# Study of jet energy redistribution and broadening using acoplanarity measurements in Pb-Pb collisions with ALICE

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*21-25 August 2023*

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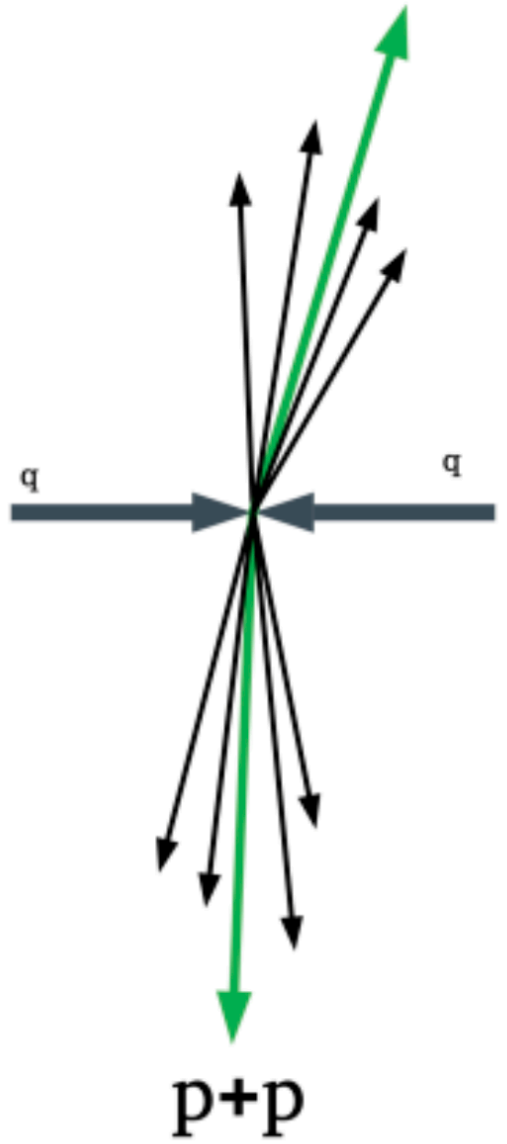
# Motivation

- Jets - collimated bunches of stable hadrons, originating from partons after fragmentation and hadronization
- Jet production in vacuum
  - Provides constraints to pQCD calculation
  - Serves as a reference for measurements in heavy-ion collisions



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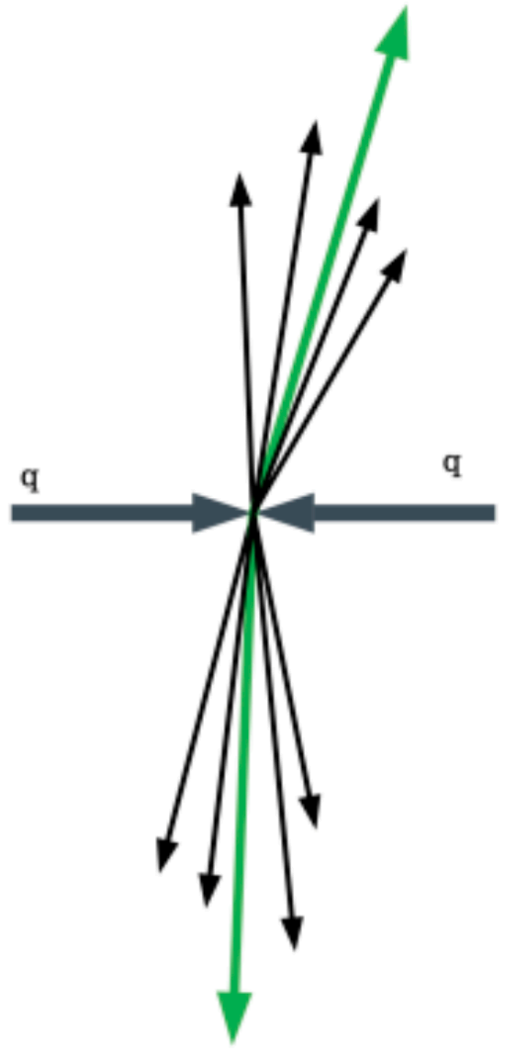
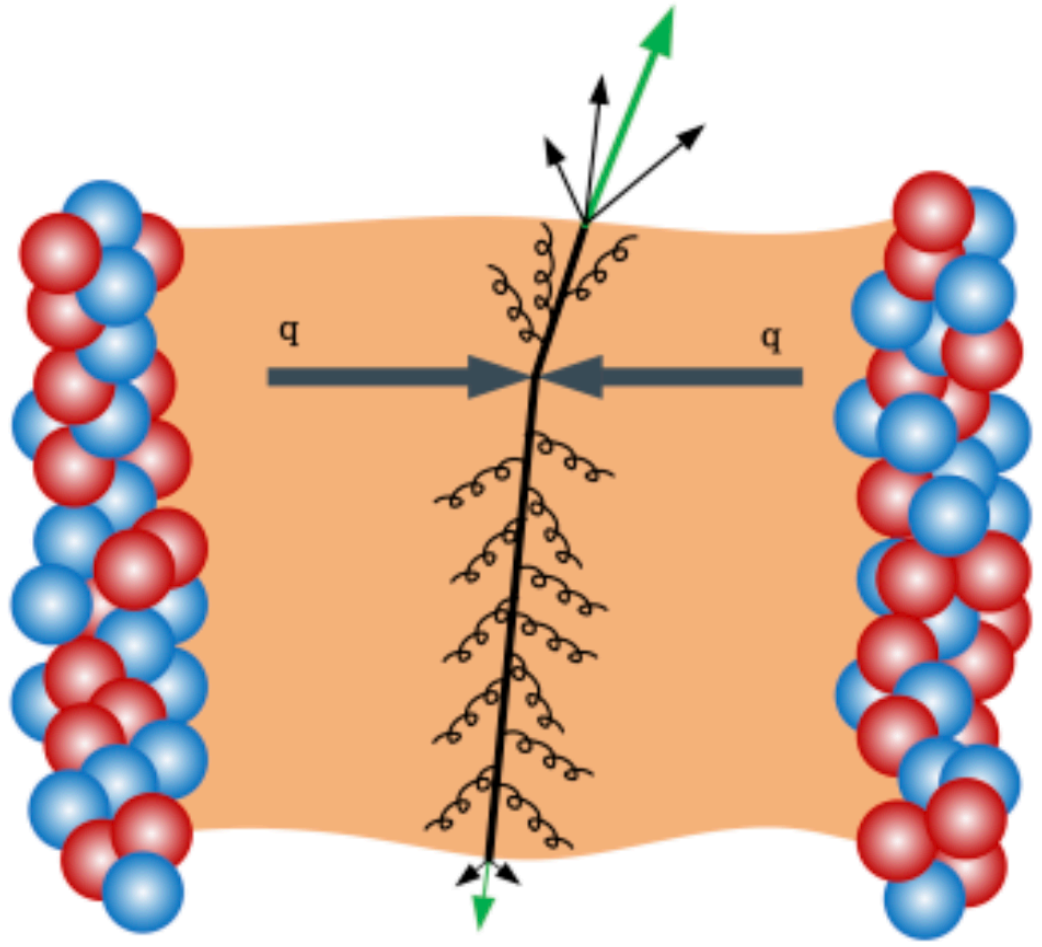
  - **Jet energy redistribution**
  - **Medium-induced acoplanarity**



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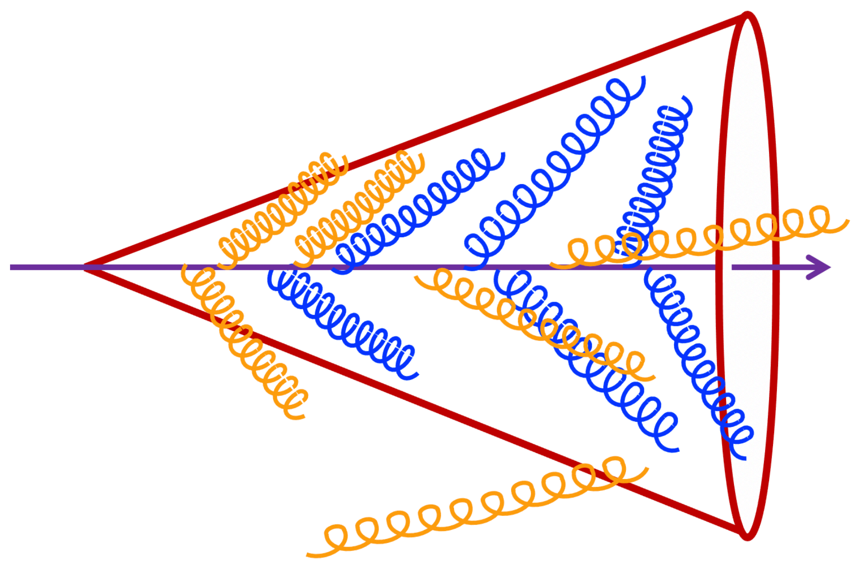

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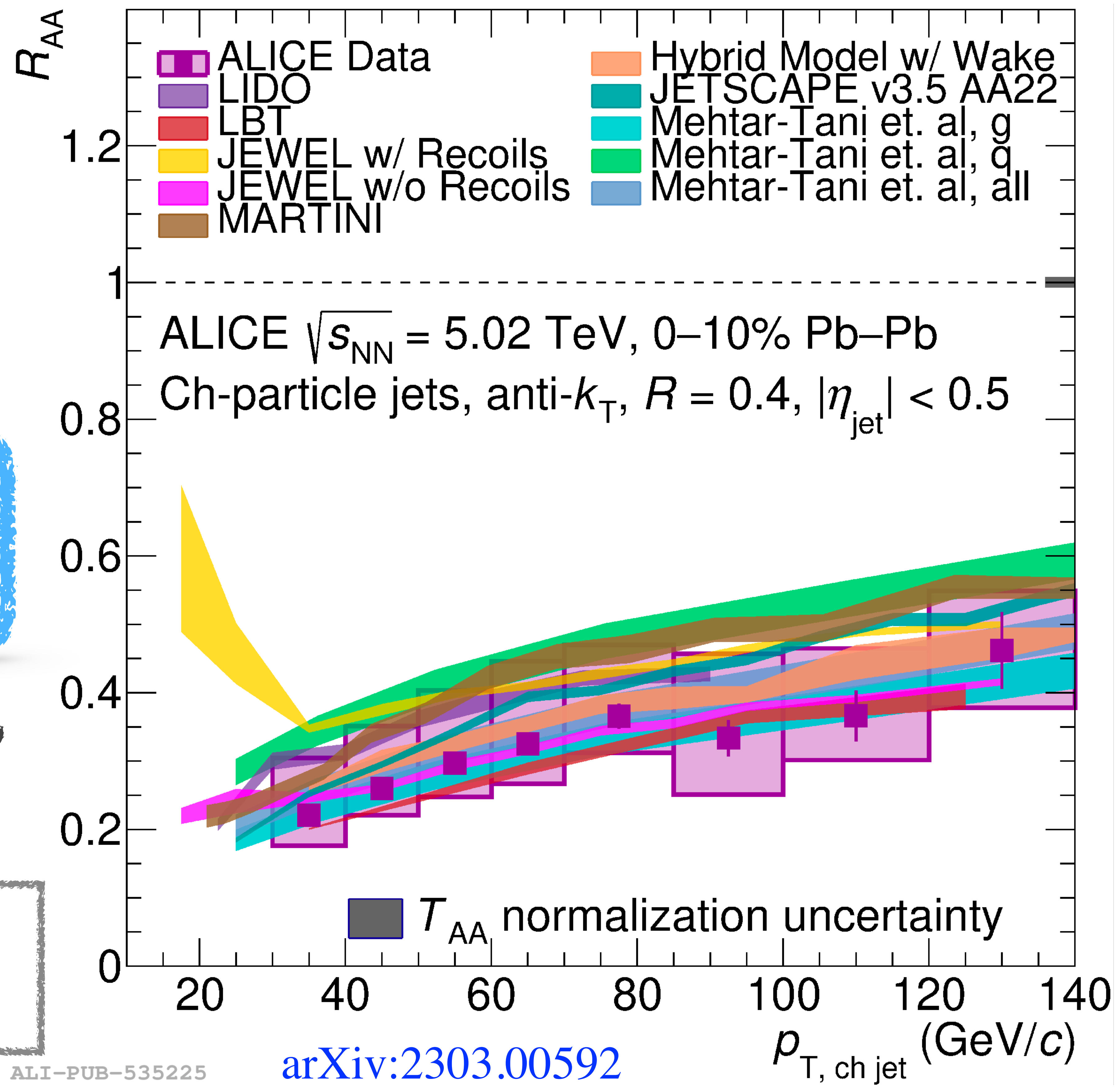
$$R_{AA} = \frac{dN^{AA}_{jets}/dp_T d\eta}{\langle T_{AA}\rangle \, d\sigma^{pp}_{jets}/dp_T d\eta}$$

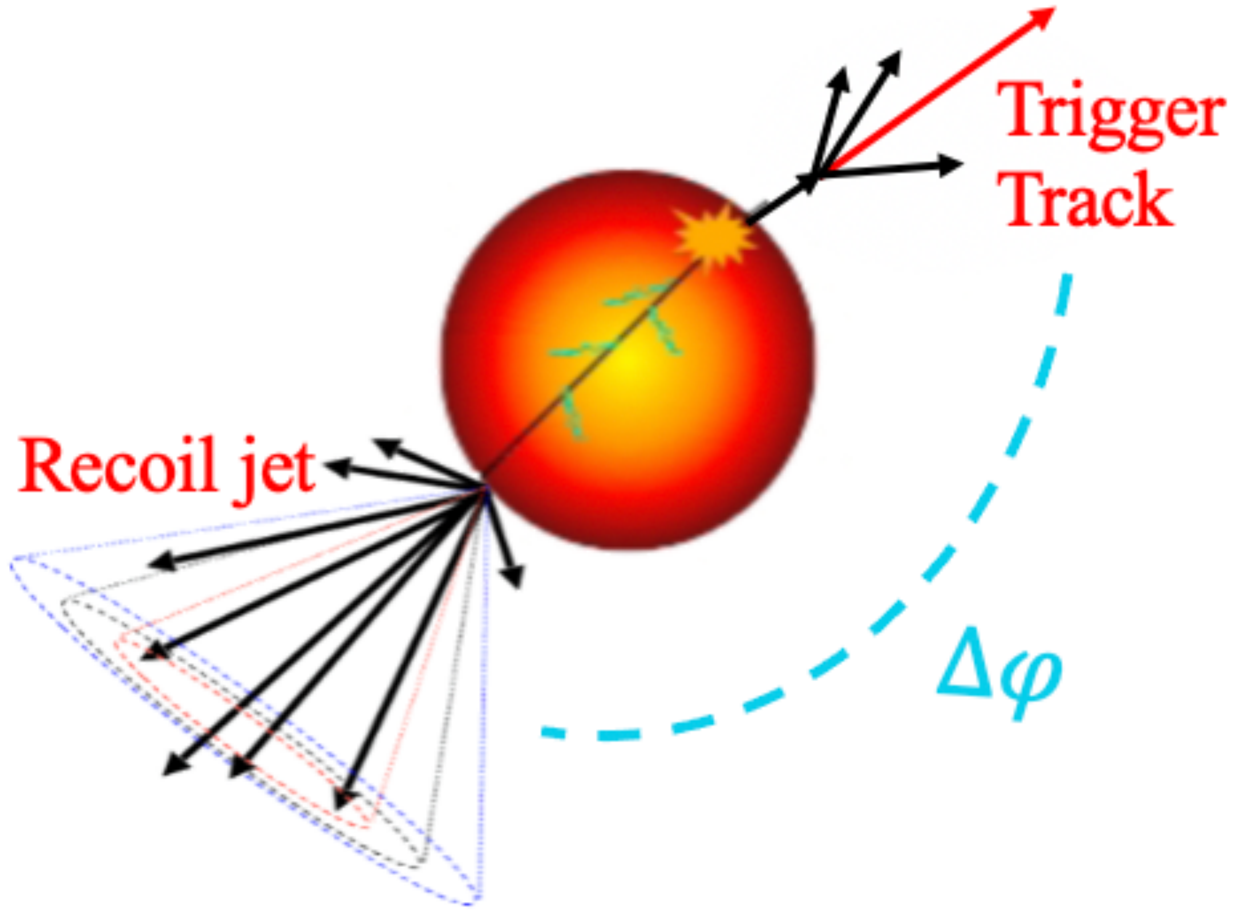
**Inclusive jet measurements show significant quenching at high $p_T$ in central Pb-Pb collisions**




arXiv:2303.00592

# Motivation

- **Opening angle** ($\Delta\varphi$) of the recoil jet relative to trigger axis
- Azimuthal distributions provide additional insight into QGP properties
- Provide a good handle of combinatorial background by varying the yields in two trigger track intervals → access low $p_{\mathrm{T}}$, large $R$ jets



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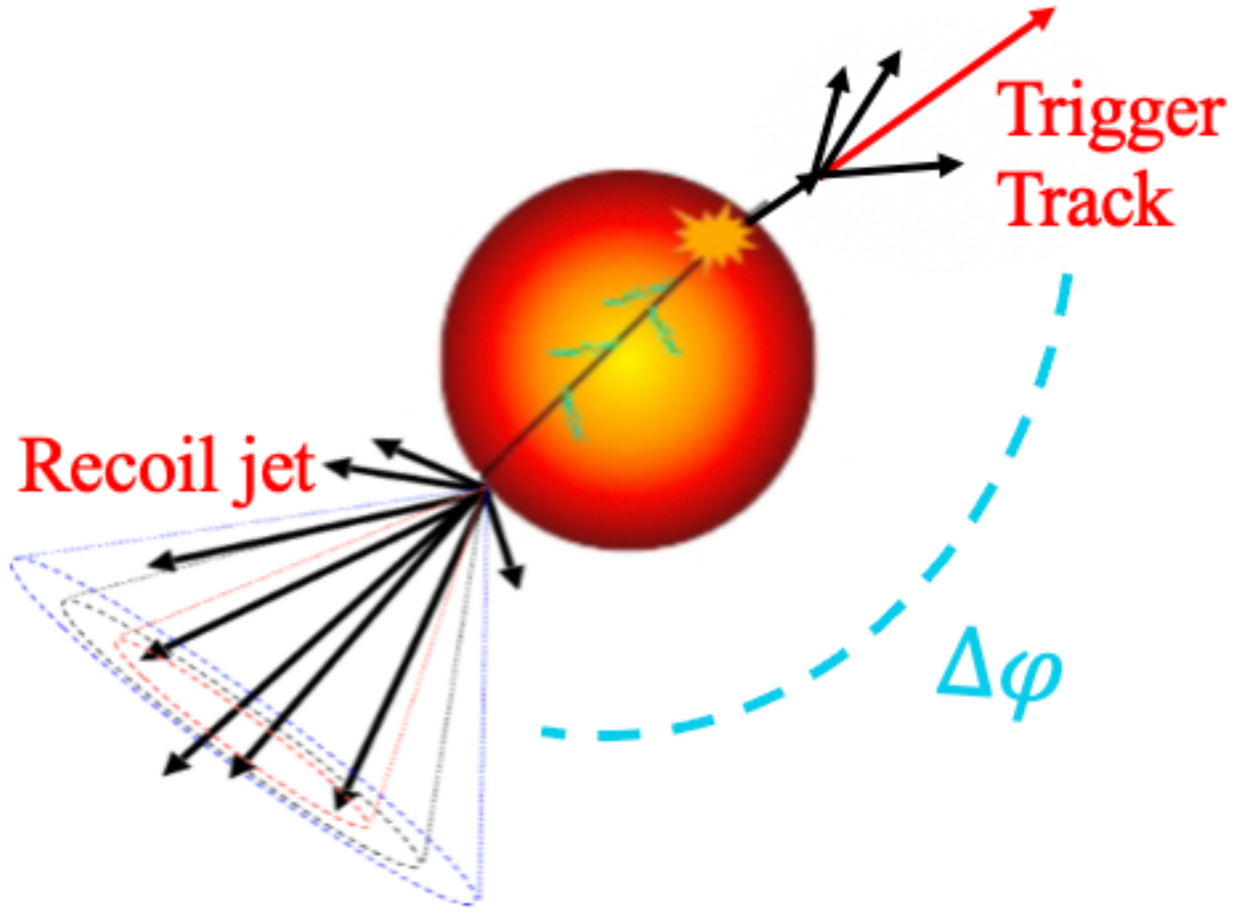


