Jet modification studies over a broad p_{T} range and large radii with ALICE

Daniel Jones

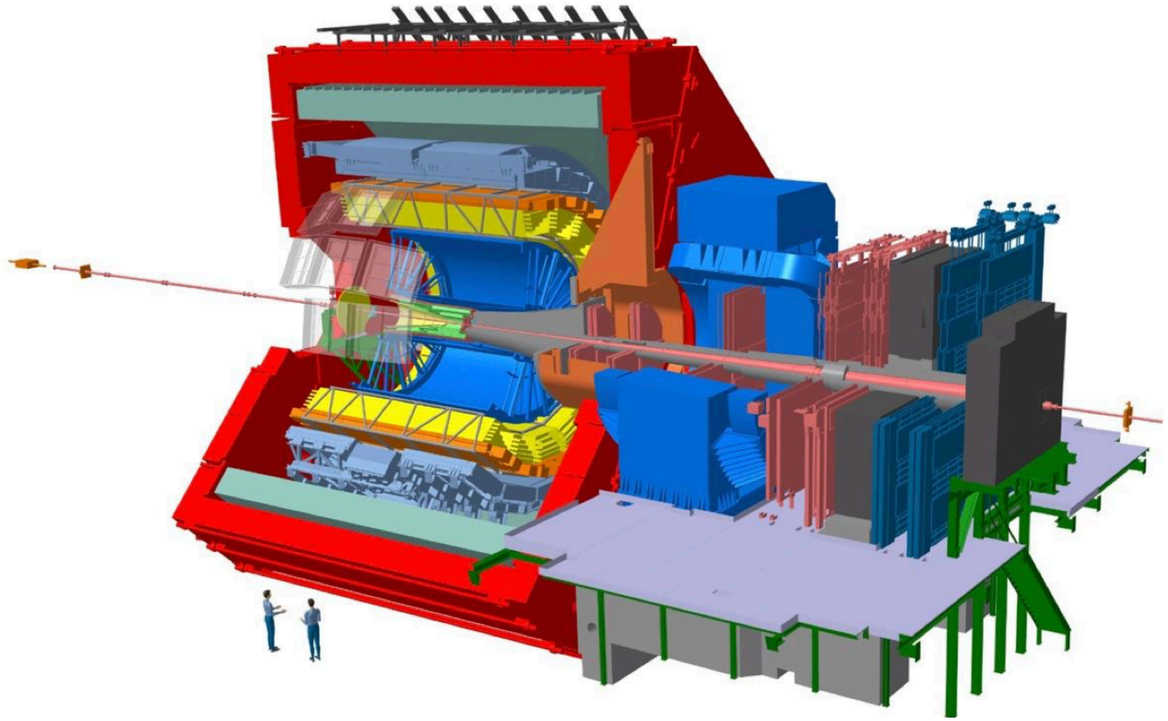
On behalf of ALICE

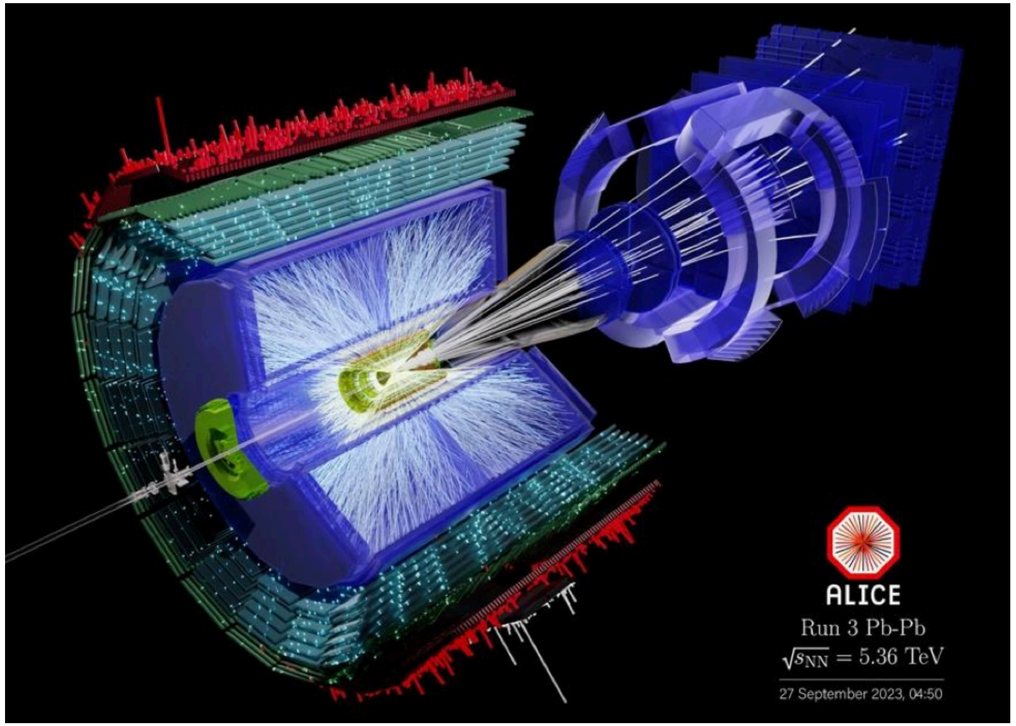
7th July 2025

University of Liverpool

EPS-HEP 2025

ALICE and heavy-ion collisions

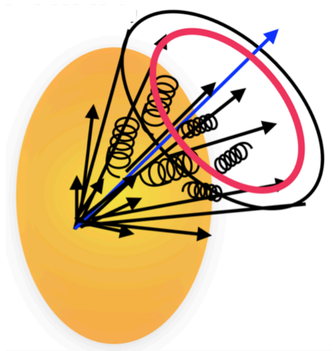




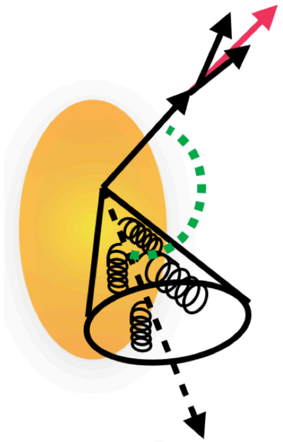
- At ALICE we use ultra-relativistic collisions of heavy ions to study the quark-gluon plasma (QGP)
- Jets → Hadronic remnants of hard-scattered partons; probe the QGP

Jet quenching at low p_{T}

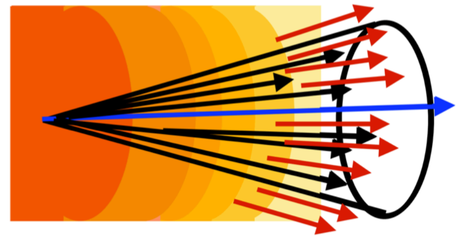
- **We study the modification of the jet p_{T} and azimuthal spectra in Pb-Pb collisions with respect to pp**



Out of cone transport



Large angle scatterings (azimuthal broadening)



Medium response (i.e. the wake)

We want to study these effects over a wide kinematic range

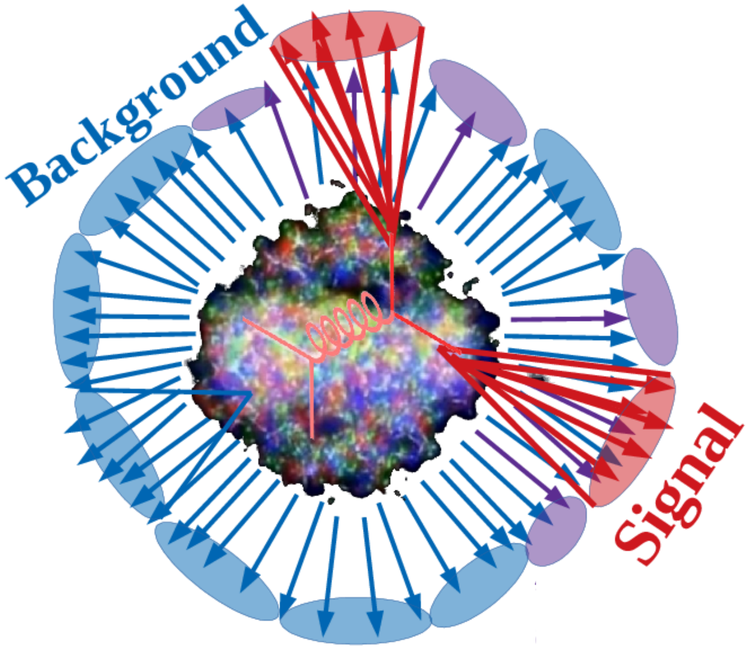
→ Uncover the scale dependance of the QGP

Study low energy jets!

