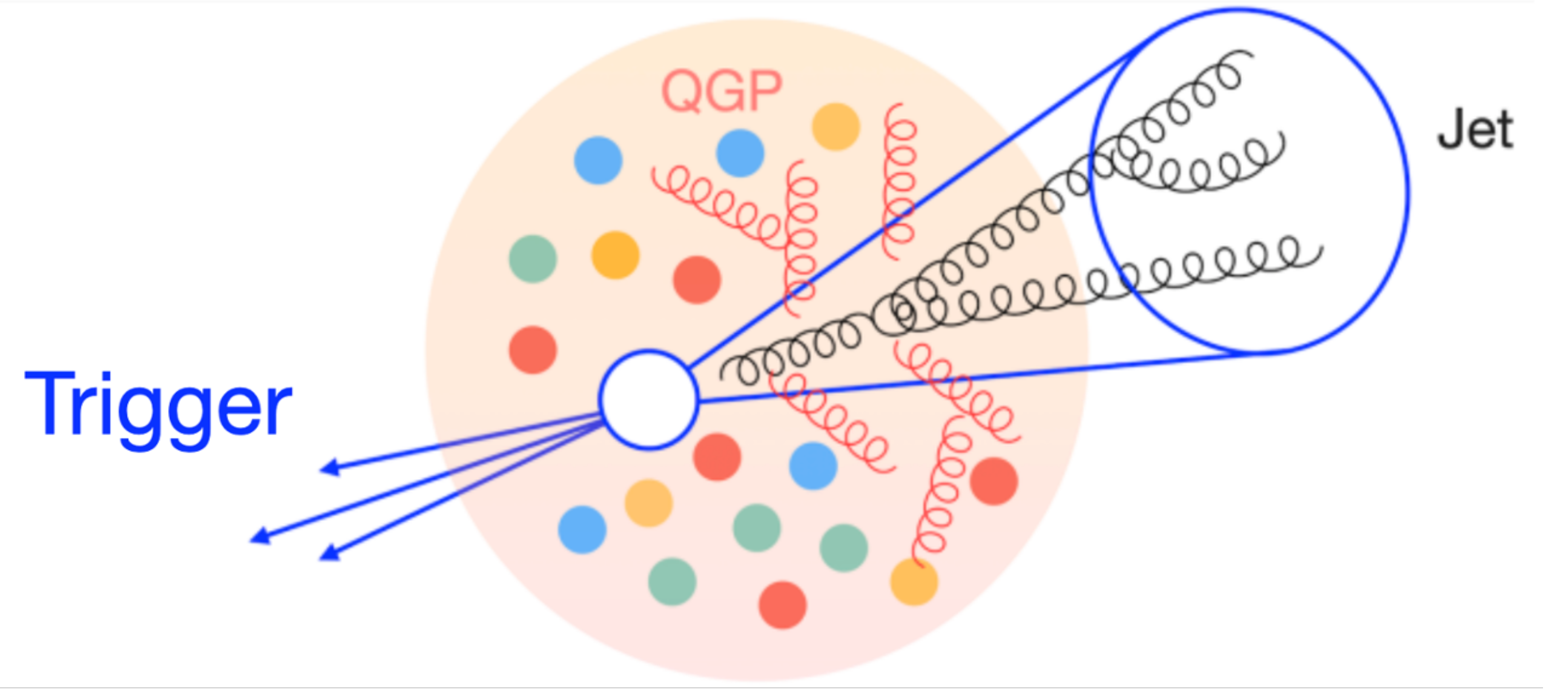
CLHCP2025 新乡

第十一届中国LHC物理会议

The 11th China LHC Physics Conference

Jet quenching studies via hadron-jet correlations with ALICE



Yongzhen Hou (侯永珍)， CUG & GSI

The 11th China LHC Physics Conference

Xinxiang, 30 October 2025

A few measurements I will cover today

- **Hadron-jet correlations in pp collisions at 13.6 TeV (Run 3 preliminary)**
- **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

Jet probes

Jets are **collimated sprays of particles** originating from initially hard-scattered partons

Jets in small collision systems (pp, p-Pb)

- Investigate the parton splitting functions
- Test the Cold Nuclear Matter (CNM) effects in p-Pb collisions
- Serves as a reference for **jet-quenching measurements** in heavy-ion collisions
- Search for possible **QGP droplet formation** in small collision systems

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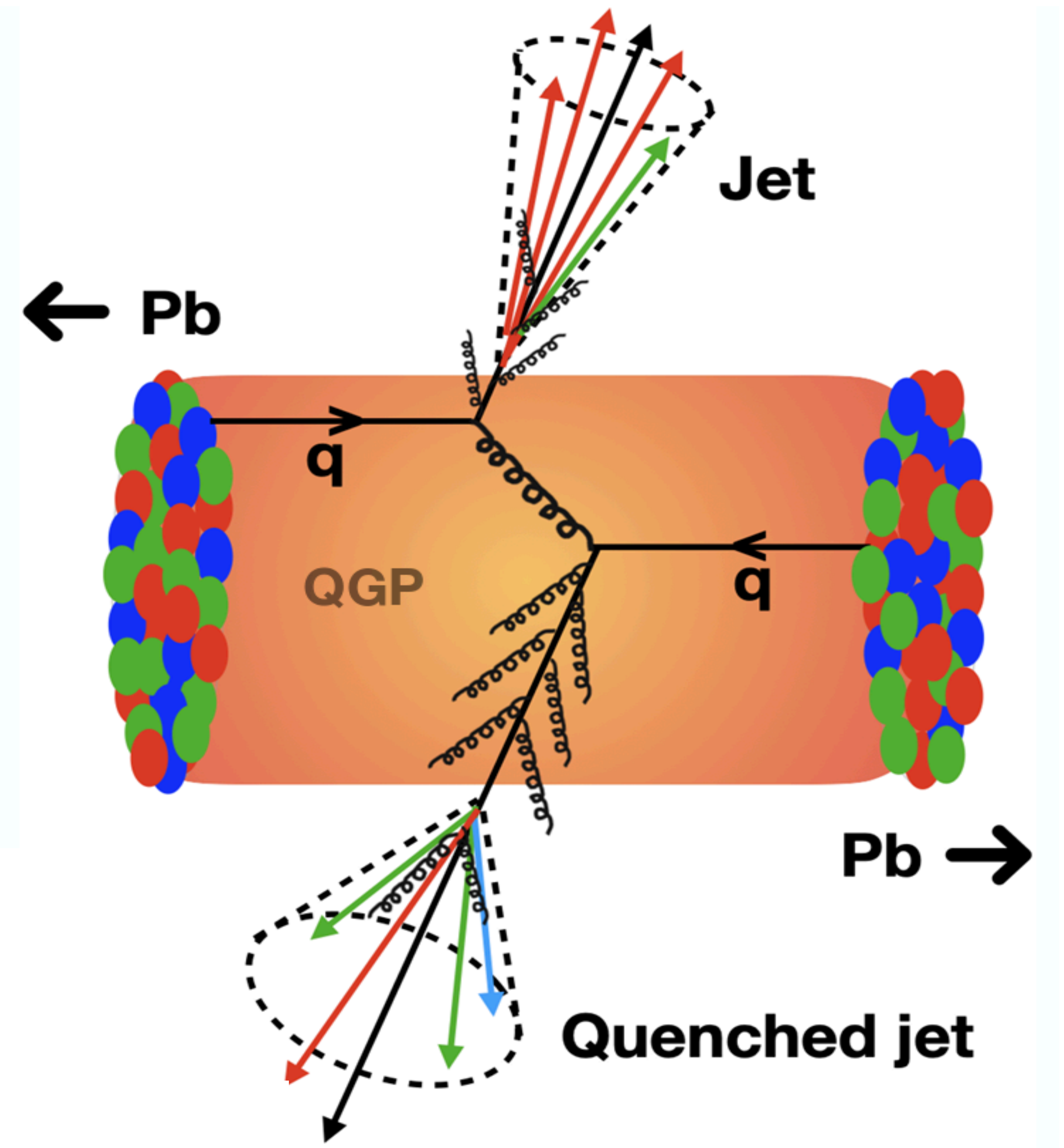
Jets in heavy-ion collisions → study the transport properties of the QGP

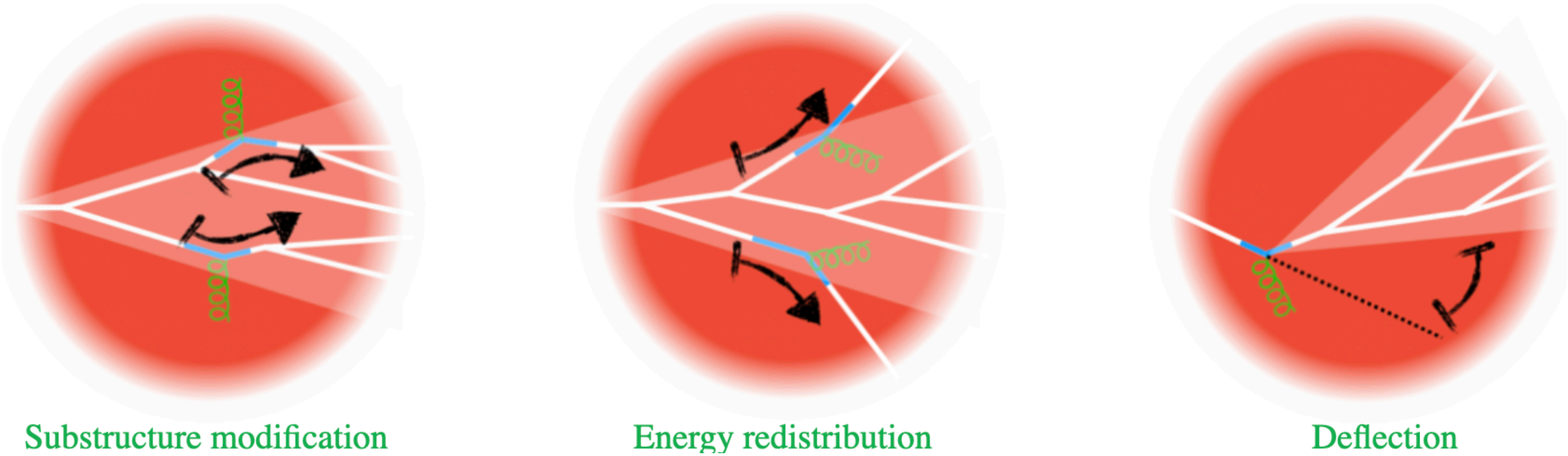
- Partons interact with QGP and lose energy through medium-induced gluon radiations (inelastic) and collisions (elastic) with medium constituents:
  - $\mathrm{Jet}(E) \rightarrow \mathrm{Jet}(E' - \Delta E) + \text{soft particles}(\Delta E)$



Jet observables

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 → **suppression and energy redistribution** (R_{AA}, I_{AA})
  - Jet angular correlation → **jet deflection** (**$\Delta\varphi$**)



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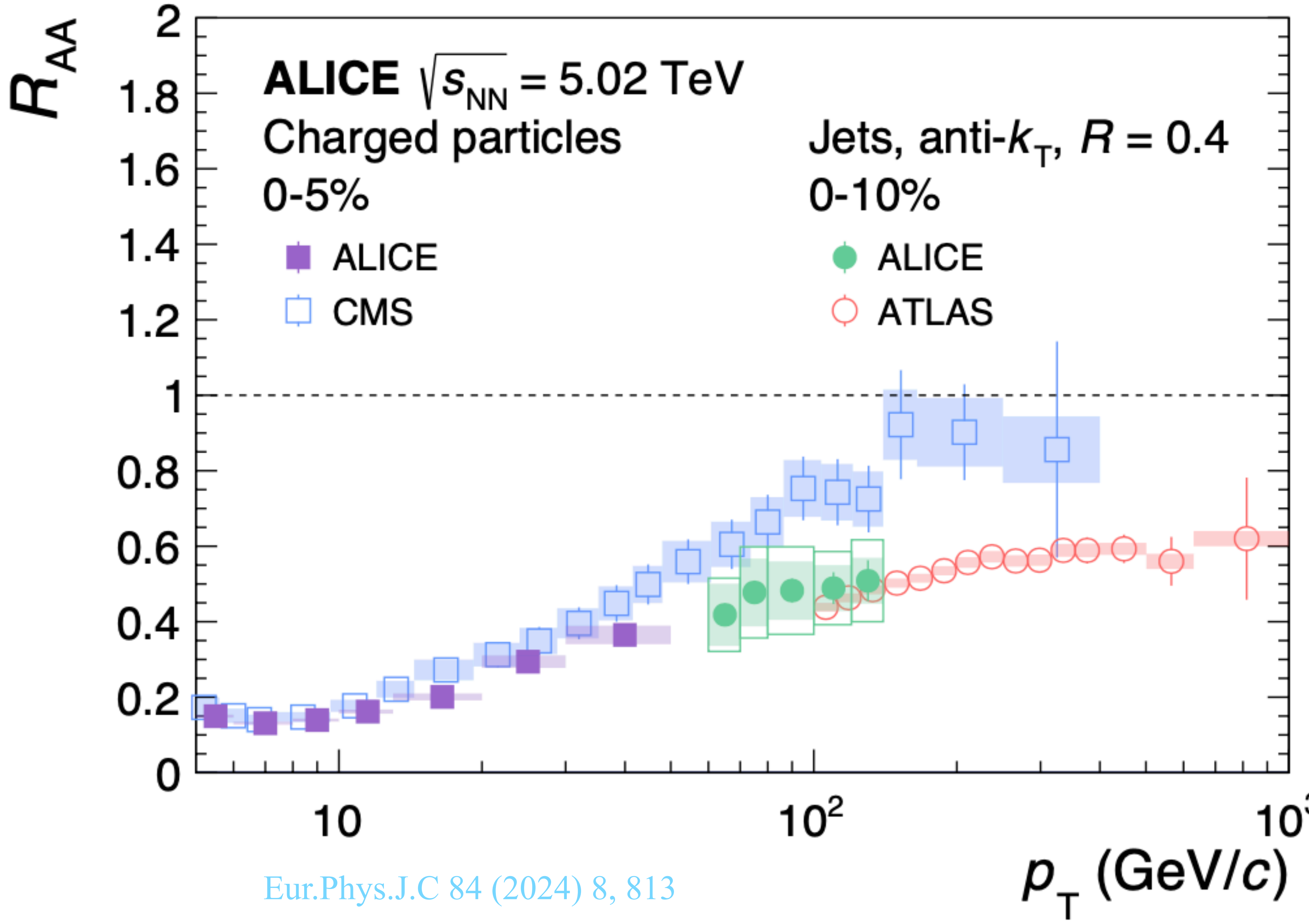
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle \, d\sigma_{pp}/dp_T}$$

QGP medium

QCD vacuum



Eur.Phys.J.C 84 (2024) 8, 813

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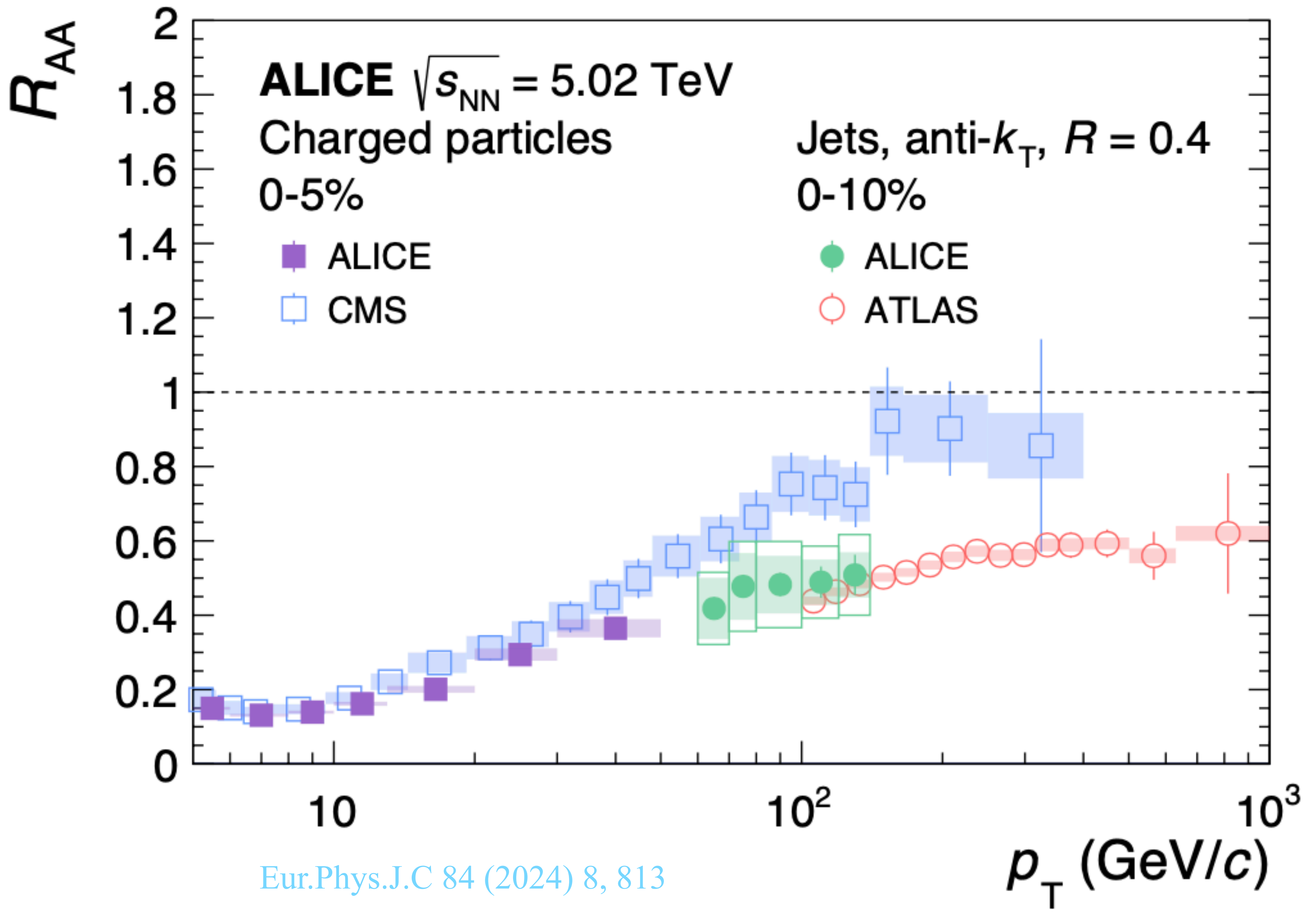
  - Jet angular correlation → **jet deflection ($\Delta\varphi$)**

    ➡**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



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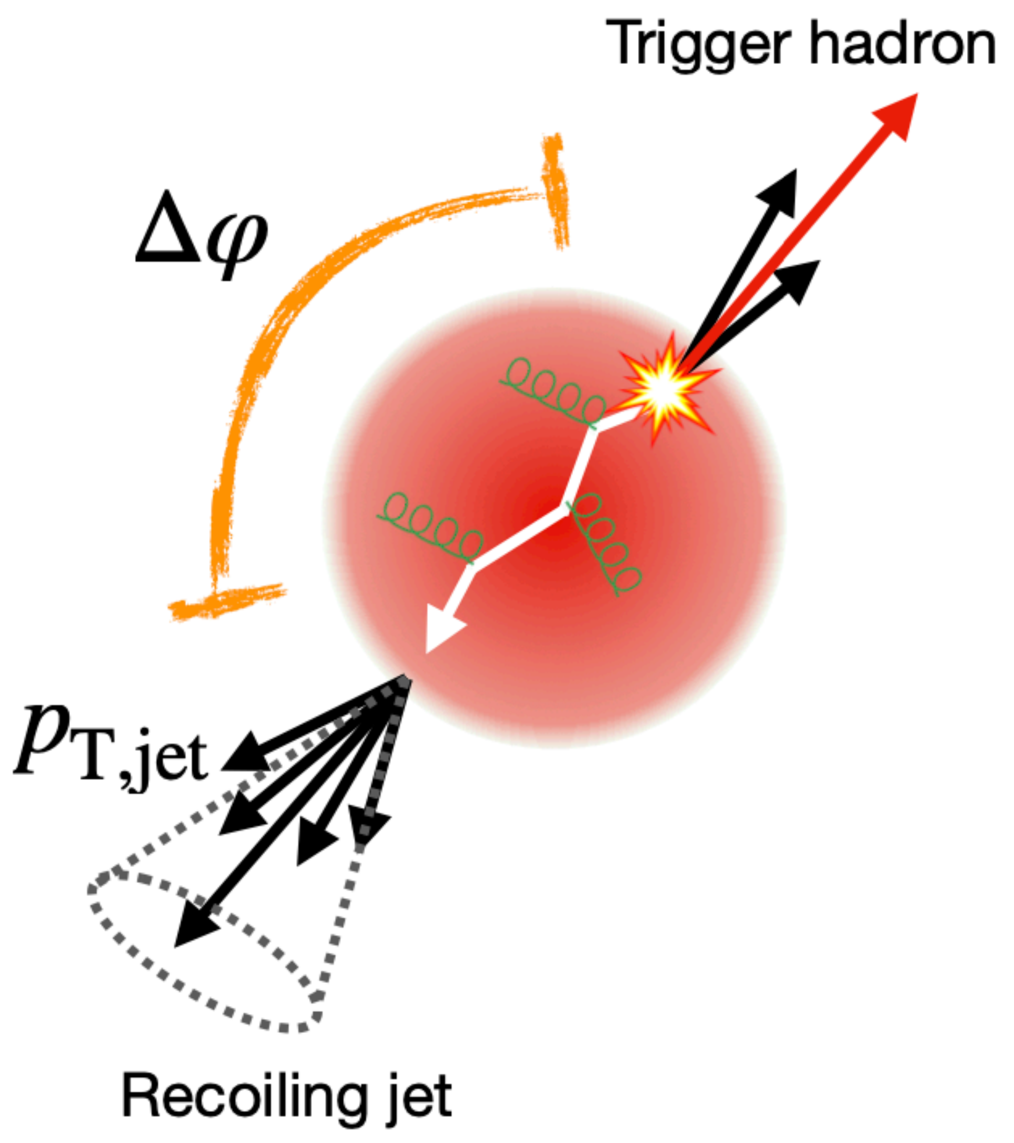
Hadron-jet correlations

- Measurements of semi-inclusive jets recoiling from a trigger hadron provide a good handle on combinatorial background by varying the trigger track intervals → **access low p_{T}, large R jets**
- **Opening angle ($\Delta\varphi$)** measurements of the recoil jet relative to the trigger axis provide additional insight into QGP properties → **broadening transverse to its initial direction**



