Jet yield measurements with ALICE

Yongzhen HOU

IOPP, Central China Normal University

IPHC, University of Strasbourg

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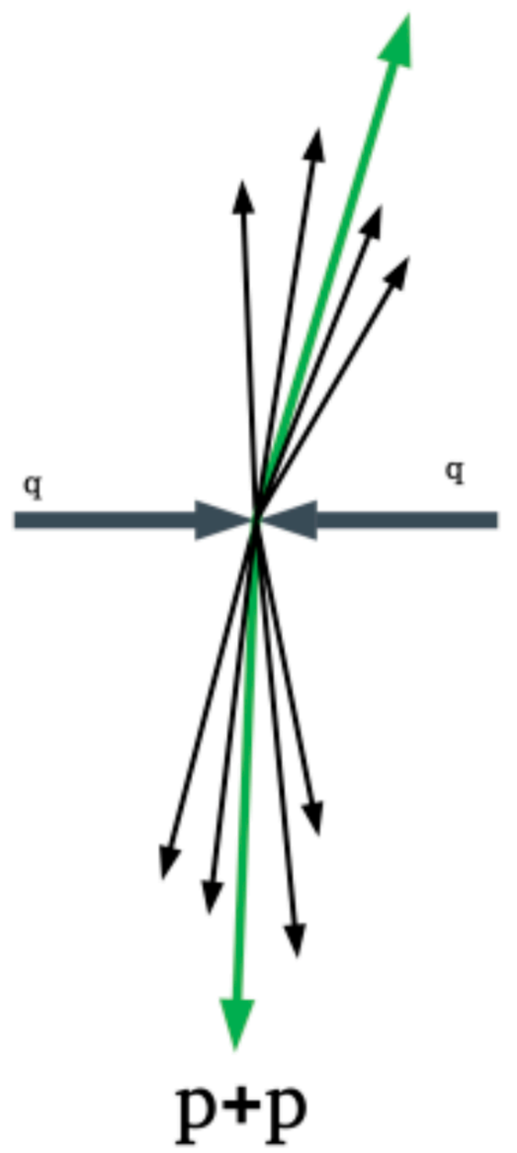
Why jets?

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



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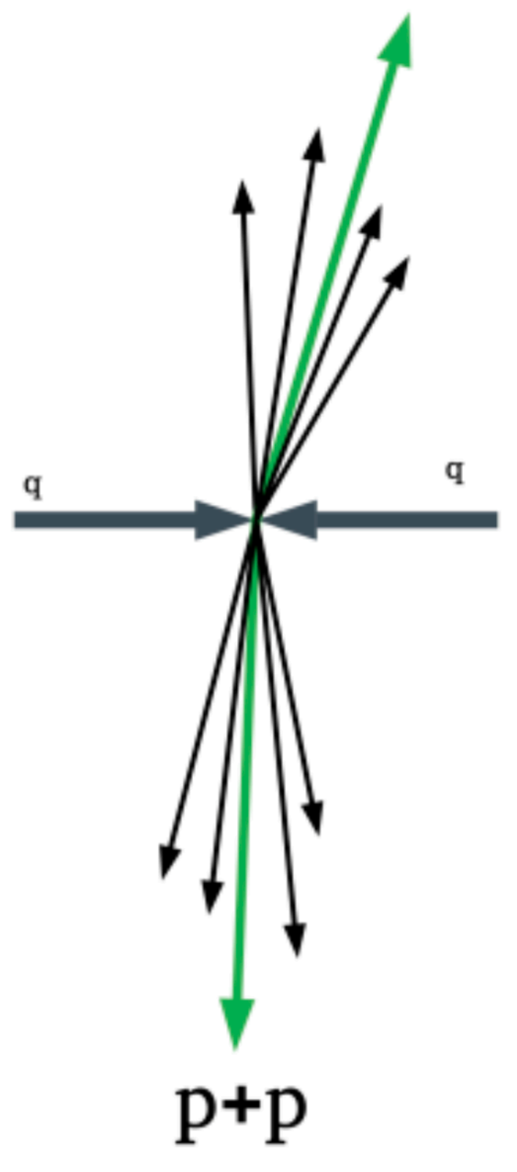
Jets in pp collisions → study the strong force using jet production

- **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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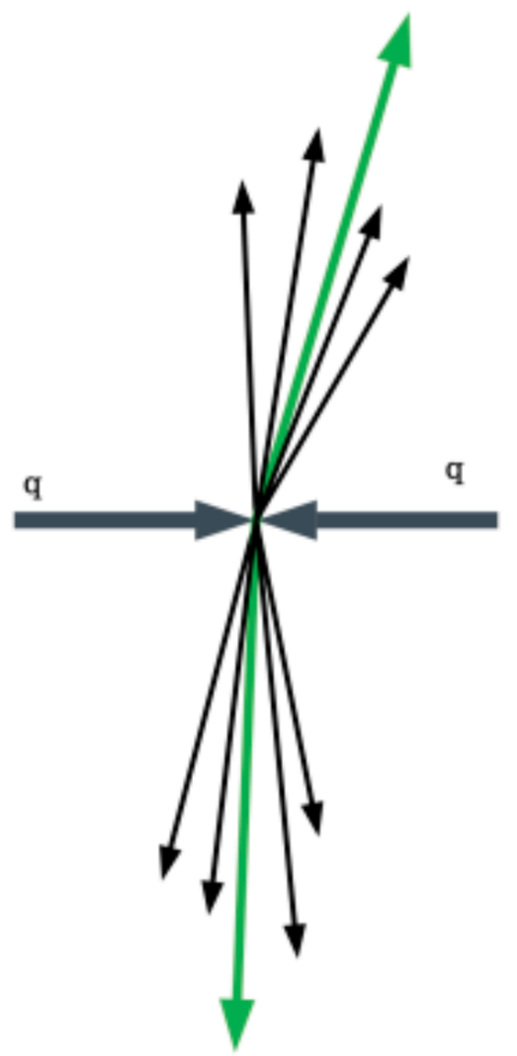

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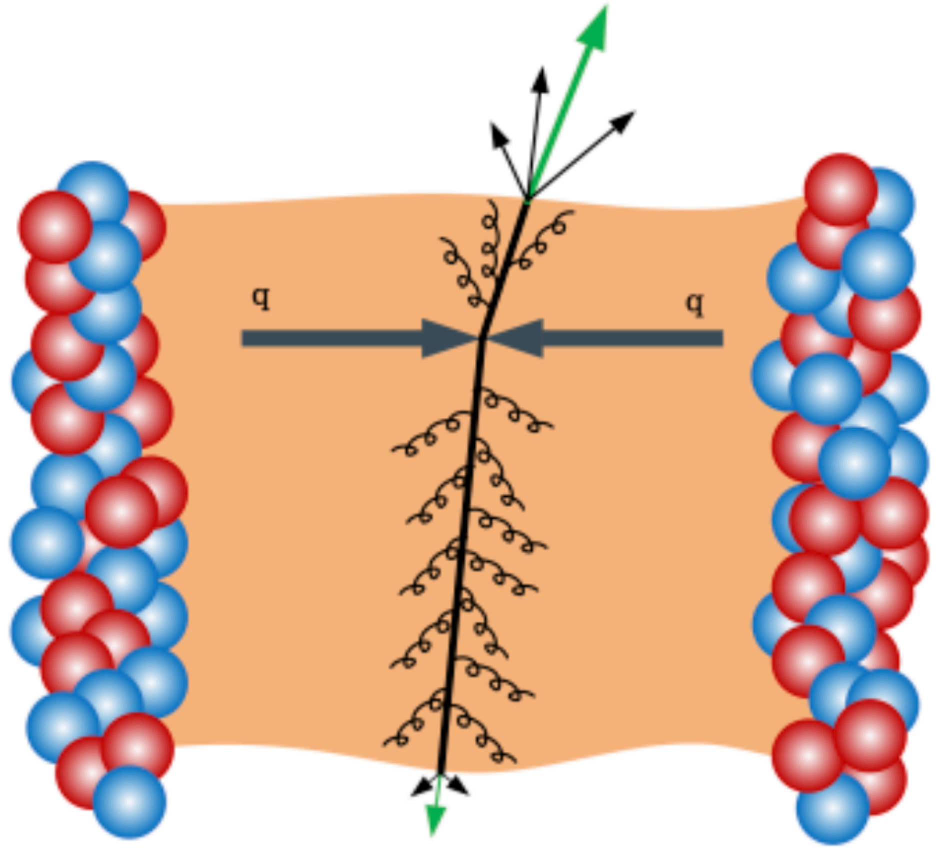
Jets in heavy-ion collisions → study the transport properties of the QGP

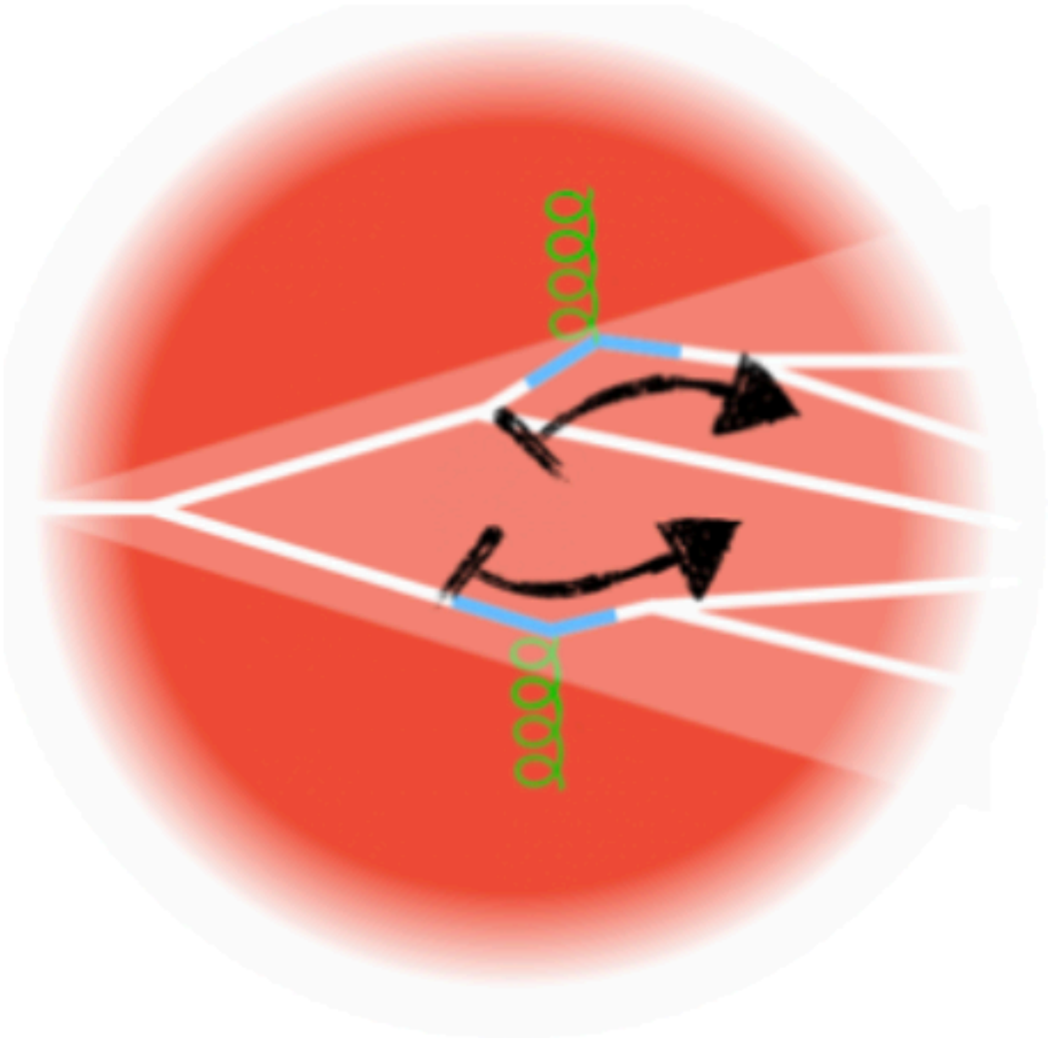
- Partons interact with QGP and lose energy through medium-induced gluon radiations (inelastic) and collisions (elastic) with medium constituents
  - $\text{Jet}(E) \rightarrow \text{Jet}(E' - \Delta E) + \text{soft particles}(\Delta \text{E})$

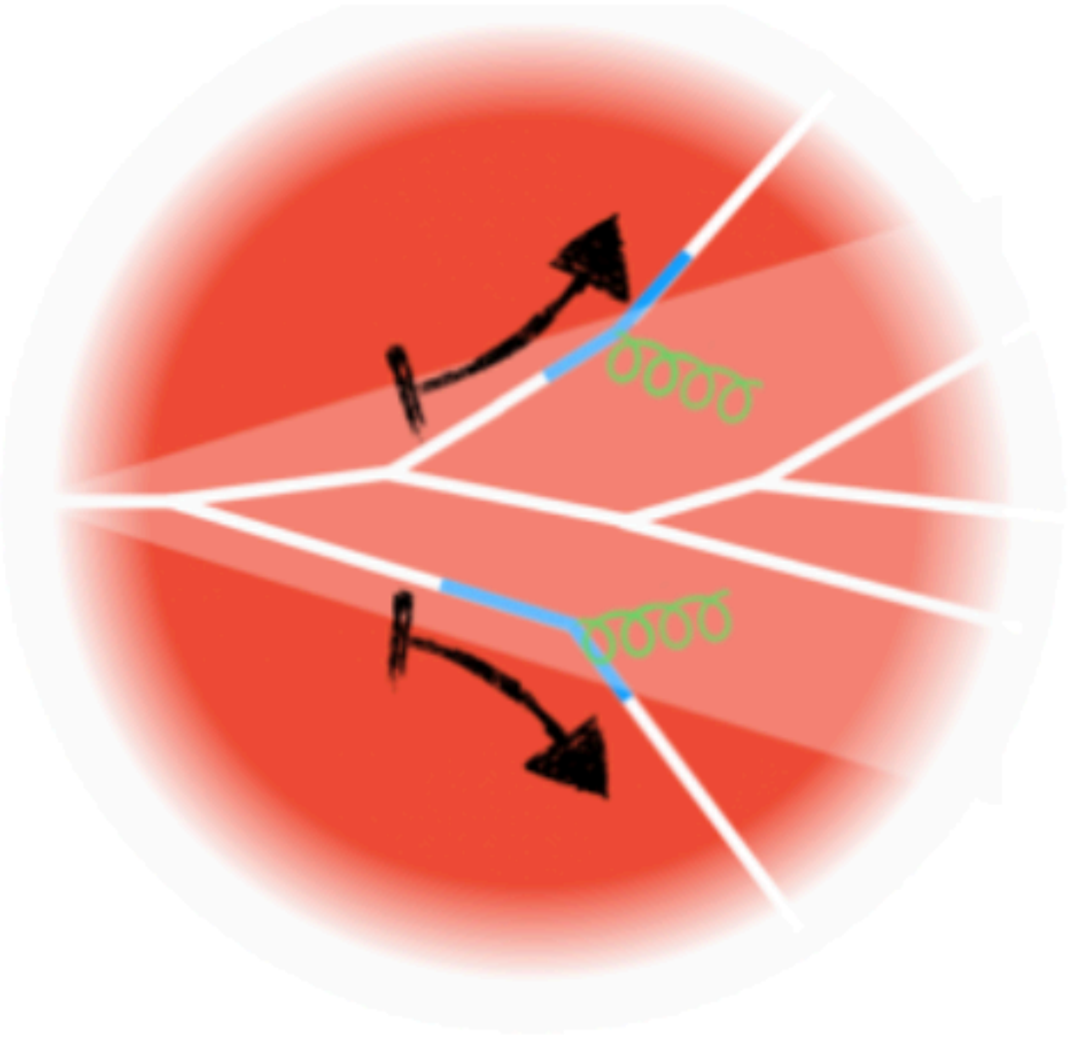


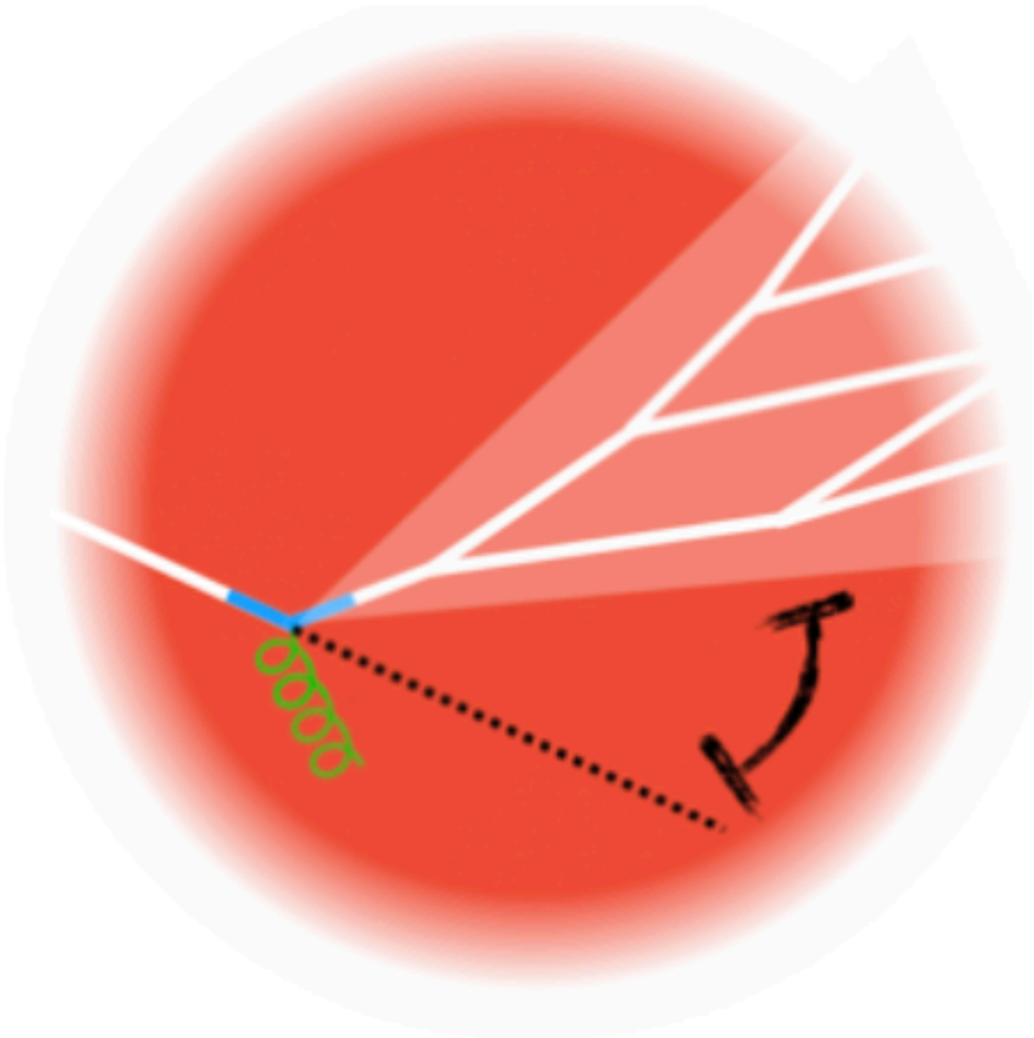
Jet observables

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

- Several types of jet observables
  - Jet reconstruction and declustering → **jet 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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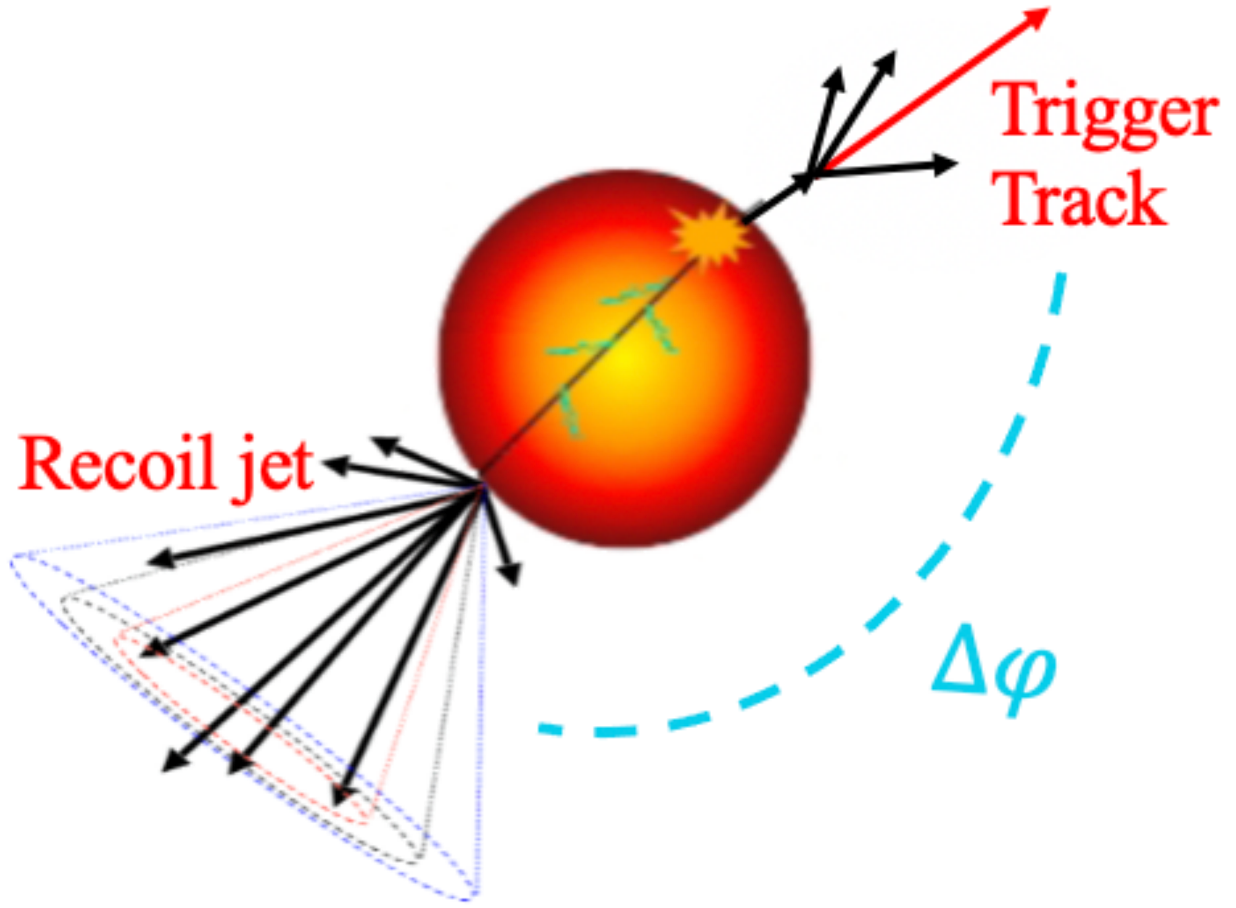
  - Jet yields and constituents → **jet suppression and energy redistribution** (R_{AA}, $\mathbf{I_{AA}}$)
  - Angular correlation → **jet deflection** ($\boldsymbol{\Delta\varphi}$)
    - Can be studied through semi-inclusive measurements of a jet recoiling from a trigger (e.g. γ-jet , Z-jet, or **hadron-jet**)

Why hadron-jets?

