Recent jet measurements to probe the Quark-Gluon Plasma with ALICE

Jaime Norman (University of Liverpool)

IOP Joint APP, HEPP and NP Annual Conference

10th April 2024

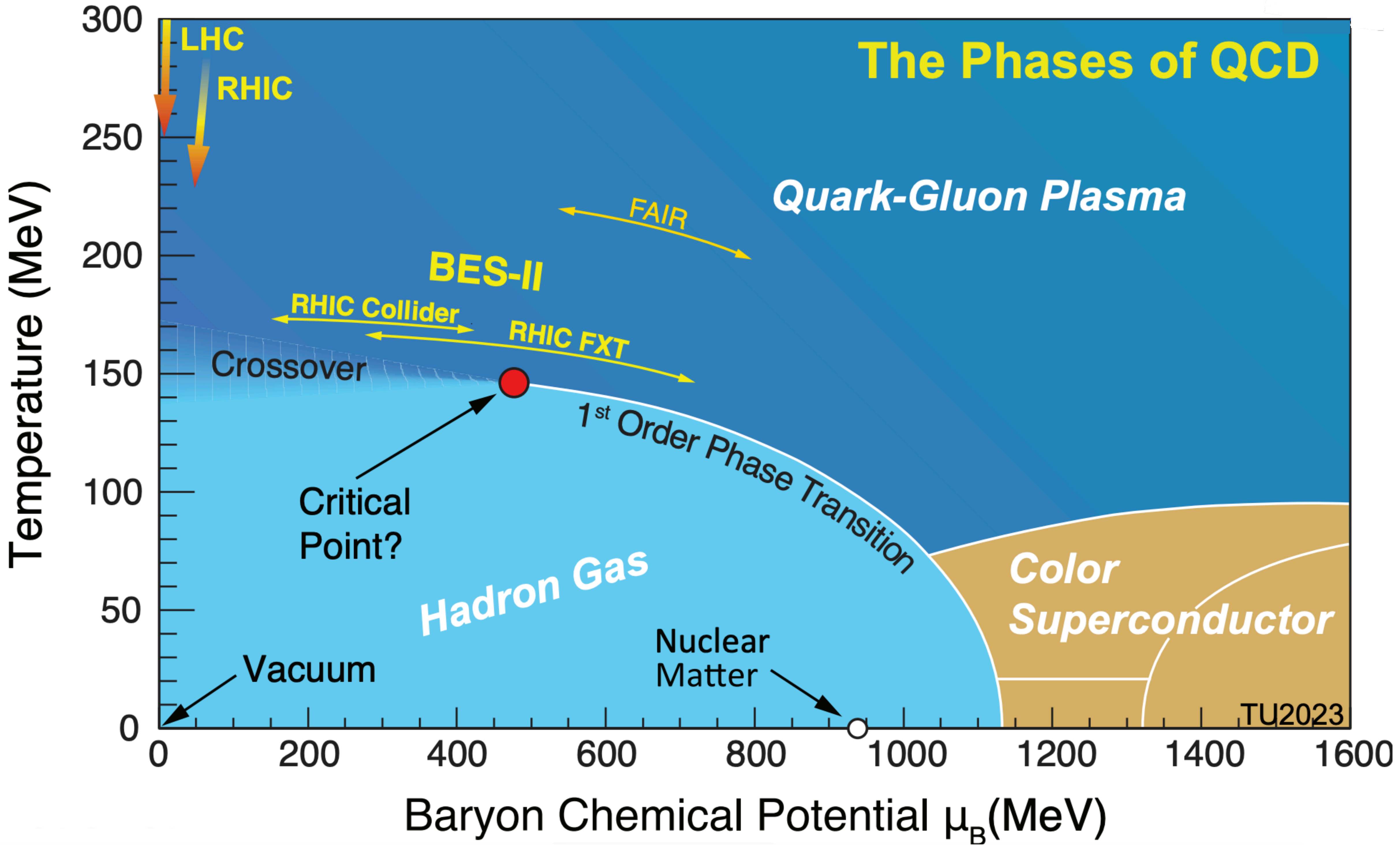
jknorman@liverpool.ac.uk

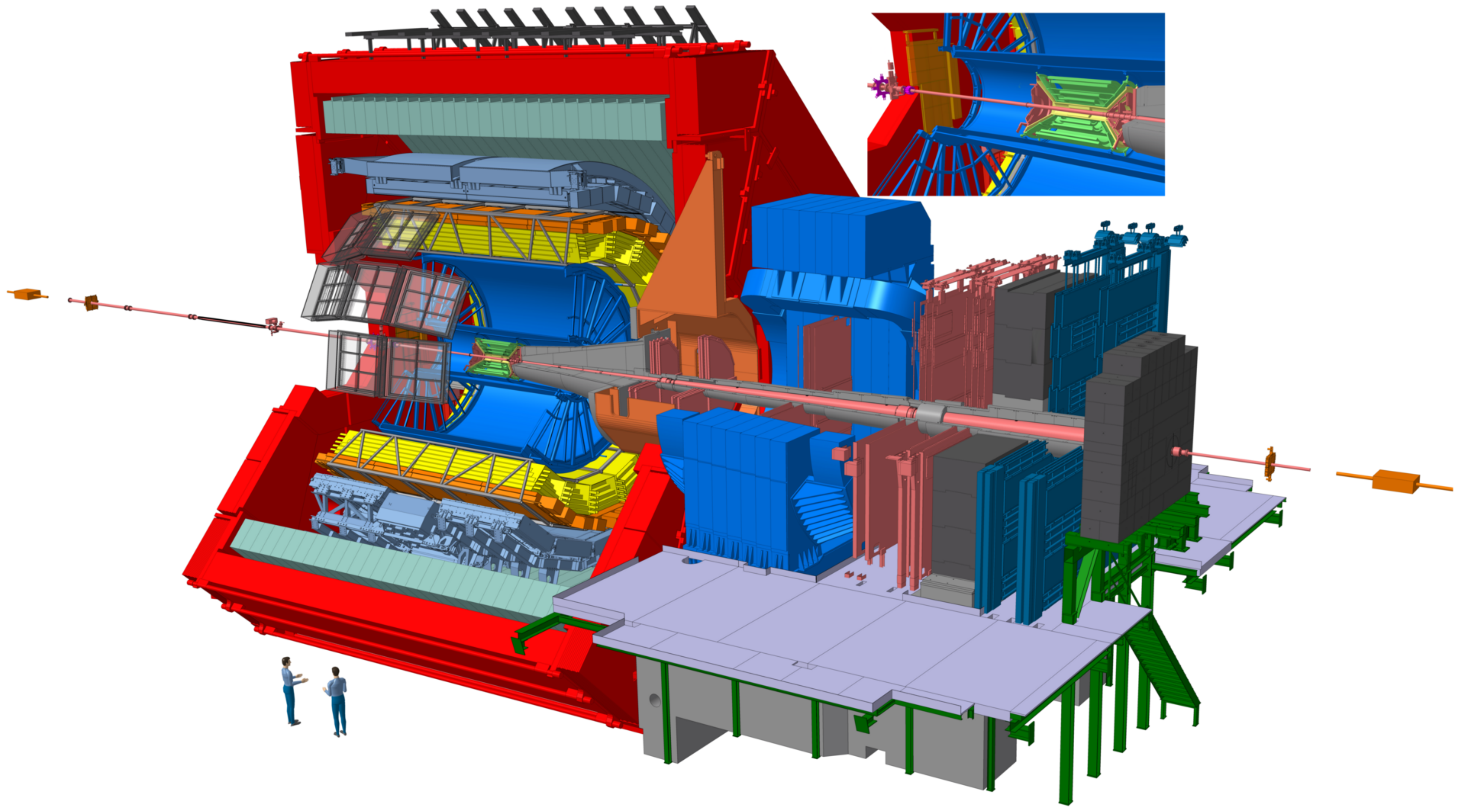
Studying the Quark-Gluon Plasma at the LHC

- Phase transition of QCD matter at very high temperature or density to deconfined state of quarks and gluons
  - **Quark-Gluon Plasma (QGP) - the 'primordial' liquid**

- 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





ALICE is the dedicated LHC heavy-ion experiment

Jets as a probe of the QGP

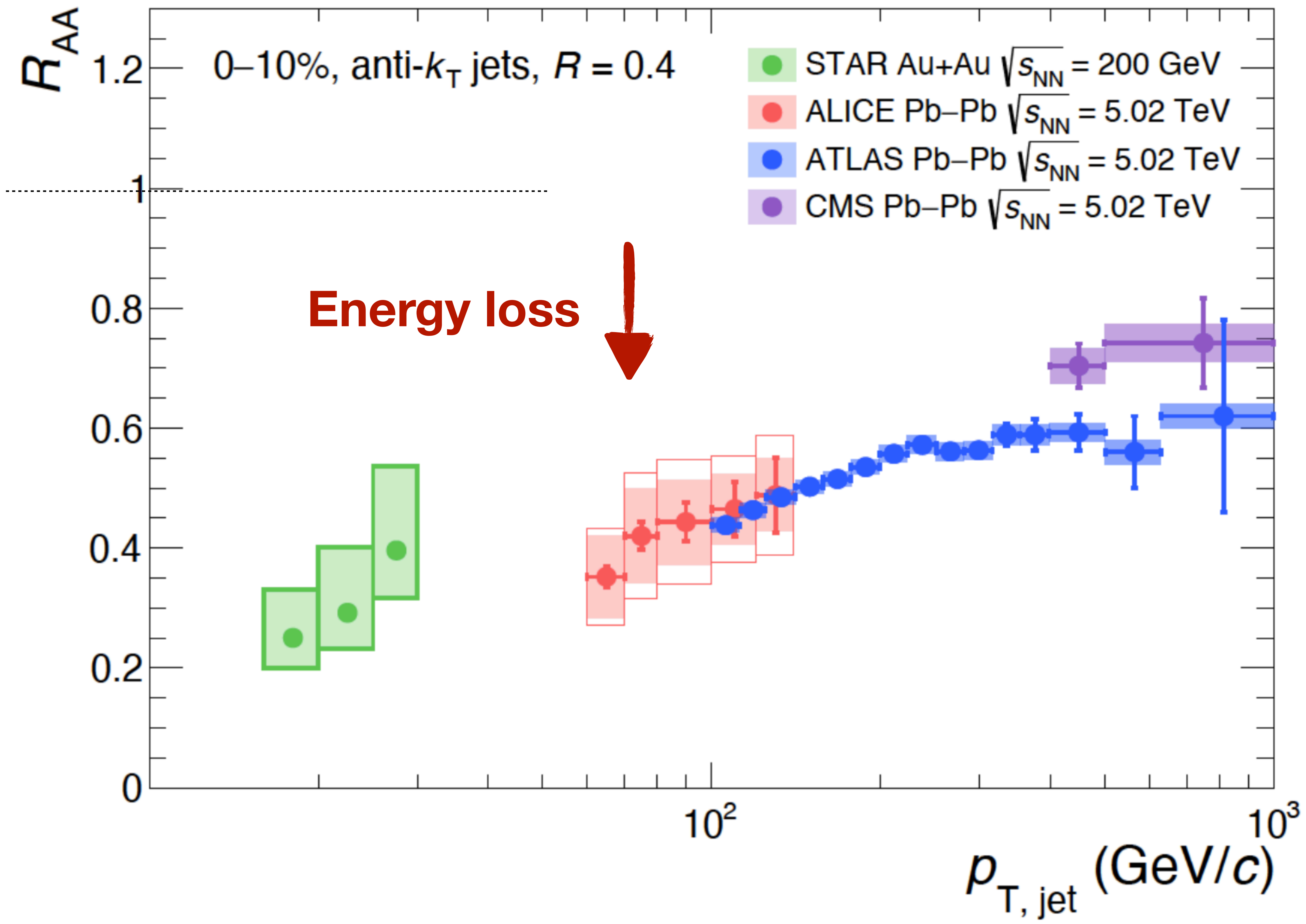
$$R_{\mathrm{AA}} = \frac{\mathrm{Yield(PbPb)}}{< N_{\mathrm{coll}} > \times \mathrm{Yield(pp)}}$$

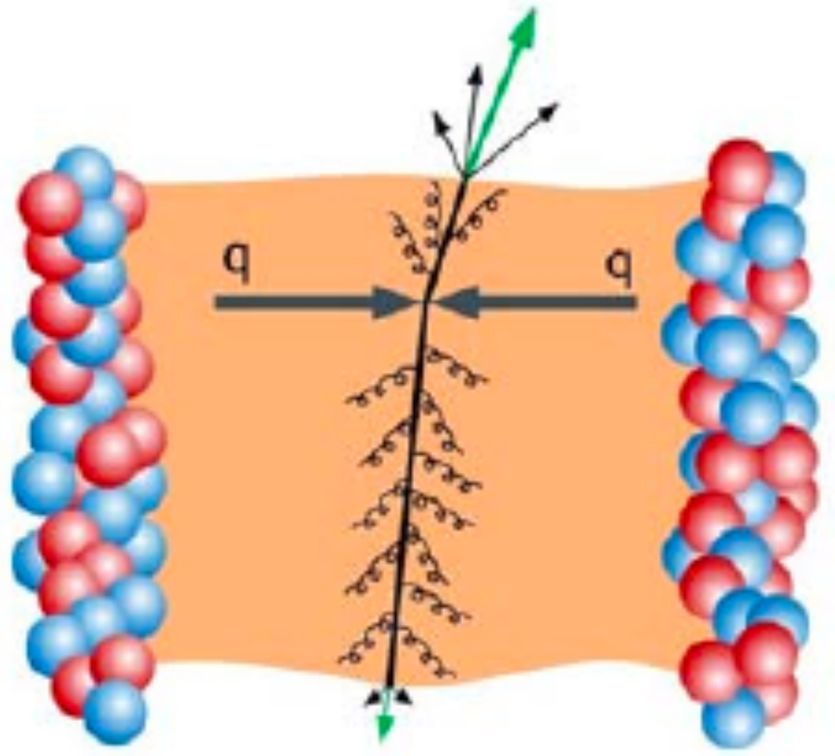
Jet production in heavy-ion (Pb-Pb) collisions:

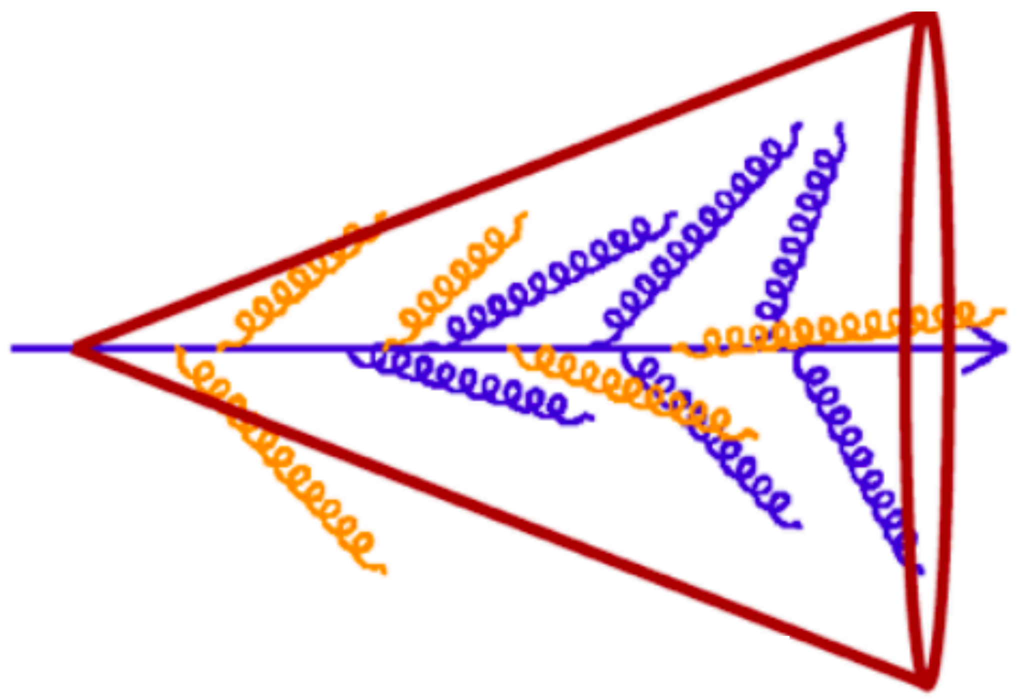
- Evolution of hard parton (quark or gluon) → gluon radiation *(in 'vacuum', pp collisions)*
- inelastic (medium-induced gluon emission) and elastic (collisional) processes over full parton shower *(in 'medium', AA collisions)*

→ Jets provide unique probes of the QGP

J. Harris, B. Müller, arxiv:2308.05743





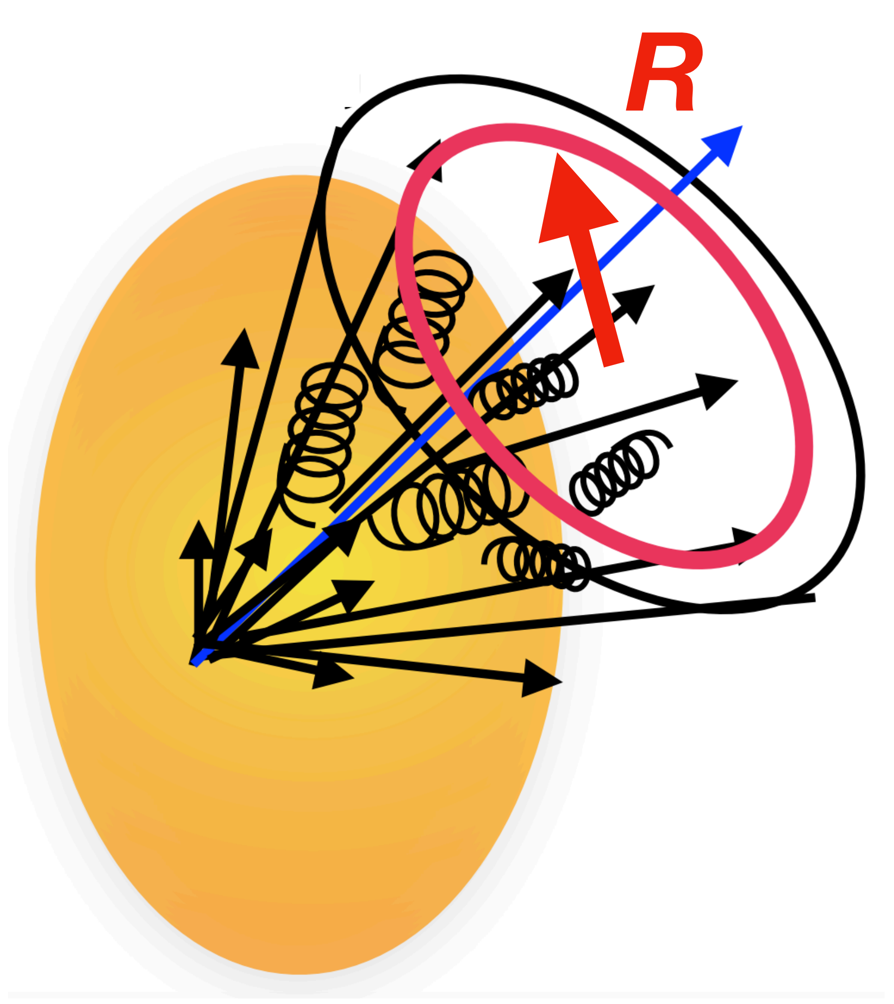


$R_{AA} < 1$ **- energy loss, 'jet quenching'**

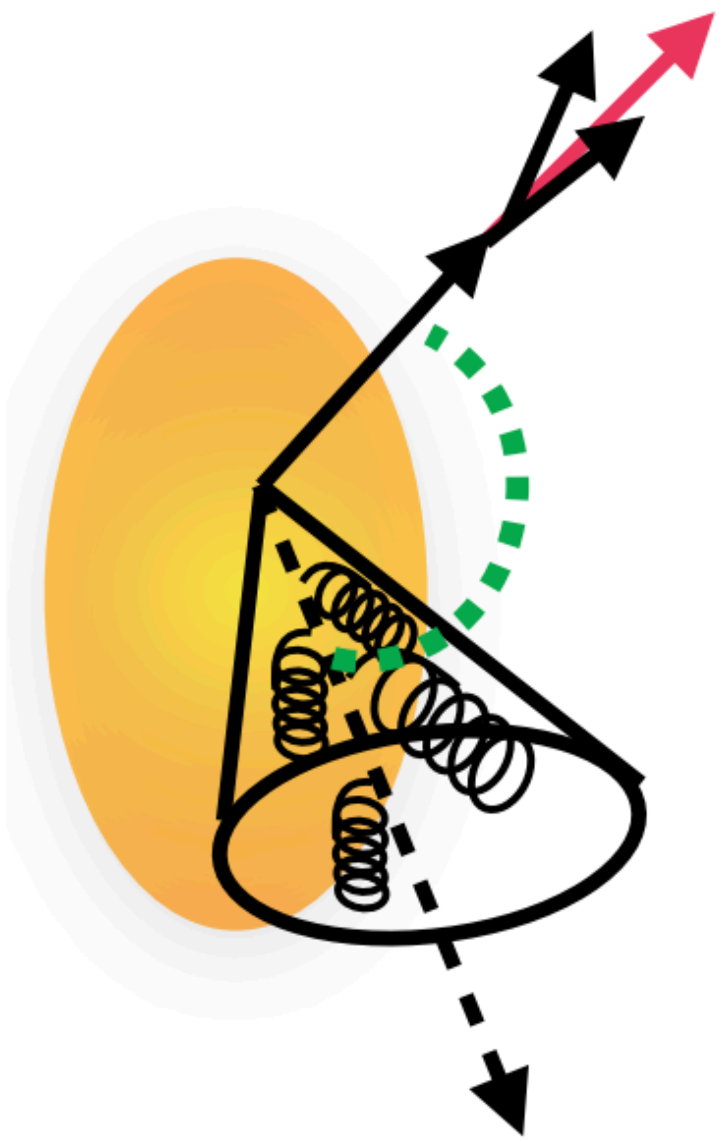
A+A)

