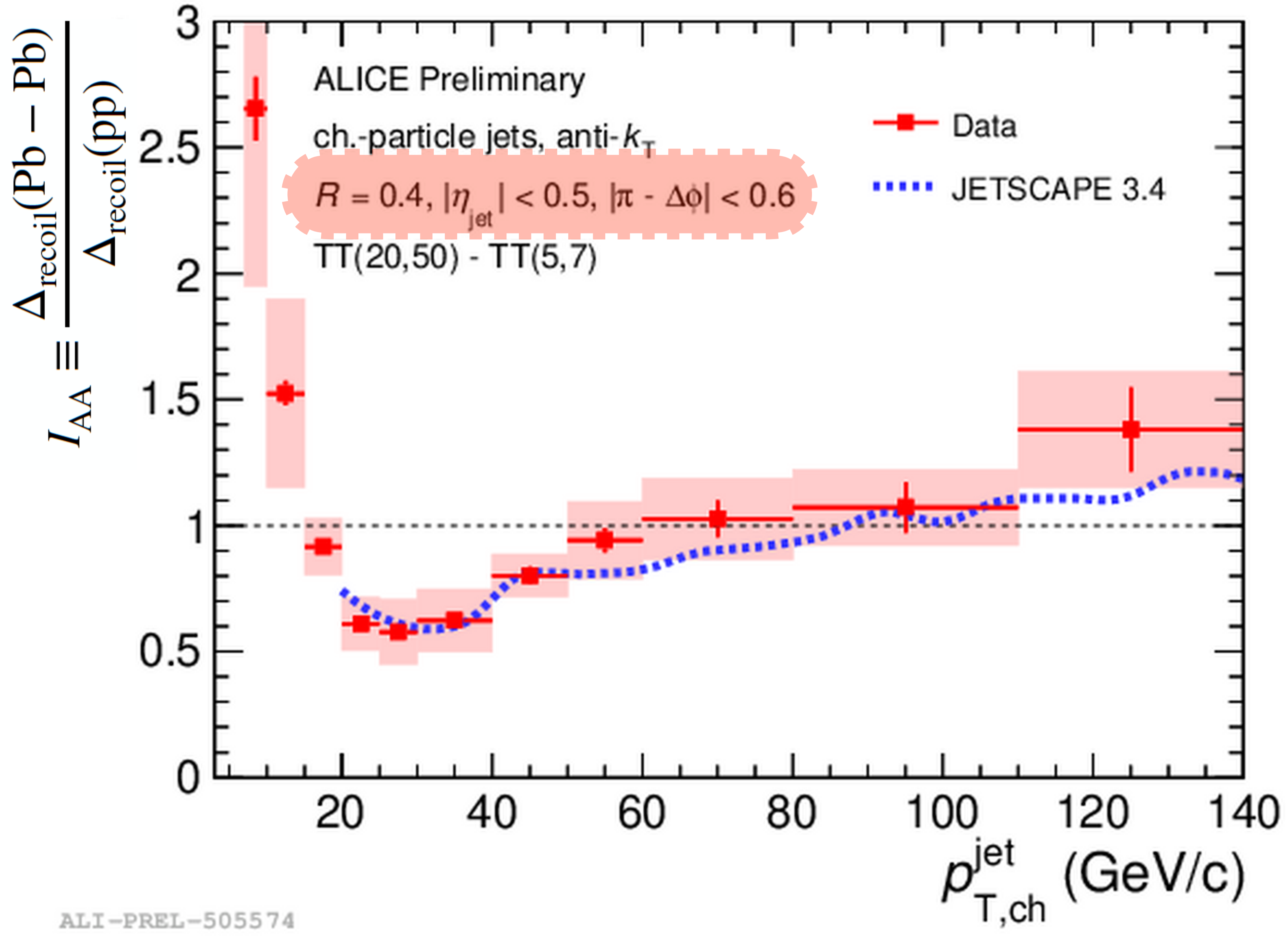
$$\Delta_{\mathrm{recoil}} = \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2N^{AA}_{\mathrm{jet}}}{dp^{\mathrm{ch}}_{\mathrm{T,jet}} d\eta_{\mathrm{jet}}} \Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT_{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2N^{AA}_{\mathrm{jet}}}{dp^{\mathrm{ch}}_{\mathrm{T,jet}}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



- 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

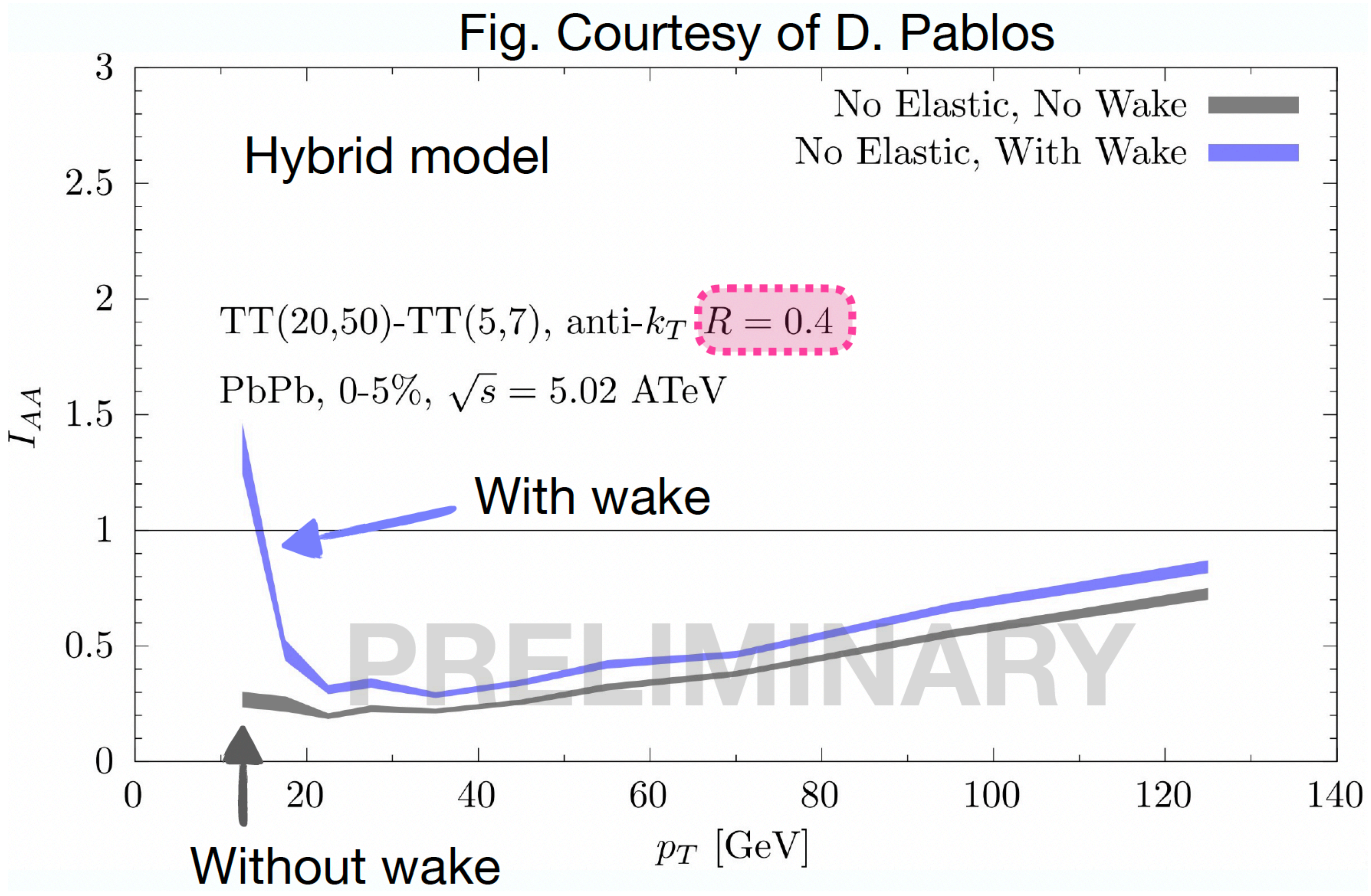
Sensitivity to medium response ("the wake")



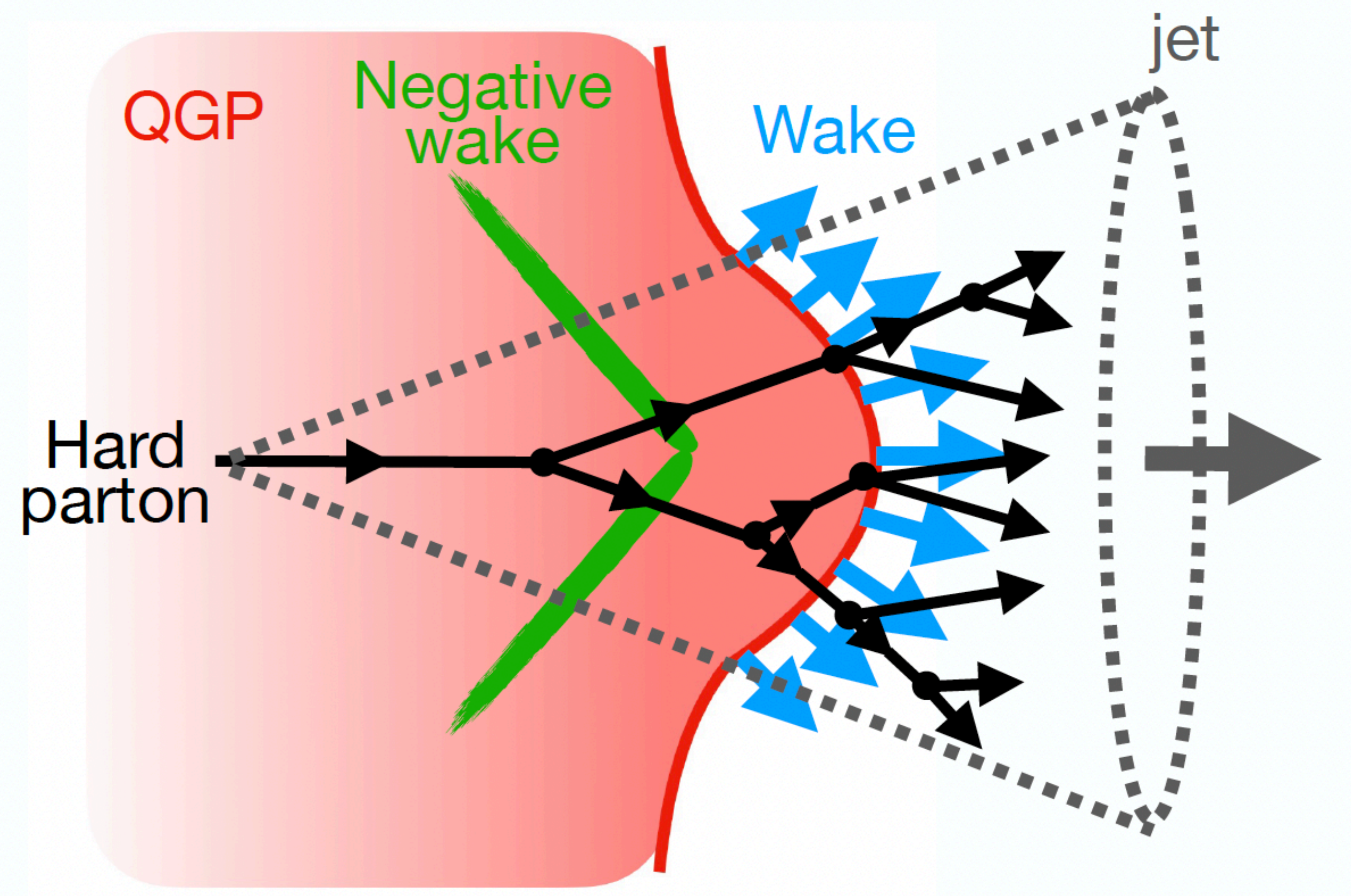


- Uprise at low p_T explained by medium response within Hybrid model

Sensitivity to medium response ("the wake")

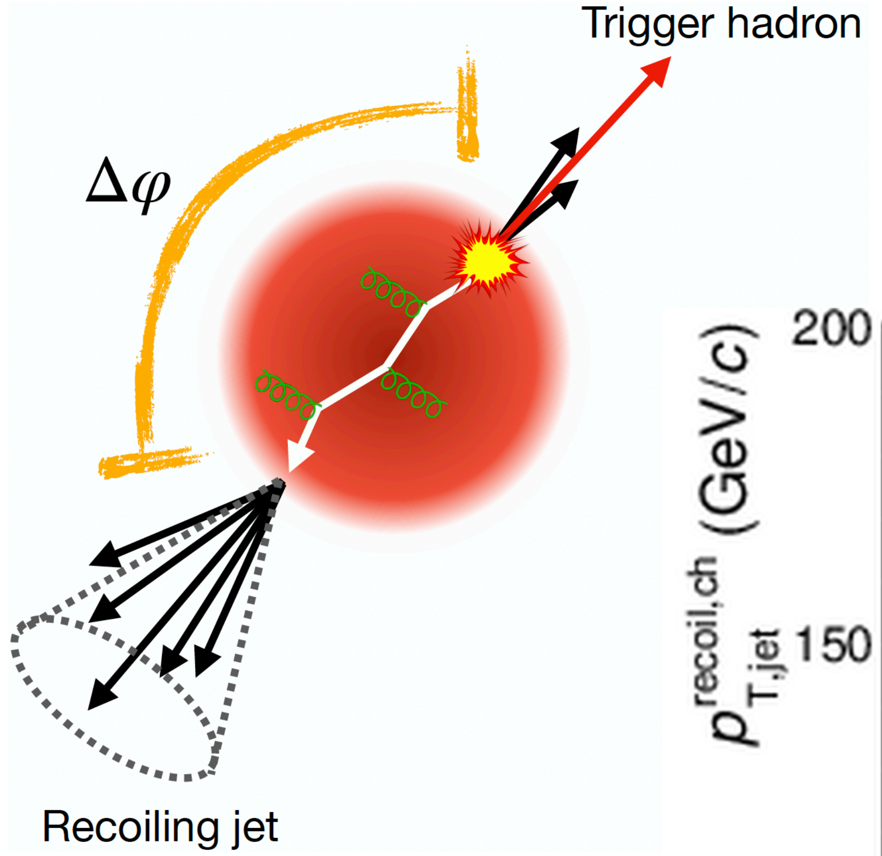


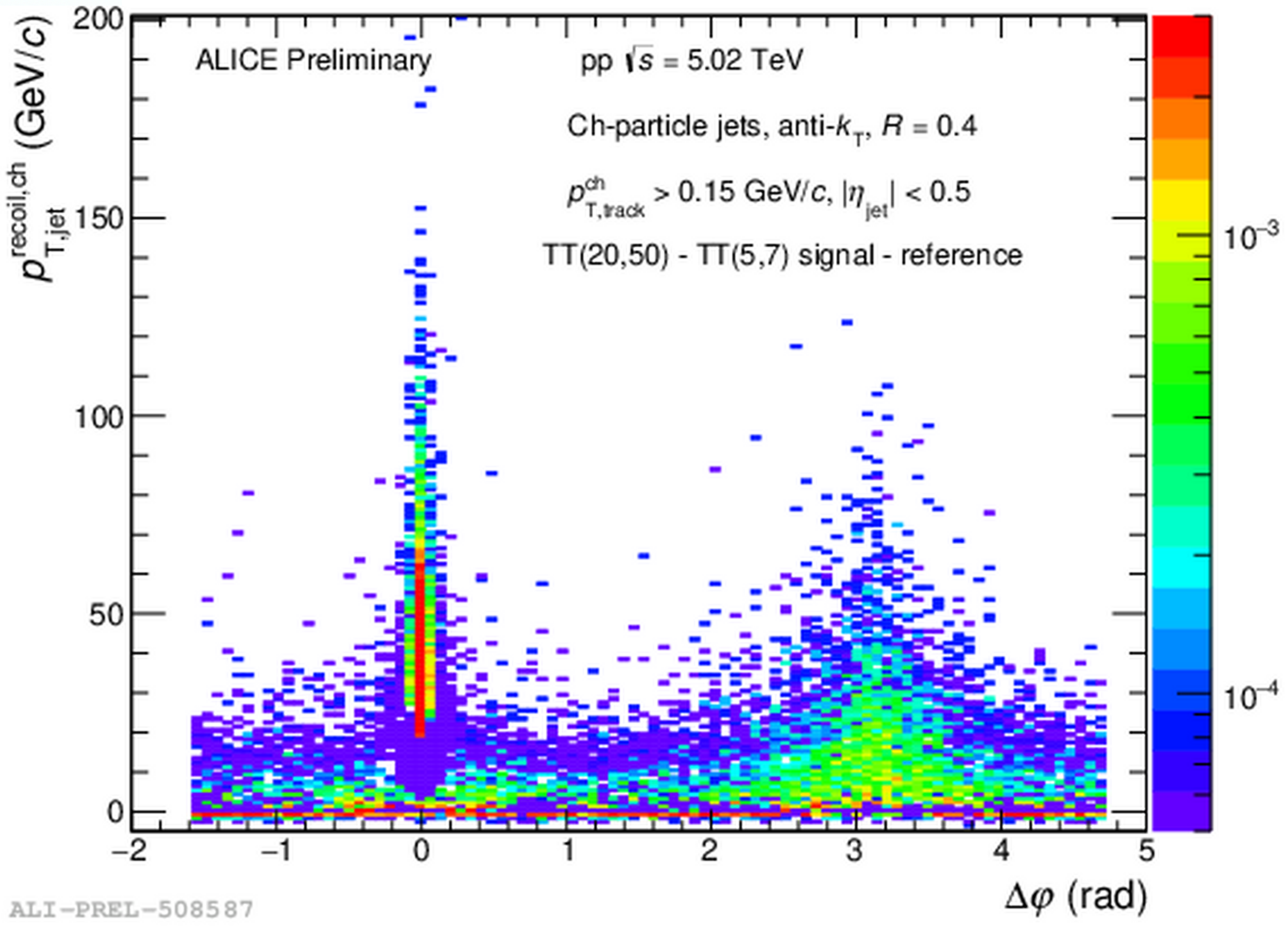
From jet-medium interaction, medium partons acquire additional momentum that correlates their direction with the jet



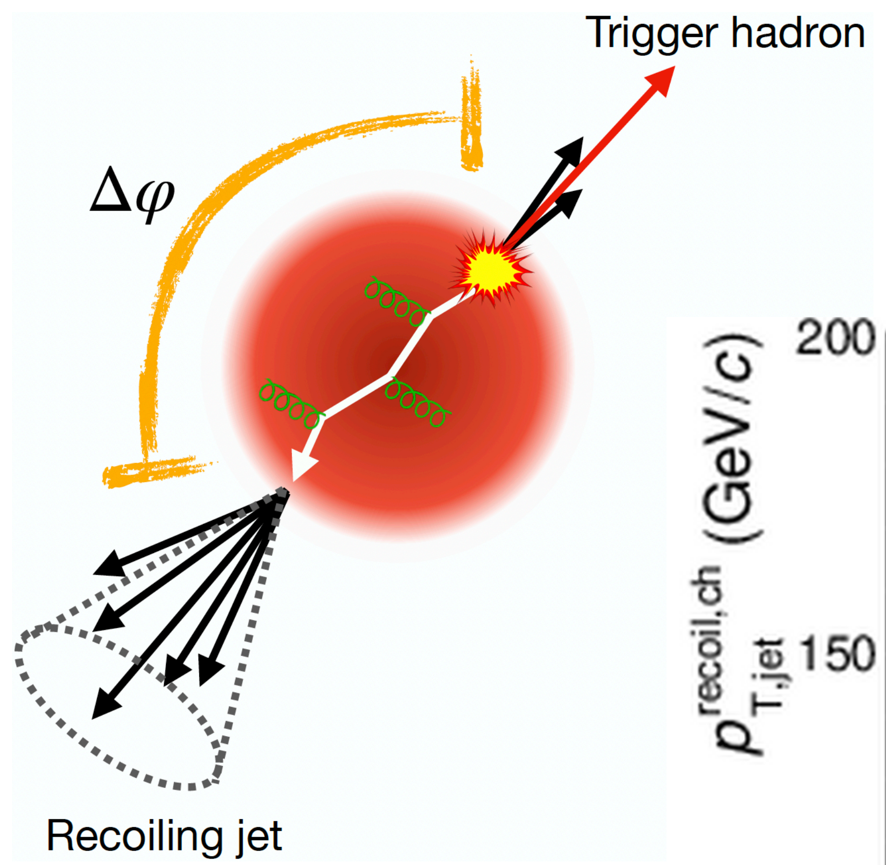
- Medium response important for:
  - full characterization of QGP
  - QGP bulk properties (velocity of sound, viscosities)
  - thermalization: how fast is the jet energy propagated and thermalized with the rest of QGP?

