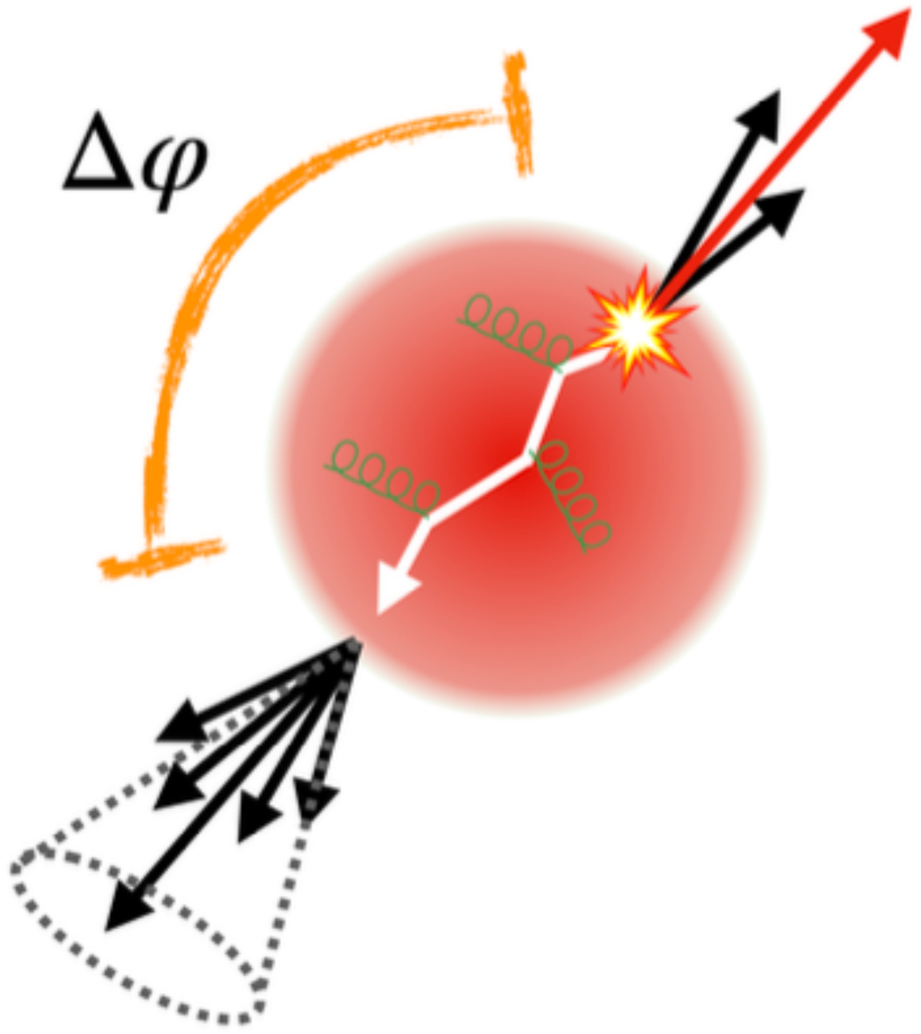
Study of jet quenching effects through hadron-jet correlations with ALICE at the LHC



Yongzhen HOU（侯永珍）

IOPP, Central China Normal University

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

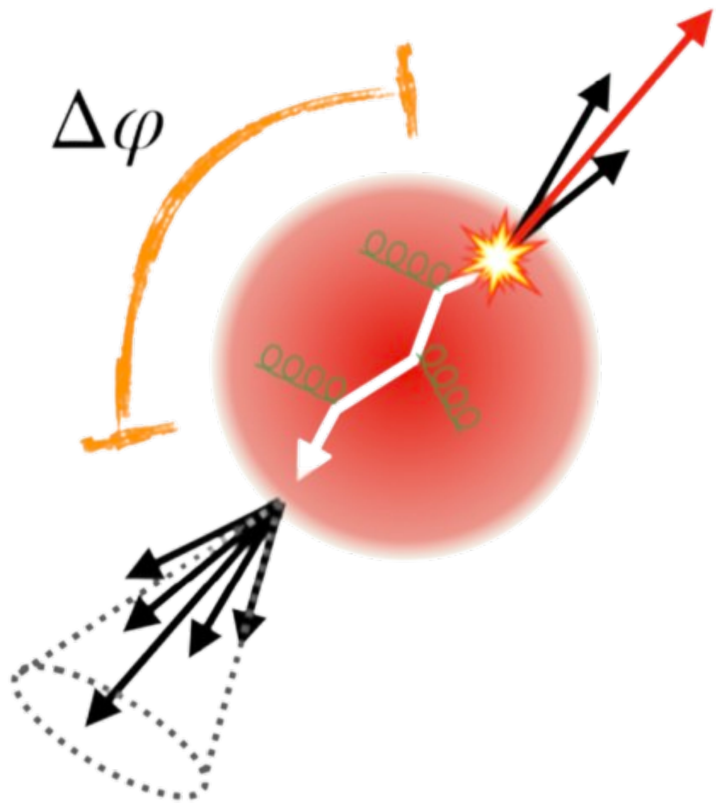
- **Hadron-jet correlations in pp collisions at 13.6 TeV (Run 3, New preliminary)** New

- **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)**

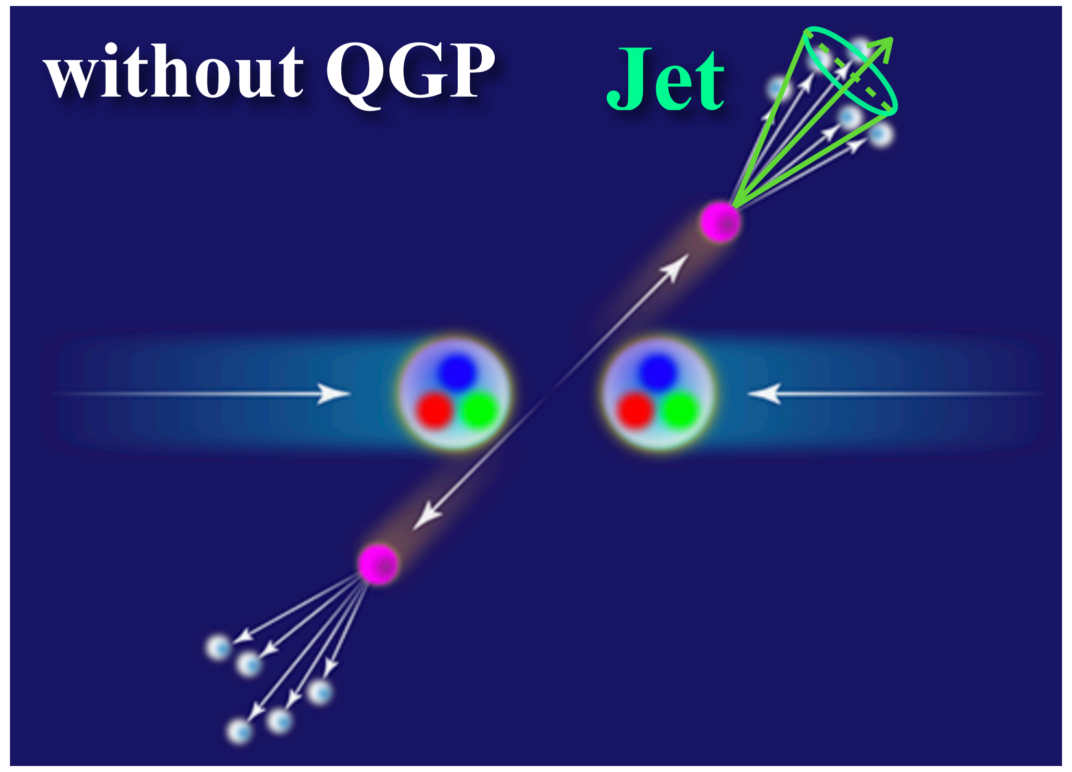
  PRL 133 (2024) 022301, PRC 110 (2024) 014906



Jet Probes

Yongzhen HOU
yongzhen.hou@cern.ch

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



Yongzhen HOU
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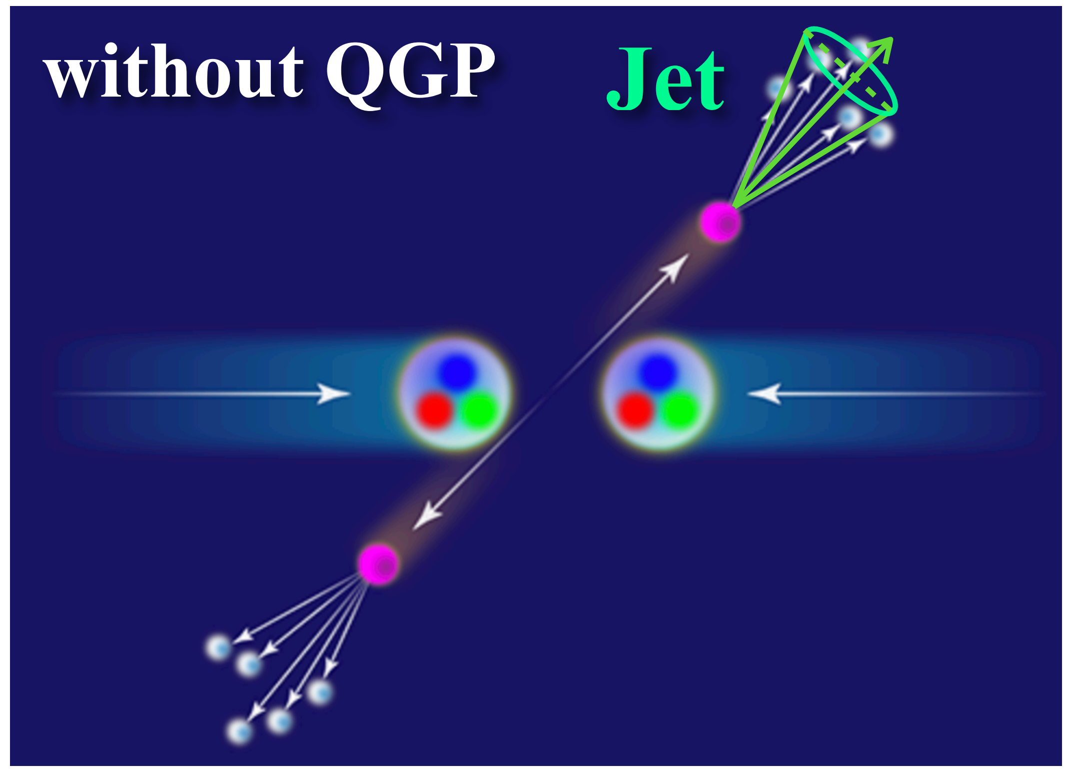
Jets in pp collisions → study the strong force

- 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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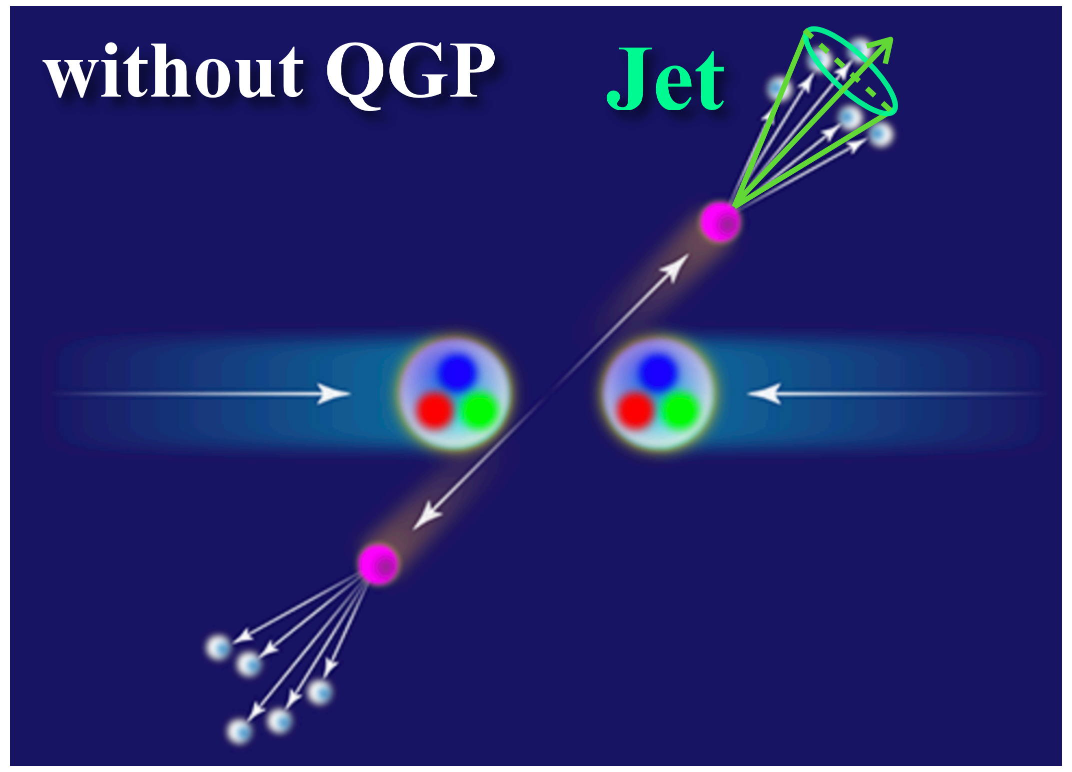
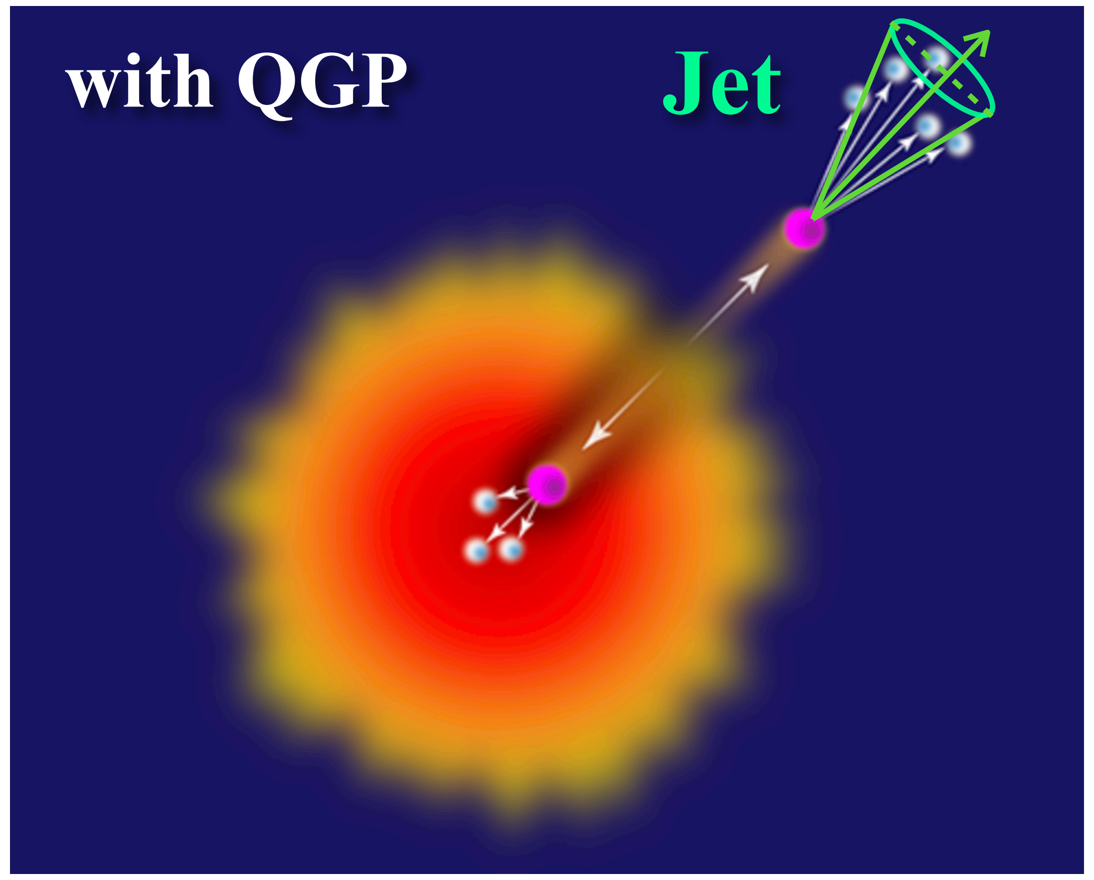


Jets in heavy-ion collisions → study the transport properties of the QGP

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



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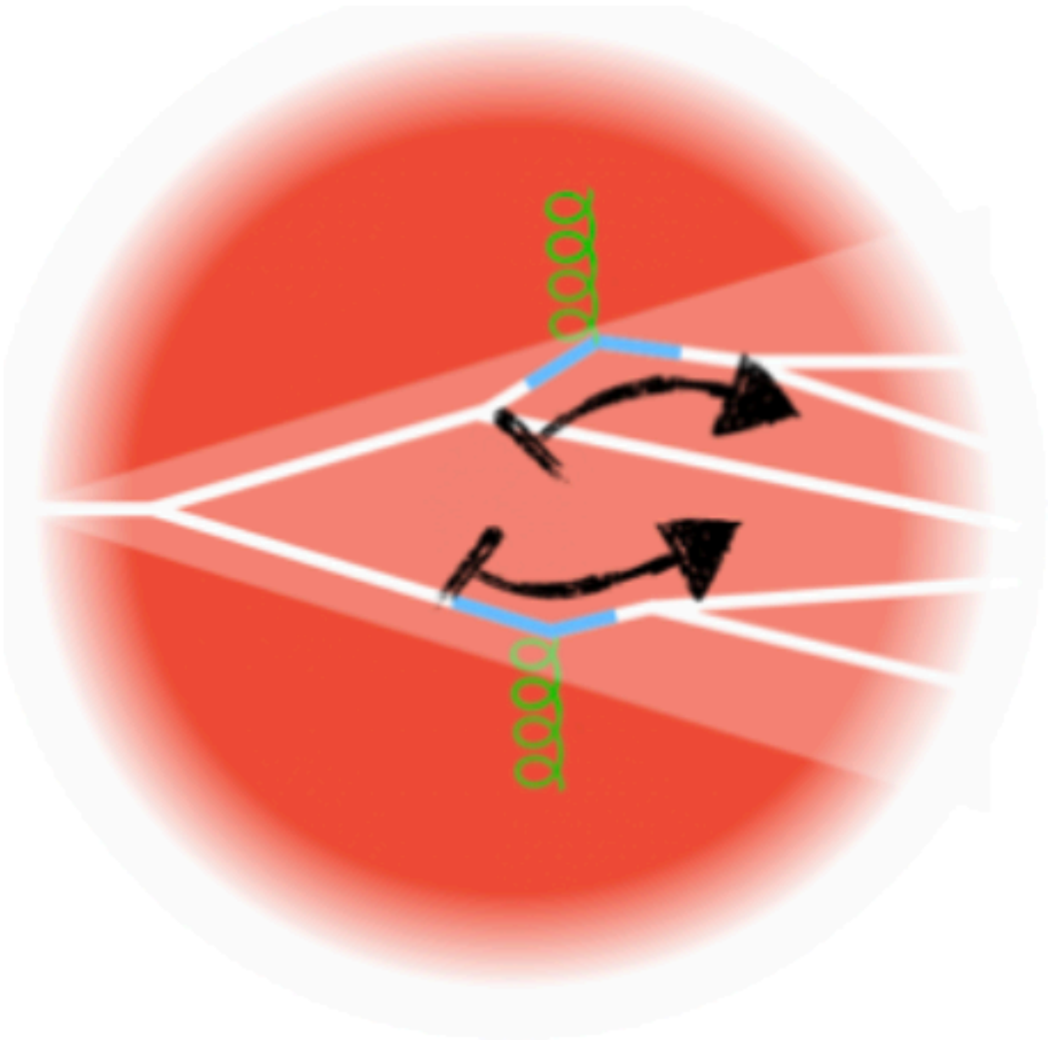
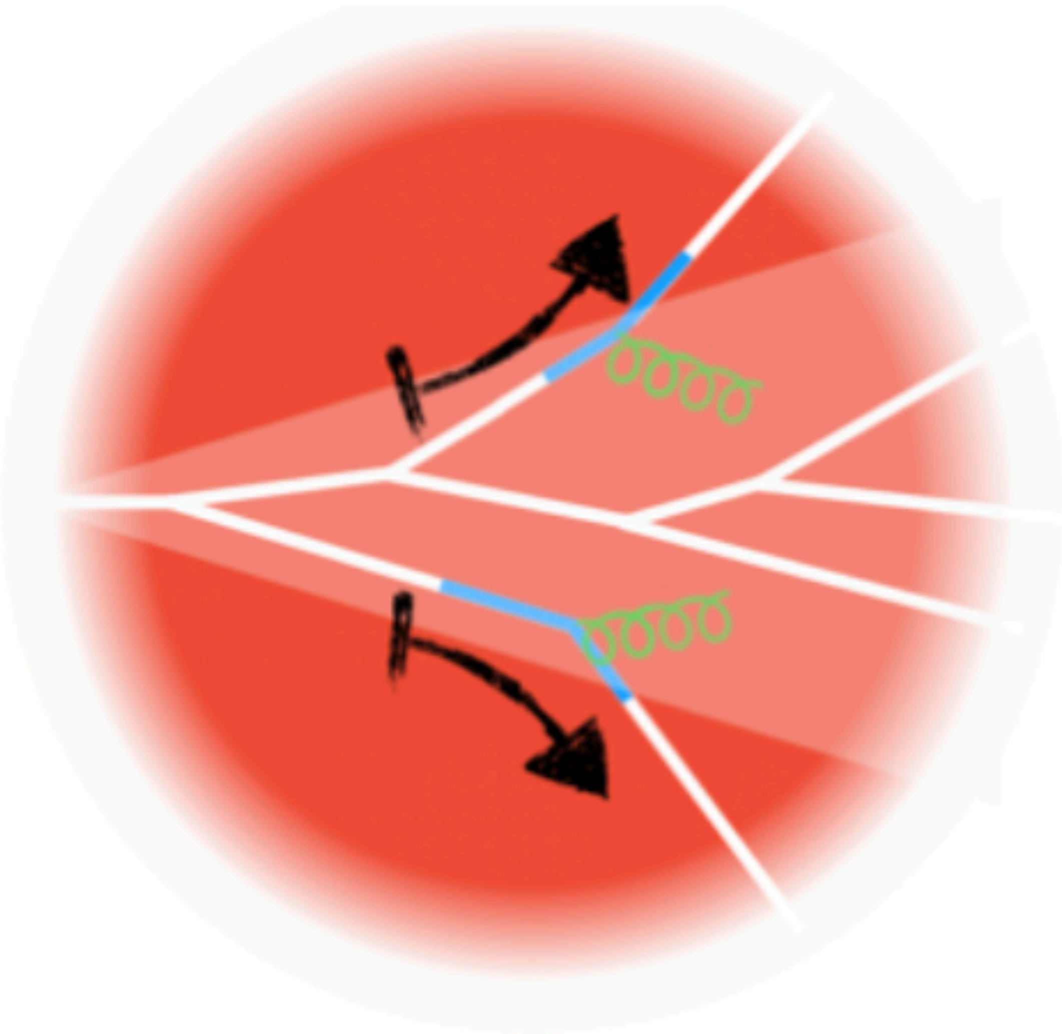
Study structure of QGP by understanding jet modification from medium interaction **(quenching)**

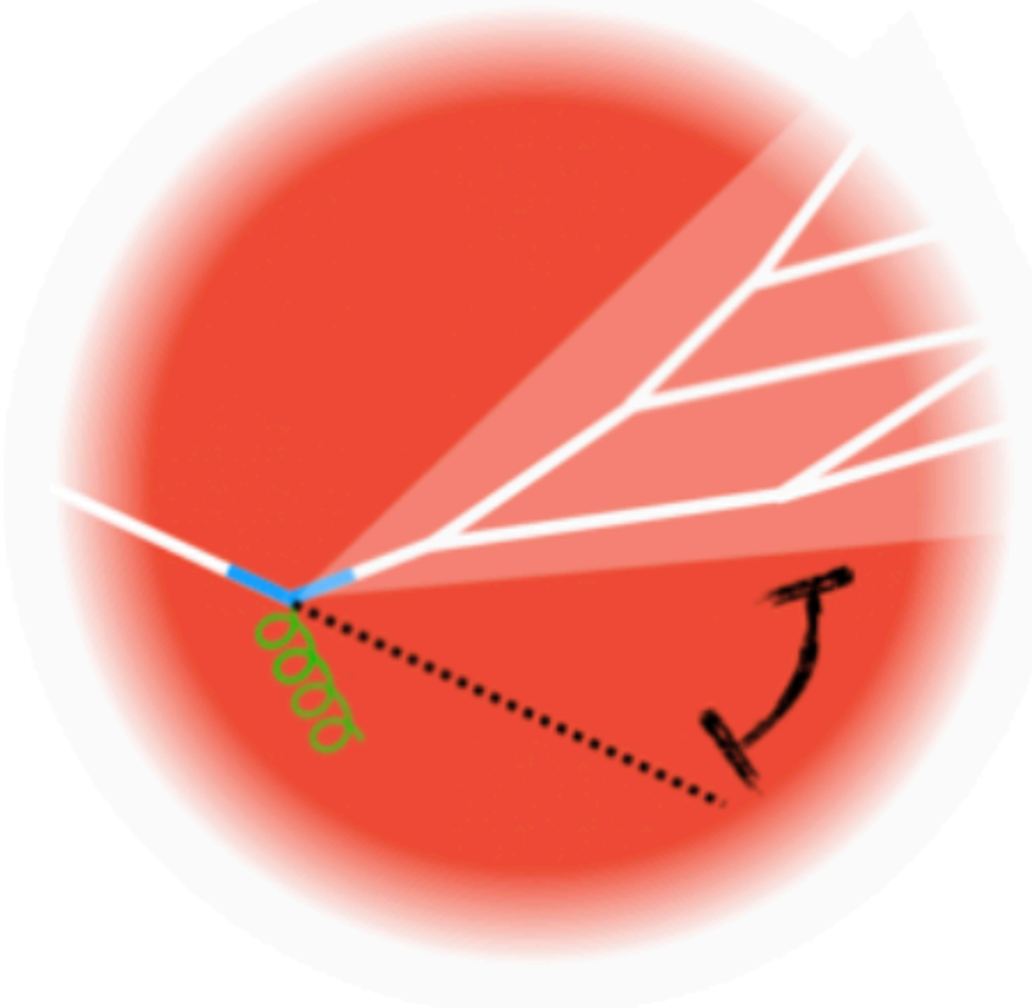
- **Several types of jet observables**
  - Jet reconstruction and declustering → substructure (r_g, θ_g) modification
  - Jet yields and constituents → jet suppression and energy redistribution (R_{AA}, I_{AA})
  - Angular correlation → jet deflection ($\Delta\varphi$)



Substructure modification



Energy redistribution



Deflection

Jet quenching observables

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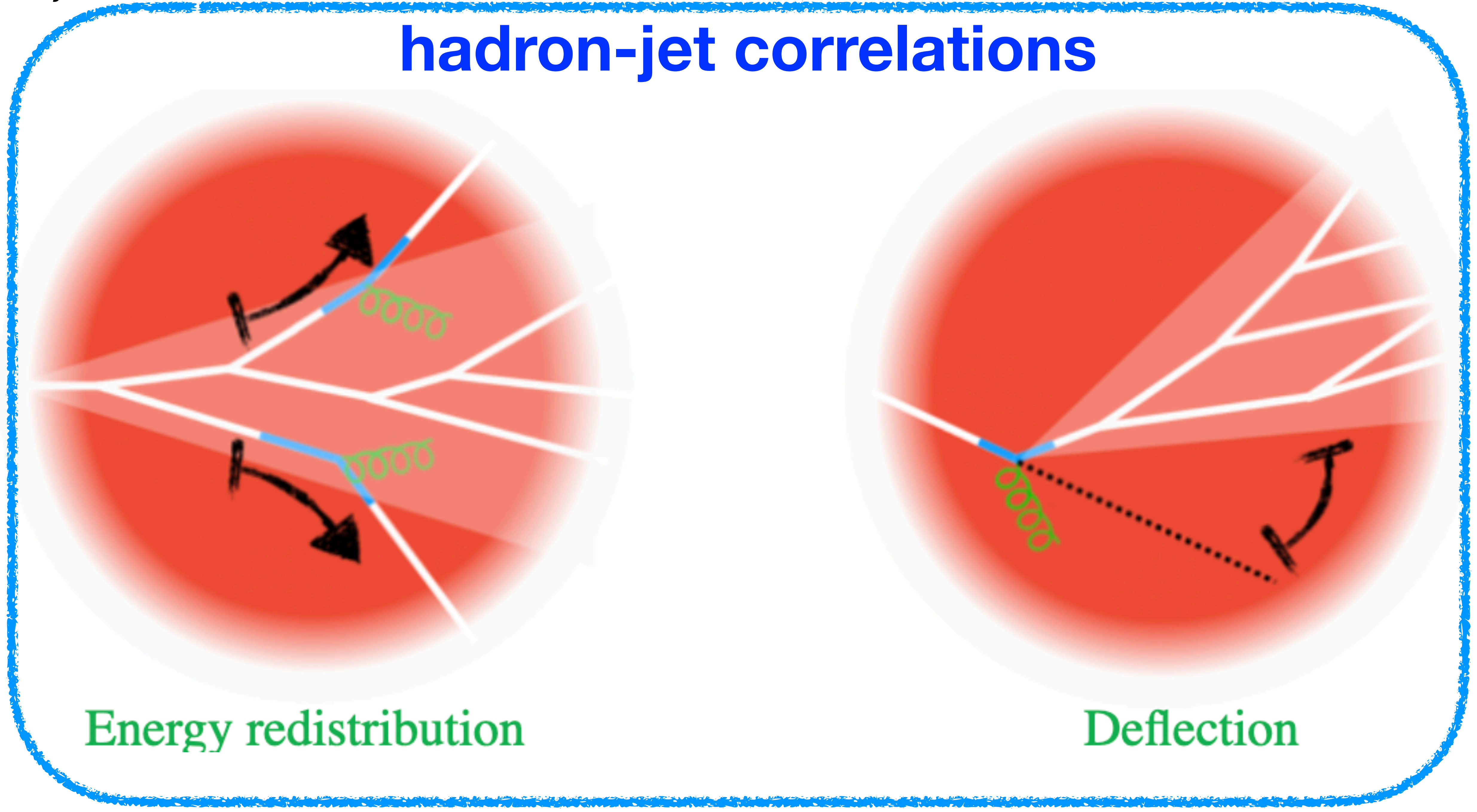
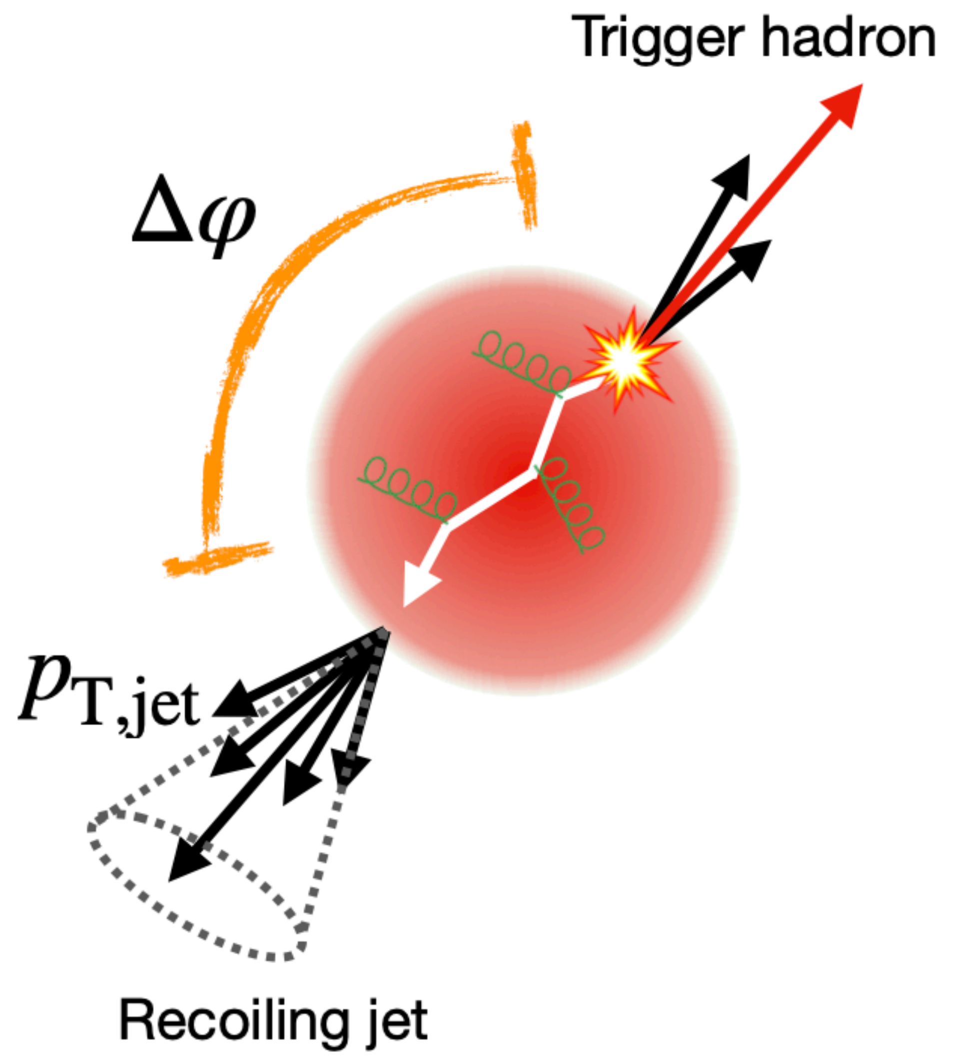
➡**Semi-inclusive measurements** of a jet recoiling from a trigger (e.g. γ-jet , Z-jet, or **hadron-jet**)

Apply statistical, data driven-approach for background yield suppression



Hadron-jet correlations

- 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**
- **Opening angle ($\Delta\varphi$)** measurements of the recoil jet relative to the trigger axis provide additional insight into QGP properties



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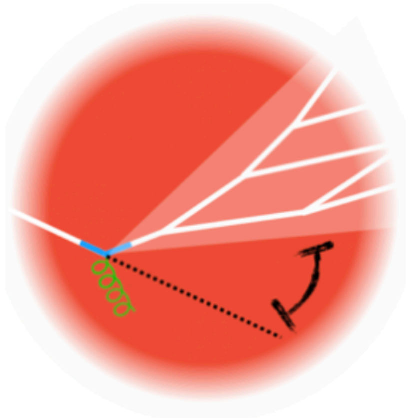