Observable consequences of jet quenching

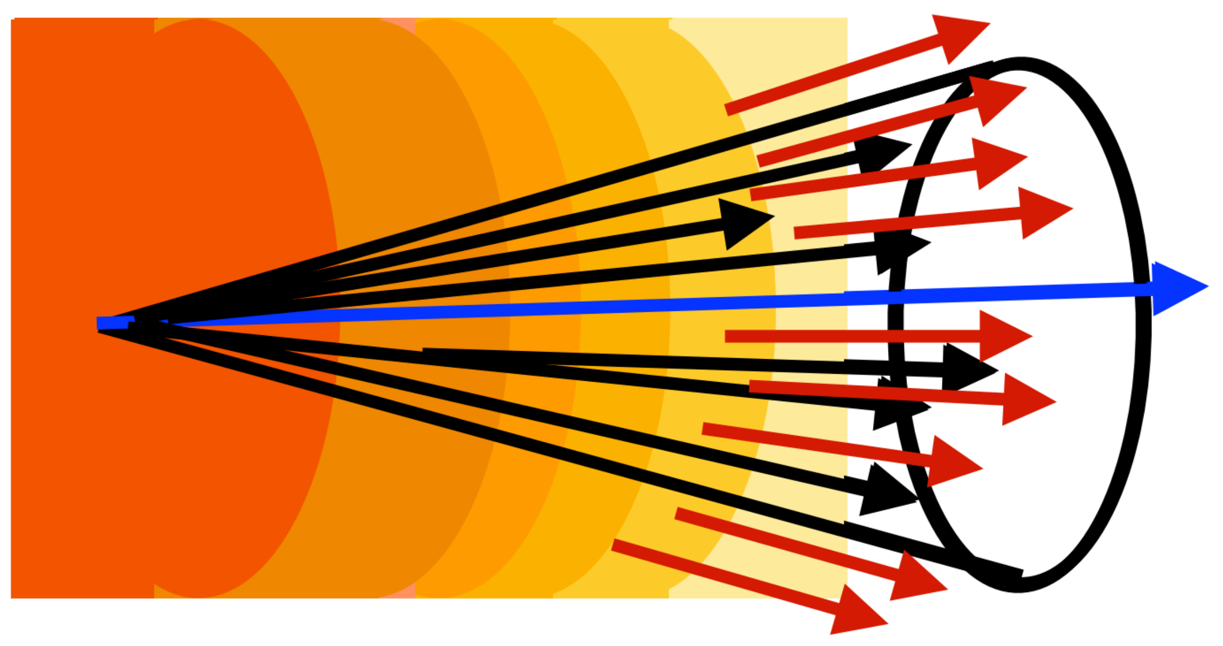
- Jets provide unique probe of QGP - jet-medium interactions manifests in different ways, for example:



Energy loss - *energy transport* outside jet cone

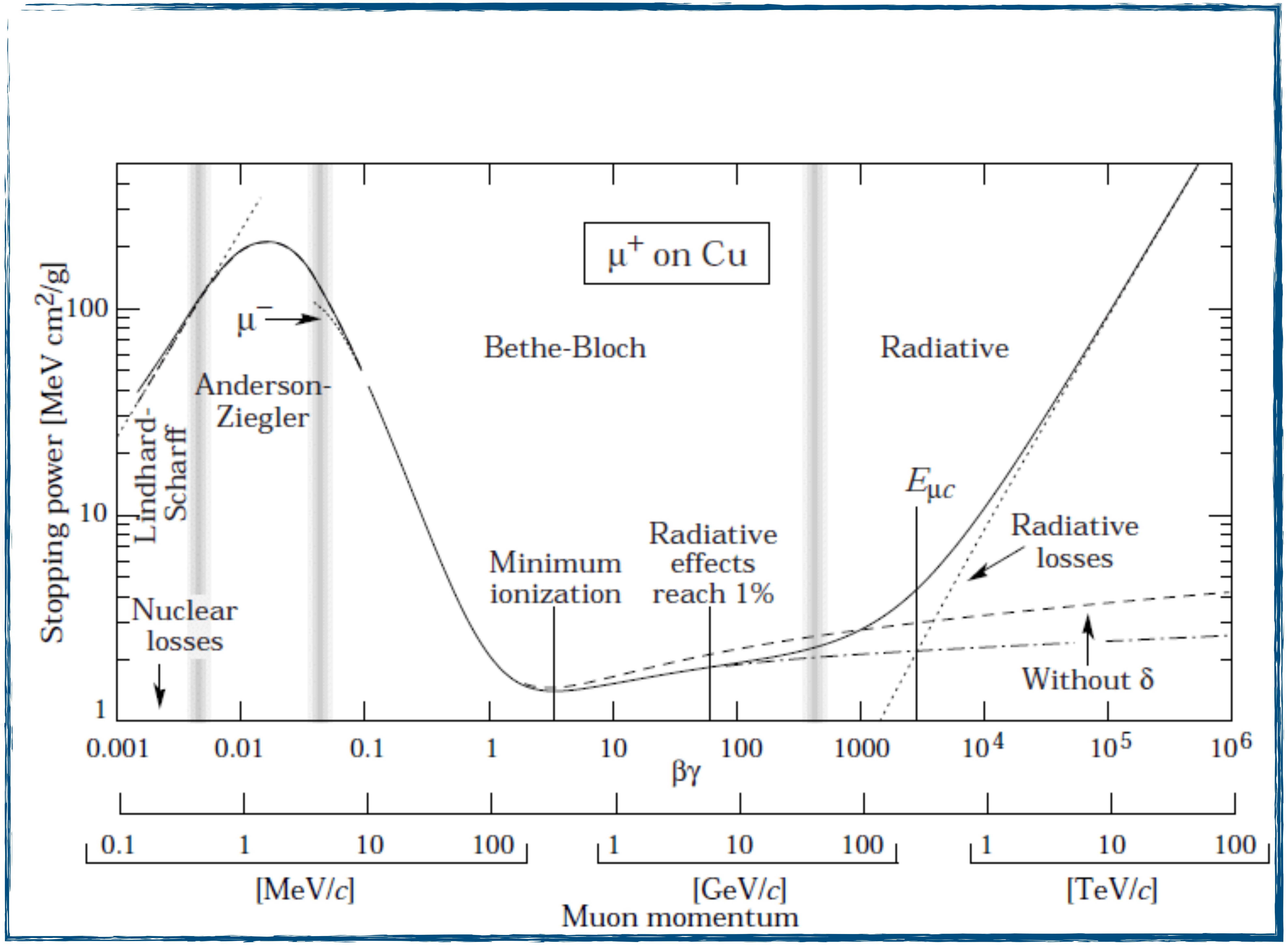


***Jet deflection* via multiple soft scatters or single hard scatters**



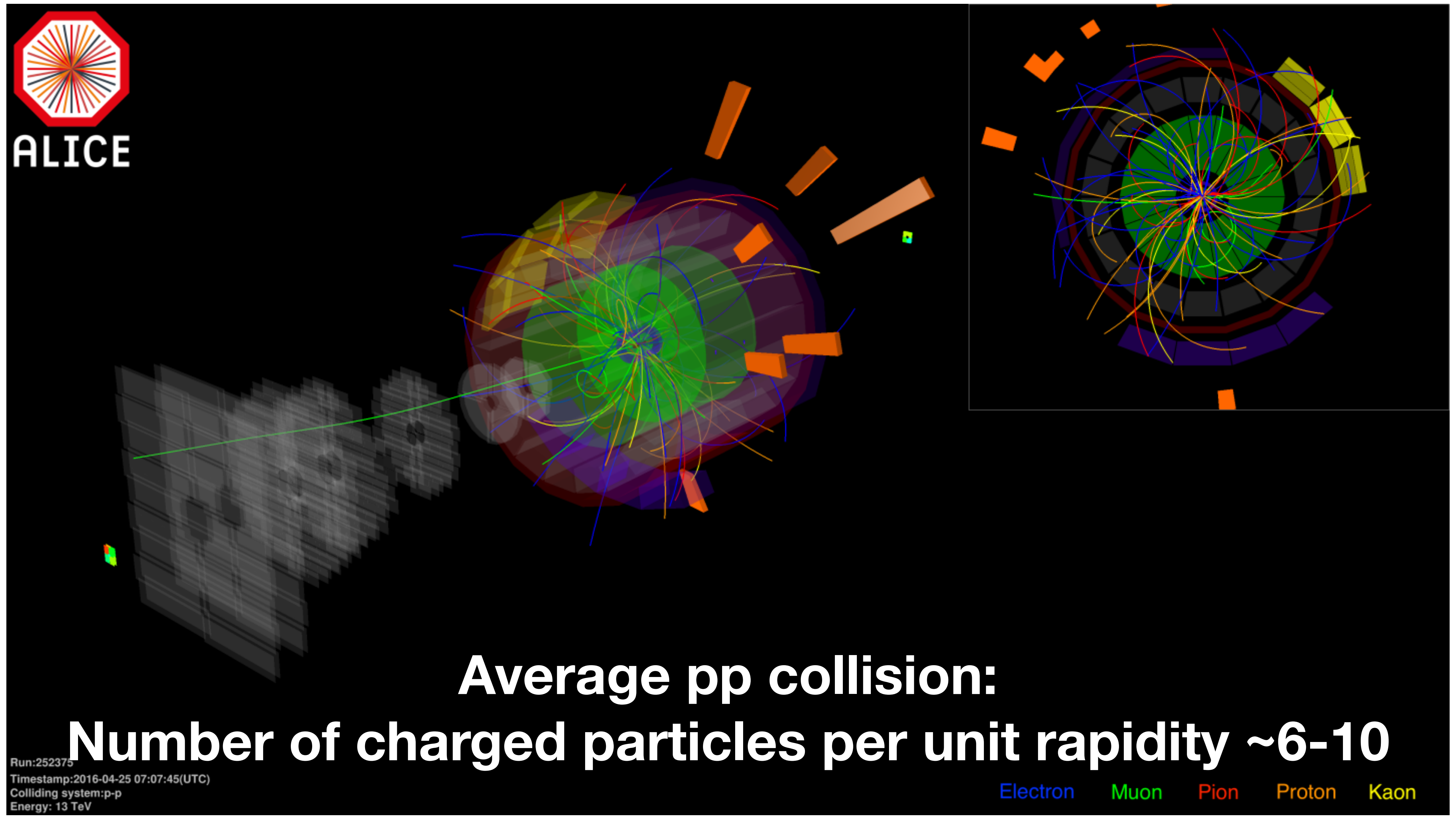
Response of medium to (out-of-equilibrium) jet probe - *wake effects*

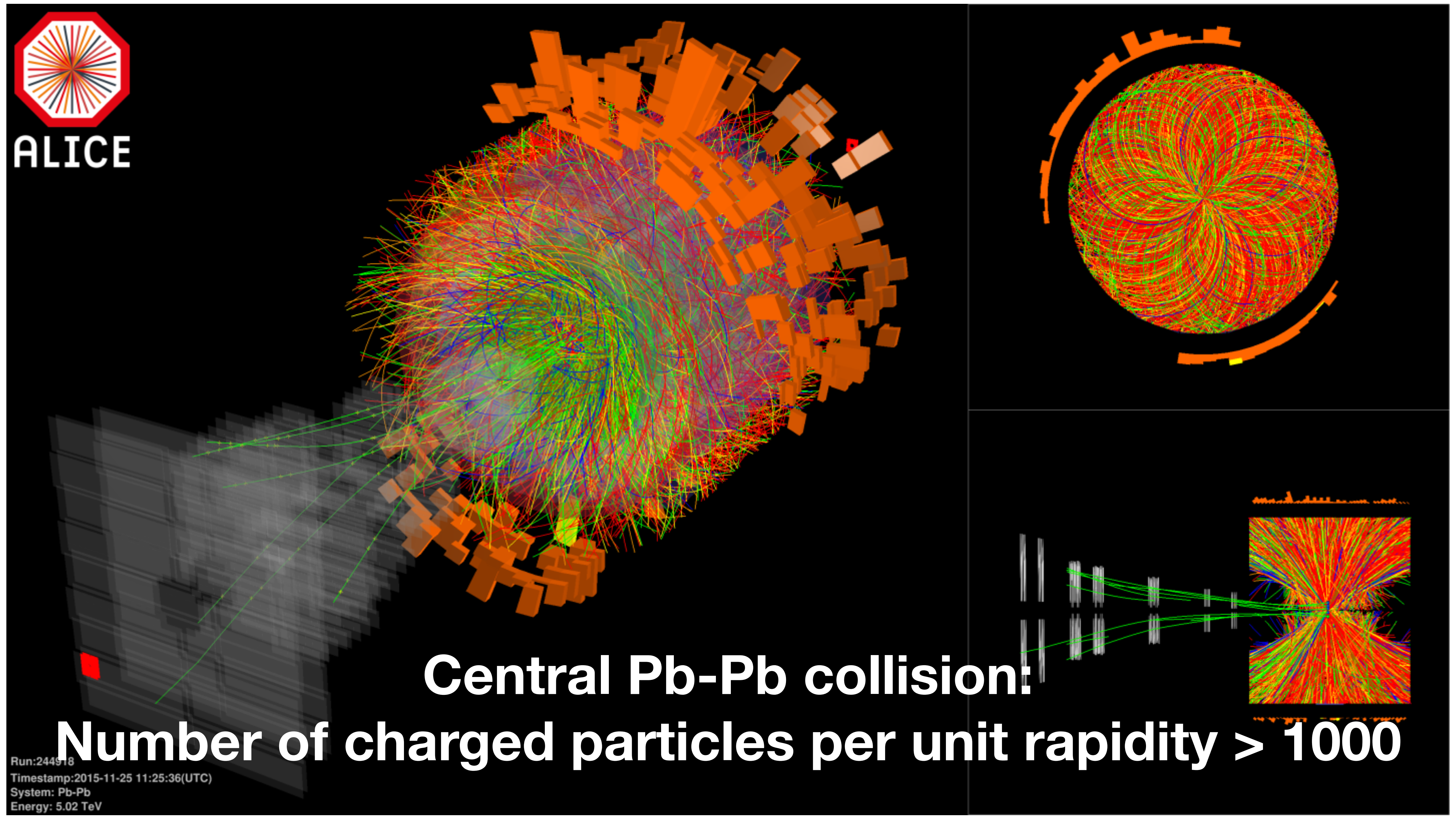
- Measure each effect to constrain QGP properties (such as transport properties, microscopic structure, equation of state…)



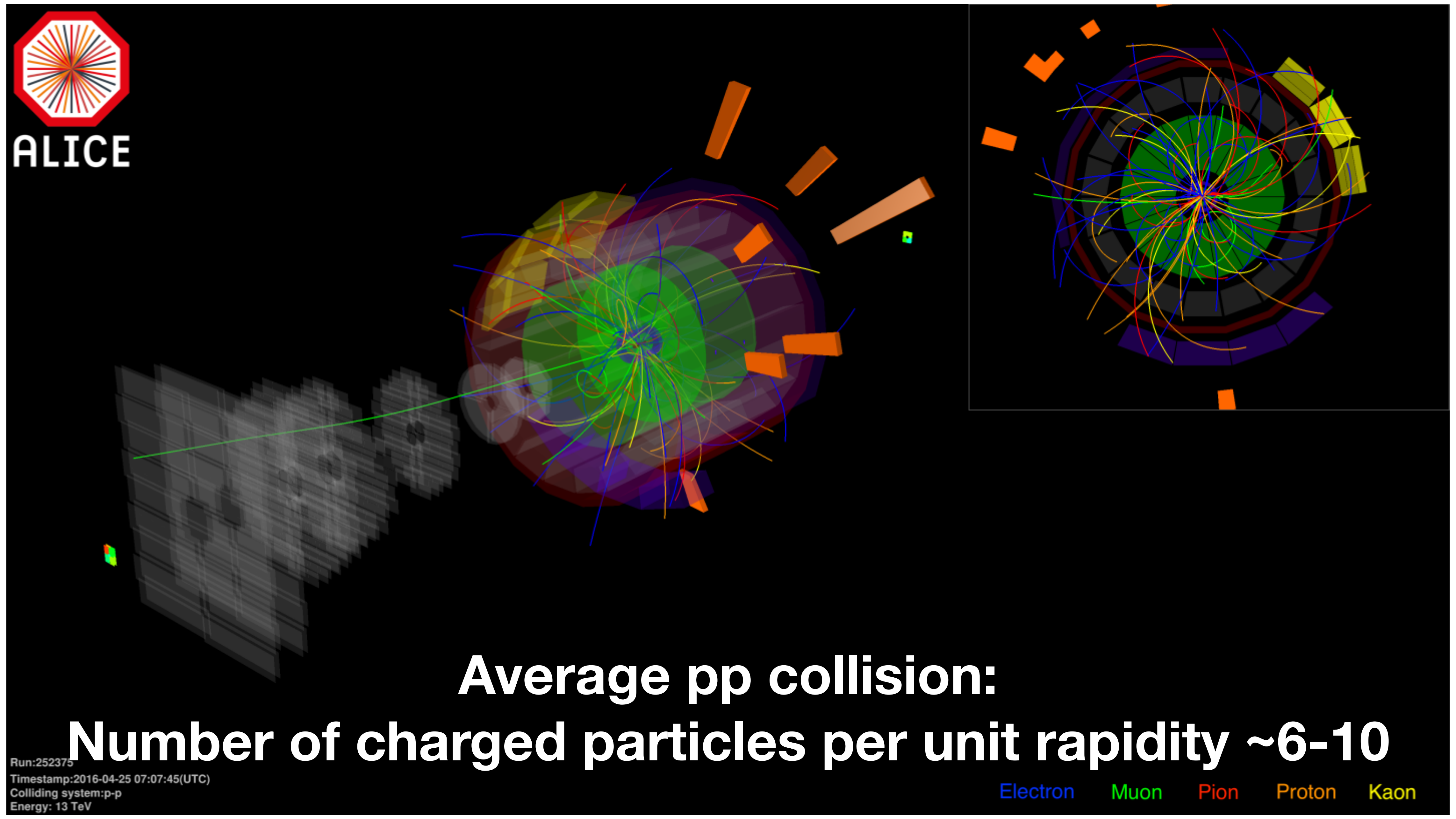
Aim - map out 'Bethe-Bloch curve' of QCD matter

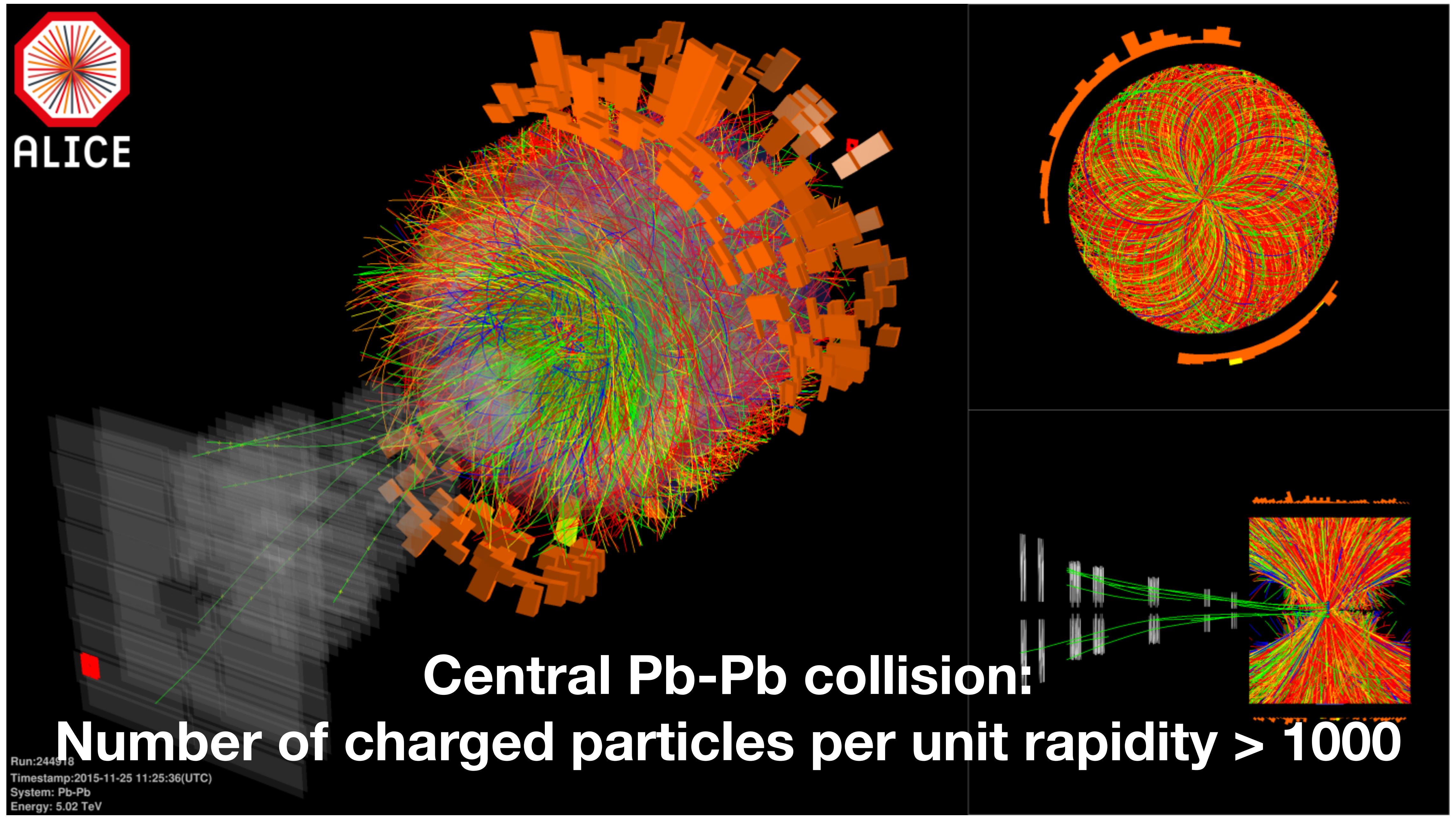
Dealing with background in heavy-ion collisions





