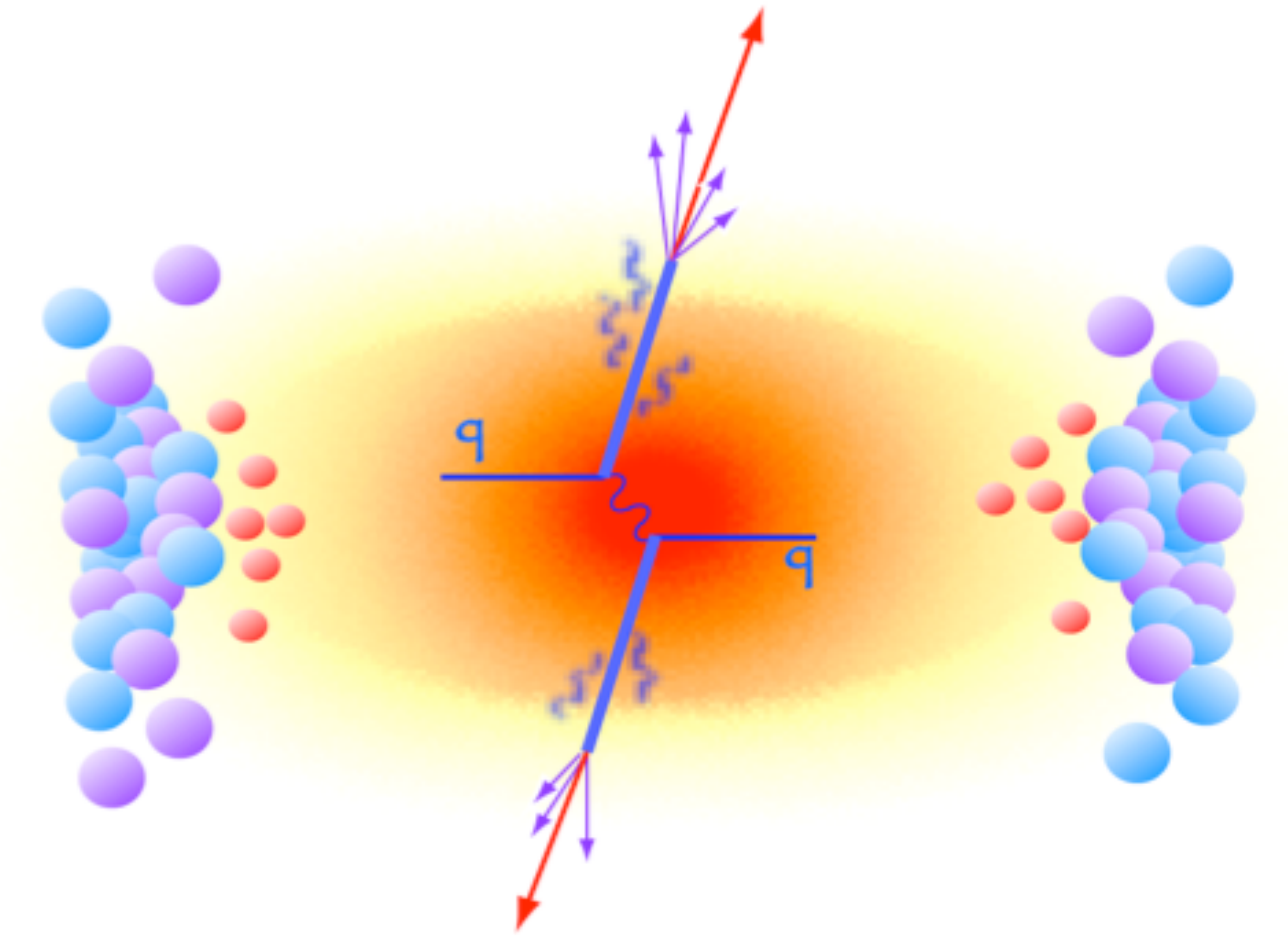
Experimental overview of jet physics
(喷注物理实验综述)



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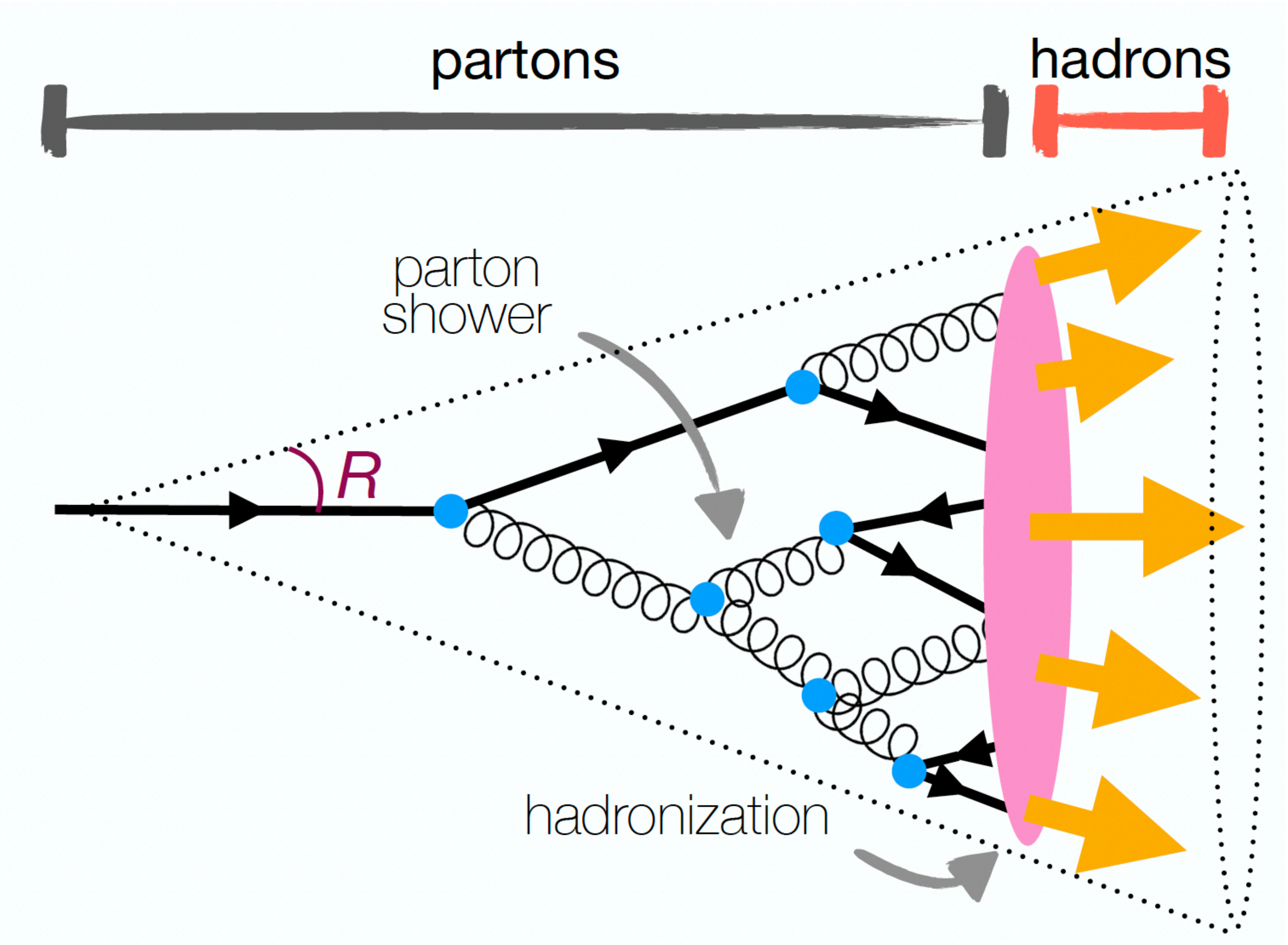
中国物理学会高能物理分会, 大连(Online), 2022/08/09

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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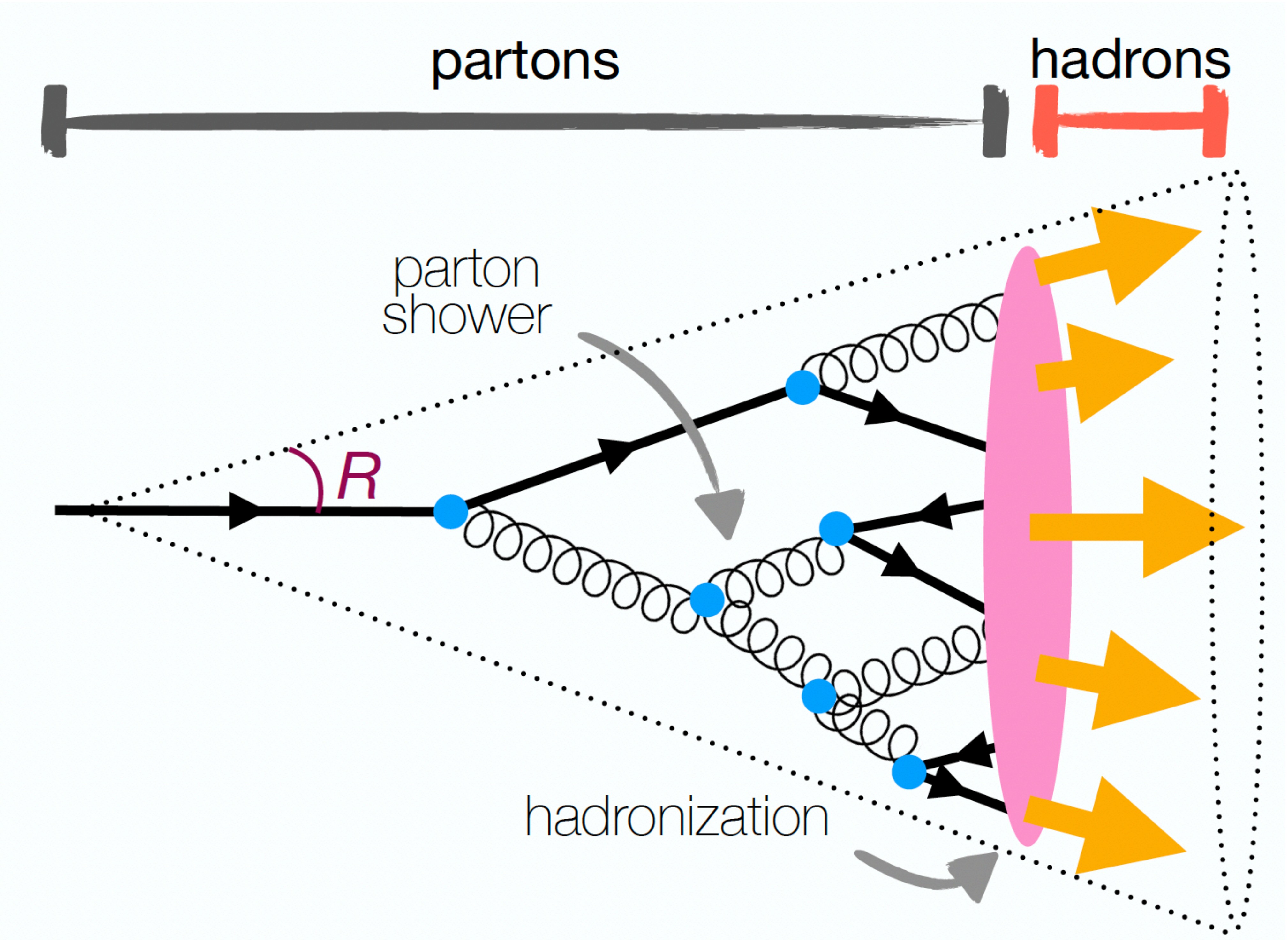
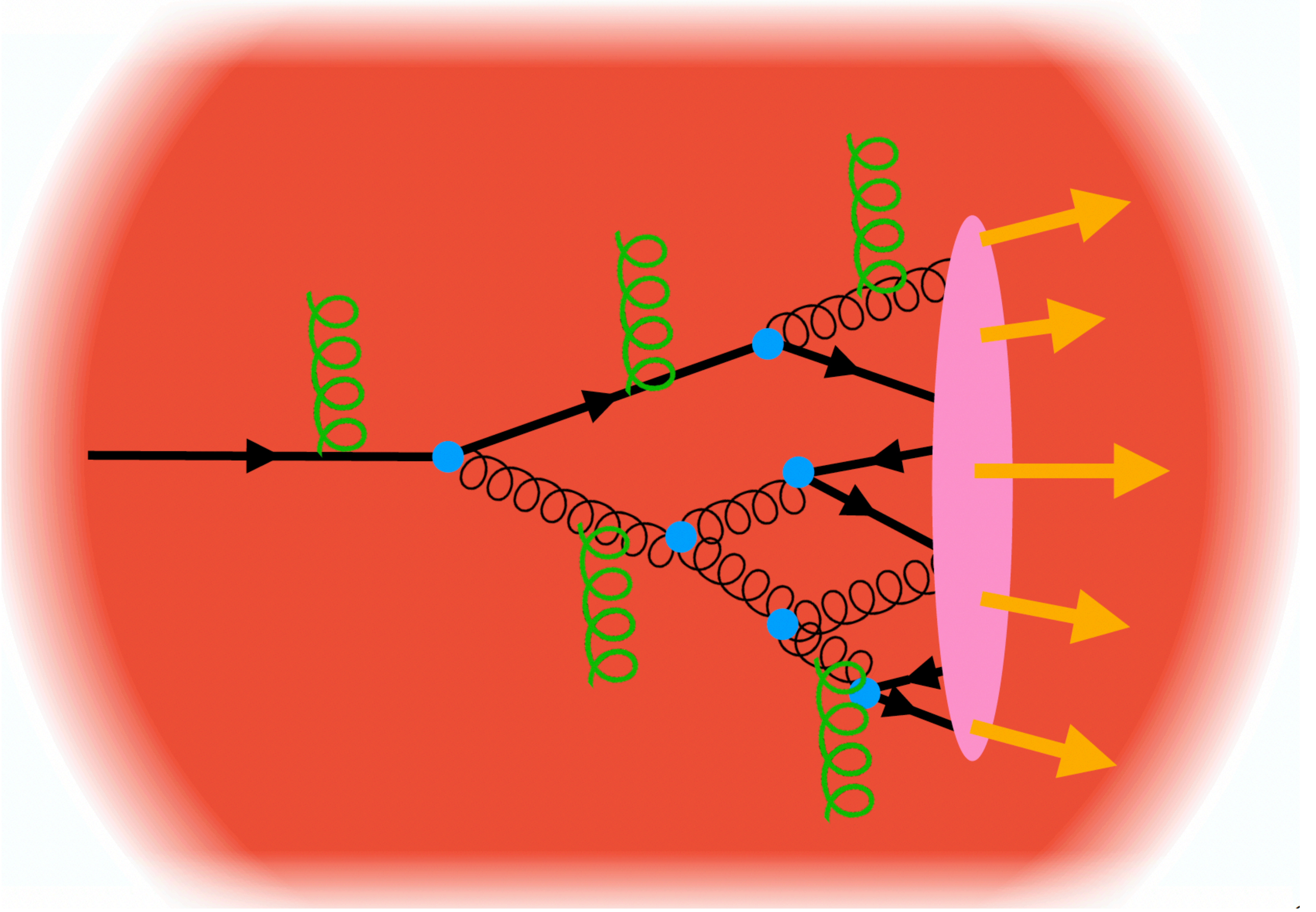


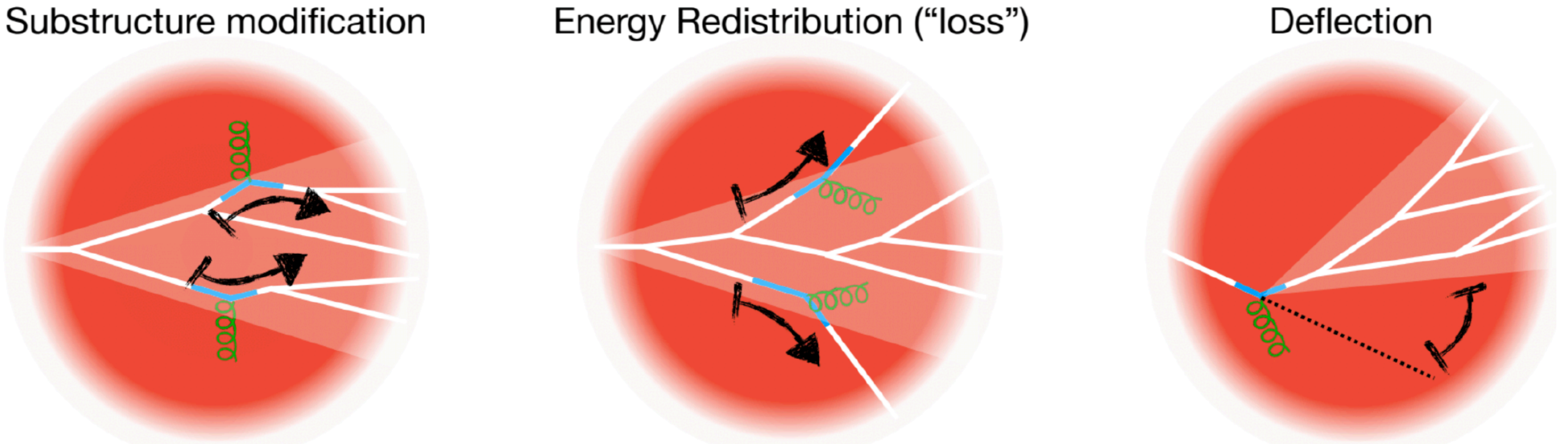
In-medium fragmentation (e.g. Pb-Pb collisions)

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



Jet quenching: an opportunity to study QGP

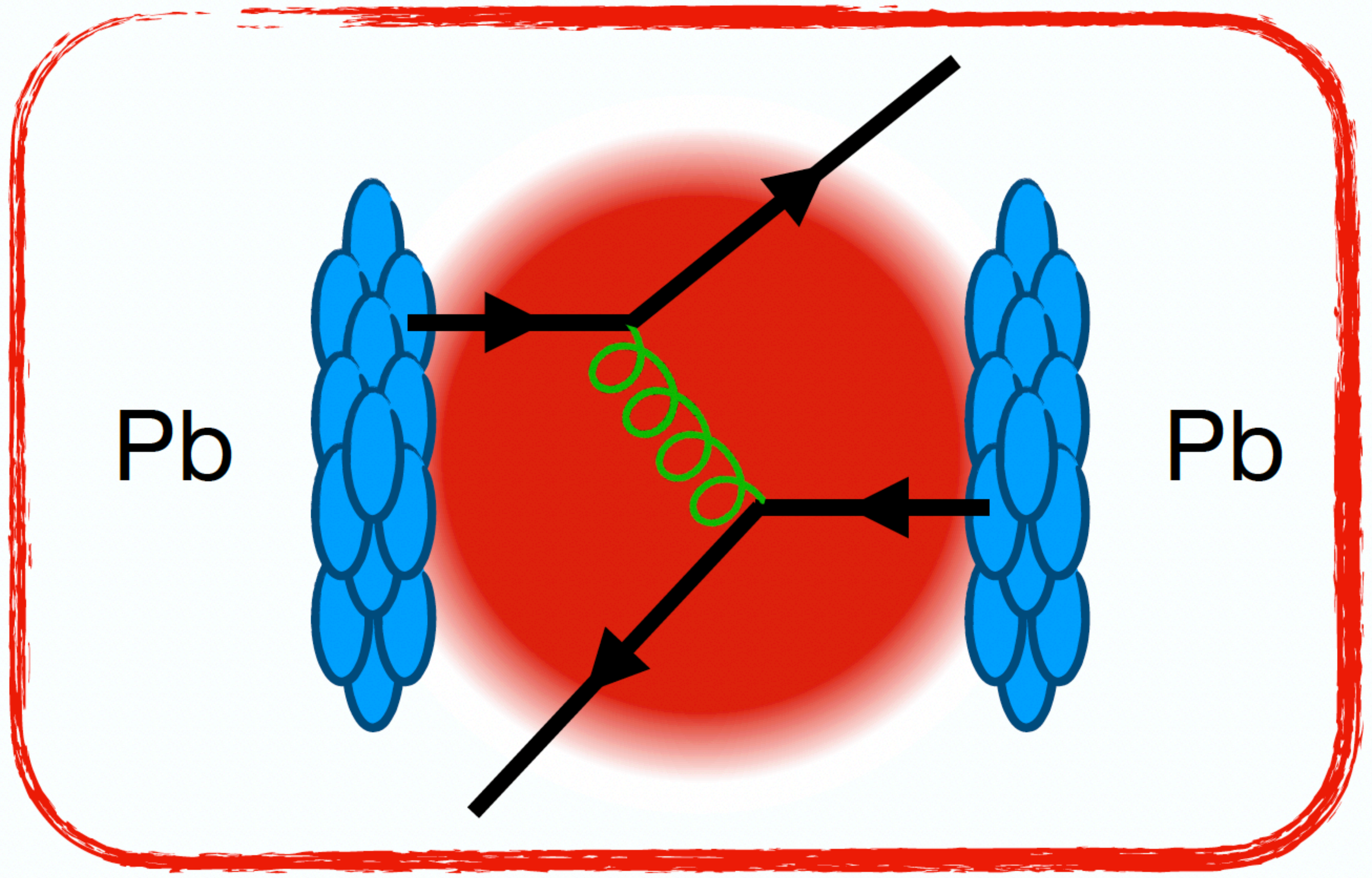
- Study structure of QGP by understanding jet modification from medium interaction (quenching)
- Several types of jet observables
  - Jet reconstruction and declustering → jet substructure (r_g, θ_g) modification
  - Jet yields and constituents → jet suppression and energy redistribution (R_{AA}, I_{AA})
  - Angular correlation → jet deflection ($\Delta\varphi$)

