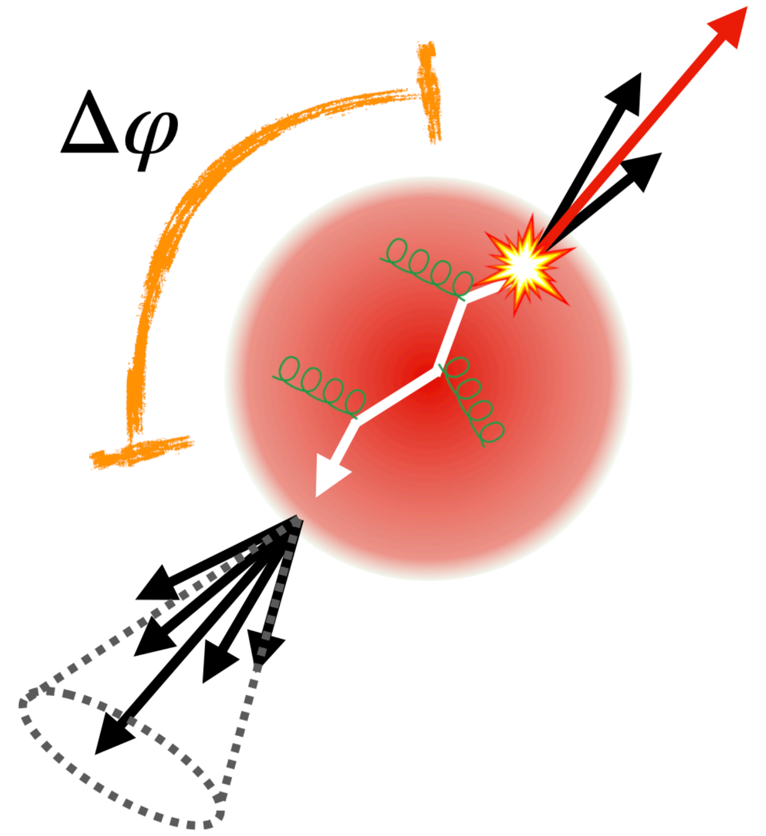


Probing jet energy redistribution and broadening in heavy-ion collisions with ALICE at the LHC

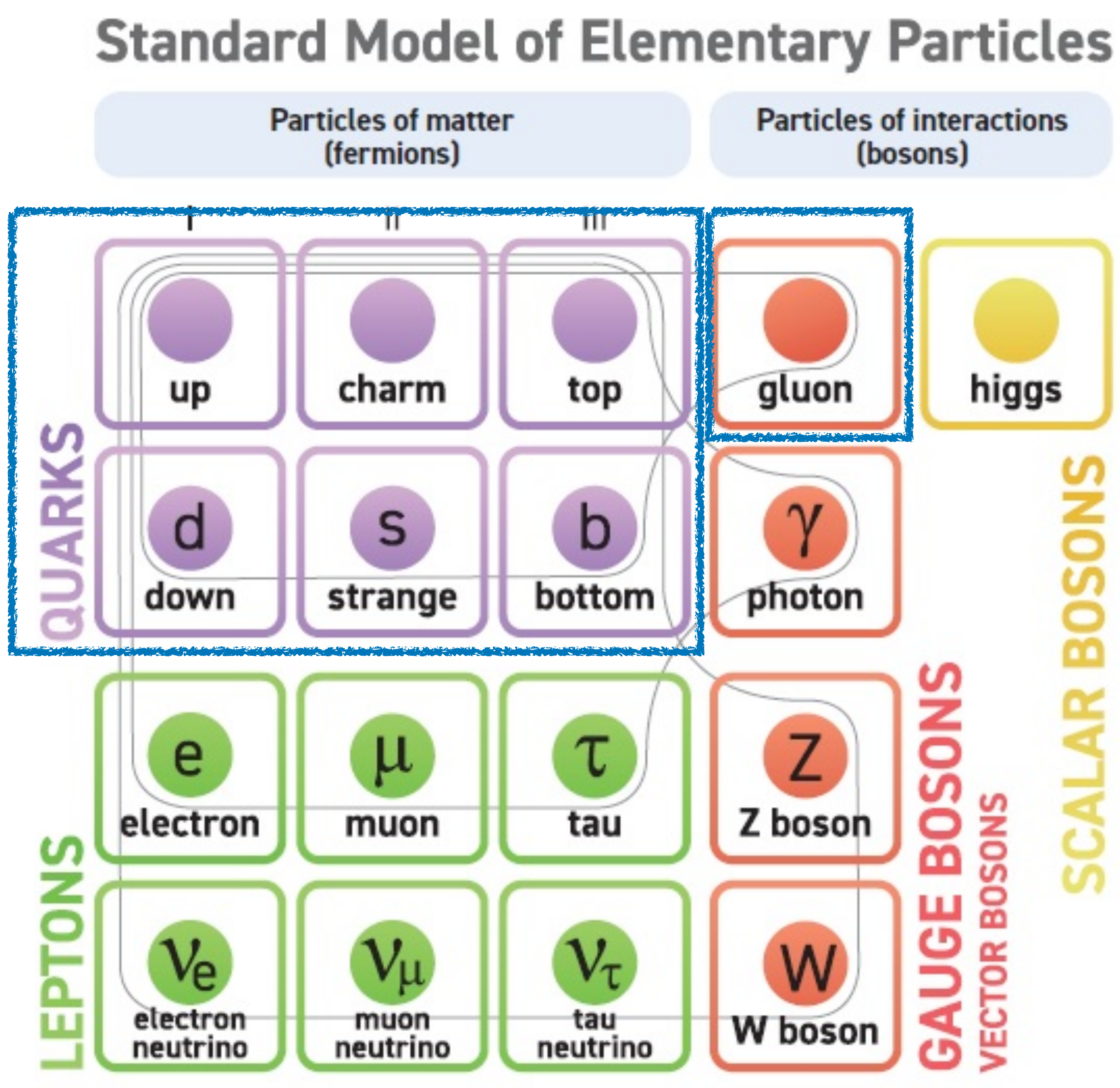
Jaime Norman (University of Liverpool)
Liverpool HEP seminar
15th March 2024

UNIVERSITY OF LIVERPOOL

ALICE

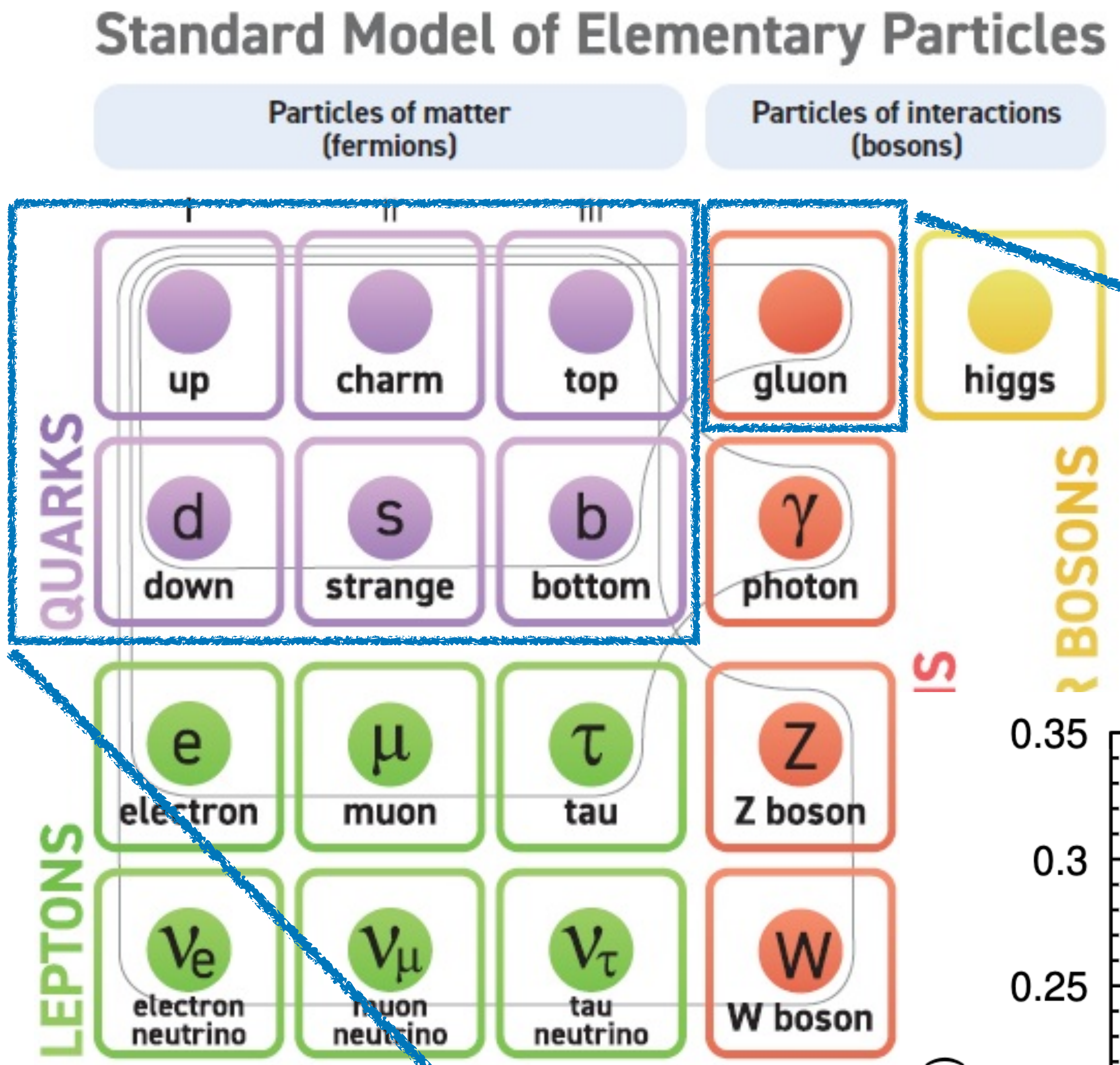
jknorman@liverpool.ac.uk

Quantum Chromodynamics within the standard model

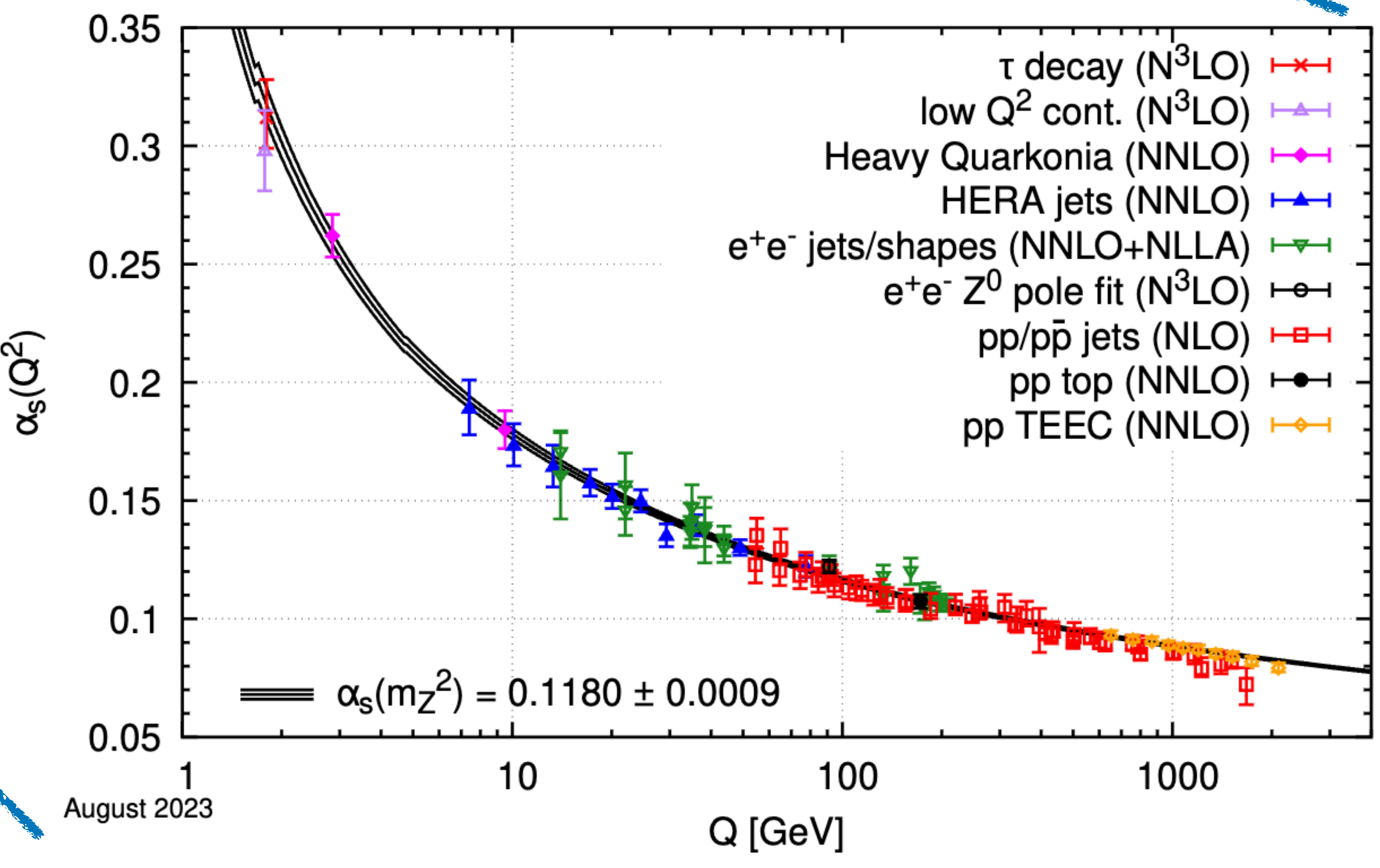


- Quantum Chromodynamics (QCD) - the Quantum field theory that describes quarks and their force mediators, gluons

Quantum Chromodynamics within the standard model



- Quantum Chromodynamics (QCD) - the Quantum field theory that describes quarks and their force mediators, gluons
- QCD coupling constant α_s weakens with increasing momentum transfer Q / decreasing distance scale
  → **asymptotic freedom**



- Quarks and gluons form hadrons and thus atomic nuclei - **QCD central to atomic/nuclear physics**
- What is the structure of QCD matter over a range of energies/densities?

The different phases of nuclear matter

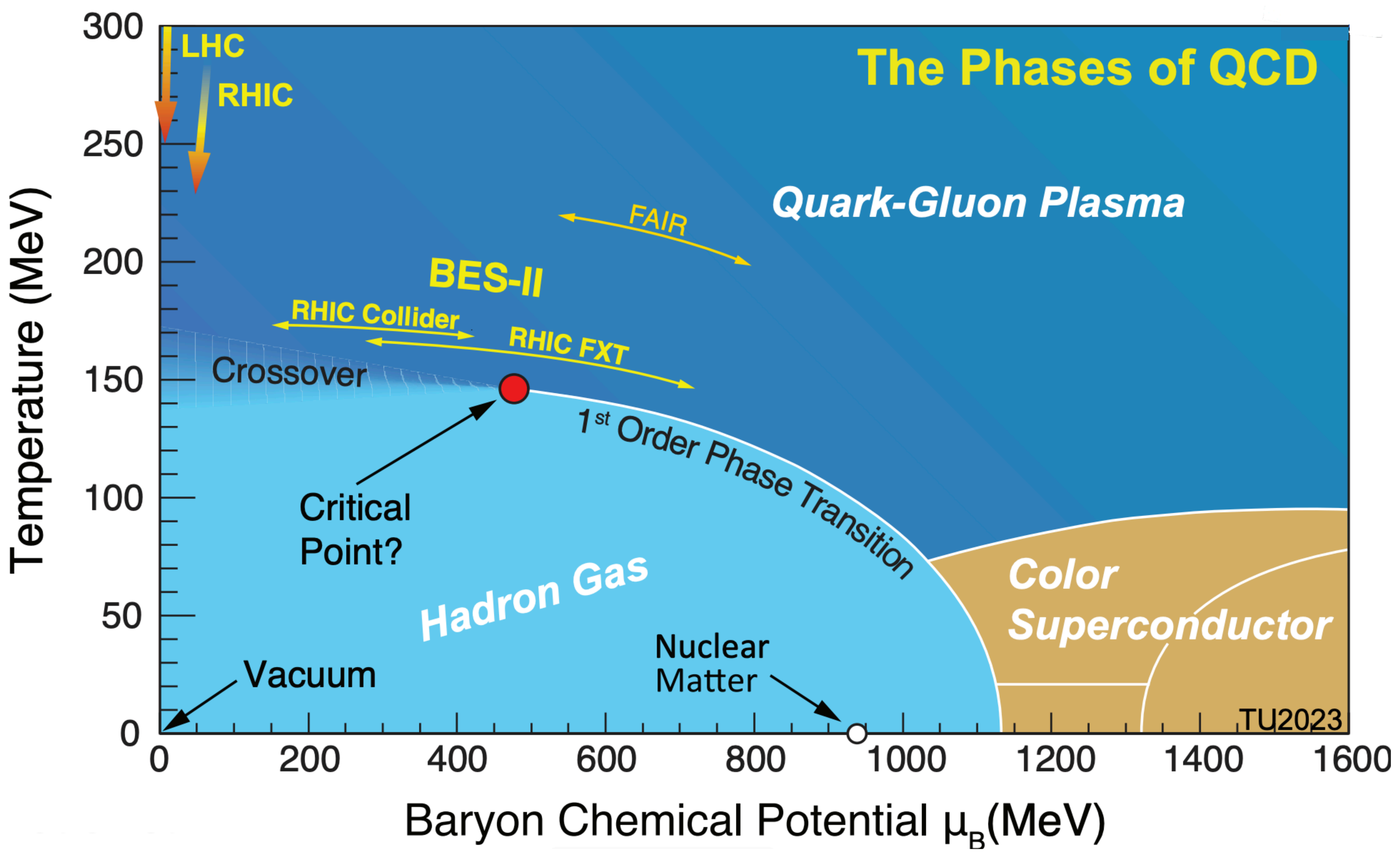


fig. H. Caines

The different phases of nuclear matter

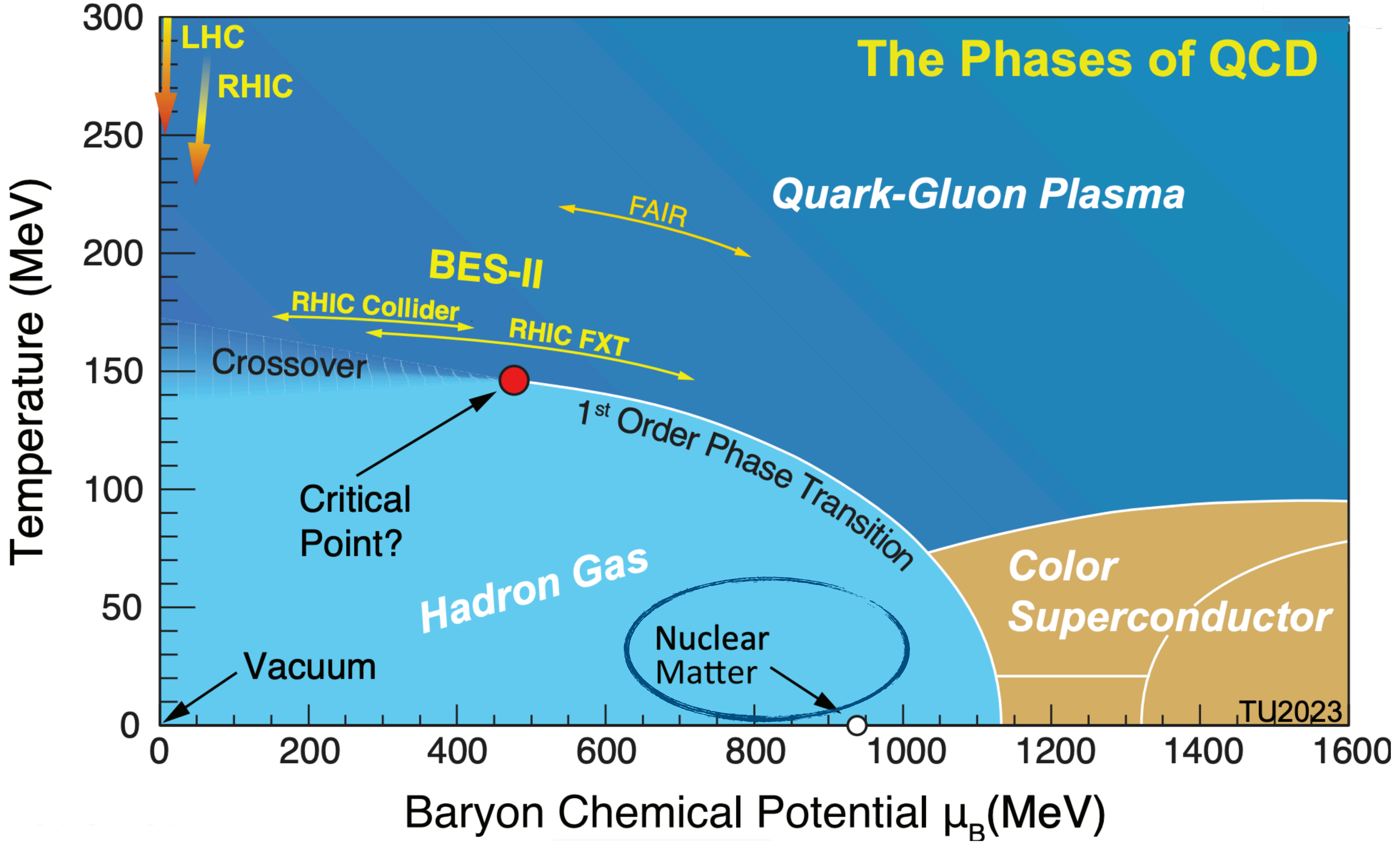


fig. H. Caines

- **Ordinary nuclei** exists at low temperature and high density

The different phases of nuclear matter

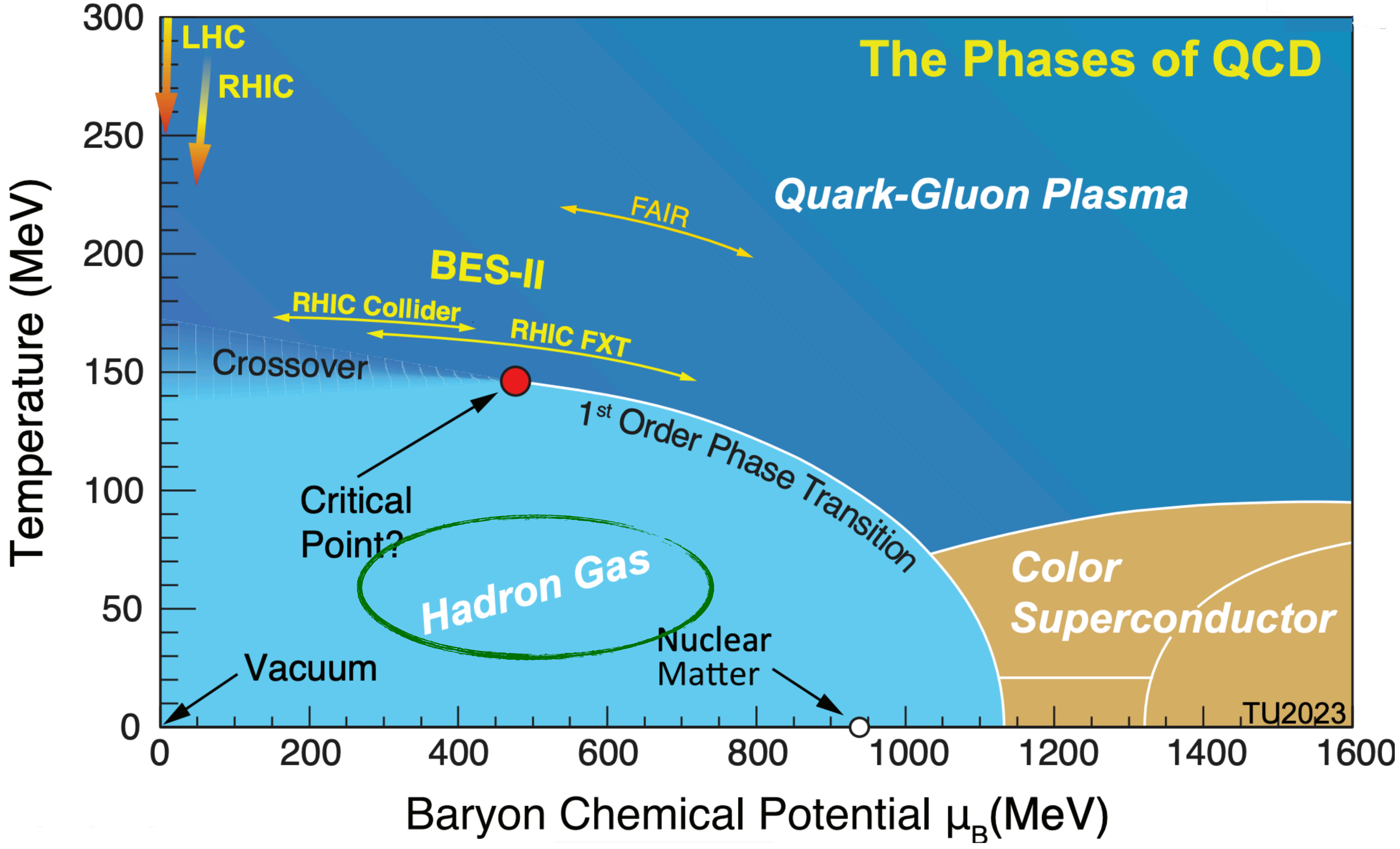


fig. H. Caines

- **Ordinary nuclei** exists at low temperature and high density
- Increasing temperature leads nuclei to break up and form **Hadron Gas**

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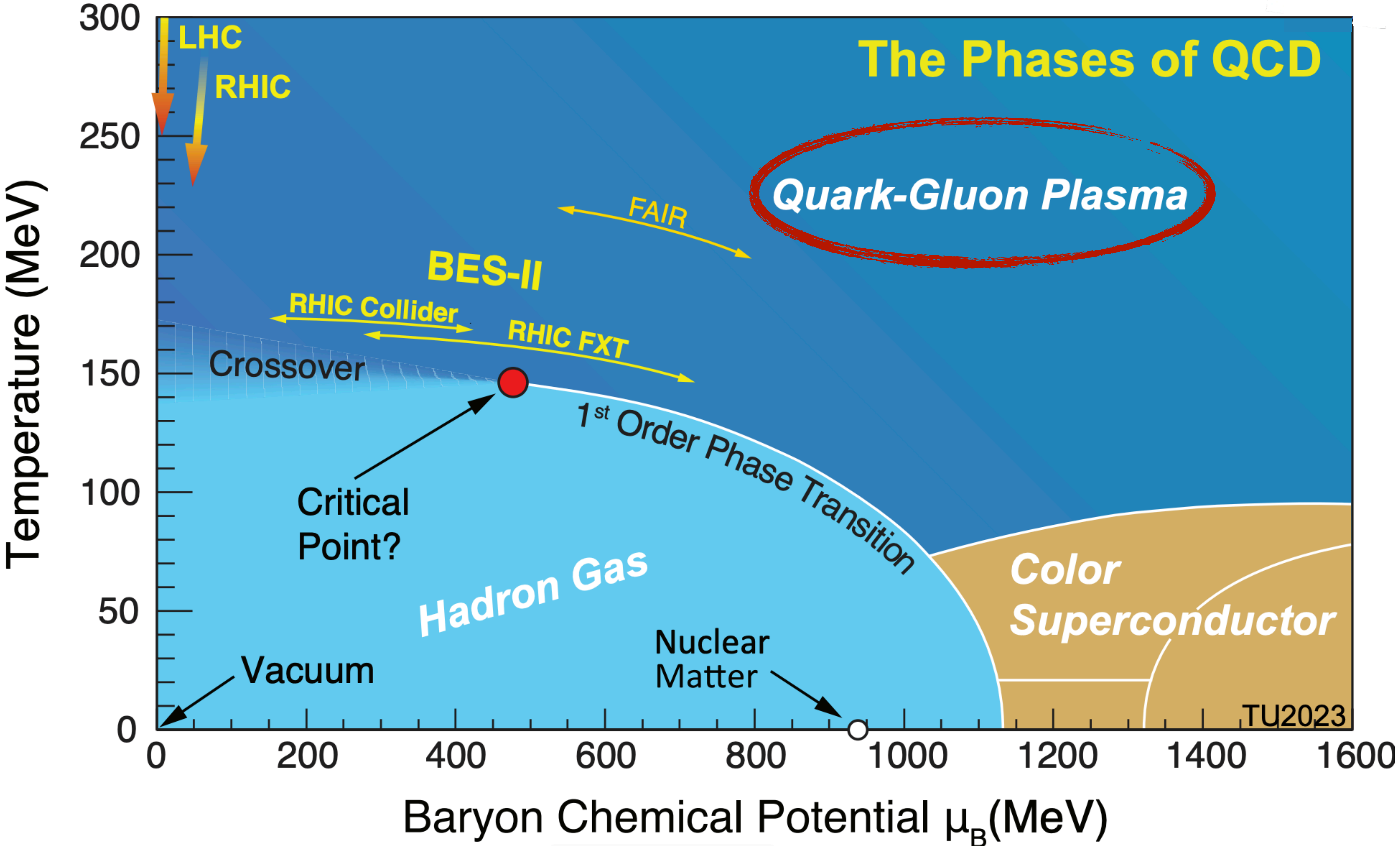

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- **Ordinary nuclei** exists at low temperature and high density
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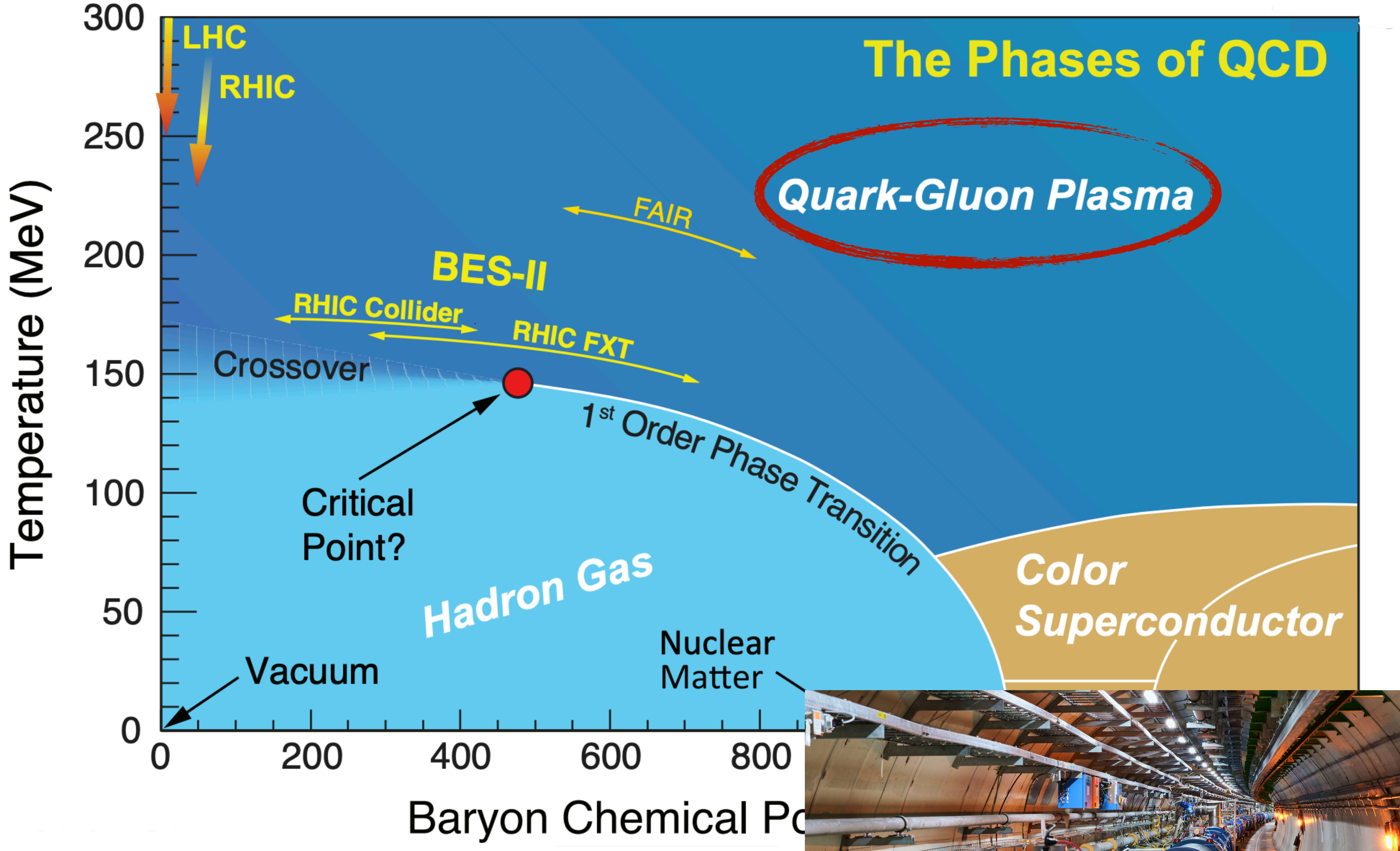
- Phase transition at very high temperature or density to deconfined state of quarks and gluons - **Quark-Gluon Plasma (QGP)**
  - smooth phase transition at ~155 MeV at low baryon density

The different phases of nuclear matter



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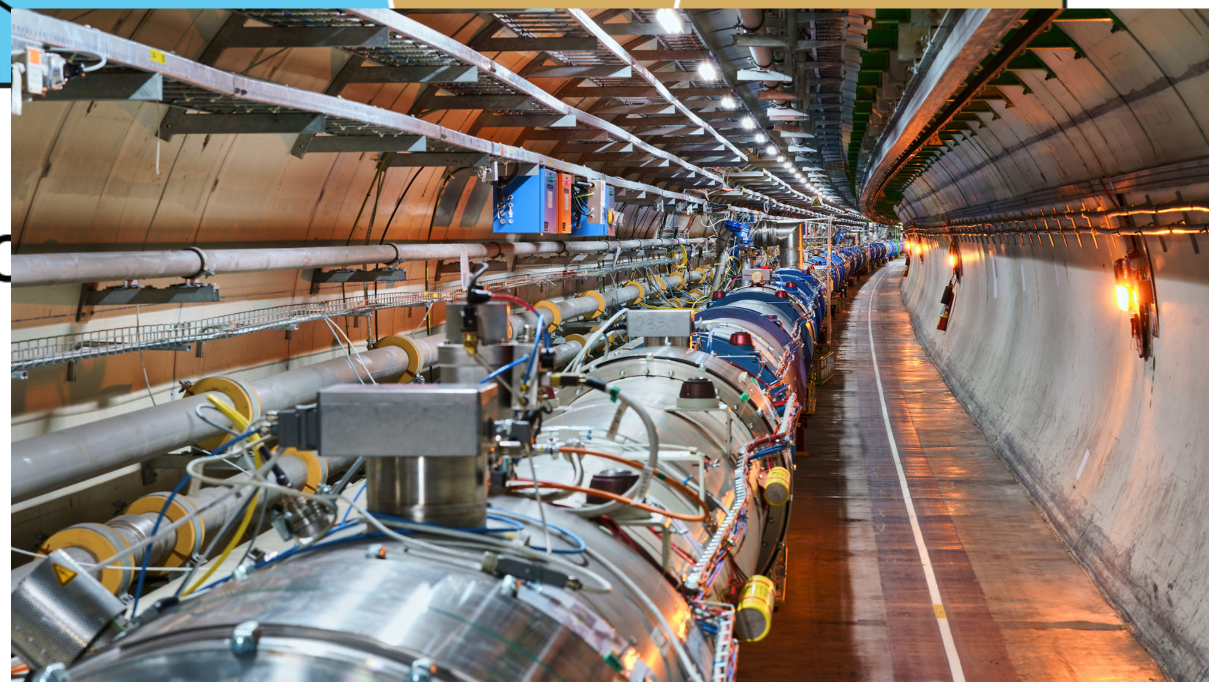
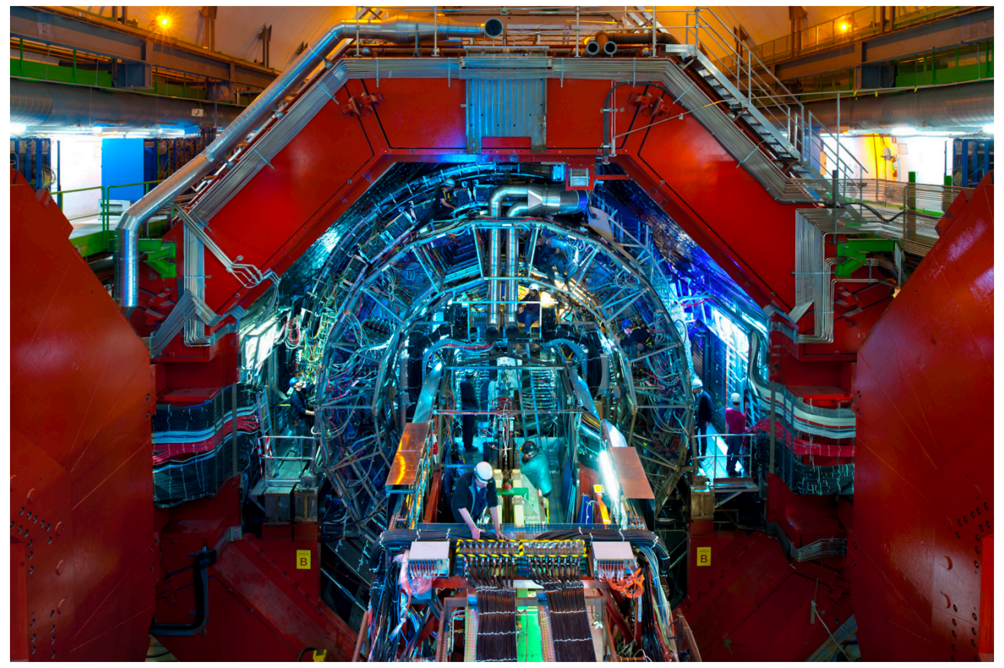


- **Ordinary nuclei** exists at low temperature and high density
- Increasing temperature leads nuclei to break up and form **Hadron Gas**
- Phase transition at very high temperature or density to deconfined state of quarks and gluons - **Quark-Gluon Plasma (QGP)**
  - smooth phase transition at ~155 MeV at low baryon density
- Created experimentally using **ultra-relativistic heavy-ion collisions**
  - For one month a year, the LHC collides lead ions (Pb-Pb collisions) to study the QGP

QGP (in a nutshell)

Long-distance structure:

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



P. Romatschke

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

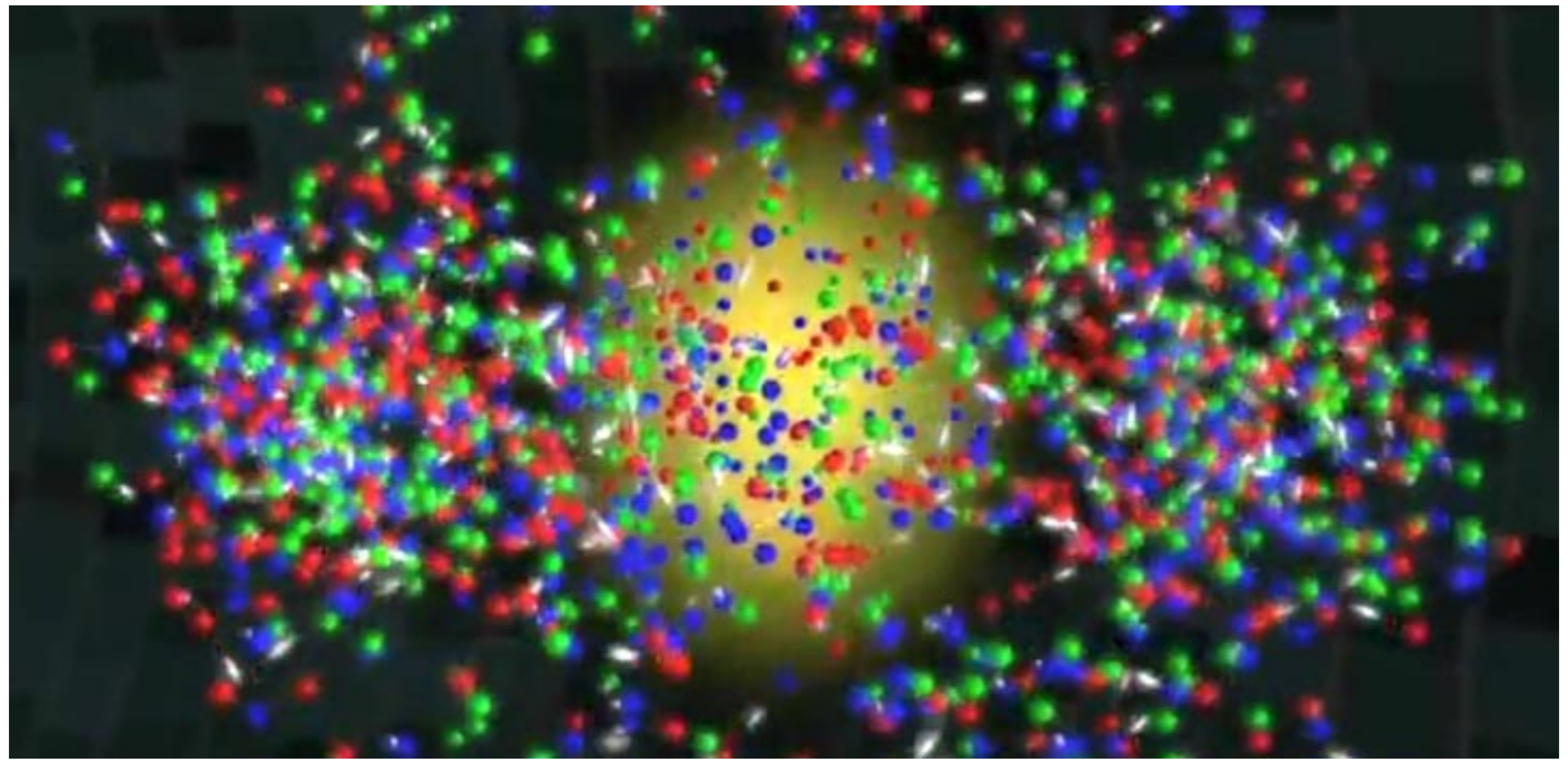
$\eta/s \sim$ **0.12**

- 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

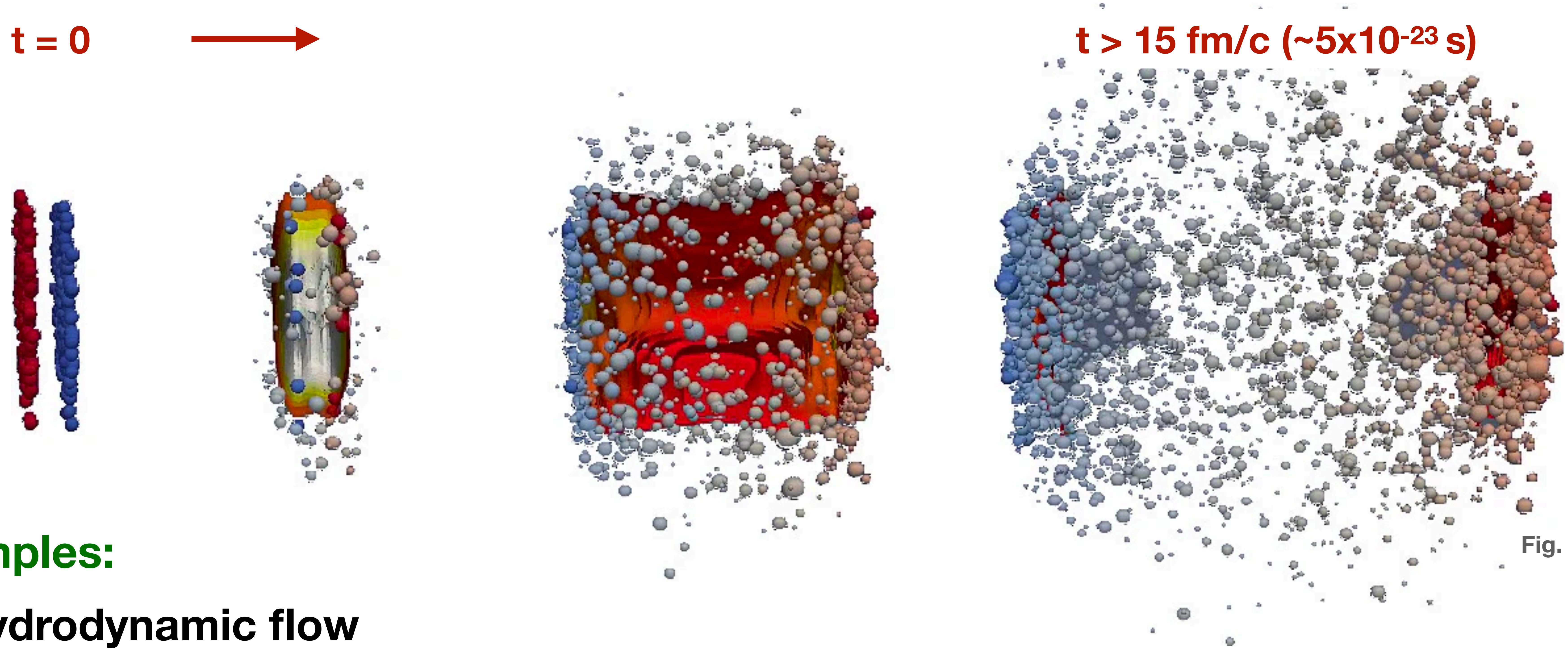


Fig. MADAI collaboration

Examples:

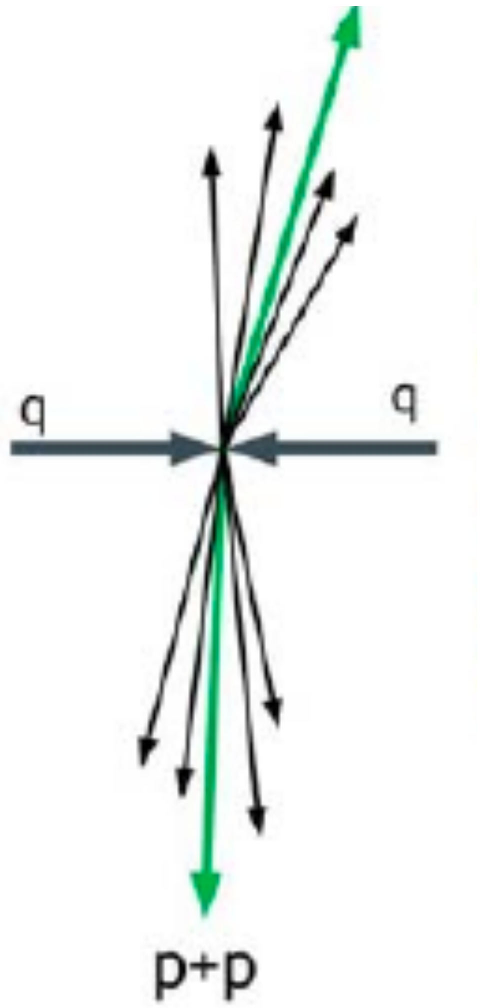
- **Hydrodynamic flow**
- **Hadron chemistry and kinematics**
- **Electromagnetic radiation from QGP**
- **Quarkonium disassociation/regeneration**
- **Partonic interactions with QGP → heavy quarks and jets**

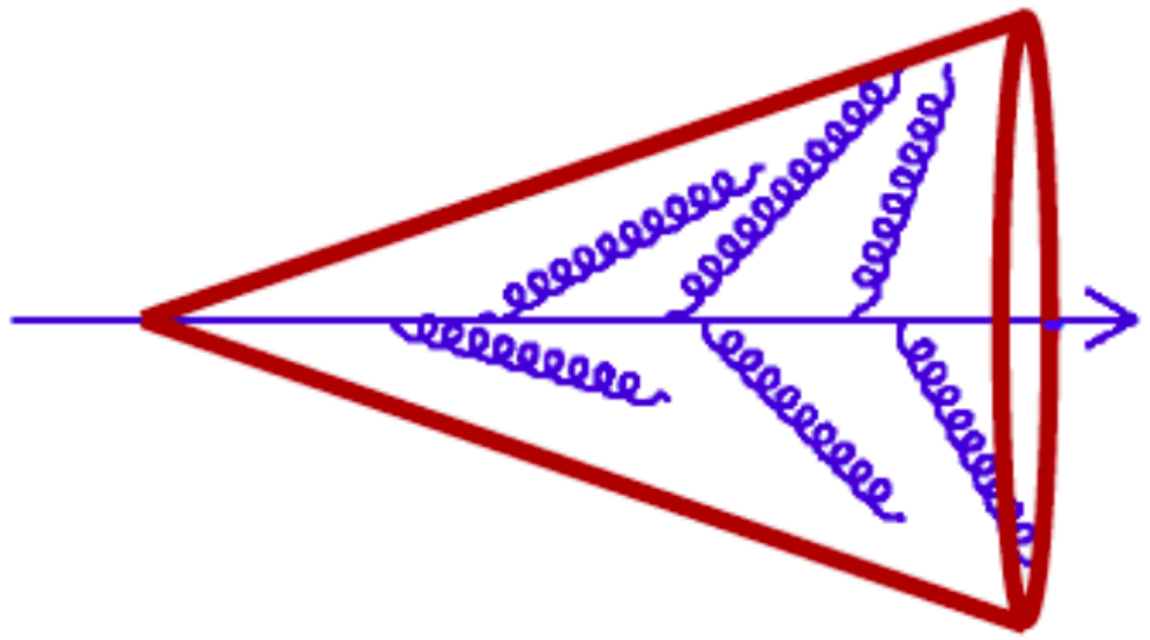
Jets (in vacuum)

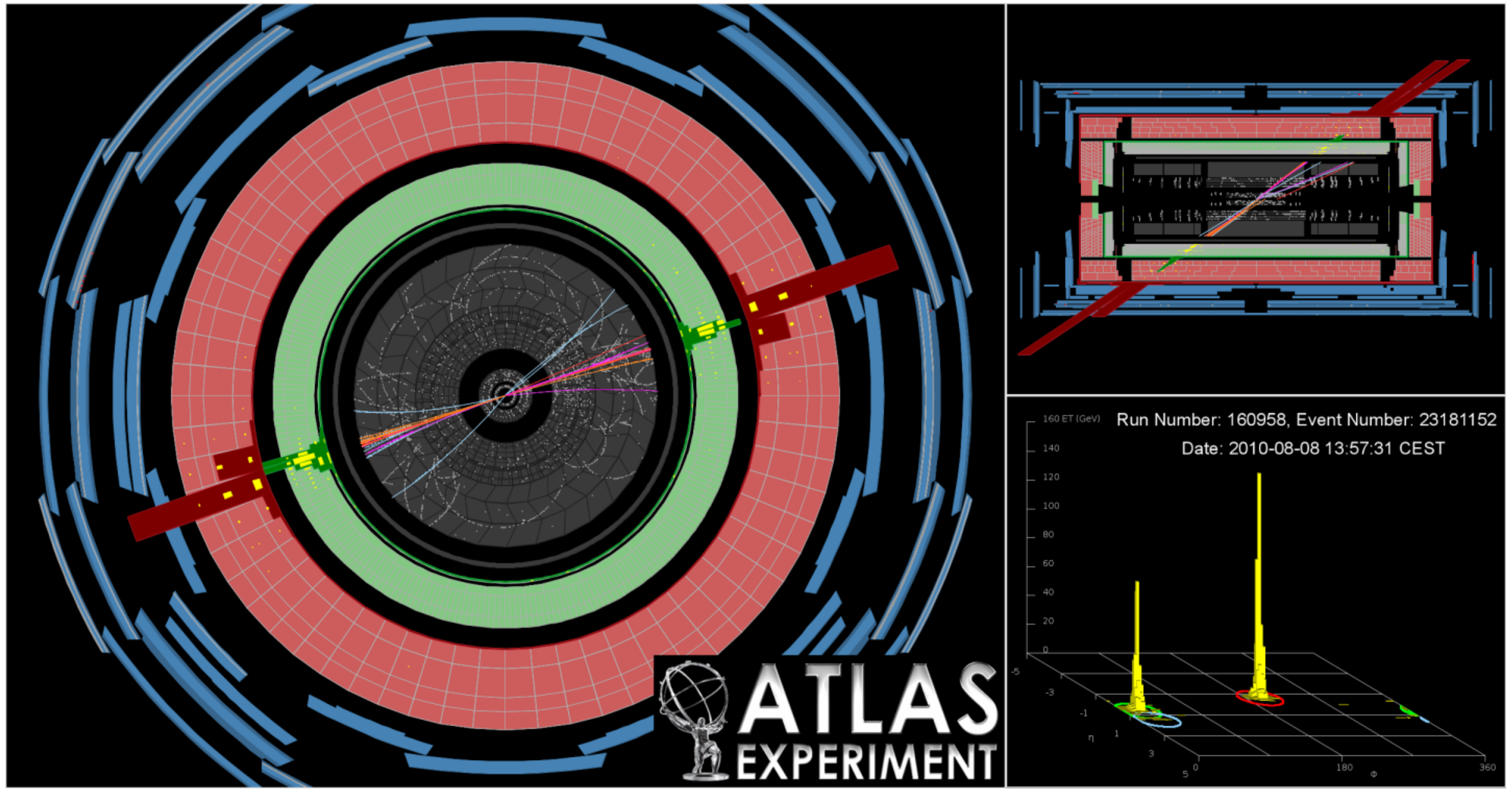
Jet production in proton-proton (pp) collisions

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

Reconstruct jets → measure initiating parton







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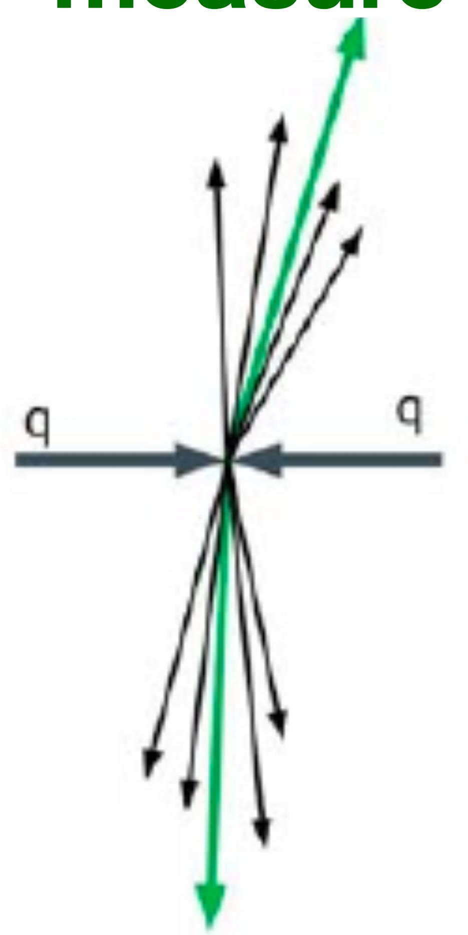
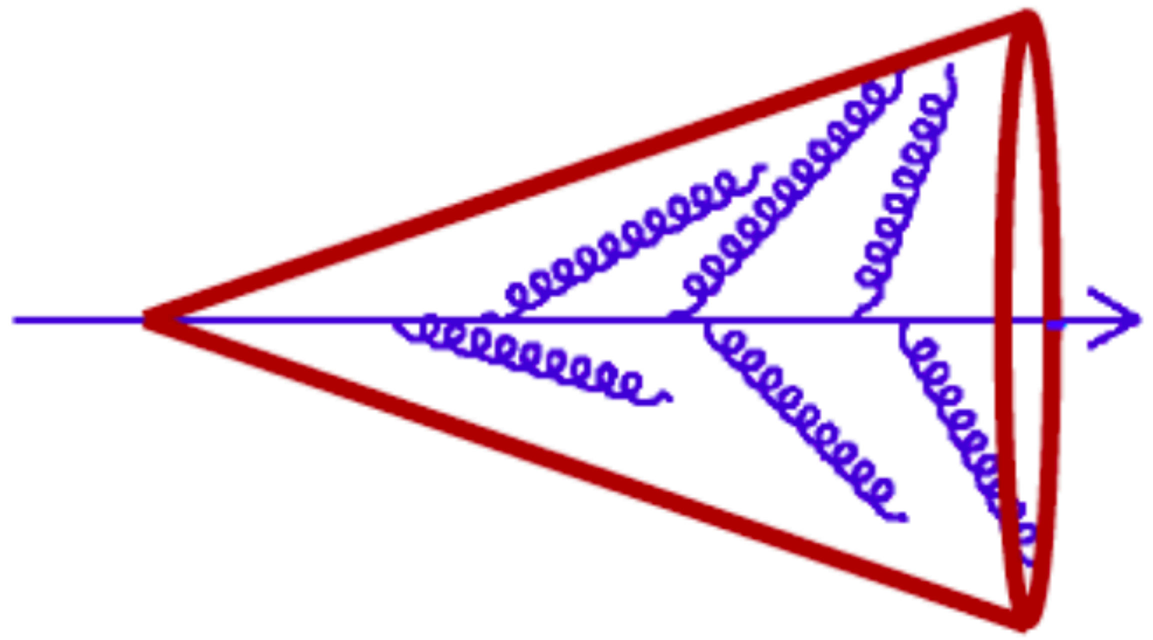
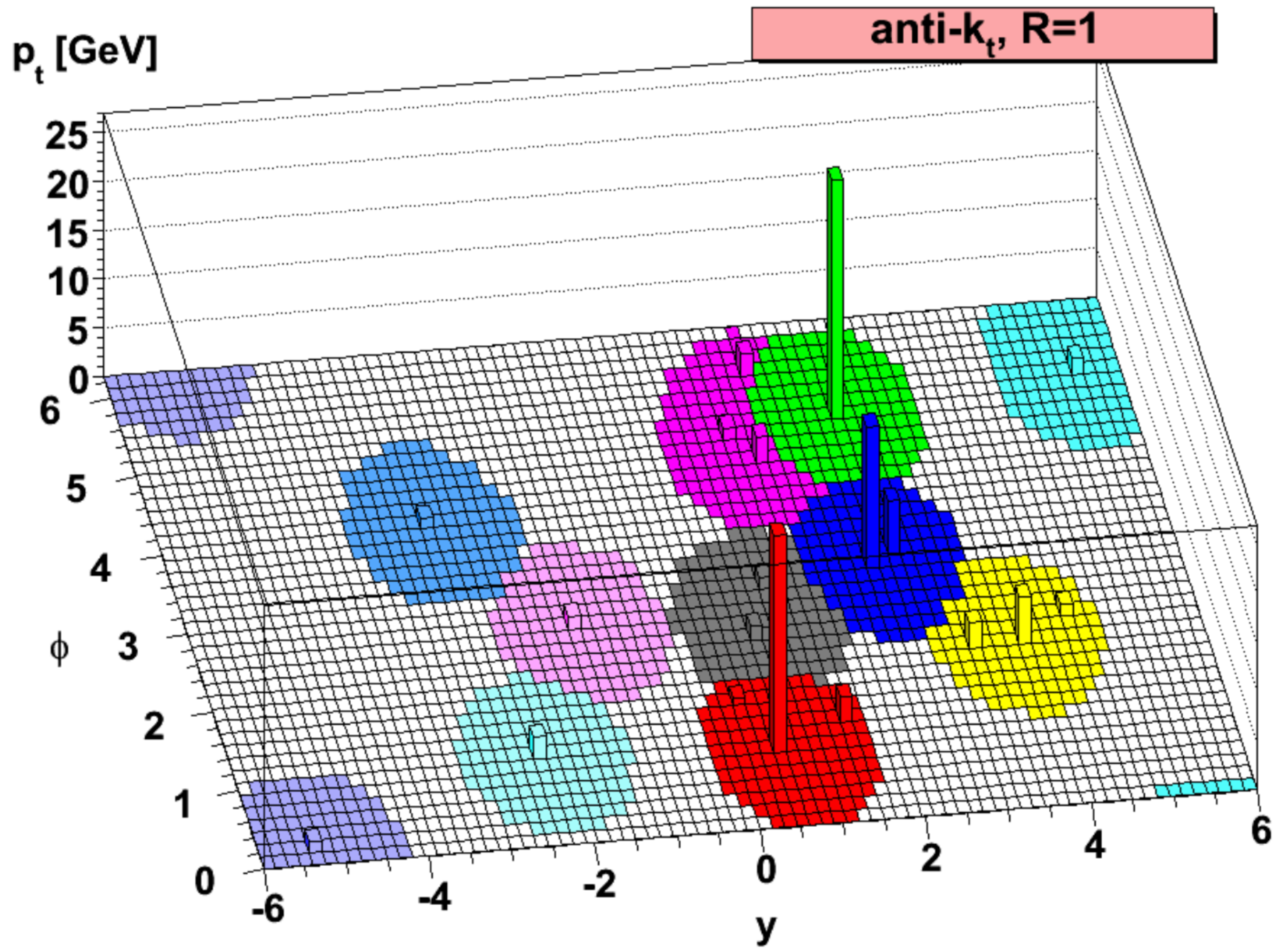