1. **Inclusive-jet R_{AA} with mixed events** (Run 2)
2. **Semi-inclusive hadron+jet measurement** (Run 2 and 3)

The uncorrelated background

- **Problem: The uncorrelated background from the underlying event (UE) is huge in this low energy region!**
  - Jet p_{T} smearing (handled with usual techniques)
  - Uncorrelated jet yield



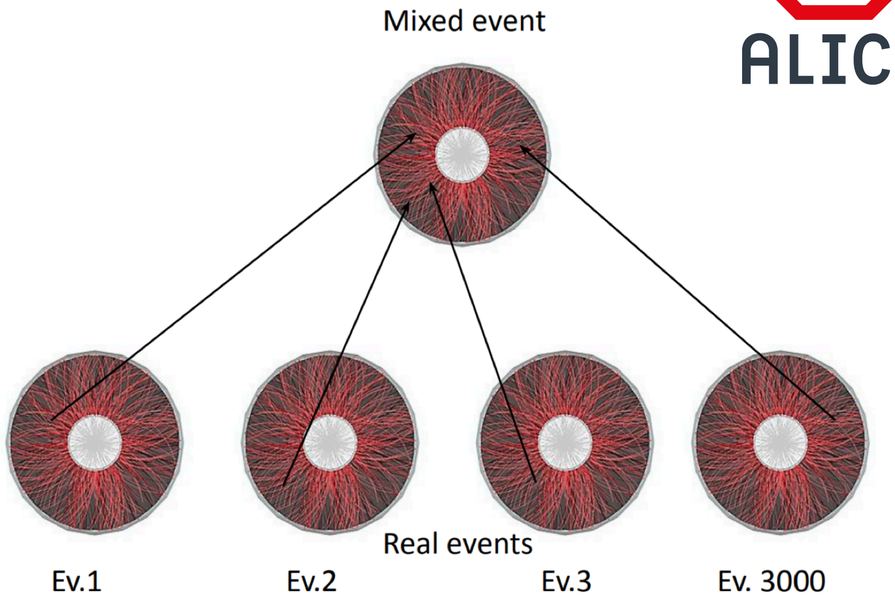
Two data-driven statistical approaches to correct background:

1. **Inclusive:** event mixing
2. **Semi-inclusive:** trigger difference

1. **Inclusive-jet R_{AA} with mixed events** (Run 2)
2. **Semi-inclusive hadron+jet measurement** (Run 2 and 3)

Mixed-event background subtraction

- **Process:**
  - Events are sorted into categories based on event properties(e.g. z-vtx, multiplicity…)
  - Generate mixed events (ME) by selecting 1 track per event from events within the same category
- **All multi-hadron correlations destroyed**
- **Analysis is performed on the original events (same events, (SE)) and ME**

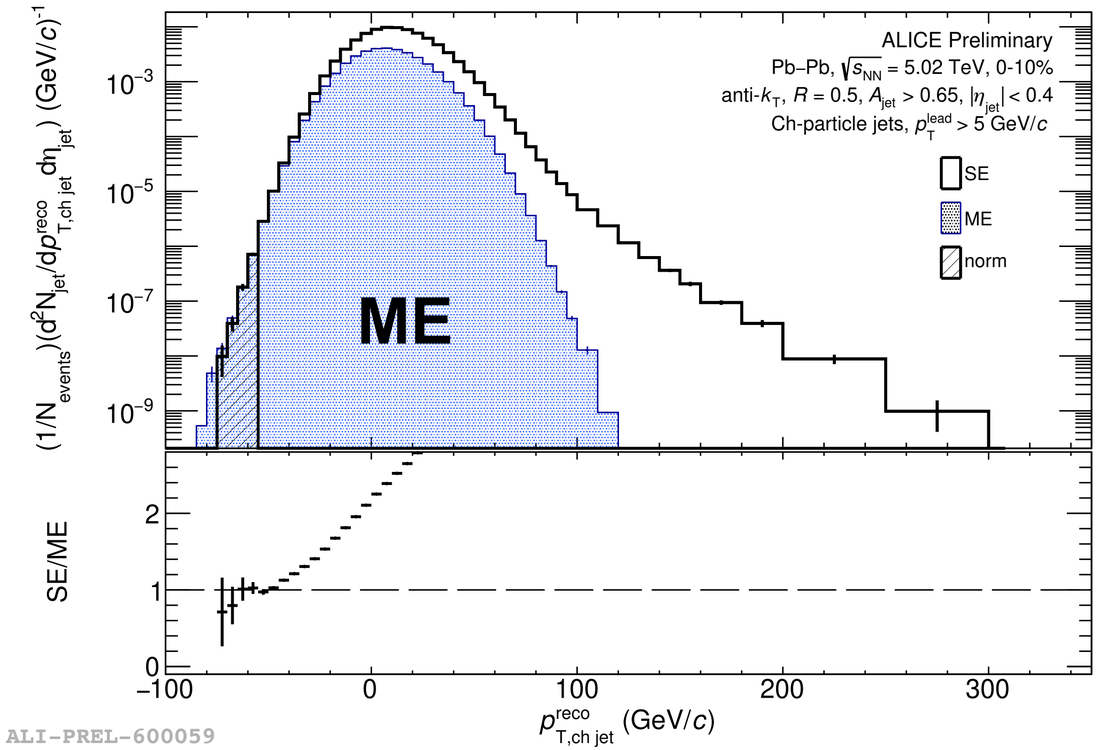


Pb-Pb data: Run 2, $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

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

New

Mixed event background subtraction



Statistical correction

- **Tracks from the UE can affect the jet p_T**
- **Correct p_T with median background density**

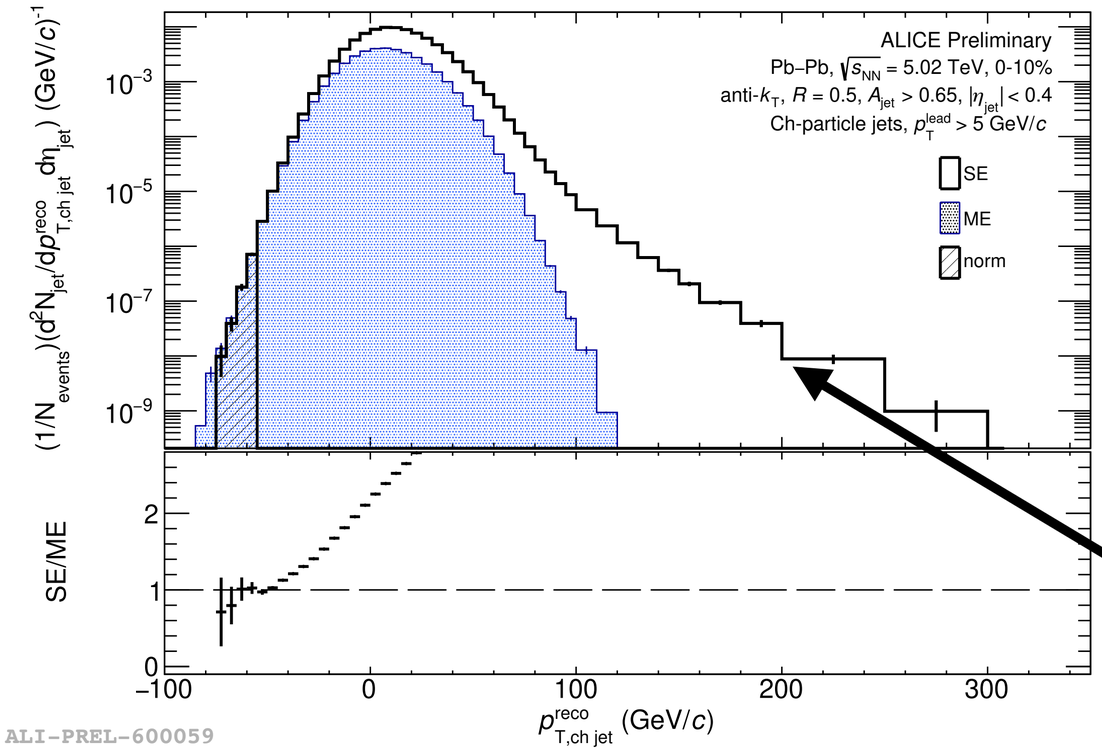
$$p_{T,jet}^{reco} = p_{T,jet}^{raw} - \rho A_{jet}$$

