

Jet energy redistribution and broadening using hadron+jet measurements in pp and Pb-Pb collisions with ALICE

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LIVERPOOL



Science and
Technology
Facilities Council

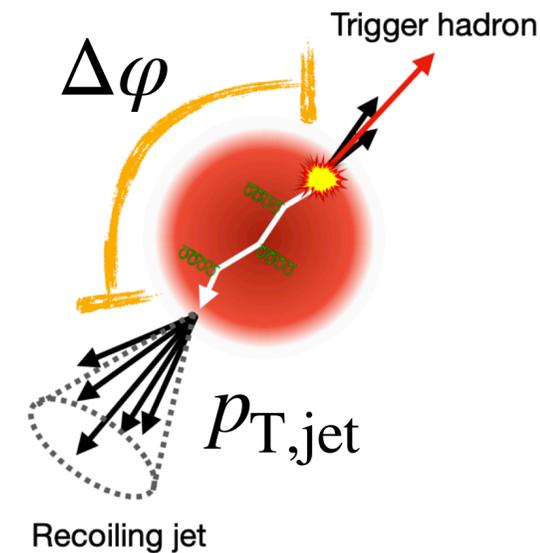
jknorman@liverpool.ac.uk



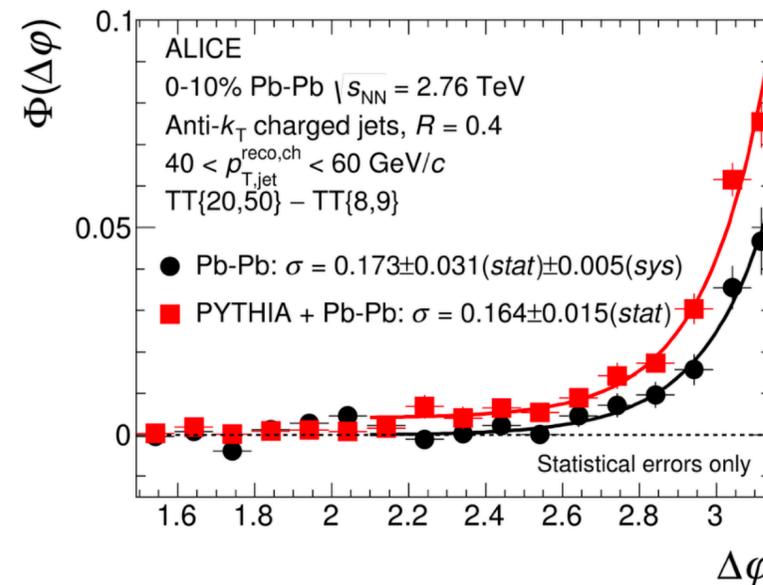
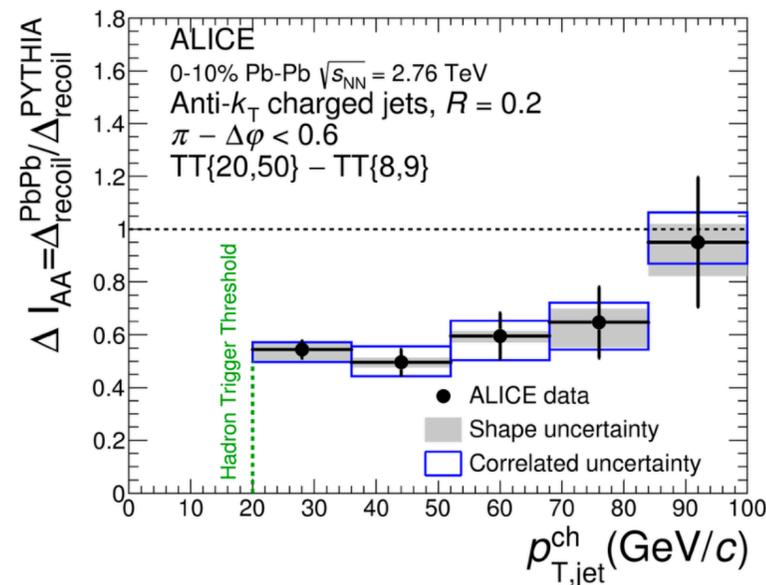
ALICE

Probing jet quenching via hadron+jet measurement

- Measure trigger-normalised yield of **charged-particle jets** recoiling from high- p_T trigger hadrons:
 - opening angle ($\Delta\varphi$) of jet relative to trigger axis
 - transverse momentum ($p_{T,jet}$) of recoil jet



Measure $p_{T,jet}$ and $\Delta\varphi$: Probe energy loss and acoplanarity simultaneously



First measurement: Run 1 data (Pb-Pb only)

[JHEP 09 \(2015\) 170](#)

This talk: Run 2 data (Pb-Pb and pp)

Two new papers: [arXiv:2308.16131](#)
[arXiv:2308.16128](#)

Jet acoplanarity

Acoplanarity distribution:

- in vacuum: Sudakov broadening
- in medium: additional broadening due to scattering

- **Multiple soft scatters** - access jet transport coefficient

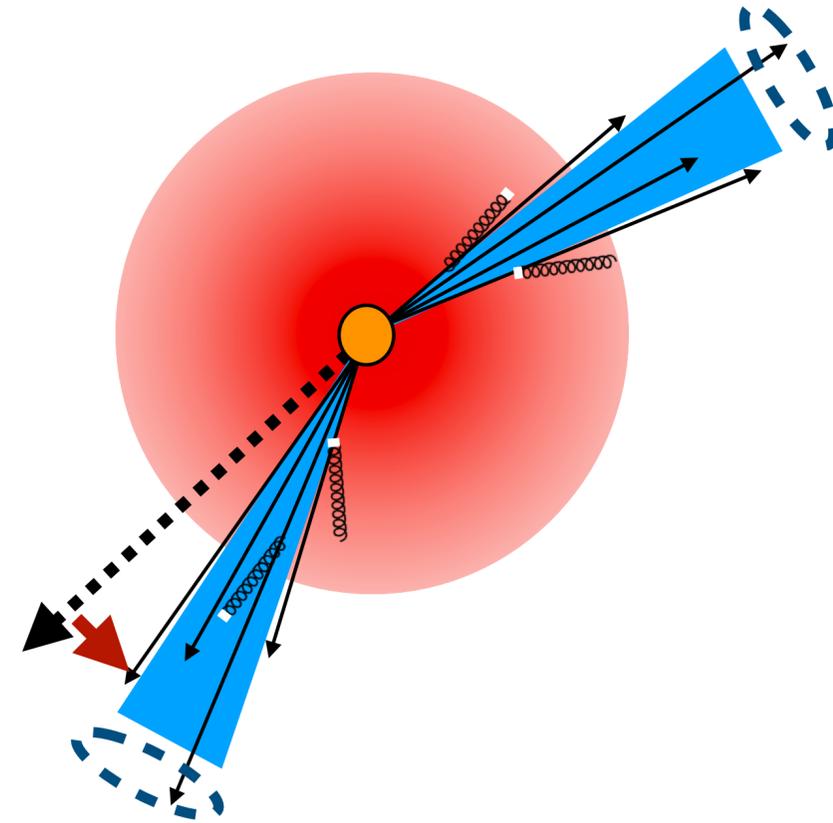
$$\langle p_{\perp}^2 \rangle = \hat{q}L$$

A.H. Mueller et al, *Phys.Lett.B* 763 (2016) 208-212
L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676

- **Single hard ‘Molière’ scattering**
- possibility to resolve weakly interacting scattering centres

F. D’eramo et al, *JHEP* 05 (2013) 031

See also substructure measurements
H. Bossi, 5th Sept 11:20



Impact of medium response

- Energy of high- p_{T} jets transferred to medium
→ **Can impact jet observables,**
in particular at low p_{T}

See also posters on other observables sensitive to medium response:
C.Pliatskas, energy flow
S. Weyhmler, PID in jets

Combinatorial background

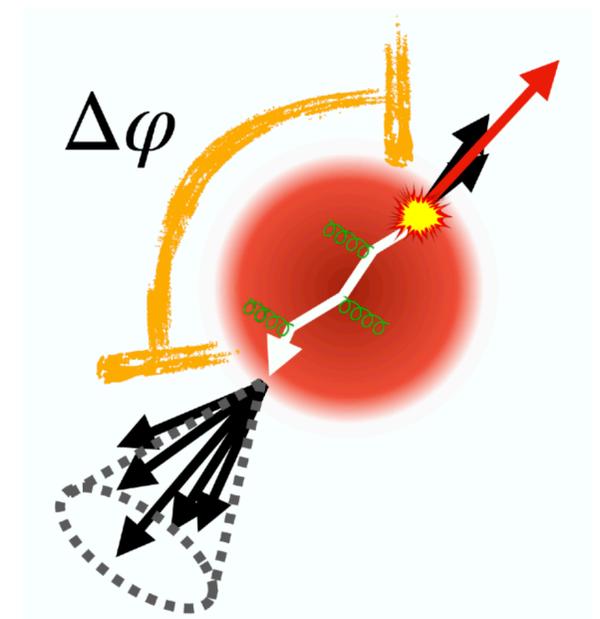
- Challenge for low- p_{T} jet measurements, but broadening effects largest at low p_{T}
→ **to access this region, treatment of underlying event crucial**

See also mixed event technique
N. Gruenwald, 5th Sept 11:40

Measurement technique: statistical approach

- **Subtract combinatorial background:** difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Bigg|_{p_{\text{T,trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Bigg|_{p_{\text{T,trig}} \in \text{TT}_{\text{Ref}}}$$



c_{Ref} : normalisation constant

- **Statistical approach** - uncorrelated yield corrected solely at level of ensemble-averaged distributions
- **data-driven subtraction of *all* combinatorial background**
low- p_{T} , large R measurements possible
- **Perturbatively calculable**
difference of ratios between high- p_{T} hadron and jet production cross sections

Measurement technique: raw distributions

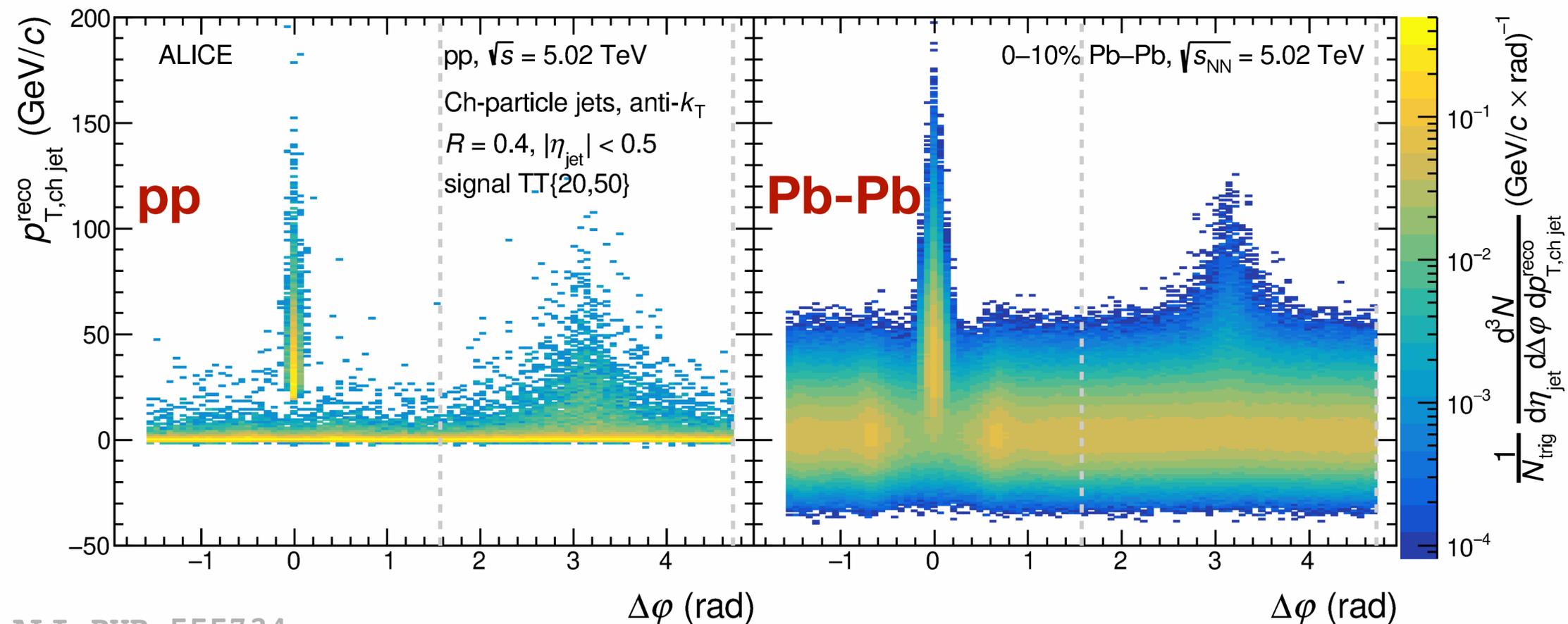
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$$p_{\text{T,jet}}^{\text{reco,ch}} = p_{\text{T,jet}}^{\text{raw,ch}} - \rho A_{\text{jet}}$$

$$\text{TT}_{\text{sig}}: 20 < p_{\text{T,trig}} < 50 \text{ GeV}/c$$

$$\text{TT}_{\text{ref}}: 5 < p_{\text{T,trig}} < 7 \text{ GeV}/c$$



ALI-PUB-555734

Measurement technique: raw distributions

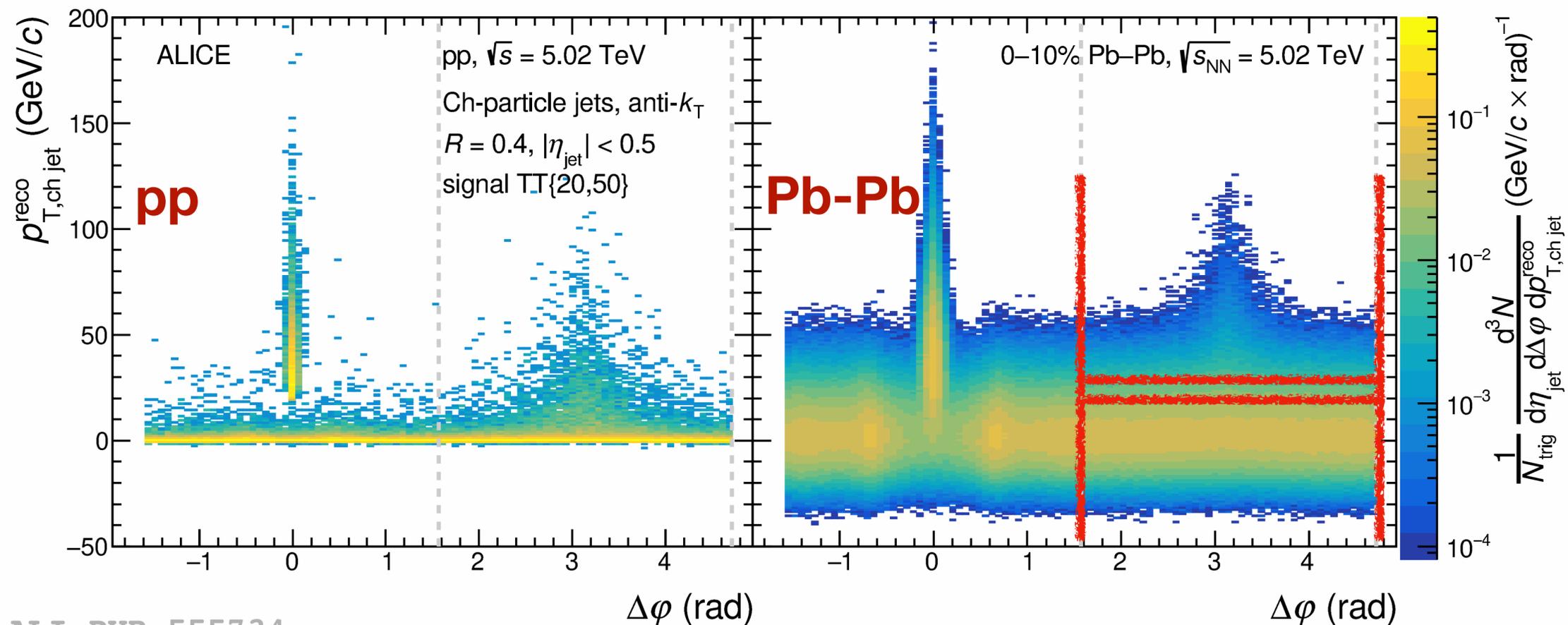
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$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{\text{T,trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{\text{T,trig}} \in \text{TT}_{\text{Ref}}}$$

