Search for jet quenching effects in high-multiplicity proton-proton collisions at $\sqrt{s}$ = 13 TeV

follow up of analysis presented at QM 2019 arXiv:2001.09517
with extensive PYTHIA studies

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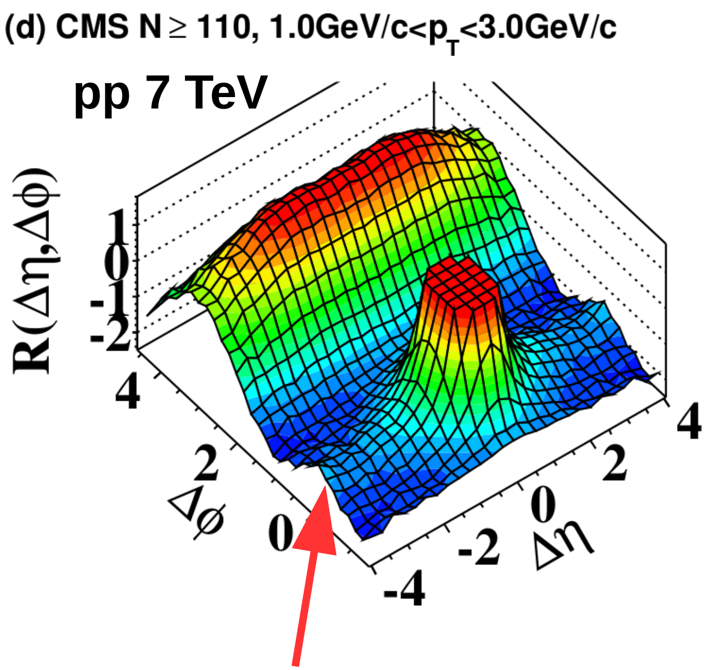
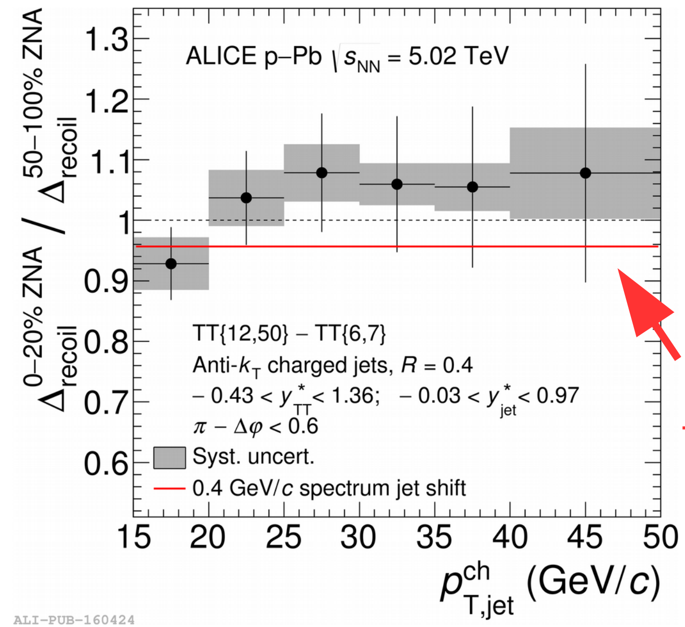
QGP in small collision systems?

CMS, JHEP 09 (2010) 091



ALICE, PLB 783 (2019) 95



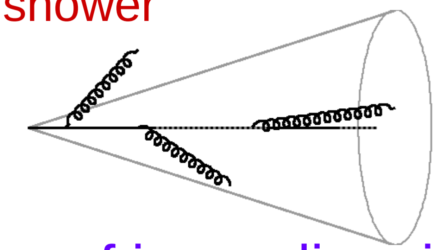
Energy-loss limit for p-Pb 400 MeV @ 90% CL

- Evidence of collective effects in small collision systems
- No significant evidence of jet quenching

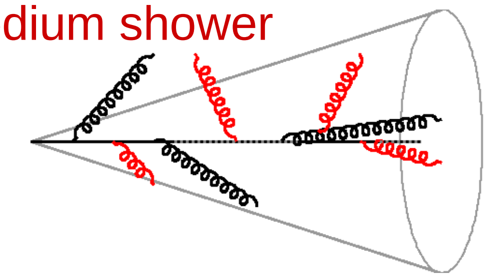
- Next steps for jet quenching searches
  - improve precision
  - other observables
  - other small collision systems

Jet quenching

in-vacuum shower



in-medium shower



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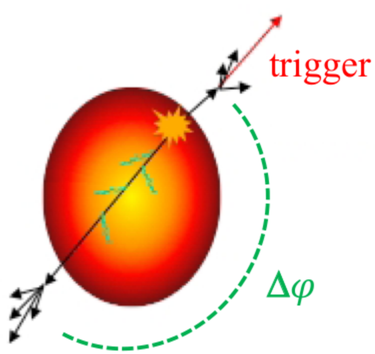
Signatures of in-medium interactions

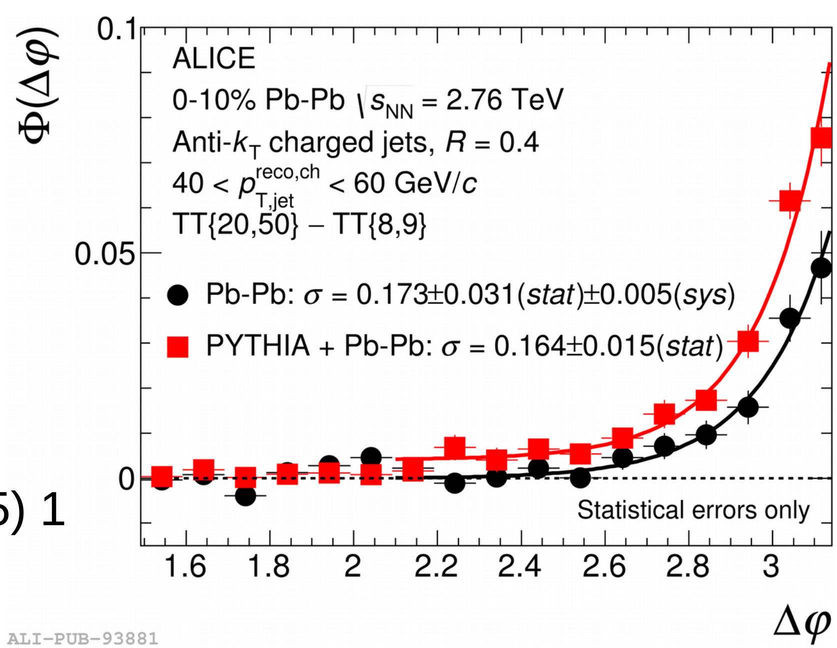
- Energy transport out of cone → yield suppression at high p_T
- Jet substructure modification
- Jet deflection → acoplanarity

Jet quenching in high-multiplicity pp collisions

- Inclusive R_{AA} - Glauber scaling undefined → measurement not possible
- Acoplanarity



ALICE, JHEP 09 (2015) 1



Initial state Sudakov radiation background

L. Chen et al. PLB 773 (2017) 617

pp collisions at $\sqrt{s}$ = 13 TeV

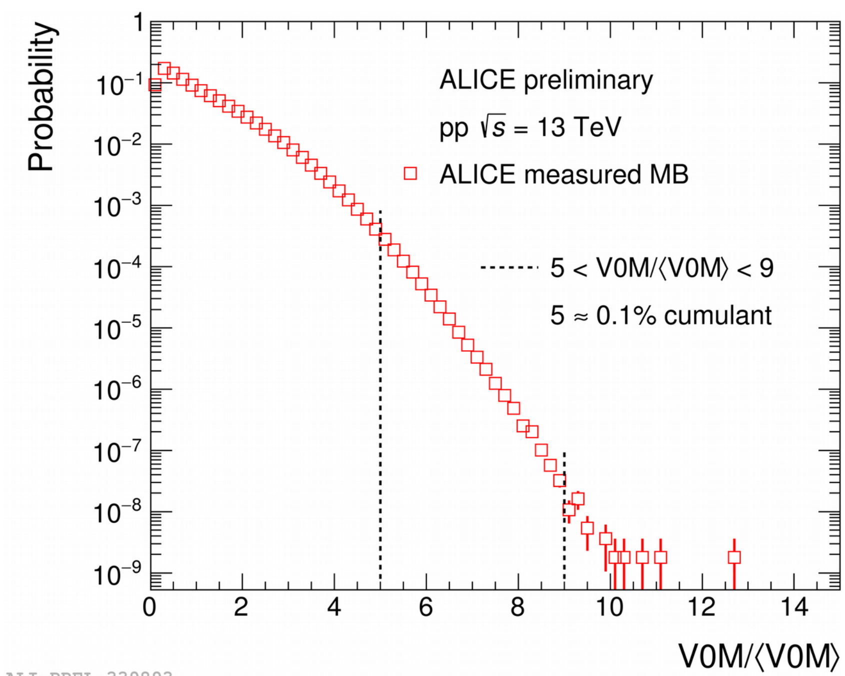
- Data from 2016-2018
- Online triggers:
  - Minimum bias (MB) 0.098 pb^{-1} (3.2G events)
  - High multiplicity (HM): 13 pb^{-1}
- Offline event activity (EA) selection:

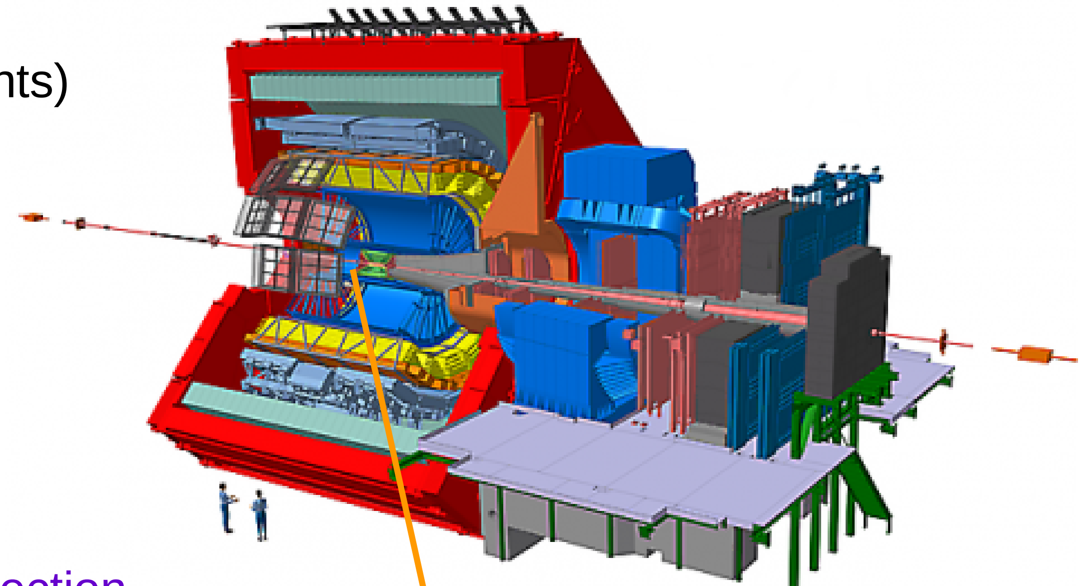
  V0M = V0A + V0C

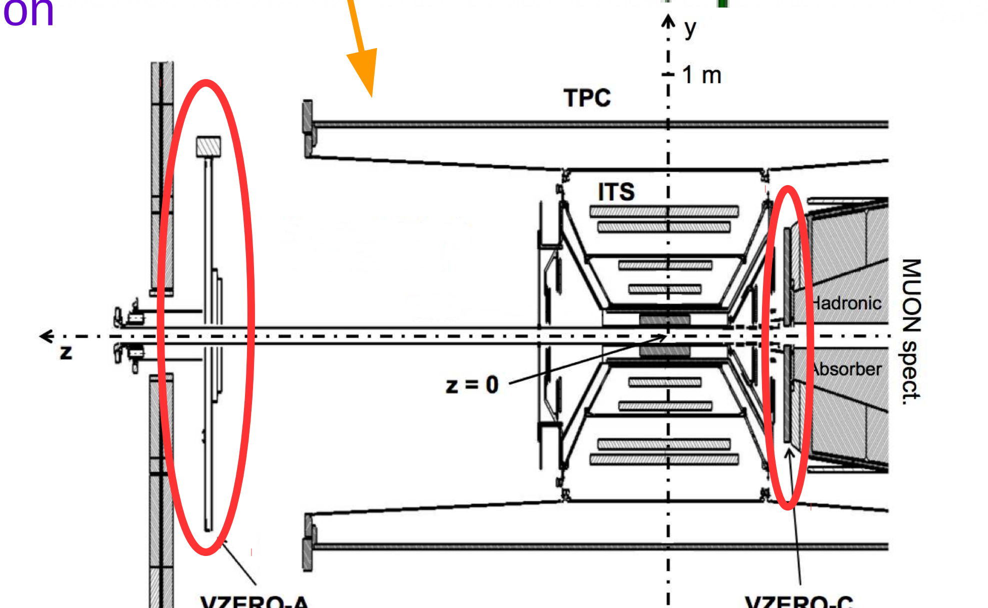
  Scaled multiplicity V0M/⟨V0M⟩

  ⟨V0M⟩ = mean of MB distribution

  Enables comparison of runs with differing V0 gain, and with theory
- 5 < V0M/⟨V0M⟩ < 9 ≈ 0.1% of MB cross section



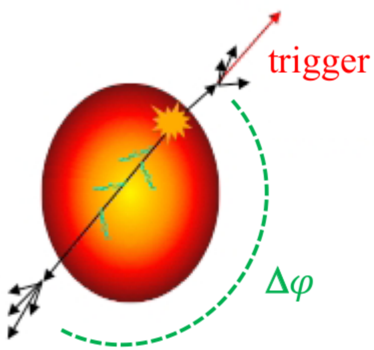


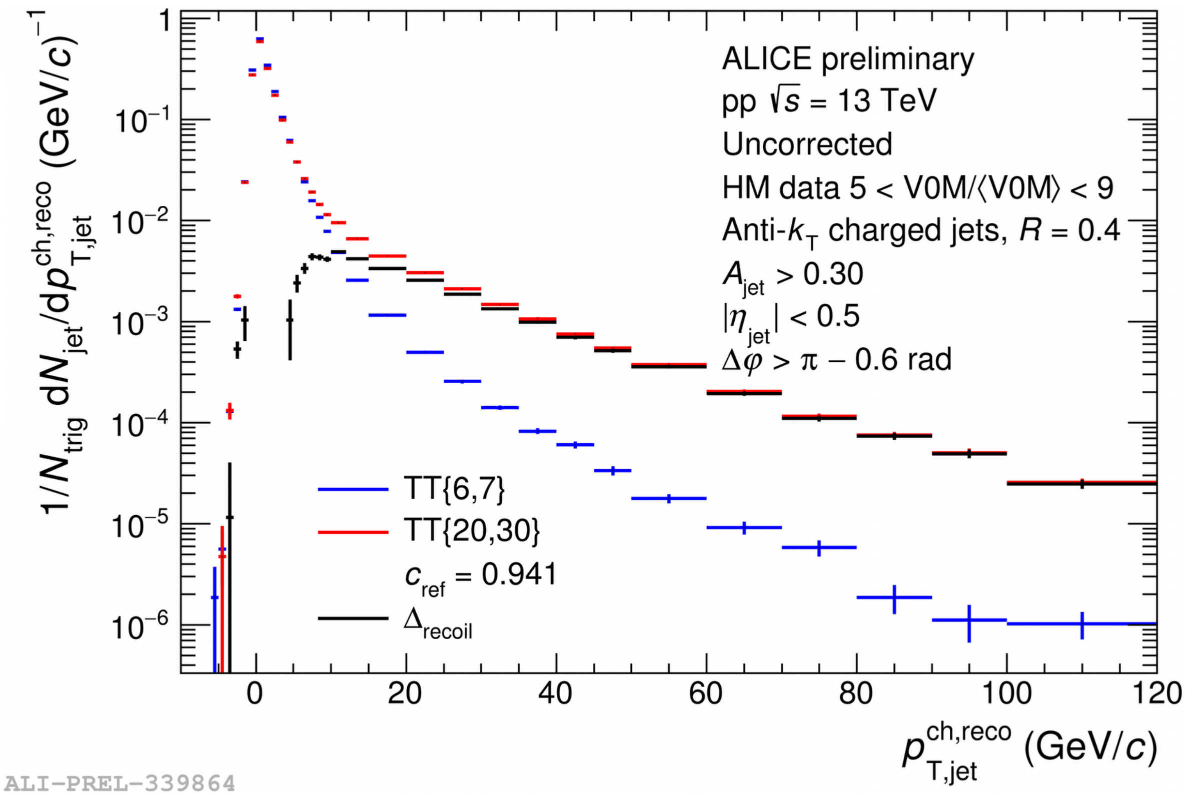


V0A : 2.8 < η < 5.1

V0C : -3.7 < η < -1.7

Semi-inclusive recoil jet analysis





Not corrected for instrumental effects and background p_T-smearing

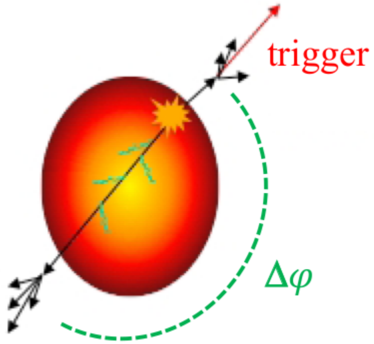
A_{jet} = jet area

- Charged-particle jets recoiling from high-p_T hadron (Trigger Track, TT)
- Jet-wise correction for estimated event density ρ: $p_{T,jet}^{ch\ reco} = p_{T,jet}^{ch\ raw} - \rho \cdot A_{jet}$
- Ensemble-level: correct for uncorrelated jet yield

$$\Delta_{recoil}\left(p_{T,jet}^{ch}\right) = \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_{T,jet}^{ch}}\Bigg|_{TT\{20,30\}} - c_{ref} \cdot \frac{1}{N_{trig}} \frac{dN_{jet}}{dp_{T,jet}^{ch}}\Bigg|_{TT\{6,7\}}$$

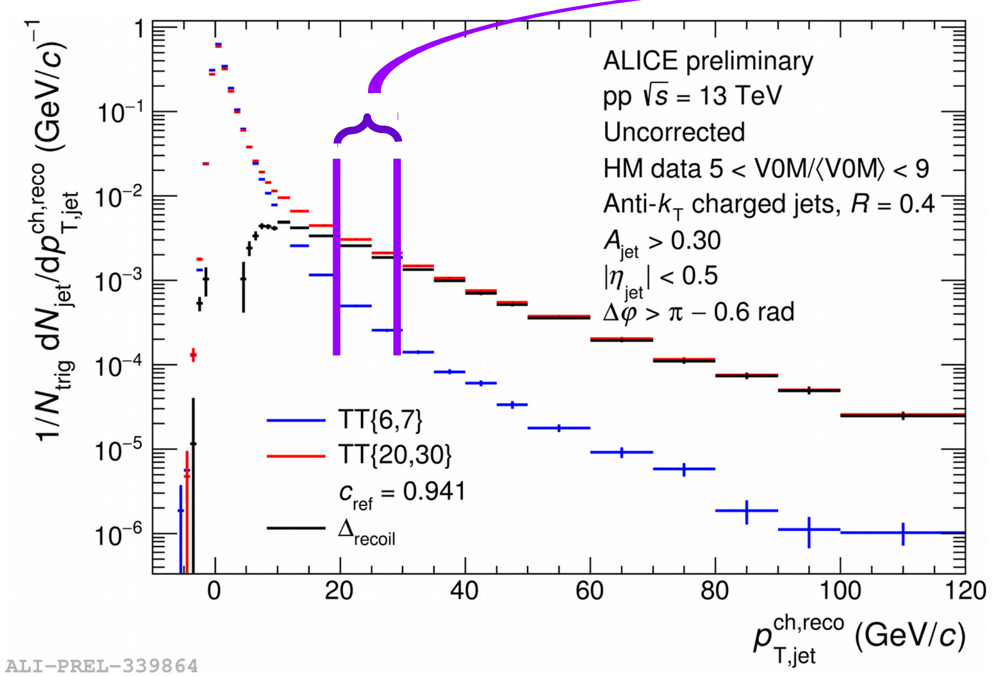
c_{ref} ~0.95 data-driven correction factor due to observed conservation of total jet number

Acoplanarity with Δ_{recoil}

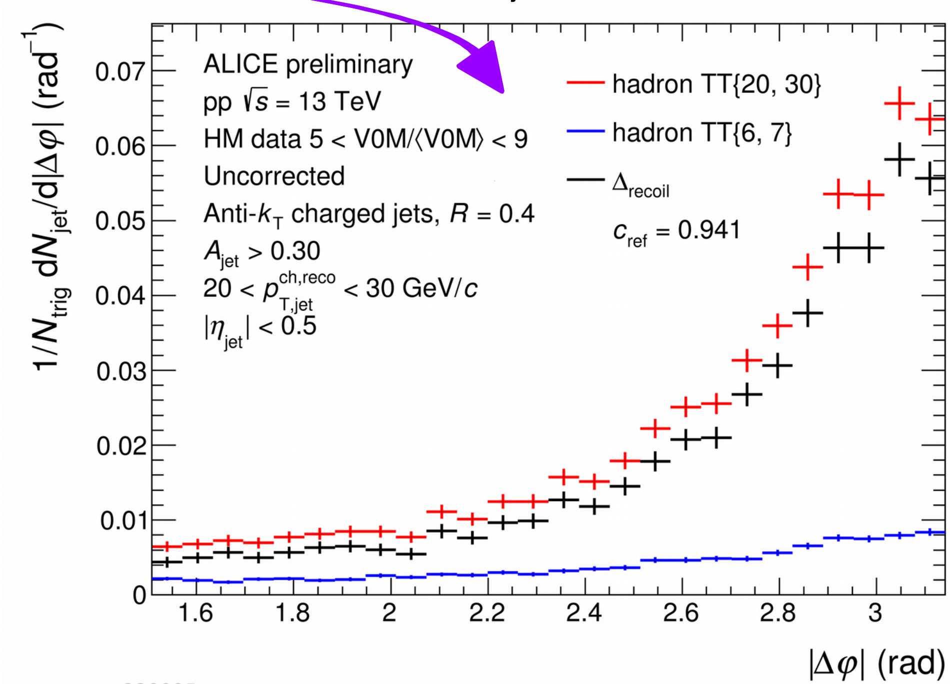


Construct Δ_{recoil} as a function of TT-jet opening angle:

$$\Delta_{recoil}(\Delta\varphi) = \frac{1}{N_{trig}} \frac{dN_{jet}}{d\Delta\varphi}\bigg|_{TT\{20,30\}\,\&\,p_{T,jet}^{ch}} - c_{ref} \cdot \frac{1}{N_{trig}} \frac{dN_{jet}}{d\Delta\varphi}\bigg|_{TT\{6,7\}\,\&\,p_{T,jet}^{ch}}$$



