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

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Central China Normal University

ICHEP 2024

PRAGUE

42nd International Conference on High Energy Physics

18-24 July · 2024 · Prague · Czech Republic

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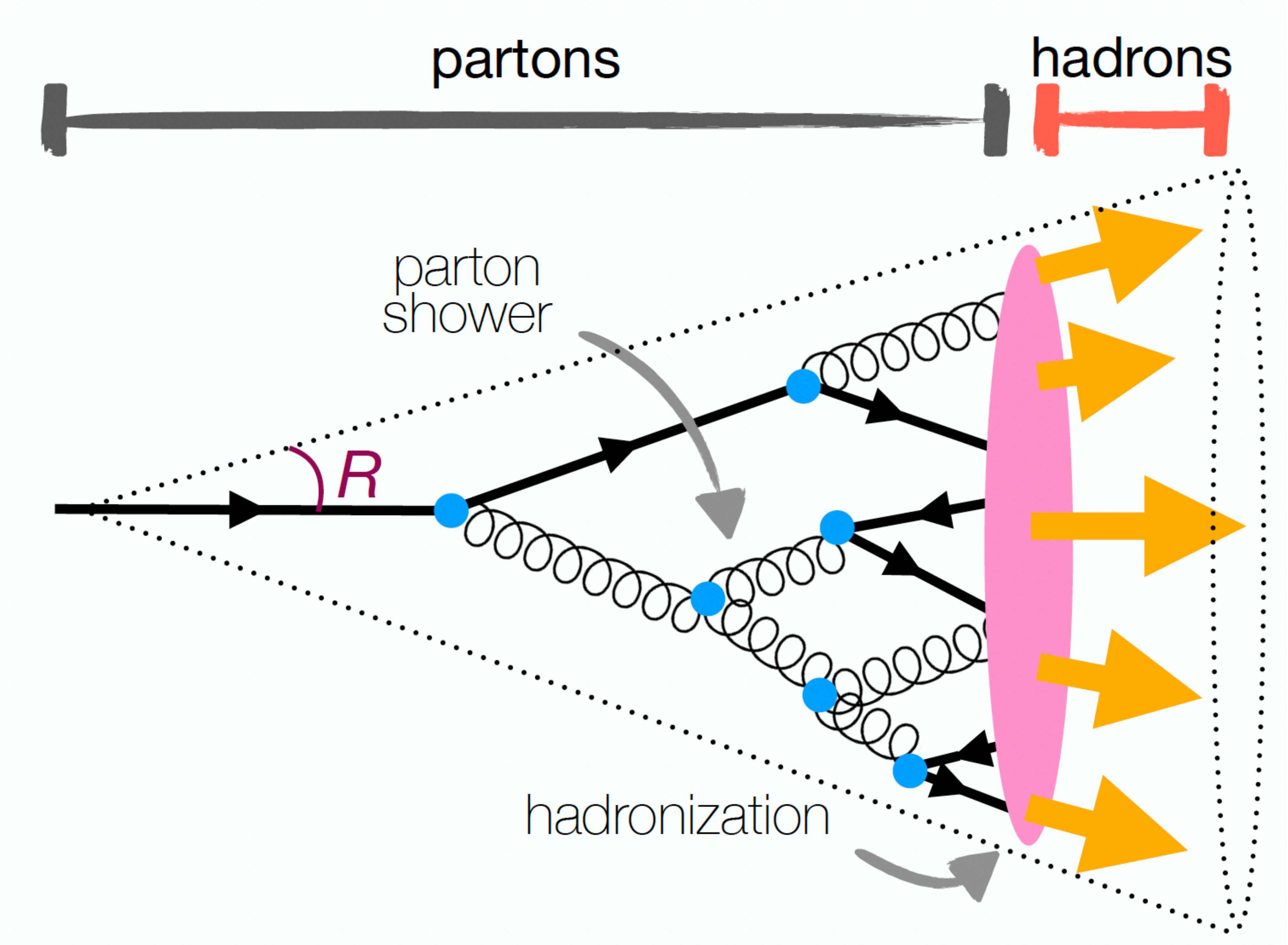
Probing QGP with jets

Vacuum fragmentation (e.g. pp collisions)

Collimated sprays of hadrons resulting from fragmentation and subsequent hadronization of "high-energy" partons (quarks&gluons)



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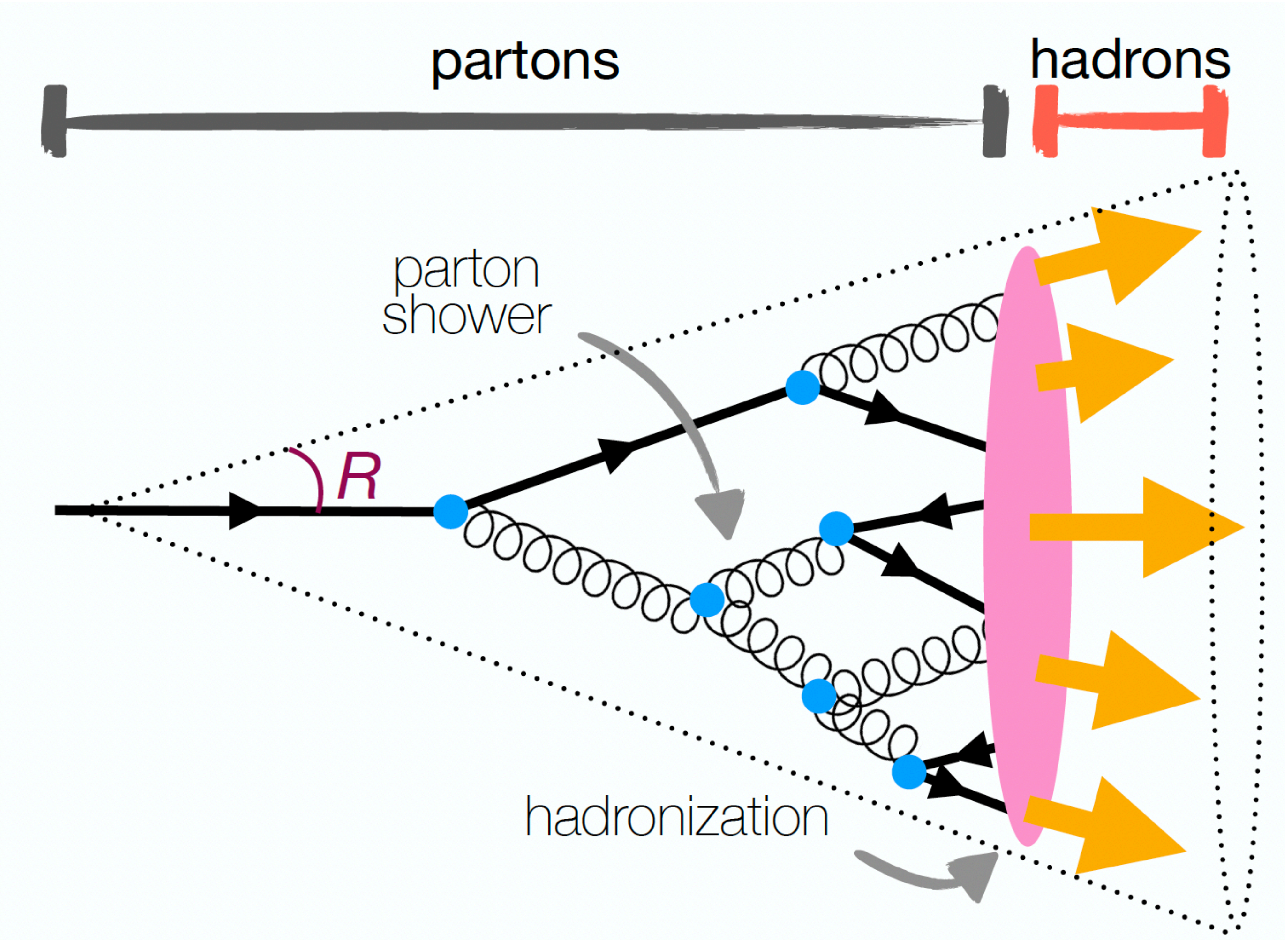
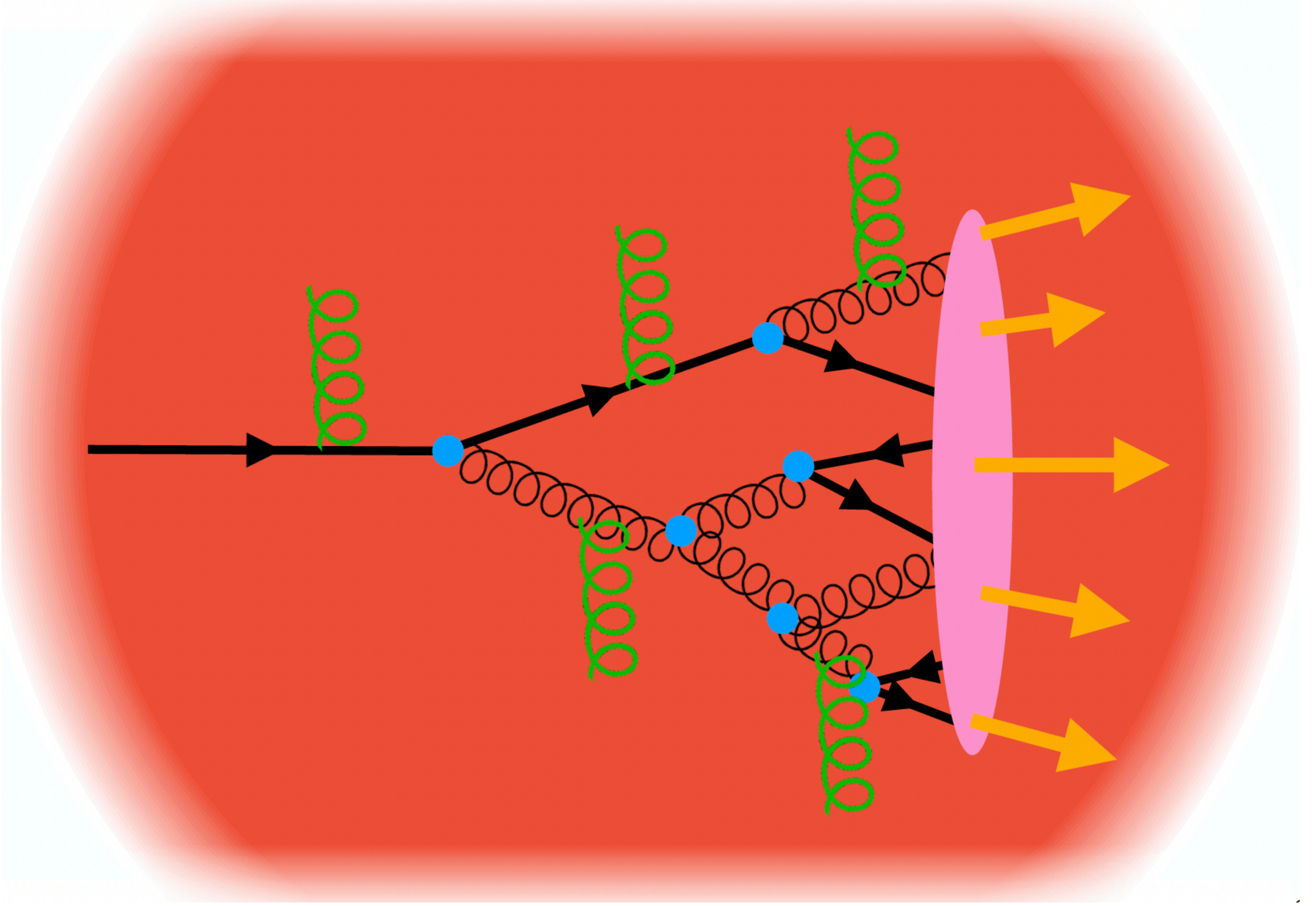


In-medium fragmentation (e.g. Pb−Pb collisions)

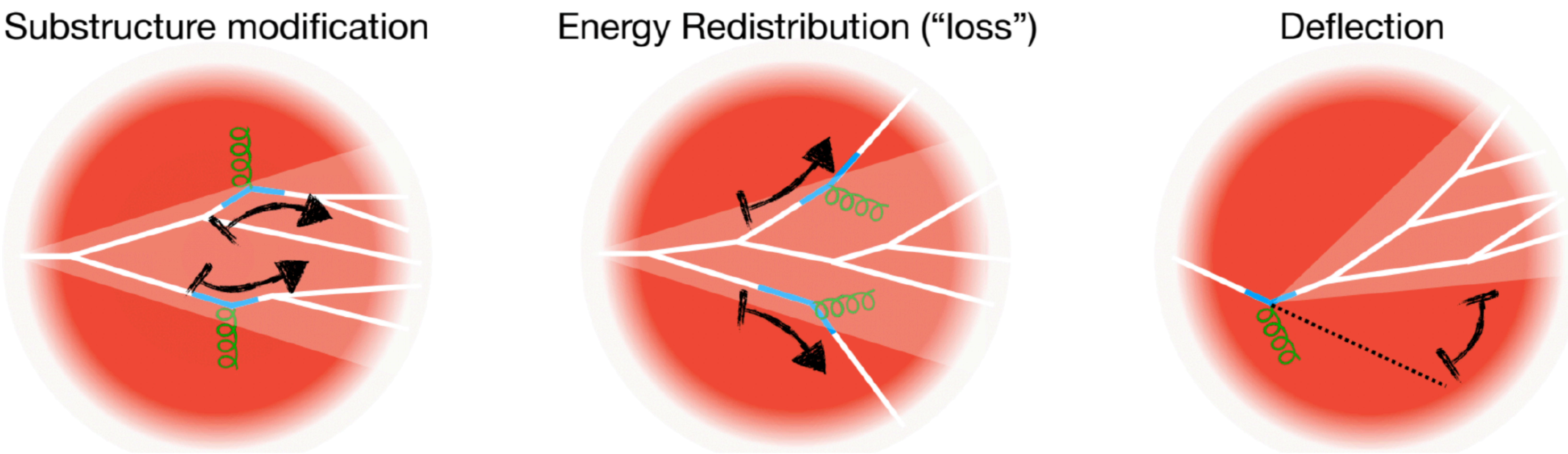
Quenching→partons lose energy through medium-induced gluon radiation and collisions with medium constituents



Jet quenching: an opportunity to study QGP

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

- Several types of jet observables
  - Jet yields and constituents → jet suppression and energy redistribution
  - Jet fragmentation and substructure → modification of parton showers
  - Angular correlation → jet deflection



Study of different effects in a complementary way must yield consistent picture

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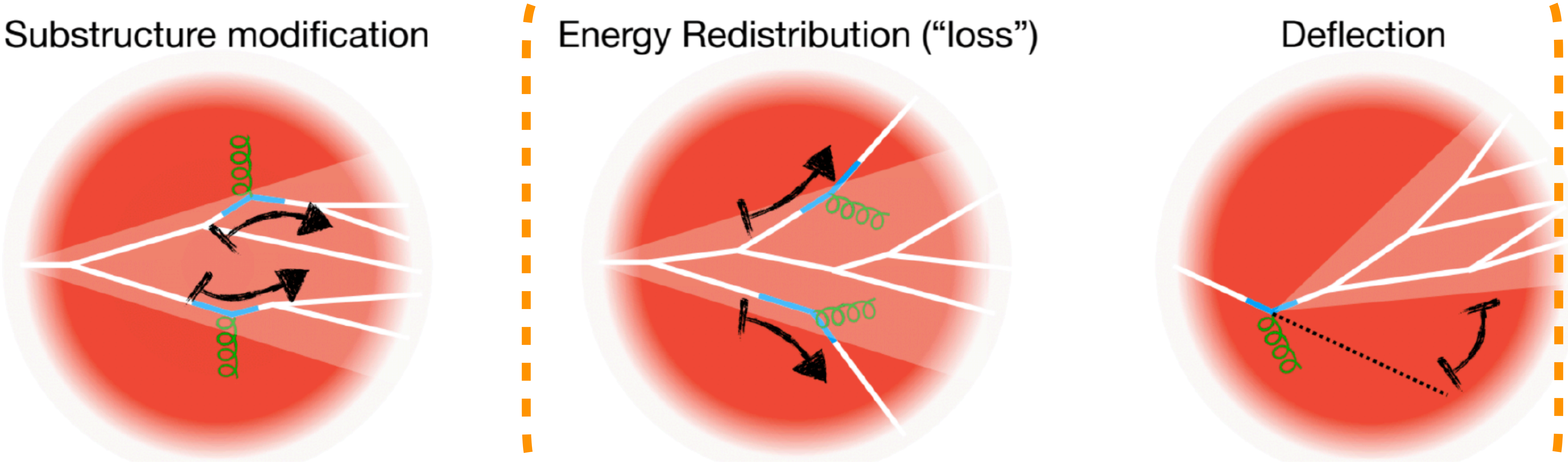
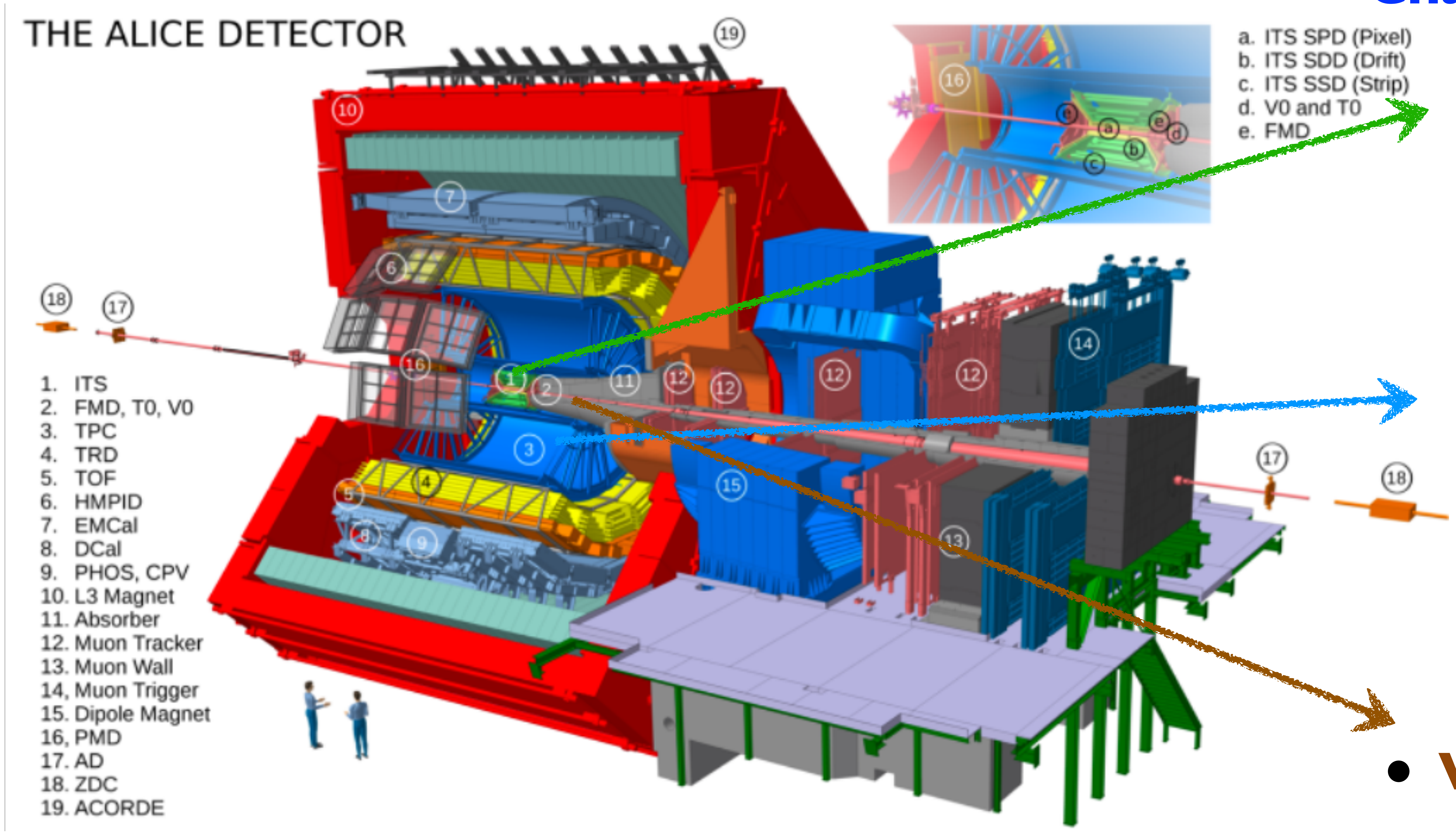
Focus on this talk today…