ρ: median bkg density

- **No cut on $p_{T,jet}^{reco}$, consider entire jet population**

New

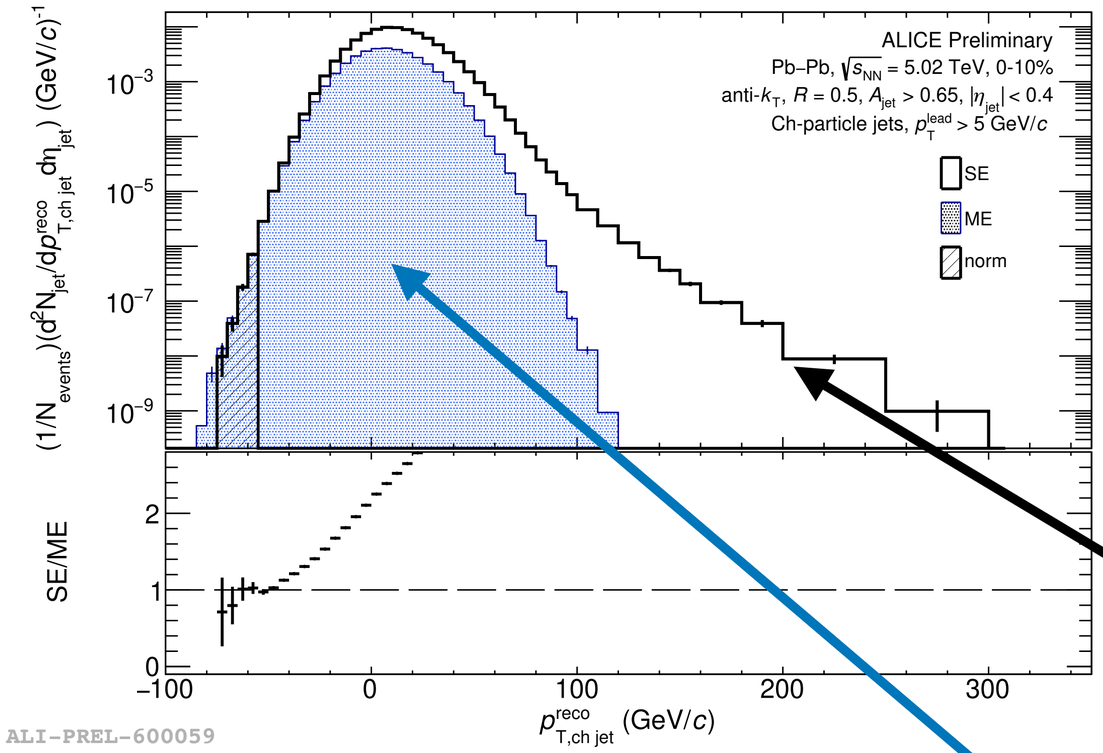
Mixed event background subtraction



SE: Signal dominated at high-p_T and background dominated at low-p_T

New

Mixed event background subtraction

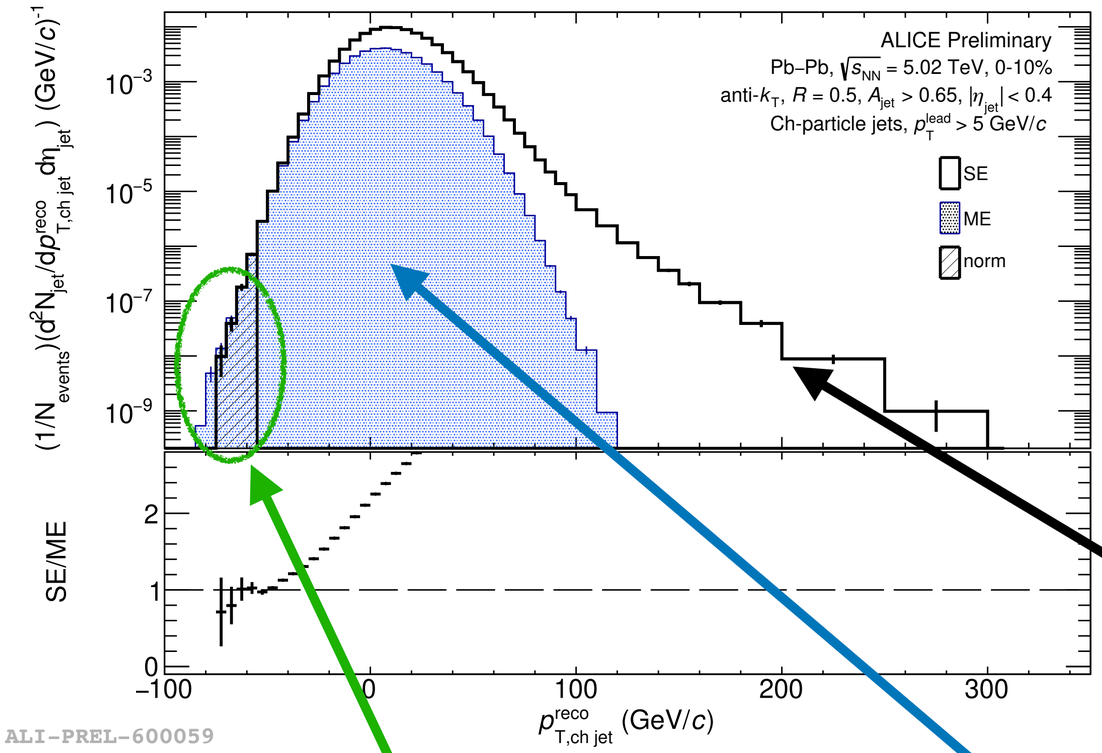


SE: Signal dominated at high-p_T and background dominated at low-p_T

ME: Accurately models the combinatorial background

New

Mixed event background subtraction



SM = ME at very low p_T (background dominated)

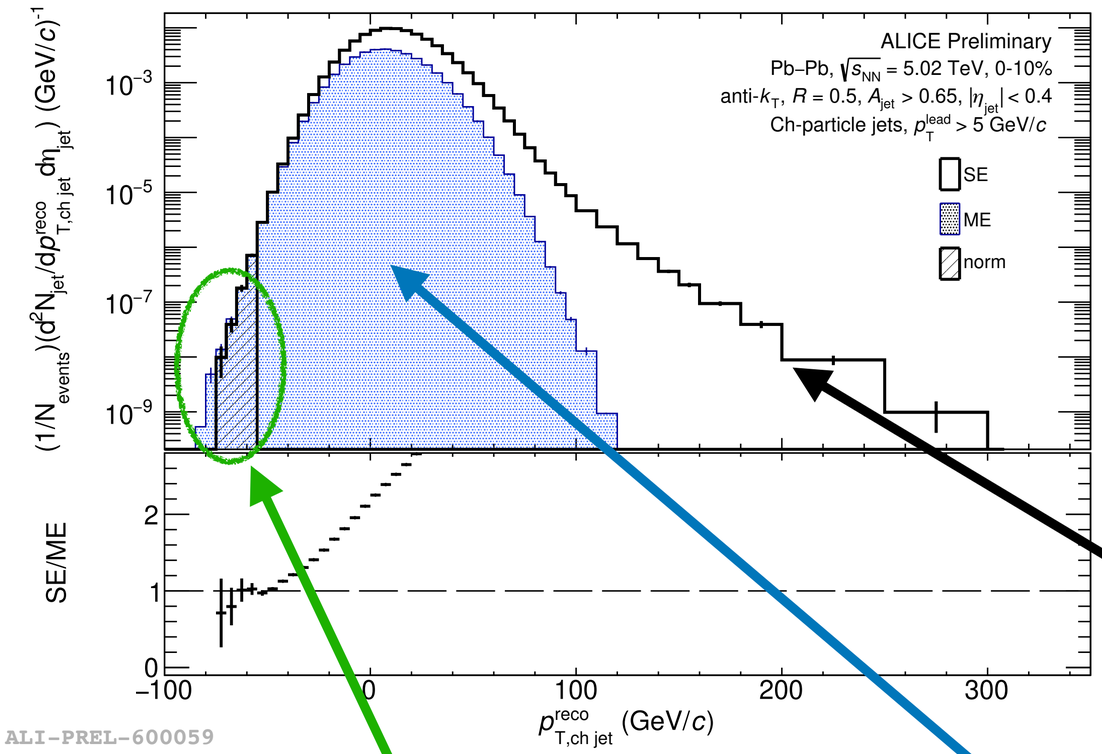
→ Normalise ME to SE in this region!

SE: Signal dominated at high-p_T and background dominated at low-p_T

ME: Accurately models the combinatorial background

New

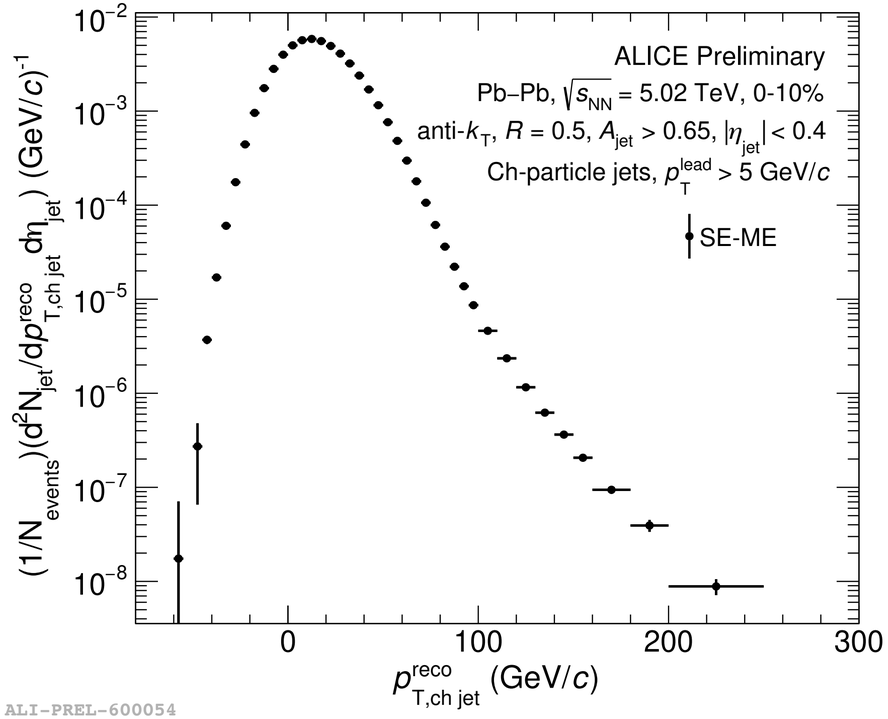
Mixed event background subtraction



ALI-PREL-600059

Small difference of two large numbers

SE - ME



ALI-PREL-600054

SM = ME at very low p_T (background dominated)

→ Normalise ME to SE in this region!

SE: Signal dominated at high-p_T and background dominated at low-p_T

ME: Accurately models the combinatorial background

Corrections and bias

- **Jet spectra must be corrected**

Effect	Correction
Combinatorial jet yield	Mixed events
p_{T} smearing	Unfolding
Tracking efficiency	Unfolding
Background fluctuations	Unfolding

- **A leading low track-p_{T} cut is applied to deal with denumerable, overlapping jets in this kinematic region**
  - Result separated into biased and unbiased regions (see backup)