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ALI-PUB-555734

Measurement technique: raw distributions

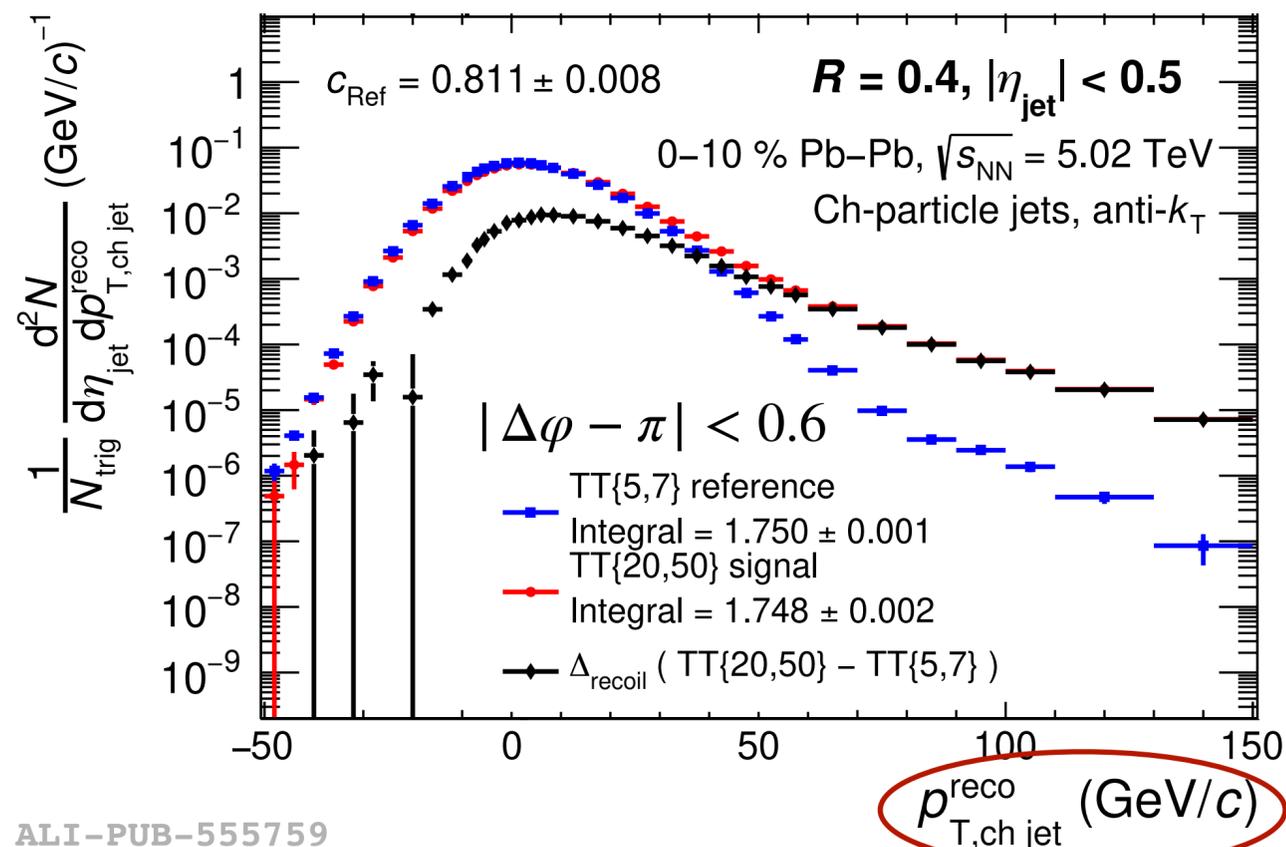
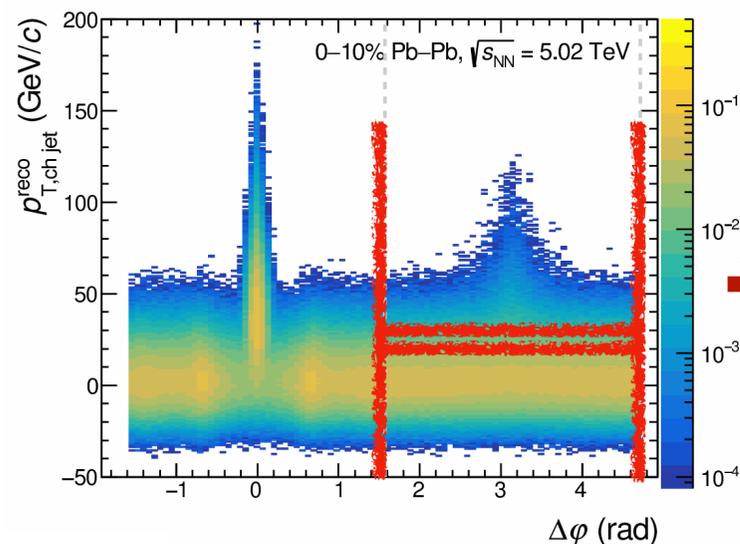
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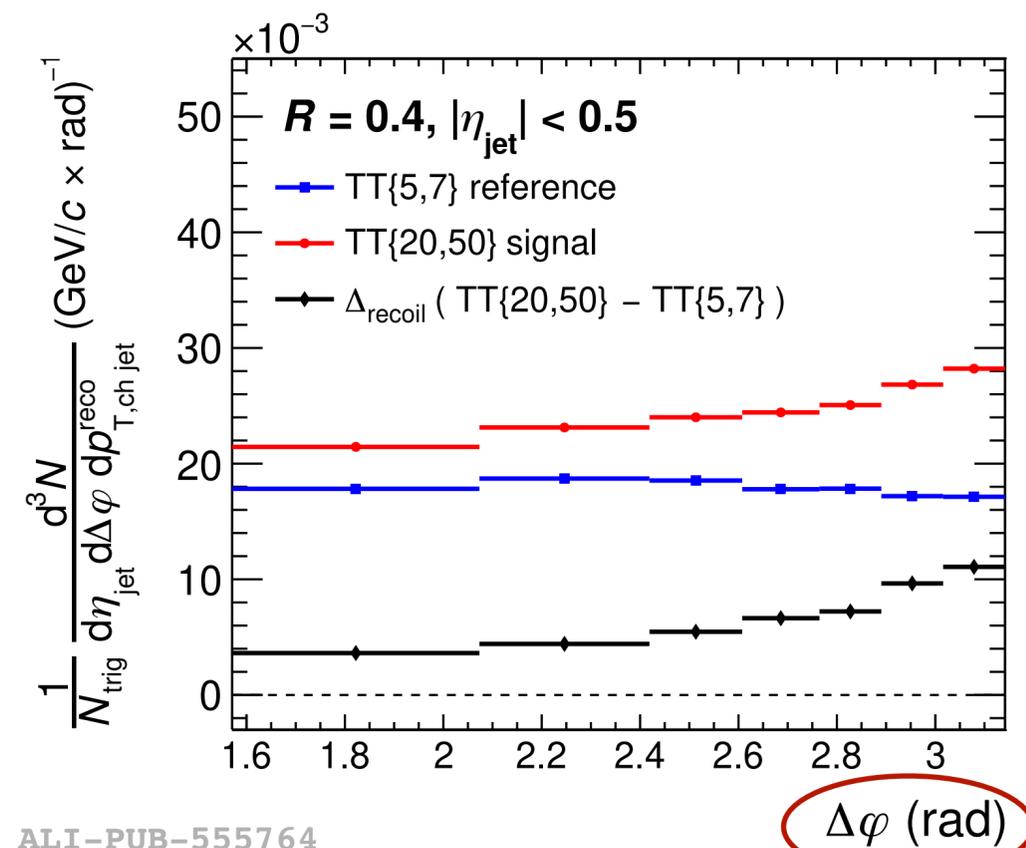
$$p_{\text{T,jet}}^{\text{reco,ch}} = p_{\text{T,jet}}^{\text{raw,ch}} - \rho A_{\text{jet}}$$

$$\text{TT}_{\text{sig}}: 20 < p_{\text{T,trig}} < 50 \text{ GeV}/c$$

$$\text{TT}_{\text{ref}}: 5 < p_{\text{T,trig}} < 7 \text{ GeV}/c$$



ALI-PUB-555759



ALI-PUB-555764

Measurement technique: corrections to raw distributions

- **Subtract combinatorial background:** difference between two exclusive trigger track-classed distributions: **‘signal’** and **‘reference’**:

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{\text{T,trig}} \in \text{TT}_{\text{Sig}}} - c_{\text{ref}} \cdot \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{d^3 N_{\text{jet}}^{\text{AA}}}{dp_{\text{T,jet}}^{\text{ch}} d\Delta\varphi d\eta_{\text{jet}}} \Big|_{p_{\text{T,trig}} \in \text{TT}_{\text{Ref}}}$$

- **Calibration of reference distribution** for precise uncorrelated background subtraction:

1. $p_{\text{T,jet}}^{\text{reco}}$ scale (*‘horizontal’*)

STAR: Phys. Rev. C 96, 024905 (2017)

2. Yield scale (*‘vertical’*) c_{Ref}

→ extracted from data, $\Delta\varphi/R/\text{coll.}$ syst. dependent, takes values between 0.75 and 1

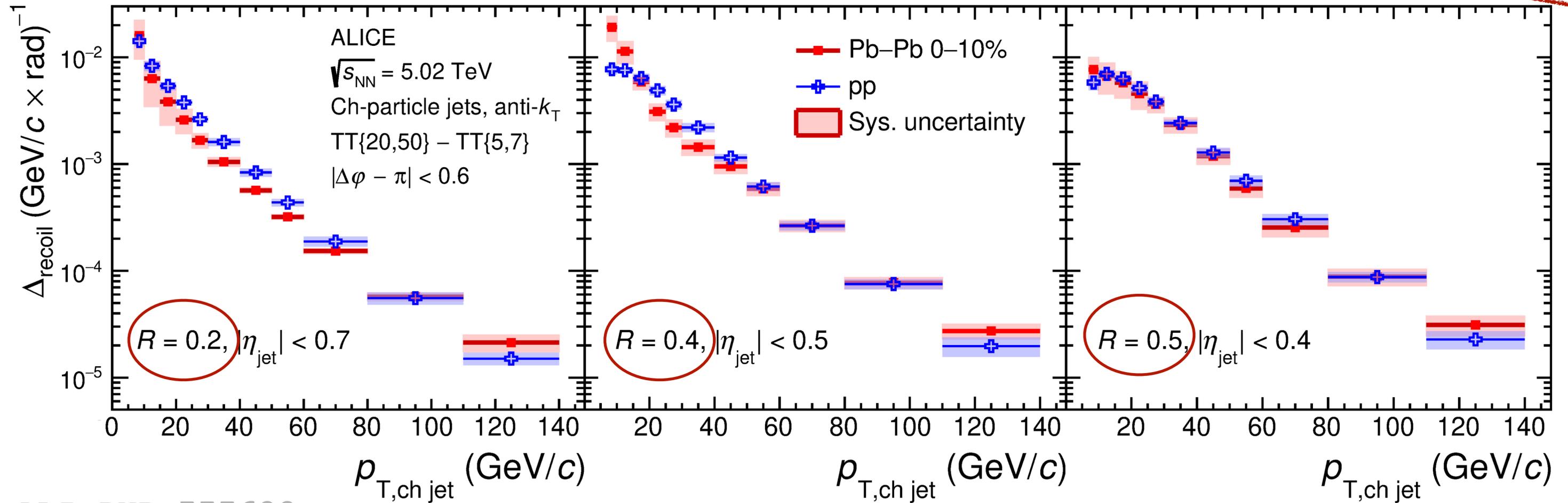
ALICE: JHEP 09 (2015) 170

- **Raw distributions unfolded** for detector effects and residual background fluctuations
- **All correction steps fully validated** via closure test (PYTHIA embedded into Pb-Pb, compare unfolded to truth)

Fully-corrected $\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ distributions in pp and Pb-Pb collisions

arXiv:2308.16131
arXiv:2308.16128

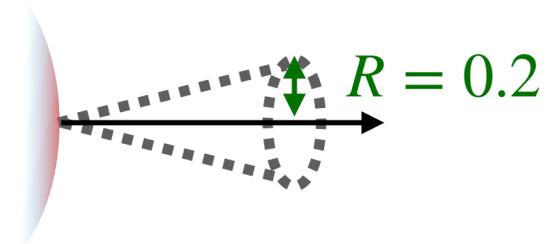
New paper



ALI-PUB-555699

- Δ_{recoil} distributions measured from $7 < p_{T,\text{ch jet}} < 140 \text{ GeV}/c$ in pp and Pb-Pb collisions
Among lowest jet p_T measurement in Pb-Pb collisions at the LHC!

$I_{AA}(p_{T, \text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions

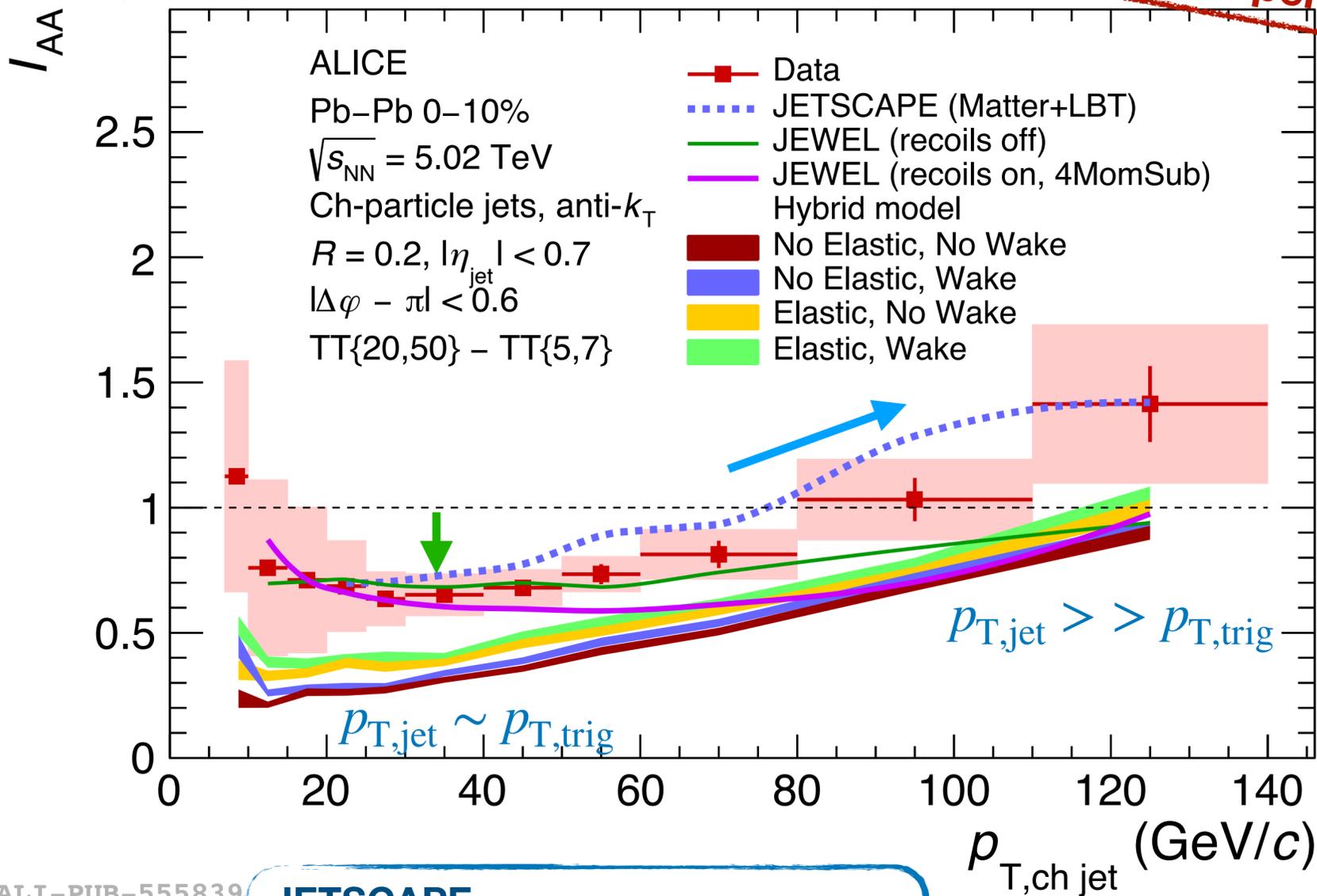
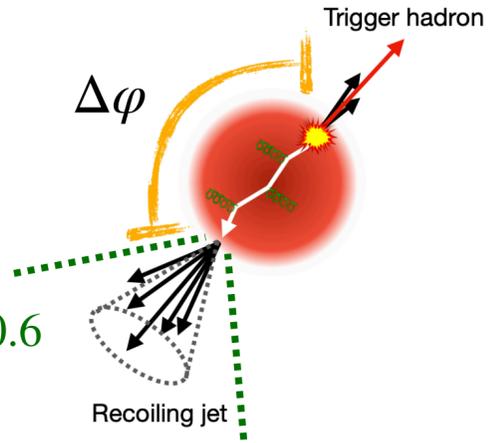


arXiv:2308.16131
arXiv:2308.16128

New paper

$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

$$|\Delta\phi - \pi| < 0.6$$



- **Suppression** at $20 < p_{T, \text{ch jet}} < 80 \text{ GeV}/c$
→ jet energy loss
- **Rising trend with $p_{T, \text{ch jet}}$**
→ interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T, \text{jet}} \gg p_{T, \text{trig}}$

Models (Hybrid, JETSCAPE) capture rising trend

ALI-PUB-555839

JETSCAPE

Energy loss based on MATTER (high virtuality) and LBT (low virtuality)

JETSCAPE, Phys. Rev. C 107, 034911

JEWEL

Medium response effects via treatment of 'recoils'

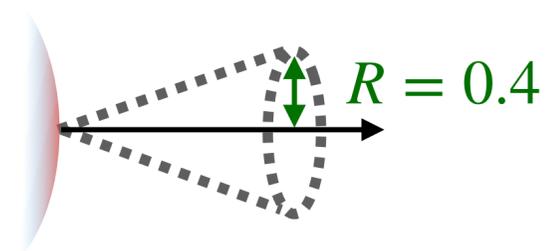
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Hybrid model

