Recent results on jet ~~suppression~~ *quenching* at the LHC

ISMD 2022

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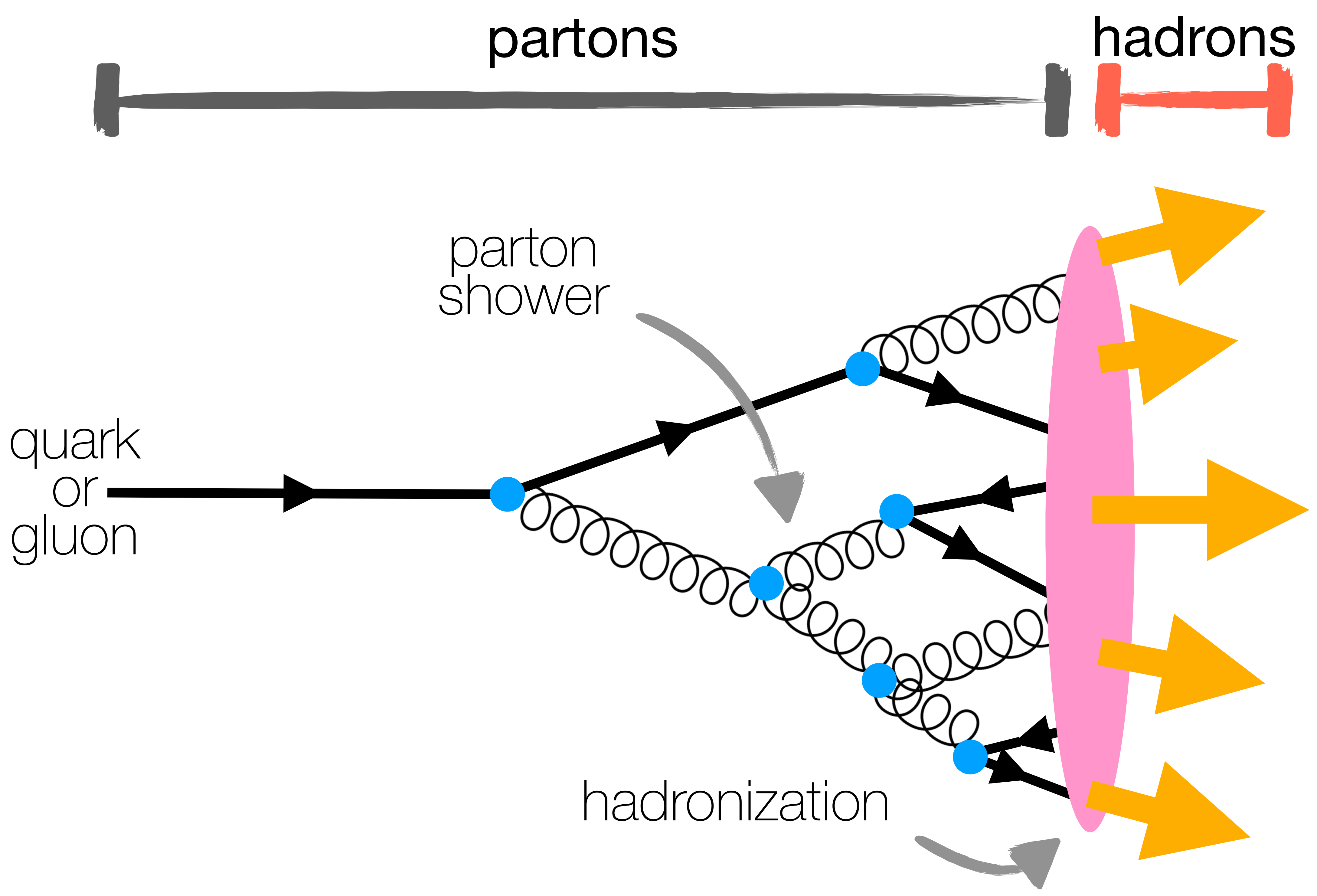
on behalf of the ALICE Collaboration
08/01/2022

Jets 101

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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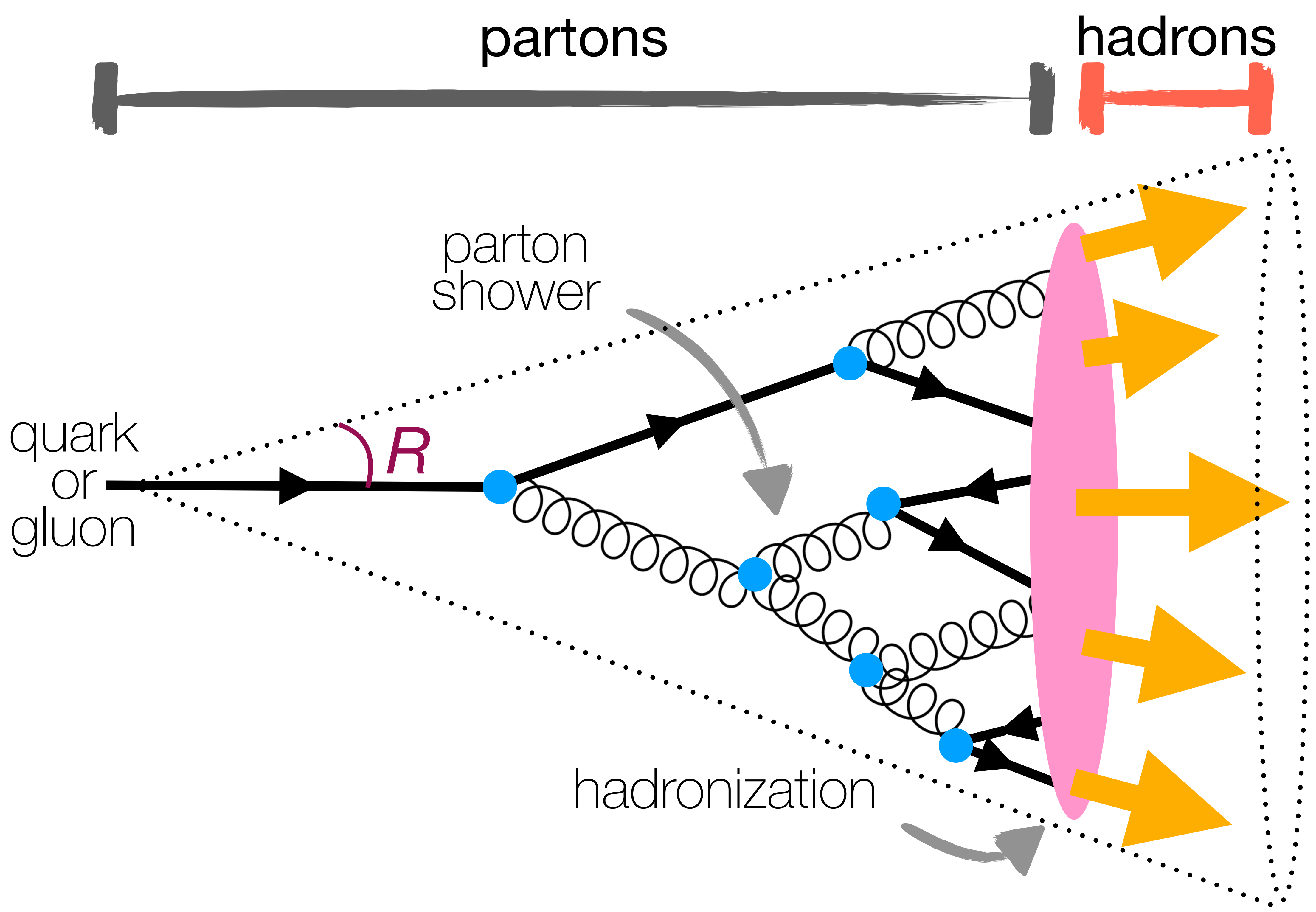

Recipe for reconstructing a jet:

Jet-finding algorithm:
which two prongs to combine next
(e.g. anti-k_{T}, k_{T}, Cambridge-Aechen (C-A), …)

Recombination scheme:
how to combine the two prongs
(e.g. *E* scheme, Winer-Takes-All (WTA), …)

Jet radius or resolution parameter (*R*):
How wide the jet cone will be
(e.g. 0.2, … 1.0)

All these choices have to be clearly specified in each measurement

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(e.g. pp collisions)

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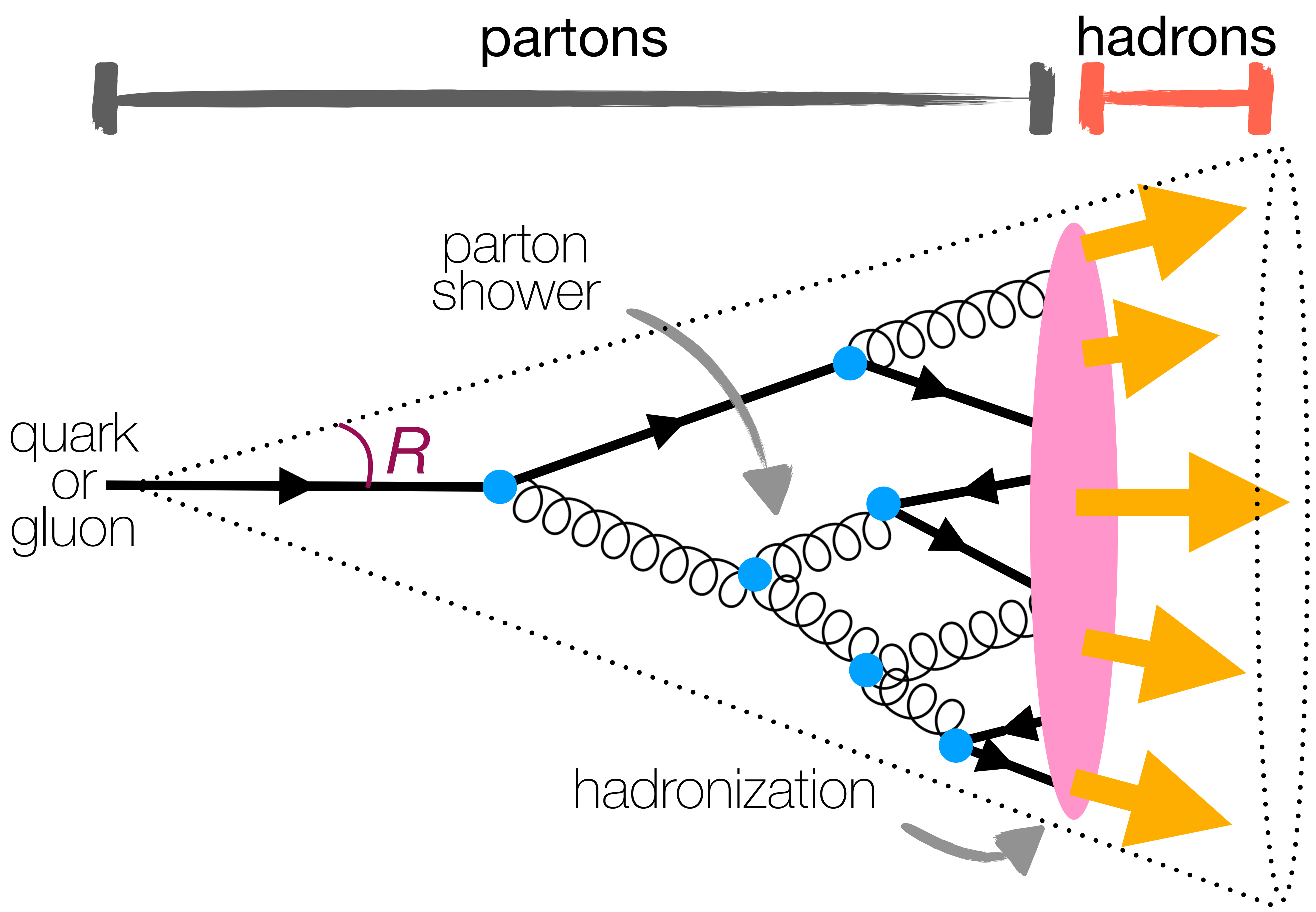
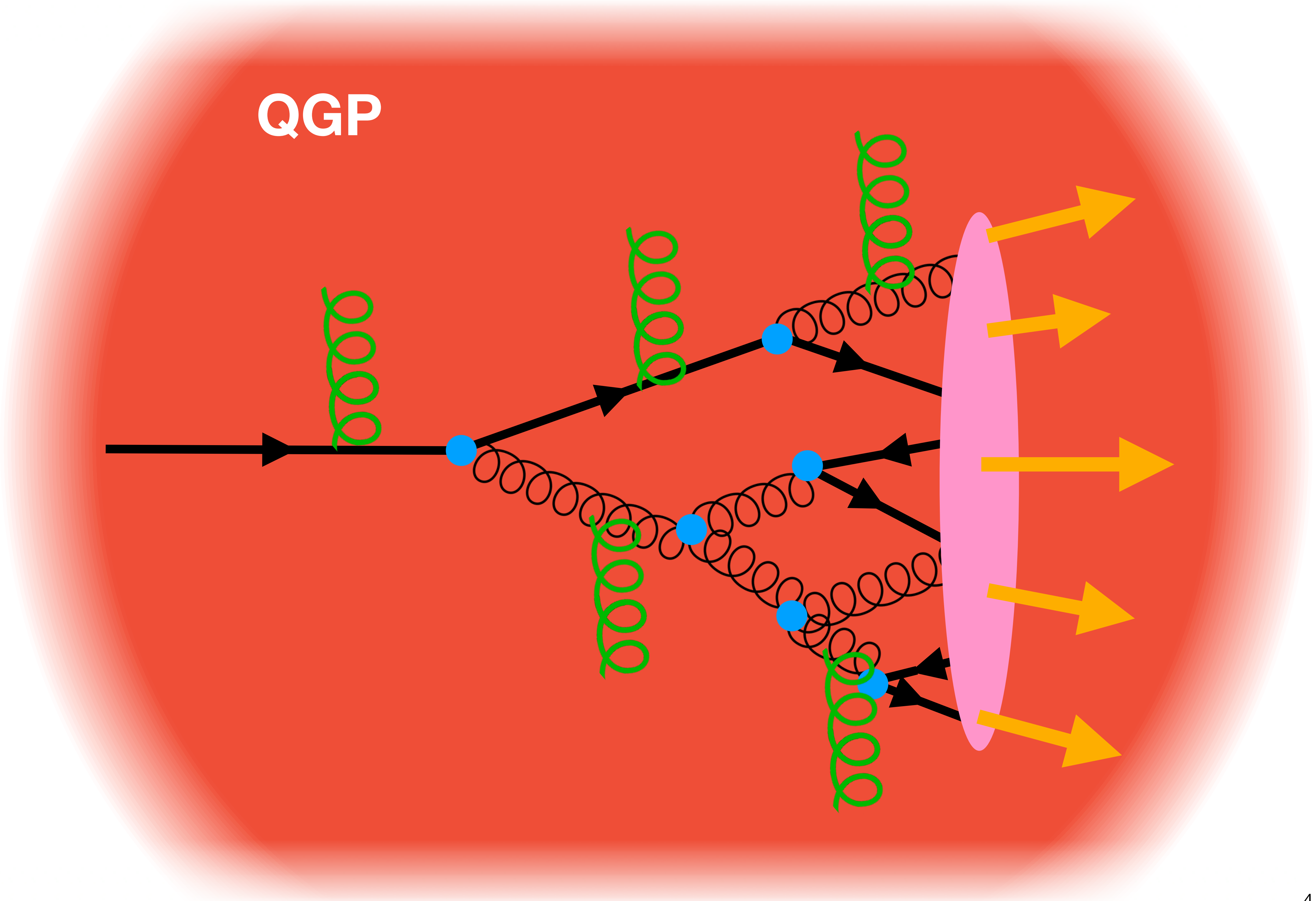


In-medium fragmentation
(e.g. Pb—Pb collisions)

Quenching → parton energy loss through medium-induced gluon radiation and collisions with medium constituents

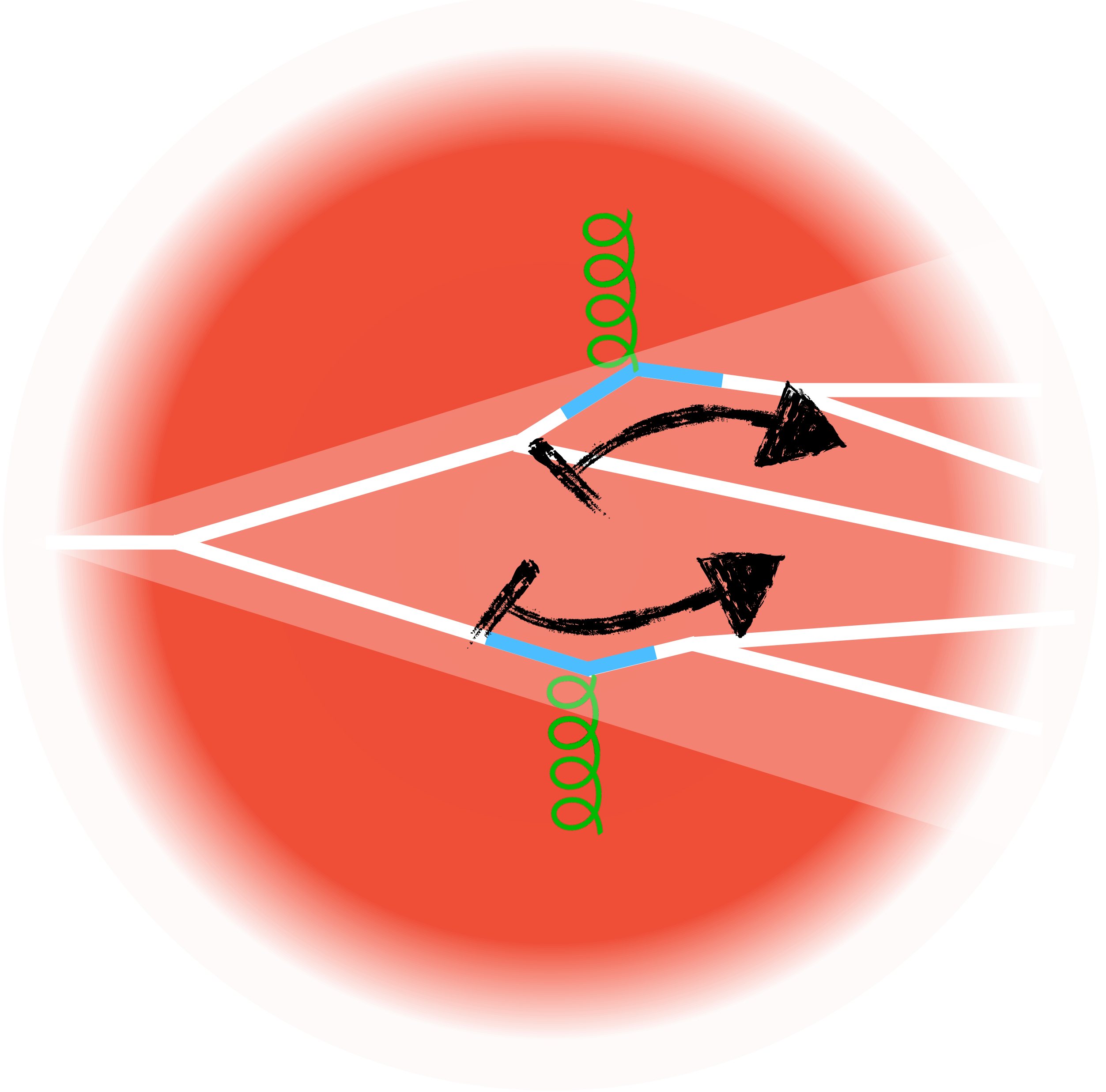


Jet quenching: an opportunity to study QGP

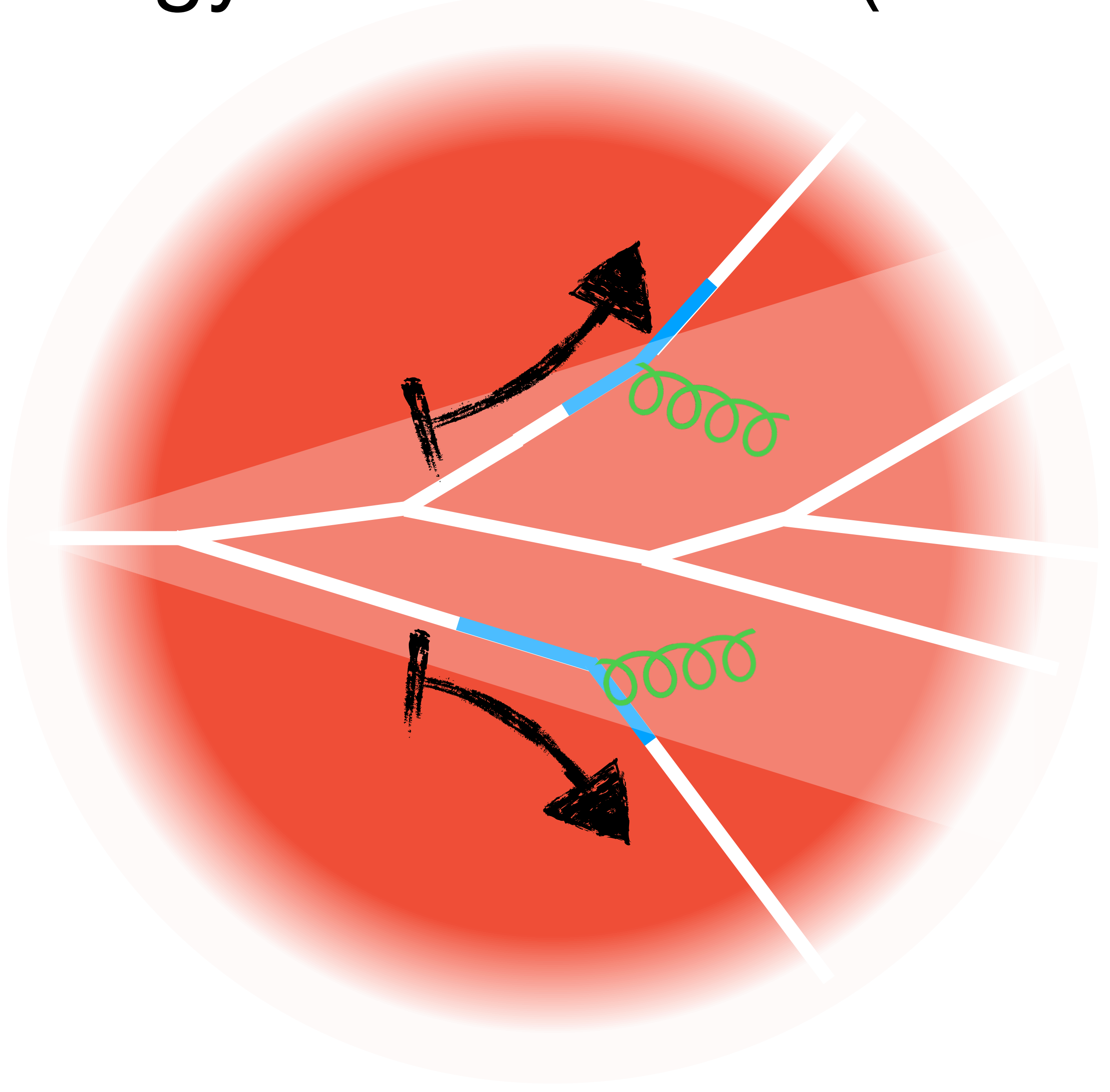
Study structure of QGP by understanding jet modification from medium interaction (quenching)

There are several manifestations of jet quenching:

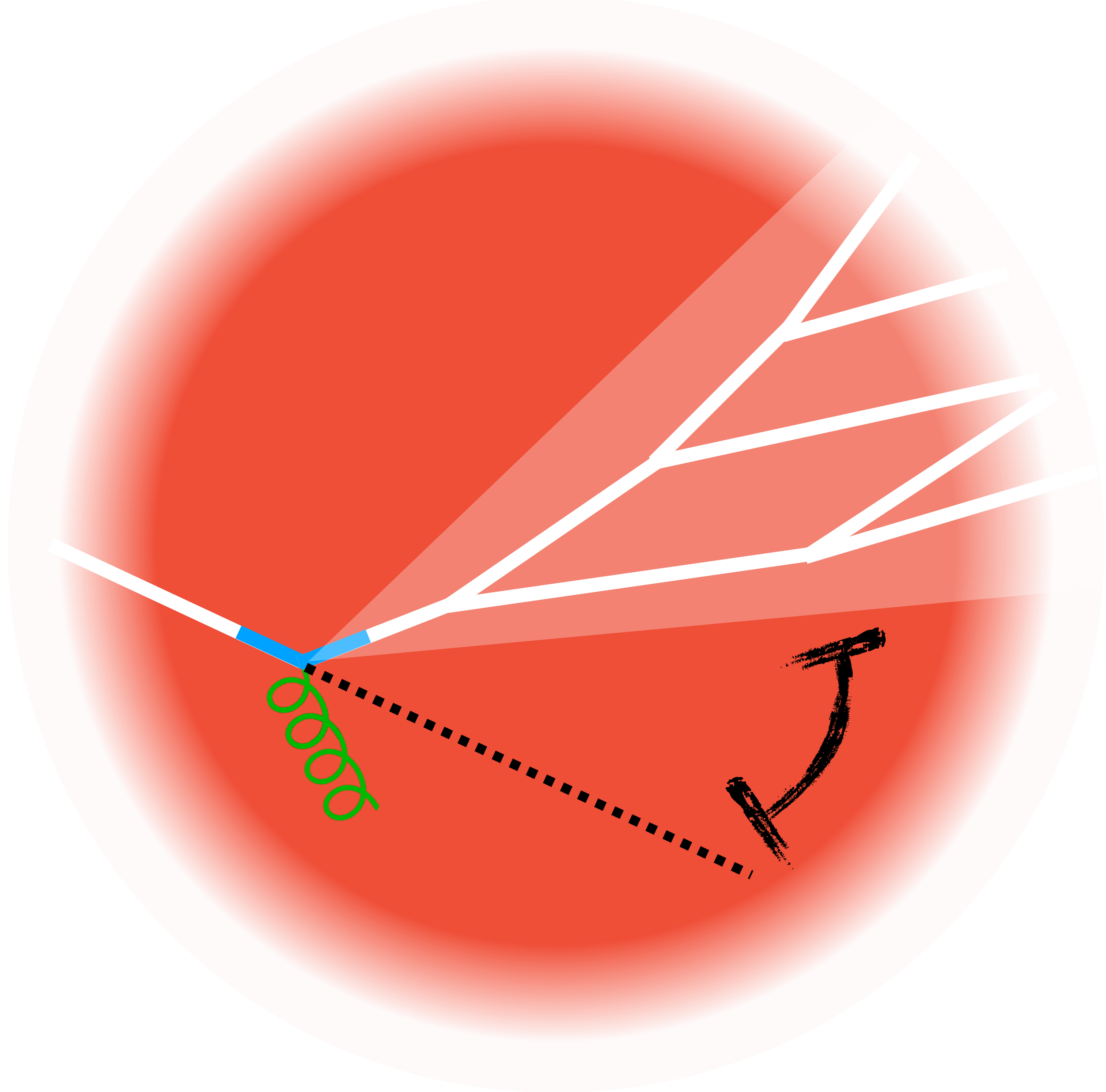
Substructure modification



Energy redistribution (“loss”)



Deflection

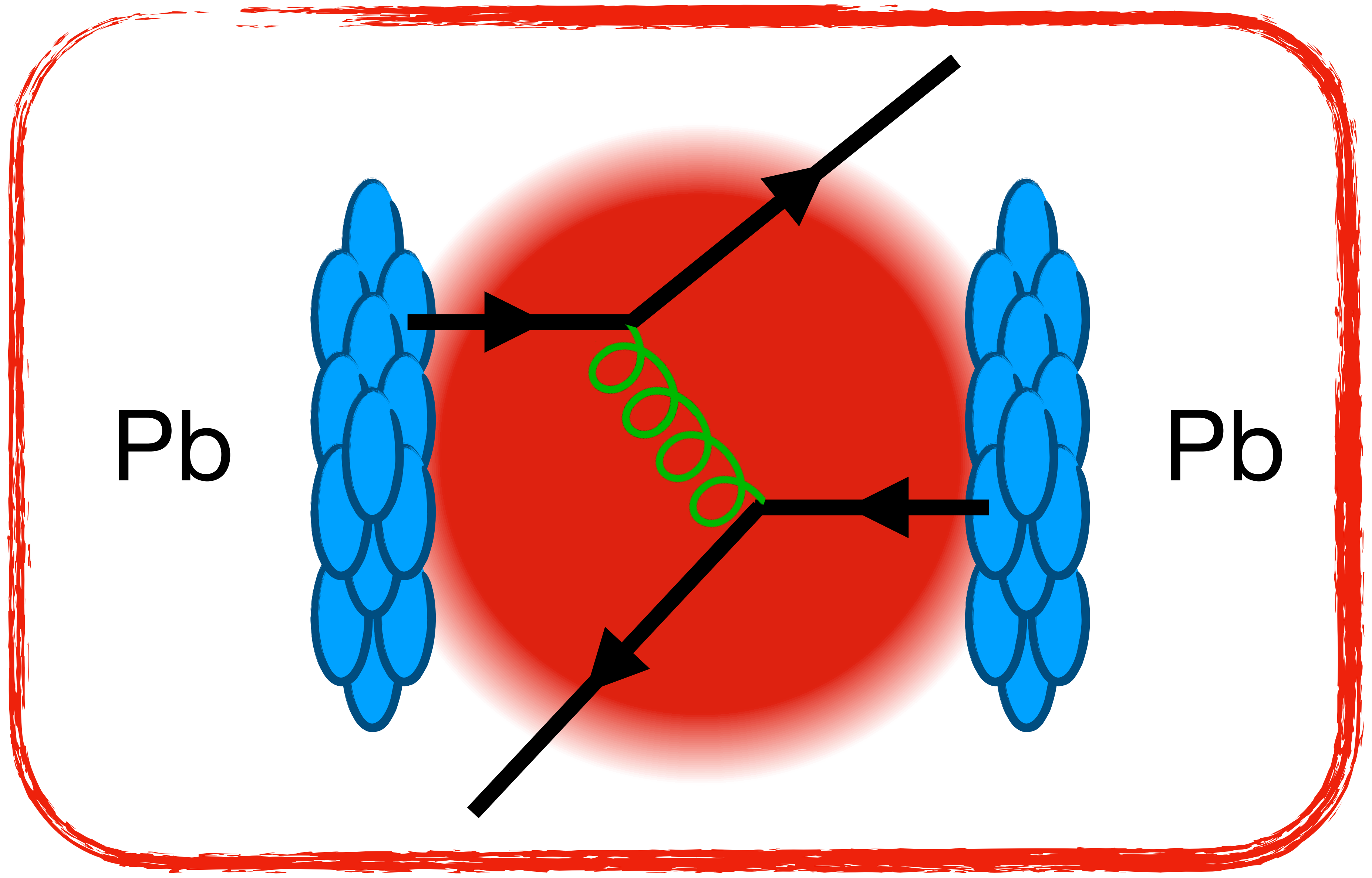


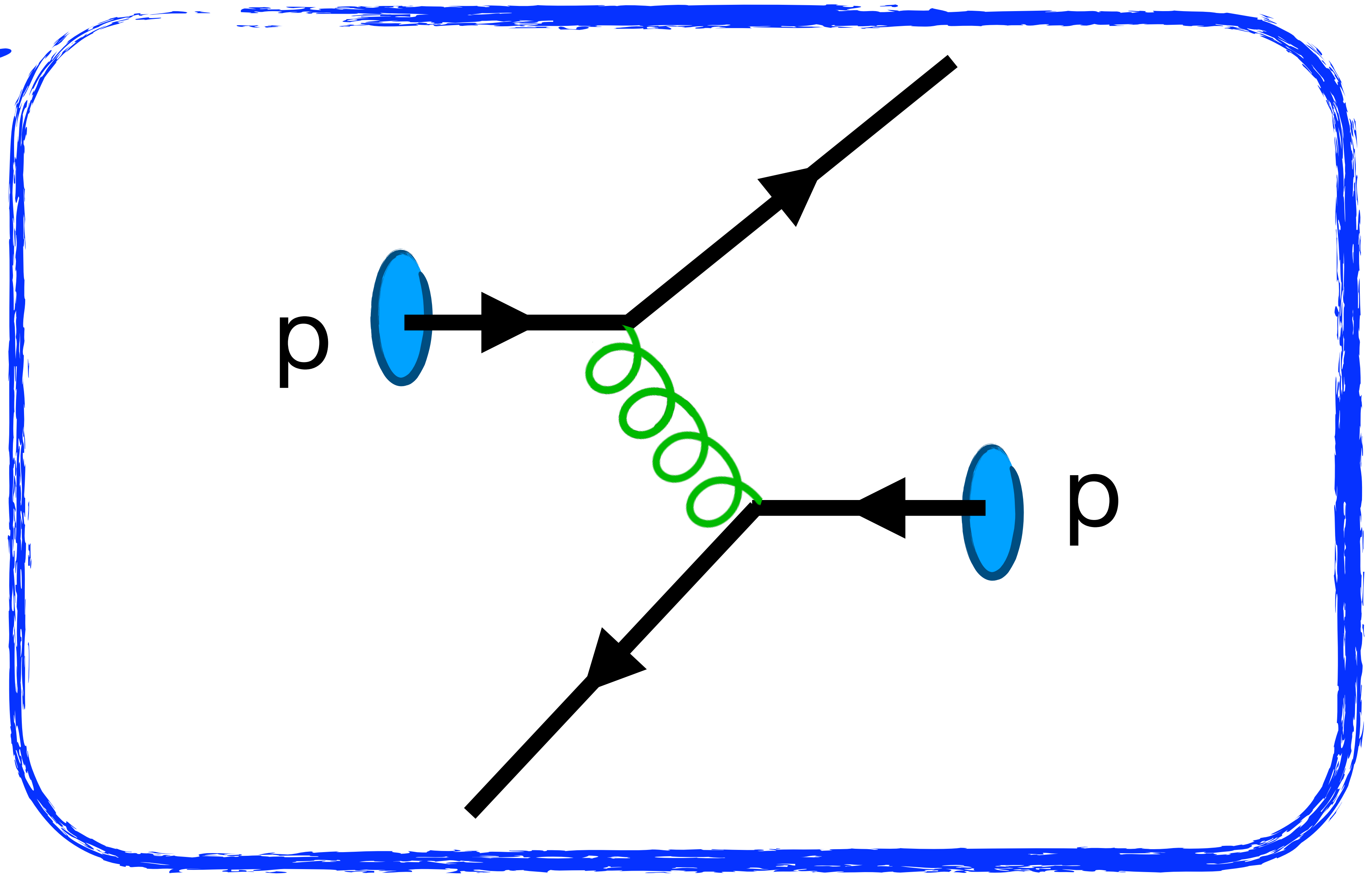
Study of different effects in a complementary way must yield consistent picture