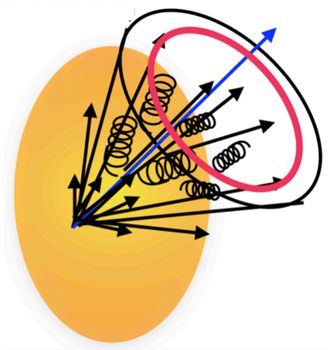
New

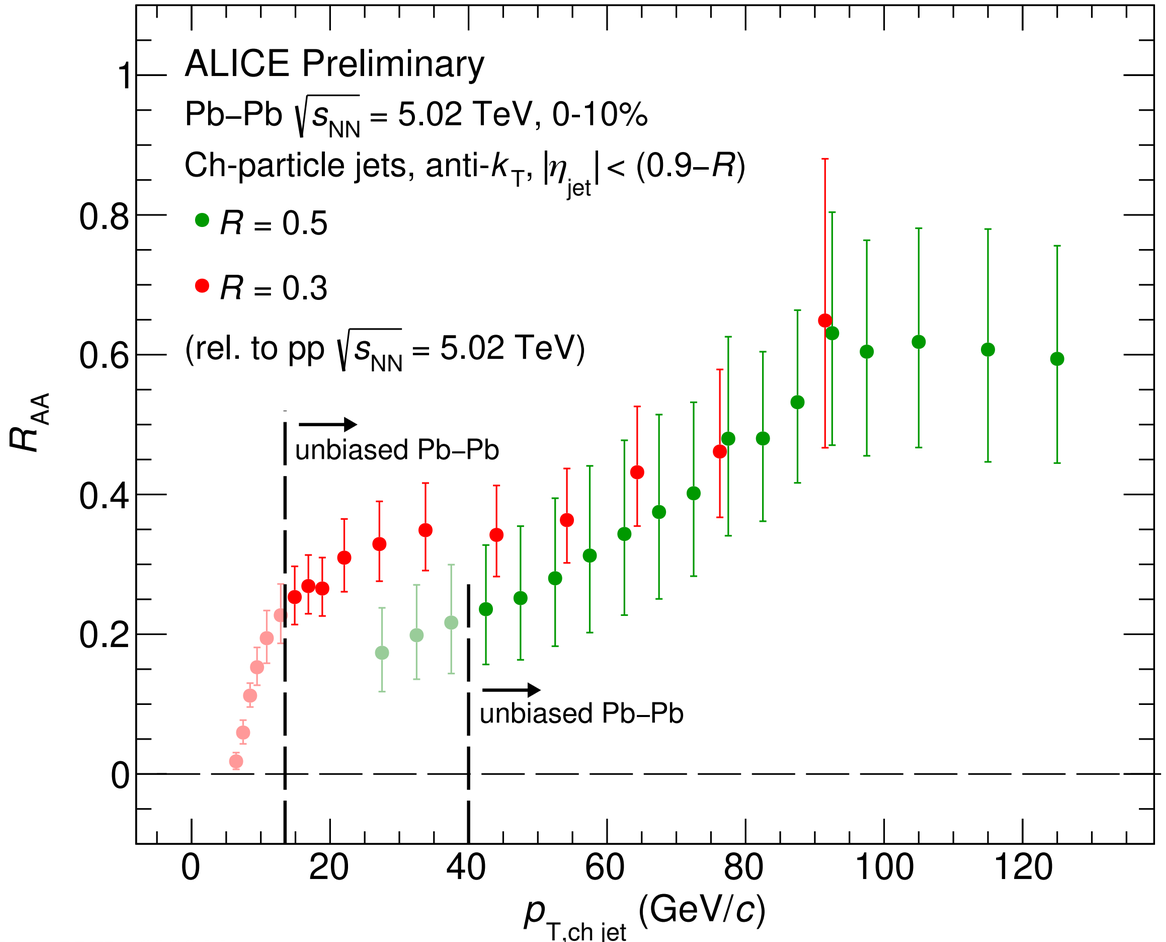
Inclusive jet R_{AA} with the mixed event analysis

- **The lowest p_{T} inclusive jet measurement in Pb-Pb!**

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

$R_{AA} < 1 \rightarrow$ **suppression wrt pp**





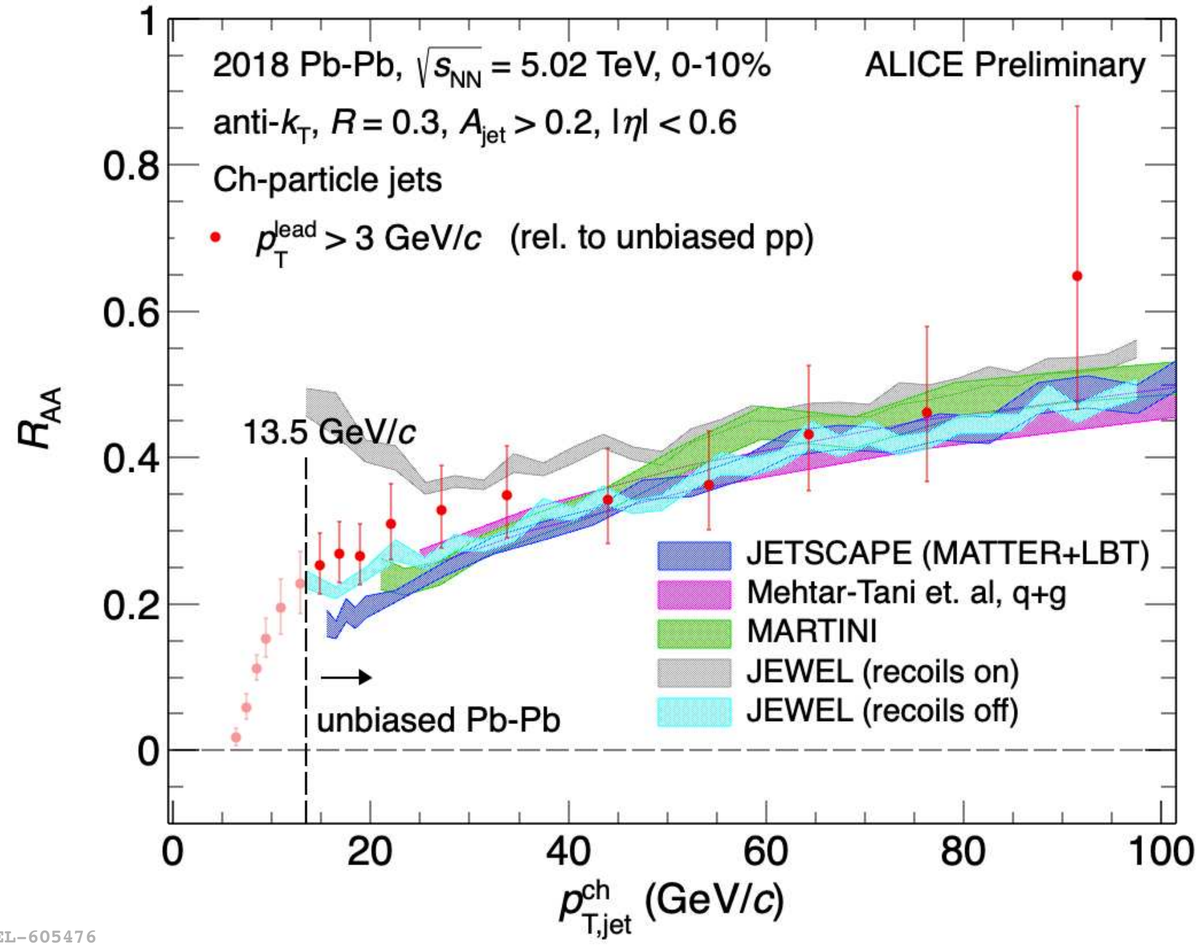
ALI-PREL-600044

Unbiased pp:
ALICE, Phys. Rev. D 100, 092004
ALICE, Phys. Lett. B 849, 138412

Model comparisons

Recoils on/off → with/without medium response

- **Model comparisons**
  - Different theoretical approaches to jet quenching and QGP response
- **Variable agreement over full kinematic range**
  - JEWEL (recoils on) significantly over predicts at low p_{T}



ALI-PREL-605476

Mehtar, Phys. Rev. Lett. 127, 252301
Shi, Phys. Rev. C 107, 034908
Raghav, JHEP 1707 (2017) 141
JETSCAPE, Putschke, J. H., et al.

1. **Inclusive-jet R_{AA} with mixed events** (Run 2)
2. **Semi-inclusive hadron+jet measurement** (Run 2 and 3)

Semi-inclusive hadron+jet measurement

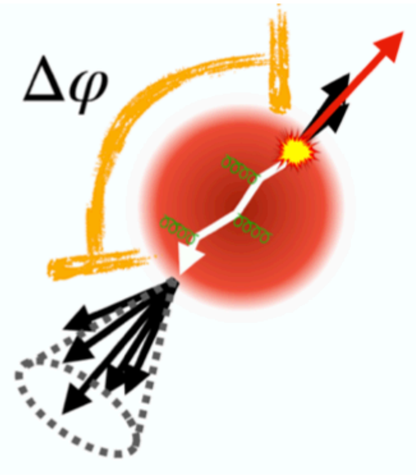
- **Yield of charged-particle jets recoiling from a high-p_{T} hadron:**
  - Jet transverse momentum ($p_{\mathrm{T,jet}}$)
  - Trigger-jet opening angle ($\Delta\varphi$)

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

TT: Trigger track

- **Uncorrelated background correction: Alternative to event mixing**
  - Difference between two semi-inclusive, trigger-normalised jet yields: signal and reference

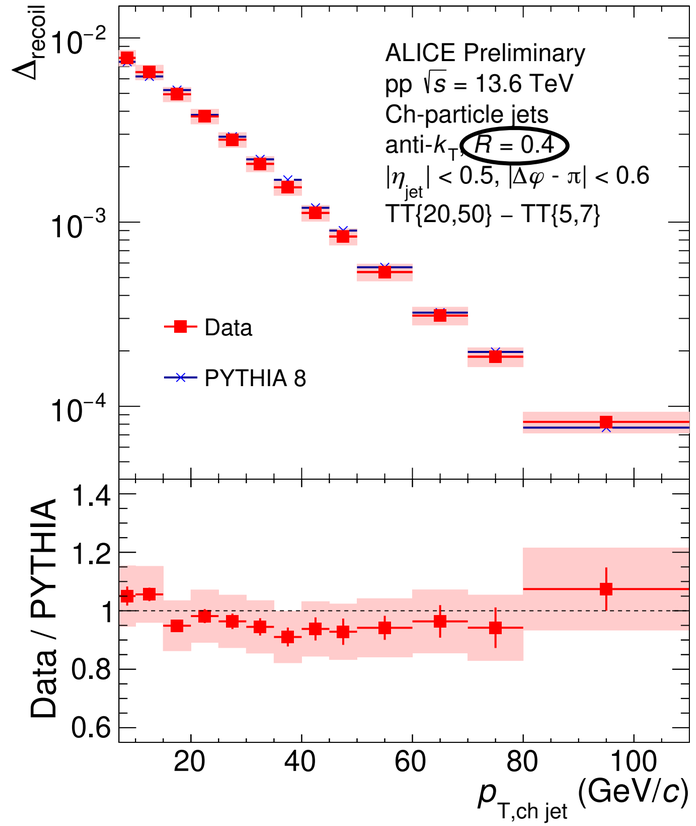
$$\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}}, \Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T}}^{\mathrm{trig}} \in \mathrm{TT_{sig}}} - c_{\mathrm{Ref}} \times \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T}}^{\mathrm{trig}} \in \mathrm{TT_{ref}}}$$

