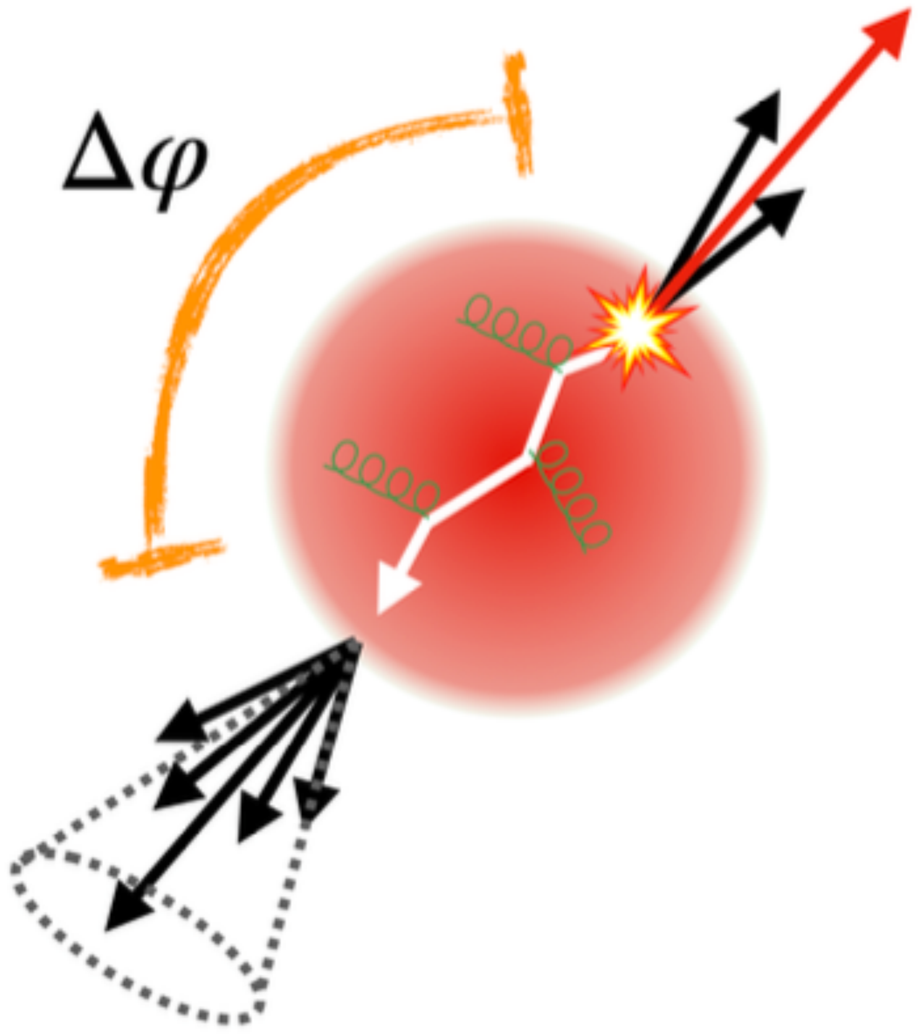
Study of jet energy redistribution and broadening effect via h-jet correlations with ALICE



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29 September 2024

PRL 133 (2024) 022301, PRC 110 (2024) 014906, JHEP 05 (2024) 229

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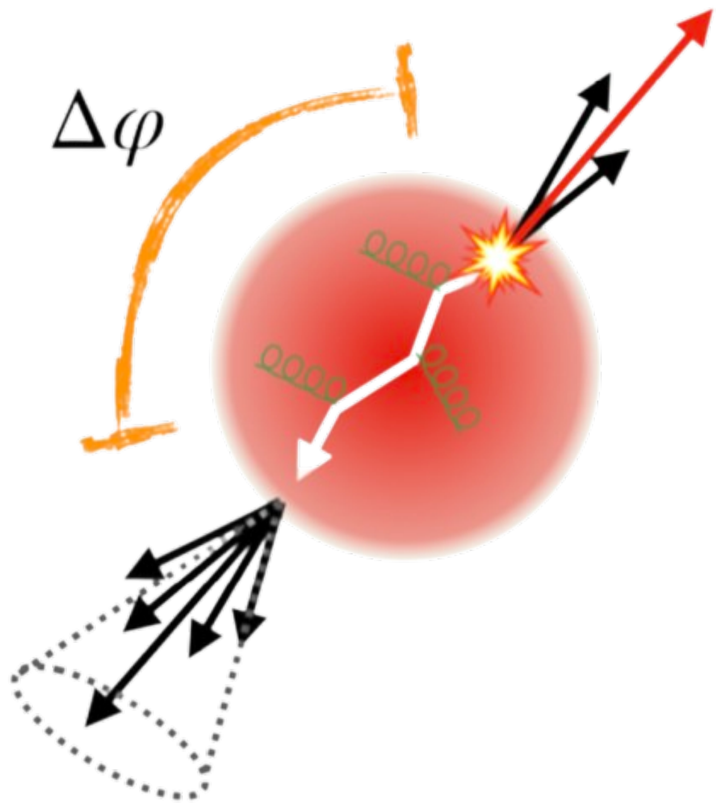
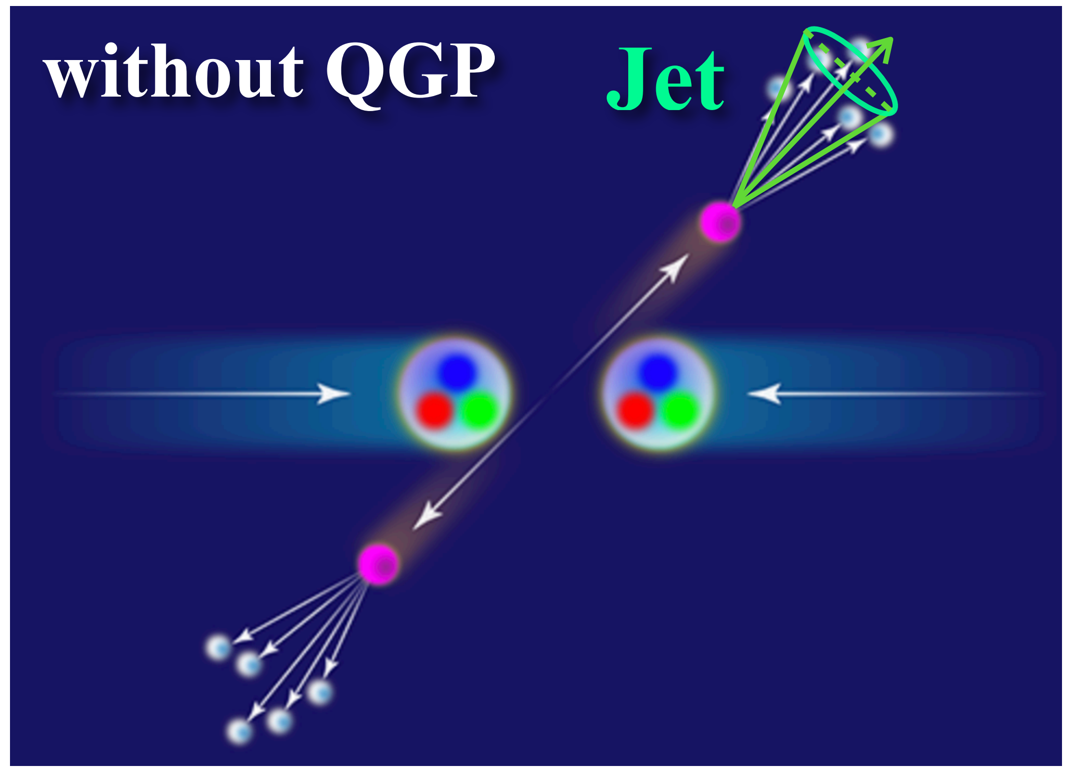
- **Hadron-jet correlations in pp collisions at 13.6 TeV (Run 3, New preliminary)** New
- **Hadron-jet correlations in high multiplicity pp collisions at 13 TeV (Run 2)**

  JHEP 05 (2024) 229
- **Hadron-jet correlations in pp and central Pb–Pb collisions at 5.02 TeV (Run 2)**

  PRL 133 (2024) 022301, PRC 110 (2024) 014906



Jets are defined as collimated sprays of particles originating from initial hard scattered partons



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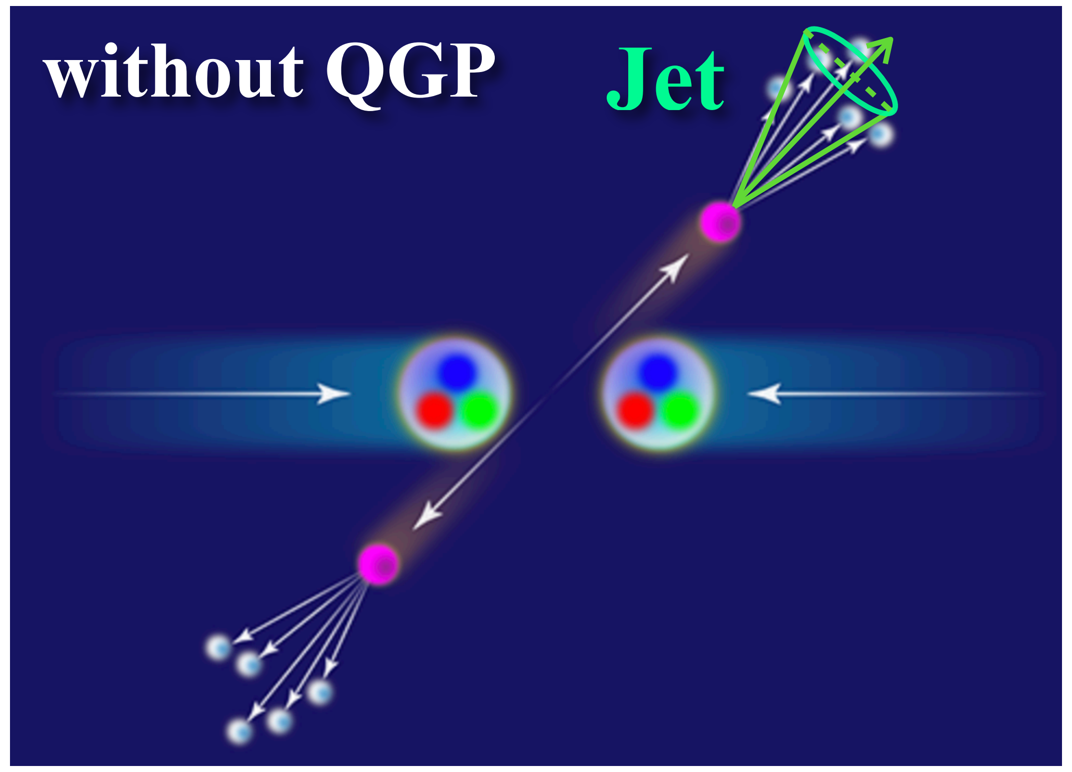

Jets in pp collisions → study the strong force

- Well described by pQCD calculations
- Investigate the parton splitting functions in vacuum
- Serves as a reference for jet measurements in heavy-ion collisions to study jet quenching
- Searching for **QGP droplet formation** in small collision systems

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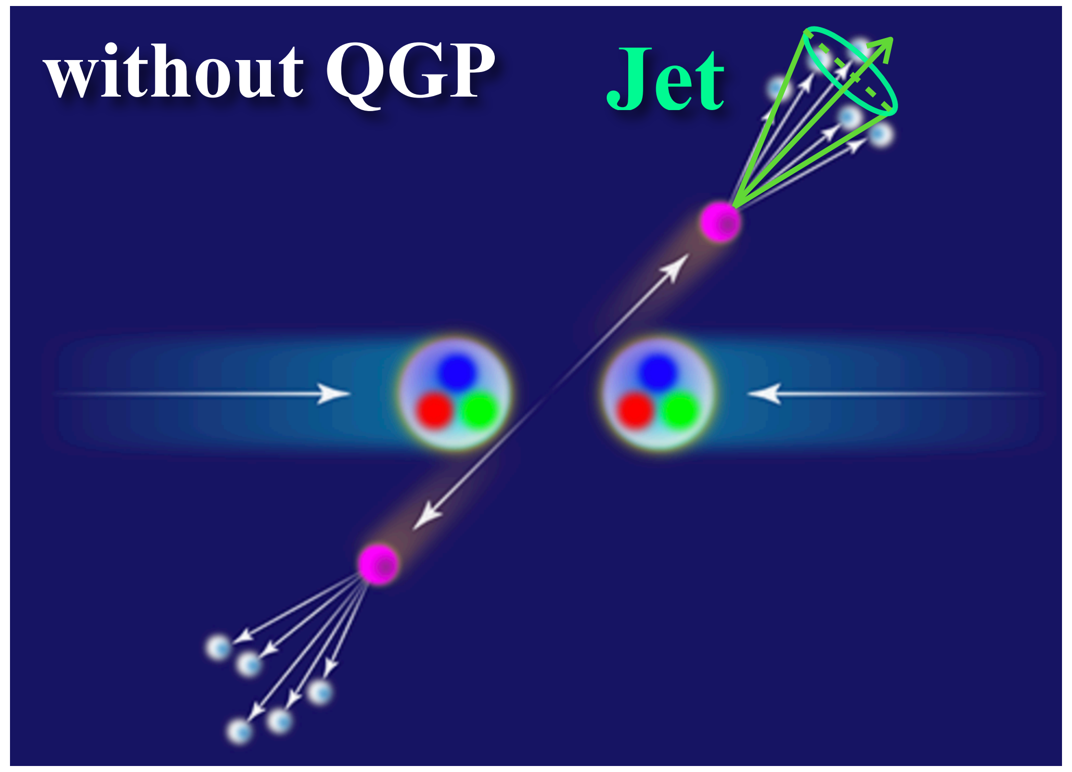

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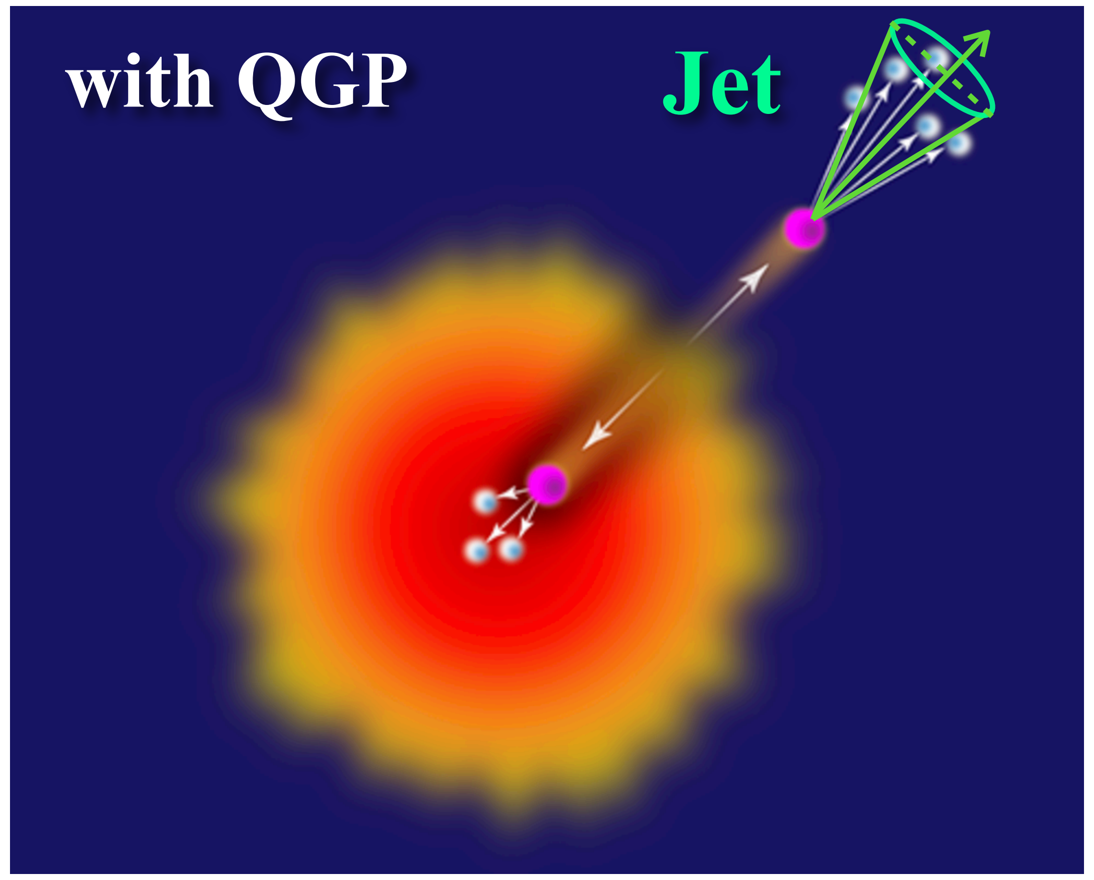
Jets in heavy-ion collisions → study the transport properties of the QGP

- Partons **interact with QGP** and lose energy through medium-induced gluon radiations (inelastic) and collisions (elastic) with medium constituents
  - $\text{Jet}(E) \rightarrow \text{Jet}(E' - \Delta E) + \text{soft particles}(\Delta E)$



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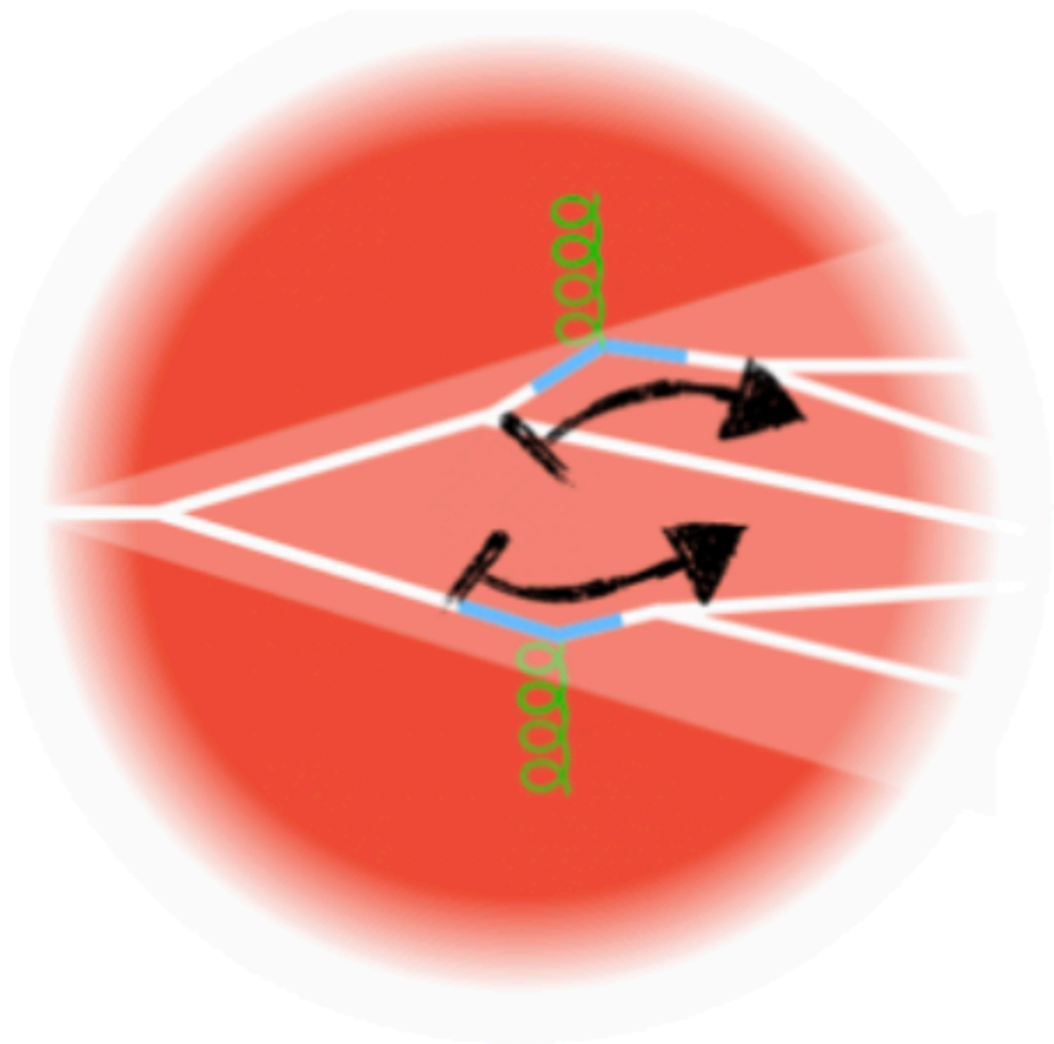
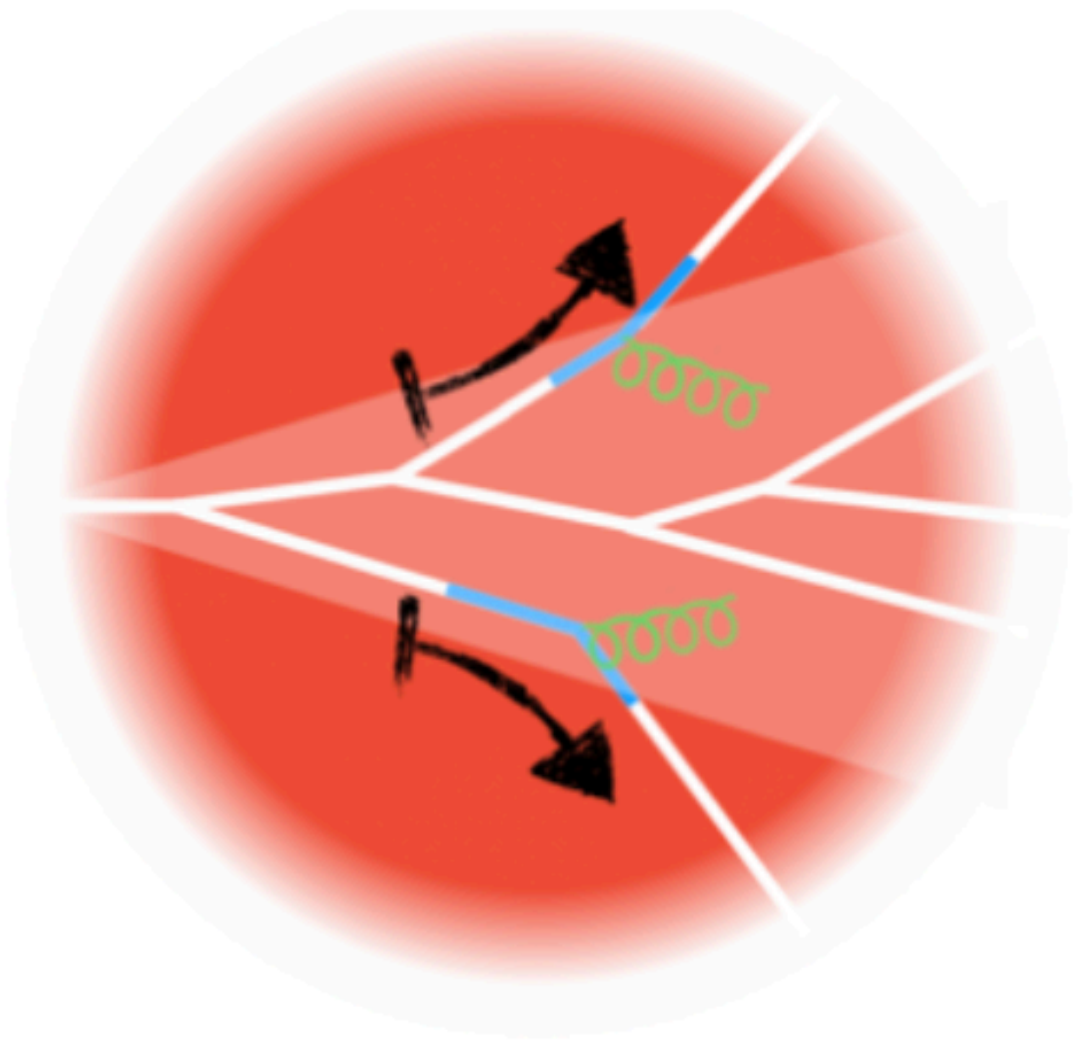
Study structure of QGP by understanding jet modification from medium interaction **(quenching)**

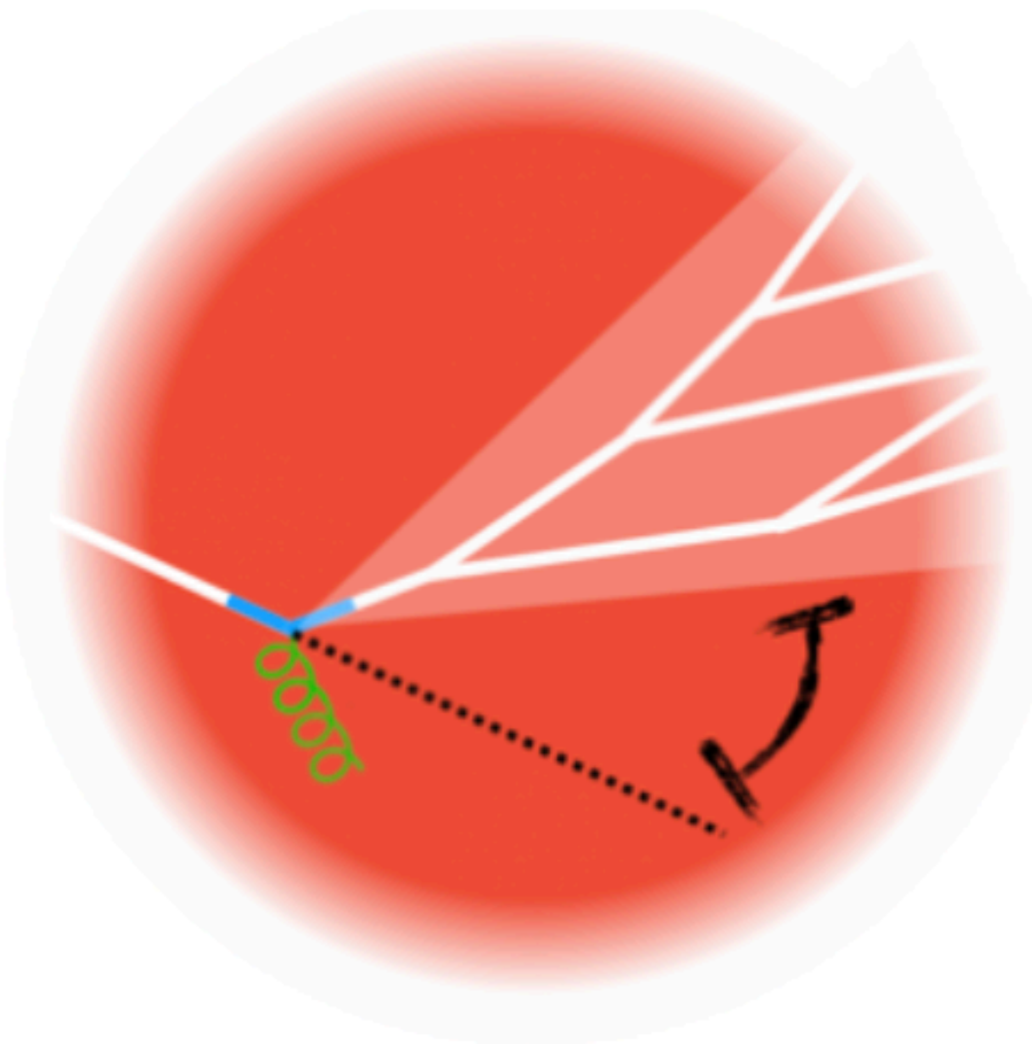
- **Several types of jet observables**
  - Jet reconstruction and declustering → substructure (r_g, θ_g) modification
  - Jet yields and constituents → **jet suppression and energy redistribution** (R_{AA}, I_{AA})
  - Angular correlation → jet deflection ($\Delta\varphi$)



Substructure modification



Energy redistribution



Deflection

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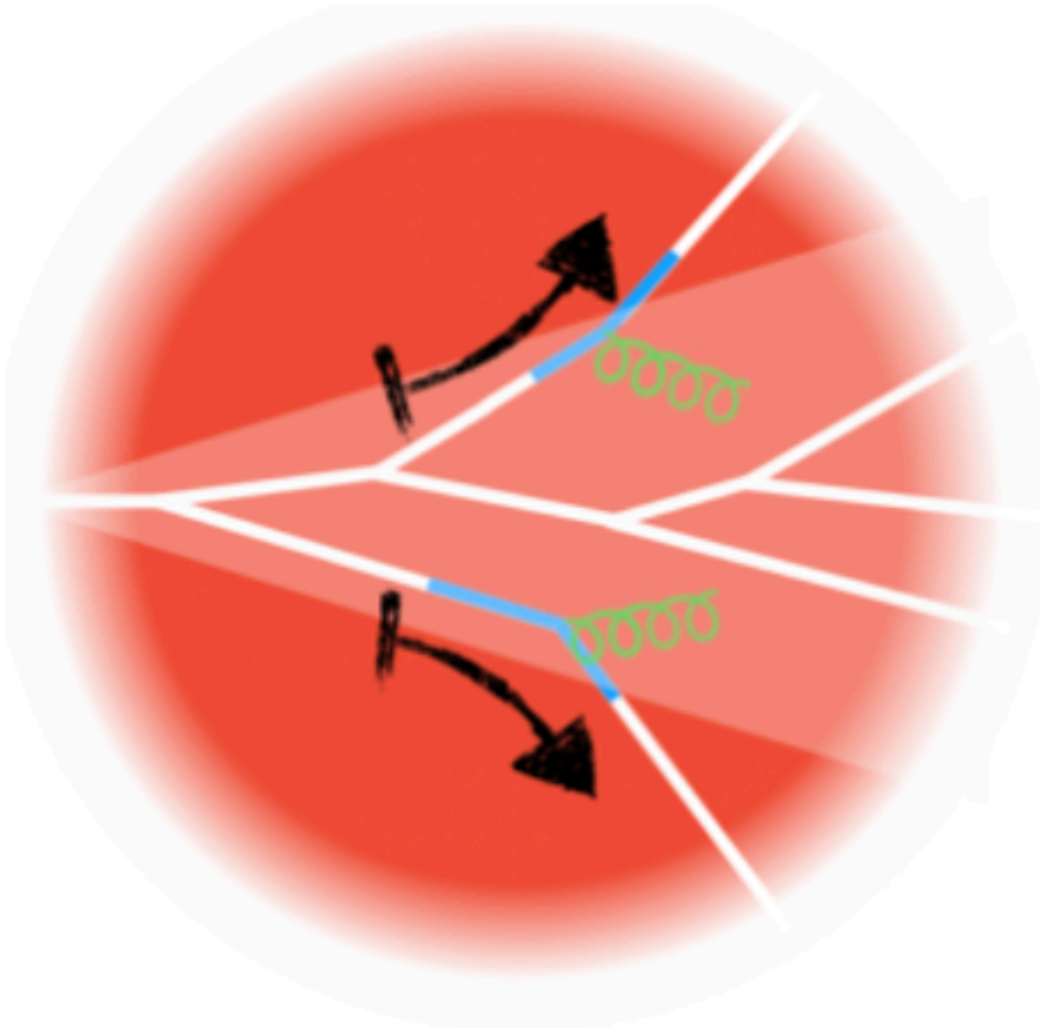


Energy redistribution

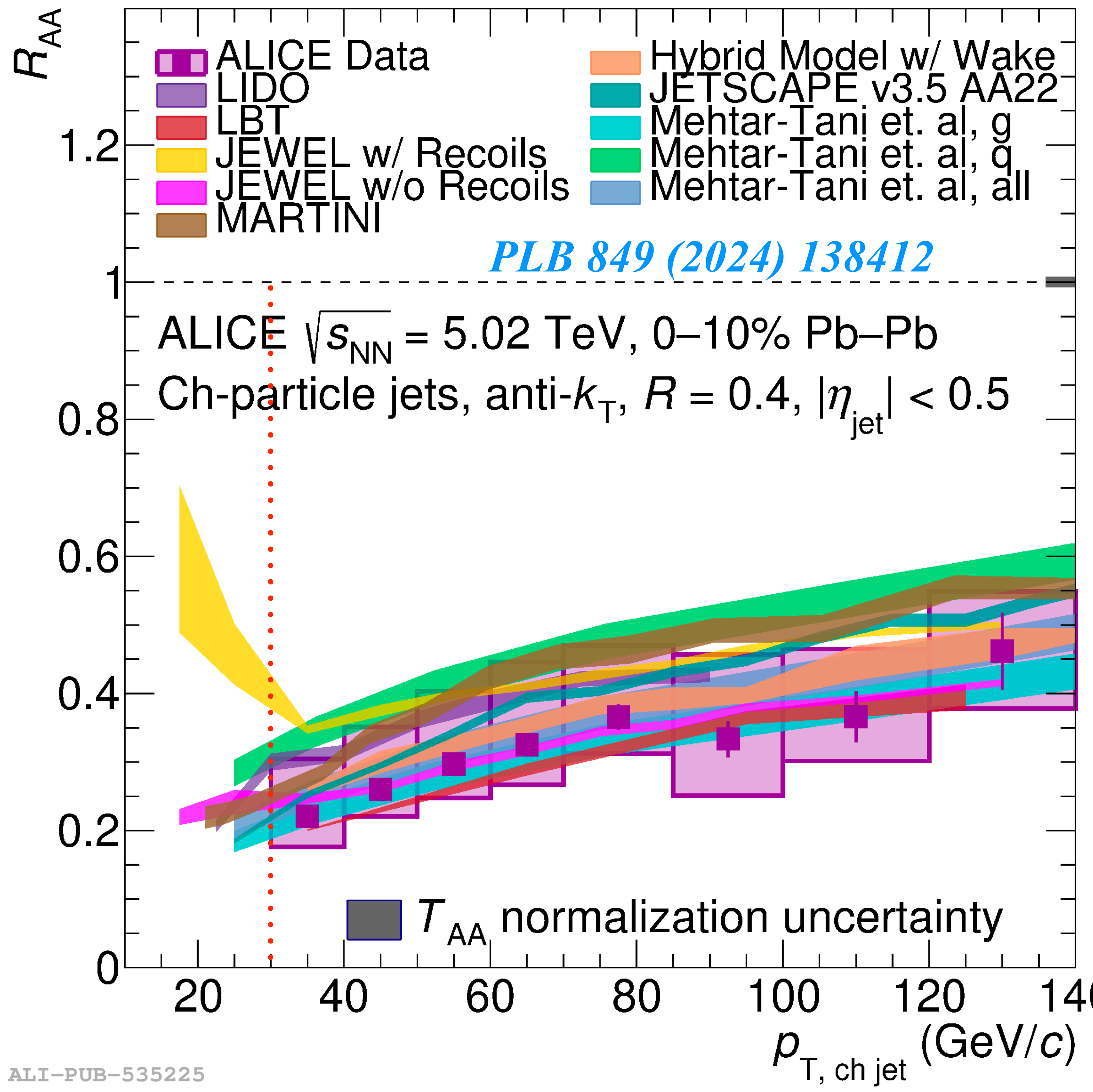
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle\, d\sigma_{pp}/dp_T}$$

QGP medium

QCD vacuum

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

- $p_T > 30$ GeV/c



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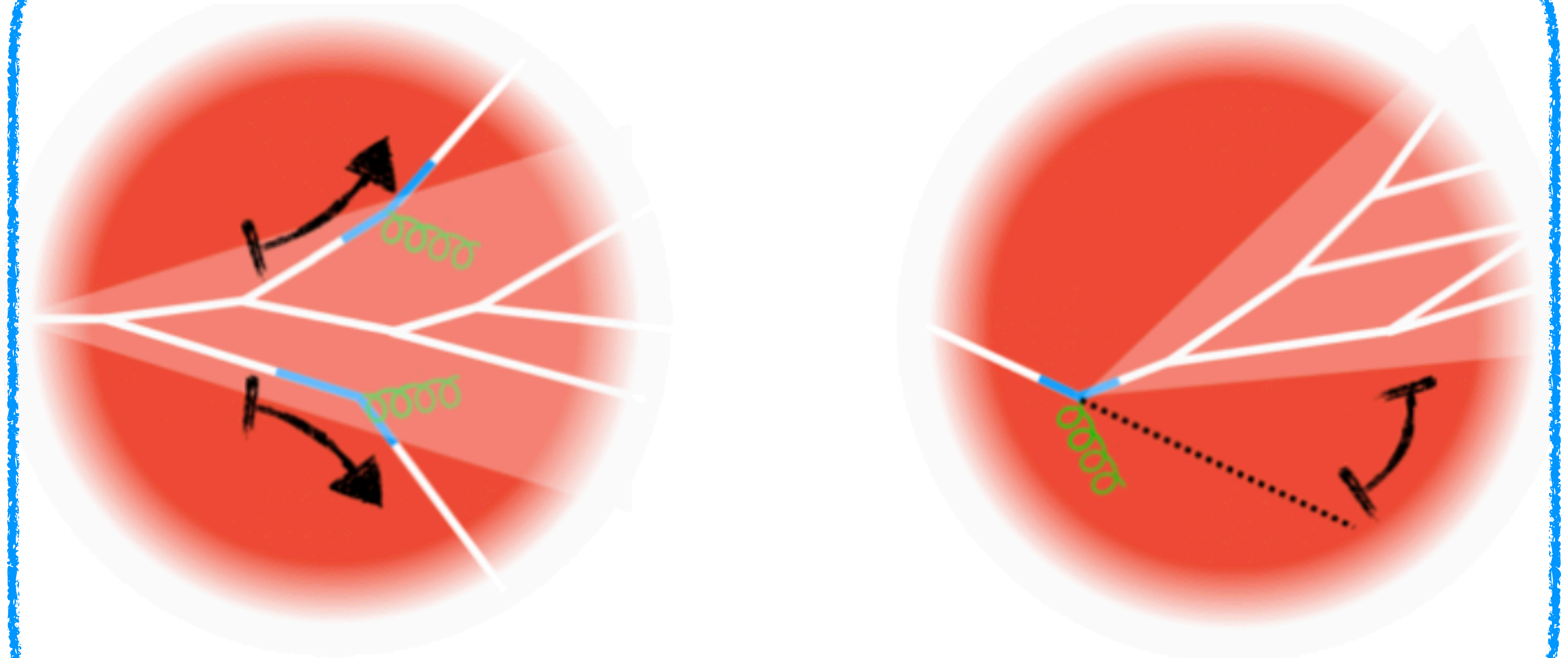
➡**Semi-inclusive measurements** of a jet recoiling from a trigger (e.g. γ-jet , Z-jet, or **hadron-jet**)

Apply statistical, data driven-approach for background yield suppression

hadron-jet correlations



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- Measurements of **semi-inclusive jets recoiling from a trigger hadron** provide a good handle of combinatorial background by varying the trigger track intervals → **access low p_{T}, large R jets**
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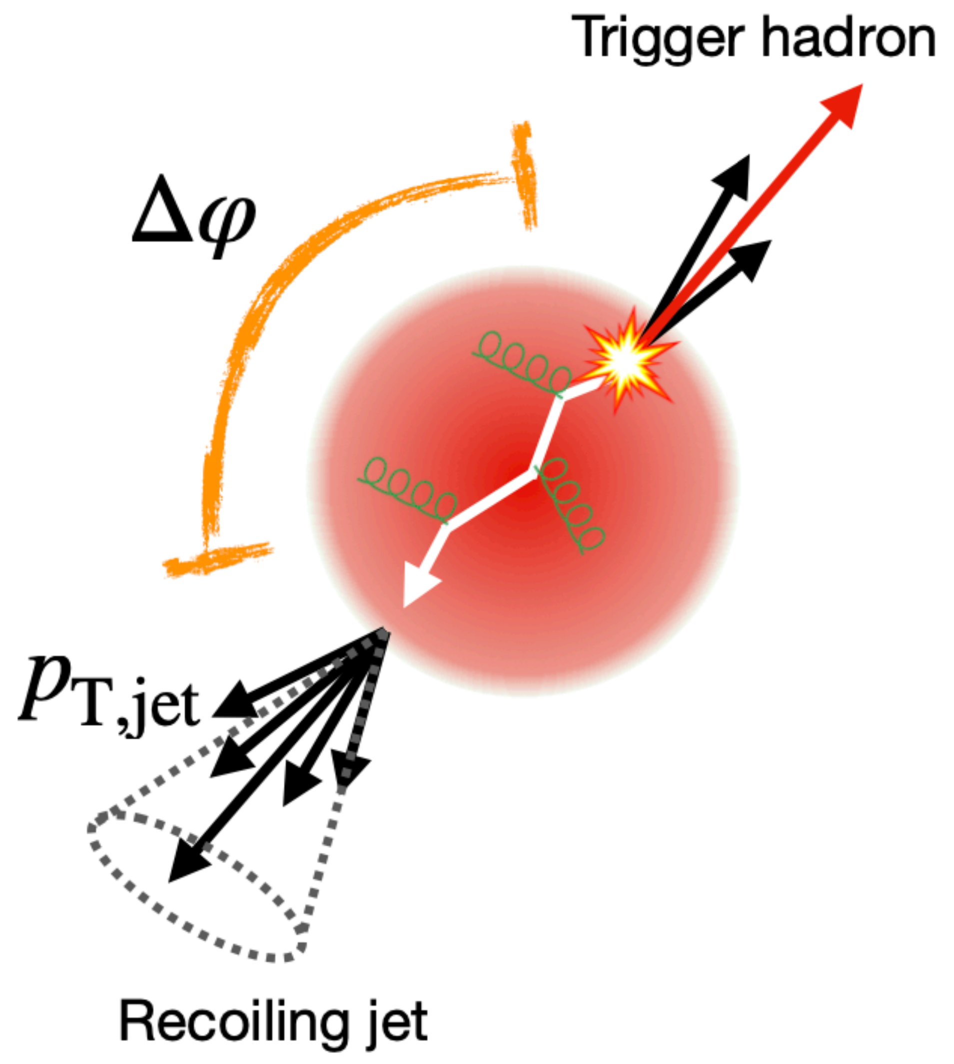

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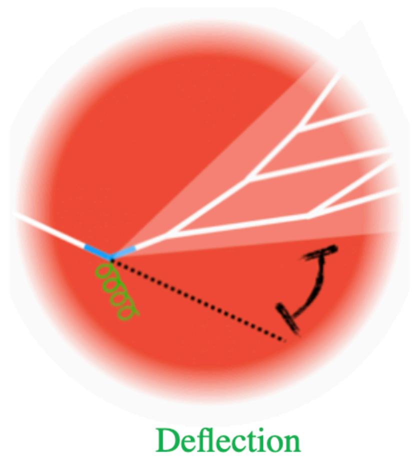

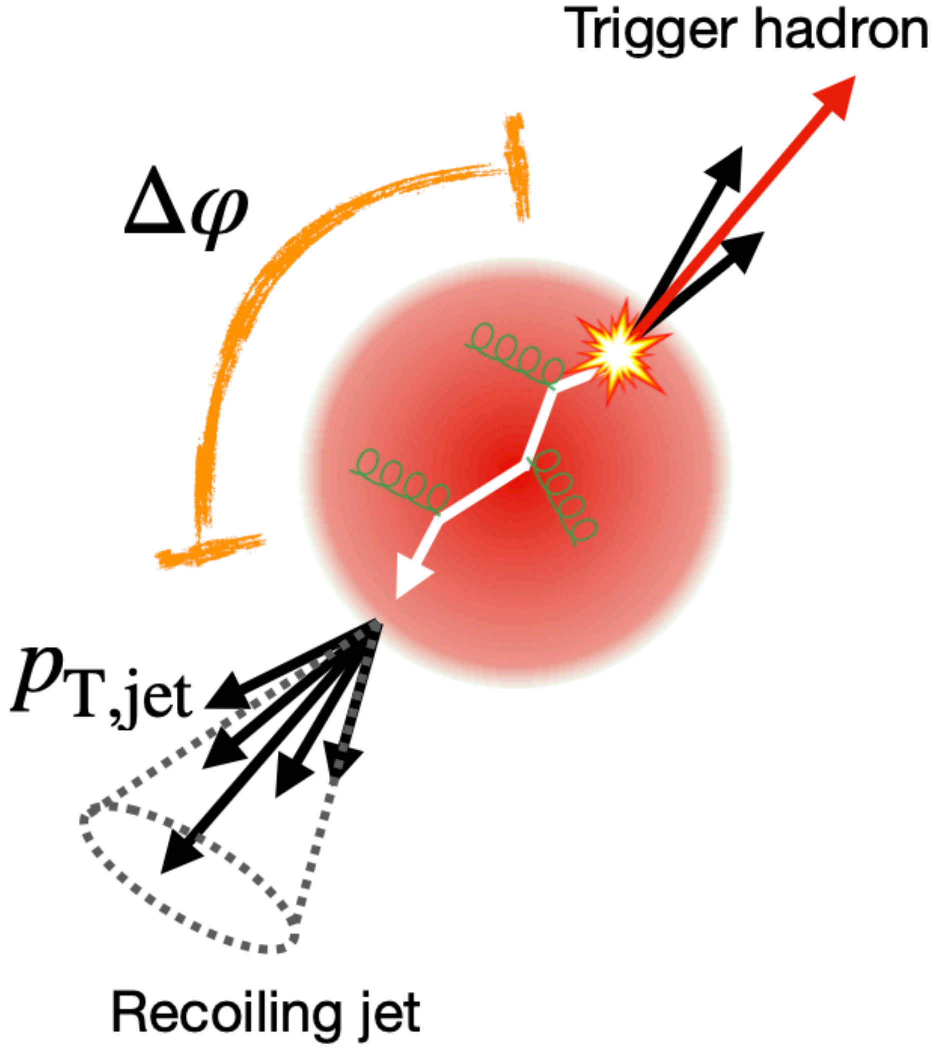

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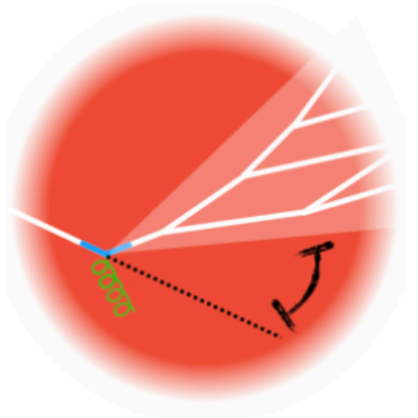

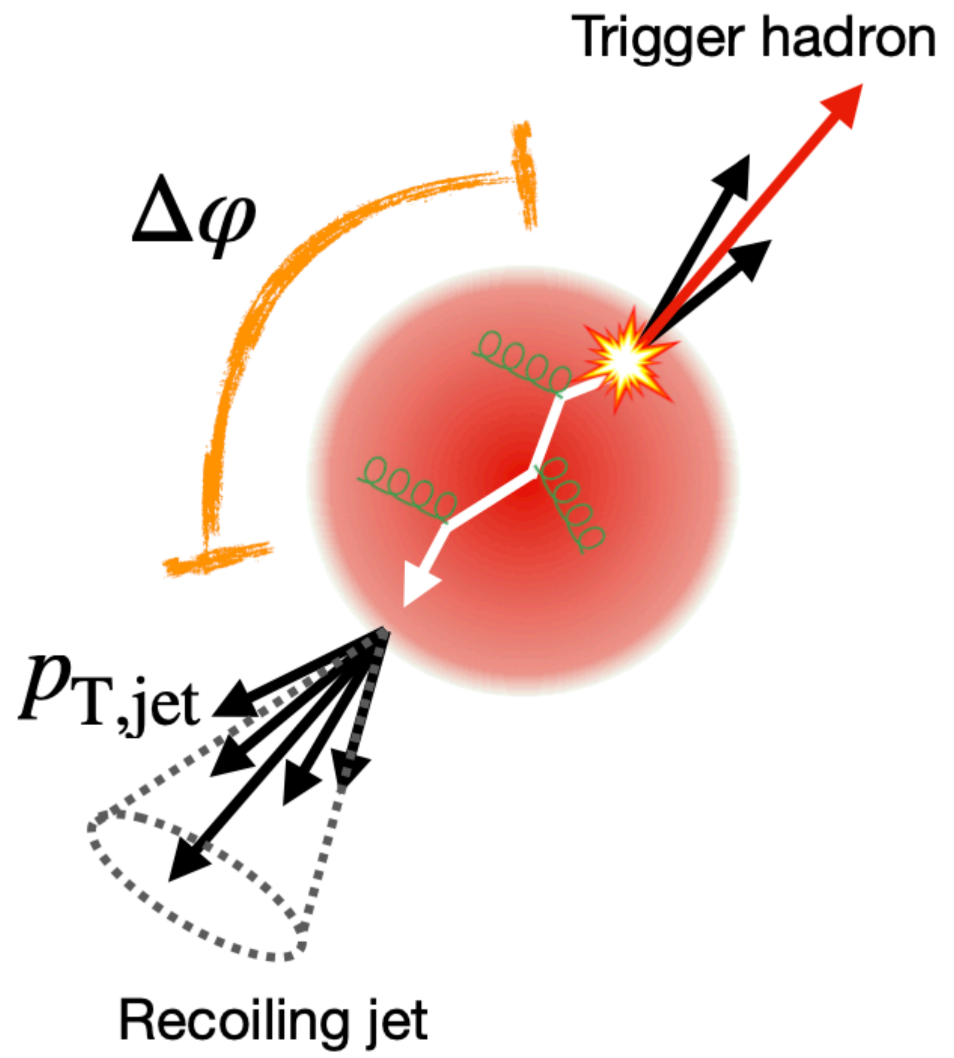

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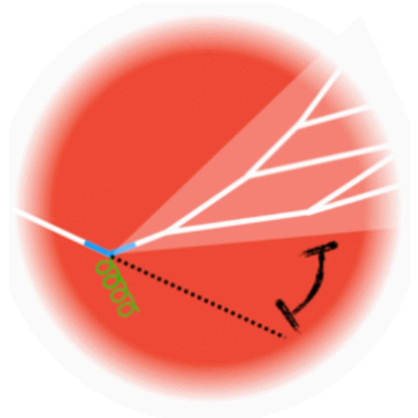

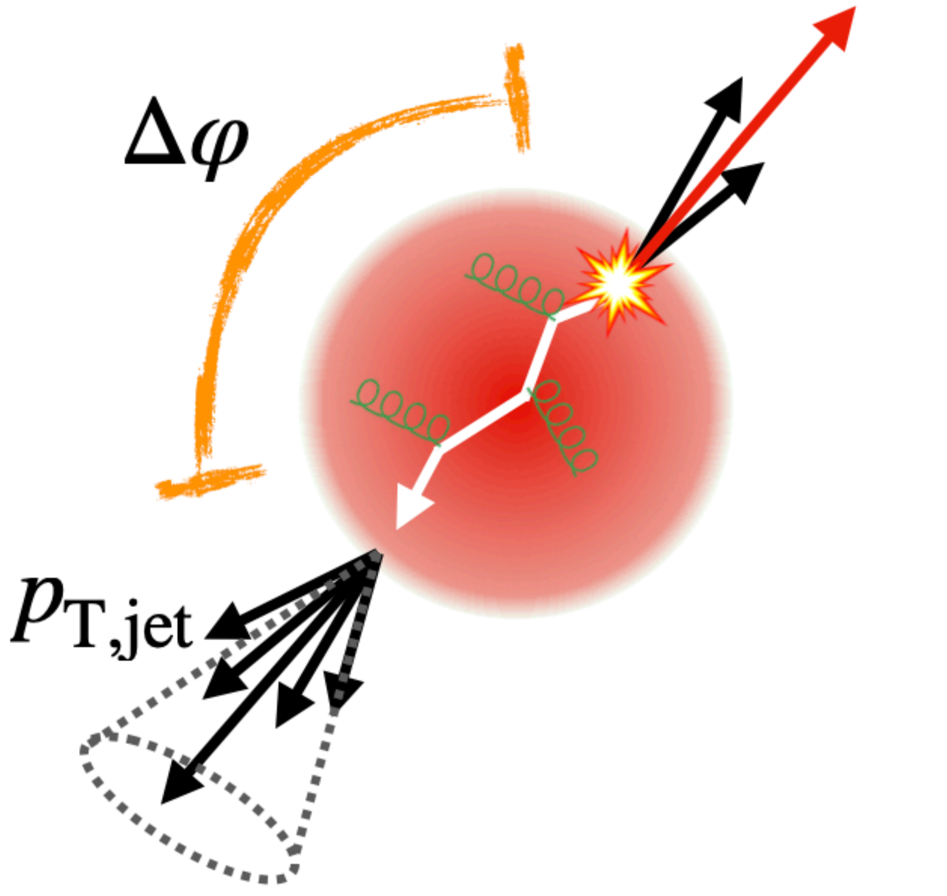

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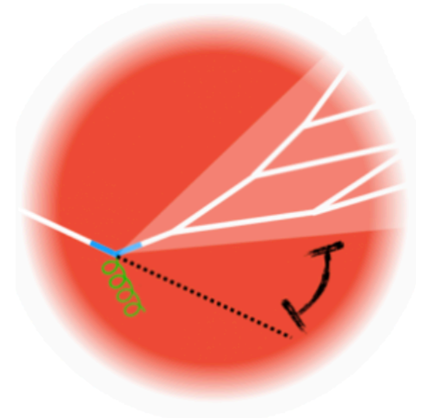
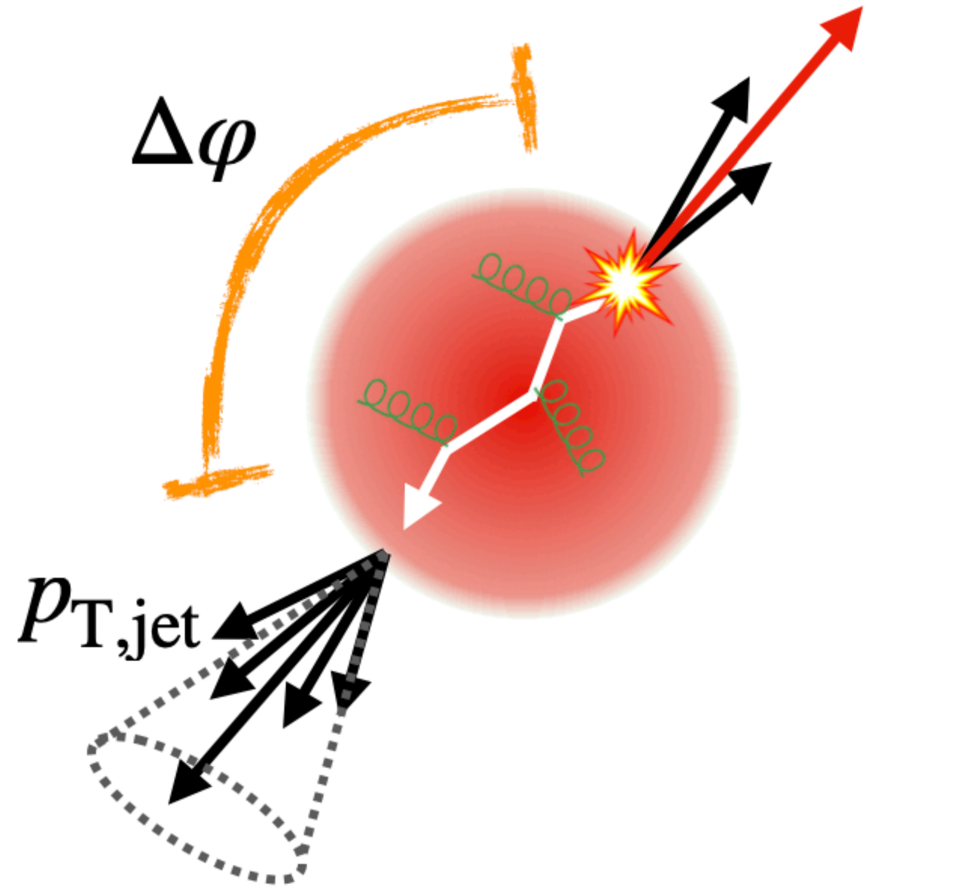
      - Related to transport coefficient $\hat{q} \sim \langle k_{\perp}^{2} \rangle / L \sim \langle \Delta\varphi^{2} \rangle / L$





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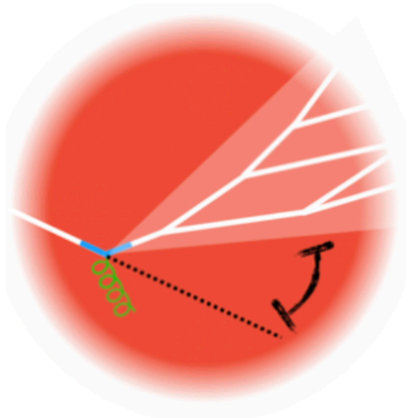
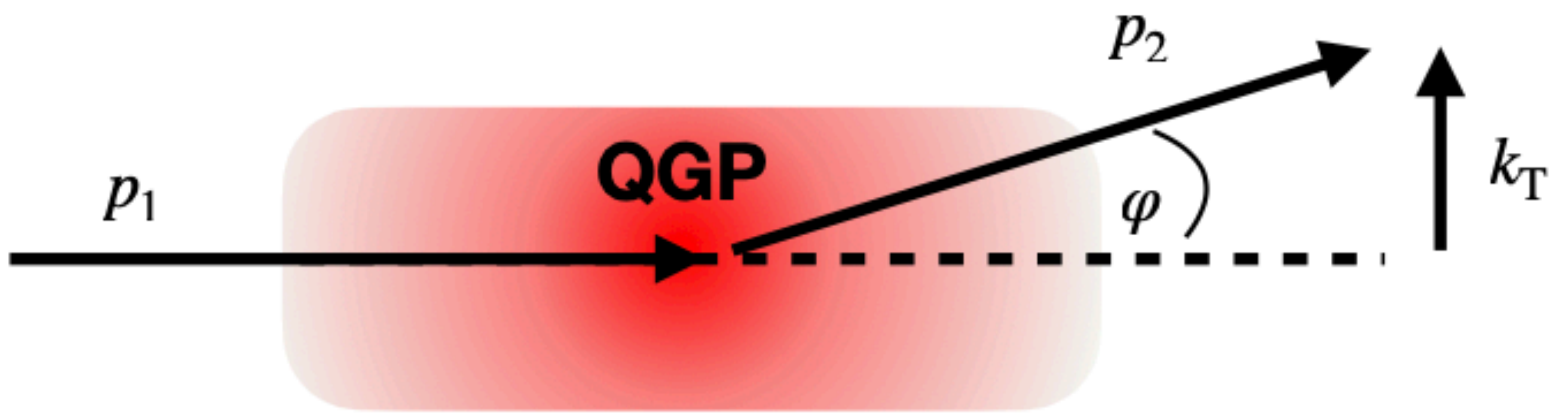
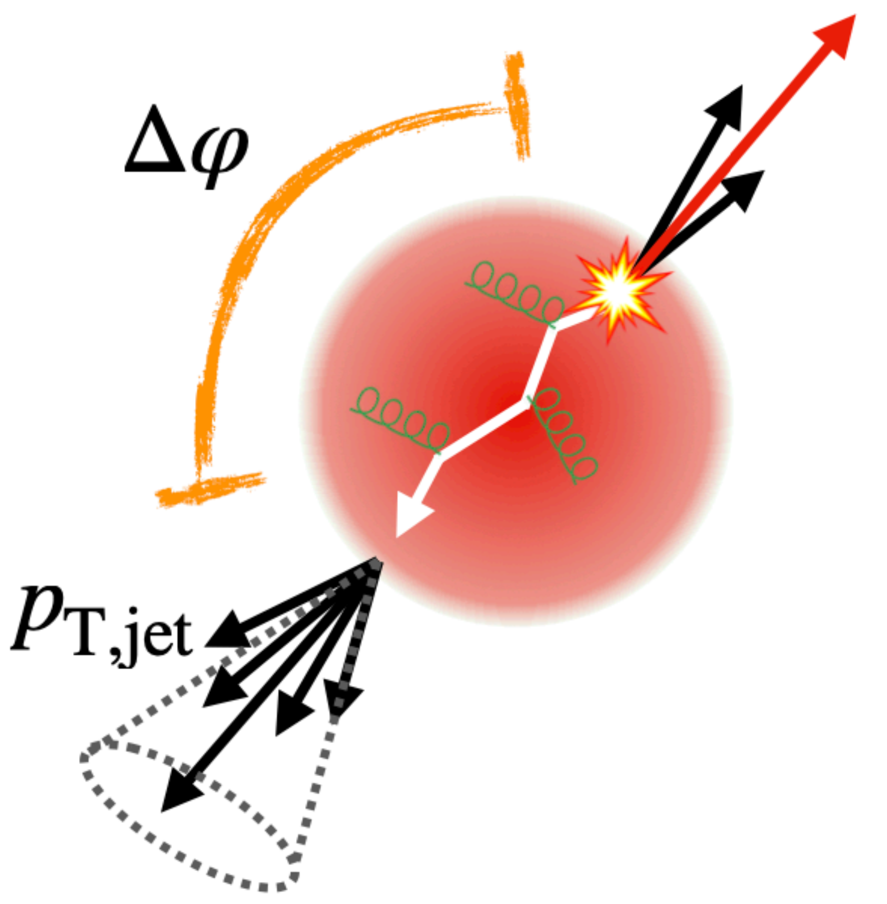
    - **Large-angle deflection** ($\Delta\varphi < \pi$) of hard partons off quasi-particle[3]?