Study of different effects in a complementary way must yield consistent picture

Charged-particle jet measurements in ALICE

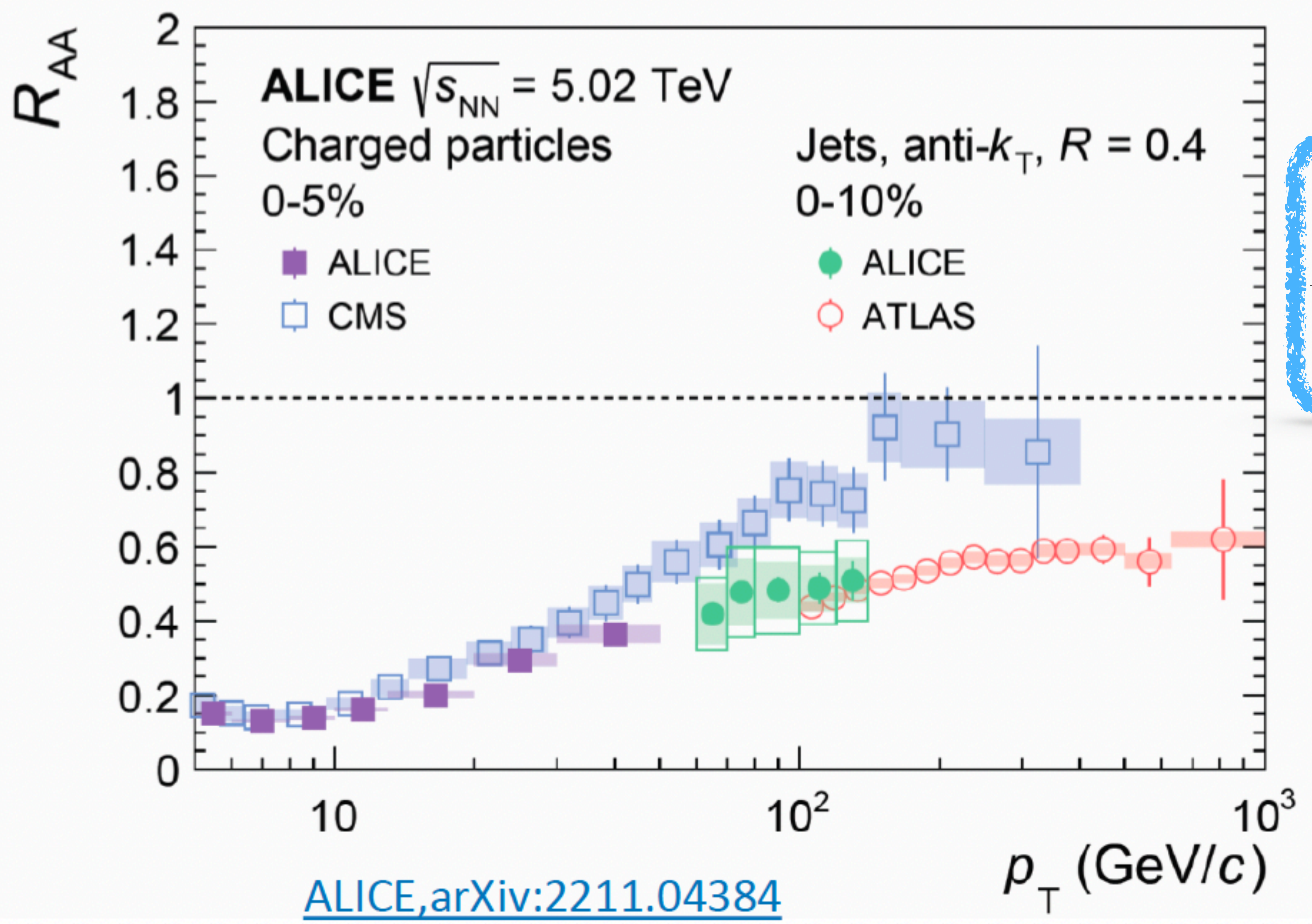


Charged-particle&jet reconstruction

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

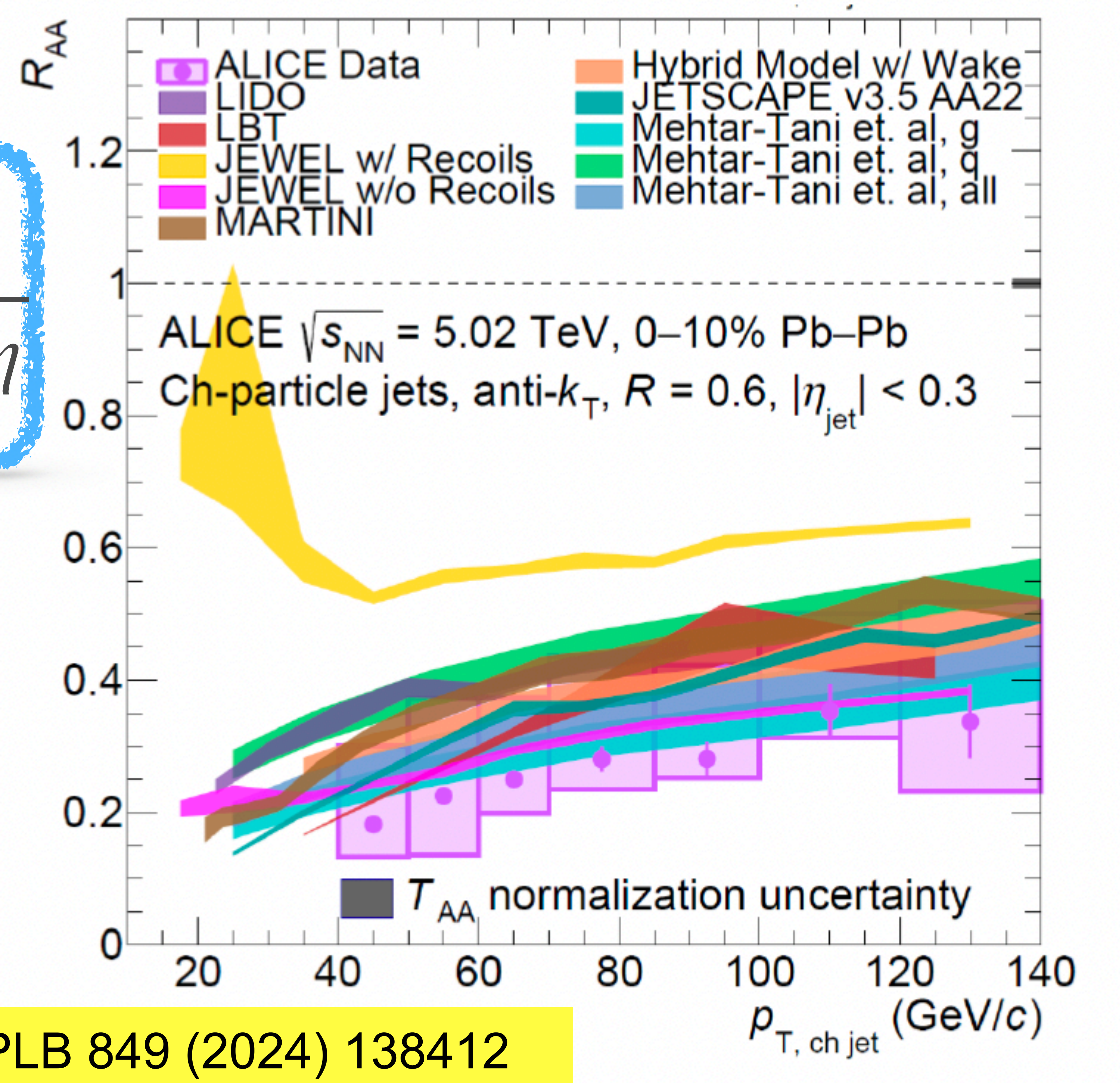
Run 2 data: pp and 0 −10% Pb−Pb samples at $\sqrt{S_{\rm NN}} = 5.02$ TeV

Jet suppression and energy redistribution



ALICE,arXiv:2211.04384

$$R_{AA} = \frac{dN^{AA}_{jets} / dp_T d\eta}{\langle T_{AA} \rangle \, d\sigma^{pp}_{jets} / dp_T d\eta}$$

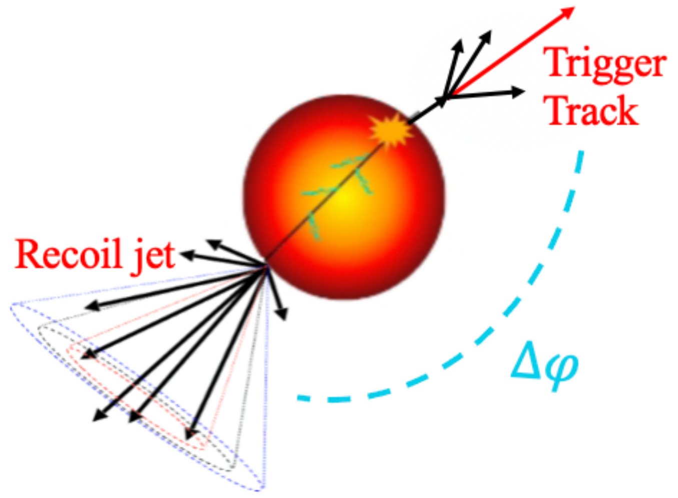


PLB 849 (2024) 138412

- Jet and high p_T hadron suppression observed over extensive range
  - Interplay between high p_T hadron and jet results
- New ML-based techniques allow for the extension to lower jet p_T and large R = 0.6
  - Important since stronger quenching effects for low p_T jet

Hadron-jet correlations

- Measurements of semi-inclusive jets recoiling from a high p_T hadron provide a good handle on combinatorial background by varying the trigger track intervals



  - access to low p_T jet quenching and intra-jet broadening

- **Angle ($\Delta\varphi$)** of the recoil jet relative to trigger track axis provides additional insights into QGP properties
  ➡ In vacuum: transverse broadening due to gluon emissions (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 $\hat{q} \sim \langle k_\perp^2 \rangle / L \sim \langle \Delta\varphi^2 \rangle / L$
  - Large-angle deflection ($\Delta\varphi < \pi$) of hard partons off of quasi-particle[3]?

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2. Phys.Lett.B 763 (2016) 208-212
3. JHEP 01 (2019) 172

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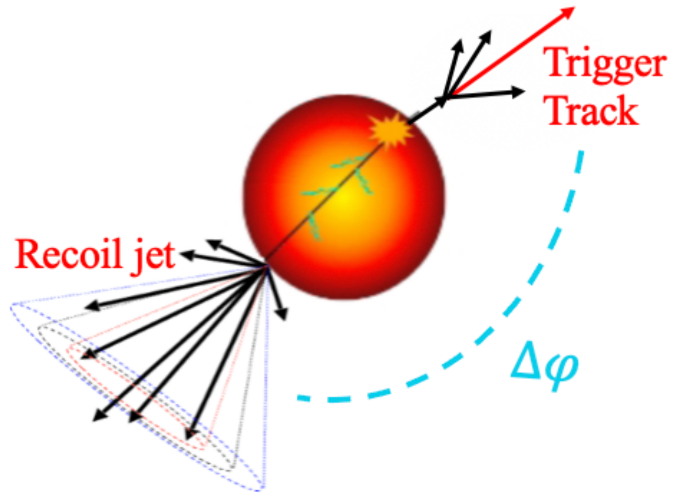

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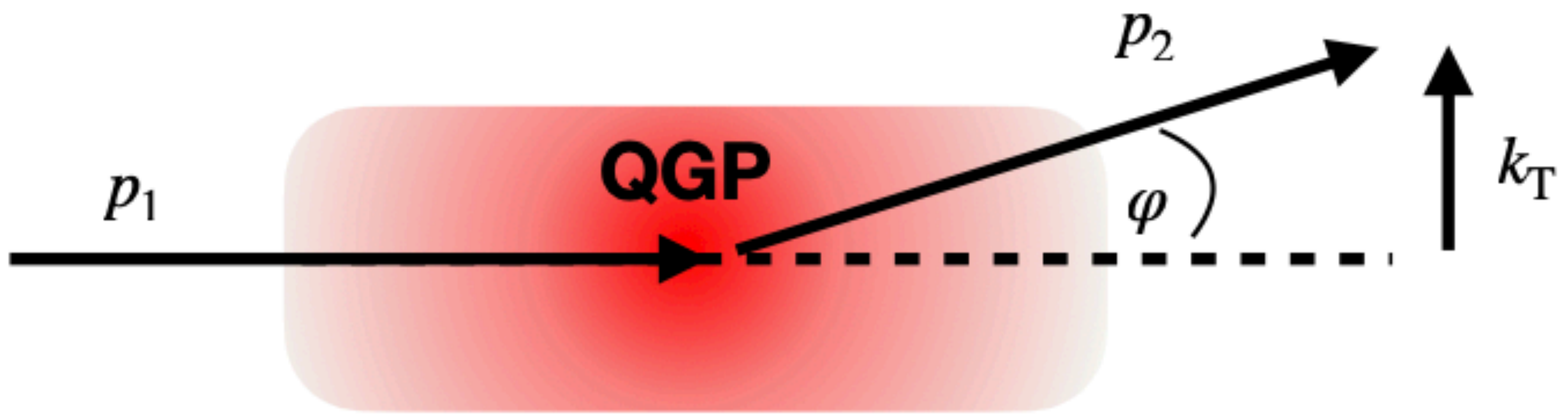

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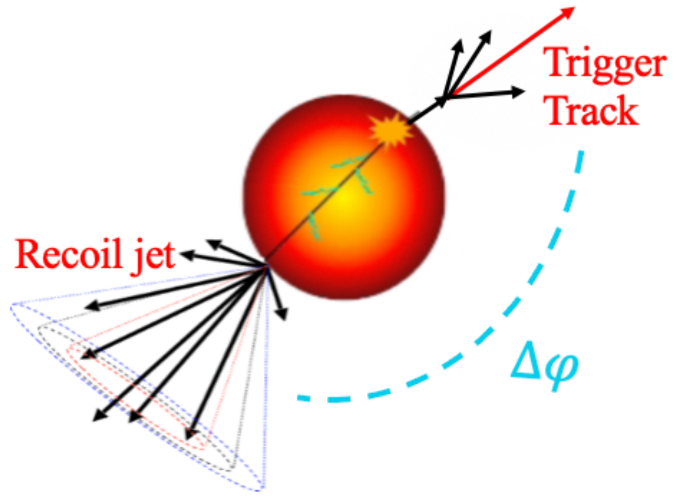