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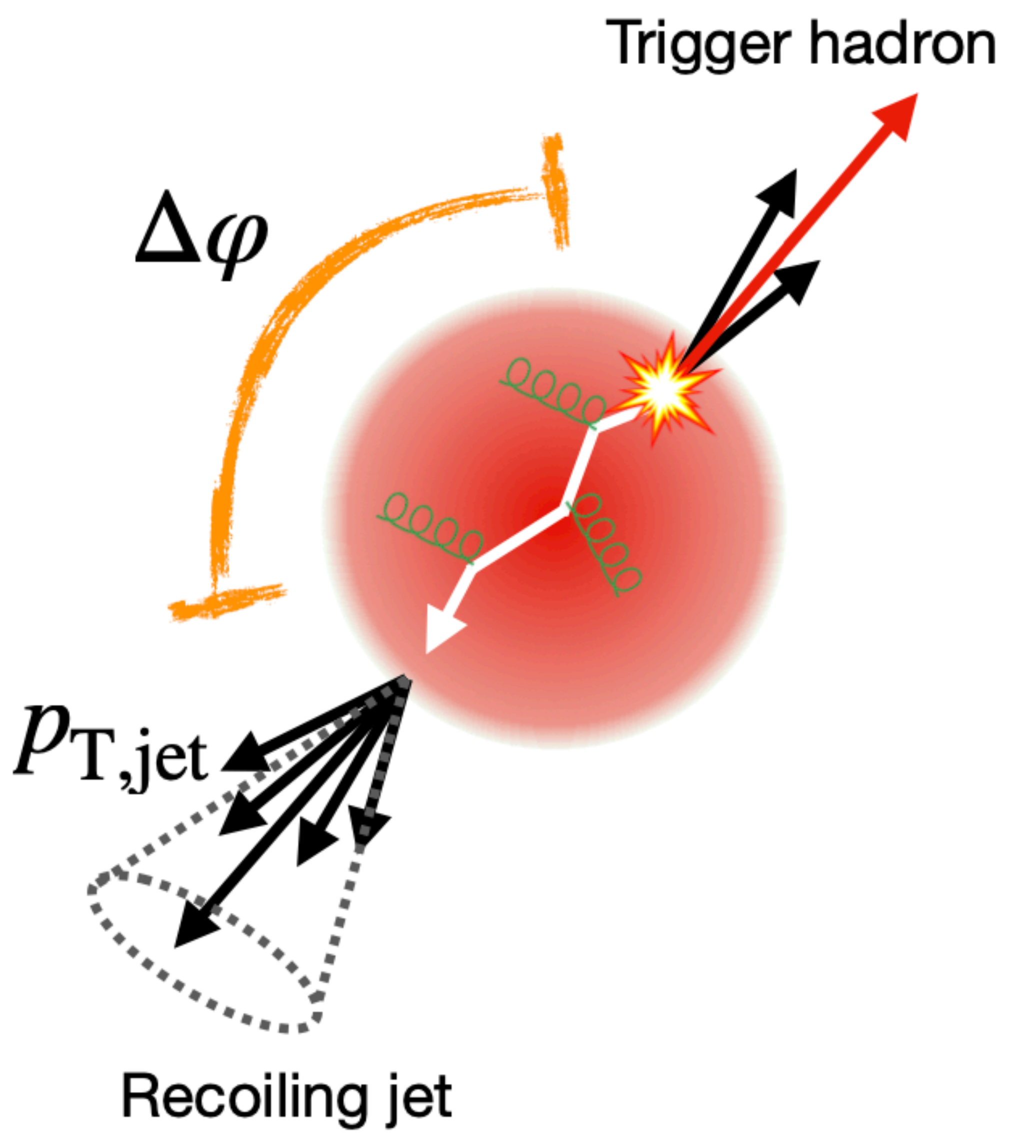

1. L Chen, Phys. Lett. B 773 (2017) 672
2. Phys.Lett.B 763 (2016) 208-212
3. JHEP 01 (2019) 172

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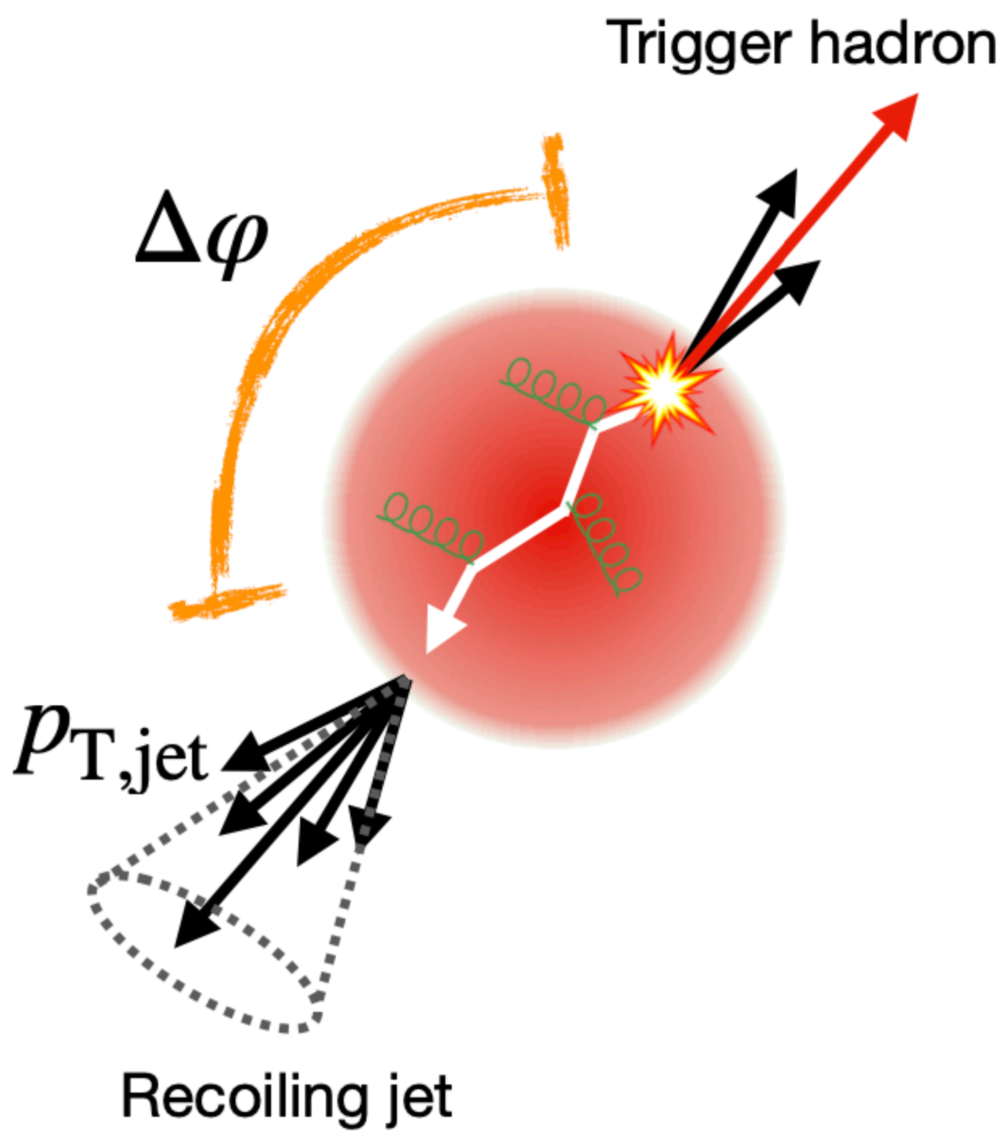
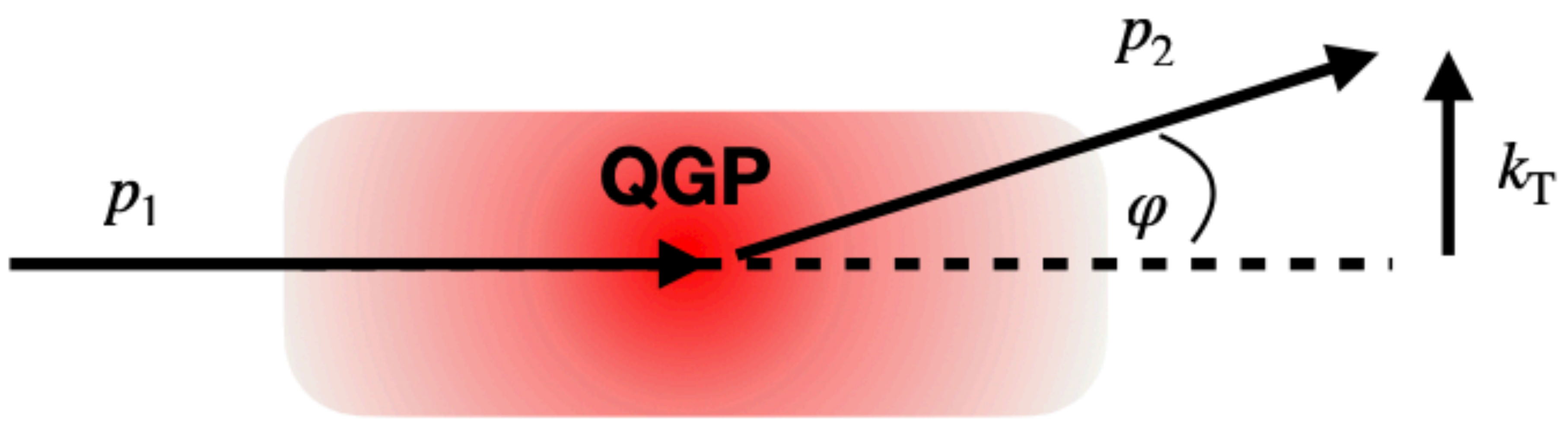
  - **In vacuum:** transverse broadening from gluon emission (**Sudakov broadening**)[1,2]
  - **In medium:** additional broadening from scatterings with medium constituents[1,2]
    - Transverse broadening due to **multiple soft scatterings** in the QGP
      - Related to transport coefficient $\hat{q} \sim \langle k_{\perp}^2 \rangle / L \sim \langle \Delta\varphi^2 \rangle / L$
    - **Large-angle deflection** ($\Delta\varphi < \pi$) of hard partons off quasi-particle[3]?





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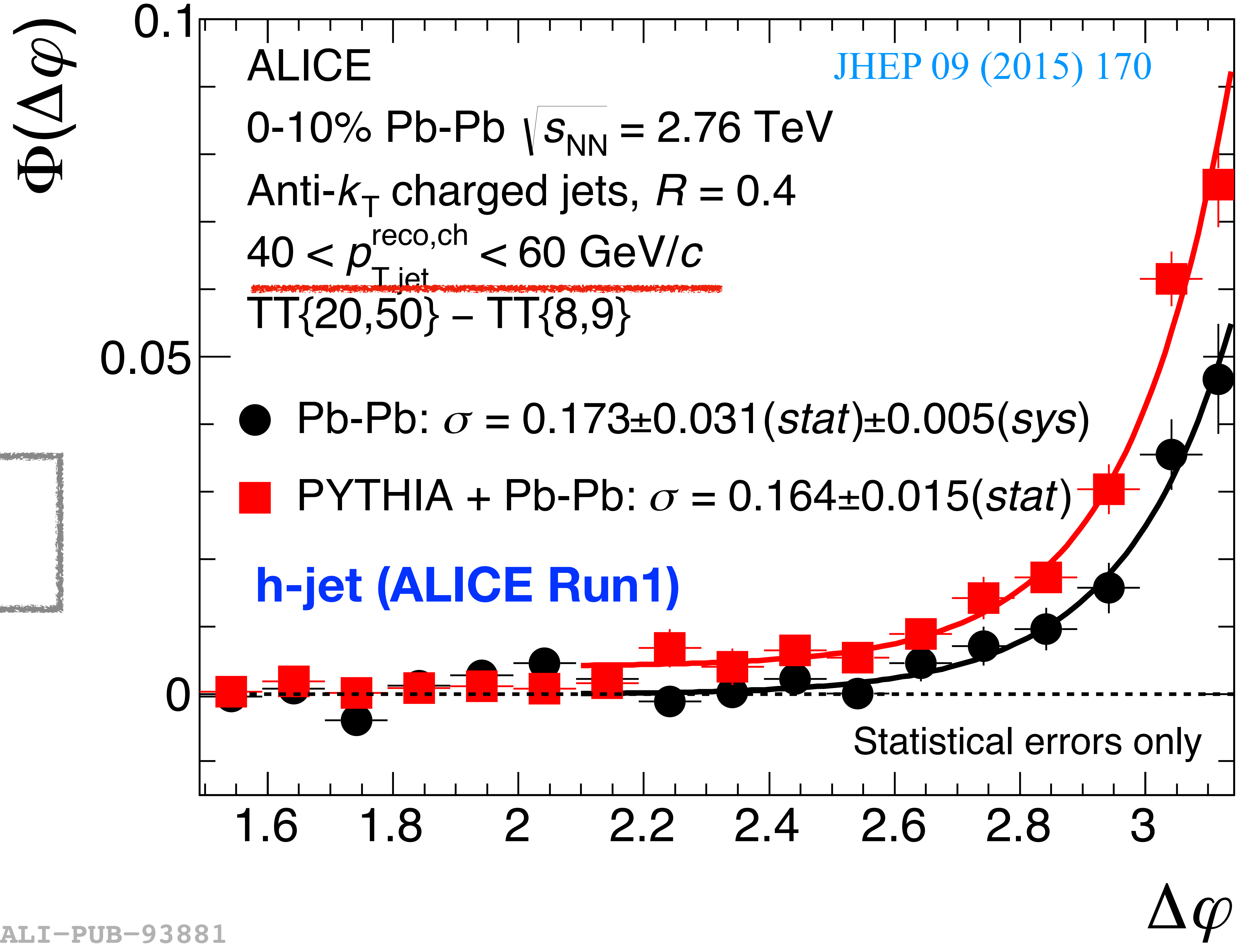
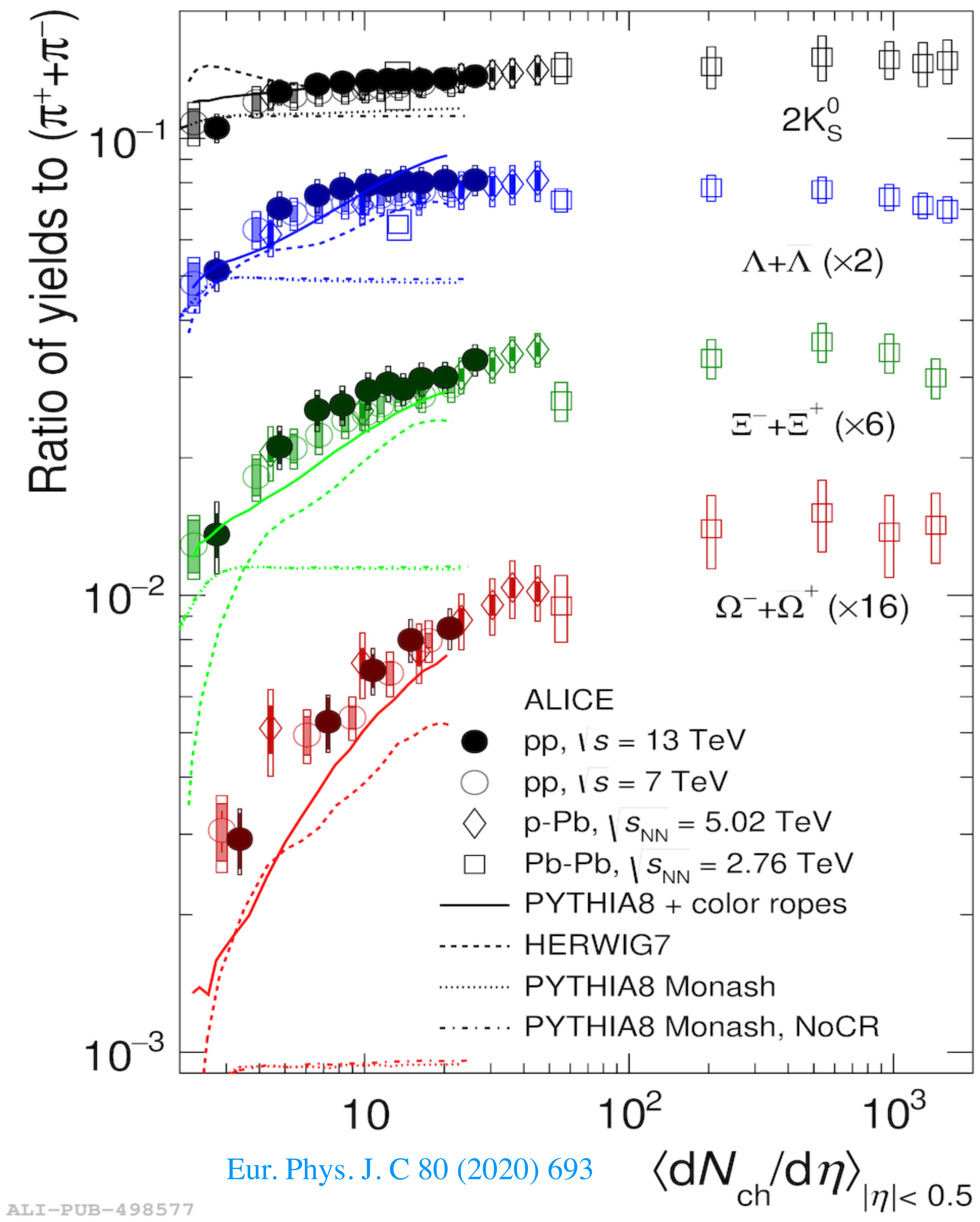


No medium-induced acoplanarity broadening observed

QGP-like behavior in small collision systems

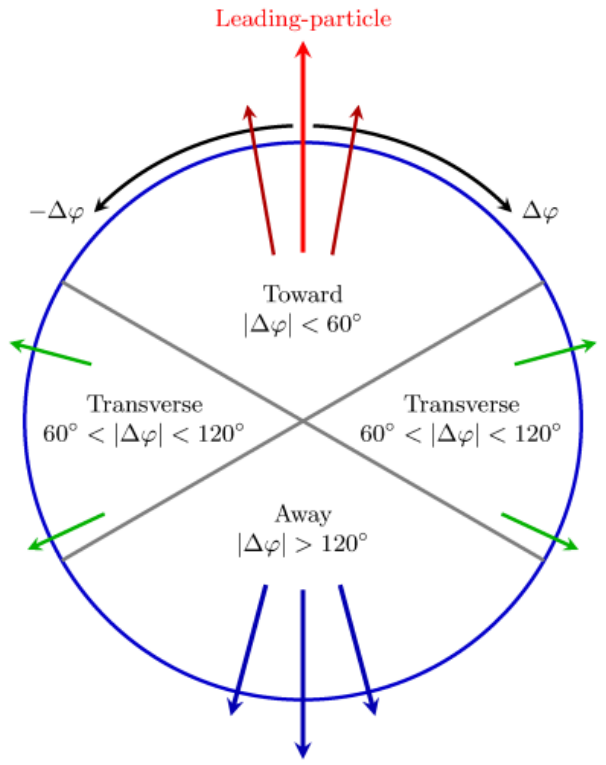
- Effects regarded as QGP signatures in heavy-ion collisions, e.g., collectivity and **strangeness enhancement**, have also been observed in small systems.



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

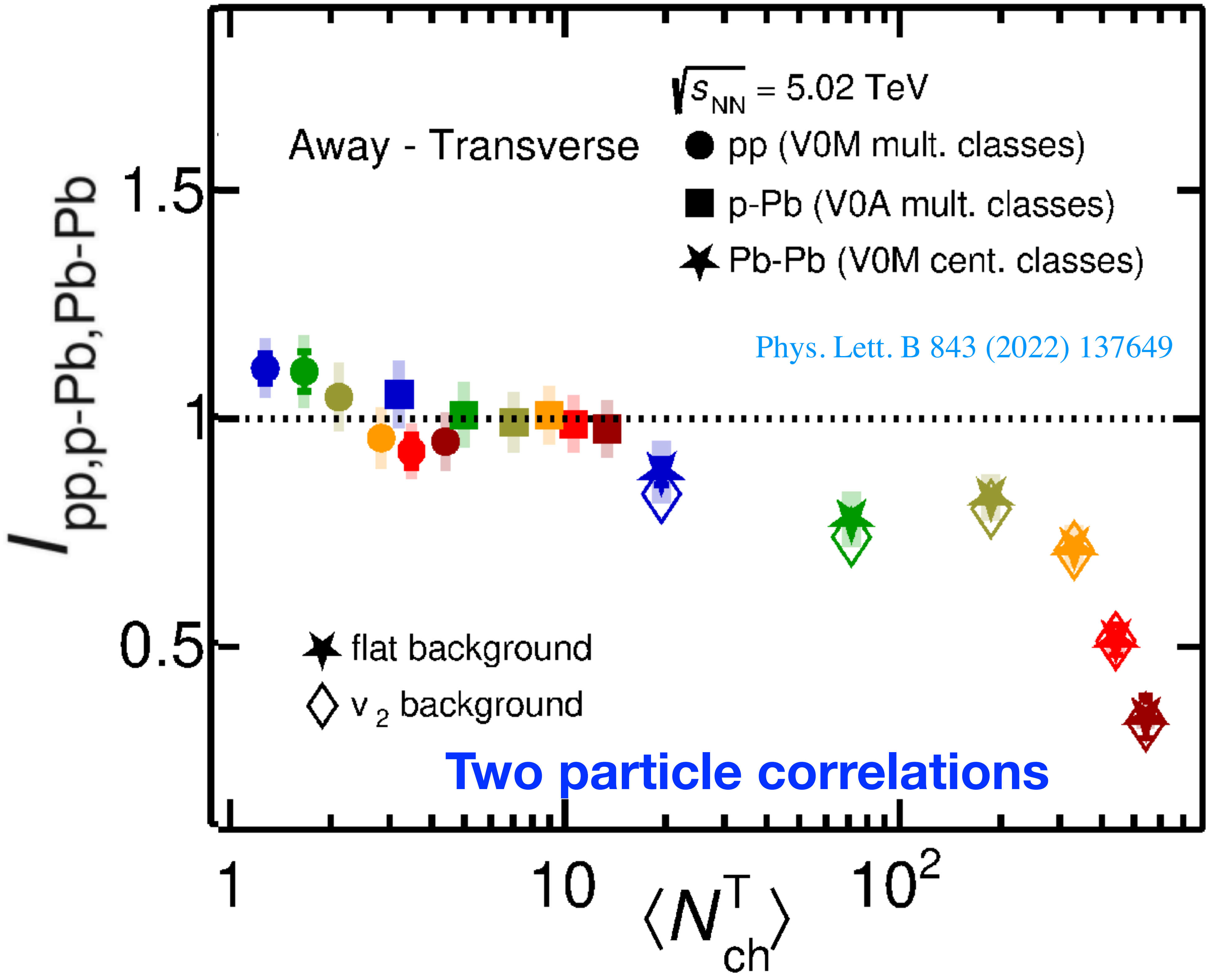
QGP-like behavior in small collision systems