Jet algorithms - precise connection between QCD theory and experiment

- 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

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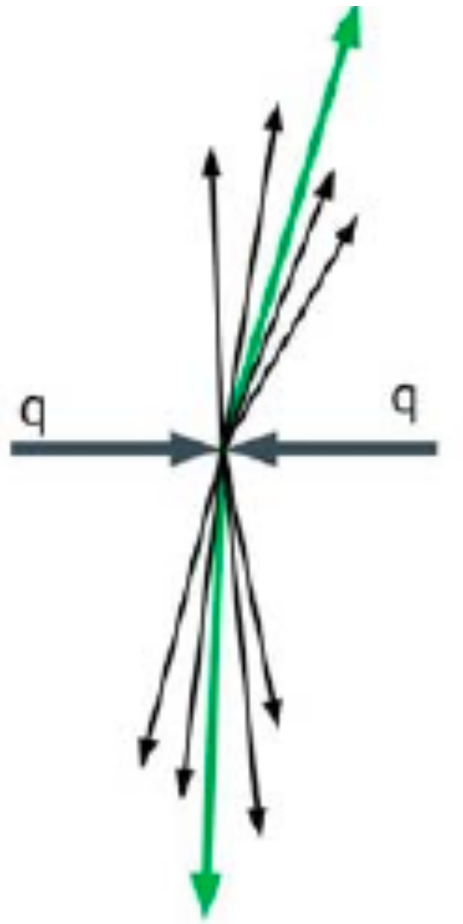
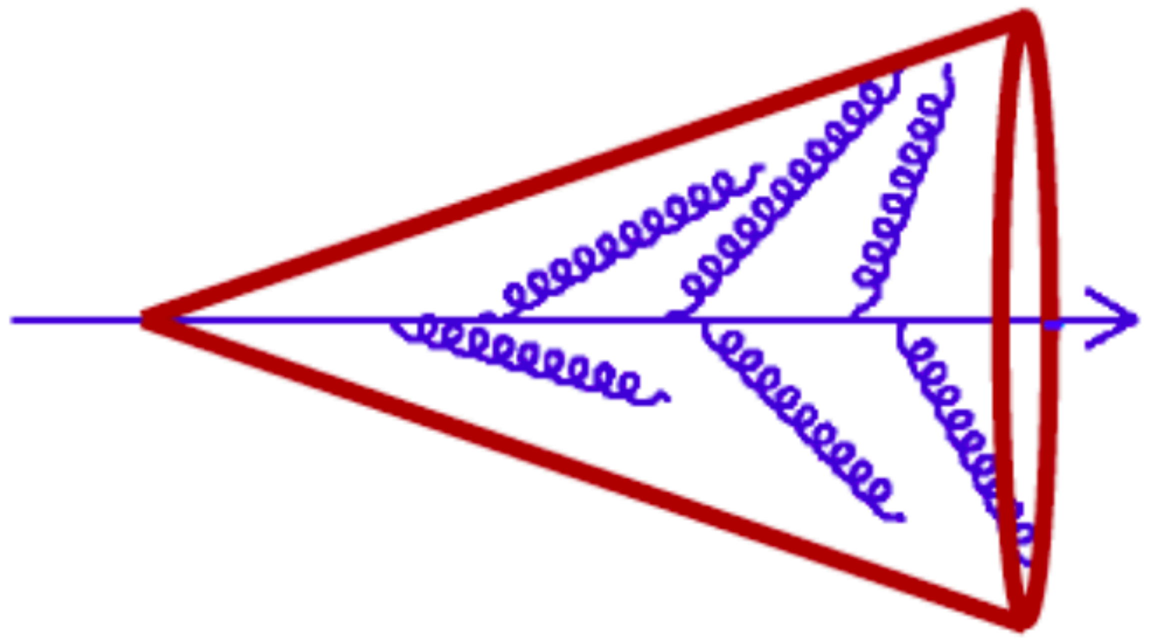
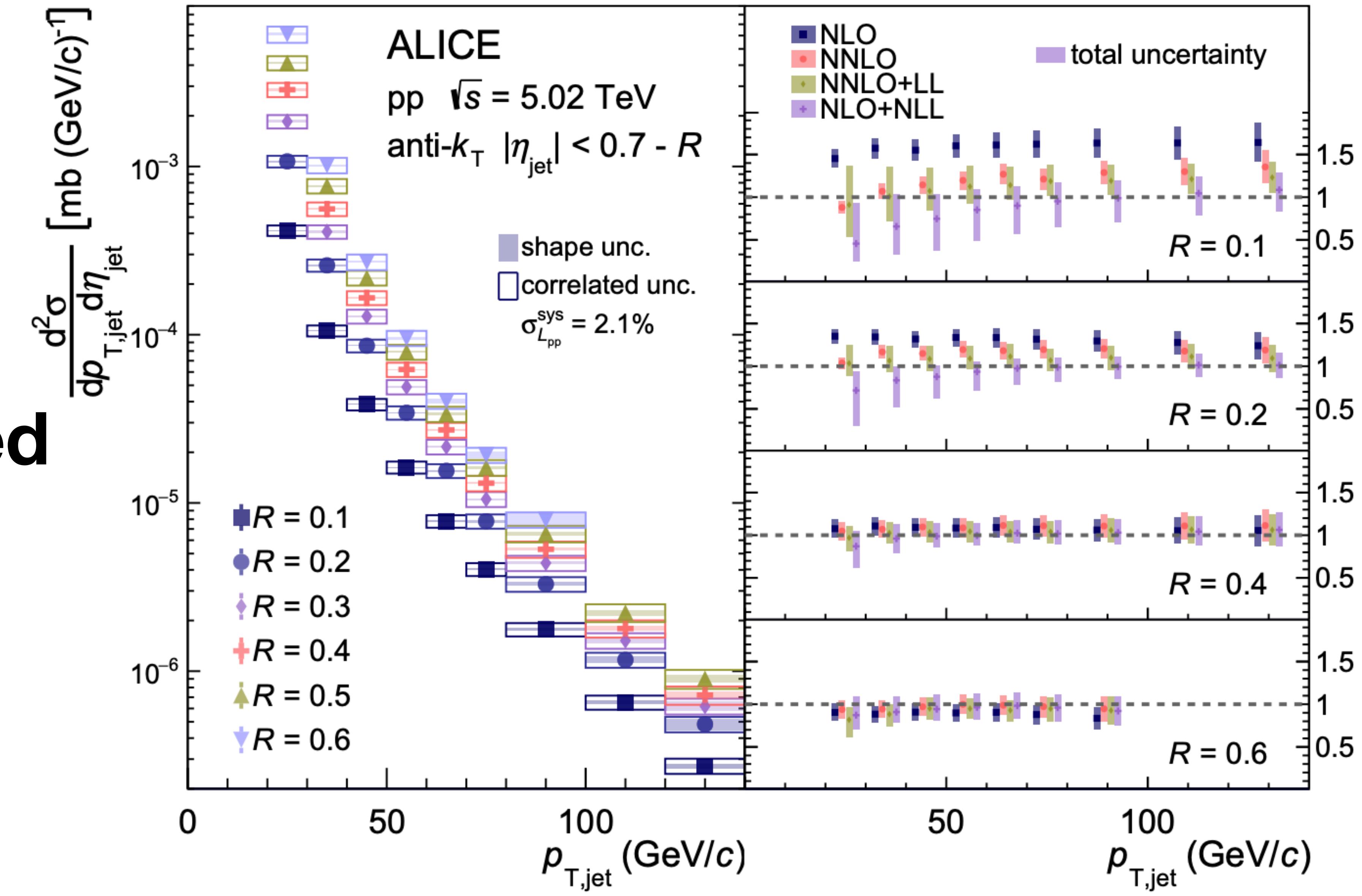
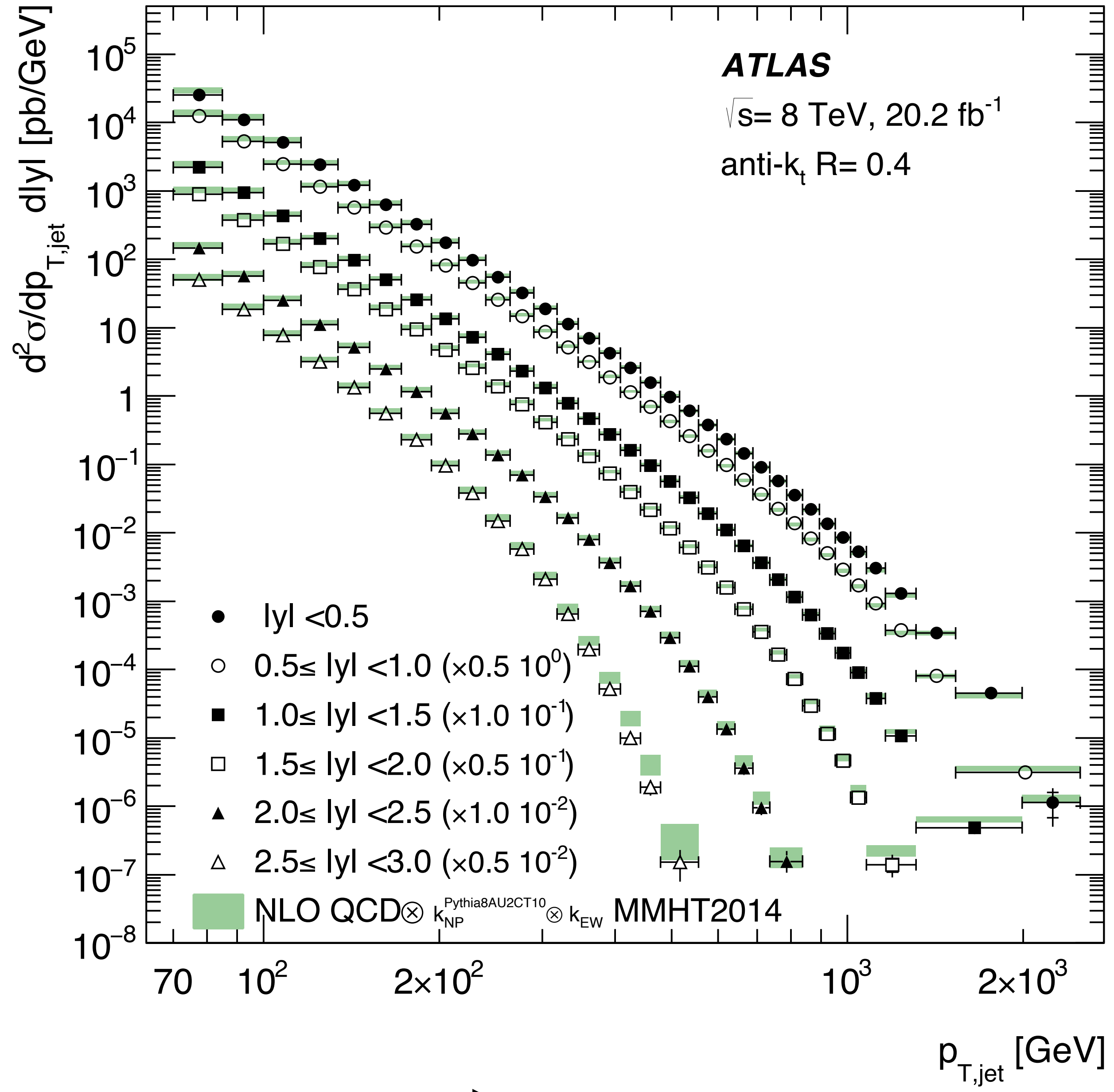




ALICE: arxiv:2211.04384



ATLAS: *JHEP* 09 (2017) 020



$\longrightarrow$ $p_{\mathrm{T,jet}}$

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

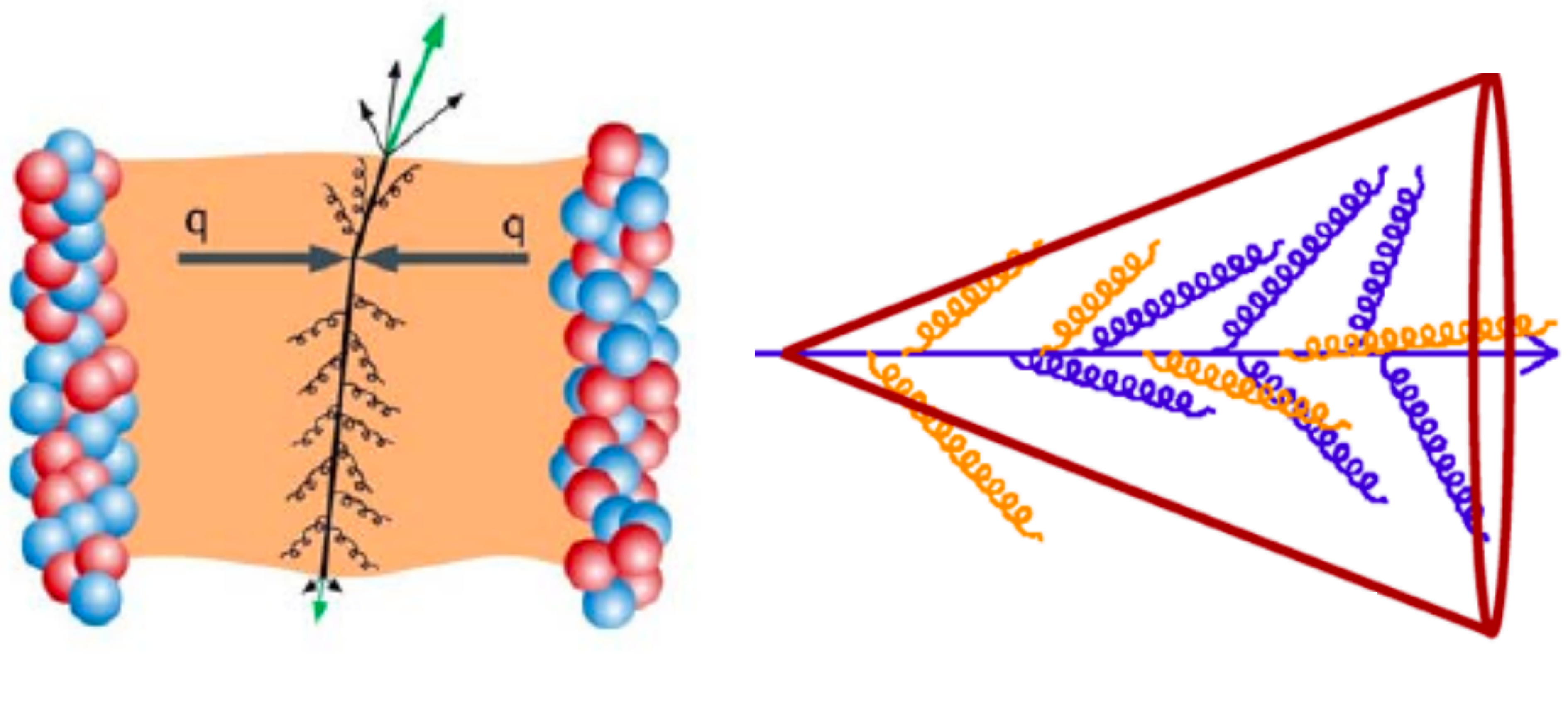
Jets (in medium)

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

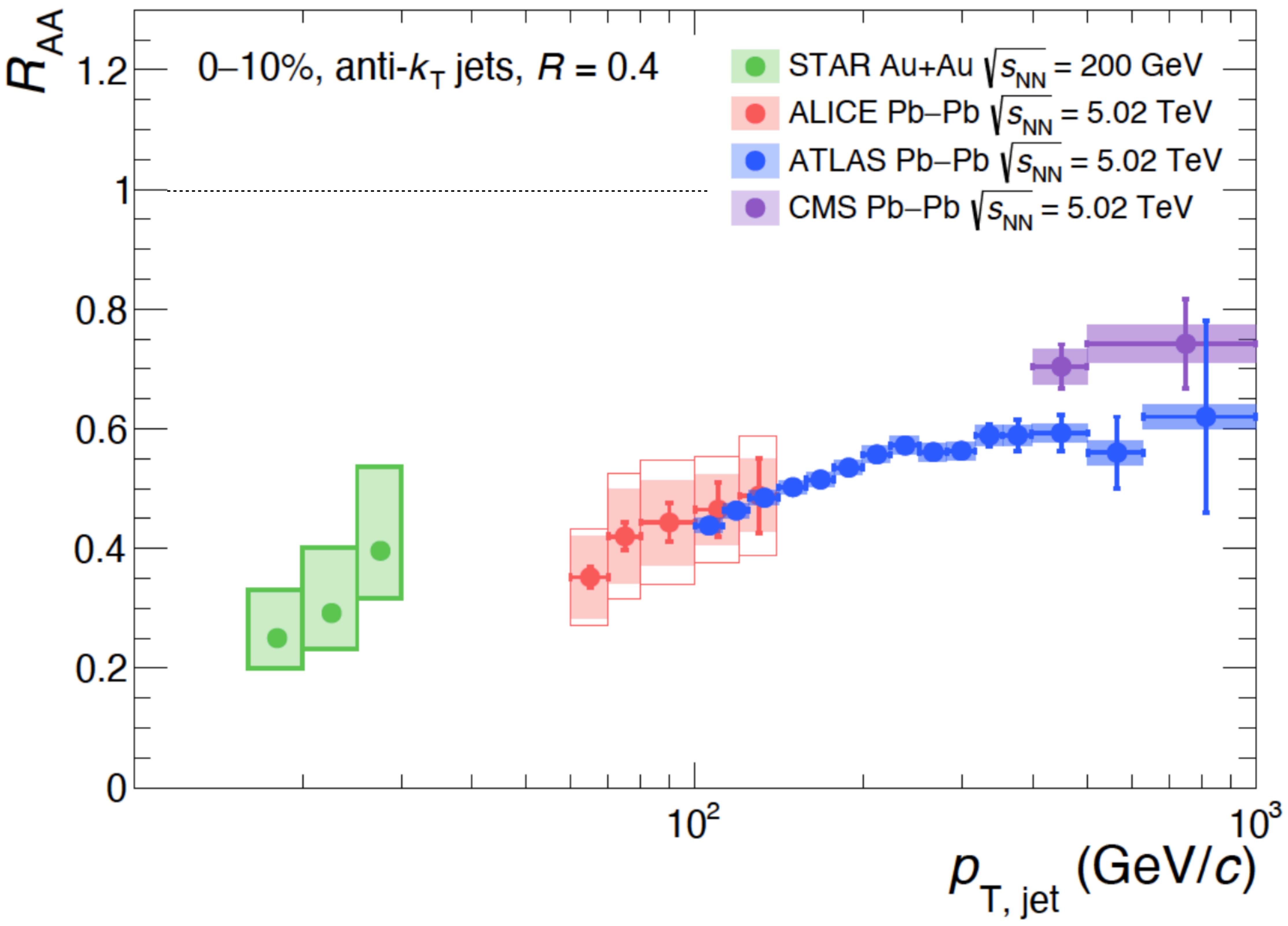
‘Jet quenching’ - partonic interactions in the QGP

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

Jets provide unique probes of the QGP at multiple scales



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

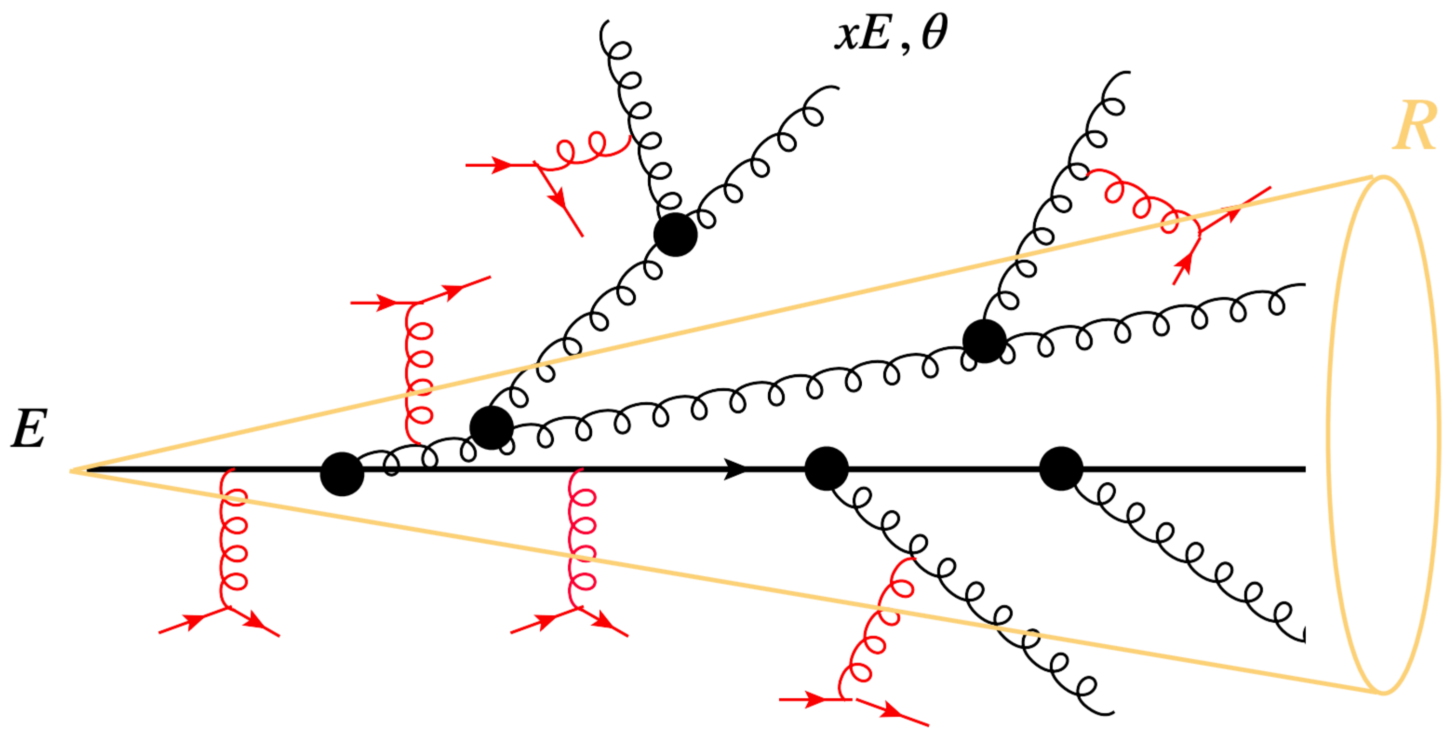


Fig. Y. Mehtar-Tani, S. Schlichting, I. Soudi, JHEP05 (2023) 091

Non-perturbative description

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

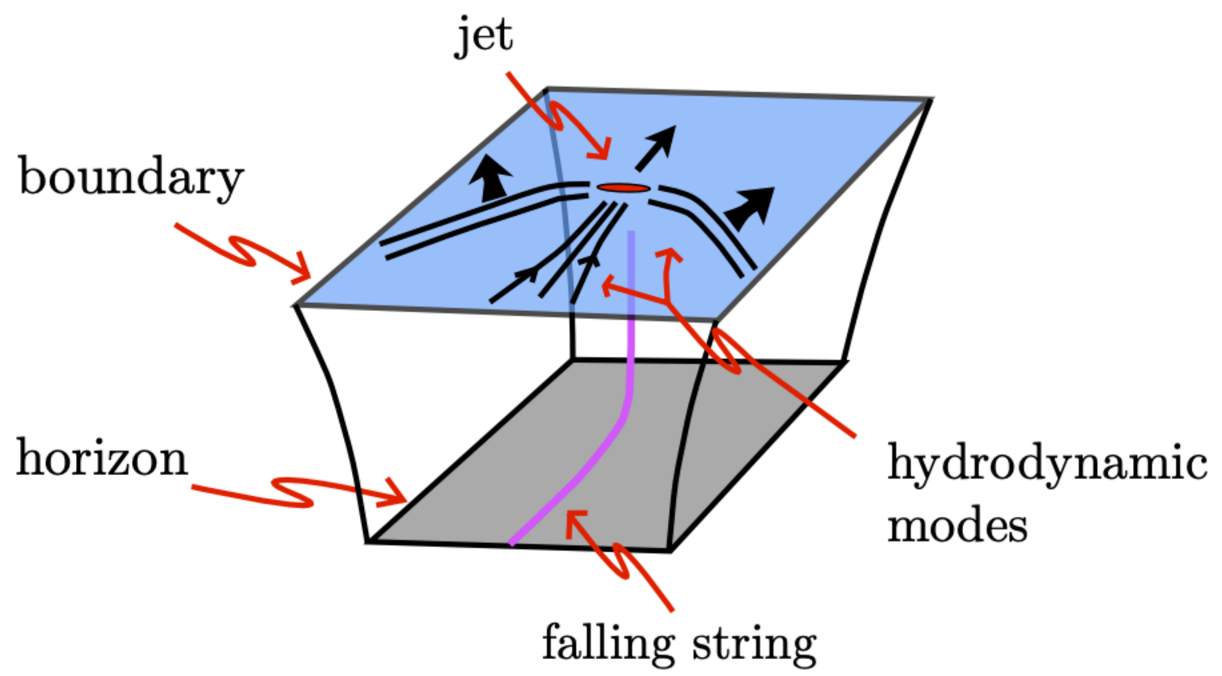


Fig. P. Chesler, K. Rajagopal, *JHEP* 05 (2016) 098

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

How can we probe the inner structure of matter?

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Physicists like scattering experiments!

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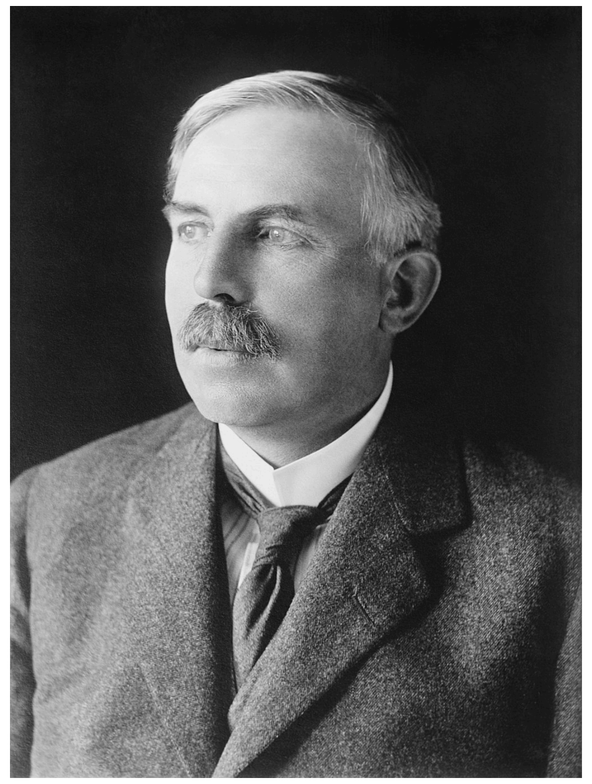
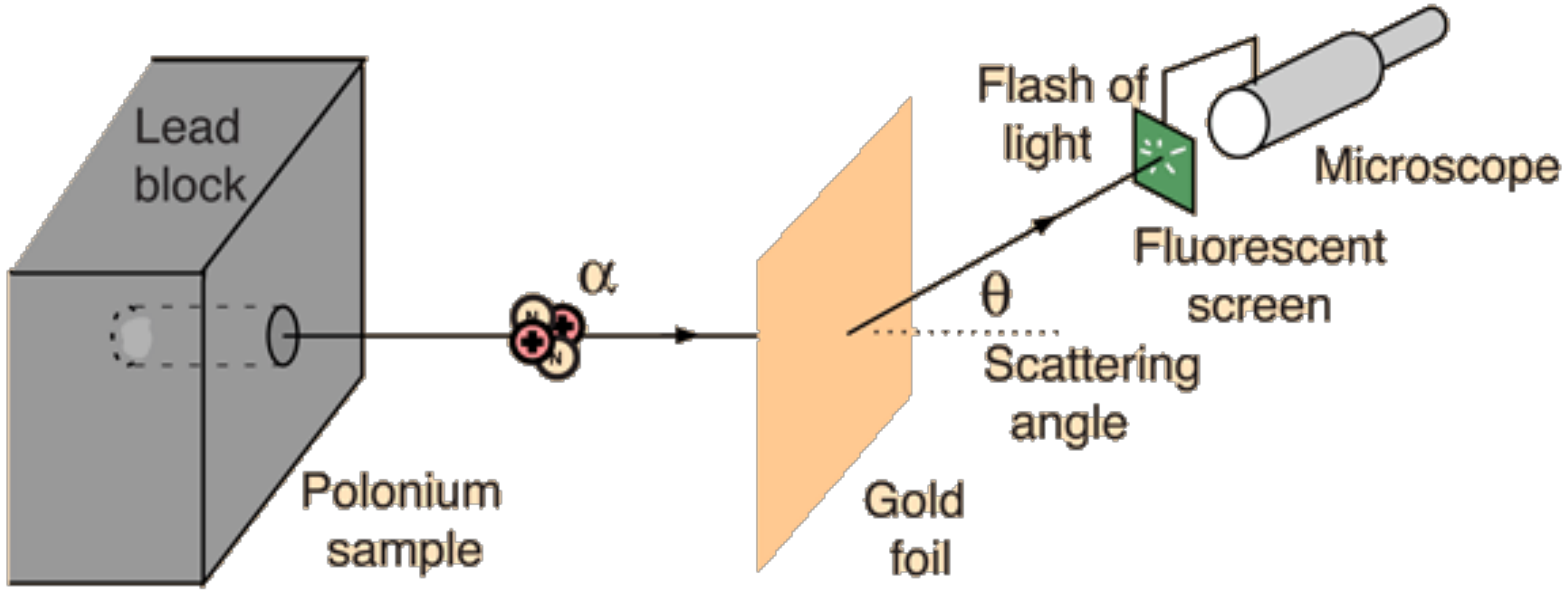
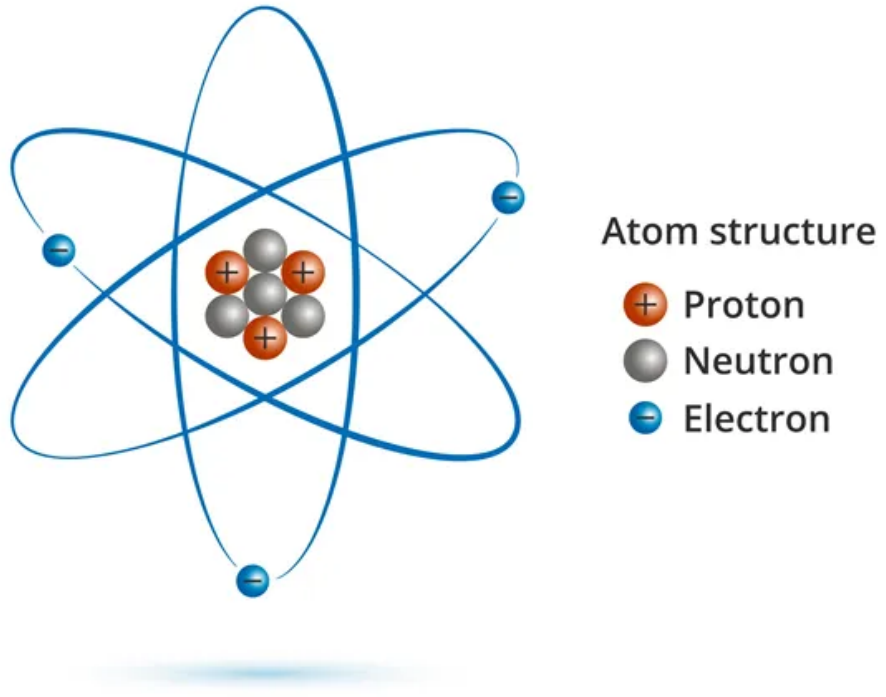
Rutherford, 1911







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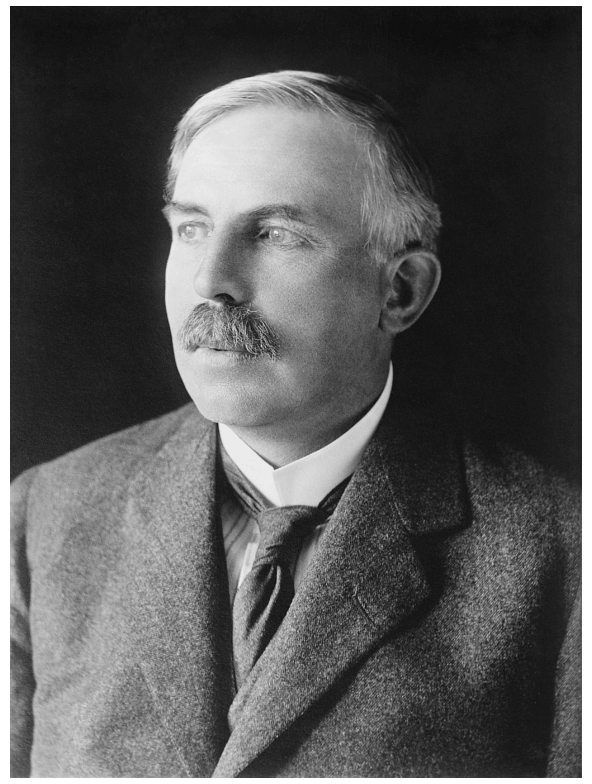
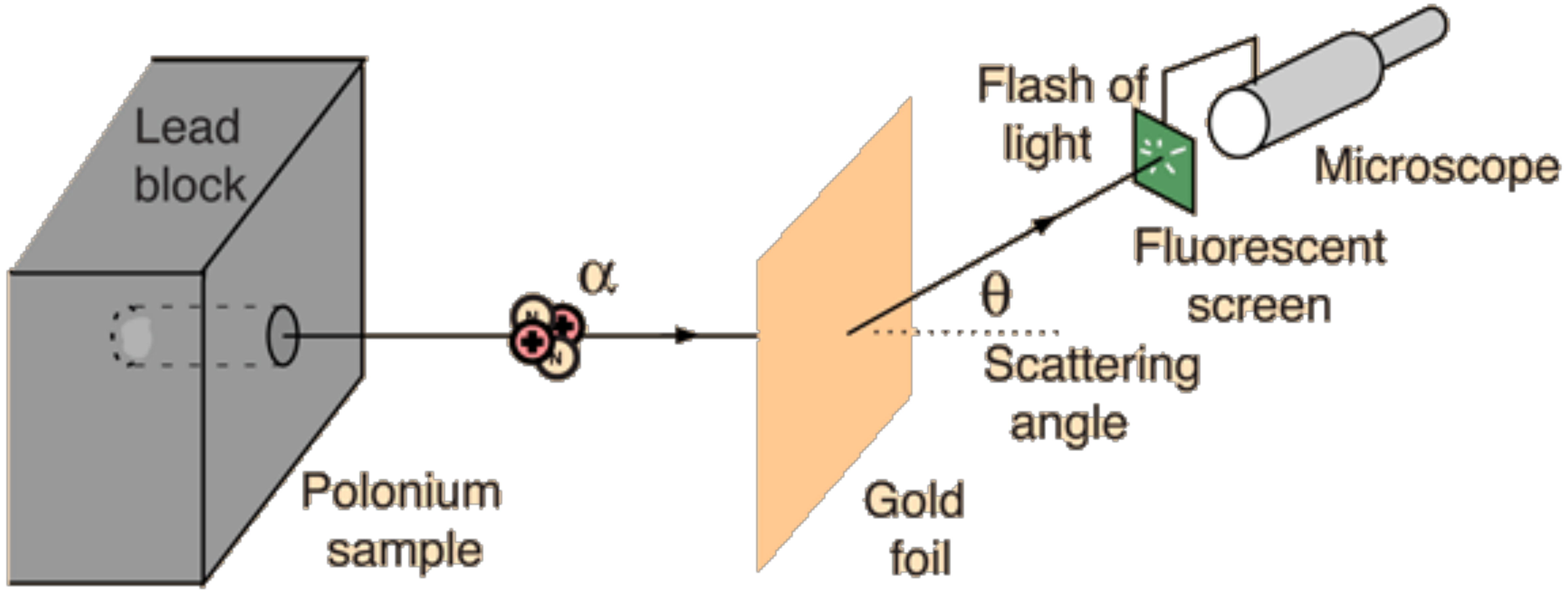
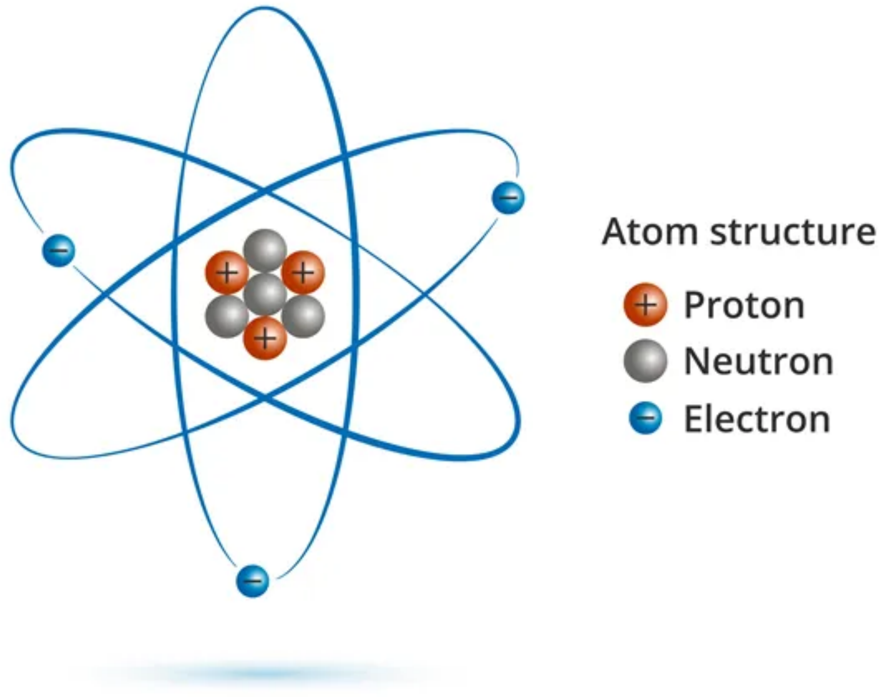
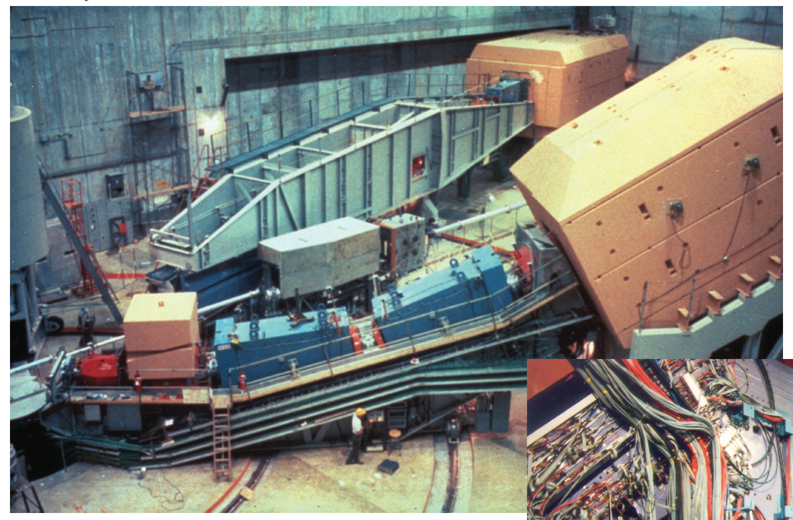


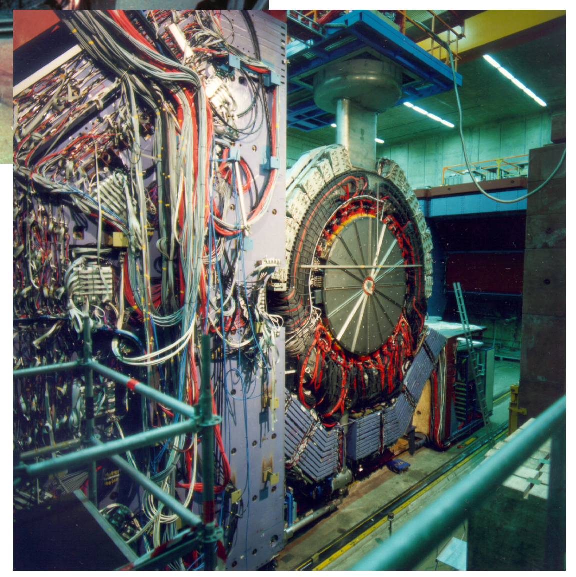




SLAC, 1968



HERA/H1



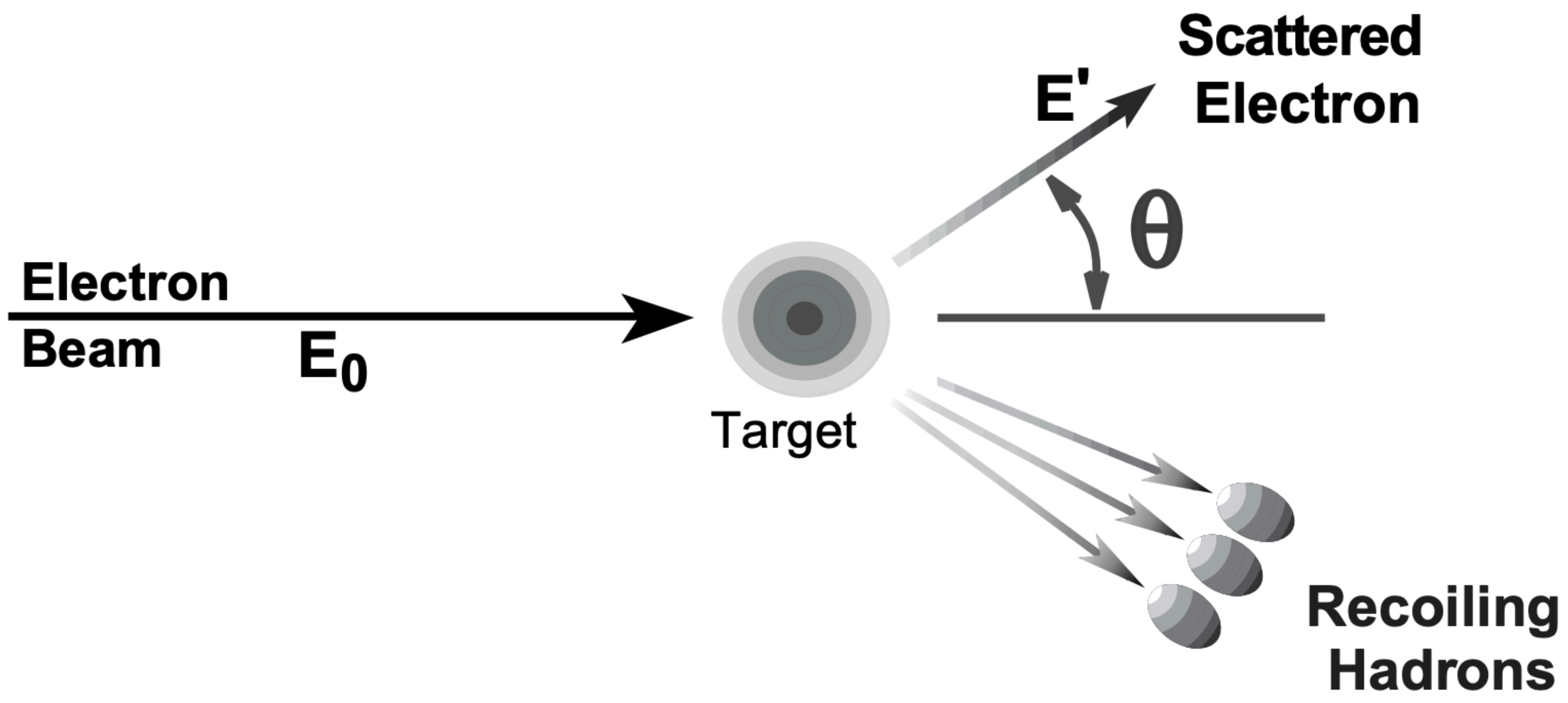
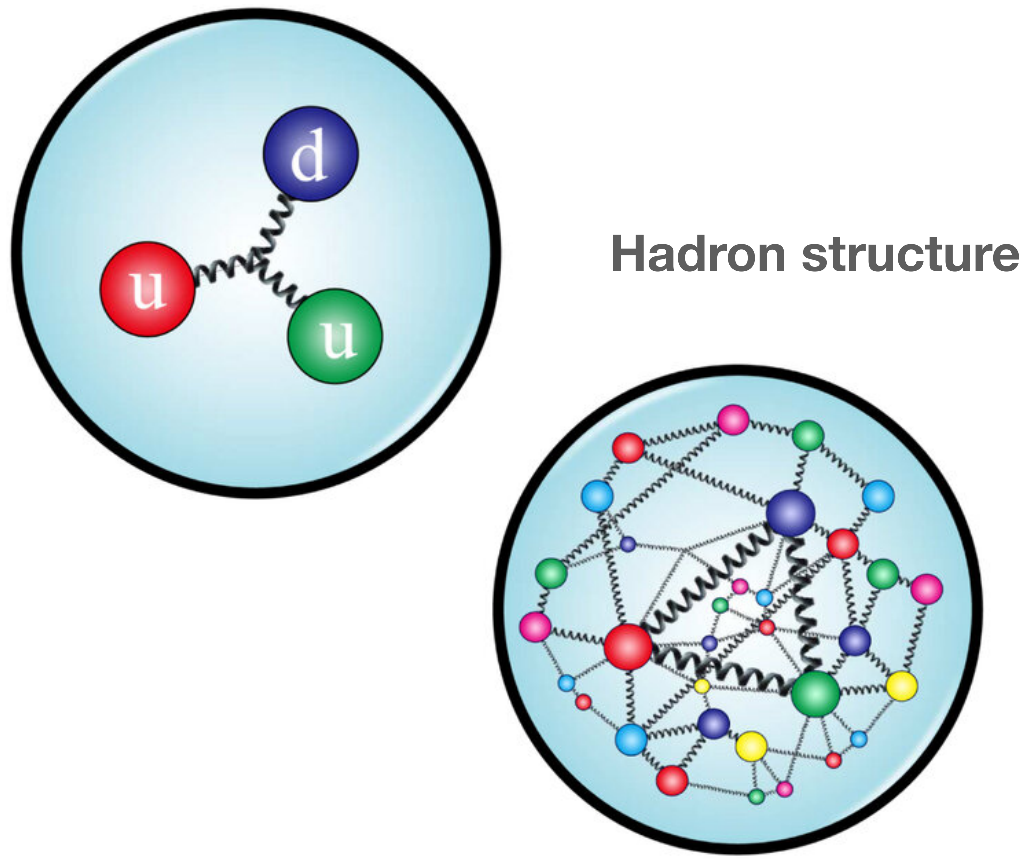
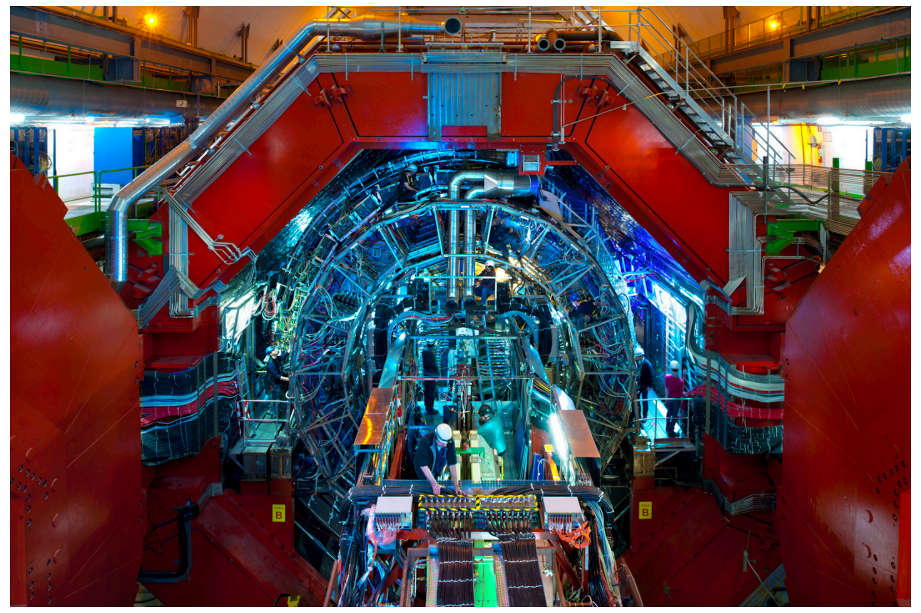


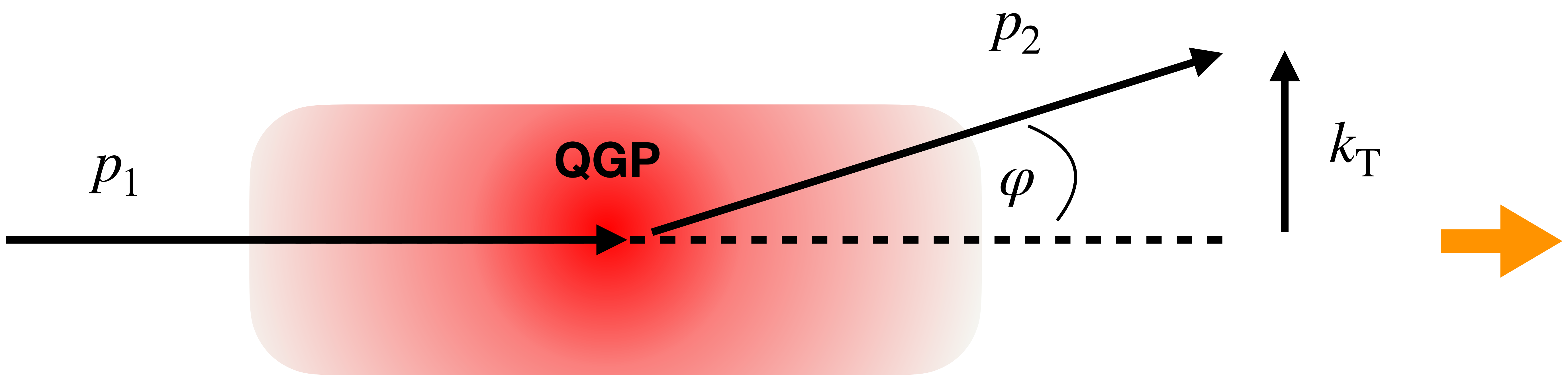
Fig. R.E. Taylor



How can we probe the inner structure of hot QCD matter?

ALICE, 2020s





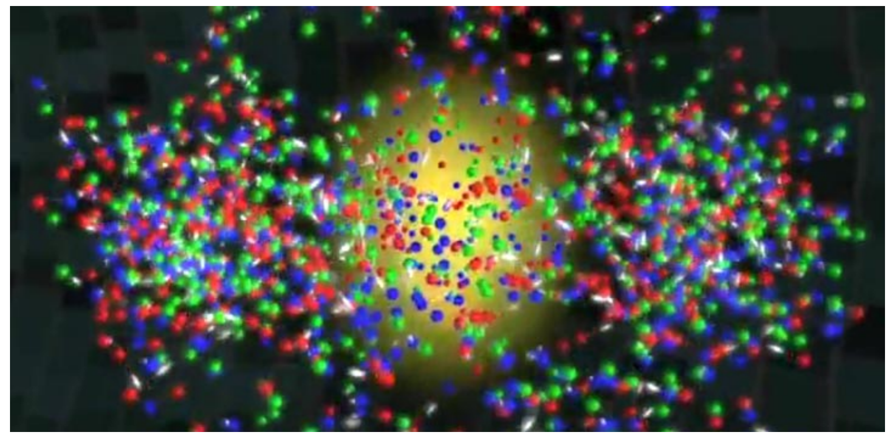


Fig. modified from F. D'eramo, K. Rajagopal, Y. Yin *JHEP* 01 (2019)

- **Can a 'Rutherford-like' scattering experiment be performed in the QGP?**
  - → constrain transport properties of the QGP
  - → may allow to determine 'quasi-particle' structure of QGP and study how strongly-coupled liquid emerges from constituent degrees of freedom

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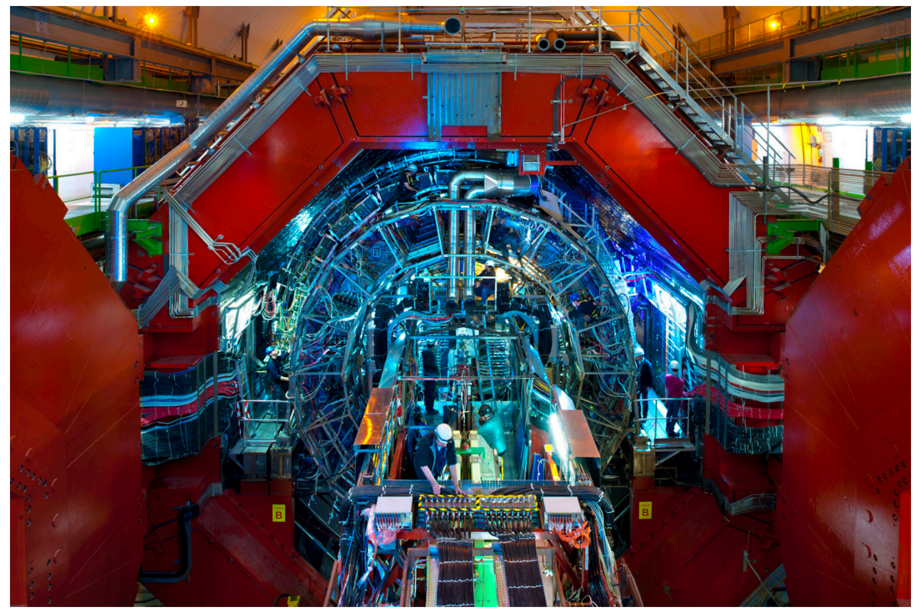
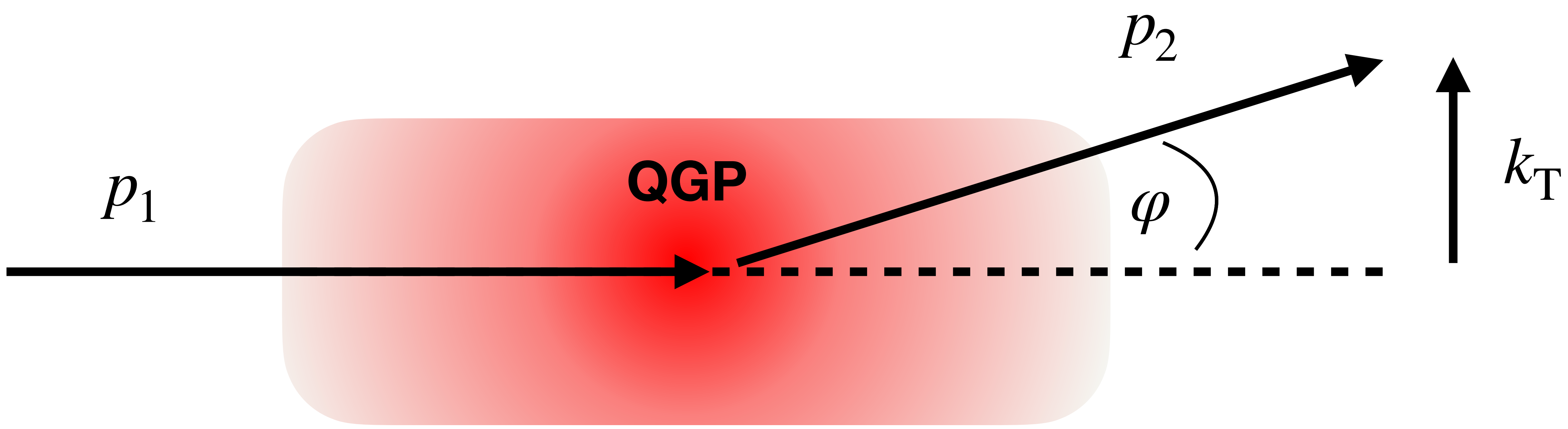
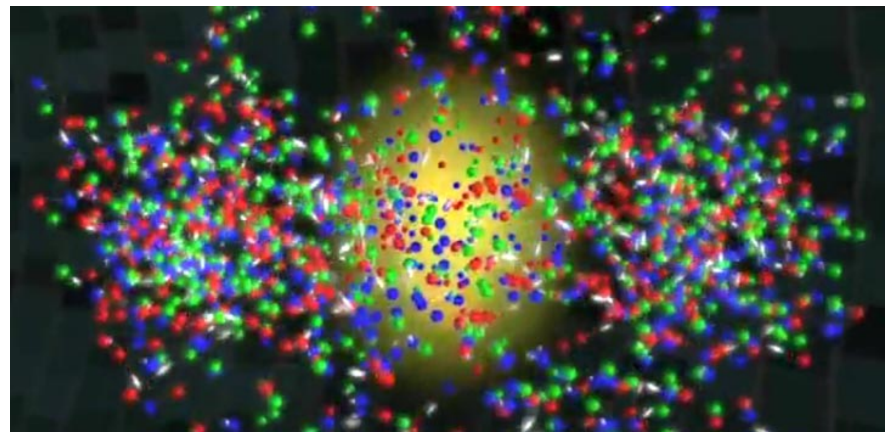
ALICE, 2020s







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  - → constrain transport properties of the QGP
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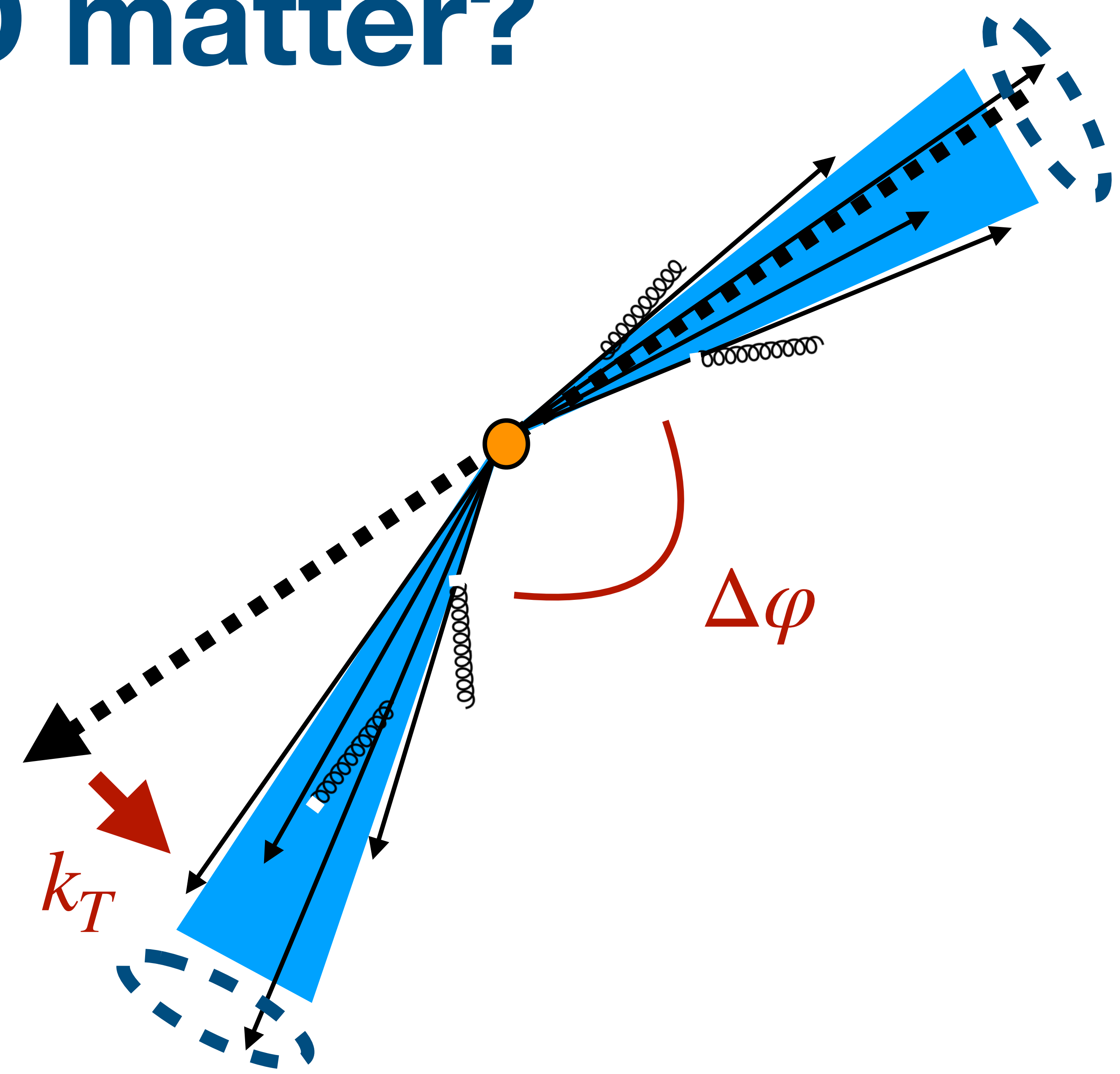
Jets suited for this task - high energy 'probe' which experiences full evolution of the system

- Compare measurements in heavy-ion collisions to a 'vacuum' reference made in proton-proton collisions

How can we probe the inner structure of hot QCD matter?