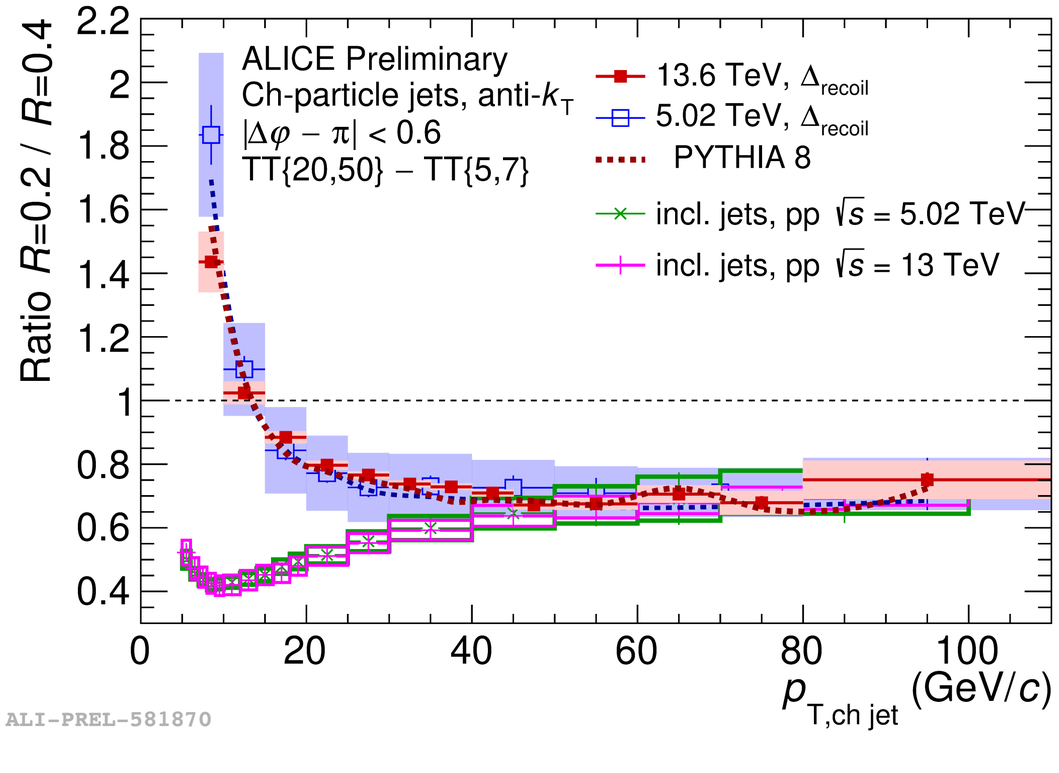


c_{Ref}: normalisation factor - derived from data

- **Uncorrelated background is the same in both distributions**

Fully corrected semi-inclusive hadron+jet yield - pp





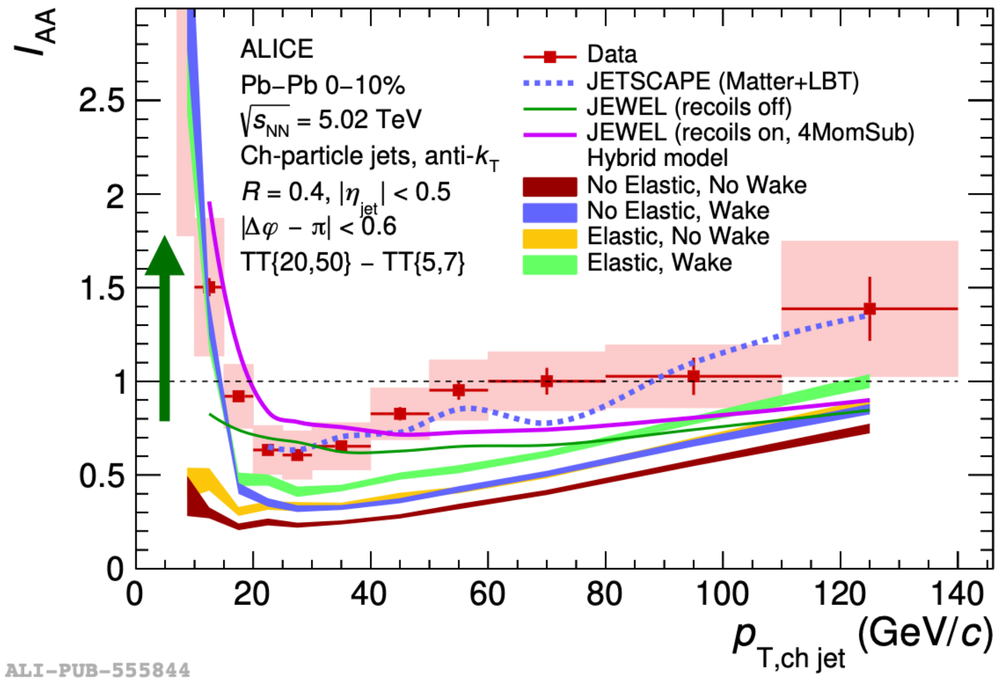
See Joonsuk's talk (08/07, 09:30) for more on pp results!

- **PYTHIA describes the data well within uncertainties**

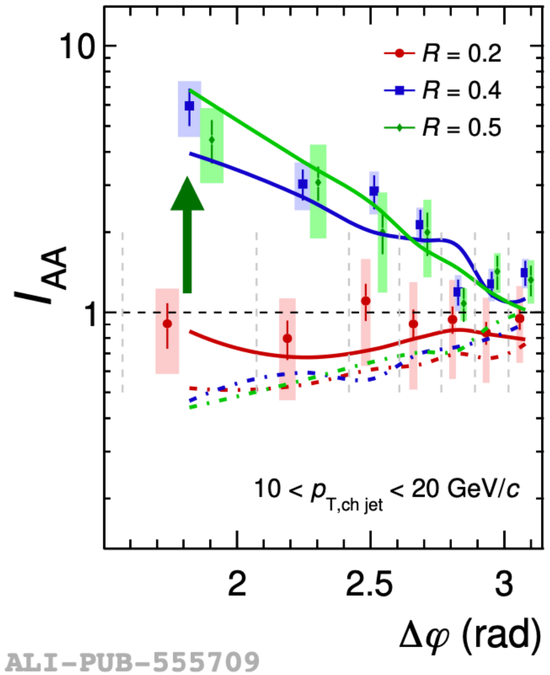
  → Well understood baseline for future heavy-ion studies

Hadron+jet in Run 2

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



ALI-PUB-555844

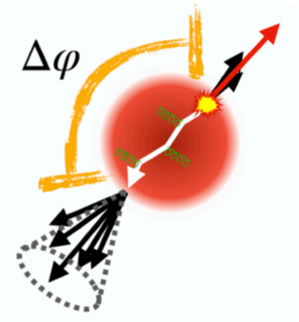


ALI-PUB-555709

$\sqrt{s_{NN}}$ = 5.02 TeV, Pb–Pb 0–10 %
Ch-particle jets, anti-k_T
TT{20,50} – TT{5,7}

R = 0.2
R = 0.4
R = 0.5

JEWEL:
recoils off
recoils on, 4MomSub



Enhancement in Pb-Pb yield at low p_T

→ Energy recovery?

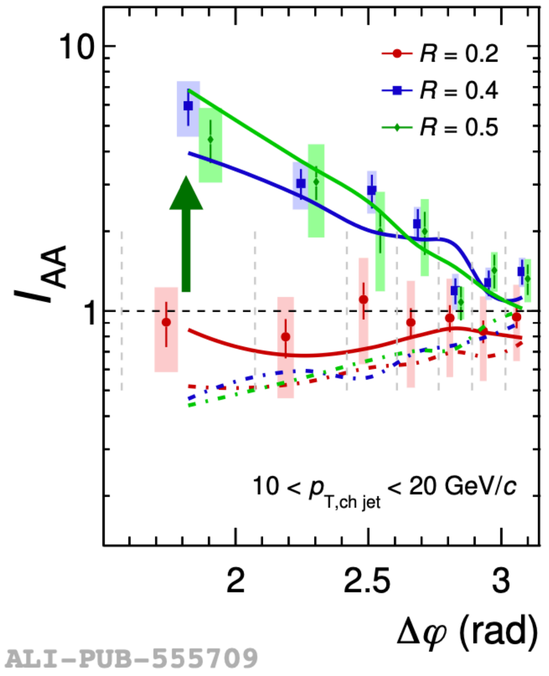
ALICE, Phys. Rev. Lett. 133, 022301

Both effects described well by JEWEL (recoils off)

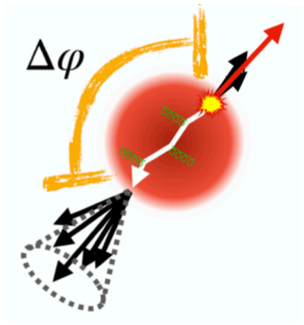
Azimuthal broadening at low p_T and large R

→ Medium response or large angle scatterings?