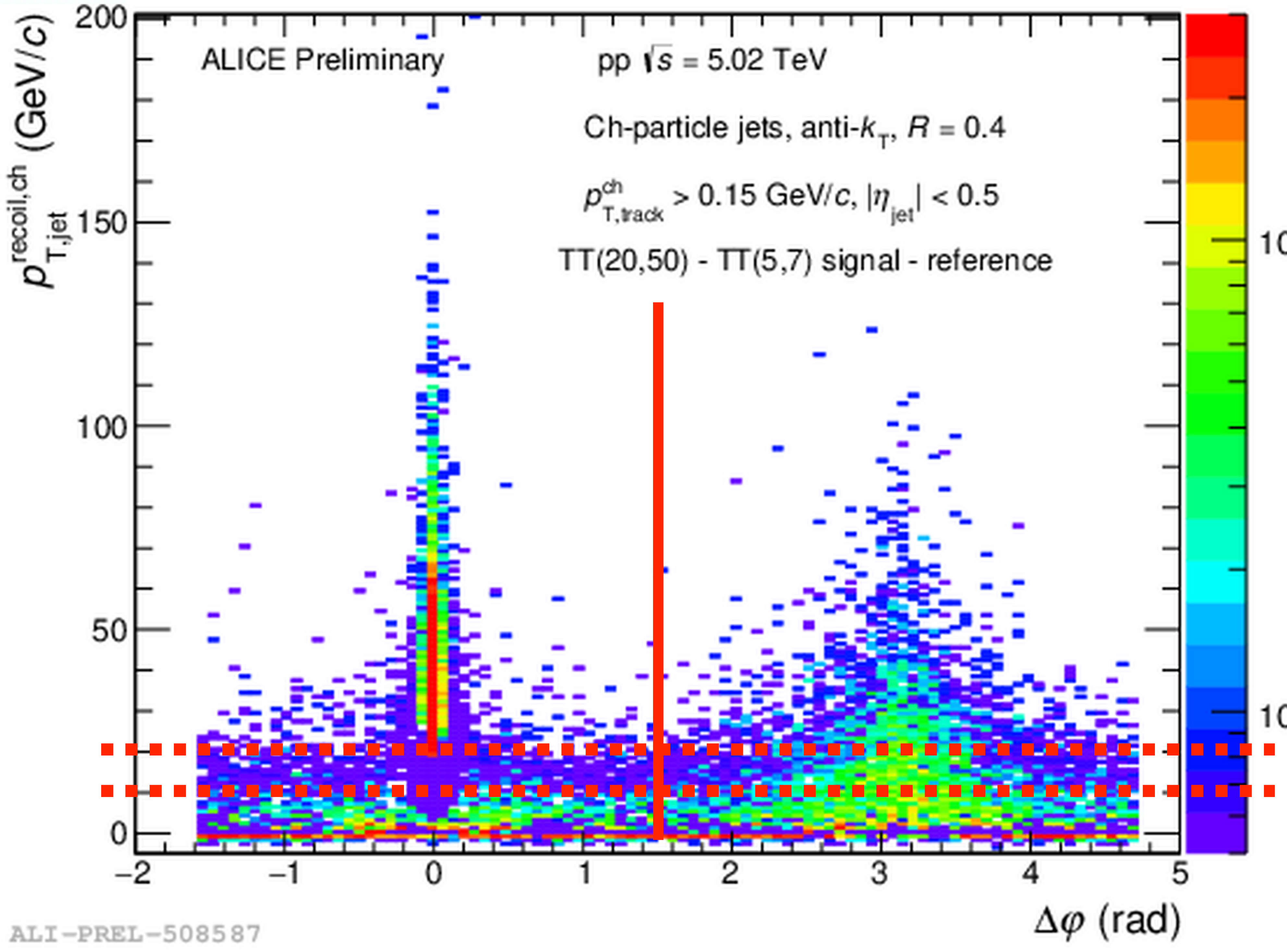
$\Delta\varphi$ results - angular deflections