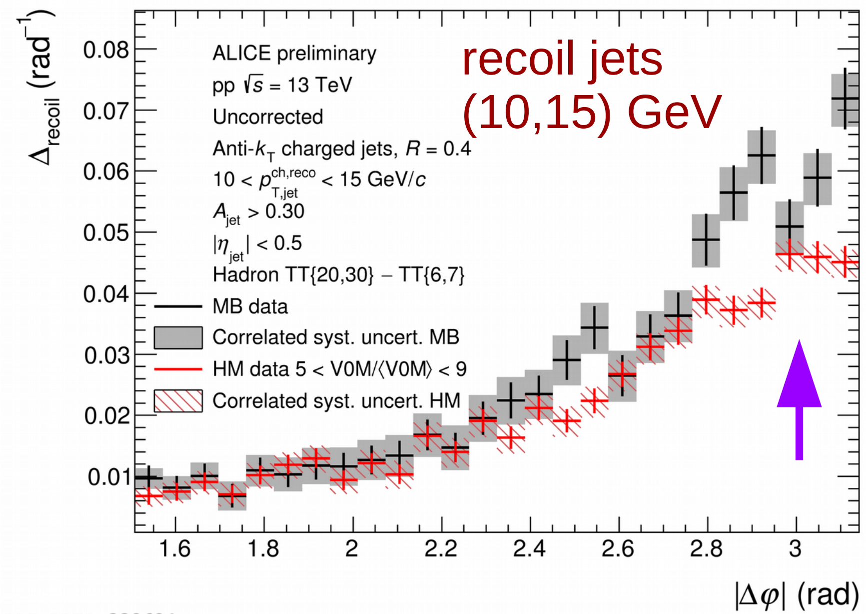
$20 < p_{T,jet}^{ch} < 30$ GeV/c



Acoplanarity versus event activity

Data not unfolded; estimated uncertainty from tracking efficiency

Significant suppression of HM wrt MB; effect is stronger for recoil jets with lower p_T



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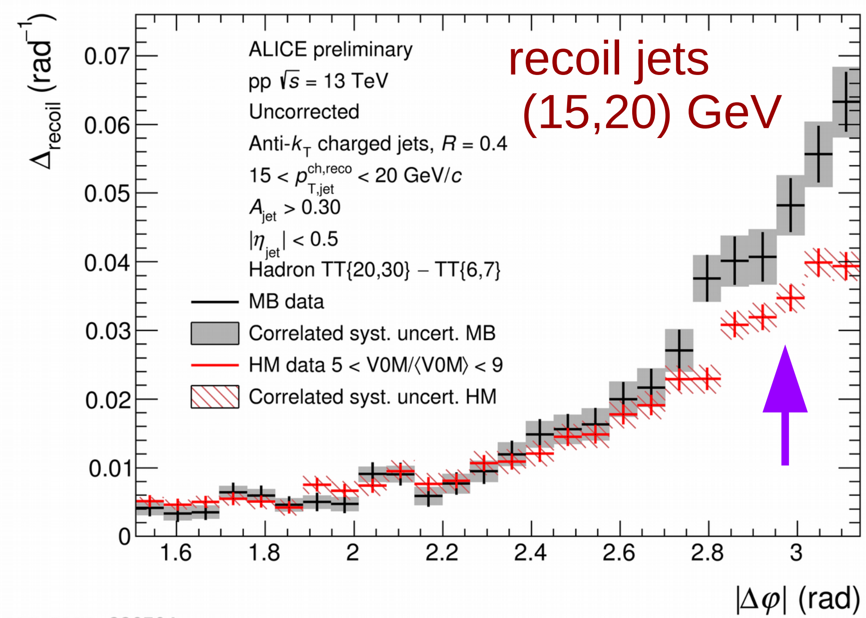

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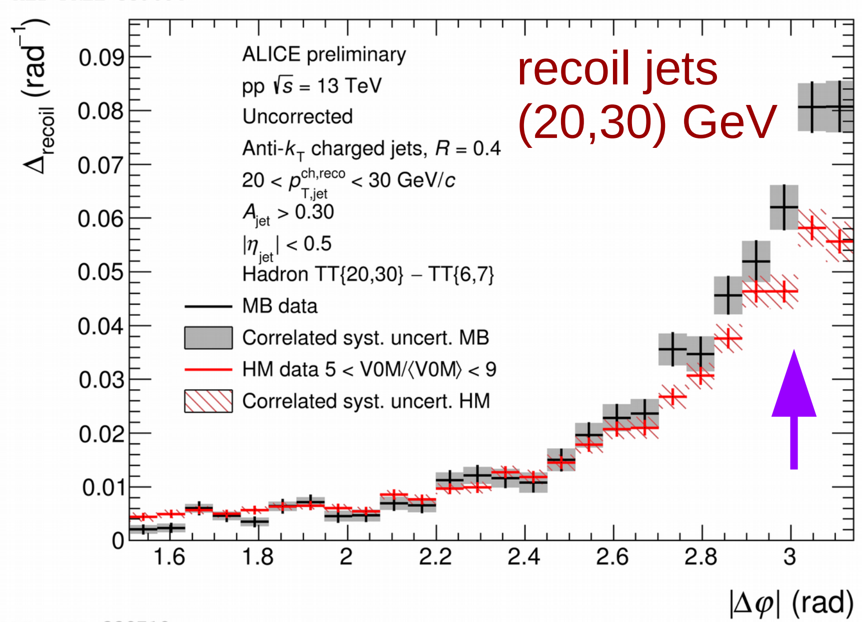

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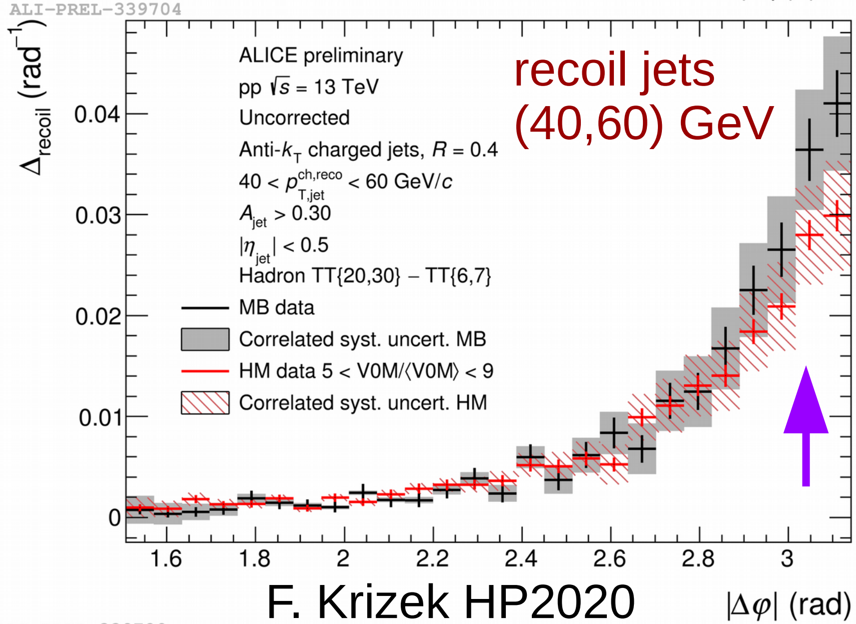

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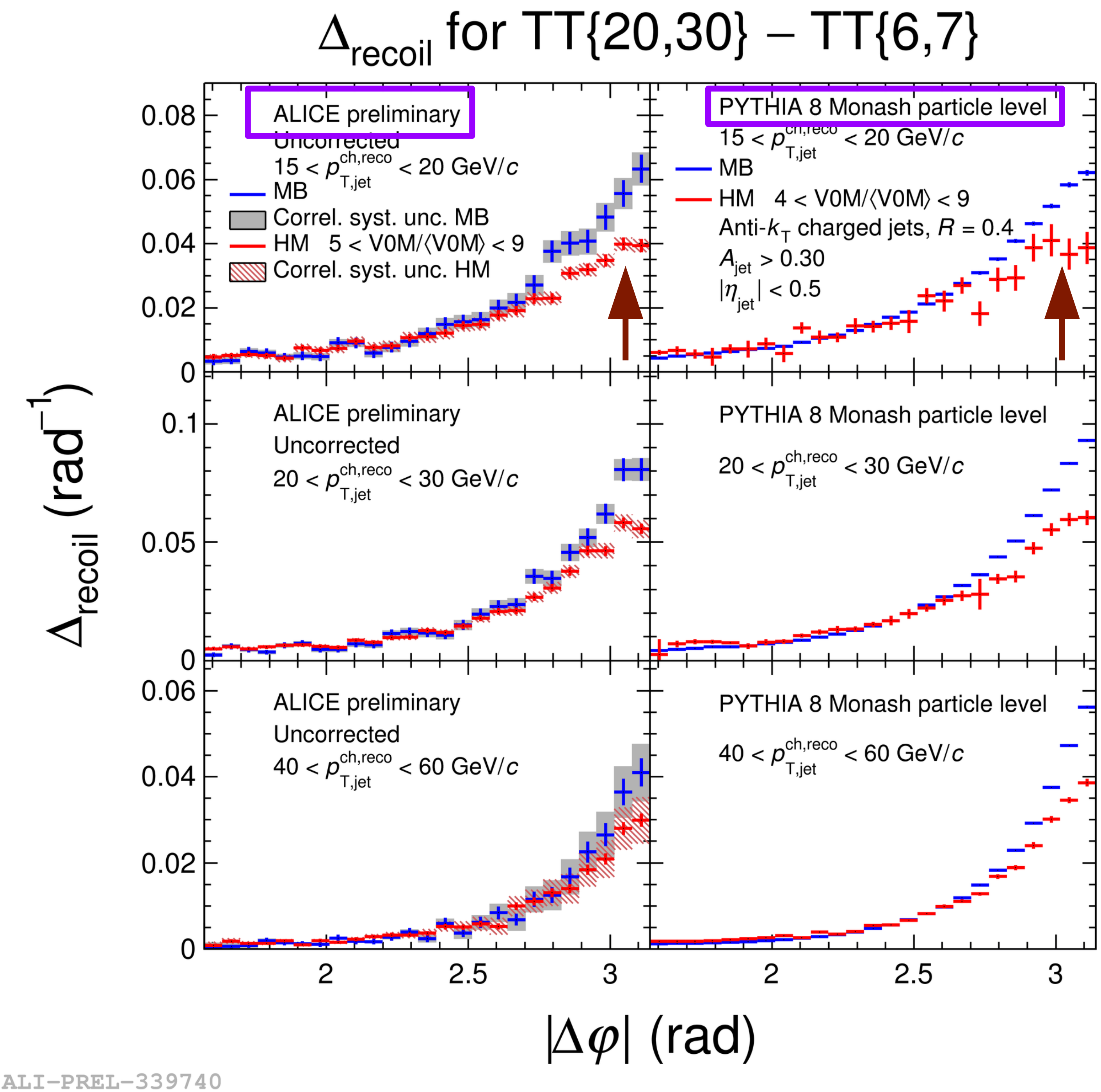
Δ_{recoil} in raw data and PYTHIA



Qualitative comparison to PYTHIA 8 Monash shows similar suppression pattern →

The effect may not be due to jet quenching

Use PYTHIA to explore the origin of the effect

Open questions from QM

- Is the enhanced acoplanarity at HM seen in PYTHIA due to color reconnections?

  - compare PYTHIA color reconnections on/off

- Does the HM requirement bias towards multi-jet final states?