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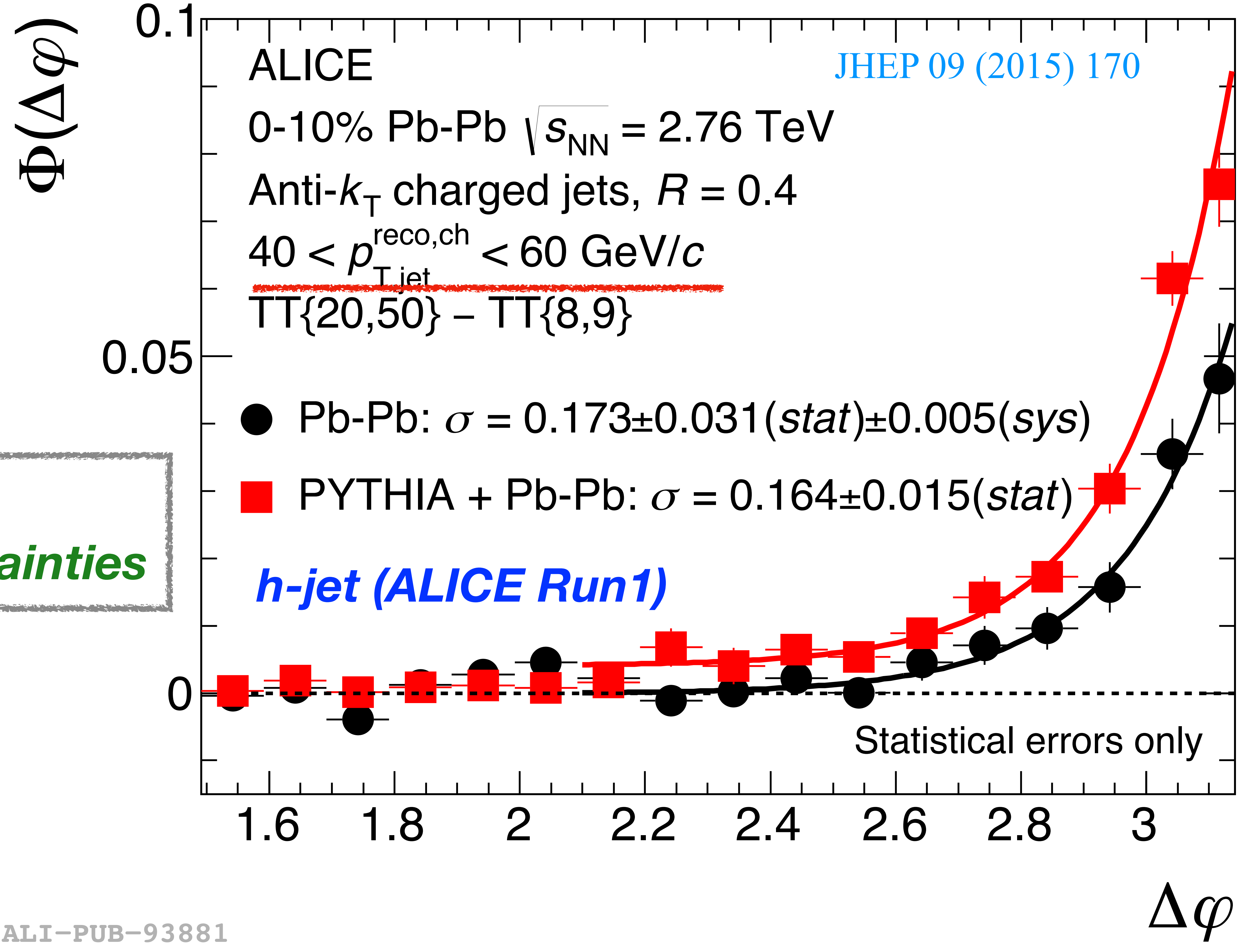
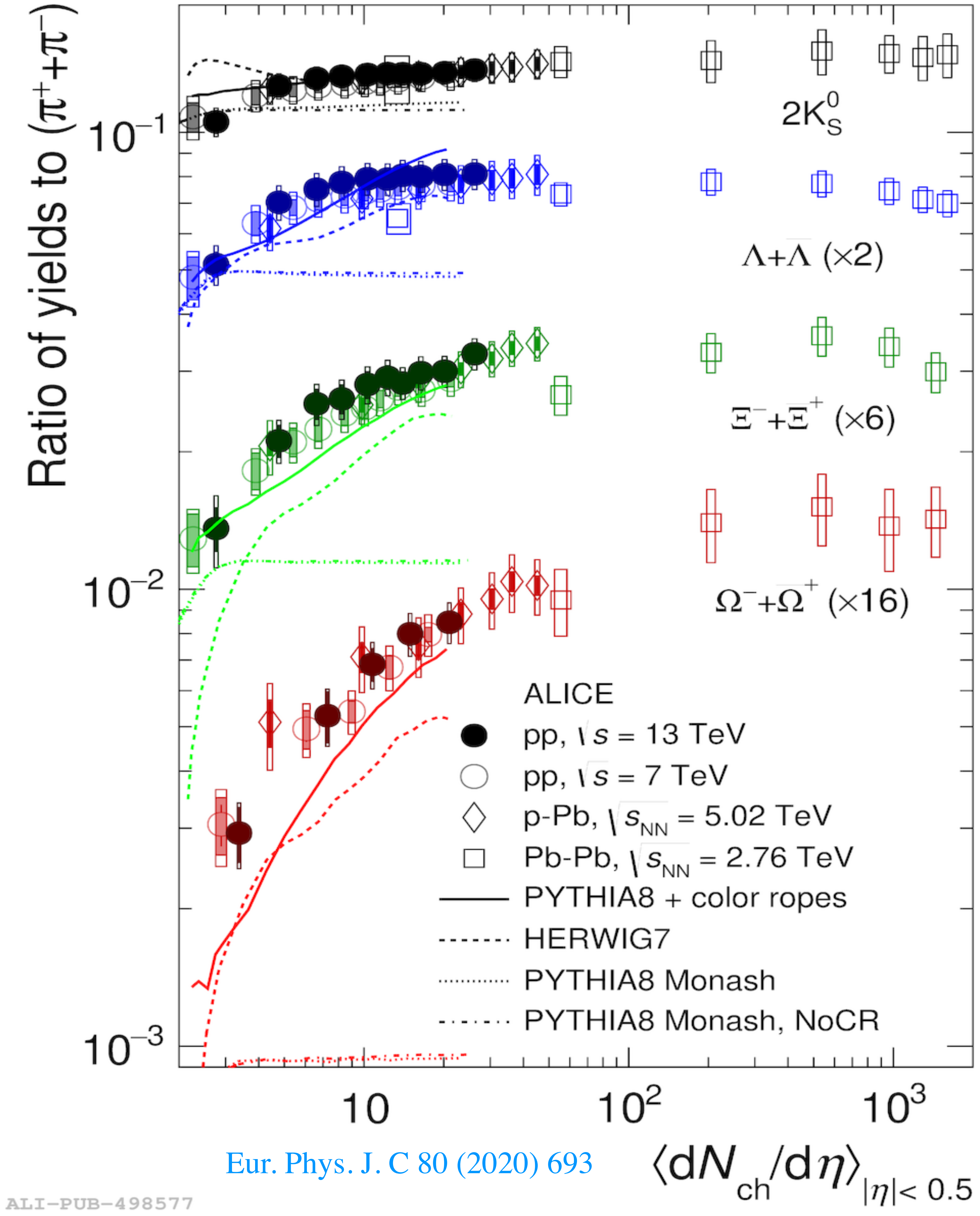
No medium-induced acoplanarity broadening observed within uncertainties

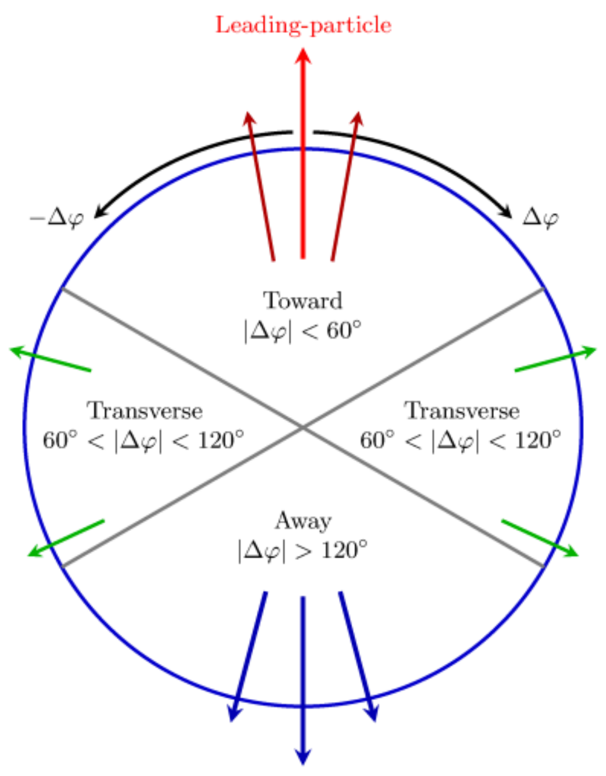


- Effects considered as signatures of QGP formation in heavy-ion collisions are observed in small systems: collectivity, **strangeness** enhancement …



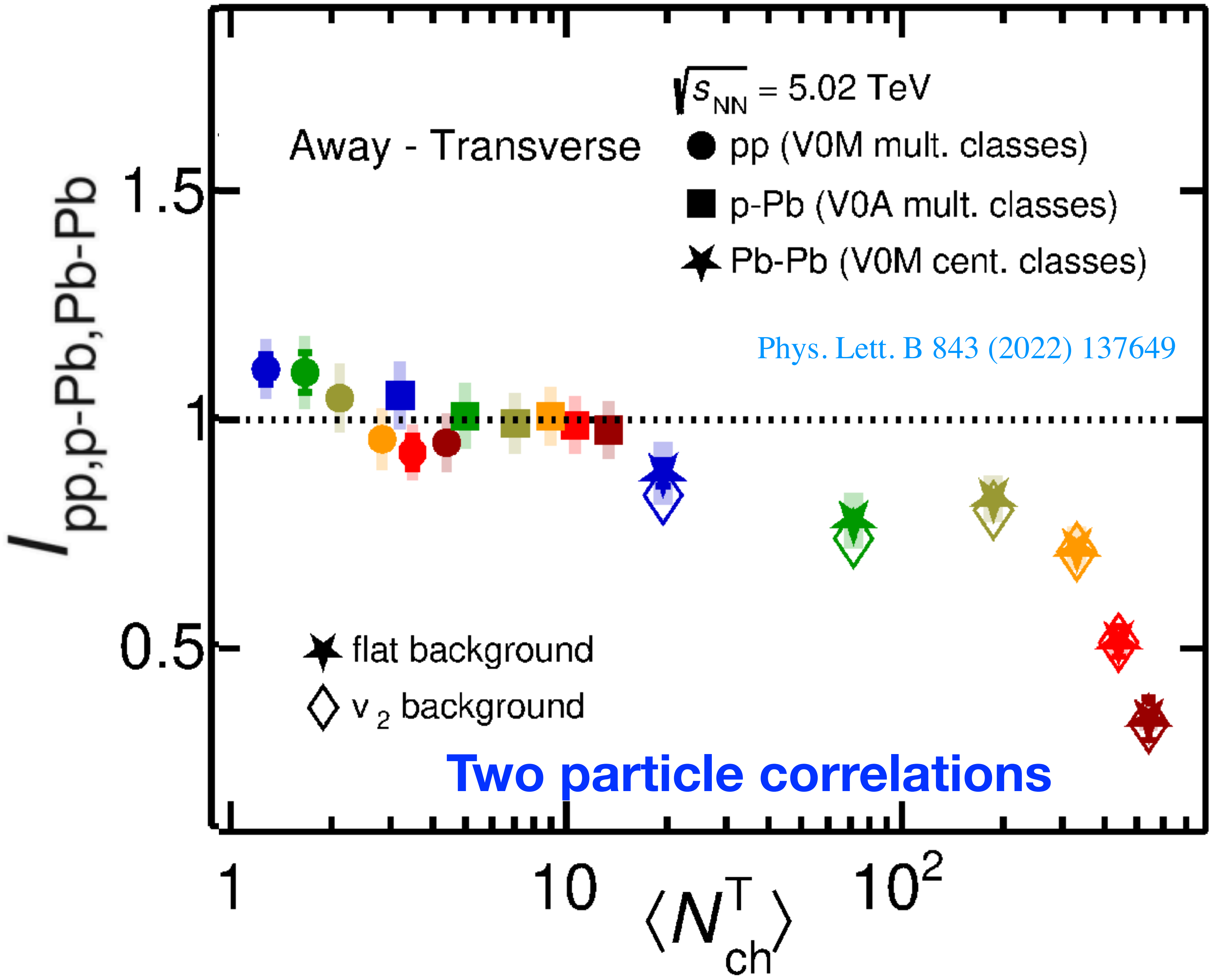
Eur. Phys. J. C 80 (2020) 693

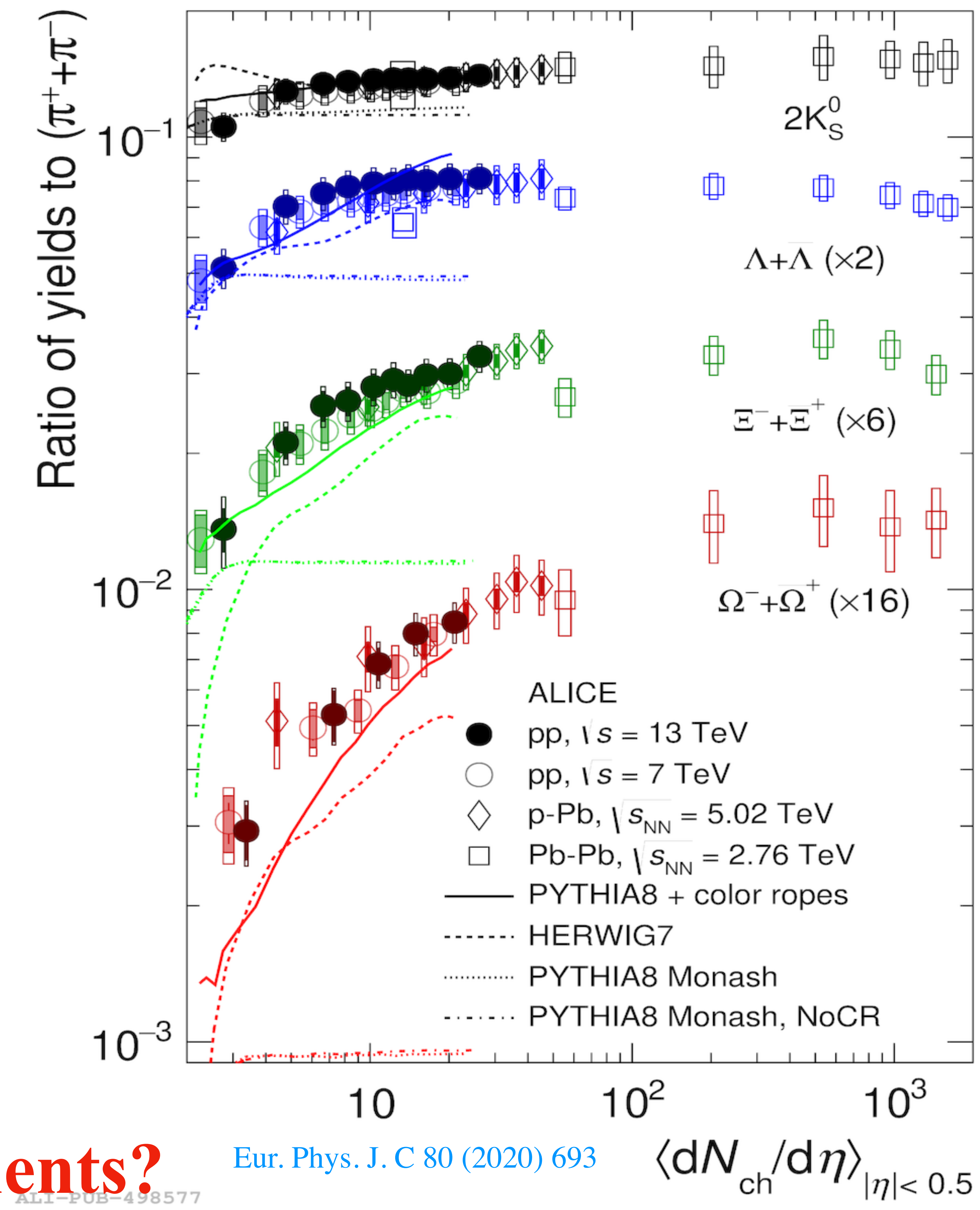
- Effects considered as signatures of QGP formation in heavy-ion collisions are observed in small systems: collectivity, **strangeness** enhancement …
  - However, no **jet quenching** observed so far



Δφ=|φ$_{leading}$ - φ$_{associate}$|

$$I_{pp/pA/AA} = \frac{Yield^{pp/pA/AA}_{NS/AS}}{(Yield^{pp/pA/AA}_{NS/AS})_{min.bias}}$$





➡ **How does jet production behave in high-multiplicity environments?**

➡ **What is the limit for QGP formation?**

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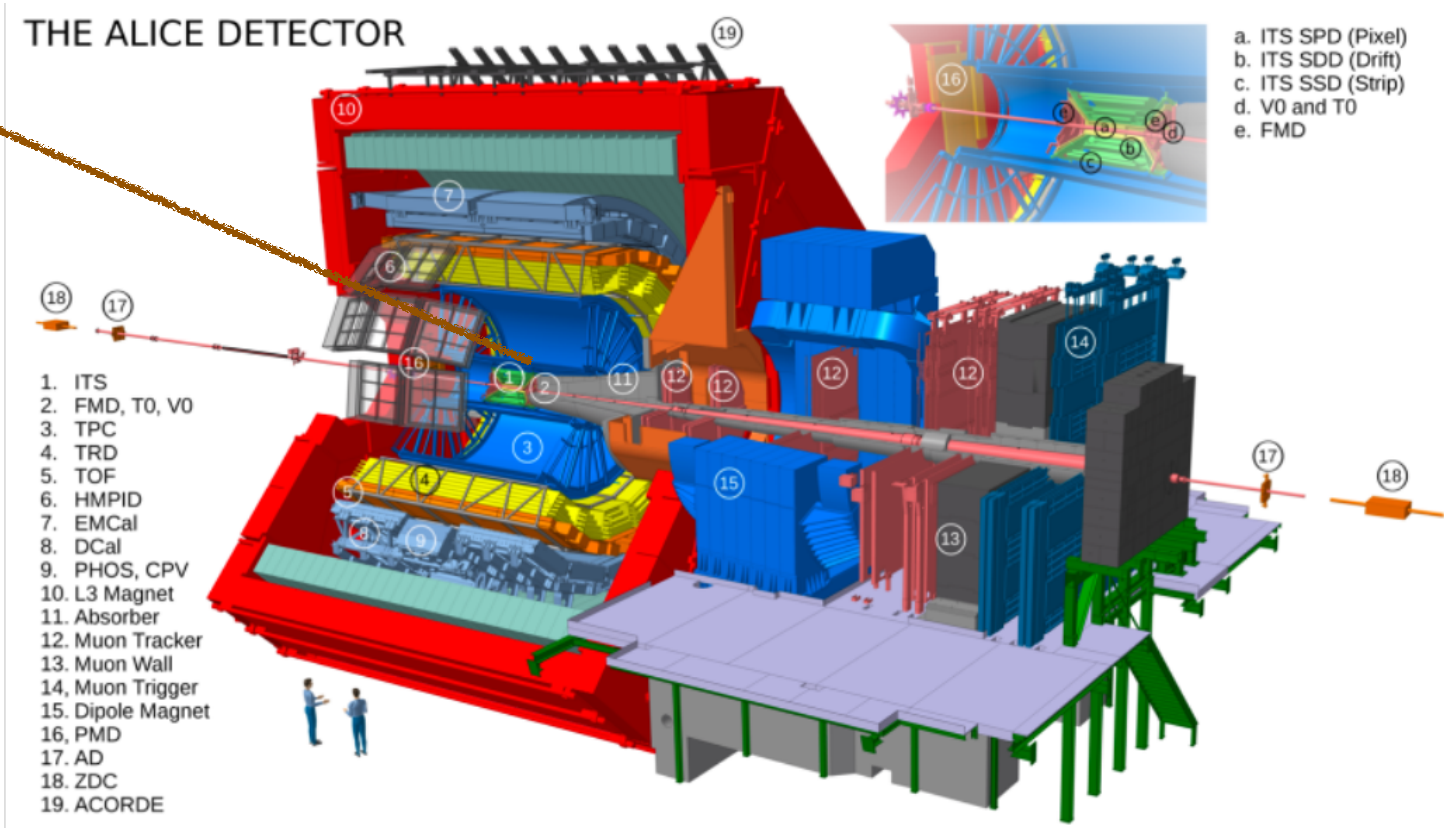
- **V0** (V0C + V0A)
  - $-3.7 < \eta < -1.7,\ 2.8 < \eta < 5.1$
  - Event trigger
  - Event multiplicity, centrality determination



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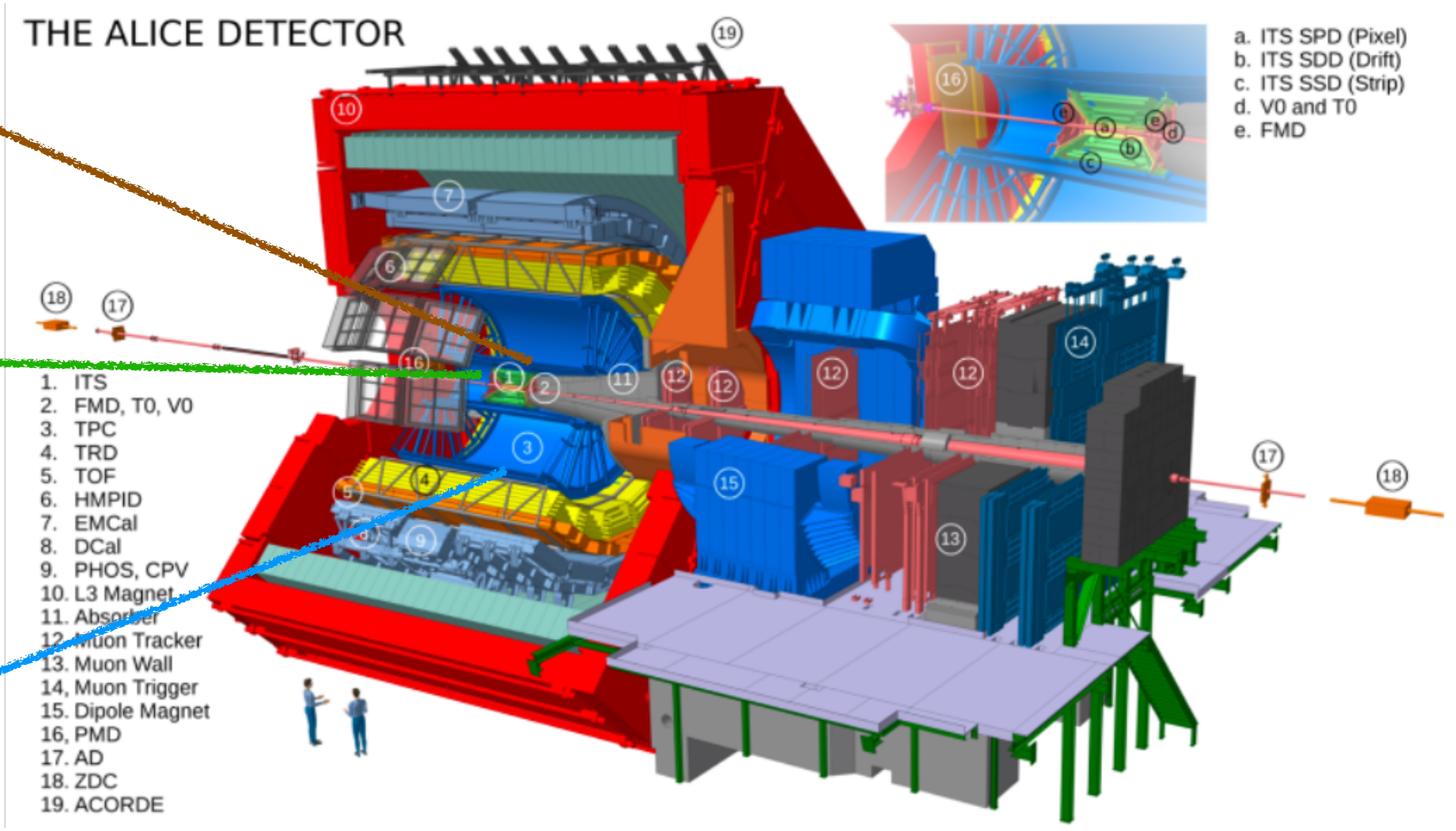
Charged-particle tracks and jets

- **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



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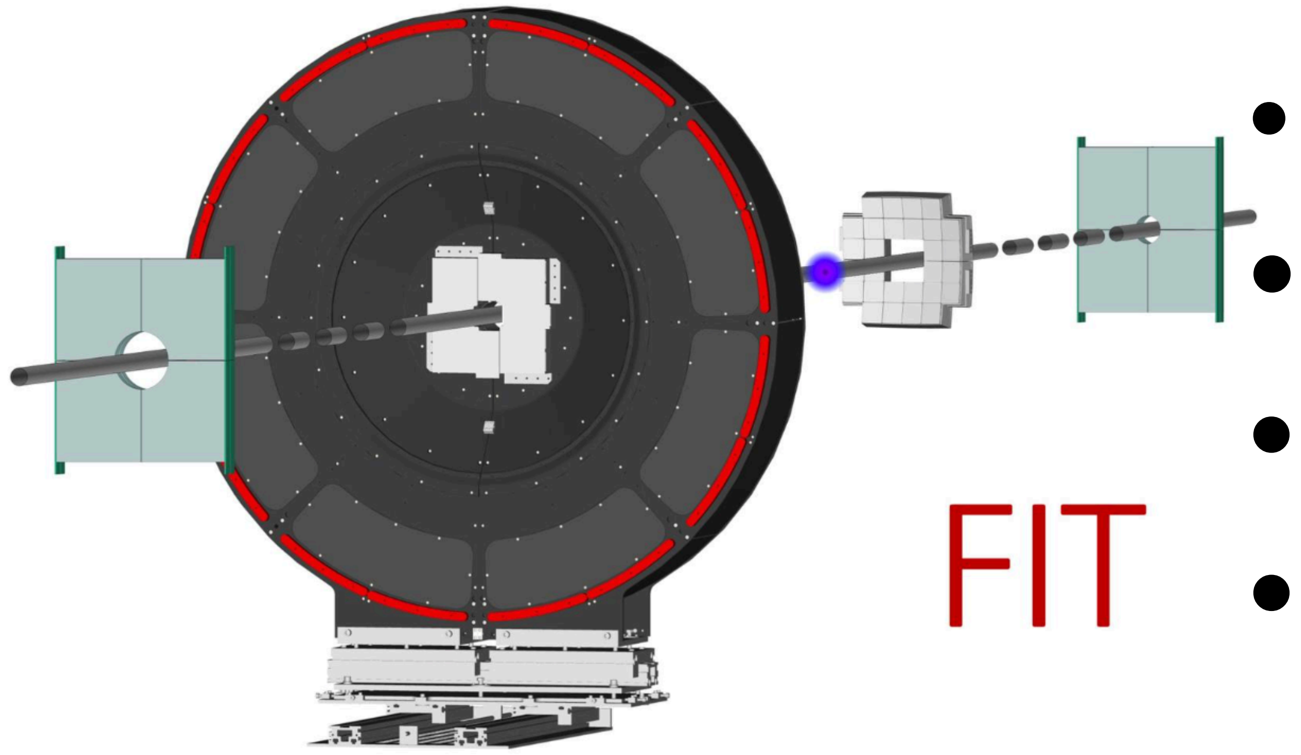
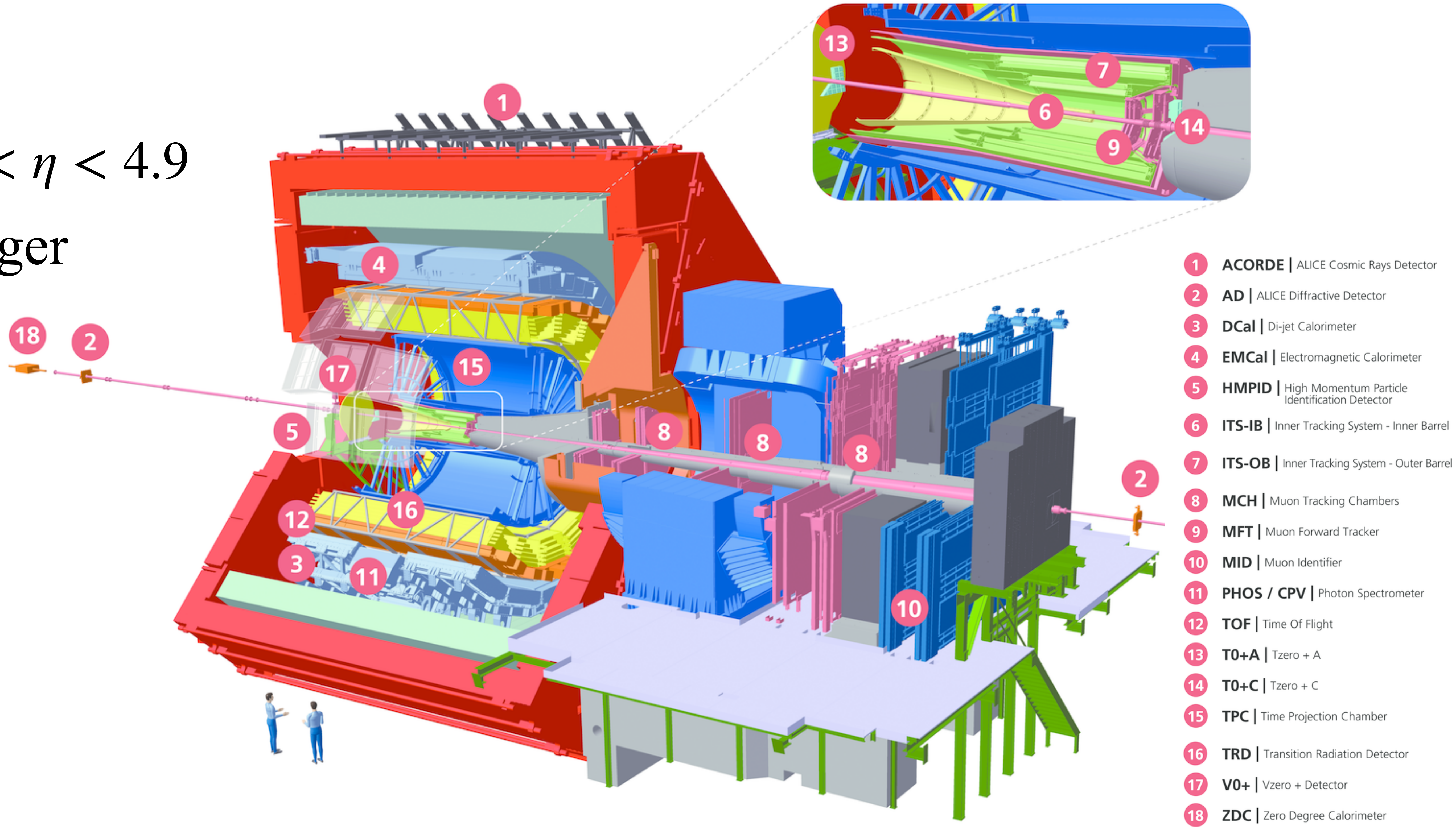
Fast Interaction Trigger (FT0C + FT0A)



FIT

- $-3.3 < \eta < -2.1$, $3.5 < \eta < 4.9$
- Luminosity, event trigger
- Centrality, event plane
- Interaction time



Jet measurements in ALICE (Run 3)

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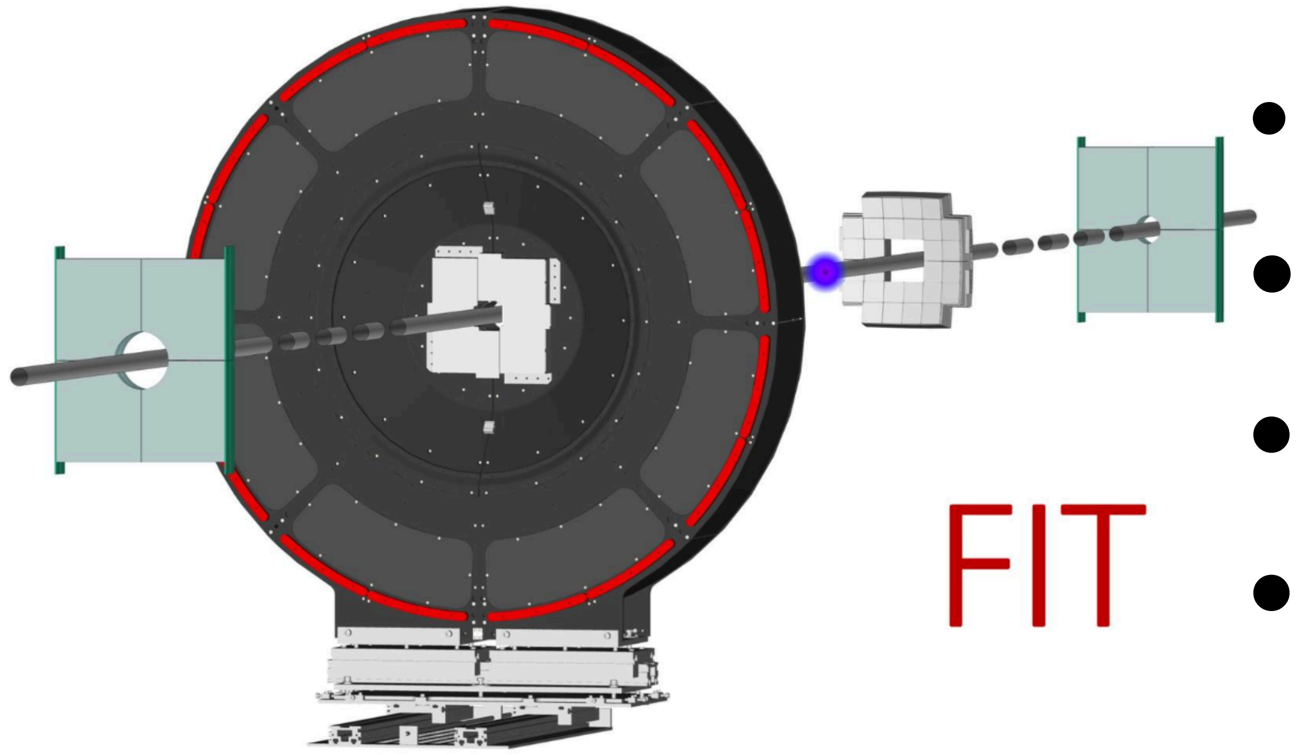

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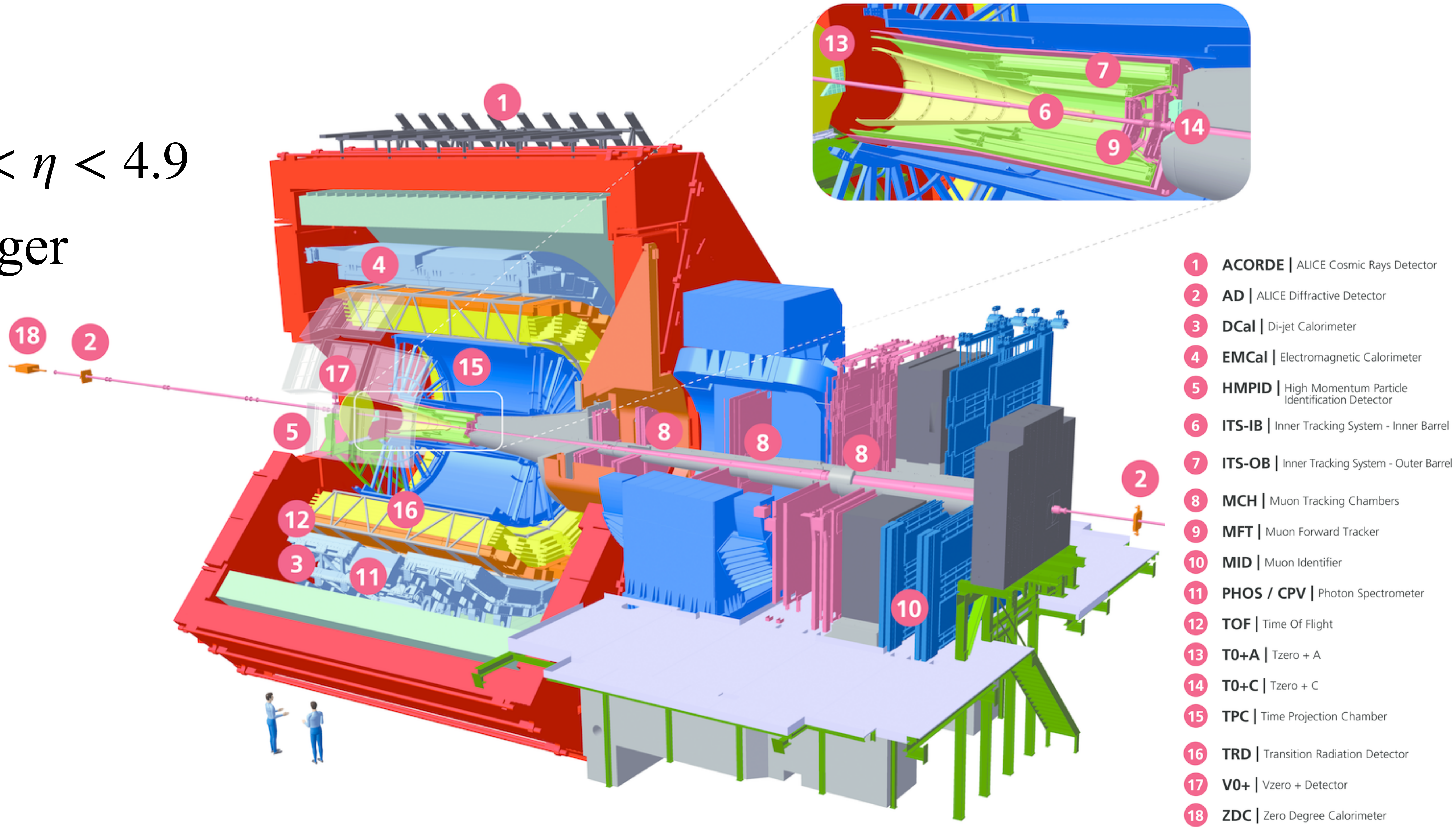
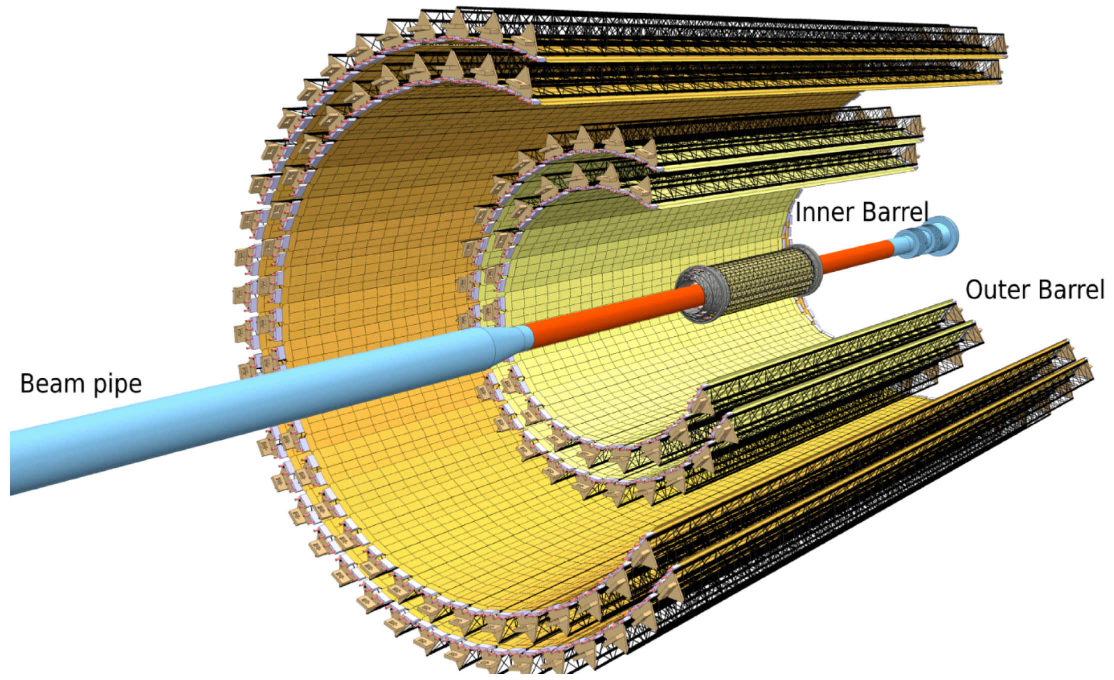
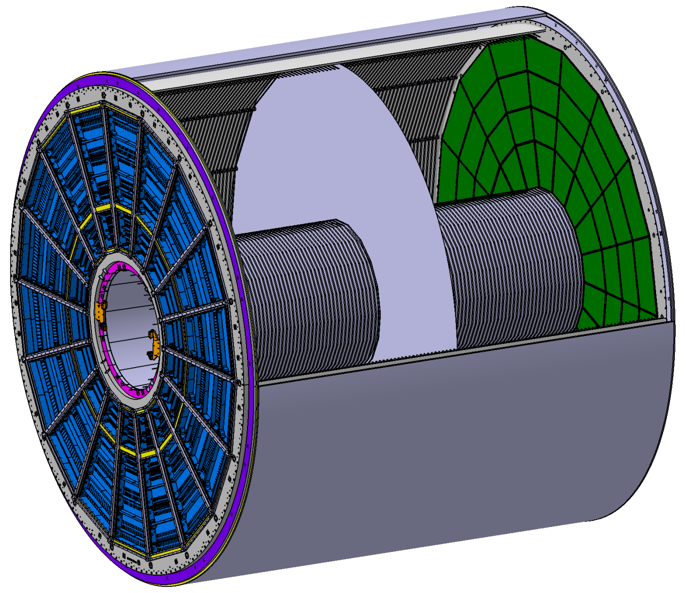


New Inner Tracking System



- $|\eta| < 1.3,\ 0 < \varphi < 2\pi$
- New Si inner tracker
- 3 inner layers 0.36% X0 each
- 50 kHz continuous readout

Time Projection Chamber



- $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
- 4 layers of GEM
- 50 kHz continuous readout

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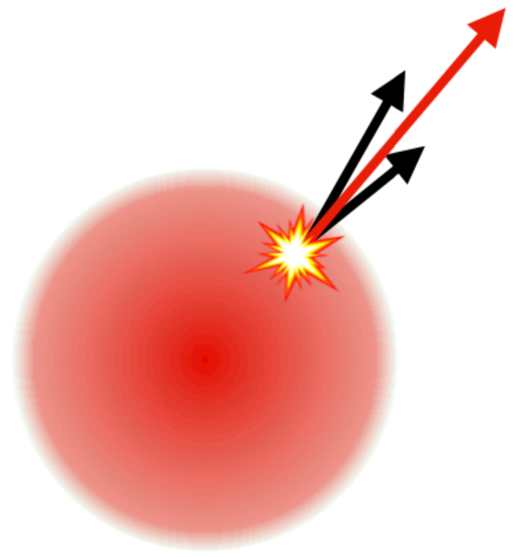
- Select events based on the presence of a high-p_T 'trigger' hadron (track)



Analysis procedure and observables

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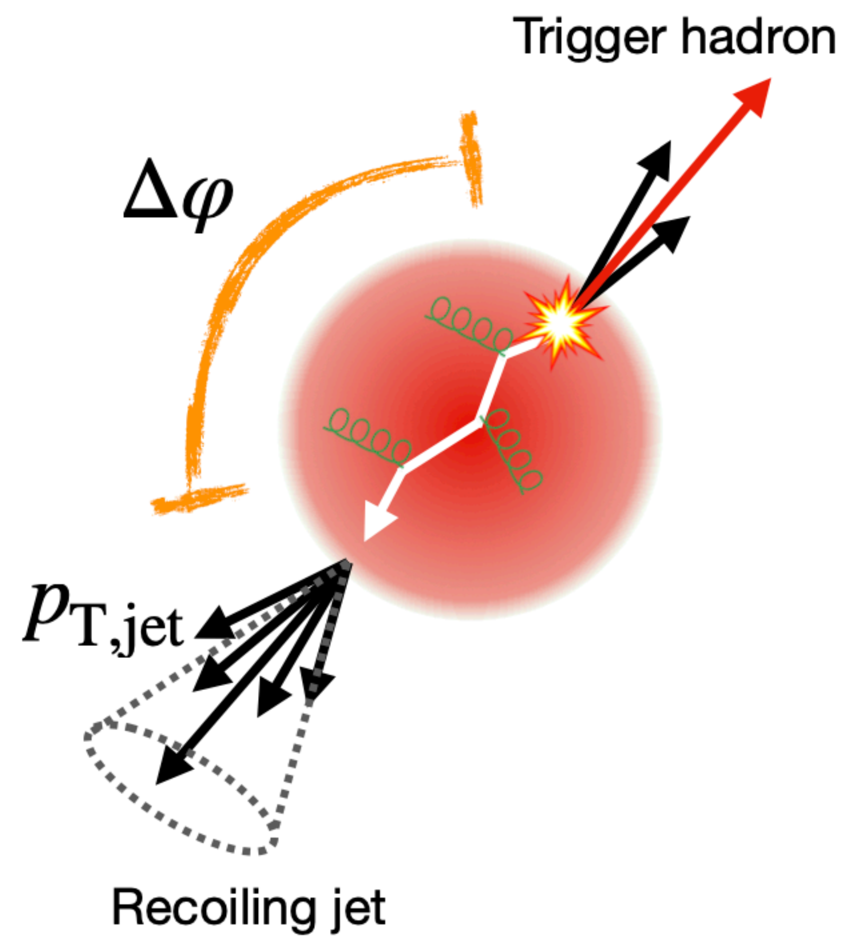
- Do jet reconstruction on these events
- Count jets recoiling from the trigger hadron **as a function of p_T and $\Delta\varphi$**



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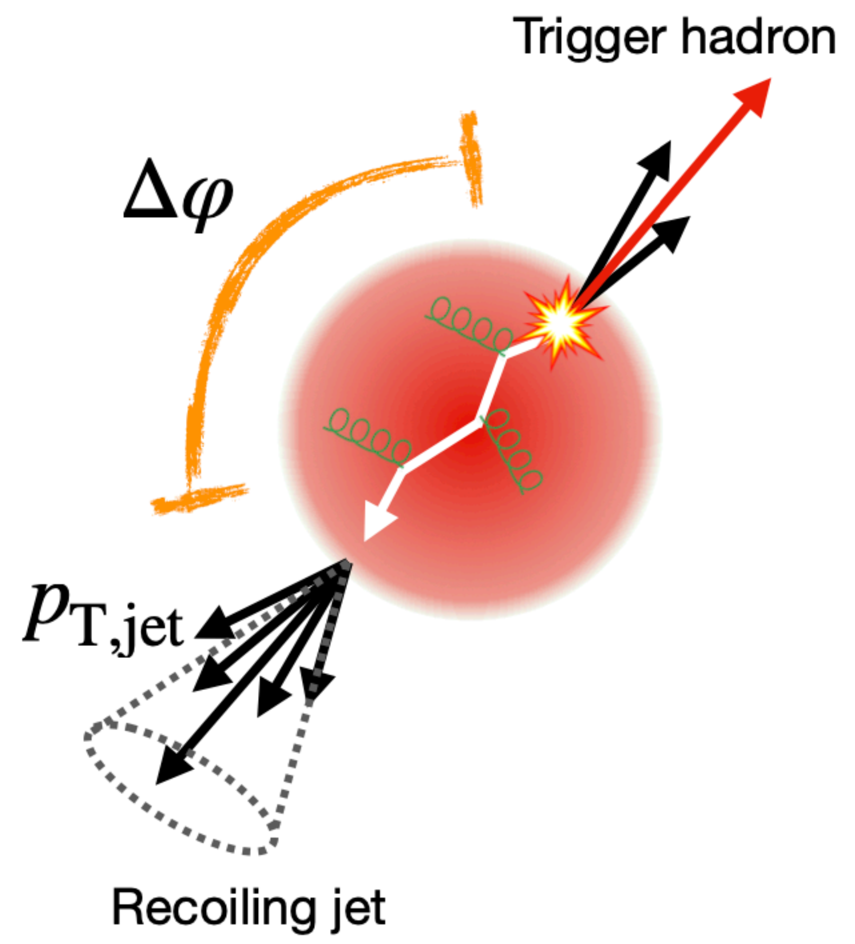
- Measure **trigger-normalised yield** of jets recoiling from a trigger hadron

