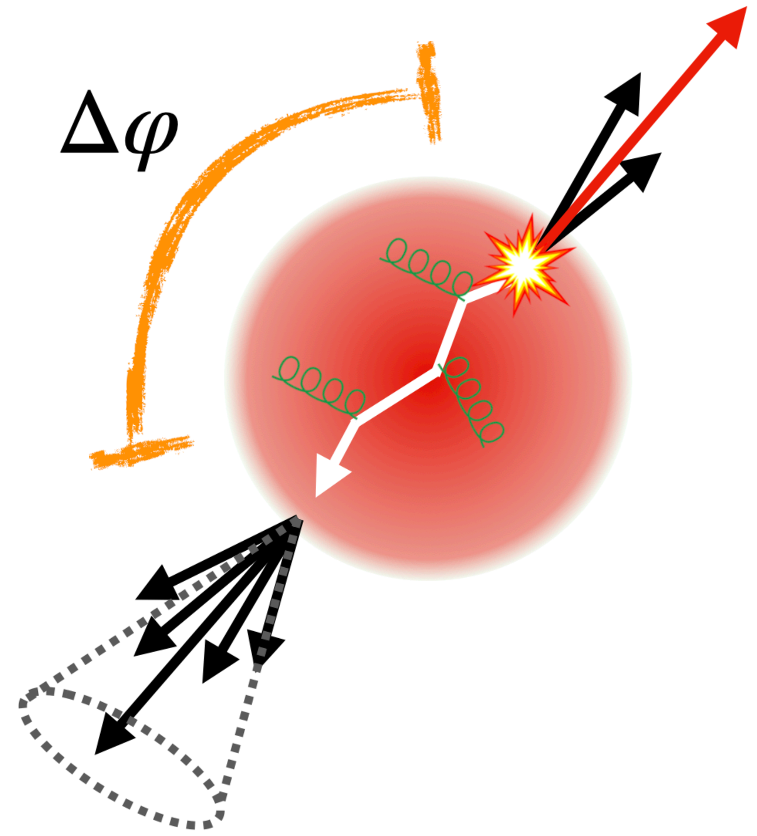


Probing jet energy redistribution and broadening in pp and Pb-Pb collisions with ALICE

Jaime Norman (University of Liverpool)
EP-LHC seminar
10th October 2023

UNIVERSITY OF LIVERPOOL

UKRI Science and Technology Facilities Council

ALICE

jknorman@liverpool.ac.uk

The quark-gluon plasma

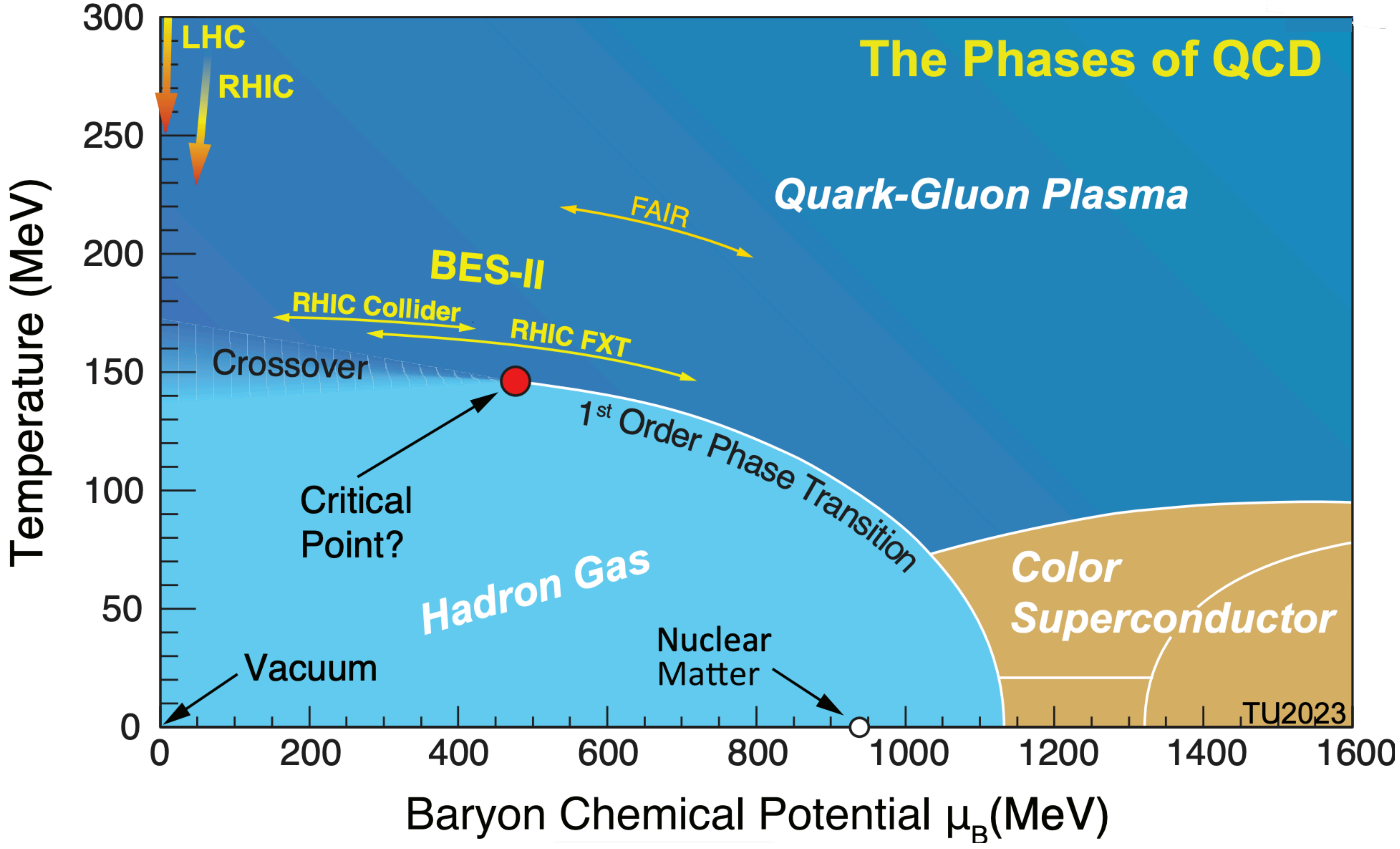


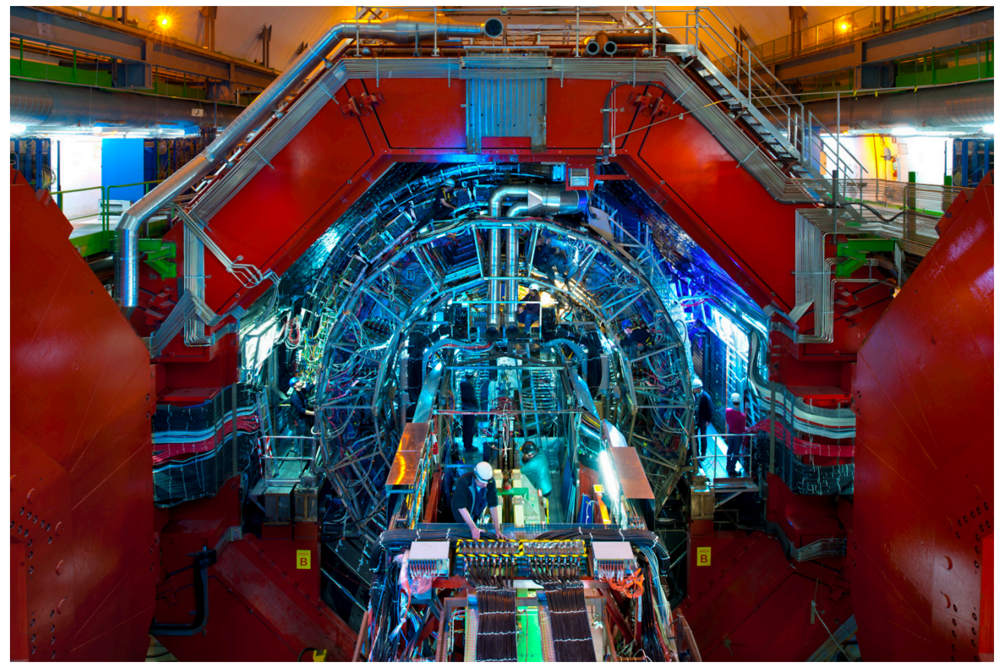
fig. H. Caines

- Phase transition at high temperature or density to deconfined state of quarks and gluons
  - **quark-gluon plasma (QGP)**
- Calculations on the lattice predicts smooth crossover at ~155 MeV at low baryon density
- Created using **ultra-relativistic heavy-ion collisions**

QGP (in a nutshell)

Long-distance structure:

QGP is a strongly-coupled liquid (with very low viscosity)



P. Romatschke

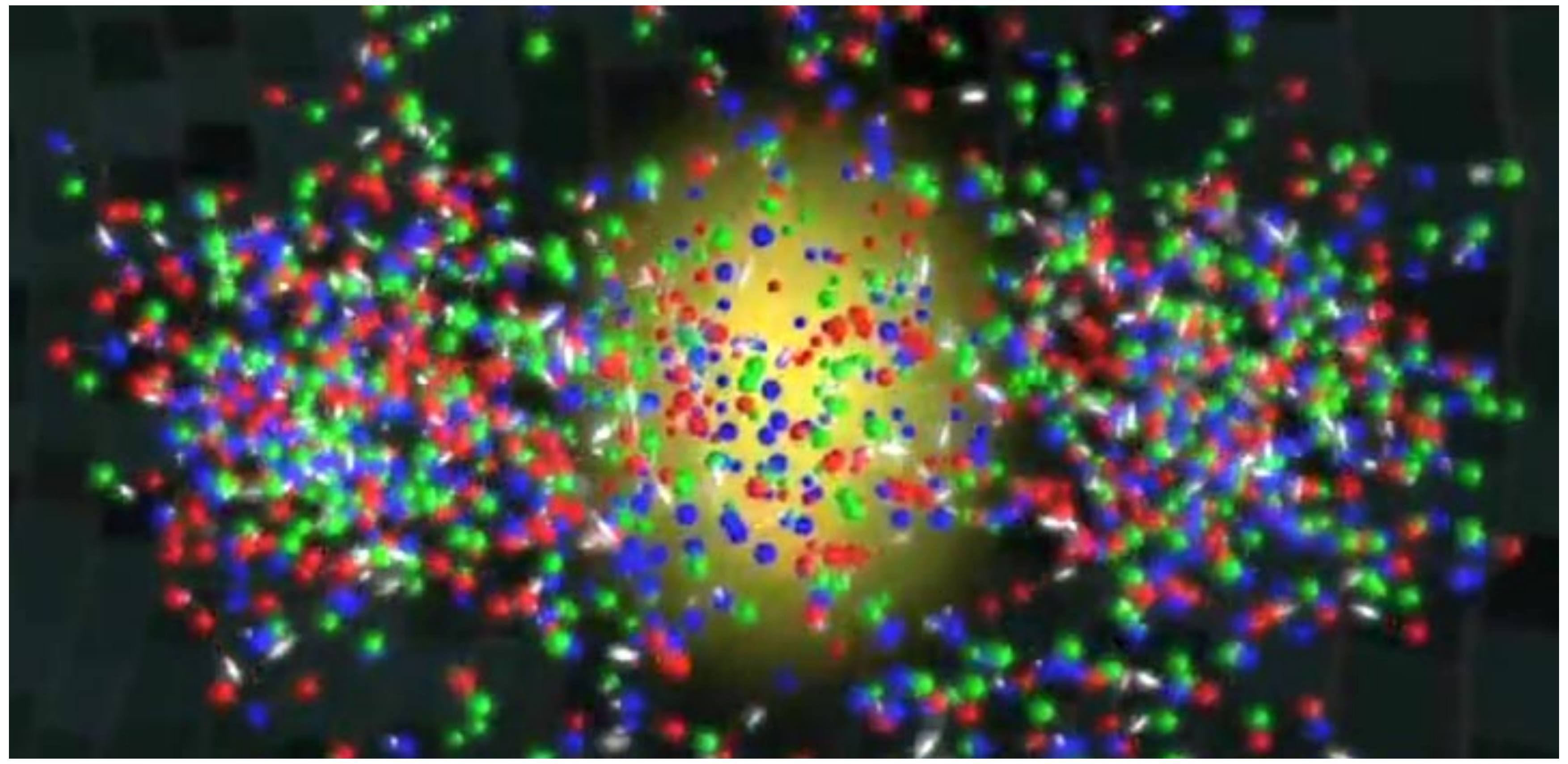
$\eta/s \sim$ **280** $\eta/s \sim$ **0.12**

- Lower bound from strongly-coupled gauge theory ~ 1 / 4π ~ 0.08

The 'perfect liquid'!

Short distance structure:

Free quarks and gluons? Complex bound states? degrees of freedom not yet established



What is the structure of the QGP as a function of resolution scale?

Probing the QGP

- To probe the QGP, we have many tools in our toolbox

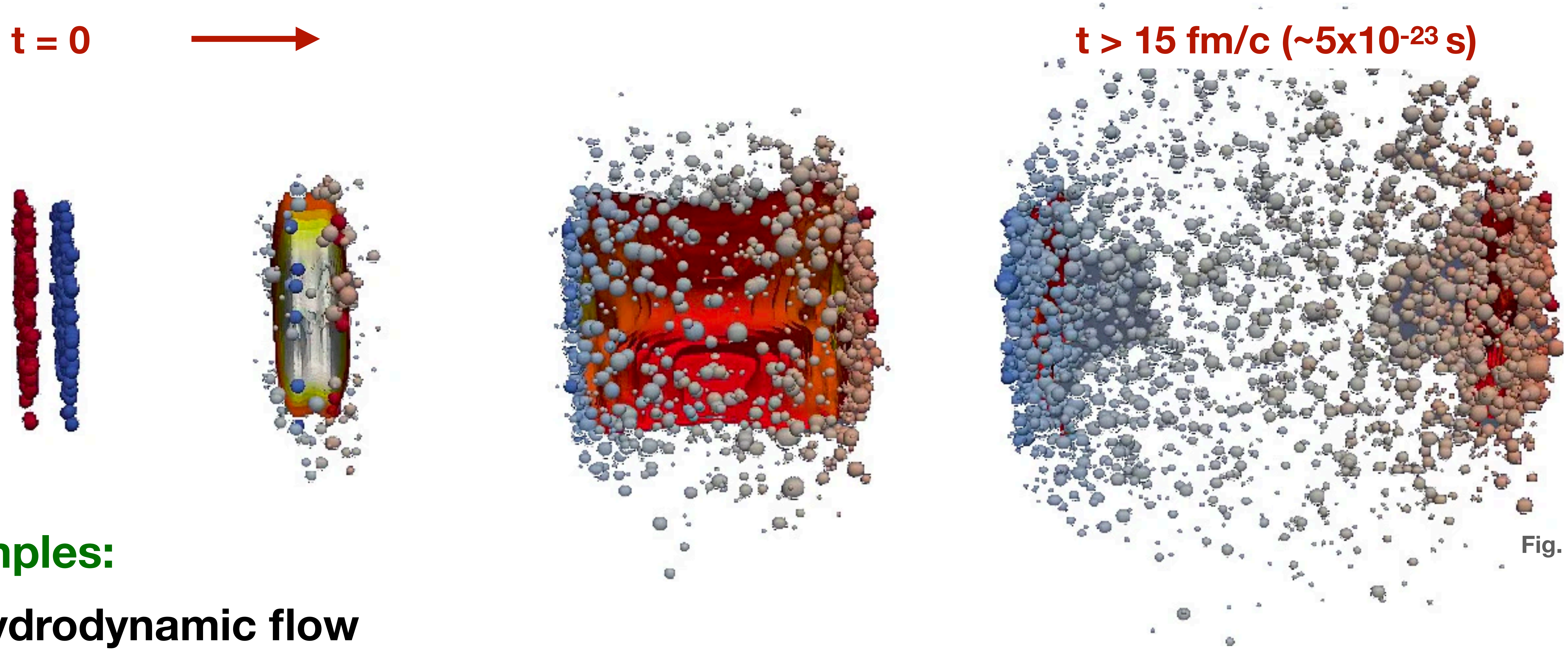


Fig. MADAI collaboration

Examples:

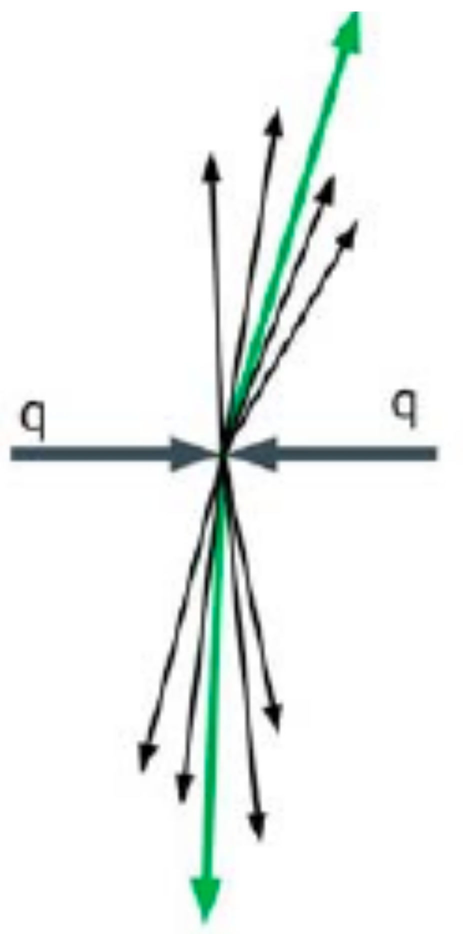
- **Hydrodynamic flow**
- **Hadron chemistry and kinematics**
- **Electromagnetic radiation from QGP**
- **Quarkonium disassociation/regeneration**
- **Partonic interactions with QGP → heavy quarks and jets**

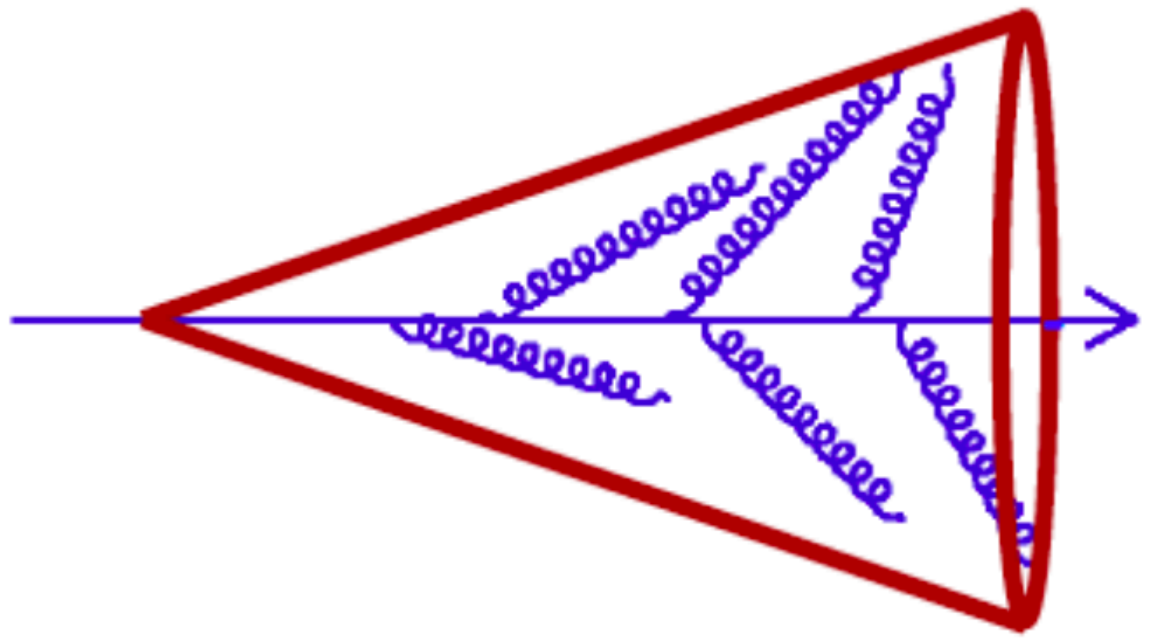
Jets (in vacuum)

Jet production in pp collisions (vacuum)

- Evolution of hard parton (quark or gluon) → gluon radiation
  - Experimentally measured as **collimated spray of hadrons**

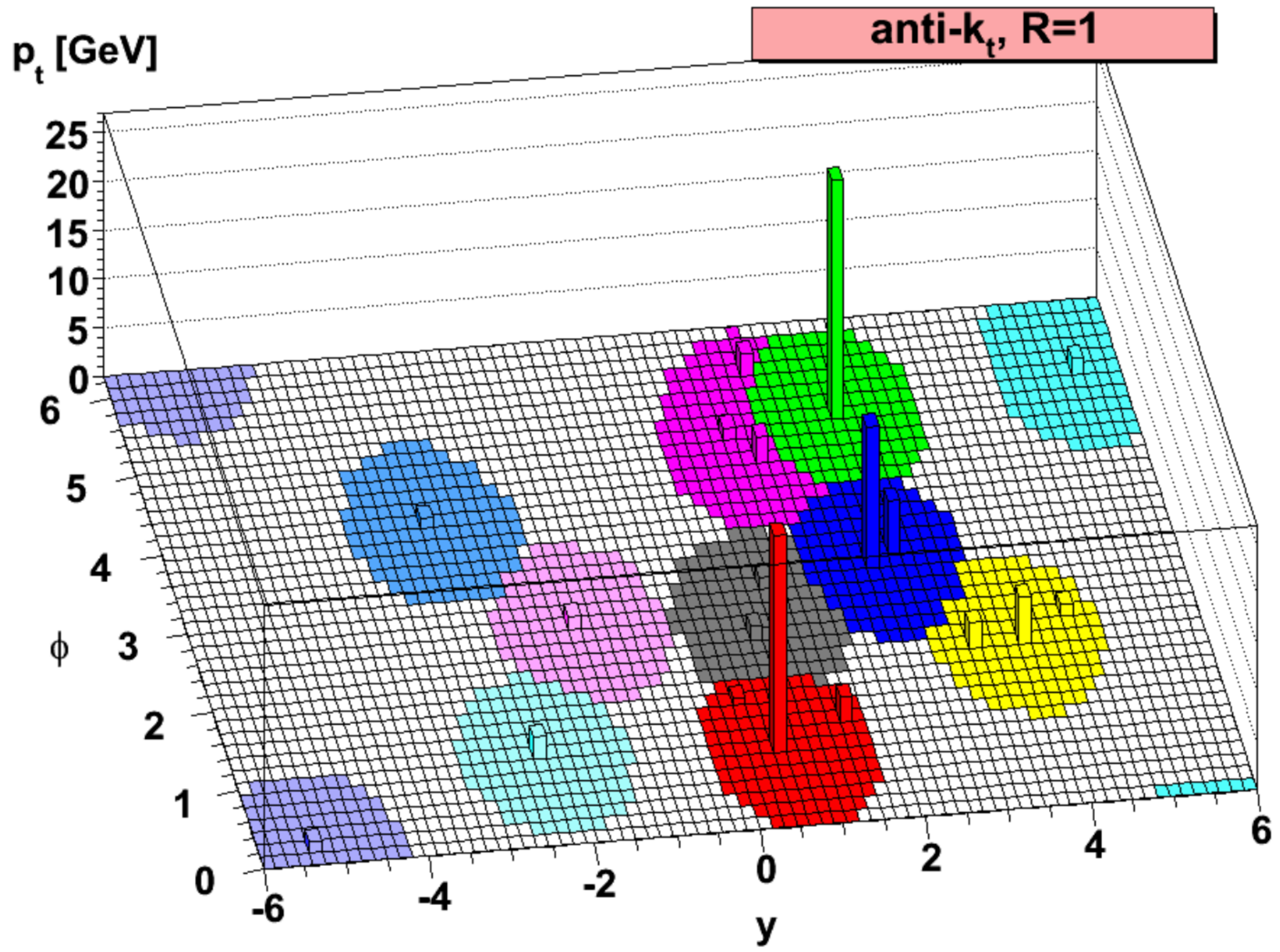
Reconstruct jets → measure initiating parton





Jet algorithms - precise connection between QCD theory and experiment

- Cluster hadrons measured by our detector, with specified resolution parameter *R* ~ cone radius
- Should be insensitive to soft/collinear radiation



e.g. anti-k_T

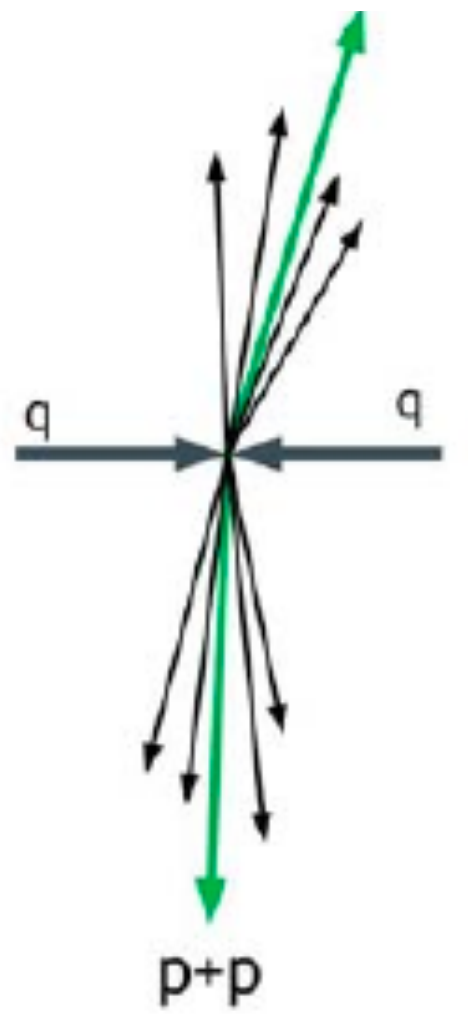
M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 063

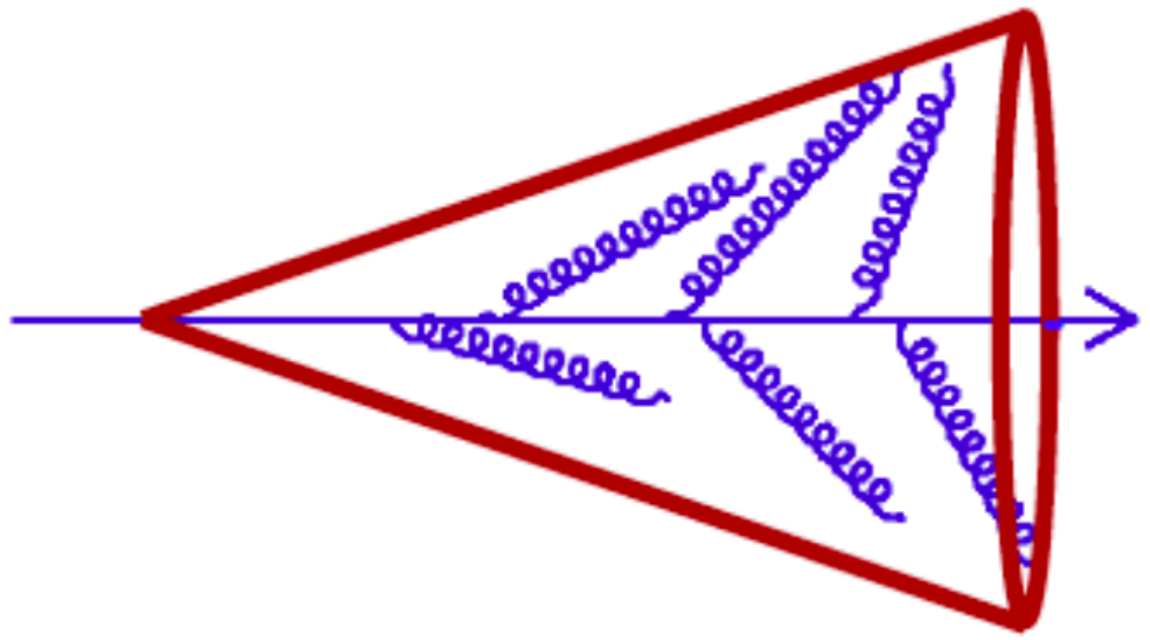
Jets (in vacuum)

Jet production in pp collisions (vacuum)

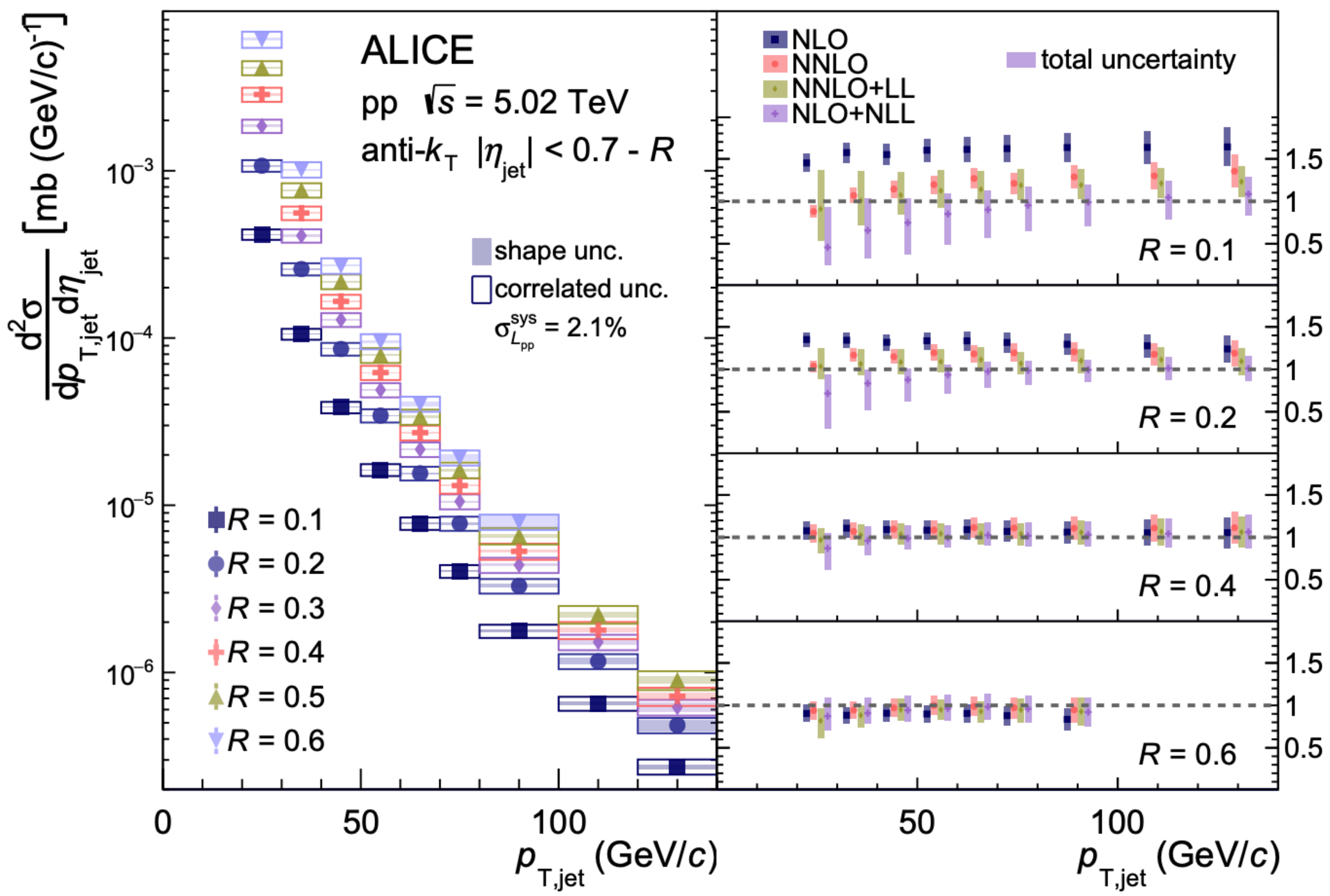
- Evolution of hard parton (quark or gluon) → gluon radiation
  - Experimentally measured as **collimated spray of hadrons**

Reconstruct jets → measure initiating parton

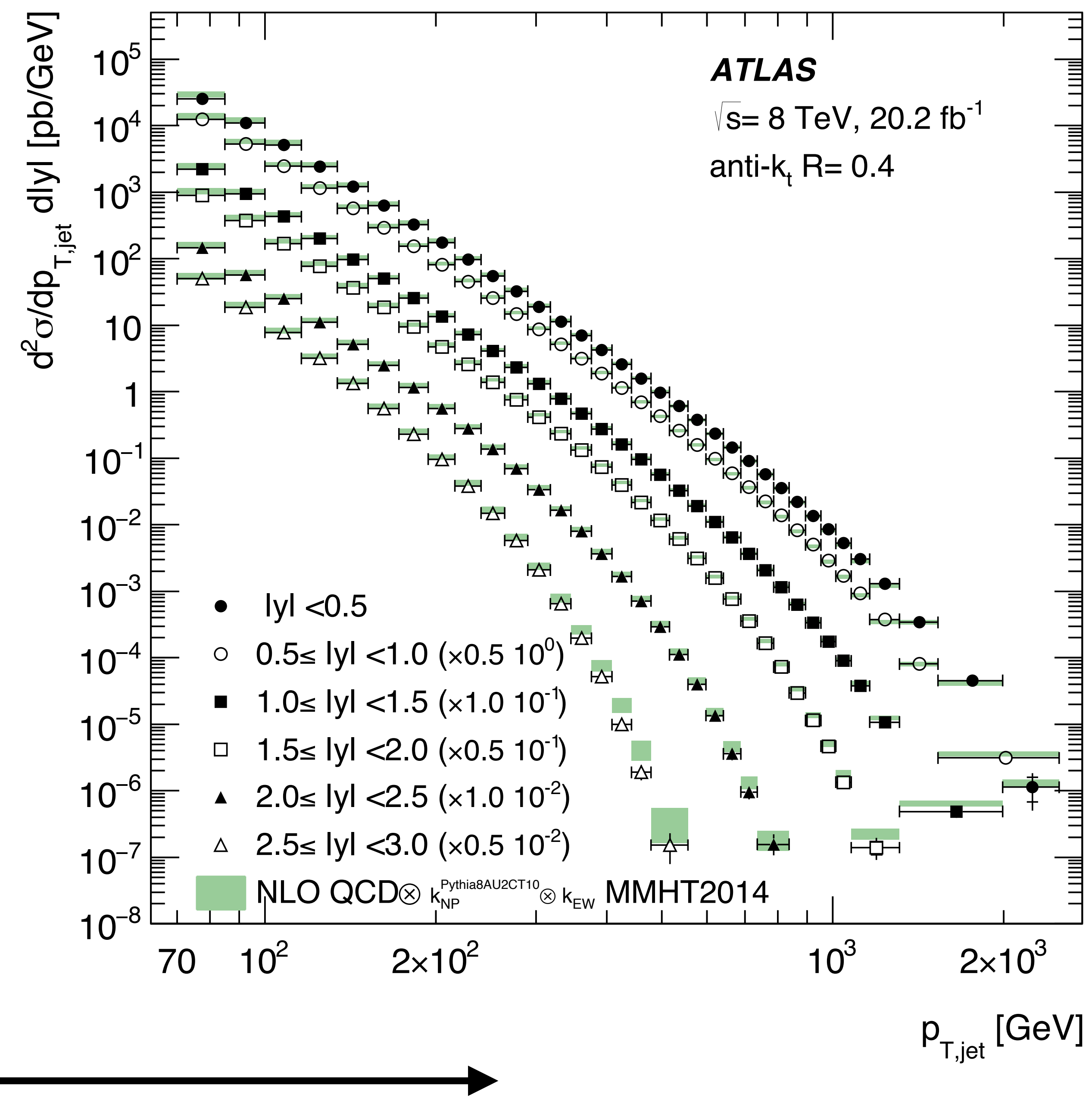




ALICE: arxiv:2211.04384



ATLAS: *JHEP* 09 (2017) 020



→ $p_{\mathrm{T,jet}}$

Production and evolution well understood over many orders of magnitude
→ huge achievement of QCD

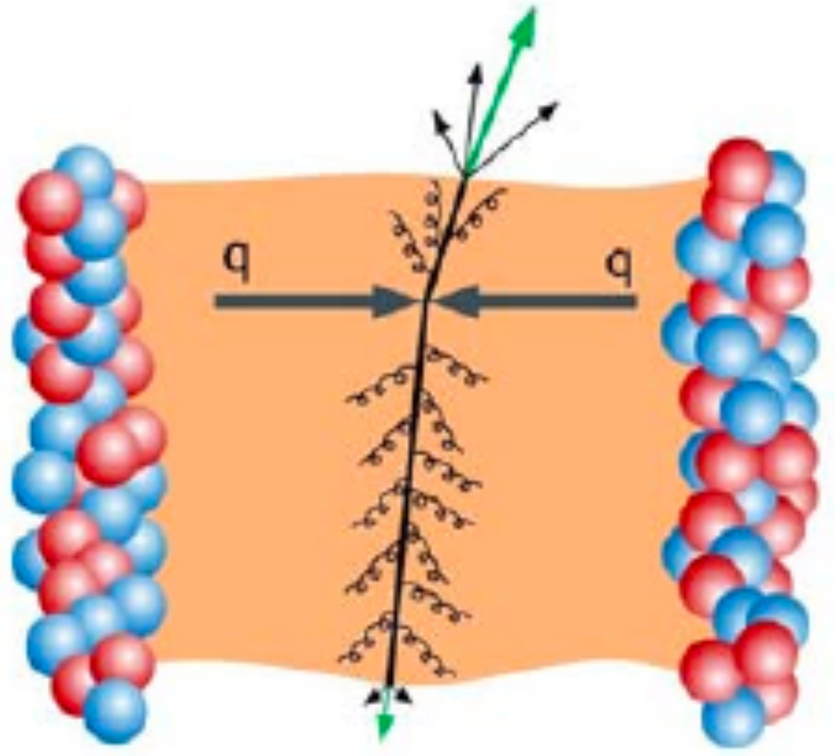
Jets (in medium)

$$R_{AA} = \frac{\text{Yield(PbPb)}}{< N_{coll} > \times \text{Yield(pp)}}$$

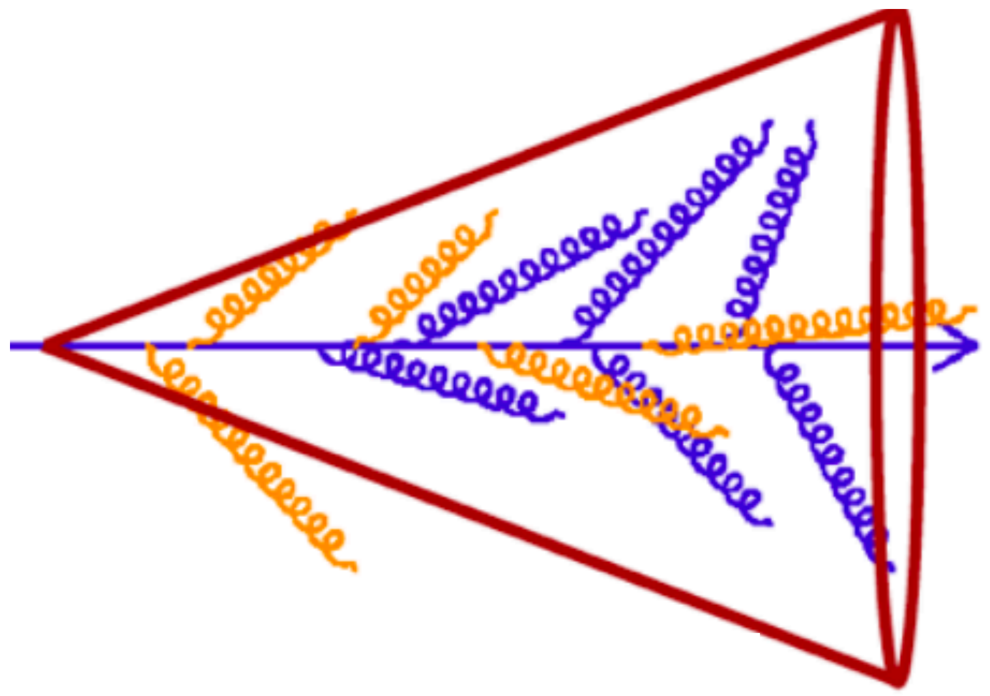
'Jet quenching' - partonic interactions in the QGP

- inelastic (medium-induced gluon emission) and elastic (collisional) processes over full parton shower

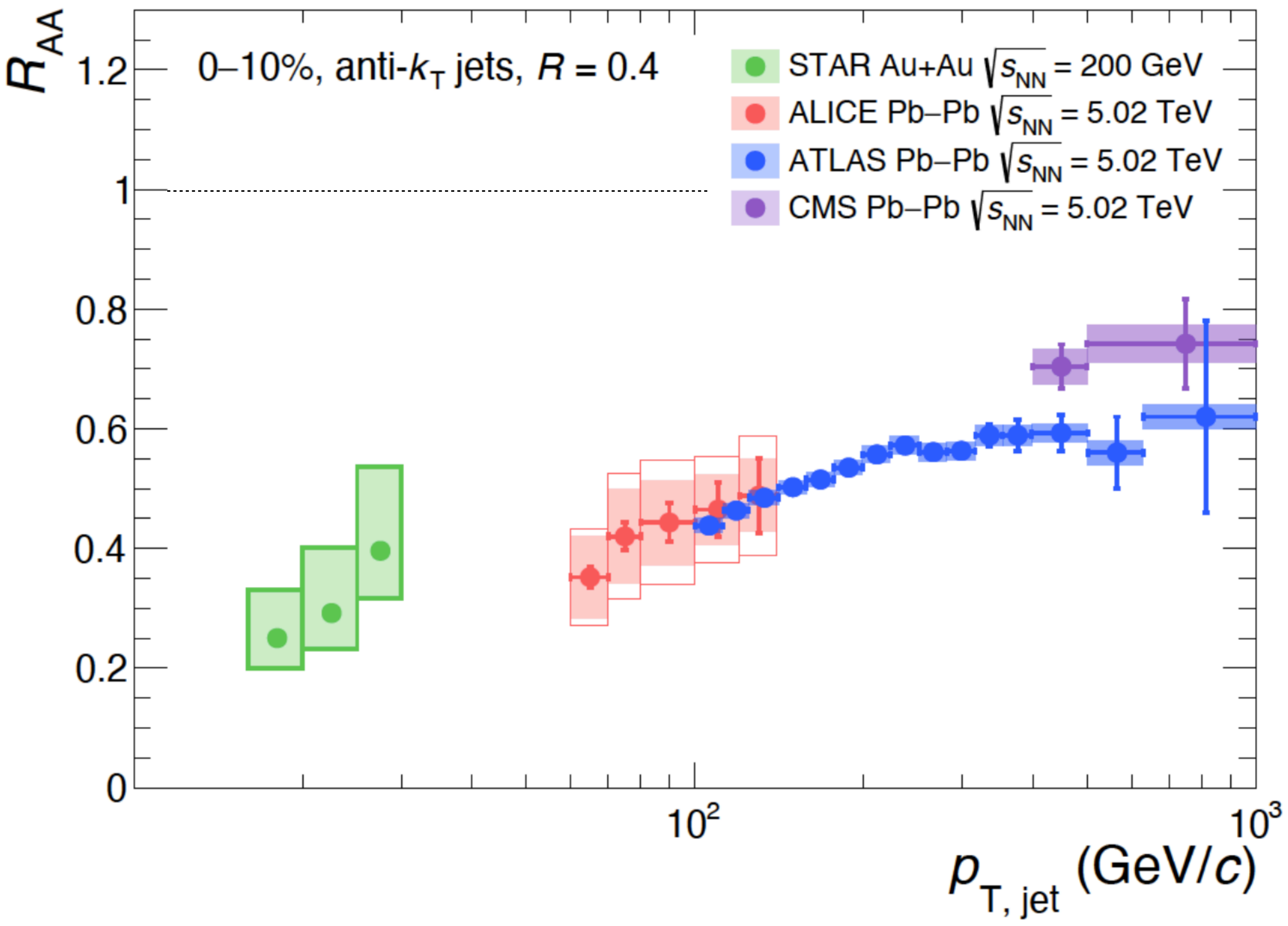
Jets provide unique probes of the QGP at multiple scales



A+A



J. Harris, B. Müller, arxiv:2308.05743



$R_{AA} < 1$ **- suppression w.r.t. pp**

Modelling of jet quenching: limiting cases

pQCD approach

- Jet-medium interaction described by scattering matrix elements
- Include additional medium-induced radiation

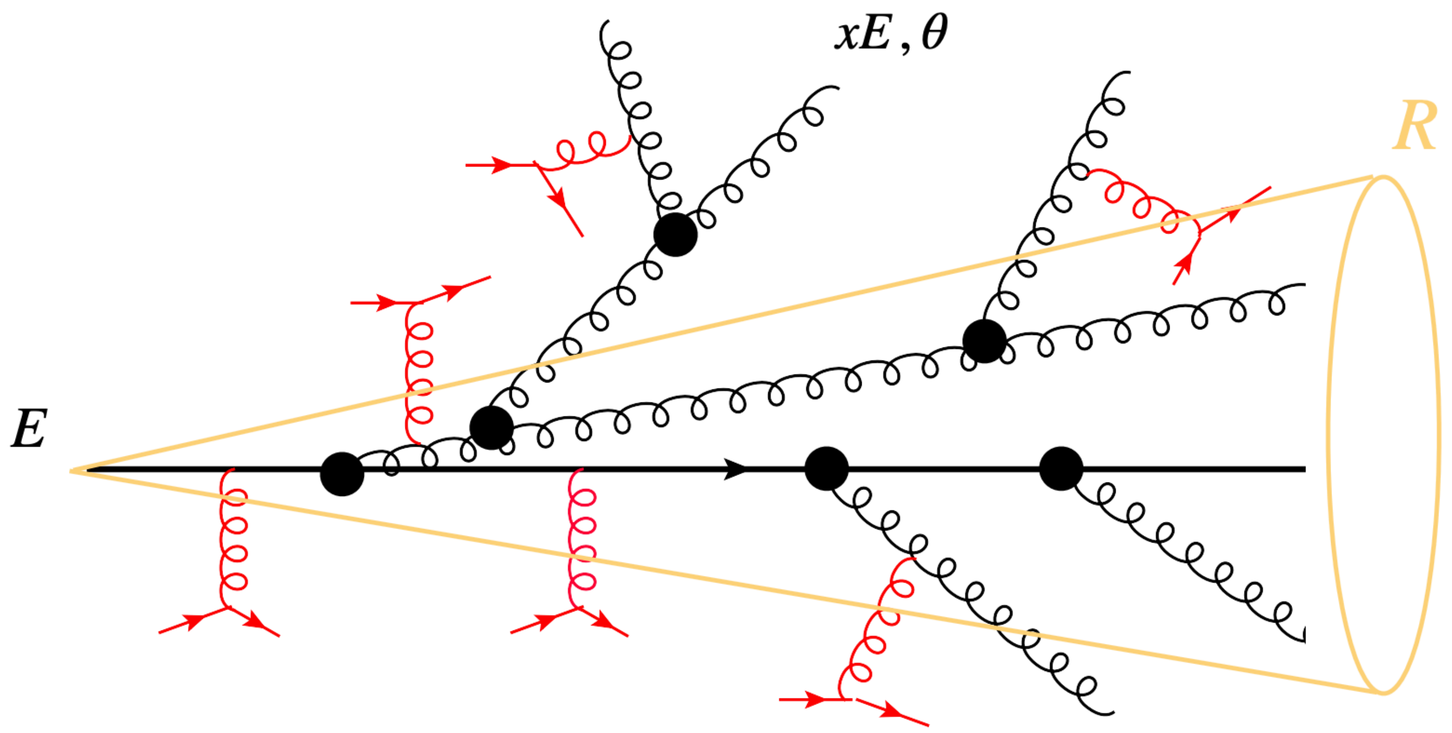


Fig. Y. Mehtar-Tani, S. Schlichting, I. Soudi, JHEP05 (2023) 091

Non-perturbative description

- Soft jet-medium interactions through gauge-gravity duality (AdS/CFT) to describe strongly-coupled plasma

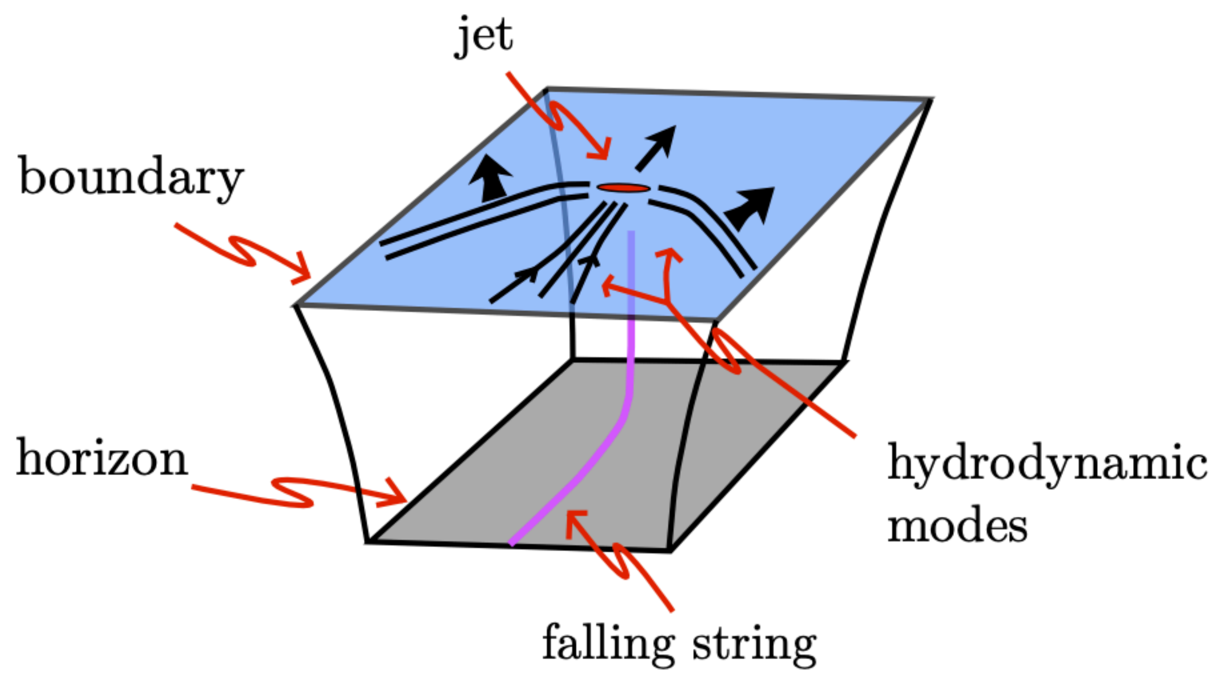
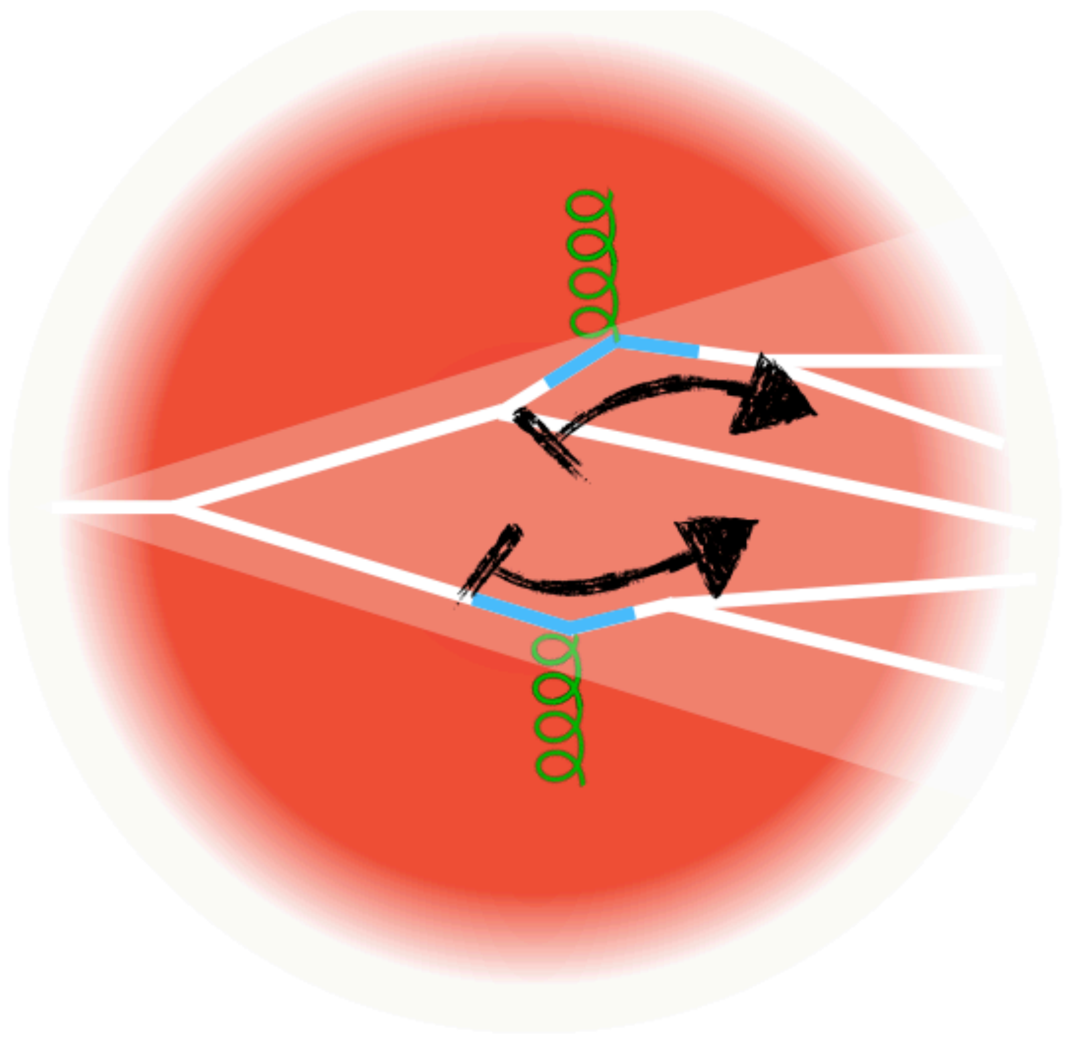