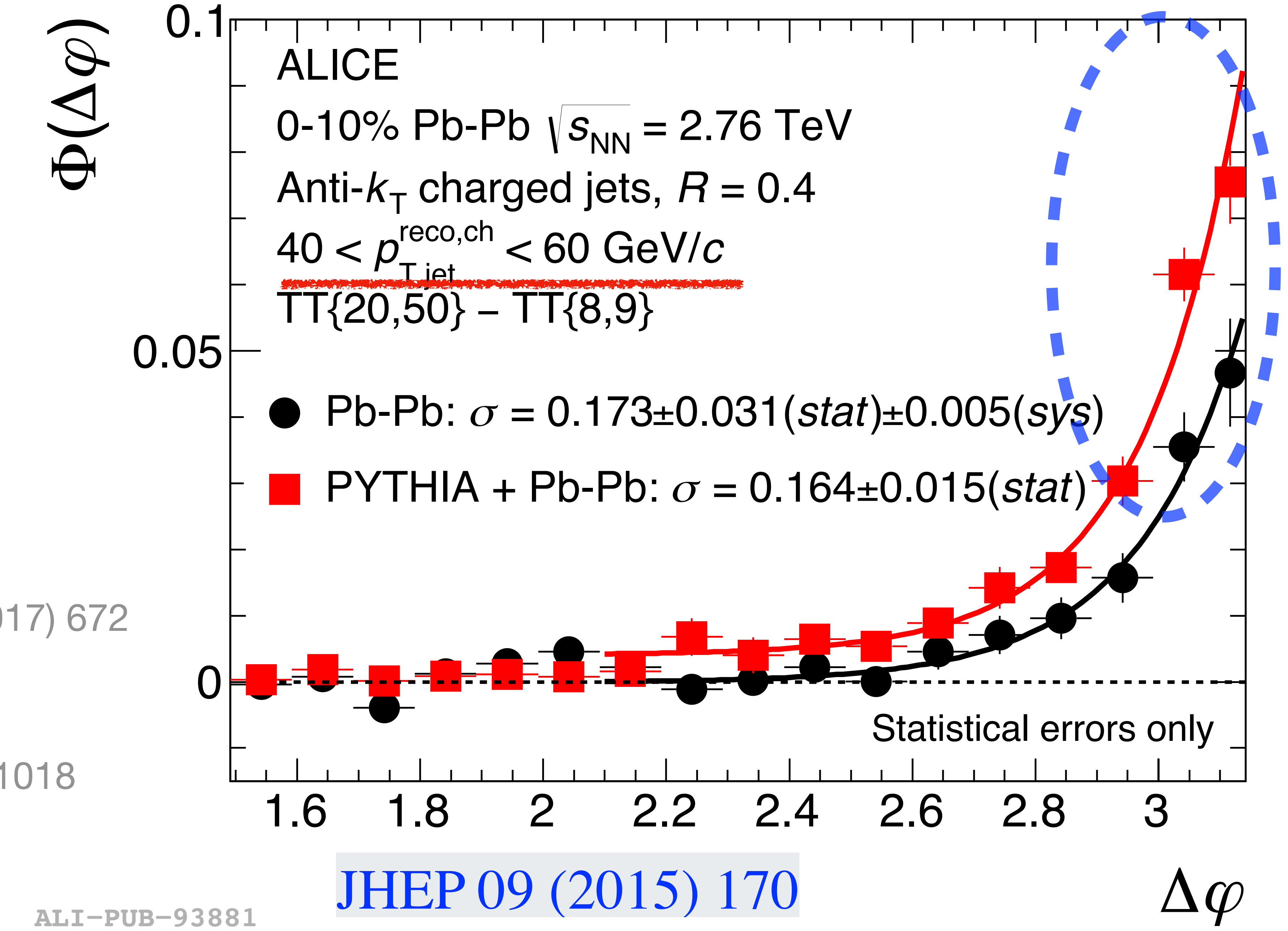

## Interesting regions:

1. $\Delta\varphi \sim \pi$
   - Hadron-jet acoplanarity broadening: Sudakov radiation
   - Multiple soft scattering in the QGP may further broaden $\Delta\varphi$
     - Related to transport coefficient $\hat{q} \sim \langle p_\perp^2 \rangle / L \sim \langle \Delta\varphi^2 \rangle / L$

L Chen, Phys. Lett. B 773 (2017) 672

   - Negative radiative correction → reduction of broadening

B. G. Zakharov, arxiv:2003.1018




JHEP 09 (2015) 170

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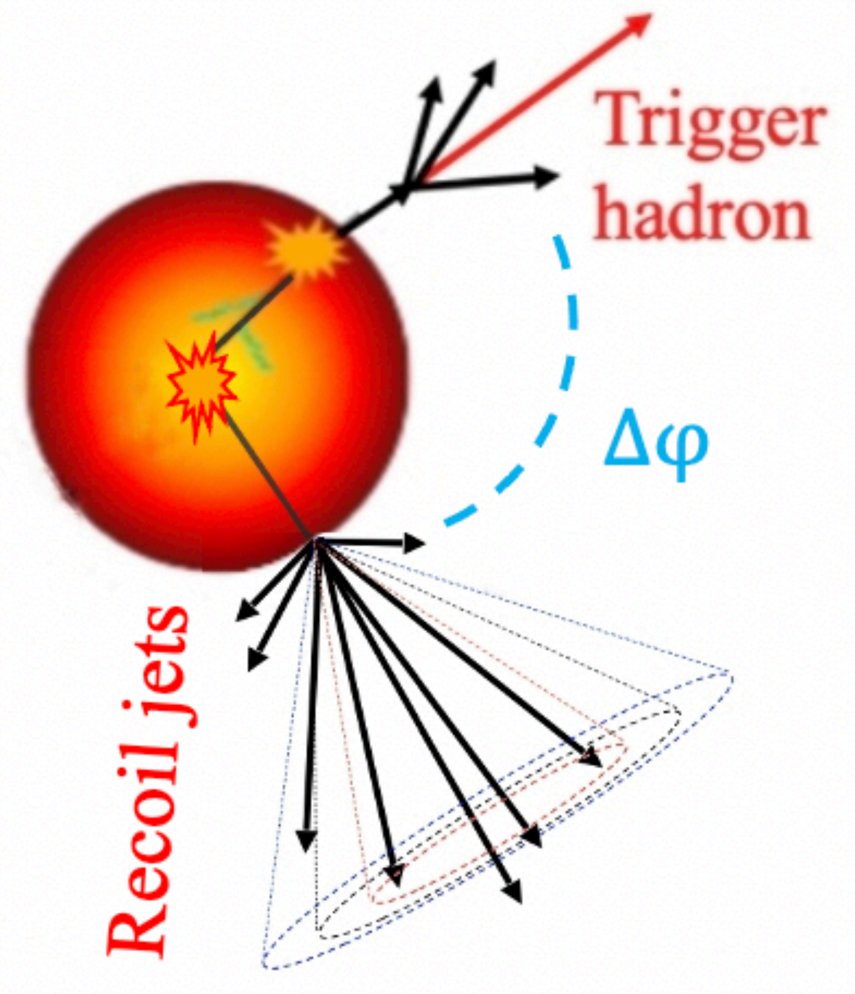
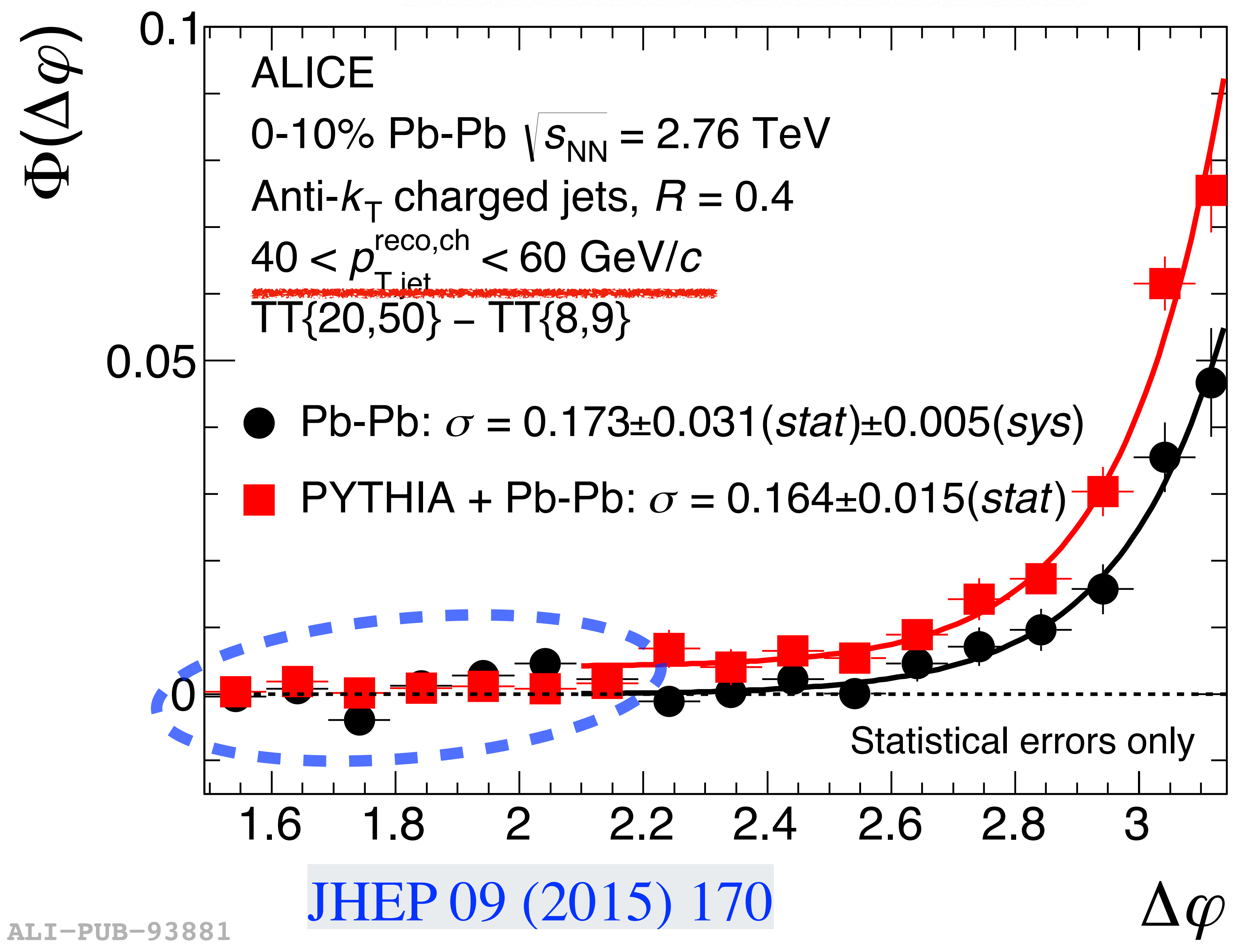



## Interesting regions:

### 2. $\Delta\varphi \ll \pi$

- Large-angle deflection of hard partons off quasi-particle
  - Probe short distance partonic structure of the QGP

F. D'Eramo, Rajagopal, Y. Yin, JHEP 01 (2019) 172

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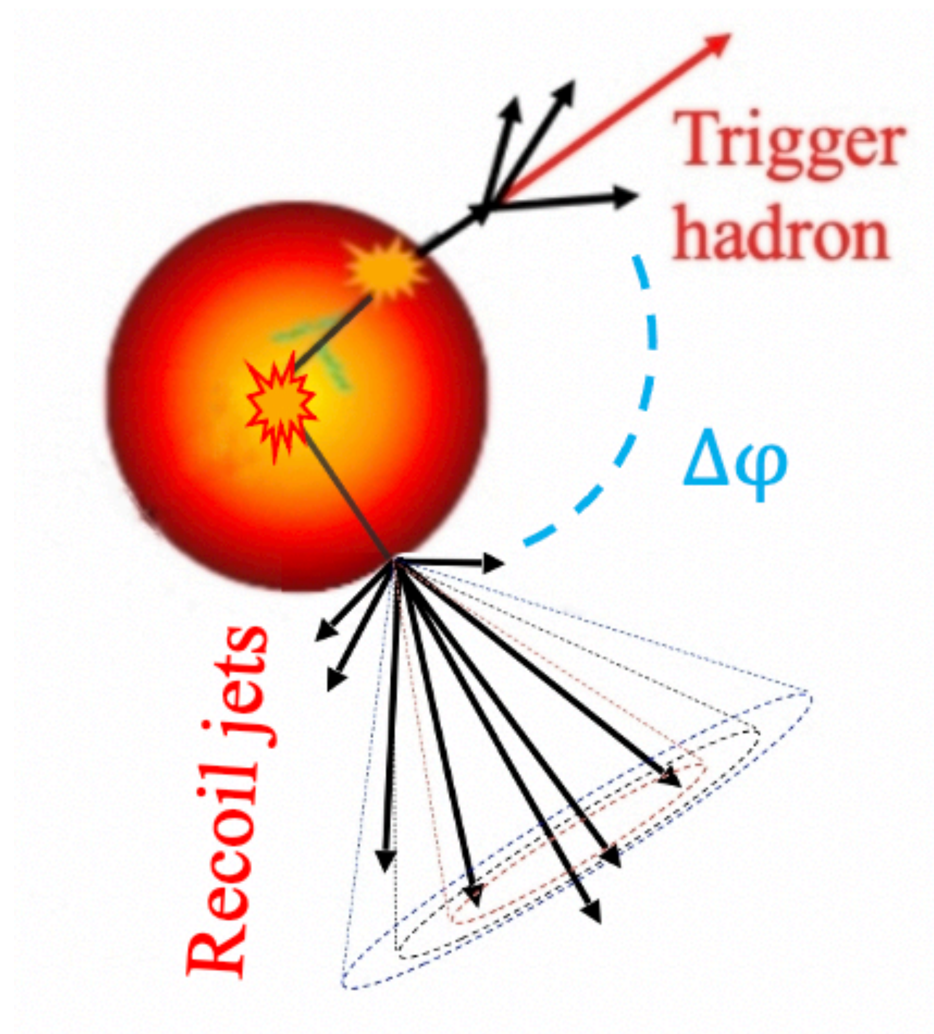


