The 11th International Conference on **Hard and Electromagnetic Probes of High-Energy Nuclear Collisions**

Observation of medium-induced yield enhancement and acoplanarity broadening in pp and Pb-Pb collisions

Yongzhen HOU for the ALICE collaboration

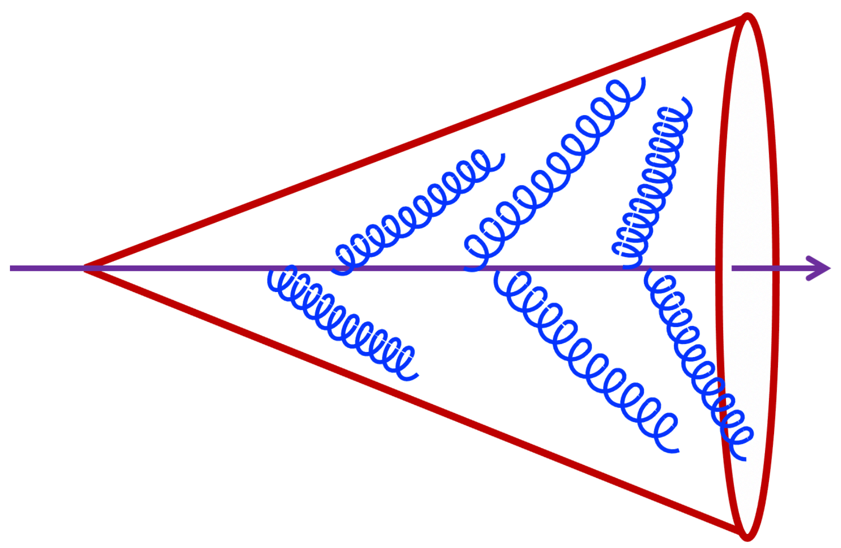
Central China Normal University, University of Strasbourg

26-31 March 2023

Aschaffenburg, Bavaria, Germany

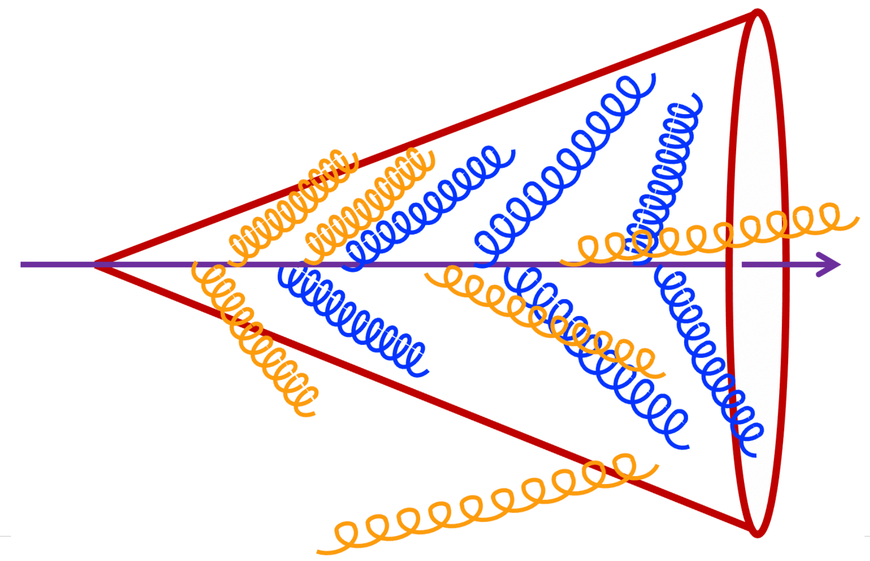
Motivation

- Jet production in vacuum
  - Provides constraints to pQCD calculation
  - Serves as a reference for measurements in heavy-ion collisions



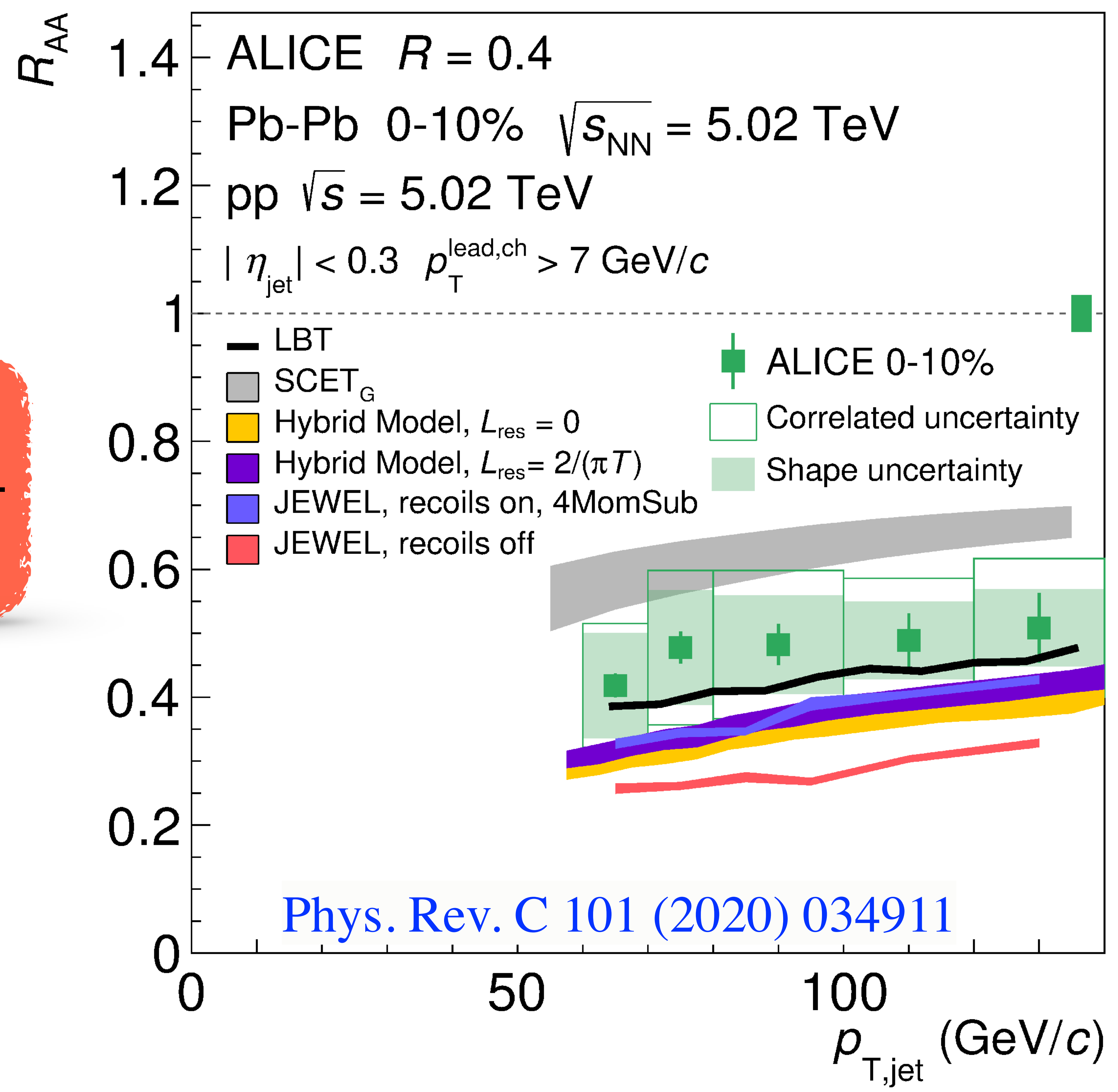
Motivation

- Jet production in vacuum
  - Provides constraints to pQCD calculation
  - Serves as a reference for measurements in heavy-ion collisions



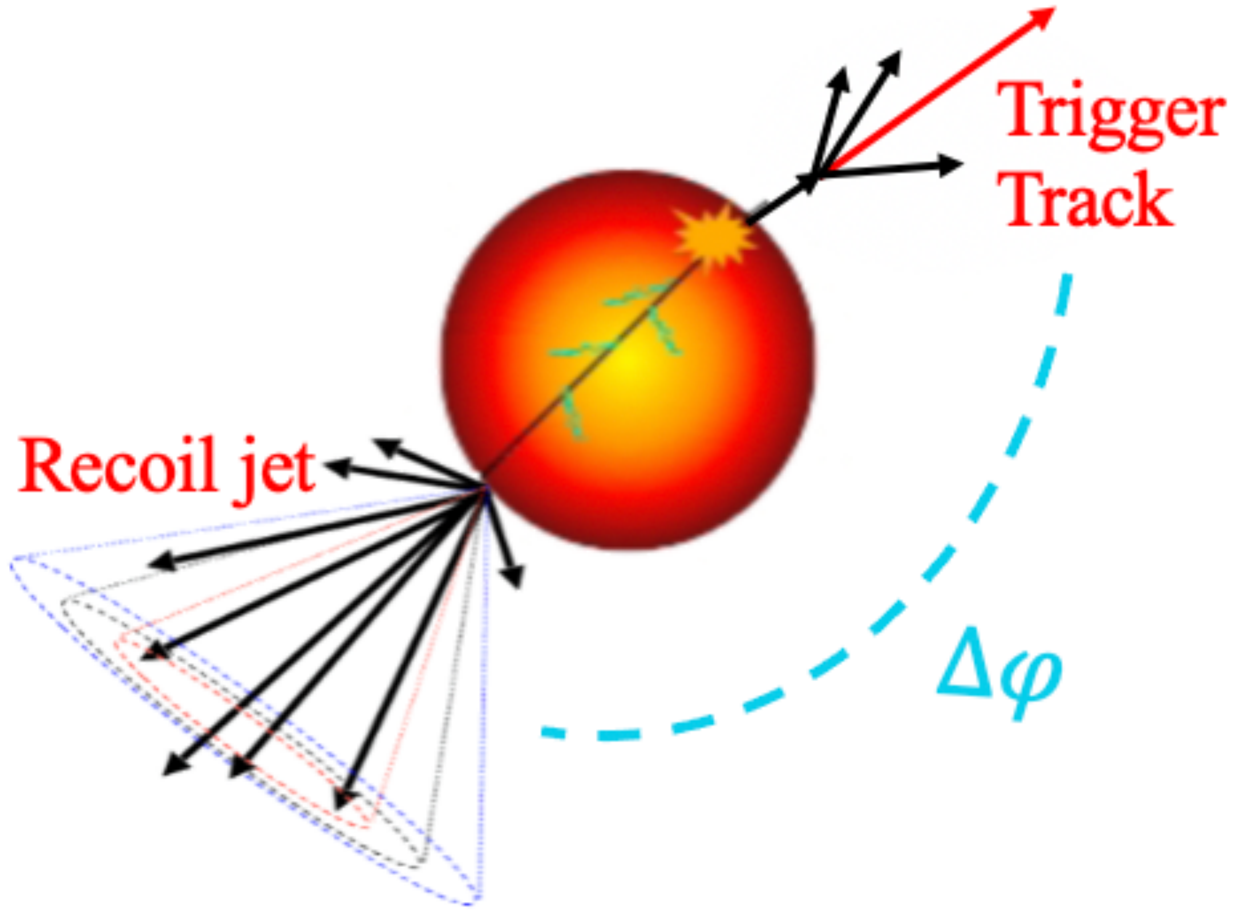
- Jet modification in heavy-ion collisions
  - **Jet energy redistribution** (energy loss)
  - **Jet angular deflection**
  - Modification of jet substructure

$$R_{AA} = \frac{\mathrm{d}N^{AA}_{\mathrm{jets}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\langle T_{AA}\rangle\, \mathrm{d}\sigma^{pp}_{\mathrm{jets}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$



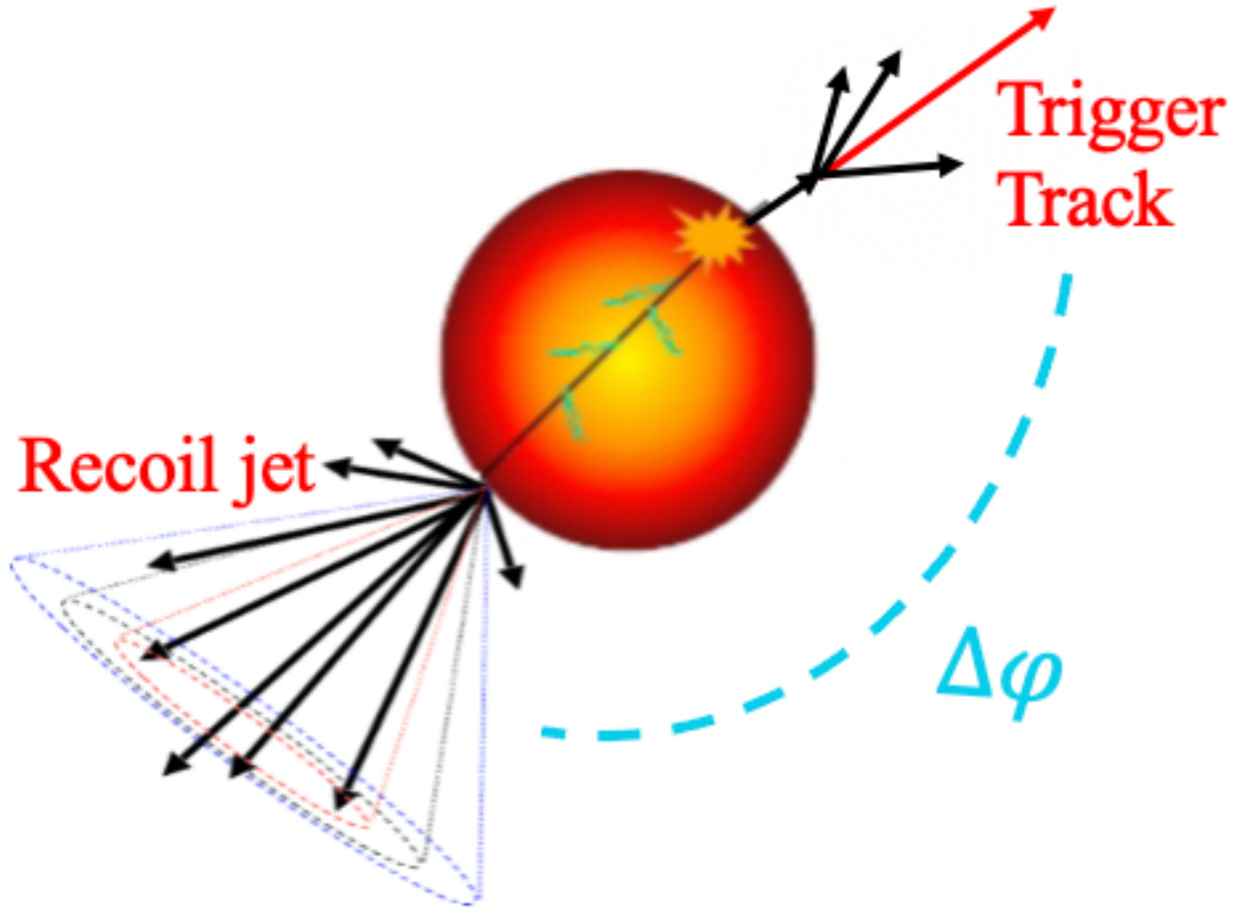
Motivation

- **Opening angle** ($\Delta\varphi$) of the recoil jet relative to trigger axis
- Azimuthal distributions provide additional insight into QGP properties
- Trigger track (TT) close to the surface, but no bias on recoil jets
- Provide a good handle of combinatorial background by varying the trigger track intervals → access low p_T, large R jets



Motivation

- **Opening angle** ($\Delta\varphi$) of the recoil jet relative to trigger axis
- Azimuthal distributions provide additional insight into QGP properties
- Trigger track (TT) close to the surface, but no bias on recoil jets
- Provide a good handle of combinatorial background by varying the trigger track intervals → access low p_{T}, large R jets

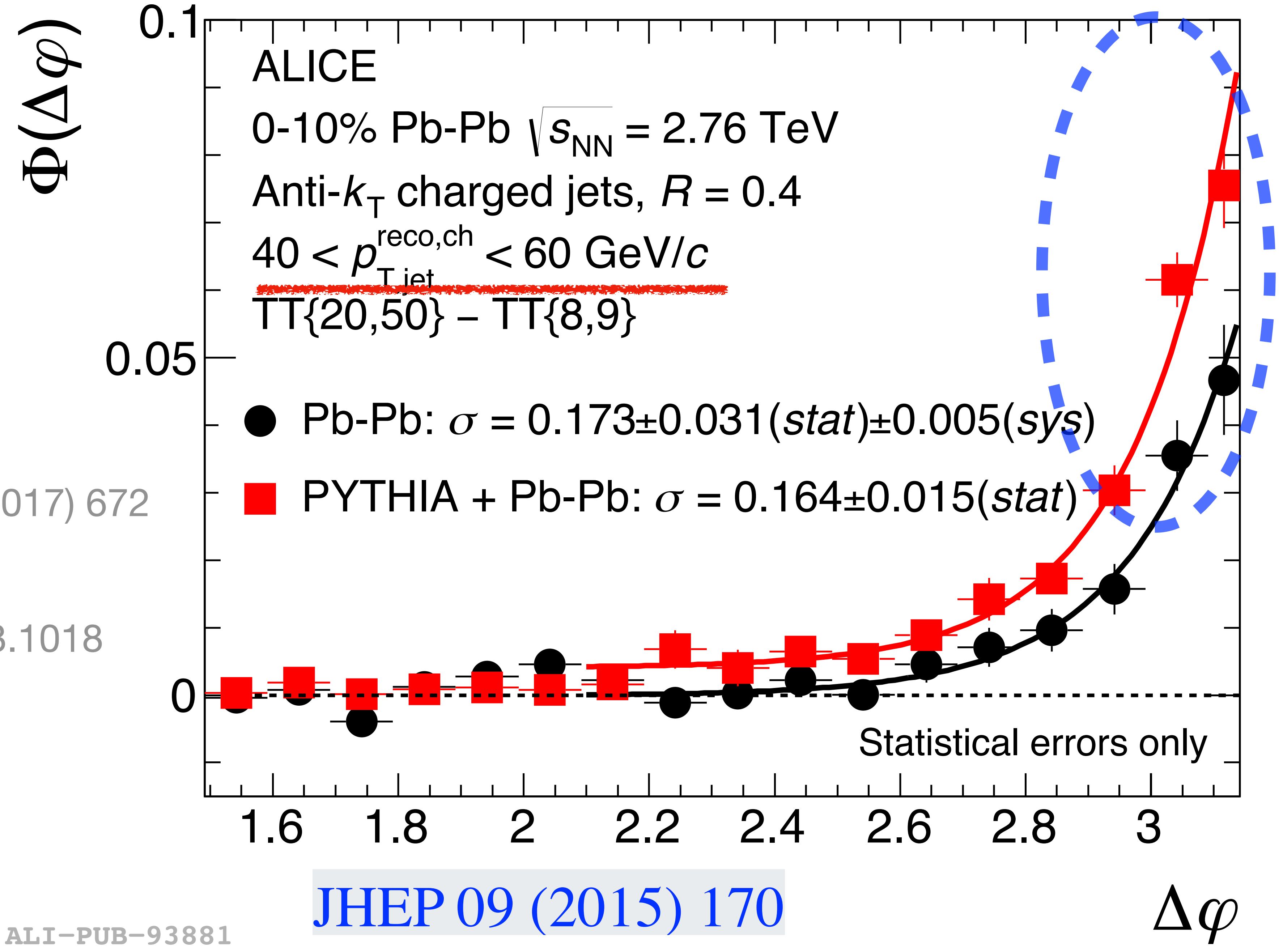


2 regions of interest: $\Delta\varphi \sim \pi$

- Hadron-jet acoplanarity broadening: vacuum (Sudakov) radiation
- Multiple soft scattering in the QGP may further broaden $\Delta\varphi$
  - Related to transport coefficient $\hat{q} \sim \langle p_{\perp}^{2} \rangle / L \sim \langle \Delta\varphi^{2} \rangle / L$
- Negative radiative correction → reduction of broadening