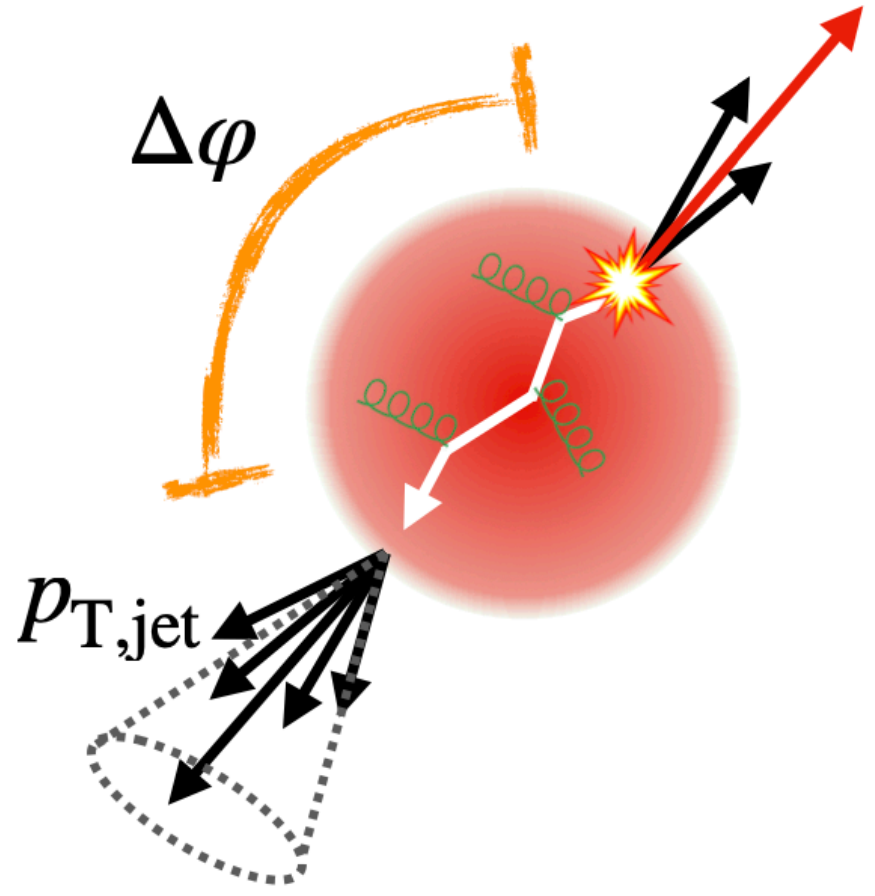

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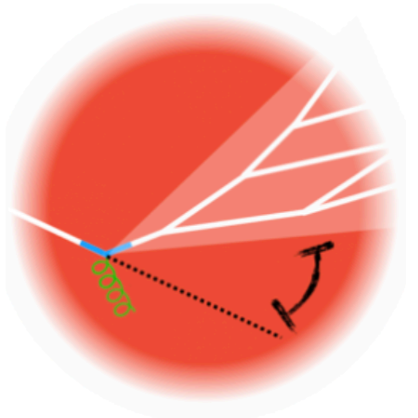

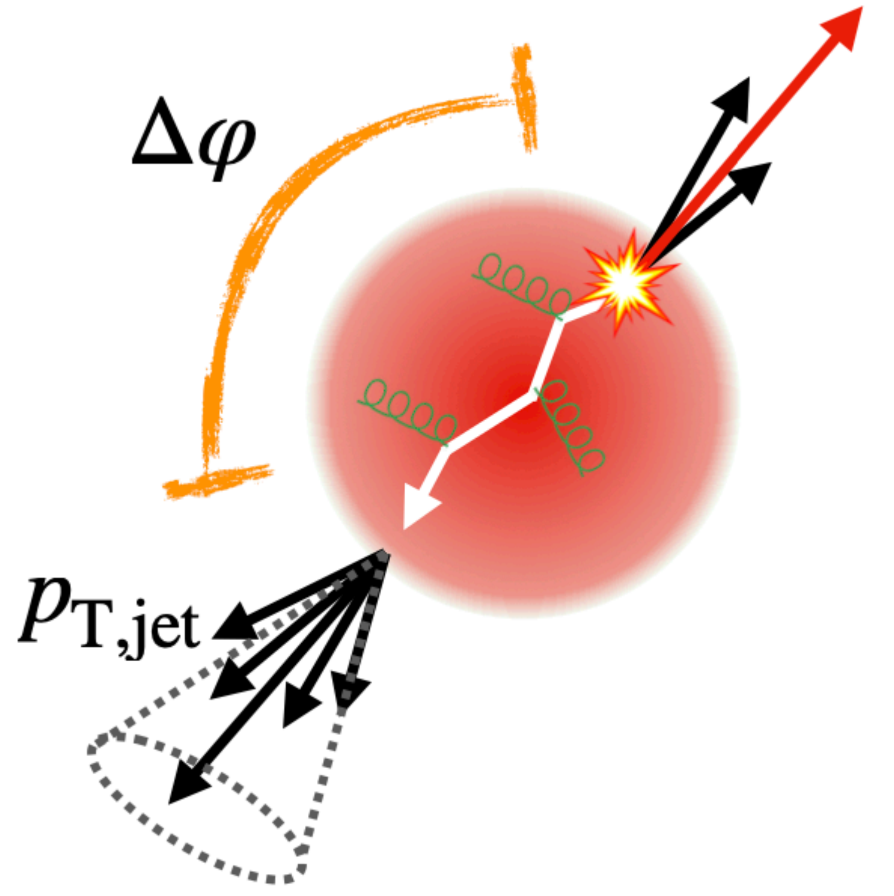

1. L Chen, Phys. Lett. B 773 (2017) 672
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3. JHEP 01 (2019) 172

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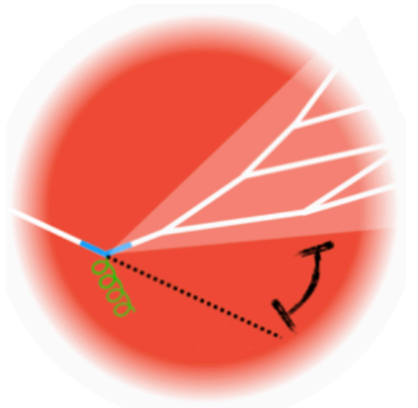

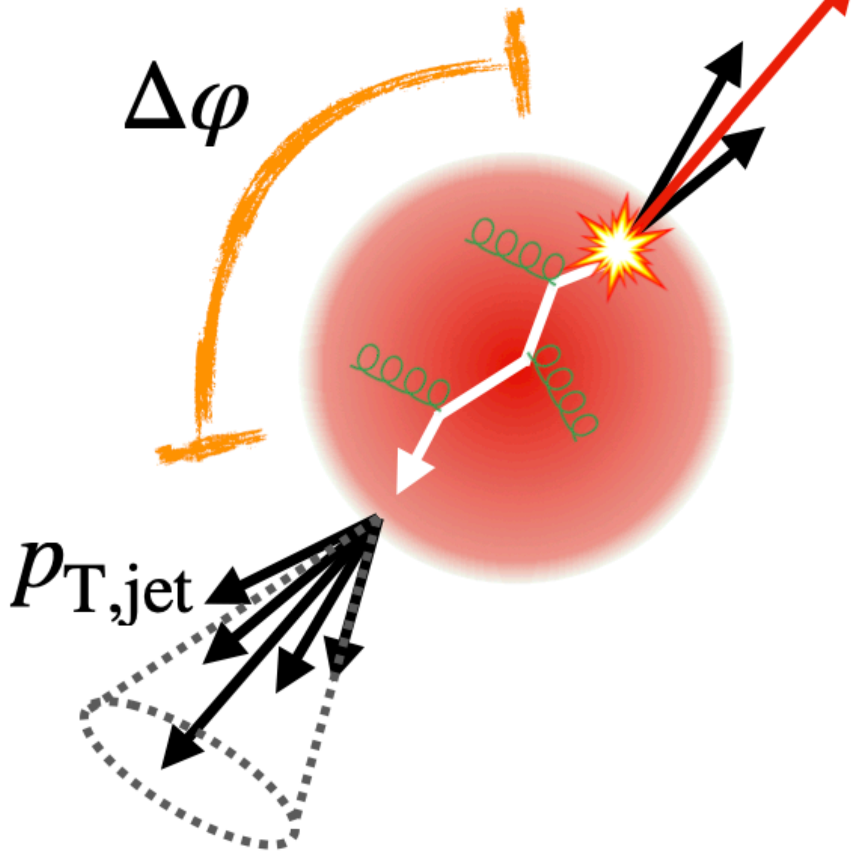

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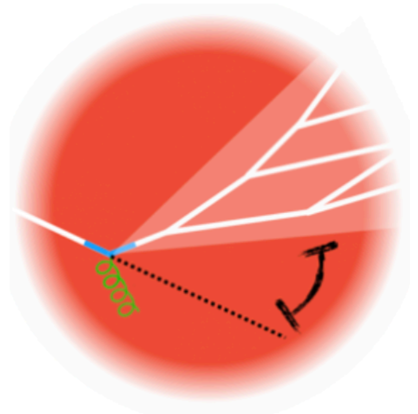

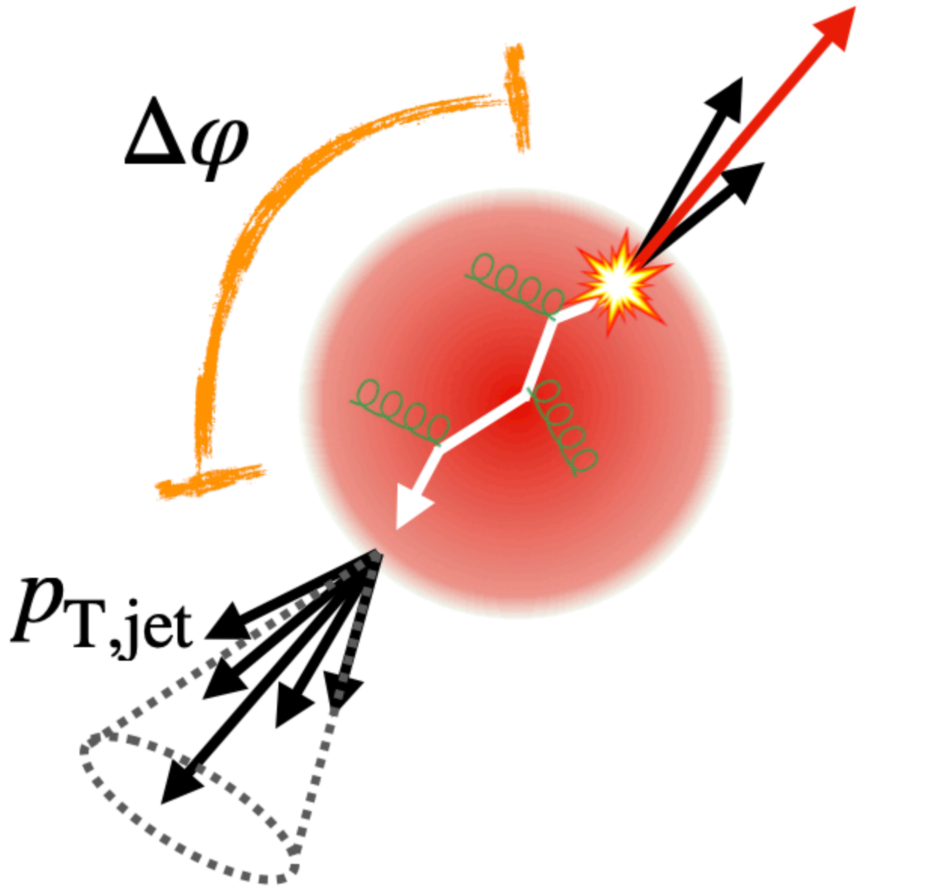

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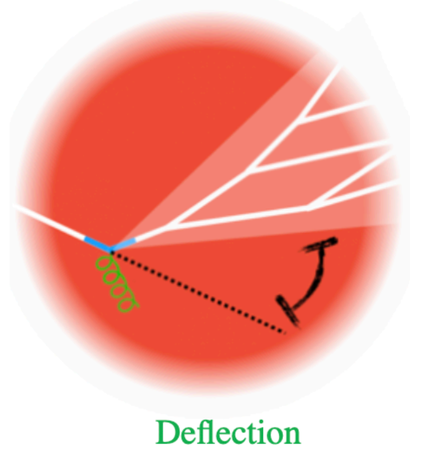
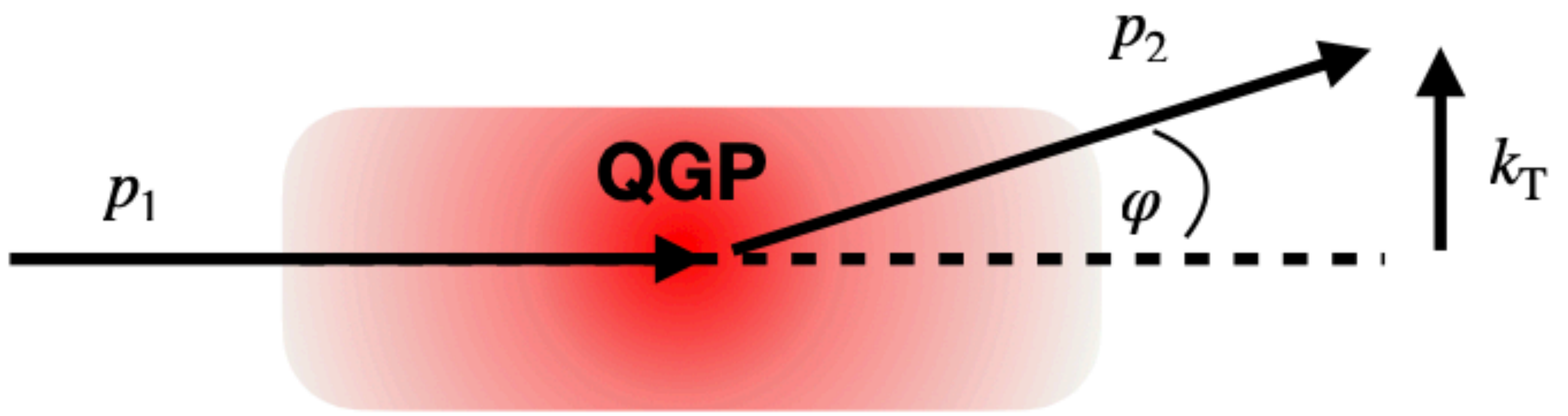
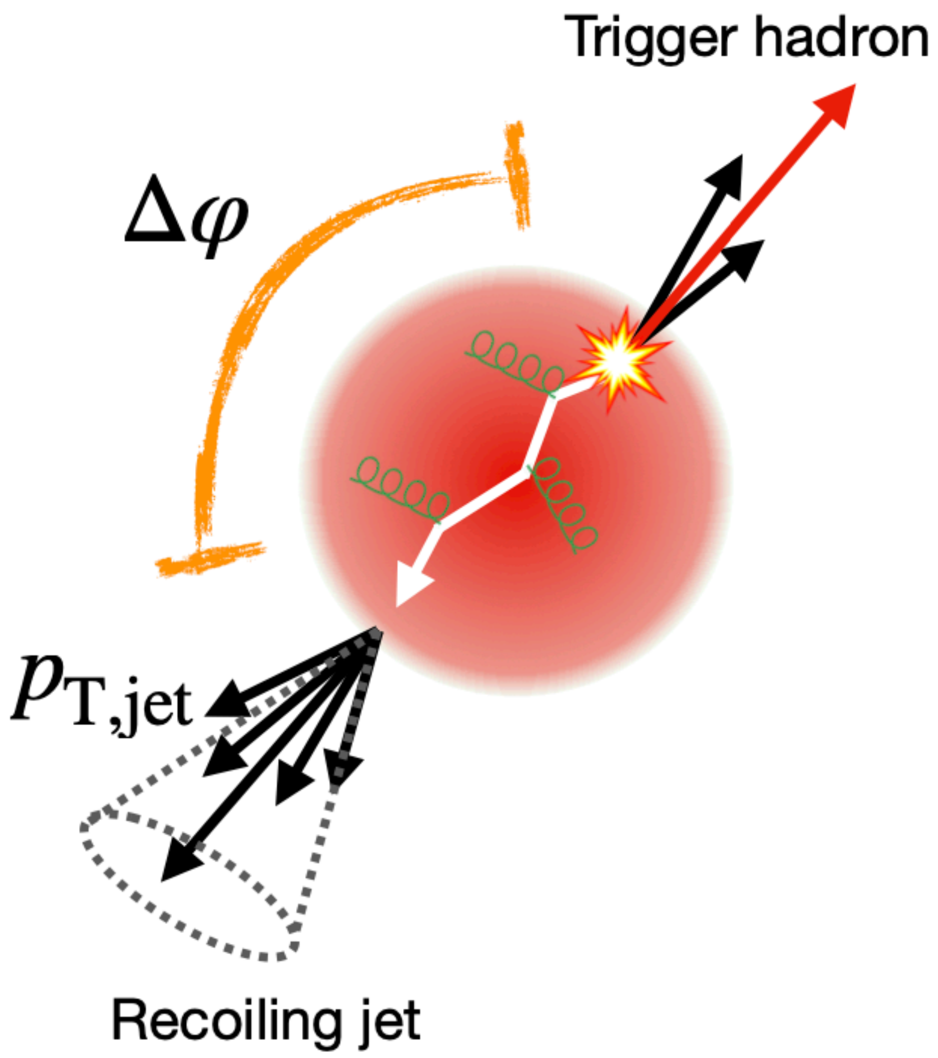
    - **Large-angle deflection** ($\Delta\varphi < \pi$) of hard partons off quasi-particle[3]?







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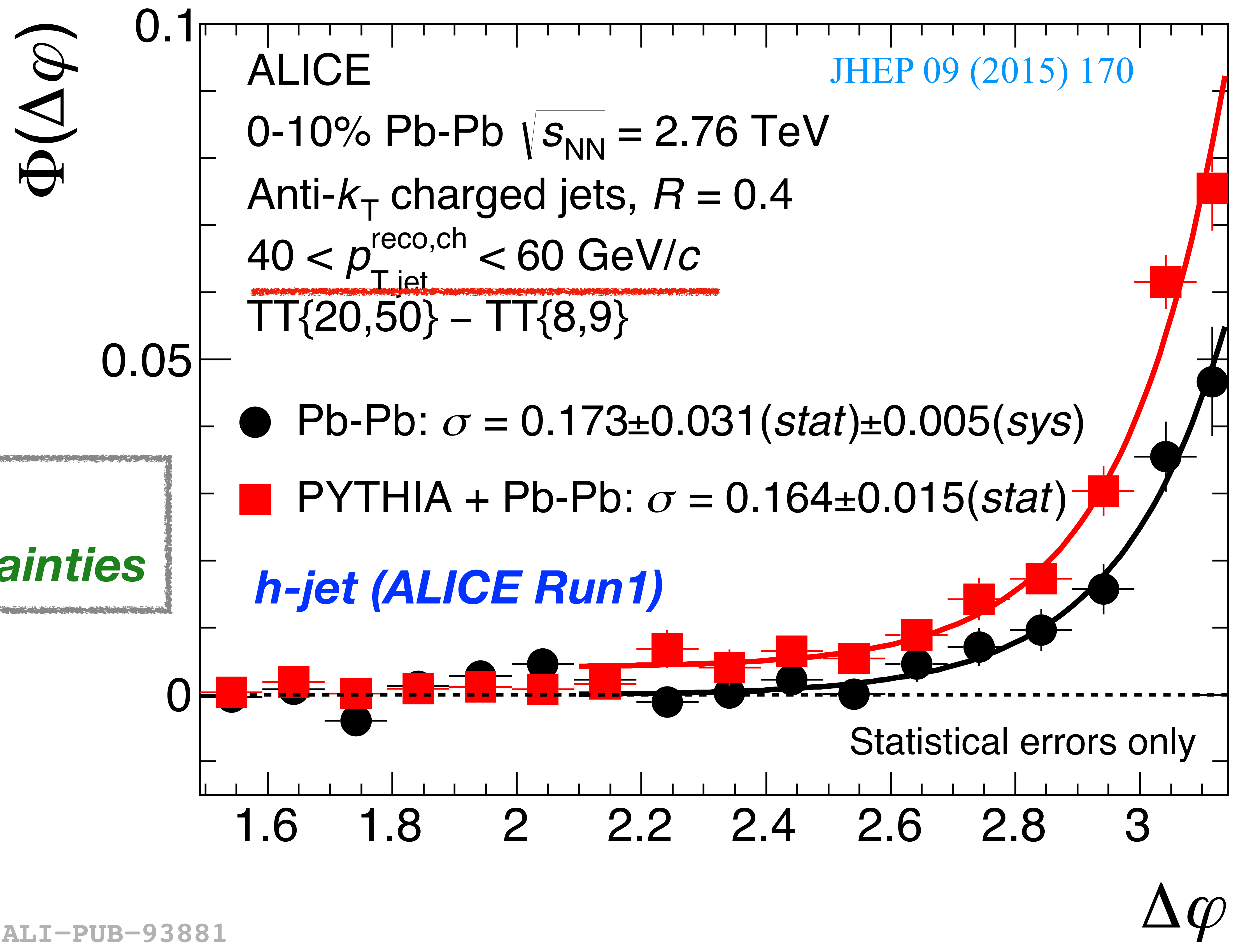
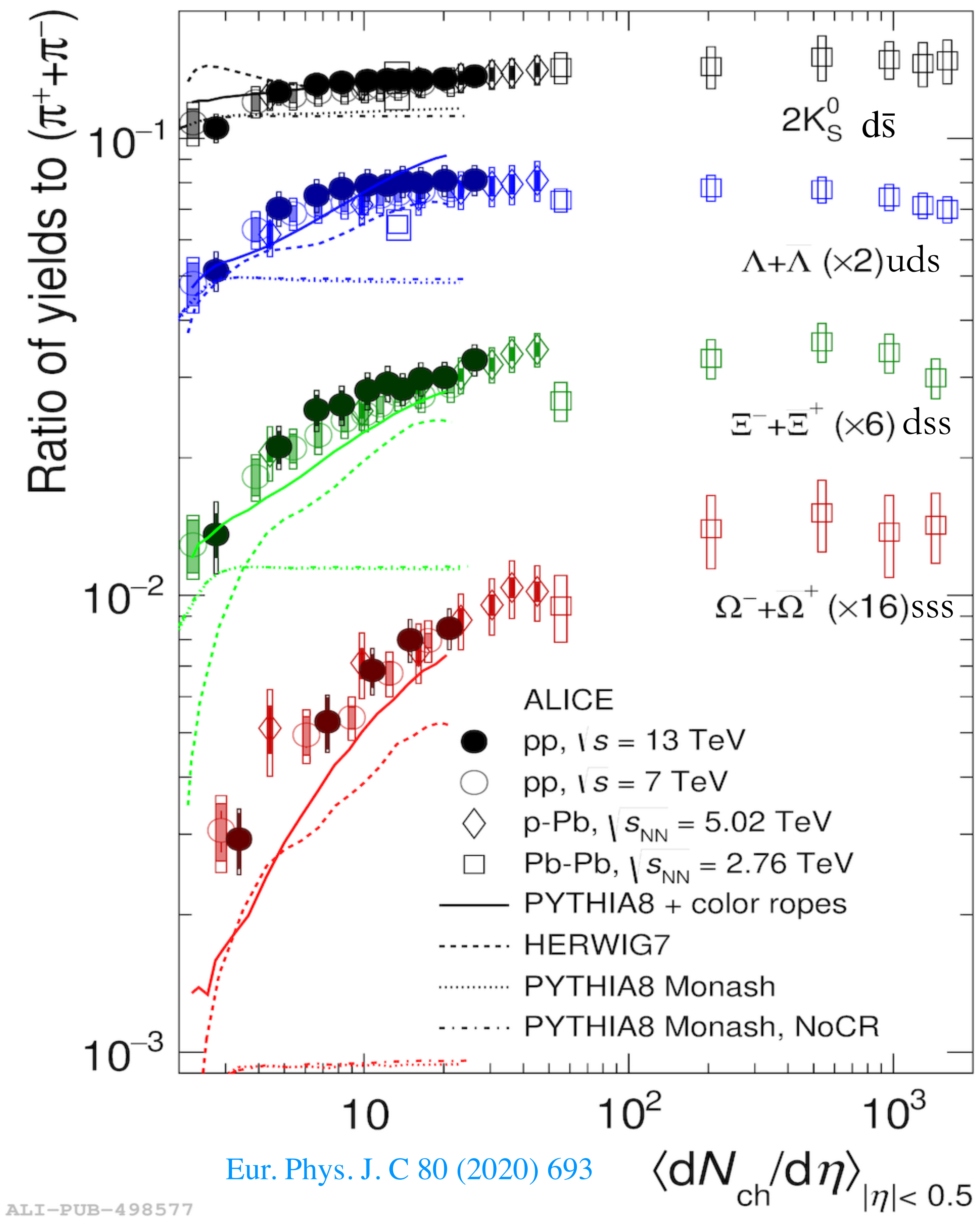


No medium-induced acoplanarity broadening observed within uncertainties

Yongzhen HOU
yongzhen.hou@cern.ch

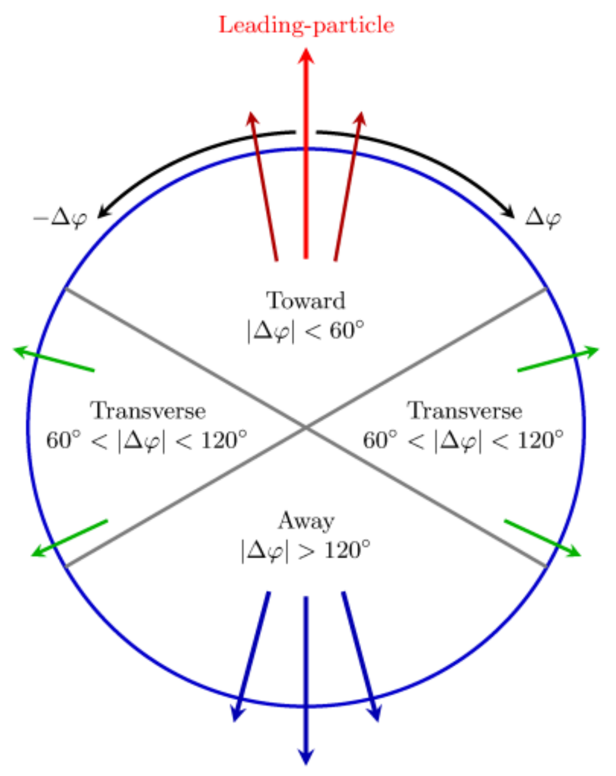
- Effects considered as signatures of QGP formation in heavy-ion collisions are observed in small systems: collectivity, **strangeness** enhancement …



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

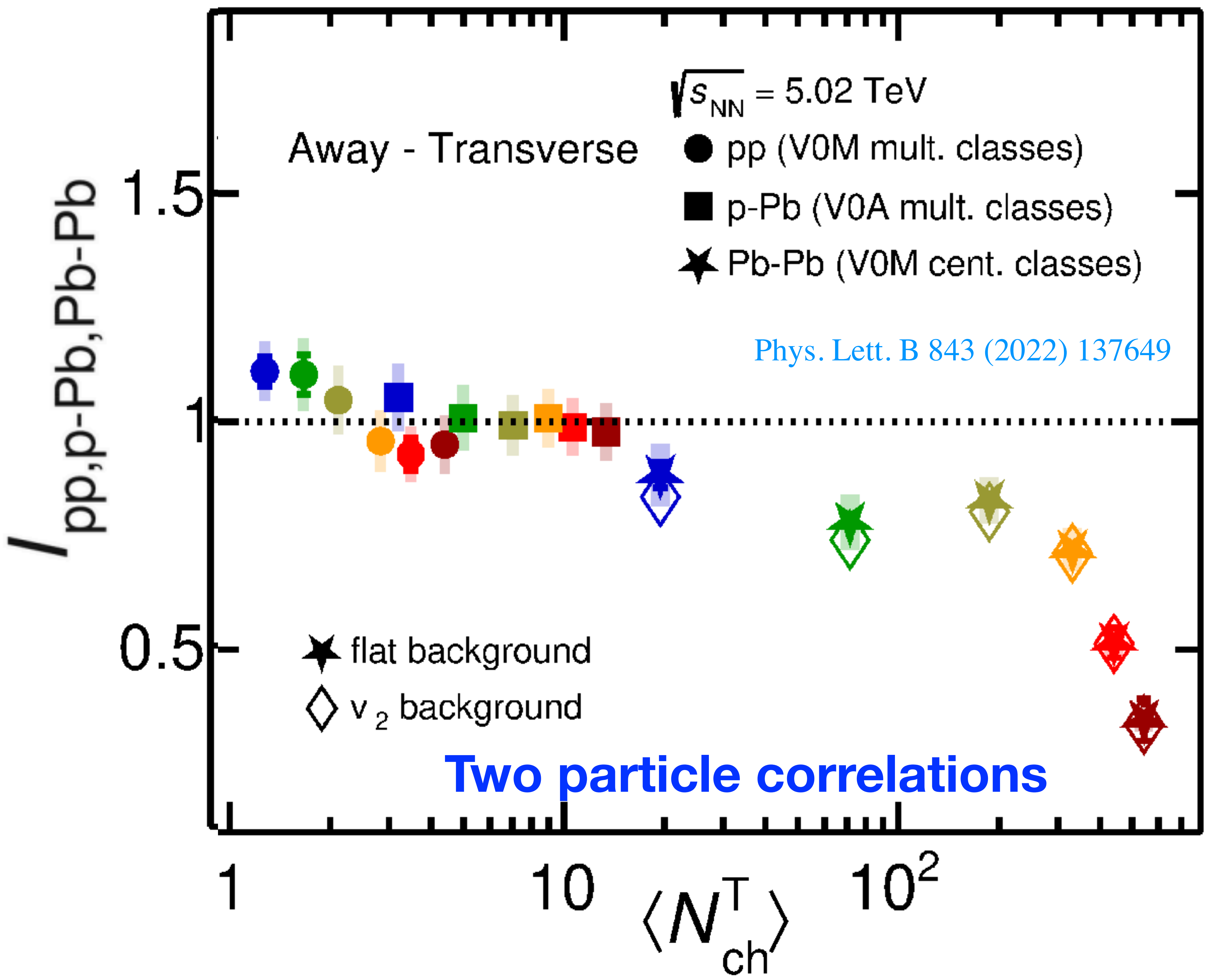
QGP-like behavior in small collision systems

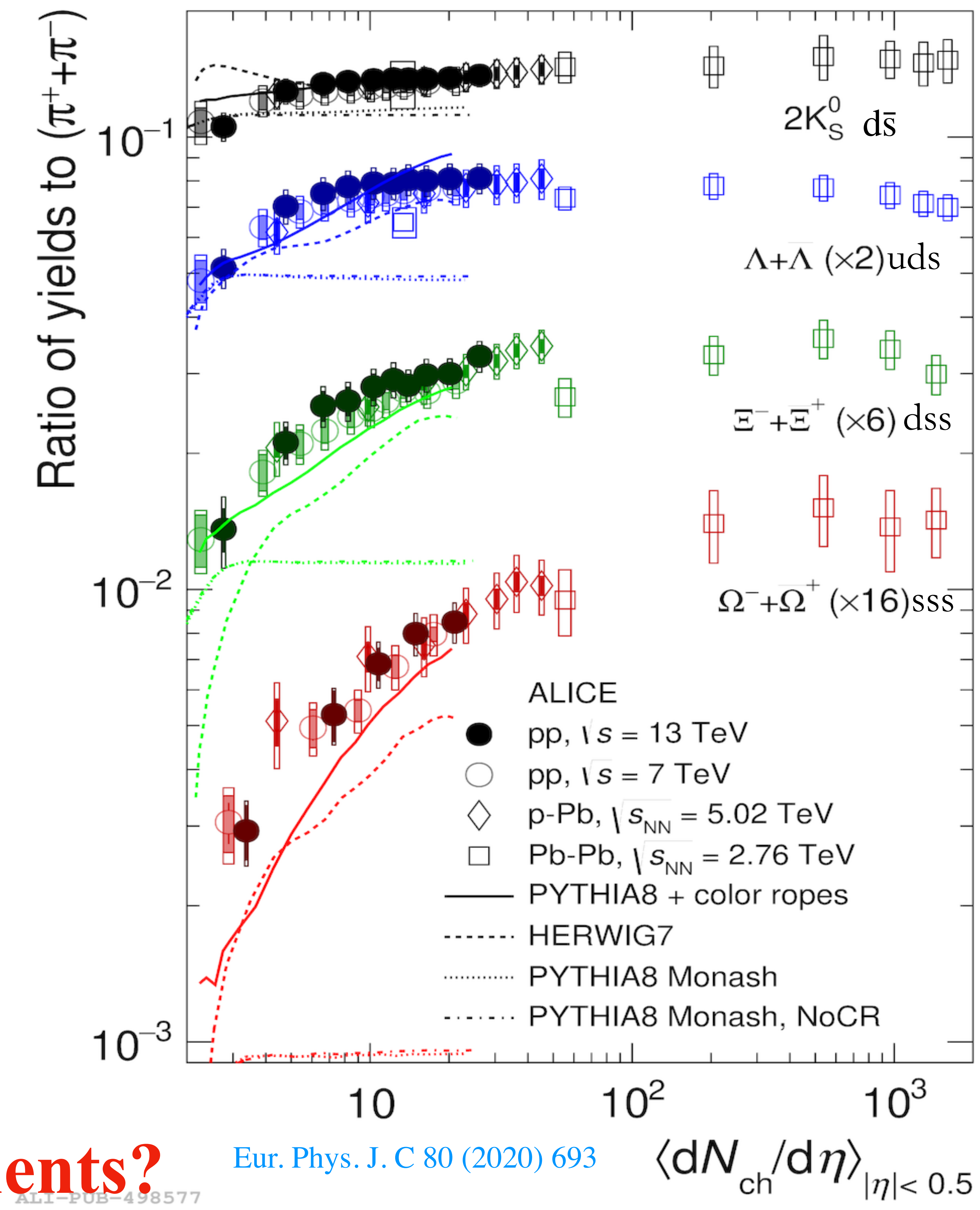
- Effects considered as signatures of QGP formation in heavy-ion collisions are observed in small systems: collectivity, **strangeness** enhancement …
  - However, no **jet quenching** observed so far