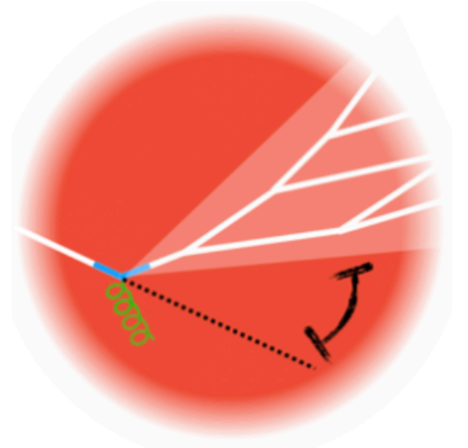
- Provide a good handle of combinatorial background by varying trigger track intervals → **access low p_T, large R jets**
- **Opening angle ($\Delta\varphi$)** of the recoil jet relative to trigger axis
- $\Delta\varphi$ distributions provide additional insight into QGP properties



Hadron-jet correlations

Jet broadening transverse to its initial direction

- **In vacuum:** transverse broadening due to gluon emission (**Sudakov broadening**)[1,2]
- **In medium:** additional broadening due to scatterings with medium constituents[1,2]
  - Transverse broadening due to **multiple soft scatterings** in the QGP
    - Related to transport coefficient $\hat{q} \sim \langle k_{\perp}^{2} \rangle / L \sim \langle \Delta\varphi^{2} \rangle / L$



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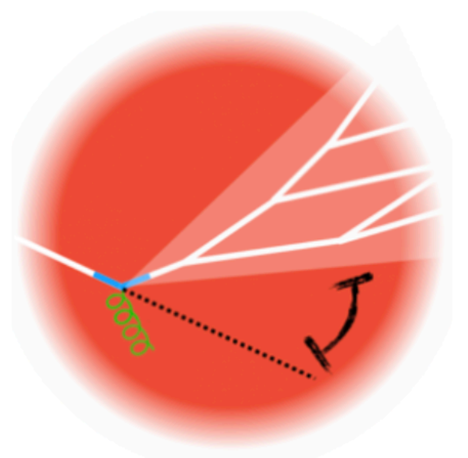

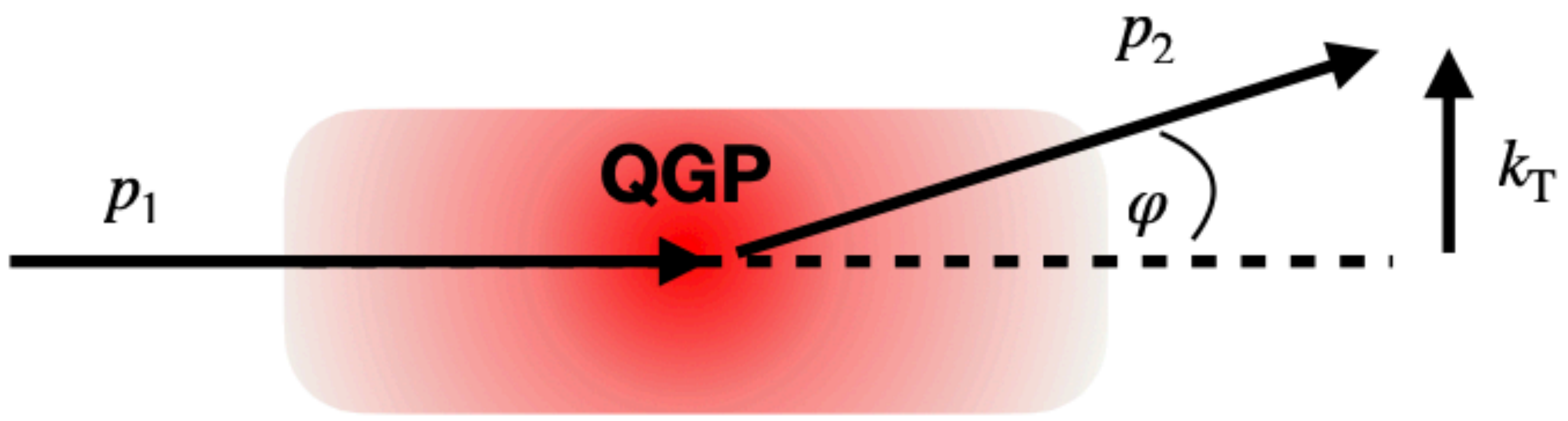

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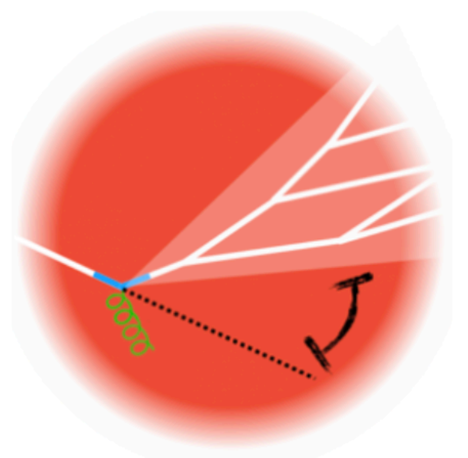
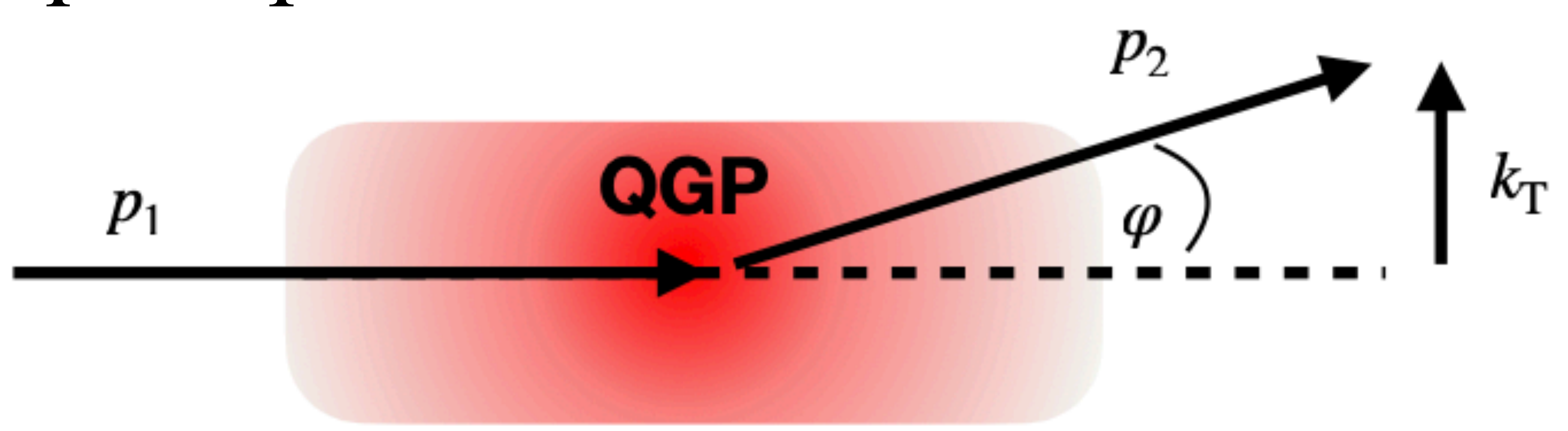
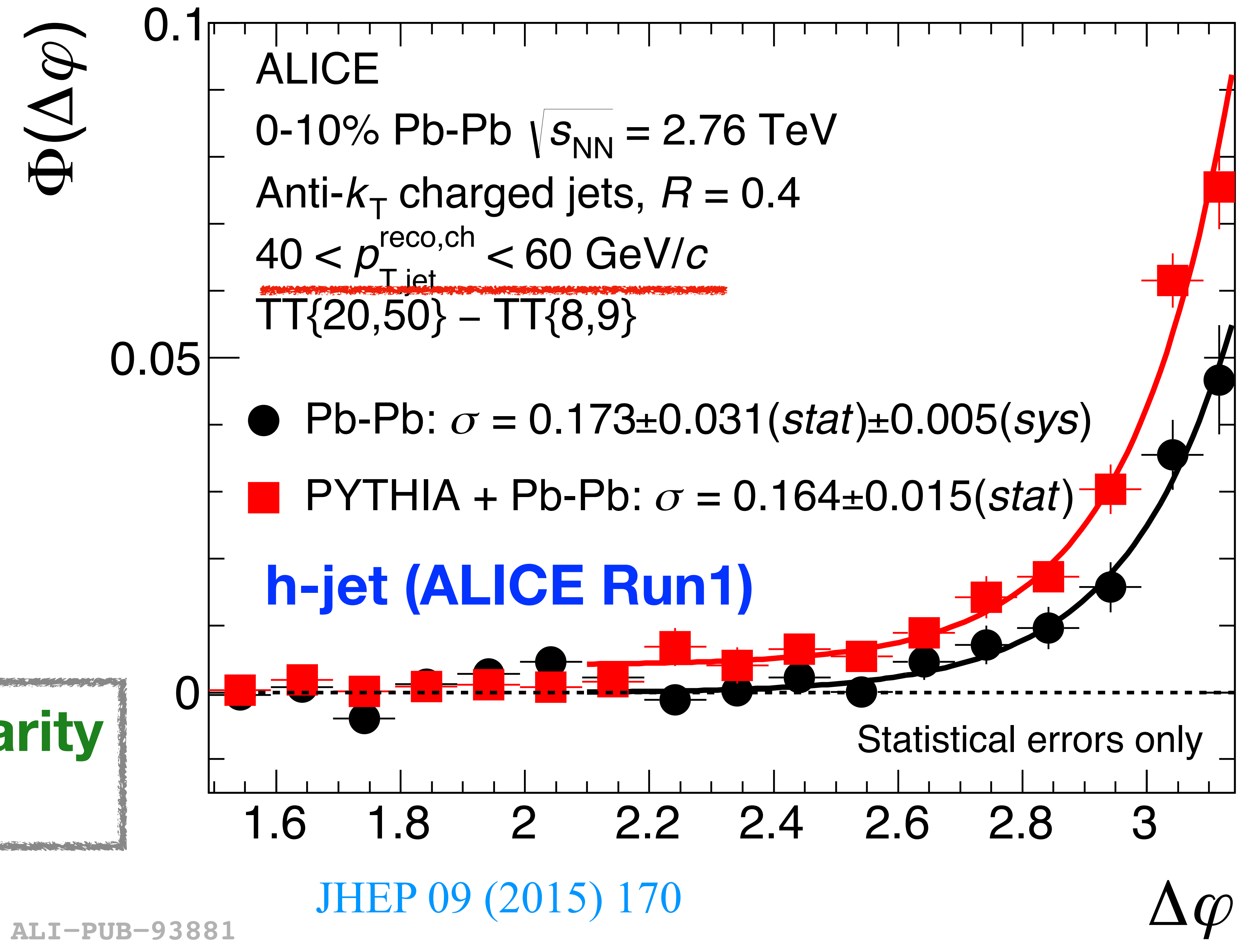




No medium-induced acoplanarity broadening observed



JHEP 09 (2015) 170

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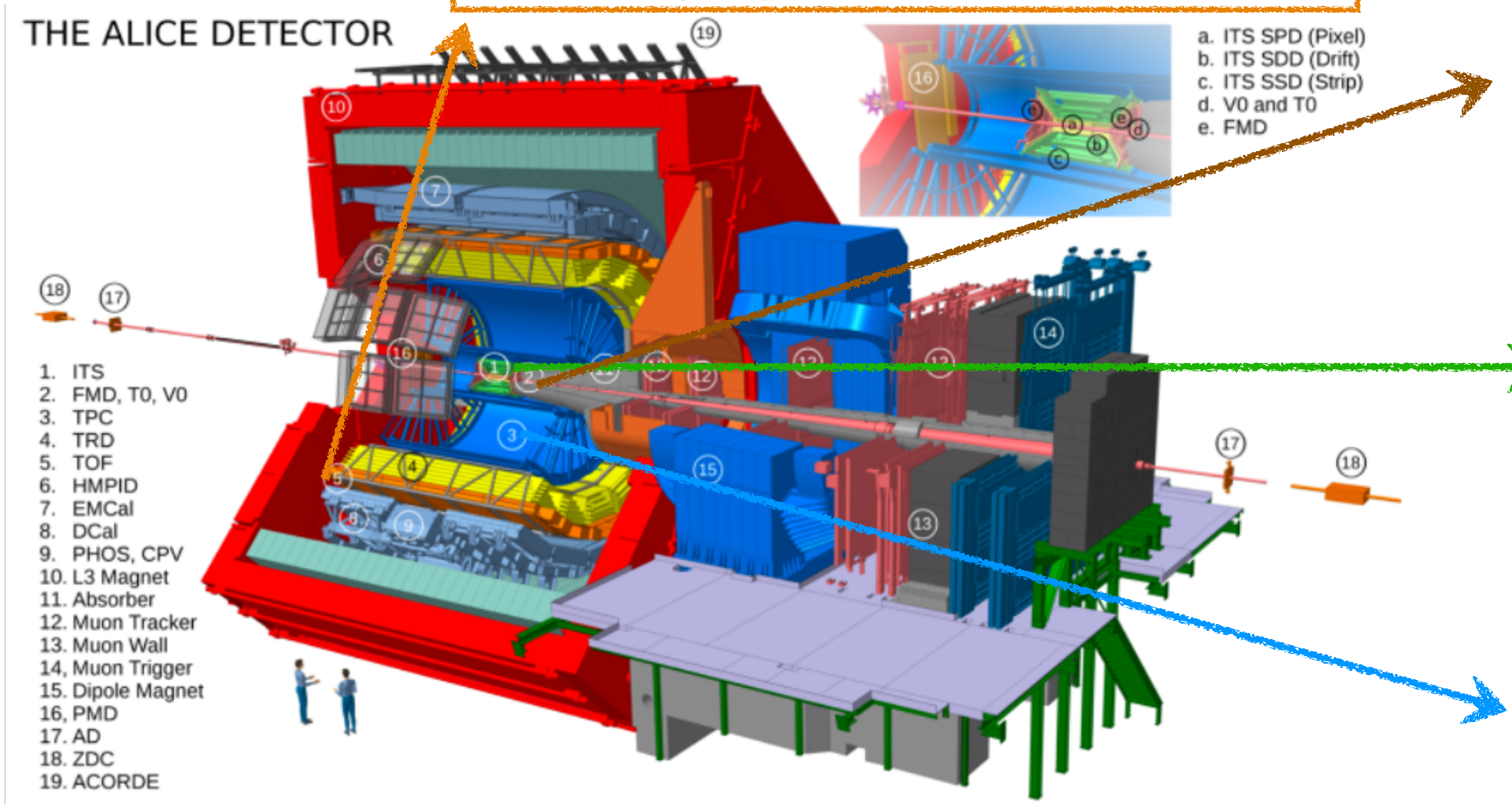
ALICE detector

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

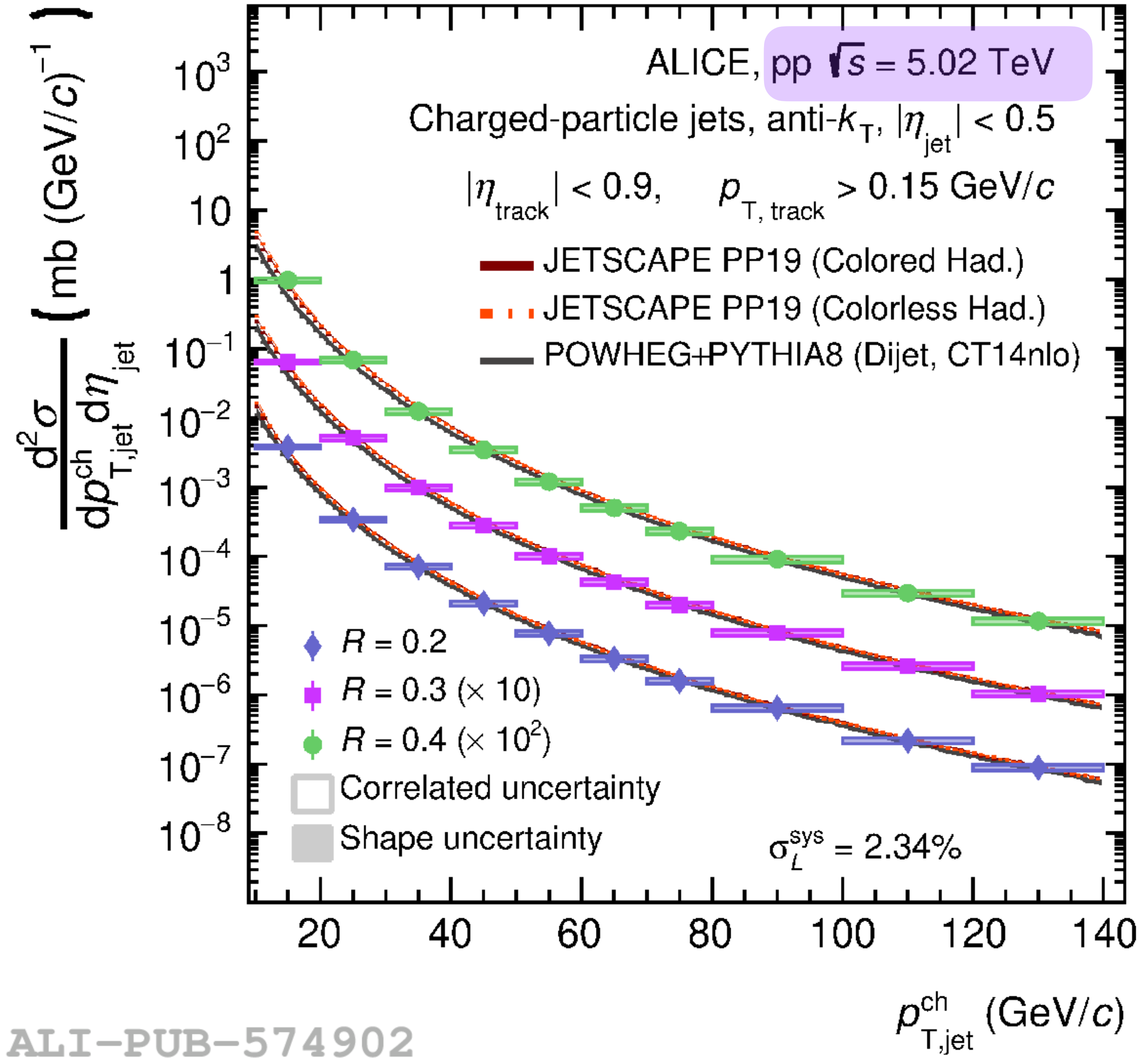


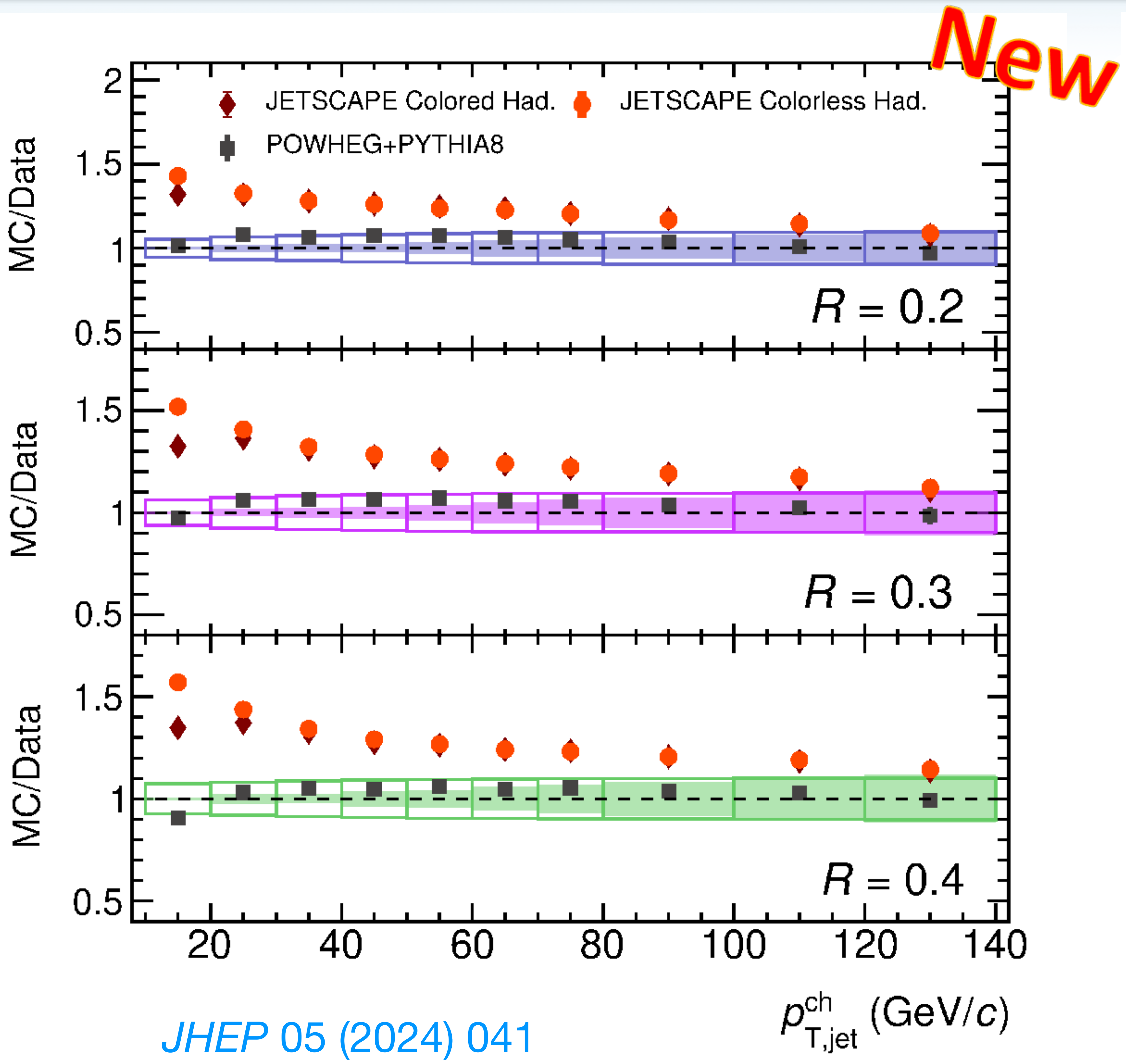
- **V0** (V0C + V0A)
  - $-3.7 < \eta < -1.7,\ 2.8 < \eta < 5.1$
  - Event trigger
  - Event multiplicity, centrality determination

Charged-particle tracks and jets

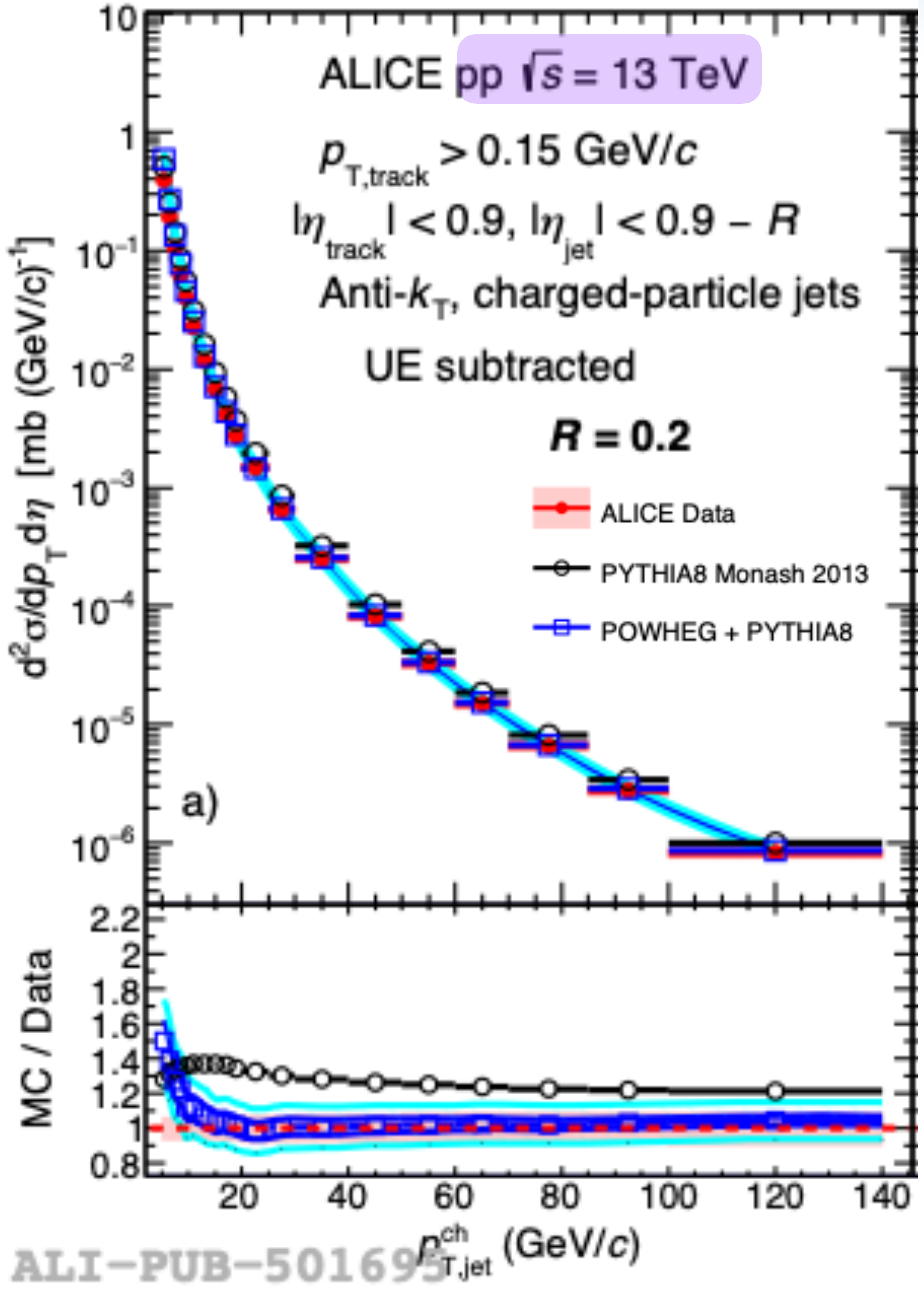
- **ITS** (Inner Tracking System)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Primary vertex reconstruction
  - Charged particle tracking
- **TPC** (Time Projection Chamber)
  - $|\eta| < 0.9,\ 0 < \varphi < 2\pi$
  - Charged particle tracking
  - Particle identification

Inclusive jet cross section in pp collisions





JHEP 05 (2024) 041



Eur. Phys. J. C 82 (2022) 514

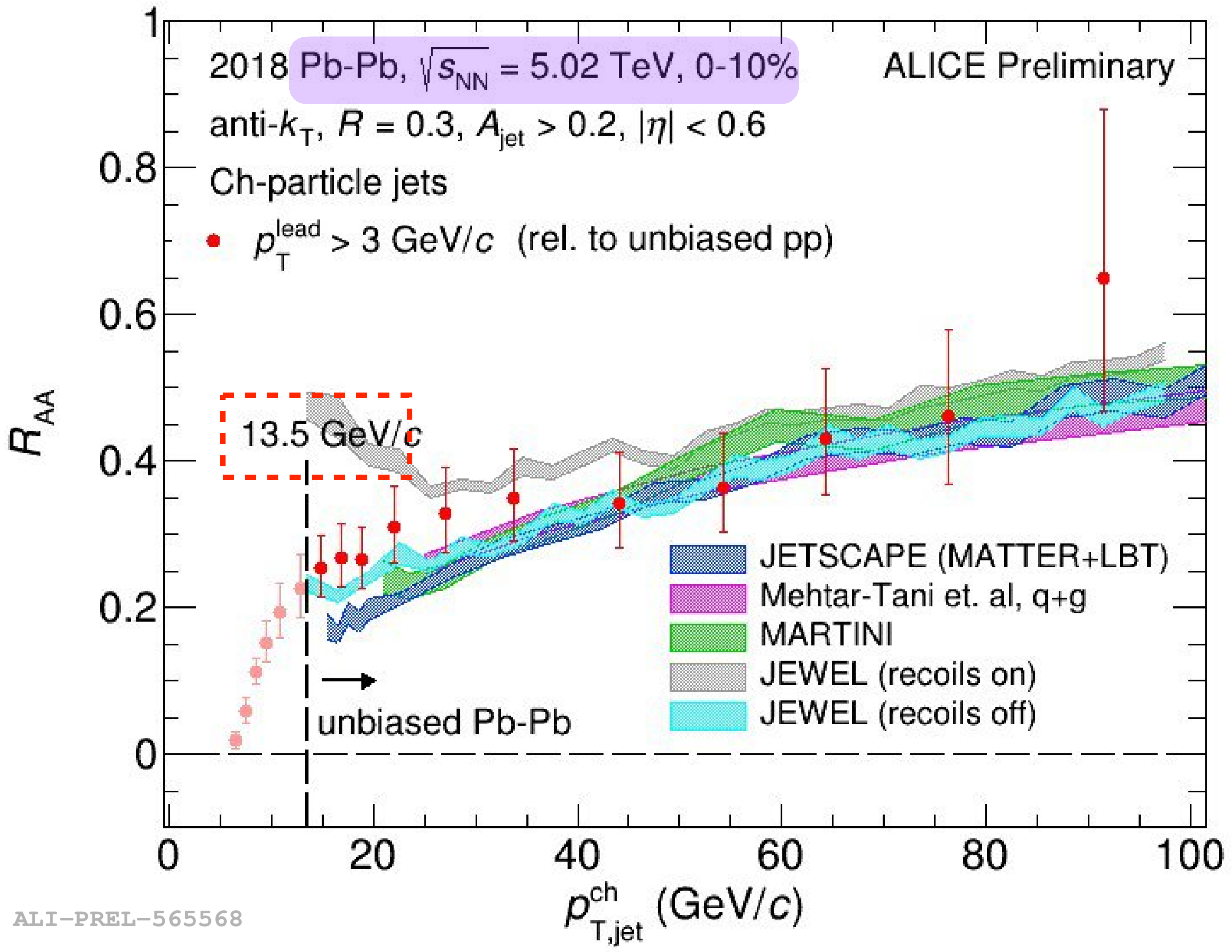
- Cross sections are compared with different MC calculations
  - Connection of jets to **pQCD**