Nuclear modification factor

Nuclear modification factor

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





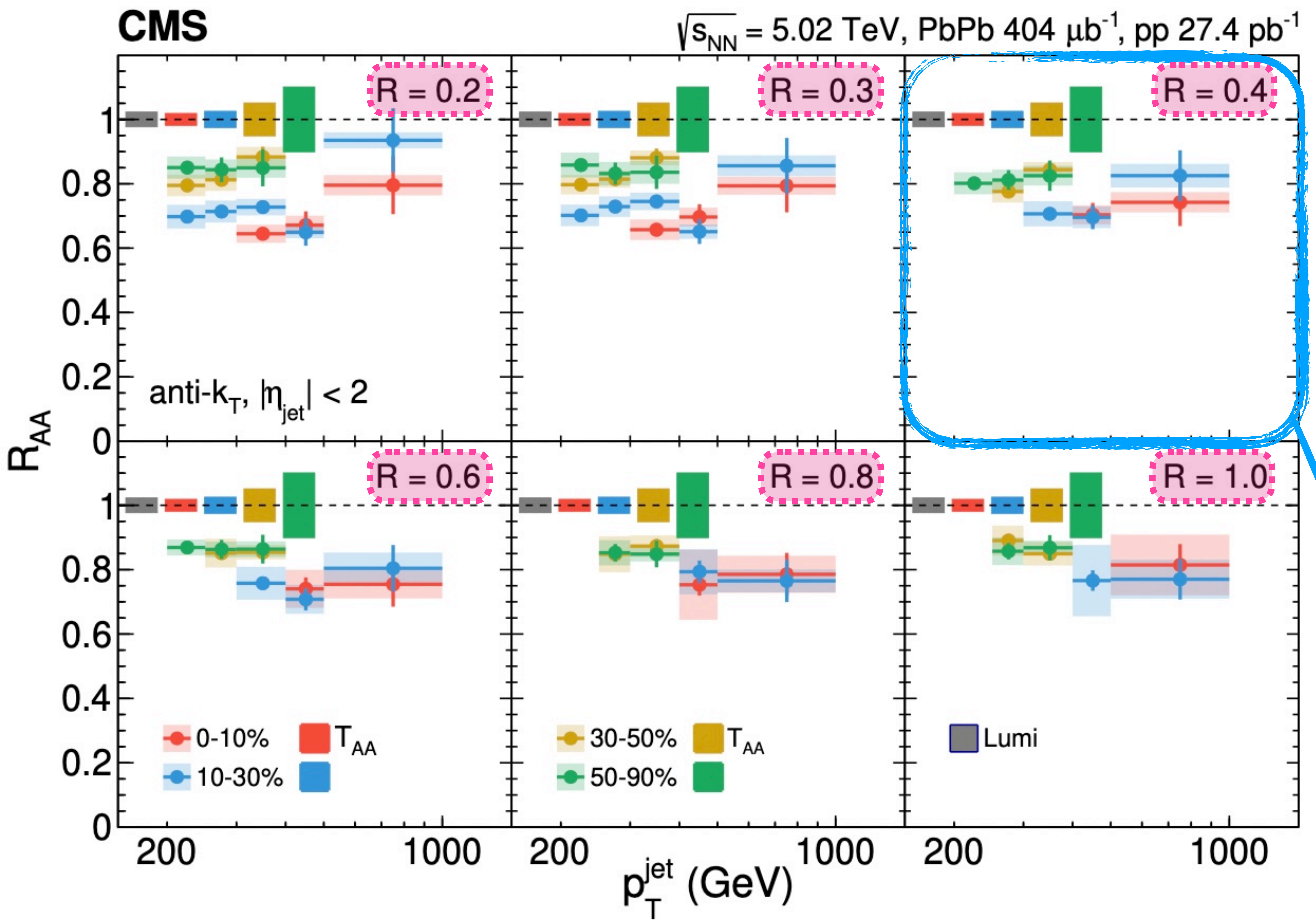
$R_{AA} > 1 \rightarrow$ enhancement

$R_{AA} = 1 \rightarrow$ no medium modification

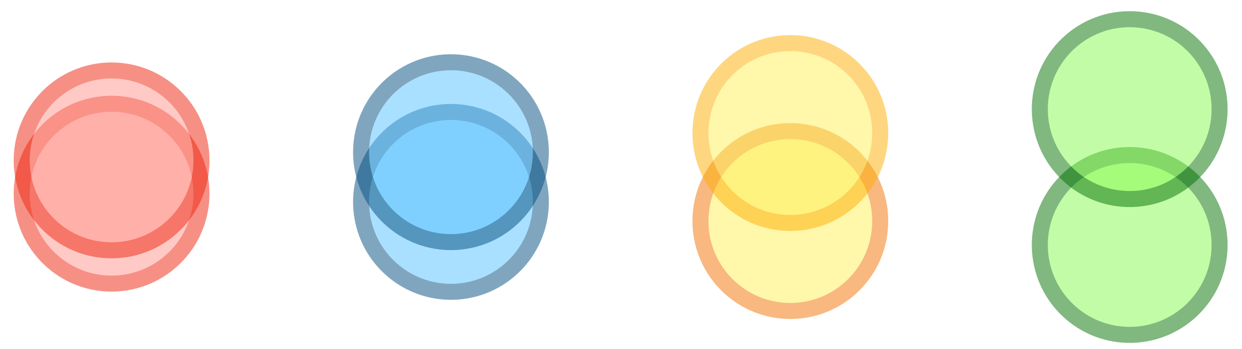
$R_{AA} < 1 \rightarrow$ supression

Jet R_{AA}

CMS JHEP 05 (2021) 284



Centrality

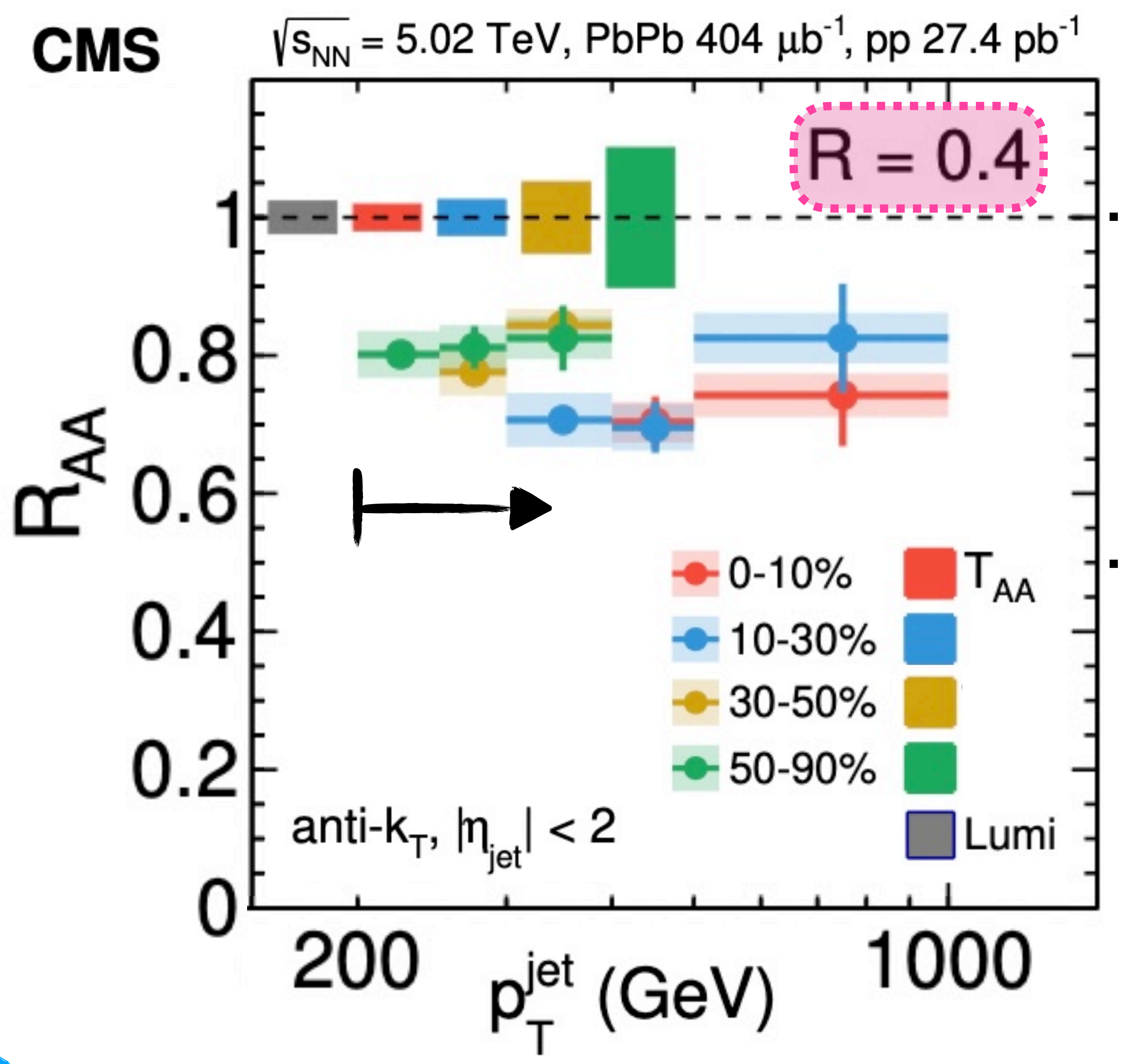


$R_{AA} < 1$
Suppression!

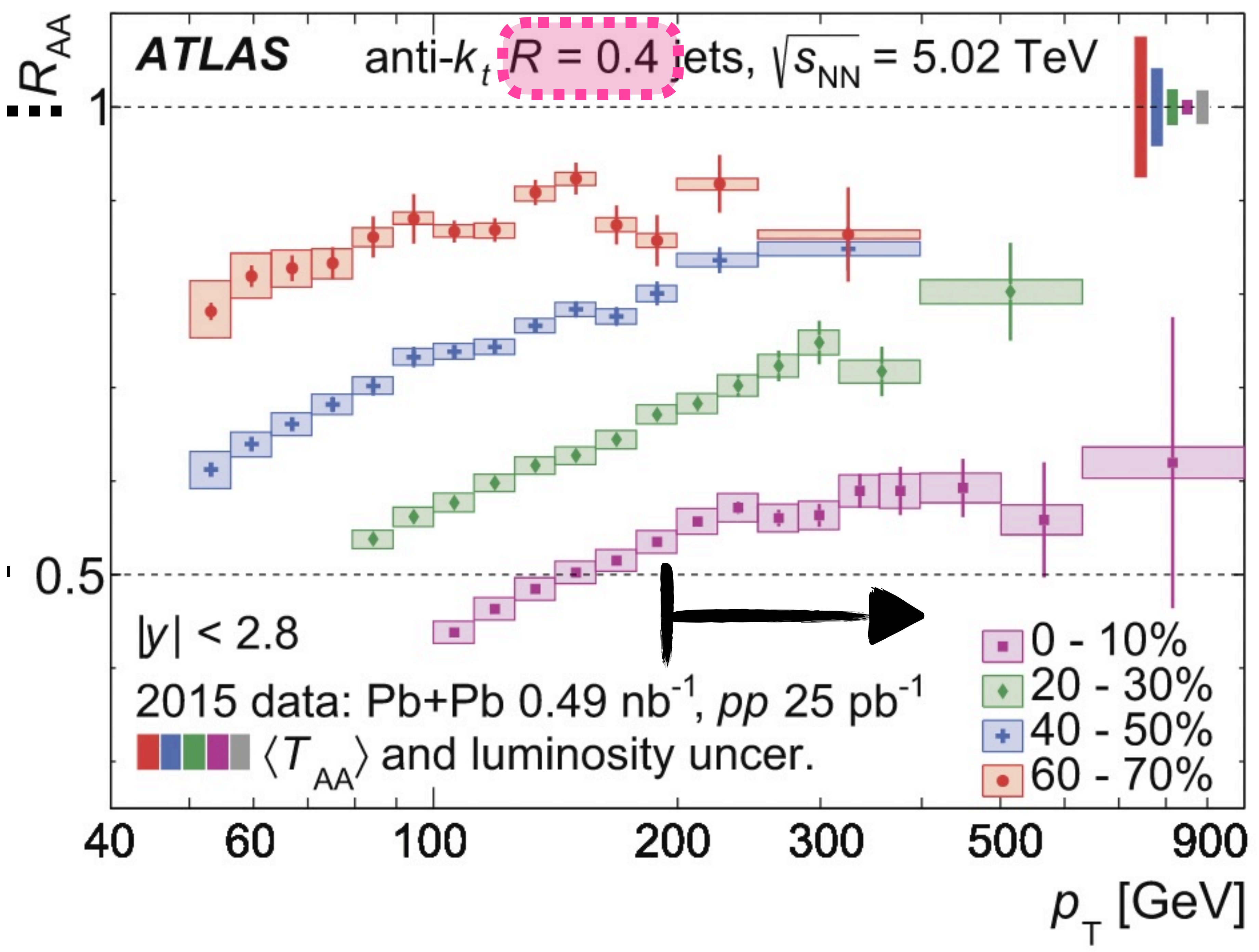
Overlapping kinematics with ATLAS result

Tension with previous result?

CMS JHEP 05 (2021) 284



ATLAS PLB 790 (2019) 108

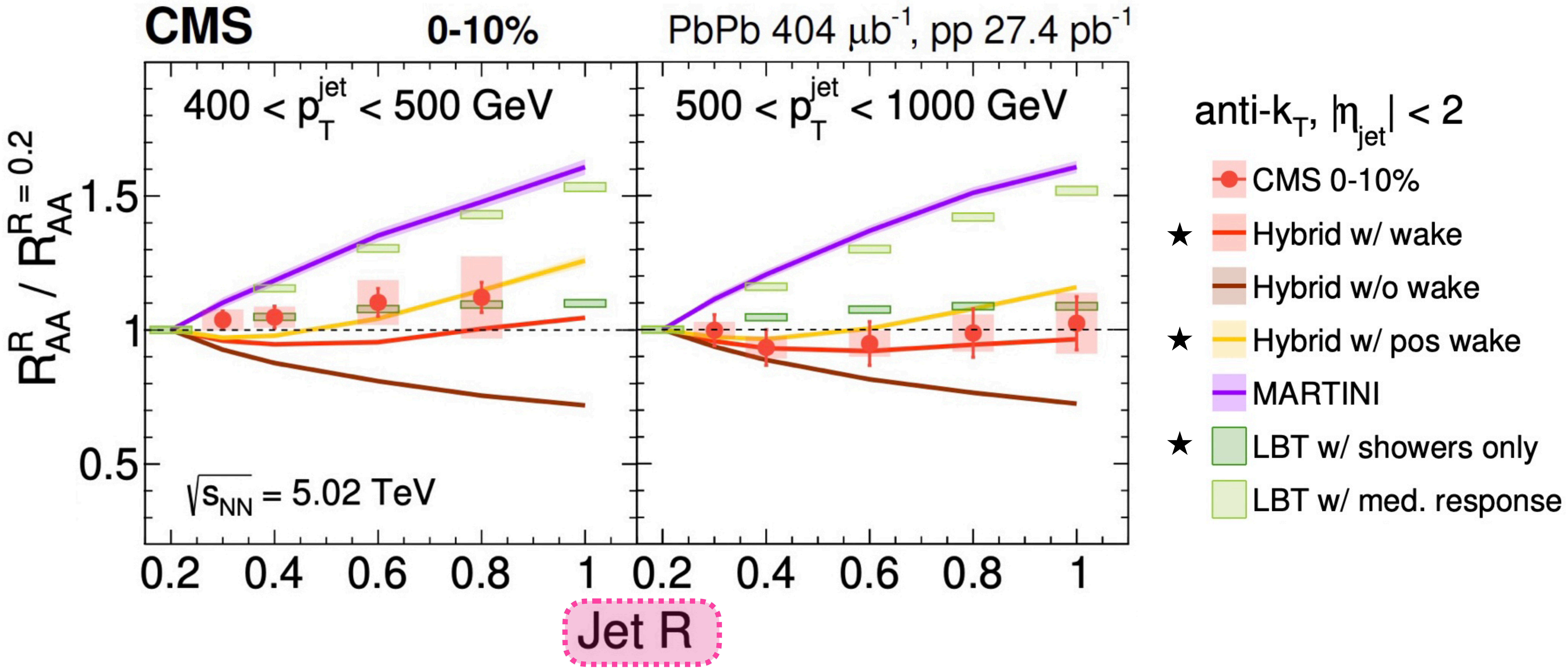


2-3 σ differences between these results

Both ATLAS and CMS working on updated result with 2018 data

Jet R_{AA} ratios vs R

CMS JHEP 05 (2021) 284

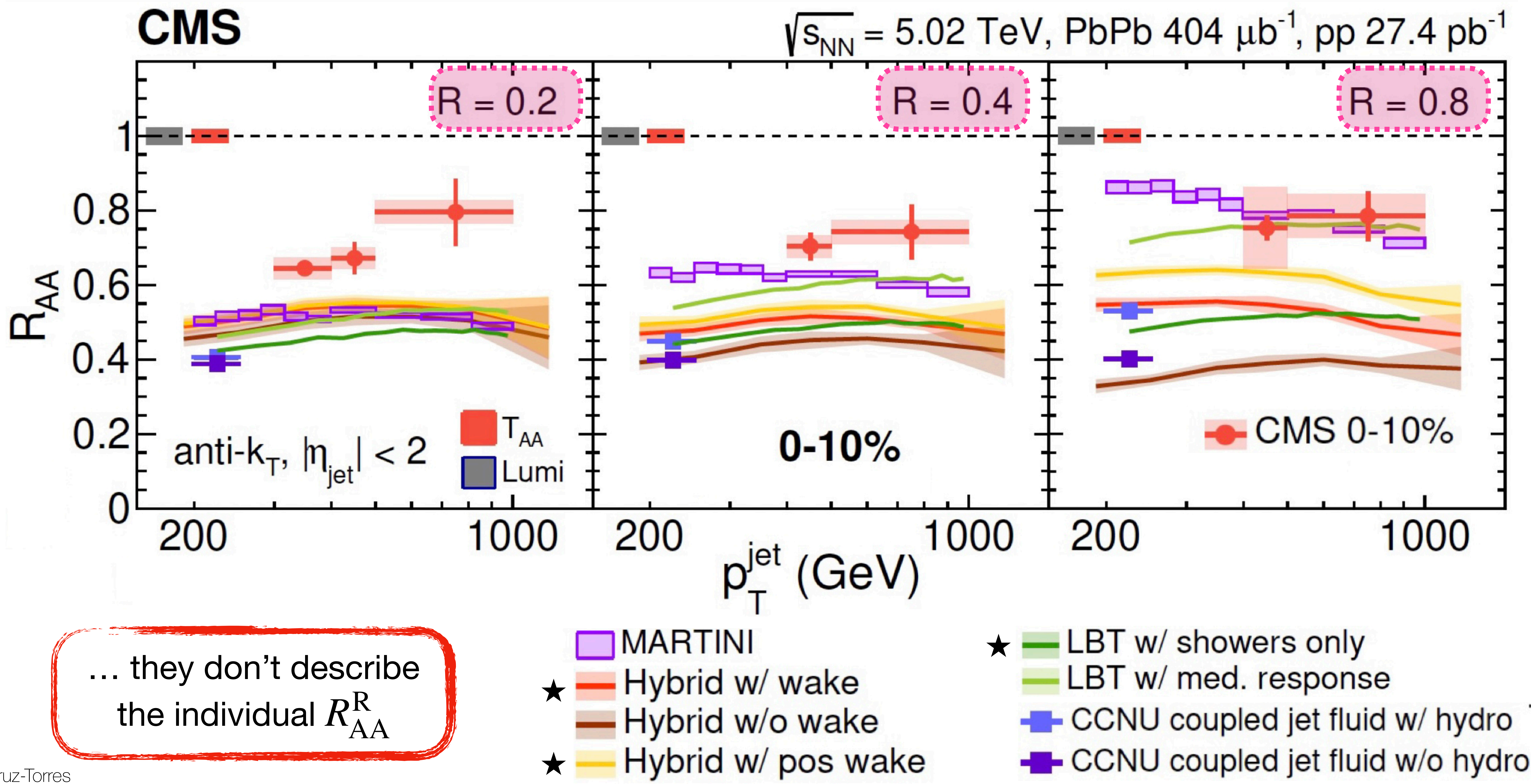


- Data: R_{AA} little dependence on R
- (cancellation of physical effects?)

★ Some models describe the $R^{R}_{AA}/R^{R=0.2}_{AA}$ but…

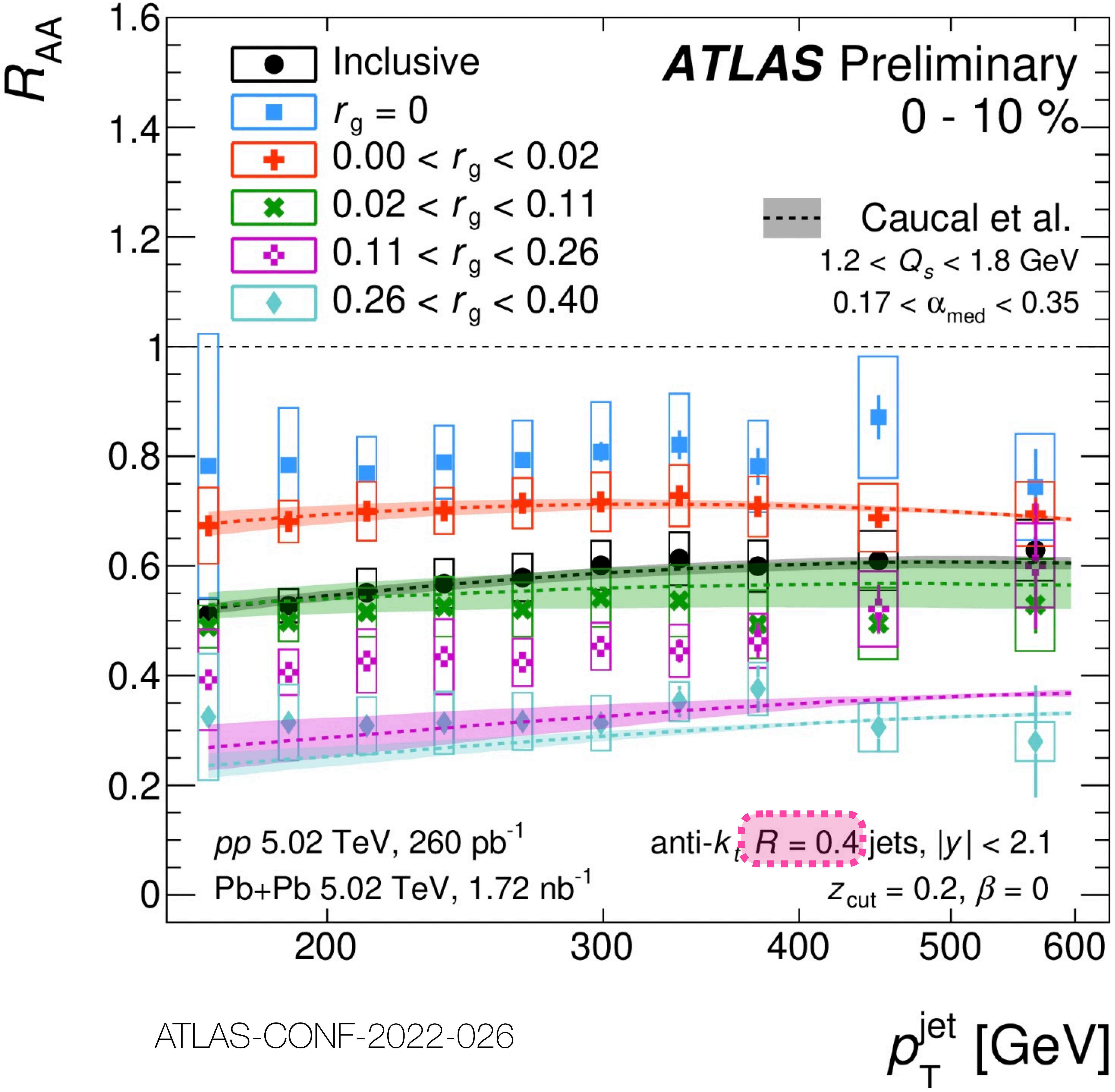
Jet R_{AA}

CMS JHEP 05 (2021) 284



… they don't describe the individual R^{R}_{AA}

R_{AA} - substructure interplay



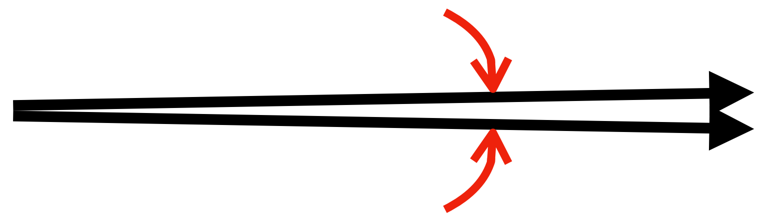
ATLAS-CONF-2022-026

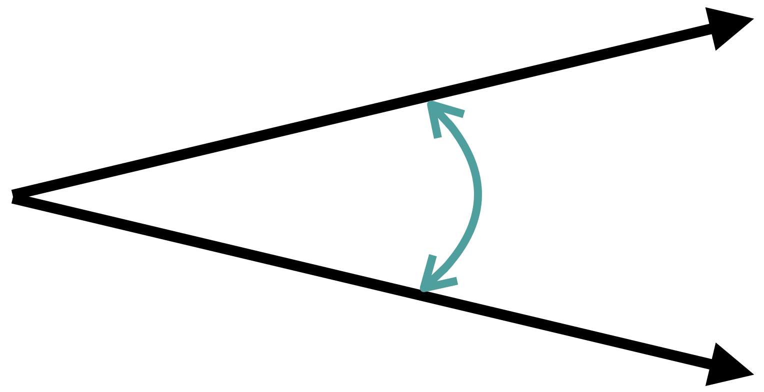
strong r_g dependence of R_{AA}.
Large r_g jets are more suppressed

small r_g

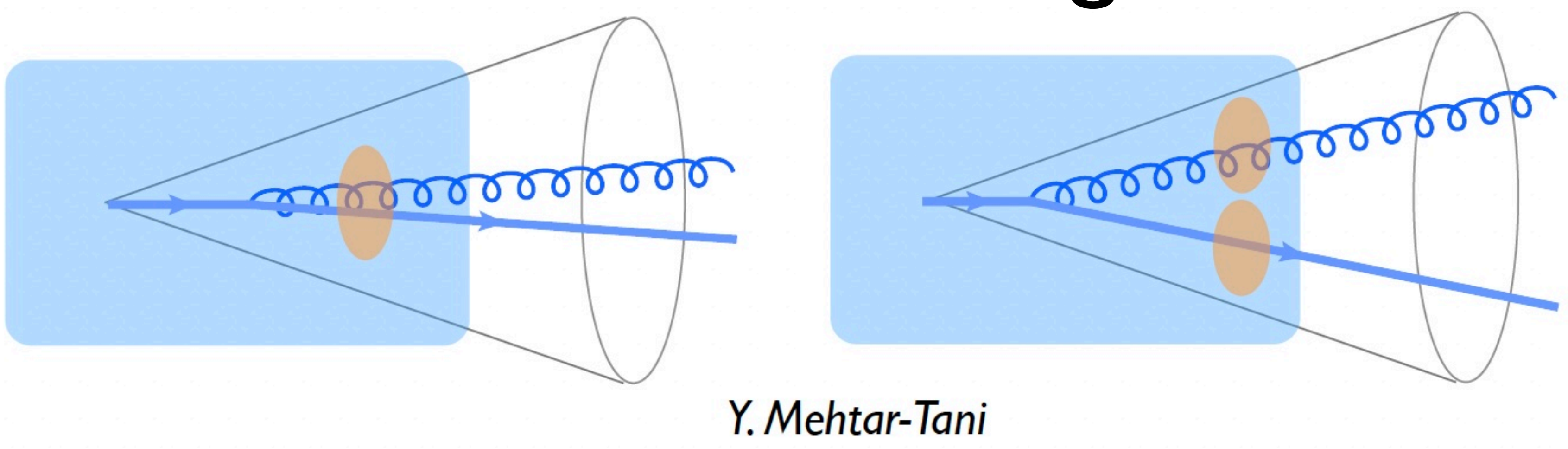
inclusive

large r_g





Relationship between r_g and medium resolution length



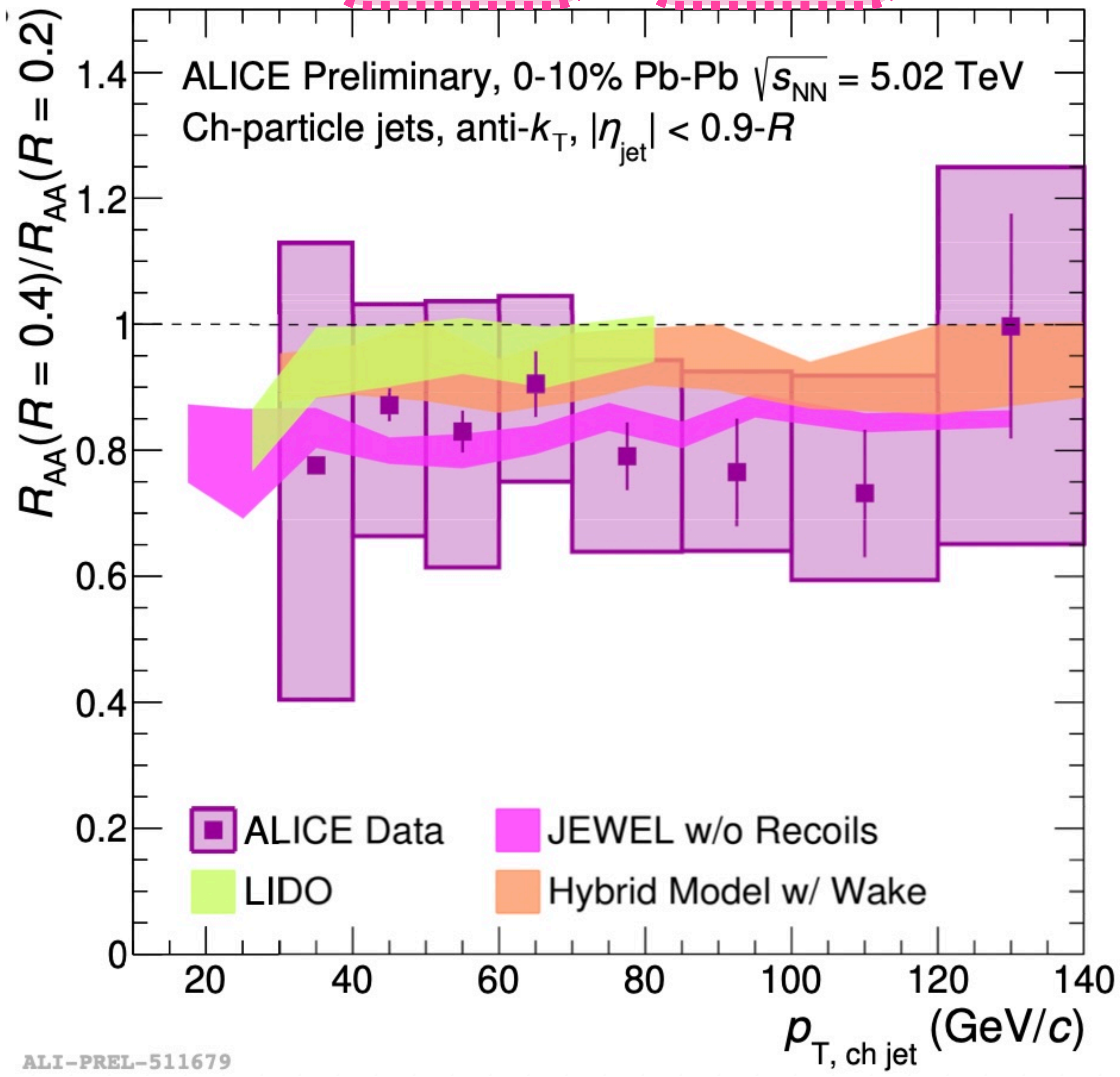
New tools to study R_{AA} at unprecedented low p_T