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

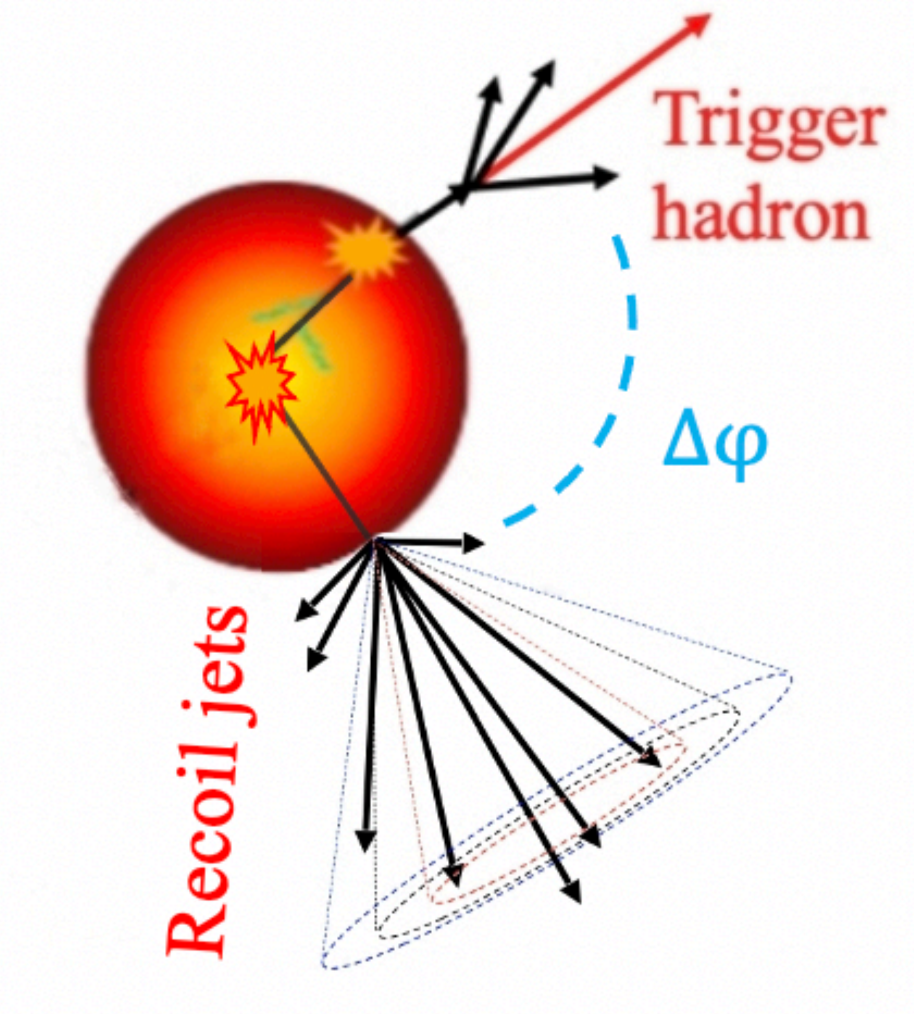
B. G. Zakharov, arxiv:2003.1018



JHEP 09 (2015) 170

Motivation

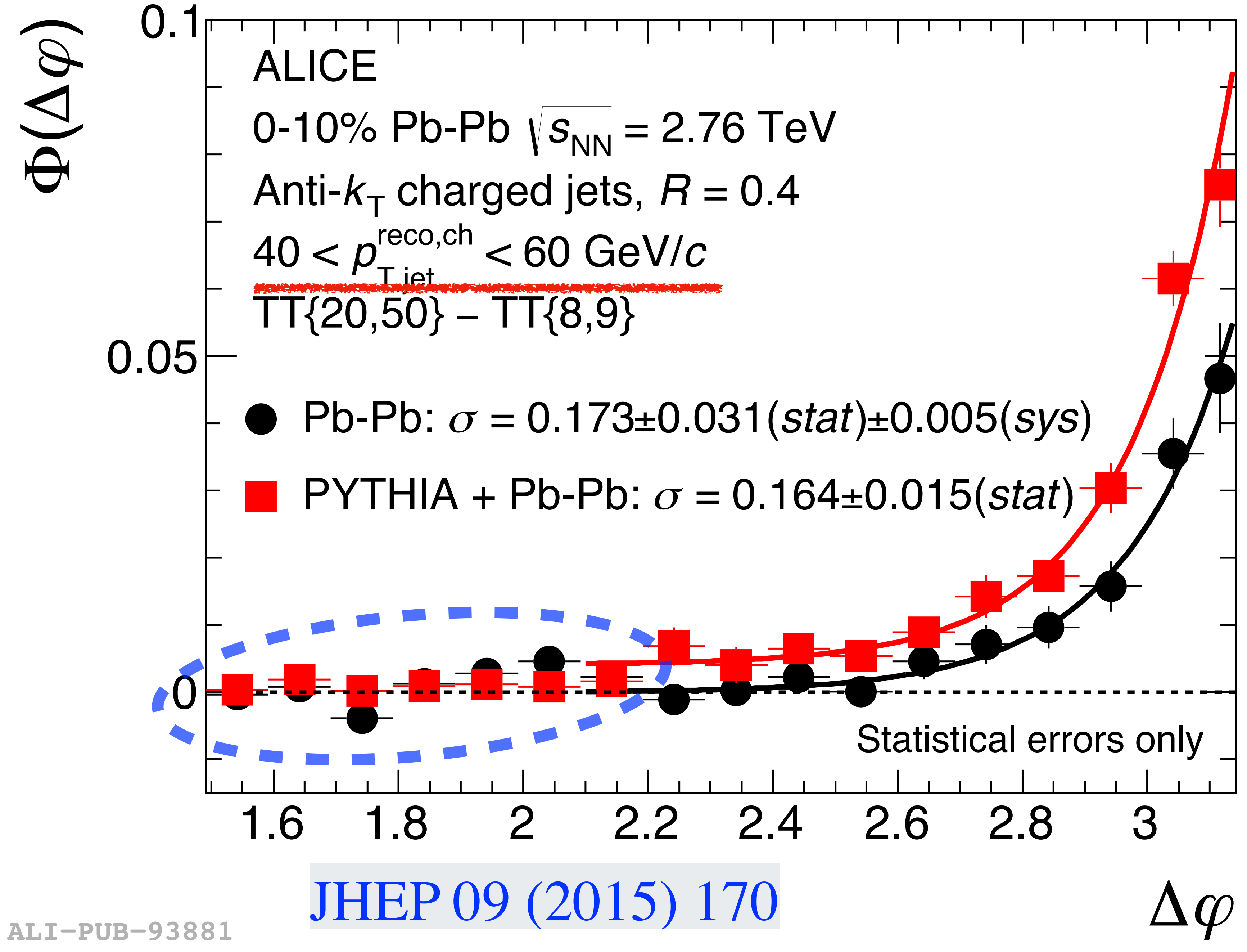
- **Opening angle** ($\Delta\varphi$) of the recoil jet relative to trigger axis
- Azimuthal distributions provide additional insight into QGP properties
- Trigger track (TT) close to the surface, but no bias on recoil jets
- Provide a good handle of combinatorial background by varying the trigger track intervals → access low p_T, large R jets



2 regions of interest: $\Delta\varphi \ll \pi$

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

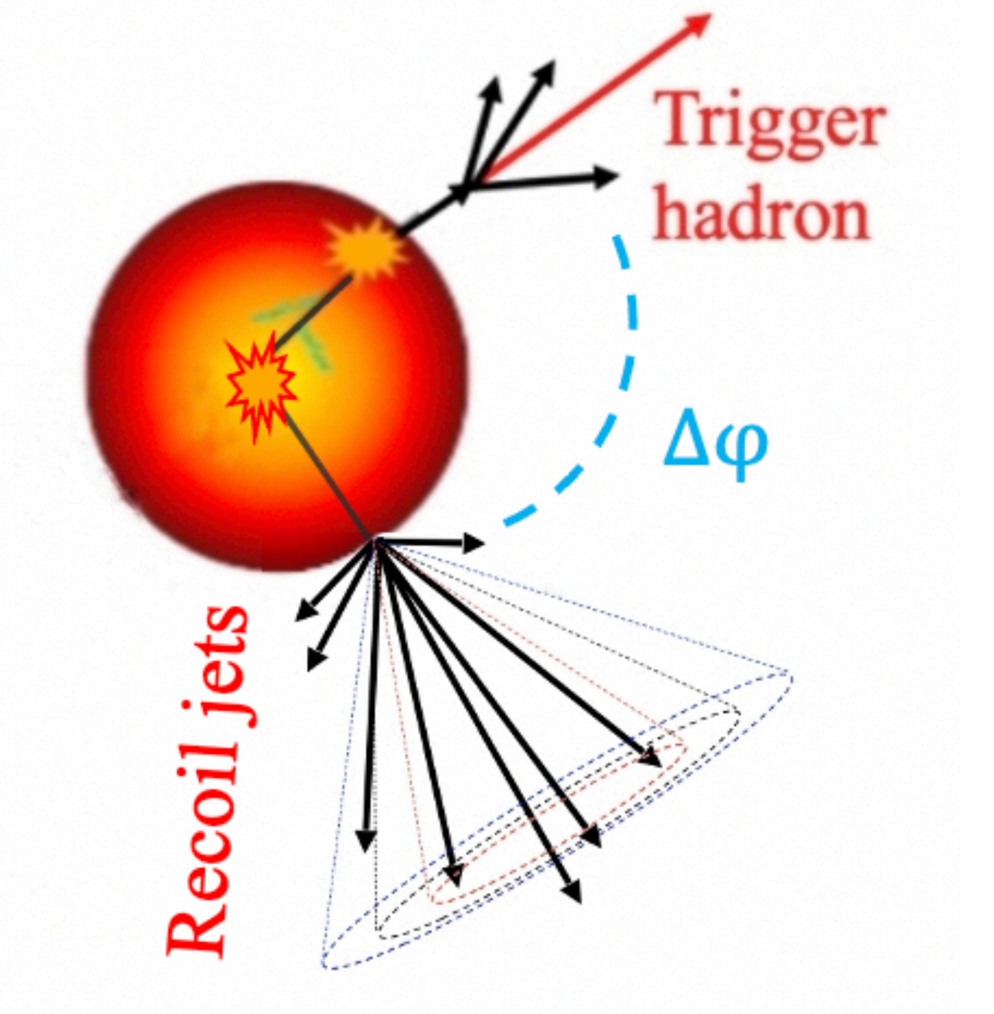
F. D'Eramo, Rajagopal, Y. Yin, JHEP 01 (2019) 172



JHEP 09 (2015) 170

Motivation

- **Opening angle** ($\Delta\varphi$) of the recoil jet relative to trigger axis
- Azimuthal distributions provide additional insight into QGP properties
- Trigger track (TT) close to the surface, but no bias on recoil jets
- Provide a good handle of combinatorial background by varying the trigger track intervals → access low p_{T}, large R jets



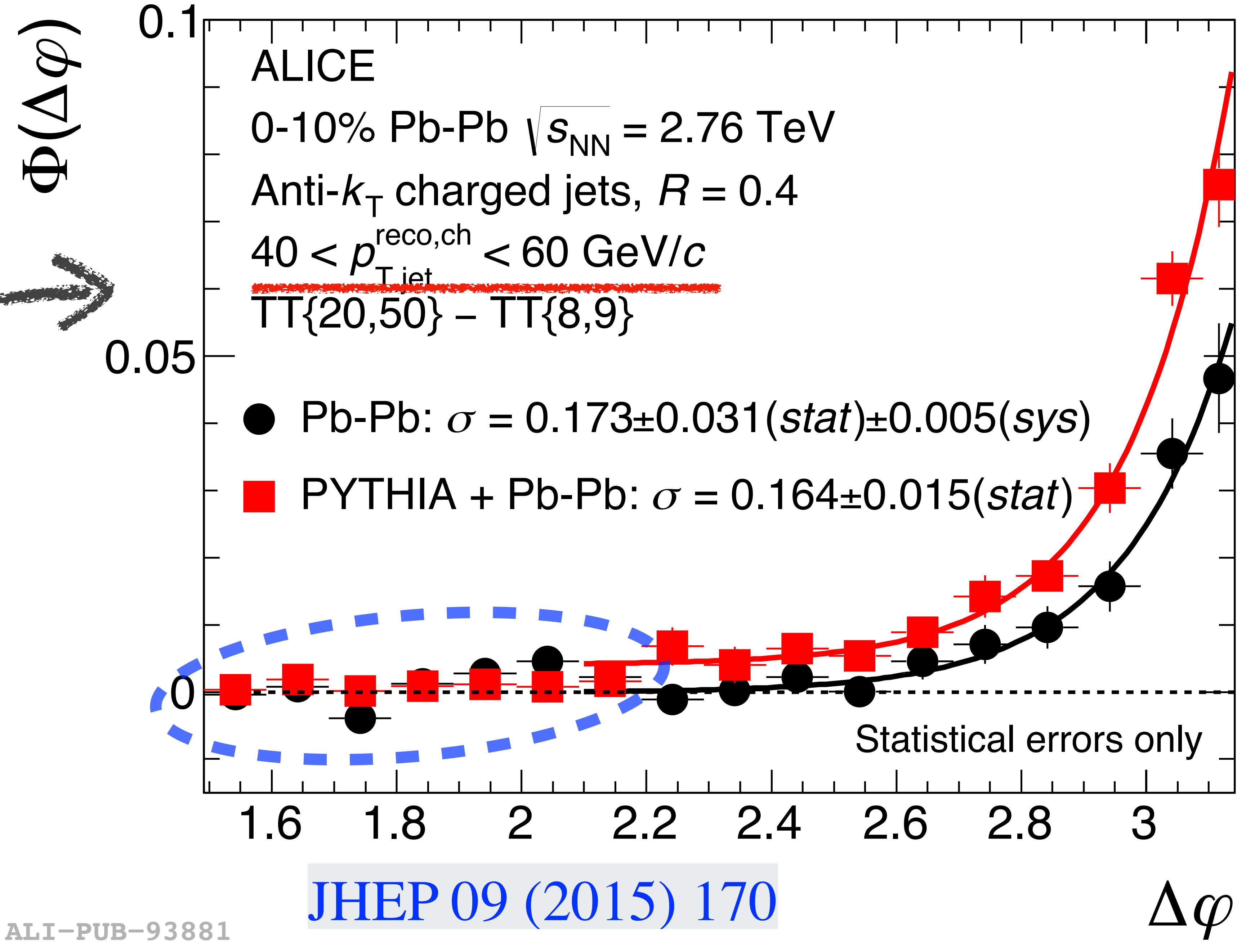
2 regions of interest: $\Delta\varphi \ll \pi$

- 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

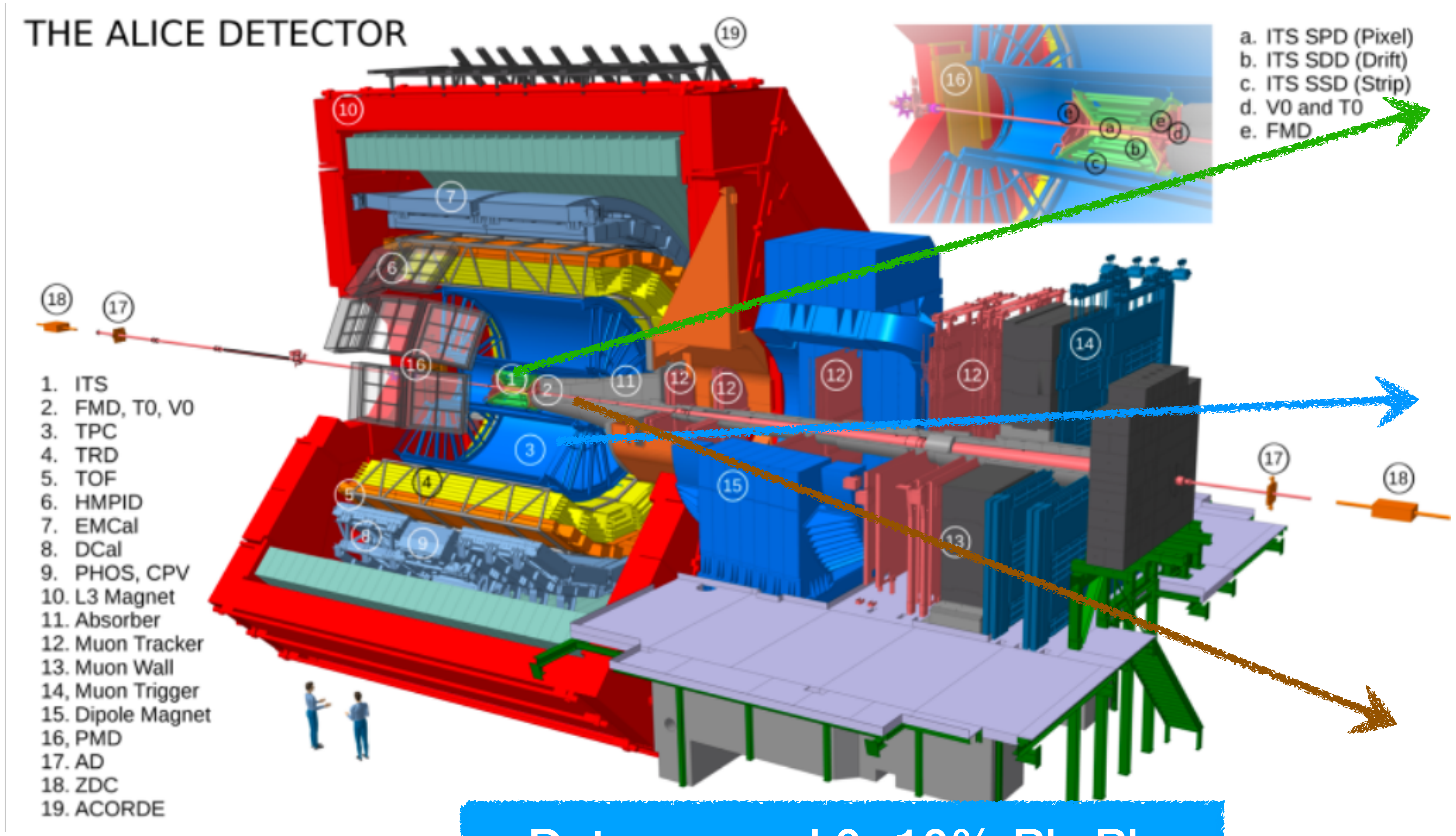
No medium-induced acoplanarity observed within uncertainties

- 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 $\sqrt{S_{NN}} = 5.02$ TeV