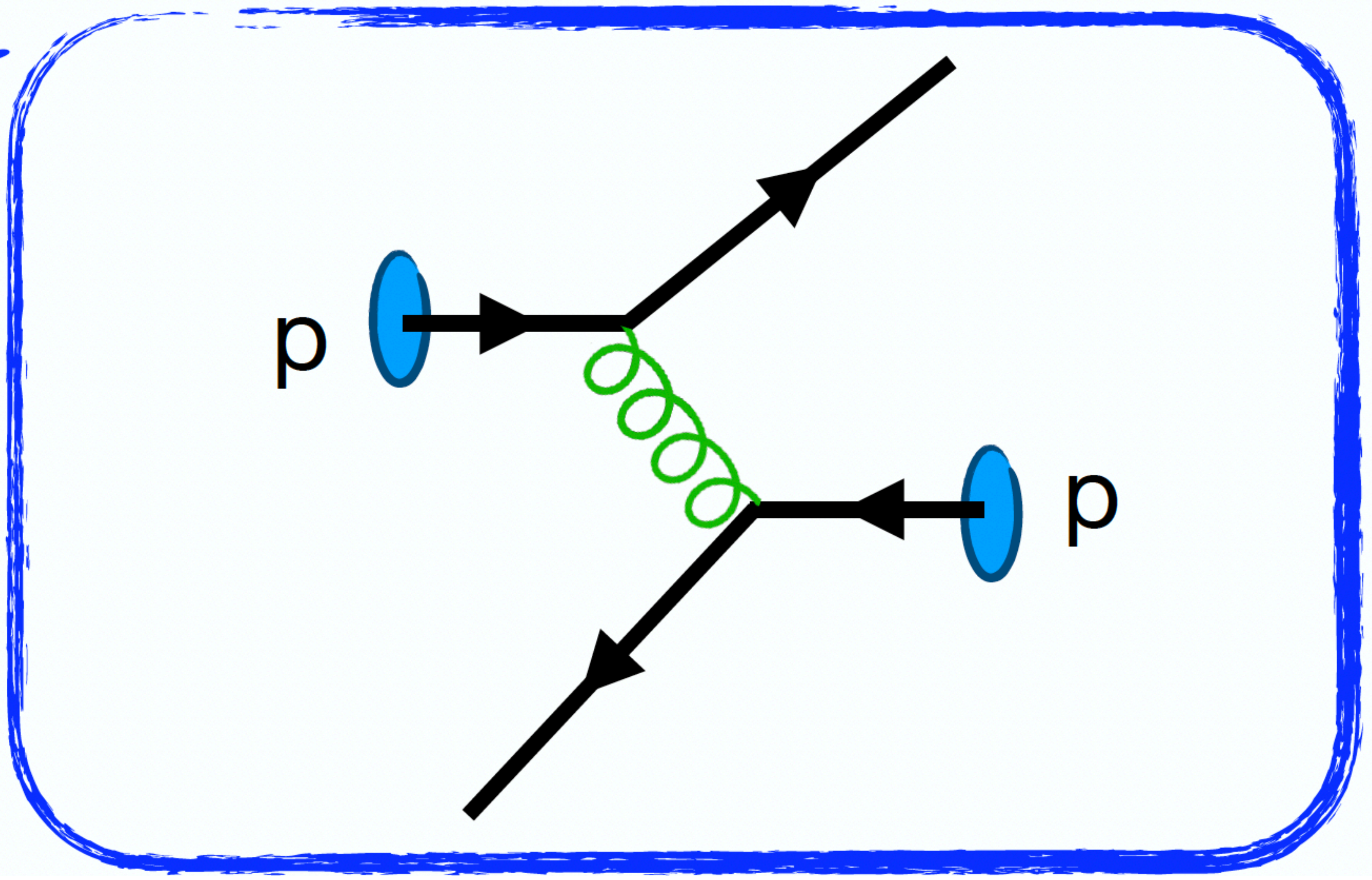


Study of different effects in a complementary way must yield consistent picture

Nuclear modification factor

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



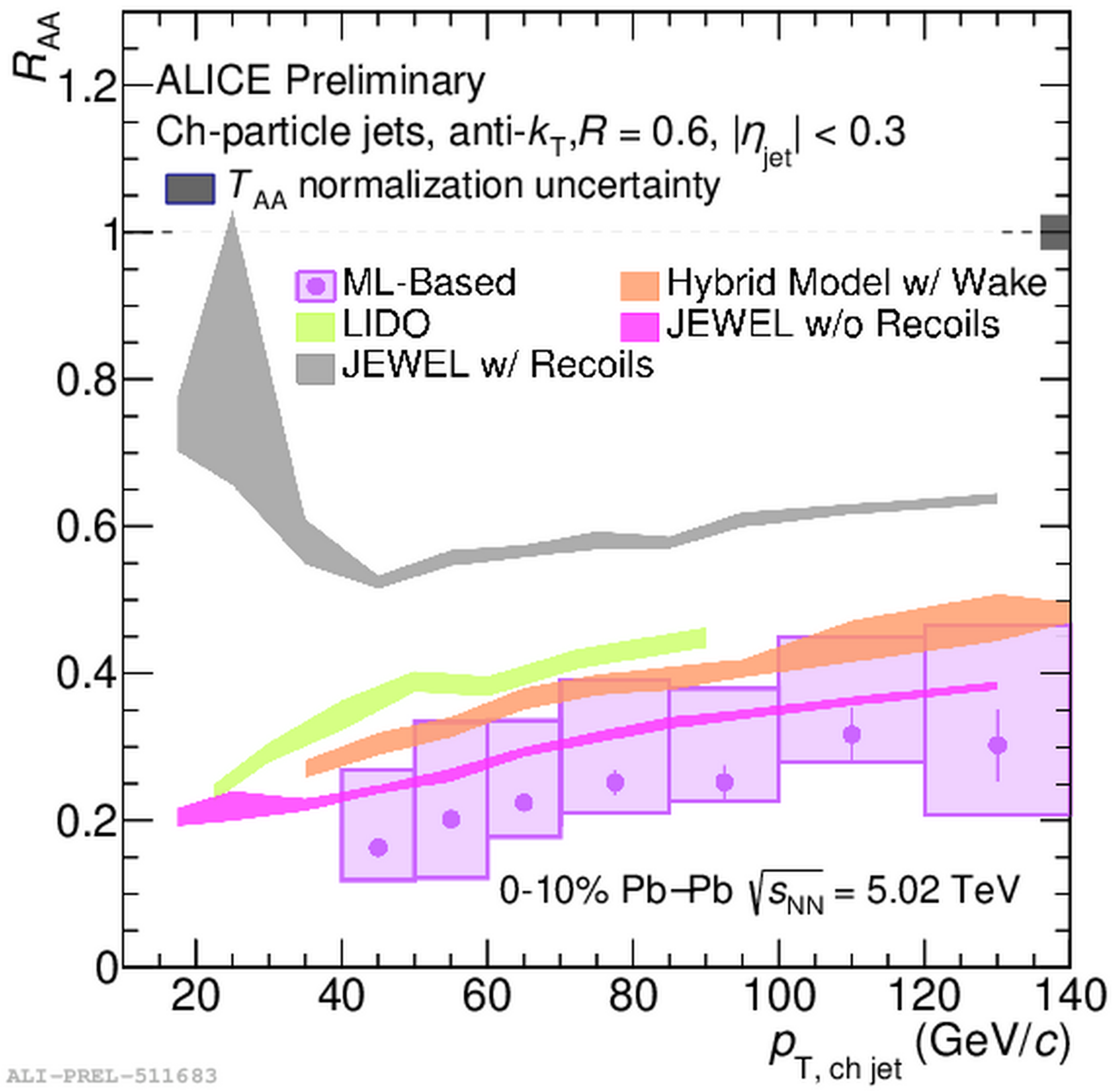


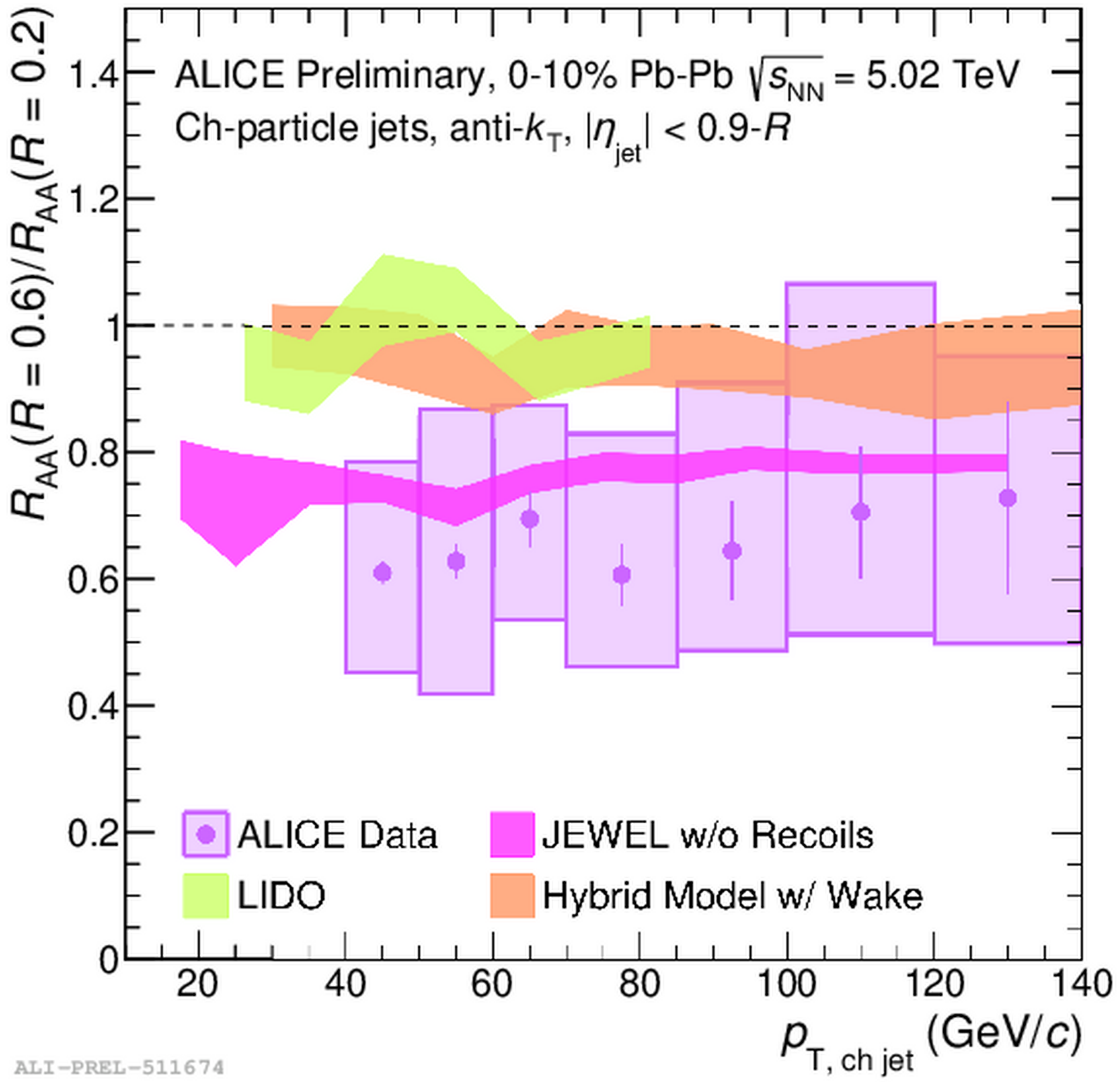
$R_{\mathrm{AA}} > 1$ $\rightarrow$ enhancement

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

$R_{\mathrm{AA}} < 1$ $\rightarrow$ supression

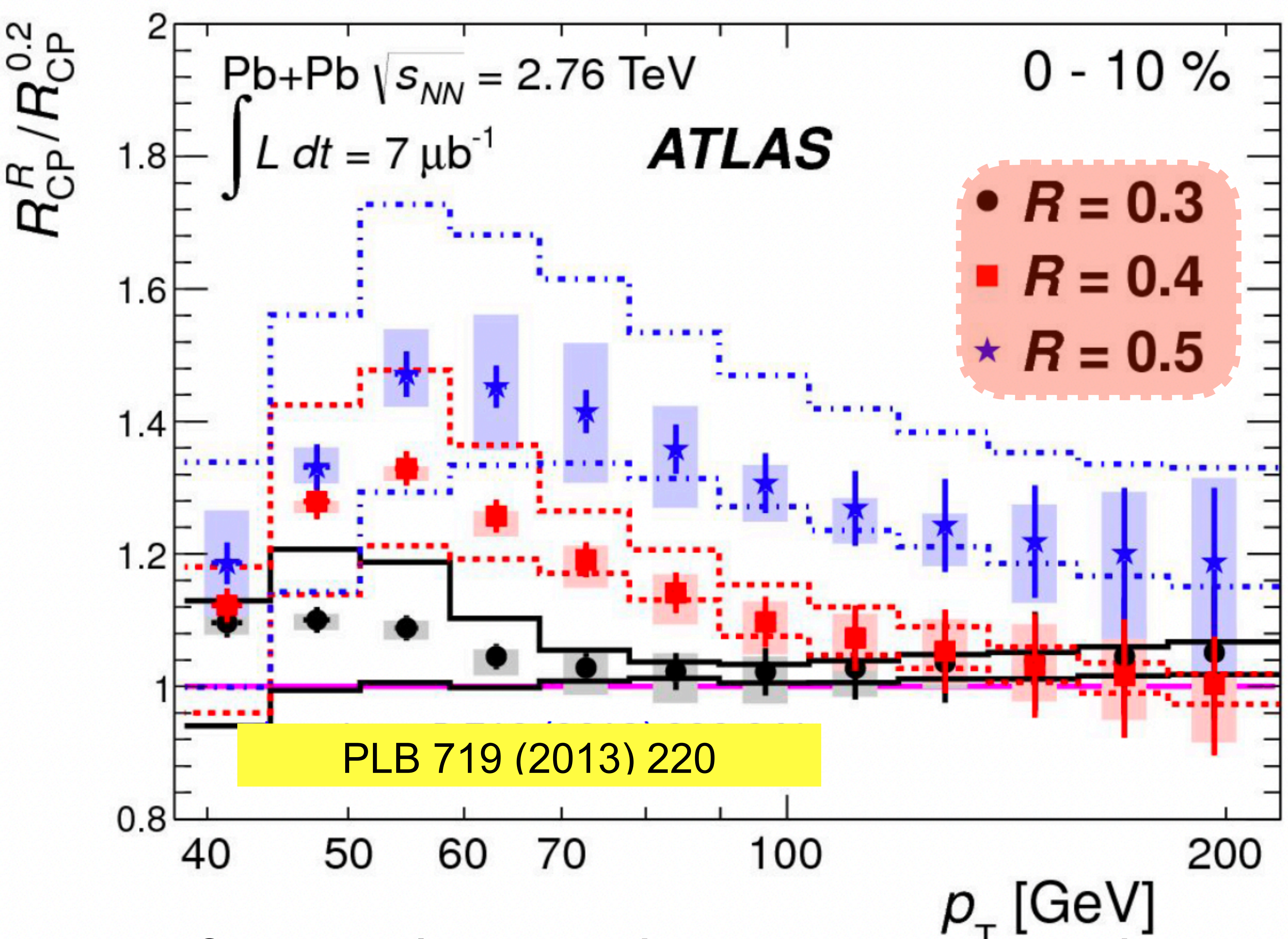
Jet suppression and energy redistribution



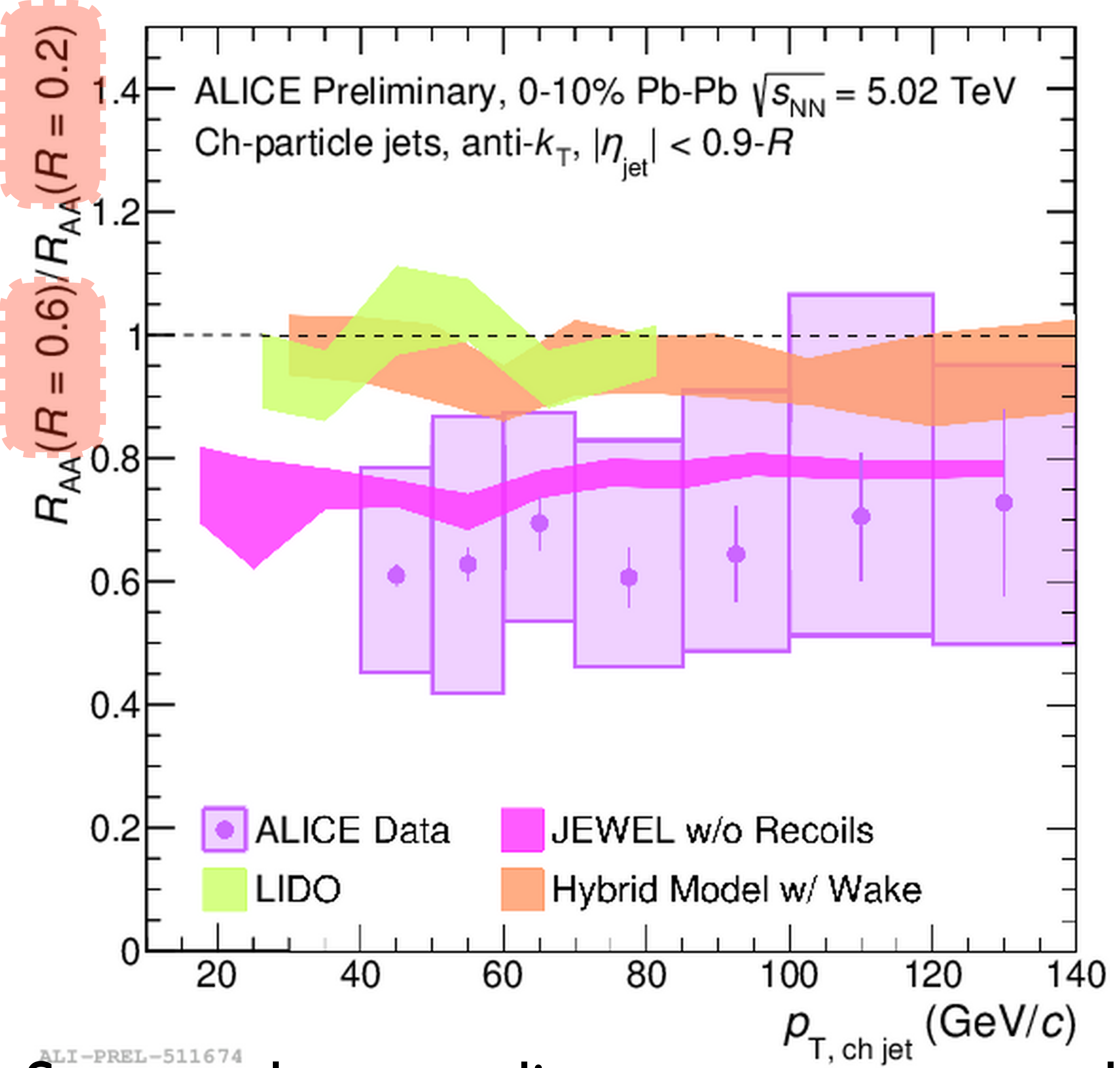


- Jet measurements extended to lower jet p_T and large R using machine learning (ML)
  - improvements on background subtraction and systematics
- Large R (= 0.6) jets indicate a stronger suppression than smaller R (= 0.2) jets
  - suggesting R-dependence of jet energy loss

Tension with previous ATLAS results



Suggests larger radius **less** suppressed



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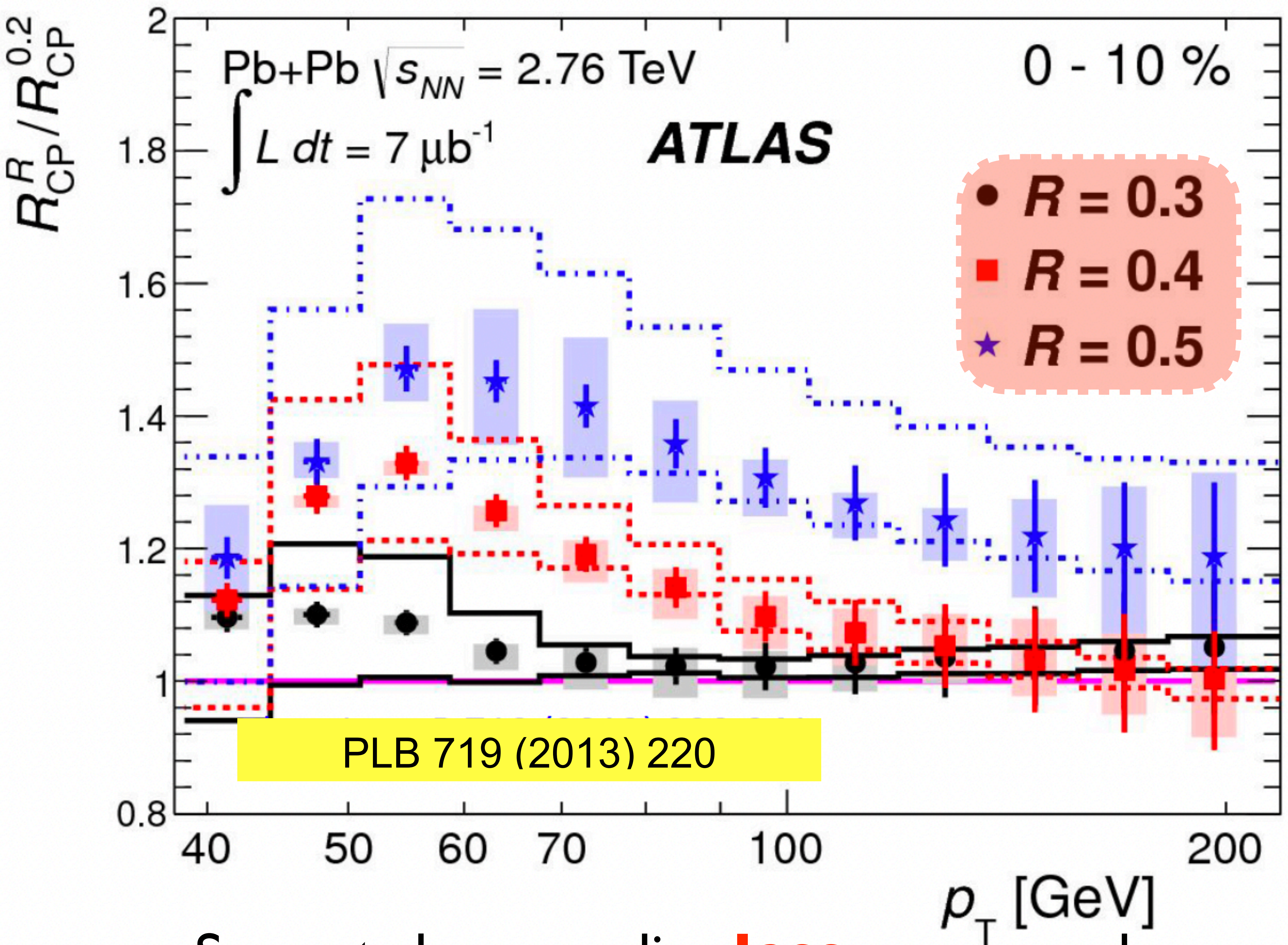
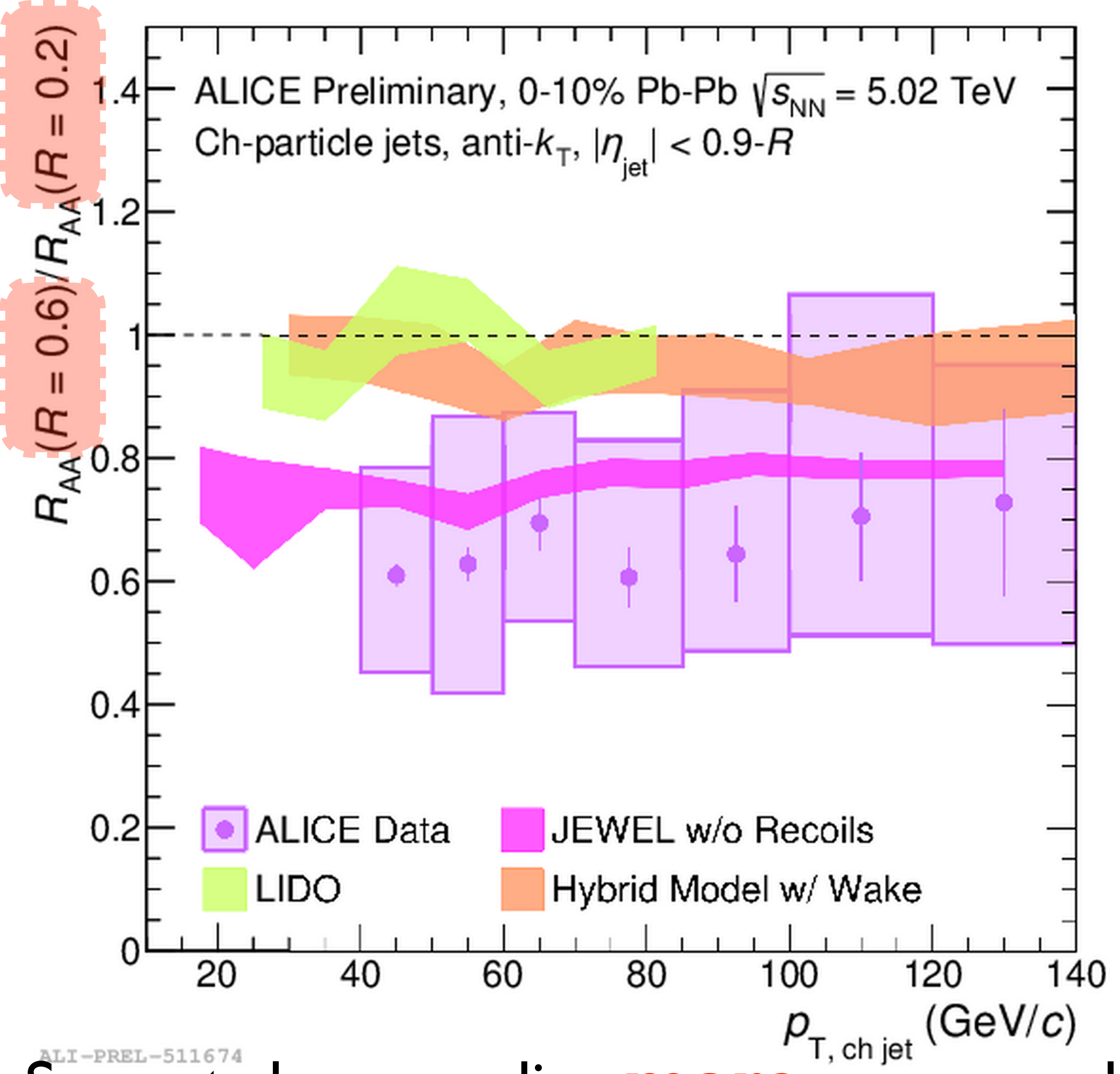




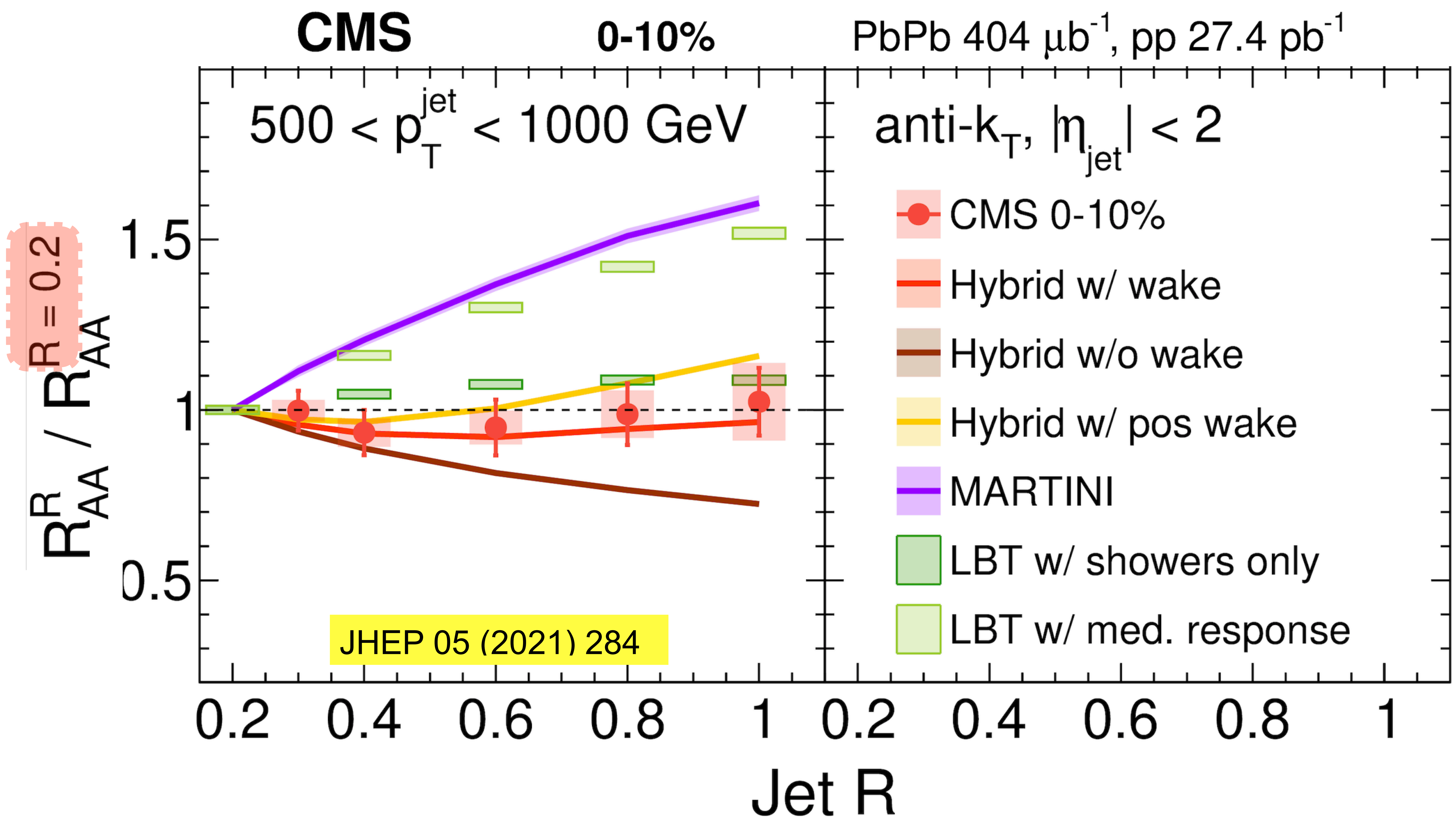
Suggests larger radius **less** suppressed

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 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

R_{AA} - substructure interplay

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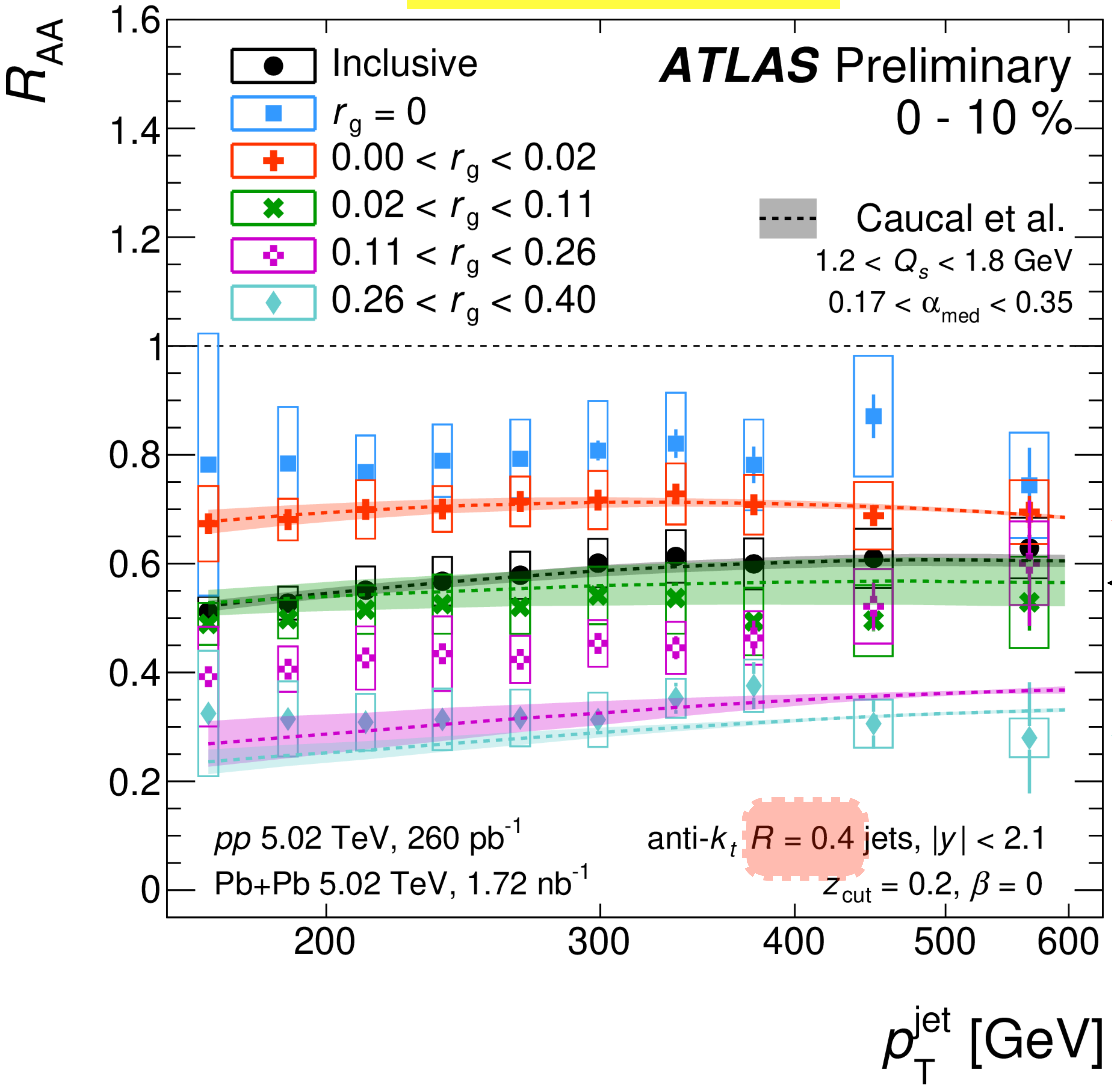
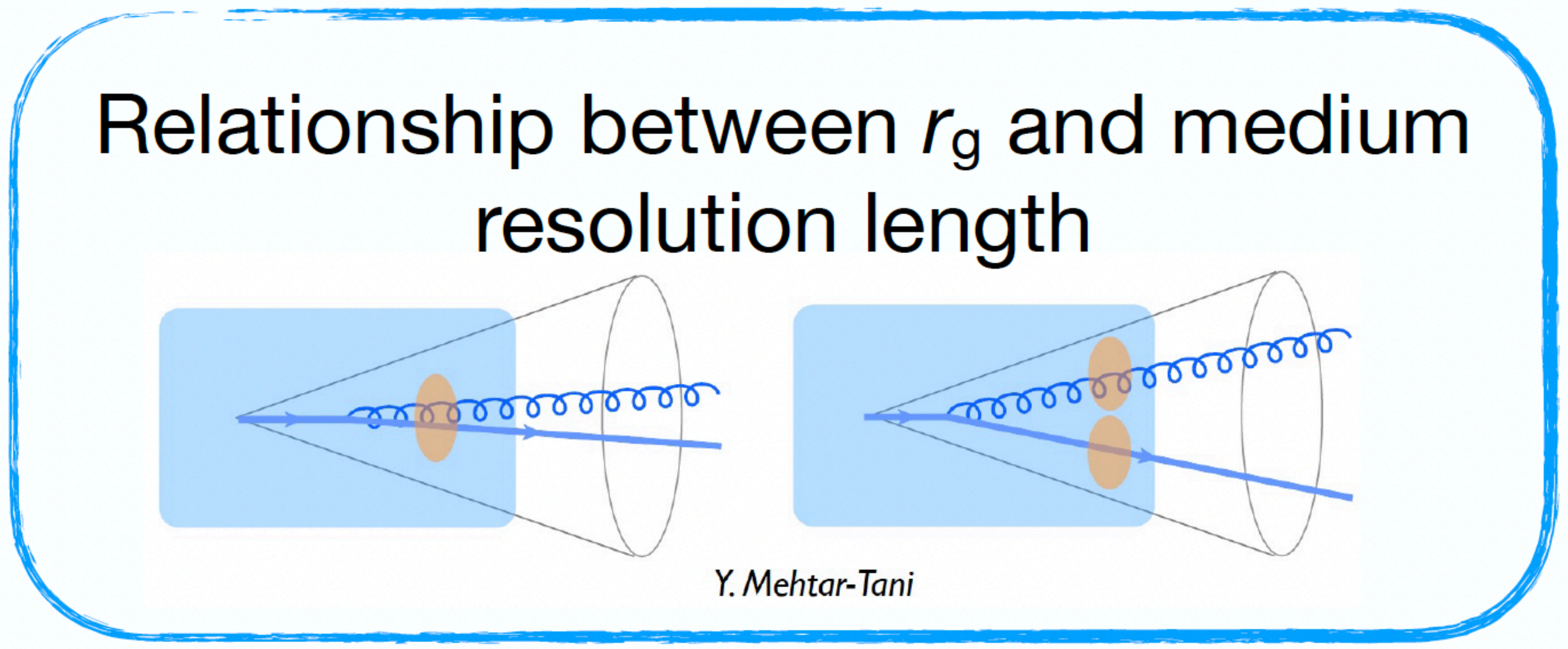
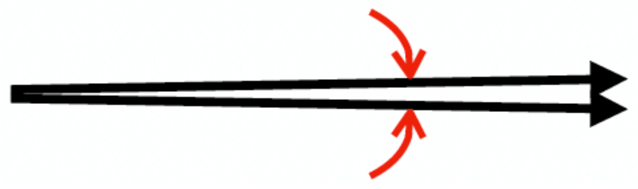
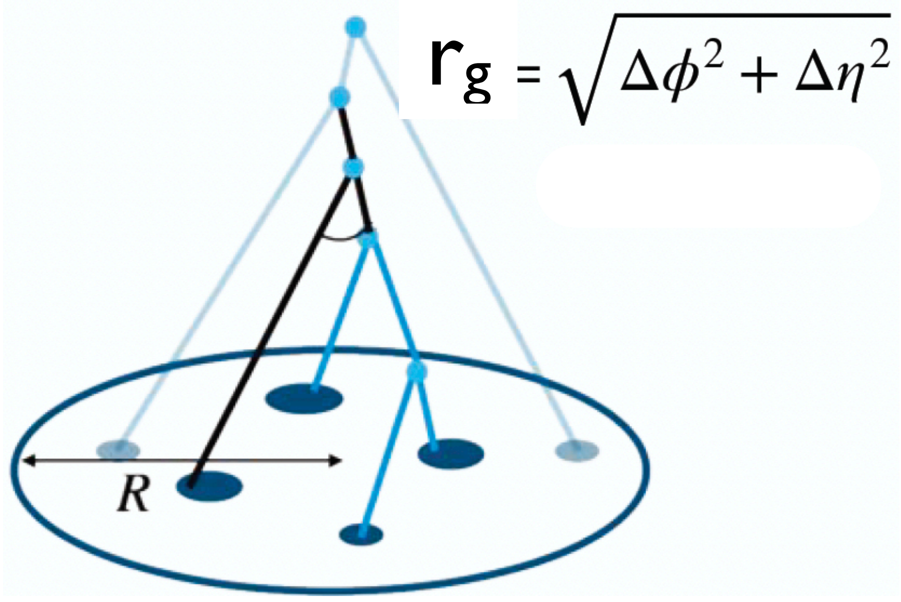