Inclusive jet yield modification

- Nuclear modification factor: $R_{AA} = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle \, d\sigma_{pp}/dp_T}$

- **Energy loss and redistribution**: lost energy transported to larger angles
- Recent years: expanding phase space to **larger *R*, lower p_T**
  - New background subtraction techniques

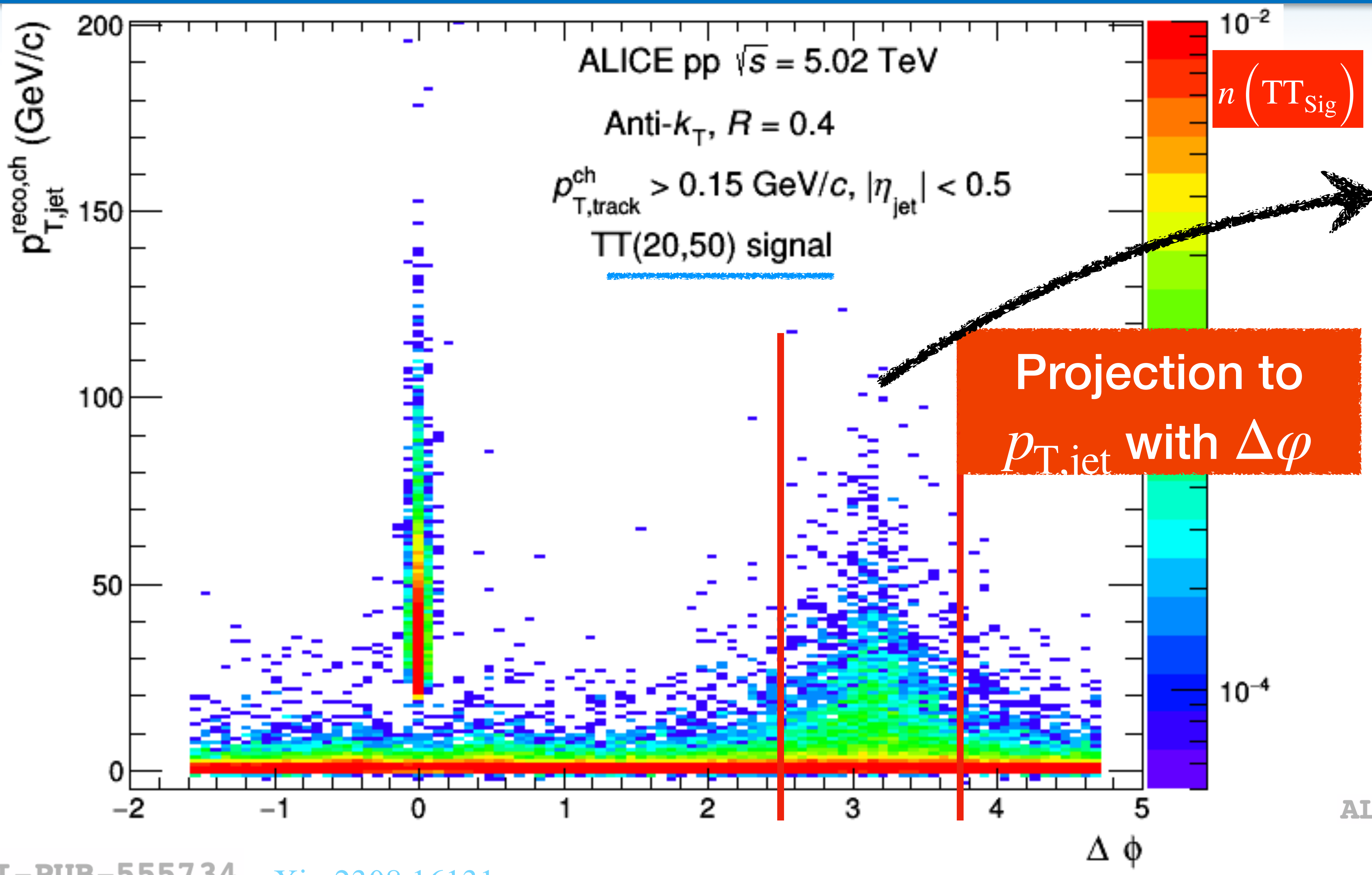
  → Use **Mixed Events (ME)** to determine the distribution of combinatorial jets



Nuclear modification factor **down to low** p_T

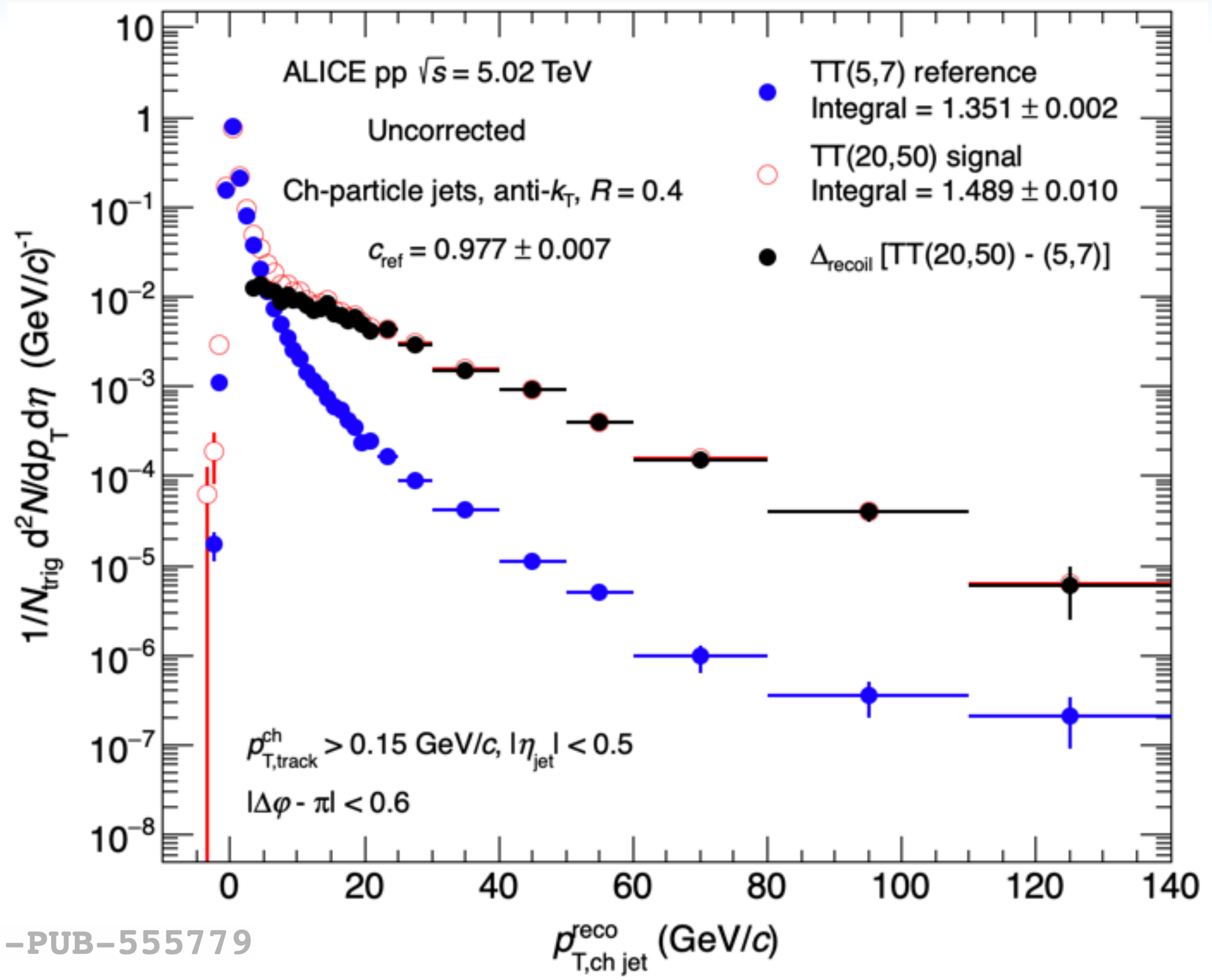
→ where impact of jet quenching is largest

Semi-inclusive jet p_T distributions



ALI-PUB-555734 arXiv:2308.16131

arXiv:2308.16128

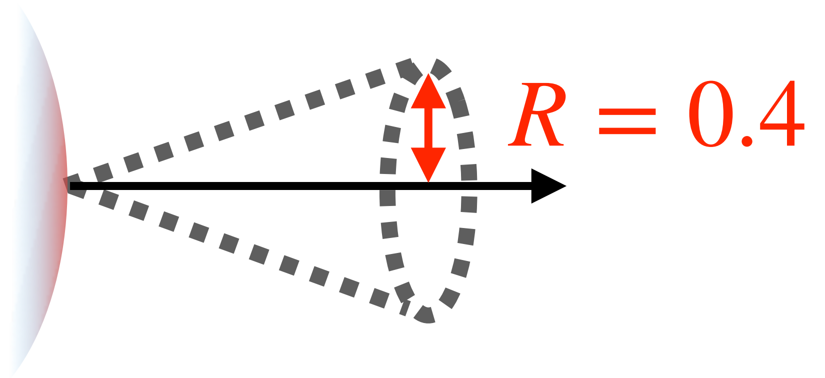


ALI-PUB-555779

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

- Recoil jet p_T **vs $\Delta\varphi$ 2-dimensional** distributions in two trigger track p_T intervals
- **Recoil jet p_T distributions** in two trigger track p_T intervals are then obtained from 2D projection
    - **Combinatorial background** can be removed by taking the difference of the recoil jet distributions in two TT intervals

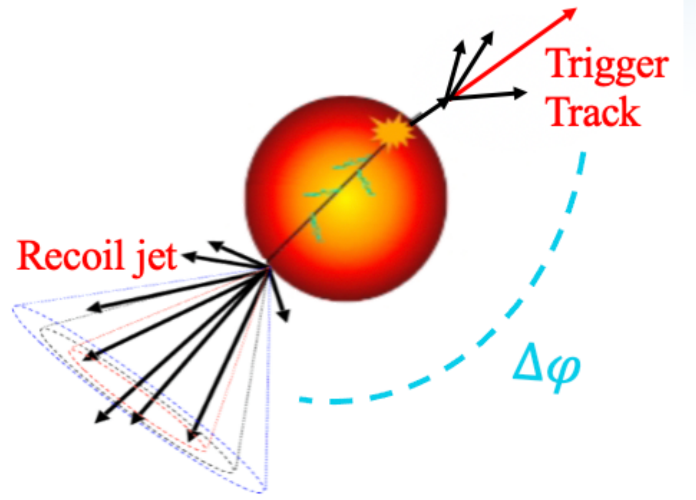
Semi-inclusive jet energy redistribution

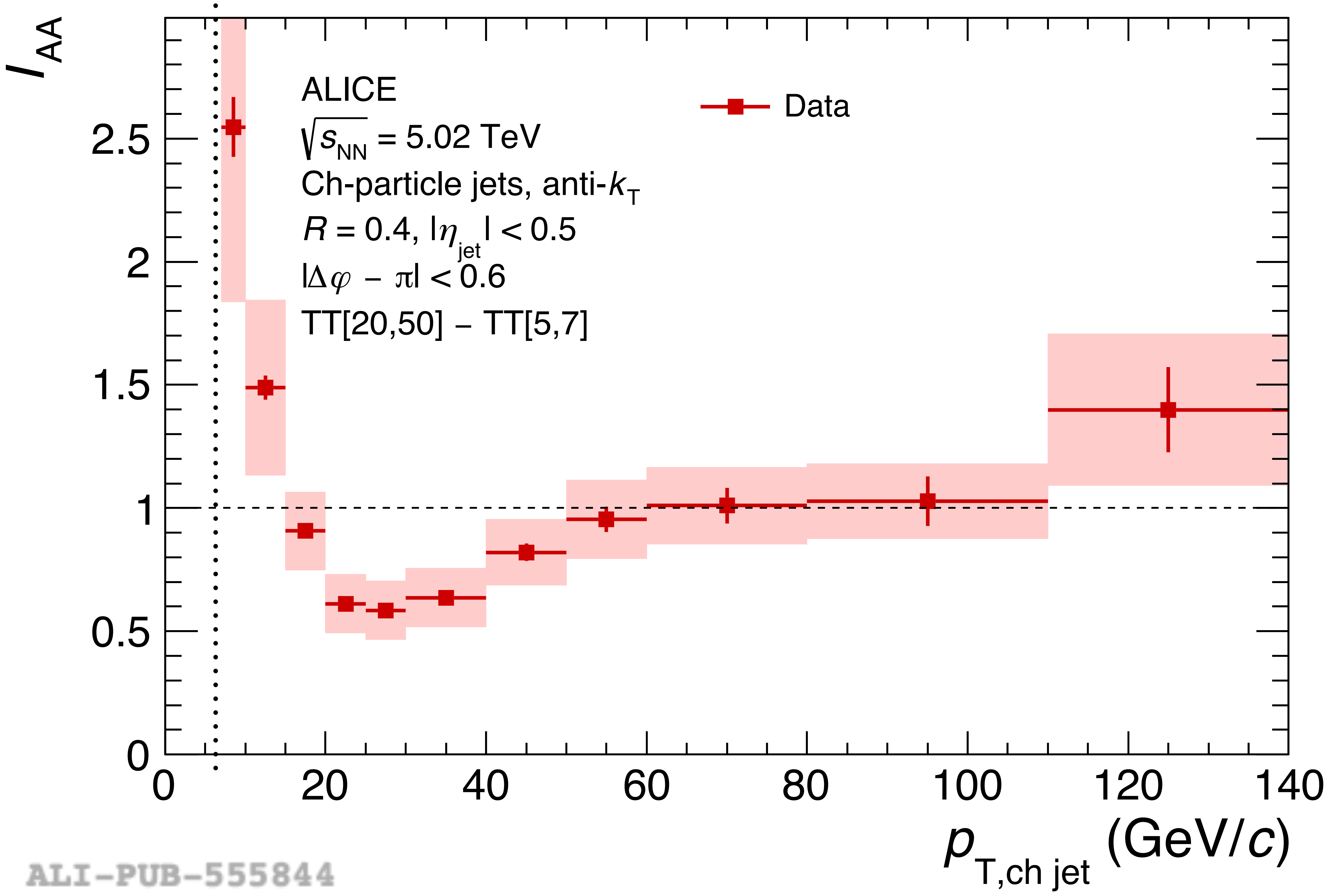


0 – 10 %

R = 0.4

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





- First measurements of semi-inclusive recoil jet yields down to very **low** p_T (7 GeV/c) with ALICE

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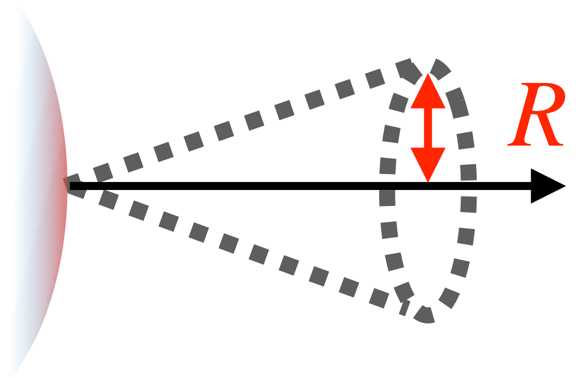

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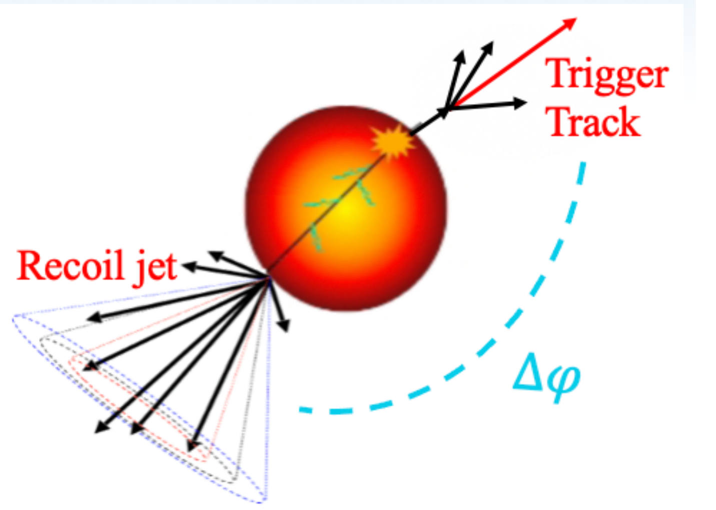

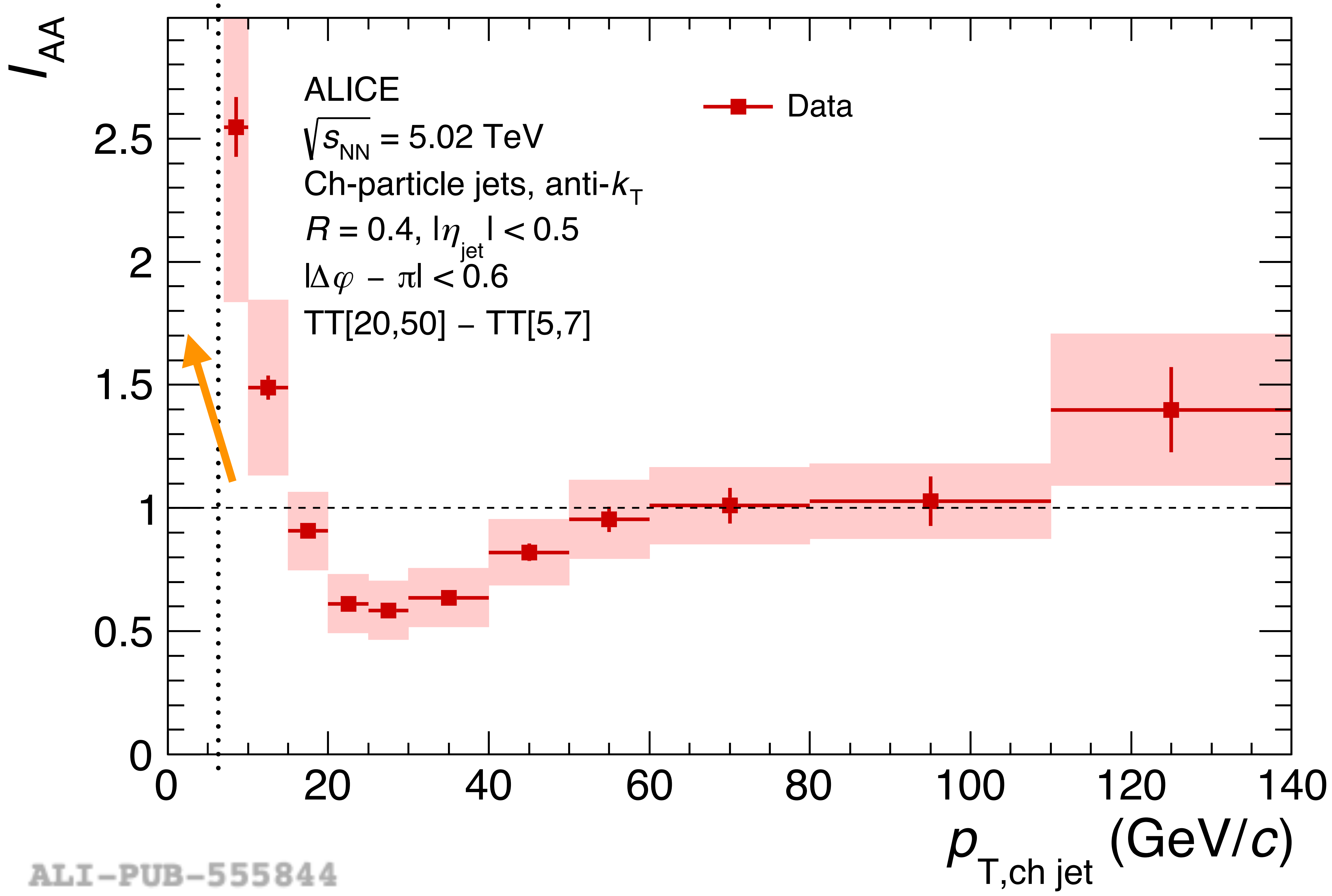

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→ hint of energy recovery in low p_T jets?

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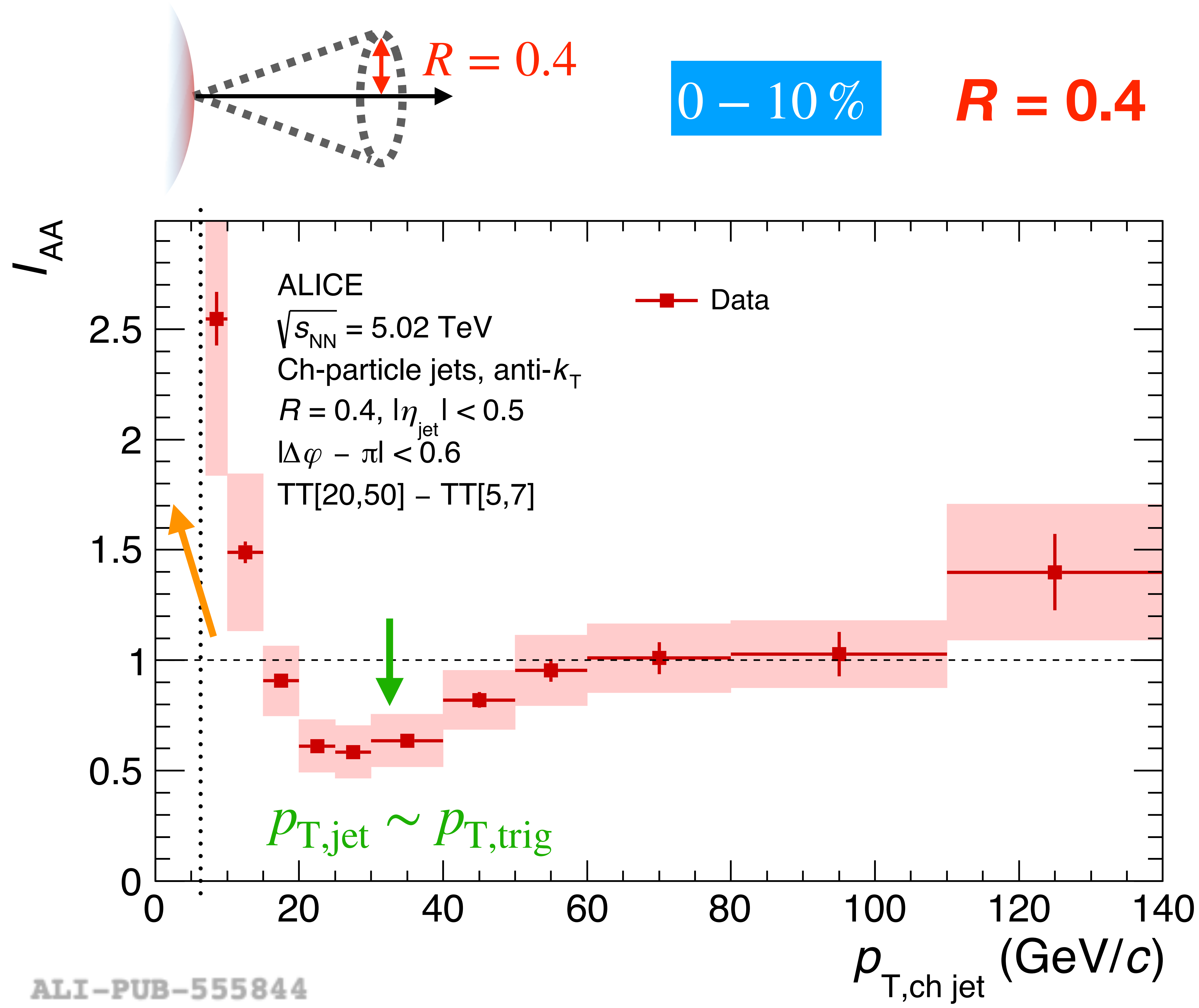