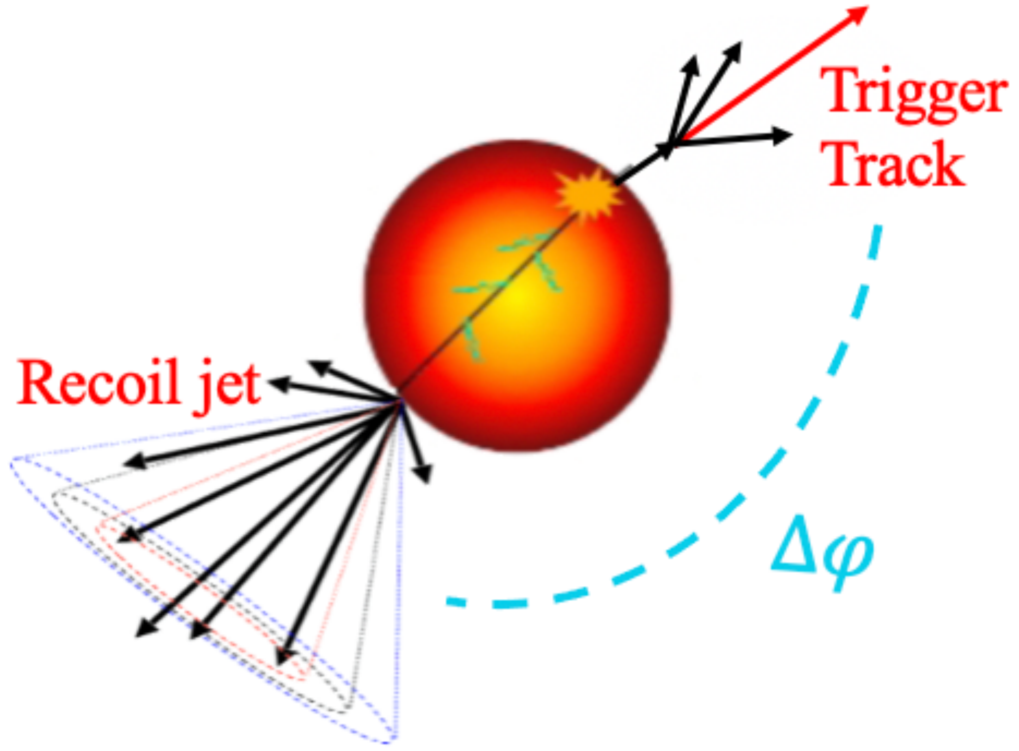
Charged-particle tracks and jets

- **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

$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm AA}}{{\rm d}\eta_{\rm jet}\, {\rm d}p_{\rm T,jet}}\Bigg|_{p_{\rm T}^{\rm trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm AA\rightarrow h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm AA\rightarrow h+jet+X}}{{\rm d}\eta_{\rm jet}\, {\rm d}p_{\rm T,jet}} \right)\Bigg|_{p_{\rm T,h}\in {\rm TT}}$$

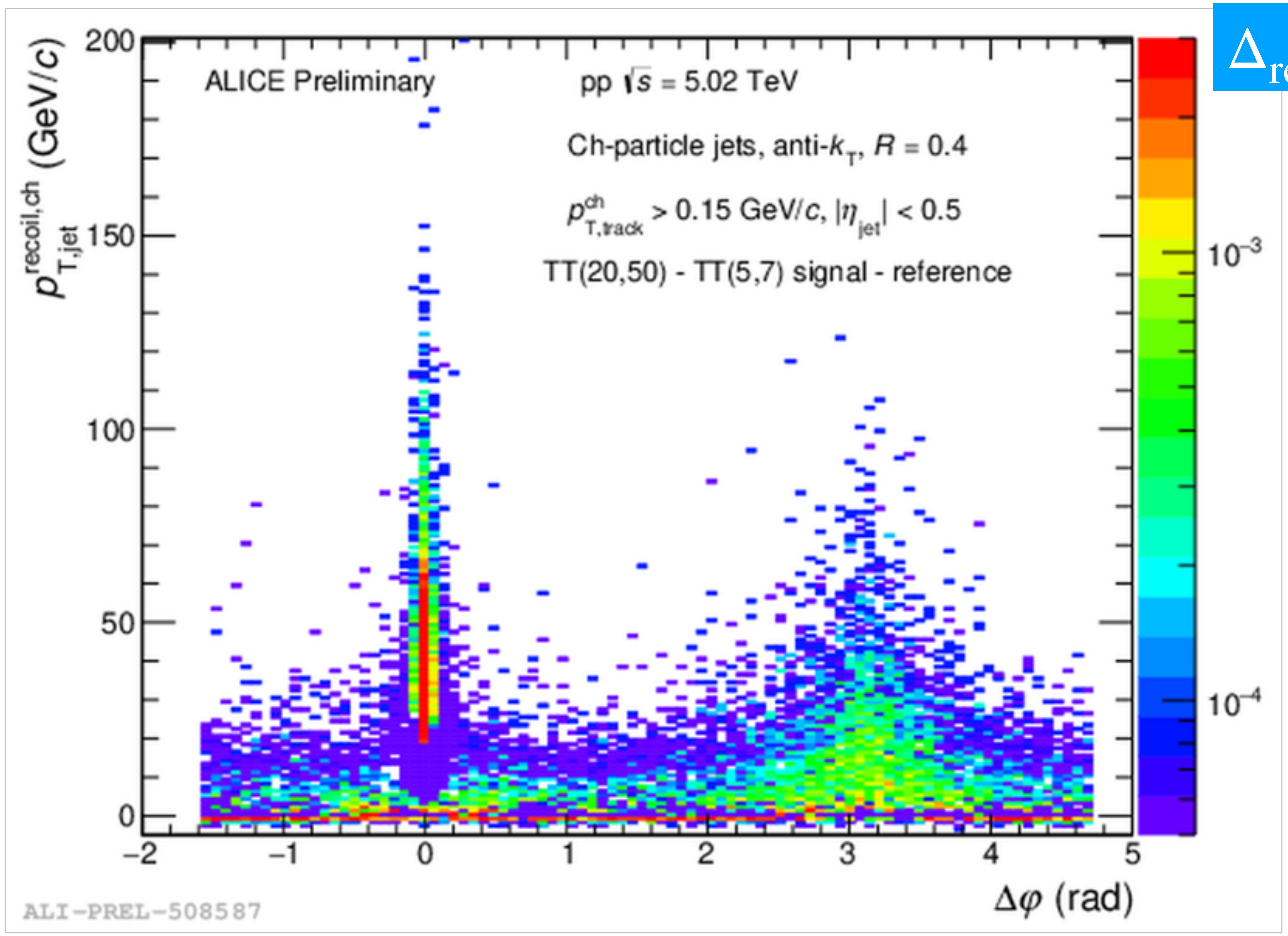


- Observables defined as **the difference** between trigger-normalised recoil jet yields in **two trigger track intervals** in order to **remove uncorrelated background jets**

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

  - TT signal: $p_{\rm T} \in (20,\ 50)$ GeV/c, TT reference: $p_{\rm T} \in (5,\ 7)$ GeV/c, jet R: 0.2, 0.4
  - $c_{\rm ref}$: "alignment" constant extracted from data; precise subtraction of uncorrelated jet yield

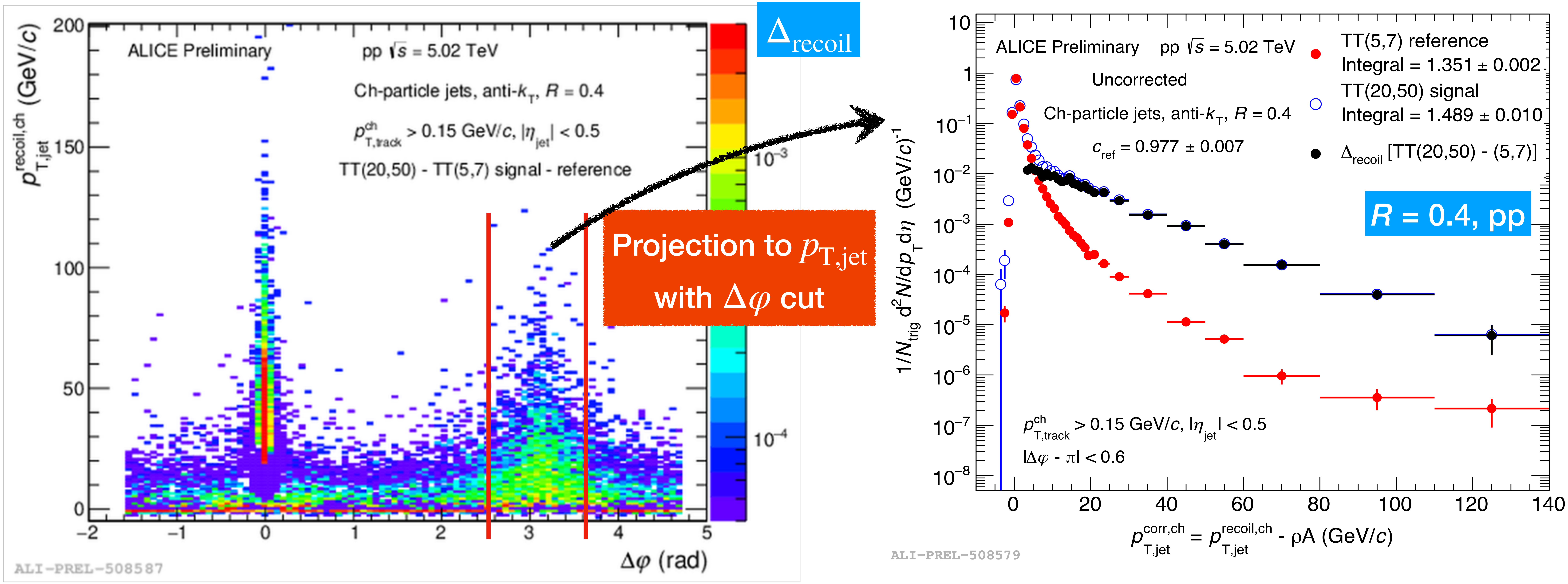
Analysis details



Δ_{recoil}

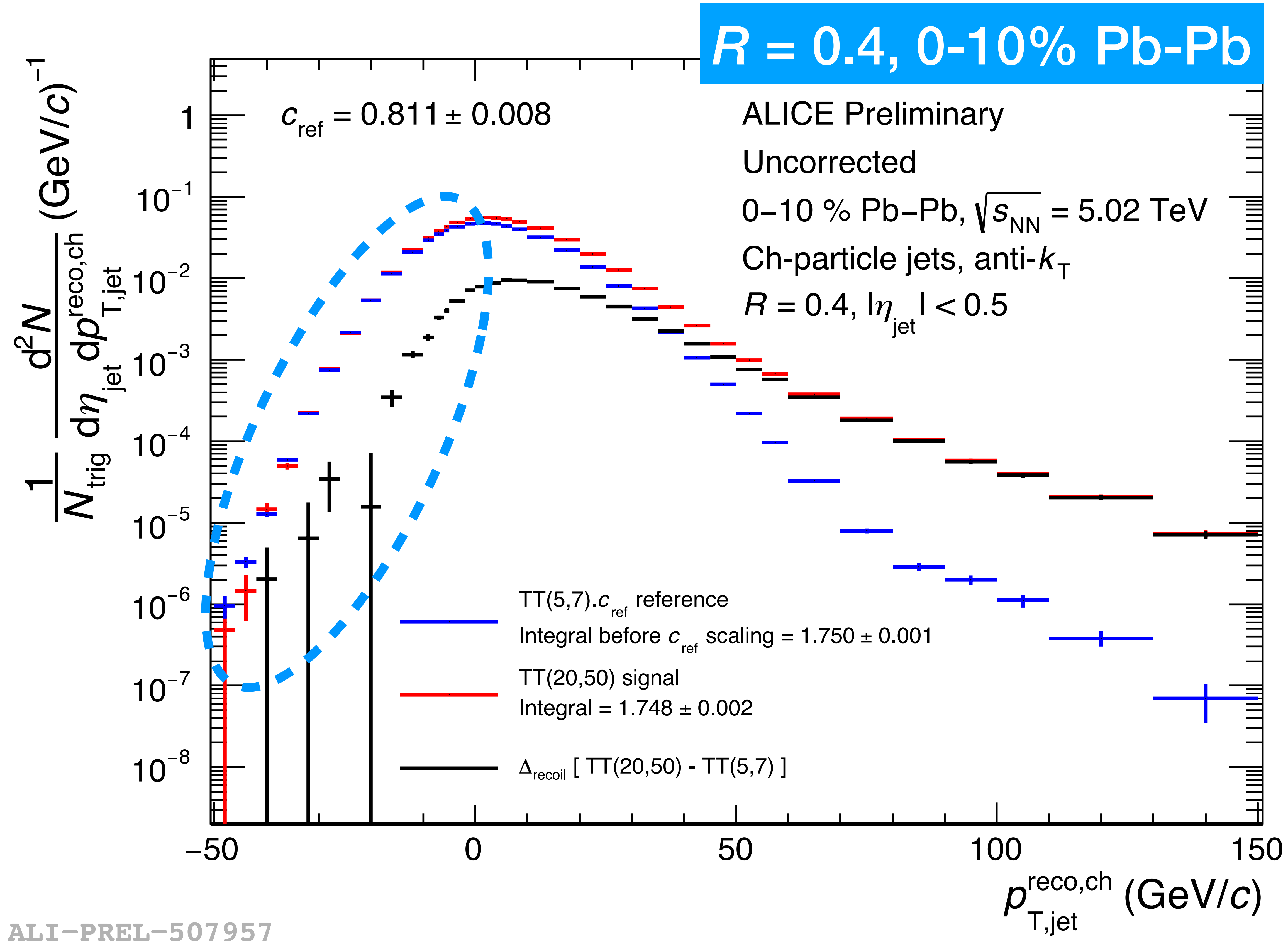
- Get **the raw p_T vs $\Delta\varphi$ 2-dimensional** distributions for two trigger track p_T intervals and Δ_{recoil}

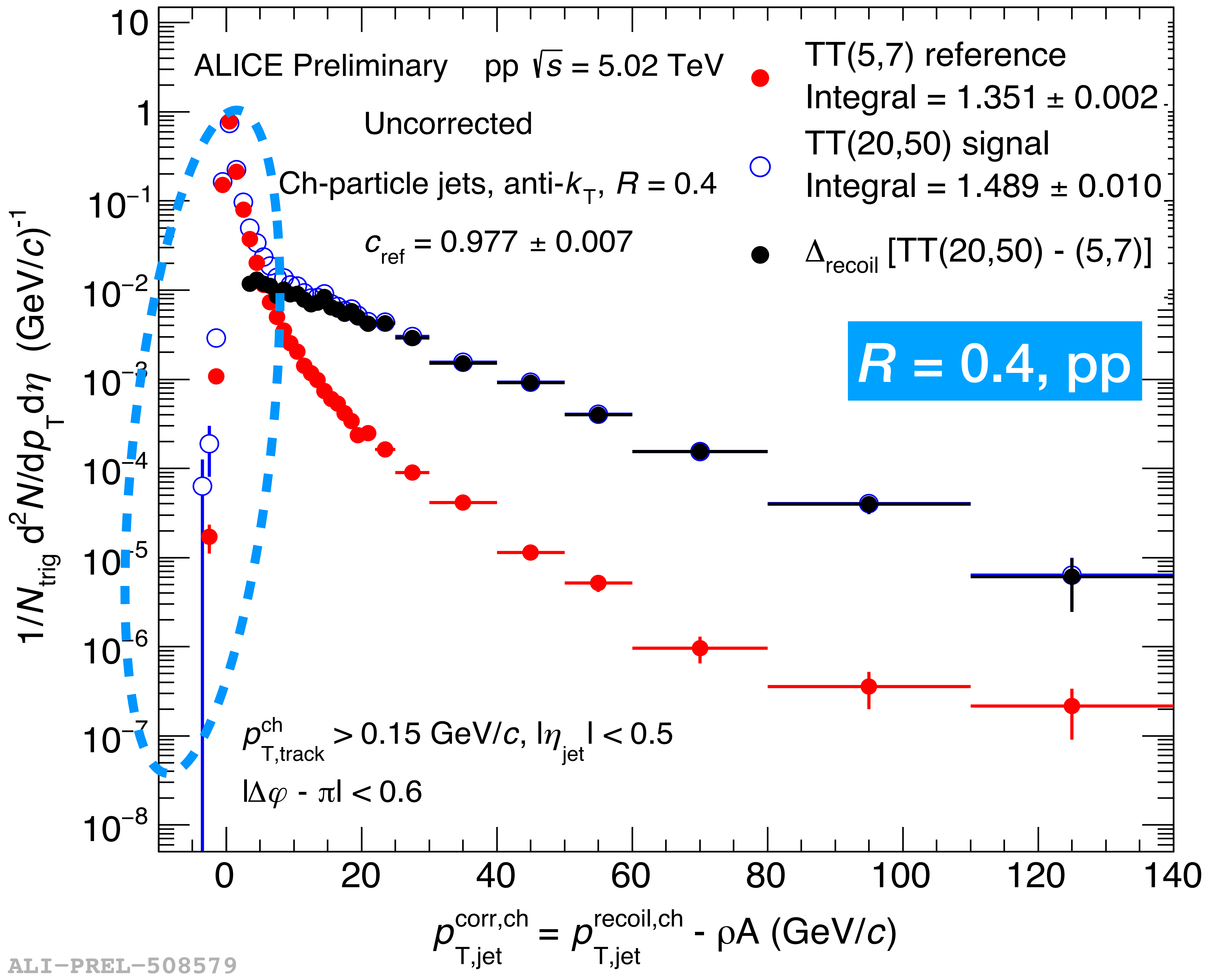
Analysis details



- Get **the raw p_{T} vs $\Delta\varphi$ 2-dimensional** distributions for two trigger track p_{T} intervals and Δ_{recoil}
- **Recoil jet p_{T} distributions** measured for two p_{T} trigger track classes using 2D projection