ML-based background estimator

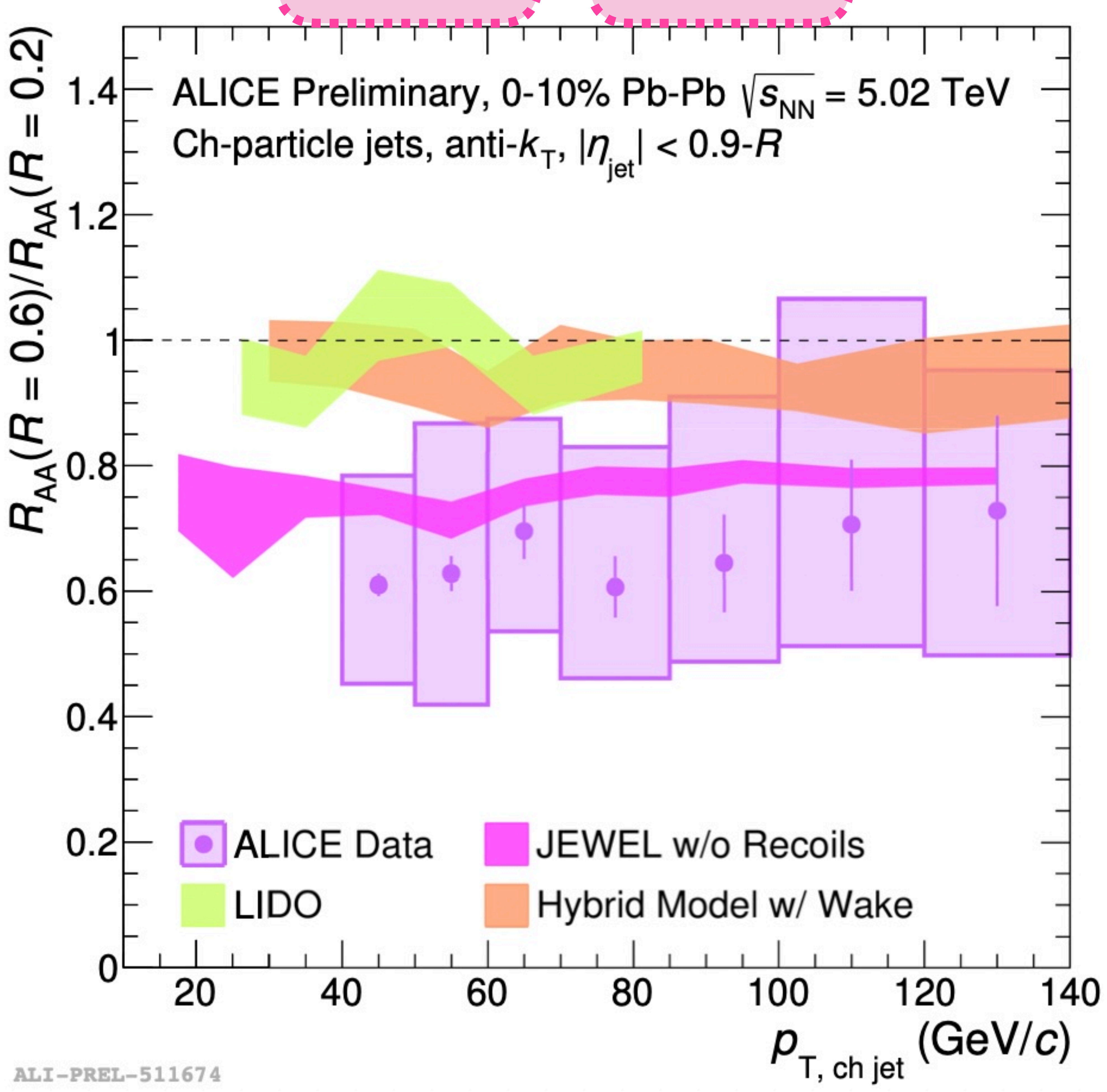
Measuring down to lower p_T and larger R

R dependence of R_{AA}

R = 0.4 / R = 0.2



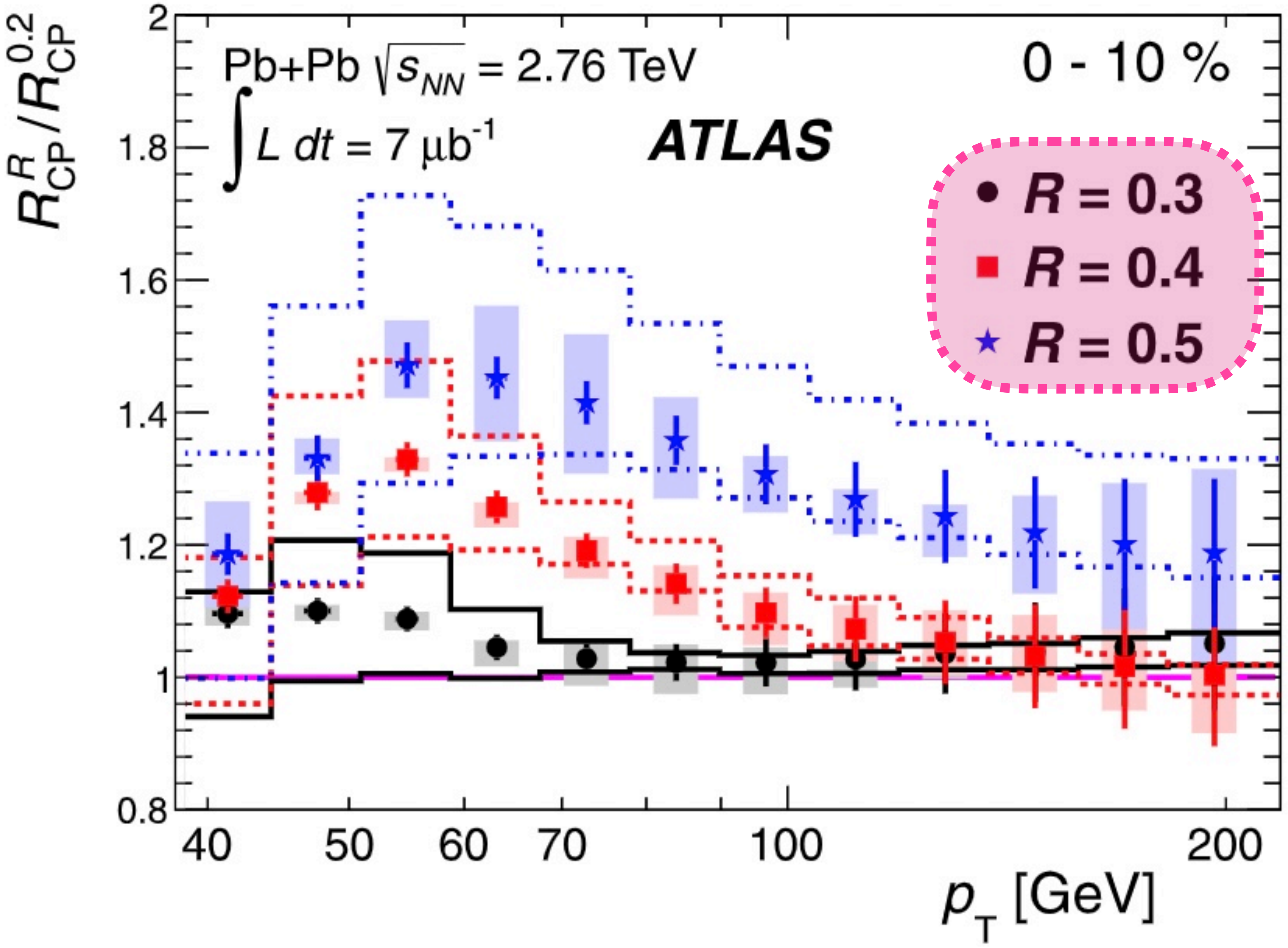
R = 0.6 / R = 0.2

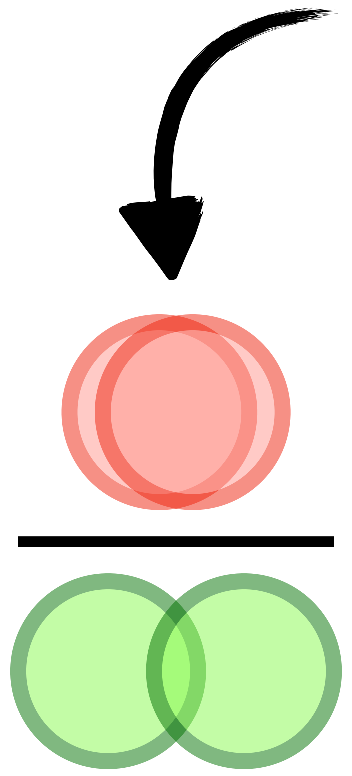


- No strong evidence of R-dependence between R = 0.2 and R = 0.4
- R = 0.6 jets appear more suppressed than R = 0.2 jets → R-dependence

Tension with previous result?

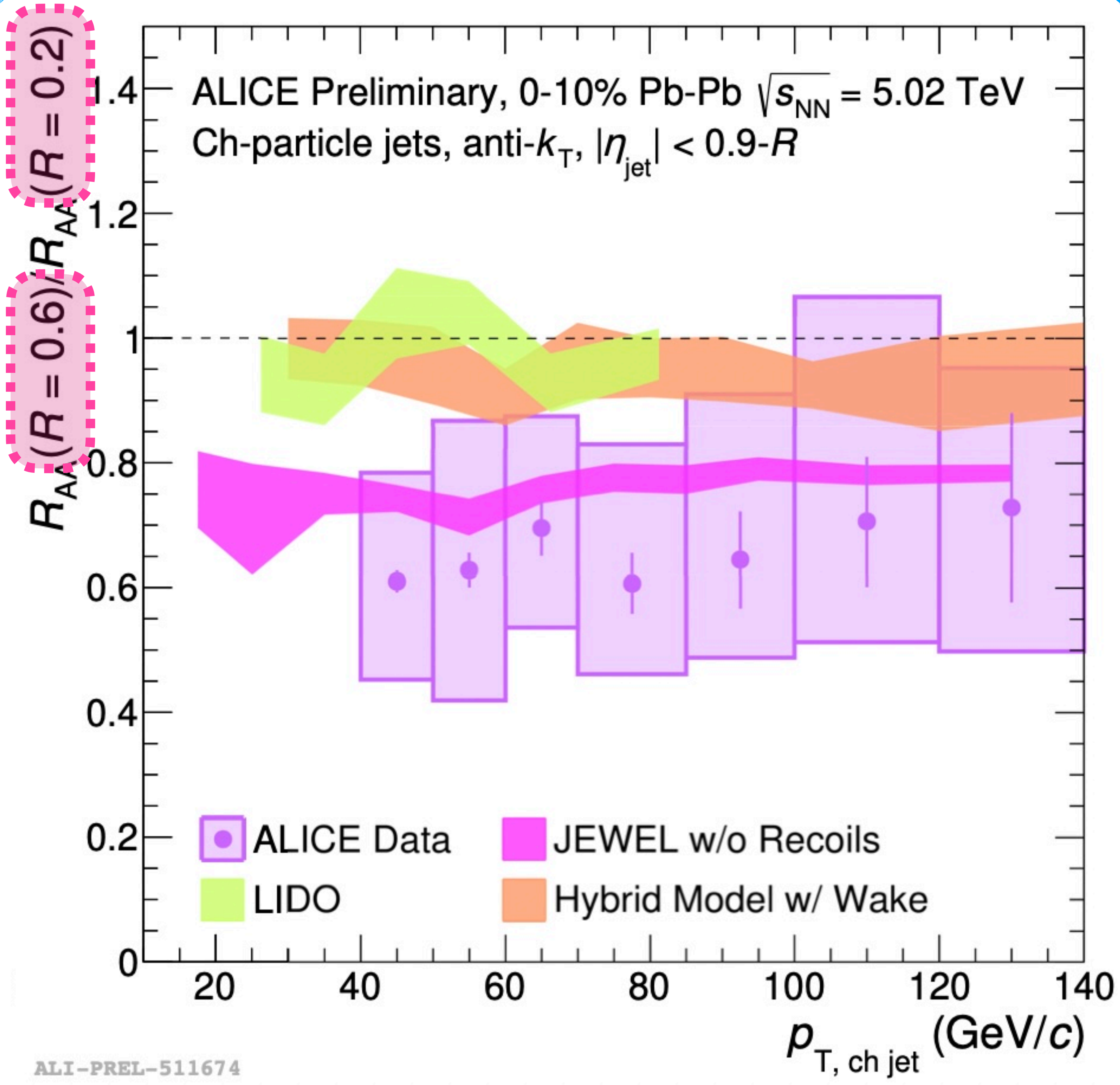
ATLAS, PLB 719 (2013) 220





Pb—Pb central / Pb—Pb peripheral

Suggests larger radius **less** suppressed



Suggests larger radius **more** suppressed

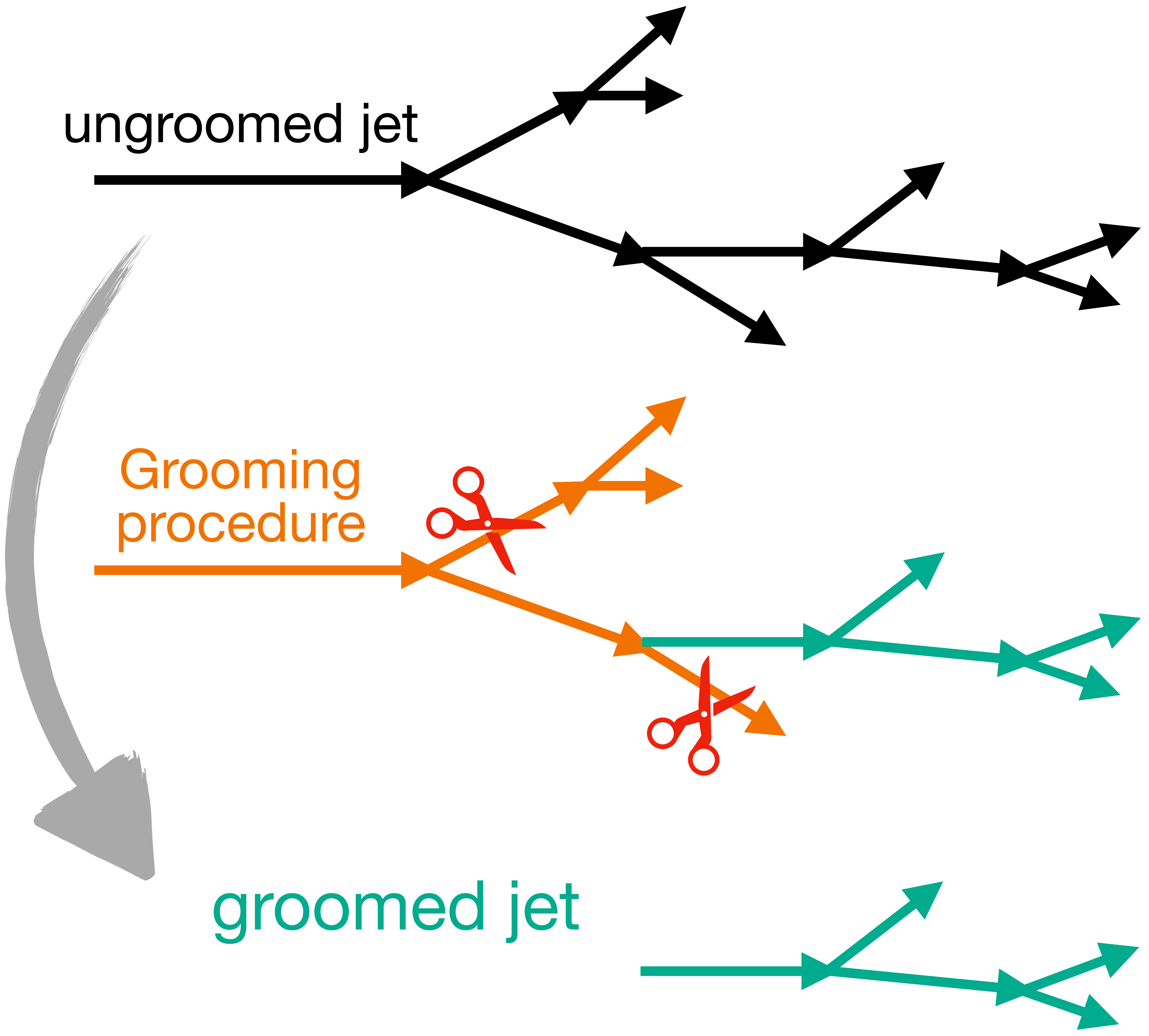
- Not exactly the same observables
- Larger systematics in ALICE case
- Charged vs full jets
- Different center-of-mass energy and phase-space

More detailed comparison and future studies are needed

Substructure Modification

Grooming and Soft Drop

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



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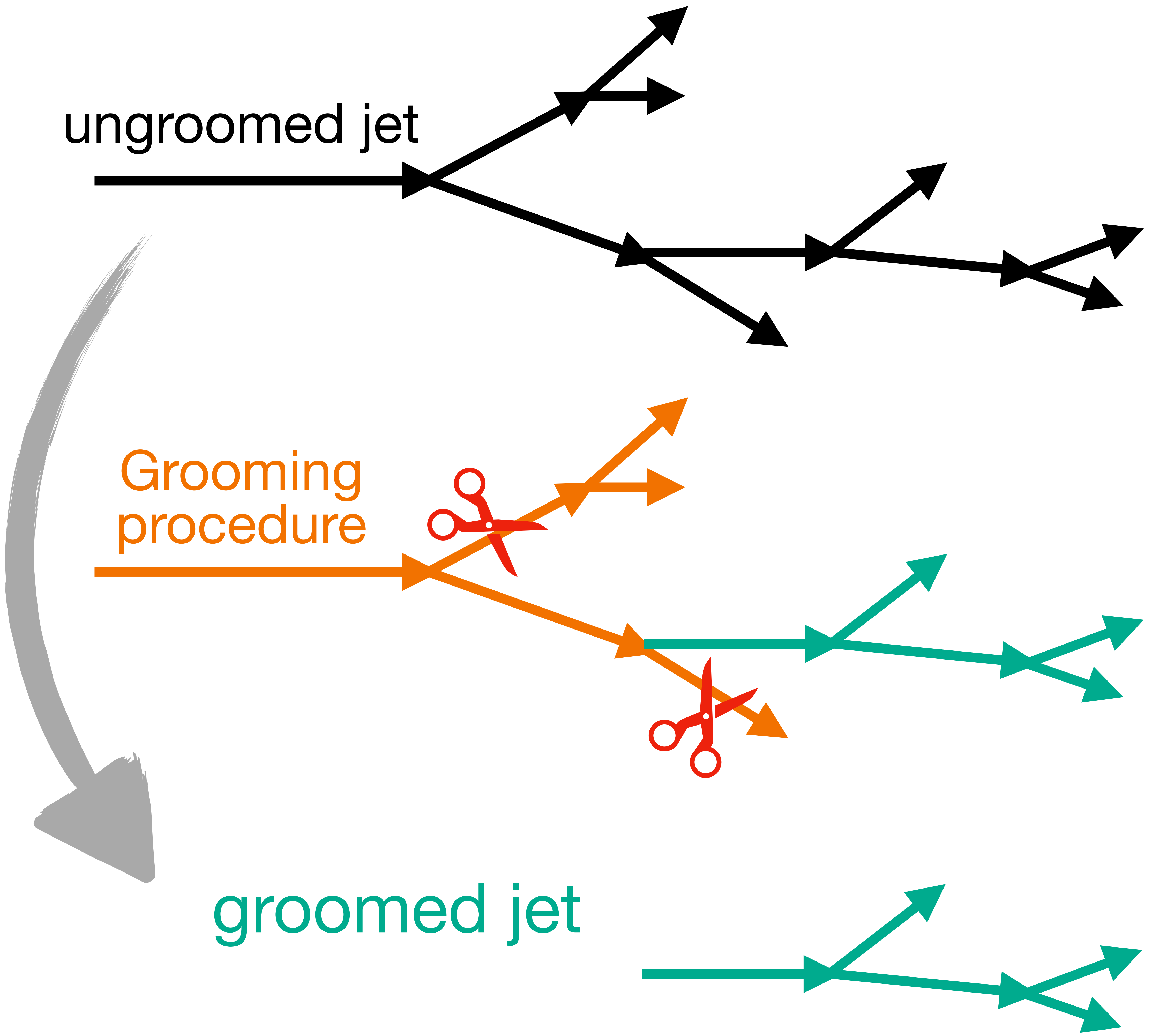


Soft Drop: JHEP 1405 (2014) 146

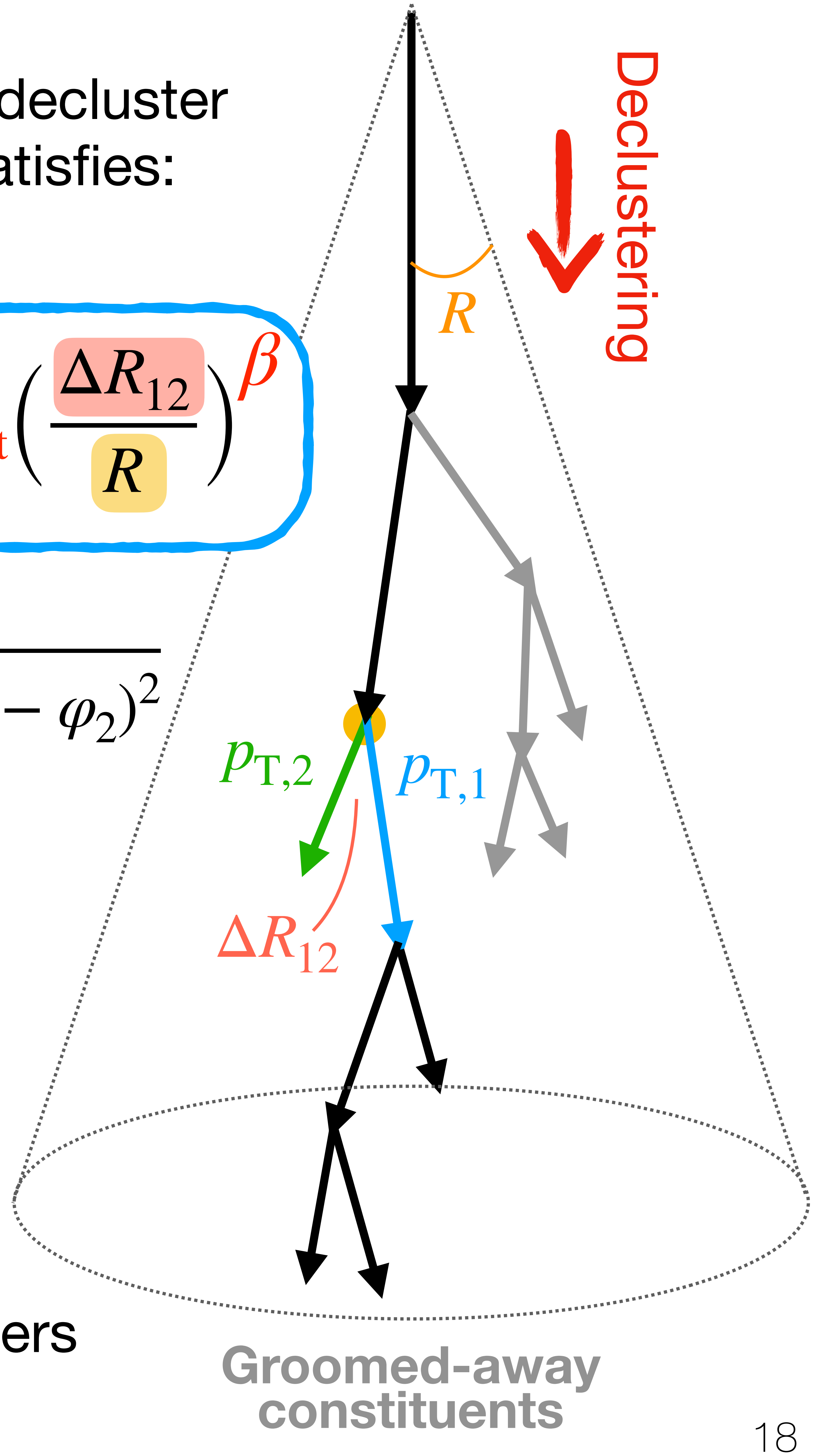
After reclustering with C-A, decluster and find first splitting that satisfies:

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

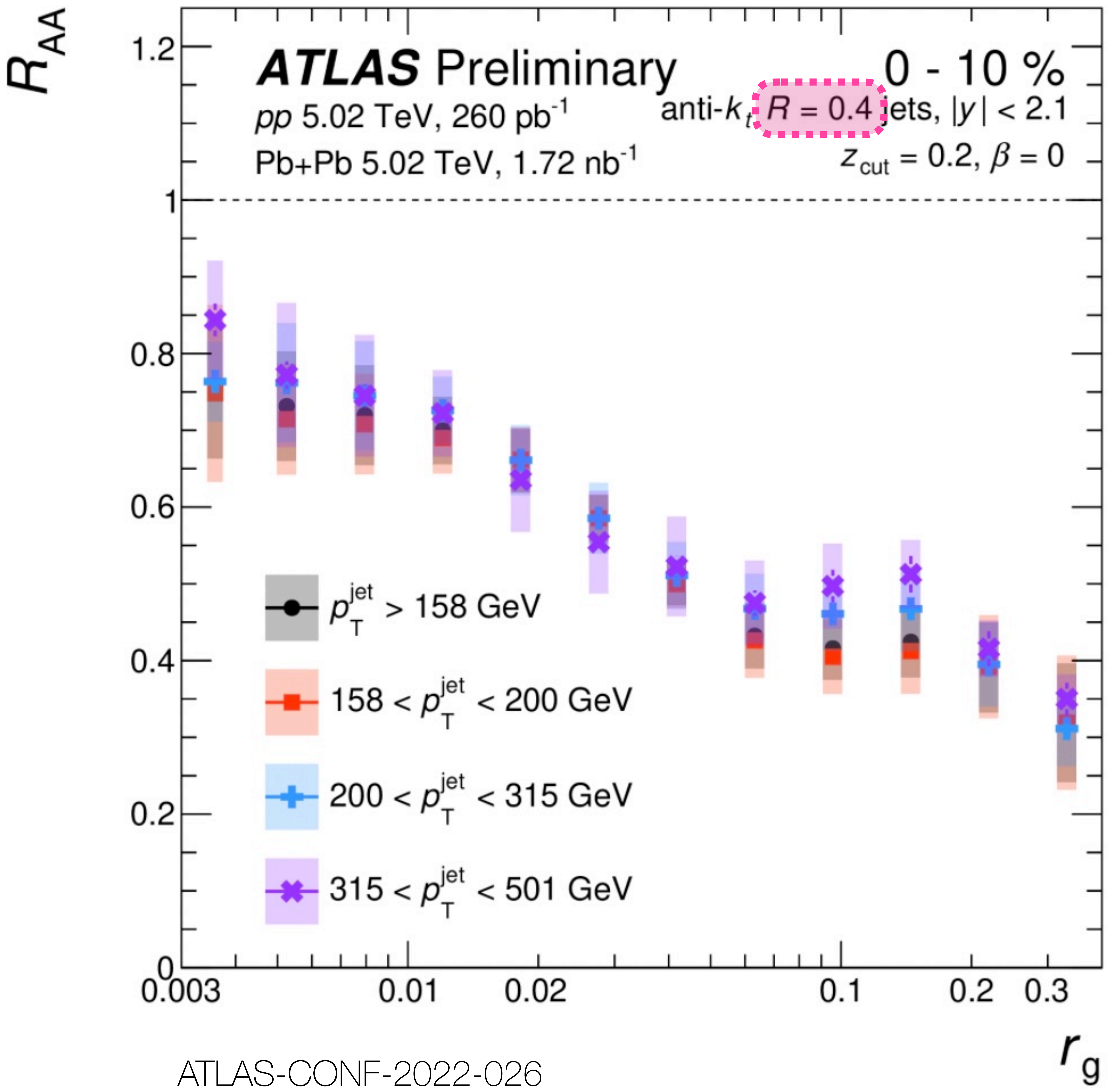
$$\Delta R_{12} = \sqrt{(y_1 - y_2)^2 + (\varphi_1 - \varphi_2)^2}$$