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



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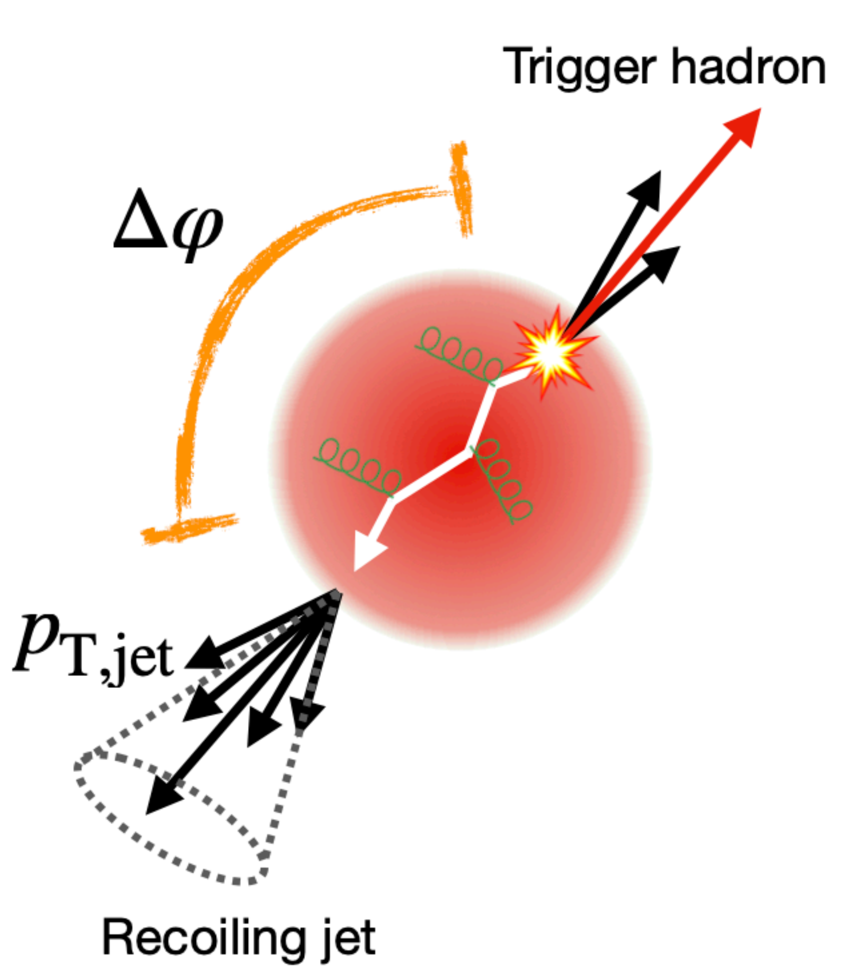

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$$\left.\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}\eta_{\mathrm{jet}}\ \mathrm{d}p_{\mathrm{T,jet}}\ \mathrm{d}\Delta\varphi_{\mathrm{jet}}}\right|_{p_{\mathrm{T}}^{\mathrm{trig}}\in\mathrm{TT}} = \left.\left(\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}}\cdot\frac{\mathrm{d}^2\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}\eta_{\mathrm{jet}}\ \mathrm{d}p_{\mathrm{T,jet}}\ \mathrm{d}\Delta\varphi_{\mathrm{jet}}}\right)\right|_{p_{\mathrm{T,h}}\in\mathrm{TT}}$$

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

TT signal: $p_{\mathrm{T}} \in (20, 50)$ GeV/c, TT reference: $p_{\mathrm{T}} \in (5, 7)$ GeV/c (except pp 13 TeV, $\mathrm{TT_S}$ [20,30], $\mathrm{TT_R}$: [6,7])

- Select events based on the presence of a high-p_{T} 'trigger' hadron (track)
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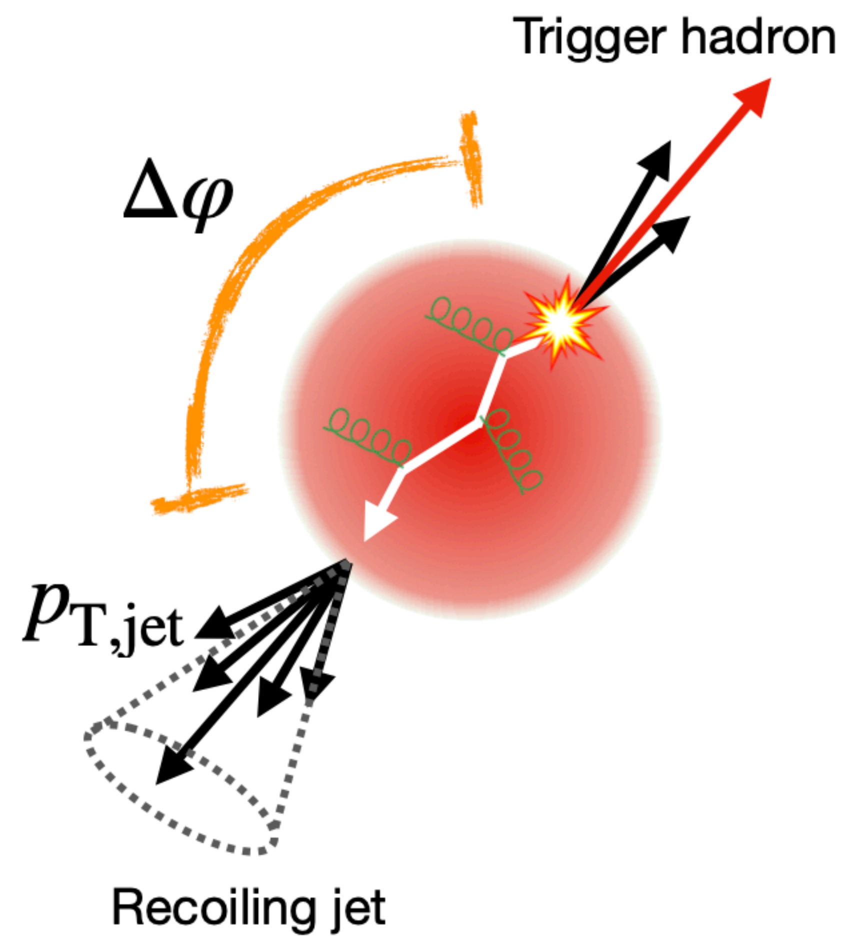
- Count jets recoiling from the trigger hadron **as a function of** p_{T} **and** $\Delta\varphi$
- Measure **trigger-normalised yield** of jets recoiling from a trigger hadron



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

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

TT signal: $p_{\mathrm{T}} \in (20, 50)$ GeV/c, TT reference: $p_{\mathrm{T}} \in (5, 7)$ GeV/c (except pp 13 TeV, $\mathrm{TT_S}$ [20,30], $\mathrm{TT_R}$: [6,7])

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

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

  - c_{Ref}: "alignment" constant extracted from data
  - Allow for precise measurements down to very **low** p_{T} and **large** $\boldsymbol{R}$

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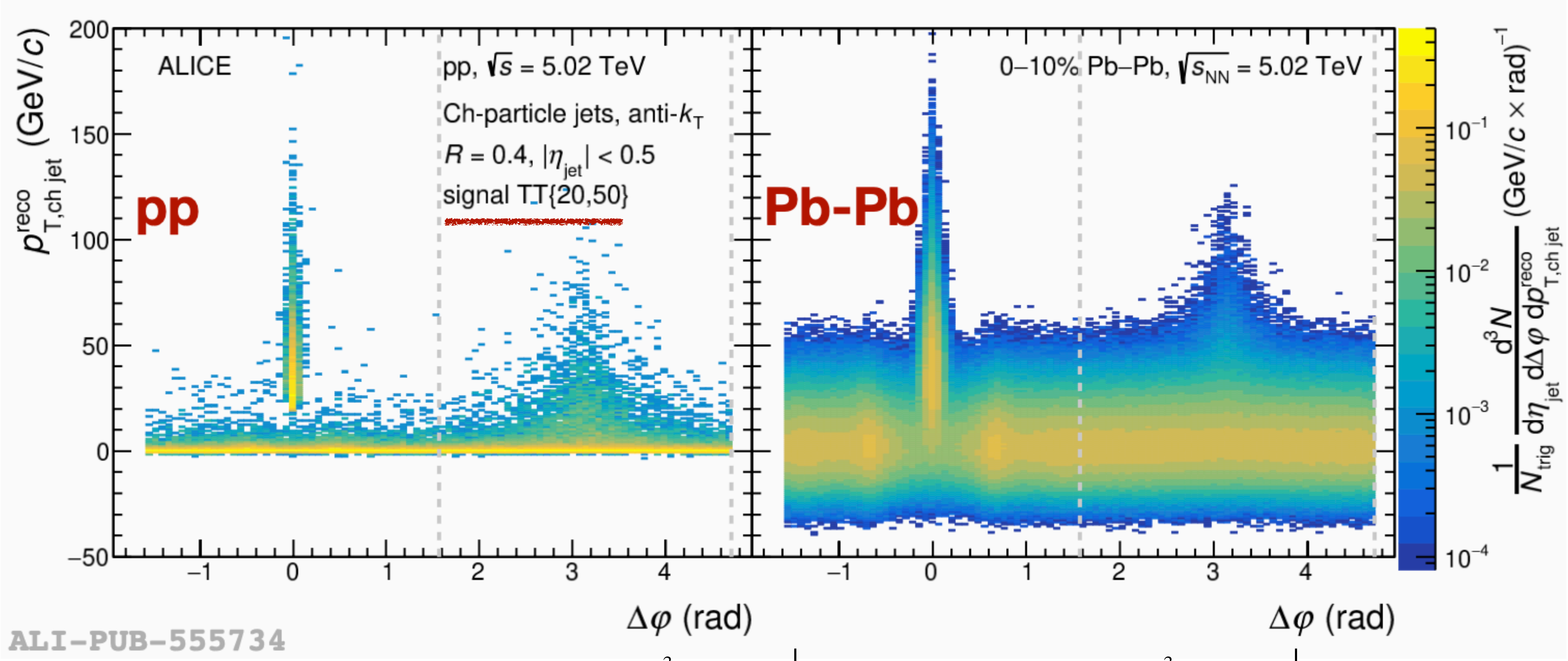

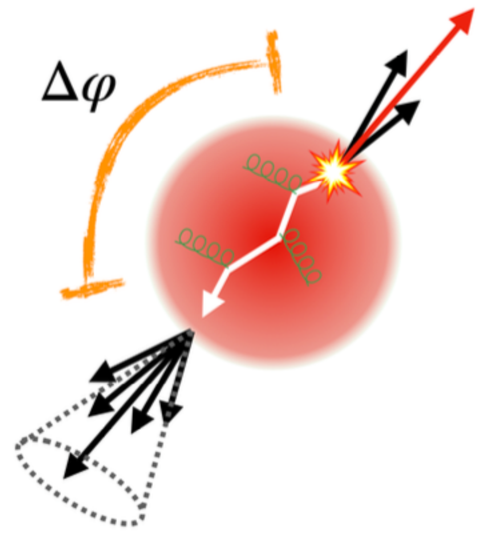

$$\Delta_{recoil}\left(p_{T,jet}, \Delta\varphi\right) = \frac{1}{N_{trig}} \left. \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi} \right|_{p_T^{trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \left. \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi} \right|_{p_T^{trig}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

- Recoil jet p_T **vs Δφ 2-dimensional** distributions in two trigger track p_T intervals

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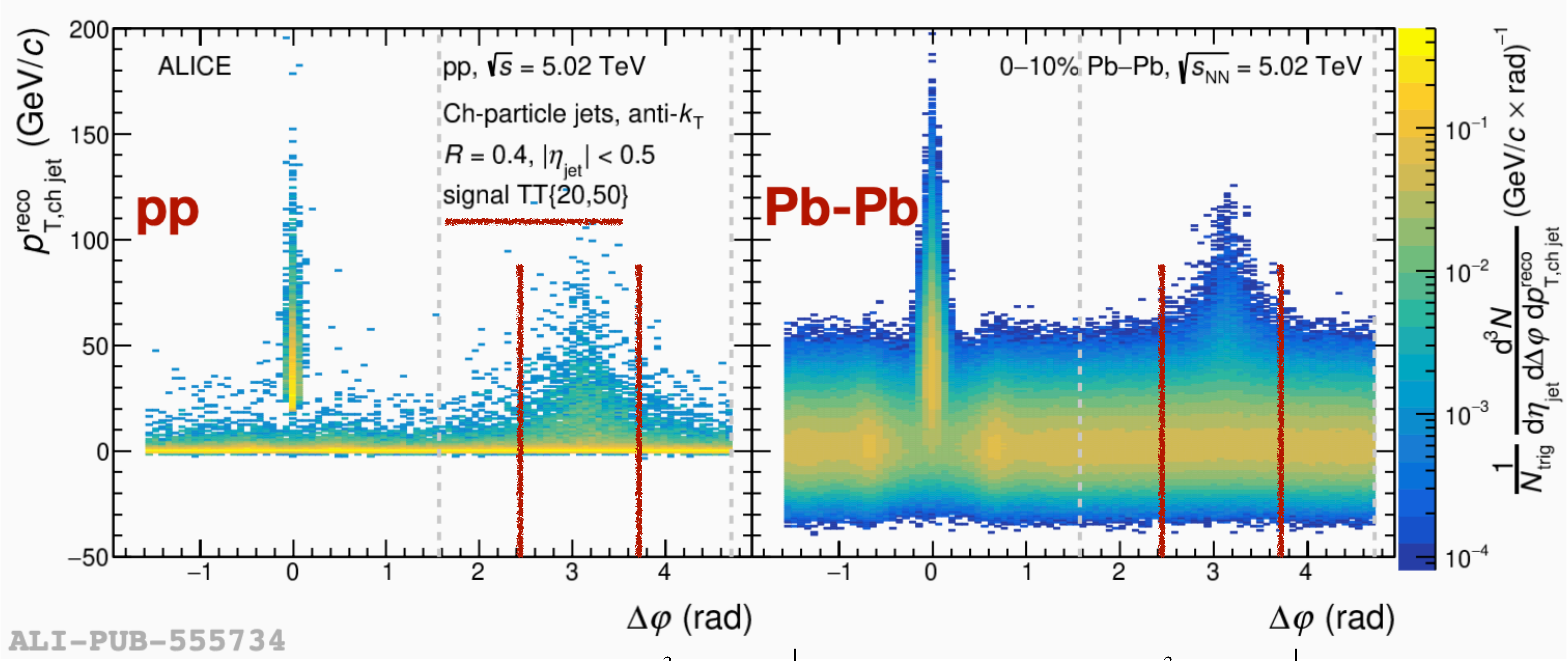
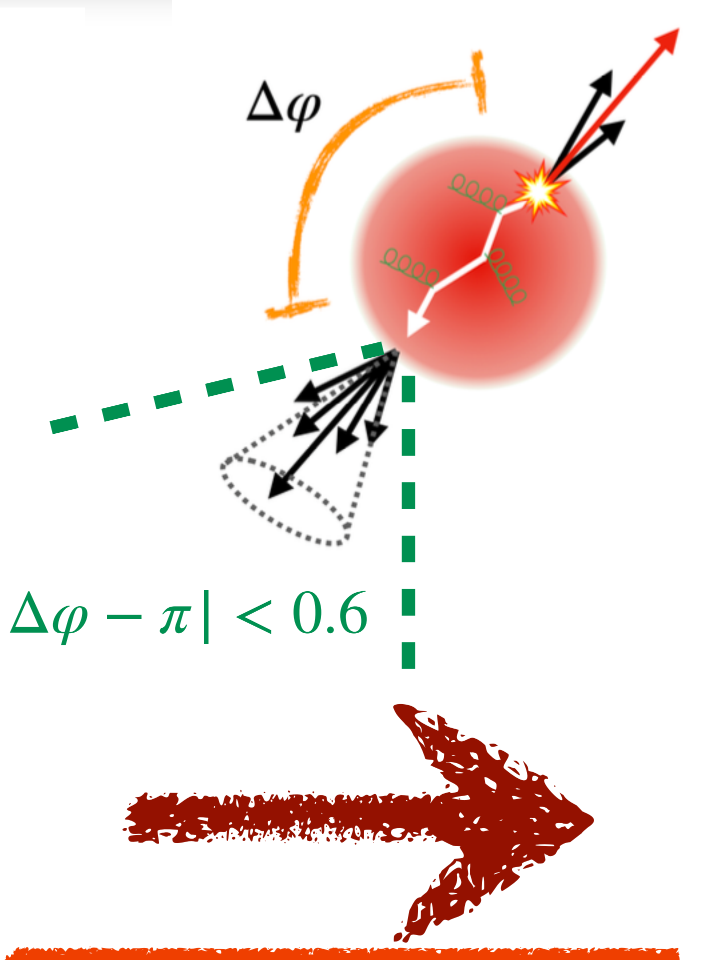


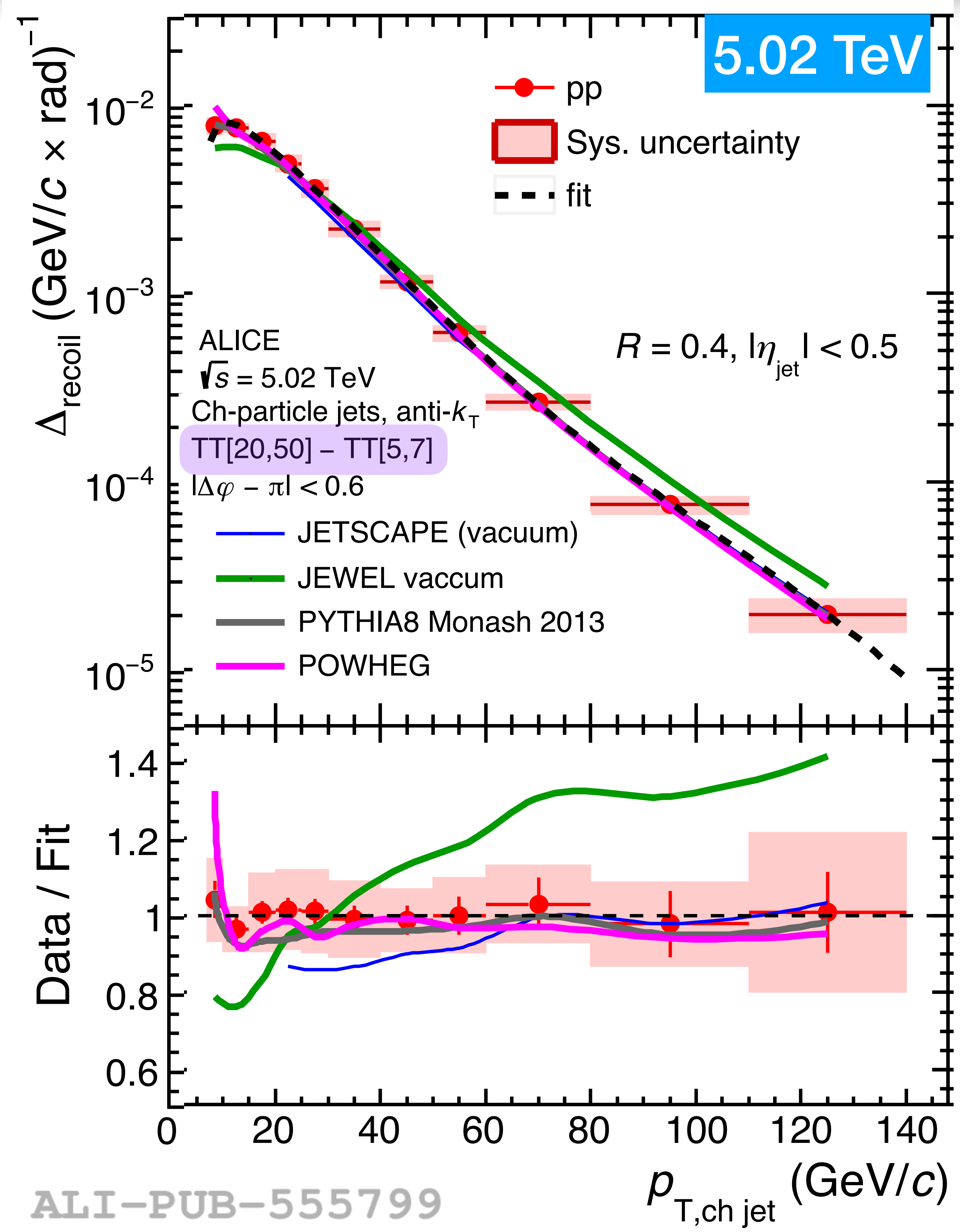


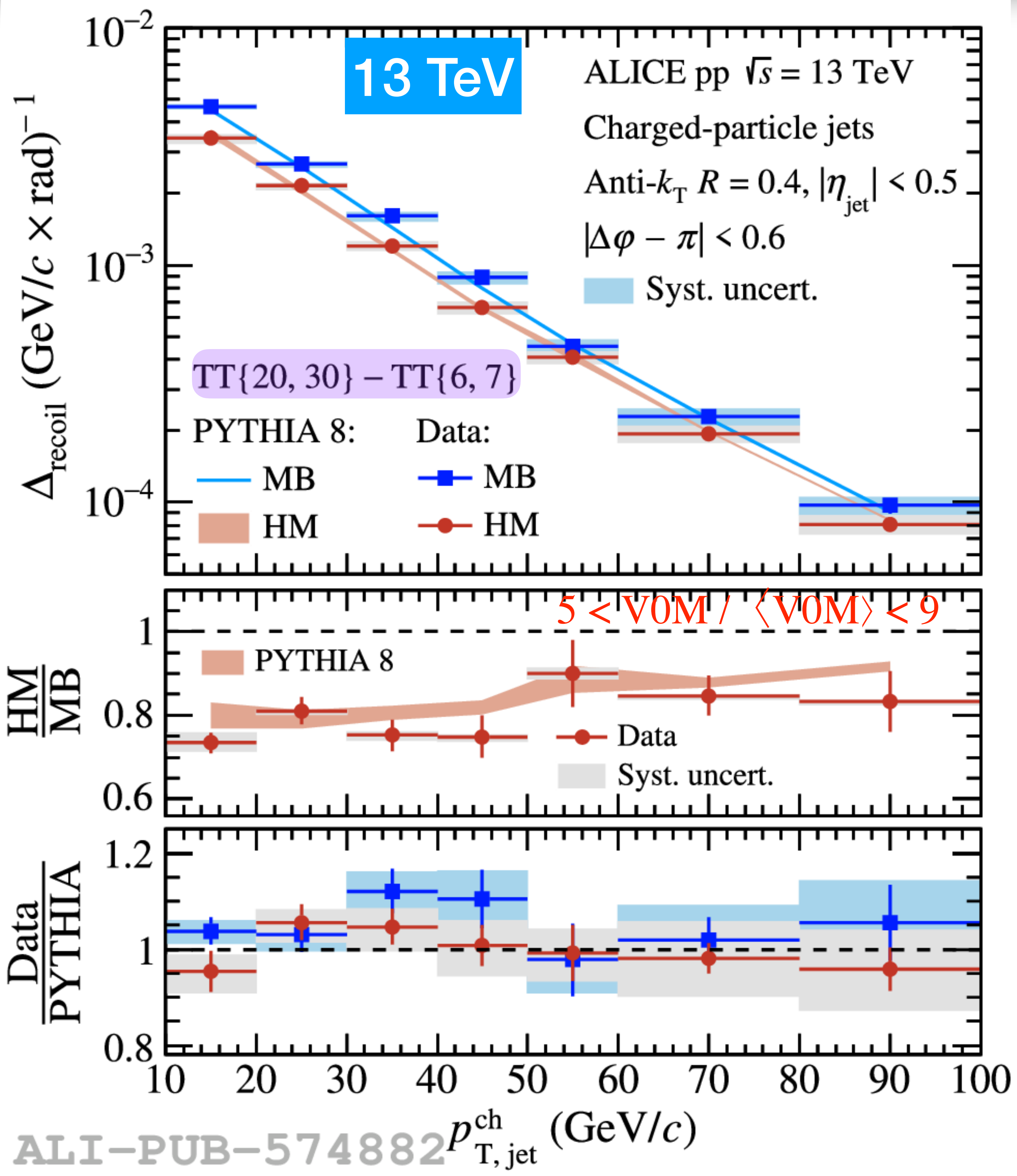
Projection to $p_{T,jet}$ with $\Delta\varphi$

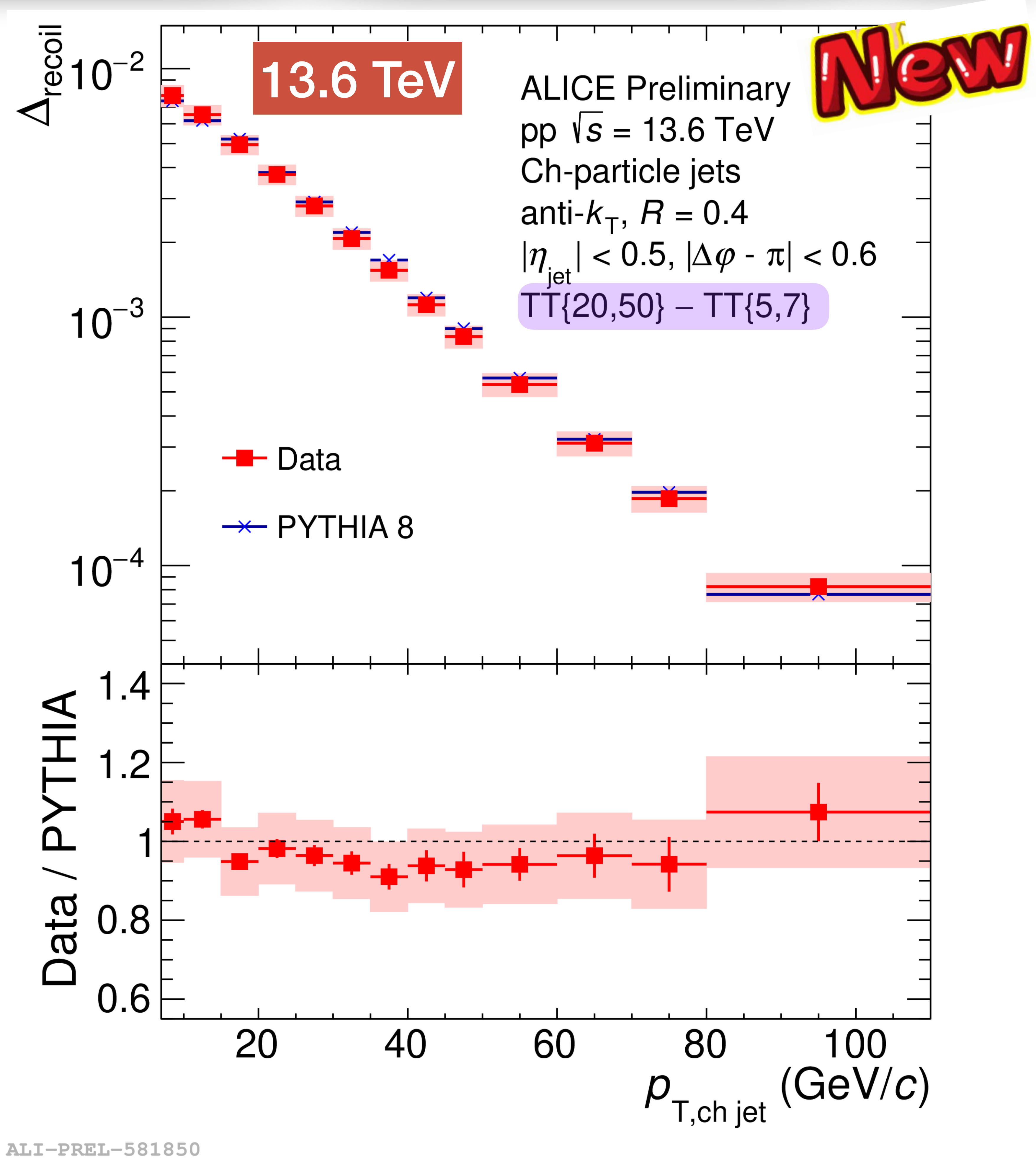
$$\Delta_{recoil}(p_{T,jet}, \Delta\varphi) = \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Ref}}$$

- Recoil jet p_T **vs $\Delta\varphi$ 2-dimensional** distributions in two trigger track p_T intervals

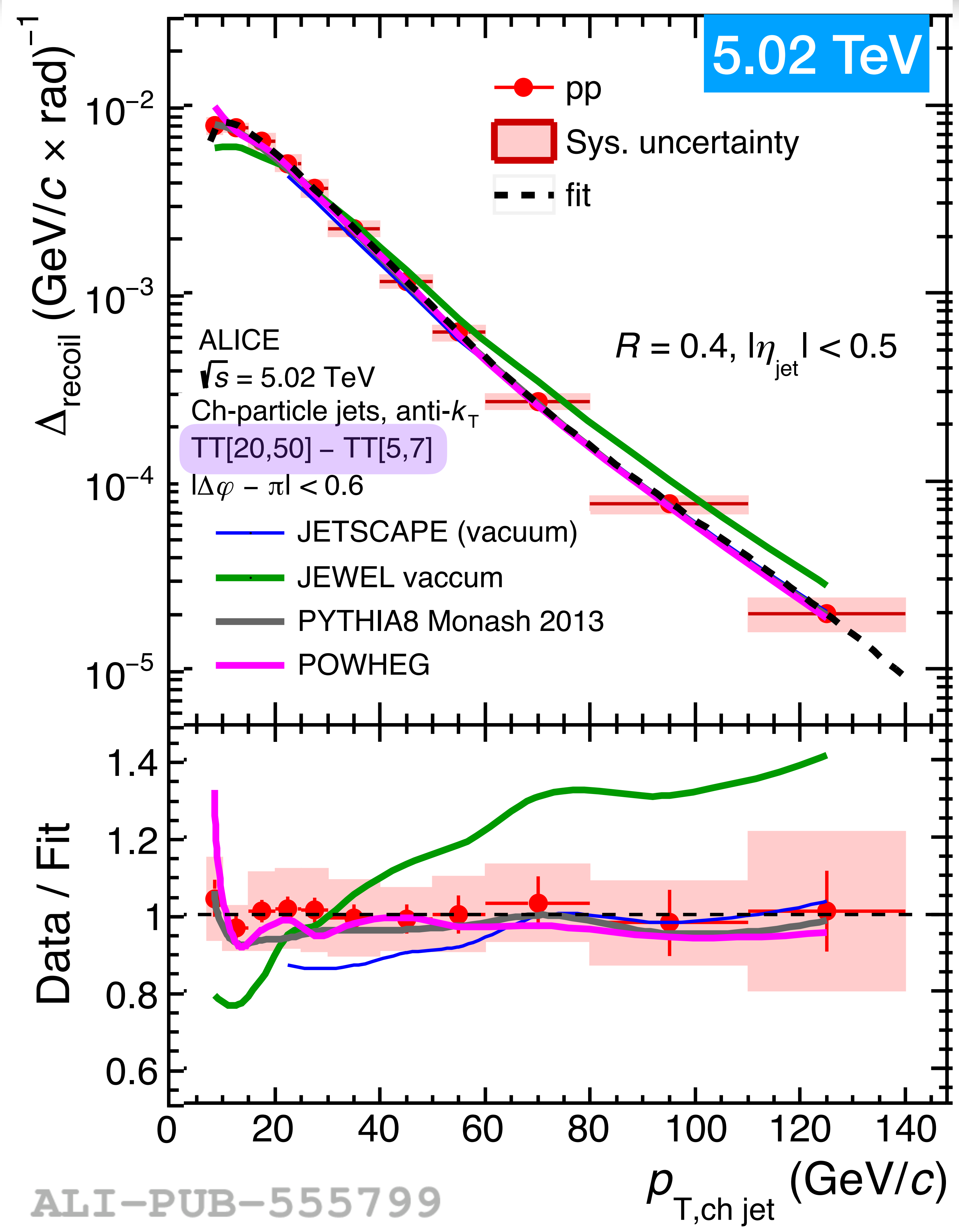
Fully-corrected Δ_{recoil} (p_T) distributions in pp collisions

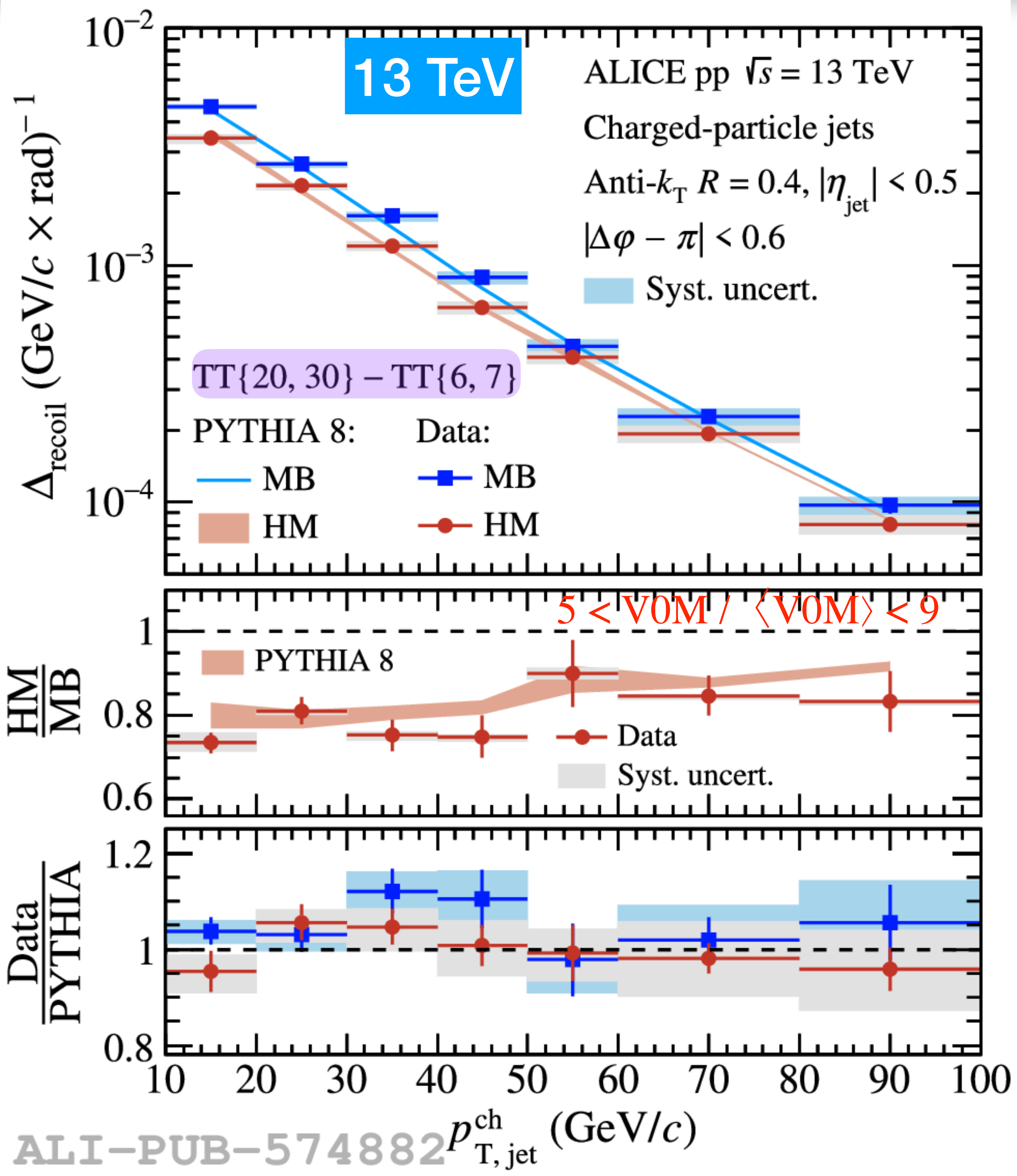


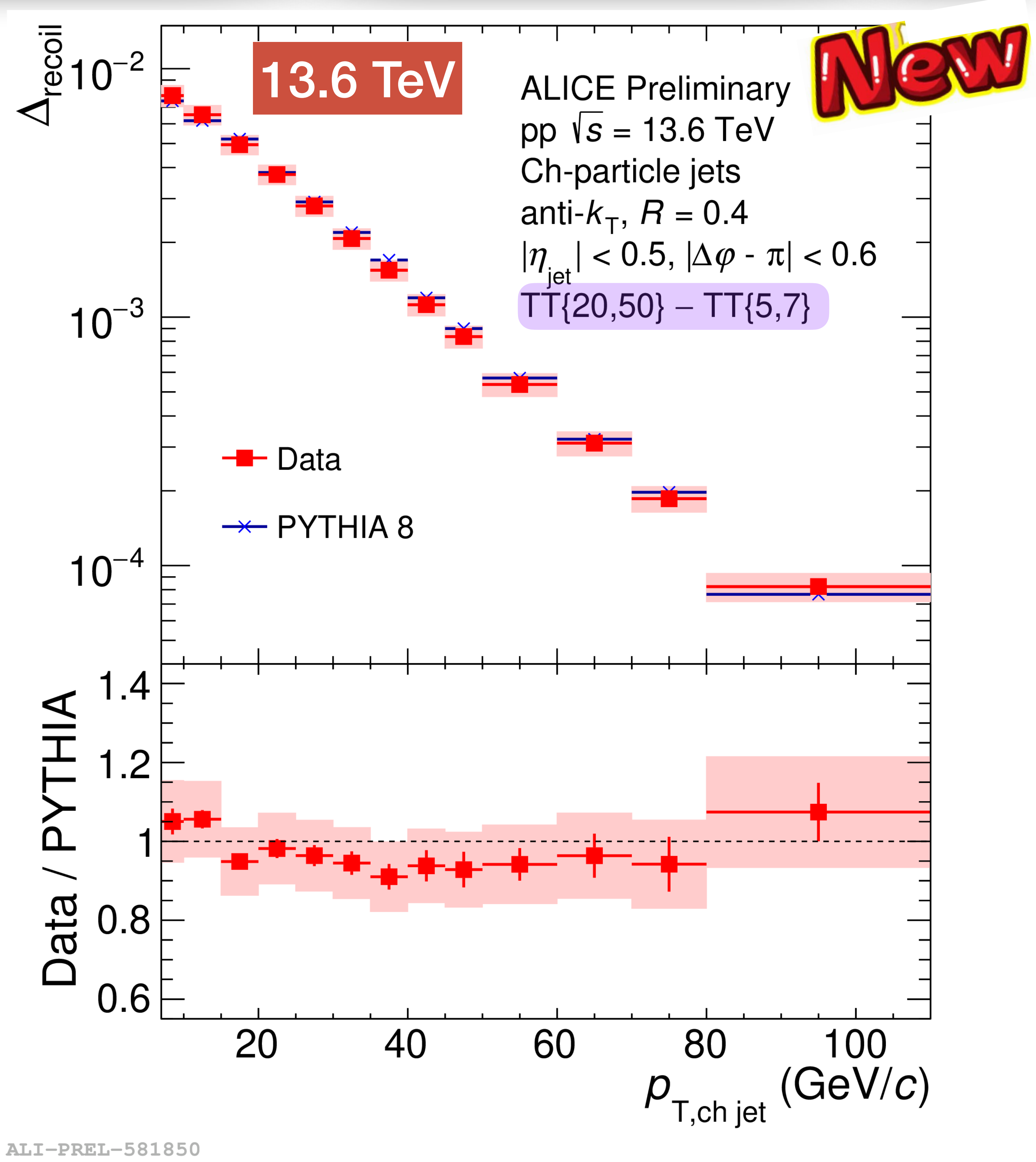




- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for $R = 0.4$ in pp collisions at 5.02, 13, 13.6 TeV
- All model calculations, except JEWEL, reproduce the ALICE data within uncertainties

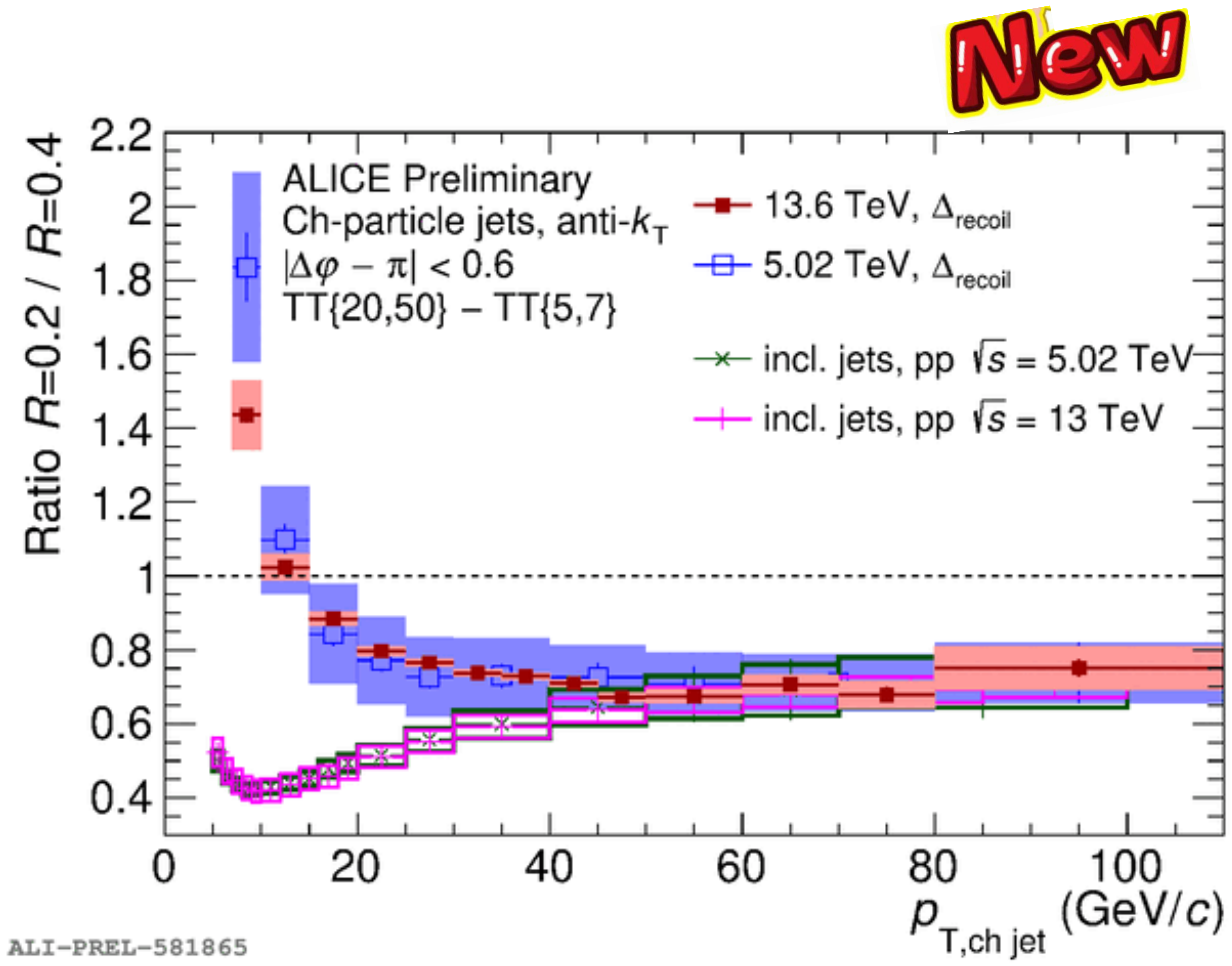






- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for $R = 0.4$ in pp collisions at 5.02, 13, 13.6 TeV
- All model calculations, except JEWEL, reproduce the ALICE data within uncertainties
- **A yield suppression in the HM** collisions with respect to MB events → **independent of p_T**

Fully corrected yield ratio: $R = 0.2$ / $R = 0.4$



- **The jet yield ratios** of inclusive and simi-inclusive for R = 0.2 / 0.4
  - **Agreement** between inclusive jets and semi-inclusive at high p_T

Fully corrected yield ratio: $R = 0.2$ / $R = 0.4$

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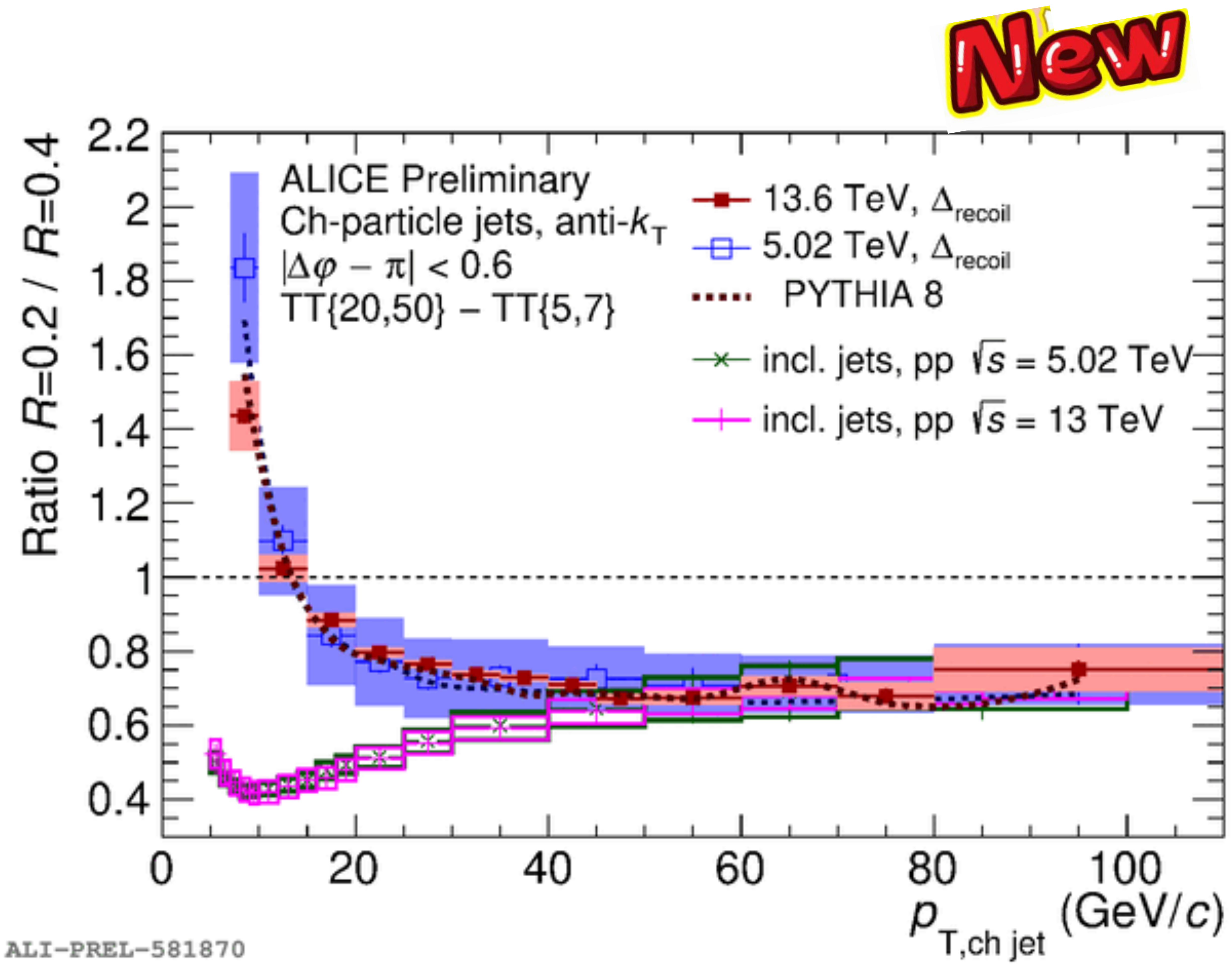
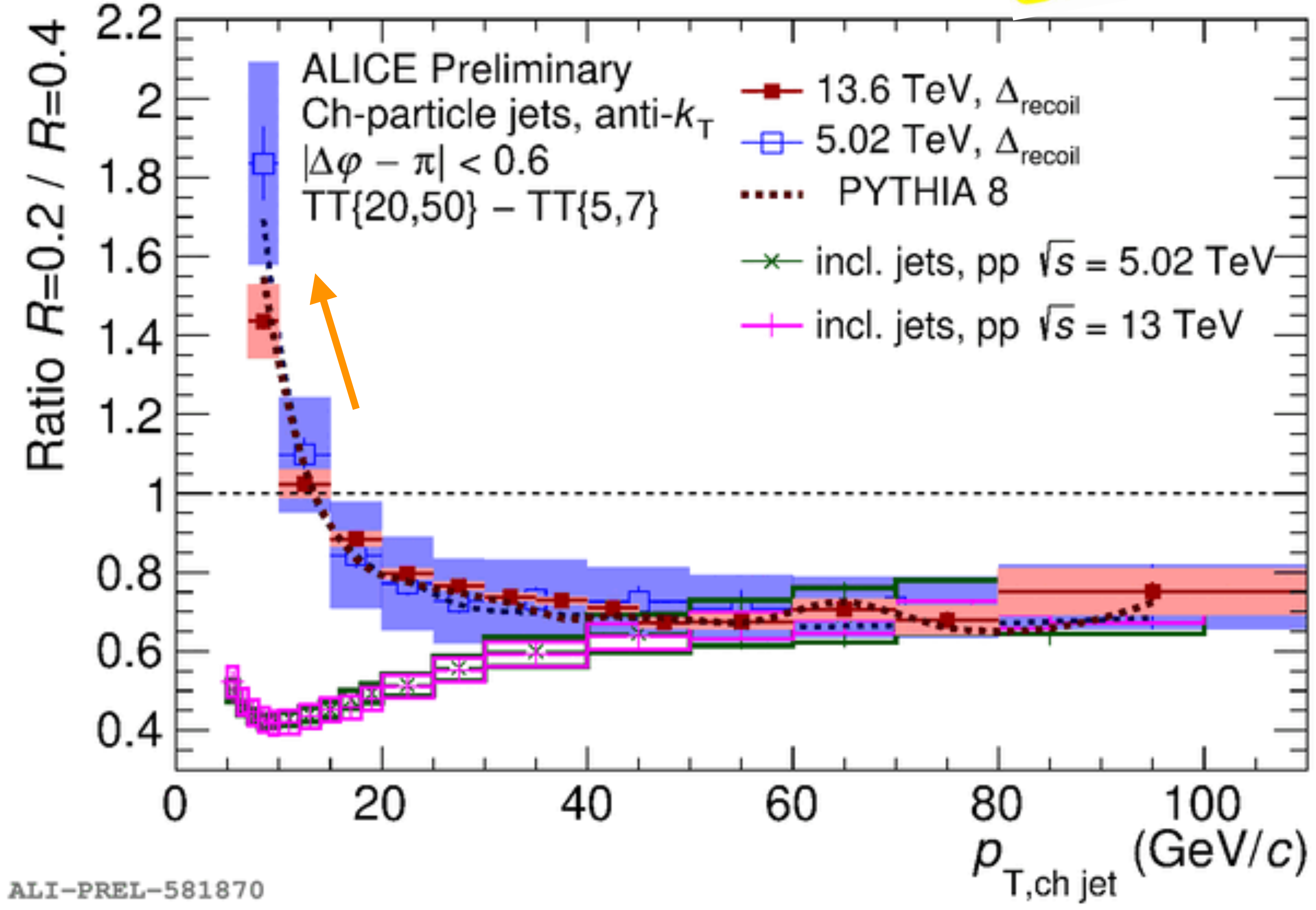


- **The jet yield ratios** of inclusive and simi-inclusive for R = 0.2 / 0.4
  - **Agreement** between inclusive jets and semi-inclusive at high p_T
  - **Well described** by PYTHIA
  - Good agreement between Run 2 and Run 3 results

New



- **The jet yield ratios** of inclusive and simi-inclusive for R = 0.2 / 0.4
  - **Agreement** between inclusive jets and semi-inclusive at high p_T
  - **Well described** by PYTHIA
  - Good agreement between Run 2 and Run 3 results
- Difference at low p_T due to **TT selection**
- Enhancement in $R = 0.2$ **recoil jet yield** at low p_T

→ preference for more, small R jets w.r.t. large R jets to be reconstructed?

→ bias towards LO processes suppressed when $p_T^{jet} < p_T^{trig}$?

Fully-corrected $\Delta_{recoil}(p_T)$ distributions in pp & Pb-Pb

- $\Delta_{recoil}(p_T)$ distributions measured **down to $p_T \sim$ 7 GeV/c** in pp and Pb-Pb collisions

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- $\Delta_{recoil}(p_T)$ distributions measured **down to** p_T **~ 7 GeV/c** in pp and Pb-Pb collisions

Among the lowest jet measurement in Pb-Pb collisions with ALICE at the LHC!