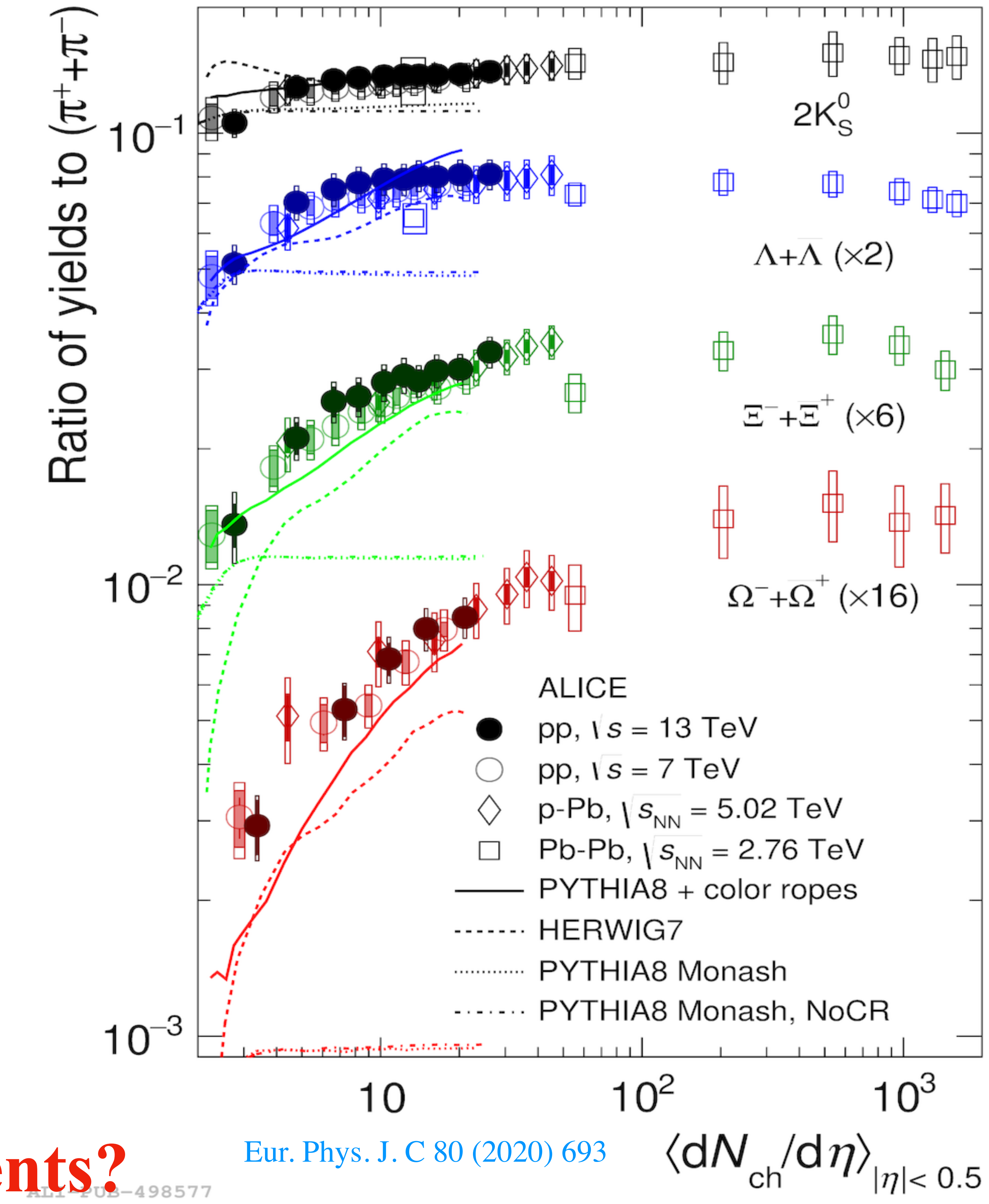
- Effects regarded as QGP signatures in heavy-ion collisions, e.g., collectivity and **strangeness enhancement**, have also been observed in small systems.
- However, no **jet quenching** has been observed so far



Δφ=|φ$_{leading}$ - φ$_{associate}$|

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





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

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

Analysis procedure and observables

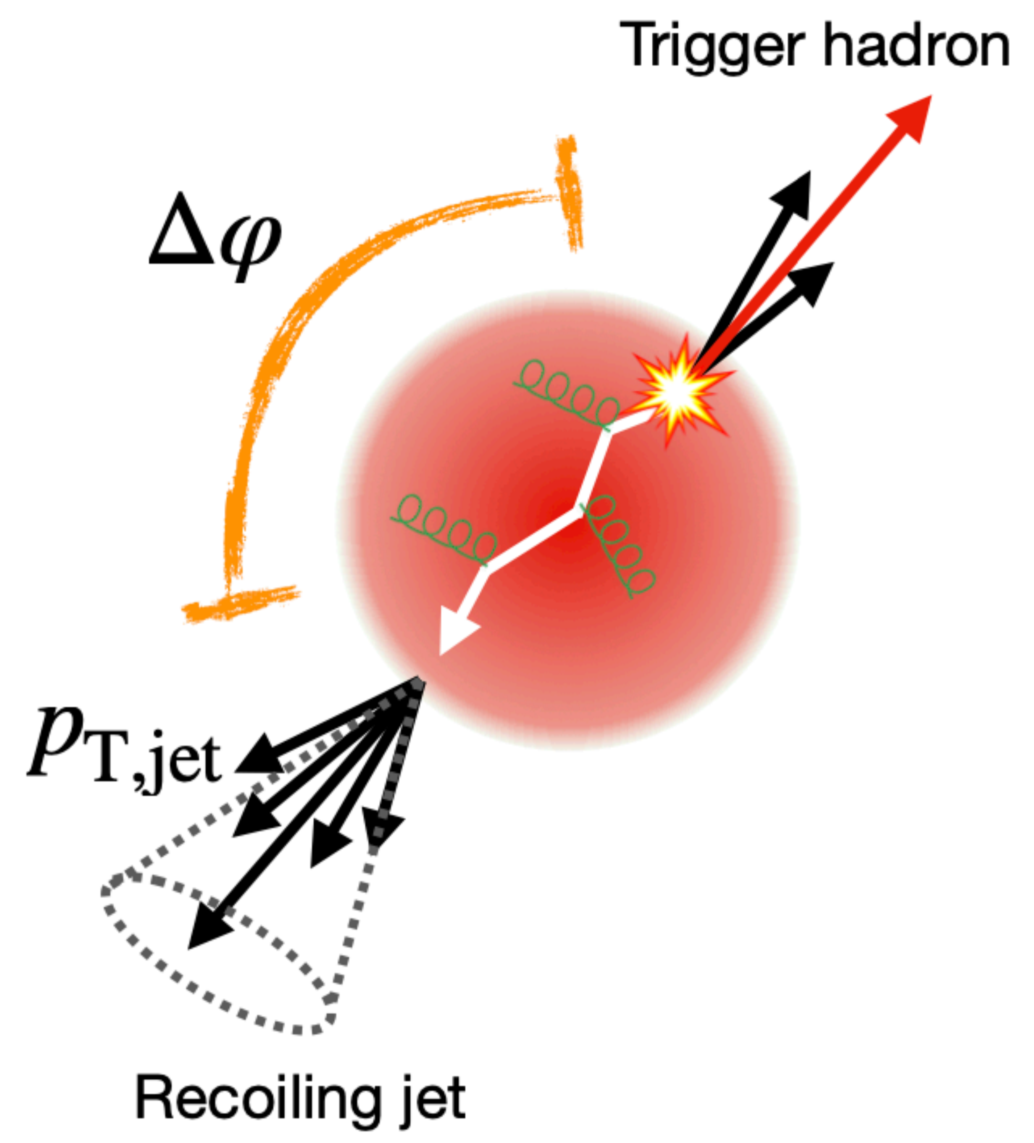
- Measure **trigger-normalised yield** of jets recoiling from a trigger hadron

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

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

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

(except pp at 13 TeV, TT$_{\rm S}$ [20,30], TT$_{\rm R}$: [6,7])



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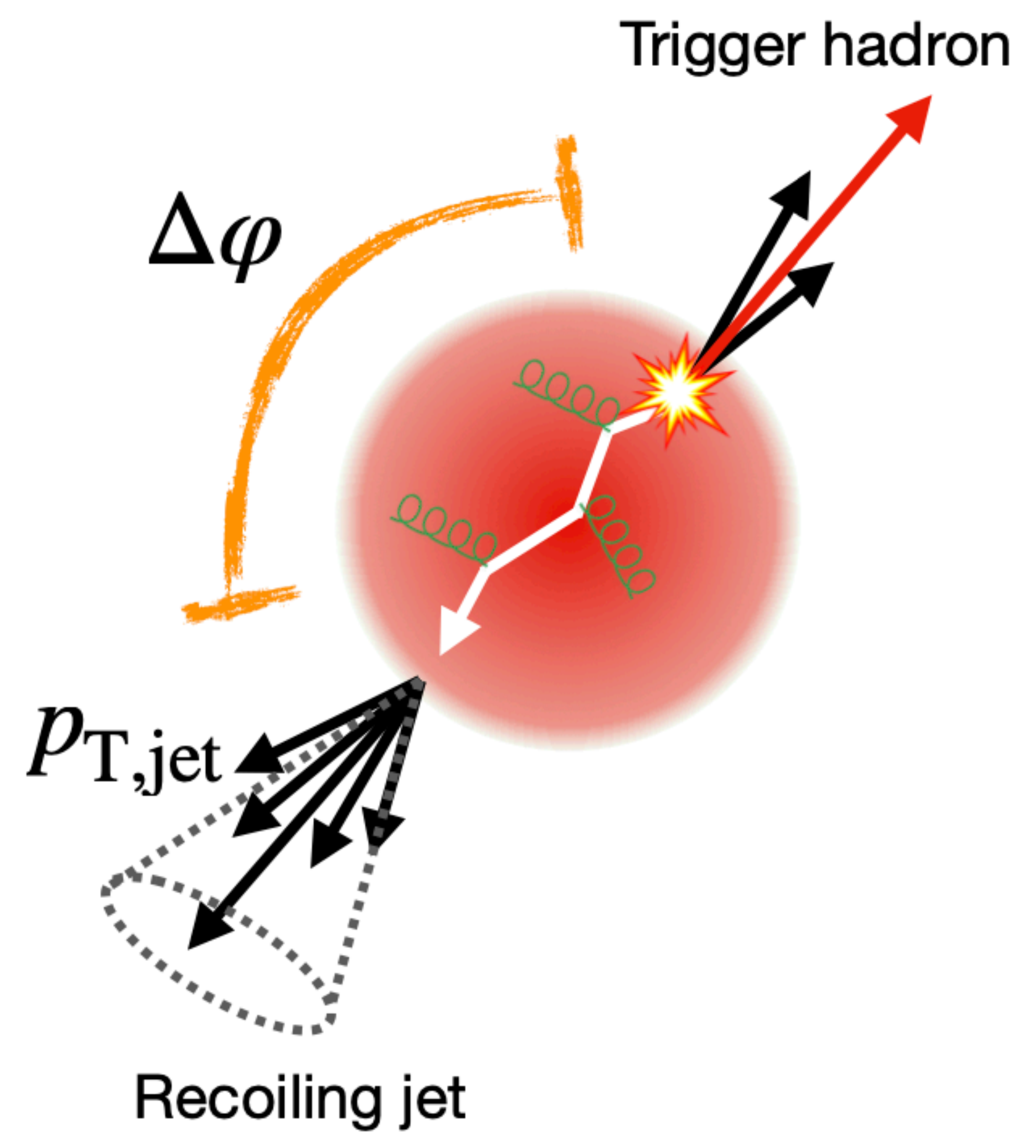

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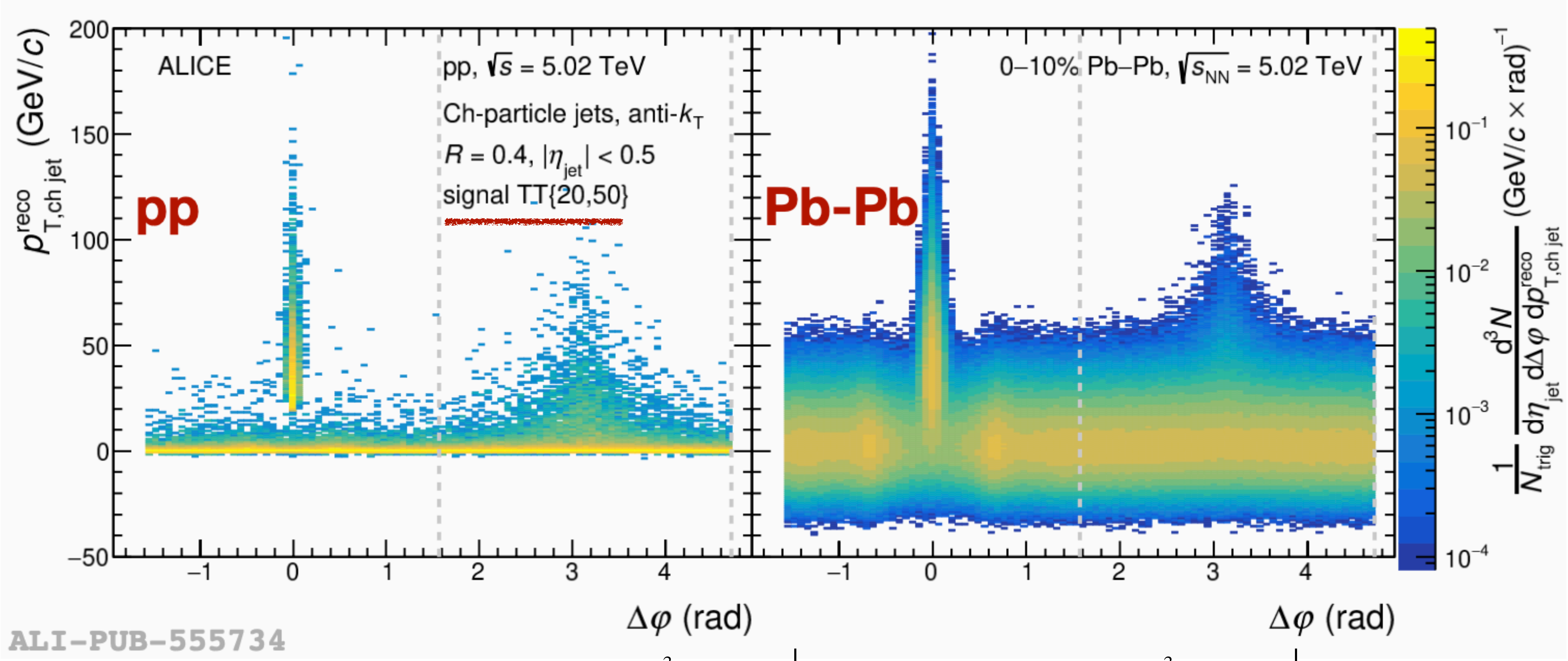
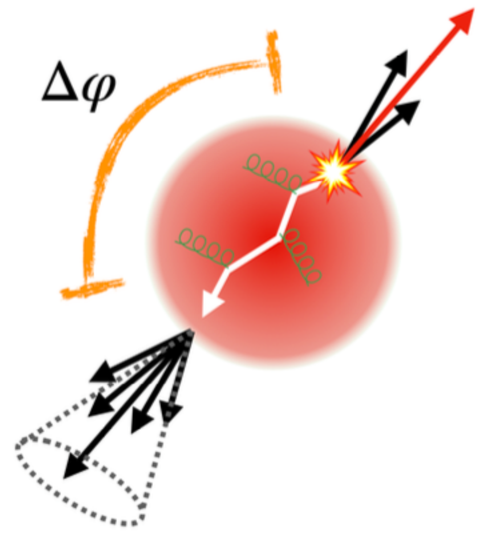
- Observables defined as **the difference** between trigger-normalised recoil jet yields in **two TT intervals** to **remove the uncorrelated combinatorial background**

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

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

2D raw yield distributions

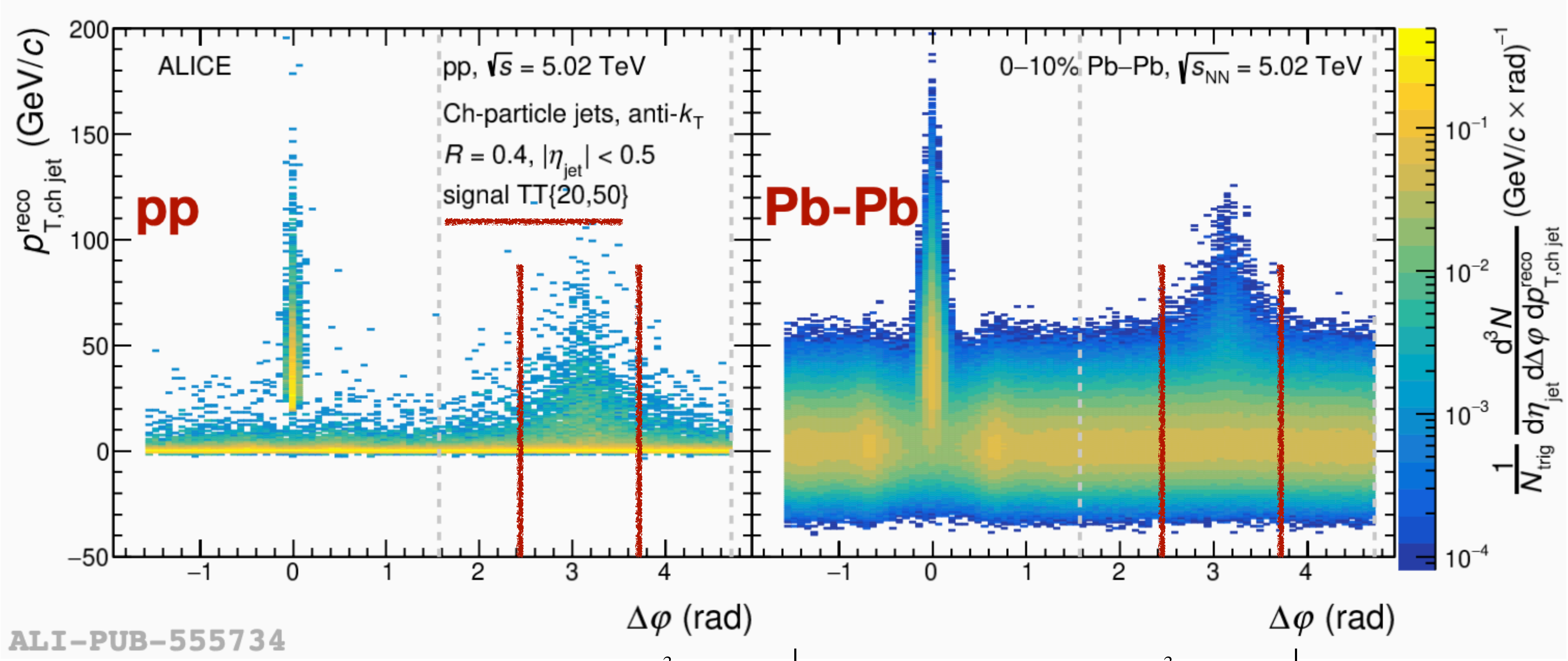


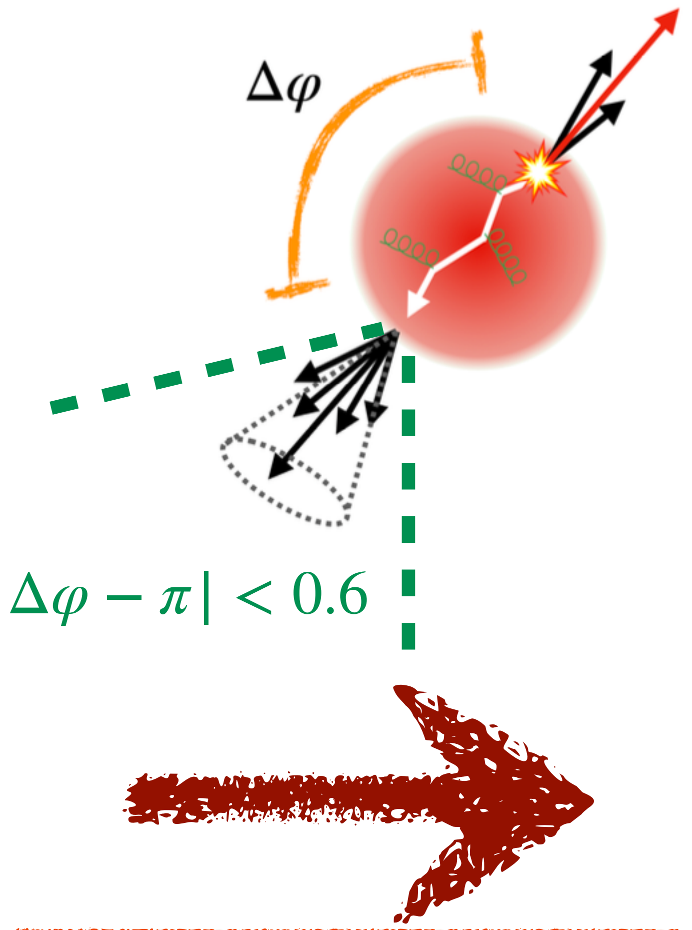


$$\Delta_{recoil}\left(p_{T,jet}, \Delta\varphi\right) = \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{Ref}}$$