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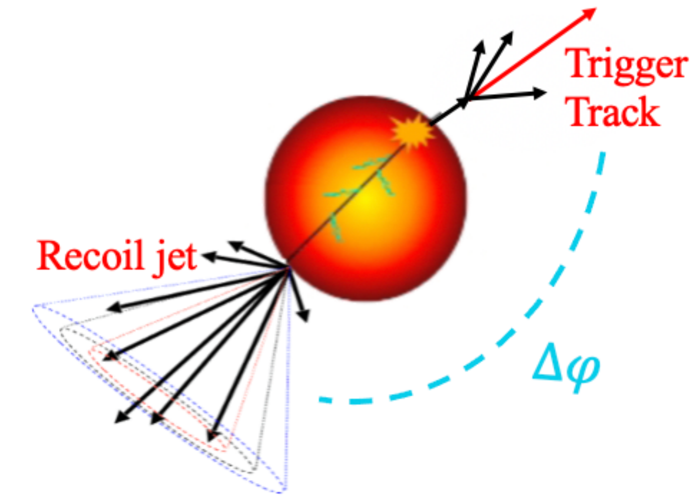

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  → Jet energy loss

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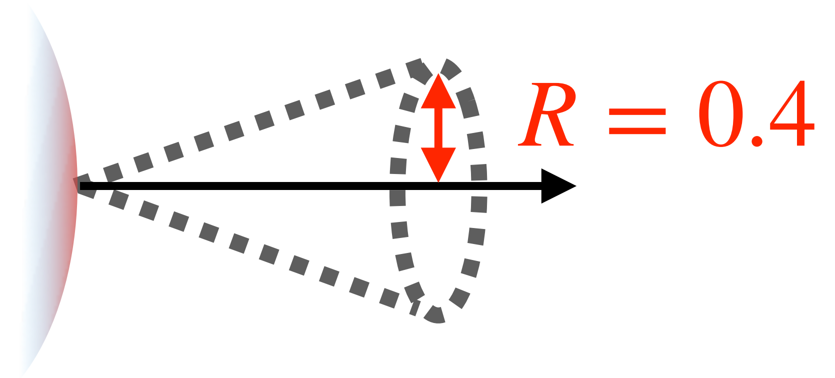

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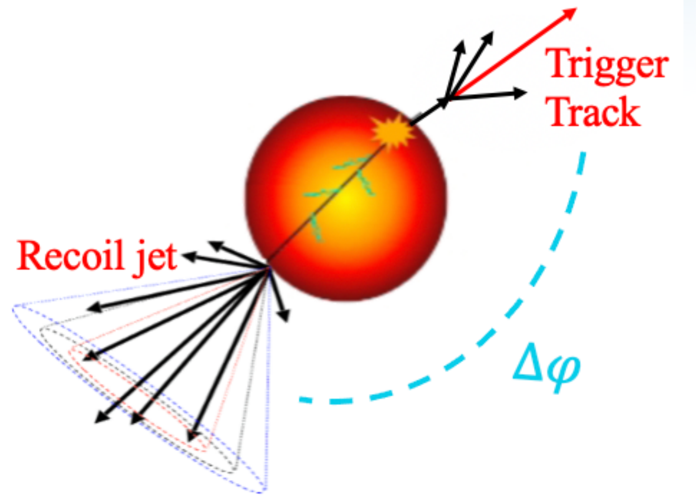

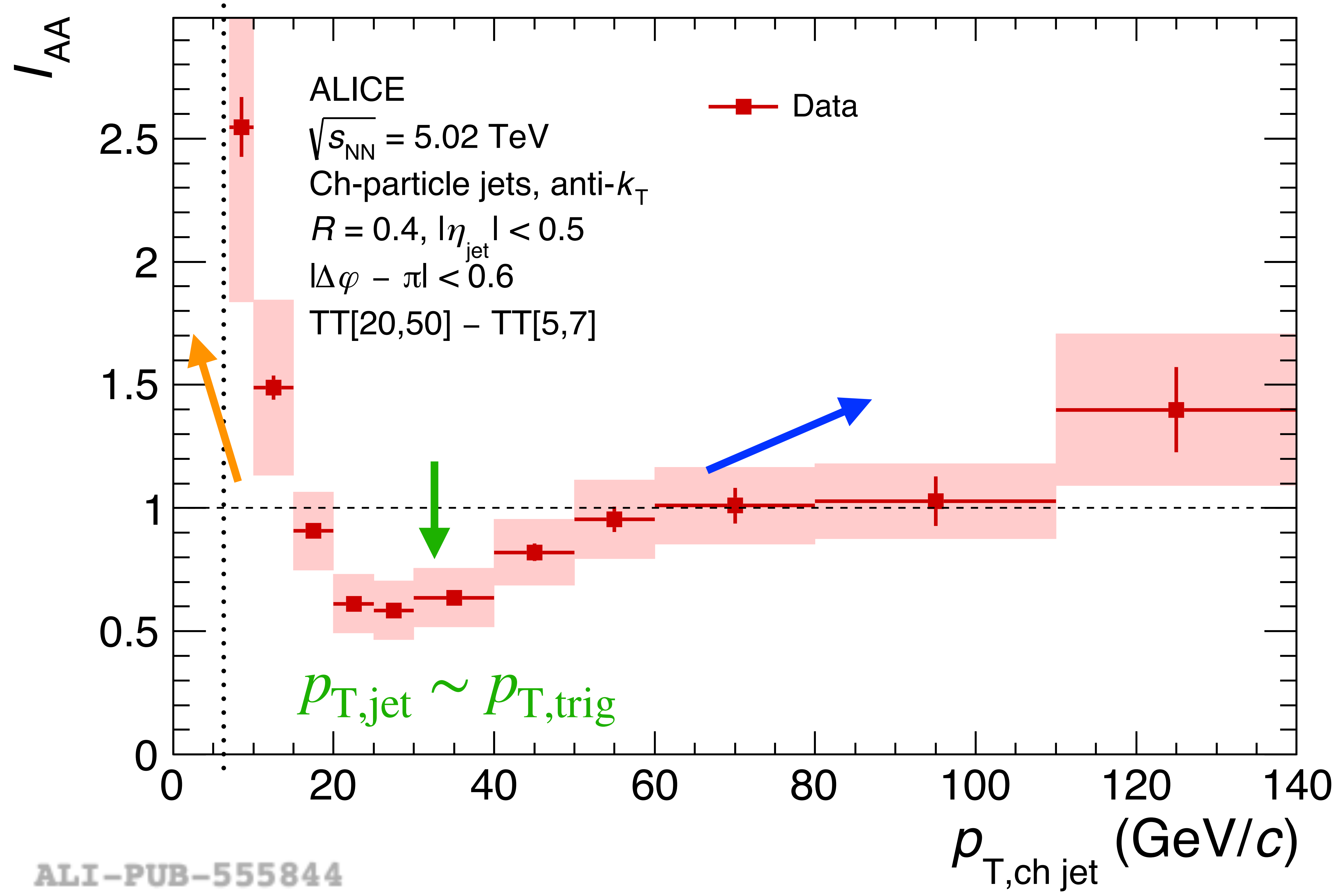

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- **Jet yield enhancement** at low p_T

  → 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

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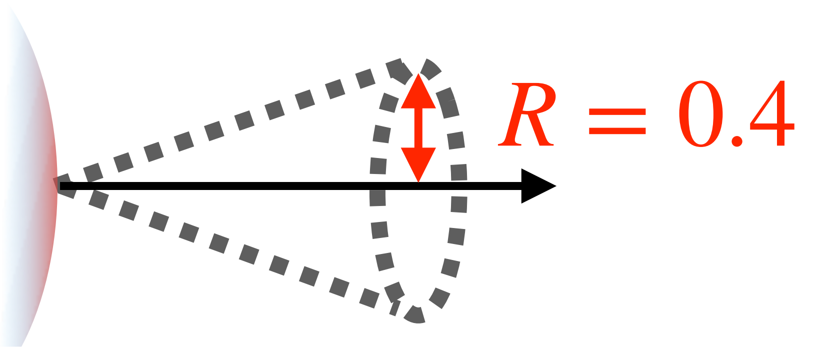
Semi-inclusive jet energy redistribution



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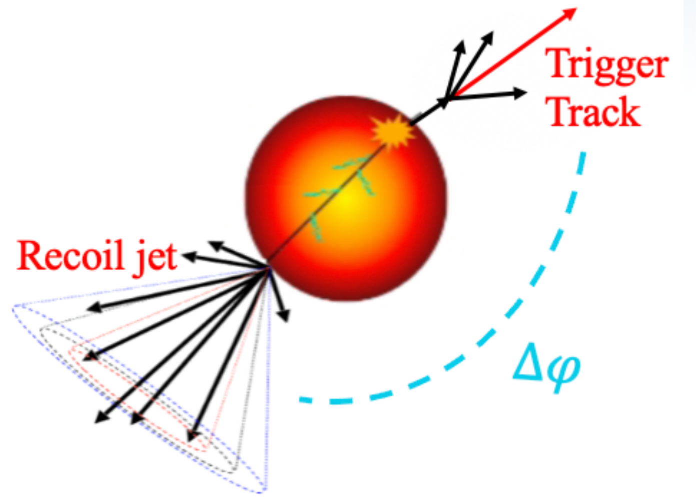
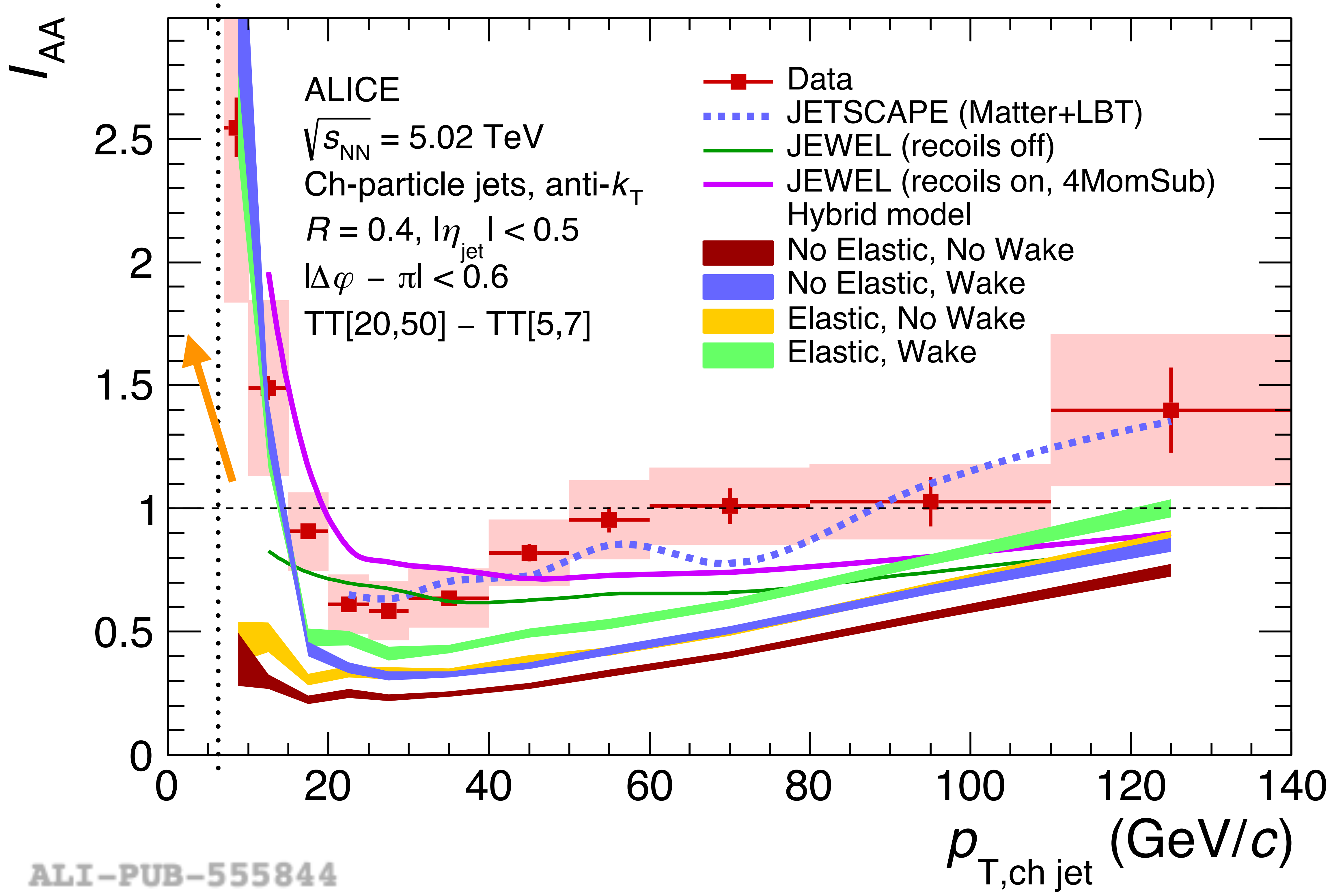




JETSCAPE with Pb-Pb tune:

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

Multi-stage energy loss MATTER+LBT

JEWEL:

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

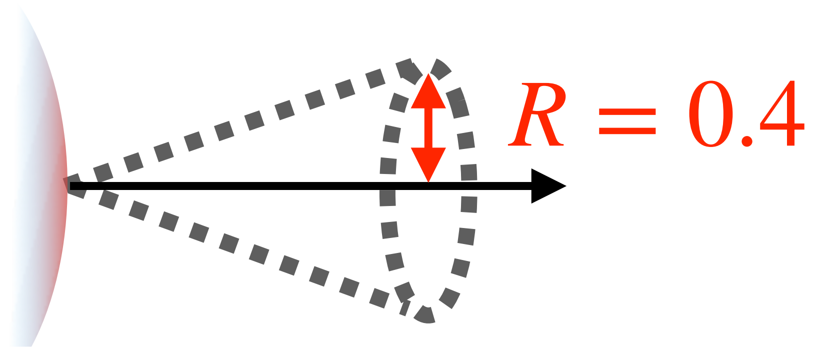
Includes collisional and radiative parton energy loss mechanisms in a pQCD approach. medium response effects via treatment of 'recoils'

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.

Semi-inclusive jet energy redistribution



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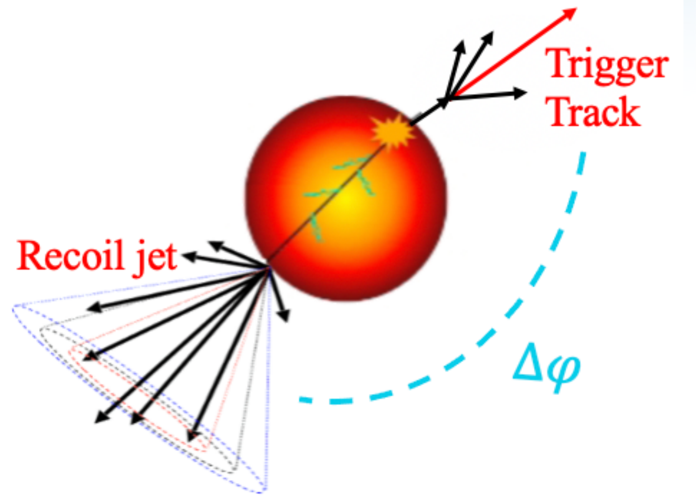
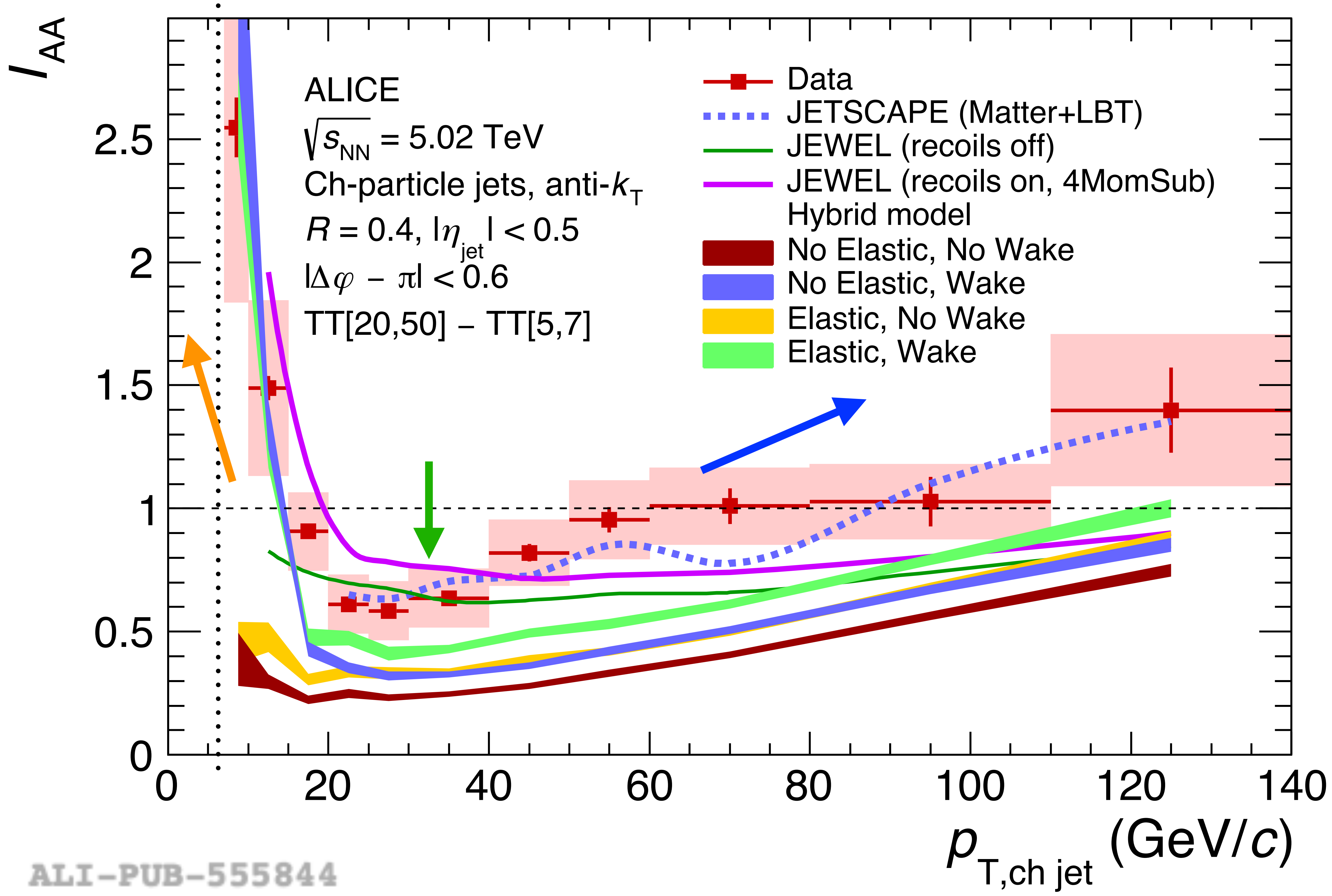
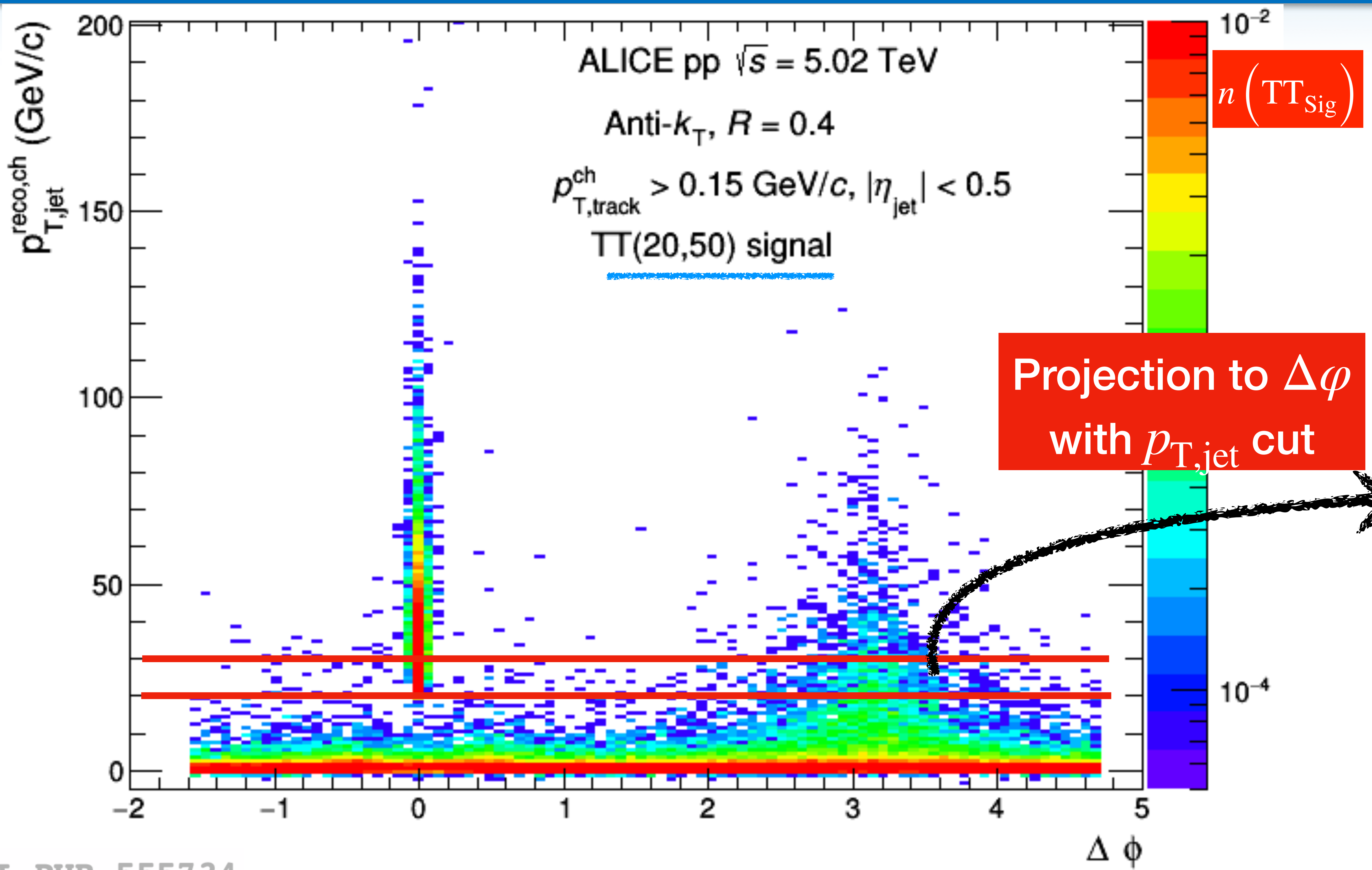




- The **rising trend** is qualitatively described by all predictions
  - **JETSCAPE largely reproduces** the I_{AA} distributions
  - **Hybrid Model** and **JEWEL** predictions **overestimate the suppression** at high p_T
- **Hybrid Models** with wake effect and **JEWEL with recoils on** seem to catch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

Semi-inclusive jet angular distributions



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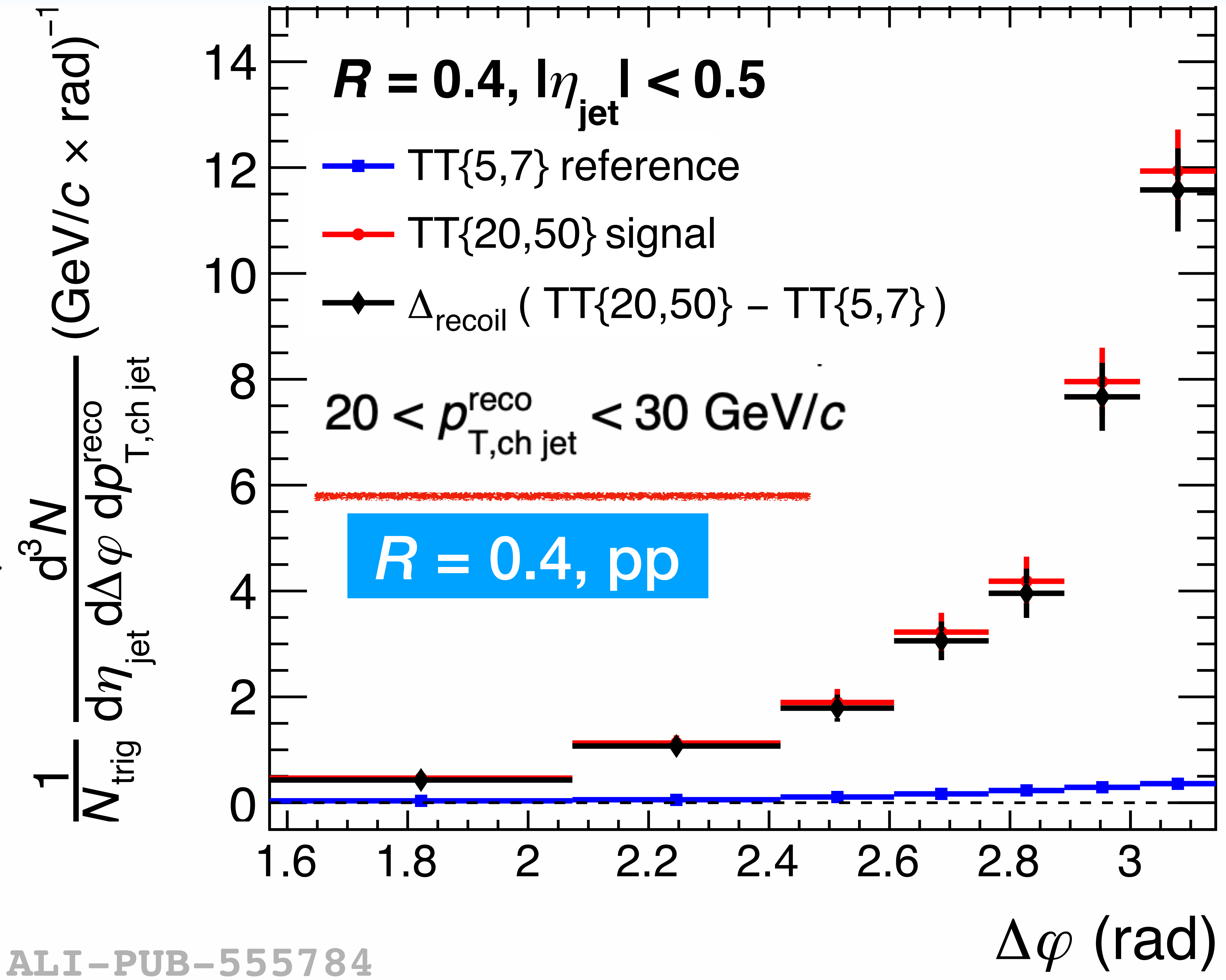