Fig. P. Chesler, K. Rajagopal, *JHEP* 05 (2016) 098

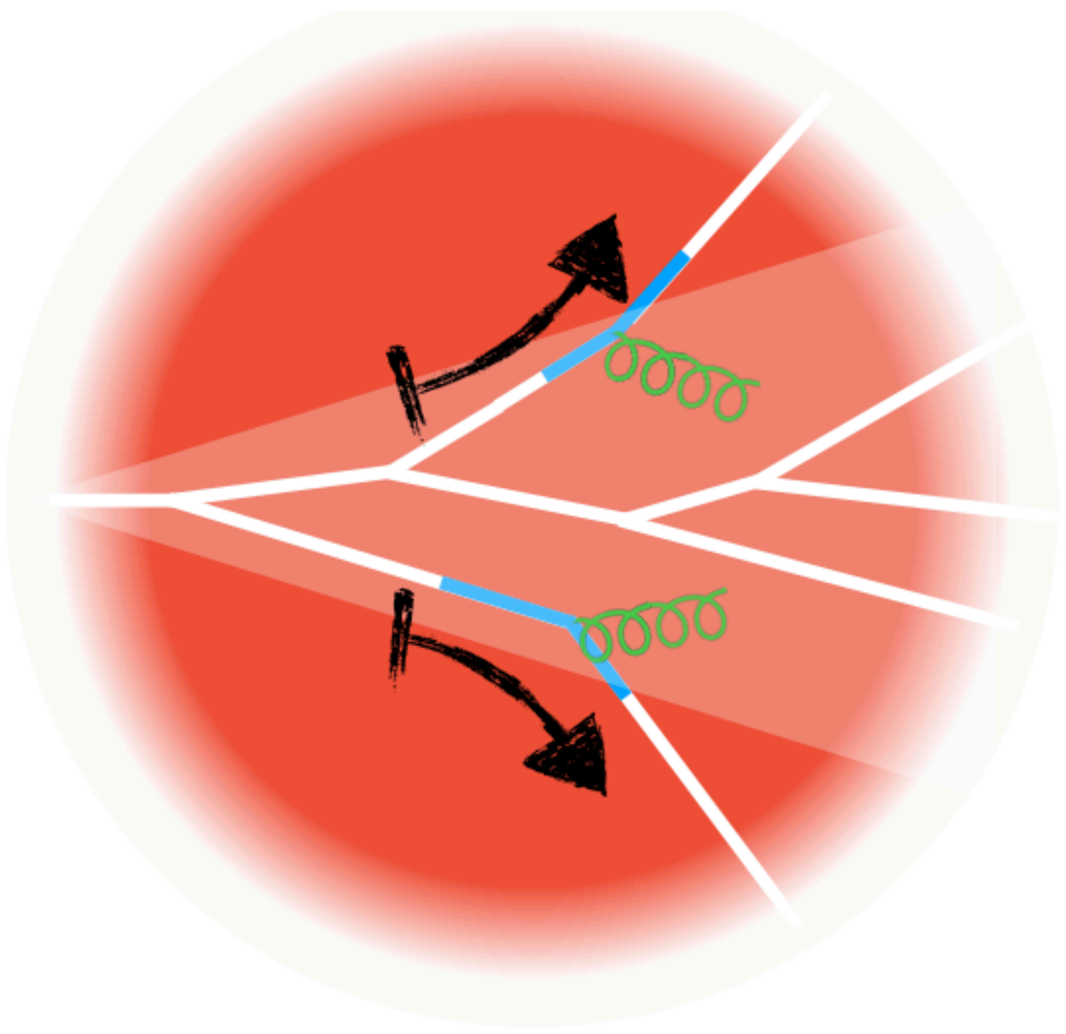
Implementation in Monte Carlo generators: simulation of initial state, medium fluid dynamics, multi-stage jet evolution, hadronisation…

Experimentally observable consequences of jet quenching

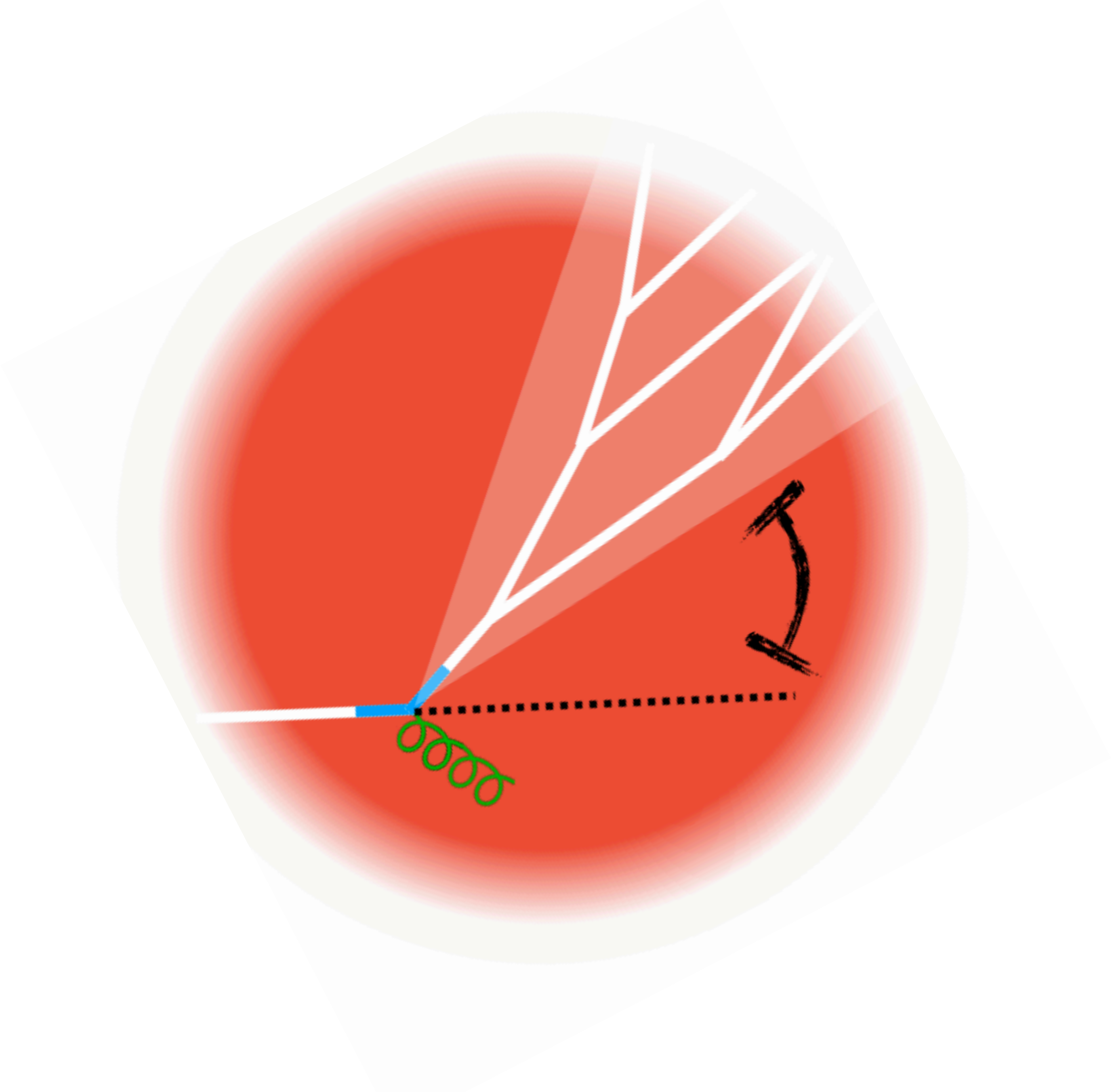
- Today - multi-pronged measurements of jet and medium modification



Substructure modification



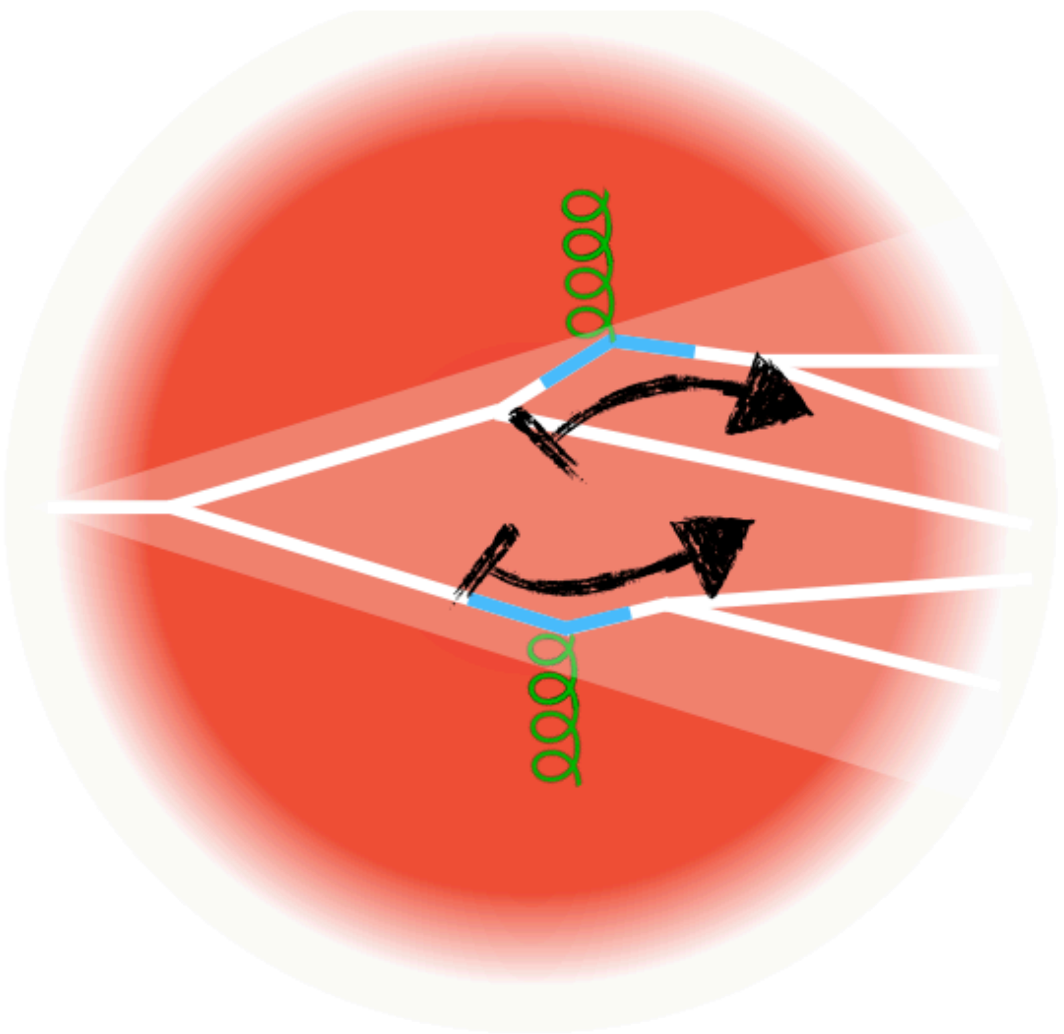
Energy redistribution



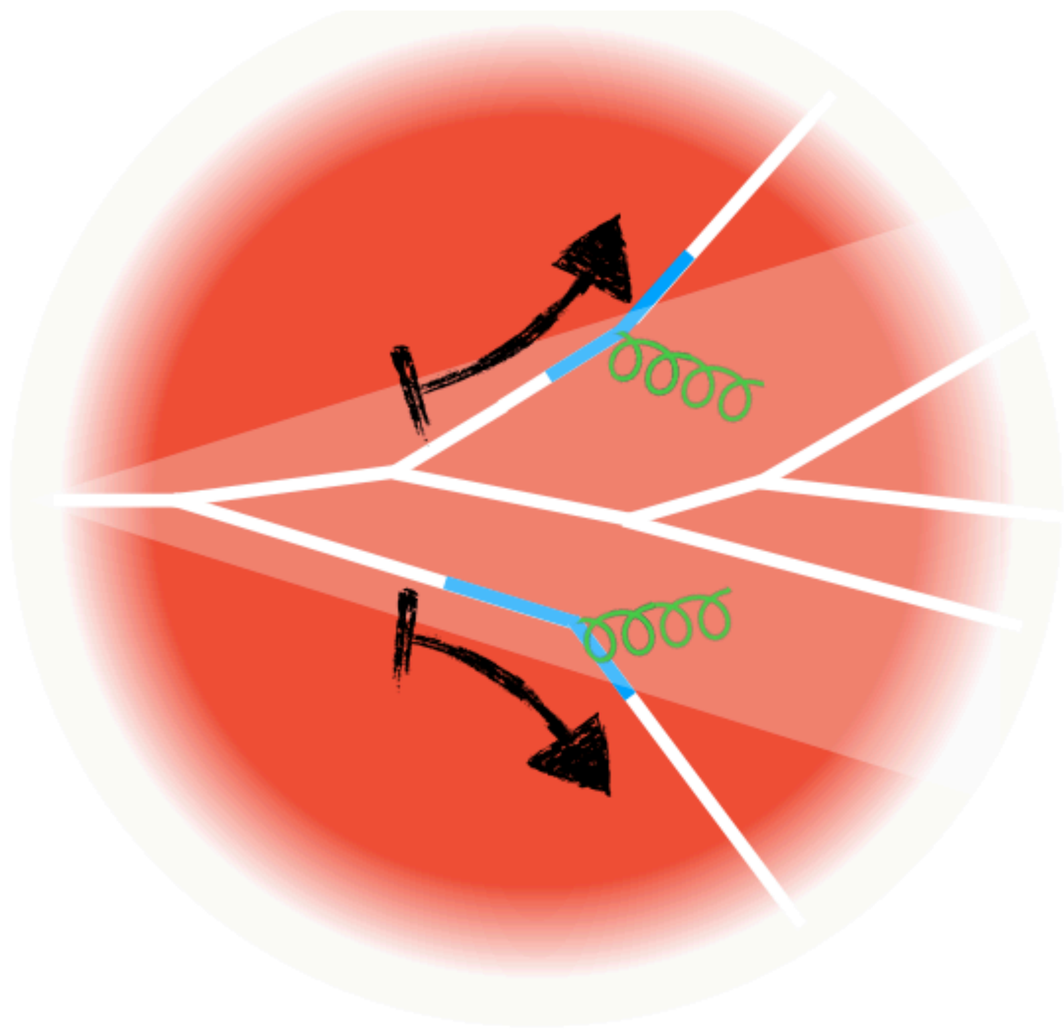
Deflection

Experimentally observable consequences of jet quenching

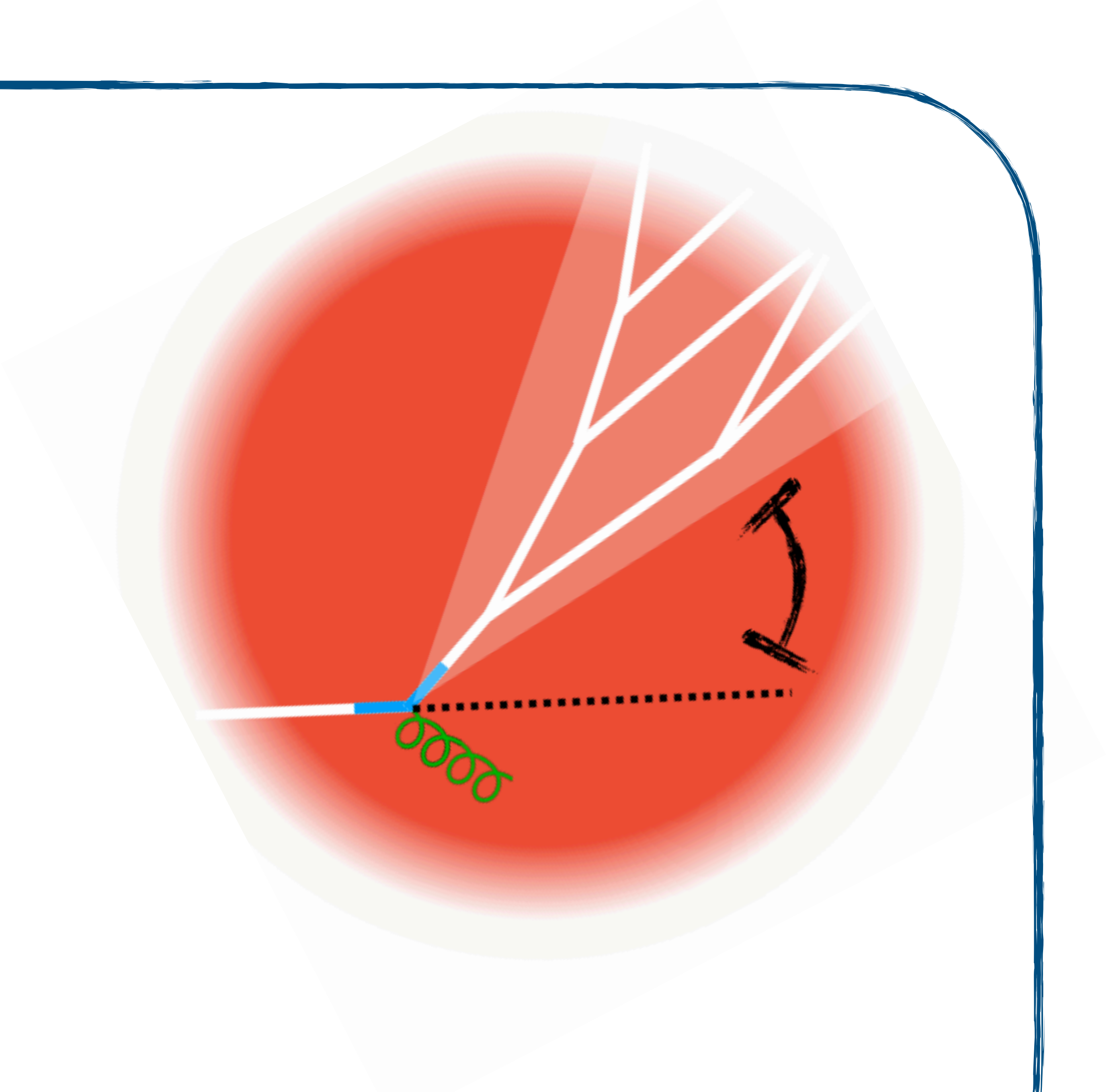
- Today - multi-pronged measurements of jet and medium modification



Substructure modification

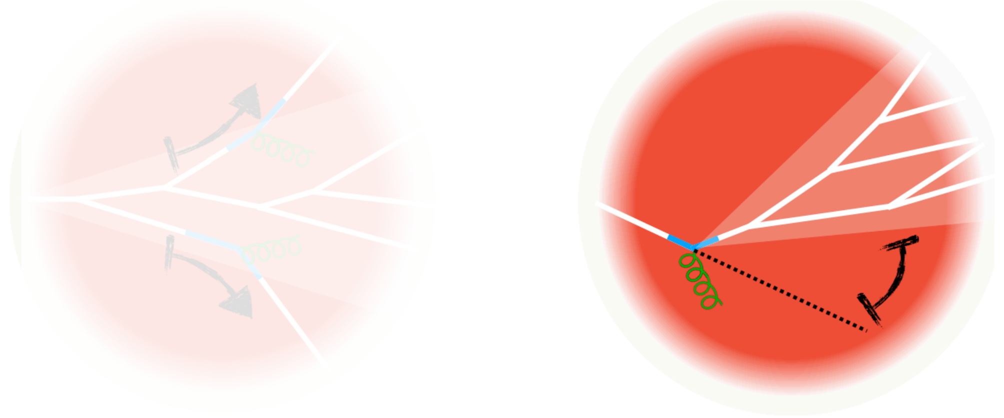


Energy redistribution



Deflection

Jet acoplanarity



Broadening of jet transverse to its initial direction

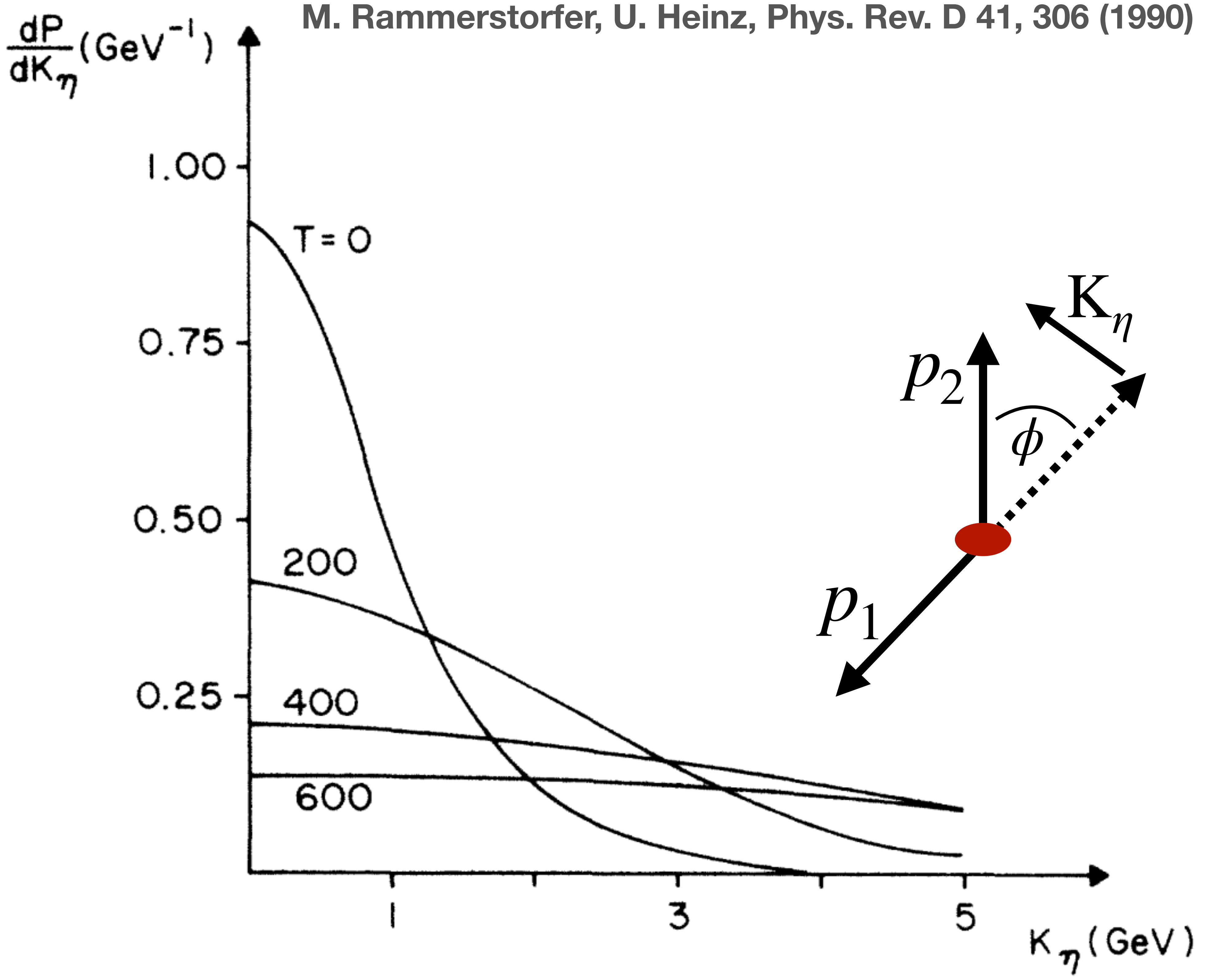
In vacuum:

- Transverse broadening due to gluon emission (Sudakov broadening)

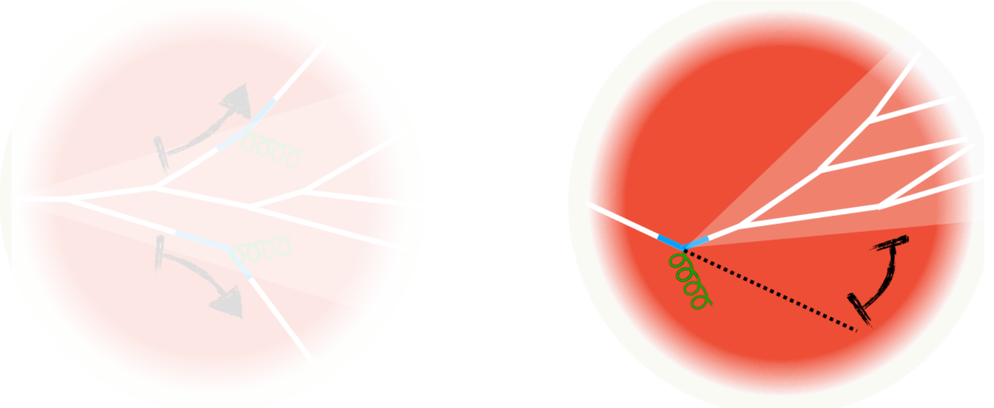
In medium:

- Transverse broadening due to **multiple soft scattering**

David A. Appell, Phys. Rev. D 33, 717 (1986)
see also:
J. P. Blaizot, L. D. McLerran Phys. Rev. D 34, 2739 (1986)
M. Rammerstorfer, U. Heinz, Phys. Rev. D 41, 306 (1990)



Jet acoplanarity



Broadening of jet transverse to its initial direction

In vacuum:

- Transverse broadening due to gluon emission (Sudakov broadening)

In medium:

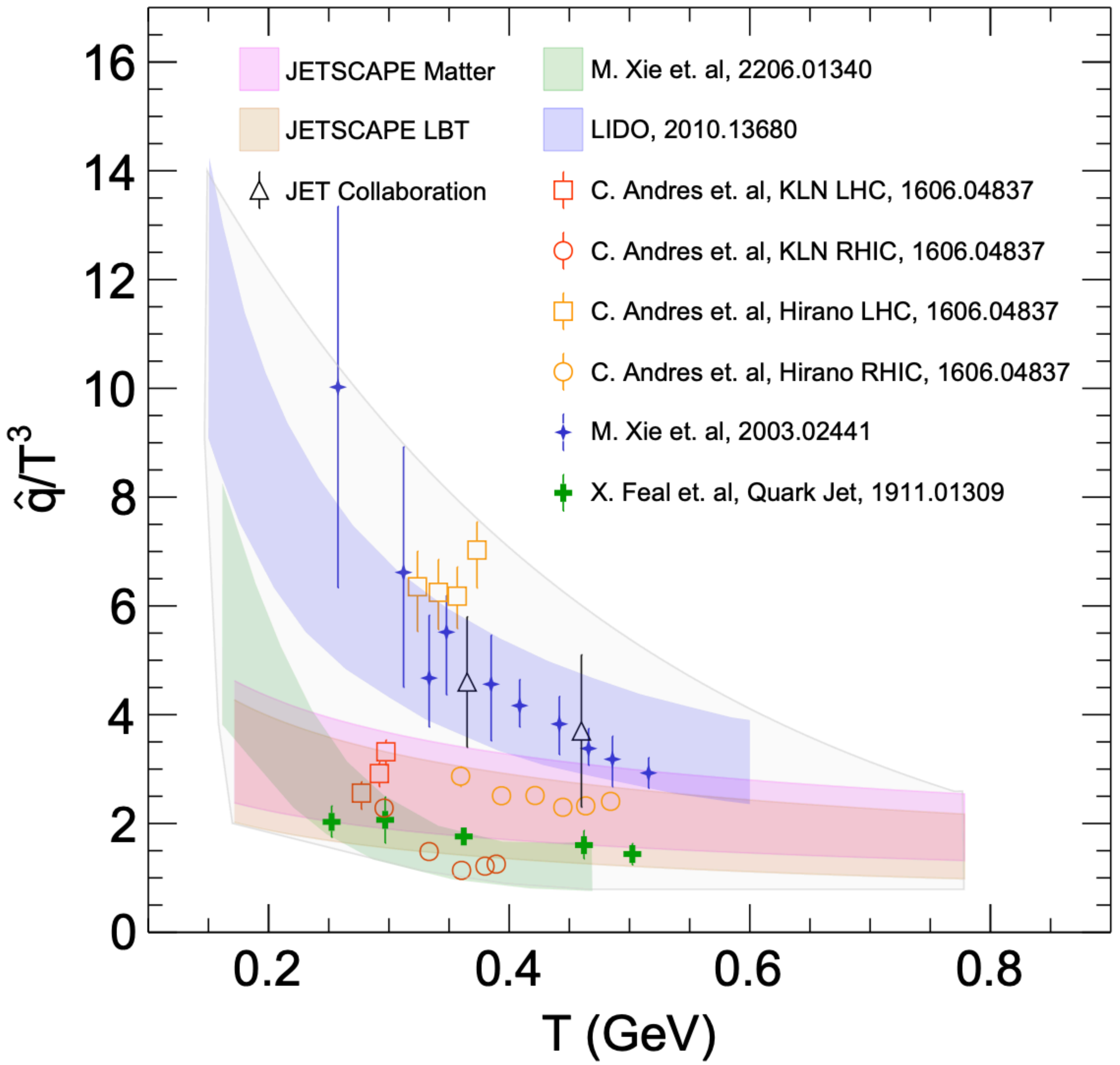
- Transverse broadening due to **multiple soft scattering**

- Quantified by jet transport coefficient $\hat{q} = \frac{< k_\perp^2 >}{L}$

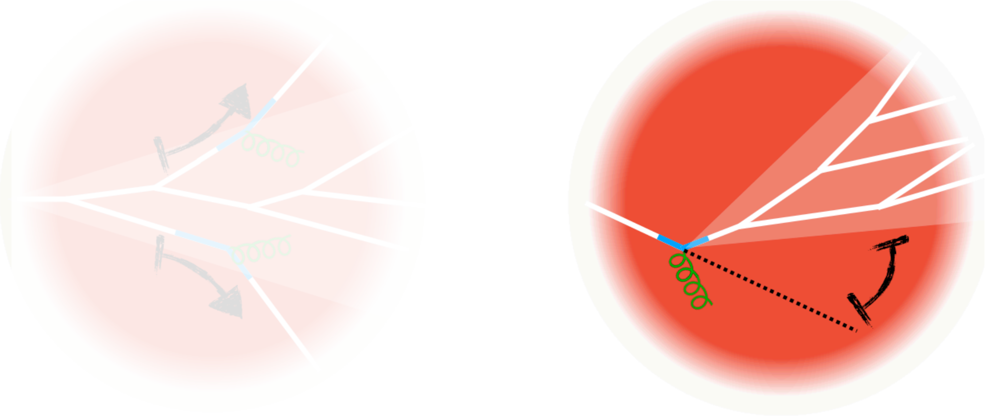
(average transverse momentum squared gained per unit path length travelled)

→ **Jet acoplanarity provides direct probe of QGP transport coefficient $\hat{q}$**

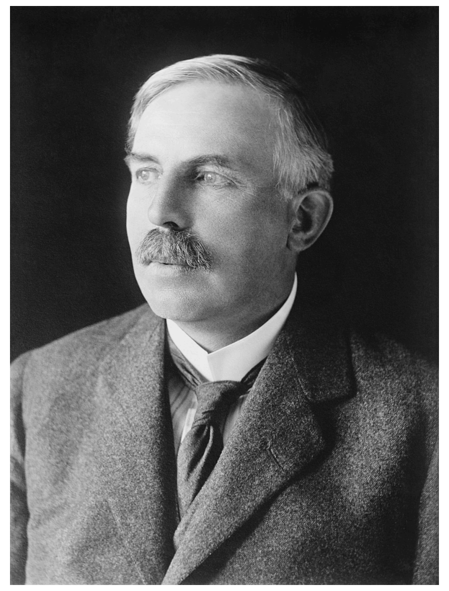
L. Apolinário, Y.-J. Lee, M. Winn
Progress in Particle and Nuclear Physics, 103990 (2022)

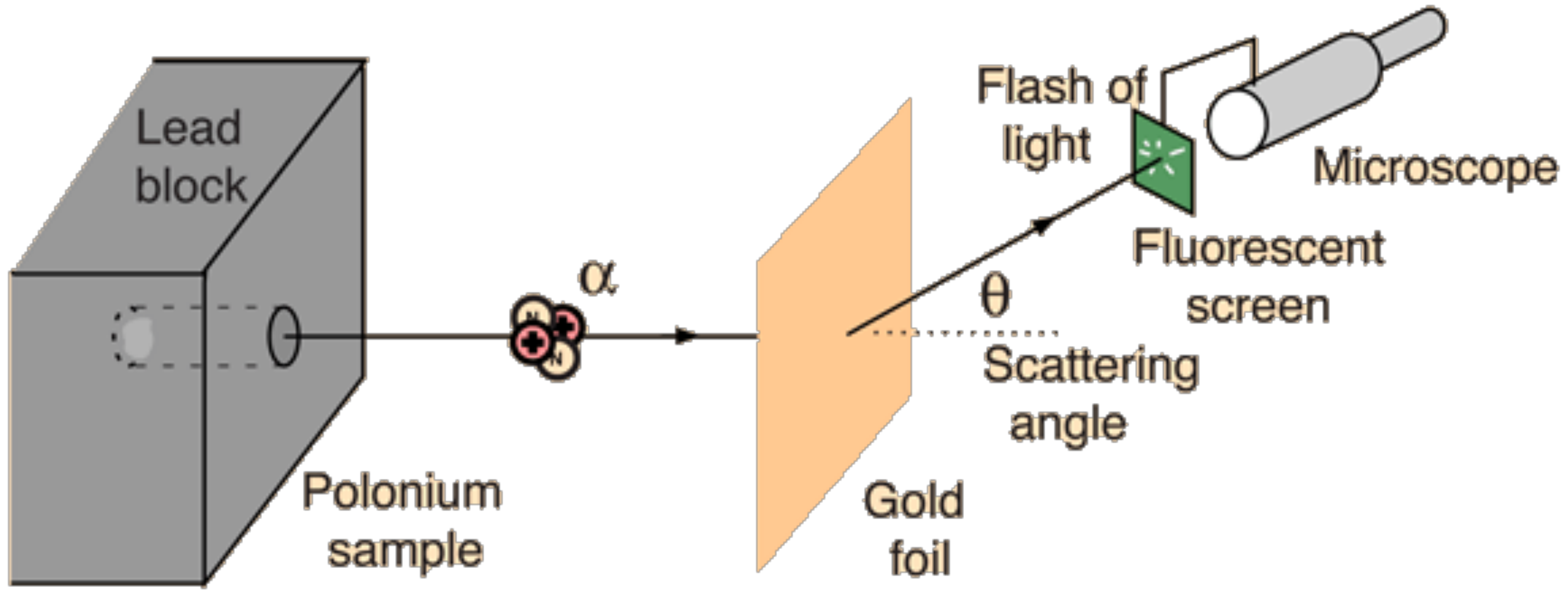


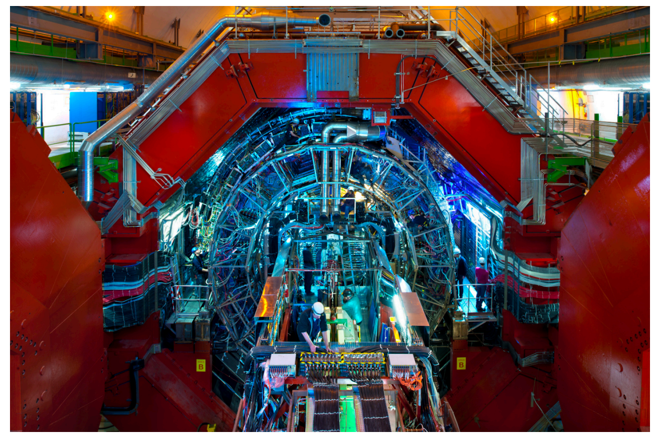
Probing short-distance QGP structure



- Lots of recent interest in whether **point-like, single hard (Molière) scatters** can be detected







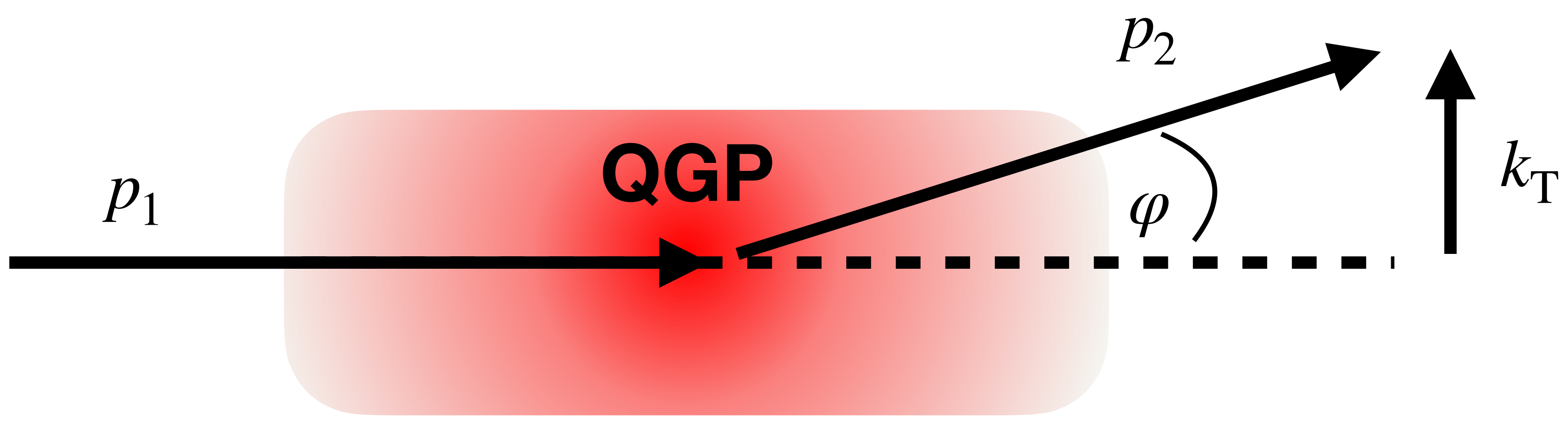
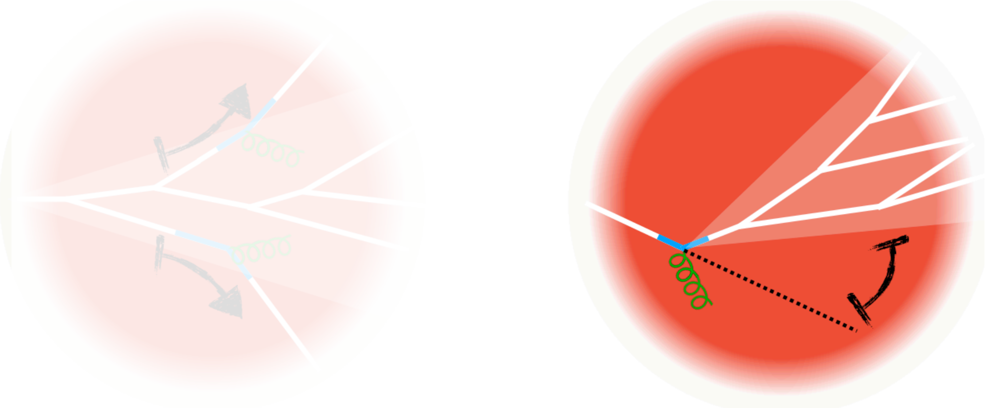


Fig. modified from F. D'eramo, K. Rajagopal, Y. Yin *JHEP* 01 (2019)

- **Can a Rutherford scattering experiment be performed in the QGP?**

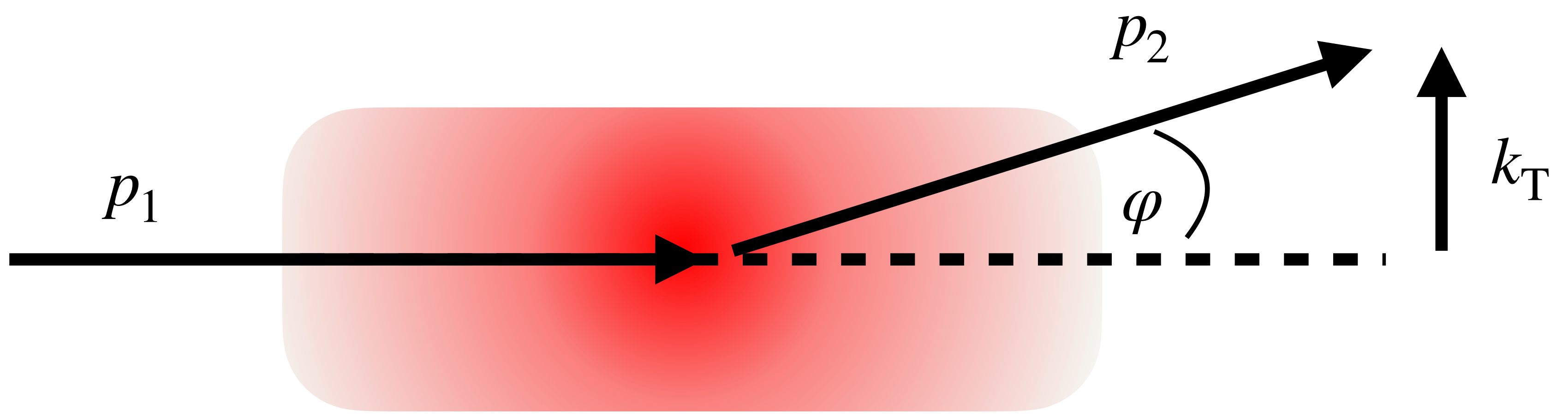
  → determine quasi-particle structure of QGP and study how strongly-coupled liquid emerges from constituent degrees of freedom

Probing short-distance QGP structure

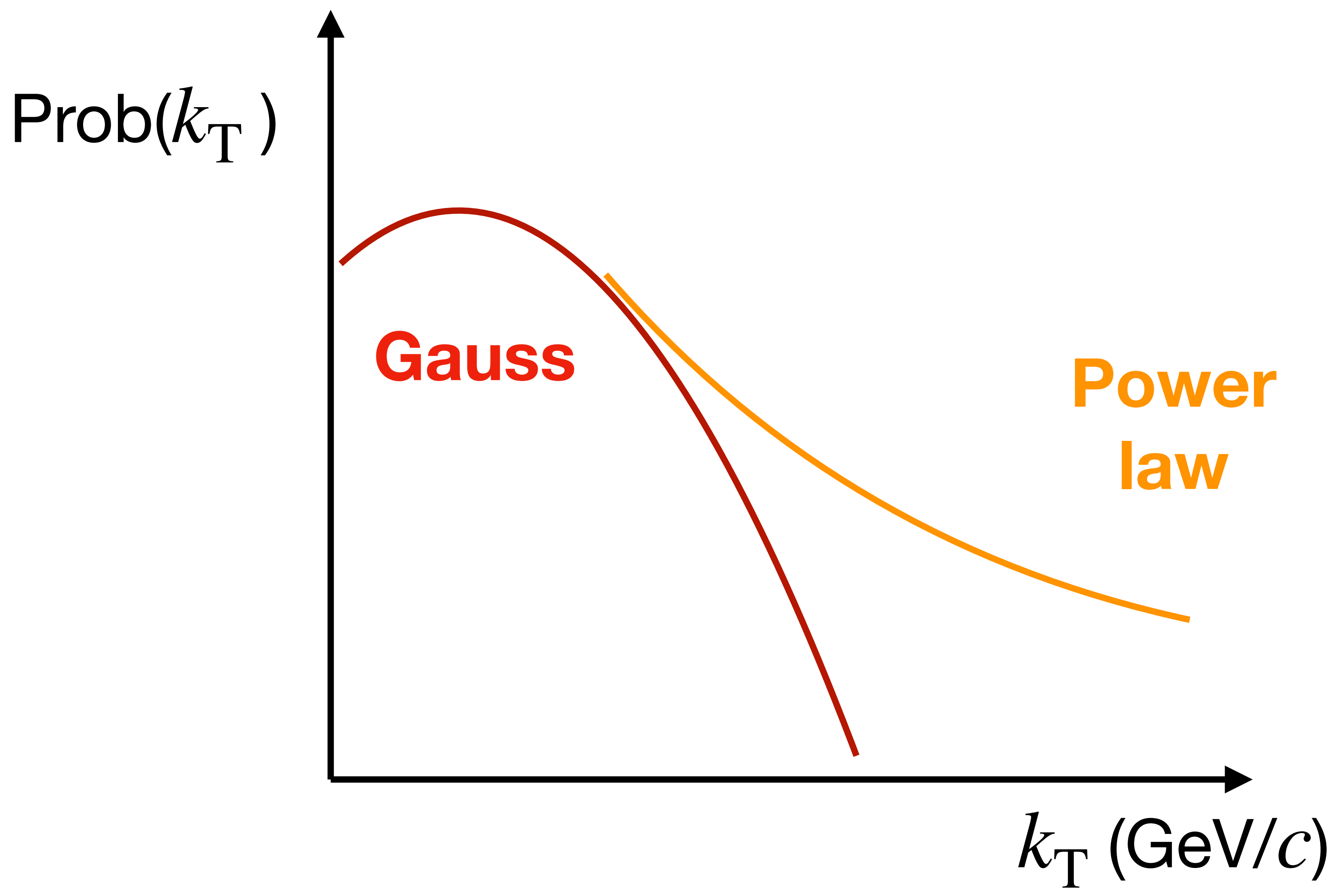


- **Strong-coupling limit** - probability of parton to obtain momentum k_T is Gaussian (exponential) distributed

- If medium probed at **short enough distance scales** - scatter off weakly-interacting quasiparticle with probability distribution 'Rutherford-Like' power-law distributed ~ $1/(k_T)^4$ (ignoring radiative corrections)



F. D'eramo, M. Lekaveckas, H. Liu, K. Rajagopal, *JHEP* 05 (2013) 031
F. D'eramo, K. Rajagopal, Y. Yin *JHEP* 01 (2019)

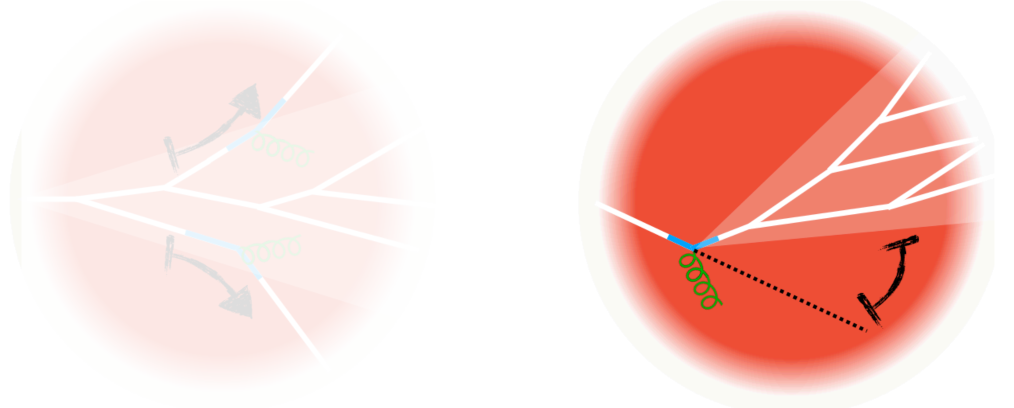


- Radiative corrections lead to harder power law $1/(k_T)^{4-2\beta}$ - hard scatters more likely

P. Caucal, Y. Mehtar-Tani: *Phys.Rev.D* 106 (2022) 5, L051501
JHEP 09 (2022) 023
Phys.Rev.D 108 (2023) 1, 014008

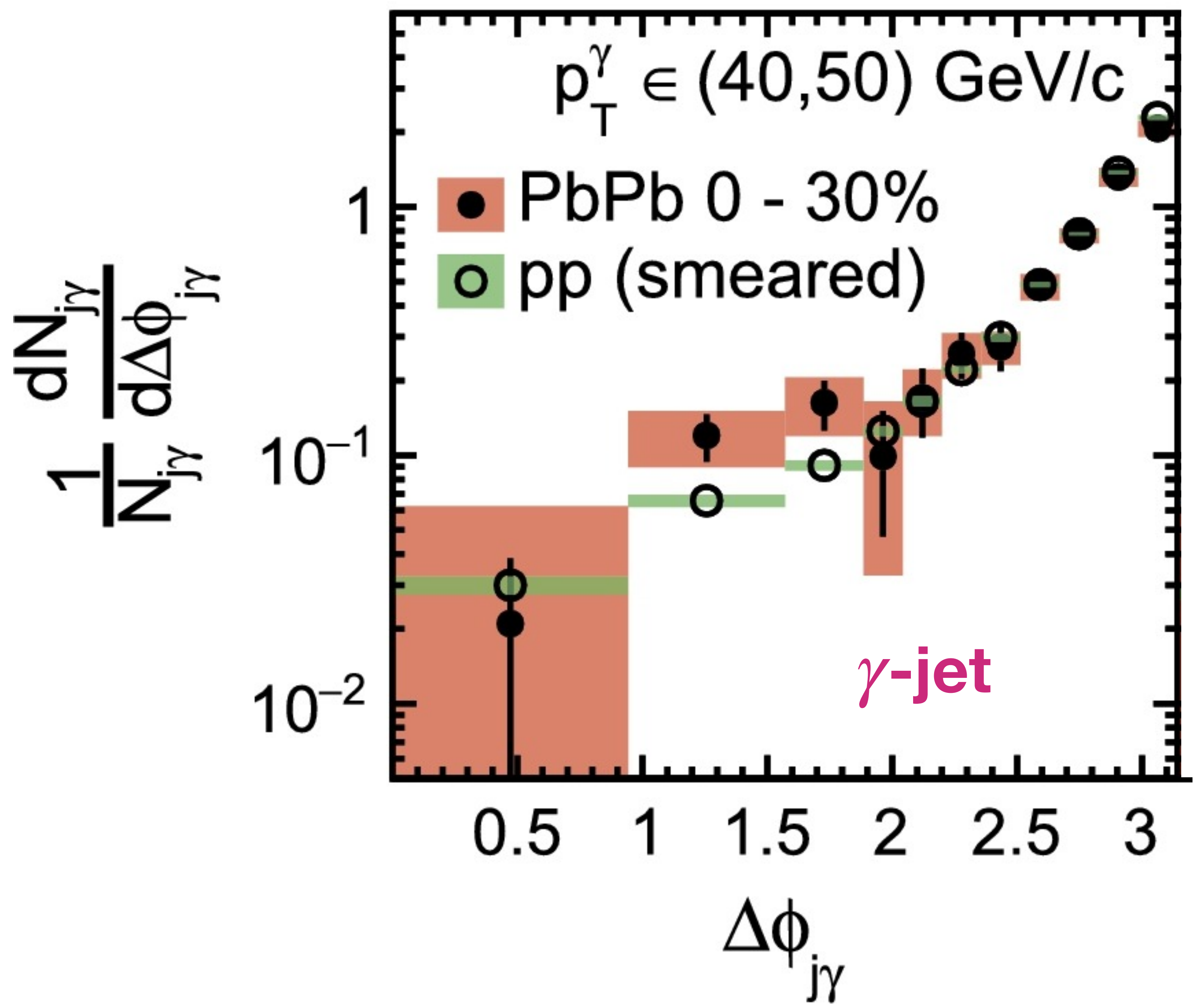
- **Experimentally - can hard scattering be discovered in tails of jet acoplanarity distribution?**

Jet acoplanarity measurements

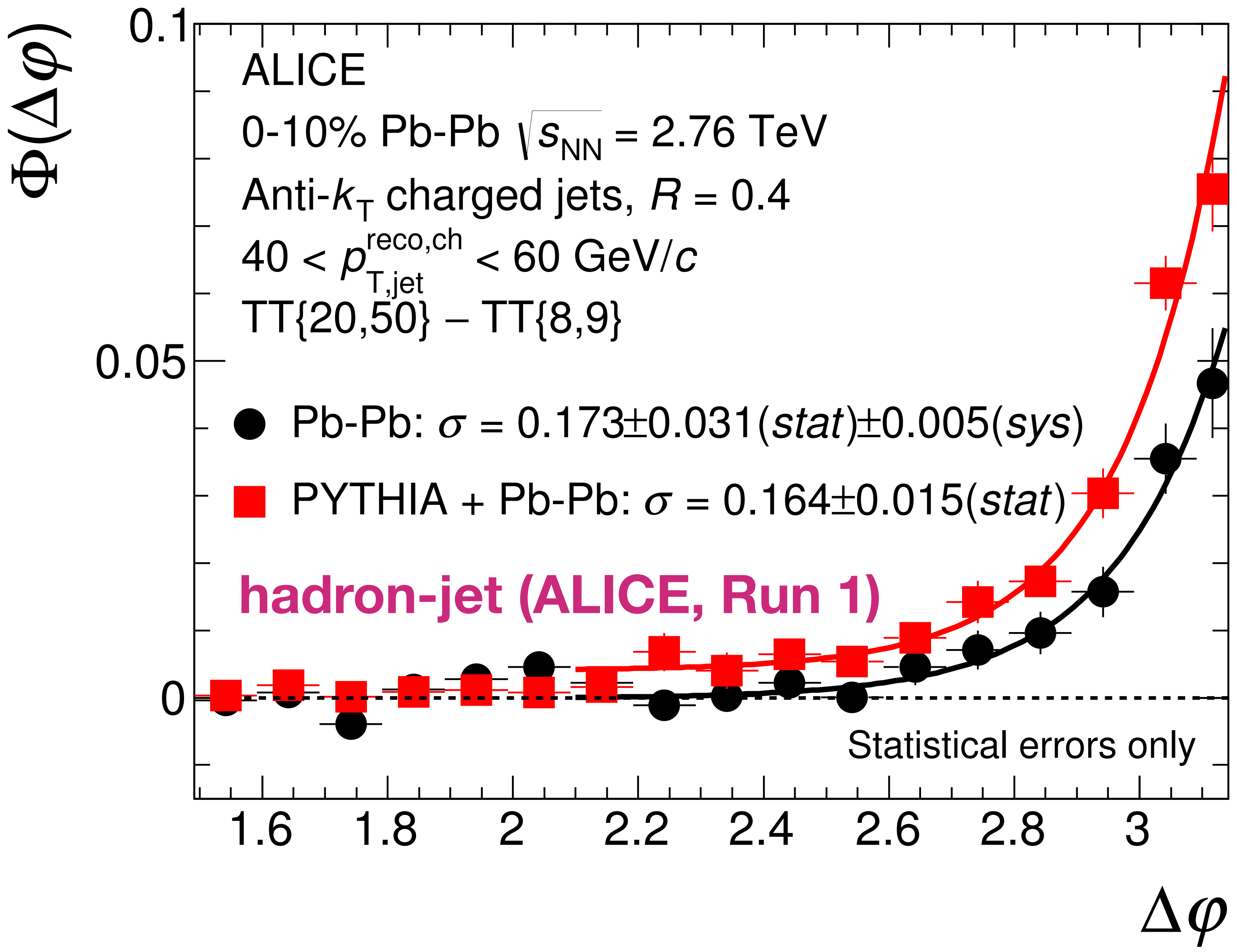


CMS: PRL 119, 082301 (2017)