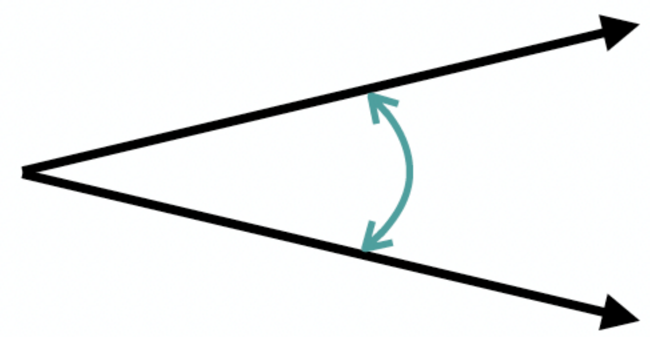
Small r_g



Inclusive



Large r_g



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

R_{AA} vs groomed jet radius

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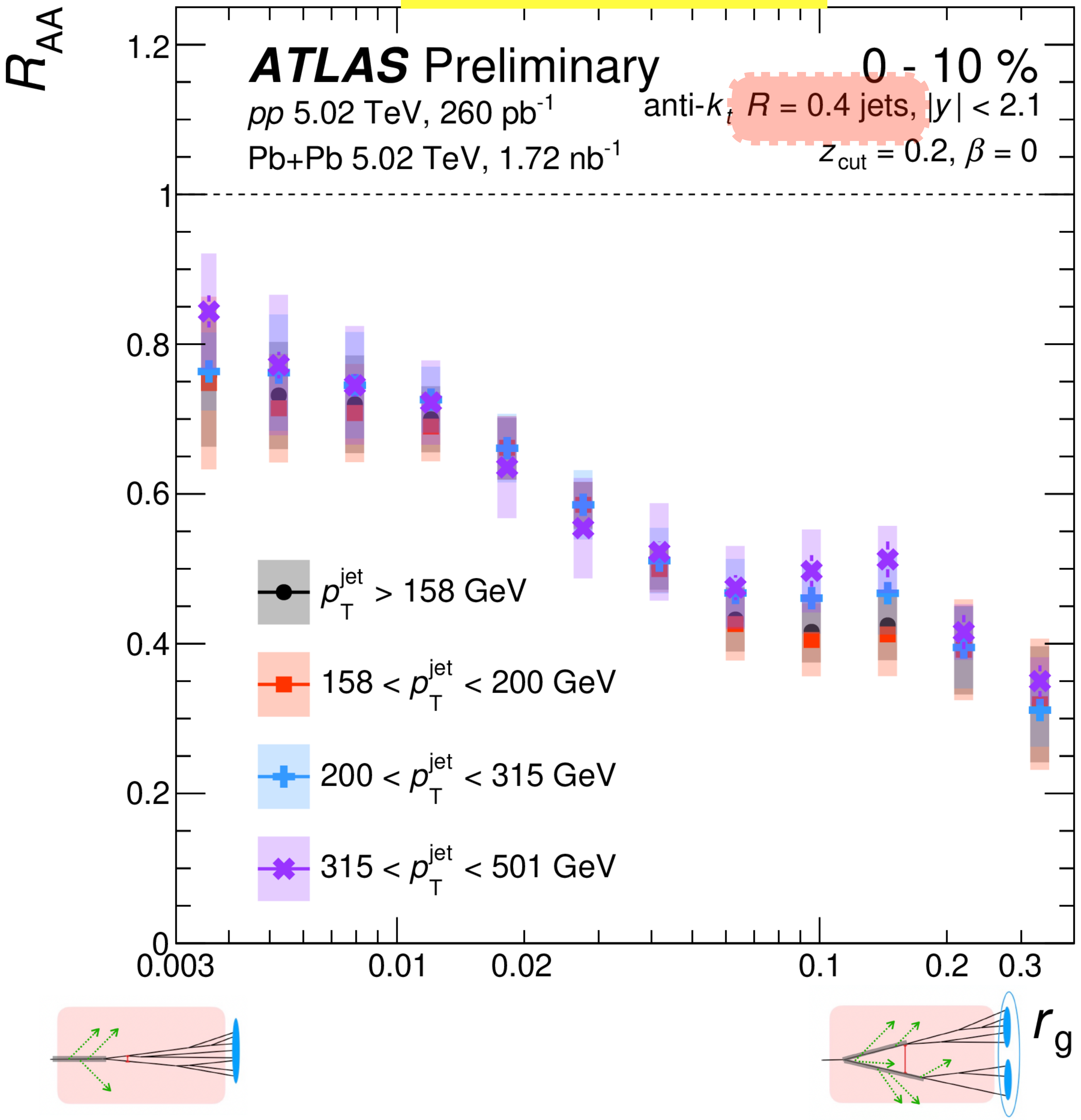
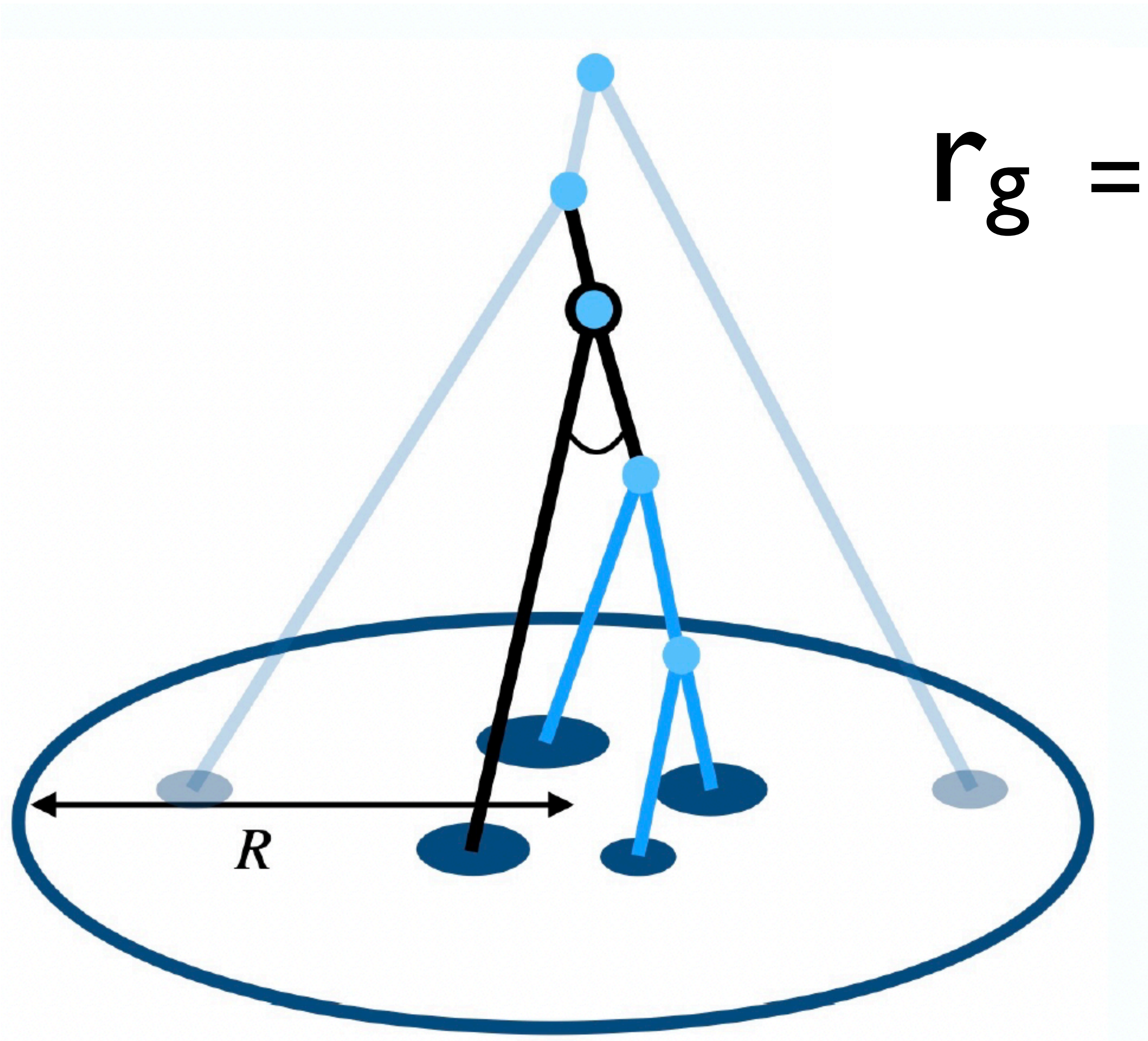


Absolutely-normalized results



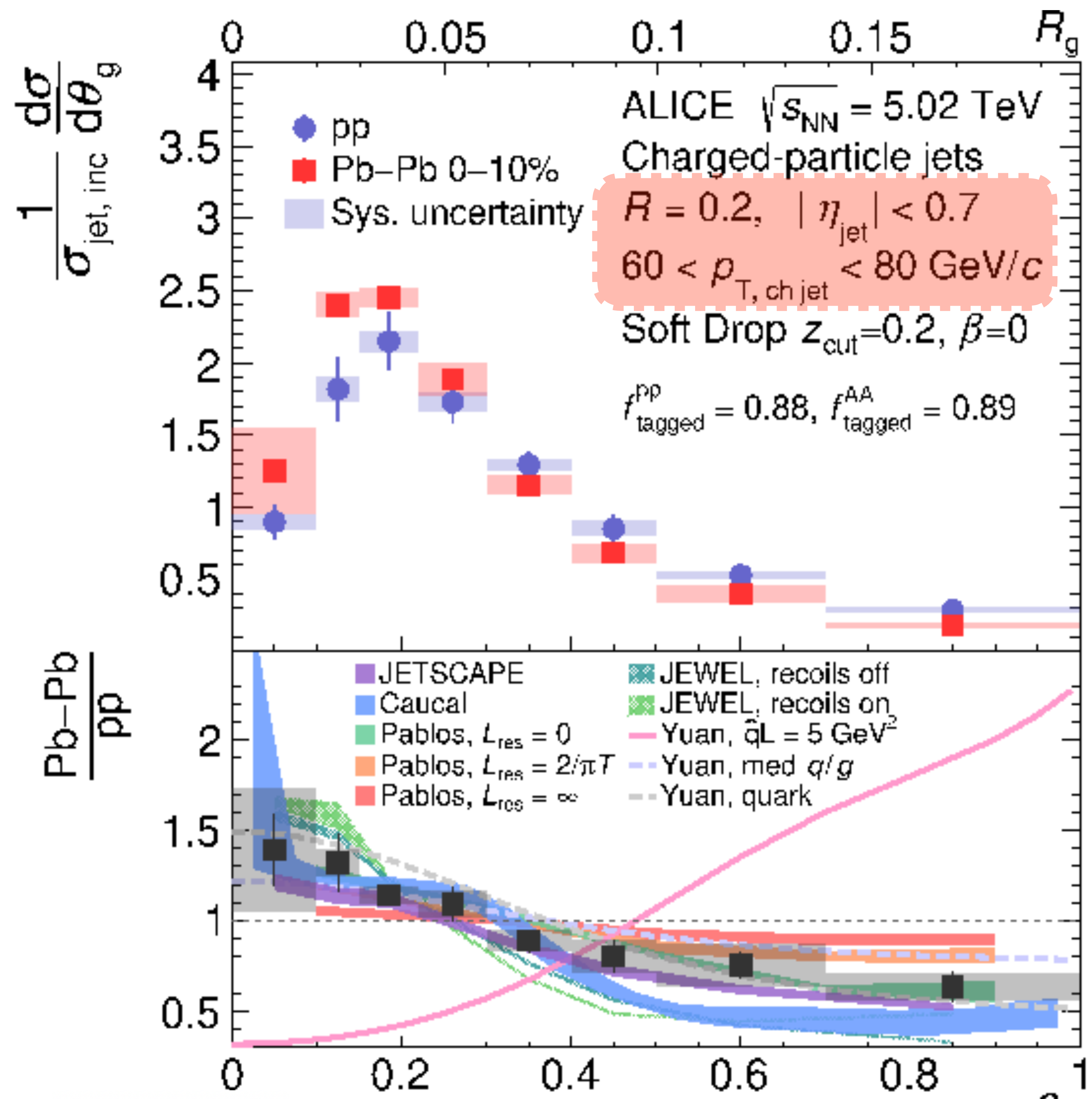
$$r_g = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

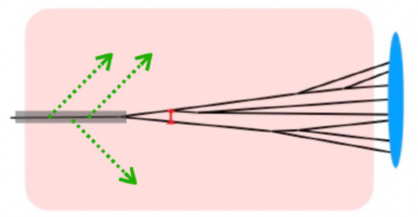
- No significant p_T dependence
- Strong r_g dependence of R_{AA}

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

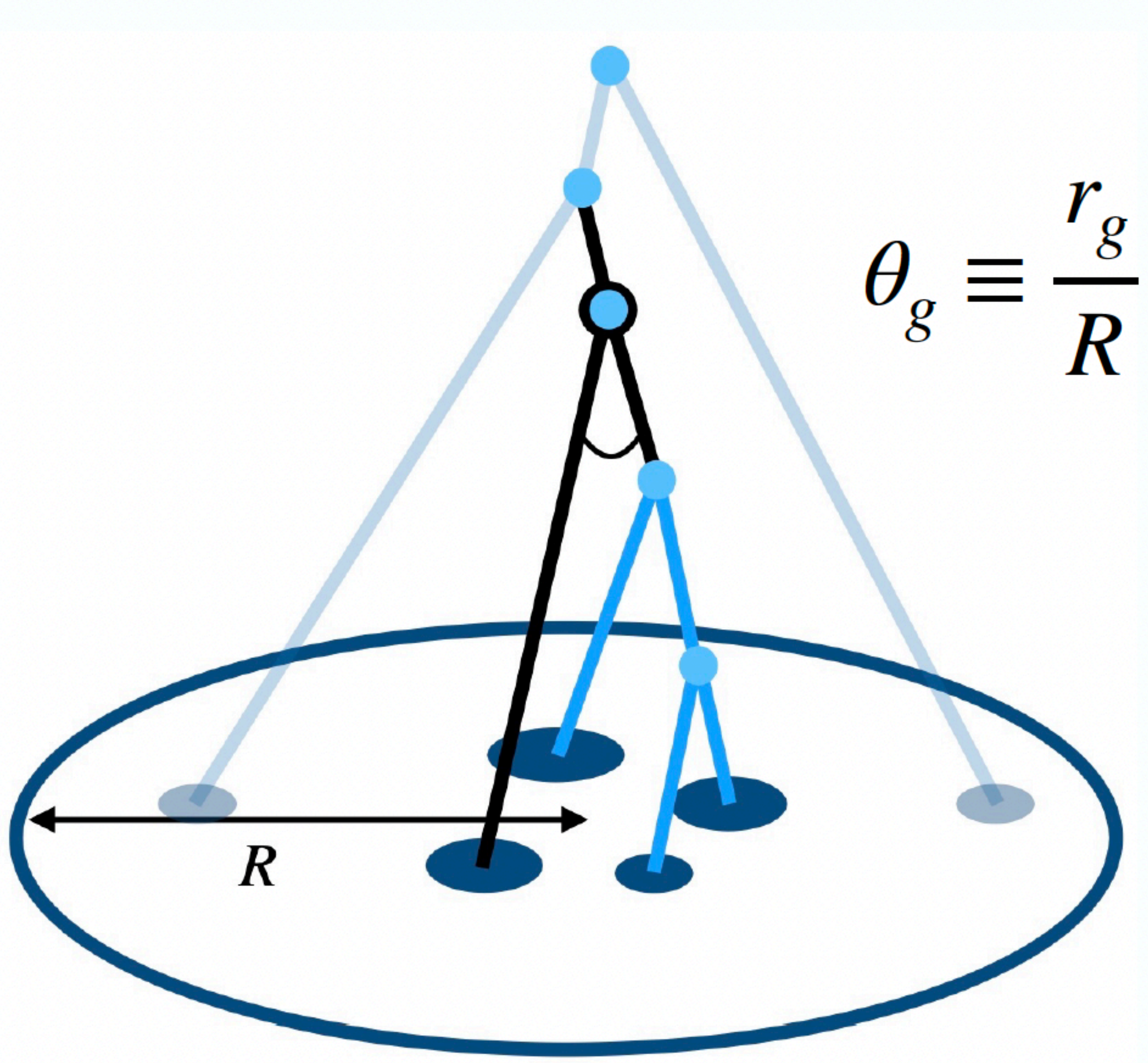
Groomed jet radius

ALICE, PRL 128 (2022) 102001



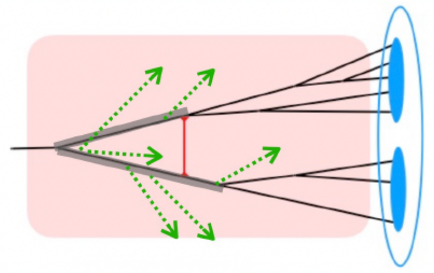


Self-normalized results → shapes!

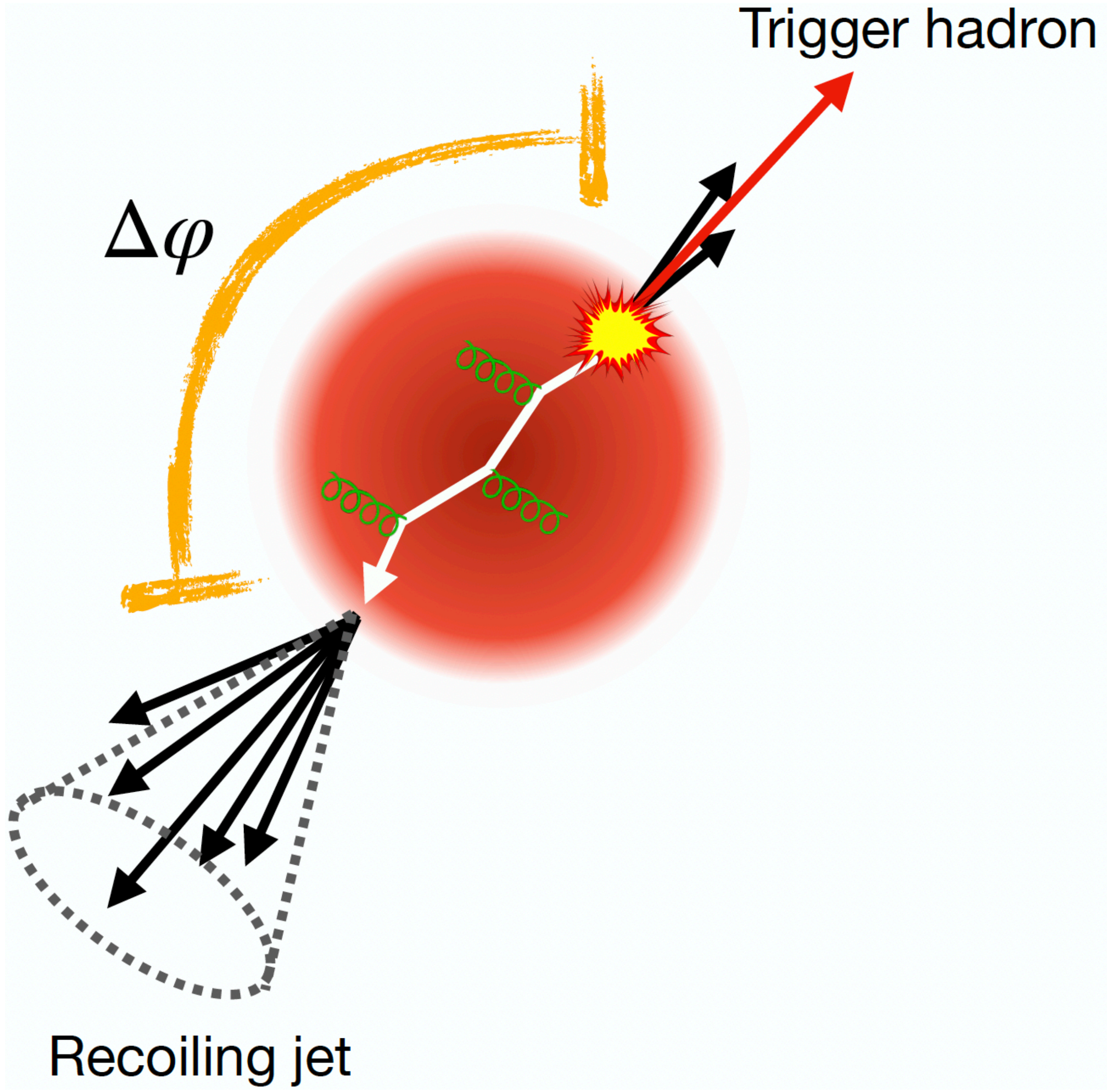


$$\theta_g \equiv \frac{r_g}{R} = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

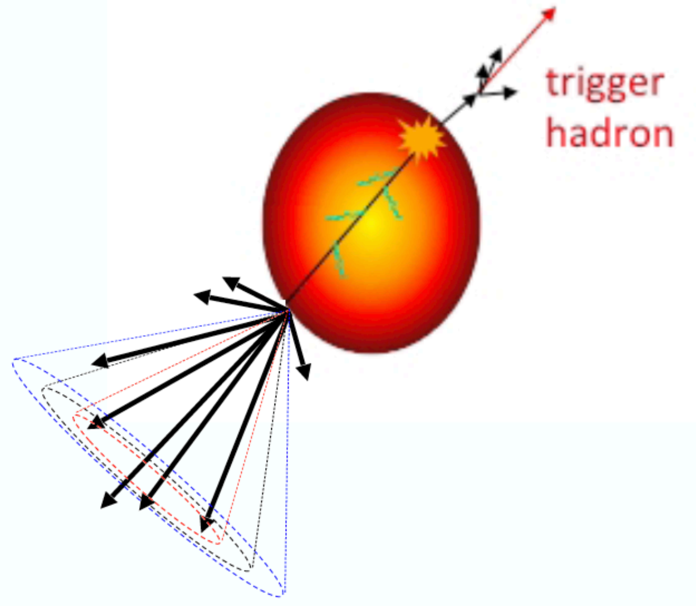
- Large θ_g jets are more suppressed → narrowing of the Pb-Pb distributions
- At fixed jet p_T, large R-jet has higher probability to have large θ_g splittings