Dealing with background in heavy-ion collisions





- **What is a ‘true’ jet from a hard scattering and what is from uncorrelated sources?**
- **What is the fraction of reconstructed jet energy from uncorrelated sources?**
  - **Especially important for low p_T measurements** where jet energy ~ background energy density
  - Larger-*R* jets include larger background fraction

Approaches to remove jet background component:

→ *Leading-track bias*

ALICE: Phys. Rev. C 101 (2020) 034911
Phys. Lett. B 746 (2015) 1

→ *Neural-network to reduce background fluctuations*

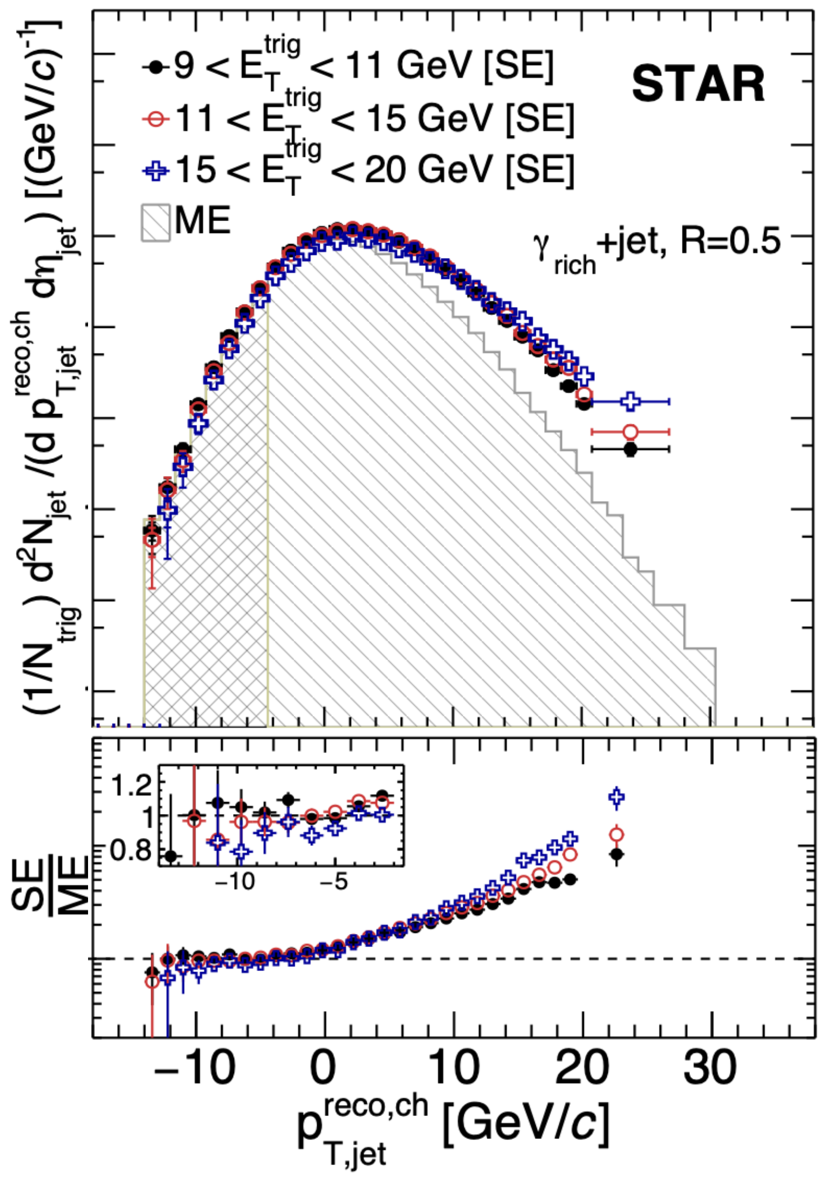
ALICE: Phys. Lett. B 849 (2024) 138412

This talk - ***statistical approach*** to measure jets at low p_T

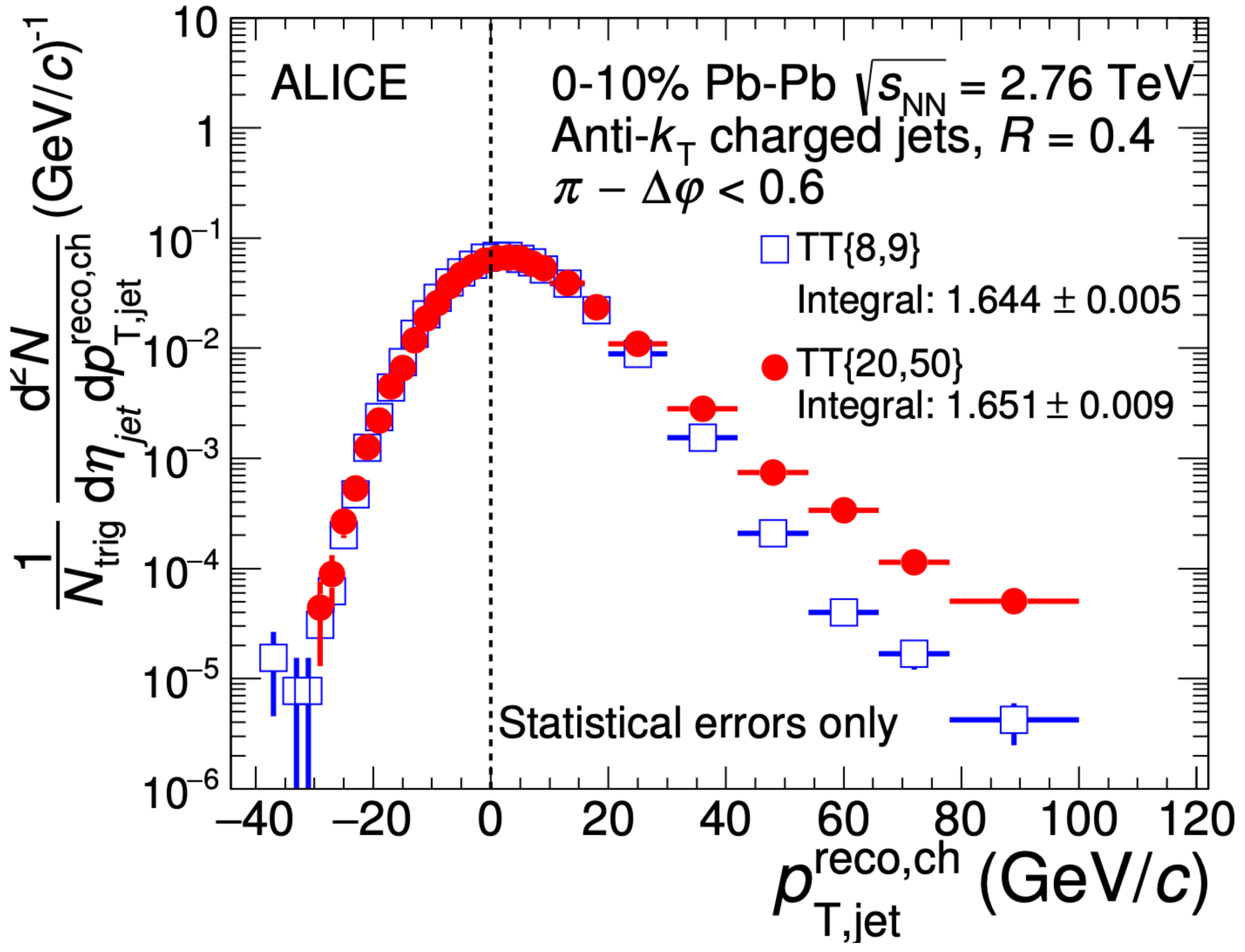
arXiv:2308.16128
arXiv:2308.16131

- **Correct for background at the level of *ensemble-averaged distributions***
  - Data-driven
  - No fragmentation bias
- Techniques developed at STAR and ALICE, now applied to LHC Run 2 data

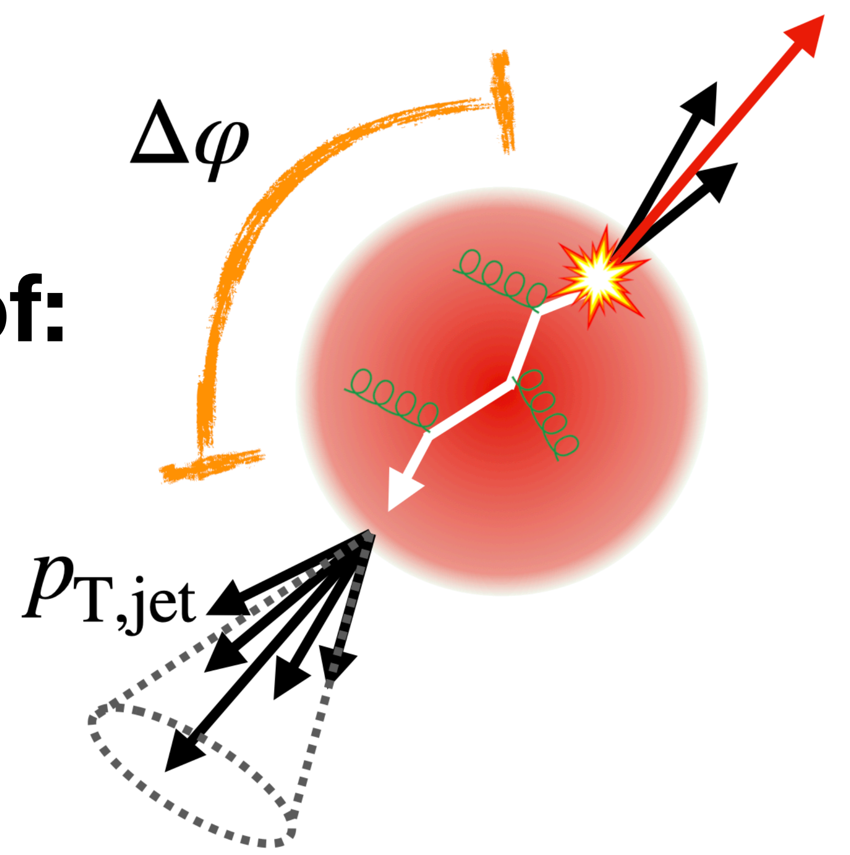
STAR: Phys. Rev. C 96, 024905 (2017)



ALICE: JHEP 09 (2015) 170



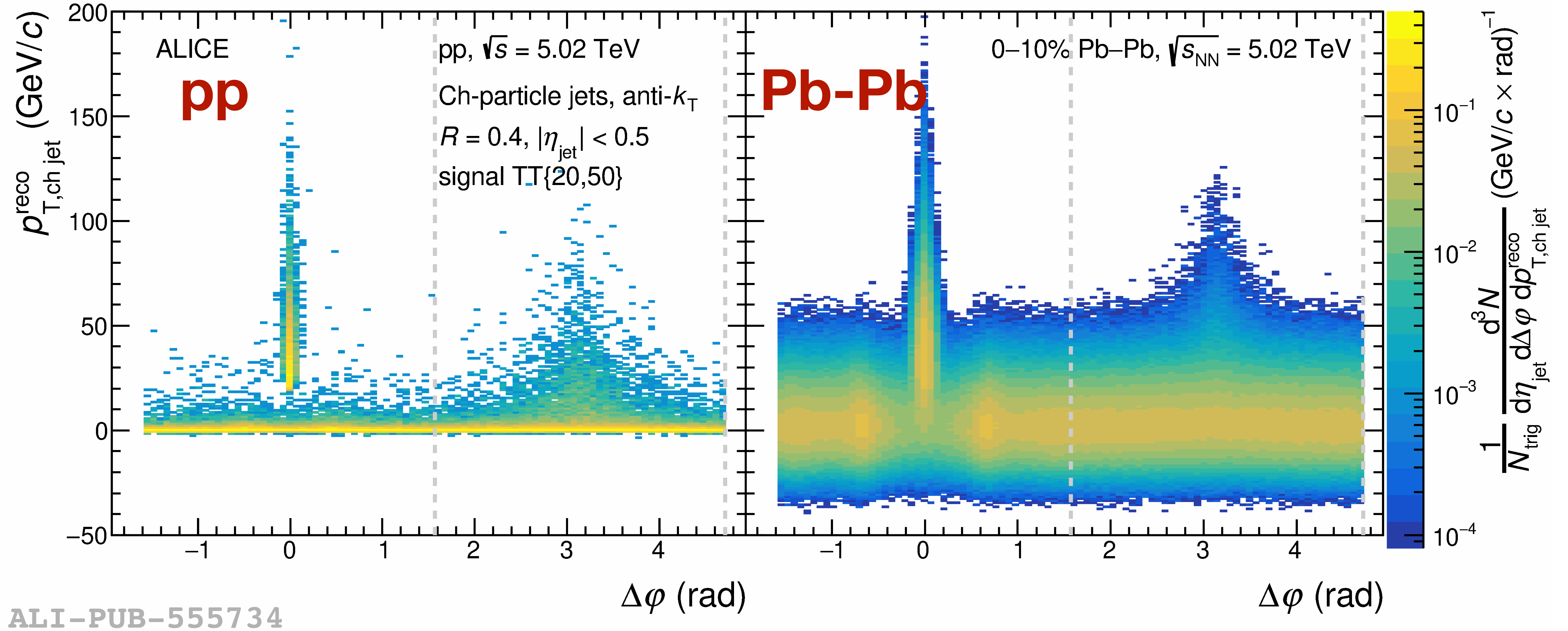
hadron+jet measurement in Pb-Pb collisions



- **Measure yield of charged jets recoiling from a high-p_T trigger hadron as function of:**
  a) opening angle ($\Delta\varphi$) of jet relative to trigger axis
  b) transverse momentum ($p_{T,jet}$) of recoil jet
- **Subtract uncorrelated background**: yield difference between two exclusive trigger track-classed distributions: **'signal'** and **'reference'**:

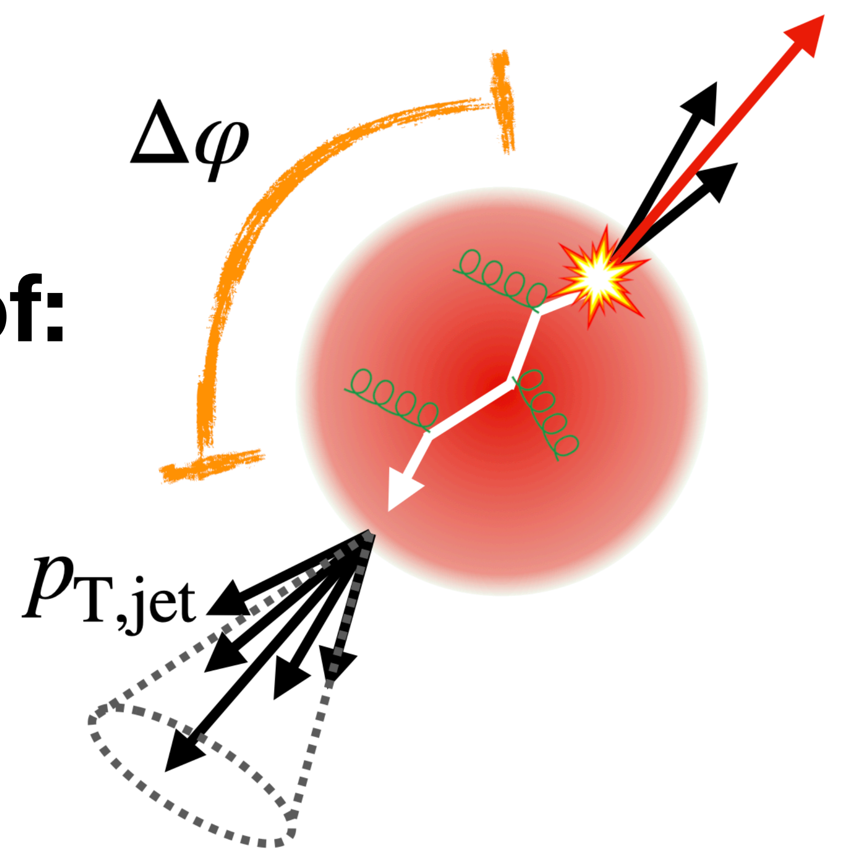
$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^3 N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta_{jet}} \Bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^3 N_{jet}^{AA}}{dp_{T,jet}^{ch} d\Delta\varphi d\eta_{jet}} \Bigg|_{p_{T,trig} \in TT_{Ref}}$$

c_{Ref}: normalisation constant extracted from data



TT_{sig}: 20 < $p_{T,trig}$ < 50 GeV/c
TT_{ref}: 5 < $p_{T,trig}$ < 7 GeV/c

hadron+jet measurement in Pb-Pb collisions

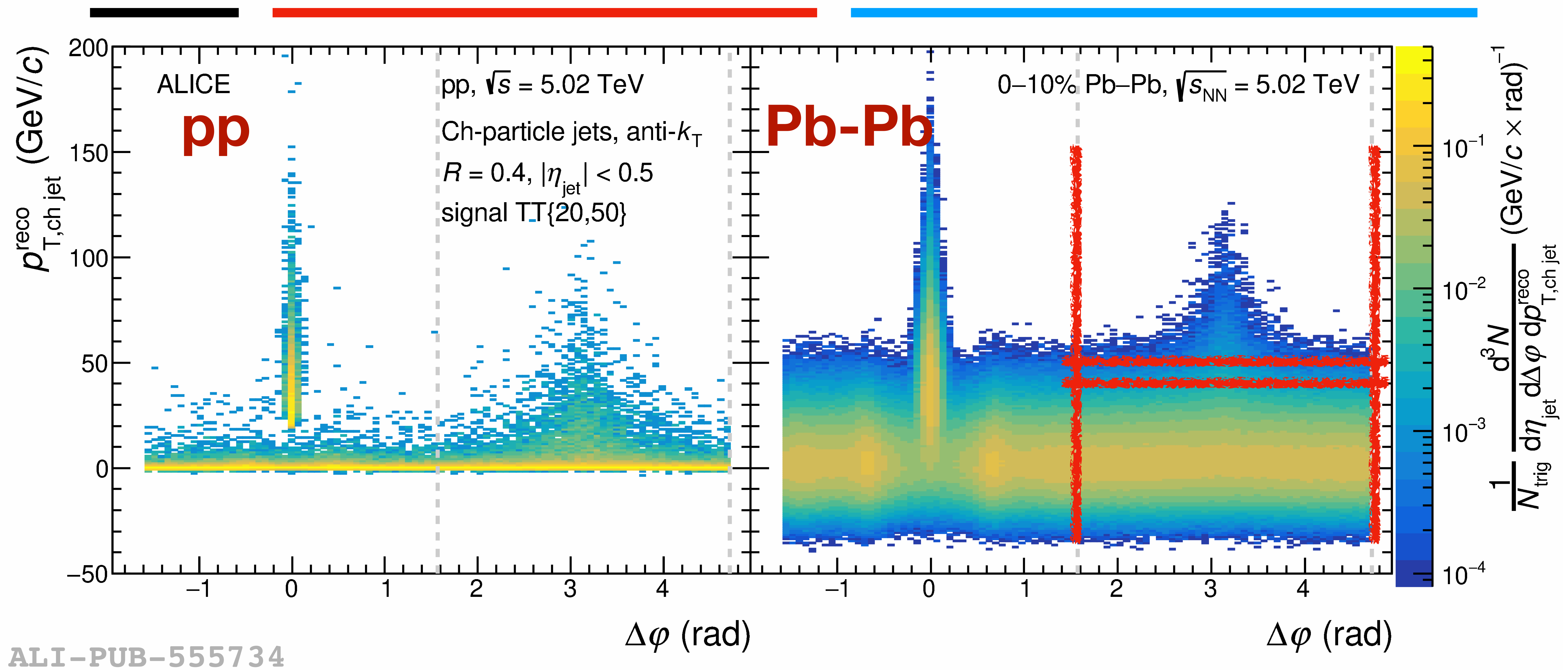


- **Measure yield of charged jets recoiling from a high-p_{T} trigger hadron as function of:**
  a) opening angle ($\Delta\varphi$) of jet relative to trigger axis
  b) transverse momentum ($p_{\mathrm{T,jet}}$) of recoil jet