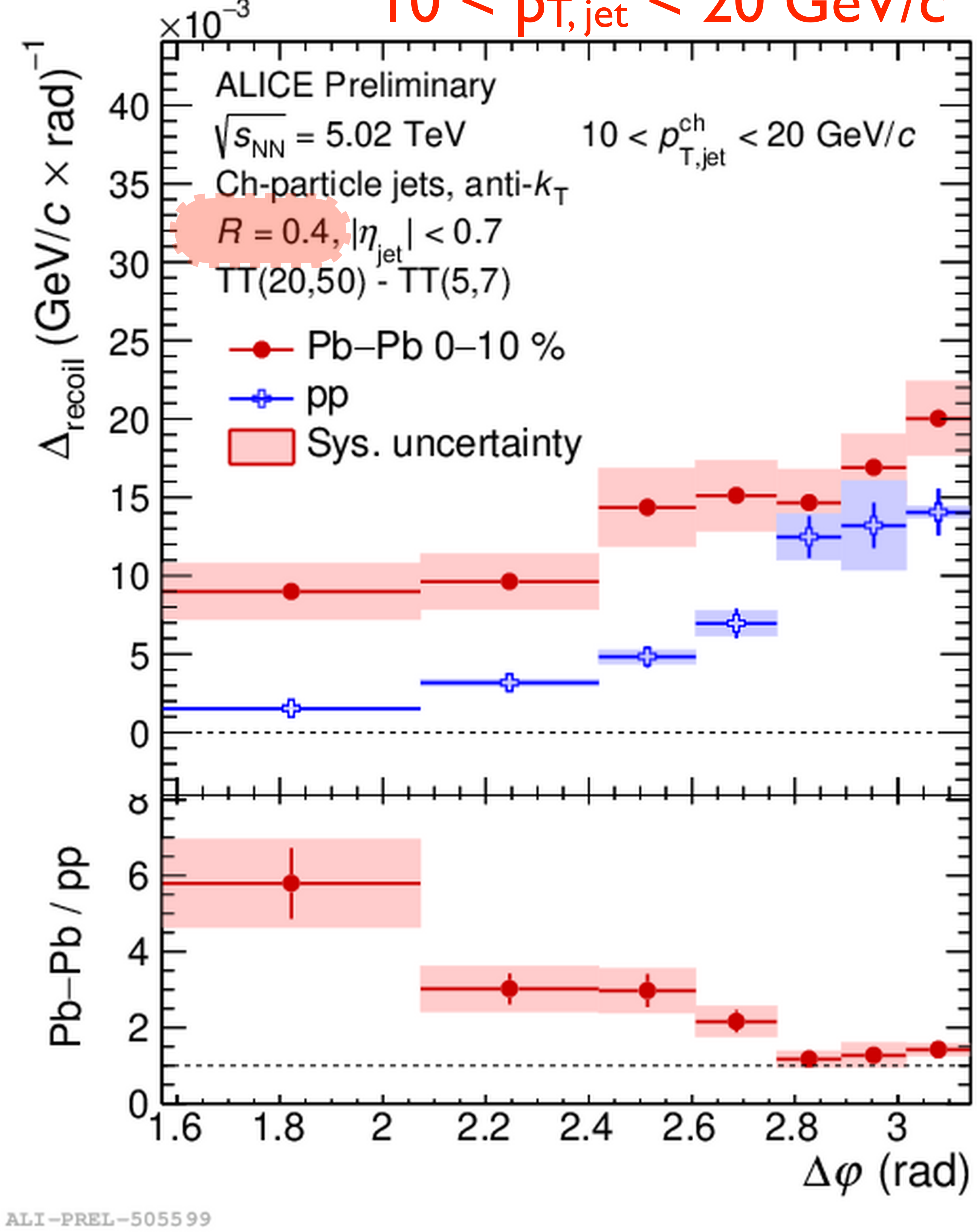


$\Delta\varphi$ results - angular deflections

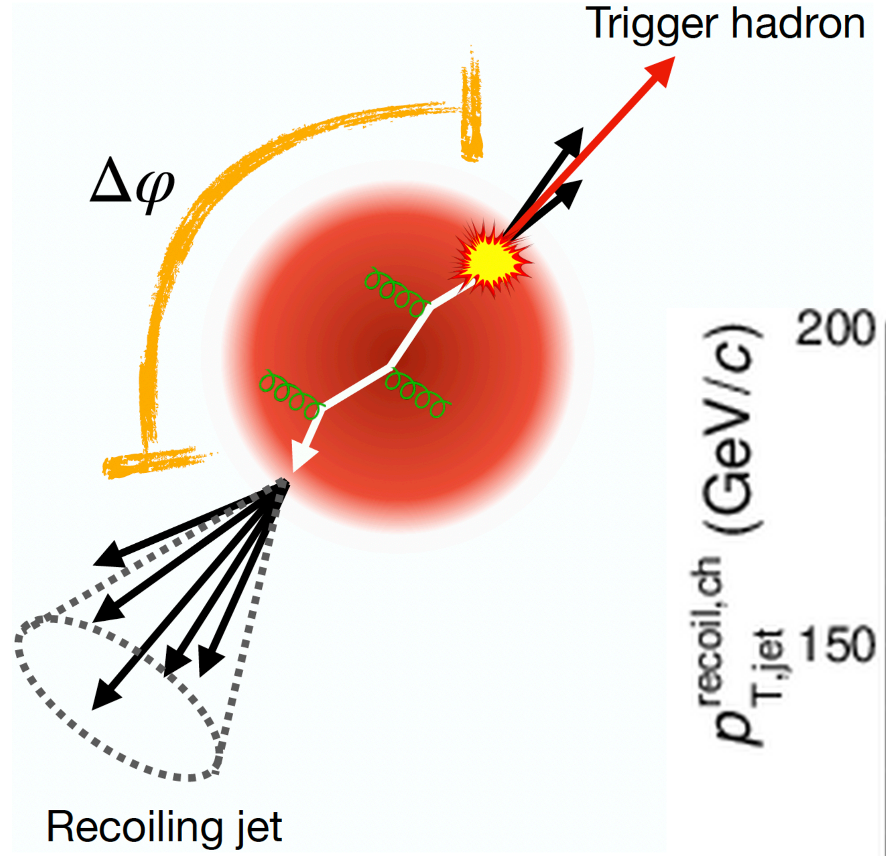


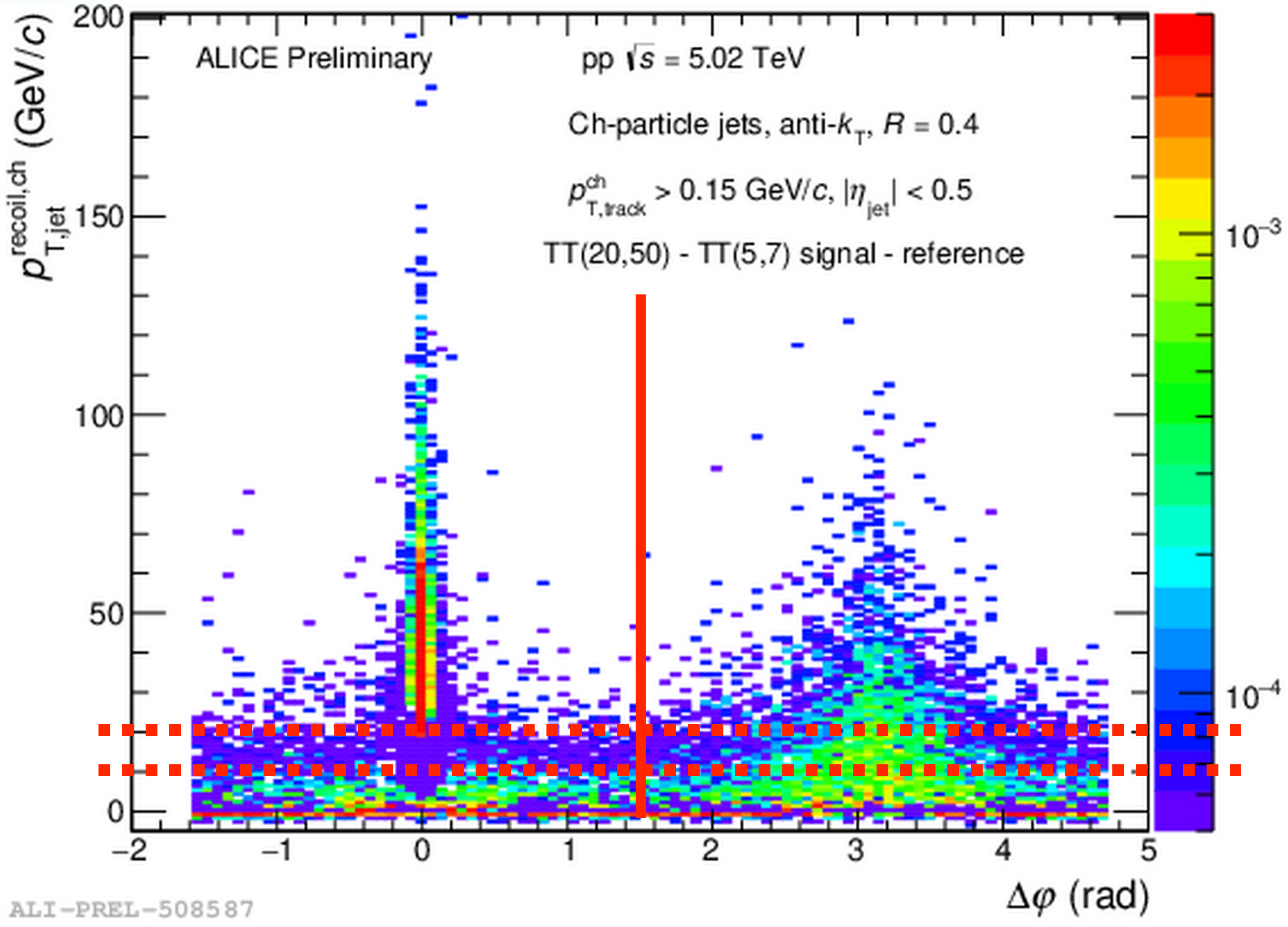


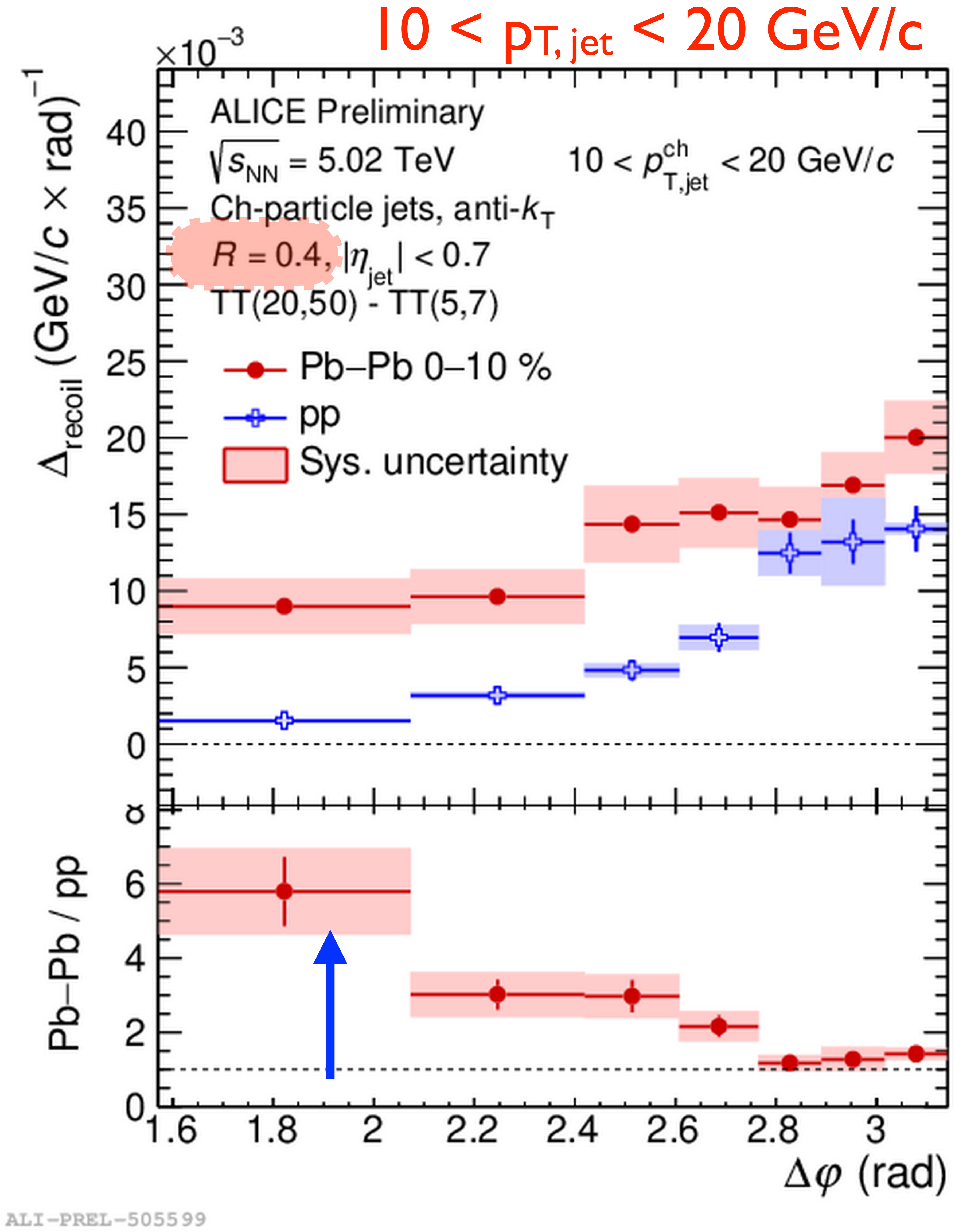
10 < $p_{T,jet}$ < 20 GeV/c



$\Delta\varphi$ results - angular deflections

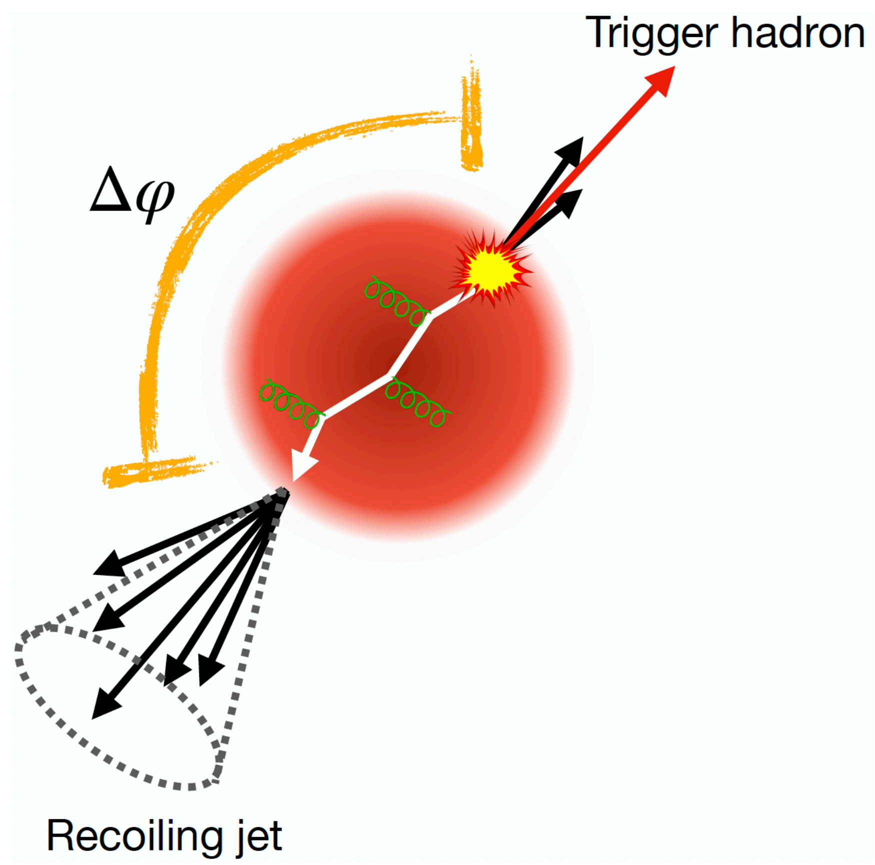




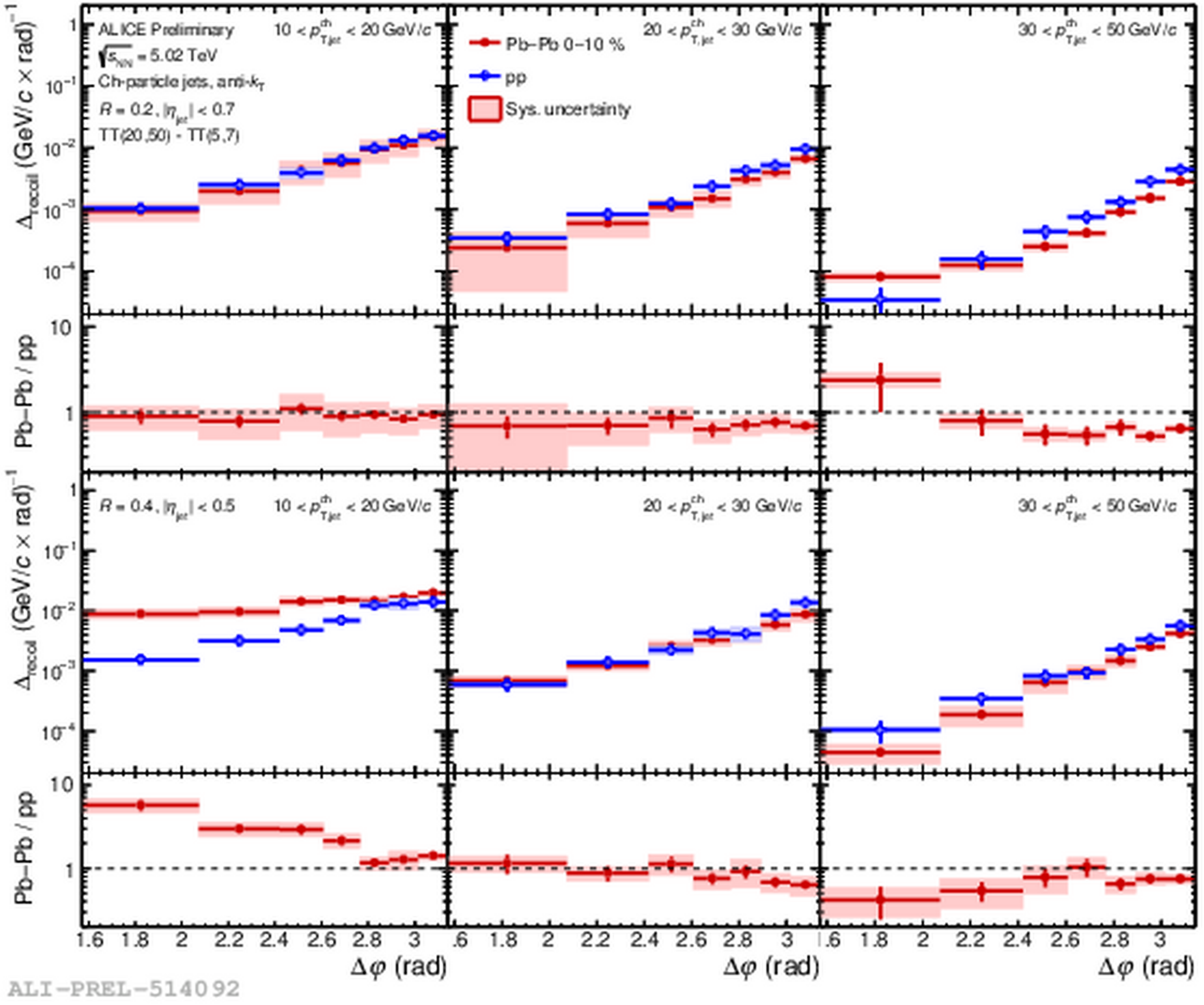


- First evidence of broadening of h-jet azimuthal correlations for soft jets

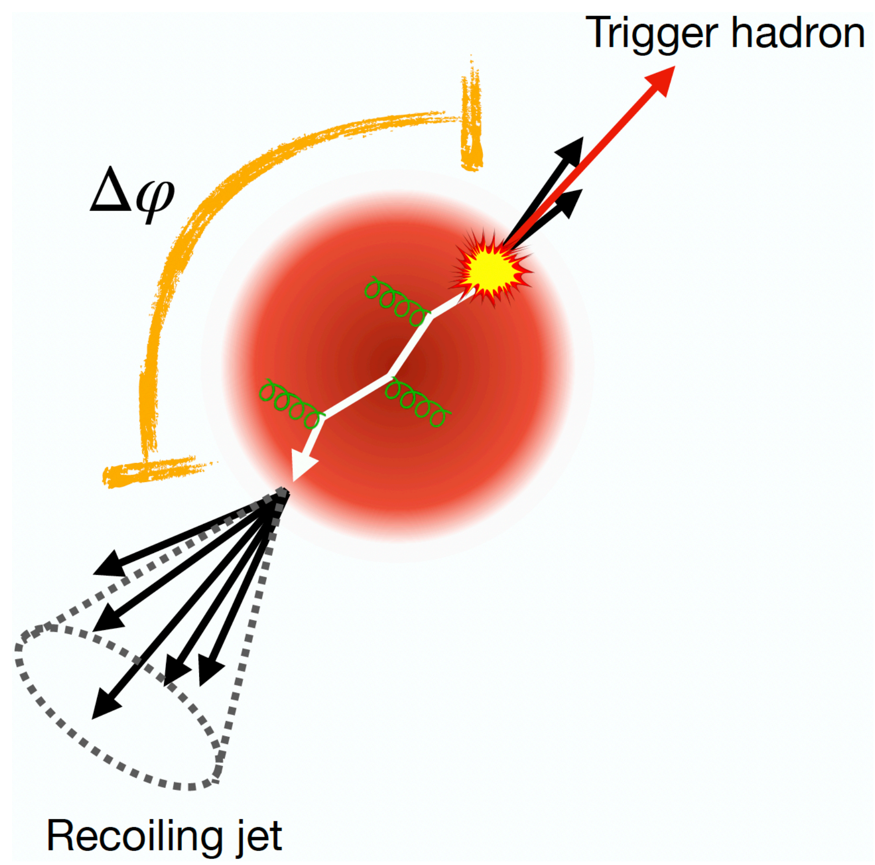
$\Delta\varphi$ results - angular deflections



- Scan wide kinematics:
  - no modification (small R, large p_T)
  - large modification (large R, low p_T)

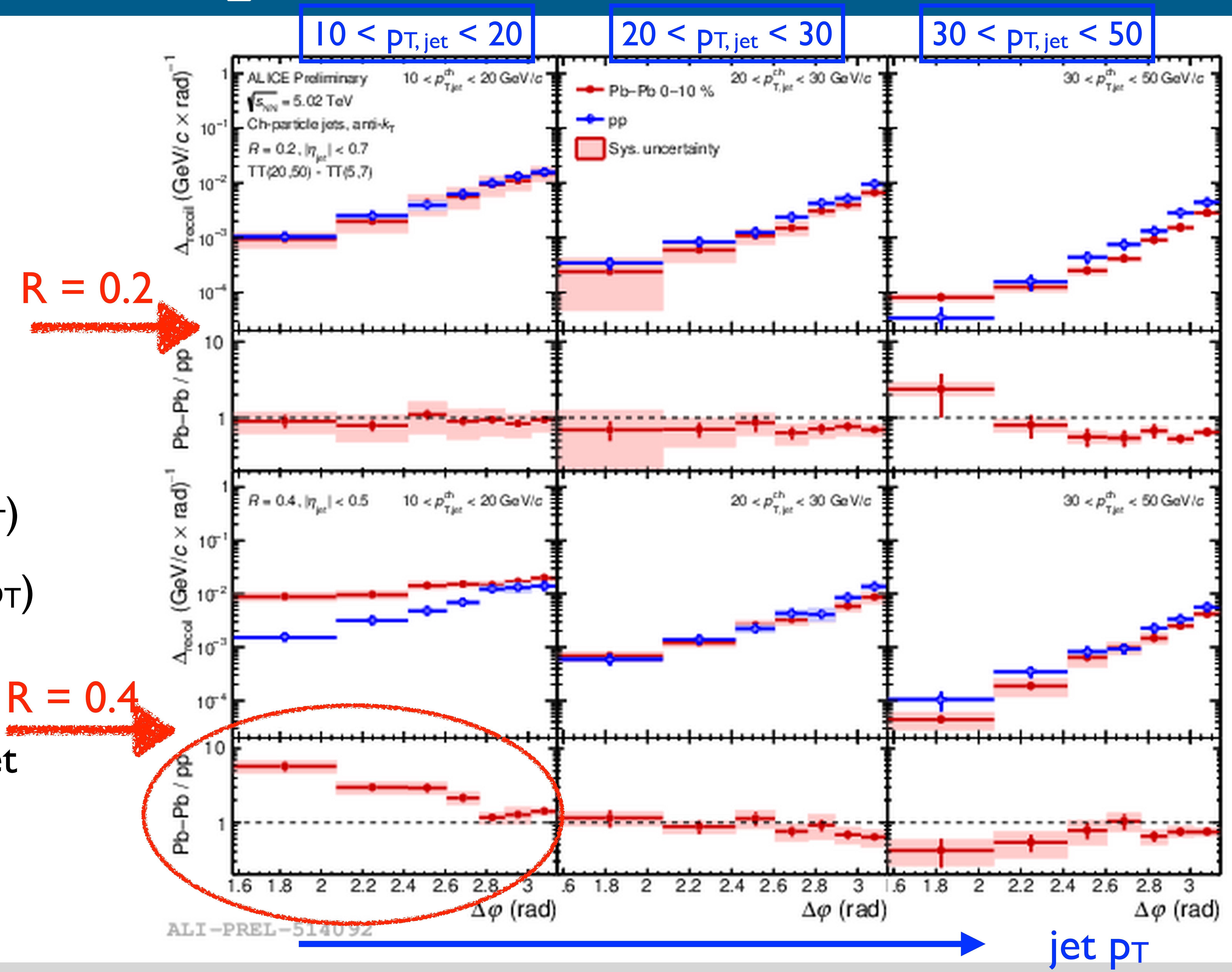


$\Delta\varphi$ results - angular deflections

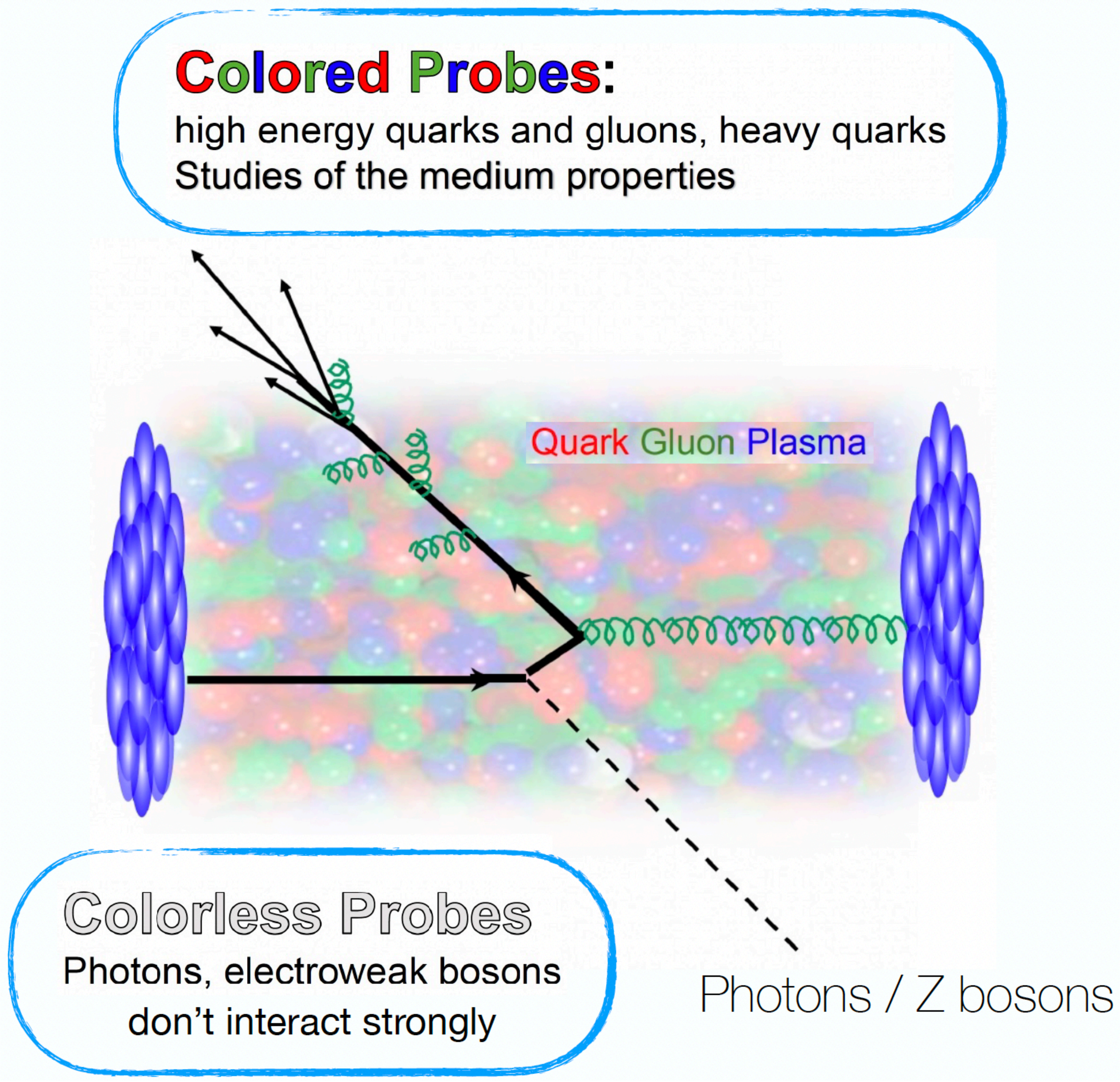


- Scan wide kinematics:
  - no modification (small R, large p_T)
  - large modification (large R, low p_T)