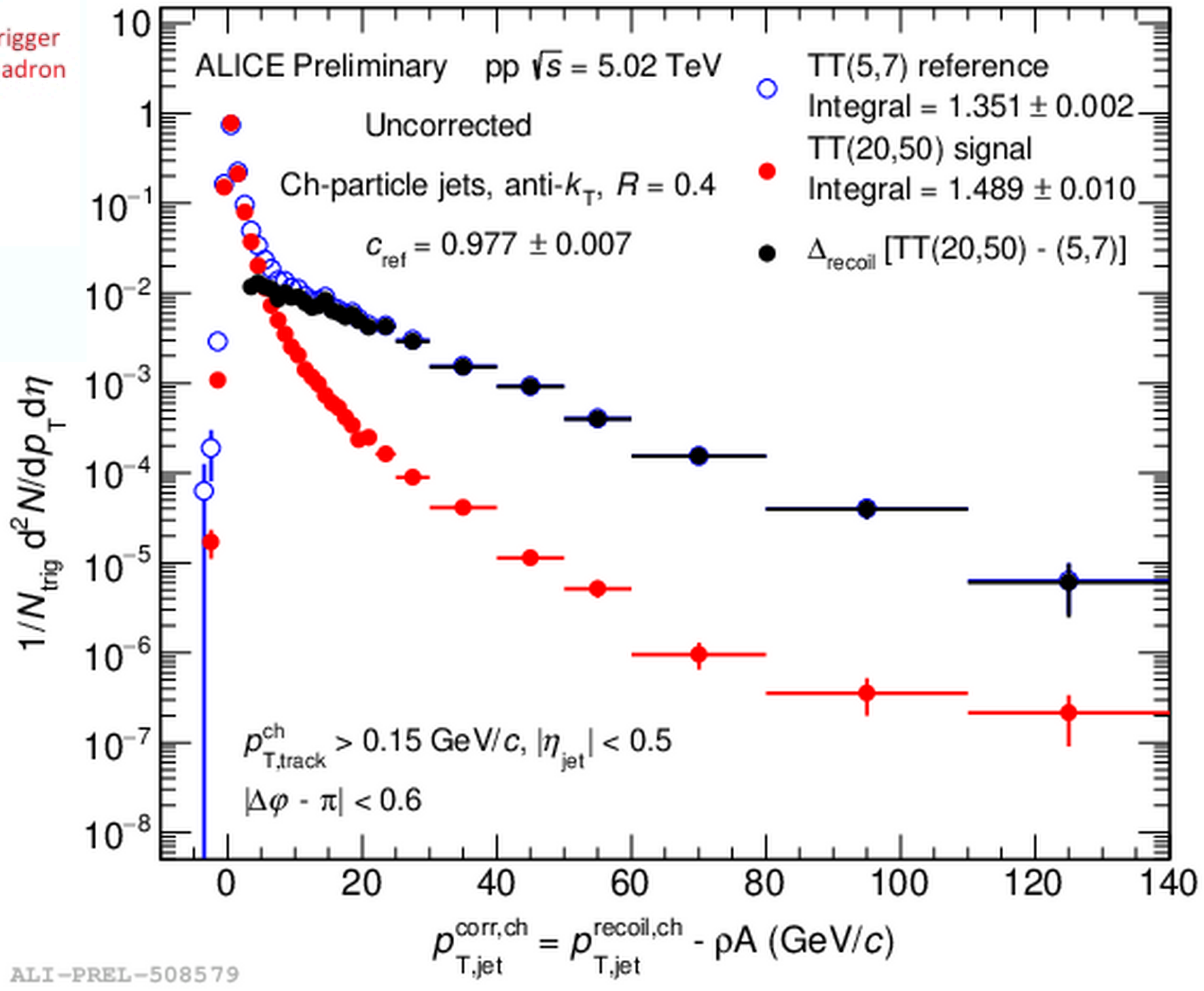


Correlations with high-p_T hadrons



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

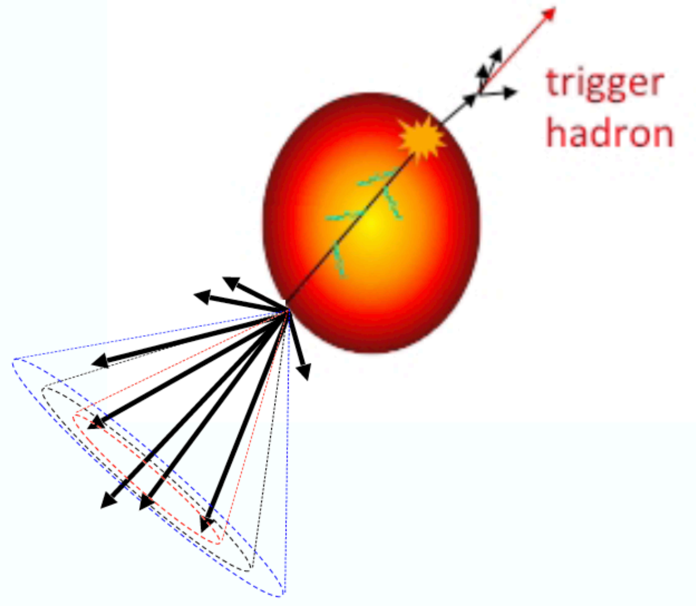


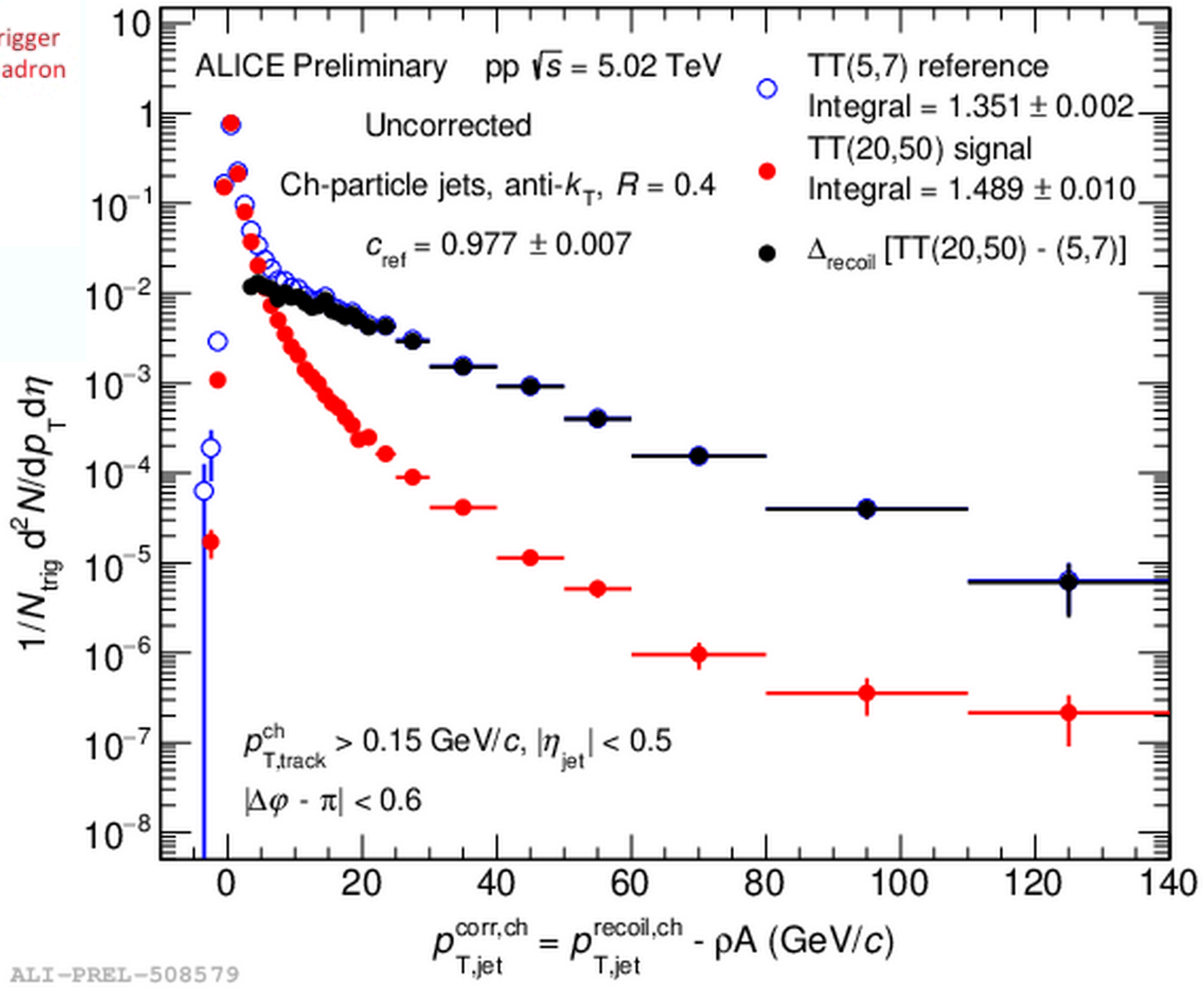


$$\Delta_{\rm recoil} = \frac{1}{\mathrm{N}^{\rm AA}_{\rm trig}} \frac{\mathrm{d}^2\mathrm{N}^{\rm AA}_{\rm jet}}{\mathrm{d}p^{\rm ch}_{\rm T,jet}\mathrm{d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in{\rm TT_{Sig}}} - c_{\rm Ref}\cdot\frac{1}{\mathrm{N}^{\rm AA}_{\rm trig}} \frac{\mathrm{d}^2\mathrm{N}^{\rm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

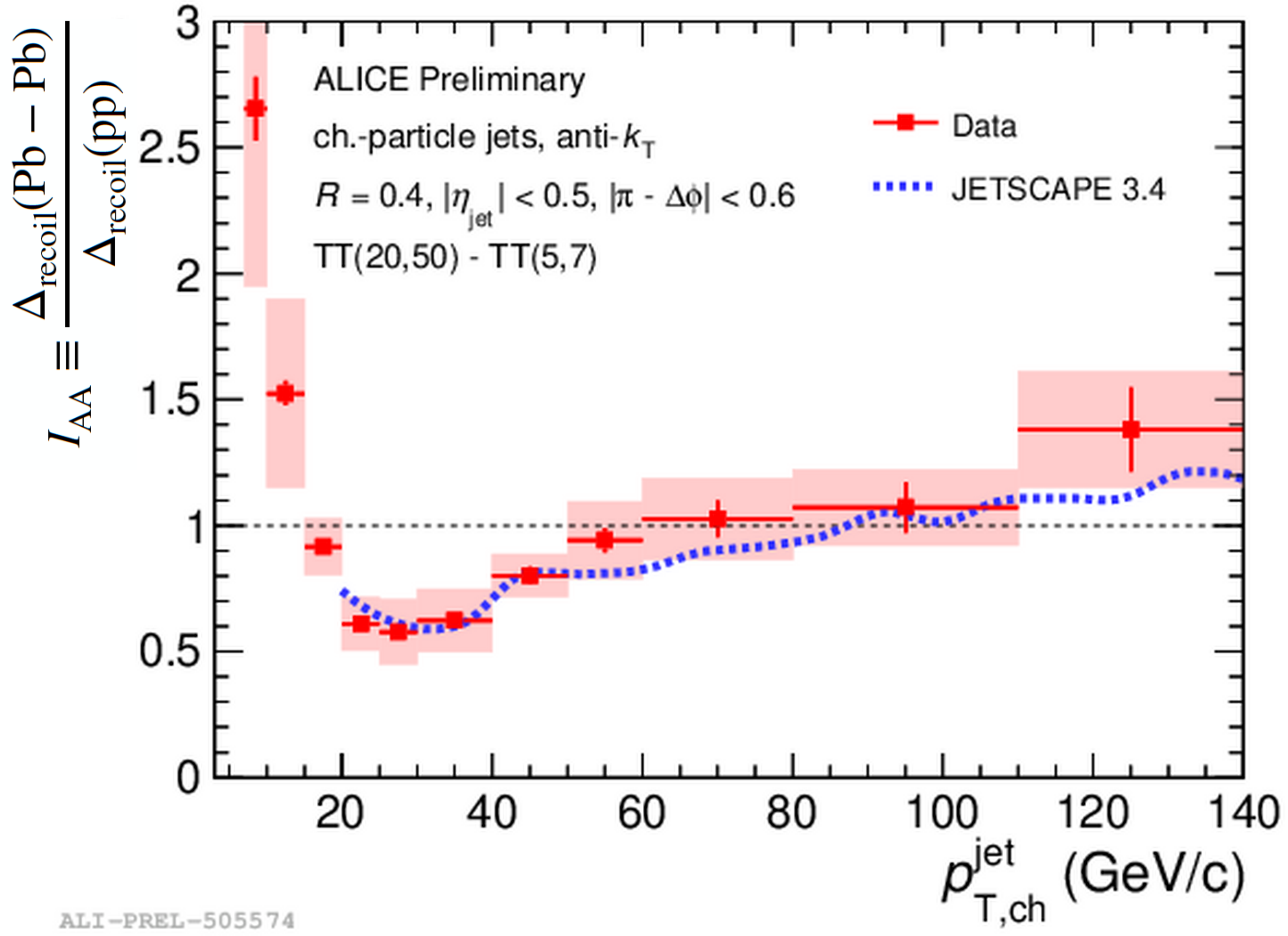
- Measurements of semi-inclusive yield of jets recoiling from a high p_T hadron can push the kinematics down to very low p_T and large R
  - access to low p_T jet quenching and intra-jet broadening

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



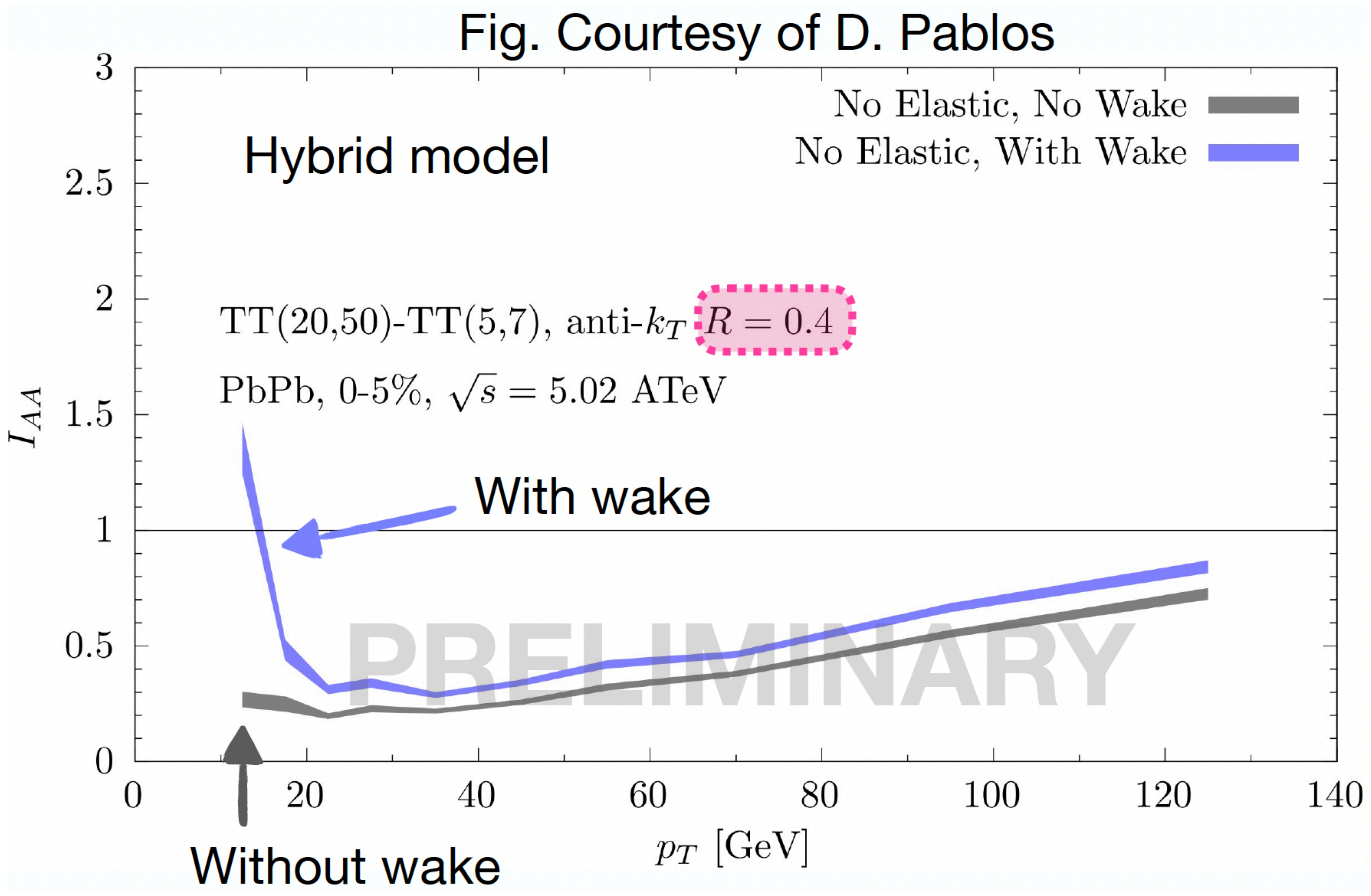


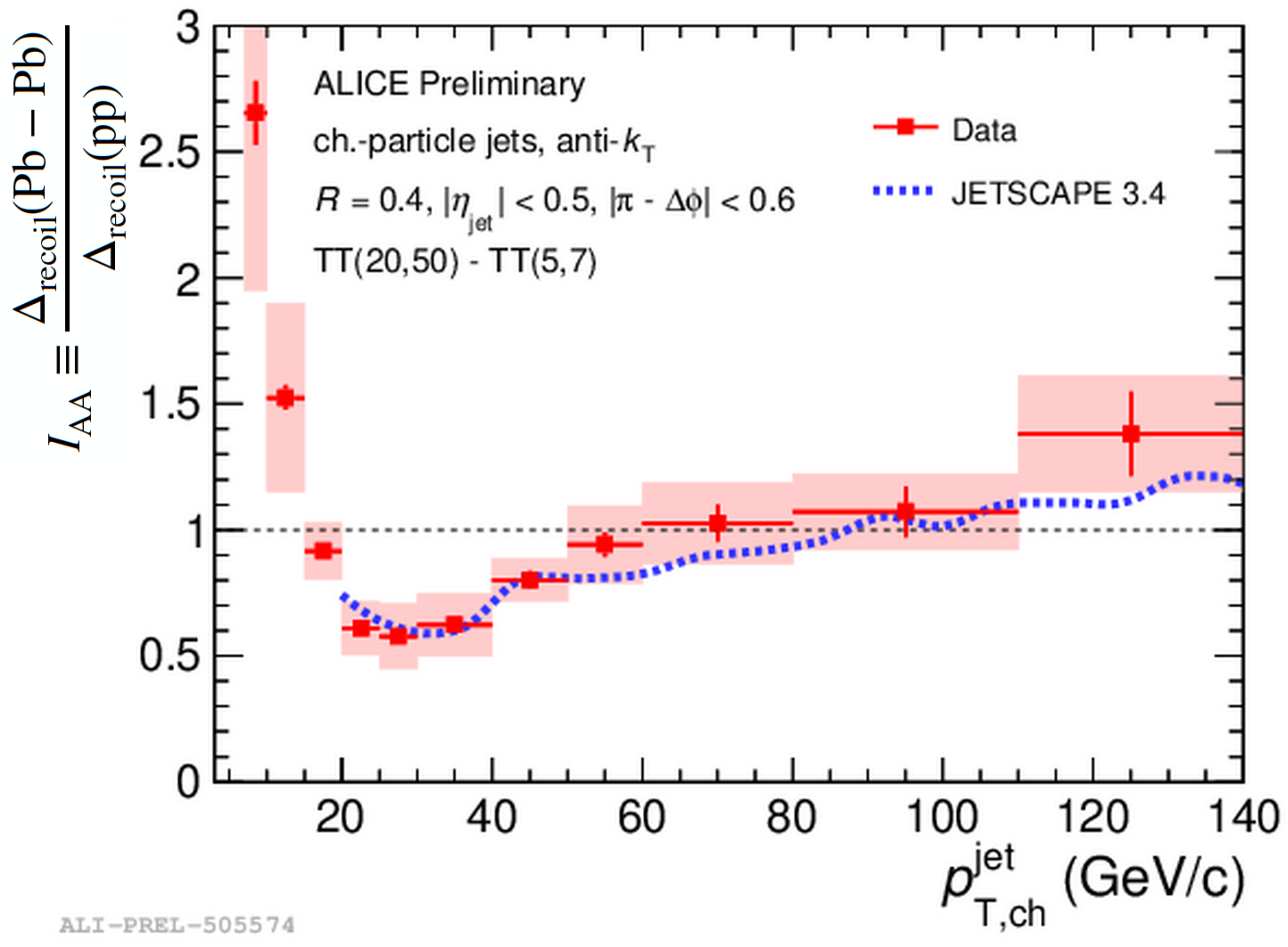
$$\Delta_{\mathrm{recoil}} = \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2N^{AA}_{\mathrm{jet}}}{dp^{ch}_{T,\mathrm{jet}}\, d\eta_{\mathrm{jet}}}\Bigg|_{p_{T,\mathrm{trig}}\in TT_{\mathrm{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2N^{AA}_{\mathrm{jet}}}{dp^{ch}_{T,\mathrm{jet}}\,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



- 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
- Increase of low p_T yields → hints of energy recovery for very low p_T jets

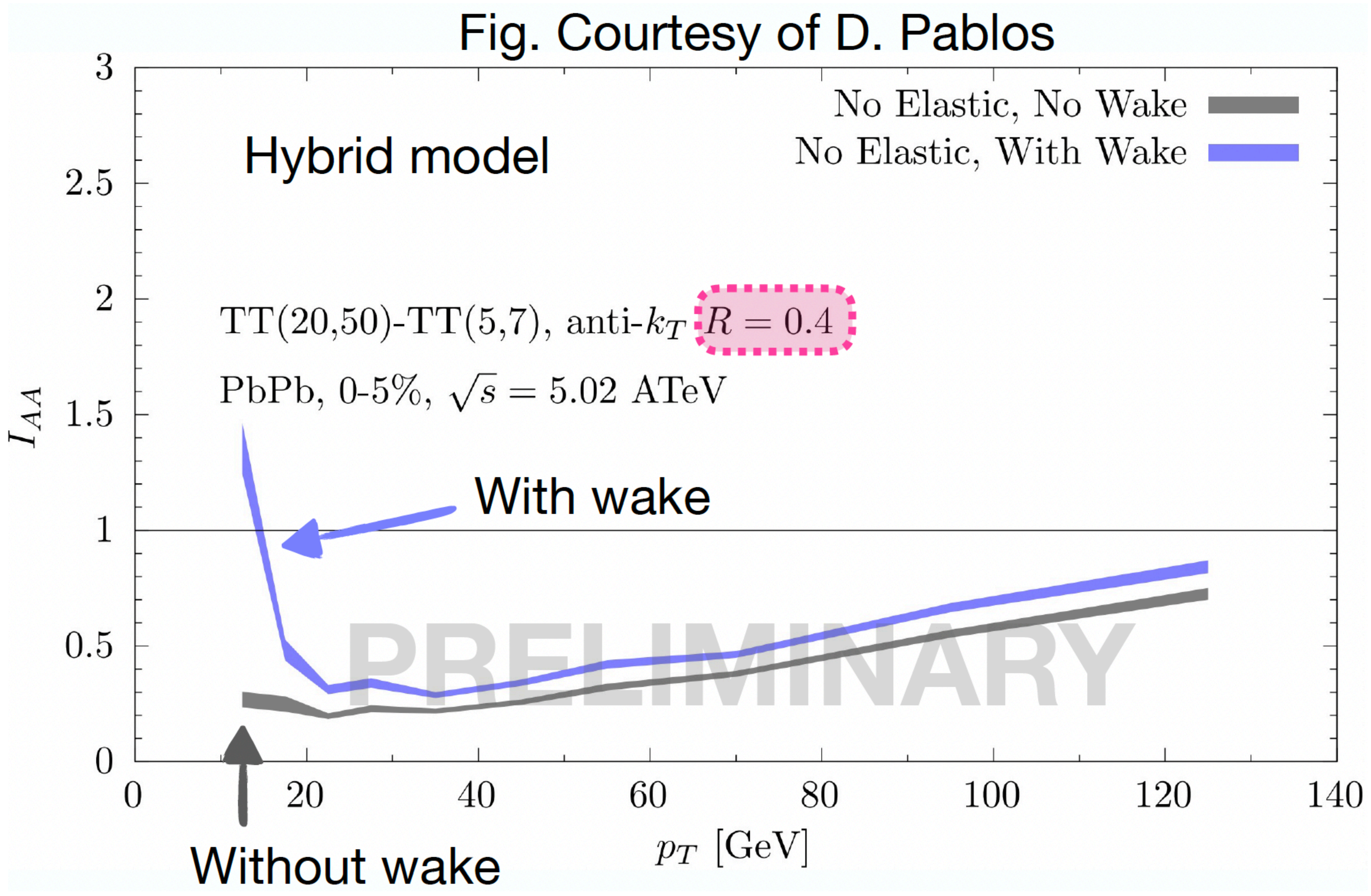
Sensitivity to medium response ("the wake")



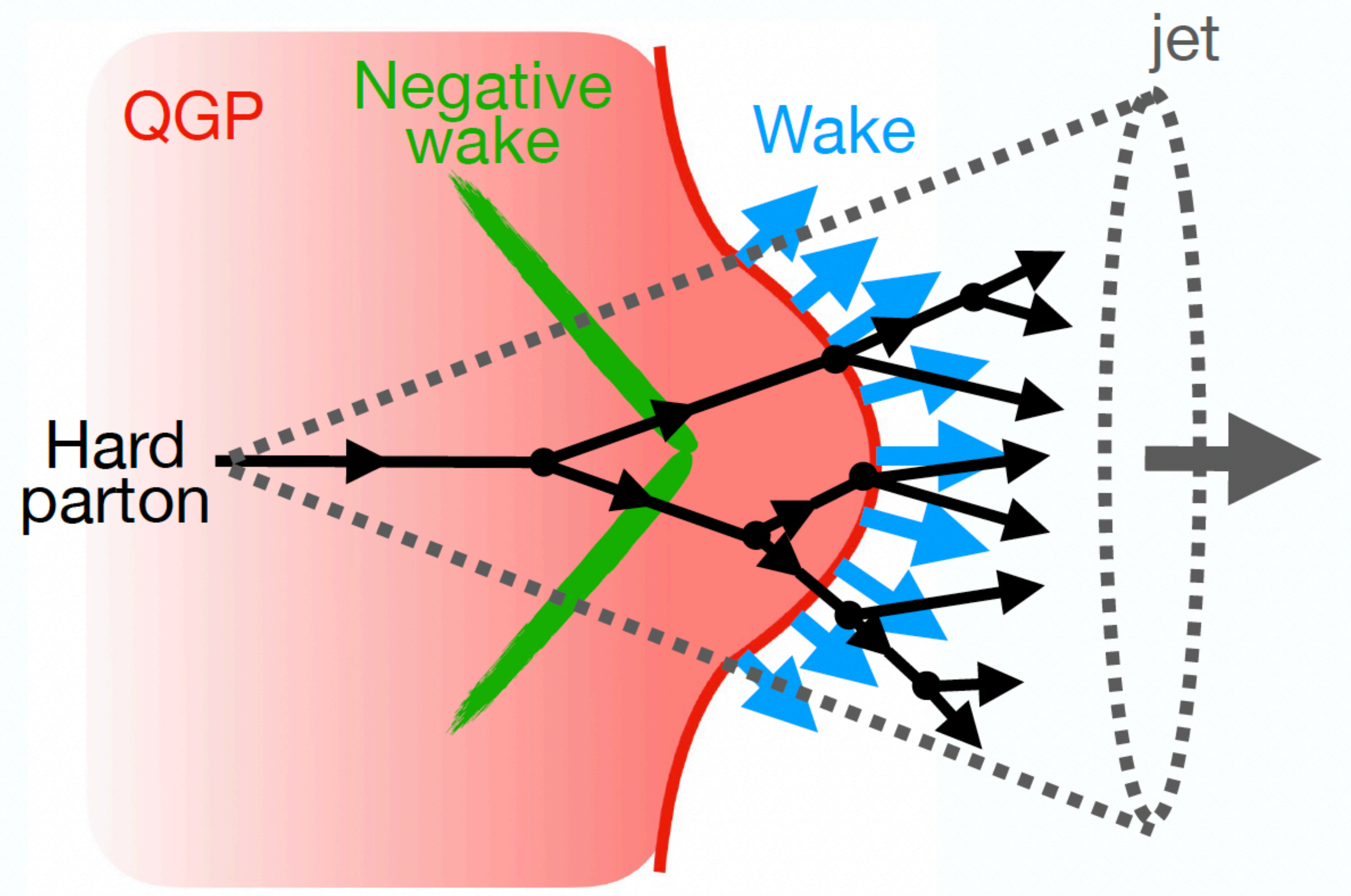


- Uprise at low p_T explained by medium response within Hybrid model

Sensitivity to medium response (“the wake”)