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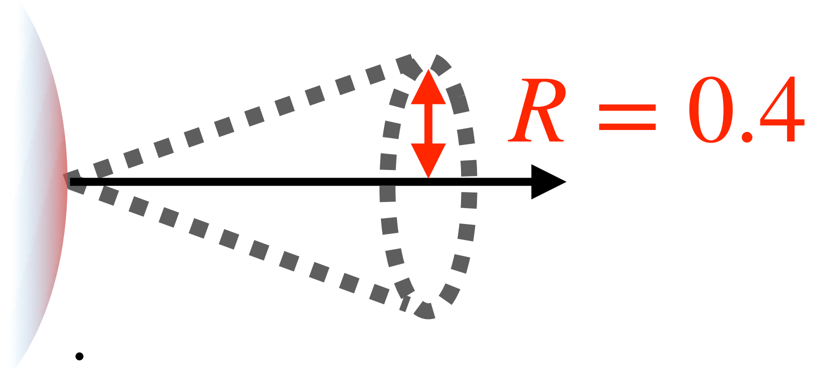
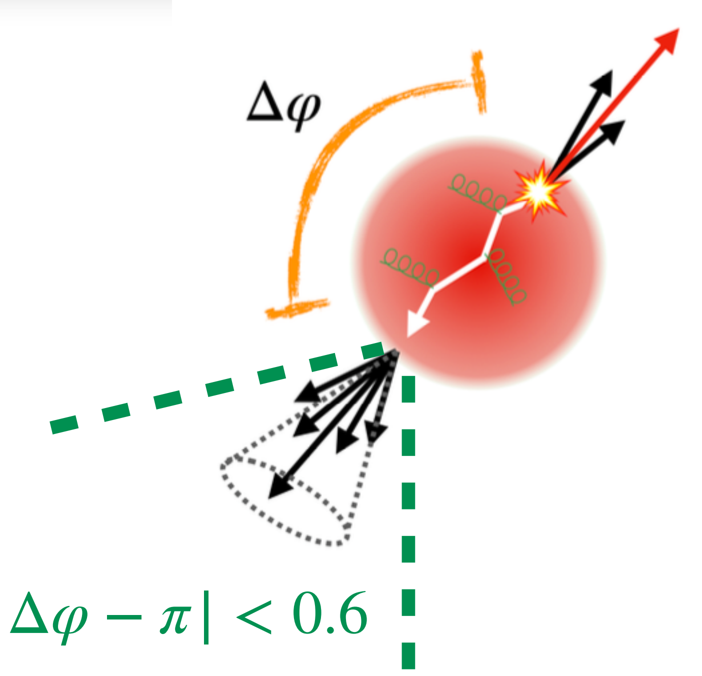
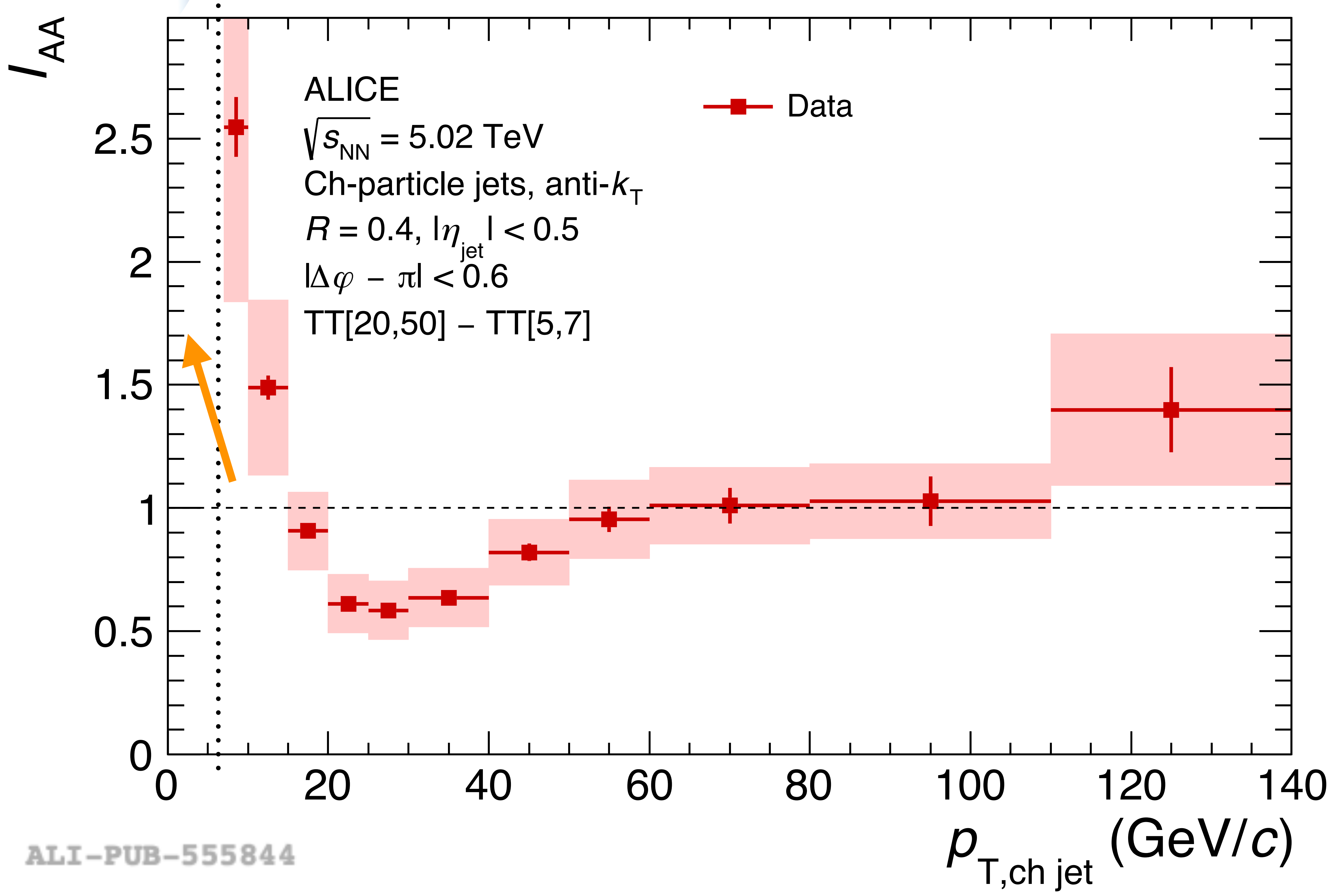


0 – 10 %

R = 0.4

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





- **Jet yield enhancement** at low p_T

  → hint of energy recovery in low p_T jets?

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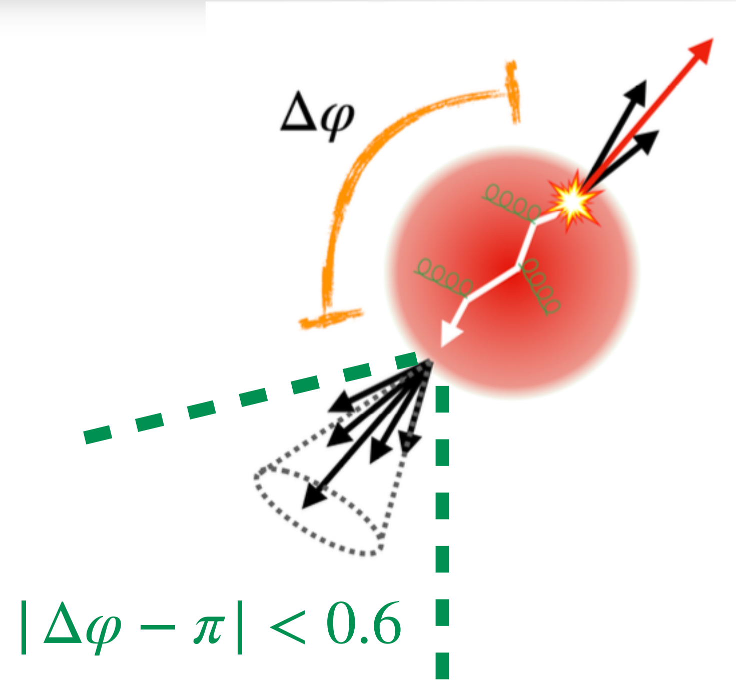
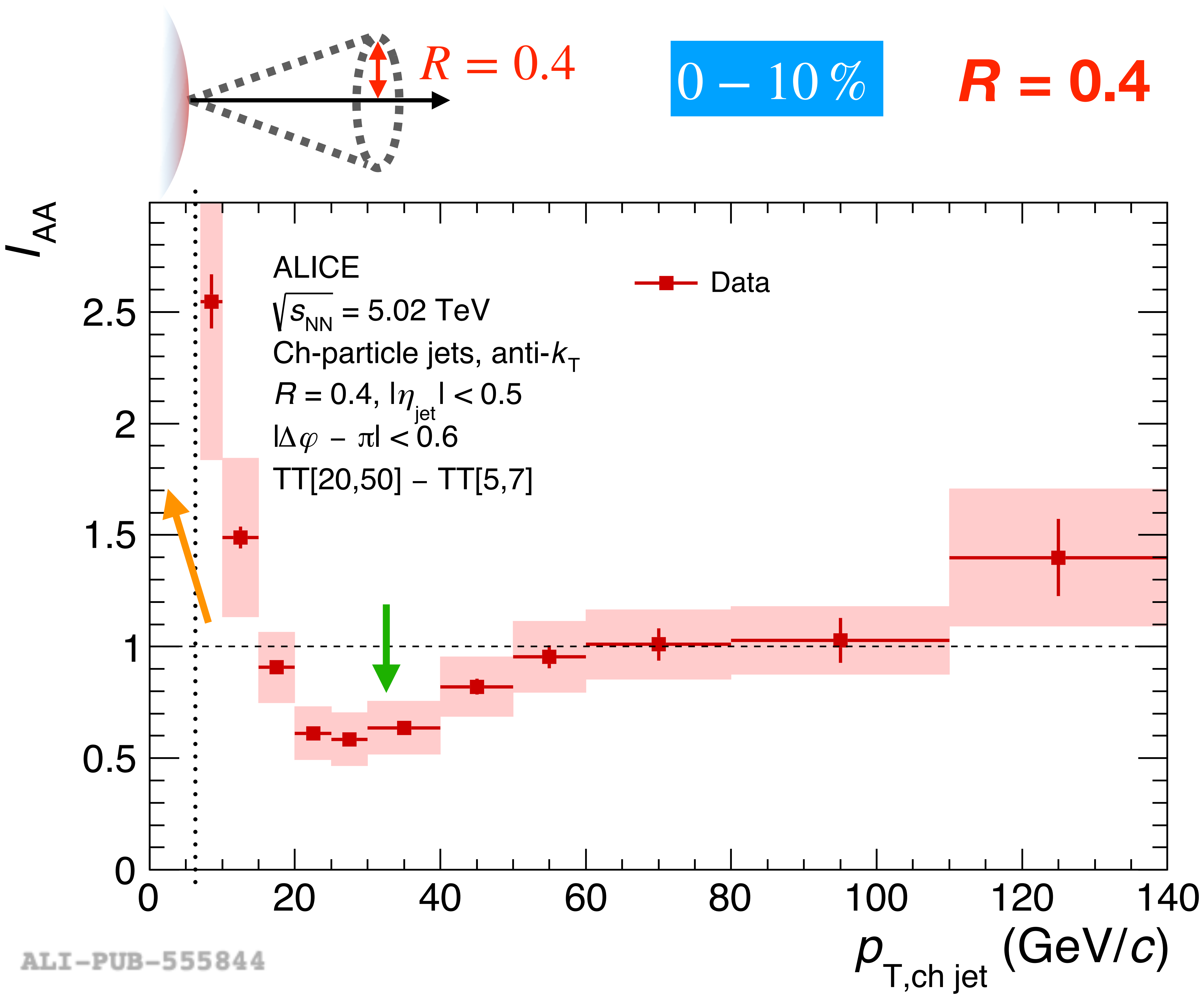
$$I_{AA} \equiv \frac{\Delta_{recoil}\ (p_T)_{AA}}{\Delta_{recoil}\ (p_T)_{pp}}$$



0 – 10 %

R = 0.4



- **Jet yield enhancement** at low p_T

  → hint of energy recovery in low p_T jets?

- **Jet yield suppression** at $20 < p_{T,jet} < 60$ GeV/c

  → Jet energy loss

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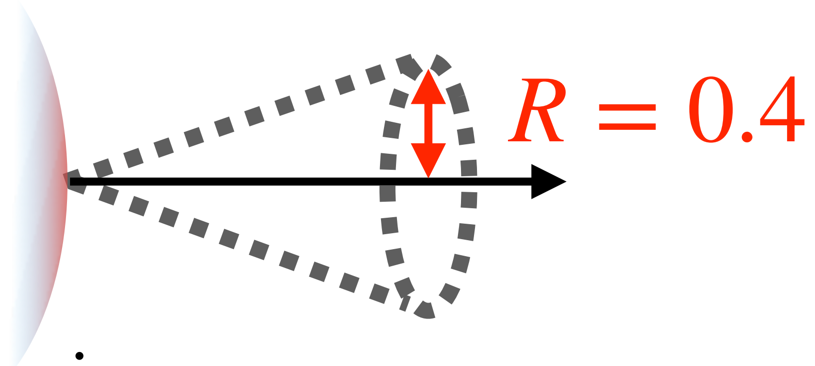

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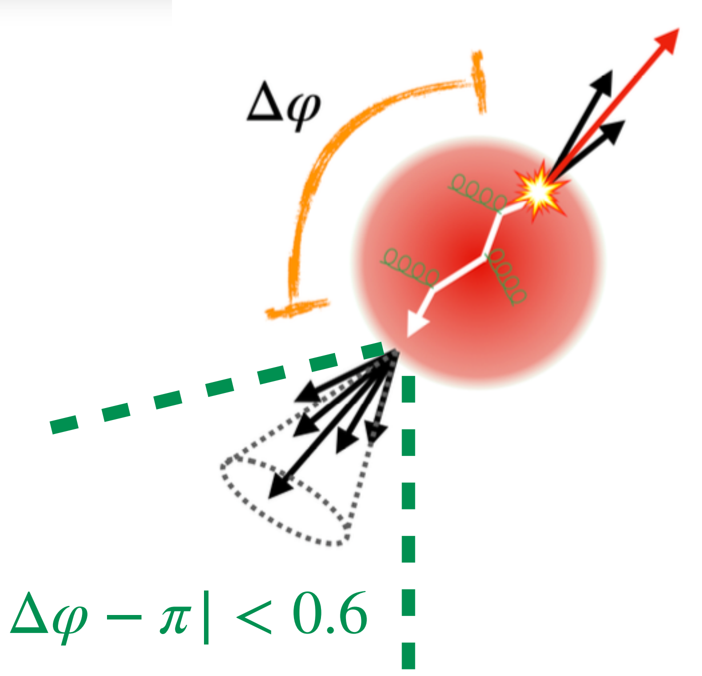

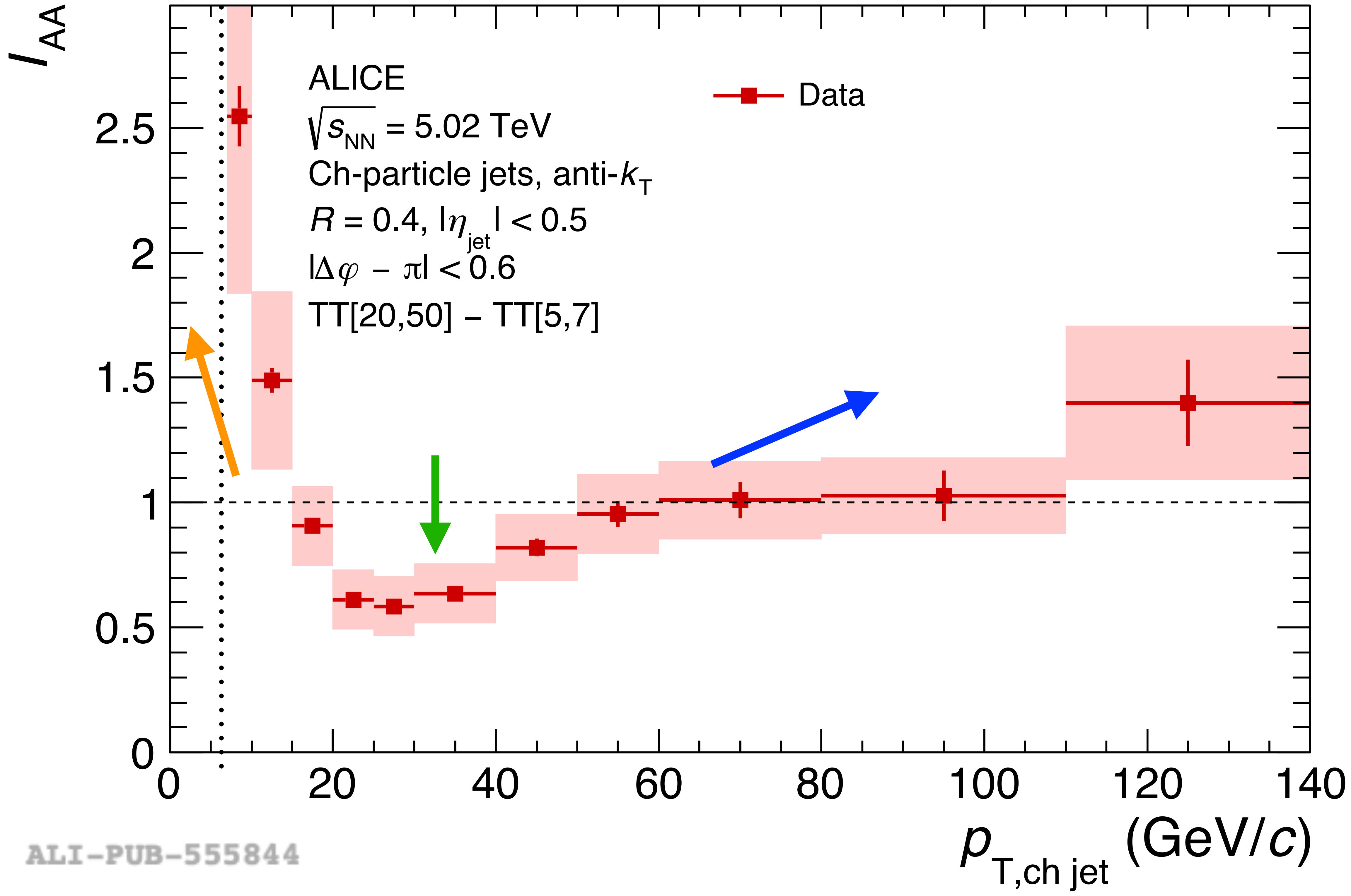

- **Jet yield enhancement** at low p_T

  → hint of energy recovery in low p_T jets?

- **Jet yield suppression** at $20 < p_{T,jet} < 60$ GeV/c

  → Jet energy loss

- **Rising trend** with increasing jet p_T

  → Interplay of jet quenching and jet production or hadron energy loss?

Phys.Lett.B 854 (2024) 138739

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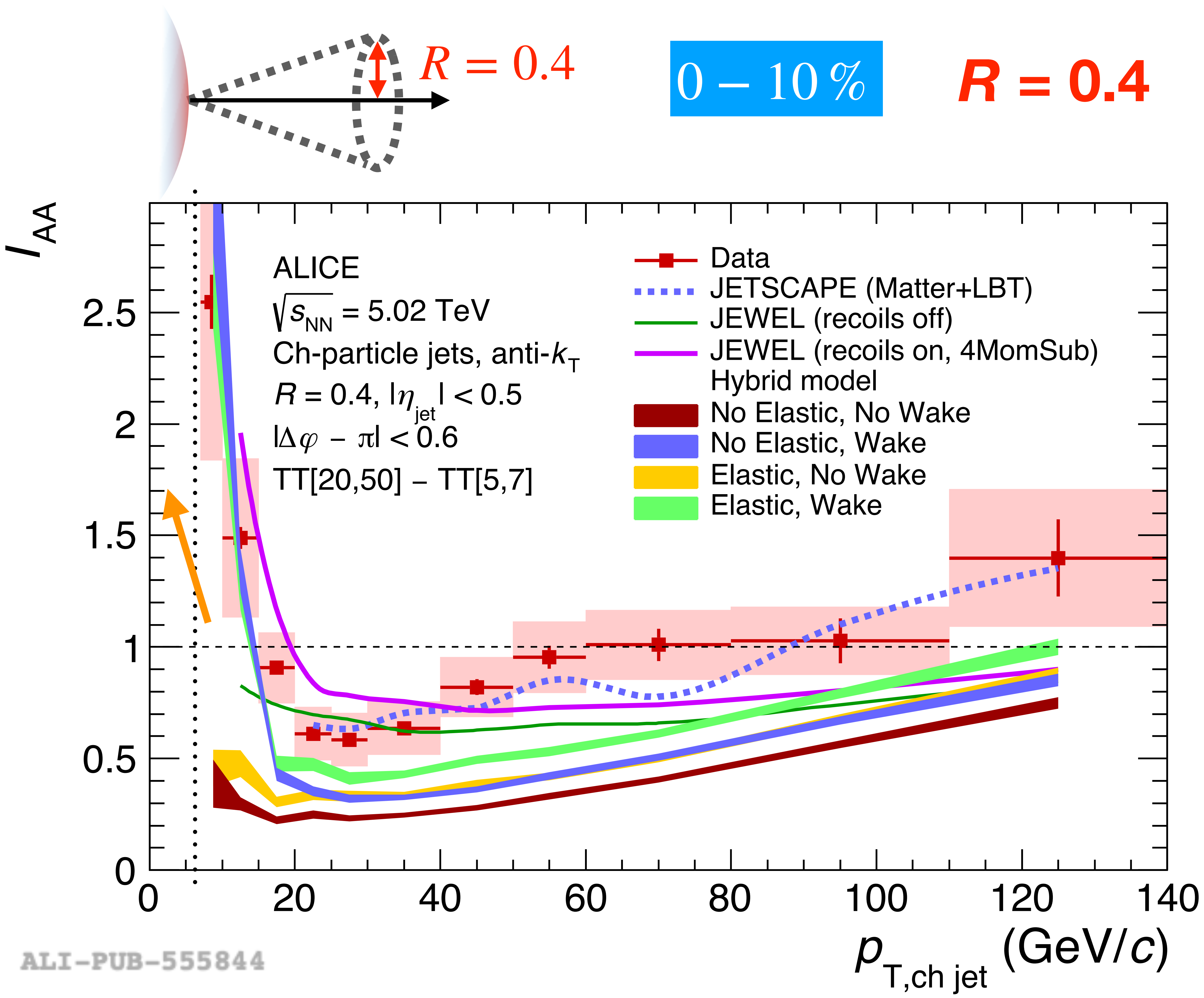
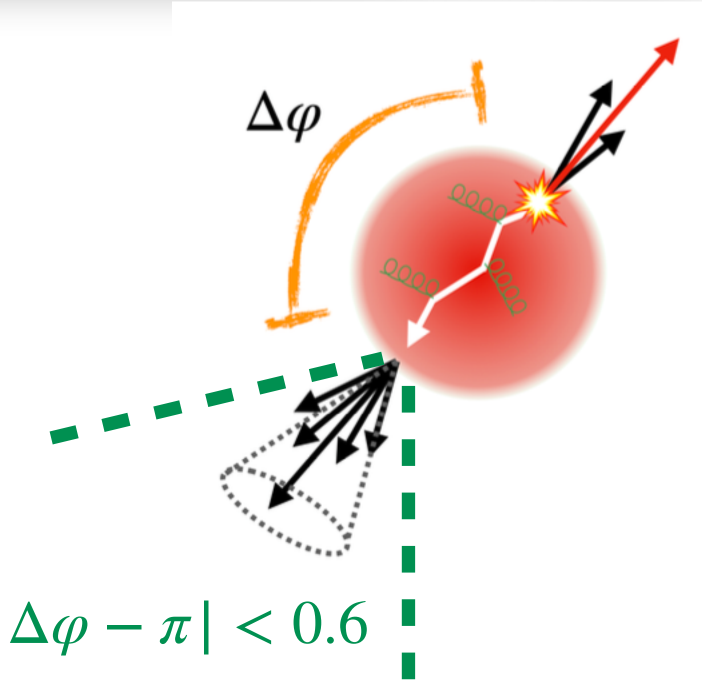


$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}\,(p_T)_{AA}}{\Delta_{\mathrm{recoil}}\,(p_T)_{pp}}$$



JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss based on MATTER (high virtuality) + LBT (low virtuality)

JEWEL: perturbative treatment to jet quenching
arXiv:1311.0048, https://jewel.hepforge.org/
Includes collisional and radiative parton energy loss mechanisms in a pQCD approach. medium response effects via the treatment of 'recoils'

Hybrid Model: strong (DGLAP) / weak (AdS/CFT) coupling 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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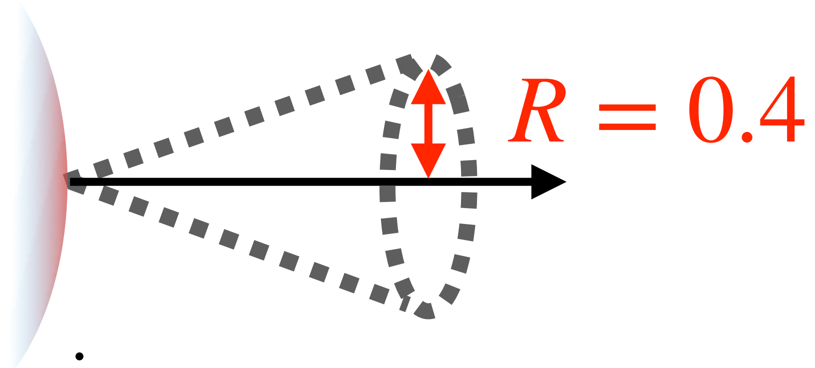

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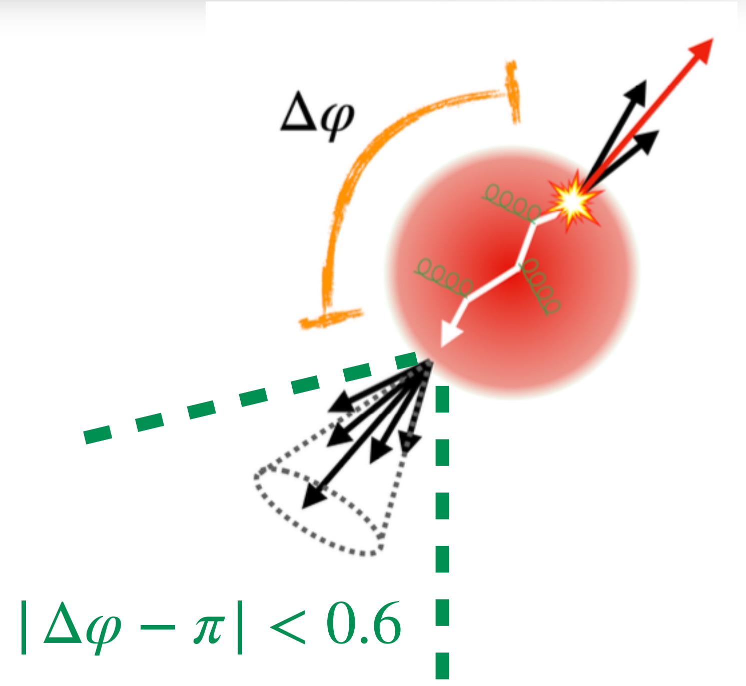
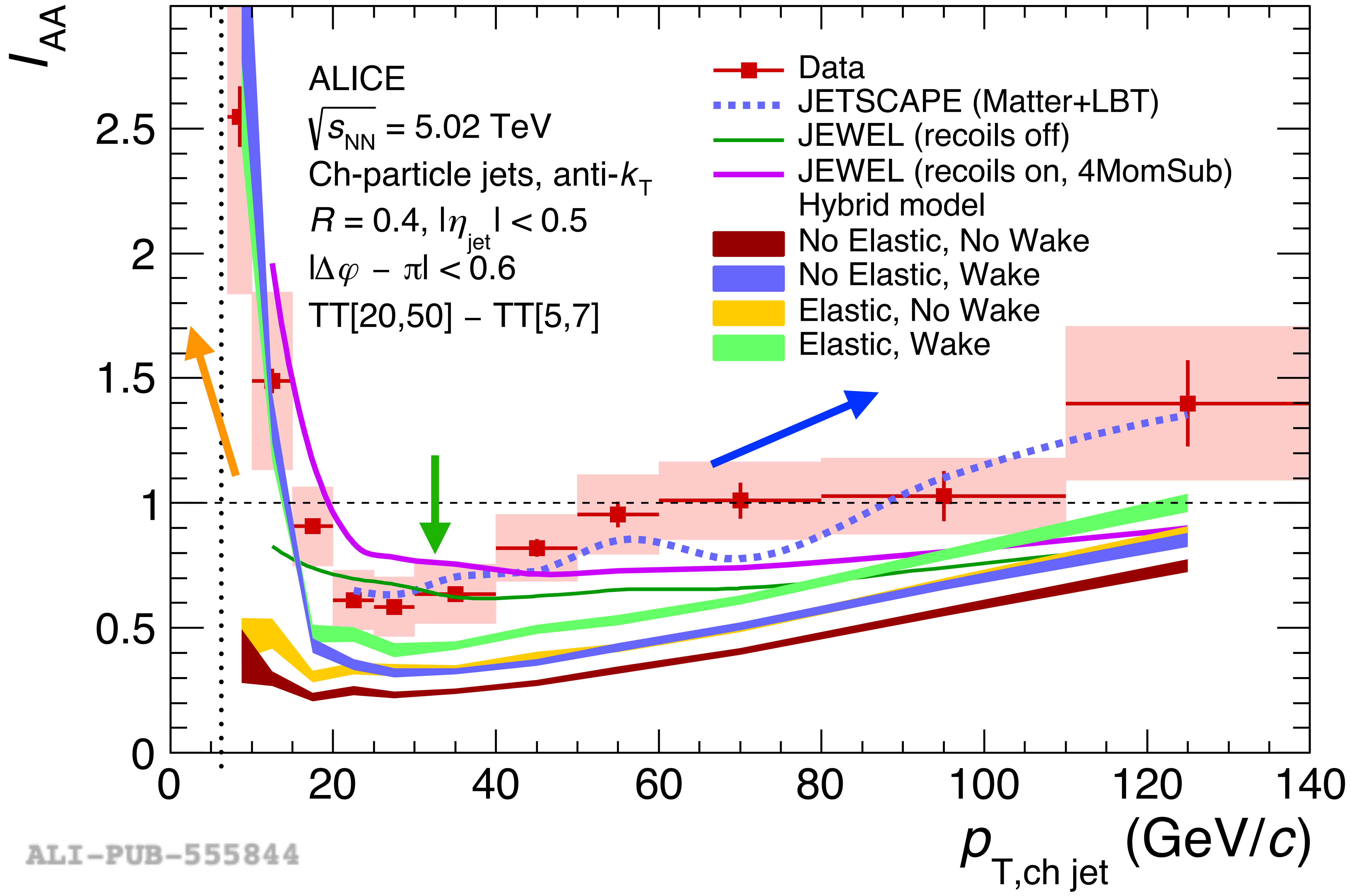
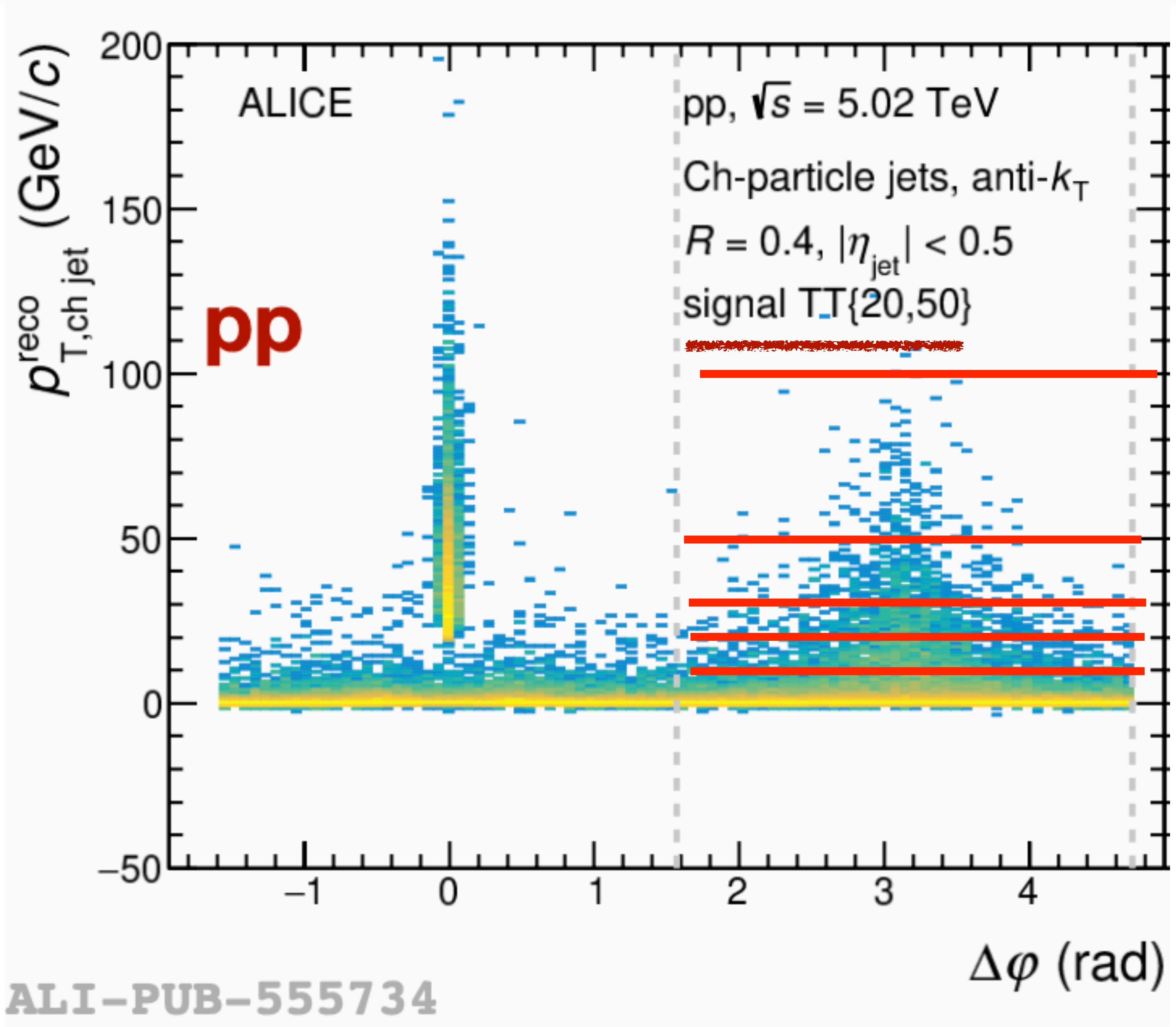
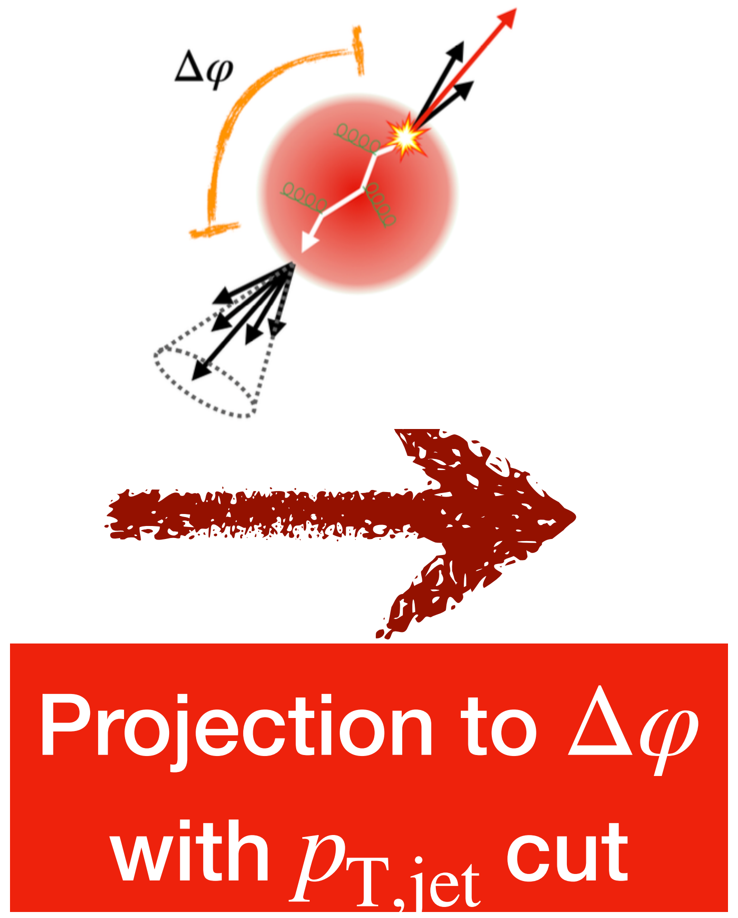


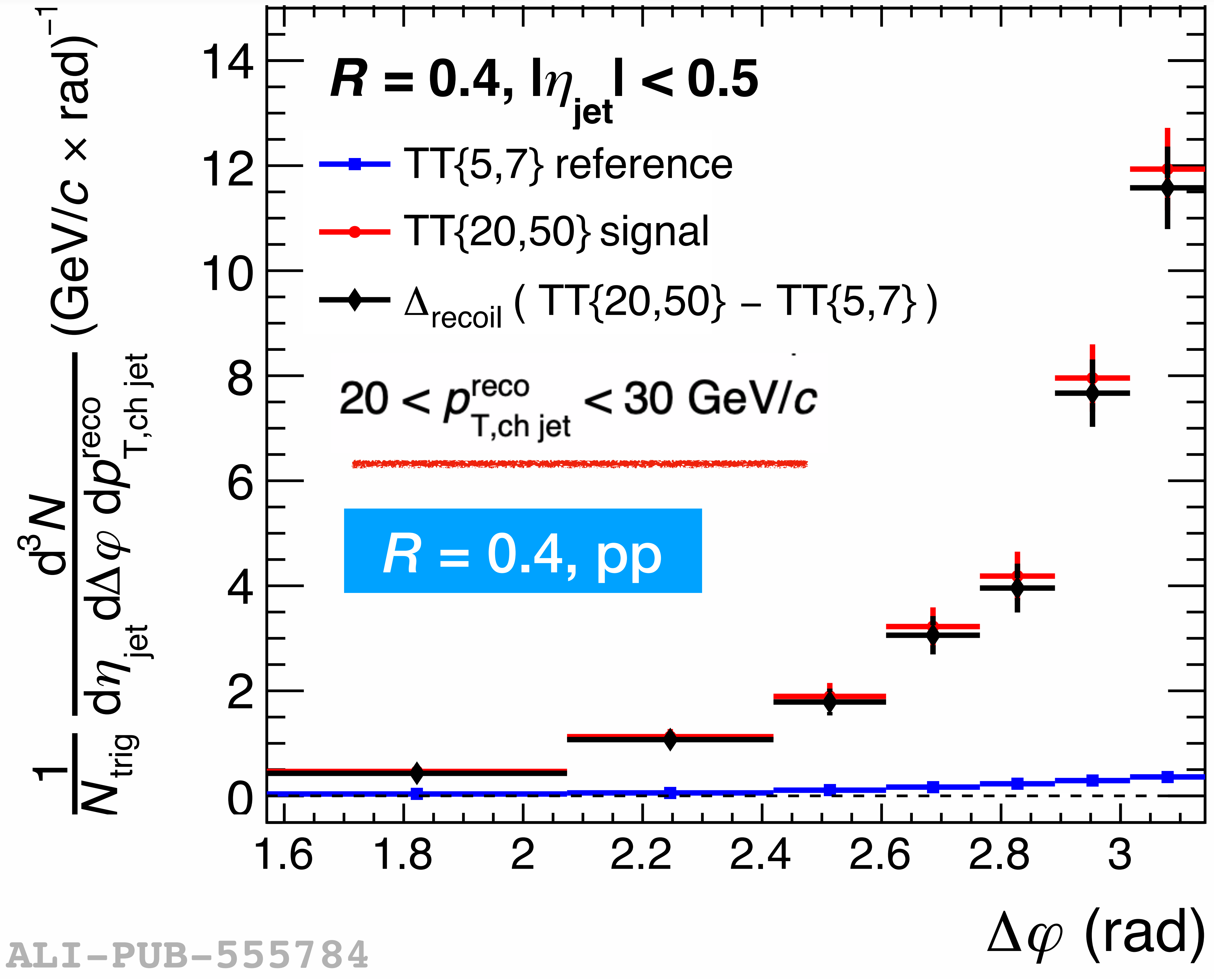


- The **rising trend** is qualitatively described by all predictions
  - **JETSCAPE largely reproduces** the I_{AA} distributions
  - **Hybrid Model** and **JEWEL** predictions **overestimate the suppression** at high p_T
- **Hybrid Models** with wake effect and **JEWEL with recoils on** seem to catch the yield enhancement at low p_T
  - **Medium response** could be responsible for the yield **enhancement**

Recoil jet $\Delta\varphi$ distributions







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

- Recoil jet p_T **vs $\Delta\varphi$ 2-dimensional** distributions in two trigger track p_T intervals
- **$\Delta\varphi$ distributions** measured for the two TT classes using 2D projections

Δ_{recoil} ($\Delta\varphi$) distributions in pp at 13 TeV: $R = 0.4$

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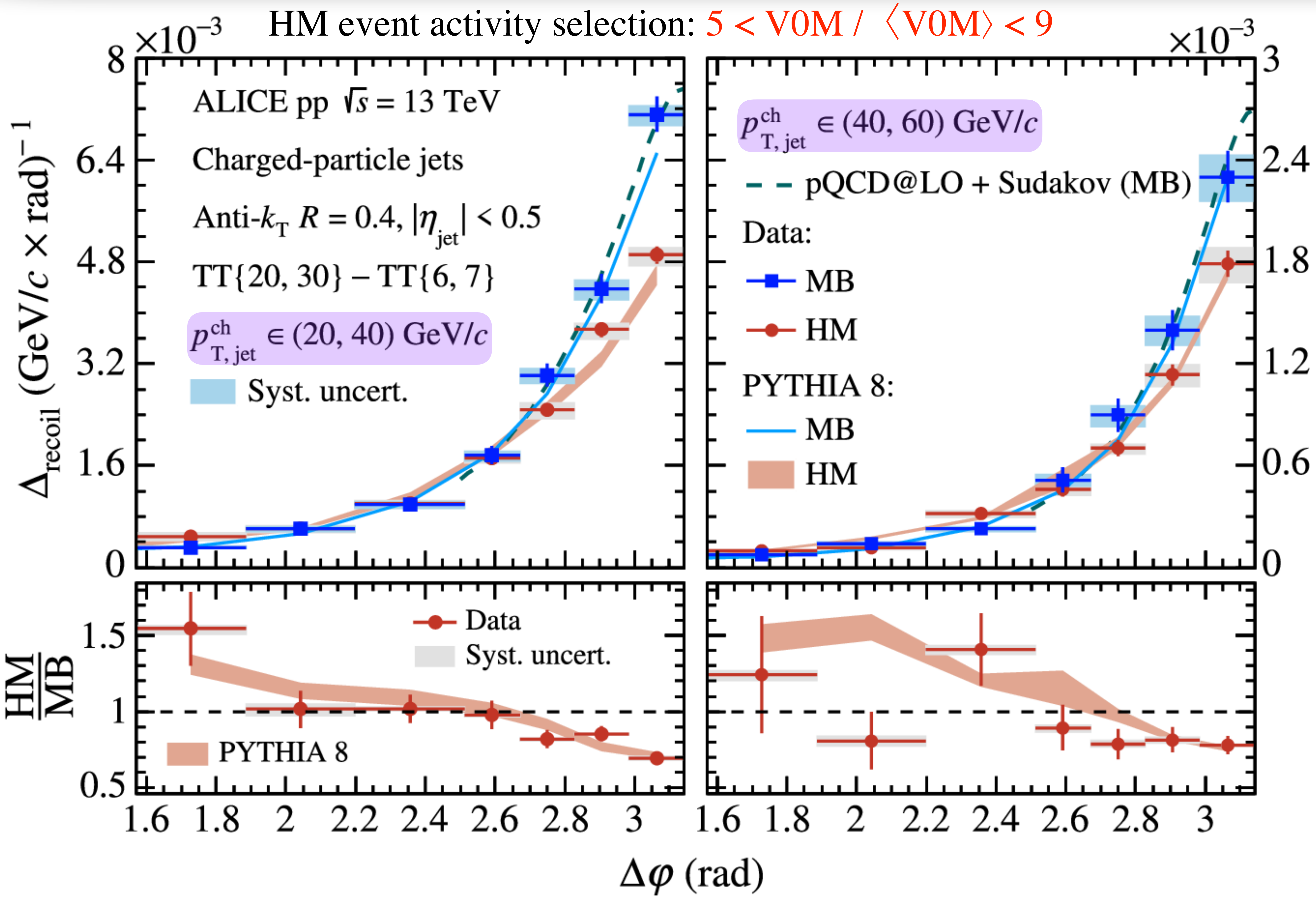
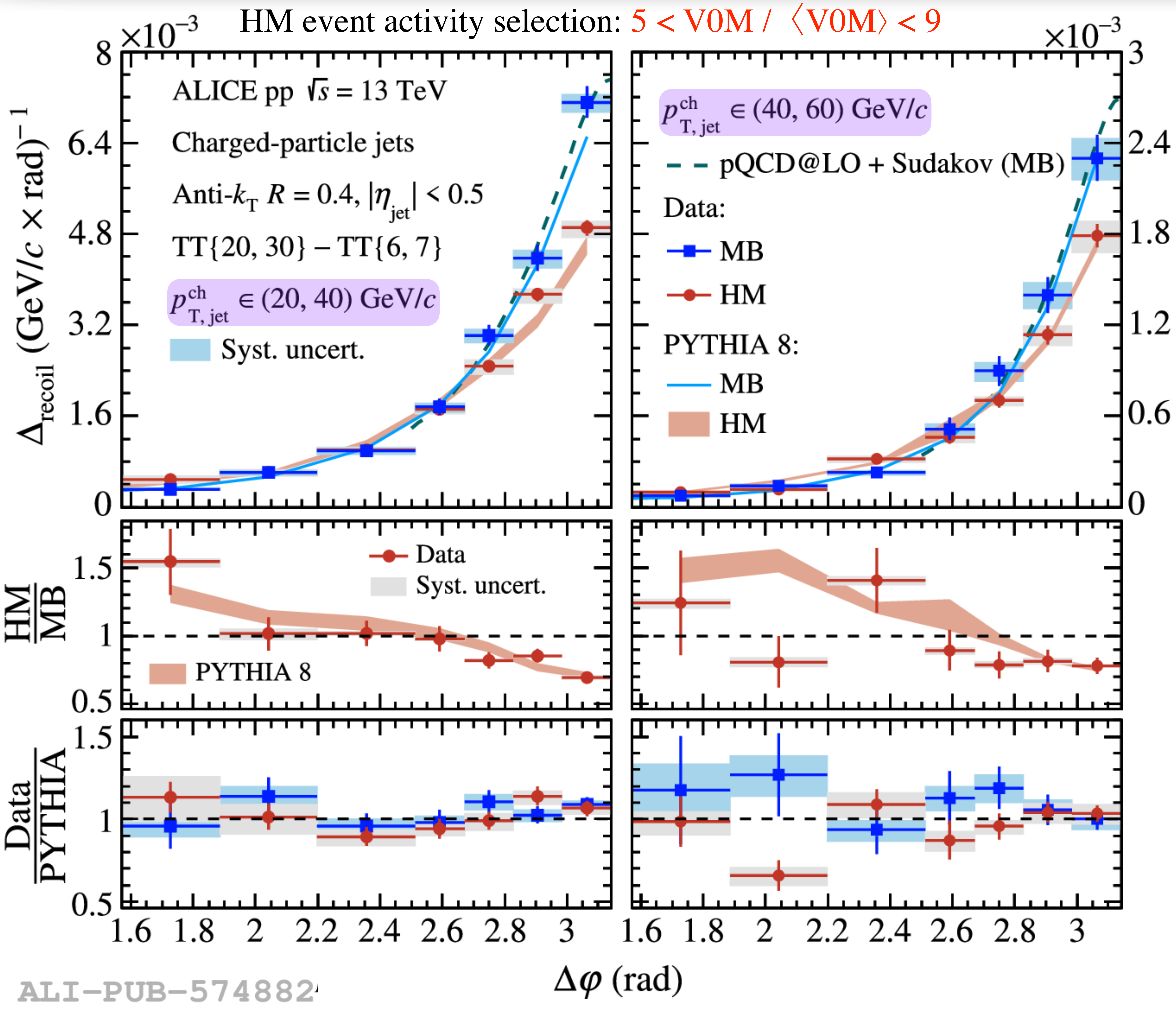
HM event activity selection: 5 < V0M / ⟨V0M⟩ < 9



- **Suppression** of back-to-back jet production
- **Broadening** of HM acoplanarity distribution with respect to MB
  - The effect is stronger for low p_T jets
  - Resembles jet quenching effects?



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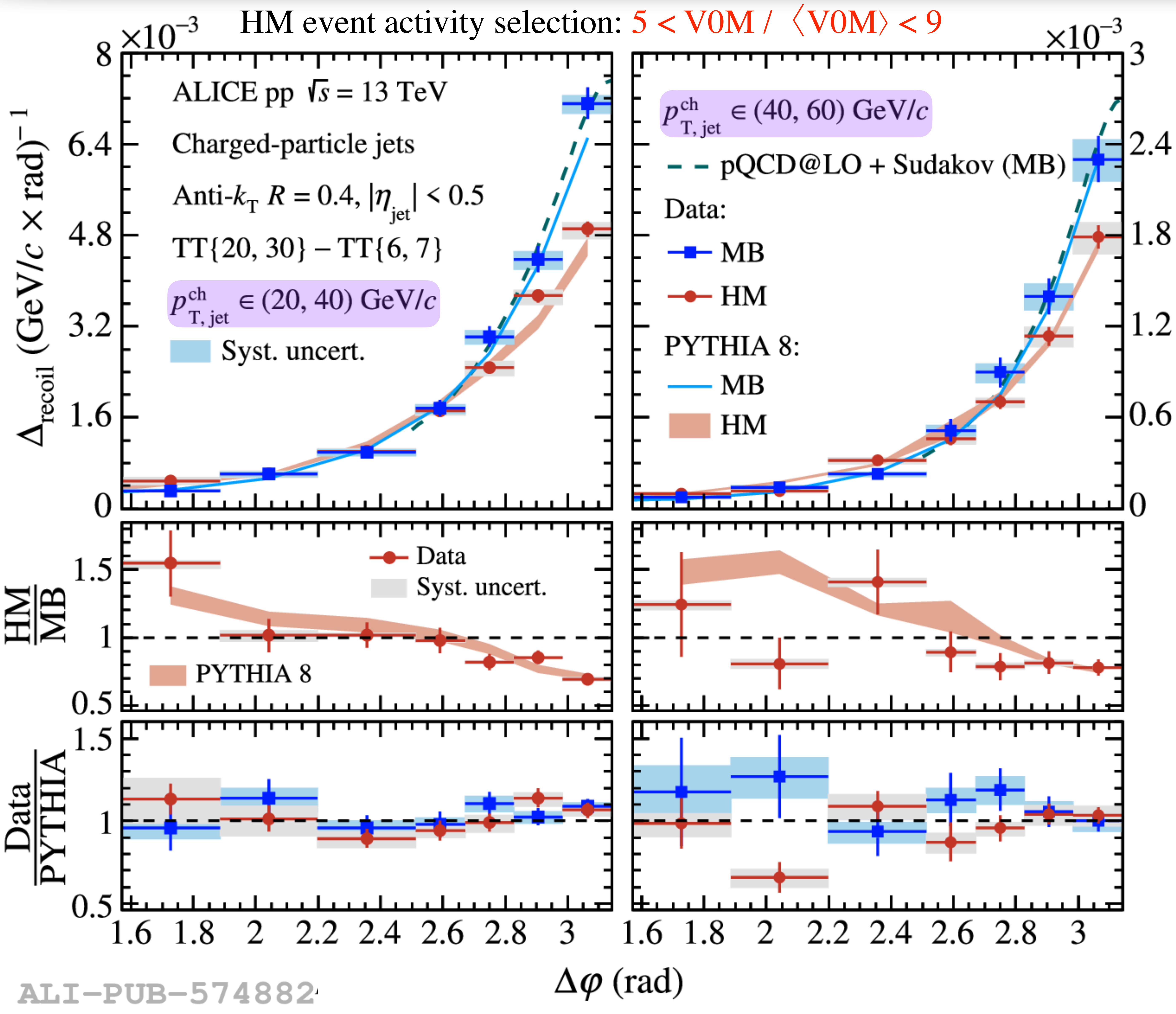
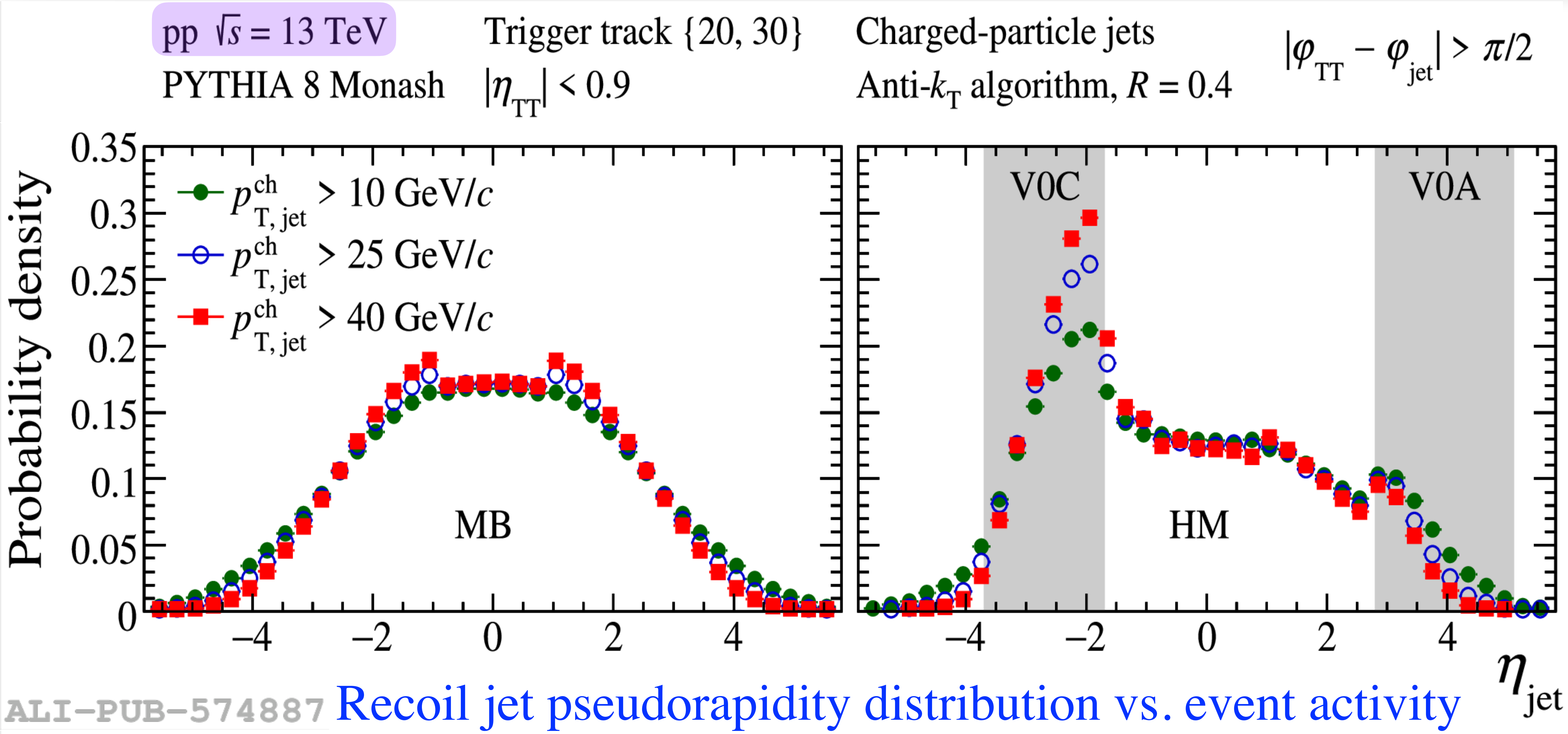
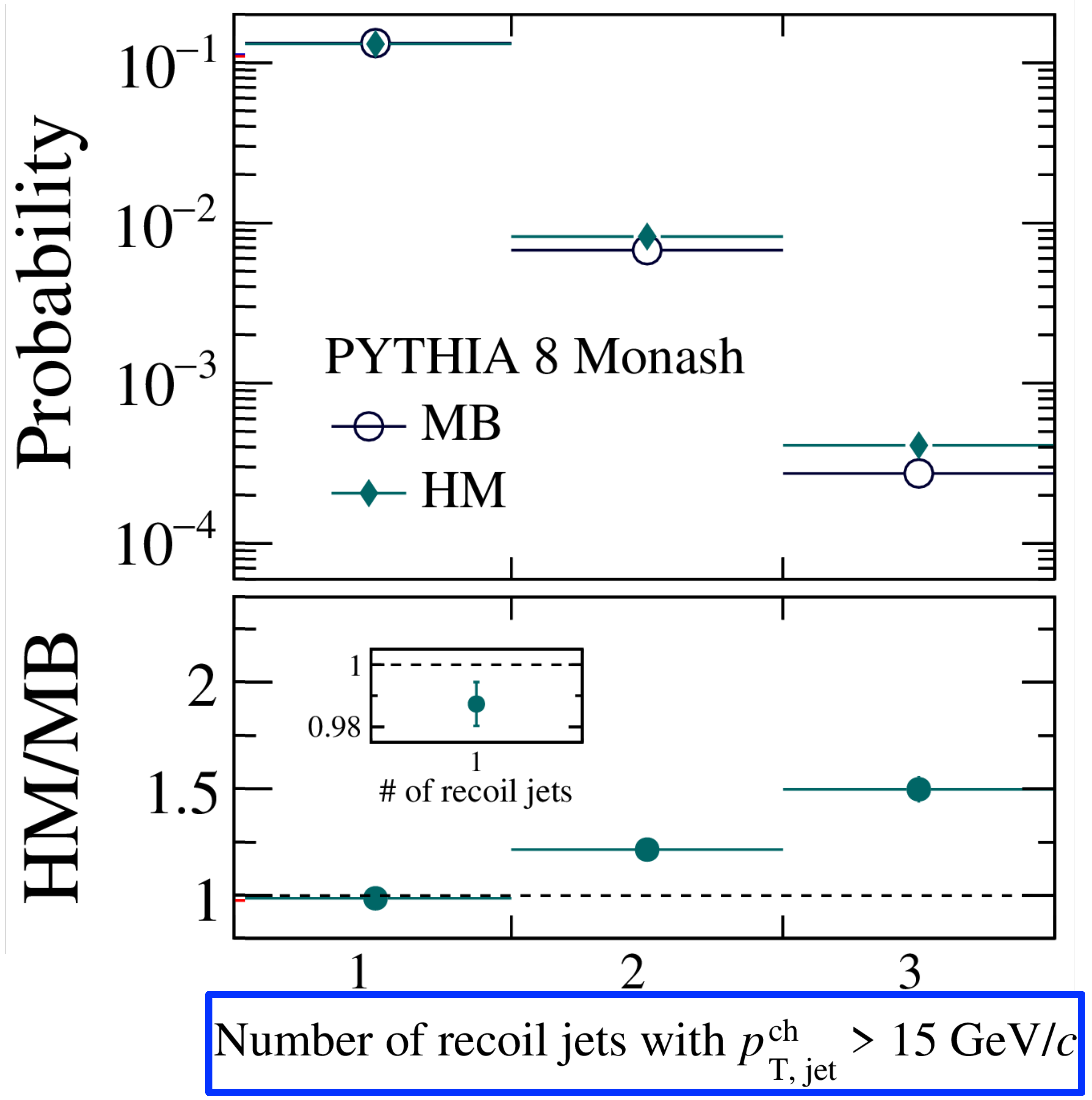


- **Suppression** of back-to-back jet production
- **Broadening** of HM acoplanarity distribution with respect to MB
  - The effect is stronger for low p_T jets
  - Resembles jet quenching effects?