Elastic (Molière) scatterings and wake (medium response) included

F. d'Eramo, K. Rajagopal, Y. Yin, JHEP 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

$I_{AA}(p_{T, \text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions

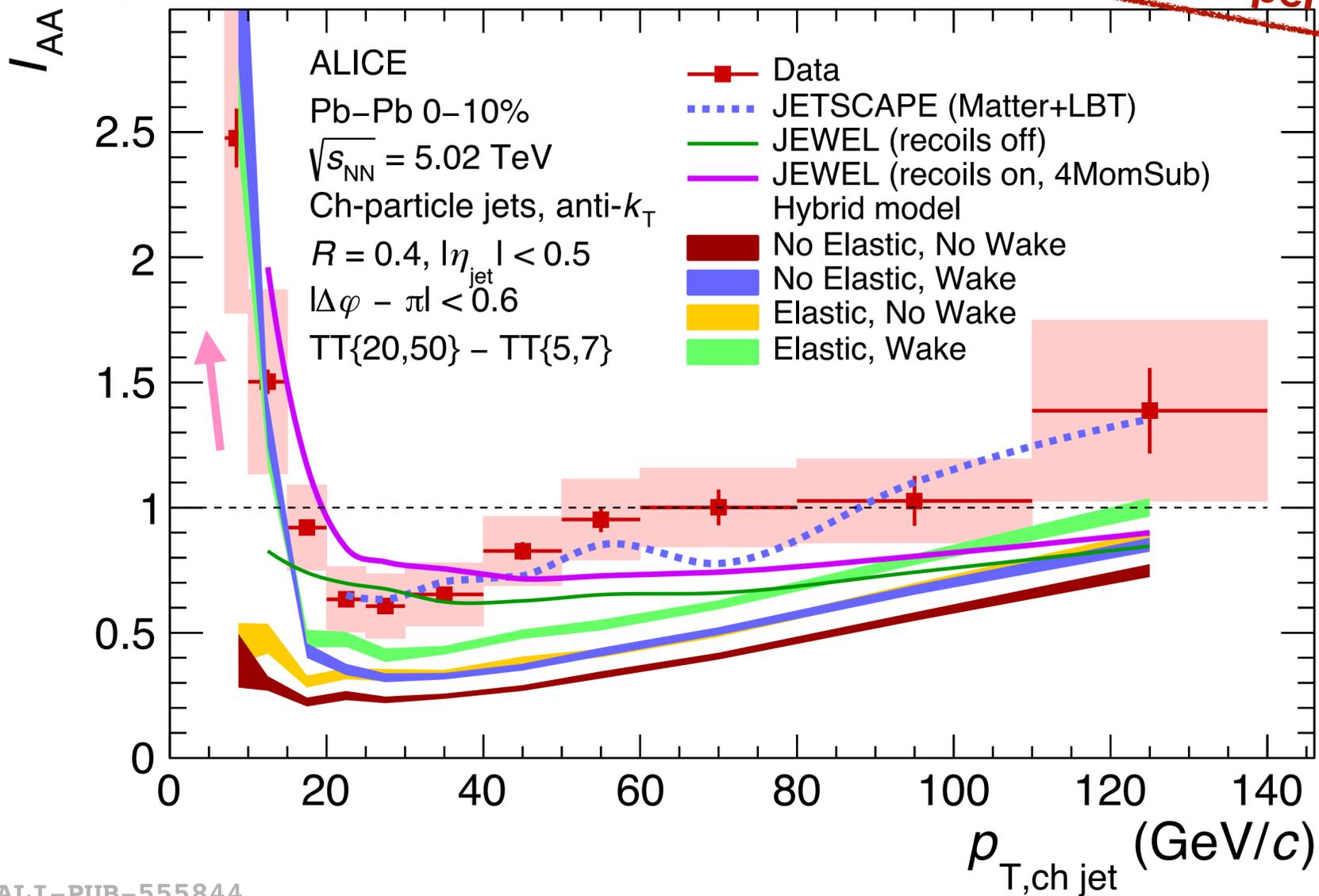
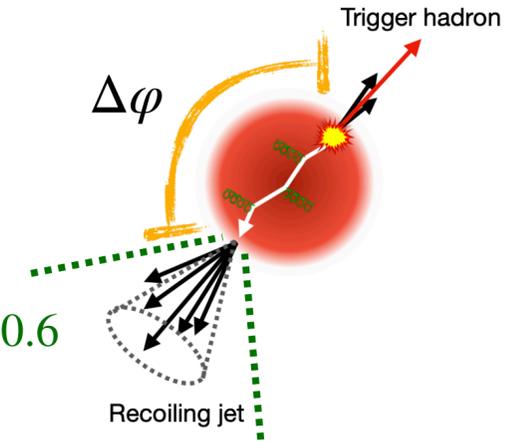


arXiv:2308.16131
arXiv:2308.16128

New paper

$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

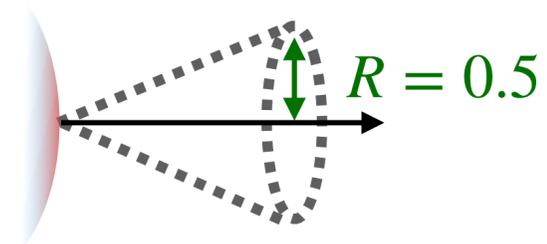
$$|\Delta\varphi - \pi| < 0.6$$



- **Suppression** at $20 < p_{T, \text{ch jet}} < 80 \text{ GeV}/c$
→ jet energy loss
- **Rising trend with $p_{T, \text{ch jet}}$**
→ interplay between hadron and jet energy loss? Less trigger surface bias when $p_{T, \text{jet}} \gg p_{T, \text{trig}}$
- **Rise at low $p_{T, \text{ch jet}}$**
→ Energy recovery? Reproduced by models including medium response

ALI-PUB-555844

$I_{AA}(p_{T, \text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions

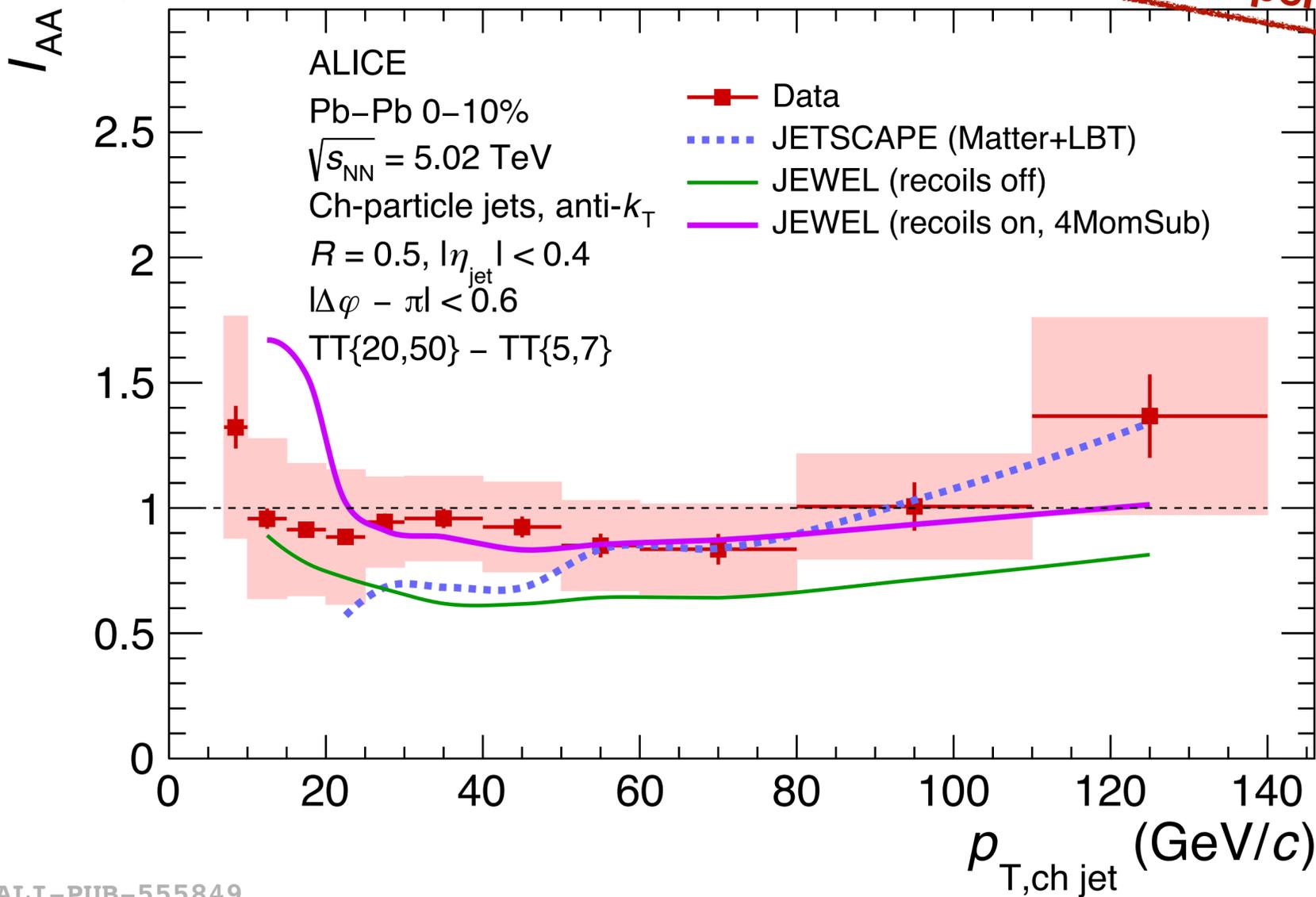
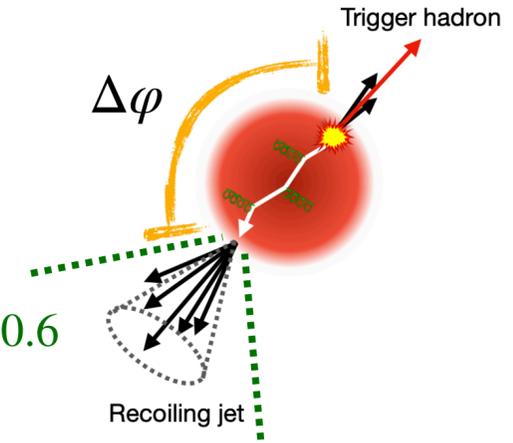


arXiv:2308.16131
arXiv:2308.16128

New paper

$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

$$|\Delta\varphi - \pi| < 0.6$$



- **$R=0.5$ consistent with no suppression**
- Little suppression captured by JEWEL (recoils on)
- Indication of intra-jet energy recovery within cone radius ~ 0.5 for mid- $p_{T, \text{ch jet}}$?

ALI-PUB-555849

$\Delta_{\text{recoil}}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

$p_{T,\text{ch jet}}$: [10,20] GeV/c

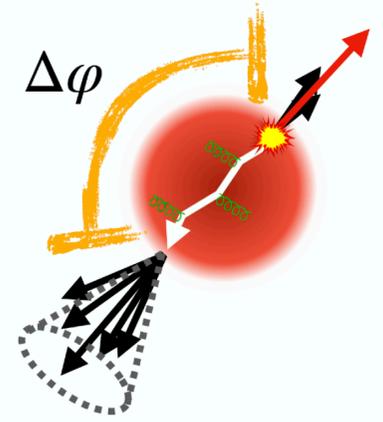
[20,30] GeV/c

[30,50] GeV/c

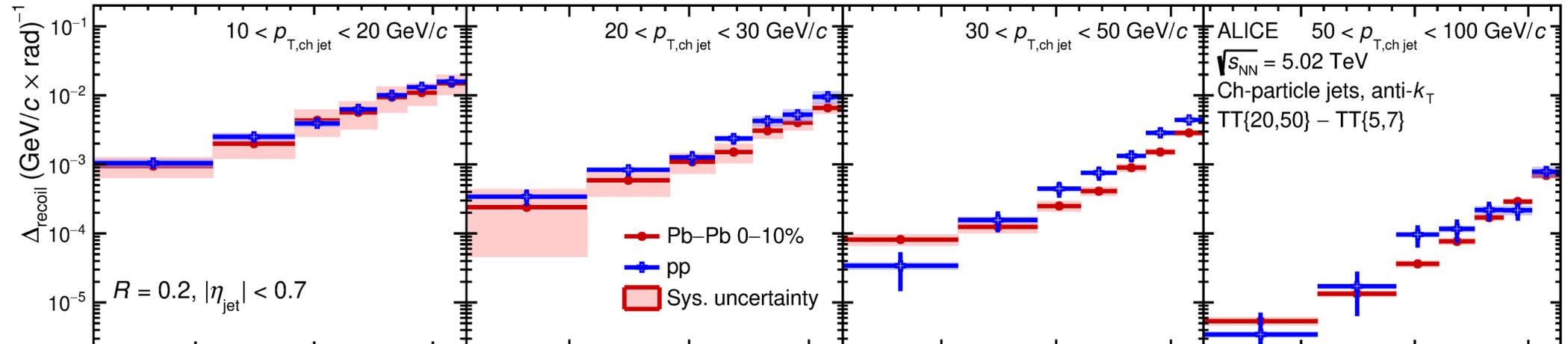
[50,100] GeV/c

New paper

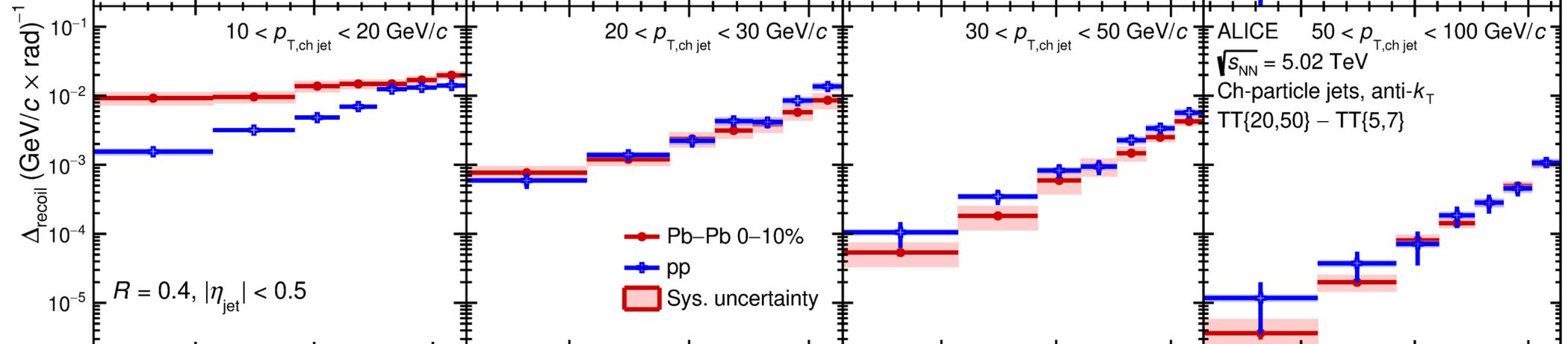
arXiv:2308.16131
arXiv:2308.16128



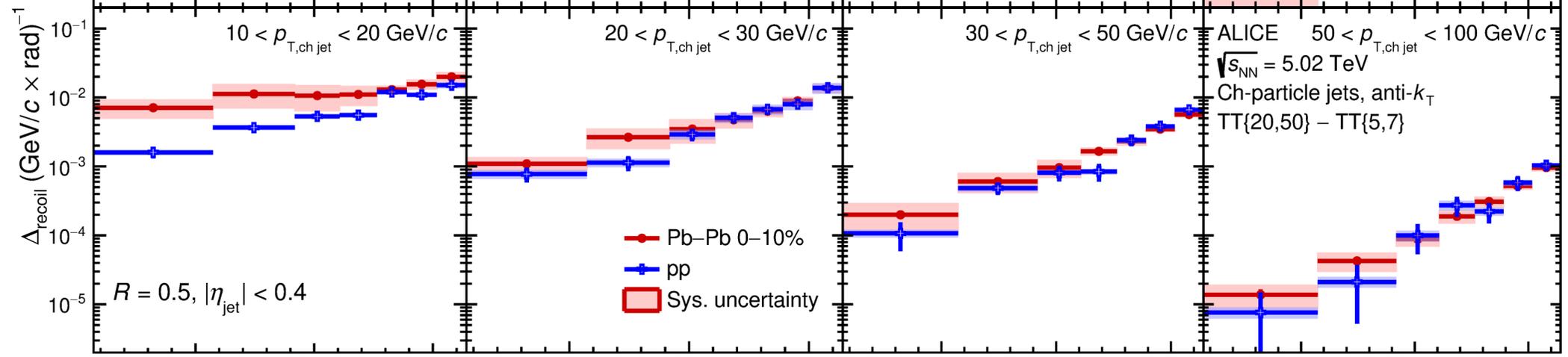
$R=0.2$



$R=0.4$



$R=0.5$



ALI-PUB-555894

Jaime Norman (University of Liverpool)

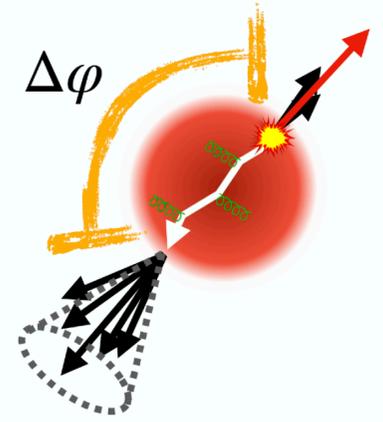
n+jet energy redistribution and broadening with ALICE

$\Delta_{\text{recoil}}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

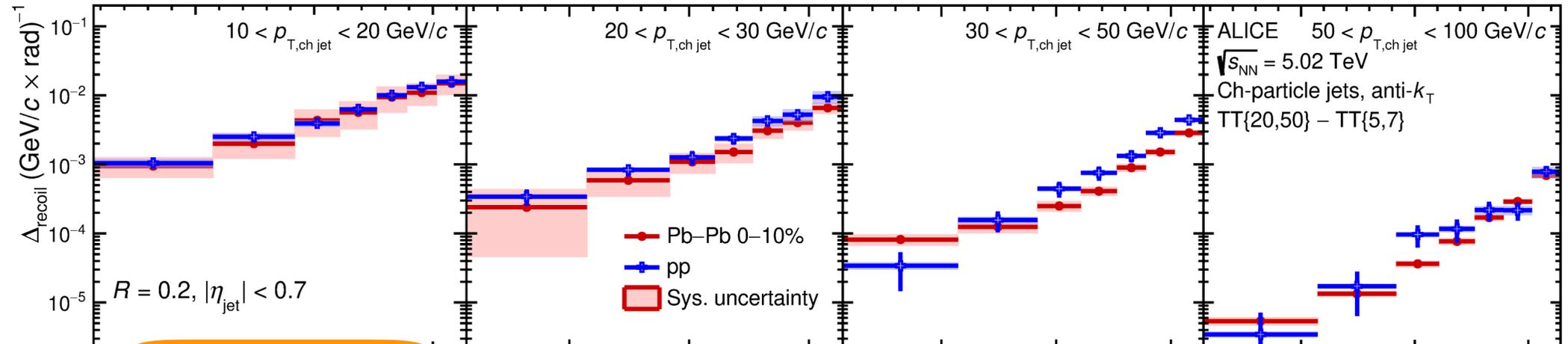
$p_{T,\text{ch jet}}$: **[10,20] GeV/c** **[20,30] GeV/c** **[30,50] GeV/c** **[50,100] GeV/c**