Comparison with inclusive R_{AA}



ALICE, Phys. Rev. Lett. 133, 022301



R = 0.2
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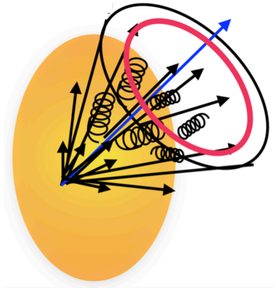
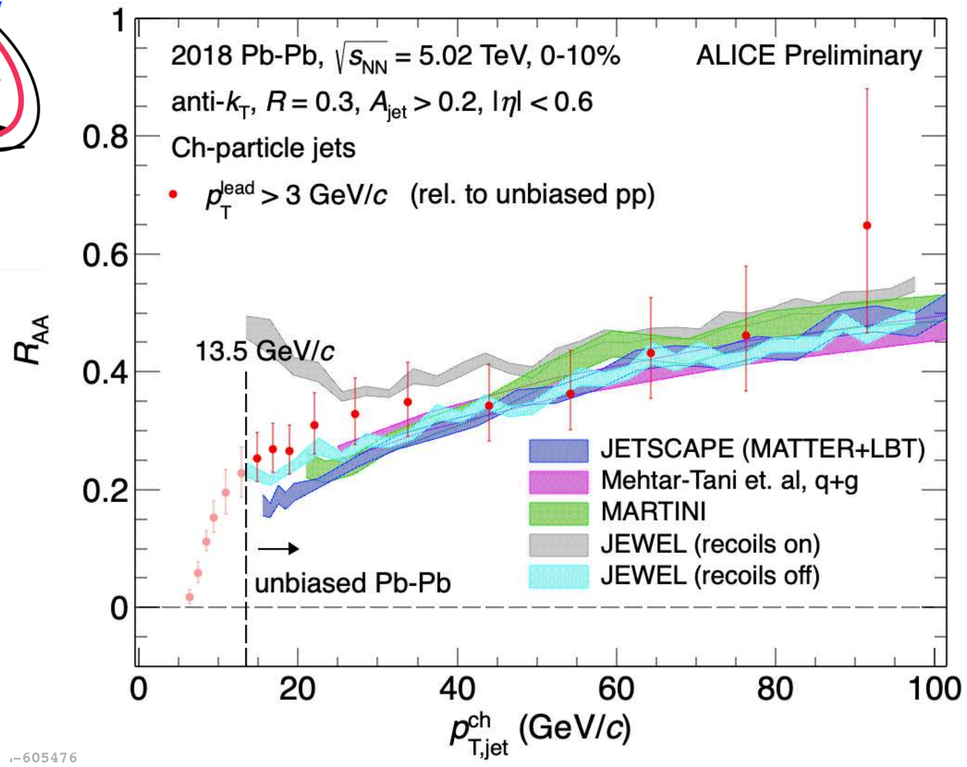
JEWEL:
recoils off
recoils on, 4MomSub

$\sqrt{s_{NN}}$ = 5.02 TeV, Pb–Pb 0–10 %
Ch-particle jets, anti-k_T
TT{20,50} – TT{5,7}





Opposite picture for JEWEL recoils on/off between recoil and inclusive jets!

→ No consistent model of the medium response

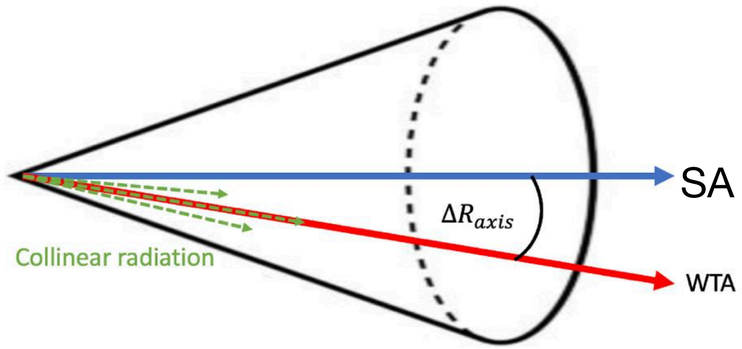
Next steps: recoil jet substructure

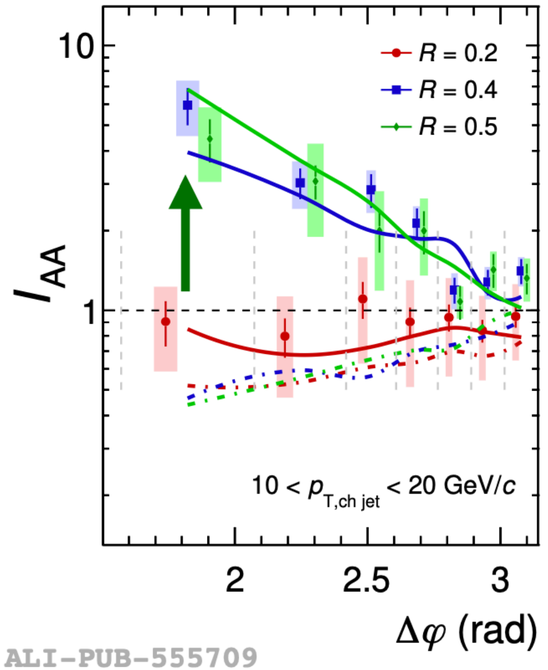
- **Introduce a 3rd observable: ΔR**
  - Separation between 2 reconstructed jet axis: standard axis (SA) and winner-takes-all (WTA)
  - Sensitive to the soft radiation content of a jet
- **Should be an observable sensitive to the medium response**

$$\Delta R = \sqrt{(\eta_{SA} - \eta_{WTA})^2 + (\phi_{SA} - \phi_{WTA})^2}$$

ALICE, arXiv:2303.13347

$$\Delta_{\text{recoil}} = \left.\frac{1}{N_{\text{trig}}} \frac{\mathrm{d}^3 N_{\text{jet}}}{\mathrm{d}p_{\text{T,jet}}^{\text{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\Delta R}\right|_{TT_{sig}} - c_{ref} \left.\frac{1}{N_{\text{trig}}} \frac{\mathrm{d}^3 N_{\text{jet}}}{\mathrm{d}p_{\text{T,jet}}^{\text{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\Delta R}\right|_{TT_{ref.}}$$

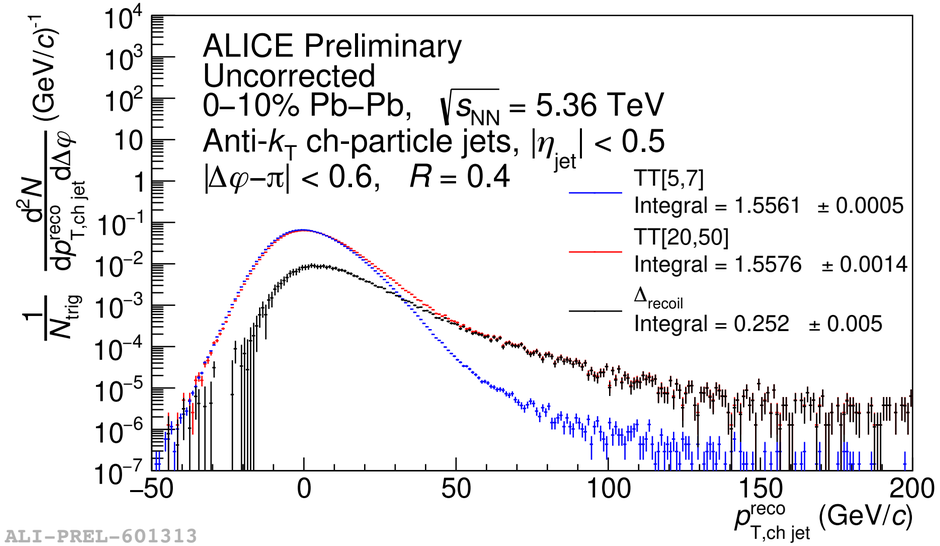




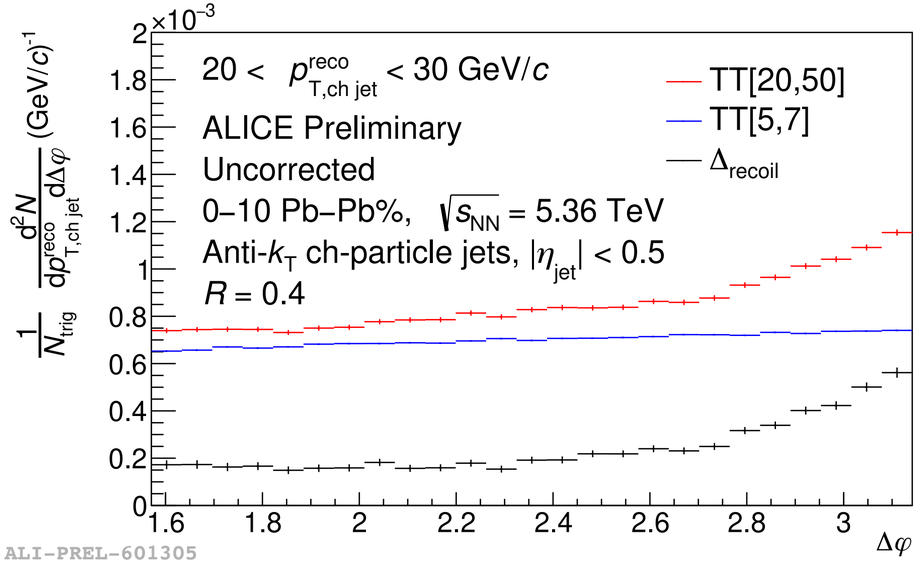
ALI-PUB-555709

New

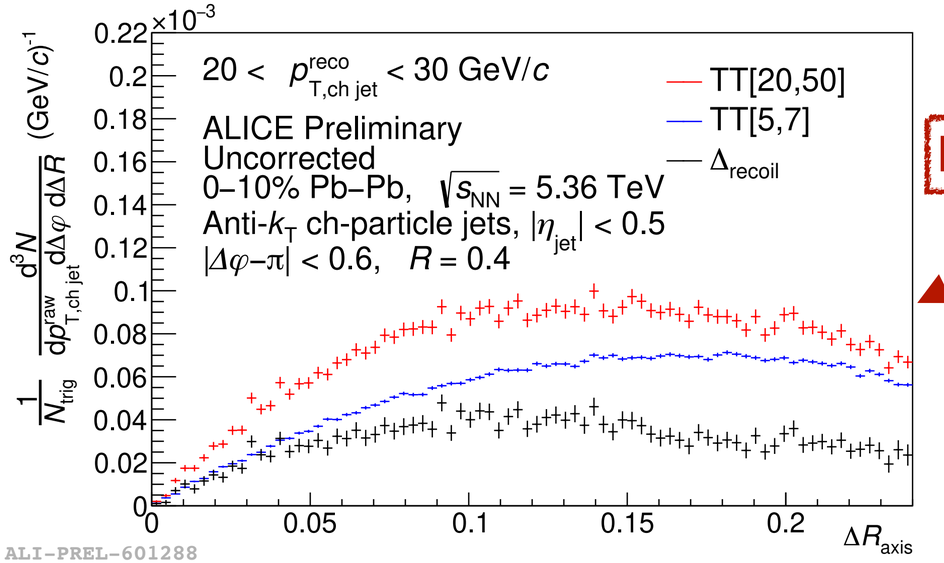
Raw semi-inclusive hadron+jet yield in Pb-Pb



ALI-PREL-601313



ALI-PREL-601305



ALI-PREL-601288

New in Run 3!