- Quantitative comparison to PYTHIA 8 Monash (does not account for jet quenching effects) shows similar suppression pattern
  - Indicate the effect is not from the jet-medium interaction
  - Use PYTHIA to explore the origin of the effect → **HM event selection**

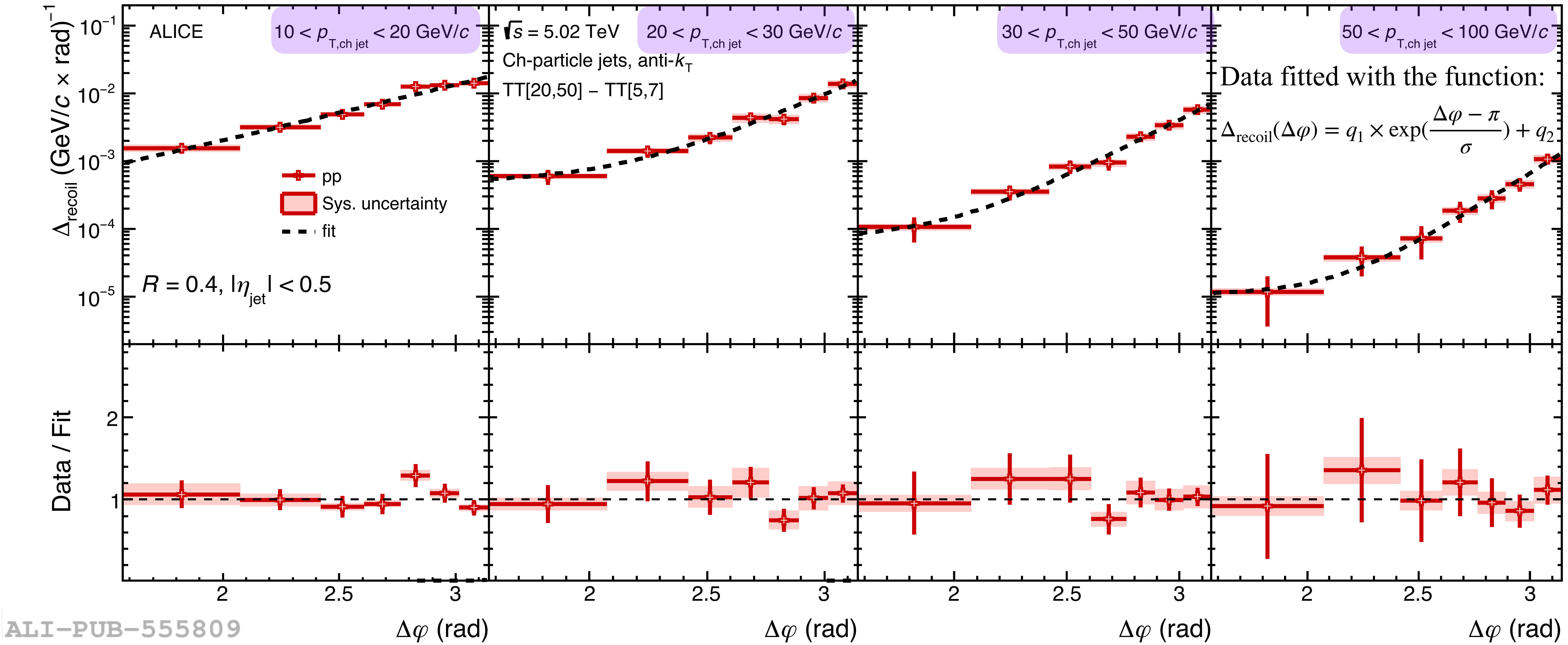


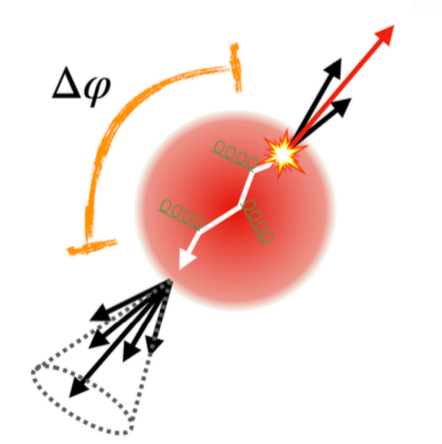
Recoil jet pseudorapidity distribution vs. event activity



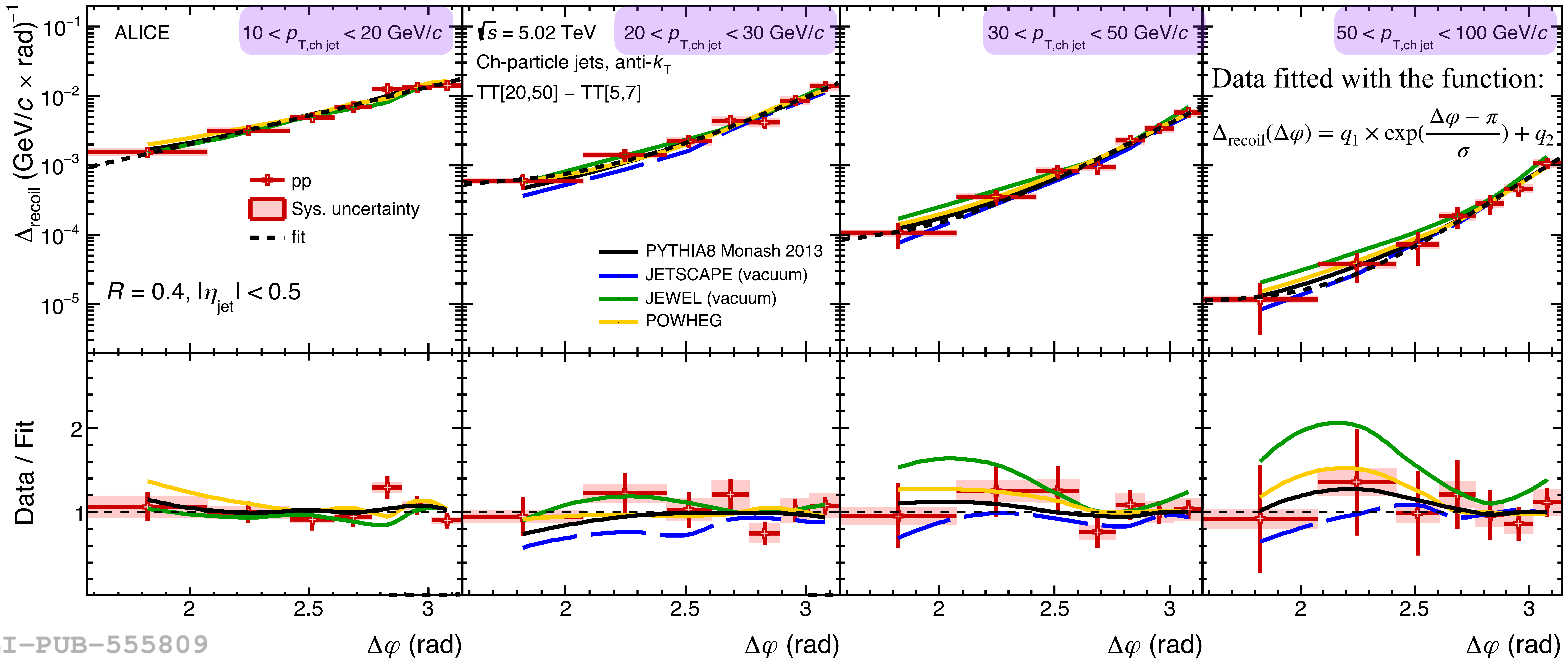
- **Larger enhancement in V0C** resulting from the asymmetric pseudorapidity acceptance of V0A and V0C **in HM events**
  → significant bias in the distribution of high-$p_{\rm T}$ recoil jets
- Broader jets are selected more **in the V0C for HM events** could hide the jet-medium interaction signal
  → Jet quenching signals **can be masked by effects coming from trigger**

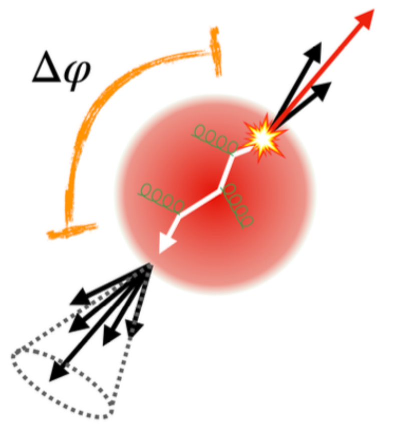
$\Delta_{\rm recoil}$ ($\Delta\varphi$) distributions in pp at 5.02 TeV: $R = 0.4$





- Corrected $\Delta_{\rm recoil}(\Delta\varphi)$ distributions for $R = 0.4$ in different jet $p_{\rm T}$ bins (10-20-30-50-100 GeV/c)





- Corrected $\Delta_{recoil}(\Delta\varphi)$ distributions for $R = 0.4$ in different jet p_T bins (10-20-30-50-100 GeV/c)
- Described well by different model calculations within uncertainties

Δ_{recoil} ($\Delta\varphi$) distributions in pp & Pb-Pb

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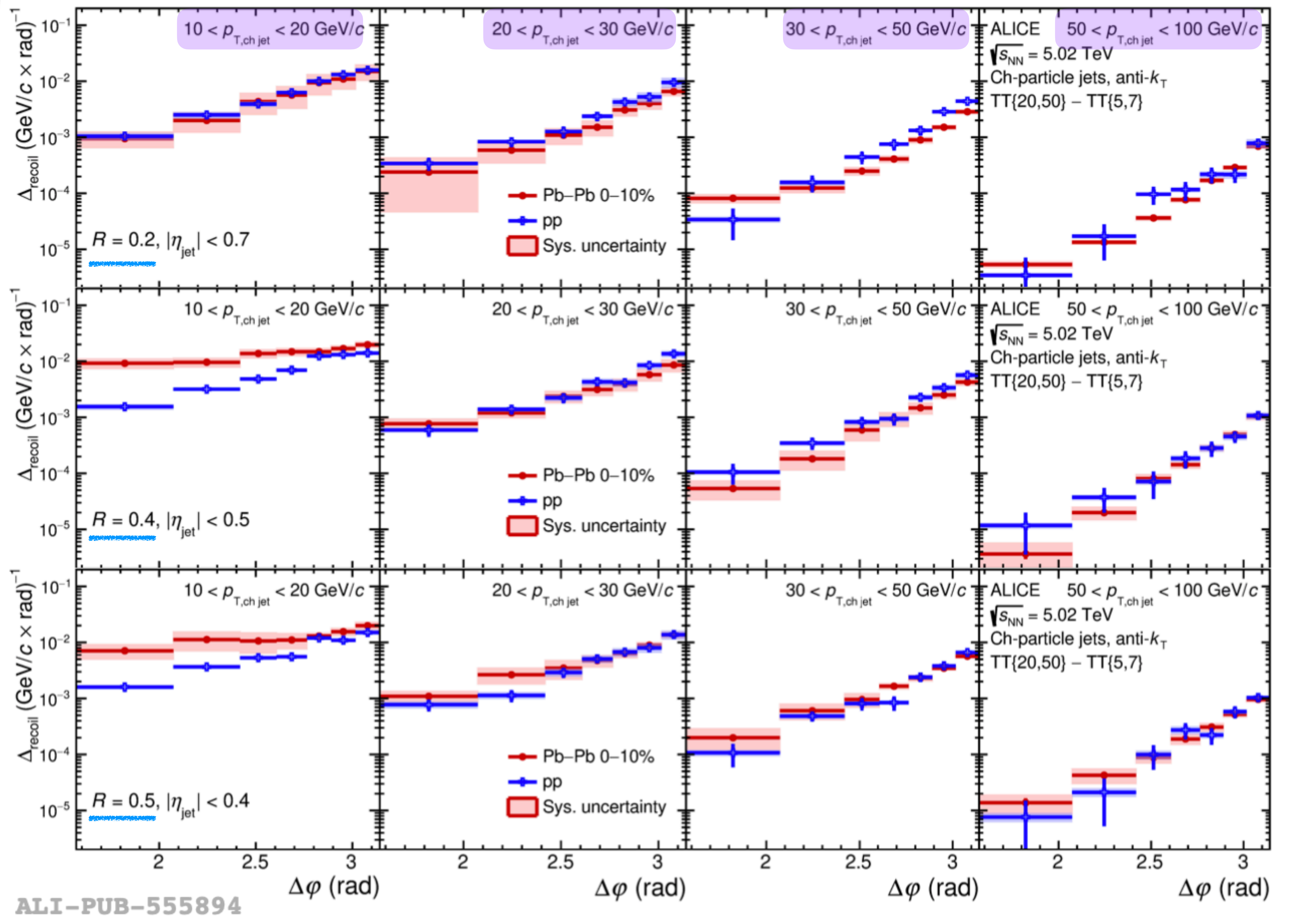

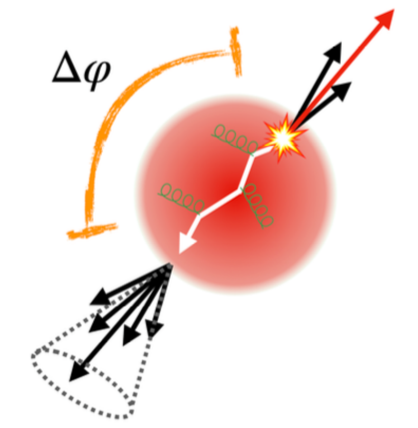

pp

Pb-Pb

Δ_{recoil} $(\Delta\varphi)$ distributions in pp & Pb-Pb

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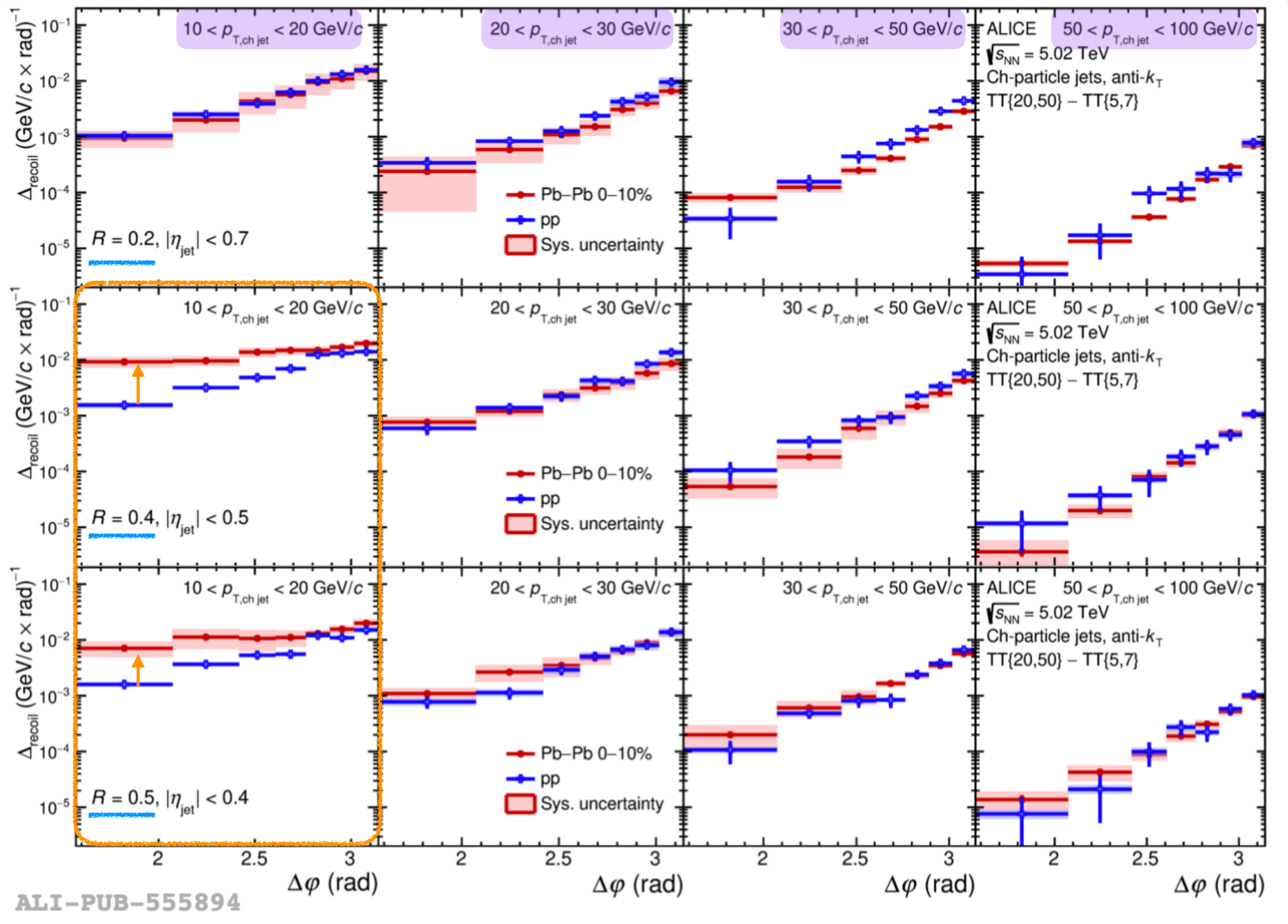
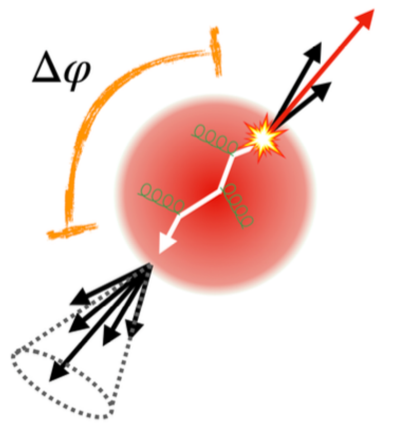
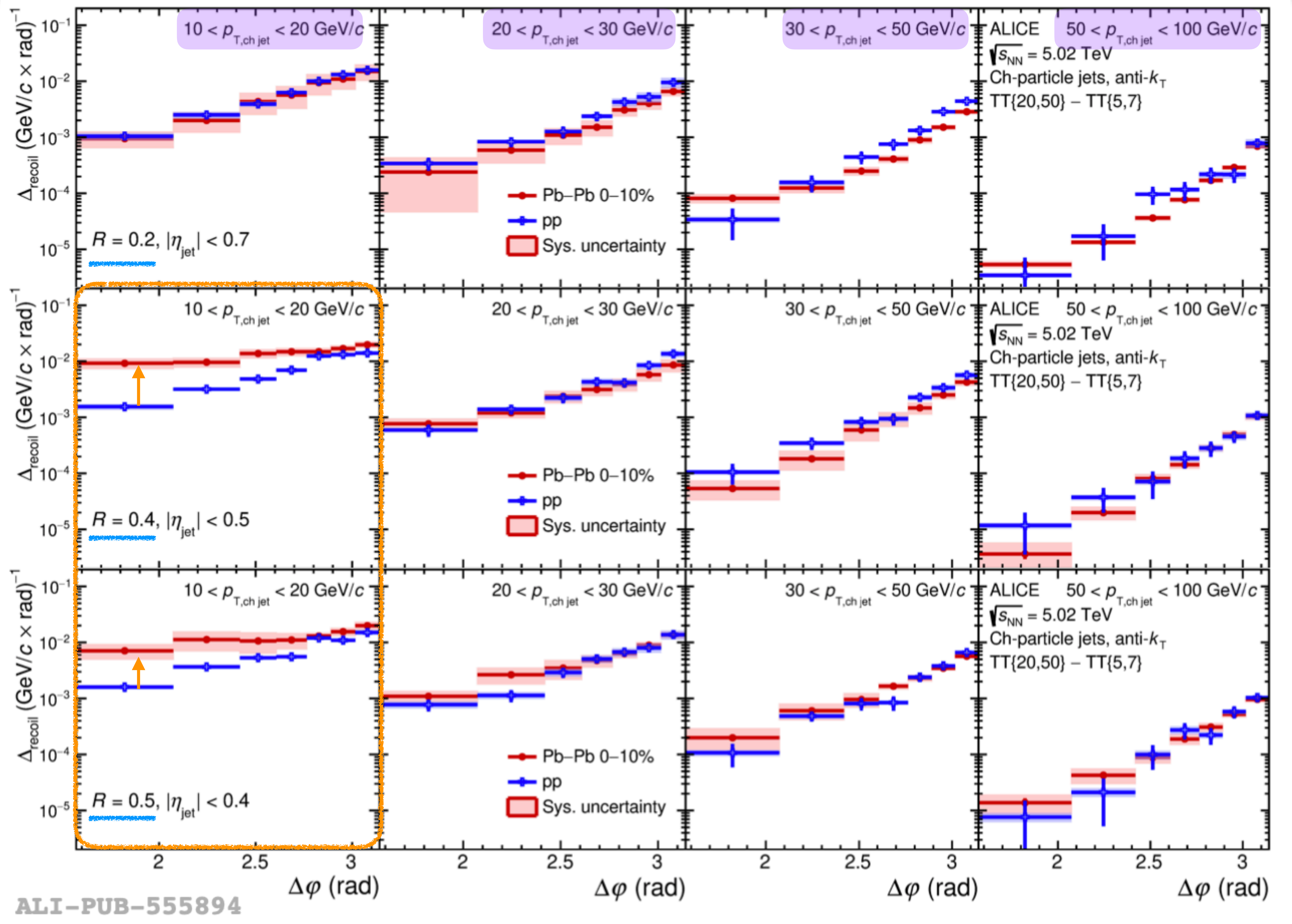


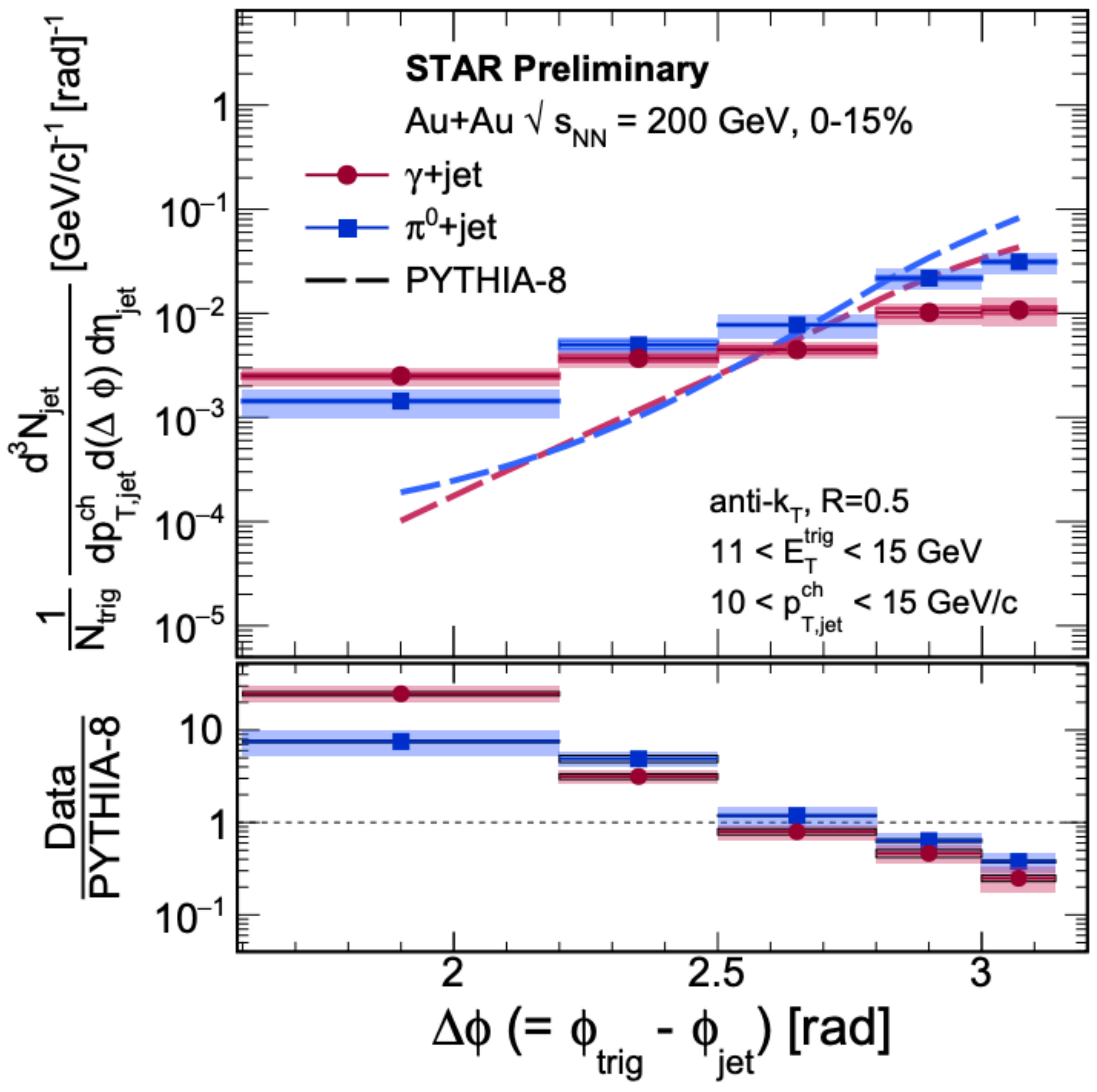


pp

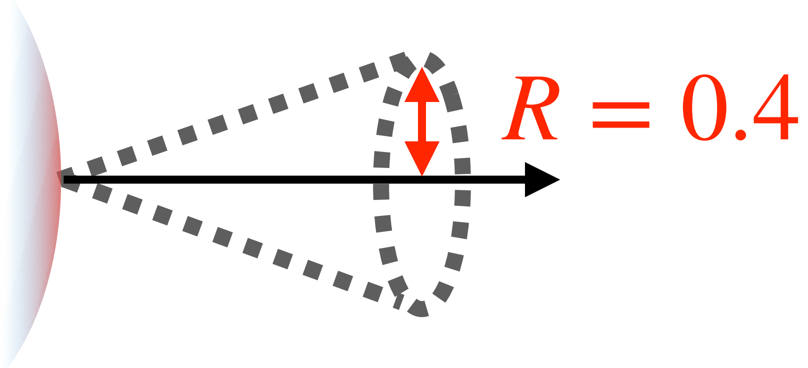
Pb-Pb

- **Significant acoplanarity broadening** for $R = 0.4$ and $R = 0.5$ at low p_T interval





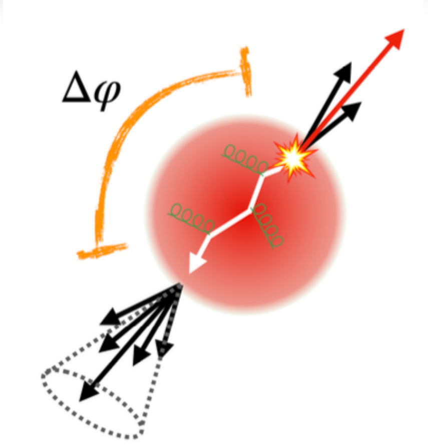
- **Significant acoplanarity broadening** for $R = 0.4$ and $R = 0.5$ at low p_T interval
- **Similar observation** also found by STAR

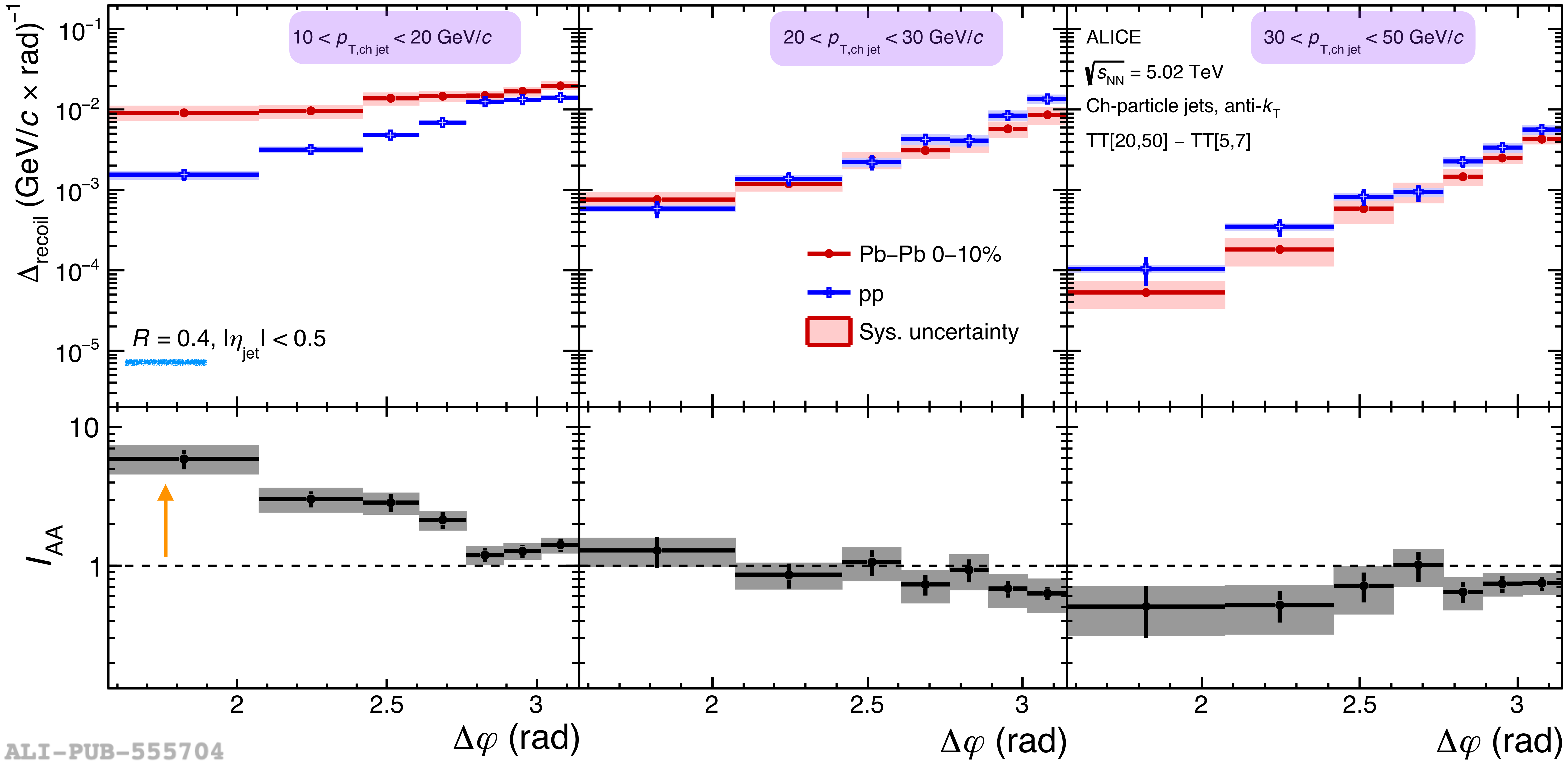


0 – 10 %

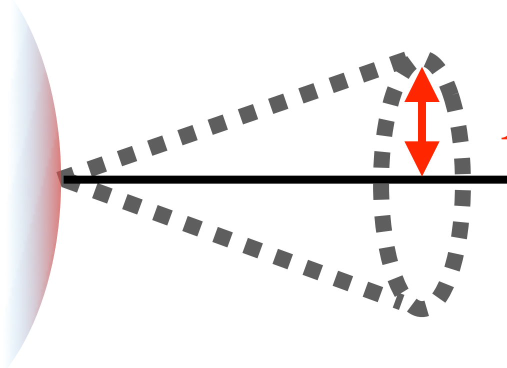
R = 0.4

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





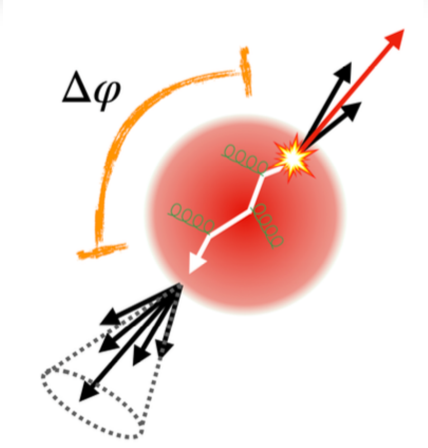
- **Significant broadening** for $p_T \in [10,20]$ GeV/c

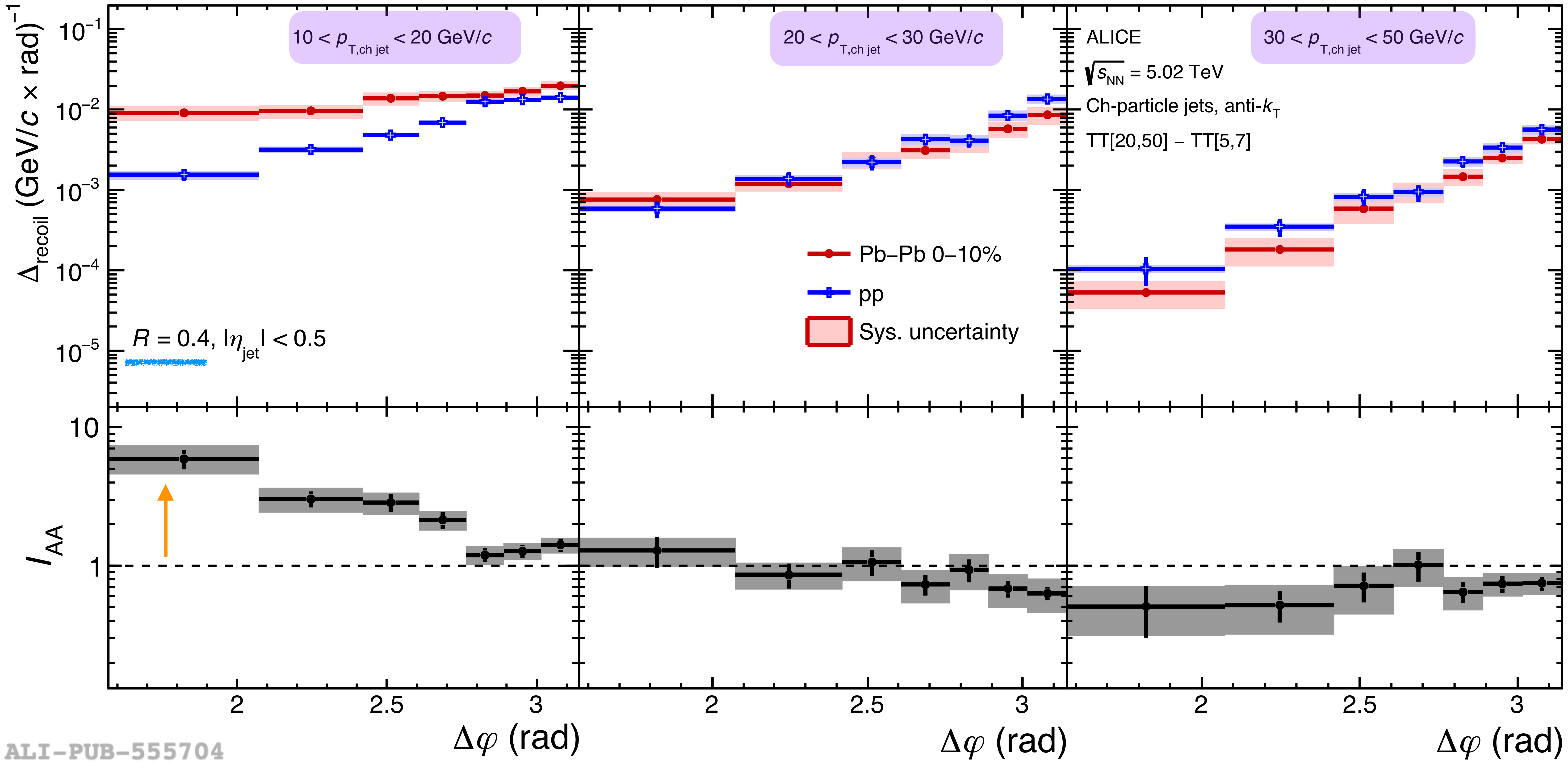


0 – 10 %

R = 0.4

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





- **Significant broadening** for $p_T \in [10,20]$ GeV/c
- **No broadening or suppression** for $p_T \in [20,30]$ GeV/c

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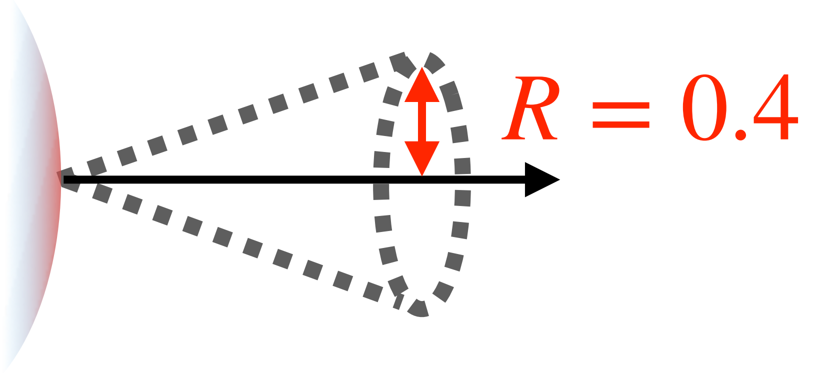

0 – 10 %

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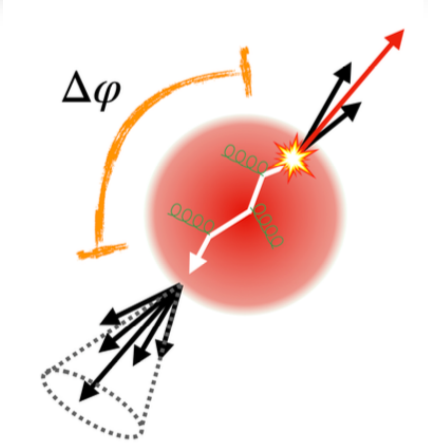
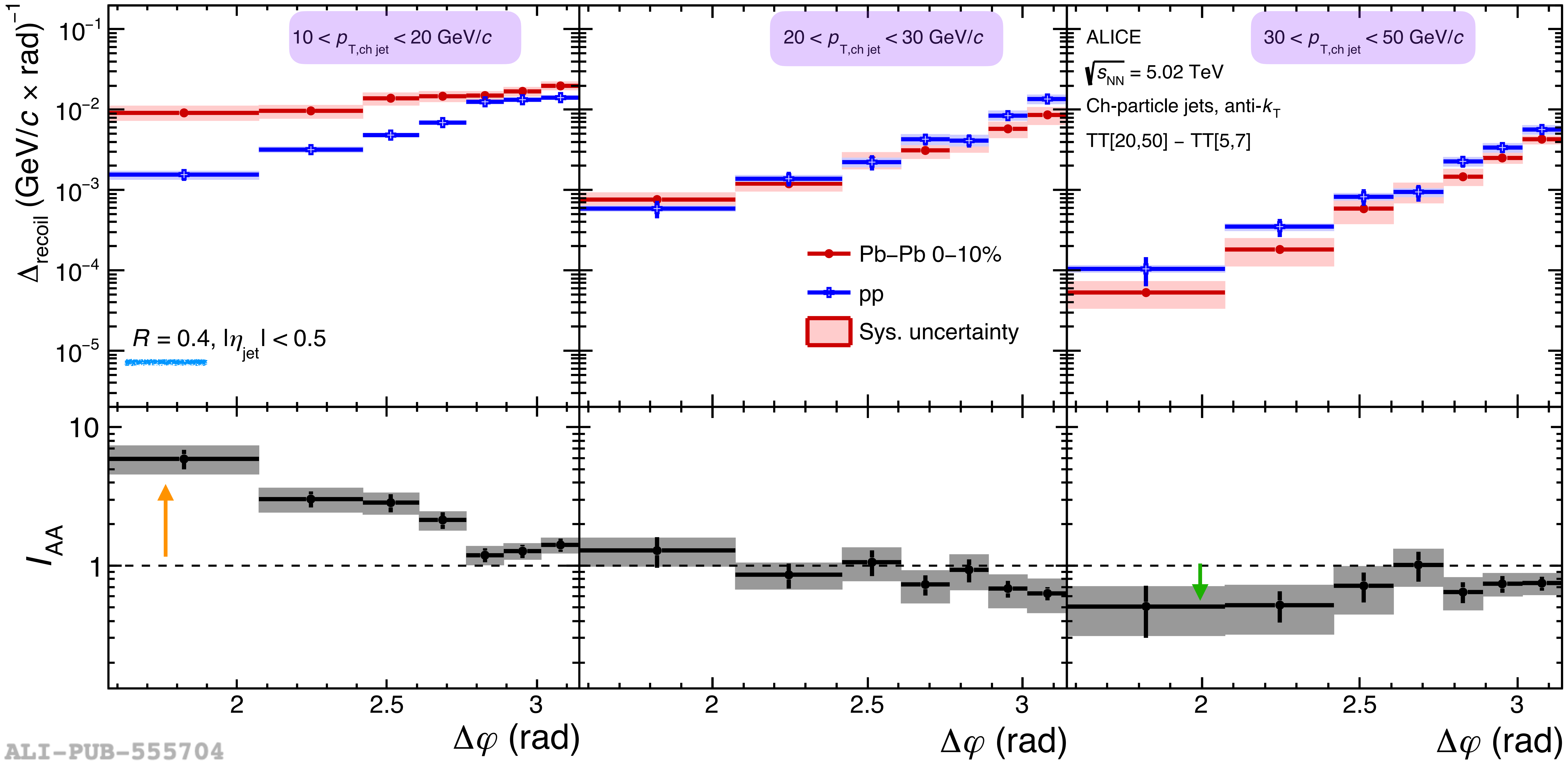
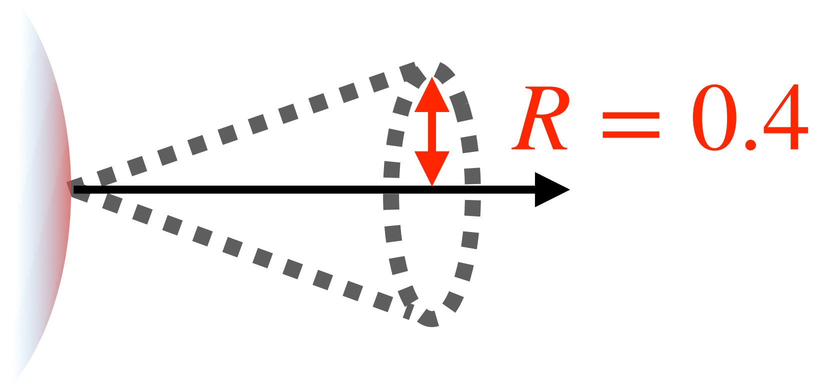
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$





- **Significant broadening** for $p_T \in [10,20]$ GeV/c
- **No broadening or suppression** for $p_T \in [20,30]$ GeV/c
- **Jet yield suppression** for $p_T \in [30,50]$ GeV/c

$I_{AA}(\Delta\varphi)$ compared to models



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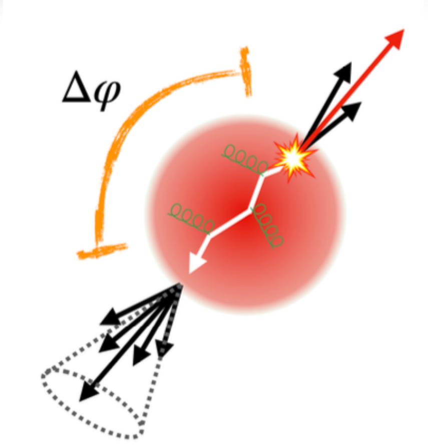

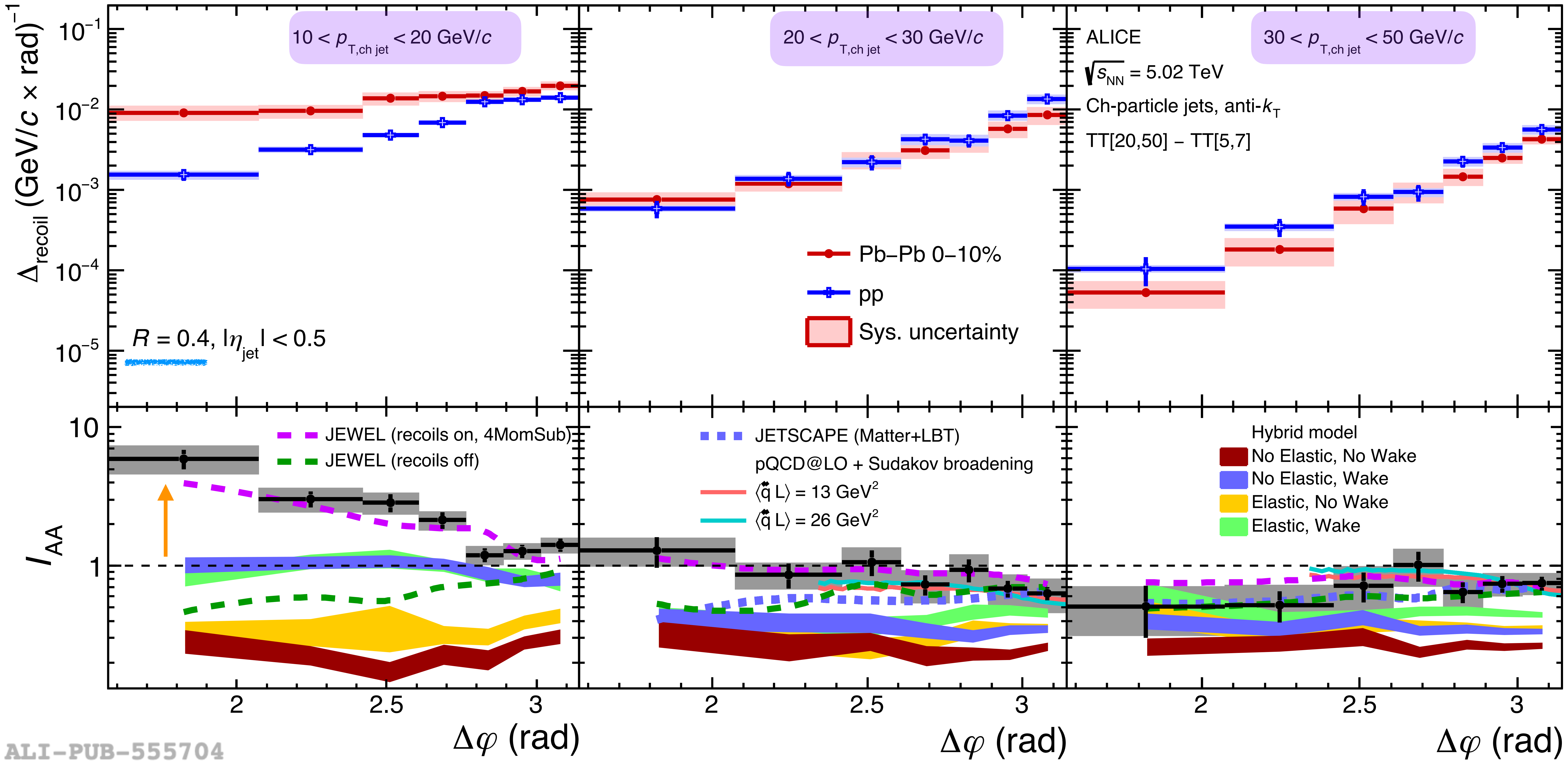

JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss based on MATTER (high virtuality) + LBT (low virtuality)

JEWEL: perturbative treatment to jet quenching
arXiv:1311.0048, https://jewel.hepforge.org/
Includes collisional and radiative parton energy loss mechanisms in a pQCD approach. medium response effects via the treatment of 'recoils'

Hybrid Model: strong (DGLAP) / weak (AdS/CFT) coupling 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
Leading order pQCD, azimuthal broadening via jet transport coefficient

$I_{AA}(\Delta\varphi)$ compared to models

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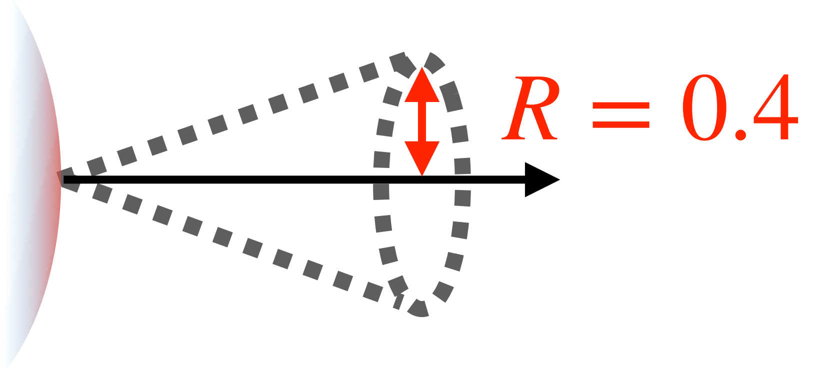