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

2D raw yield distributions



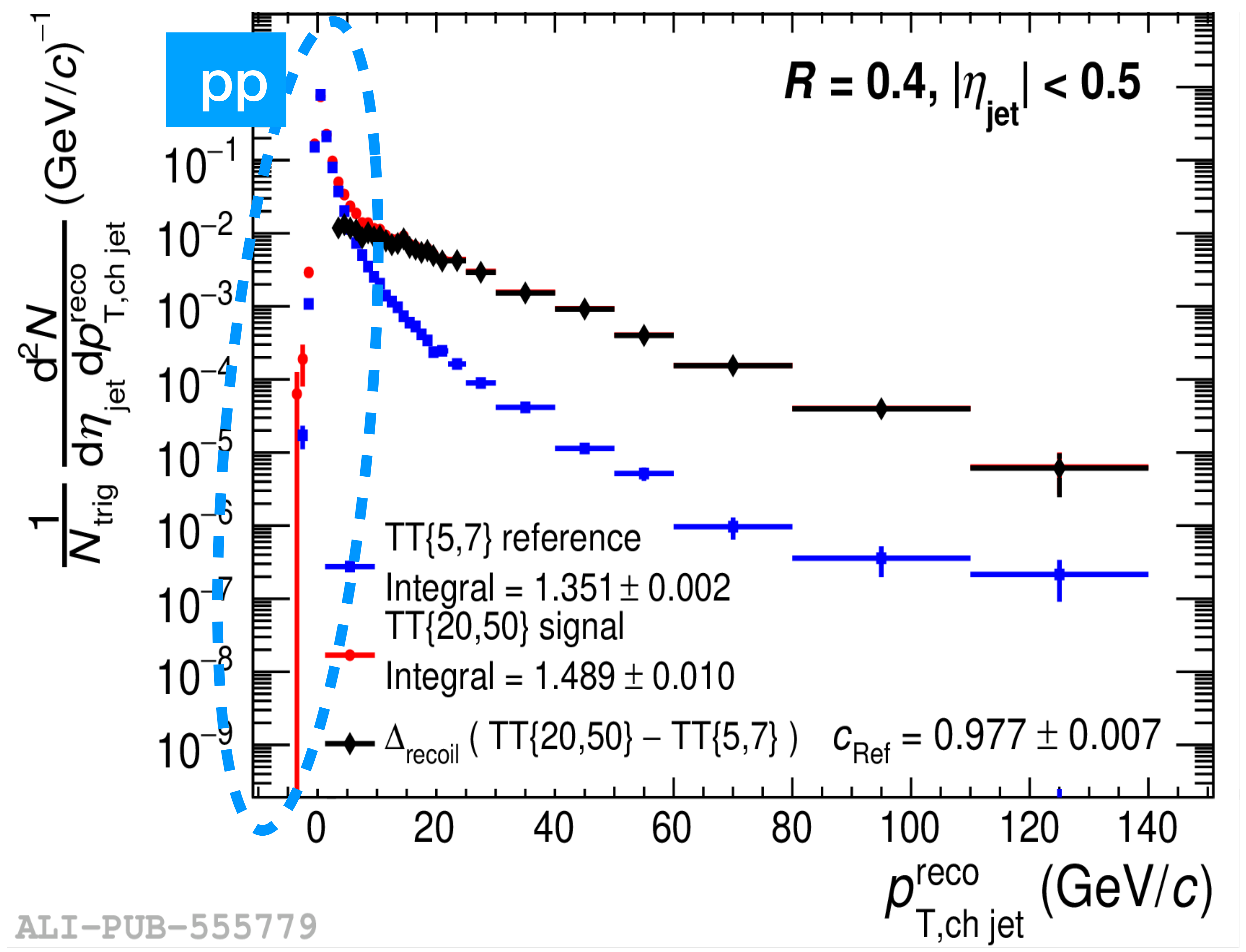


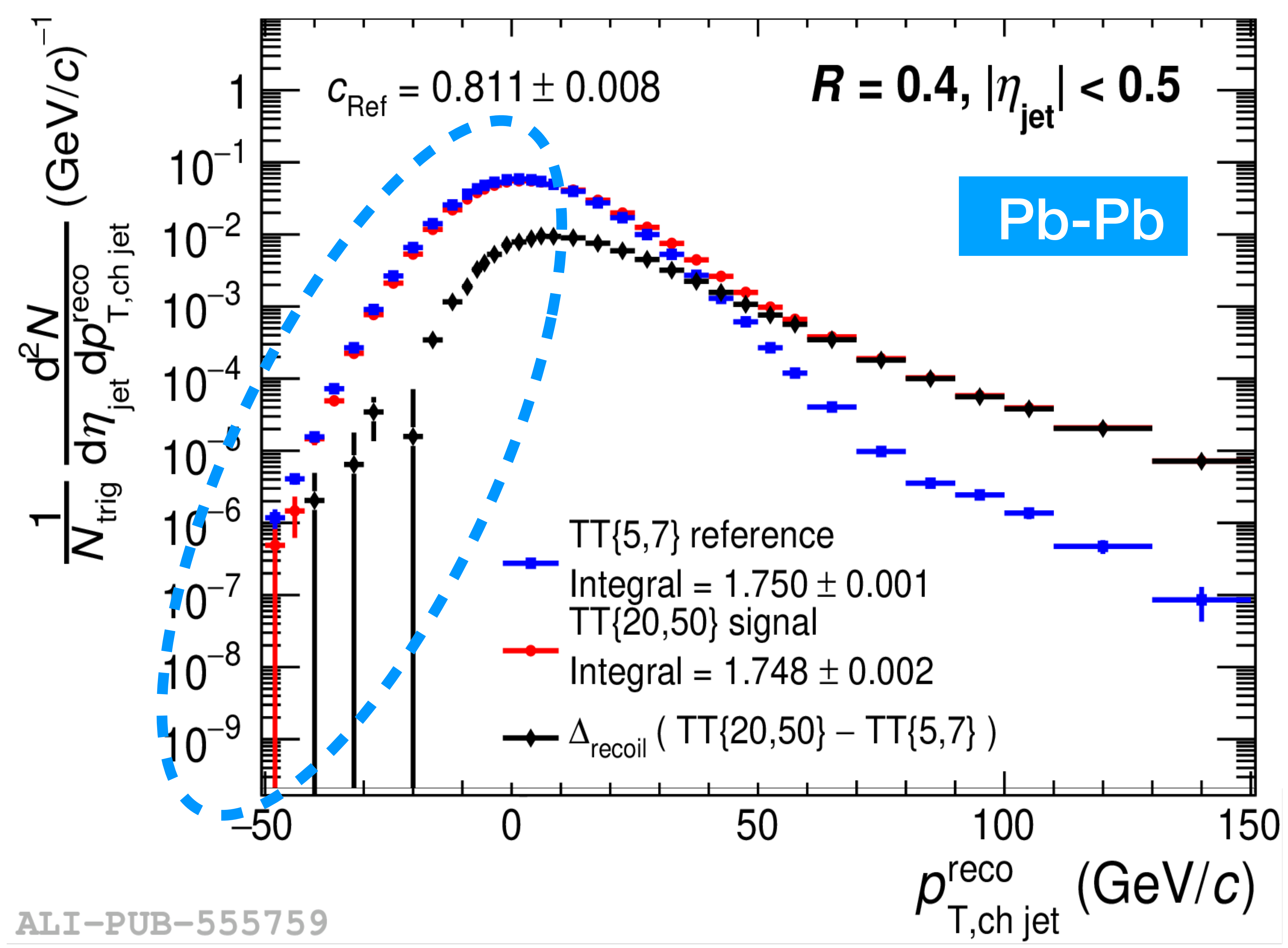
Projection to $p_{T,jet}$ with $\Delta\varphi$

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

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

Raw p_T distributions



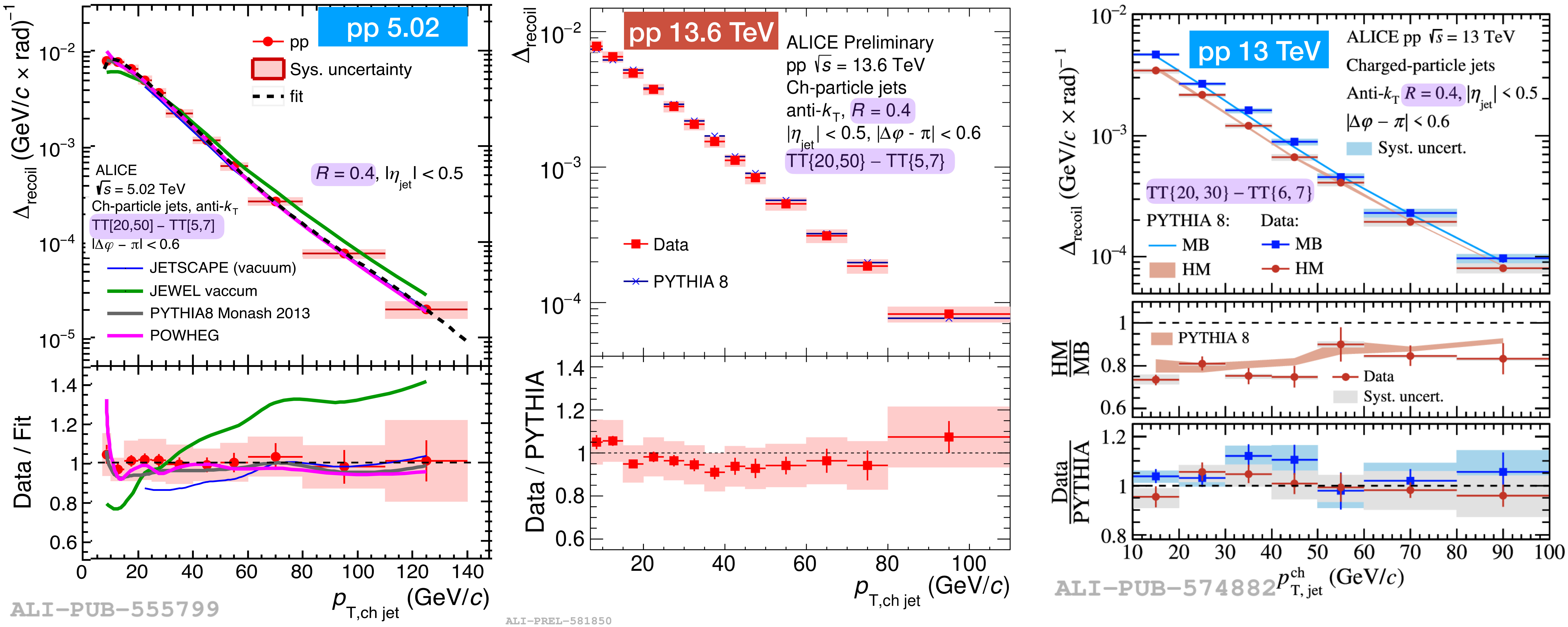


- **Recoil jet p_T distributions** in two TT intervals are obtained from the 2D projections
- **Combinatorial background** uncorrelated with the trigger

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

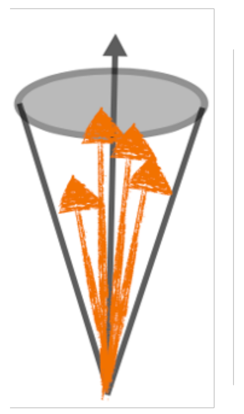
  - Small background contribution in pp, much larger in Pb-Pb
  - Taking the **difference** of recoil jet distributions in two TT intervals

Fully-corrected $\Delta_{recoil}(p_T)$ distributions in small systems

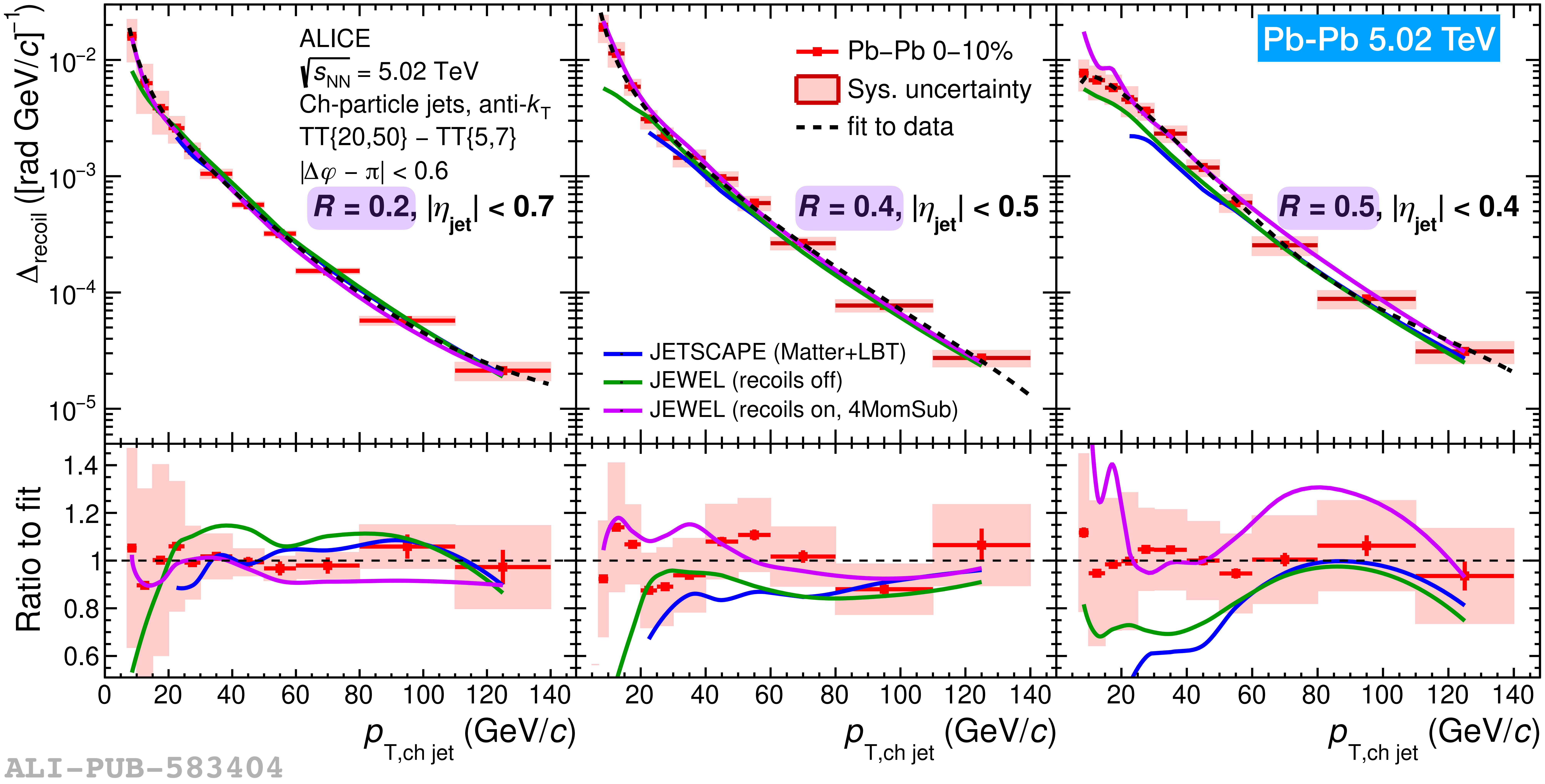


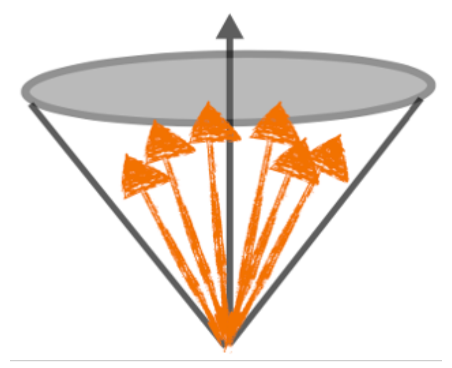
- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for R = 0.4 in pp collisions at 5.02, 13.6 TeV
- All model calculations, except JEWEL, reproduce the ALICE data within uncertainties
- In HM p-Pb collisions, recoil jet yield shows **no significant dependence** on event activity

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



Small R



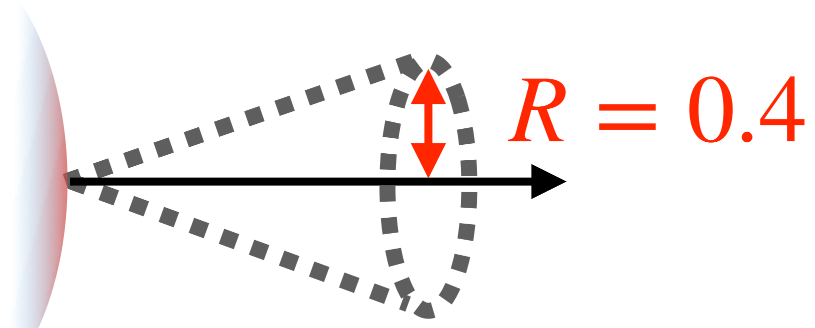


Larger R

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

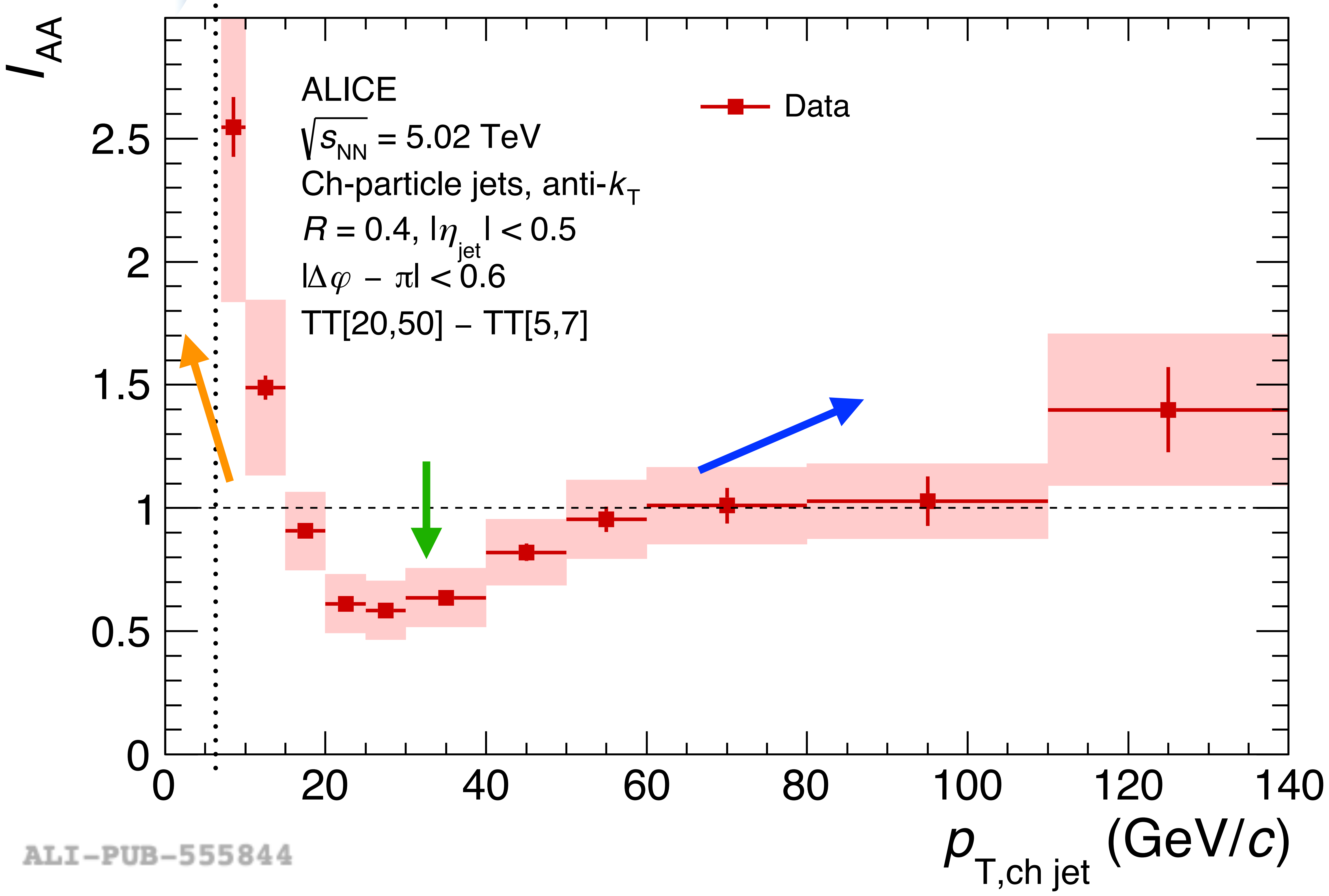
  →Among the lowest jet measurement in Pb-Pb collisions with ALICE at the LHC!

$I_{AA}(p_T)$ - recoil jet yield modification in Pb-Pb

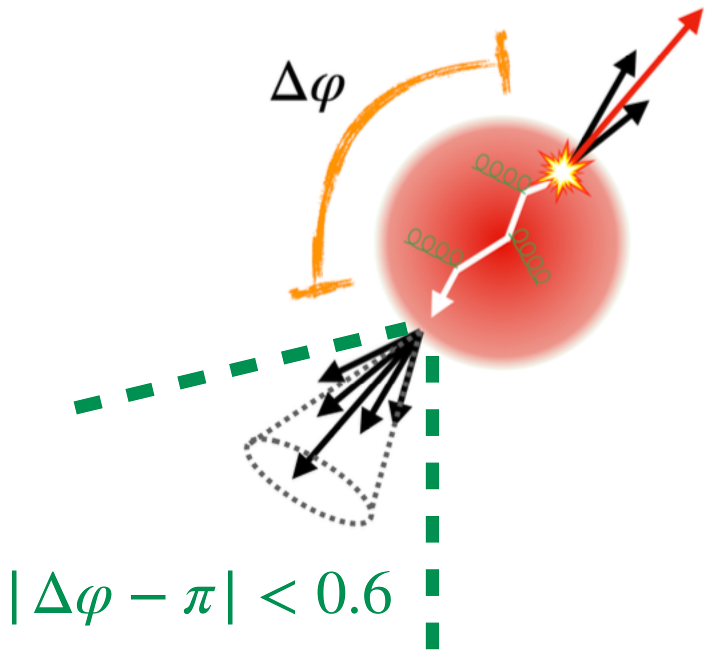


0 – 10 %

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

- **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

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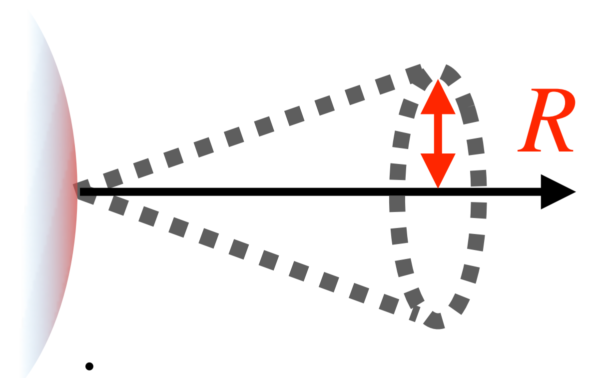
$I_{AA}(p_T)$ compared to models