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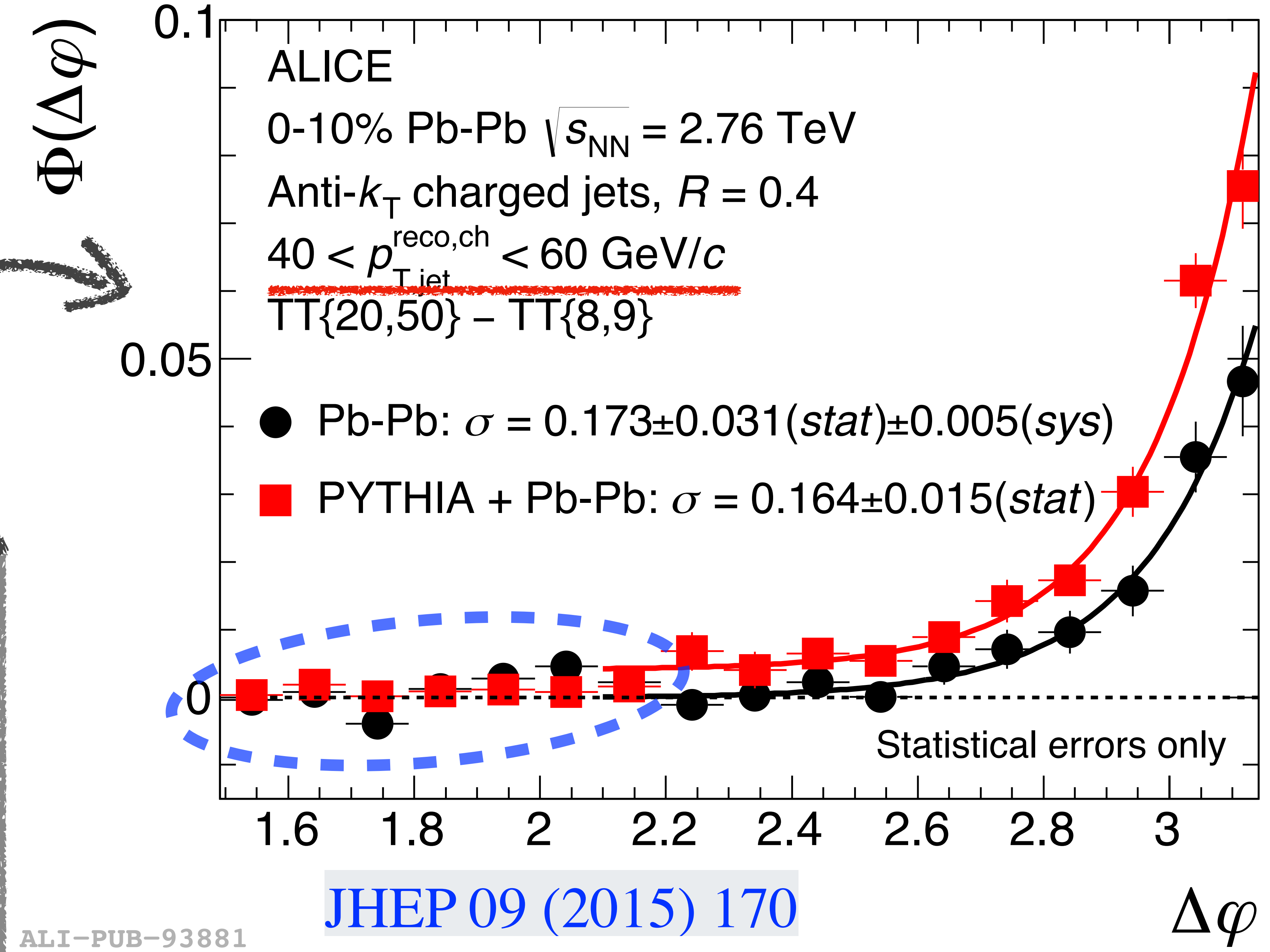
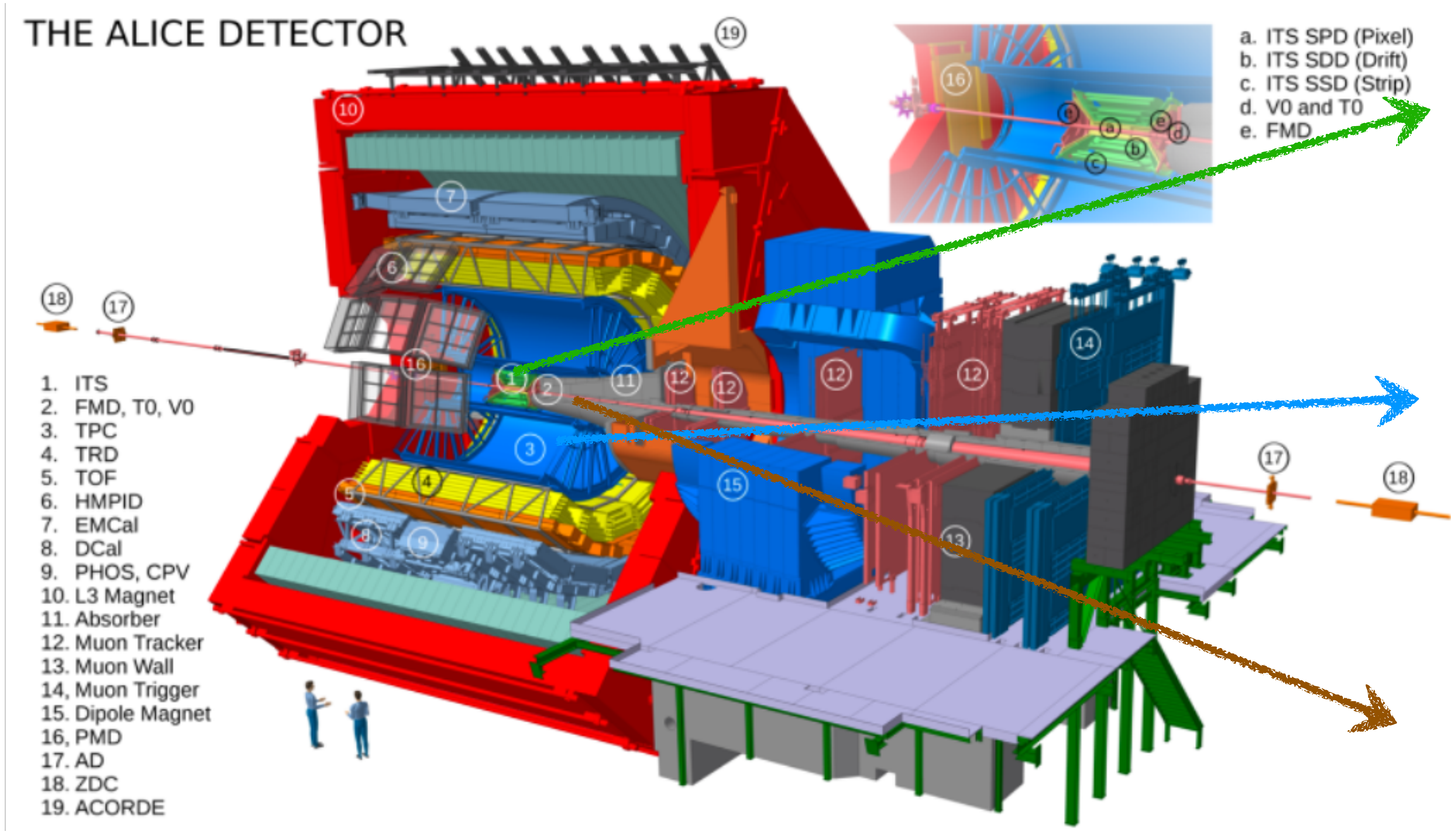
**No medium-induced acoplanarity observed within uncertainties**

- Statistics-limited
- Uncorrected for angular / $p_T$ smearing
- Mid-$p_T$ R=0.4 jets




JHEP 09 (2015) 170

# Jet measurements in ALICE




Data: pp and 0 -10% Pb-Pb samples at $\sqrt{S_{\mathrm{NN}}} = 5.02$ TeV

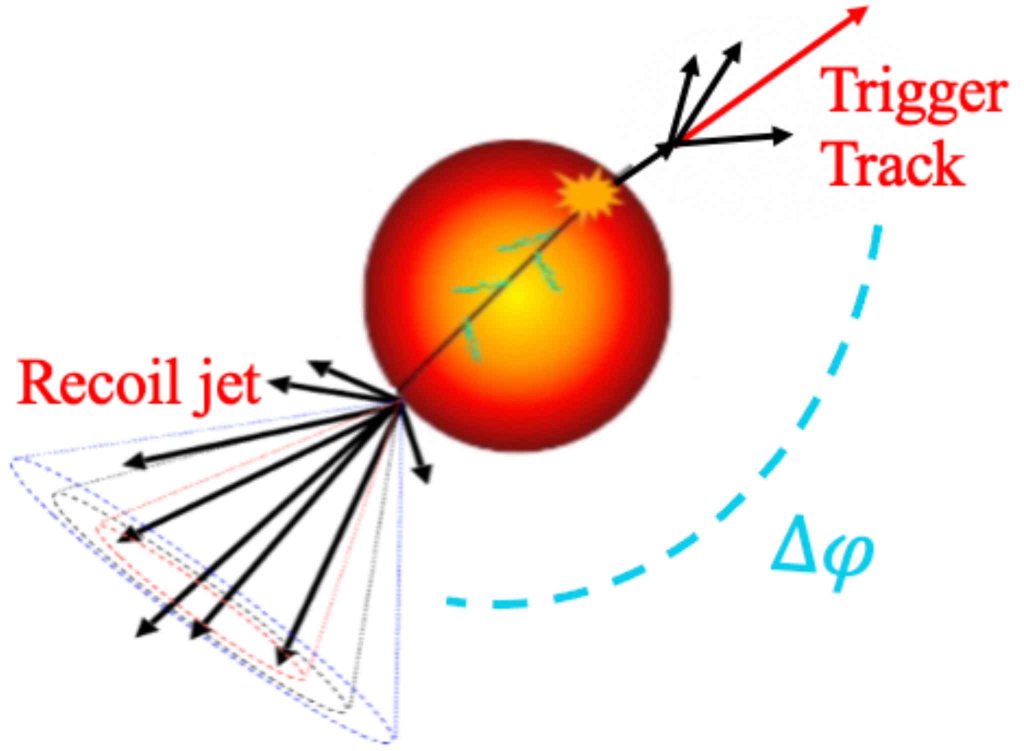
## Charged-particle tracks and jets

- **ITS** (Inner Tracking System)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Primary vertex reconstruction
  - Charged particle tracking
- **TPC** (Time Projection Chamber)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Charged particle tracking
  - Particle identification
- **V0** (V0C + V0A)
  - $-3.7 < \eta < -1.7,\ 2.8 < \eta < 5.1$
  - Event trigger
  - Event multiplicity, centrality determination

# Observables

- Measure **trigger-normalised yield** of jets recoiling from a trigger hadron

$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^3 N_{\rm jet}^{\rm AA}}{{\rm d}\eta_{\rm jet}\,{\rm d}\Delta\varphi_{\rm jet}\,{\rm d}p_{\rm T,jet}}\bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{{\rm d}^3\sigma^{\rm AA\to h+jet+X}}{{\rm d}\eta_{\rm jet}\,{\rm d}\Delta\varphi_{\rm jet}\,{\rm d}p_{\rm T,jet}}\right)\bigg|_{p_{\rm T,h}\in {\rm TT}}$$




- Yield measured in two exclusive trigger track (TT) intervals:

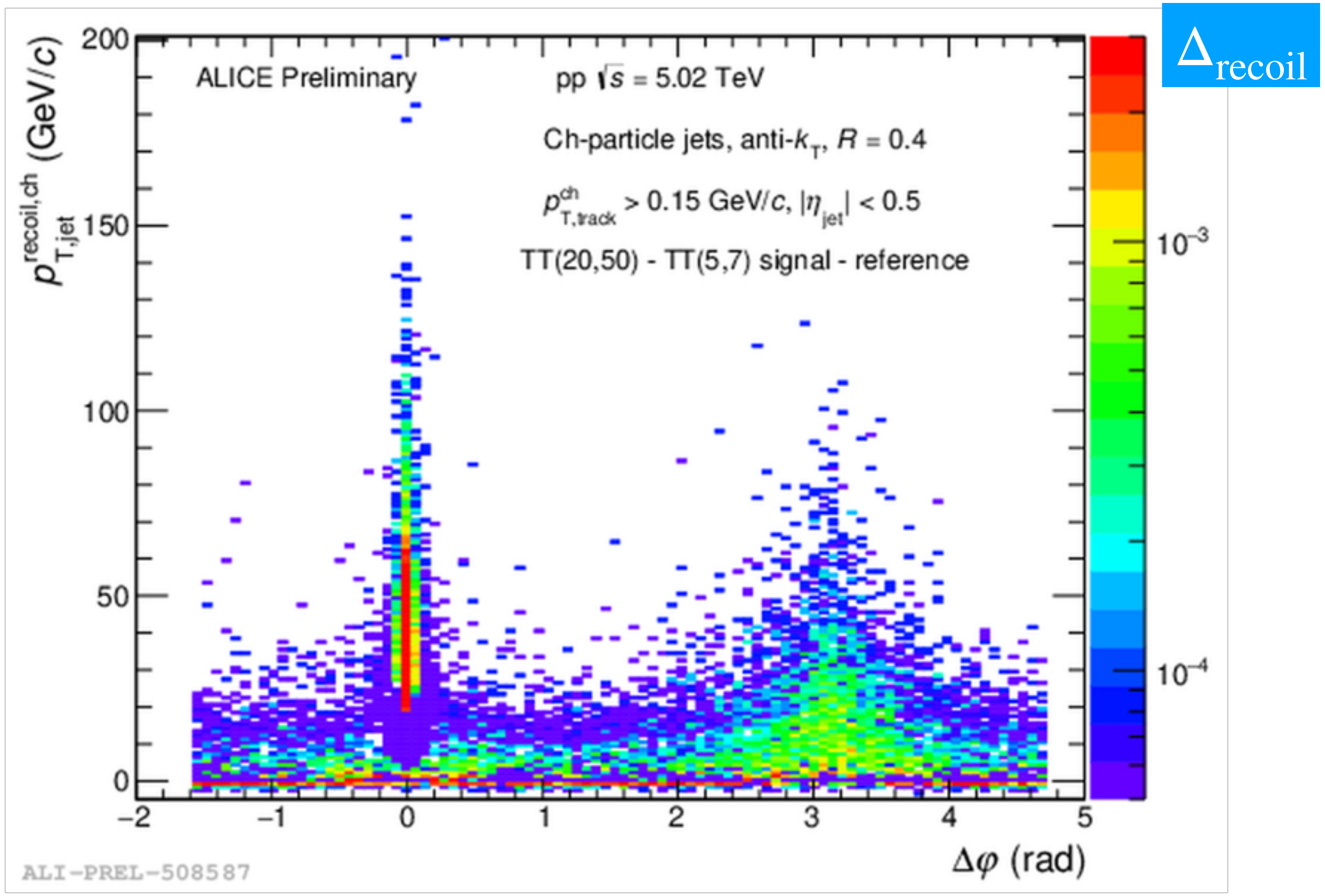
TT signal: $p_{\rm T} \in (20,\ 50)$ GeV/$c$, TT reference: $p_{\rm T} \in (5,\ 7)$ GeV/$c$

- Observables defined as **the difference** between trigger-normalised recoil jet yields in **two trigger track intervals** in order to **remove uncorrelated background jets**

$$\Delta_{\rm recoil}\ (p_{\rm T,jet},\ \Delta\varphi) = \frac{1}{N_{\rm trig}} \frac{{\rm d}^3 N_{\rm jet}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}\,{\rm d}\Delta\varphi}\bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT_{Sig}}} - c_{\rm Ref} \cdot \frac{1}{N_{\rm trig}} \frac{{\rm d}^3 N_{\rm jet}}{{\rm d}\eta_{\rm jet}\,{\rm d}p_{\rm T,jet}\,{\rm d}\Delta\varphi}\bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT_{Ref}}}$$

- $c_{\rm ref}$: "alignment" constant extracted from data; precise subtraction of uncorrelated jet yield

# Analysis details




- **Raw $p_T$ vs $\Delta\varphi$ 2-dimensional** distributions for two trigger track $p_T$ intervals and $\Delta_{recoil}$

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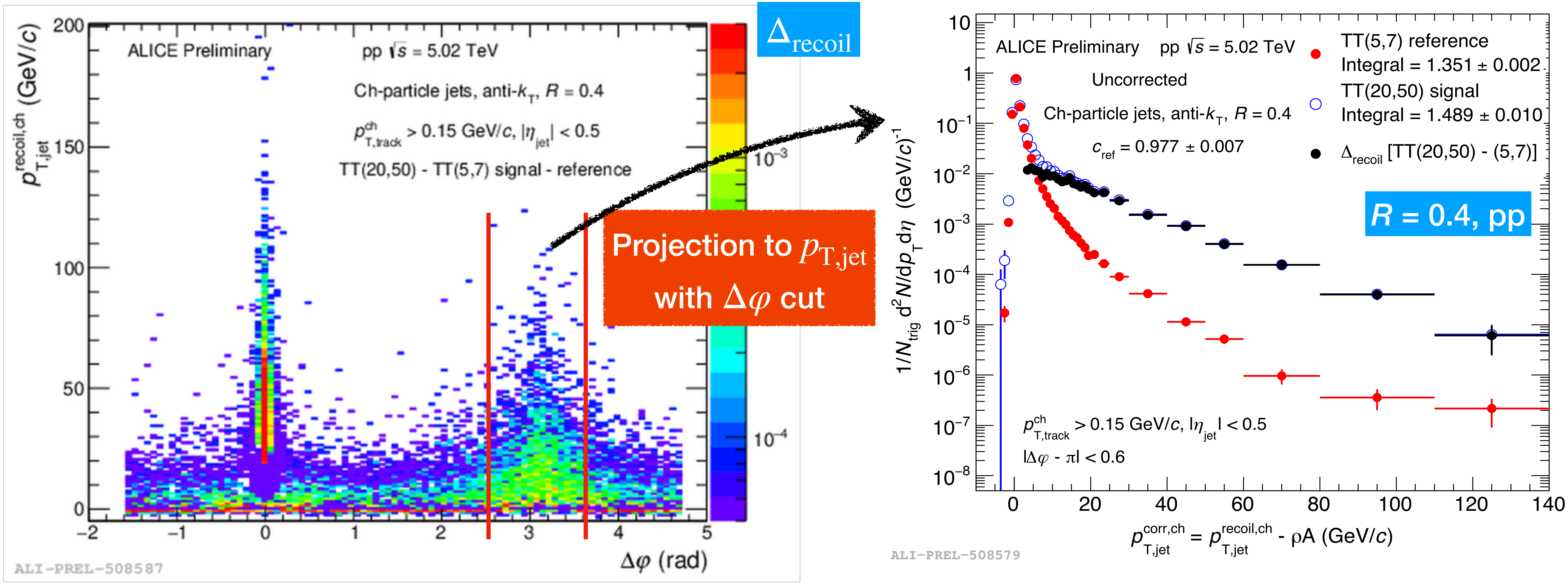
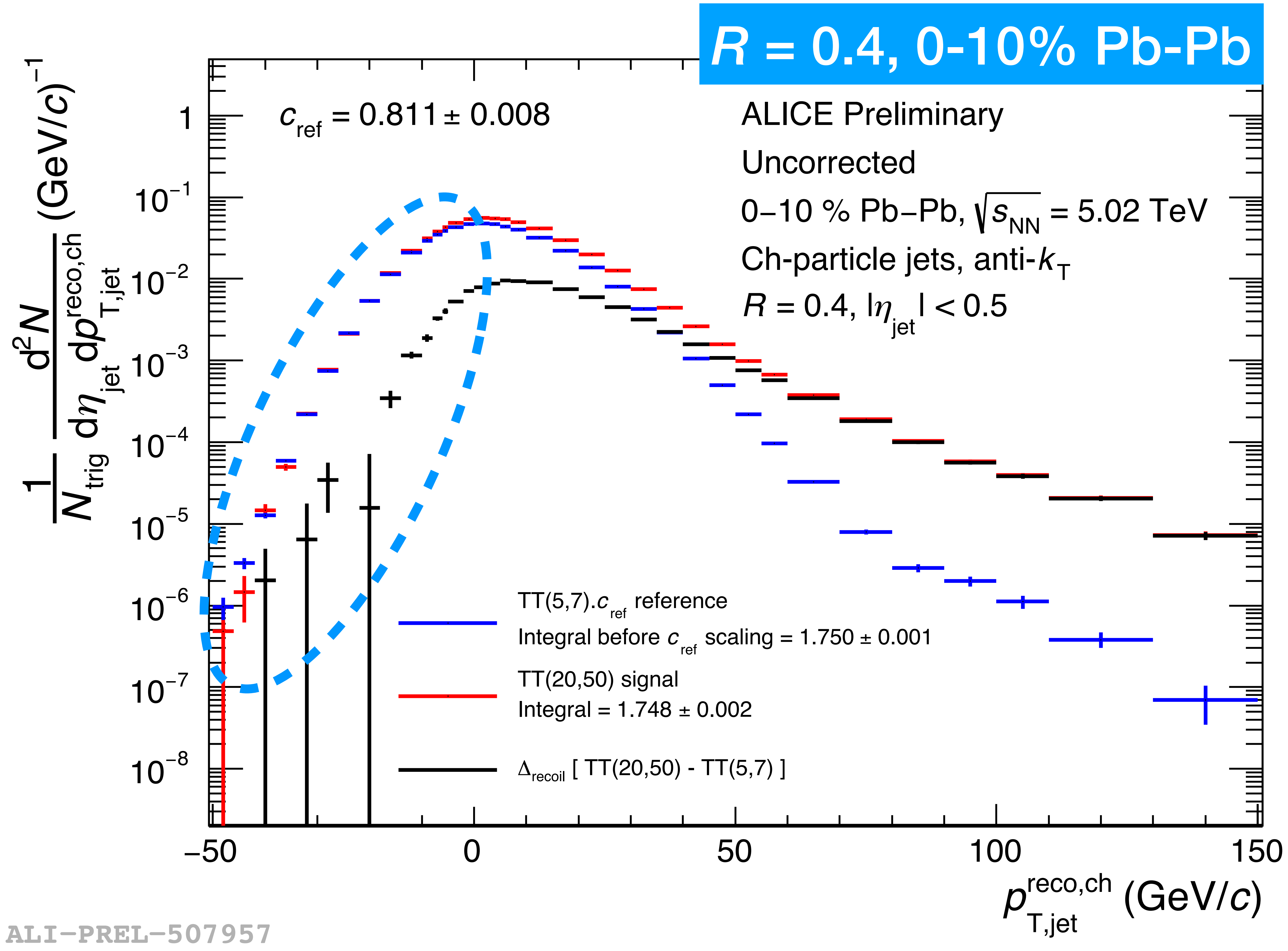
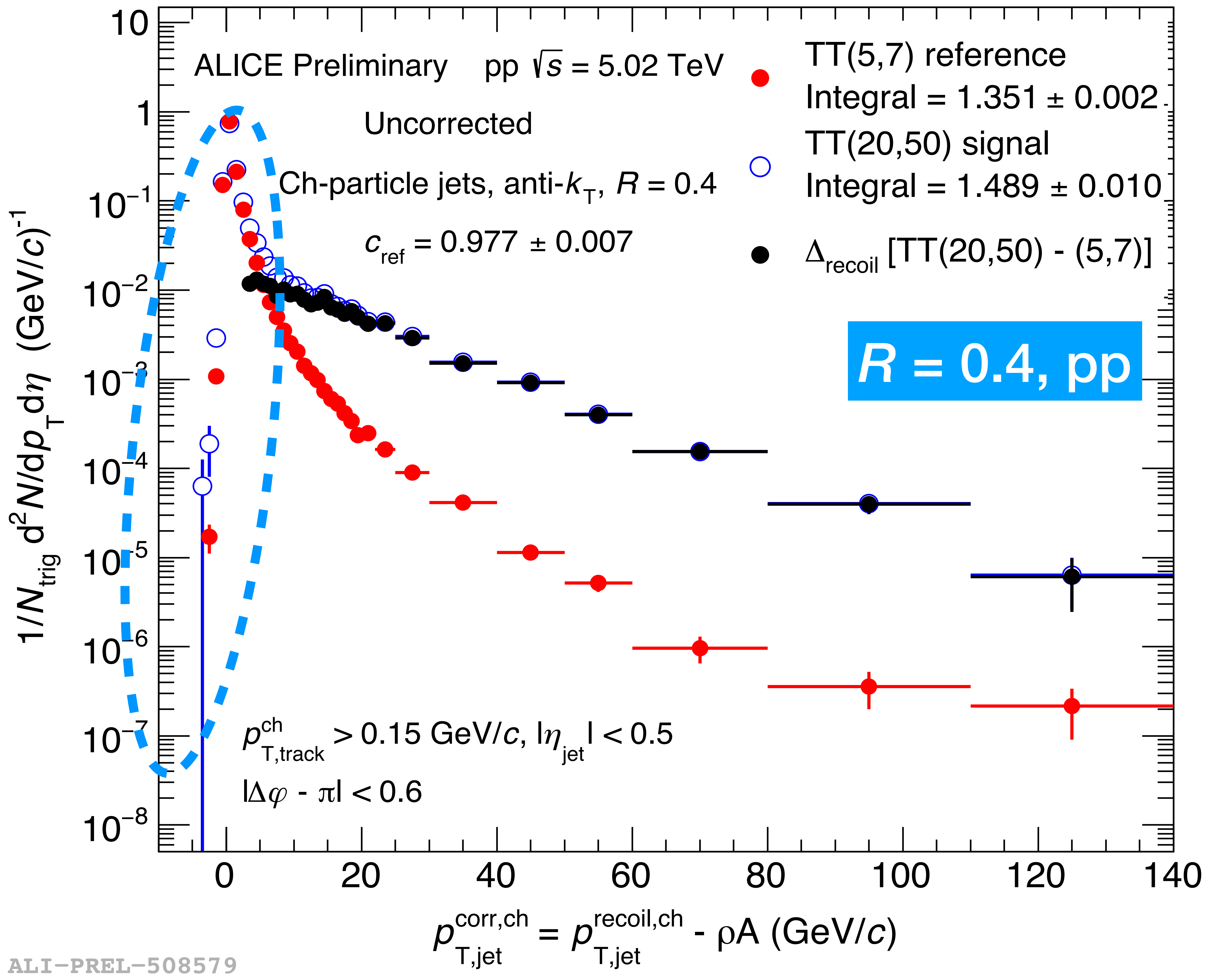