- Measure transverse broadening of dijet system **(acoplanarity)**
  - Old idea! One of first proposed ‘signatures’ of QGP formation

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



- **Two regions of interest:**
  1. $\Delta\varphi \sim \pi$ (small k_T)
  2. $\Delta\varphi \sim \pi/2$ (large k_T)

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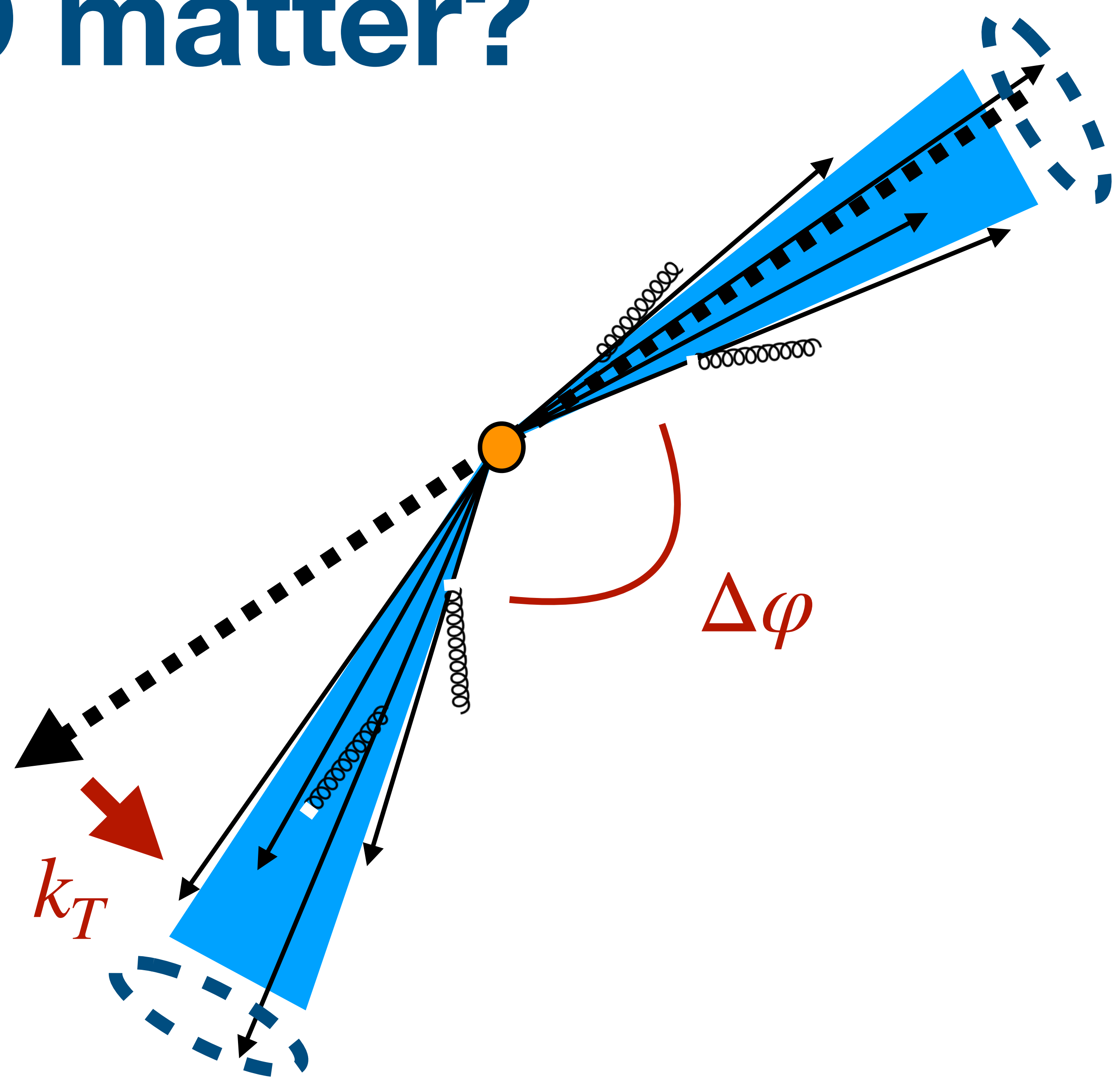

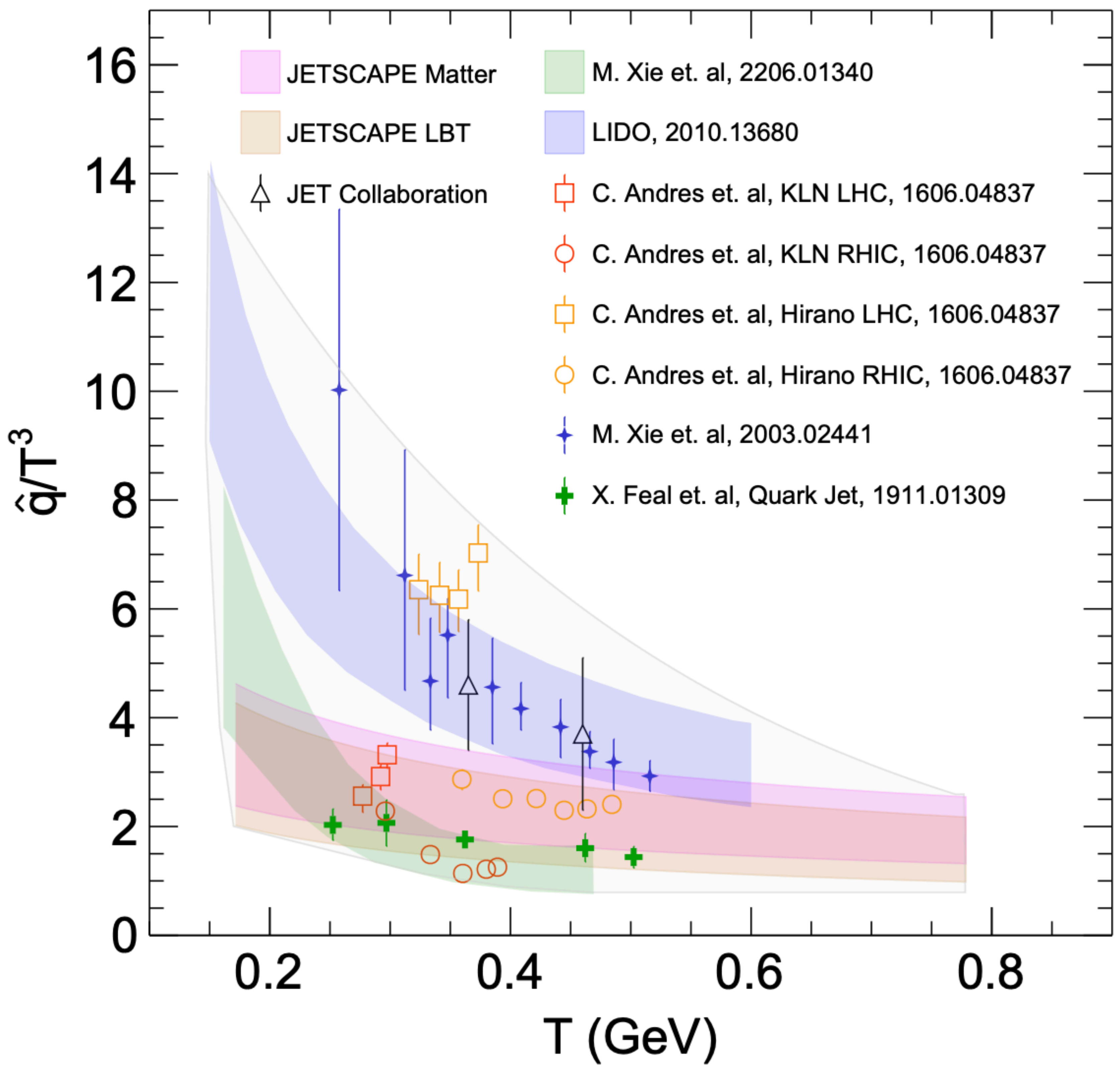

L. Apolinário, Y.-J. Lee, M. Winn
Progress in Particle and Nuclear Physics, 103990 (2022)

- **Two regions of interest:**

1. $\Delta\varphi \sim \pi$ (small k_T)
2. $\Delta\varphi \sim \pi/2$ (large k_T)

- Transverse broadening due to **multiple soft scattering**
- Quantified by jet transport coefficient $\hat{q} = \dfrac{d < k_\perp^2 >}{dL}$

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

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

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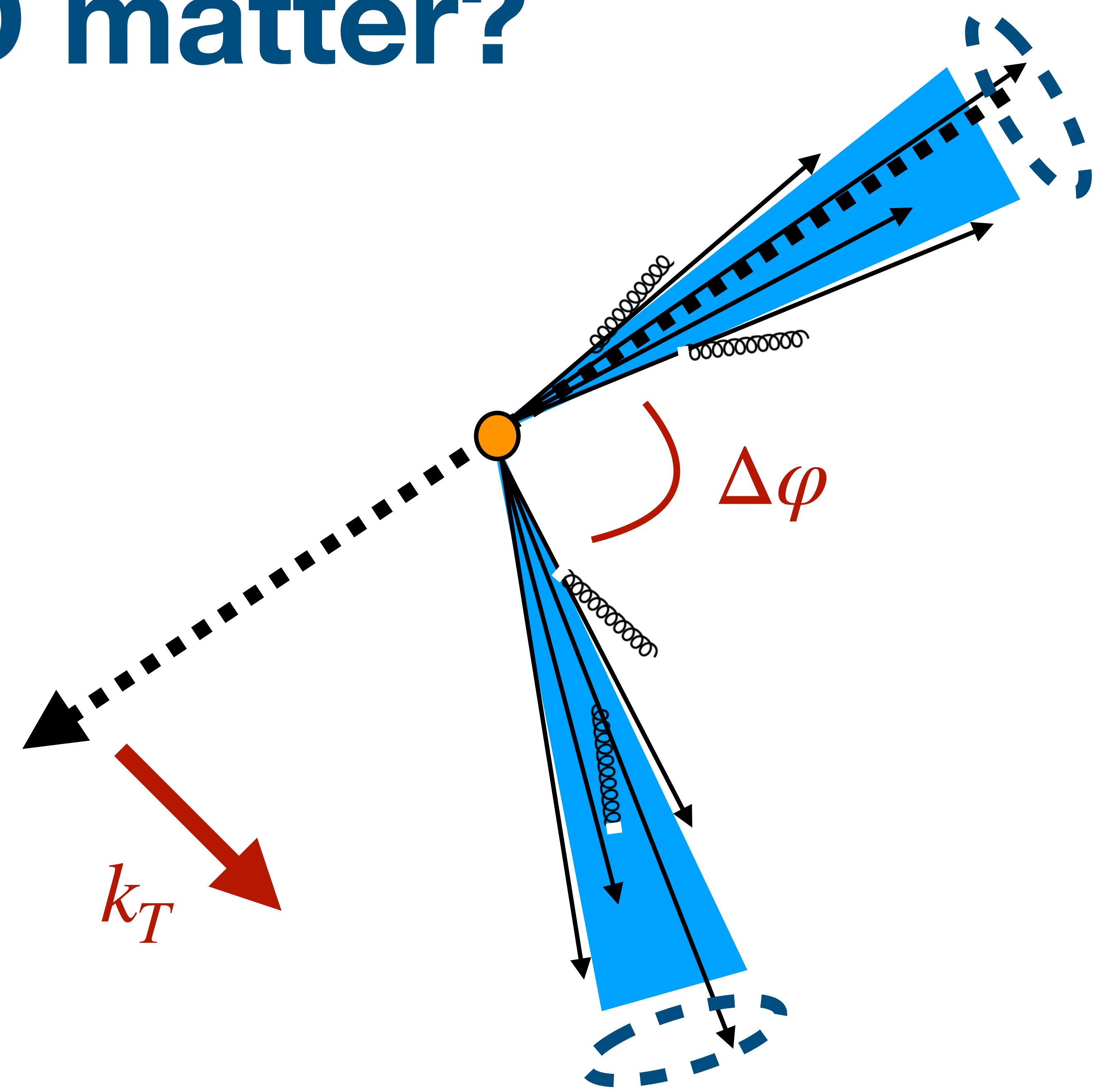
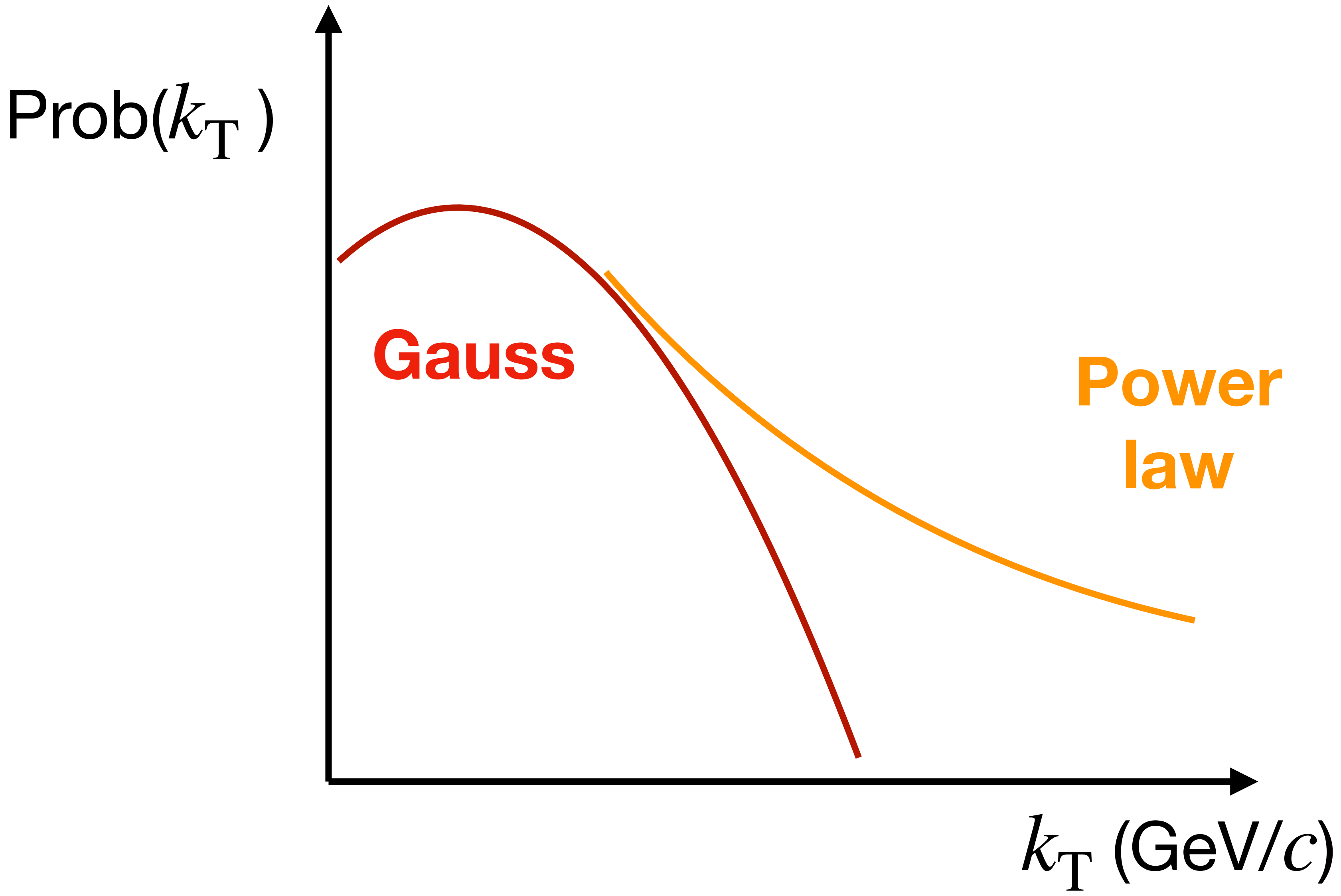


- **Two regions of interest:**

1. $\Delta\varphi \sim \pi$ (small k_T)
2. $\Delta\varphi \sim \pi/2$ (large k_T)
   - **Strong-coupling limit** - probability of parton to obtain momentum k_{T} is Gaussian (exponential) distributed
   - Scatter off **weakly-interacting** quasi-particle with probability distribution 'Rutherford-Like' power-law distributed ~ $1/(k_{\mathrm{T}})^4$ (ignoring radiative corrections)

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

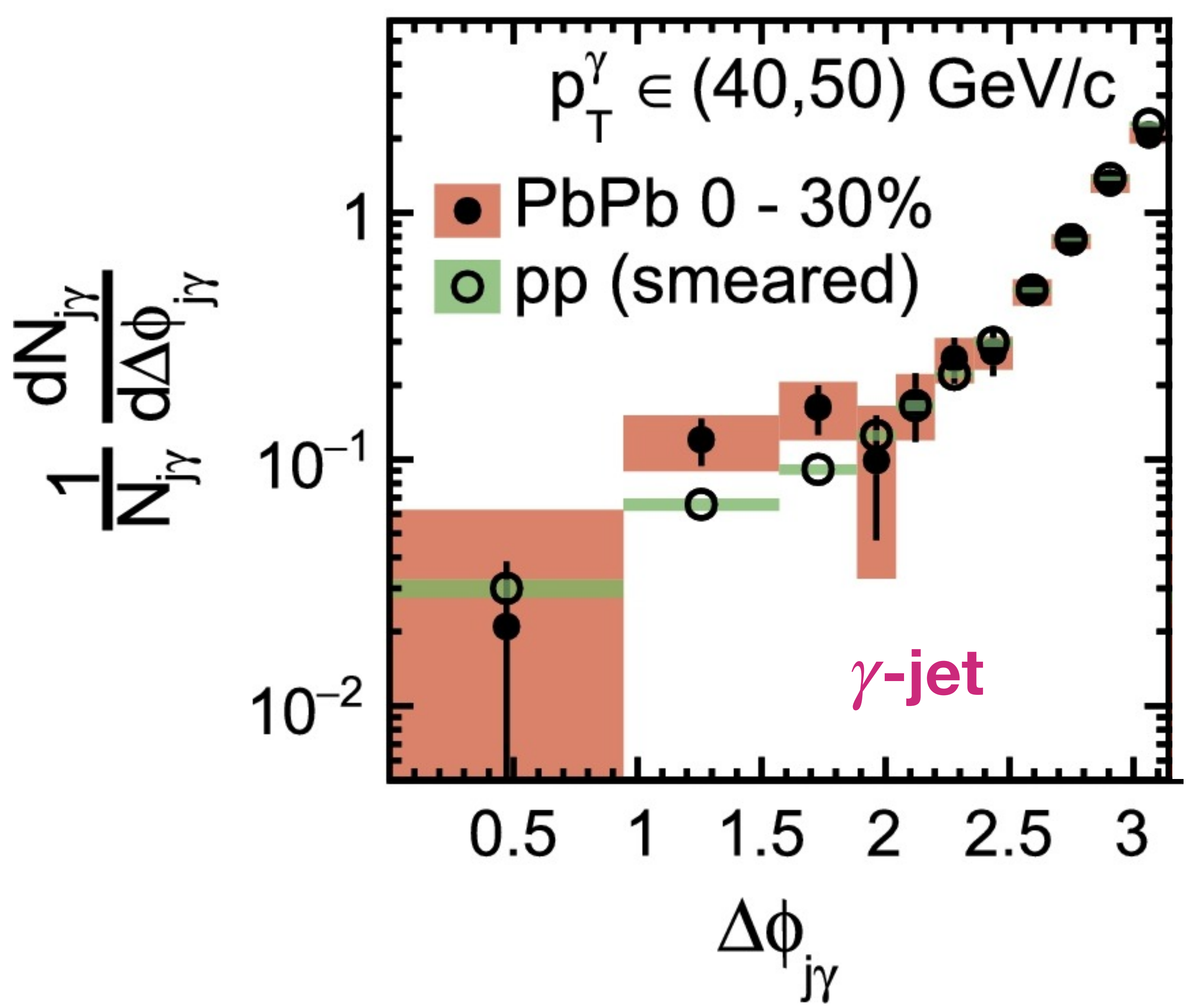


F. D'eramo, M. Lekaveckas, H. Liu, K. Rajagopal, *JHEP* 05 (2013) 031
F. D'eramo, K. Rajagopal, Y. Yin *JHEP* 01 (2019)

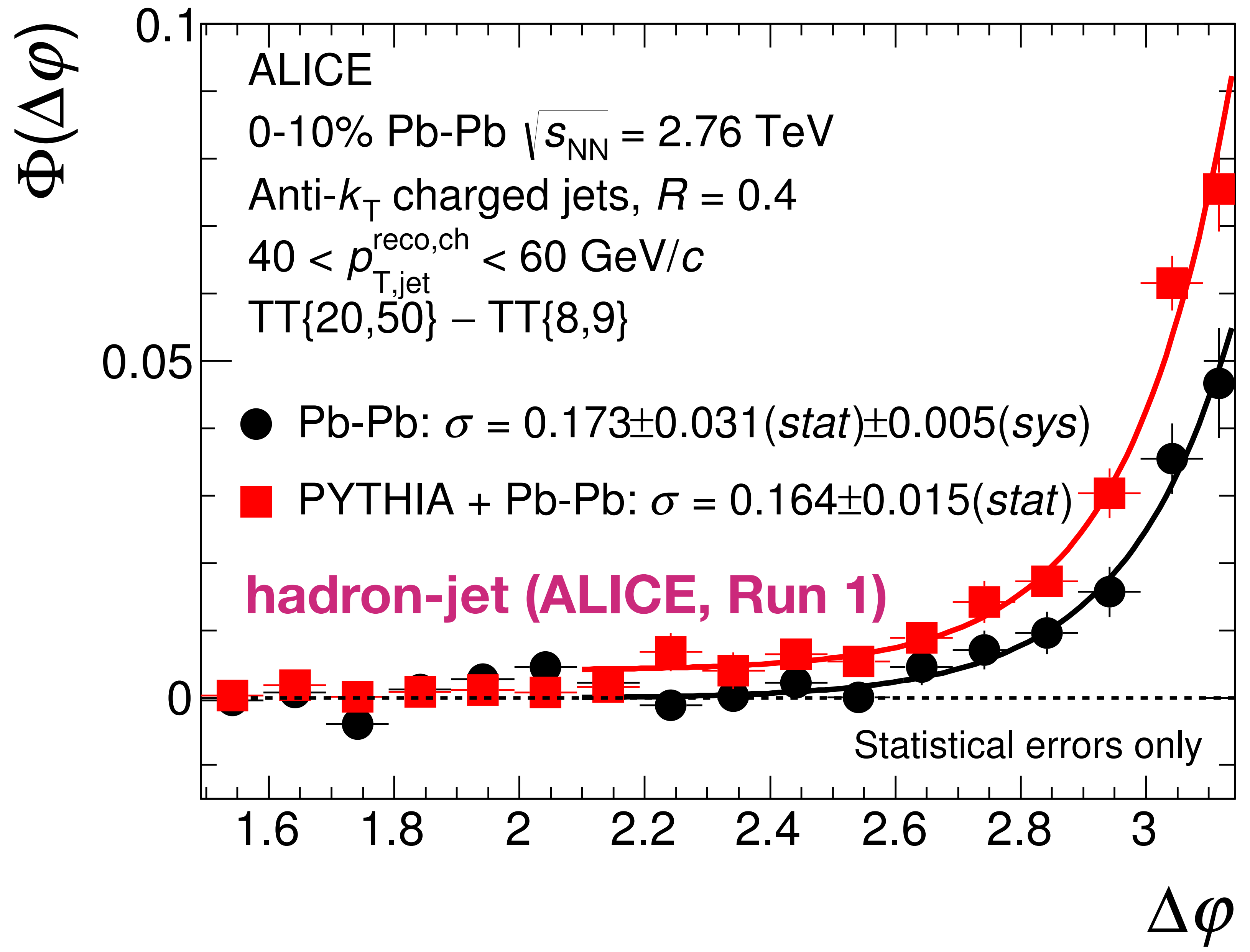
P. Caucal, Y. Mehtar-Tani: *Phys.Rev.D* 106 (2022) 5, L051501
JHEP 09 (2022) 023
Phys.Rev.D 108 (2023) 1, 014008

Jet acoplanarity measurements

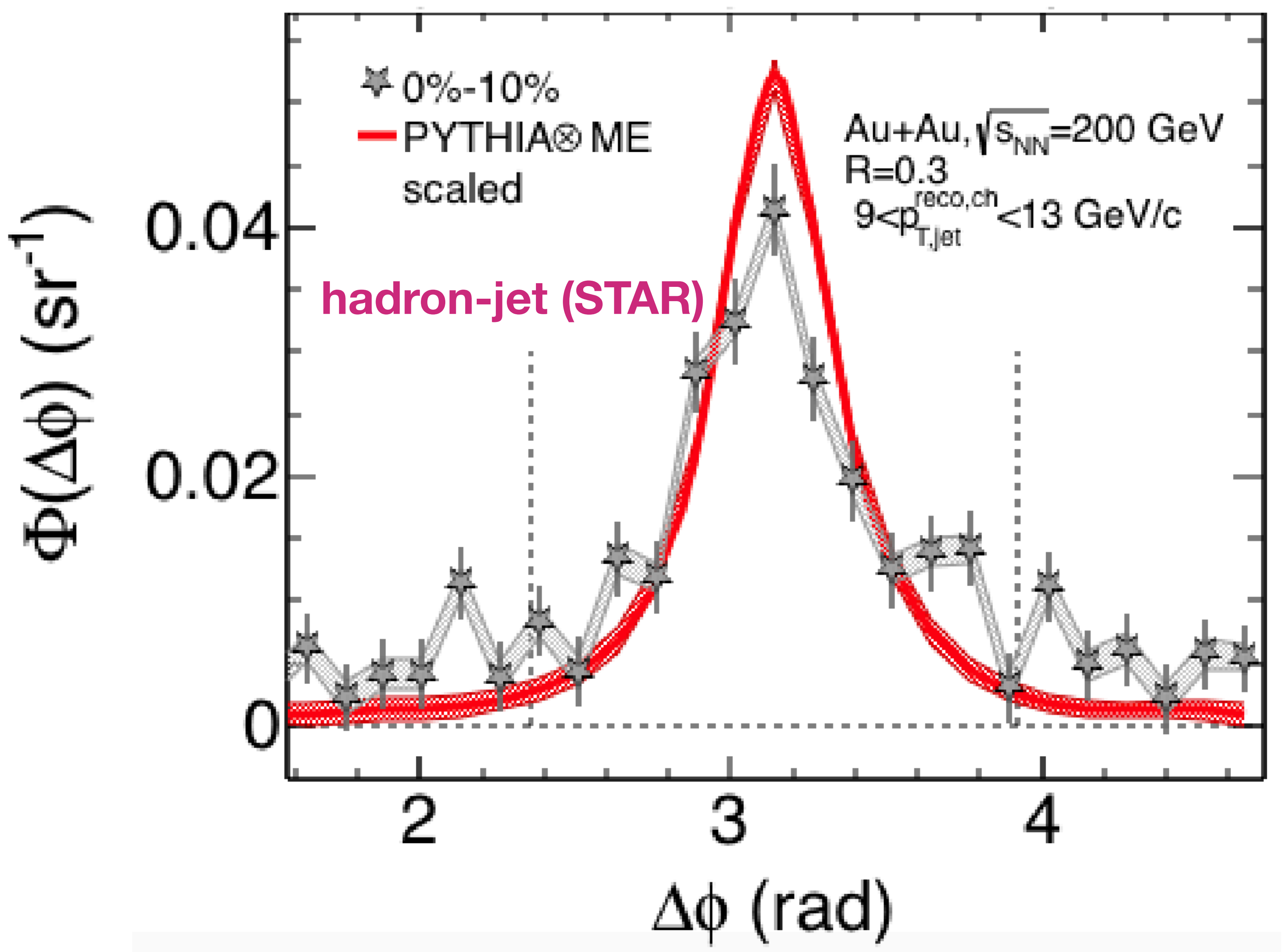
CMS: PRL 119, 082301 (2017)
CMS: Phys. Lett. B 785 (2018) 14

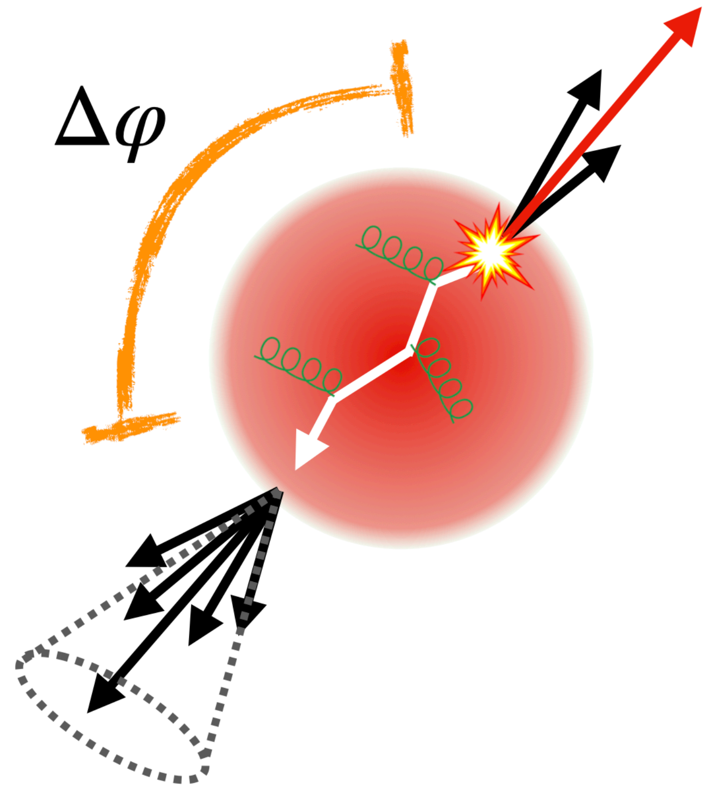


ALICE: JHEP 09 (2015) 170



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

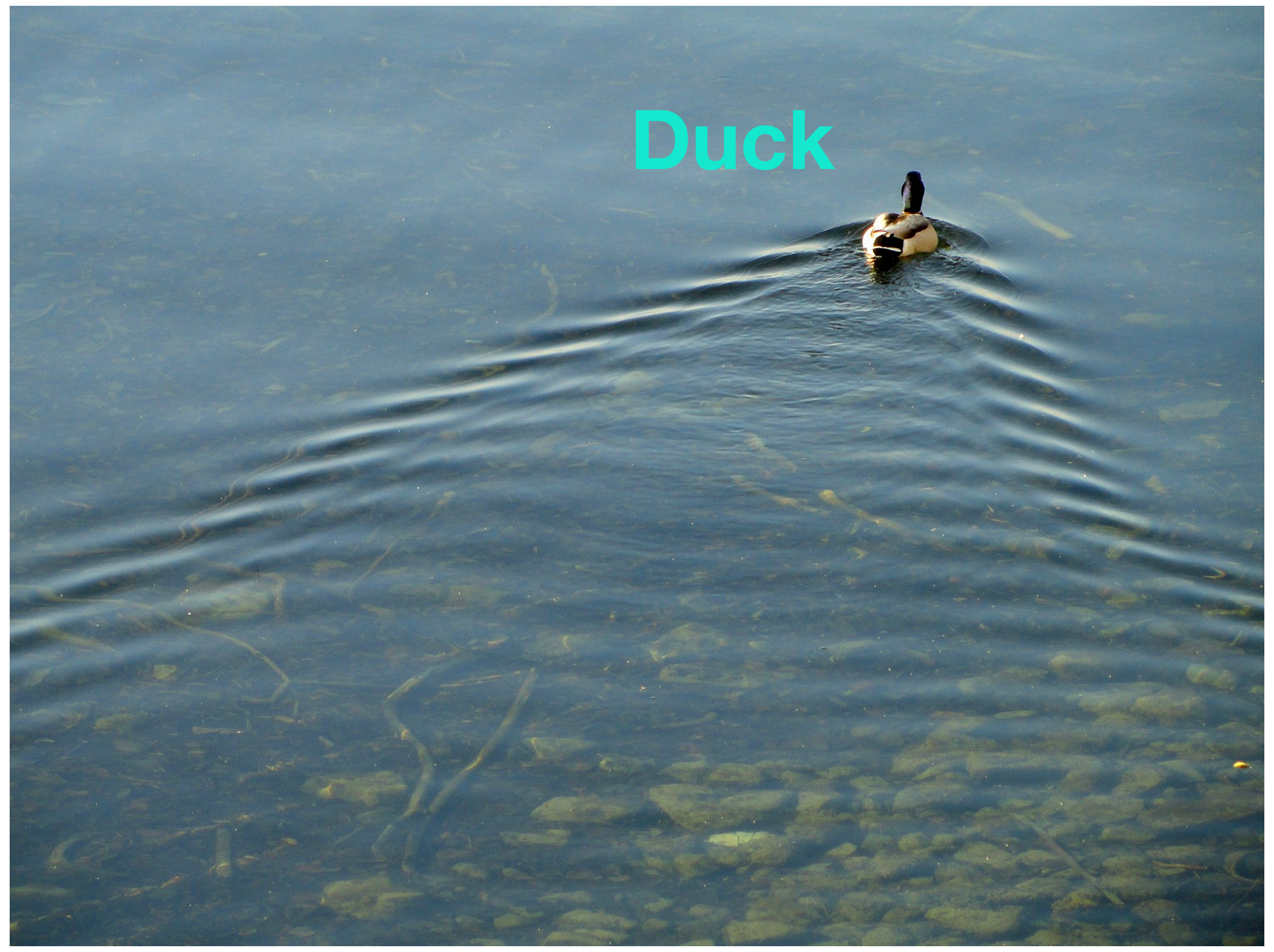




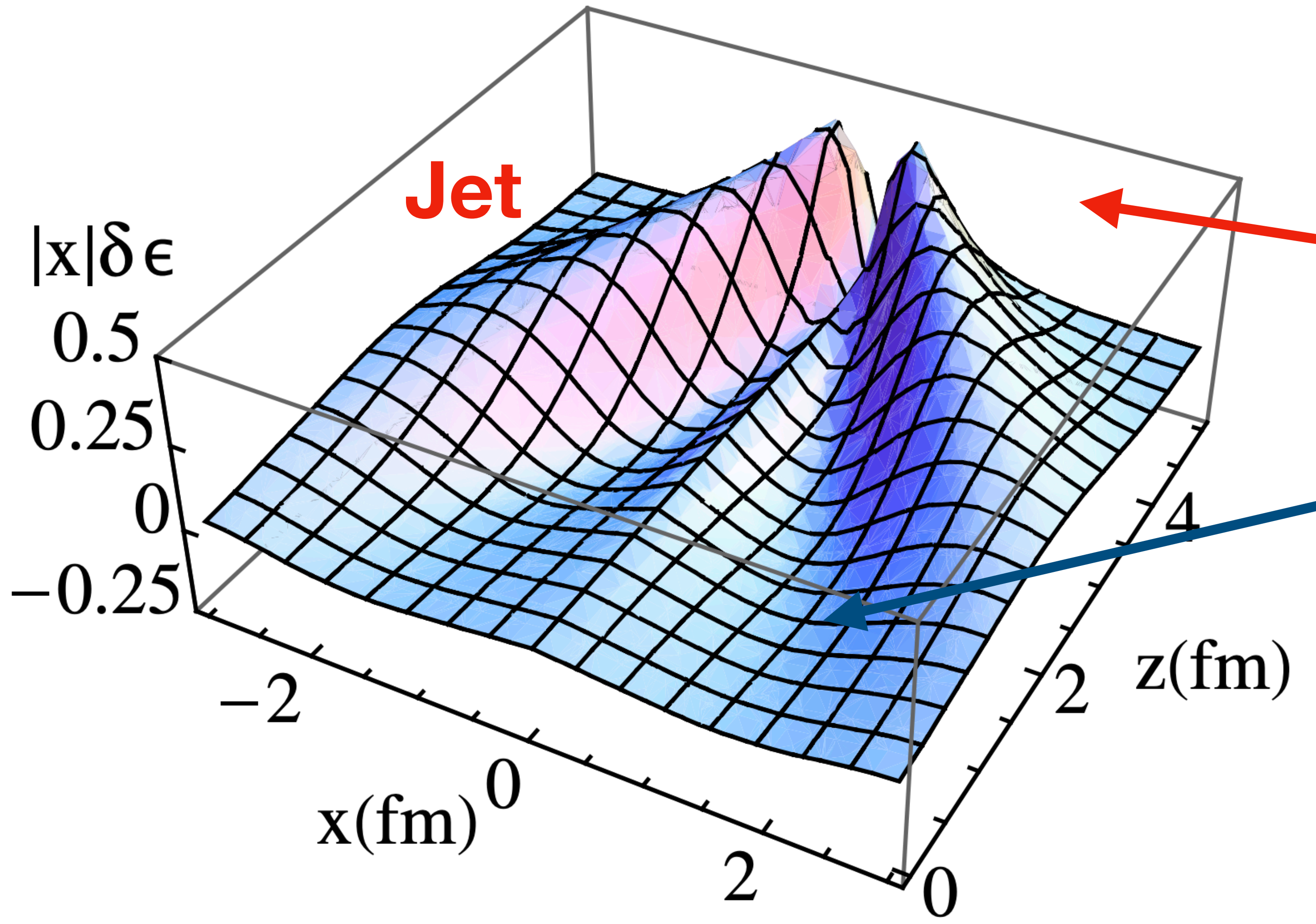
- **No evidence for QGP-induced acoplanarity so far**
  - Theory indicates low p_T jets most sensitive to broadening effects

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)



Expected 'wake' effects:

Enhancement around jet

Deletion opposite jet

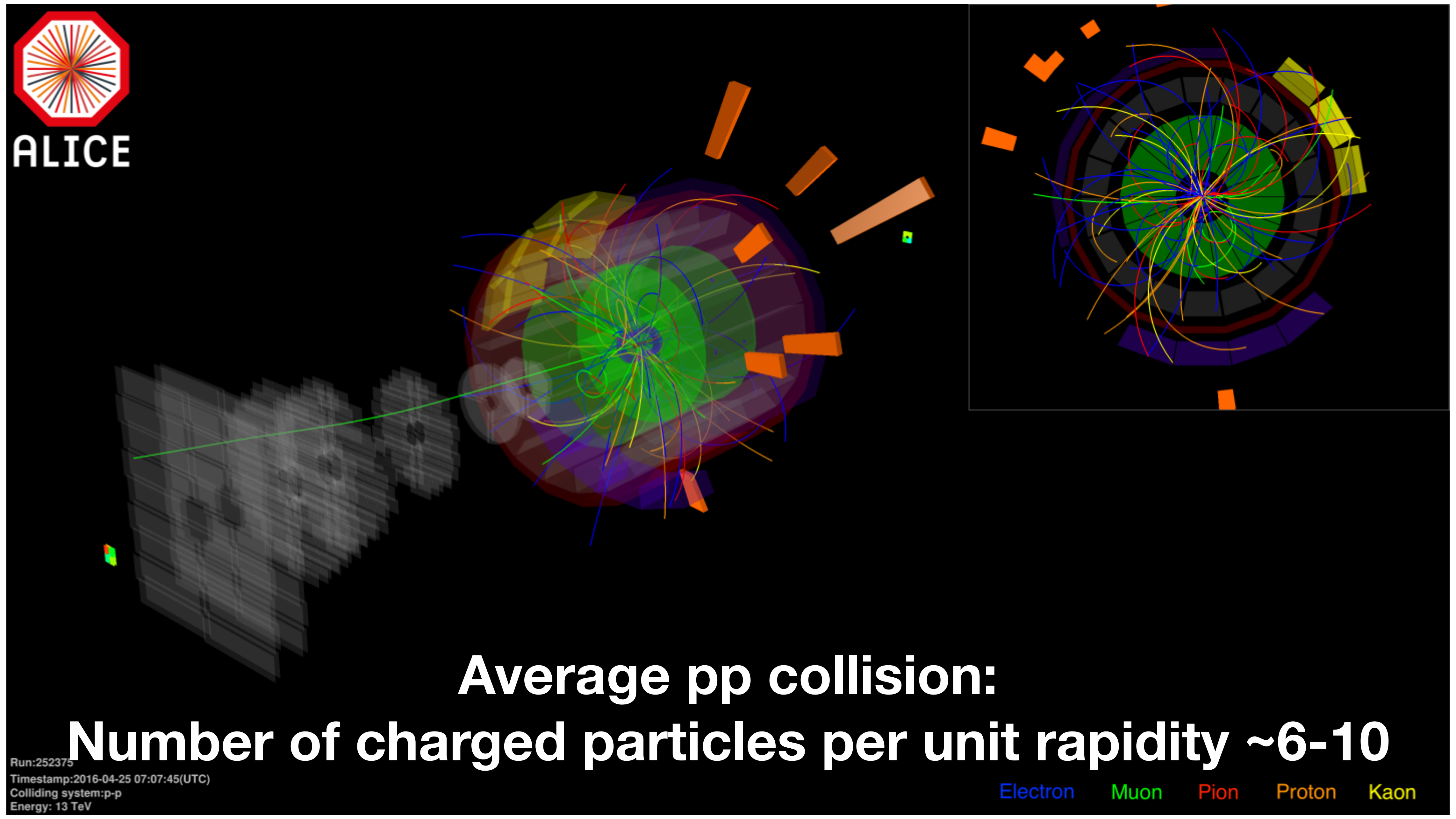
Sonic boom - $v_{\mathrm{jet}} > c_s \sim 0.5c$

Insert out-of-equilibrium probe - see how medium responds

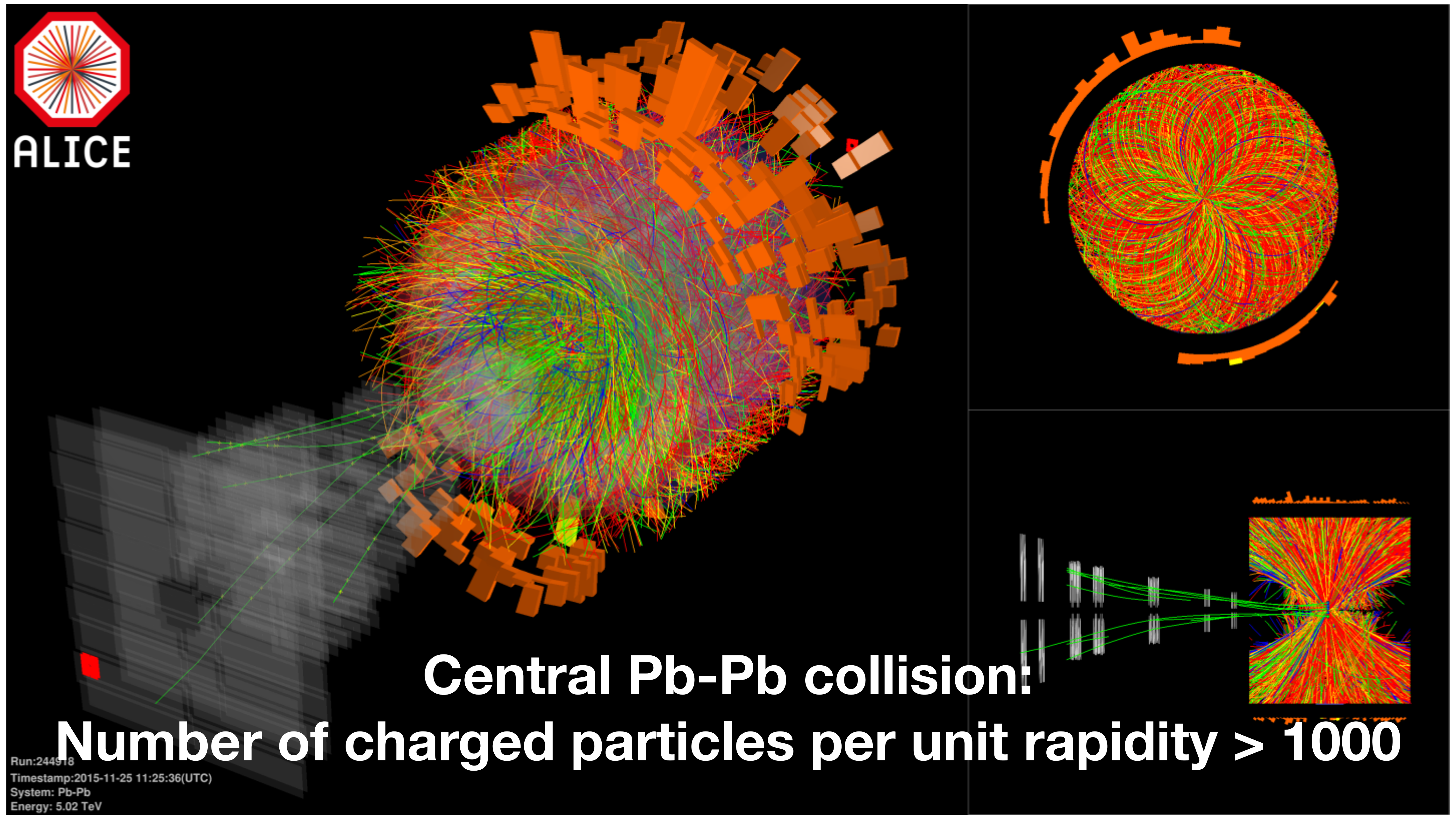
→ transport coefficients, equation of state

→ May also affect interpretation of jet measurements - can we separate 'medium' from 'jet' ?

Dealing with background in heavy-ion collisions



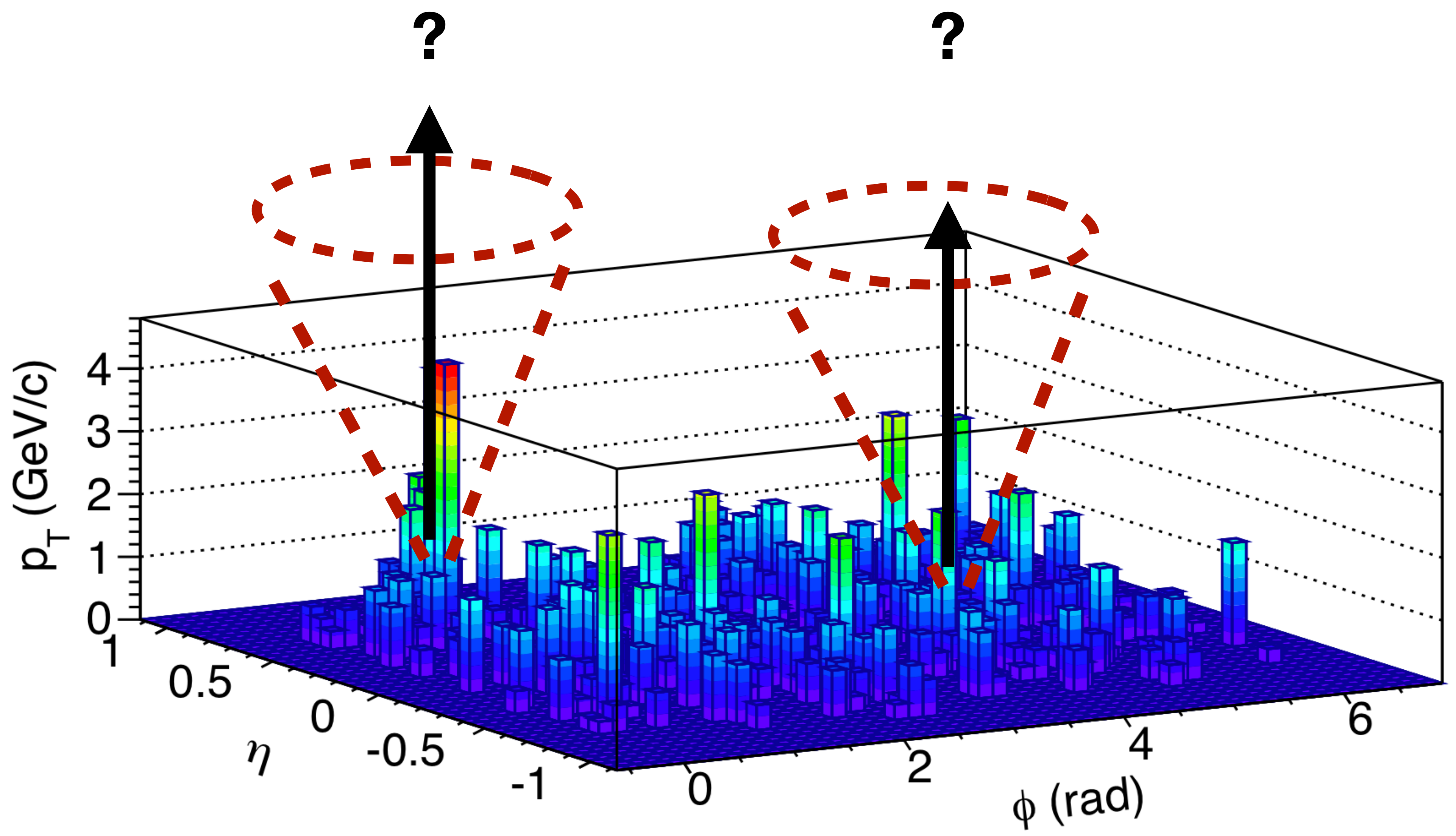
Average pp collision:
Number of charged particles per unit rapidity ~6-10



Central Pb-Pb collision:
Number of charged particles per unit rapidity > 1000

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 jet energy ~ background energy density
  - Larger-*R* jets include larger background fraction

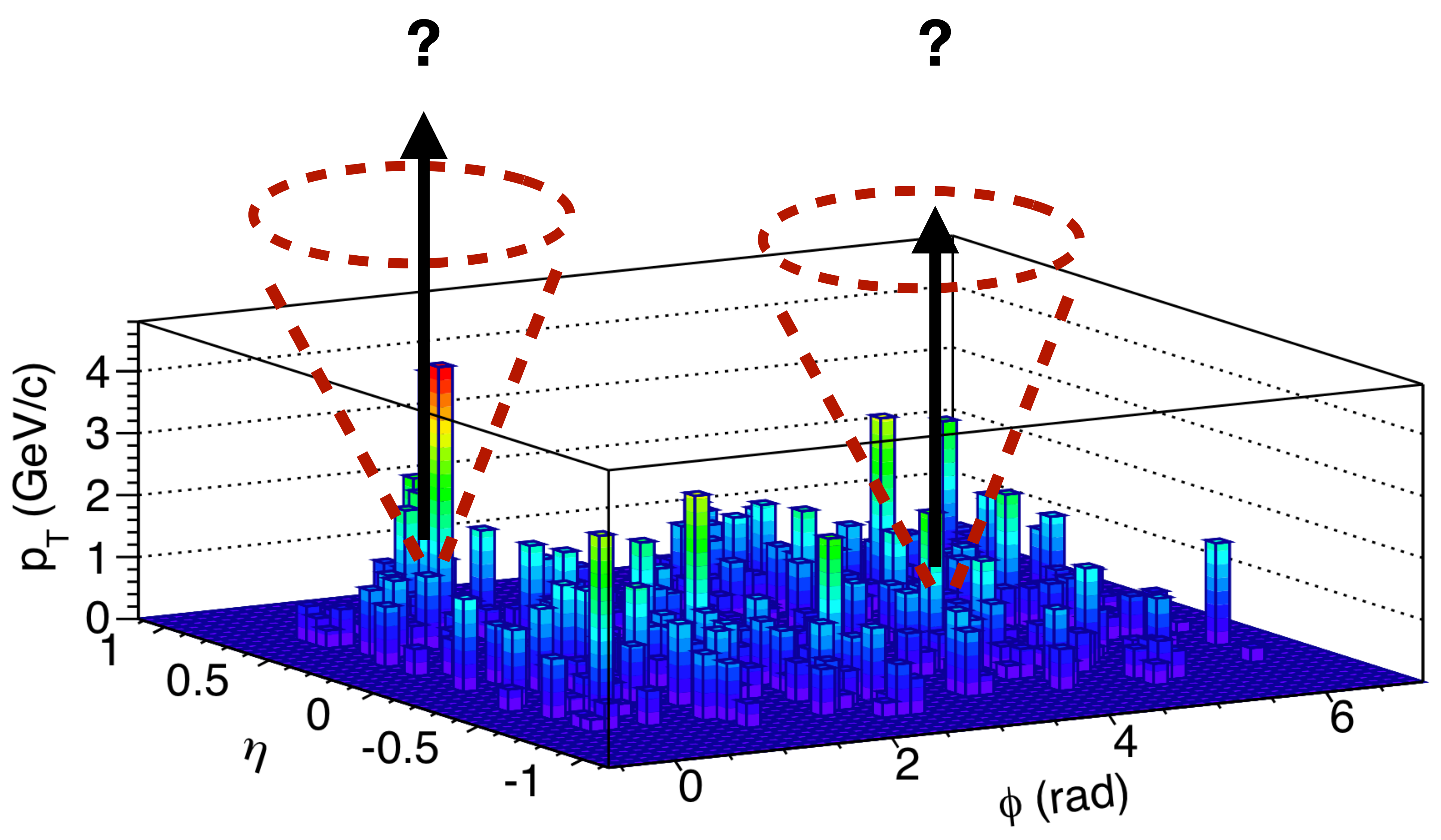


Dealing with background in heavy-ion collisions

- 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 jet energy ~ background energy density
  - Larger-*R* jets include larger background fraction

- This talk: **correct for background *statistically***
  - Construct background distribution to subtract from background+signal distribution

    - **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

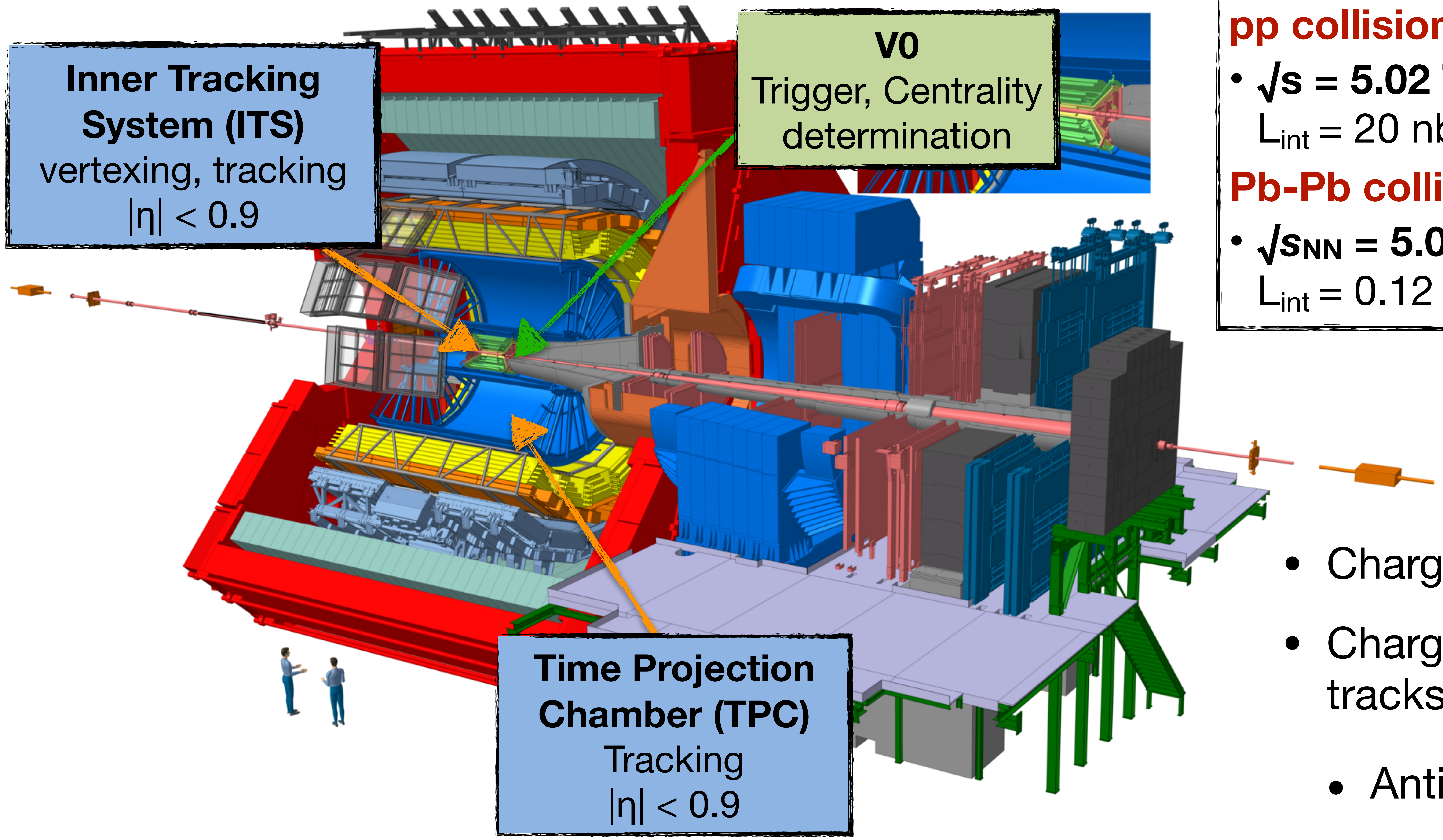
Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_T jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:2308.16131

Submitted to PRL

Experiment, datasets and jet reconstruction

The ALICE apparatus



Data samples (from Run 2, 2017-2018):

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}

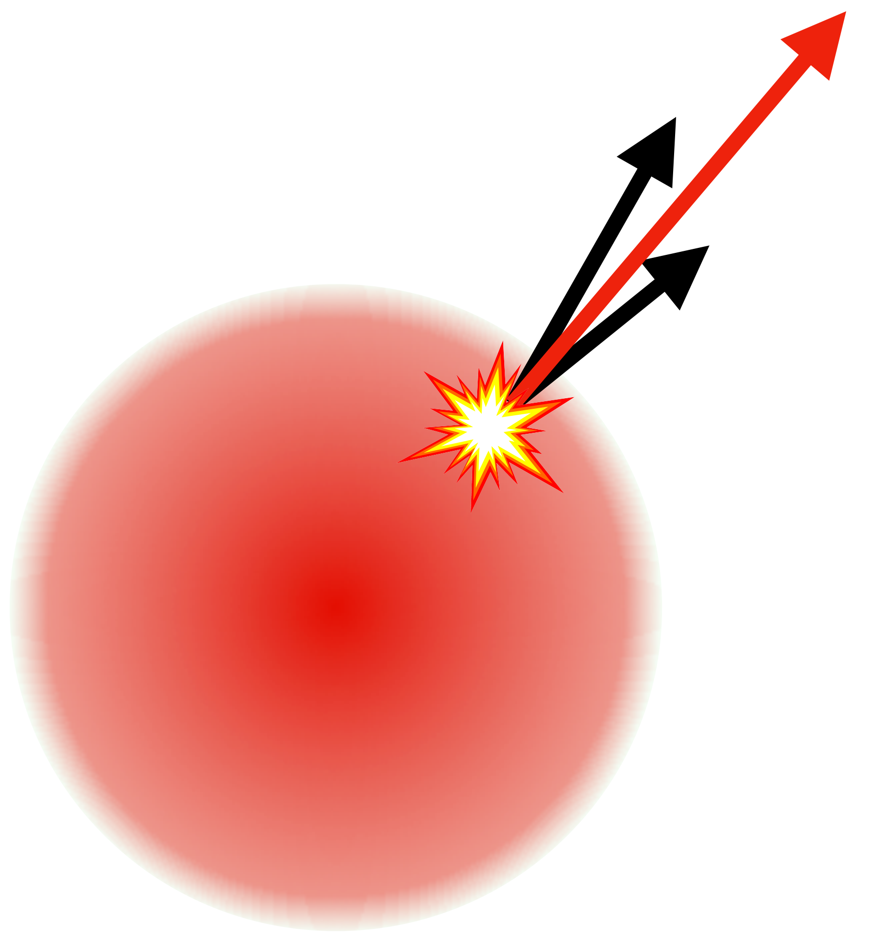
Pb-Pb collisions: centrality-enhanced trigger using V0

- **$\sqrt{s_{NN}}$ = 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

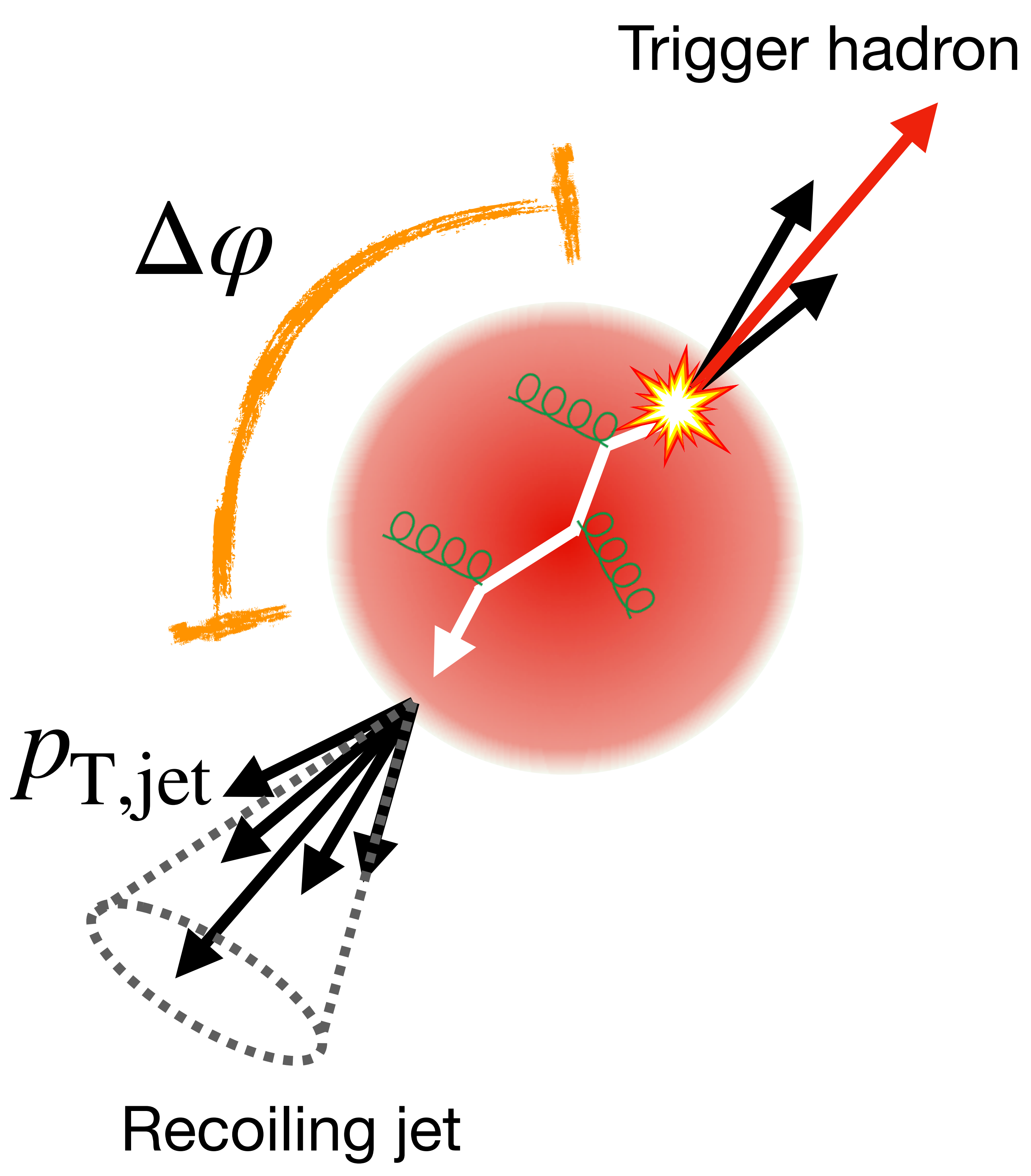
Analysis procedure

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**
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



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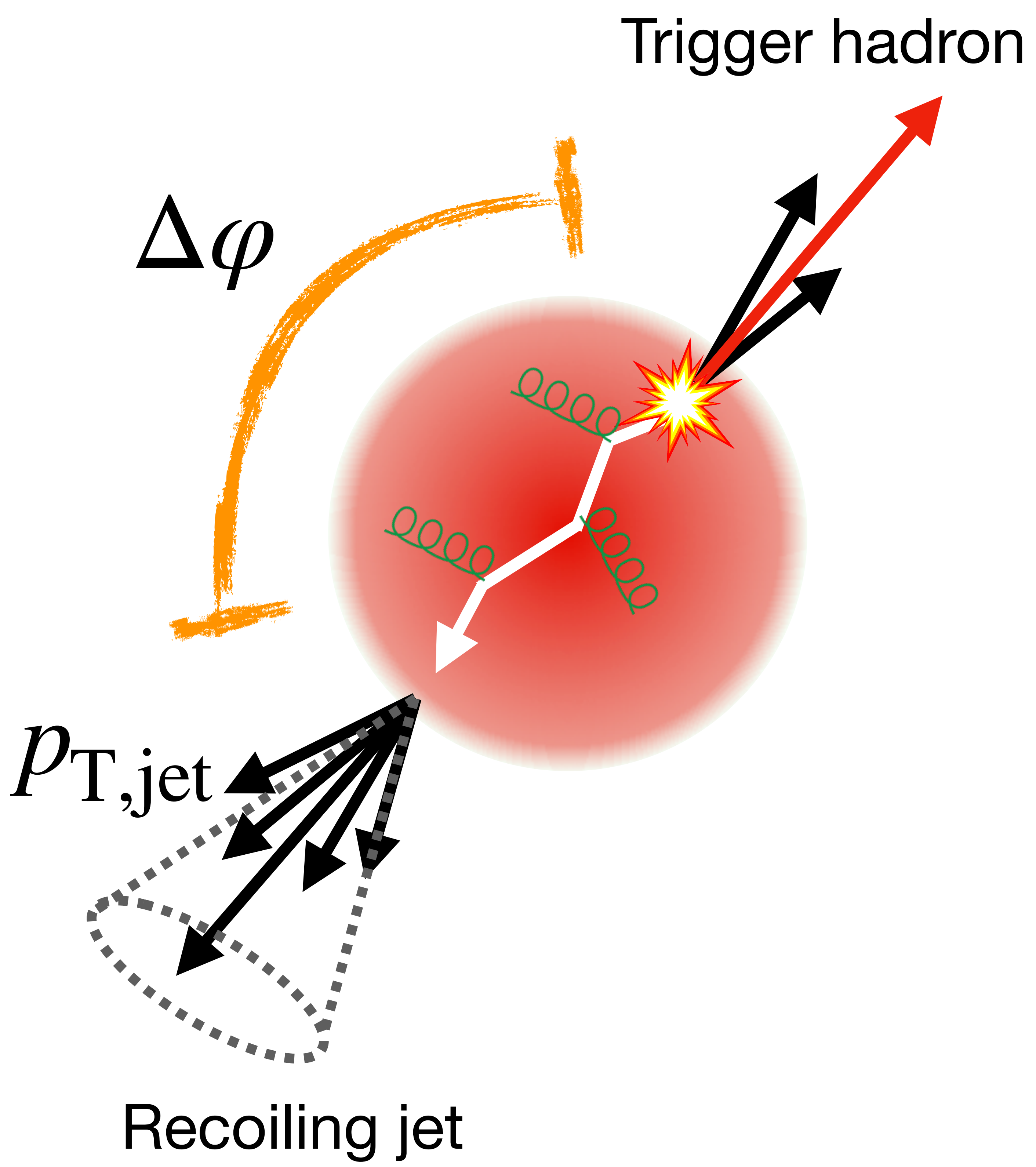
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_{T,jet}$) of recoil jet
4. **Define observable:**

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

Trigger-normalised yield of charged-particle jets recoiling from high-p_T trigger hadrons



Analysis procedure

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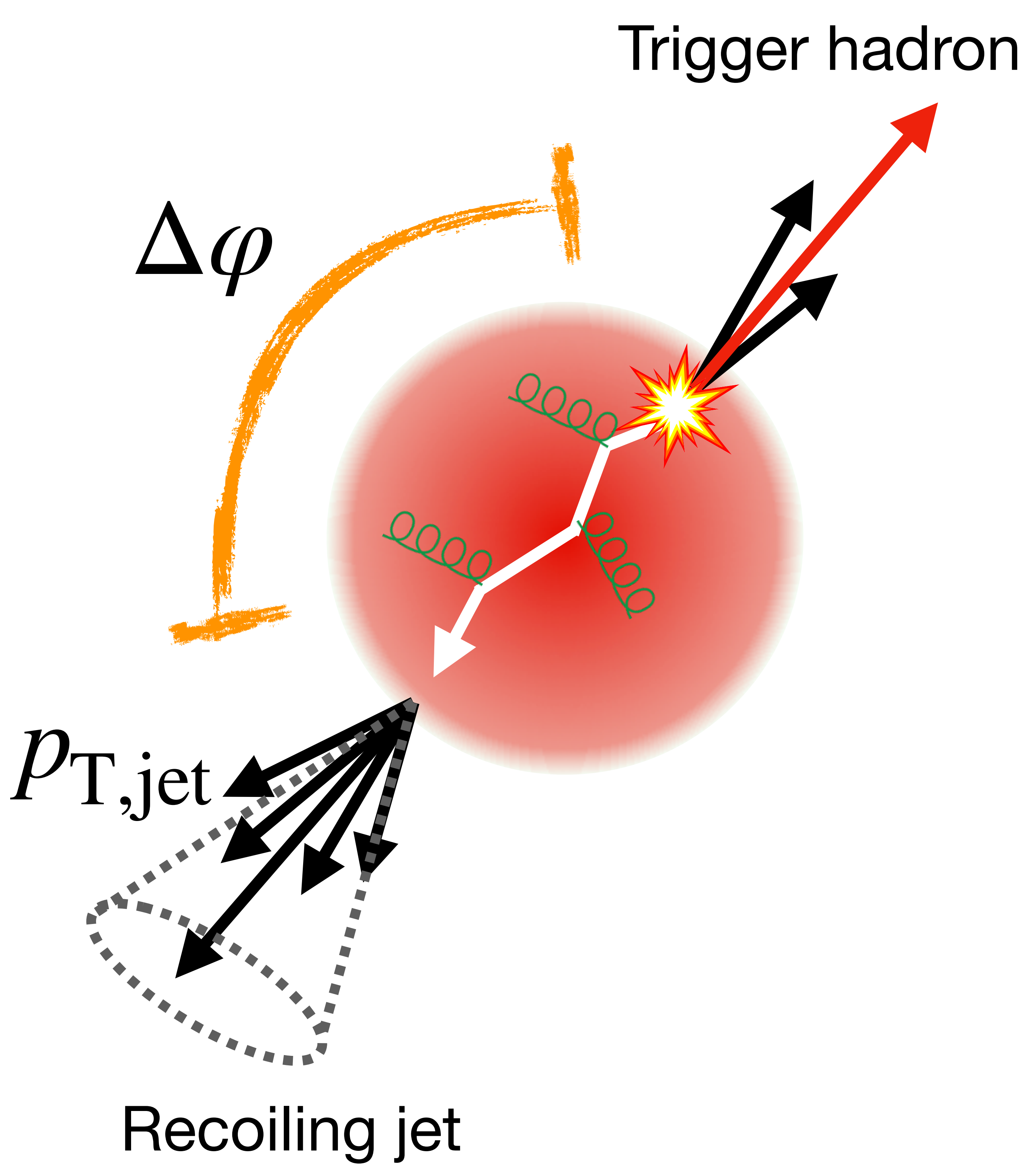
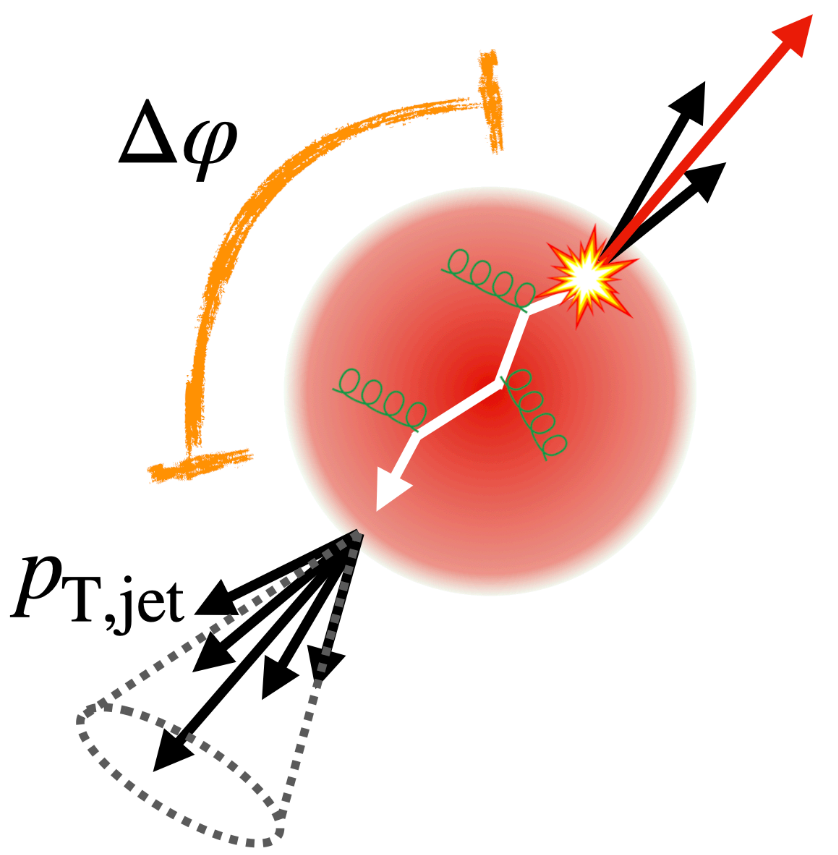
- **Perturbatively calculable**
  Ratio between high-p_{T} hadron and jet production cross sections
- **Semi-inclusive**
  events selected based on presence of trigger → count all recoil jets in defined acceptance