0 – 10 %

***R* = 0.4**

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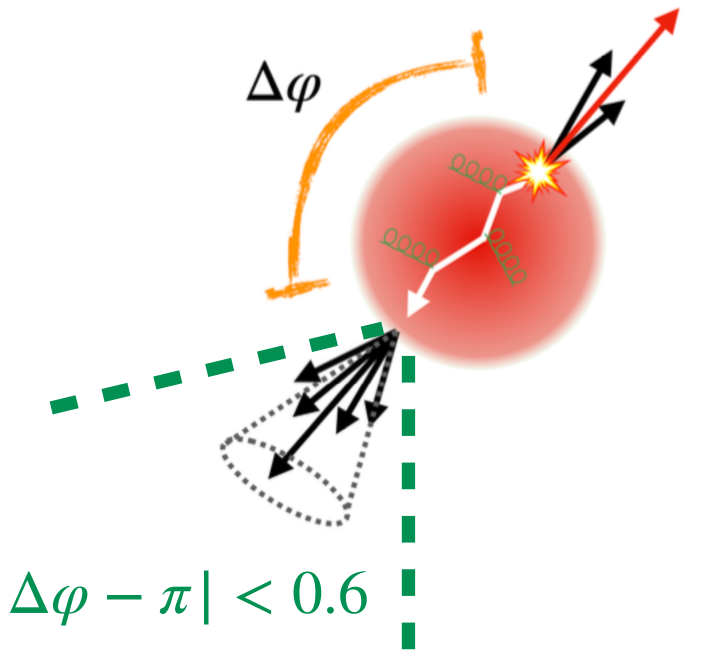
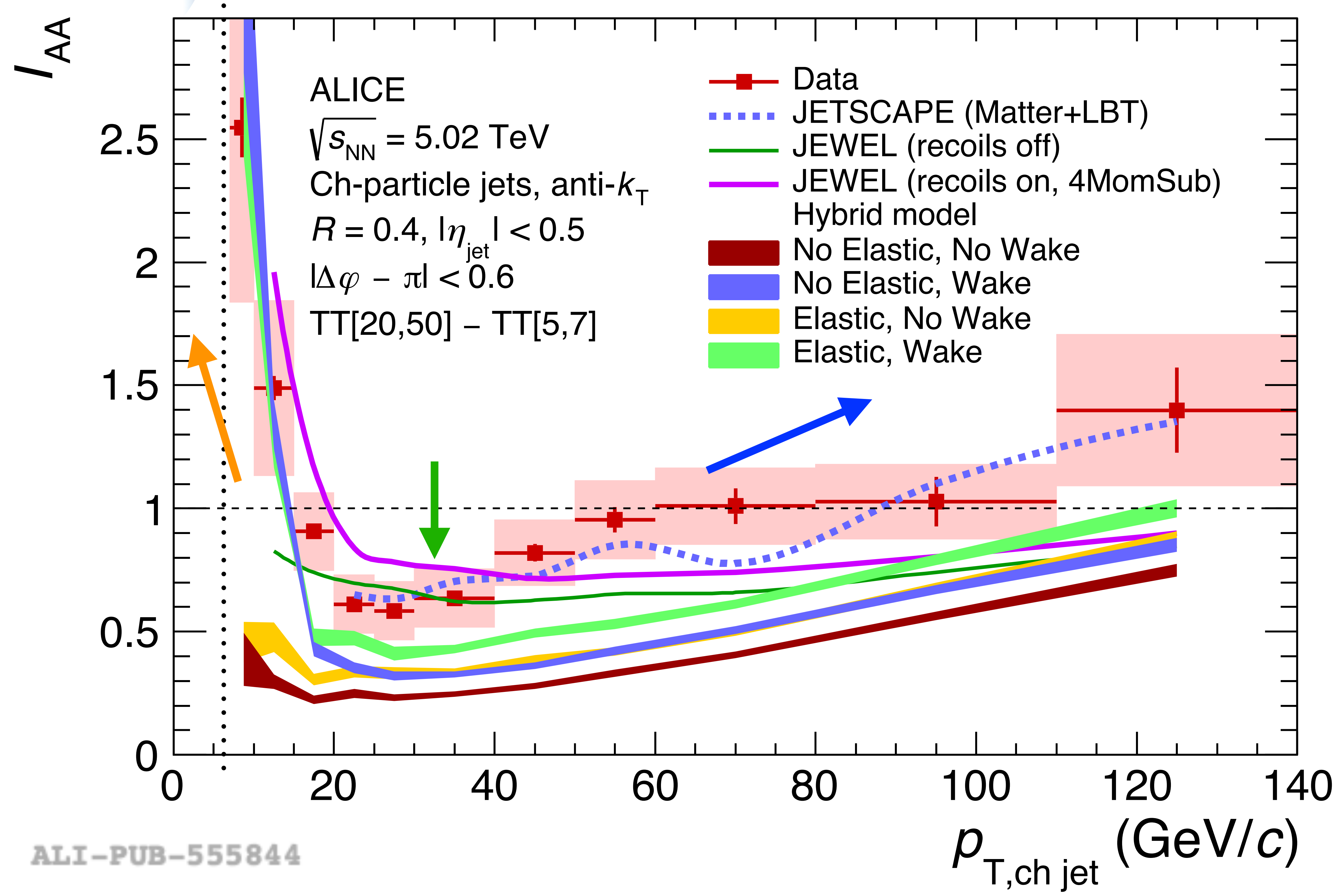
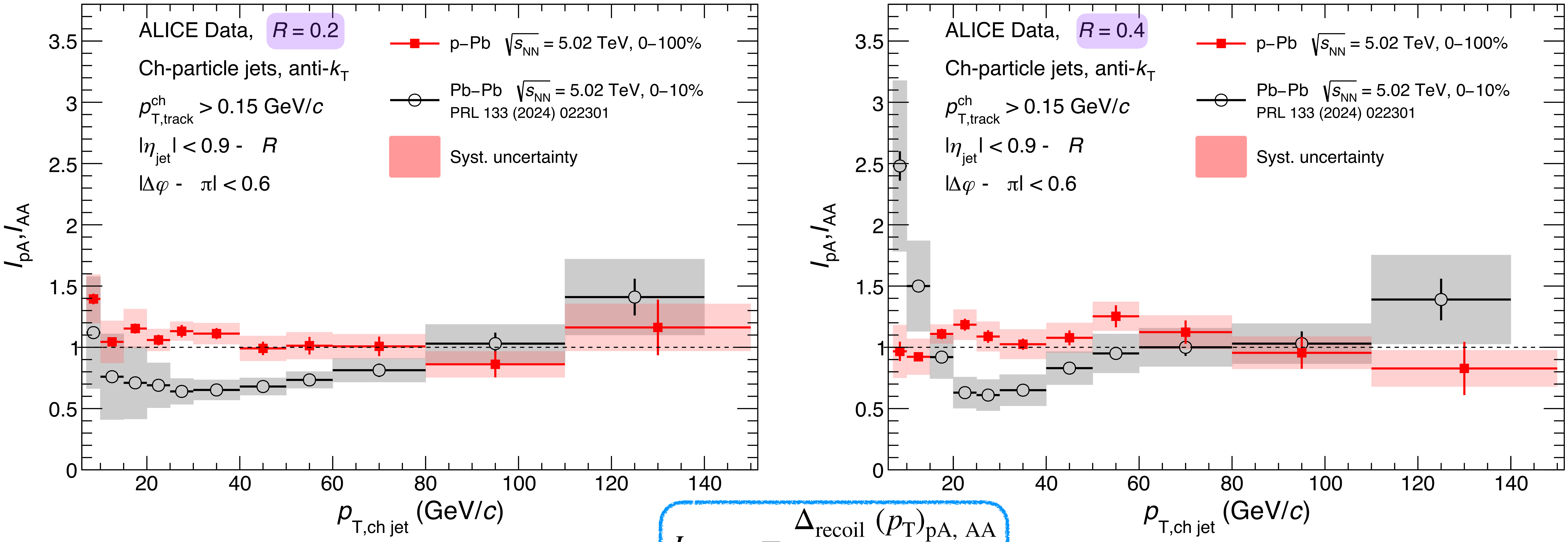




- The **rising trend** is qualitatively described by all predictions
  - **JETSCAPE largely reproduces** the I_{AA} distributions
  - **Hybrid Model** and **JEWEL** predictions tend to **overestimate the suppression** at high p_T
- **Hybrid Models** with wake effect and **JEWEL with recoils on** seem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

Comparison of $I_{AA}(p_T)$ and $I_{pA}(p_T)$



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

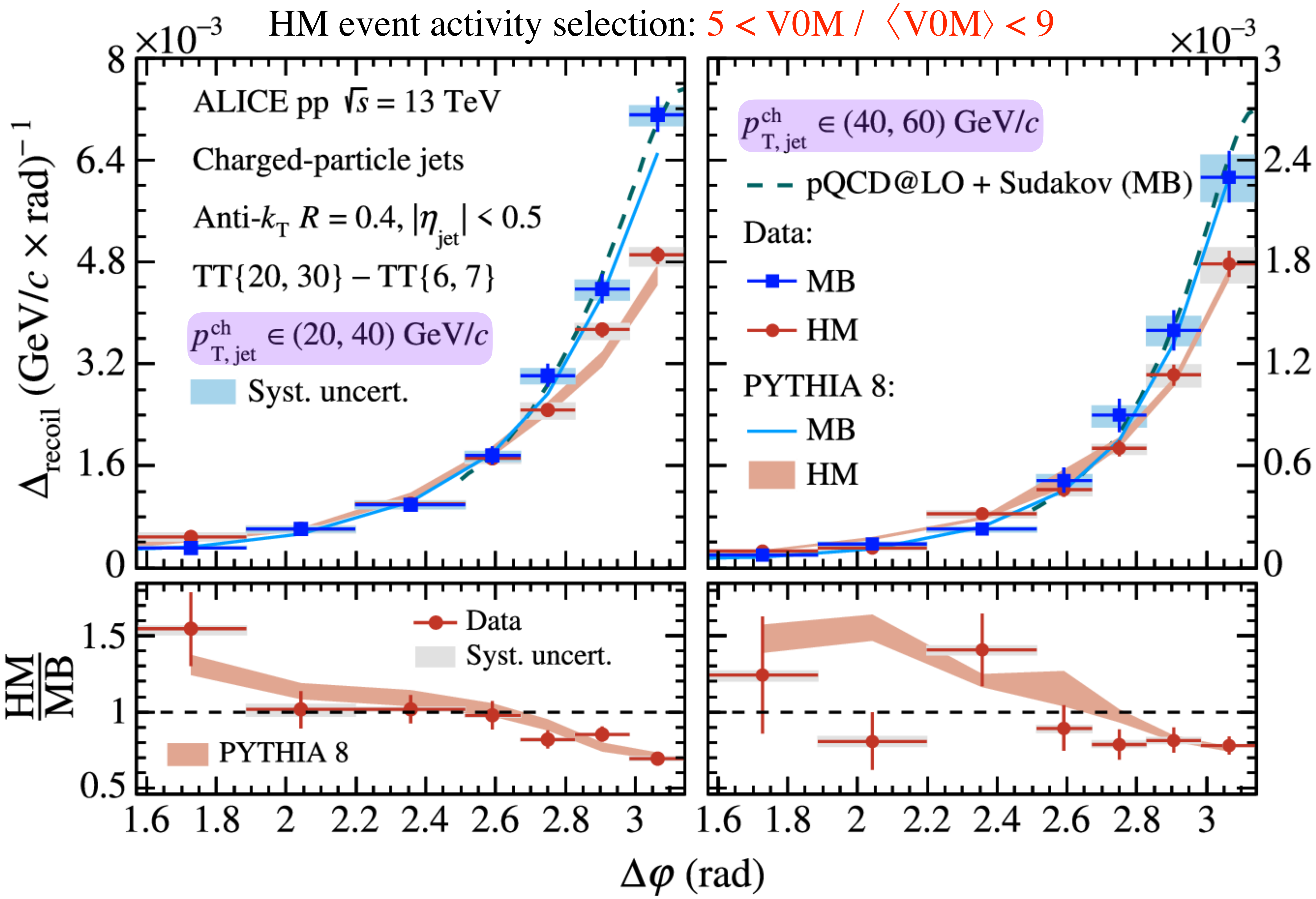
- For the I_{pA} (p–Pb/pp ratios), the uncertainties in pp and p–Pb collisions are treated as uncorrelated and are added in quadrature. (Same as I_{AA})
- **No significant modification** is observed with uncertainties in p-Pb collisions

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

- Corrected $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ distributions for R = 0.4 in **pp collisions** with different jet p_{T} bins
- Different model calculations **described the data** within uncertainties

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

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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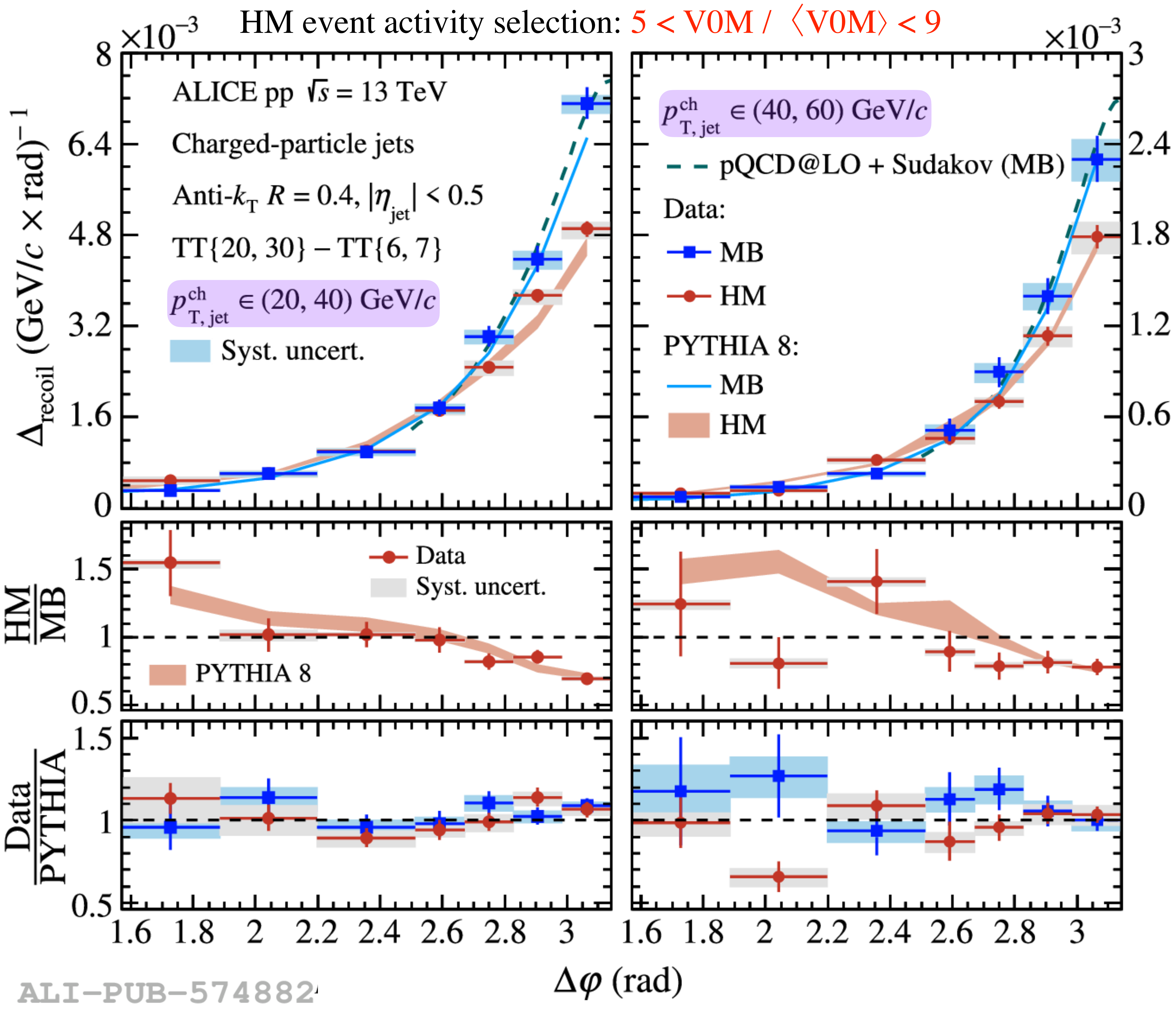

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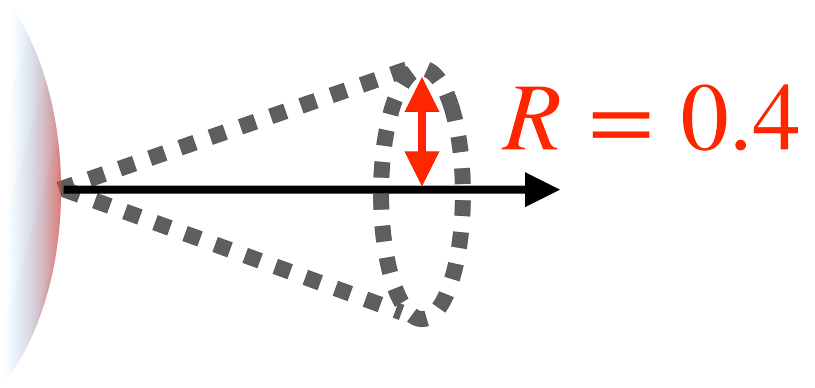
- **Broadening** of HM acoplanarity distribution with respect to MB
  - The effect is stronger for low p_{T} jets
  - Resembles jet quenching effects?

- 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**

Δ_{recoil} $(\Delta\varphi)$ distributions in Pb-Pb at 5.02 TeV: $R = 0.4$

- Corrected $\Delta_{recoil}(\Delta\varphi)$ distributions for $R = 0.4$ in **Pb-Pb collisions** with different jet p_T bins
- Models show better agreement at larger $\Delta\varphi$

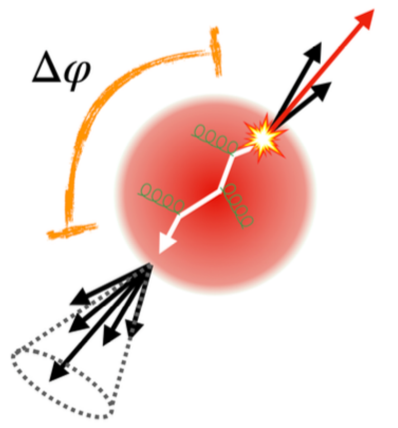
$I_{AA}(\Delta\varphi)$ - recoil jet angular modification in Pb-Pb

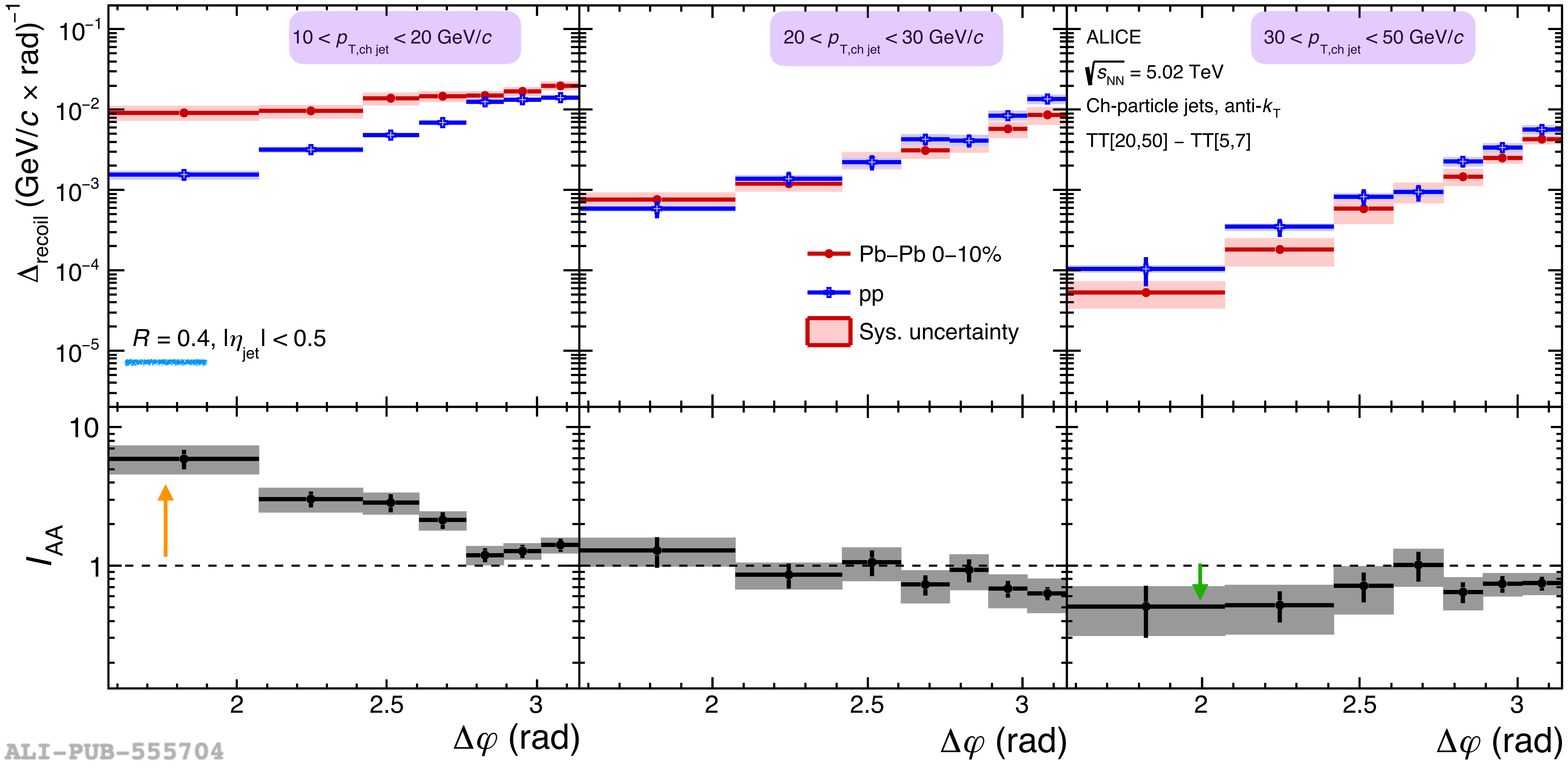


0 – 10 %

R = 0.4

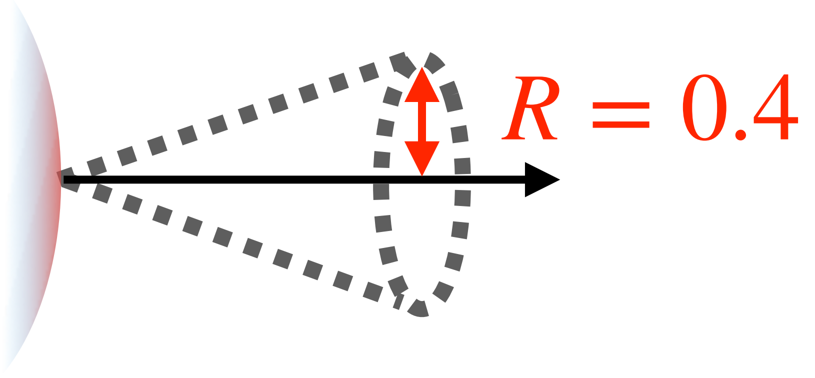
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(\Delta\varphi)_{AA}}{\Delta_{\text{recoil}}(\Delta\varphi)_{pp}}$$





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

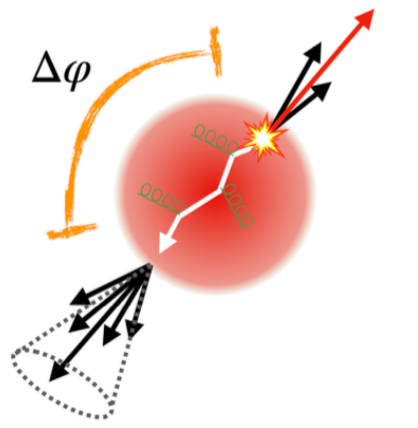
$I_{AA}(\Delta\varphi)$ compared to models

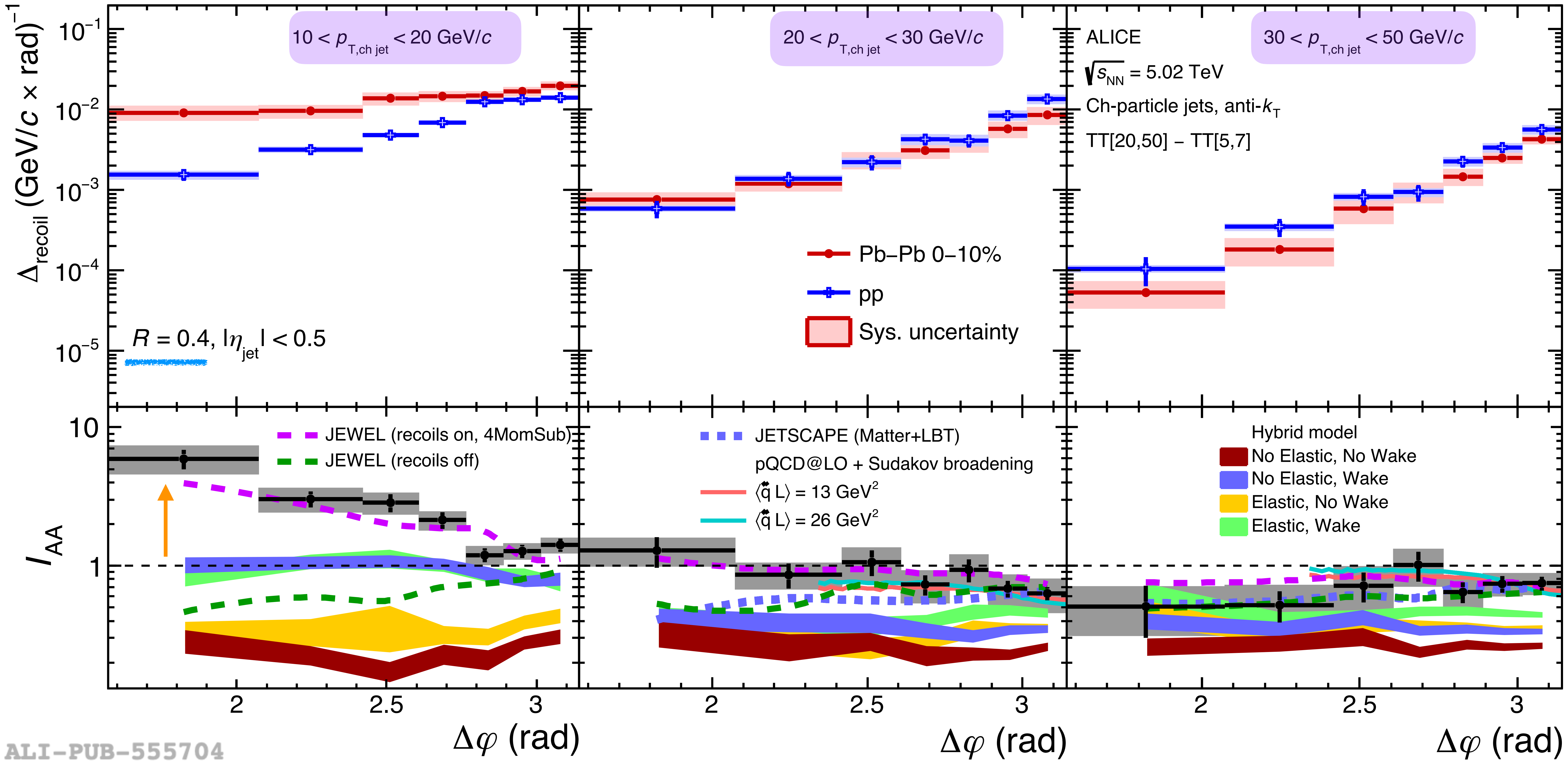


0 – 10 %

R = 0.4

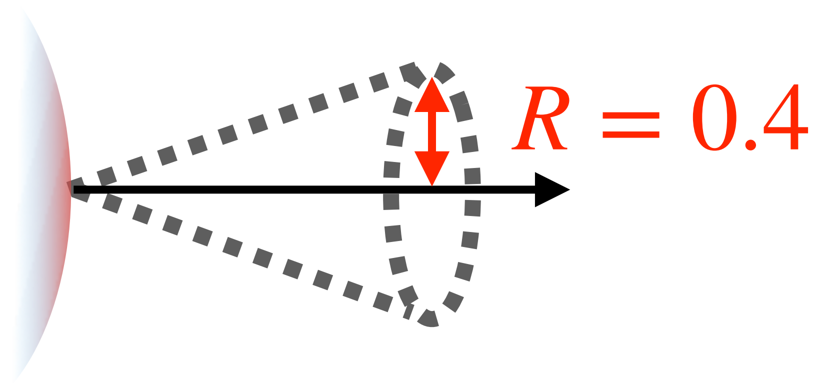
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$