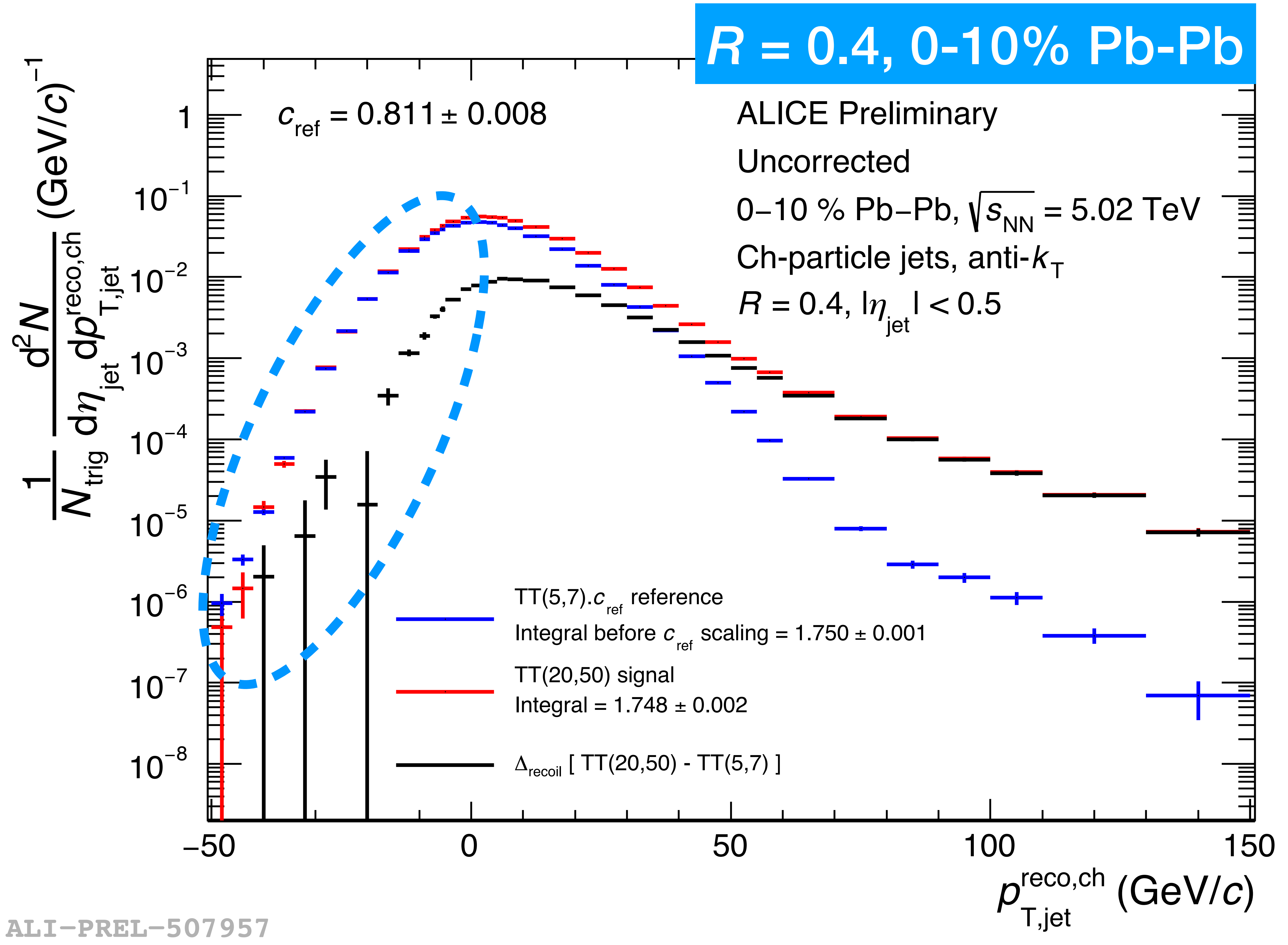
Semi-inclusive recoil jet p_T distributions

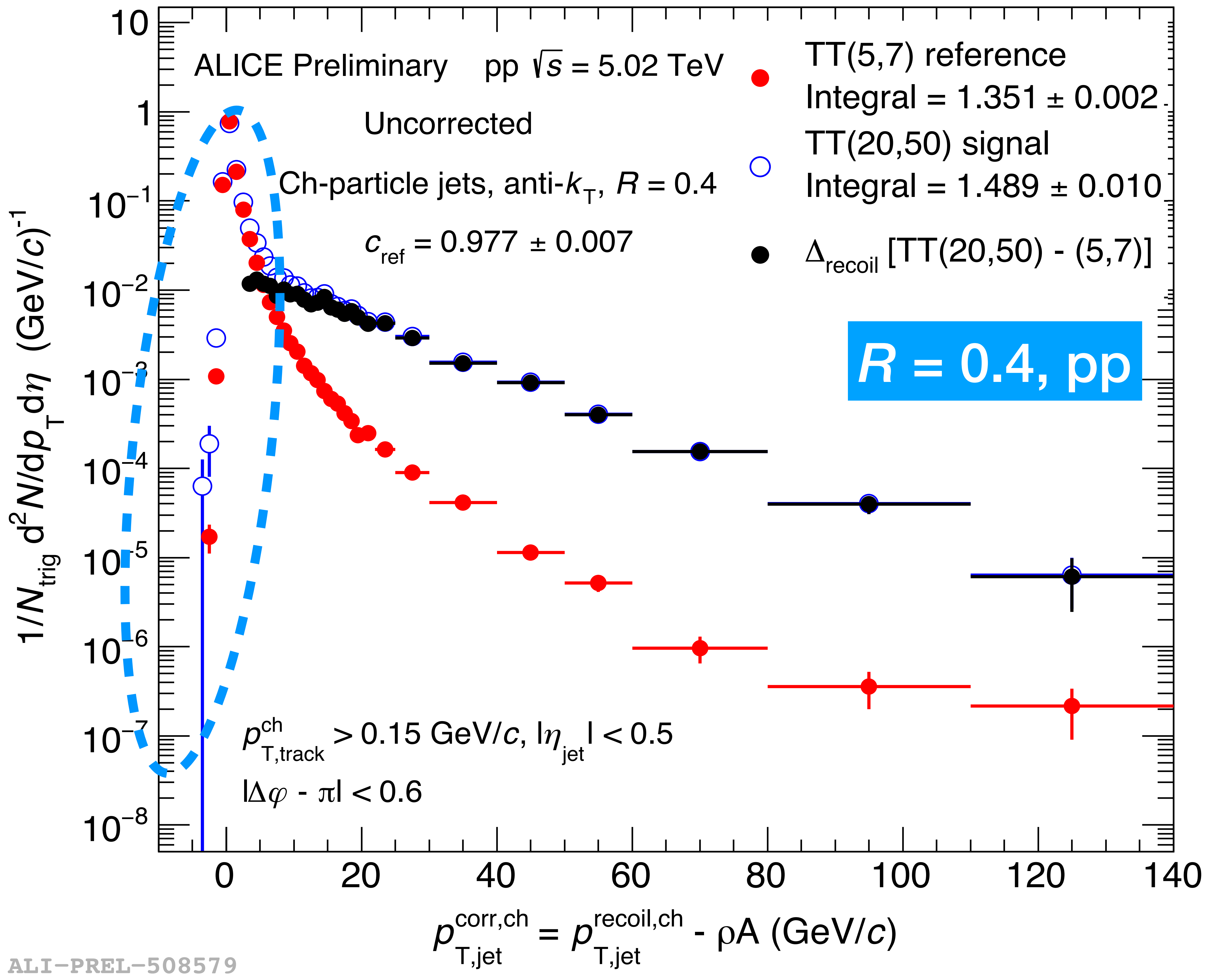




- **Combinatorial background** uncorrelated with the trigger
  - Small background contribution in pp, much larger in Pb-Pb
  - Combinatorial background can be removed by taking the difference of the recoil jet distributions in two TT intervals

Semi-inclusive recoil jet p_T distributions



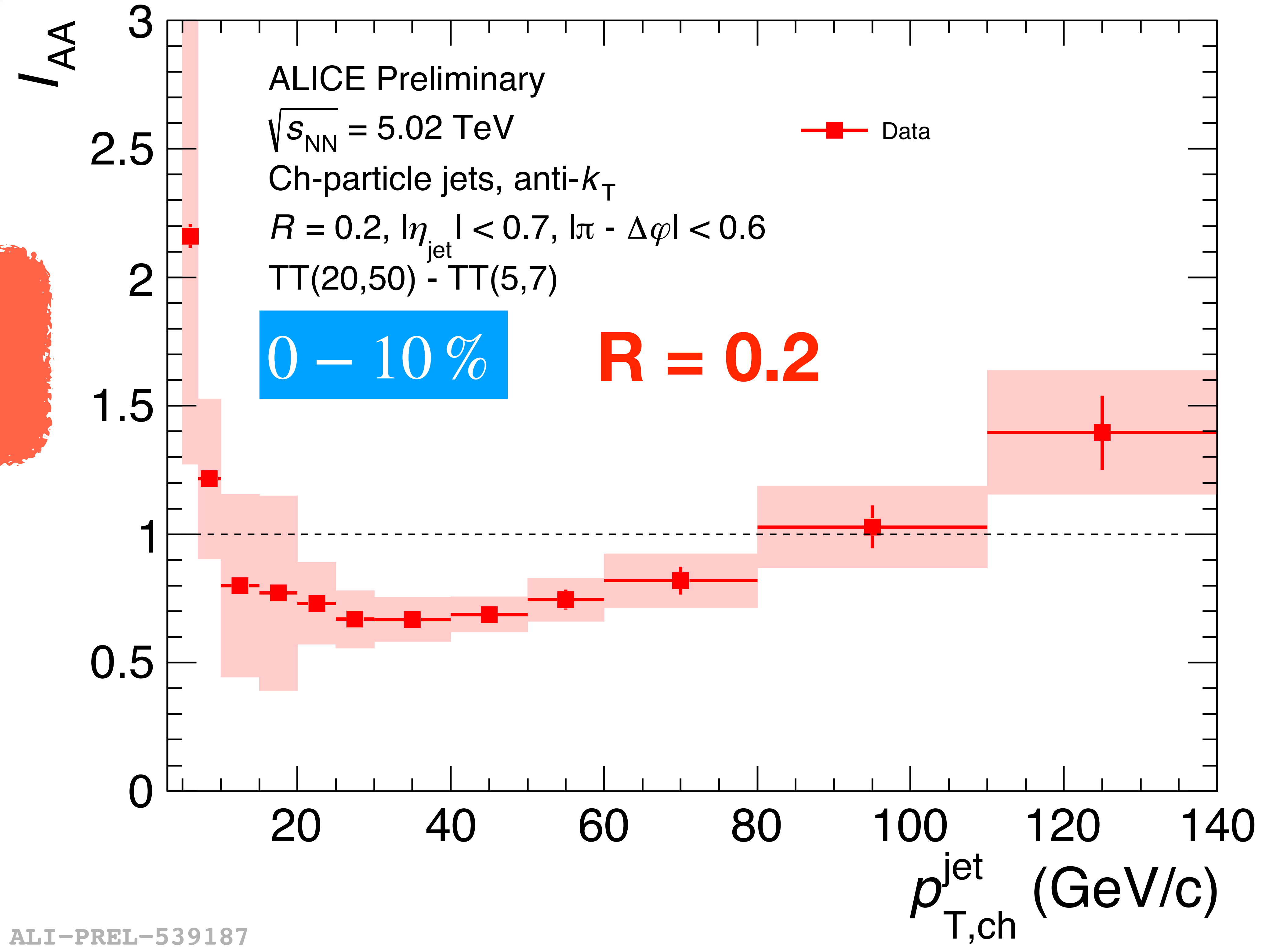


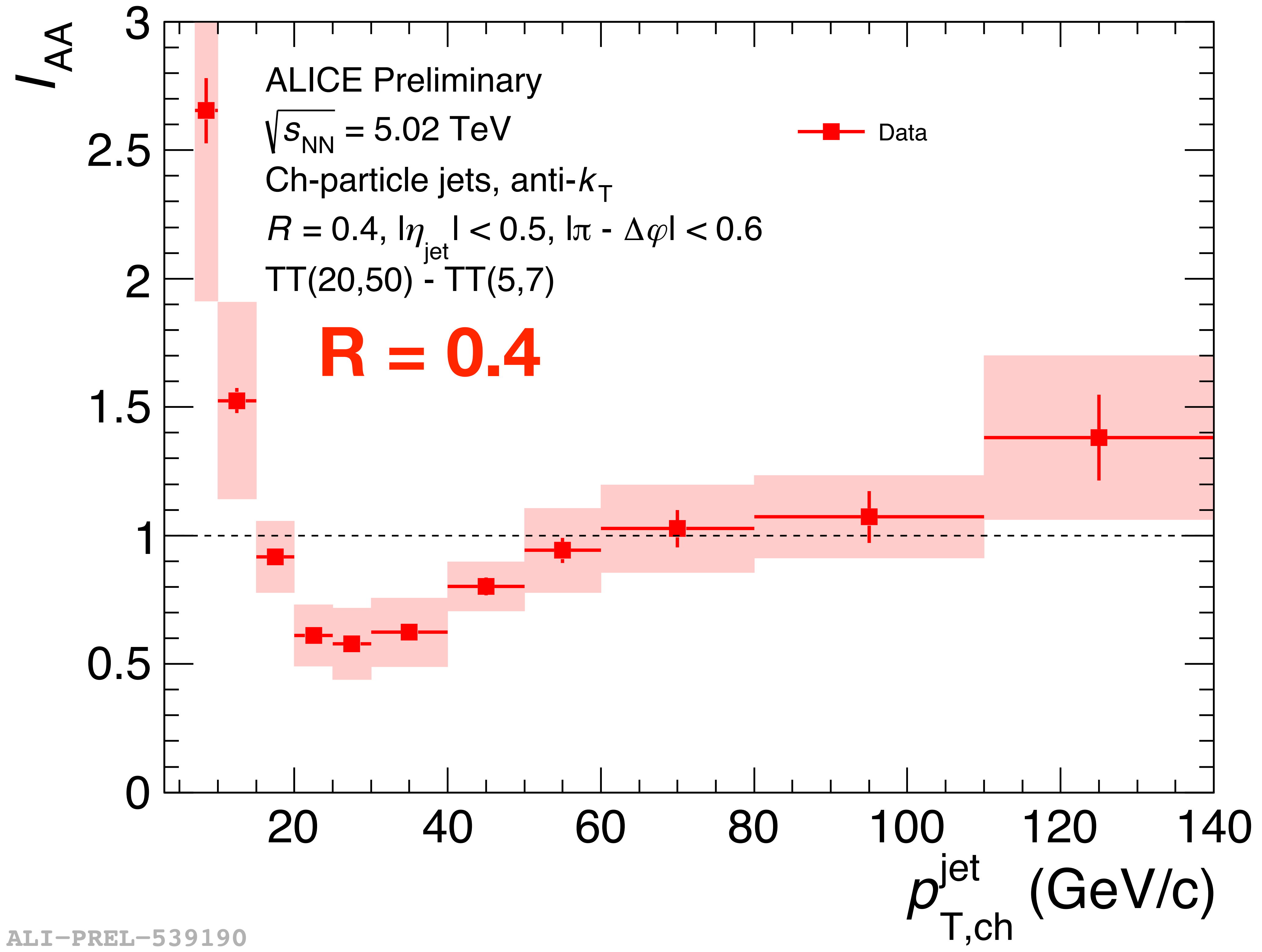
- **Combinatorial background** uncorrelated with the trigger

$$\Delta_{\text{recoil}}(p_{\text{T,jet}}) = \left.\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N_{\text{jet}}}{\mathrm{d}\eta_{\text{jet}}\,\mathrm{d}p_{\text{T,jet}}}\right|_{p_{\text{T}}^{\text{trig}}\in\text{TT}_{\text{Sig}}} - c_{\text{Ref}}\cdot\left.\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N_{\text{jet}}}{\mathrm{d}\eta_{\text{jet}}\,\mathrm{d}p_{\text{T,jet}}}\right|_{p_{\text{T}}^{\text{trig}}\in\text{TT}_{\text{Ref}}}$$

Recoil jet energy redistribution

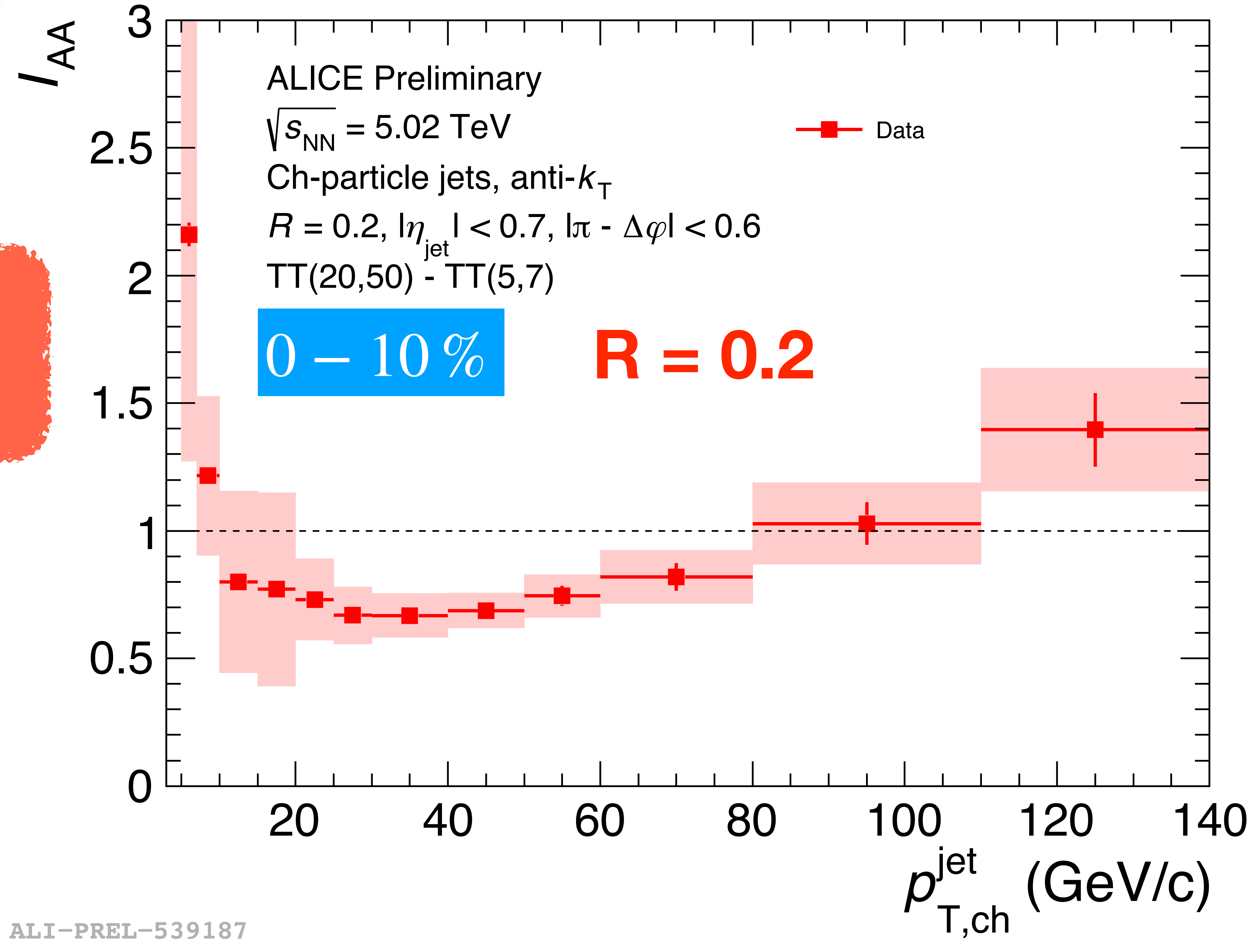
$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{AA}}}{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{pp}}}$$