The branches left define the groomed jet

z_{cut} and β are free parameters



R_{AA} vs groomed jet radius



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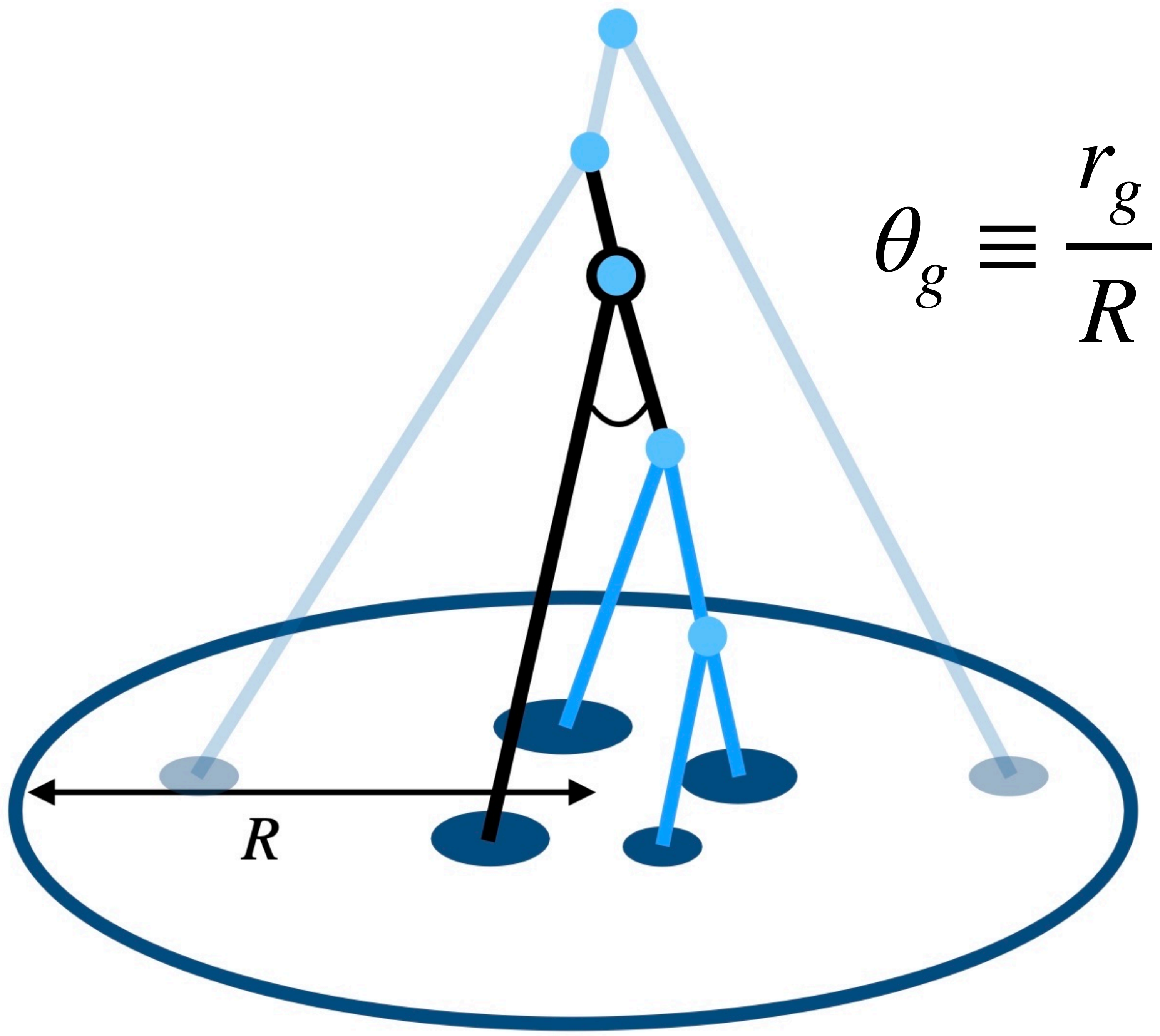
Absolutely-normalized result

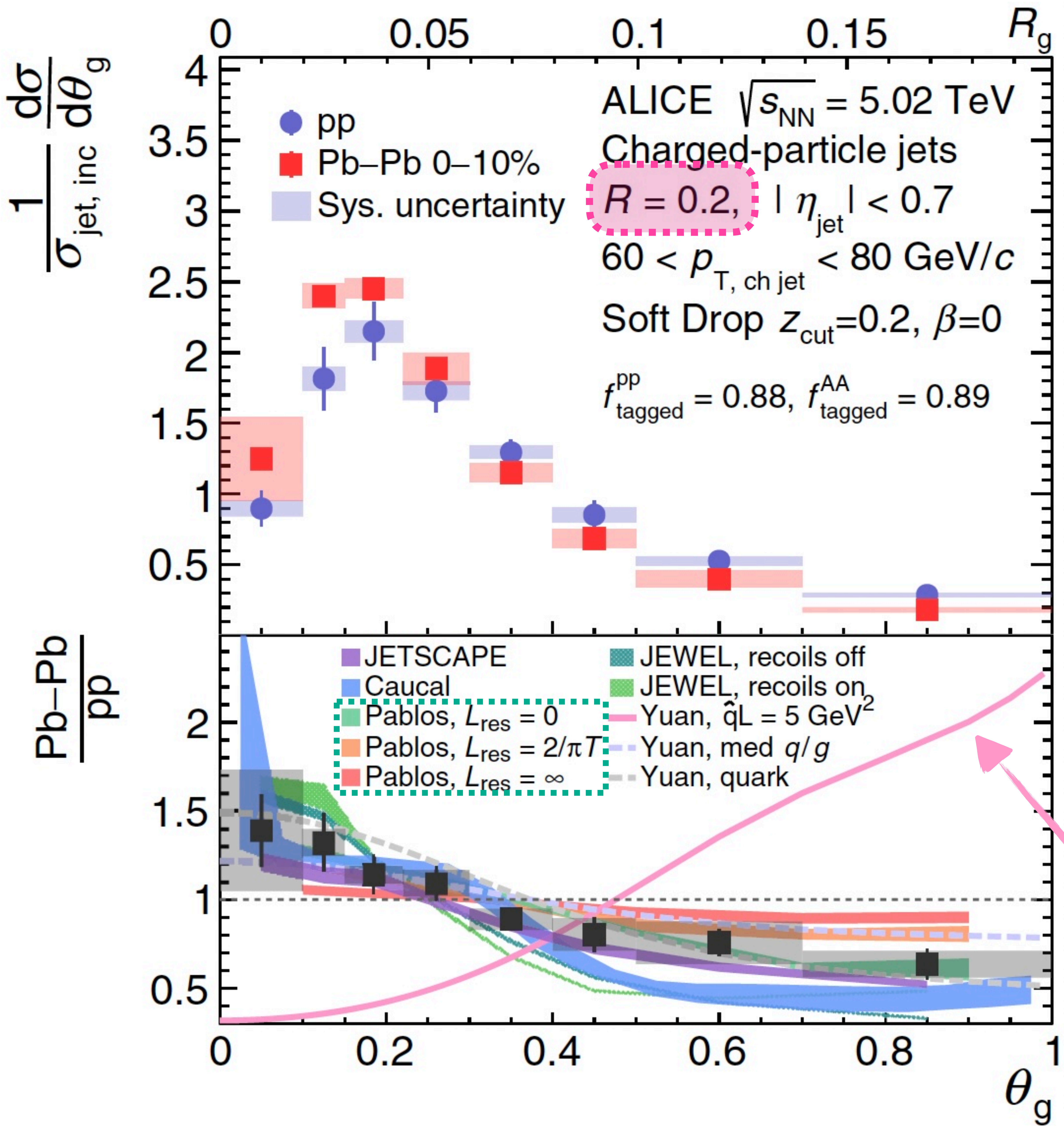


$$\theta_g \equiv \frac{r_g}{R} = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

No significant p_T dependence

Strong R_{AA} dependence on r_g

Groomed jet radius

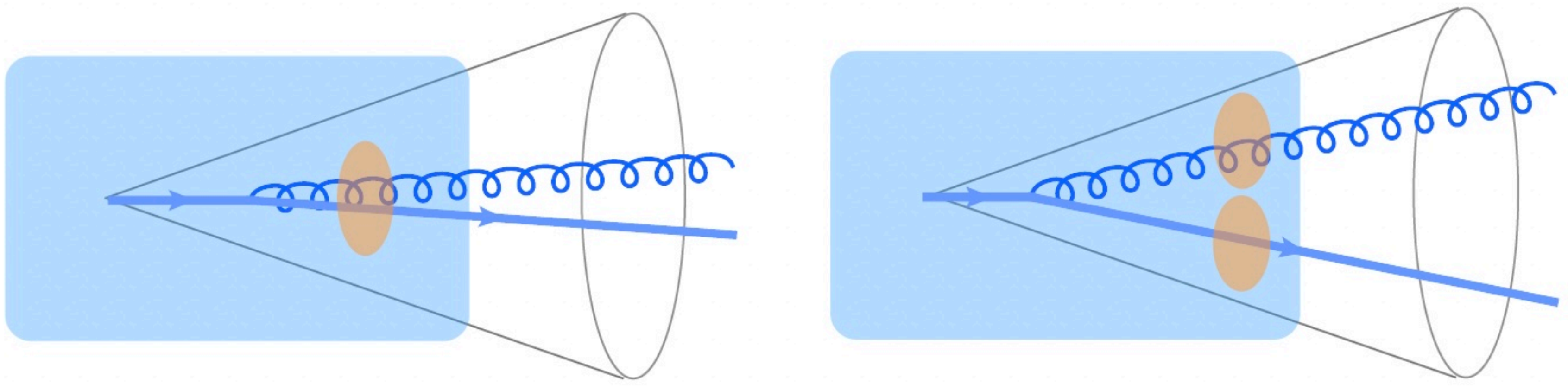


Self-normalized result → shapes!

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

Narrowing of the Pb—Pb distribution

Sensitive to QGP resolution length



Y. Mehtar-Tani

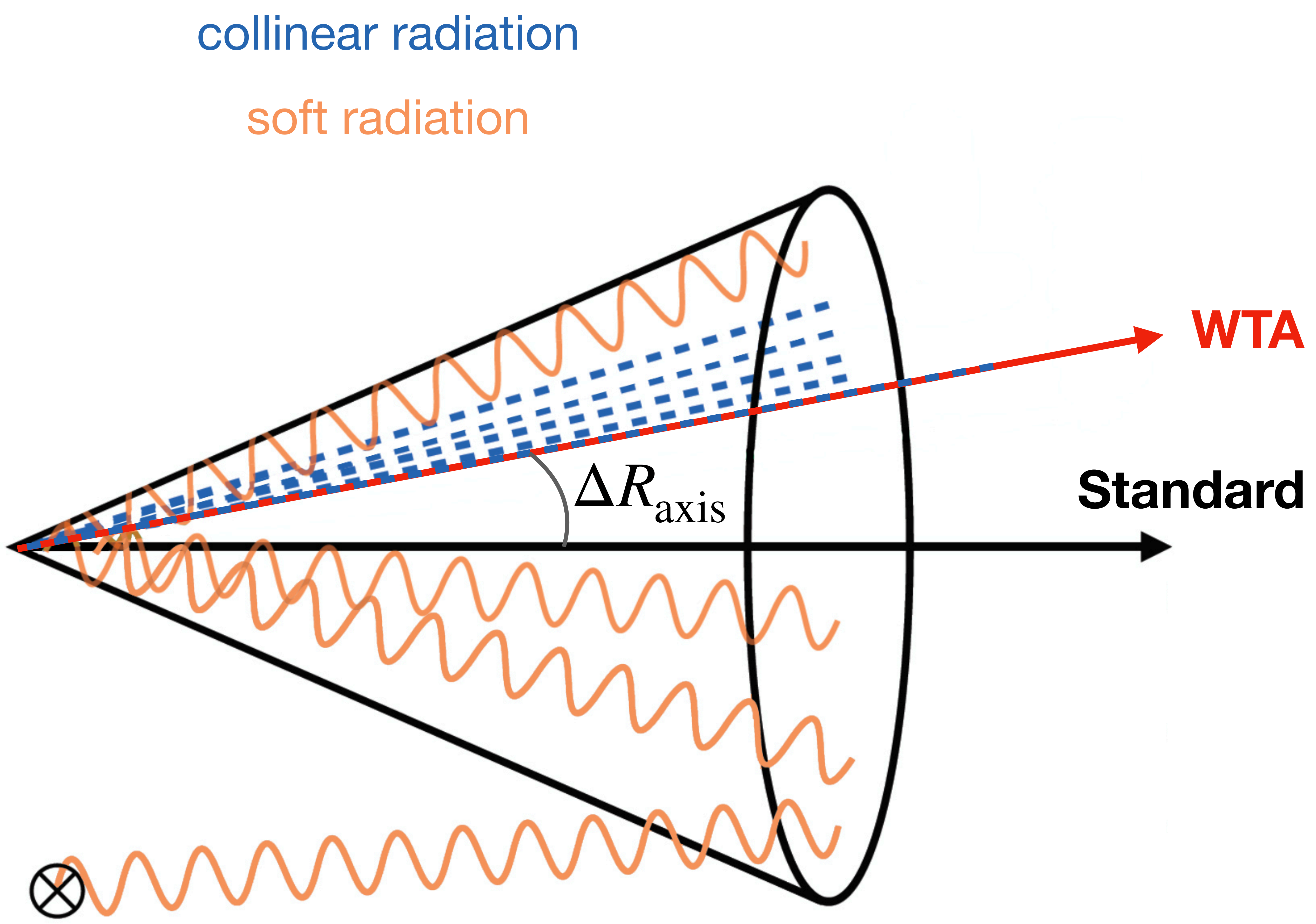
in-jet p_T broadening model

Could this disagreement be induced by grooming? → study ungroomed angular substructure observable

Angle between jet axes

- **Standard axis:**
  coordinates in (y, φ) of jet clustered with anti-k_T algorithm and combined with E-Scheme

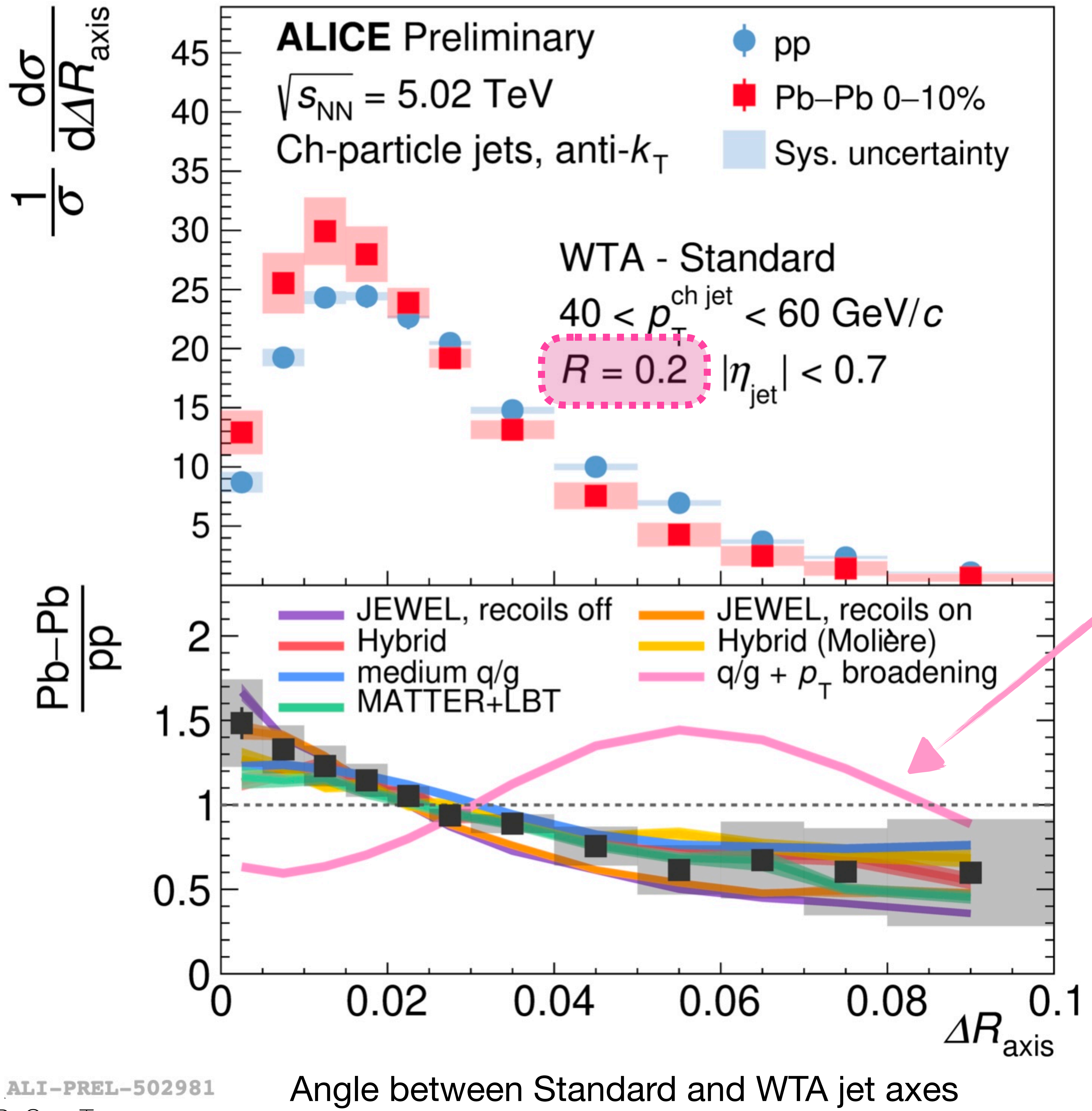
- **Winner-Takes-All (WTA) axis:**
  - Can be thought of as the direction of the hardest hadron in the jet



P. Cal et al., JHEP 04 (2020) 211

$$\Delta R_{\text{axis}} = \sqrt{(y_{\text{standard}} - y_{\text{WTA}})^2 + (\varphi_{\text{standard}} - \varphi_{\text{WTA}})^2}$$

Jet-axis differences



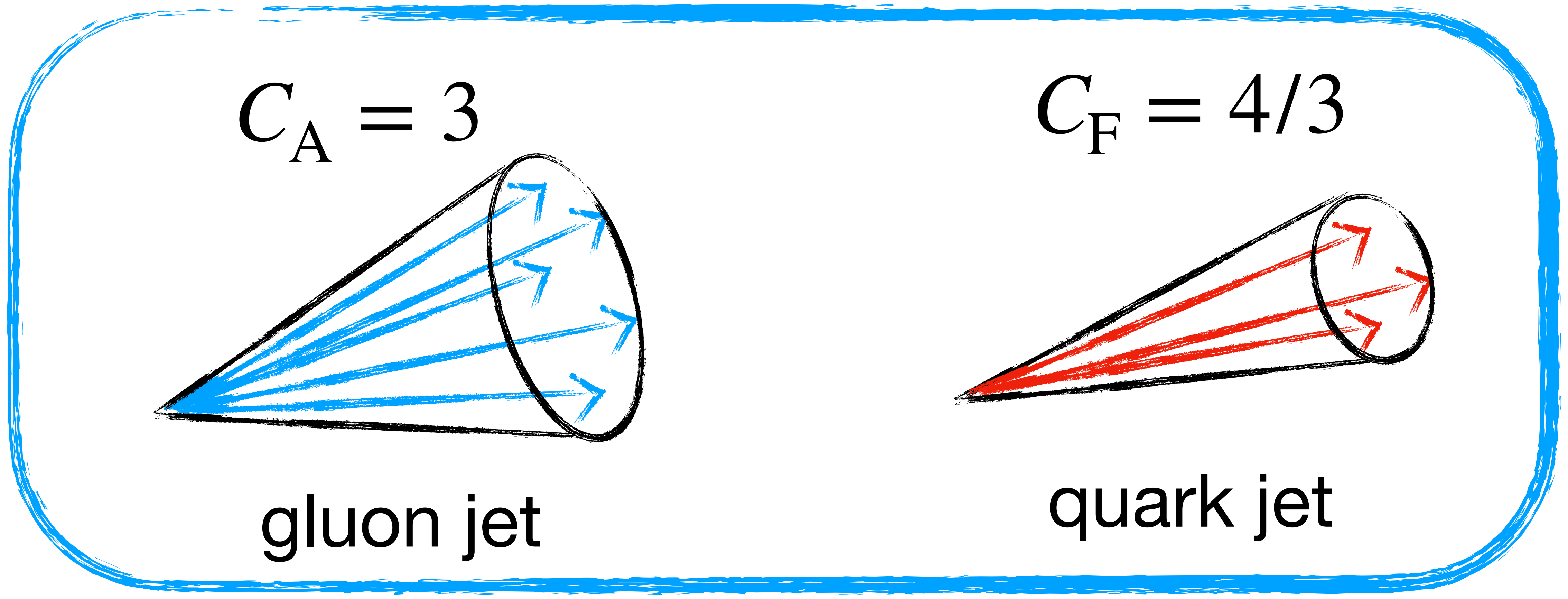
Angle between Standard and WTA jet axes

Narrowing of the angular substructure. Selection bias?

in-jet p_T broadening model

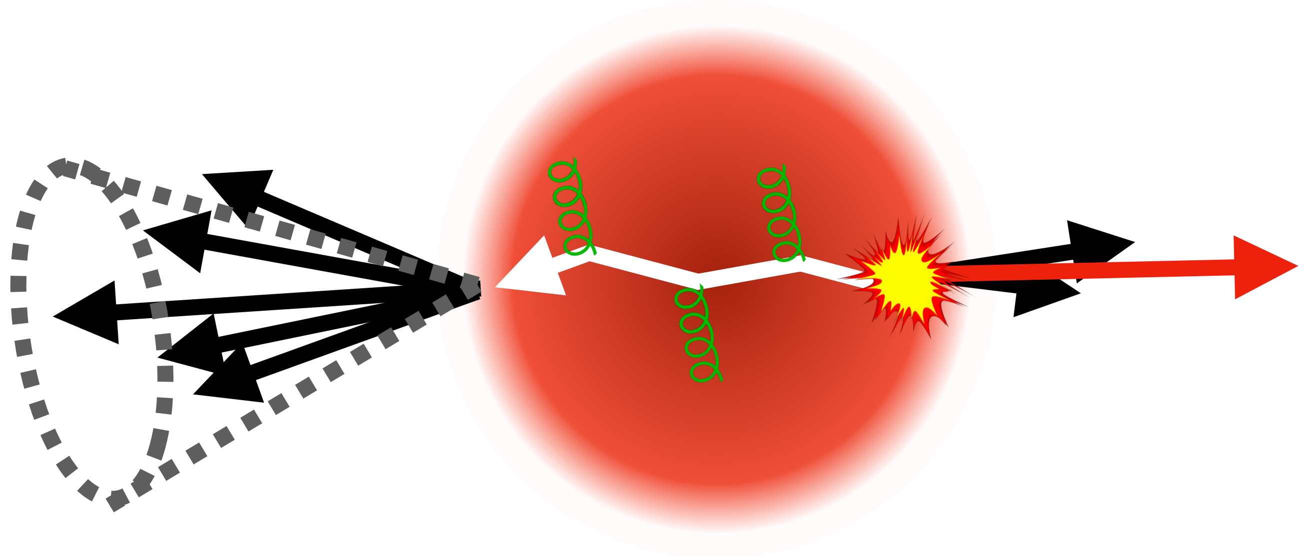
The disagreement seen in θ_g cannot be explained by grooming

Quark-jet fraction higher in medium?



Correlations with high-p_T trigger

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



$$n \equiv \frac{1}{N_{\rm trig}^{\rm AA}} \frac{d^2 N_{\rm jet}^{\rm AA}}{dp_{\rm T,ch}^{\rm jet} d\eta_{\rm jet}}$$

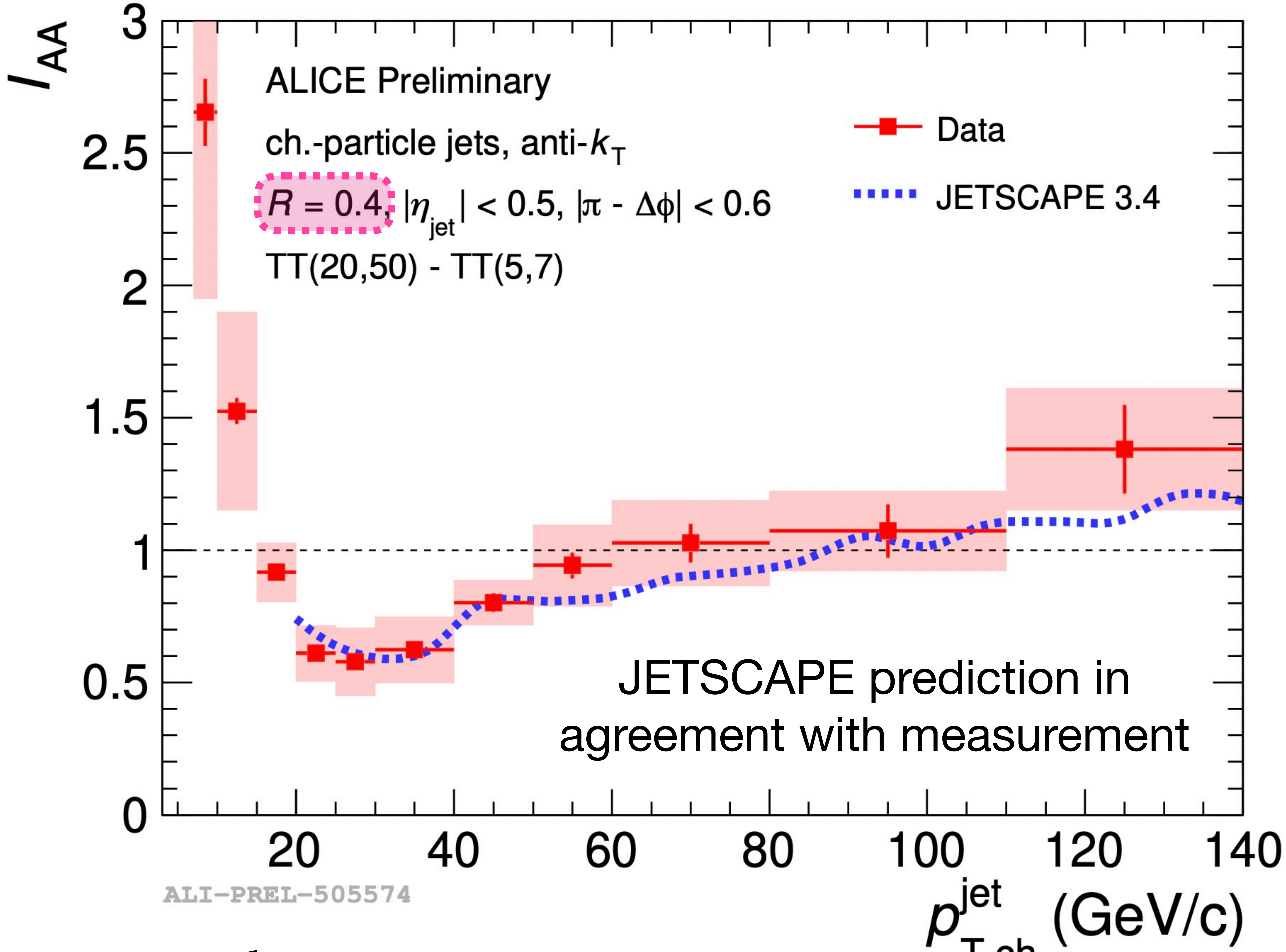
Data-driven subtraction of uncorrelated background by taking difference between signal and reference spectra allows for measurement down to low p_T and high R

$$\Delta_{\rm recoil} = n({\rm TT_{Sig}}) - c_{\rm Ref} \cdot n({\rm TT_{Ref}})$$

$${\rm TT_{Sig}} : 20 < p_{\rm T,\,trig} < 50 \ {\rm GeV}/c$$

$${\rm TT_{Ref}} : 5 < p_{\rm T,\,trig} < 7 \ {\rm GeV}/c$$

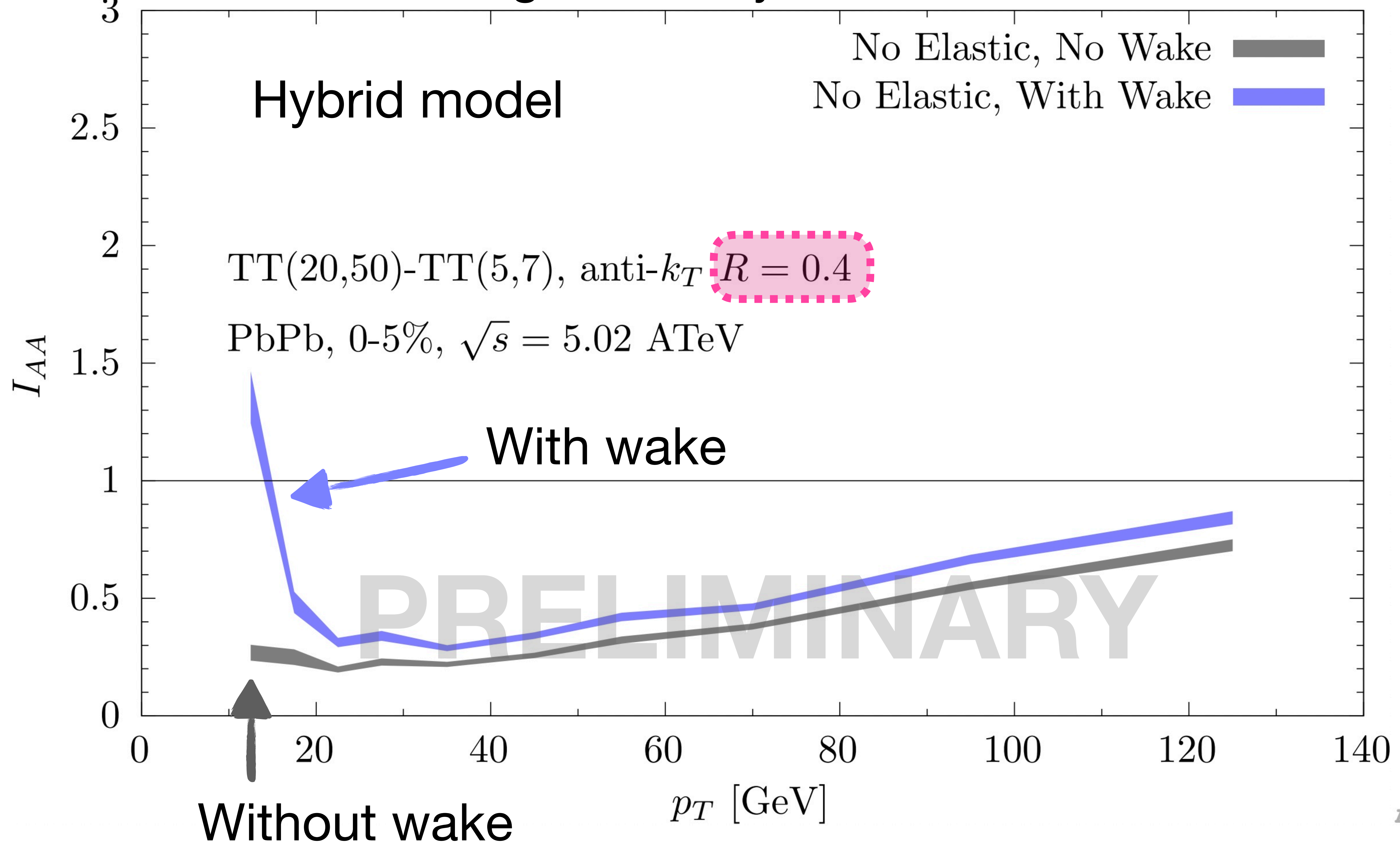
$$I_{\rm AA} \equiv \frac{\Delta_{\rm recoil}(\rm Pb-Pb)}{\Delta_{\rm recoil}(\rm pp)}$$