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

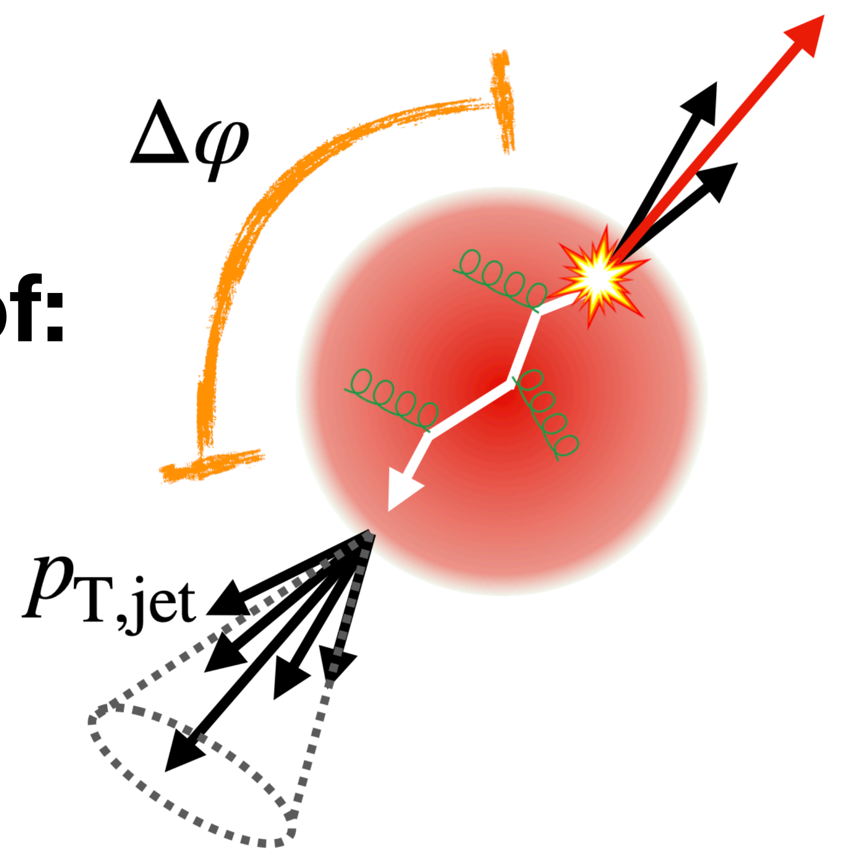
$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^3 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}}\,\mathrm{d}\Delta\varphi\,\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT_{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}}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

c_{Ref}: normalisation constant extracted from data



$\mathrm{TT_{sig}}$: 20 < $p_{\mathrm{T,trig}}$ < 50 GeV/c
$\mathrm{TT_{ref}}$: 5 < $p_{\mathrm{T,trig}}$ < 7 GeV/c

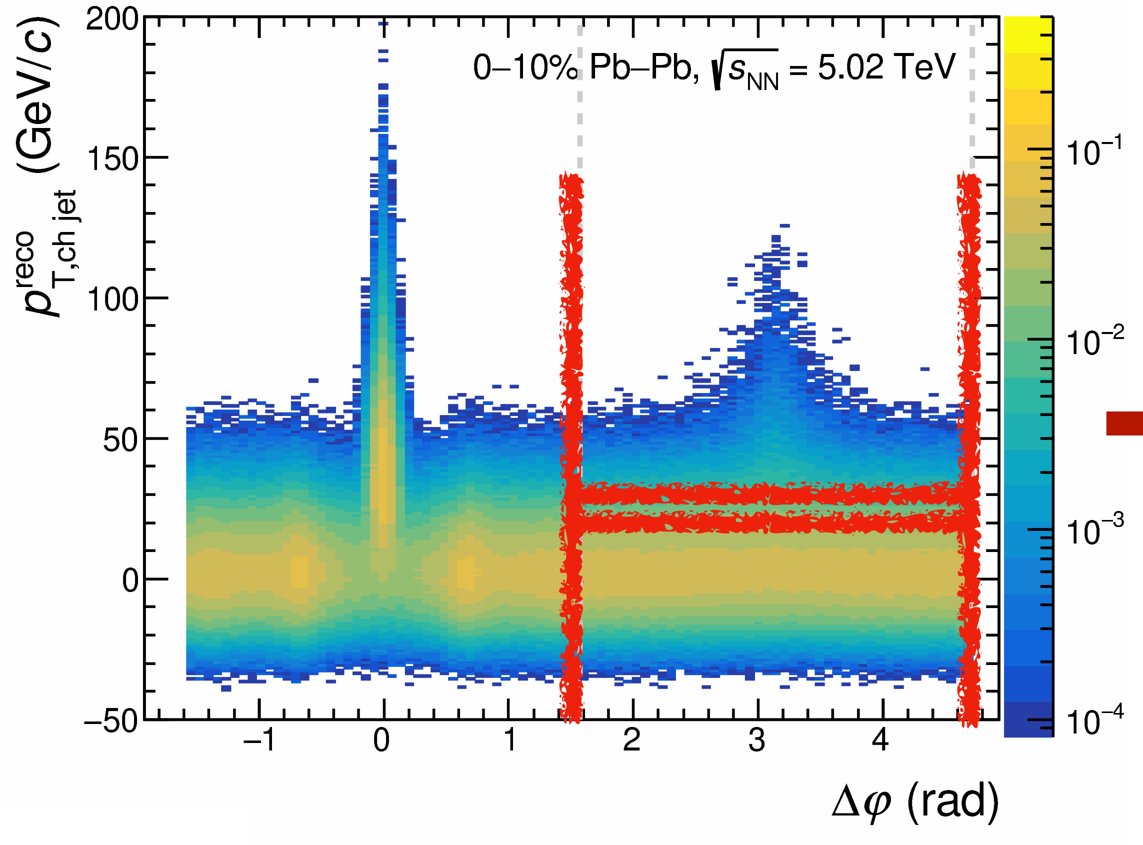
hadron+jet measurement in Pb-Pb collisions

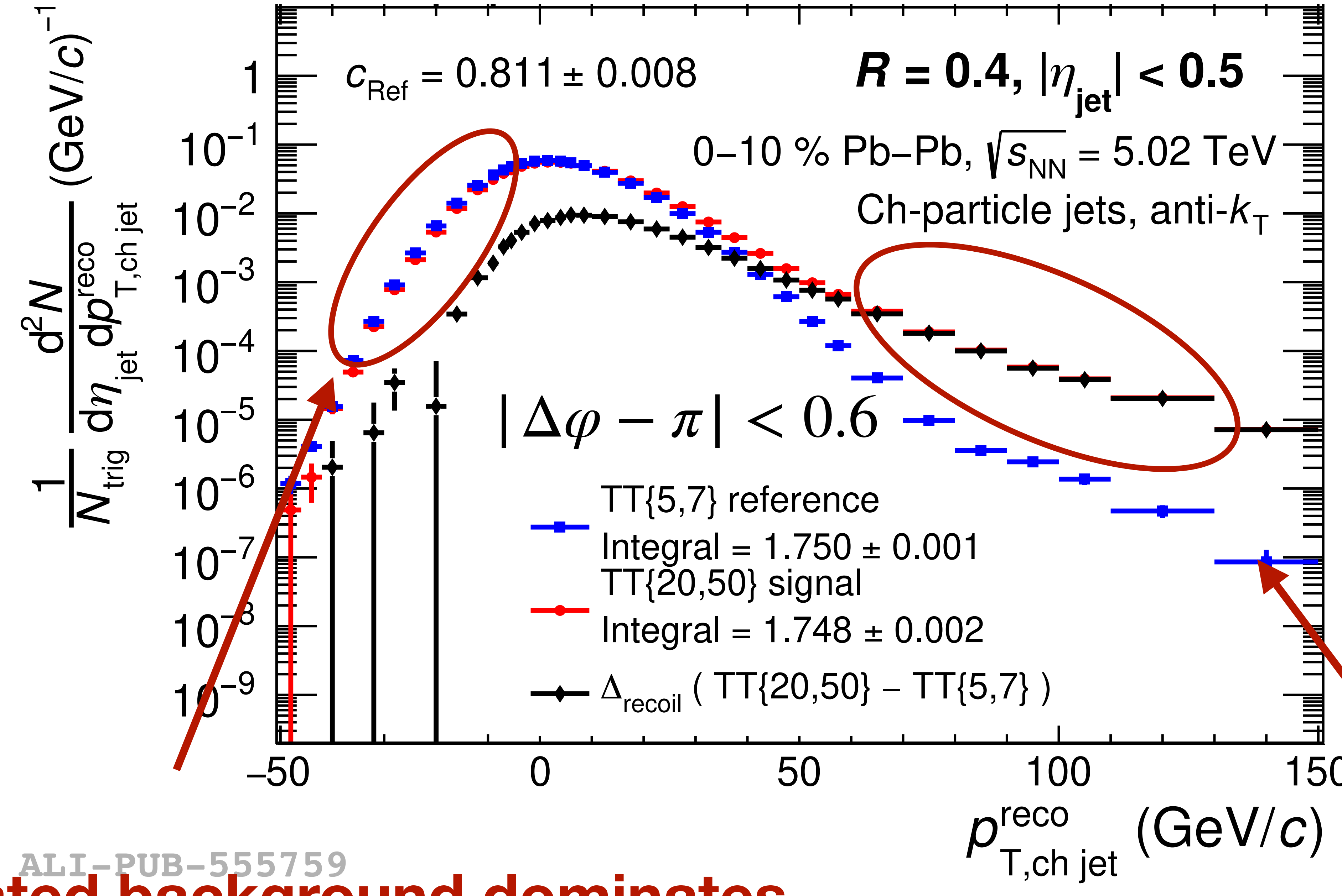


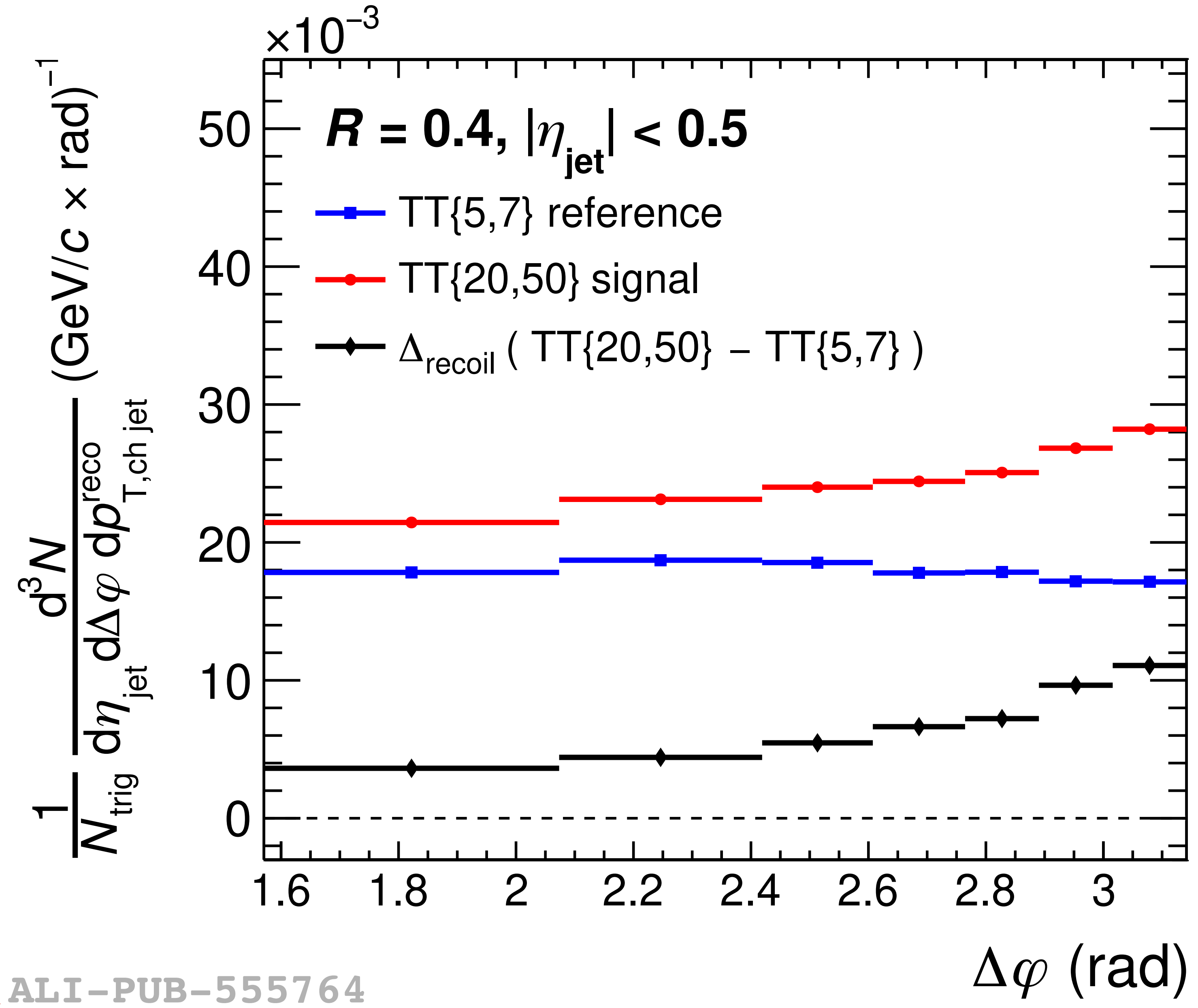
- **Measure yield of charged jets recoiling from a high-p_{T} trigger hadron as function of:**
  a) opening angle ($\Delta\varphi$) of jet relative to trigger axis
  b) transverse momentum ($p_{\mathrm{T,jet}}$) of recoil jet
- **Subtract uncorrelated background**: yield difference between two exclusive 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



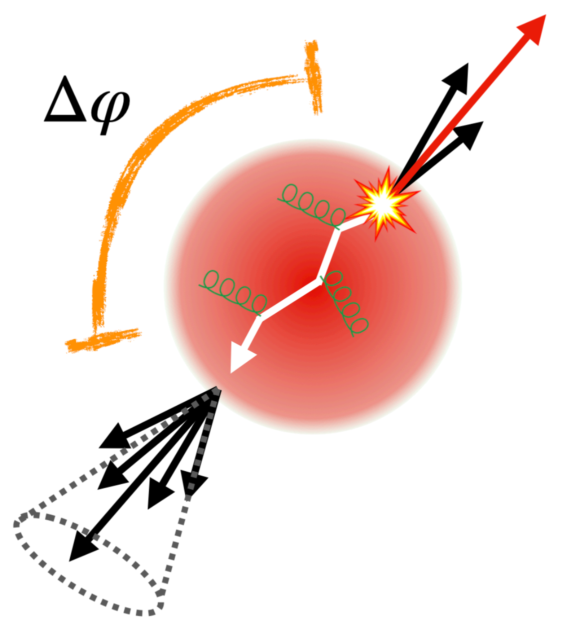




Uncorrelated background dominates

Signal jets dominate

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

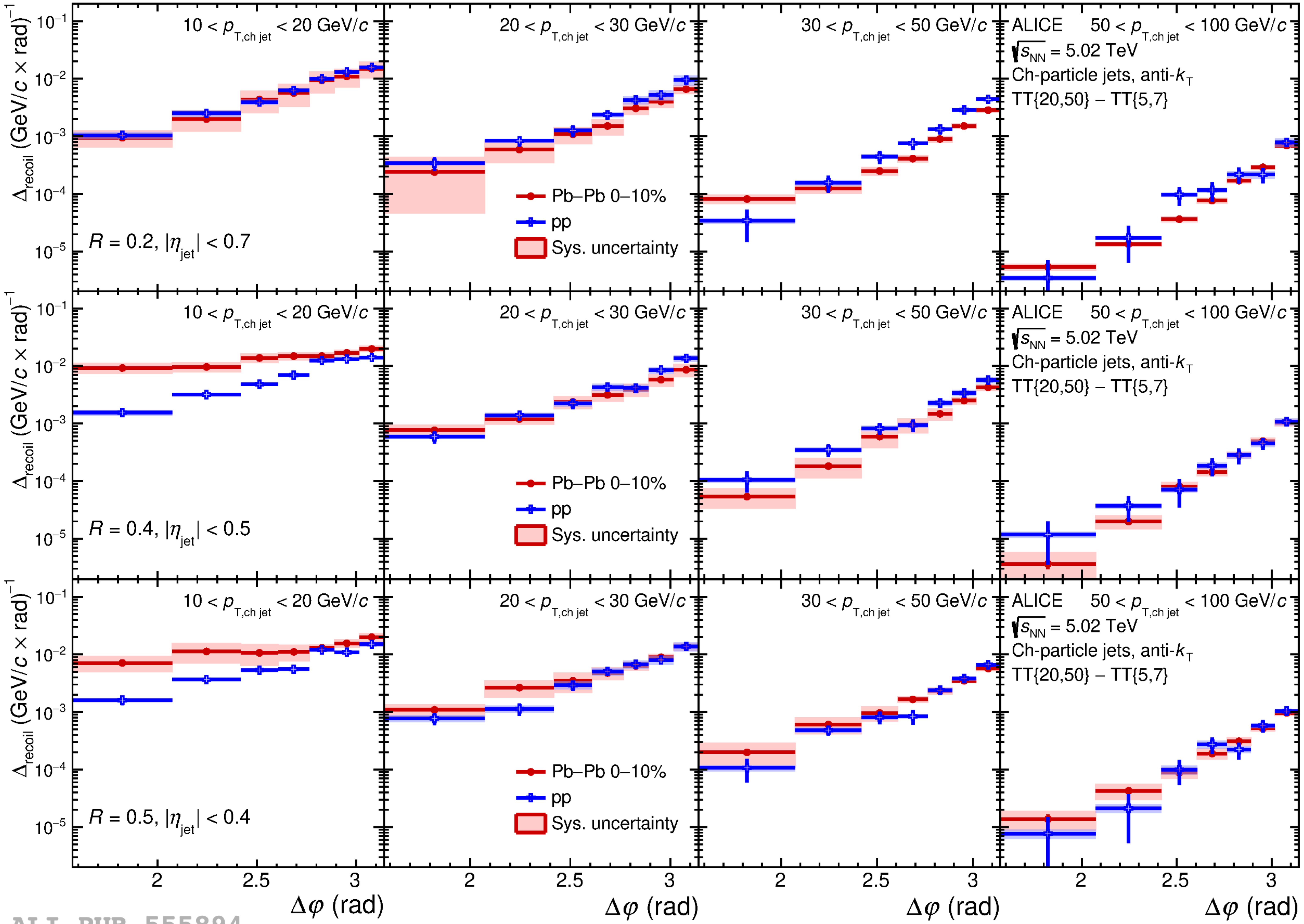


$p_{\mathrm{T,chjet}}$: [10,20] GeV/*c* [20,30] GeV/*c* [30,50] GeV/*c* [50,100] GeV/*c*