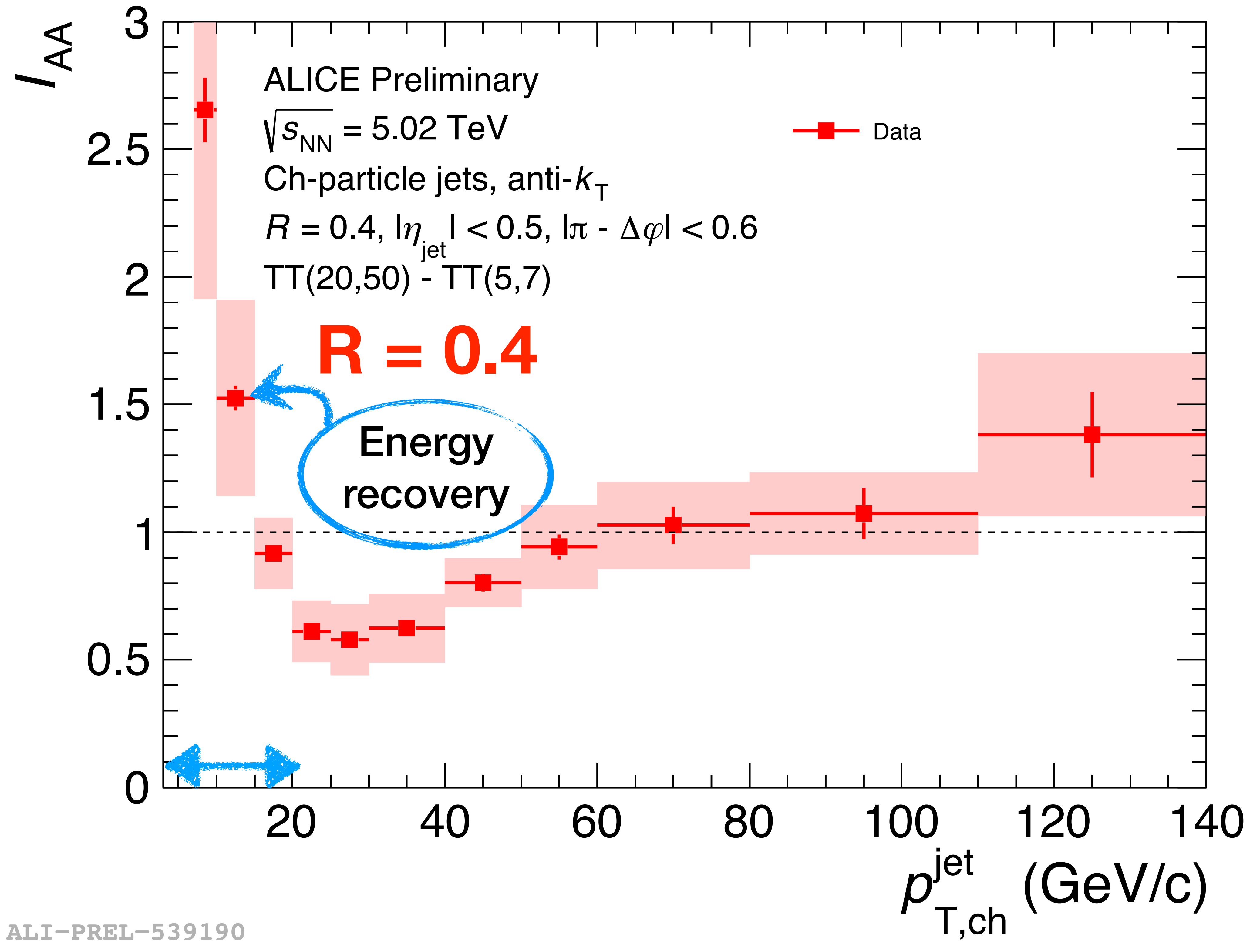




Recoil jet energy redistribution

$$I_{AA} \equiv \frac{\Delta_{\rm recoil}\,(p_{\rm T})_{\rm AA}}{\Delta_{\rm recoil}\,(p_{\rm T})_{\rm pp}}$$

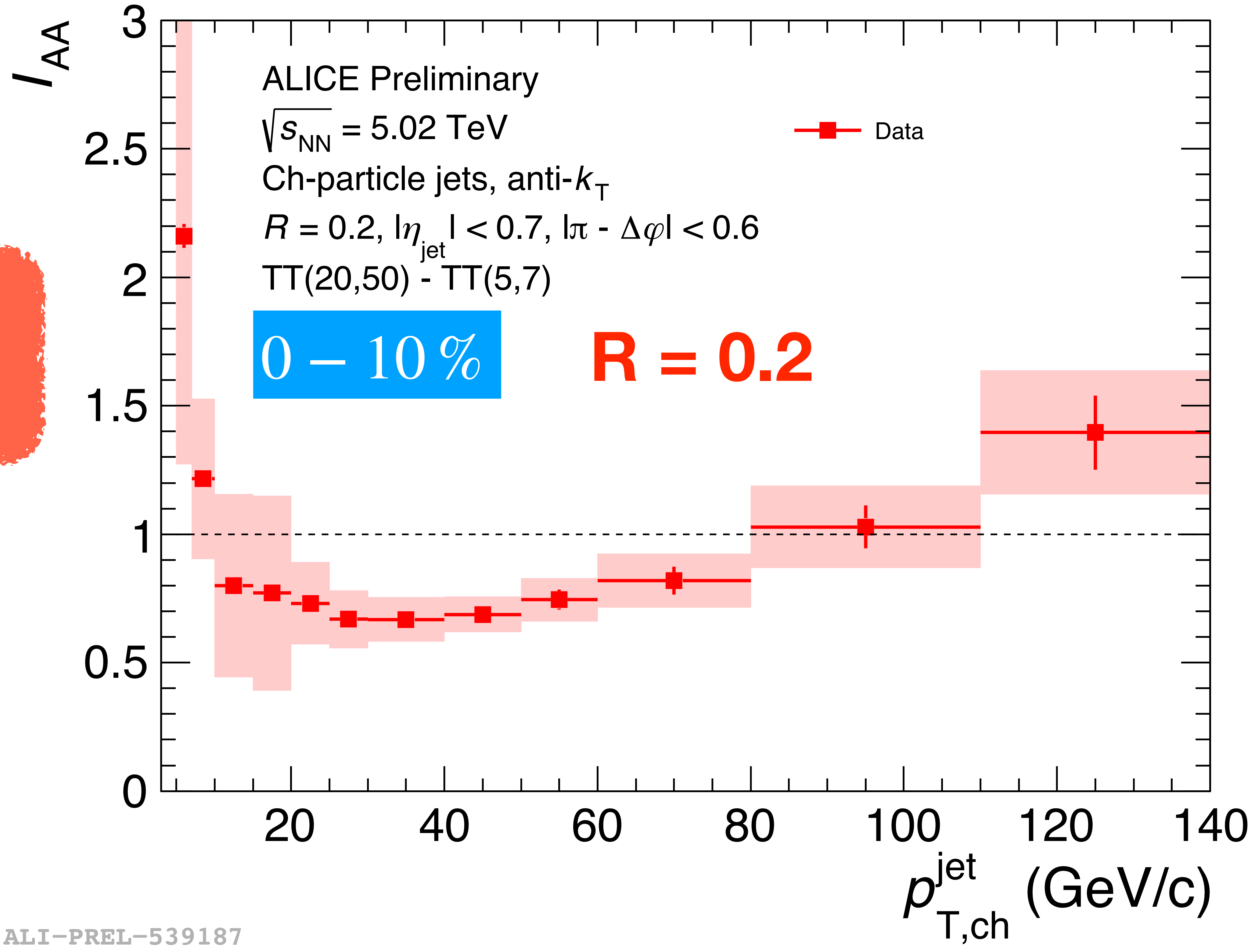


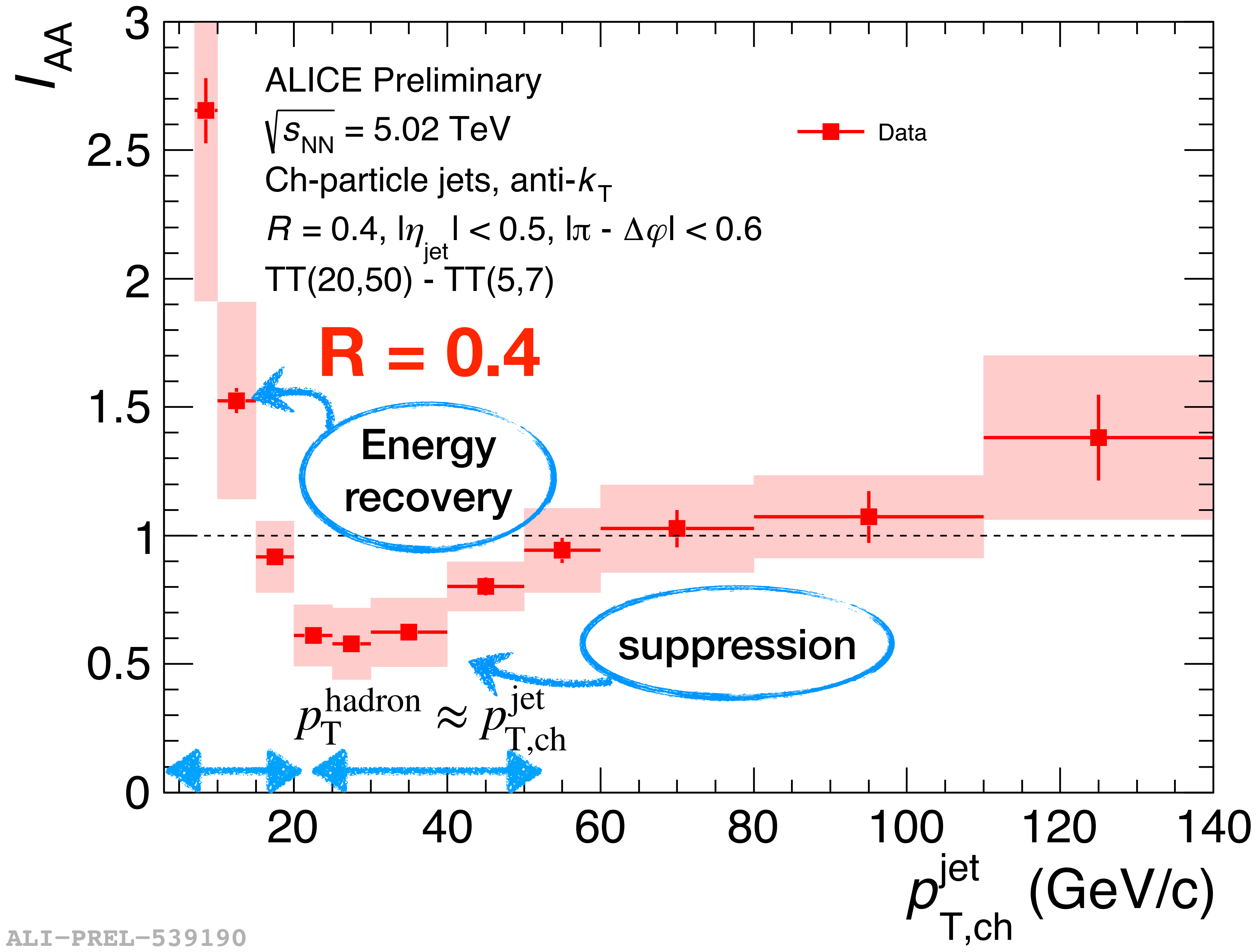


- First measurements of semi-inclusive recoil jet yields down to very **low** p_T (5 GeV/c)
  - Connection to low p_T jet quenching and intra-jet broadening
- Increase of low p_T yields → hint of energy recovery in low p_T jets

Recoil jet energy redistribution

$$I_{AA} \equiv \frac{\Delta_{recoil}\ (p_T)_{AA}}{\Delta_{recoil}\ (p_T)_{pp}}$$

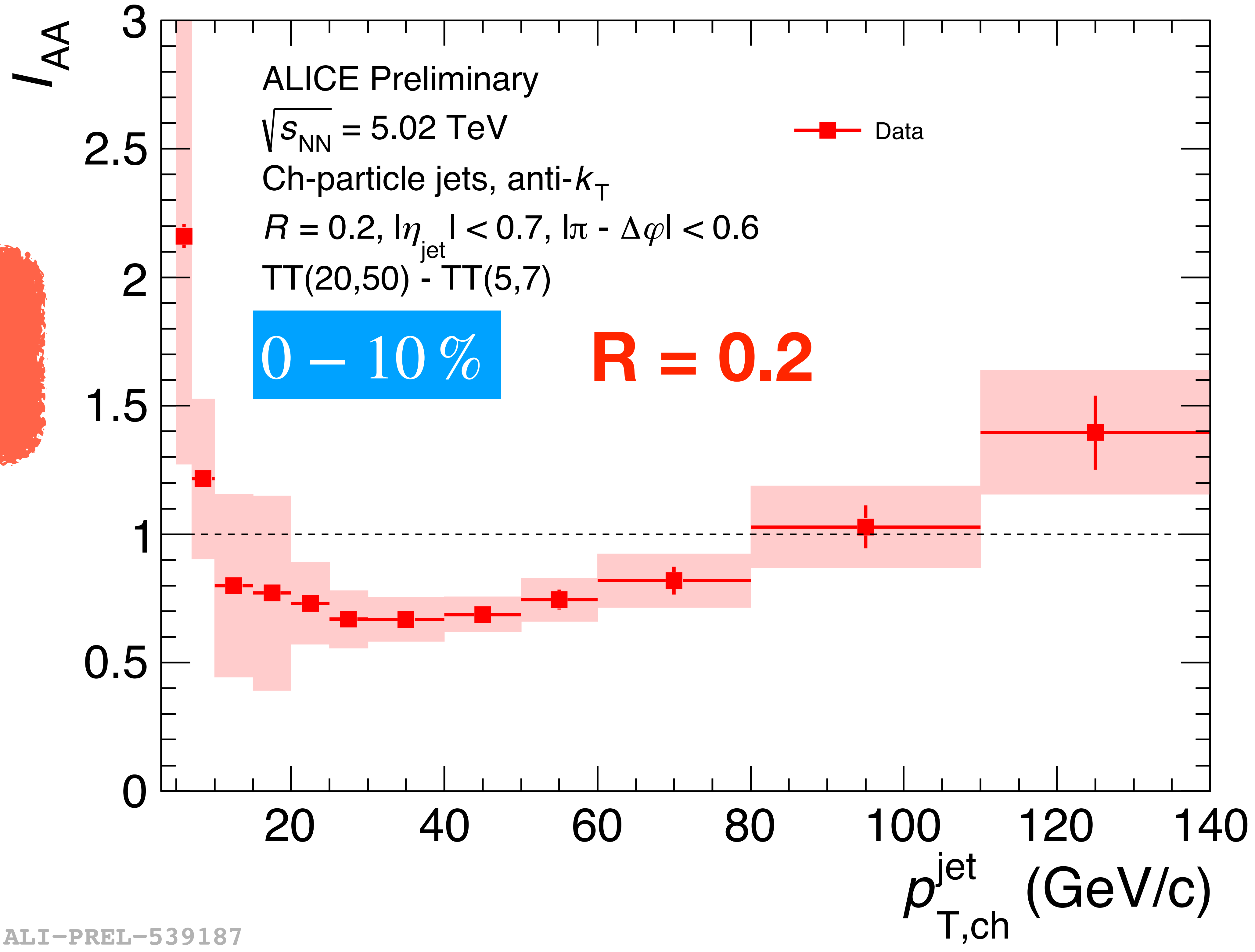


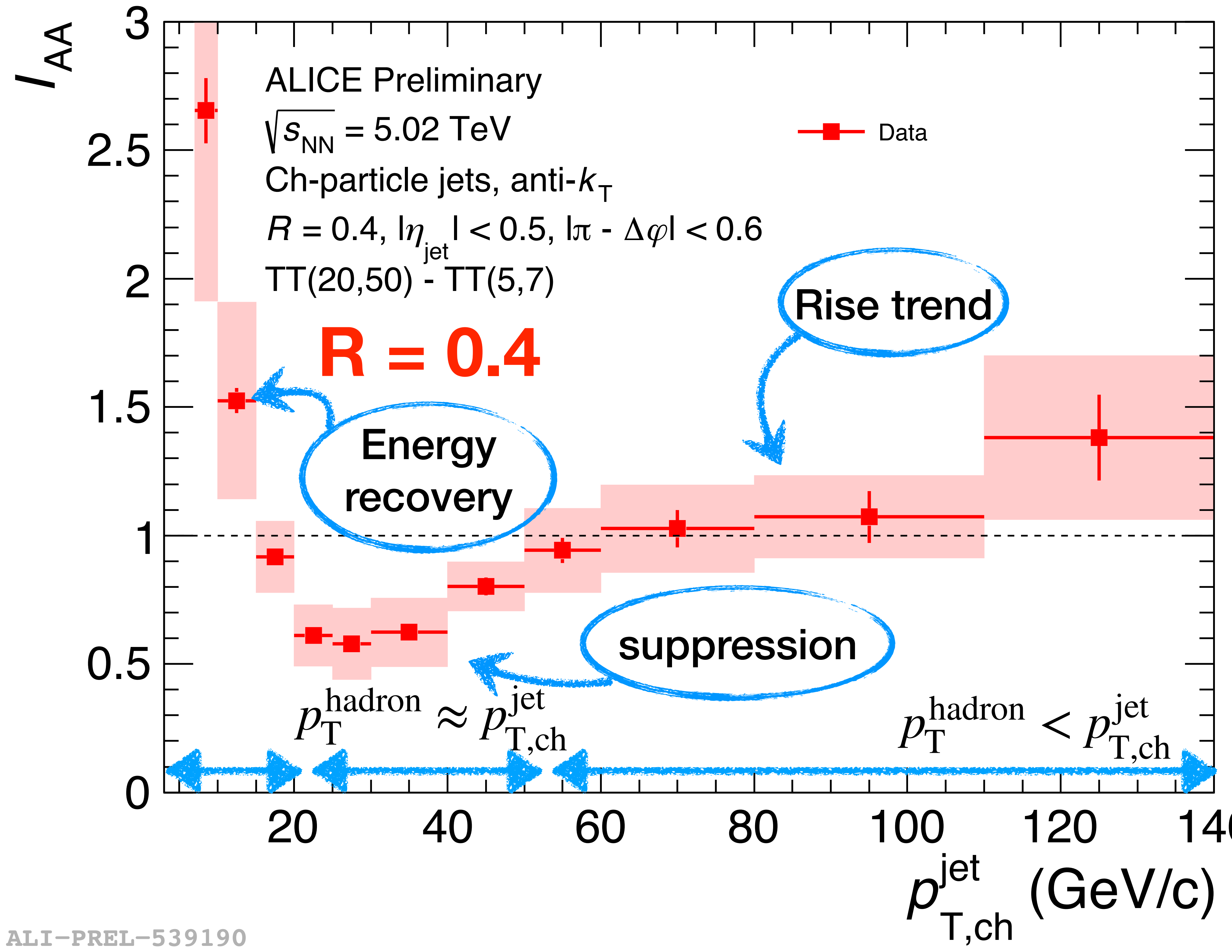


- First measurements of semi-inclusive recoil jet yields down to very **low** p_T (5 GeV/c)
  - Connection to low p_T jet quenching and intra-jet broadening
- Increase of low p_T yields → hint of energy recovery in low p_T jets

Recoil jet energy redistribution

$$I_{AA} \equiv \frac{\Delta_{recoil}(p_T)_{AA}}{\Delta_{recoil}(p_T)_{pp}}$$





- First measurements of semi-inclusive recoil jet yields down to very **low** p_T (5 GeV/c)
  - Connection to low p_T jet quenching and intra-jet broadening
- Increase of low p_T yields → hint of energy recovery in low p_T jets
- Rising trend: interplay of jet quenching effects on hadron and jet production?