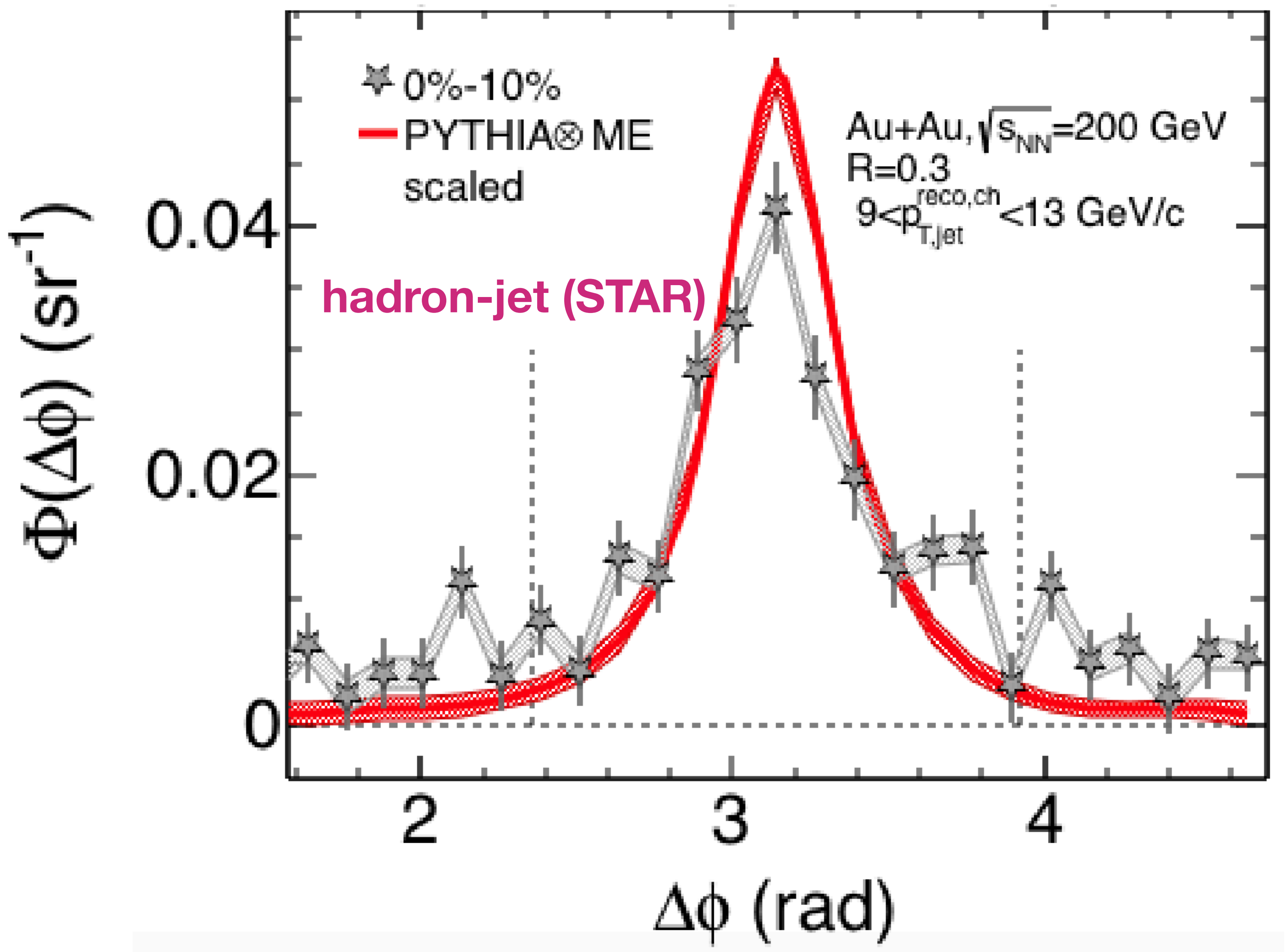
CMS: Phys. Lett. B 785 (2018) 14

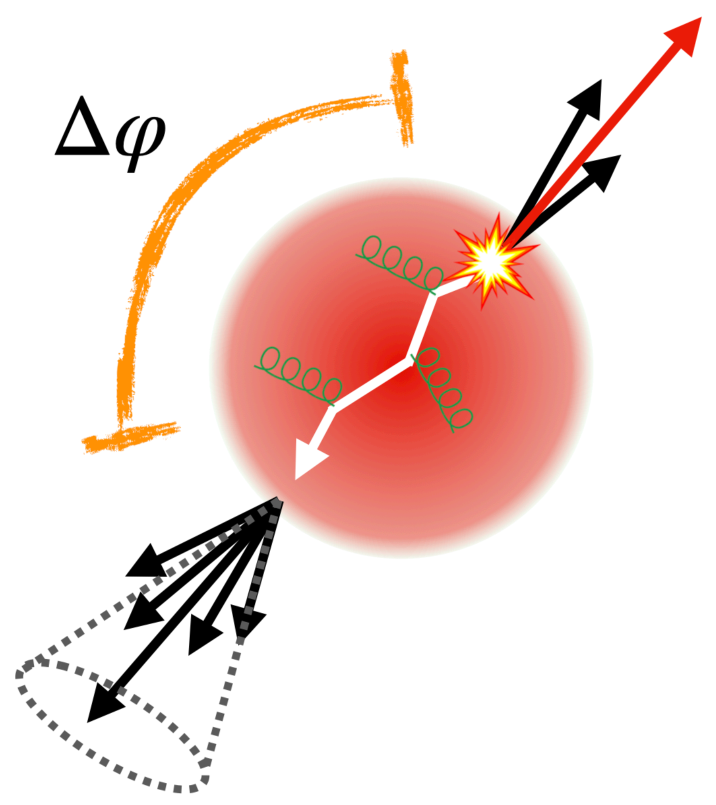


ALICE: JHEP 09 (2015) 170



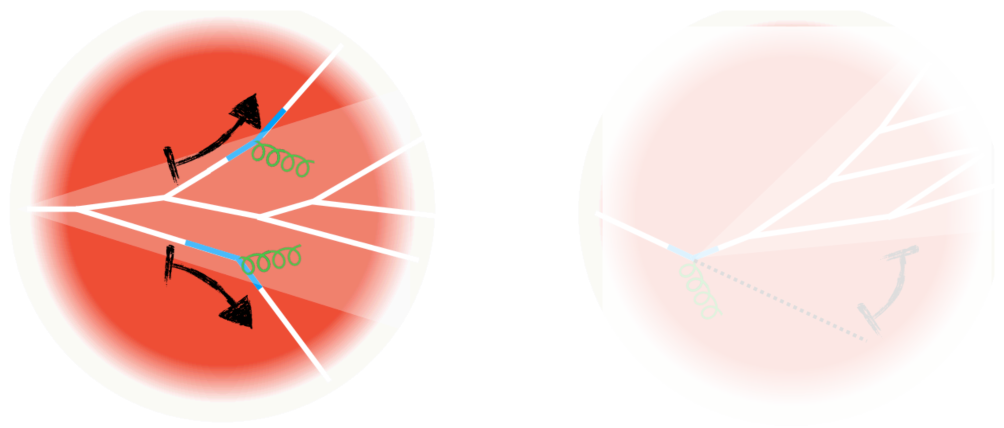
STAR: Phys. Rev. C 96, 024905 (2017)



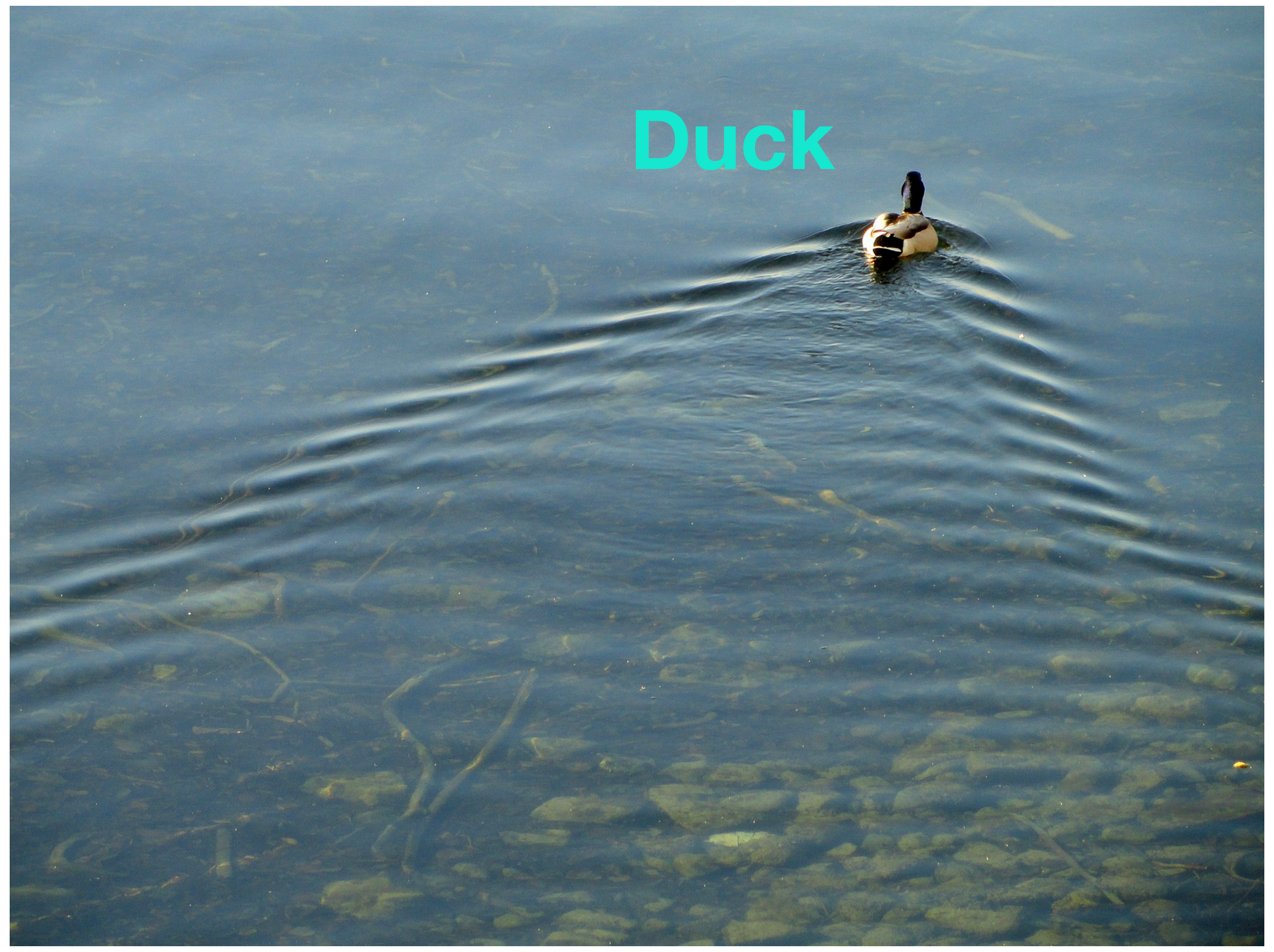


- **No evidence for QGP-induced acoplanarity so far**
  - Theory indicates low p_T jets most sensitive to broadening effects

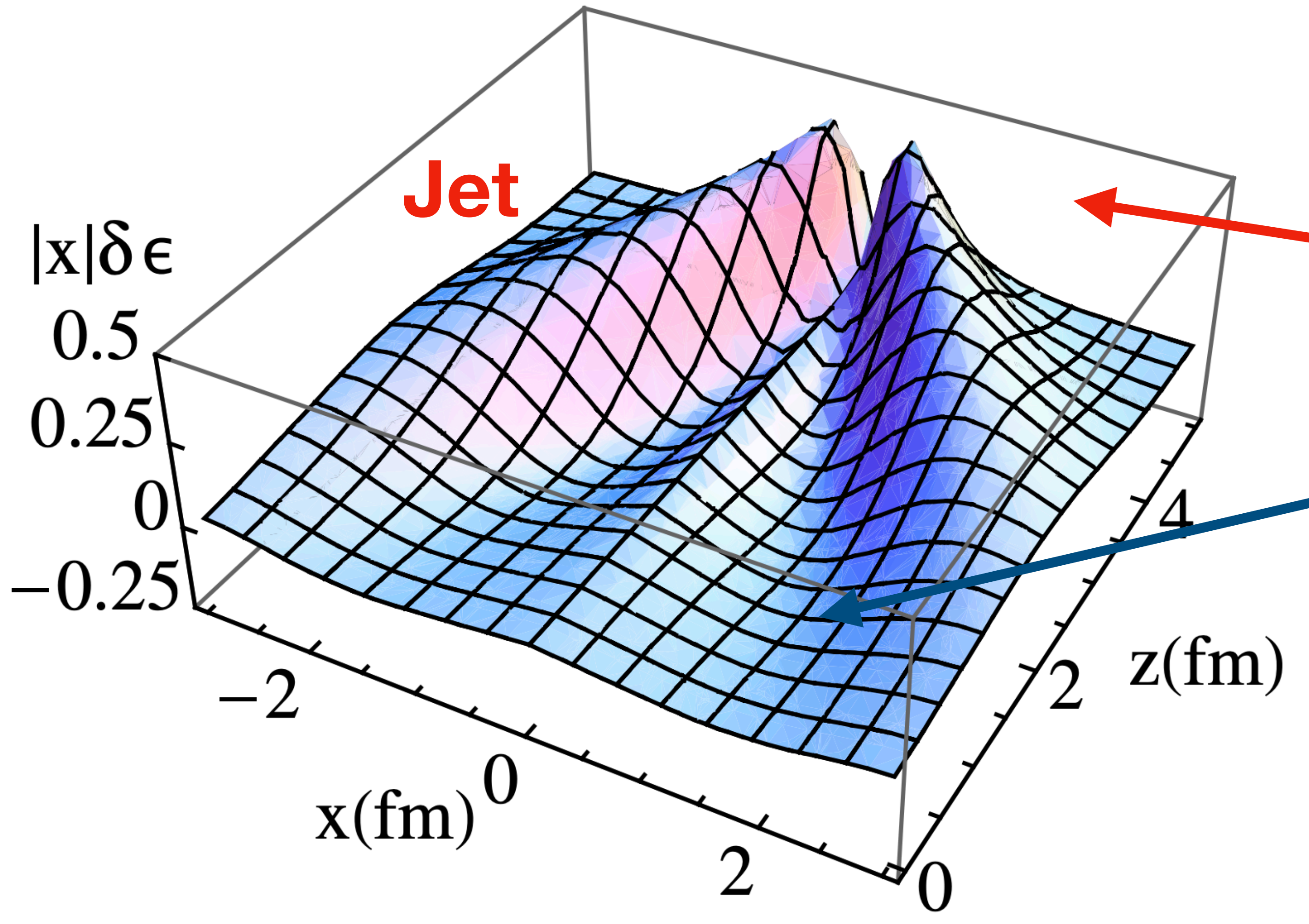
Medium response to propagating parton



- Jets lose energy due to interaction with medium
  → Medium modified by jets!



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



Expectation: 'wake' effects:

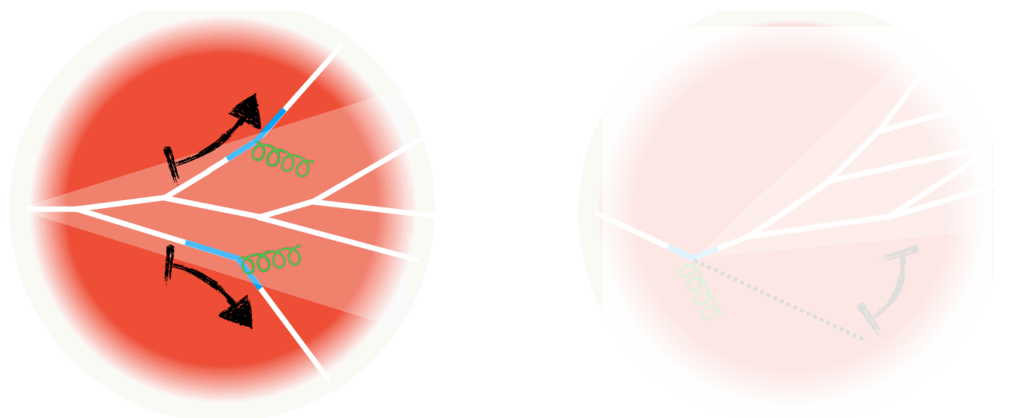
Enhancement around jet

Deletion opposite jet

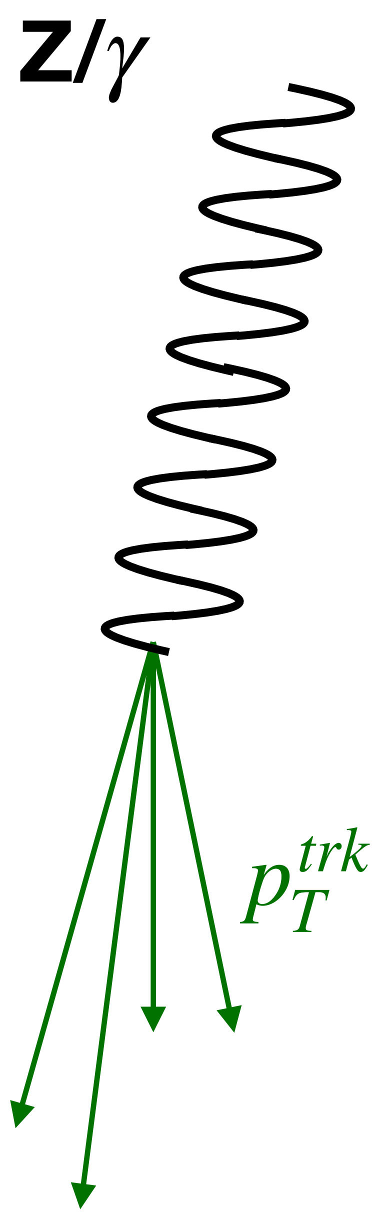
Sonic boom - $v_{jet} > c_s \sim 0.5c$

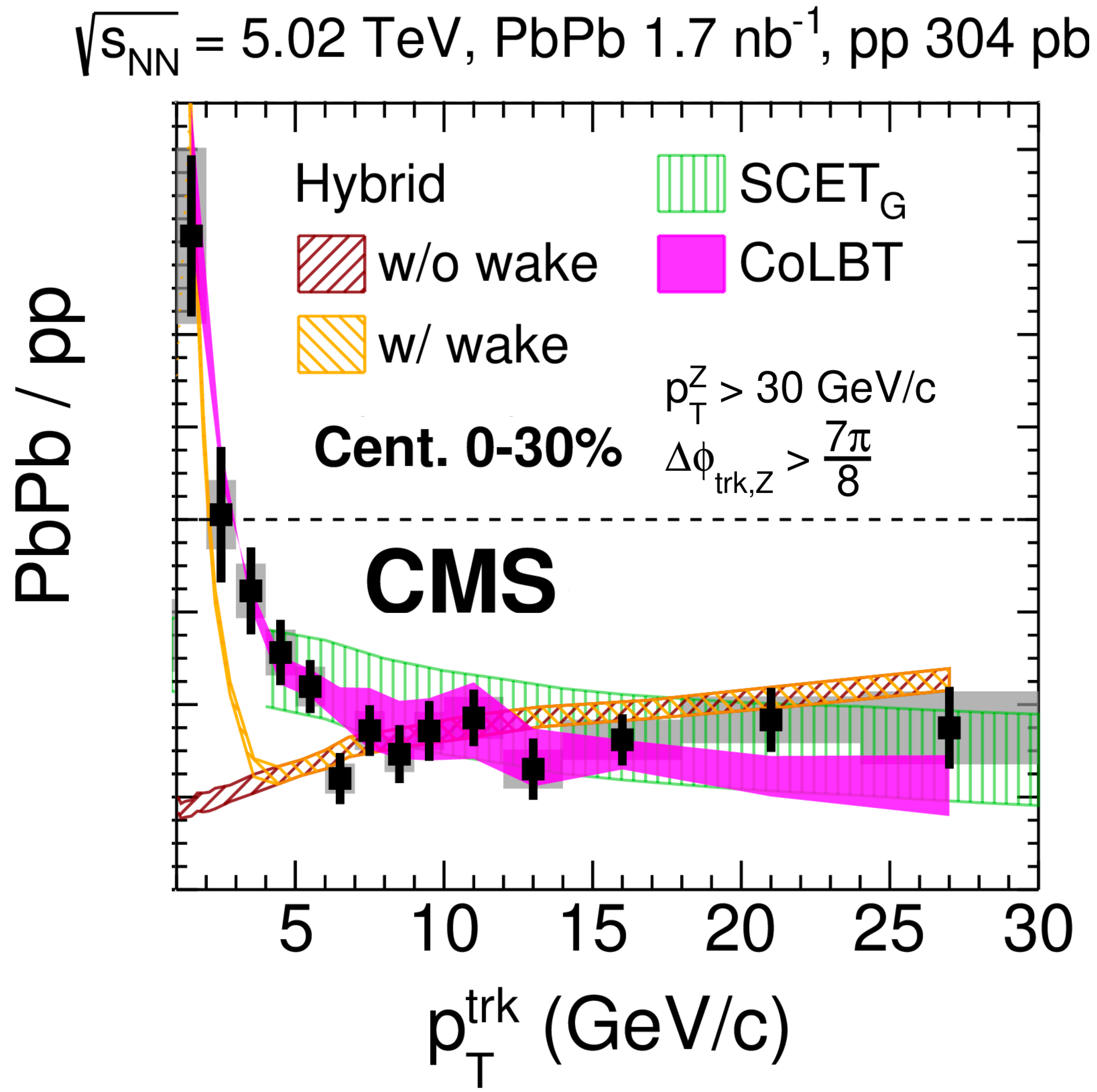
Insert out-of-equilibrium probe - see how medium responds
→ transport coefficients, equation of state

Measured consequences of medium response

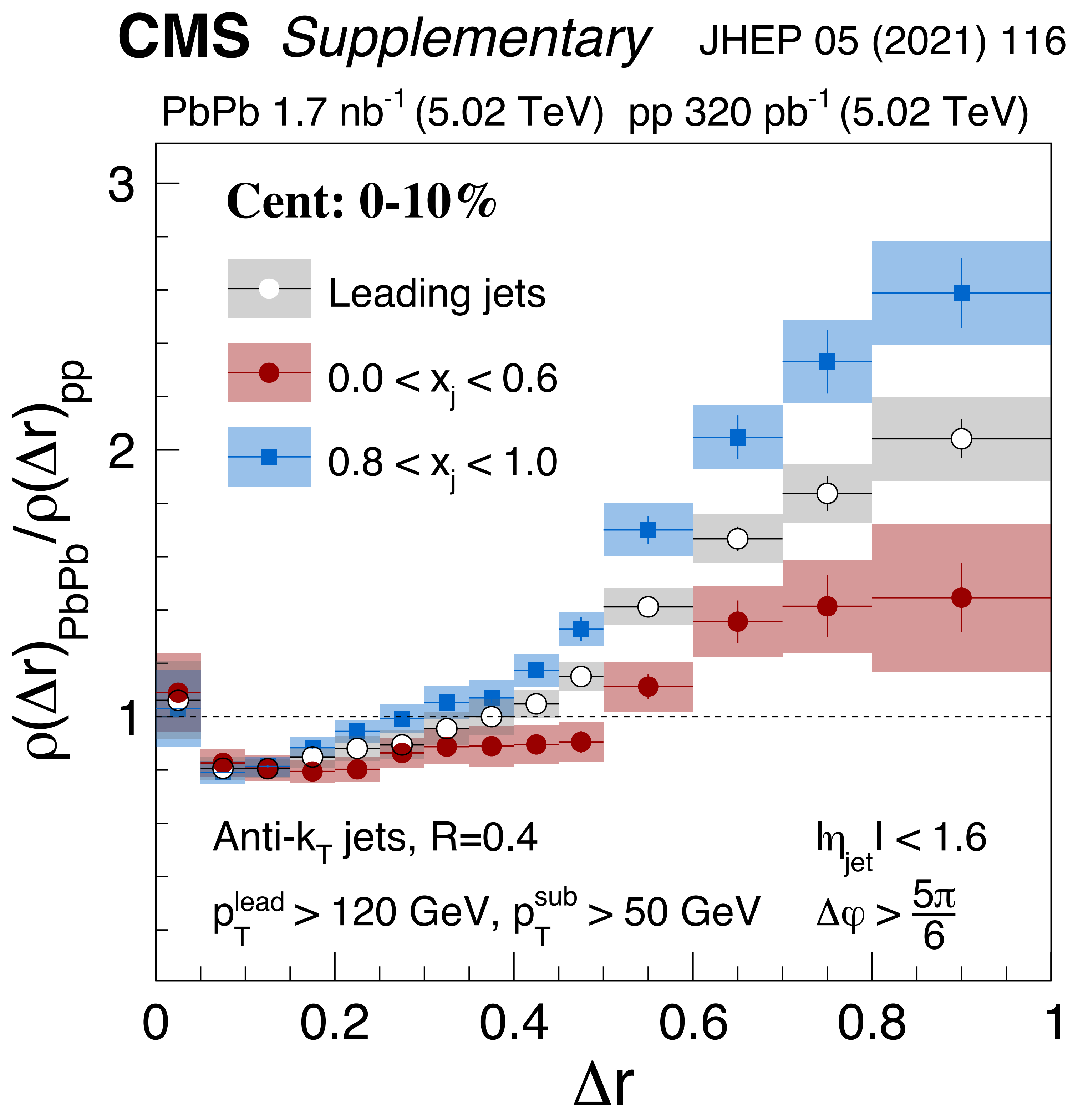


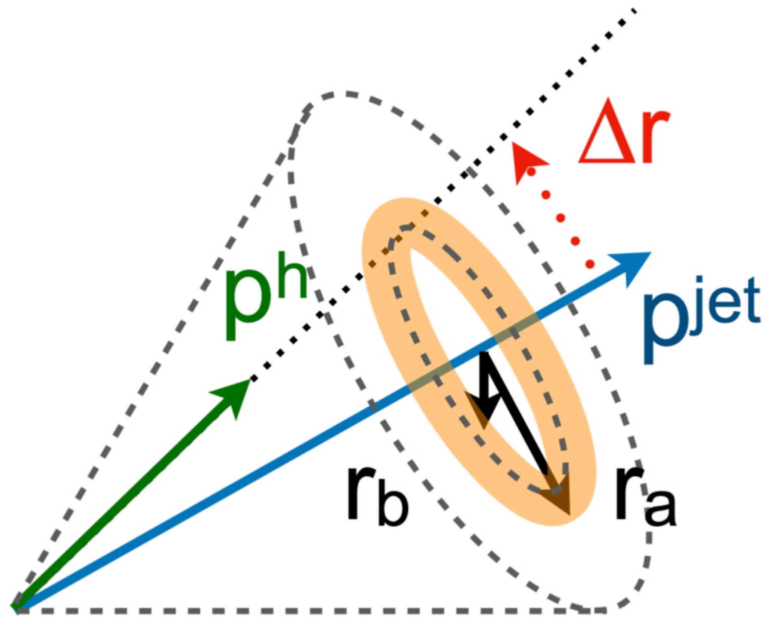
CMS: Phys. Rev. Lett. 128 (2022) 122301
See also ATLAS: Phys. Rev. Lett. 126, 072301 (2021)





hard particle suppression, soft particle excess
when recoiling from electroweak boson



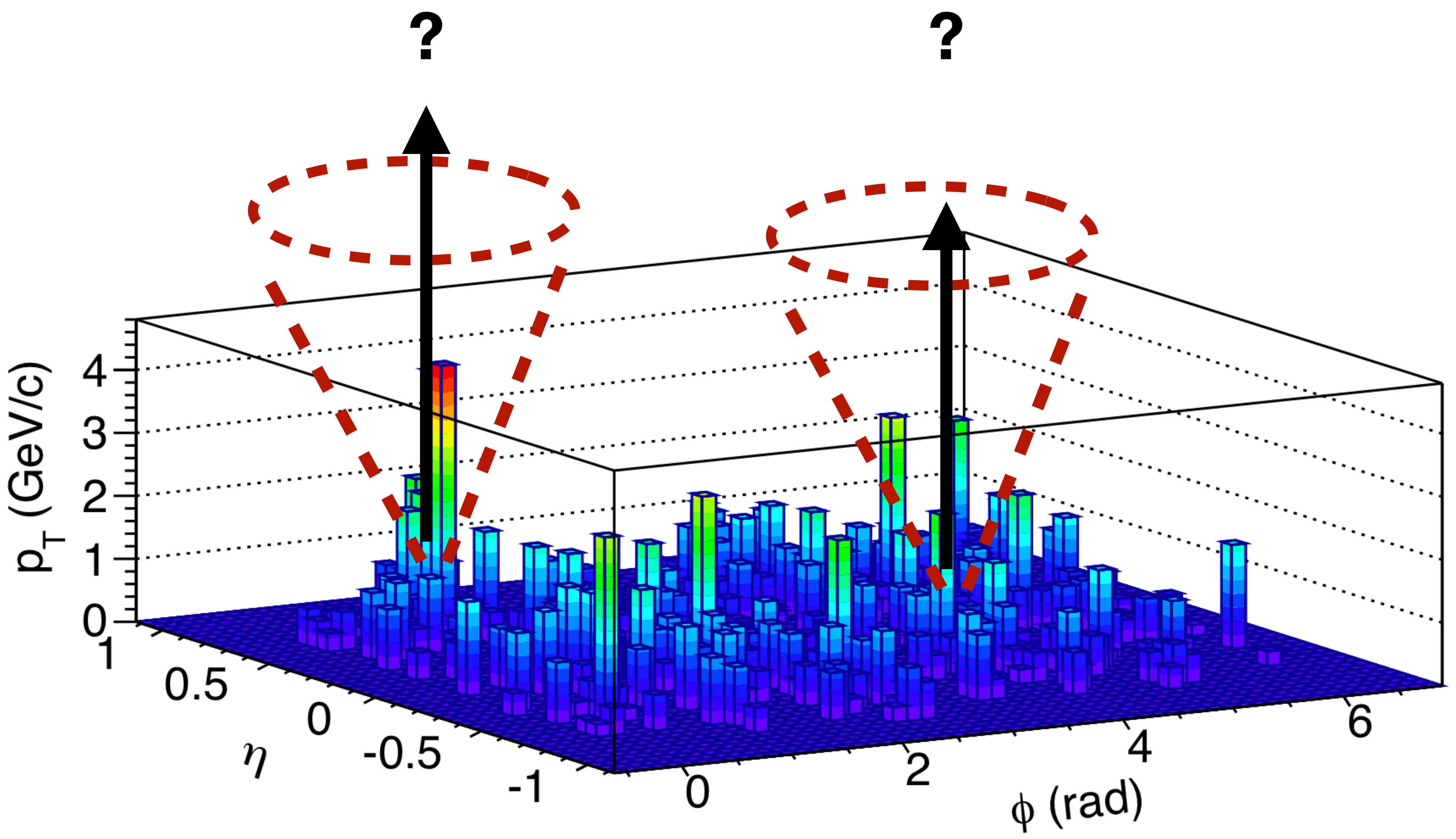


Soft particle excess surrounding a jet

→ Track-level effects explained by wake effects: how about jets?

Dealing with background in heavy-ion collisions

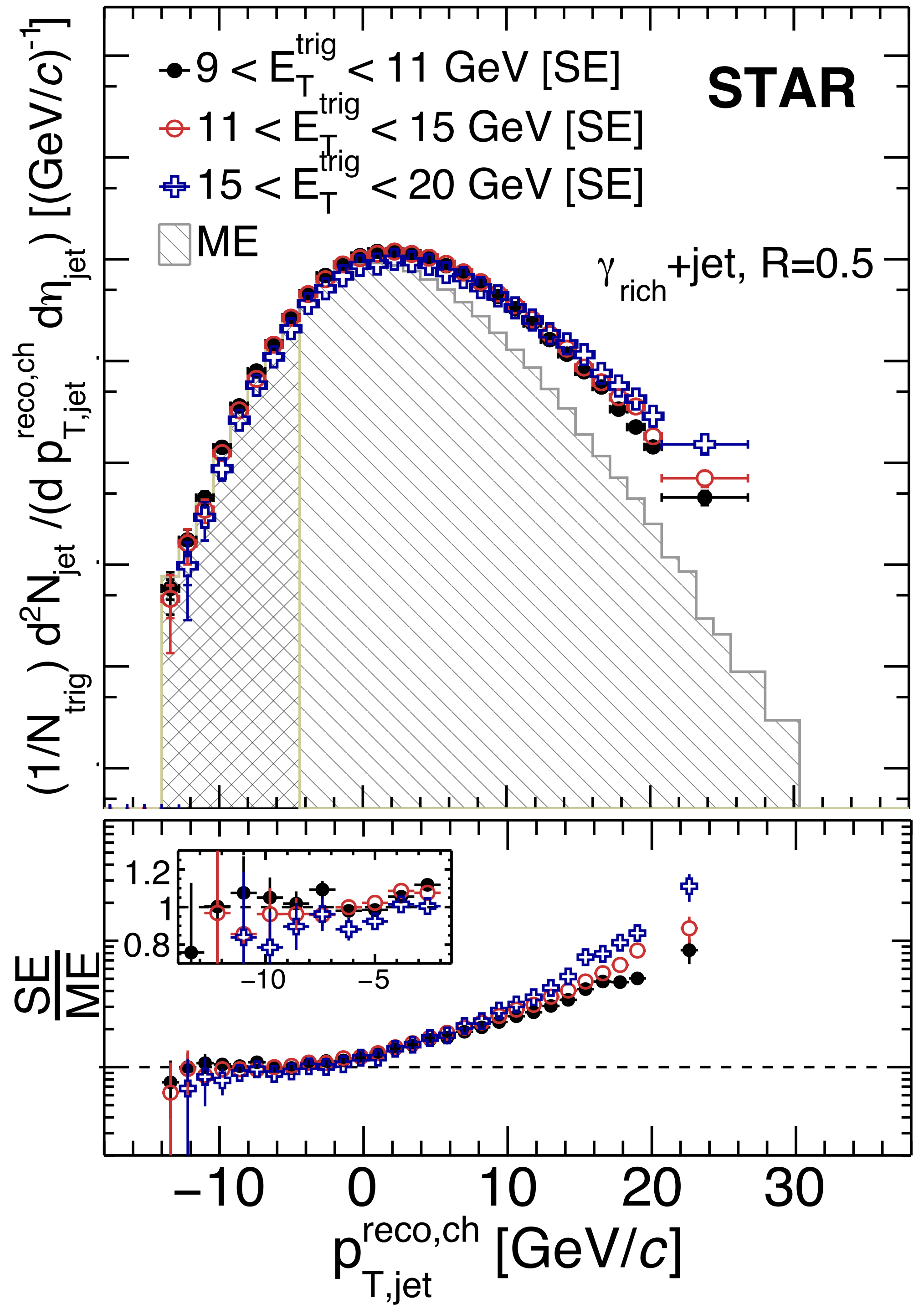
- Uncorrelated background: a major challenge for jet measurements in heavy ion collisions - what is a ‘true’ jet from a hard scattering and what is from uncorrelated sources?
  - **Especially important for low p_T measurements** where $p_{\mathrm{T}}^{\mathrm{jet}} \sim p_{\mathrm{T}}^{\mathrm{bkg}}$
  - Larger-*R* jets include larger background fraction



Dealing with background in heavy-ion collisions: Statistical correction

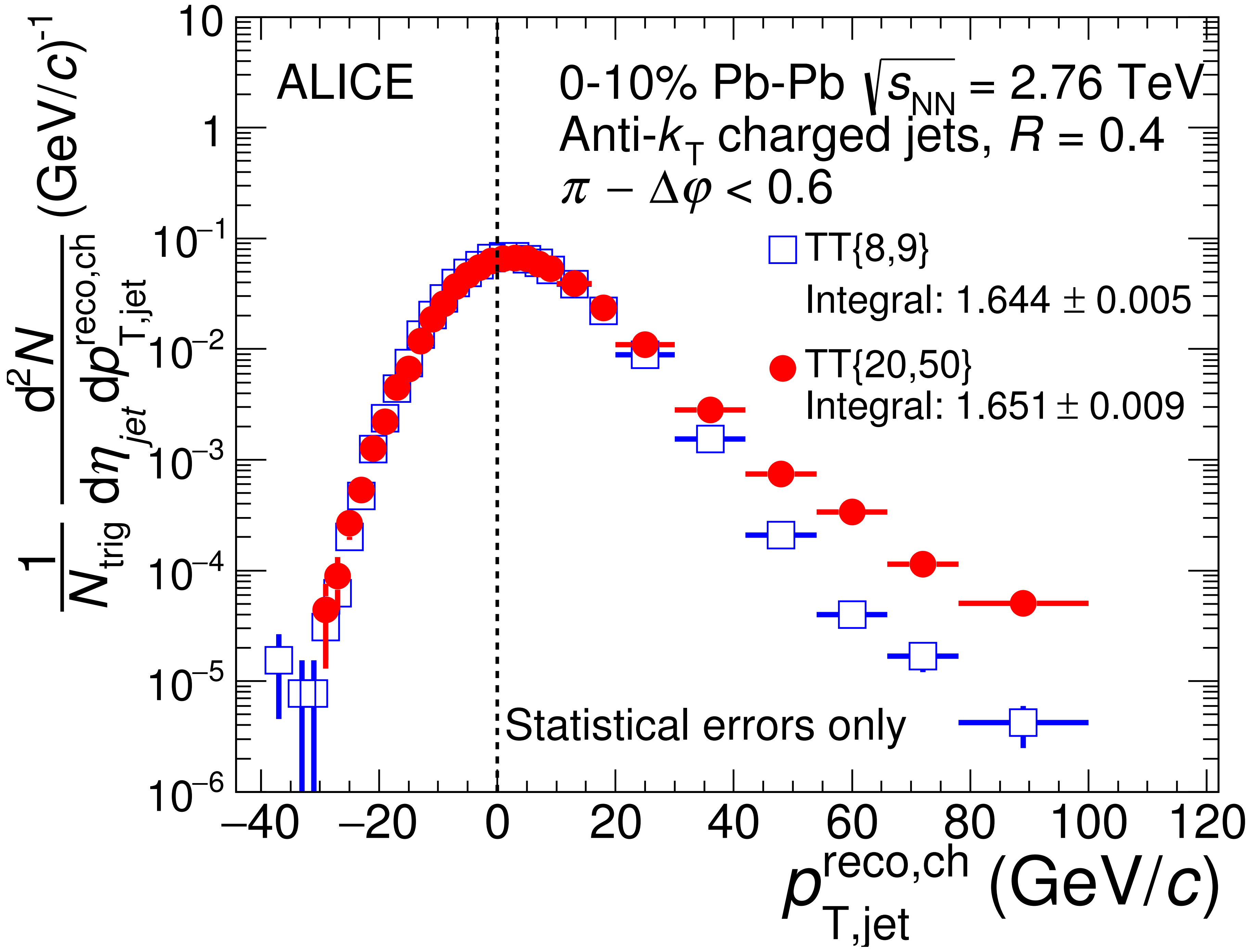
- Uncorrelated background: a major challenge for jet measurements in heavy ion collisions - what is a 'true' jet from a hard scattering and what is from uncorrelated sources?
  - **Especially important for low p_T measurements** where $p_{\mathrm{T}}^{\mathrm{jet}} \sim p_{\mathrm{T}}^{\mathrm{bkg}}$
  - Larger-*R* jets include larger background fraction

STAR: Phys. Rev. C 96, 024905 (2017)



Mixed event bkg

ALICE: JHEP 09 (2015) 170



'Reference' distribution bkg

- This talk: **correct for background at the level of *ensemble-averaged distributions***
  - Data-driven
  - No fragmentation bias

- **See also jet-wise approaches:**
  Leading track bias
  ALICE: Phys. Rev. C 101 (2020) 034911
  Phys. Lett. B 746 (2015) 1
  ML-based background estimation
  ALICE: arXiv:2303.00592
  H. Bossi, CERN-EP seminar

Probing energy redistribution and jet broadening with ALICE using hadron+jet measurement

Measurements of jet quenching using semi-inclusive hadron+jet distributions in pp and central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:2308.16128

Submitted to PRC

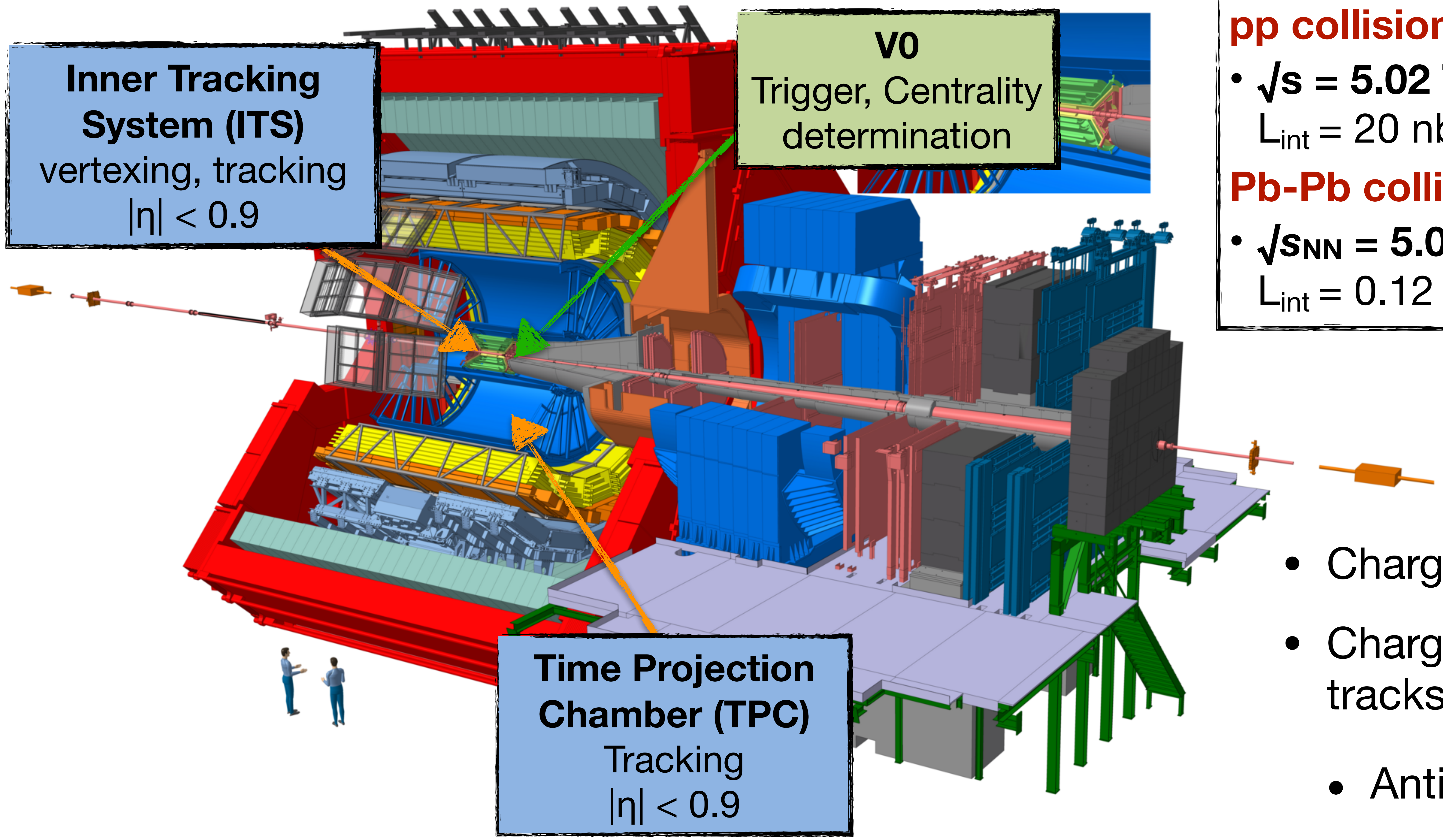
Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_T jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:2308.16131

Submitted to PRL

Analysis: datasets and jet reconstruction

The ALICE apparatus



Data samples (from Run 2):

pp collisions: min. bias trigger using V0, ITS inner layers

- **$\sqrt{s}$ = 5.02 TeV :** 1040x10^6 min. bias events, L_{int} = 20 nb^{-1}

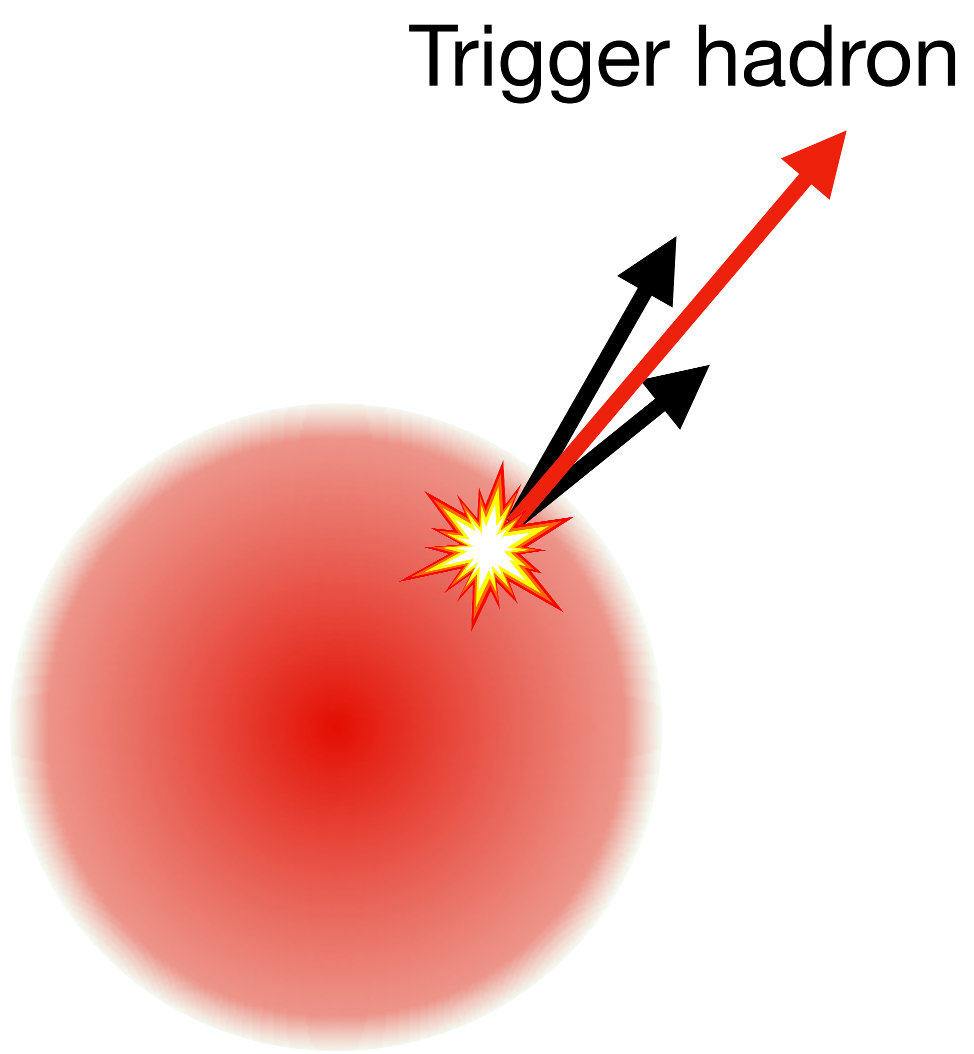
Pb-Pb collisions: centrality-enhanced trigger using V0

- **$\sqrt{s_{NN}}$ = 5.02 TeV :** 89x10^6 0-10% most central events, L_{int} = 0.12 nb^{-1}

- Charged tracks reconstructed using ITS+TPC
- Charged-particle jets reconstructed using charged tracks as jet constituents
  - Anti-k_T algorithm, $p_{T,track} > 0.15$ GeV/c, p_T-recombination scheme
  - Three separate jet radii: R=0.2, 0.4 and 0.5

Analysis procedure

1. **Select events** based on the **presence of a high-p_{T} 'trigger' hadron**



Analysis procedure

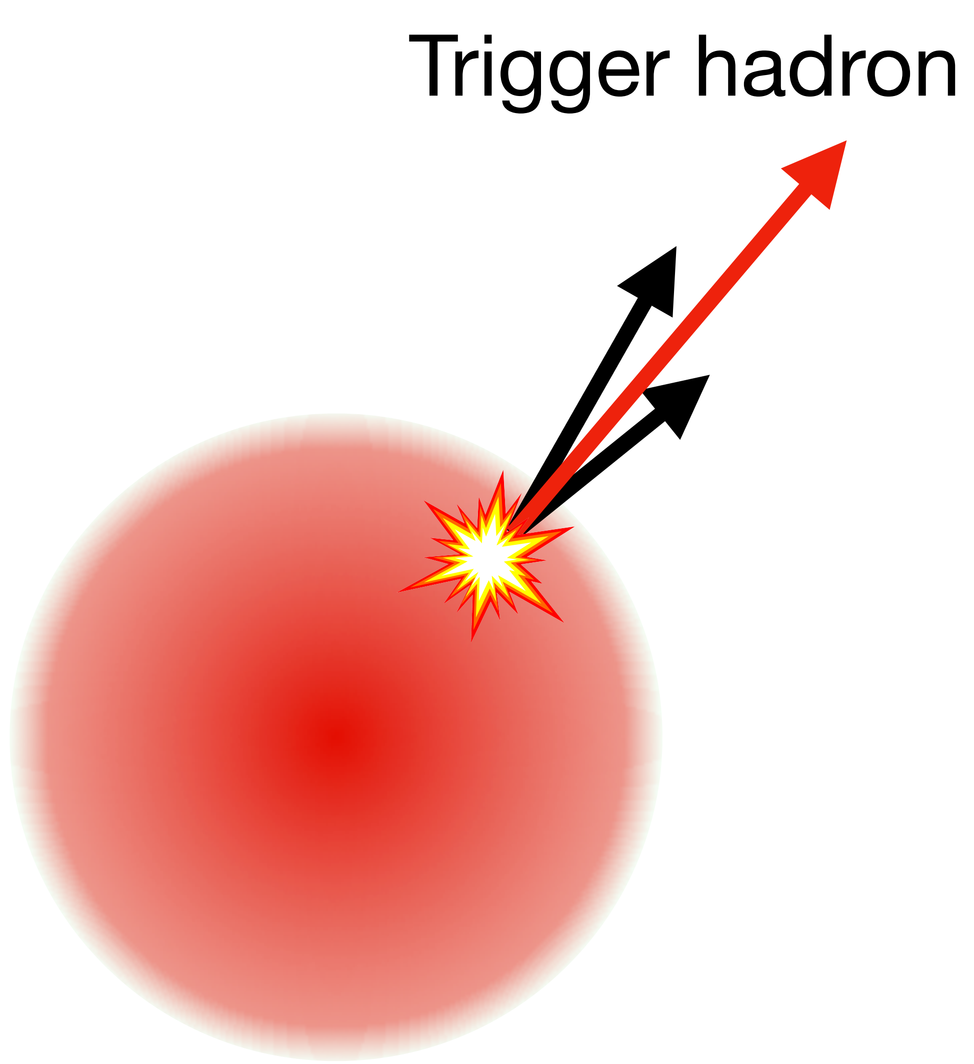
1. **Select events** based on the **presence of a high-p_{T} 'trigger' hadron**

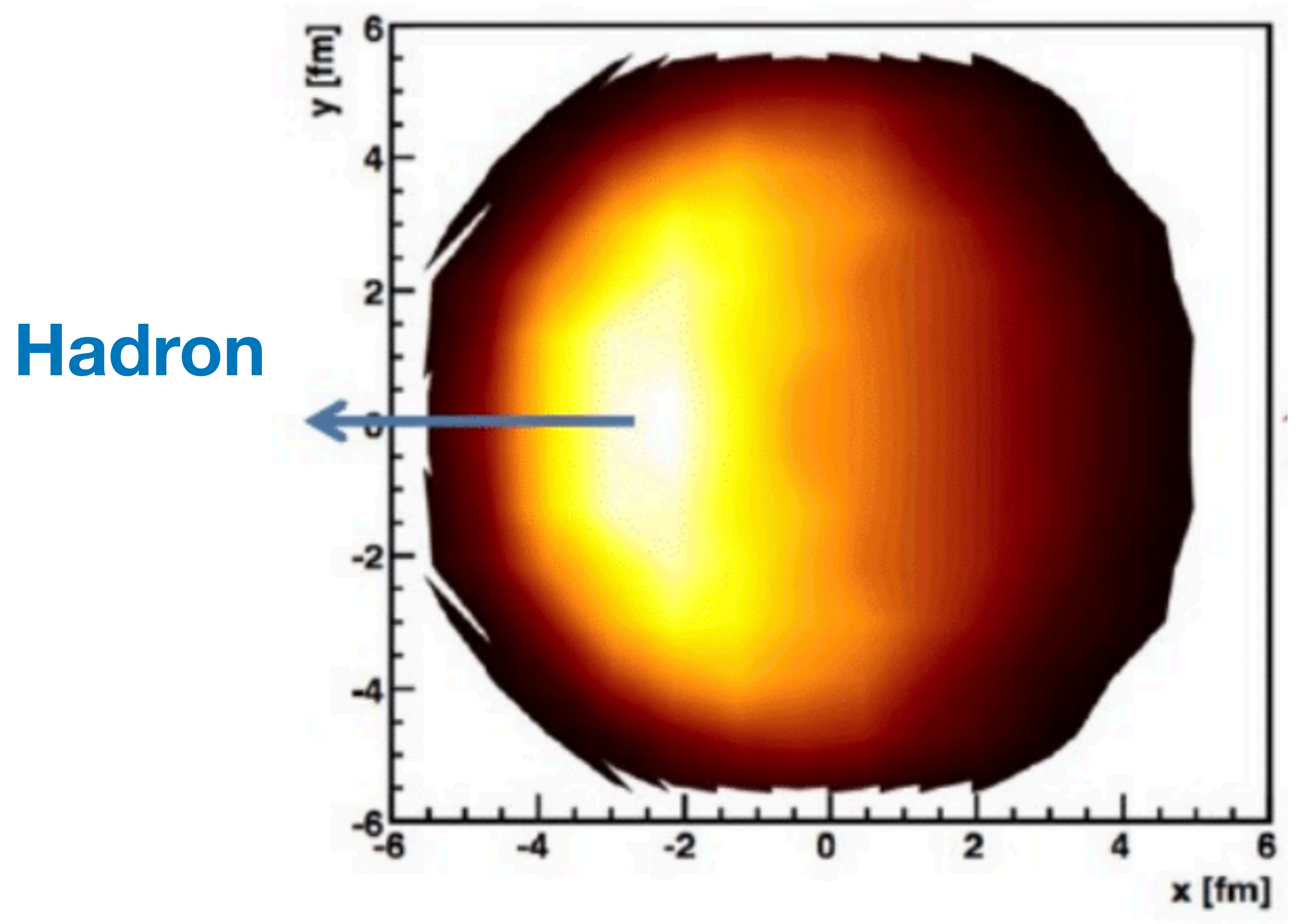
- Hadron distribution follows that of inclusive yield
  → event selection bias solely due to choice of trigger

- Hadron forms 'clean' trigger (e.g. no bkg correction necessary)

- Observed high-p_{T} hadrons have surface bias
  → interplay of jet spectrum, FF, energy loss…

  and bias events towards having jets in final state



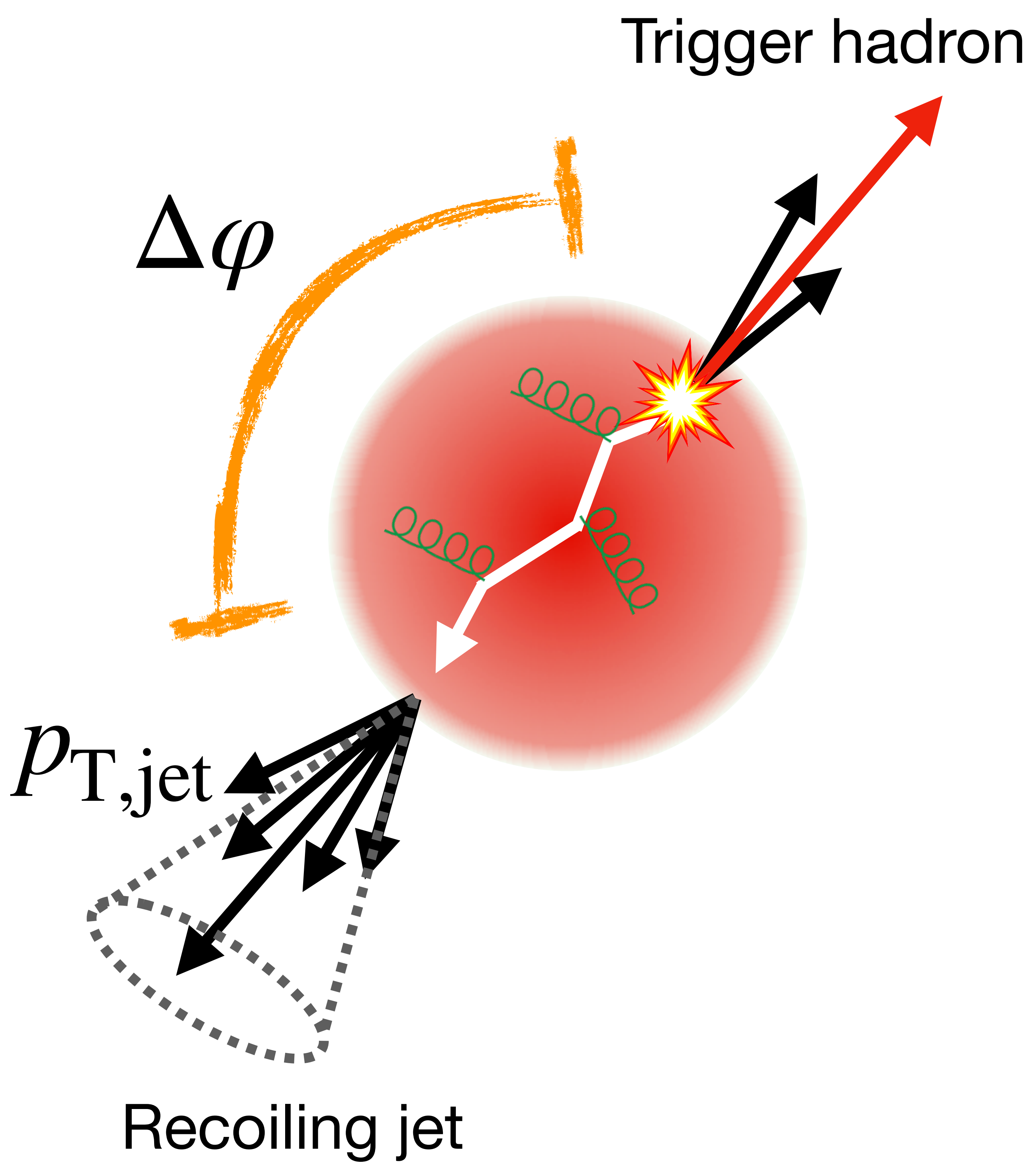


Adapted from T. Renk, Phys. Rev. C 88, 054902 (2013)