ALI-PUB-555784

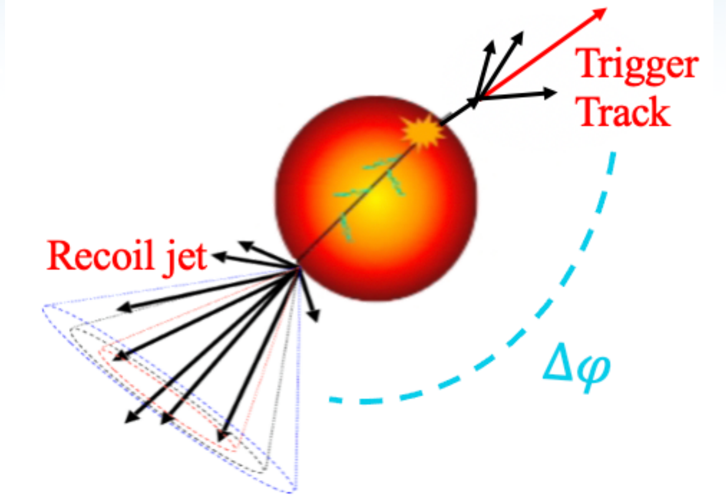
$$\Delta_{recoil}(p_{T,jet}, \Delta\varphi) = \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\bigg|_{p_T^{trig}\in \mathrm{TT_{Sig}}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^3N_{jet}}{d\eta_{jet}\, dp_{T,jet}\, d\Delta\varphi}\bigg|_{p_T^{trig}\in \mathrm{TT_{Ref}}}$$

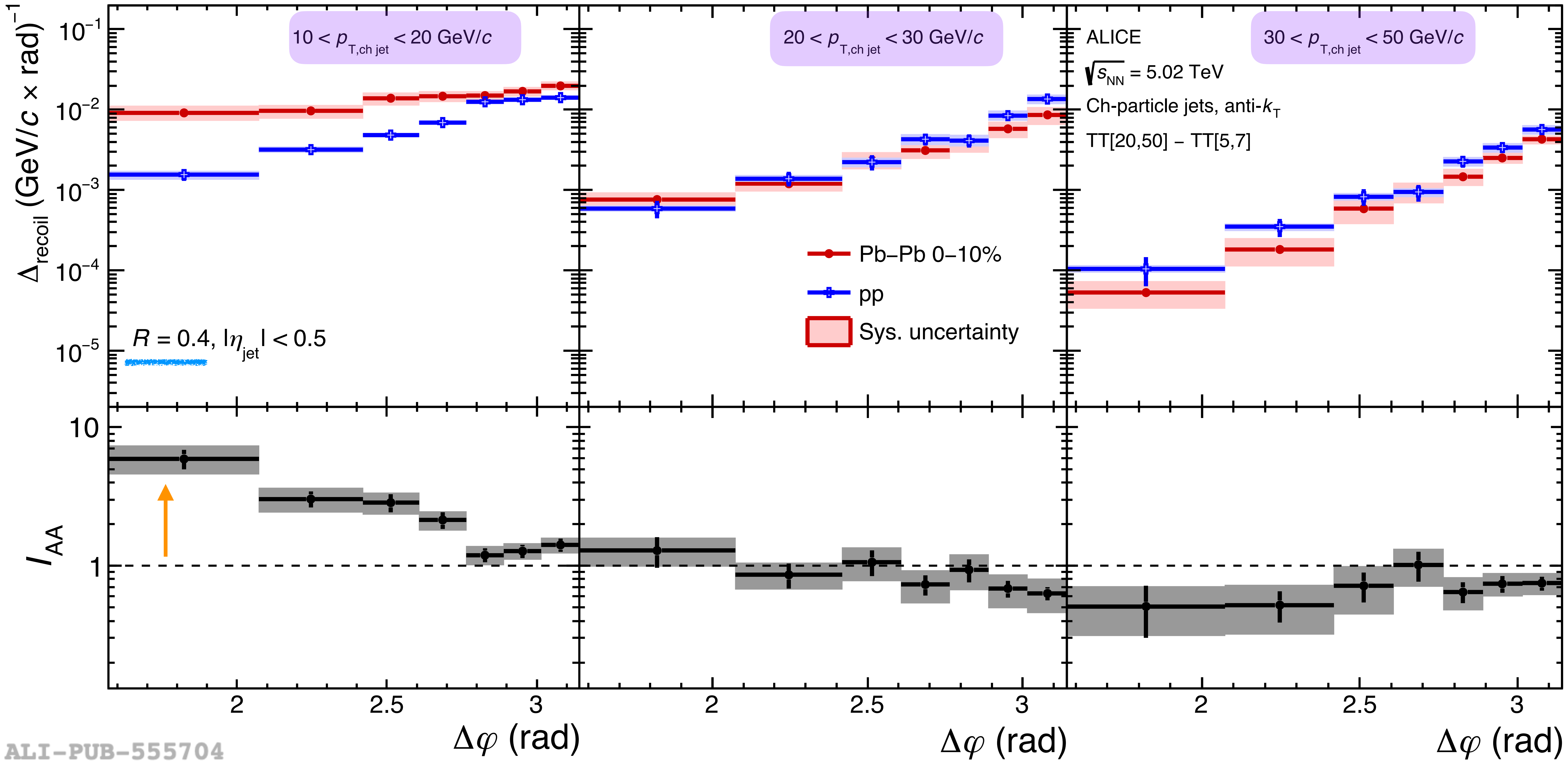
- Get **the raw p_T vs $\Delta\varphi$ 2-dimensional** distributions for two trigger track p_T intervals
- **$\Delta\varphi$ distributions** measured for the two TT classes using 2D projections

Semi-inclusive jet angular distributions in Pb-Pb

0 – 10 %   **R = 0.4**

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





- **Significant broadening** for $p_{\rm T} \in [10,20]$ GeV/c

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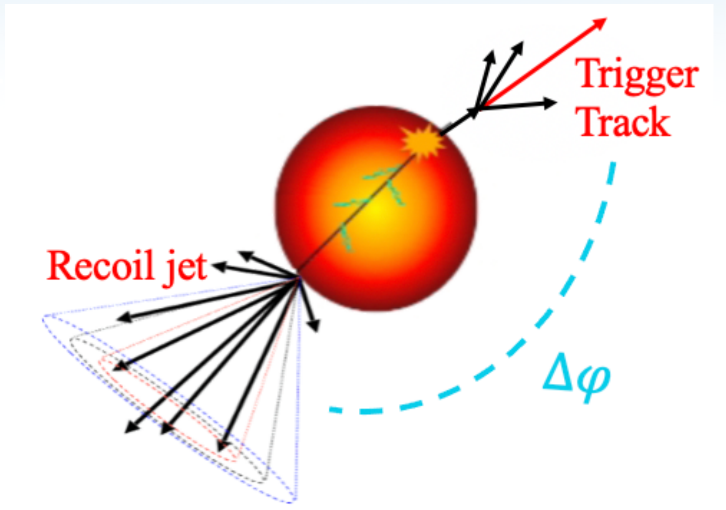

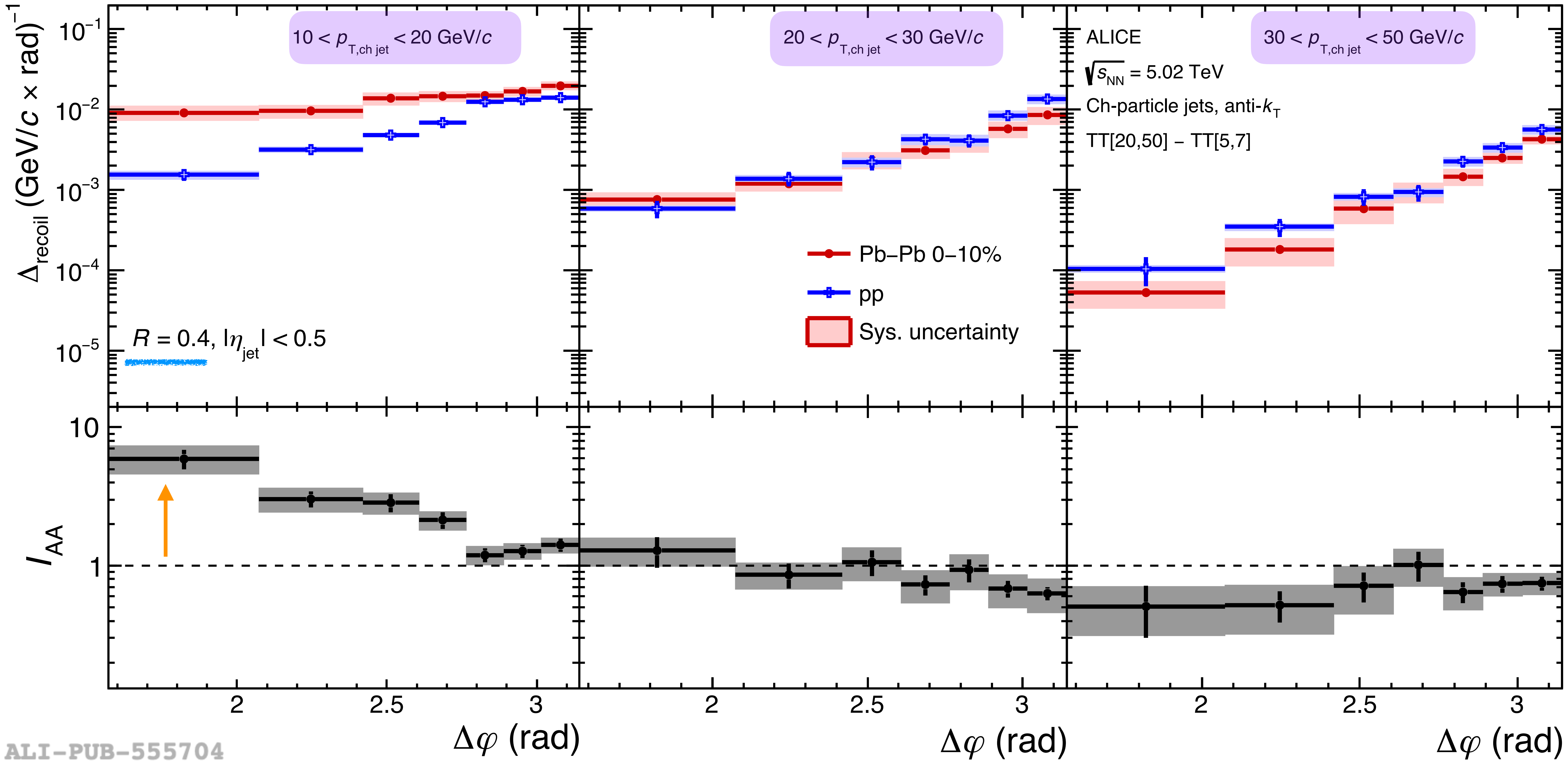

- **Significant broadening** for $p_T \in [10,20]$ GeV/c
- **No broadening or suppression** for $p_T \in [20,30]$ GeV/c

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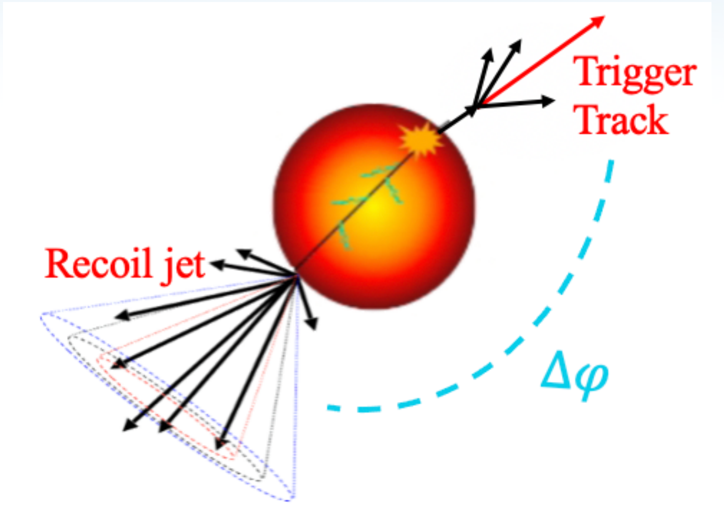
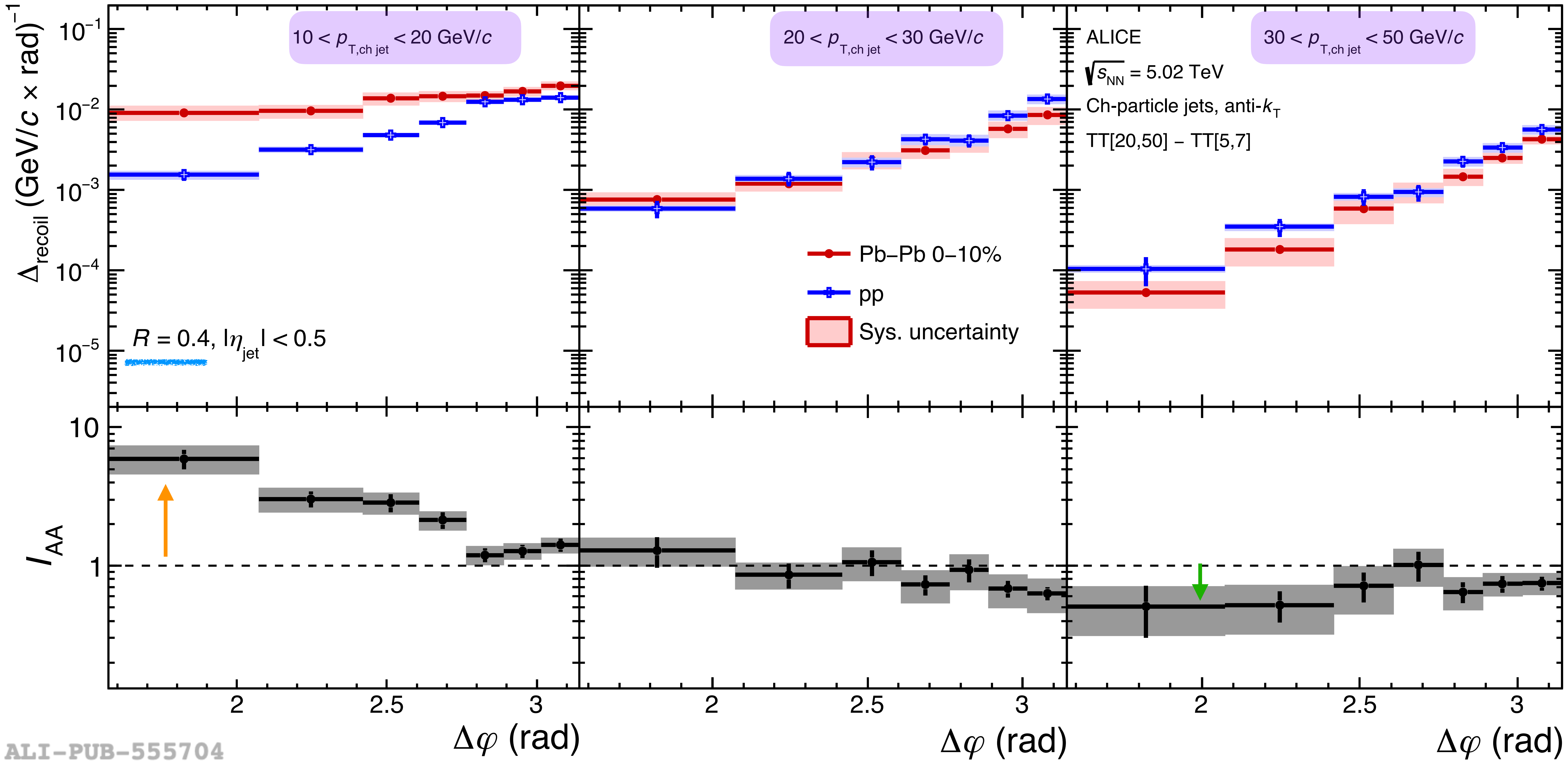
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(\Delta\varphi)_{AA}}{\Delta_{\text{recoil}}(\Delta\varphi)_{pp}}$$





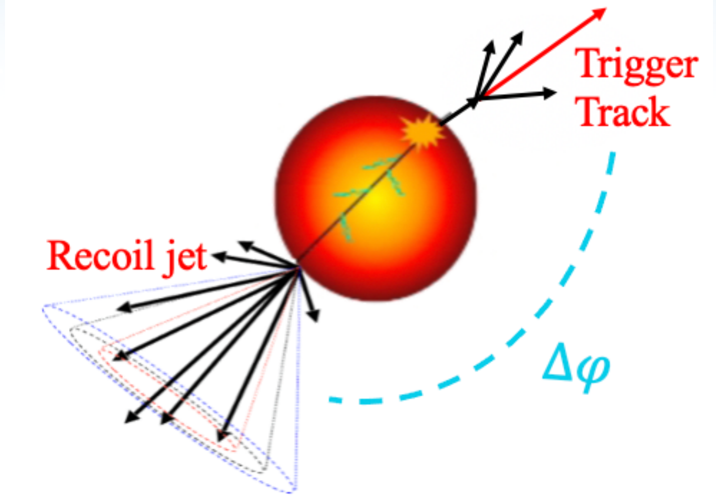
- **Significant broadening** for $p_T \in [10,20]$ GeV/c
- **No broadening or suppression** for $p_T \in [20,30]$ GeV/c
- **Jet yield suppression** for $p_T \in [30,50]$ GeV/c

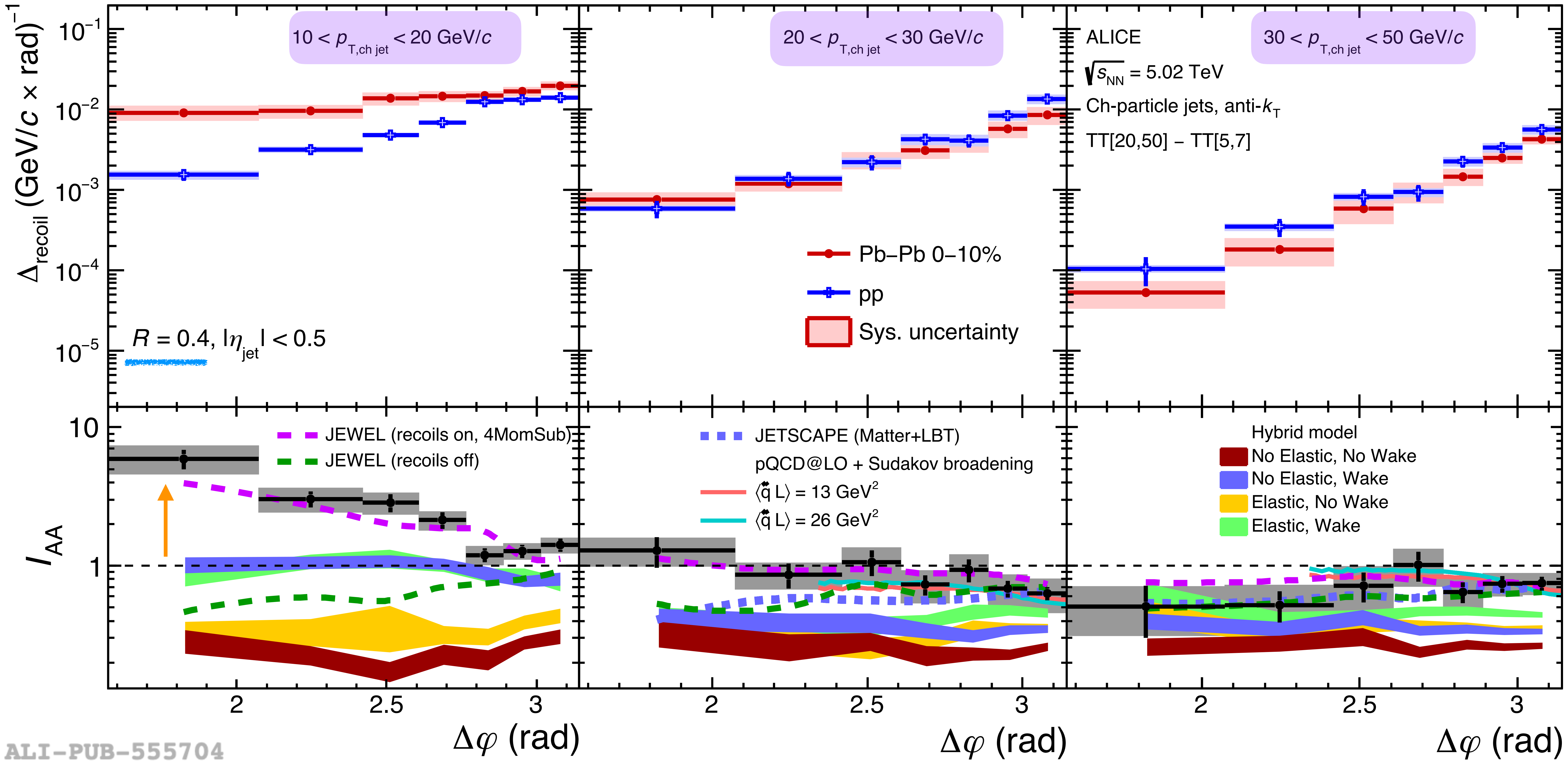
Semi-inclusive jet angular distributions in Pb-Pb

0 – 10 %

R = 0.4

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





JETSCAPE with Pb-Pb tune:

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

Multi-stage energy loss MATTER+LBT

JEWEL:

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

Includes collisional and radiative parton energy loss mechanisms in a pQCD approach. medium response effects via treatment of 'recoils'

Hybrid Model:

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

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

pQCD@LO + Sudakov broadening:

Phys.Lett.B 773 (2017) 672

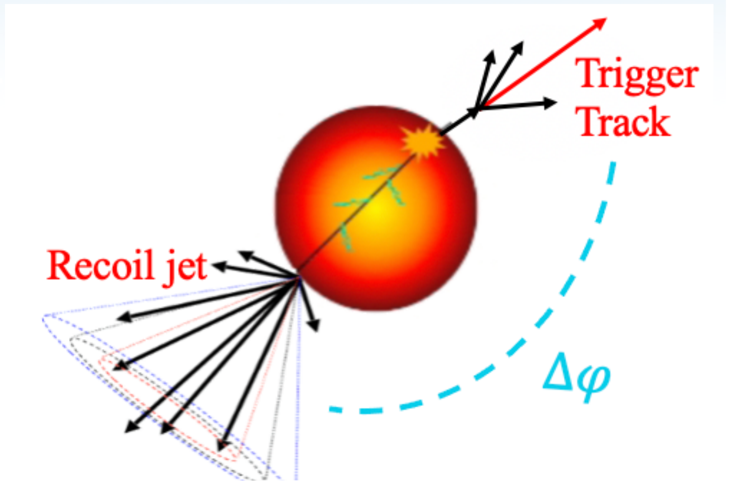
Leading order pQCD, azimuthal broadening via jet transport coefficient

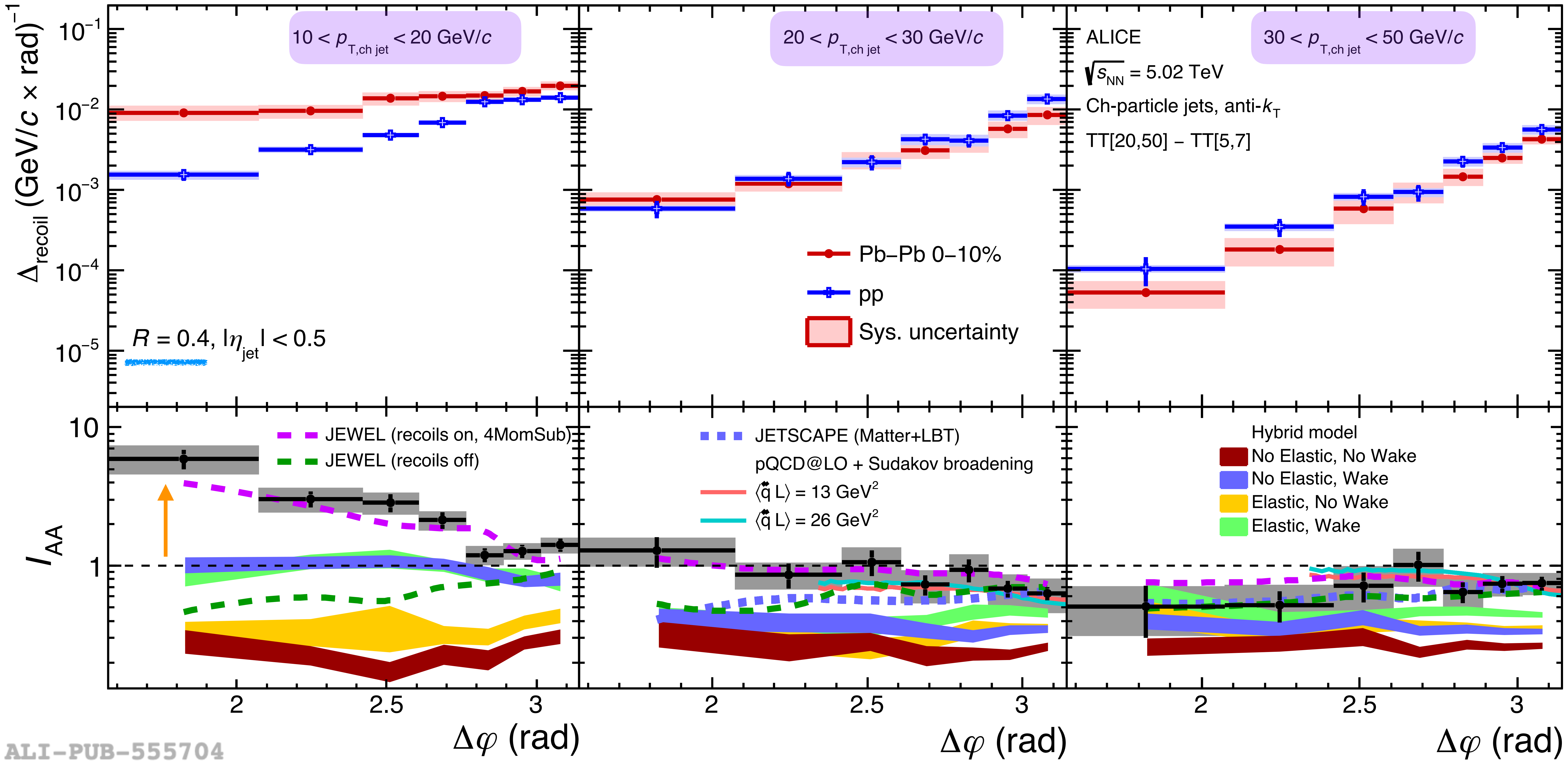
Semi-inclusive jet angular distributions in Pb-Pb