Analysis procedure

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

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



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

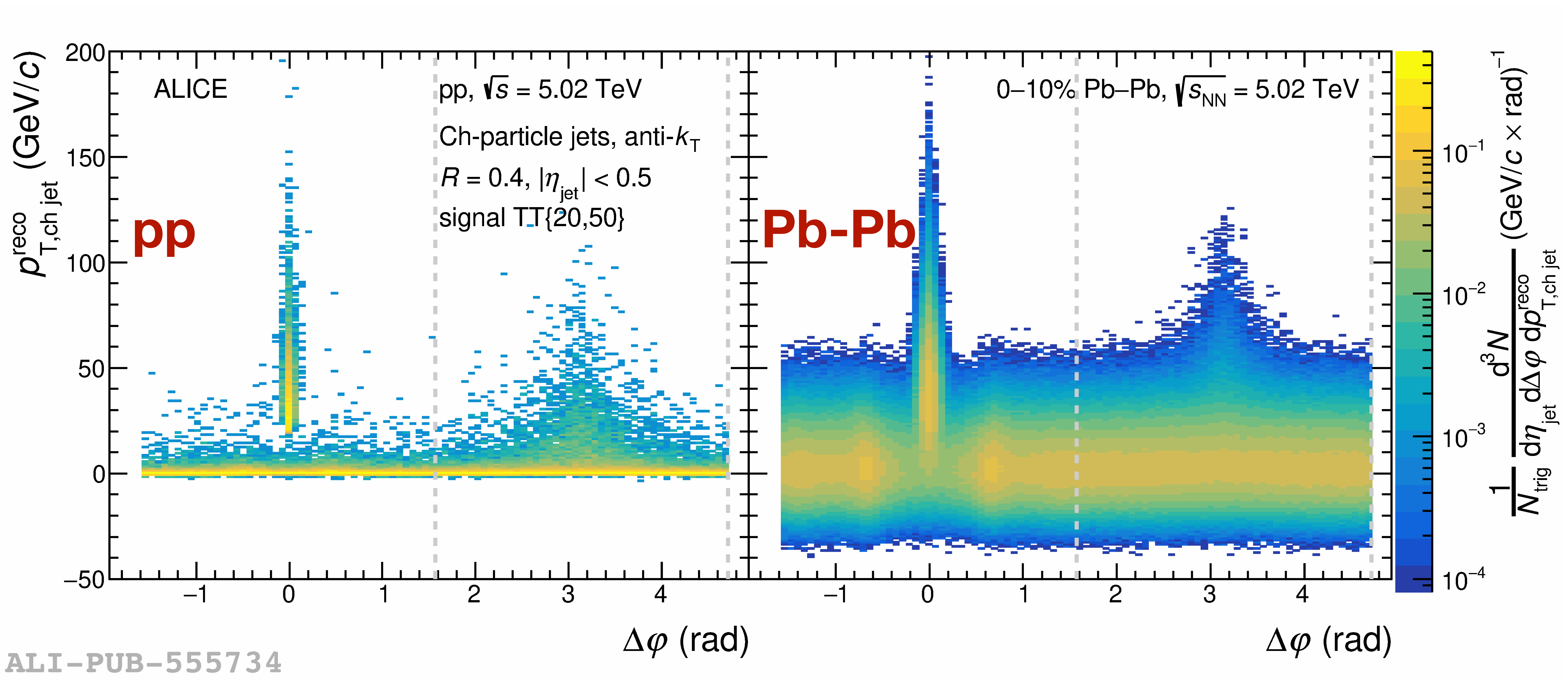
- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

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

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

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

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



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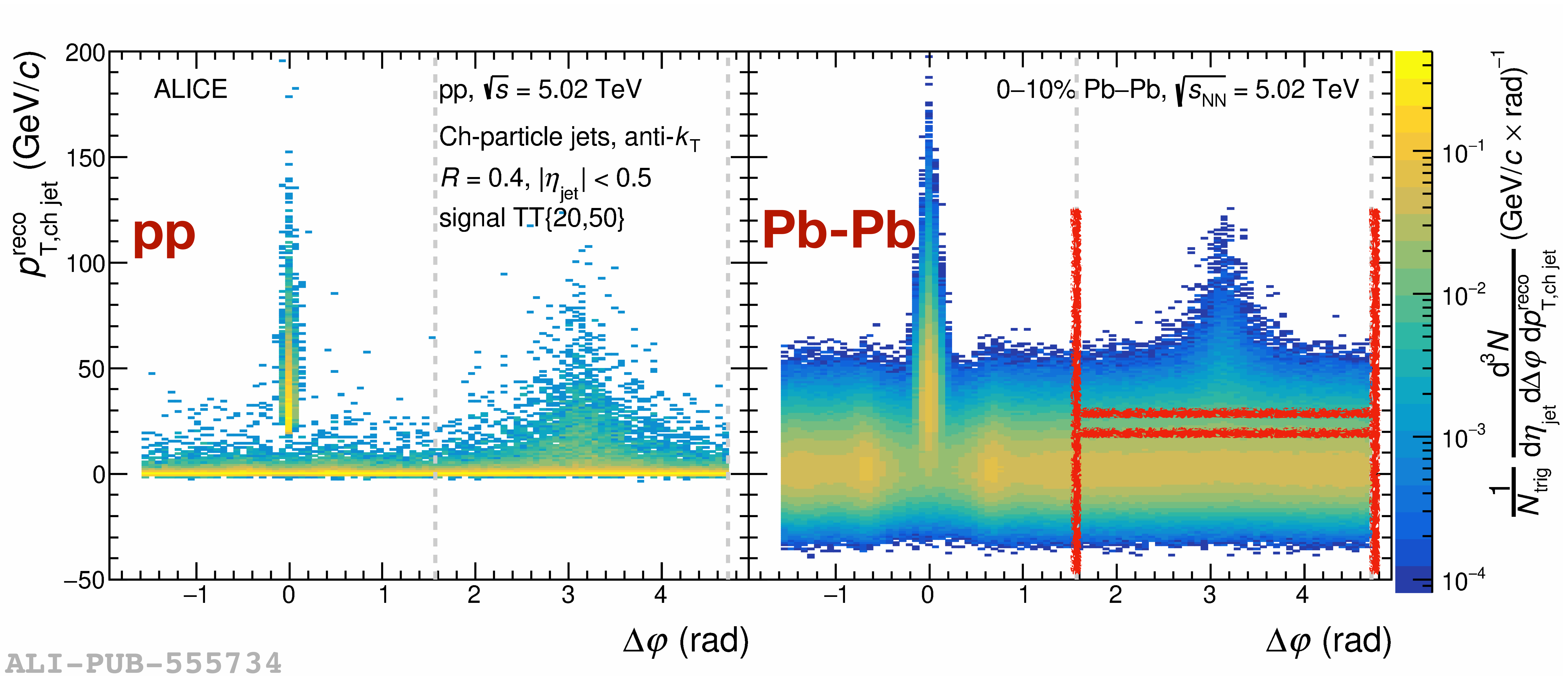

ALI-PUB-555734

Analysis procedure: raw distributions

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

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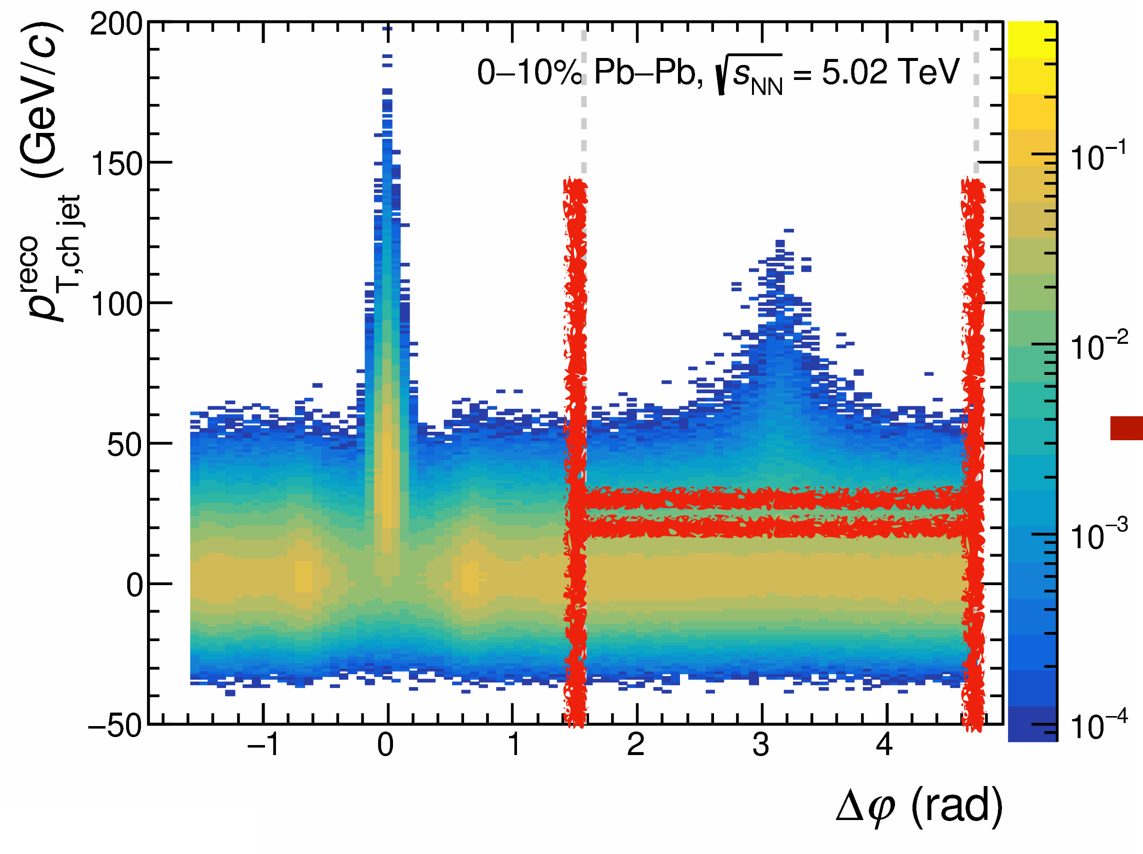

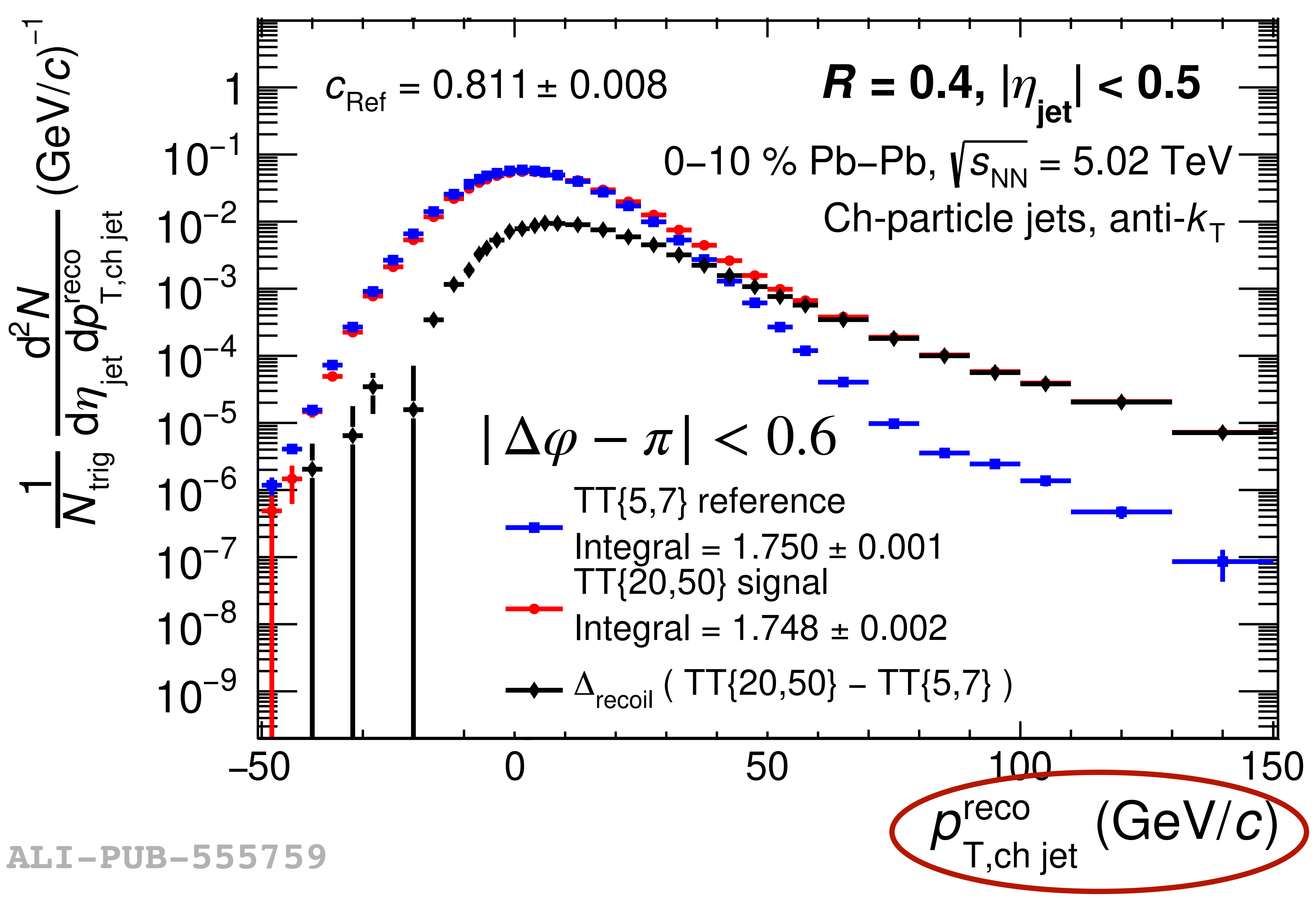

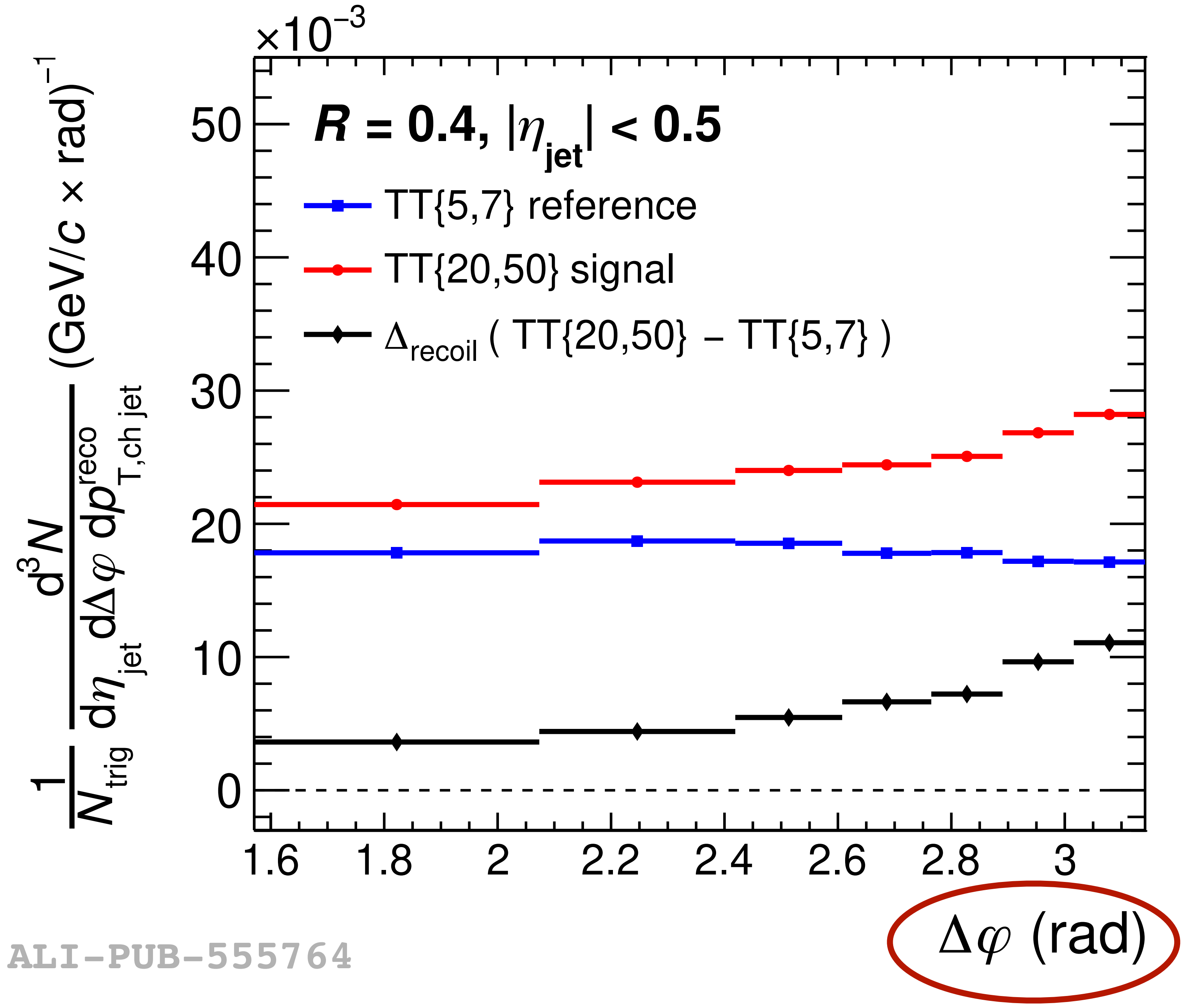

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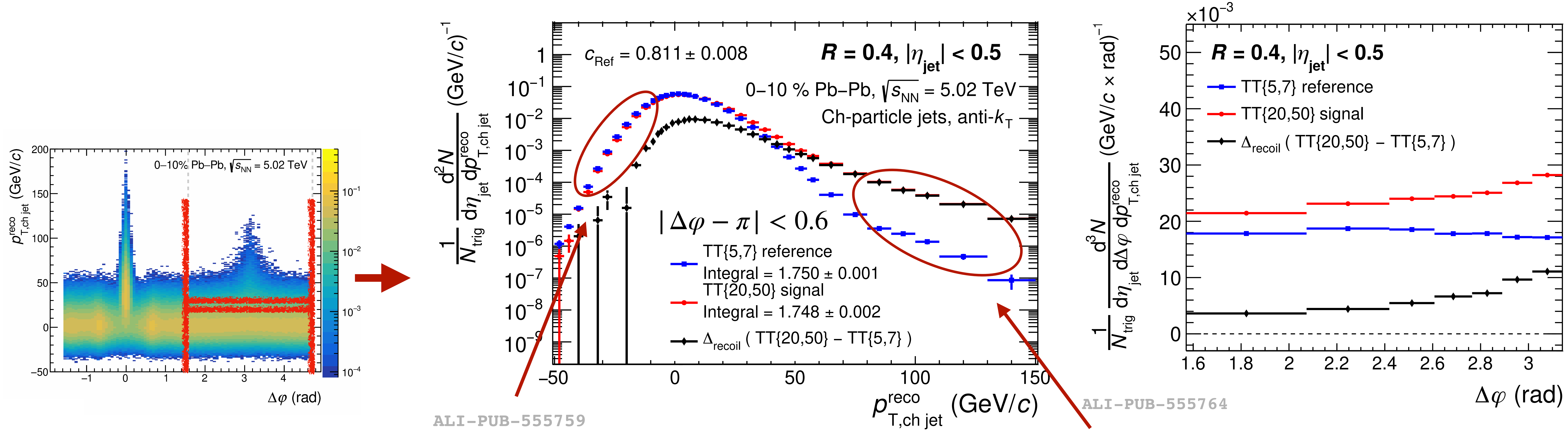


Uncorrelated background dominates

Signal jets dominate

Unfolding

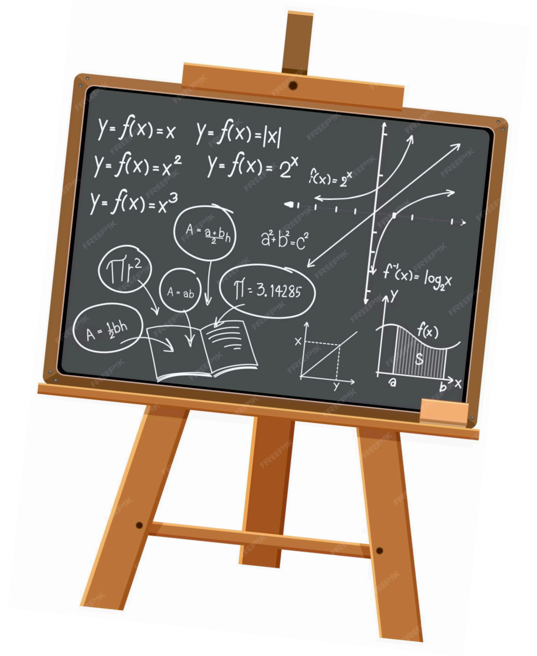
- **Raw distributions unfolded** for detector effects and residual background fluctuations in both pp and Pb-Pb collisions
  - $\Delta_{\rm recoil}(p_{\rm T,jet})$: Unfolded in 1 dimension ($p_{\rm T,jet}$) - minimal $\Delta\varphi$ smearing
  - $\Delta_{\rm recoil}(\Delta\varphi)$: Unfolded in 2 dimensions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

Systematic uncertainties

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

- Dominant:
  - pp: Tracking
  - Pb-Pb: Unfolding (prior)

Models



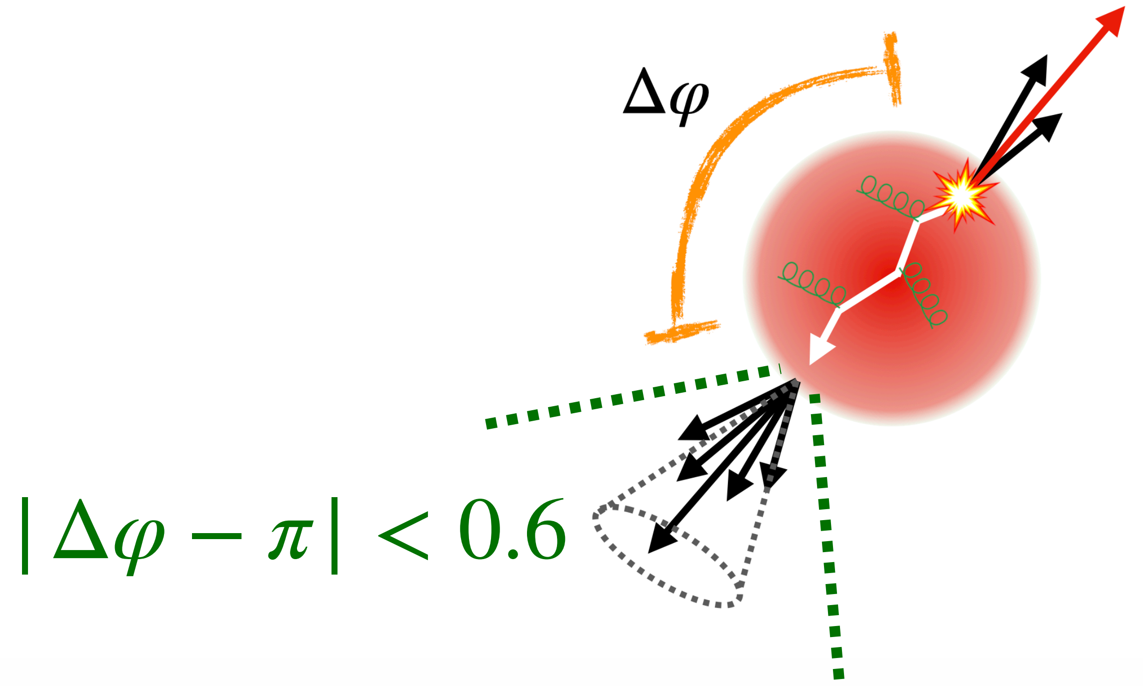
- **JETSCAPE - Multi-stage event generator** JETSCAPE collaboration - Phys. Rev. C 107, 034911
  - Jet energy loss based on MATTER (high virtuality) and LBT (low virtuality)
- **JEWEL - perturbative treatment to jet quenching** K. Zapp, EPJ C, Volume 74, Issue 2, 2014; R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141
  - Medium response studied by switching ‘recoils’ on and off (recoil momenta within jet subtracted using prescribed methods) **(with help from Danny!)**
- **Hybrid model - strong (AdS/CFT) / weak (DGLAP) 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

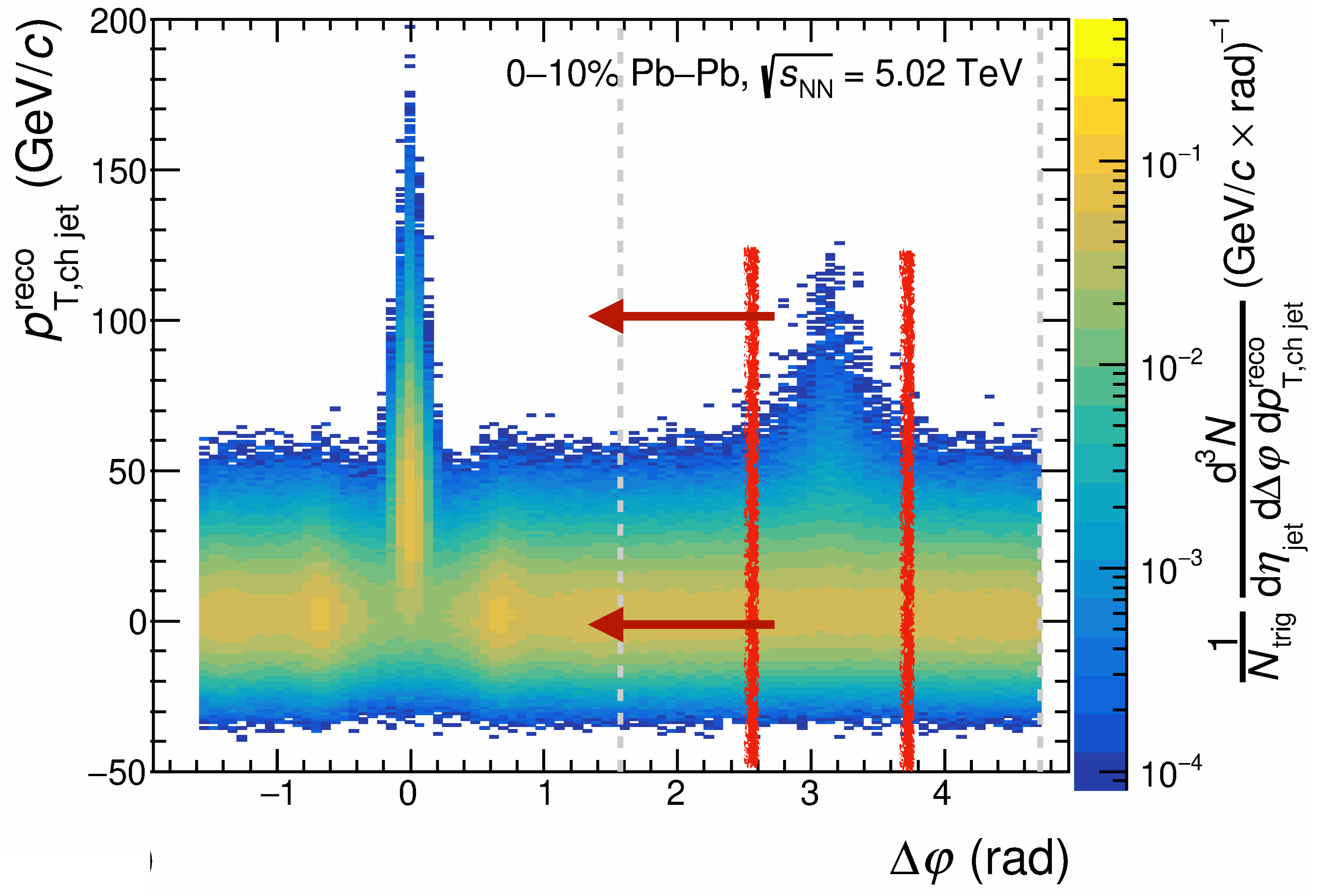
‘Vacuum’ reference crucial for each model - based on PYTHIA

- **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

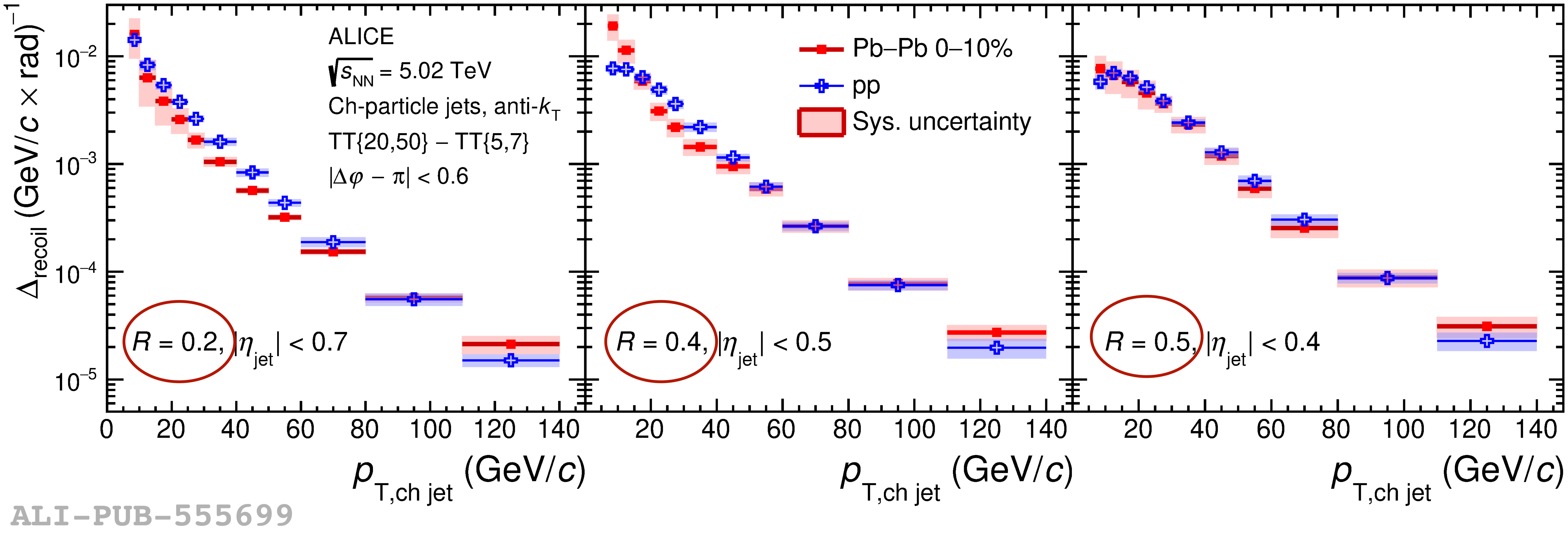
Results

- $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$: 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





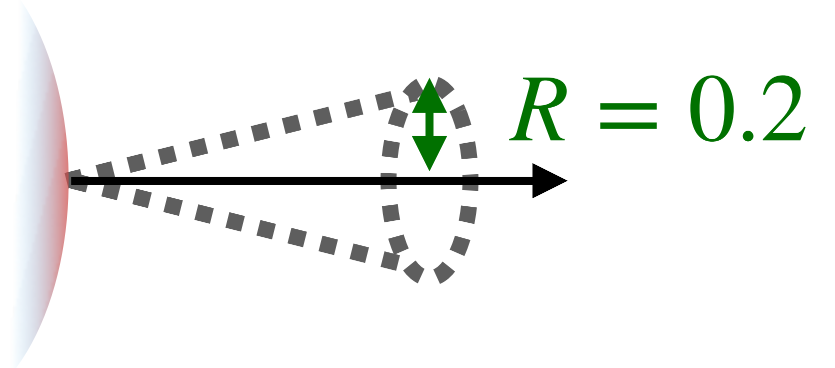
Fully-corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\,jet}})$ distributions in pp and Pb-Pb collisions



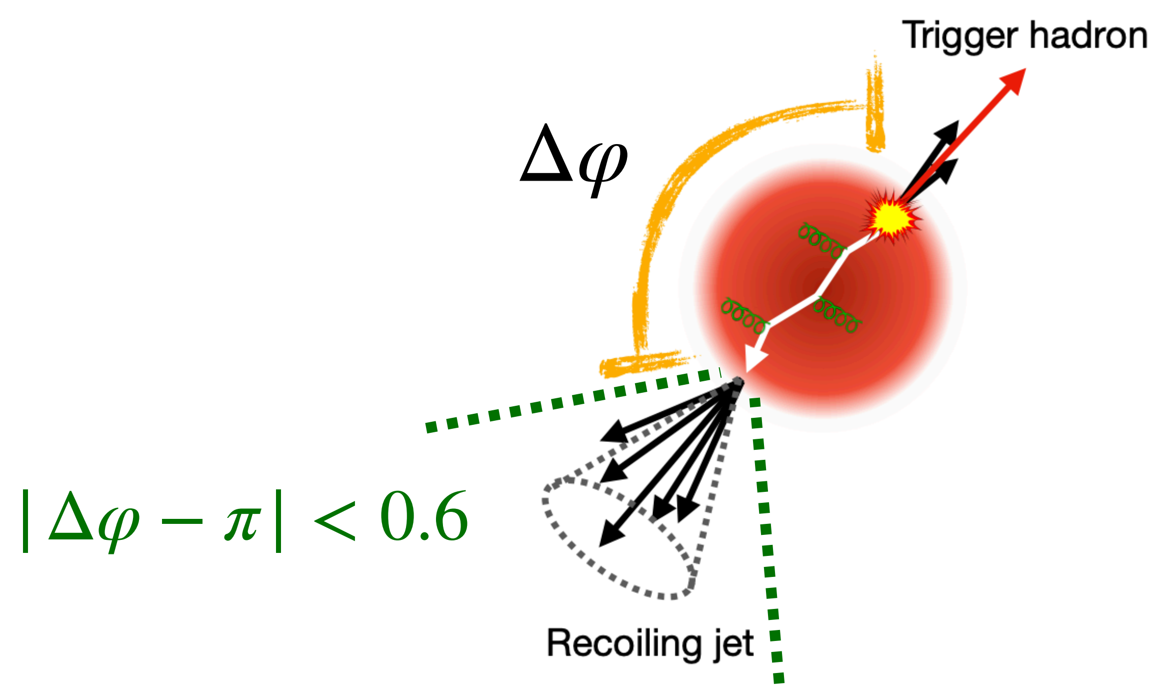
- Δ_{recoil} distributions measured down to $p_{\mathrm{T,jet}}$ ~ 7 GeV/c in pp and Pb-Pb collisions

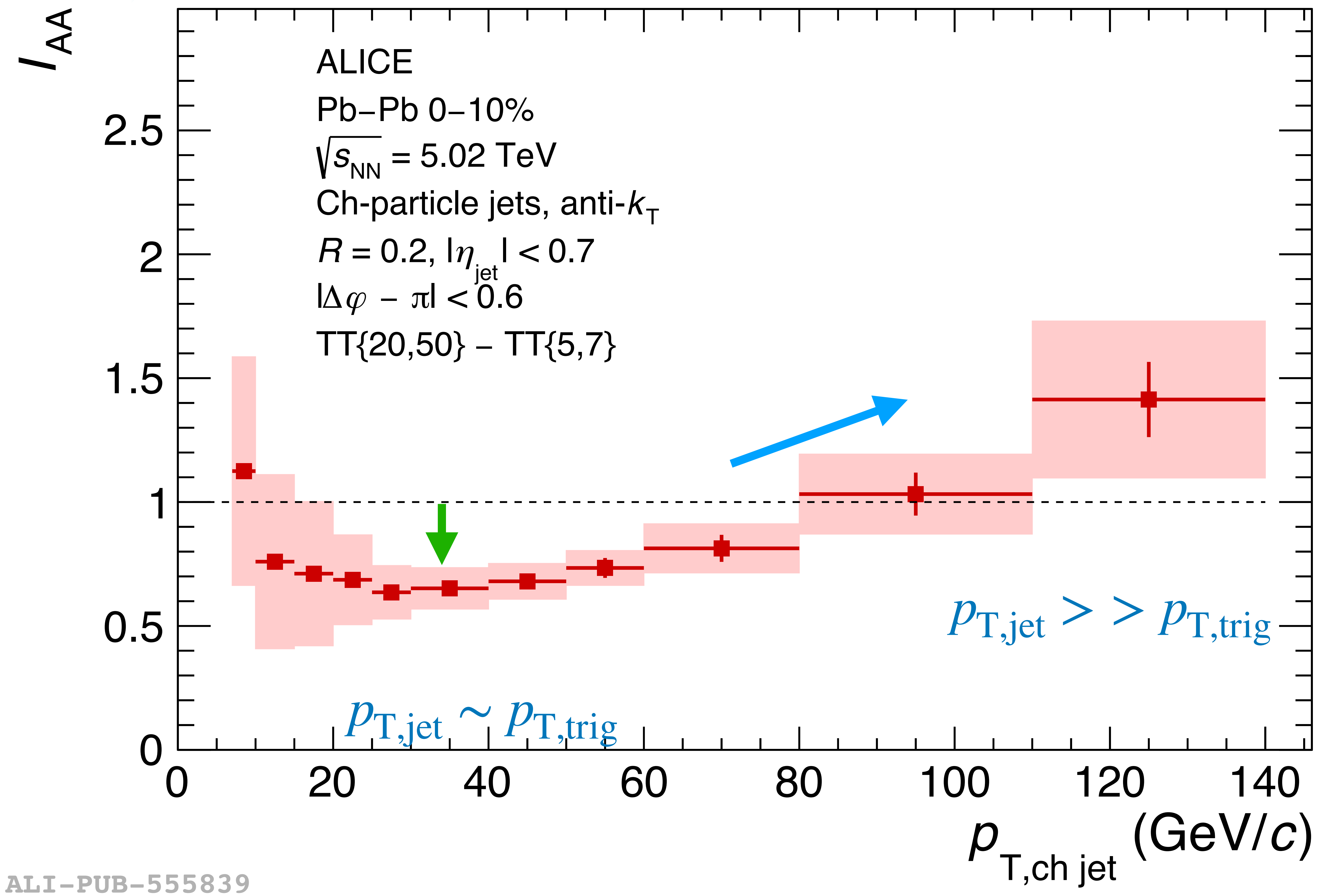
Among lowest jet p_{T} measurement in Pb-Pb collisions at the LHC!

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



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



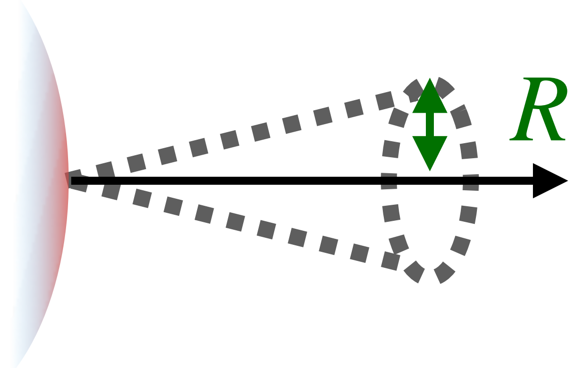


ALI-PUB-555839

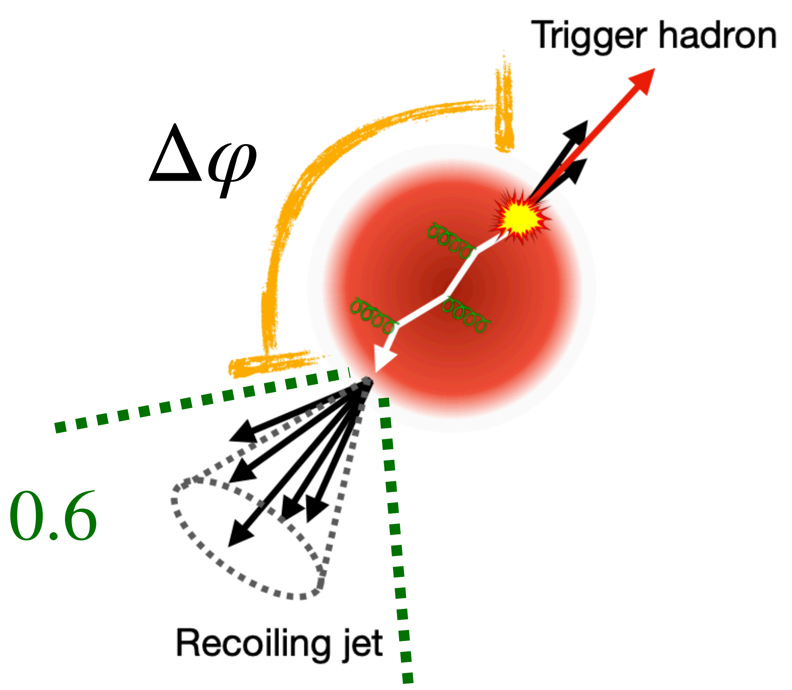
- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Larger energy loss of trigger when $p_{T,jet} >> p_{T,trig}$

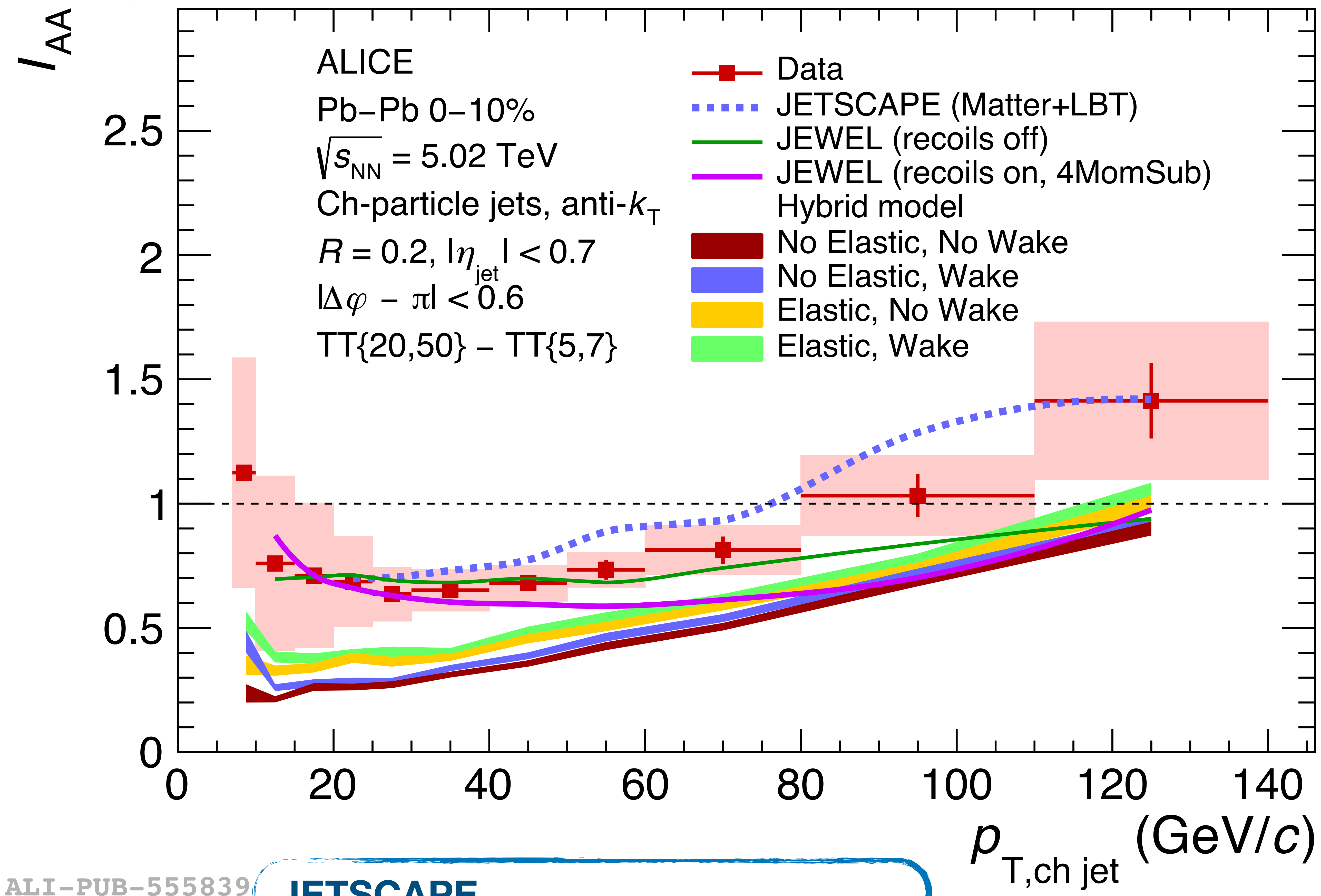
Y. He et al, arxiv:2401.05238

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



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





- **Suppression** at $20 < p_{T,\mathrm{ch\,jet}} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$**
  → interplay between hadron and jet energy loss?
  Larger energy loss of trigger when $p_{T,\mathrm{jet}} >> p_{T,\mathrm{trig}}$
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low-$p_{T,\mathrm{jet}}$ 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'

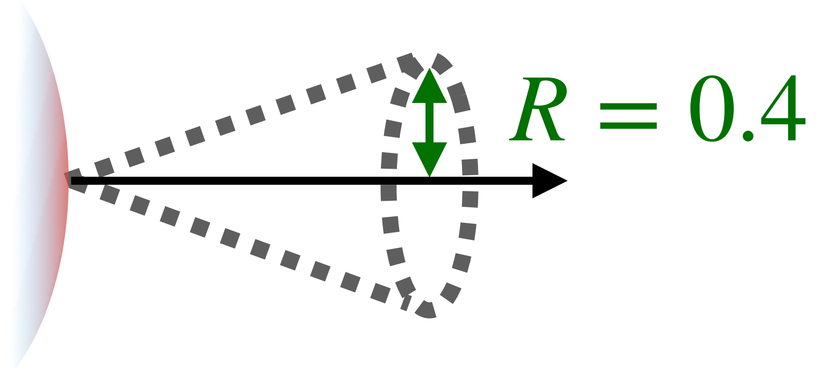
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

Hybrid model

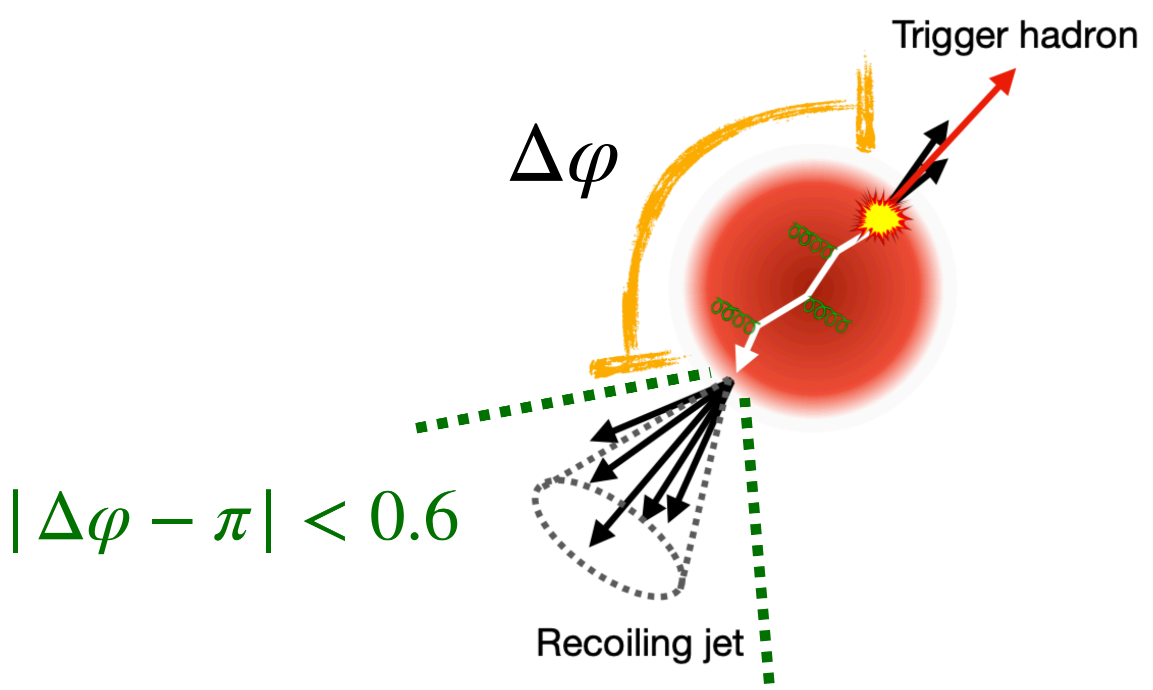
Elastic (Moliére) scatterings and wake (medium response) included

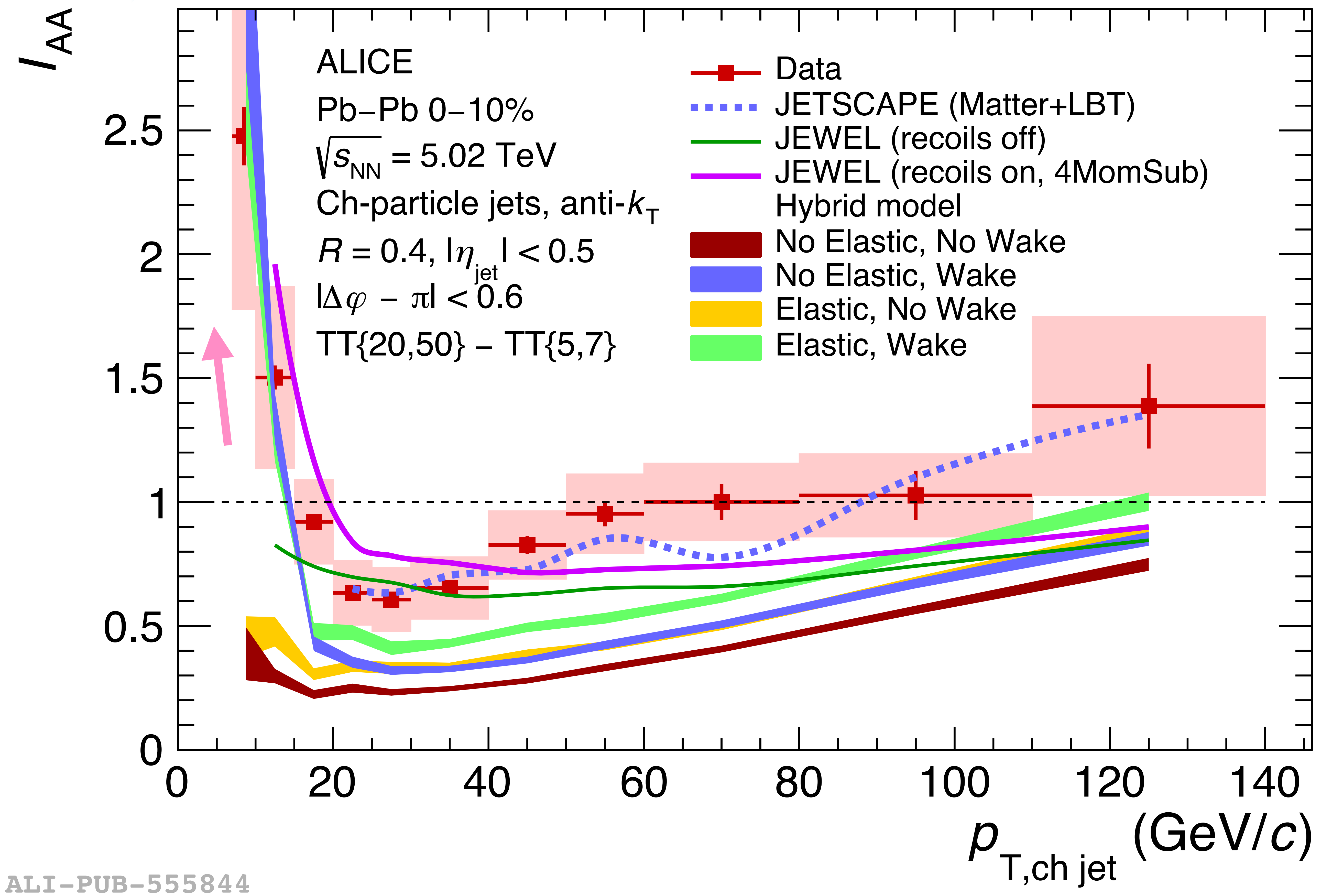
F. d'Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

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



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





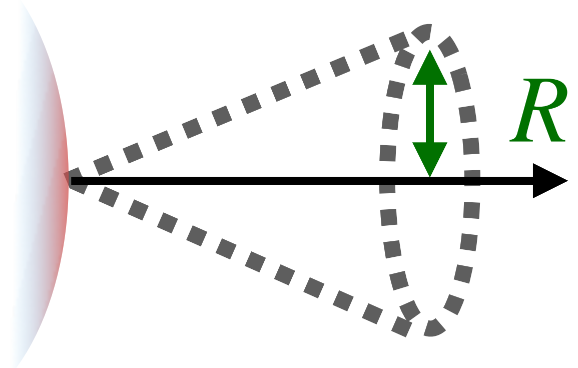
ALI-PUB-555844

- **Suppression** at $20 < p_{T,ch\,jet} < 80$ GeV/c
  → jet energy loss

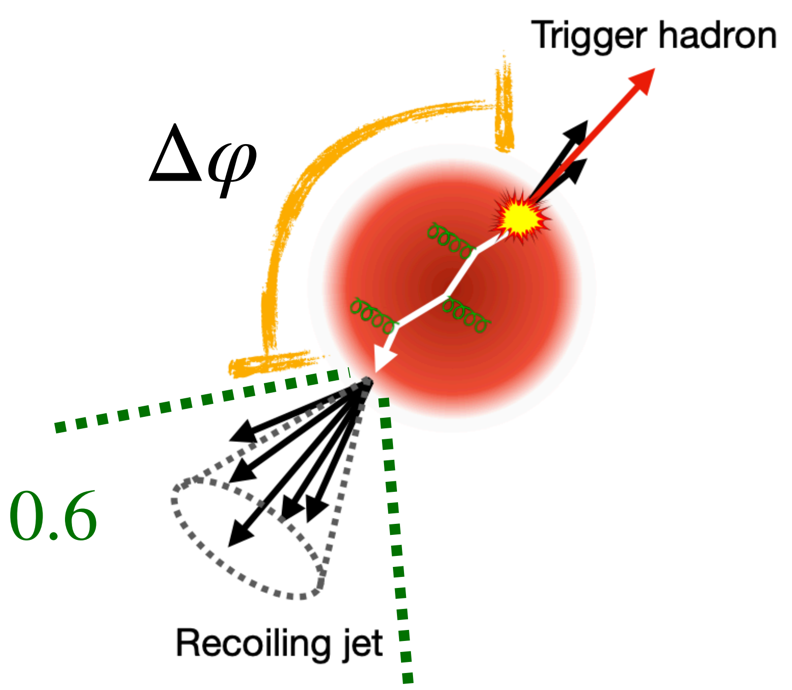
- **Rising trend with $p_{T,ch\,jet}$**
  → interplay between hadron and jet energy loss?
  Larger energy loss of trigger when $p_{T,jet} >> p_{T,trig}$

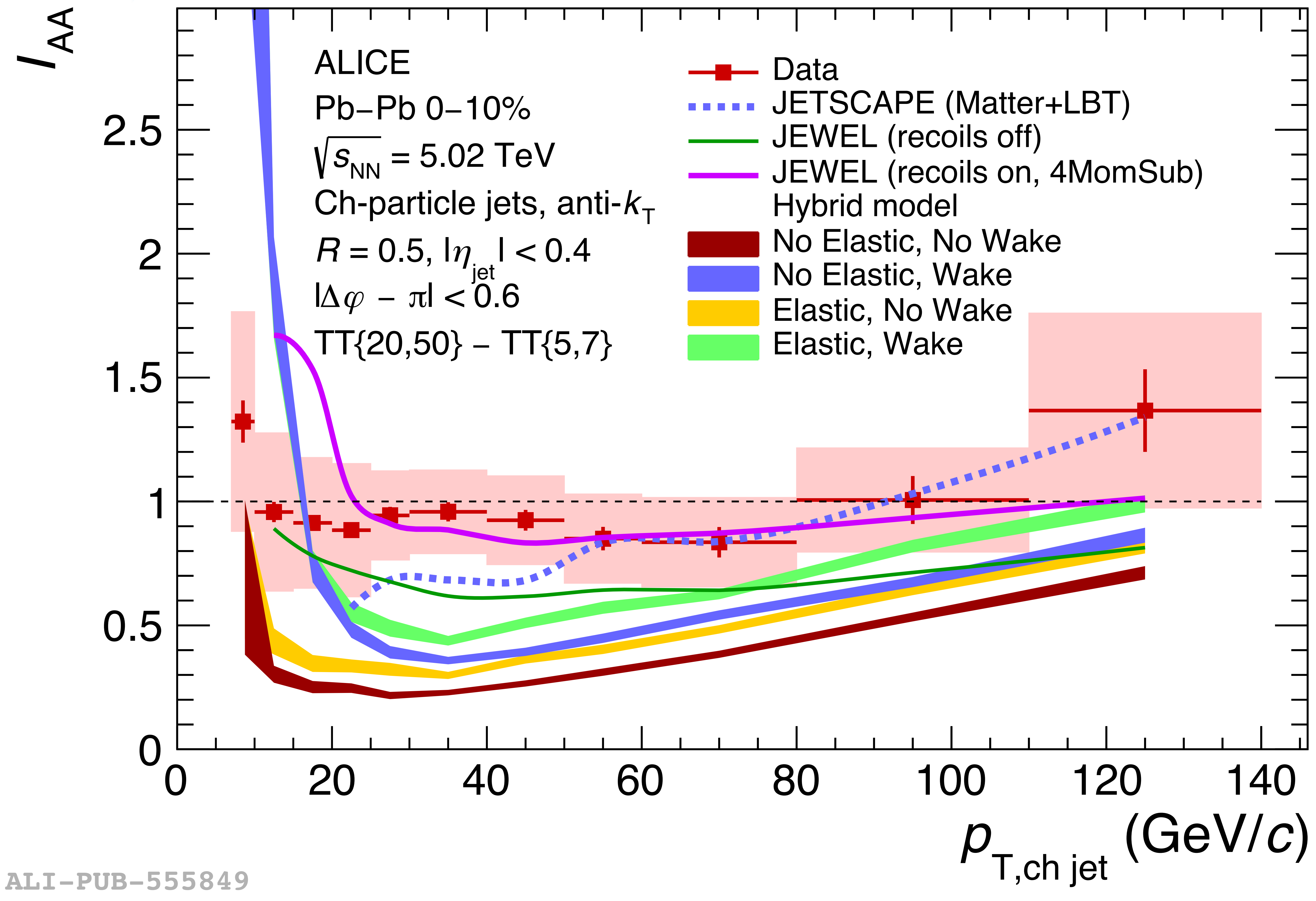
- **Rise at low $p_{T,ch\,jet}$**
  → Energy recovery? Reproduced by models including medium response

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

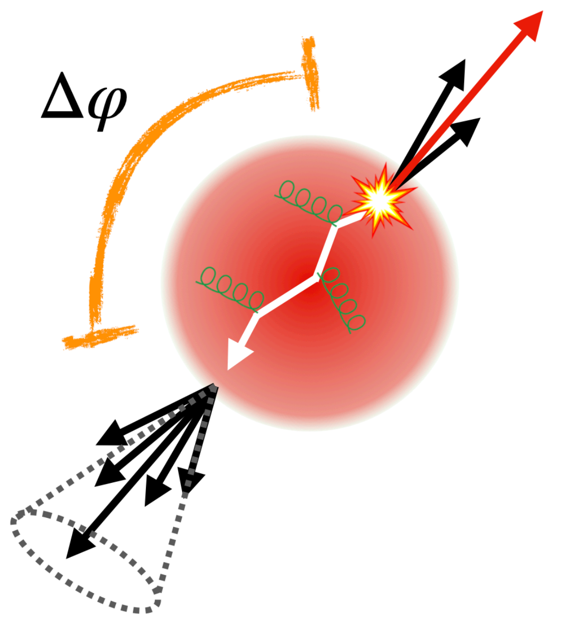


$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$



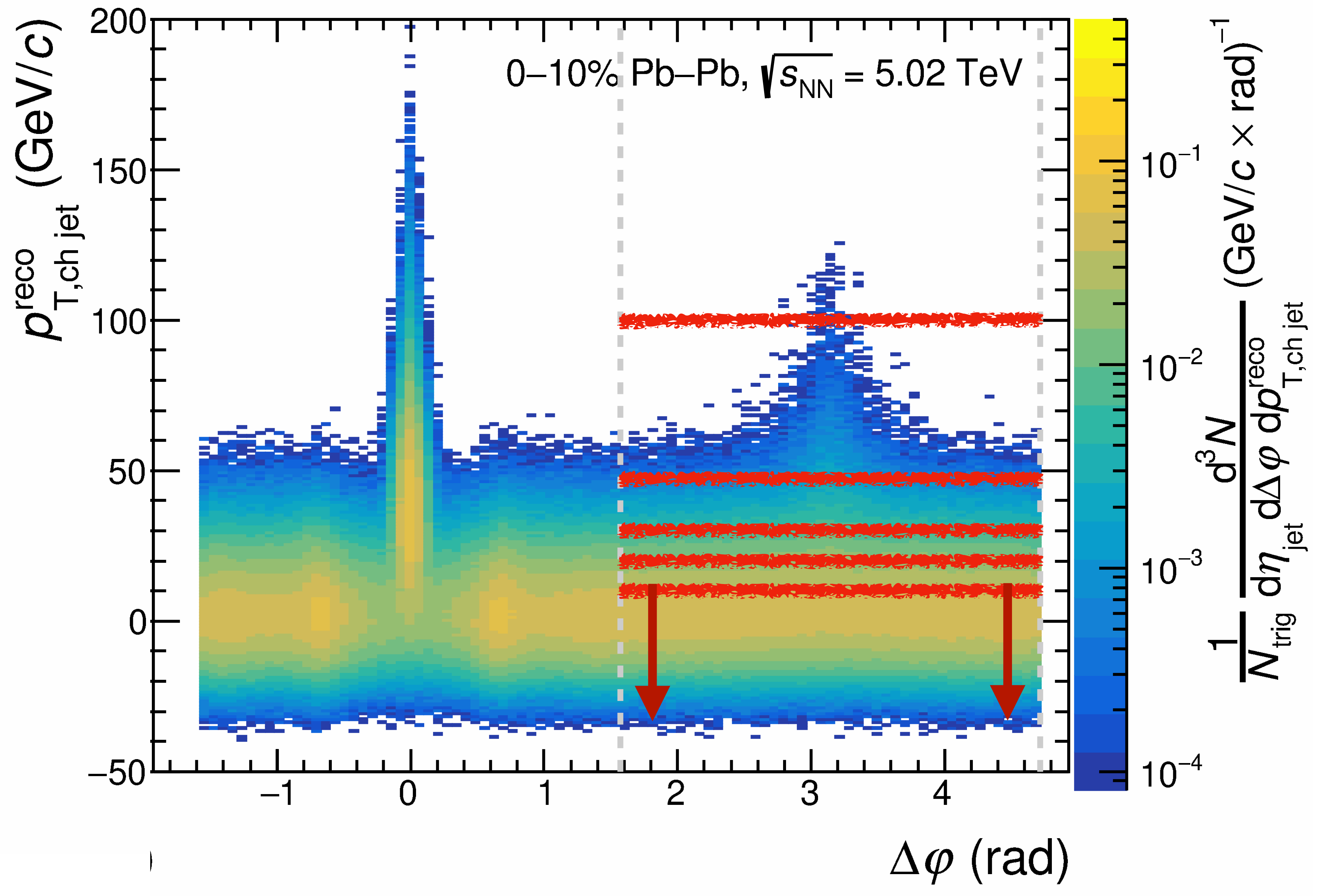


- ***R*=0.5 consistent with no suppression**
  - Little suppression captured by JEWEL (recoils on)
- Indication of intra-jet energy recovery within cone radius~0.5 for mid-$p_{T,ch\,jet}$?
- Redistribution of energy for *R*=0.5 jets more challenging for models

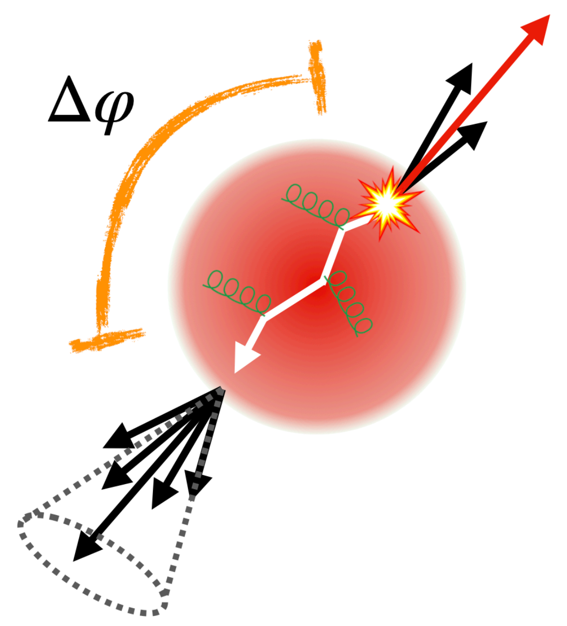


Results

- $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}})$: 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