Comparing to models

JETSCAPE with Pb-Pb tune:

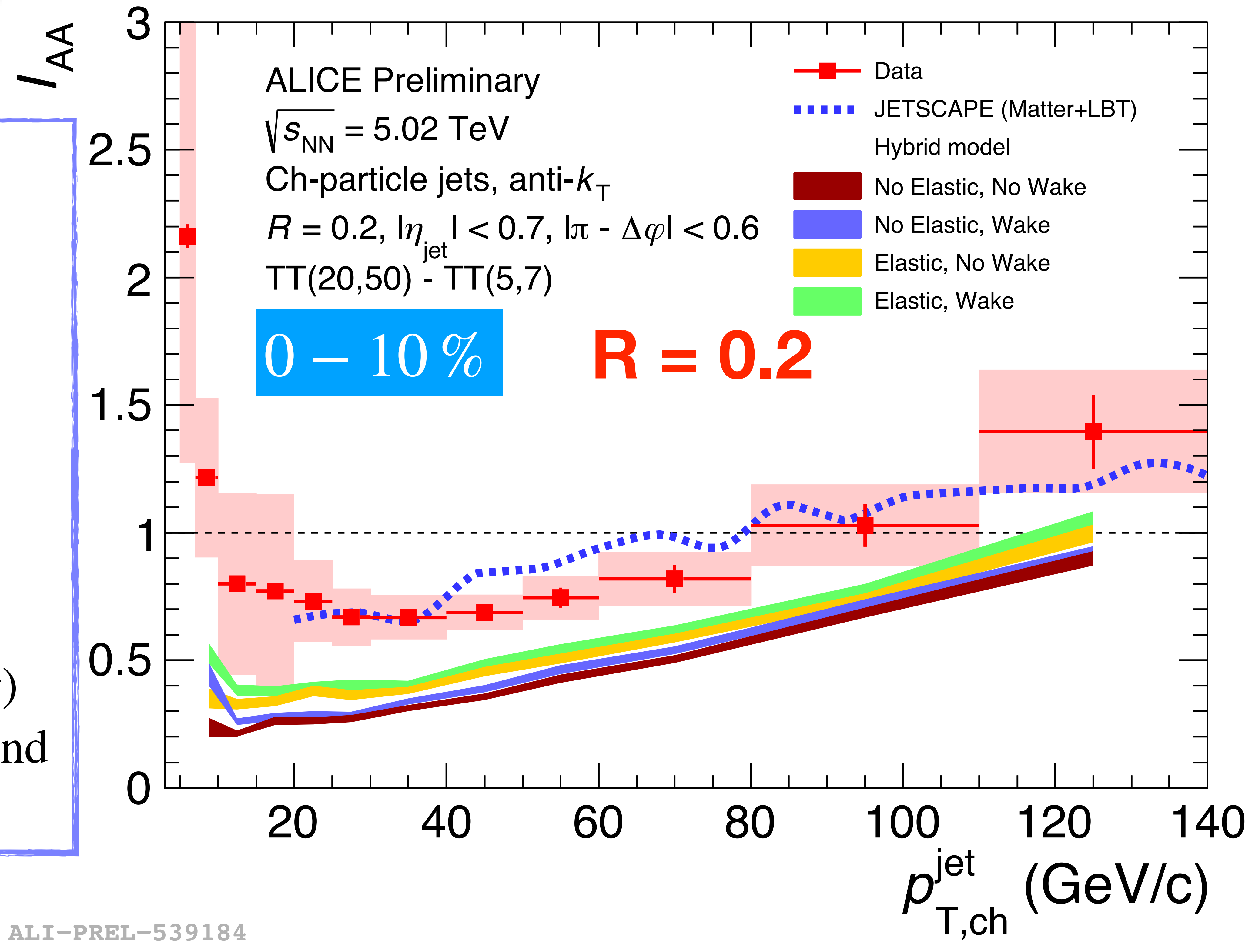
1903.07706, Phys.Rev.C 107 (2023) 3

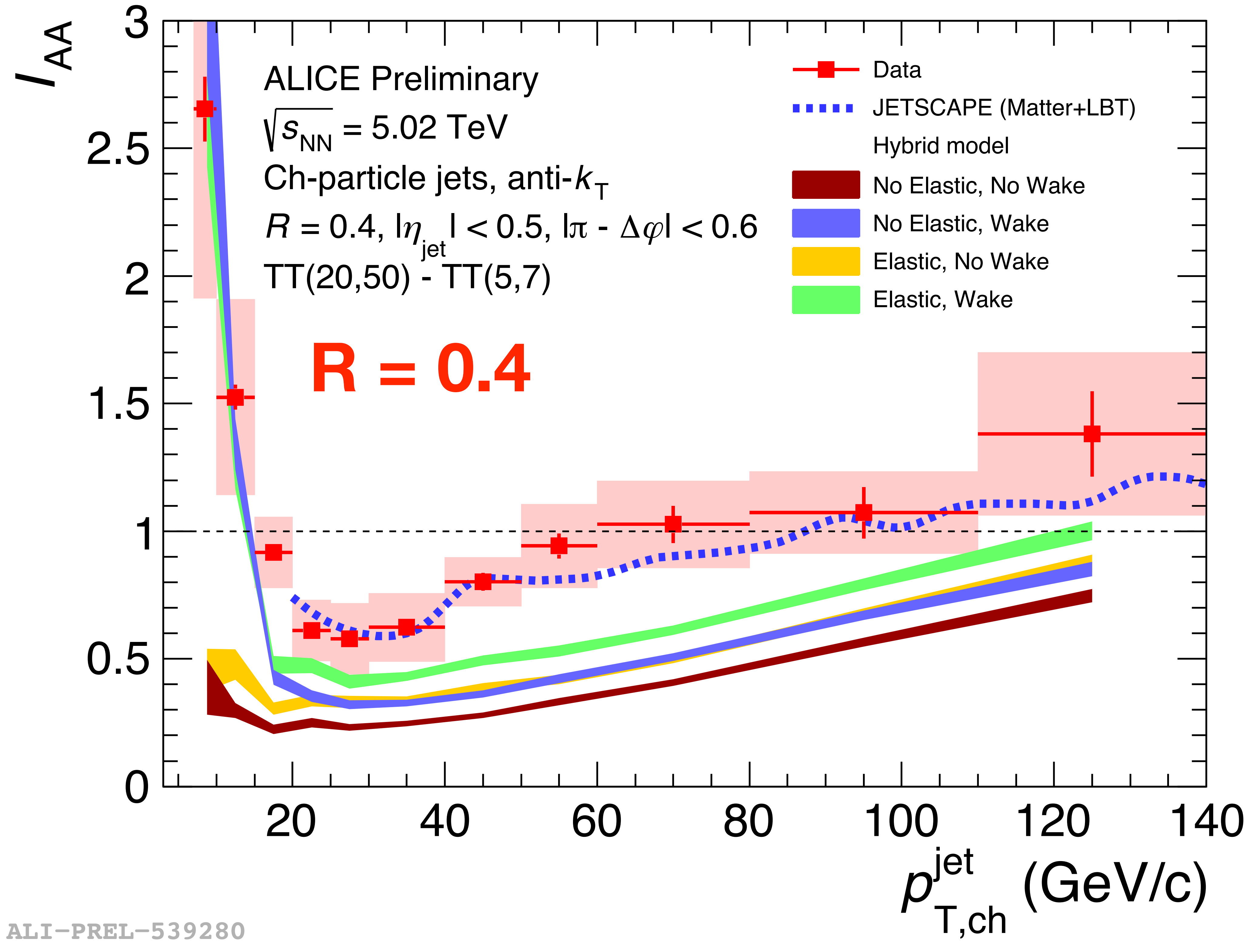
Multi-stage energy loss MATTER+LBT

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.





Comparing to models

JETSCAPE with Pb-Pb tune:

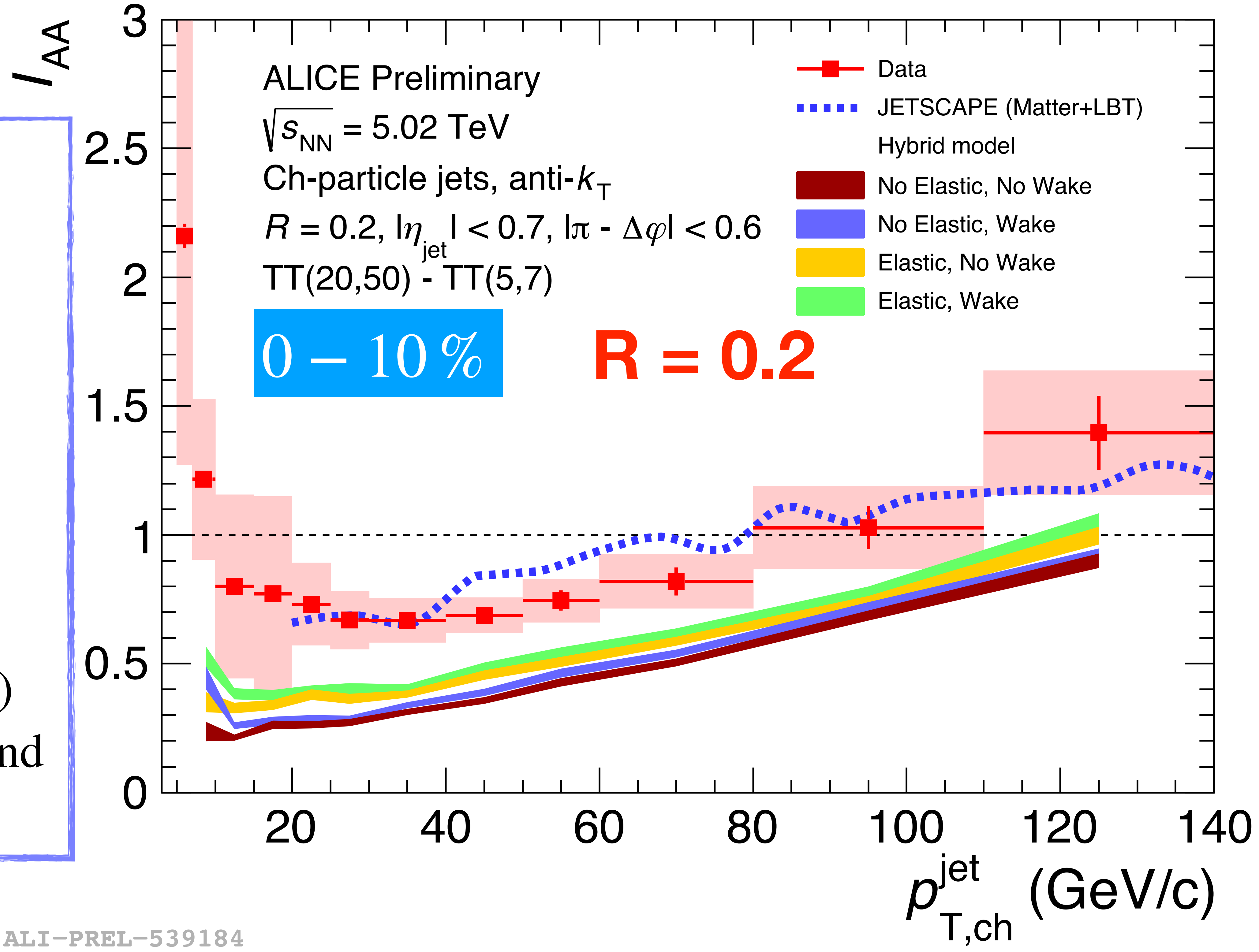
1903.07706, Phys.Rev.C 107 (2023) 3

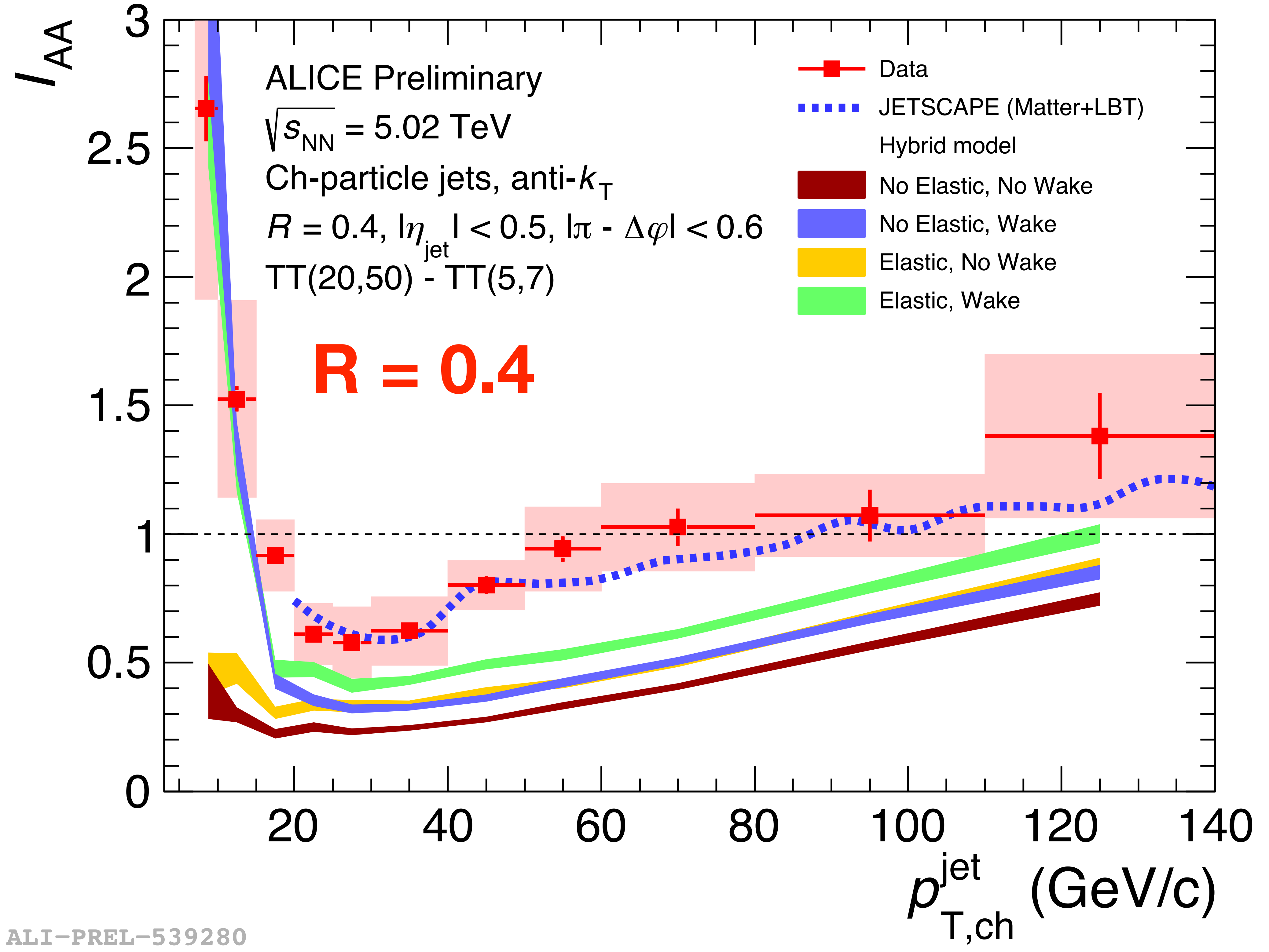
Multi-stage energy loss MATTER+LBT

Hybrid Model:

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

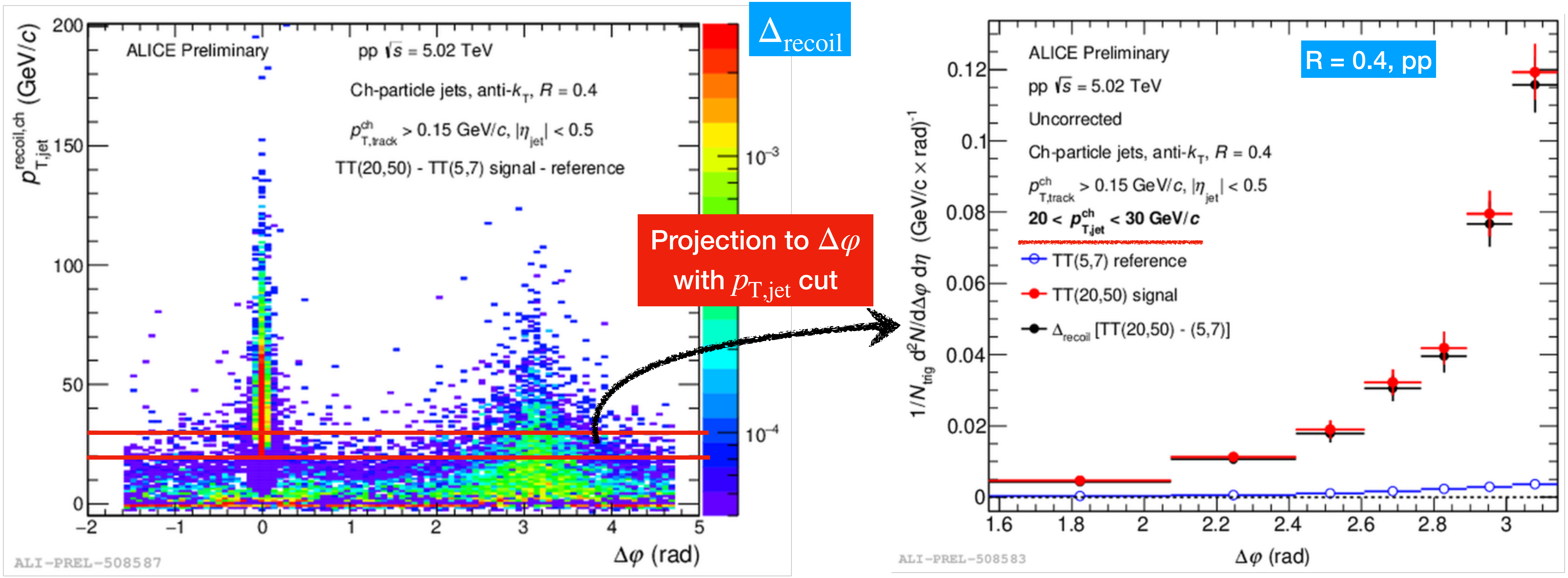
With/without elastic energy loss (i.e 'Moliere' scattering) medium response via with and without wake.