- **Raw $p_T$ vs $\Delta\varphi$ 2-dimensional** distributions for two trigger track $p_T$ intervals and $\Delta_{recoil}$
- **Recoil jet $p_T$ distributions** measured for two $p_T$ trigger track classes using 2D projection

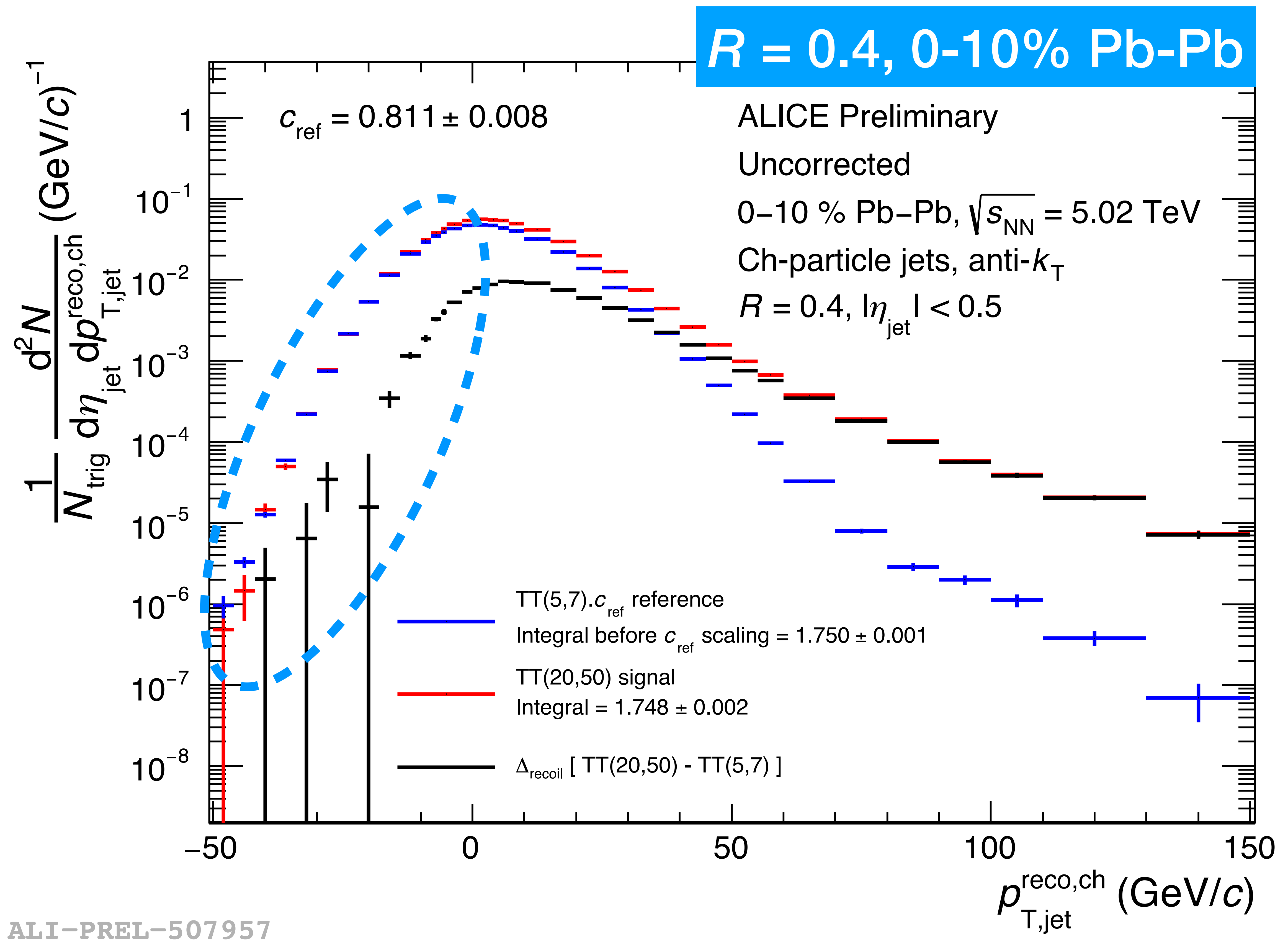
# Semi-inclusive recoil jet $p_T$ distributions

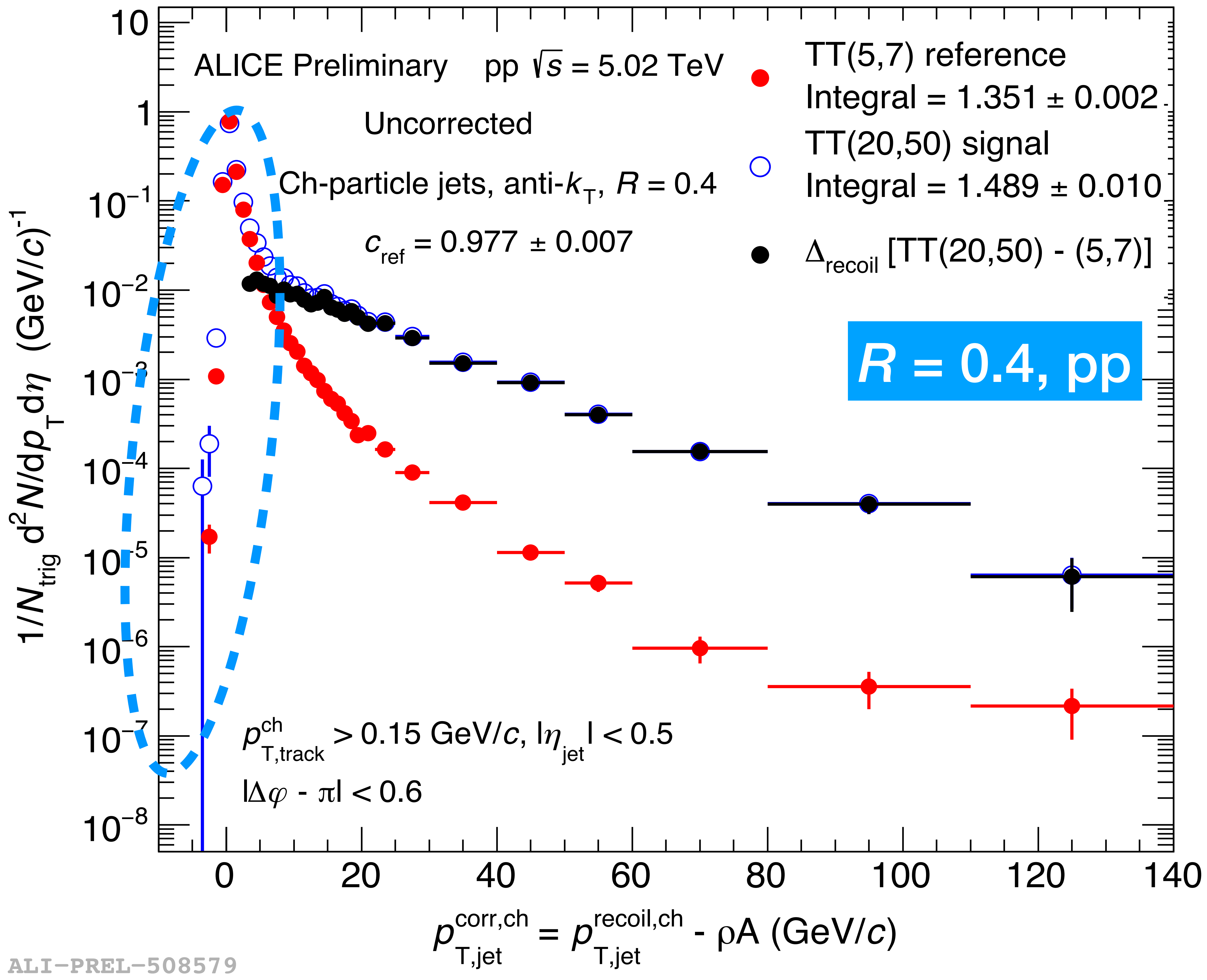



- **Combinatorial background** uncorrelated with the trigger
  - Small background contribution in pp, much larger in Pb-Pb
  - Combinatorial background can be removed by taking the difference of the recoil jet distributions in two TT intervals

# Semi-inclusive recoil jet $p_{\mathrm{T}}$ distributions

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# Recoil jet energy redistribution

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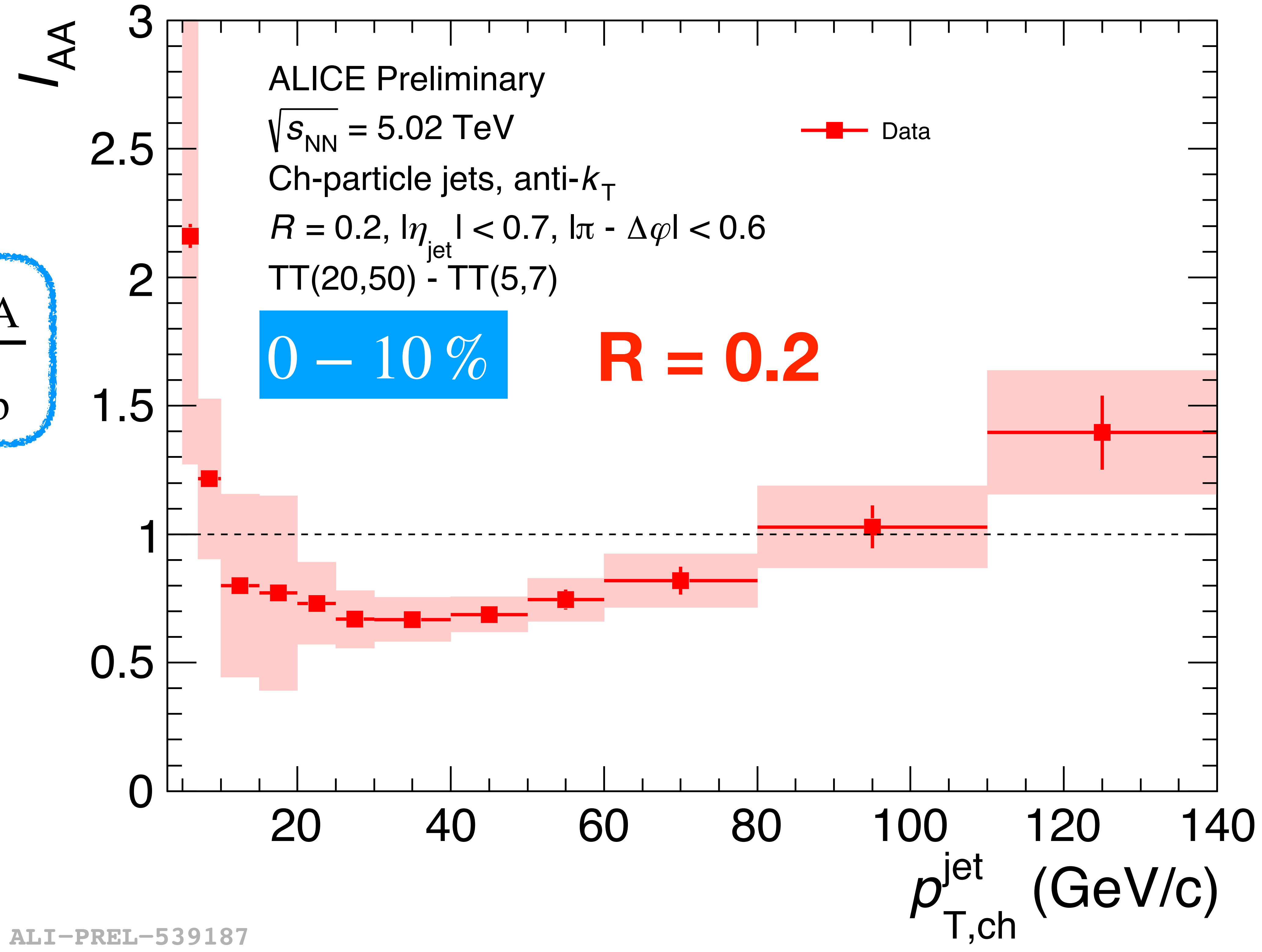