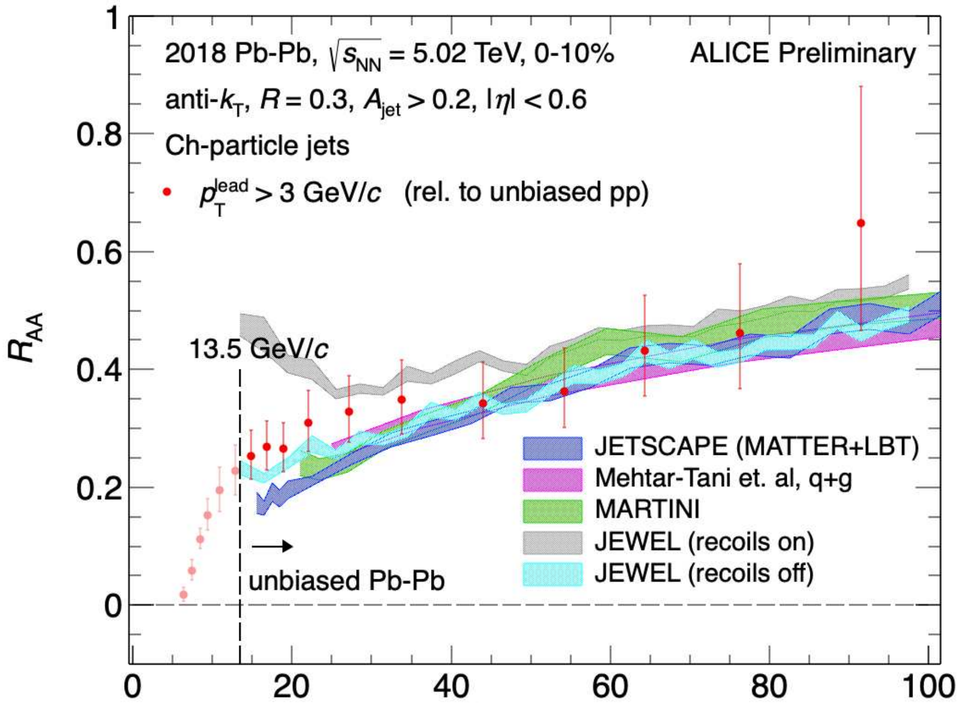
- **We take advantage of the Run 3 statistics**

→ Multi-dimensional measurement

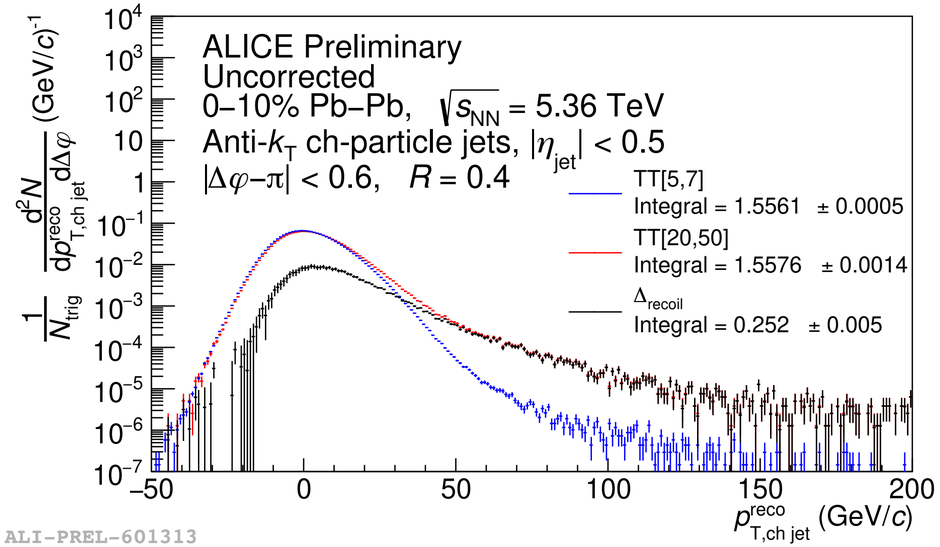
$$\Delta_{recoil} = \left.\frac{1}{N_{trig}} \frac{d^3N_{jet}}{dp^{ch}_{T,jet} d\Delta\varphi d\Delta R}\right|_{TT_{sig}} - c_{ref} \left.\frac{1}{N_{trig}} \frac{d^3N_{jet}}{dp^{ch}_{T,jet} d\Delta\varphi d\Delta R}\right|_{TT_{ref.}}$$

Summary and Outlook

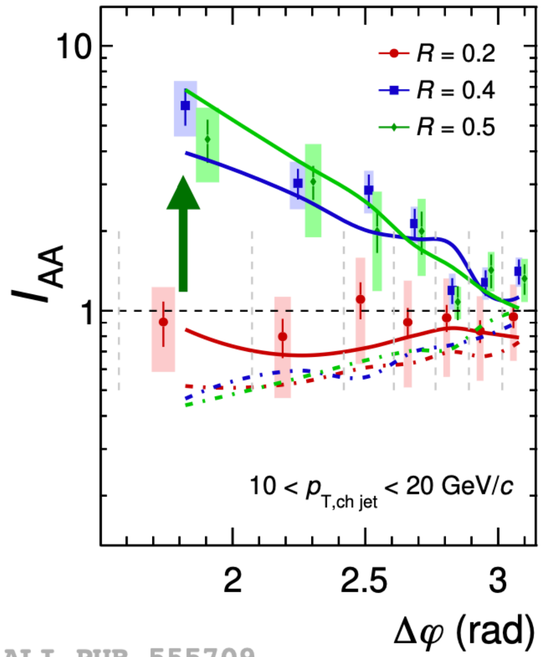
- **Statistical background correction enables incisive measurements at low $p_{\mathrm{T,jet}}$ and large R**
- **Striking phenomena at low $p_{\mathrm{T,jet}}$: QGP response**
  - Models fail to describe data
- **Next step: elucidate using jet substructure**