Analysis procedure

1. **Select events** based on the **presence of a high-p_{T} 'trigger' hadron**
2. **Do jet reconstruction** on these events
3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{\mathrm{T,jet}}$) of recoil jet

Jet biased to longer in-medium path length



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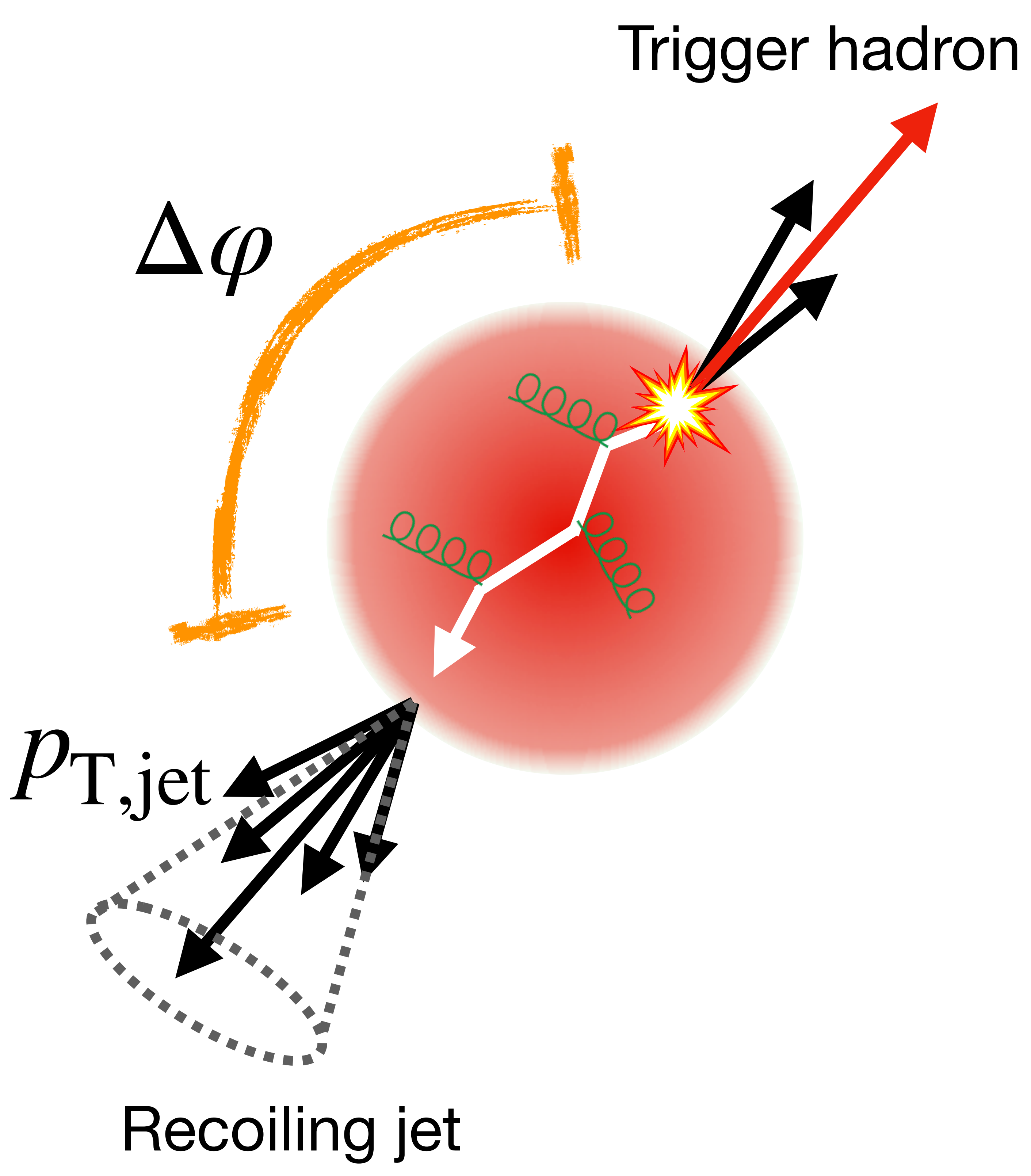
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{\mathrm{T,jet}}$) of recoil jet
4. **Define observable:**

$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^3 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\eta_{\mathrm{jet}}} \Bigg|_{p_{\mathrm{T,h}} \in \mathrm{TT}}$$

Trigger-normalised yield of charged-particle jets recoiling from high-p_{T} trigger hadrons



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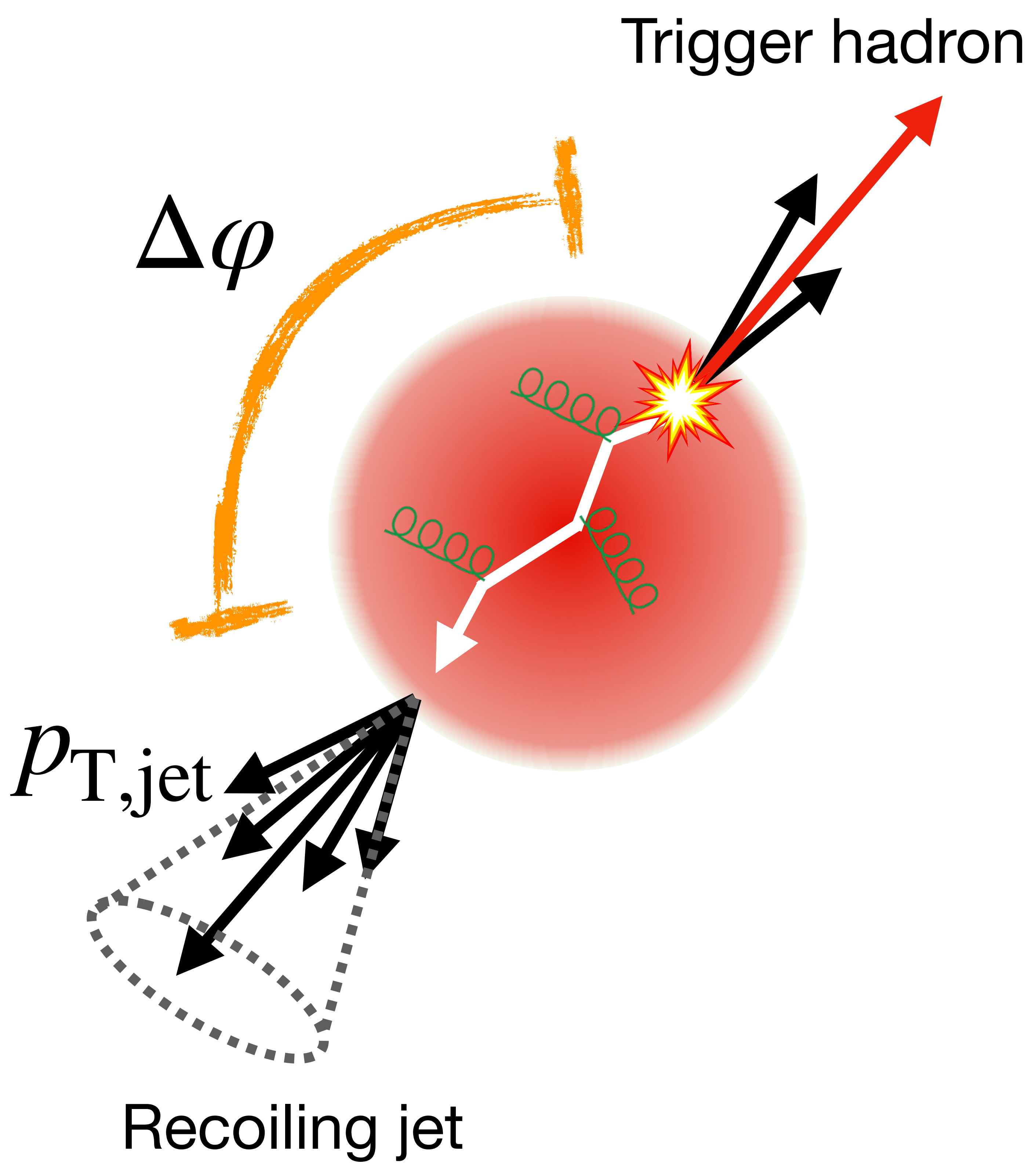
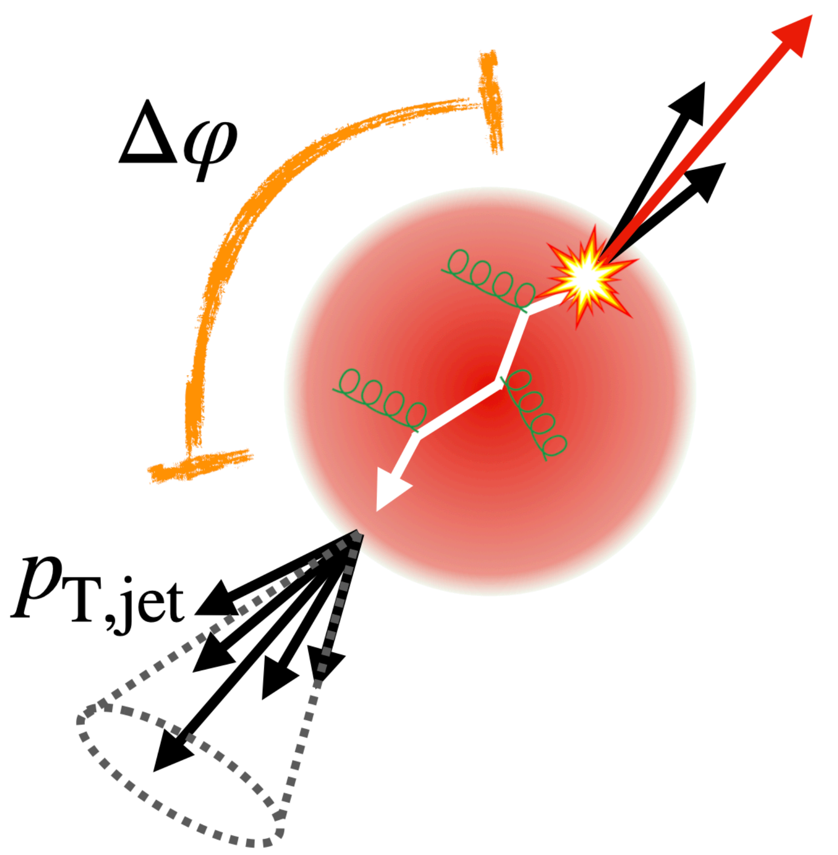
- **Perturbatively calculable**
  Ratio between high-p_{T} hadron and jet production cross sections
- **Semi-inclusive**
  events selected based on presence of trigger → count all recoil jets in defined acceptance



Analysis procedure

- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

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



c_{Ref}: normalisation constant extracted from data

- **Statistical approach** - uncorrelated yield corrected solely at level of ensemble-averaged distributions

- **data-driven subtraction of *all* uncorrelated background**
  → Includes multi-parton interaction removal - improves sensitivity to large-angle scattering
  → low-p_{T}, large *R* measurements possible

Analysis procedure: raw distributions

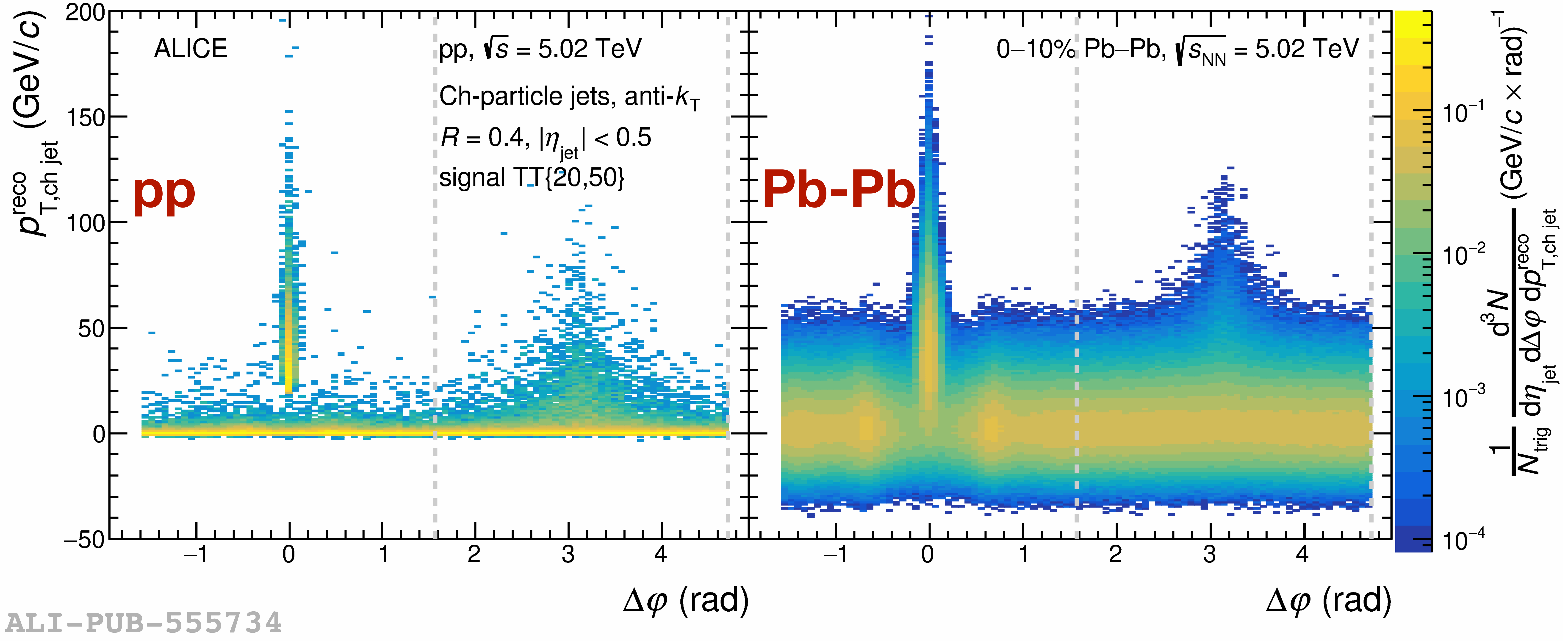
- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

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

$$p_{\mathrm{T,jet}}^{\mathrm{reco,ch}} = p_{\mathrm{T,jet}}^{\mathrm{raw,ch}} - \rho A_{\mathrm{jet}}$$

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

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



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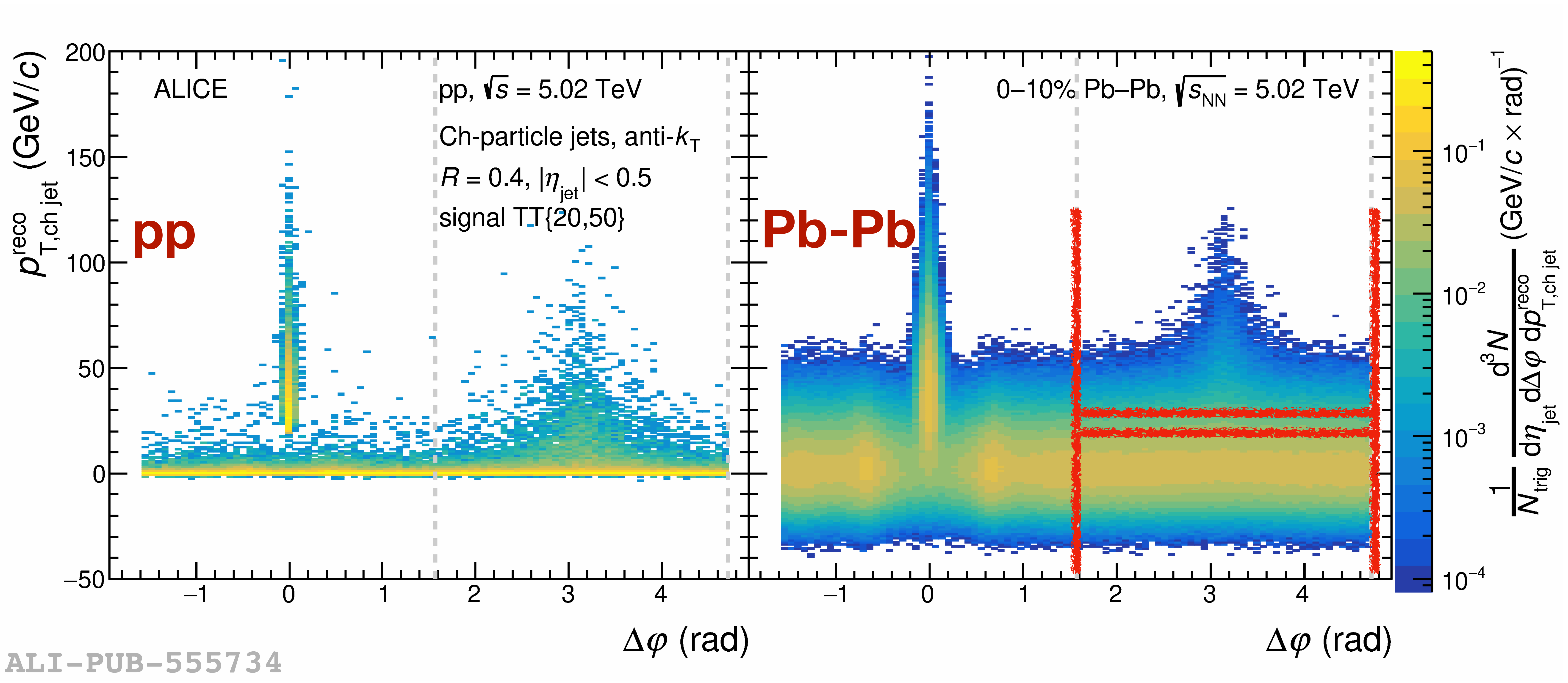

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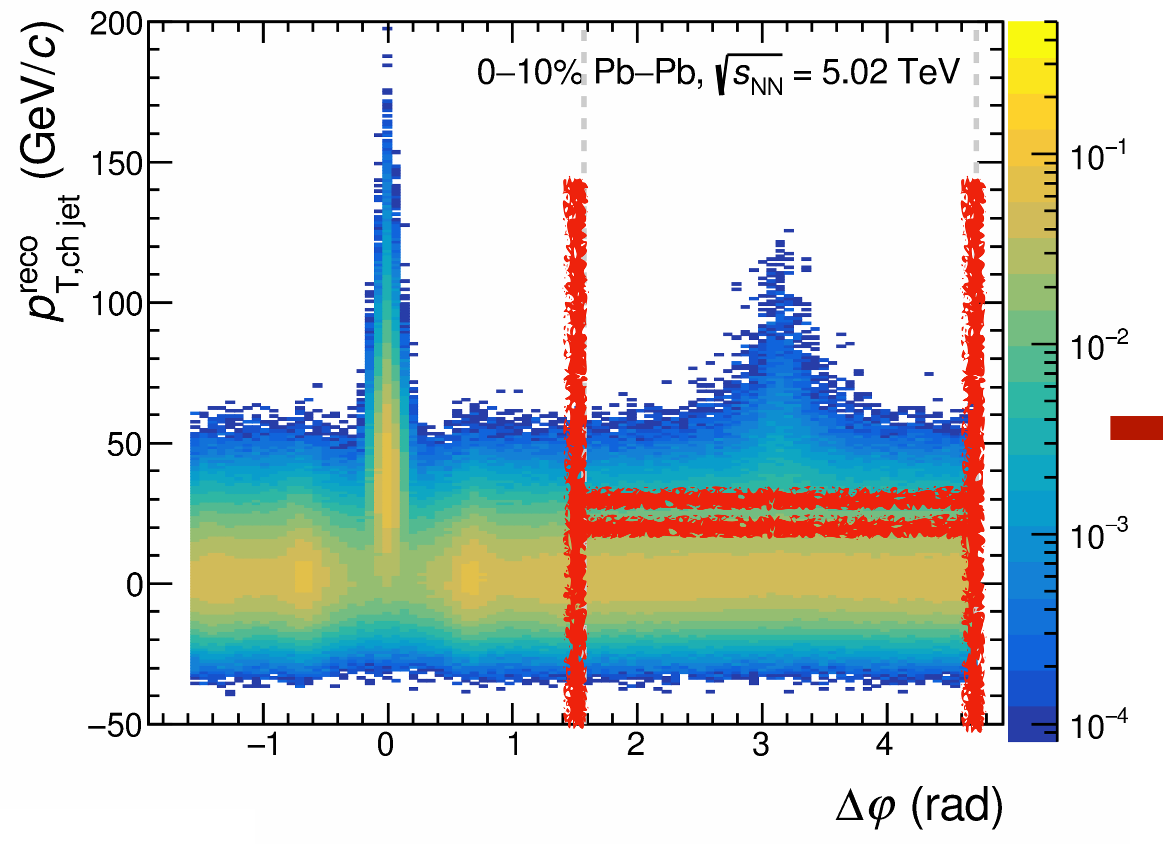

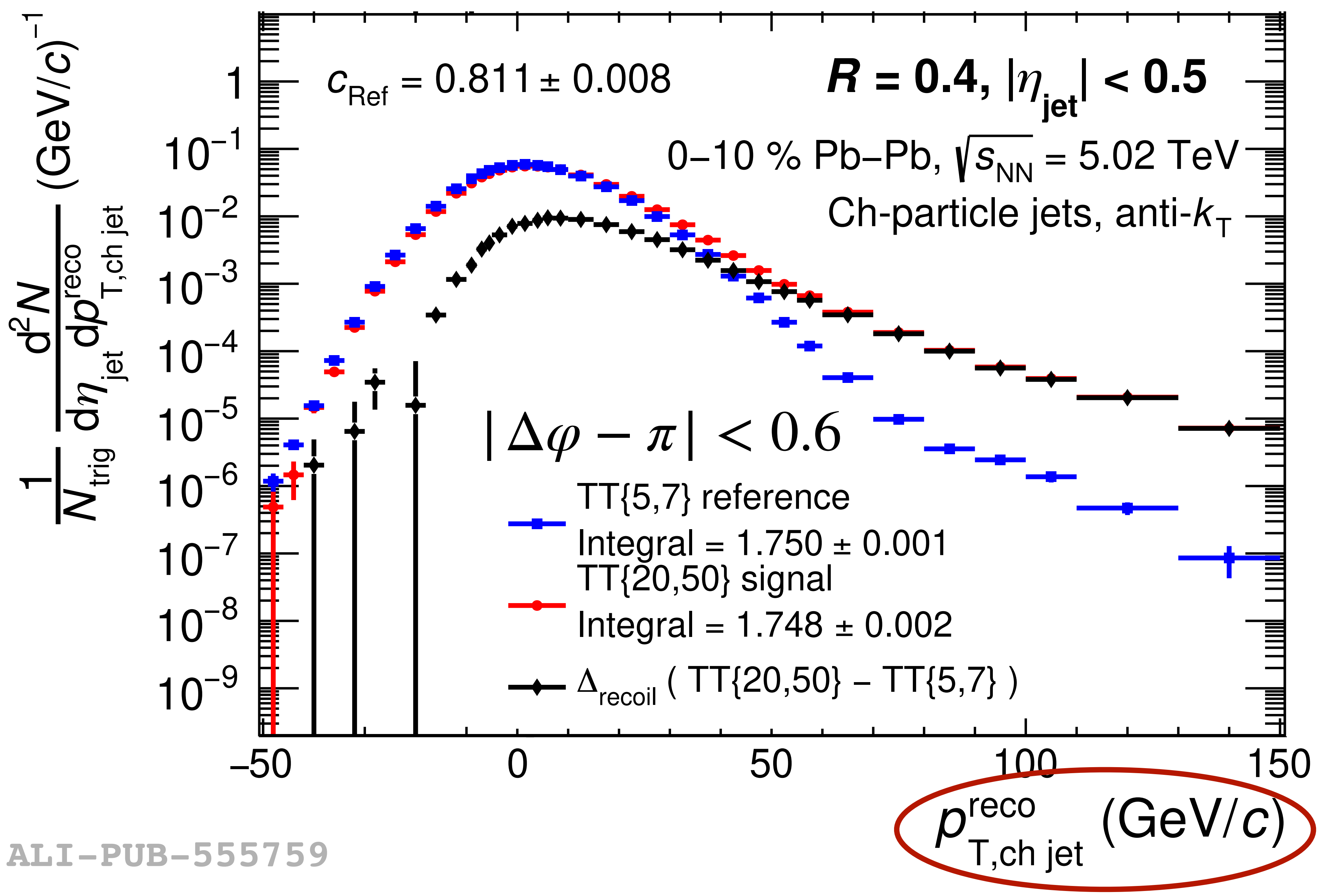

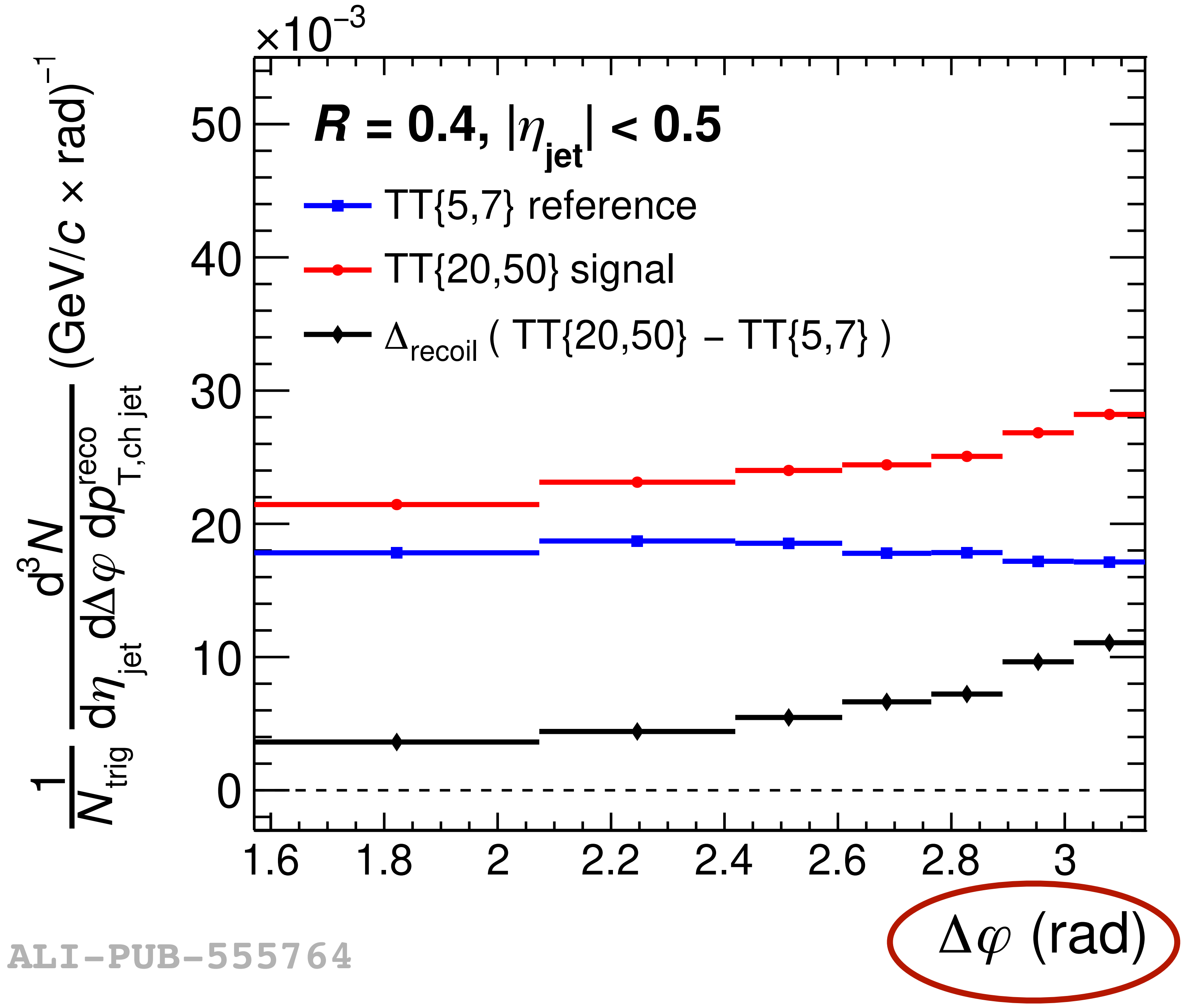

Analysis procedure: raw distributions

- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

$$\Delta_{\rm recoil} = \underline{\frac{1}{N^{\rm AA}_{\rm trig}}\frac{{\rm d}^3N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\Delta\varphi{\rm d}\eta_{\rm jet}}\bigg|_{p_{\rm T,trig}\in{\rm TT}_{\rm Sig}}} - c_{\rm Ref}\cdot\underline{\frac{1}{N^{\rm AA}_{\rm trig}}\frac{{\rm d}^3N^{\rm AA}_{\rm jet}}{{\rm d}p^{\rm ch}_{\rm T,jet}{\rm d}\Delta\varphi{\rm d}\eta_{\rm jet}}\bigg|_{p_{\rm T,trig}\in{\rm TT}_{\rm Ref}}}$$

$$p^{\rm reco,ch}_{\rm T,jet} = p^{\rm raw,ch}_{\rm T,jet} - \rho A_{\rm jet}$$

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

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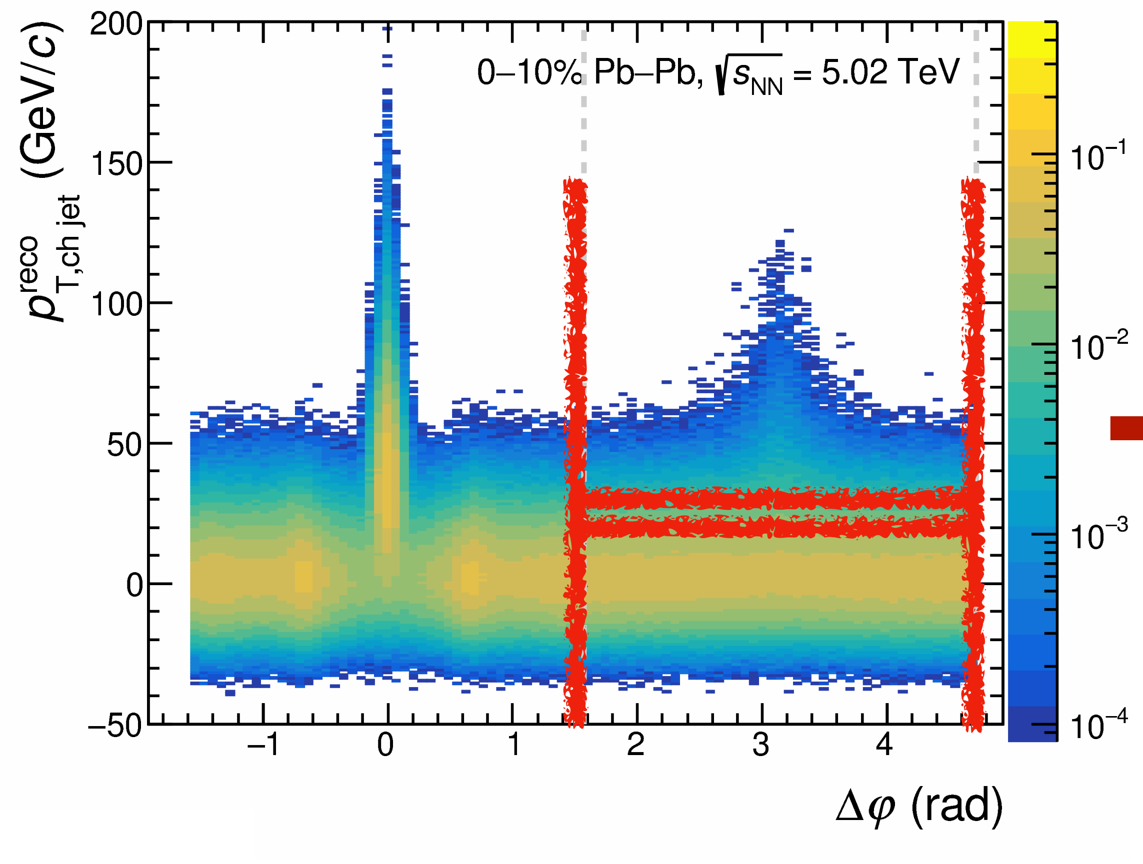
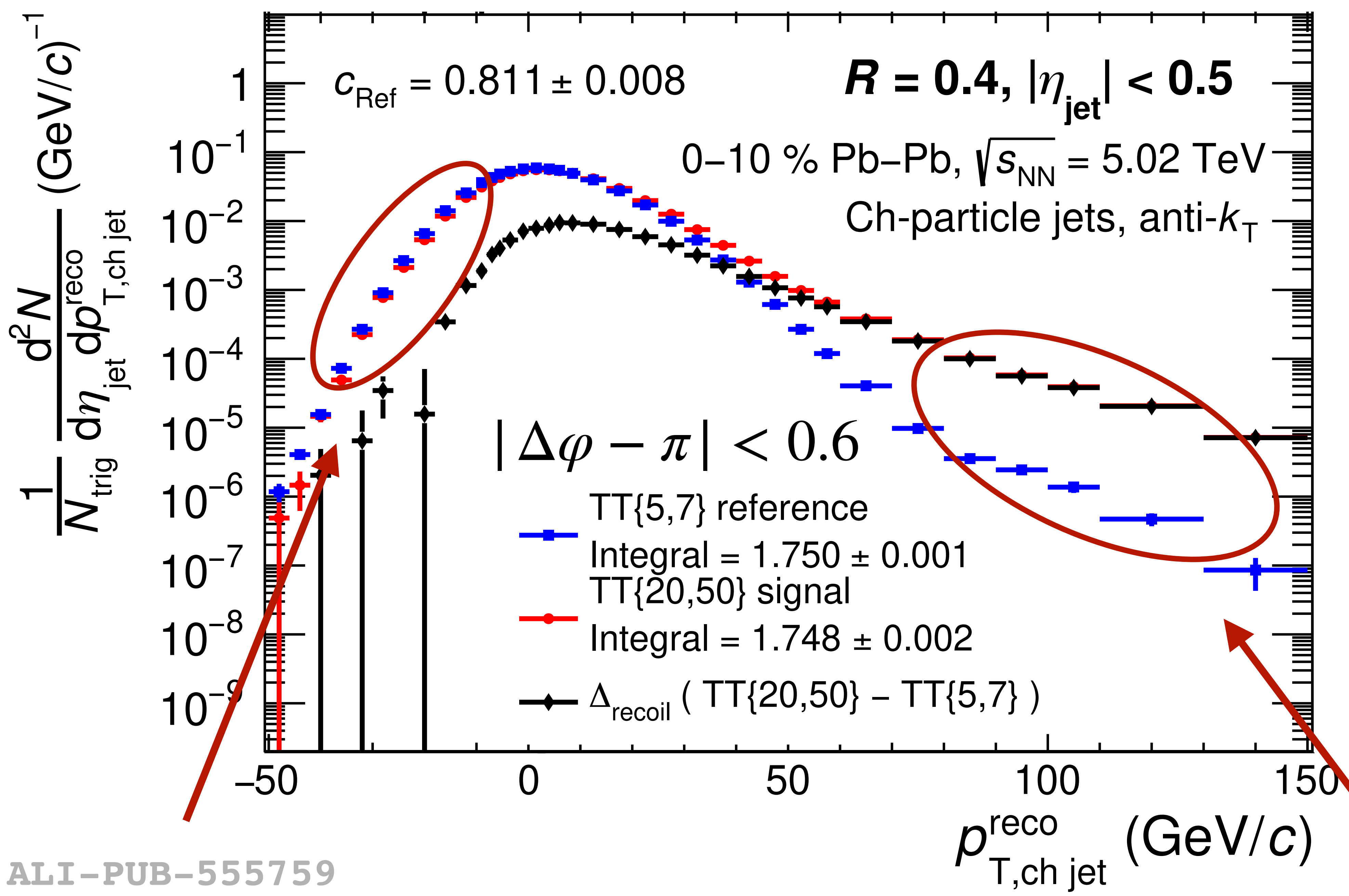
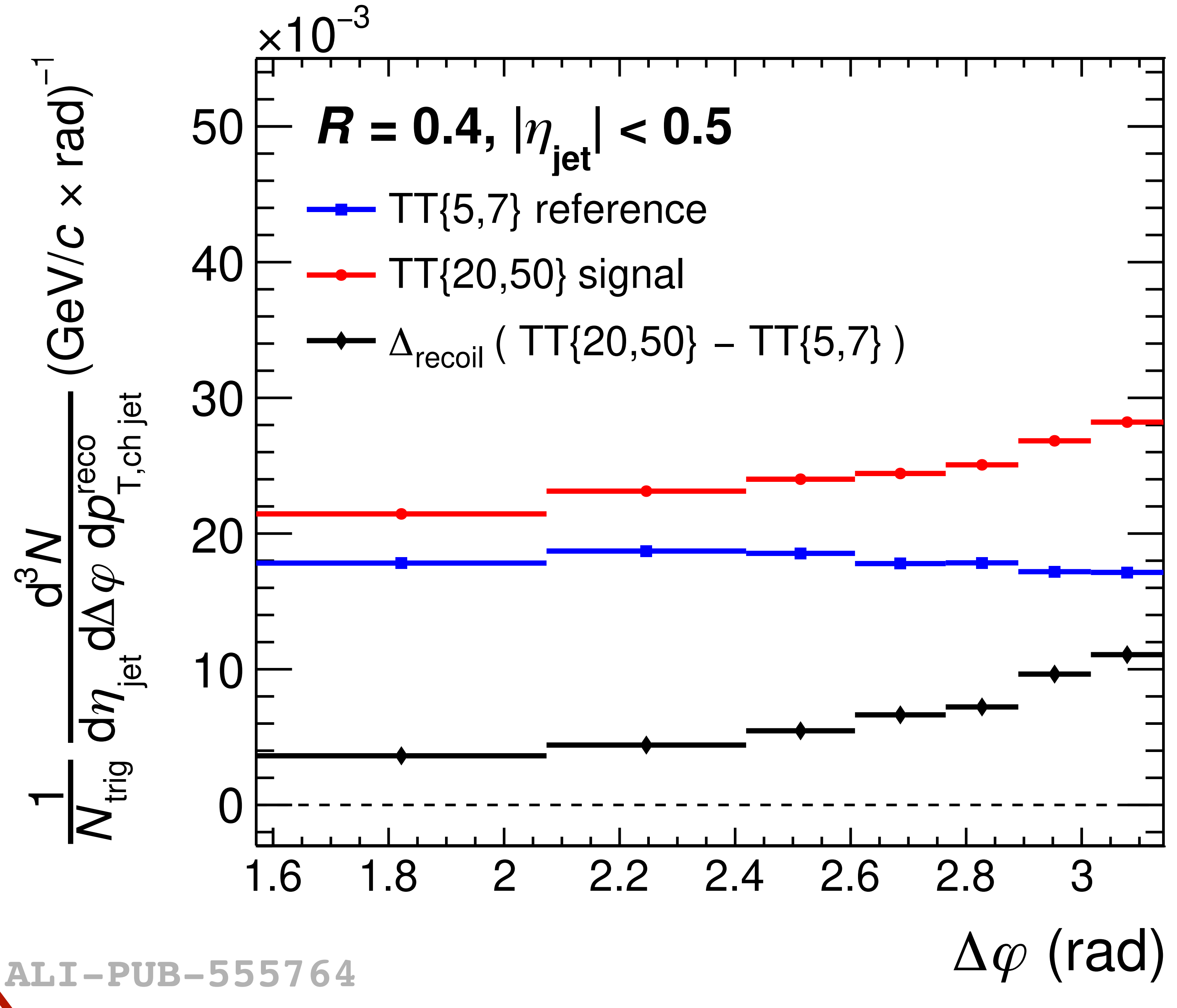




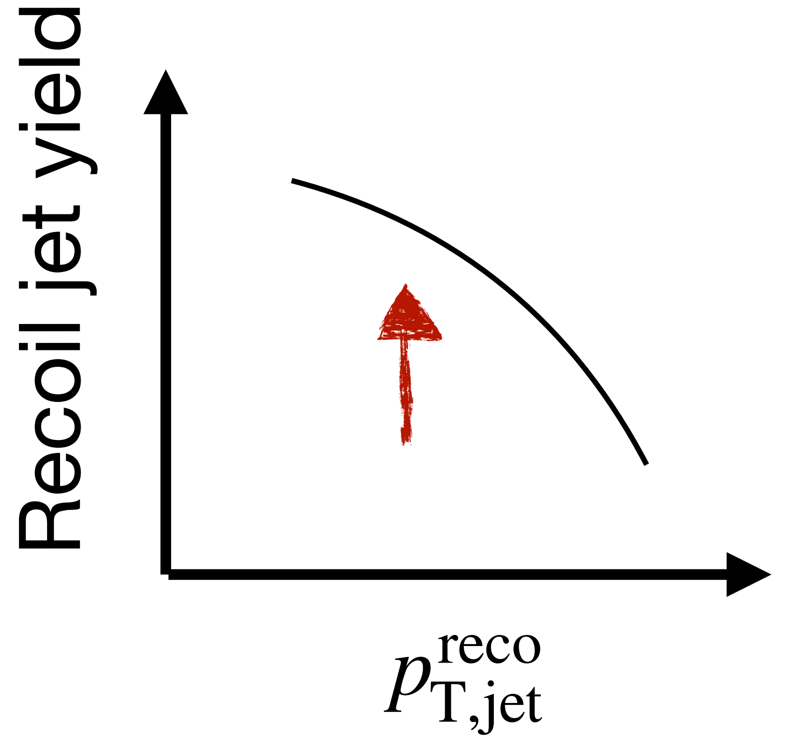


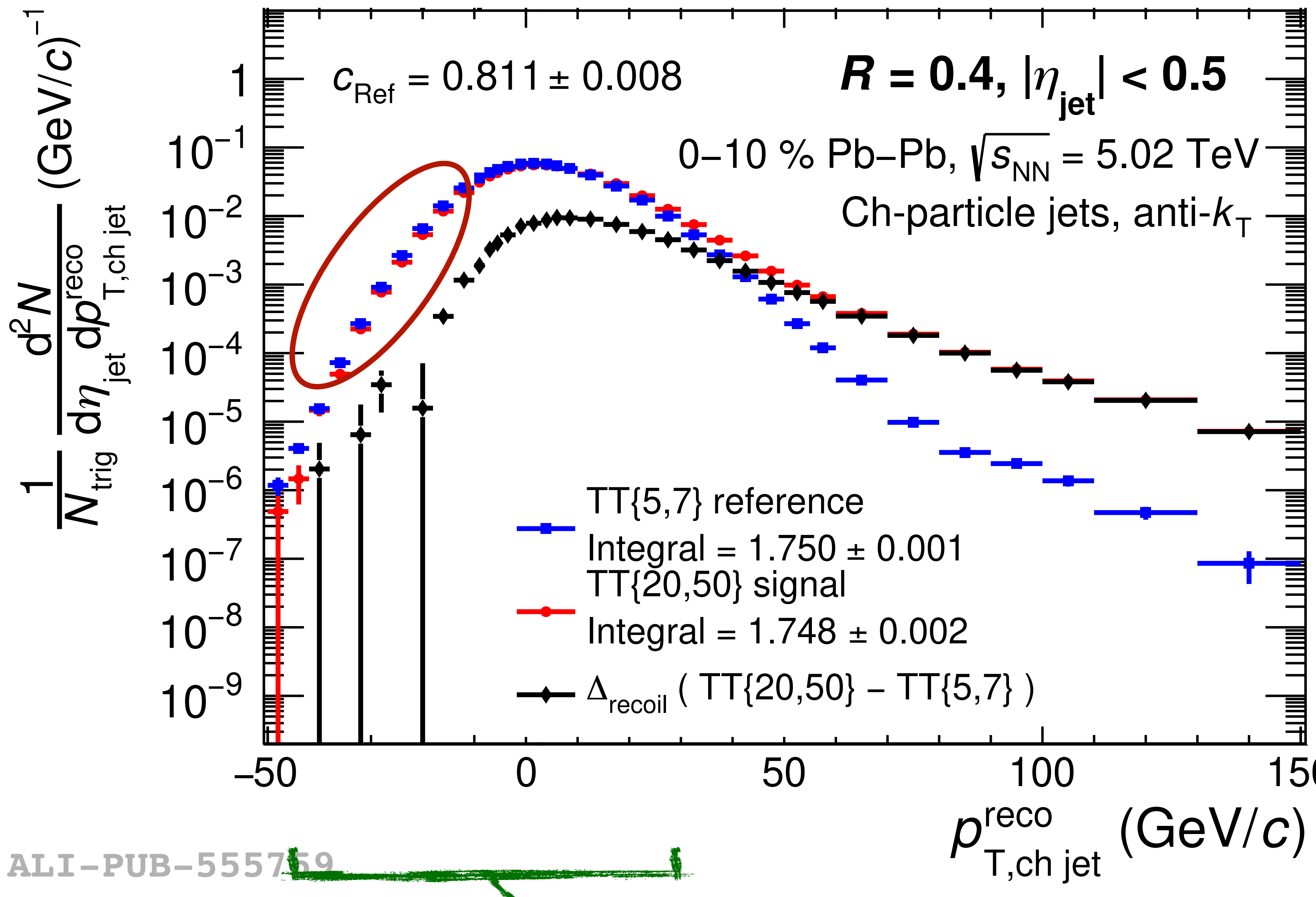
Uncorrelated background dominates — **Signal jets dominate**

Δ_{recoil} 'reference' calibration

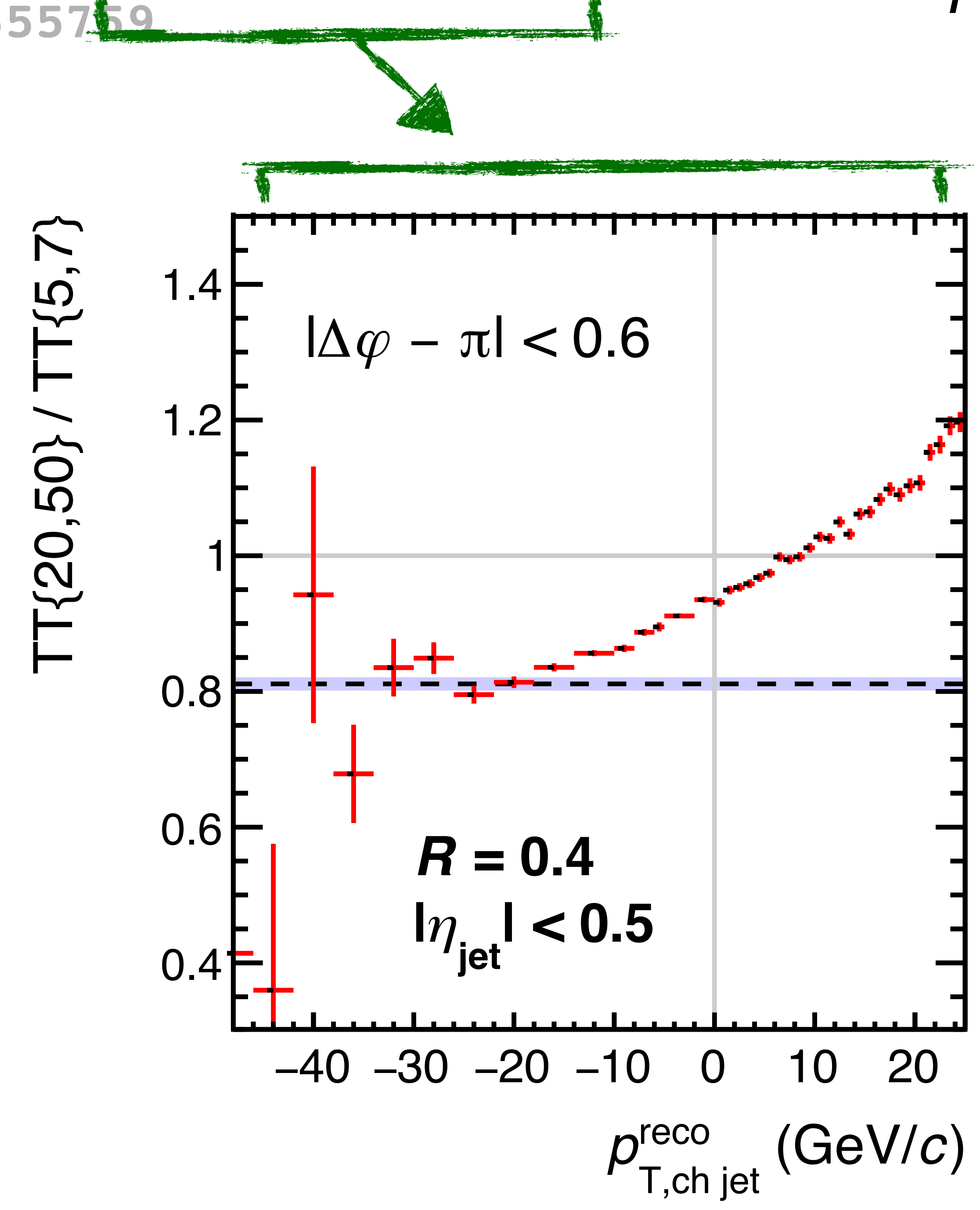
Calibration of reference distribution required for precise background subtraction:

- Yield scale ('*vertical*')
- $p_{\mathrm{T,jet}}^{\mathrm{reco}}$ scale ('*horizontal*')





- Conservation of jet density - uncorrelated low-$p_{\mathrm{T,jet}}$ region 'misaligned' due to difference in correlated jet yield at high $p_{\mathrm{T,jet}}$
- factor 'c_{Ref}' applied to reference distribution to align signal and reference distributions in low-$p_{\mathrm{T,jet}}$ region



$\rightarrow c_{\mathrm{Ref}} = 0.811$

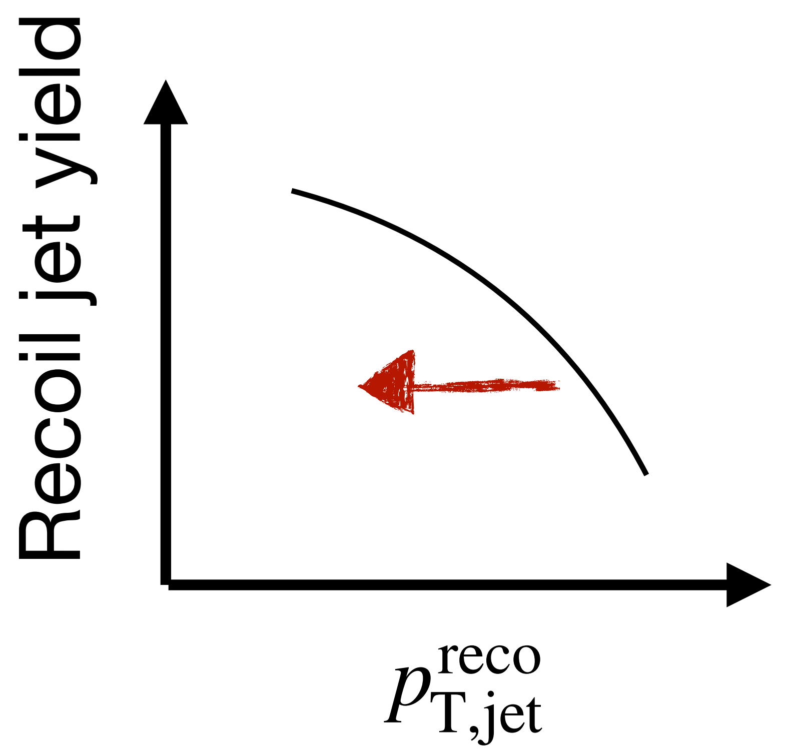
Established technique

ALICE: *JHEP* 09 (2015) 170

Δ_{recoil} 'reference' calibration

Calibration of reference distribution required for precise background subtraction:

- Yield scale (*'vertical'*)
- $p_{\mathrm{T,jet}}^{\mathrm{reco}}$ scale (*'horizontal'*)

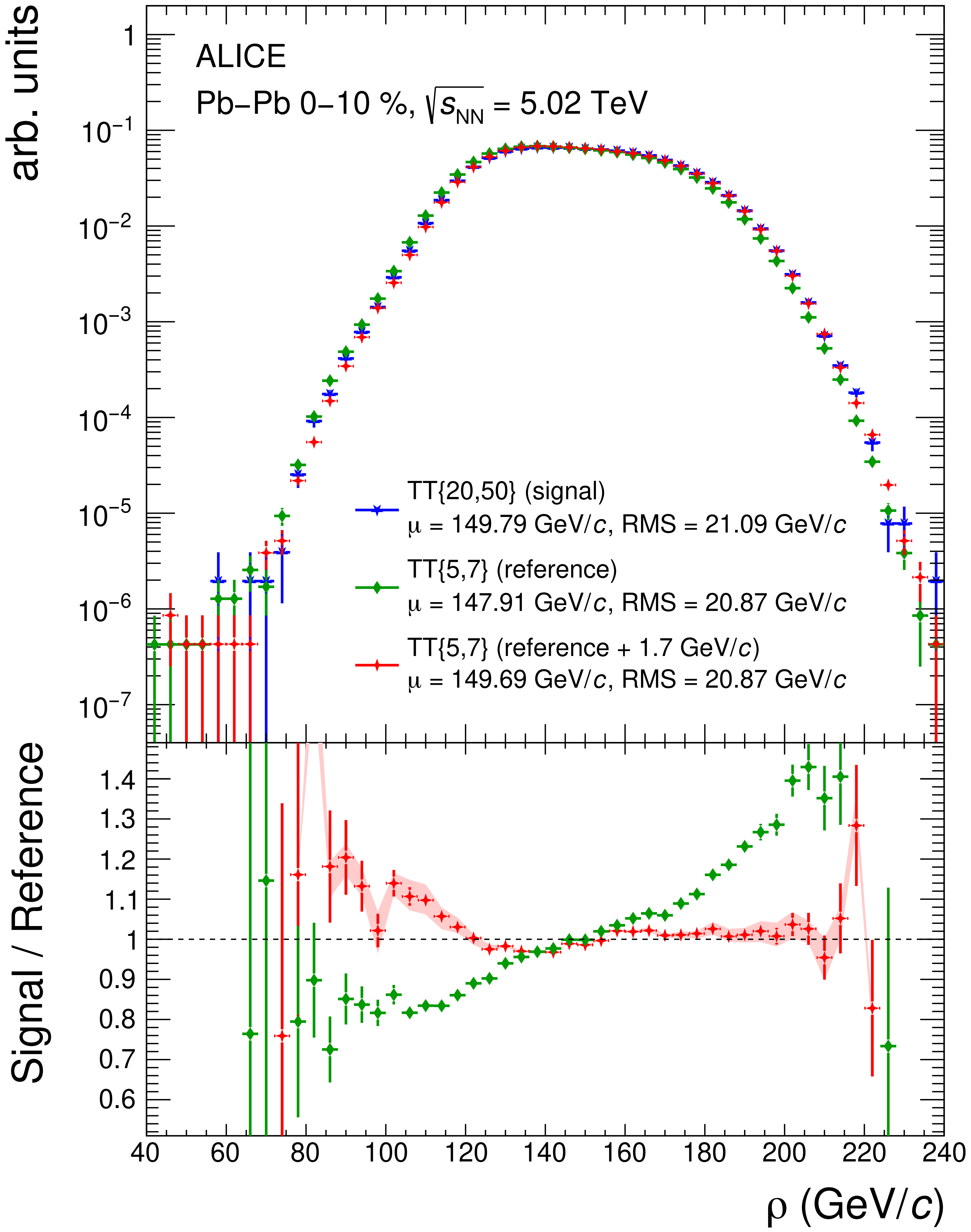


$$p_{\mathrm{T,jet}}^{\mathrm{reco}} = p_{\mathrm{T,jet}}^{\mathrm{raw}} - A \cdot \rho$$