- 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

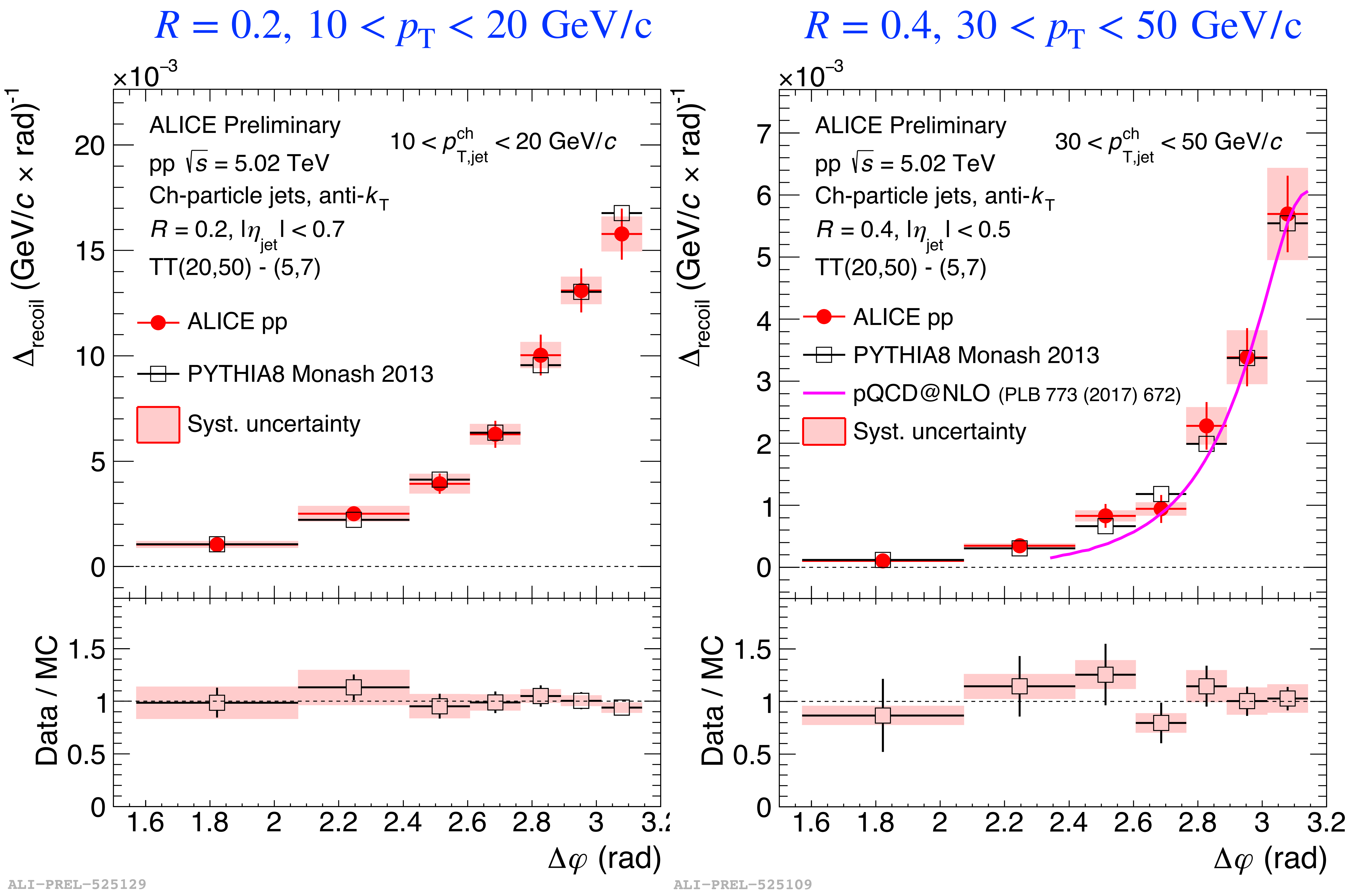


$$\Delta_{recoil}(\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\bigg|_{p_T^{trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\bigg|_{p_T^{trig}\in TT_{Ref}}$$

Recoil jet angular distributions in pp

- First **measurement of the fully-corrected** hadron-jet $\Delta\varphi$ distribution in pp collisions at $\sqrt{s} = 5.02$ TeV
- PYTHIA 8 (LO) and pQCD@NLO[1] predictions describe the data well

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

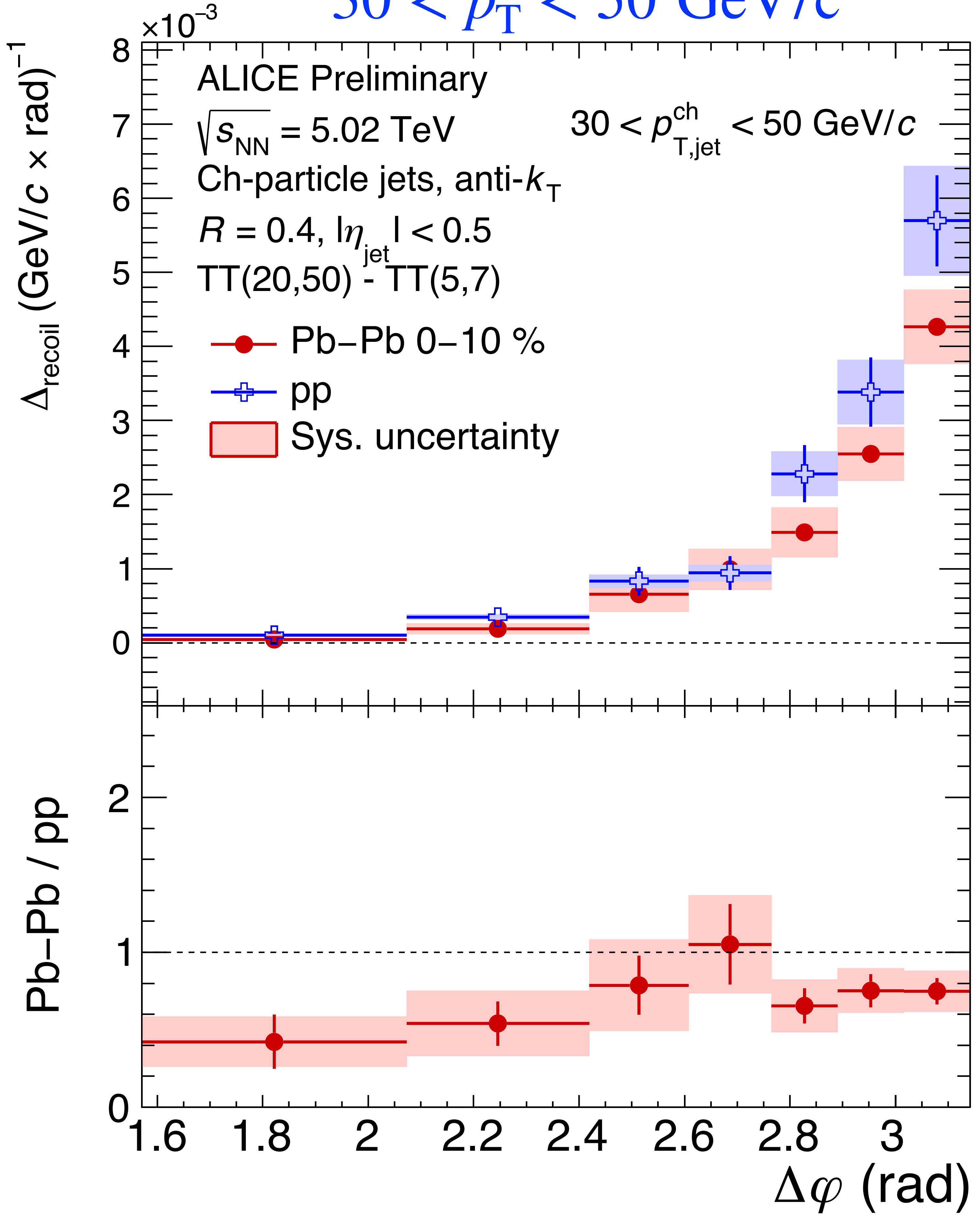


Recoil jet angular distributions in Pb-Pb

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

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

$30 < p_T < 50$ GeV/c



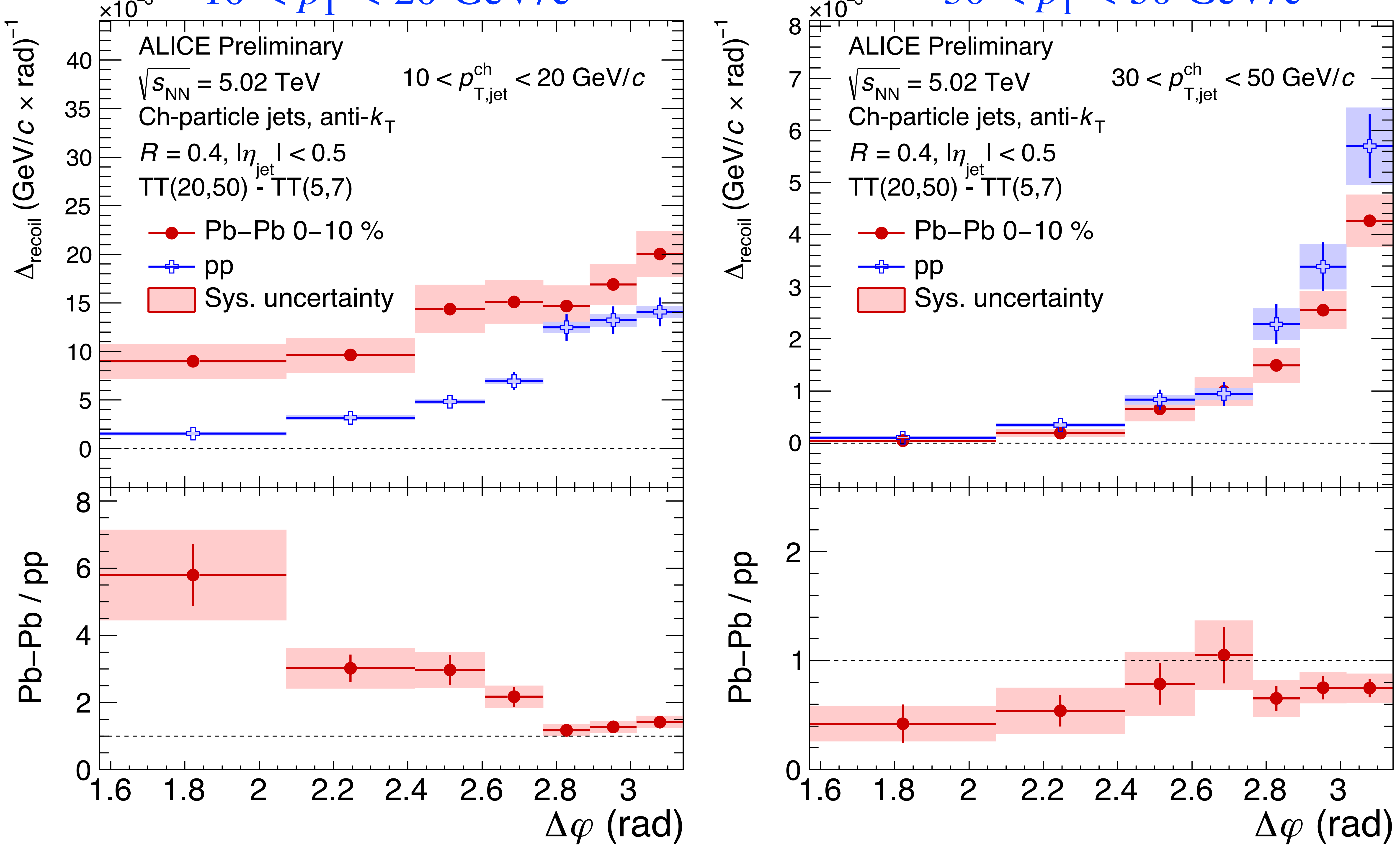
Recoil jet angular distributions in Pb-Pb

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

$10 < p_{\mathrm{T}} < 20$ GeV/c

$30 < p_{\mathrm{T}} < 50$ GeV/c

- Recoil jet **yield suppressed** at higher p_{T}
- Medium-induced yield excess and **acoplanarity broadening** at low p_{T}



ALI-PREL-540382

ALI-PREL-540388

Comparison of jet angular distributions in Pb-Pb

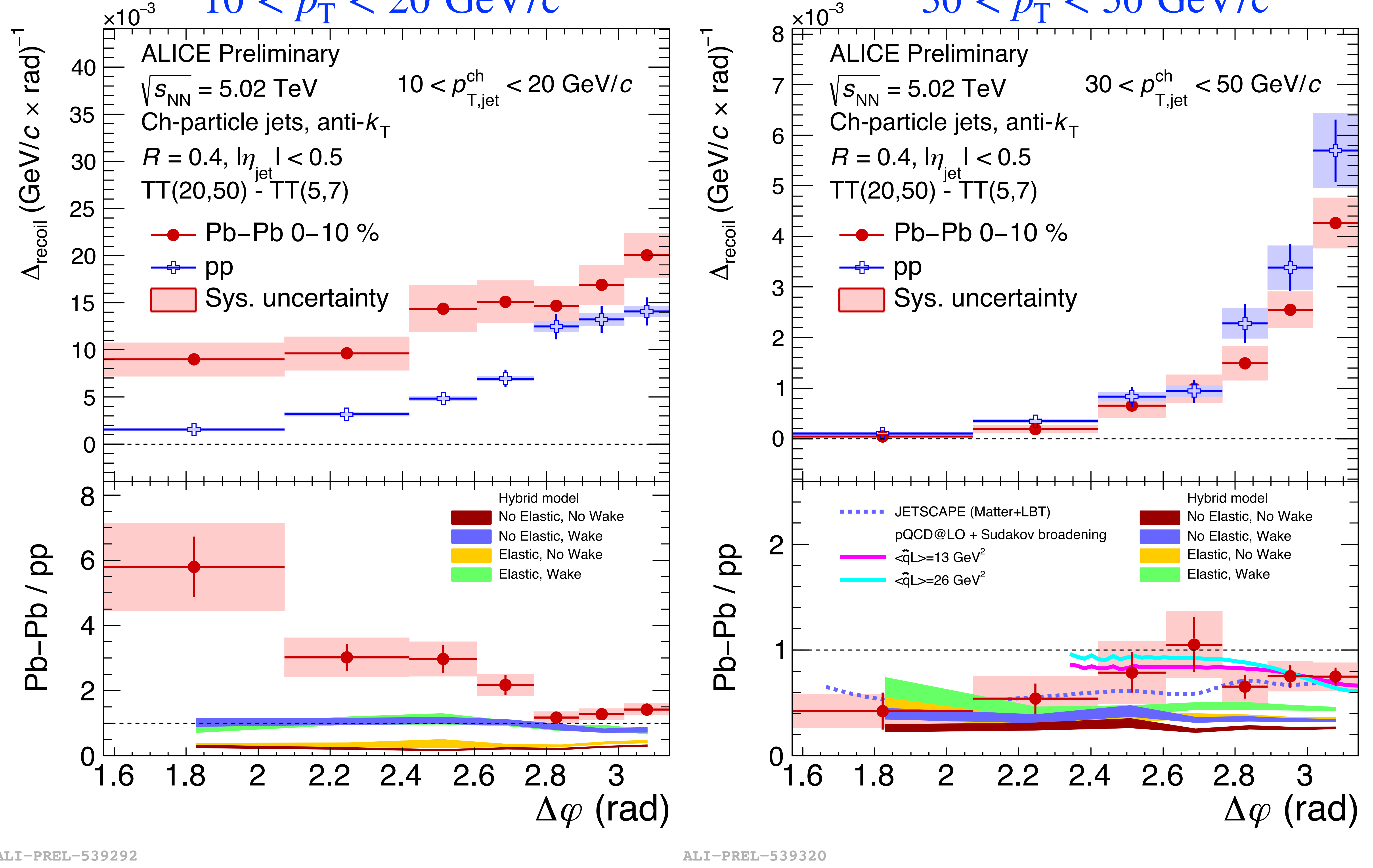
$R = 0.4,\ 0-10\,\%$

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.

pQCD@LO + Sudakov broadening:
Phys.Lett.B 773 (2017) 672
include medium-induced p_{T} broadening

$10 < p_{\mathrm{T}} < 20$ GeV/c $30 < p_{\mathrm{T}} < 50$ GeV/c

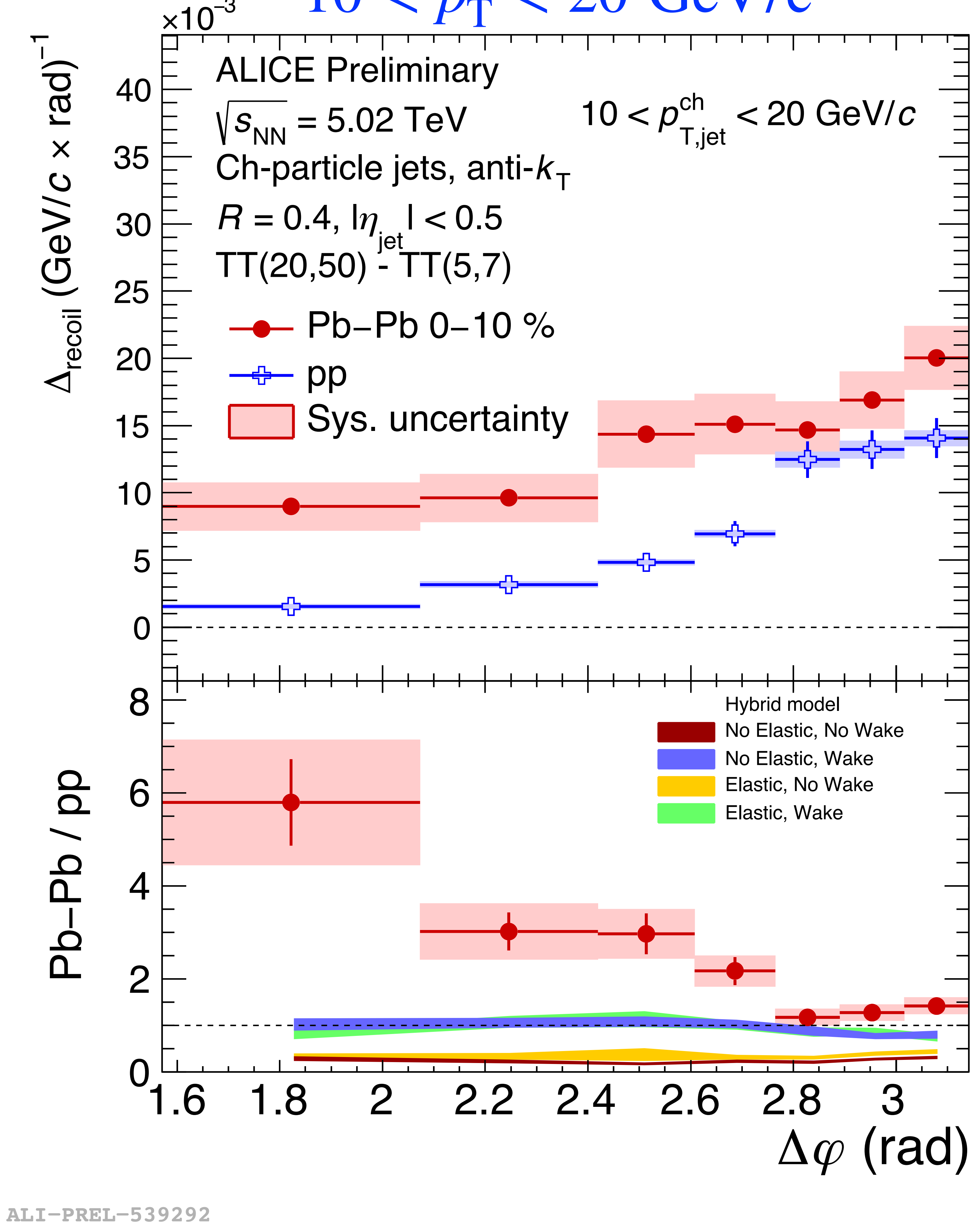


Comparison of jet angular distributions in Pb-Pb

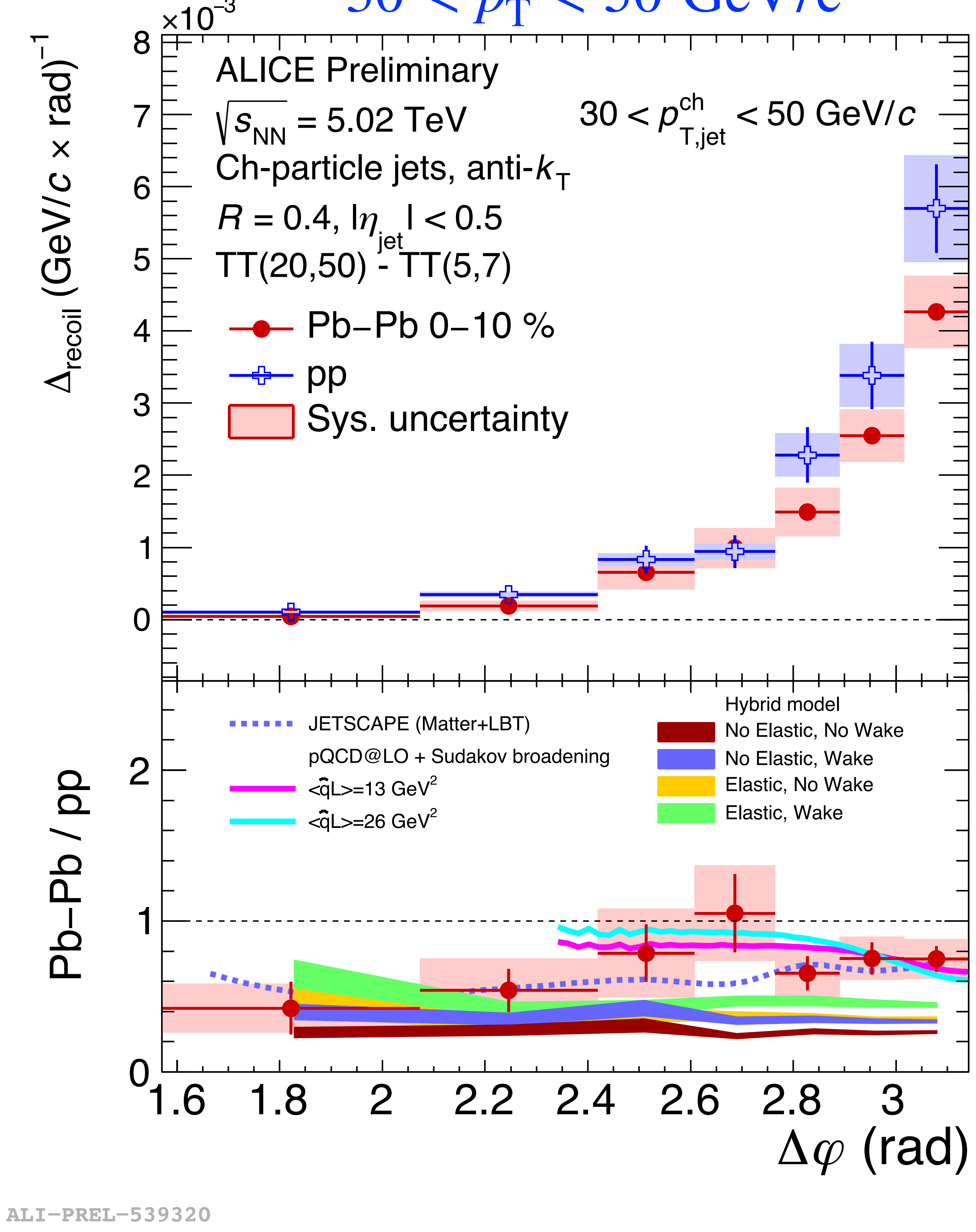
- JETSCAPE and calculations include medium-induced p_T broadening **reasonably describe the data at high jet p_T**, low p_T these calculations not available yet