ALI-PREL-605476



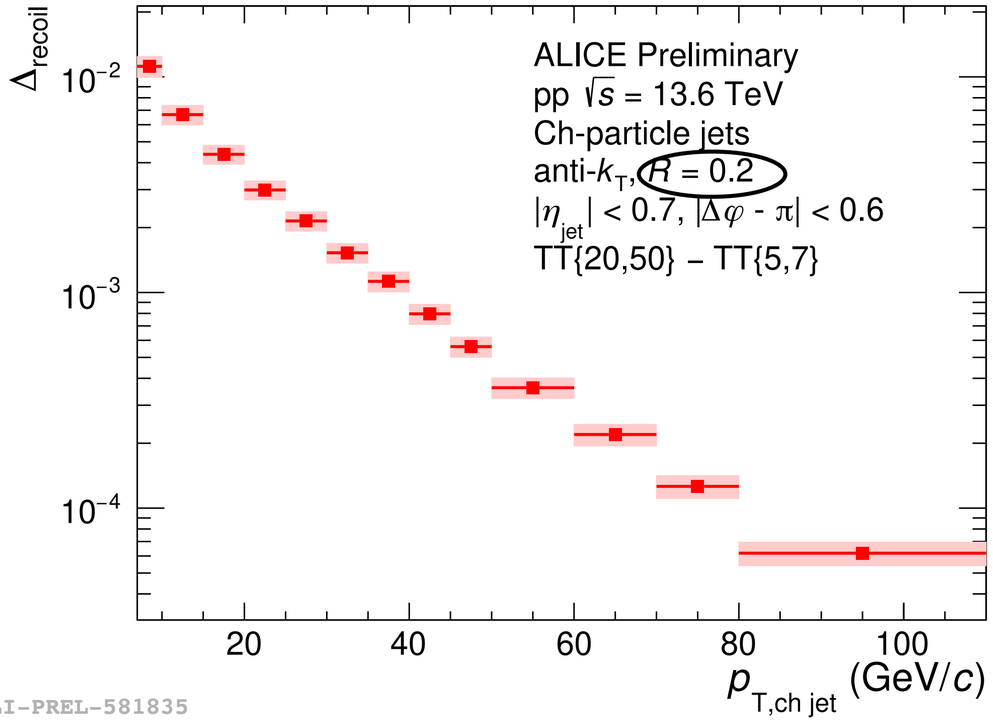
ALI-PREL-601313



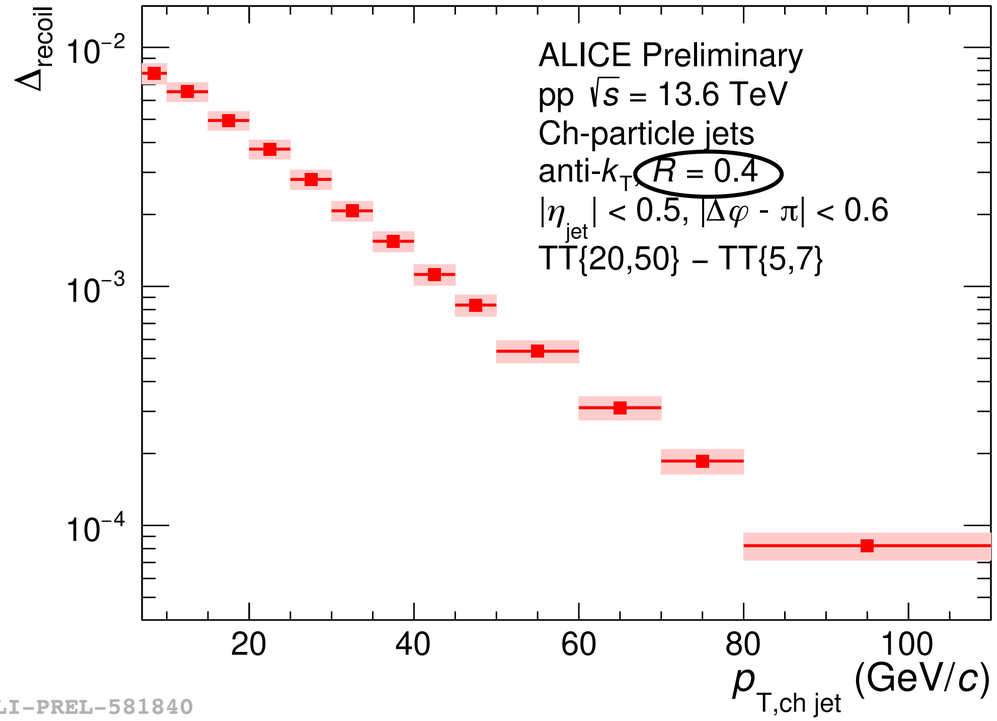
ALI-PUB-555709

Backup

Fully corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T}})$



ALI-PREL-581835



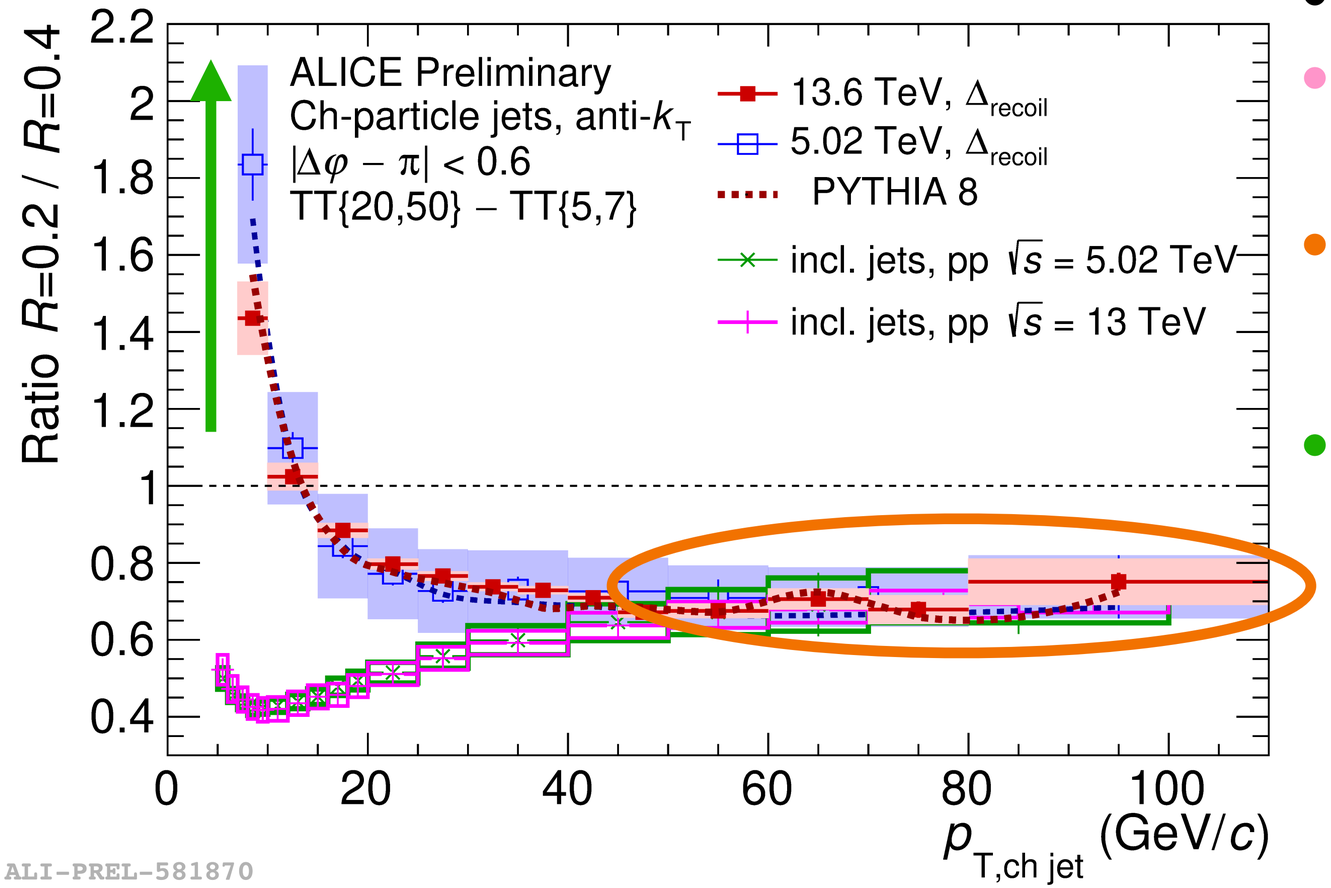
ALI-PREL-581840

- Measure $\Delta_{\mathrm{recoil}}(p_{\mathrm{T}})$ from 7 GeV/c to 110 GeV/c for $R = 0.2$ and $R = 0.4$

Fully corrected yield ratio, $(R = 0.2)/(R = 0.4)$ - pp

Robust jet shape observable - precise theory and experiment

pQCD: Dasgupta, JHEP 04 (2015) 039

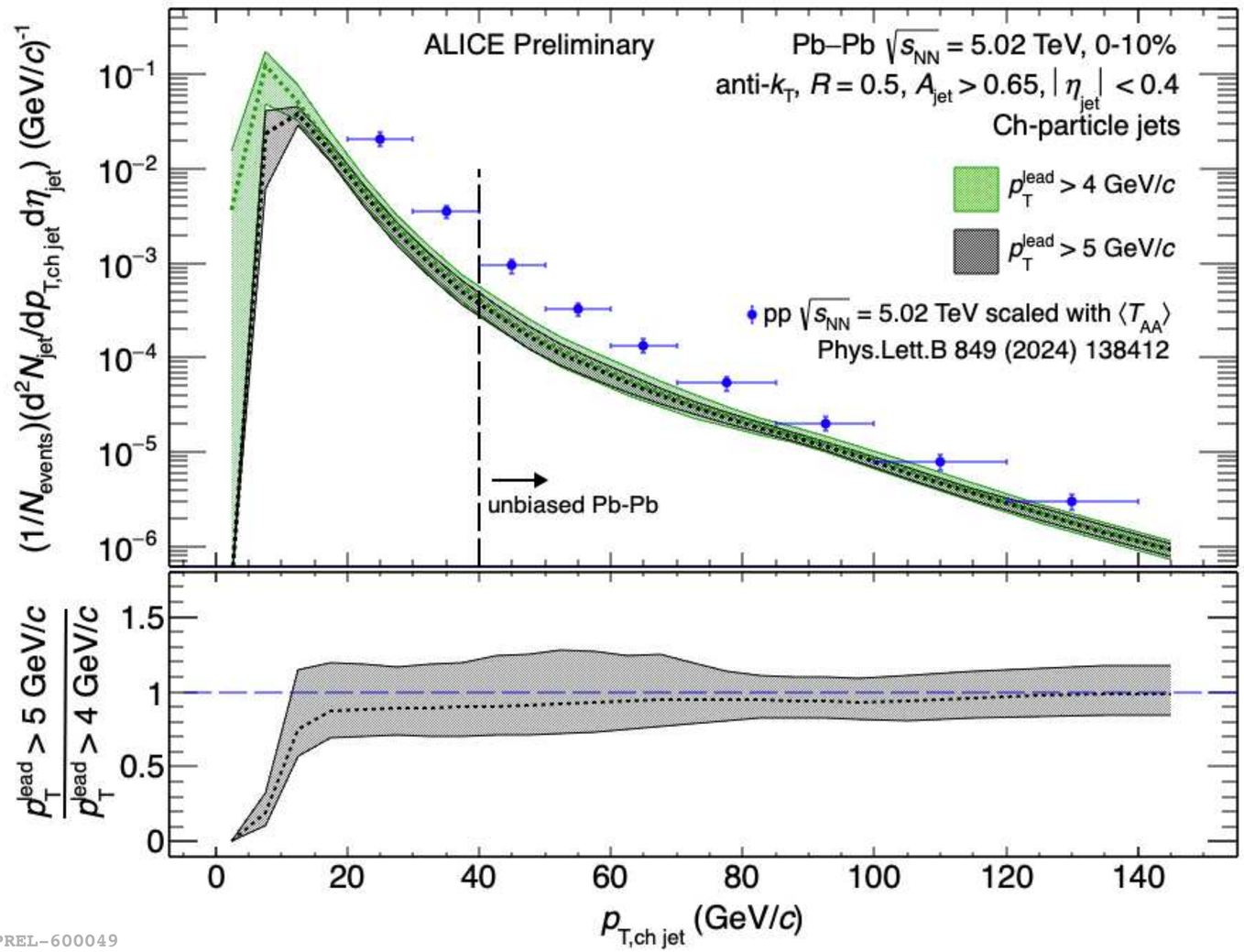


- **Good agreement with Run 2 result**
- **Substantial improvement in the uncertainties with respect to Run 2**
- **Agreement between inclusive jets and semi-inclusive at high p_T**
- **Enhancement in $R = 0.2$ recoil jet yield at low p_T**
  - Bias towards NLO effects when $p_{T,jet} < p_{T,trig}$?
  - Jet splitting?

ALICE, Phys.Rev.C 110 (2024) 1, 014906

Leading track bias

- **Effect of bias < 10% for** $p_{\mathrm{T}} > 40$ **GeV/**c
  - Within systematic uncertainty



ALI-PREL-600049