0 – 10 %

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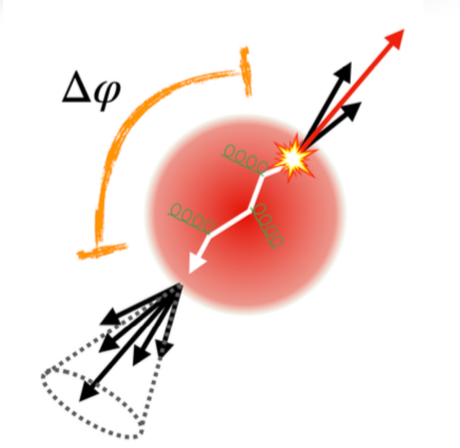
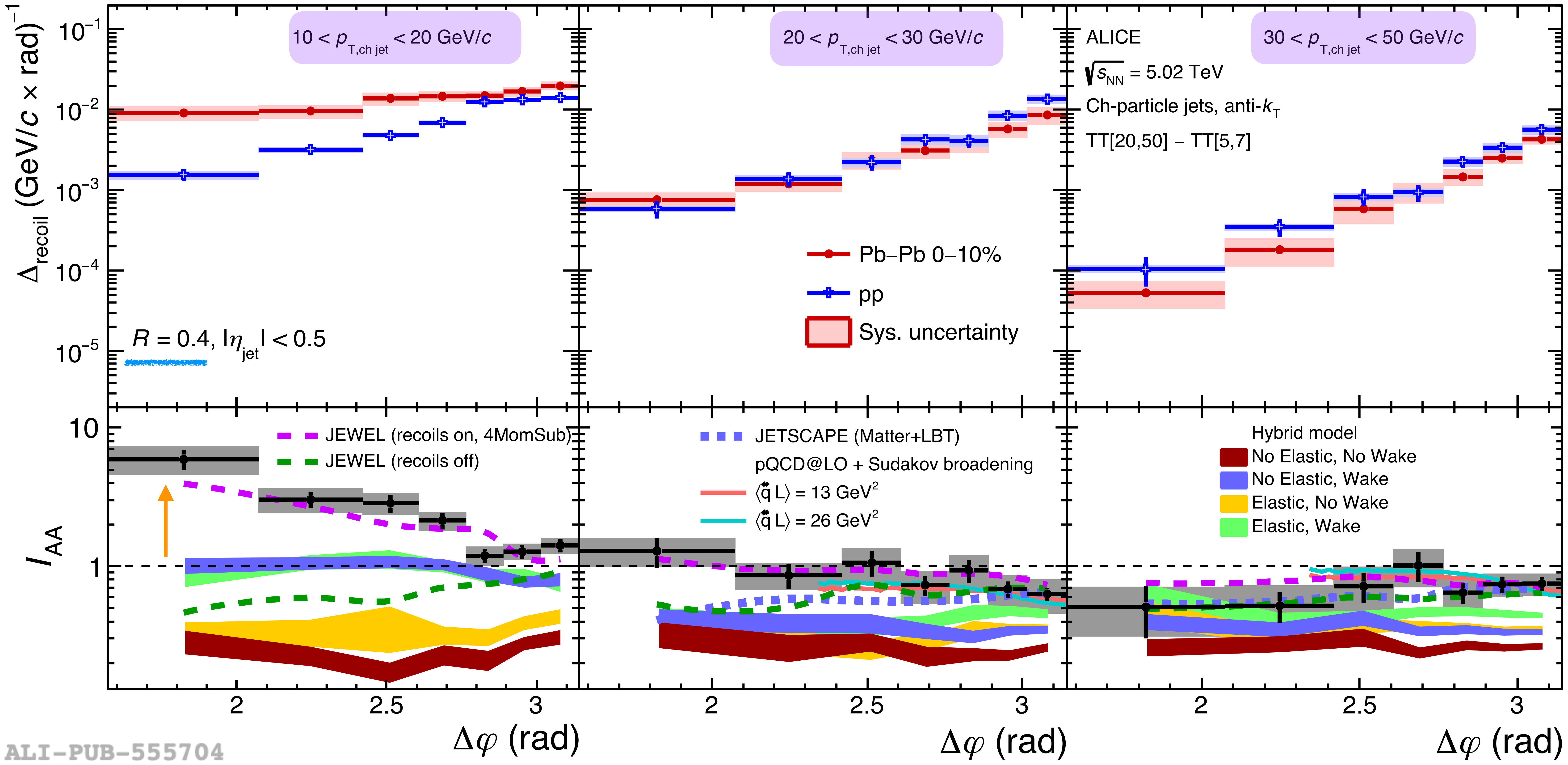
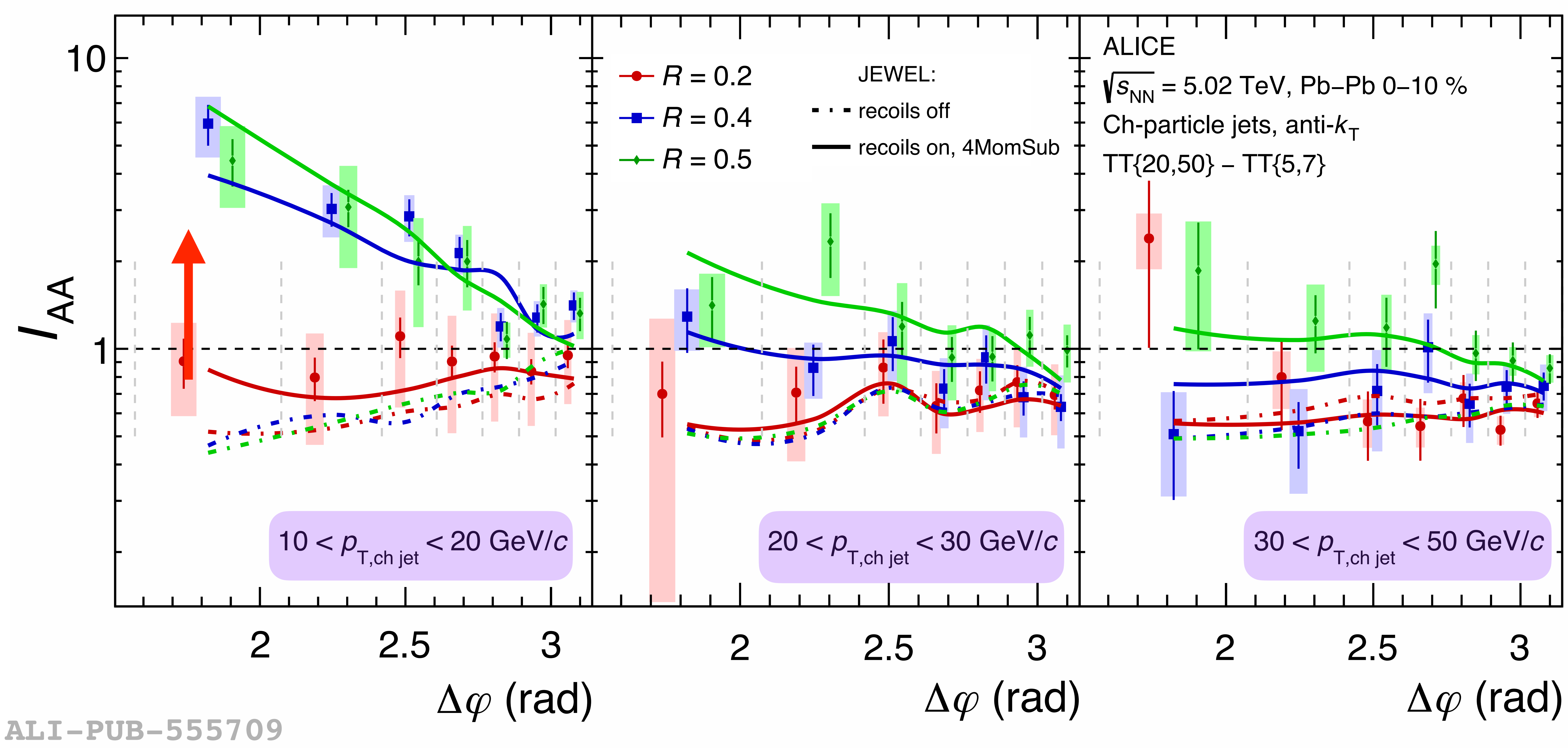
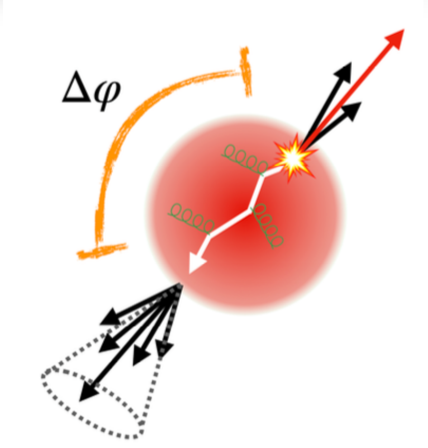




- **JETSCAPE** and **pQCD w/ broadening reasonably describe** the data for jet $p_T \in [20,50]$ GeV/c → lacking precision to resolve the difference between two $\hat{q}$ values
- **JEWEL** (recoils-on) **describes well the I_{AA} in-all p_T bins**
- **Hybrid model** captures the yield enhancement, but no broadening effects are seen when including elastic and wake components





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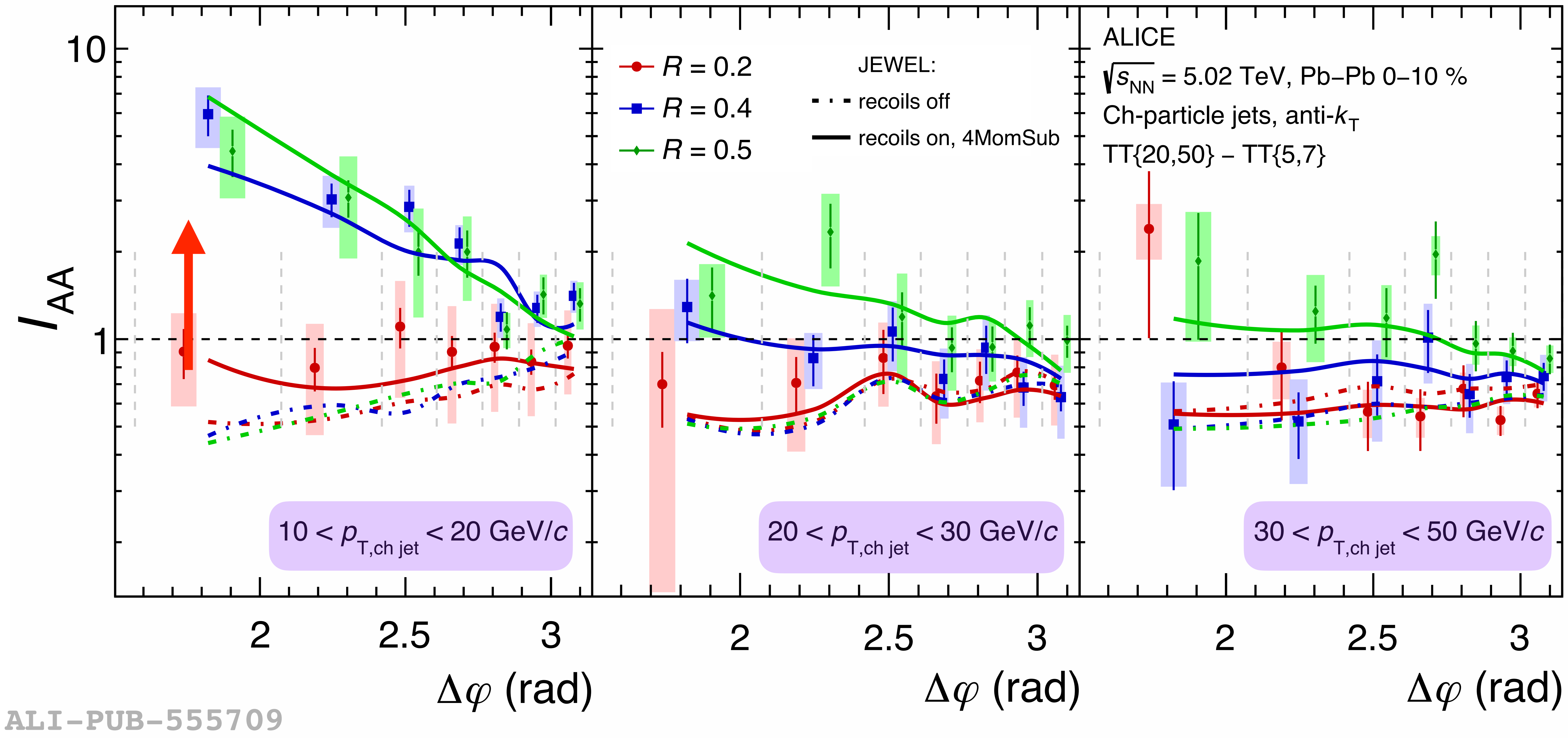
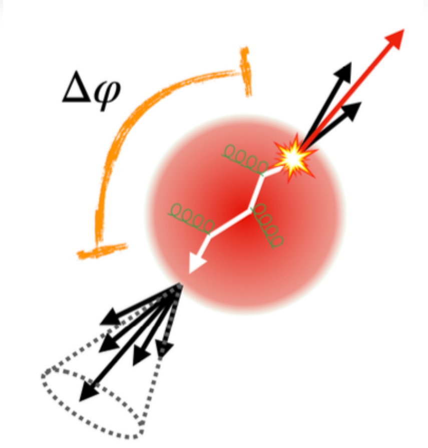
- Transition to broadening from $R = 0.2$ to $R = 0.4$ for $p_T \in [10,20]$ GeV/c → soft particles from the **medium response** clustered inside a jet scale with R^2

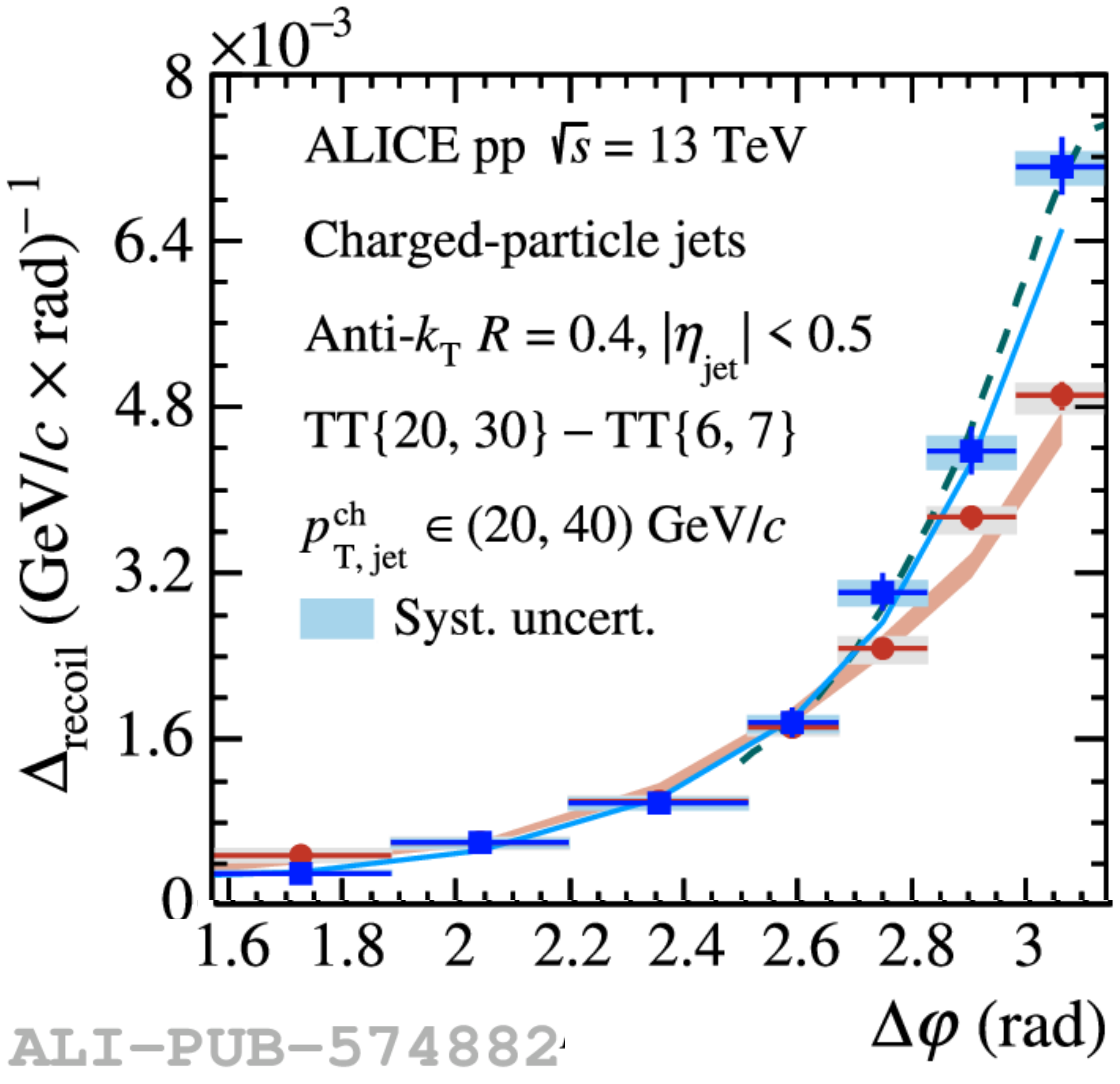


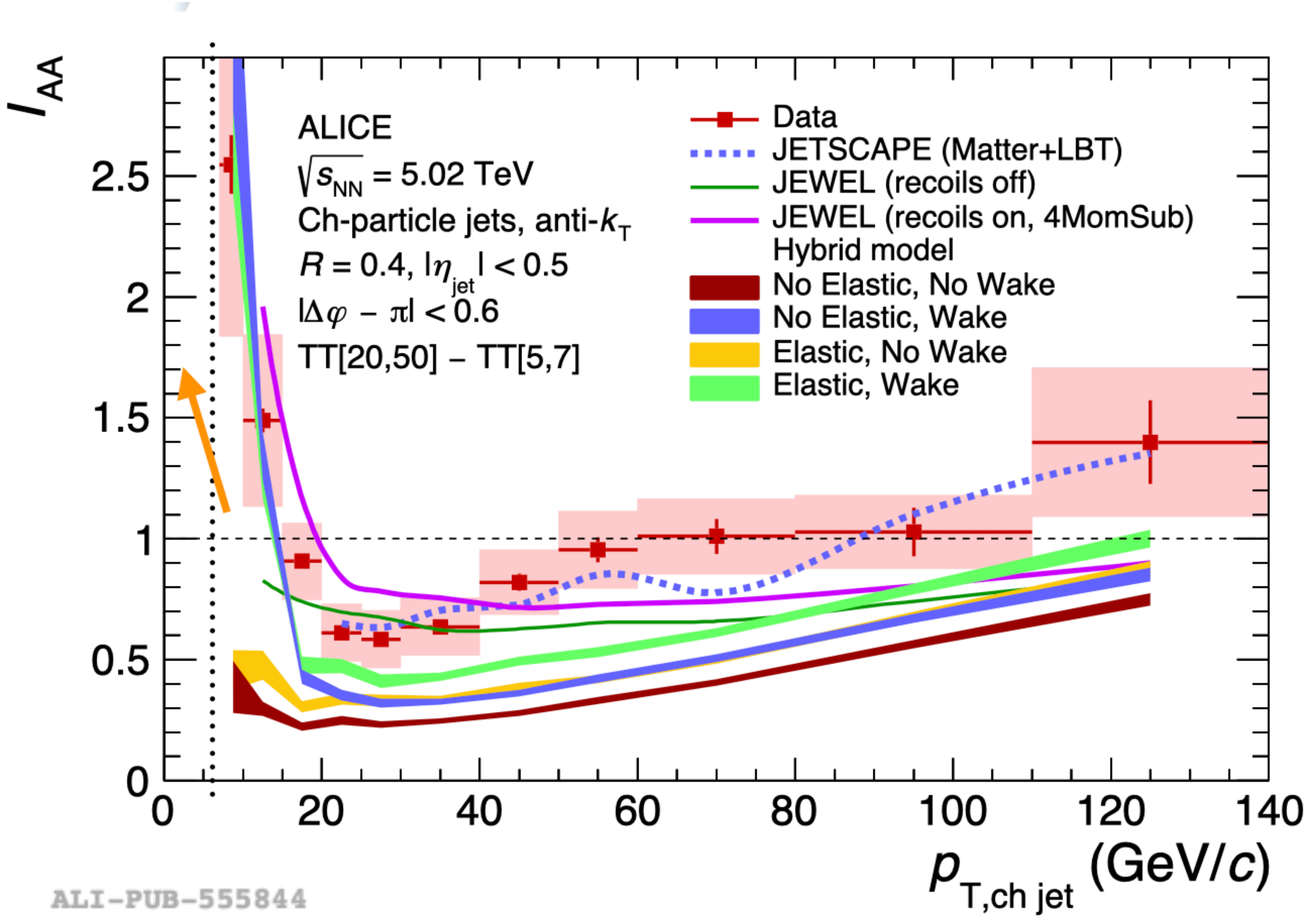


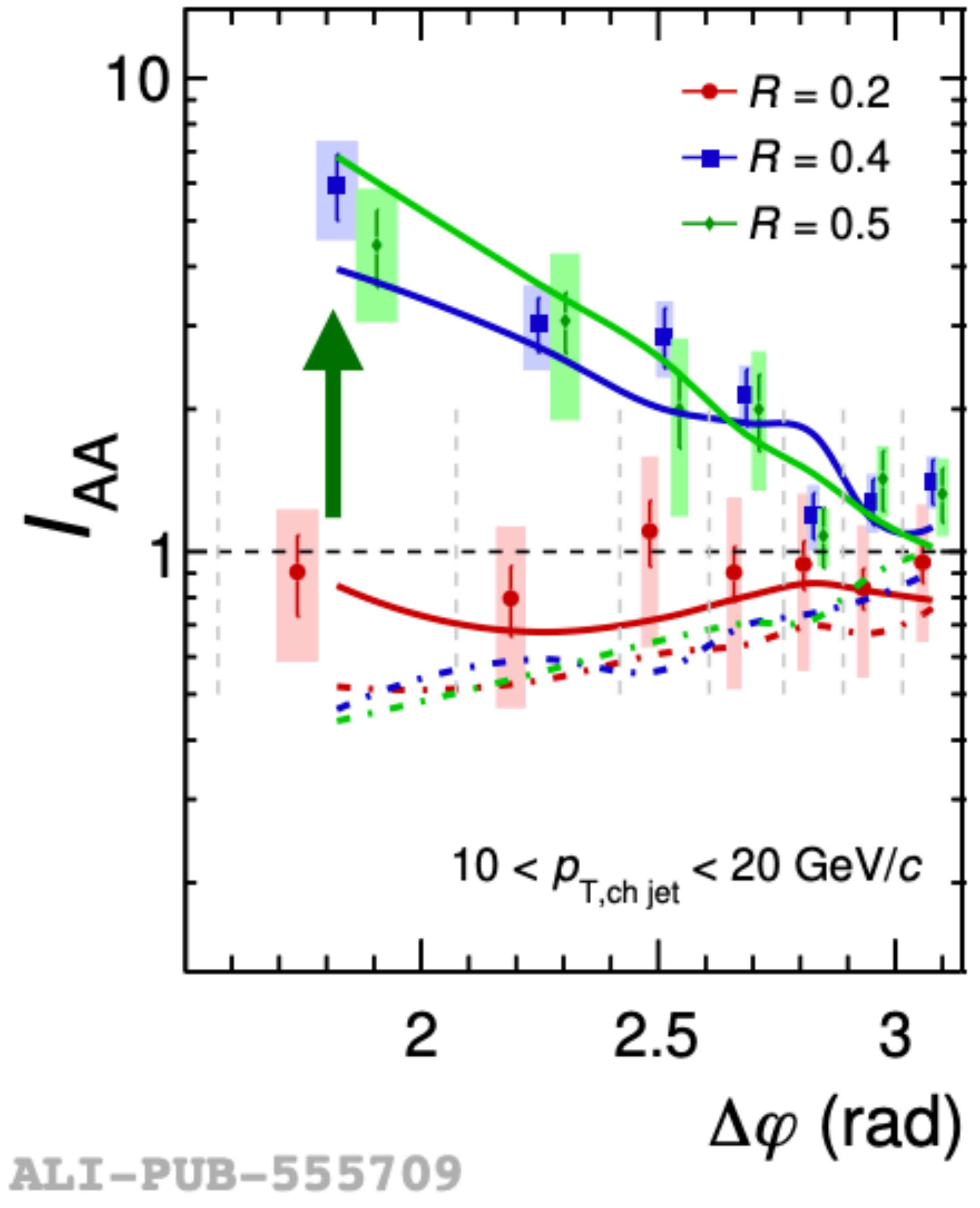
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$

- Transition to broadening from $R = 0.2$ to $R = 0.4$ for $p_T \in [10,20]$ GeV$/c$ → soft particles from the **medium response** clustered inside a jet scale with R^2
- All features of distribution **reproduced by JEWEL with recoils on** → observed broadening consistent with **medium response** rather than Molière scattering

- **Search for QGP signatures in high multiplicity pp collisions**
  - Jet quenching like effects masked by **generic** event selection bias
- **First observation of significant low-p_{T} jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
  - Medium response is favored instead of Molière scattering as the cause for both effects
- **First look at recoil jet spectra in Run 3**







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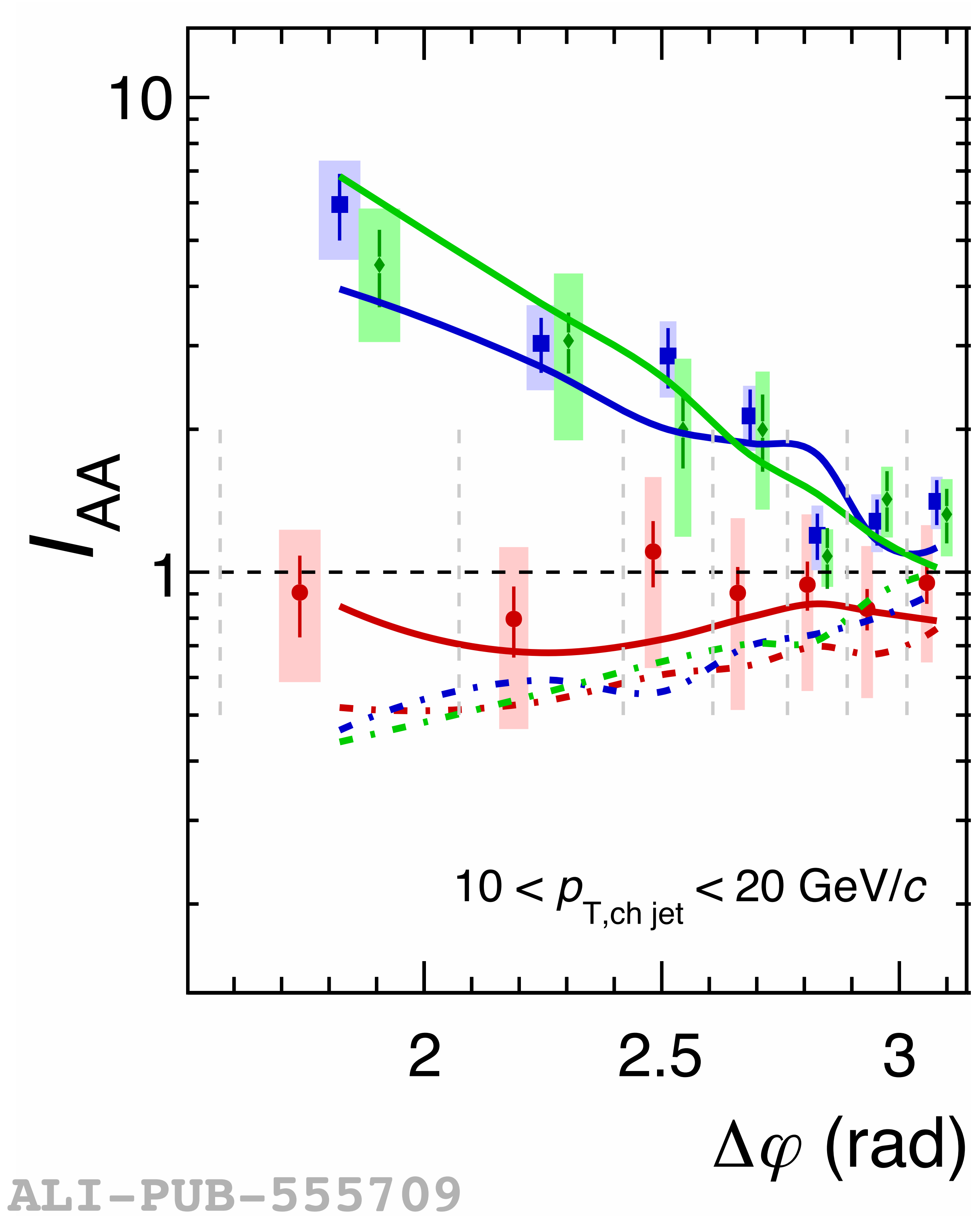
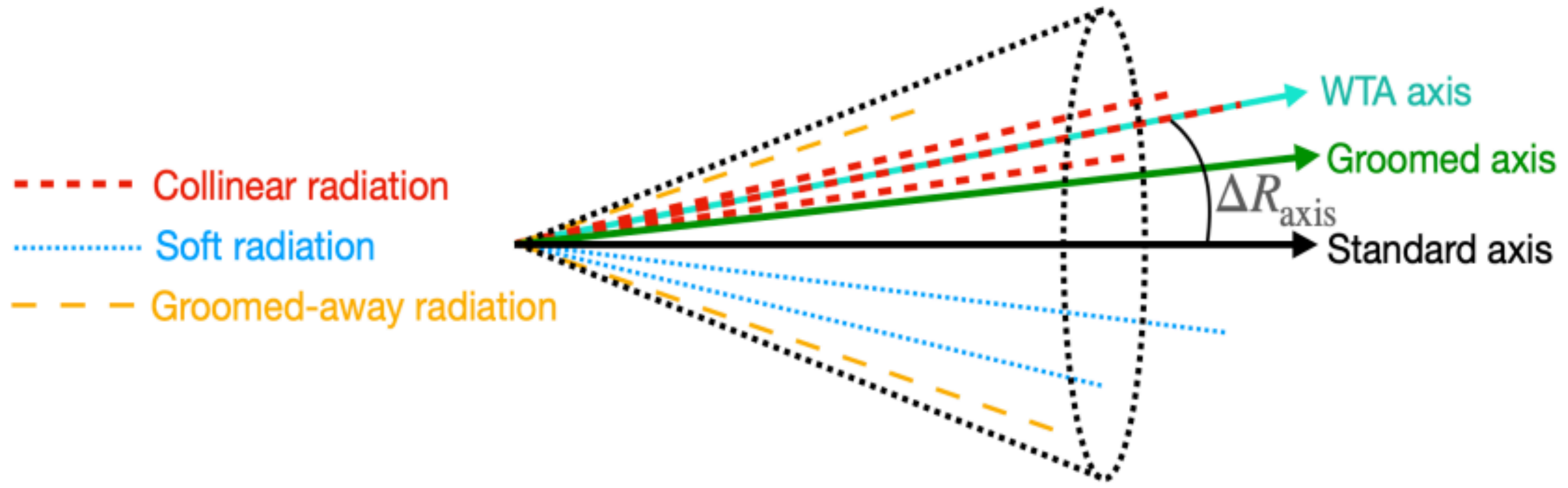
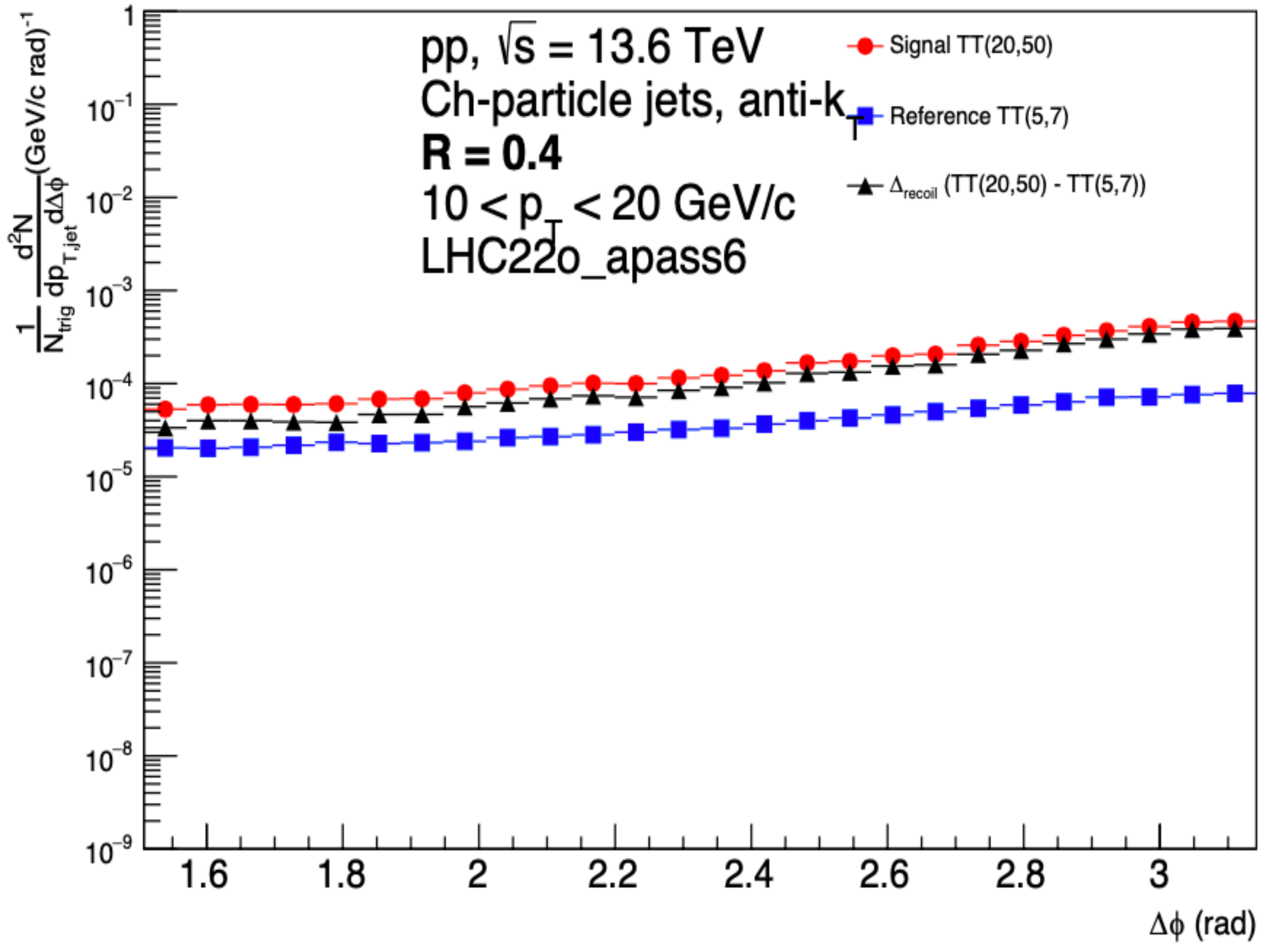
Characterise broadening

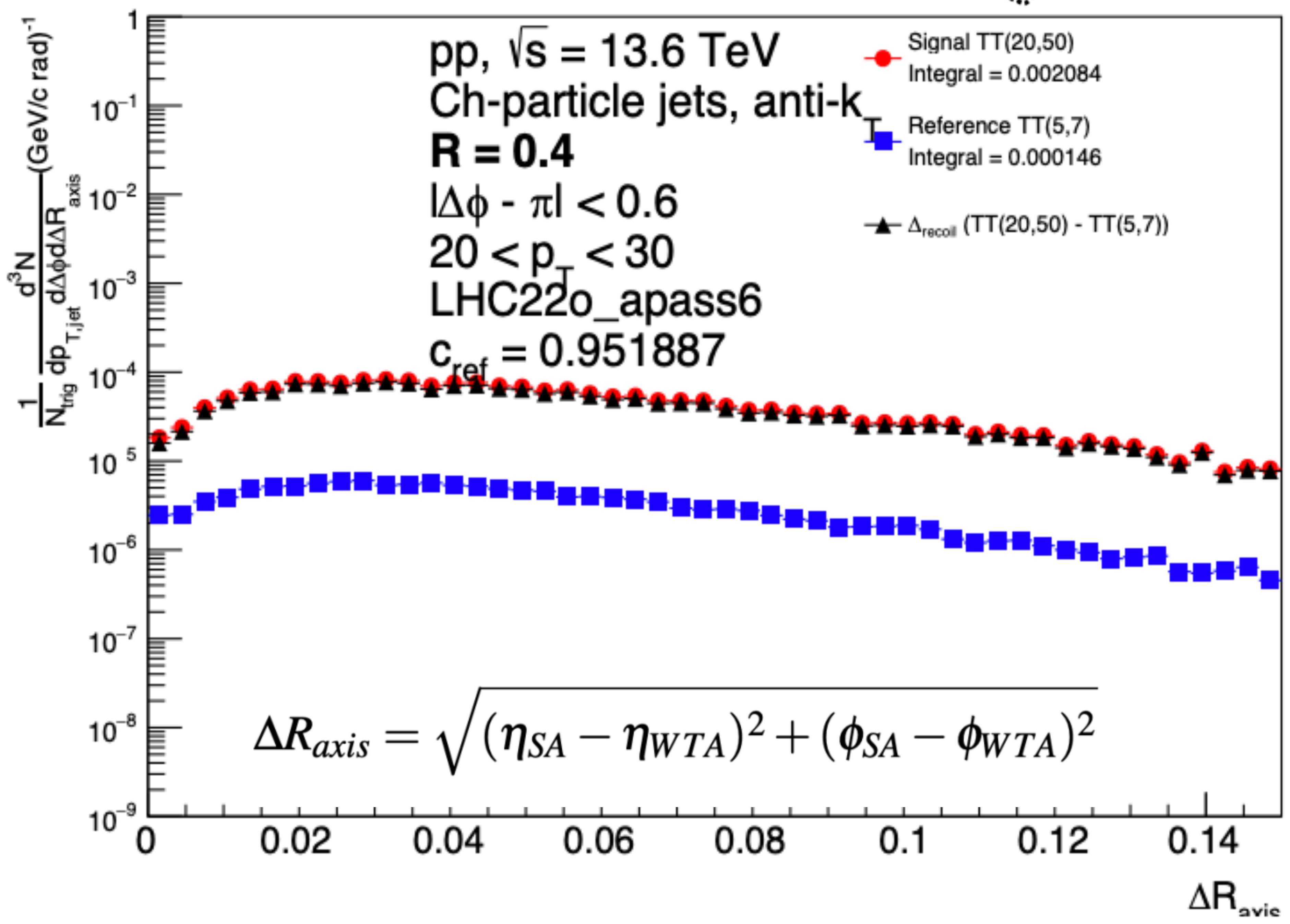


ALI-PUB-555709

Run3: Hadron-jet







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

  → Study profile and substructure measurements of jets

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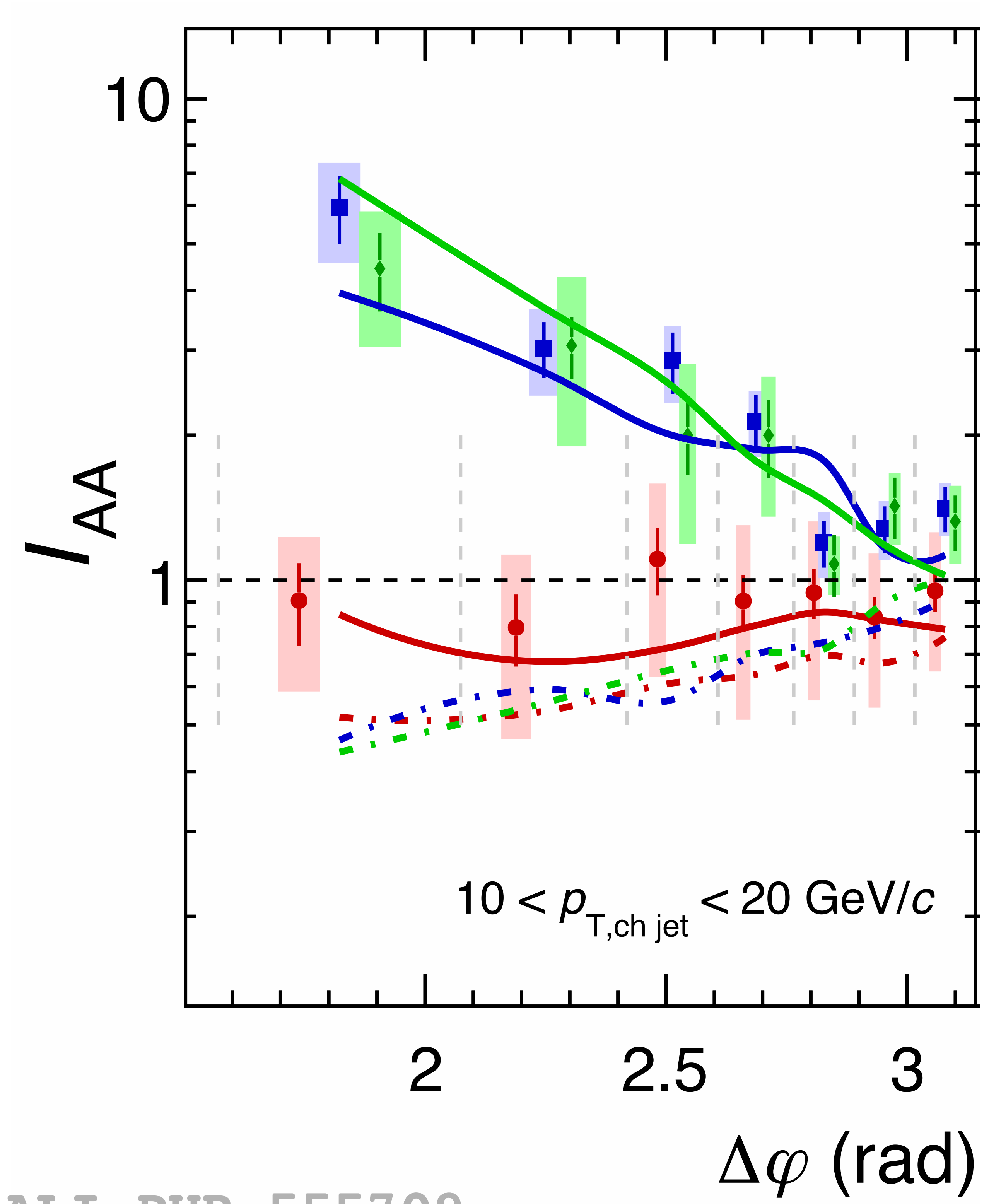
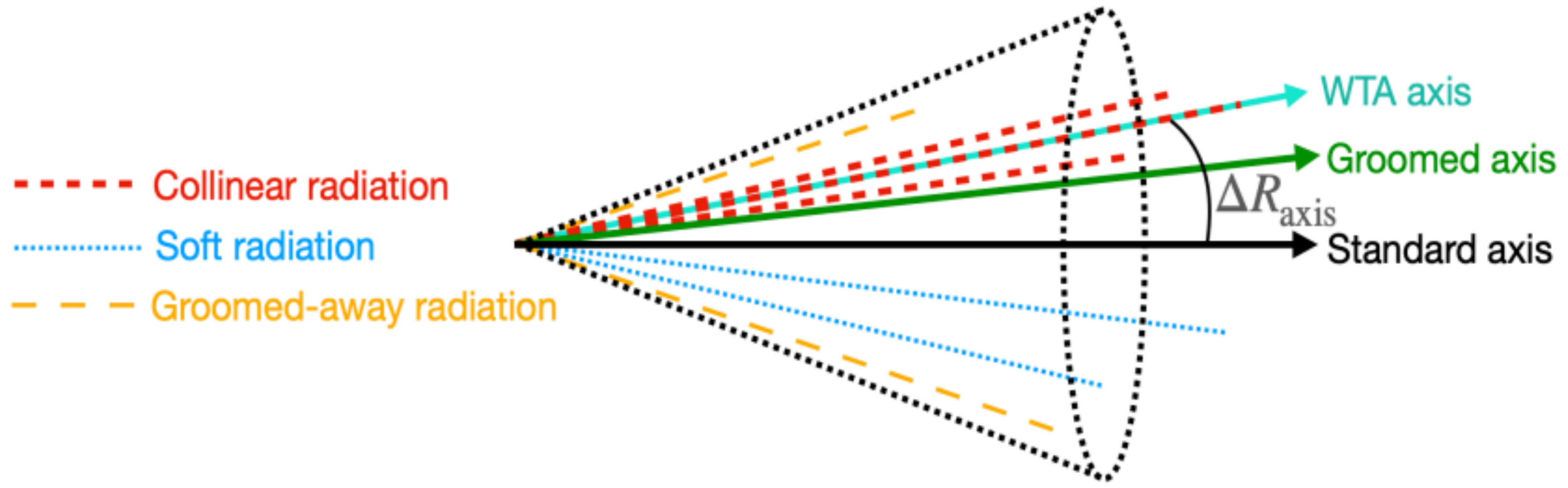
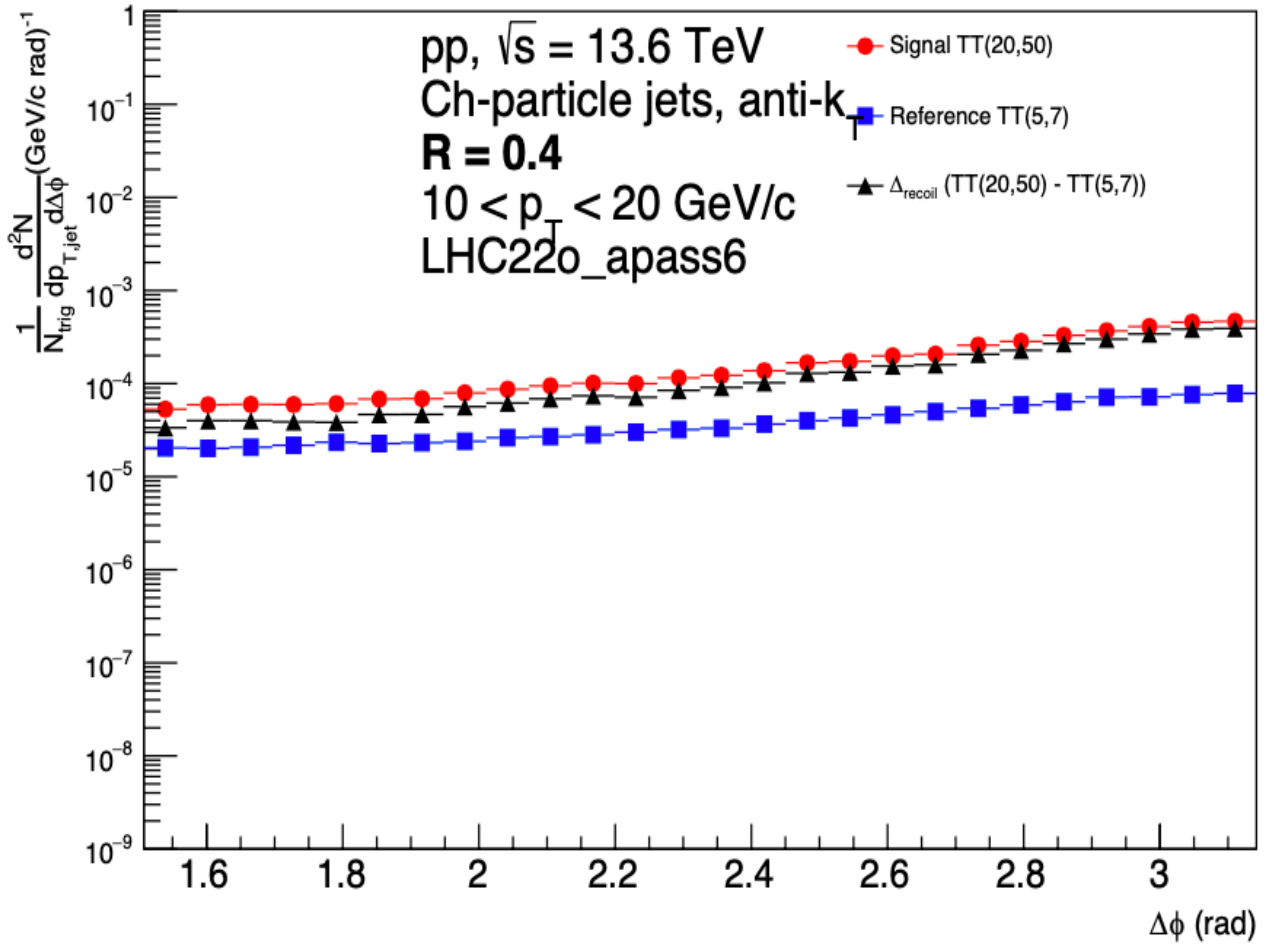
- *Looking forward to further studies with **Run 3** data with ALICE* ***~~ investigate recoil jet substructure including in Pb-Pb***

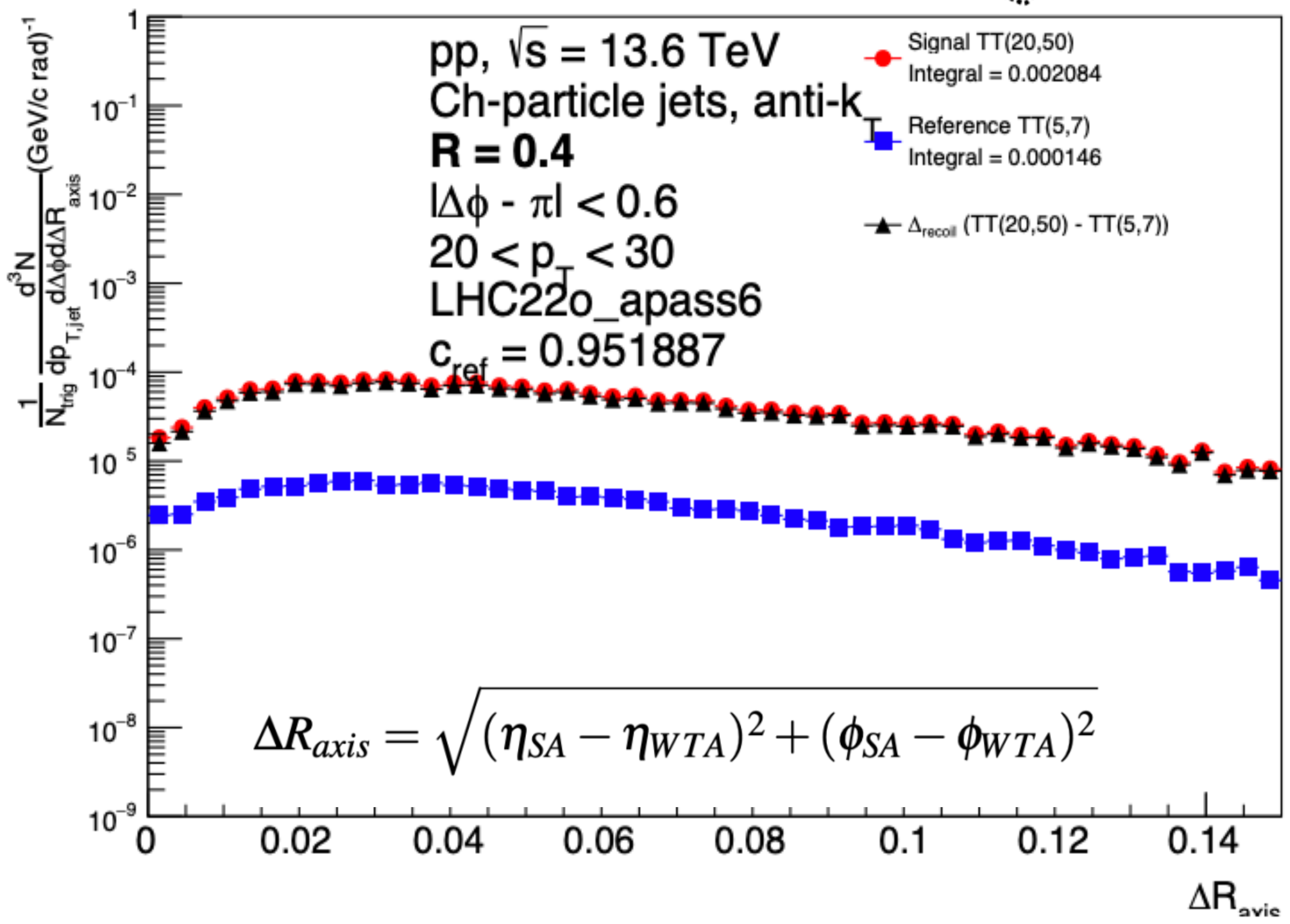
Characterise broadening



Run3: Hadron-jet







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Thanks for your listening and discussion

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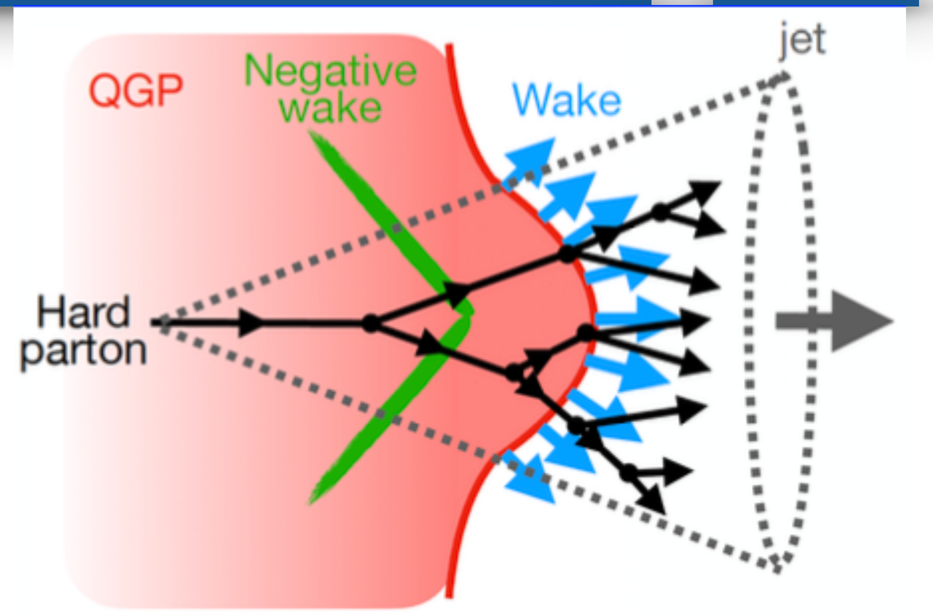
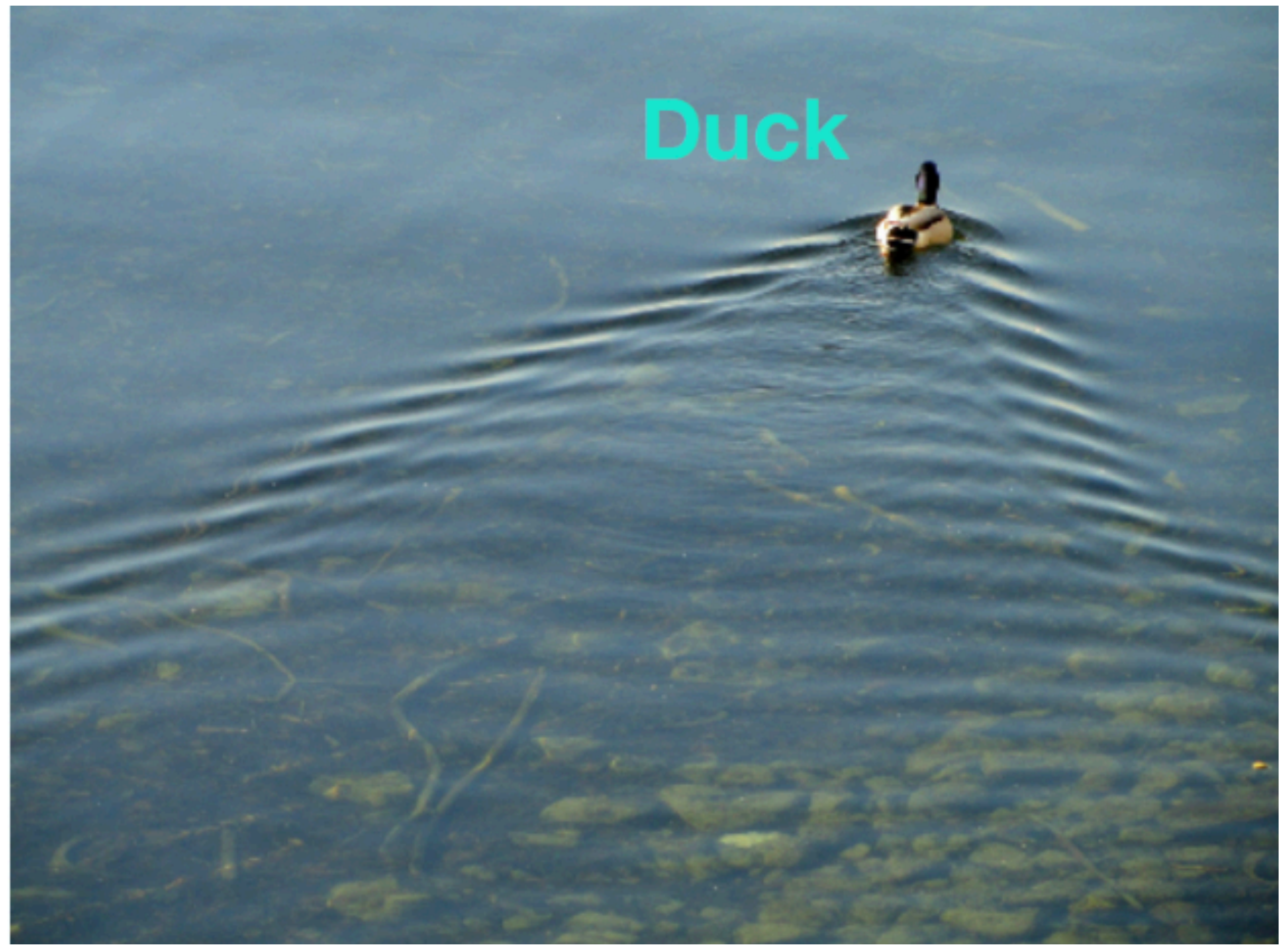
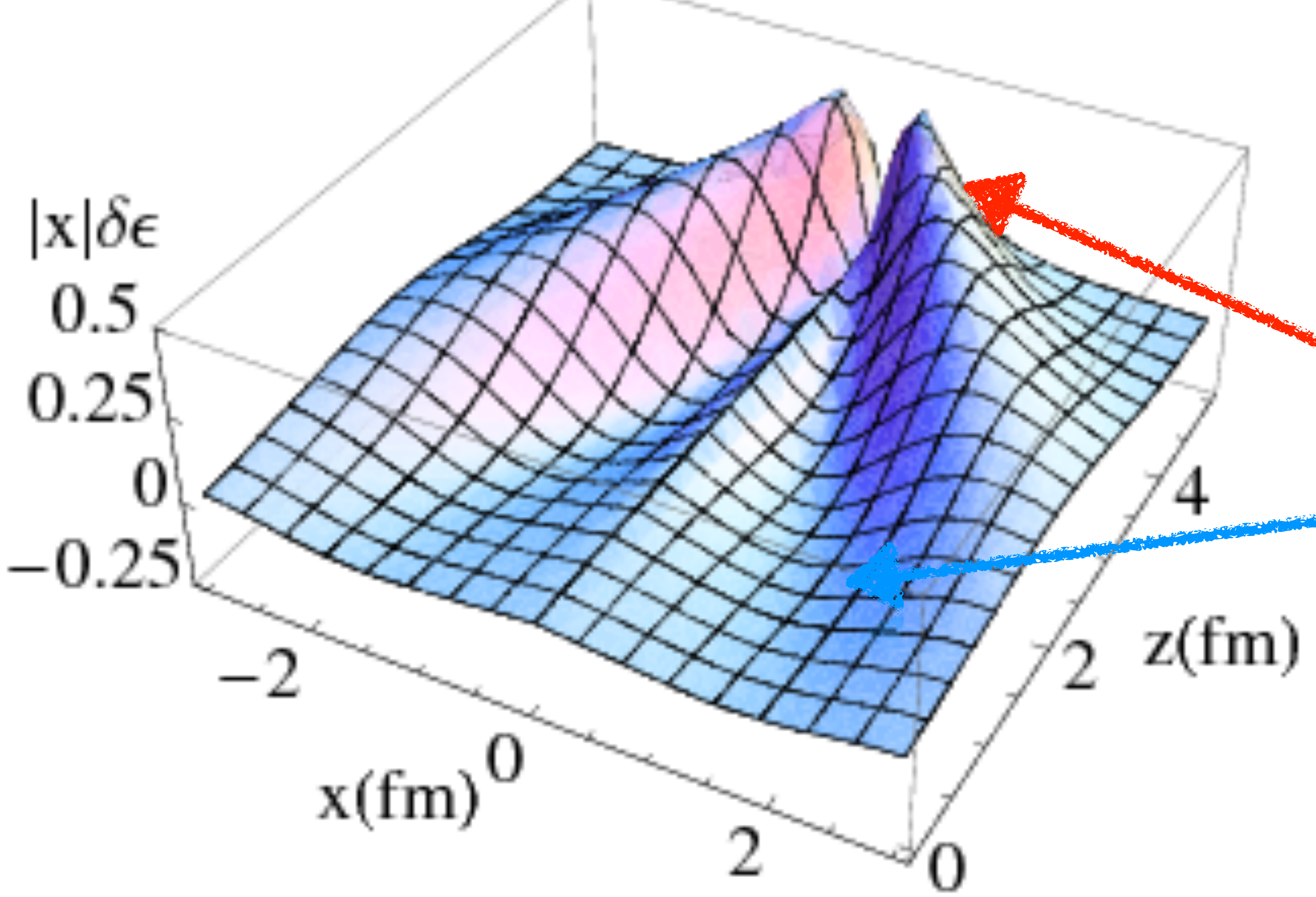


- Jets lose energy due to interaction with medium constituents

  ➡ Medium modified by jets!