0 – 10 %

R = 0.4

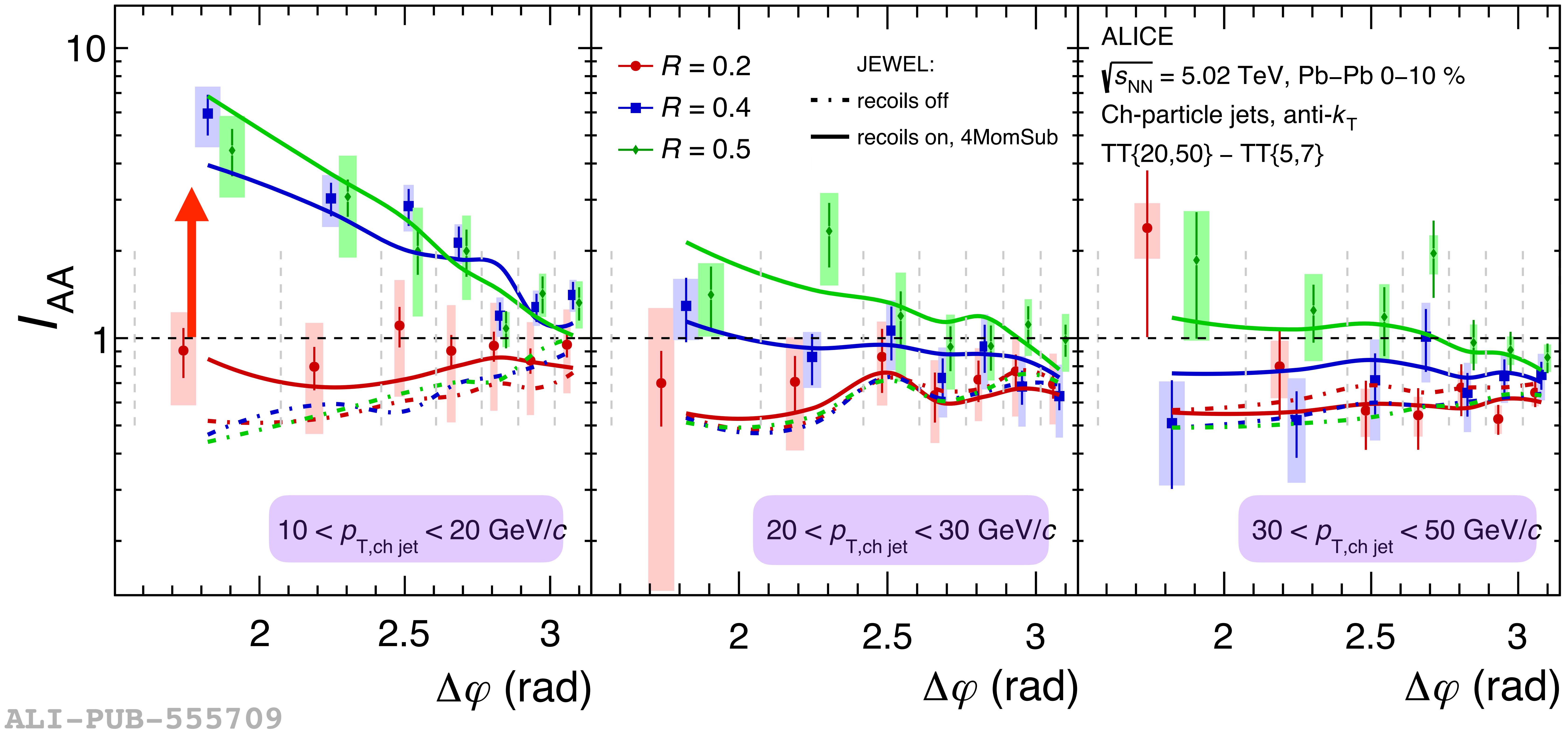
$$I_{AA} \equiv \frac{\Delta_{recoil}(\Delta\varphi)_{AA}}{\Delta_{recoil}(\Delta\varphi)_{pp}}$$

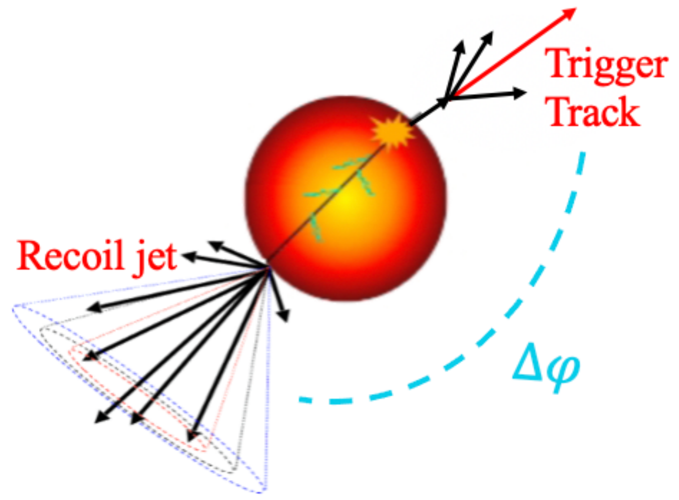




- **JETSCAPE** and **pQCD w/ broadening reasonably describe** the data for jet $p_T \in [20,50]$ GeV/c → lacking precision to resolve the difference between two $\hat{q}$ values
- **JEWEL** (recoils-on) **describes well the I_{AA} in-all p_T bins**
- **Hybrid model** captures yield enhancement, but no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

Semi-inclusive jet angular modification $I_{AA}(\Delta\varphi)$: different R





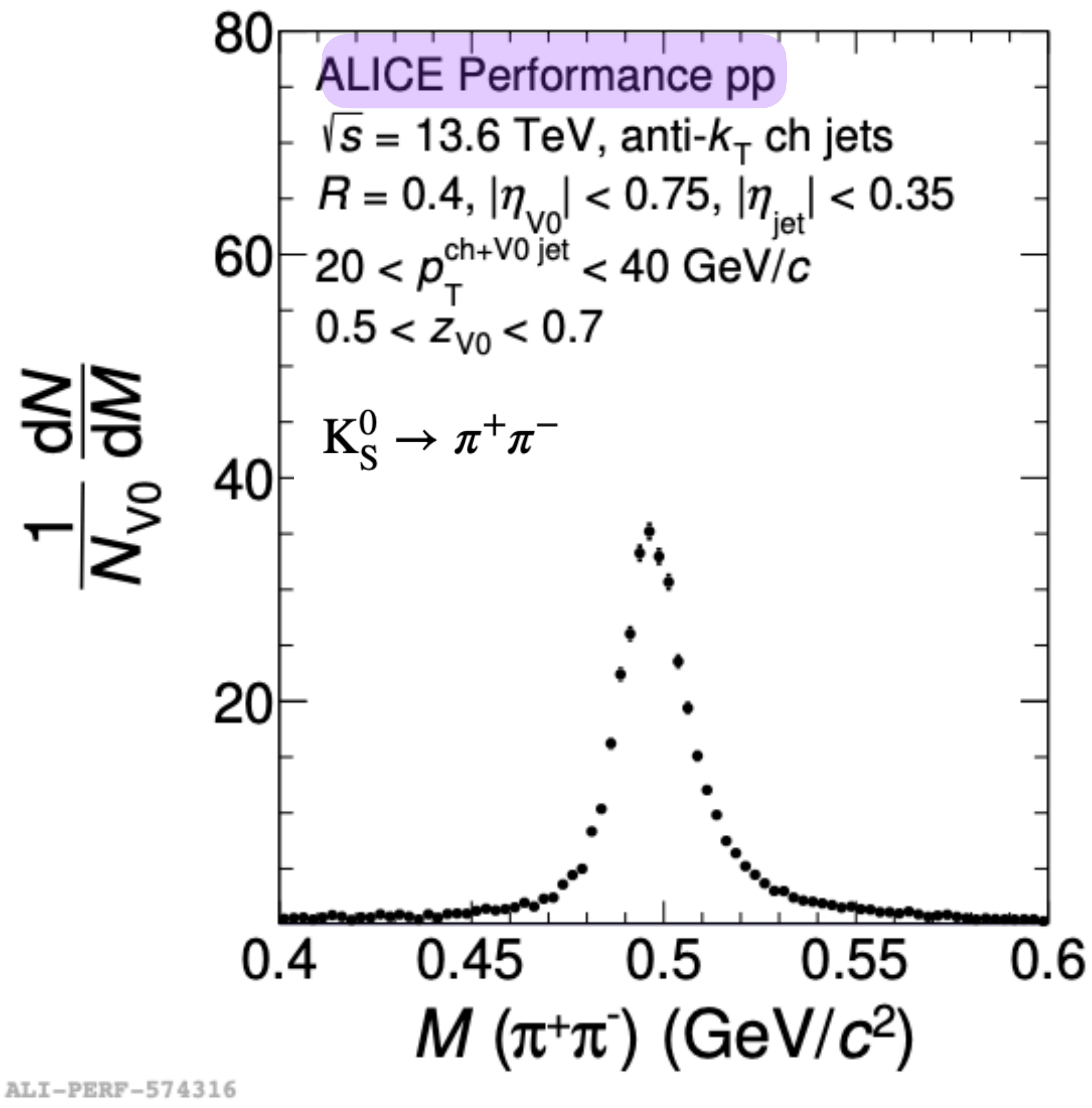
$$I_{AA} \equiv \frac{\Delta_{recoil}\,(\Delta\varphi)_{AA}}{\Delta_{recoil}\,(\Delta\varphi)_{pp}}$$

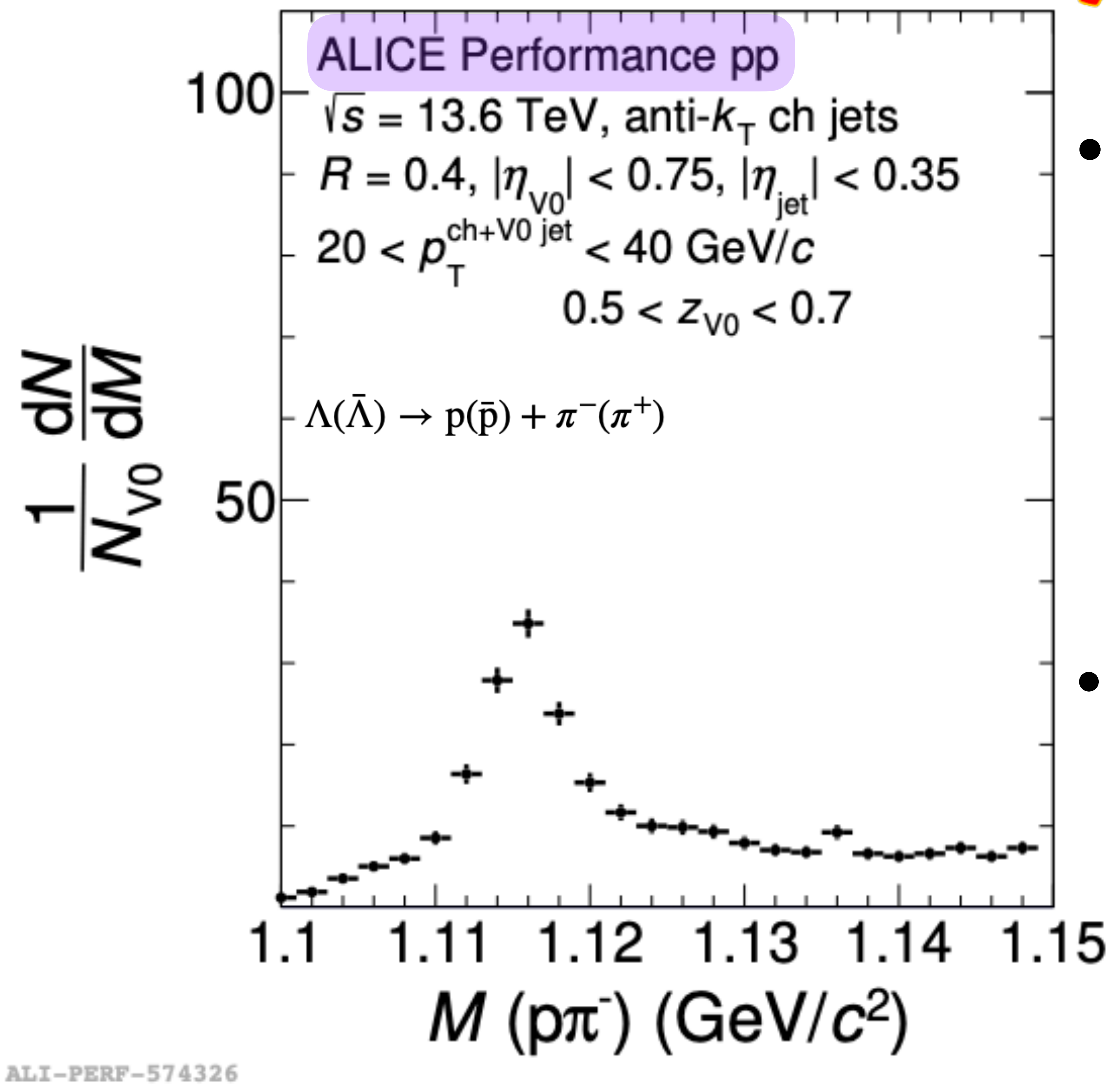
- Transition to broadening from $R = 0.2$ to $R = 0.4$ for $p_T \in [10,20]$ GeV/c: soft particles from the **medium response** clustered inside a jet scale with R^2
- All features of distribution **reproduced by JEWEL** with recoils on

V0 in jets with Run3

$0.5 < z_{v0} < 0.7$: the majority of jet momentum carried by V0

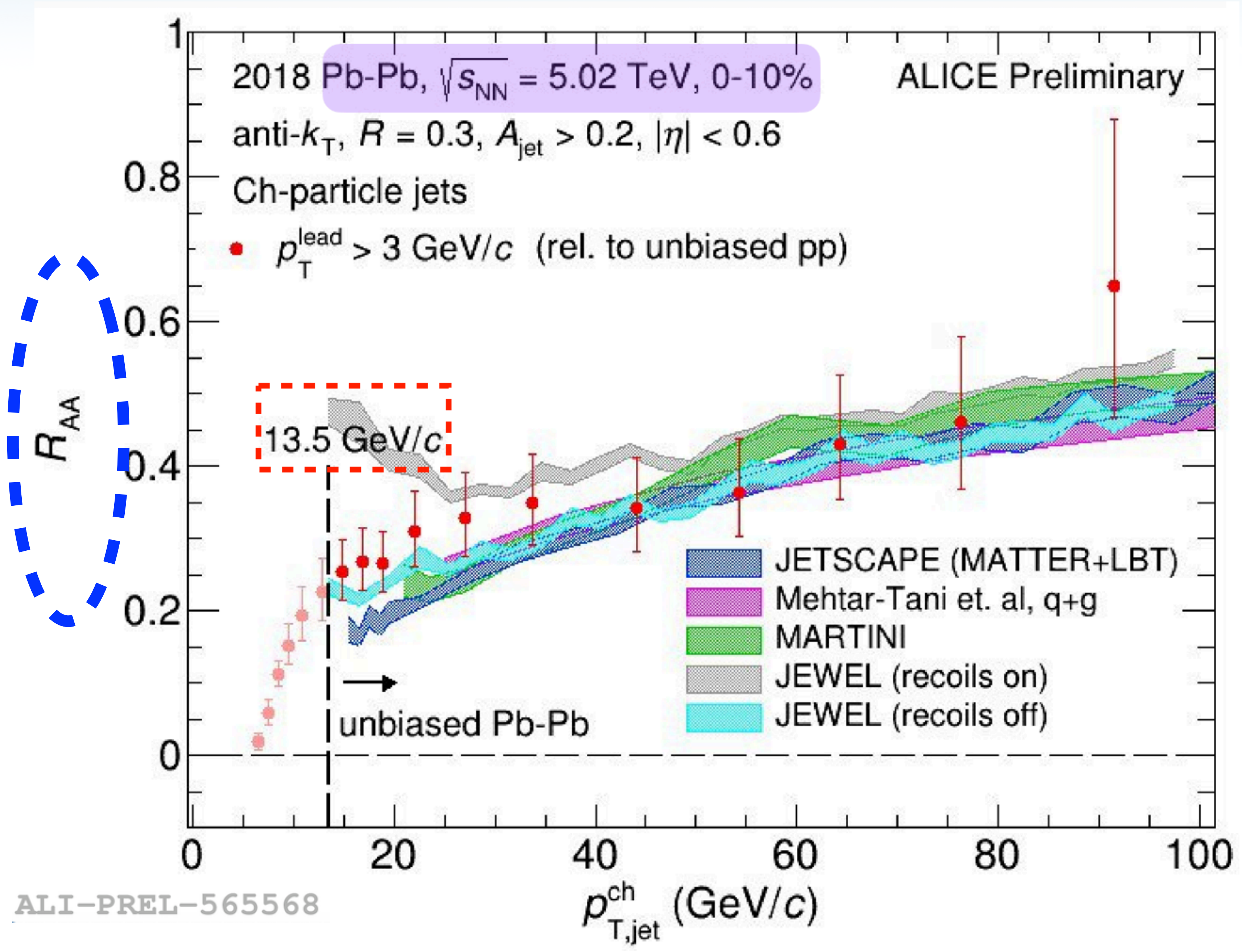
New





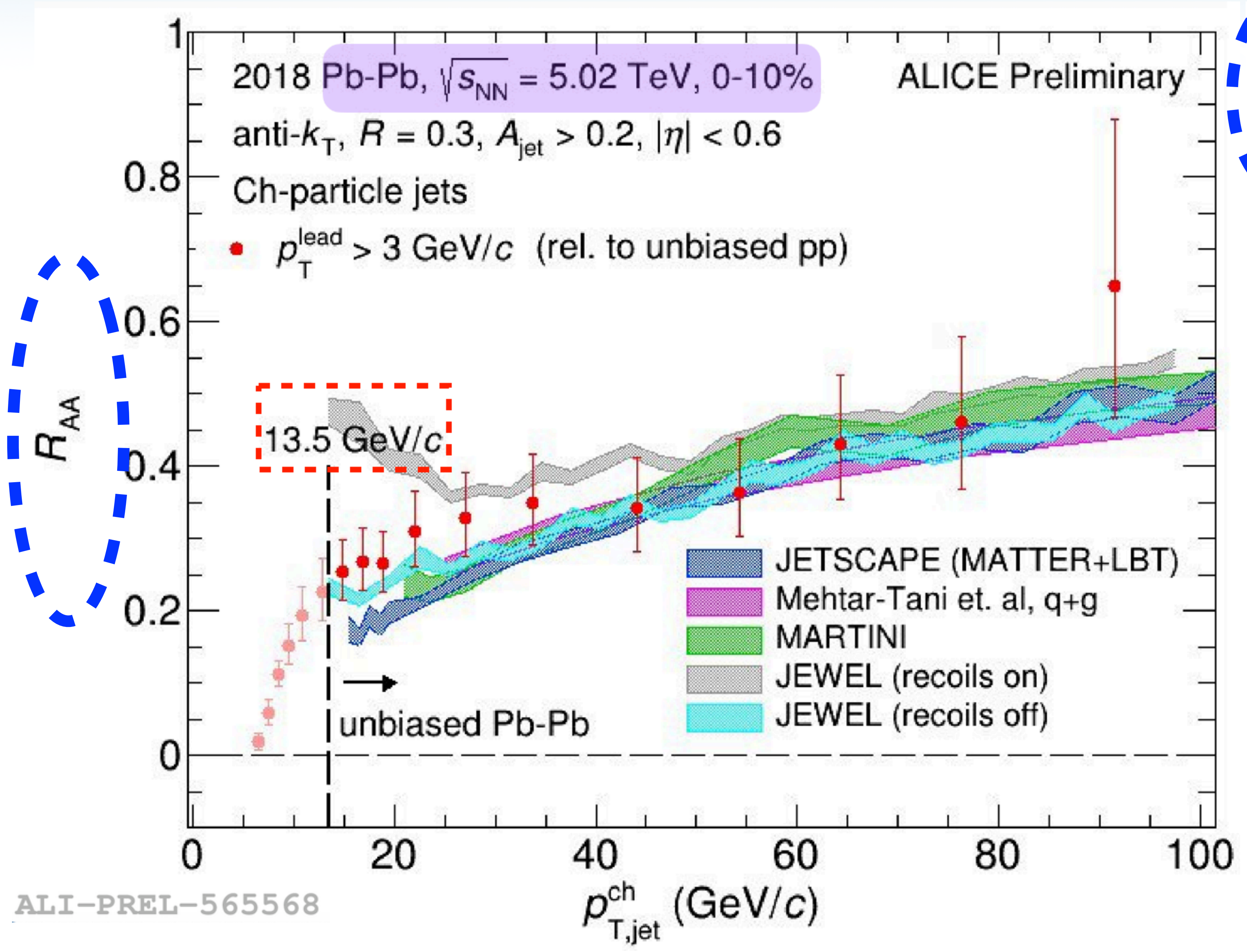
- Run 3: enough statistics for p_T-differential analysis (Λ, K_s^0)
- Capable of identifying Λ, K_s^0 up to very high p_T