New paper

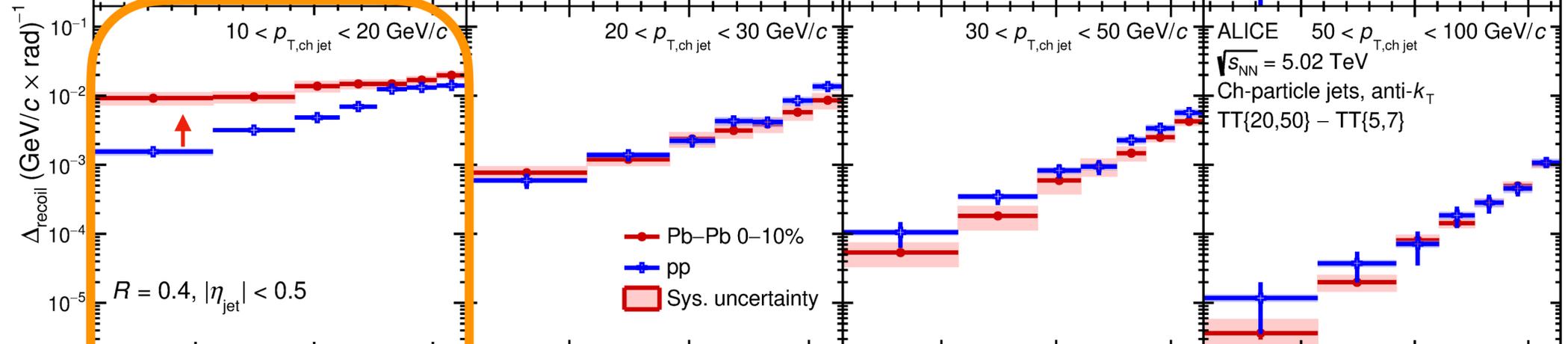
arXiv:2308.16131
arXiv:2308.16128



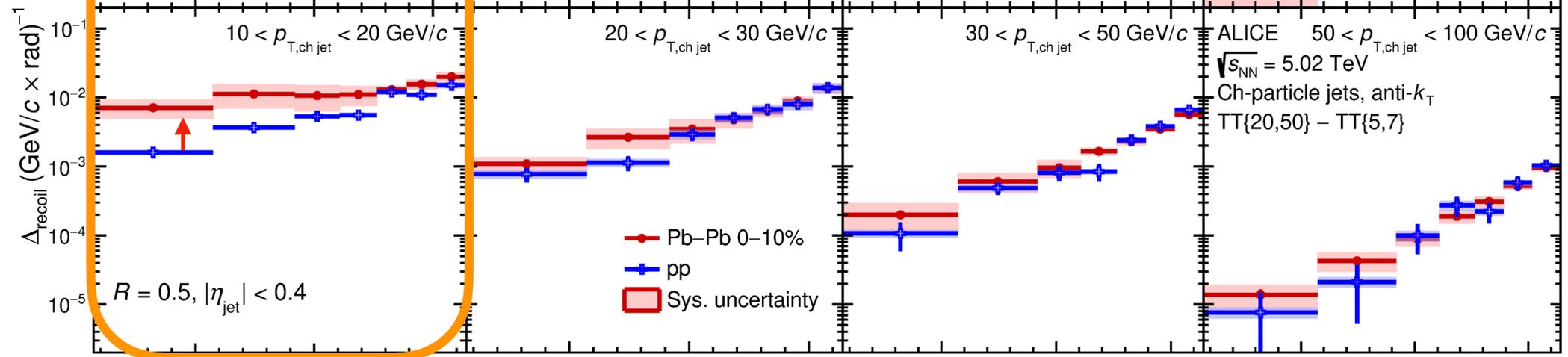
$R=0.2$



$R=0.4$

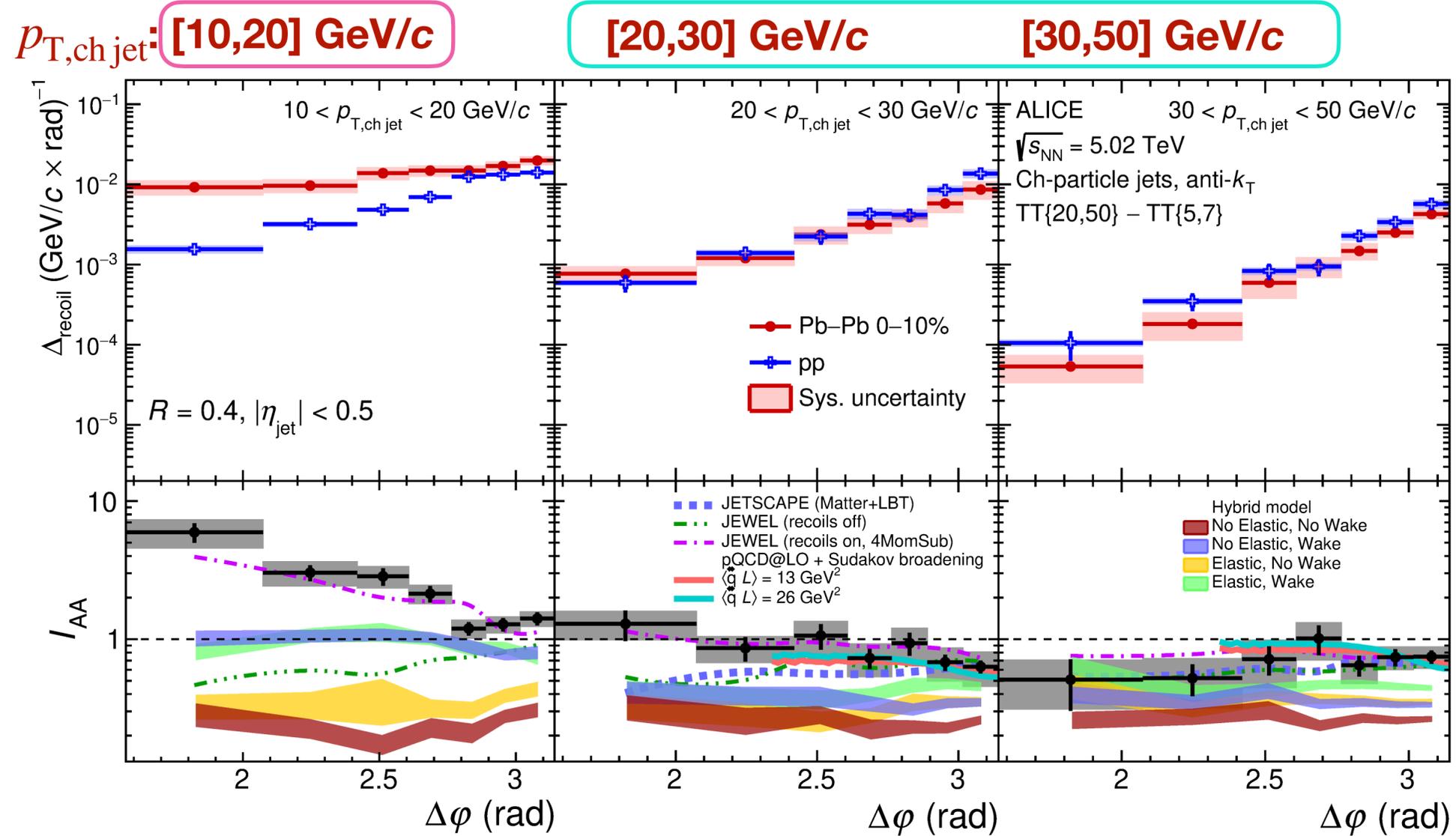
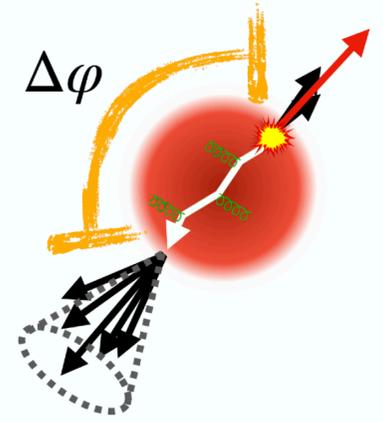


$R=0.5$



- **Significant azimuthal broadening** for $R=0.4$ and $R=0.5$ at low $p_{T,\text{ch jet}}$

$I_{AA}(\Delta\varphi)$ - recoil jet azimuthal modification in Pb-Pb collisions



New paper

arXiv:2308.16131
arXiv:2308.16128

pQCD + Sudakov broadening
Leading order pQCD, azimuthal broadening via jet transport coefficient
L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676

$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

- **No broadening for [20,100] GeV/c** → **significant broadening for [10,20] GeV/c** (4.7σ deviation of I_{AA} from flat)
- Wake in Hybrid model captures yield enhancement, but no broadening seen when including elastic component
- pQCD w/ broadening agrees with data - lacking precision to resolve difference between two \hat{q} values
- JEWEL (recoils on) captures all features of data

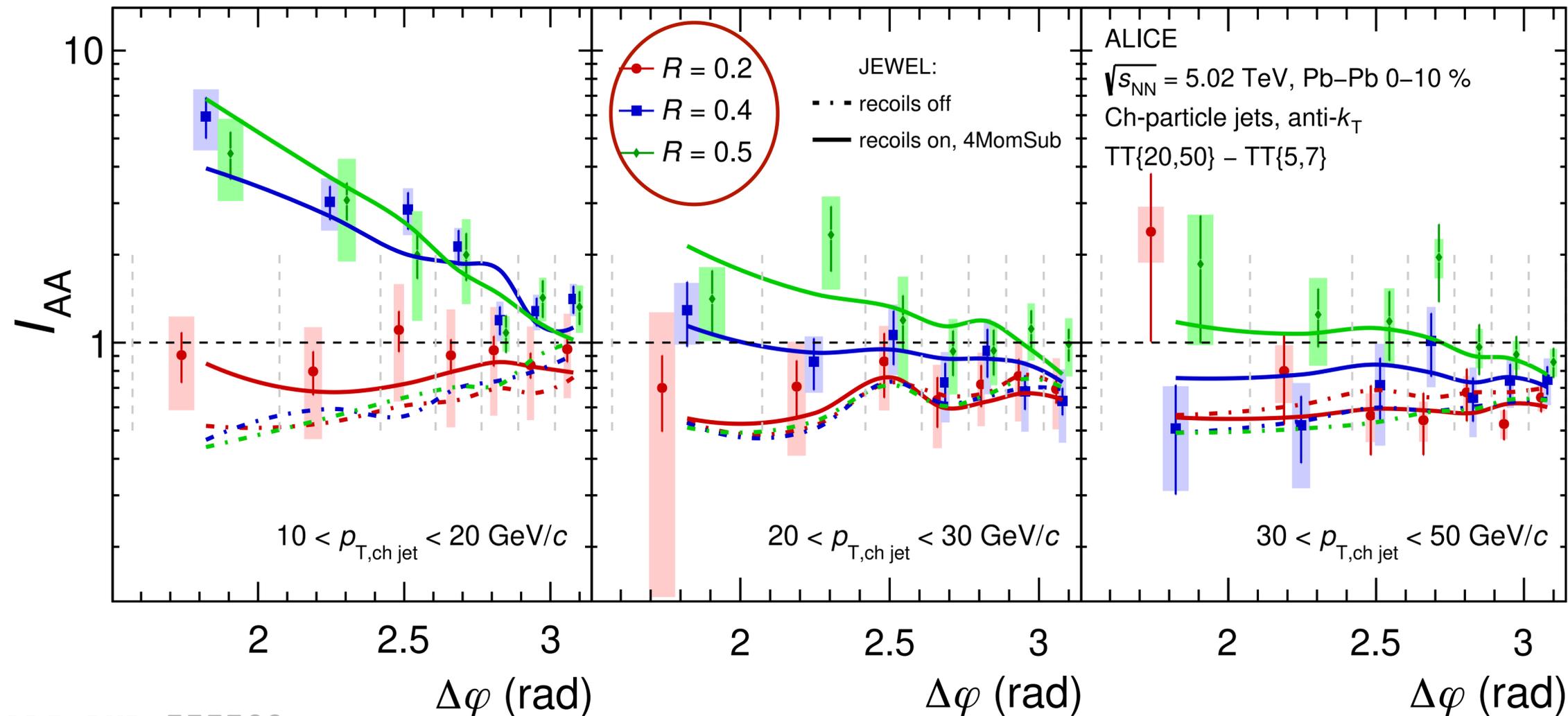
ALI-PUB-555704

$I_{AA}(\Delta\varphi)$ vs R

$p_{T, \text{ch jet}}: [10,20] \text{ GeV}/c$

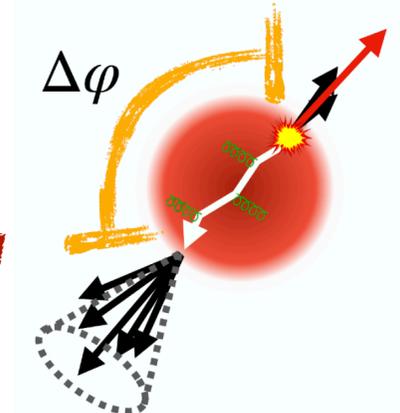
$[20,30] \text{ GeV}/c$

$[30,50] \text{ GeV}/c$



New paper

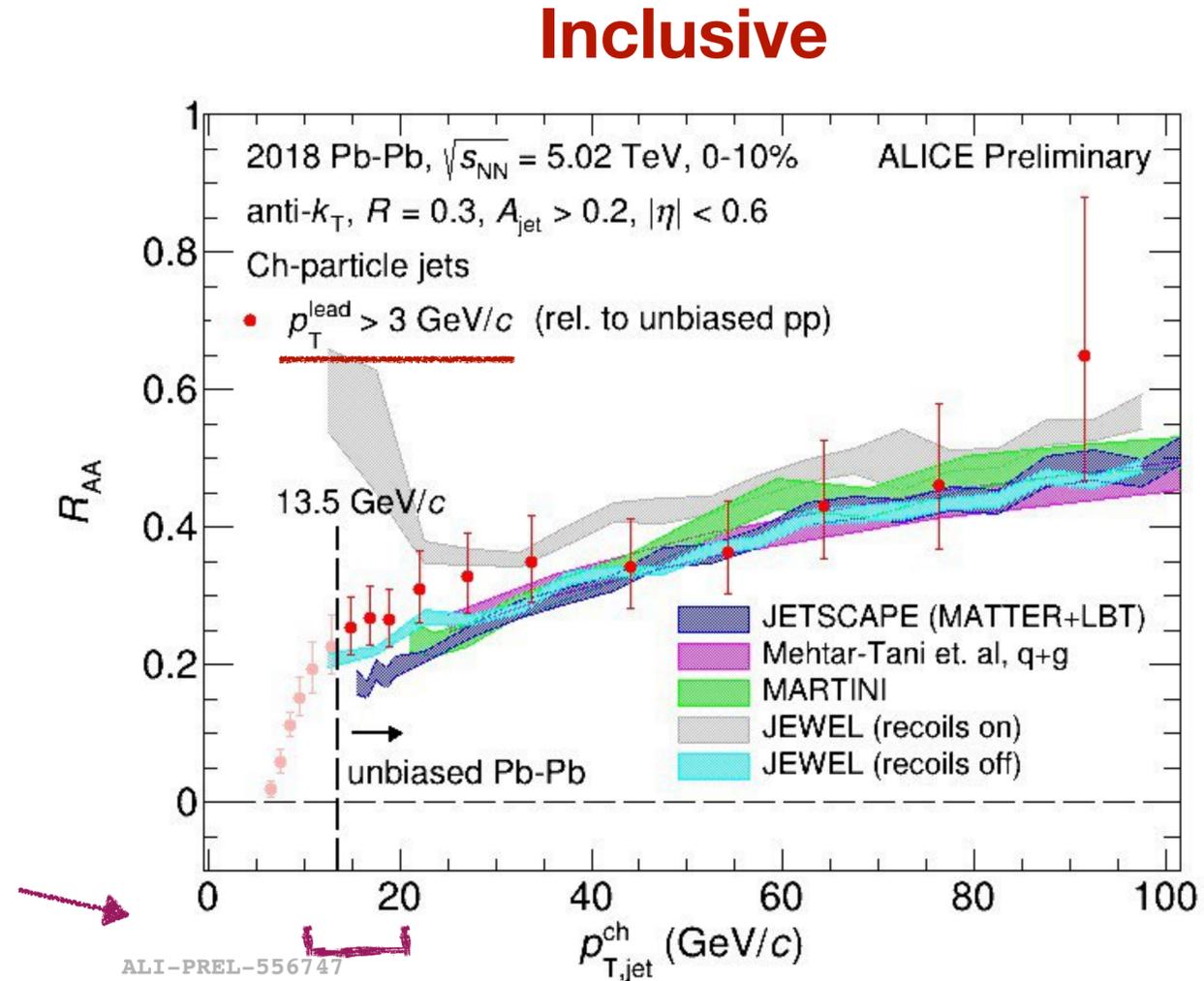
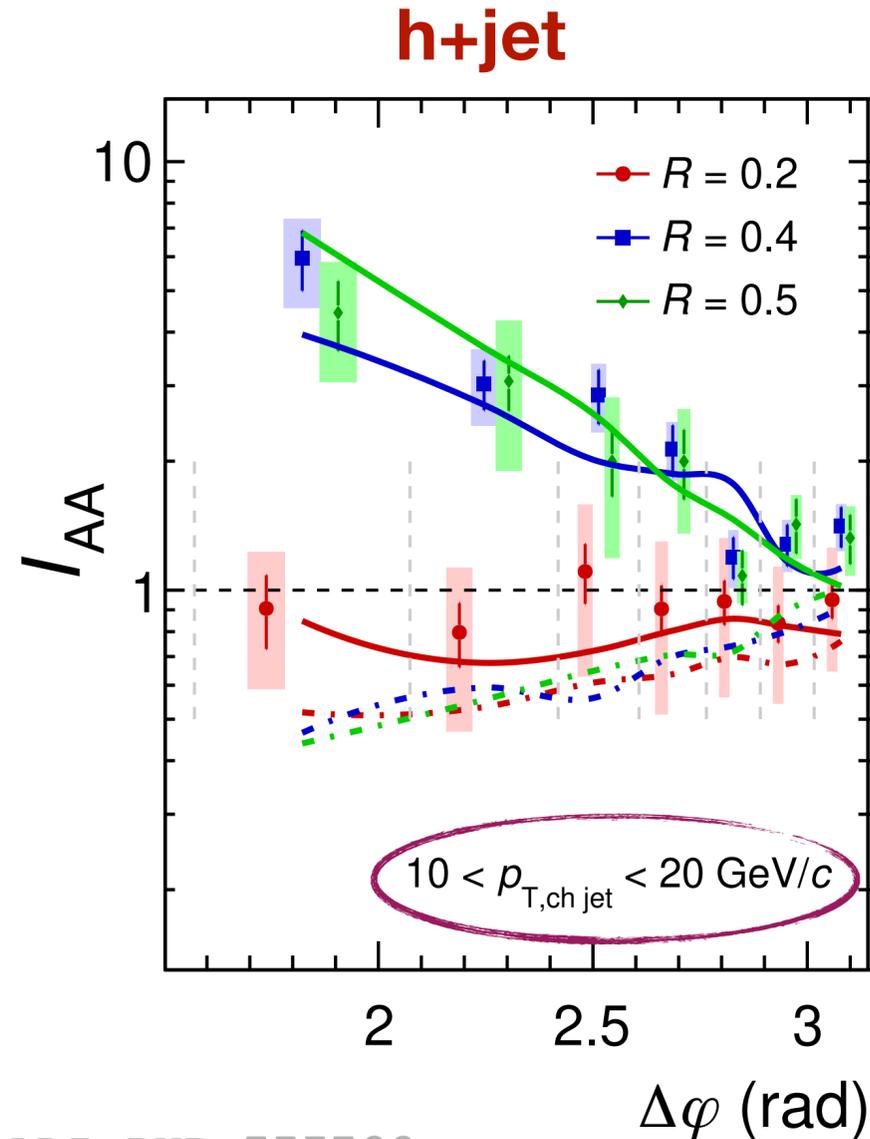
arXiv:2308.16131
 arXiv:2308.16128