  - look at jet distributions in PYTHIA

New PYTHIA high statistics simulations

- Charged particles $|\eta_{\mathrm{trk}}| < 6$

  Fully covering V0C : $-3.7 < \eta < -1.7$ and V0A : $2.8 < \eta < 5.1$

- Events containing TT{20,30} or TT{6,7} in $|\eta| < 0.9$
- Anti-k_{T} track-based jets with $R = 0.4$ in

  1) ALICE central barrel: $|\eta_{\mathrm{jet}}| < 0.5$

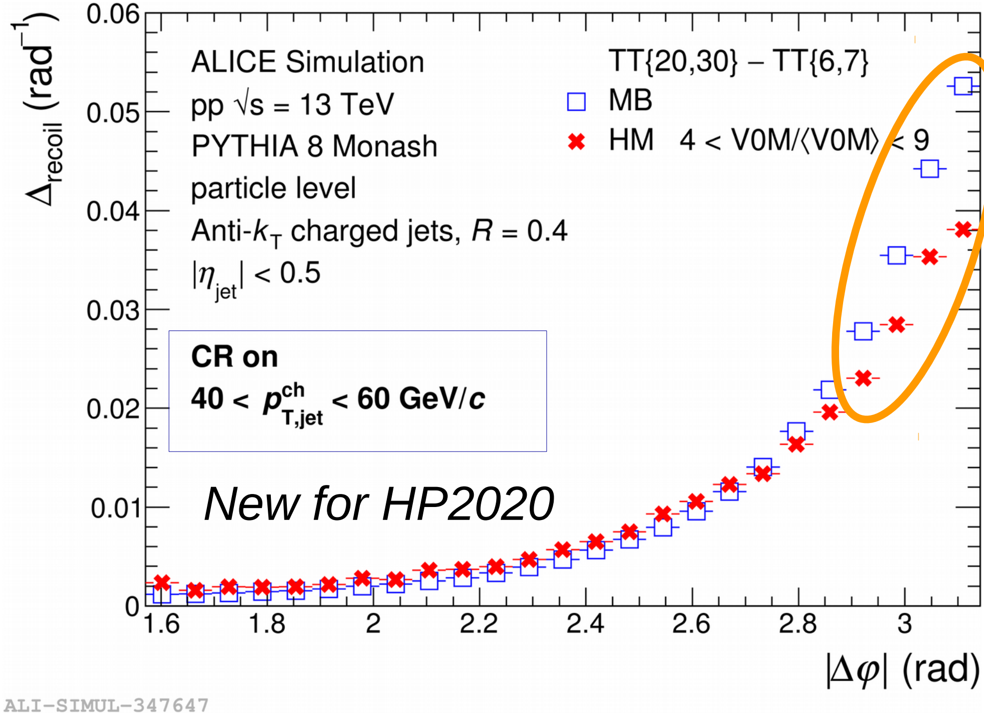
  2) broad η range: $|\eta_{\mathrm{jet}}| < 5.6$

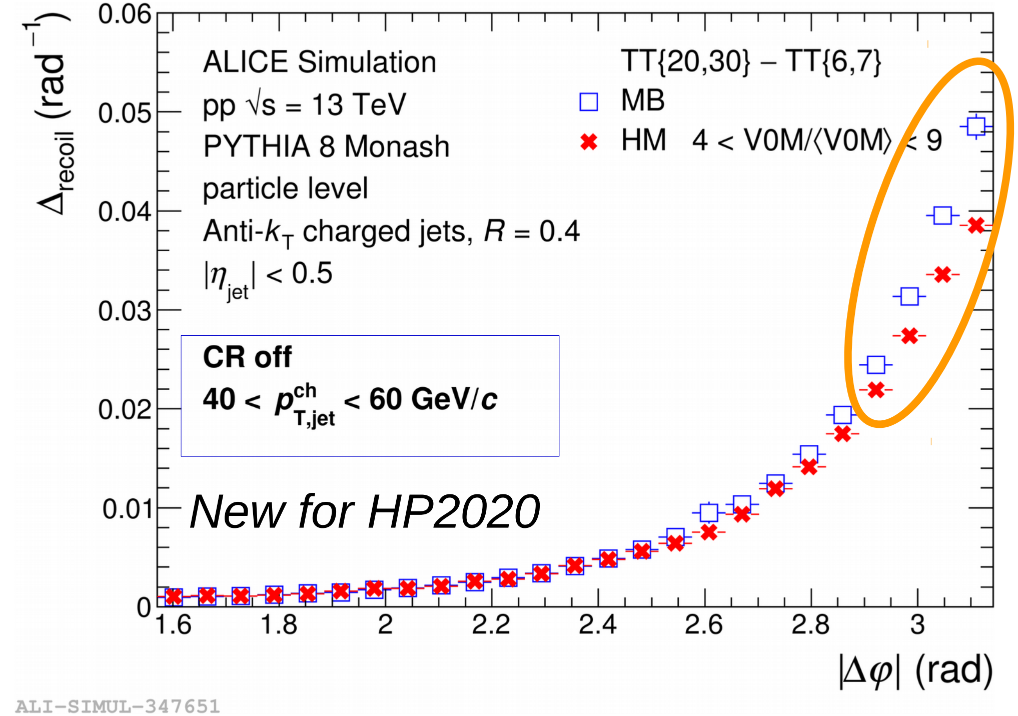
- Color reconnection on/off

V0M defined by the number of charged, final state particles in V0A & V0C

HM in PYTHIA is $4 < \mathrm{V0M}/\langle\mathrm{V0M}\rangle < 9$; HM in real data is $5 < \mathrm{V0M}/\langle\mathrm{V0M}\rangle < 9$

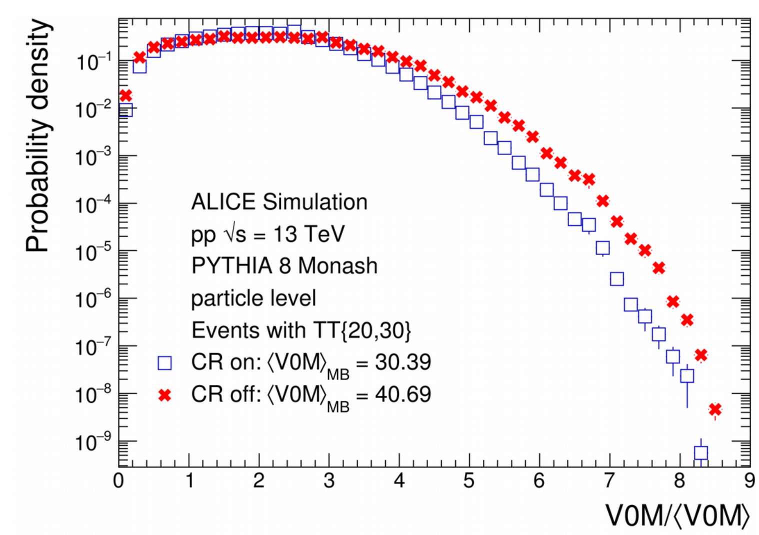
PYTHIA 8 Monash: Δ_{recoil} in ALICE acceptance for CR on/off





Does color reconnection on/off show qualitative difference? → No

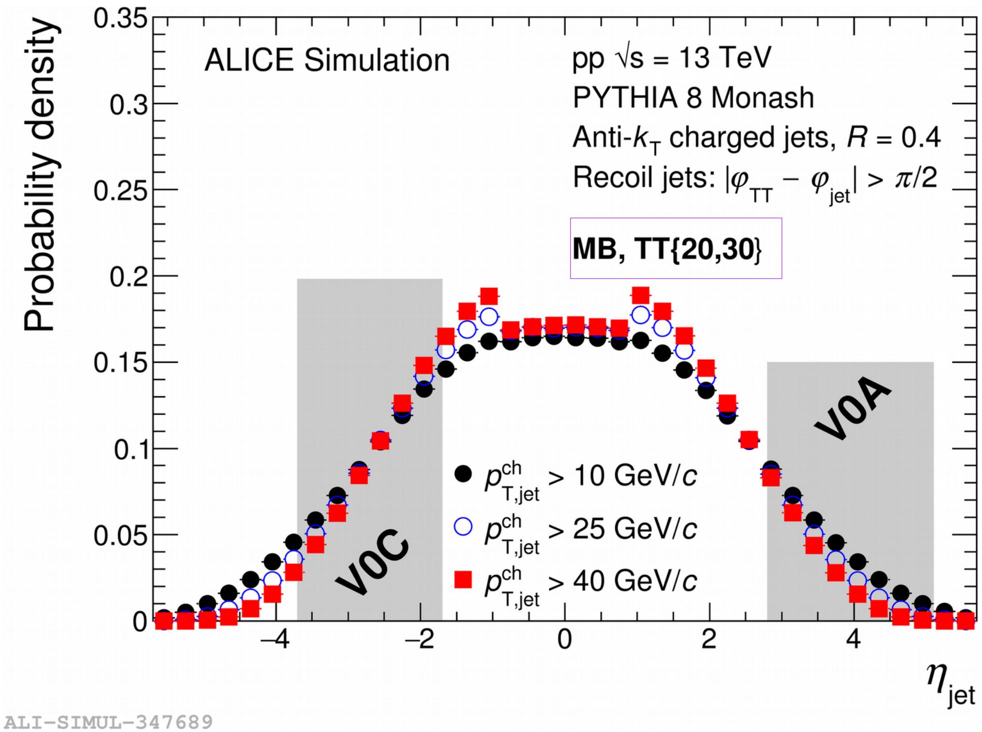
CR is not the primary factor generating enhanced acoplanarity in HM events



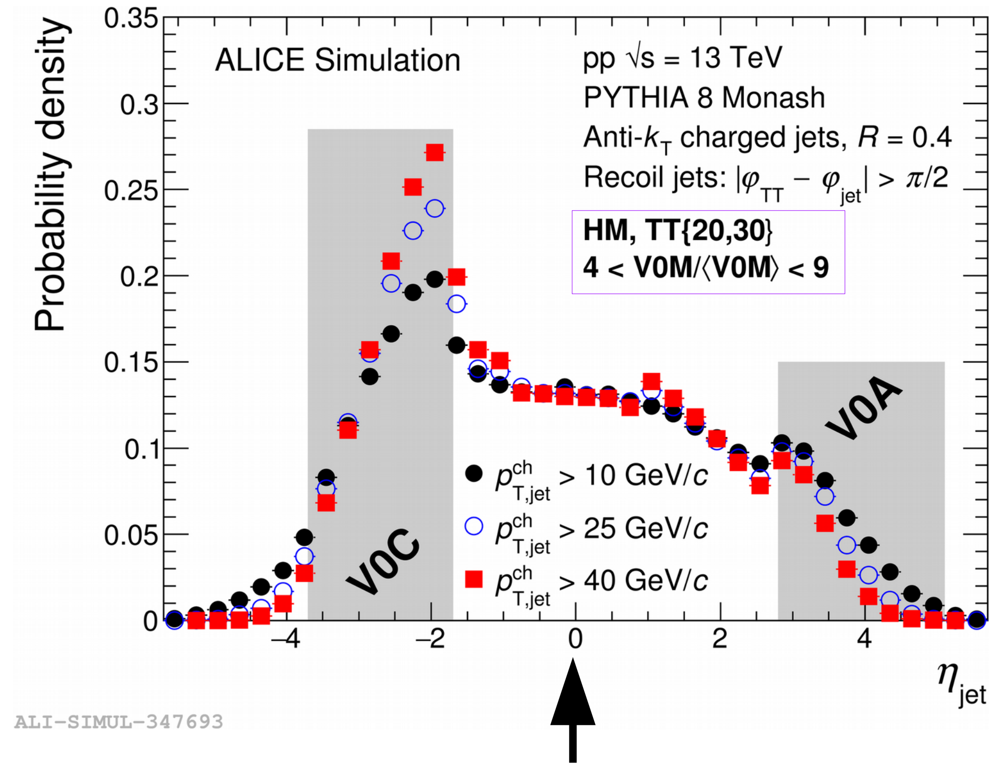
PYTHIA 8 Monash: recoil jet η distribution vs $p_{T,jet}$