G.-Y. Qin, A. Majumder, H. Song, and U. Heinz, Phys. Rev. Lett. 103, 152303 (2009)



Expectations: "wake effects"

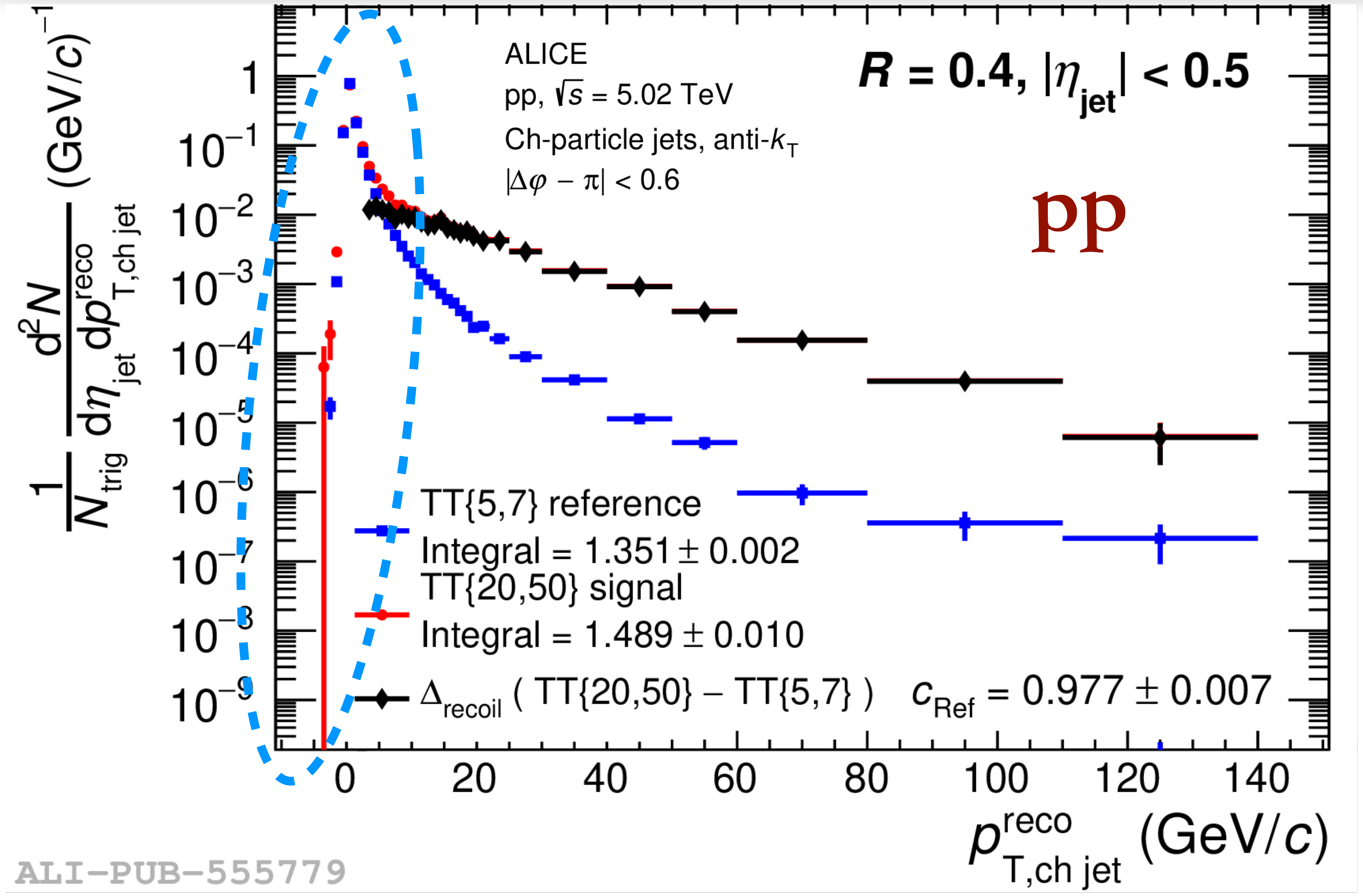
Enhancement around jet

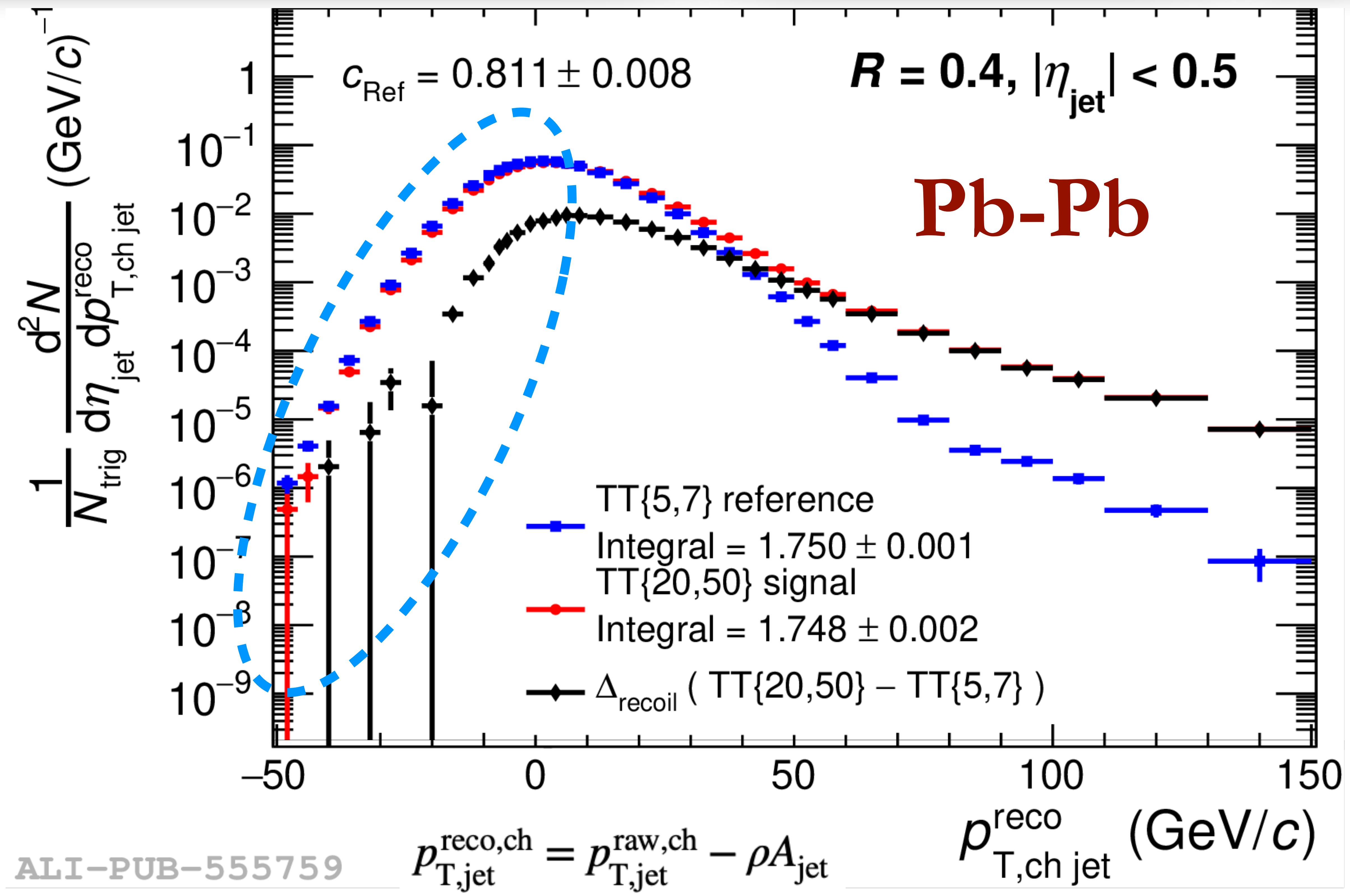
Depletion opposite to jet

- Insert out-of-equilibrium probe → see how the medium responds

  ➡ transport coefficients, equation of state

Recoil jet p_T distributions





- **Recoil jet p_T distributions** in two trigger track p_T intervals are then obtained from 2D projection
- **Combinational 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 recoil jet distributions in two TT intervals

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

Recoil jet p_T distributions

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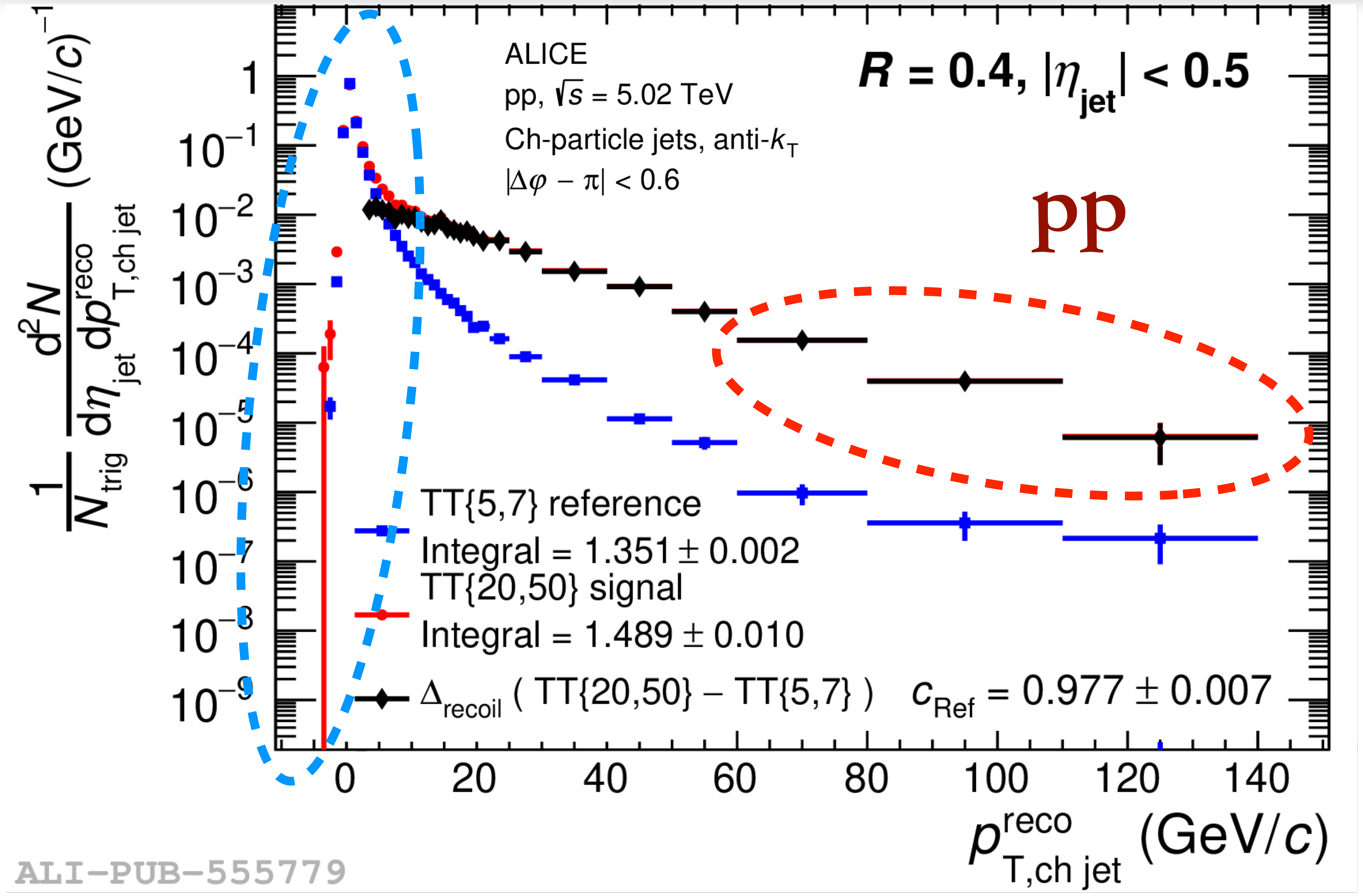

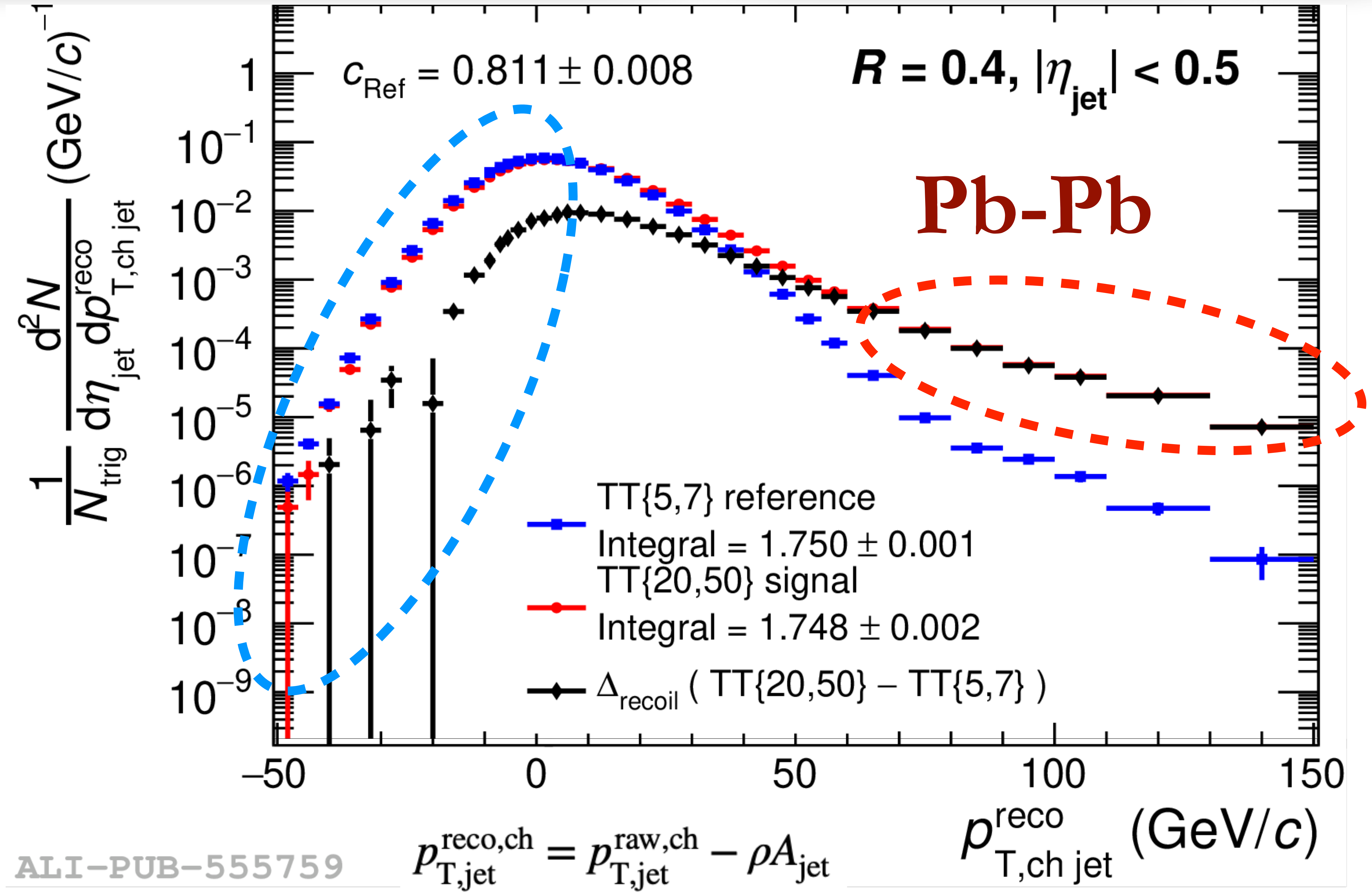

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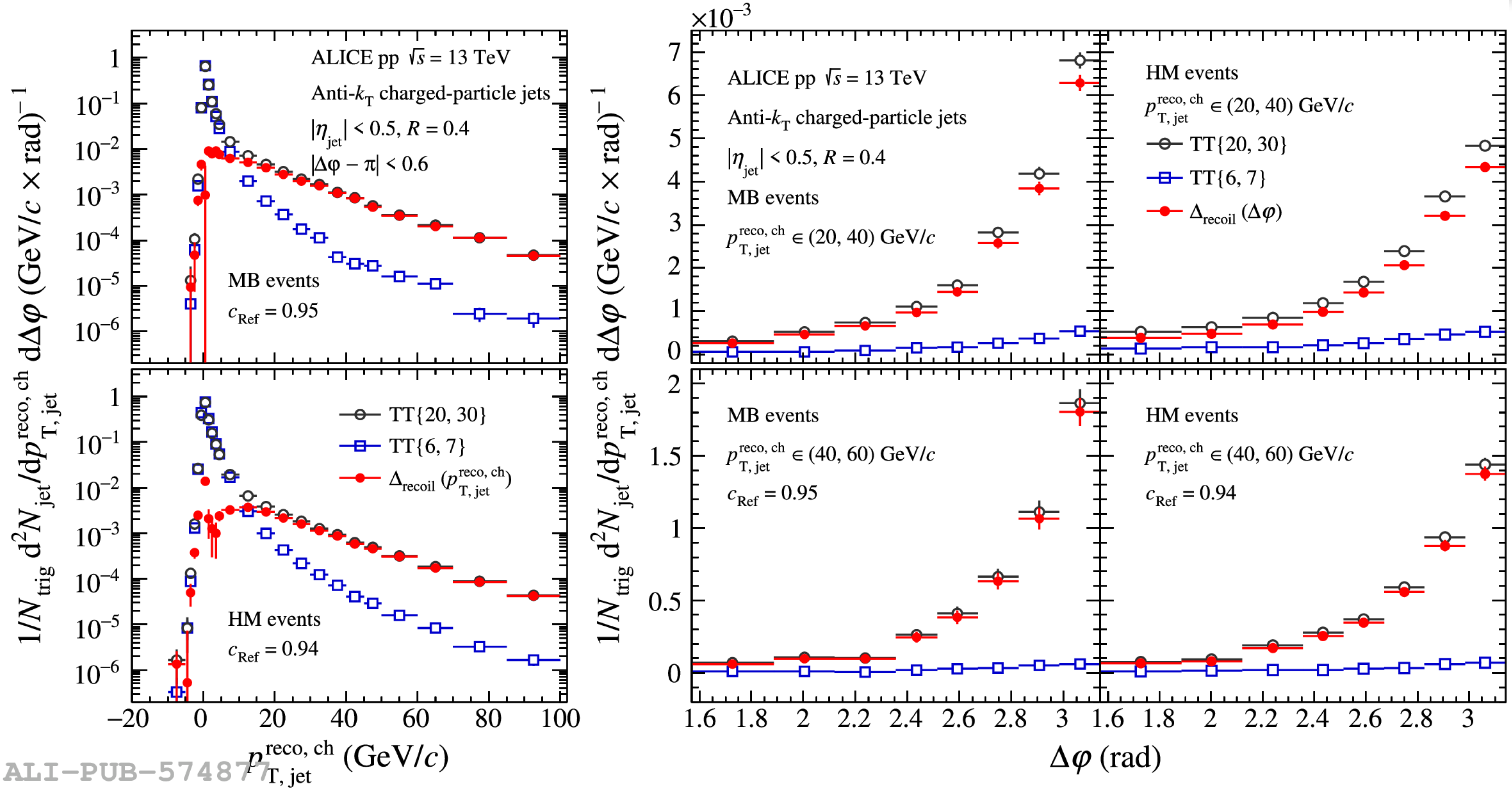

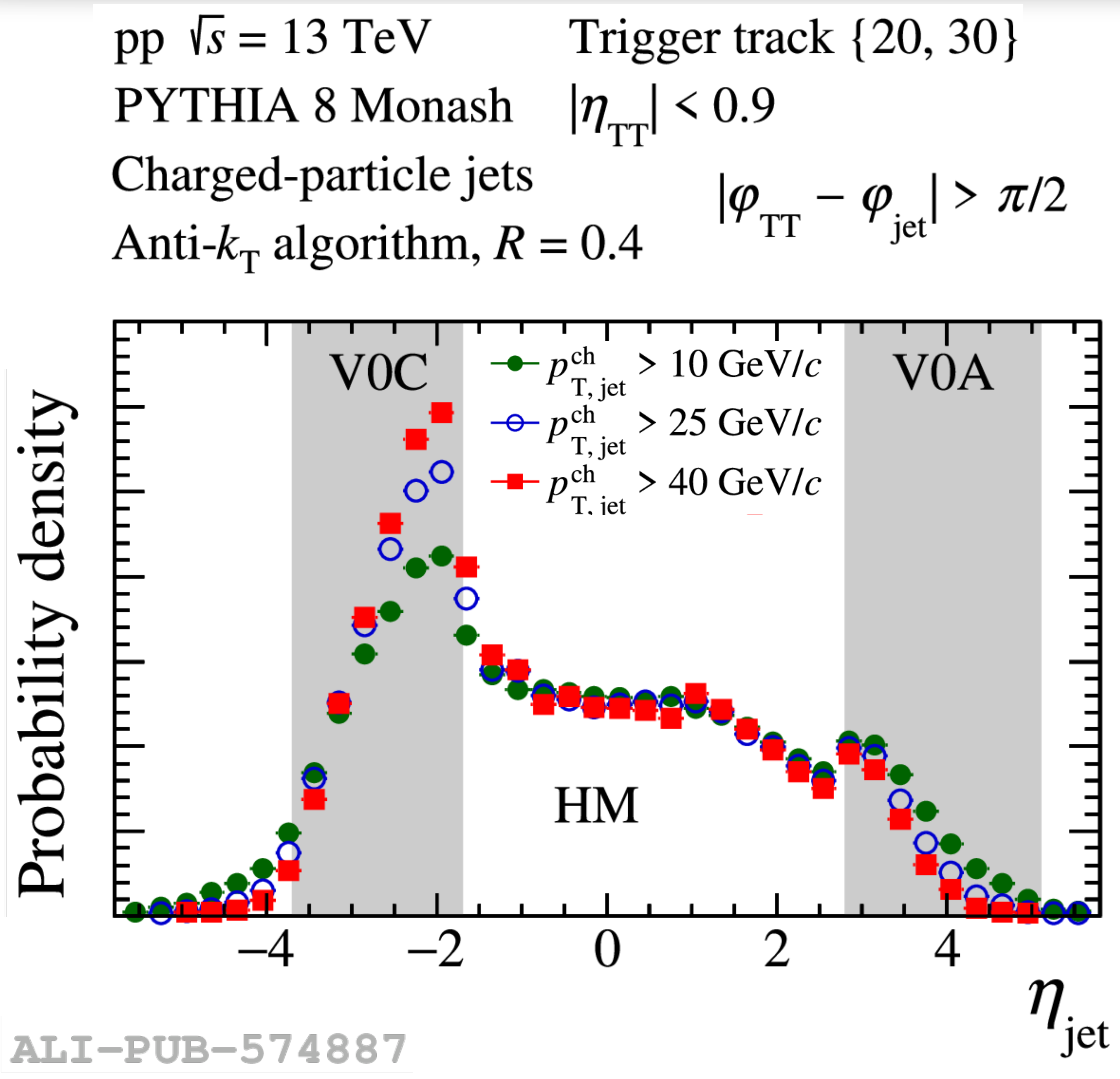

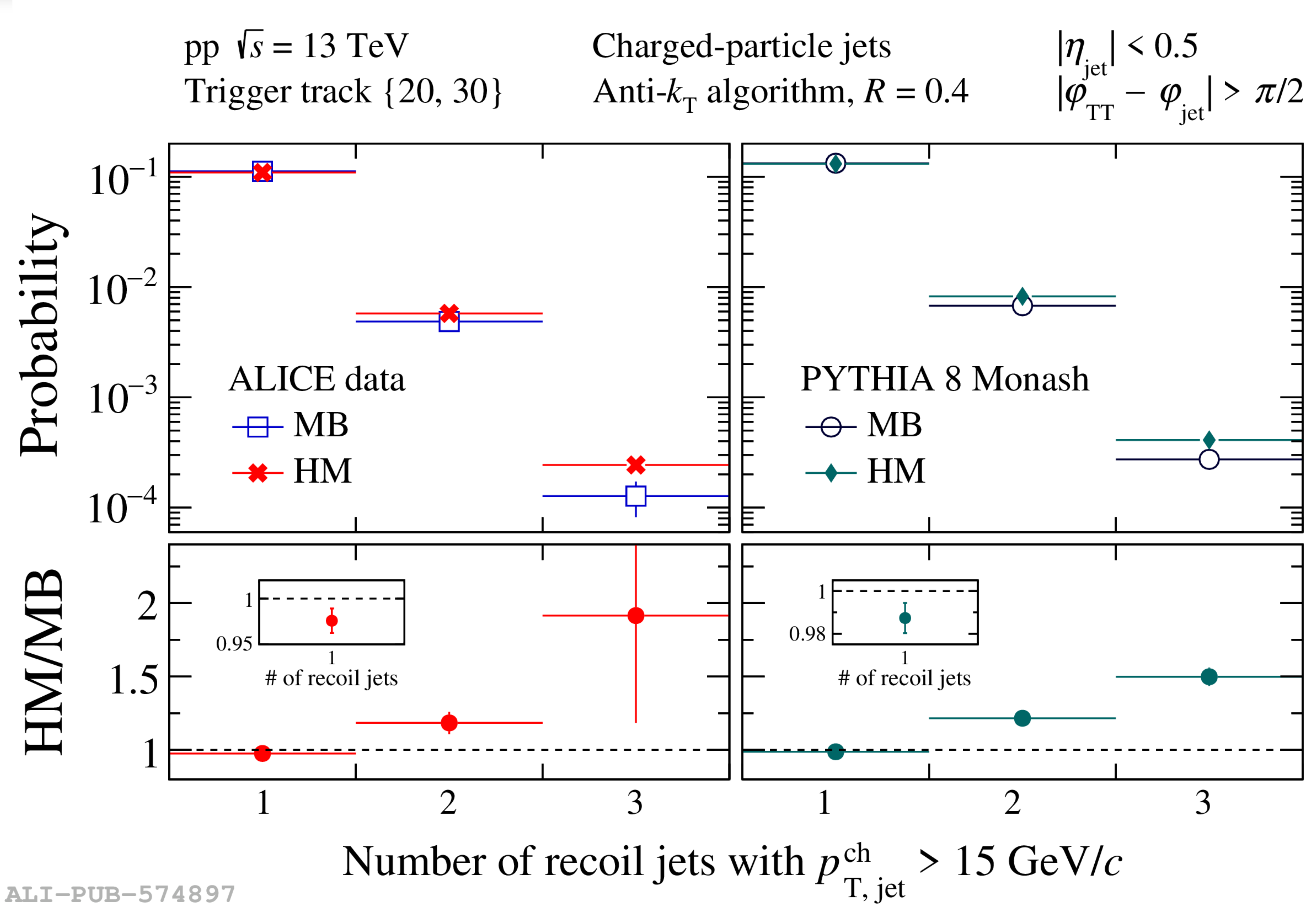

- HM event selection

  → significant bias in the distribution of high-p_T recoil jets, enhancing jets in the backward detector acceptance (V0C)
- V0A and V0C have asymmetric coverage
- Jet quenching signals can be masked by effects coming from trigger

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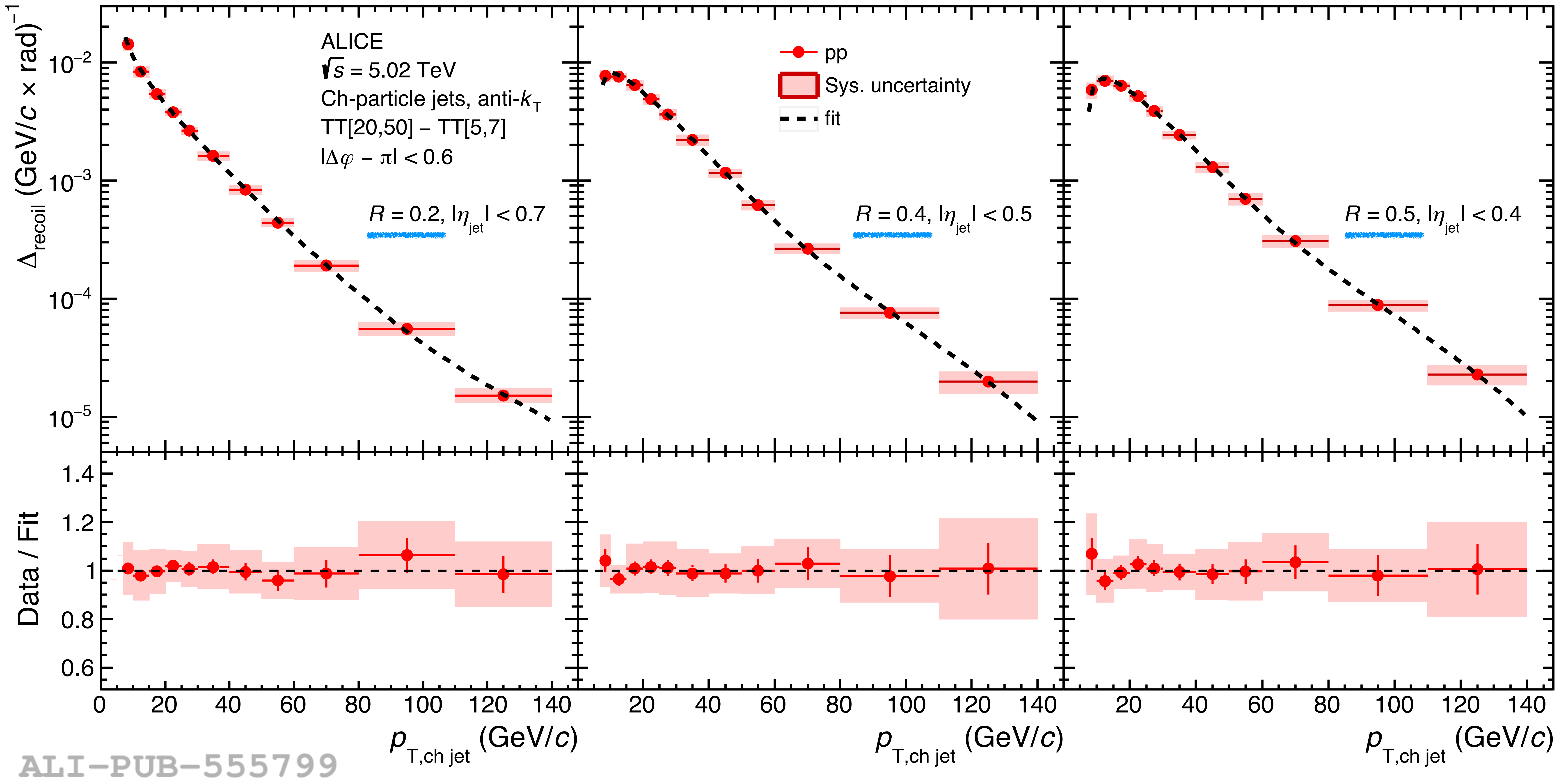
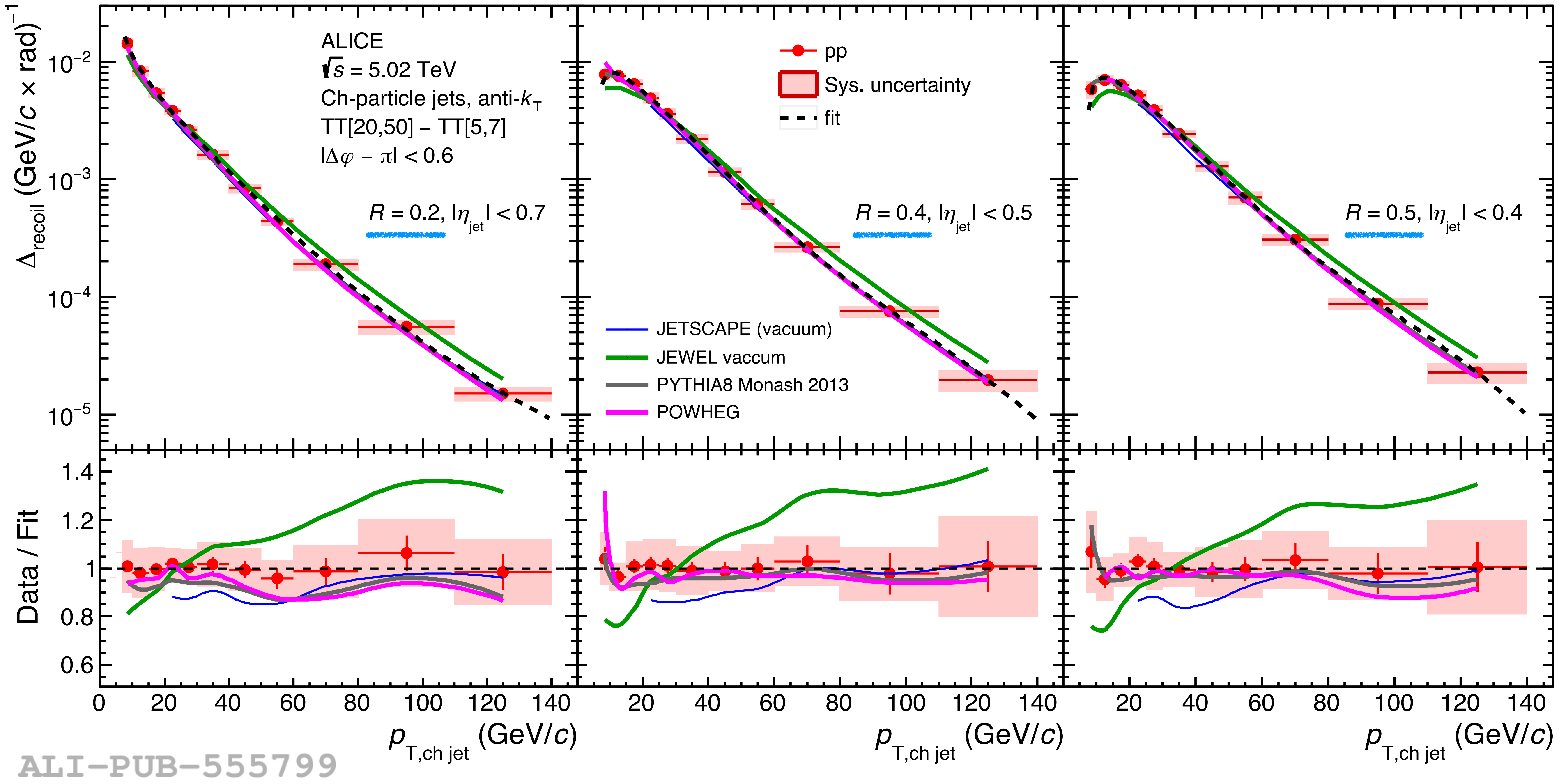


Data fitted with the function:

$$\Delta(p_T) = p_0 \exp(-p_1 \times p_T) + p_2 \times (p_T)^{p_3}$$

- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for R = 0.2, 0.4, and 0.5 in pp collisions

Fully-corrected $\Delta_{\text{recoil}}(p_T)$ distributions in pp collisions



Data fitted with the function:

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PYTHIA (8.125, Monash 2013 tune): LO pQCD calculation
arXiv:1404.5630

POWHEG: NLO pQCD calculation
arXiv:hep-ph/0409146

JETSCAPE PP19 tune: based on PYTHIA8, with modified parton shower.
arXiv:1910.05481

JEWEL vaccum: based on PYTHIA6, which has no medium related parameters (no medium)
arXiv:1311.0048, https://jewel.hepforge.org/

- Fully-corrected $\Delta_{\text{recoil}}(p_T)$ distributions for R = 0.2, 0.4, and 0.5 in pp collisions
- The model calculations except JEWEL can reproduce the ALICE data within uncertainties

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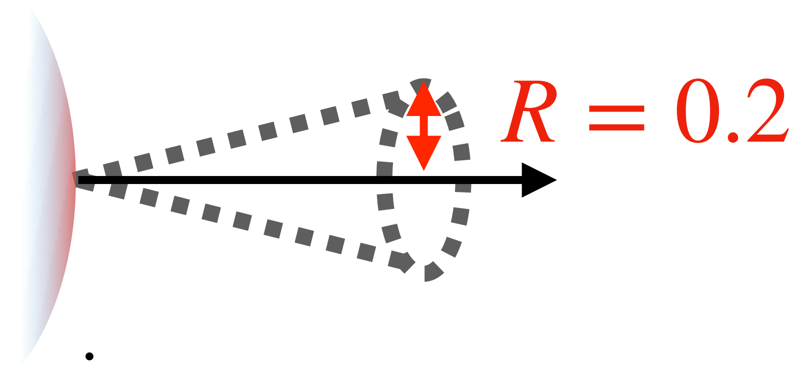
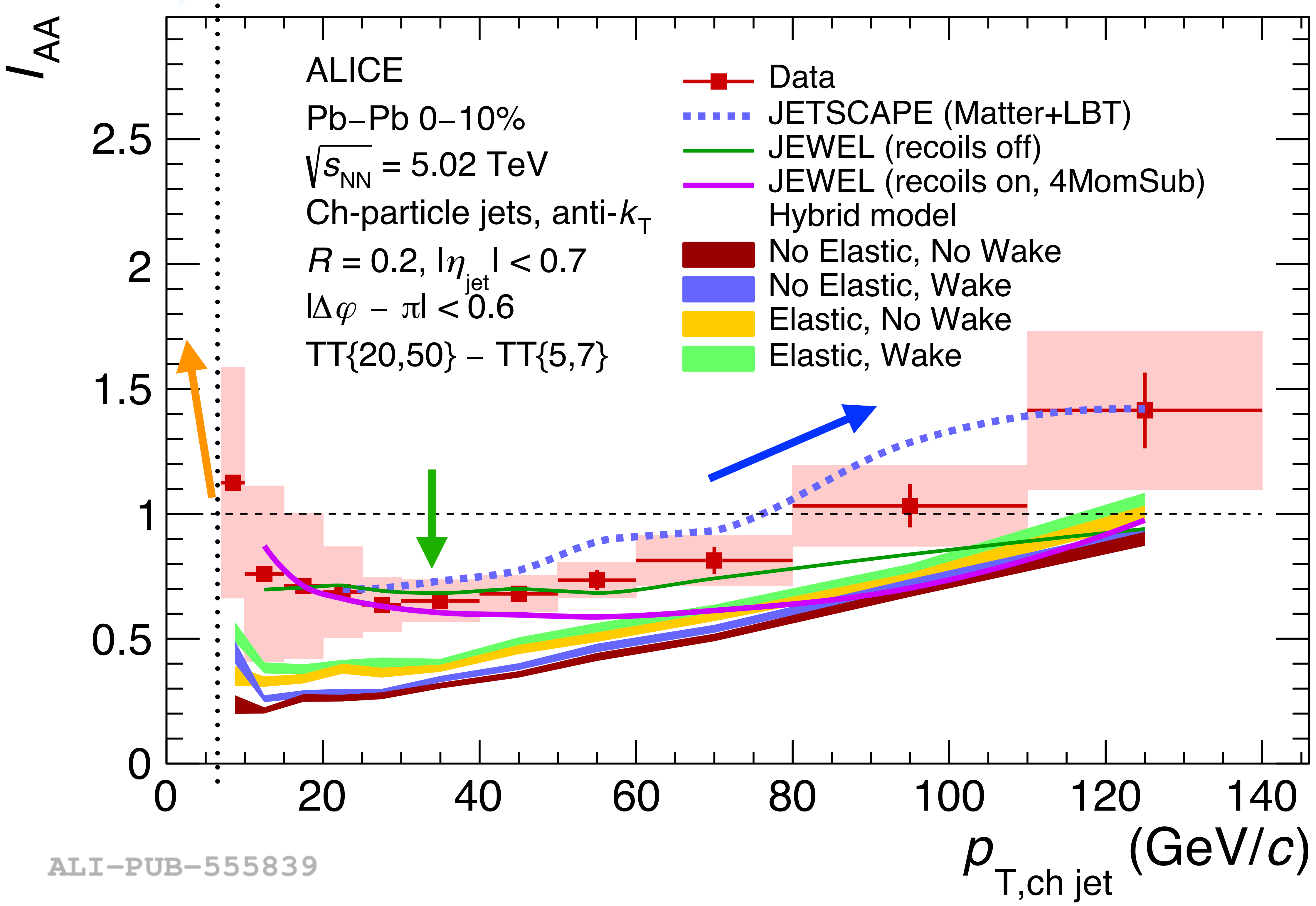


0 – 10 %

R = 0.2



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JETSCAPE with Pb-Pb tune:

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

Multi-stage energy loss MATTER+LBT

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arXiv:1311.0048, https://jewel.hepforge.org/

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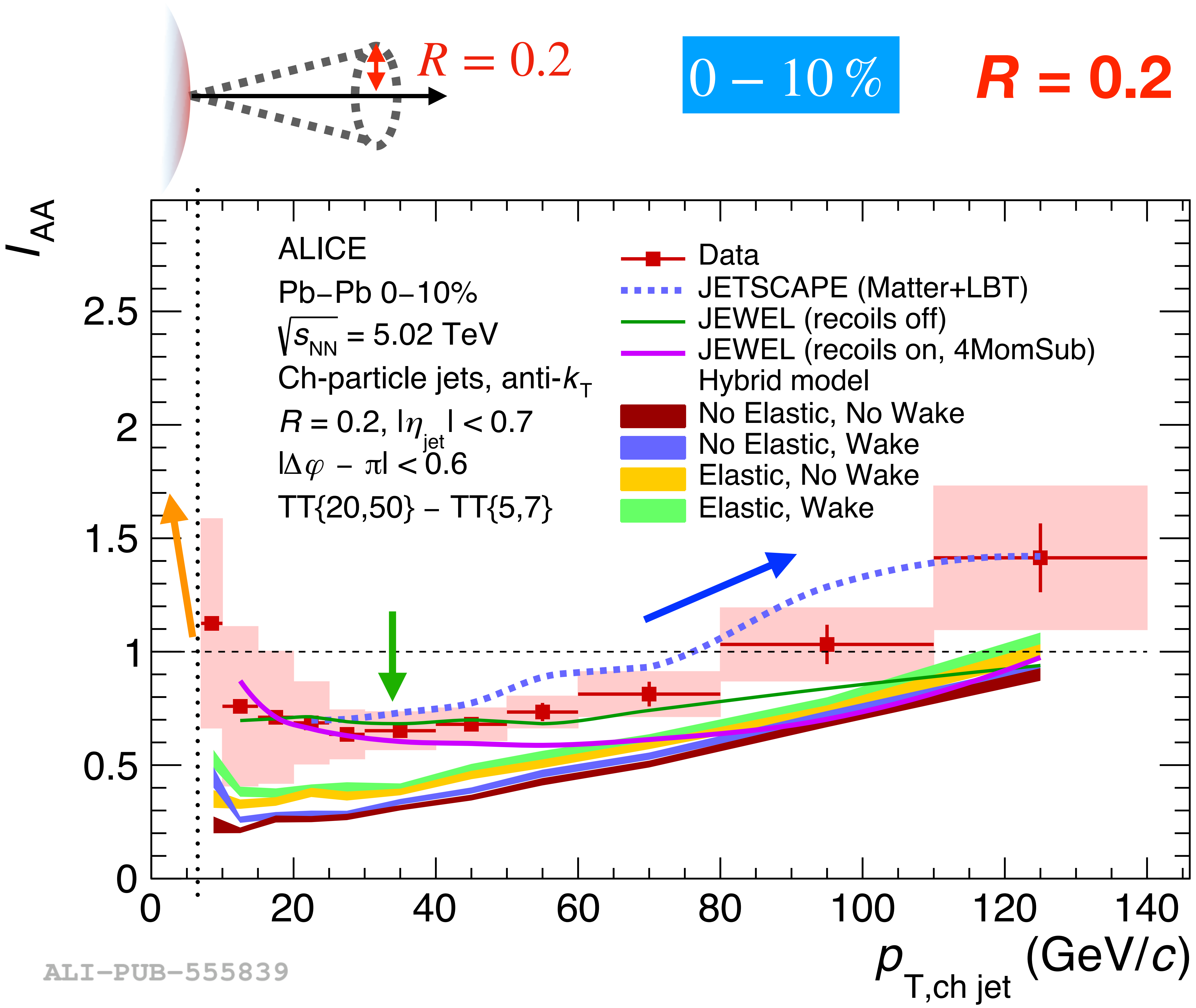
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(p_T)_{AA}}{\Delta_{\text{recoil}}(p_T)_{pp}}$$

0 – 10 %

R = 0.2



- The **rising trend** is qualitatively described by all predictions
  - **JETSCAPE largely reproduces** the I_{AA} distributions
  - **Hybrid Model** and **JEWEL** predictions **overestimate the suppression** at high p_T
- **JEWEL calculations** seems to be consistent with measurements at low p_T

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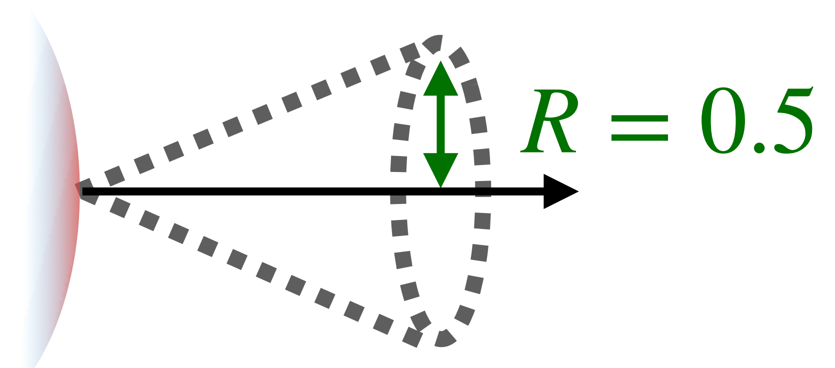
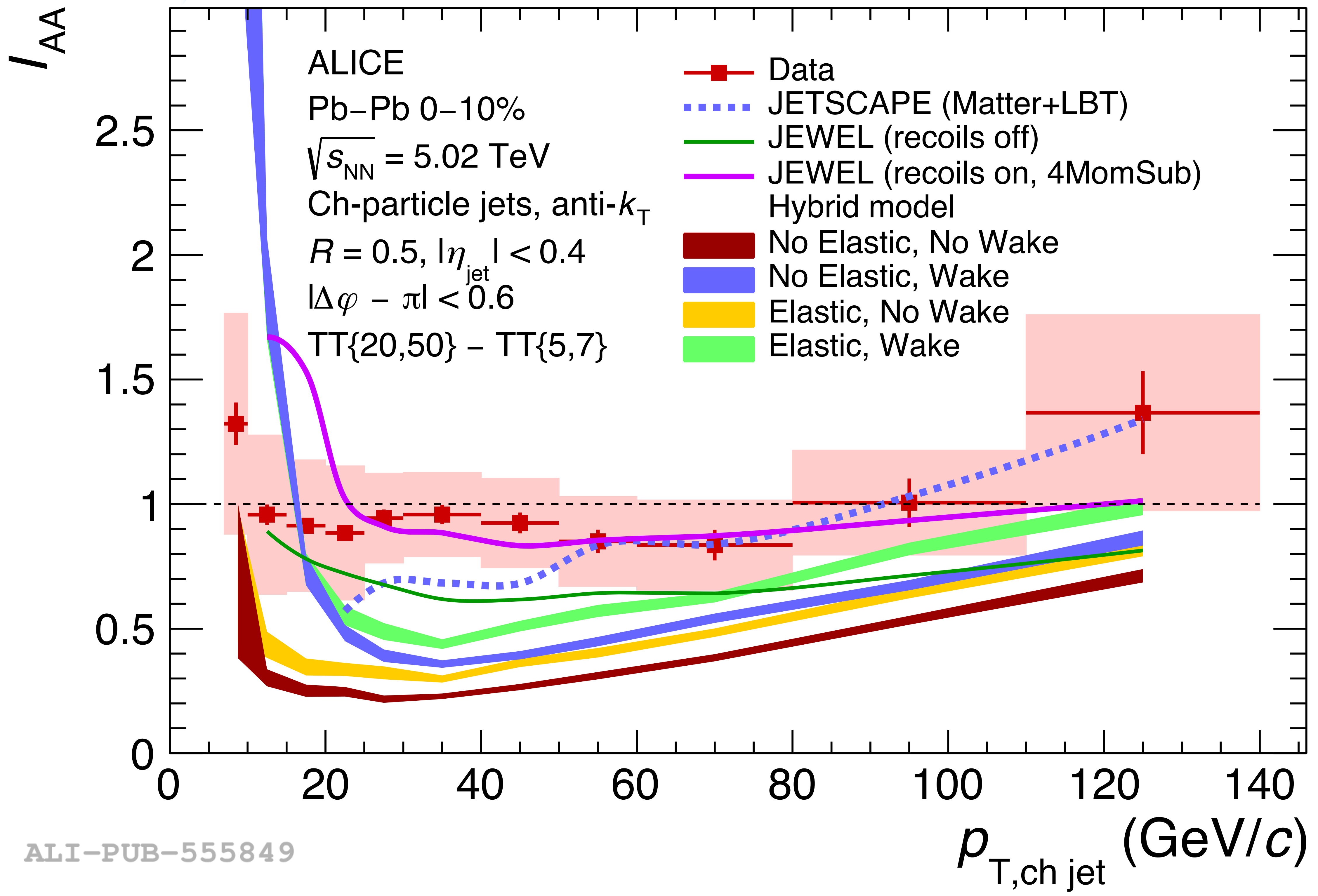