***R*=0.2**

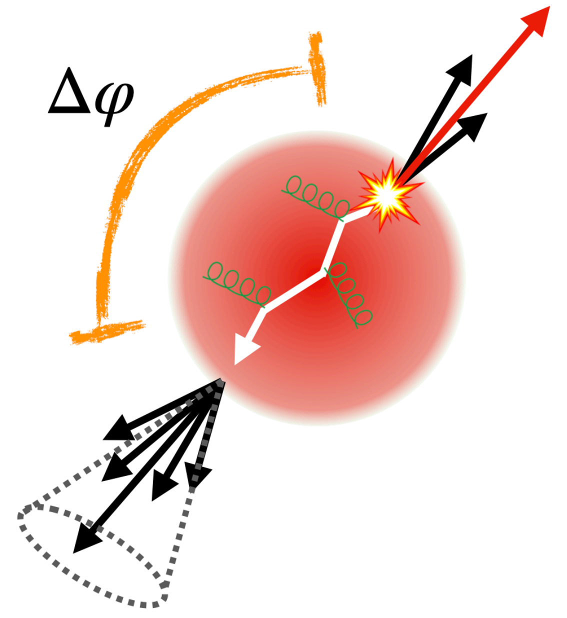
***R*=0.4**

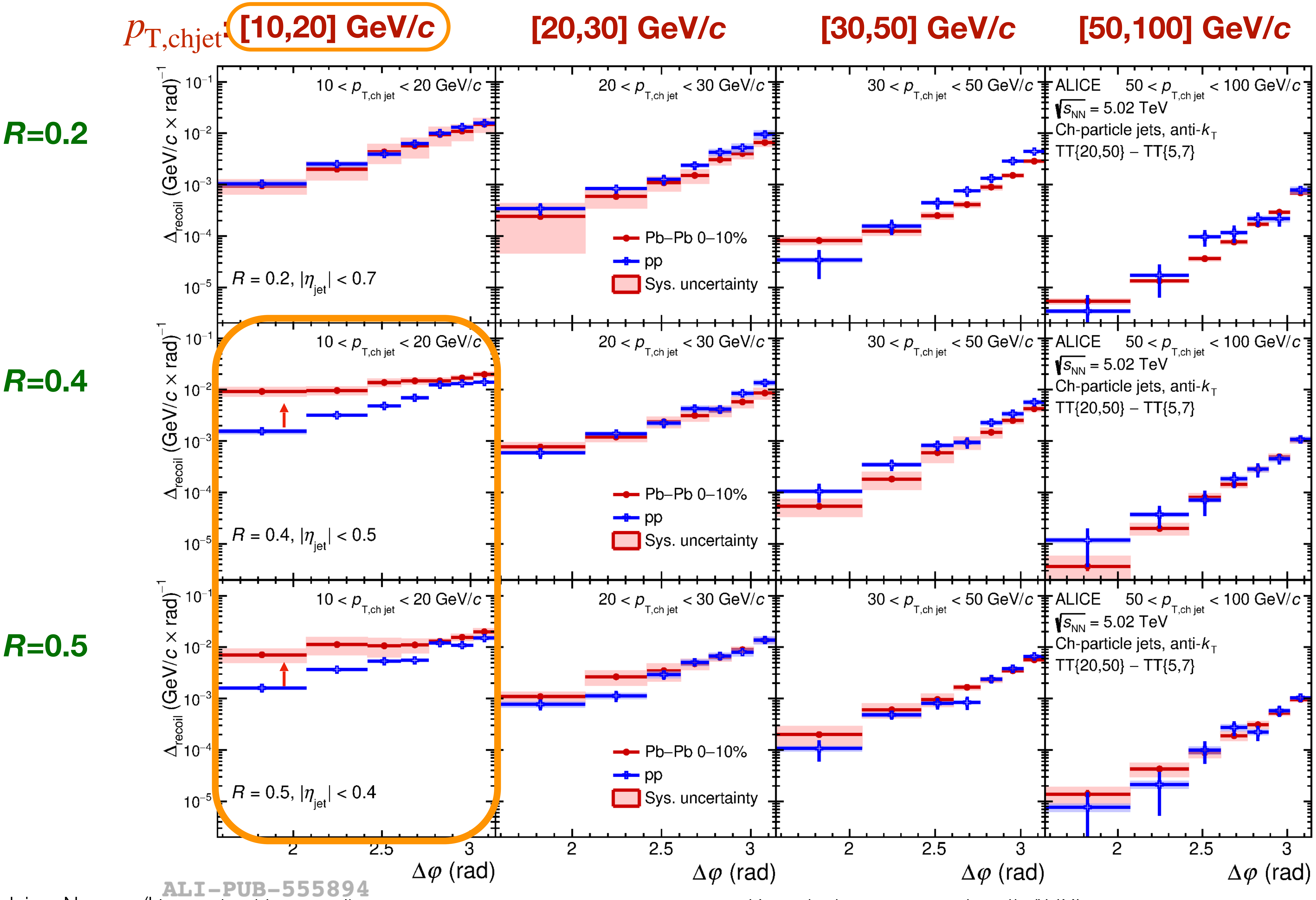
***R*=0.5**



ALI-PUB-555894

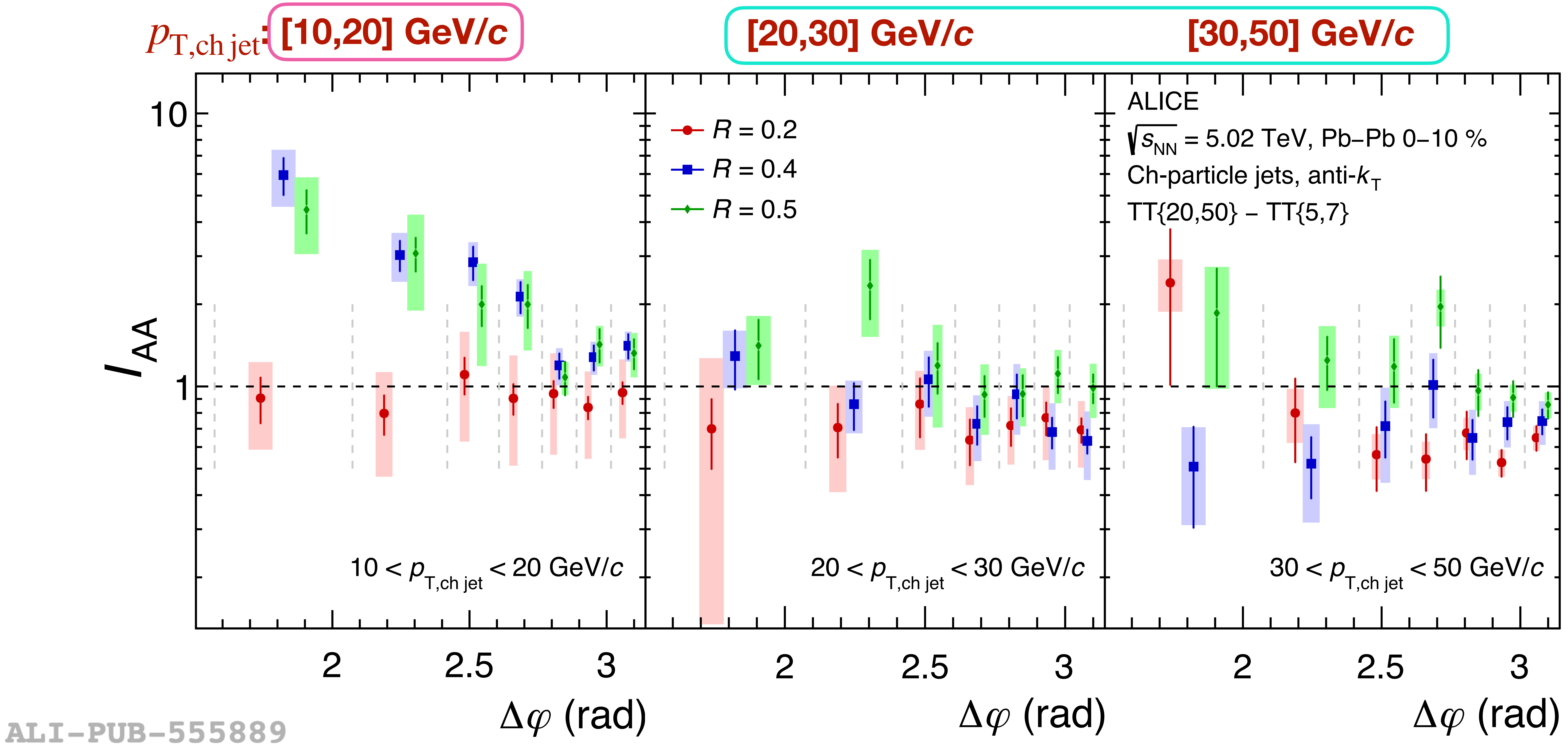
Results - $\Delta_{recoil}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

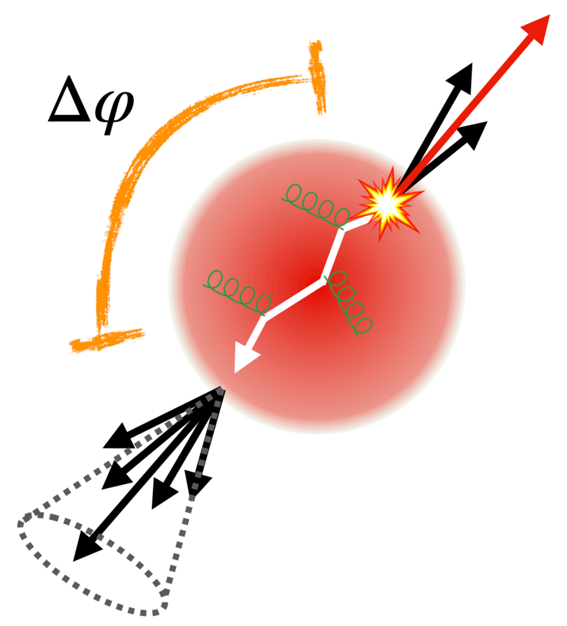




- Jets measured down to 10 GeV/c - lowest p_T measurement to date
- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{T,chjet}$

Results - recoil jet azimuthal broadening



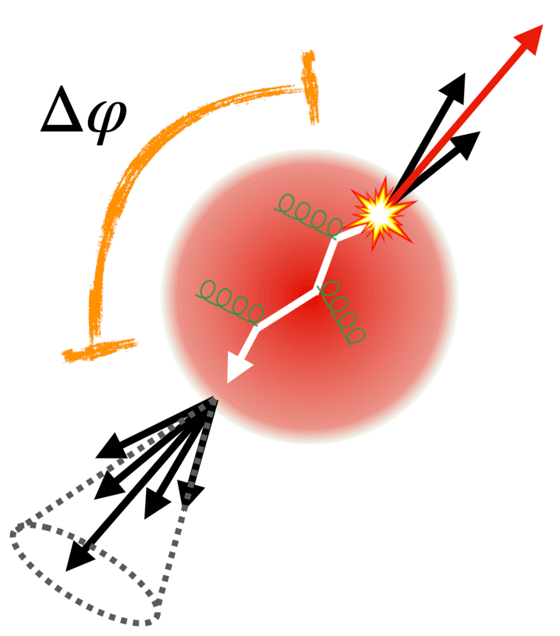


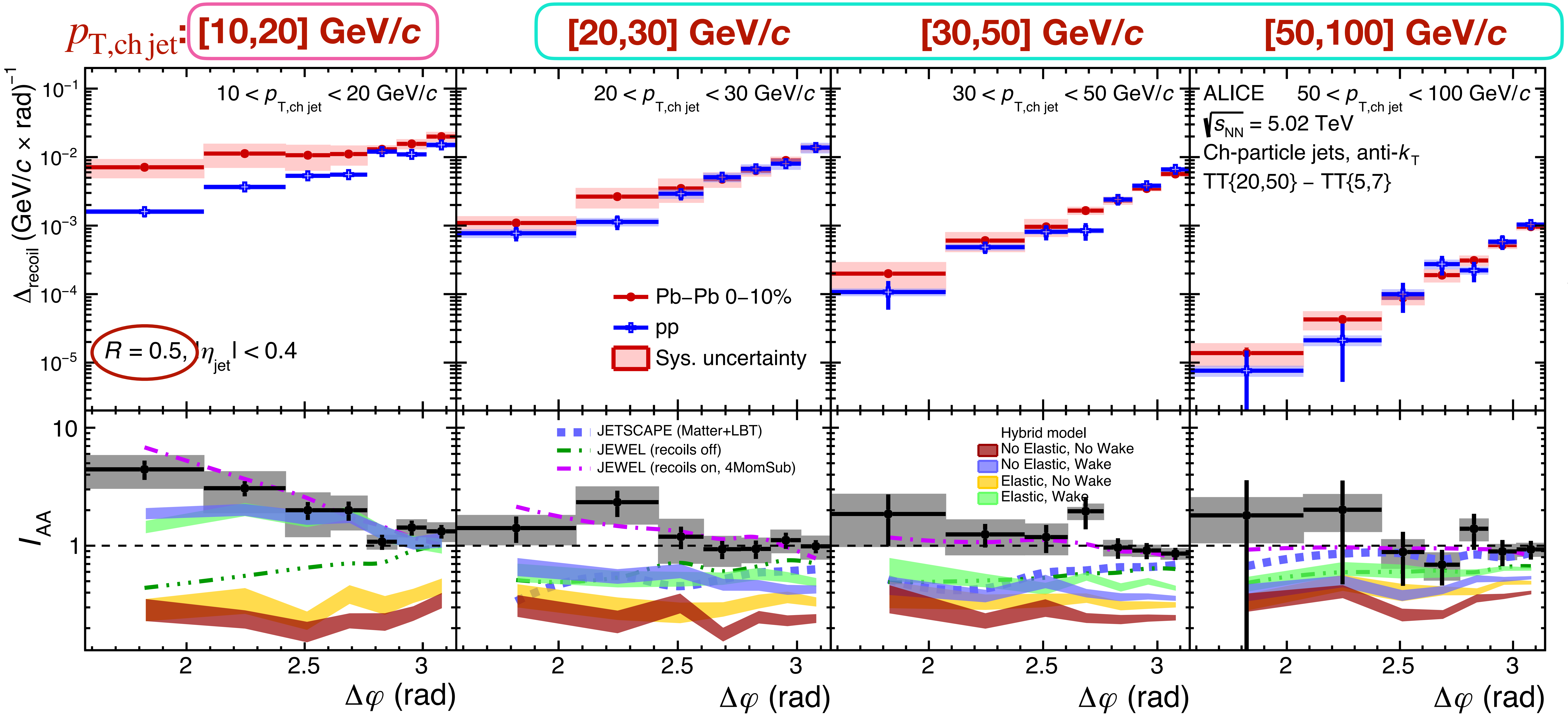
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

- **Transition to broadening from *R*=0.2 -> *R*=0.4 for [10,20] GeV/c** **(4.7σ deviation of I_{AA} from flat for *R*=0.4)**
  - Large-angle 'elastic' scattering - *R*-dependence not expected
  - Soft radiation mimicking a jet may scale with R^2

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

Results - recoil jet azimuthal broadening





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

- Broadening captured IF medium response effects switched on (**Hybrid model**, **JEWEL**)
- Negligible broadening if elastic scattering switched on (**Hybrid model**)

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

JEWEL: K. Zapp, Eur.Phys.J. C74 (2014) 2762
R. Kunnawalkam-Elayavalli, K. Zapp, arXiv:1707.01539
JETSCAPE: arXiv:1903.07706

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

Summary and outlook

- **ALICE developing and applying pioneering techniques to make measurements of jets in large background environment!**
  - New measurements of jets at low p_{T} - significant constraints to models / jet-medium interactions
  - First measurement of azimuthal broadening - access jet-medium 'wake' to characterise QGP

arXiv:2308.16128
arXiv:2308.16131

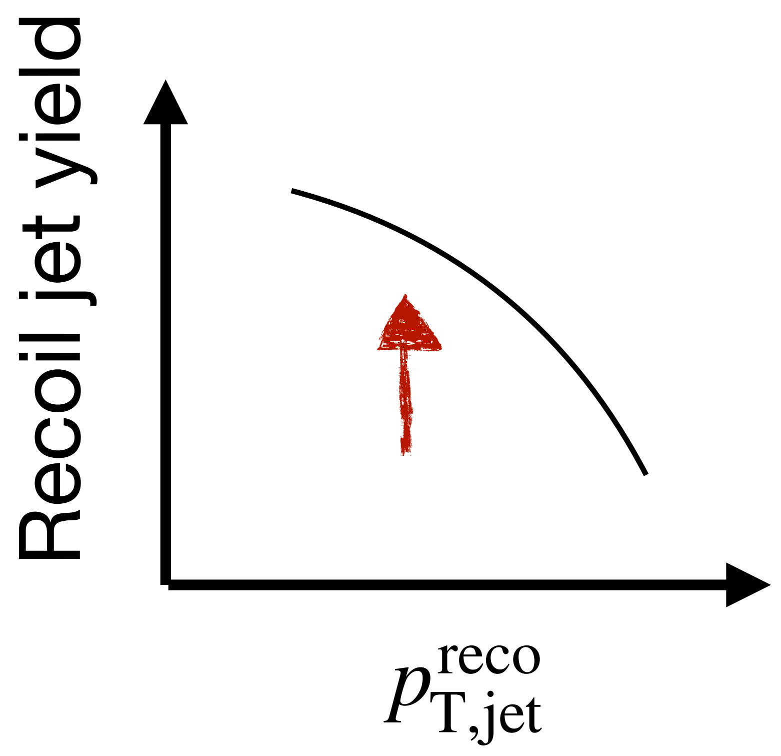
  - Other background-subtraction techniques - see details and results from mixed event procedure here or here
- **Busy analysing LHC Run 3 data after significant ALICE upgrade programme and Pb-Pb run last year**

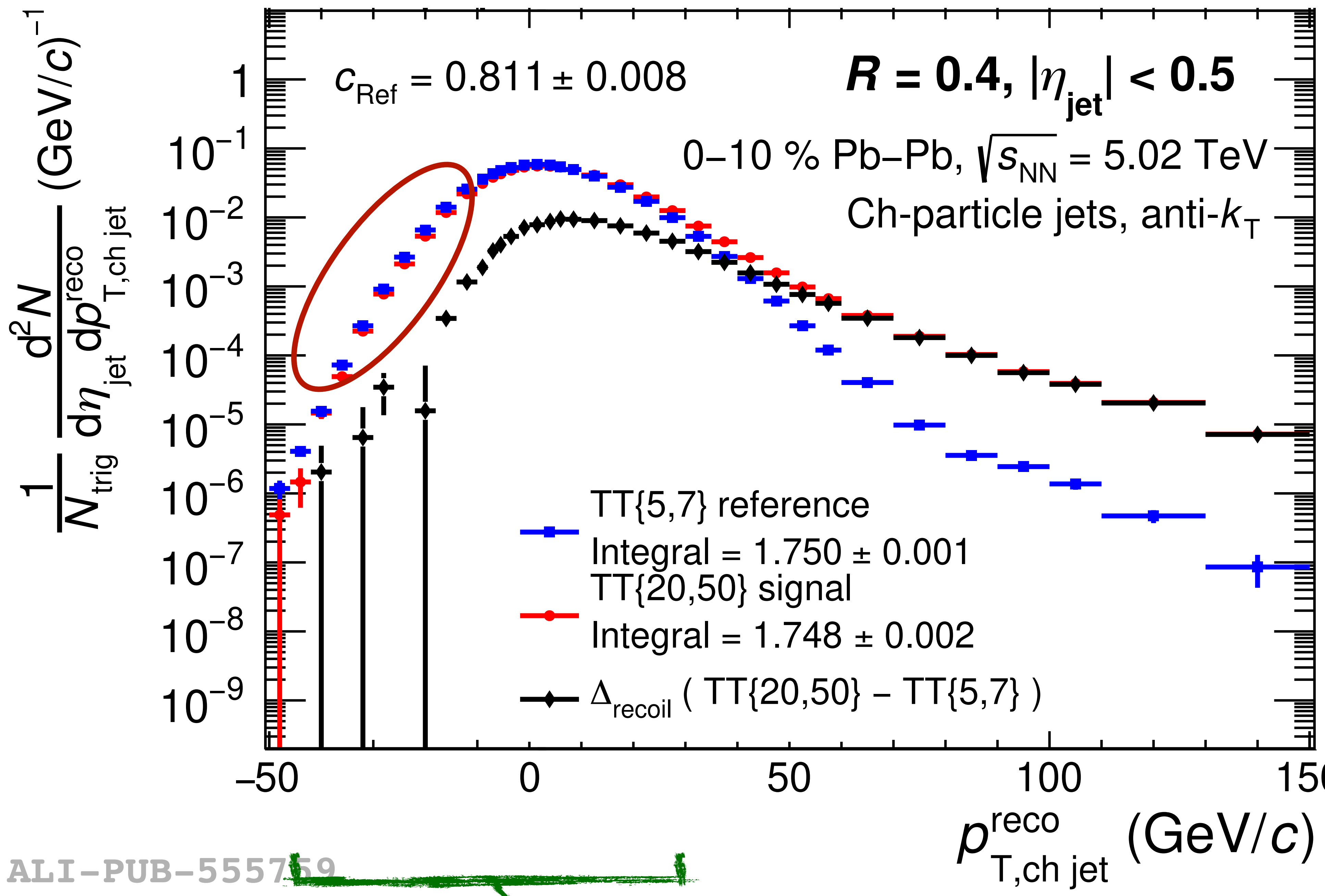
Backup

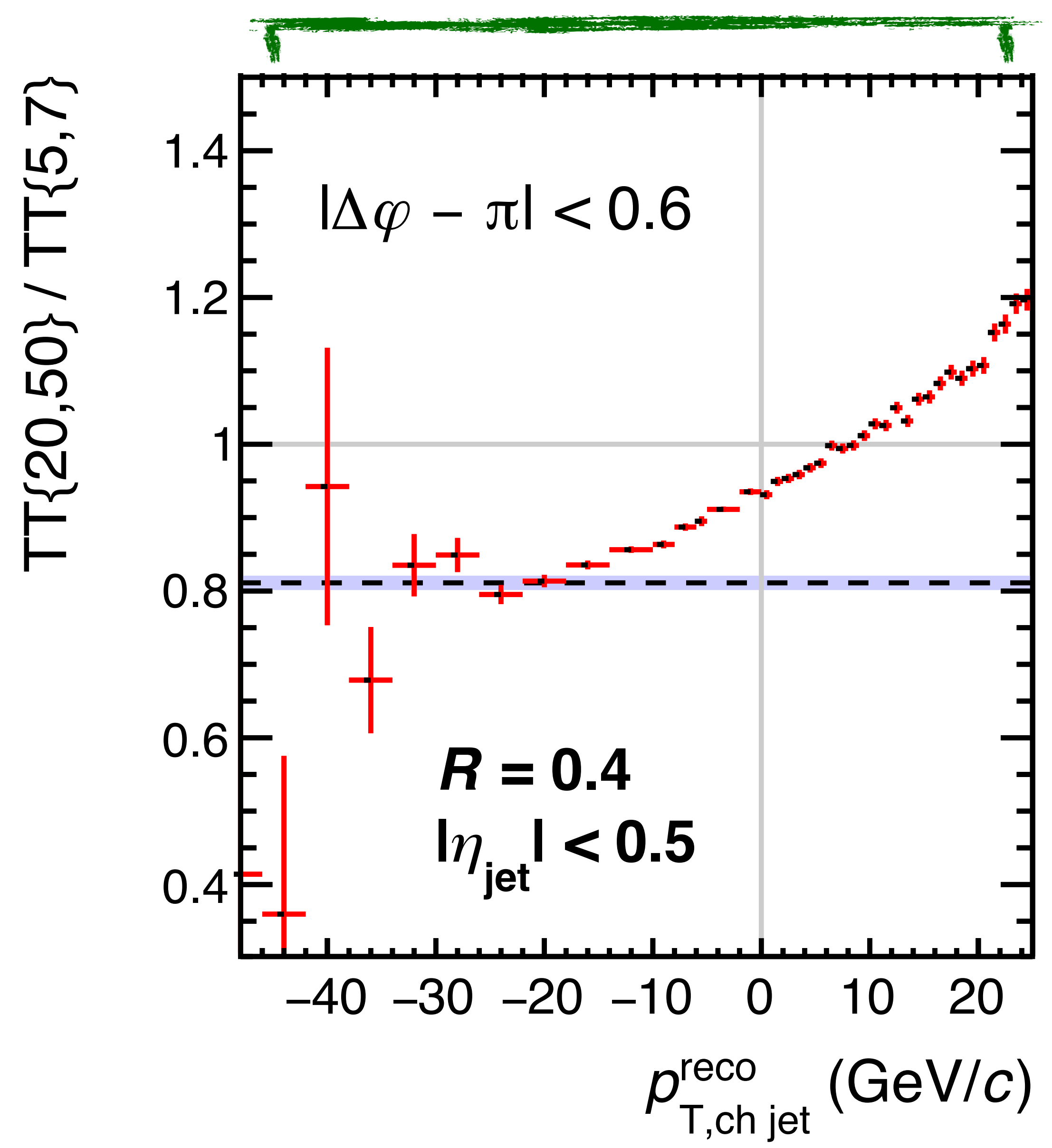
Δ_{recoil} 'reference' calibration

Calibration of reference distribution required for precise background subtraction:

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







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

- 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

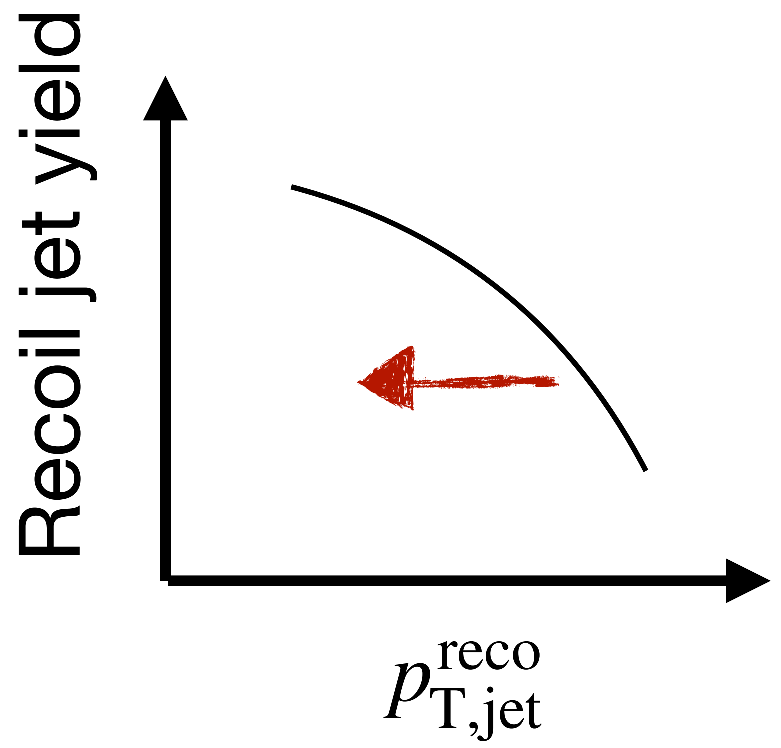
Established technique

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*’)

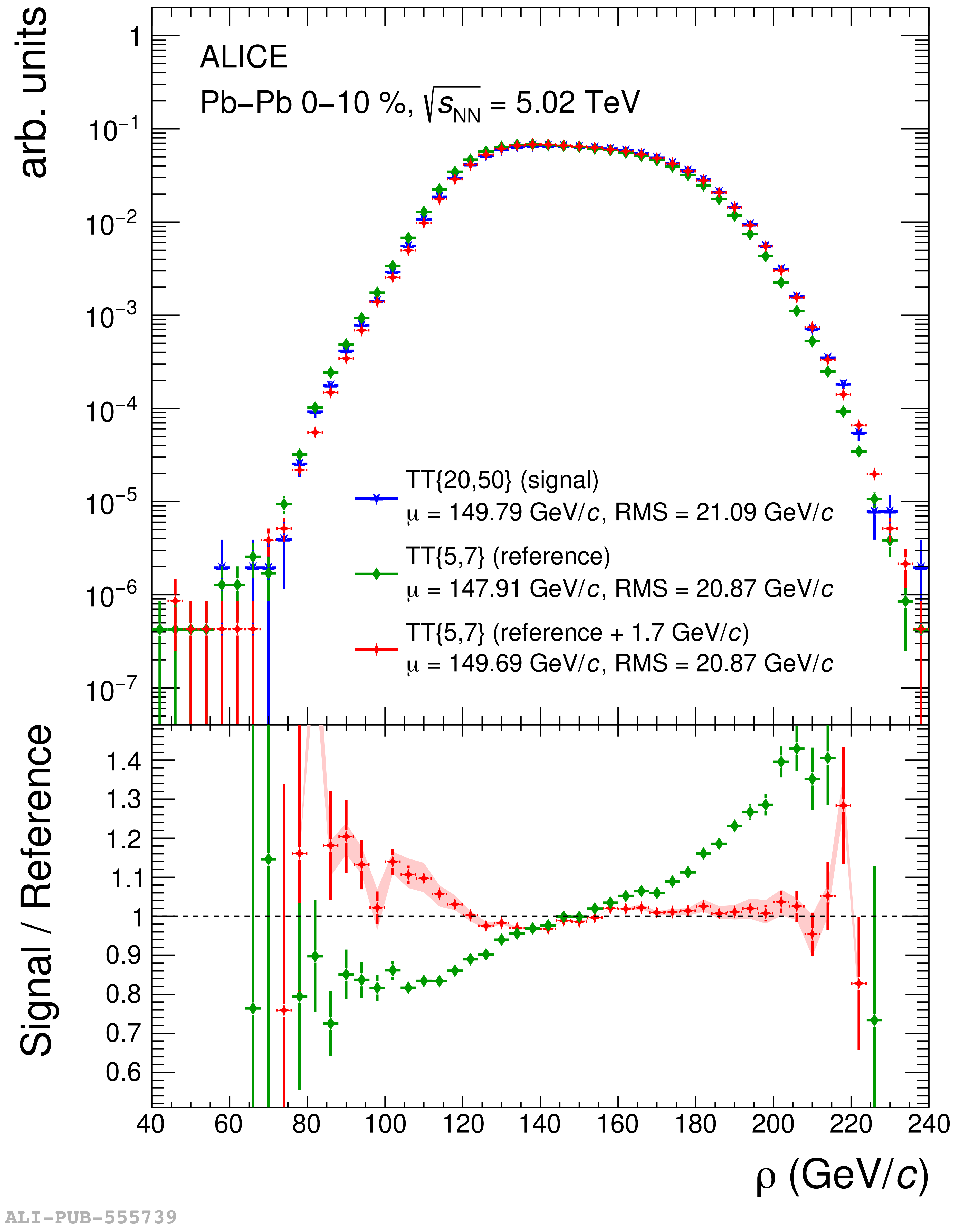


$$p_{\mathrm{T,jet}}^{\mathrm{reco}} = p_{\mathrm{T,jet}}^{\mathrm{raw}} - A \cdot \rho$$

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

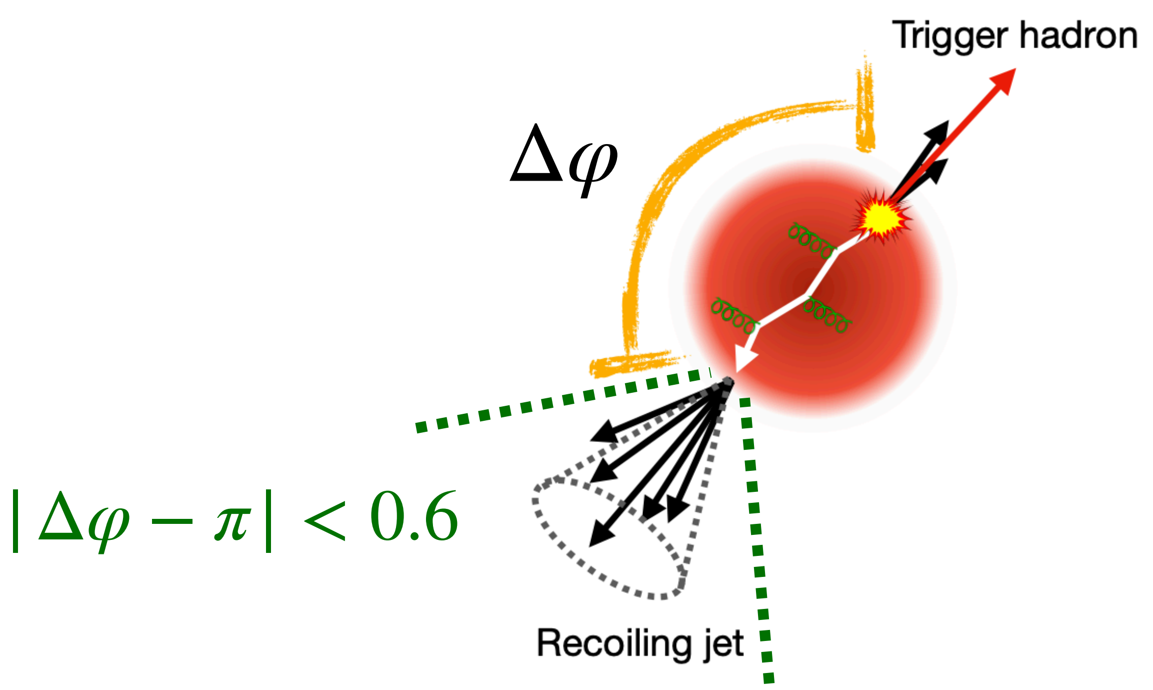
Established technique

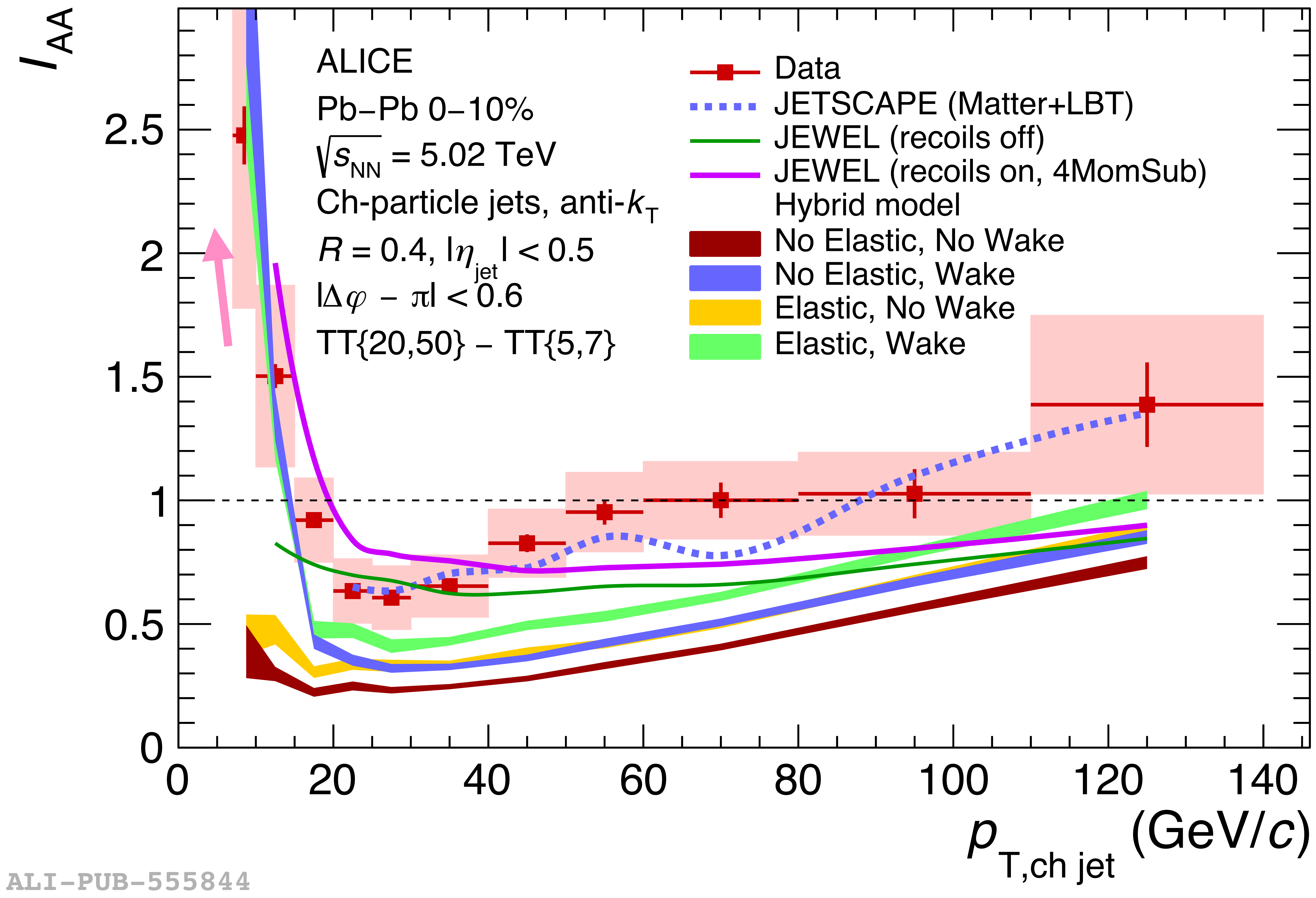
STAR: Phys. Rev. C 96, 024905 (2017)



Results - recoil jet $I_{AA}(p_{T,\mathrm{ch\,jet}})$

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

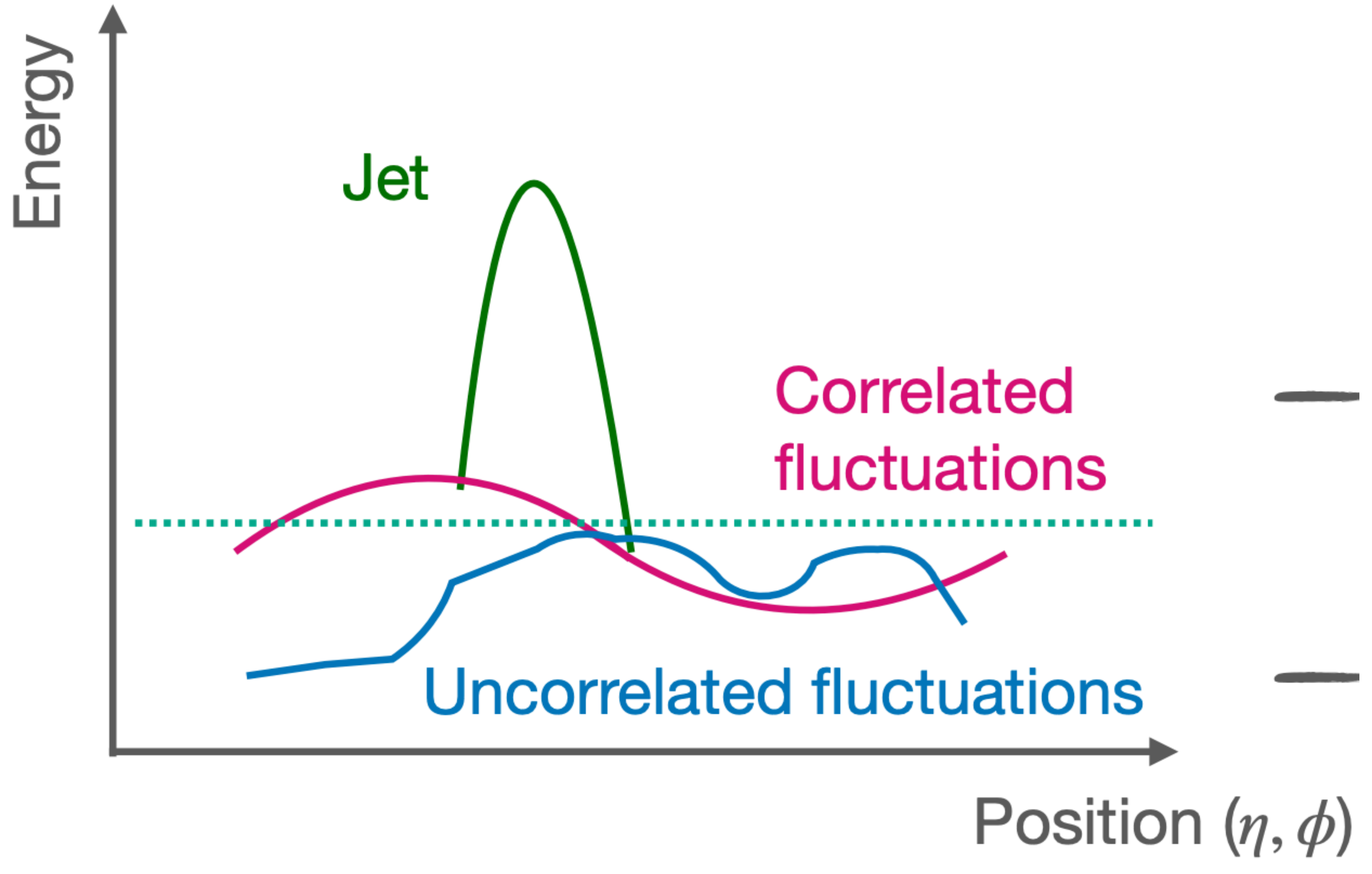




- **Suppression** at $20 < p_{T,\mathrm{ch\,jet}} < 80$ GeV/c
  → jet energy loss
- **Rising trend with $p_{T,\mathrm{ch\,jet}}$**
  → interplay between hadron and jet energy loss?
  Larger energy loss of trigger when $p_{T,\mathrm{jet}} >> p_{T,\mathrm{trig}}$
- **Rise at low $p_{T,\mathrm{ch\,jet}}$**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

Neural-network-based background estimator

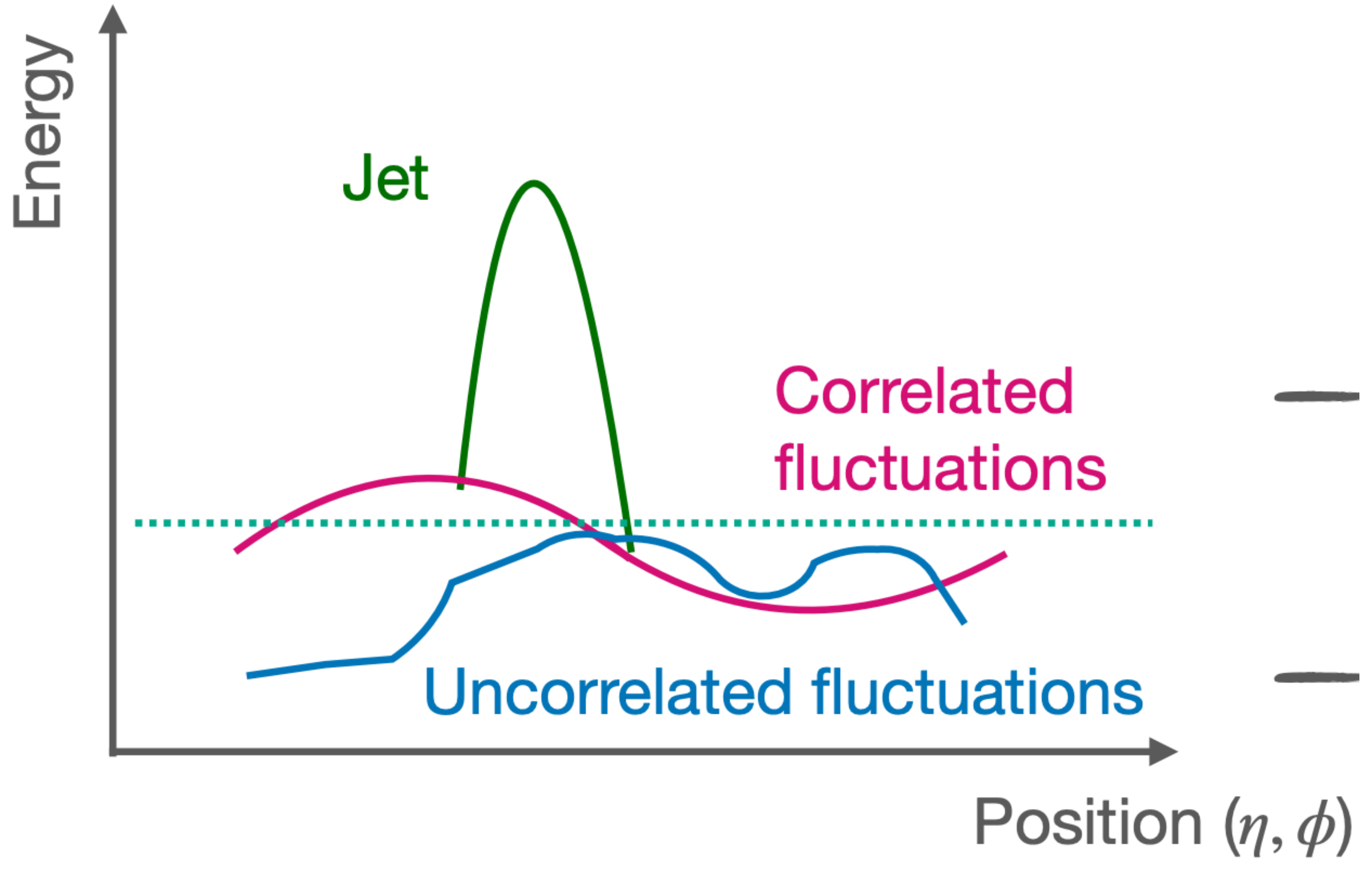
- Usual method - **area-based** pedestal subtraction of the event-averaged momentum density ρ
  - Per-event background fluctuations limits the precision with which we can determine ρ in jet acceptance
  - Unfold residual background fluctuations
    - Residual fluctuations increase with increasing R



Can method to estimate ρ be improved?