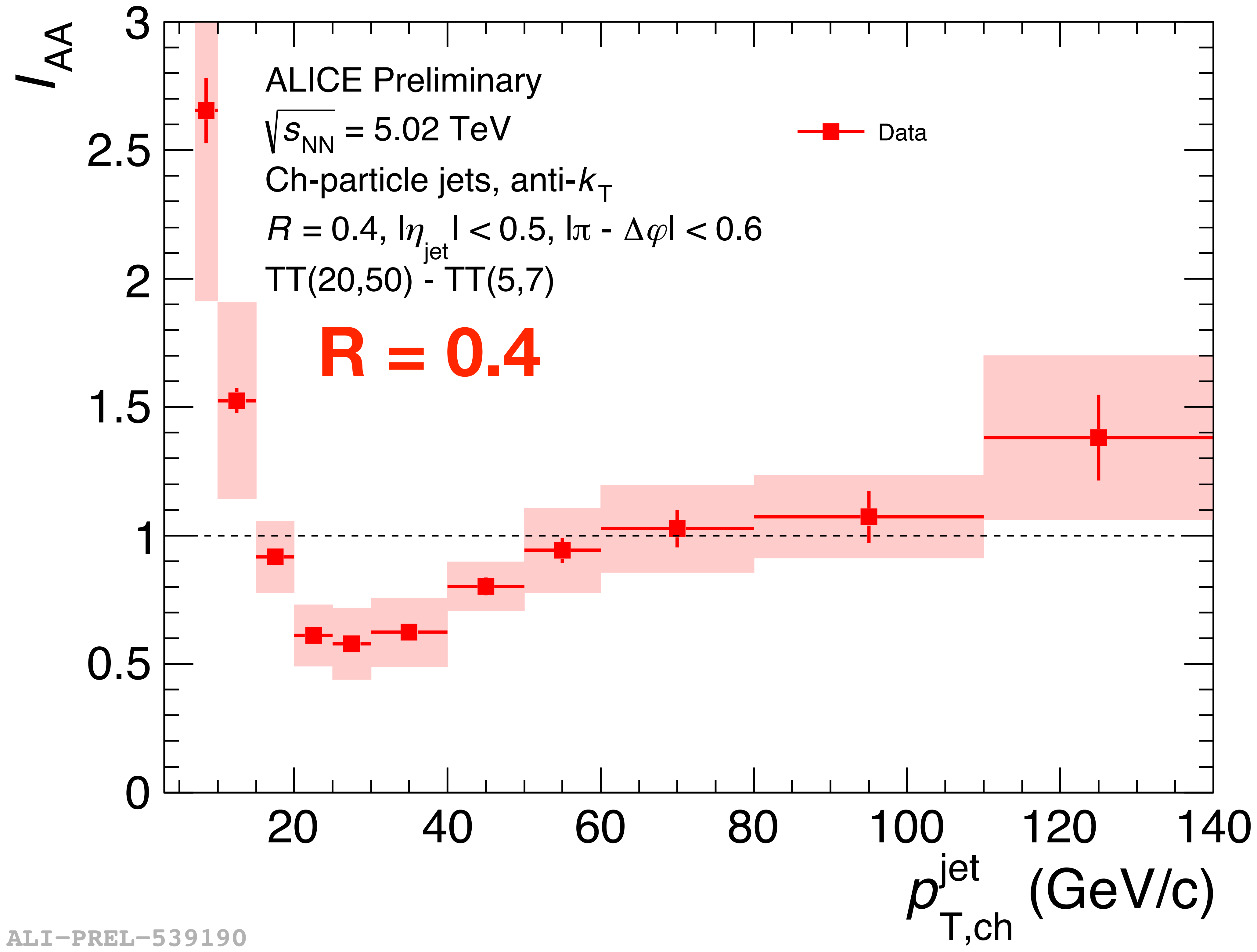


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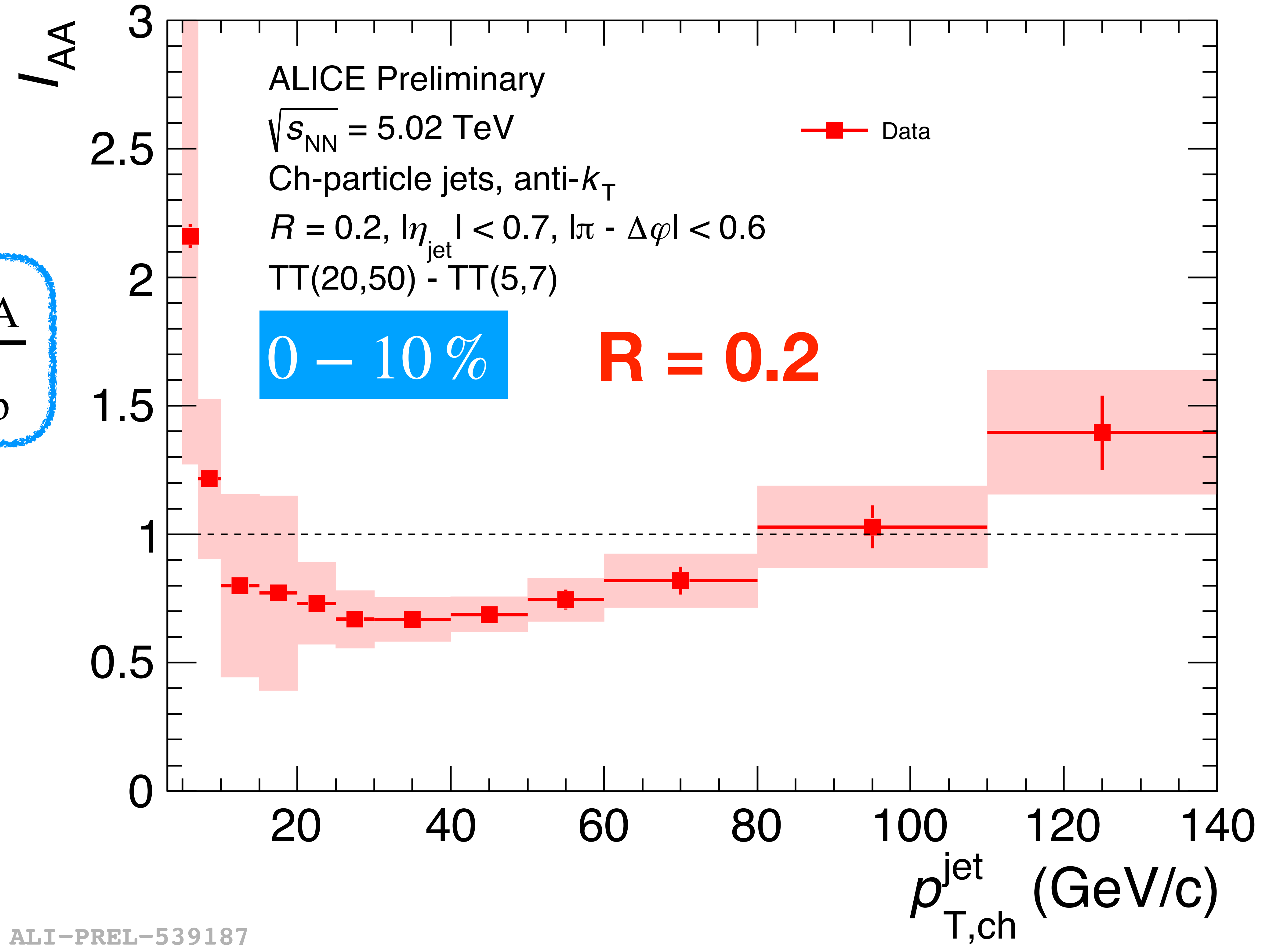


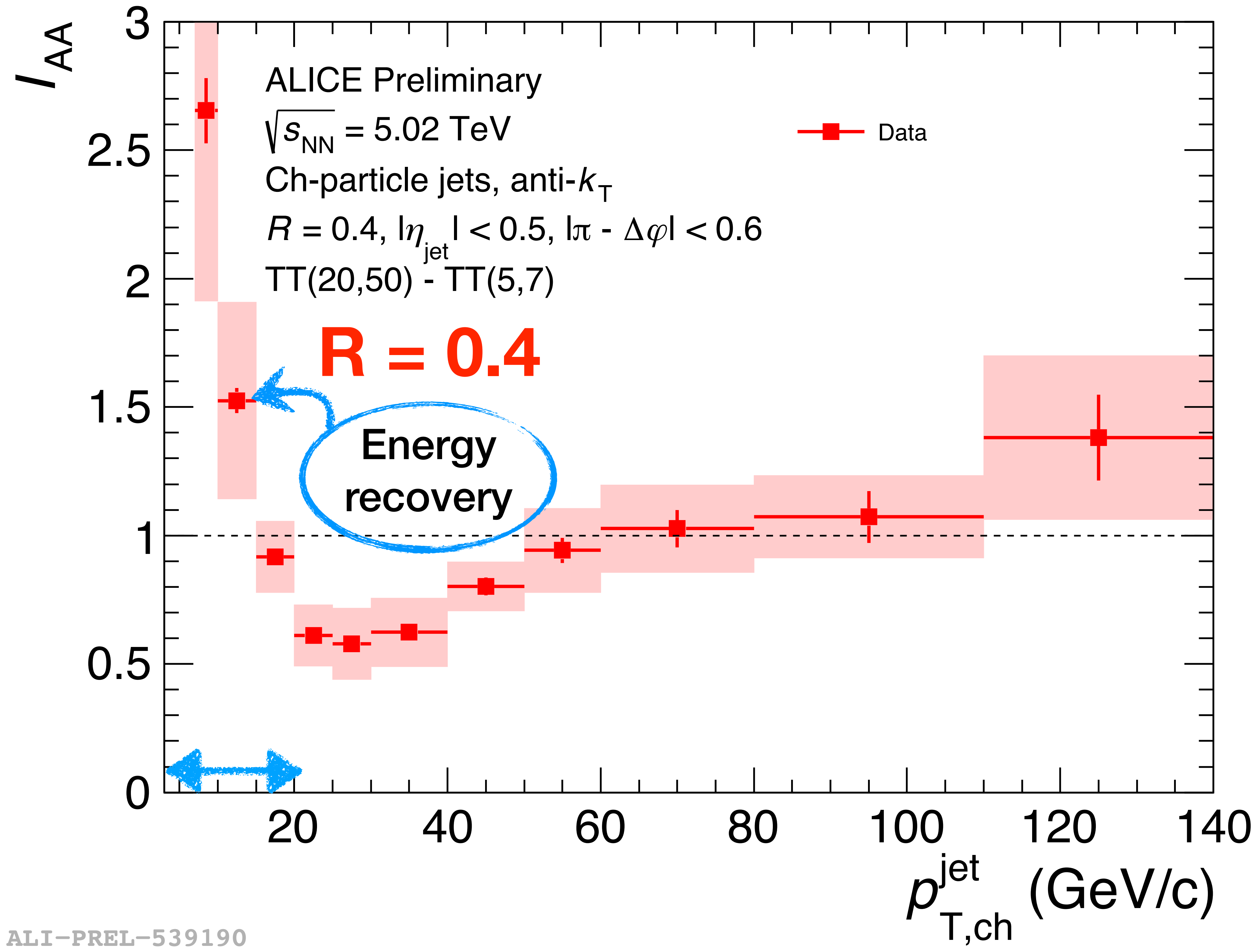


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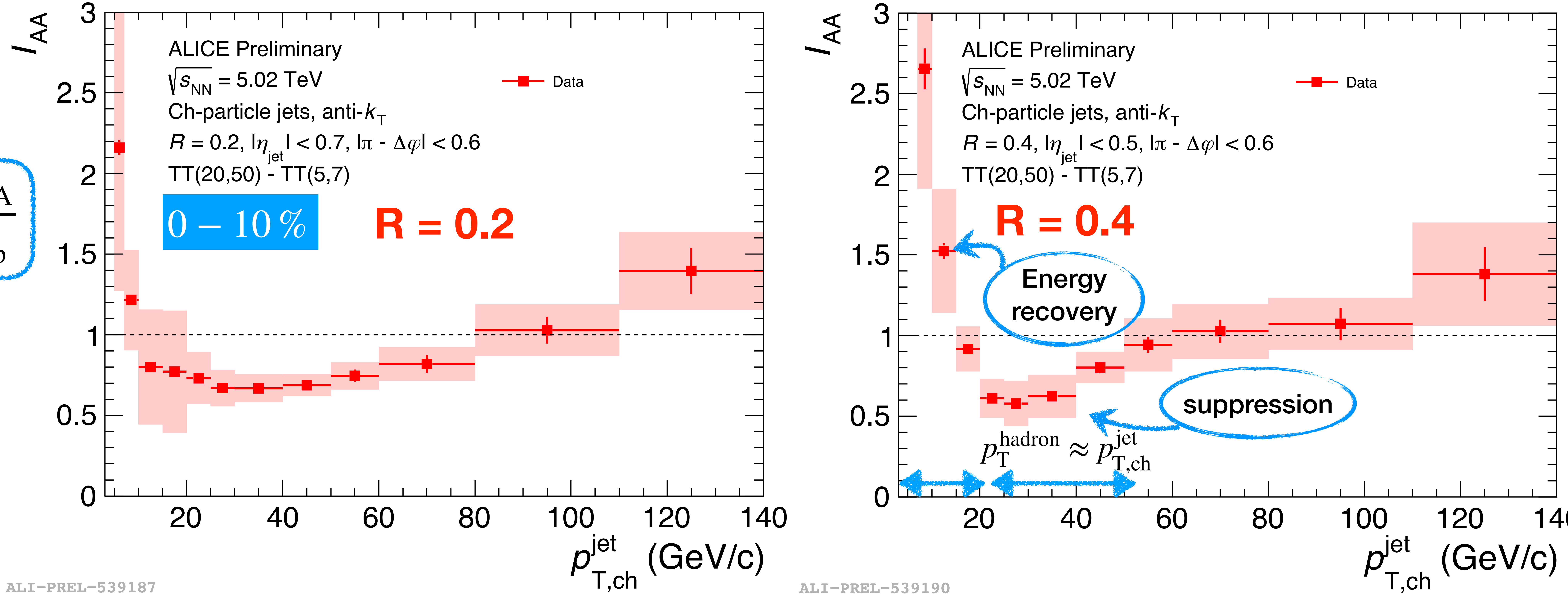


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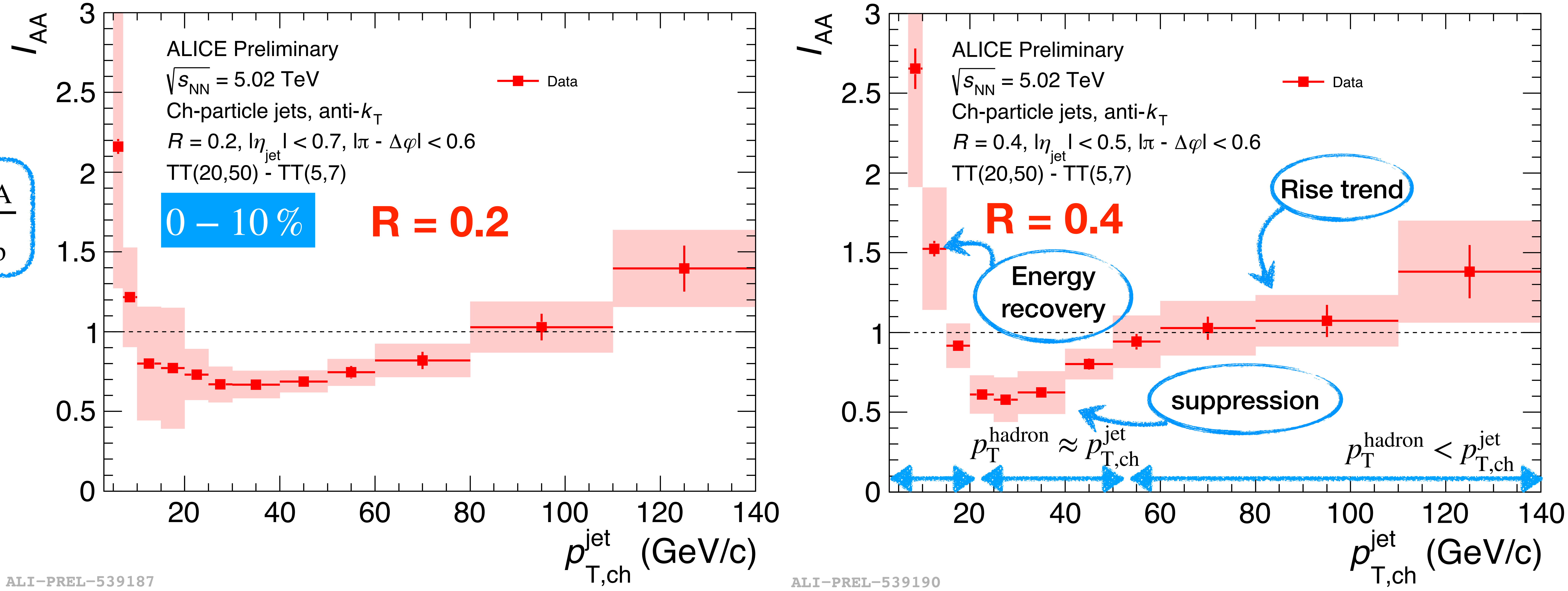


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- Rising trend: interplay of jet quenching effects on hadron and jet production?