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

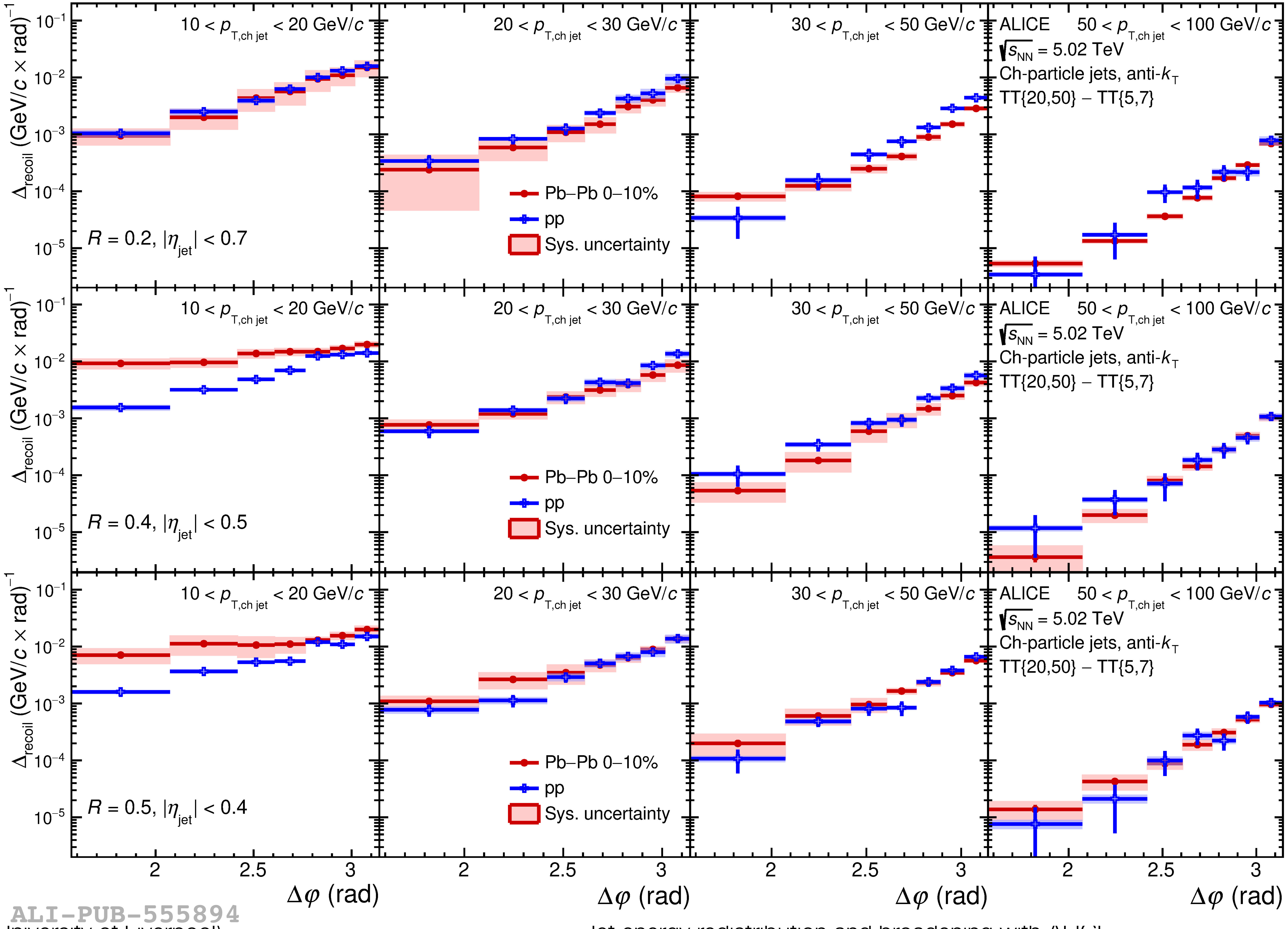


$p_{\mathrm{T,ch\,jet}}$: [10,20] GeV/*c* [20,30] GeV/*c* [30,50] GeV/*c* [50,100] GeV/*c*

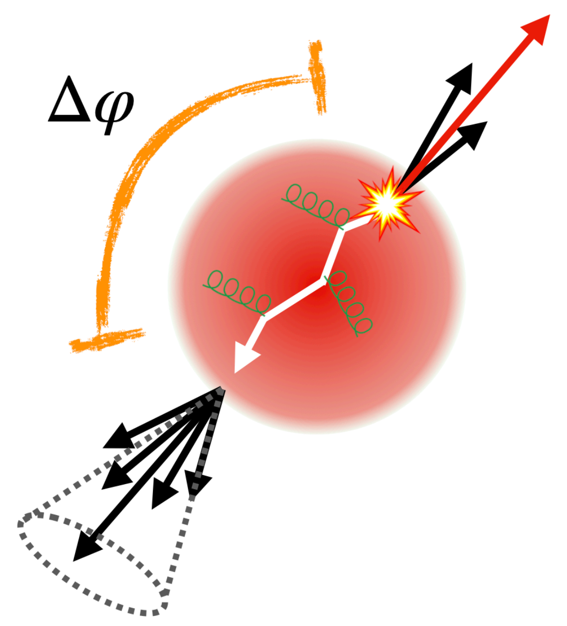
***R*=0.2**

***R*=0.4**

***R*=0.5**



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

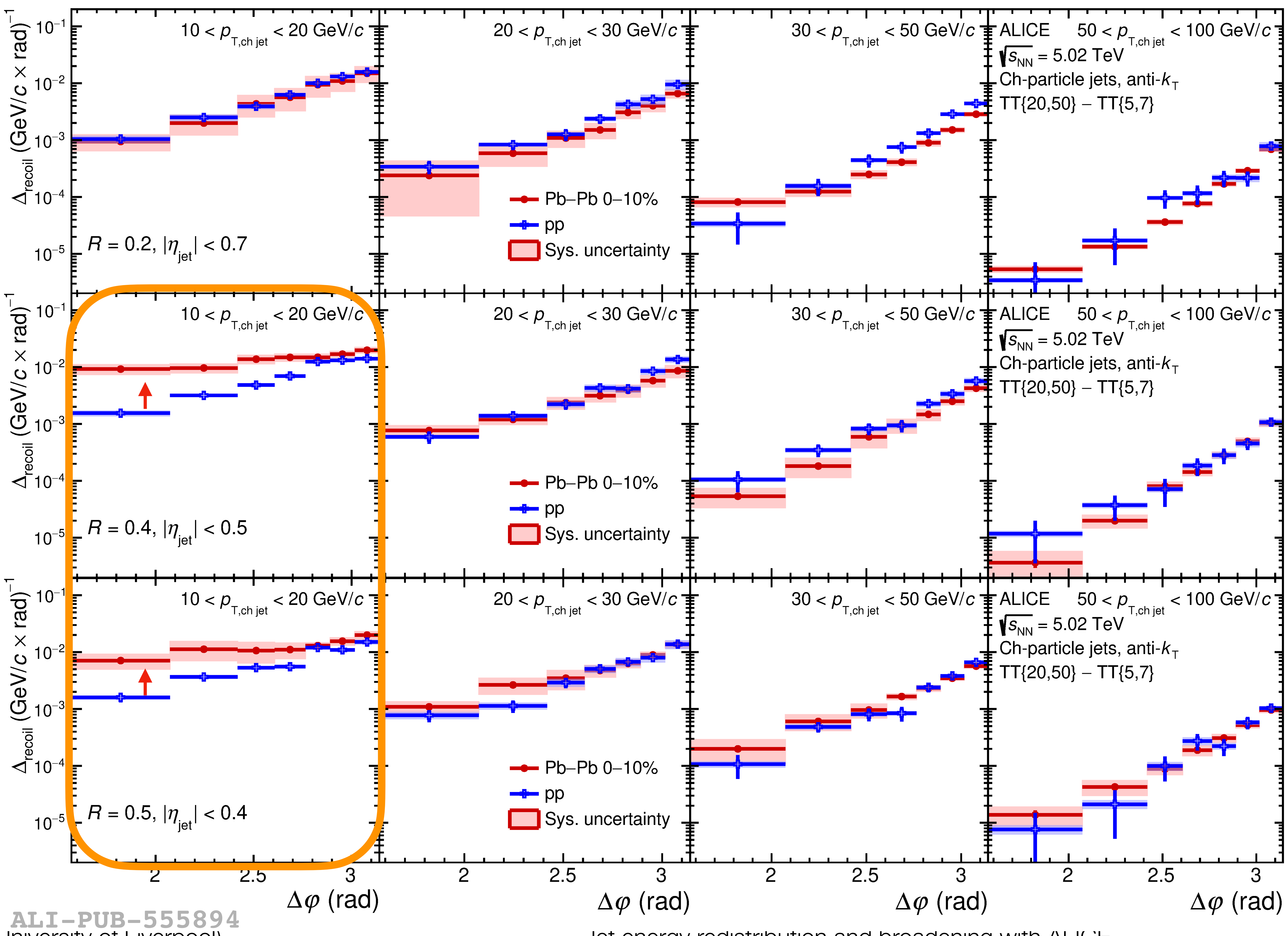


$p_{\rm T,ch\,jet}$: [10,20] GeV/c | [20,30] GeV/c | [30,50] GeV/c | [50,100] GeV/c

R=0.2

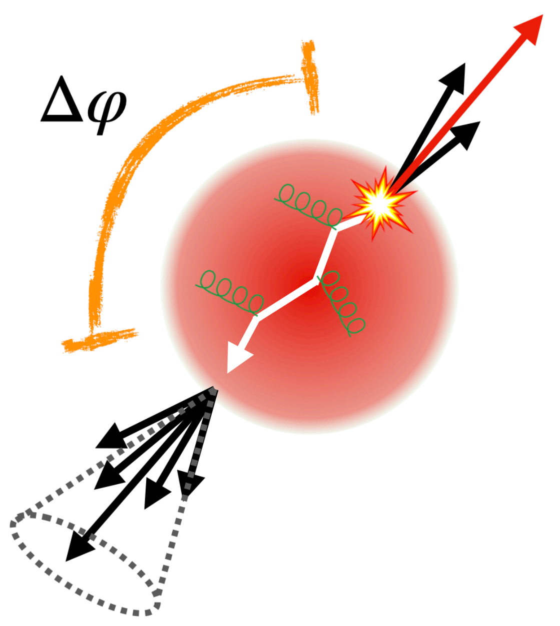
R=0.4

R=0.5

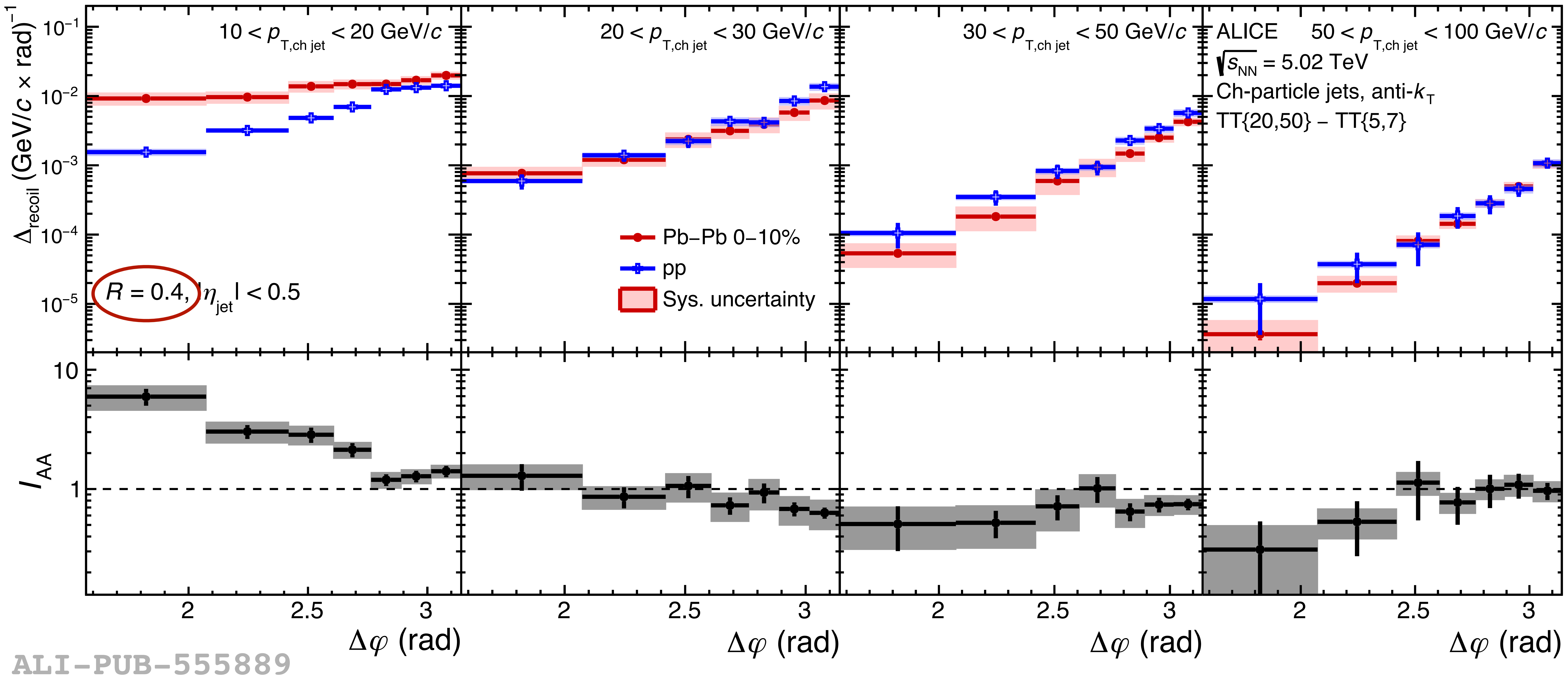


- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{\rm T,ch\,jet}$

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



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

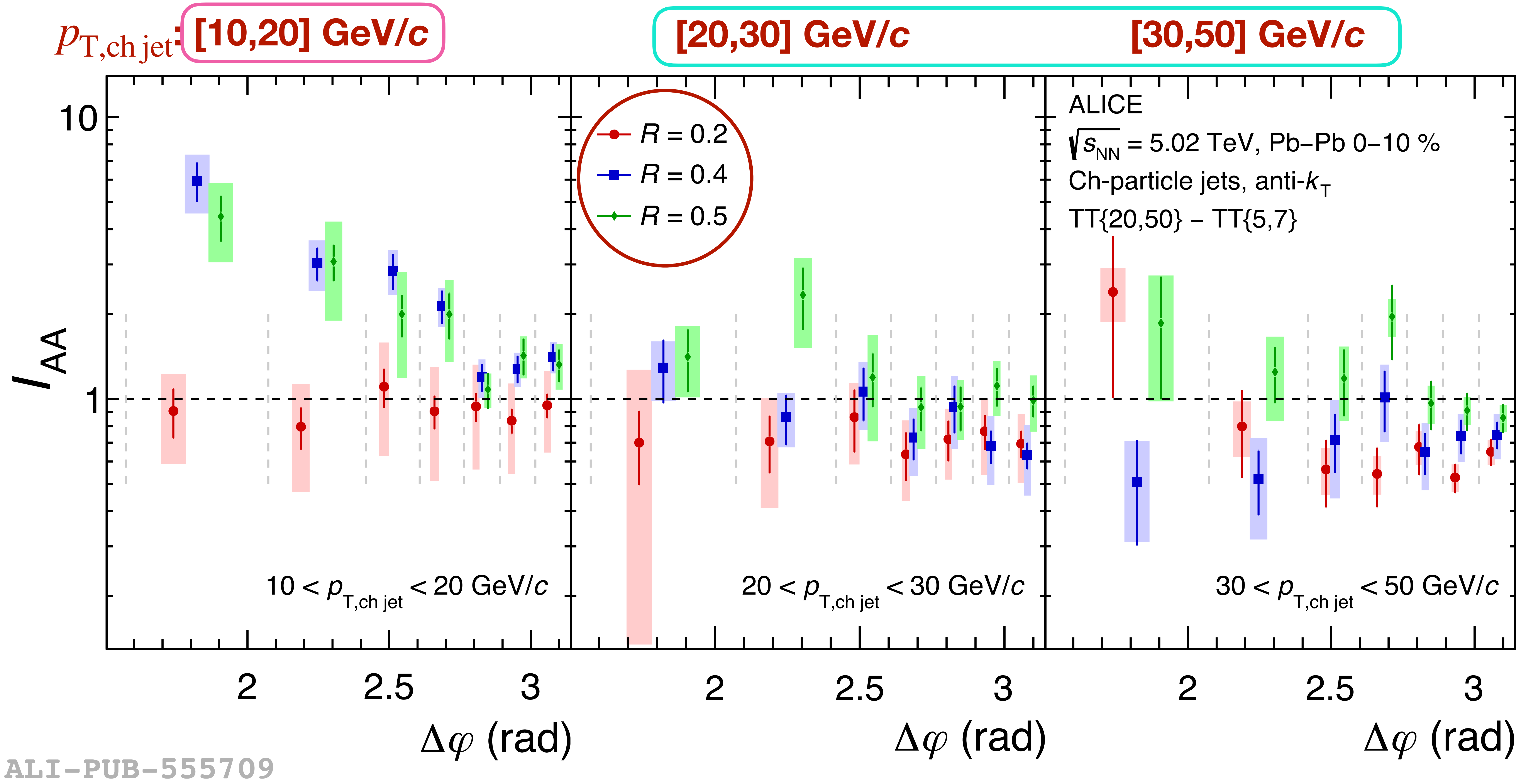


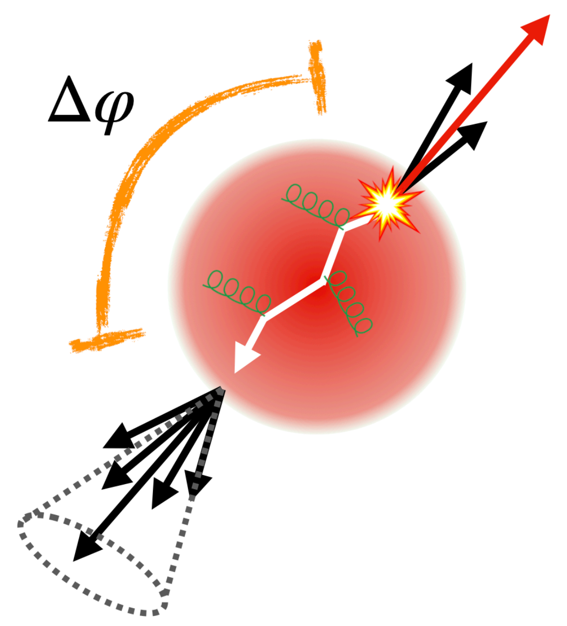
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

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

(4.7σ deviation of I_{AA} from flat)

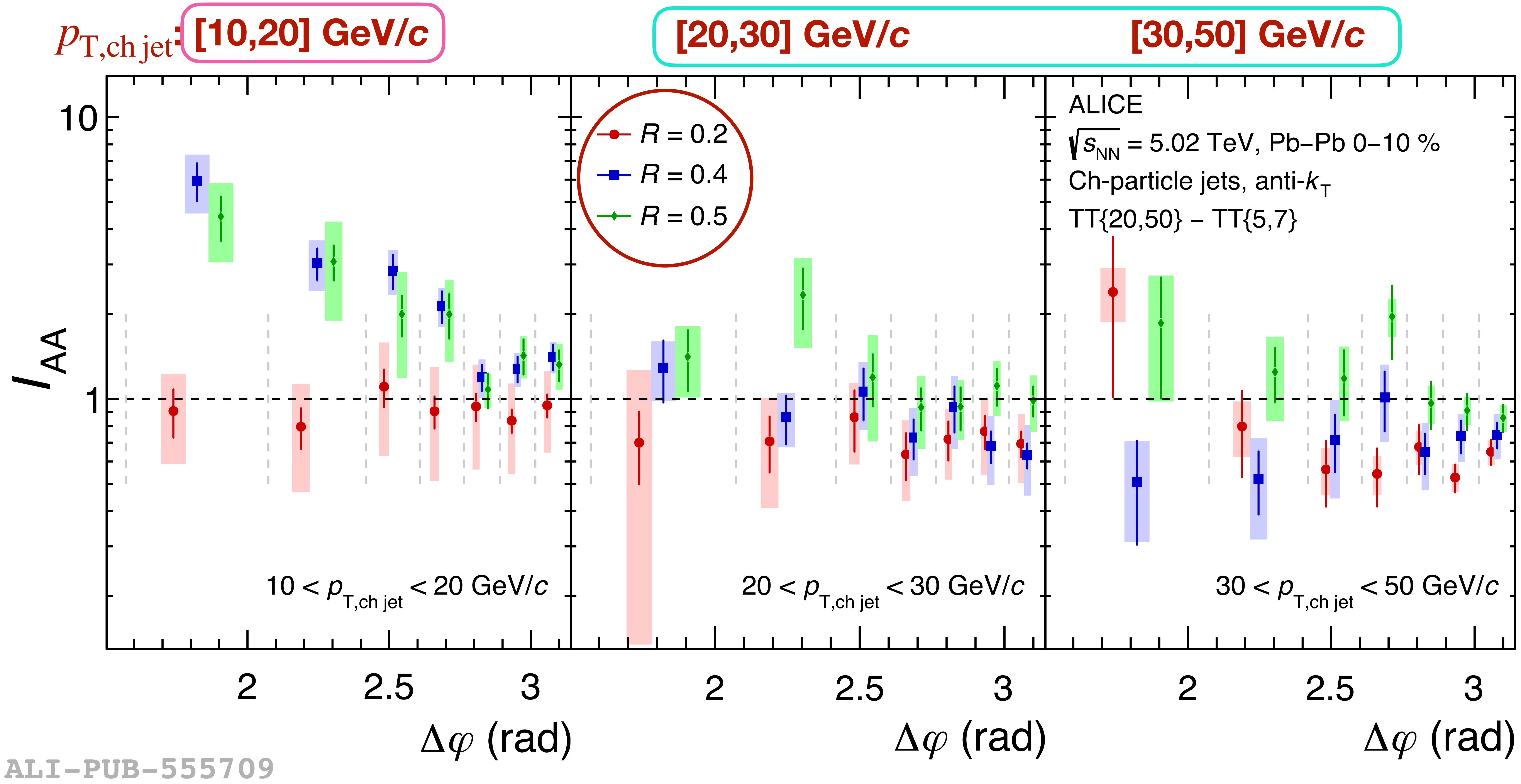
$I_{AA}(\Delta\varphi)$ vs R

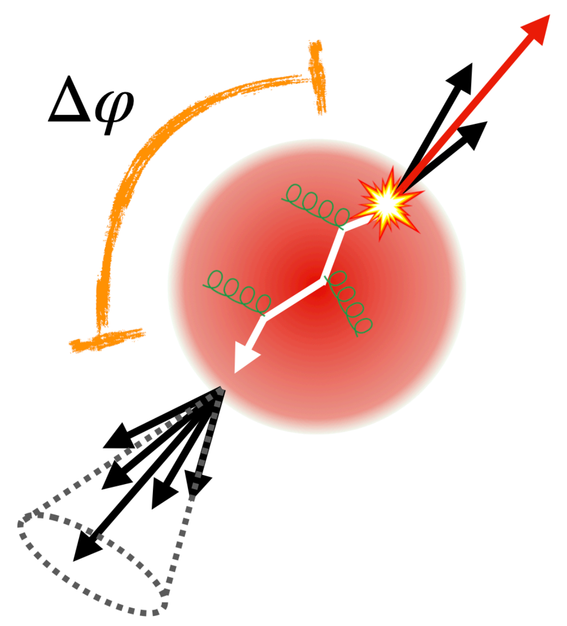




- **Transition to broadening from *R*=0.2 -> *R*=0.4 for [10,20] GeV/c:**
  - Soft radiation mimicking a jet may scale with R^2
  - Molière scattering off QGP quasiparticles - *R*-dependence not expected

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



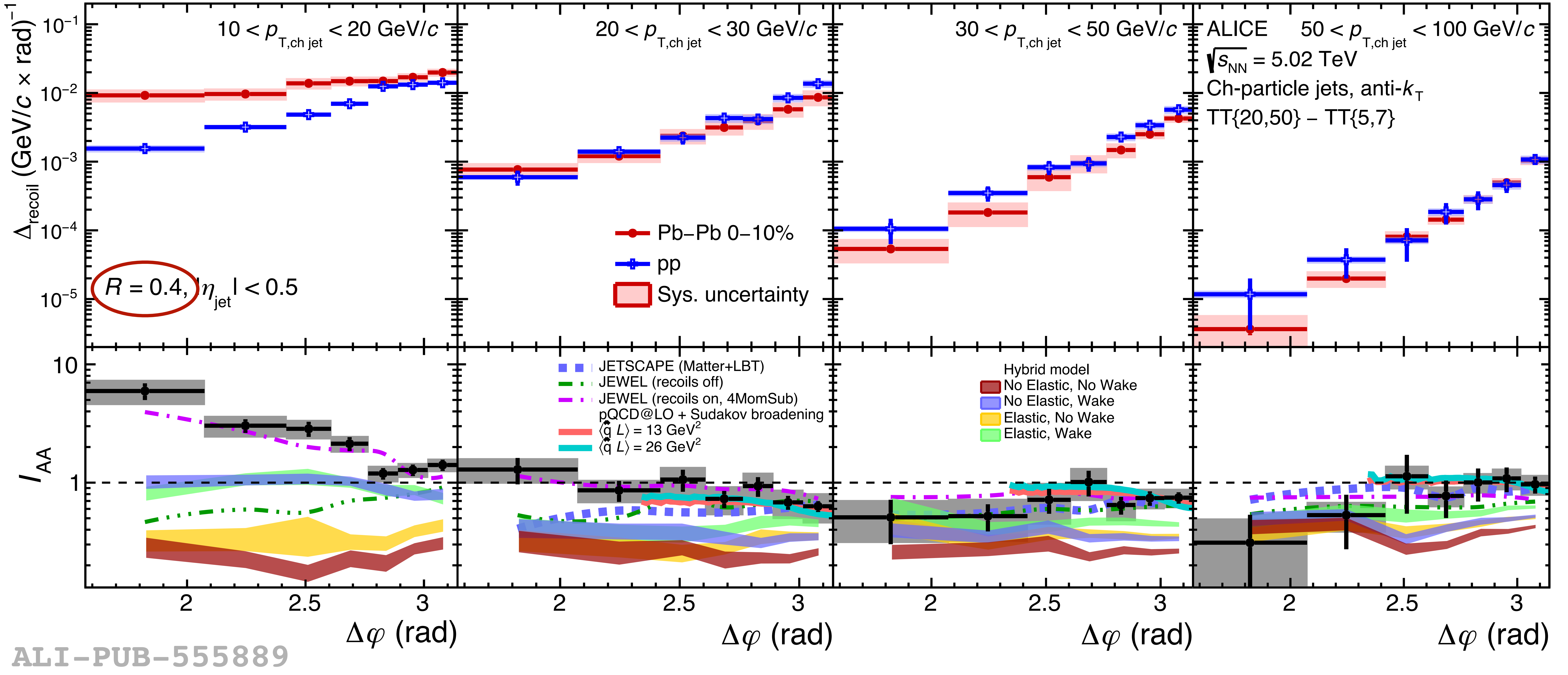


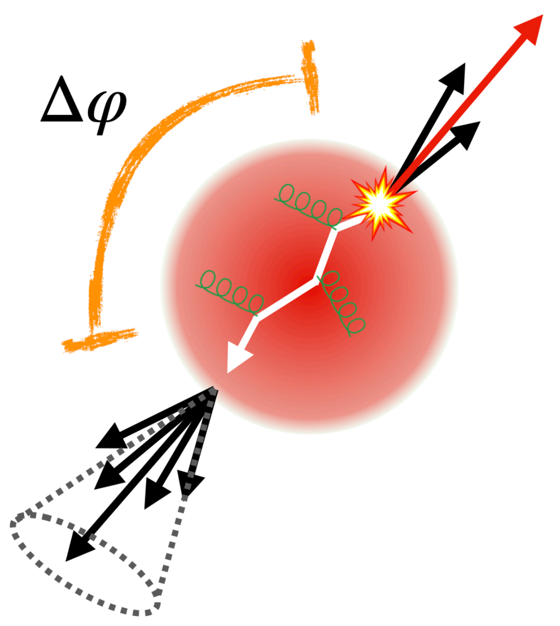
- **Transition to broadening from *R*=0.2 -> *R*=0.4 for [10,20] GeV/c:**
  - Soft radiation mimicking a jet may scale with R^2
  - Molière scattering off QGP quasiparticles - *R*-dependence not expected

→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

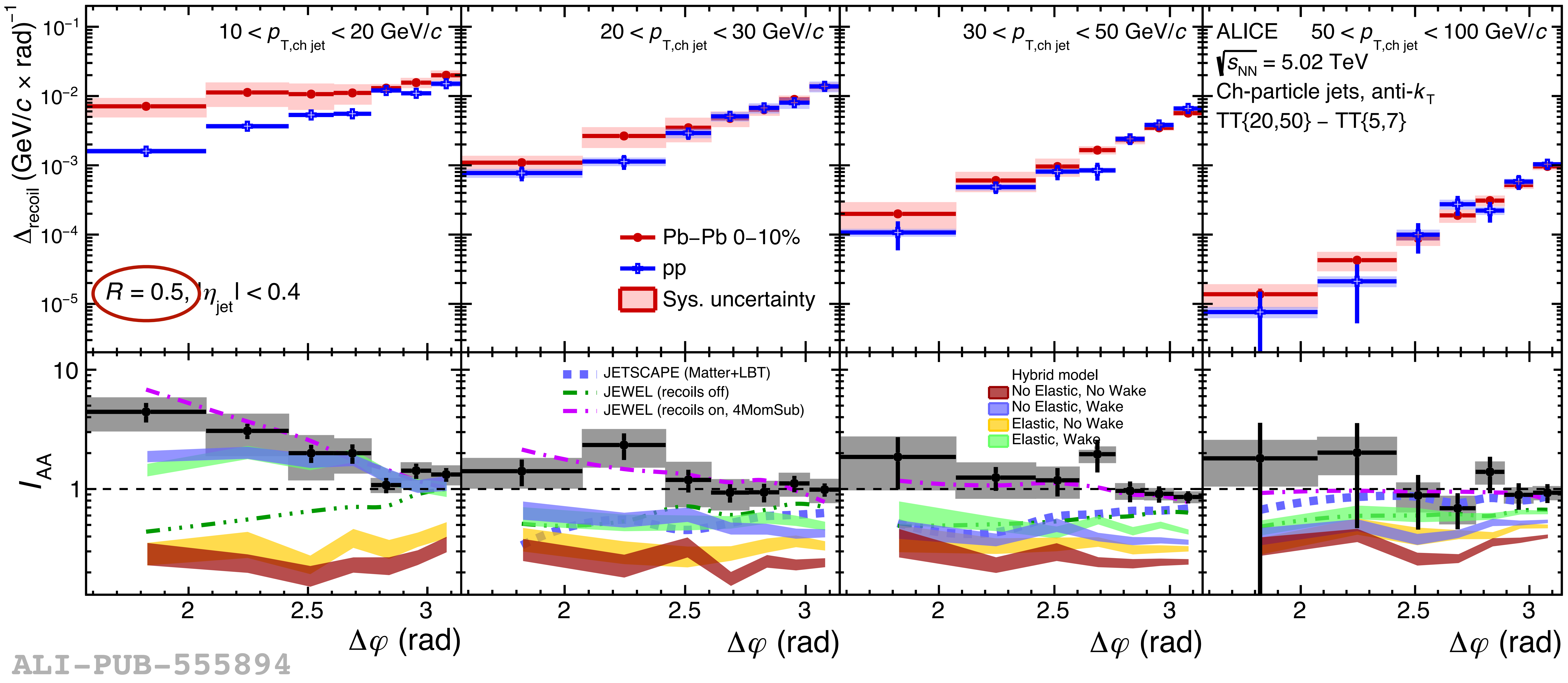
L. Chen et al, *Phys.Lett.B* 773 (2017) 672-676

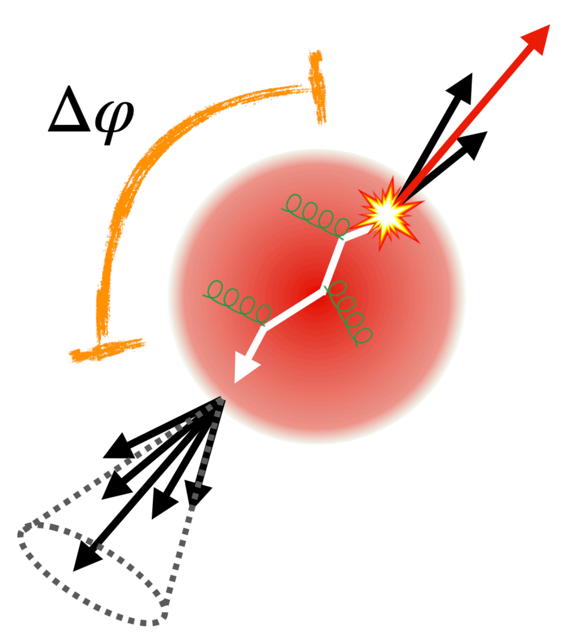
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

- 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

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



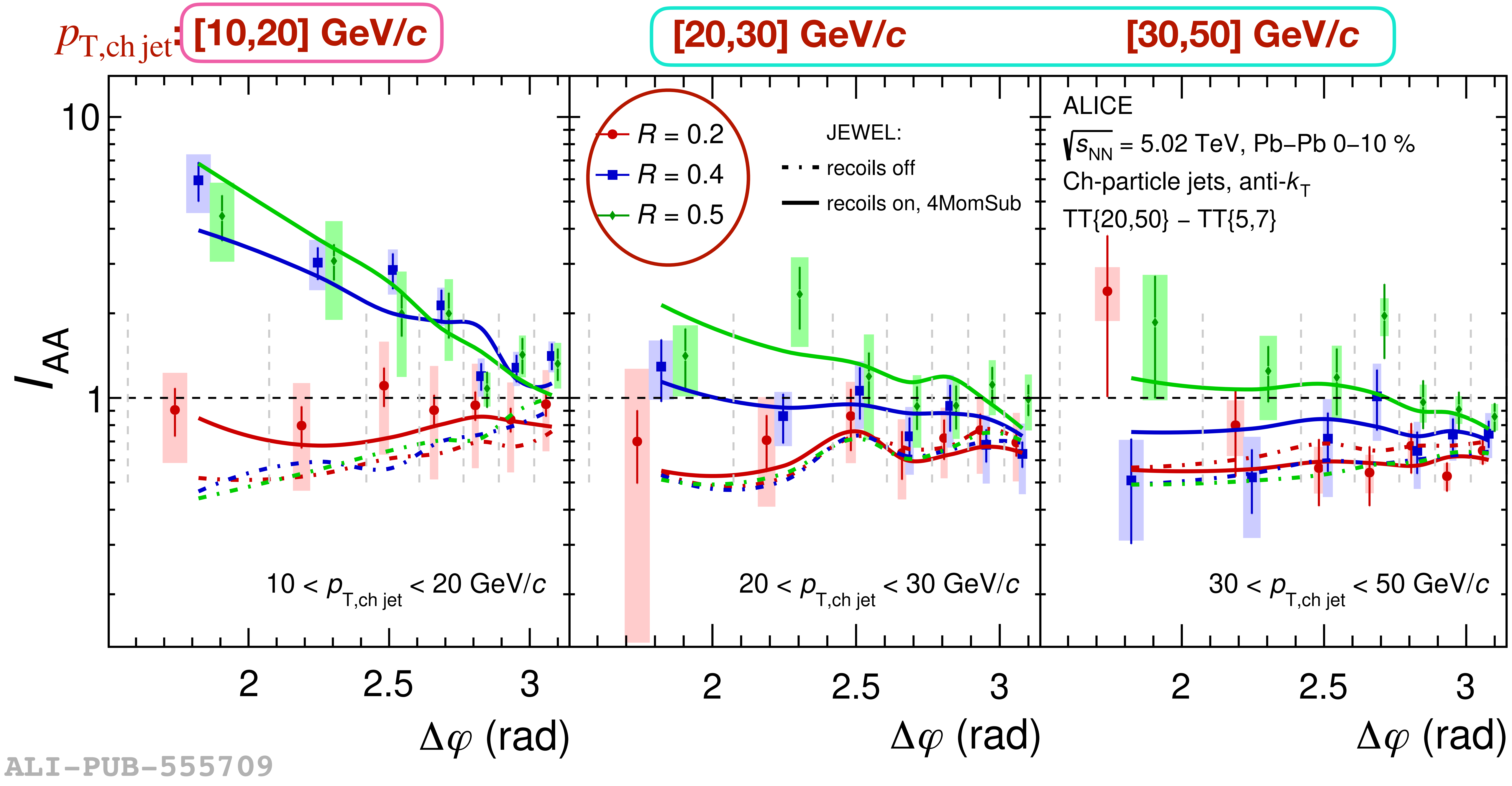


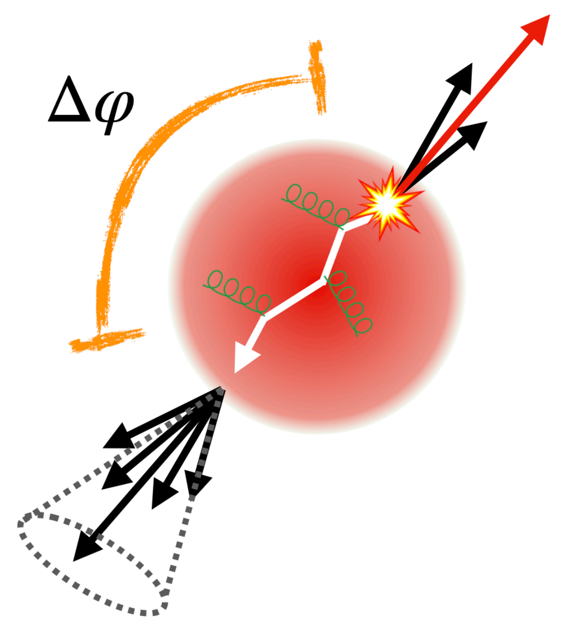
$$I_{AA} = \frac{\Delta_{recoil}(\text{Pb}-\text{Pb})}{\Delta_{recoil}(\text{pp})}$$

- 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

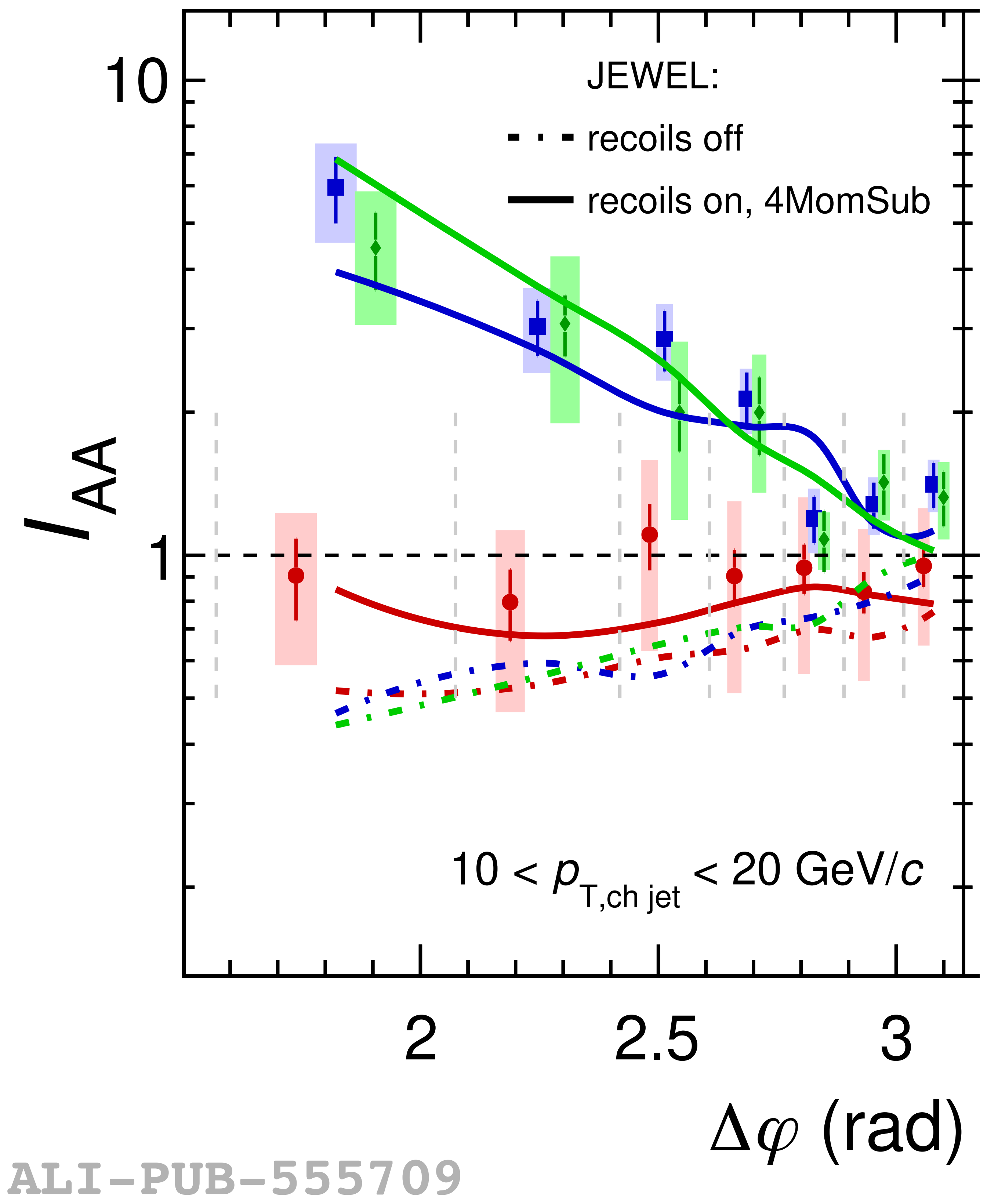




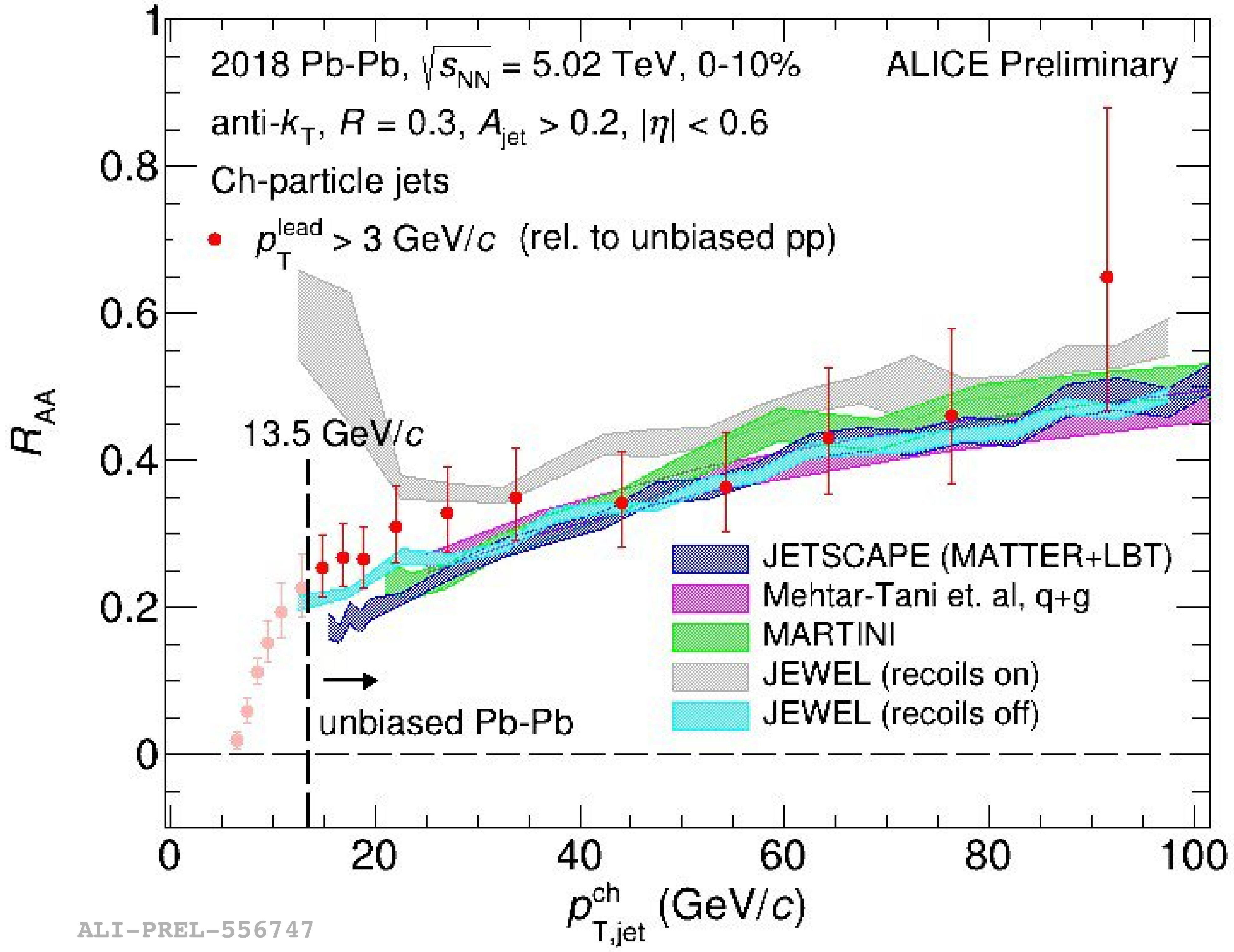
- All features of distribution **reproduced by JEWEL** with recoils on

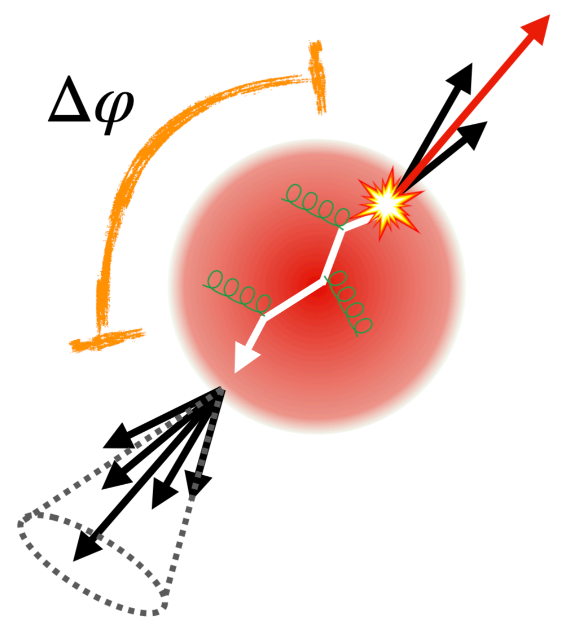
$I_{AA}(\Delta\varphi)$ vs R compared to JEWEL

h+jet



Inclusive

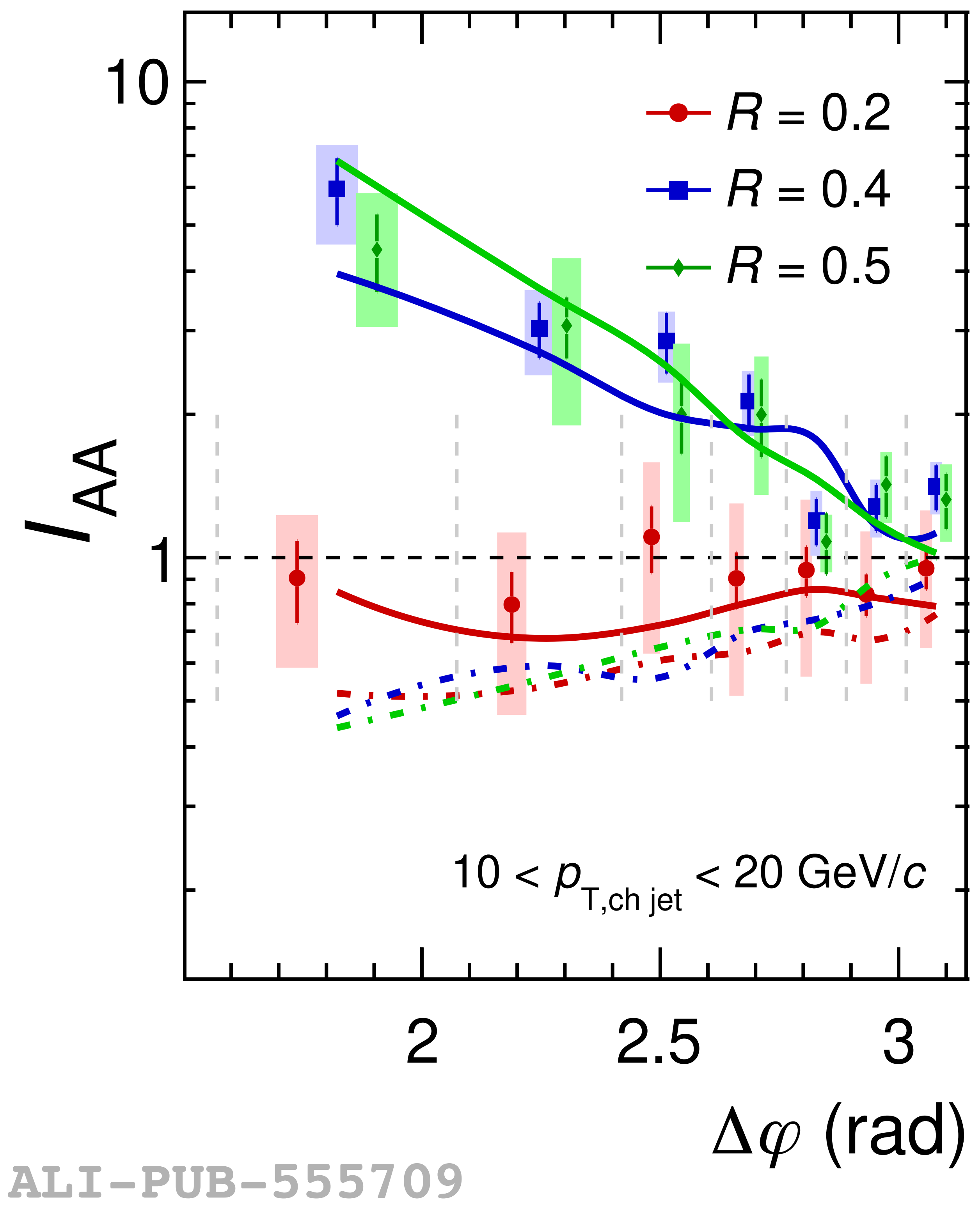




- All features of distribution **reproduced by JEWEL** with recoils on …
- … but no model incorporating medium response describes all measured observables

Next steps - precise characterisation of quenching effects

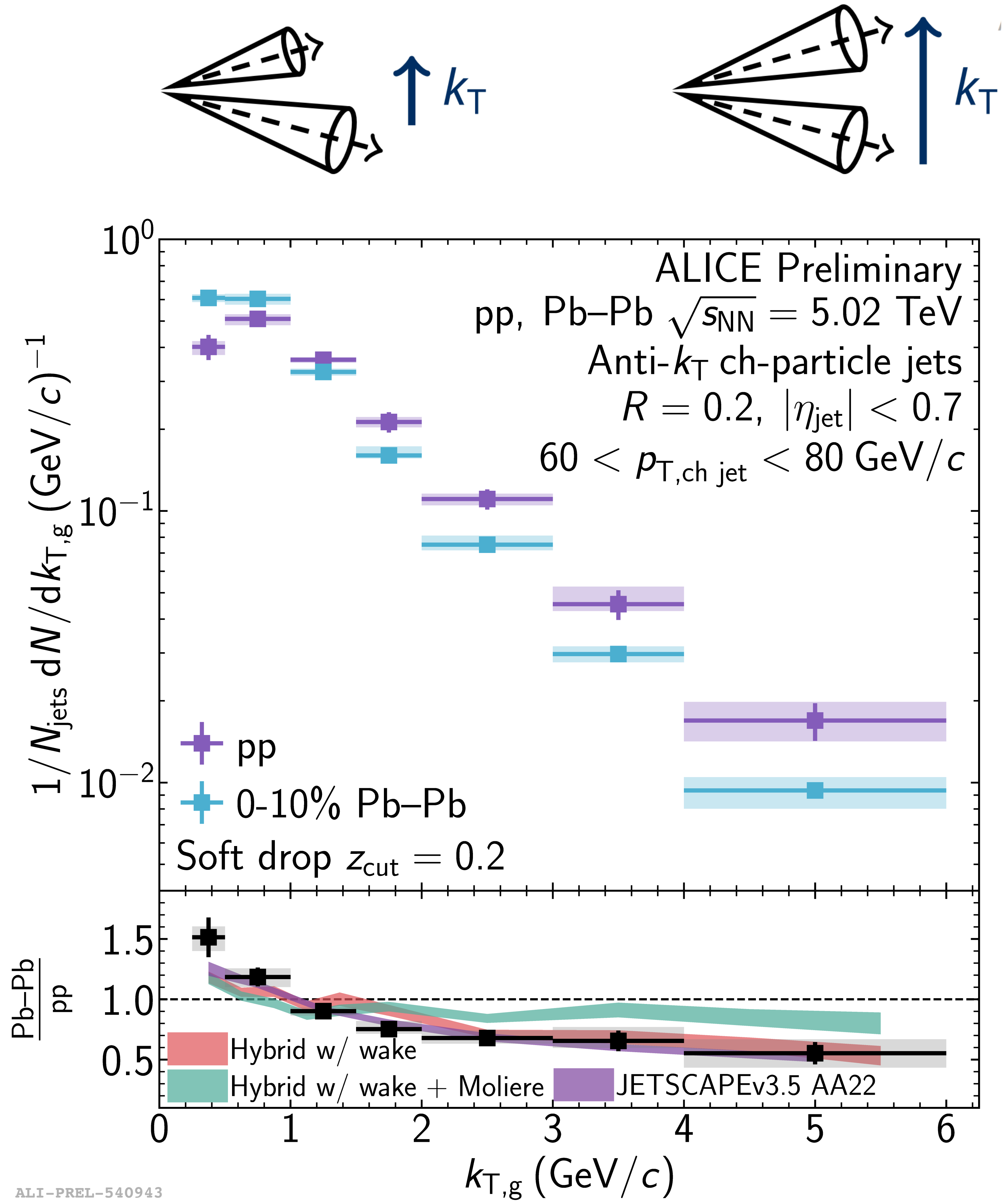
Characterise broadening

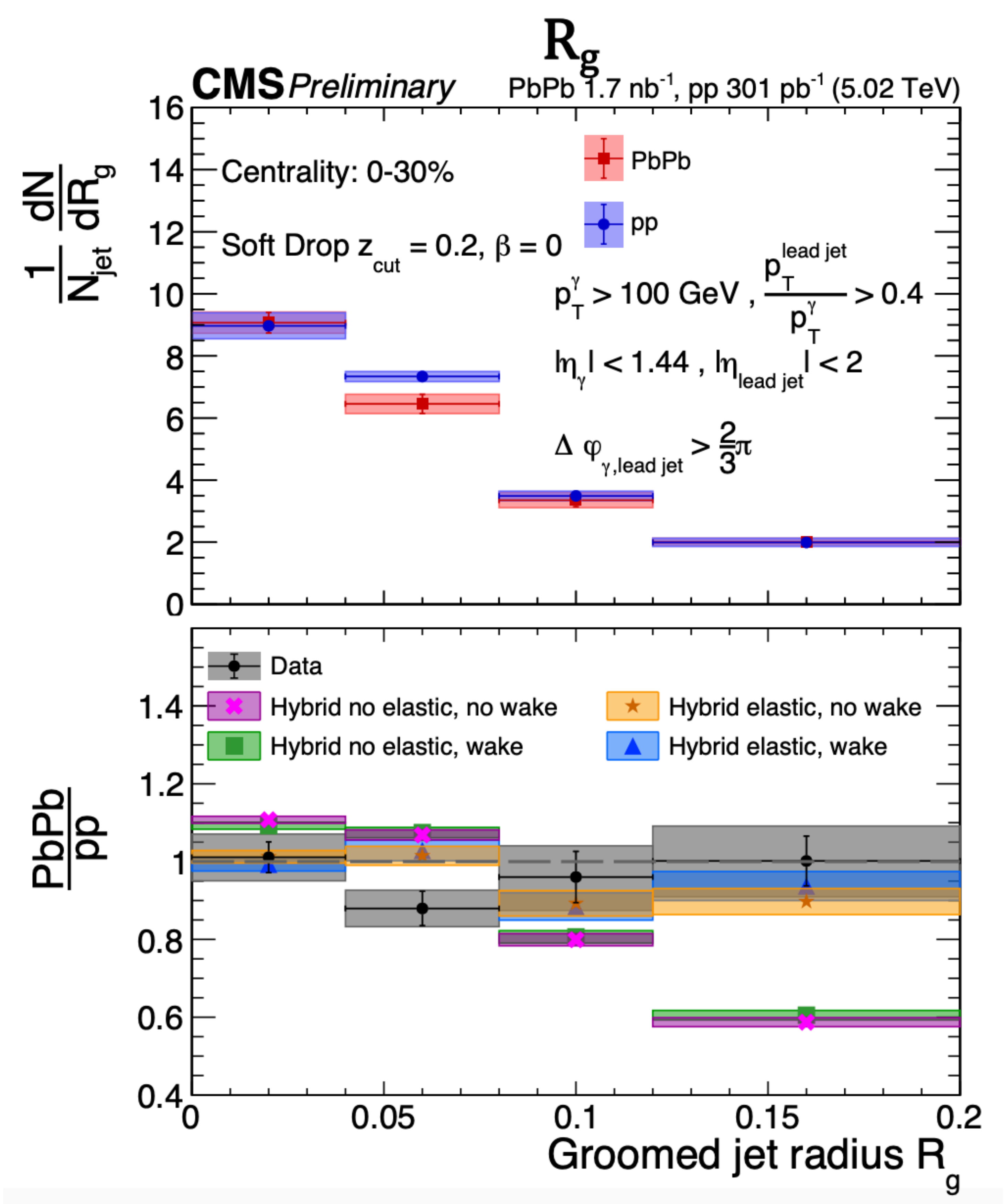


Thermalised jets? Hard component?

- Study substructure/fragmentation pattern
- Study jet axis definition

Substructure measurements offer promising way to find scatterings



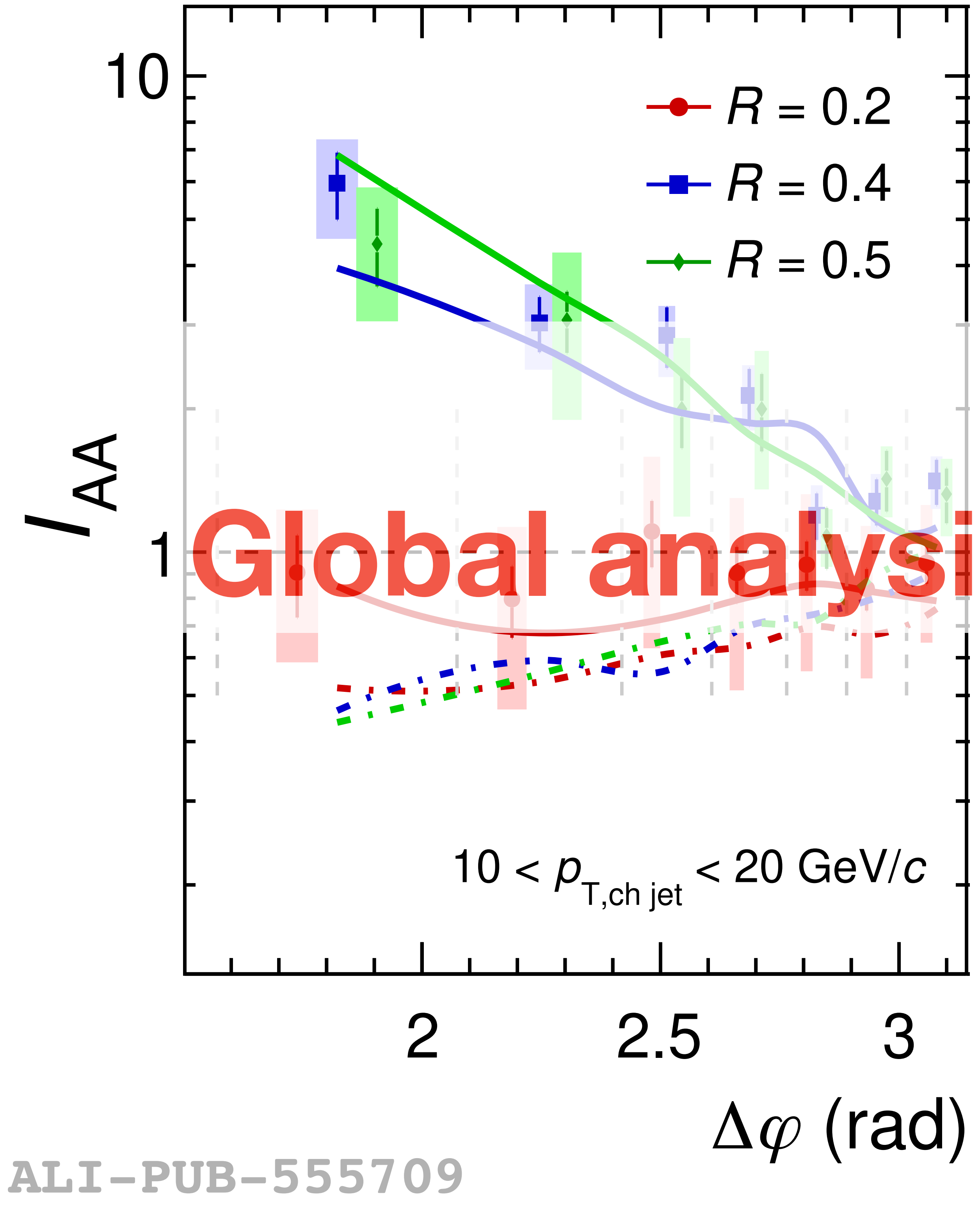


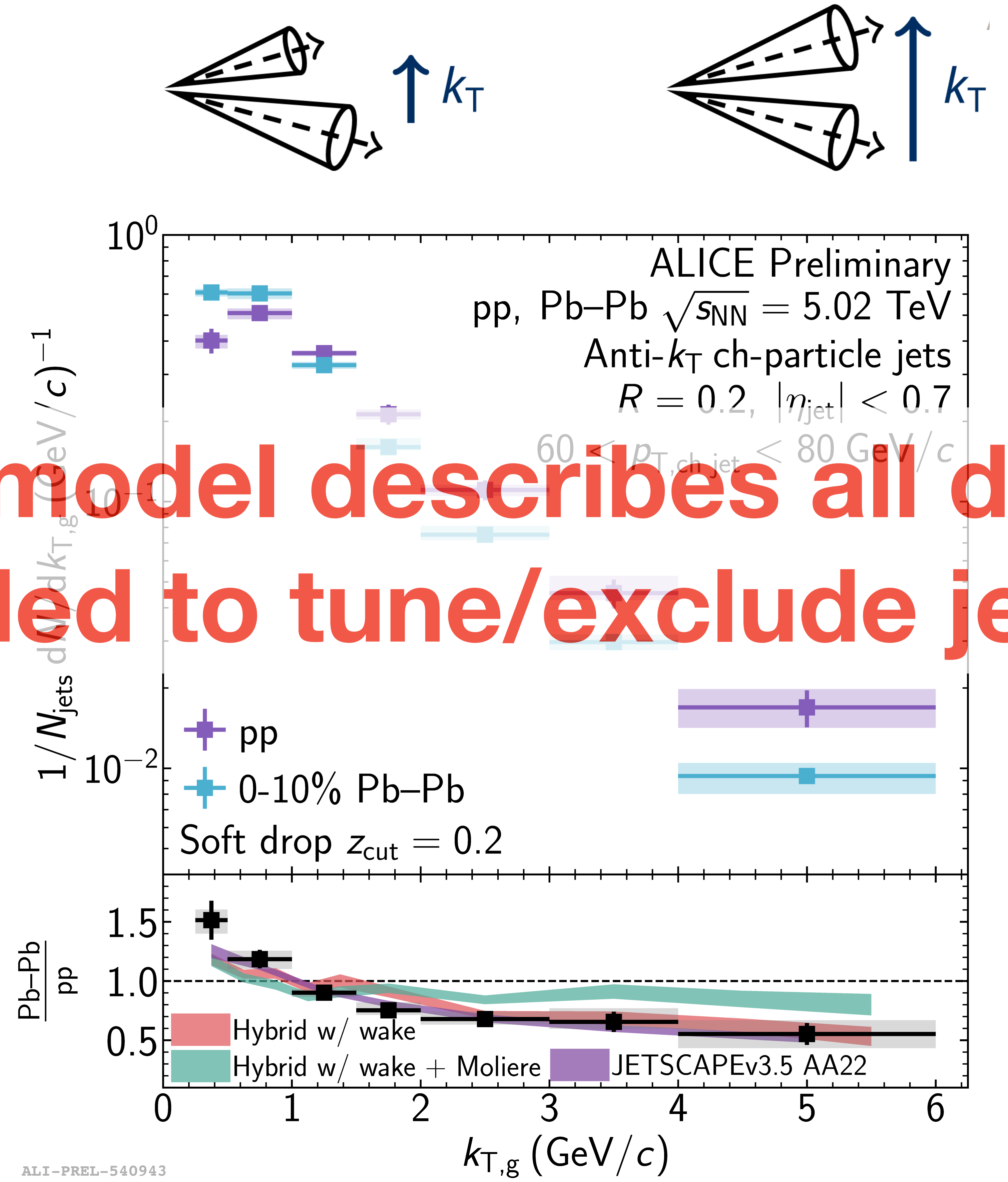
No clear evidence for Molière scattering

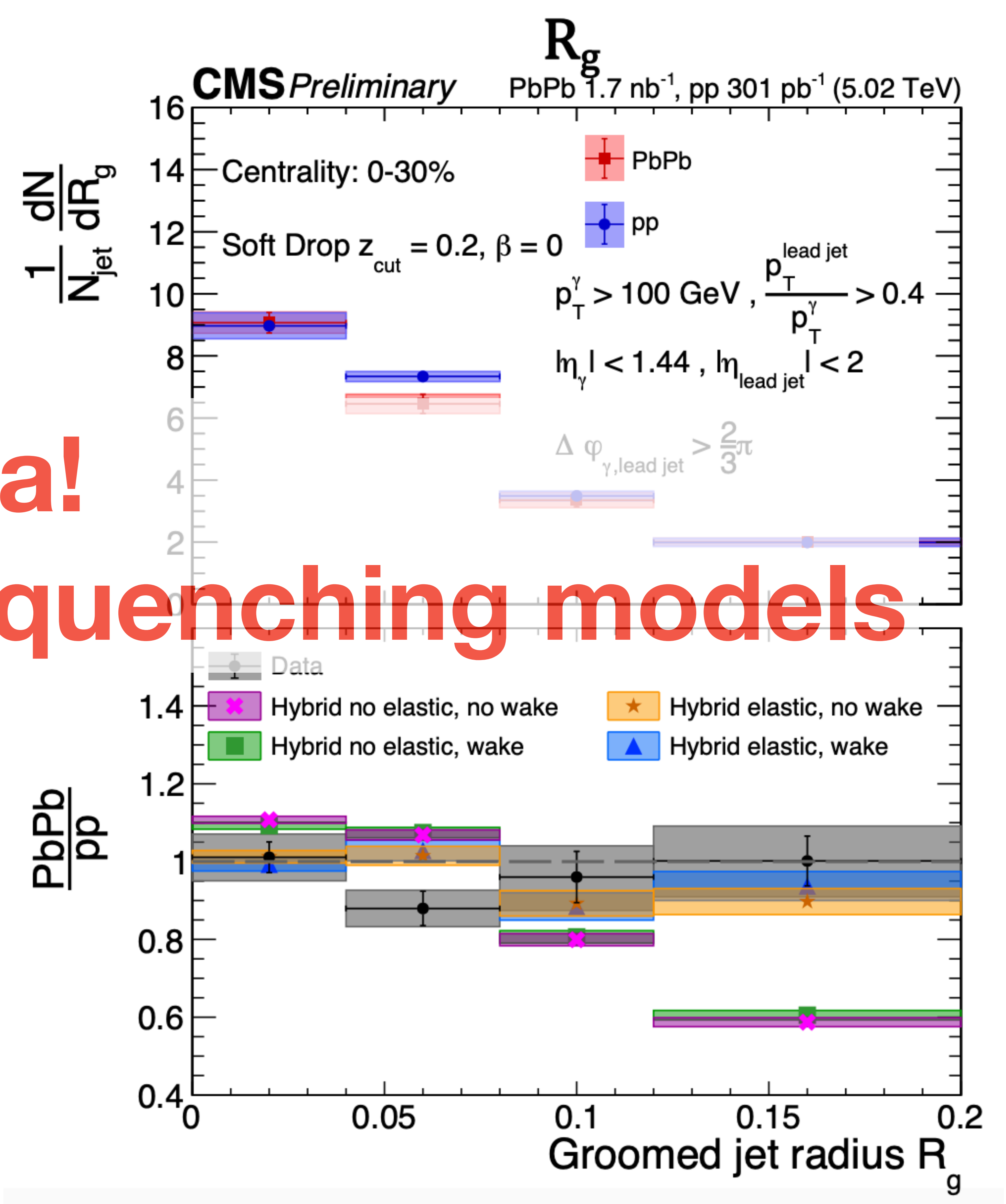
Next steps - precise characterisation of quenching effects

Characterise broadening

Substructure measurements offer promising way to find scatterings







No model describes all data!