Neural-network-based background estimator

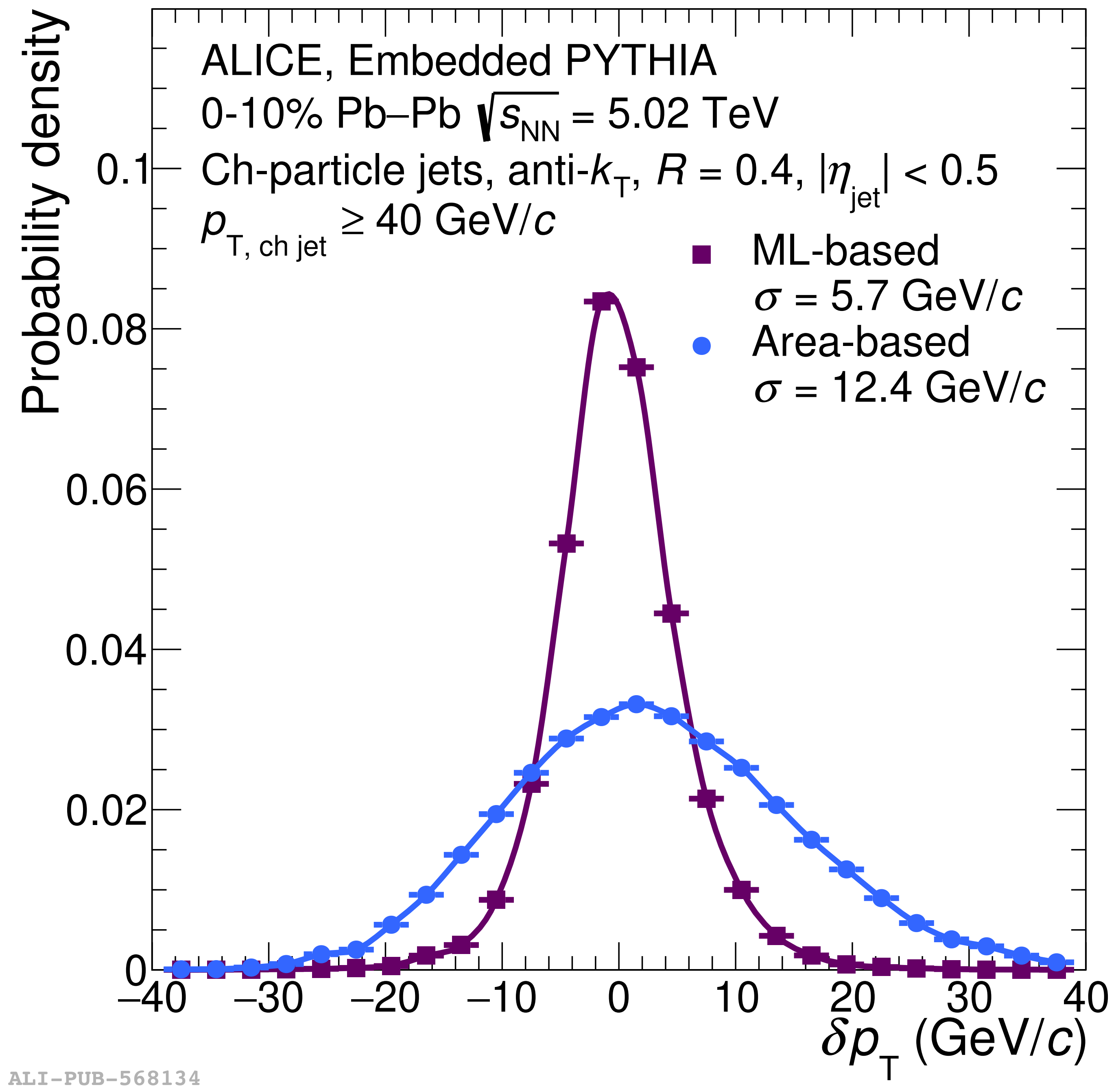
- Usual method - **area-based** pedestal subtraction of the event-averaged momentum density ρ
  - Per-event background fluctuations limits the precision with which we can determine ρ in jet acceptance
  - Unfold residual background fluctuations
    - Residual fluctuations increase with increasing R



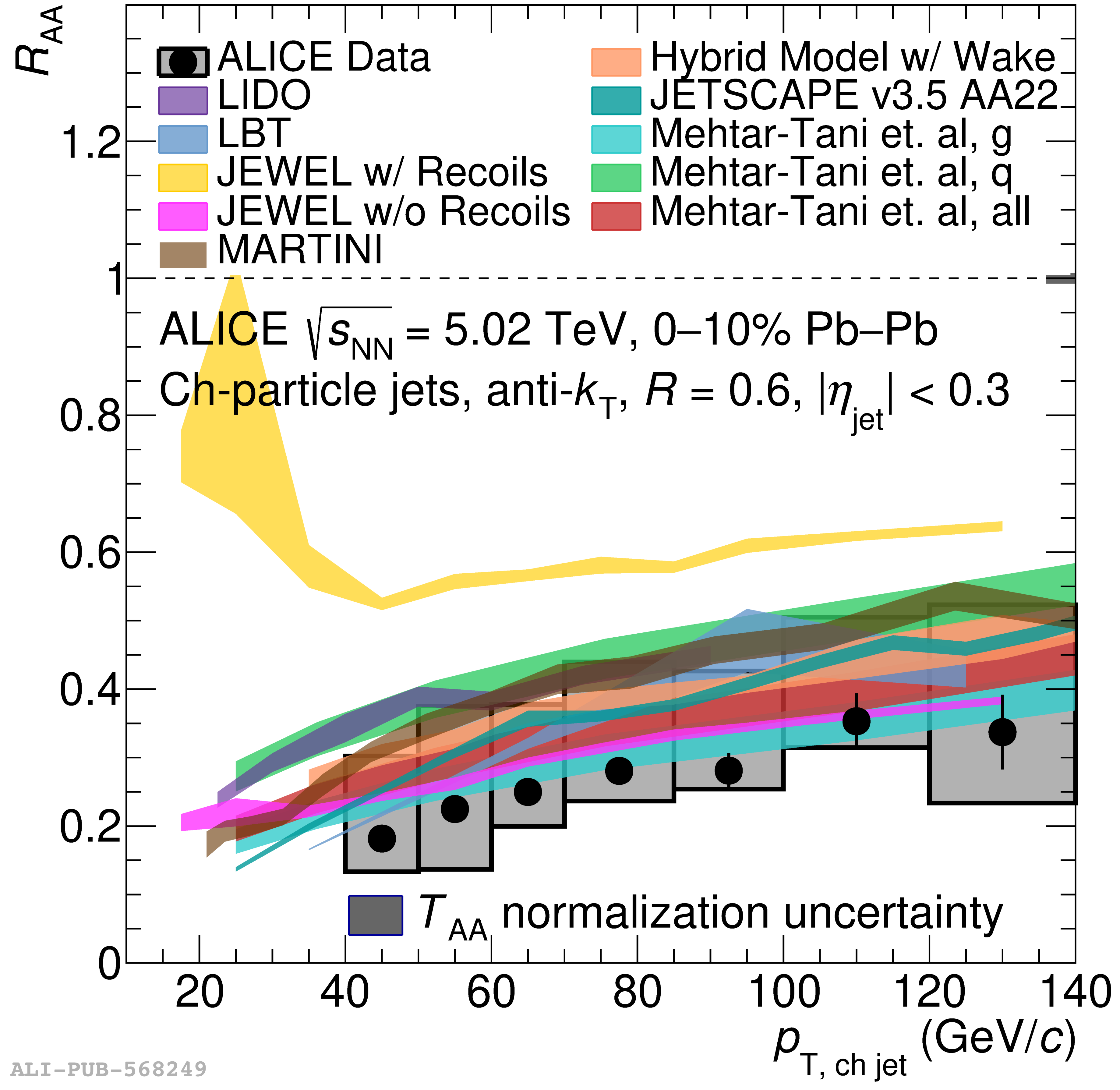
R. Haake, C. Loizides, Phys. Rev. C 99, 064904 (2019)

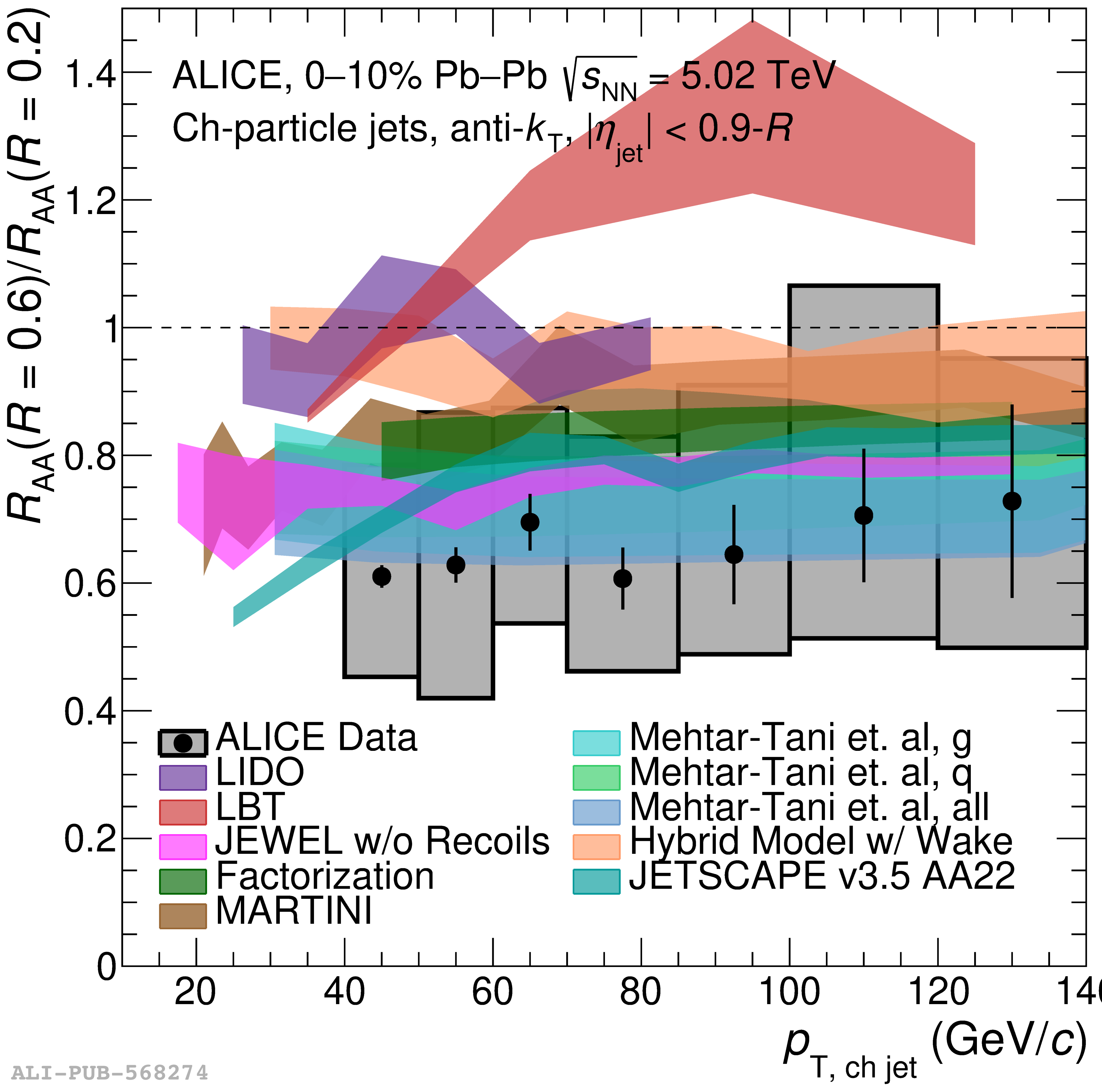
- Use properties of the jet to estimate background contribution *per-jet* using Neural network - regression task
  - N constituents, p_{T} of leading tracks, jet angularity, background estimated by area-based method used as features of jet
  - Train on jets from PYTHIA embedded into background - impact of model-dependence and fragmentation bias carefully studied

Improve background fluctuations by factor ~2



Results - Inclusive jet R_{AA} and R-dependence





Mehtar-Tani, D. Pablos, K. Tywoniuk, Phys. Rev. Lett. 127 (2021) 252301

MARTINI: B. Schenke, C. Gale, S. Jeon, Phys. Rev. C 80 (2009) 054913

JEWEL: K. Zapp, Eur.Phys.J. C74 (2014) 2762
R. Kunnawalkam-Elayavalli, K. Zapp, arXiv:1707.01539

JETSCAPE: arXiv:1903.07706

- **First ALICE measurement of R=0.6 jets in Pb-Pb collisions**
- Significant suppression of large-*R* jets

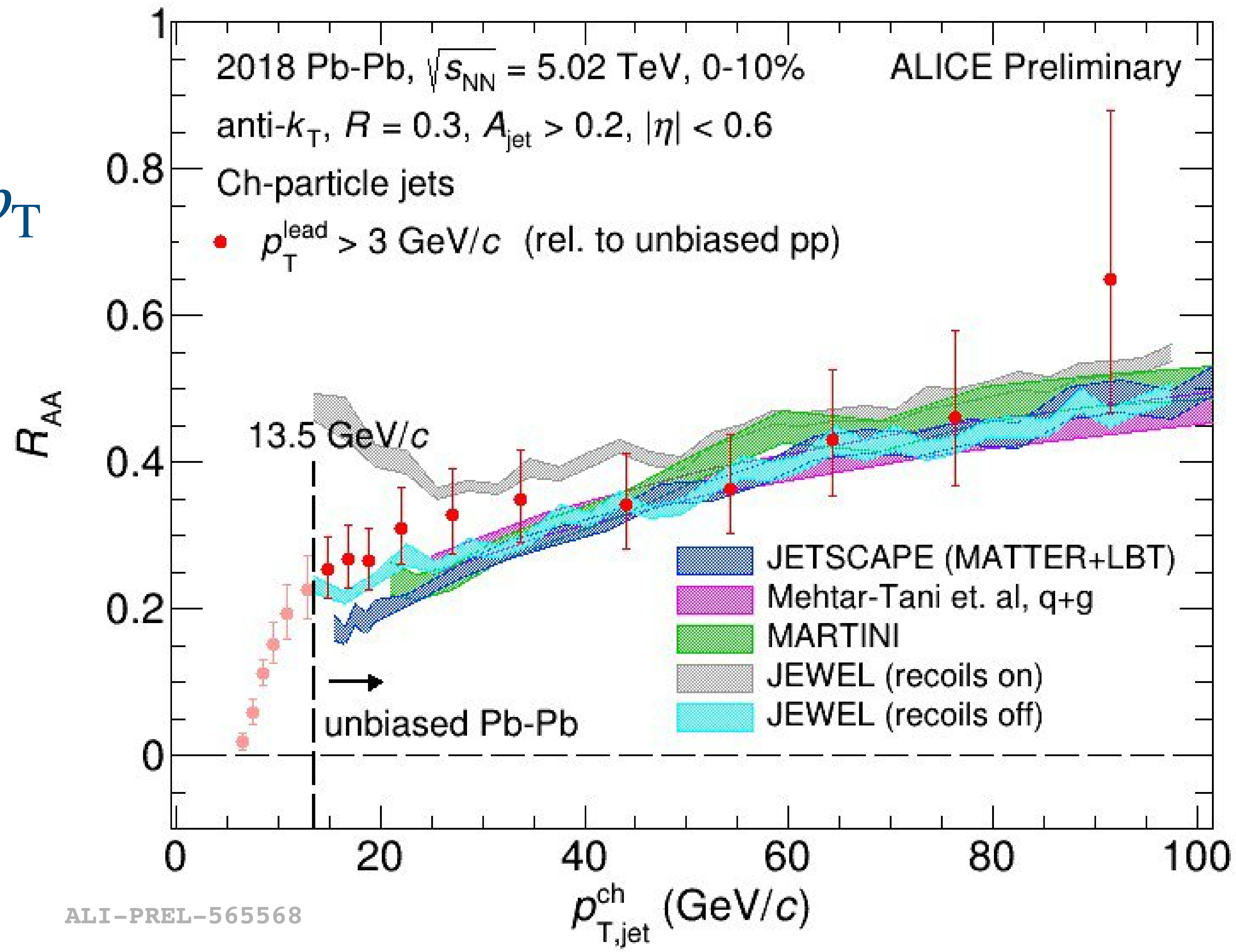
- *R*=0.6 jets appear to be more suppressed than *R*=0.2 jets

General agreement with many models - some deviations

Results - inclusive charged jet R_{AA} vs models

Significant model constraining power at low p_T

- Generally good agreement with **Mehtar-Tani et. al**, **MARTINI**, **JEWEL (recoils off)**, **JETSCAPE**
  - **JETSCAPE** and **MARTINI** on lower side of measurement
  - **JEWEL (recoils on)** significantly over predicts



Mehtar-Tani, D. Pablos, K. Tywoniuk, Phys. Rev. Lett. 127 (2021) 252301
MARTINI: B. Schenke, C. Gale, S. Jeon, Phys. Rev. C 80 (2009) 054913
JEWEL: K. Zapp, Eur.Phys.J. C74 (2014) 2762
R. Kunnawalkam-Elayavalli, K. Zapp, arXiv:1707.01539
JETSCAPE: arXiv:1903.07706

Jets (in deconfined QCD medium)

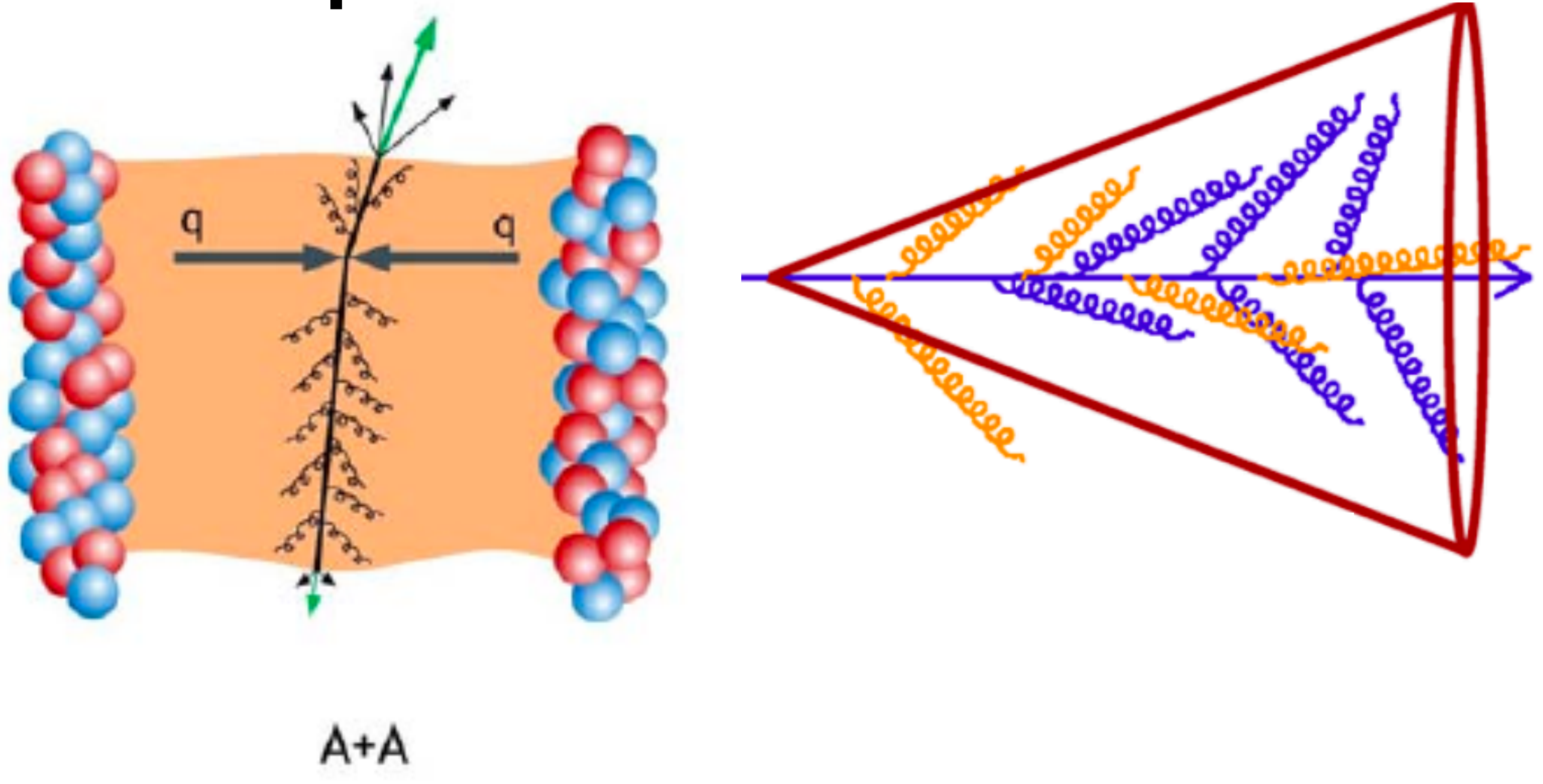
Heavy-ion collisions create deconfined phase of QCD matter → the Quark-Gluon Plasma (QGP)