- **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

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



0 – 10 %

R = 0.4

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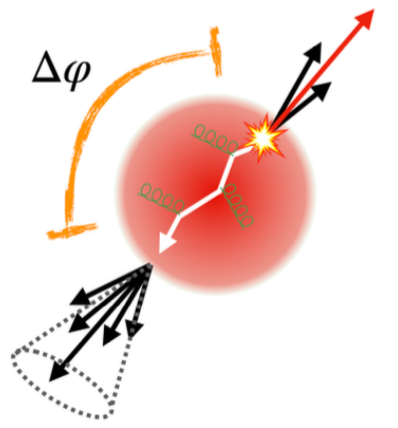

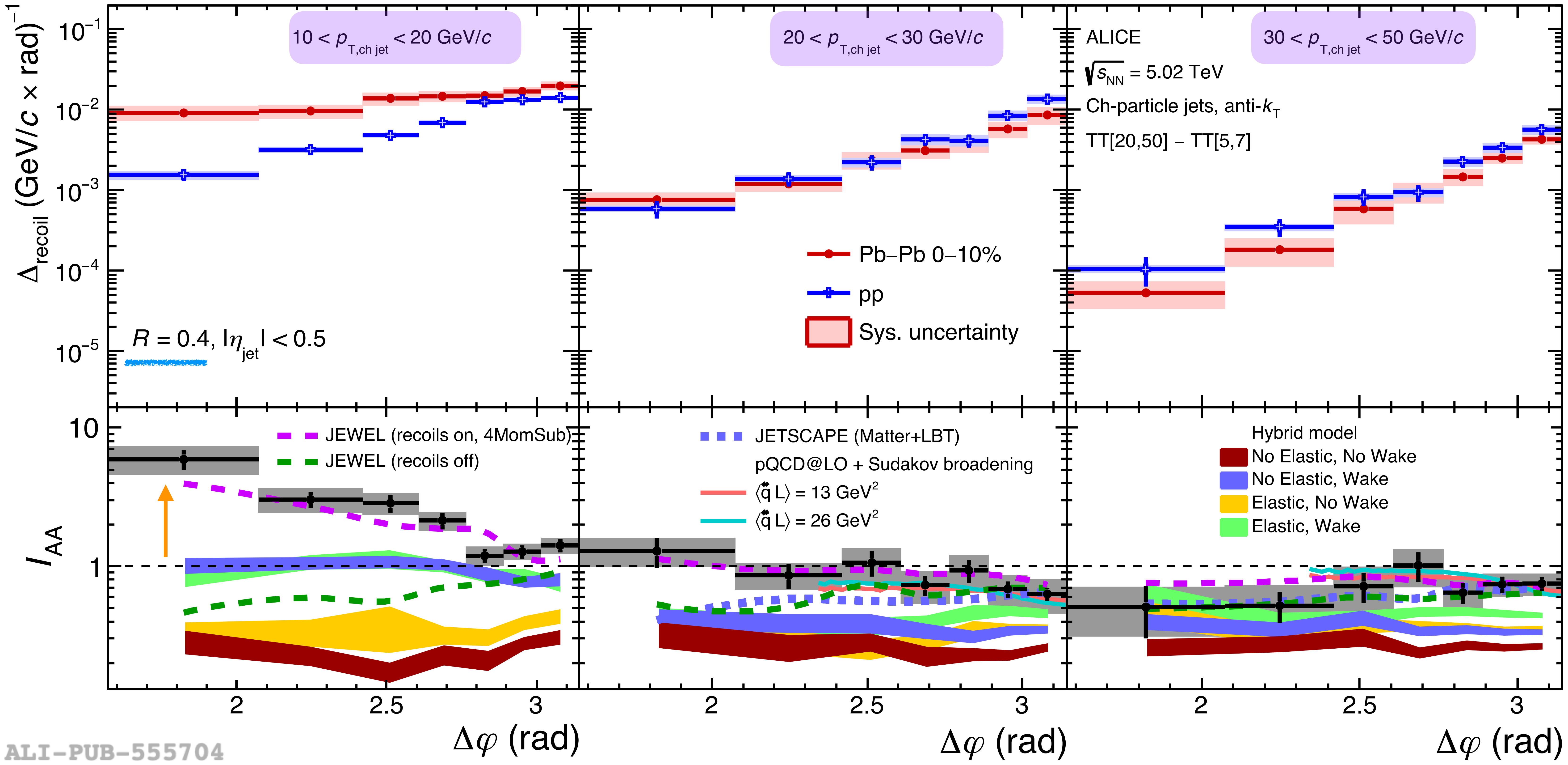

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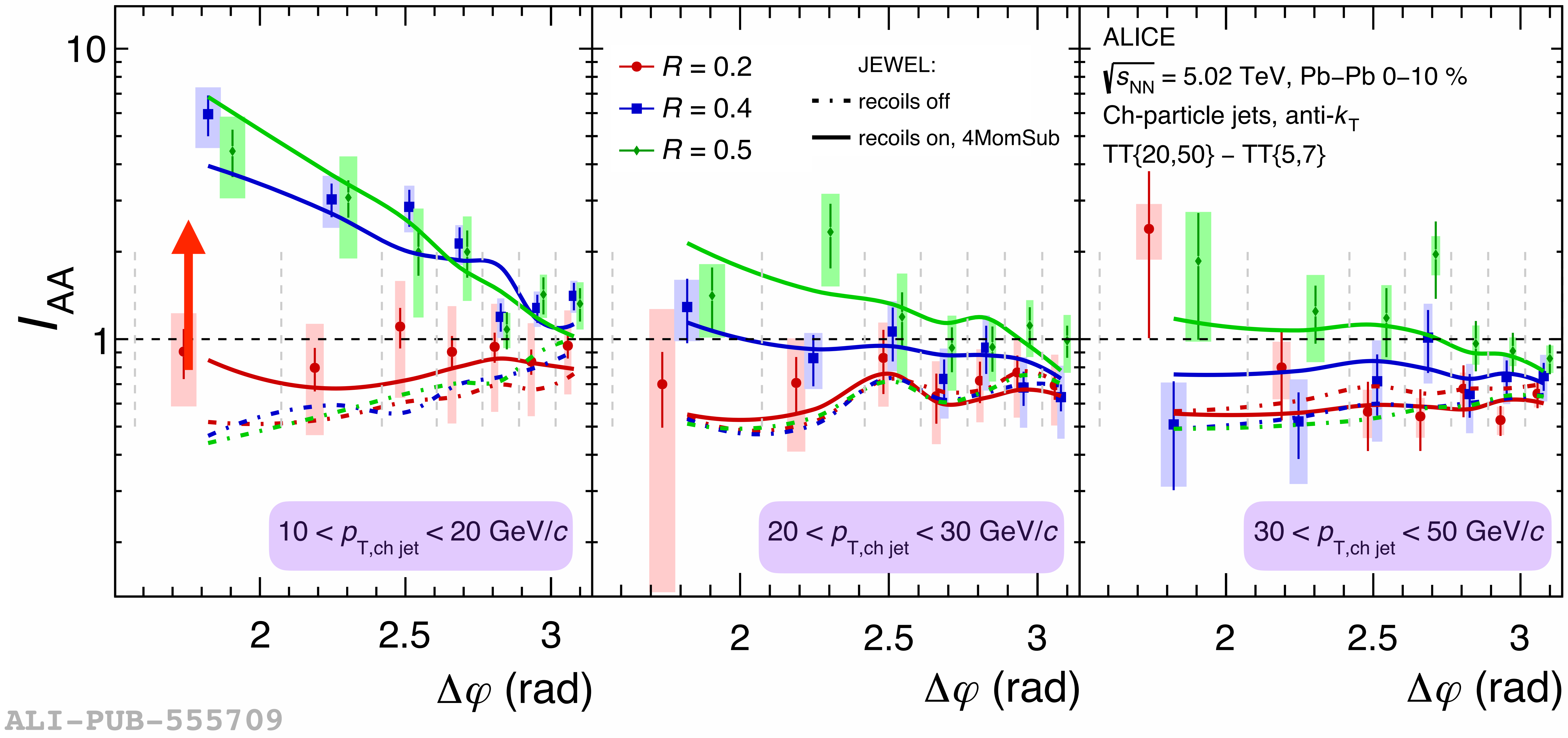
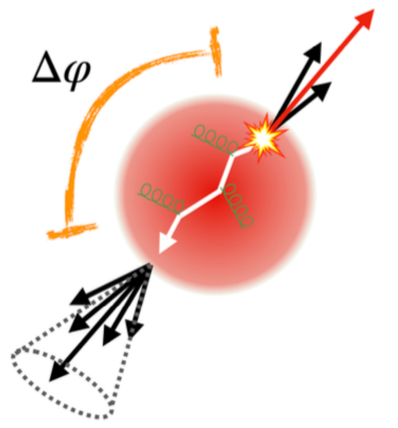
$I_{AA}(\Delta\varphi)$ vs R

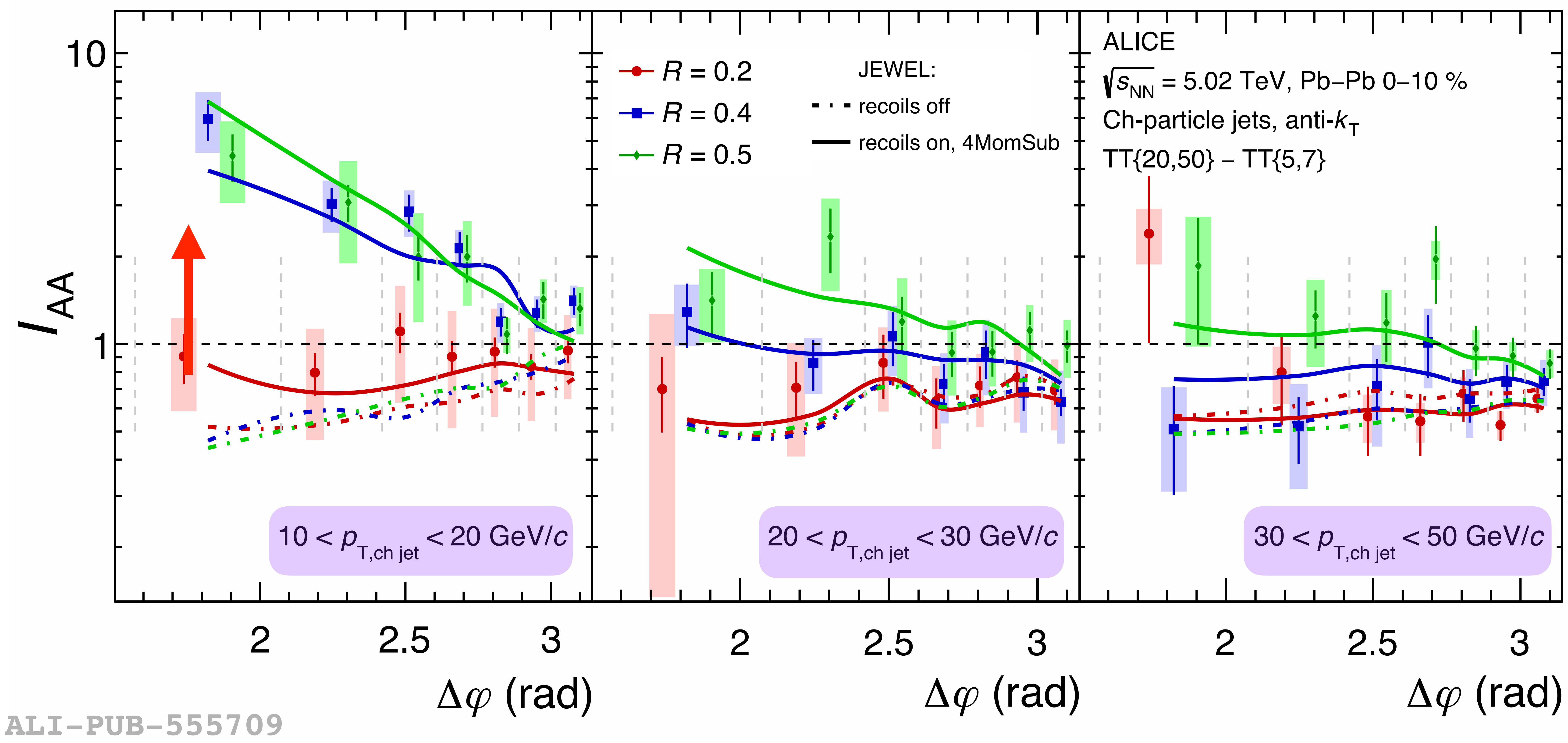


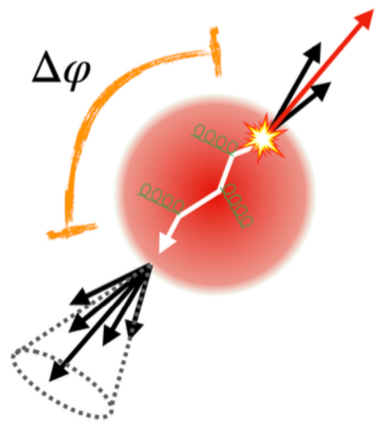


$$I_{AA} \equiv \frac{\Delta_{recoil}\,(\Delta\varphi)_{AA}}{\Delta_{recoil}\,(\Delta\varphi)_{pp}}$$

- 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

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



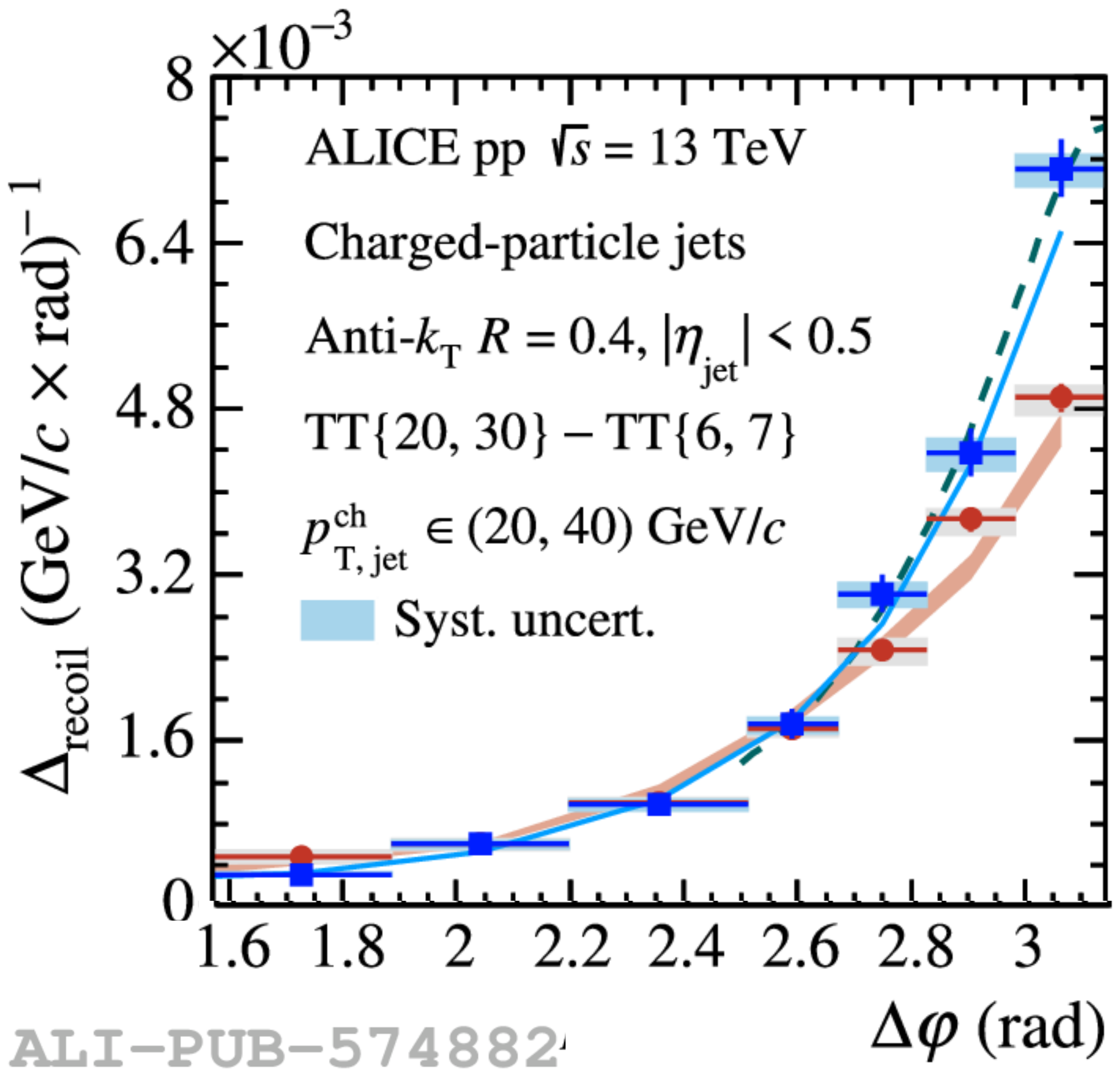


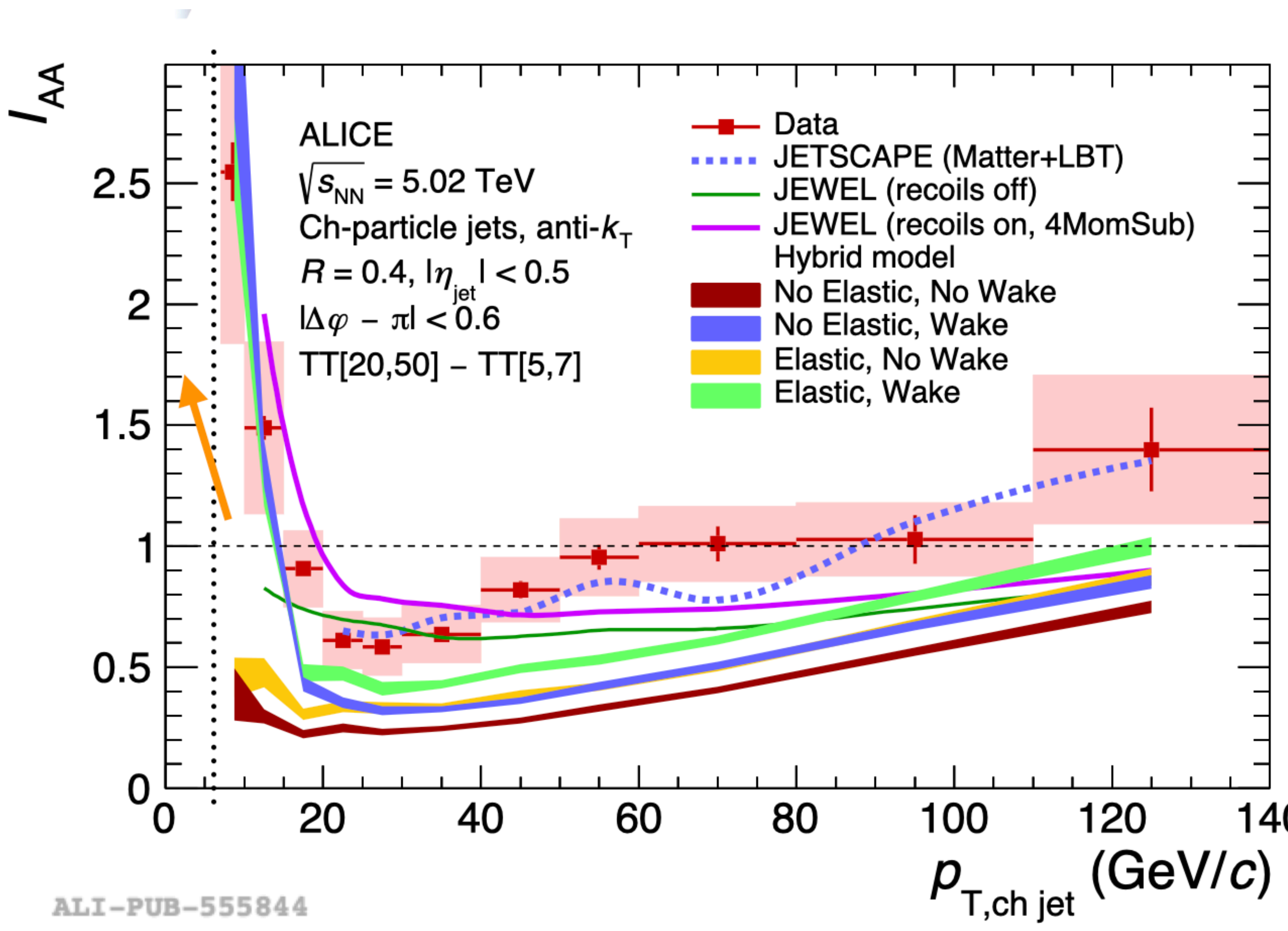
$$I_{AA} \equiv \frac{\Delta_{recoil}\,(\Delta\varphi)_{AA}}{\Delta_{recoil}\,(\Delta\varphi)_{pp}}$$