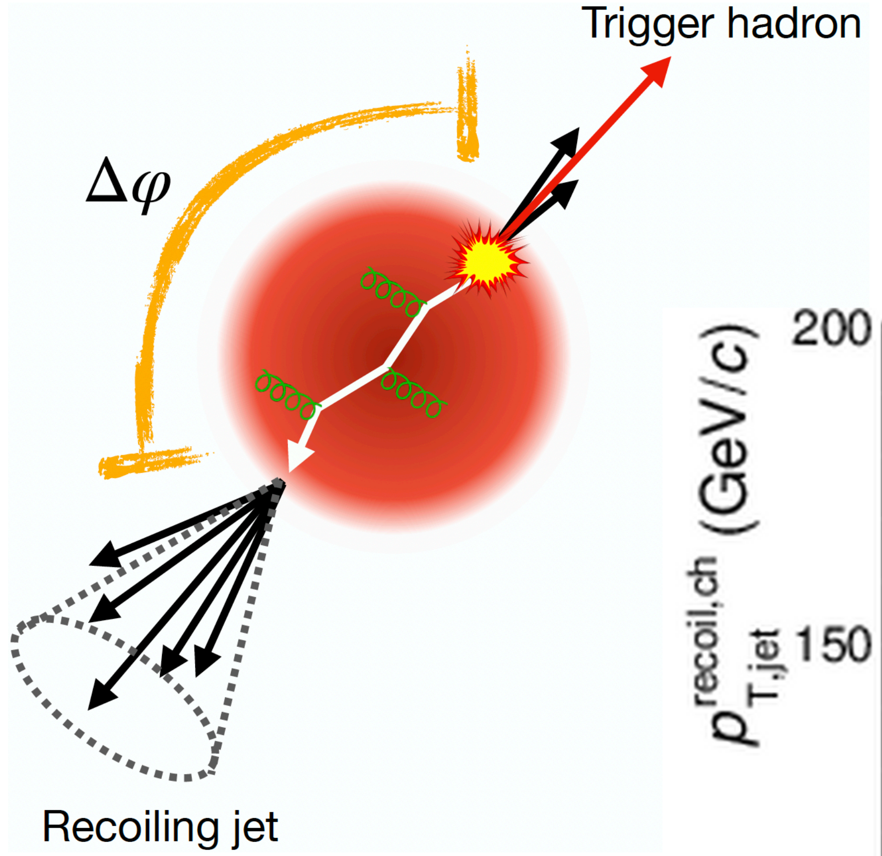


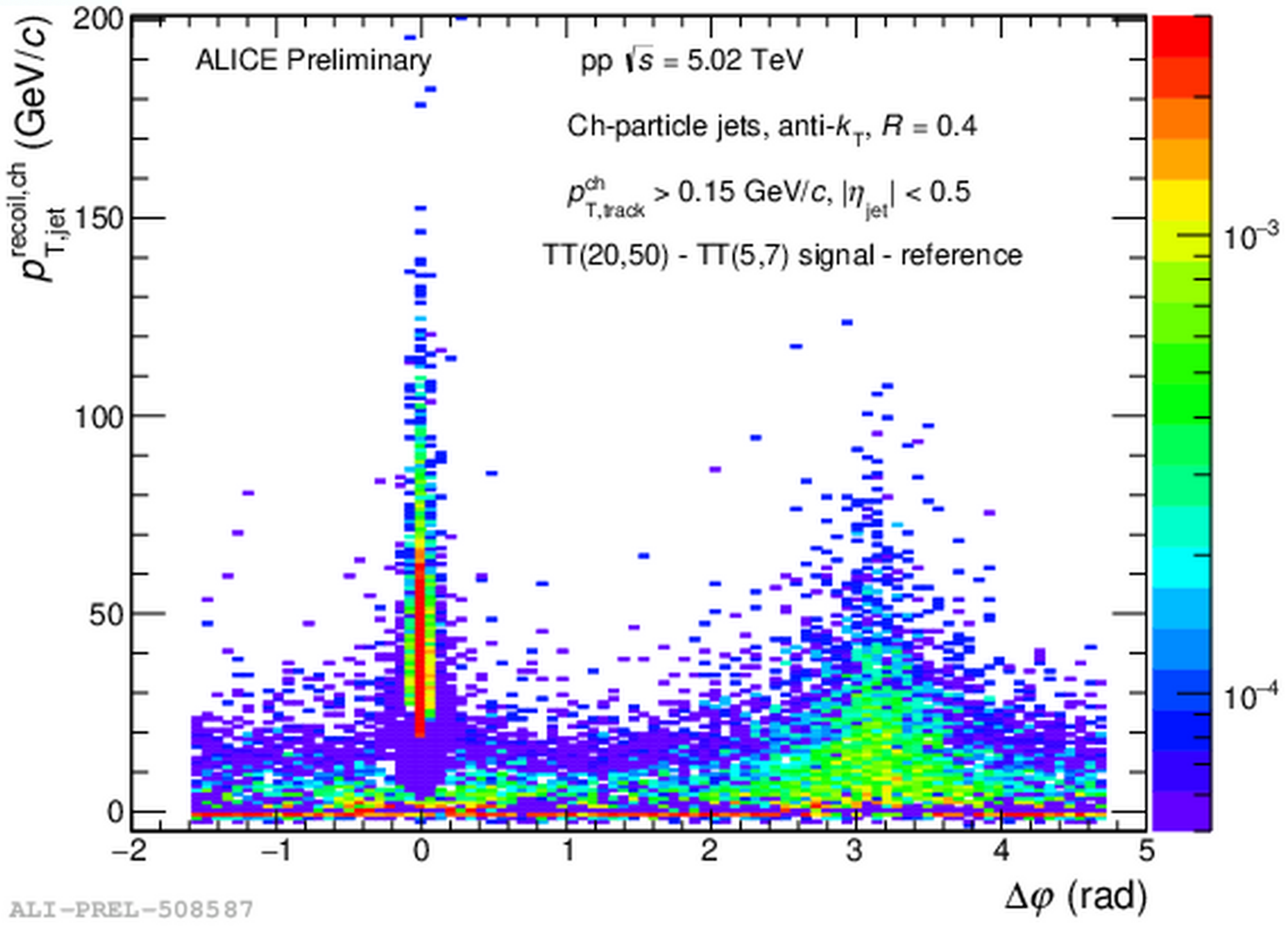
From jet-medium interaction, medium partons acquire additional momentum that correlates their direction with the jet



- 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





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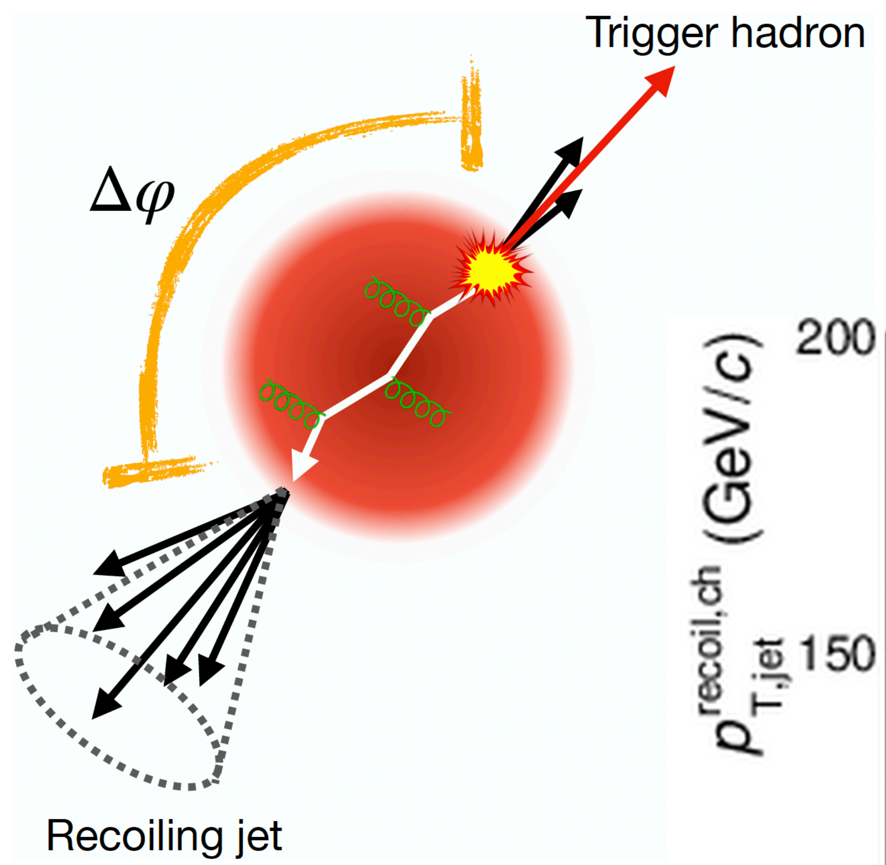
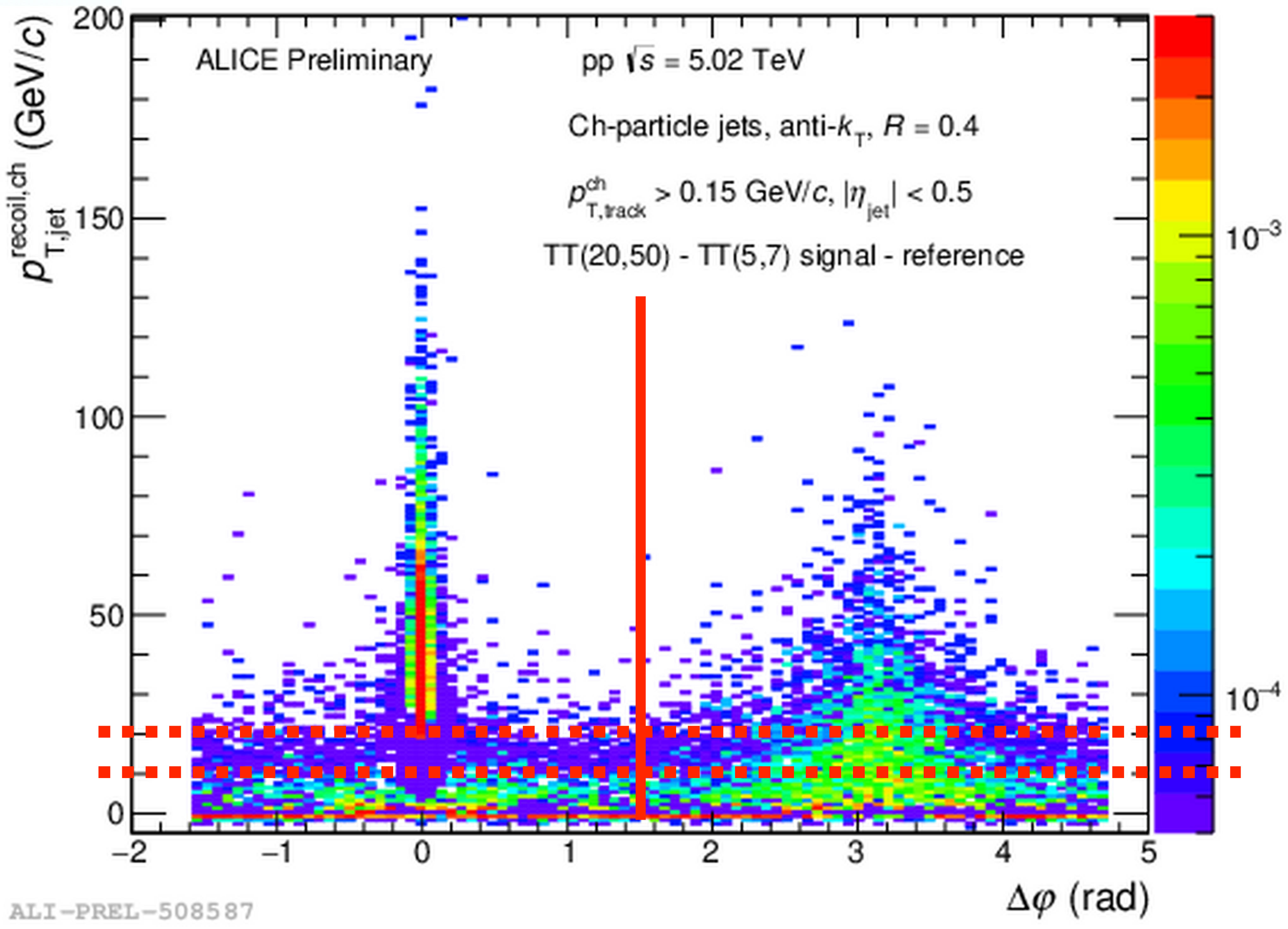
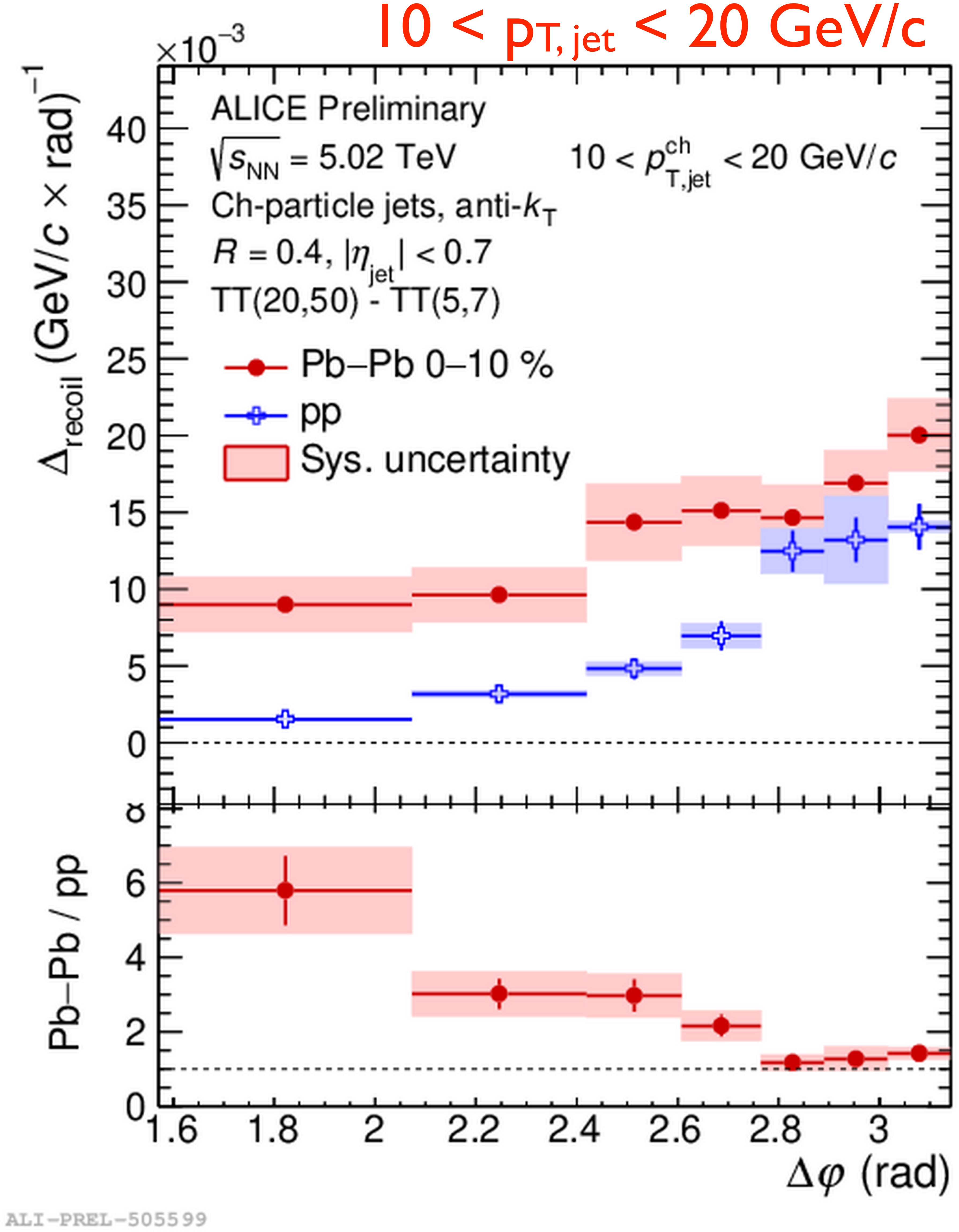




10 < $p_{T, jet}$ < 20 GeV/c



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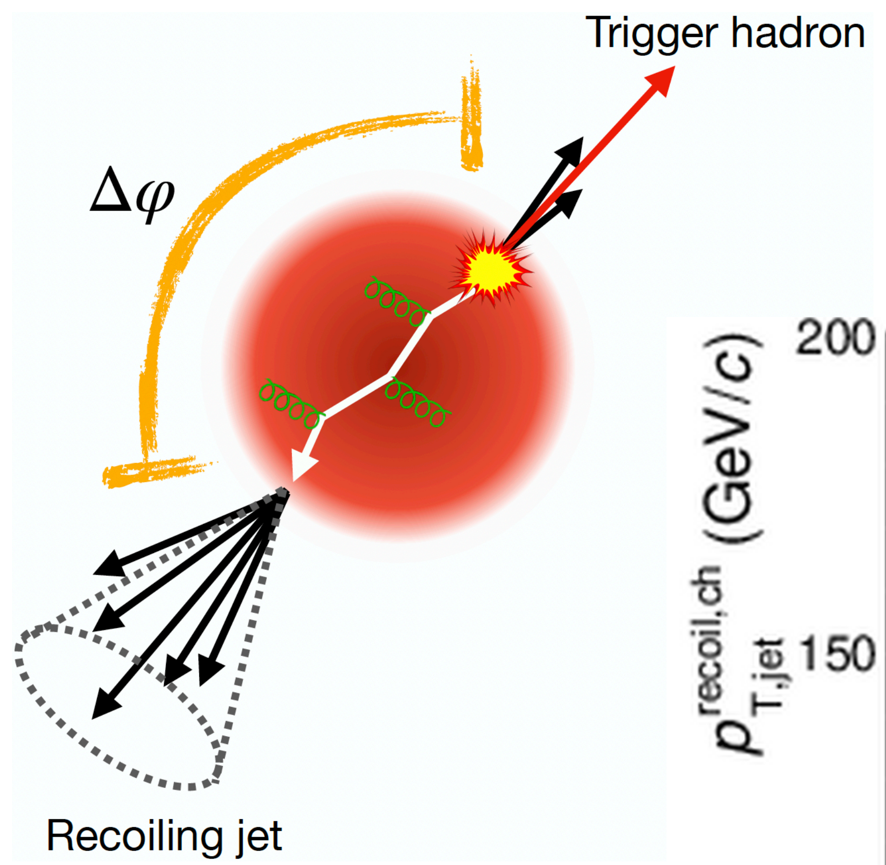
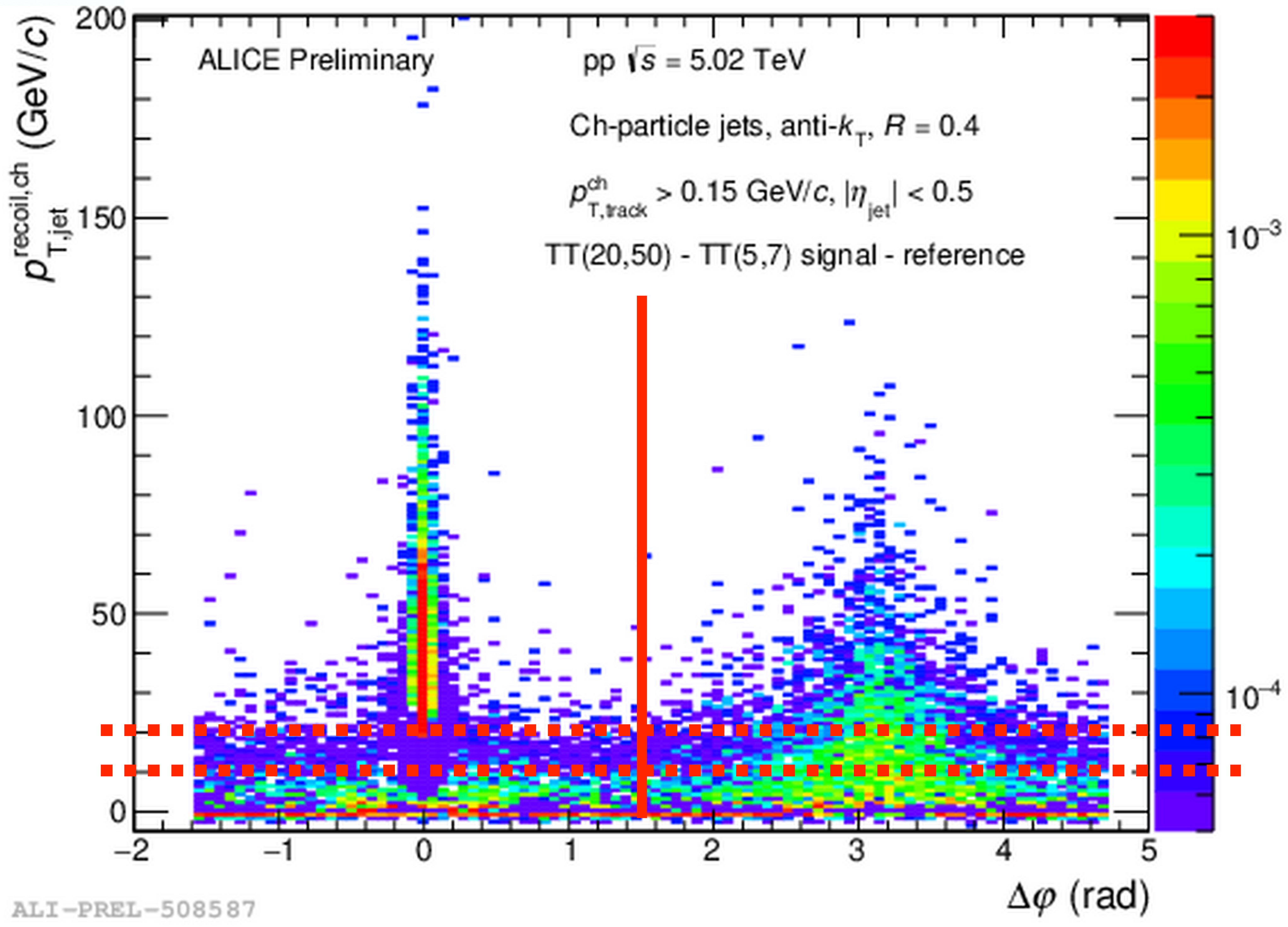
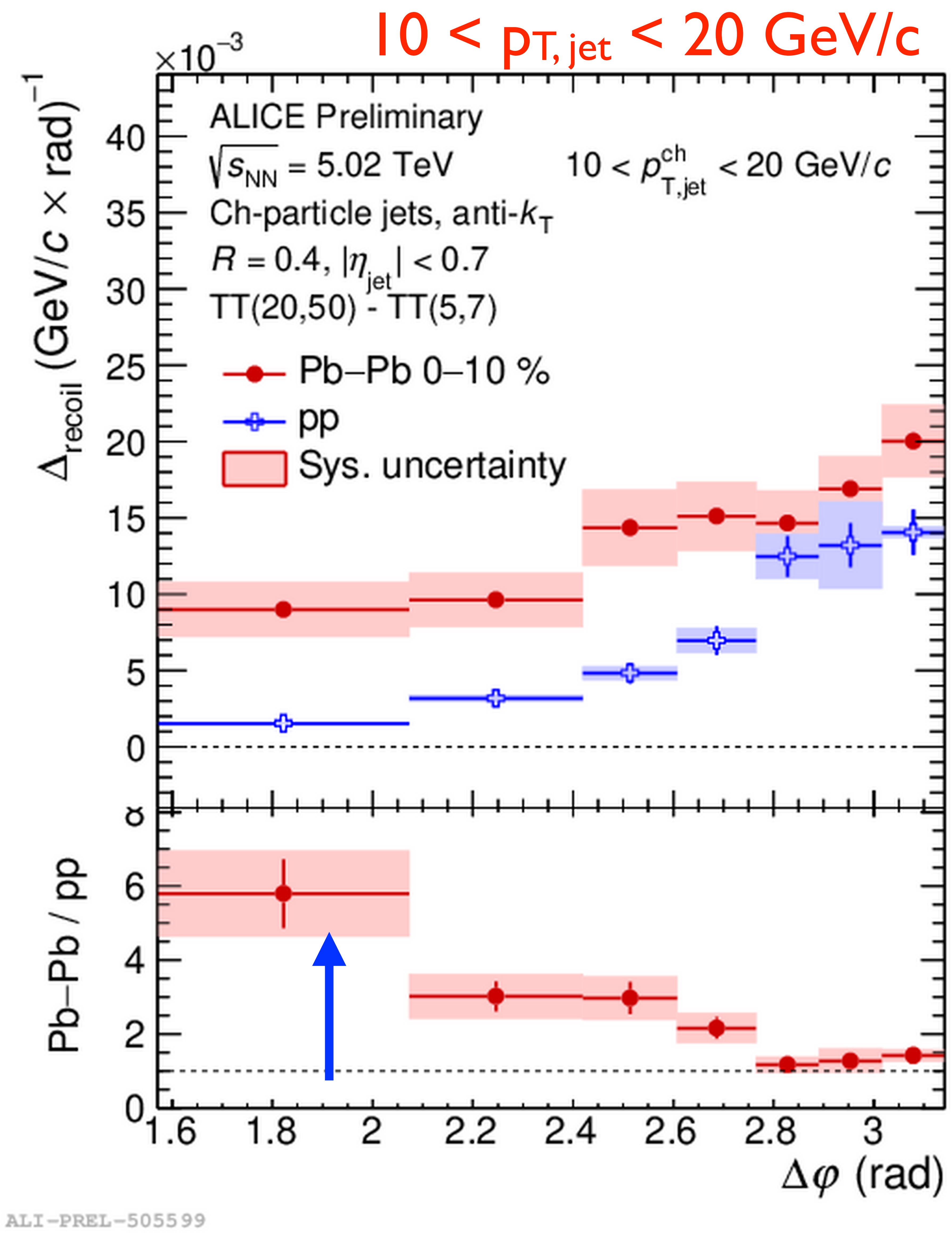
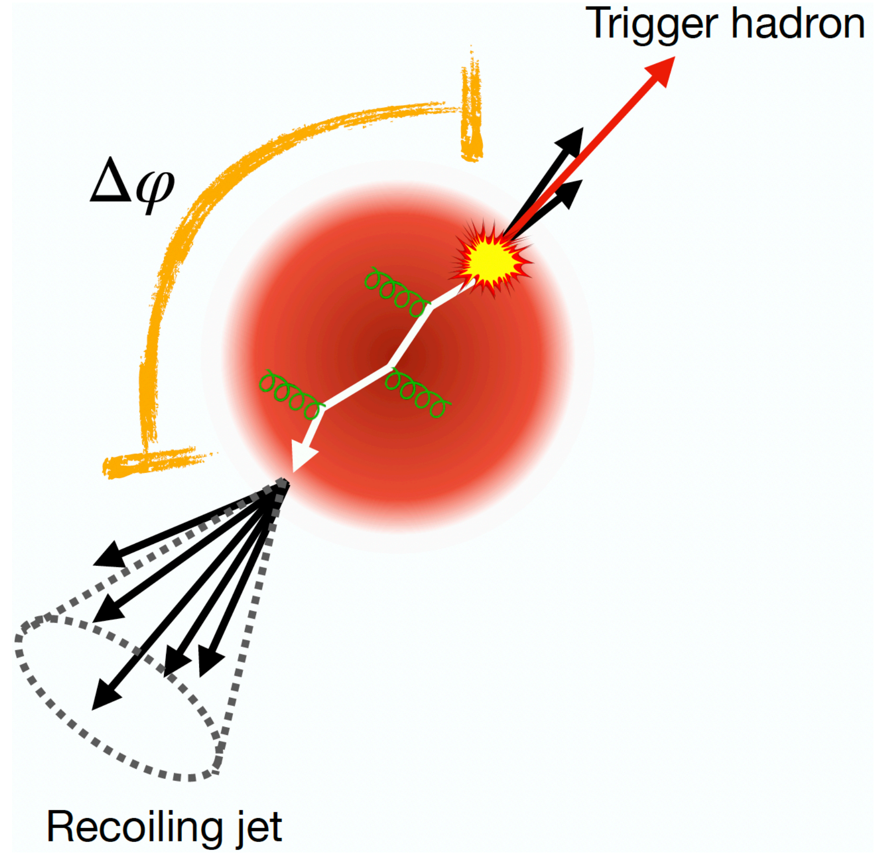