ALI-PUB-555709

- **Transition to broadening from $R=0.2 \rightarrow R=0.4$ for $[10,20] \text{ GeV}/c$:** Soft radiation mimicking a jet may scale with R^2
 - broadening due to medium response or medium-induced soft radiation rather than large-angle scattering?
- All features of distribution **reproduced by JEWEL** with recoils on

Low jet $p_{T,\text{jet}}$: inclusive vs recoil



See new low- p_T jet R_{AA} measurement.
N. Gruenwald, 5th Sept 11:40

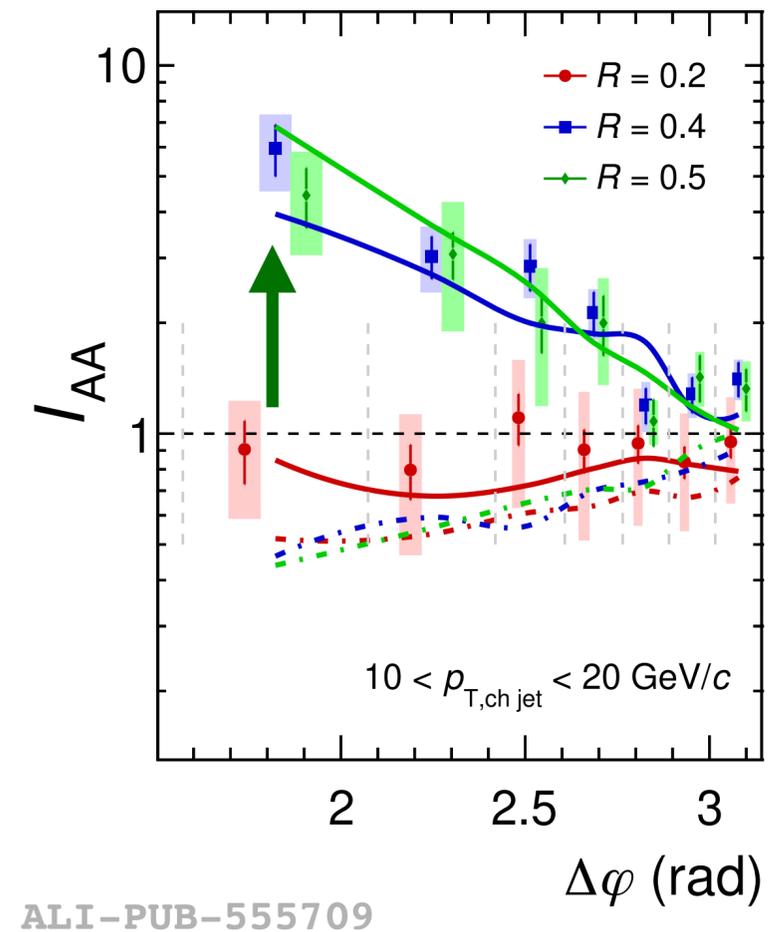
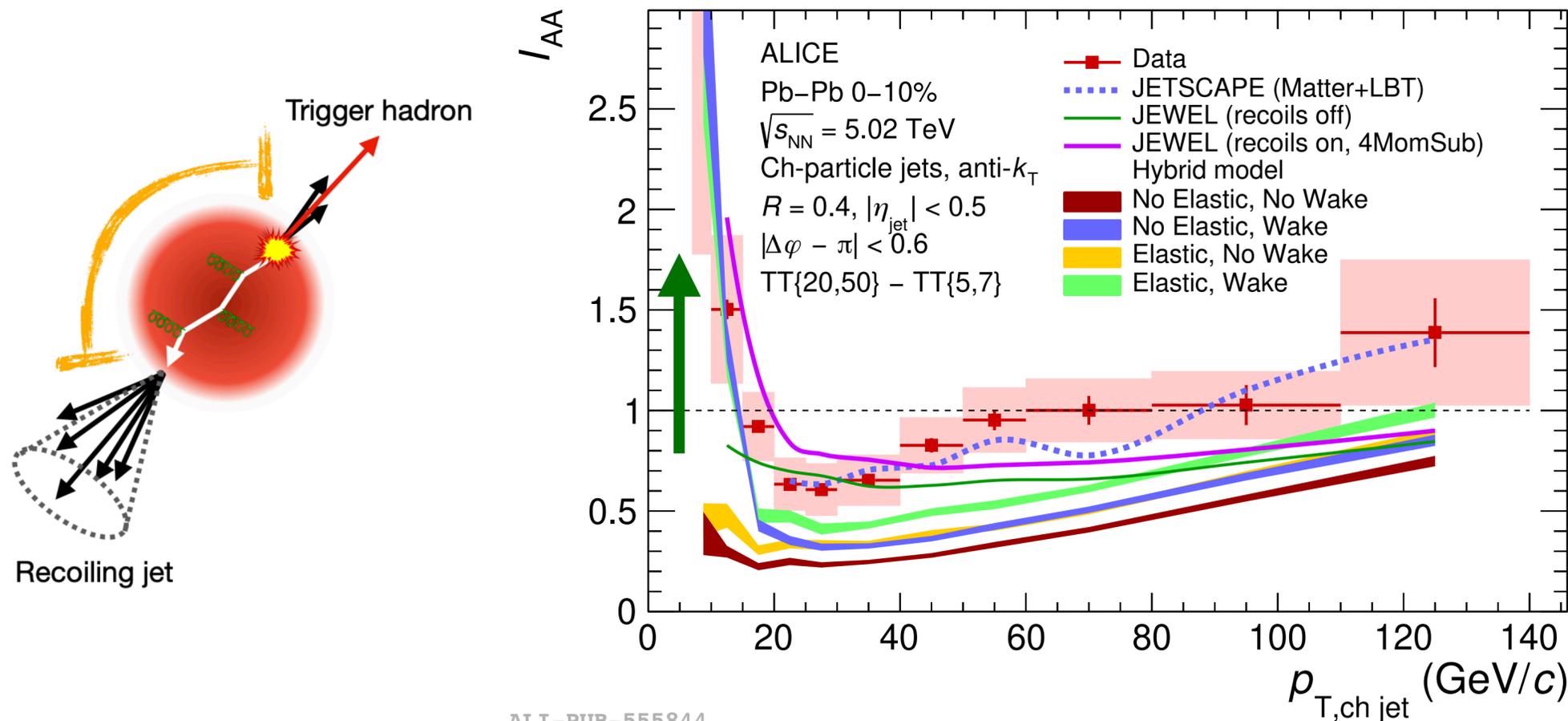
JEWEL describes other observables less well

e.g. opposite picture (recoils on/off) for inclusive jets at low $p_{T,\text{jet}}$

→ no model incorporating medium response describes all measured observables

(Recoil jet $p_{T,\text{jet}}$ spectrum also described less well in vacuum by JEWEL, see backup)

Summary and outlook

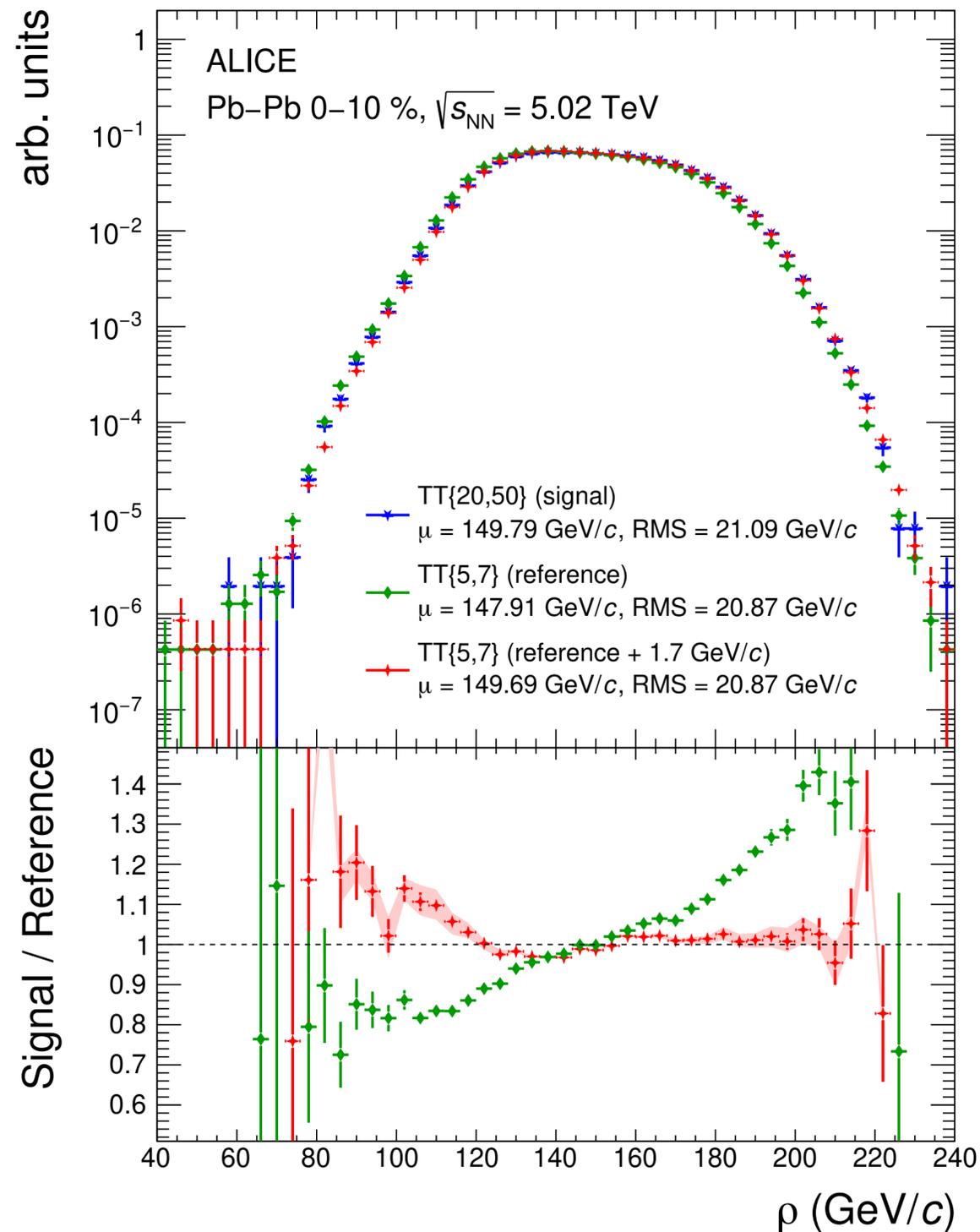


- **First observation of significant low- $p_{T,jet}$ yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response favoured as cause for both effects (Molière scattering disfavoured)
- Full interpretation requires description within a consistent theoretical framework! Future global analyses of multiple observables

See [arXiv:2308.16128](https://arxiv.org/abs/2308.16128) [arXiv:2308.16131](https://arxiv.org/abs/2308.16131) for this and more!

Backup

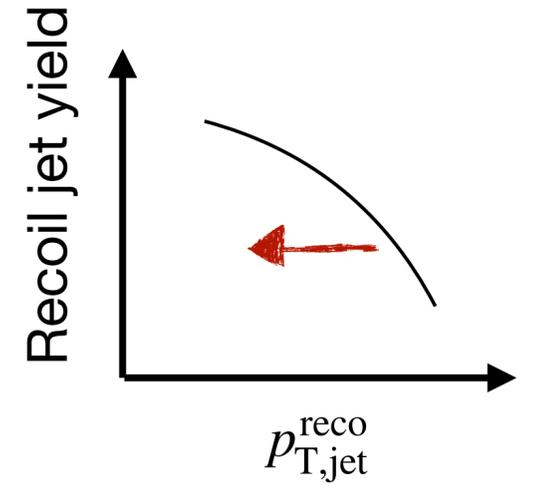
Δ_{recoil} 'reference' calibration



ALI-PUB-555739

Calibration of reference distribution required:

1. $p_{\text{T,jet}}^{\text{reco}}$ scale ('horizontal')
2. Yield scale ('vertical')



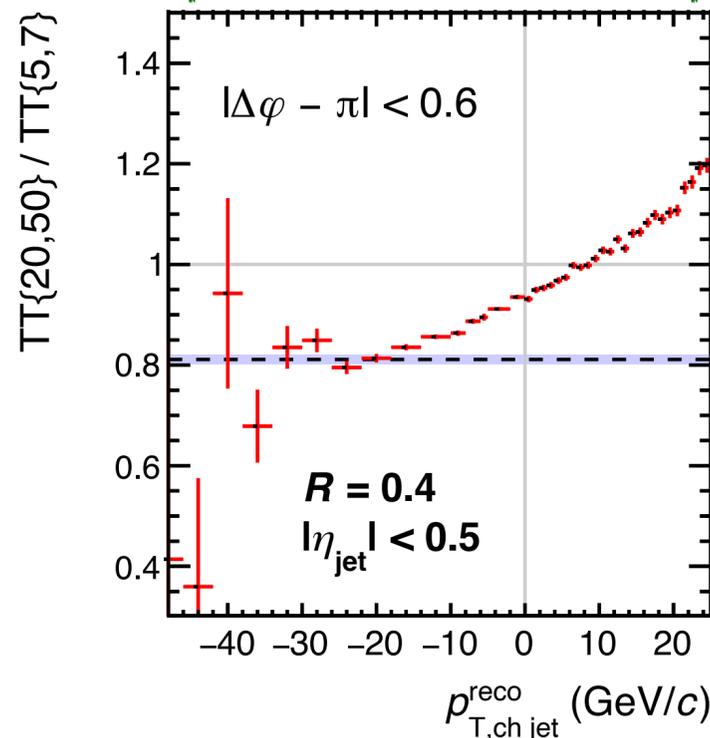
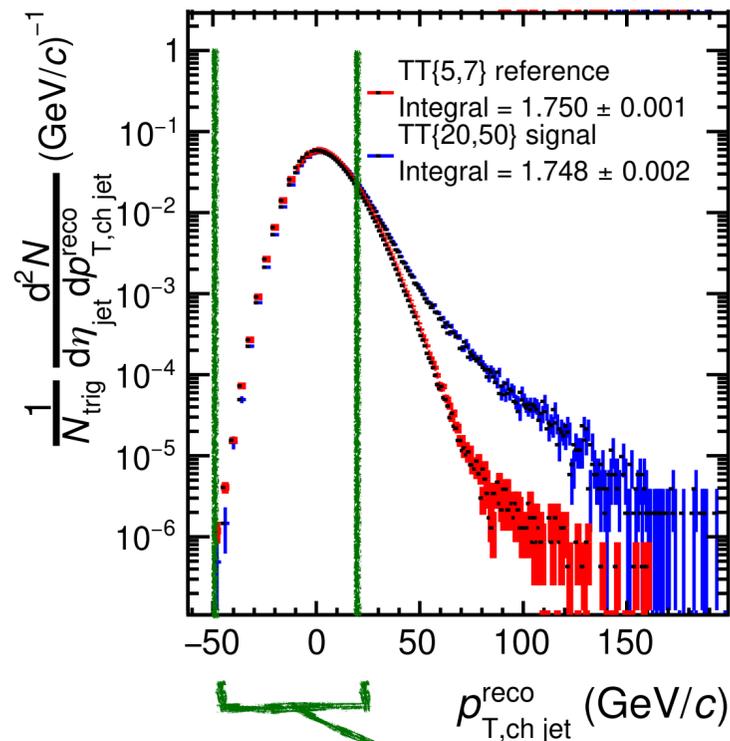
$$p_{\text{T,jet}}^{\text{reco}} = p_{\text{T,jet}}^{\text{raw}} - A \cdot \rho$$

- Jet p_{T} corrected by underlying event density ρ
- ρ depends on trigger-track content of HI event
- Harder component \rightarrow larger average ρ
- Scaling ρ in reference-classed events by 1.7 GeV/c brings absolute ρ scale into agreement in both event classes \rightarrow greater precision in subtraction of uncorrelated yield

Established technique

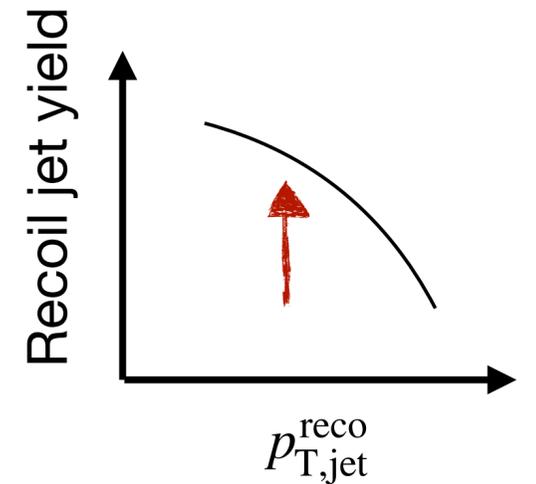
STAR: Phys. Rev. C 96, 024905 (2017)