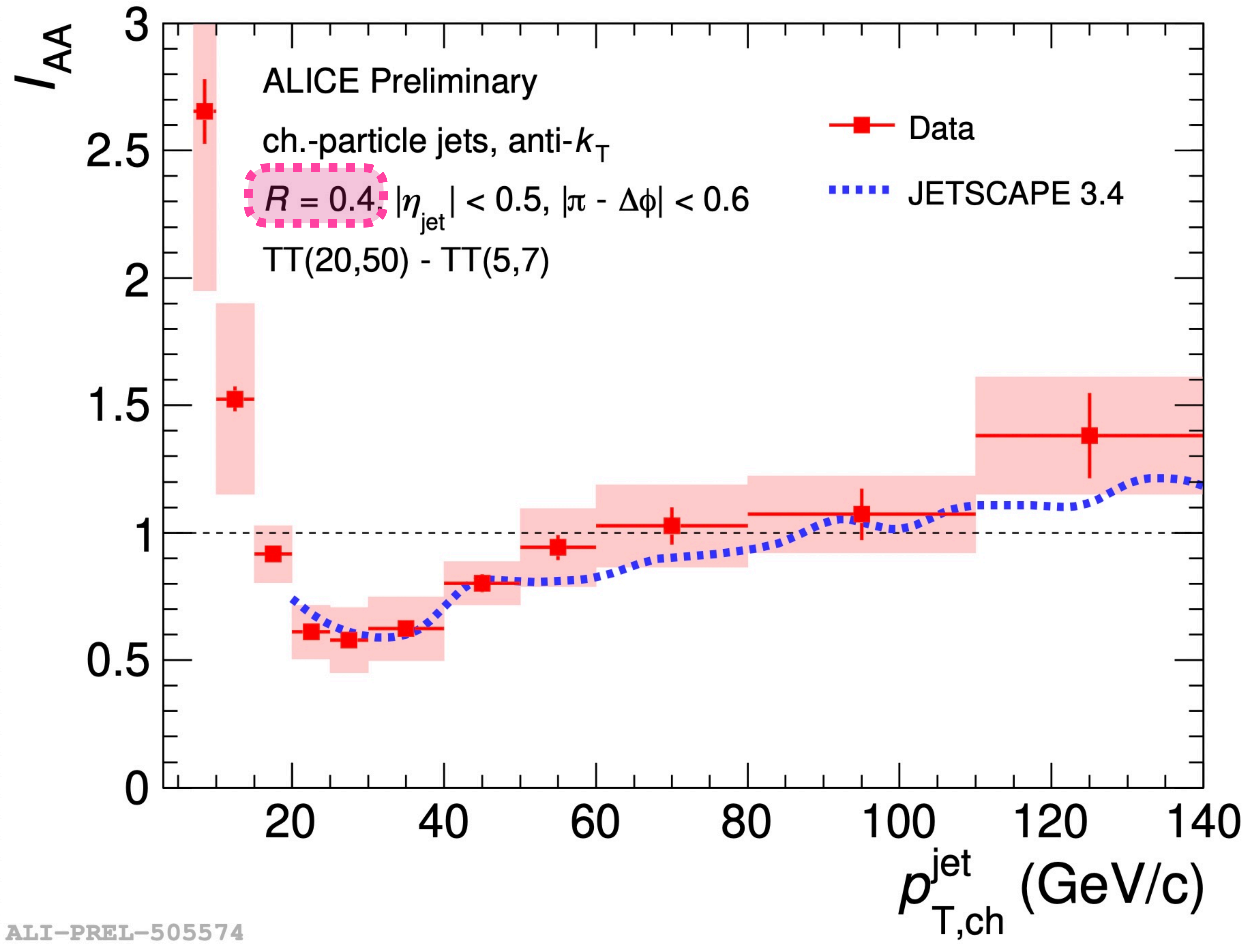


anti-k_T charged jets (R = 0.2, 0.4)

Sensitivity to medium response ("the wake")

Fig. Courtesy of D. Pablos

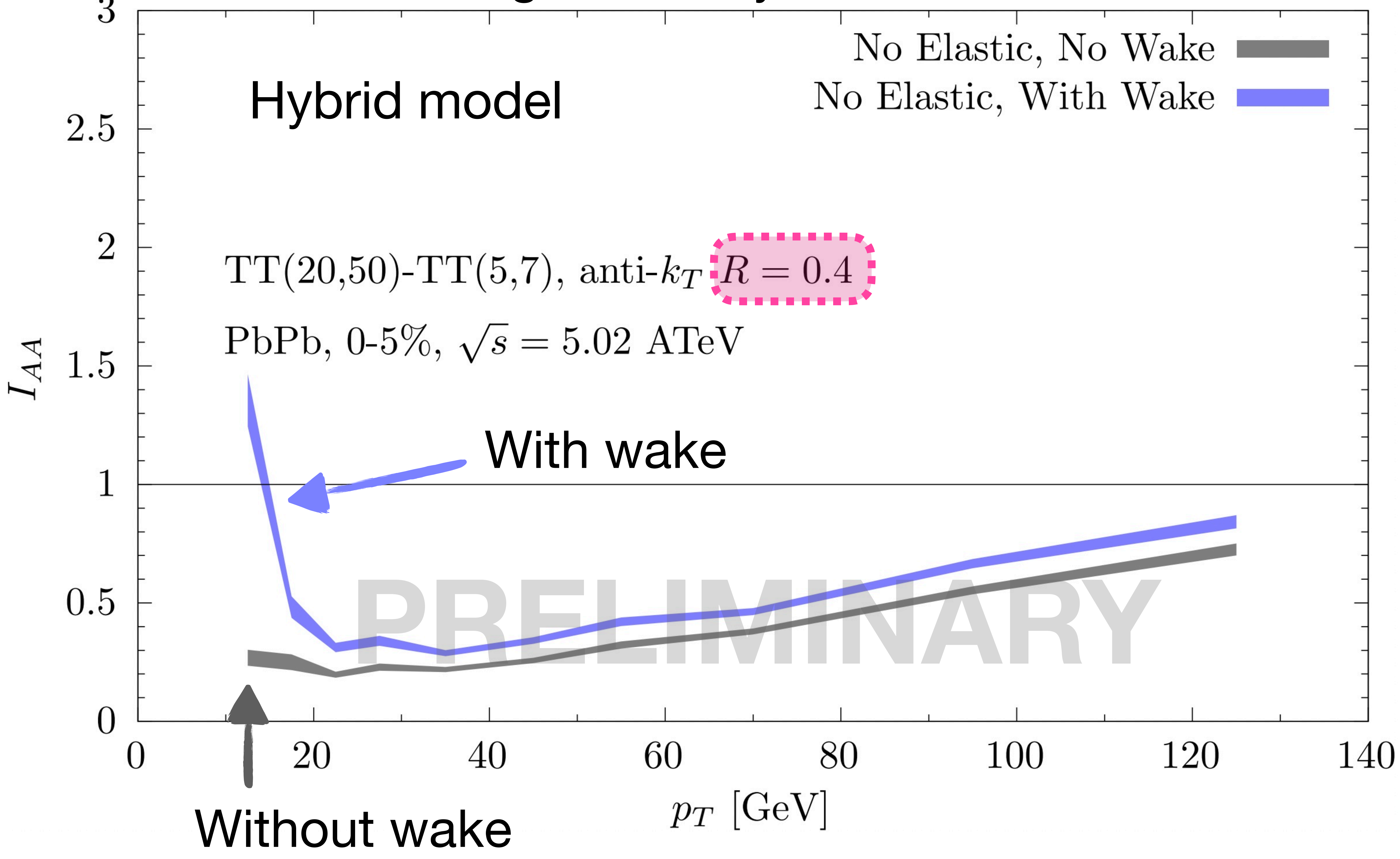




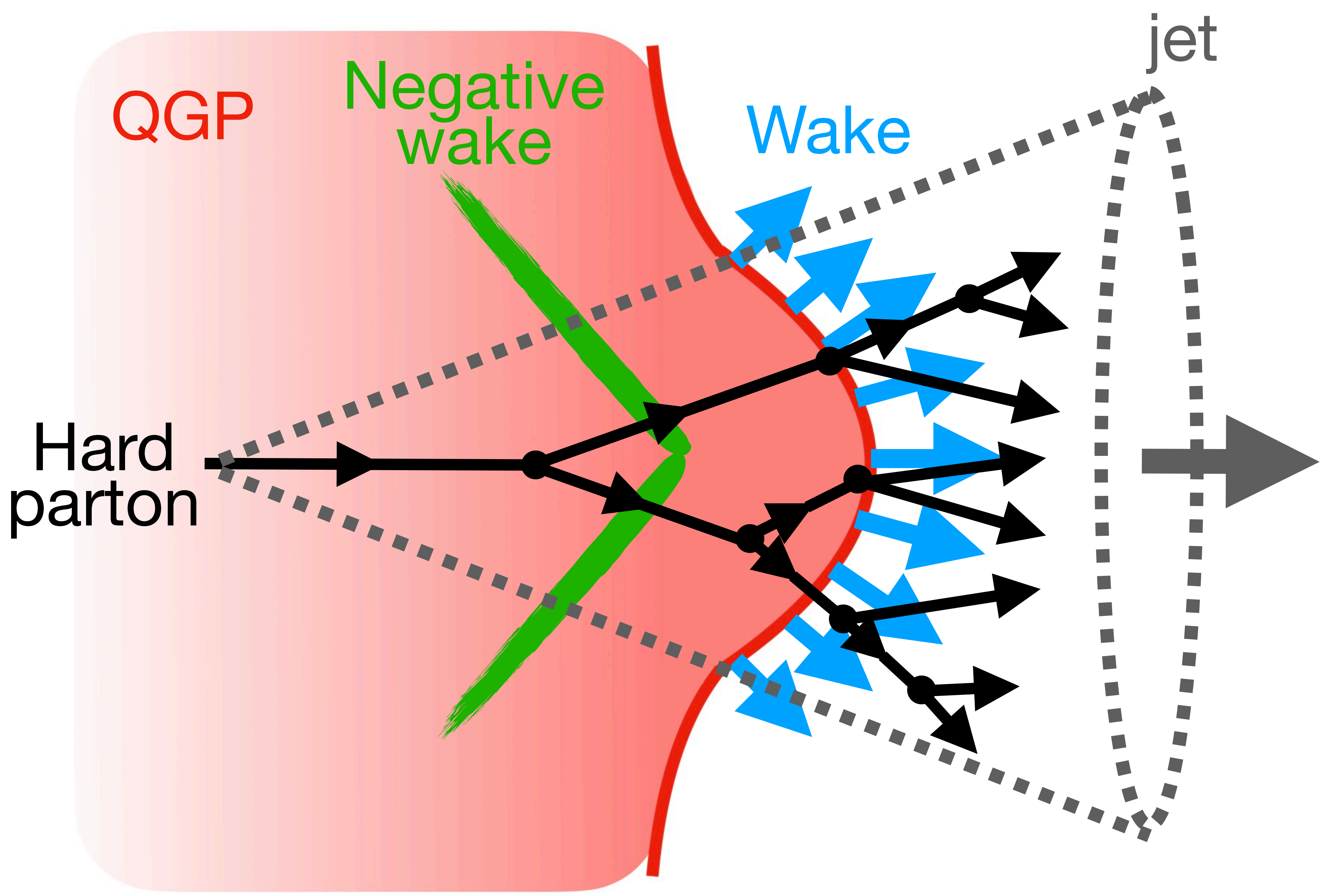
Uprise at low p_T explained by medium response within Hybrid model

Sensitivity to medium response ("the wake")

Fig. Courtesy of D. Pablos



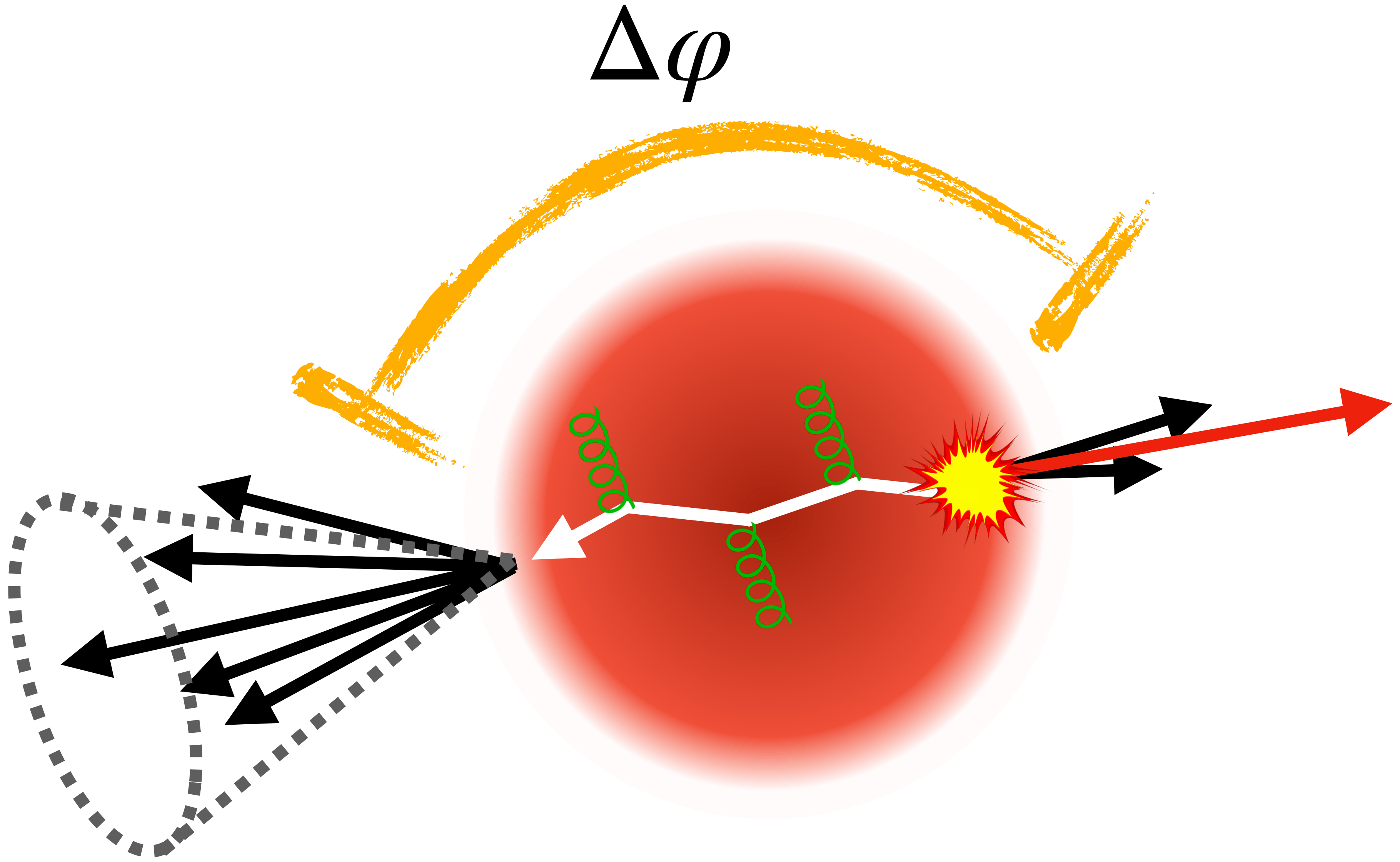
From jet-medium interaction, medium partons acquire additional momentum that correlates their direction with the jet



Medium response important for:

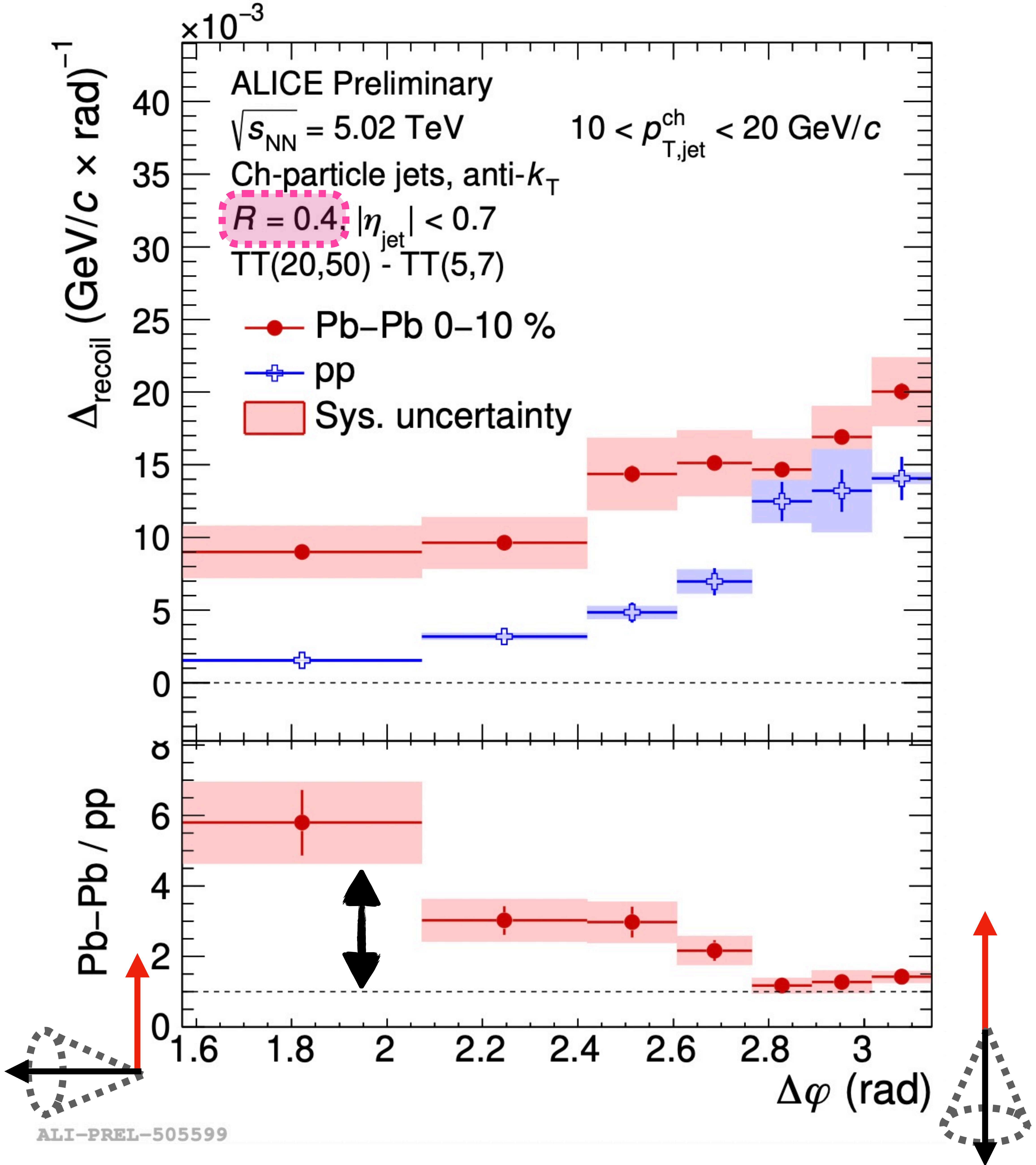
- Full characterization of QGP
- QGP bulk properties (velocity of sound, viscosities)
- thermalization: how fast is the jet energy propagated and thermalized with the rest of the QGP?

$\Delta\varphi$ results - angular deflections



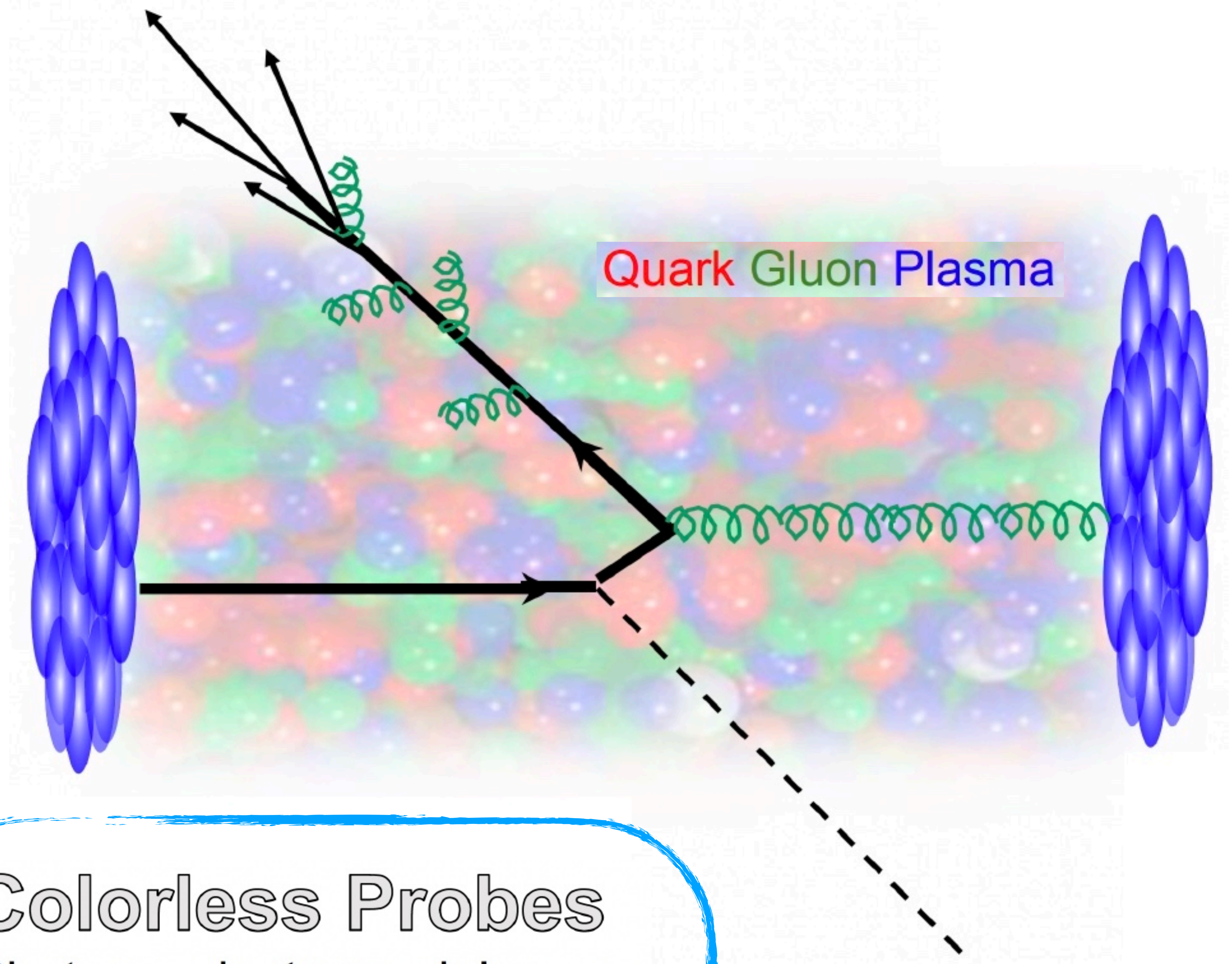
span wide kinematics:
- no modification (small R, large p_T)
- large modification (large R, low p_T)

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



Colorless probes

Colored Probes:
high energy quarks and gluons, heavy quarks
Studies of the medium properties



Colorless Probes
Photons, electroweak bosons
don't interact strongly

Photons / Z bosons

Tagging jet initial energy

Colorless probes

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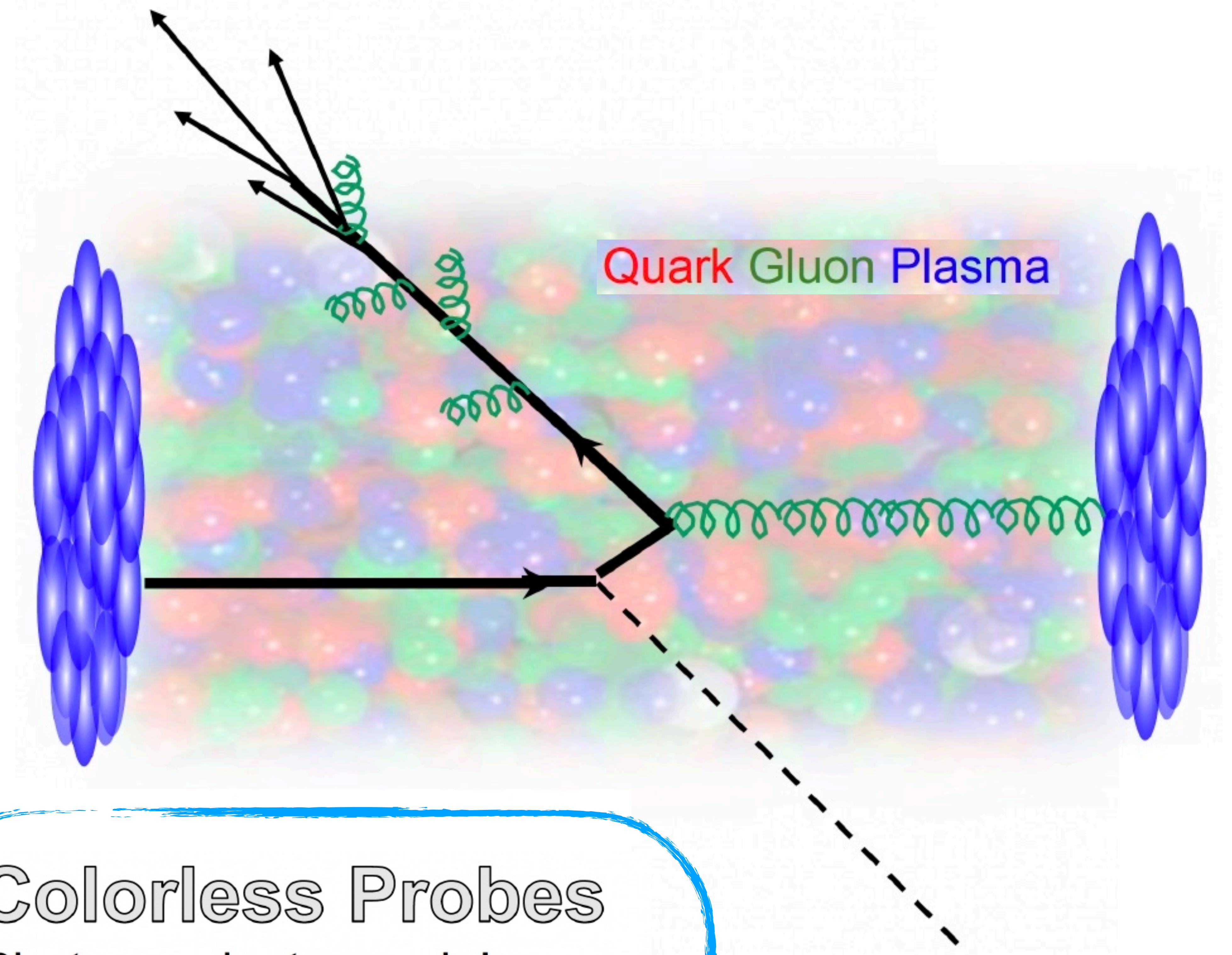