- First evidence of broadening of h-jet azimuthal correlations for soft jets

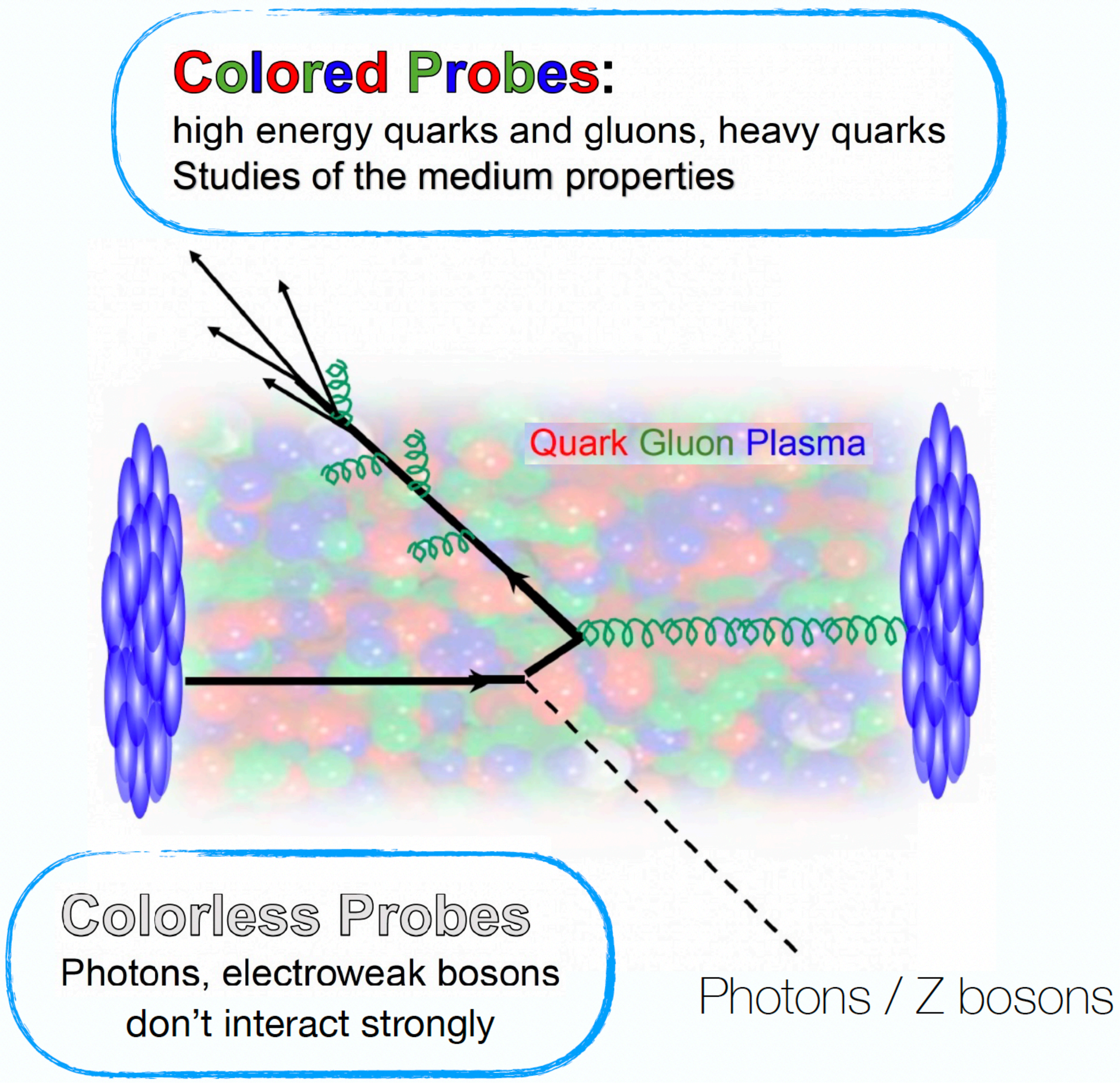


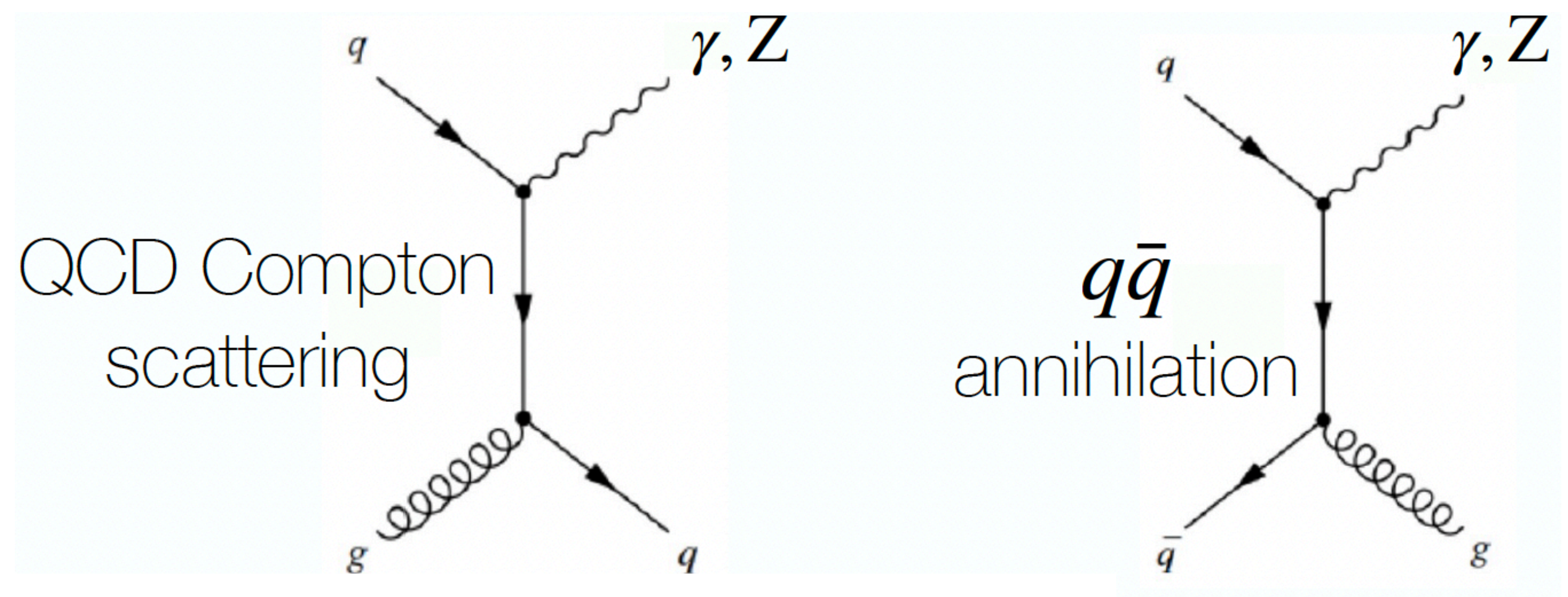
Colorless probes

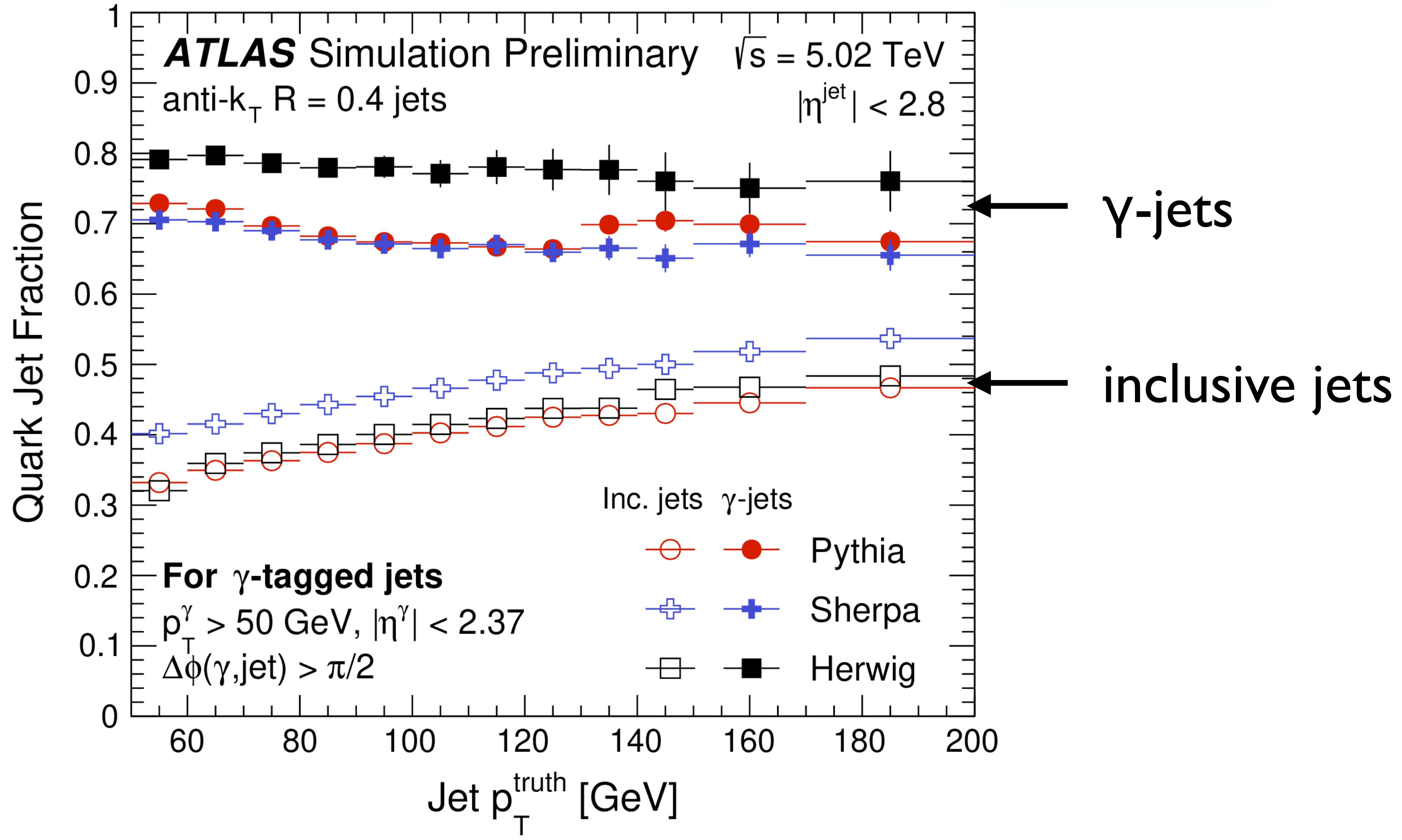


Tagging initial jet energy

Colorless probes







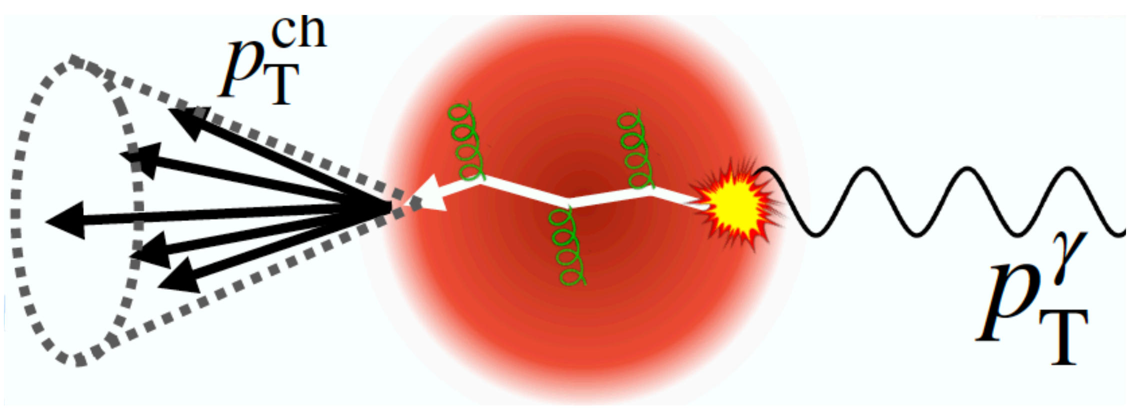
Tagging initial jet energy

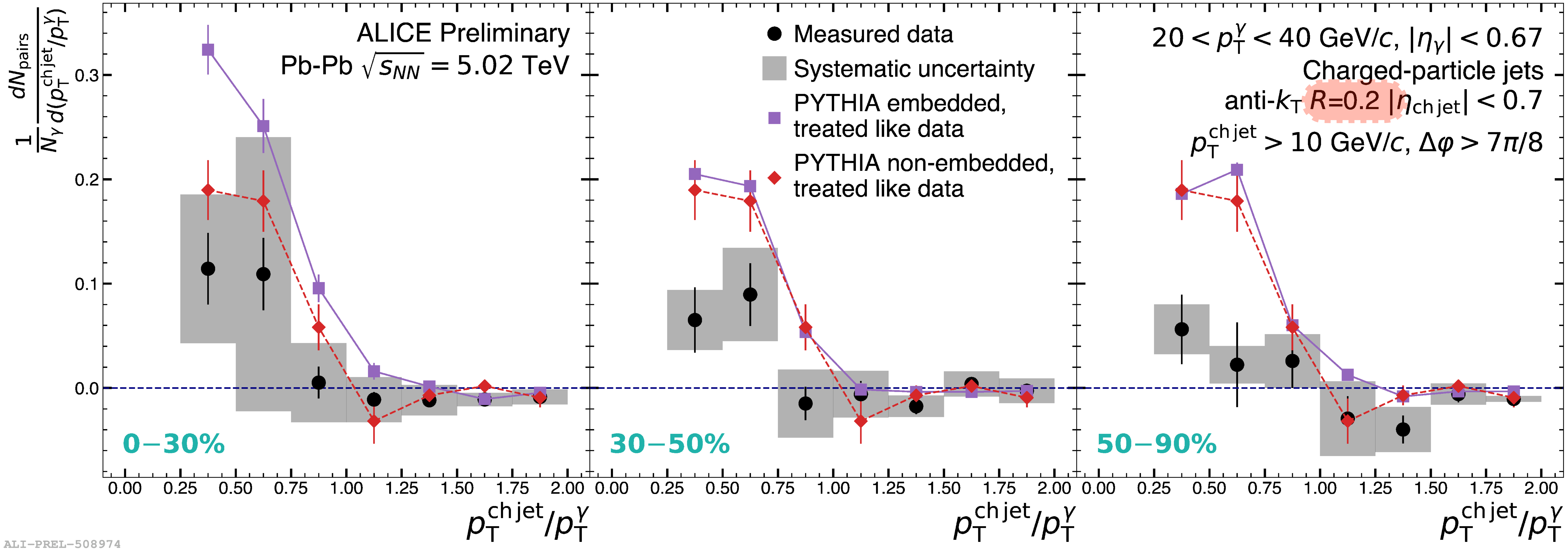
Increasing quark-jet fraction

Isolated photon-jet correlations

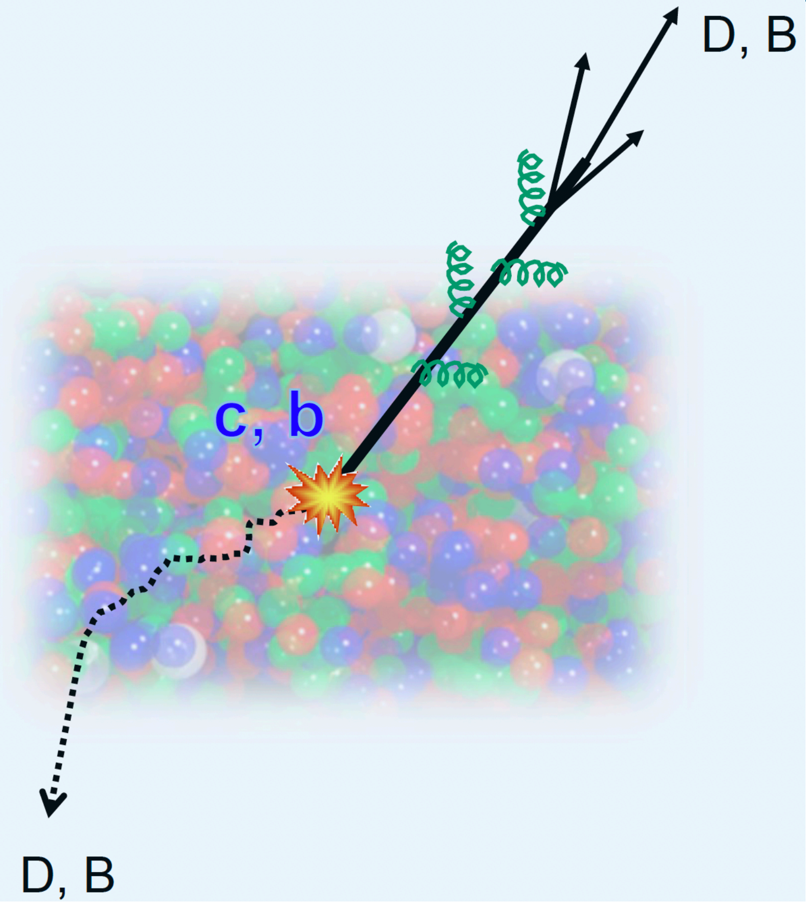
Momentum imbalance: $x_{j\gamma} = p_T^{jet}/p_T^{\gamma}$

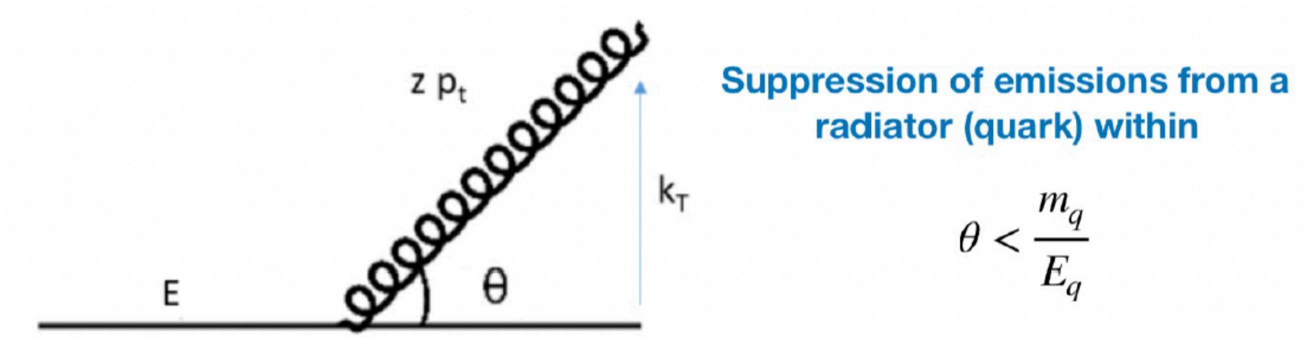
- Measurements down to p_T^{γ} = 20 GeV (first at LHC)
- Shape difference in PYTHIA from detector effects
- No centrality dependence observed within uncertainties