Δ_{recoil} 'reference' calibration



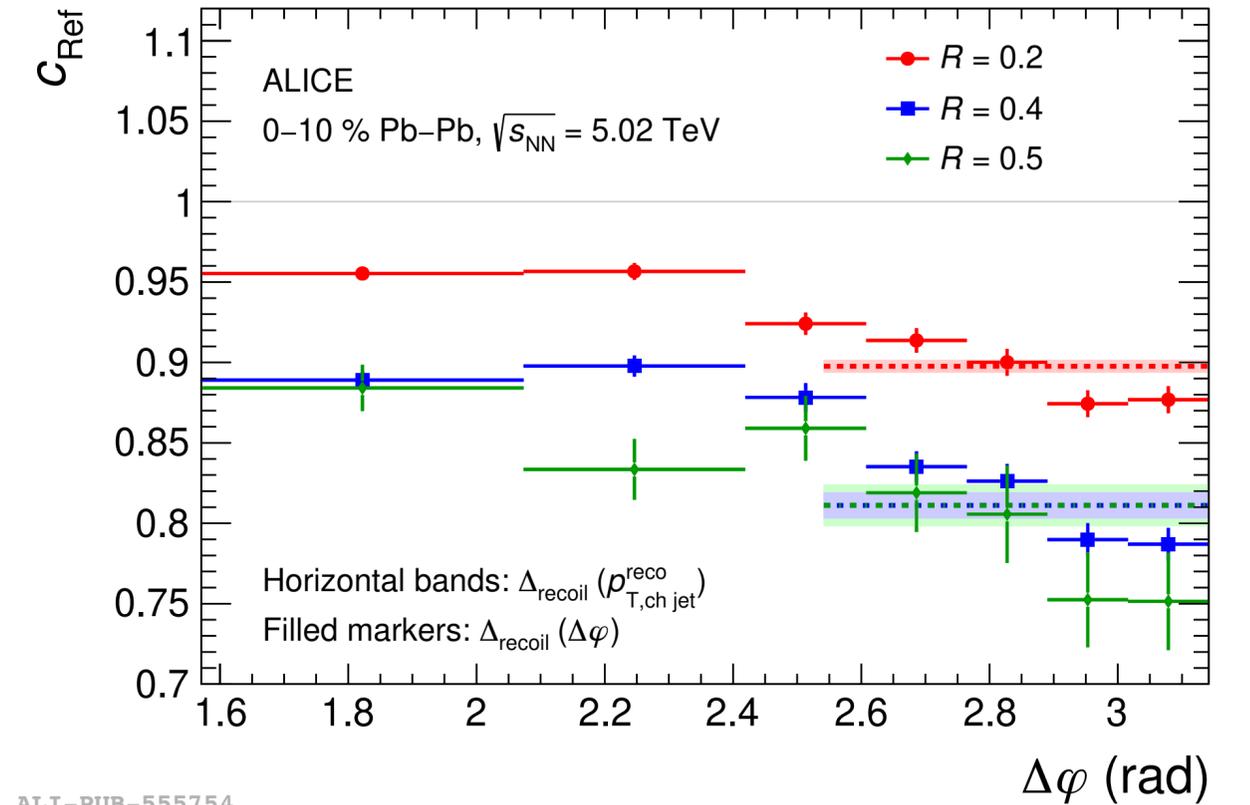
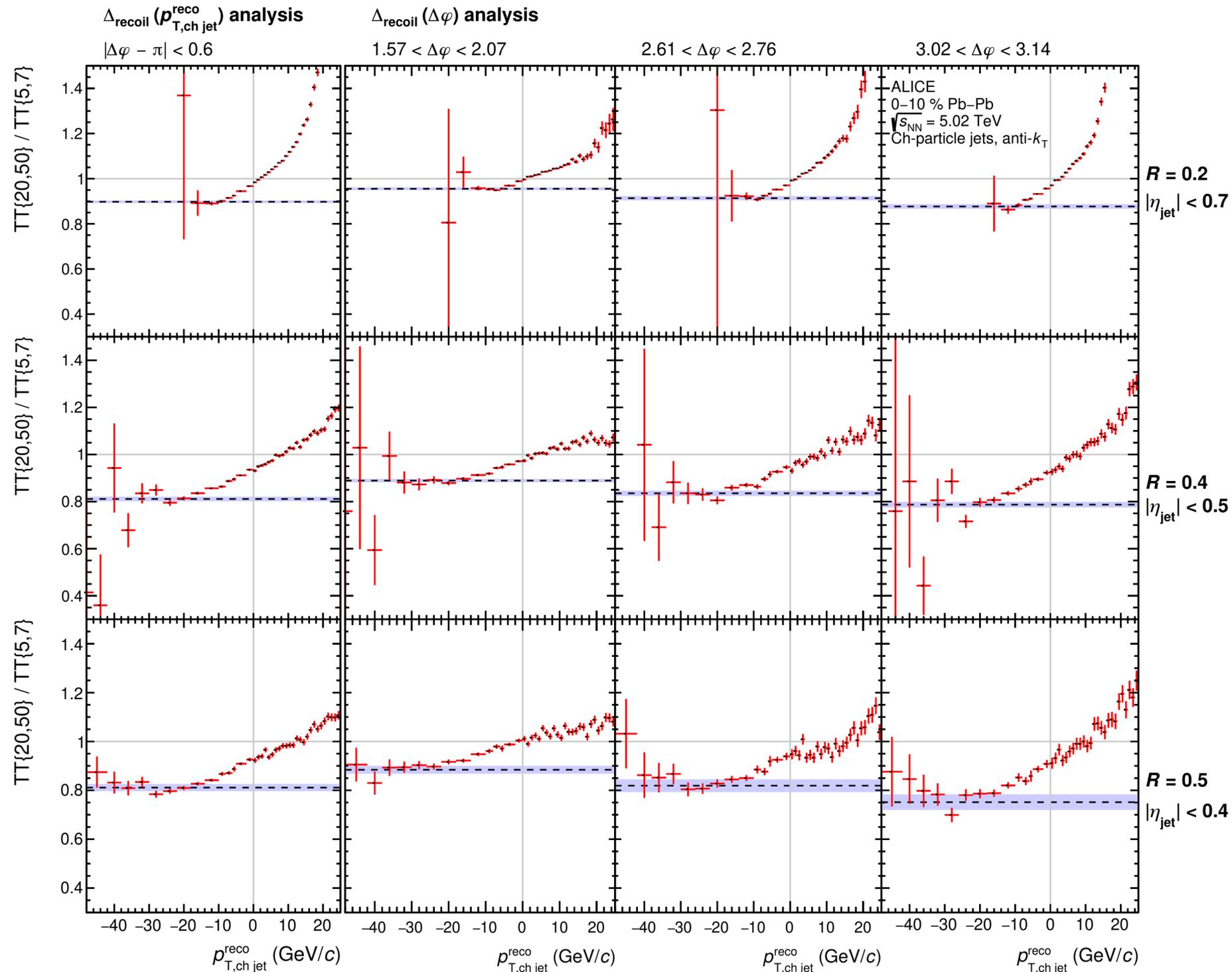
Calibration of reference distribution required:

1. $p_{T,\text{jet}}^{\text{reco}}$ scale ('horizontal')
2. Yield scale ('vertical')



- Integrals of signal and reference distributions consistent
- Conservation of jet density - uncorrelated low- $p_{T,\text{jet}}$ region 'misaligned' due to difference in correlated jet yield at high $p_{T,\text{jet}}$
- factor ' c_{Ref} ' applied to reference distribution to align signal and reference distributions in low- $p_{T,\text{jet}}$ region

Δ_{recoil} 'reference' calibration



ALI-PUB-555754

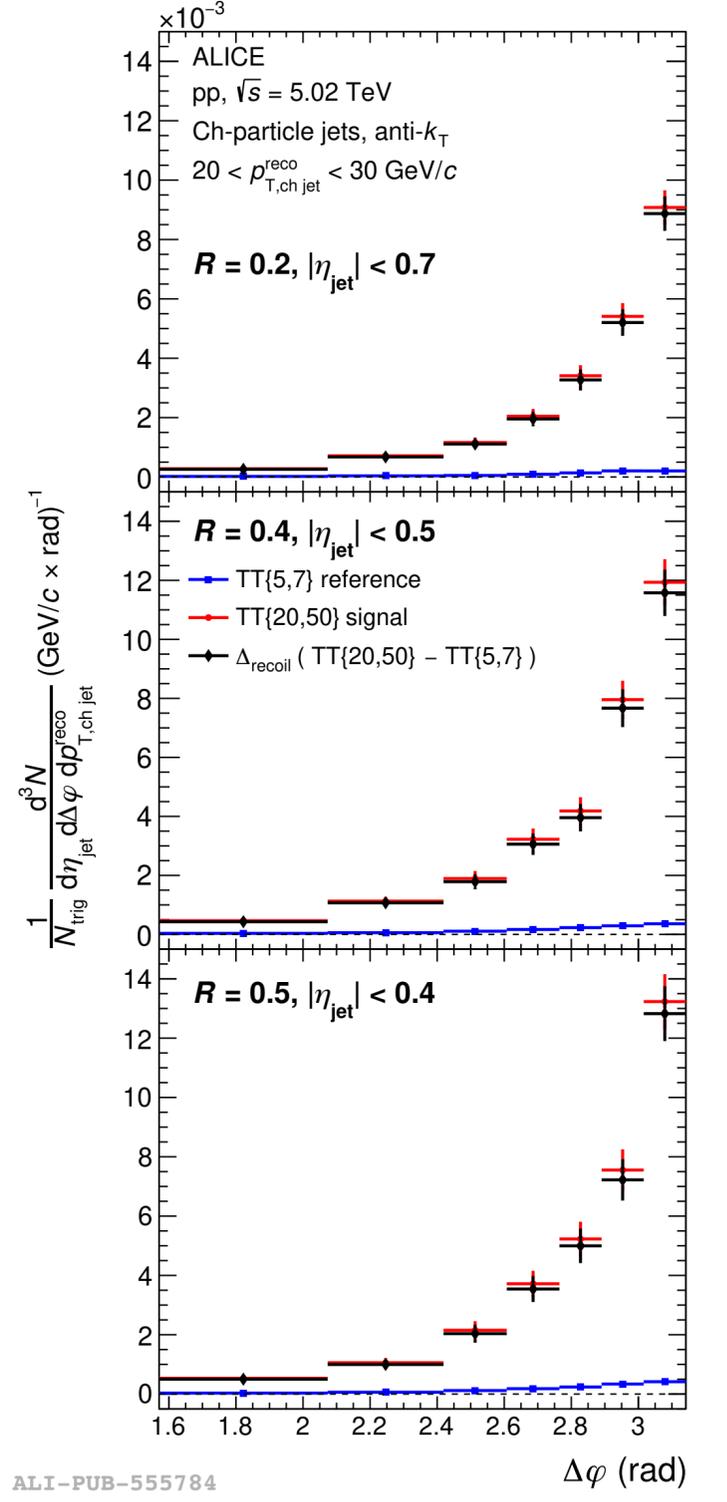
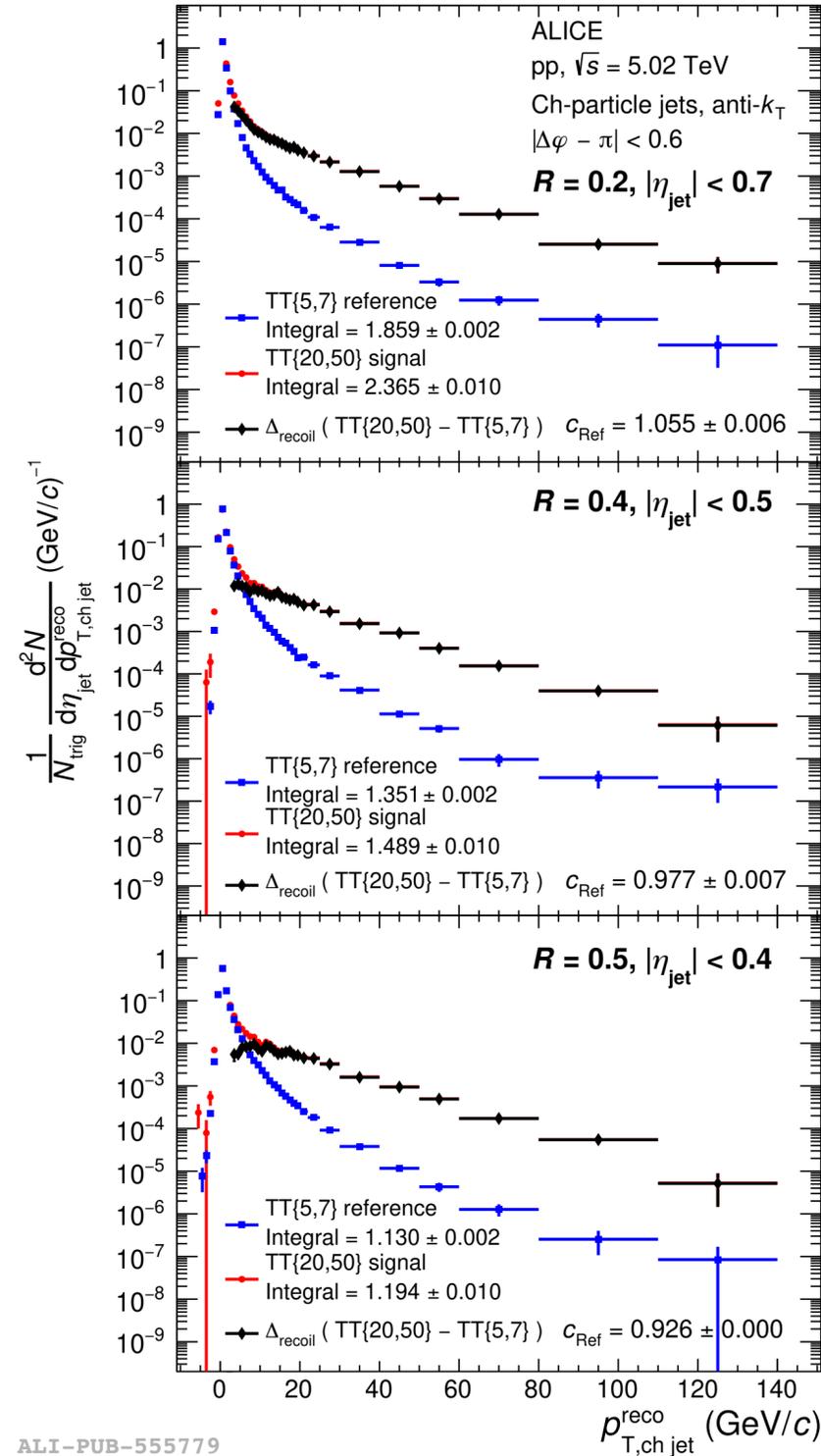
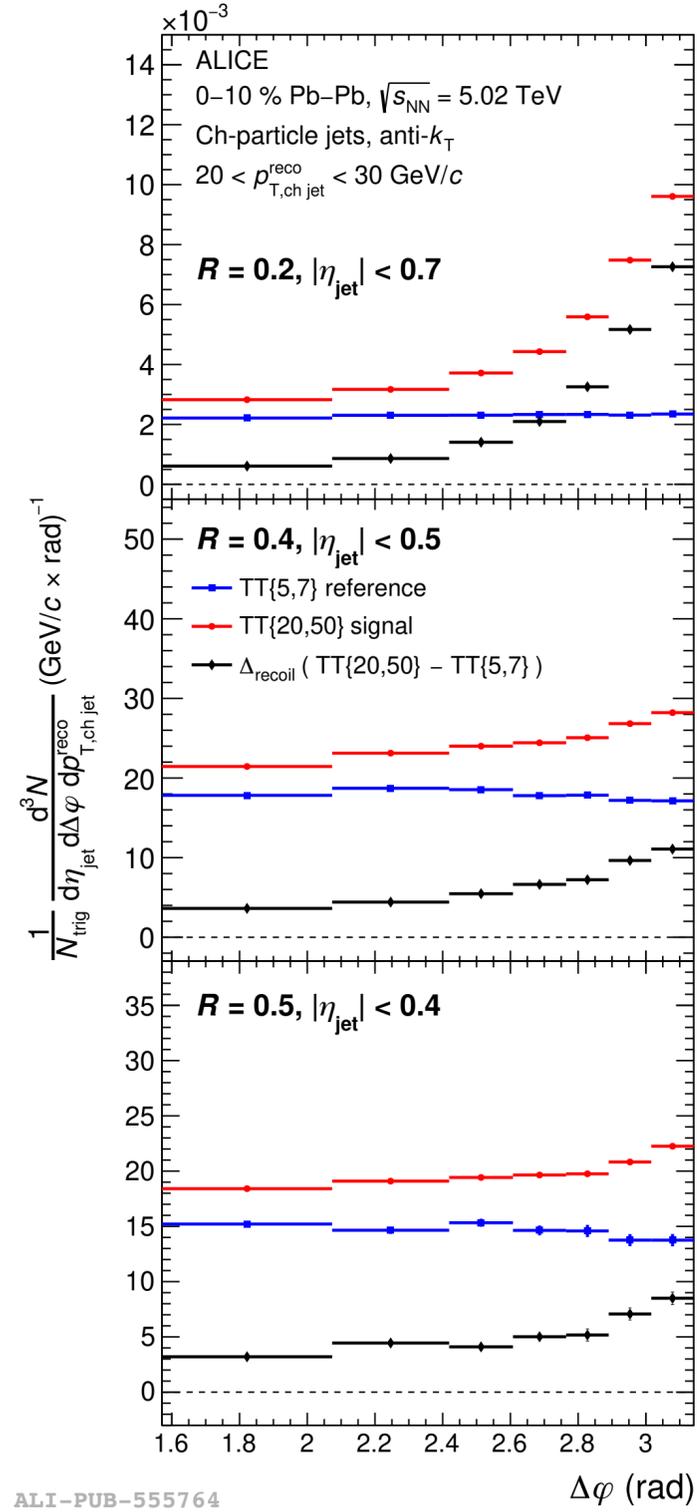
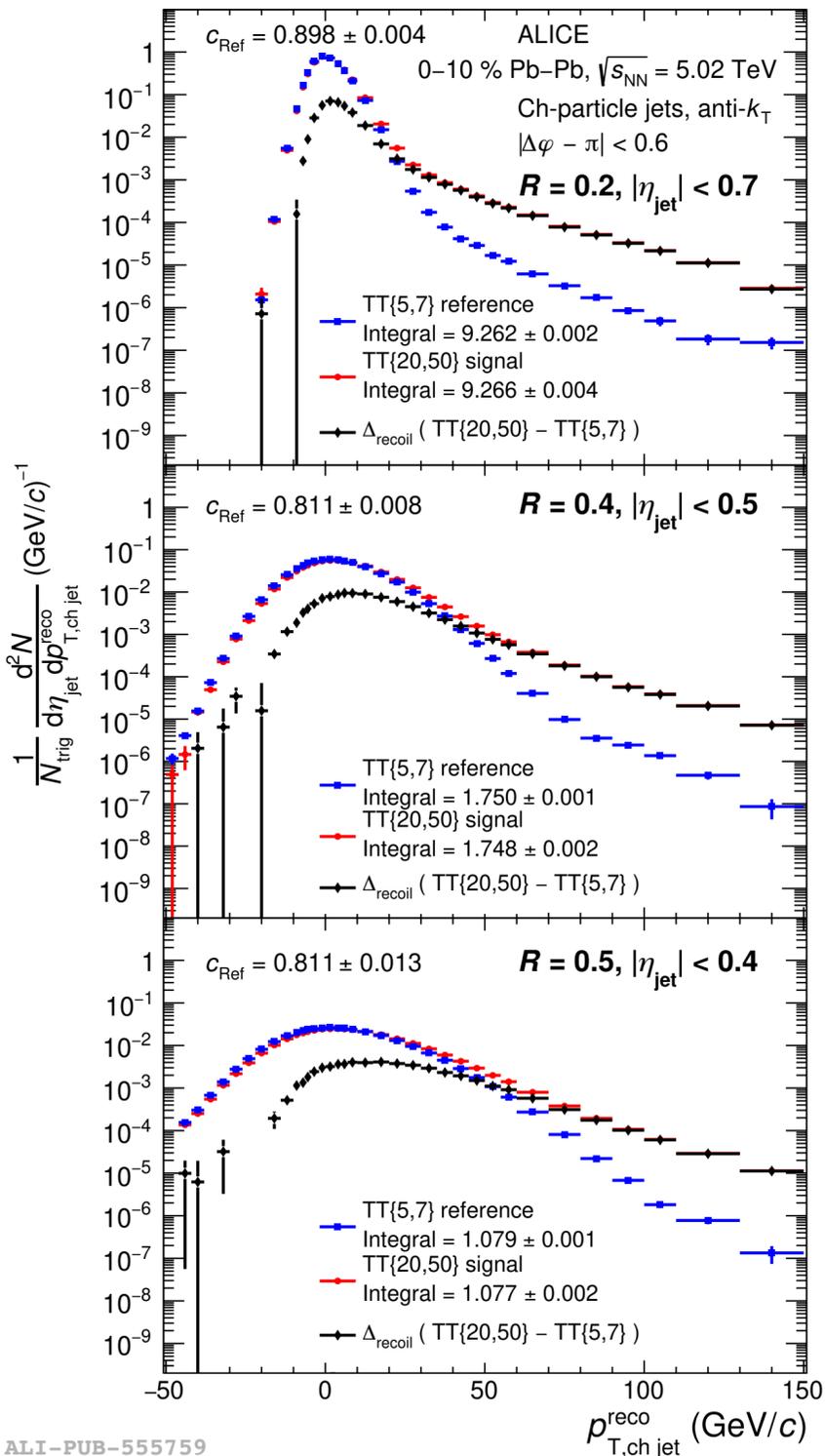
- Correction $\Delta\varphi$ -dependent
- more correlated yield
→ larger C_{Ref} correction