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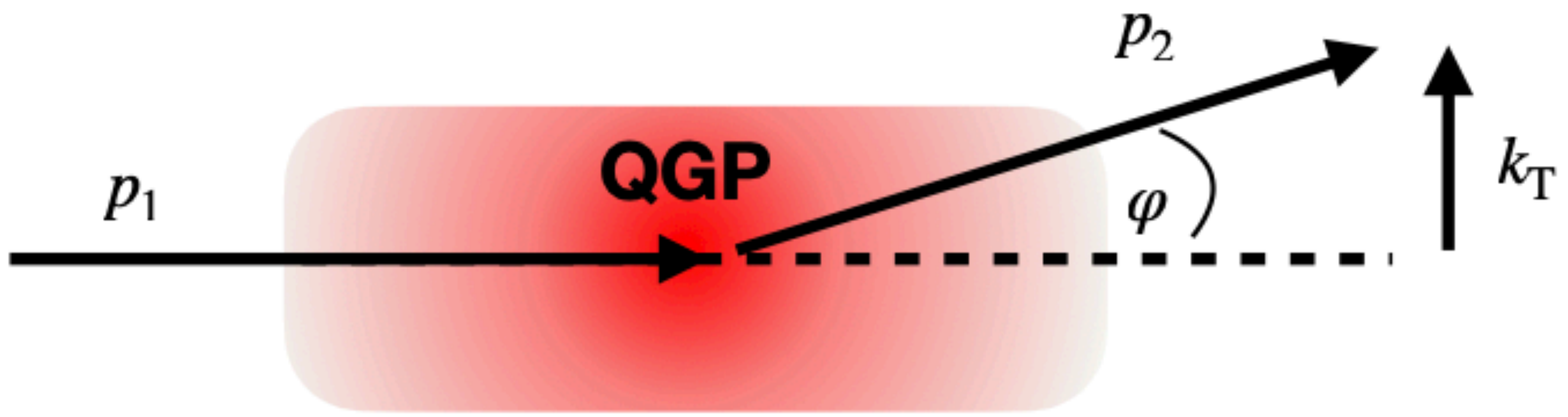
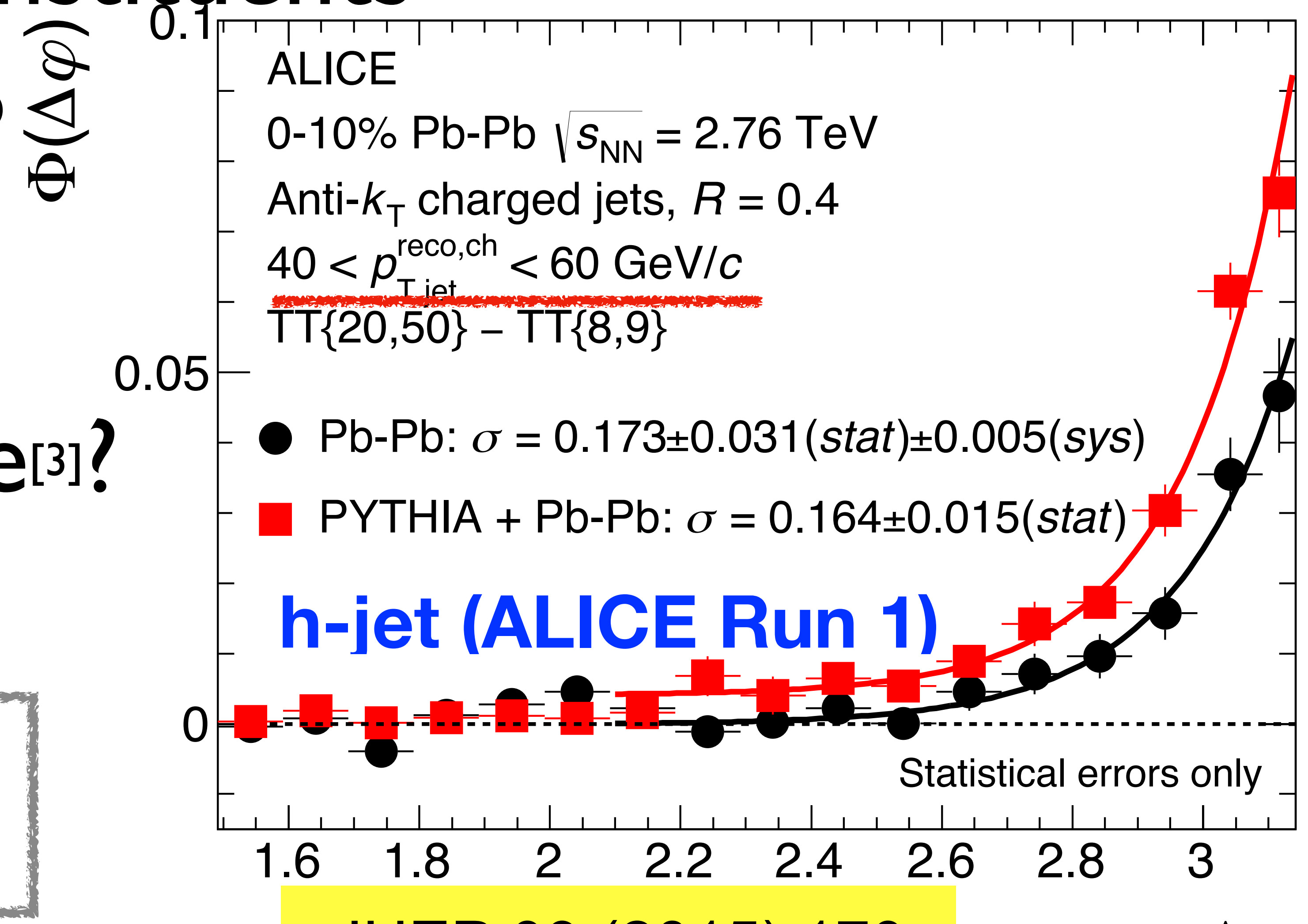
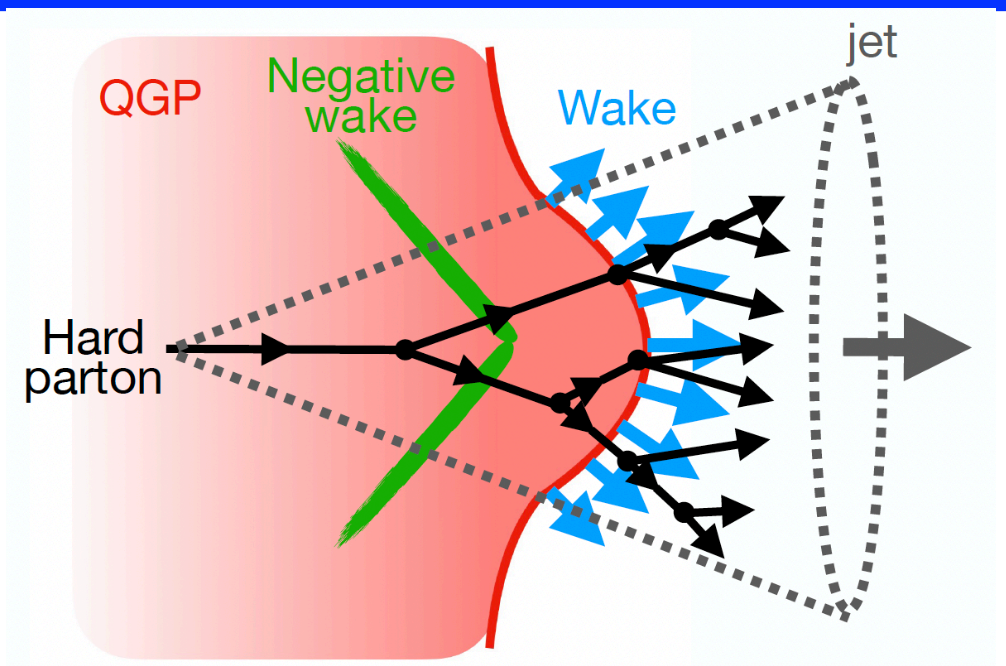


No medium-induced broadening observed

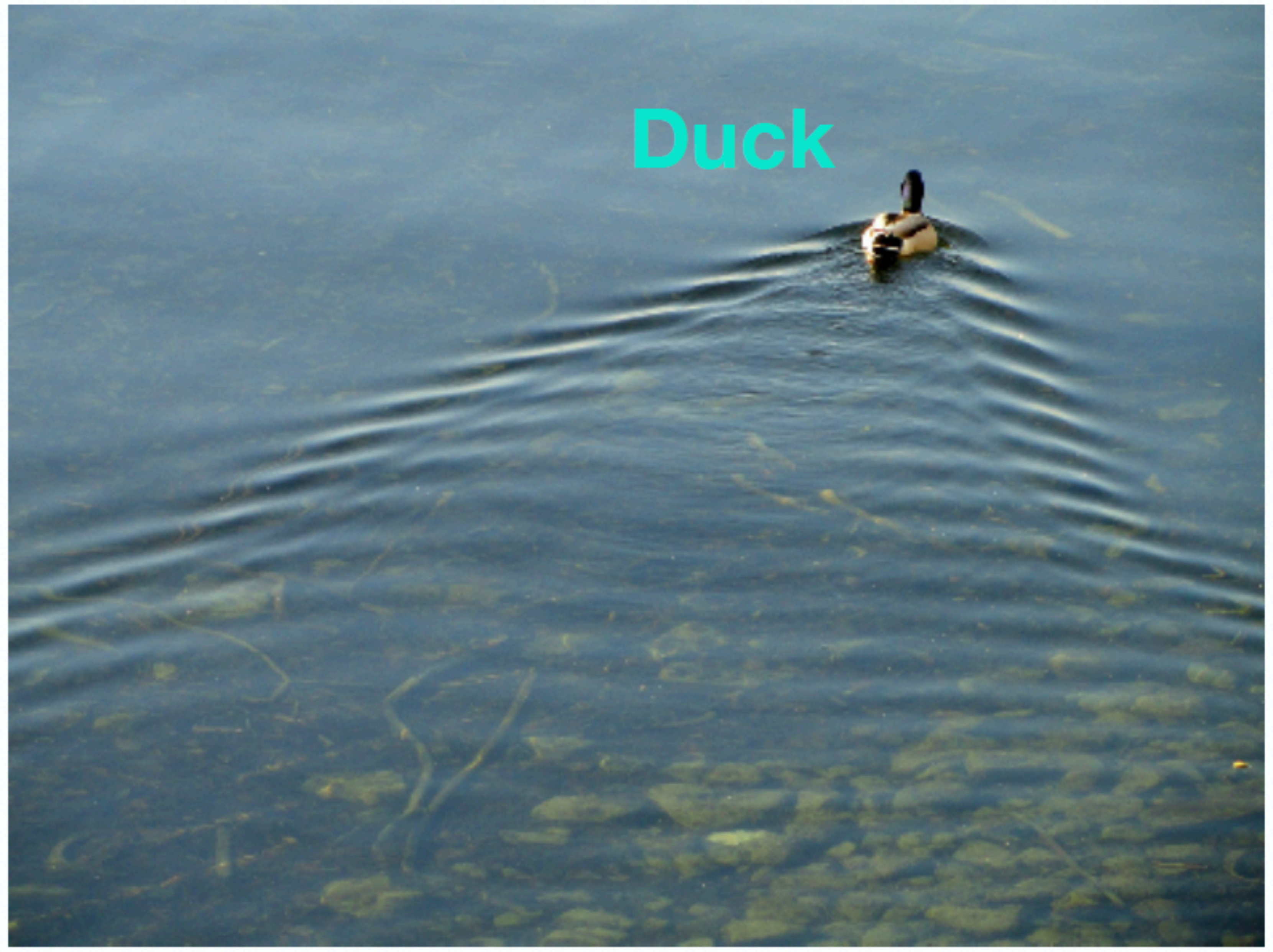


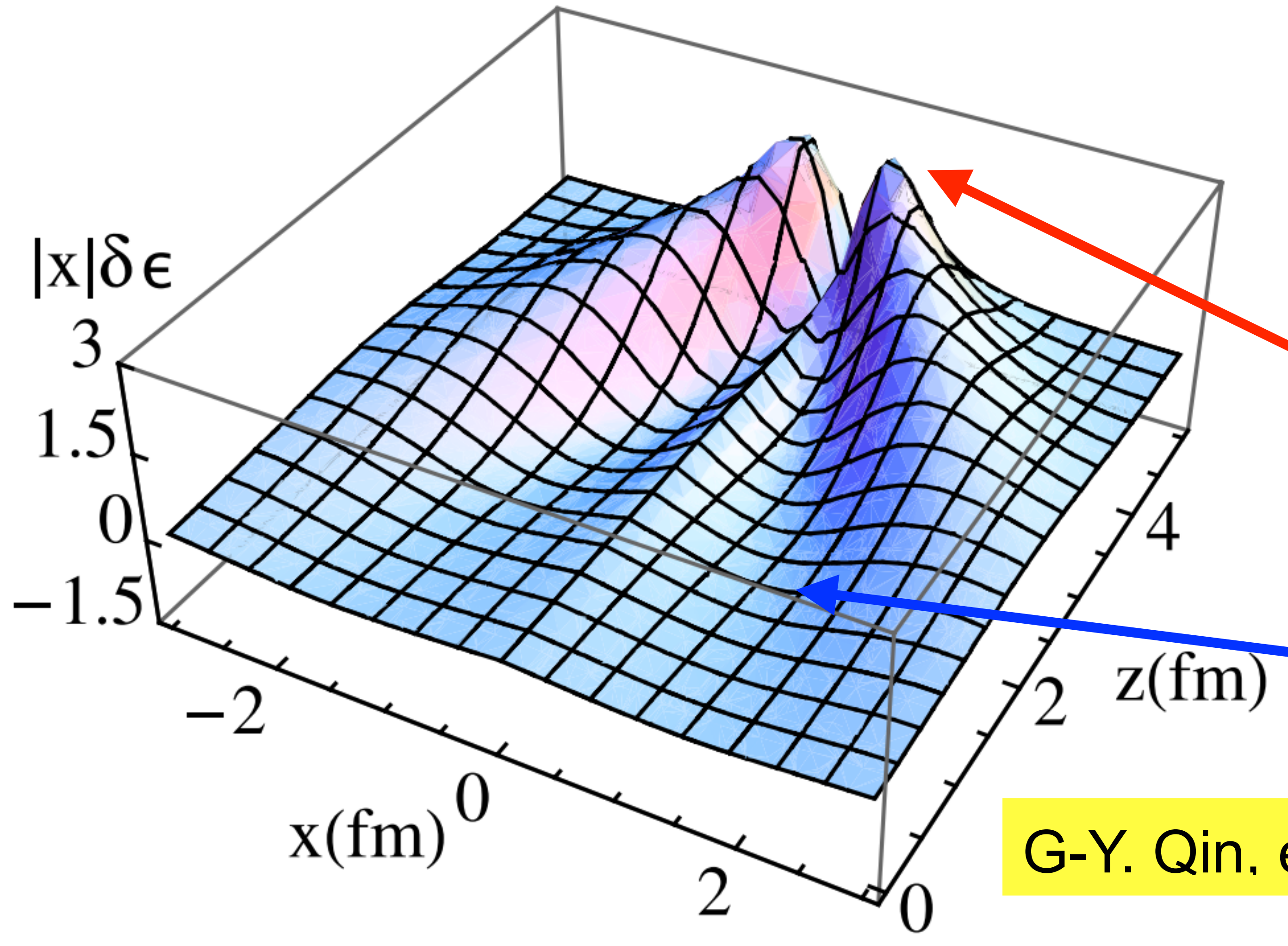
JHEP 09 (2015) 170

Medium response to propagating parton



- Jet loses energy due to interactions with medium
  - ➡ medium modified by jets





Expectations: "wake effects"

Enhancement around jet

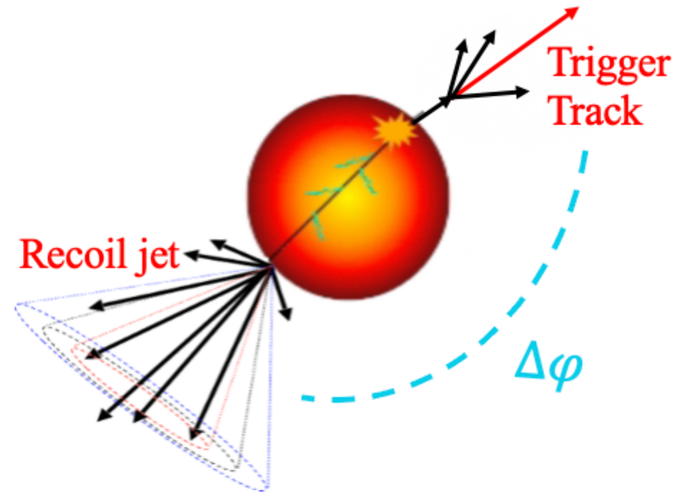
Depletion opposite to jet

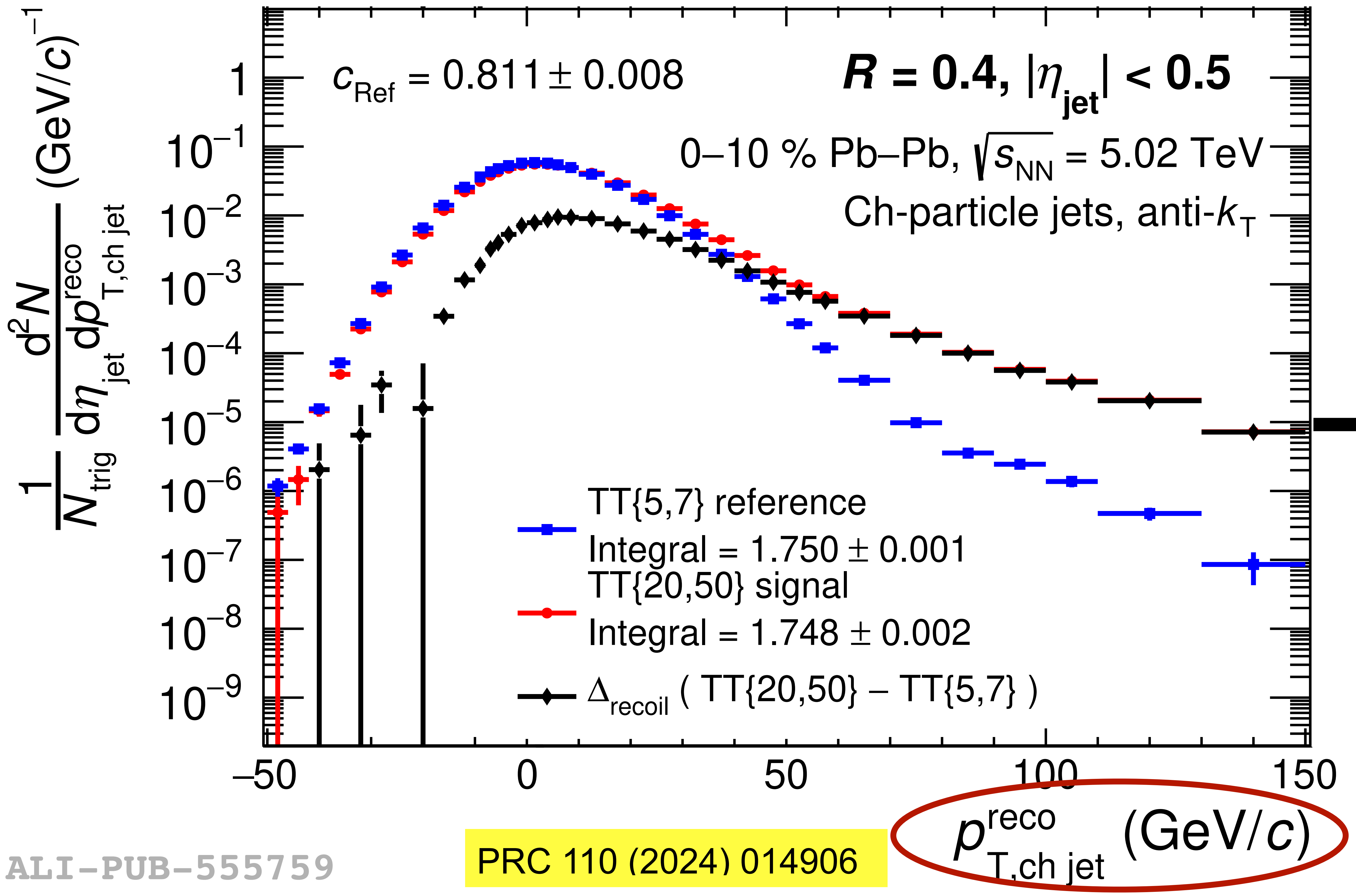
G-Y. Qin, et. al, PRL 103 (2009) 152303

- Insert out-of-equilibrium probe — see how medium responds
  - ➡ transport coefficients, equation of state

Semi-inclusive jets recoiling from trigger track

- Semi-inclusive jets recoiling from a high p_{T} hadron can push the kinematics down to very low p_{T} and large R
- Subtract uncorrelated background: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:





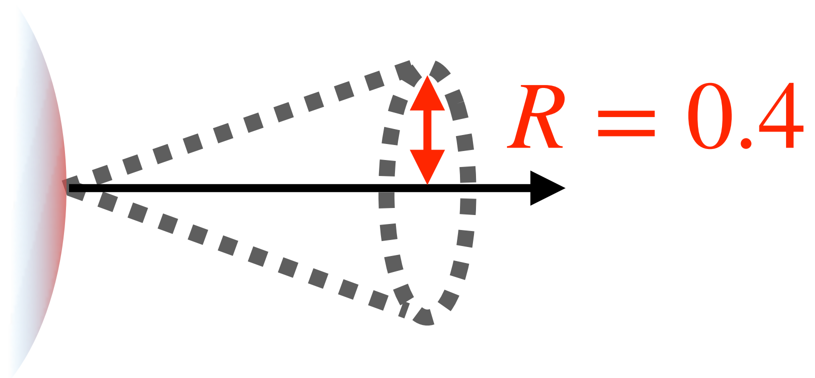
PRC 110 (2024) 014906

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

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

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

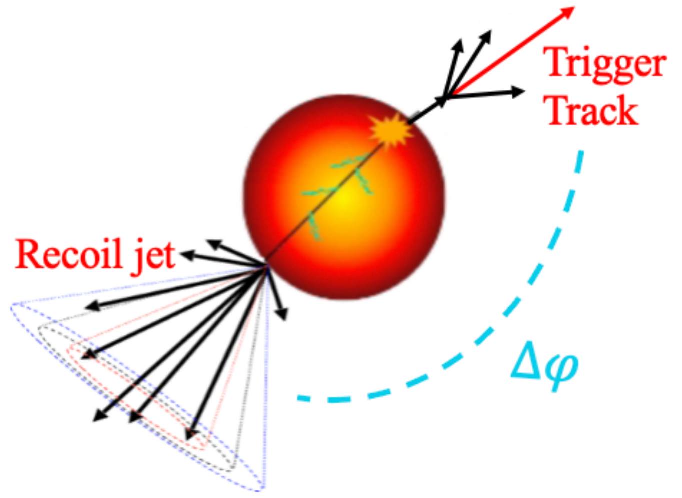
Semi-inclusive jet energy redistribution