- Jet p_{T} corrected by underlying event density ρ
- Align underlying event density ρ in signal and reference-classed events

Established technique

STAR: Phys. Rev. C 96, 024905 (2017)



ALI-PUB-555739

Unfolding

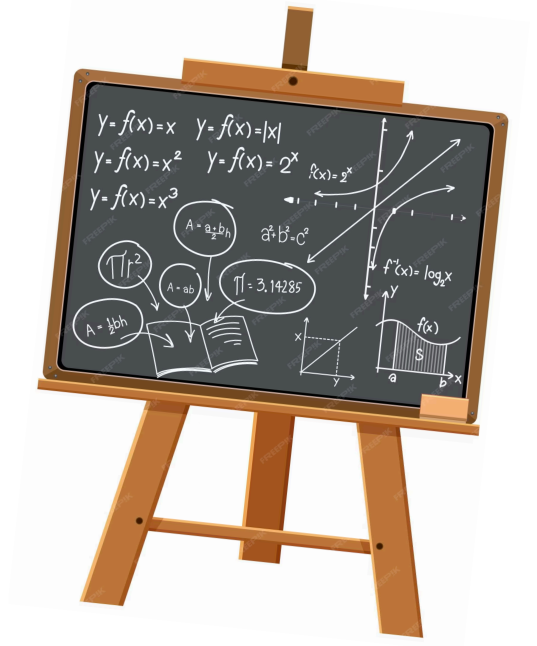
- **Raw distributions unfolded** for detector effects and residual background fluctuations in both pp and Pb-Pb collisions
  - $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$: Unfolded in 1 dimension ($p_{\mathrm{T,jet}}$) - minimal $\Delta\varphi$ smearing
  - $\Delta_{\mathrm{recoil}}(\Delta\varphi)$: Unfolded in 2 dimensions ($p_{\mathrm{T,jet}}$, $\Delta\varphi$)
- **All correction steps fully validated** via closure test (PYTHIA embedded into Pb-Pb, compare unfolded to truth)

Systematic uncertainties

- Tracking efficiency
- c_{Ref}
- Unfolding (prior, regularisation, binning, algorithm)
- Jet matching
- ρ correction
- Closure

- Dominant:
  - pp: Tracking
  - Pb-Pb: Prior

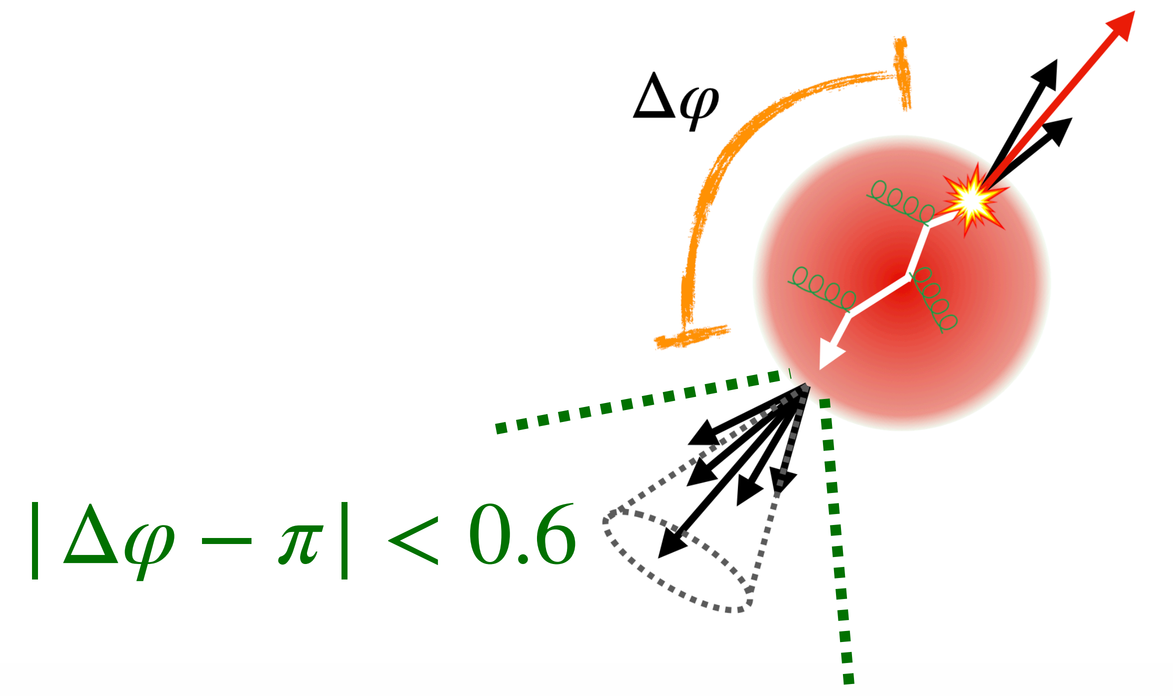
Models



- **JETSCAPE - Multi-stage event generator** JETSCAPE collaboration - Phys. Rev. C 107, 034911
  - Jet energy loss based on MATTER (high virtuality) and LBT (low virtuality)
- **JEWEL - perturbative treatment to jet quenching** K. Zapp, EPJ C, Volume 74, Issue 2, 2014
  R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141
  - Medium response studied by switching ‘recoils’ on and off
    (recoil momenta within jet subtracted using prescribed methods)
- **Hybrid model - strong (DGLAP) / weak (AdS/CFT) coupling model** F. d’Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
  Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)
  - Effect of elastic (Molière) scatterings and wake (medium response) studied by switching effects on and off

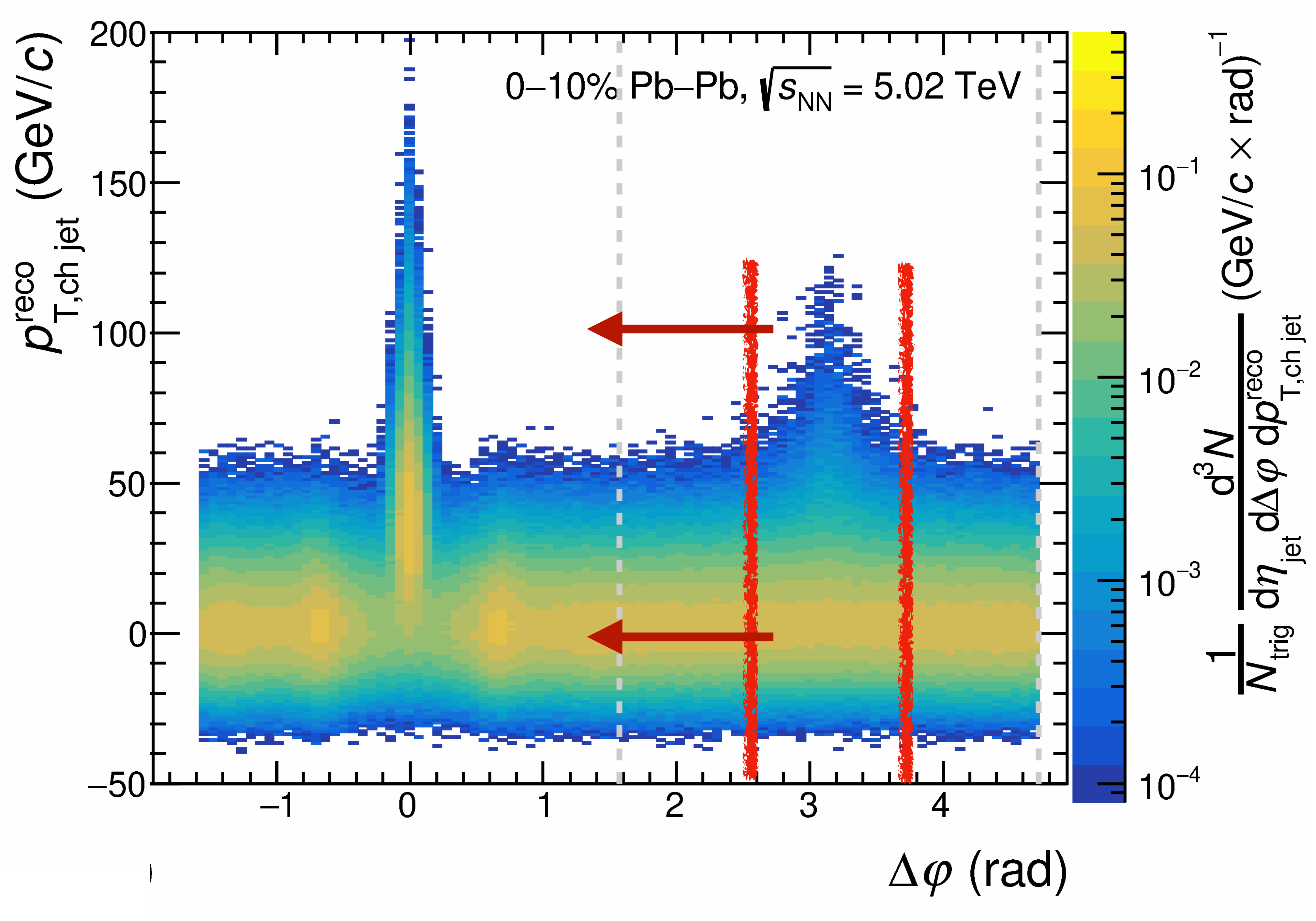
‘Vacuum’ reference crucial for each model - based on PYTHIA

- **pQCD + Sudakov broadening analytical model** L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676
  - Leading order pQCD, with azimuthal broadening governed by jet transport coefficient

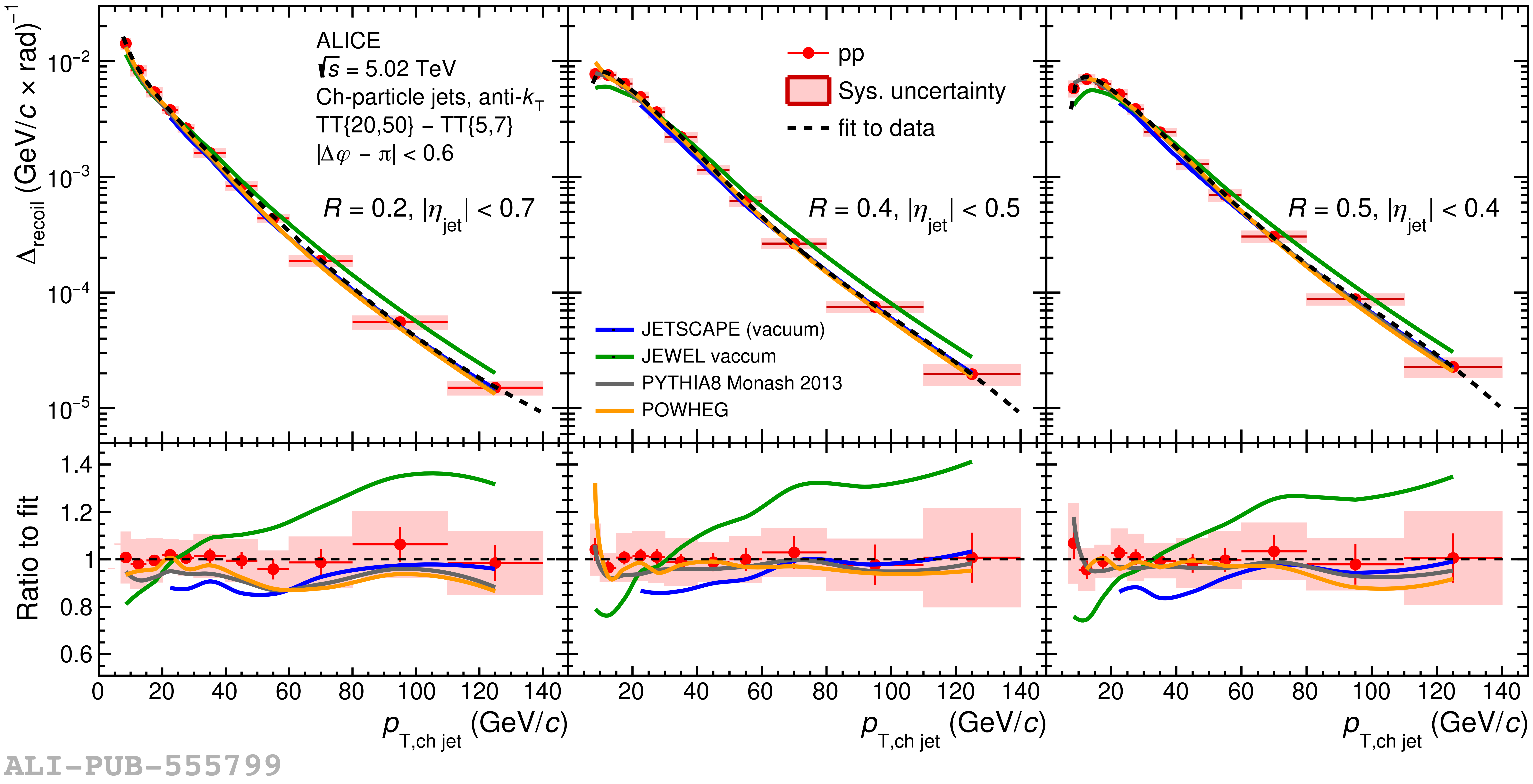


Results

- $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$: projection of 2d distribution onto $p_{\mathrm{T,jet}}$ axis within $|\Delta\varphi - \pi| < 0.6$
- $\Delta_{\mathrm{recoil}}(\Delta\varphi)$: projection of 2d distribution onto $\Delta\varphi$ axis for various $p_{\mathrm{T,jet}}$ intervals

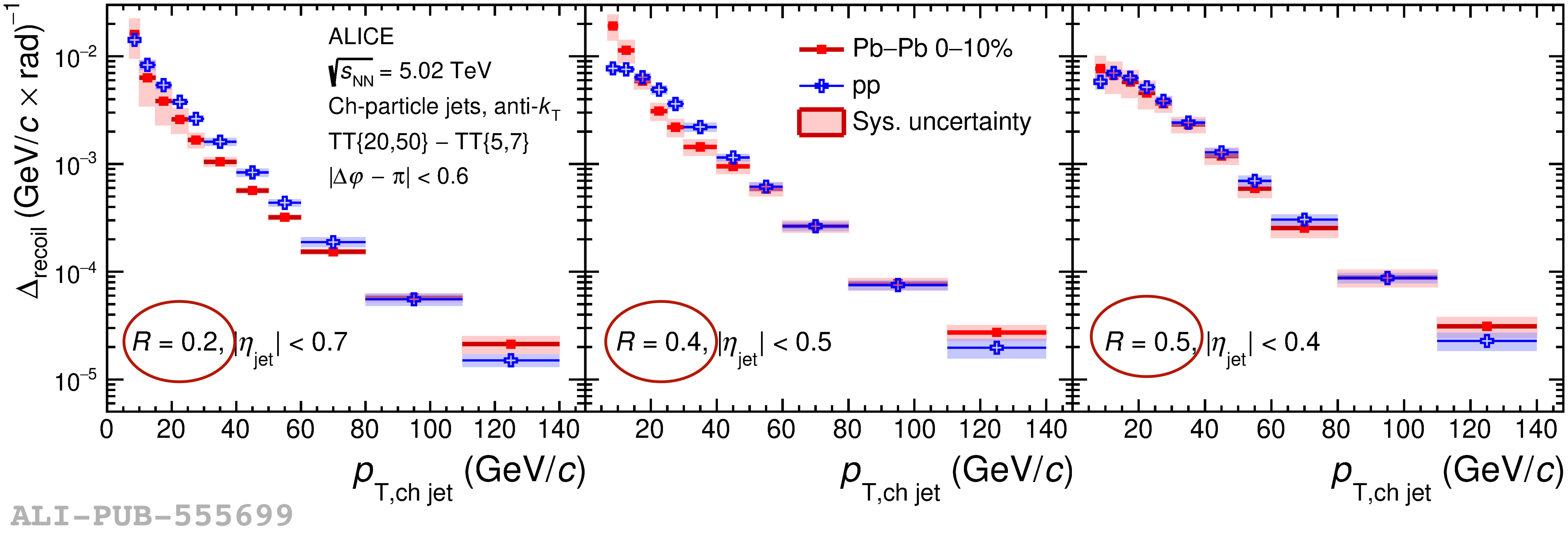


Fully-corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\,jet}})$ distribution in pp collisions



- $\Delta_{\mathrm{recoil}}(p_{\mathrm{T}})$ described well by PYTHIA8, 'vacuum' reference models, and POWHEG
- Modest discrepancy for JEWEL (vacuum) at high $p_{\mathrm{T,jet}}$

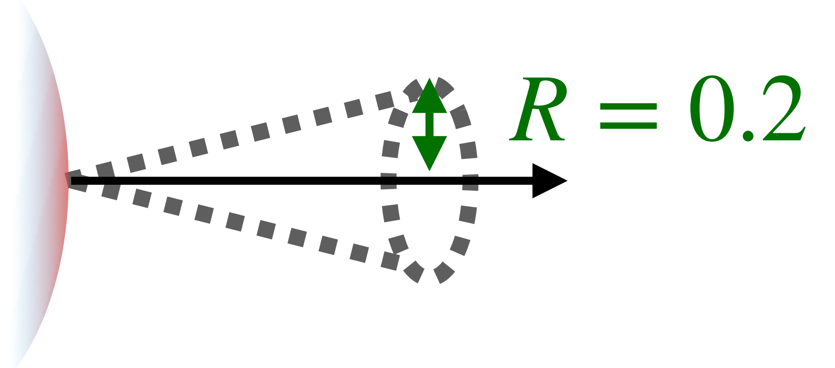
Fully-corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\,jet}})$ distributions in pp and Pb-Pb collisions

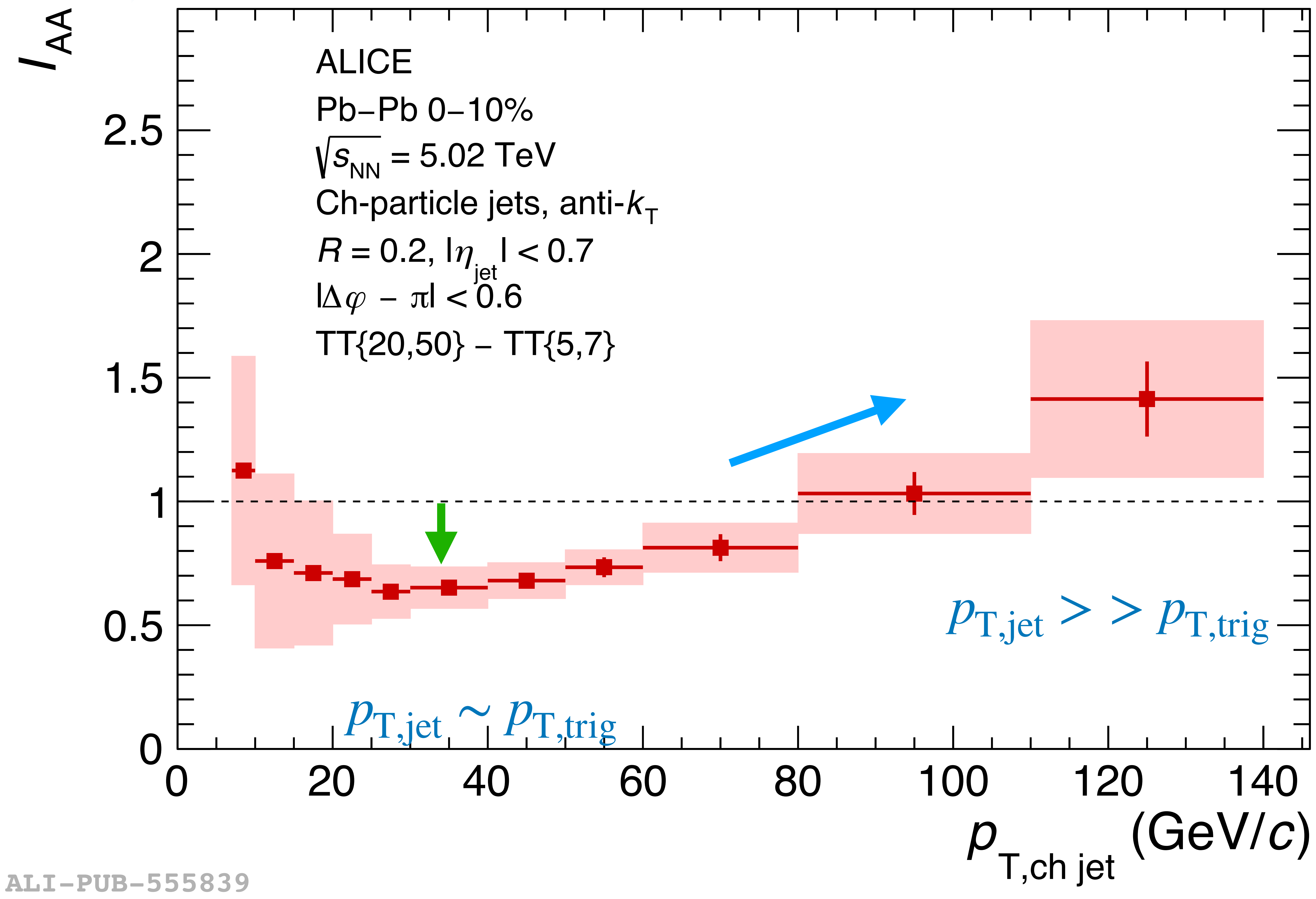


- Δ_{recoil} distributions measured down to $p_{\mathrm{T,jet}}$ ~ 7 GeV/c in pp and Pb-Pb collisions

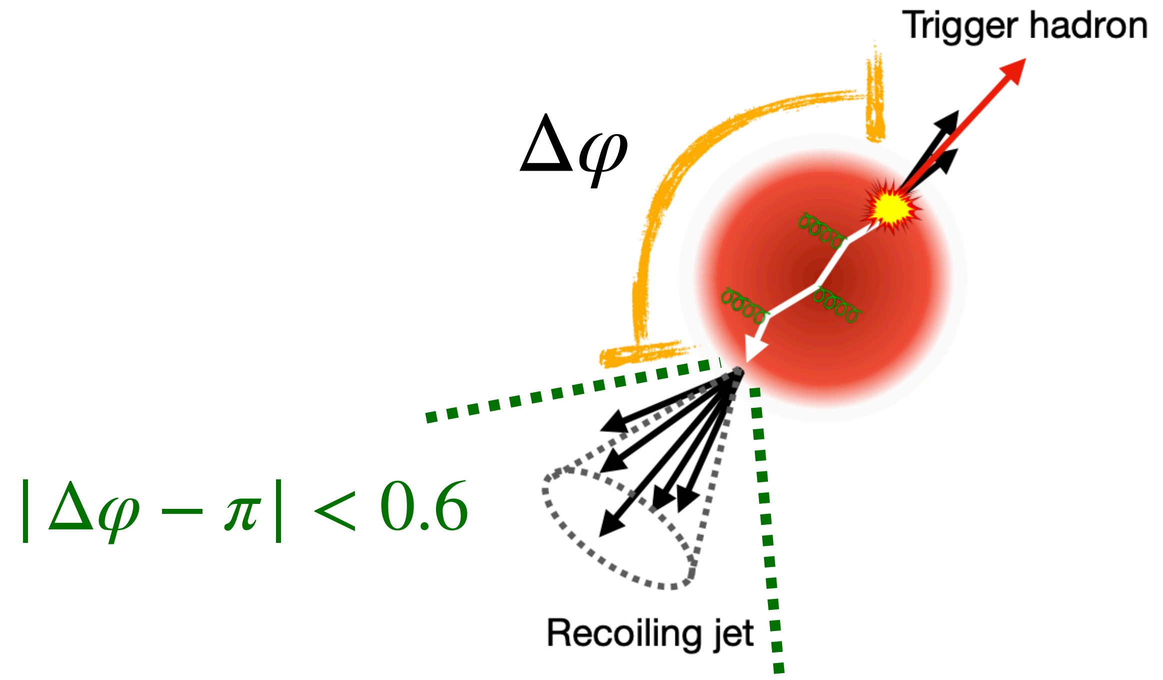
Among lowest jet p_{T} measurement in Pb-Pb collisions at the LHC!

$I_{AA}(p_{T,ch\,jet})$ - recoil jet yield modification in Pb-Pb collisions



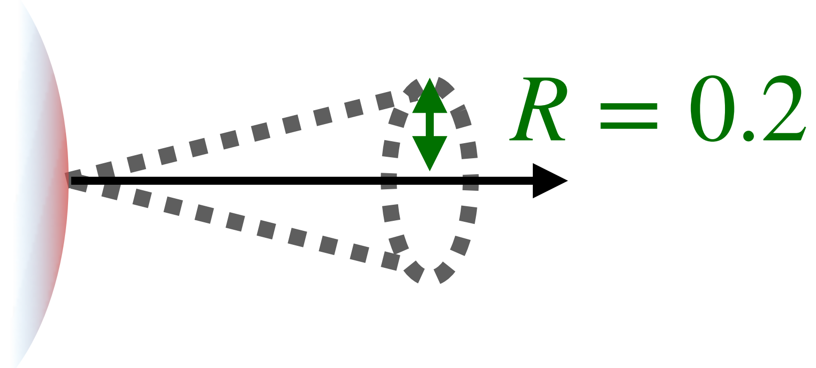


$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

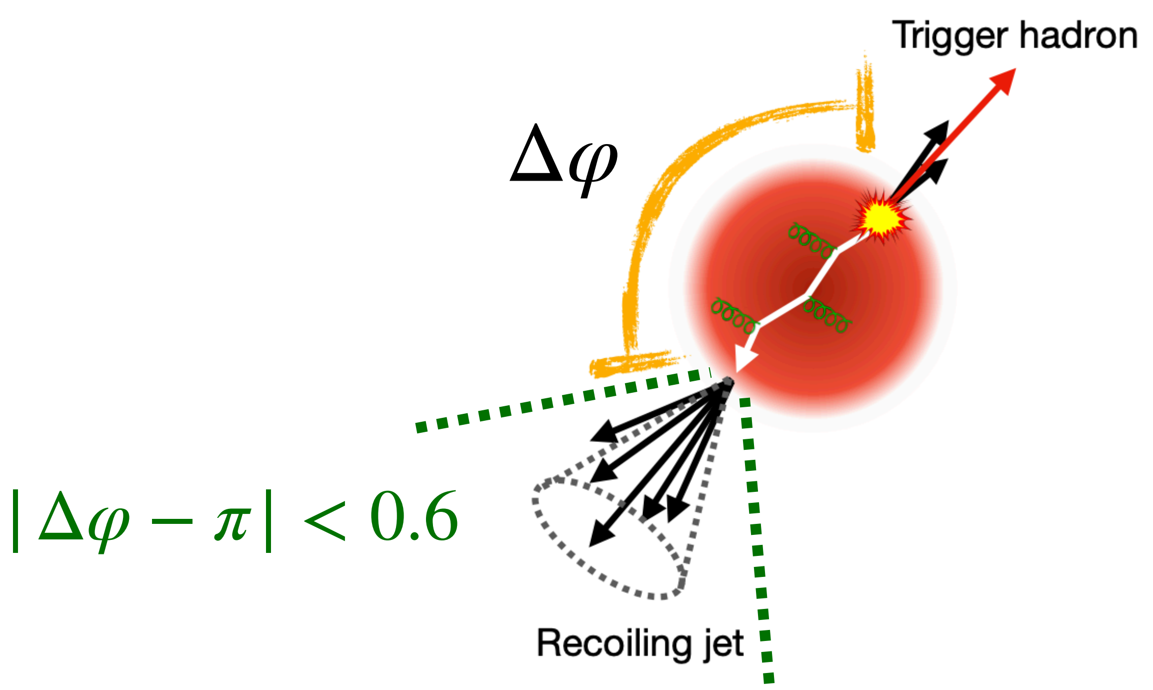


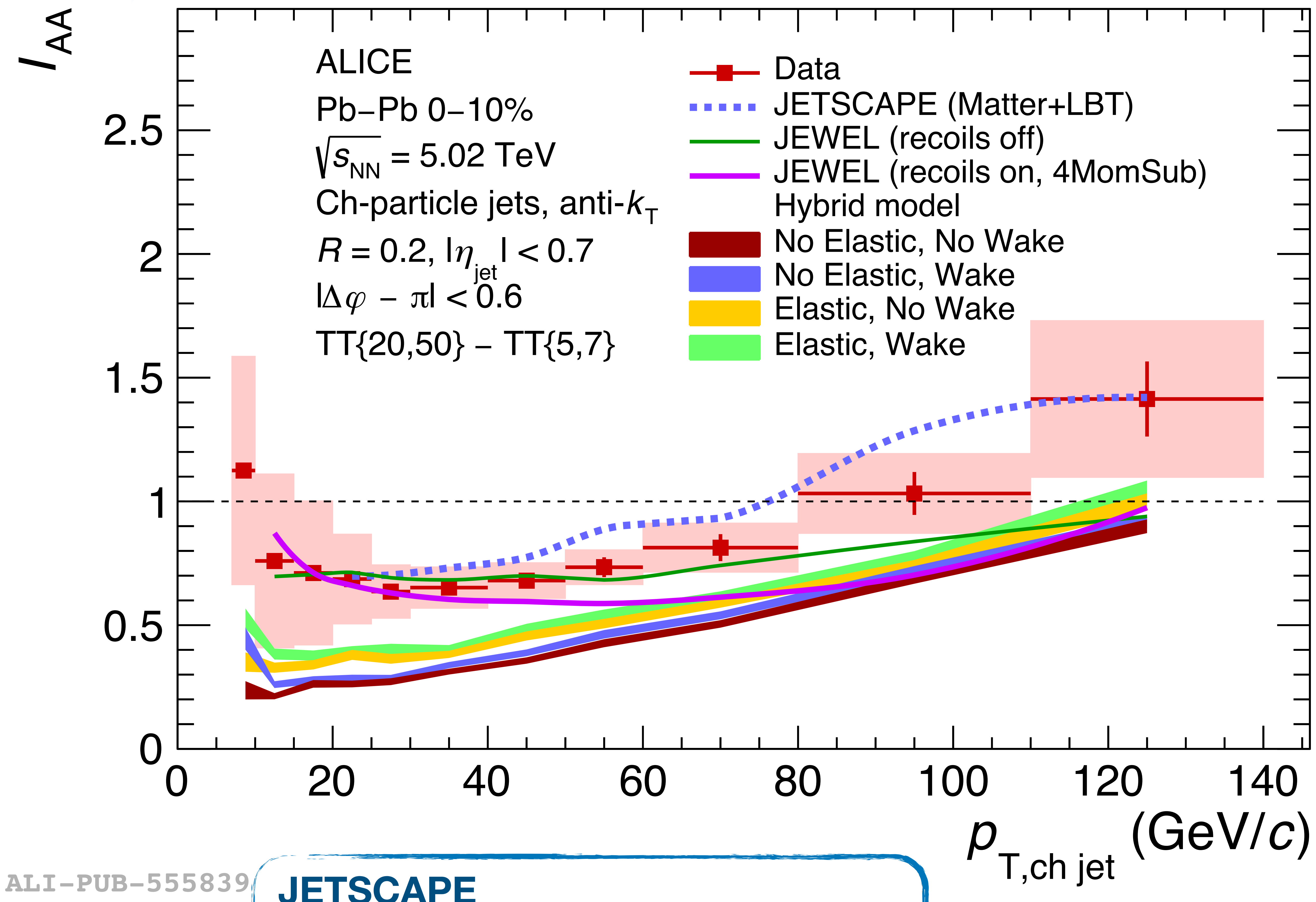
- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{T,jet} >> p_{T,trig}$?

$I_{AA}(p_{T,ch\,jet})$ - recoil jet yield modification in Pb-Pb collisions



$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$





- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{T,jet} >> p_{T,trig}$?
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low-$p_{T,jet}$ I_{AA}

JETSCAPE

Energy loss based on MATTER (high virtuality) and LBT (low virtuality)

JETSCAPE, Phys. Rev. C 107, 034911

JEWEL

Medium response effects via treatment of 'recoils'

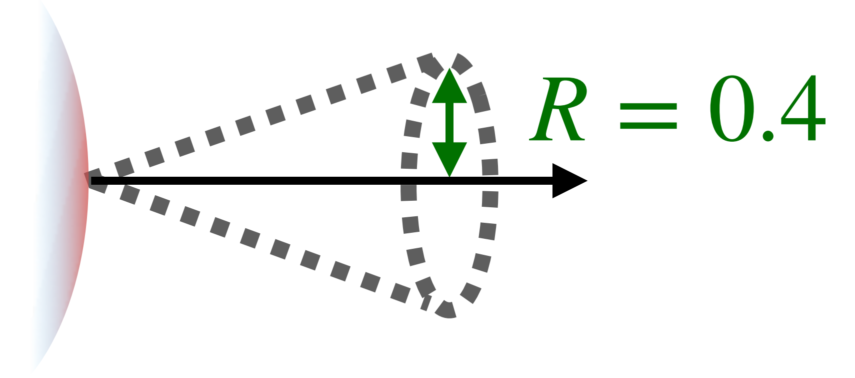
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Hybrid model

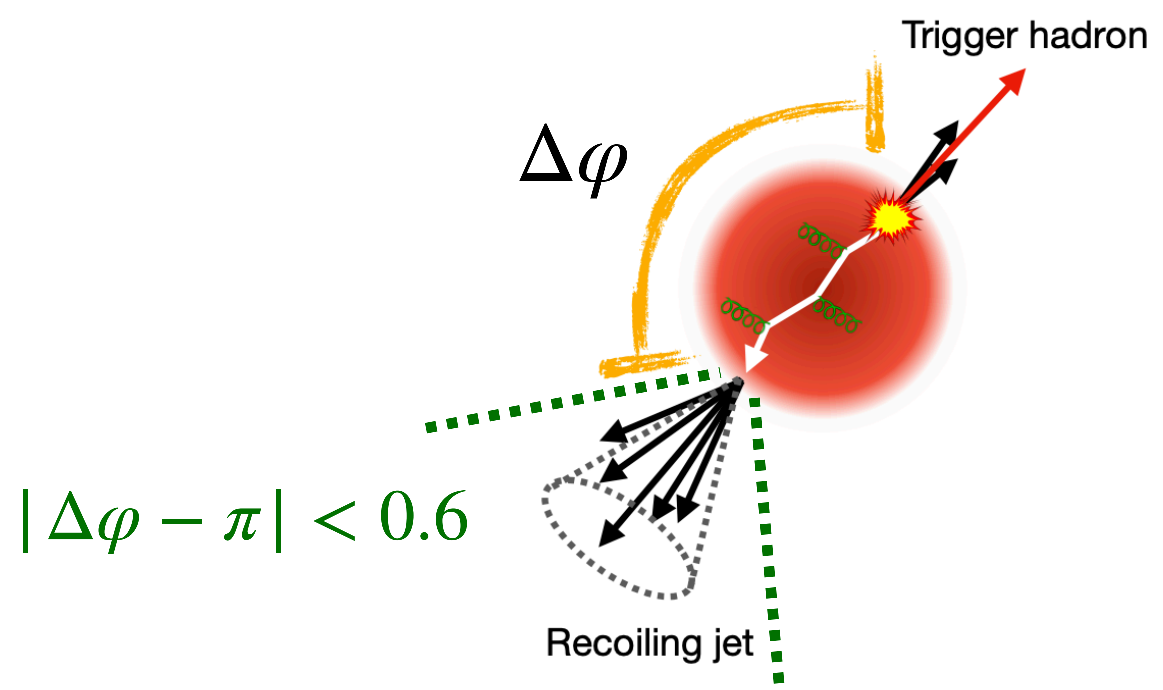
Elastic (Moliére) scatterings and wake (medium response) included

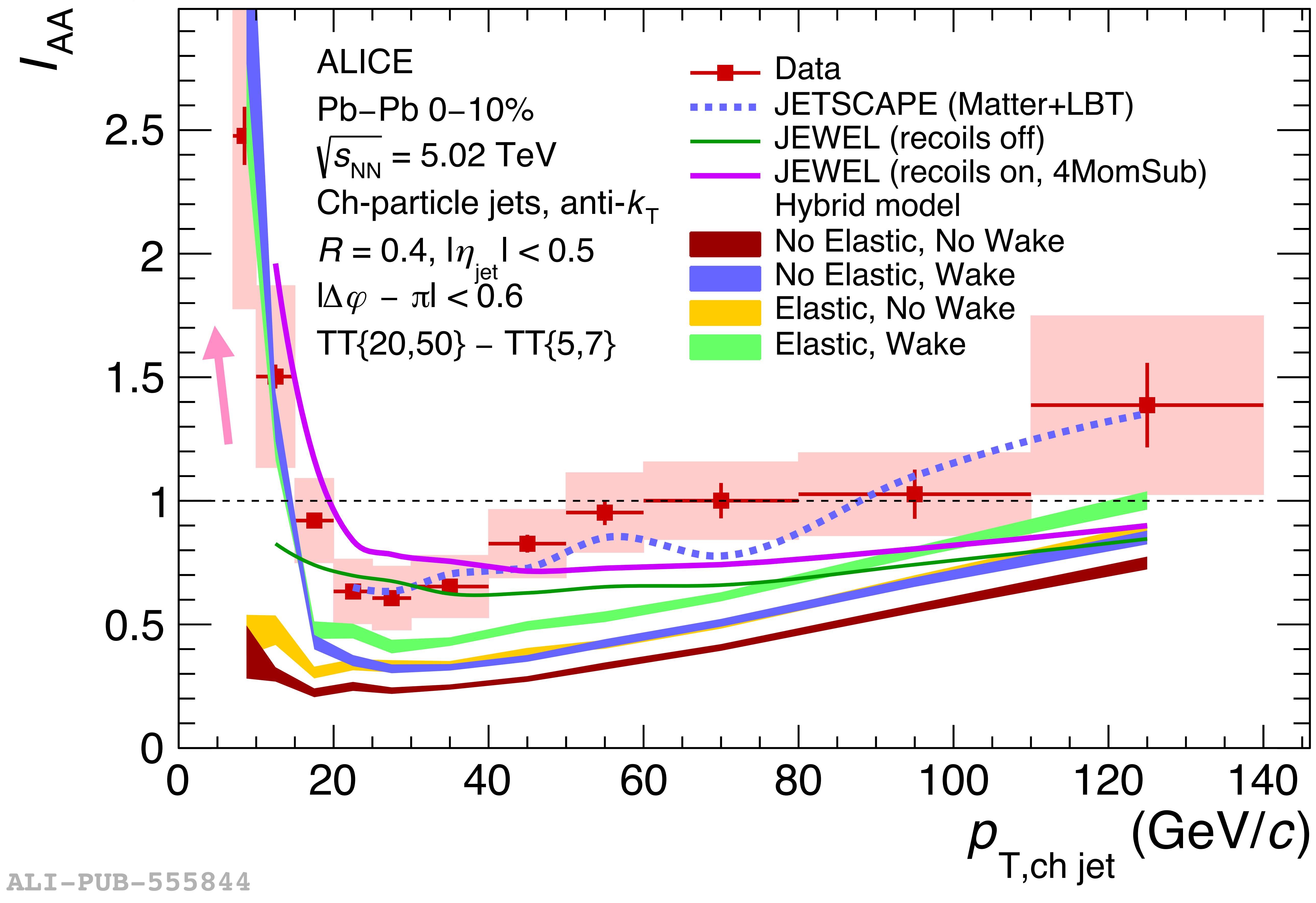
F. d'Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

$I_{AA}(p_{T,ch\,jet})$ - recoil jet yield modification in Pb-Pb collisions



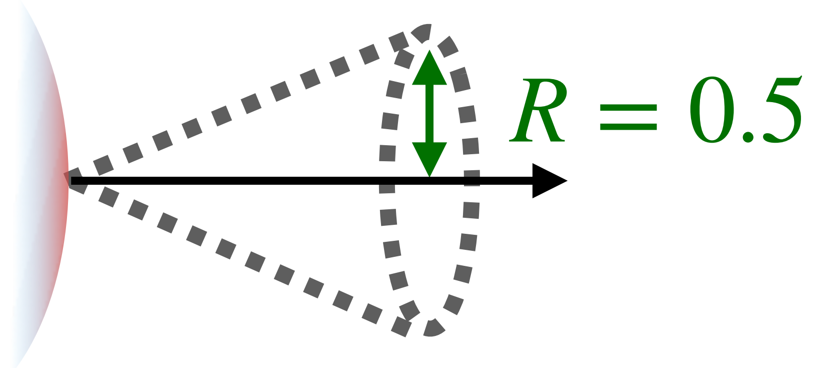
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$



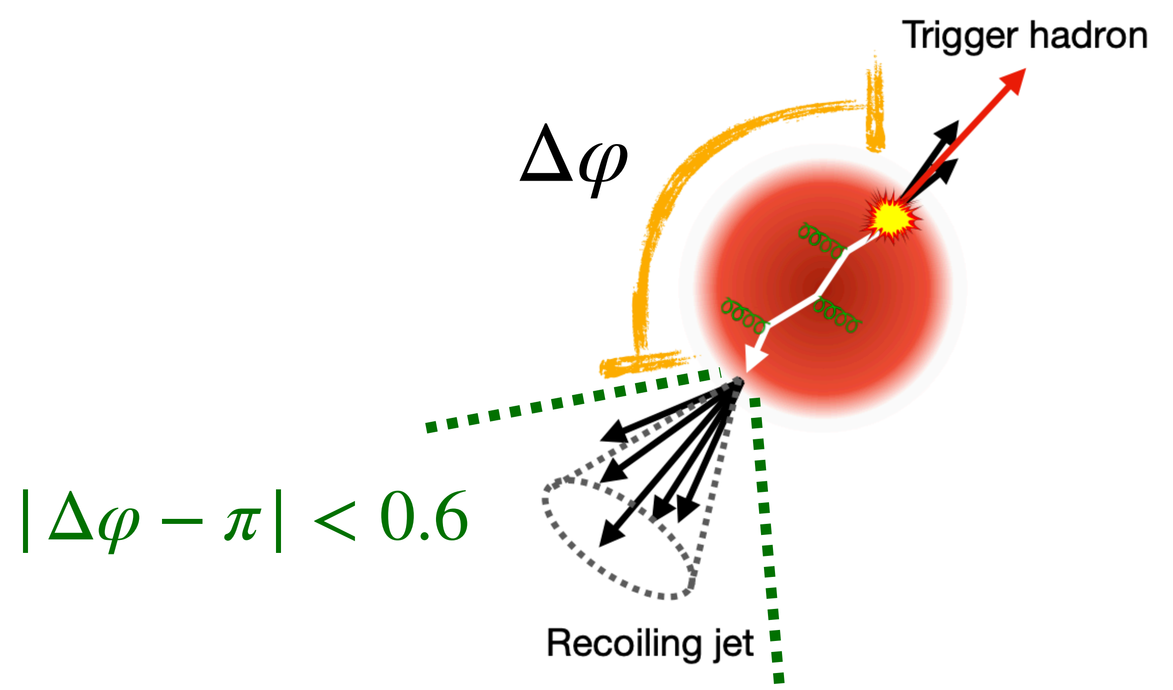


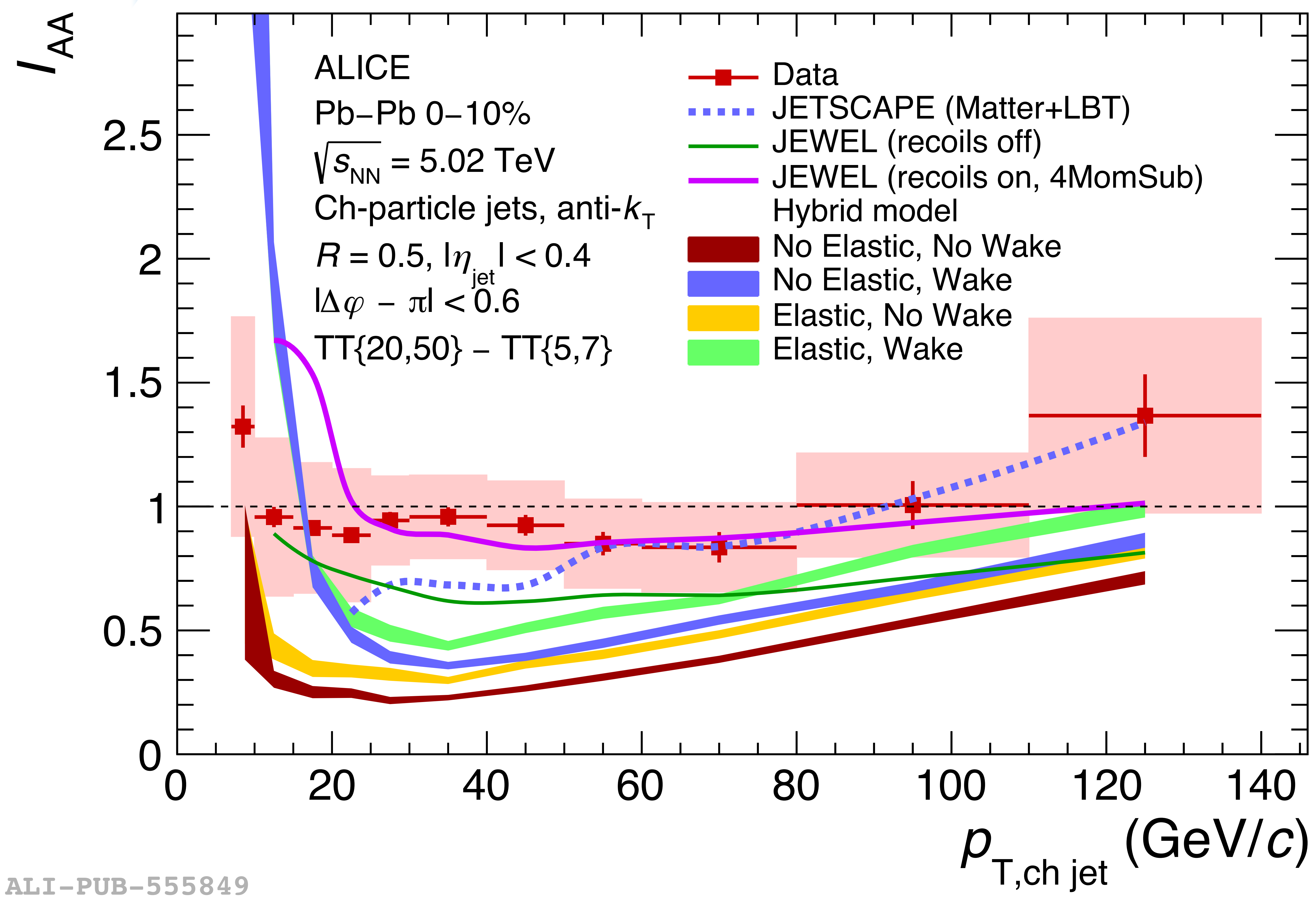
- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{T,jet} >> p_{T,trig}$?
- **Rise at low $p_{T,ch\,jet}$**
  → Energy recovery? Reproduced by models including medium response

$I_{\mathrm{AA}}(p_{\mathrm{T,ch\,jet}})$ - recoil jet yield modification in Pb-Pb collisions

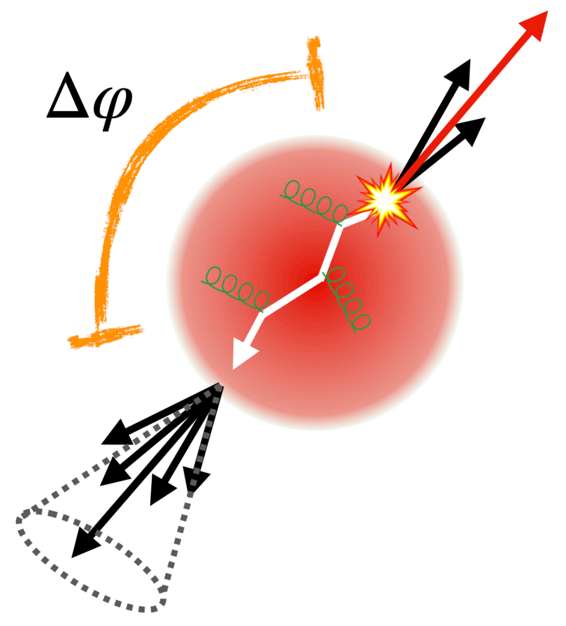


$$I_{\mathrm{AA}} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$



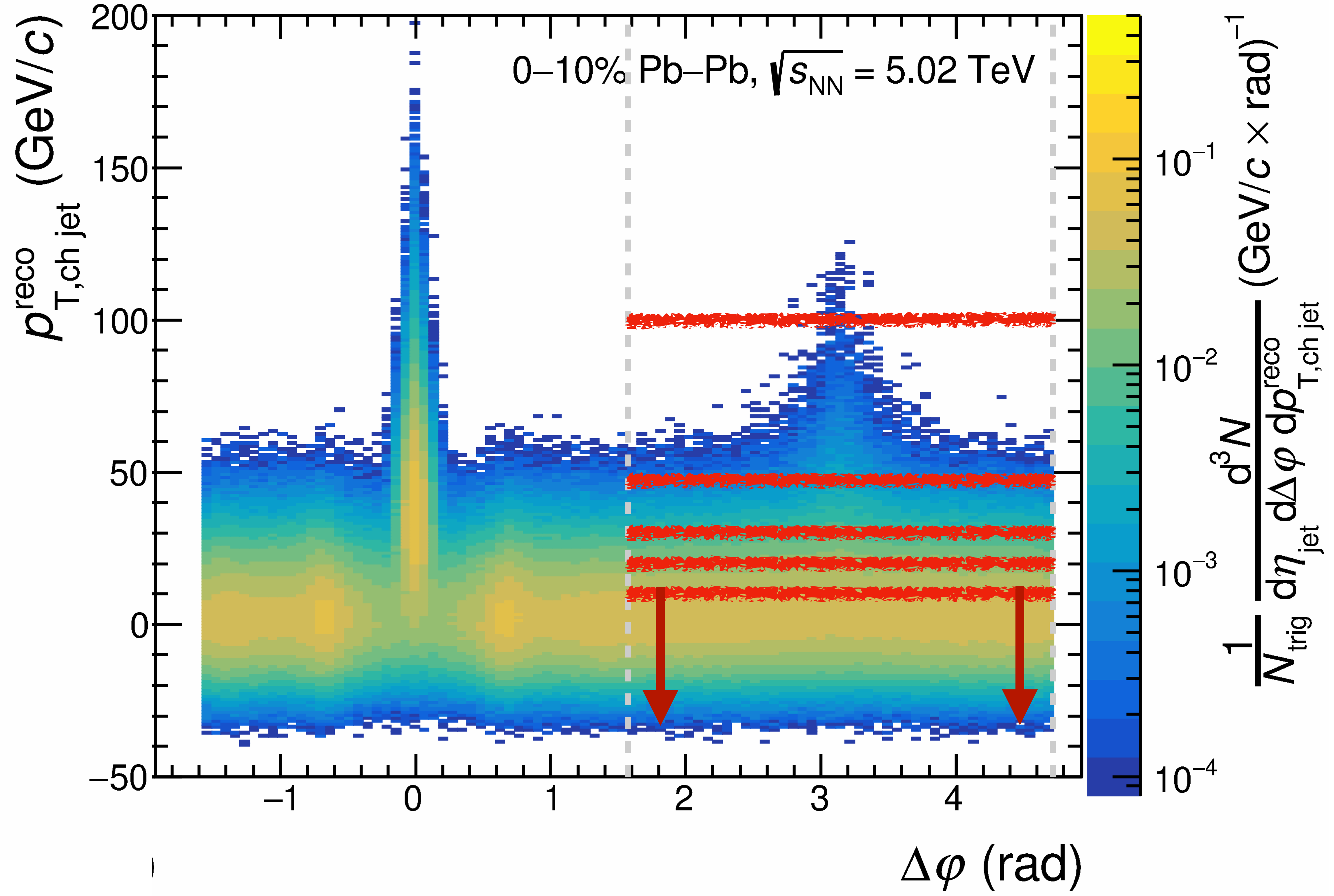


- ***R*=0.5 consistent with no suppression**
  - Little suppression captured by JEWEL (recoils on)
- Indication of intra-jet energy recovery within cone radius~0.5 for mid-$p_{\mathrm{T,ch\,jet}}$?
- Redistribution of energy for *R*=0.5 jets more challenging for models

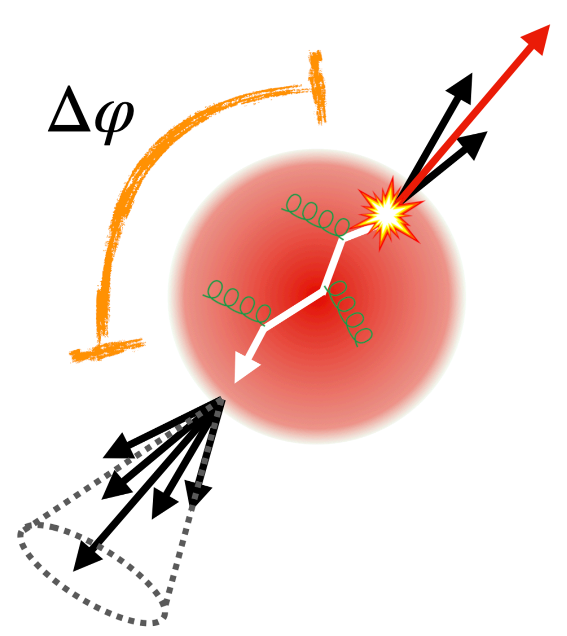


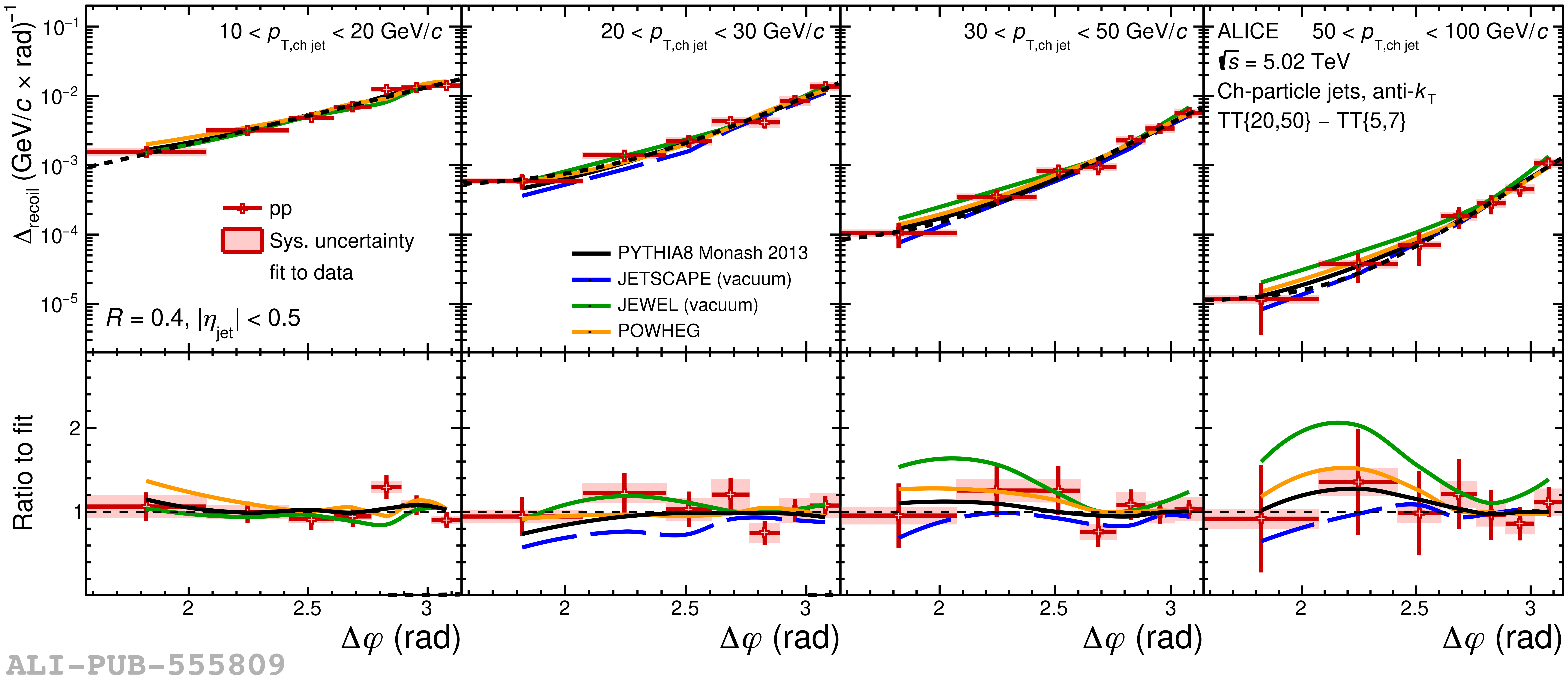
Results

- $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$: projection of 2d distribution onto $p_{\mathrm{T,jet}}$ axis within $|\Delta\varphi - \pi| < 0.6$
- $\Delta_{\mathrm{recoil}}(\Delta\varphi)$: projection of 2d distribution onto $\Delta\varphi$ axis for various $p_{\mathrm{T,jet}}$ intervals