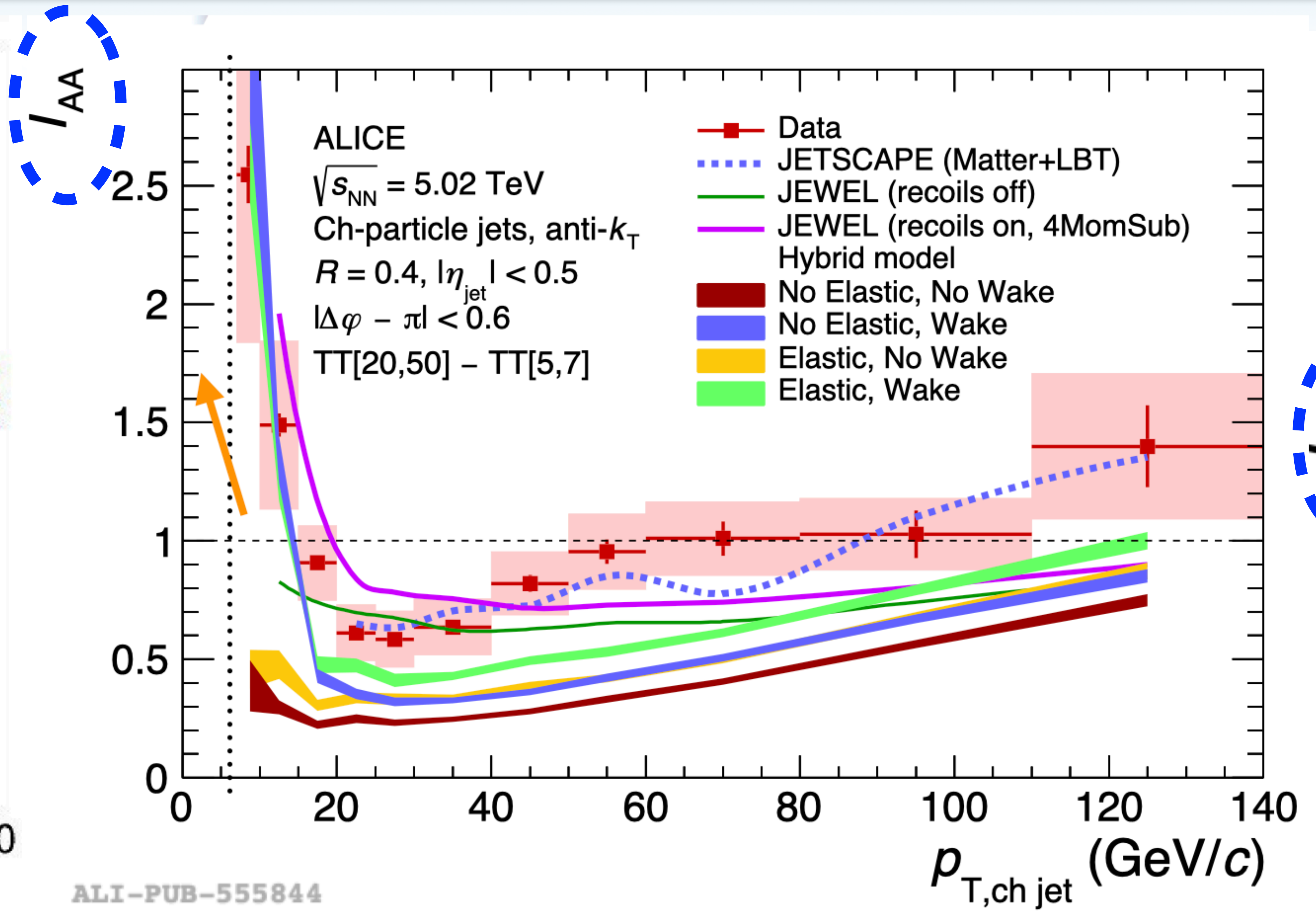
Summary and outlook

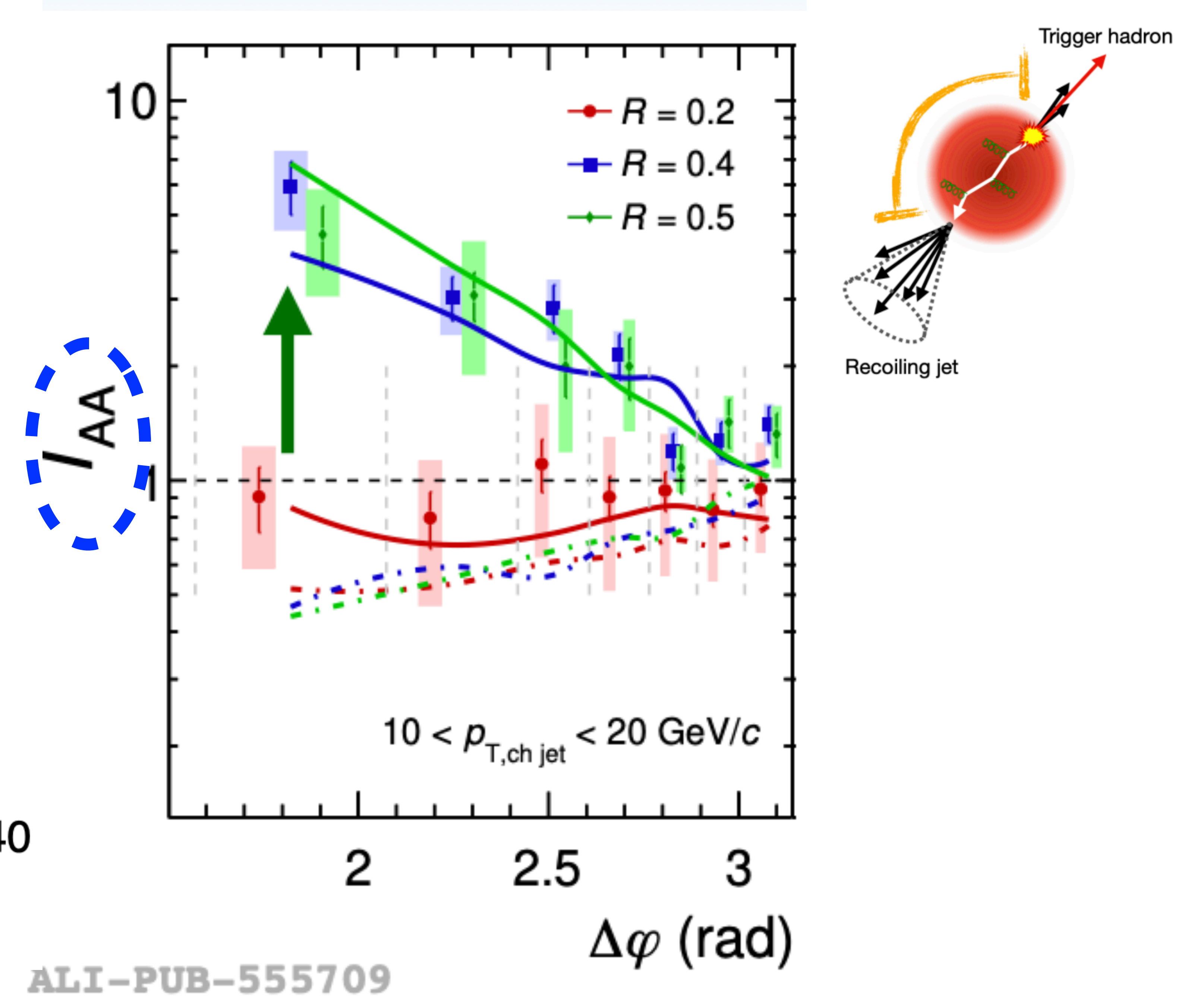


- Inclusive charged-particle jet $\boldsymbol{R_{AA}}$ **down to low** p_T **(13.5 GeV/c)** by ME technique

Summary and outlook

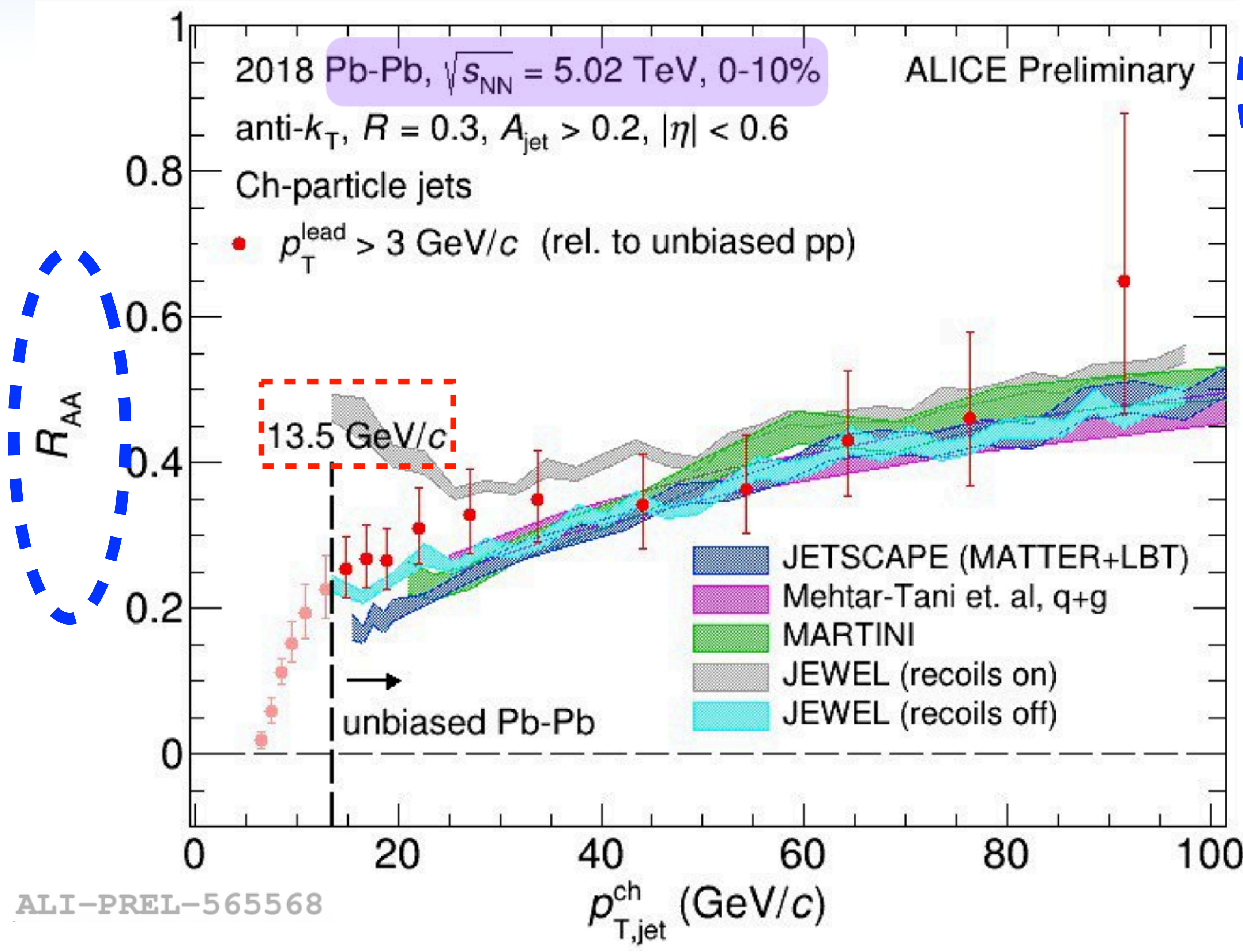


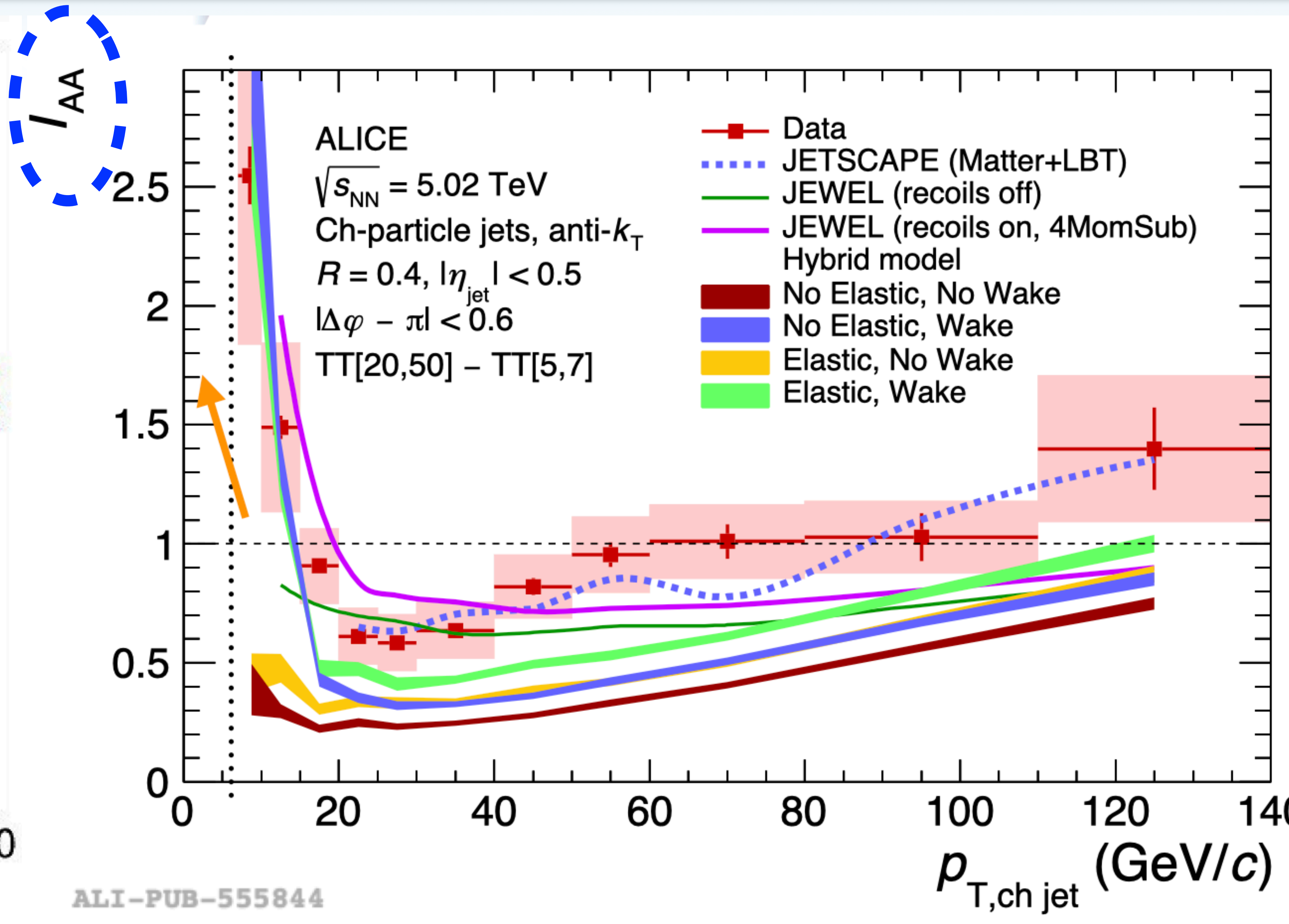


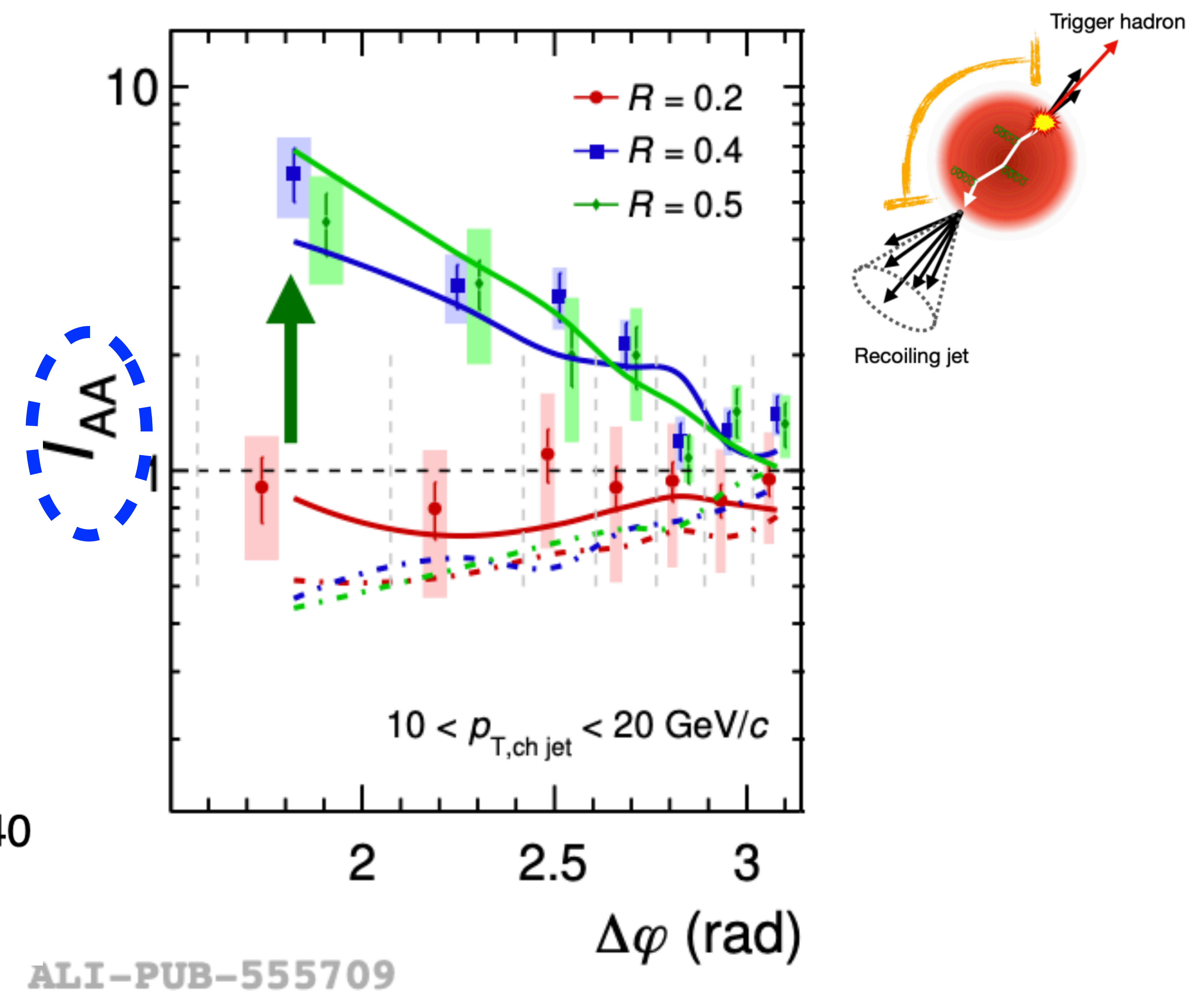


- Inclusive charged-particle jet R_{AA} **down to low p_T (13.5 GeV/c)** by ME technique
- **First observation of significant low-p_T jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**

Summary and outlook

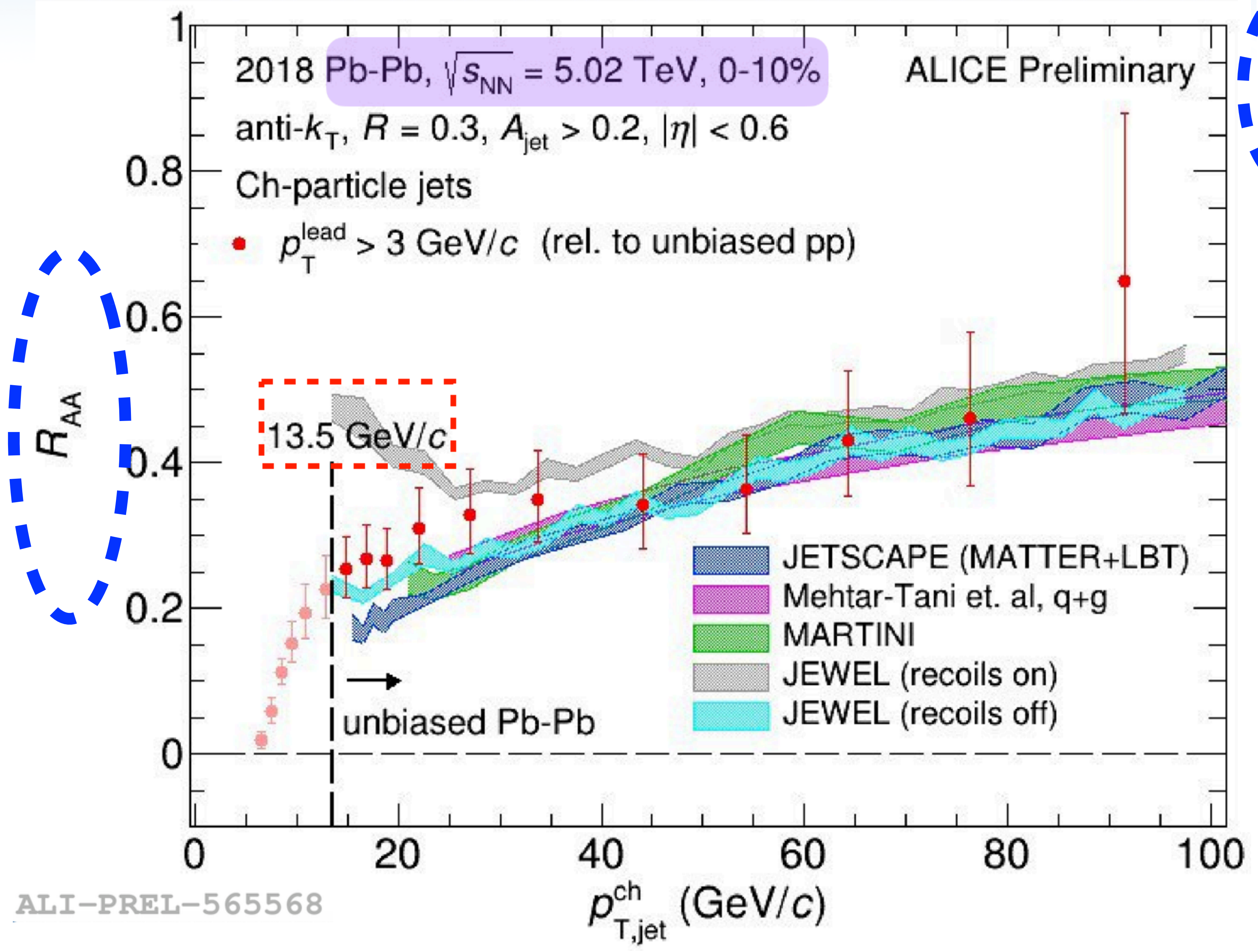


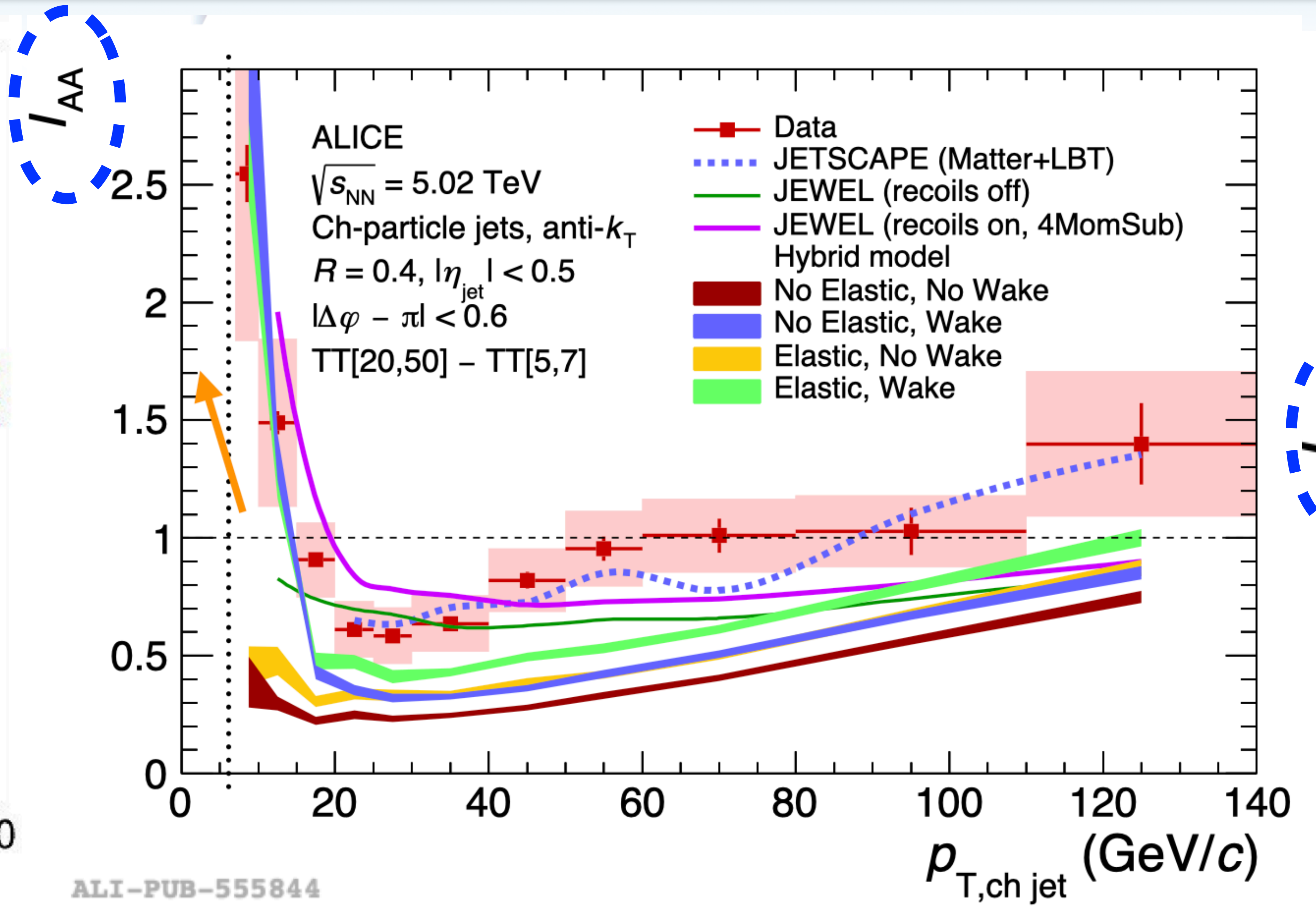


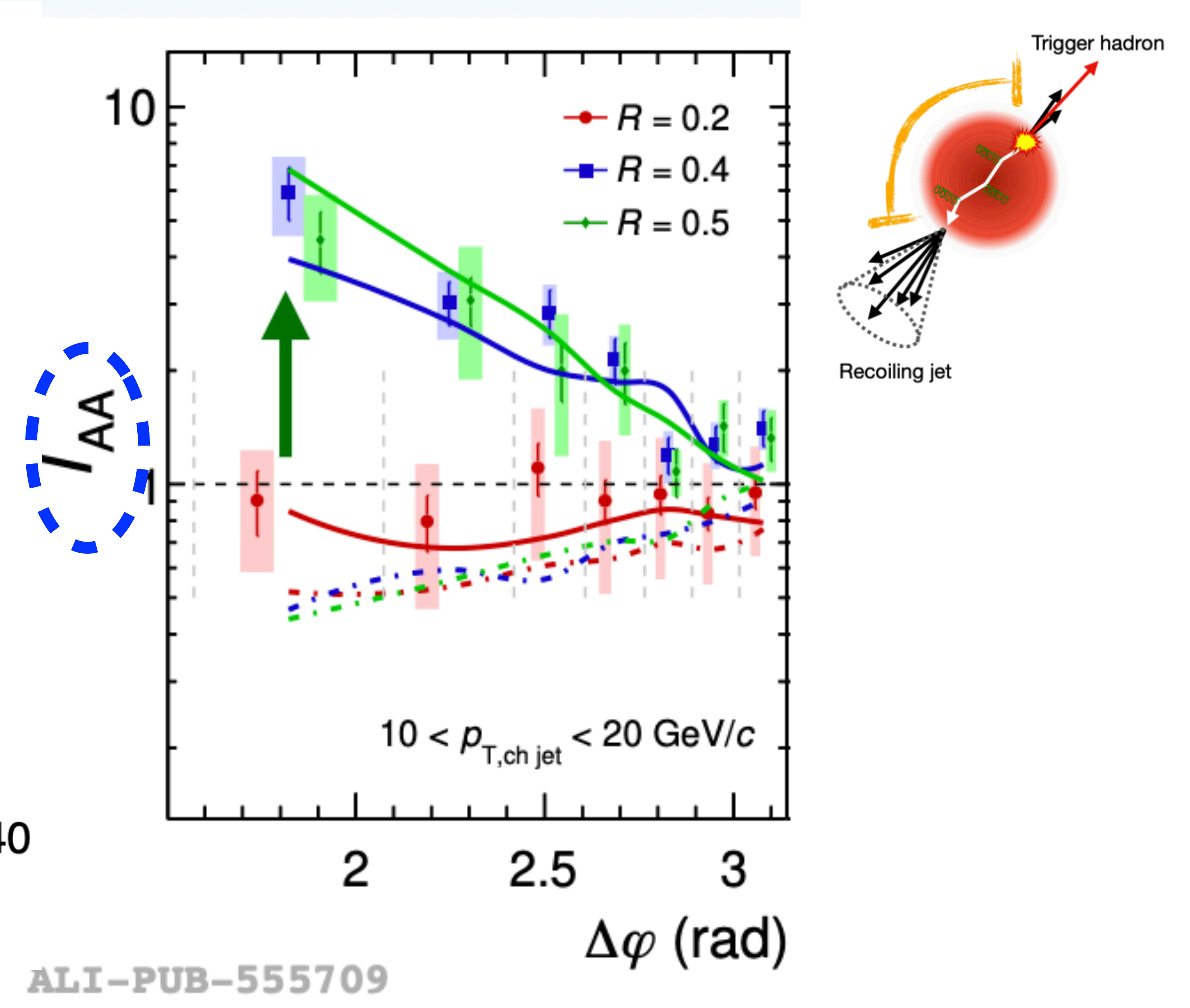


- Inclusive charged-particle jet R_{AA} **down to low p_T (13.5 GeV/c)** by ME technique
- **First observation of significant low-p_T jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- First look at the novel measurement of jet fragmentation into Λ, K_s^0 for Run 3 data