Δφ=|φ_leading - φ_associate|

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





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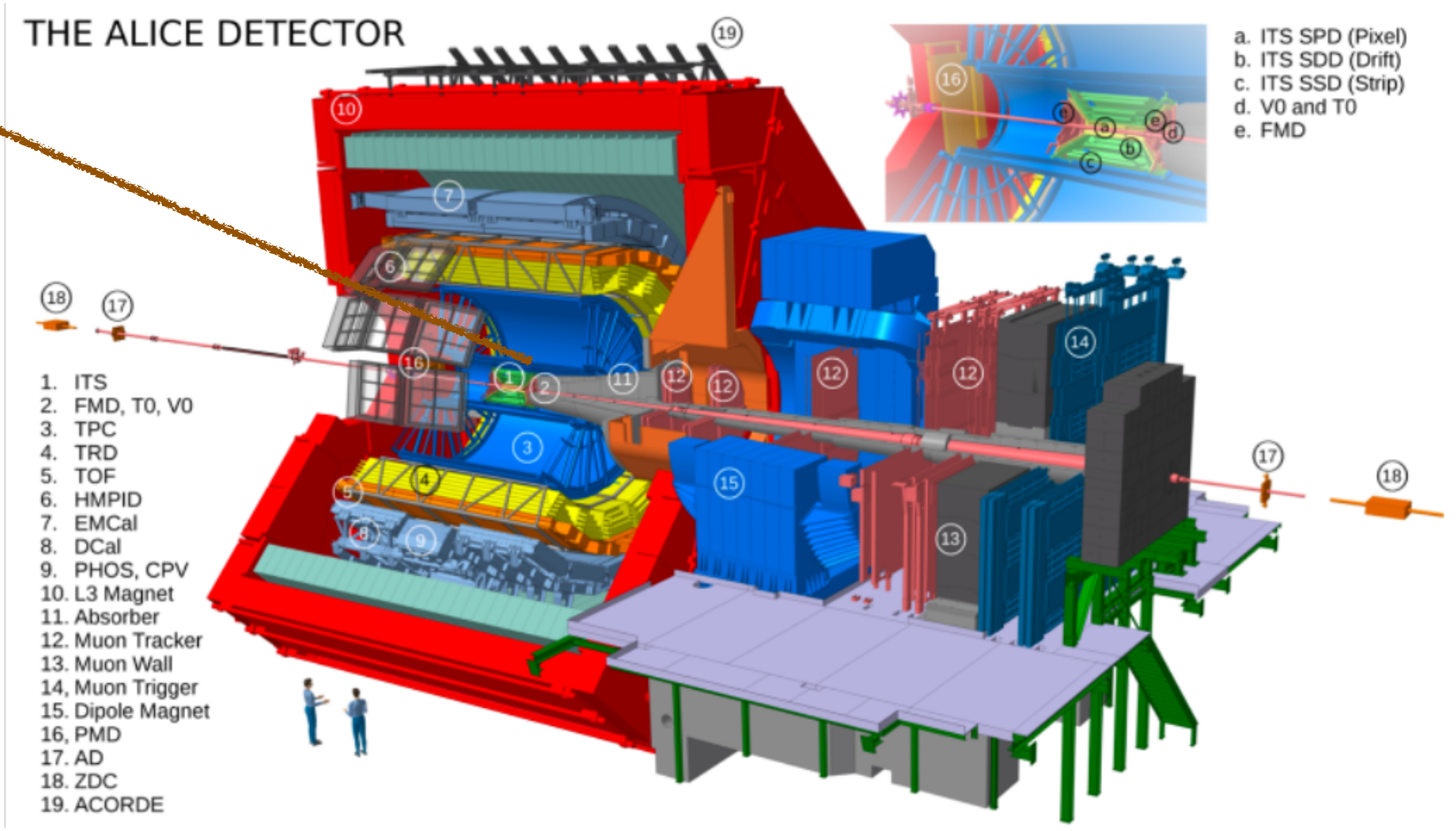
➡ **How does jet production behave in high-multiplicity environments?**

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

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



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  - Event trigger
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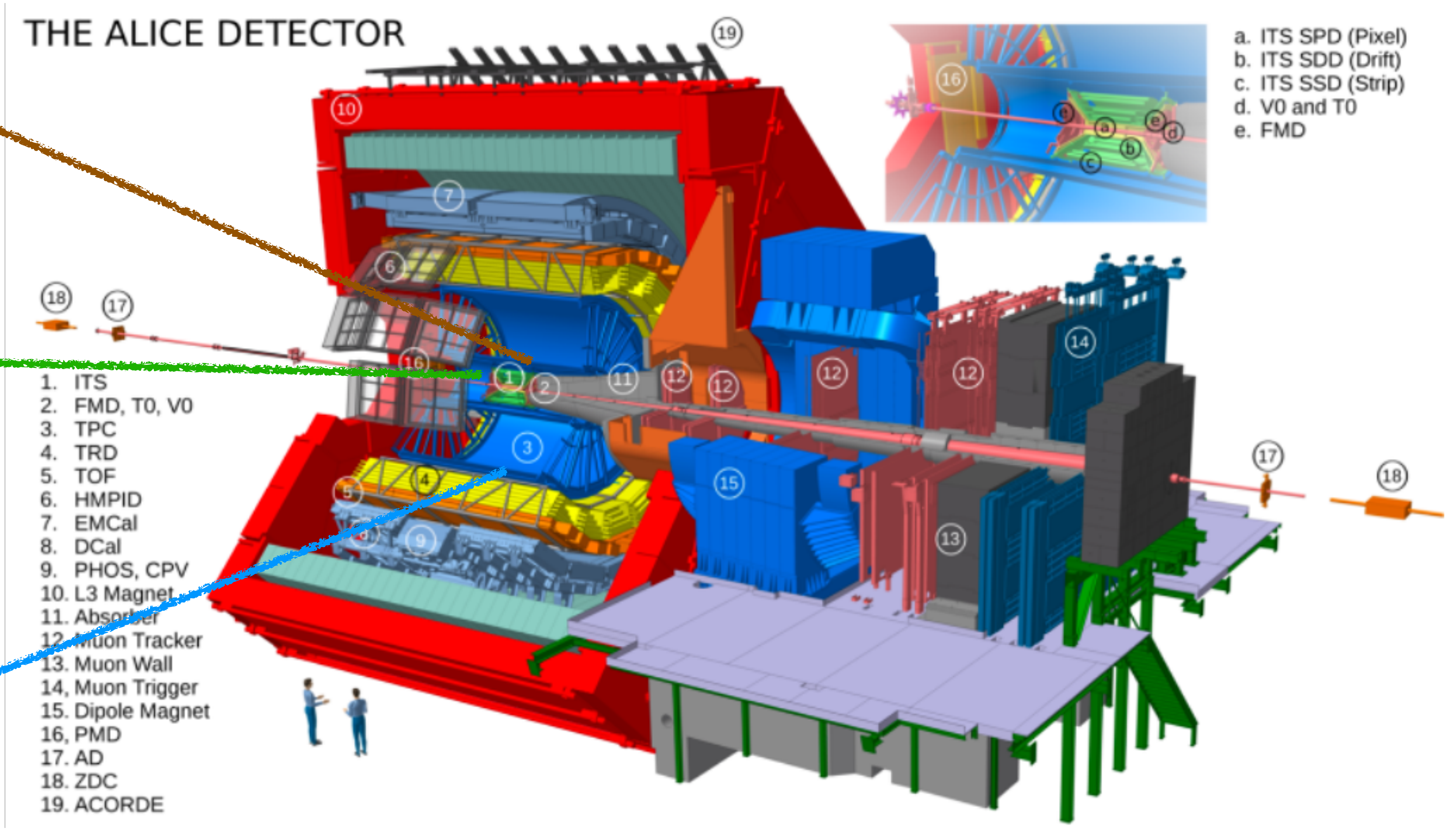
Charged-particle tracks and jets

- **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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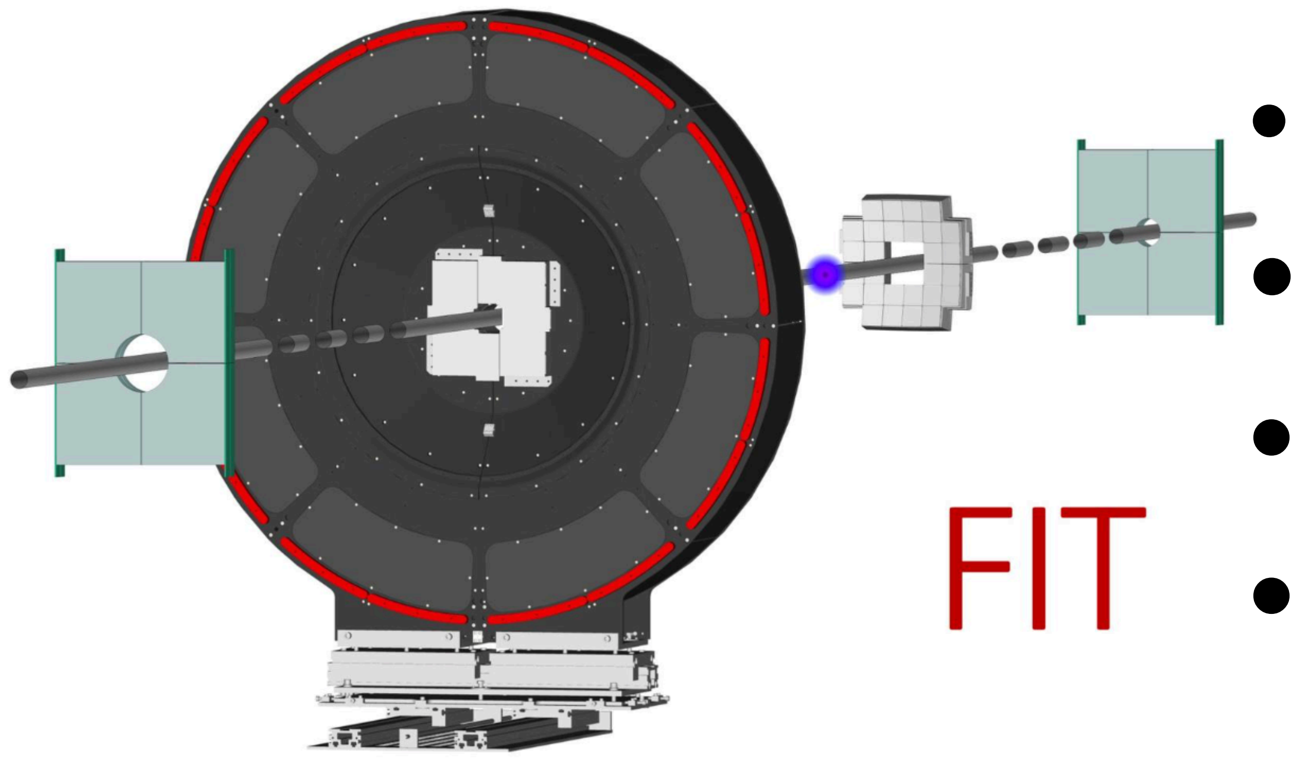
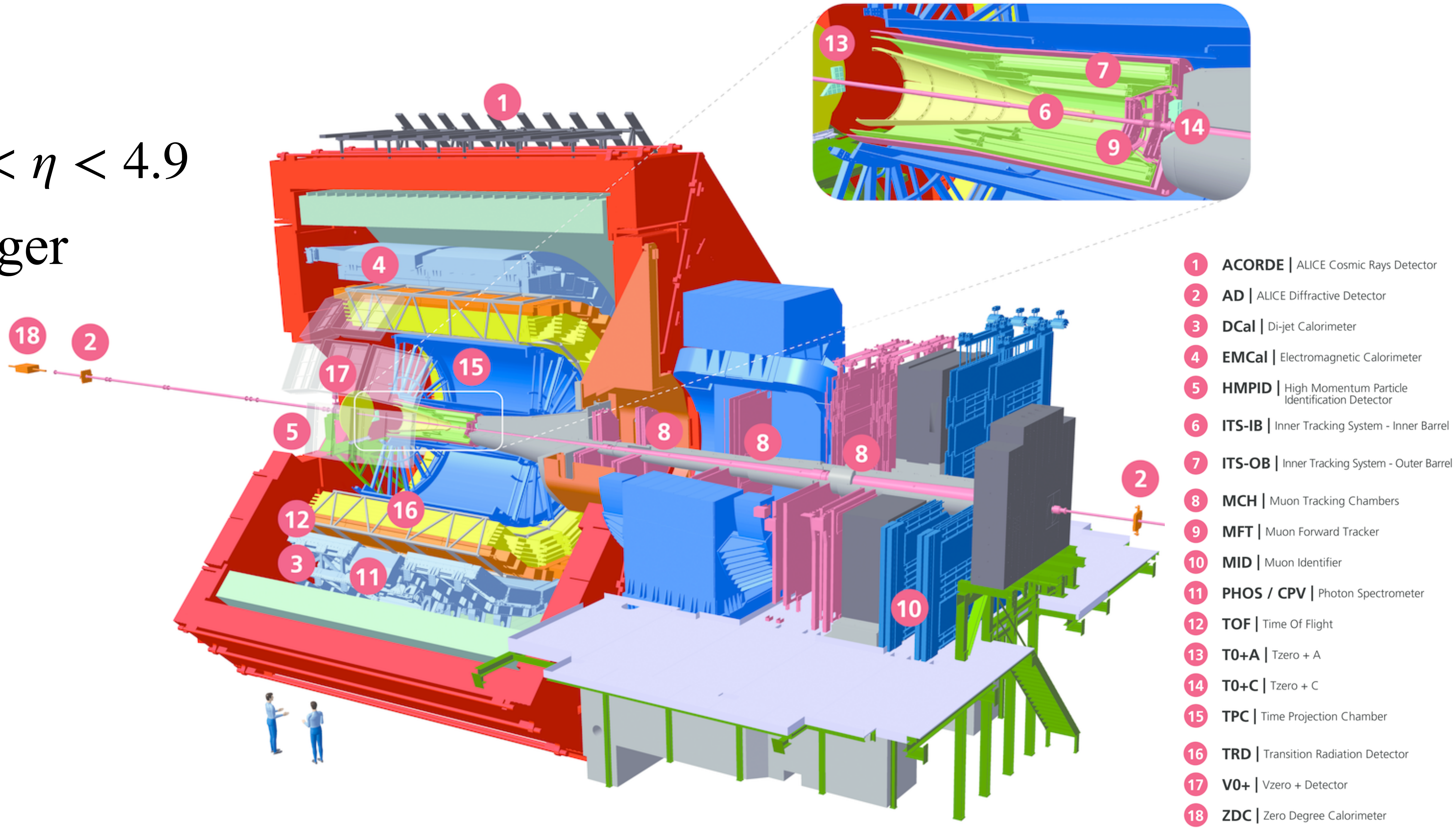
yongzhen.hou@cern.ch

Fast Interaction Trigger (FT0C + FT0A)

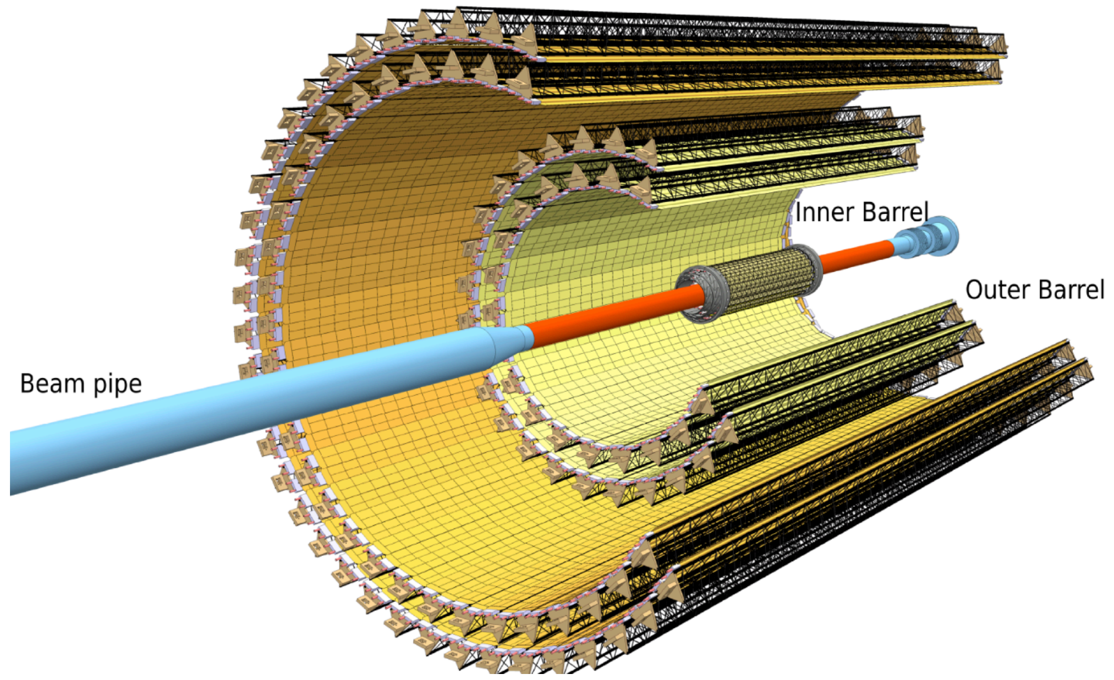


FIT

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

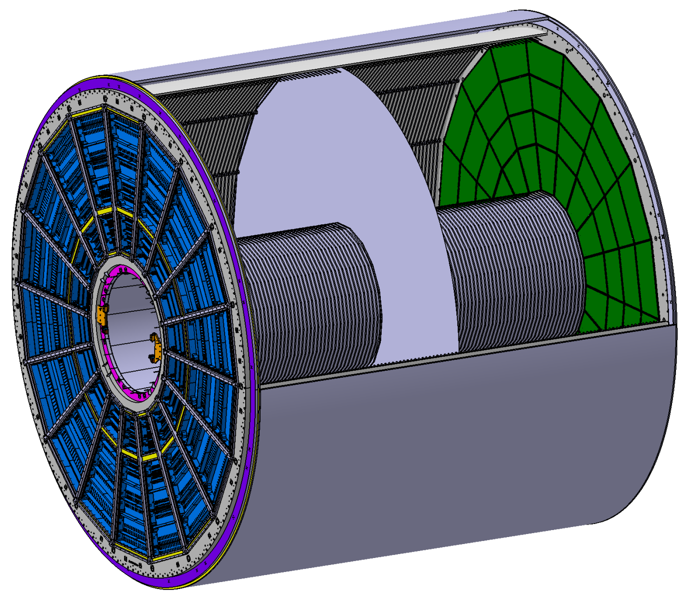


New Inner Tracking System



- $|\eta| < 1.3$, $0 < \varphi < 2\pi$
- 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

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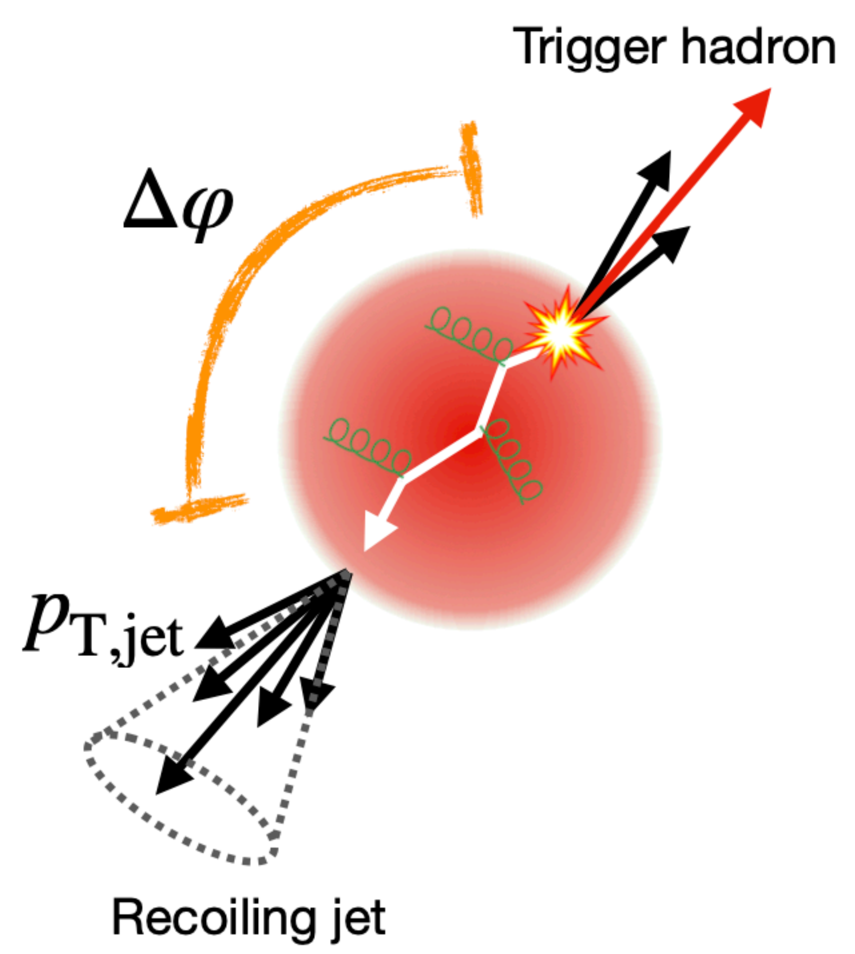
yongzhen.hou@cern.ch

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

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



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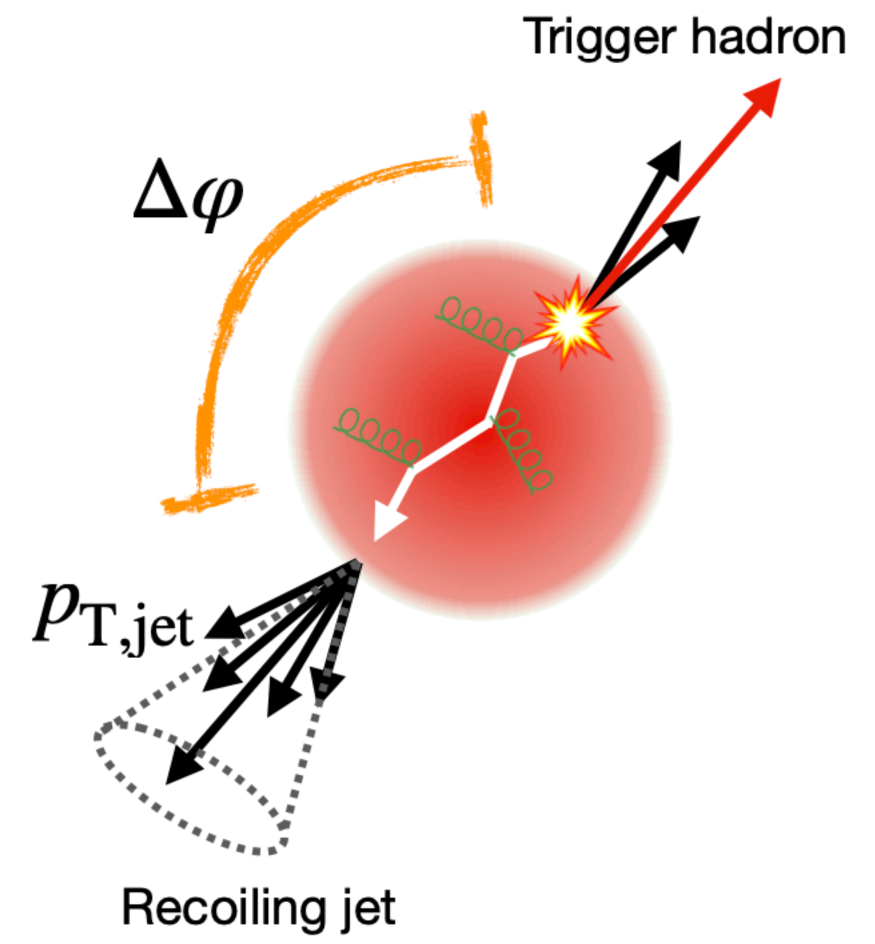

- Recoil jets measured in two exclusive trigger track (TT) intervals:

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])

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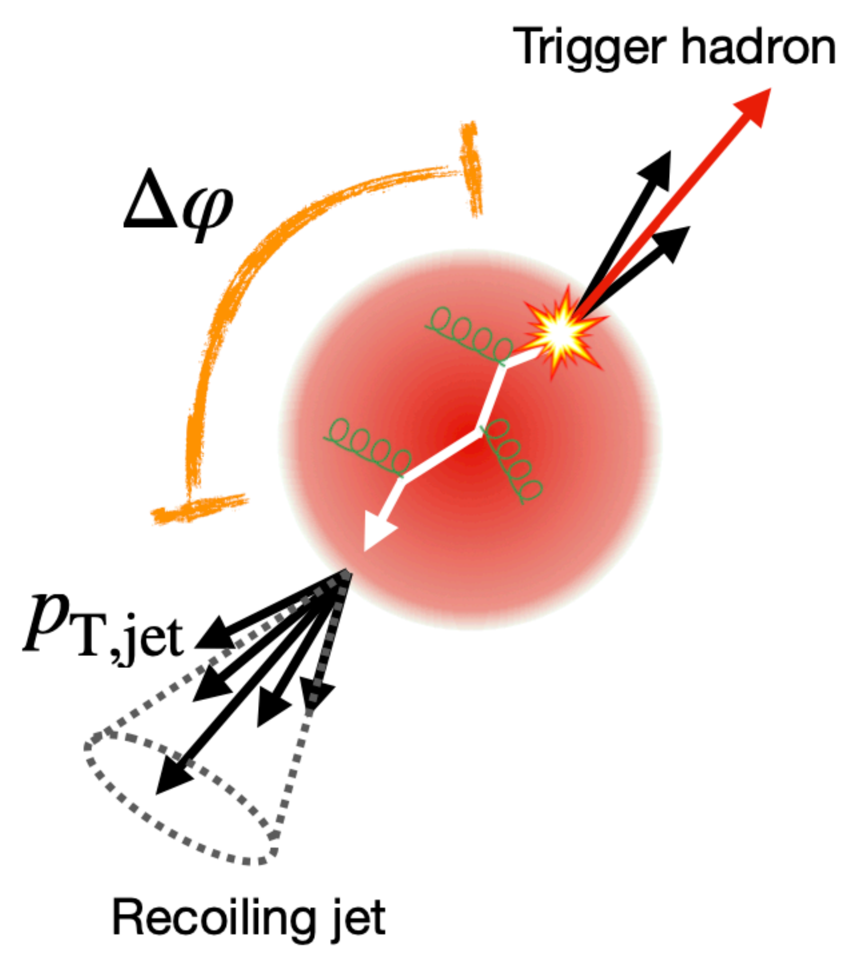

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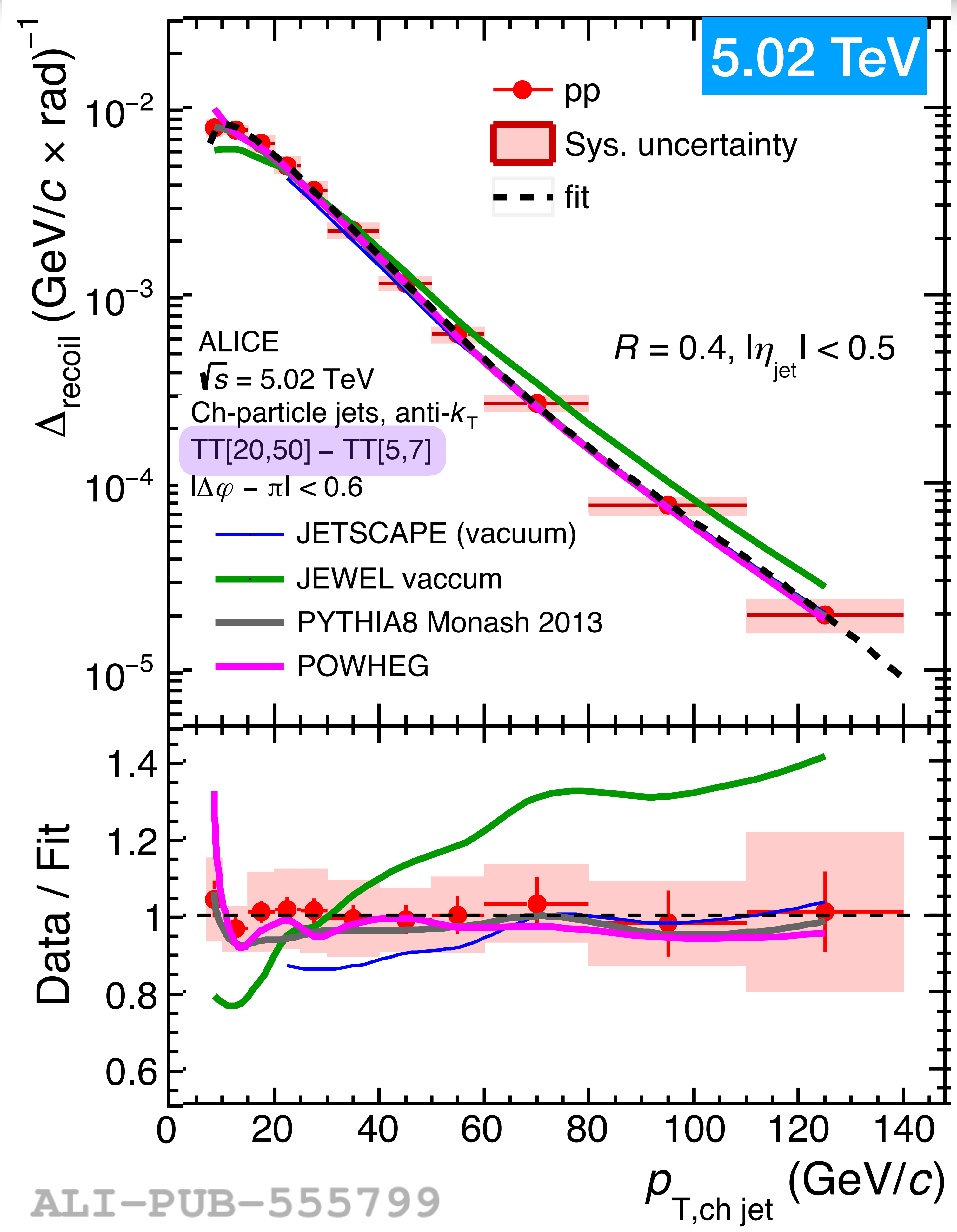
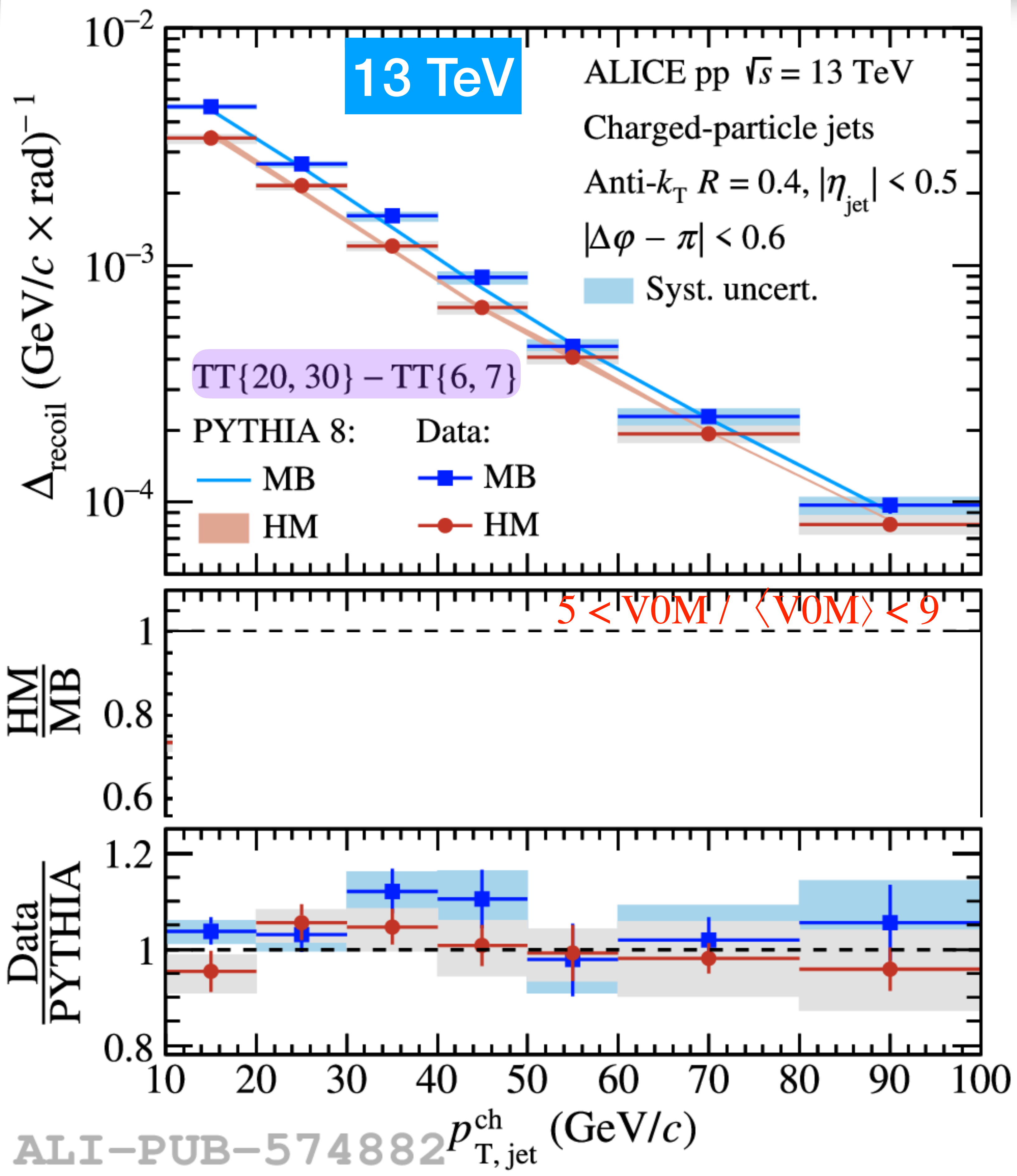
(except pp 13 TeV, $\mathrm{TT_S}$ [20,30], $\mathrm{TT_R}$: [6,7])

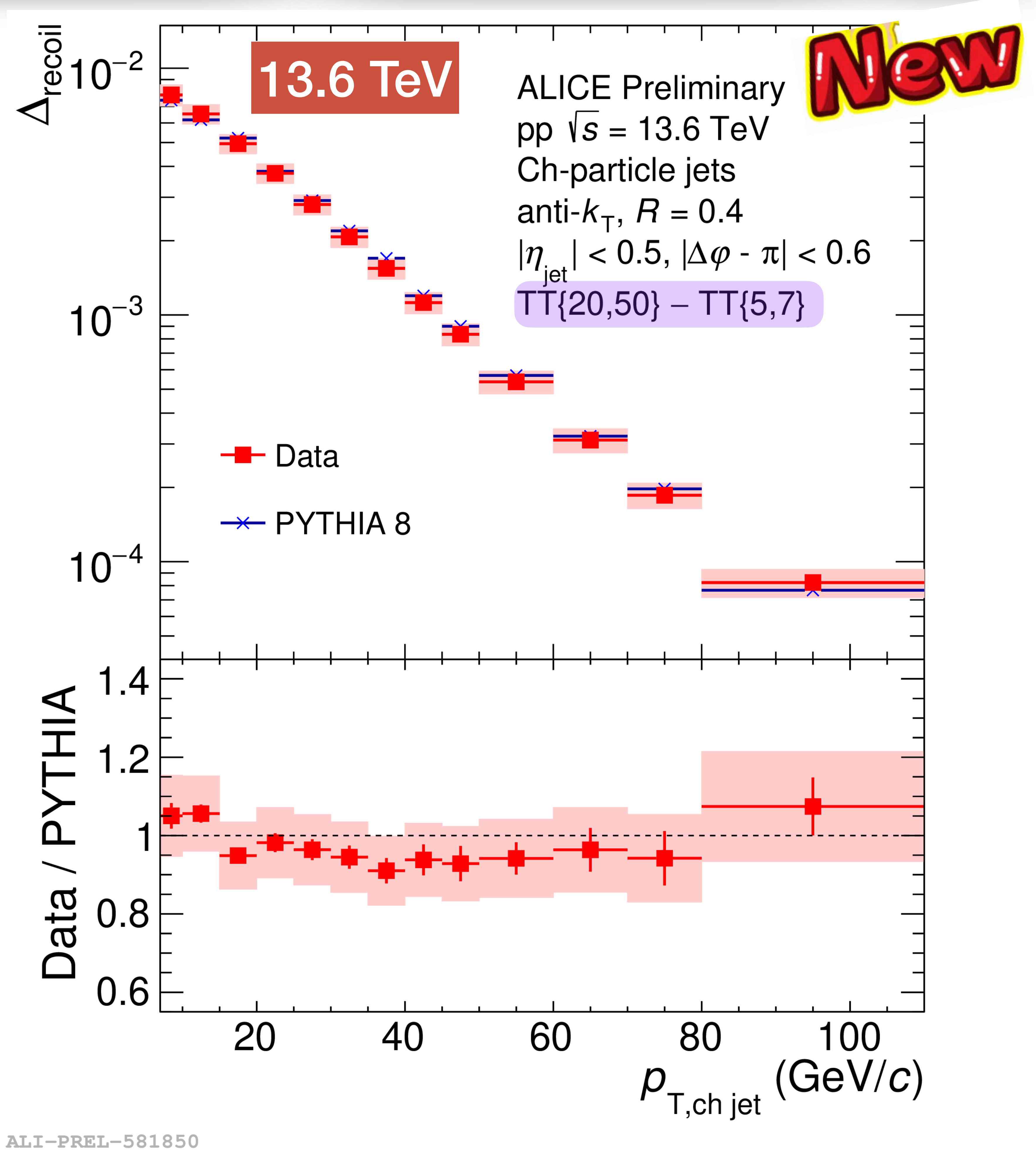
- Observables defined as **the difference** between trigger-normalised recoil jet yields in **two trigger track intervals** to **remove uncorrelated combinational background**