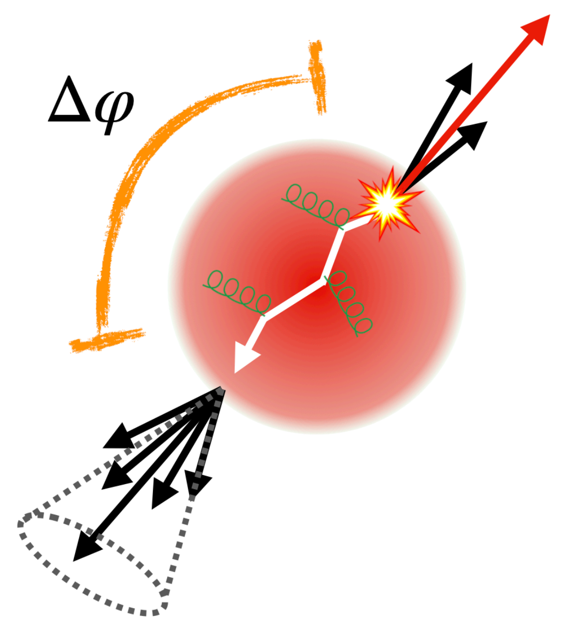
$\Delta_{recoil}(\Delta\varphi)$ in pp collisions (R=0.4)





- $\Delta_{recoil}(\Delta\varphi)$ described well by PYTHIA8, 'vacuum' reference models, and POWHEG

$\Delta_{recoil}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

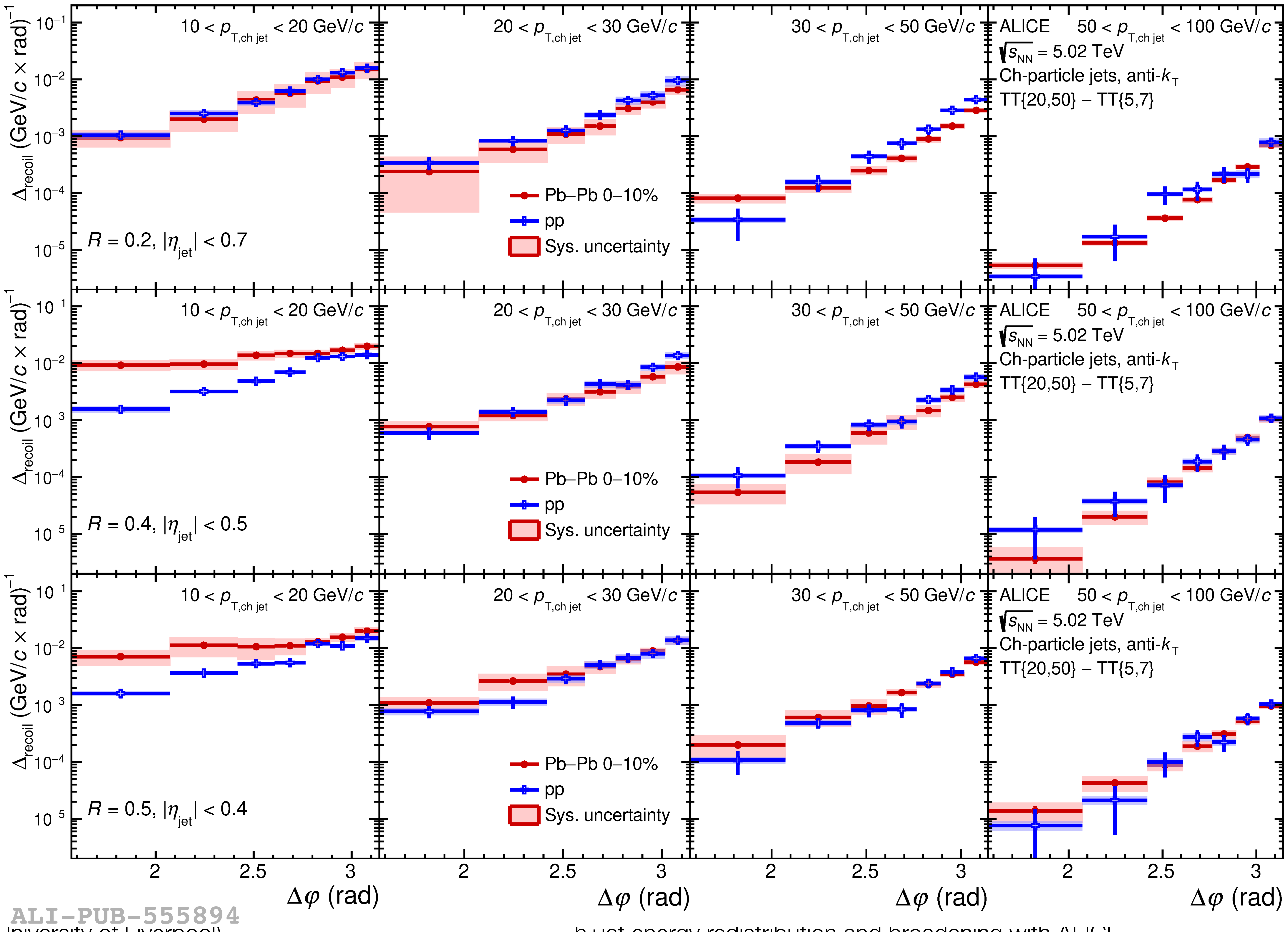


$p_{T,ch\,jet}$: [10,20] GeV/*c* [20,30] GeV/*c* [30,50] GeV/*c* [50,100] GeV/*c*

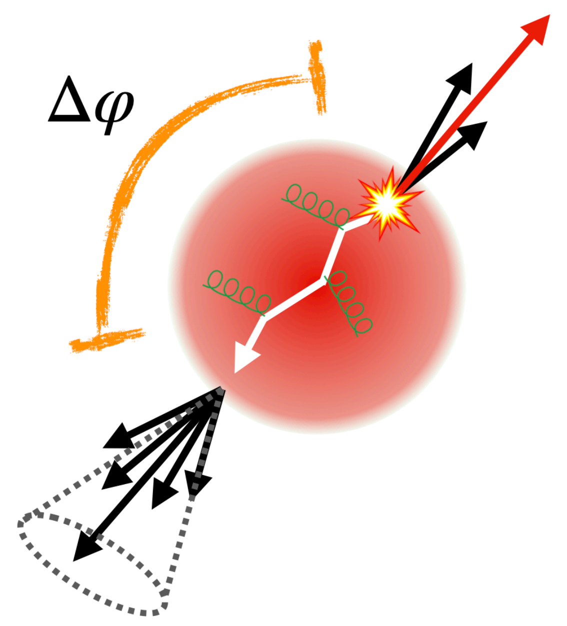
R=0.2

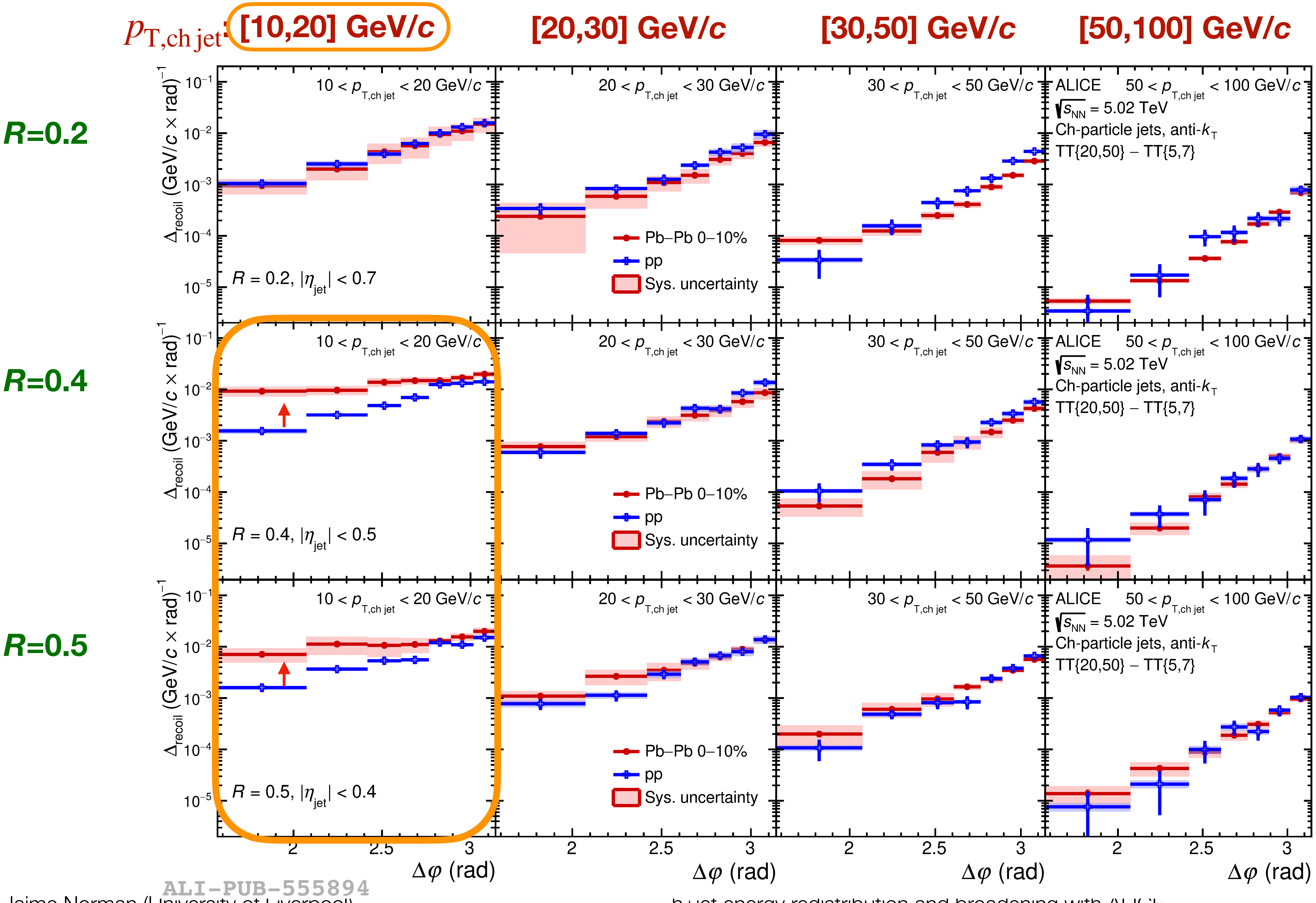
R=0.4

R=0.5



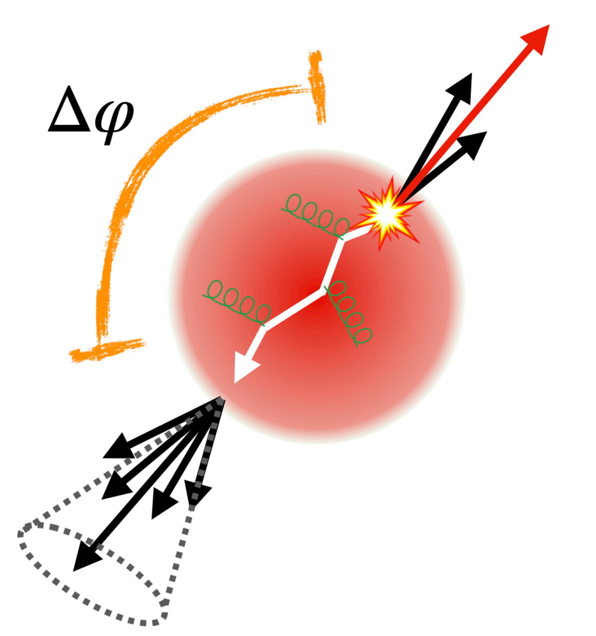
$\Delta_{recoil}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

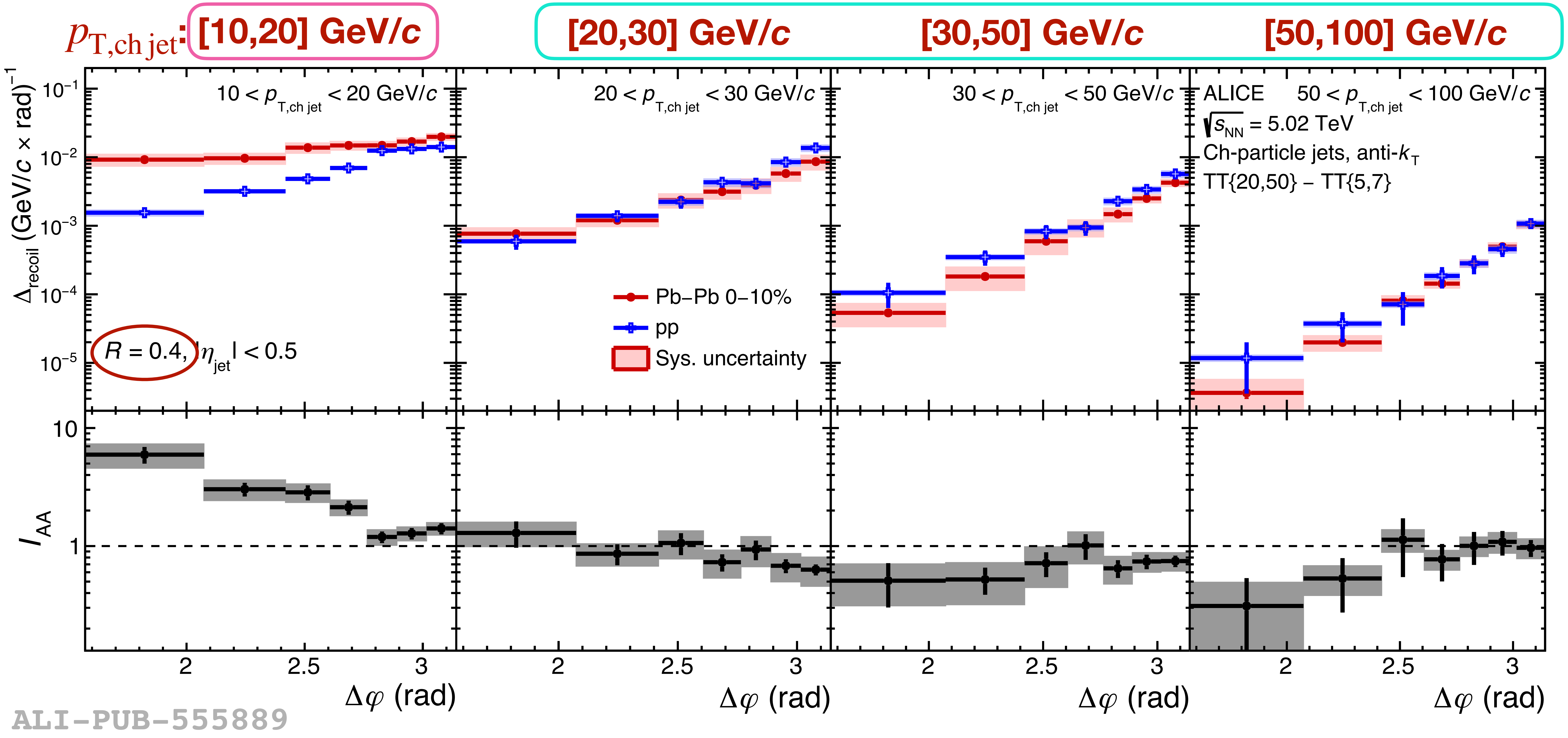




- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{T,ch\,jet}$

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



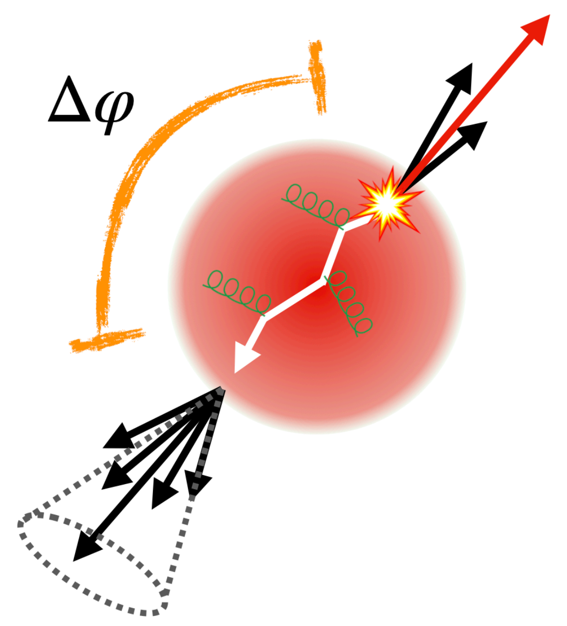


$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

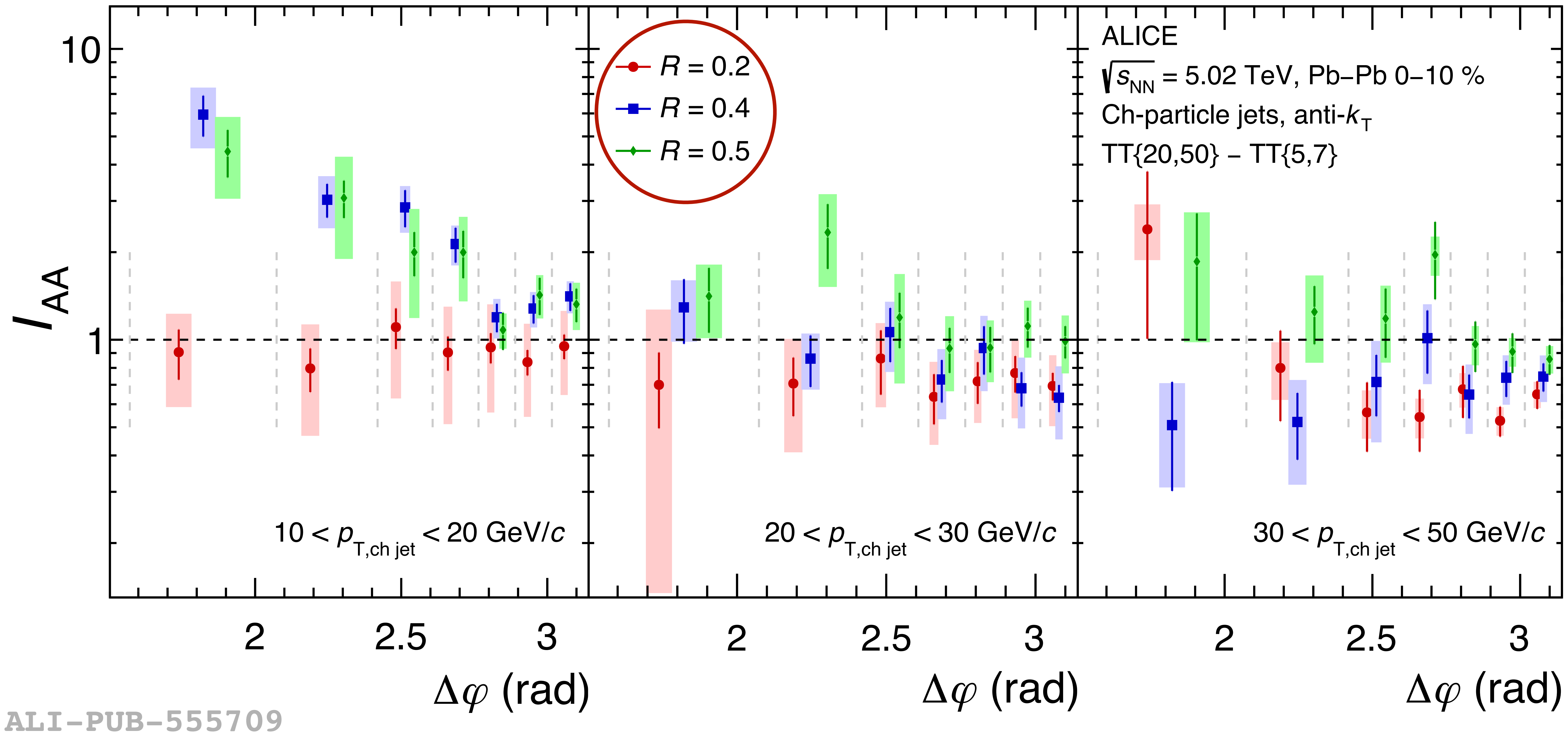
- **No broadening for [20,100] GeV/c → significant broadening for [10,20] GeV/c**

(4.7σ deviation of I_{AA} from flat)

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

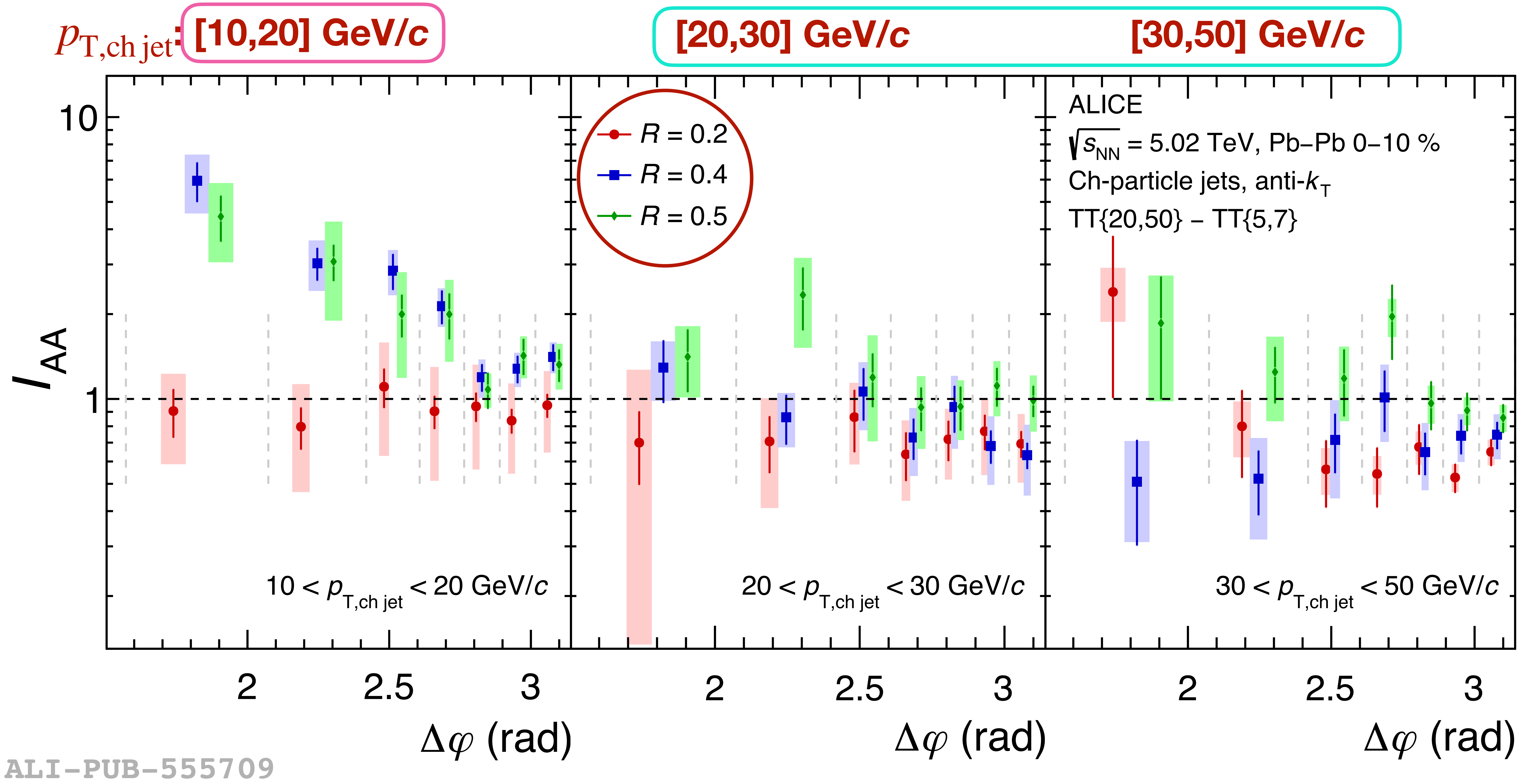


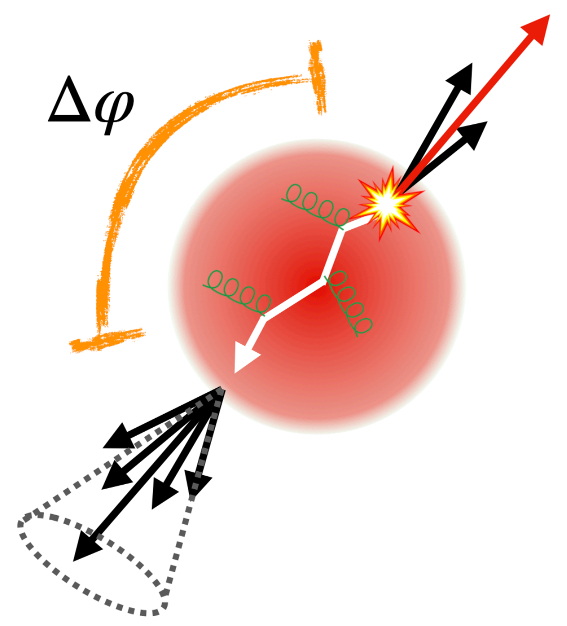
$p_{T,ch\,jet}$: **[10,20] GeV/*c*** **[20,30] GeV/*c*** **[30,50] GeV/*c***



- **Transition to broadening from *R*=0.2 -> *R*=0.4 for [10,20] GeV/c:**
  - Soft radiation mimicking a jet may scale with R^2
  - Molière scattering off QGP quasiparticles - *R*-dependence not expected

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



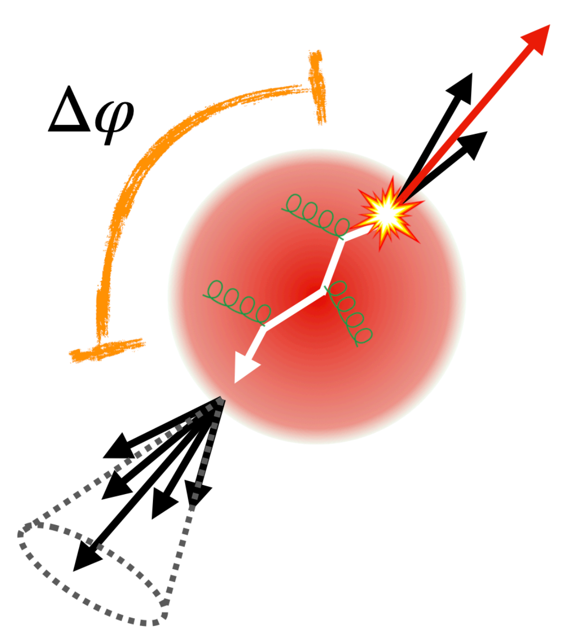


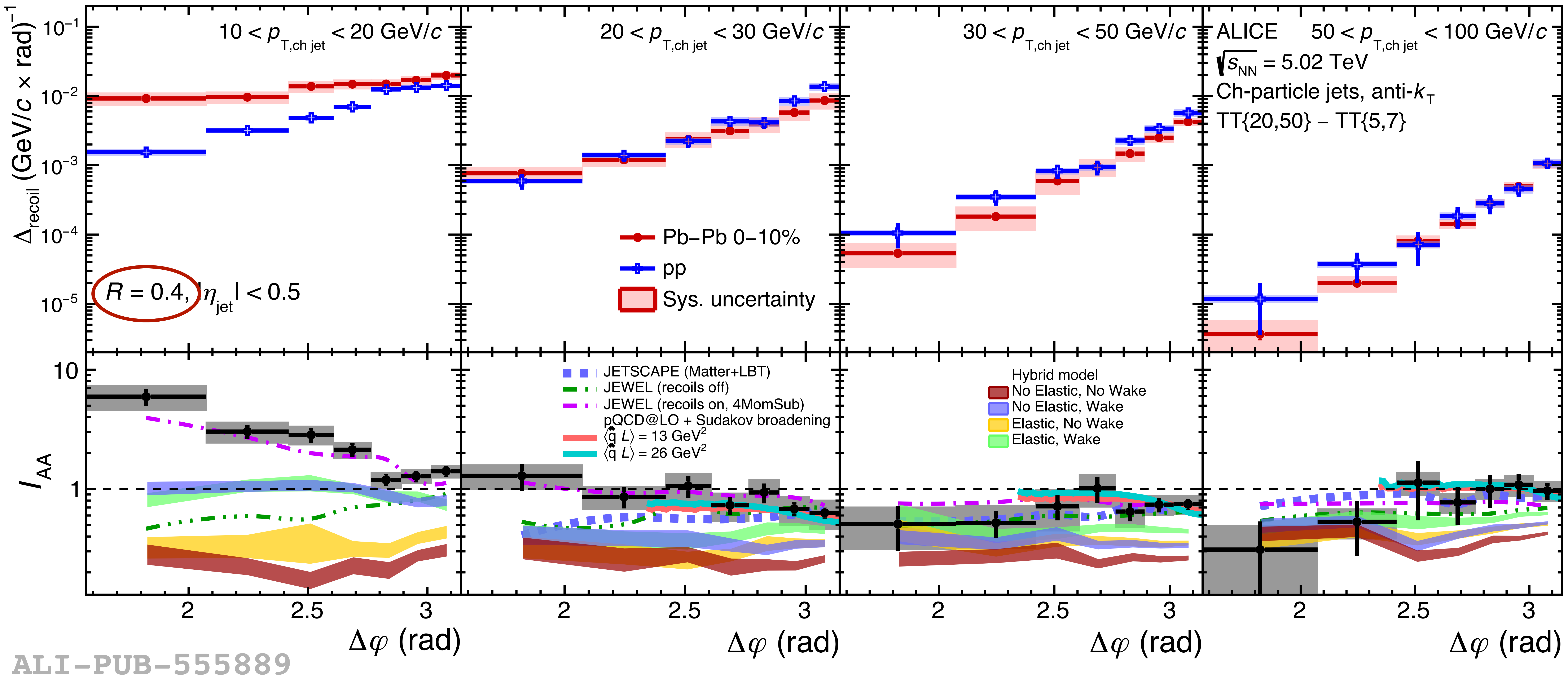
- **Transition to broadening from *R*=0.2 -> *R*=0.4 for [10,20] GeV/c:**
  - Soft radiation mimicking a jet may scale with R^2
  - Molière scattering off QGP quasiparticles - *R*-dependence not expected

→Data favours medium response to jet or medium-induced soft radiation as explanation for observed broadening

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

$p_{T,ch\ jet}$: [10,20] GeV/c [20,30] GeV/c [30,50] GeV/c [50,100] GeV/c





pQCD + Sudakov broadening

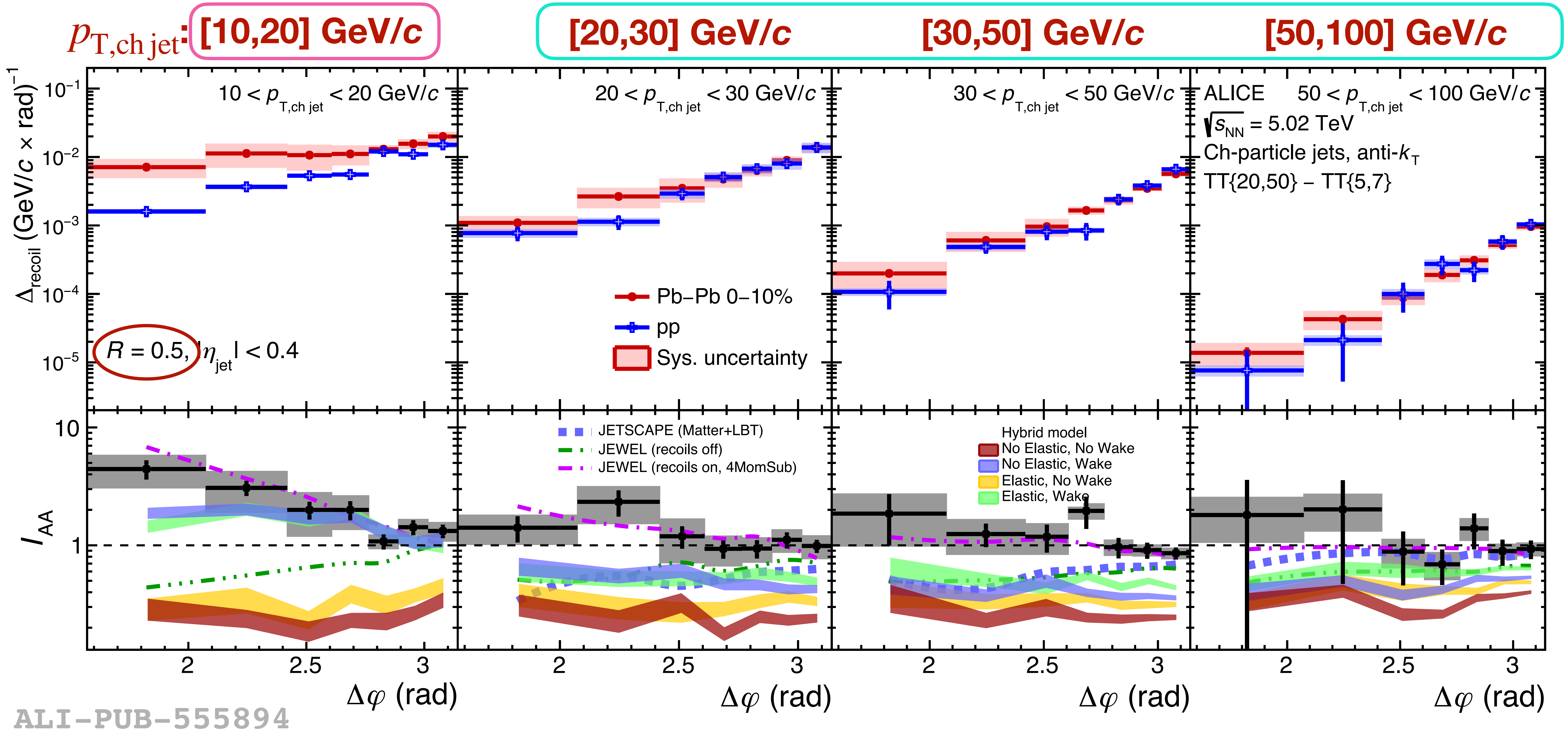
Leading order pQCD, azimuthal broadening via jet transport coefficient

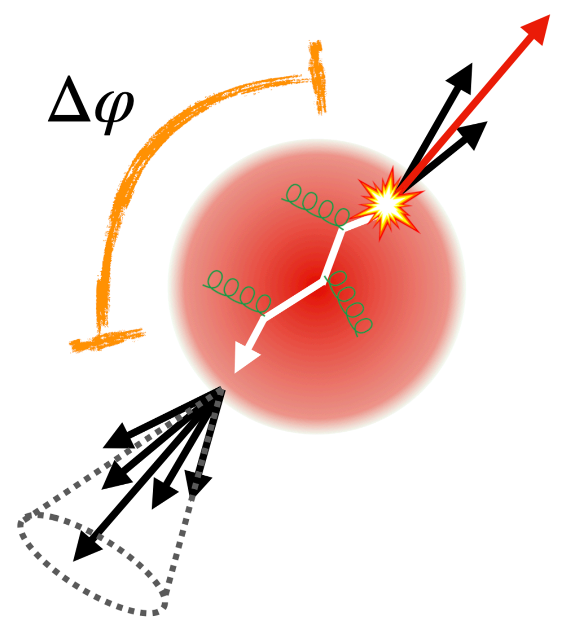
L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676

$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

- Hybrid model w/ wake: captures yield enhancement. w/ elastic: negligible broadening
- pQCD w/ broadening via $\hat{q}$: lacking precision to resolve difference between two $\hat{q}$ values
- JEWEL (recoils on): captures all features of data

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



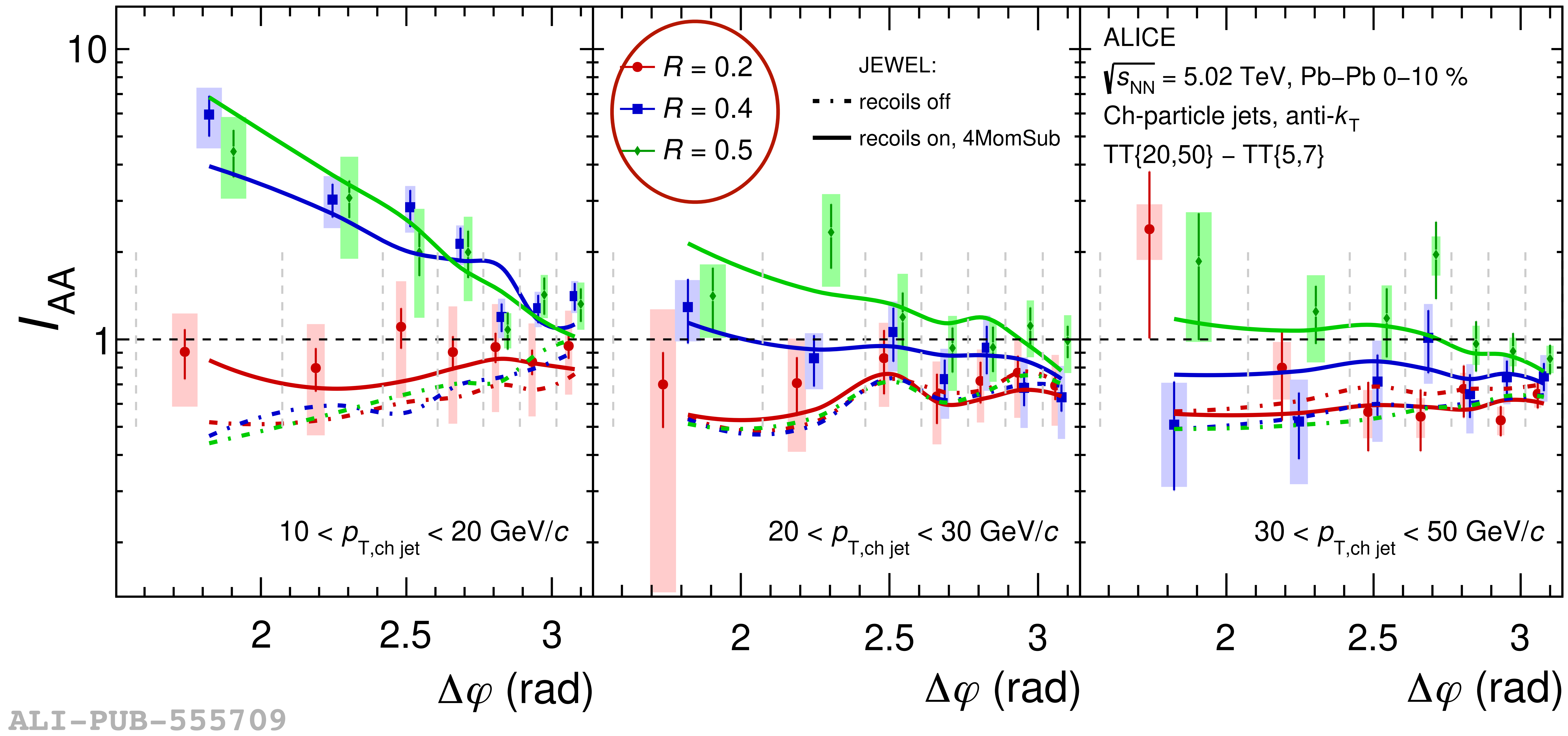


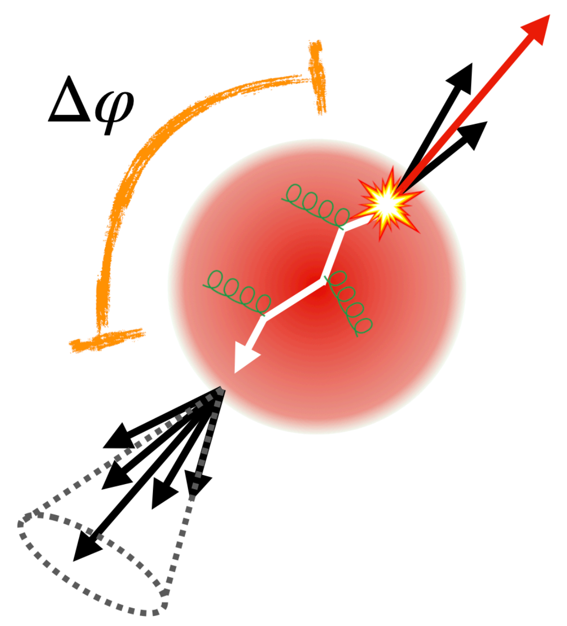
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

- Hybrid model w/ wake: captures broadening for higher *R*
- JEWEL (recoils on): captures all features of data

→ **Models further confirm picture that measured broadening predominantly due to medium response**

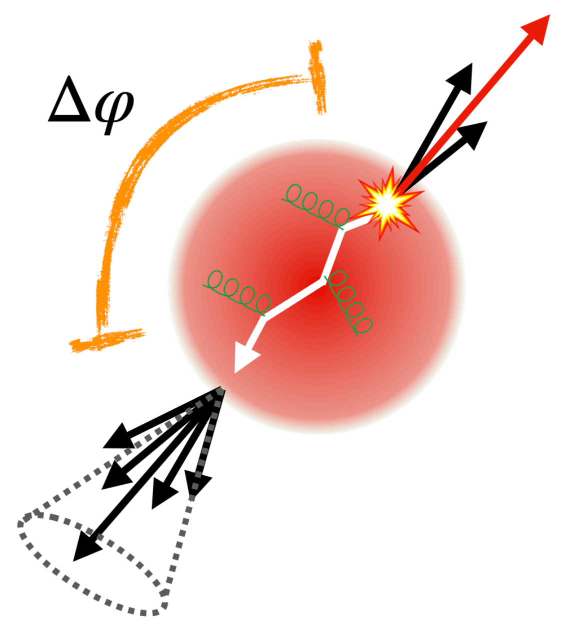
$I_{AA}(\Delta\varphi)$ vs *R* compared to JEWEL



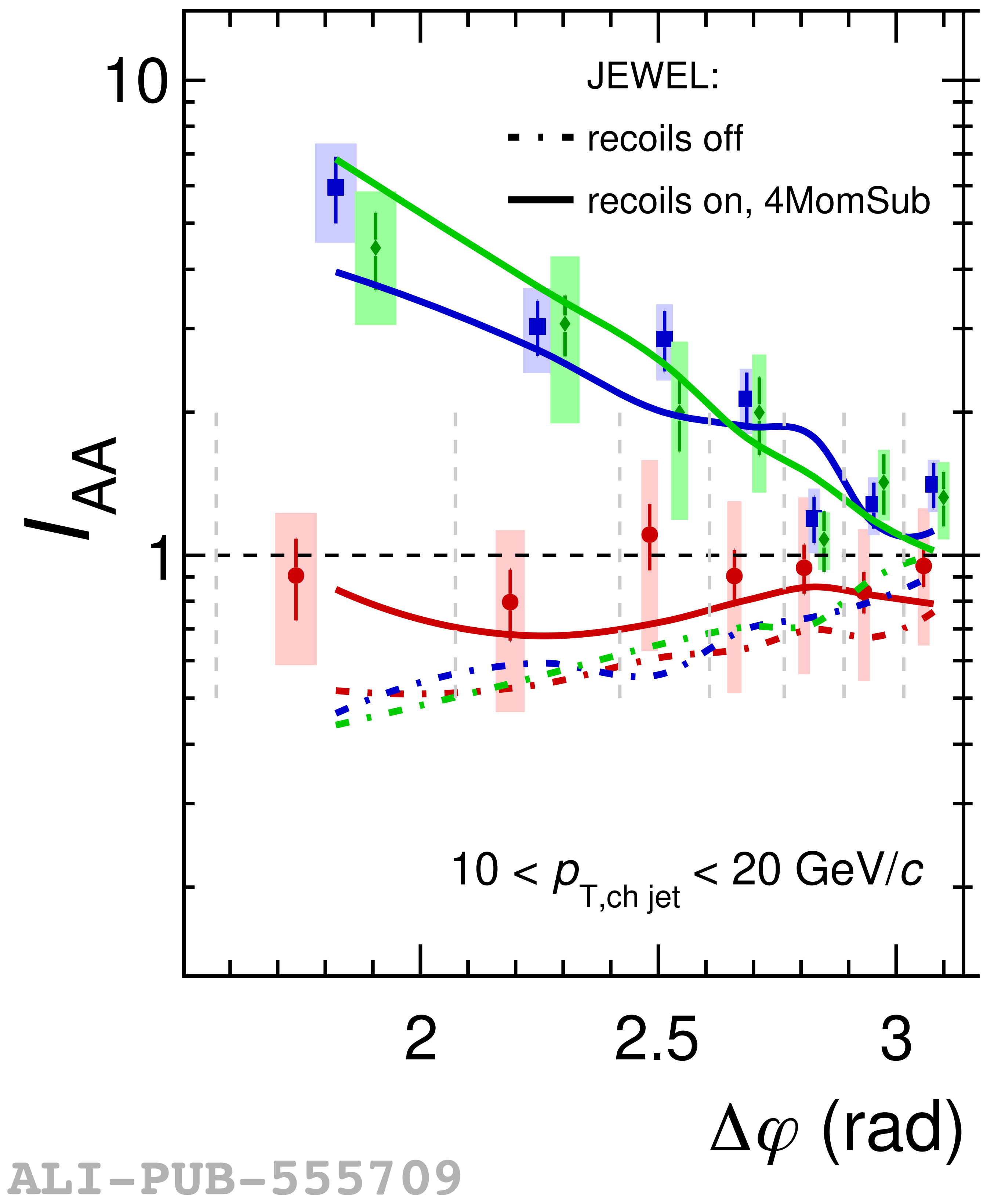


- All features of distribution **reproduced by JEWEL** with recoils on

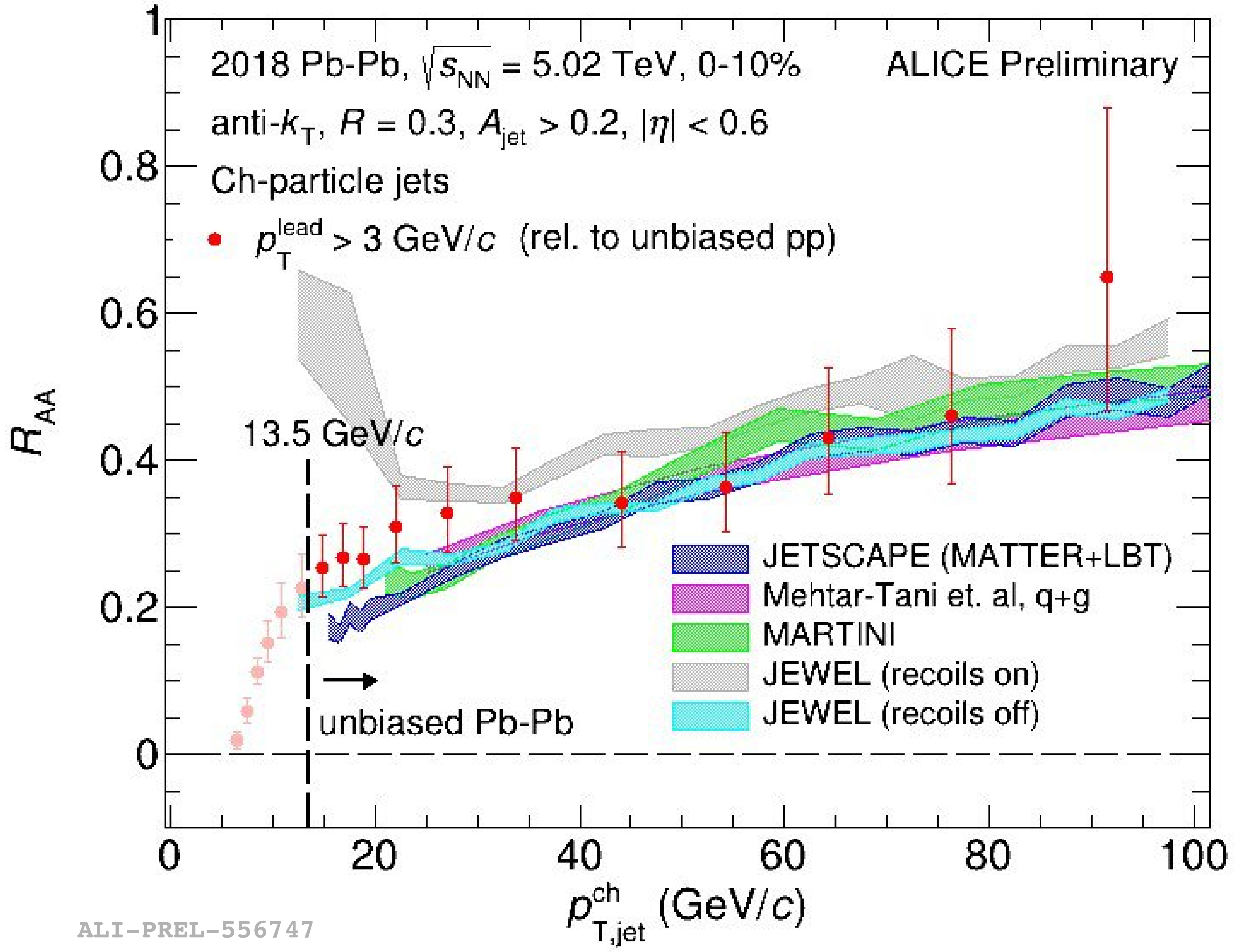
$I_{AA}(\Delta\varphi)$ vs *R* compared to JEWEL



h+jet



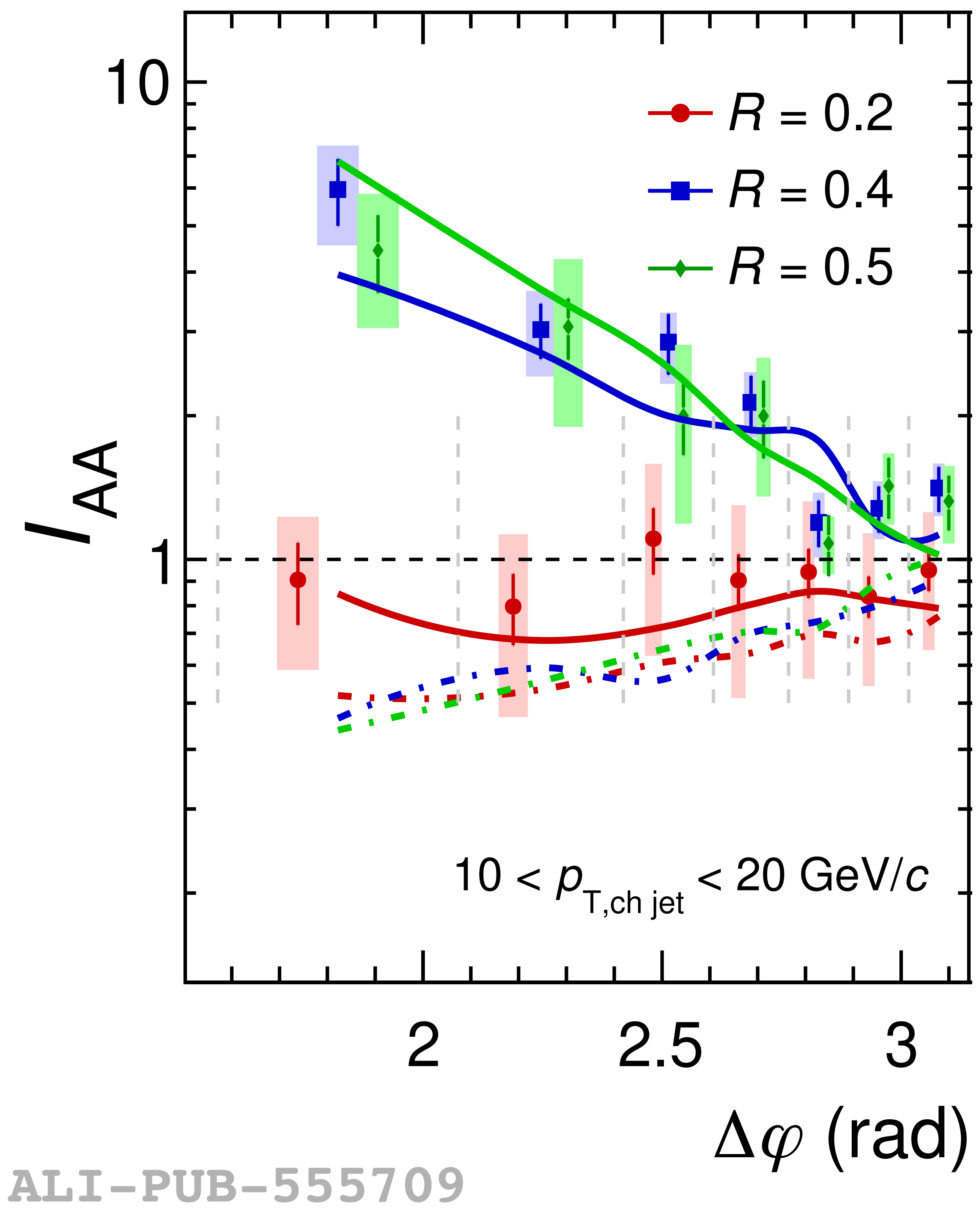
Inclusive



- All features of distribution **reproduced by JEWEL** with recoils on …
- … but no model incorporating medium response describes all measured observables