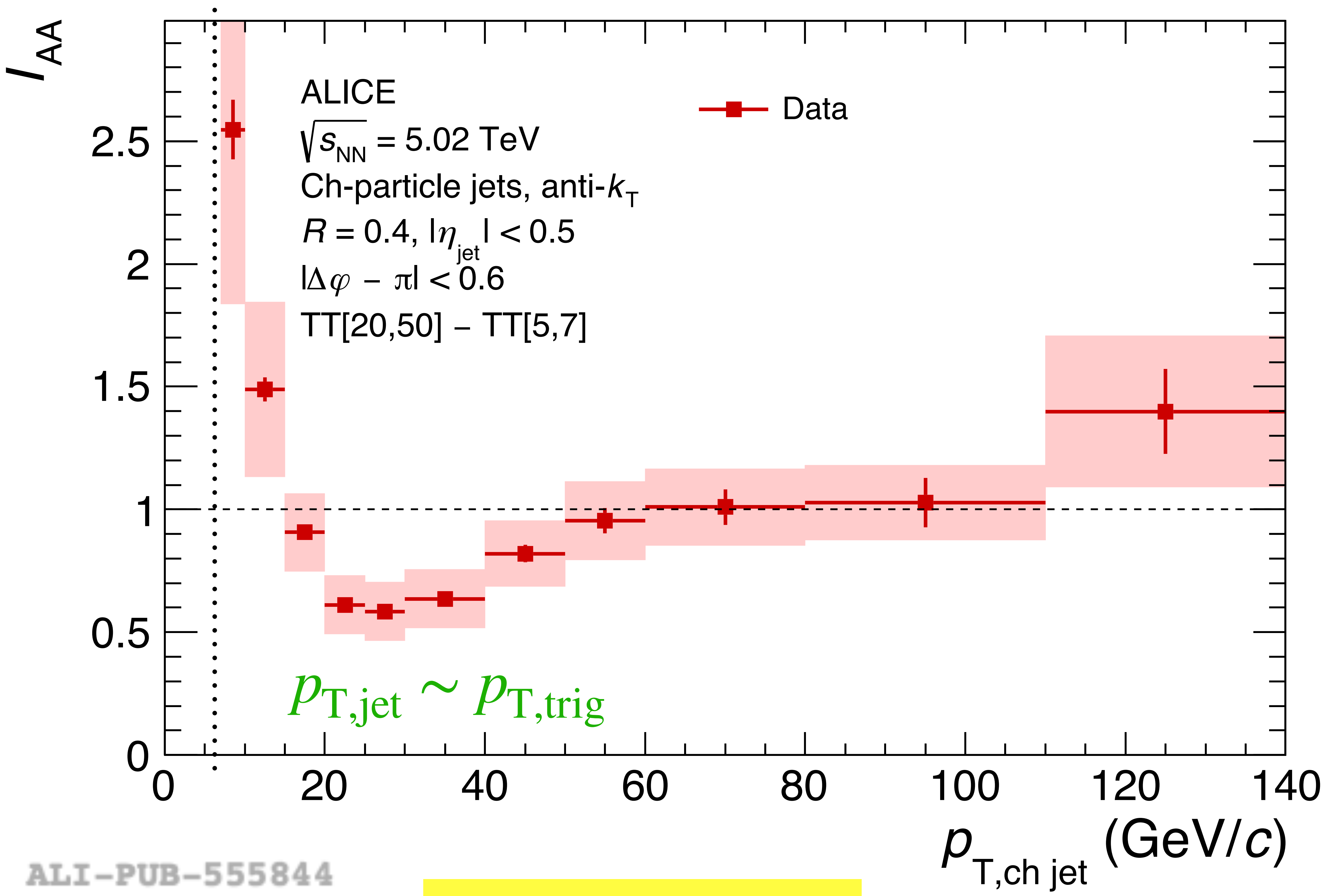


0–10%

R = 0.4

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





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

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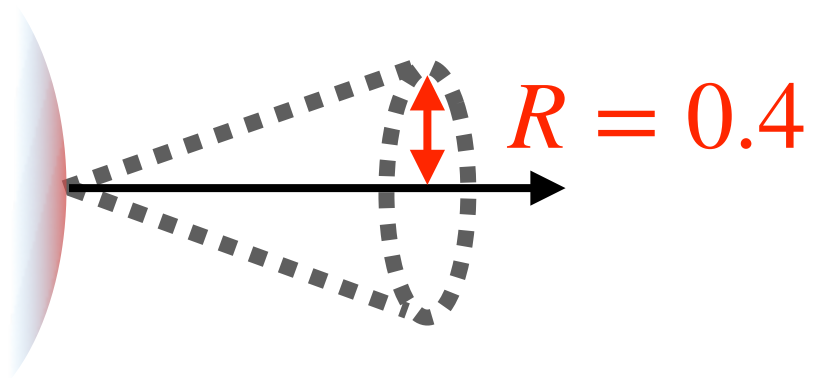

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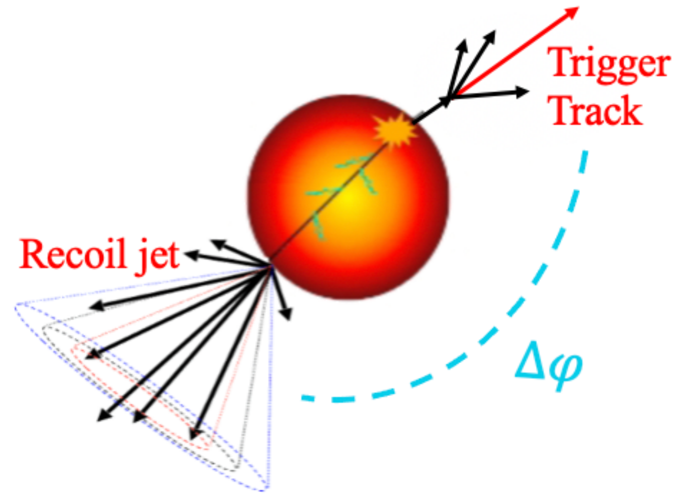
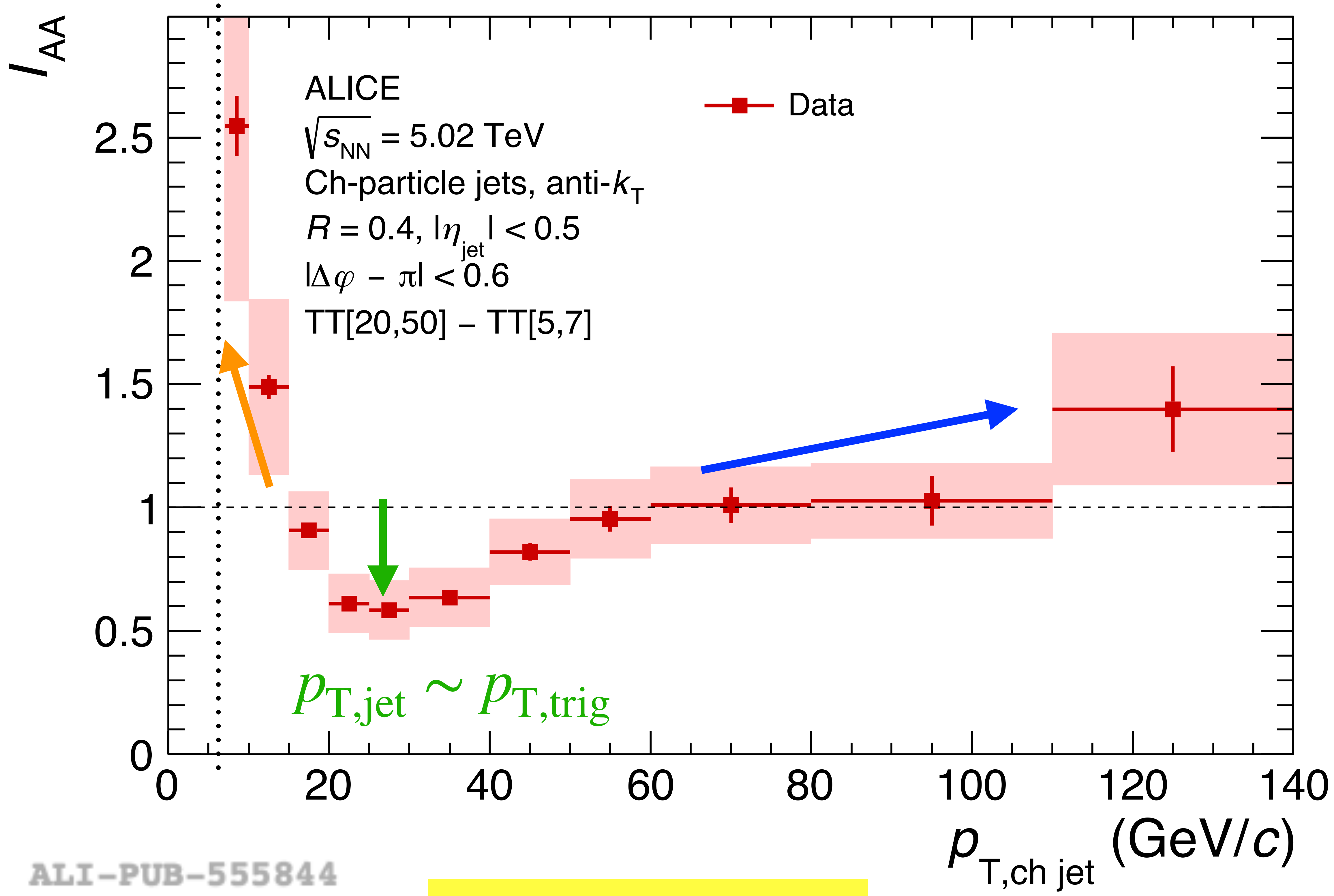
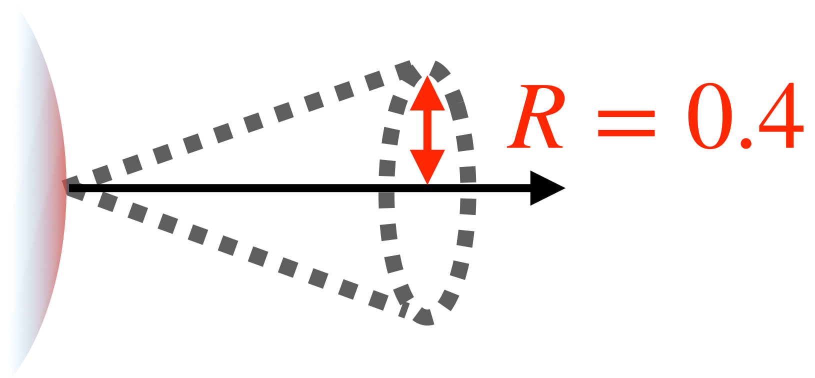




PRC 110 (2024) 014906

- First measurements of semi-inclusive recoil jet yields down to very low p_{T} (7 GeV/c) with ALICE
- Jet yield enhancement at low p_{T} → hint of energy recovery in low p_{T} jets?
- Jet yield suppression at $20 < p_{\mathrm{T,jet}} < 60$ GeV/c → Jet energy loss
- Rising trend with increasing jet p_{T} → Interplay of jet quenching and jet production

Semi-inclusive jet energy redistribution: model comparison



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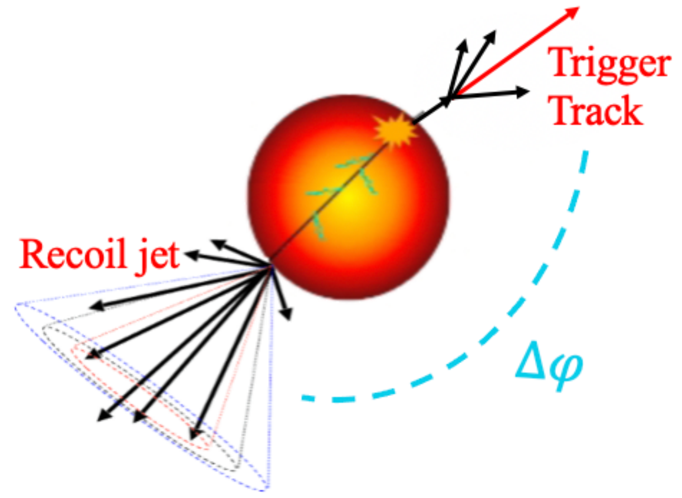

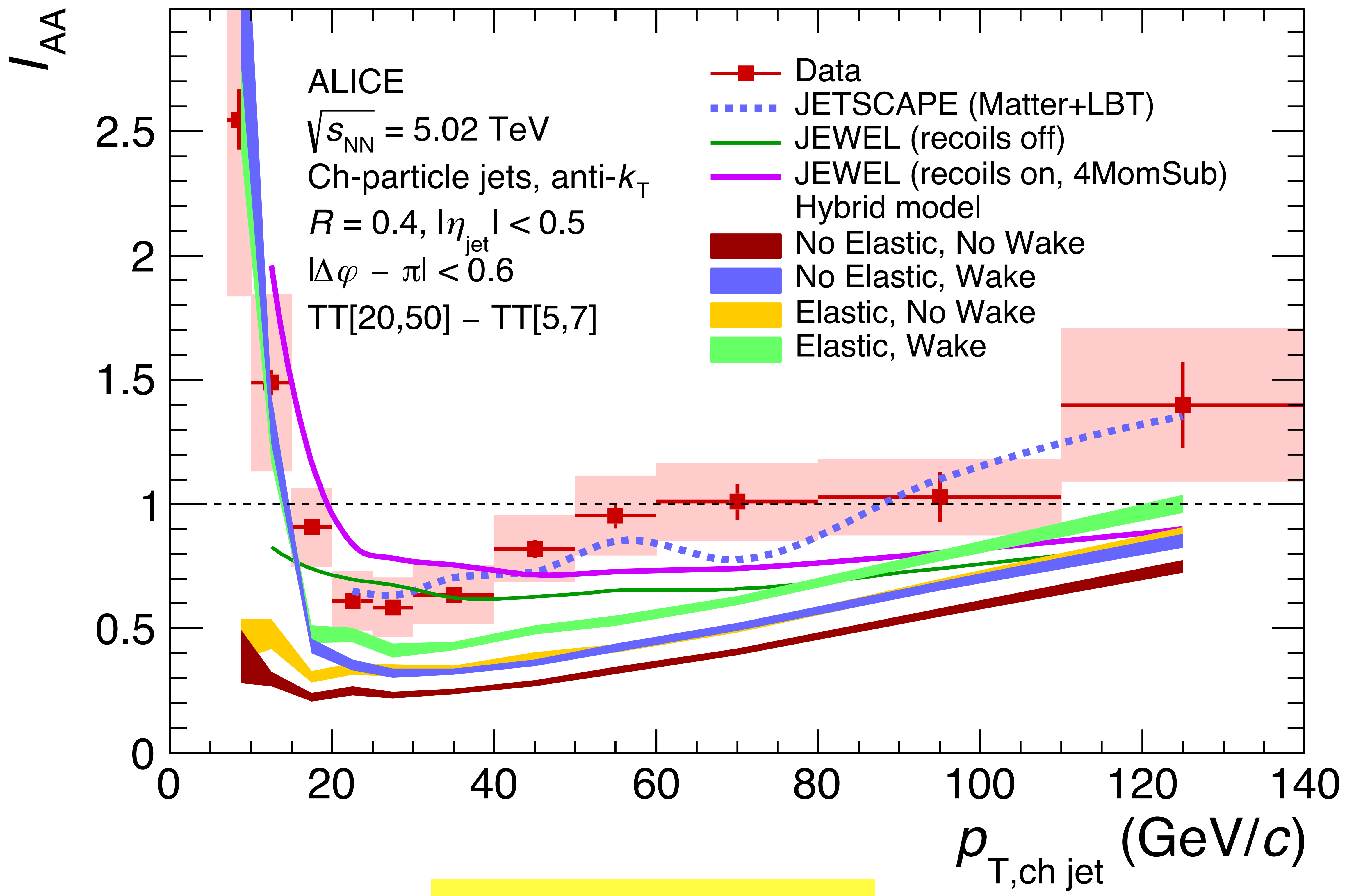

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JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss MATTER+LBT

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medium response effects via treatment of 'recoils'

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JHEP 02 (2022) 175, JHEP01(2019)172
With/without elastic energy loss (i.e 'Moliere' scattering)
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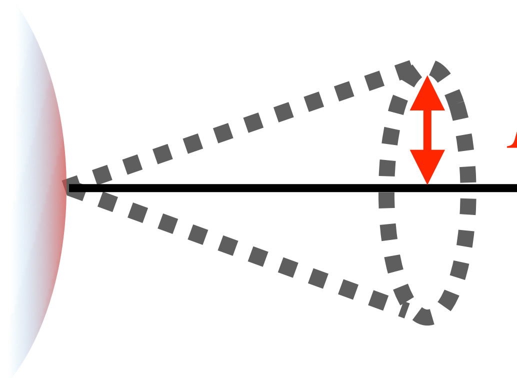