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

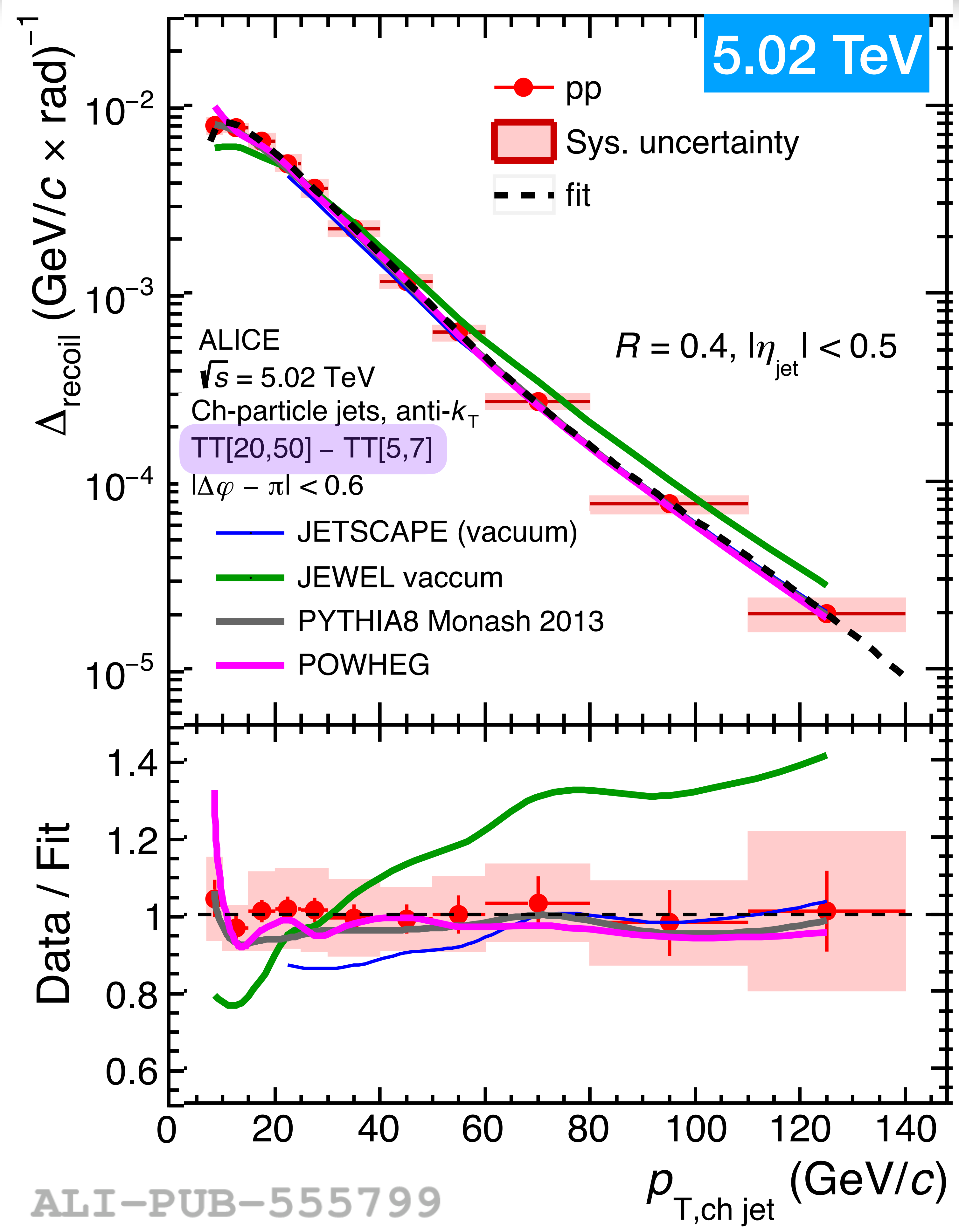
  - c_{Ref}: “alignment” constant extracted from data
  - Allow for precise measurements down to very **low** p_{T} and **large** $\boldsymbol{R}$

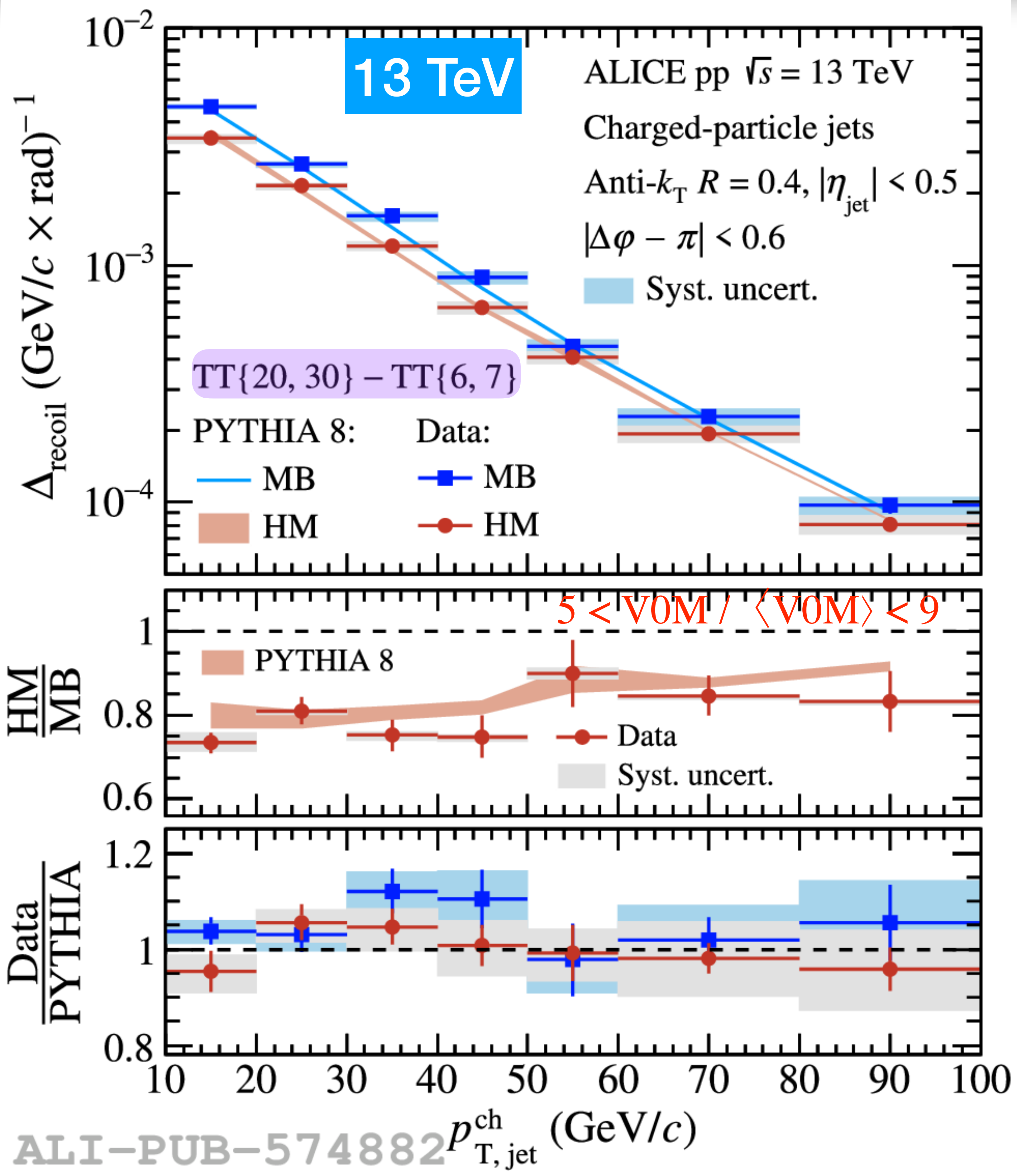


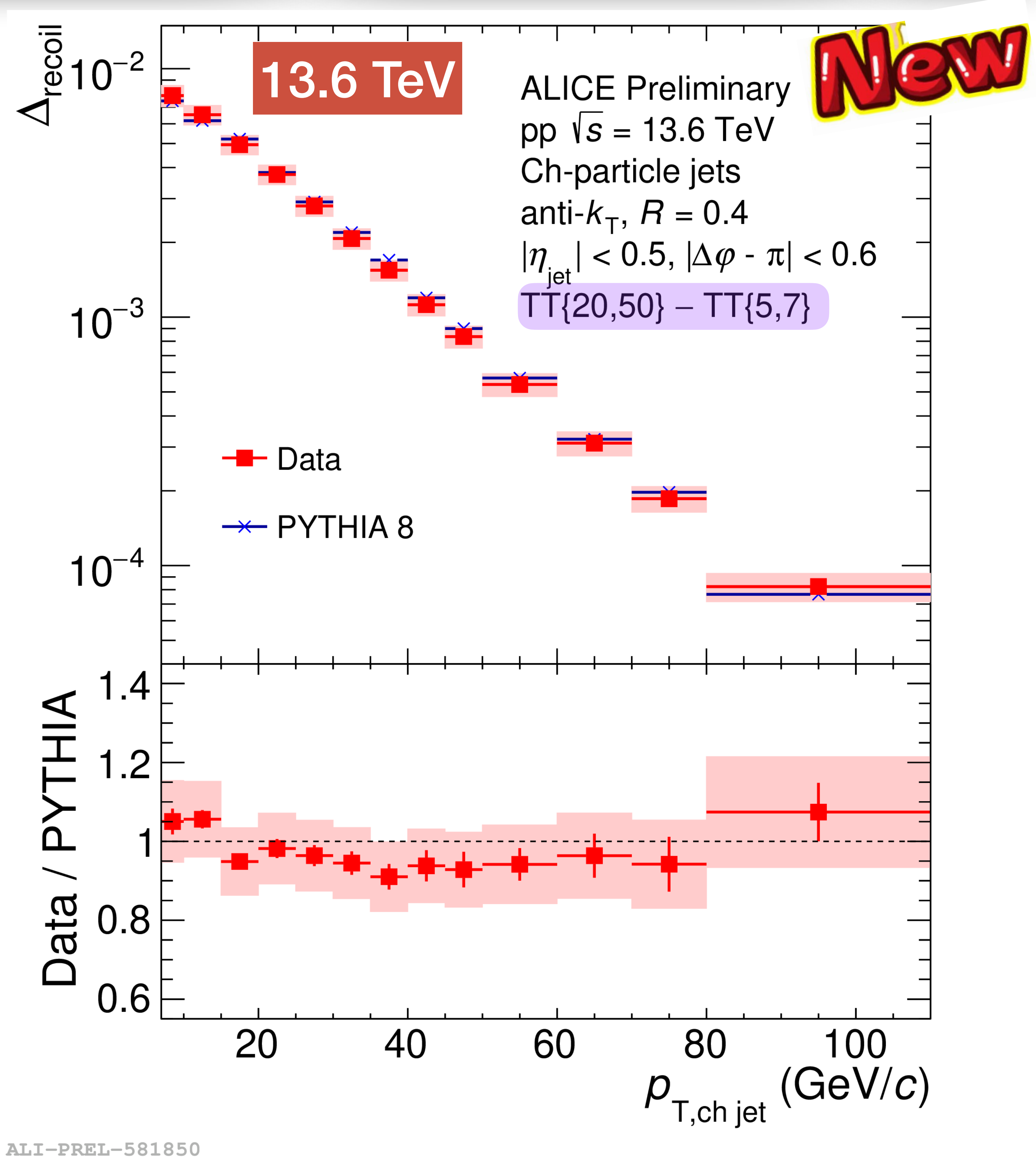




- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for $R = 0.4$ in pp collisions at 5.02, 13, 13.6 TeV
- All model calculations, except JEWEL, reproduce the ALICE data within uncertainties







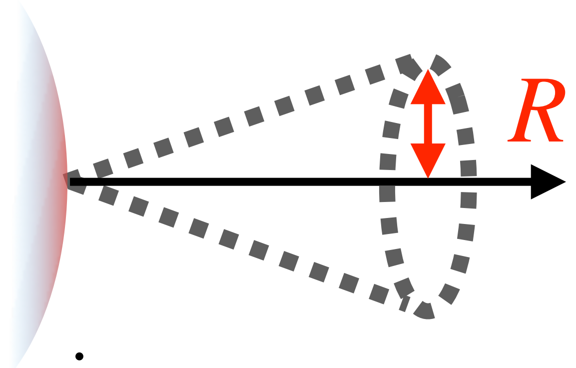
- Fully-corrected $\Delta_{recoil}(p_T)$ distributions for $R = 0.4$ in pp collisions at 5.02, 13, 13.6 TeV
- All model calculations, except JEWEL, reproduce the ALICE data within uncertainties
- **A yield suppression in the HM** collisions with respect to MB events → **independent of** p_T

Yongzhen HOU
yongzhen.hou@cern.ch

- $\Delta_{recoil}(p_T)$ 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!

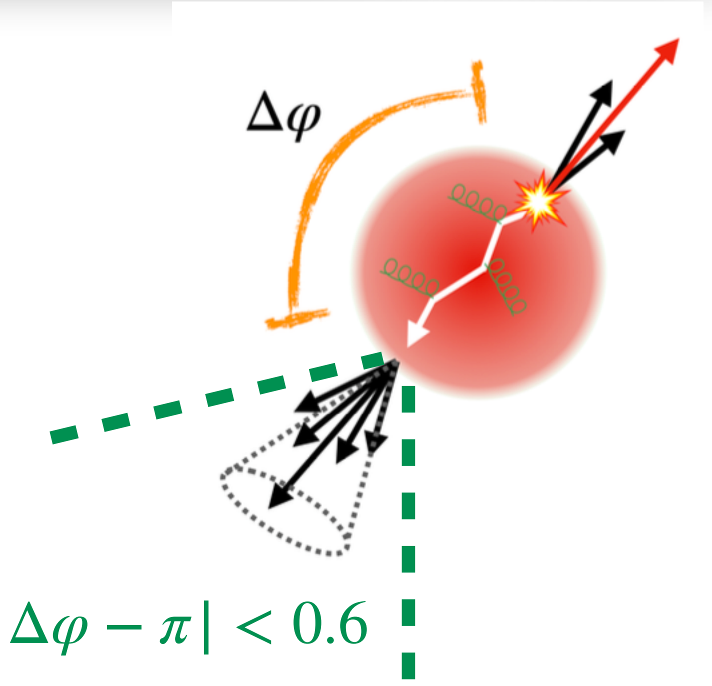
Yongzhen HOU
yongzhen.hou@cern.ch

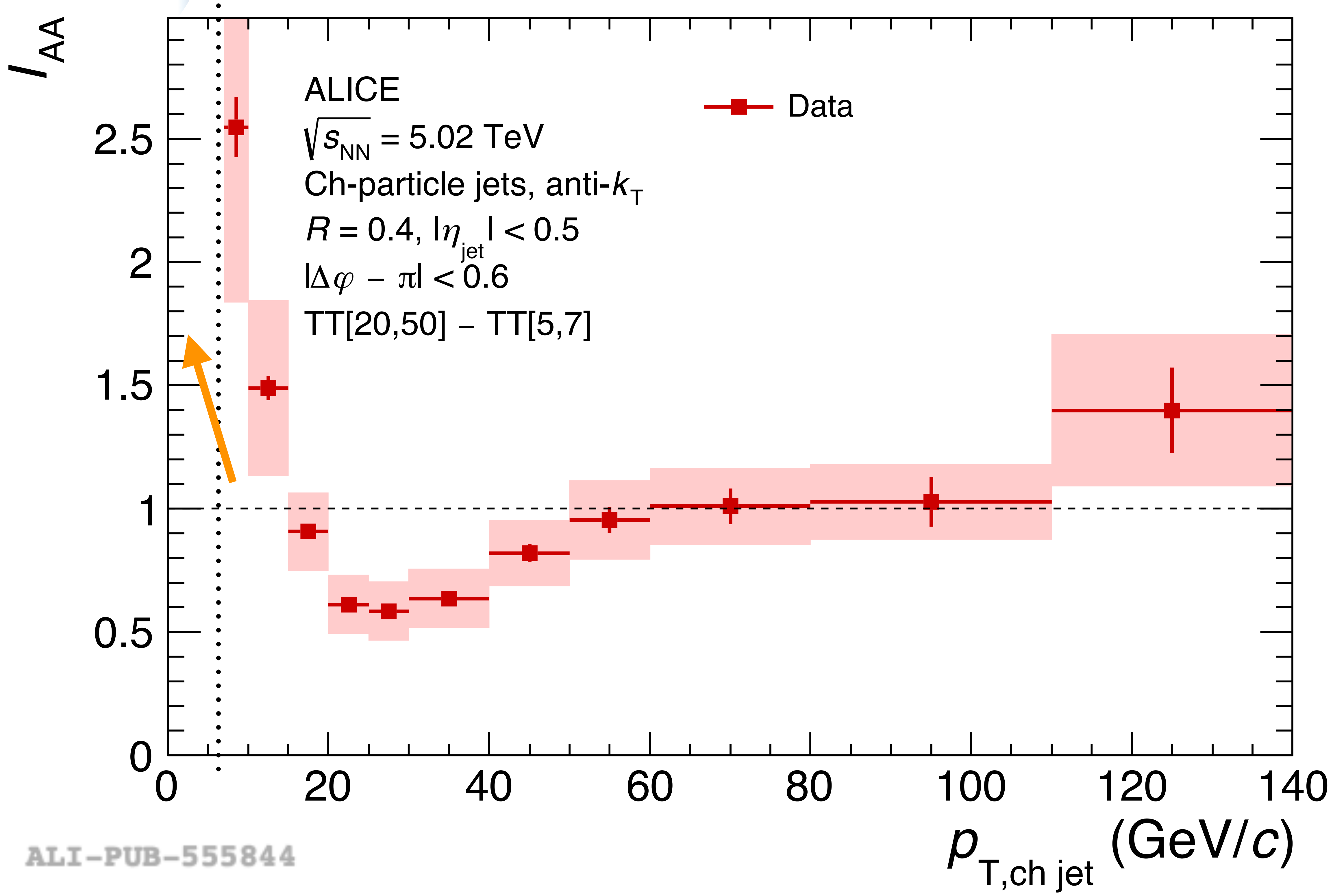


0 – 10 %

R = 0.4

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

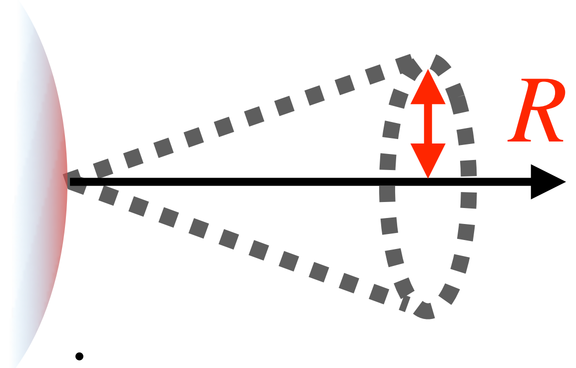




- **Jet yield enhancement** at low p_T

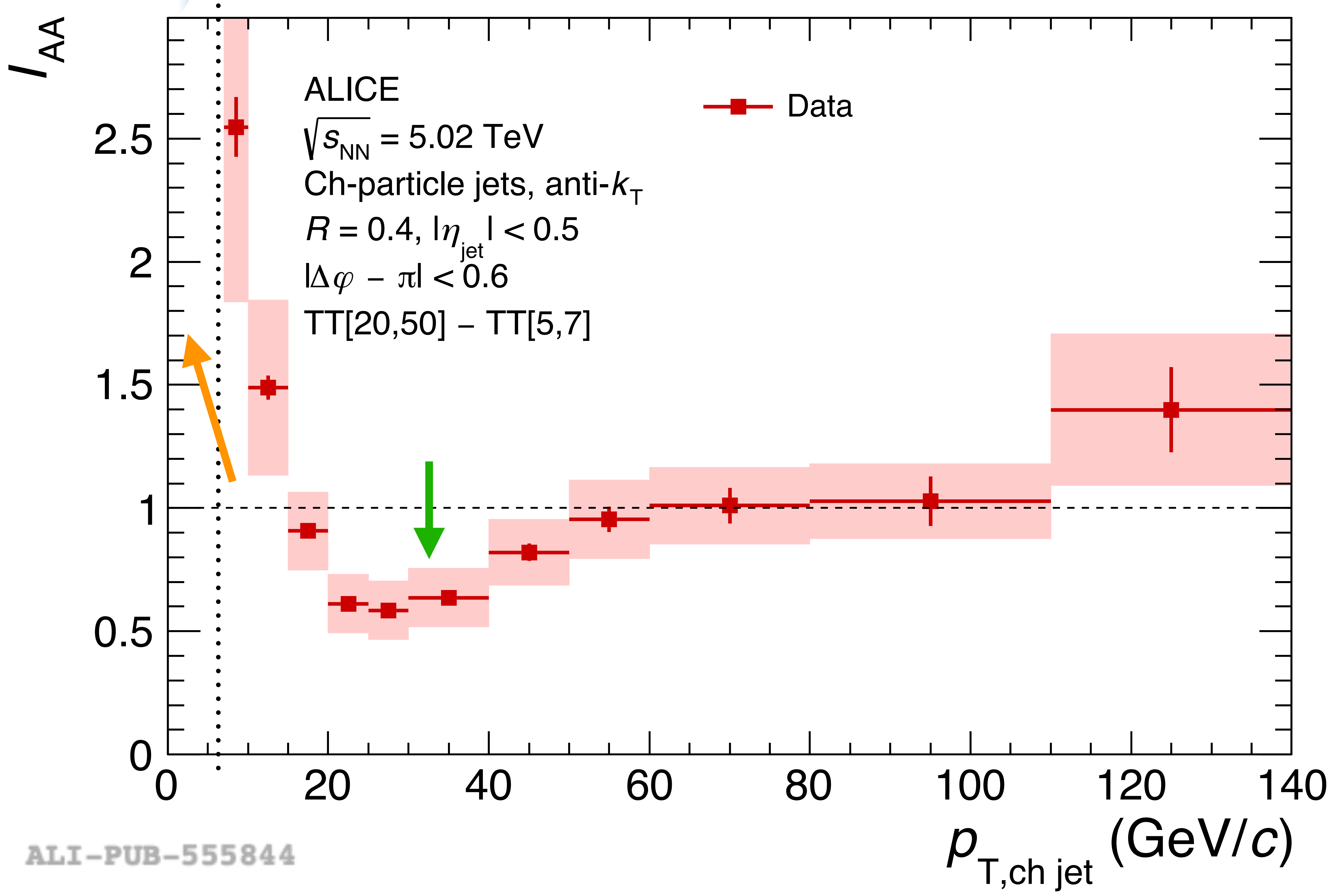
  → hint of energy recovery in low p_T jets?

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

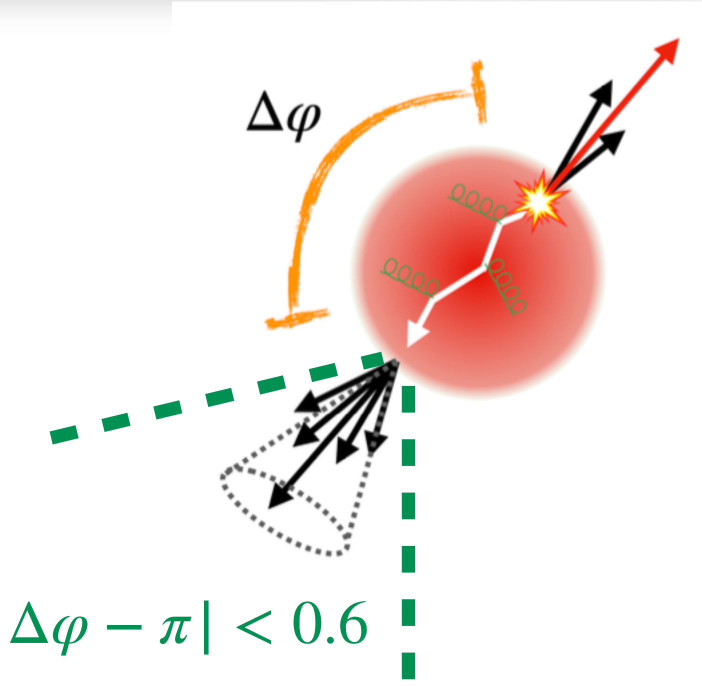


0 – 10 %

R = 0.4



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



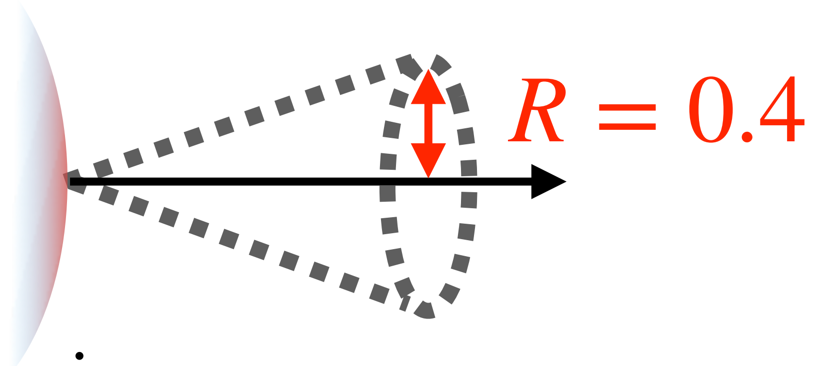
- **Jet yield enhancement** at low p_T

  → hint of energy recovery in low p_T jets?

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

  → Jet energy loss

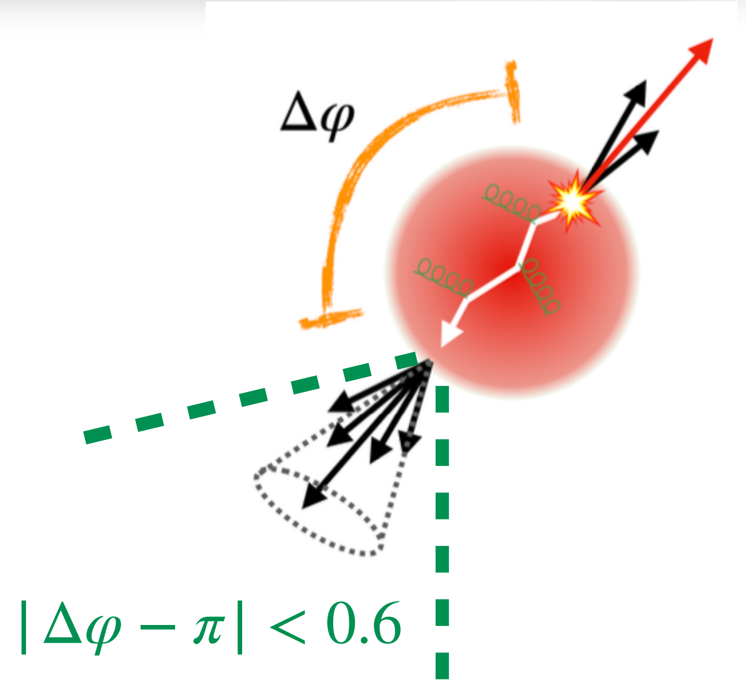
Yongzhen HOU
yongzhen.hou@cern.ch

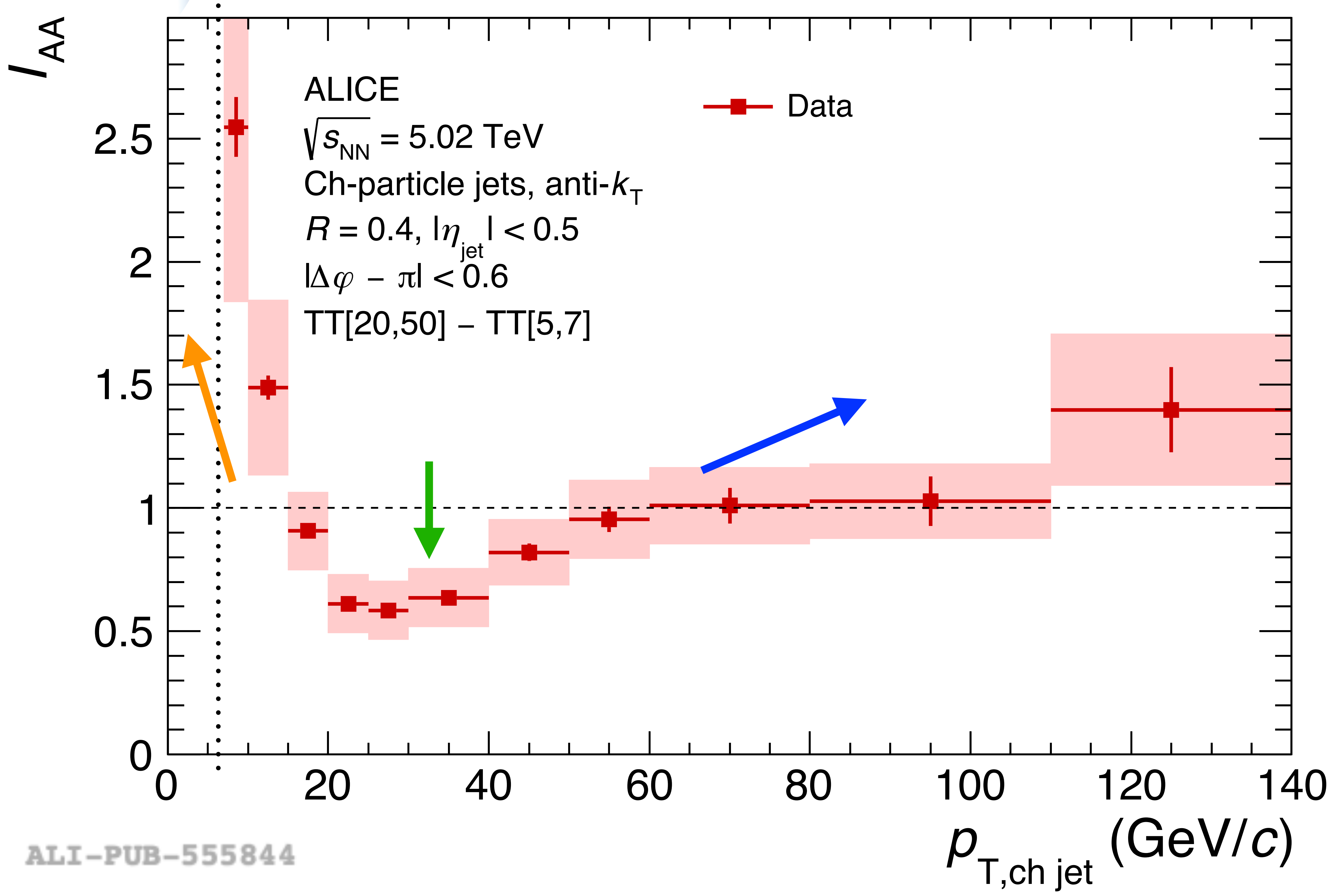


0 – 10 %

R = 0.4

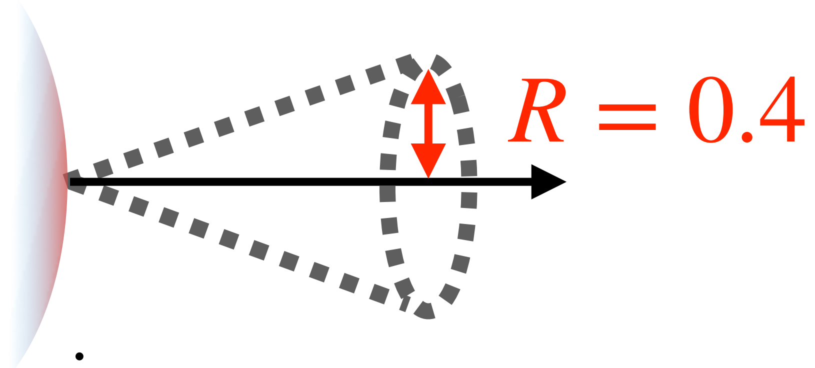
$$I_{AA} \equiv \frac{\Delta_{recoil}\,(p_T)_{AA}}{\Delta_{recoil}\,(p_T)_{pp}}$$





- **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?