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

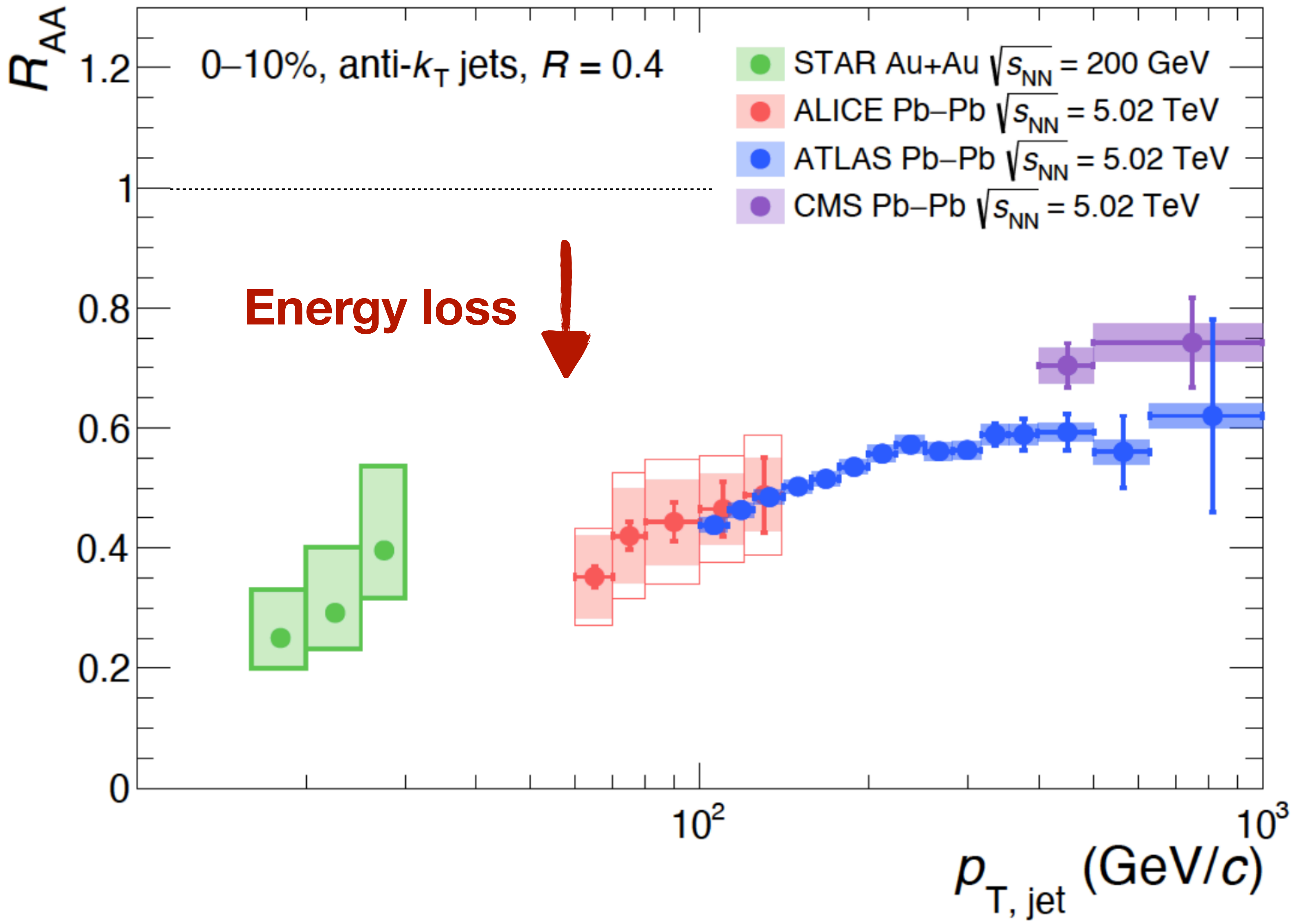
'Jet quenching' - partonic interactions in the QGP

- 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



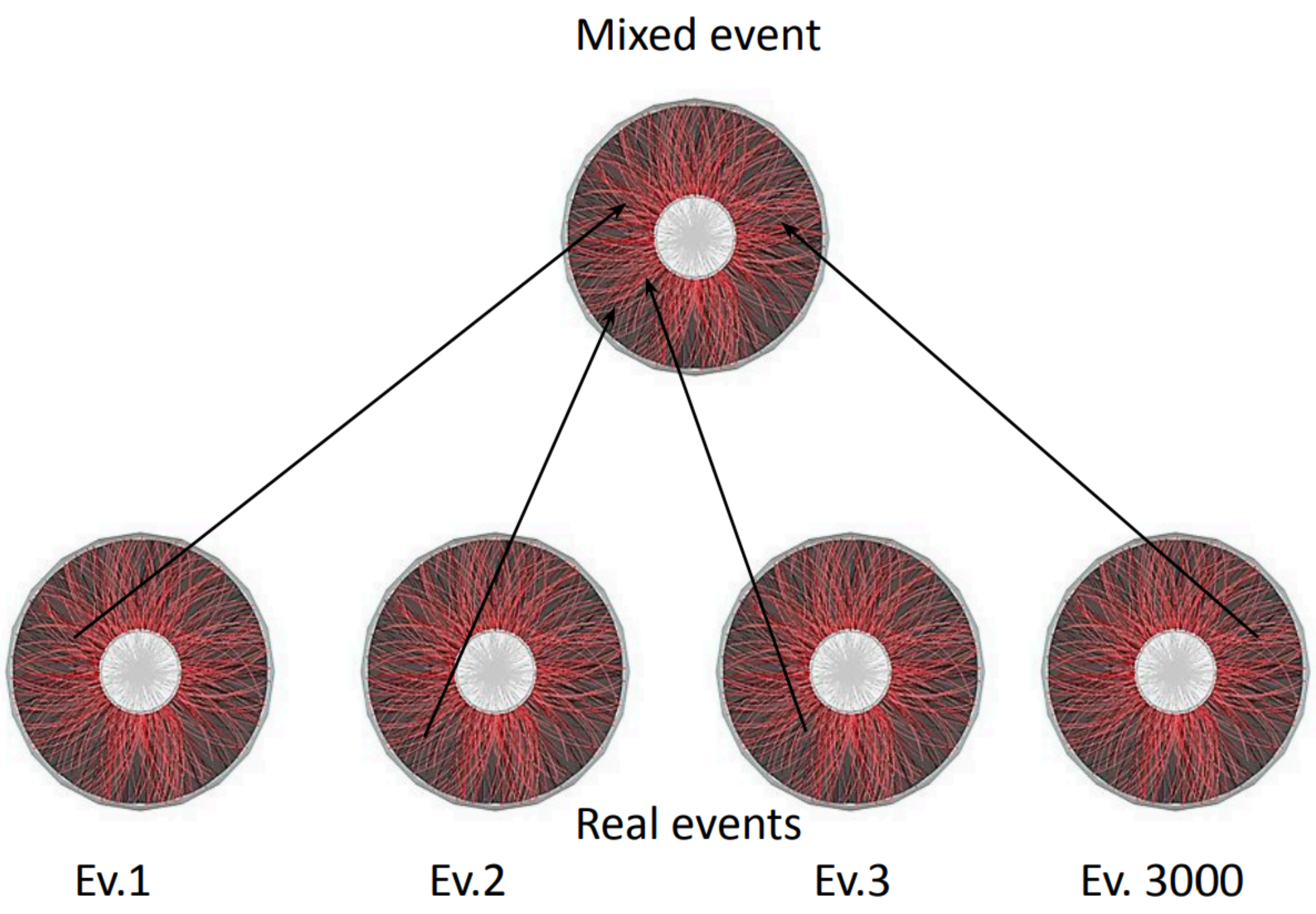
$R_{AA} < 1$ **- suppression w.r.t. pp**

Mixed event background subtraction for inclusive jets

Mixed event (ME) procedure:

- Categorise events in terms of multiplicity, z-vertex, event plane angle (Ψ_2, Ψ_3) and total measured track transverse momenta p_T^{sum}
- Generate mixed events taking one random track from each like event

Then perform same analysis on ME and same event (SE):



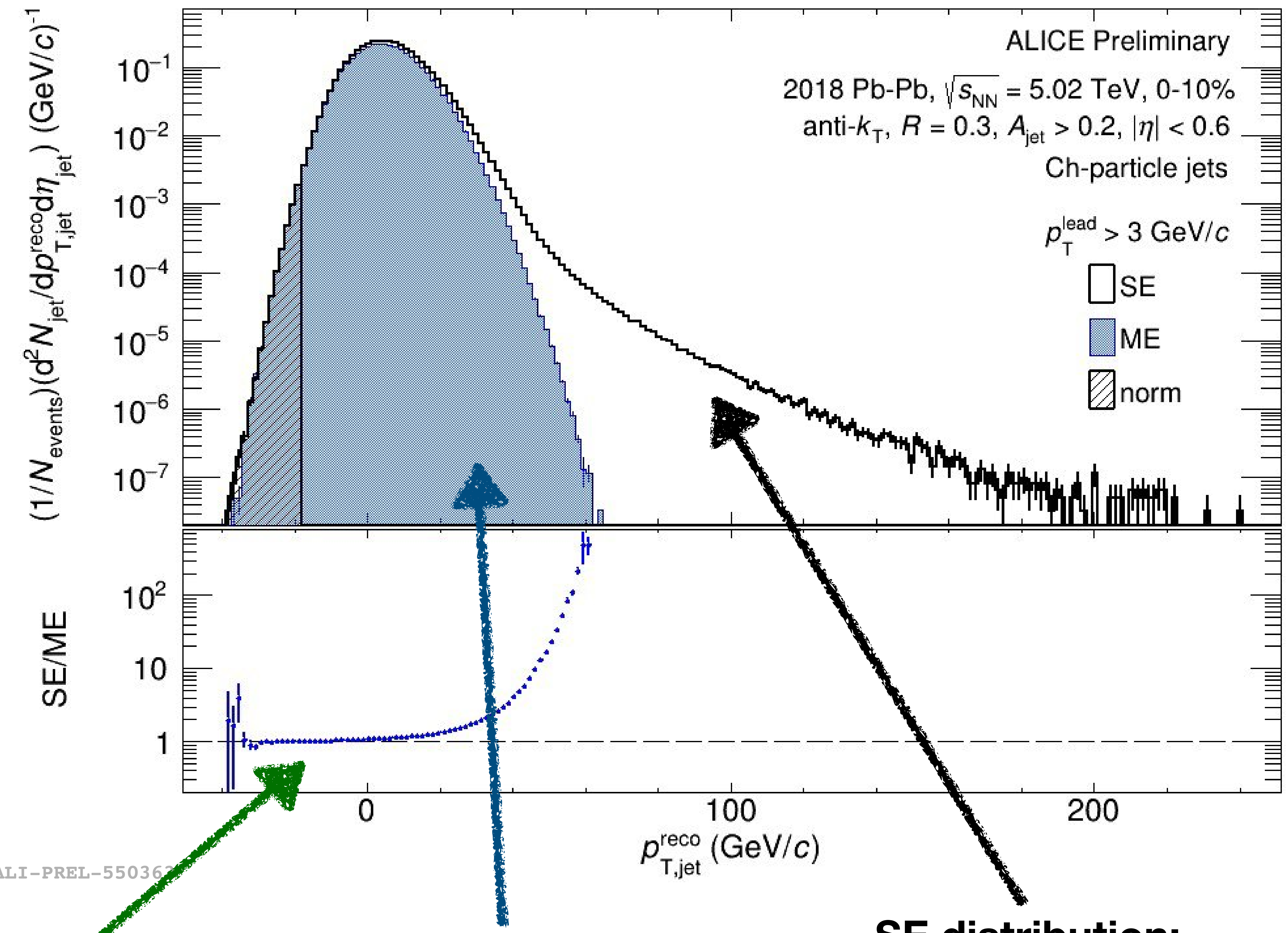
Mixed event background subtraction for inclusive jets

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

Mixed event (ME) procedure:

- Categorise events in terms of multiplicity, z-vertex, event plane angle (Ψ_2, Ψ_3) and total measured track transverse momenta $p_{\mathrm{T}}^{\mathrm{sum}}$
- Generate mixed events taking one random track from each like event

Then perform same analysis on ME and same event (SE):



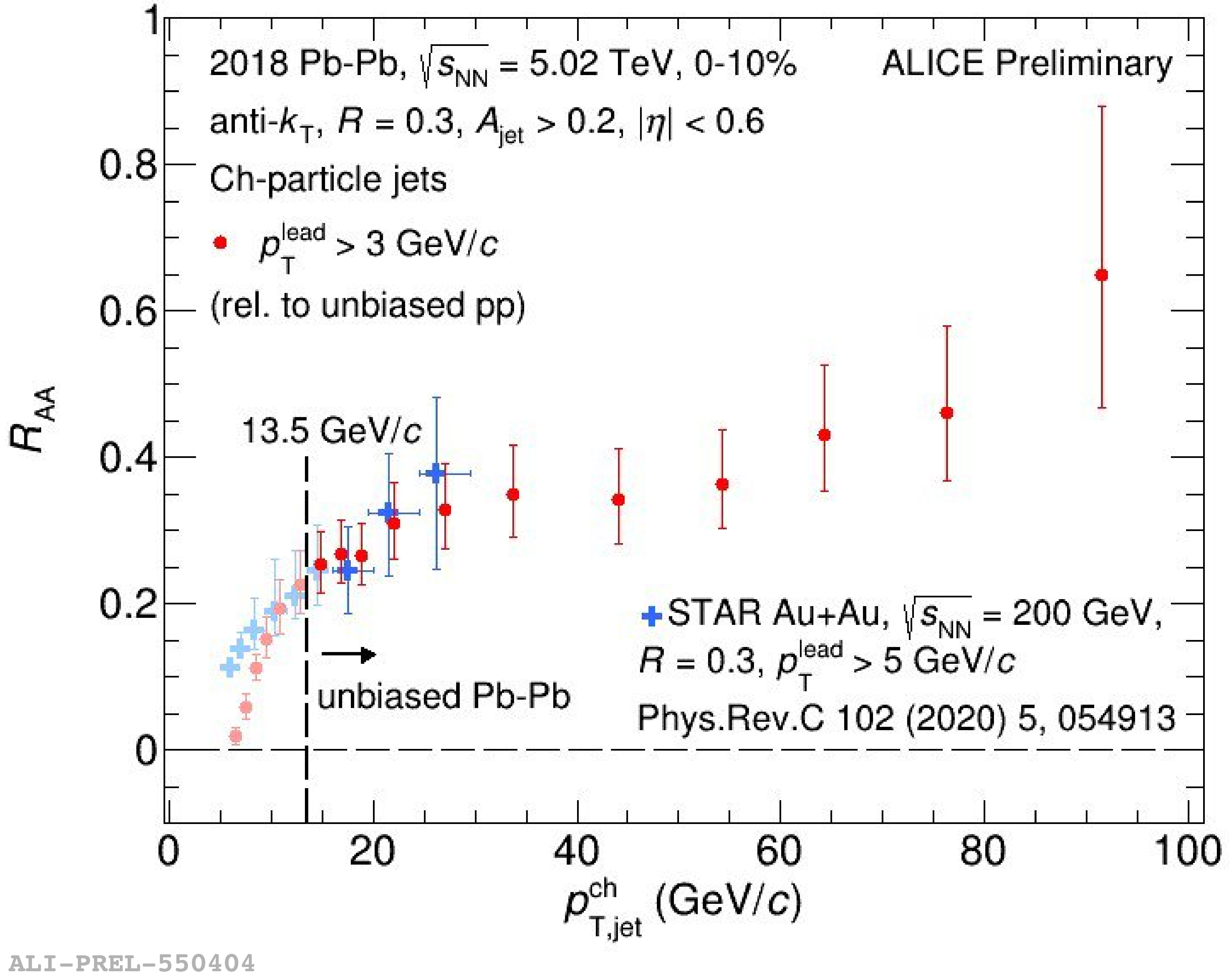
Identical SE and ME shape at low p_{T}
→ ME distribution describes background

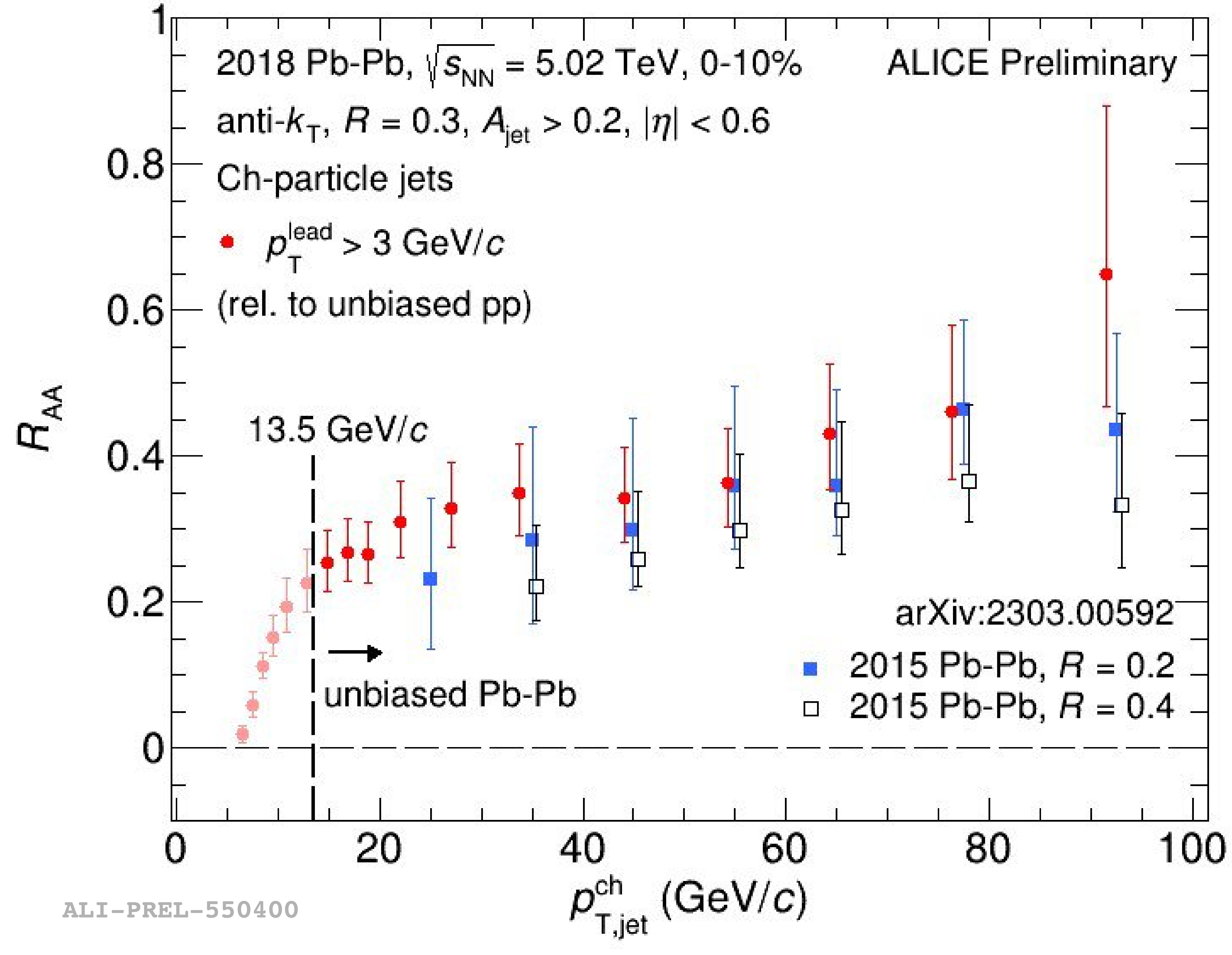
ME distribution

SE distribution:
Background dom. at low p_{T}
Signal dom. at high p_{T}

Results - inclusive charged jet R_{AA}

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





- Lowest p_T inclusive charged jet measurement to date - **overlap with RHIC kinematic region**
- **Significant reduction in systematic uncertainties** related to treatment of uncorrelated background compared to previous measurements