# Comparing to models

**JETSCAPE with Pb-Pb tune:**

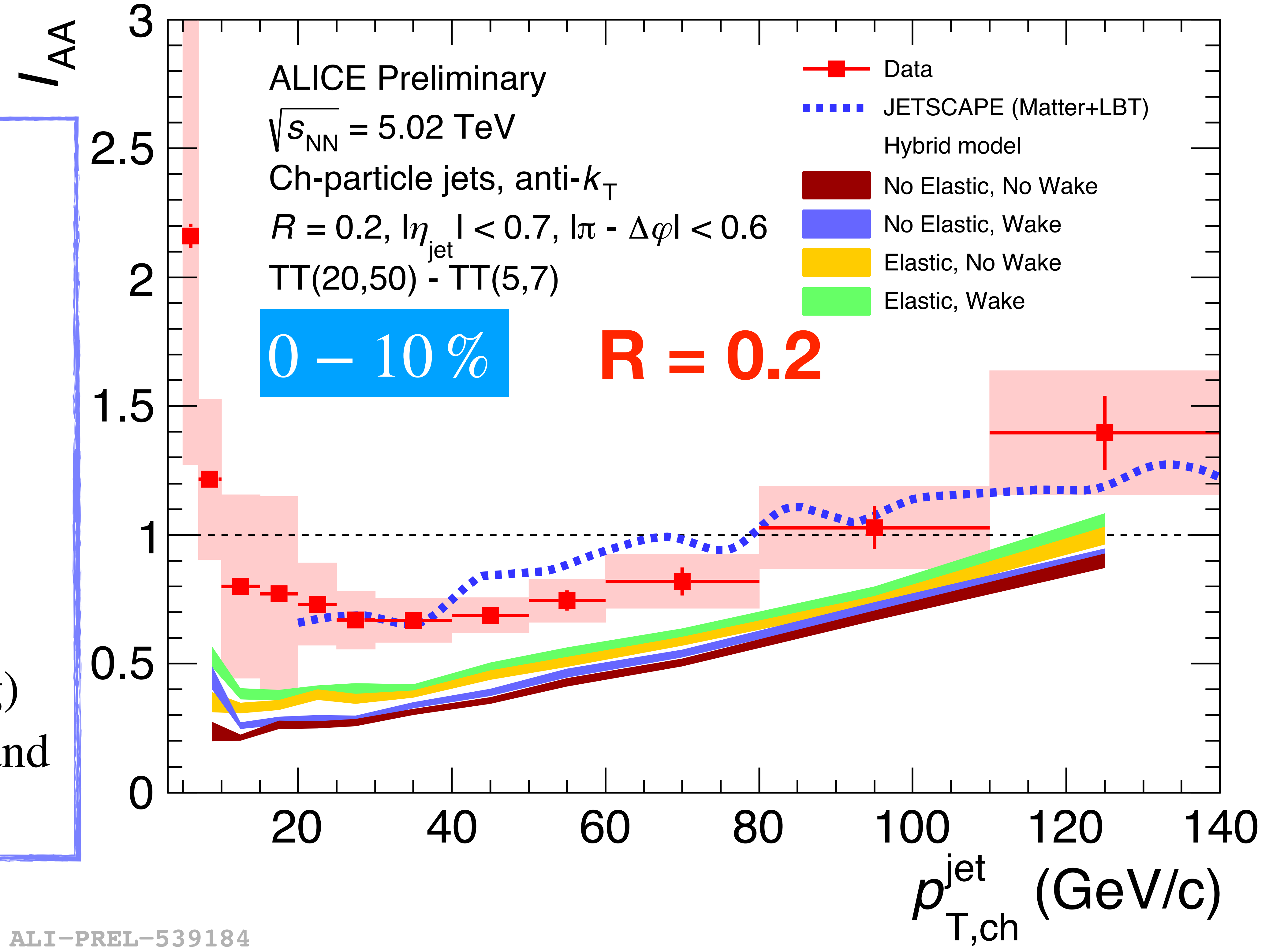
1903.07706, Phys.Rev.C 107 (2023) 3

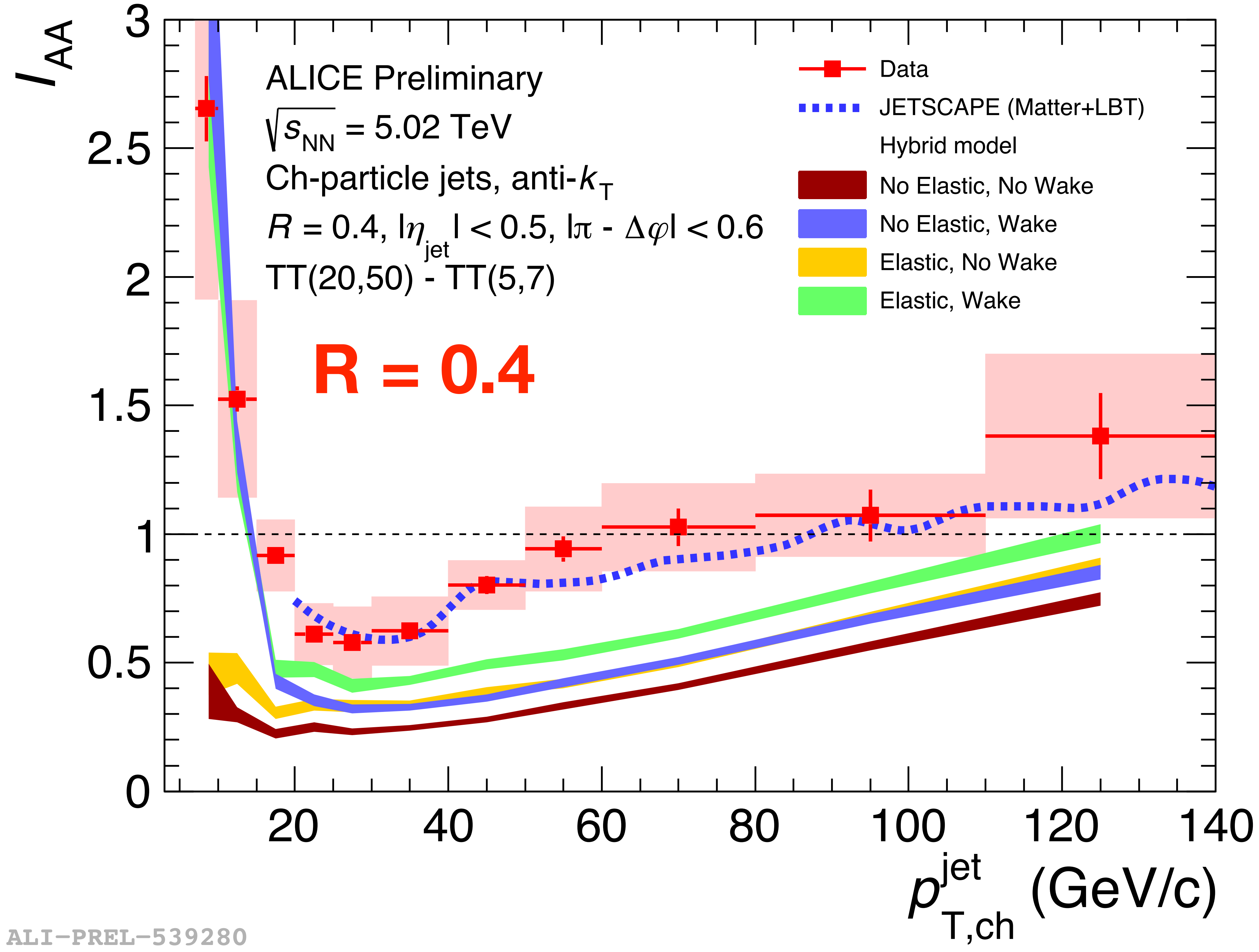
Multi-stage energy loss MATTER+LBT

**Hybrid Model:**

,JHEP 02 (2022) 175, JHEP01(2019)172

With/without elastic energy loss (i.e 'Moliere' scattering) medium response via with and without wake.



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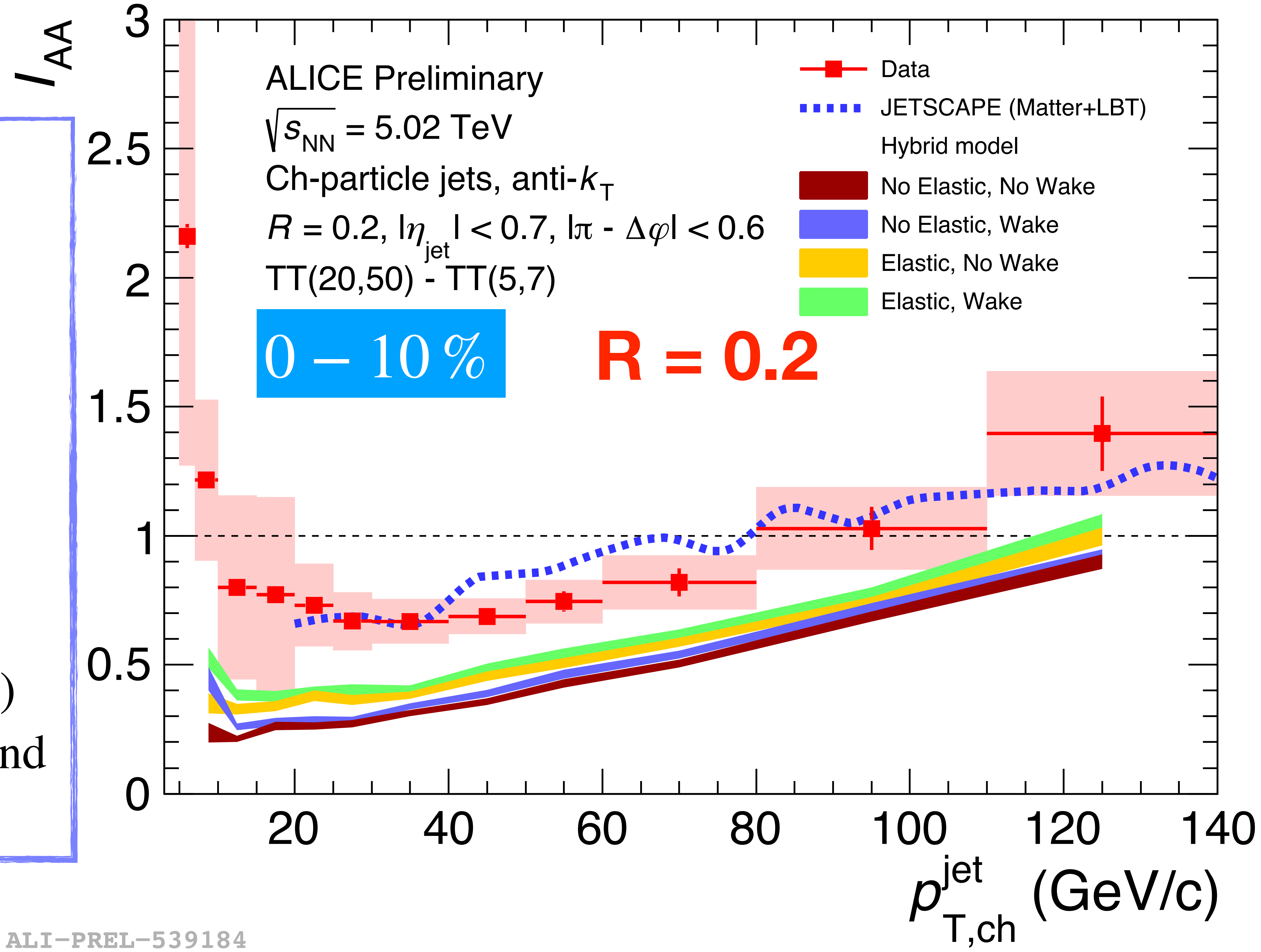
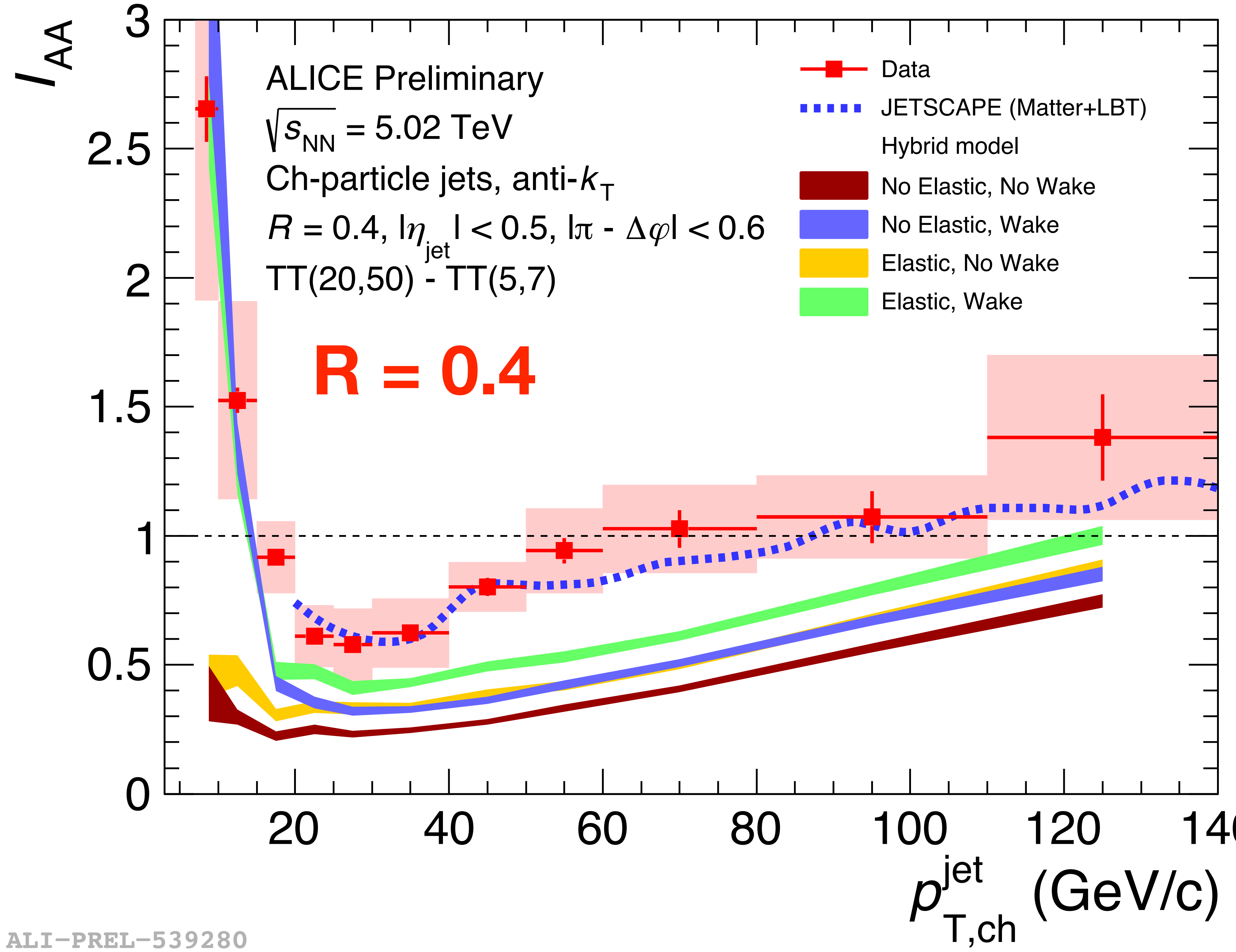


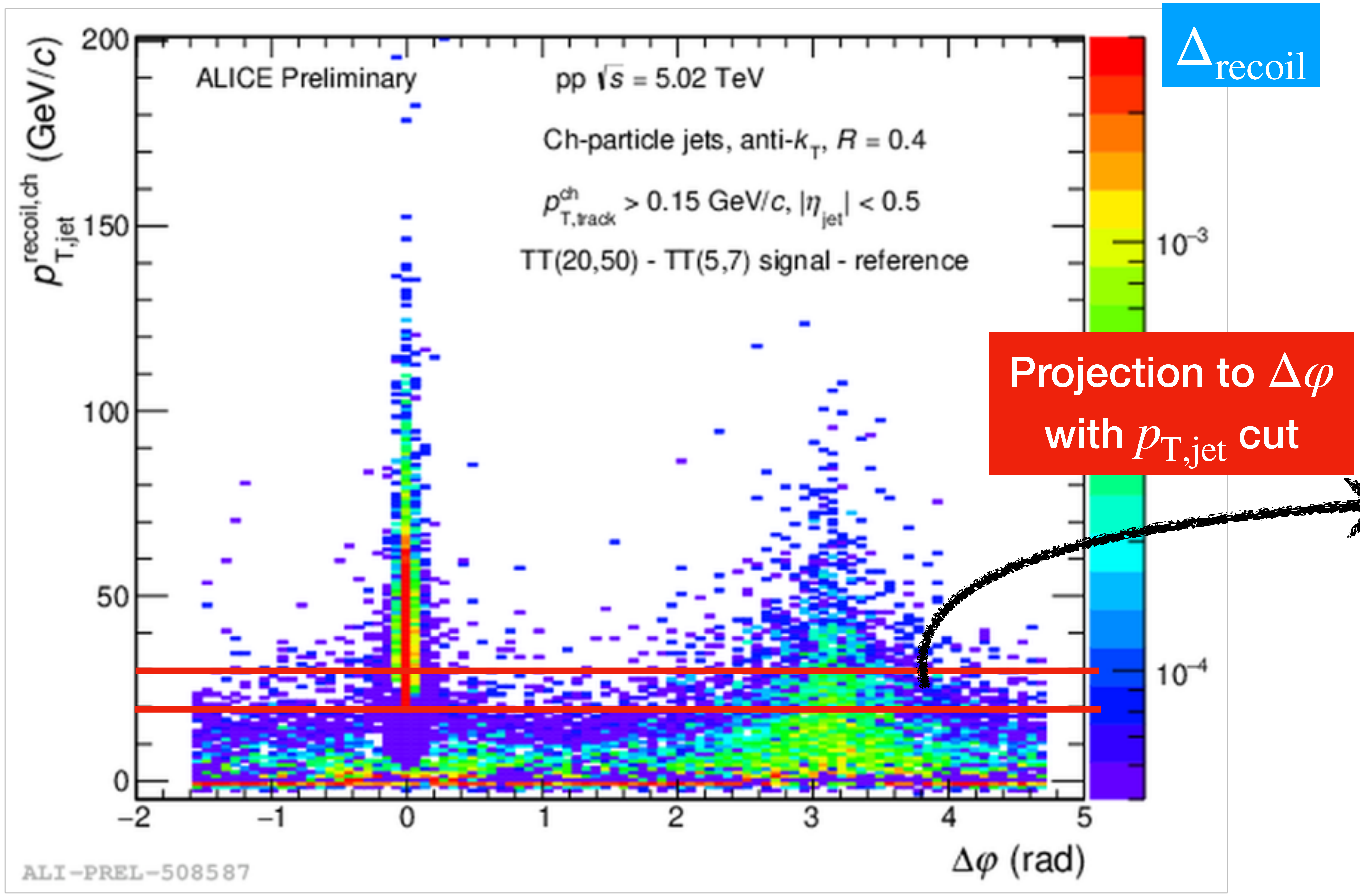

ALI-PREL-539184

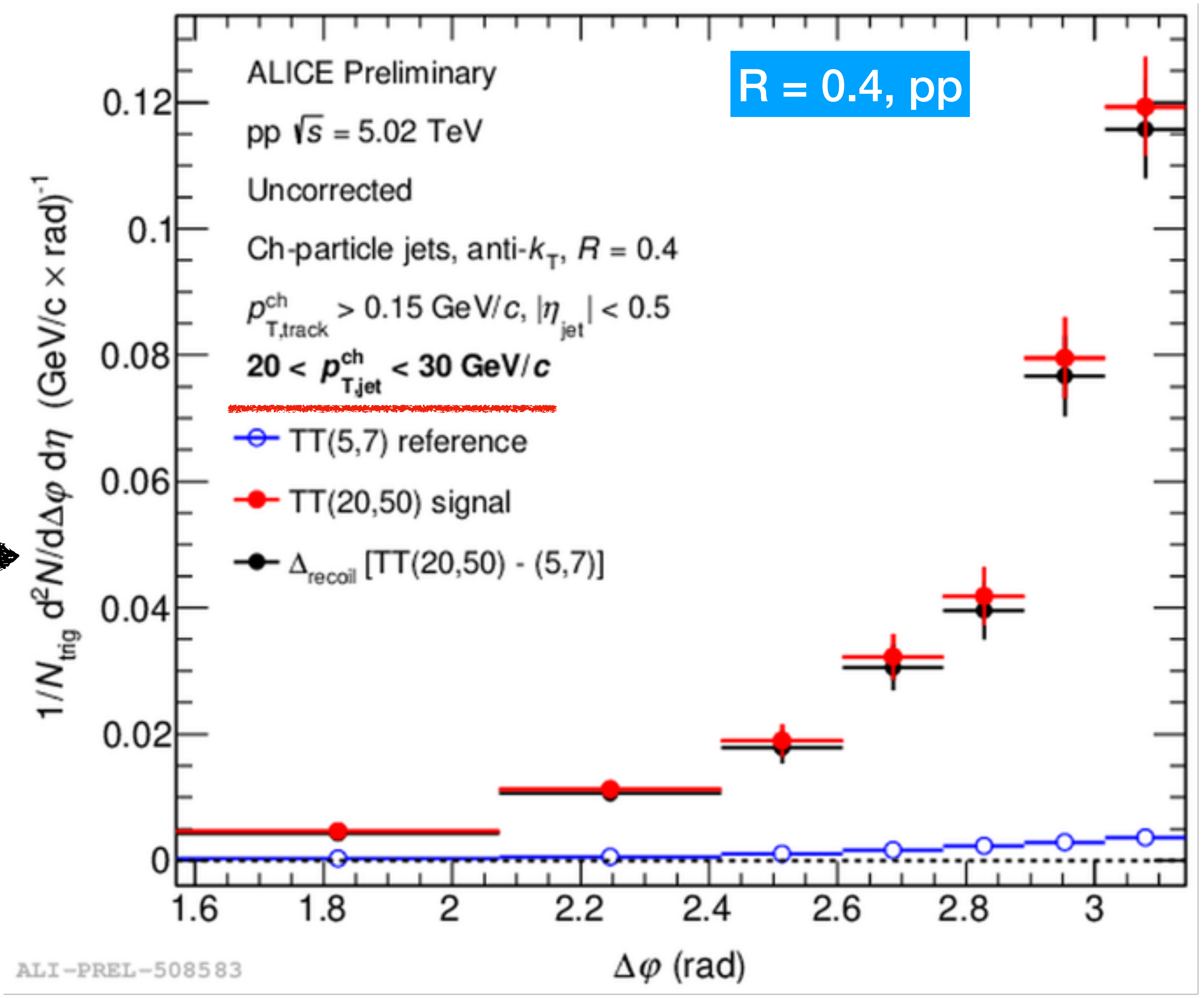



ALI-PREL-539280

- The rising trend is qualitatively described by all predictions
  - **JETSCAPE** largely reproduces the $I_{AA}$ distributions, but **Hybrid Model** predictions overestimate the suppression
- The **Hybrid Models** with wake seem to catch the yield enhancement at low $p_T$ for $R = 0.4$
  - the wake effect or medium response could be responsible for the enhancement