New for HP2020

MB



HM

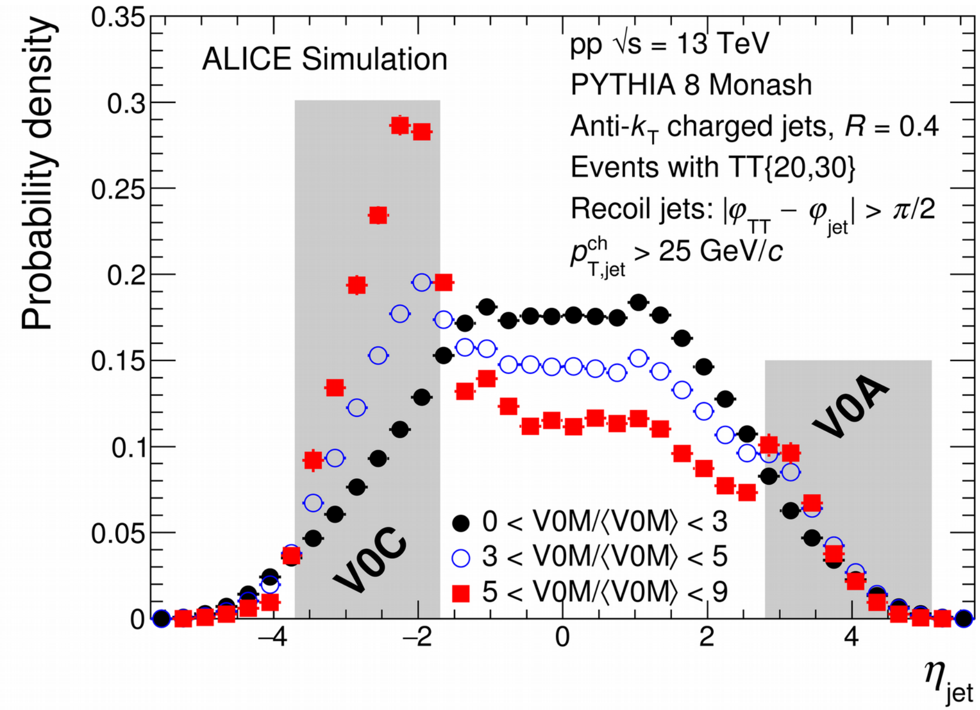


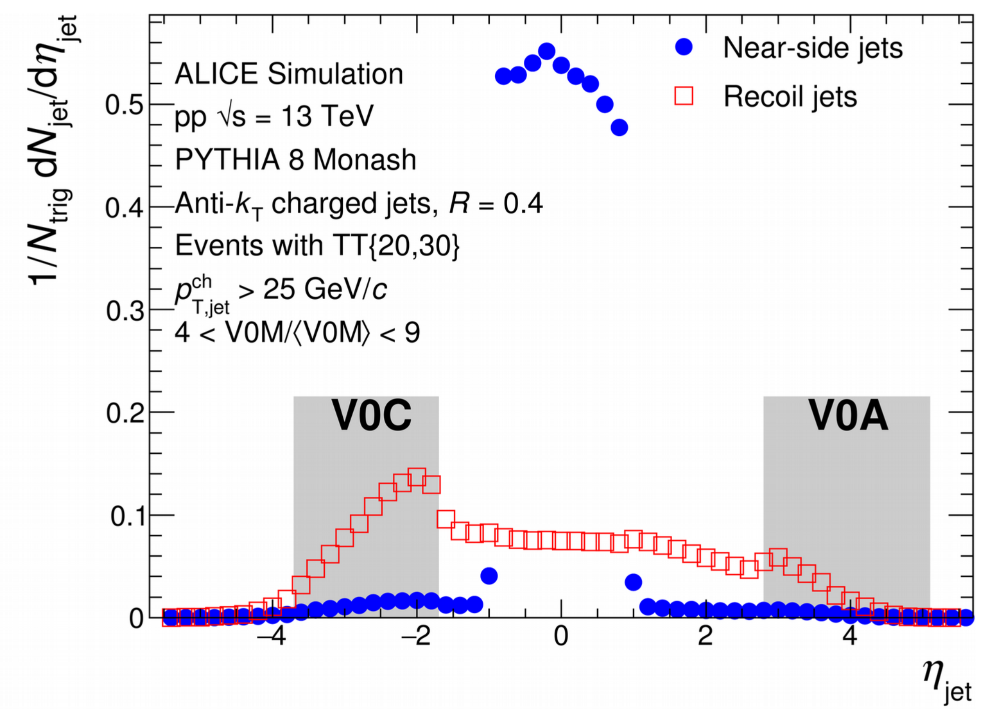
HM events:

- significant bias in distribution of high-p_T recoil jets
- strong enhancement in forward trigger acceptance
- collision system is symmetric but V0s have asymmetric coverage
  - sharply different effects on η-bias

PYTHIA 8 Monash: recoil jet η distribution vs event activity (EA)

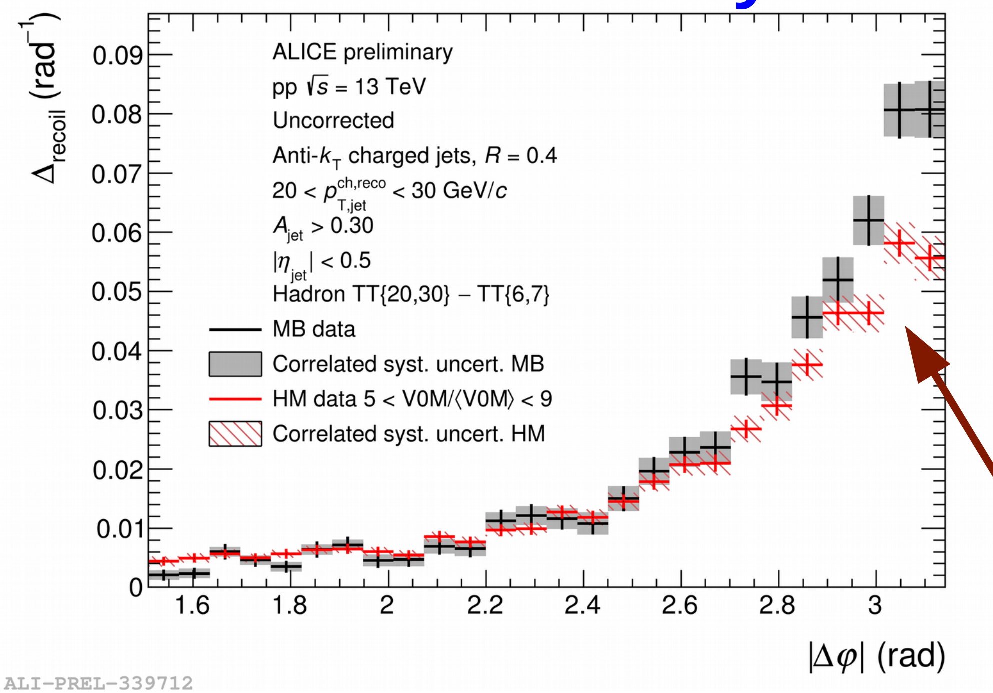
New for HP2020

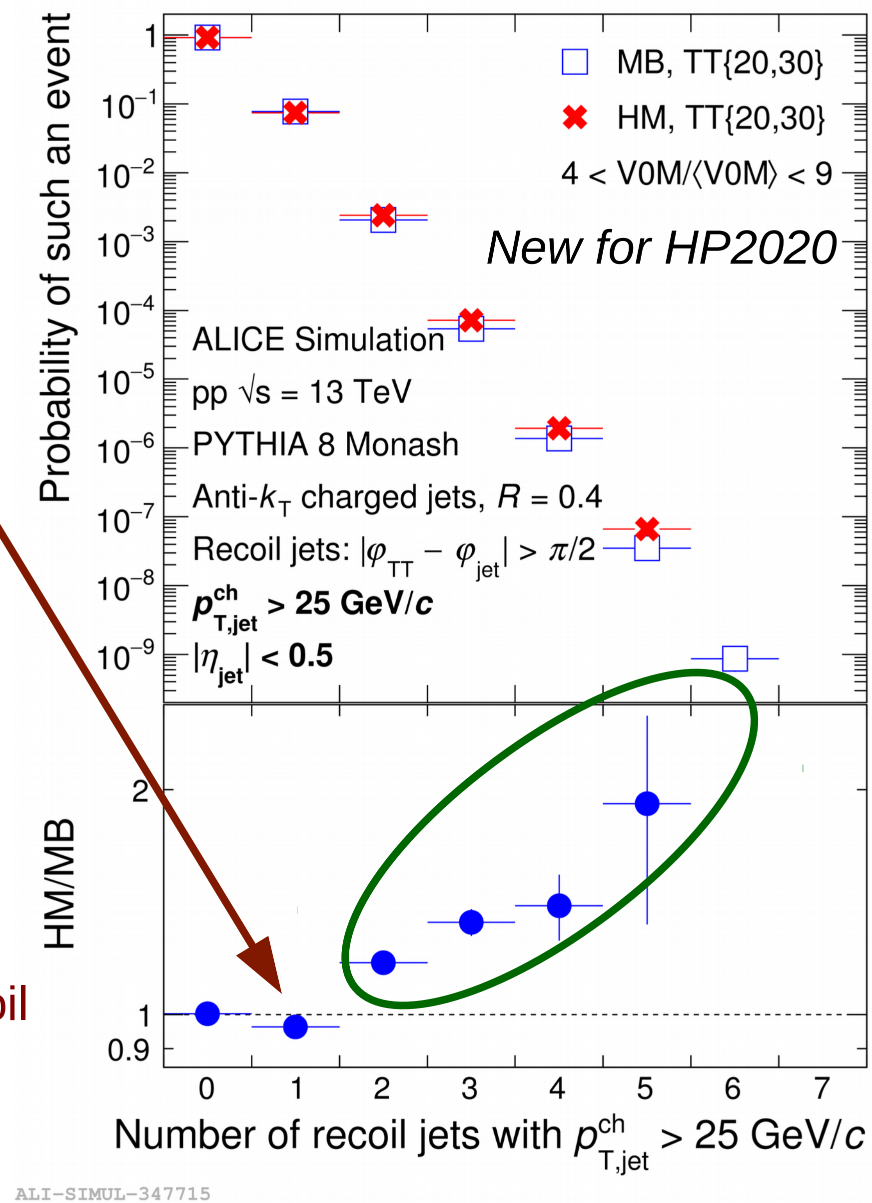




- Does high EA selection enhance:
  - recoil jet distribution at large $|\eta|$? → Yes
  - near-side jet distribution at large $|\eta|$? → No → HM selection biases recoil jets

PYTHIA 8 Monash: # high-p_T recoil jets vs Event Activity in ALICE acceptance





New observable to characterize the multi-jet distribution vs EA:

Distribution of the number of recoil jets above p_T threshold per triggered event

→ HM trigger suppresses events with 1 hard recoil jet in the ALICE central barrel