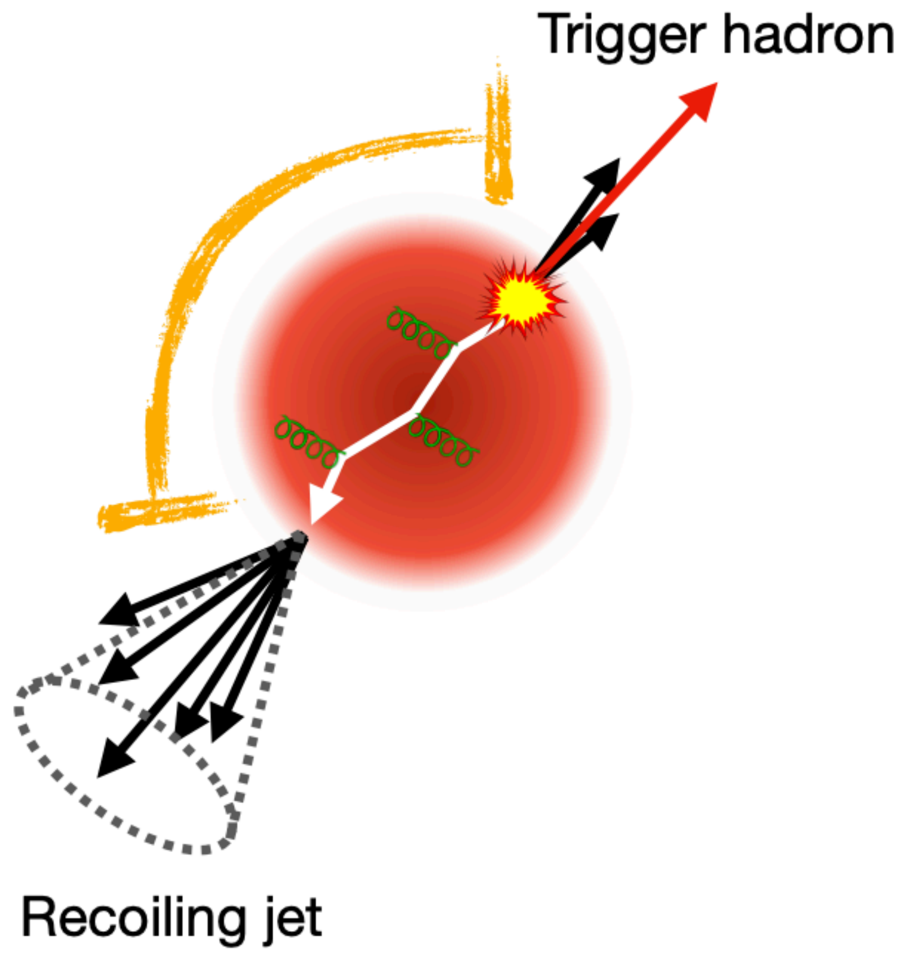
Global analysis needed to tune/exclude jet quenching models

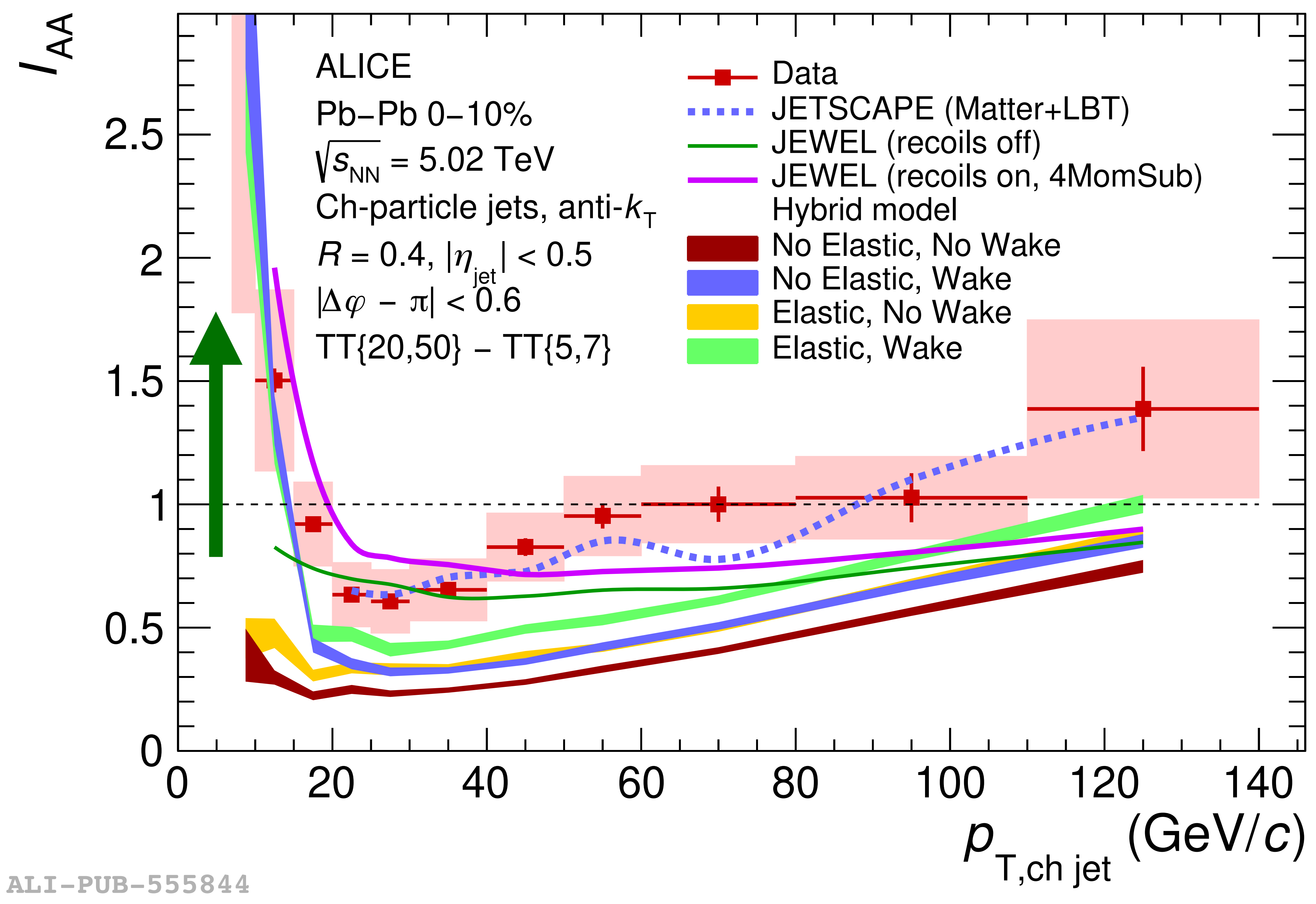
Thermalised jets? Hard component?

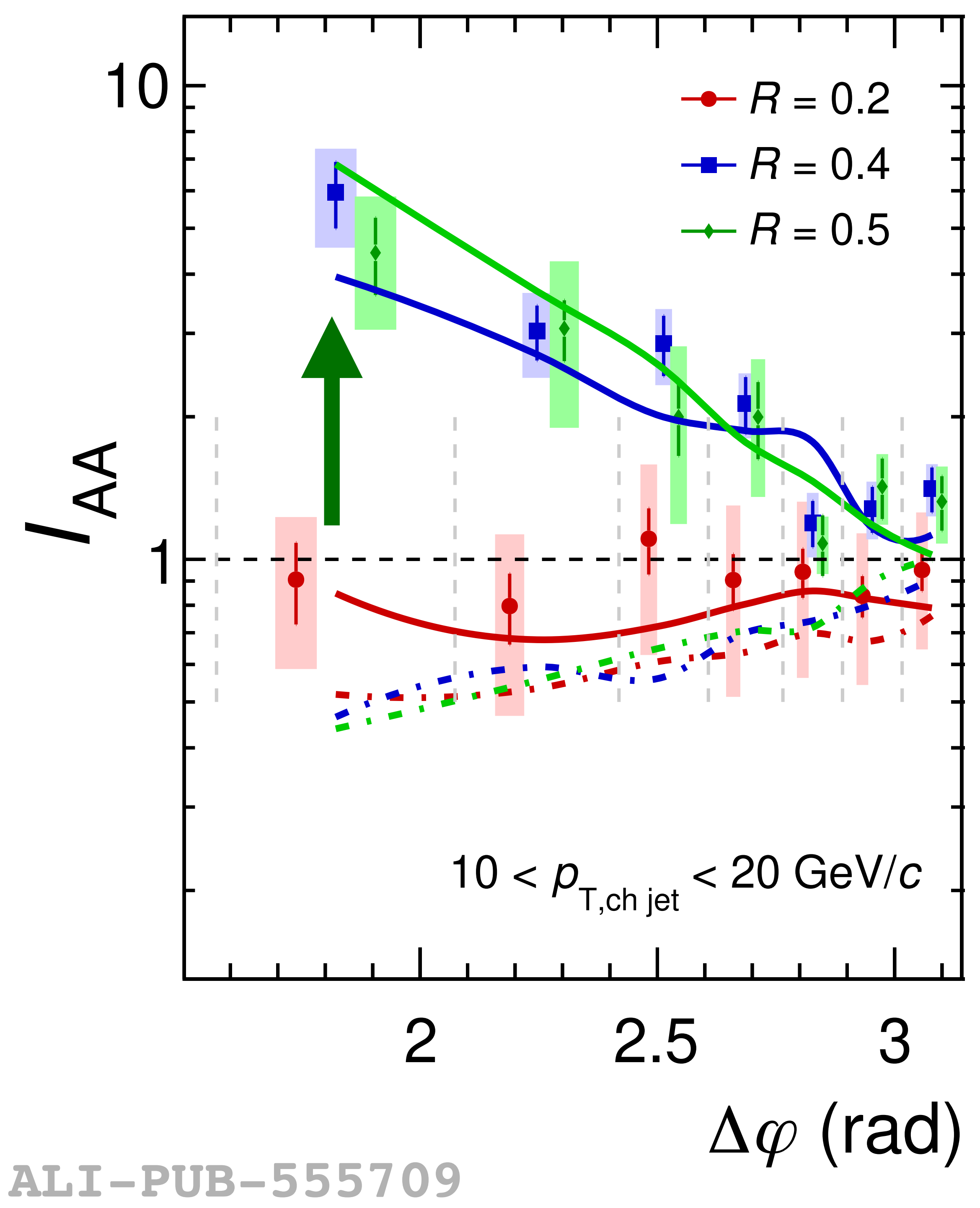
- Study substructure/fragmentation pattern
- Study jet axis definition

No clear evidence for Molière scattering

Summary and outlook





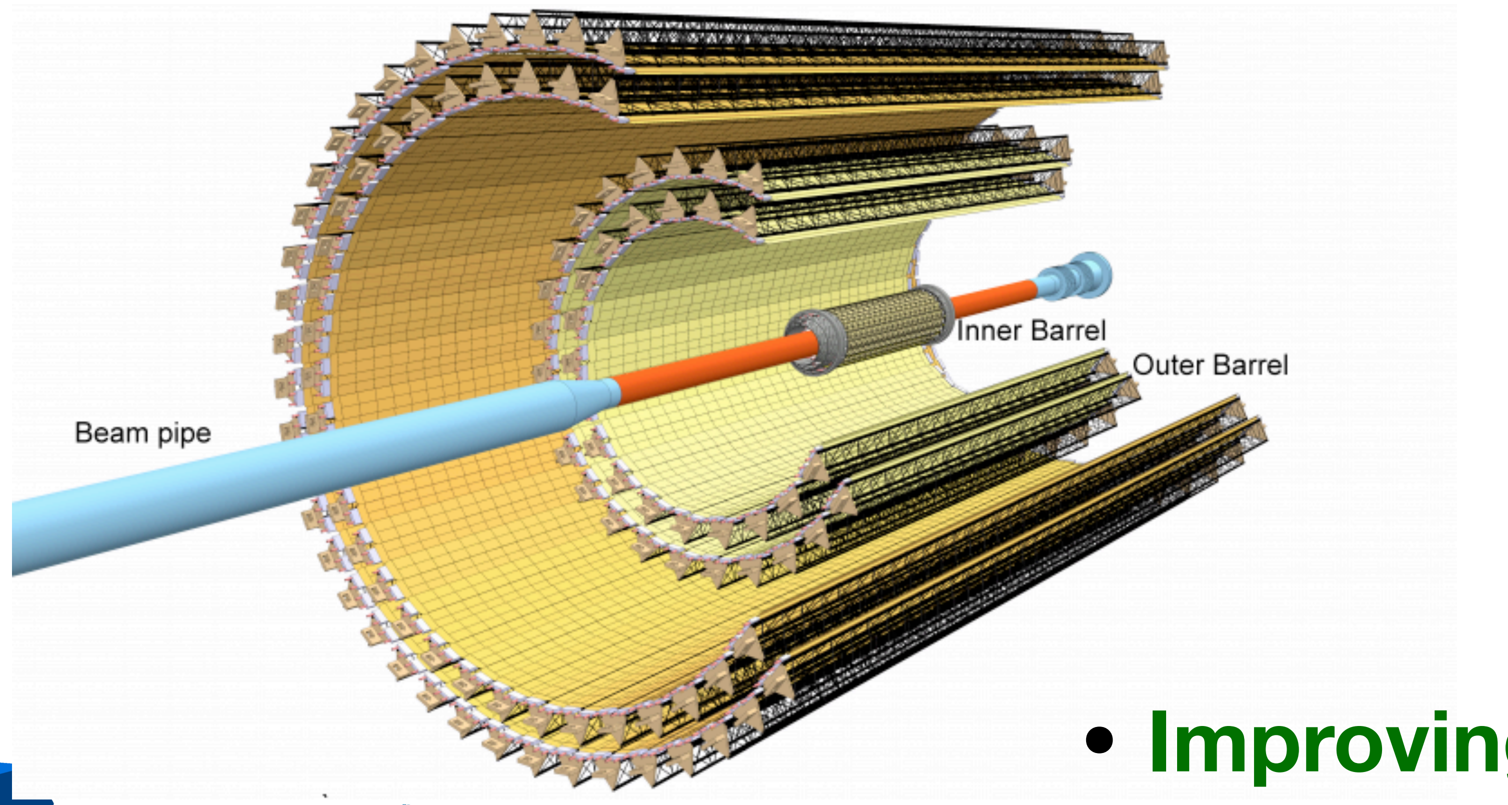


- **First observation of significant low-$p_{\mathrm{T,jet}}$ jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant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

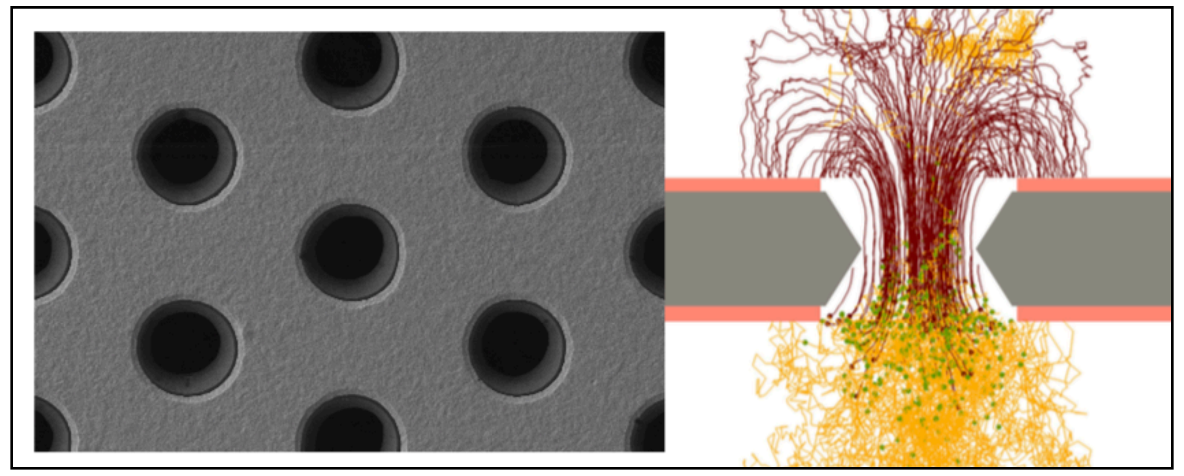
arXiv:2308.16128
arXiv:2308.16131

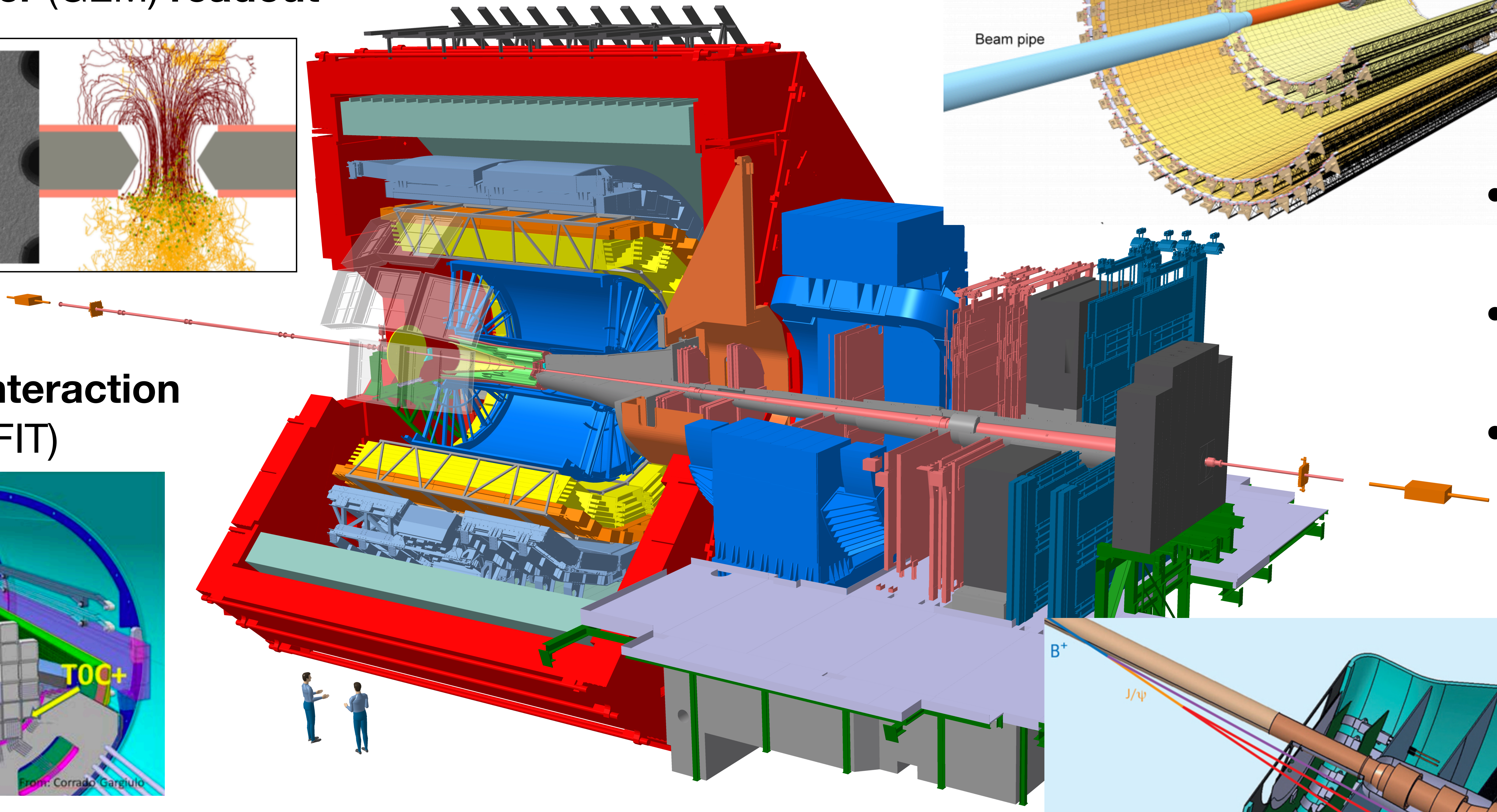
ALICE in Run 3-4

New **Inner Tracking System**

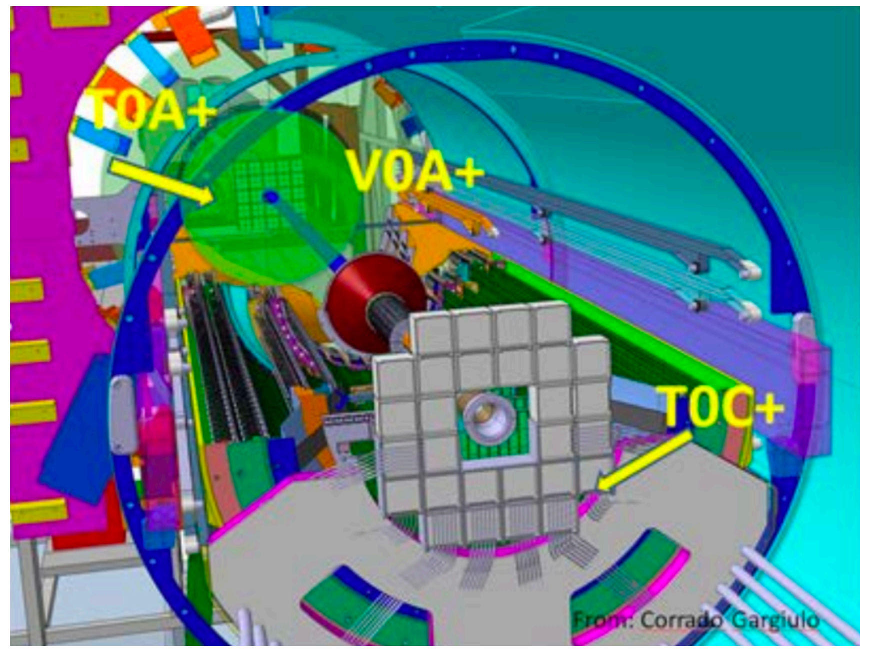


Replace TPC wire chambers with **gas electron multiplier** (GEM) **readout**

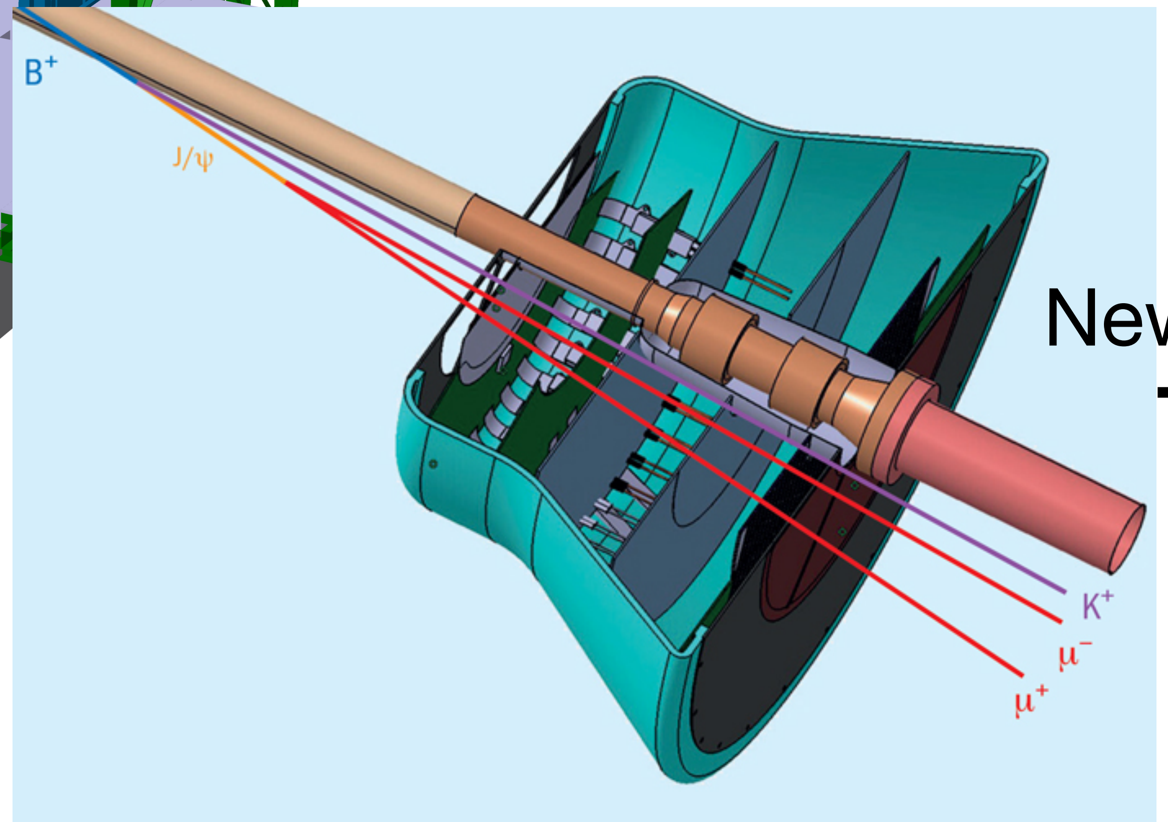




New **forward interaction trigger** (FIT)



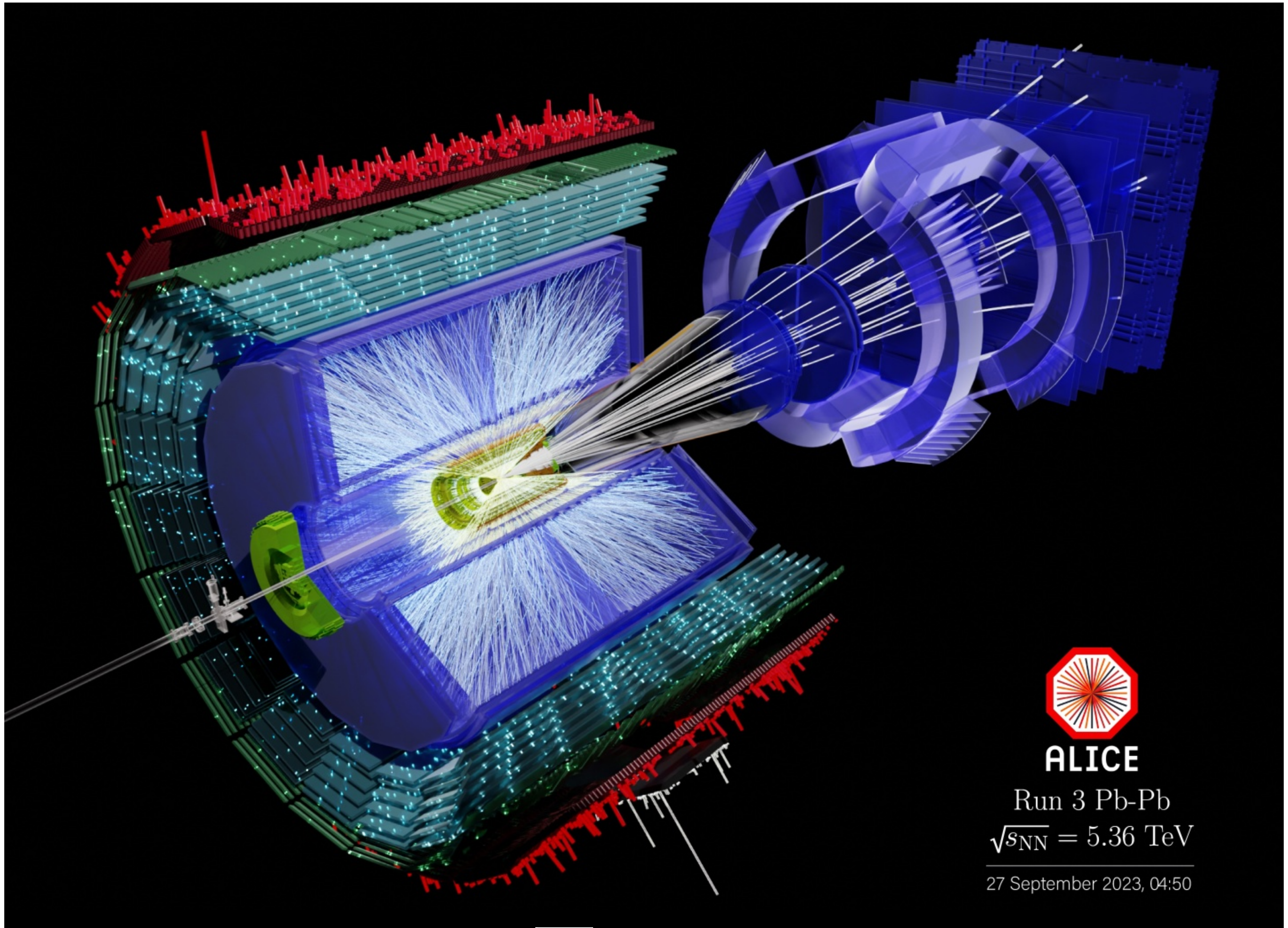
- **Improving tracking efficiency** and **resolution** at low p_T
- **Preserving particle identification** capabilities
- **Improving readout capabilities** —> trigger-less operation

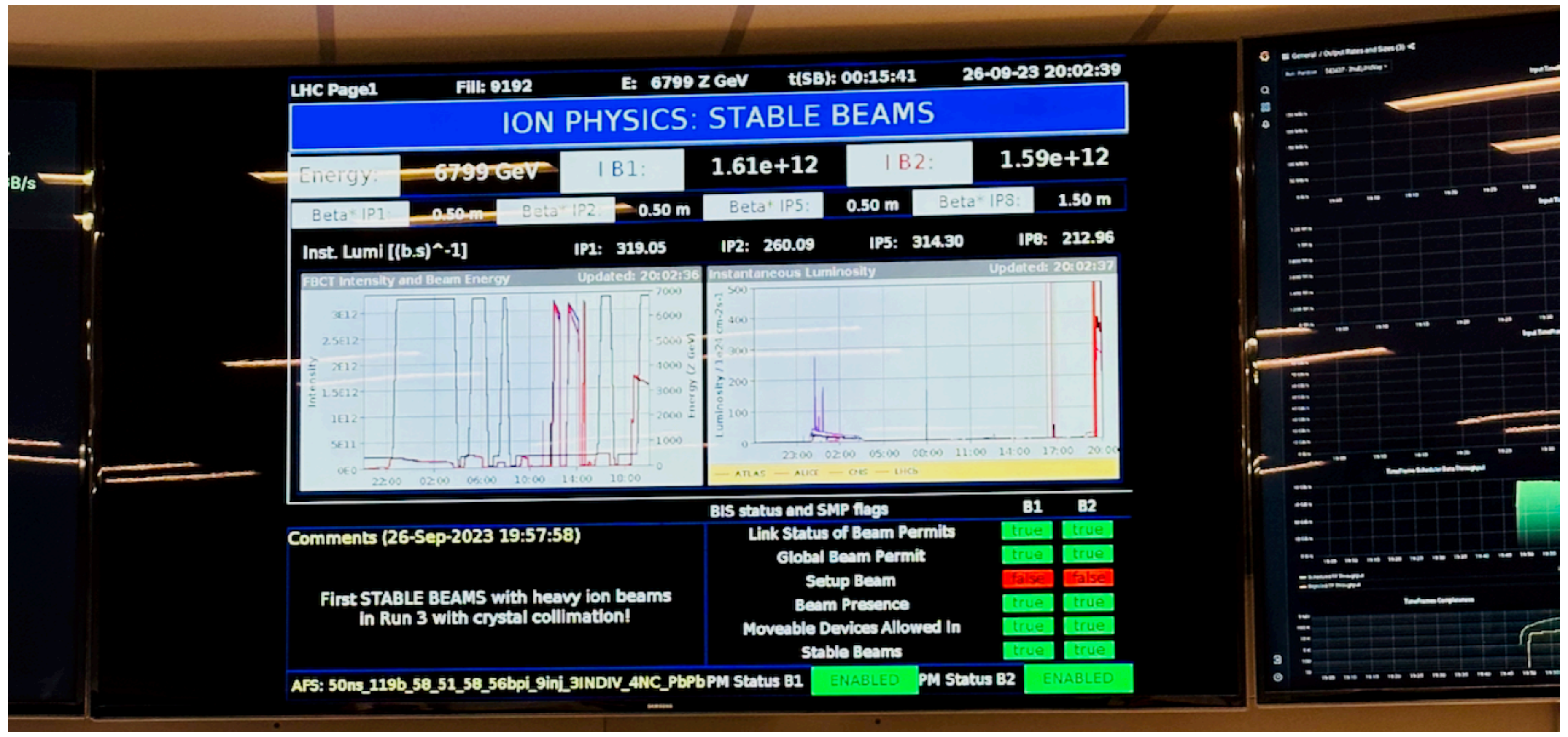


New **Muon Forward Tracker** (MFT)

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

Upgrade LOI: J.Phys. G41 (2014) 087001





Highest-energy Pb-Pb run of $\sqrt{s_{NN}} = 5.36$ TeV in September/October 2023!

12 billion collisions collected - 40x more than all previous runs (2010-2018)

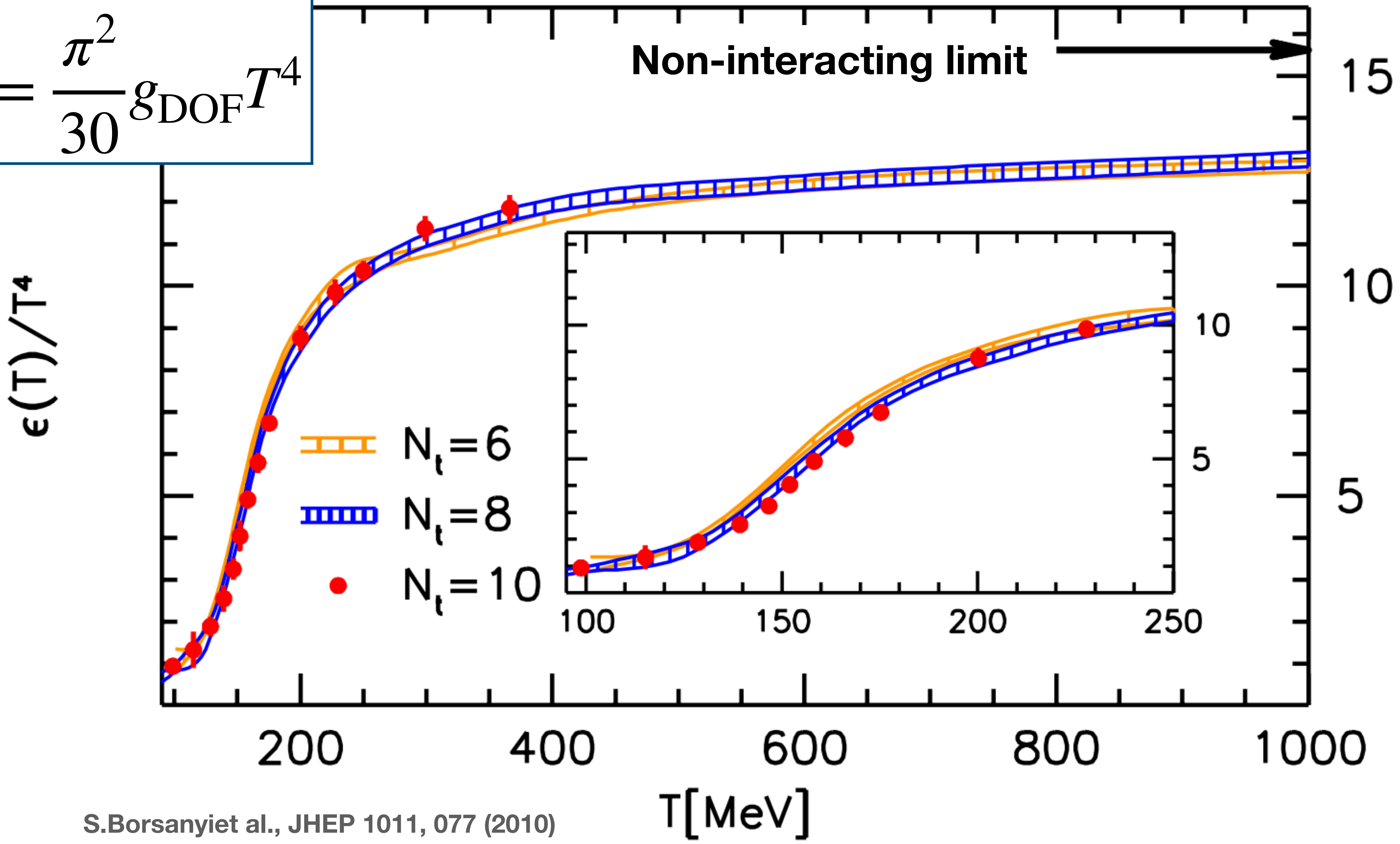
Backup

QCD equation of state

Lattice QCD used to study QCD equation of state and phase transitions

Energy density

$$\epsilon = \frac{\pi^2}{30} g_{\rm DOF} T^4$$

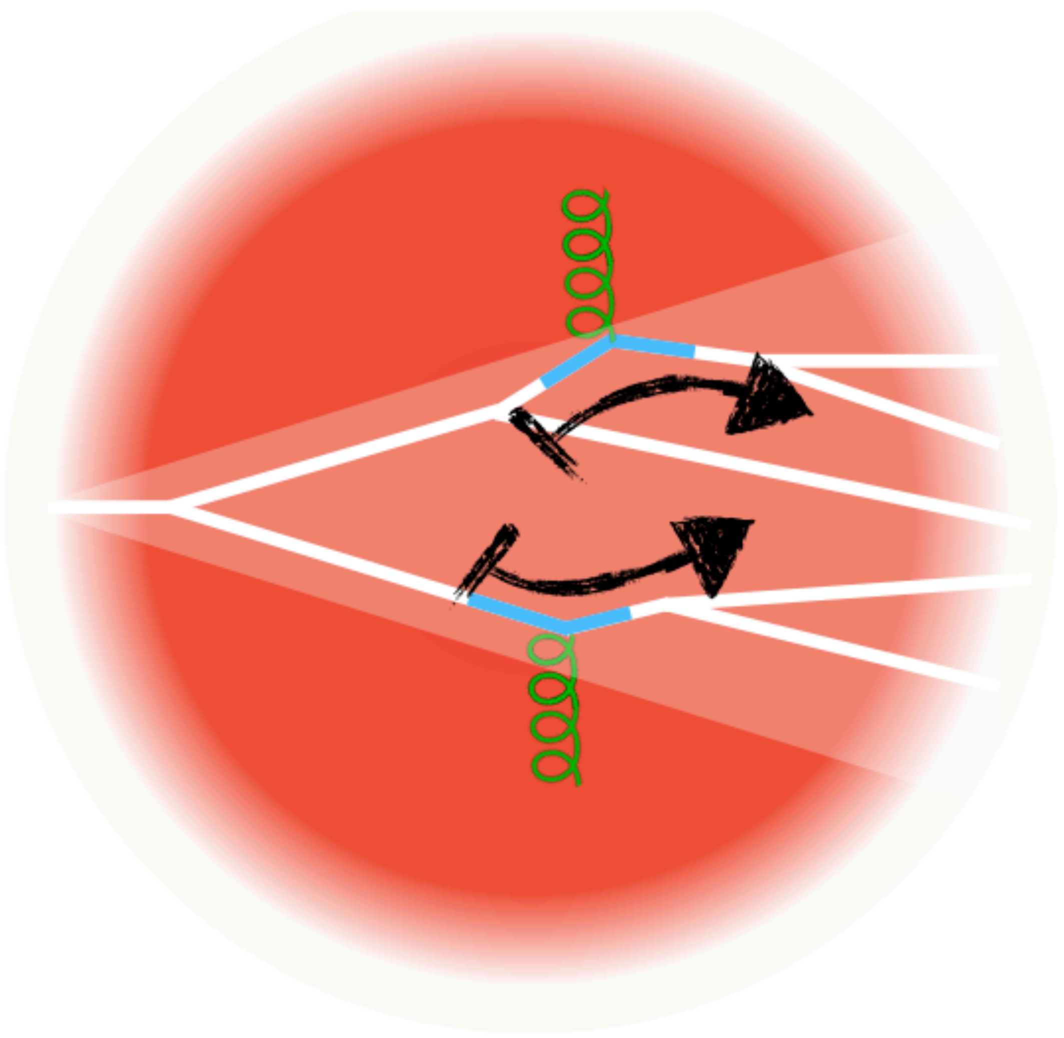


S.Borsanyiet al., JHEP 1011, 077 (2010)

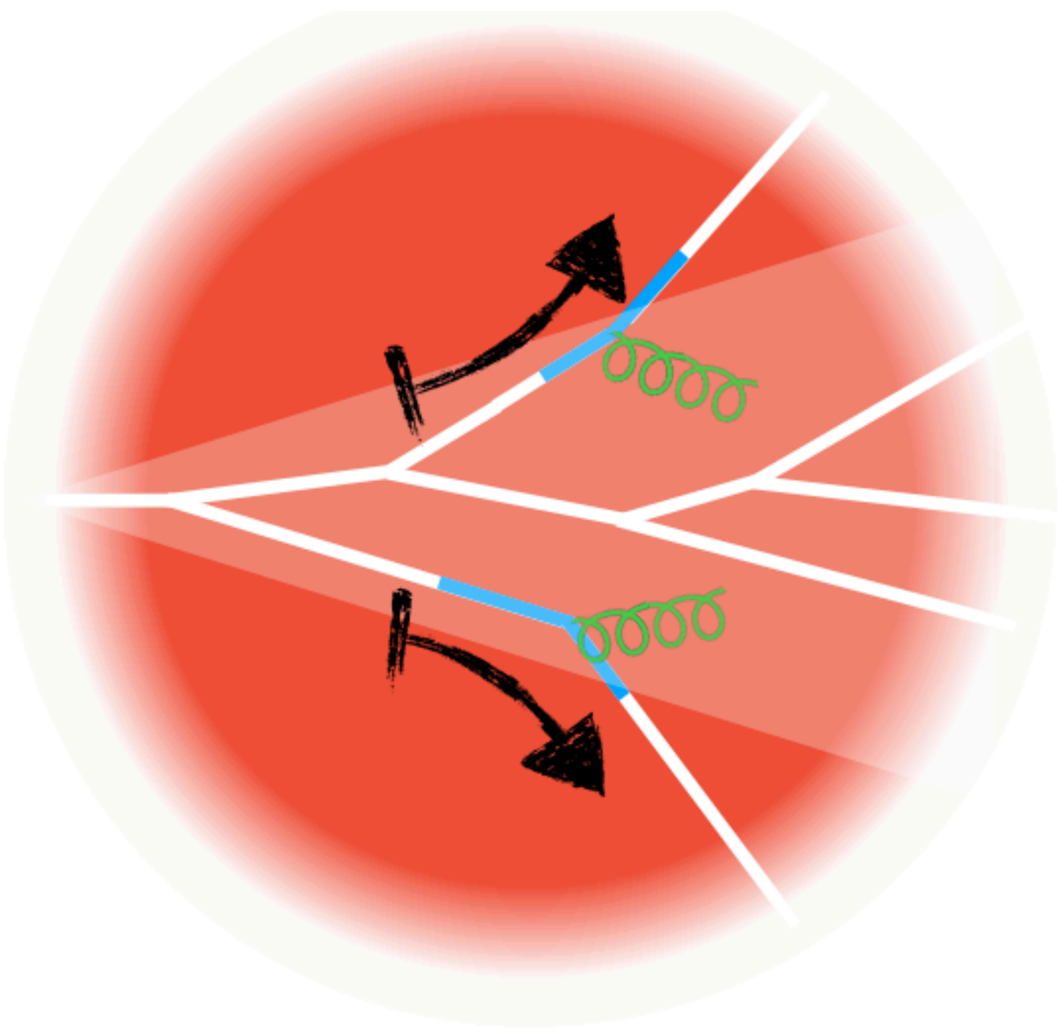
- e.g. looking at temperature of energy density:
  - Smooth crossover at ~155 MeV
  - Liberation of many new degrees of freedom → sharp increase in energy density
  - Gradually approaches non-interacting limit, but ~20% lower in experimentally accessible region

Experimentally observable consequences of jet quenching

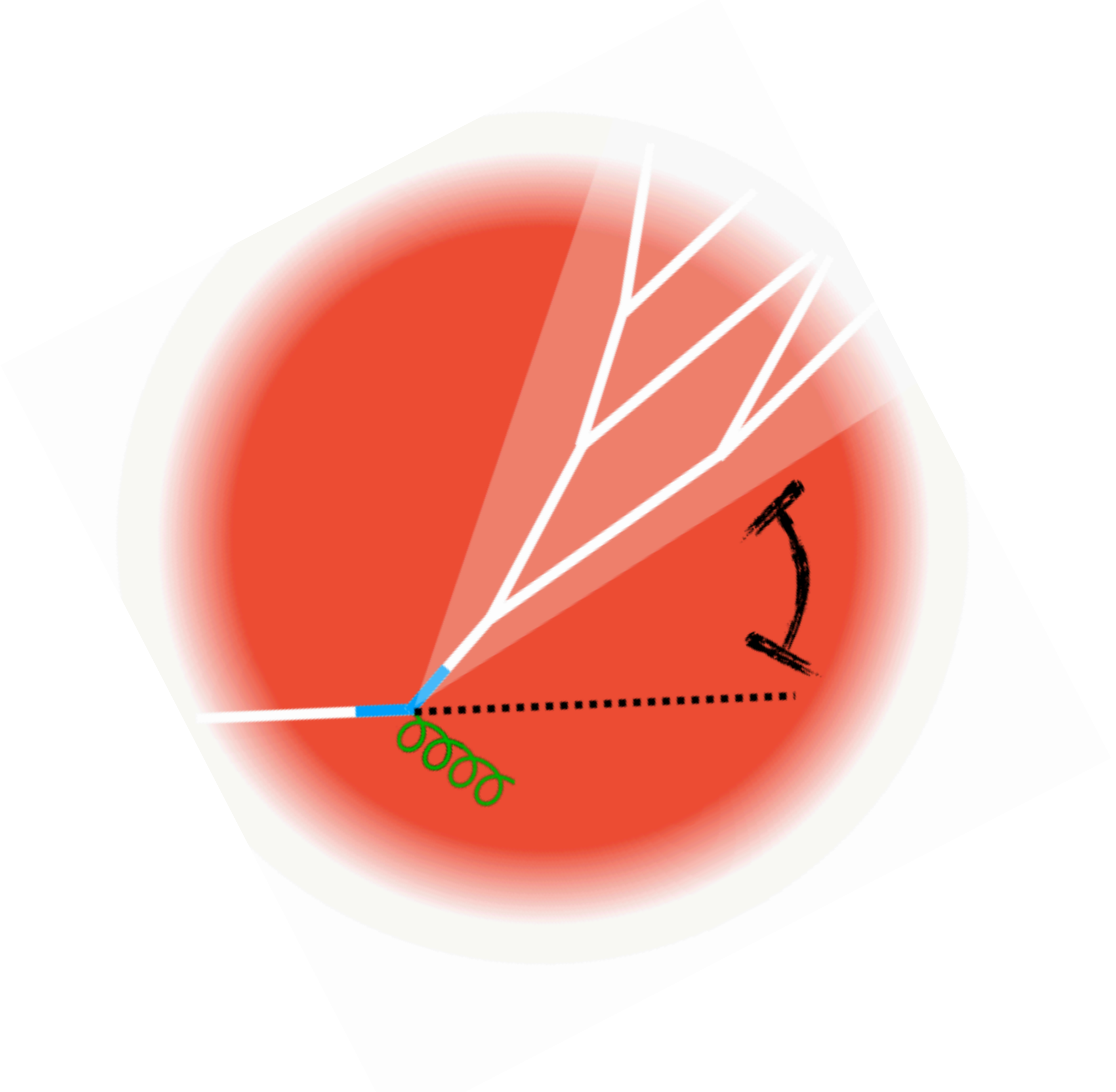
- Today - multi-pronged measurements of jet and medium modification



Substructure modification



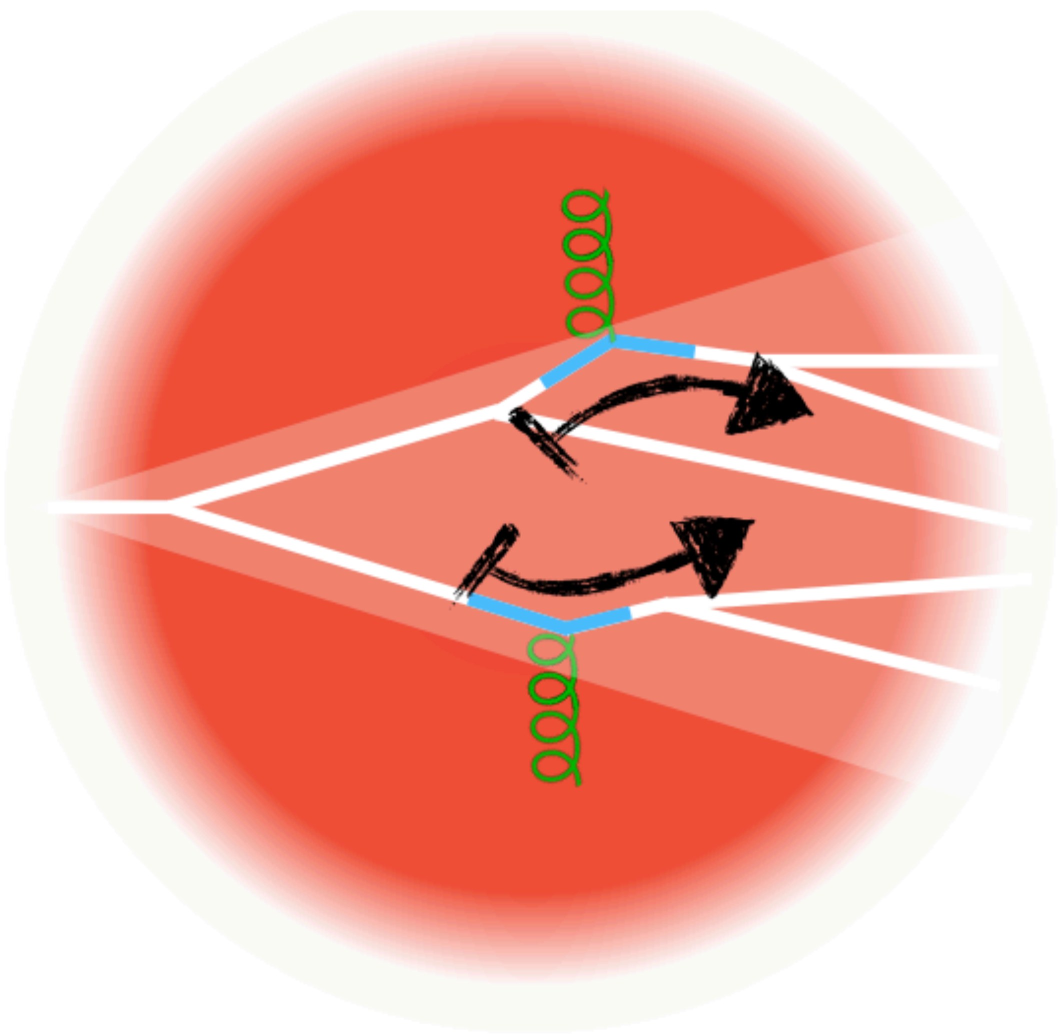
Energy redistribution



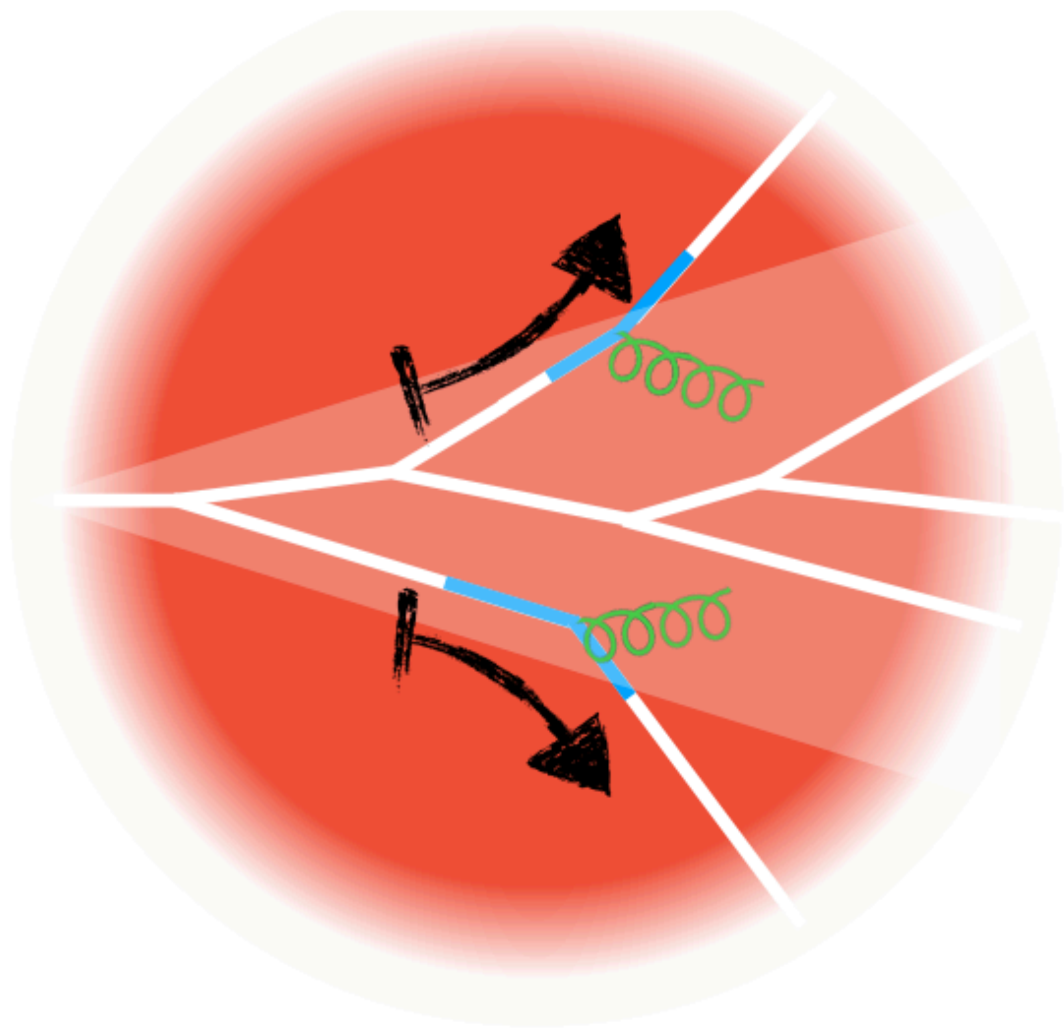
Deflection

Experimentally observable consequences of jet quenching

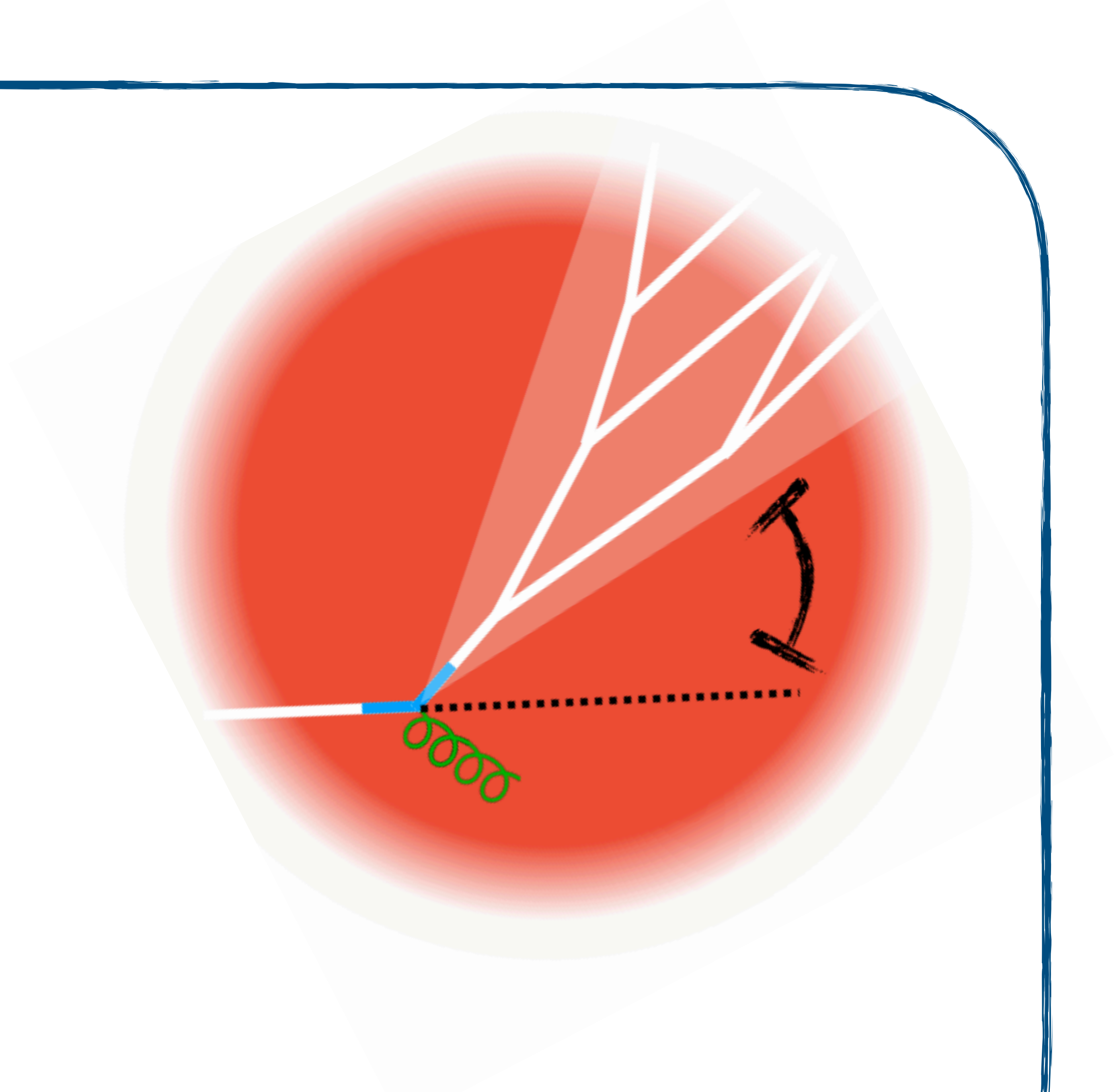
- Today - multi-pronged measurements of jet and medium modification