0 – 10 %

R = 0.5

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



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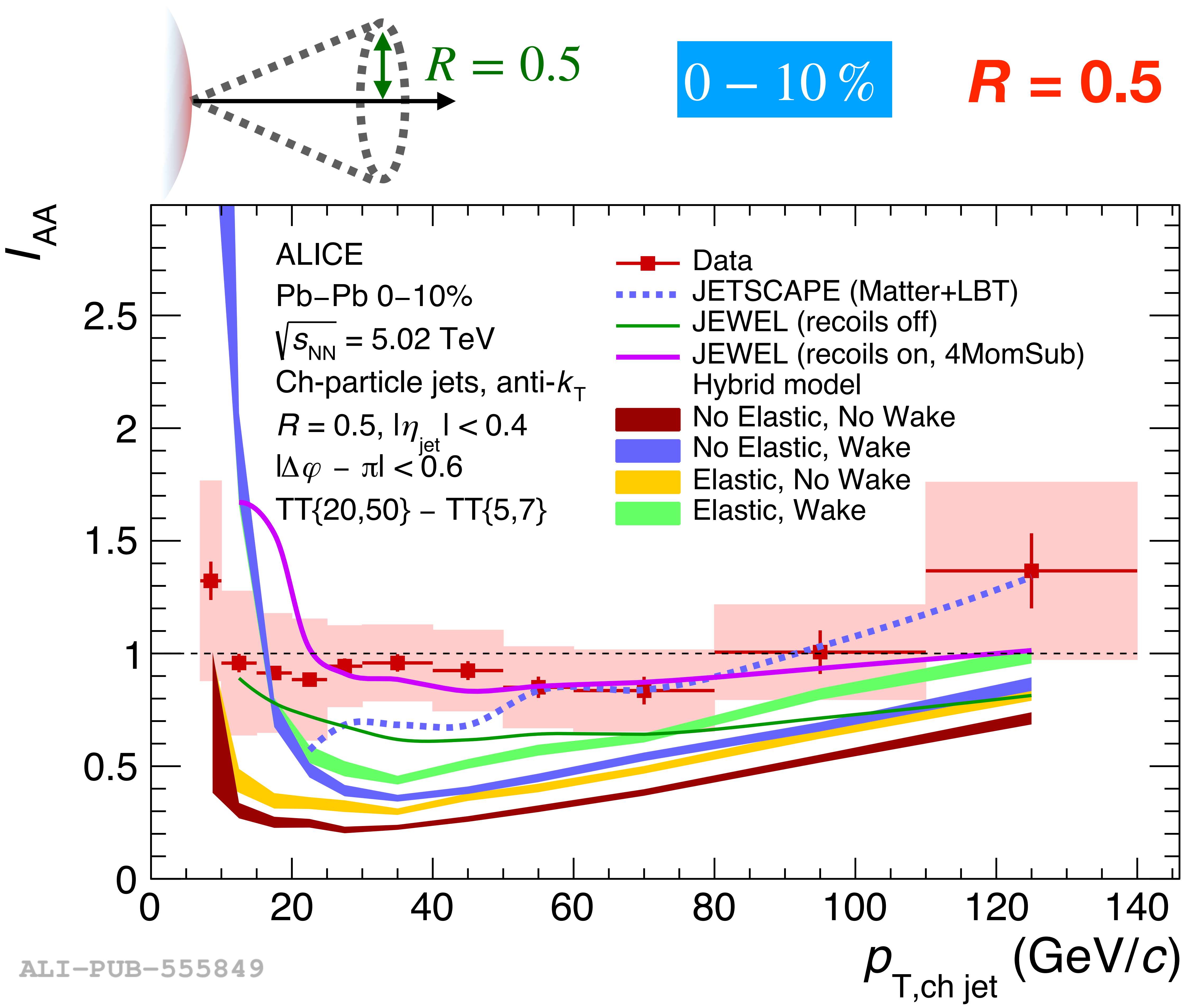
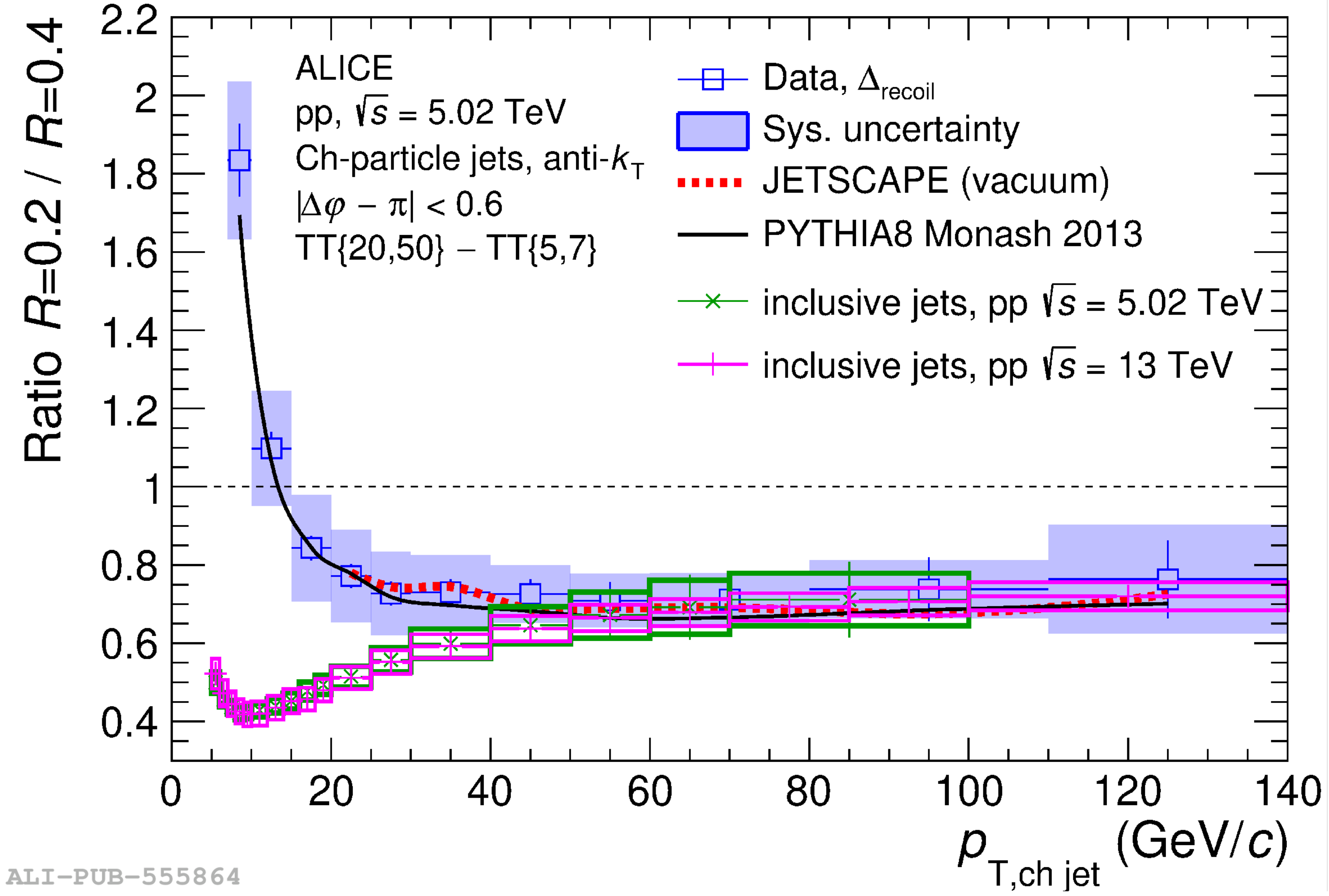
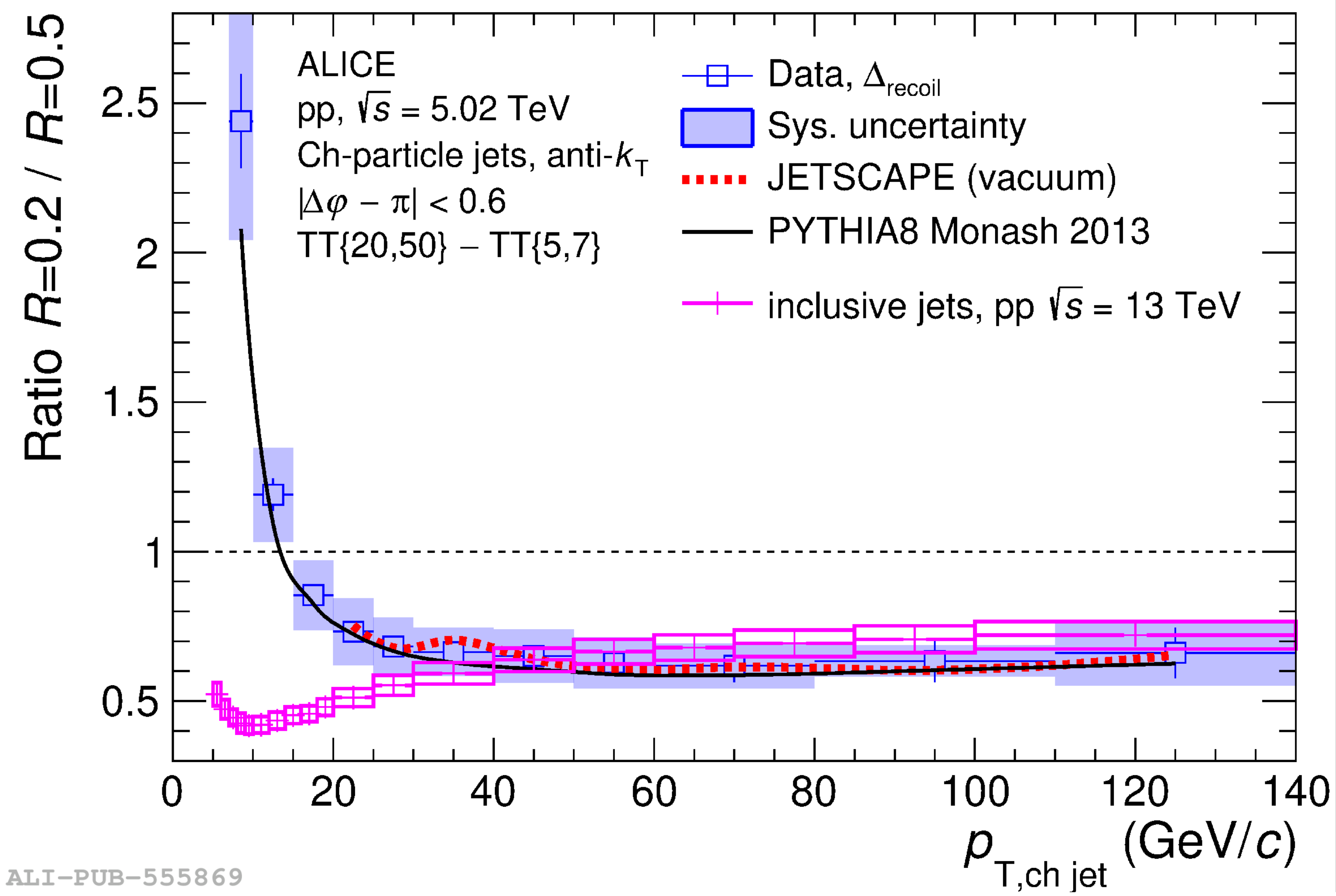


$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}\,(p_T)_{AA}}{\Delta_{\mathrm{recoil}}\,(p_T)_{pp}}$$

- *R*=0.5 consistent with the unit (no **suppression and enhancement**)
  - Little suppression captured by JEWEL (recoils on)
- Indication of intra-jet energy recovery within cone radius~0.5 for mid-p_T?
- Redistribution of energy for *R*=0.5 jets more challenging for models

Fully corrected yield ratio: $R = 0.2$ / $R = 0.4$





- Ratio of $\Delta_{recoil}(p_T)$ distributions for $R = 0.2$ / 0.4 and $R = 0.2$ / 0.5
  - Well described by JETSCAPE and PYTHIA
  - Consistent with inclusive charged jet cross section ratios at high p_T
  - Difference at low p_T due to **TT selection**

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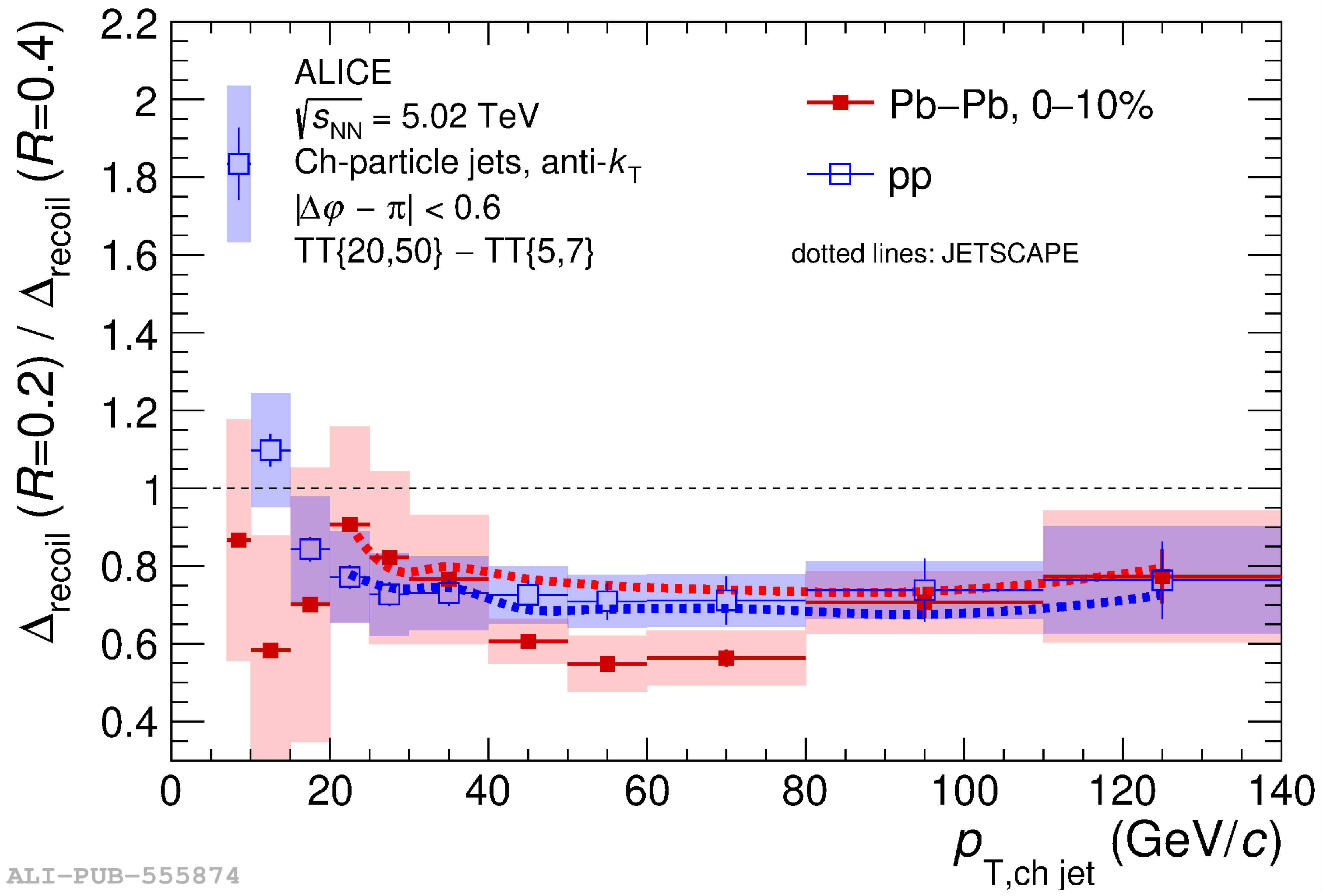
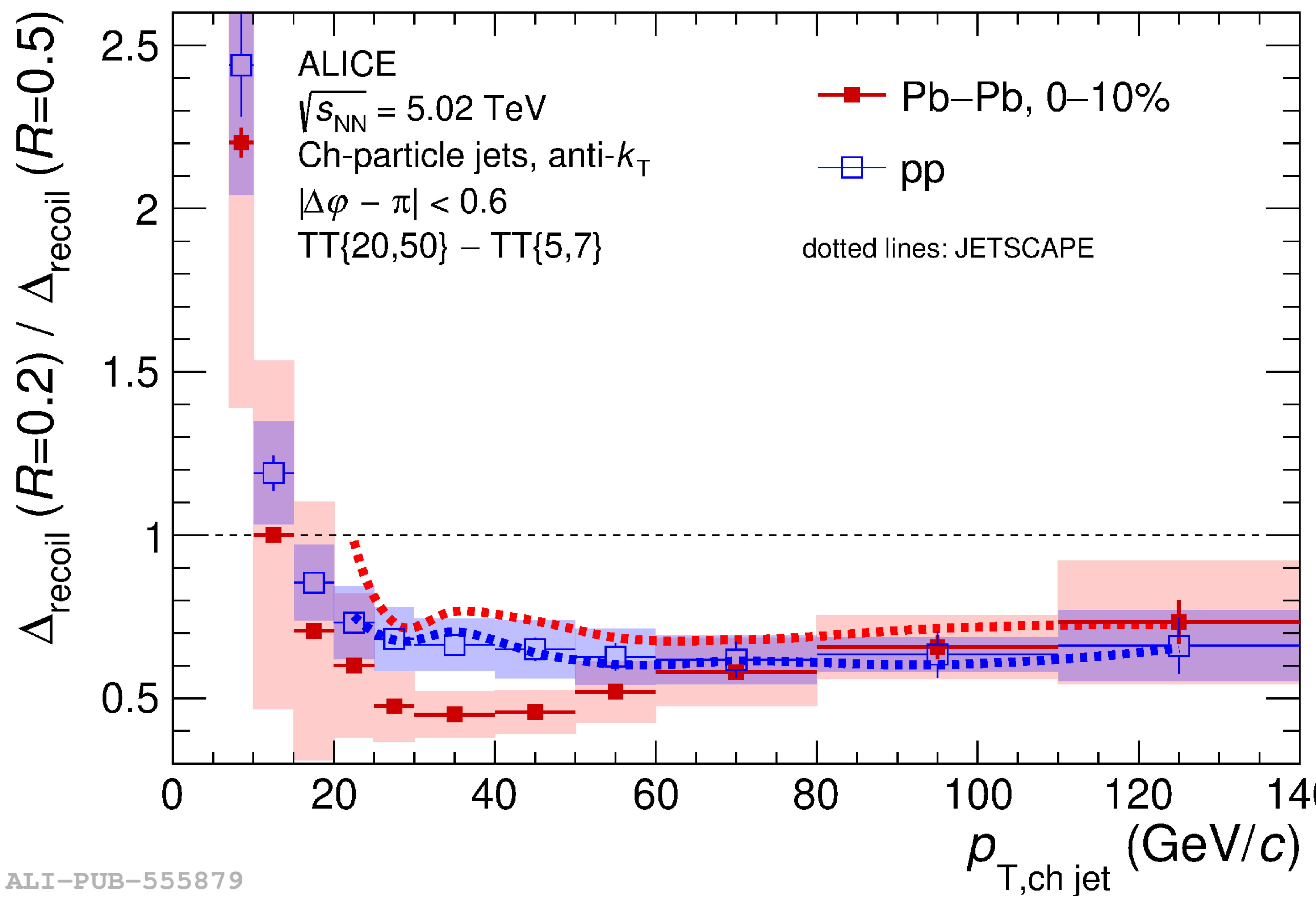
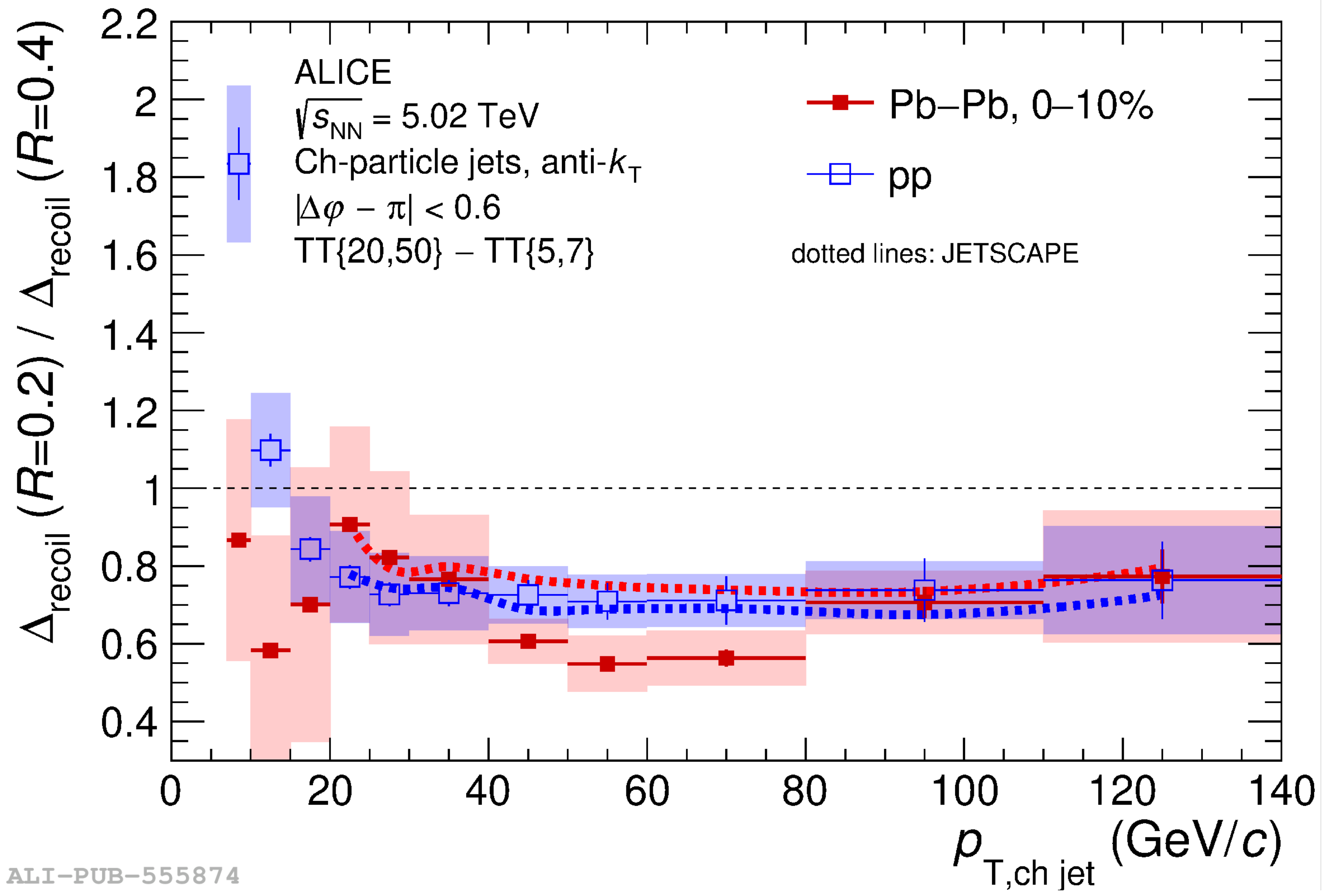
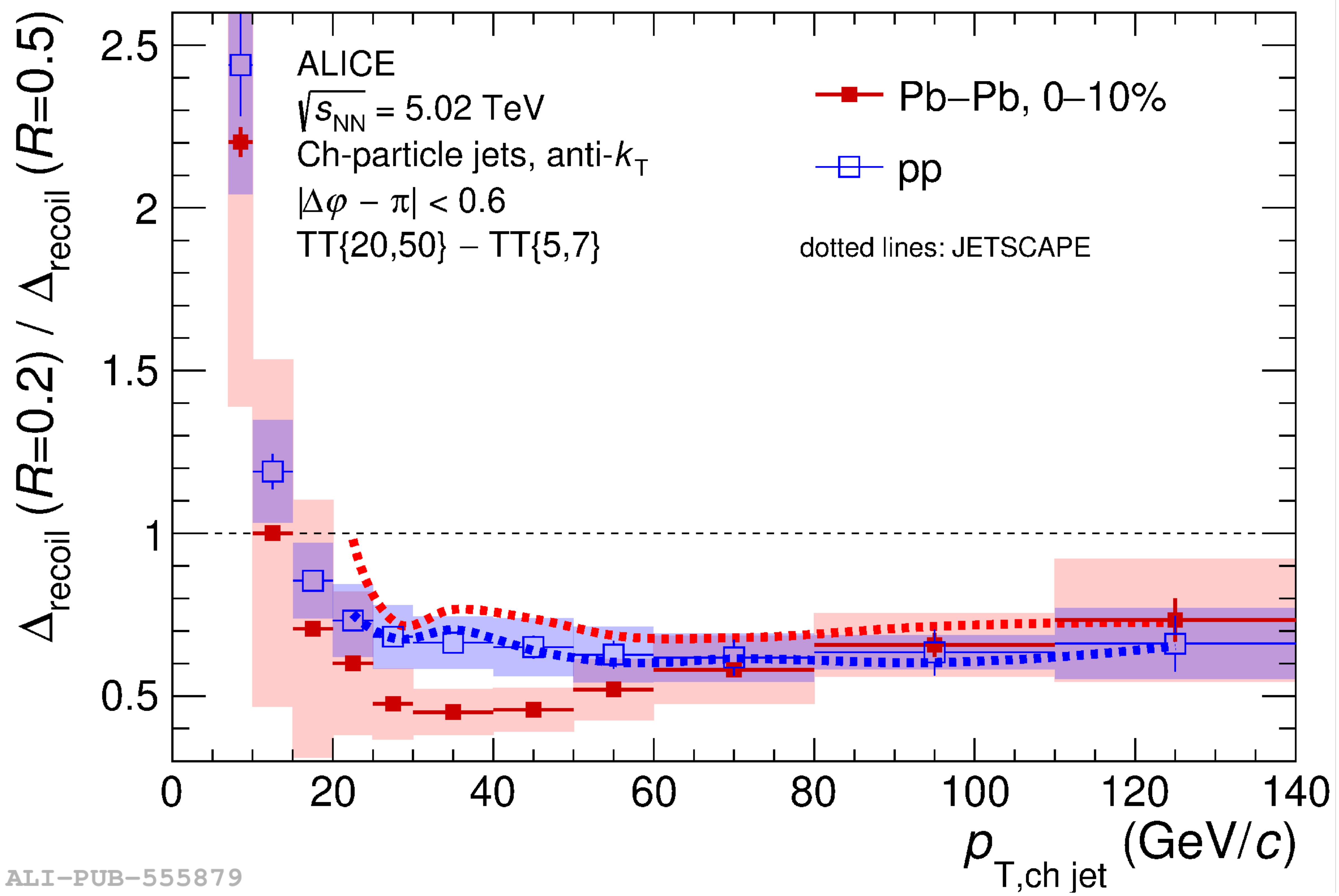




- **Comparison the ratio** of $\Delta_{recoil}(p_T)$ between pp and Pb-Pb collisions

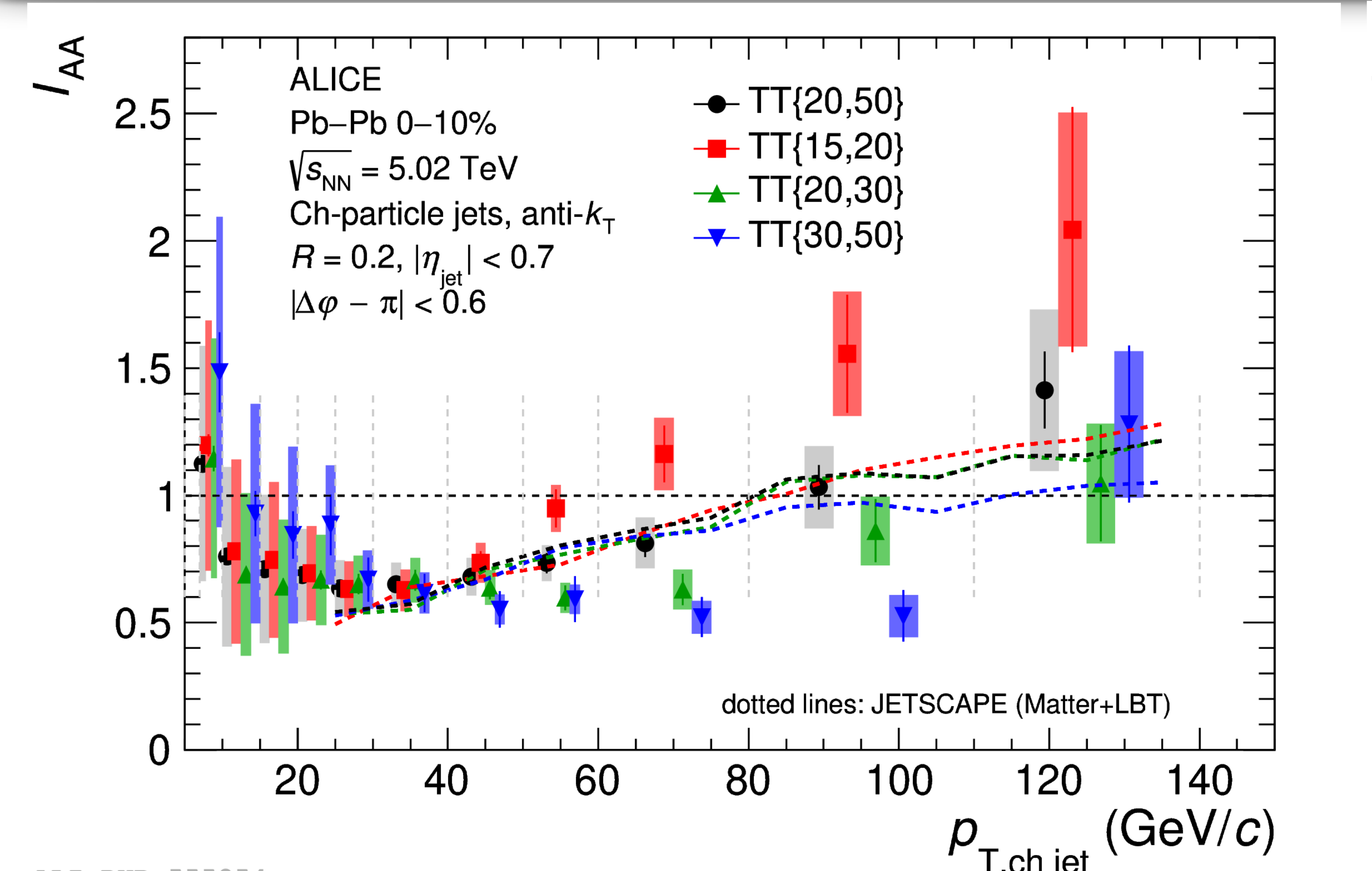
Fully corrected yield ratio: compared to Pb-Pb

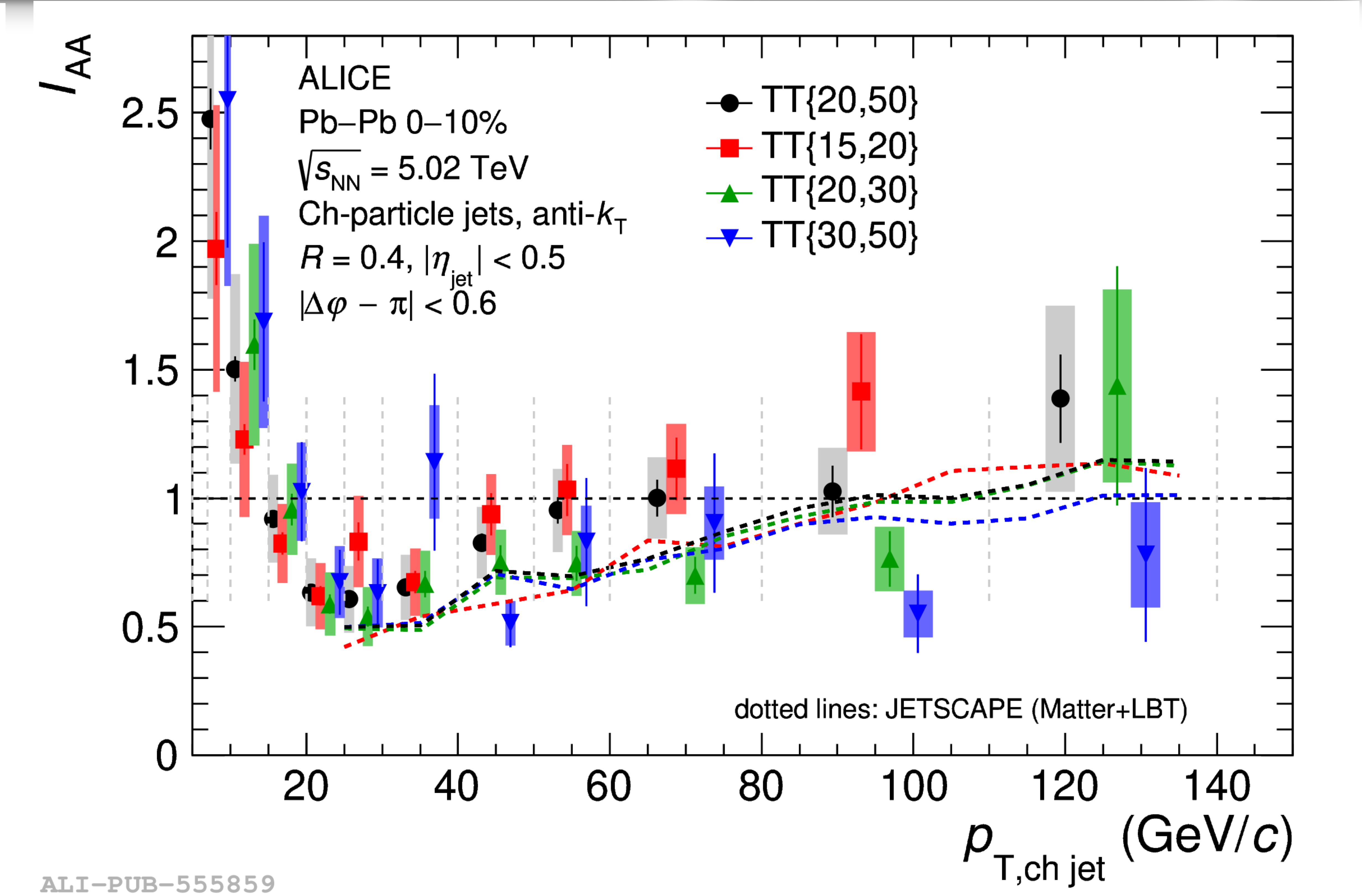




- **Comparison the ratio** of $\Delta_{recoil}(p_T)$ between pp and Pb-Pb collisions
  - **At middle p_T,** the ratios for Pb–Pb collisions **are lower than** those for pp collisions → indicating **significant medium-induced intra-jet broadening** in that region.

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





- Expected that high p_T hadrons leading fragment of jet originating from QGP surface (‘surface bias’)
- $p_T^{jet} \sim p_T^{trig}$: **suppression** - surface bias picture holds
- $p_T^{jet} \gg p_T^{trig}$: trigger hadron may not be leading fragment or from higher order process - interplay between jet and hadron
- New insight into interplay between hadron and jet suppression

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

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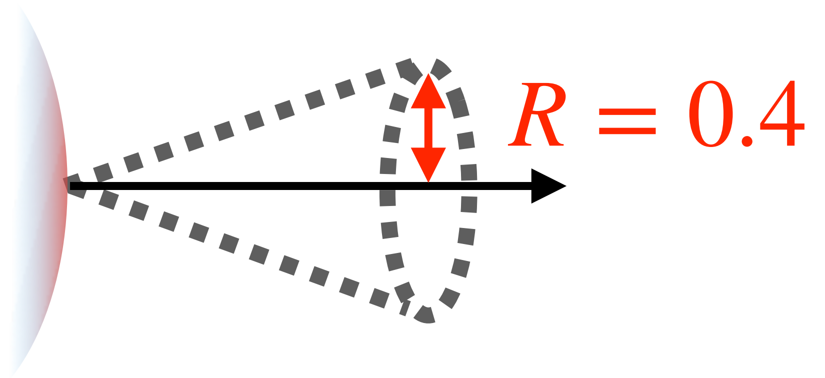
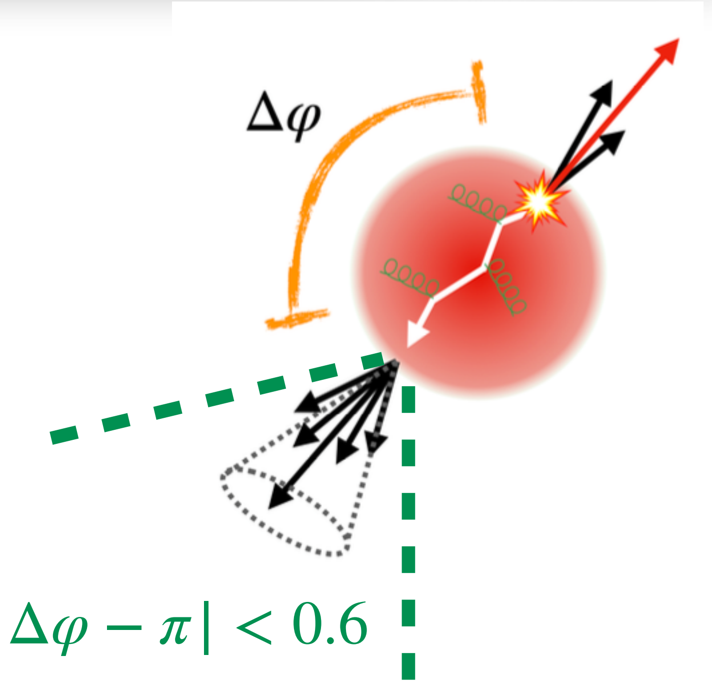
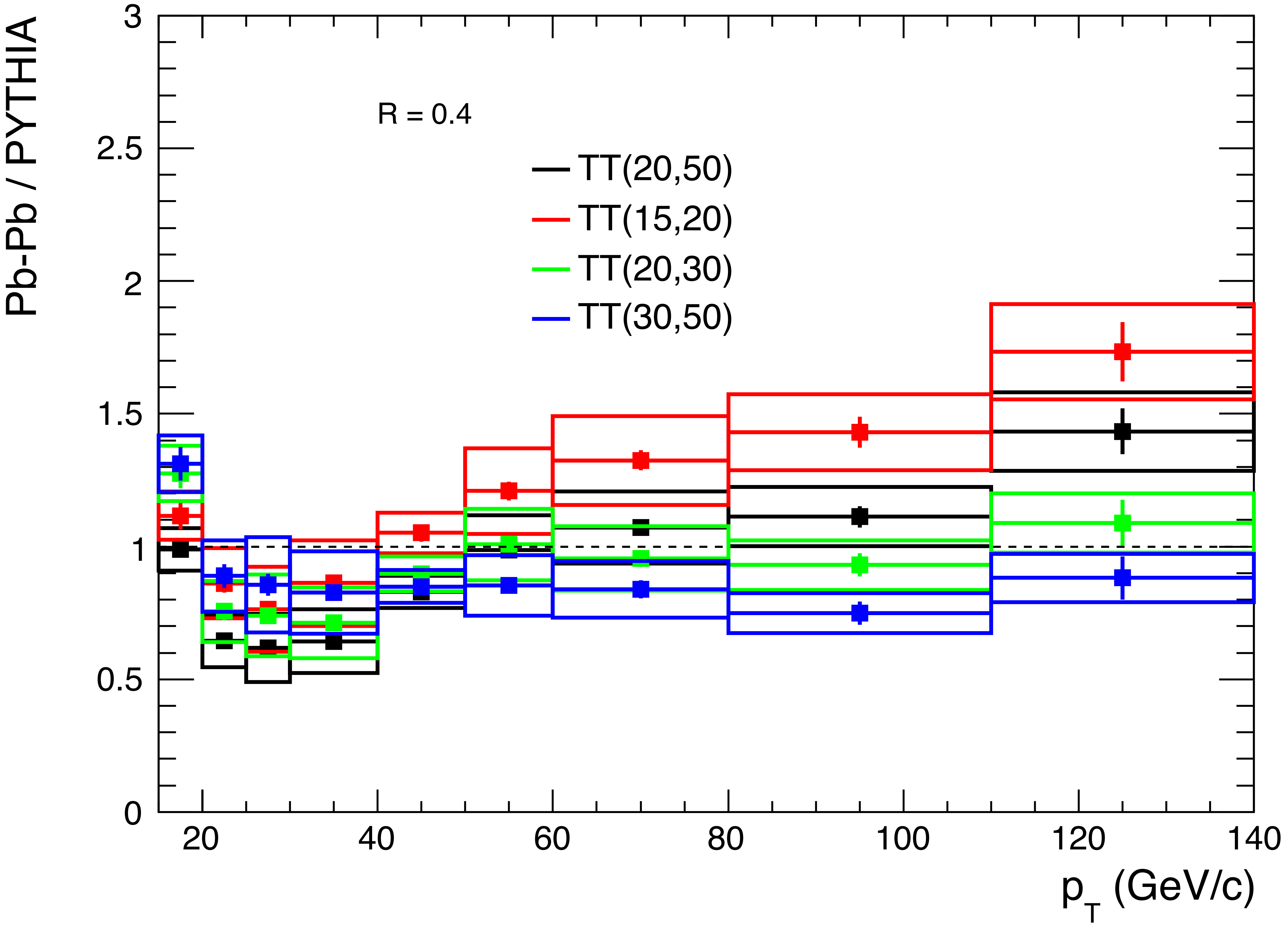


0 – 10 %

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





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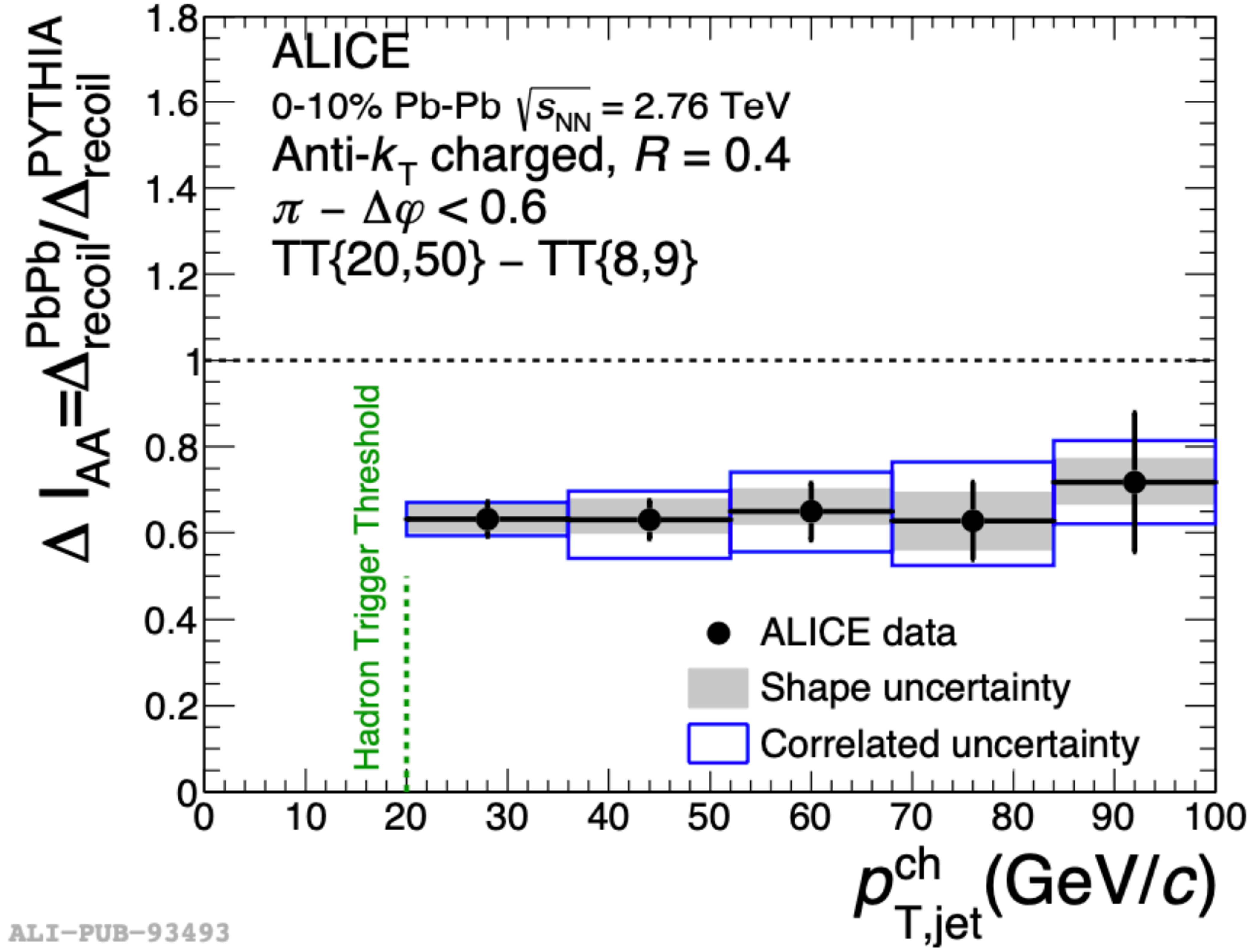

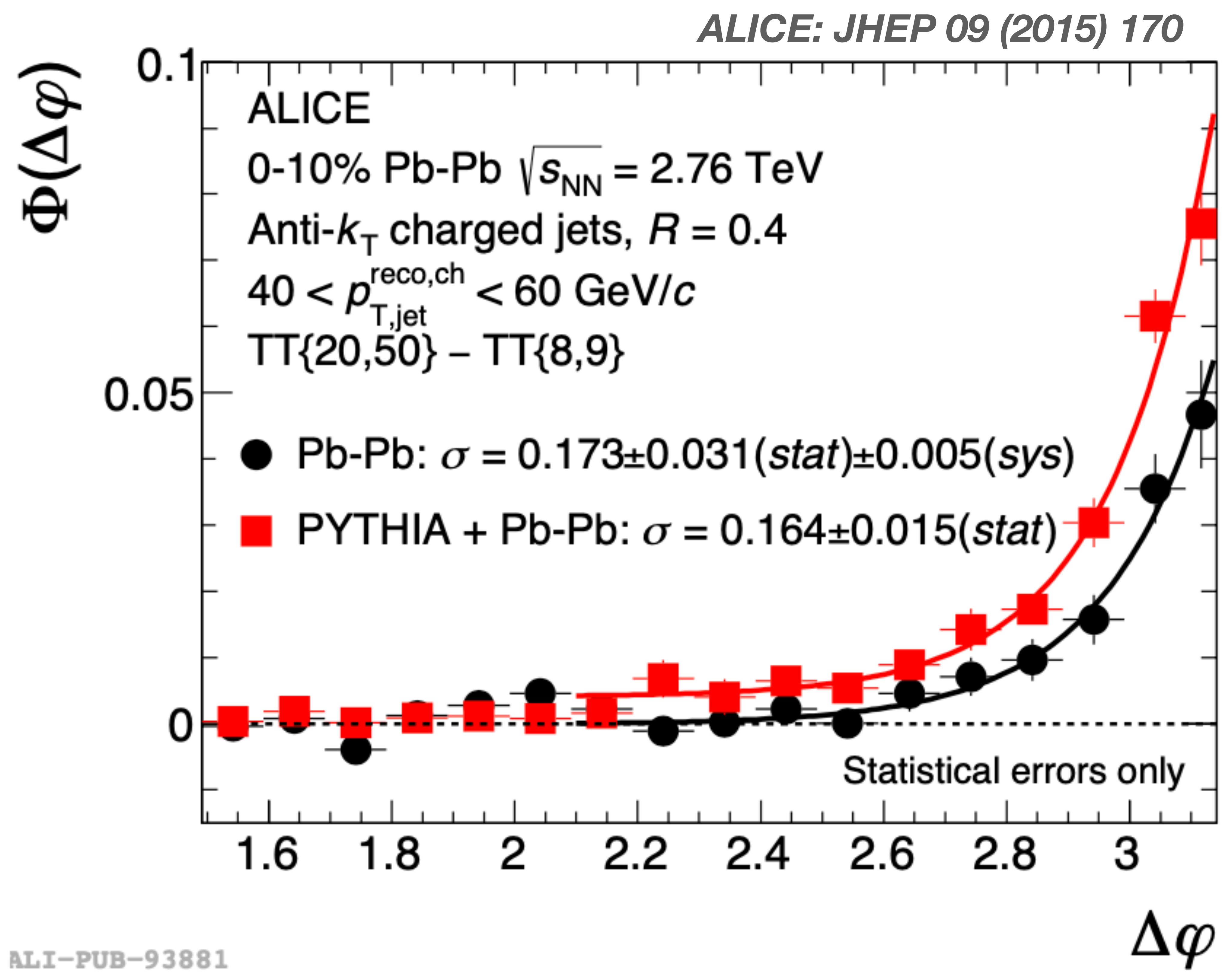

- Background-subtracted yield of jets recoiling from a high- trigger hadron:
  - Suppression with respect to a pp (PYTHIA) reference
  - No medium-induced broadening within experimental uncertainties

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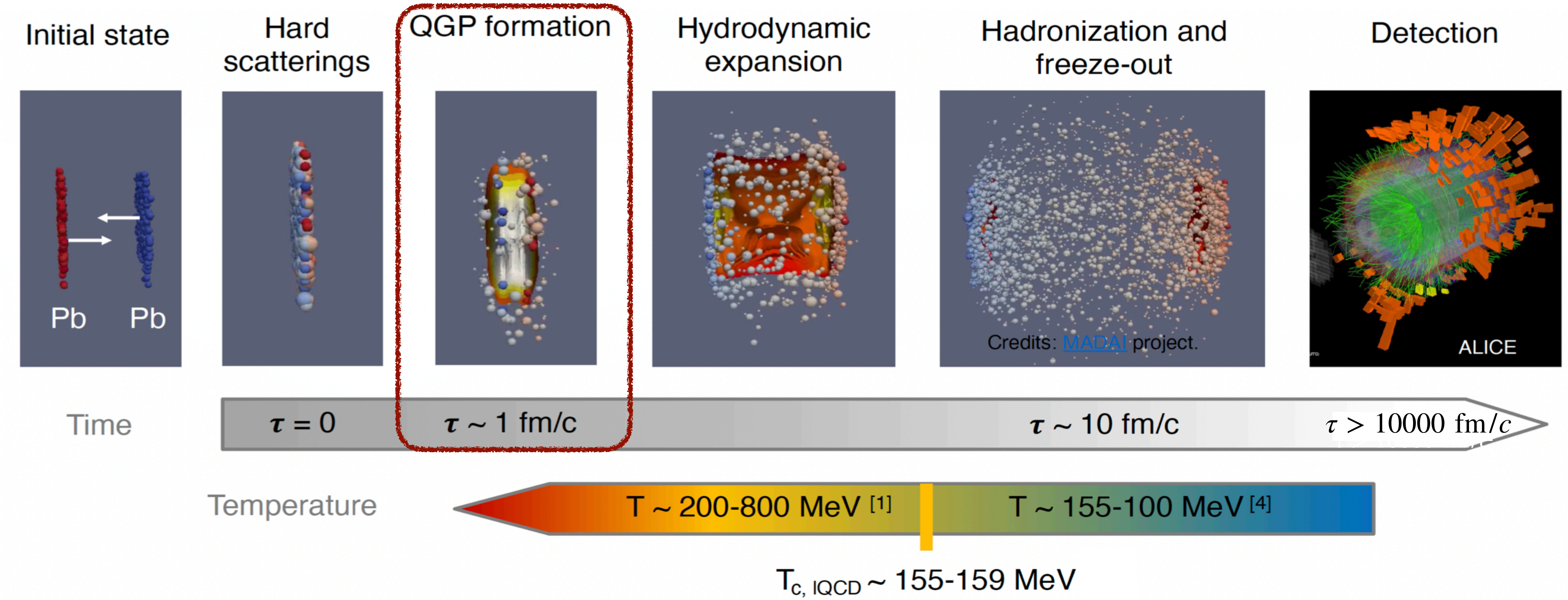

- Direct observation of QGP is impossible due to its **short lifetime** →rely on emerging particles as "probes"

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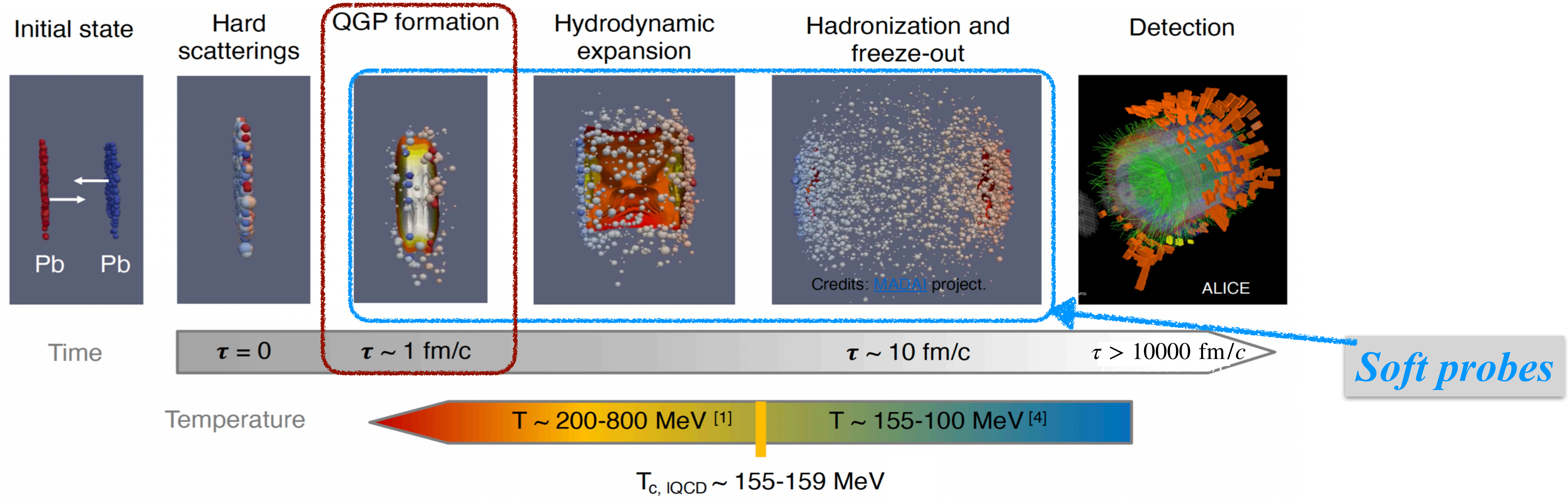

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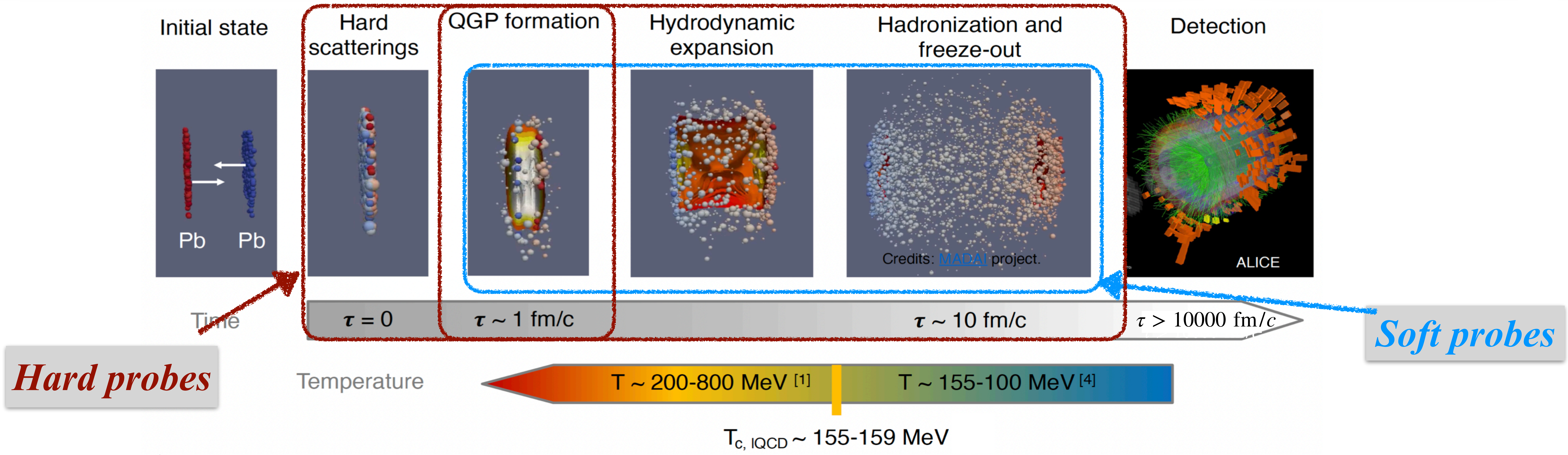
  - **Soft probes: low p_T-hadrons (light flavors)** product from hadronization of strongly-interaction, thermalized QGP
    - non-perturbative QCD regime → fingerprint of the QGP evolution



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  - **Hard probes: high-p_T partons (jets and heavy quarks)** produced in the early stages in hard scatterings (high Q^2)
    - calibrated probes, can be calculated by pQCD
    - traverse the QGP and interact with its constituents, medium-modified parton cascade due to jet quenching