→ HM trigger enhances multi-jet events in small systems

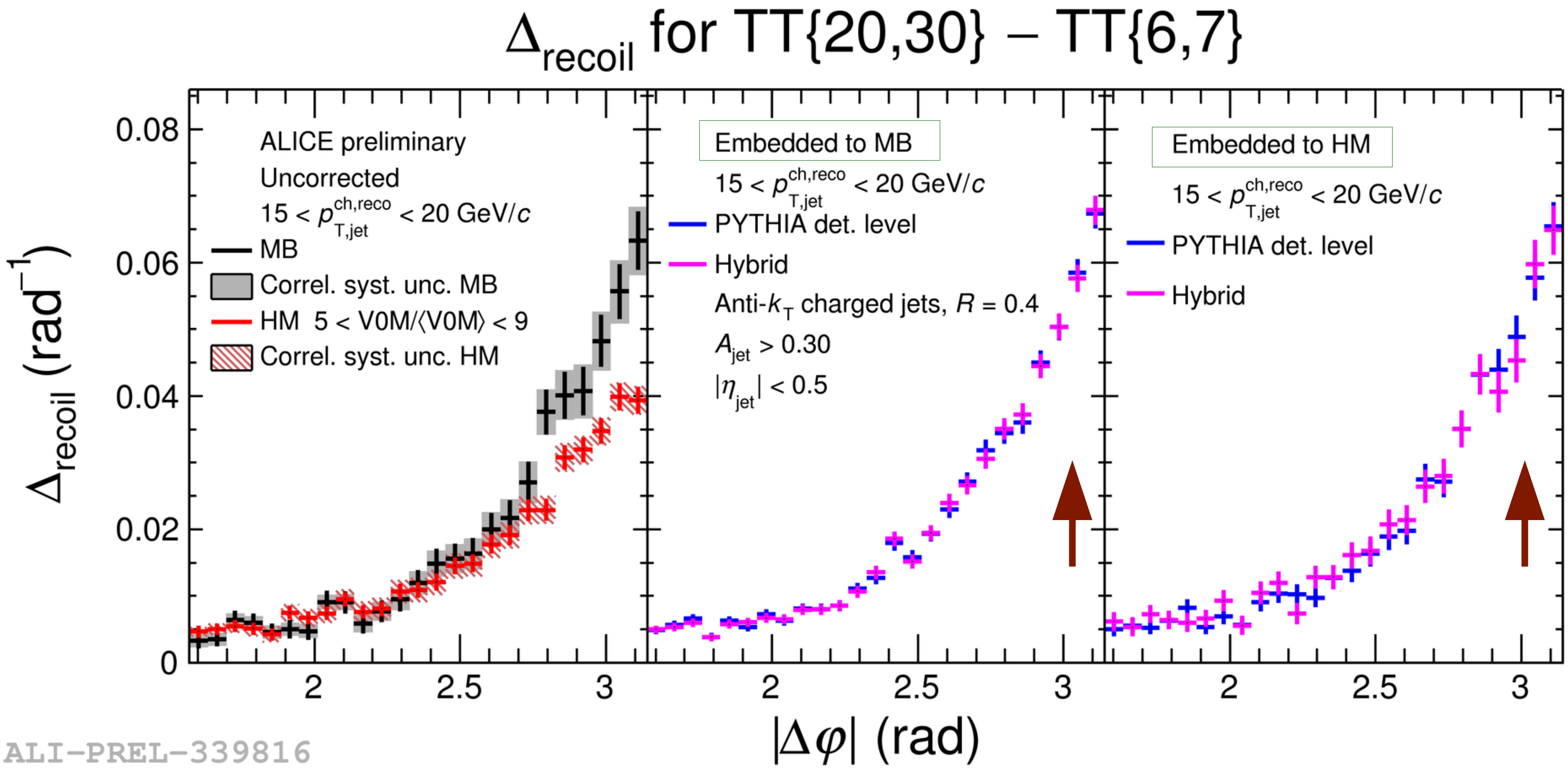
Summary

- ALICE data: Recoil jet yield suppression and broadening in HM events for $p_{T,\mathrm{ch\ jet}} < 60$ GeV/c
  - Similar effect observed in PYTHIA
- New PYTHIA studies:
  - effect not due to color reconnection in model
  - **HM induces bias towards multi-jet events in small systems**
  - **This bias must be taken into account in all studies of small collision systems at high multiplicity**
- Direct observation of multi-jet bias of ALICE HM trigger?
  - PYTHIA shows significant signal
  - Next step: apply to ALICE data

Backup

Systematic check:
Is the effect from high track density ?

ALICE

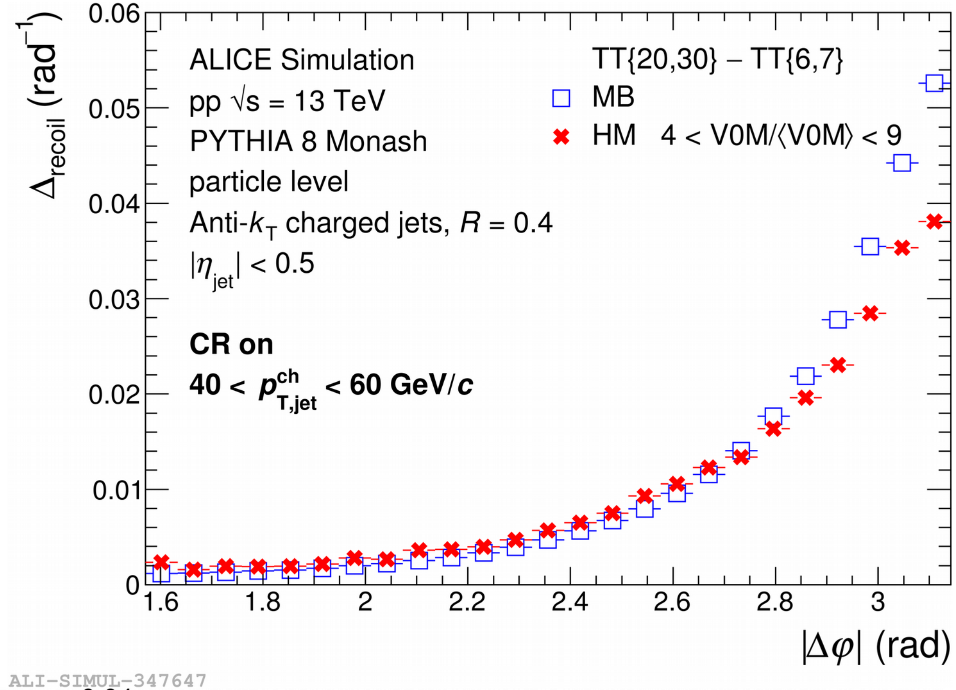


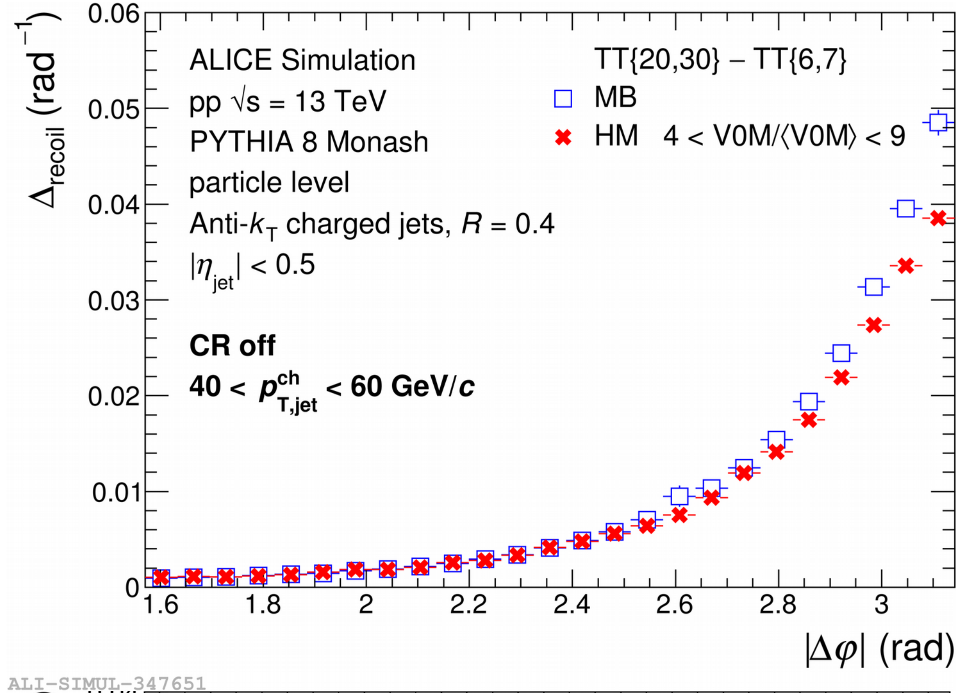
- Generated PYTHIA detector-level events with TT
- Embeded them into real MB and HM pp events
- Compared Δ_{recoil} distributions from PYTHIA Truth and Embedding (Hybrid)

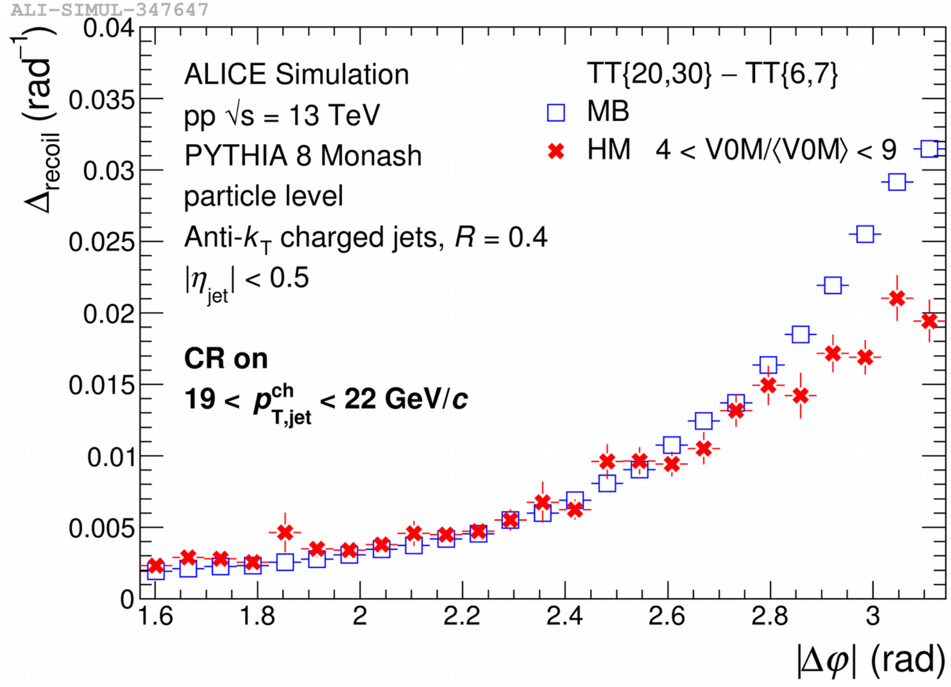
All distributions agree →

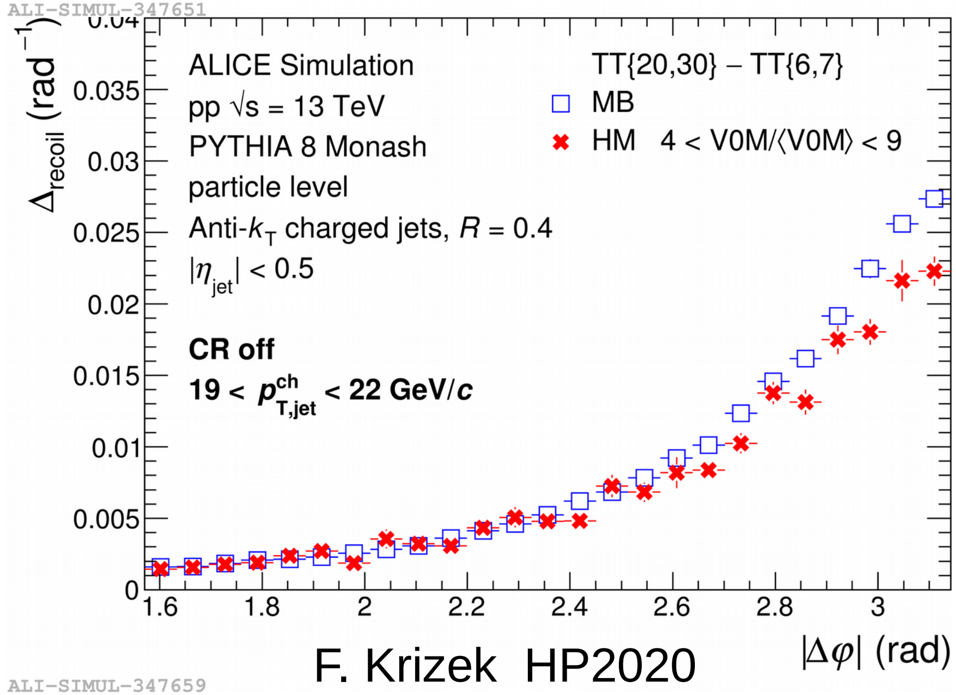
suppression is not due to instrumental effects or analysis procedure