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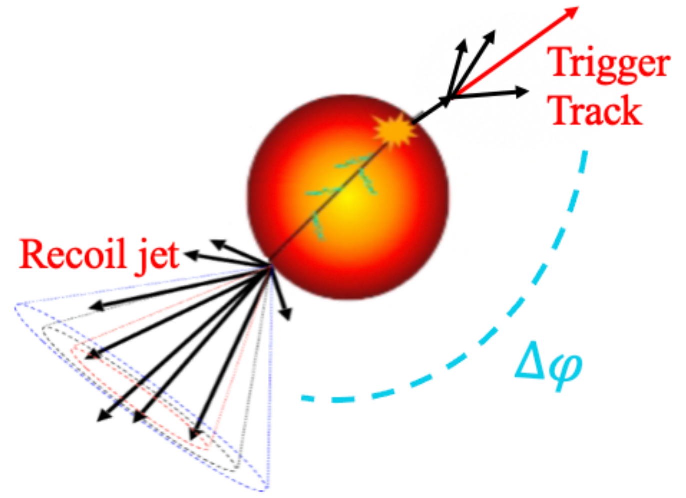
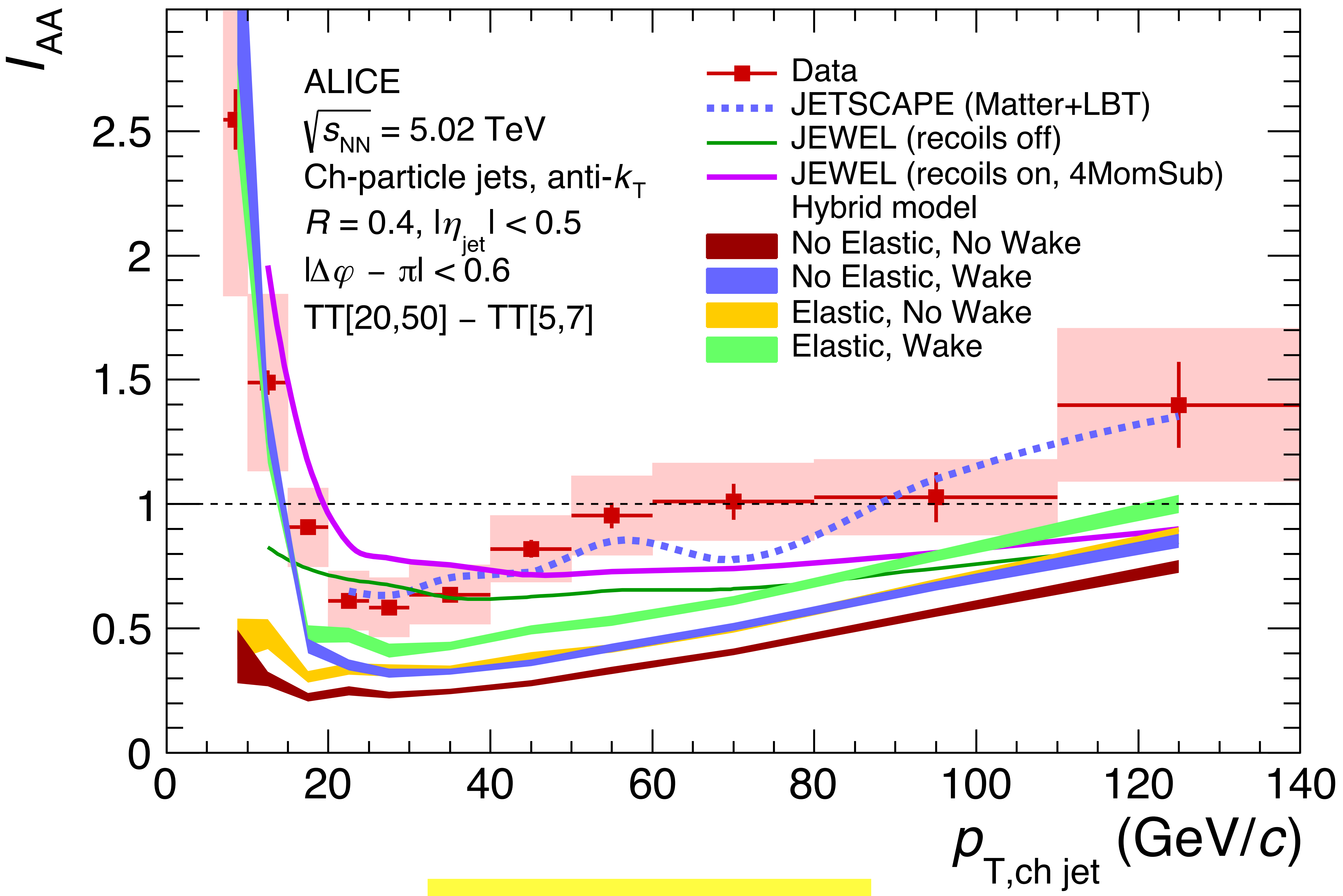
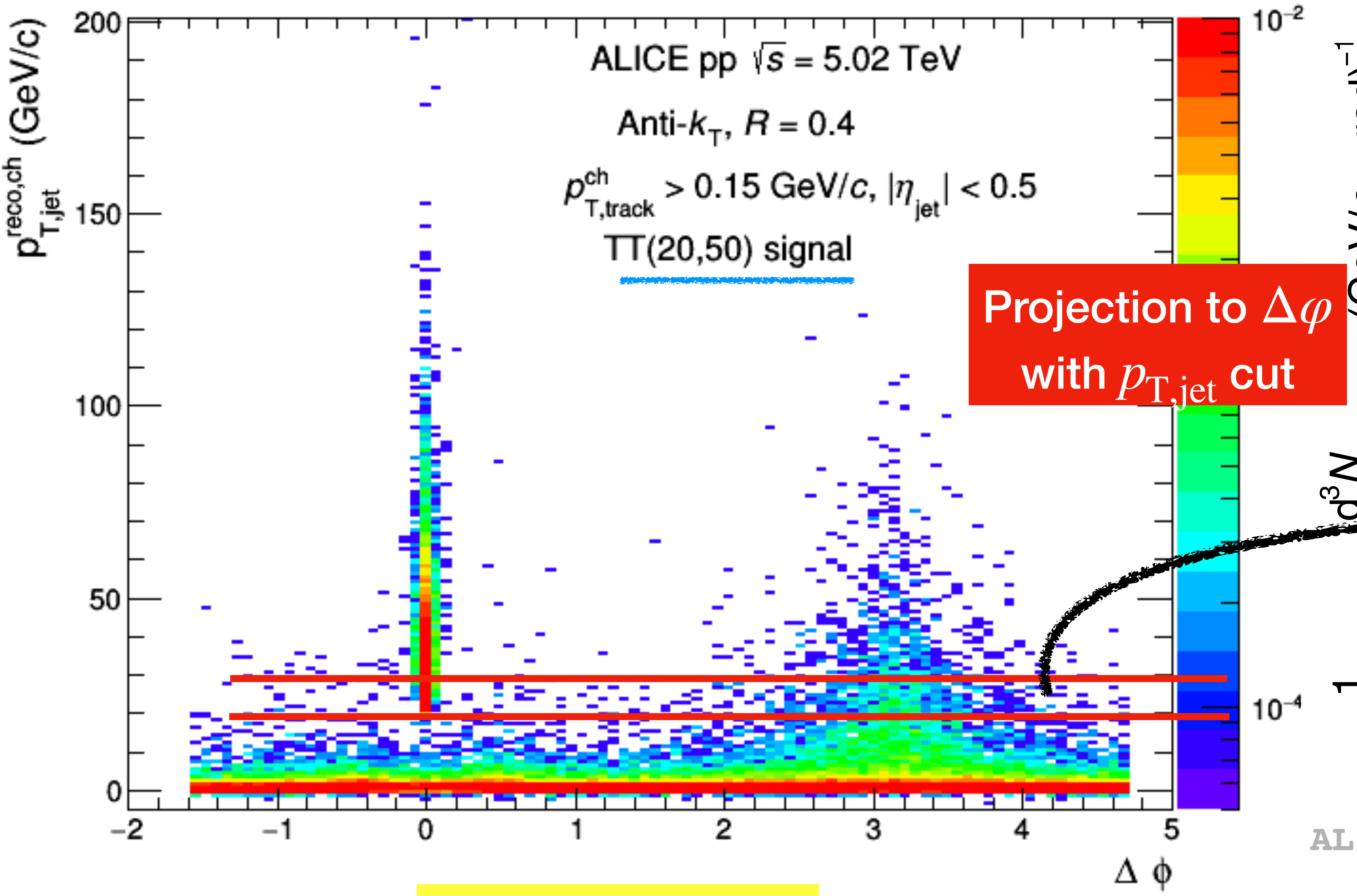




PRC 110 (2024) 014906

- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE
- The rising trend is qualitatively described by all predications
- Hybrid model and JEWEL predictions overestimate the suppression at high p_T
- Hybrid model with wake effect and JEWEL with recoils on capture the yield enhancement at low p_T
  → Medium response could be responsible for enhancement

Semi-inclusive jet angular distributions



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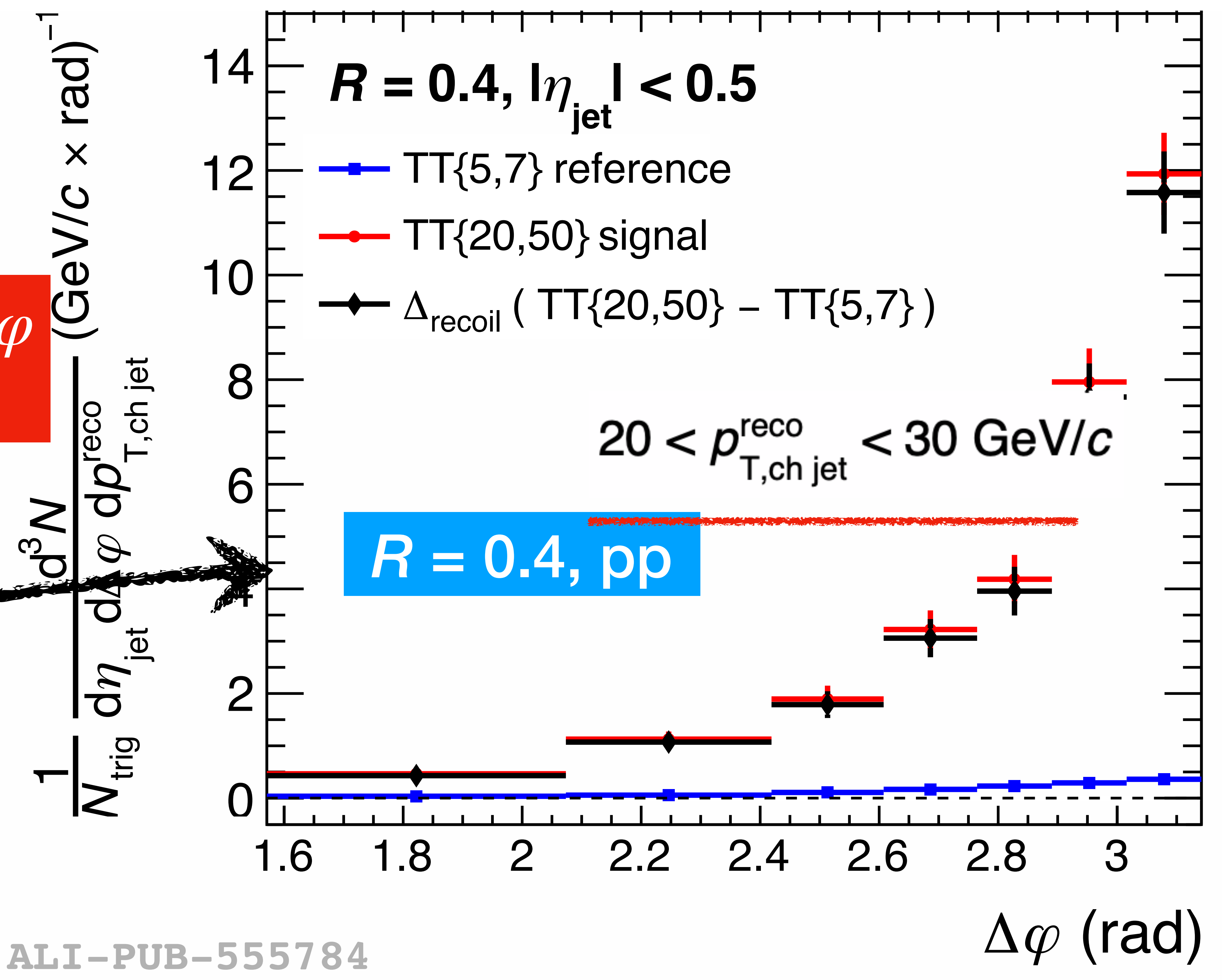
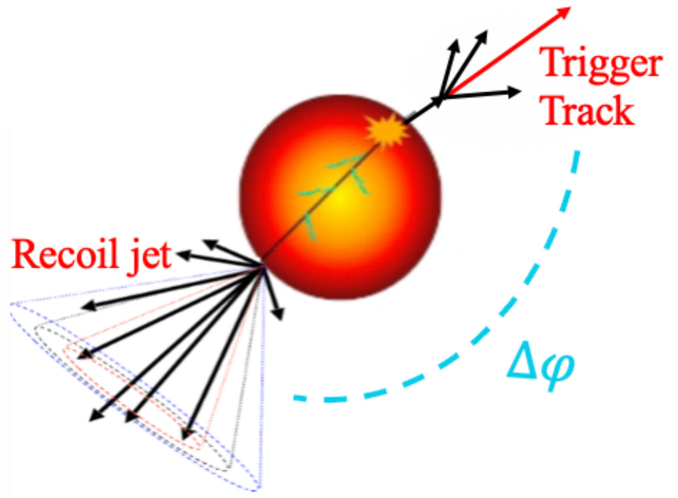
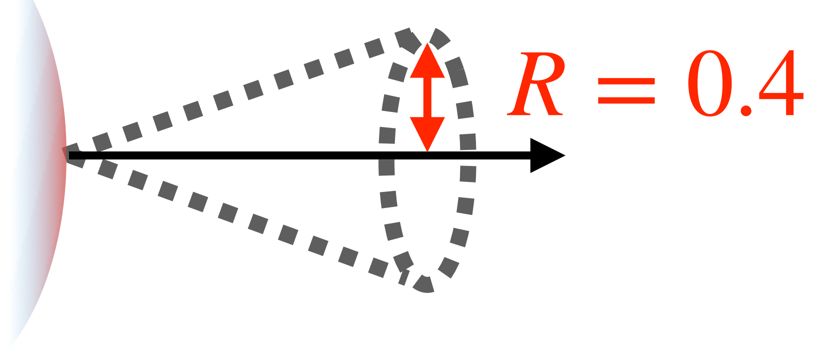




$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch}\,d\Delta\varphi\,d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref}\cdot\frac{1}{N_{trig}^{AA}} \frac{d^3N_{jet}^{AA}}{dp_{T,jet}^{ch}\,d\Delta\varphi\,d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Ref}}$$

- Get the recoil 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



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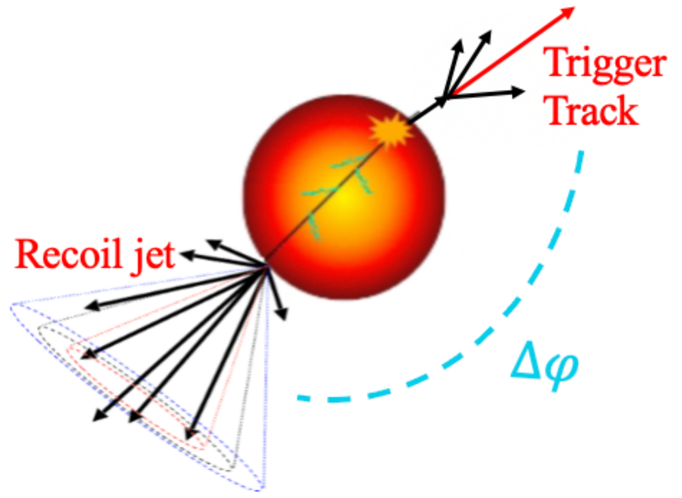

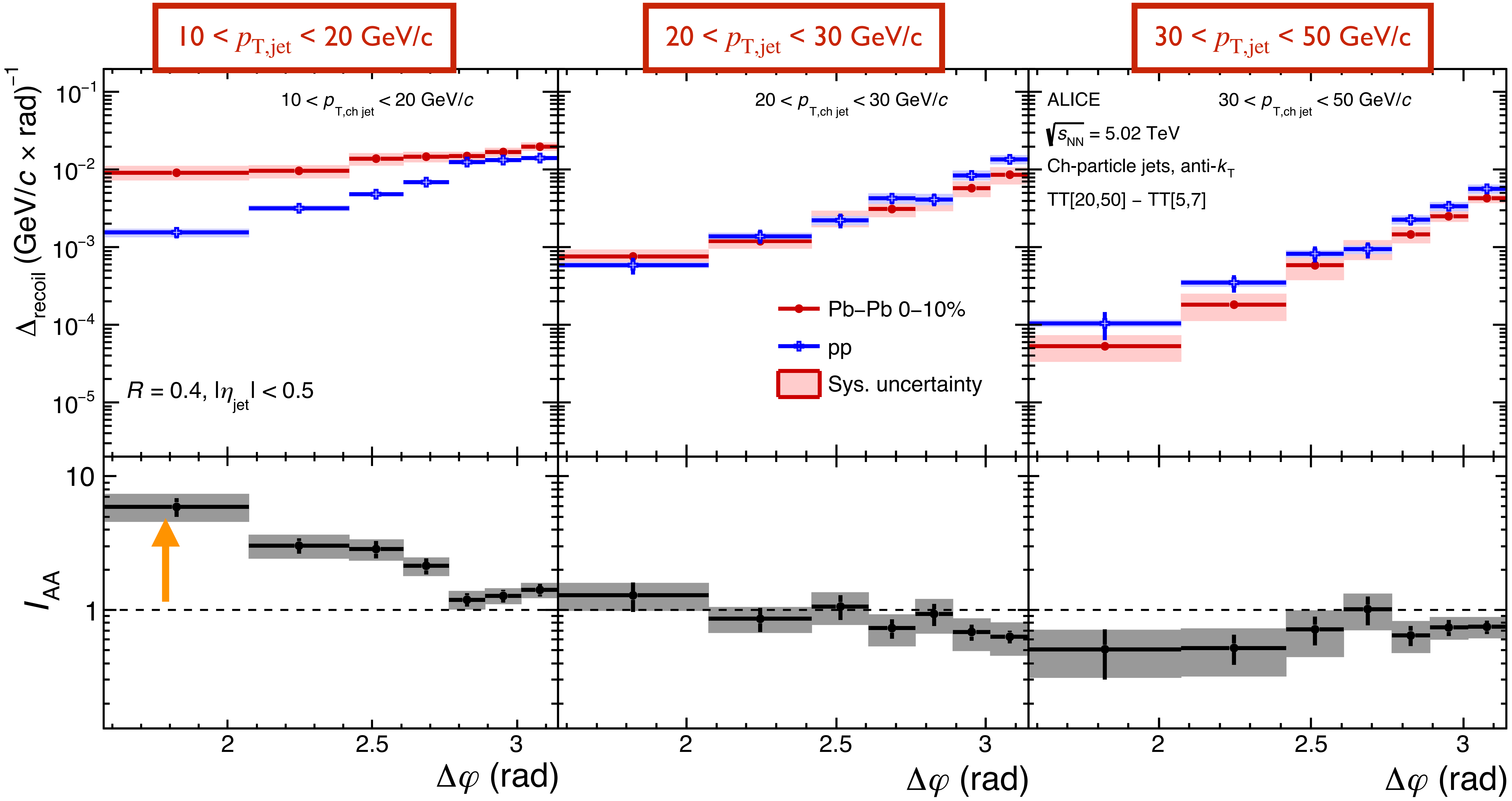

PRL 133 (2024) 022301

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

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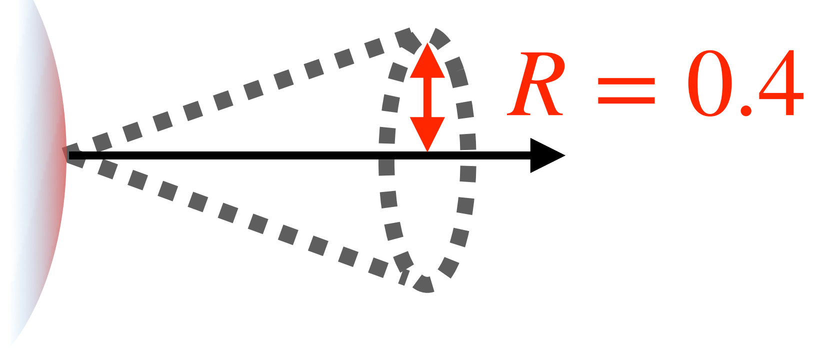