ALI-PUB-555749

Raw distributions

Pb-Pb

pp



ALI-PUB-555759

ALI-PUB-555764

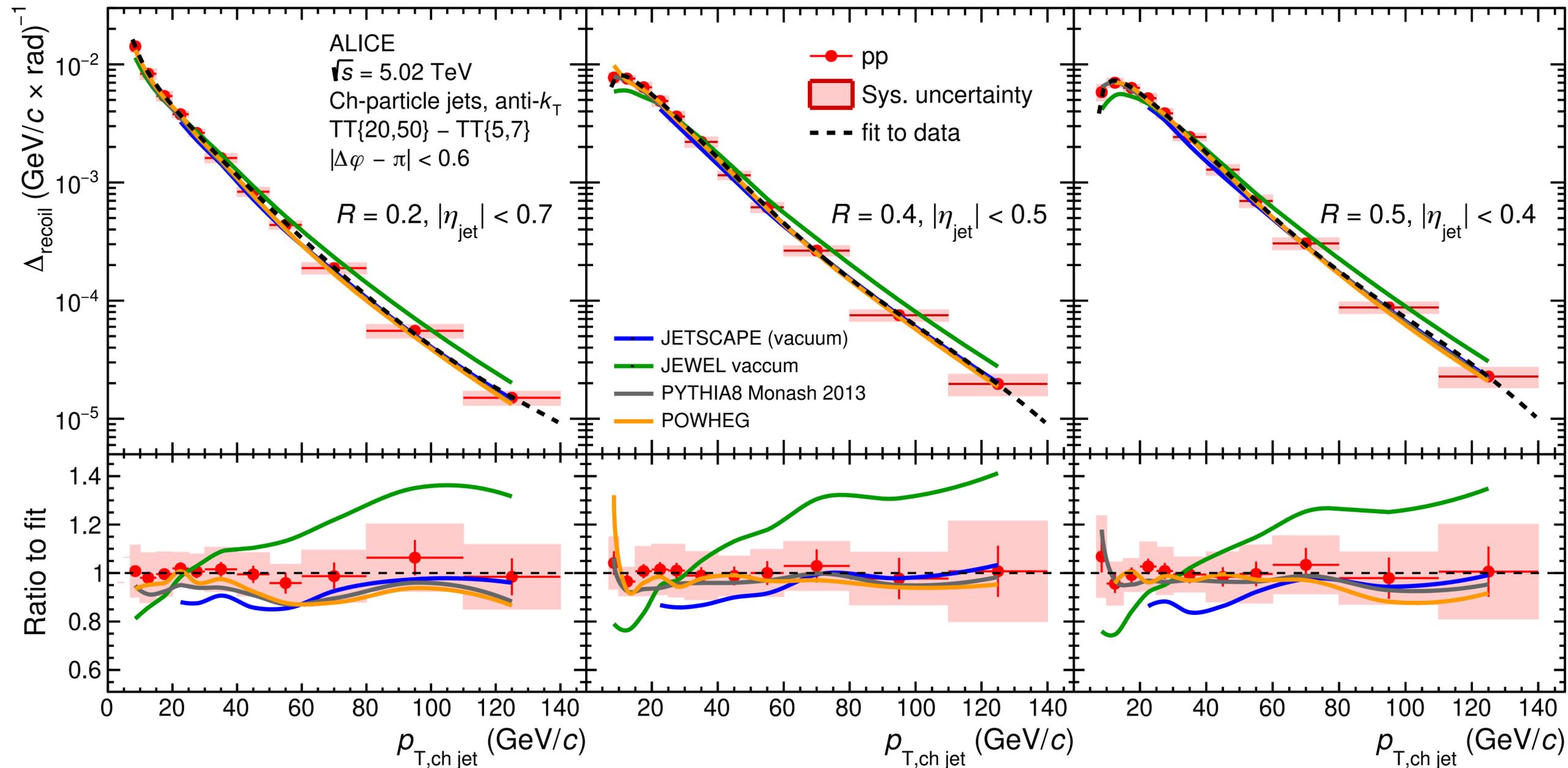
ALI-PUB-555779

ALI-PUB-555784

$\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ in pp collisions

arXiv:2308.16131
arXiv:2308.16128

New paper

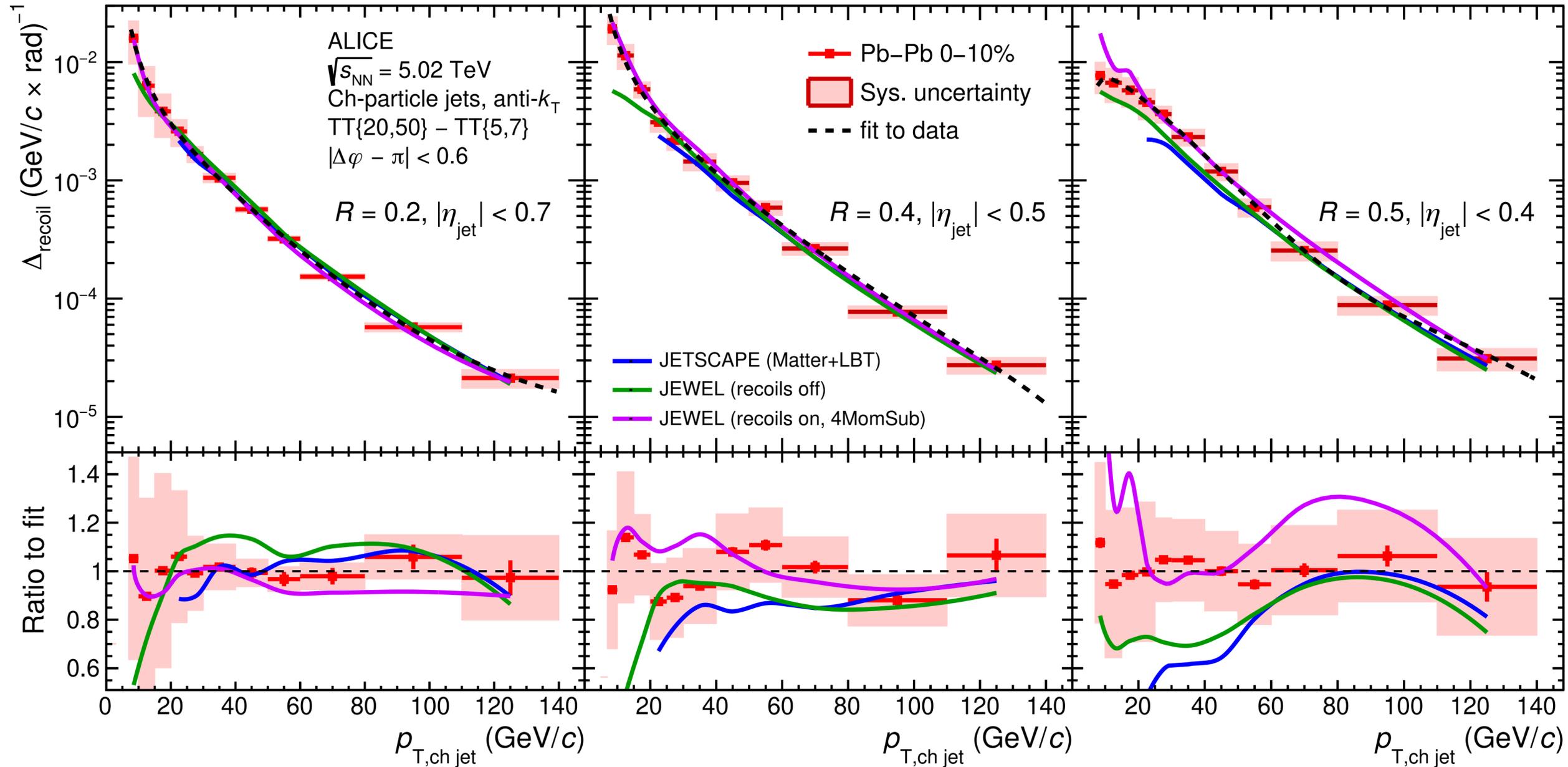


ALI-PUB-555799

$\Delta_{\text{recoil}}(p_{T,\text{ch jet}})$ in Pb–Pb collisions

arXiv:2308.16131
arXiv:2308.16128

New paper

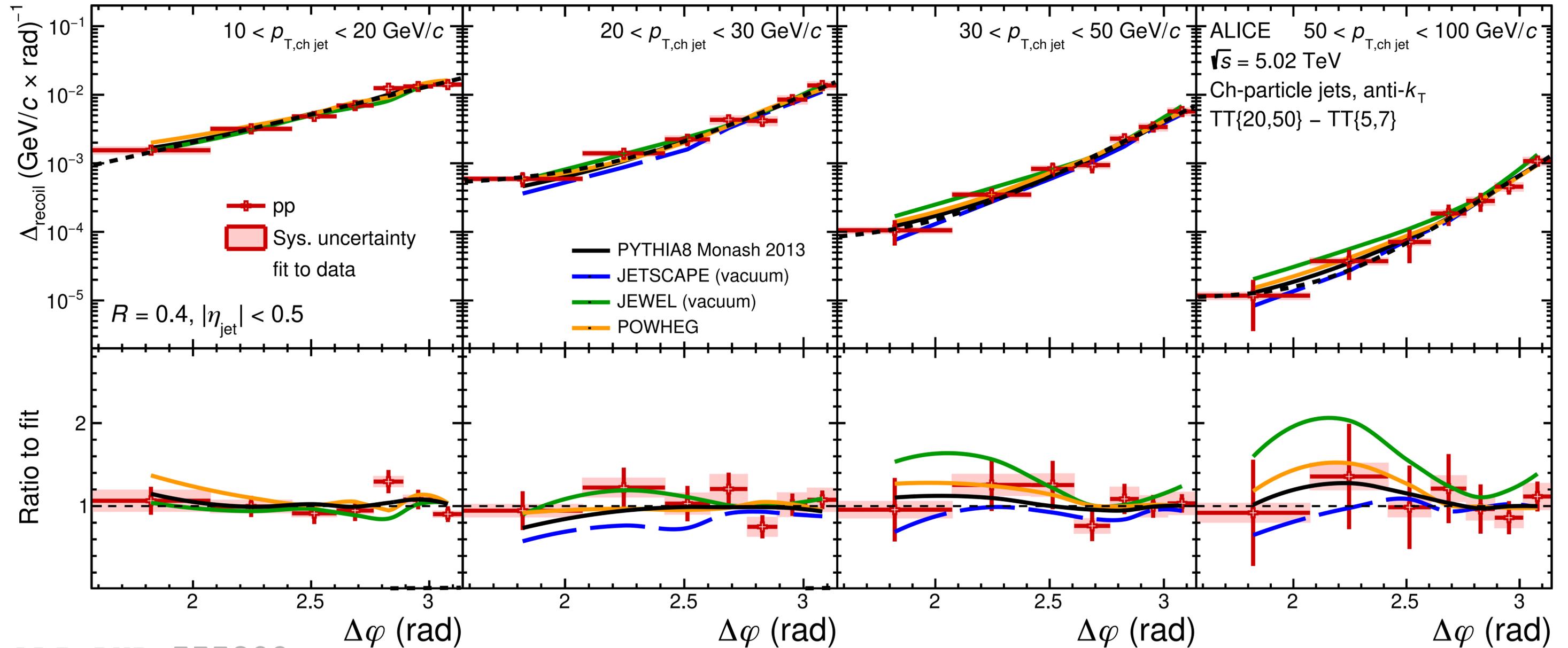


ALI-PUB-555819

Jet acoplanarity: pp collisions (R=0.4)

arXiv:2308.16131
arXiv:2308.16128

New paper



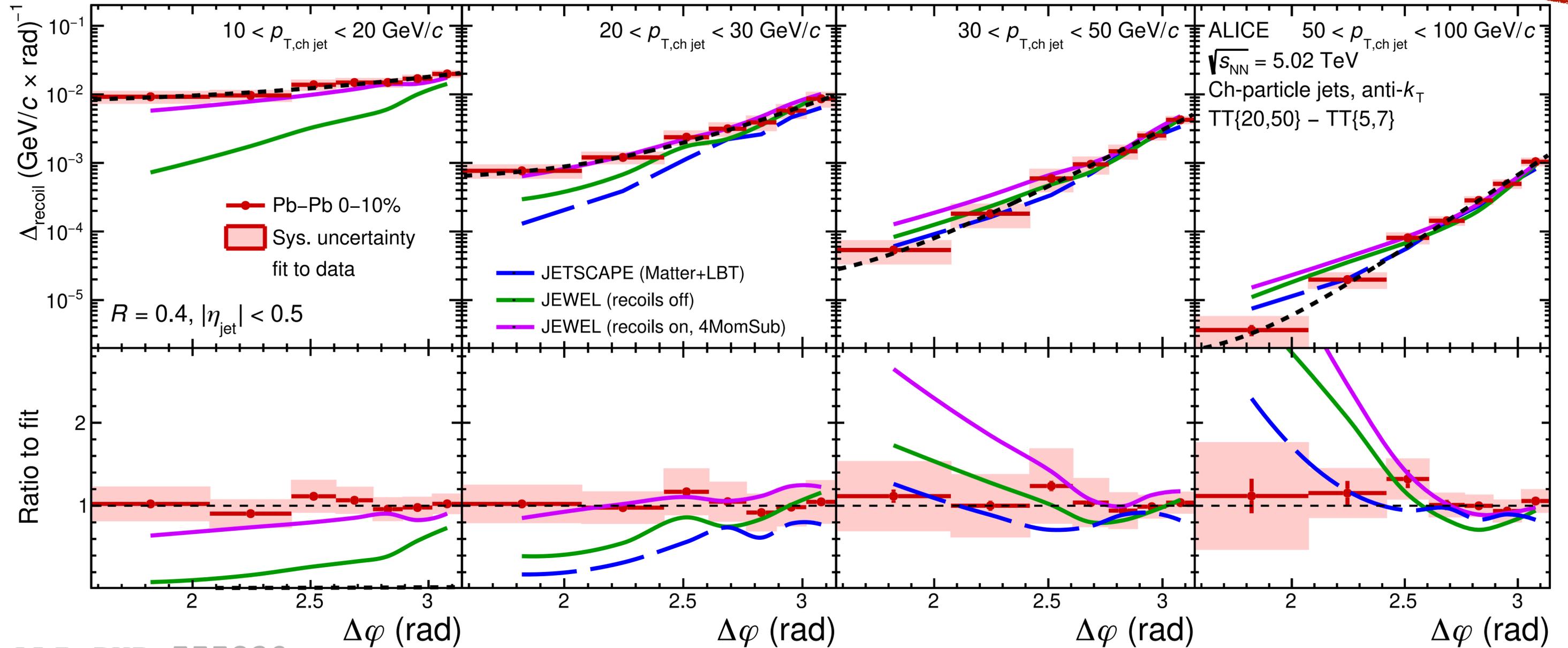
ALI-PUB-555809

- Theoretical predictions yield good description of pp $\Delta\varphi$ distributions for $10 < p_{T, \text{ch jet}} < 100 \text{ GeV/c}$