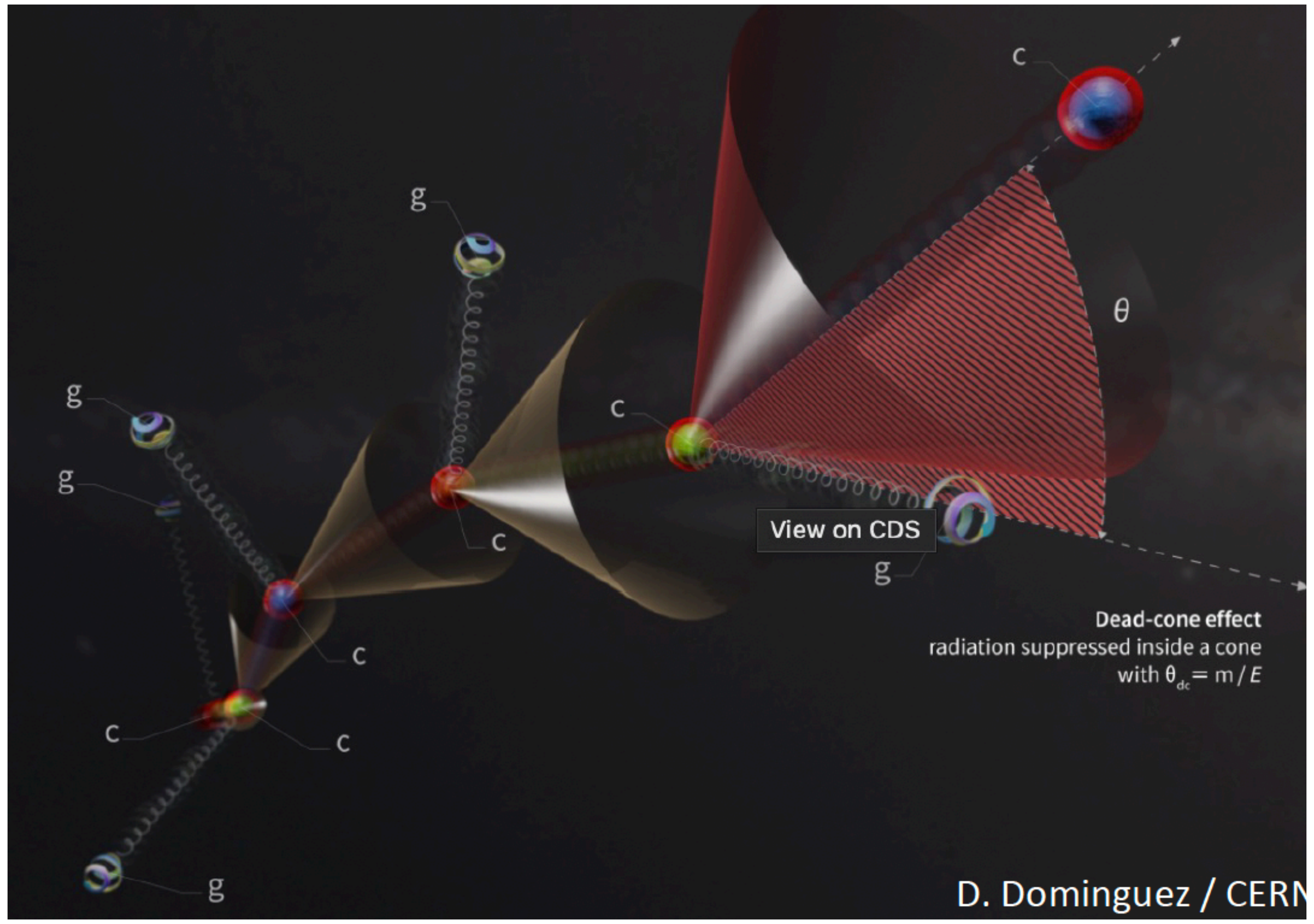


Quark mass dependence of energy loss



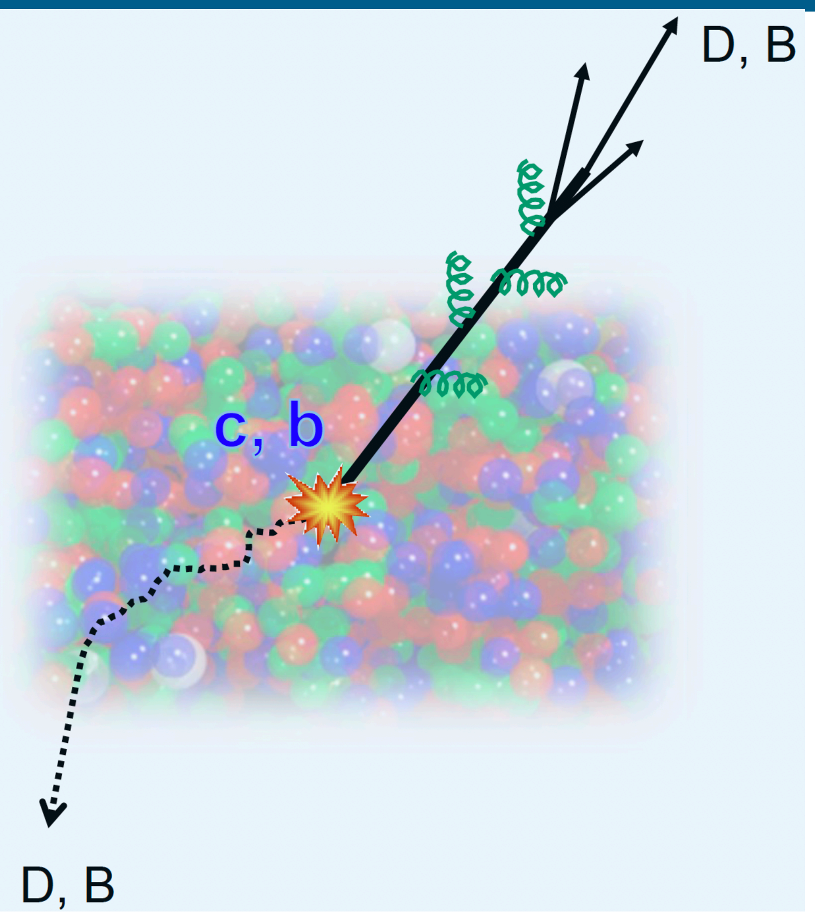


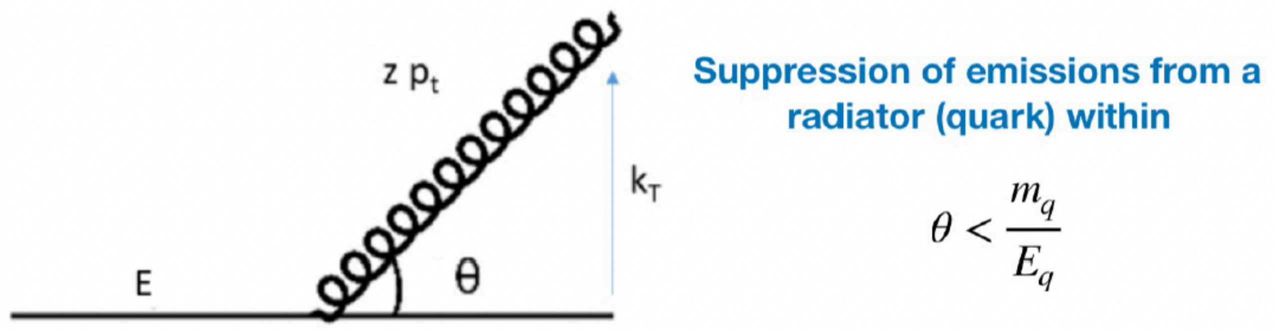
J. Phys. G 17 (1991) 1602



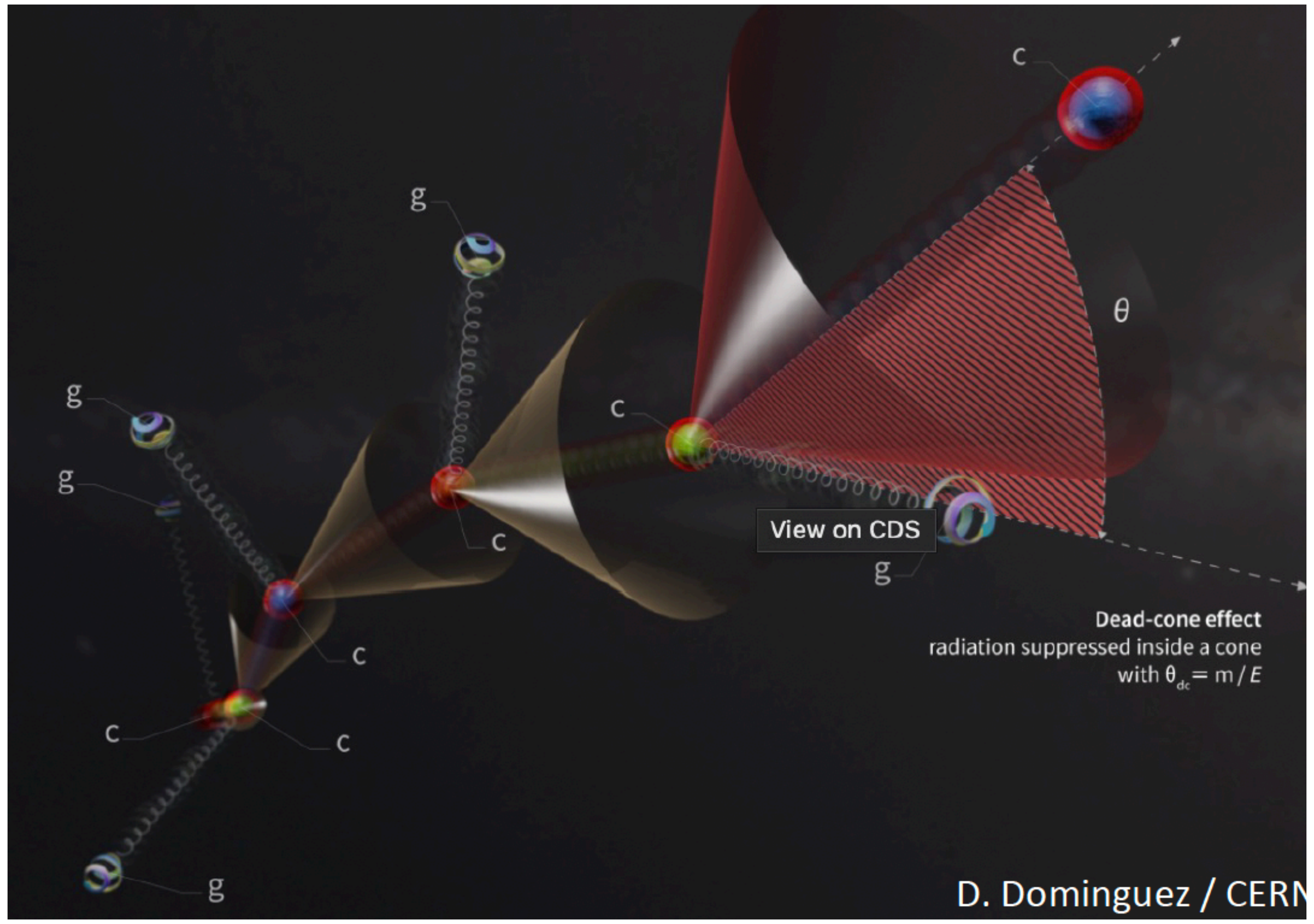
- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect

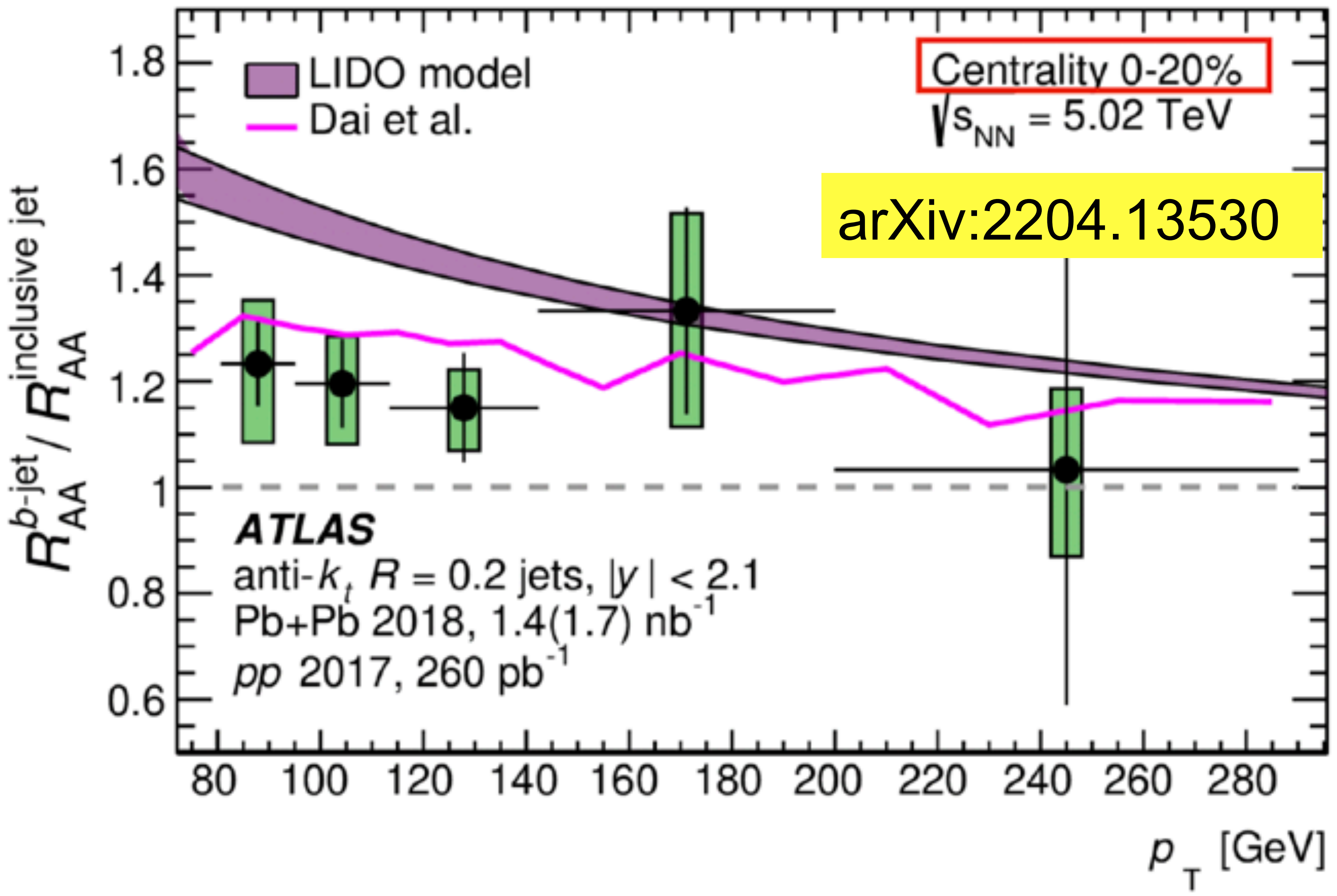
Quark mass dependence of energy loss





J. Phys. G 17 (1991) 1602

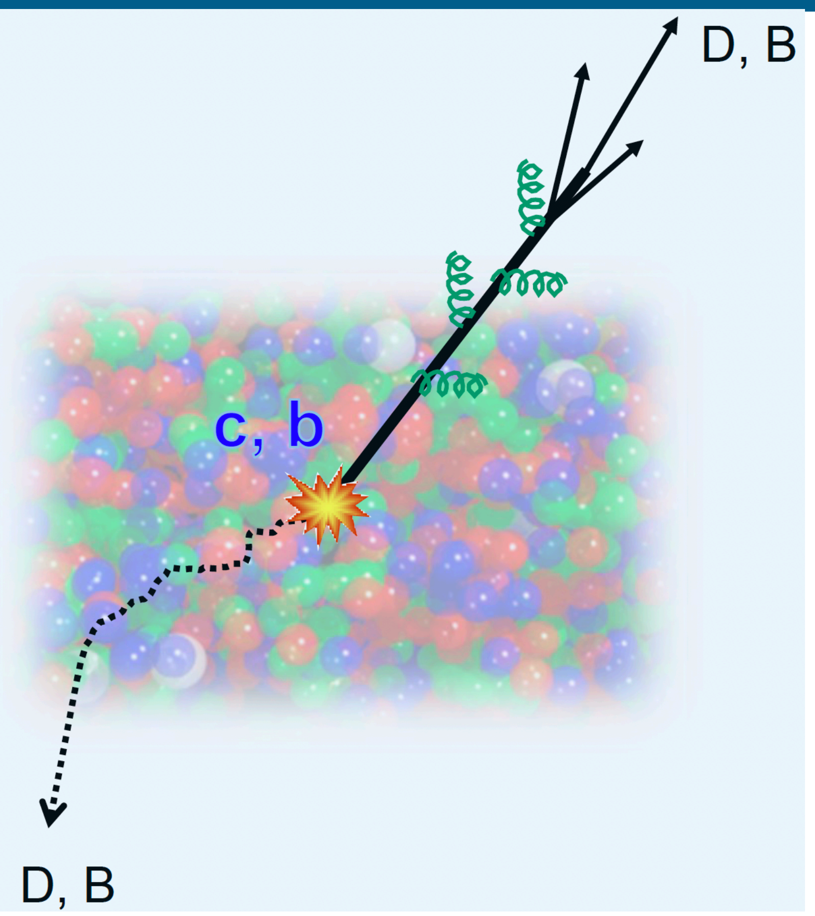


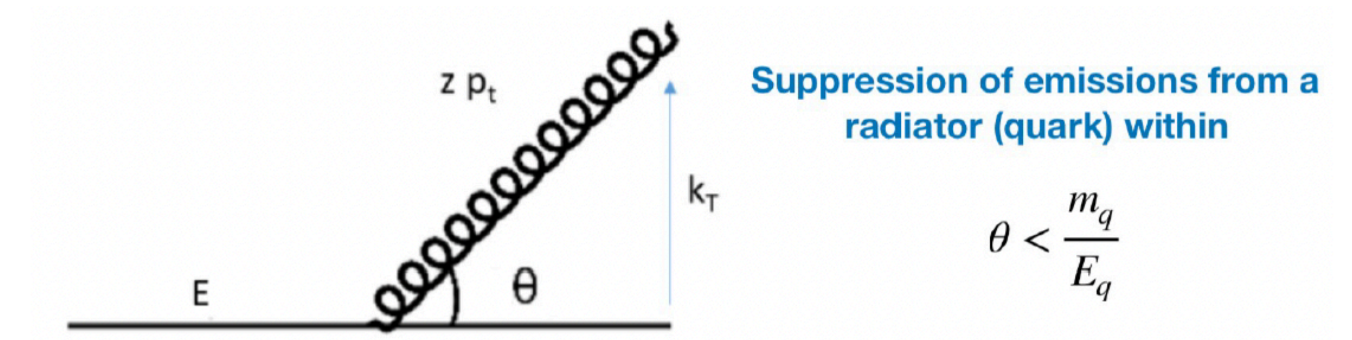


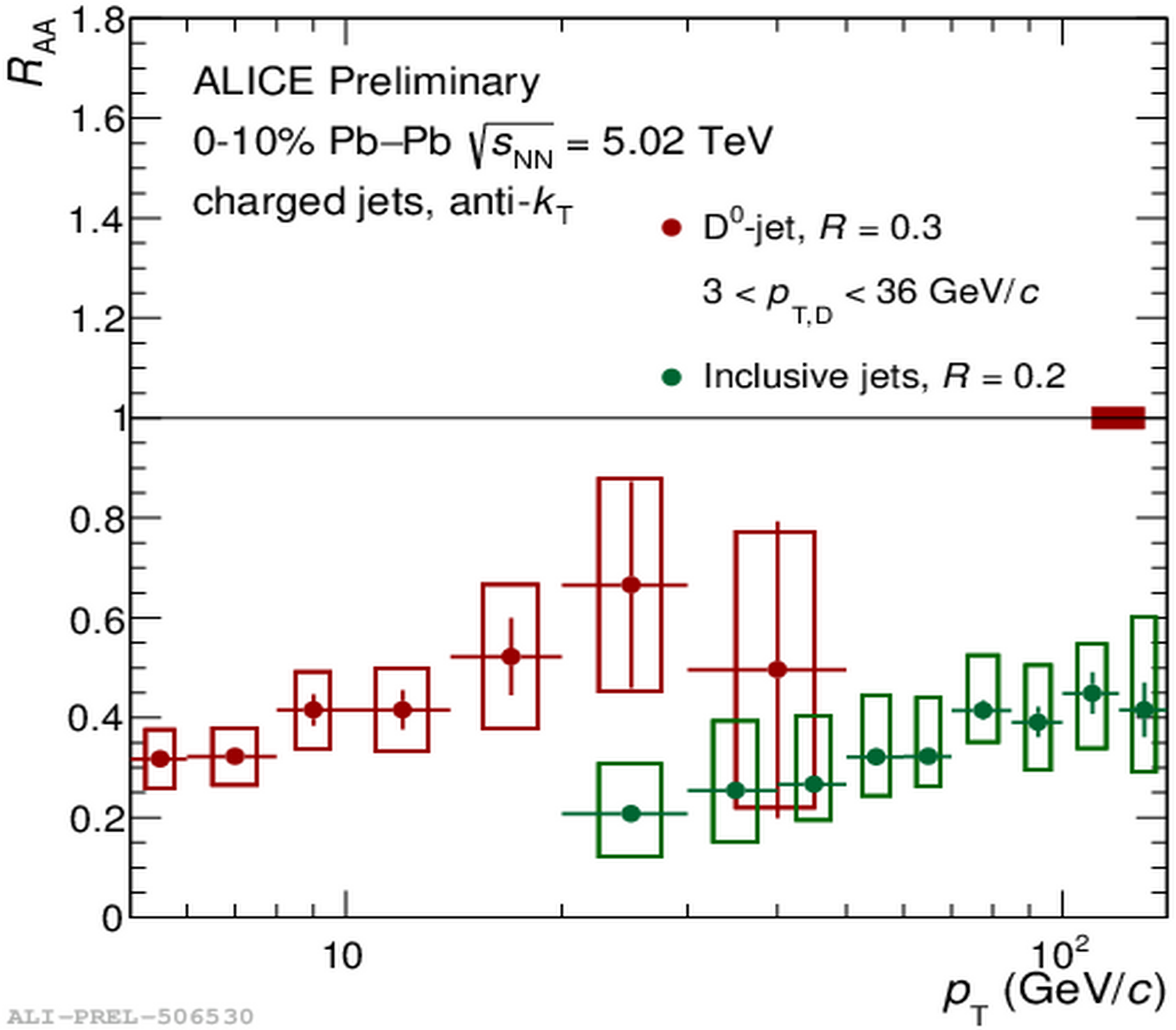
arXiv:2204.13530

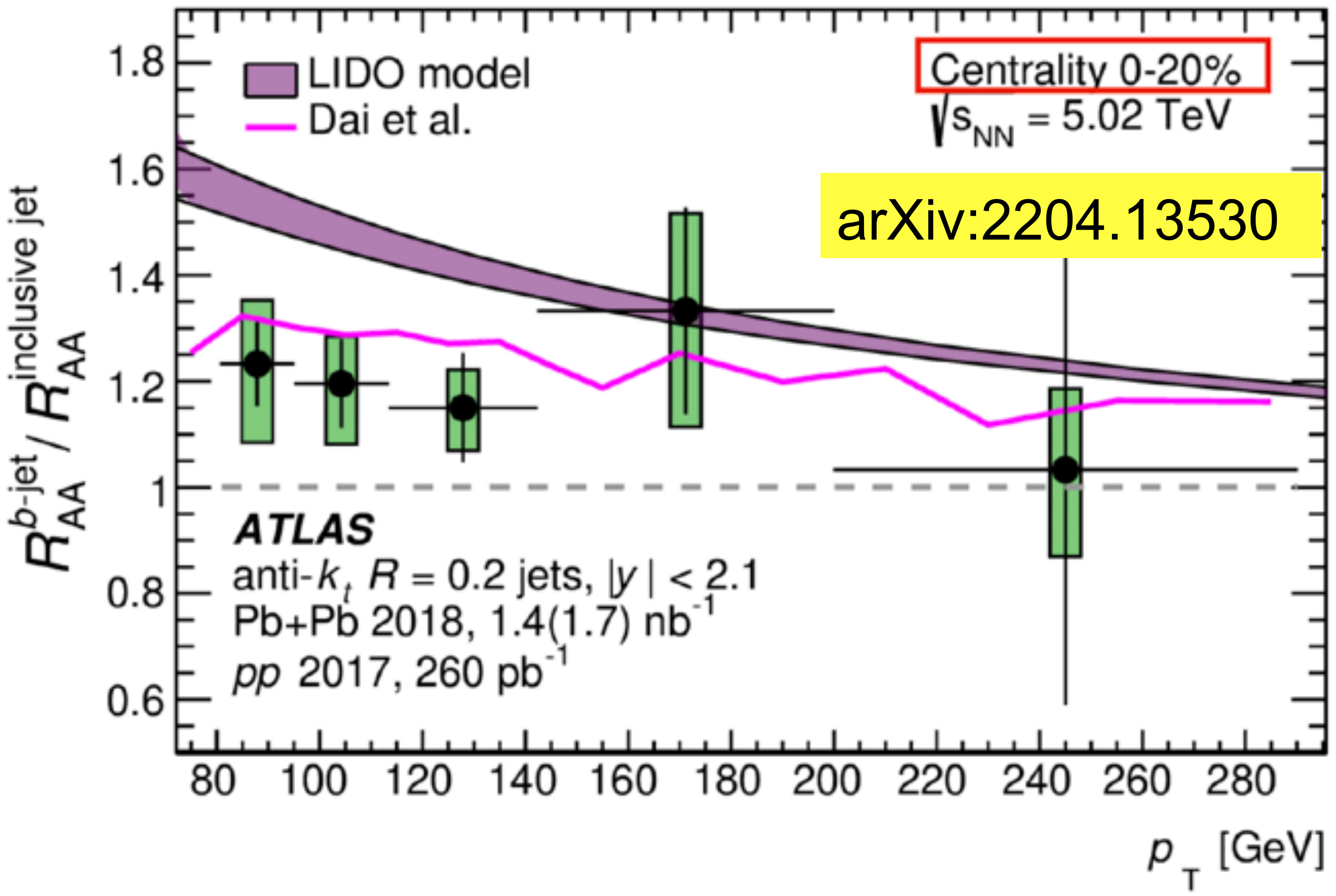
- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect
- Less suppression of b-jets than inclusive jets in most central collisions

Quark mass dependence of energy loss







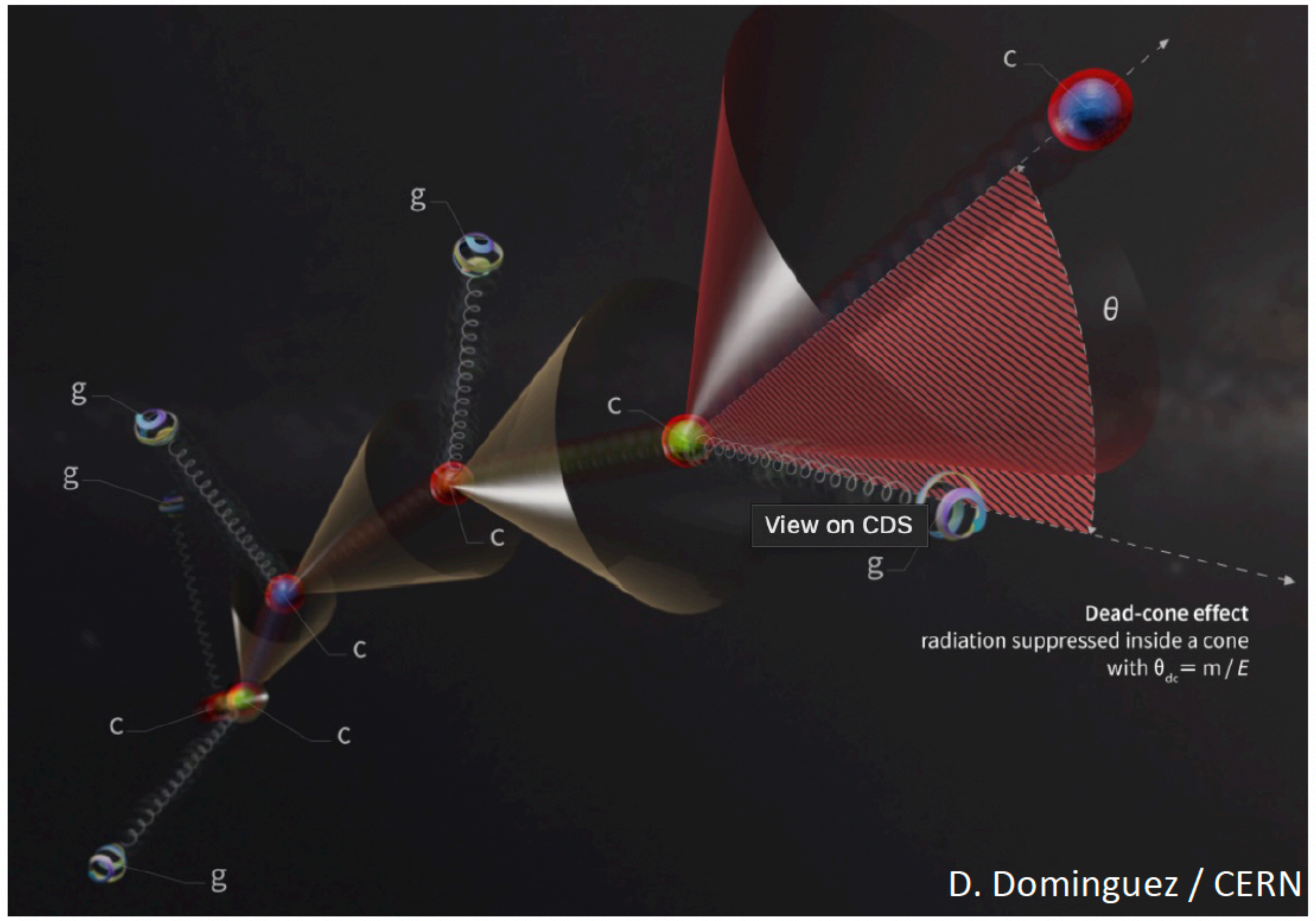


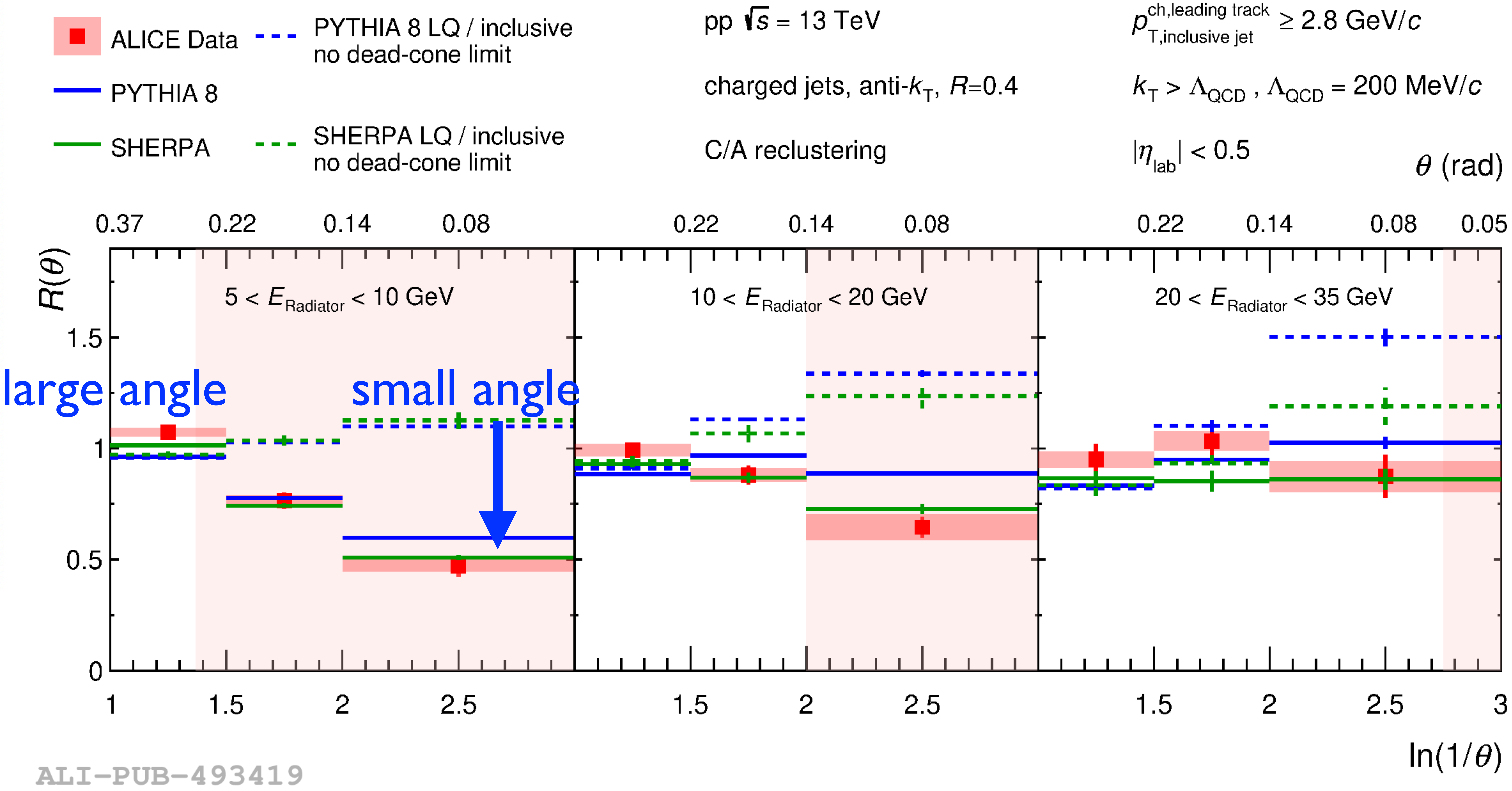
- Energy loss predicted to depend also on quark mass: reduction of gluon radiation from heavy quarks at small angles —"Dead Cone" effect
- Less suppression of b-jets than inclusive jets in most central collisions
- Similar indication is found for D^0-jets R_{AA}: less suppression compared to the inclusive one
  - NB: not the same kinematic range or same jet selection for comparisons

In pp: dead cone effect exposed by ALICE

- Reduction of gluon radiation from heavy quarks at small angles

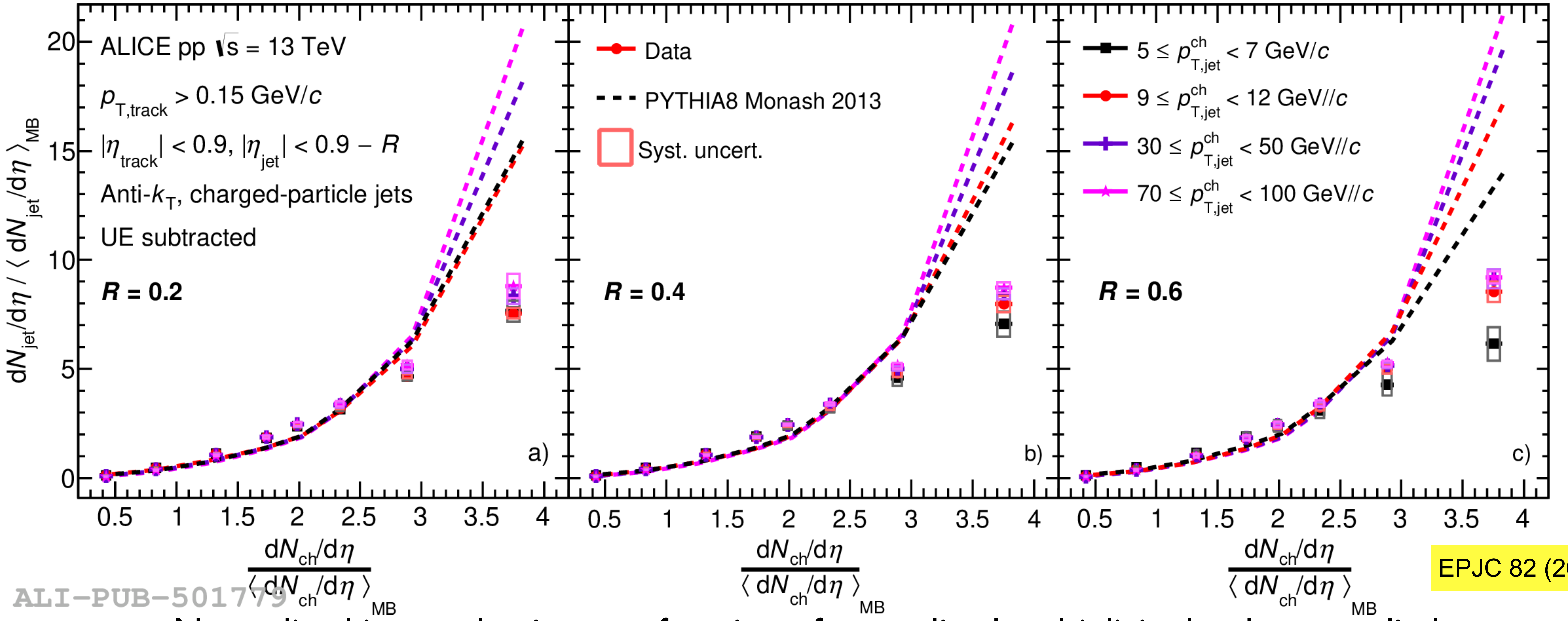
Nature 605 (2022) 7910





- First direct observation using jet iterative declustering and Lund plane analysis of jets that contain a soft D^0 meson

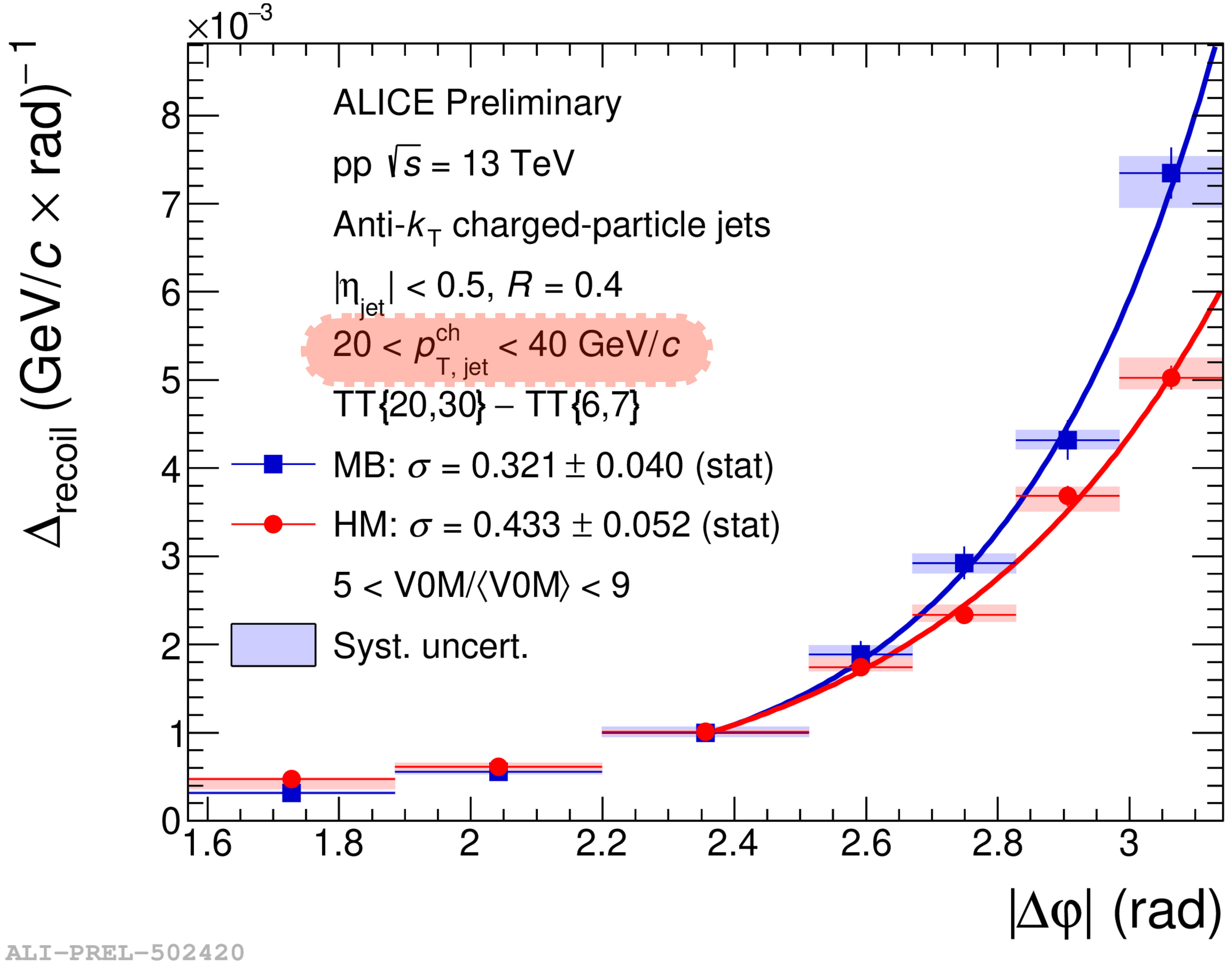
Search for jet quenching in small system