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

$10 < p_T < 20$ GeV/c

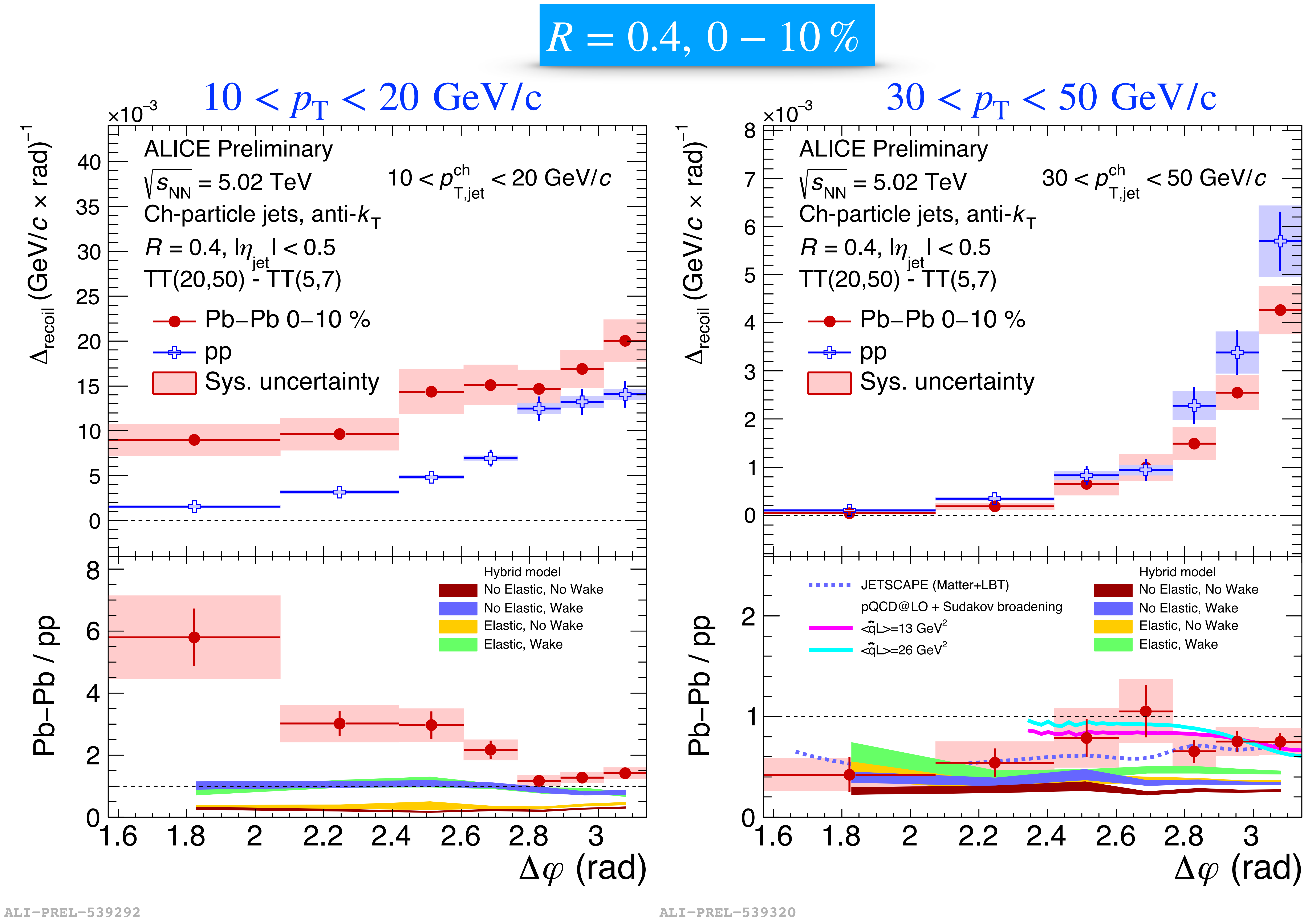


$30 < p_T < 50$ GeV/c



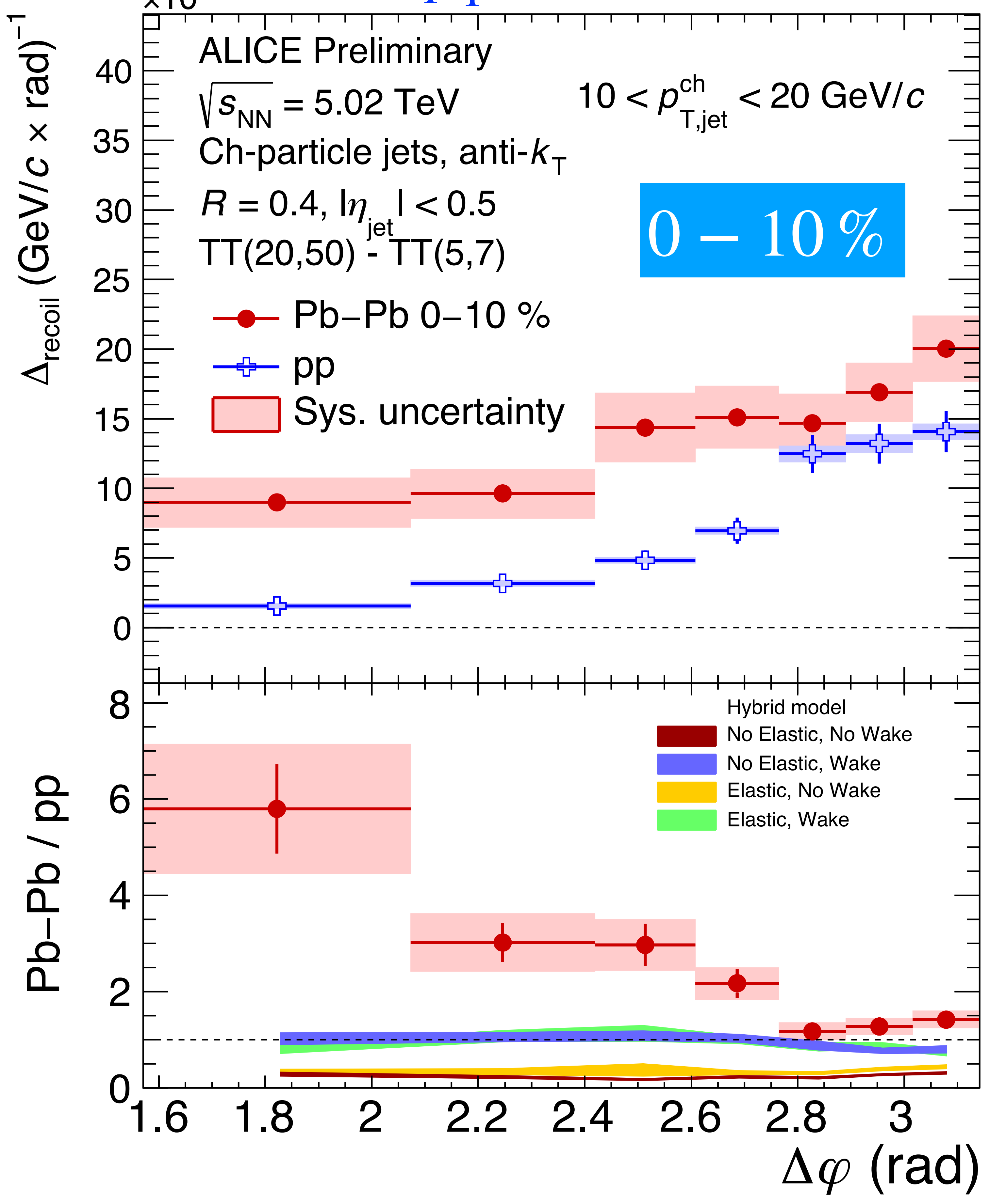
Comparison of jet angular distributions in Pb-Pb

- 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)

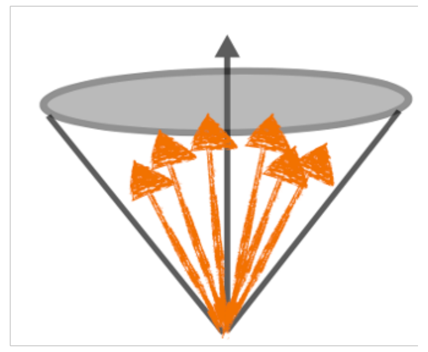


Recoil jet angular deflection

10 < p_T < 20 GeV/c



0 – 10 %



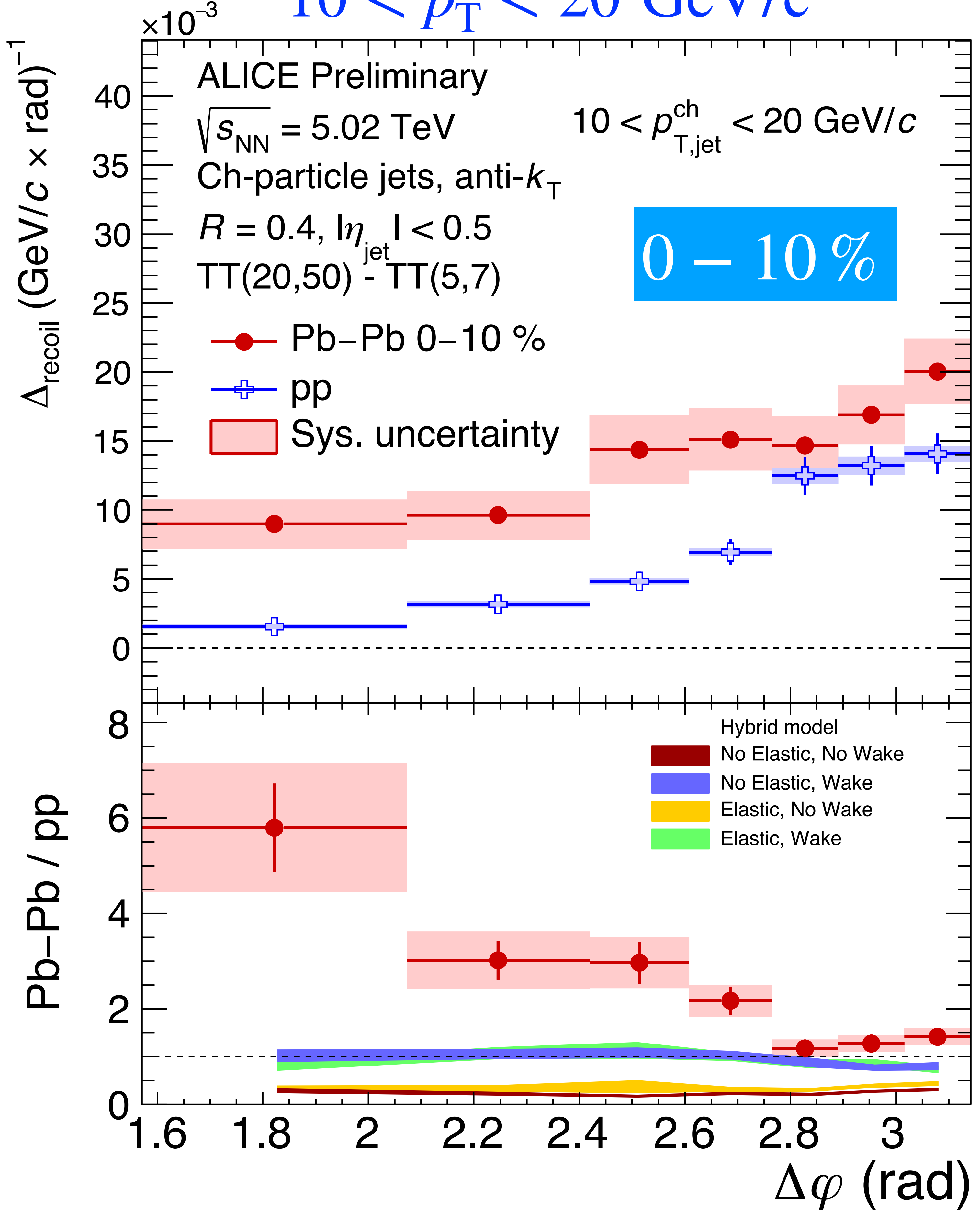
R = 0.4

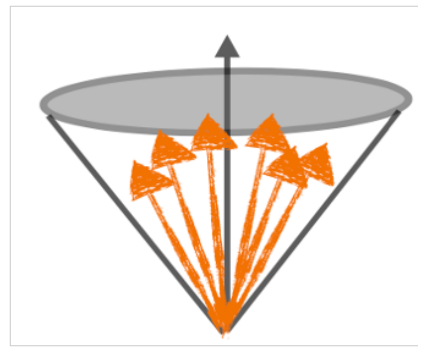
ALI-PREL-539292

- Clear signature of azimuthal decorrelation of soft jets with large R (= 0.4)

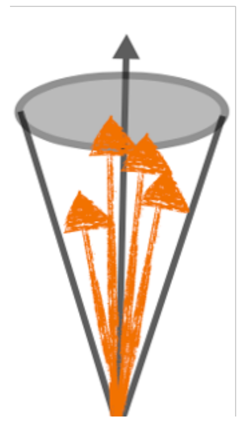
Recoil jet angular deflection

$10 < p_T < 20$ GeV/c



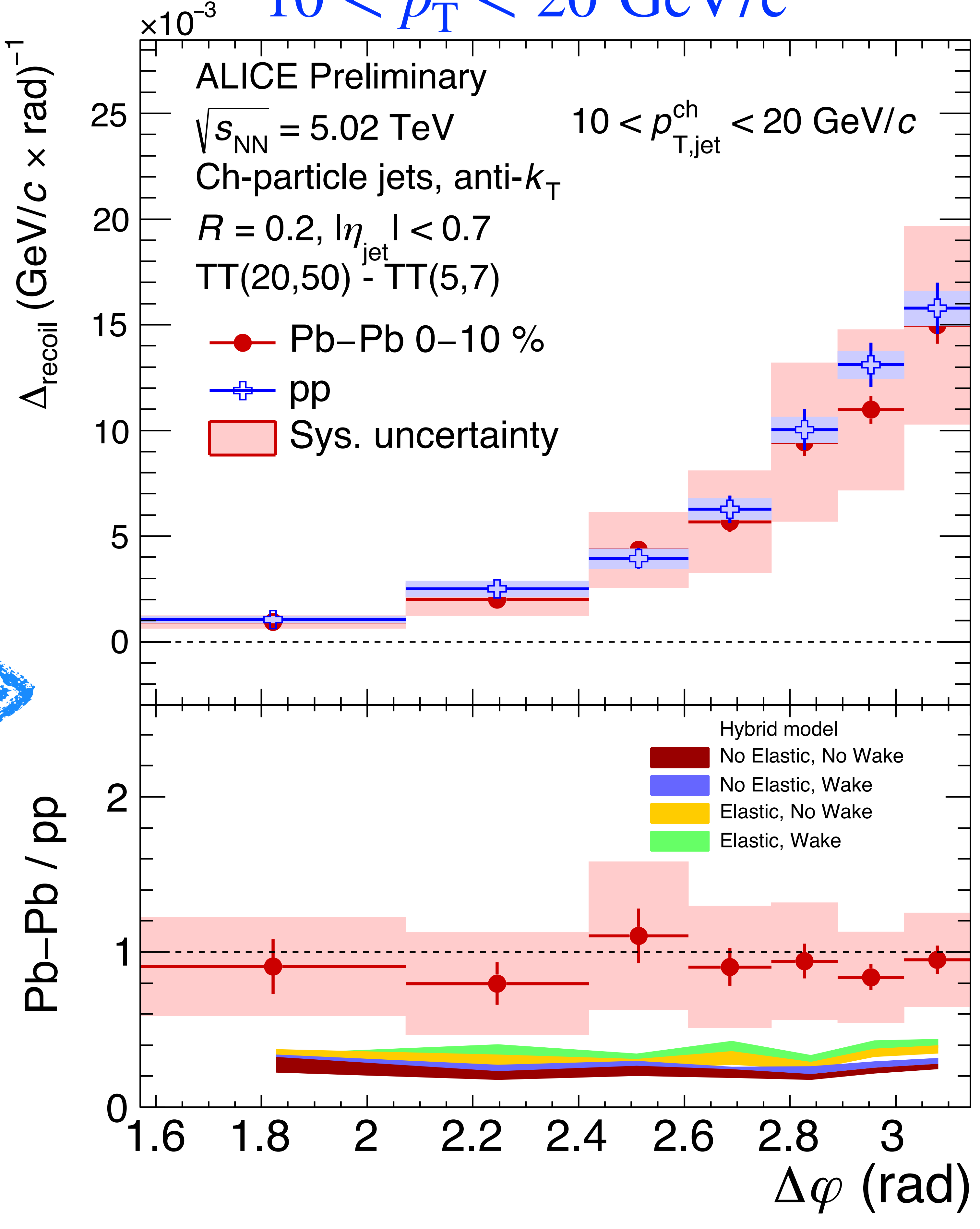


R = 0.4



R = 0.2

$10 < p_T < 20$ GeV/c



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

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 $p_{\rm T}$
  - First observation of **jet azimuthal broadening** for large $R = 0.4$ at low $p_{\rm T}$

    → Possible origins: in-medium hard scattering, multiple soft scattering, jet fragments, medium response
  - **The 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