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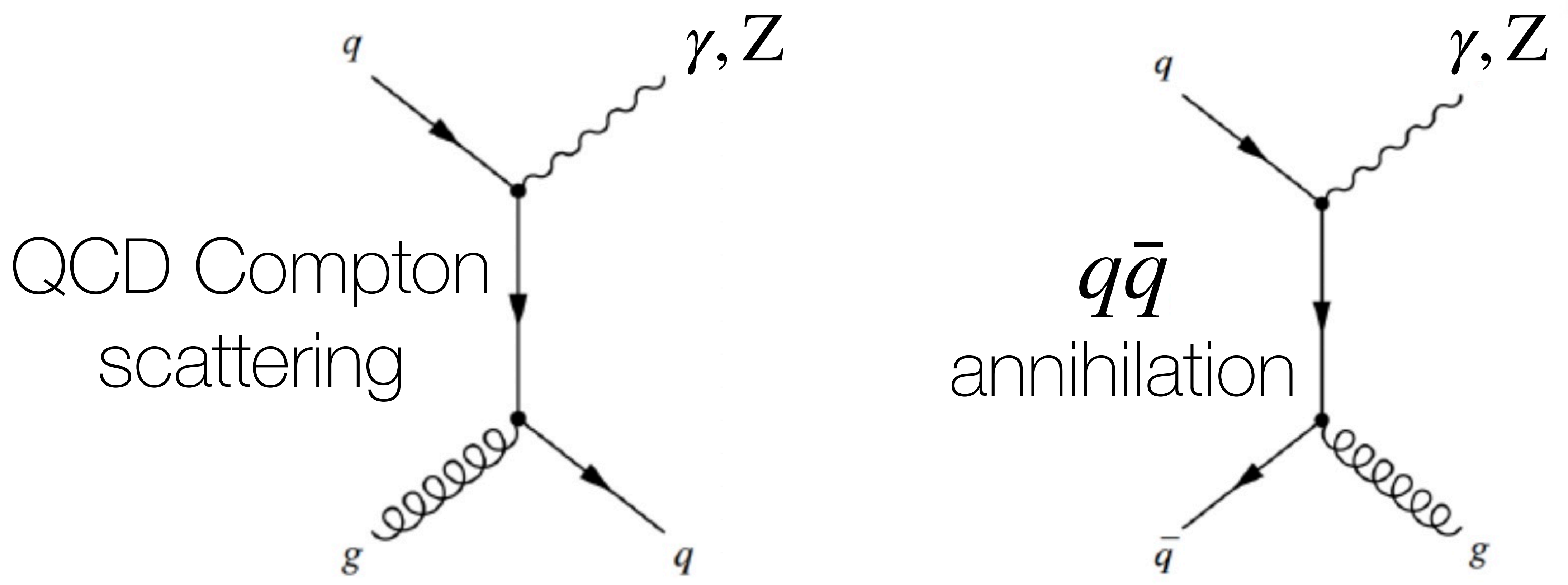
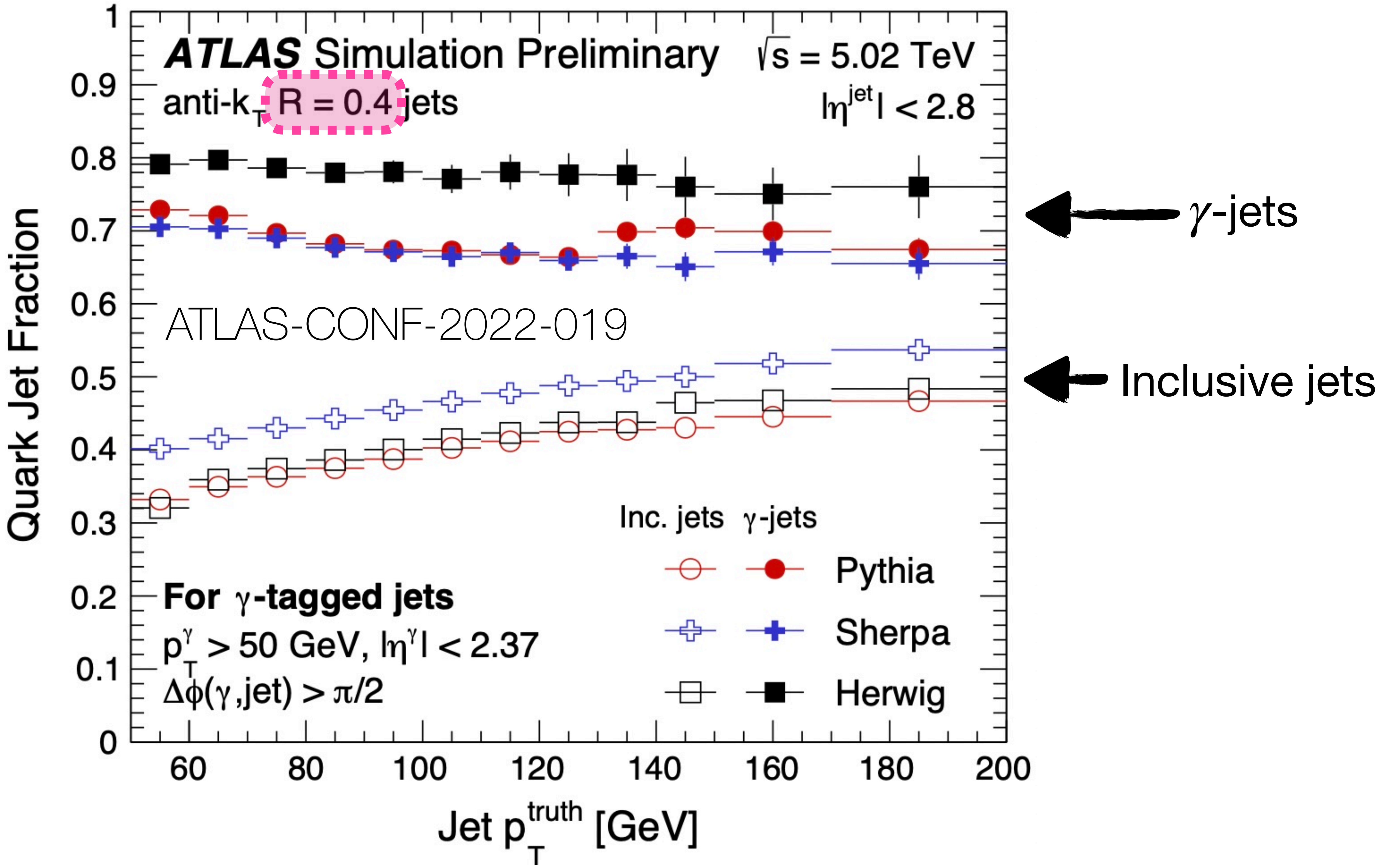
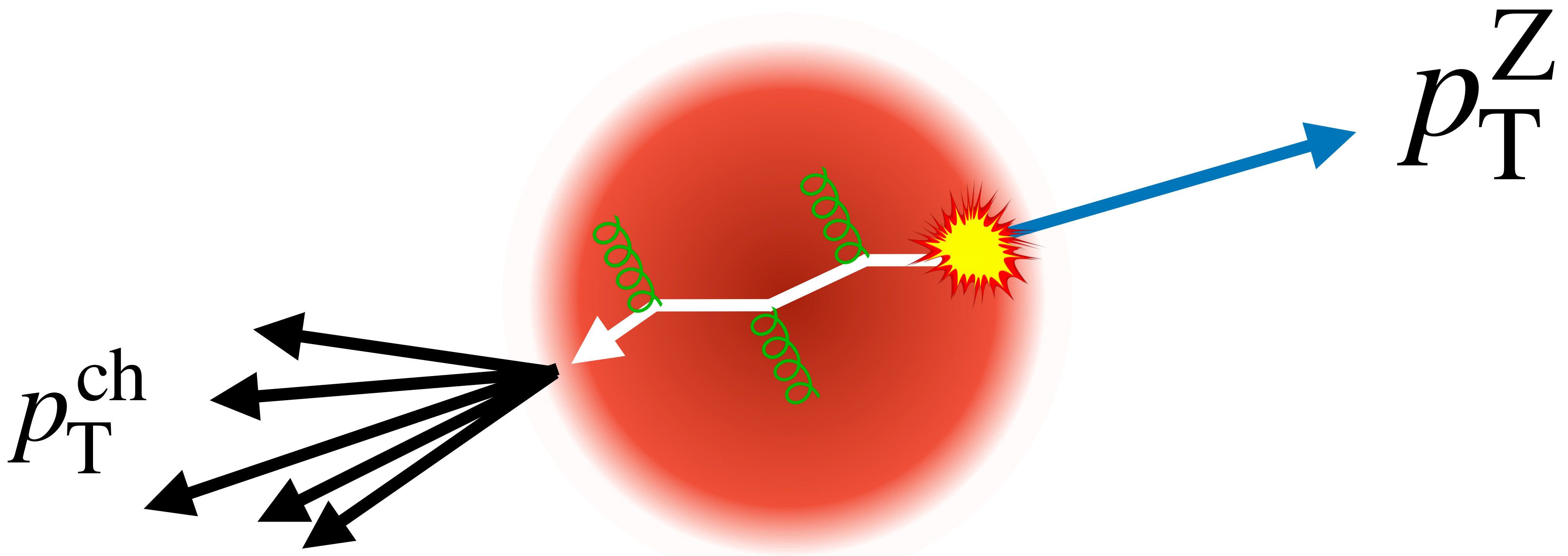


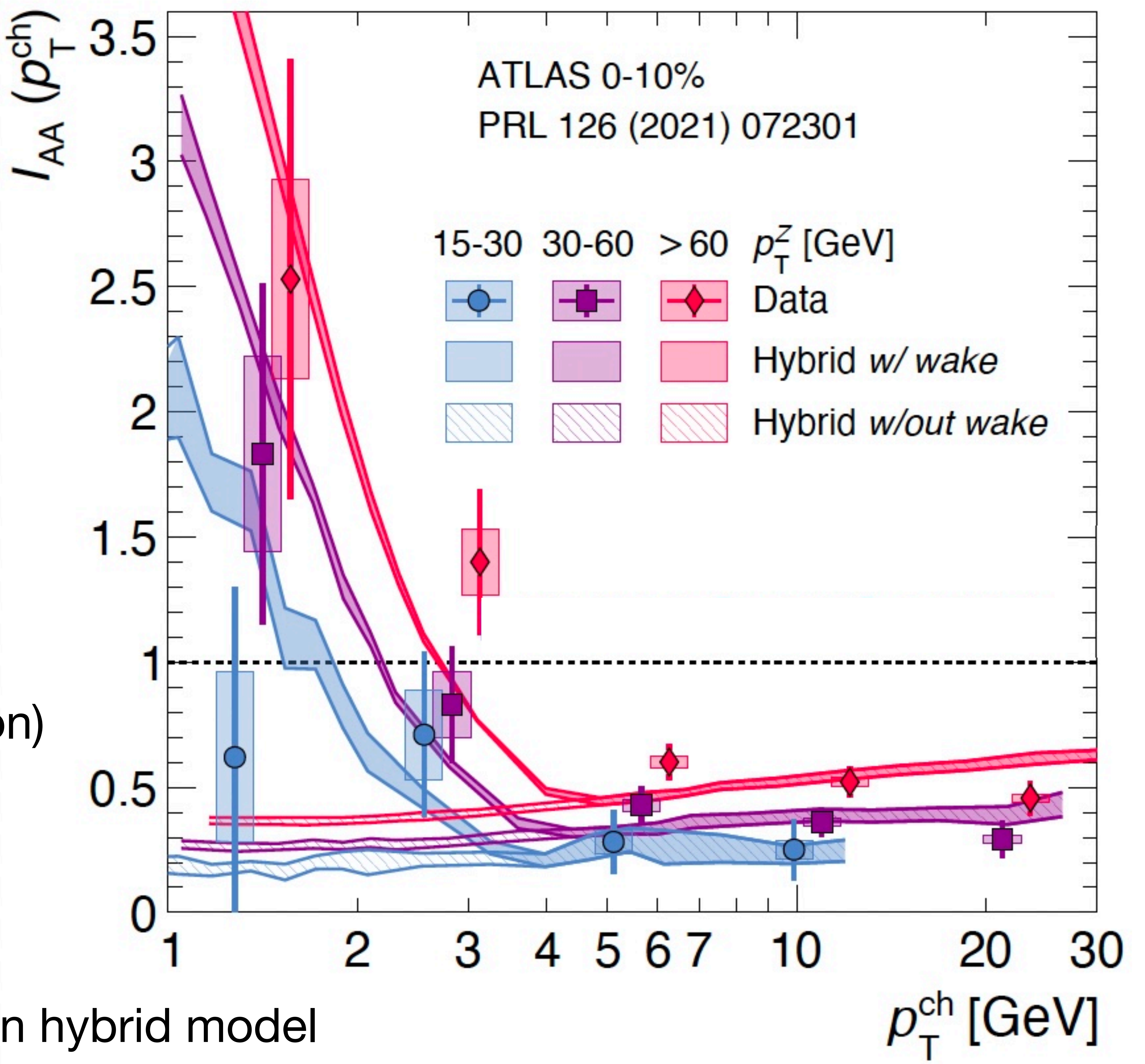


Increasing quark-jet fraction

Charged particles recoiling against a Z

$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi} \qquad I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$



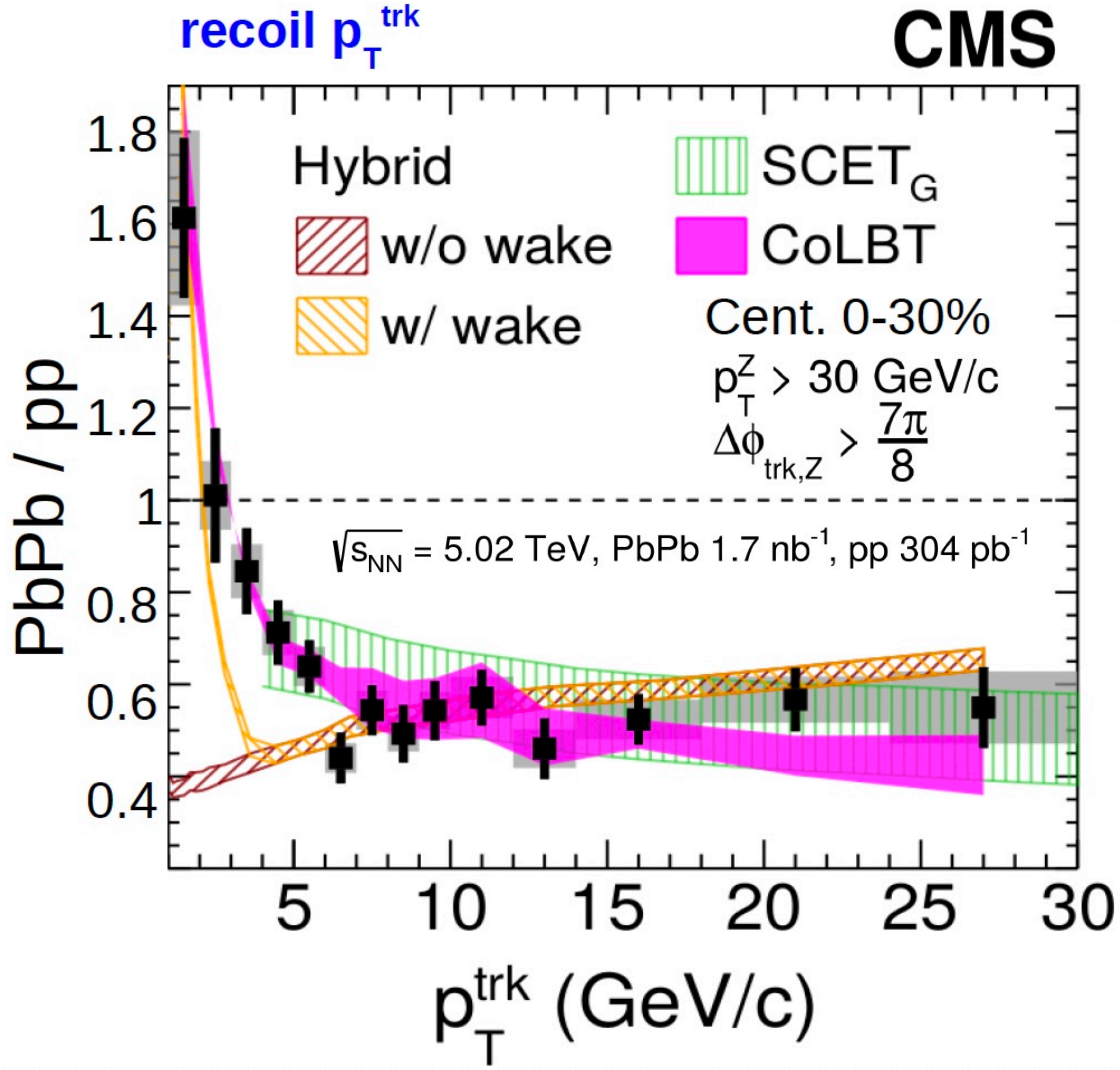


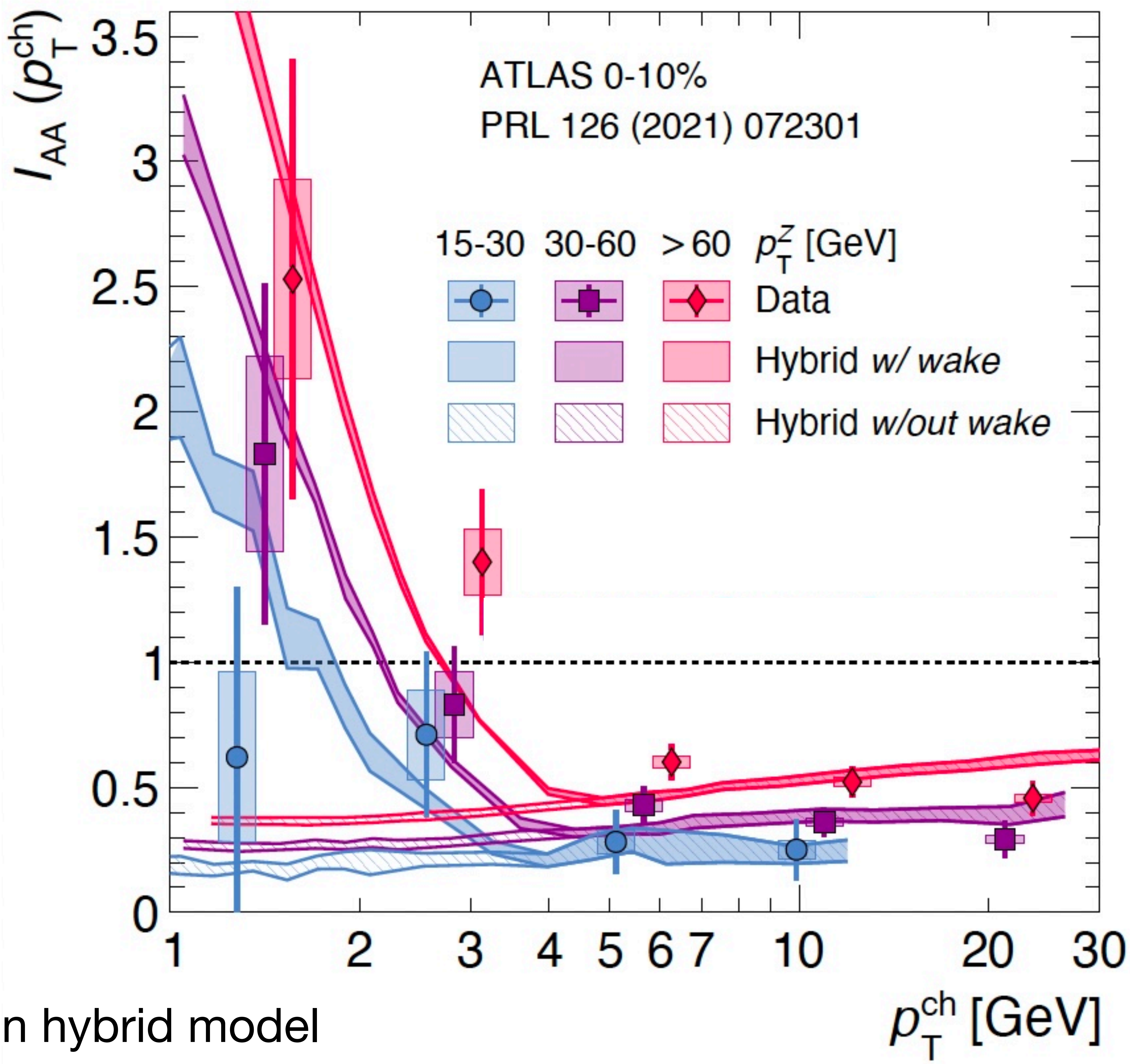
- Charged particles opposing Z (no jet reconstruction) → understanding modification of jet constituents and jet fragmentation functions

- Uprise at low p_T described by medium response in hybrid model

Charged particles recoiling against a Z

CMS PRL 128 (2022) 122301





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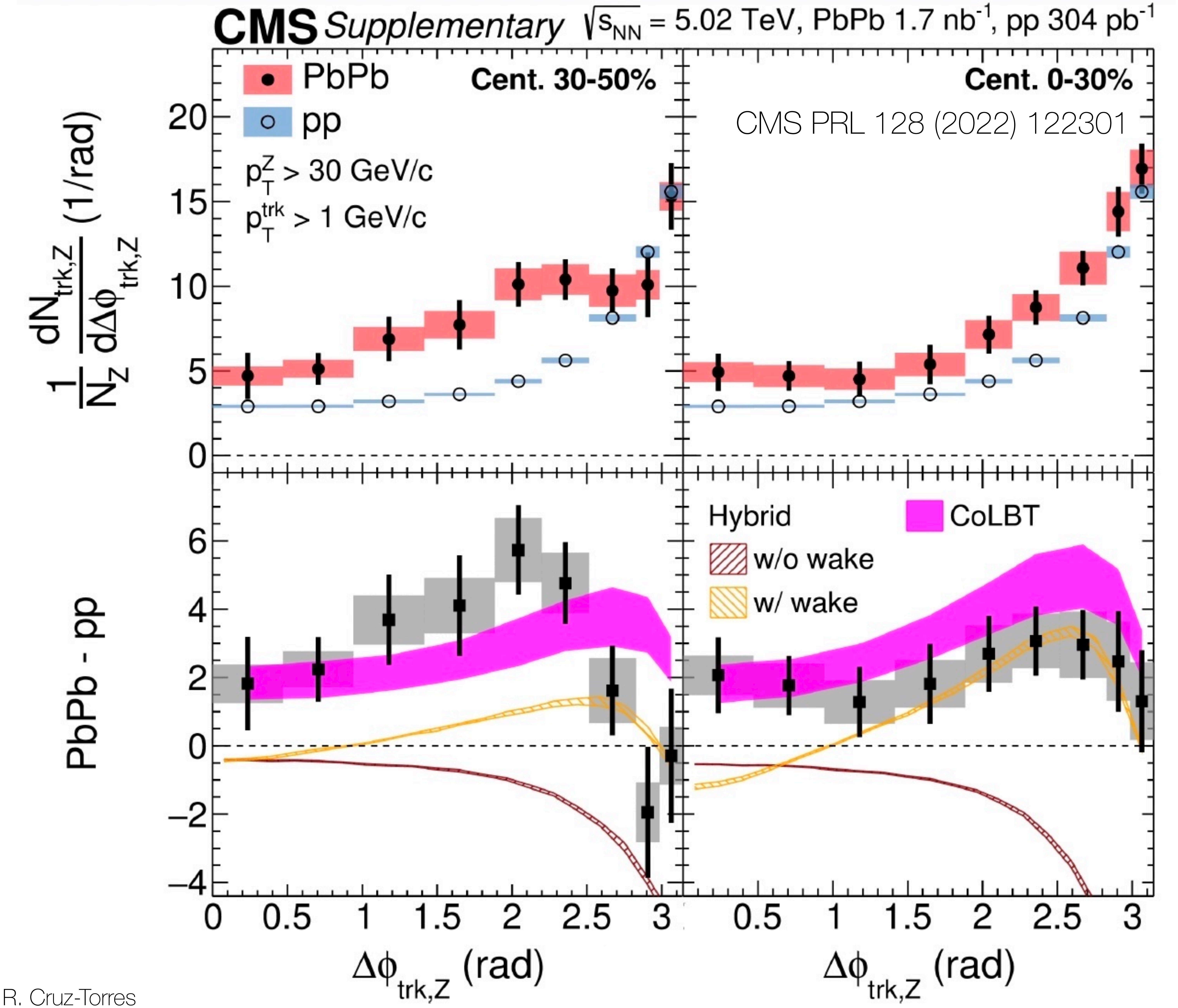
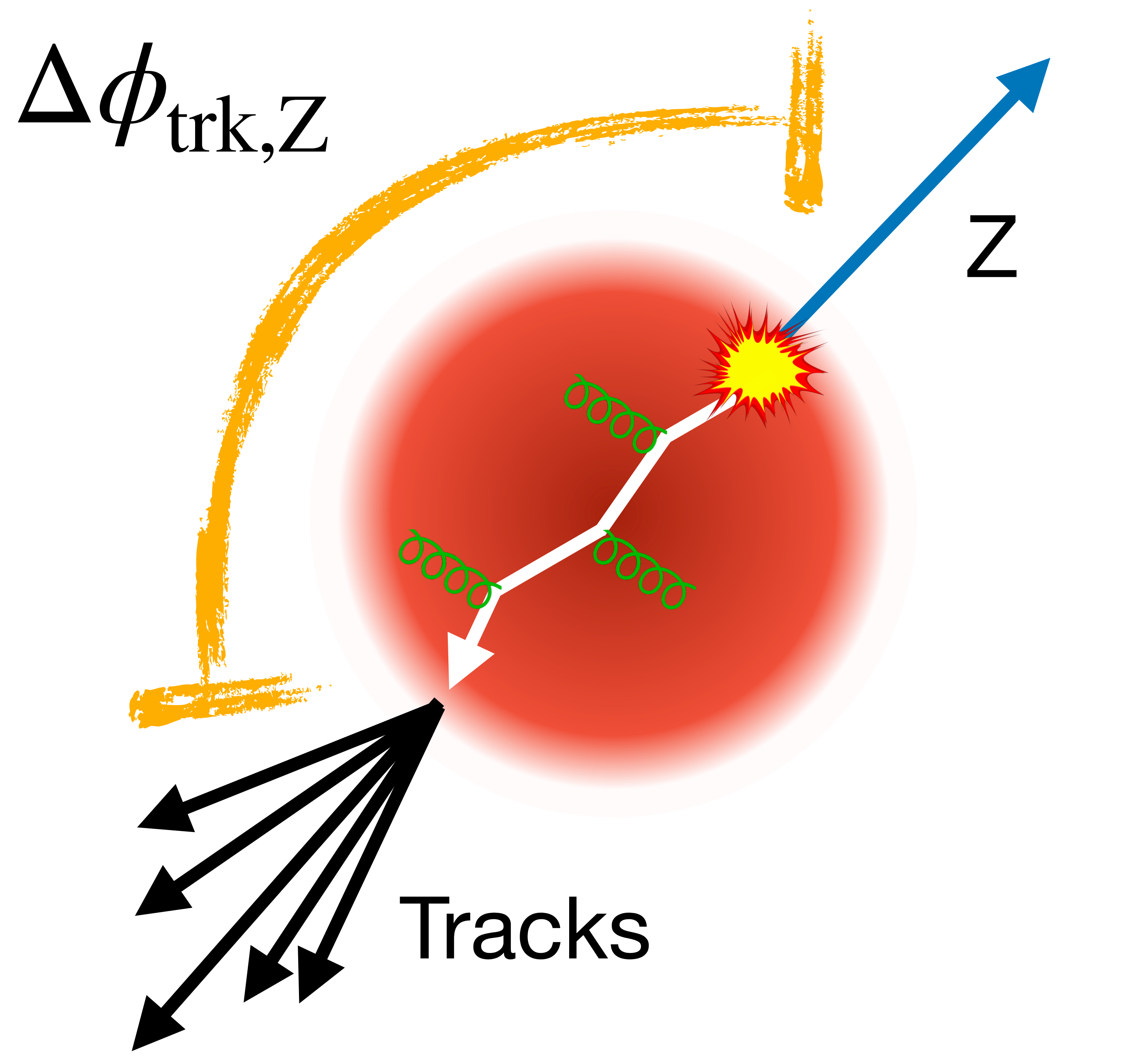
Charged particles recoiling against a Z



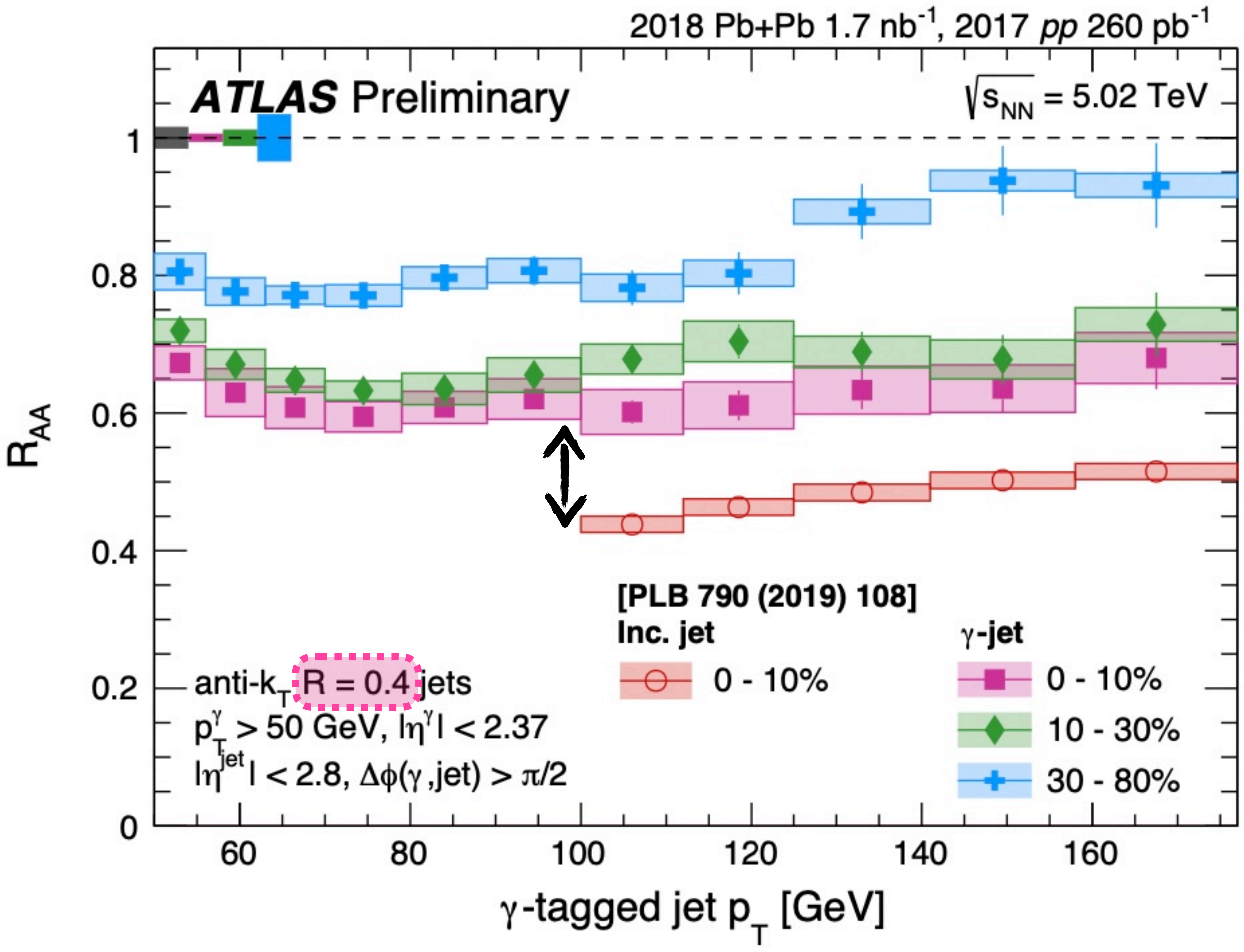


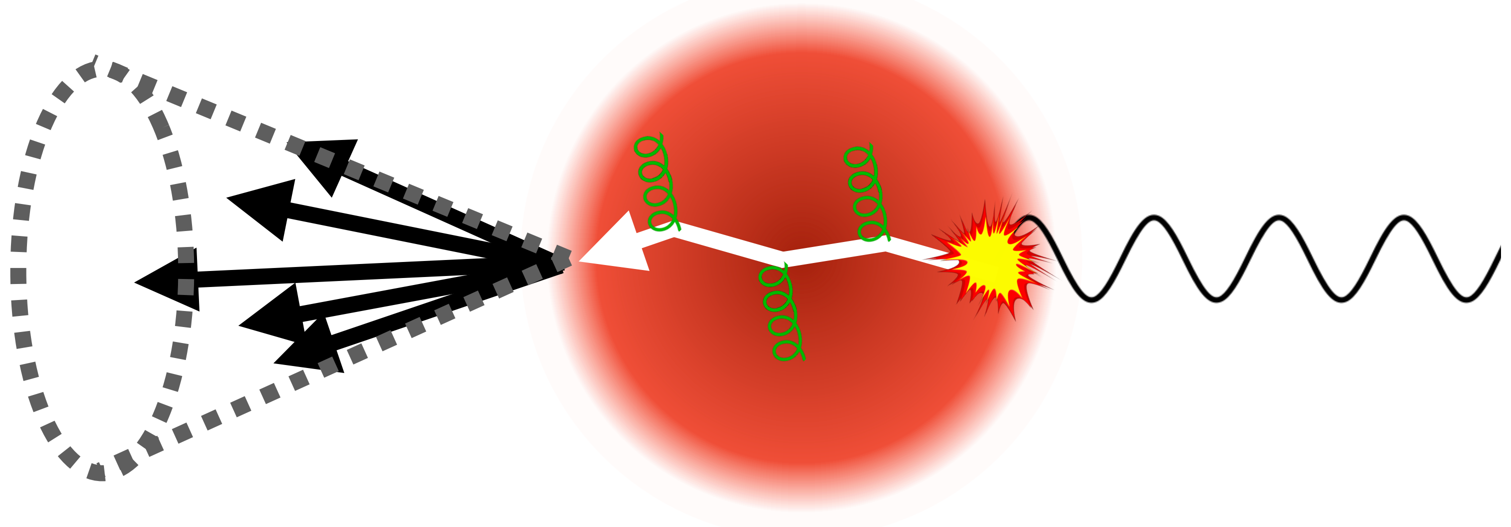
Modification down to $\phi^{\mathrm{trk}} \approx \phi^{Z}$

Qualitative agreement with models with medium response

Color-charge dependence of R_{AA}

ATLAS-CONF-2022-019

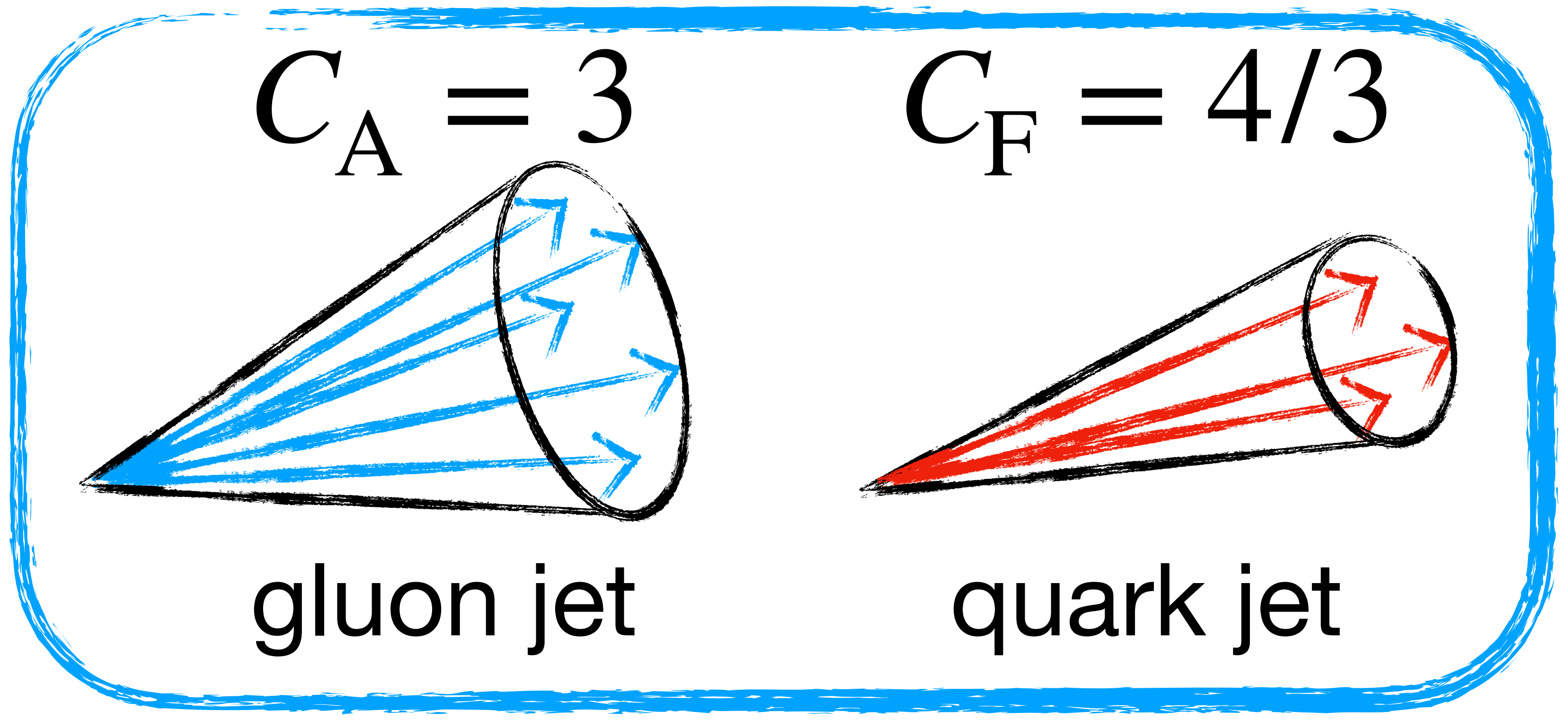




Photon-tagged (quark-enhanced) jets significantly less suppressed than inclusive (gluon-enhanced) jets

Quark enhanced

Gluon enhanced



Gluon jets more active than quark jets → color factor dependence of parton-medium interaction

Summary

- Study of jets → fertile and active field at the LHC
- Many new measurements based on **LHC Run 2** (many more not covered here)
- New tools (e.g. ML) being incorporated
- Constraints on models of energy loss and medium resolution length
- Results consistent with g jets more active than q jets in the QGP
  - Narrowing of angular substructure
  - Color-charge dependence of R_{AA}
- Effects from the medium response
- First evidence of broadening of Z-jet and h-jet azimuthal correlations for soft jets
- Entering era of jet precision studies
- Results used to extract medium properties (e.g. $\hat{q}$, viscosities, …)
- Some results are still to be understood → **ongoing studies** + **LHC Run 3**!