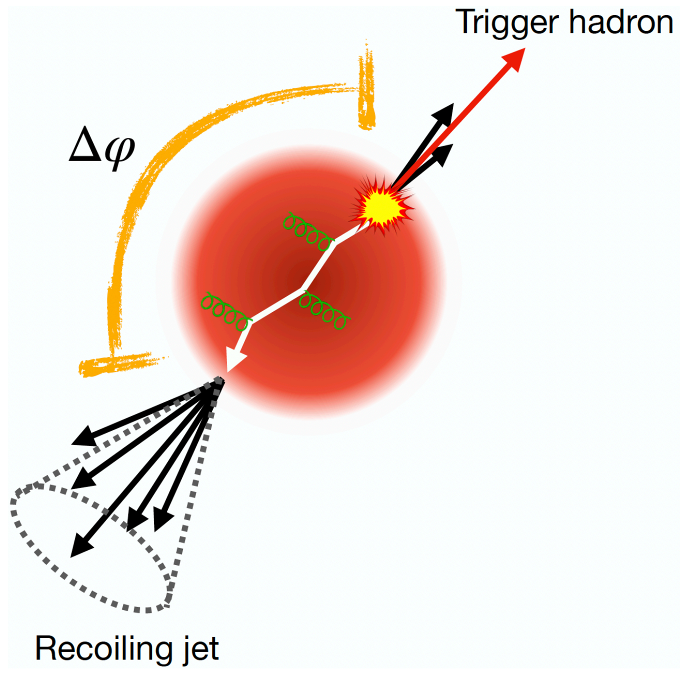


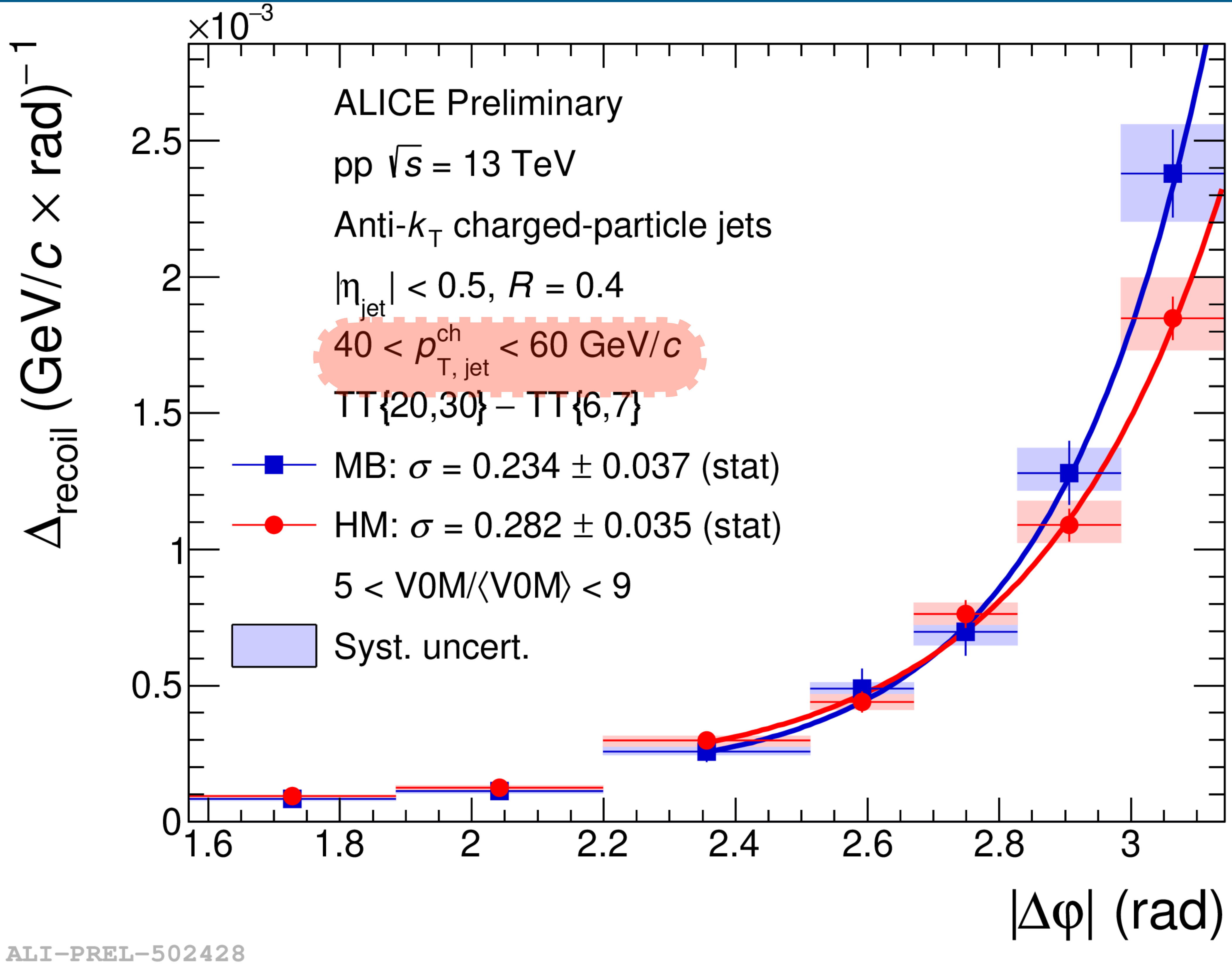
EPJC 82 (2022) 514

- Normalized jet production as a function of normalized multiplicity has been studied
  - non-linear trend increasing observed, similar to J/ψ and prompt D productions
  - overshoot of the trend by PYTHIA at high multiplicities

Search for jet quenching in small system







- Jet acoplanarity has been studied in high multiplicity (HM) environment using h-jet correlations
  - suppressed back-to-back correlation for recoiling jets
  - broader at large angle, stronger for low p_T jets

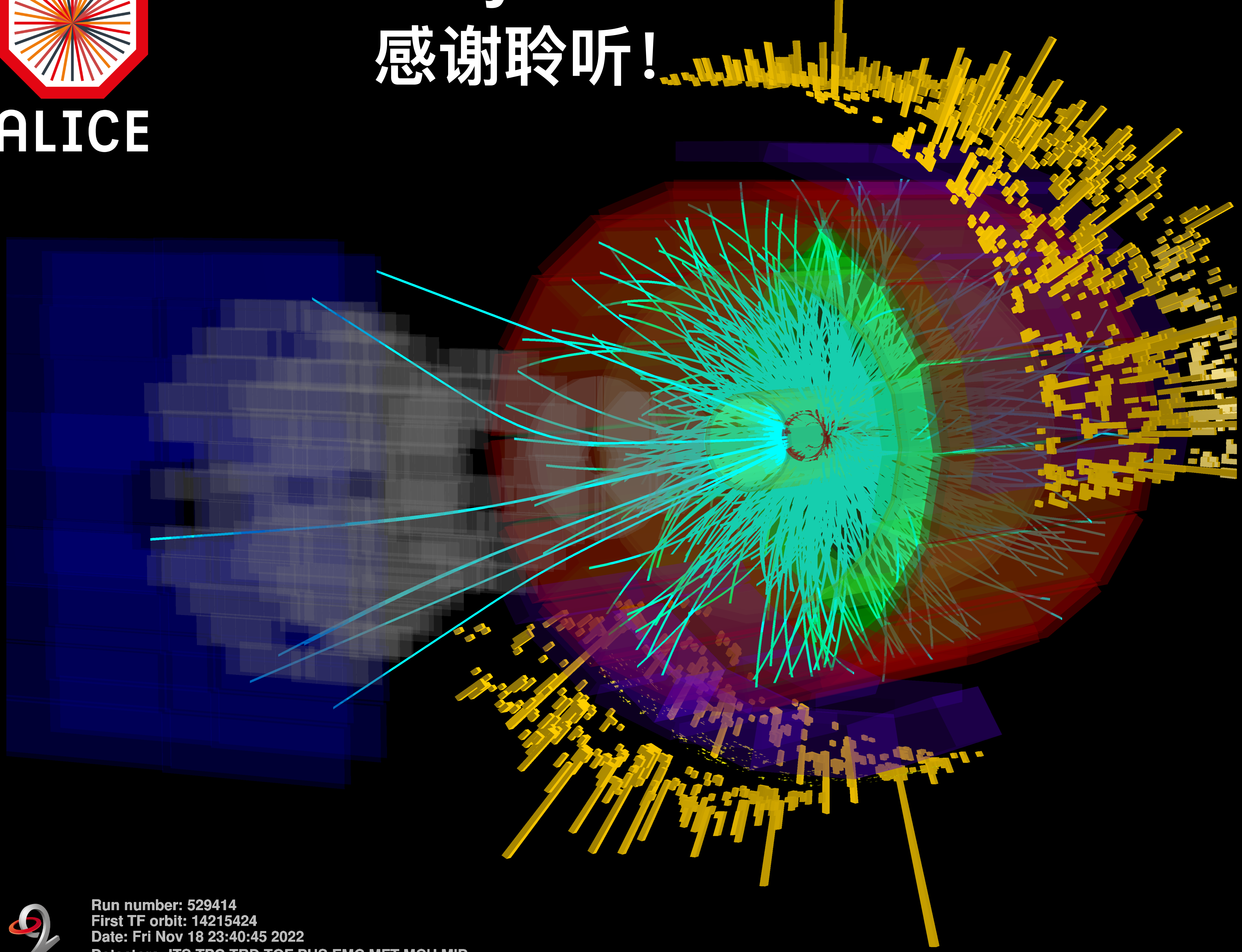
Summary

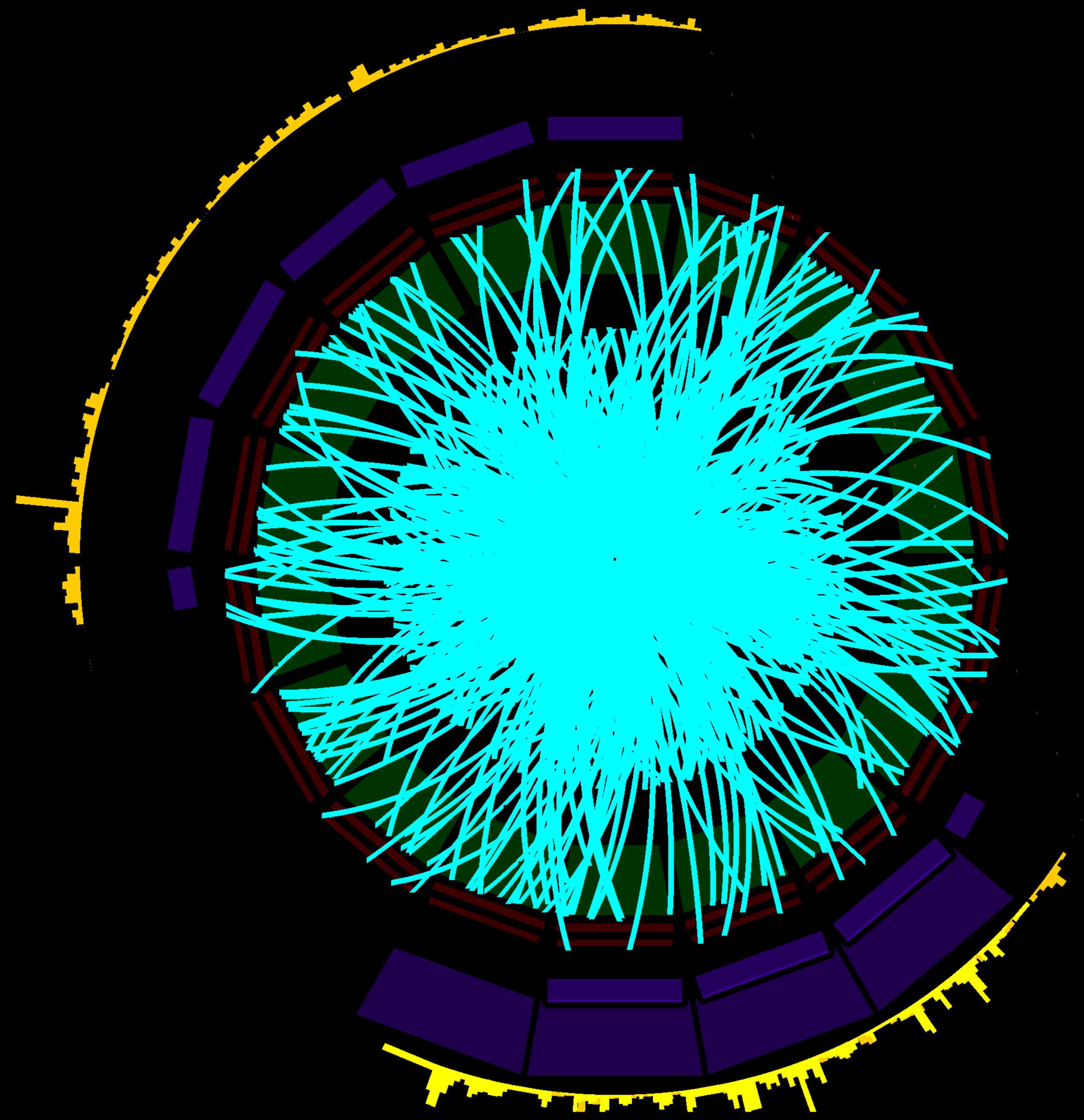
- Large number of jet results based on full Run 2 LHC data sample (many more not covered here)
  - More precision, extending to low p_T/large R, more differential, new analysis
- Detailed insights on the QGP properties
  - Energy redistribution observed for low p_T and large R jets
  - Color and mass dependent jet energy loss observation
  - First evidence of the broadening of the γ-jet and h-jet azimuthal correlations for very soft jets
- Plenty of encouraging and interesting new theoretical/experimental developments with nice results
  - some results are still to be understood → ongoing studies + LHC Run 3!

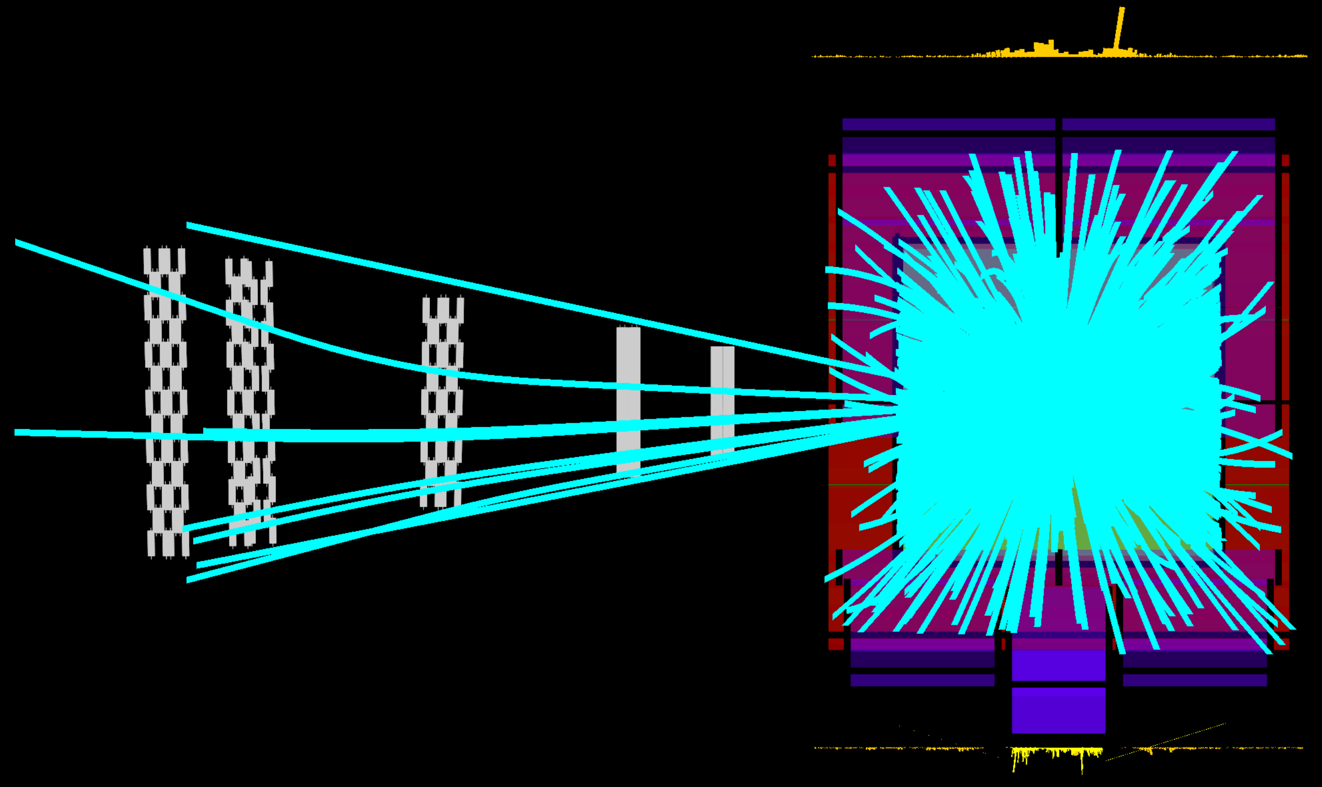
Thanks for your attention!

感谢聆听！

ALICE



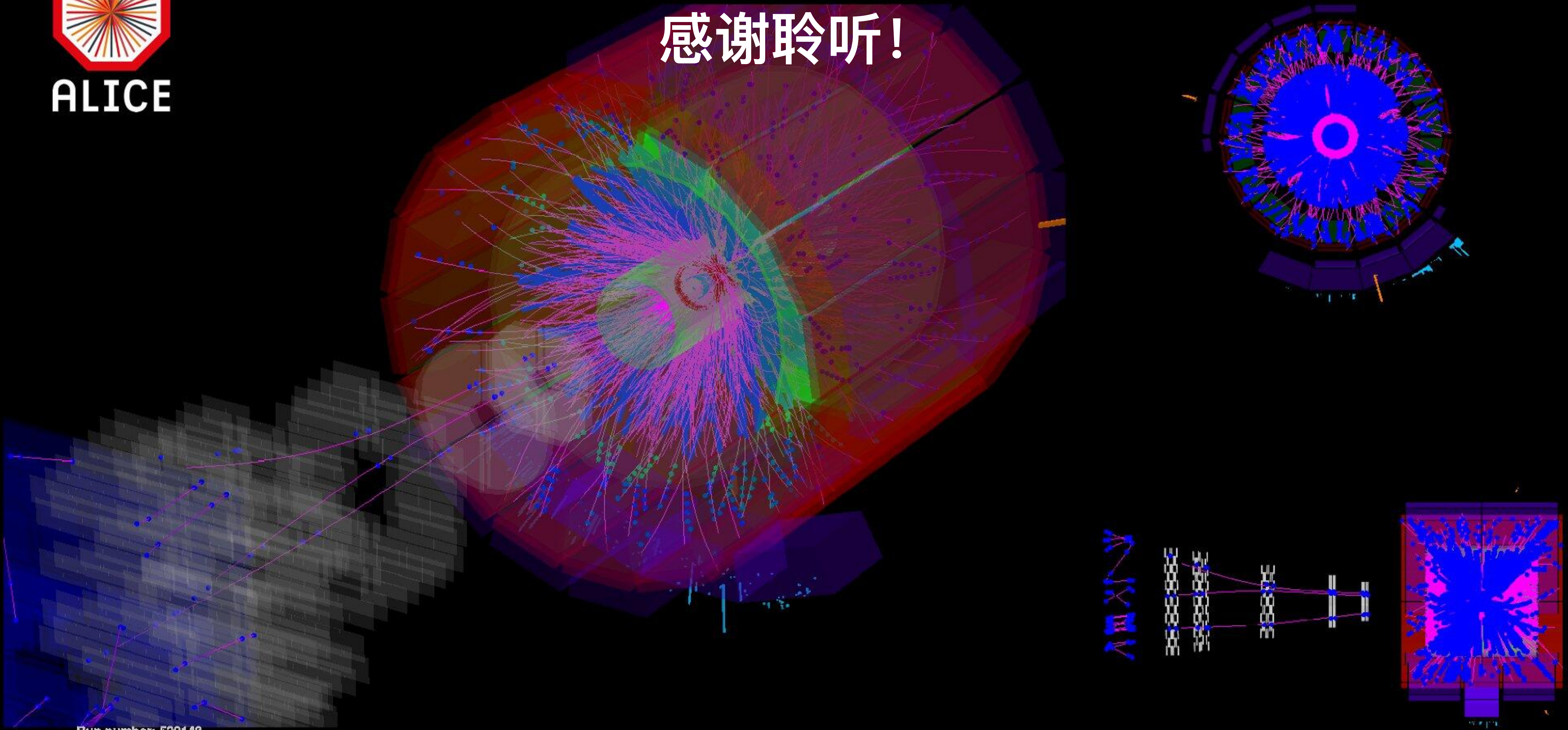




Run number: 529414
First TF orbit: 14215424
Date: Fri Nov 18 23:40:45 2022
Detectors: ITS,TPC,TRD,TOF,PHS,EMC,MFT,MCH,MID

Thanks for your attention!