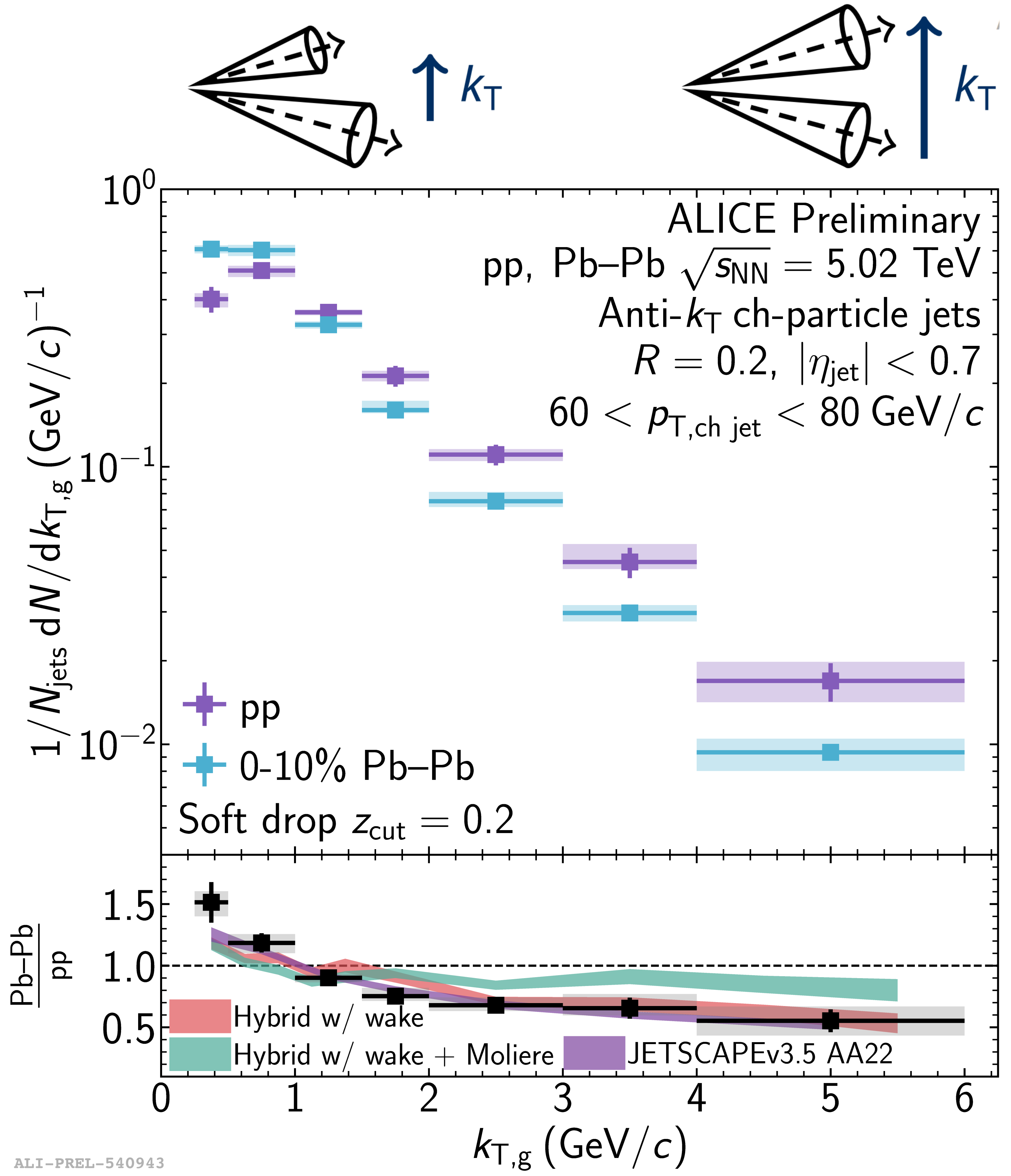
Next steps - precise characterisation of quenching effects

Characterise broadening

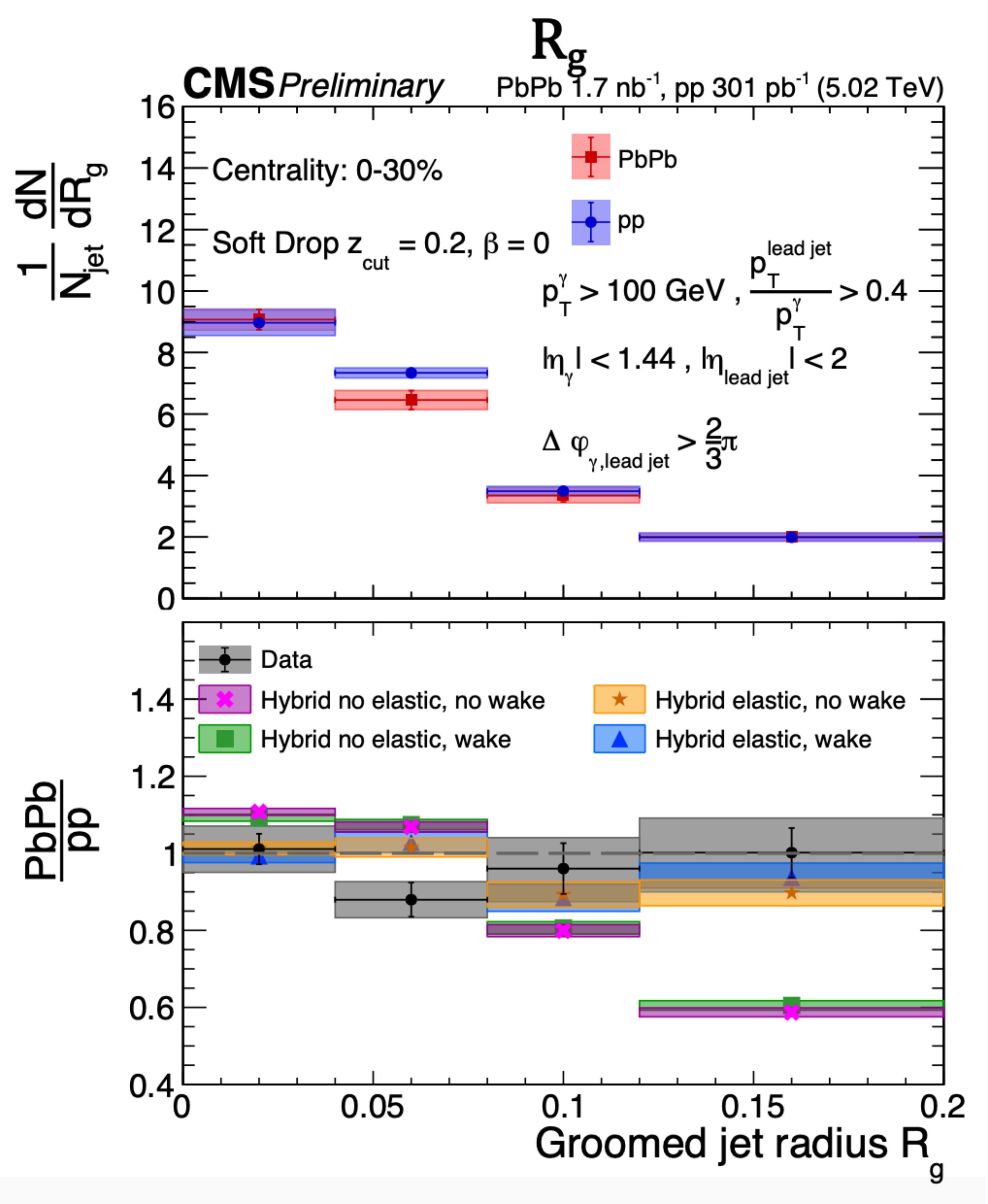


Thermalised jets? Hard component?
Study substructure/fragmentation pattern

Substructure measurements offer promising way to find scatterings

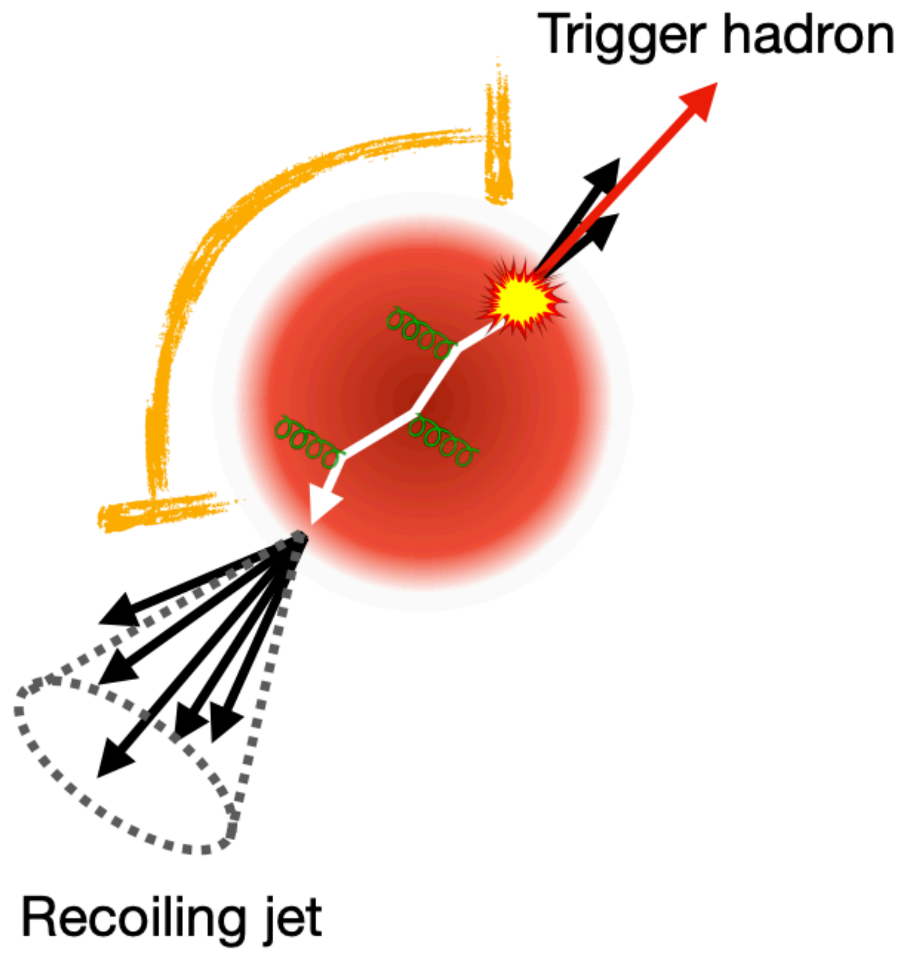


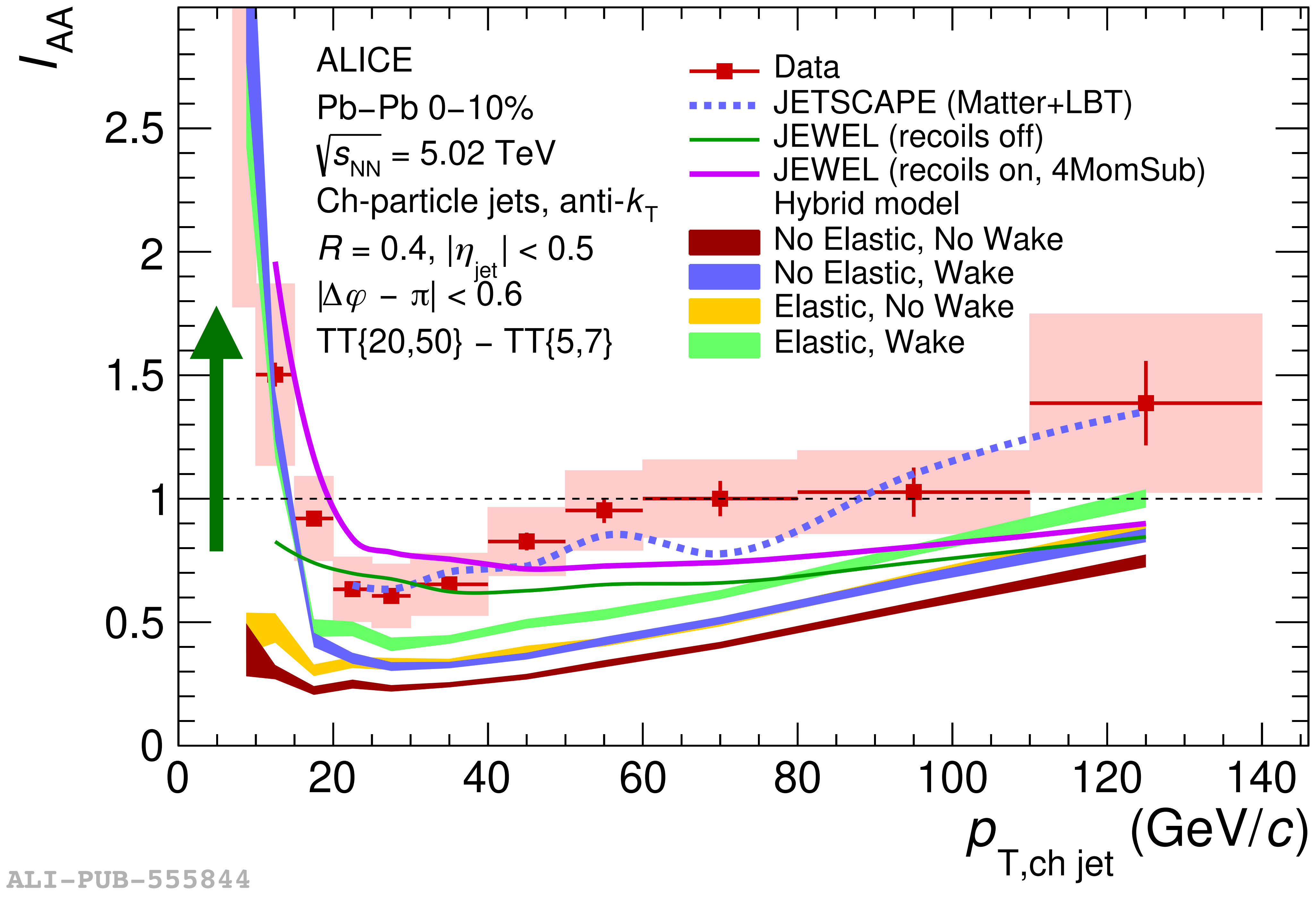
hard jet splittings - no clear evidence for Molière scattering

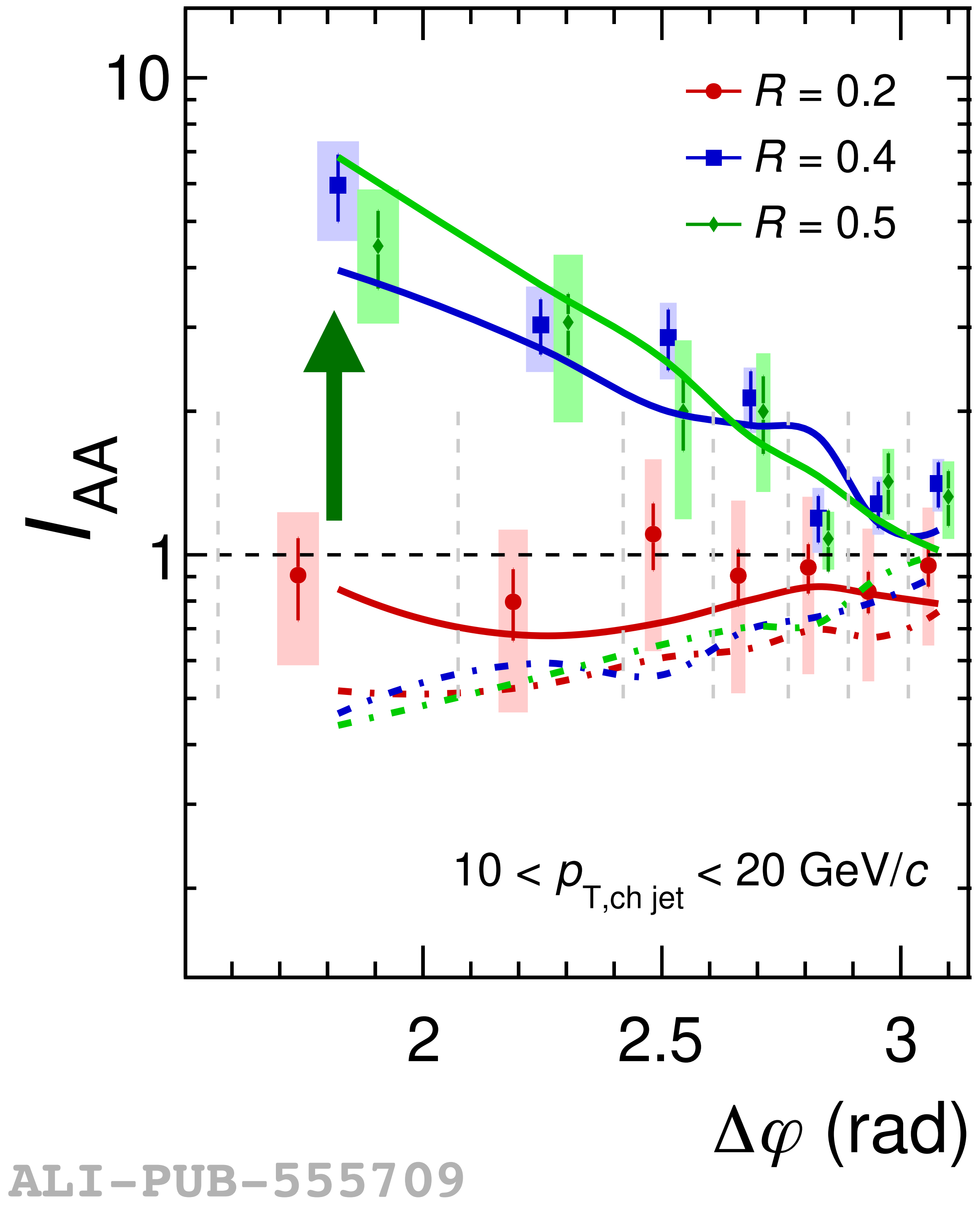


γ−tagged jet substructure
Requires Molière scattering to describe data

Summary and outlook

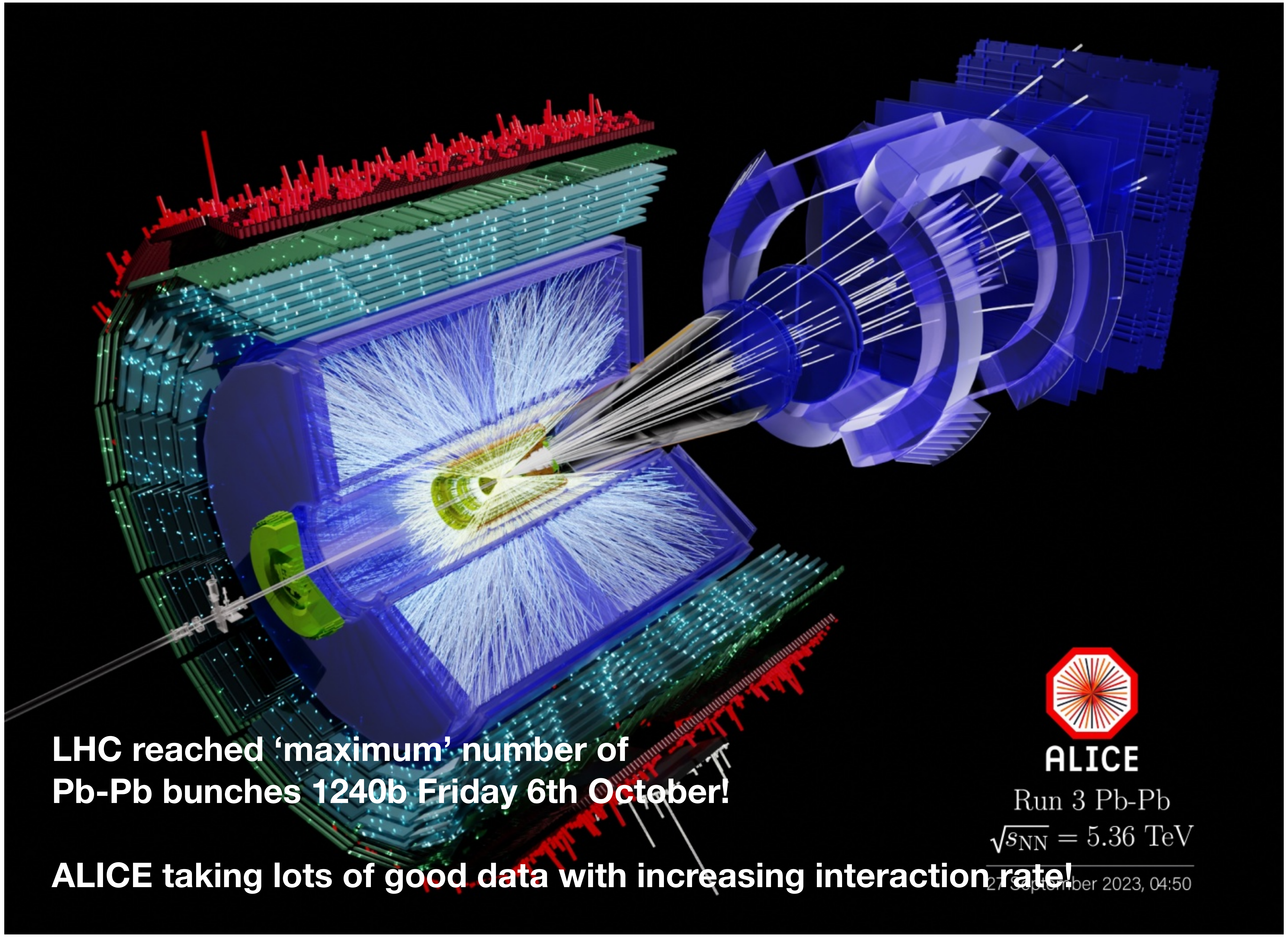






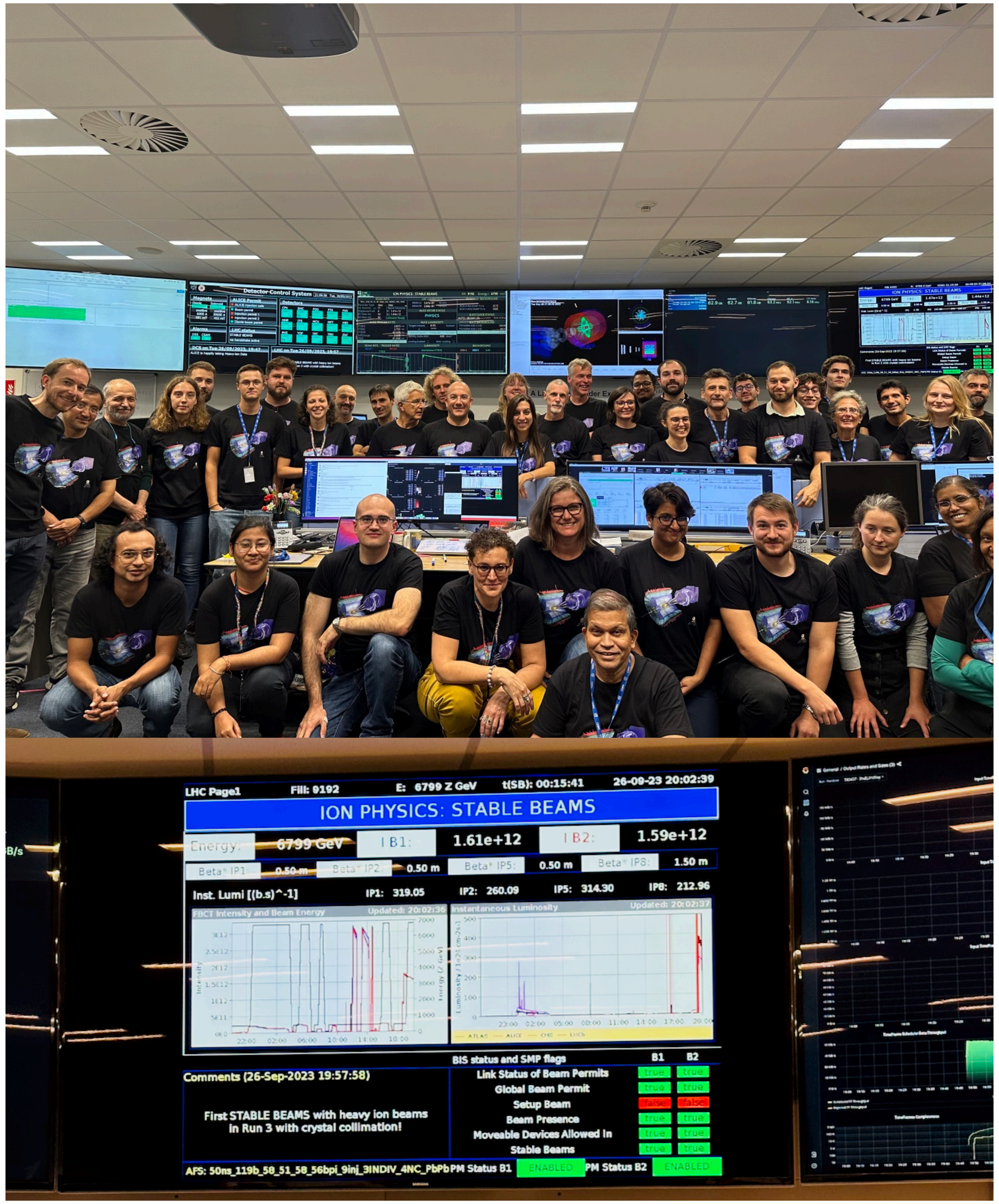
- **First observation of significant low-$p_{T,jet}$ jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant upgrade programme

arXiv:2308.16128
arXiv:2308.16131



LHC reached 'maximum' number of Pb-Pb bunches 1240b Friday 6th October!

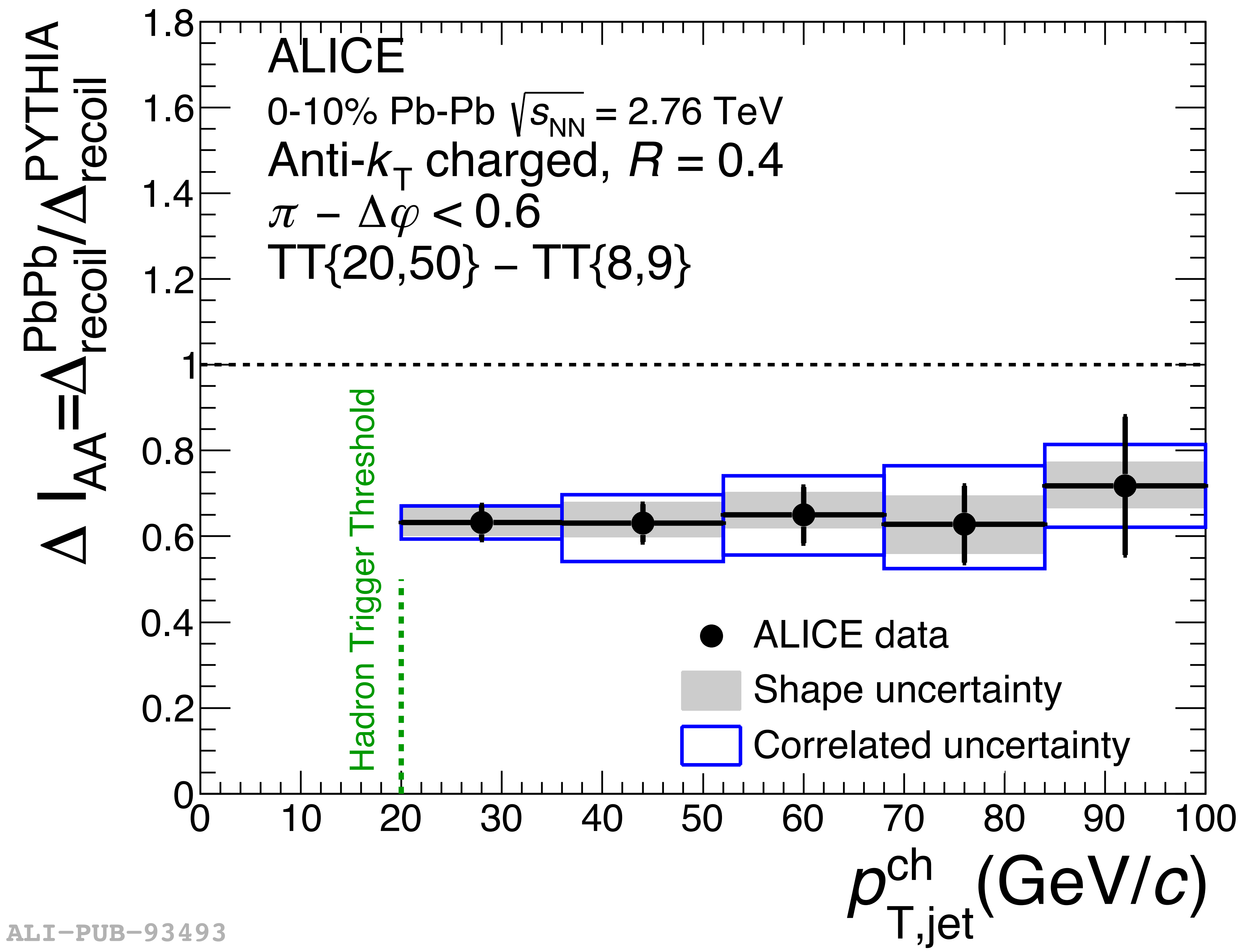
ALICE taking lots of good data with increasing interaction rate!

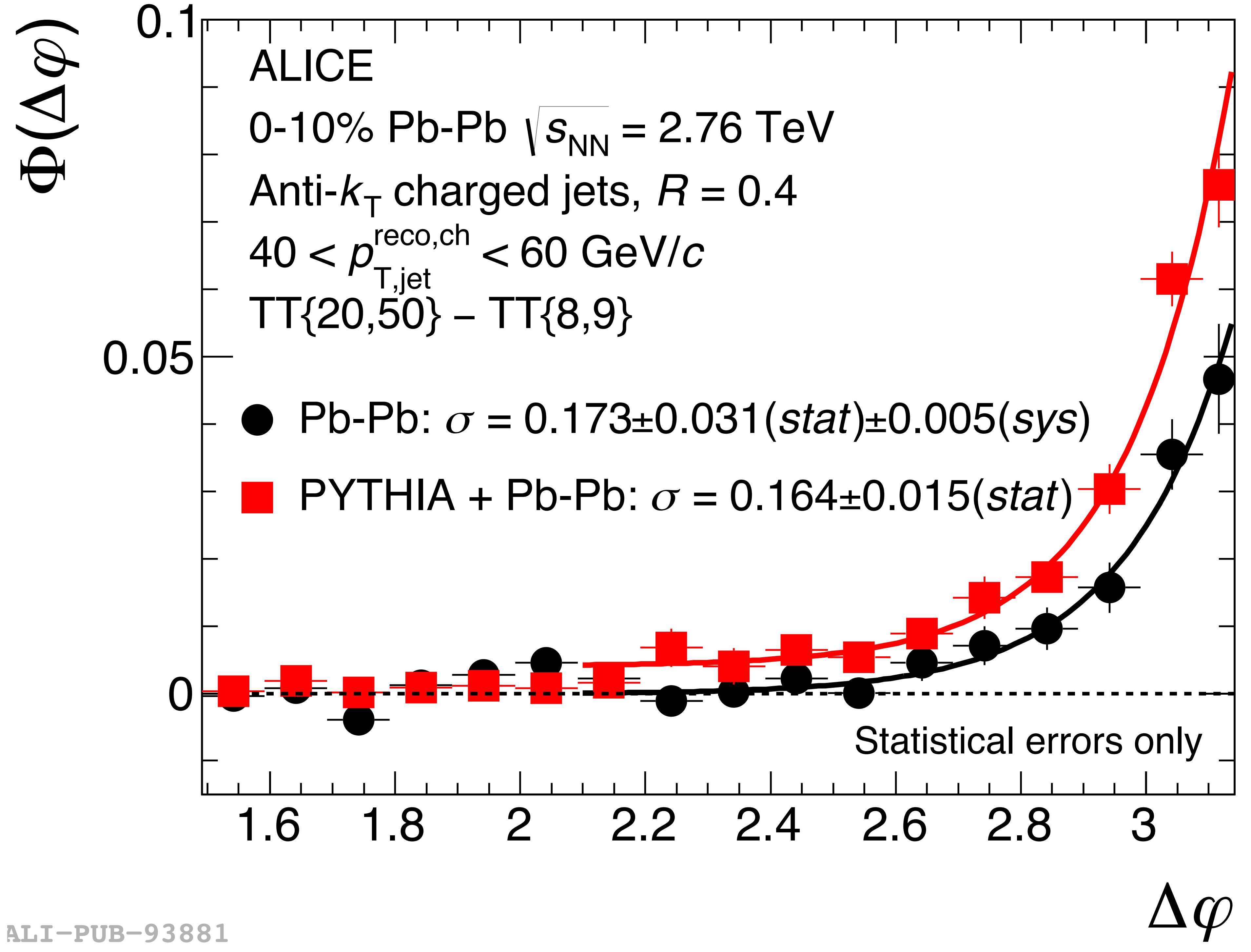


Backup

Run 1 hadron+jet measurement

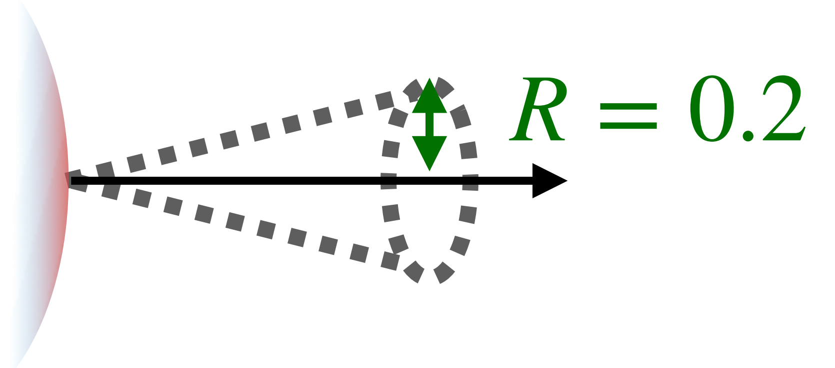
ALICE: JHEP 09 (2015) 170



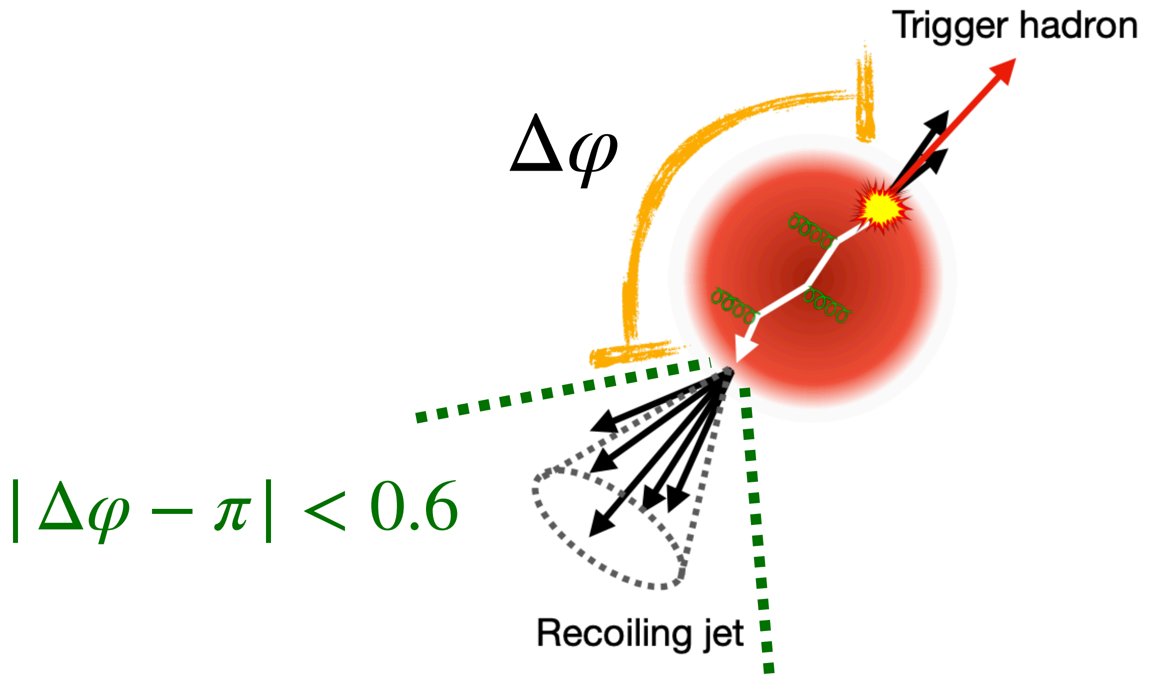


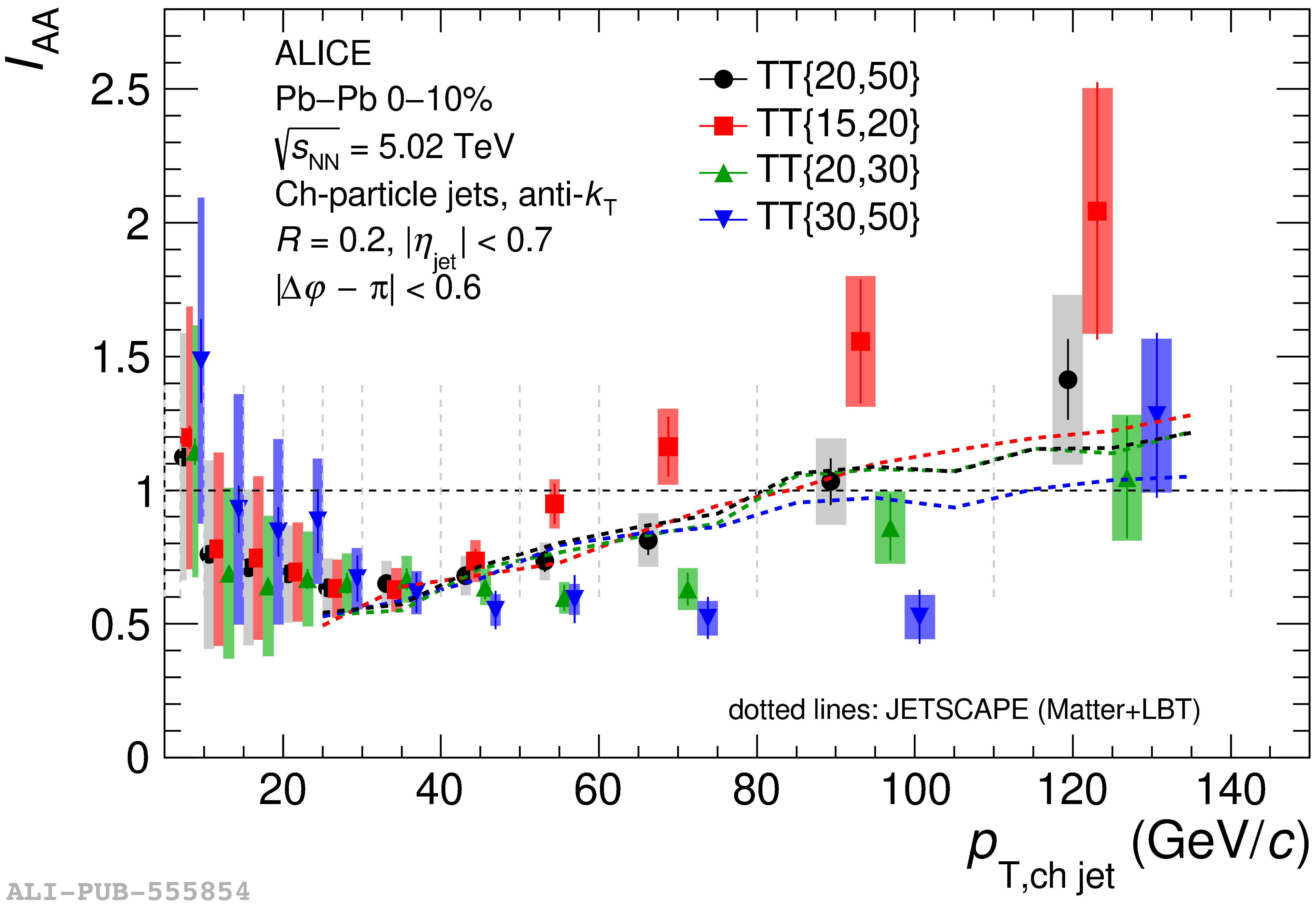
- Background-subtracted yield of jets recoiling from a high-p_T trigger hadron:
  - Suppression with respect to a pp (PYTHIA) reference
  - No medium-induced broadening within experimental uncertainties

$I_{AA}(p_{T,\mathrm{ch\,jet}})$ - recoil jet yield modification in Pb-Pb collisions



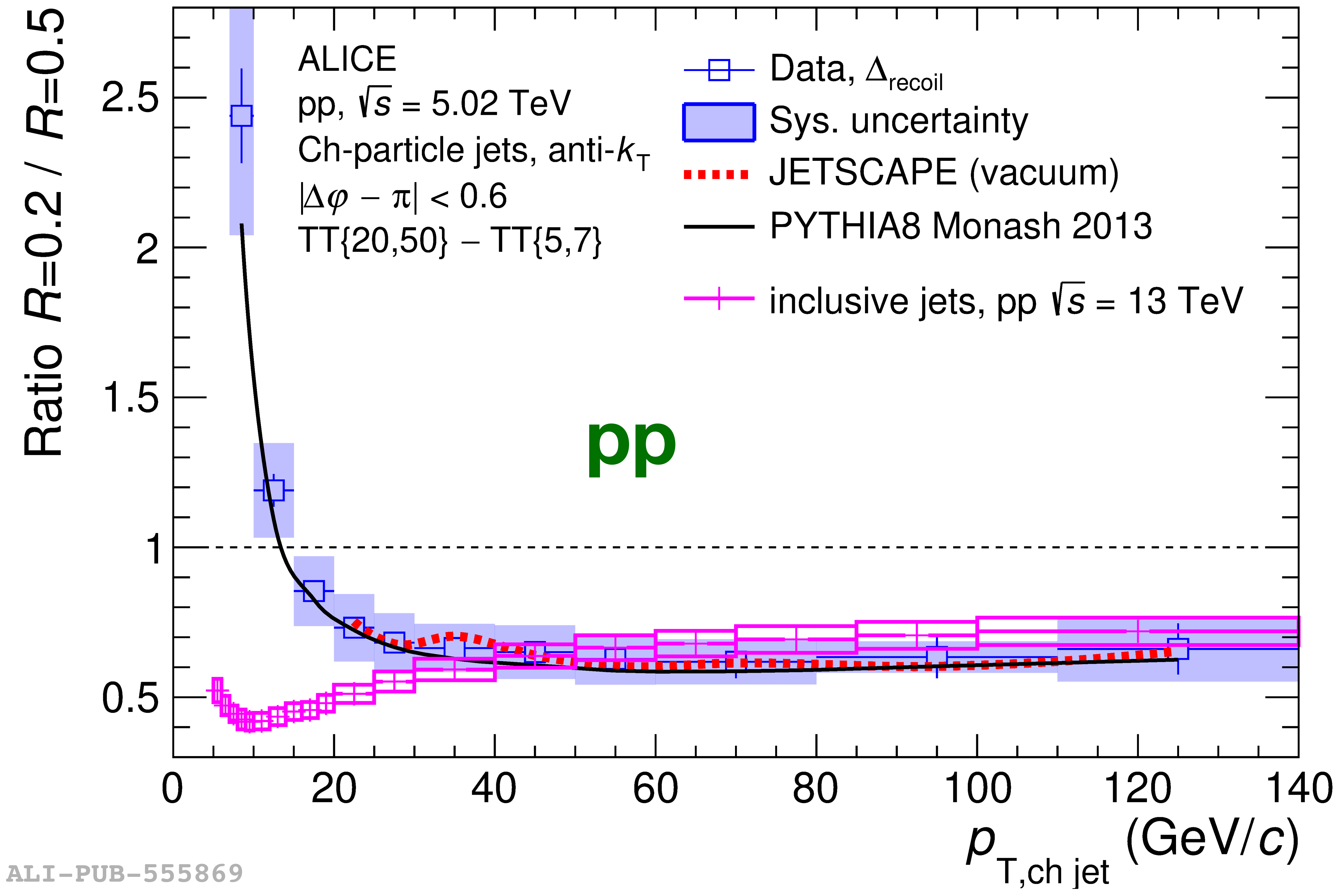
$$I_{AA} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$





- Expected that high p_T hadrons leading fragment of jet originating from QGP surface ('surface bias')
  - $p_T^{\mathrm{jet}} \sim p_T^{\mathrm{trig}}$: suppression - surface bias picture holds
  - $p_T^{\mathrm{jet}} >> p_T^{\mathrm{trig}}$: trigger hadron may not be leading fragment or from higher order process - interplay between jet and hadron suppression can lead to enhanced I_{AA}
- New insight into interplay between hadron and jet suppression

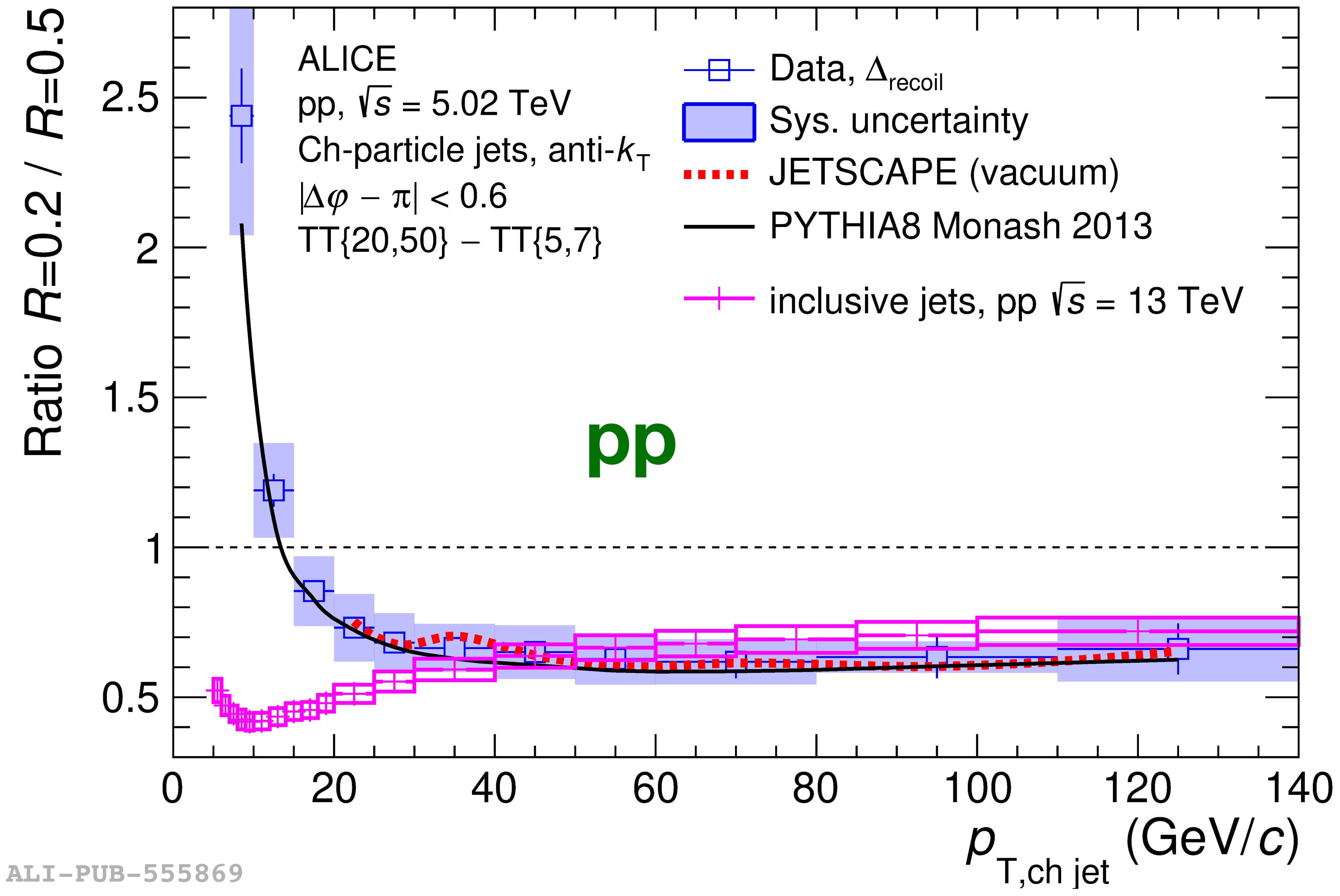
Studying intra-jet broadening through R-ratios

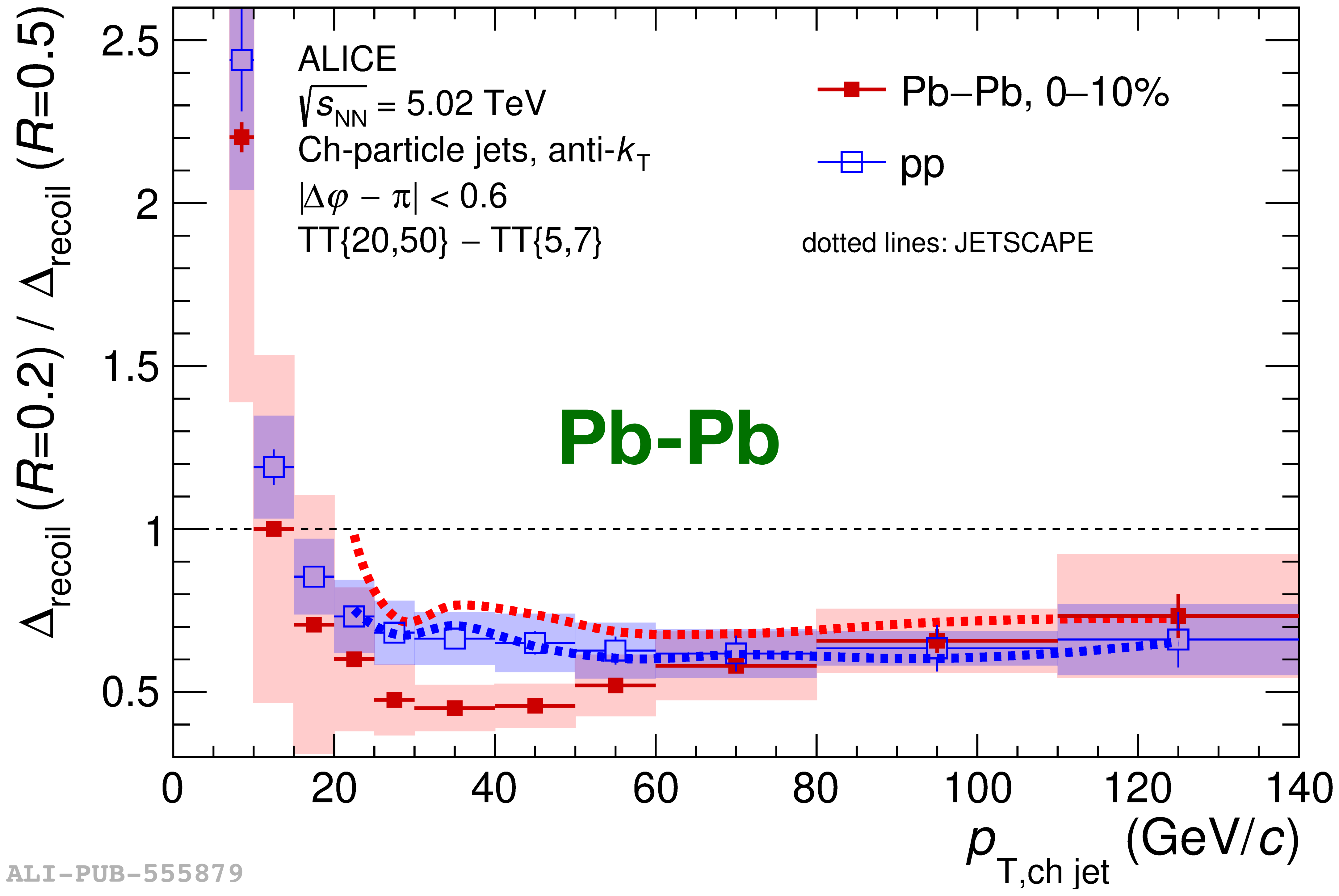


- *R*=0.2 / *R*=0.5 ratio deviates from inclusive jet ratio for $p_{T,ch\,jet} < p_T^{trig}$

- $\tilde{z} = \frac{p_T^{trig}}{p_T^{jet}}$
- $\tilde{z} > 1 \rightarrow$ LO processes suppressed
  - preference for more, small *R* jets w.r.t. large *R* jets to be reconstructed?