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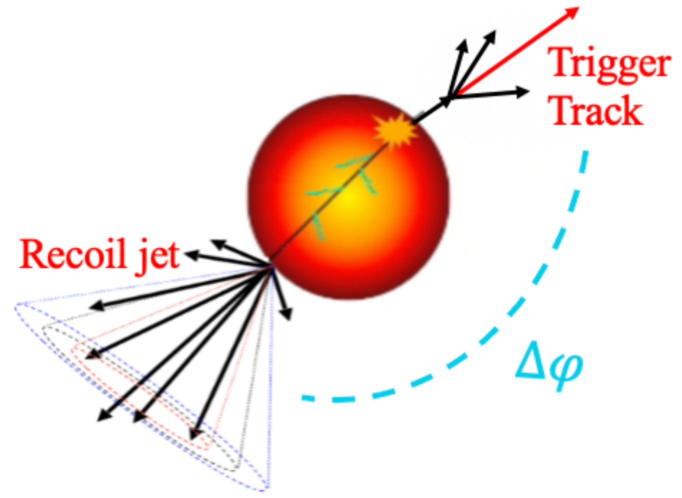
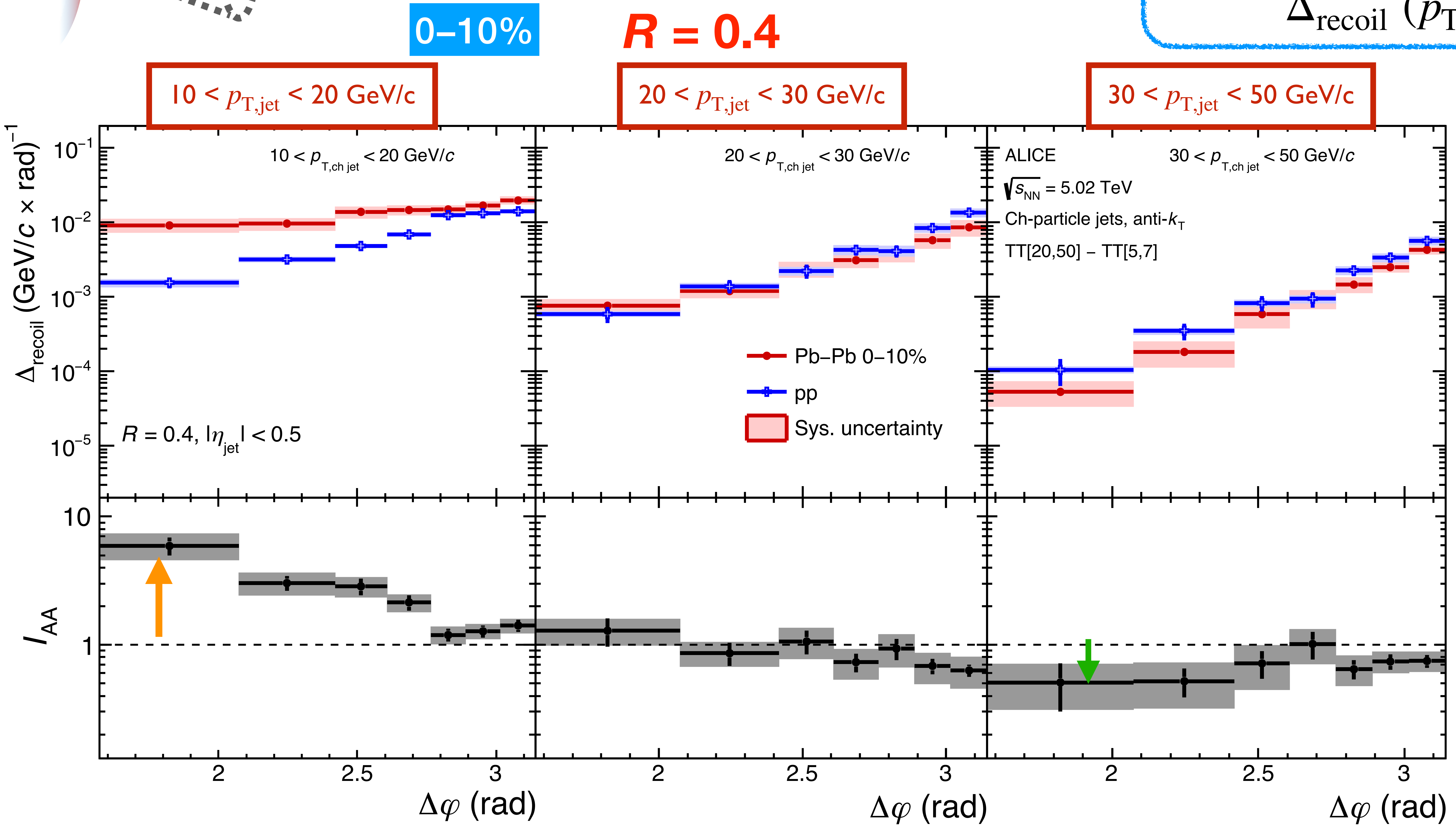
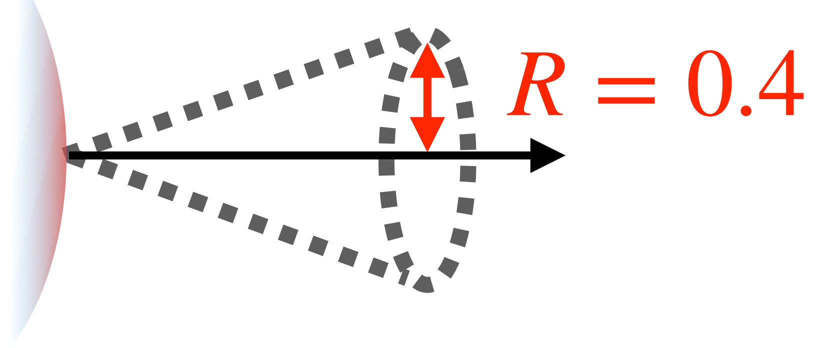




PRL 133 (2024) 022301

- Significant broadening for $p_T \in [10,20]$ GeV/c
- No significant deviation for $p_T \in [20,30]$ GeV/c
- Jets yield suppression for $p_T \in [30,50]$ GeV/c

Recoil jet azimuthal modifications: model comparison



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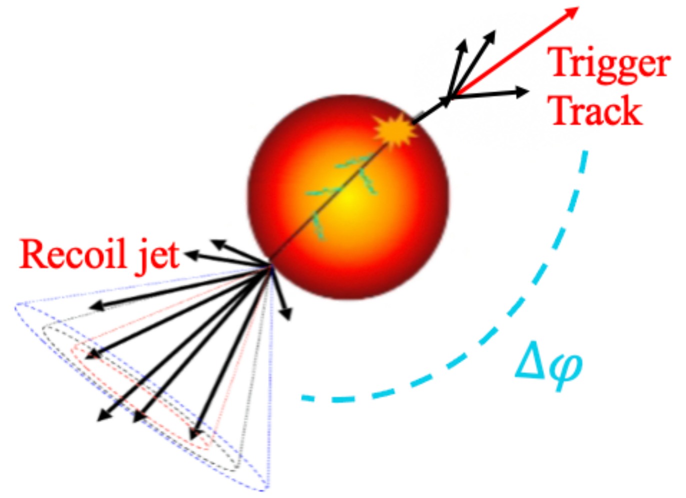

0–10%

R = 0.4

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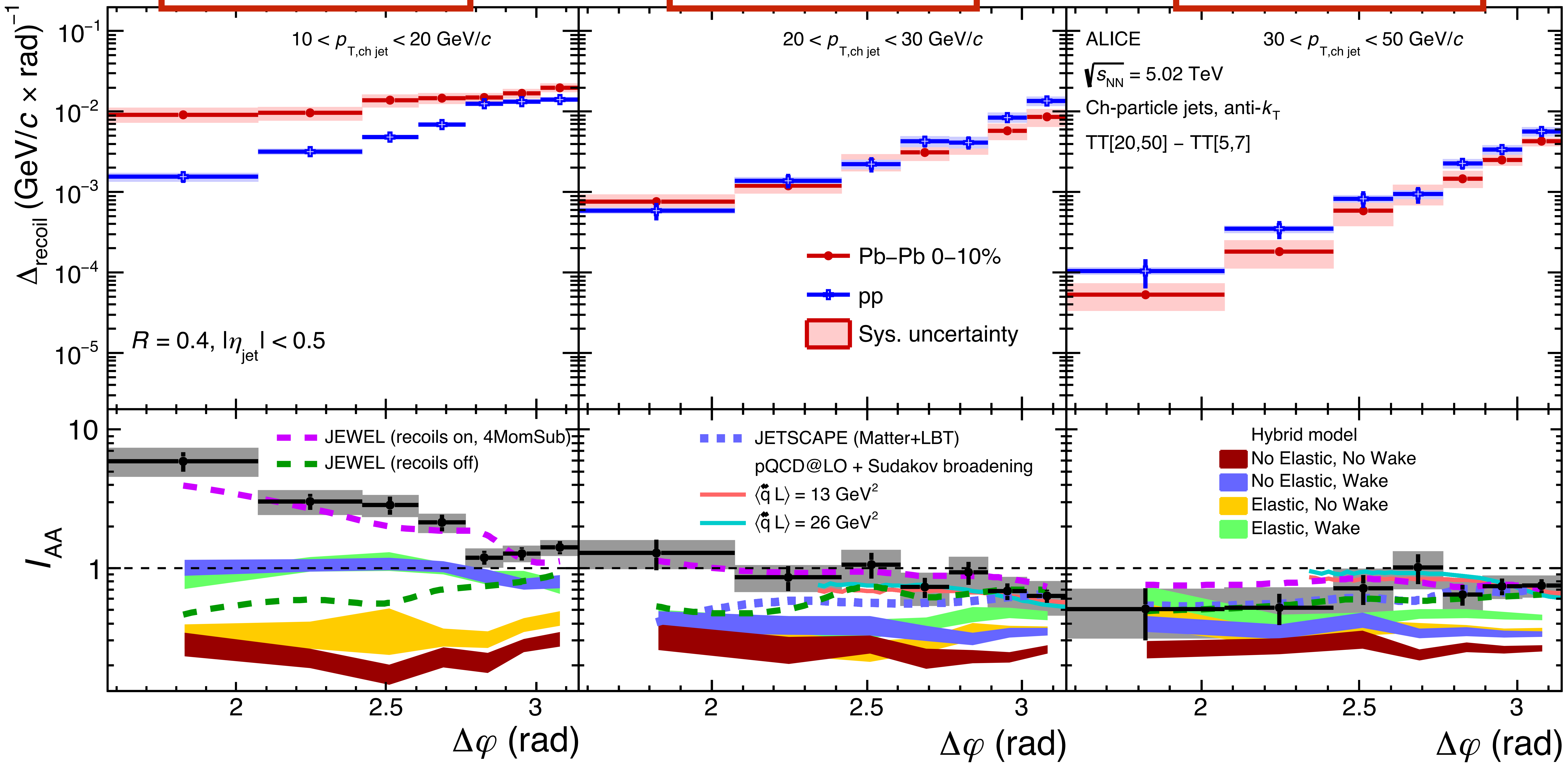

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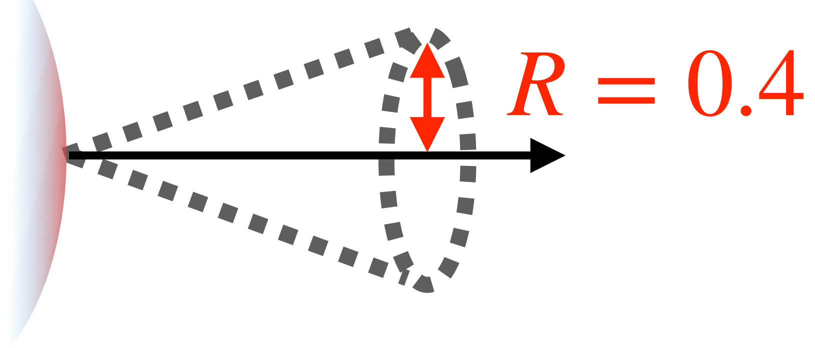
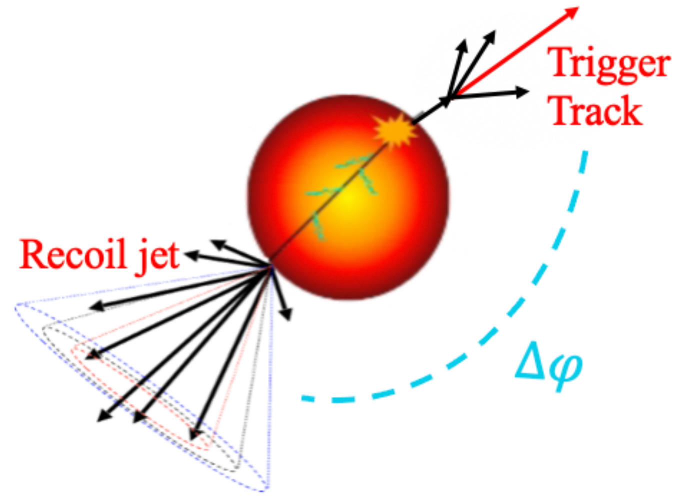
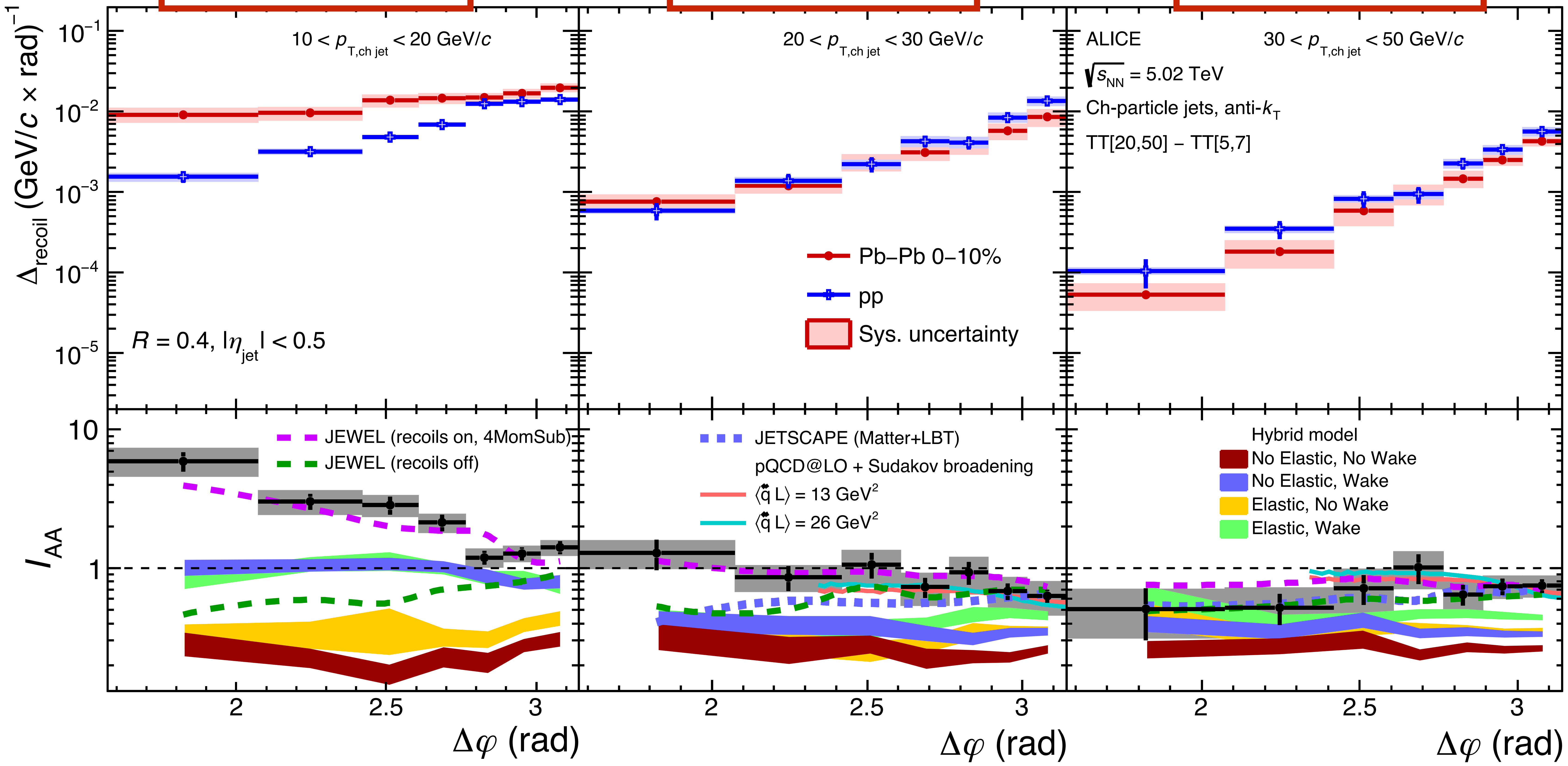


$$I_{AA} \equiv \frac{\Delta_{recoil}(p_T)_{AA}}{\Delta_{recoil}(p_T)_{pp}}$$



0–10%

R = 0.4



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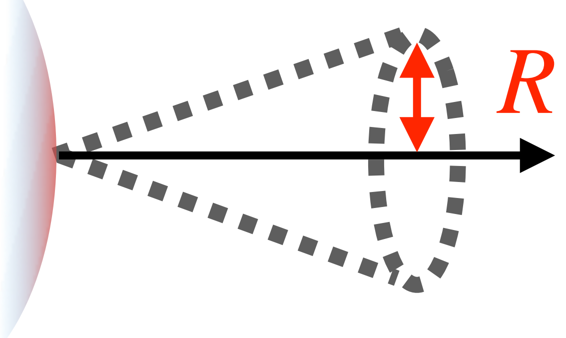
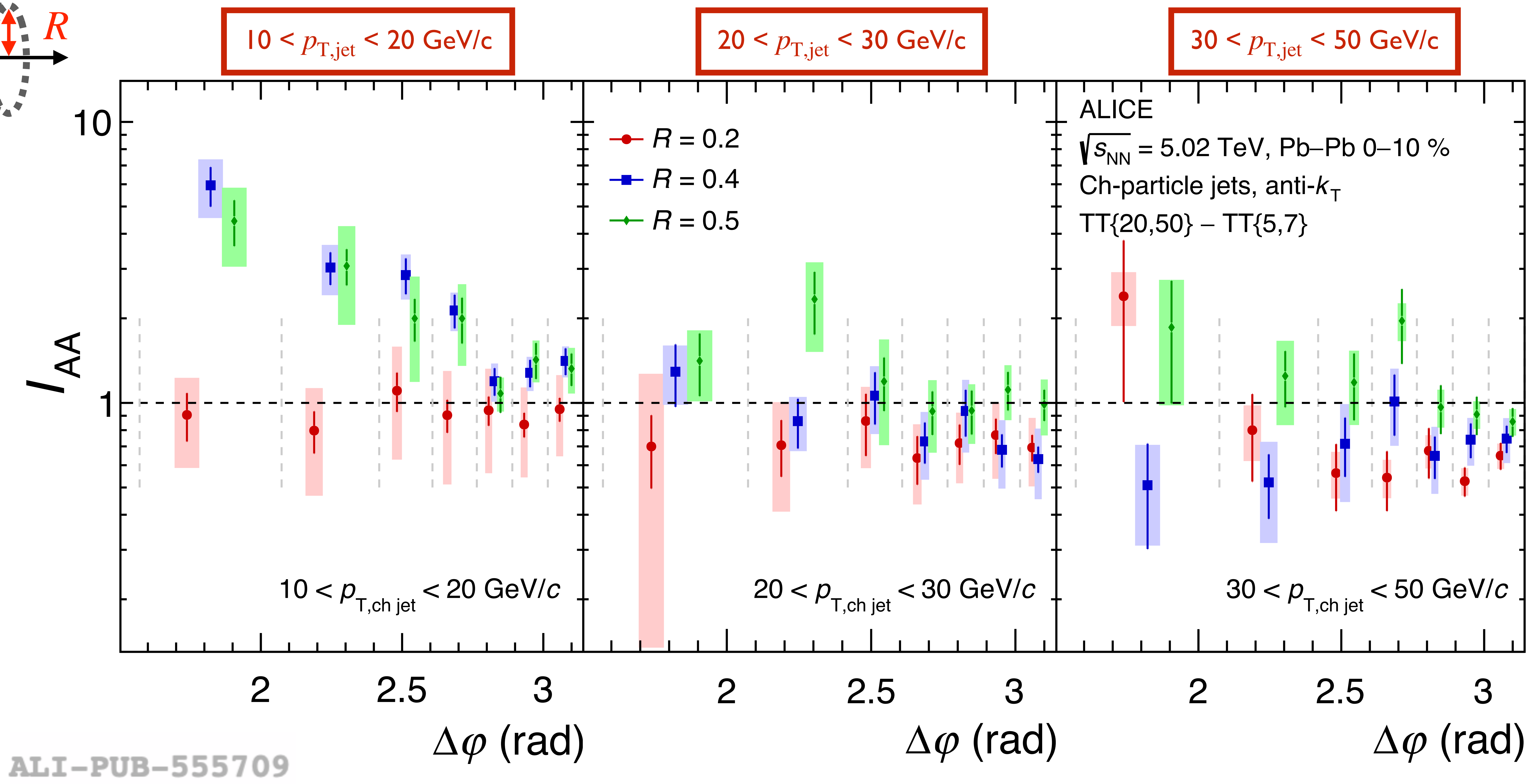
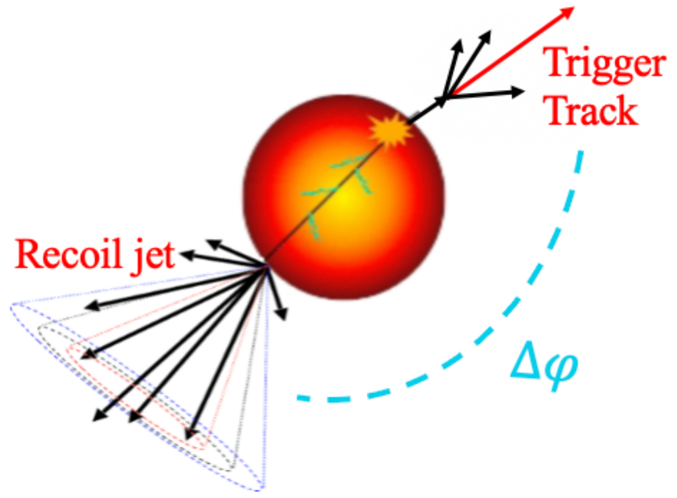
- All predictions can reasonably describe the data trend
- JEWEL with recoils-on describes the I_{AA} in all p_T bins, including the broadening effect
- Hybrid model captures the yield enhancement at low p_T (s10), but no broadening effect predicted even including elastic and wake component