Substructure modification

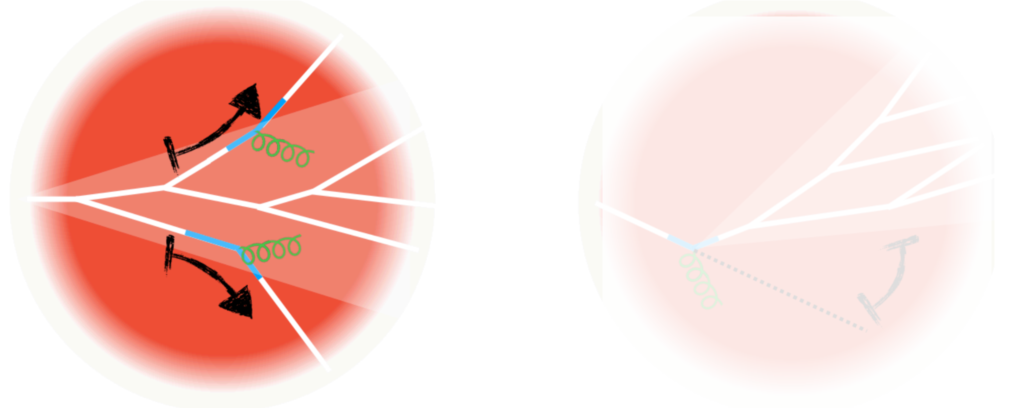


Energy redistribution

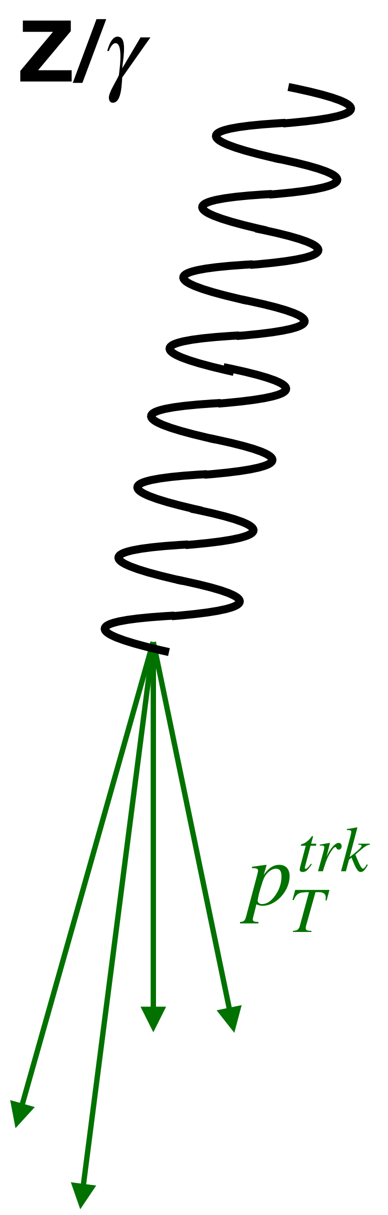


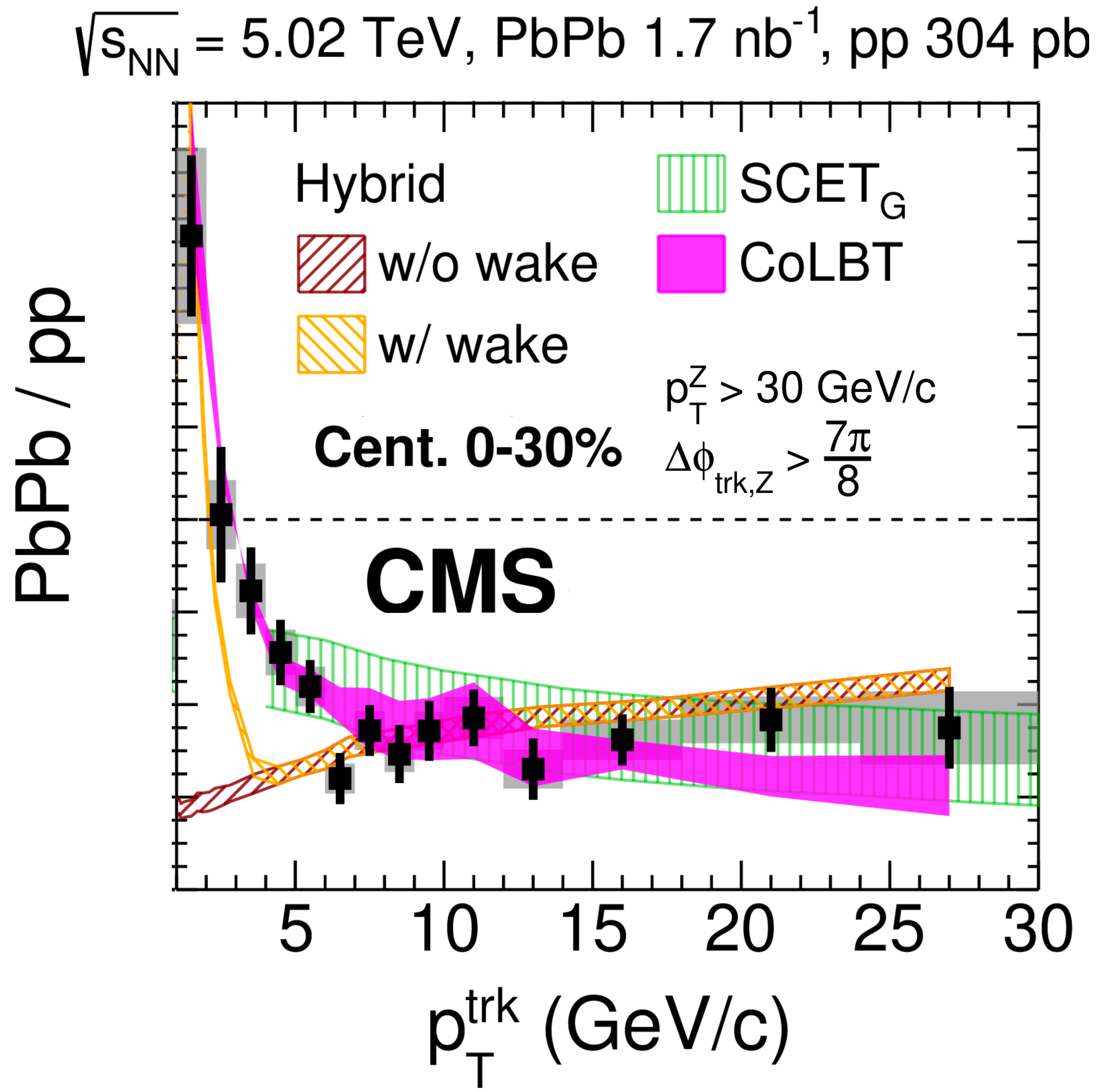
Deflection

Measured consequences of medium response

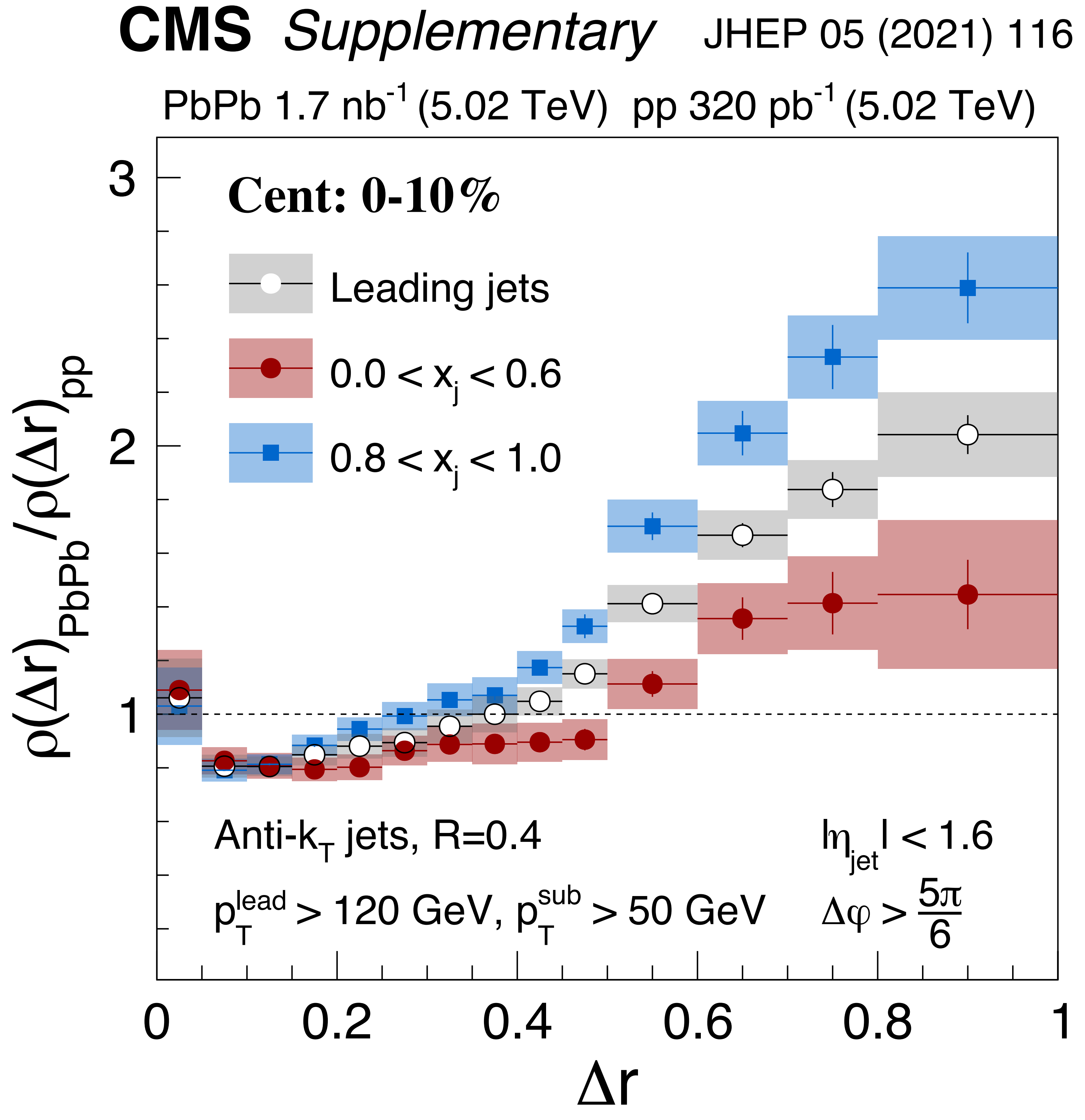


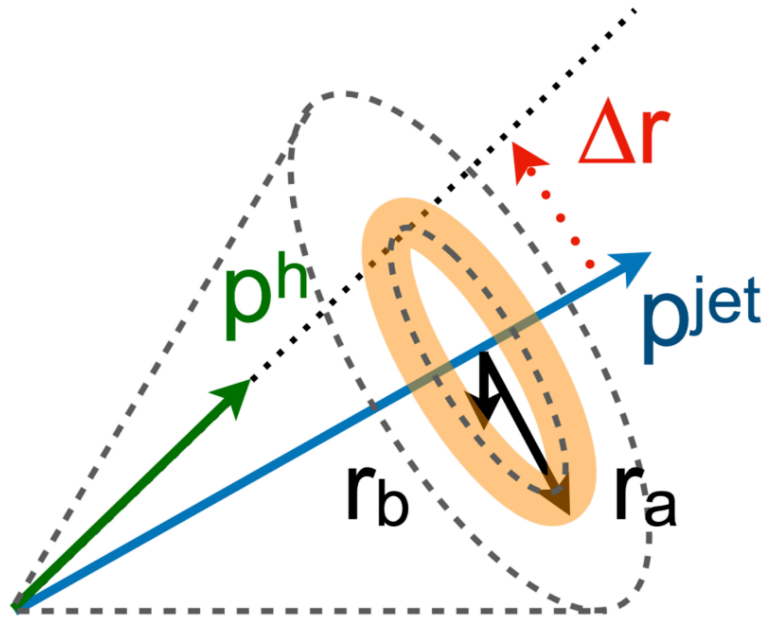
CMS: Phys. Rev. Lett. 128 (2022) 122301
See also ATLAS: Phys. Rev. Lett. 126, 072301 (2021)





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



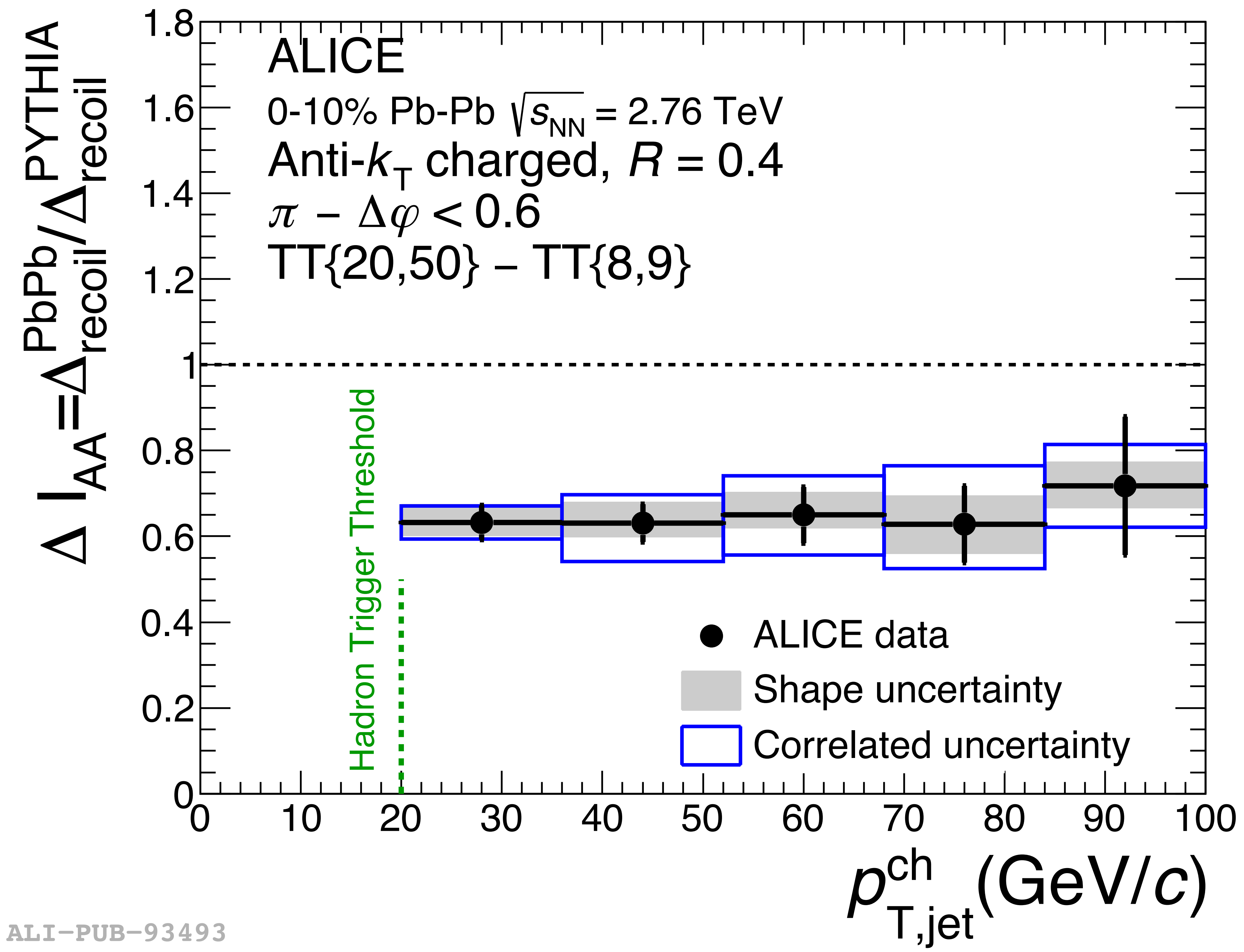


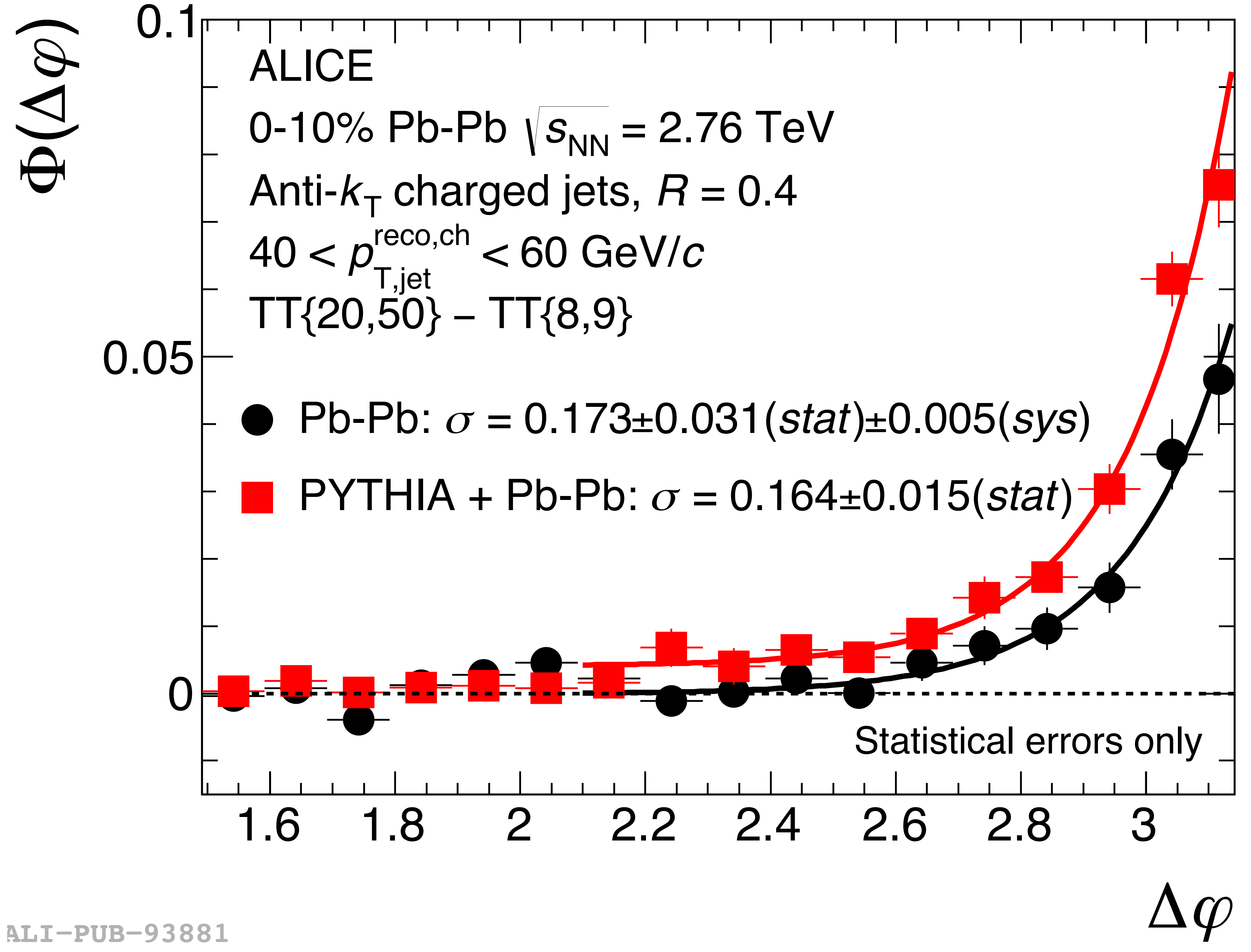
Soft particle excess surrounding a jet

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

Run 1 hadron+jet measurement

ALICE: JHEP 09 (2015) 170





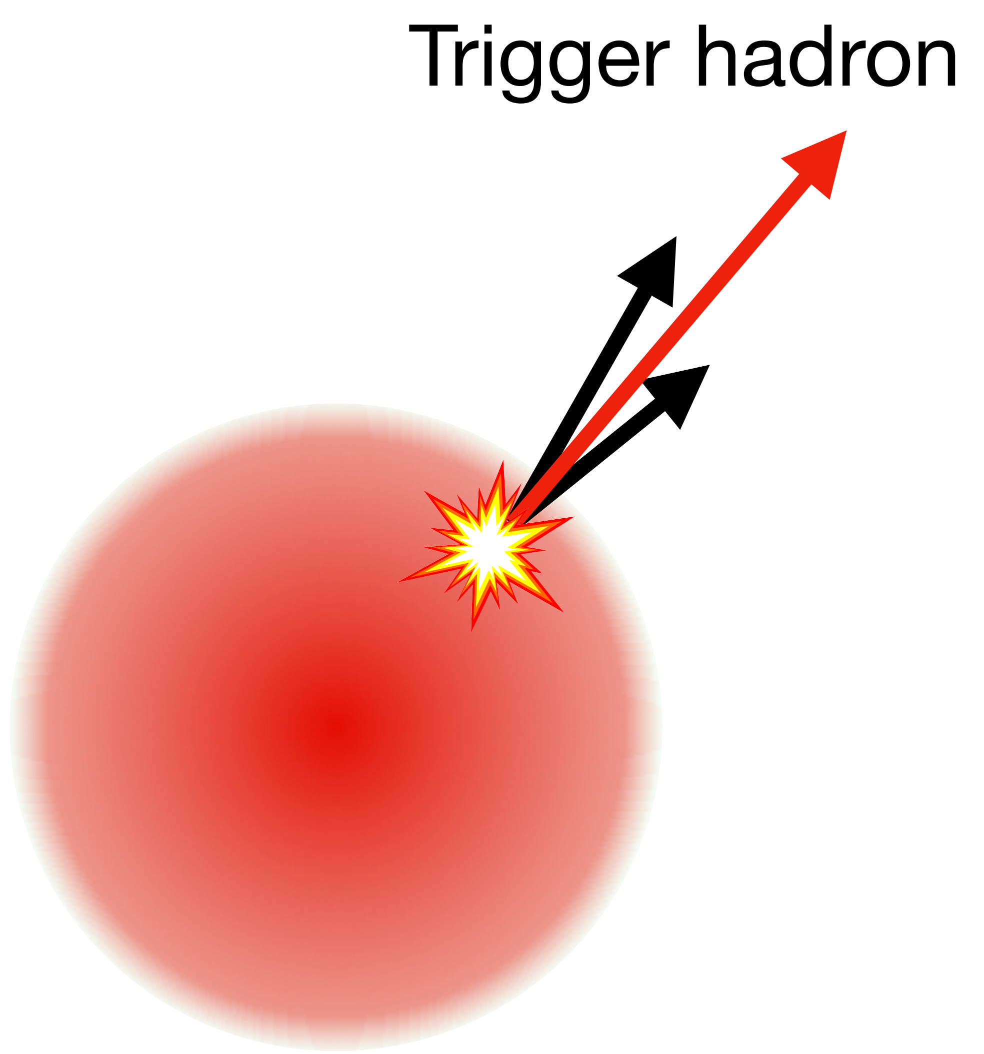
- Background-subtracted yield of jets recoiling from a high-p_T trigger hadron:
    - Suppression with respect to a pp (PYTHIA) reference
    - No medium-induced broadening within experimental uncertainties

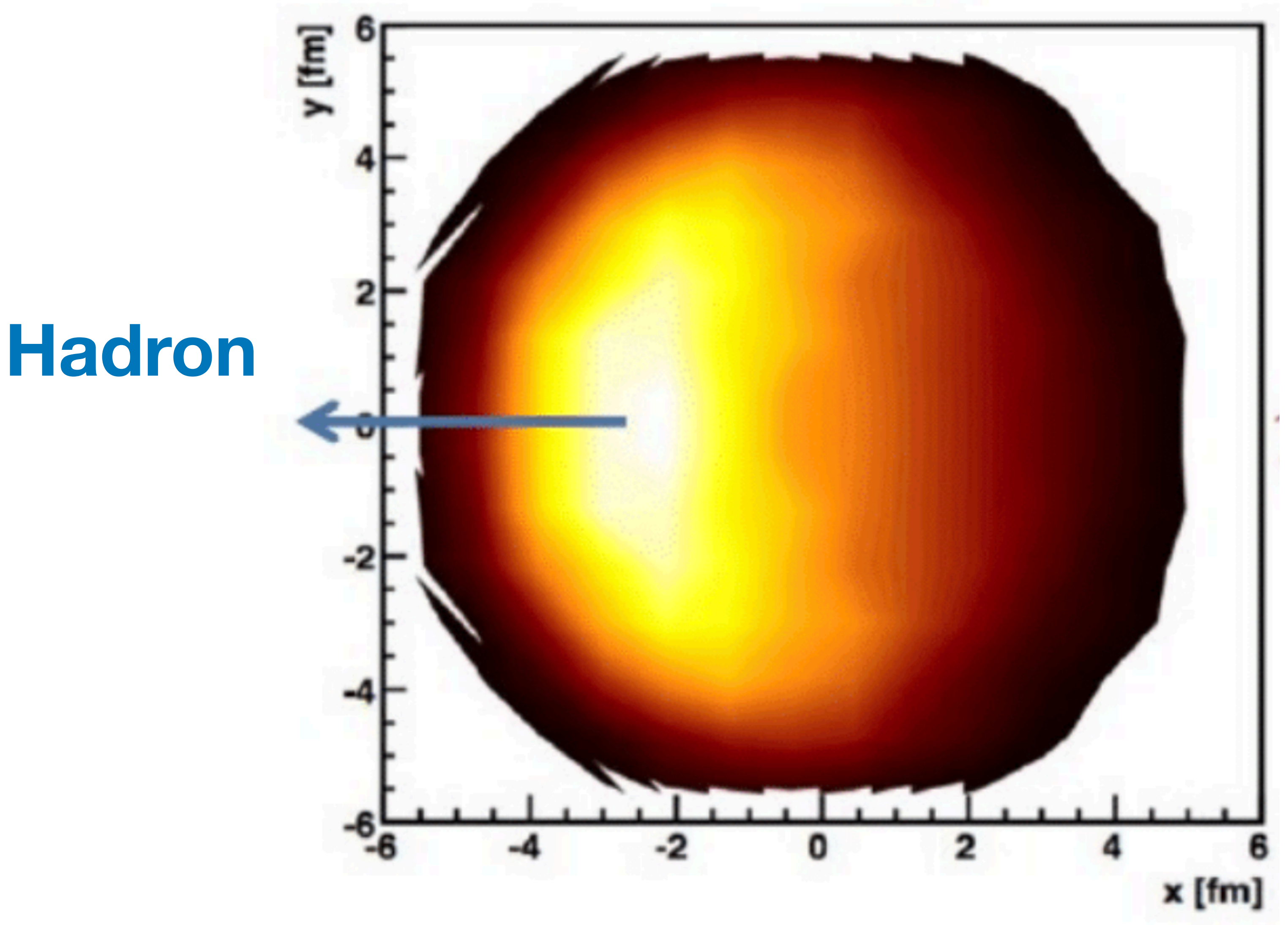
Analysis procedure

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



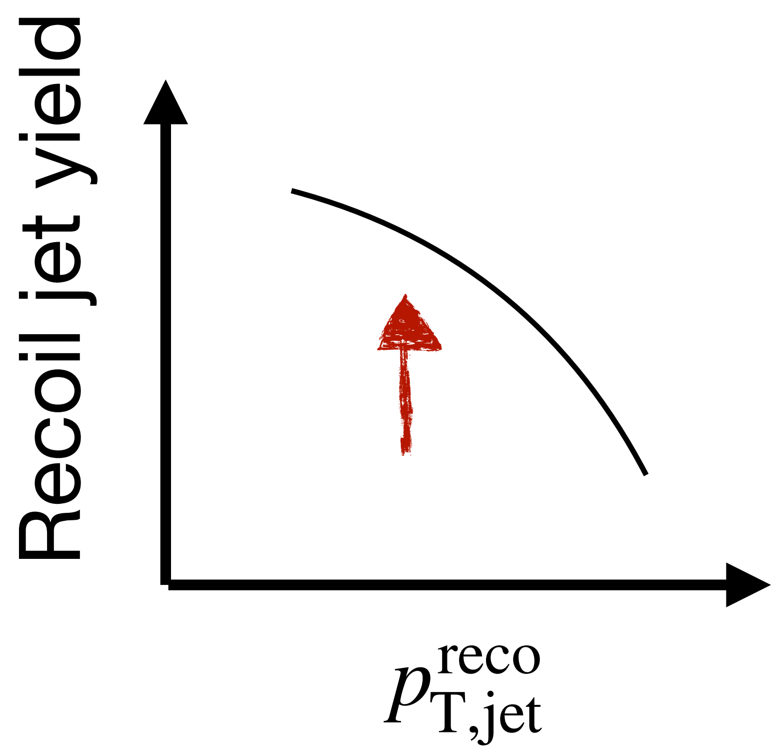


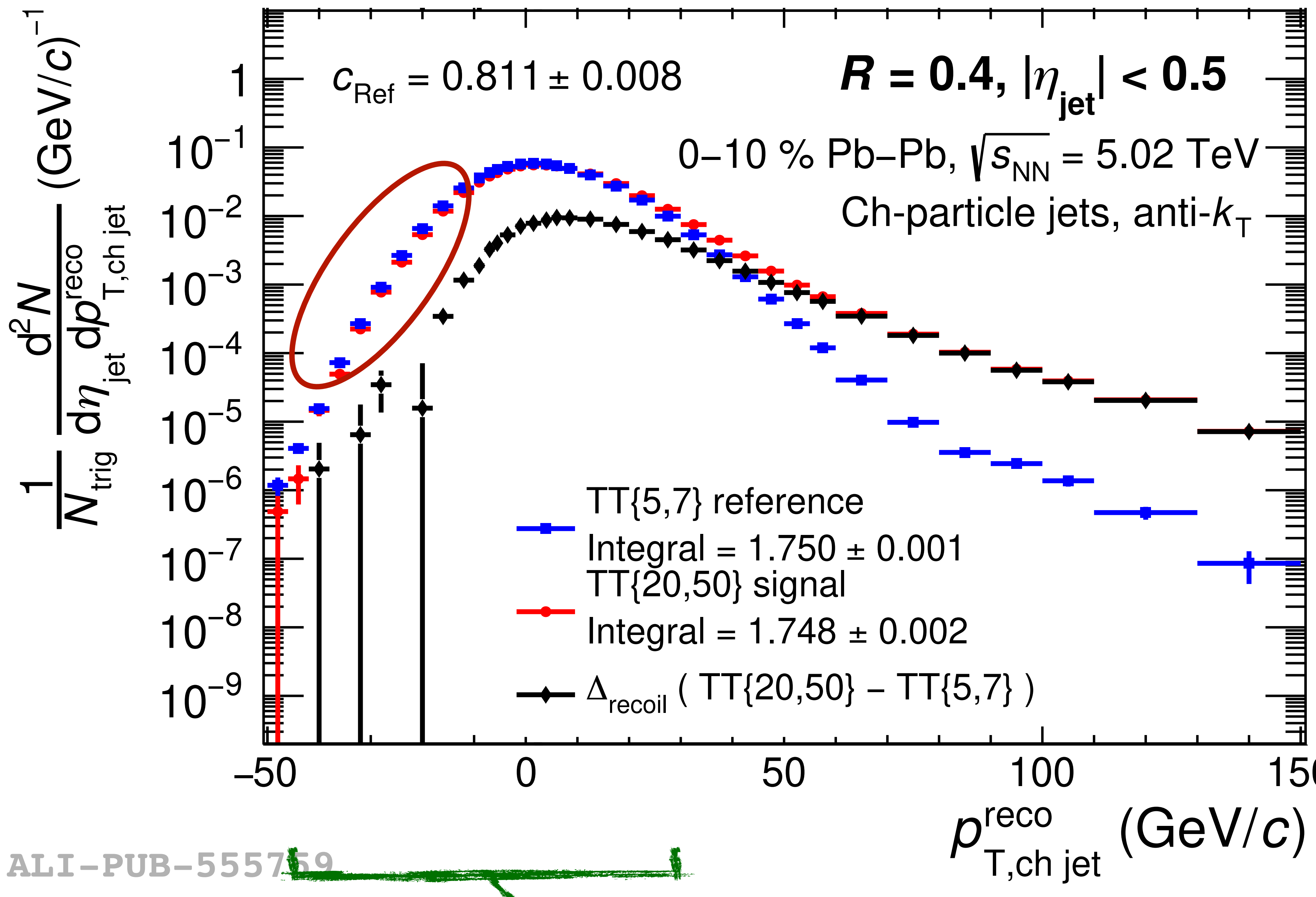
Adapted from T. Renk, Phys. Rev. C 88, 054902 (2013)

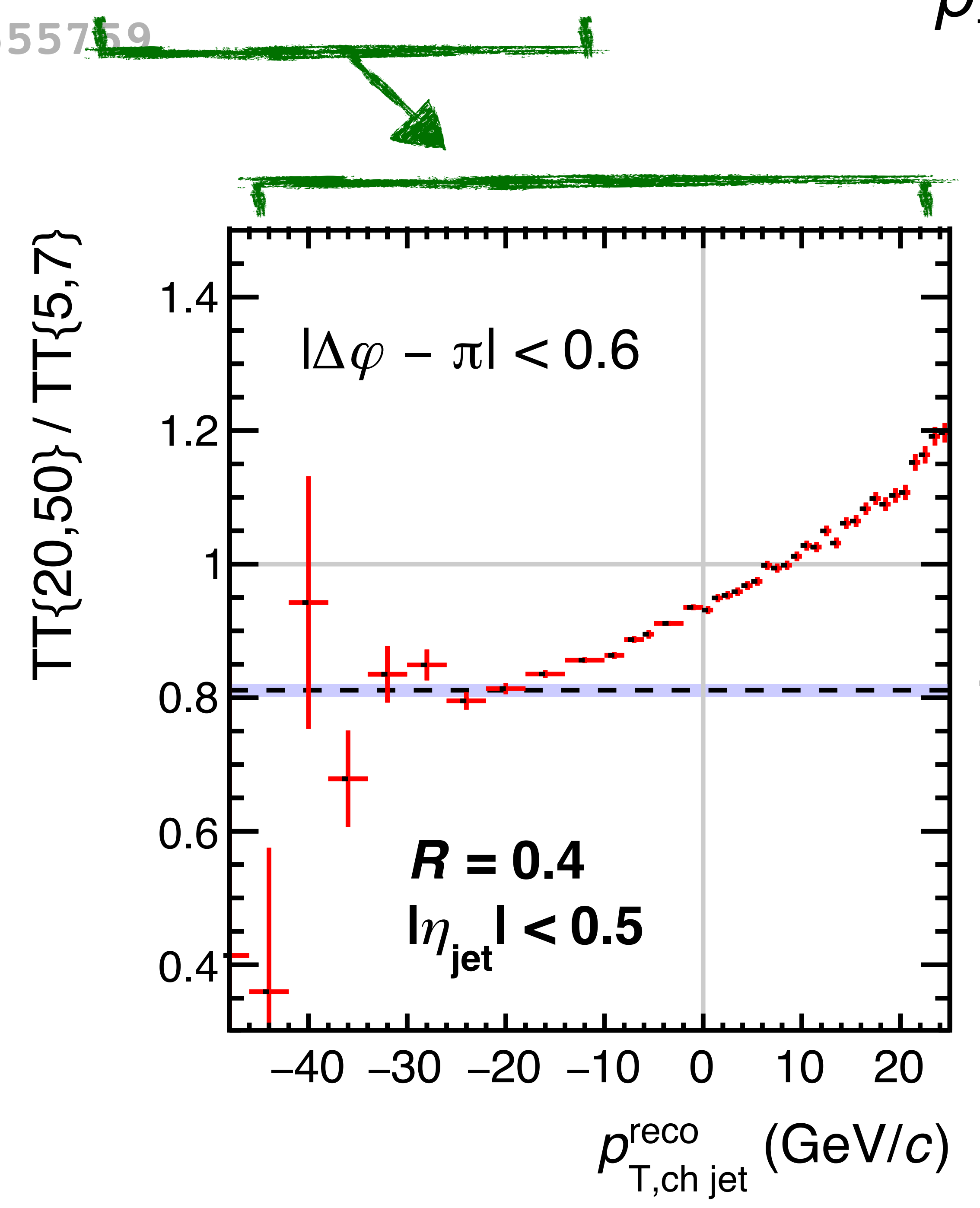
Δ_{recoil} ‘reference’ calibration

Calibration of reference distribution required for precise background subtraction:

- Yield scale (‘*vertical*’)
- $p_{T,jet}^{reco}$ scale (‘*horizontal*’)







$\rightarrow c_{Ref} = 0.811$

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

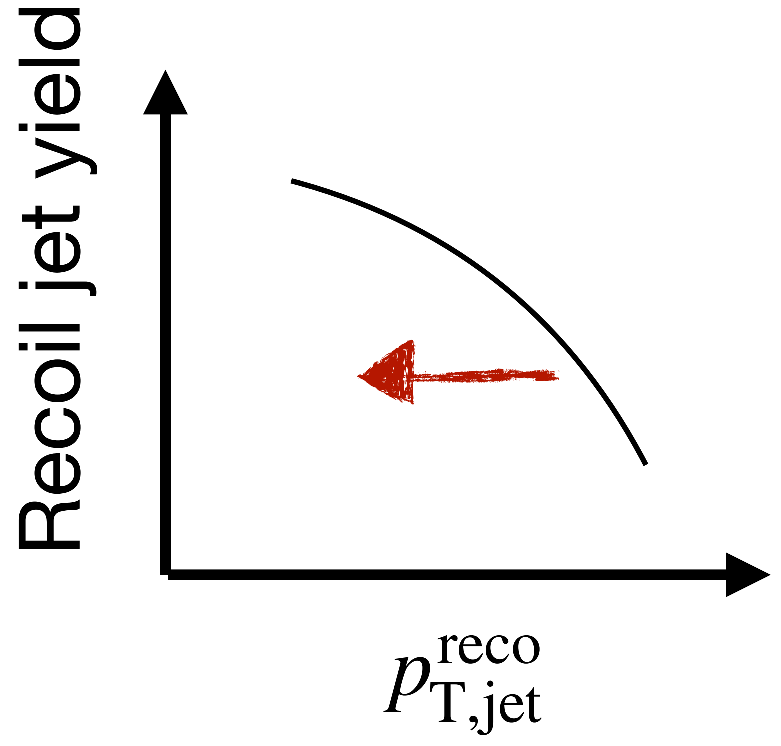
Established technique

ALICE: *JHEP* 09 (2015) 170

Δ_{recoil} 'reference' calibration

Calibration of reference distribution required for precise background subtraction:

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

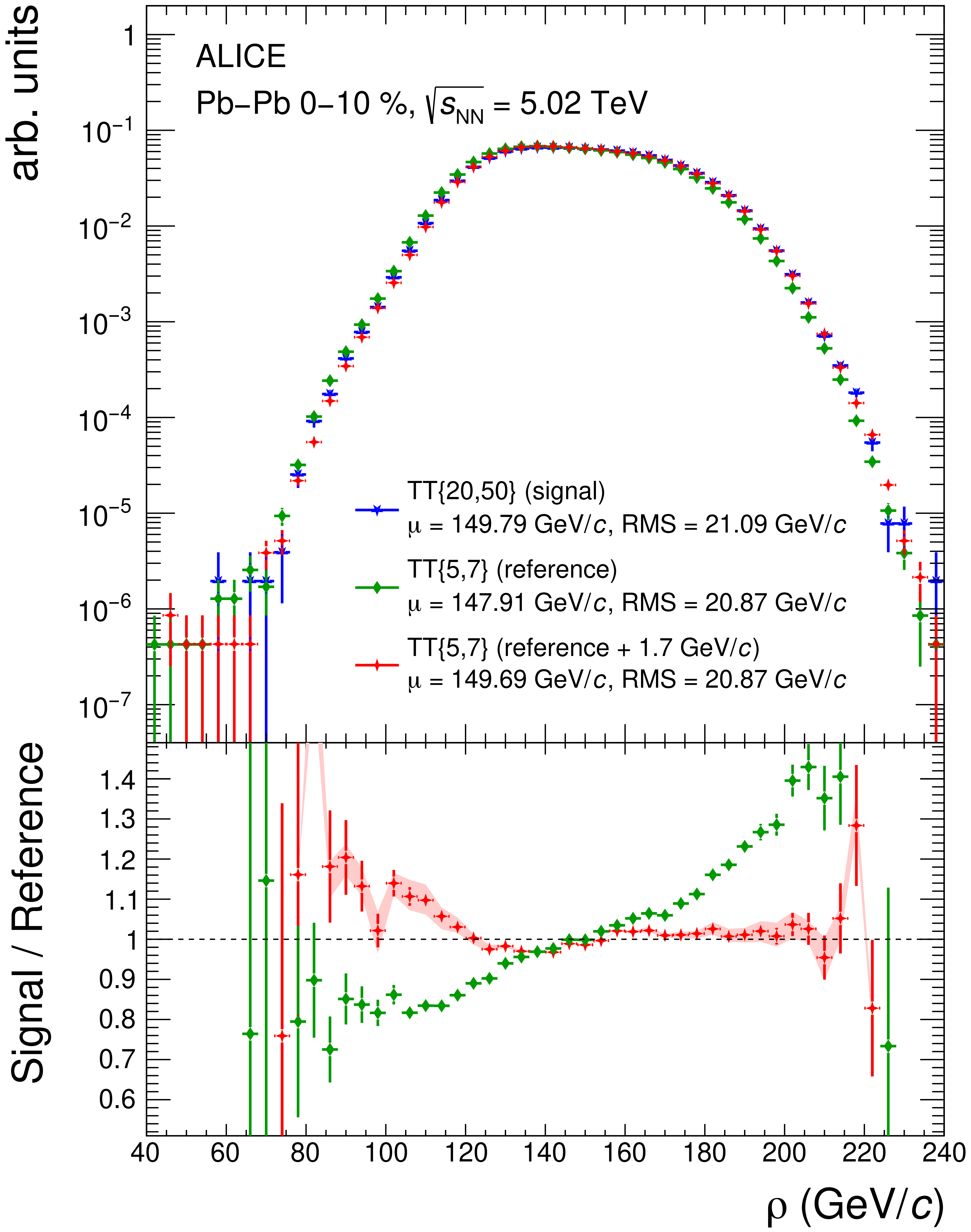


$$p_{\text{T,jet}}^{\text{reco}} = p_{\text{T,jet}}^{\text{raw}} - A \cdot \rho$$

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

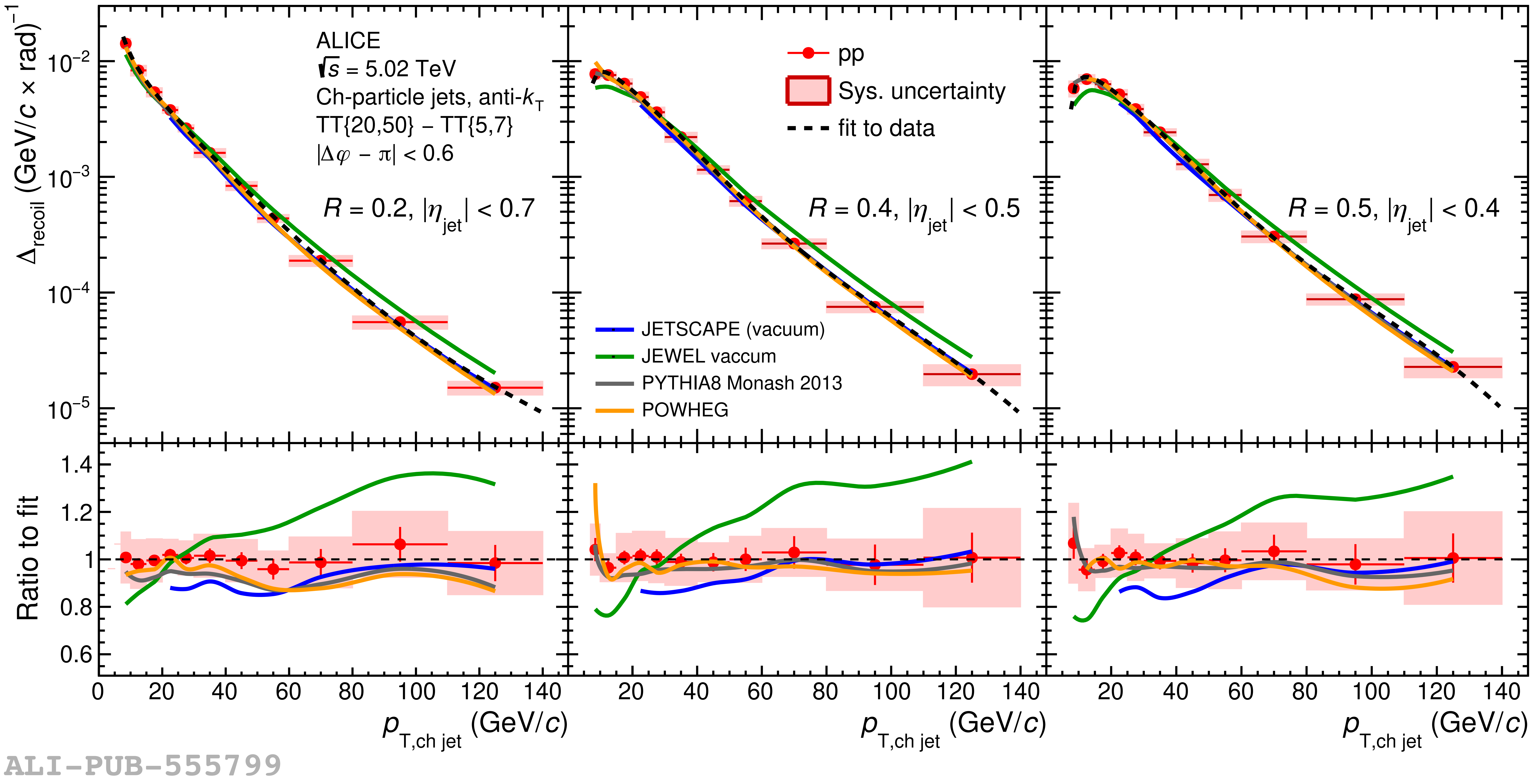
Established technique

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



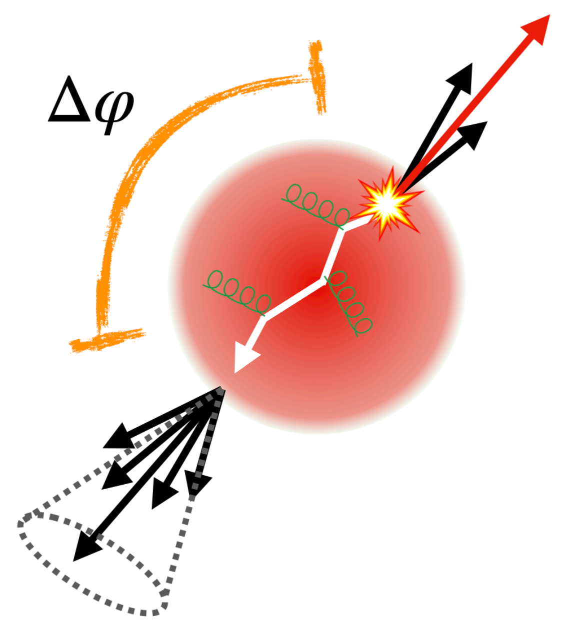
ALI-PUB-555739

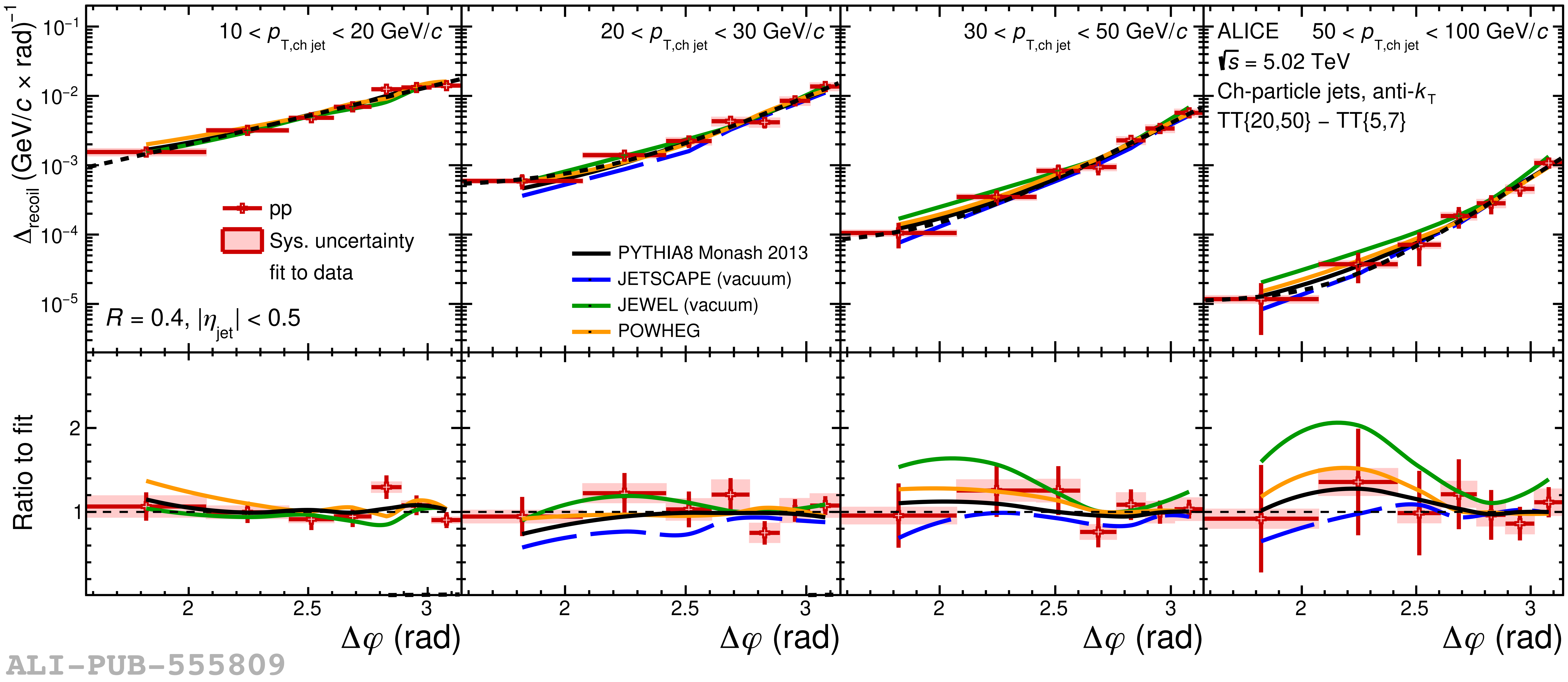
Fully-corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\,jet}})$ distribution in pp collisions



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

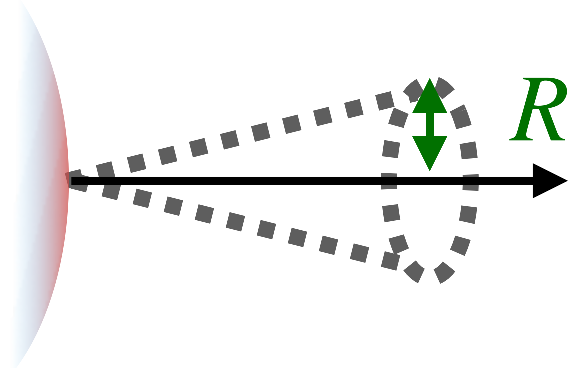
$\Delta_{recoil}(\Delta\varphi)$ in pp collisions (R=0.4)



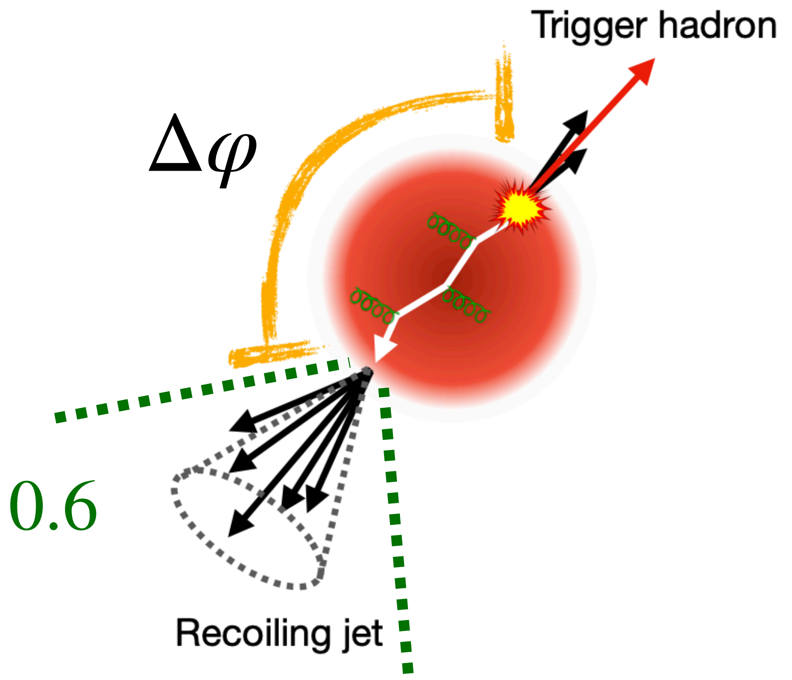


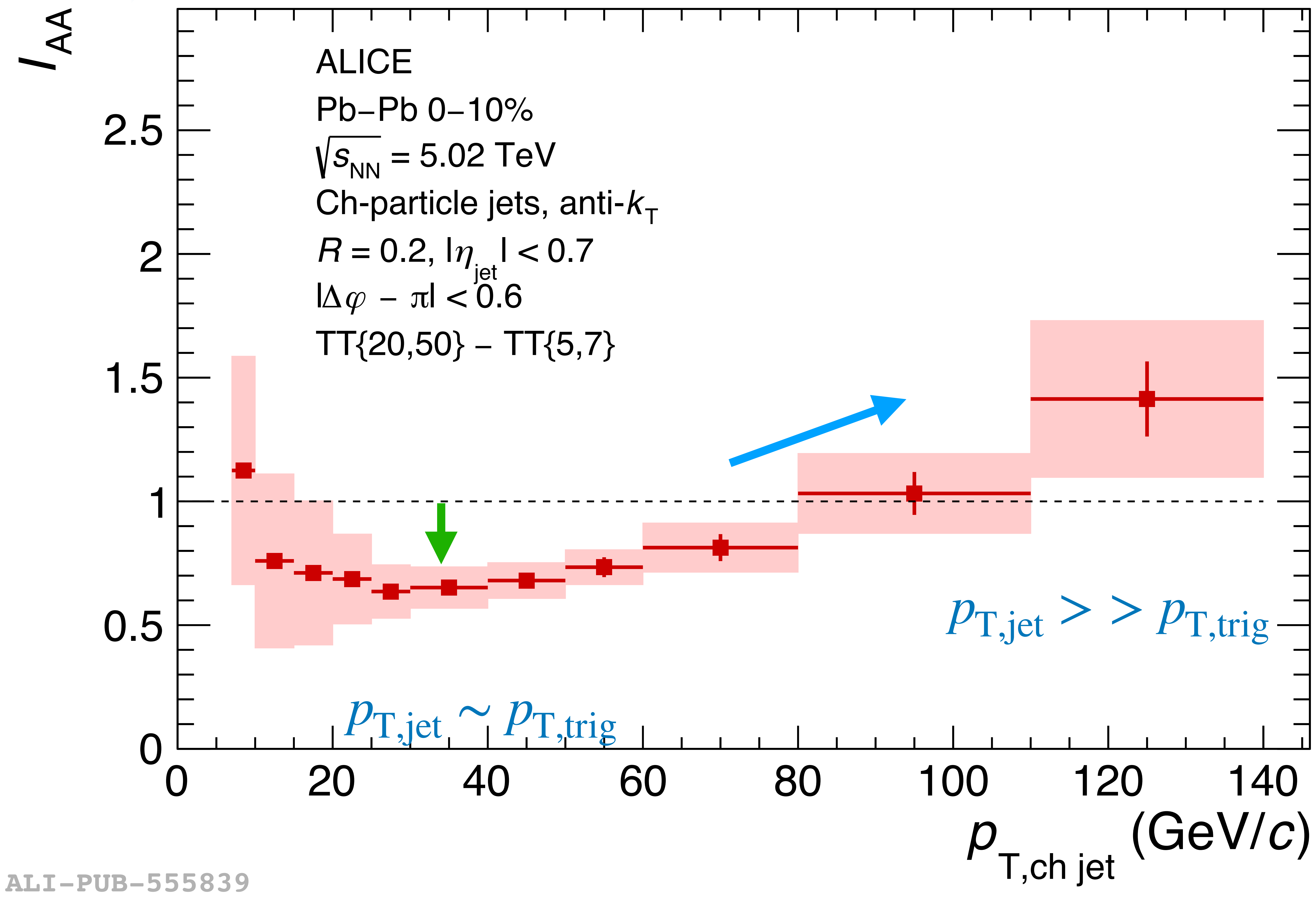
- $\Delta_{recoil}(\Delta\varphi)$ described well by PYTHIA8, 'vacuum' reference models, and POWHEG

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

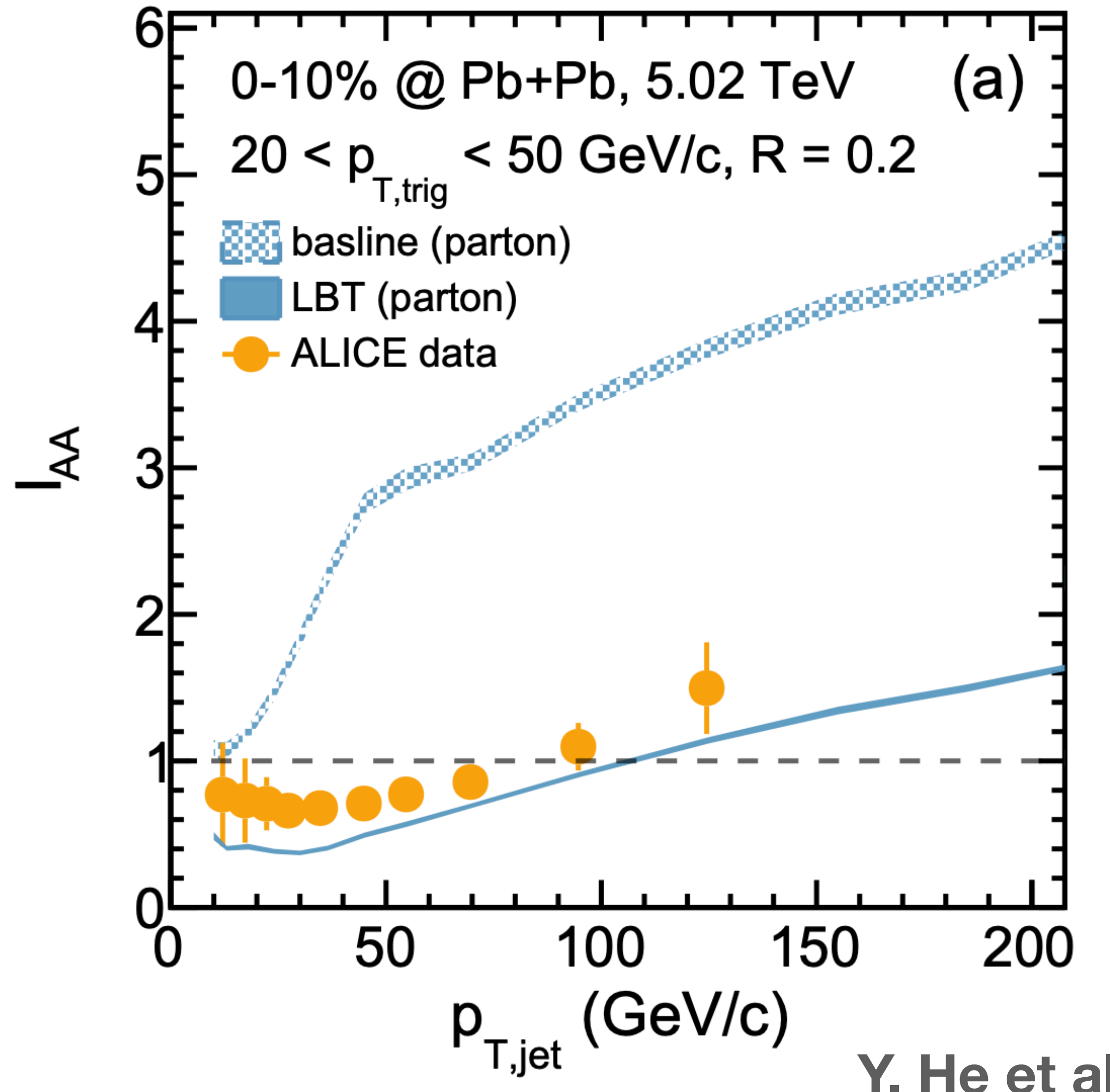


$$I_{AA} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$





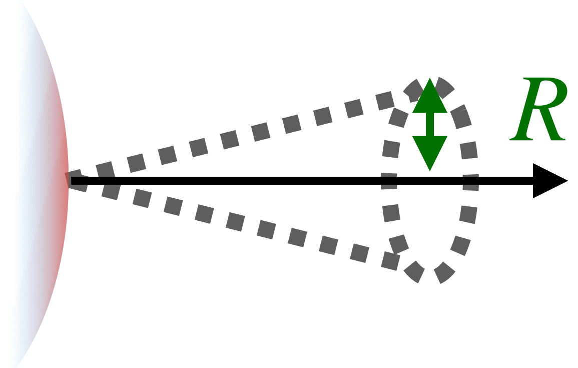
- **Suppression** at $20 < p_{T,\mathrm{ch\,jet}} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$**
  → interplay between hadron and jet energy loss?
  Larger energy loss of trigger when $p_{T,jet} >> p_{T,trig}$?