Thanks for your attention!

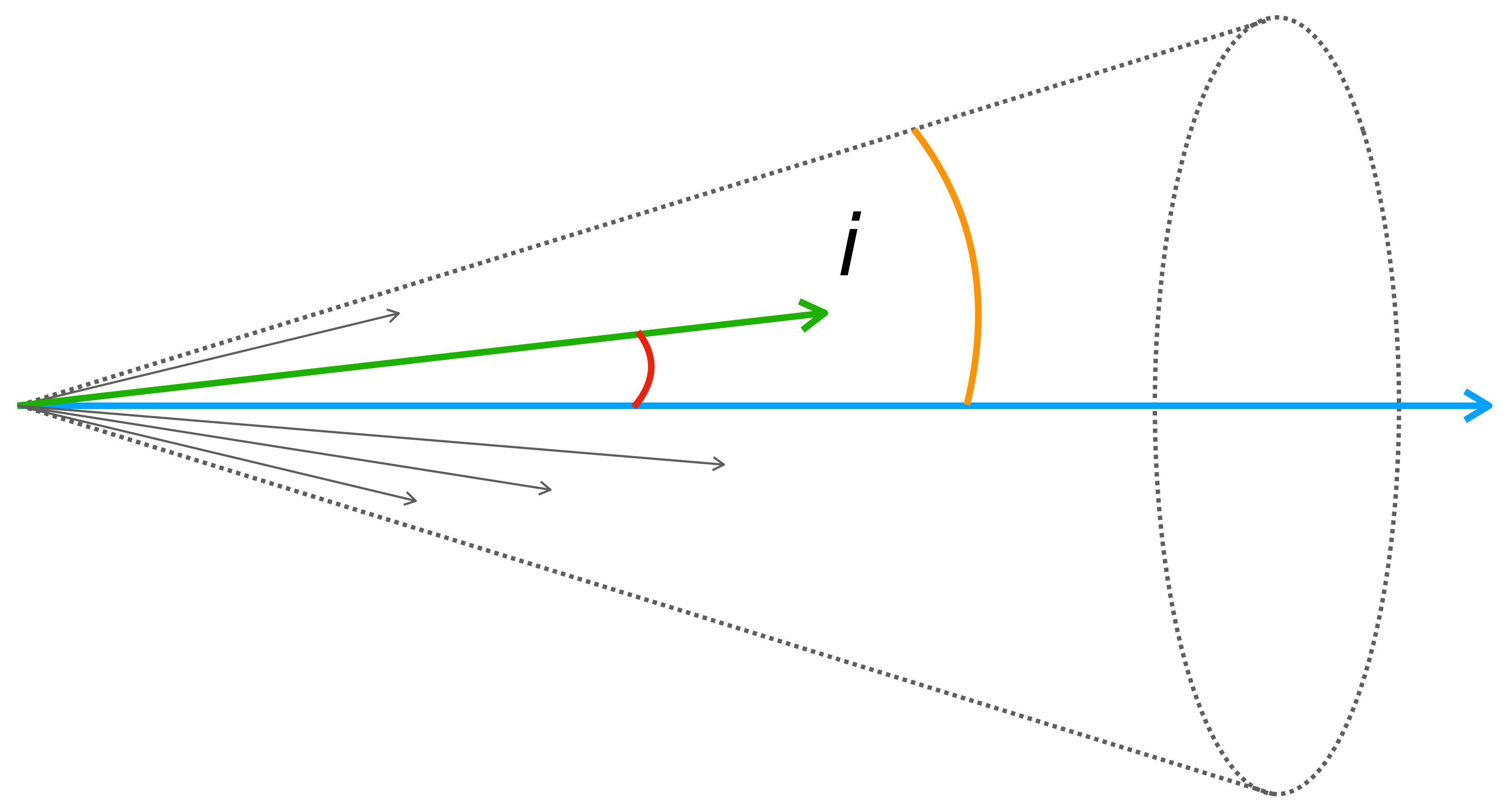
Backup

Jet angularities

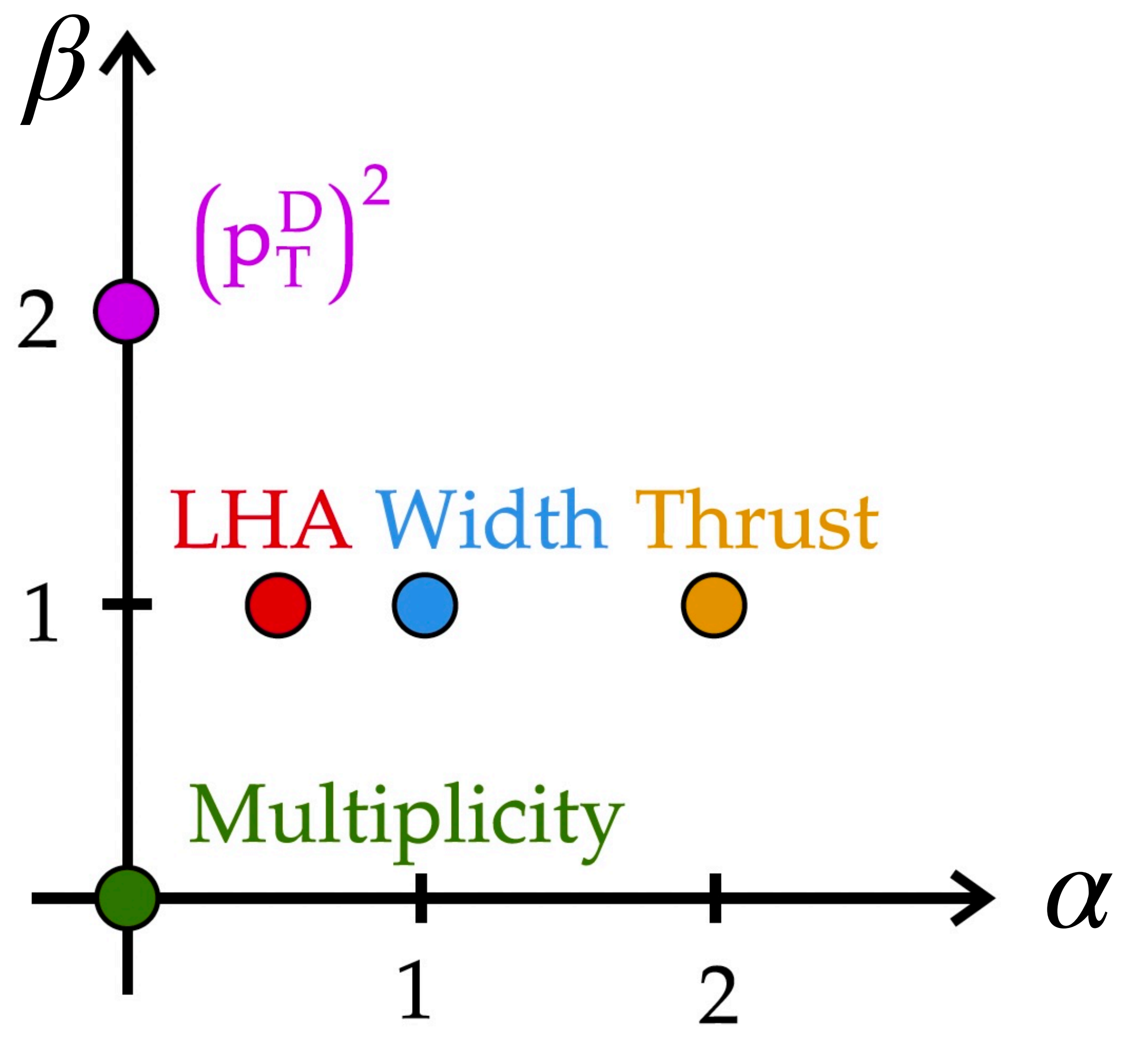
Includes both transverse-momentum and angular components with relative weights given by continuous parameters α, β

$$\lambda_\alpha^\beta \equiv \sum_{i \in \mathrm{jet}} \left(\frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}}\right)^\beta \left(\frac{\Delta R_{\mathrm{jet},i}}{R}\right)^\alpha$$

$\alpha > 0 \rightarrow$ IRC-safe observable



Examples of jet angularities:



Groomed angularities ($\lambda_{\alpha,g}^\beta$): same expression as λ_α^β but sum only runs over constituents of groomed jet

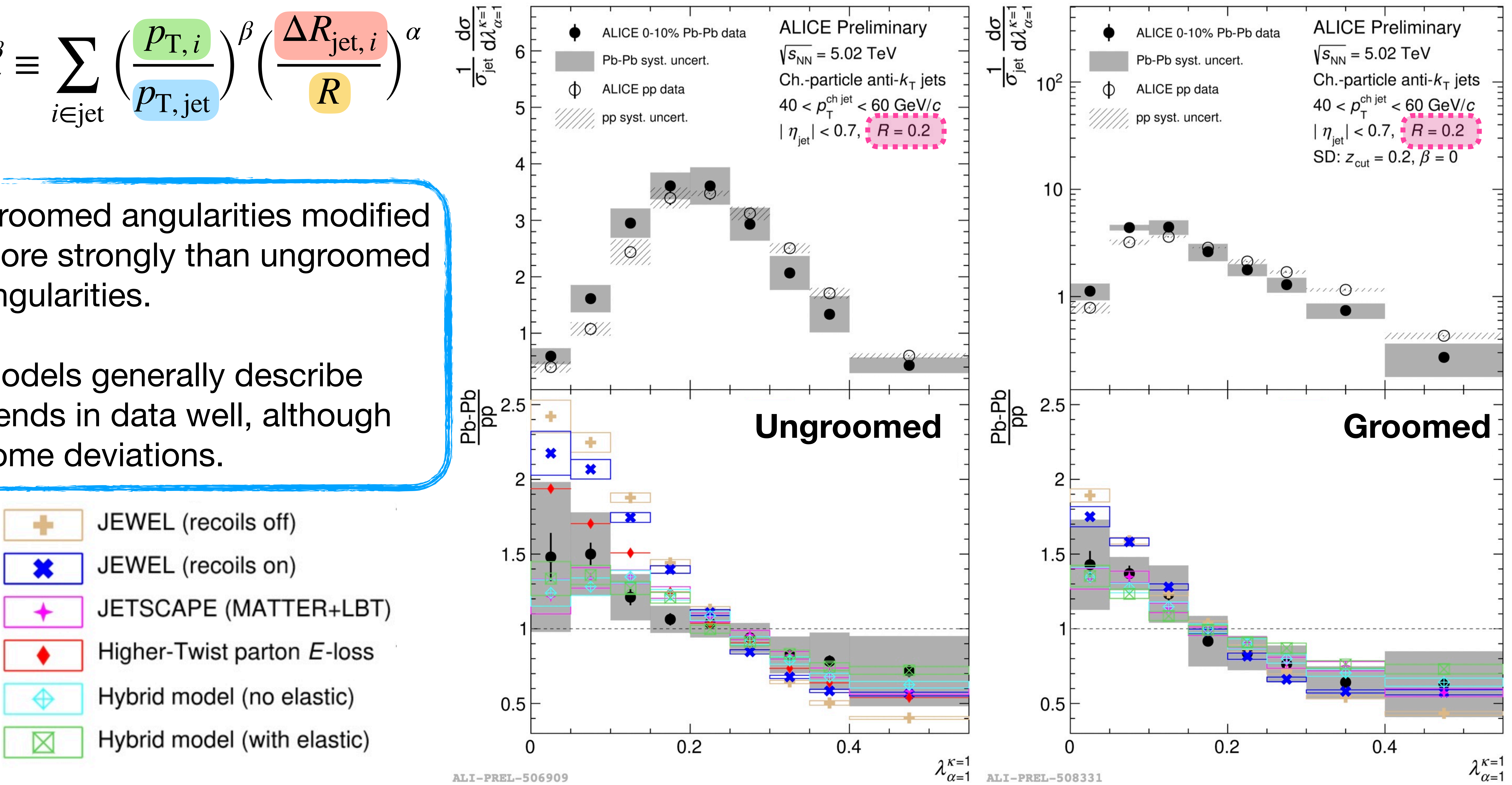
systematic variation of α, β to test pQCD calculations and universality of non-perturbative shape functions.

Jet angularities

$$\lambda_\alpha^\beta \equiv \sum_{i\in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)^\beta \left(\frac{\Delta R_{\text{jet},i}}{R}\right)^\alpha$$

- Groomed angularities modified more strongly than ungroomed angularities.

- Models generally describe trends in data well, although some deviations.



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

$$n \equiv \frac{1}{N_{\rm trig}^{\rm AA}} \frac{d^2 N_{\rm jet}^{\rm AA}}{dp_{\rm T,ch}^{\rm jet} d\eta_{\rm jet}} \equiv \frac{1}{\sigma^{\rm AA\to h+X}} \frac{d^2\sigma^{\rm AA\to h+jet+X}}{dp_{\rm T,ch}^{\rm jet} d\eta_{\rm jet}}$$

Perturbatively-calculable observable

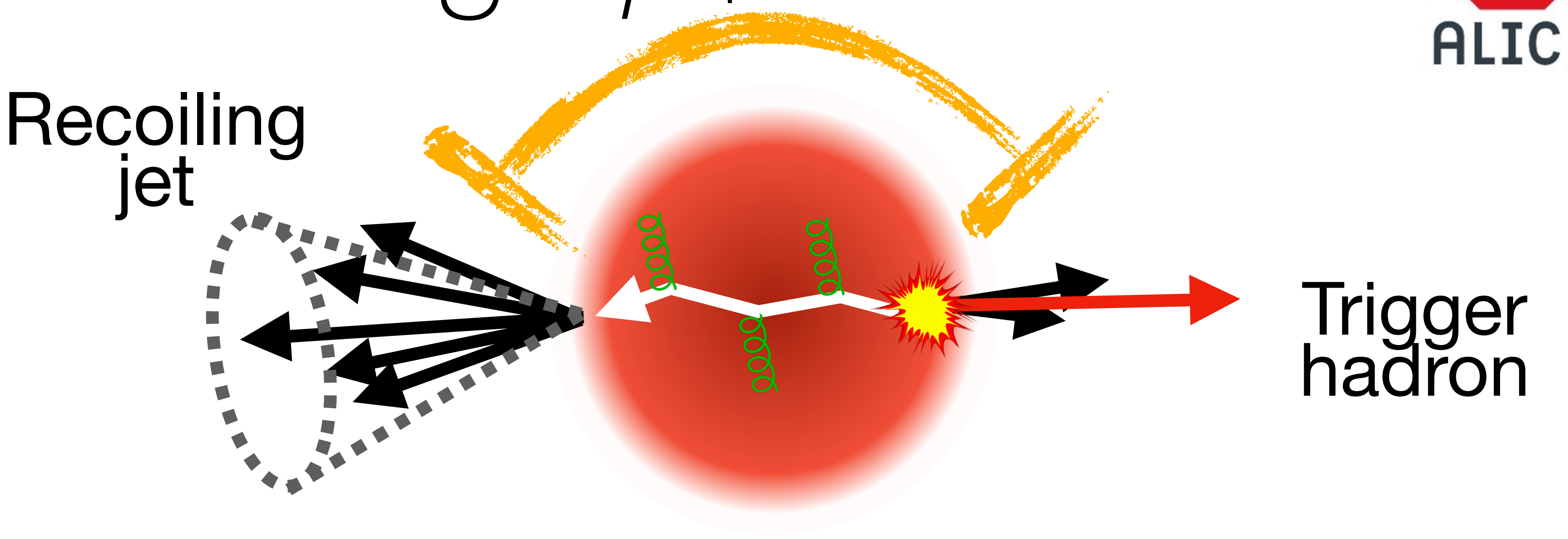
Chen et al., PLB 773 (2017) 672

Statistical background subtraction:

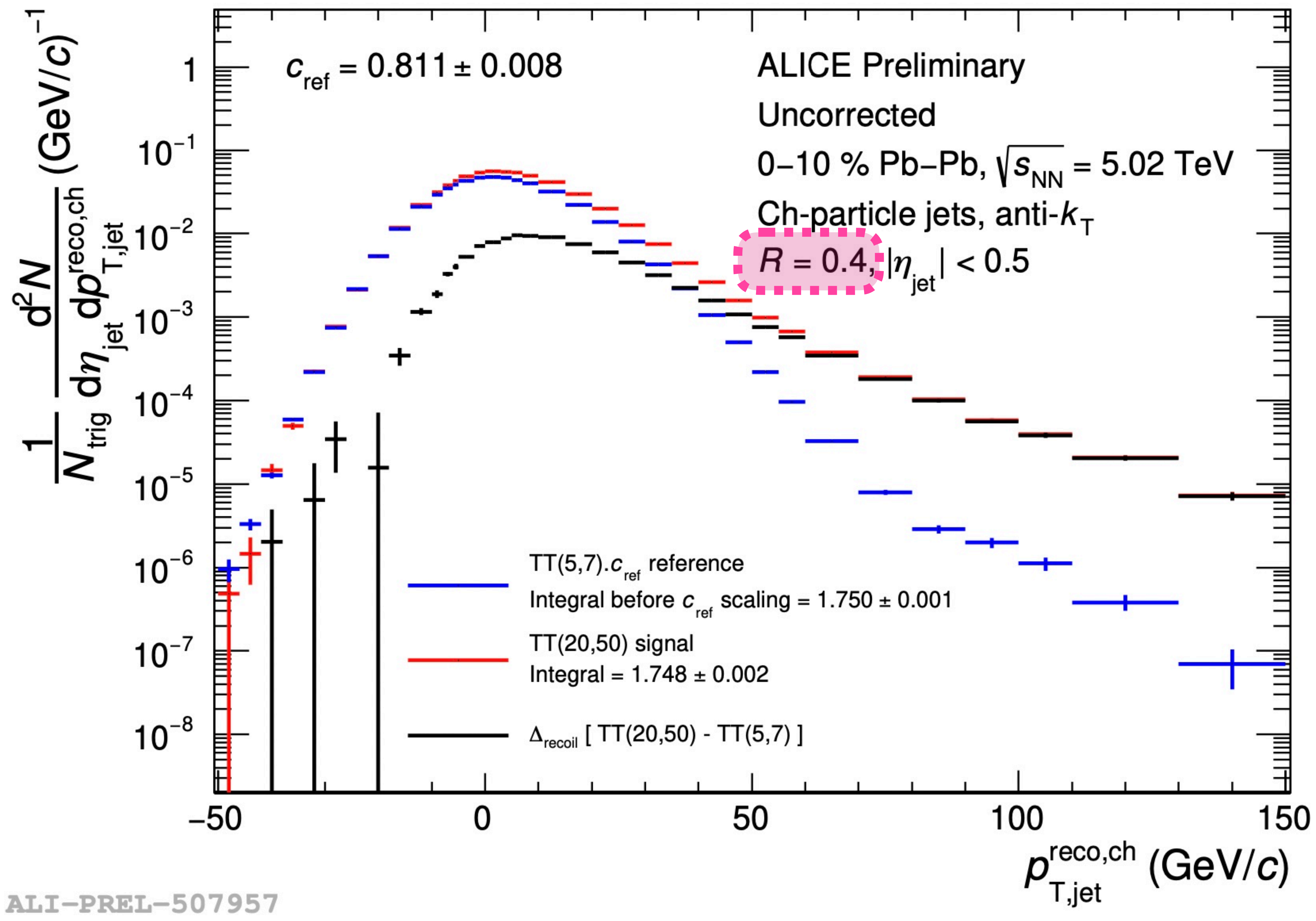
Data-driven subtraction of uncorrelated background (including MPI) by taking difference between signal and reference spectra measured in two exclusive trigger track classes:

$$\mathrm{TT_{Sig}} : 20 < p_{\rm T,\,trig} < 50\ \mathrm{GeV}/c$$
$$\mathrm{TT_{Ref}} : 5 < p_{\rm T,\,trig} < 7\ \mathrm{GeV}/c$$

$$\Delta_{\rm recoil} = n(\mathrm{TT_{Sig}}) - c_{\rm Ref} \cdot n(\mathrm{TT_{Ref}})$$

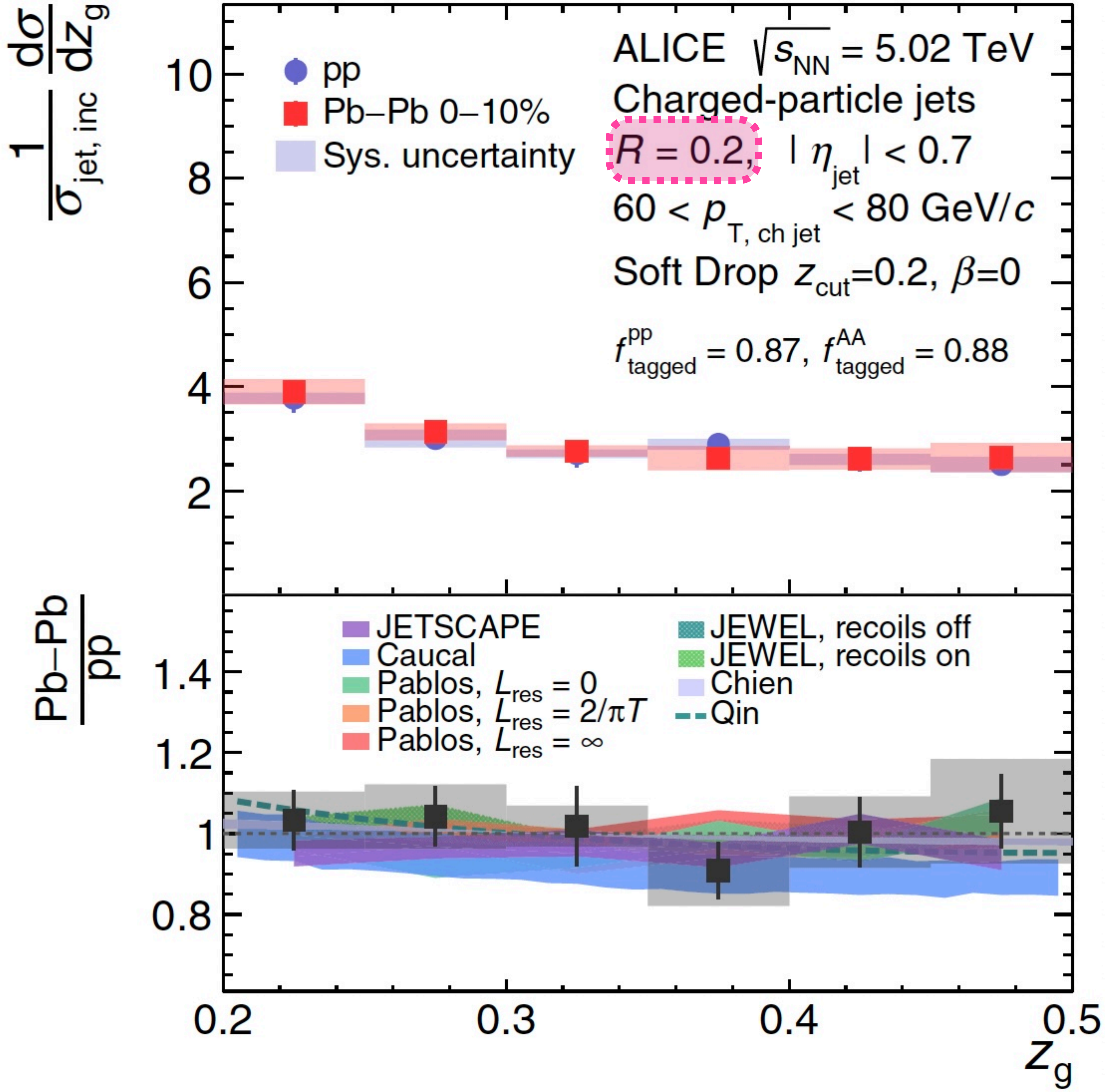


anti-k_T charged jets (R = 0.2, 0.4)



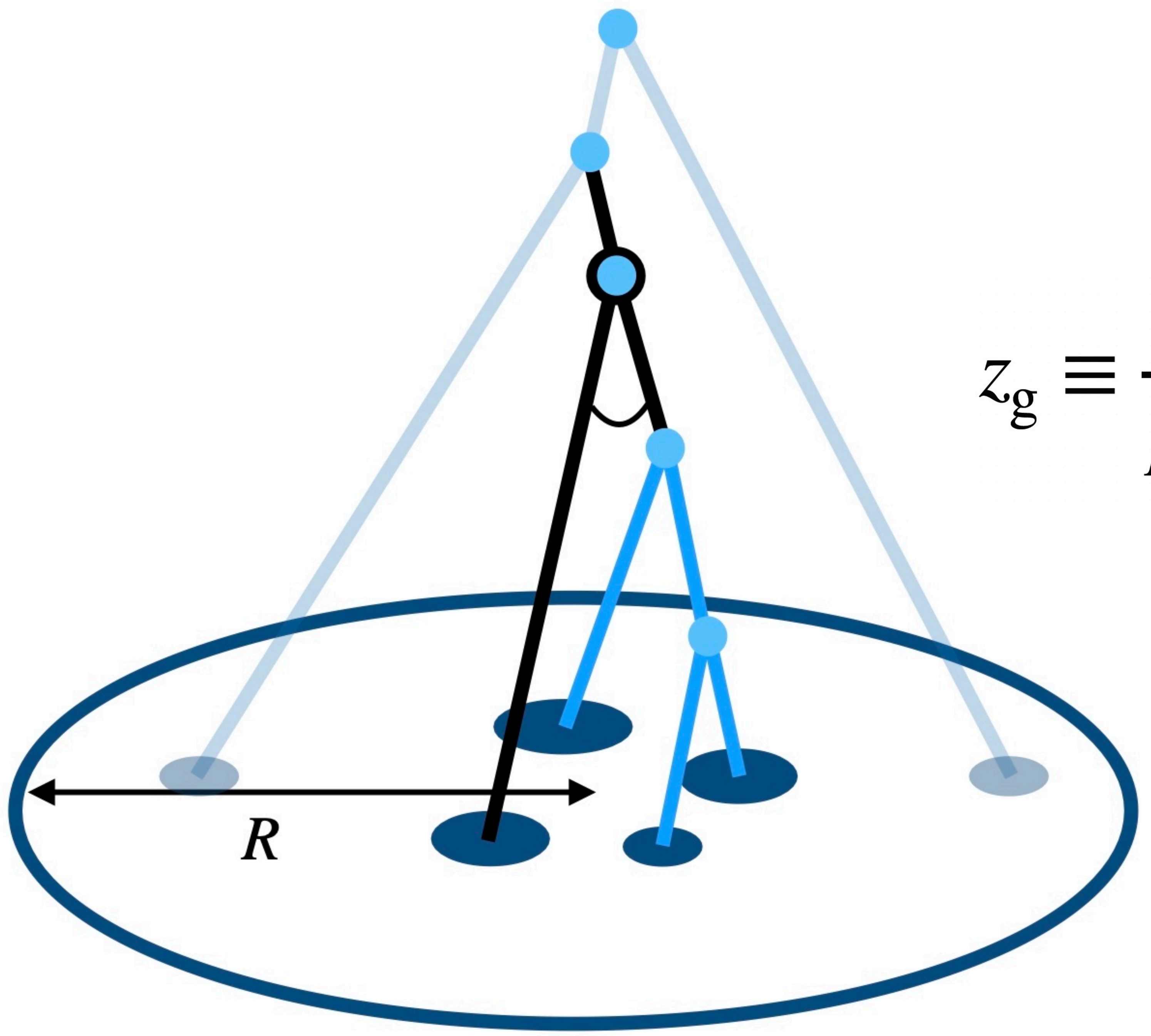
Method allows for measurement down to low p_T and high R