Jet acoplanarity: Pb-Pb collisions (R=0.4)

arXiv:2308.16131
arXiv:2308.16128

New paper

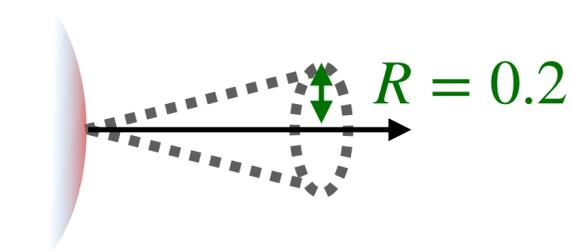


ALI-PUB-555829

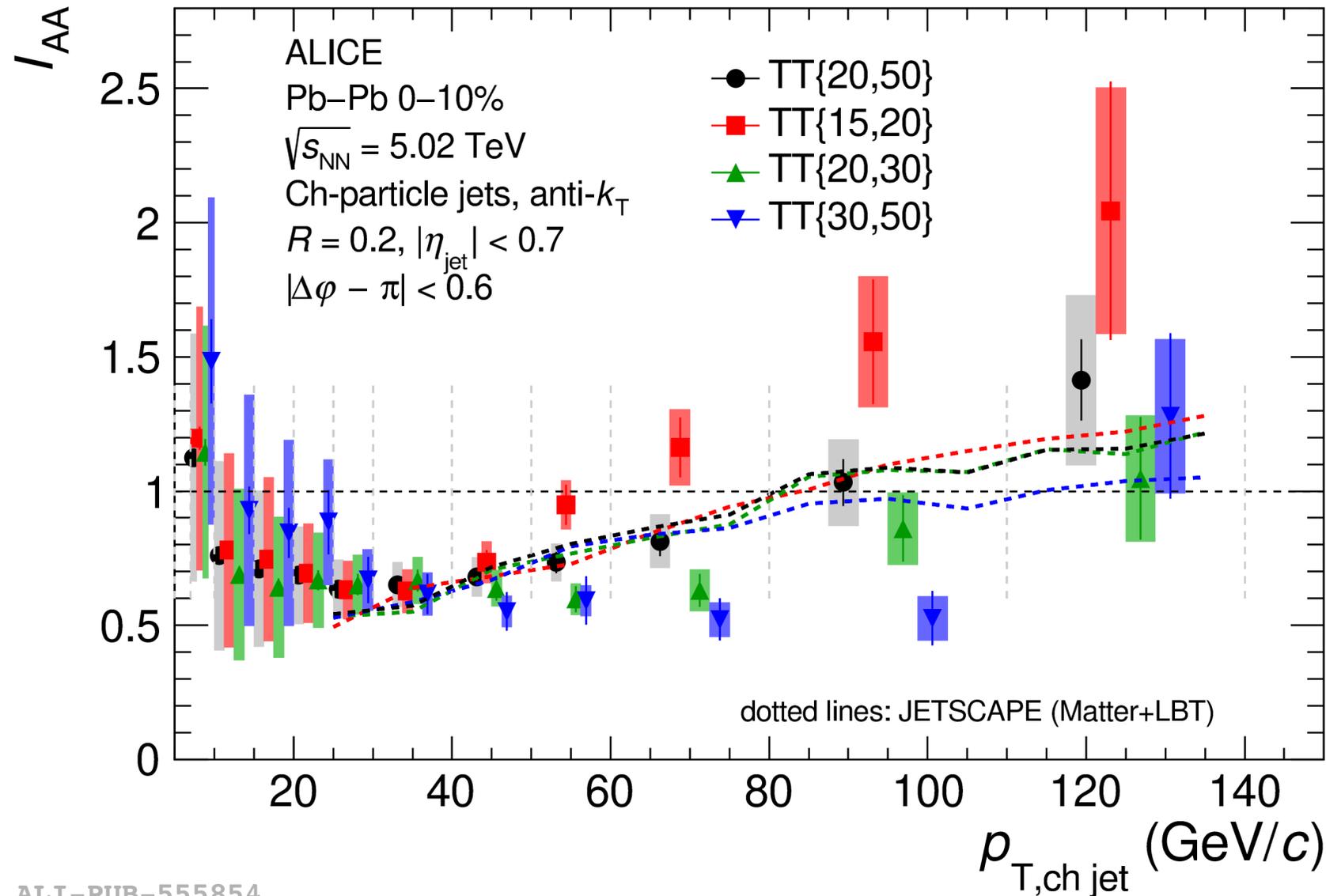
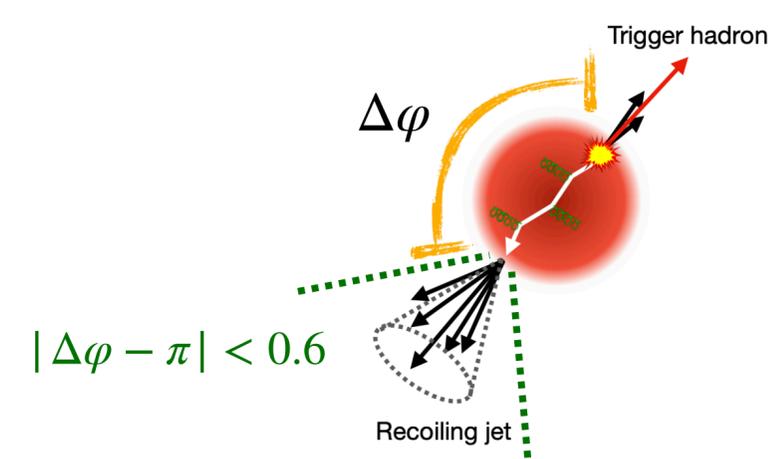
- JEWEL (recoils on) provides best low- $p_{T, \text{ch jet}}$ description of data, though over predicts high- $p_{T, \text{ch jet}}$ tails of distribution
- JETSCAPE provides best high- $p_{T, \text{ch jet}}$ description of data

Maybe simplify text

$I_{AA}(p_{T, \text{ch jet}})$ - recoil jet yield modification in Pb-Pb collisions



$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

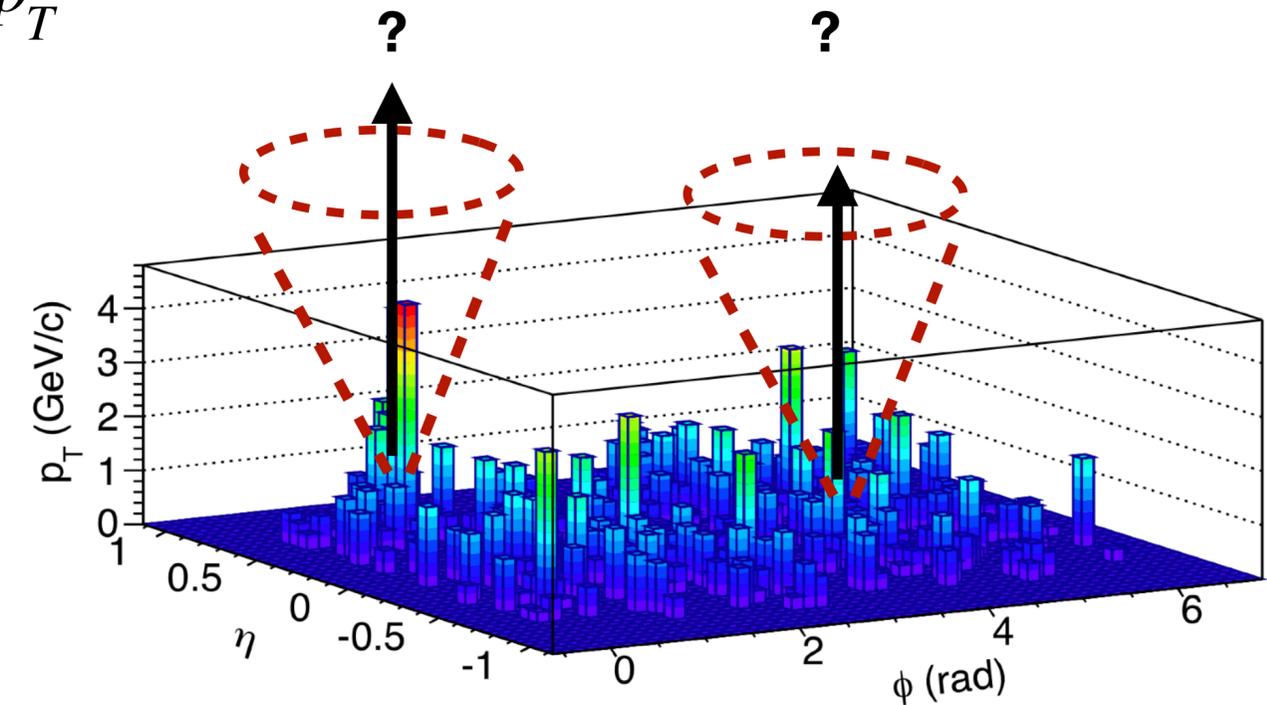


- Expected that high p_{T} hadrons leading fragment of jet originating from QGP surface ('surface bias')
- $p_{\text{T}}^{\text{jet}} \sim p_{\text{T}}^{\text{trig}}$: suppression - surface bias picture holds
- $p_{\text{T}}^{\text{jet}} \gg p_{\text{T}}^{\text{trig}}$: trigger hadron may not be leading fragment or from higher order process - interplay between jet and hadron suppression can lead to enhanced I_{AA}
- New insight into interplay between hadron and jet suppression

ALI-PUB-555854

Dealing with background in heavy-ion collisions

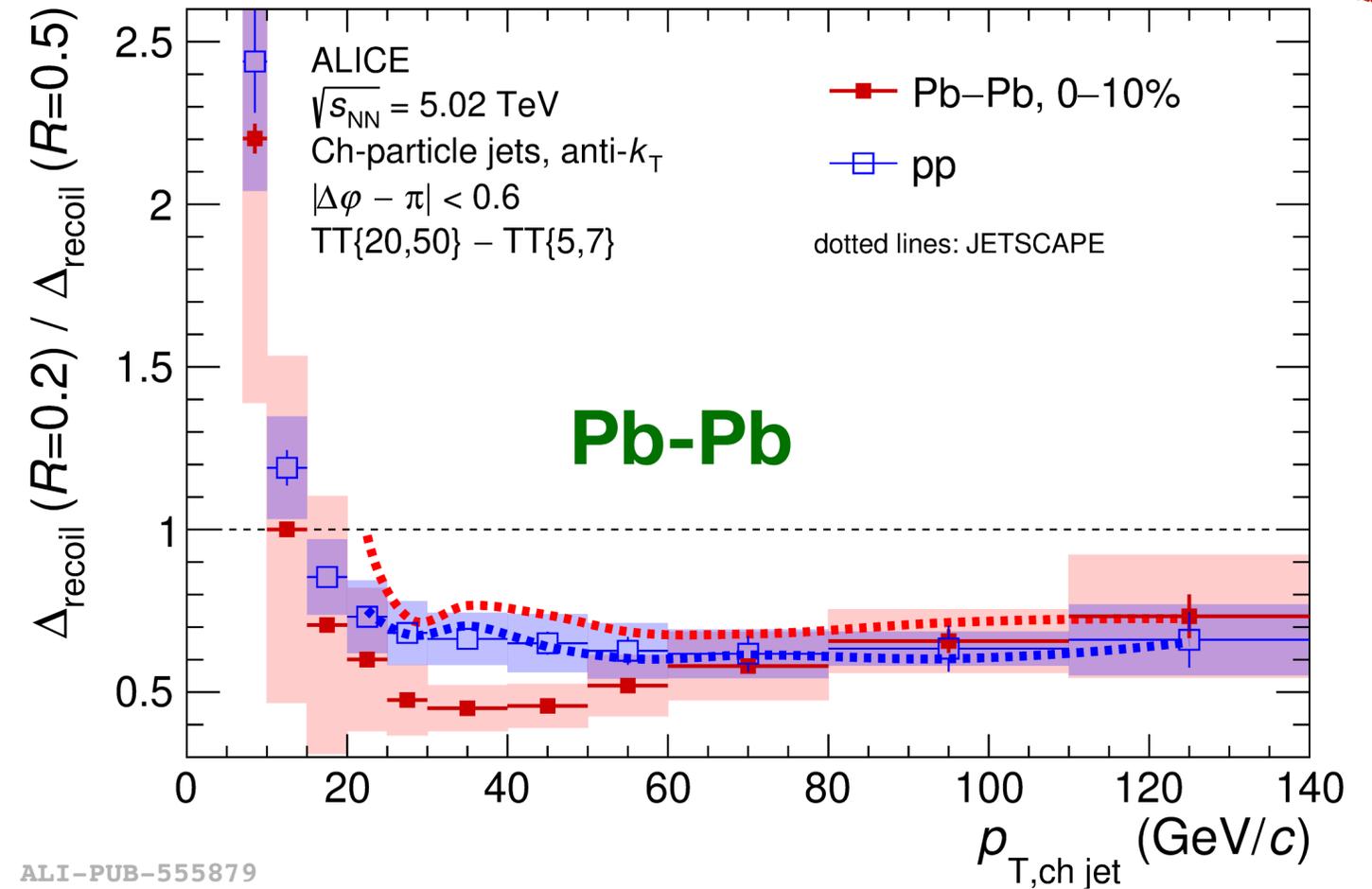
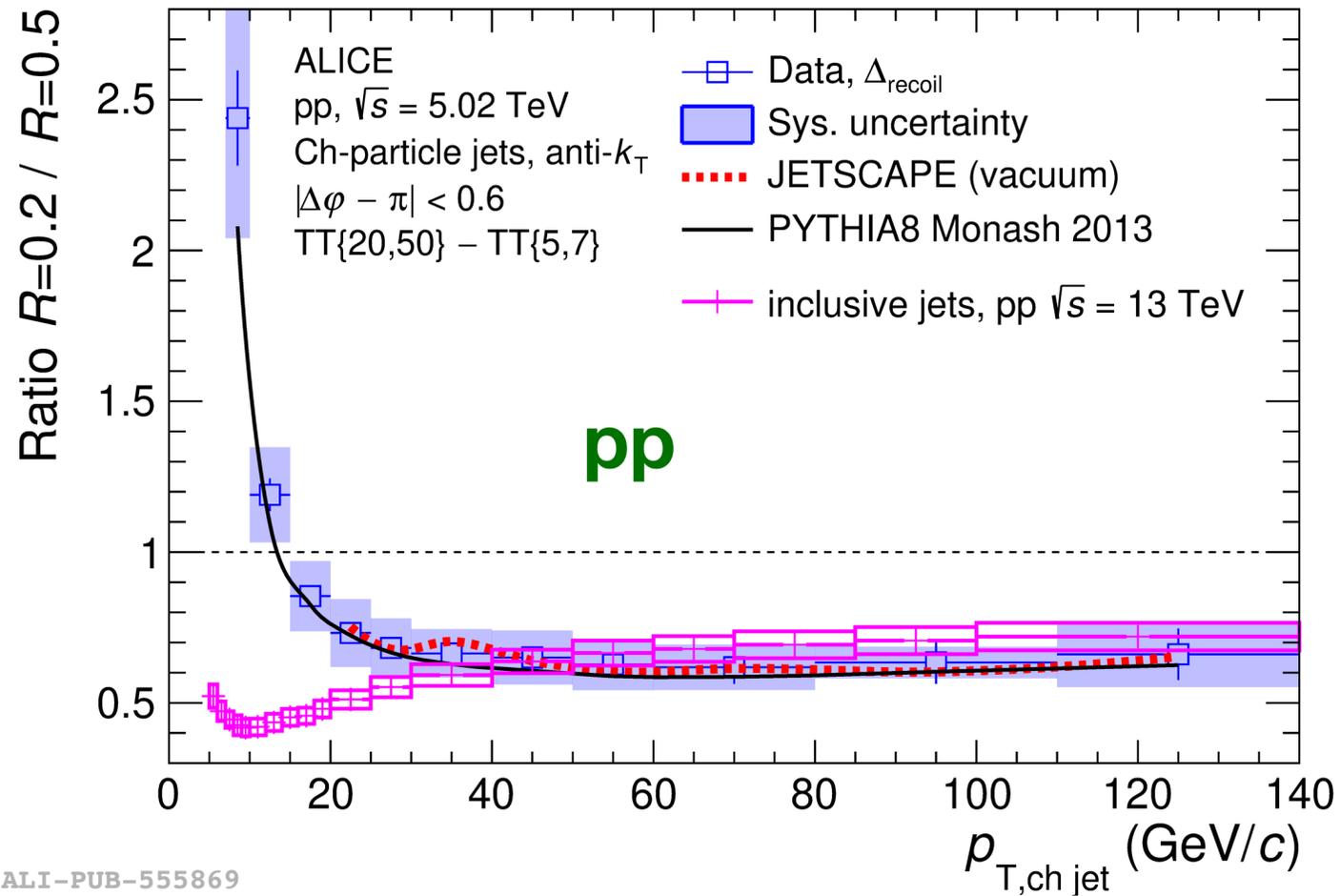
- Combinatorial background a major challenge for jet measurements in heavy ion collisions - what is a 'true' jet from a hard scattering and what is from uncorrelated sources?
- **Especially important for low p_T measurements** where $p_T^{jet} \sim p_T^{bkg}$
- Techniques developed to deal with combinatorial background



Studying intra-jet broadening through R-ratios

arXiv:2308.16131
arXiv:2308.16128

New paper



- R=0.2 / R=0.5 ratio deviates from inclusive jet ratio for $p_{T, \text{ch jet}} < p_T^{\text{trig}}$
- Suppressed LO processes - preference for more, small R jets w.r.t. large R jets to be reconstructed?

- Hints that R=0.2 jets suppressed more than R=0.5 jets in Pb-Pb w.r.t pp in 30-60 GeV/c
- Energy recovery for wider jets?