# Recoil jet angular distributions



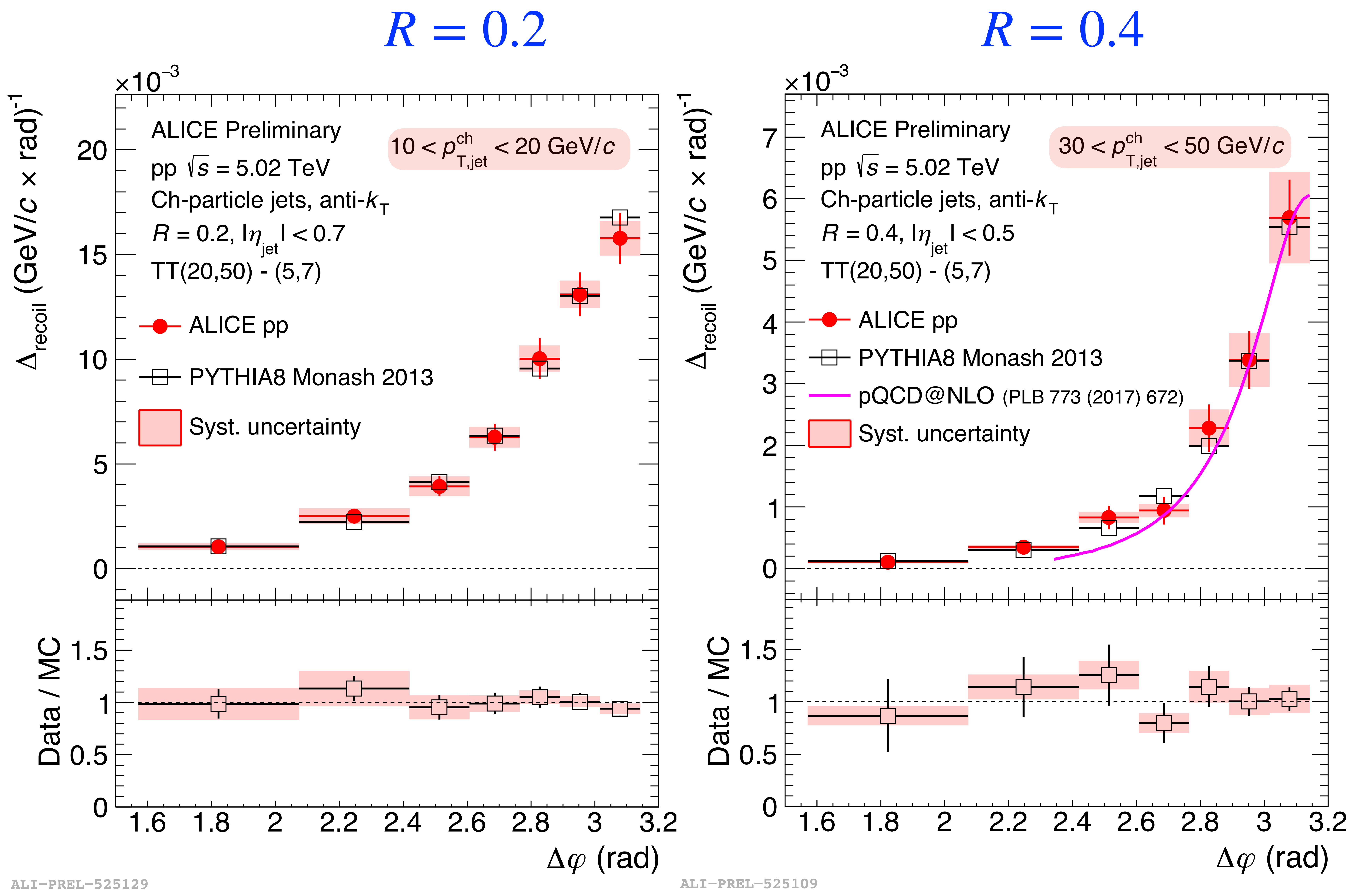




$$\Delta_{recoil}(\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Ref}}$$

# Recoil jet angular distributions in pp

- **Fully-corrected** hadron-jet $\Delta\varphi$ distribution in pp collisions at $\sqrt{s} = 5.02$ TeV
- PYTHIA 8 (LO) and pQCD@NLO[1] predictions are consistent with the data within uncertainties

1. [L Chen, Phys. Lett. B 773 (2017) 672]

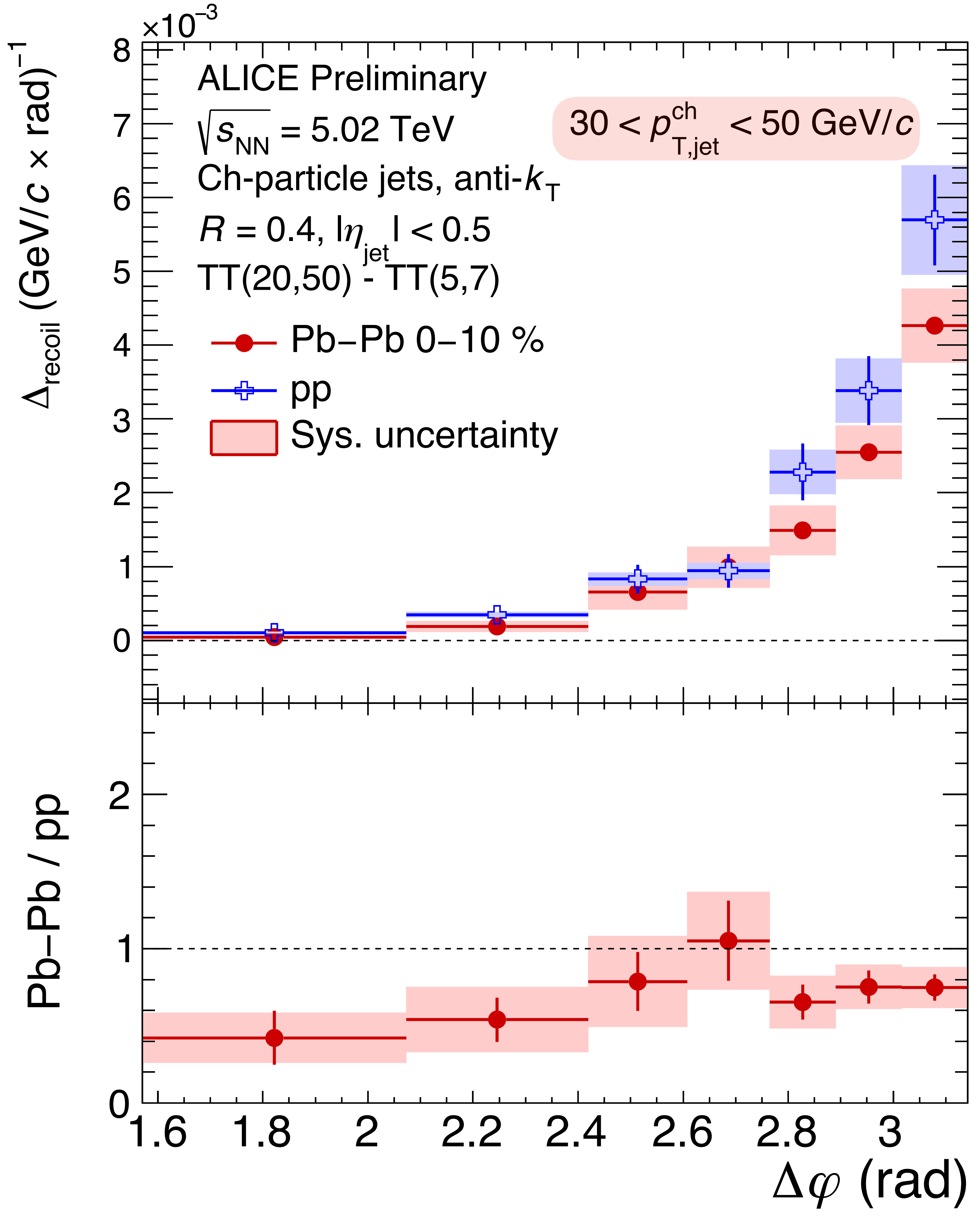


# Recoil jet angular distributions in Pb-Pb

$R = 0.4,\ 0 - 10\,\%$

$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}\ (\Delta\varphi)_{AA}}{\Delta_{\text{recoil}}\ (\Delta\varphi)_{pp}}$$

- Recoil jet **yield suppressed** at higher $p_T$



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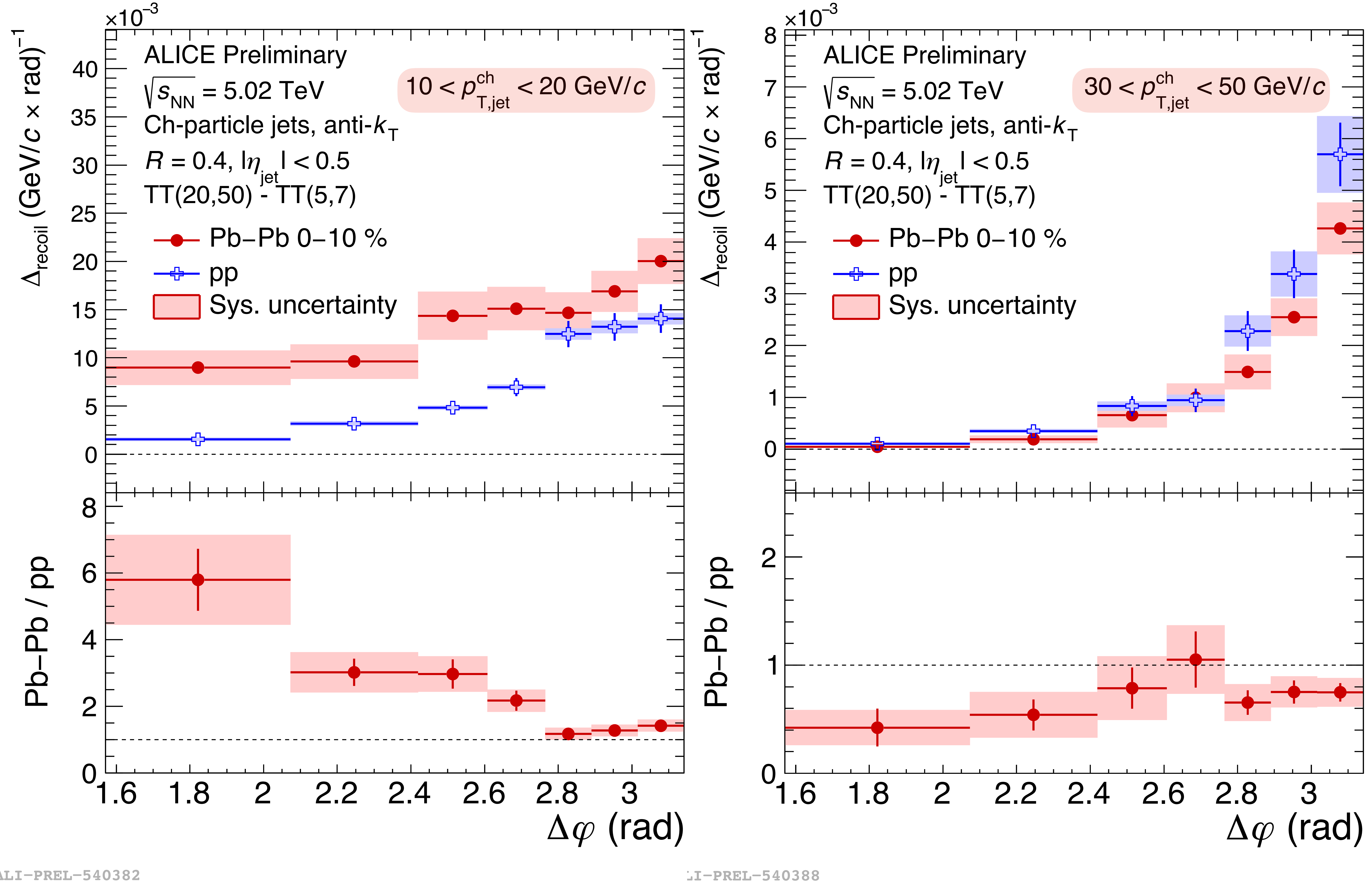
- Recoil jet **yield suppressed** at higher $p_T$
- Medium-induced yield excess and strong **acoplanarity broadening** at low $p_T$

$R = 0.4,\ 0-10\,\%$



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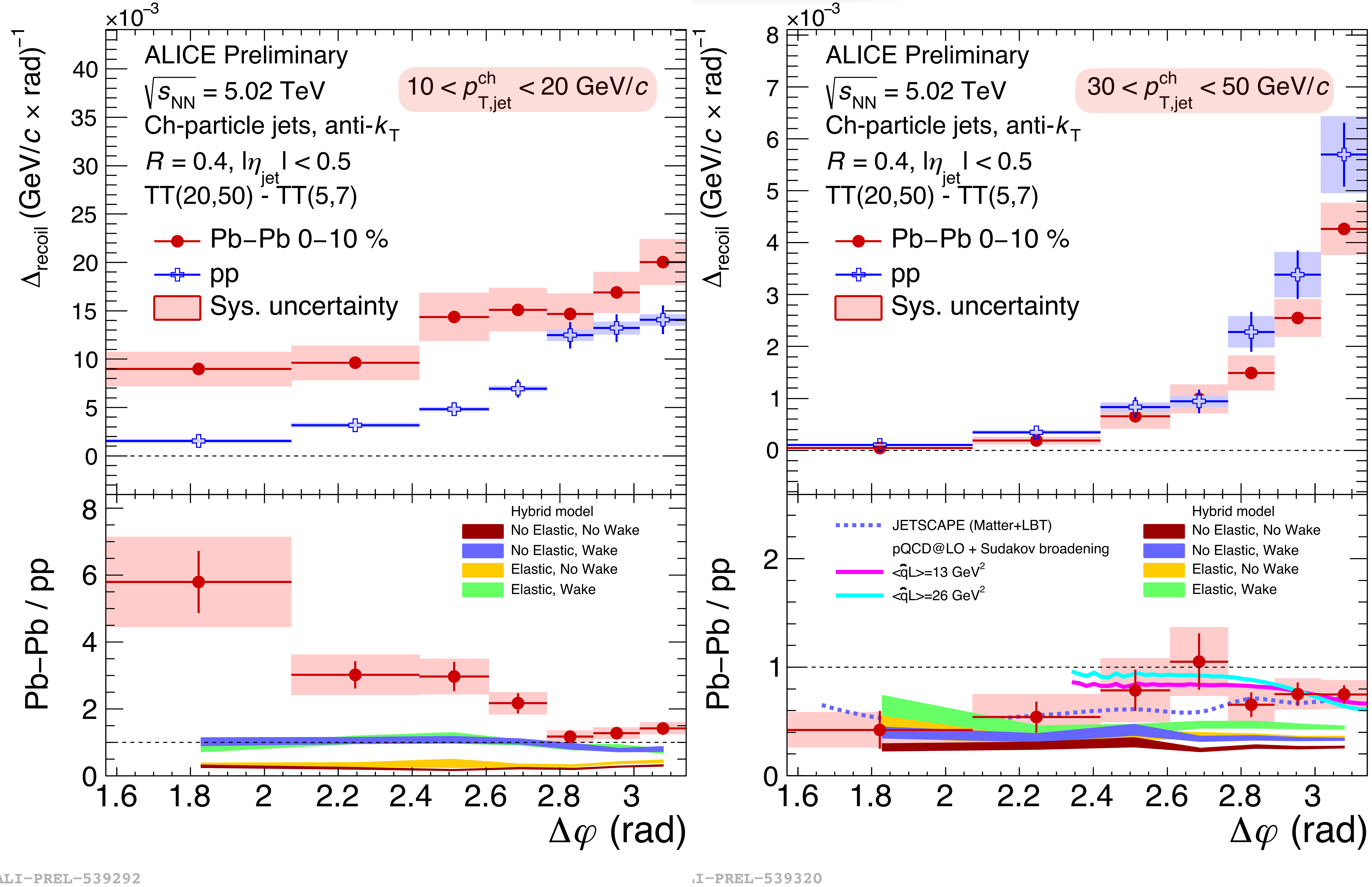
**pQCD@LO + Sudakov broadening**:

Phys.Lett.B 773 (2017) 672

include medium-induced $p_T$ broadening



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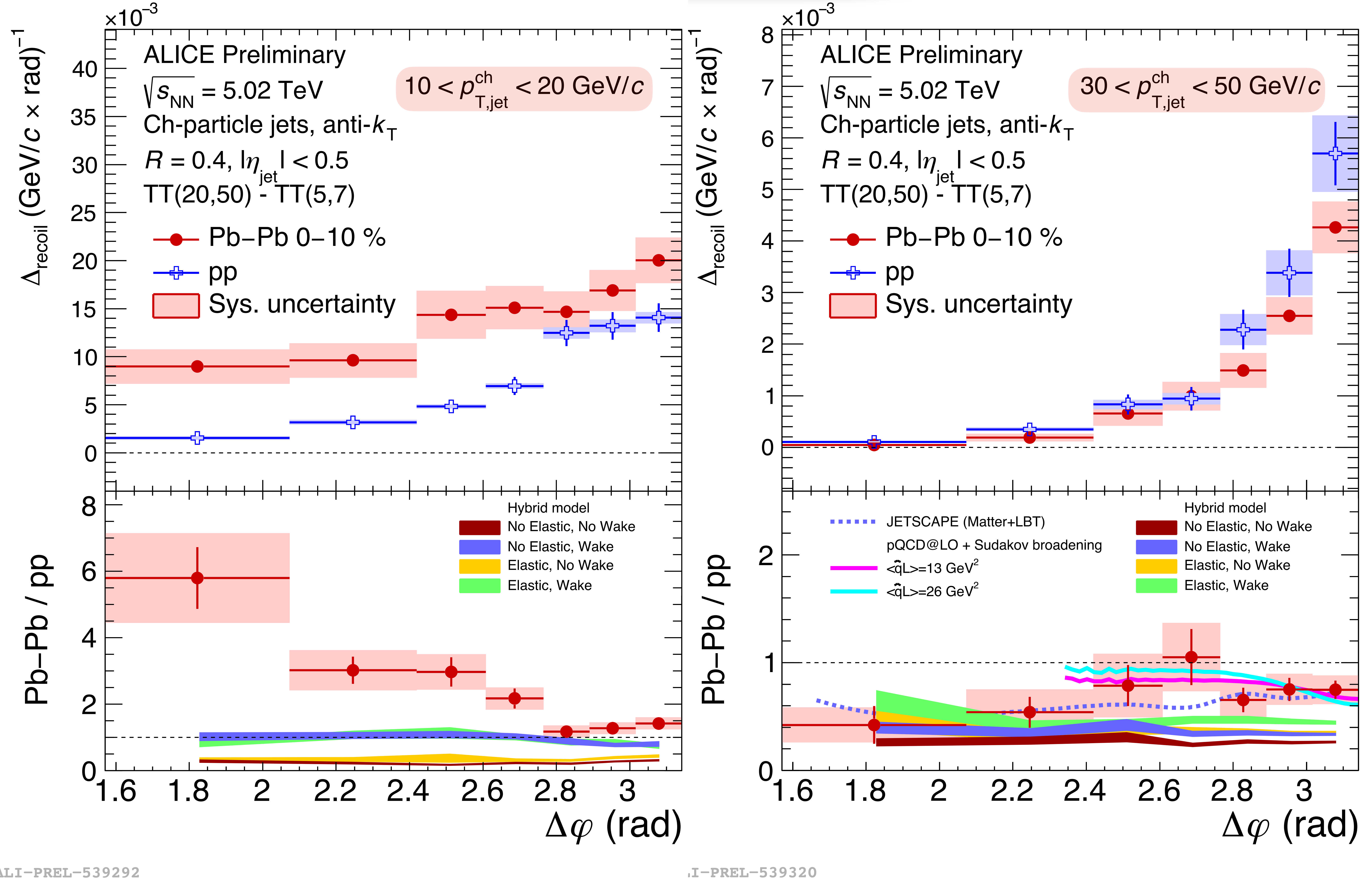
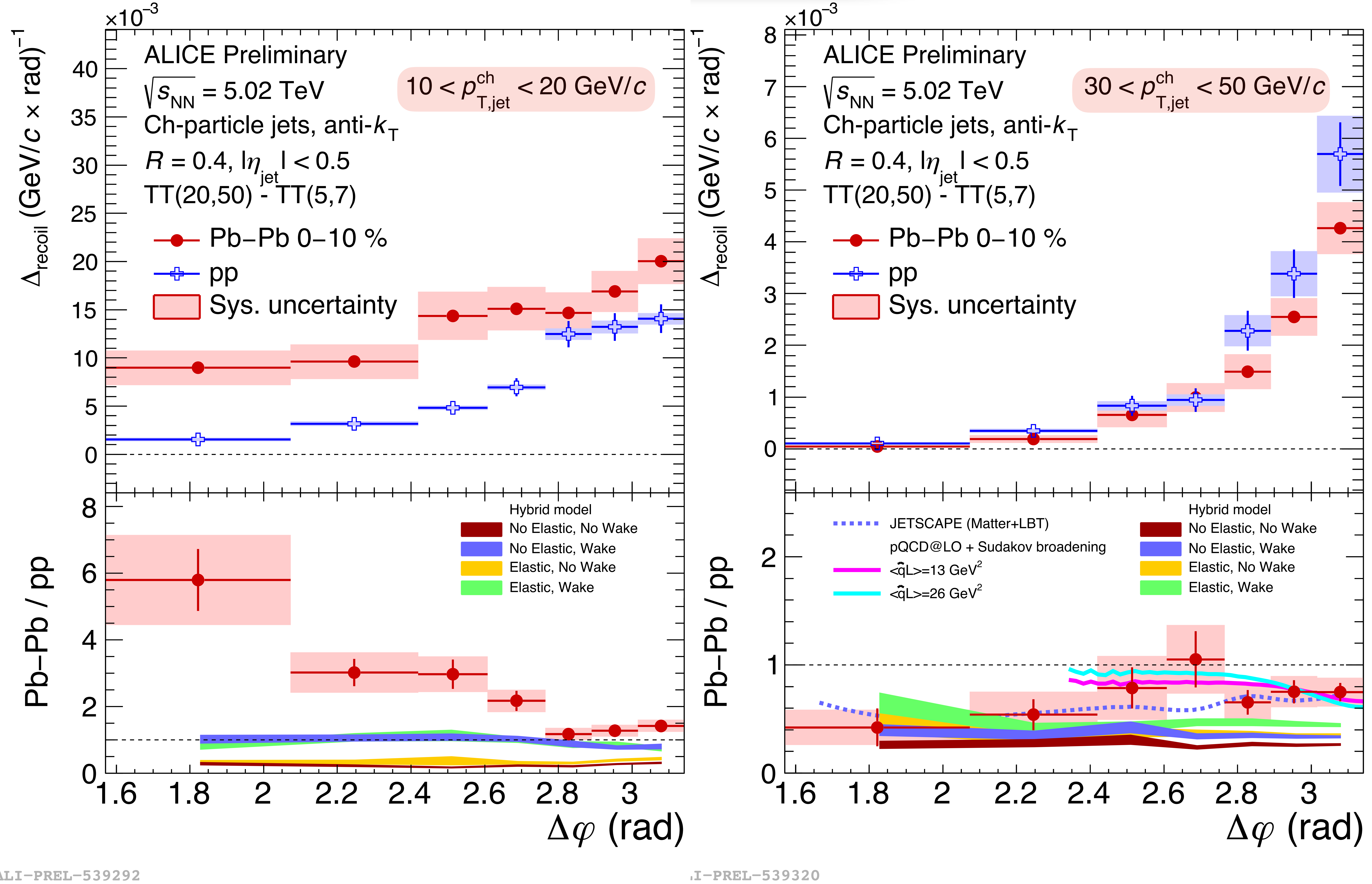


# Comparison of jet angular distributions in Pb-Pb

- JETSCAPE and calculations include medium-induced $p_T$ broadening **reasonably describe the data at high jet $p_T$**, low $p_T$ these calculations not available yet
- Hybrid model predictions with different effects
  - more significant suppression at **high jet $p_T$** in small-deflection region
  - at low $p_T$, **no broadening effect** is observed, regardless of which effect is switched on or off
  - the observable is less sensitive to Moliere scattering (elastic collisions)

$R = 0.4,\ 0-10\,\%$



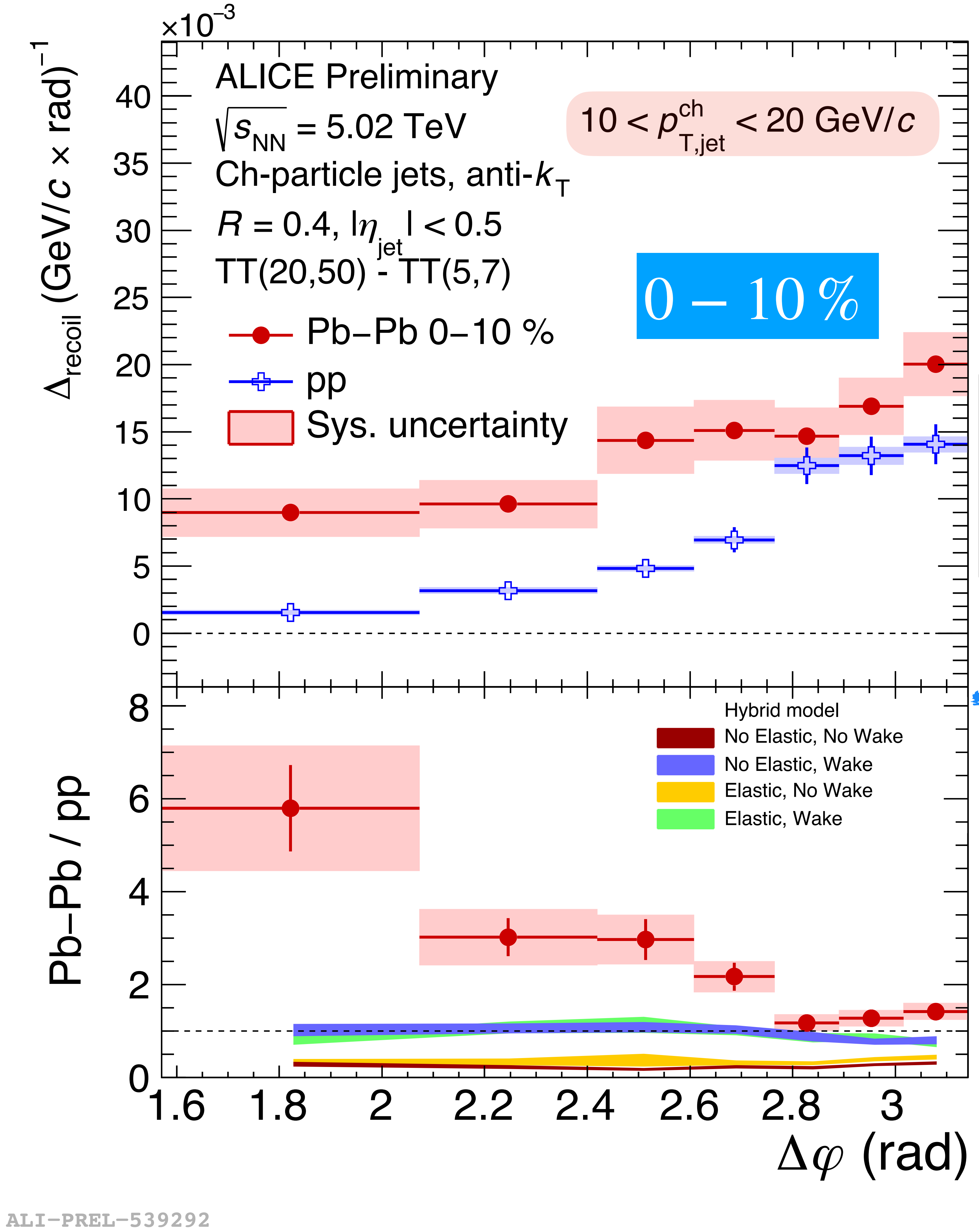
# Summary and outlook

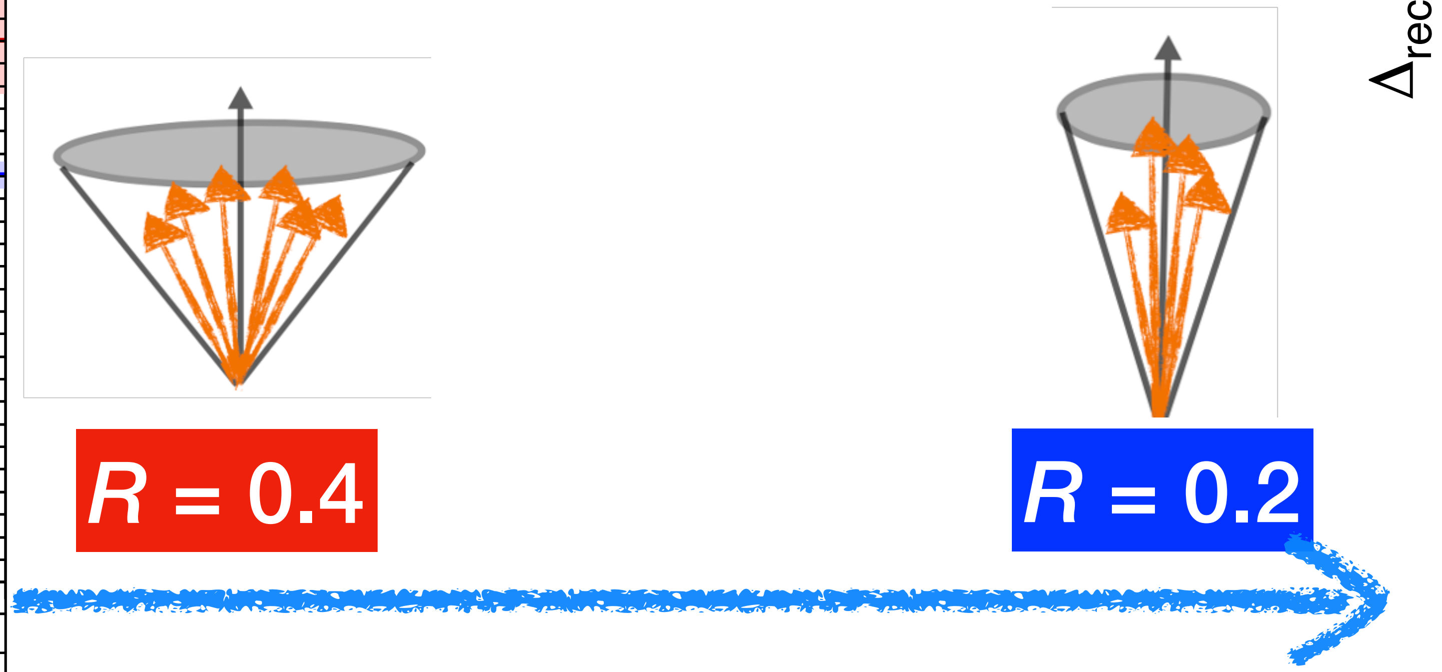
- Semi-inclusive recoil jet measurements in pp and 0-10% Pb-Pb collisions at $\sqrt{S_{\rm NN}} = 5.02$ TeV
  - **Yield suppression** in high $p_{\rm T}$ jets, jet **energy recovery** at low $p_{\rm T}$
  - Observation of **medium-induced acoplanarity broadening** for large $R = 0.4$ at low $p_{\rm T}$

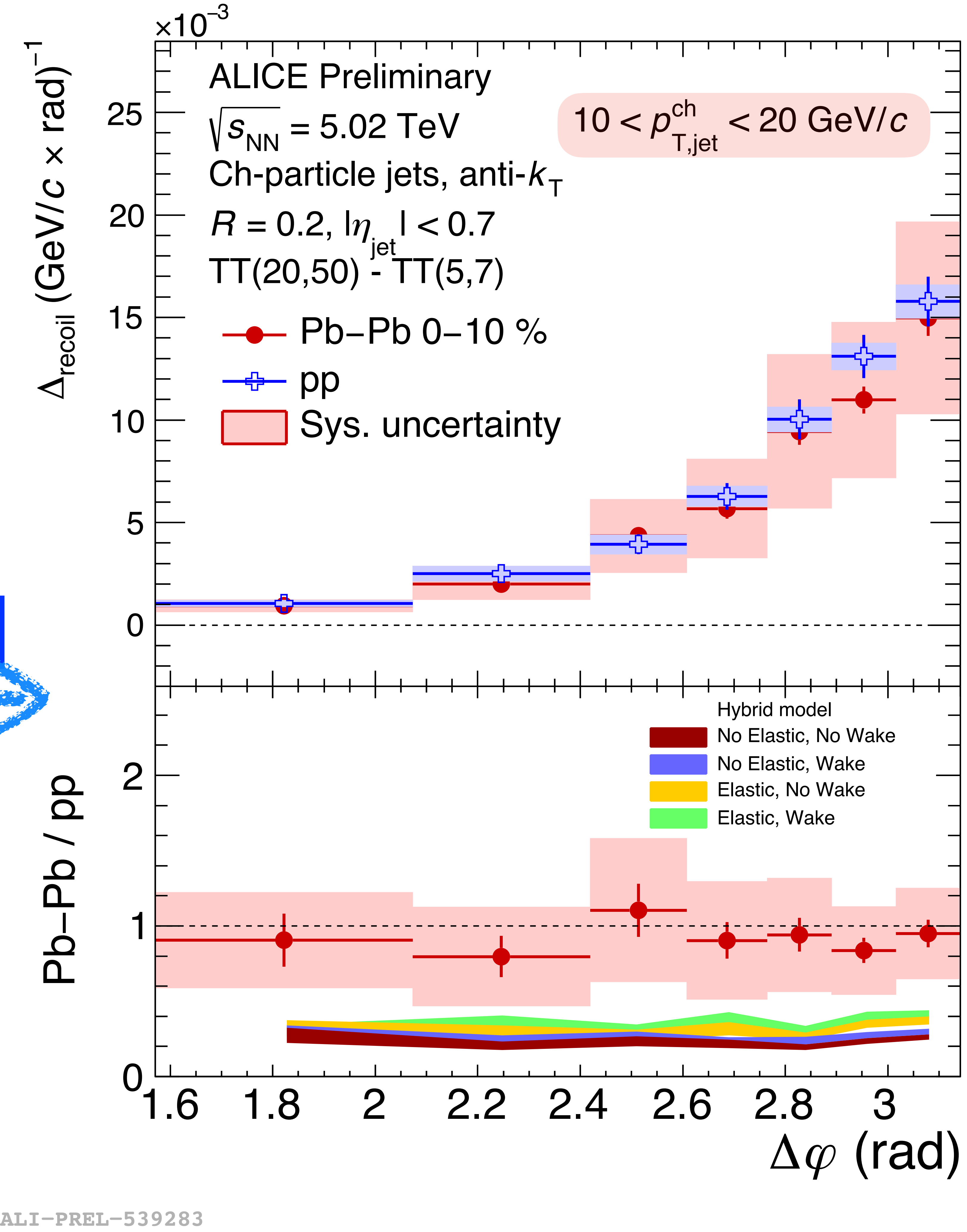
    → Possible origins: in-medium hard scattering, multiple soft scattering, jet fragments, medium response
  - **A consistent picture** between recoil jet $\Delta\varphi$ broadening and energy recovery at low $p_{\rm T}$
- Outlook
  - Looking at profile and substructure of semi-inclusive measurements to disentangle possible origins

*Thanks for your listening*

# Recoil jet angular deflection




- Clear signature of azimuthal decorrelation of soft jets with large $R$ (= 0.4)
- Negligible for small $R$ (= 0.2) jets