Recoil jet azimuthal modifications: different R







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

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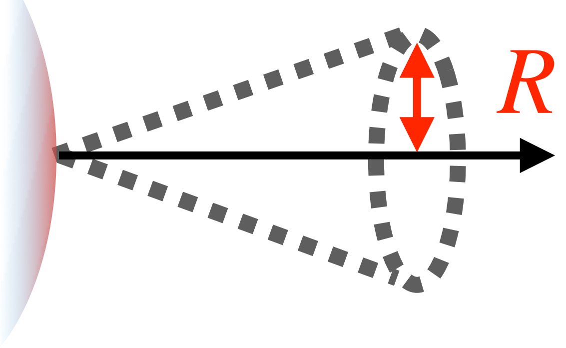
- Transition to broadening from R = 0.2 to R = 0.4 for 10 < $p_{\mathrm{T,ch\,jet}}$ < 20 GeV/c
  - Characteristic of medium response
  - soft radiation is recovered partially with increasing radius

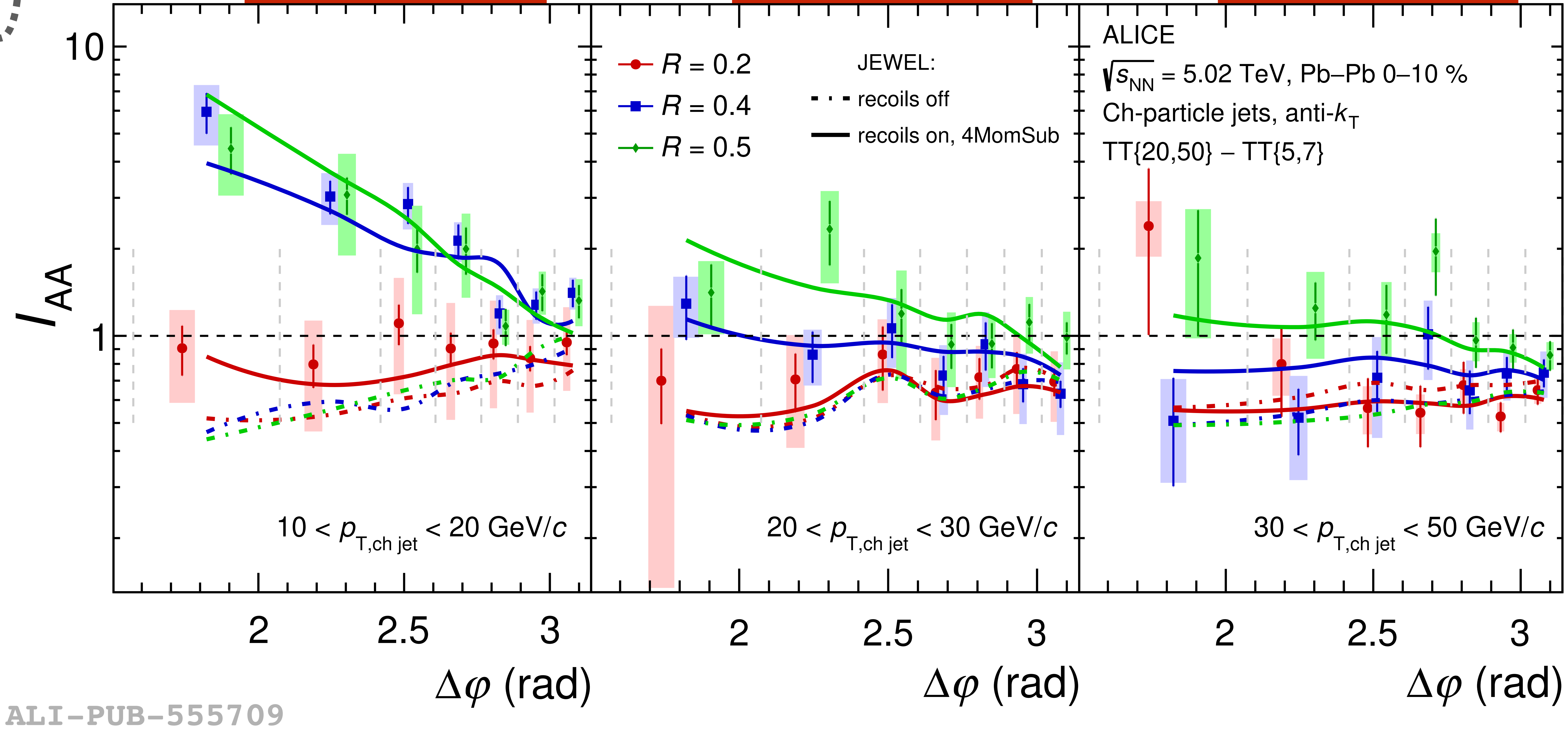
Recoil jet azimuthal modifications: model comparison

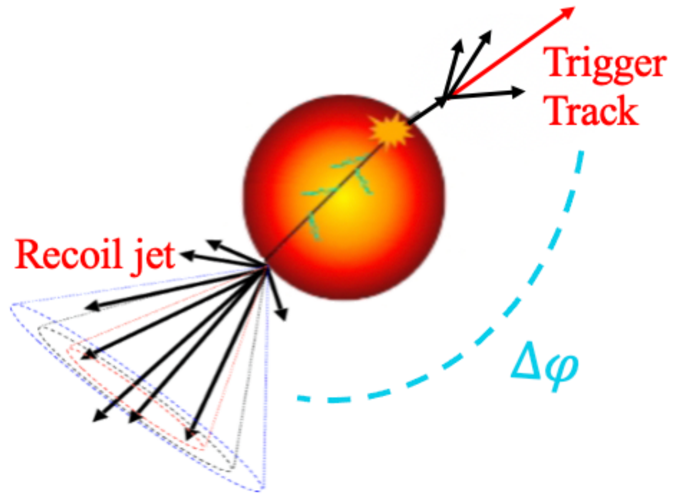


10 < $p_{T,\,jet}$ < 20 GeV/c

20 < $p_{T,\,jet}$ < 30 GeV/c

30 < $p_{T,\,jet}$ < 50 GeV/c





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

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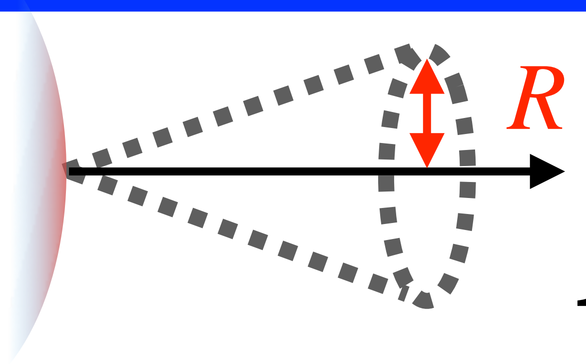
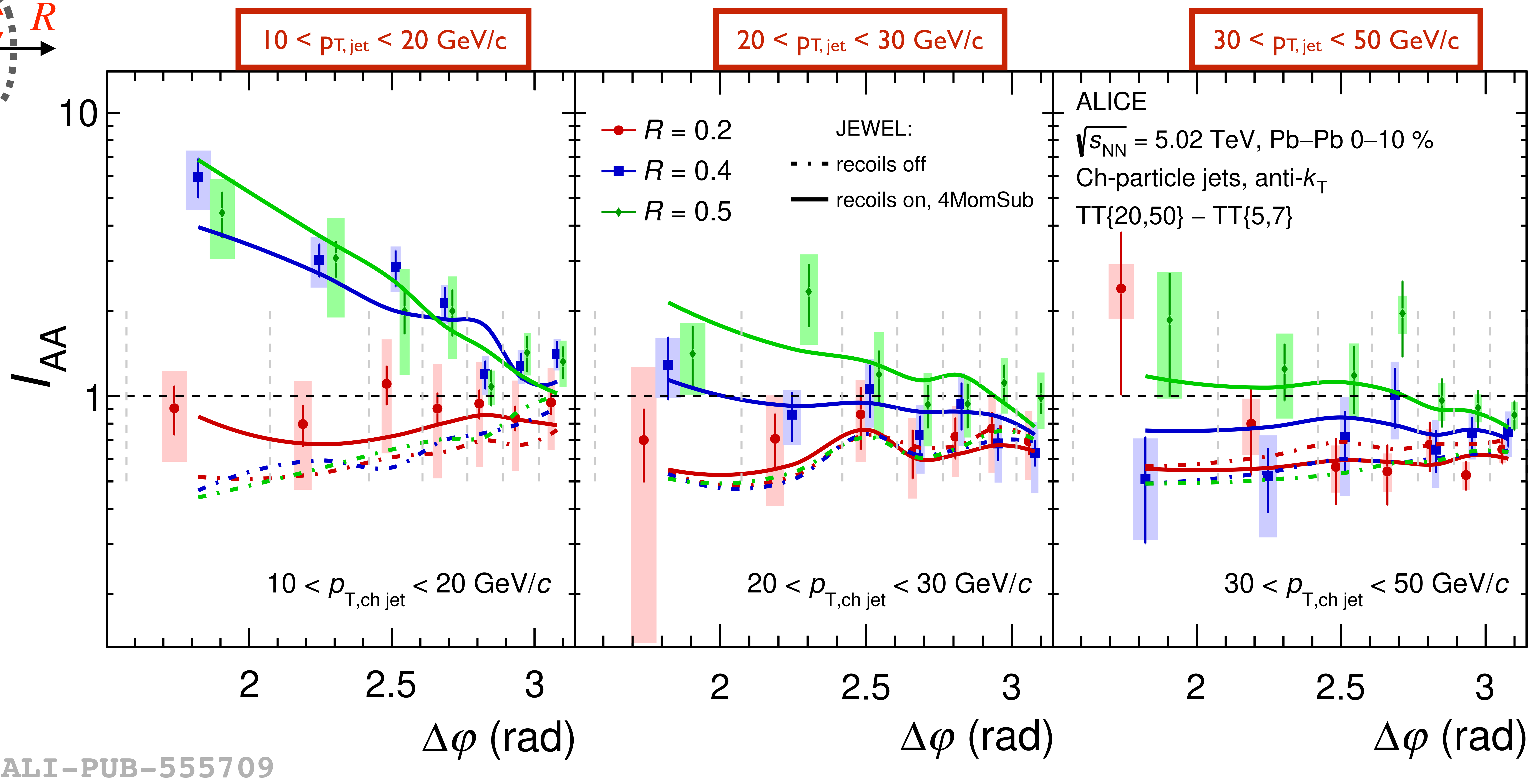
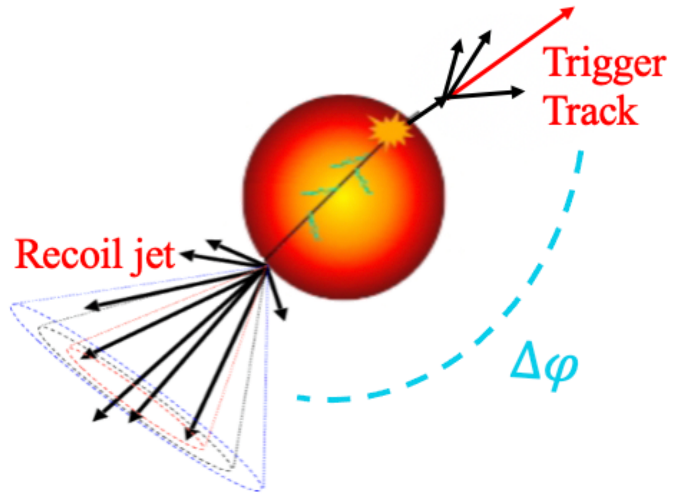
- All features of distribution **reproduced by JEWEL** with recoils on …

Recoil jet azimuthal modifications: model comparison







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

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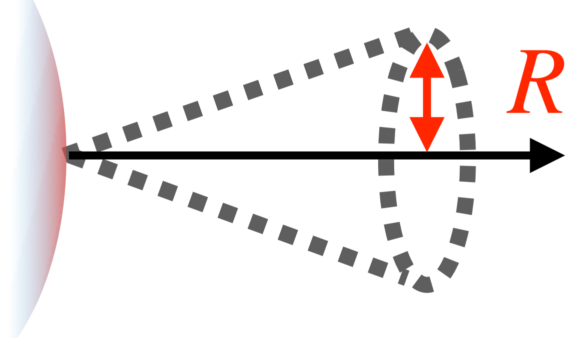
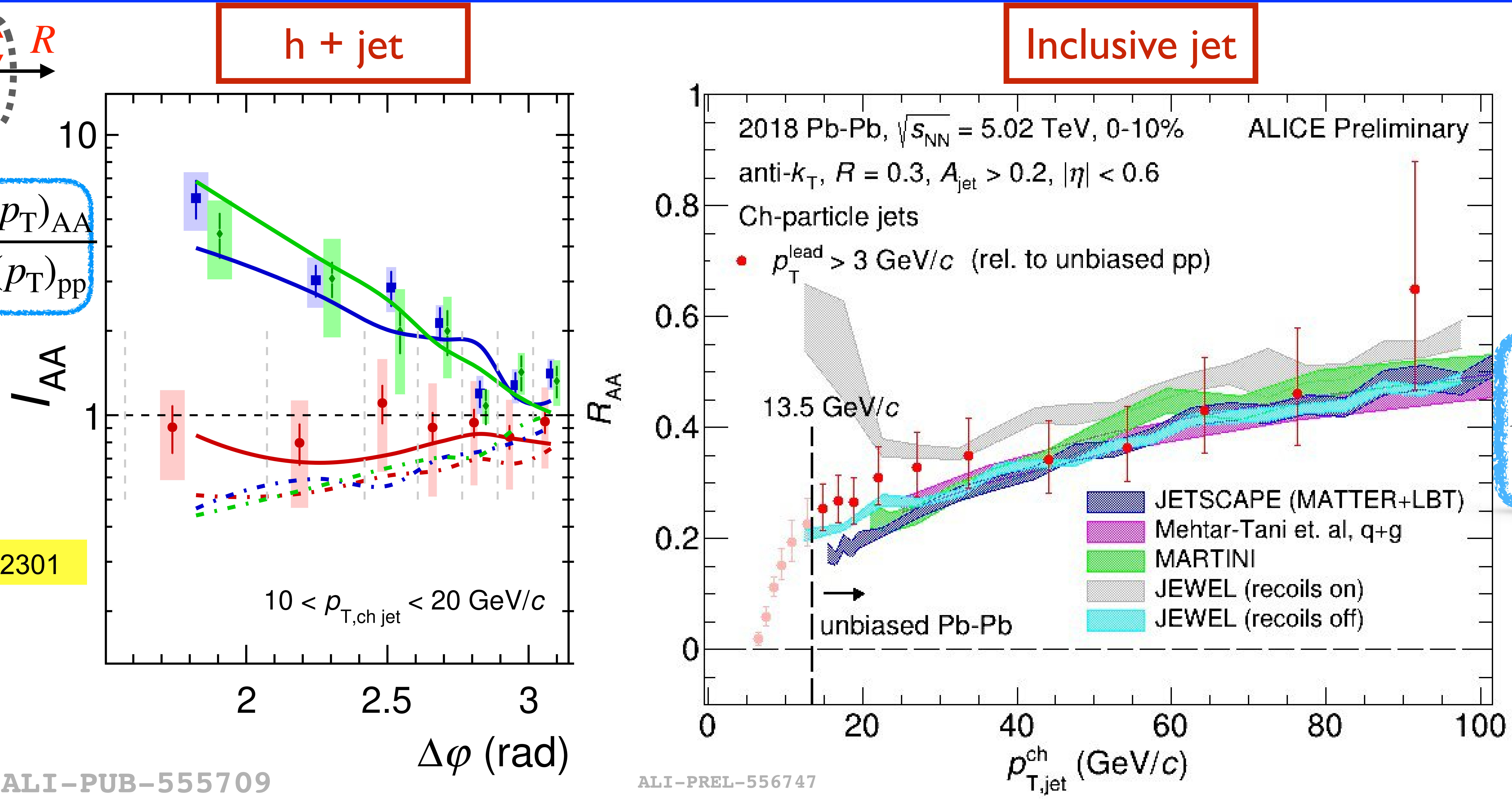
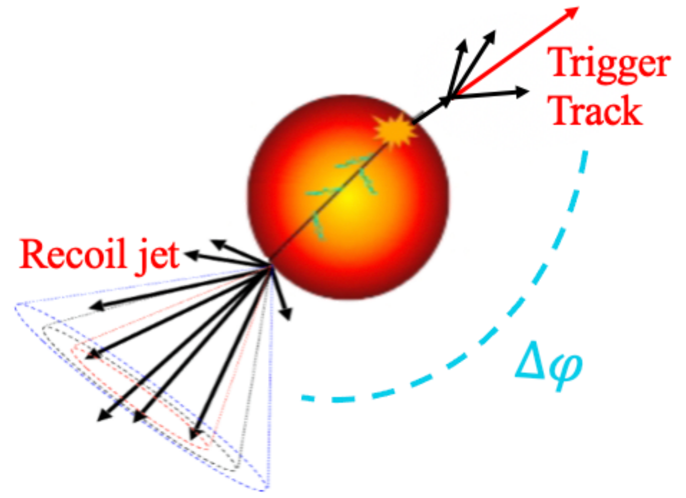
- All features of distribution **reproduced by JEWEL** with recoils on …

→Observed broadening consistent with medium response rather than Molière scattering