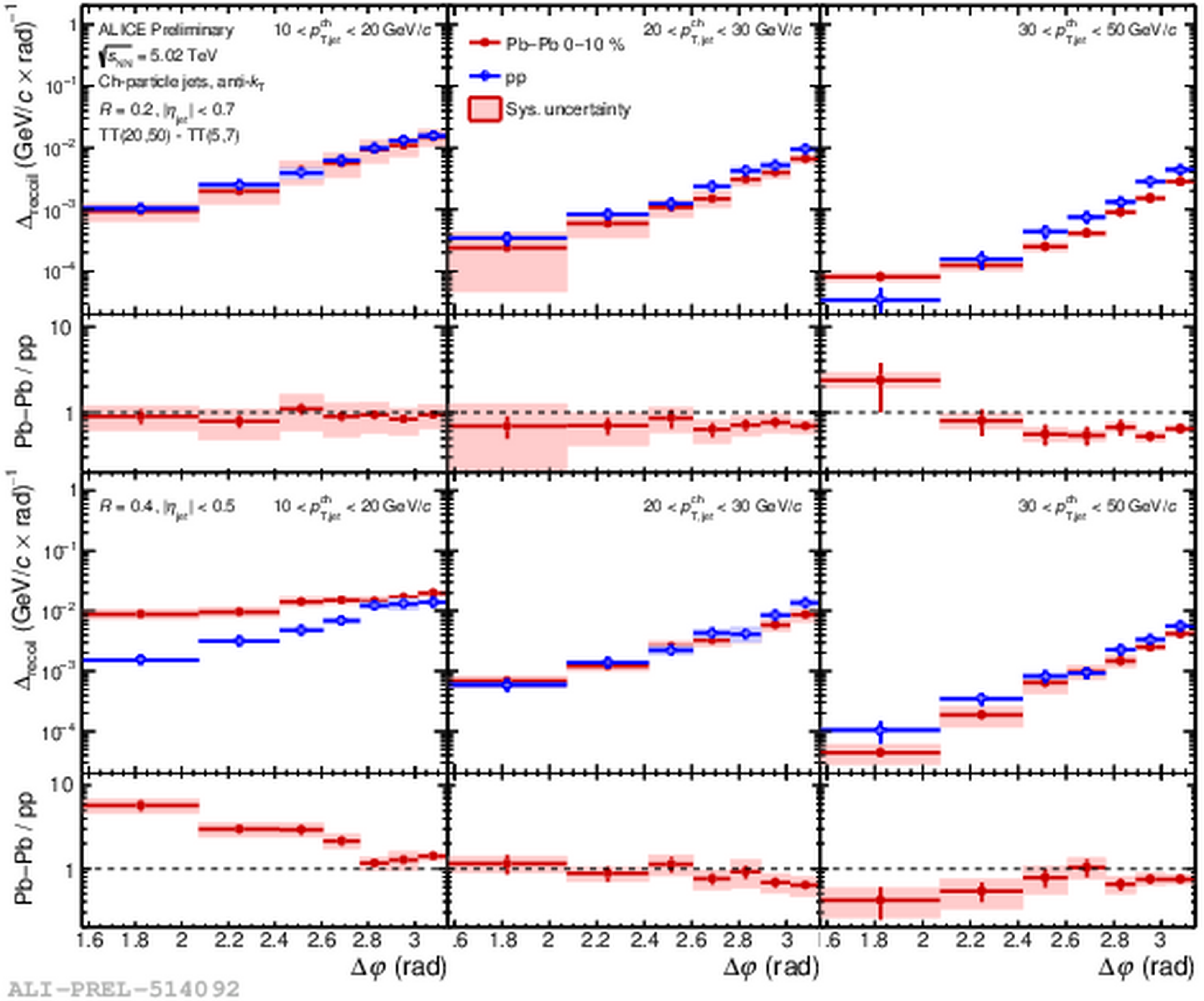


- First evidence of broadening of h-jet azimuthal correlations for soft jets

$\Delta\varphi$ results - angular deflections



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



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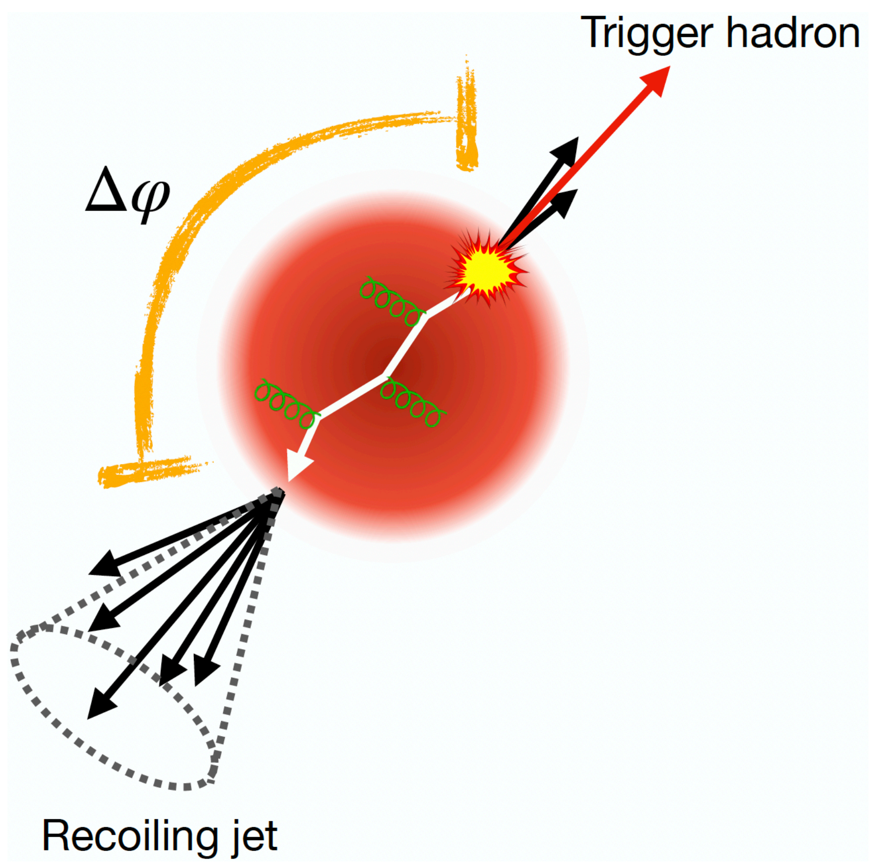
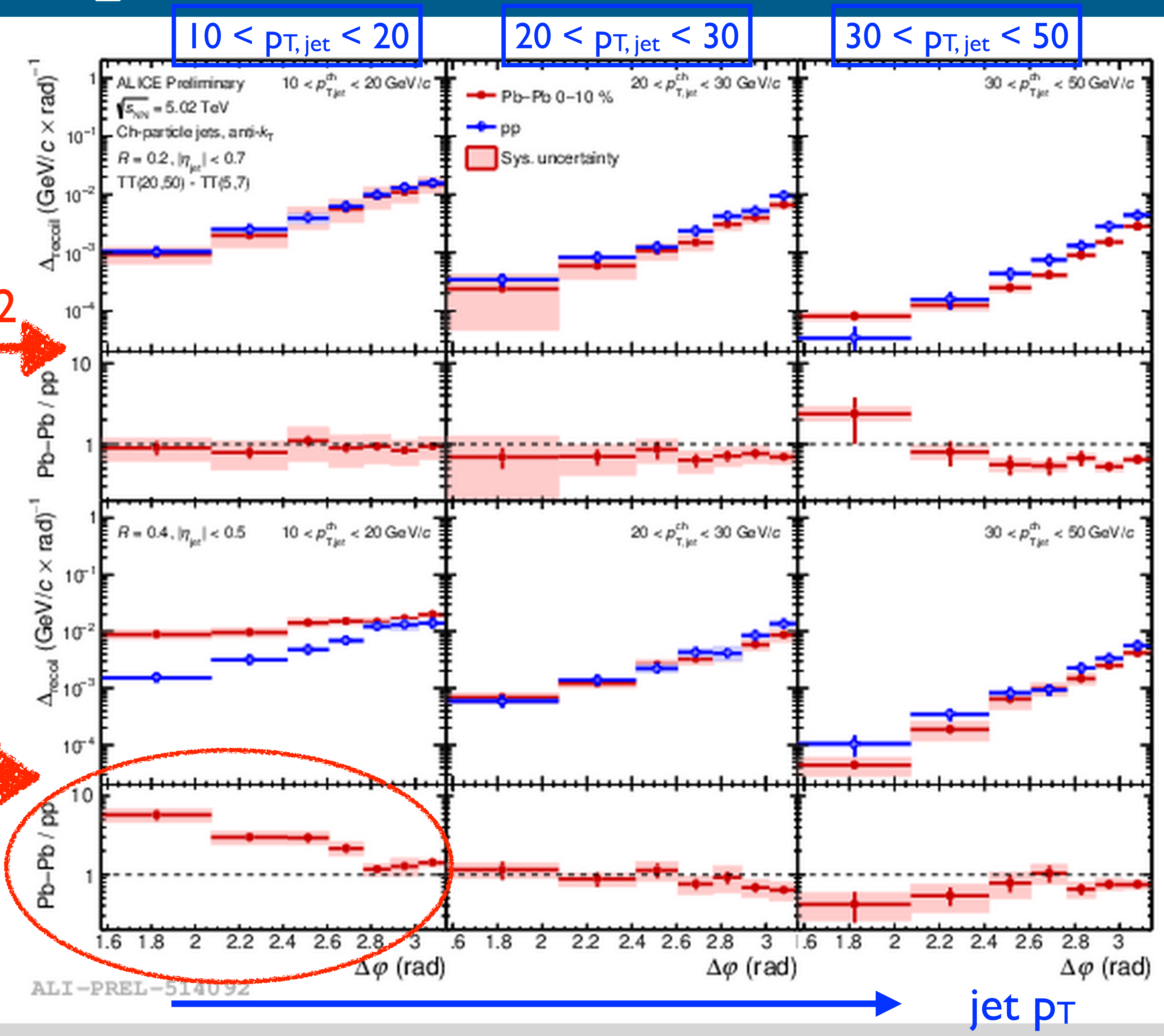


R = 0.2

R = 0.4



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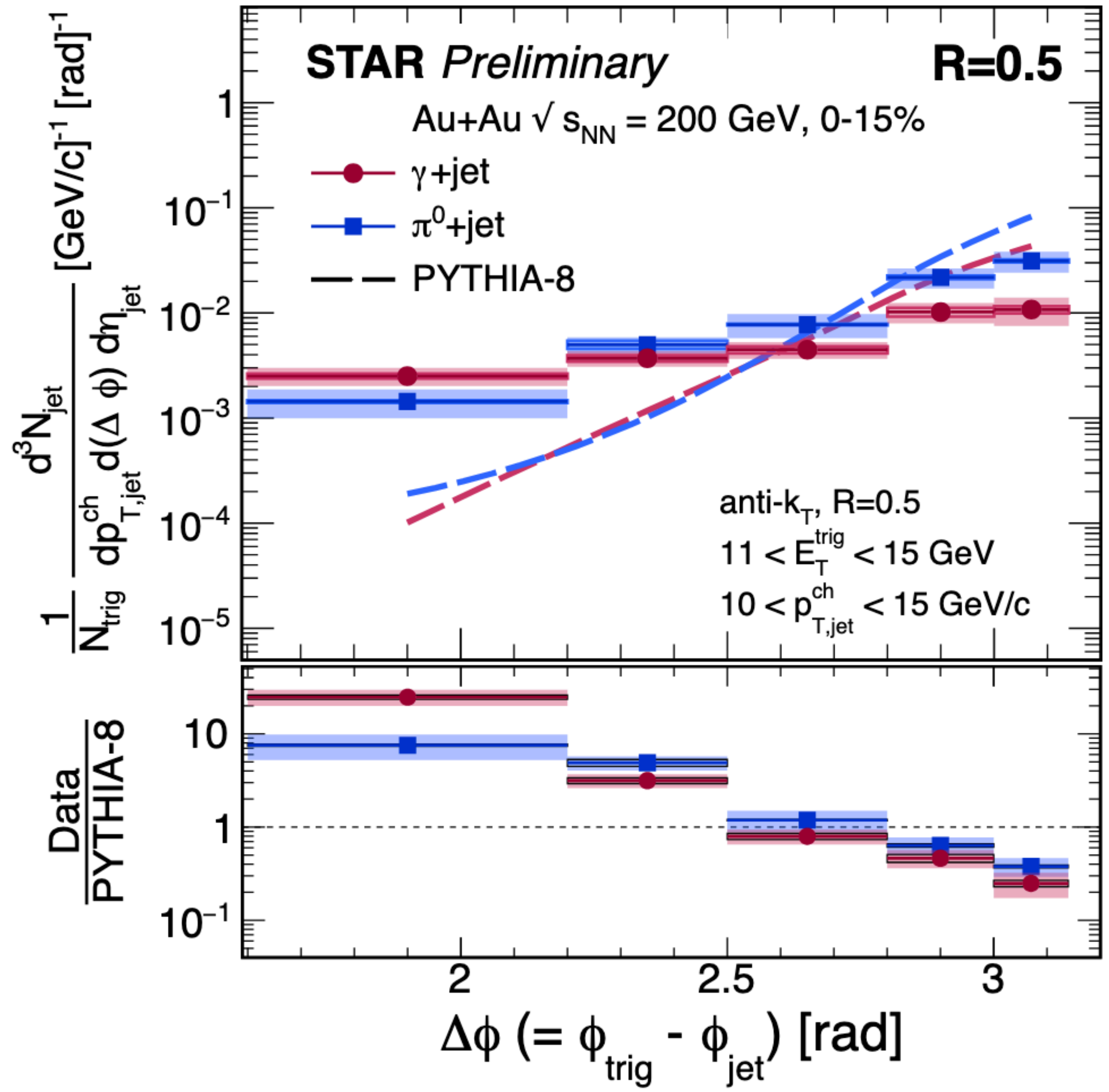
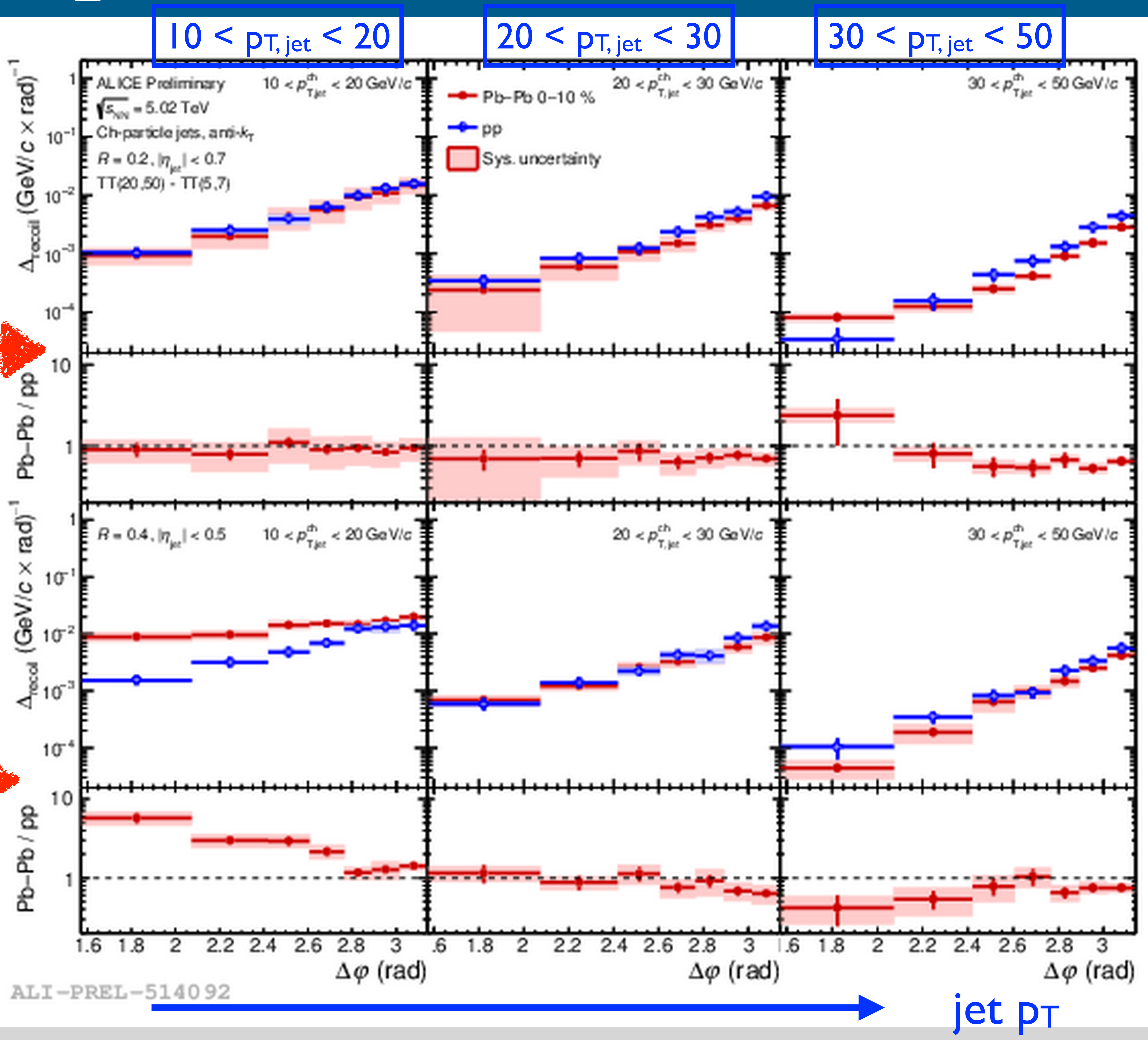
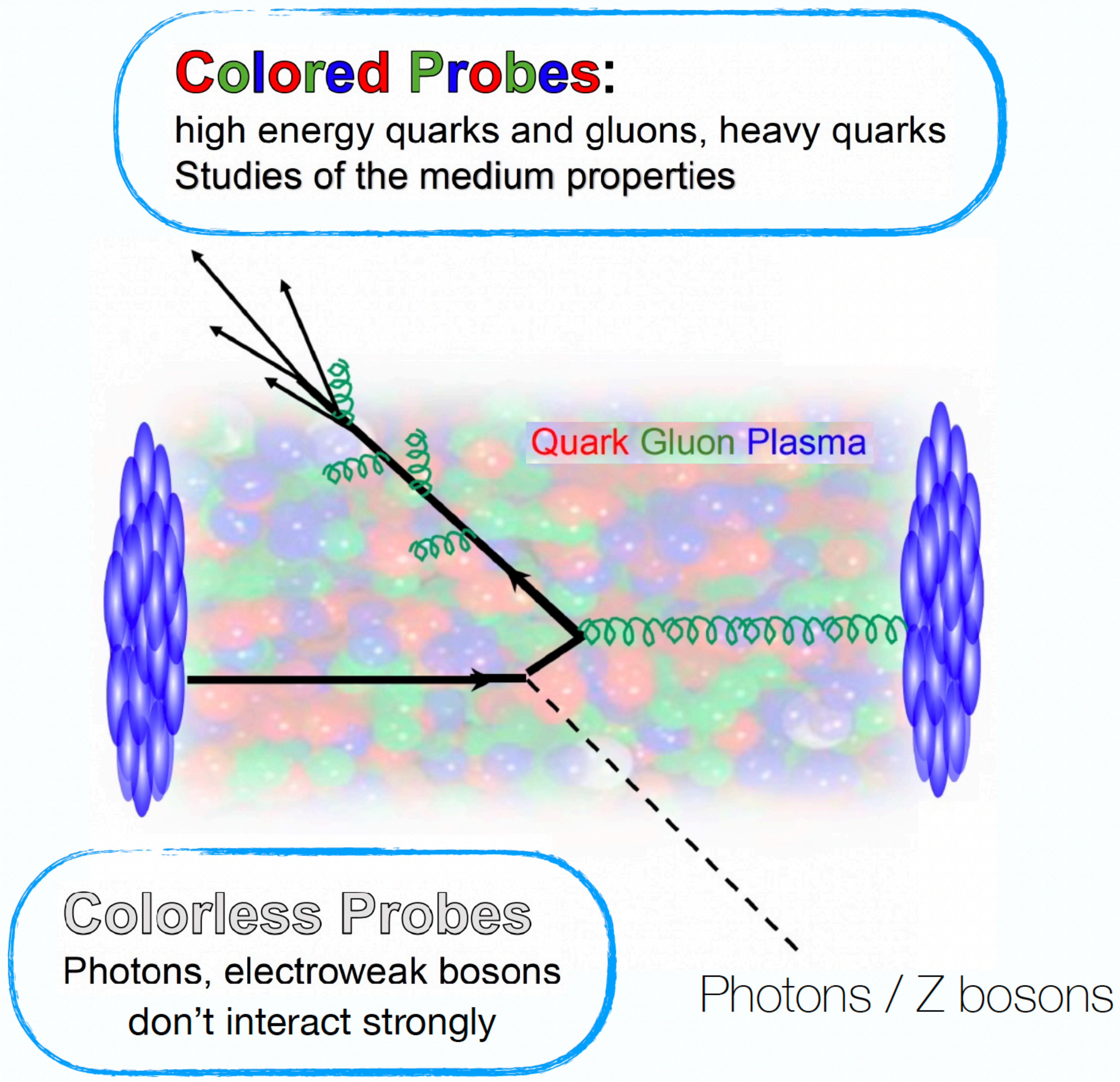
$\Delta\varphi$ results - angular deflections



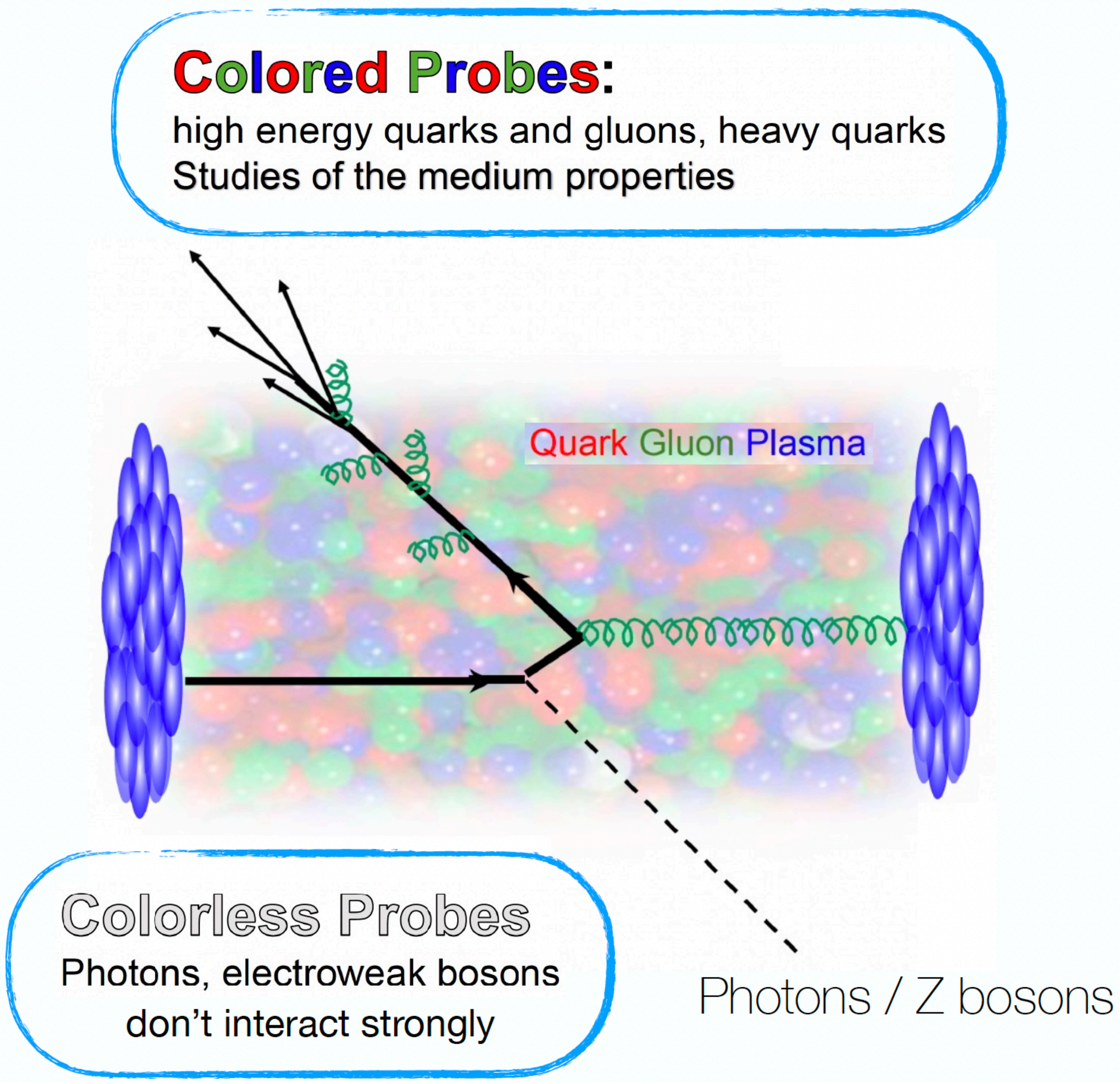


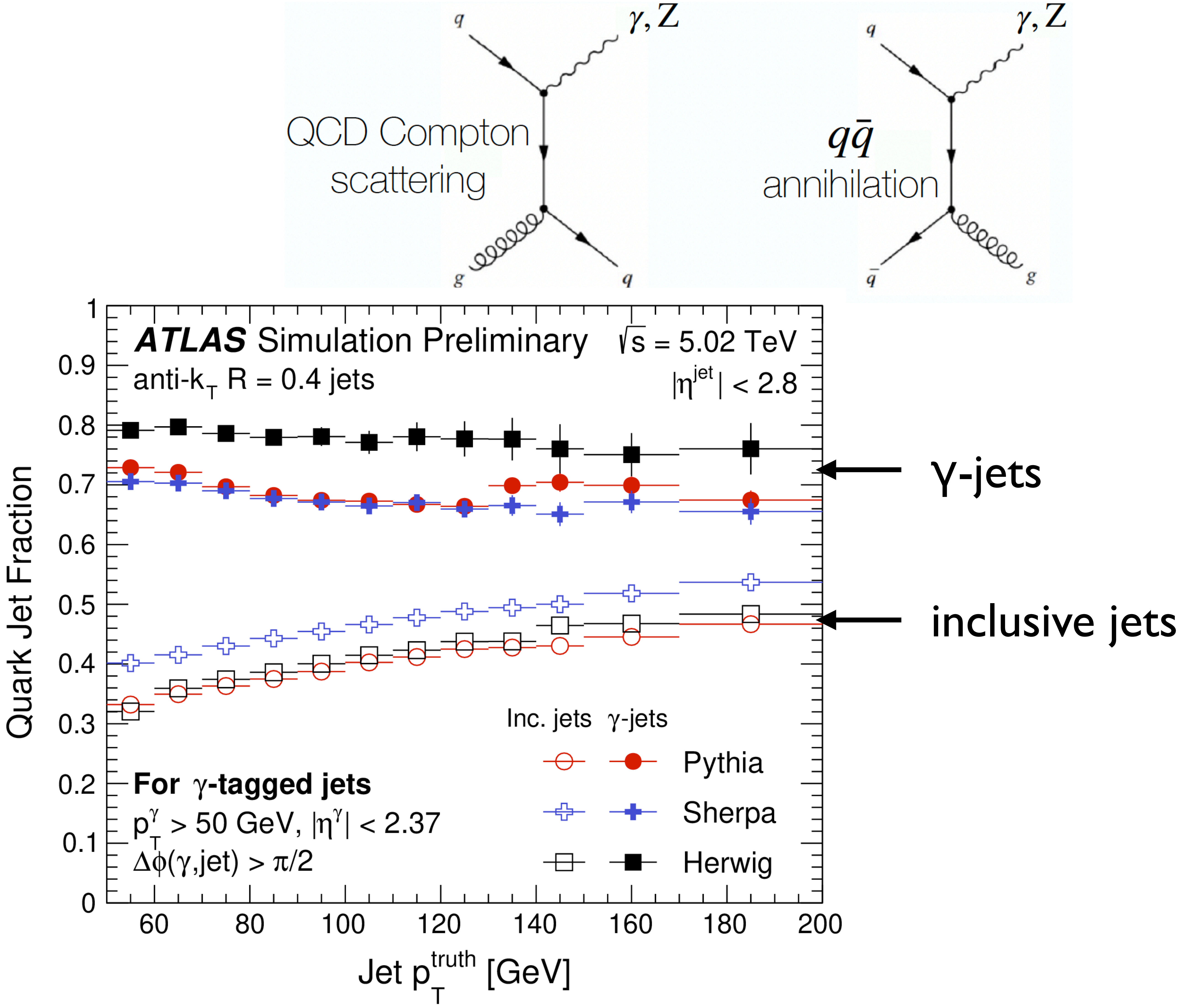
- First evidence of broadening of h-jet azimuthal correlations for soft jets
- Similar observation was also found by STAR for γ/π^0- triggered recoil jets