Studying intra-jet broadening through R-ratios

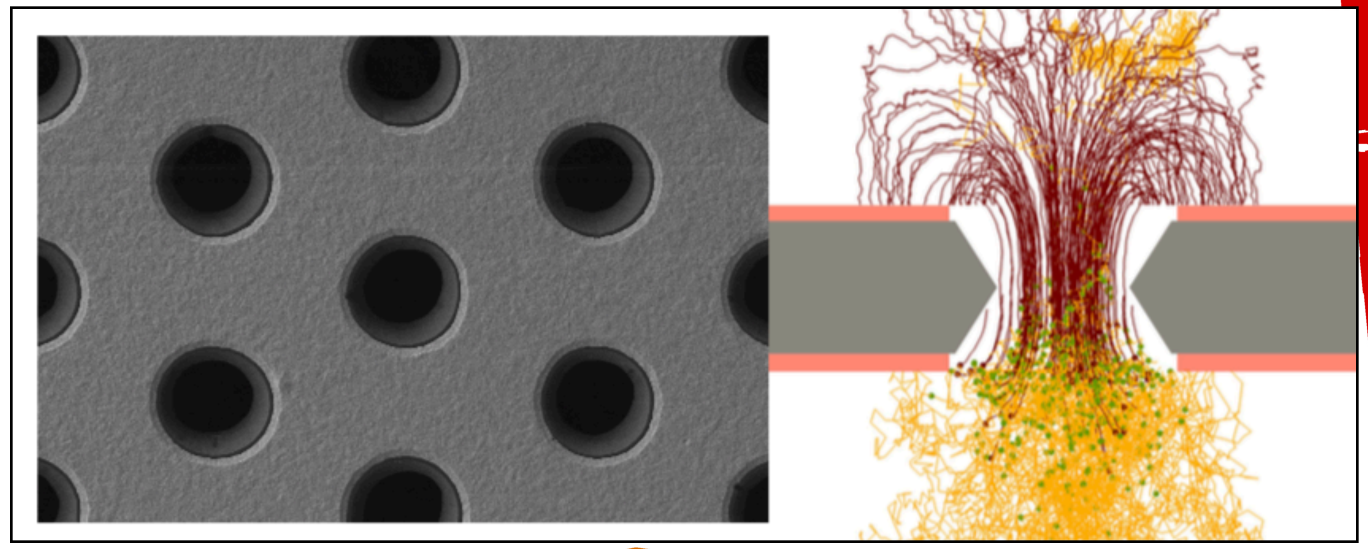


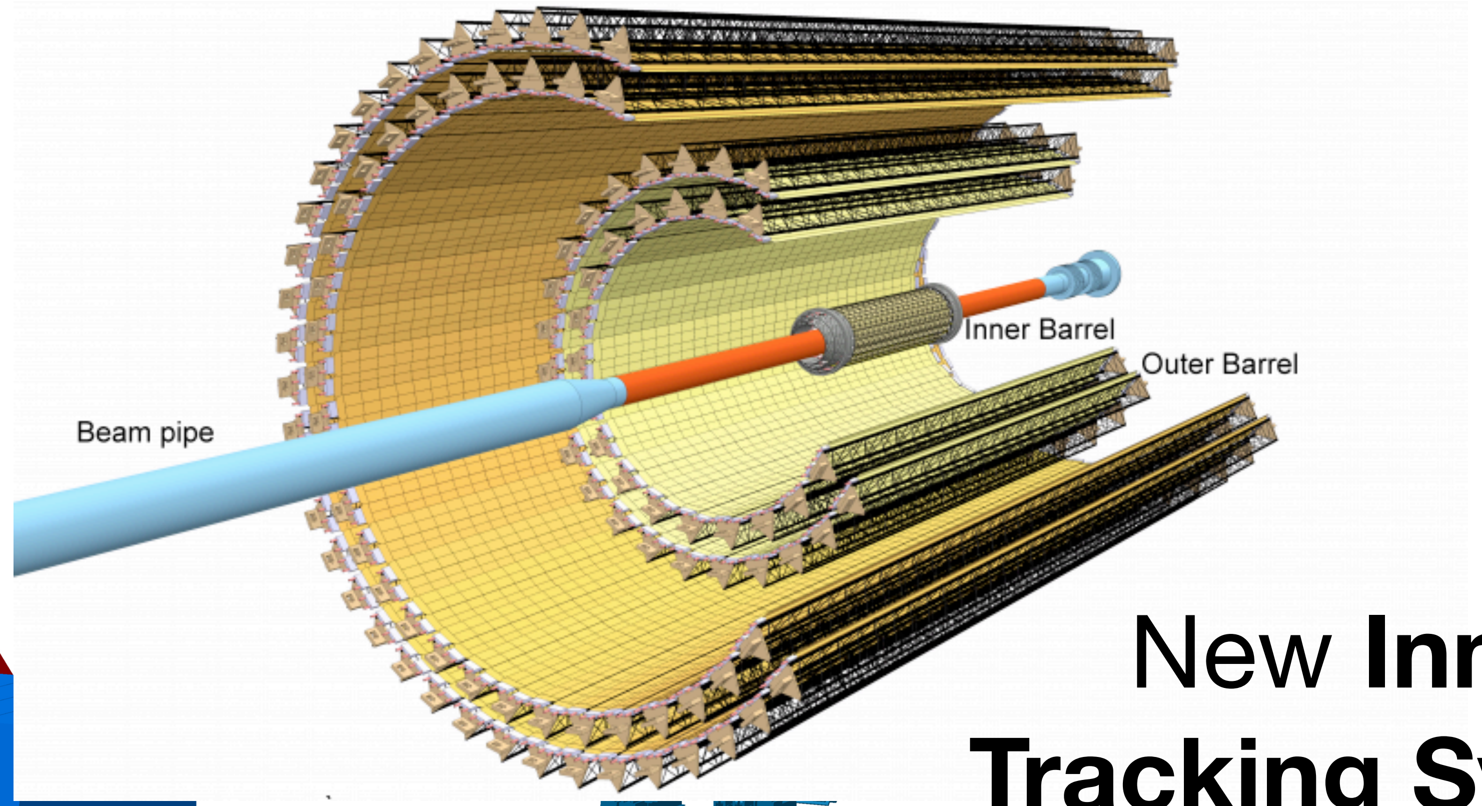


- Hints that R=0.2 jets suppressed more than R=0.5 jets in Pb-Pb w.r.t pp in 30-60 GeV/c
  - Energy recovery for wider jets?

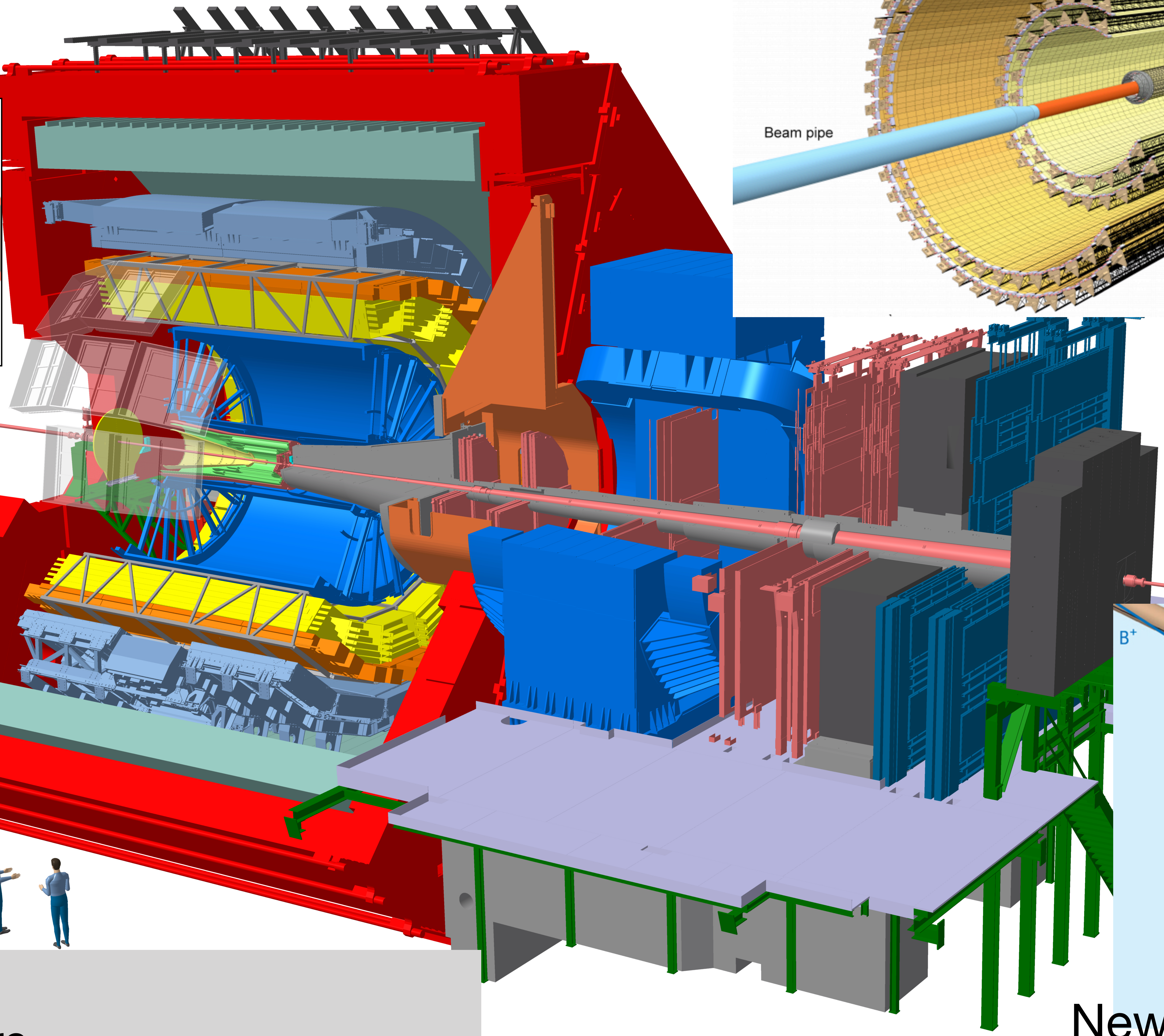
ALICE in Run 3

Replace TPC wire chambers with **gas electron multiplier** (GEM) **readout**

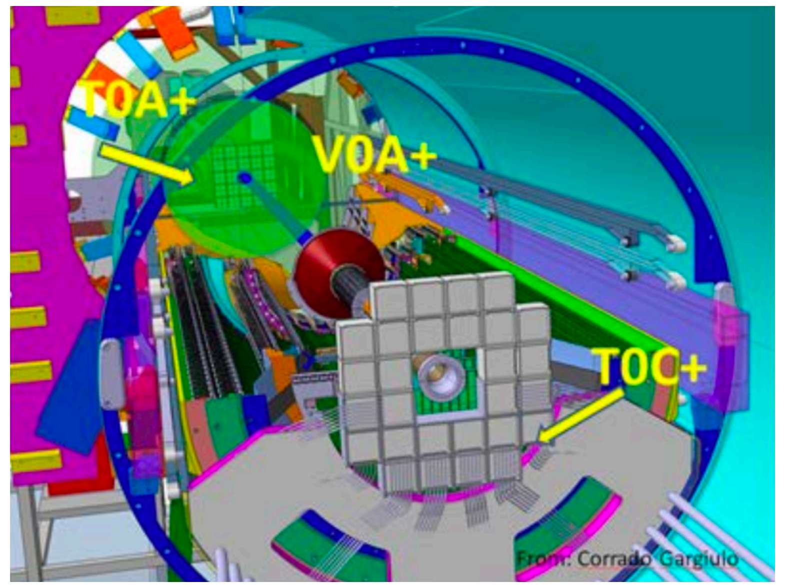




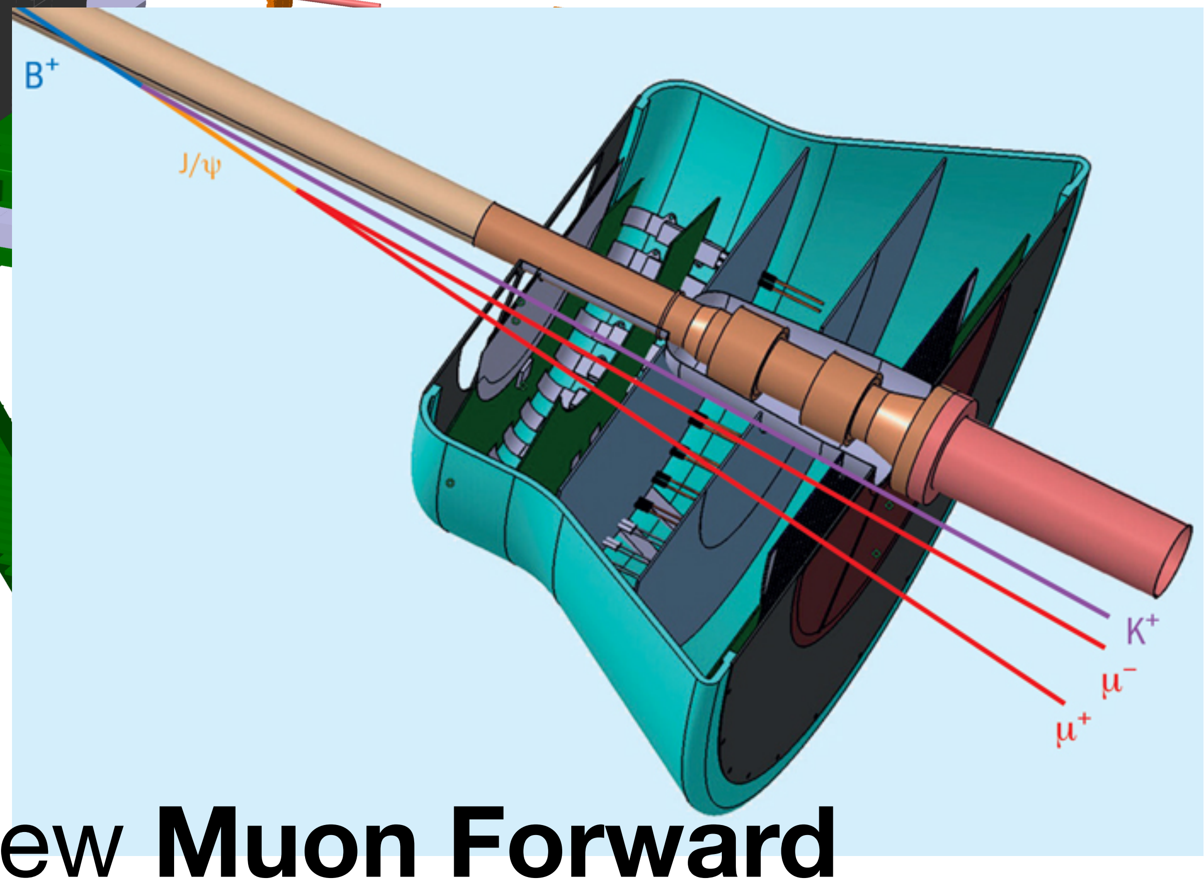
New **Inner Tracking System**



New **forward interaction trigger** (FIT)



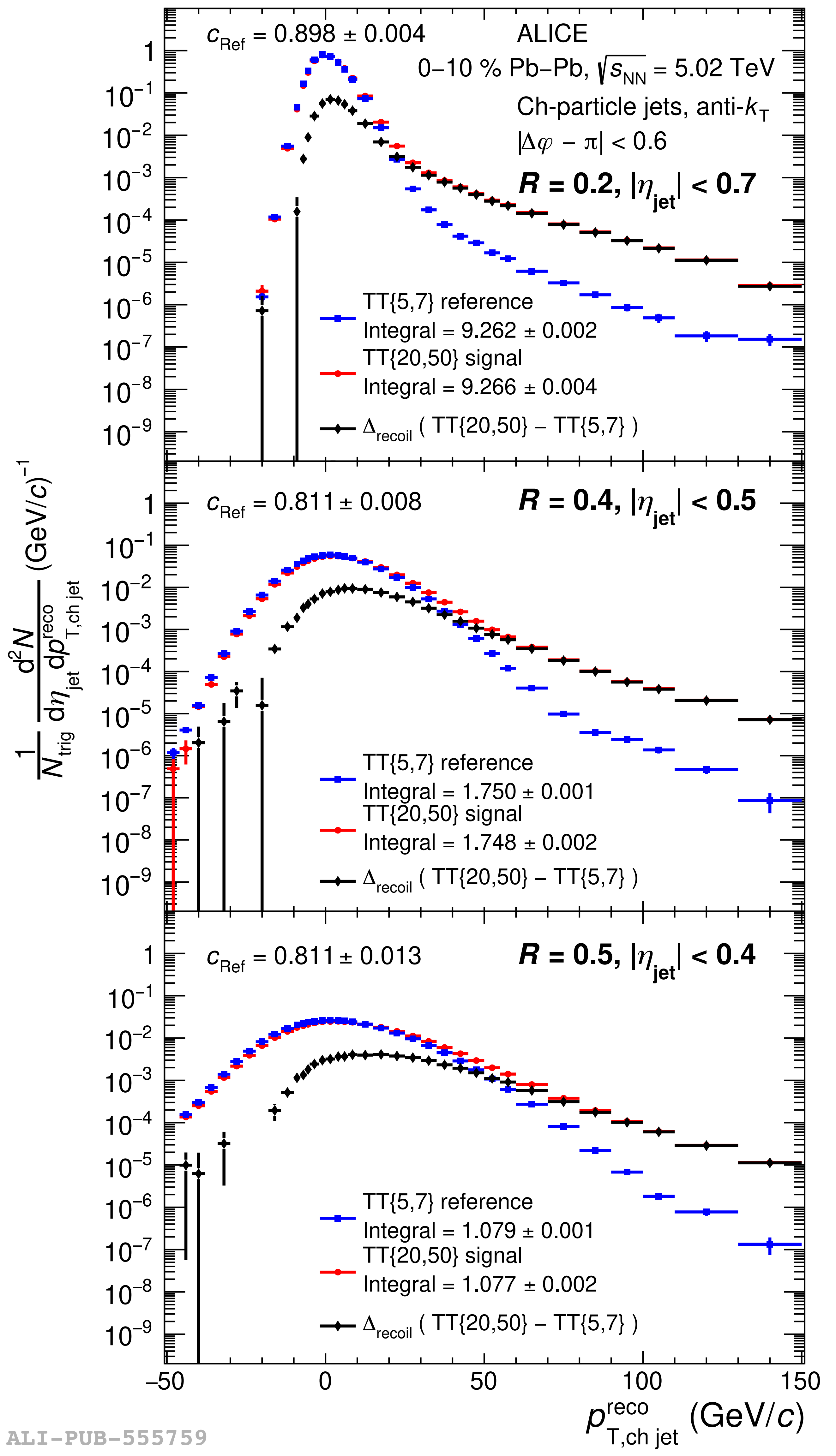
+ New beam pipe
+ New readout architecture
+ Major computing system upgrade (O2 project)

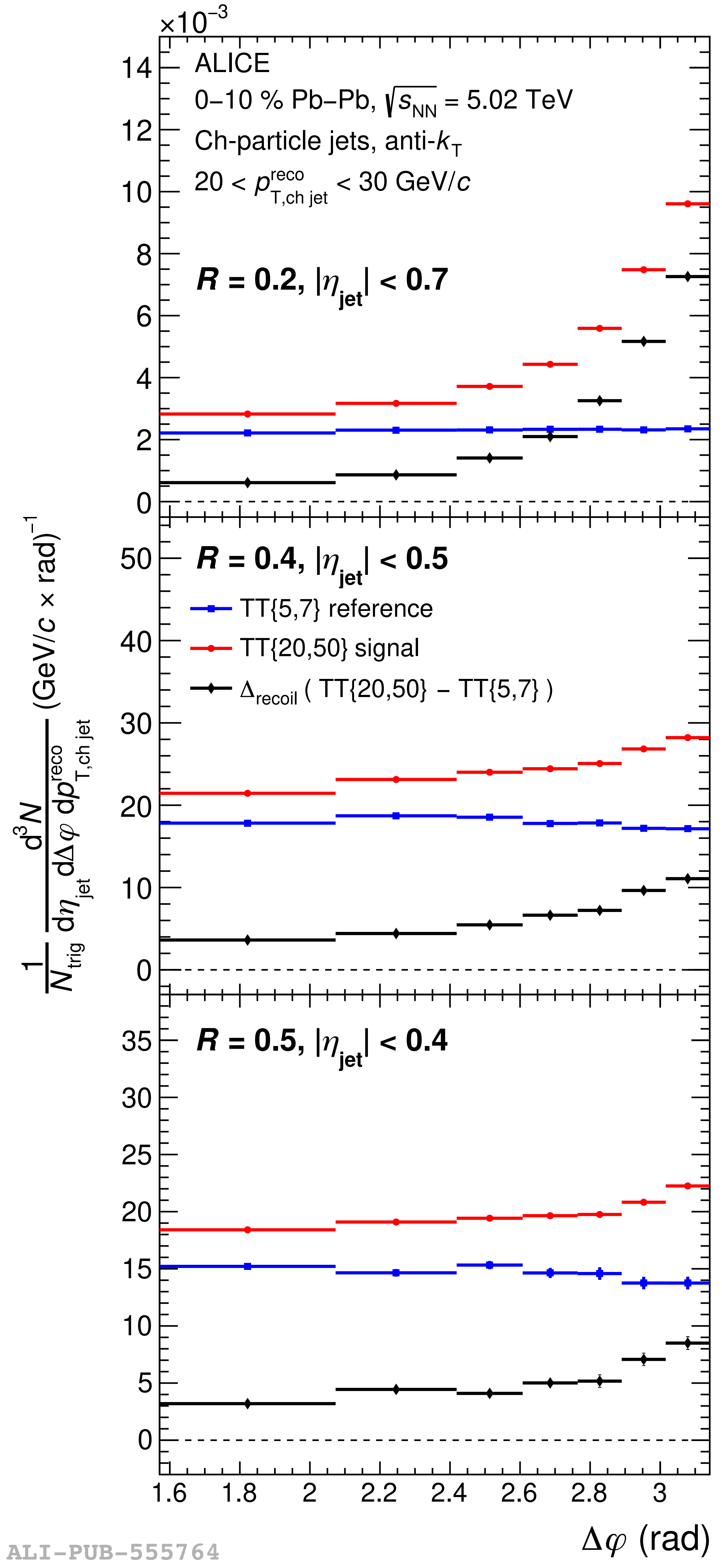


New **Muon Forward Tracker** (MFT)

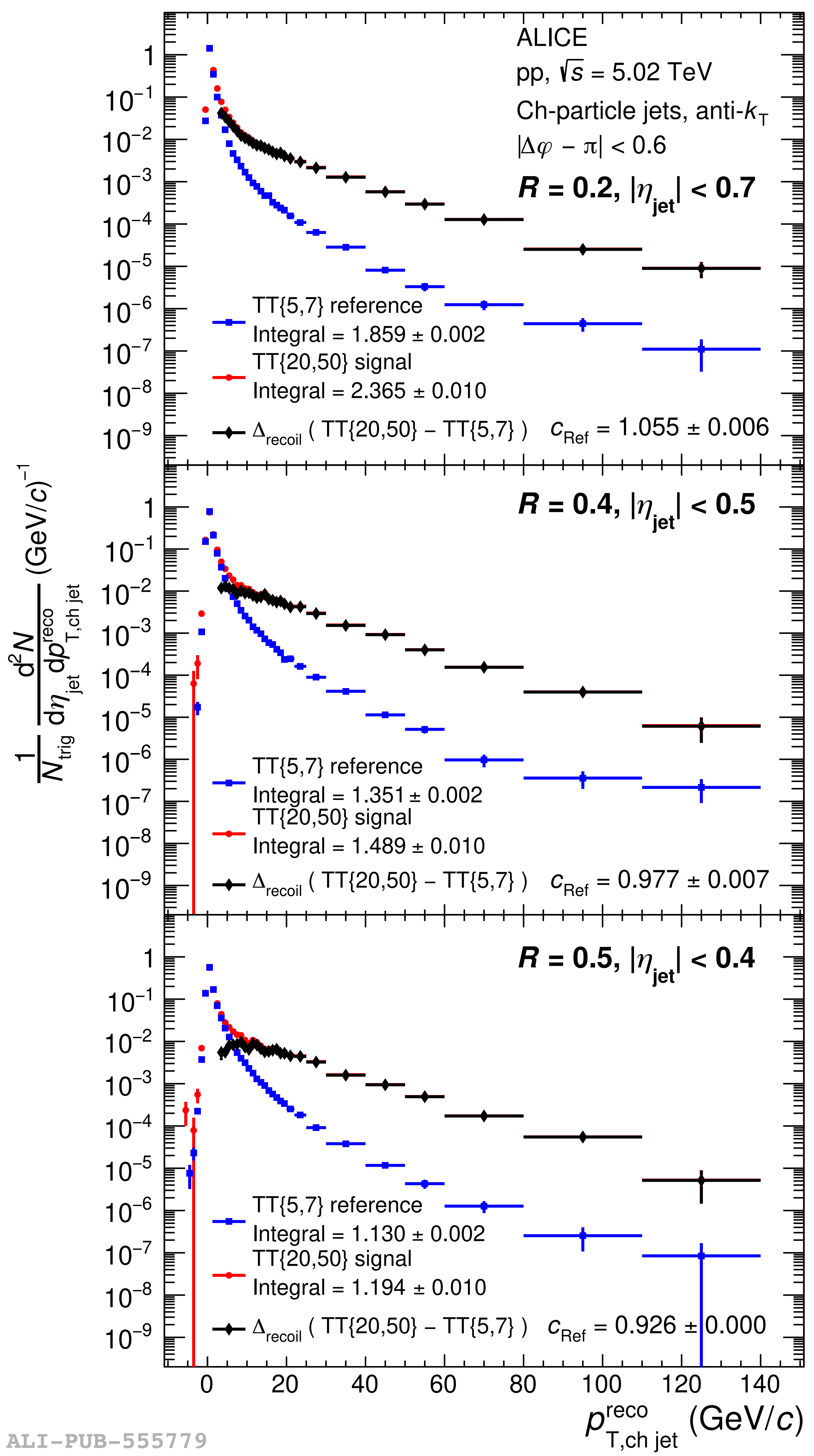
Raw distributions

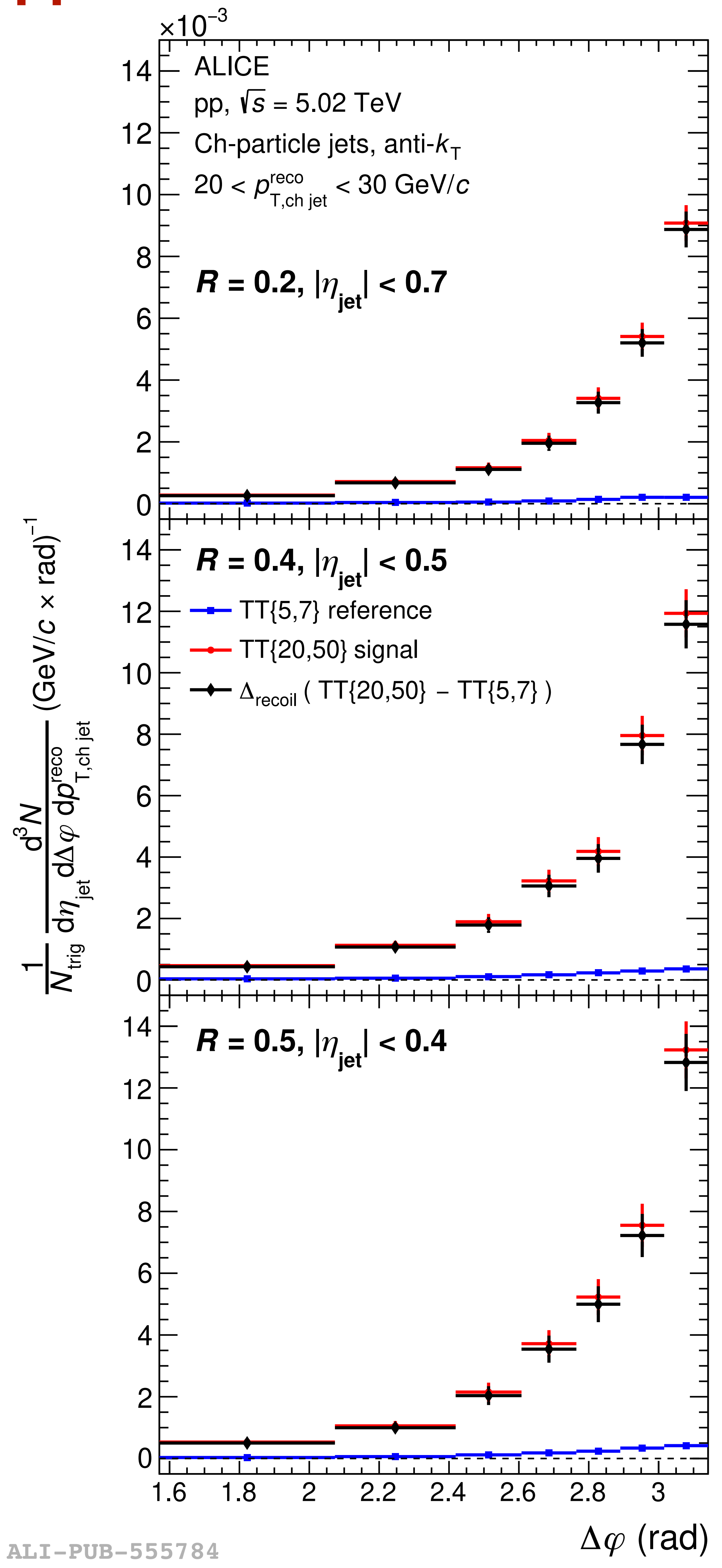
Pb-Pb



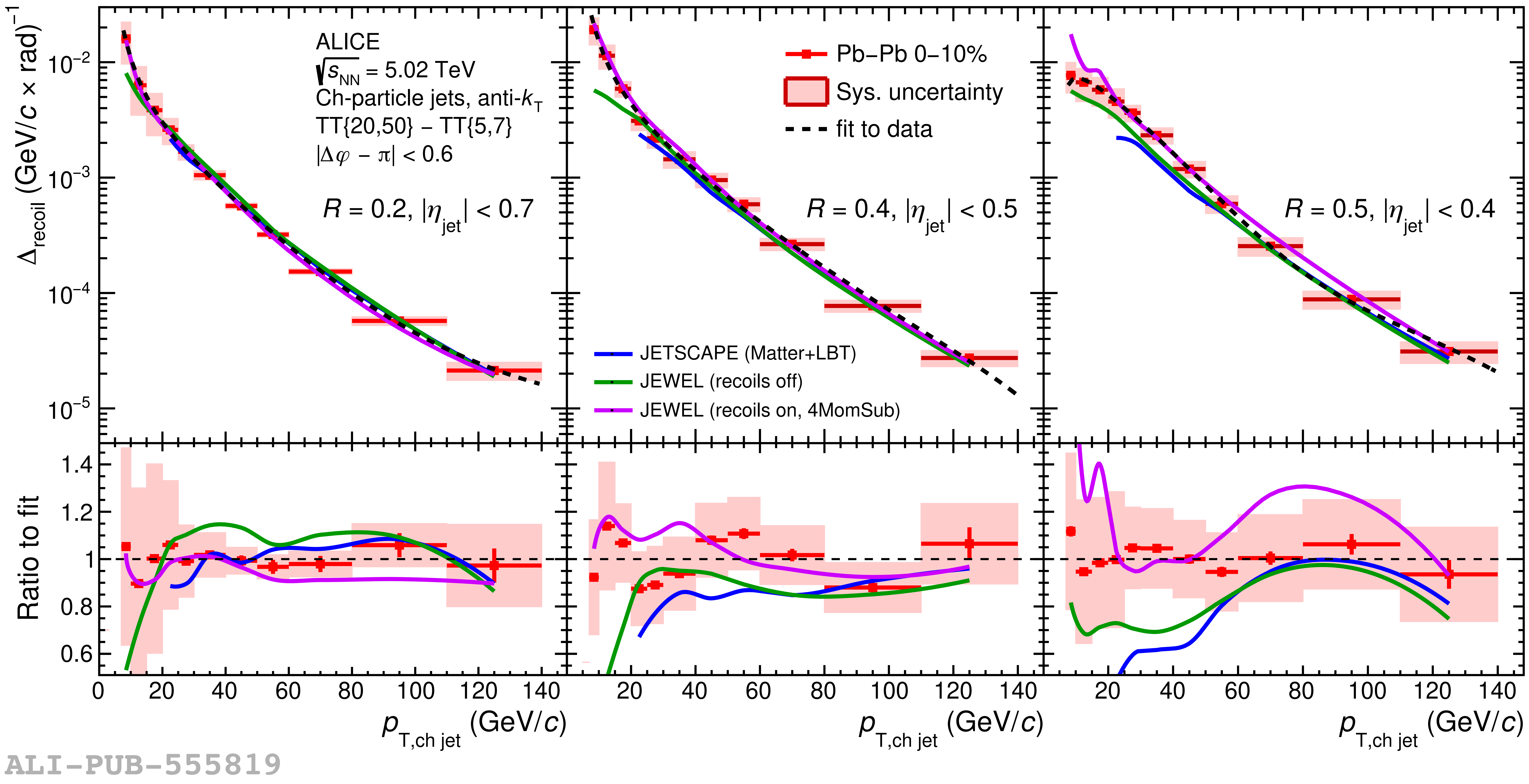


pp

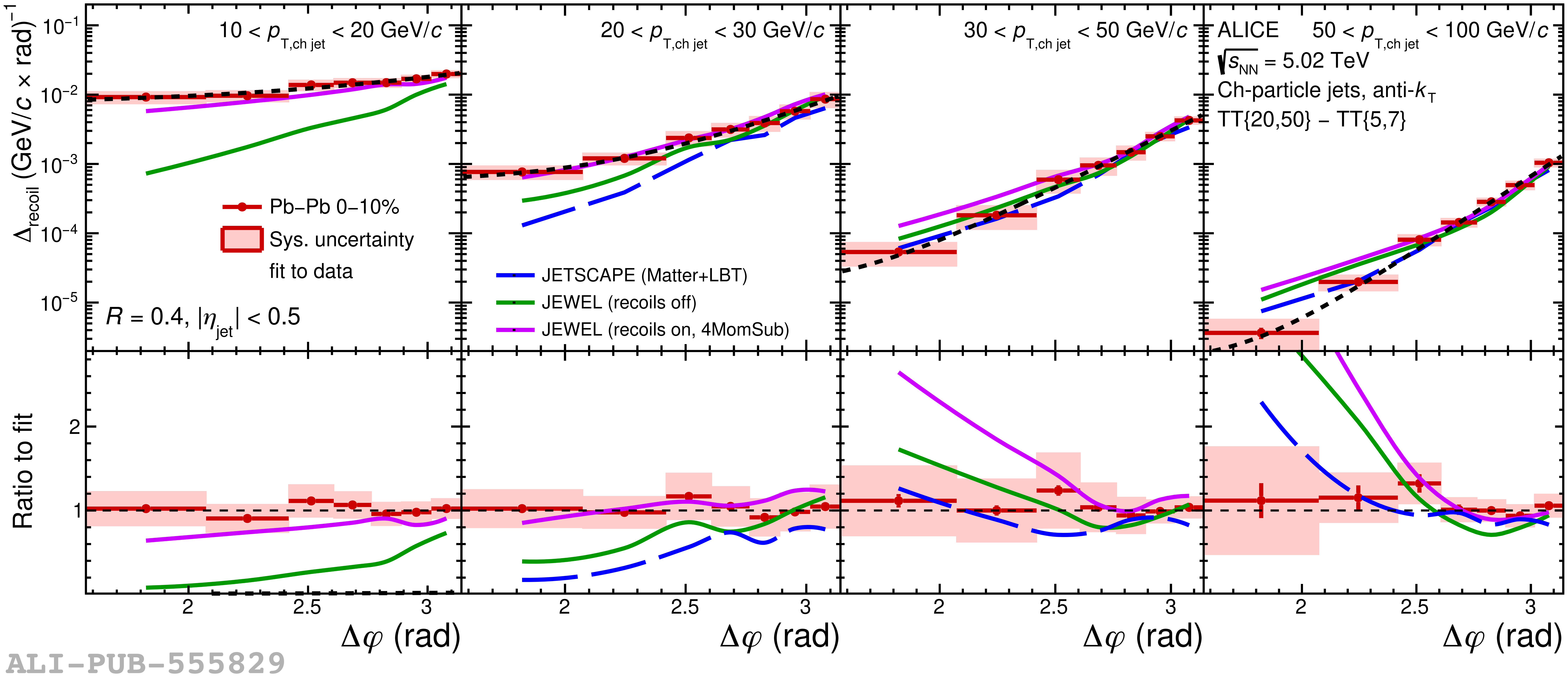




$\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\,jet}})$ in Pb—Pb collisions

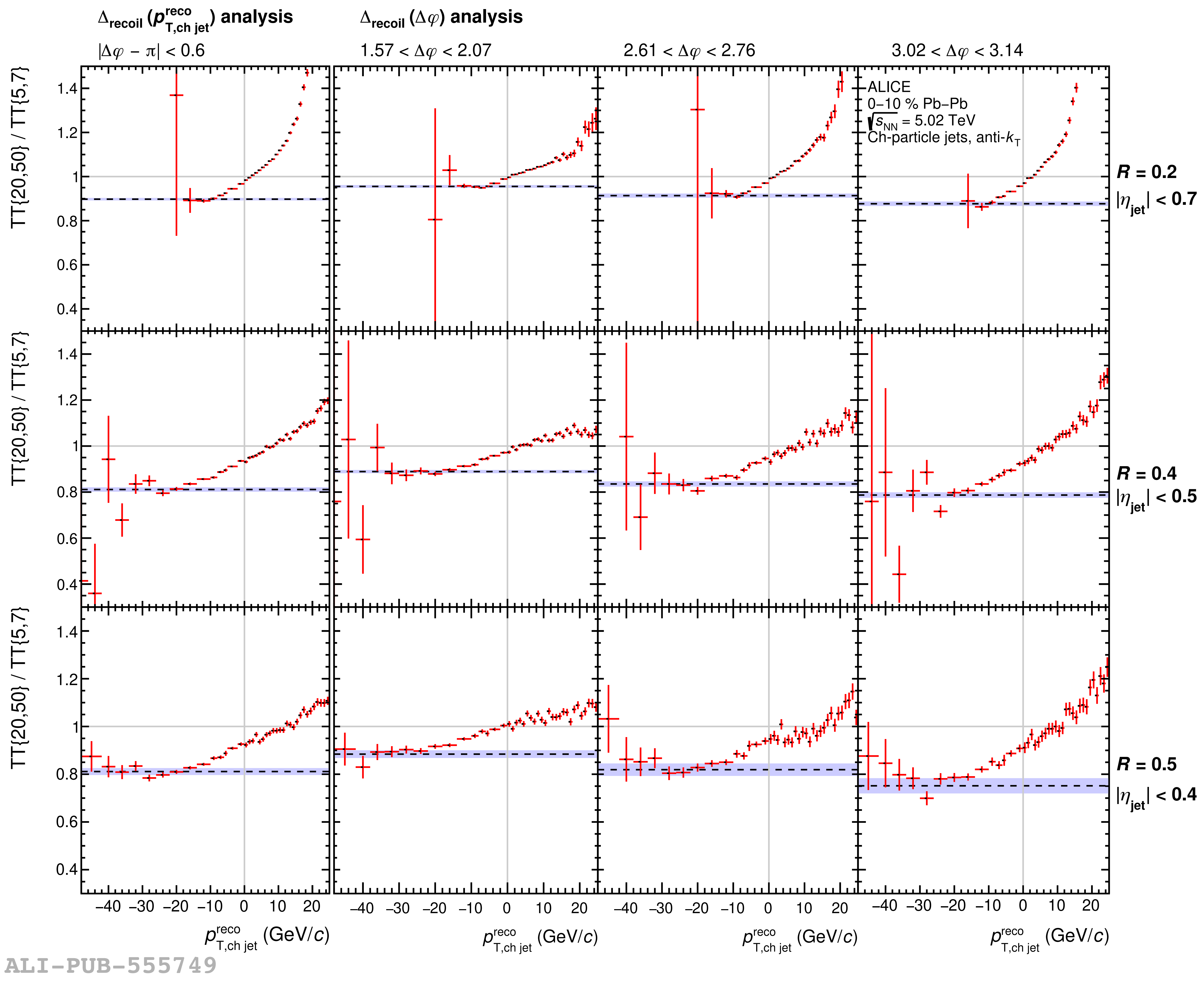


Jet acoplanarity: Pb-Pb collisions (R=0.4)

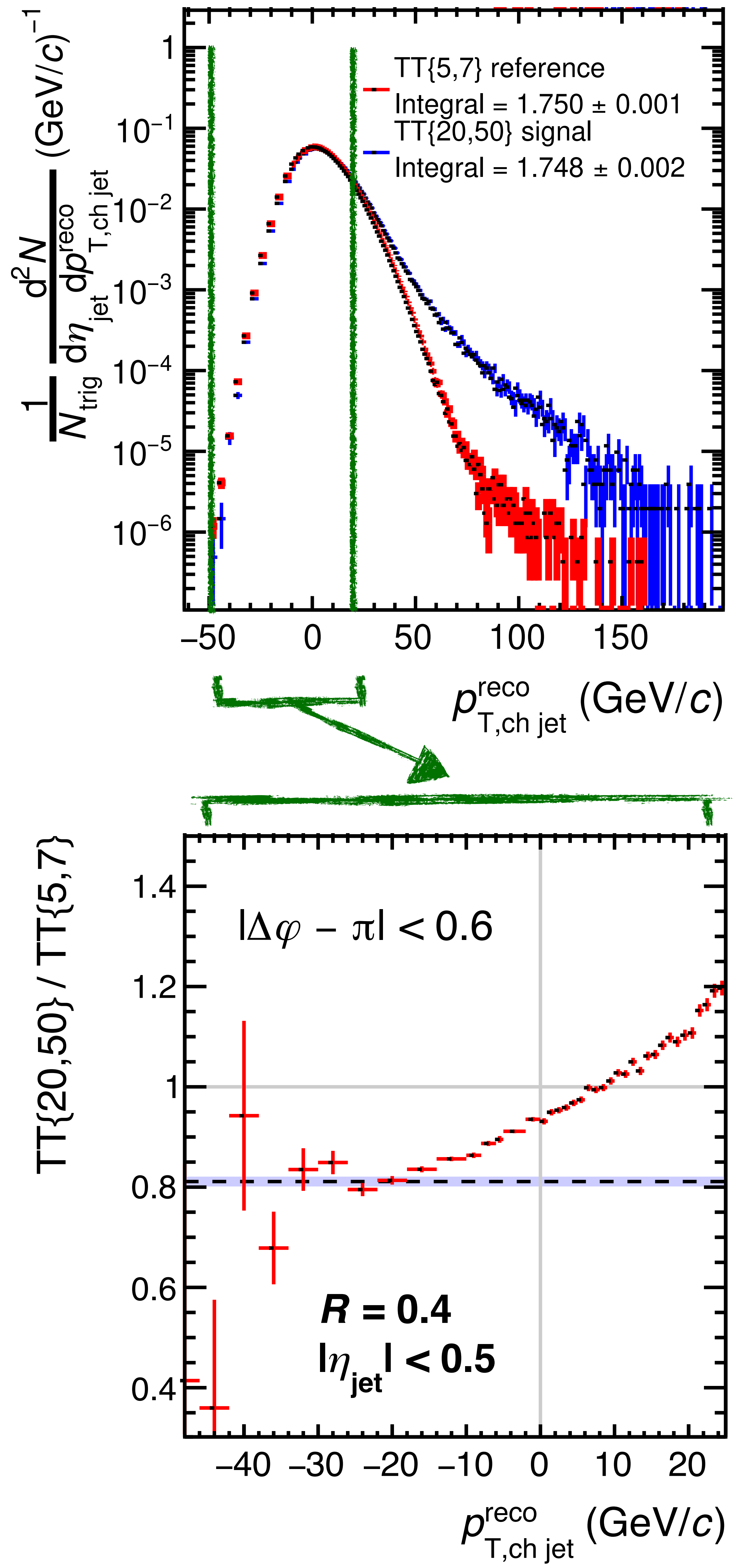


- JEWEL (recoils on) provides best low-$p_{T,ch\,jet}$ description of data, though over predicts high-$p_{T,ch\,jet}$ tails of distribution
- JETSCAPE provides best high-$p_{T,ch\,jet}$ description of data

Δ_{recoil} ‘reference’ calibration



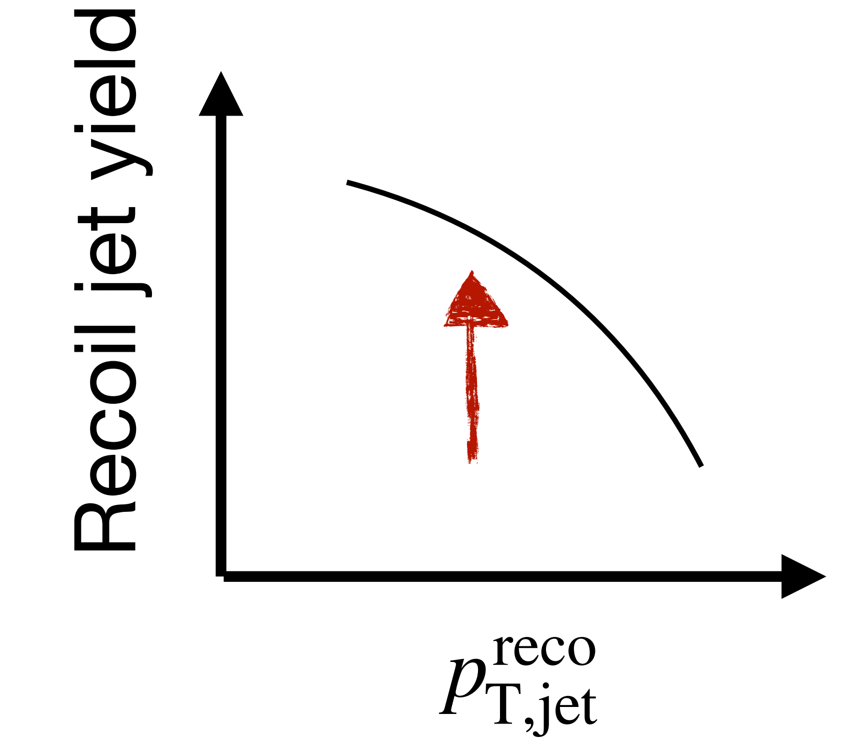
Δ_{recoil} 'reference' calibration

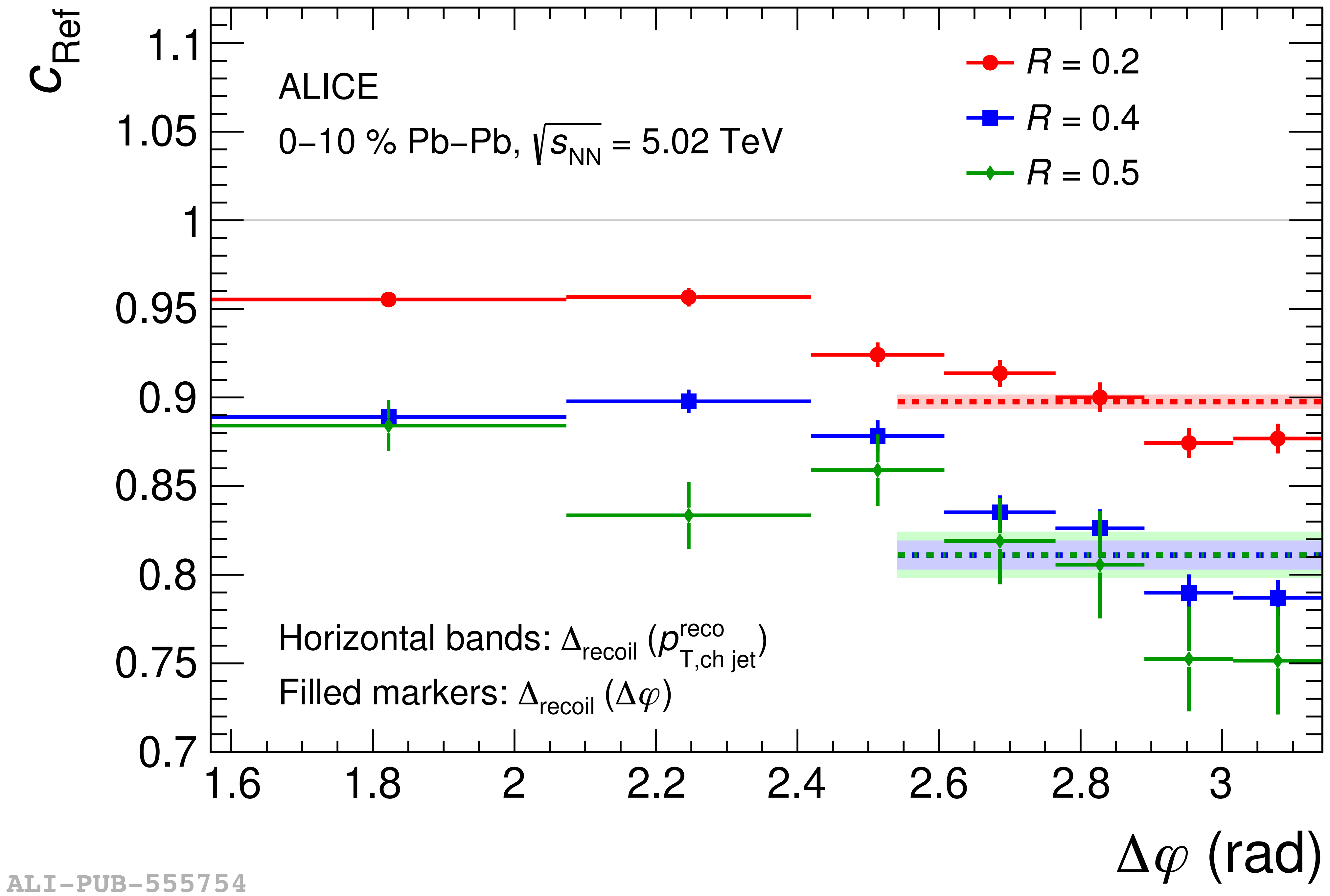


Calibration of reference distribution required for precise background subtraction:

1. $p^{reco}_{T,jet}$ scale (*'horizontal'*)

2. Yield scale (*'vertical'*)





ALI-PUB-555754

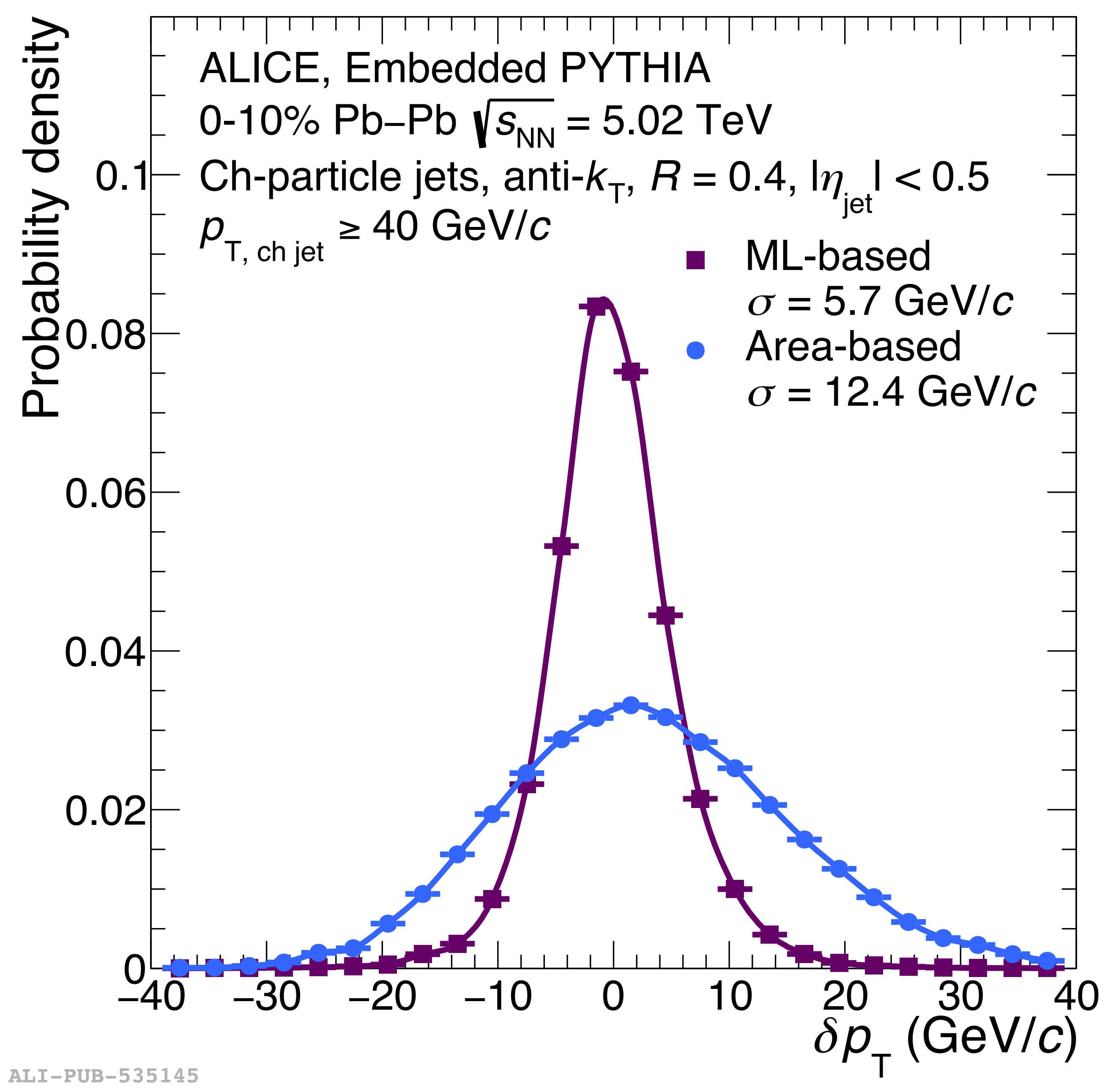
- Correction $\Delta\varphi/R$-dependent
  - more correlated yield → larger c_{Ref} correction

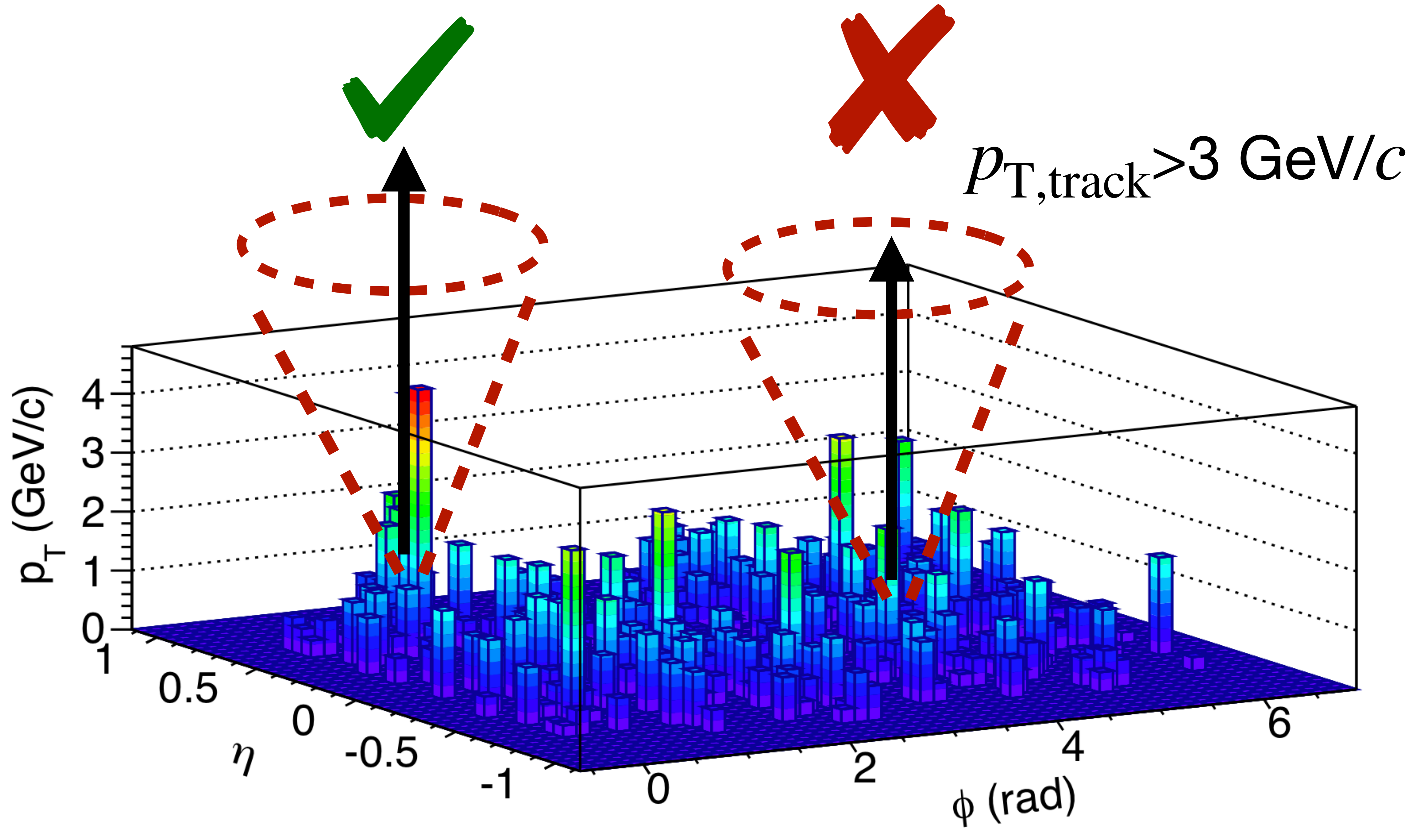
Dealing with background in heavy-ion collisions: Jet-wise correction

- Combinatorial background a major challenge for jet measurements in heavy ion collisions
  - what is a 'true' jet from a hard scattering and what is from uncorrelated sources?

- **Especially important for low p_T measurements** where $p_{\mathrm{T}}^{\mathrm{jet}} \sim p_{\mathrm{T}}^{\mathrm{bkg}}$

ALICE: arXiv:2303.00592





- **ML-based approach -** improve background resolution using NN trained on PYTHIA jets

- **Leading track bias approach -** guarantee selection jets with hard component