PYTHIA 8 Monash: Δ_{recoil} with color reconnection on/off









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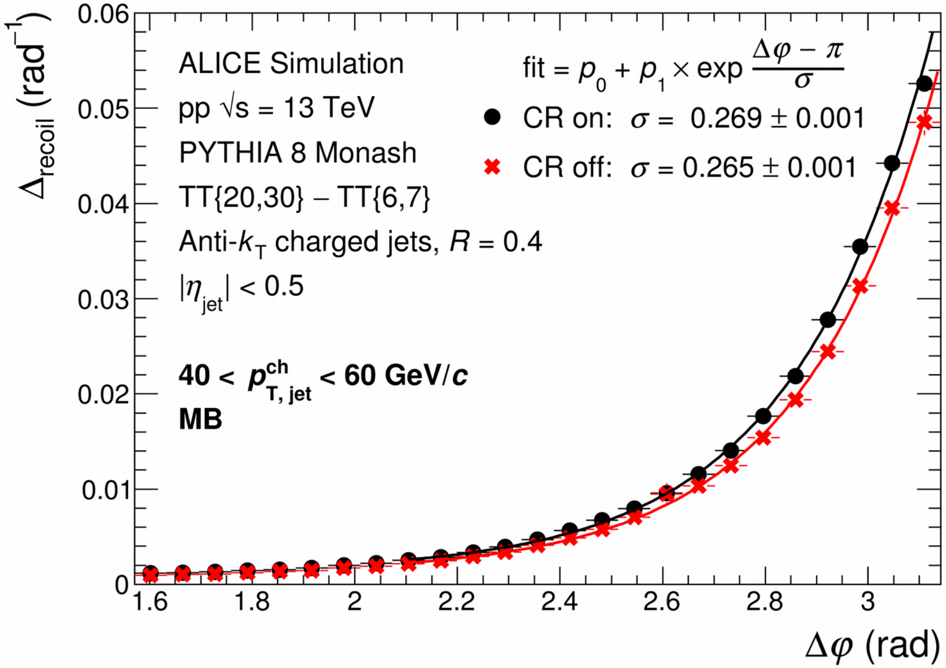
PYTHIA 8 Monash: Δ_{recoil} with color reconnection off/on



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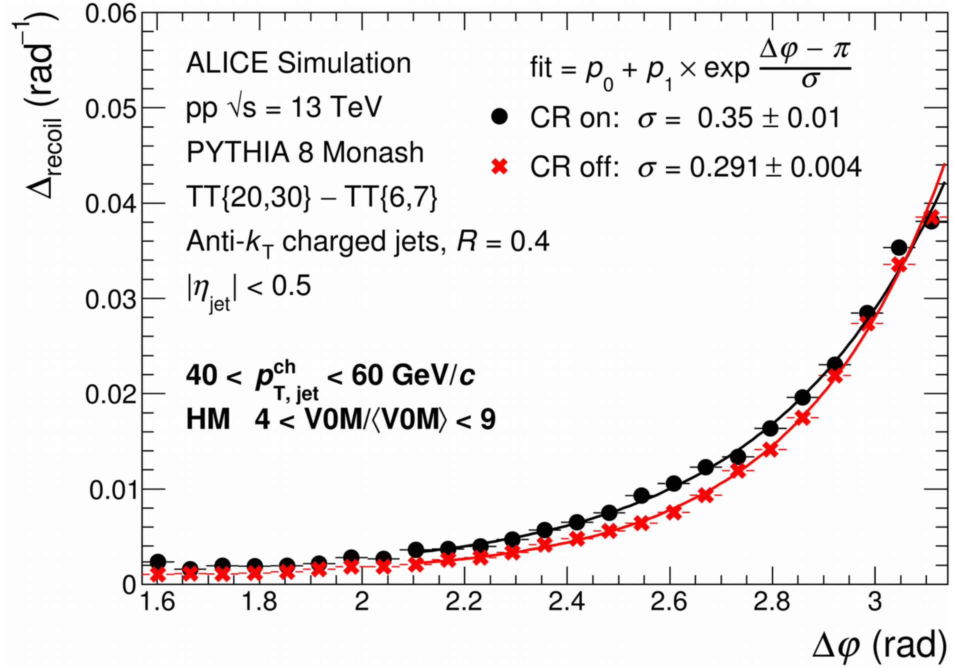

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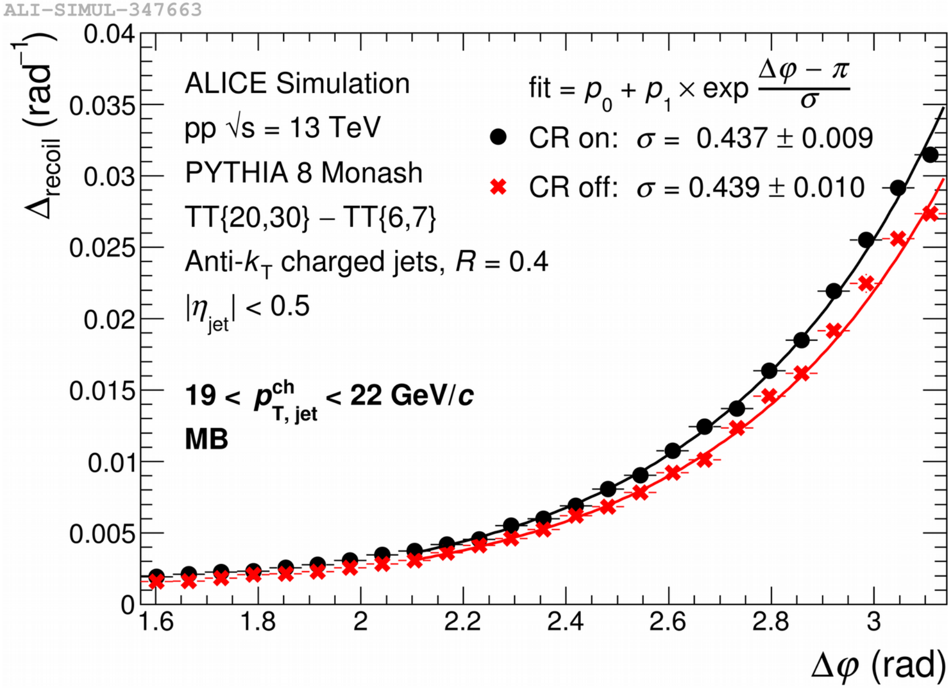

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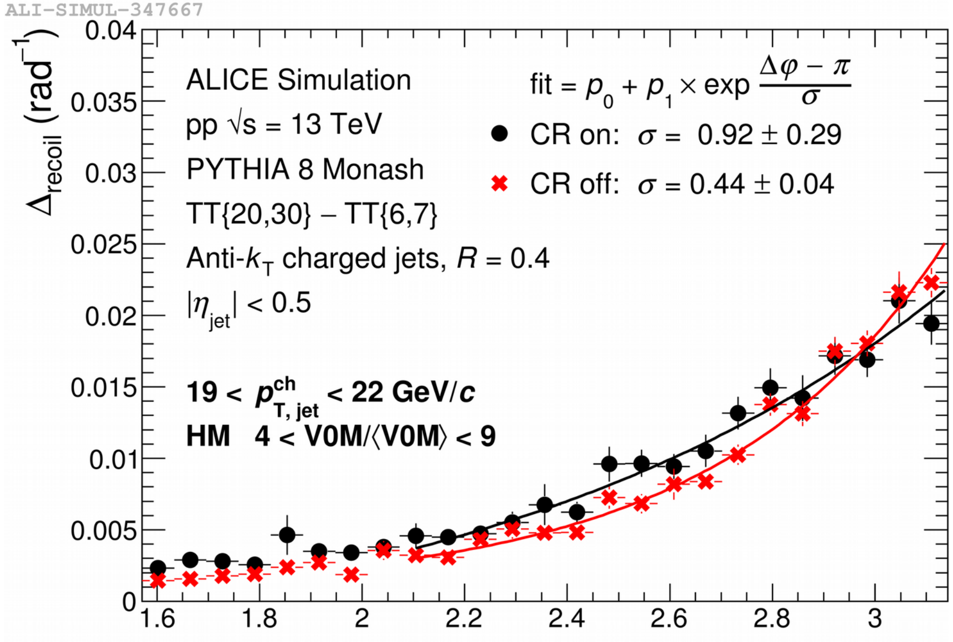