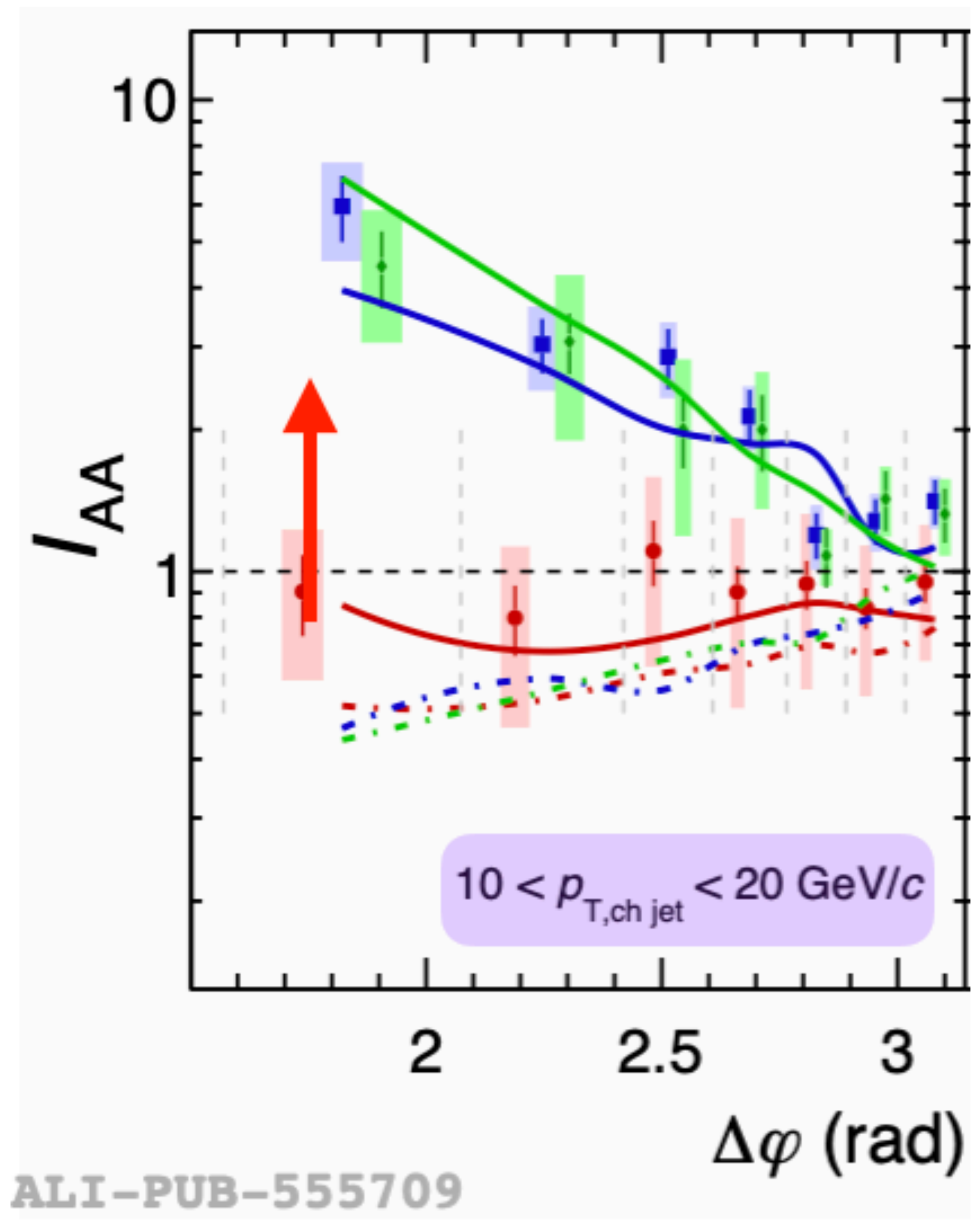
- Transition to broadening from $R = 0.2$ to $R = 0.4$ for $p_T \in [10,20]$ GeV/c → soft particles from the **medium response** clustered inside a jet scale with R^2
- All features of distribution **reproduced by JEWEL with recoils on** → observed broadening consistent with **medium response** rather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

Summary and outlook

- **Search for QGP signatures** **in samll collision systemas**
  - Jet-quenching-like effects masked by **generic event selection bias** in pp collisions
- **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** → Looking forward to performing **differential measurements**





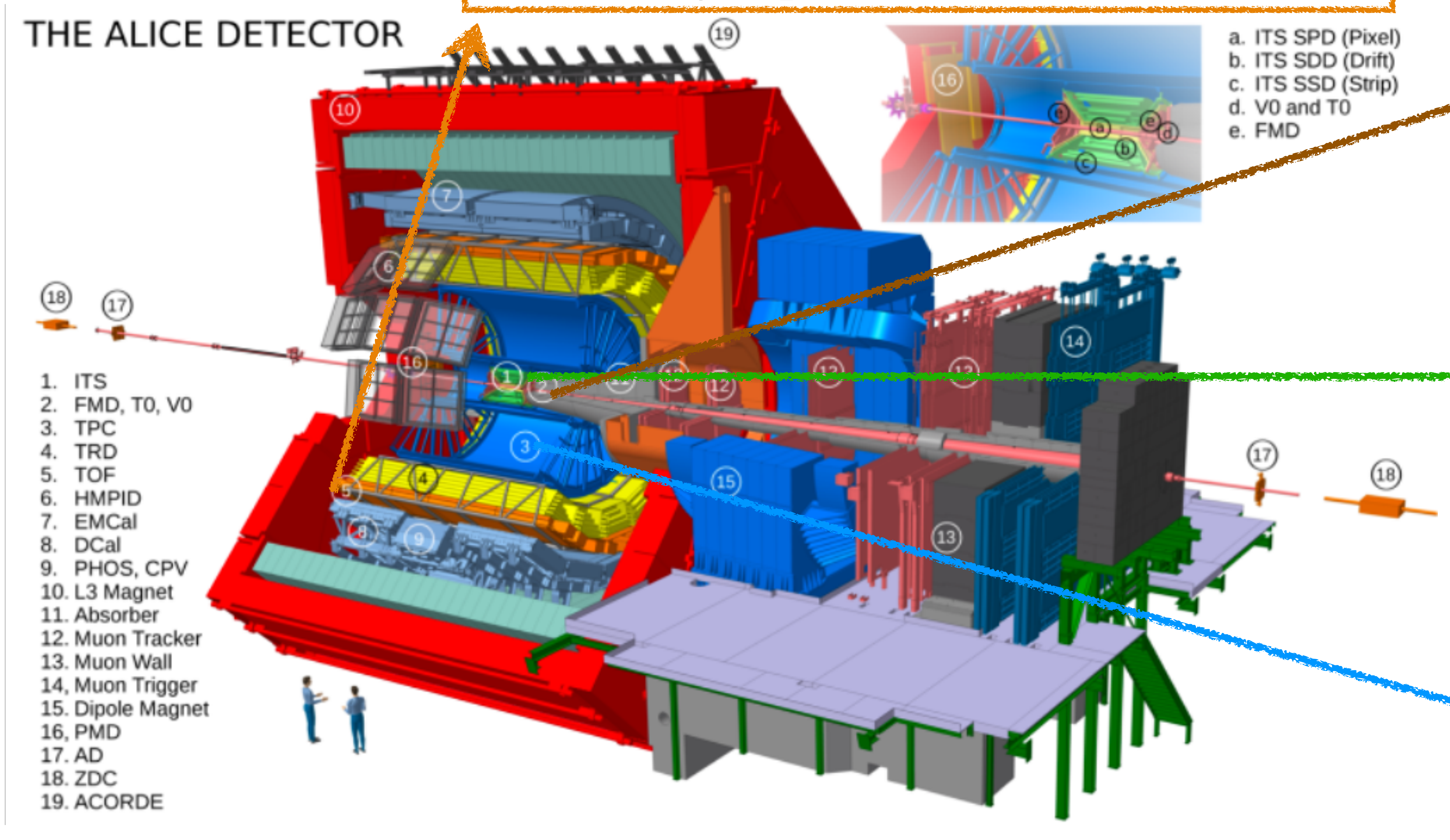


Thanks for your attention!!

BACKUP

Jet measurements in ALICE (Run 2)

- **TOF** (Time-Of-Flight)
  - $|\eta| < 0.9$
  - Charged particle identification (PID)



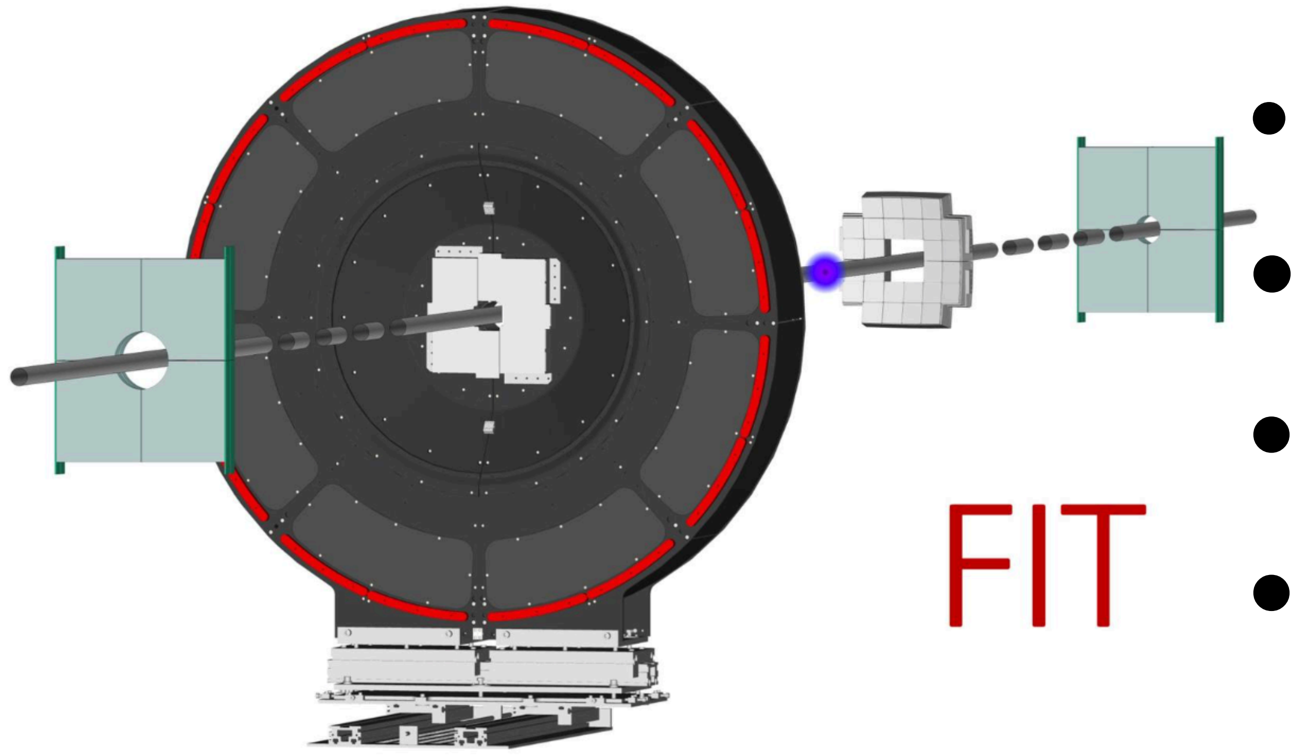
- **V0** (V0C + V0A)
  - $-3.7 < \eta < -1.7,\ 2.8 < \eta < 5.1$
  - Event trigger
  - Event multiplicity, centrality determination

Charged-particle tracks and jets

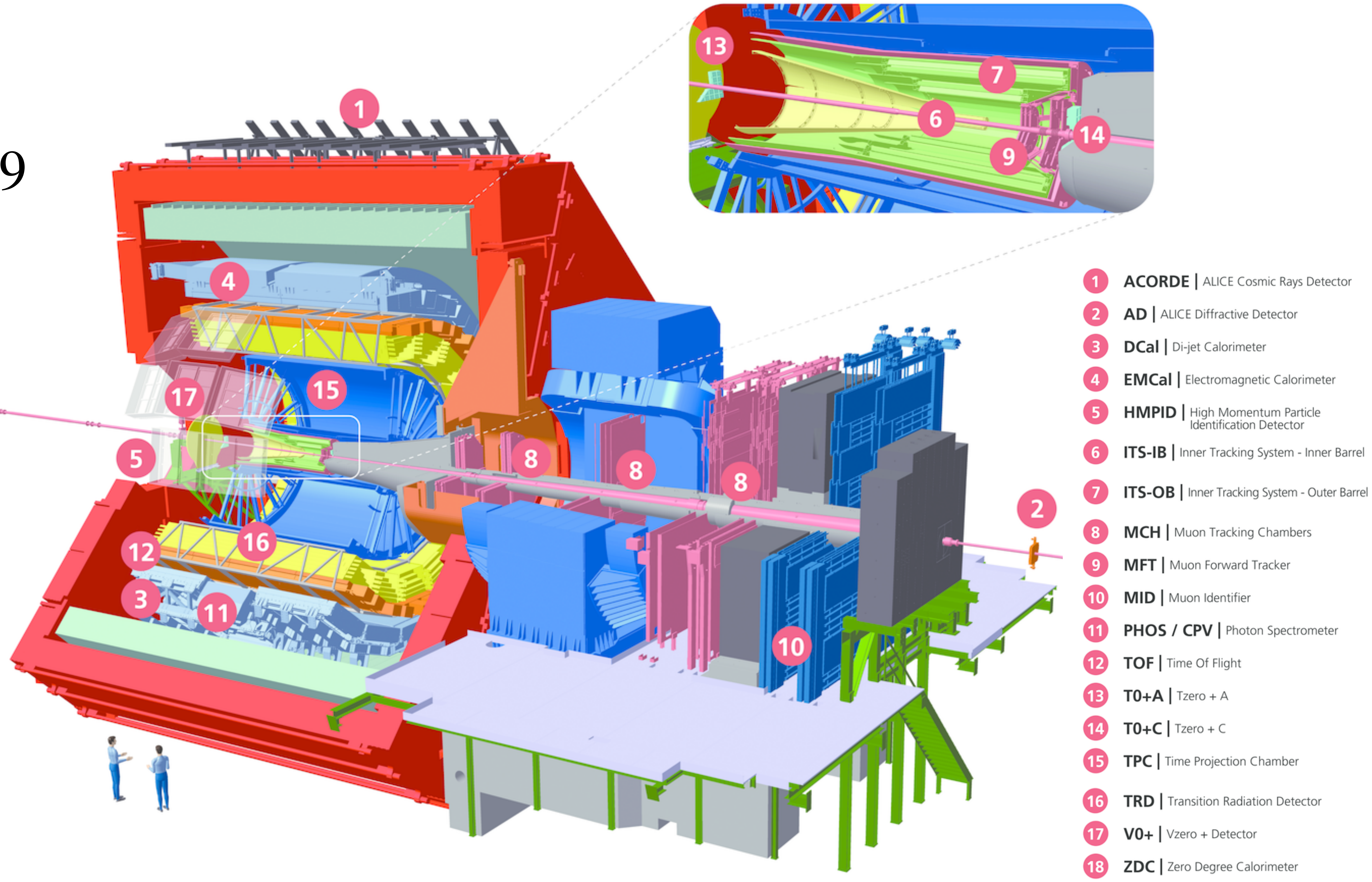
- **ITS** (Inner Tracking System)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Primary vertex reconstruction
  - Charged particle tracking
- **TPC** (Time Projection Chamber)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Charged particle tracking
  - Particle identification

Jet measurements in ALICE (Run 3)

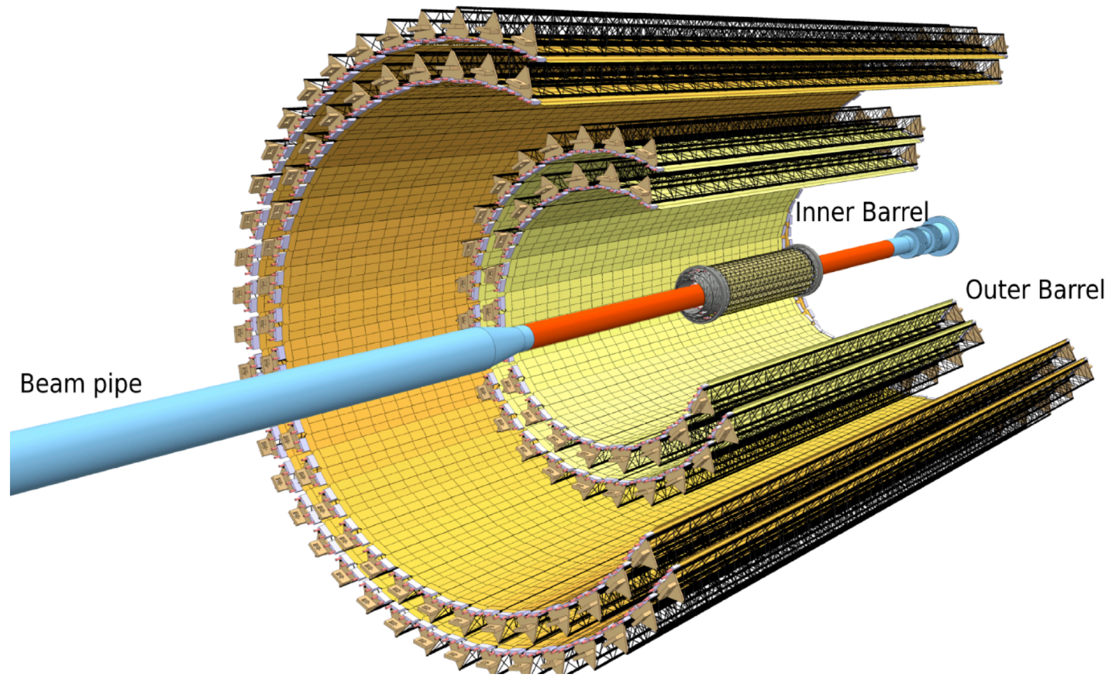
Fast Interaction Trigger (FT0C + FT0A)



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

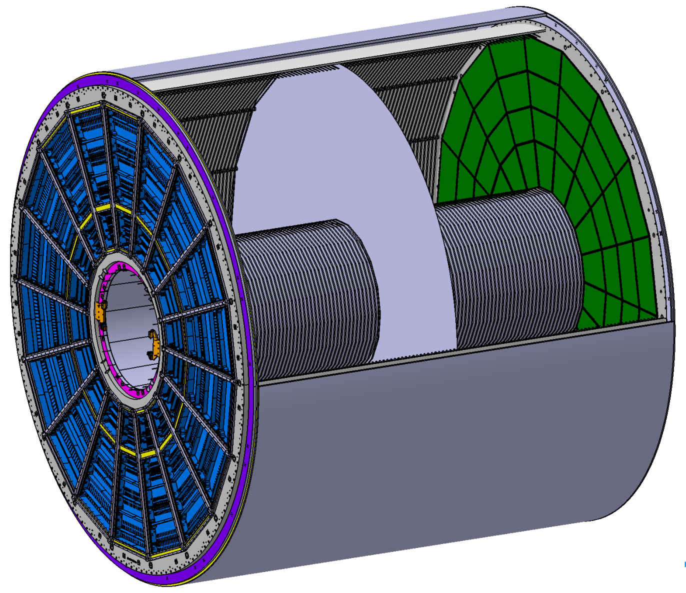


New Inner Tracking System



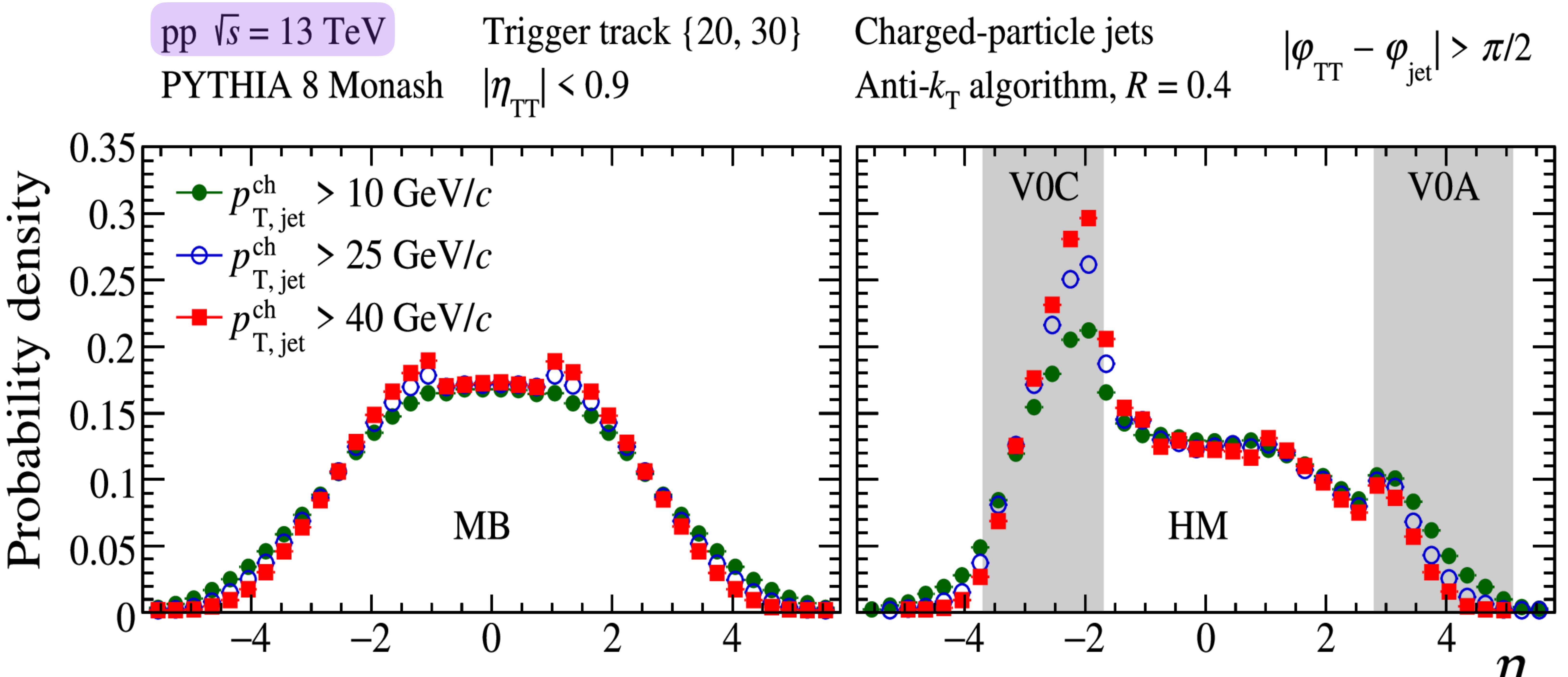
- $|\eta| < 1.3,\ 0 < \varphi < 2\pi$
- New Si inner tracker
- 3 inner layers 0.36% X0 each
- 50 kHz continuous readout