Summary and outlook







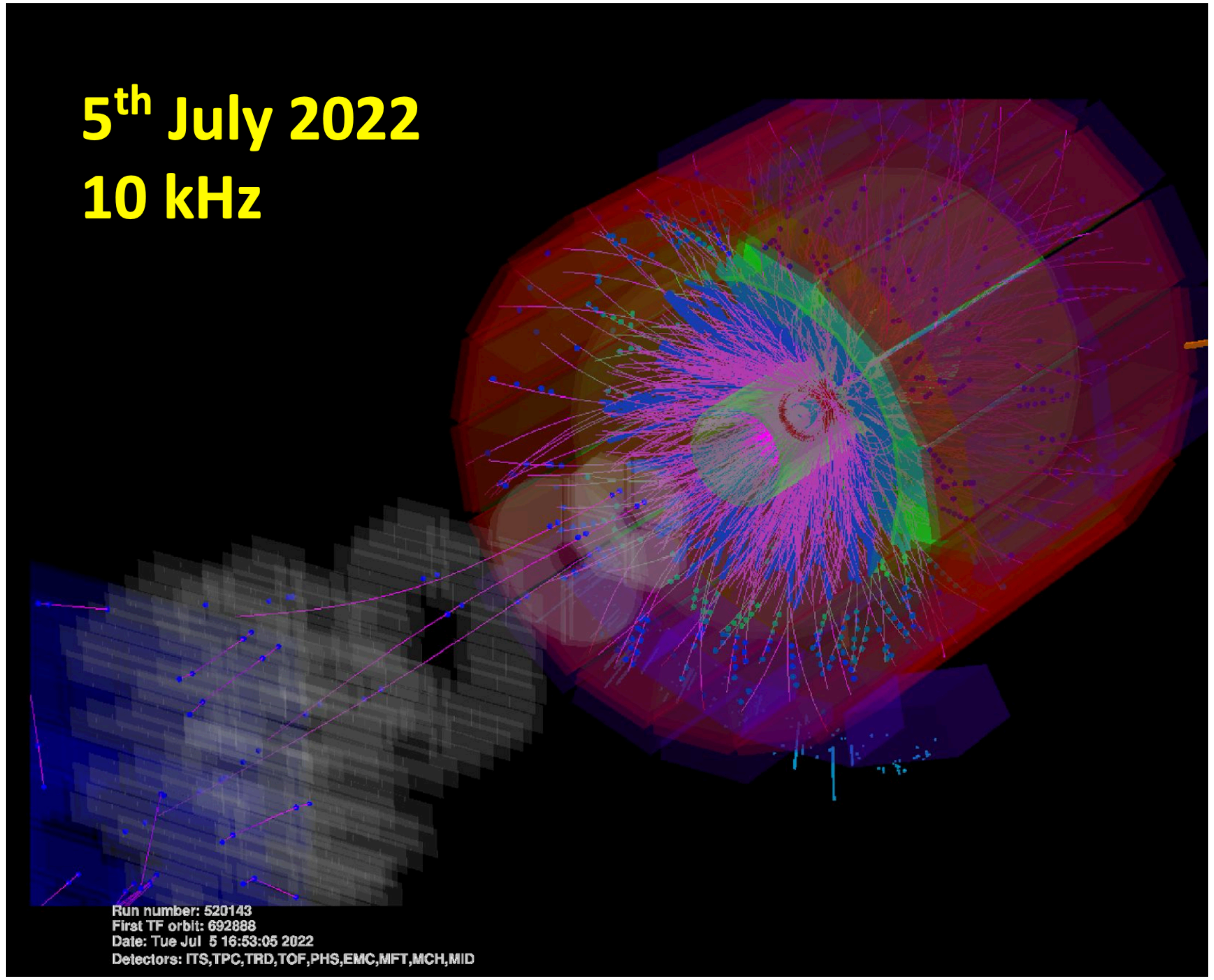
- Inclusive charged-particle jet ***R*** R_{AA} **down to low p_T (13.5 GeV/c)** by ME technique
- **First observation of significant low-p_T jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- First look at the novel measurement of jet fragmentation into Λ, K_s^0 for Run 3 data

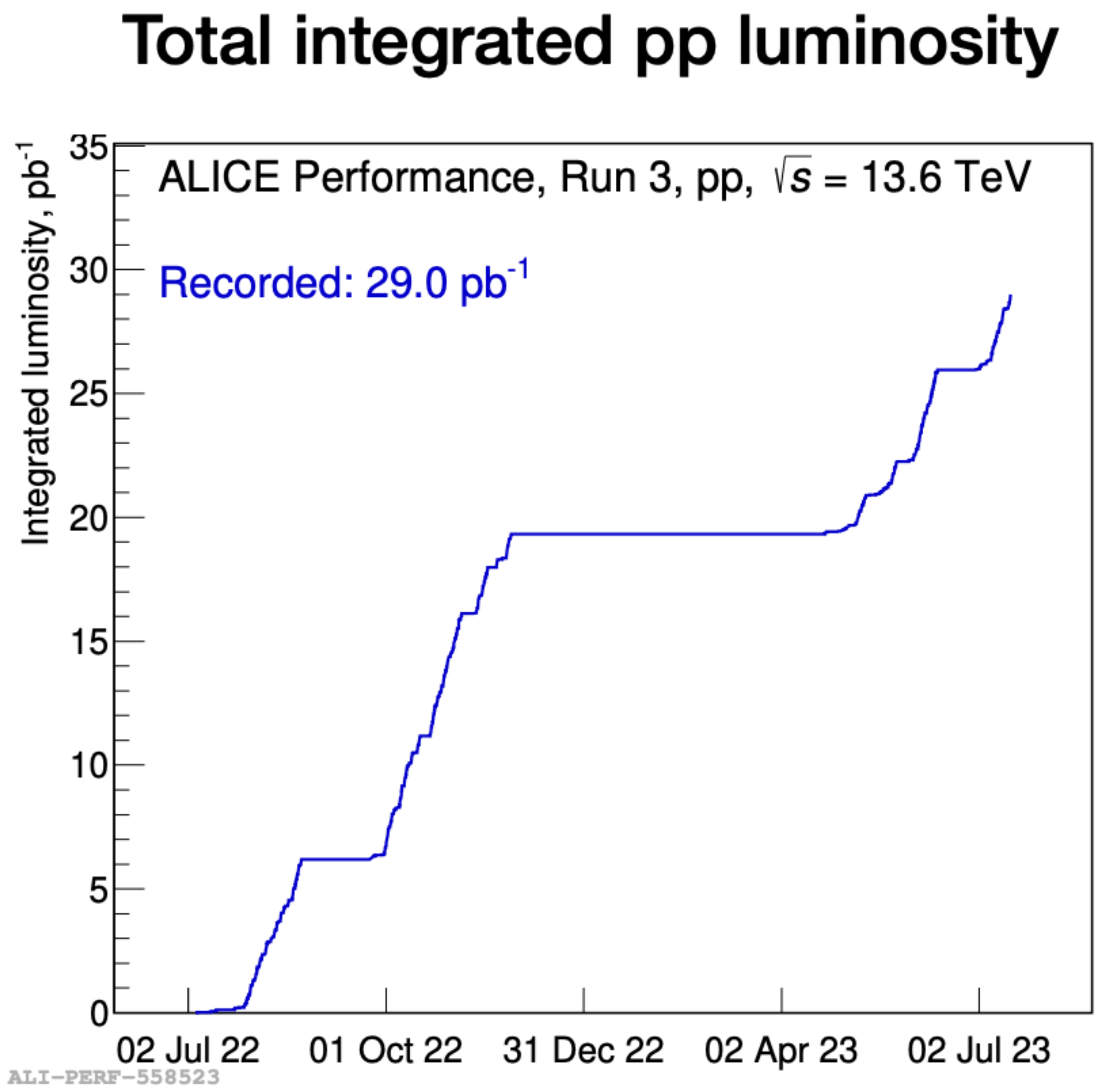
- *Looking forward to further studies with **Run 3** data with ALICE ~~ ALICE analyses on the way + LHC Run 3!!*

Thank you for your listening!

ALICE RUN3 data

- ALICE RUN3 data take ongoing
  - high statistic and high precision ITS with ALICE





V0 yield in jets and UE

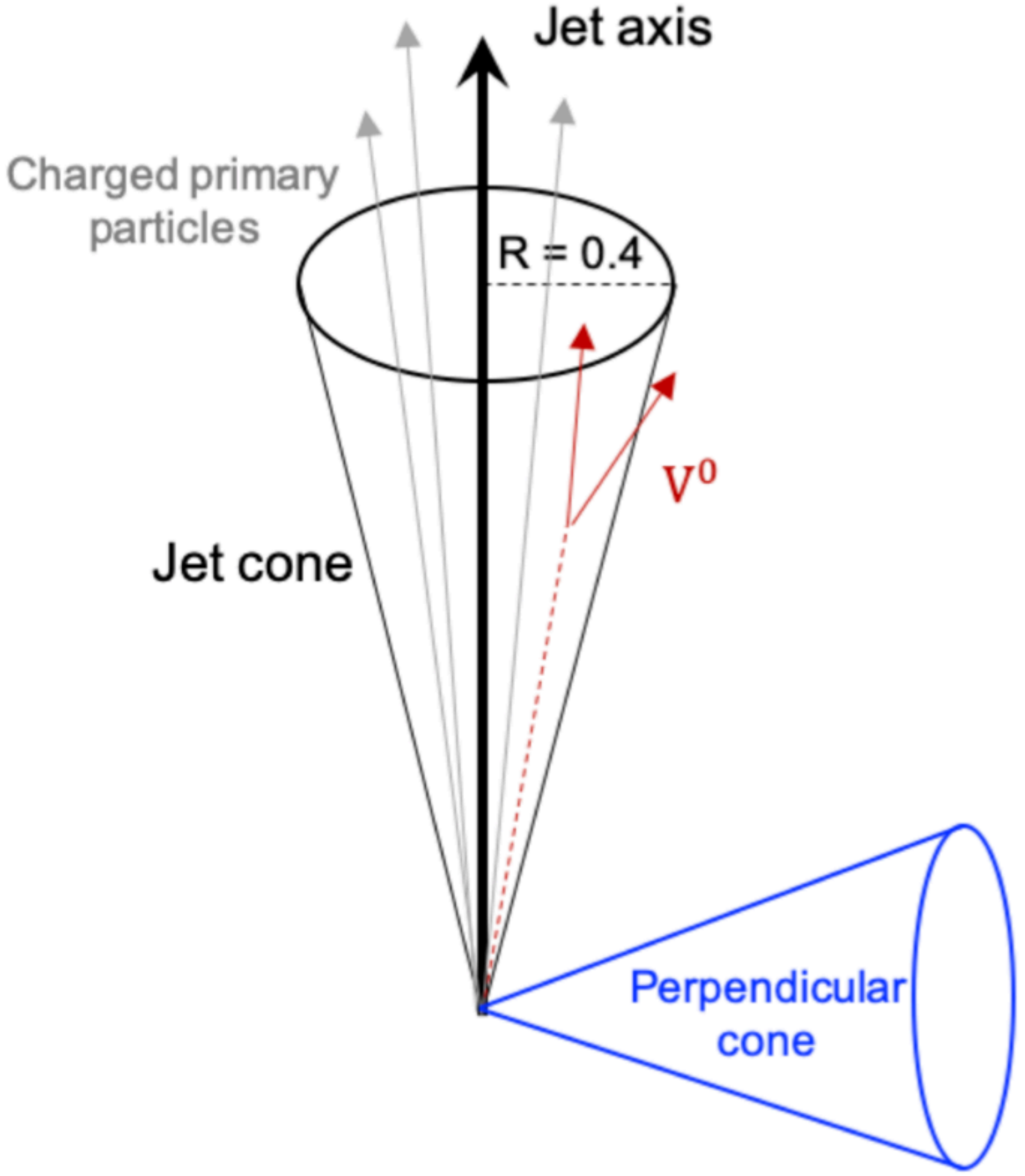
Estimate UE yields with perpendicular cone (PC) method

Jet yield = yield within jet cone (JC) - yield within PC

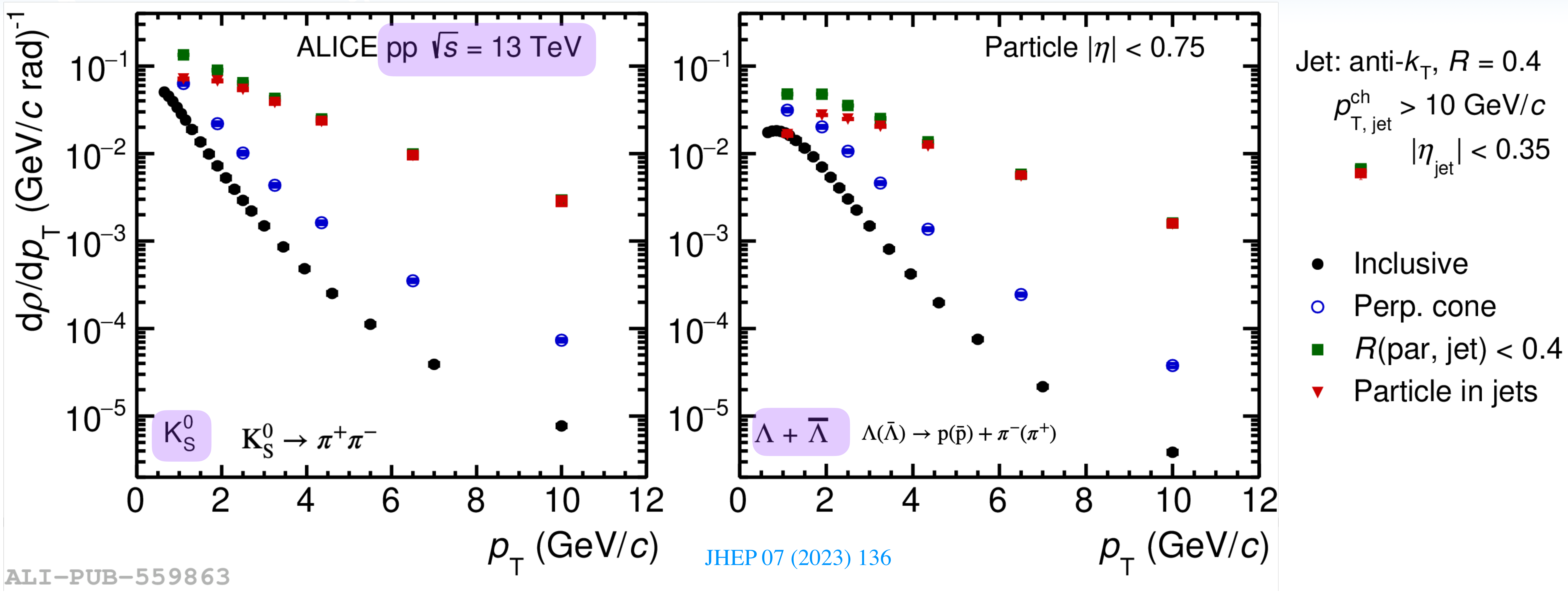
$$\frac{\mathrm{d}\rho^{\mathrm{JE}}}{\mathrm{d}p_{\mathrm{T}}} = \frac{\mathrm{d}\rho^{\mathrm{JC}}}{\mathrm{d}p_{\mathrm{T}}} - \frac{\mathrm{d}\rho^{\mathrm{UE}}}{\mathrm{d}p_{\mathrm{T}}}$$

Density distribution

$$\frac{\mathrm{d}\rho}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{N_{\mathrm{ev}}} \times \frac{1}{\langle \text{Area acceptance} \rangle} \times \frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}}$$



V0 yield in jets and UE with Run2



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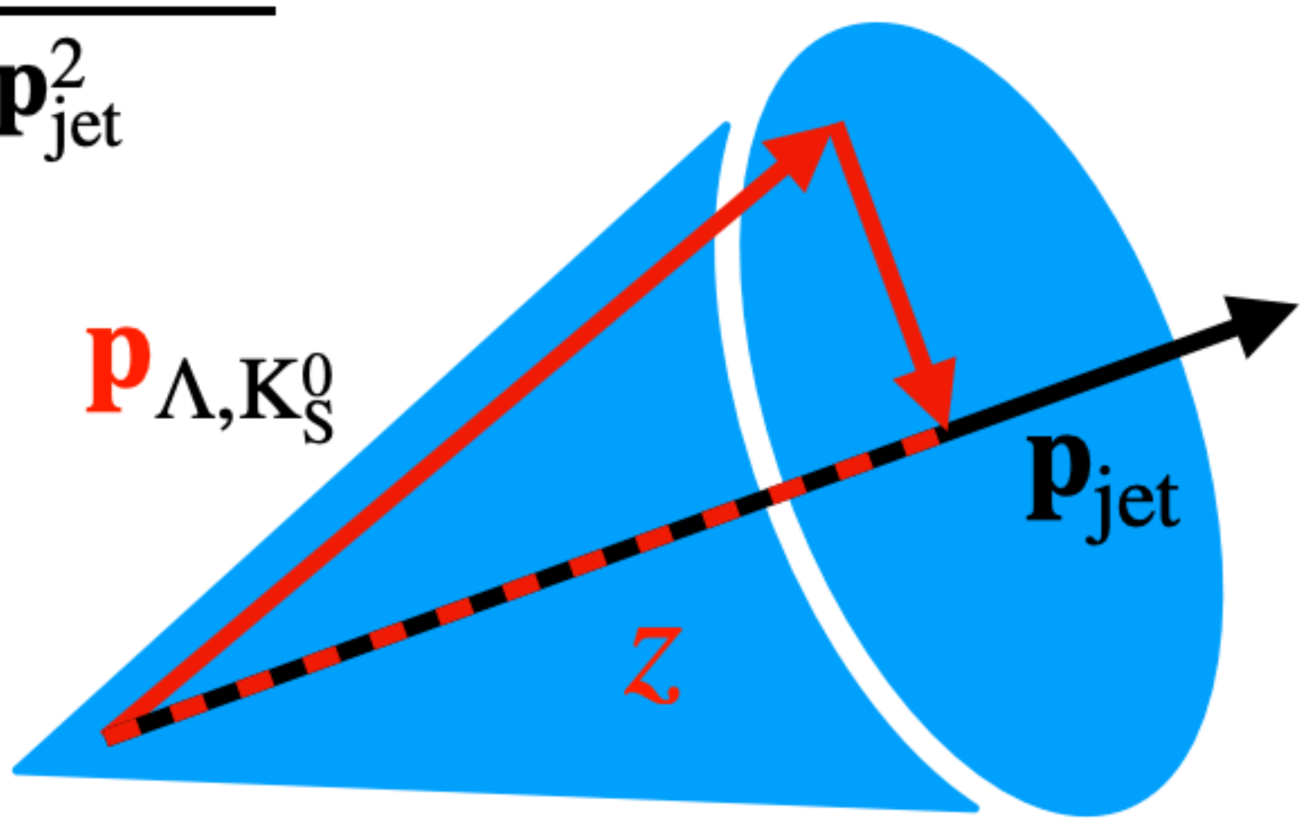
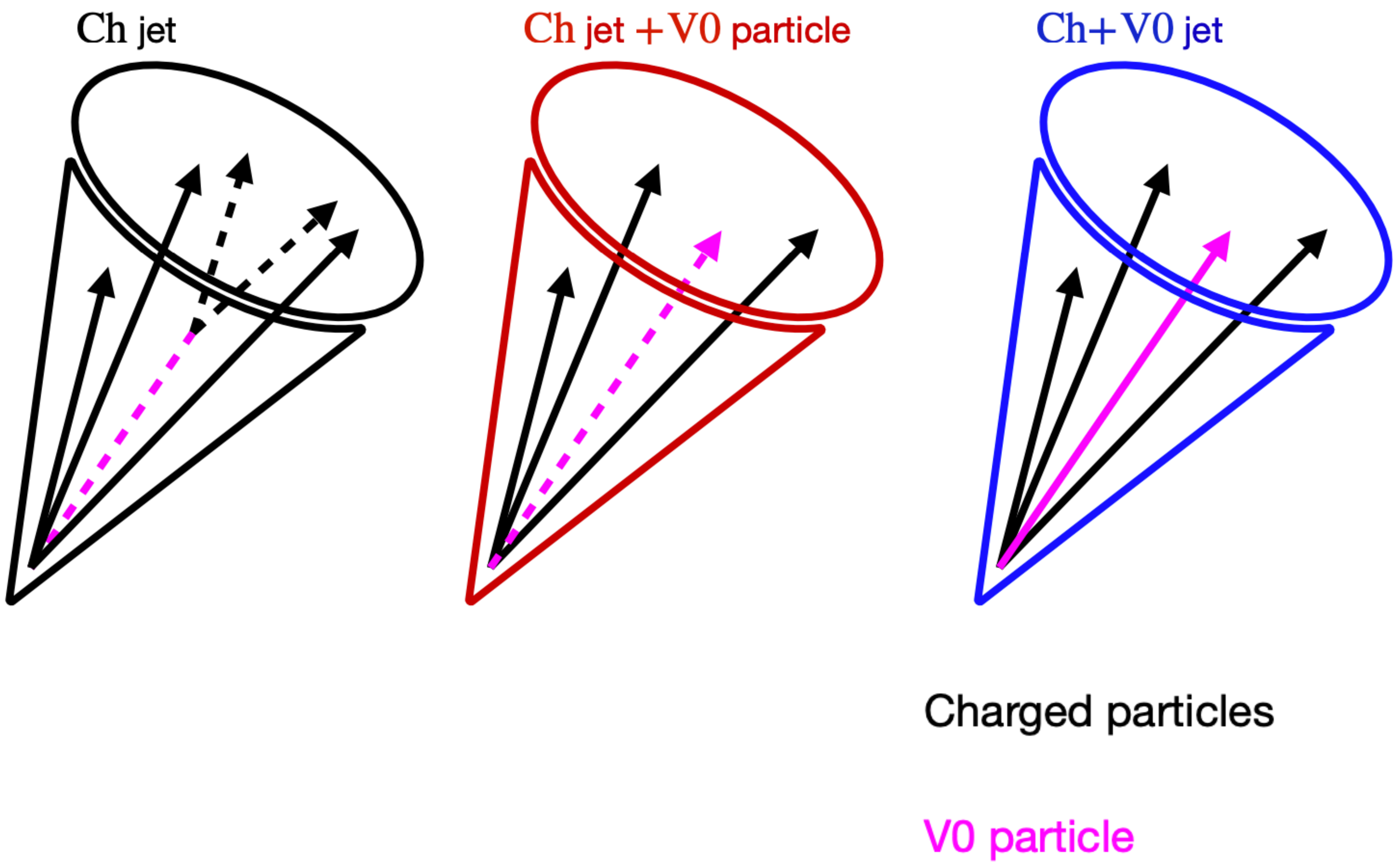
- Underlying event yield has similar slope with p_T as inclusive sample
  - UE is dominant at low p_T
- High p_T is dominated by **jet fragmentation**

Jet Fragmentation with Run 3

Jet fragmentation into Λ, K^0_s with Run 3

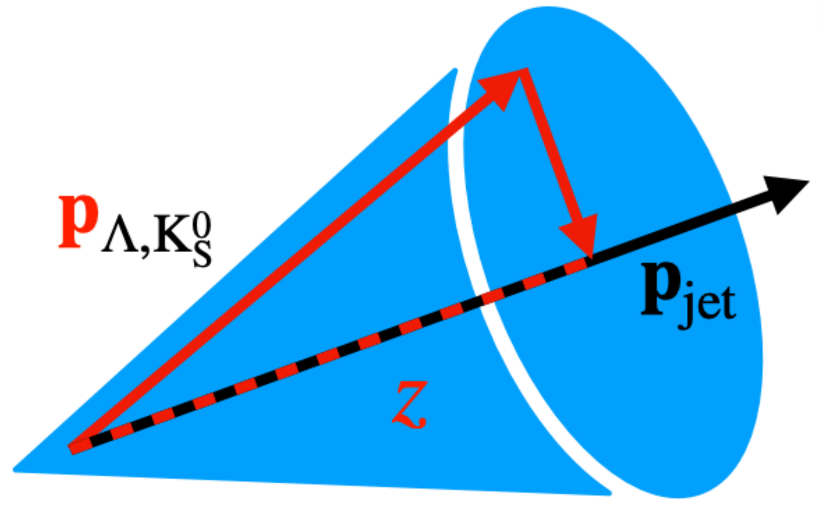
$$z_{\Lambda,K^0_S} = \frac{\mathbf{p}_{\Lambda,K^0_S} \cdot \mathbf{p}_{\text{jet}}}{\mathbf{p}^2_{\text{jet}}}$$





- Not yield inside jet cone, but Λ, K^0_s candidates (V0) included as input for jet clustering
- Due to long lifetimes, Λ, K^0_s decay daughters are removed from jet clustering input

Jet fragmentation with Run 3



V0 = Λ, K^0_s candidate

- Increased statistics per event for Ch + V0 jets
- Increased sensitivity to jets with high z_{Λ,K^0_s}

$$z_{\Lambda,K^0_S} = \frac{\mathbf{p}_{\Lambda,K^0_S} \cdot \mathbf{p}_{jet}}{\mathbf{p}^2_{jet}}$$