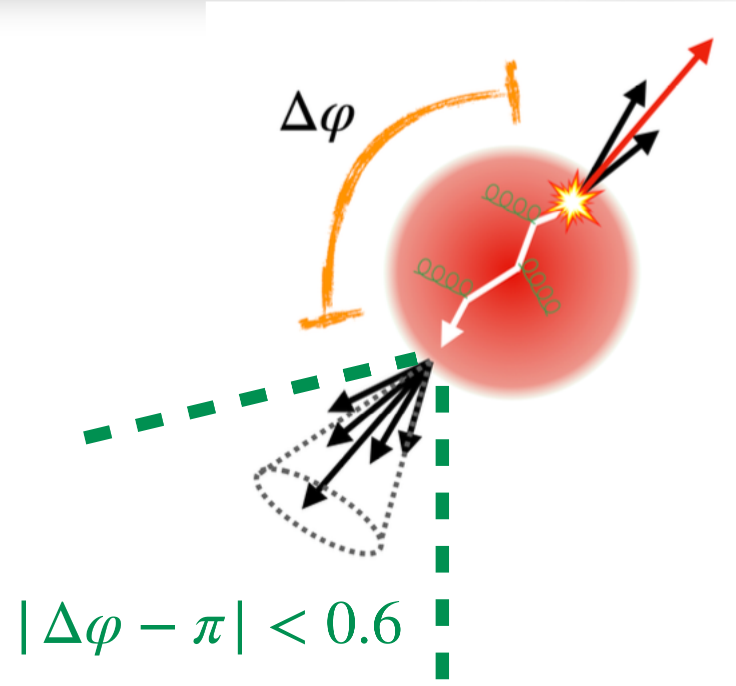
Phys.Lett.B 854 (2024) 138739

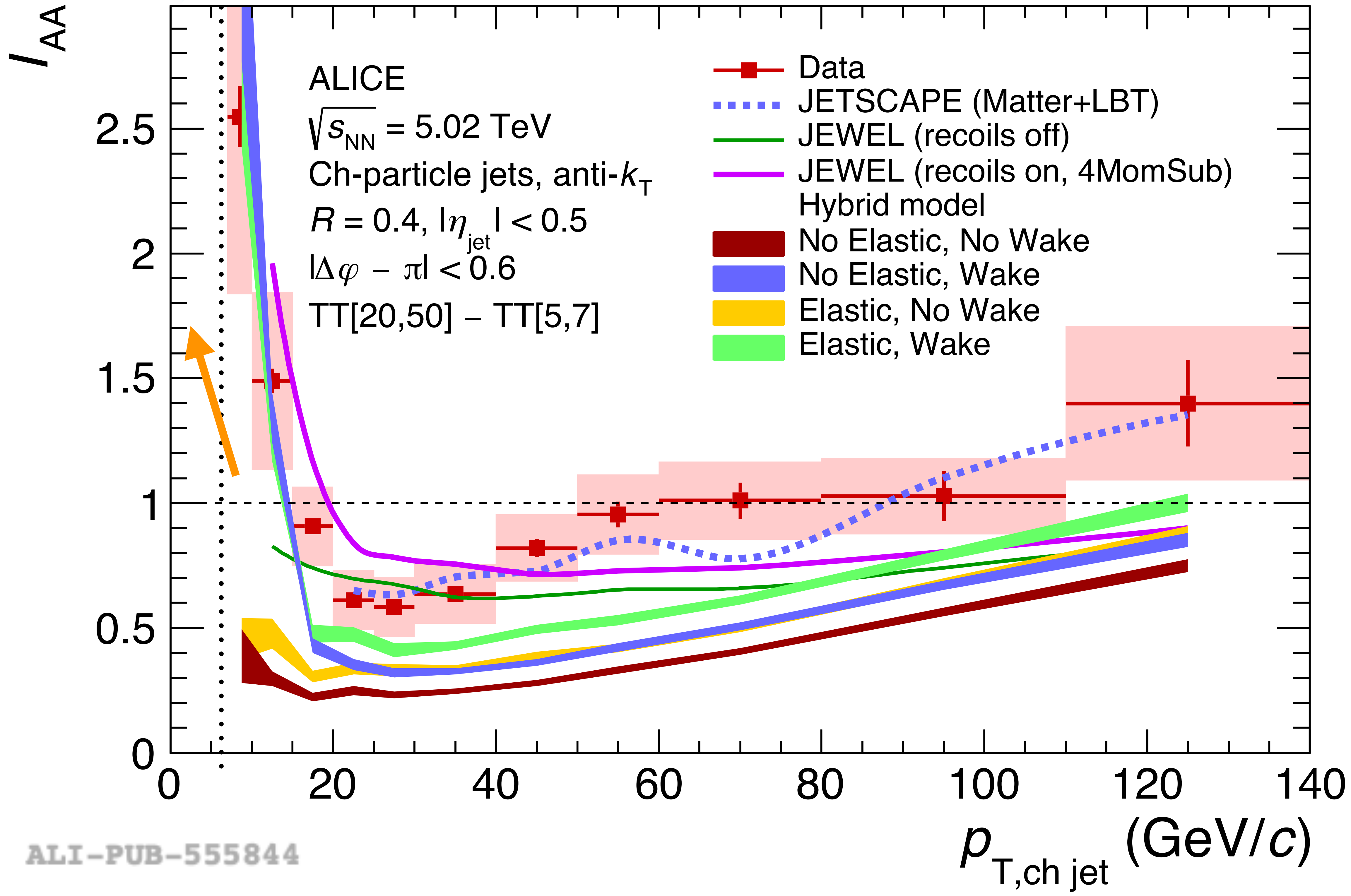


0 – 10 %

R = 0.4

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



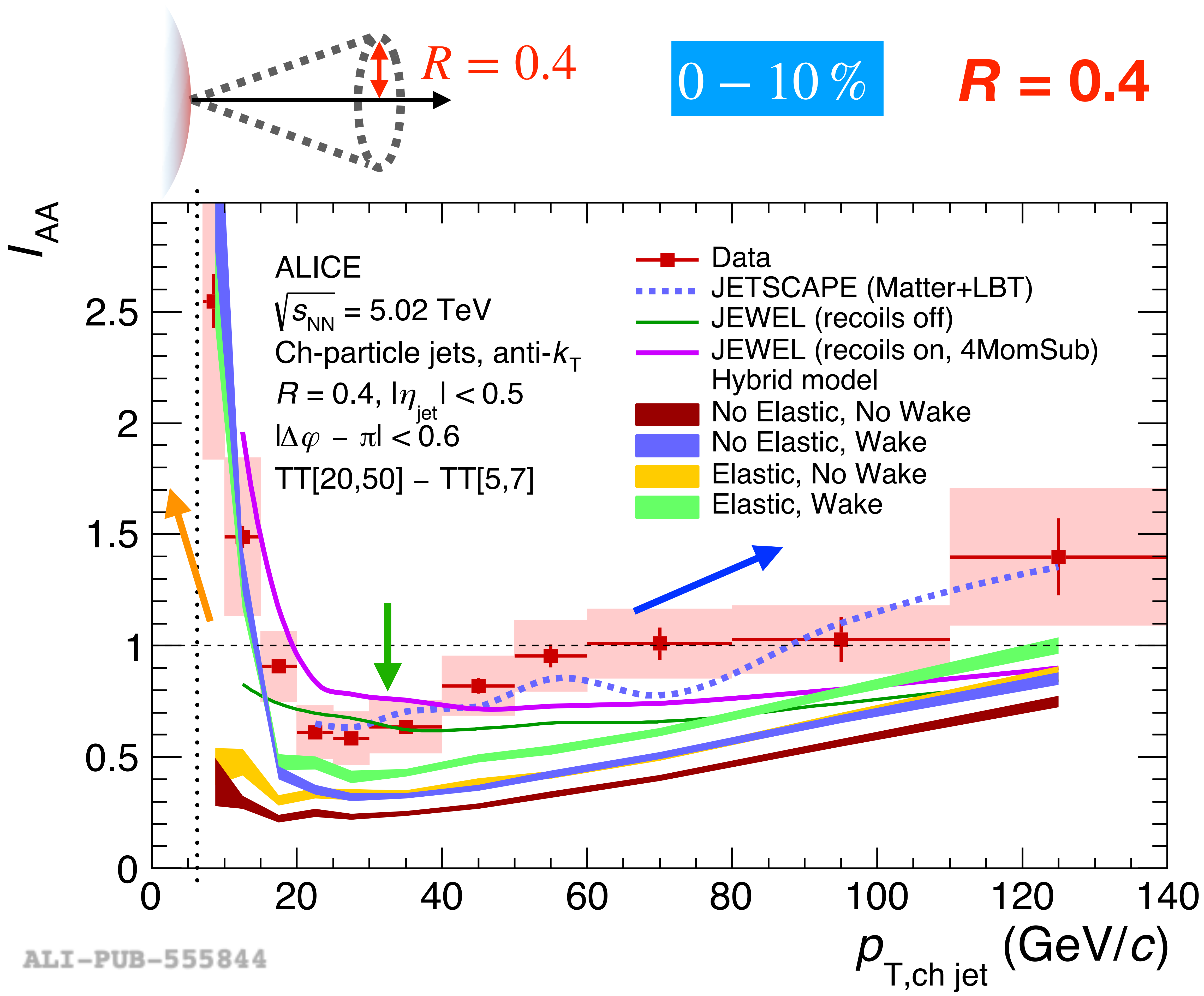


JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss based on MATTER (high virtuality) + LBT (low virtuality)

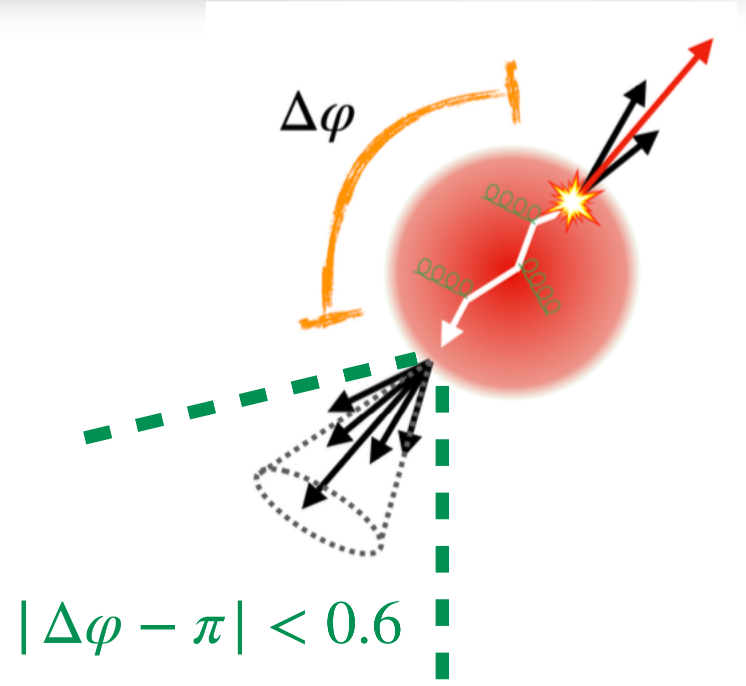
JEWEL: perturbative treatment to jet quenching
arXiv:1311.0048, https://jewel.hepforge.org/
Includes collisional and radiative parton energy loss mechanisms in a pQCD approach. medium response effects via the treatment of 'recoils'

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.

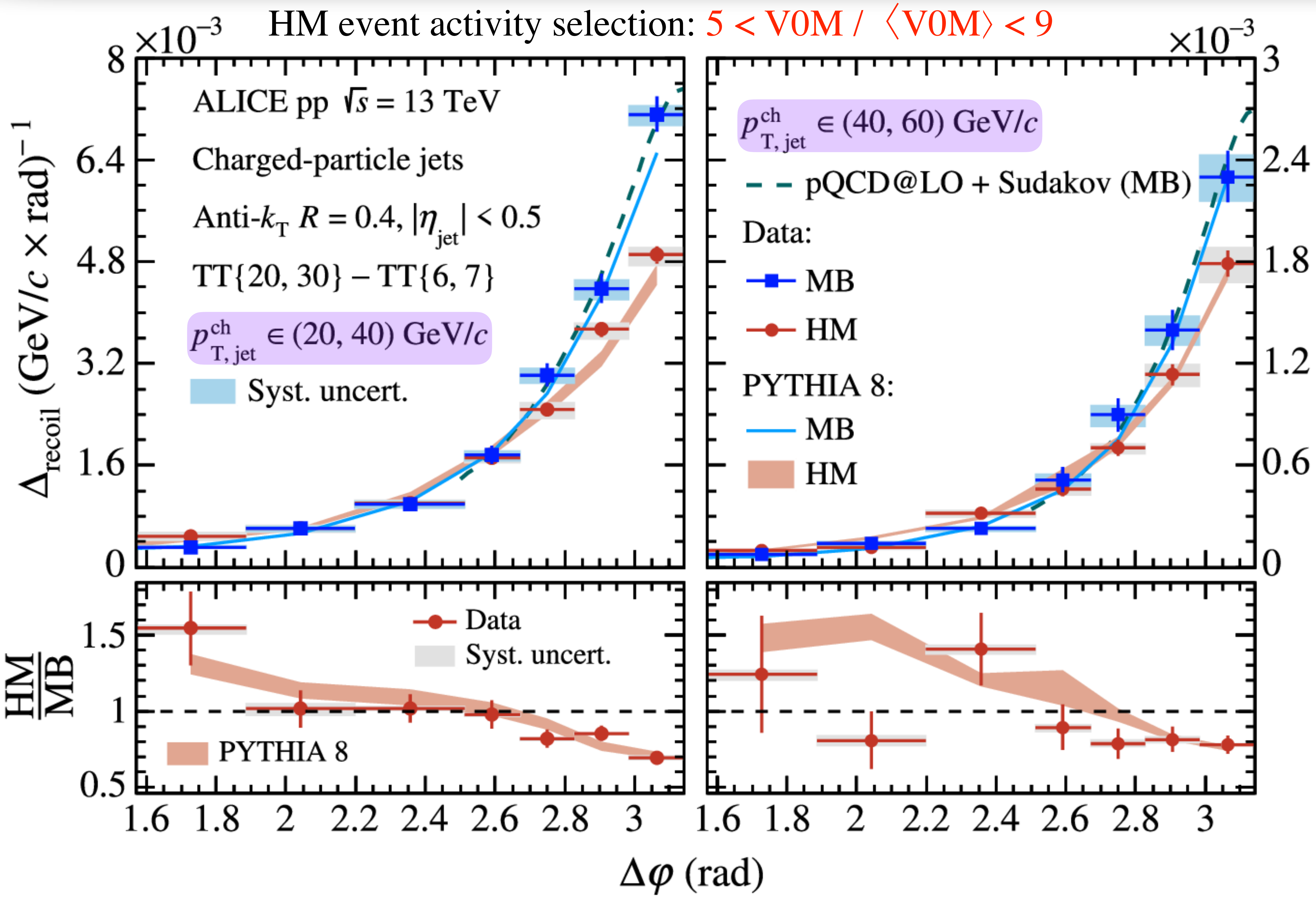
Yongzhen HOU
yongzhen.hou@cern.ch



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



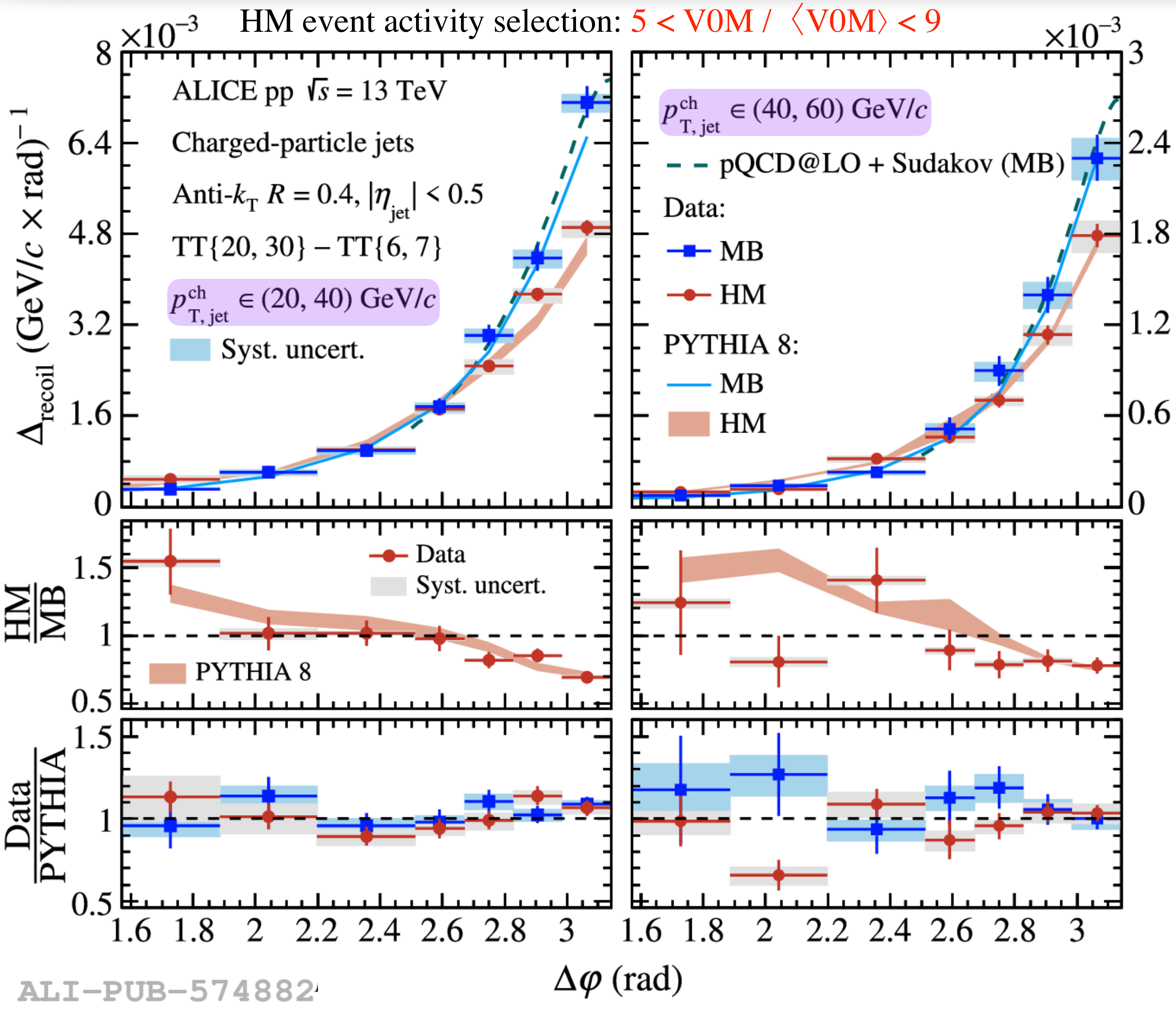
- The **rising trend** is qualitatively described by all predictions
  - **JETSCAPE largely reproduces** the I_{AA} distributions
  - **Hybrid Model** and **JEWEL** predictions **overestimate the suppression** at high p_T
- **Hybrid Models** with wake effect and **JEWEL with recoils on** seem to catch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



- **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?

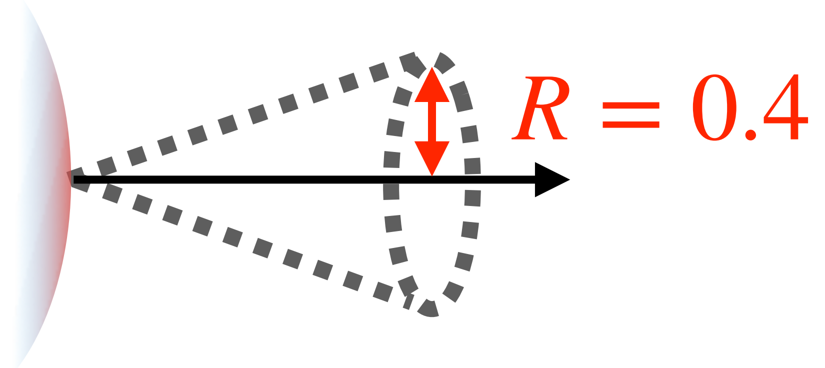
Δ_{recoil} ($\Delta\varphi$) distributions in pp at 13 TeV: $R = 0.4$

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?

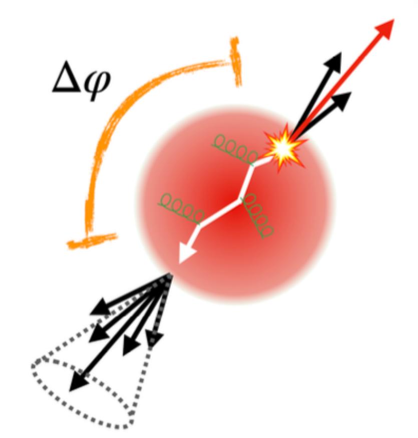
- Quantitative comparison to PYTHIA 8 Monash (does not account for jet quenching effects) shows similar suppression pattern
  - Indicate the effect is not from the jet-medium interaction
  - Use PYTHIA to explore the origin of the effect → **HM event selection bias**

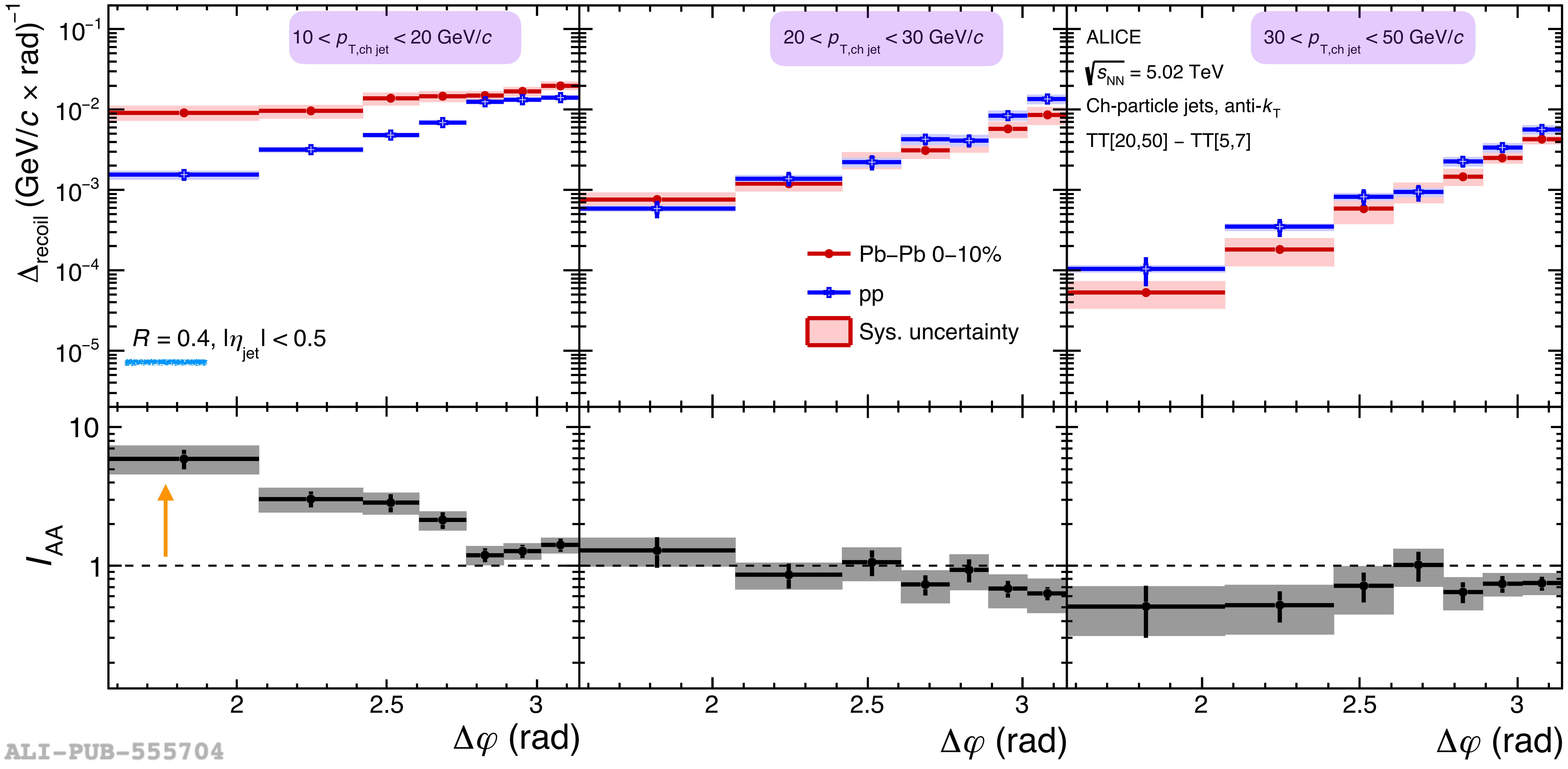


0 – 10 %

R = 0.4

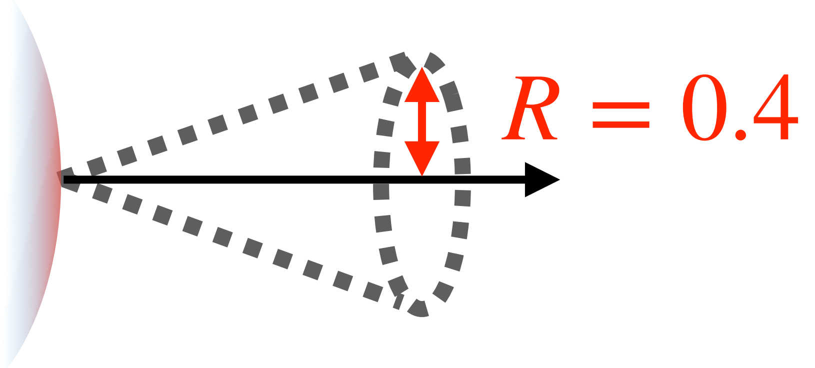
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$





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

Yongzhen HOU
yongzhen.hou@cern.ch



0 – 10 %

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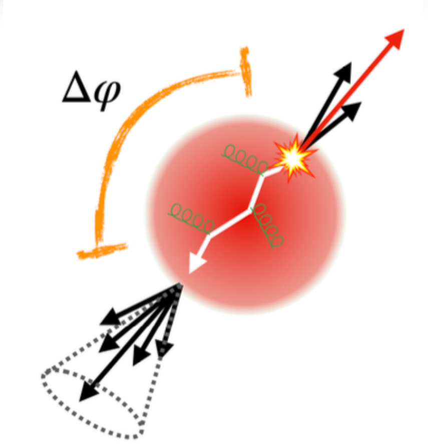
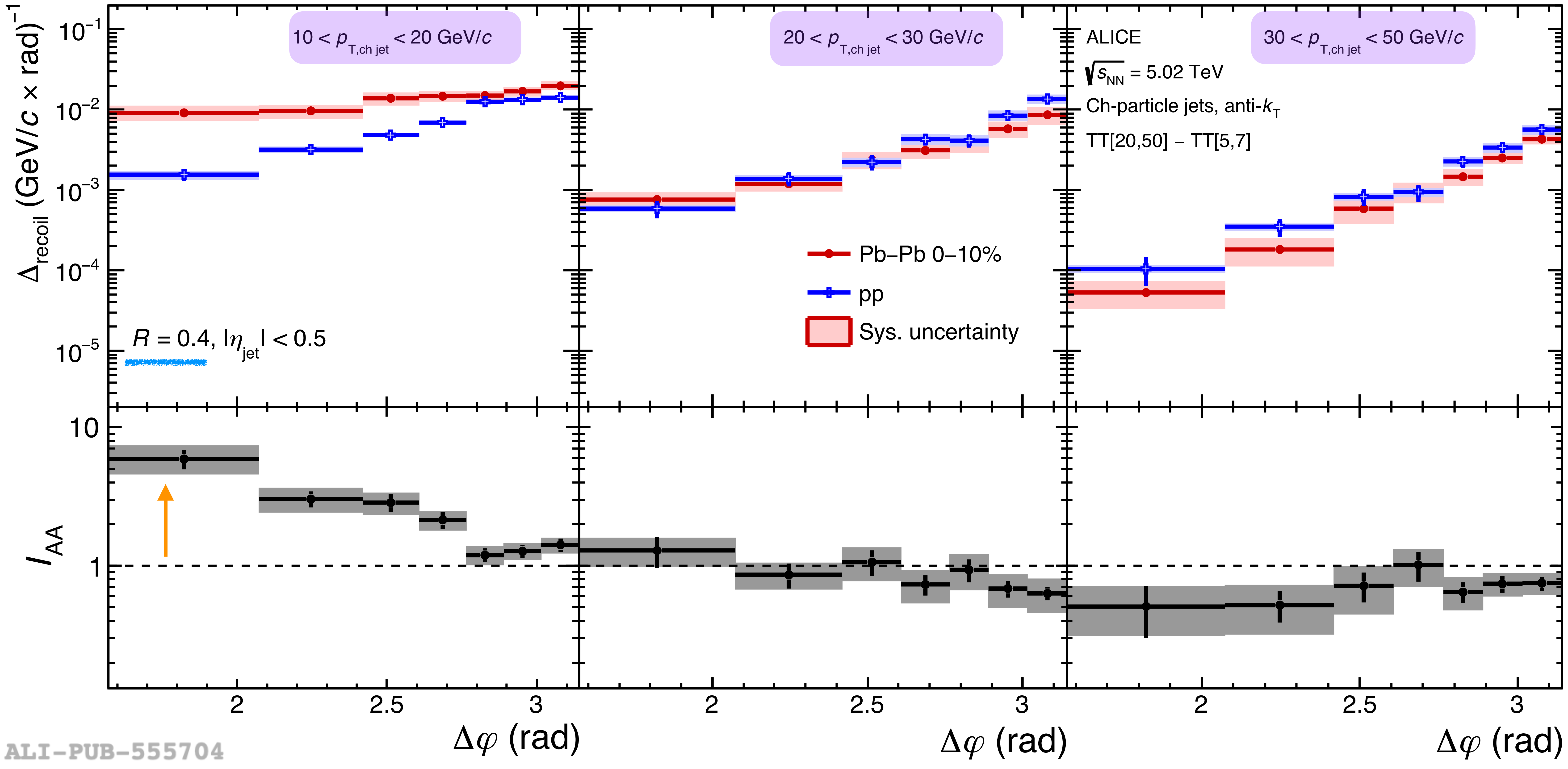
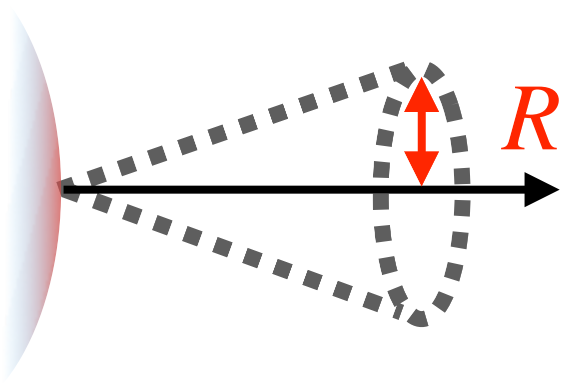
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$





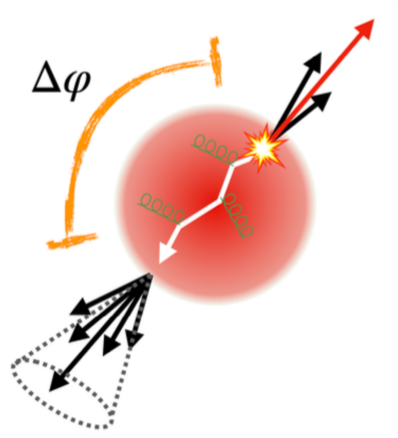
- **Significant broadening** for $p_T \in [10,20]$ GeV/c
- **No broadening or suppression** for $p_T \in [20,30]$ GeV/c

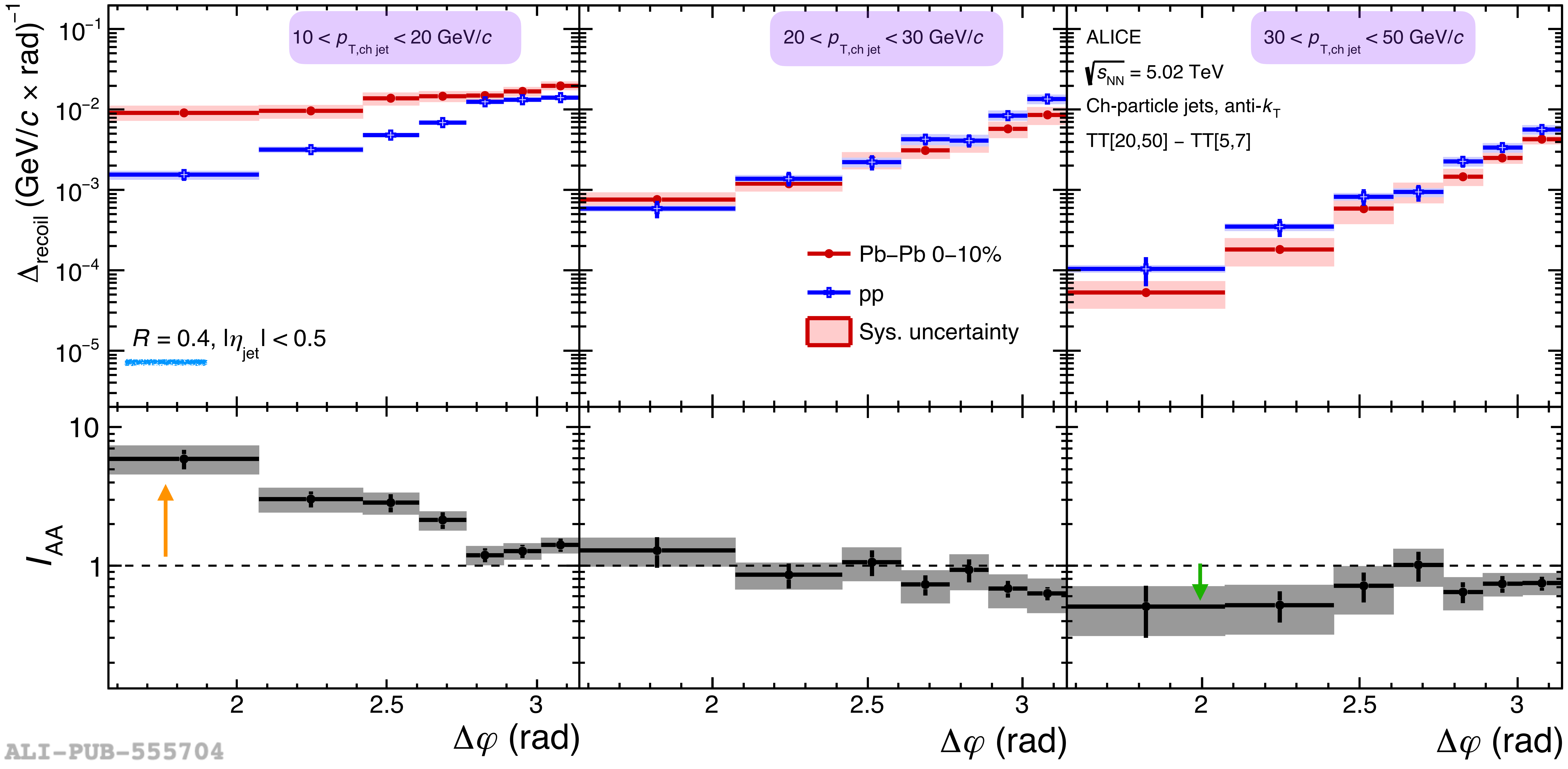
Yongzhen HOU
yongzhen.hou@cern.ch



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

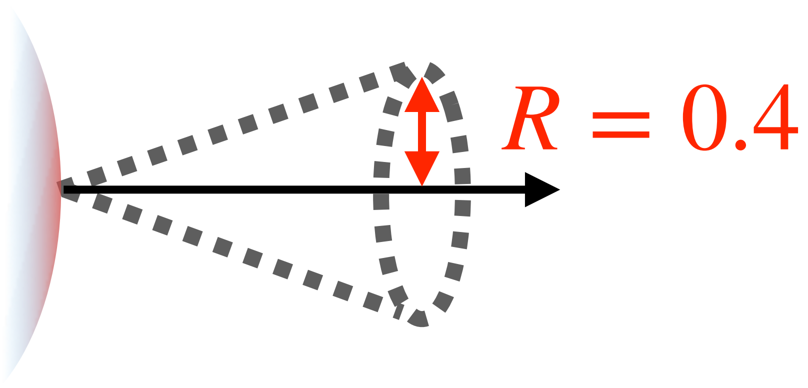
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$