Time Projection Chamber

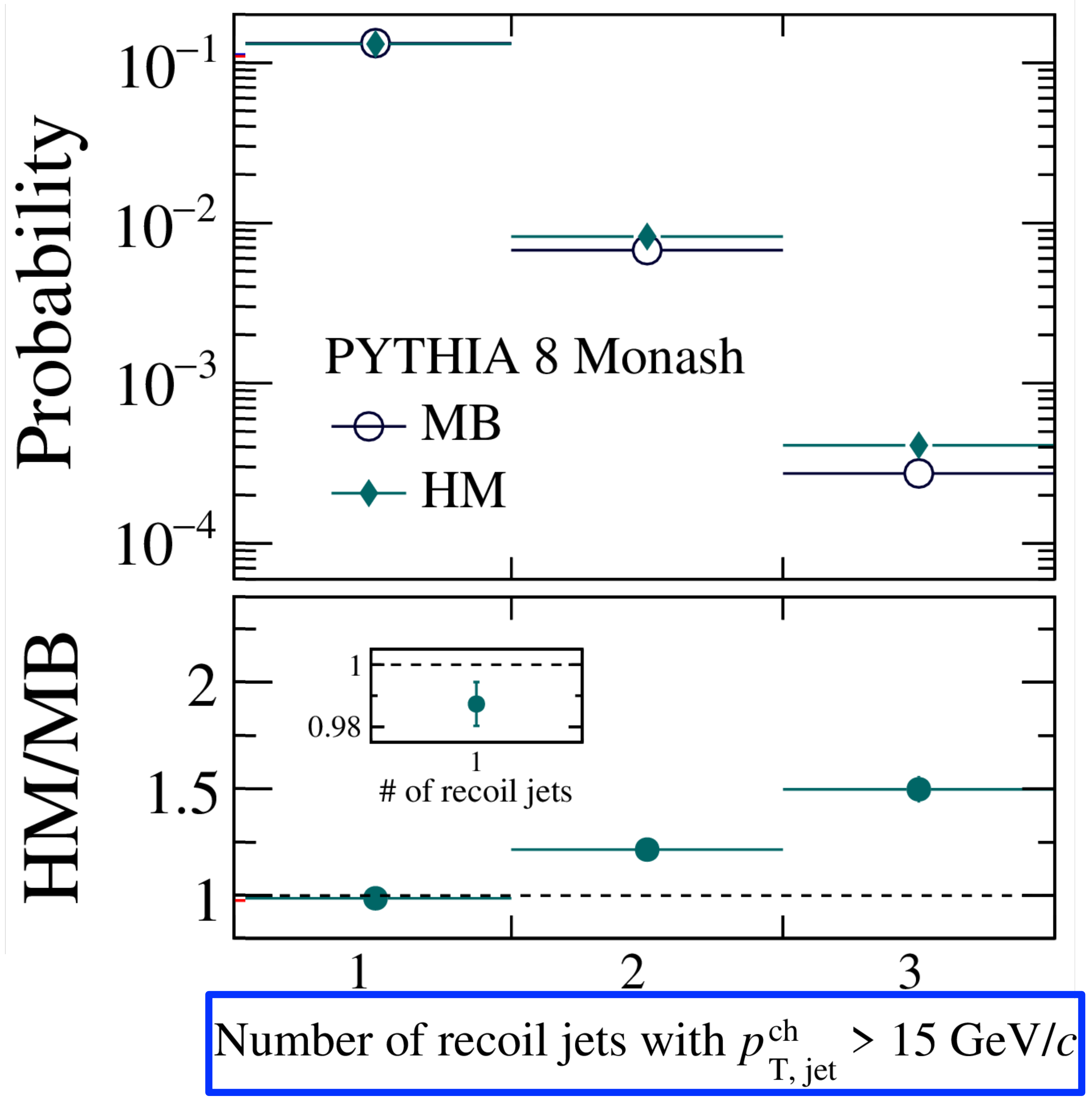


- $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
- 4 layers of GEM
- 50 kHz continuous readout

PYTHIA simulations



Recoil jet pseudorapidity distribution vs. event activity



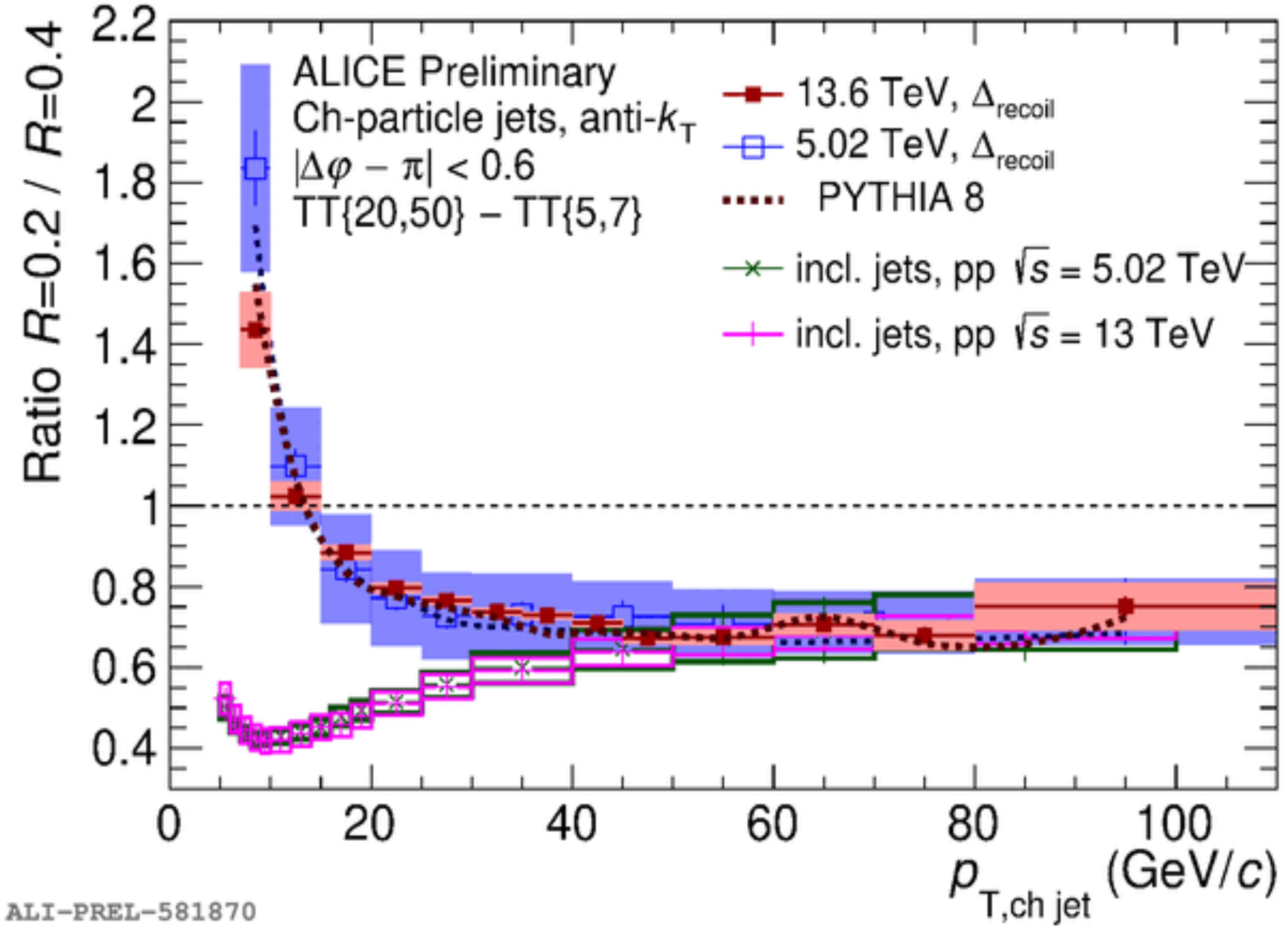
- **Larger enhancement in V0C** resulting from the asymmetric pseudorapidity acceptance of V0A and V0C **in HM events**

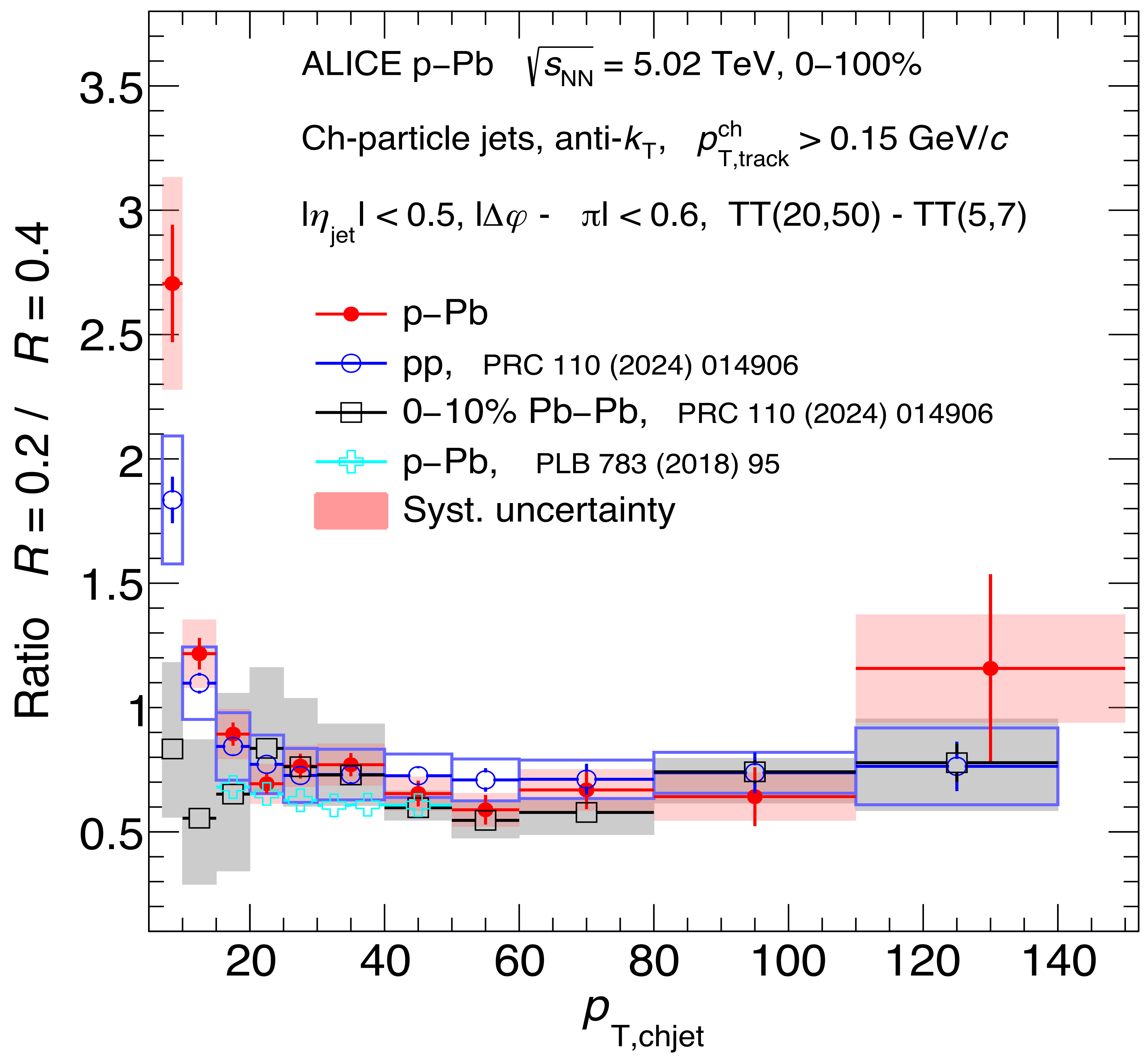
  → significant bias in the distribution of high-p_T recoil jets

- 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**

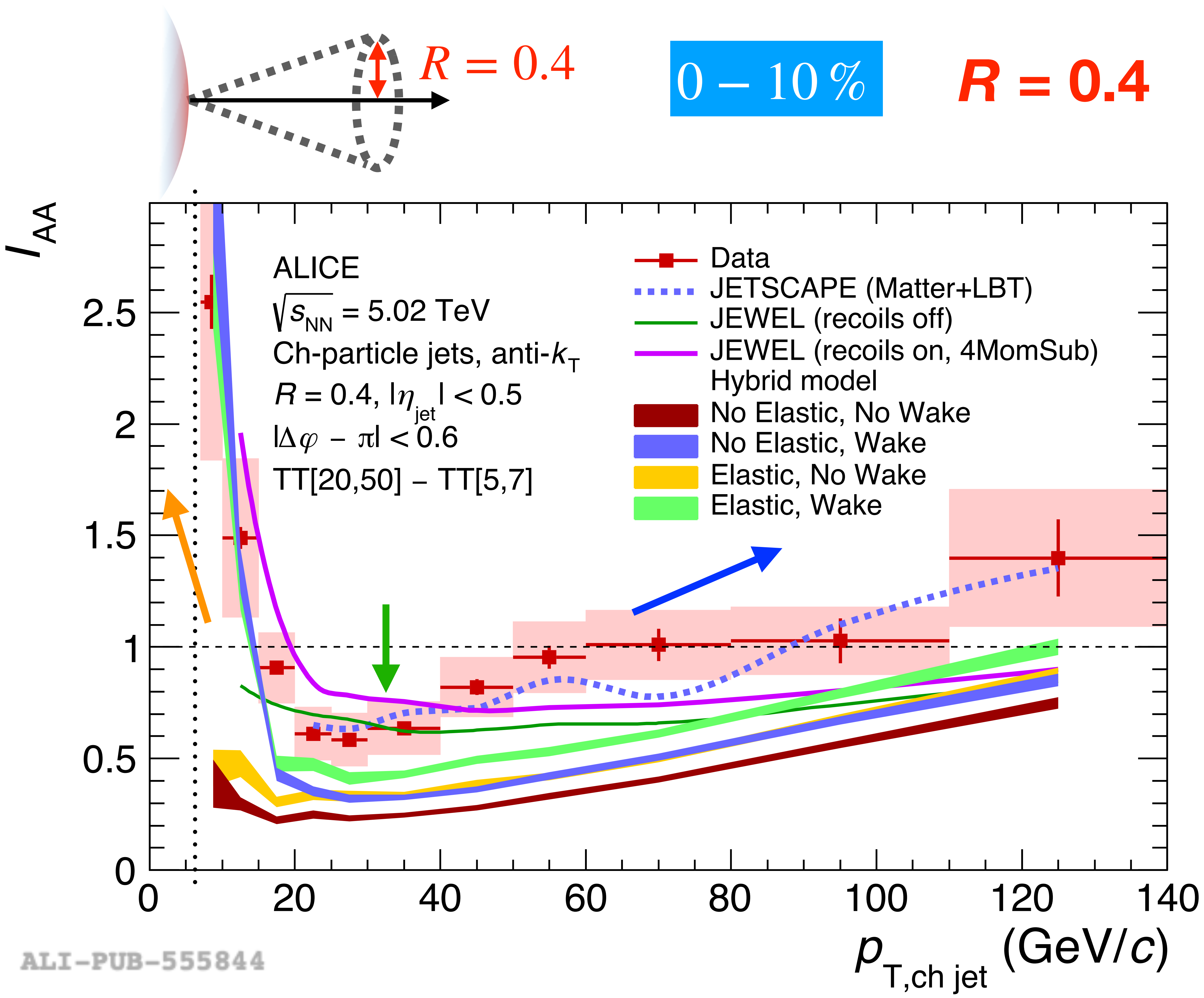
Fully corrected yield ratio: $R = 0.2$ / $R = 0.4$



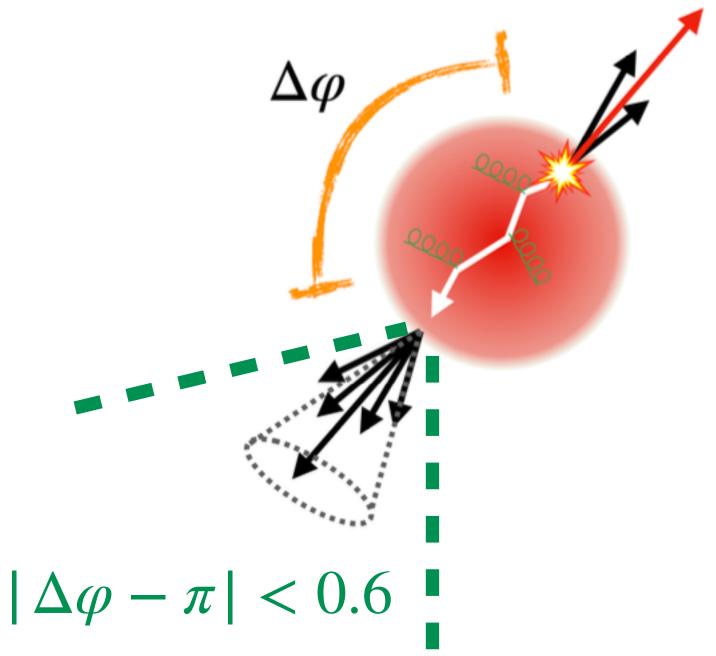


- The jet yield ratios of R = 0.2 / 0.4 provides an indirect measure of jet collimation
  - Agreement between inclusive jets and semi-inclusive at high p_T
  - No significant **collision energy** or **collision system** dependence within uncertainties
- Difference at low p_T due to TT selection → bias towards **LO processes suppressed** when $p_T^{jet} < p_T^{trig}$?

$I_{AA}(p_T)$ compared to models



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

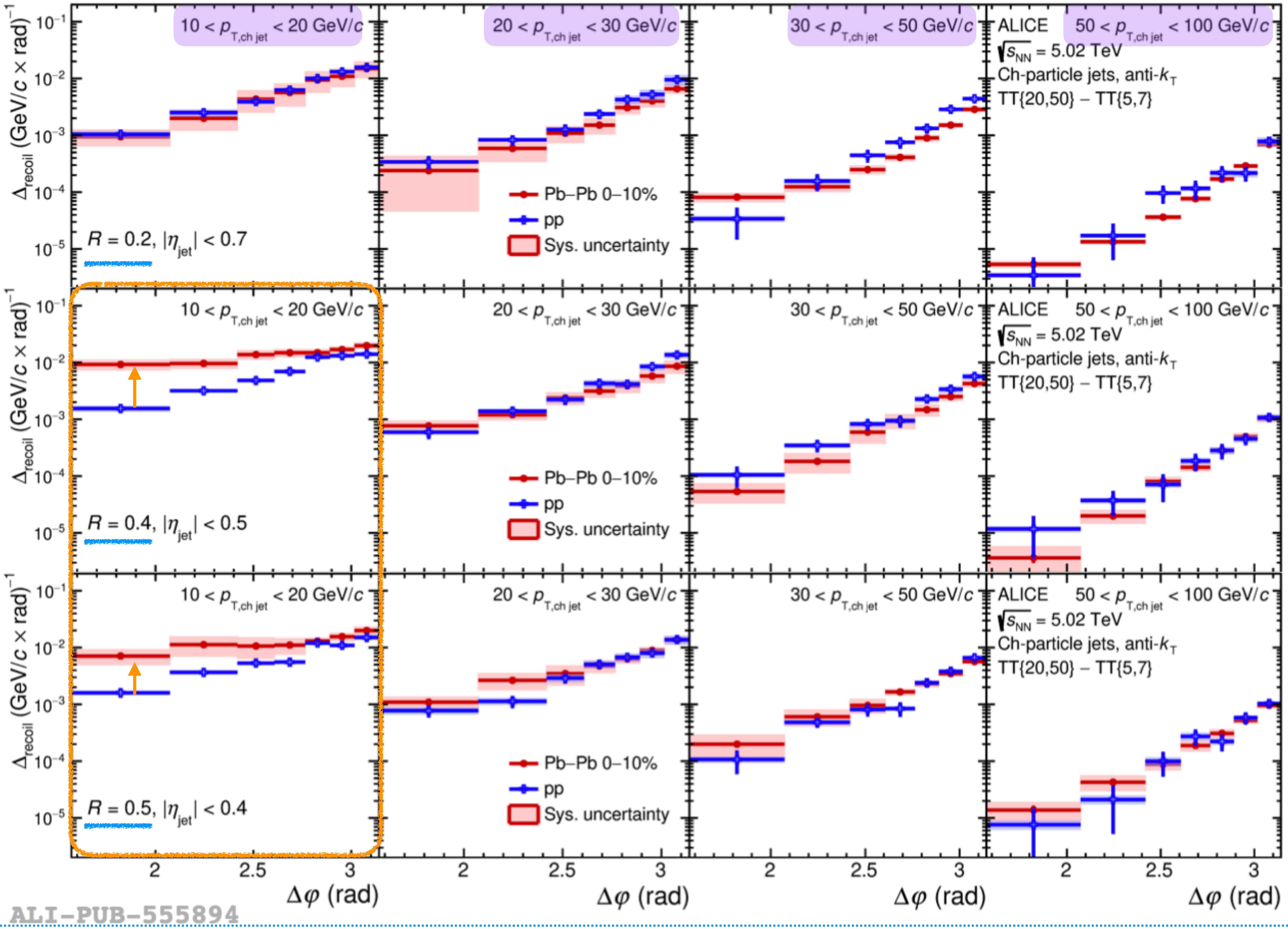


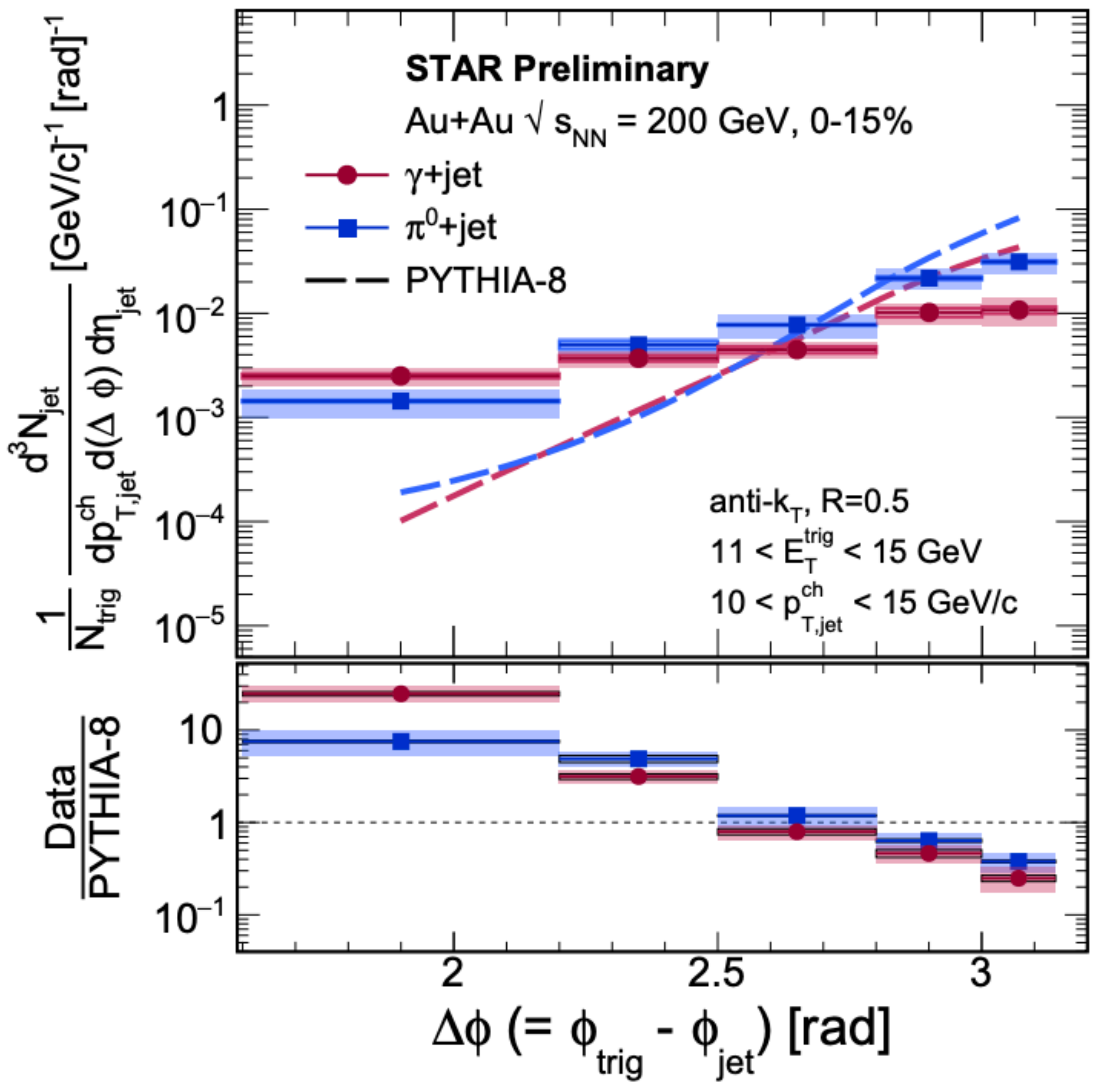
JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss based on MATTER (high virtuality) + LBT (low virtuality)

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.

Broadening effect observed with ALICE & STAR





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