Groomed momentum fraction



Properties of the "first hard"* splitting of a jet

* first splitting surviving grooming

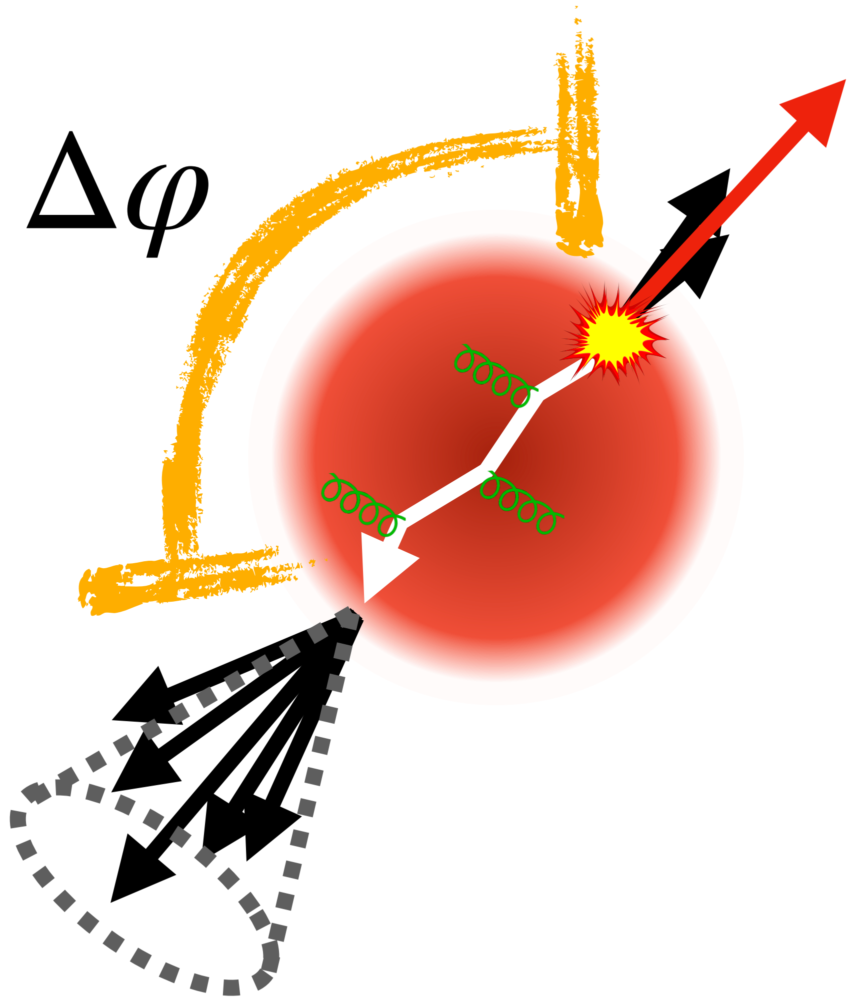


$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

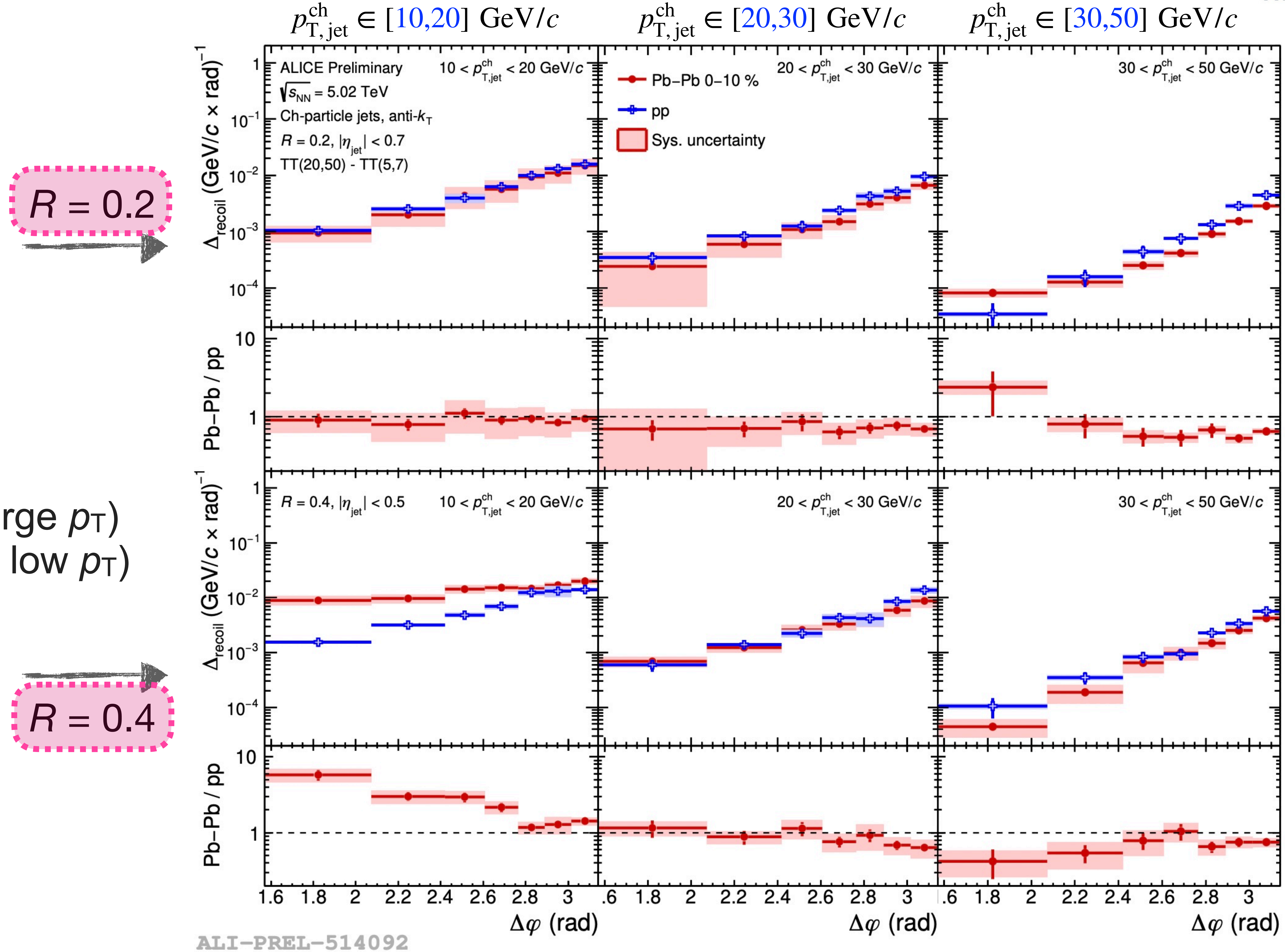
No significant modification in z_g distribution

Consistent with models

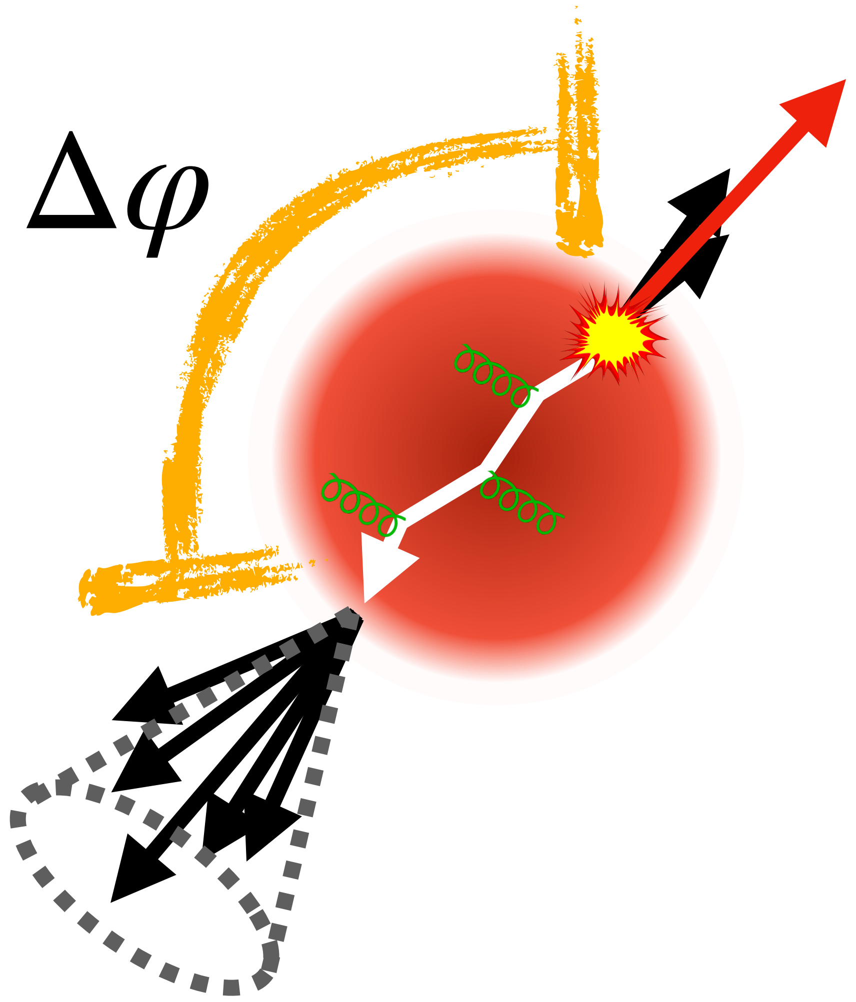
$\Delta\varphi$ results - angular deflections

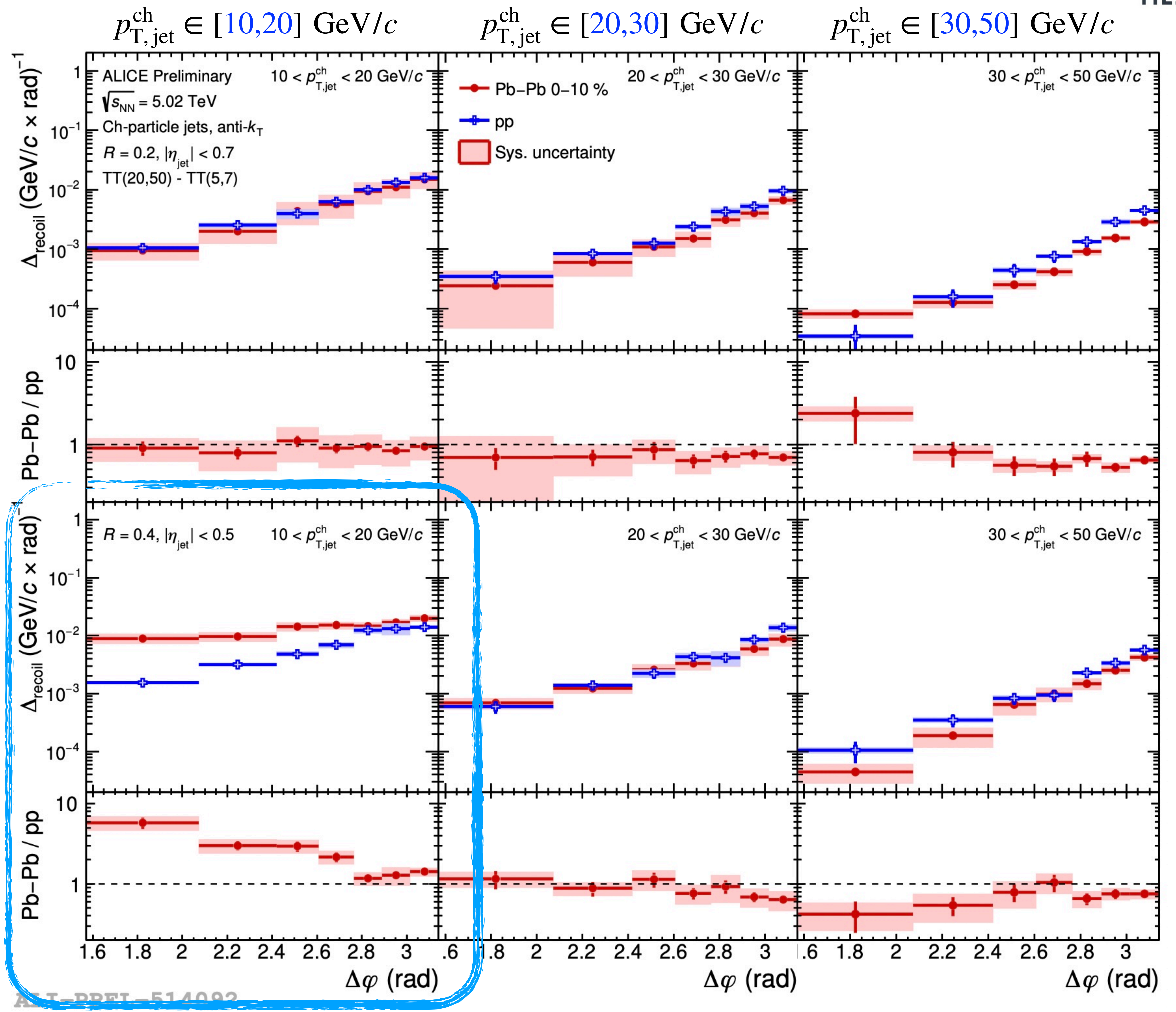


span wide kinematics:
- no modification (small R, large p_T)
- large modification (large R, low p_T)



$\Delta\varphi$ results - angular deflections





R = 0.2

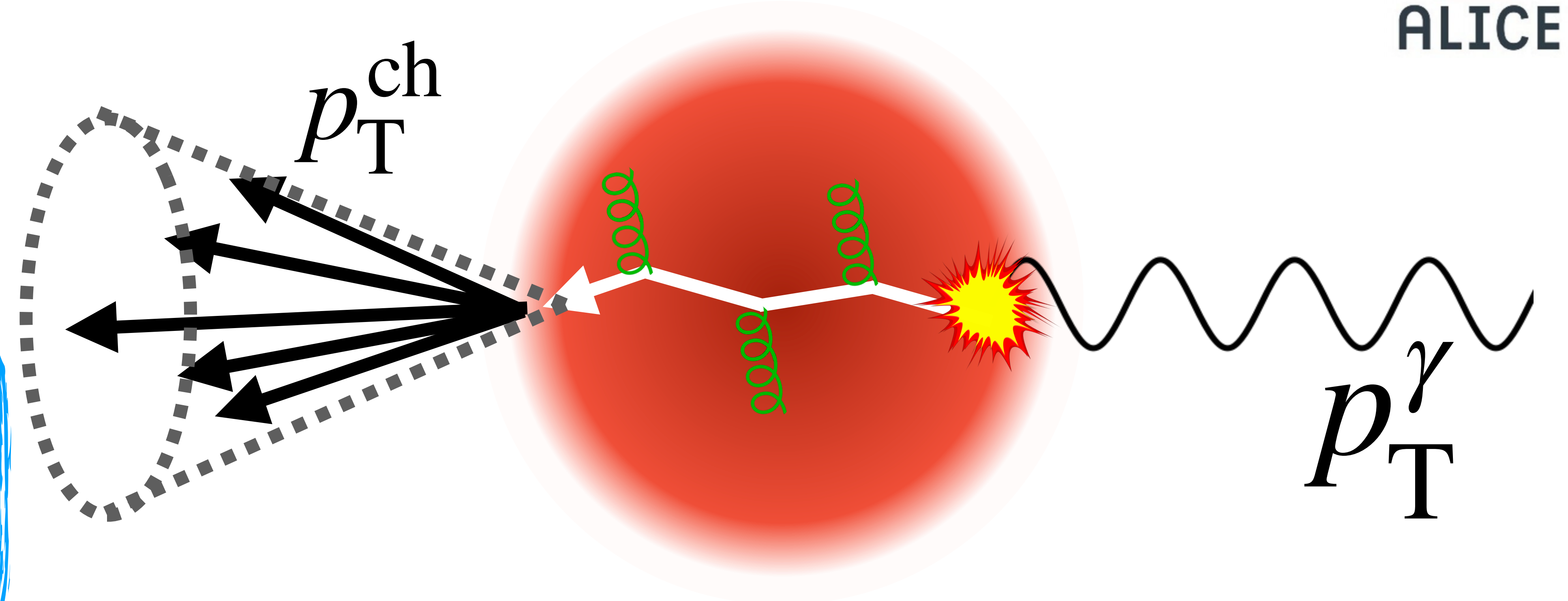
R = 0.4

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

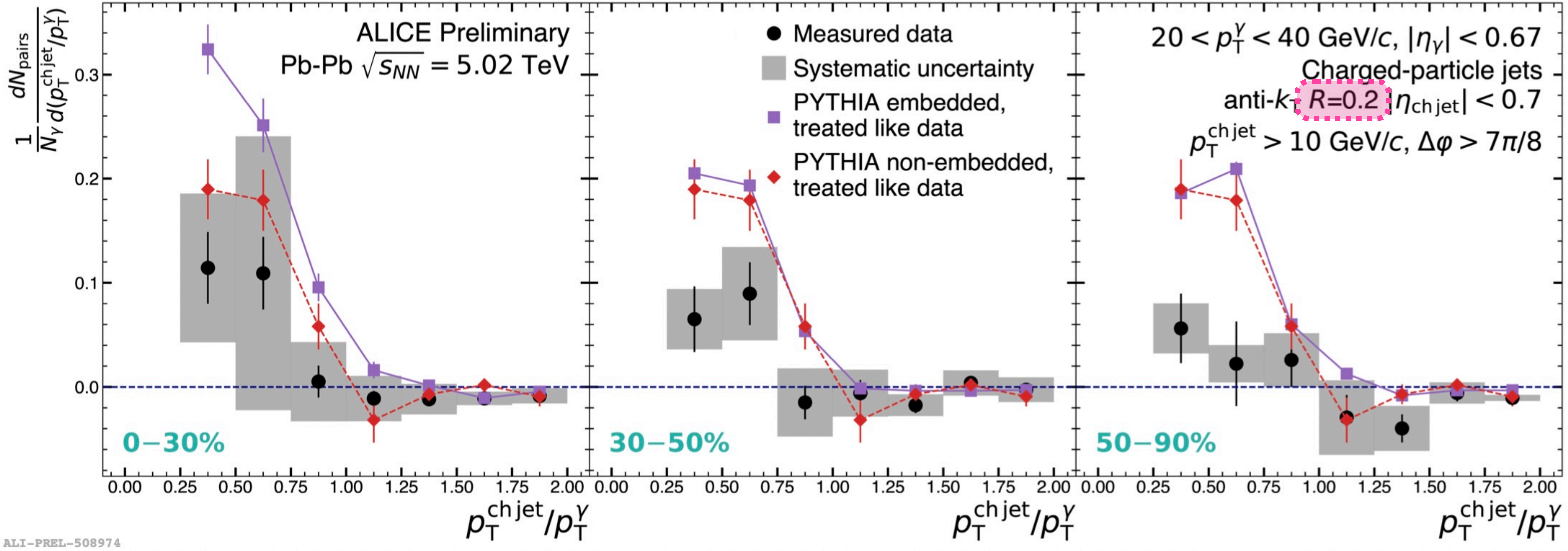
First evidence of broadening of h-jet azimuthal correlations for soft jets

Isolated photon-jet correlations

Momentum imbalance: $x_{j\gamma} \equiv p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\gamma}$

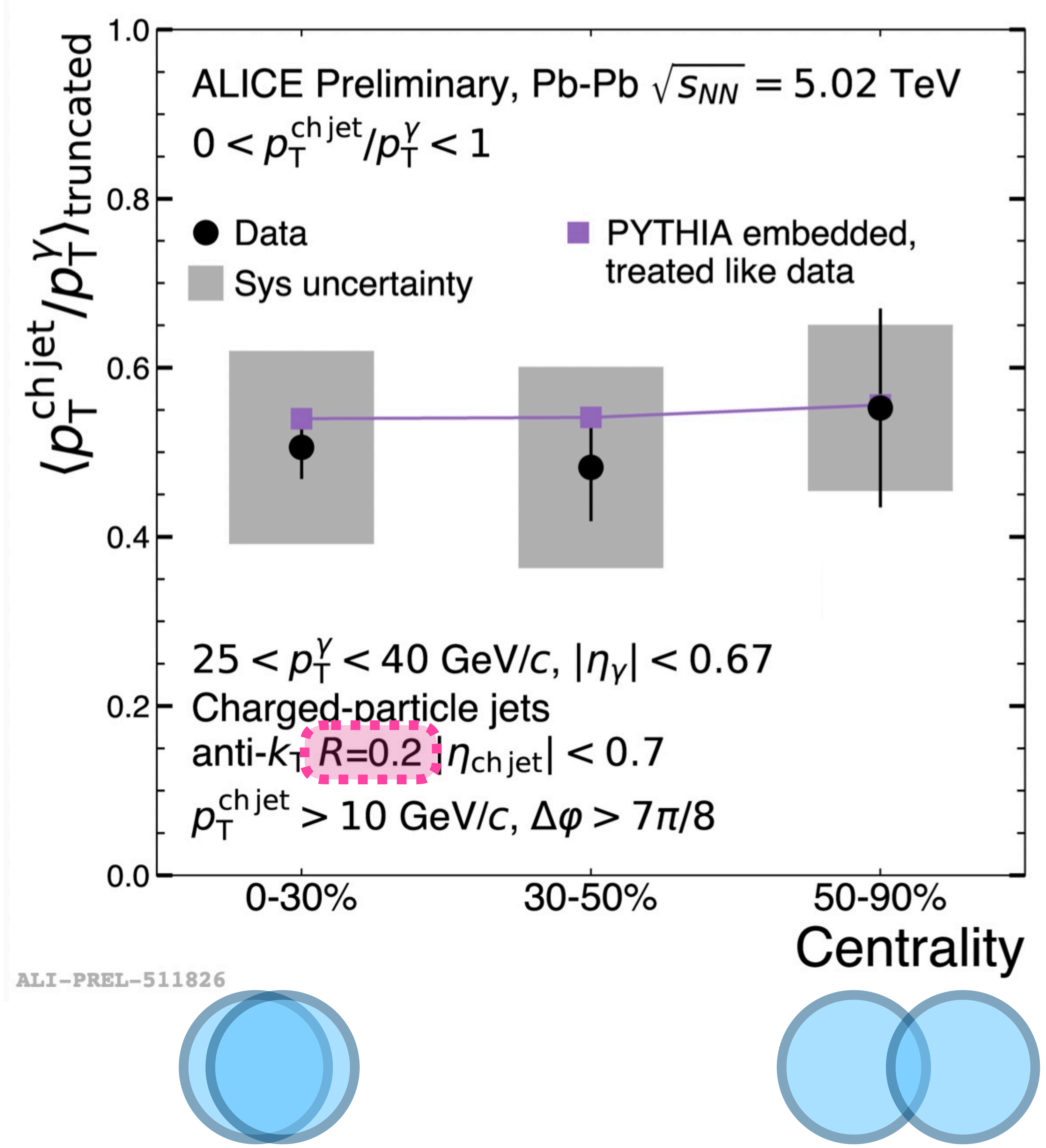


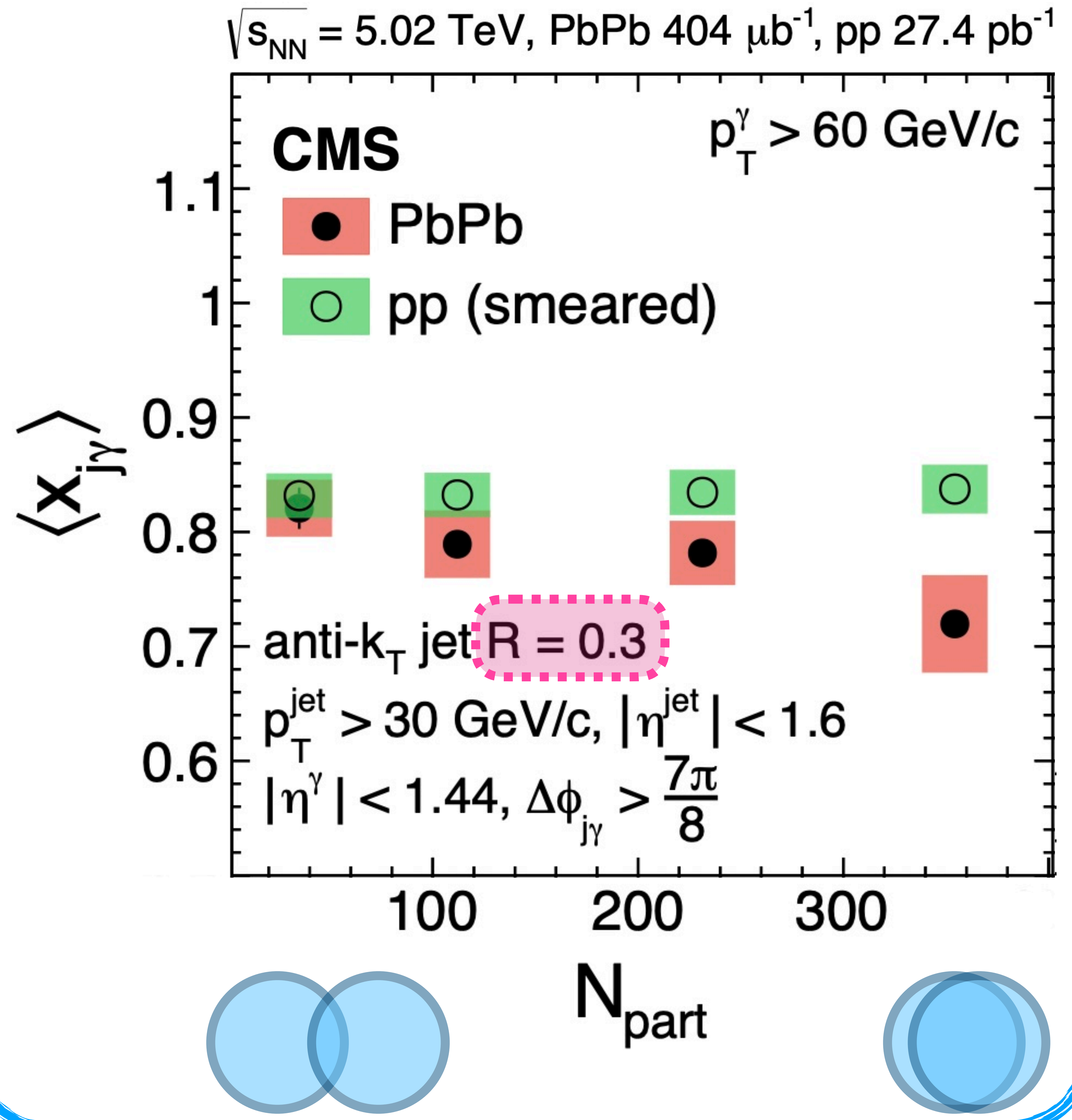
- Measurement down to $p_{\mathrm{T}}^{\gamma} = 20$ GeV (first at LHC)
- Shape difference in PYTHIA from detector effects
- No centrality dependence observed within uncertainties



Tension with previous result?

No centrality dependence observed within uncertainties





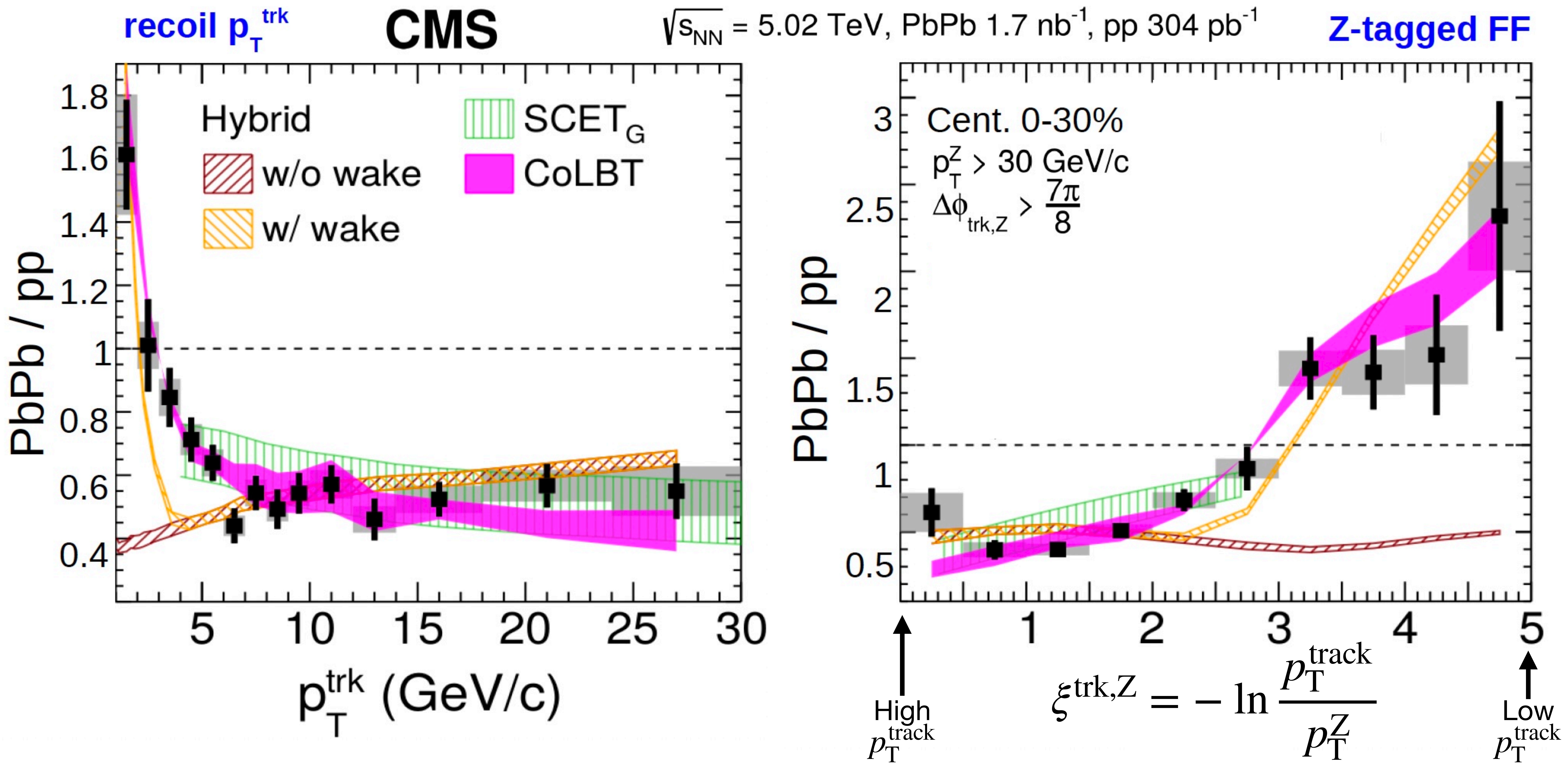
$$x_{j\gamma} \equiv p_T^{\rm jet}/p_T^{\gamma}$$

- Preliminary result
- No unfolding
- Slightly different kinematics

- Charged vs. full jets
- Ongoing work on systematics

Charged particles recoiling against a Z

CMS PRL 128 (2022) 122301



probe of longitudinal structure of parton shower inside the medium