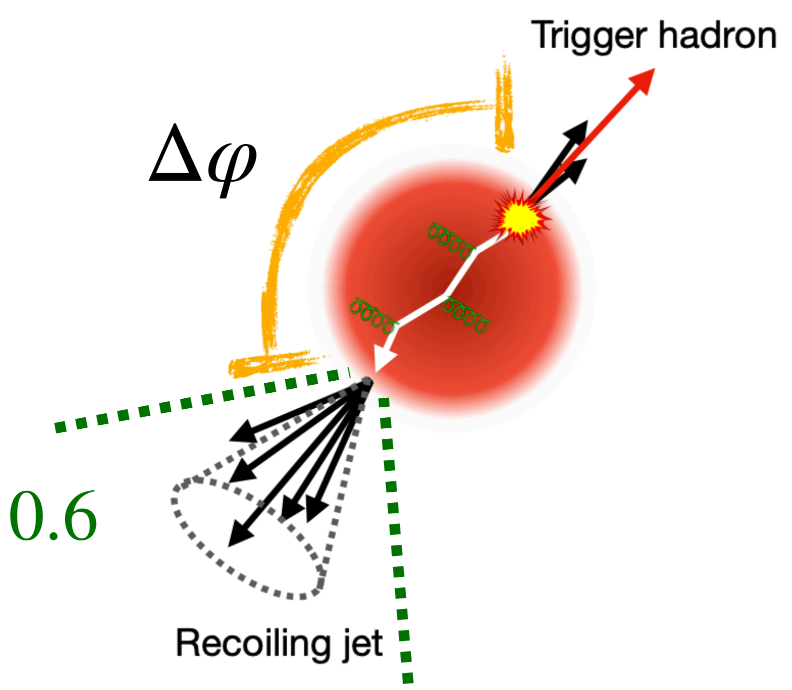
Recent model study confirms this picture

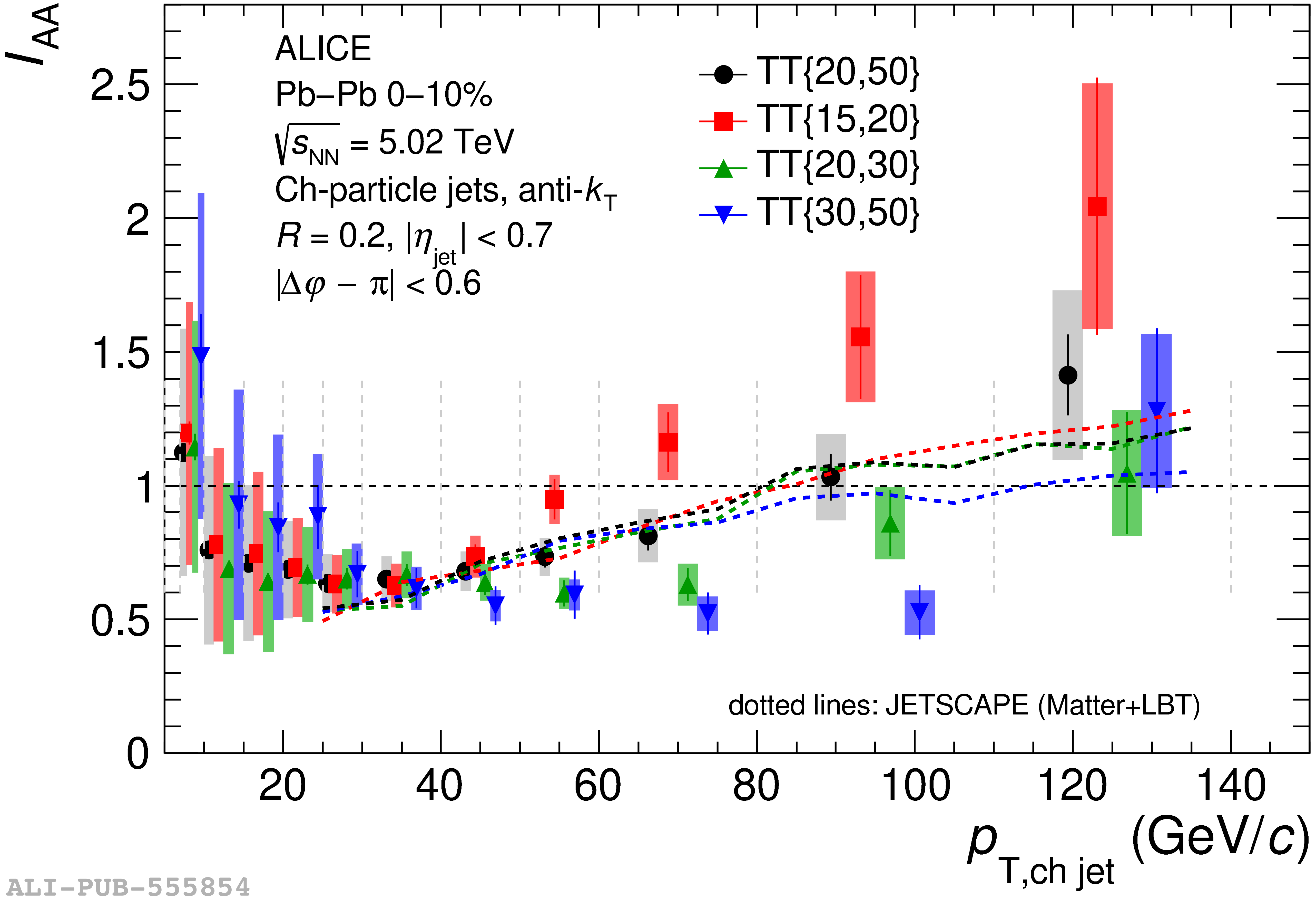
Y. He et al, arxiv:2401.05238

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



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

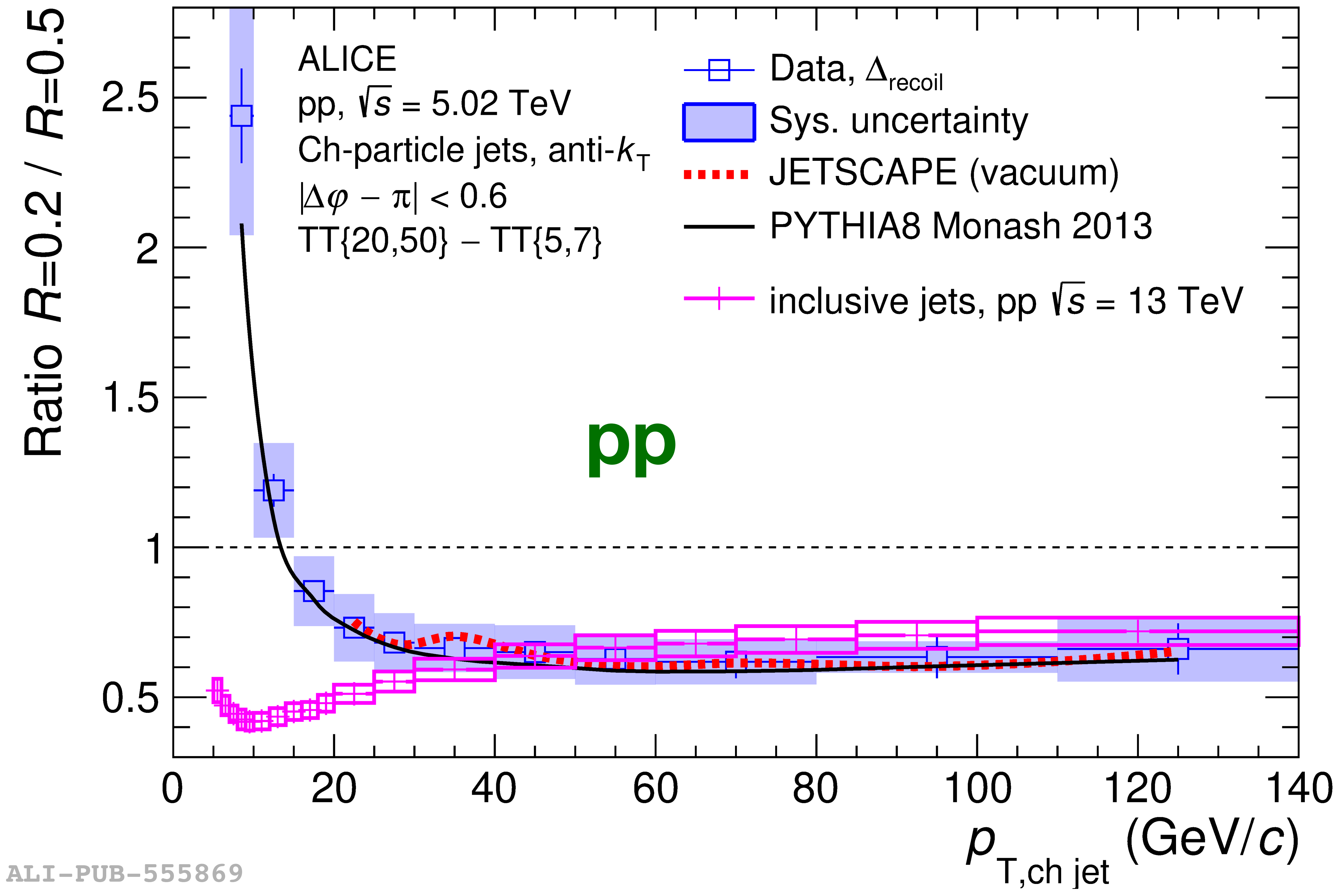




ALI-PUB-555854

- Expected that high p_T hadrons leading fragment of jet originating from QGP surface ('surface bias')
  - $p_T^{jet} \sim p_T^{trig}$: suppression - surface bias picture holds
  - $p_T^{jet} >> p_T^{trig}$: 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

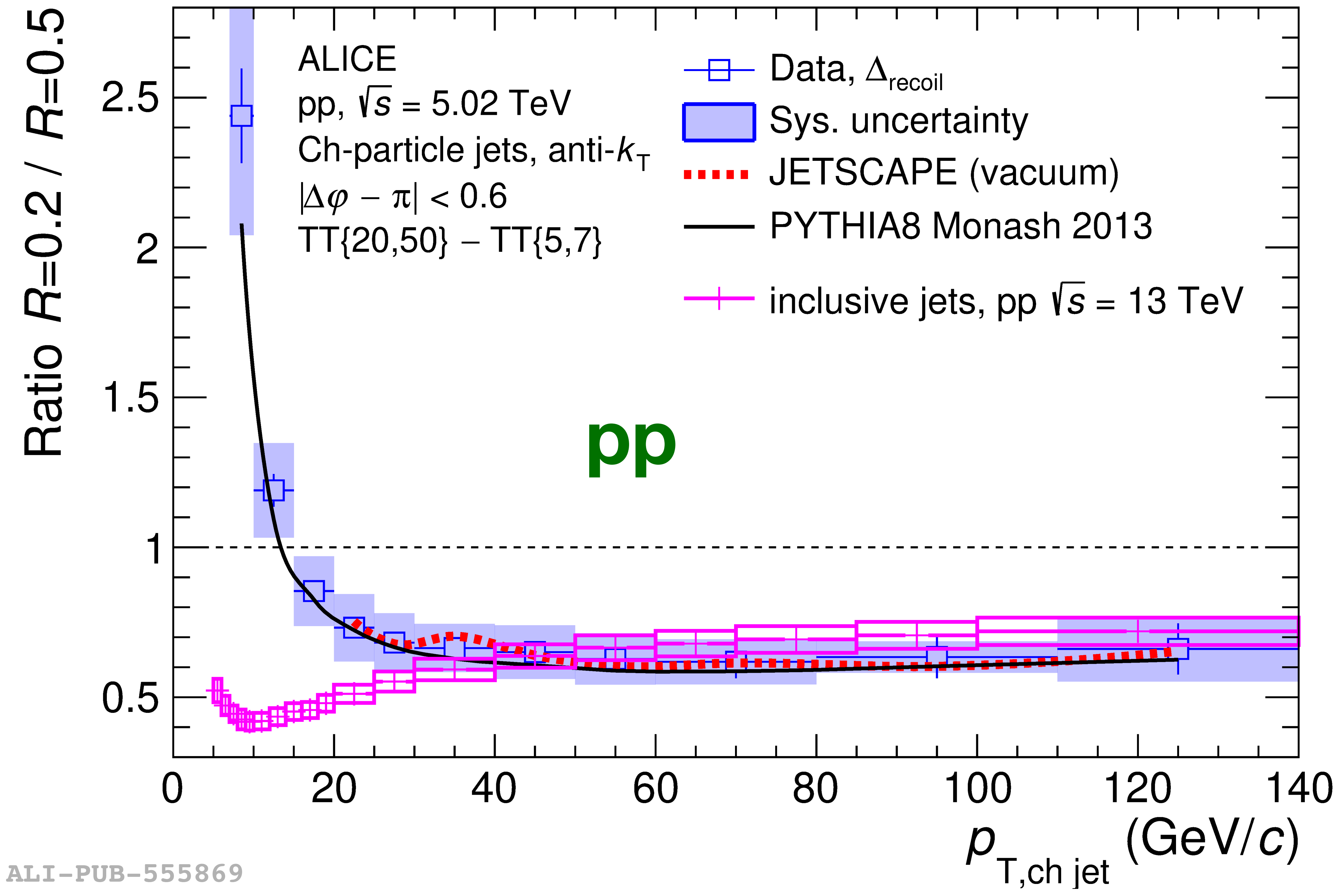
Studying intra-jet broadening through R-ratios

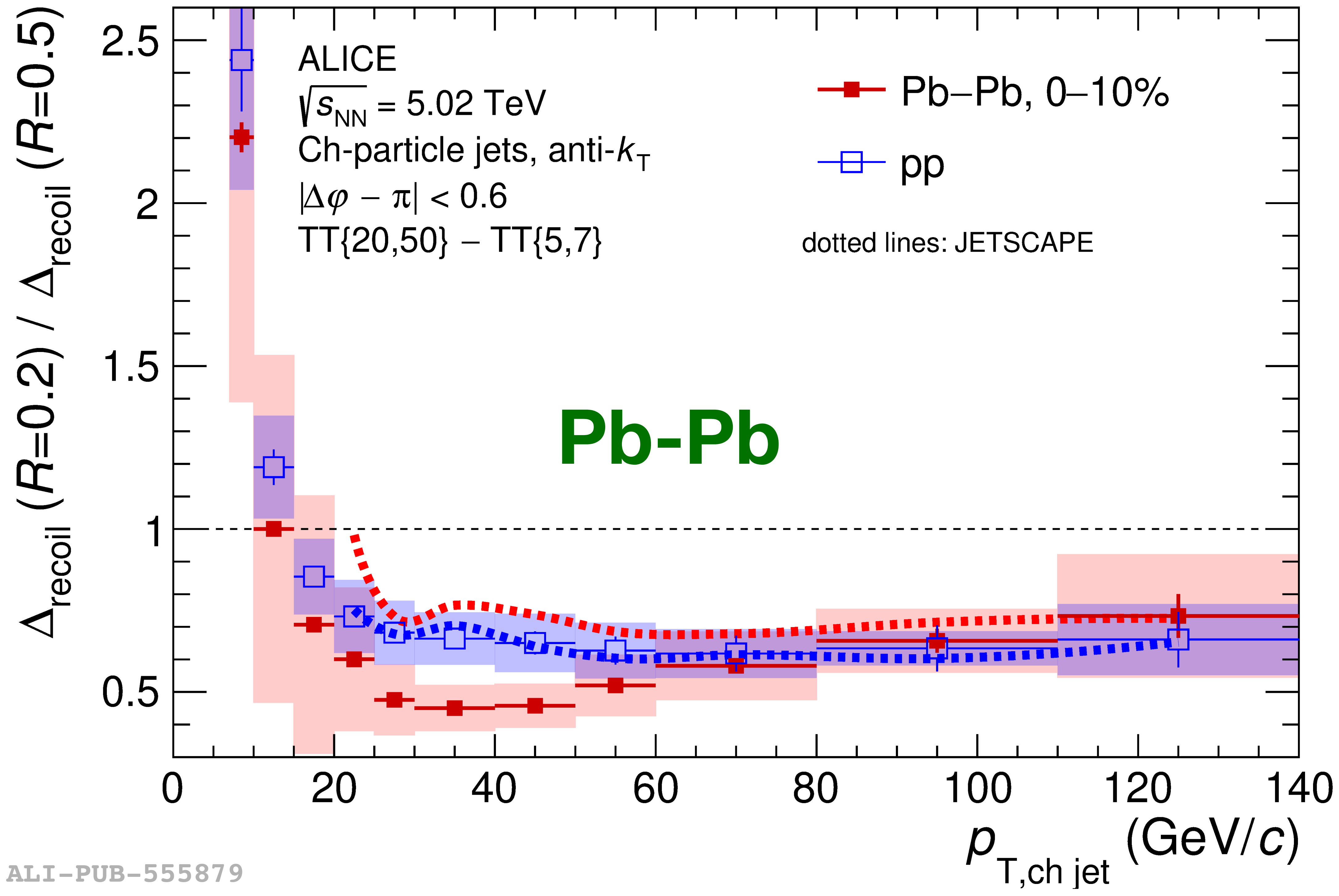


- R=0.2 / R=0.5 ratio deviates from inclusive jet ratio for $p_{T,\mathrm{ch\,jet}} < p_T^{\mathrm{trig}}$

- $\tilde{z} = \dfrac{p_T^{\mathrm{trig}}}{p_T^{\mathrm{jet}}}$
- $\tilde{z} > 1 \rightarrow$ 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

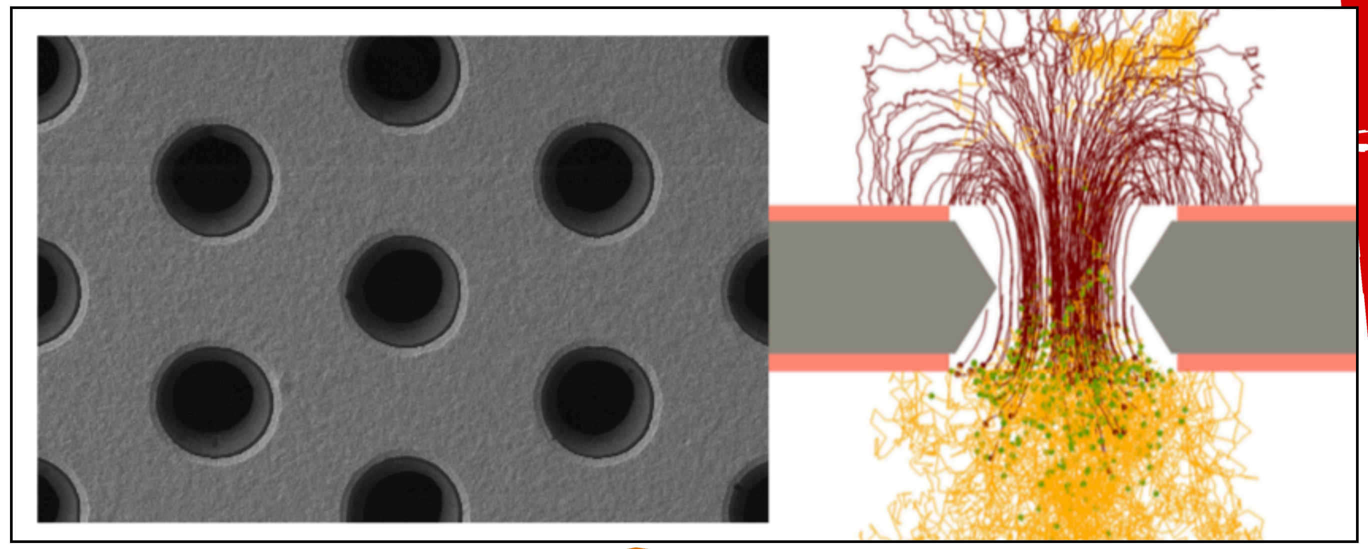


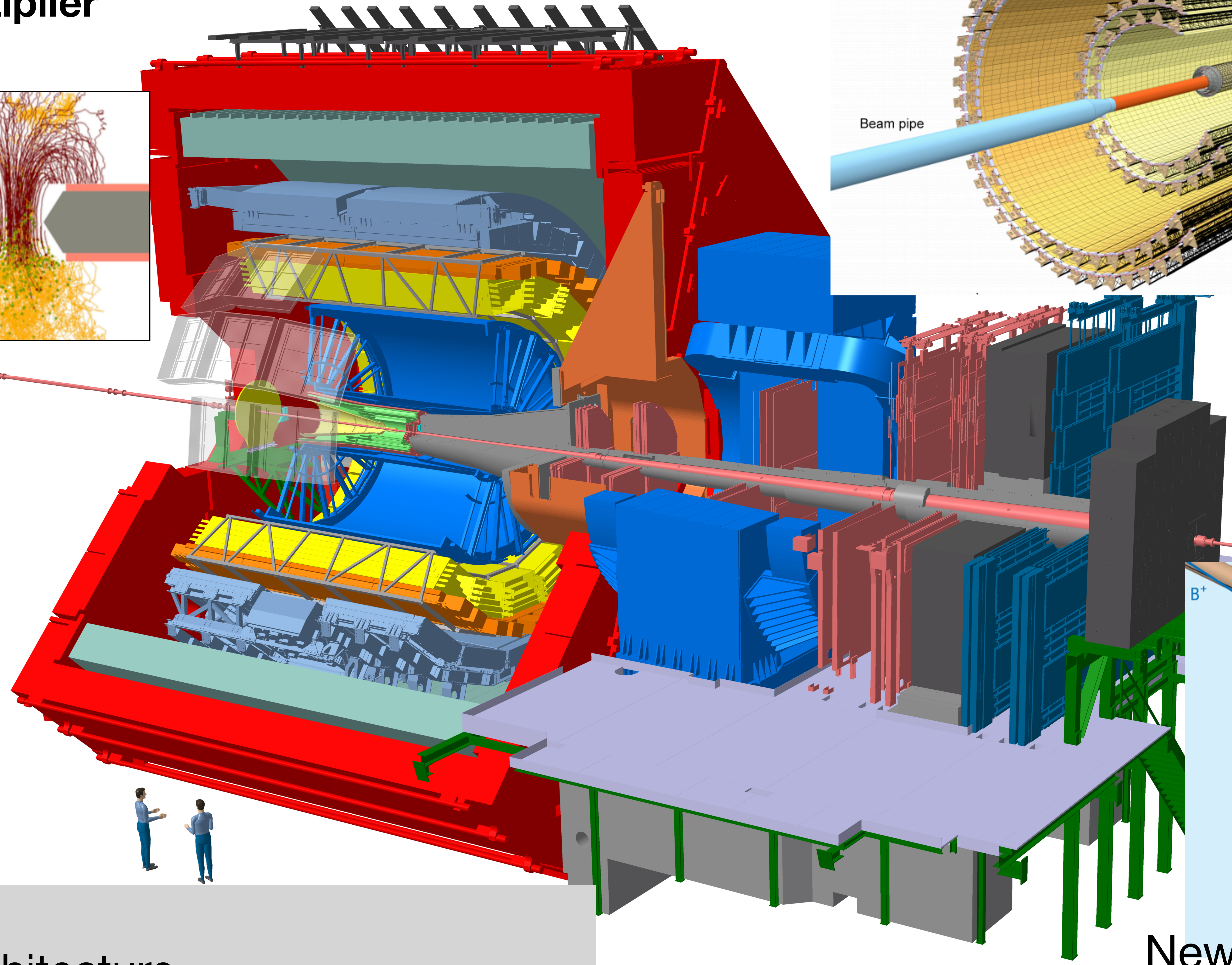


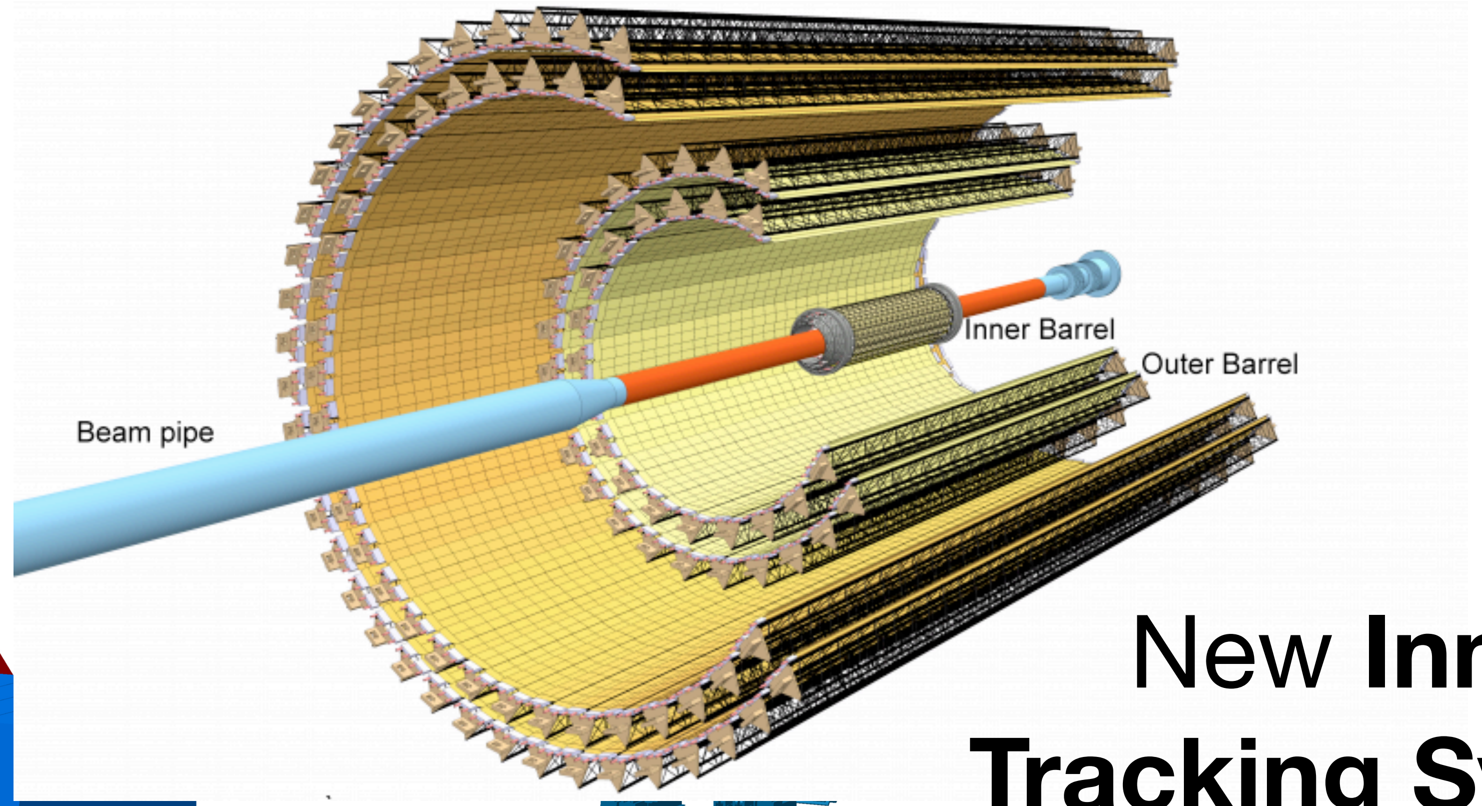
- Hints that R=0.2 jets suppressed more than R=0.5 jets in Pb-Pb w.r.t pp in 30-60 GeV/c
  - Energy recovery for wider jets?

ALICE in Run 3

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

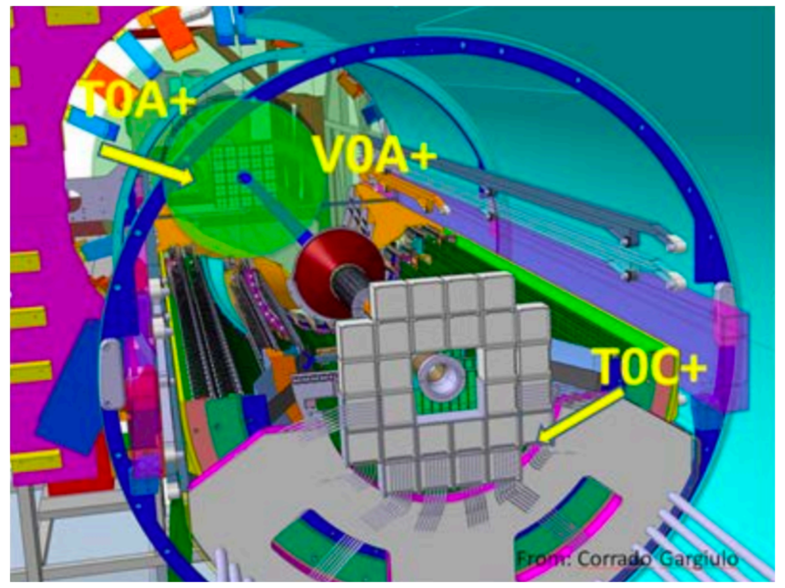


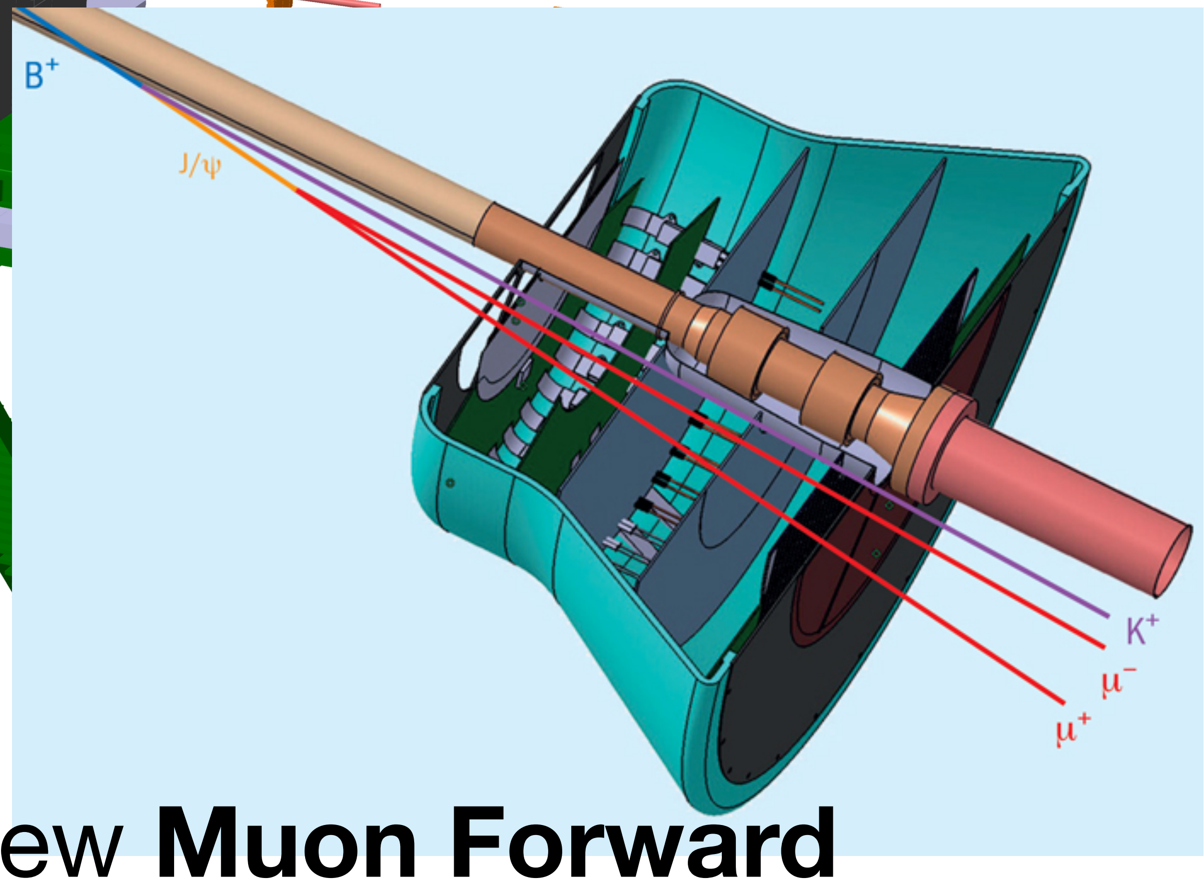




New **Inner Tracking System**

New **forward interaction trigger** (FIT)



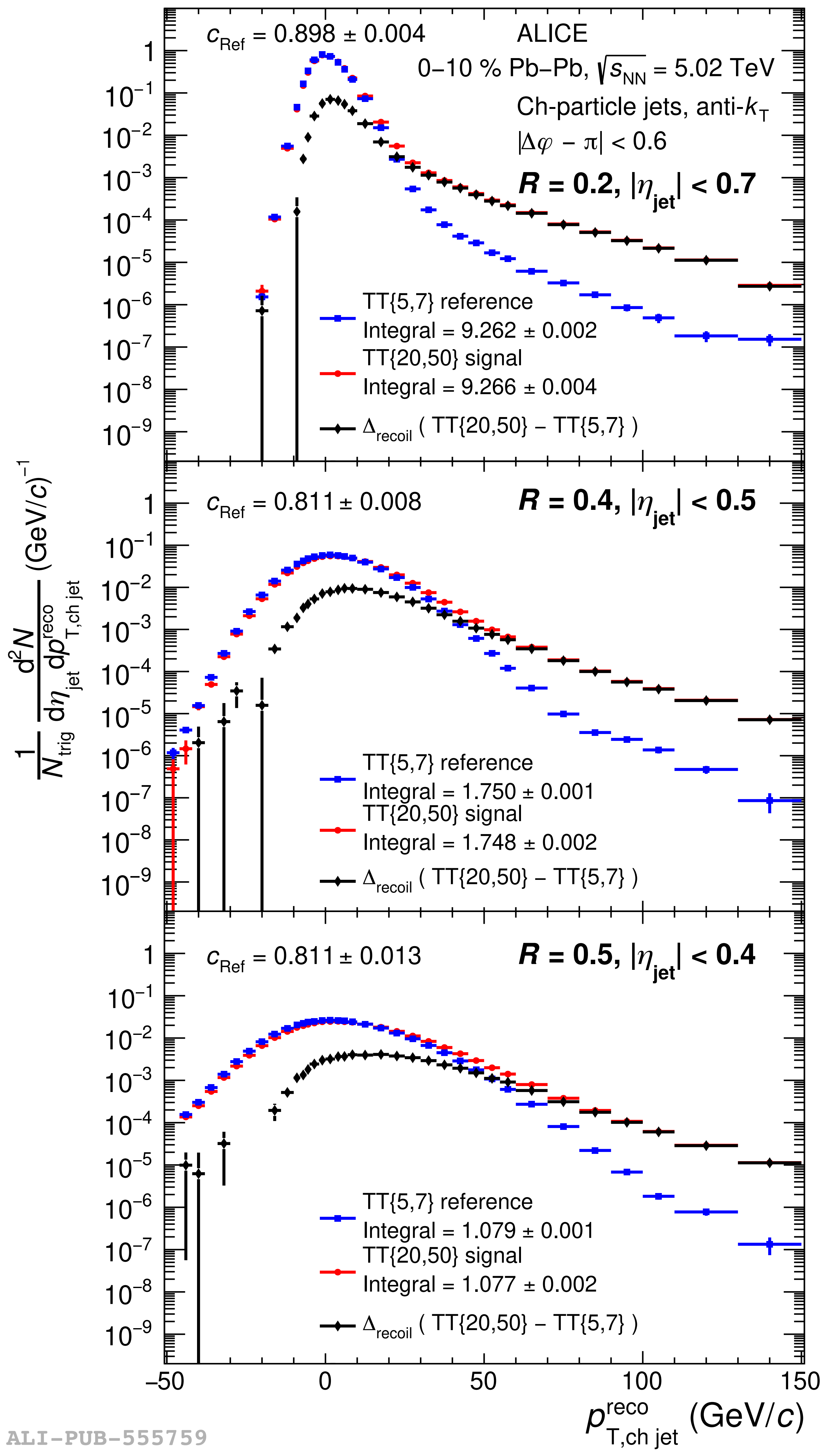


New **Muon Forward Tracker** (MFT)

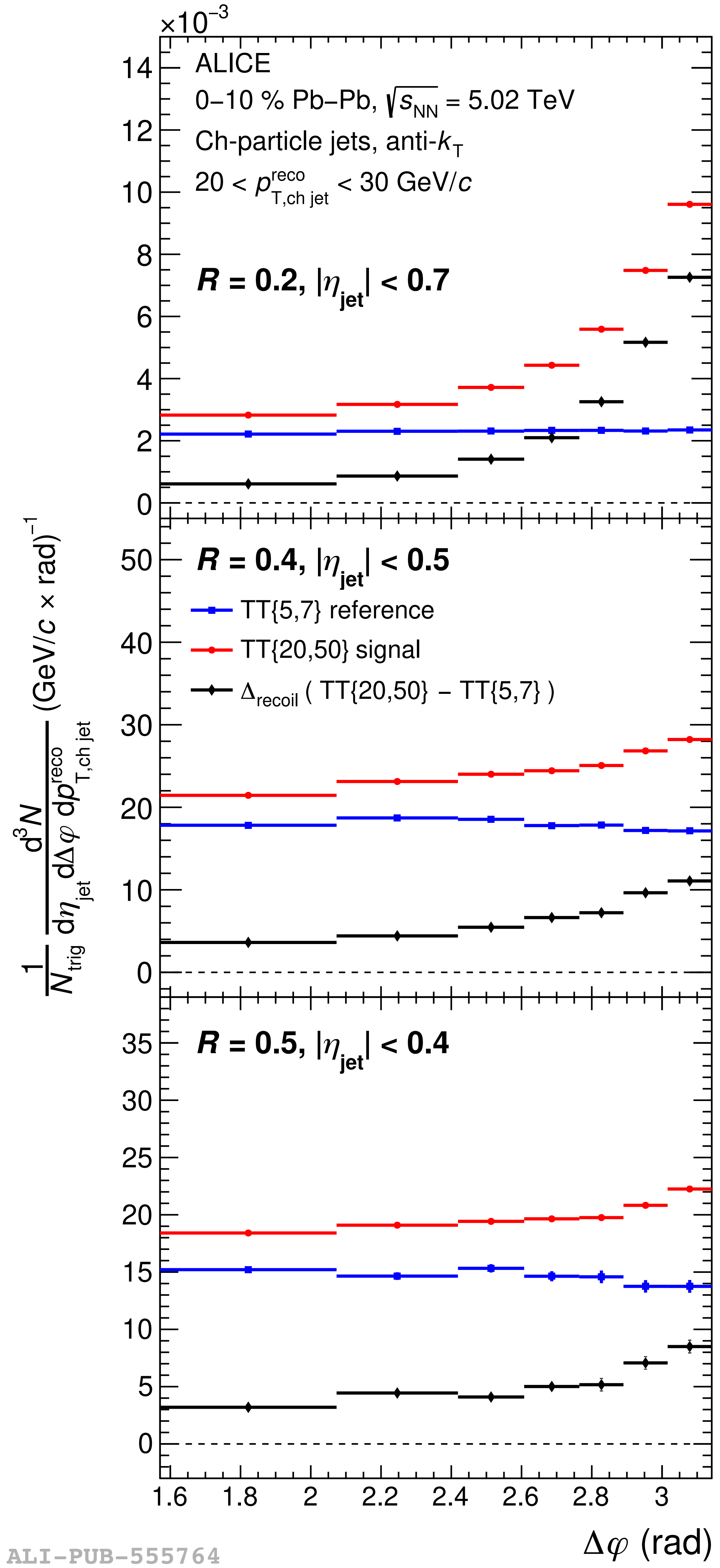
+ New beam pipe
+ New readout architecture
+ Major computing system upgrade (O2 project)

Raw distributions

Pb-Pb

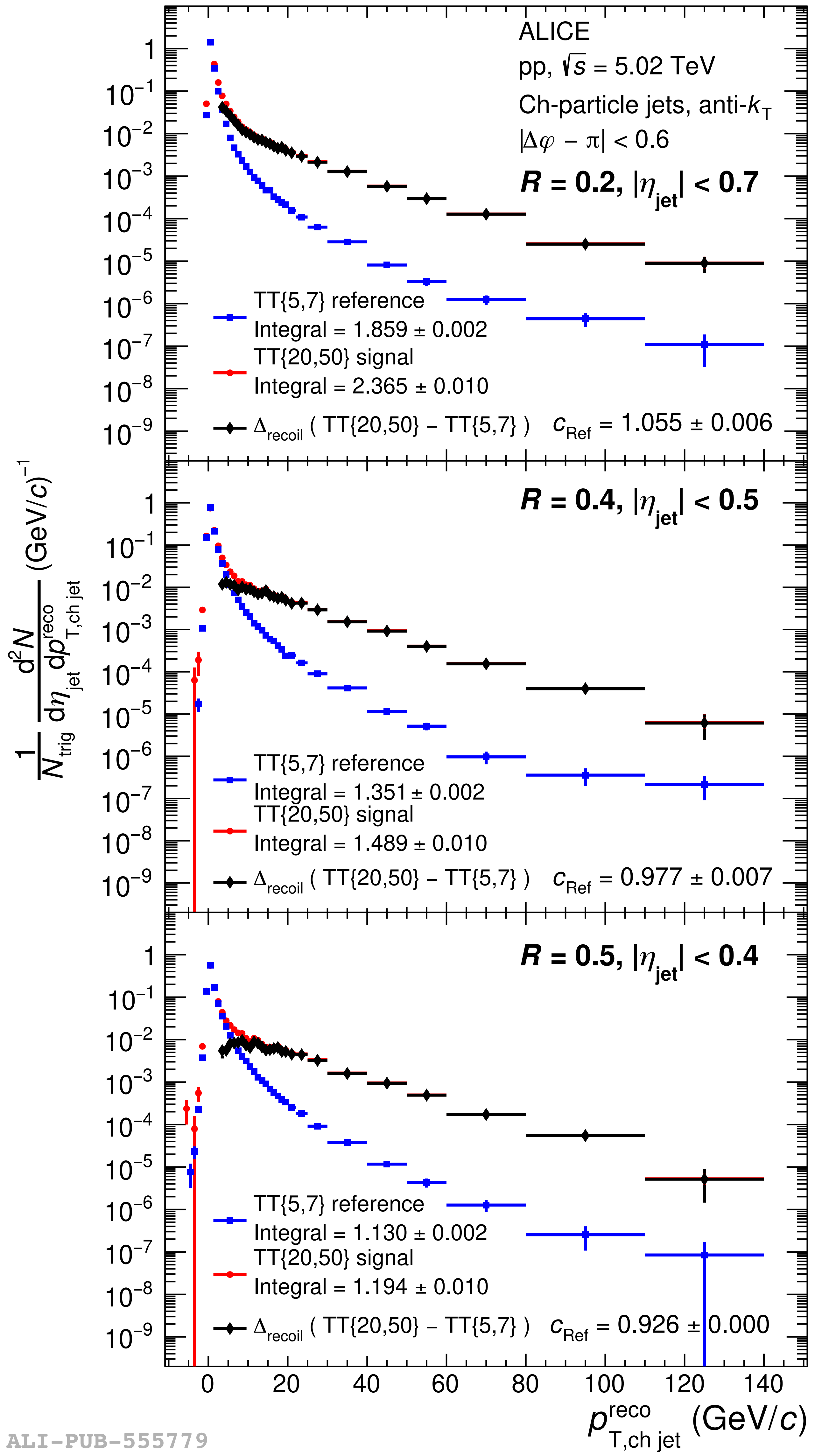


ALI-PUB-555759

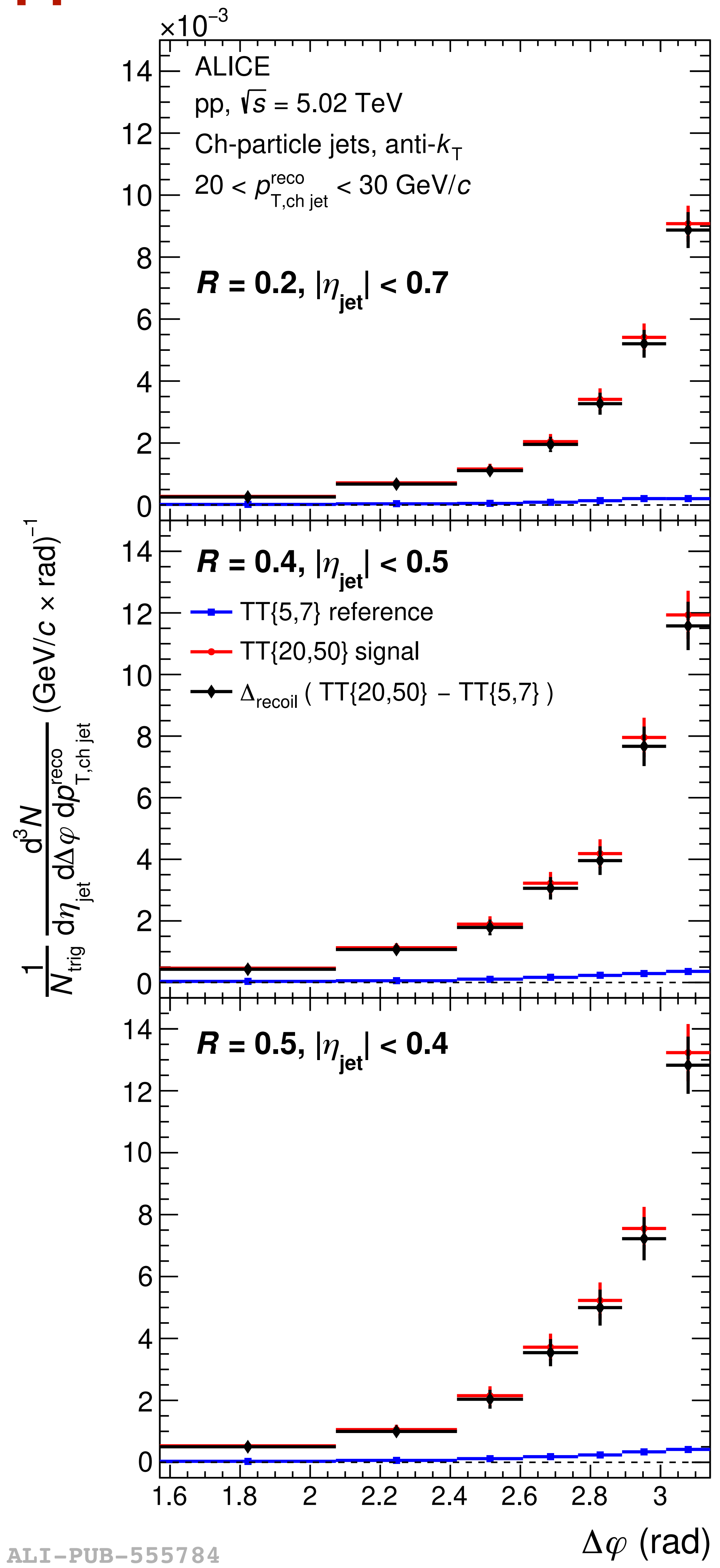


ALI-PUB-555764

pp

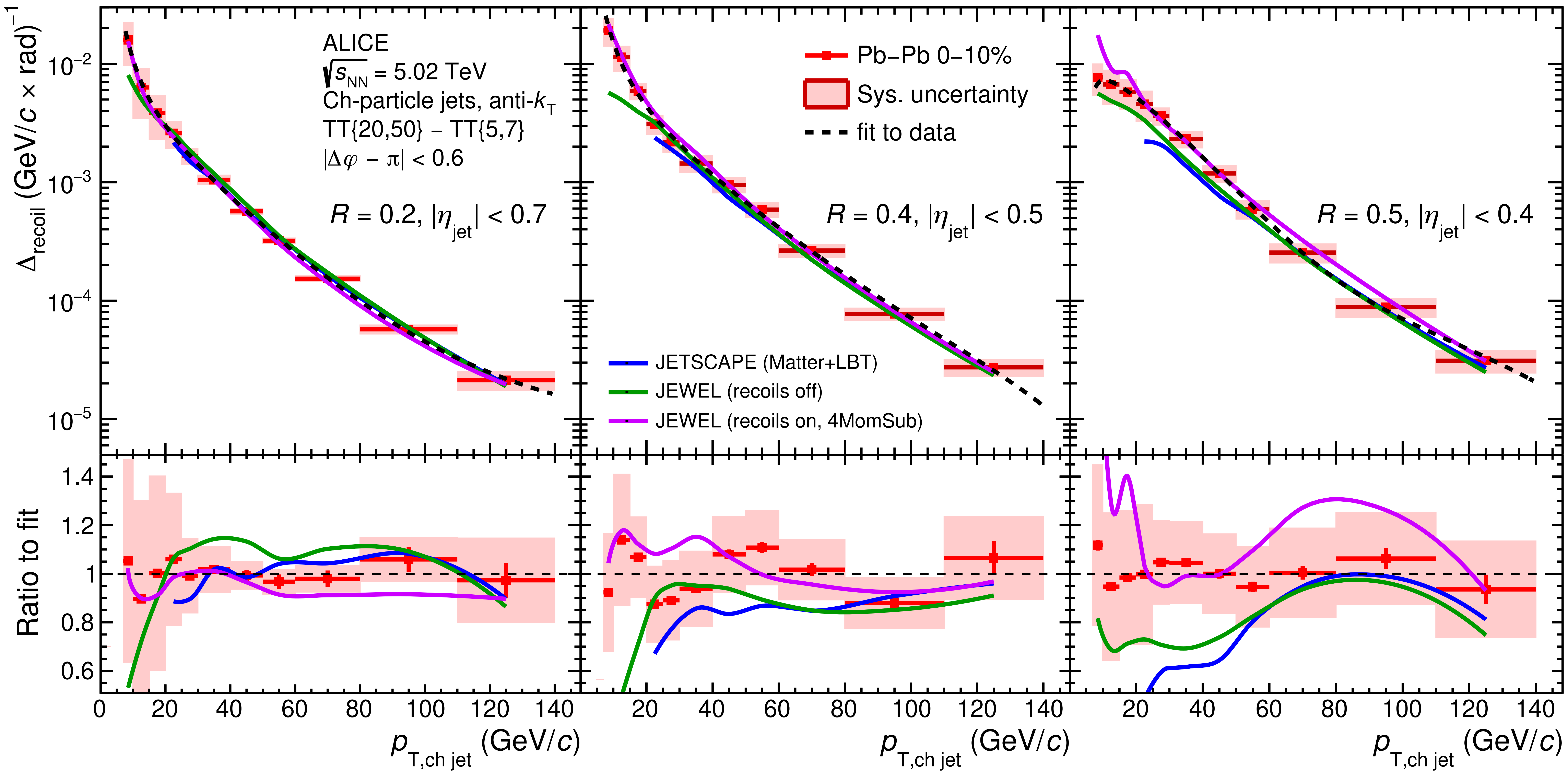


ALI-PUB-555779



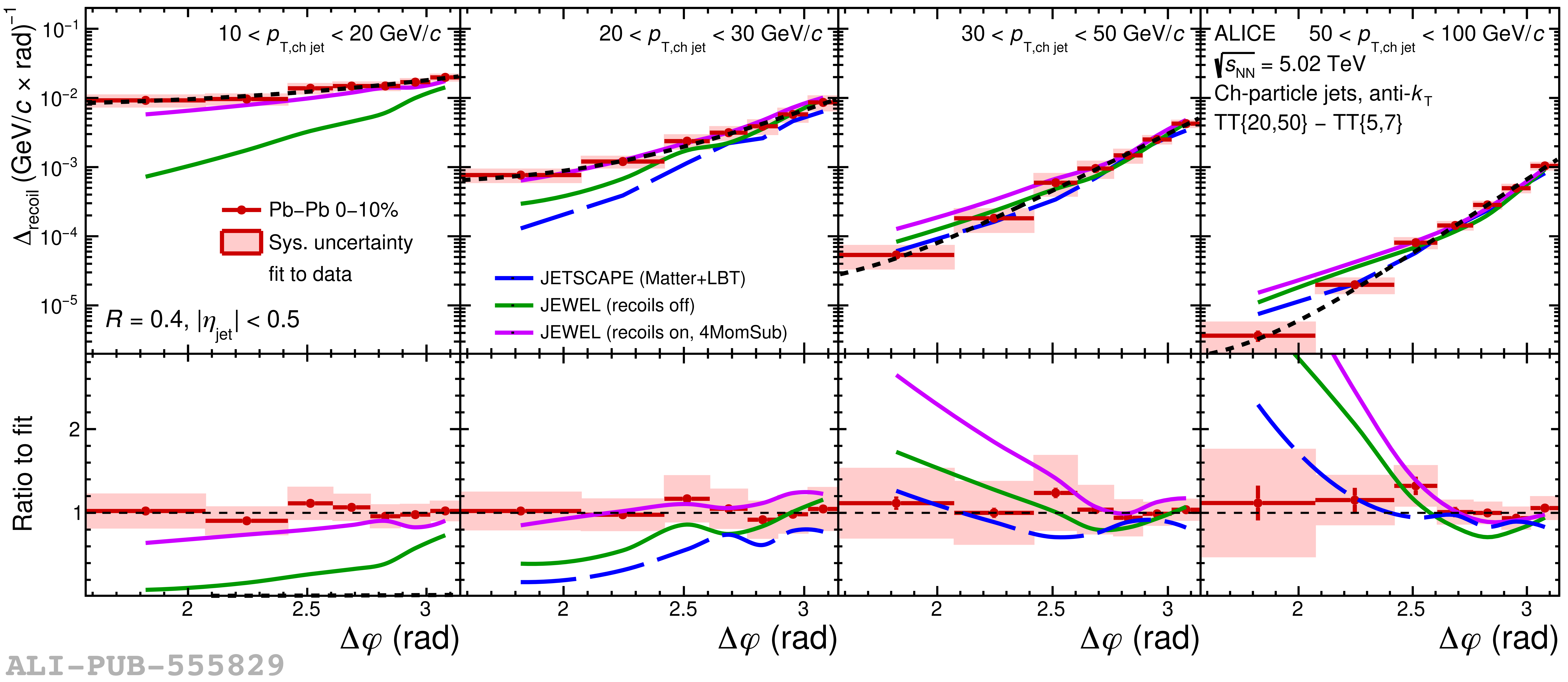
ALI-PUB-555784

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



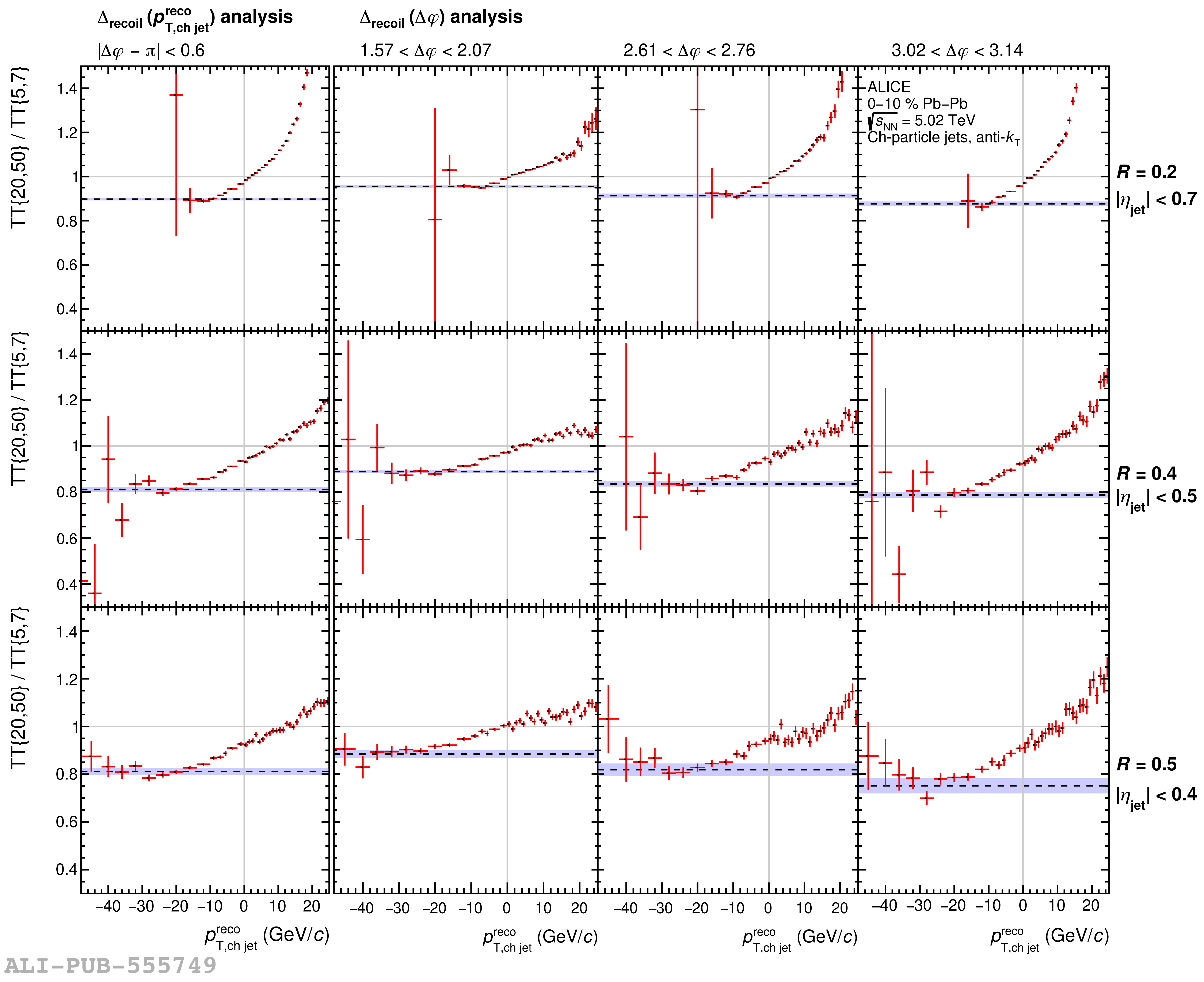
ALI-PUB-555819

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

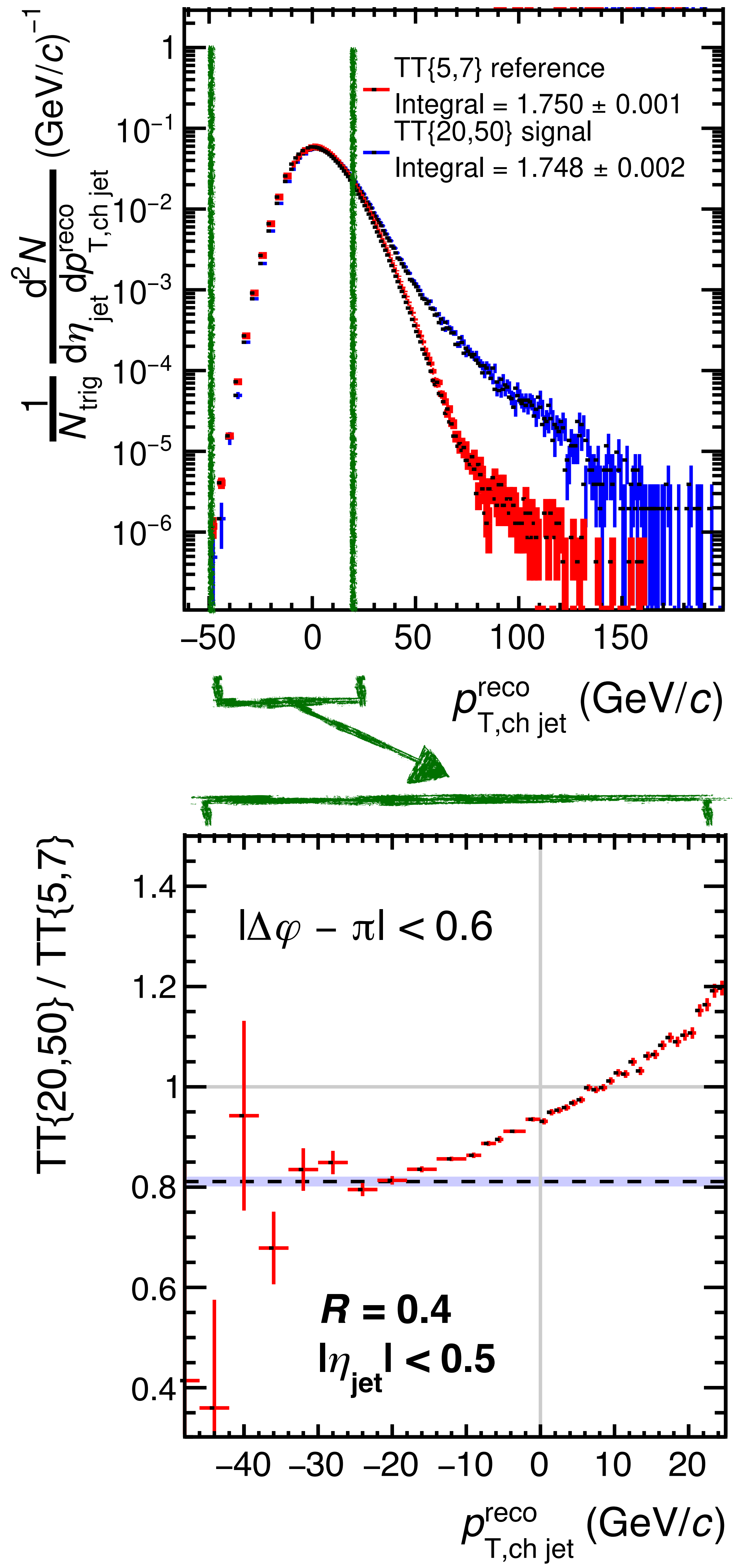


- JEWEL (recoils on) provides best low-$p_{T,ch\,jet}$ description of data, though over predicts high-$p_{T,ch\,jet}$ tails of distribution
- JETSCAPE provides best high-$p_{T,ch\,jet}$ description of data

Δ_{recoil} 'reference' calibration



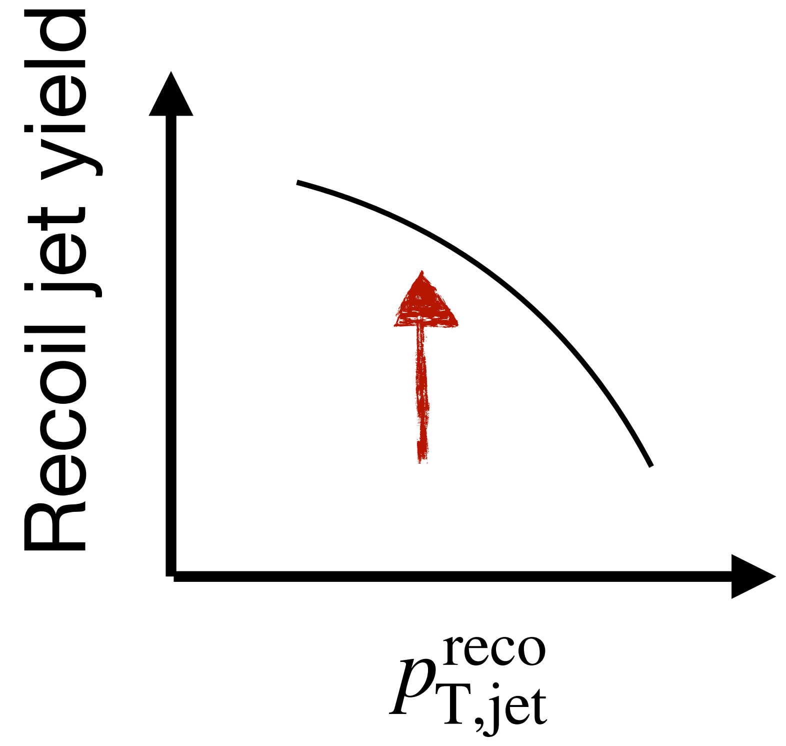
Δ_{recoil} 'reference' calibration

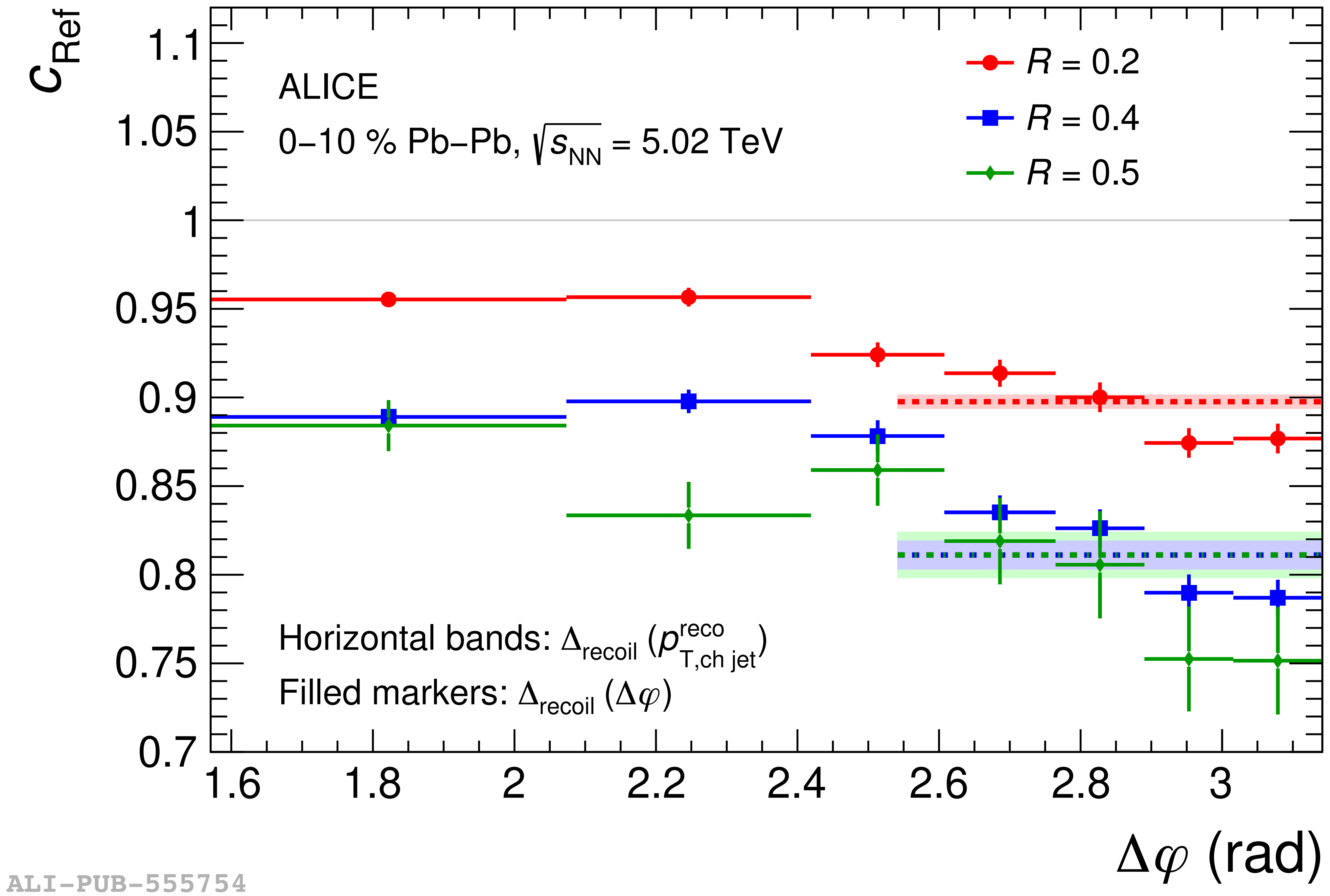


Calibration of reference distribution required for precise background subtraction:

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

2. Yield scale ('*vertical*')



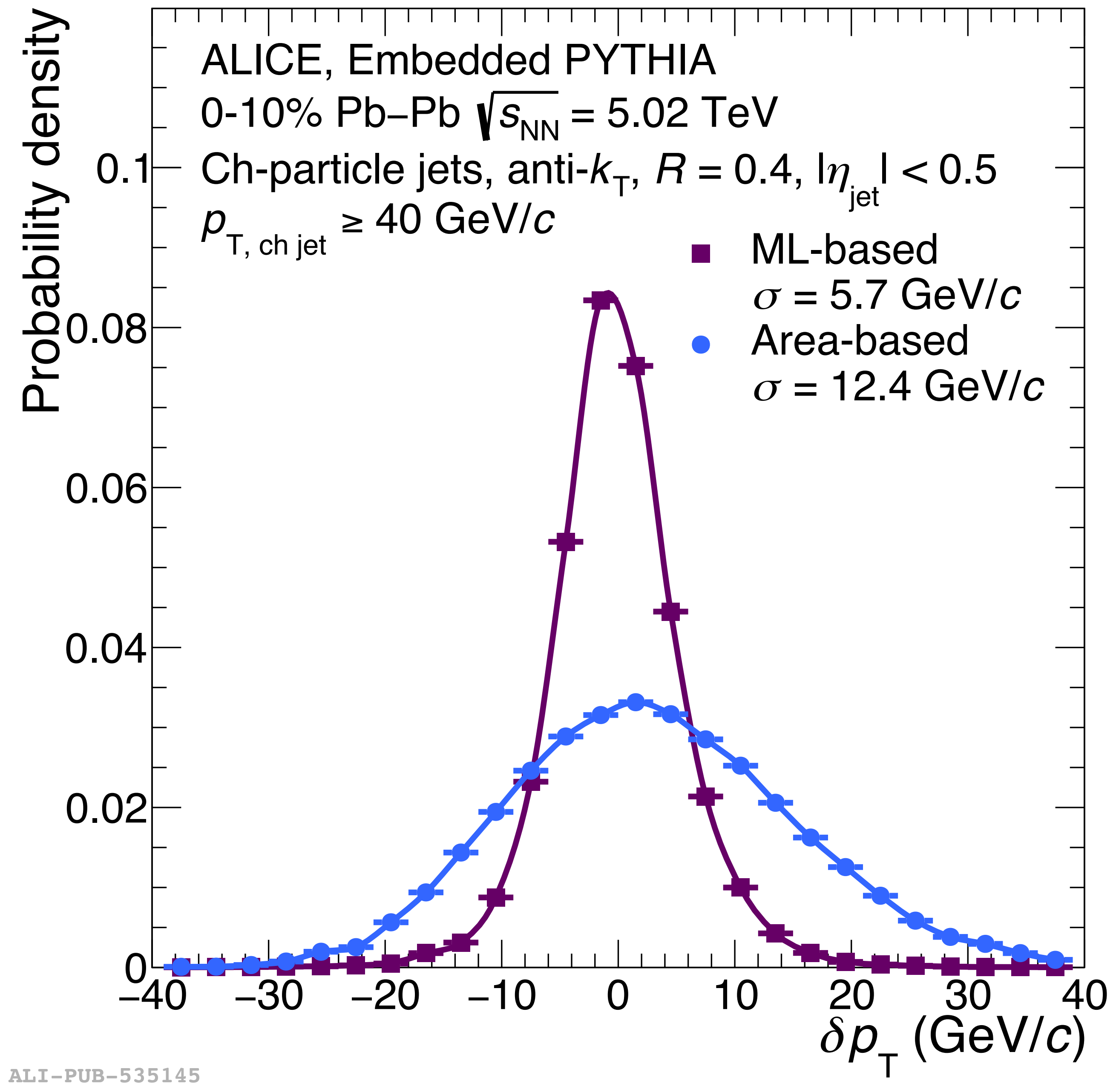


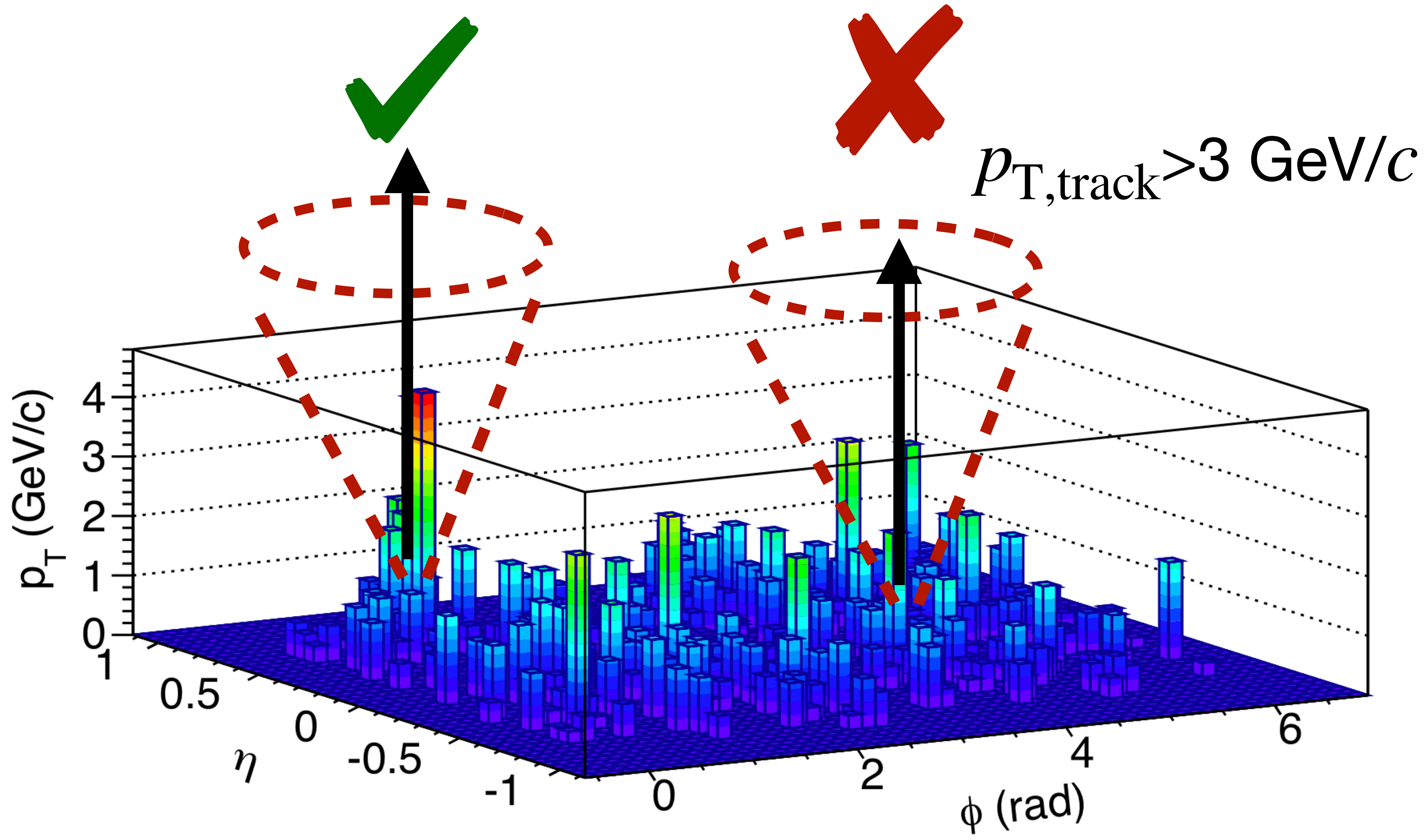
- Correction $\Delta\varphi/R$-dependent
  - more correlated yield → larger c_{Ref} correction

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