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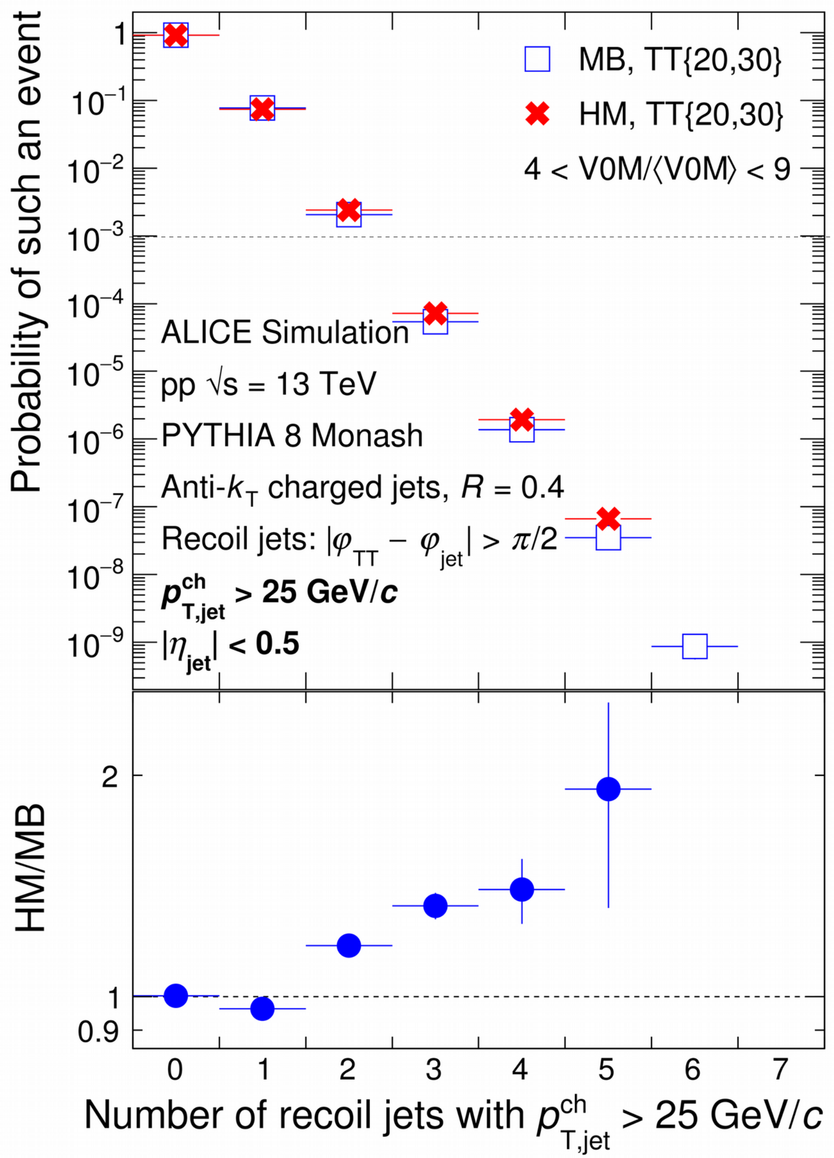
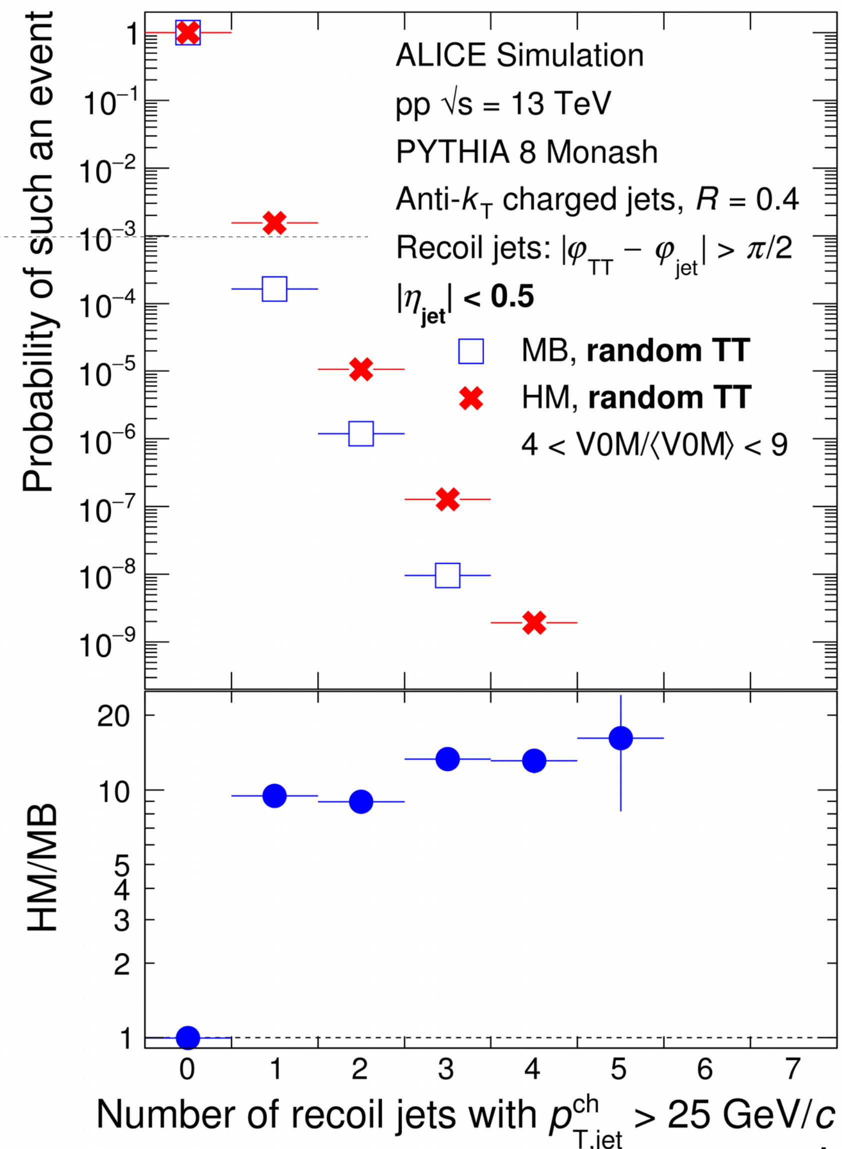
PYTIHA 8 Monash: # high-p_T jets recoiling from TT (20,30) GeV/c and random TT in ALICE





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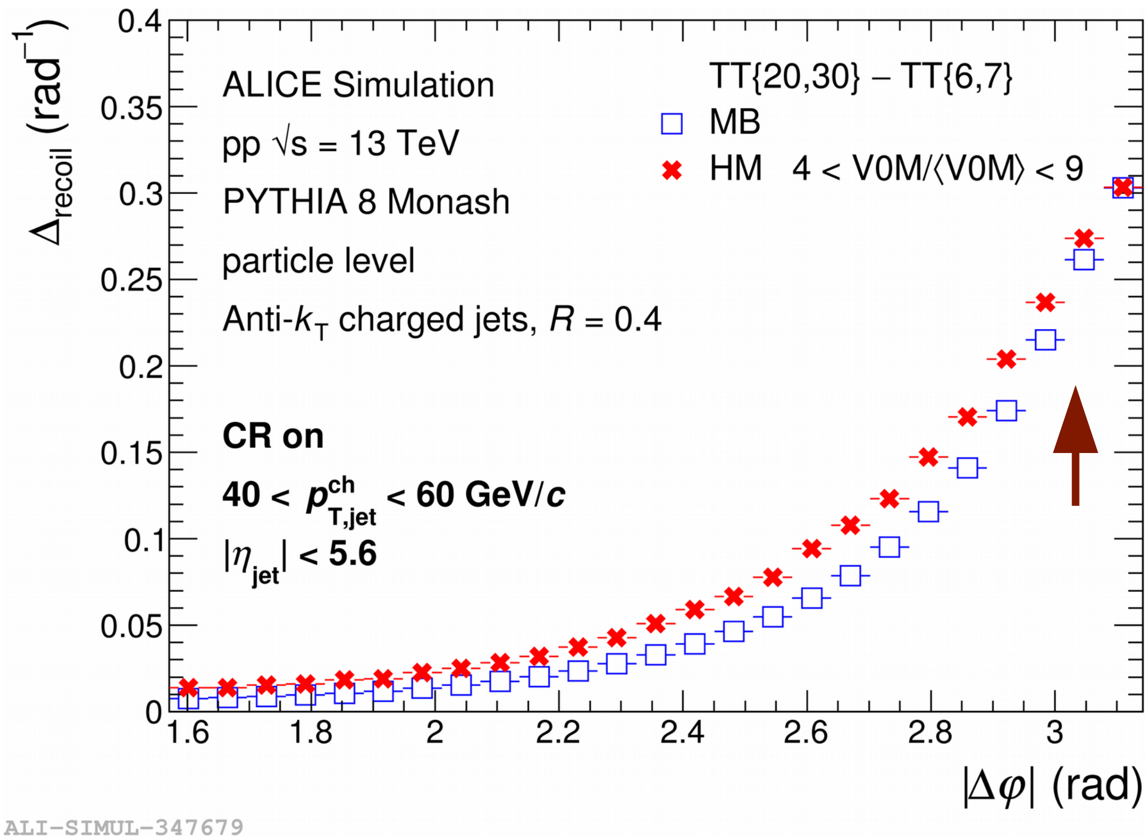
PYTHIA 8 Monash: Δ_{recoil} in $|\eta_{jet}| < 5.6$

New for HP2020



For PYTHIA V0M we count charged, final state particles $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

- No jet quenching in PYTHIA → p_T balance of back to back jets → Would Δ_{recoil} measured in much wider η range still exhibit suppression?

  → Suppression not observed

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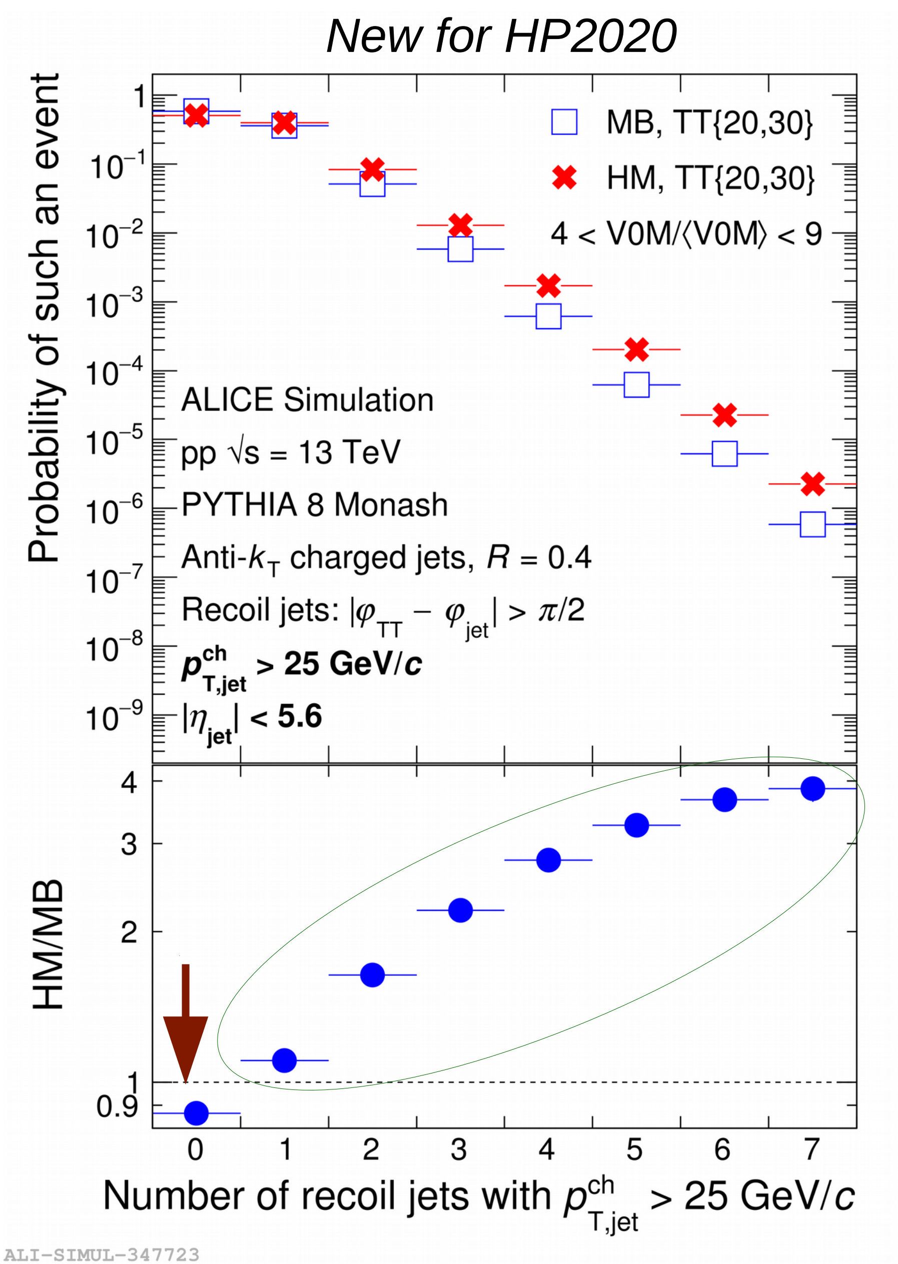
PYTHIA 8 Monash: # of high-p_T recoil jets vs Event Activity, broad acceptance



- Same calculation but for broad acceptance

→ HM condition enhances probability to have at least one high-p_T recoil jet

→ The probability of having no high-p_T jet in $|\eta_{jet}|$ < 5.6 is suppressed