Tagging initial jet energy

Colorless probes





Tagging initial jet energy

Increasing quark-jet fraction

Color-charge dependence of R_{AA}

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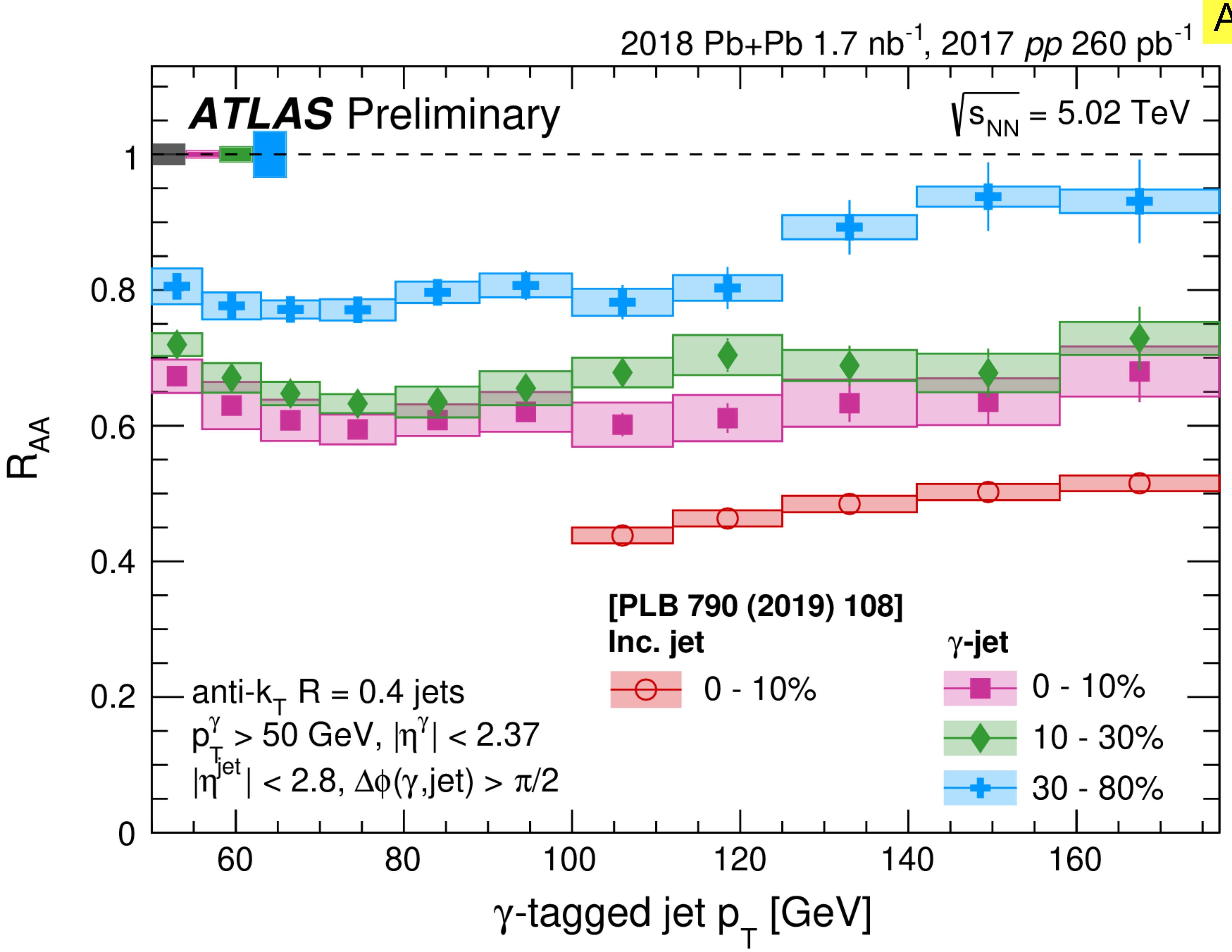
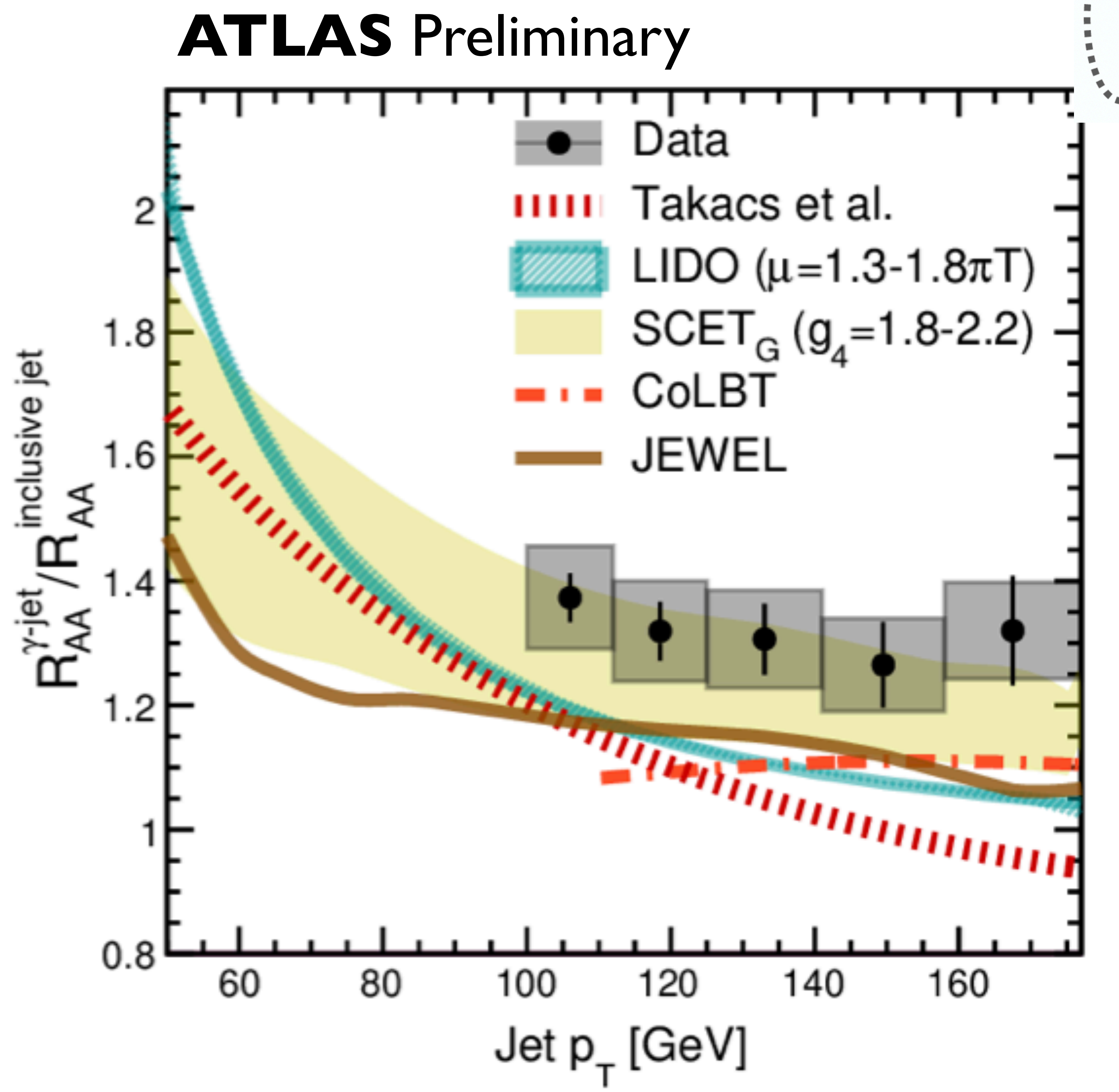
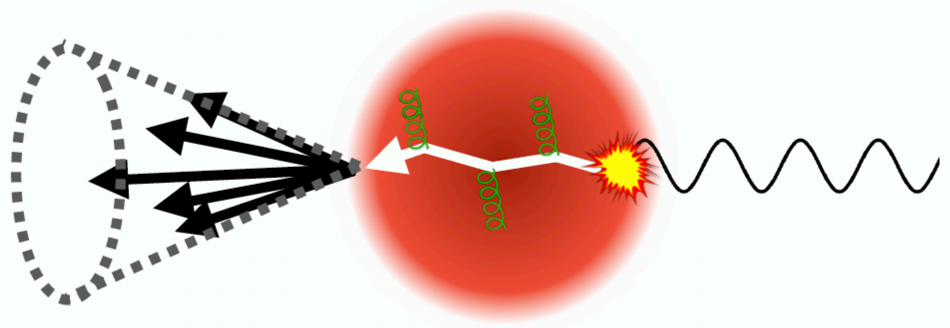
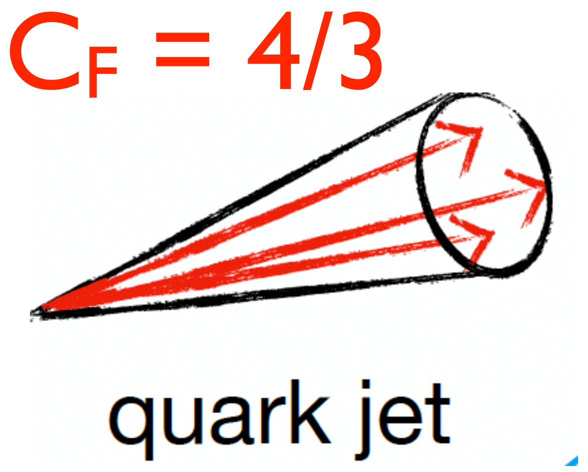
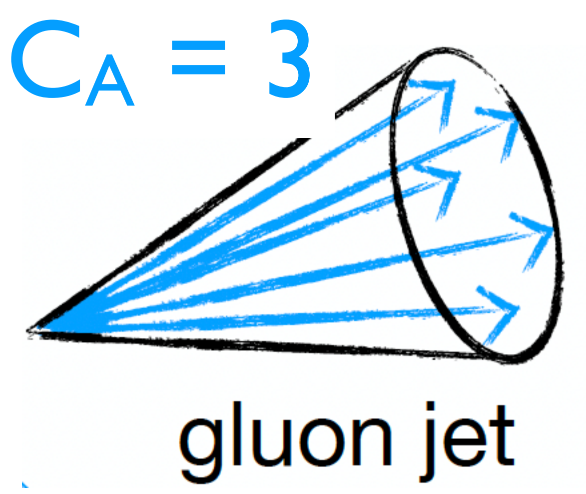




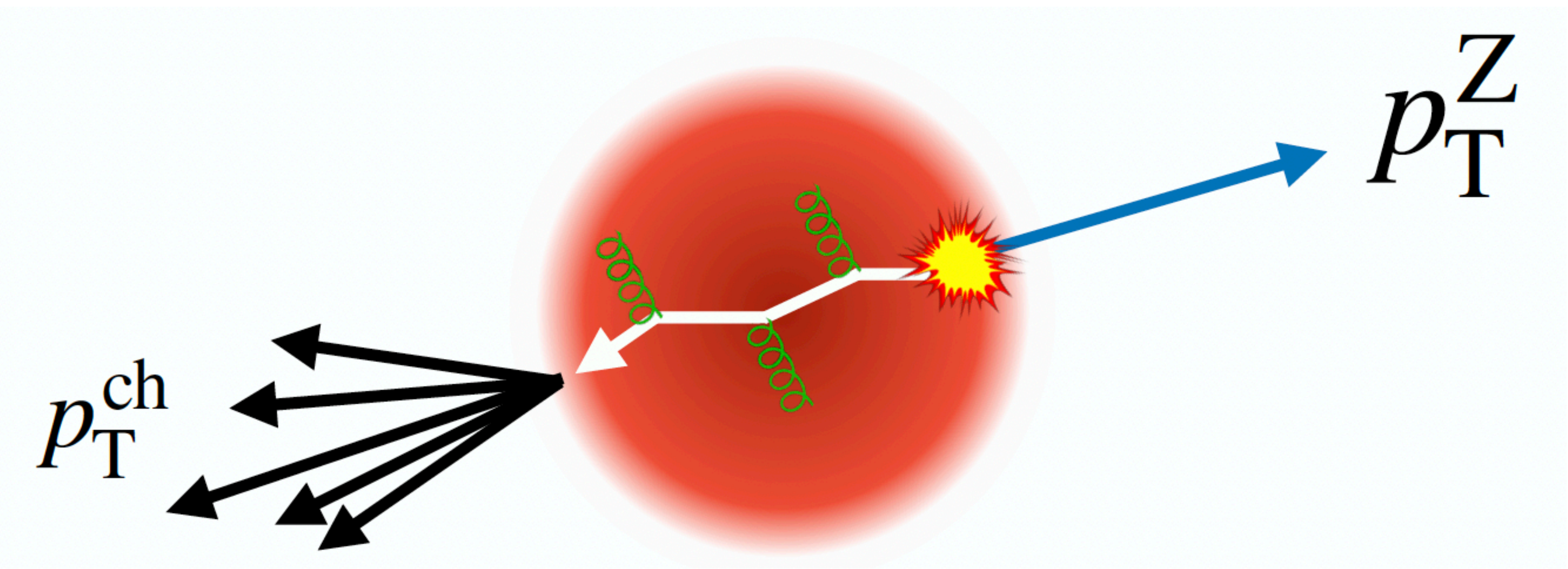






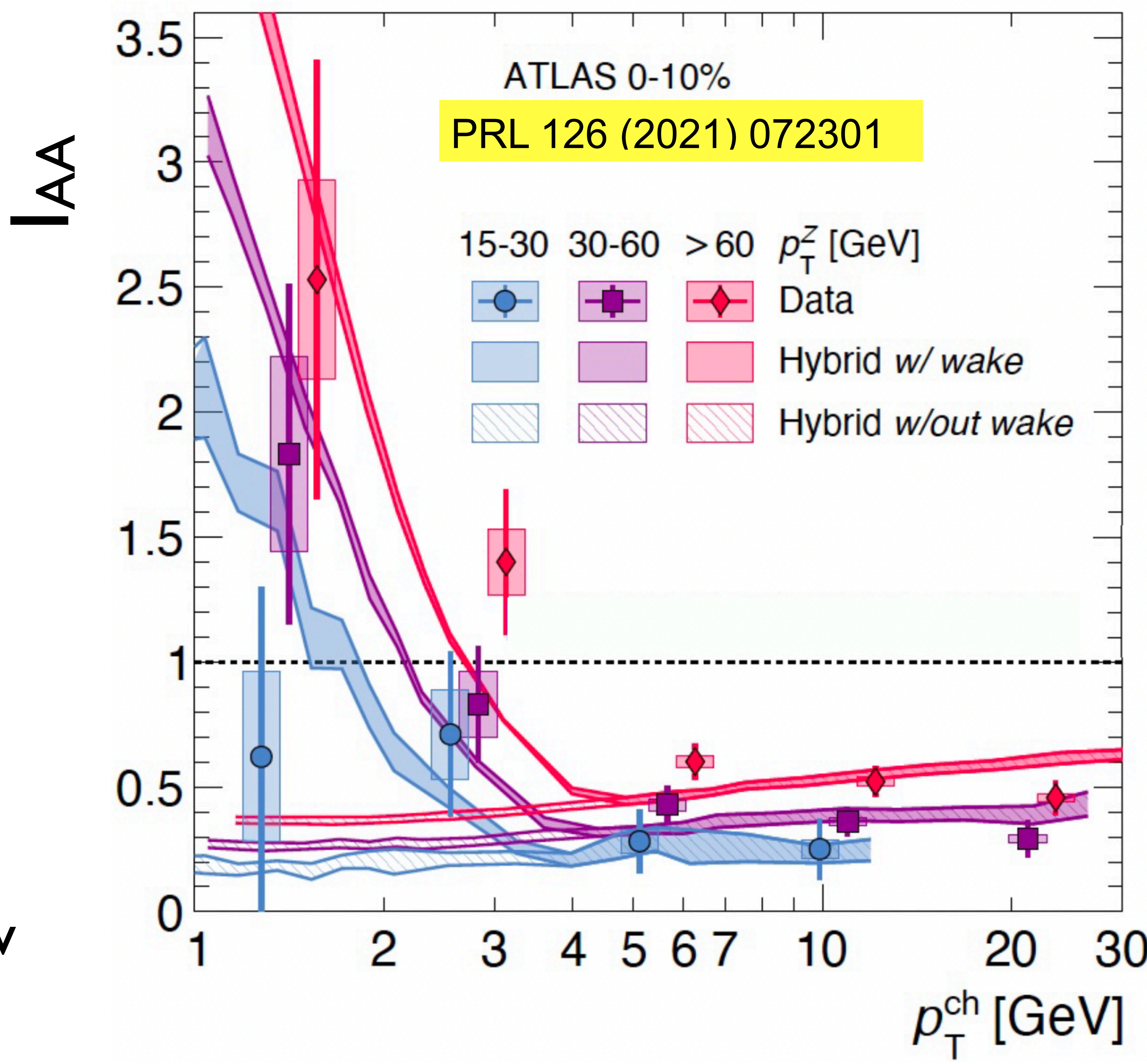
- Photon-tagged (quark-enhanced) jets being significantly less suppressed than inclusive jets
  - quark jets less active in medium, fewer radiating prongs → color factor dependence of parton-medium interaction

Charged particle yield recoiling from Z



$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi}$$

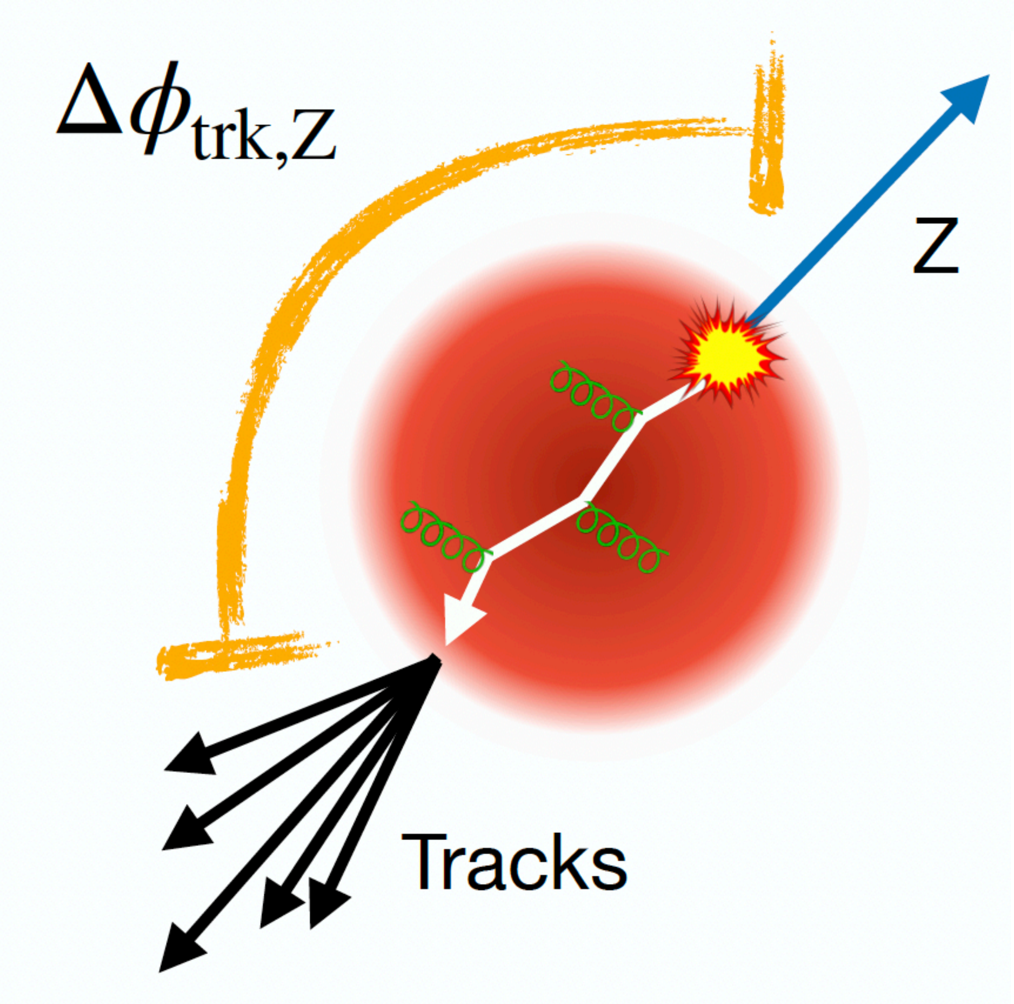
$$I_{AA} = \frac{Y_{Pb-Pb}}{Y_{pp}}$$

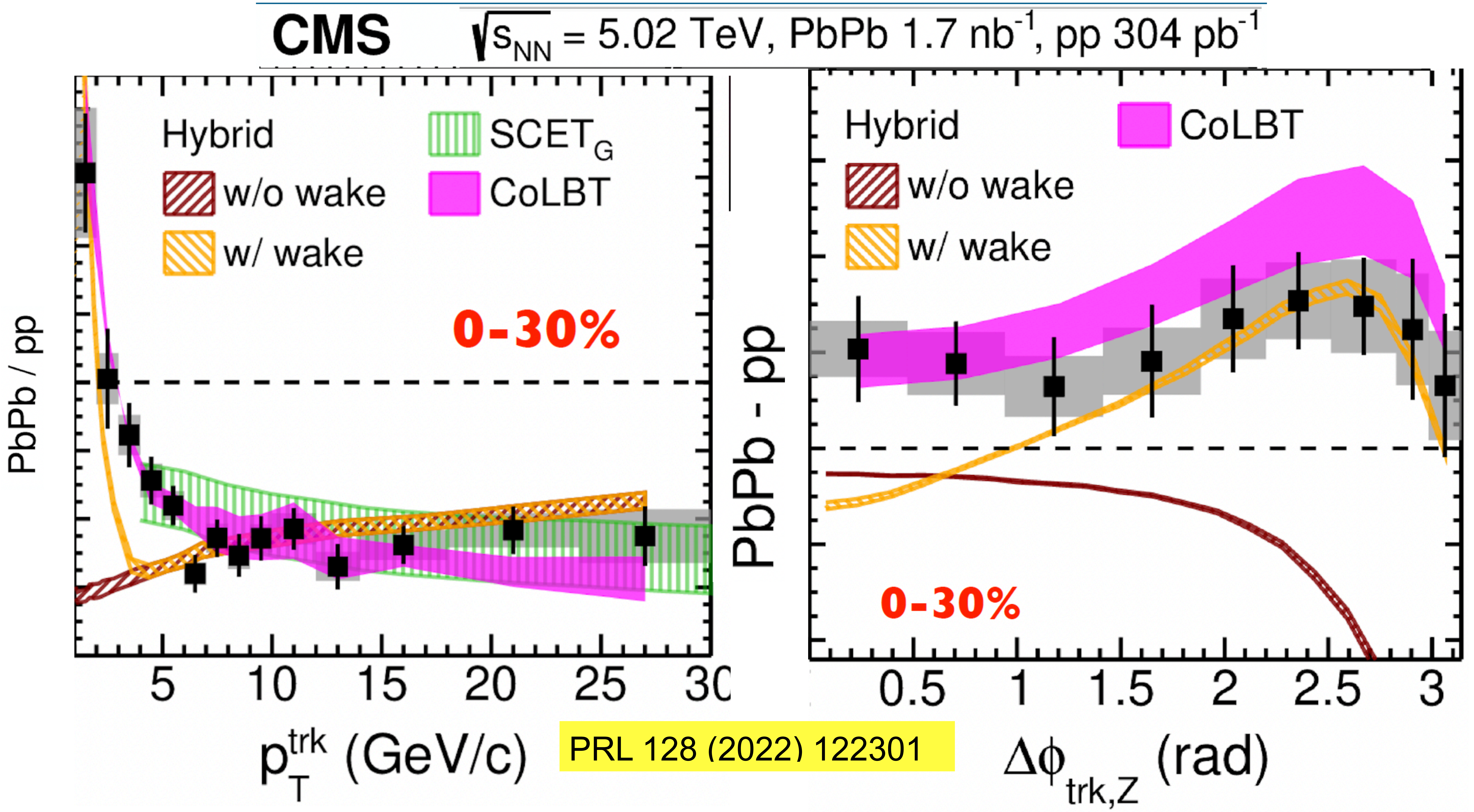


- Study of charged particles opposite to Z without jet reconstruction allows to understand the modification of jet constituents and jet fragmentation functions
  - Colorless Z sets initial scattering proxy, allows probing low pT range
- Low pT excess can be described by medium response in hybrid model →energy redistribution due to quenching

Charged particle yield recoiling from Z

$$Y \equiv \frac{1}{N_Z} \frac{d^2 N_{ch}}{dp_T^{ch}\, d\Delta\phi}$$





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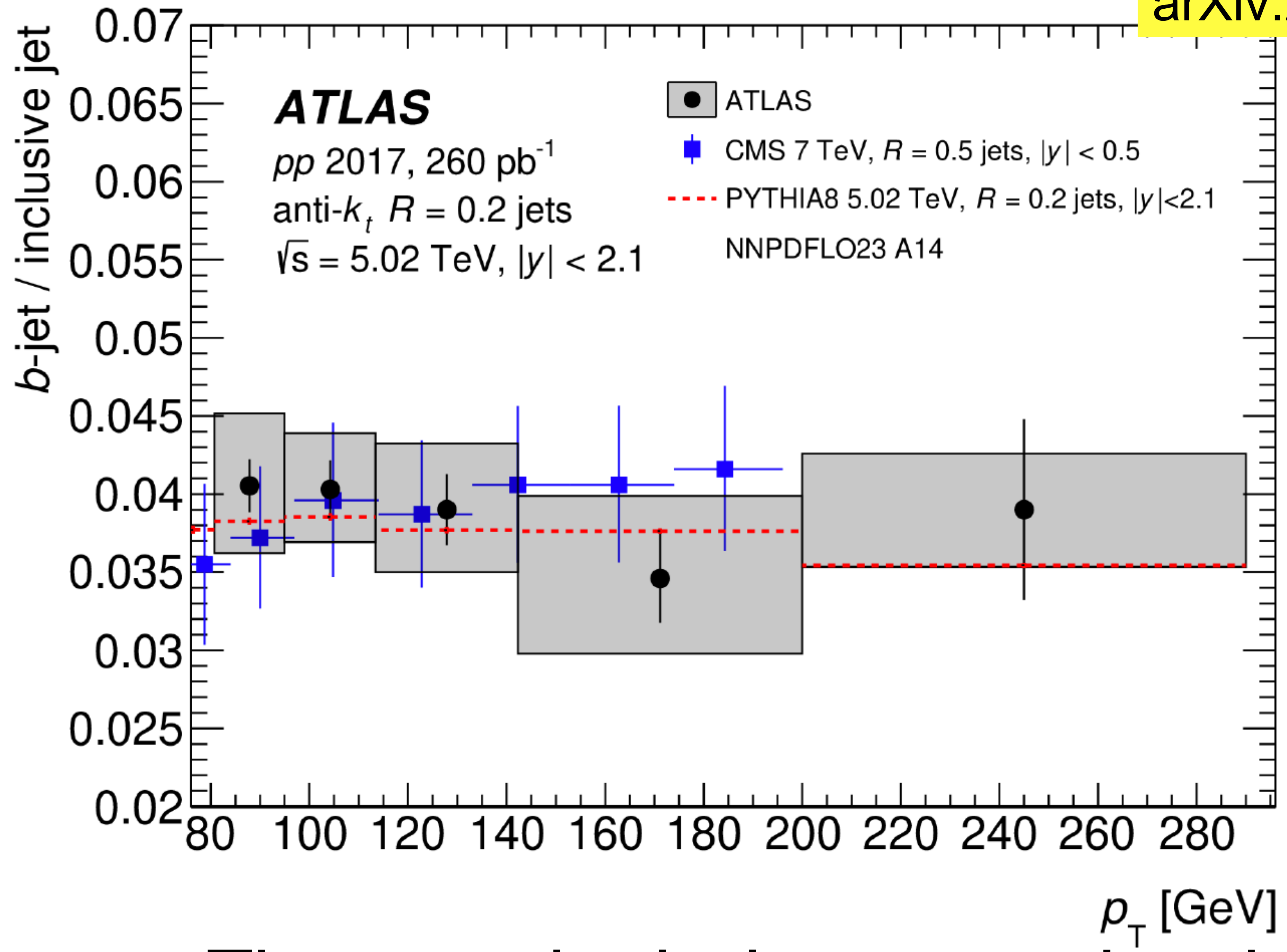
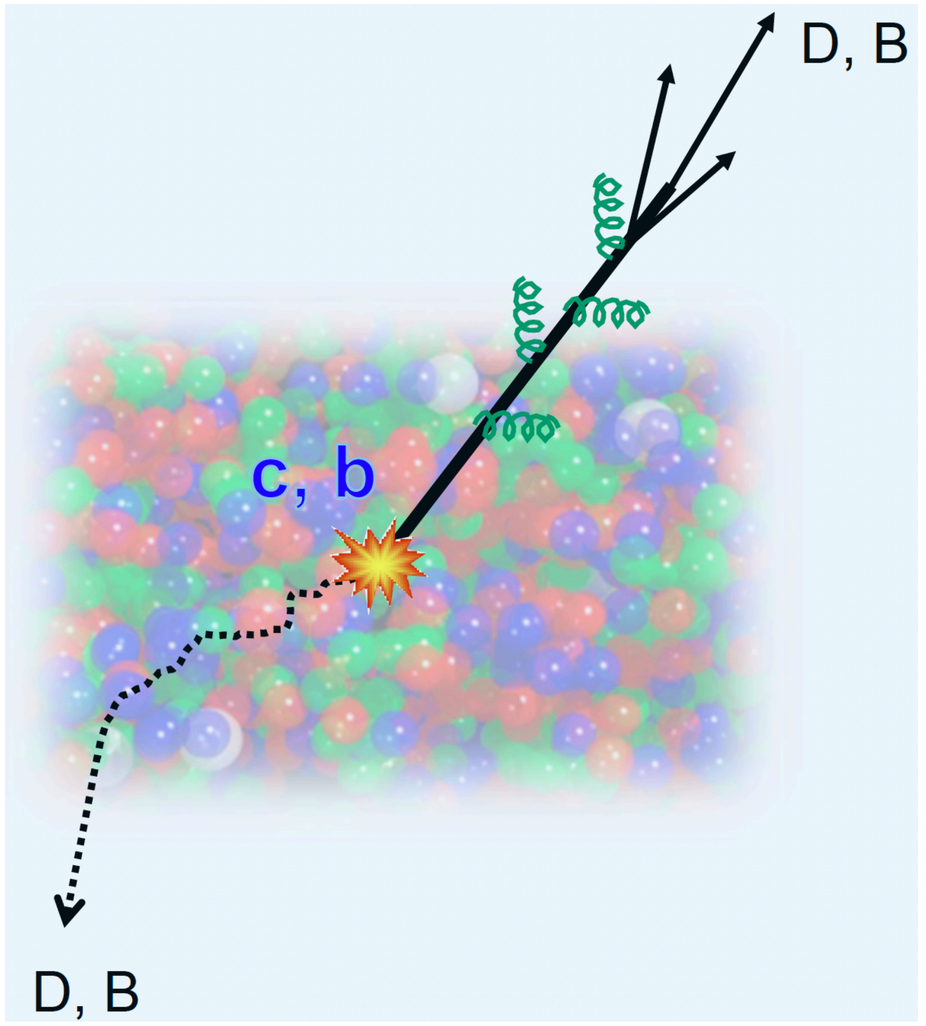
- Low p_T excess and high p_T suppression →energy redistribution due to quenching
- Excess of particle yields down to the $\phi^{trk} \approx \phi^Z$ in central PbPb collisions
  - quantitative agreement with models including medium response