感谢聆听！



Run number: 520143
First TF orbit: 692888
Date: Tue Jul 5 16:53:05 2022
Detectors: ITS,TPC,TRD,TOF,PHS,EMC,MFT,MCH,MID

R-dependence of the R_{AA}

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

ALICE

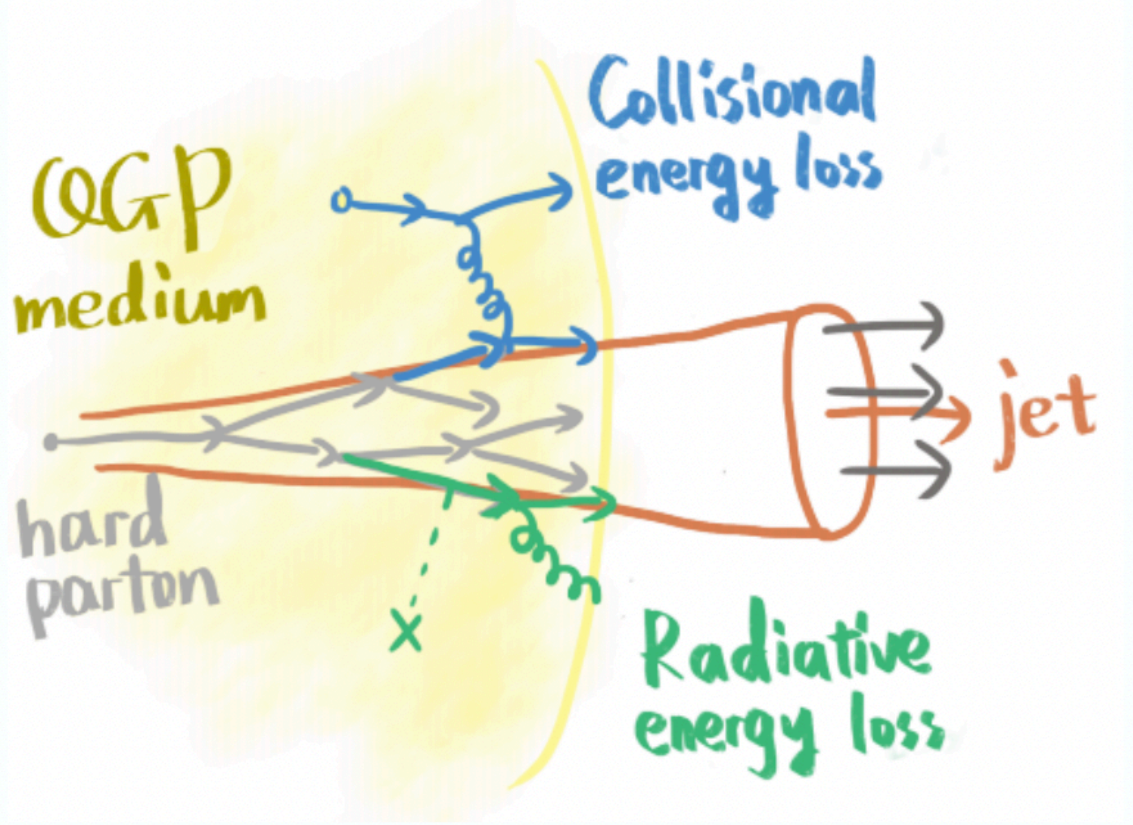
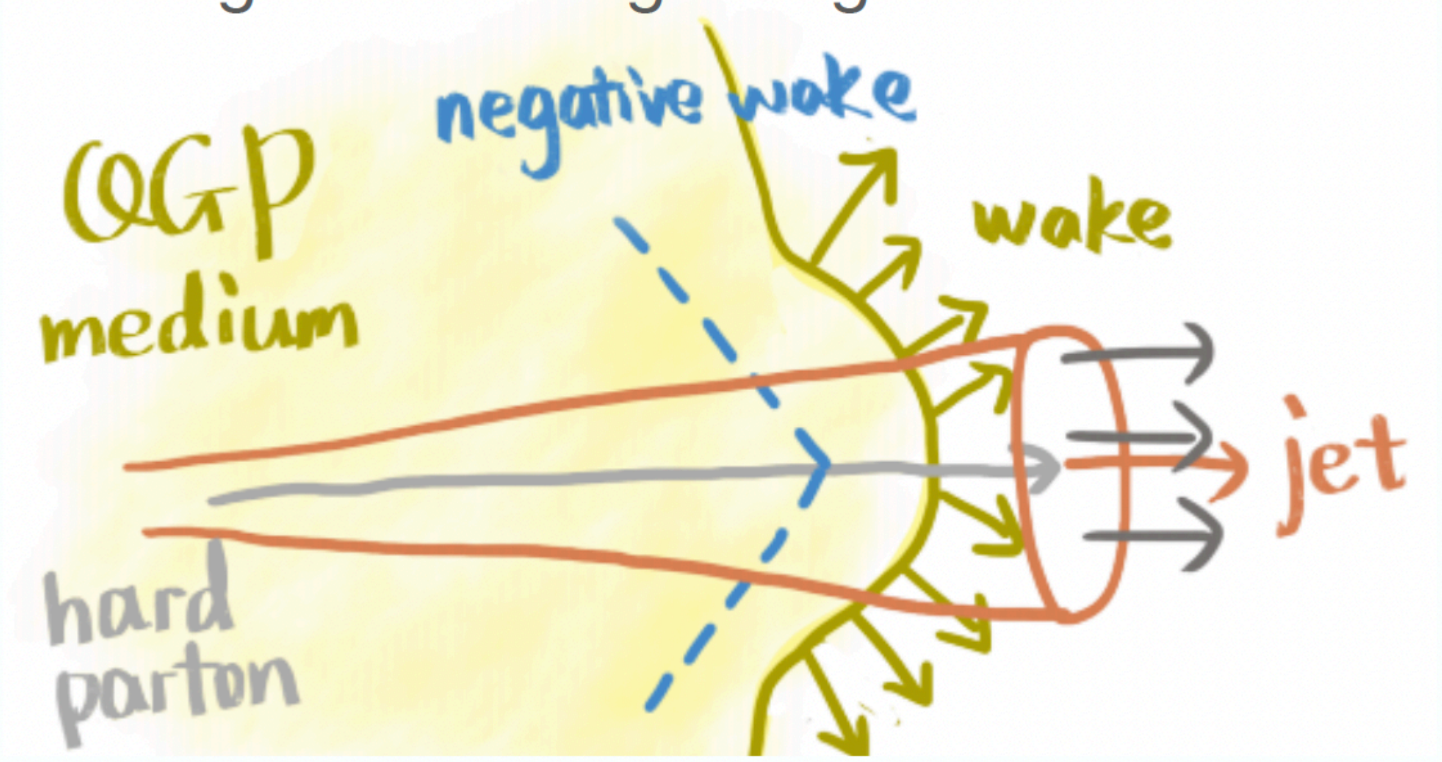


Image Credit:Jing Wang



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

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

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

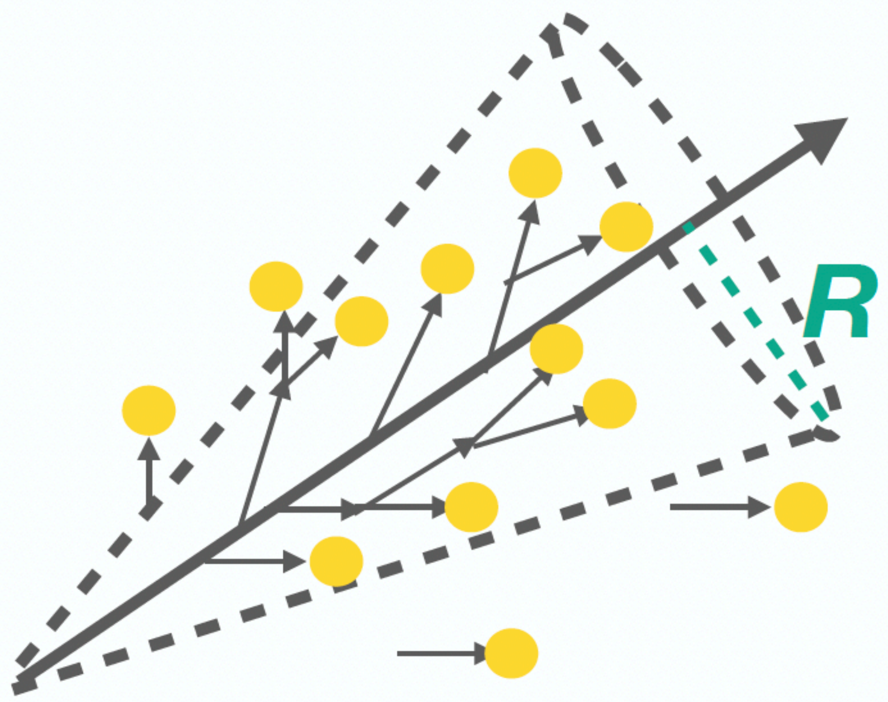
→ Increase gluon to quark ratio at fixed p_{T}, gluons lose more energy $R_{\mathrm{AA}} \searrow$

→ Inclusive jet measurements at large R and low p_{T} difficult due to the large fluctuating underlying event ($\propto R^2$)

ML-based background estimator

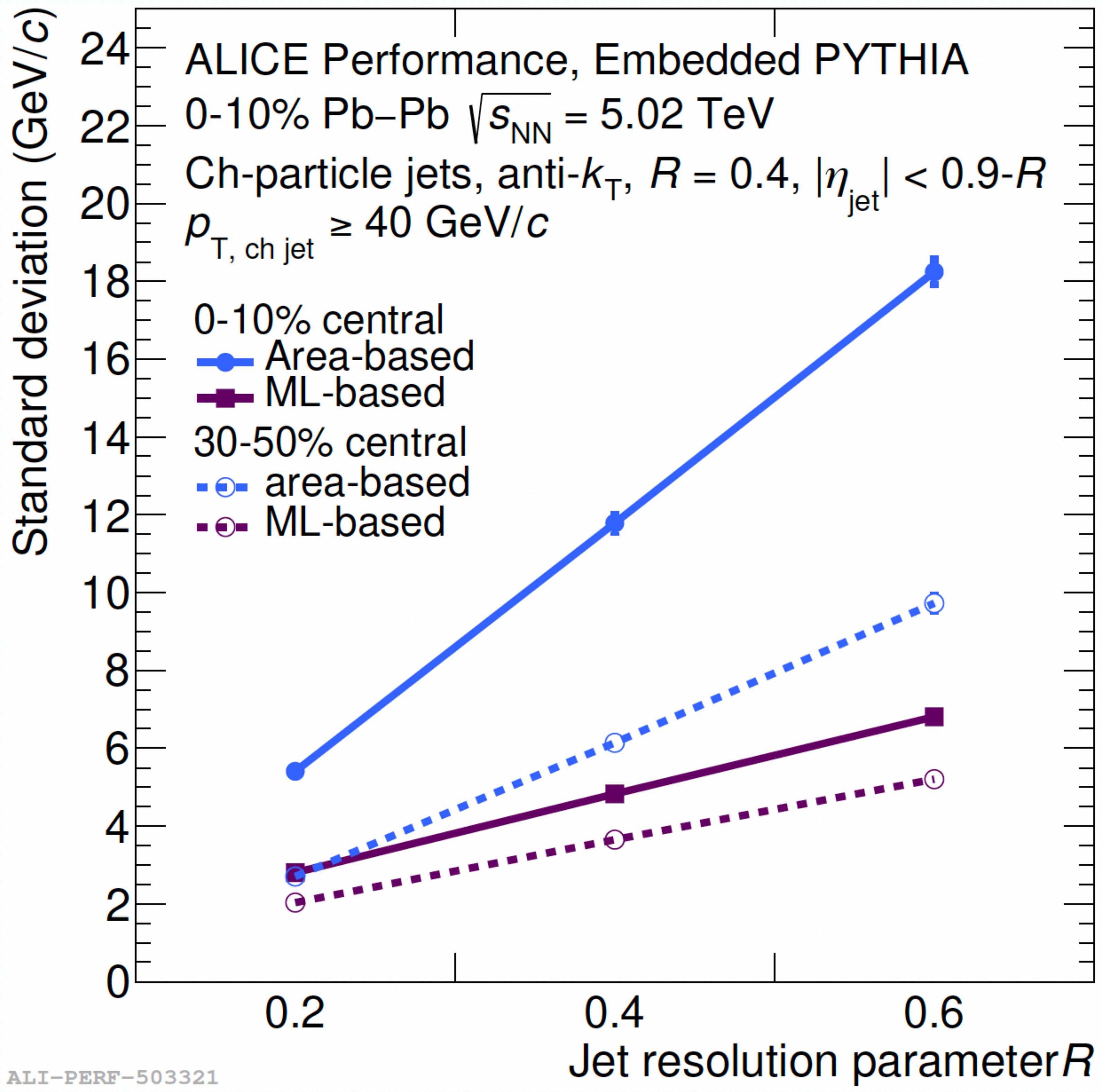
ALICE area-based approach: Correct the jet for the background with a pedestal subtraction. Apply a minimum p_T requirement on the leading track of the jet.

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



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

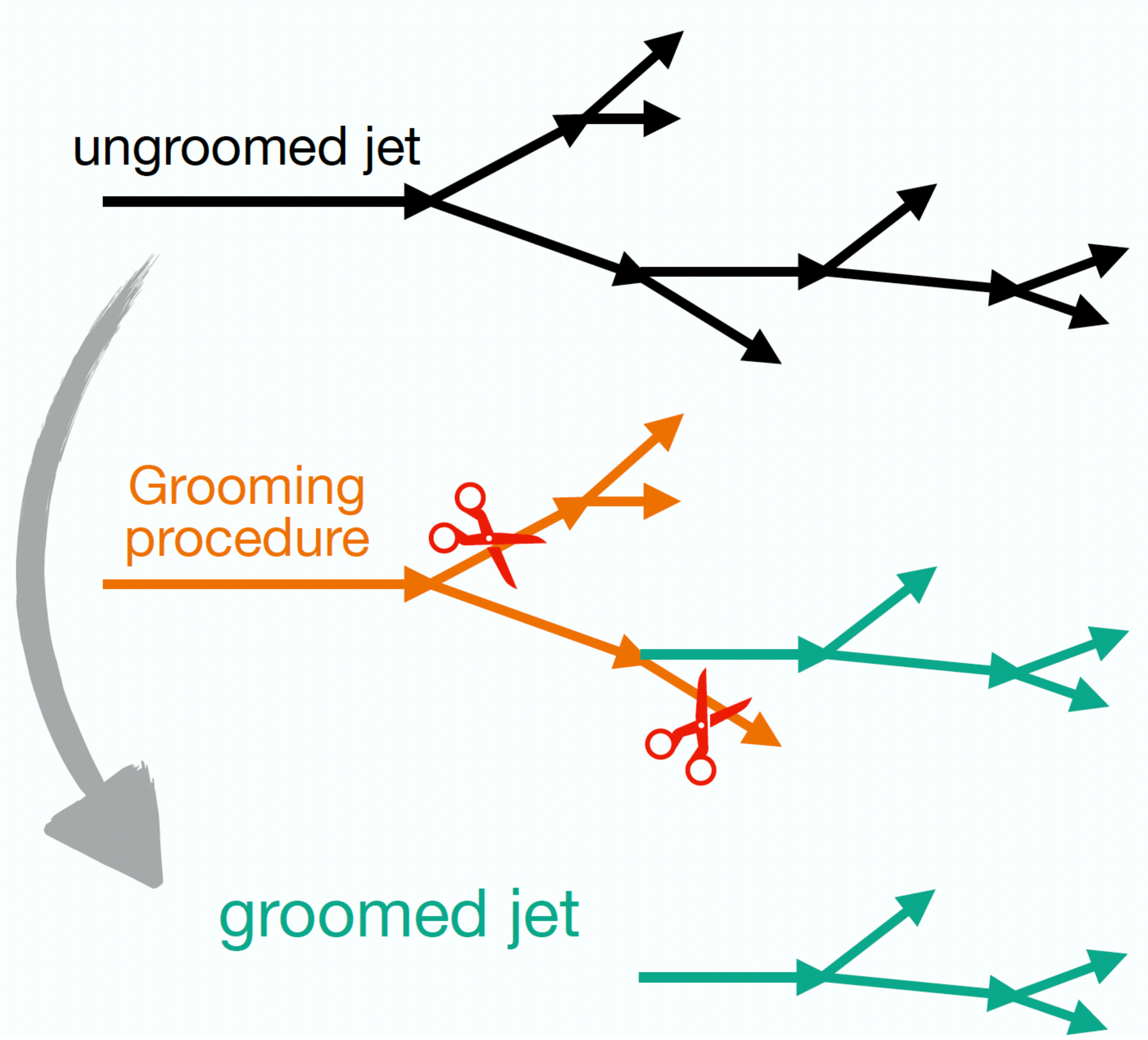
$$\delta p_{\mathrm{T}} = p_{\mathrm{T,rec}} - p_{\mathrm{T,true}}$$



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

Grooming and Soft Drop

Grooming: systematically removing soft wide-angle radiation from a jet to mitigate effects such as initial-state radiation, multi-carton interactions, and pileup



Soft Drop: JHEP 1405 (2014) 146

After reclustering with C-A, decluster and find first splitting that satisfies:

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} \overset{?}{>} z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

$$\Delta R_{12} = \sqrt{(y_1-y_2)^2+(\varphi_1-\varphi_2)^2}$$

The branches left define the groomed jet

z_{cut} and β are free parameters