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

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



0 – 10 %

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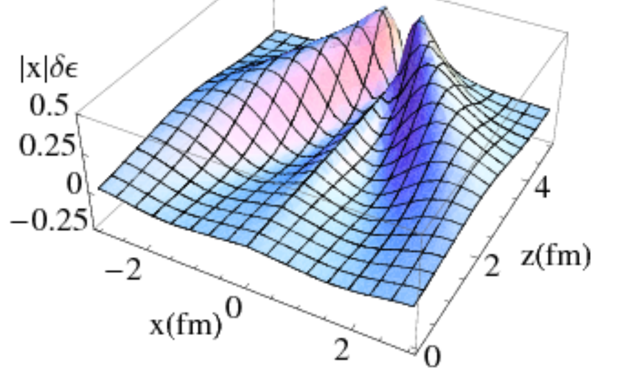
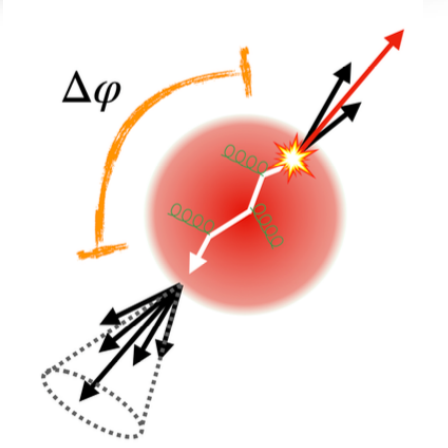
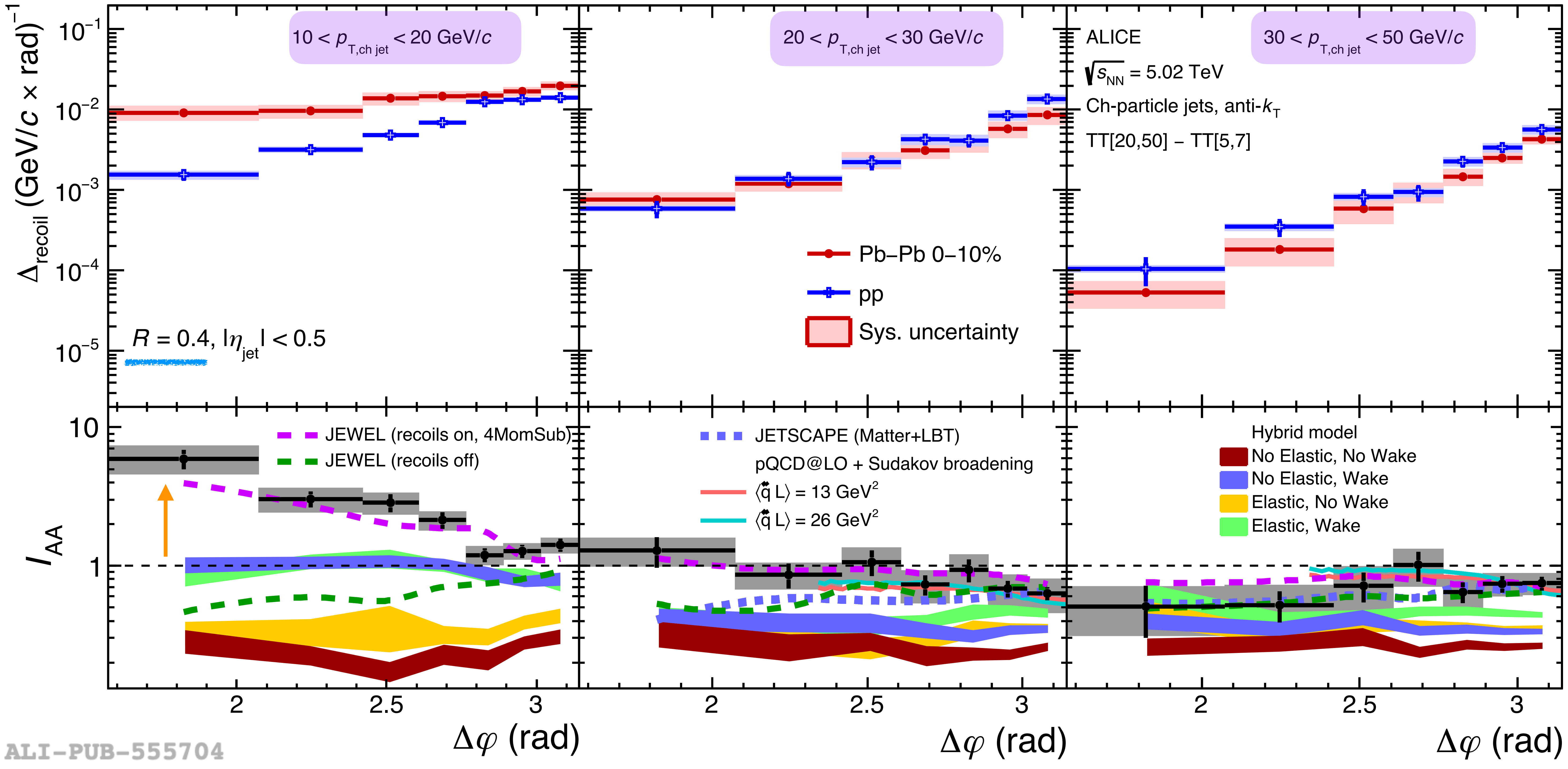
Phys. Rev. Lett. 103, 152303







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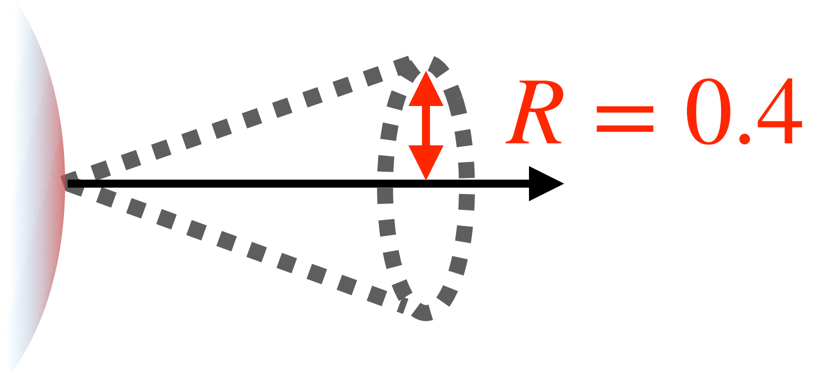
JHEP 02 (2022) 175, JHEP01(2019)172
With/without elastic energy loss (i.e 'Moliere' scattering)
medium response via with and without wake.

pQCD@LO + Sudakov broadening:
Phys.Lett.B 773 (2017) 672
Leading order pQCD, azimuthal broadening via jet transport coefficient

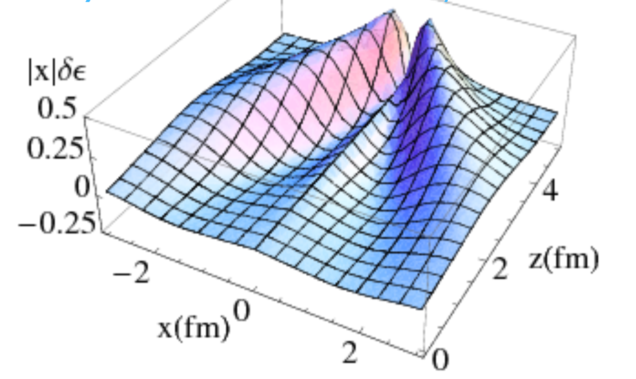


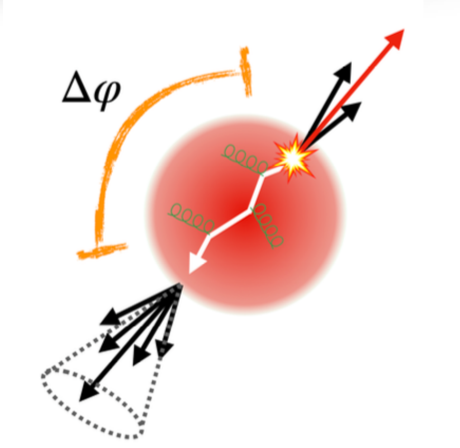
0 – 10 %

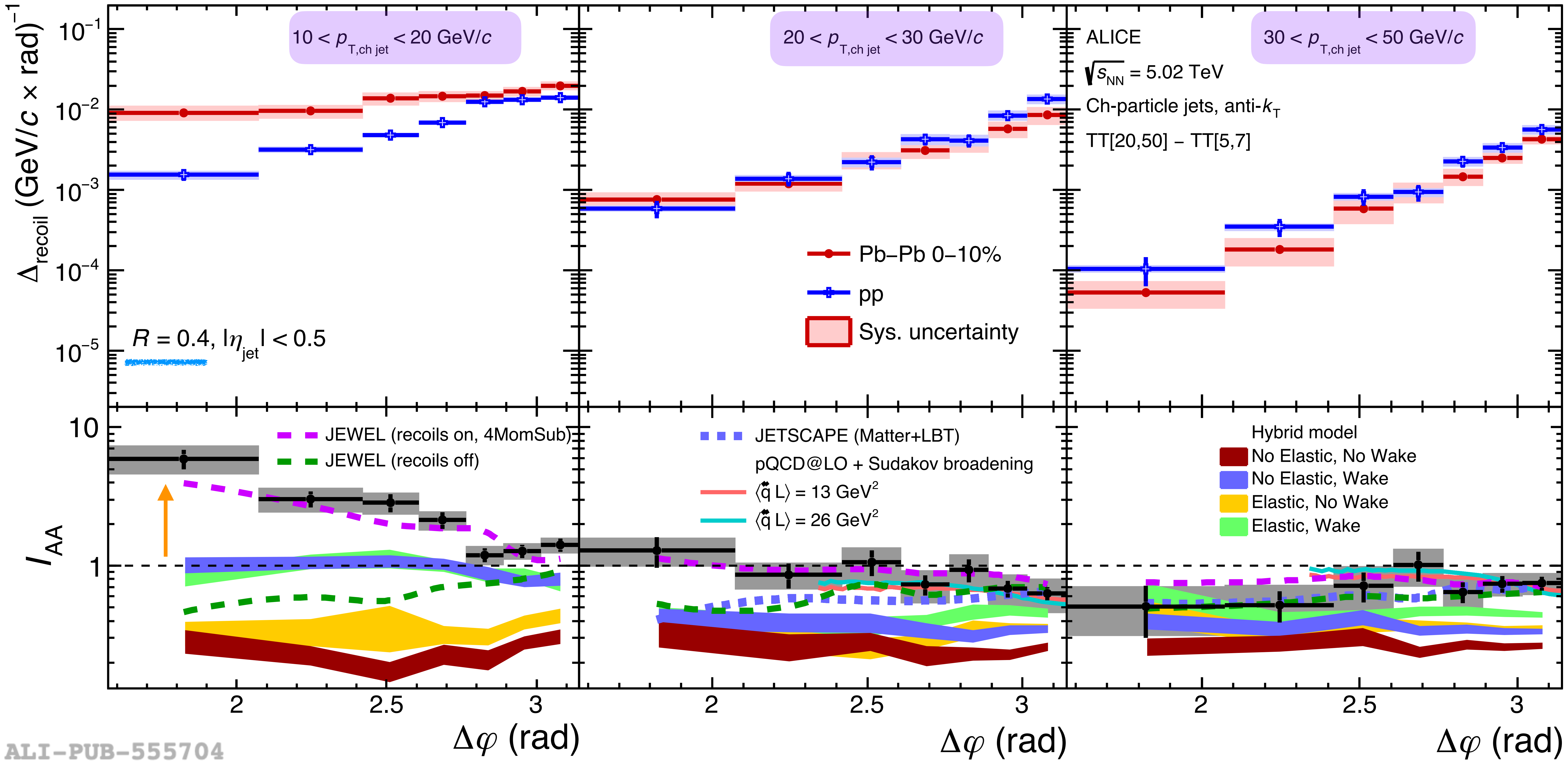
$R = 0.4$

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

Phys. Rev. Lett. 103, 152303

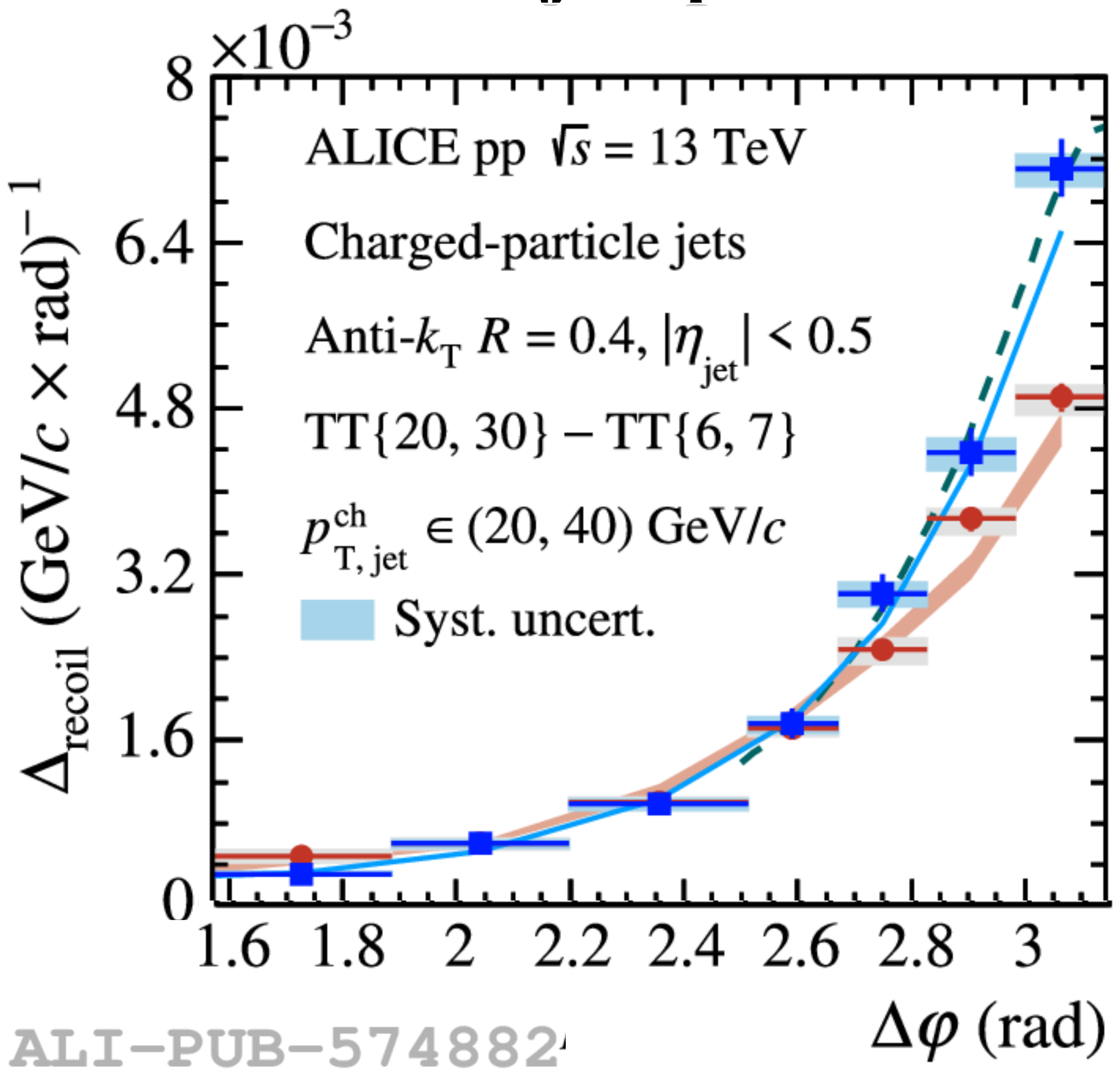


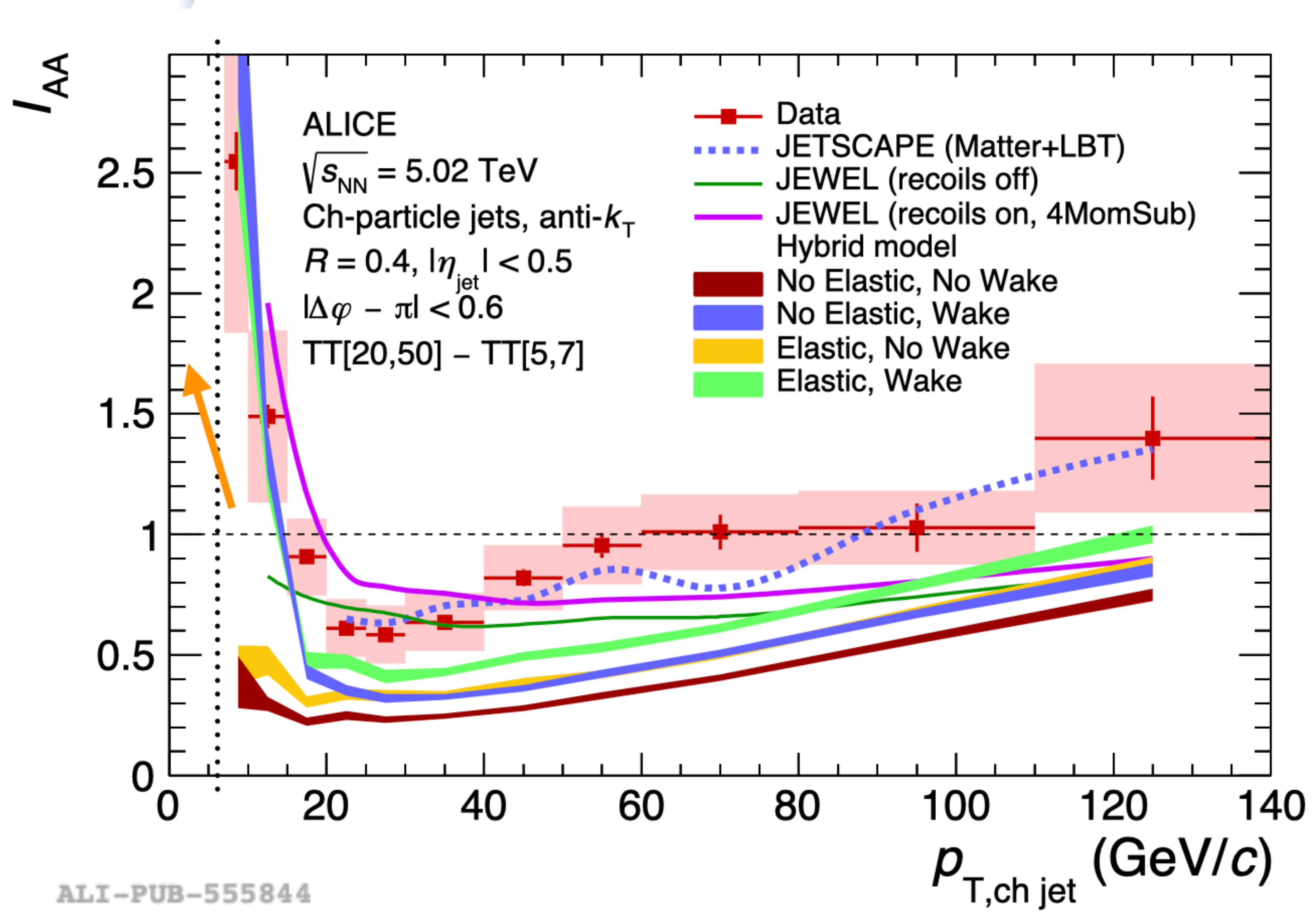


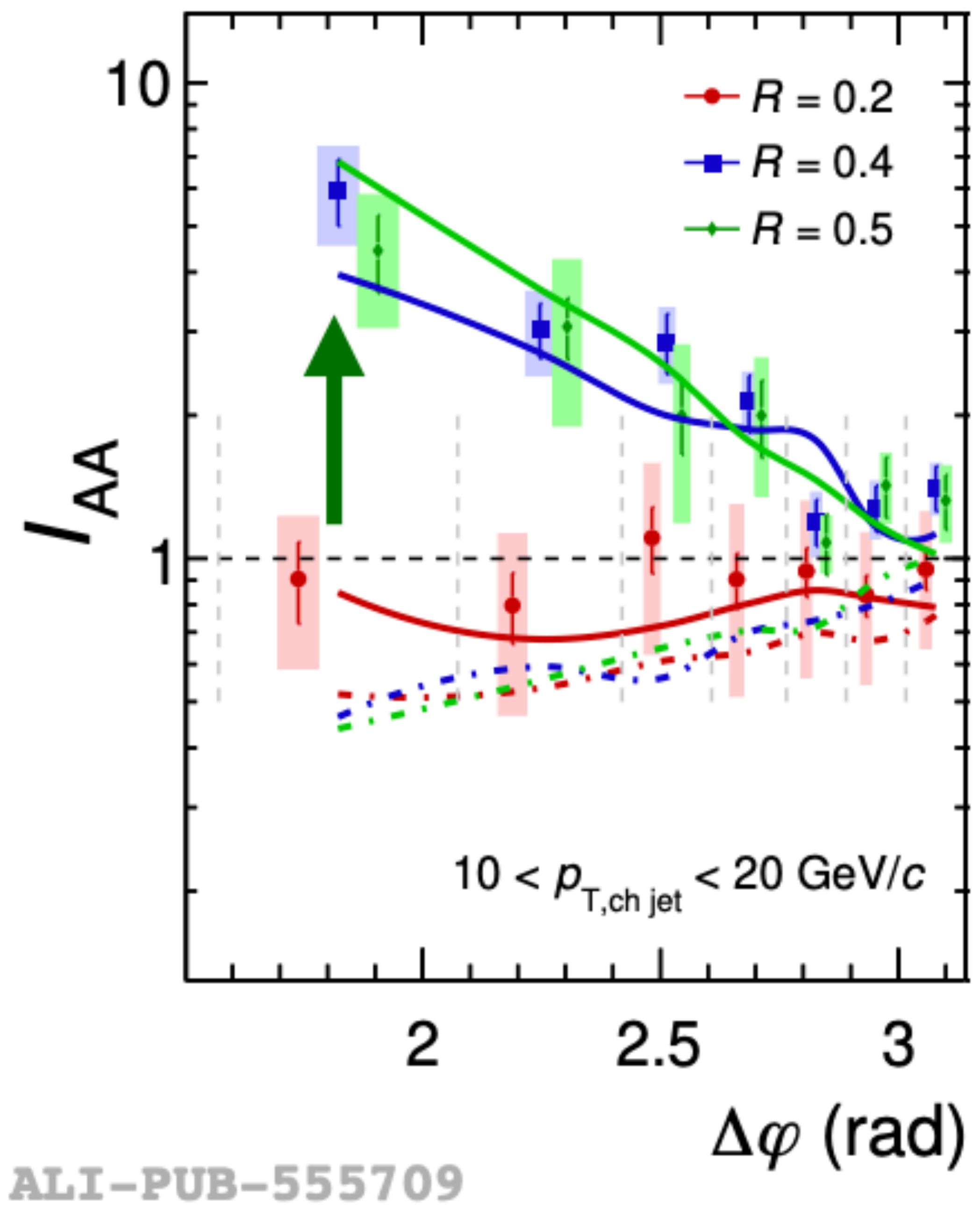


- **JETSCAPE** and **pQCD w/ broadening reasonably describe** the data for jet $p_T \in [20,50]$ GeV/c → lacking precision to resolve the difference between two $\hat{q}$ values
- **JEWEL** (recoils-on) **describes well the I_{AA} in-all p_T bins**
- **Hybrid model** captures the yield enhancement, but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

- **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**







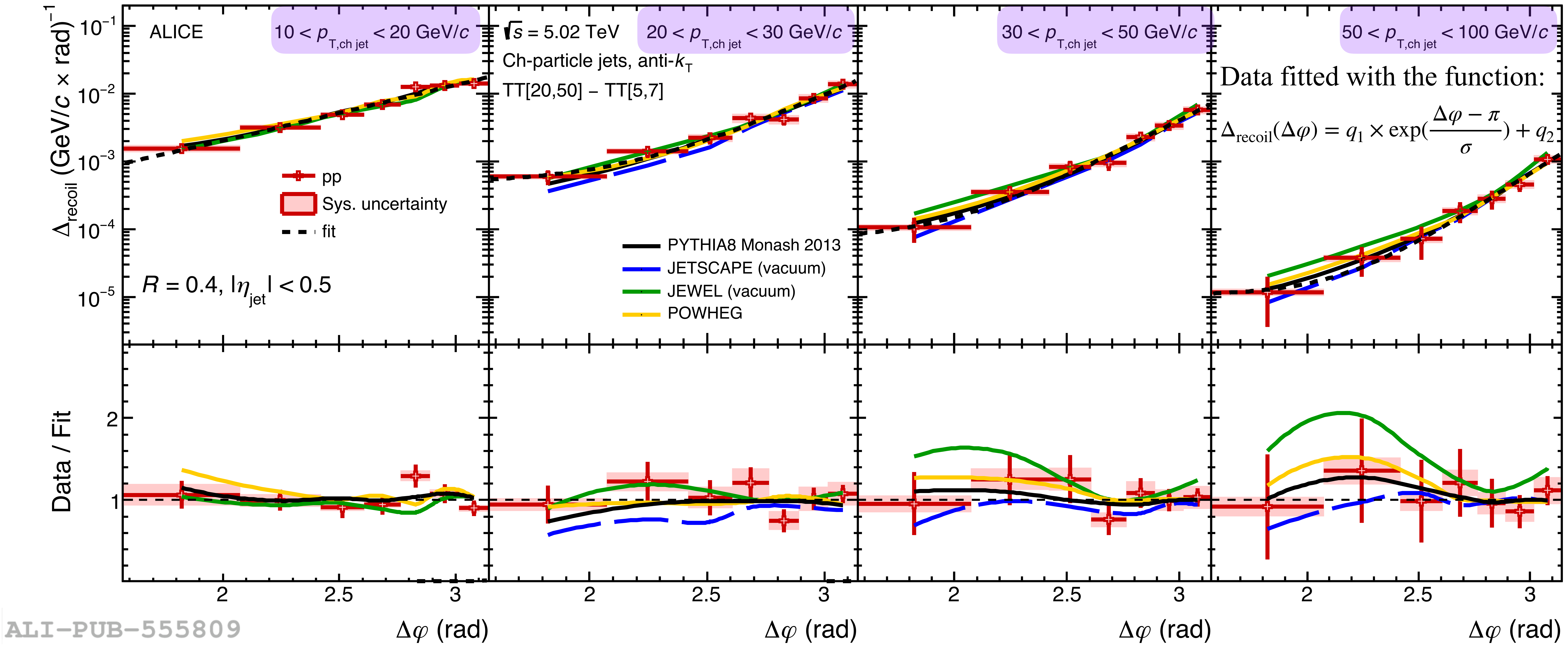
- *Looking forward to further studies with **Run 3** data with ALICE* ***~~ investigate recoil jet substructure including in Pb-Pb***

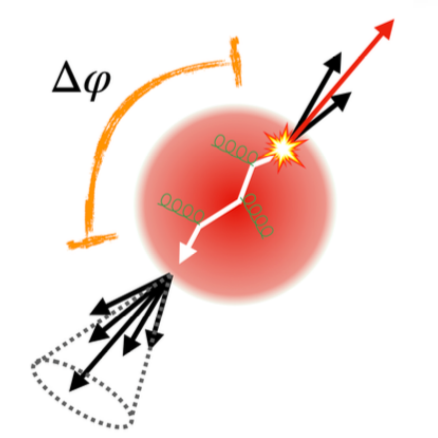
BACKUP

Yongzhen HOU
yongzhen.hou@cern.ch

Thanks for your listening and discussion

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

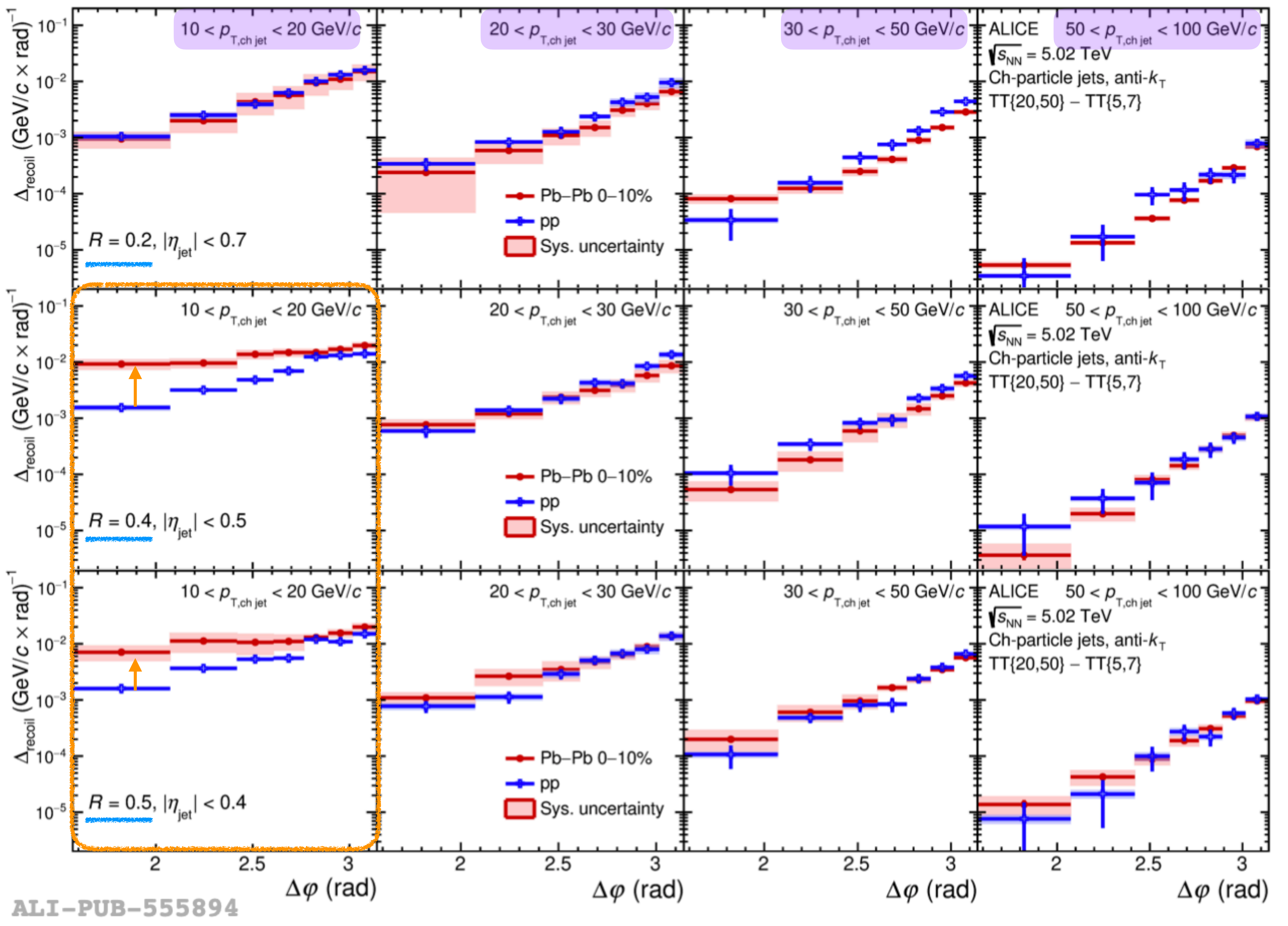


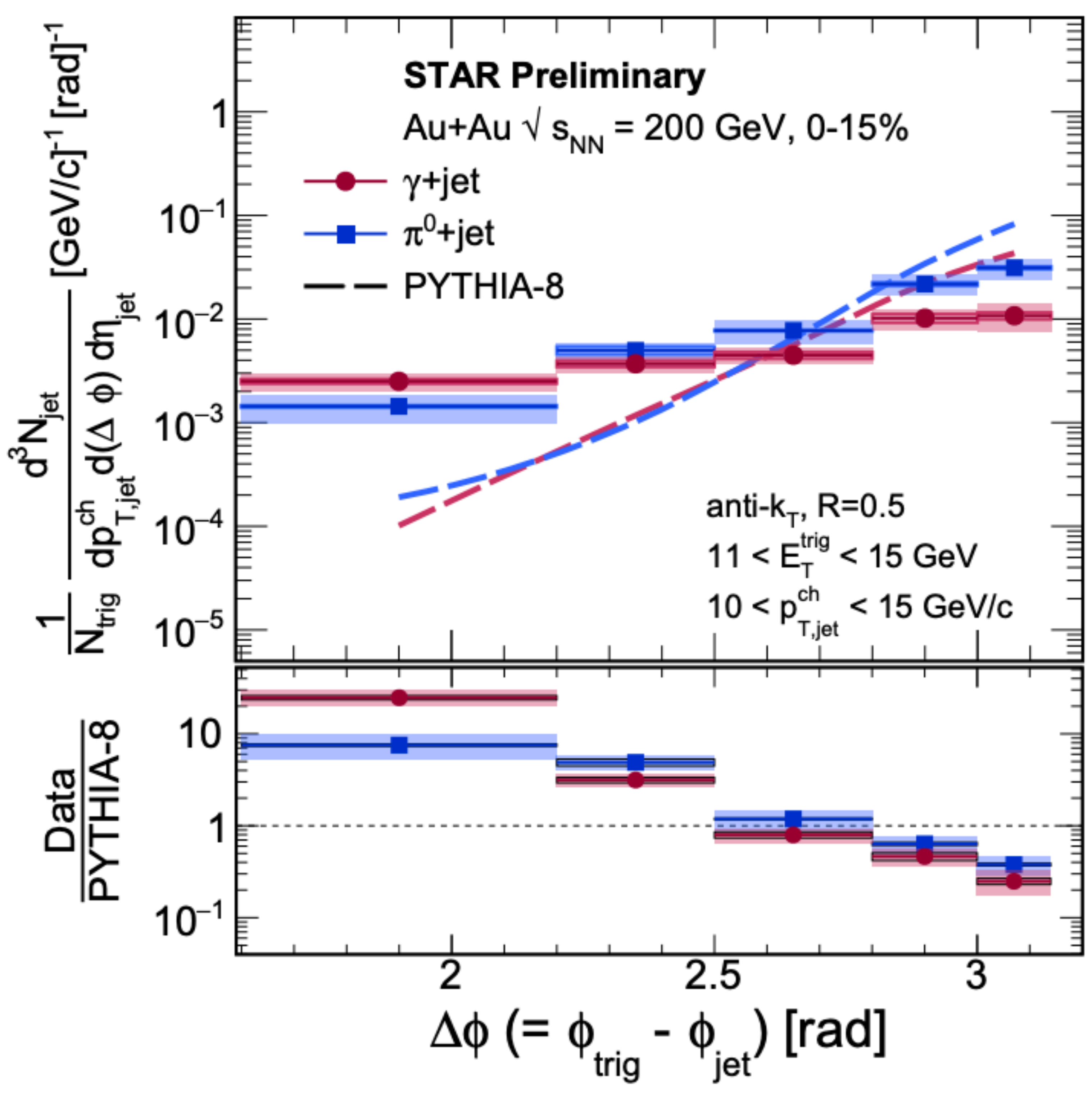


- Corrected $\Delta_{recoil}(\Delta\varphi)$ distributions for $R = 0.4$ in different jet p_T bins (10-20-30-50-100 GeV/c)
- Described well by different model calculations within uncertainties