Flavour dependence of jet suppression

arXiv:2204.13530

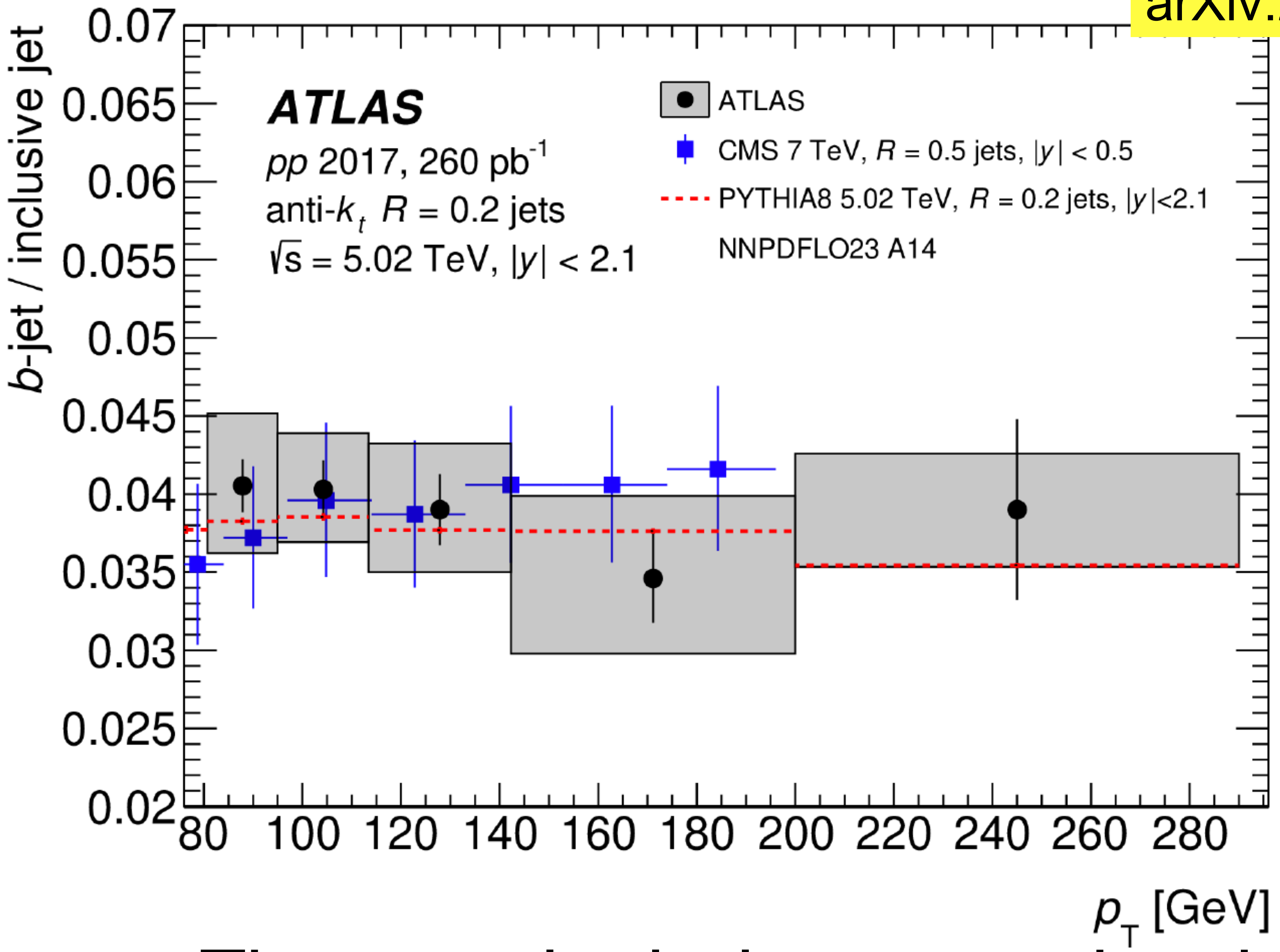


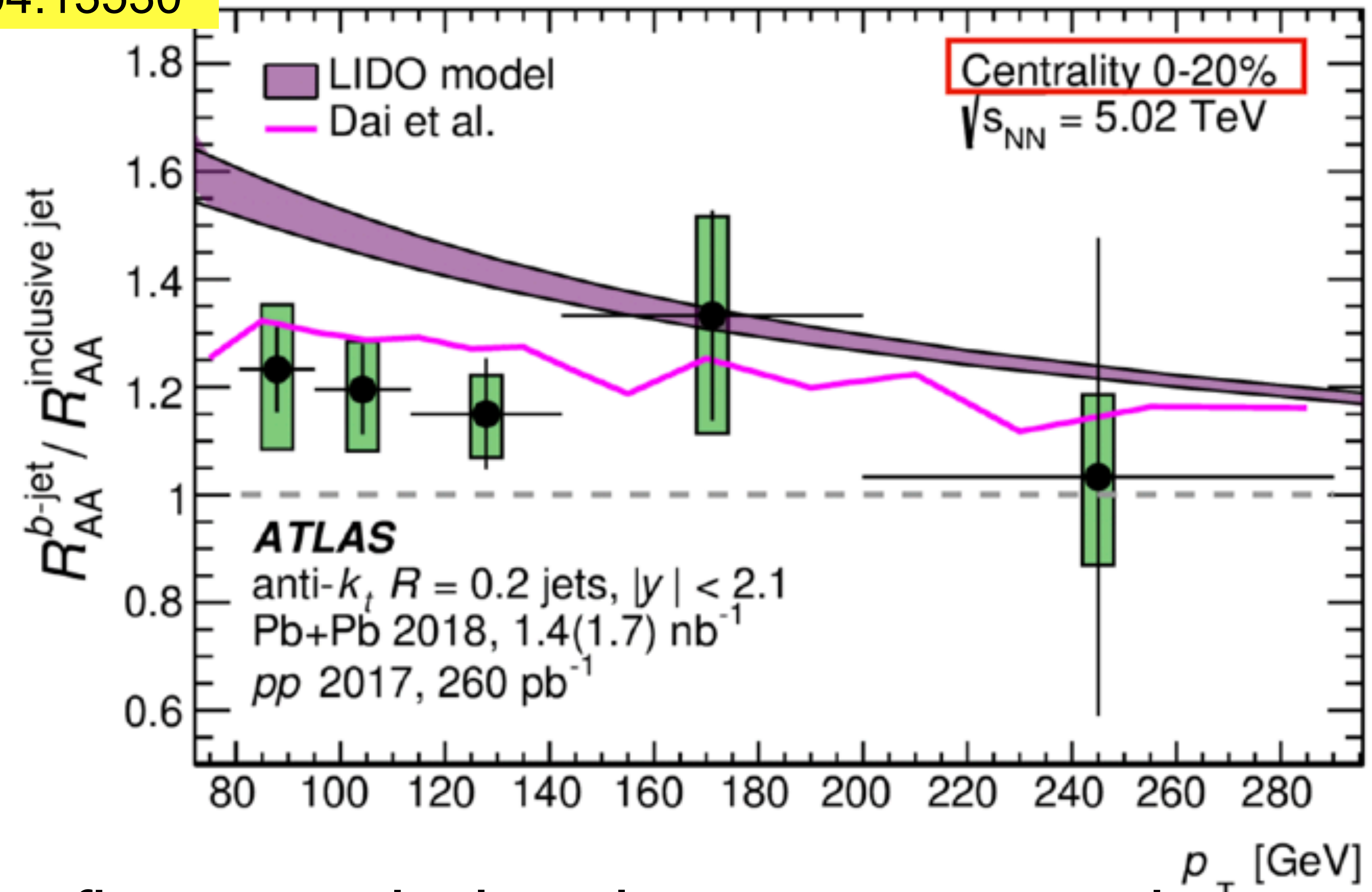


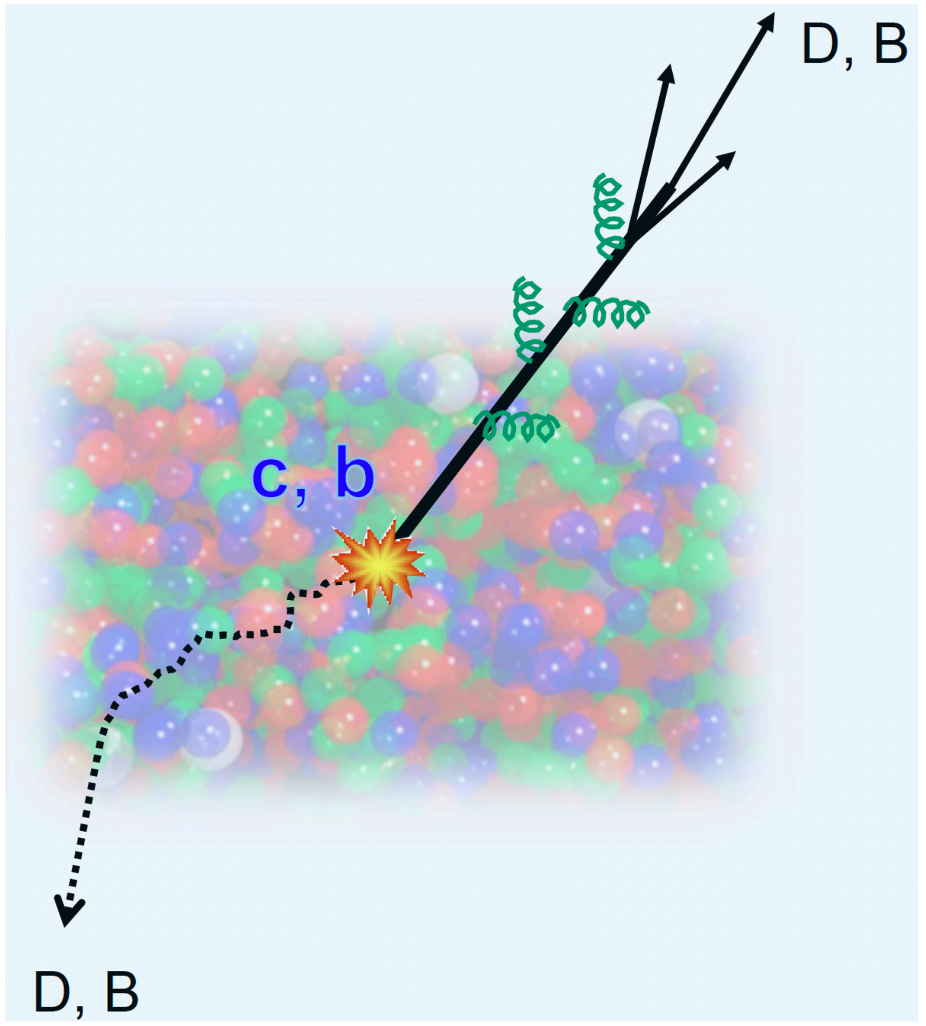
- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation

Flavour dependence of jet suppression

arXiv:2204.13530

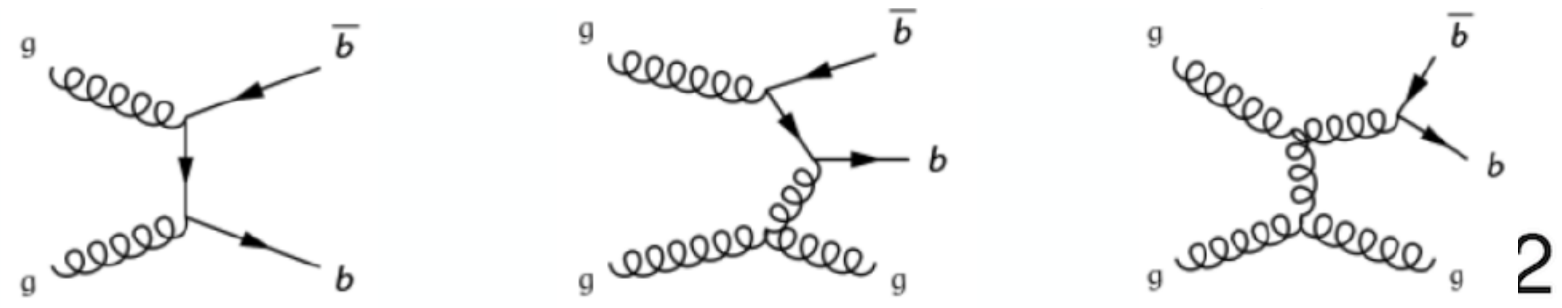


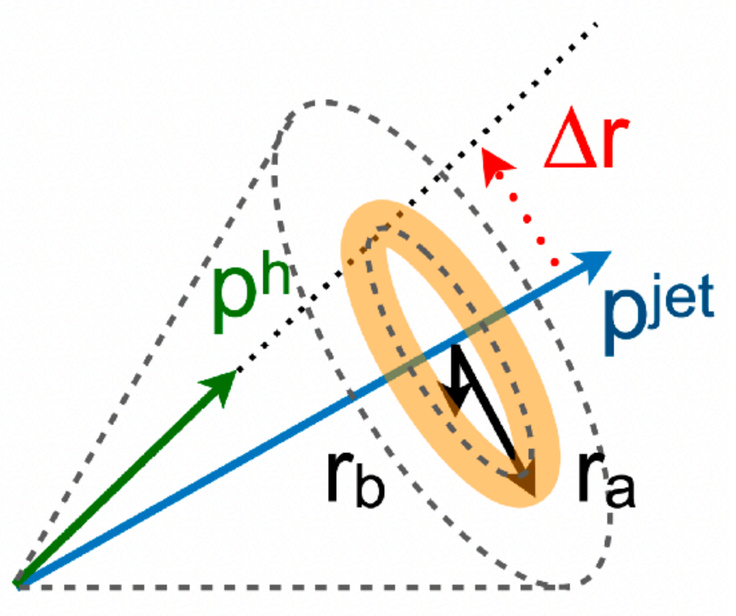




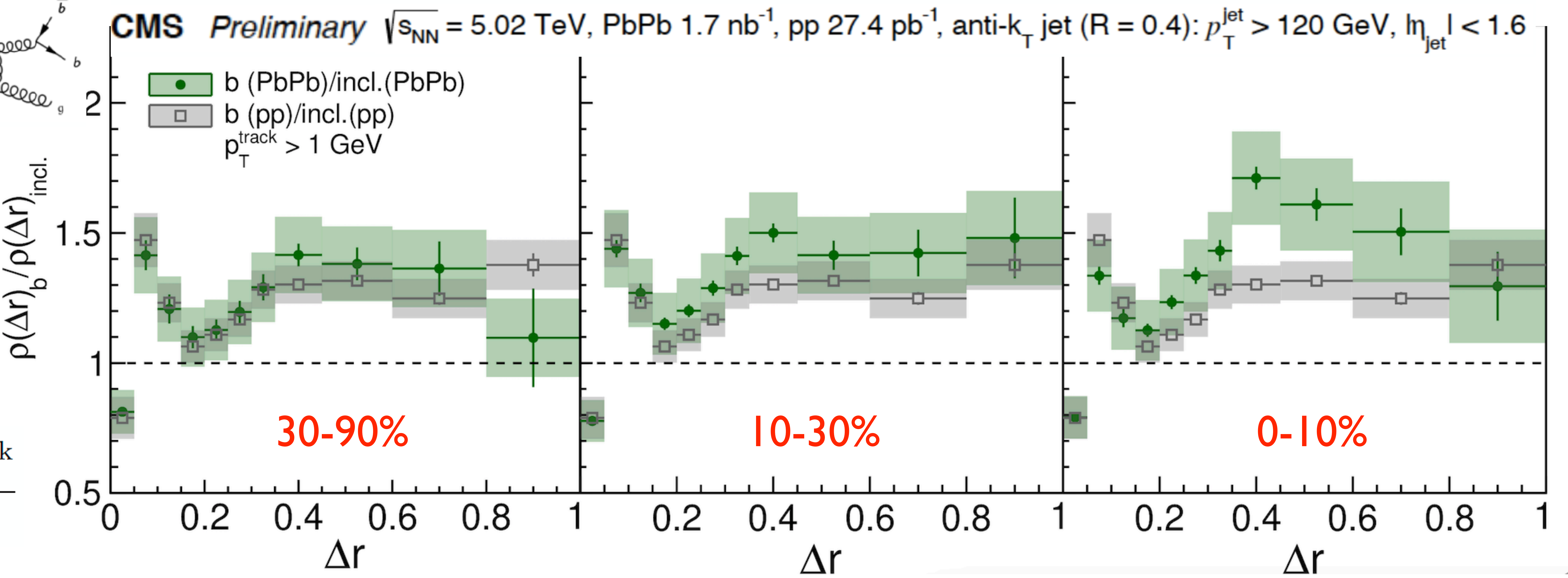
- Theoretical calculations predicts heavy flavor quarks lose less energy in medium compared to light quarks
- Fraction of b-jet to inclusive jet cross section independent of collision energy and jet p_T
  - relevant for R_{AA} modification interpretation
- Less suppression of b-jets than inclusive jets in most central collisions
  - color charge and mass dependence of energy loss

Mass dependence of jet energy redistribution



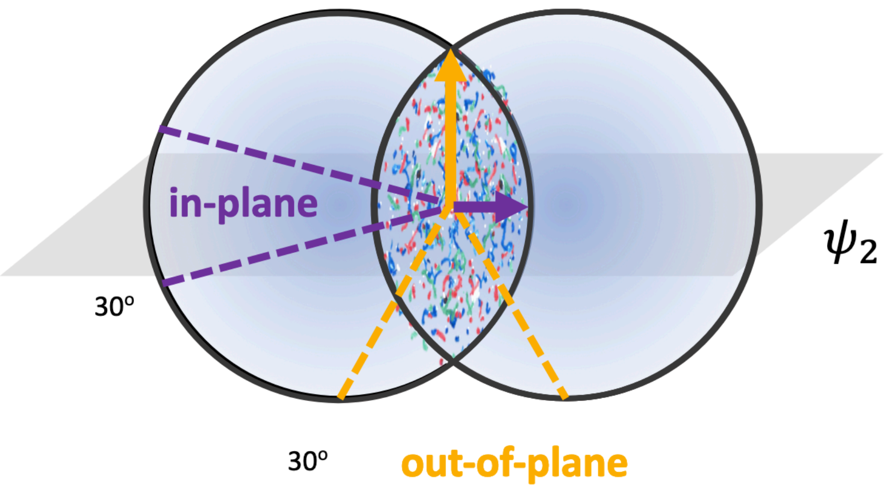


$$\rho(\Delta r) = \frac{1}{\delta r}\frac{\Sigma_{\mathrm{jet}}\Sigma_{\mathrm{trk}\in(\Delta r_a,\Delta r_b)}p_{\mathrm{T}}^{\mathrm{trk}}}{\Sigma_{\mathrm{jet}}\Sigma_{\mathrm{trk}}p_{\mathrm{T}}^{\mathrm{trk}}}$$



- b-jet shapes are sensitive to production (b-jets from GSP boarder than b jets from other processes) and fragmentation process
- Relative modification between b and inclusive jets at large r region getting larger from peripheral to central collisions
  - Soft p_T accumulation of b-jets are stronger than inclusive jets
- No obvious centrality dependence for small angle depletion

Path length dependence of jet energy loss

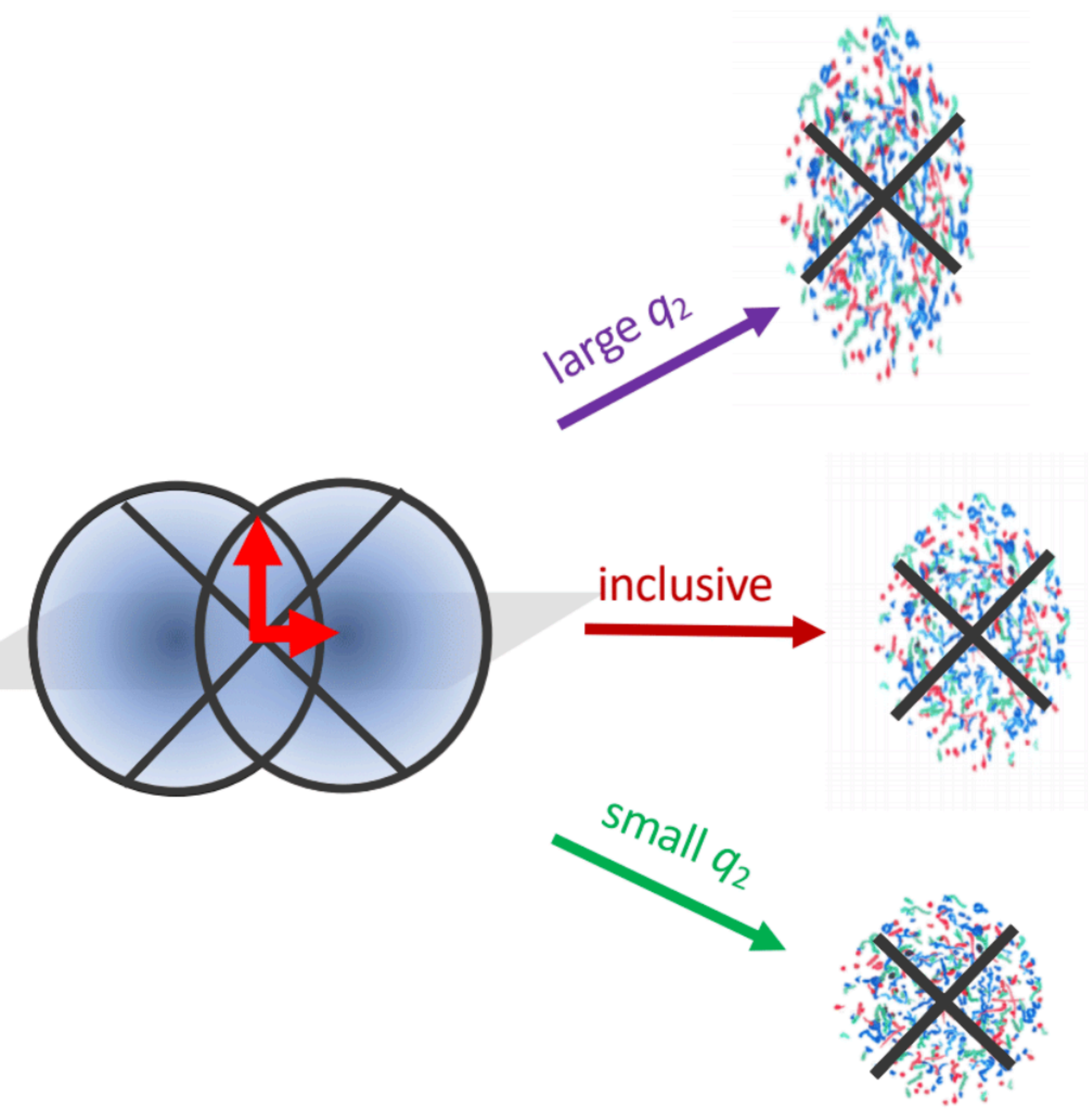


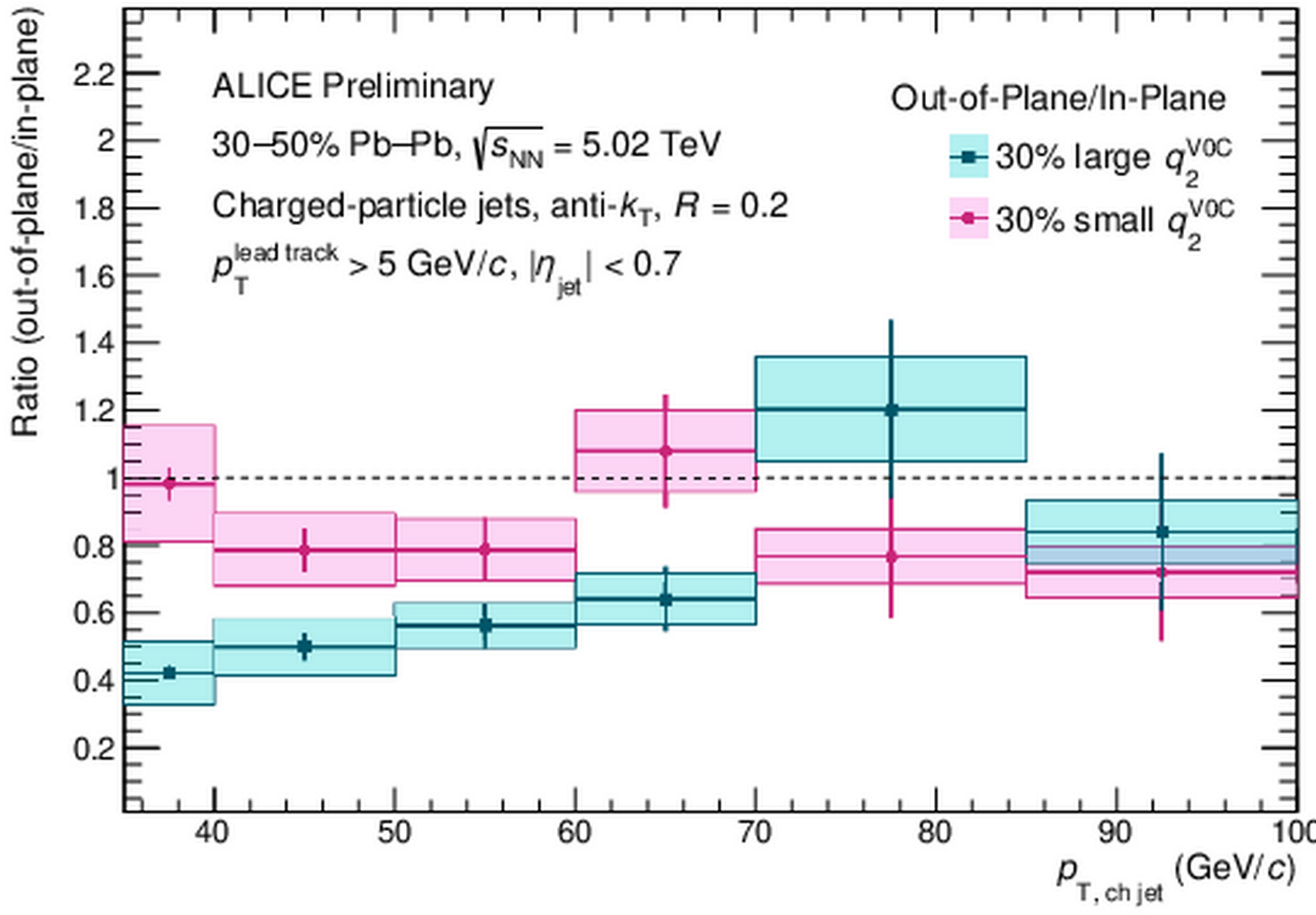
M = multiplicity

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

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

φ_i = azimuthal angle of i[th] particle





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- 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
  - consistent with stronger suppression along the out-of-plane axis

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
  - Color and mass dependent jet energy loss observation
  - Path length dependent jet quenching
  - 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