Recoil jets vs. inclusive jets modification







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

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

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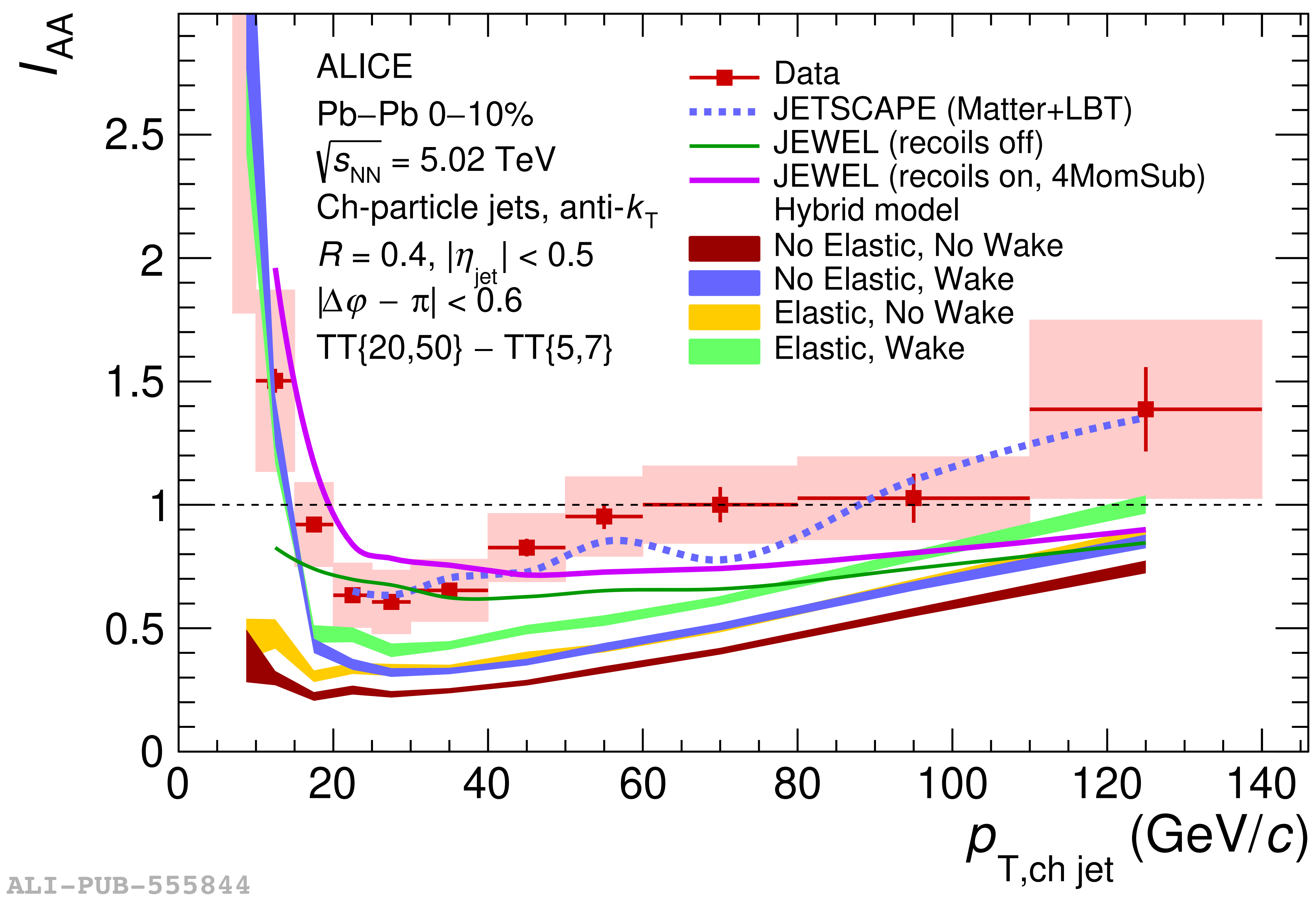
- JEWEL with recoil on can describe I_{AA} but not R_{AA}
- …but no model incorporating medium response describe all measured observables

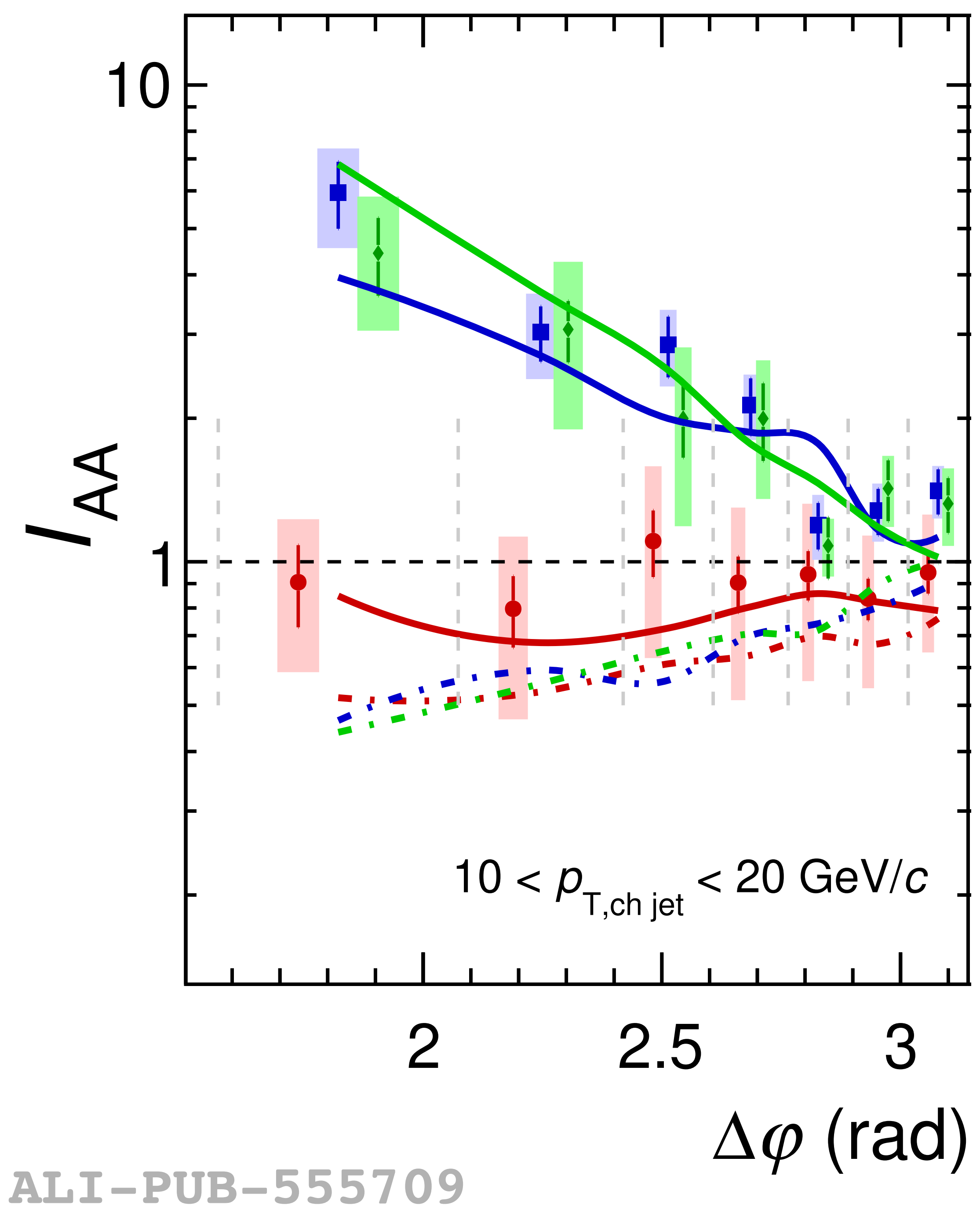
Summary and outlook

- First observation of recoil jet yield enhancement and medium-induced acoplanarity broadening at low-p_T with ALICE

→ Medium response is favored instead of Molière scattering as the cause for both effects



ALI-PUB-555844



ALI-PUB-555709

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Summary and outlook

- First observation of recoil jet yield enhancement and medium-induced acoplanarity broadening at low-p_{T} with ALICE

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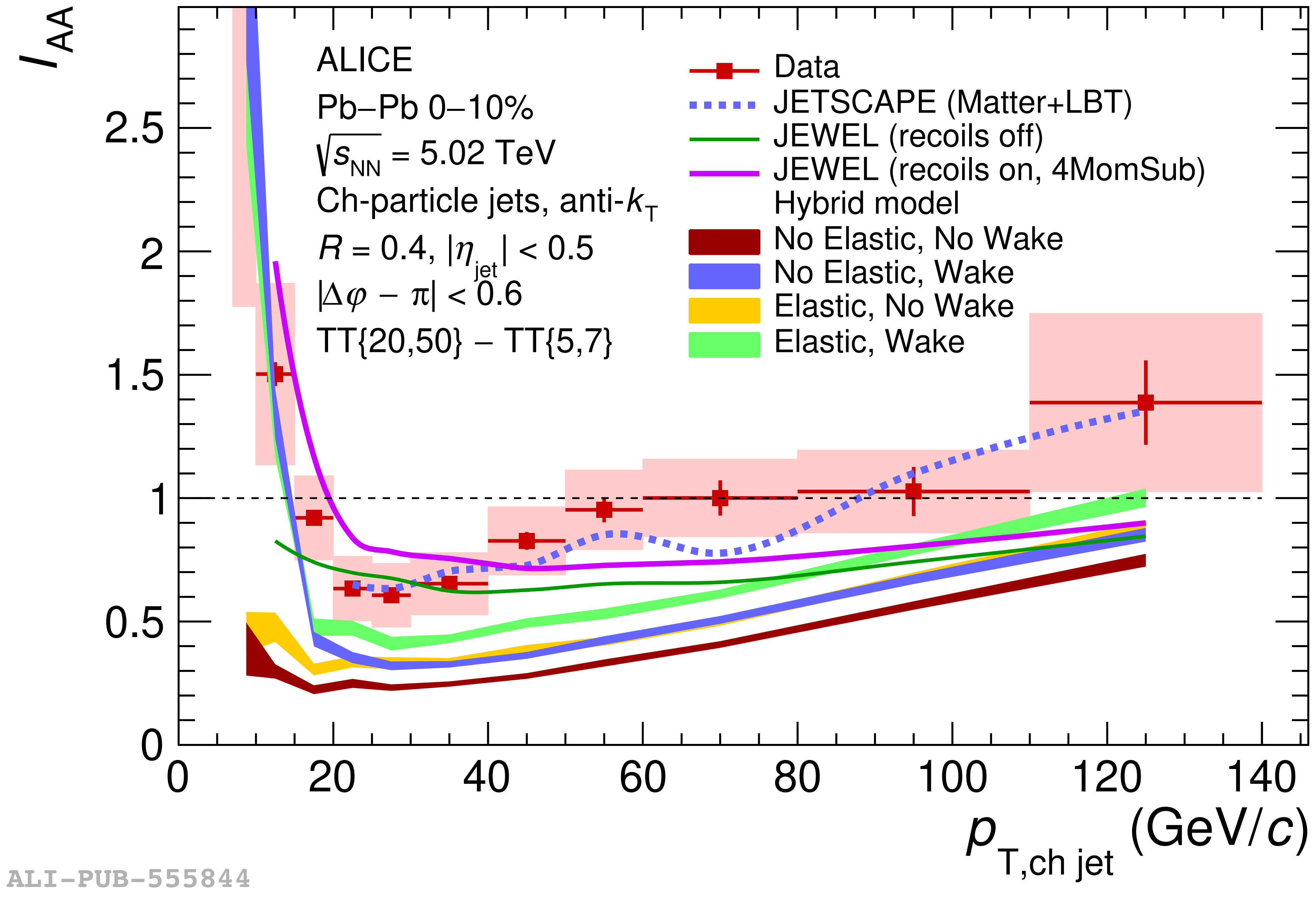

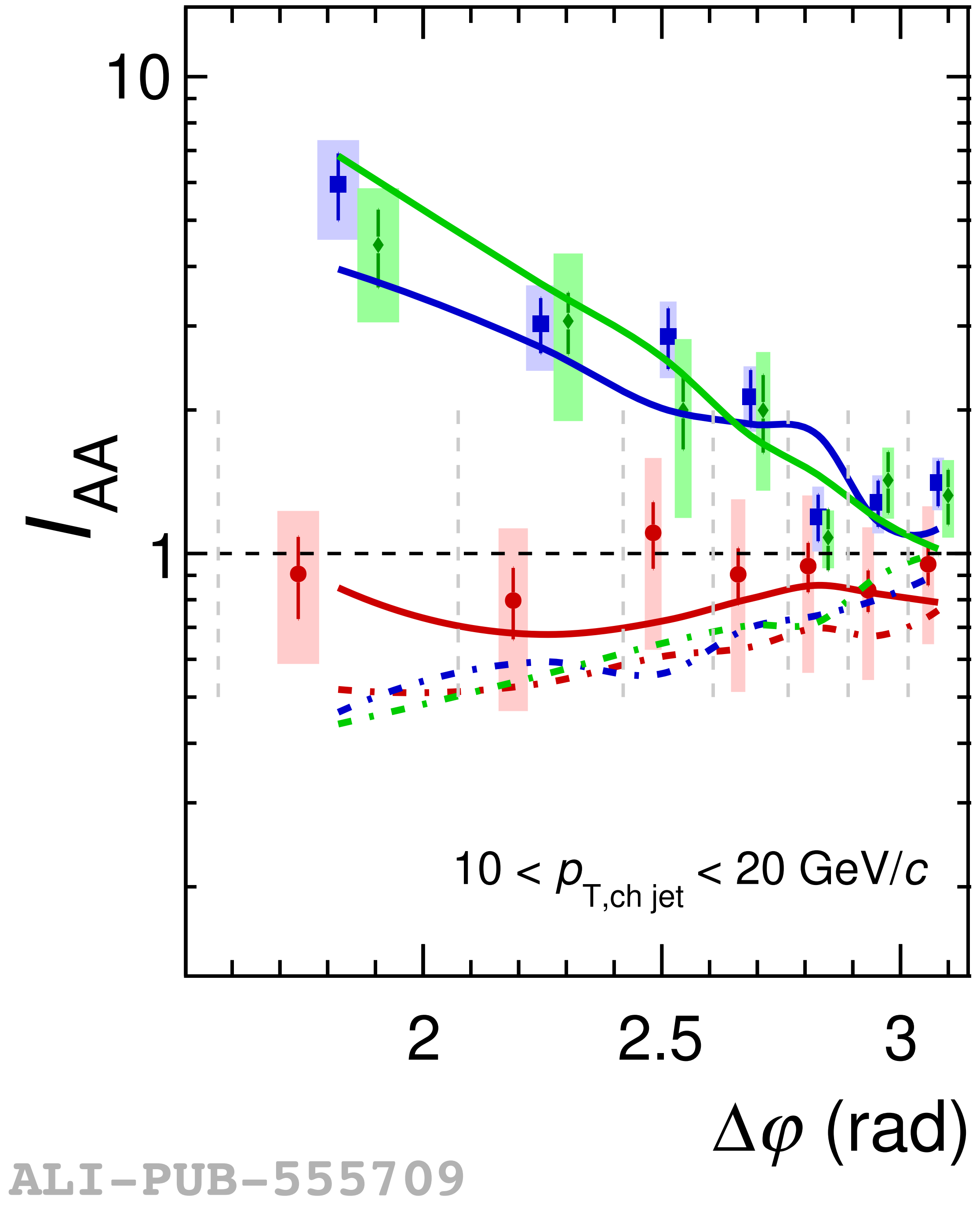

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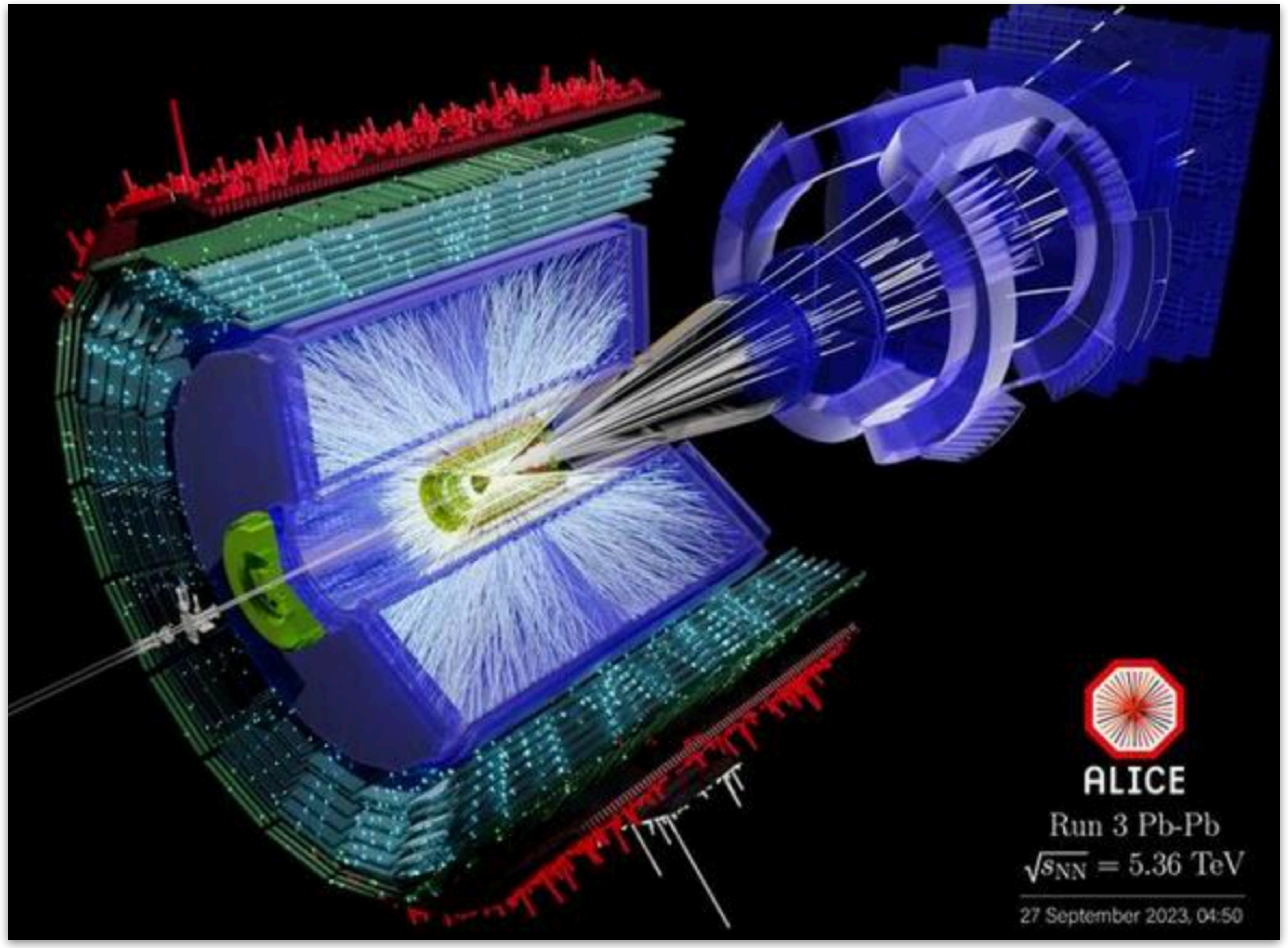

- Full interpretation requires description within a consistent theoretical framework! Future global analyses with multiple observables → stay tuned!

Backup