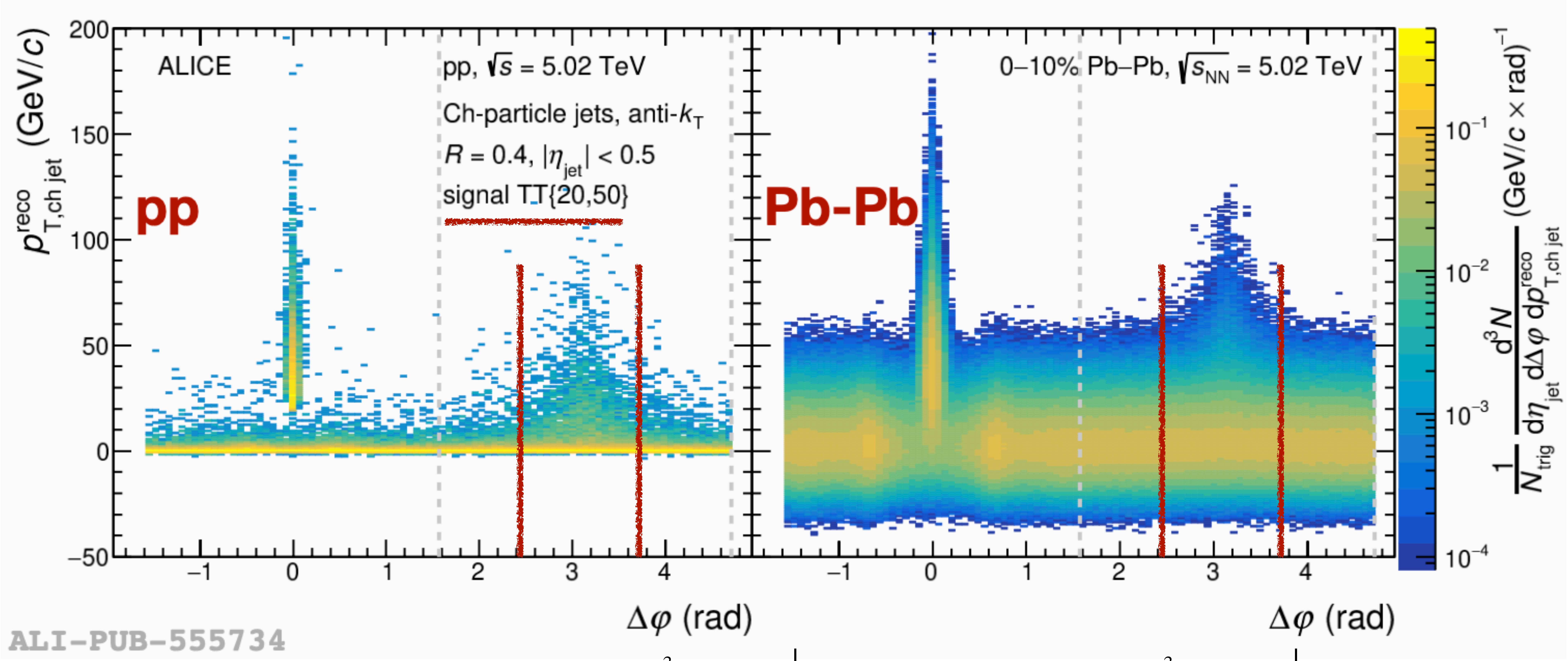
Broadening effect observed with ALICE & STAR

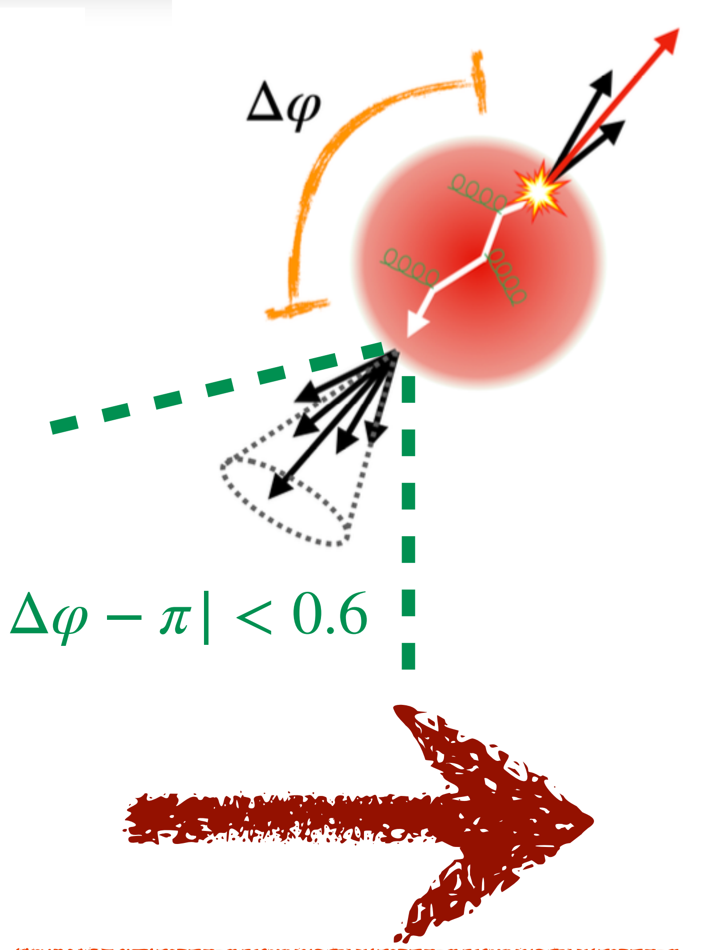
Yongzhen HOU
yongzhen.hou@cern.ch





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





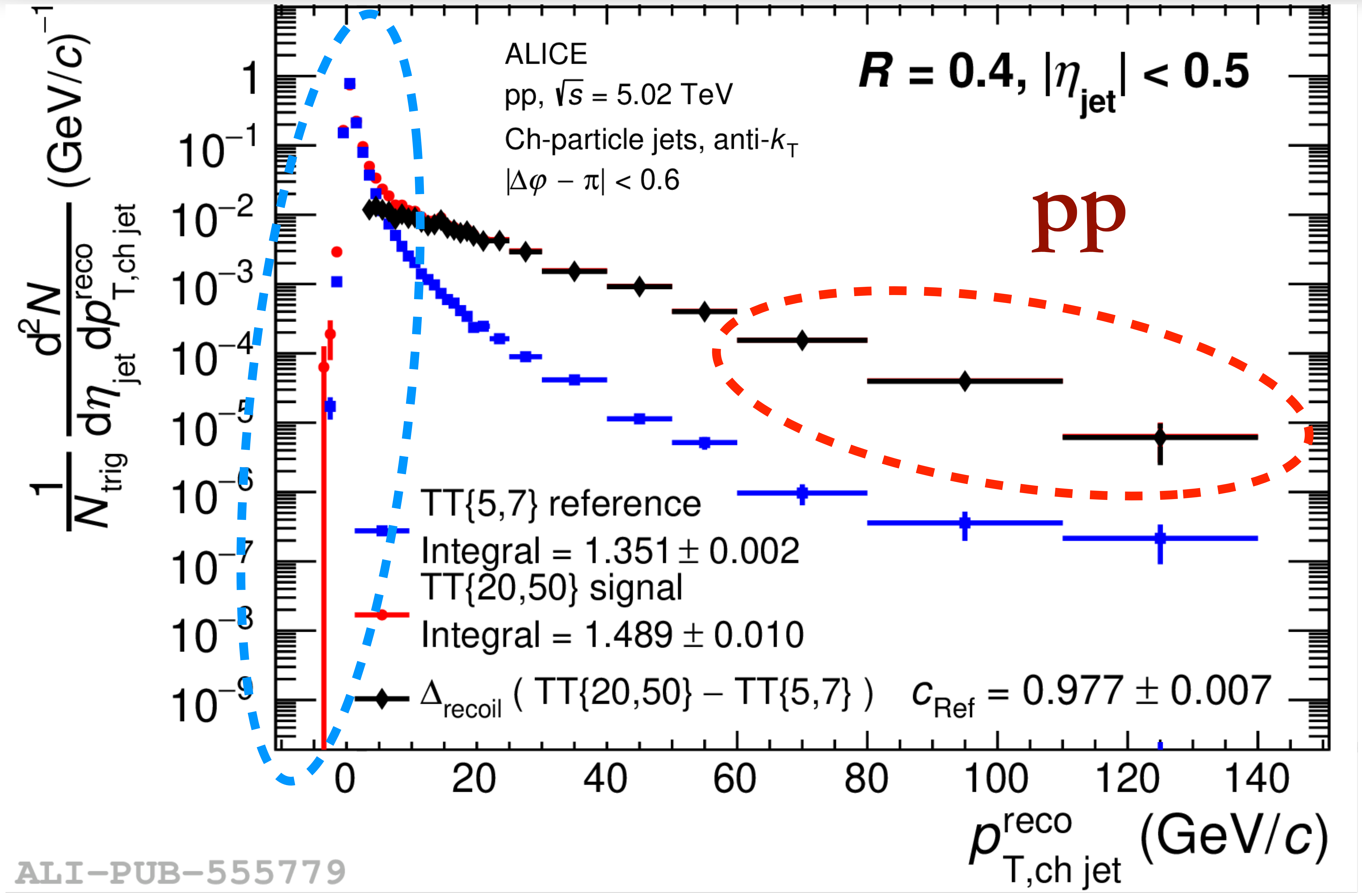
Projection to $p_{\mathrm{T,jet}}$ with $\Delta\varphi$

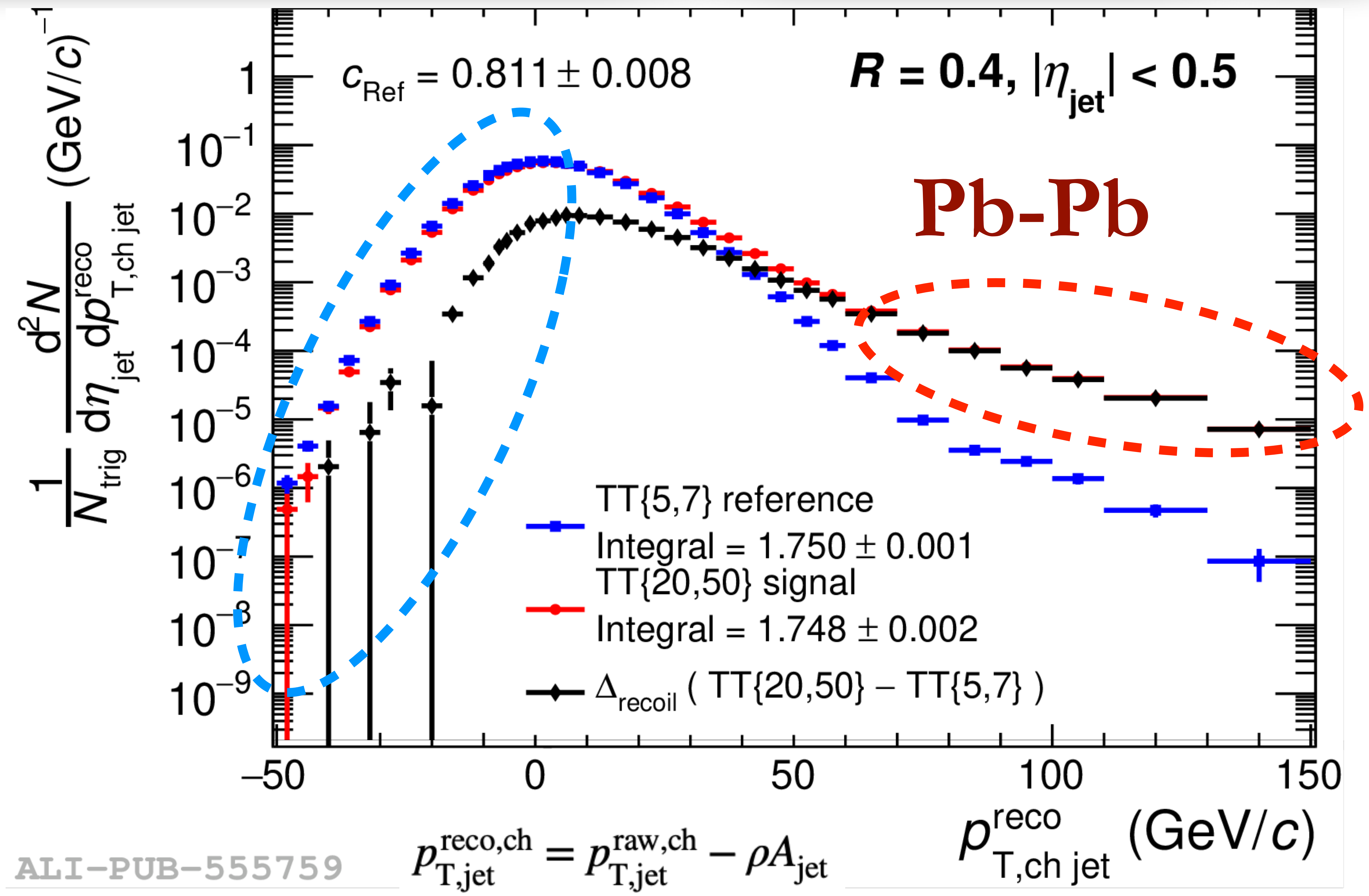
$$\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}}, \Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^3 N_{\mathrm{jet}}}{\mathrm{d}\eta_{\mathrm{jet}}\, \mathrm{d}p_{\mathrm{T,jet}}\, \mathrm{d}\Delta\varphi}\Bigg|_{p_{\mathrm{T}}^{\mathrm{trig}} \in \mathrm{TT}_{\mathrm{Sig}}} - c_{\mathrm{Ref}}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

- Recoil jet p_{T} **vs $\Delta\varphi$ 2-dimensional** distributions in two trigger track p_{T} intervals

Recoil jet p_T distributions

Yongzhen HOU
yongzhen.hou@cern.ch



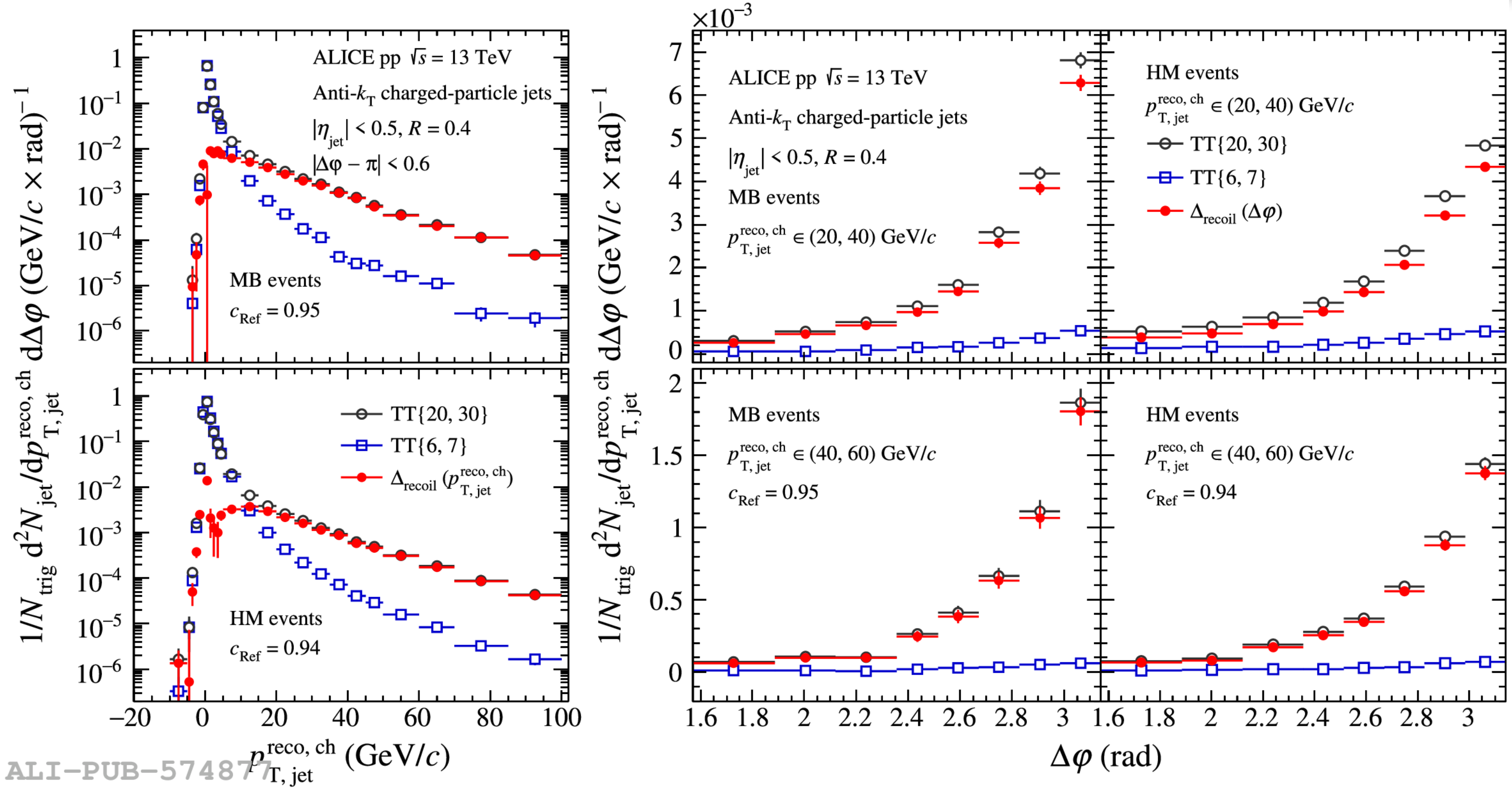


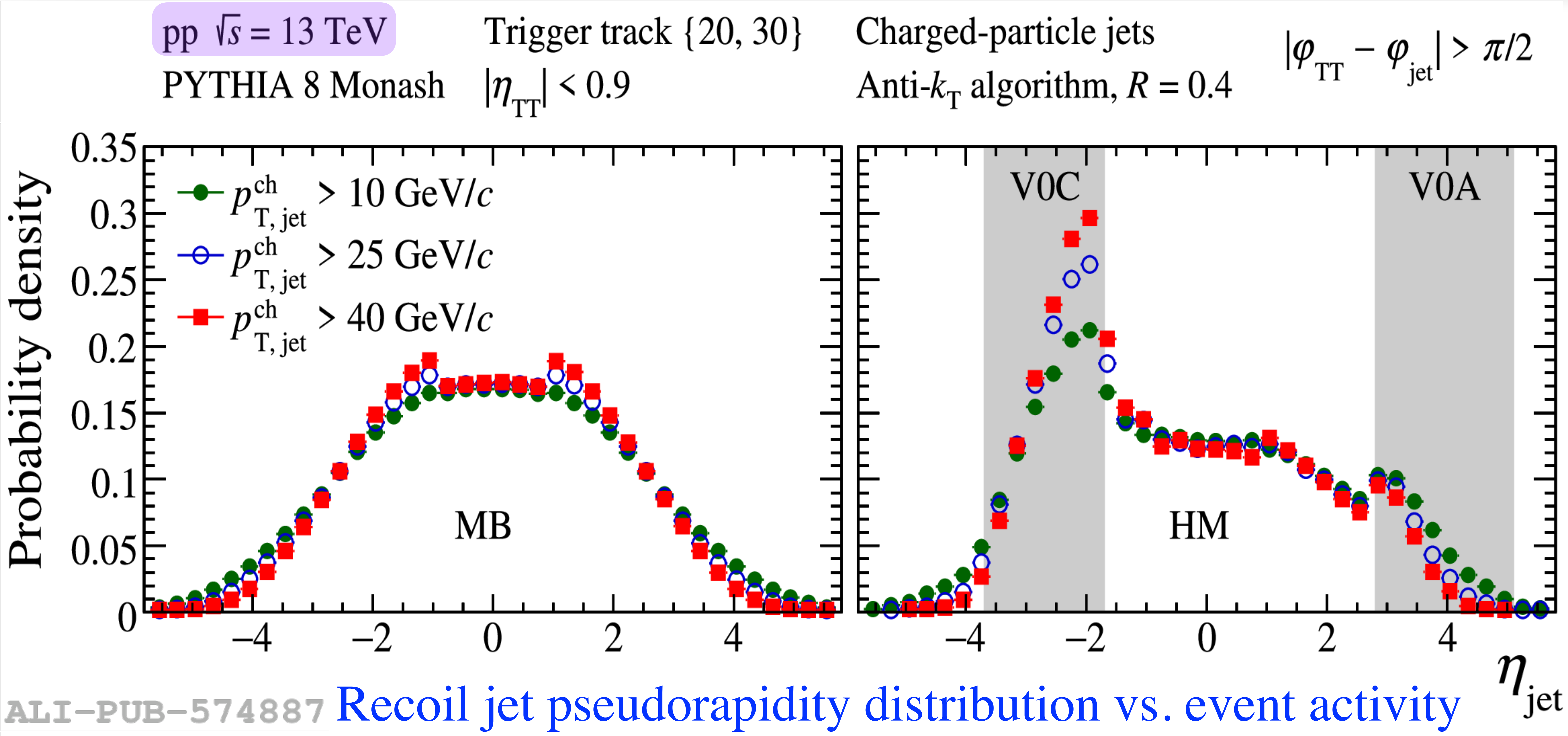
- **Recoil jet p_T distributions** in two trigger track p_T intervals are then obtained from 2D projection
- **Combinational background** uncorrelated with the trigger
  - Small background contribution in pp, much larger in Pb-Pb
  - Combinatorial background can be removed by taking the **difference** of recoil jet distributions in two TT intervals

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

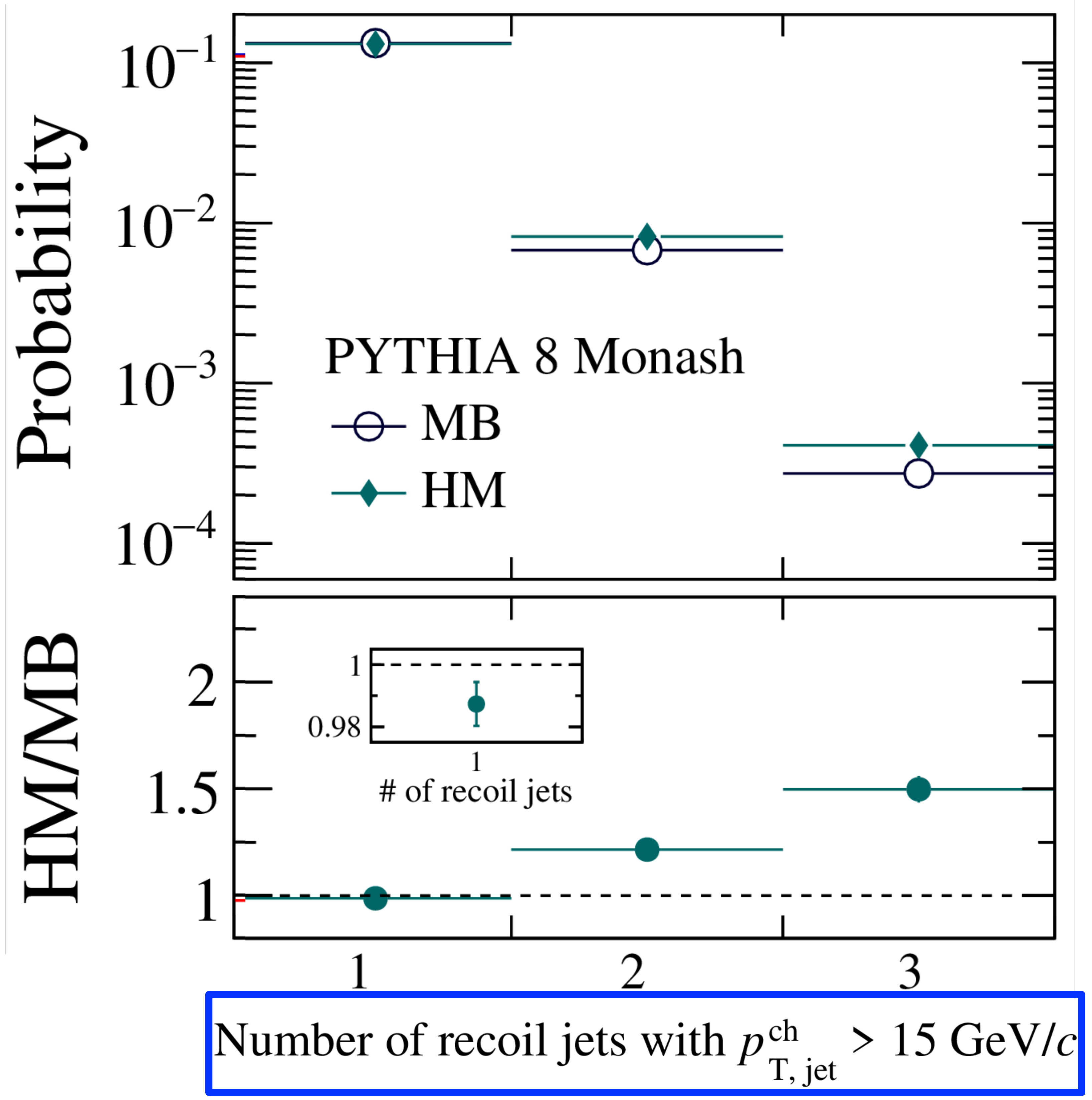
Raw distribution in pp 13 TeV

Yongzhen HOU
yongzhen.hou@cern.ch





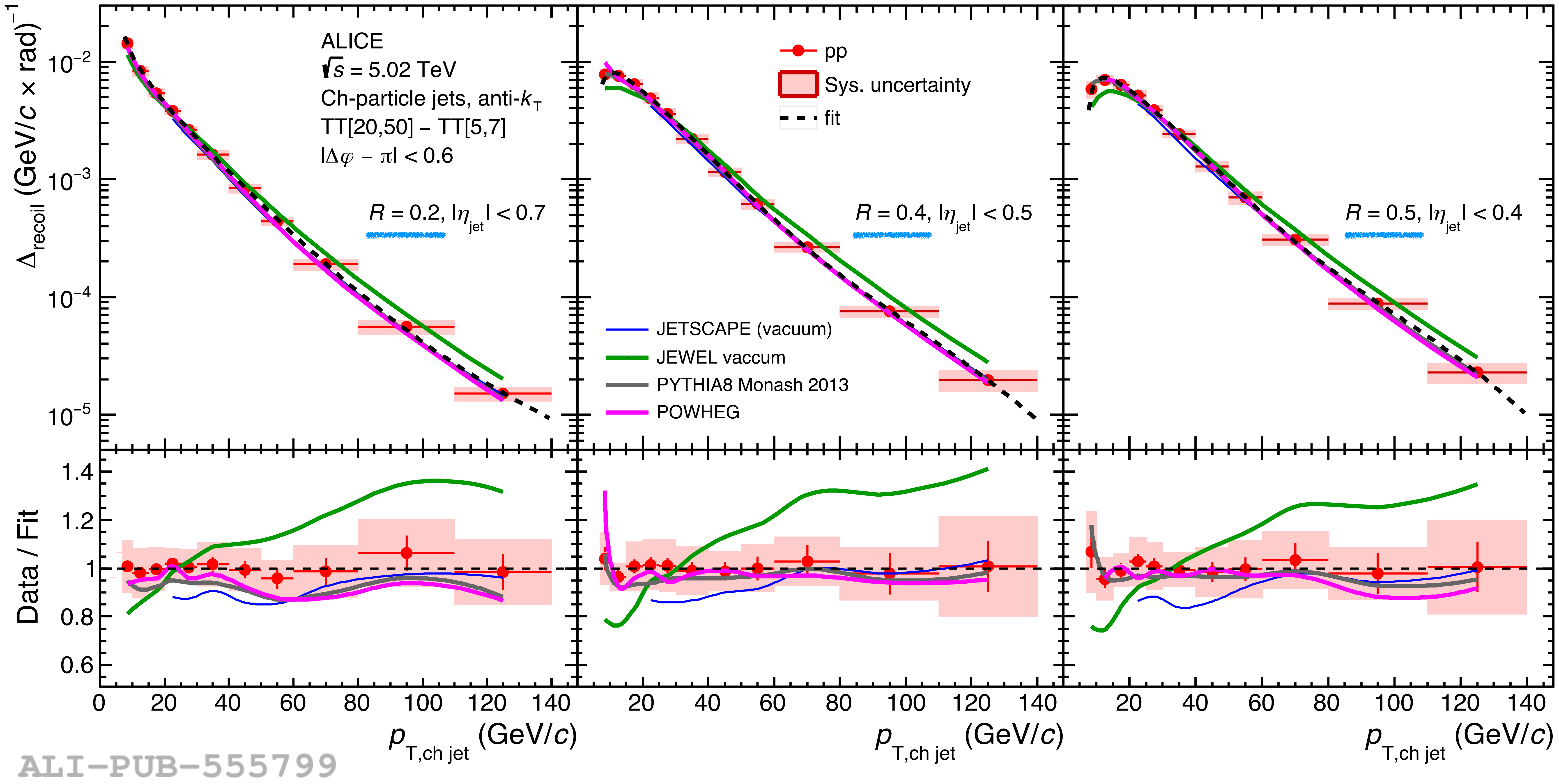
Recoil jet pseudorapidity distribution vs. event activity



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

Yongzhen HOU
yongzhen.hou@cern.ch



Data fitted with the function:

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

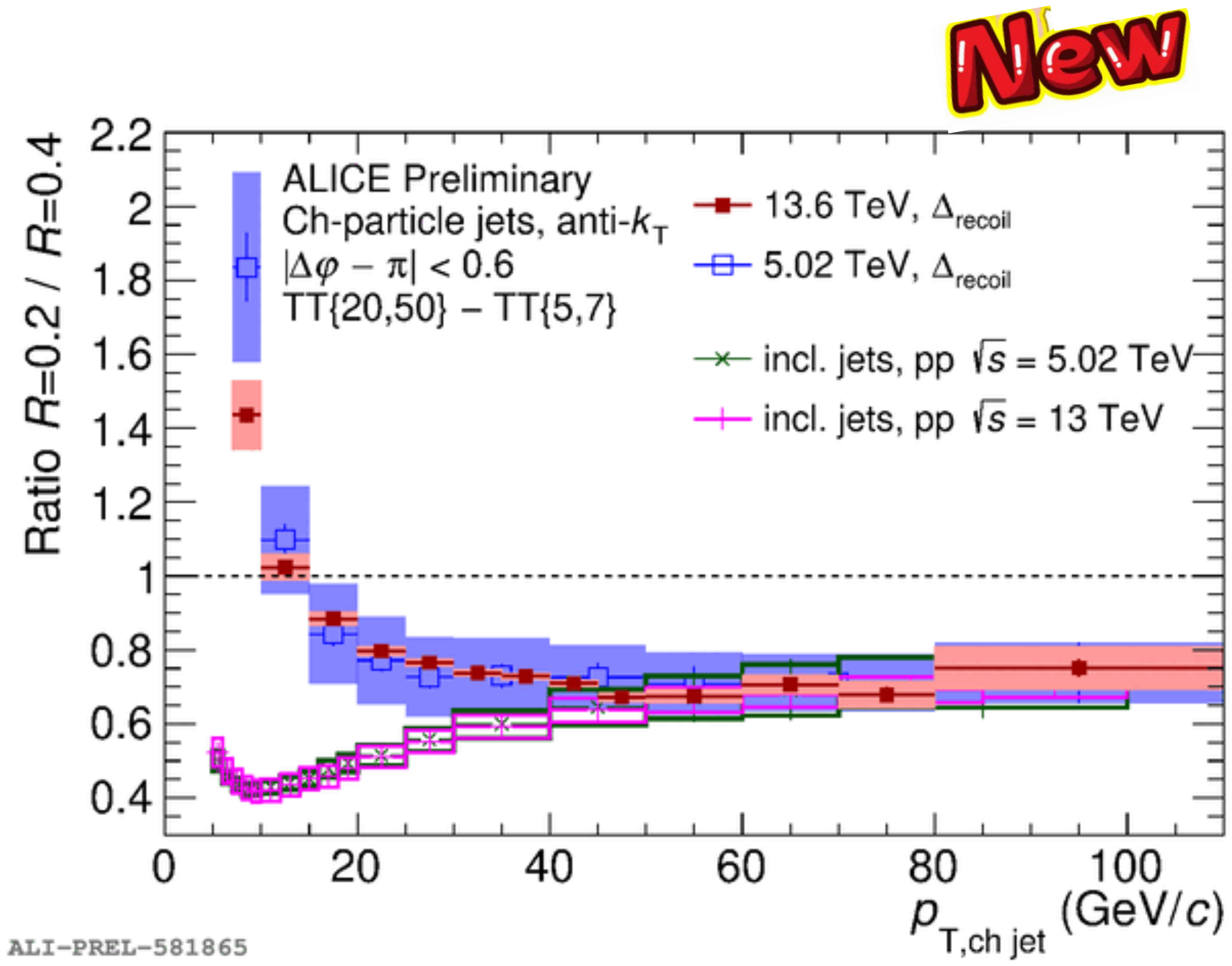
PYTHIA (8.125, Monash 2013 tune): LO pQCD calculation
arXiv:1404.5630

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 $\Delta_{recoil}(p_T)$ 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



- **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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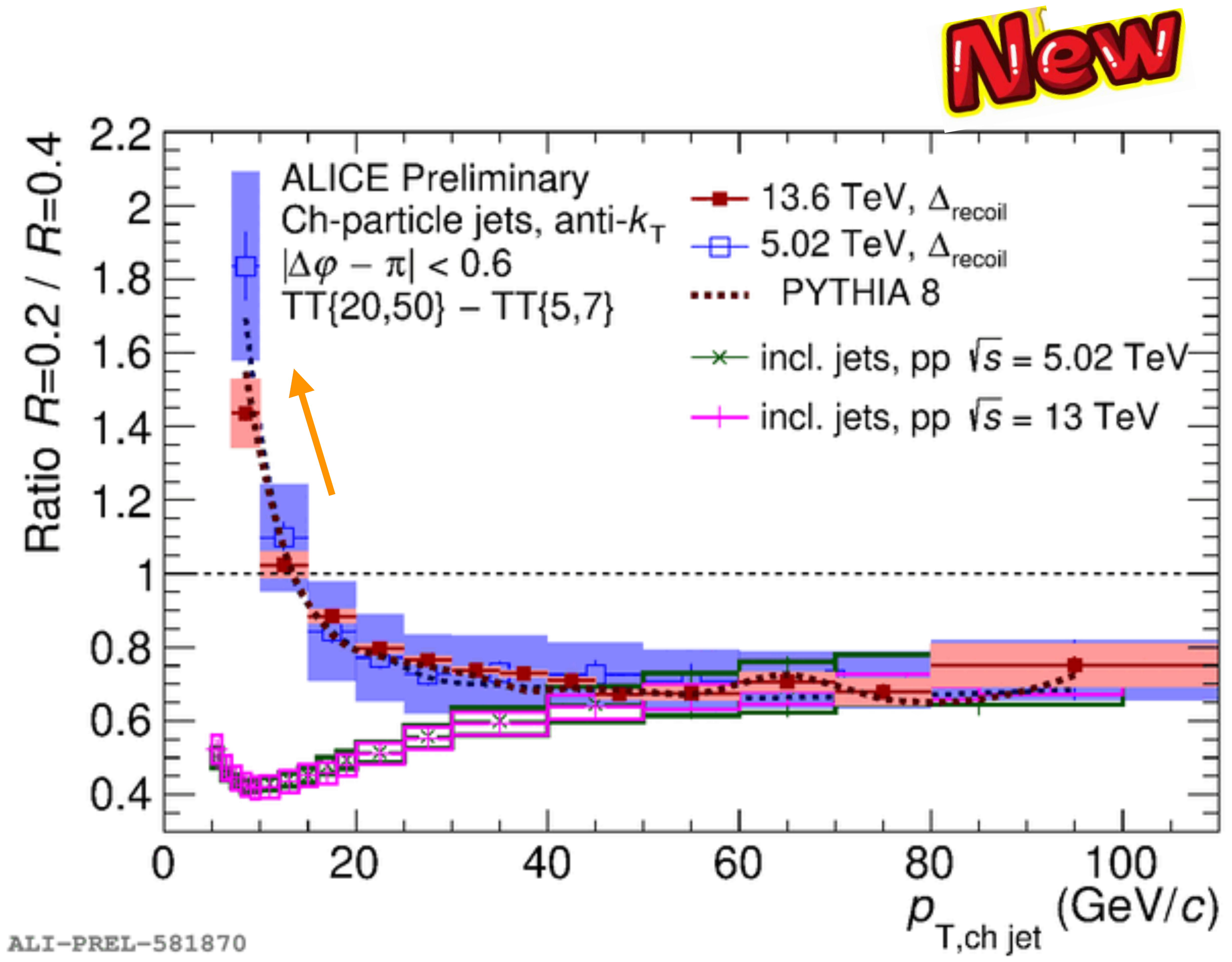

- **The jet yield ratios** of inclusive and simi-inclusive for R = 0.2 / 0.4
  - **Agreement** between inclusive jets and semi-inclusive at high p_T
  - **Well described** by PYTHIA
  - Good agreement between Run 2 and Run 3 results
- Difference at low p_T due to **TT selection**
- Enhancement in $R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

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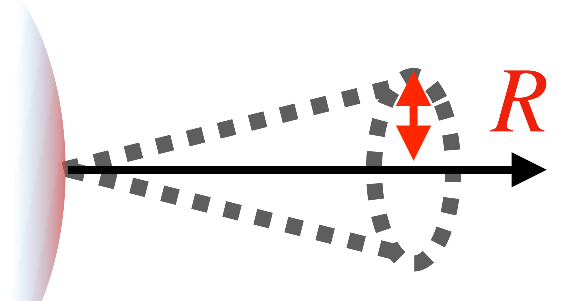
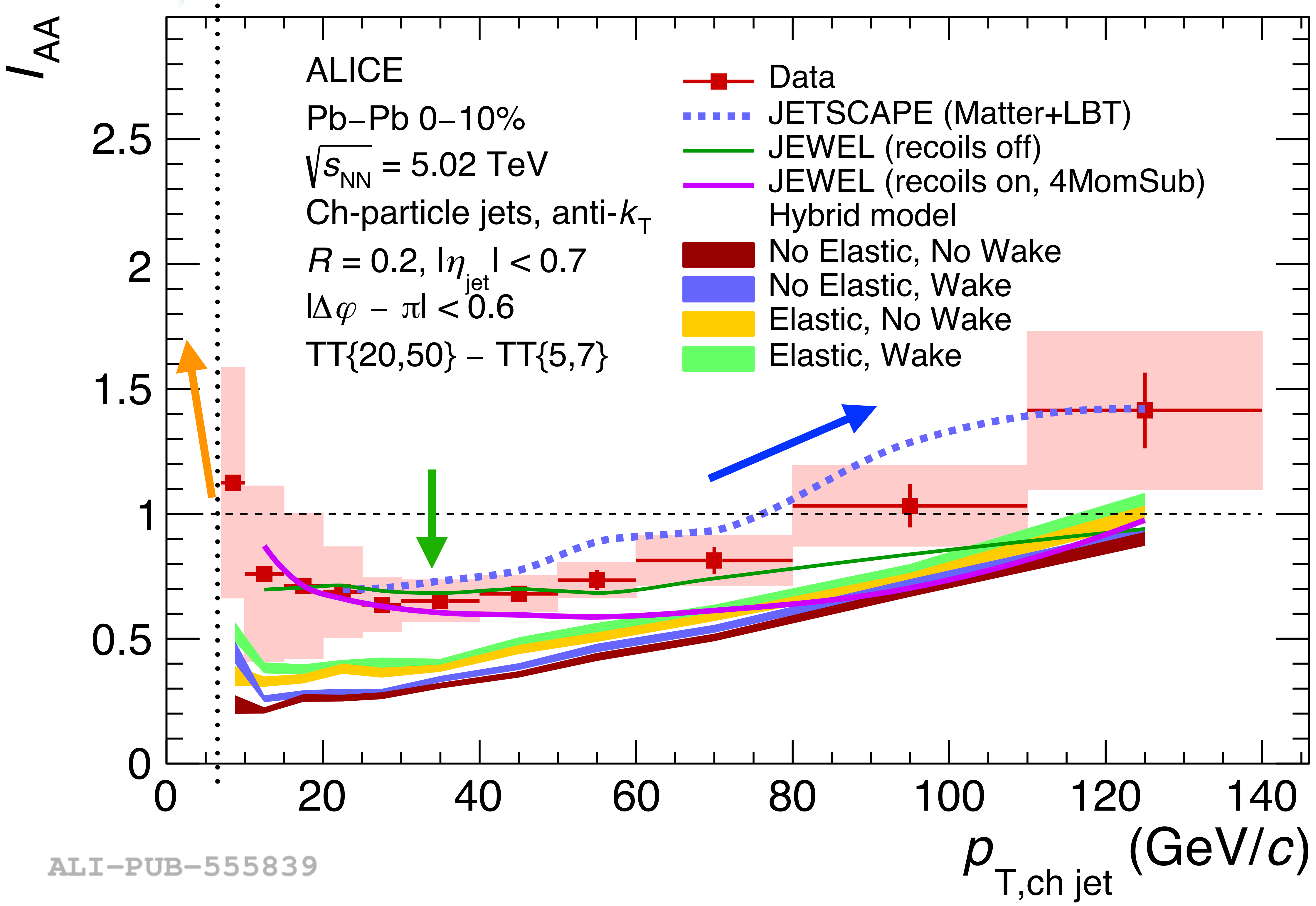


0 – 10 %

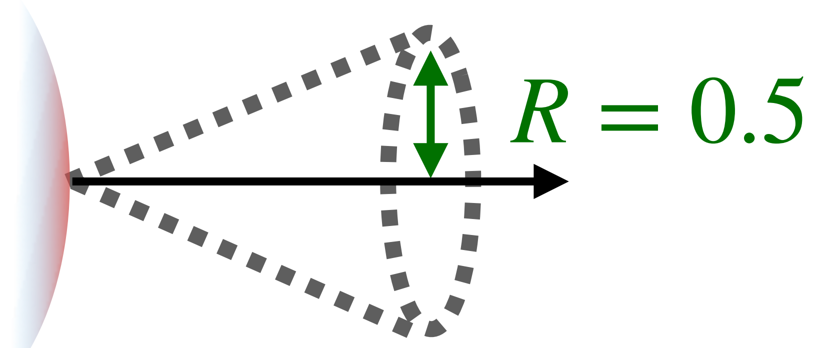
R = 0.2

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



- 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

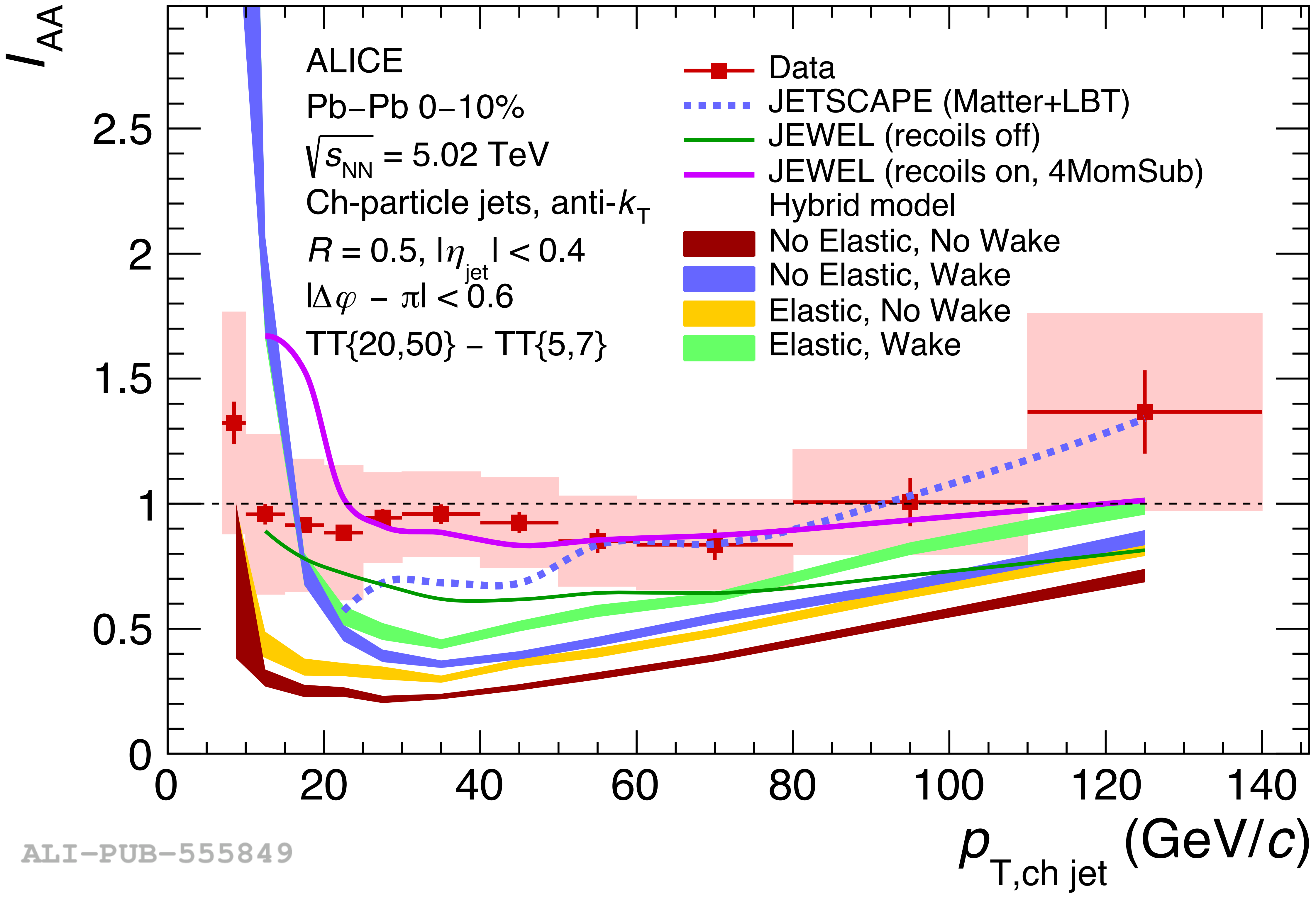
$I_{AA}(p_T)$ - recoil jet yield modification in Pb-Pb collisions



0 – 10 %

R = 0.5

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



- 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

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

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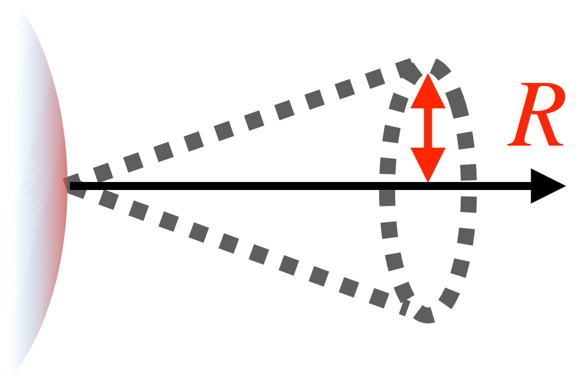
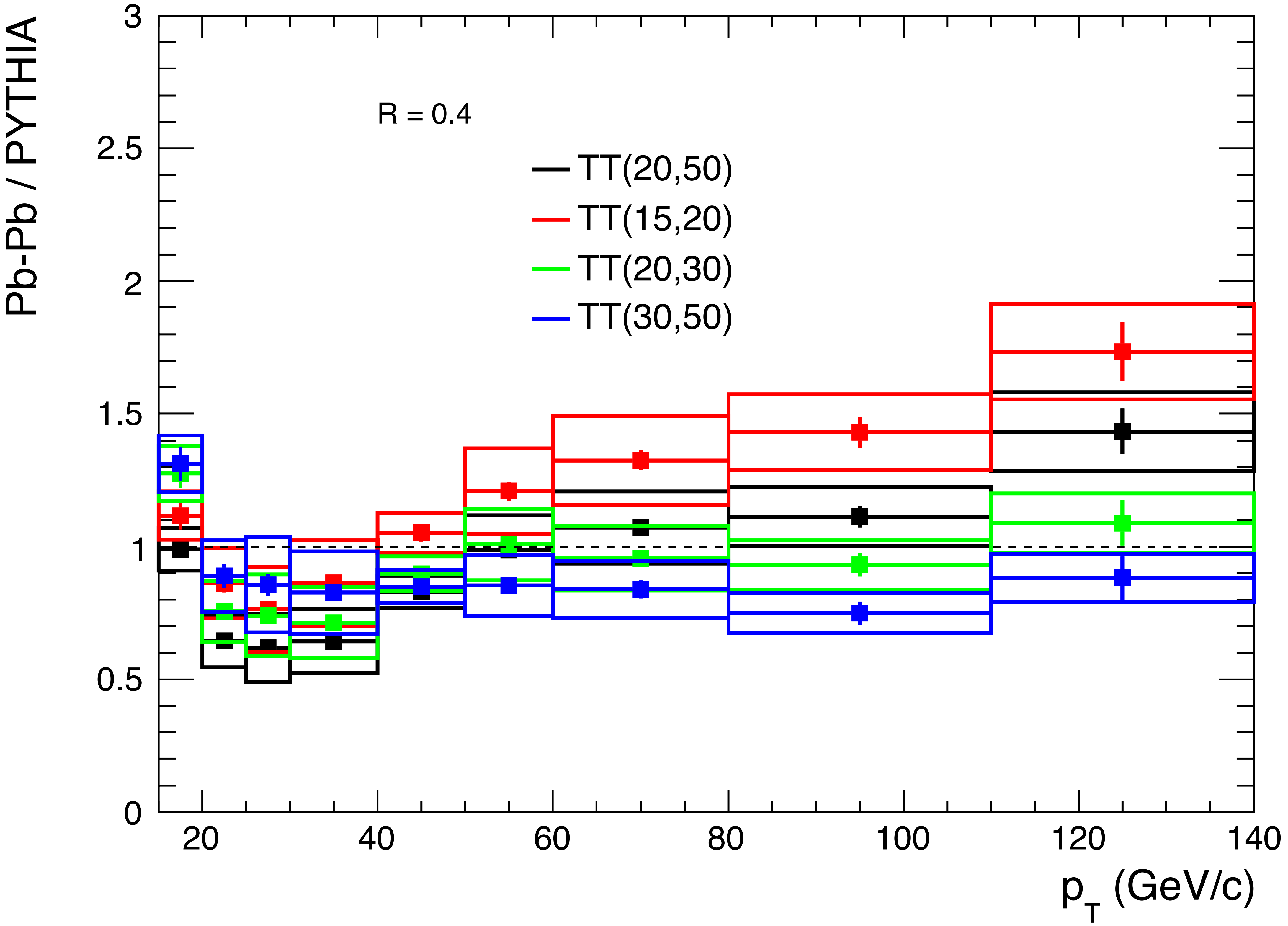
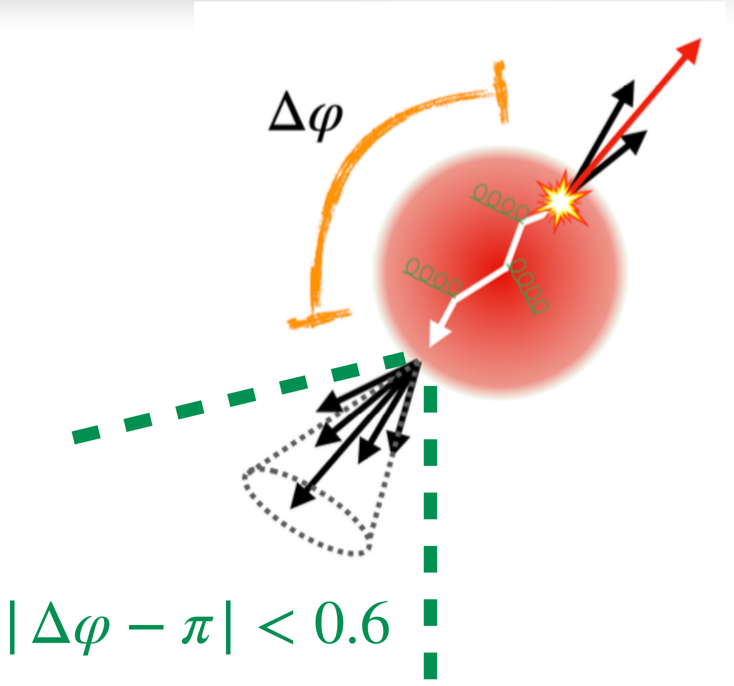


0 – 10 %



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



- 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

Recoil jet $\Delta\varphi$ distributions

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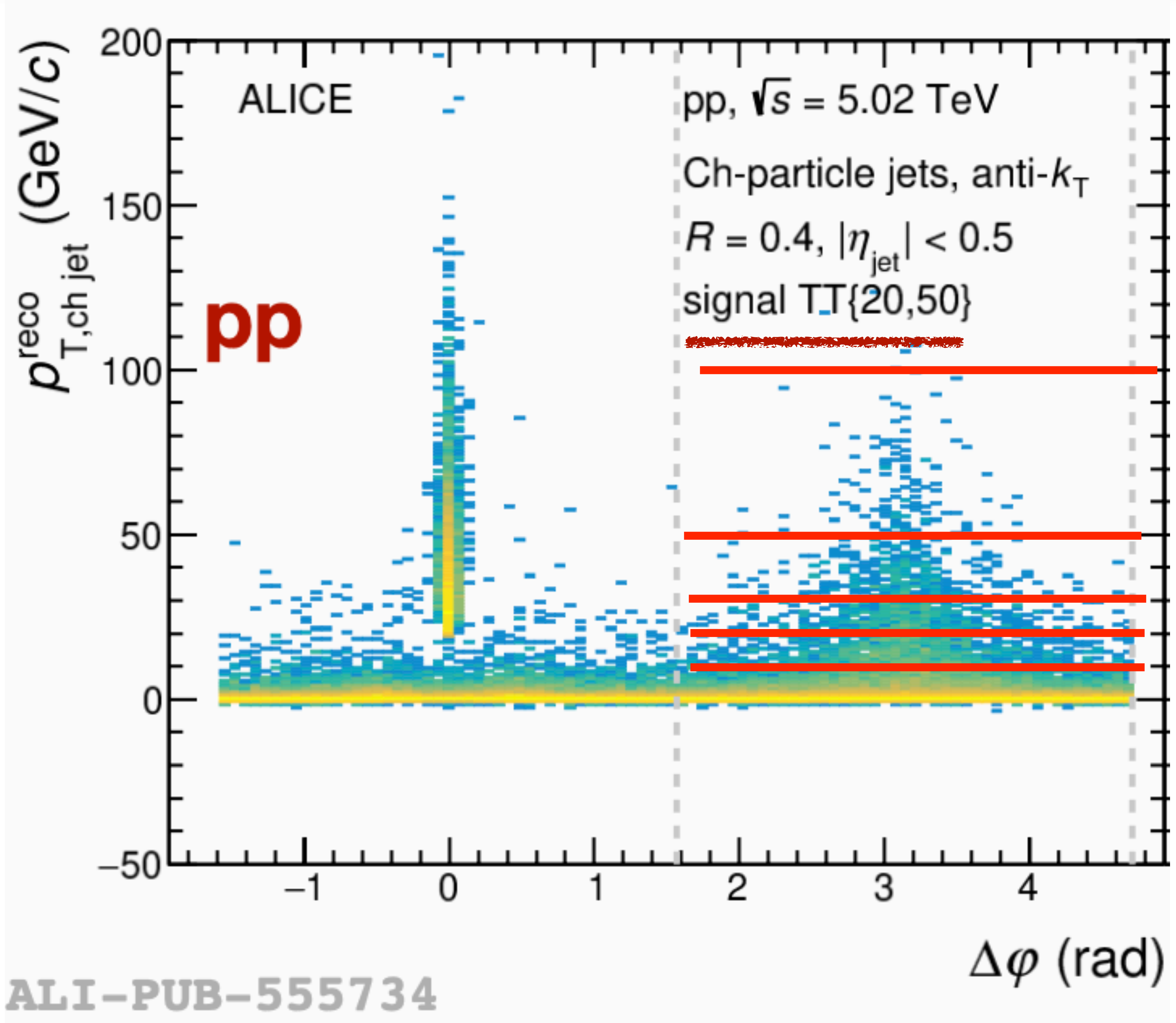
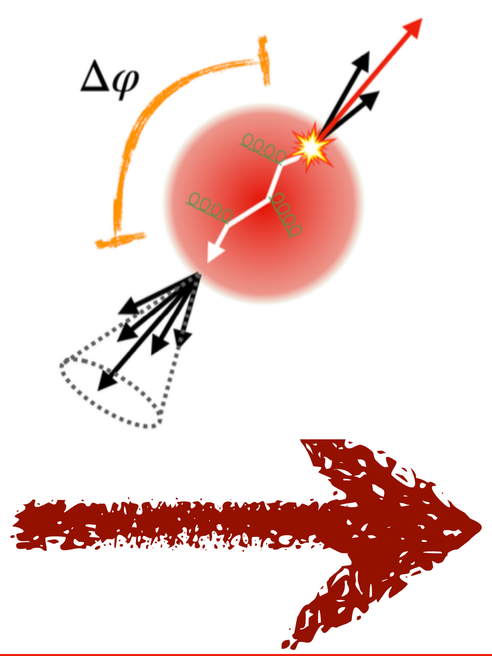
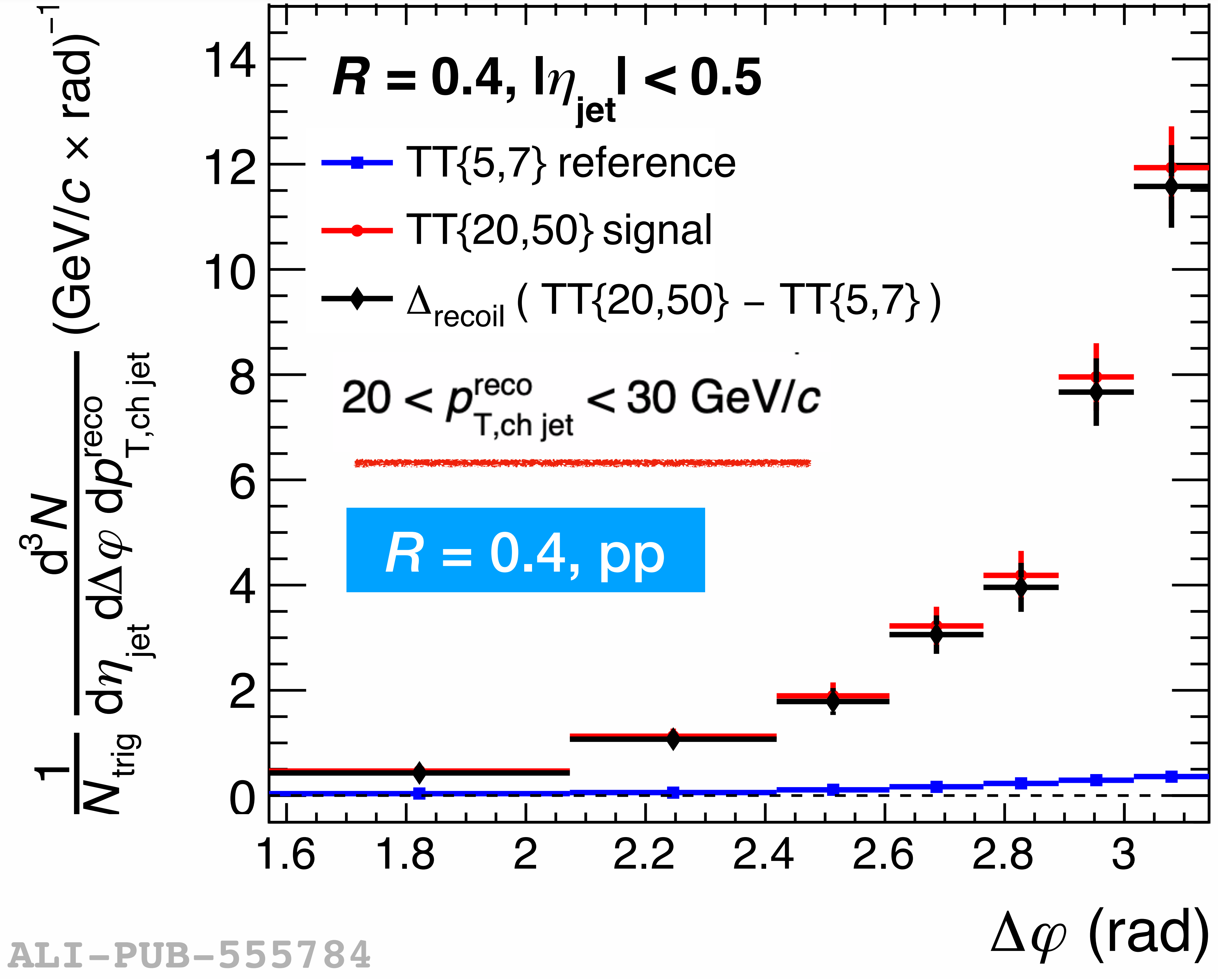




Projection to $\Delta\varphi$ with $p_{T,jet}$ cut



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

- 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 & Pb-Pb

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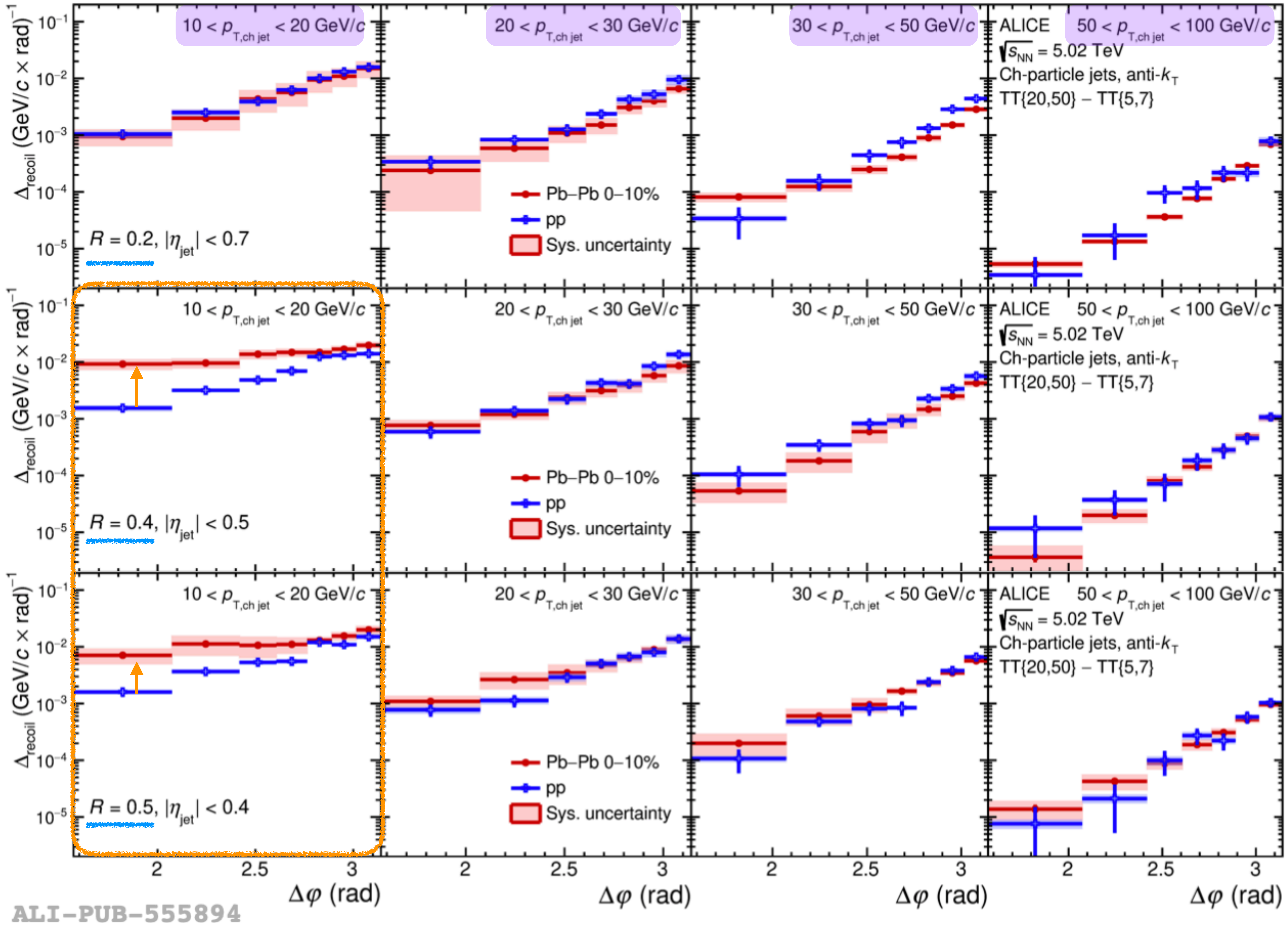
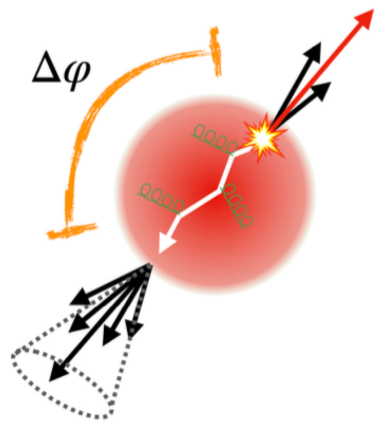
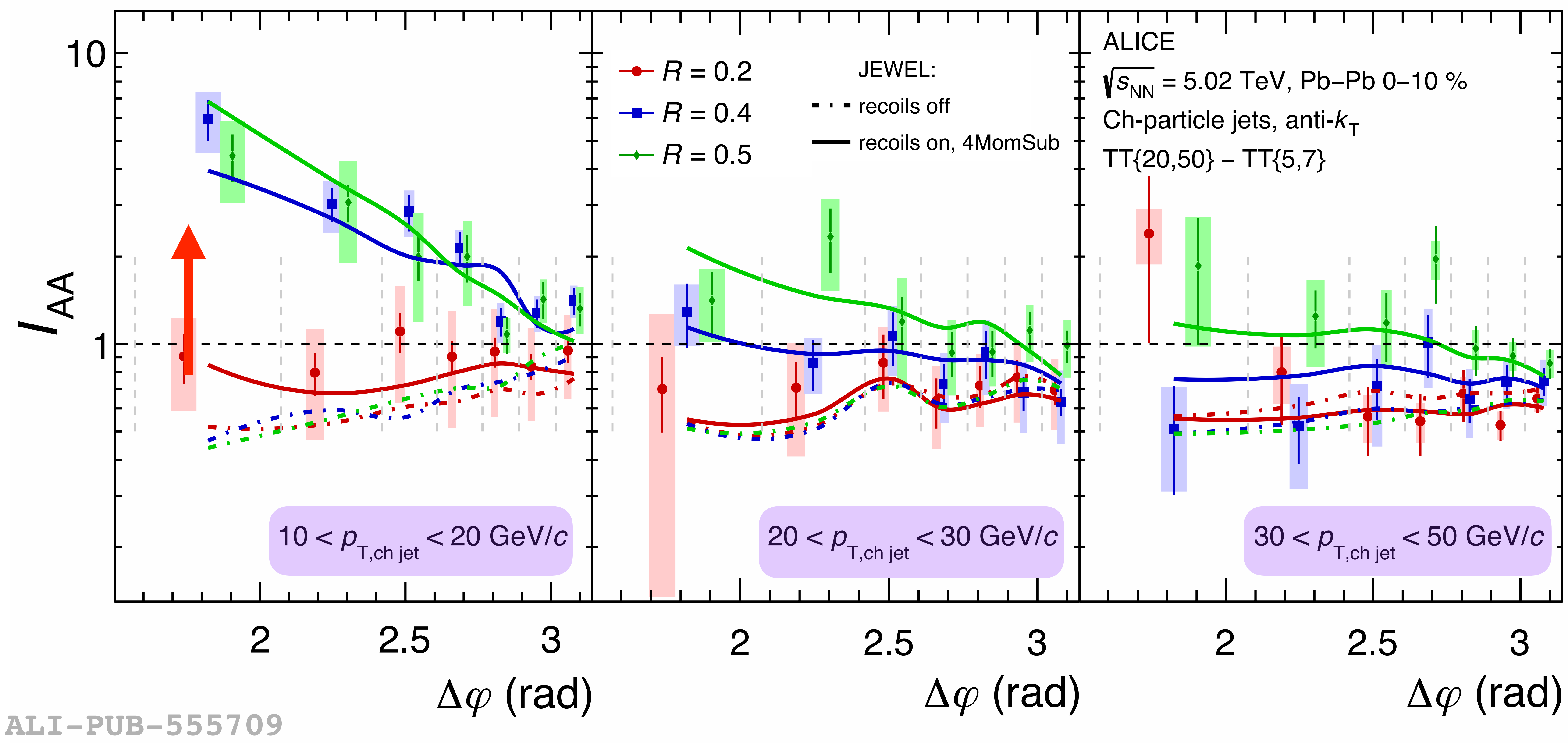


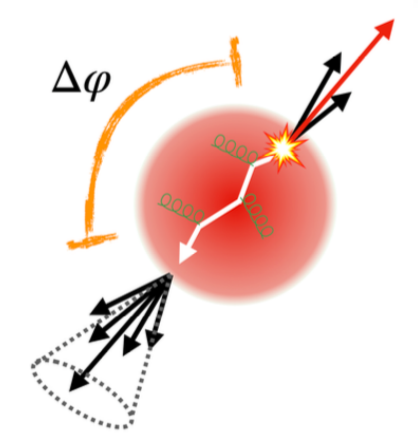


pp

Pb-Pb

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





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

- 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