Measurements of jet quenching via hadron+jet correlations in Pb-Pb and high-particle multiplicity pp collisions with ALICE

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for the ALICE Collaboration

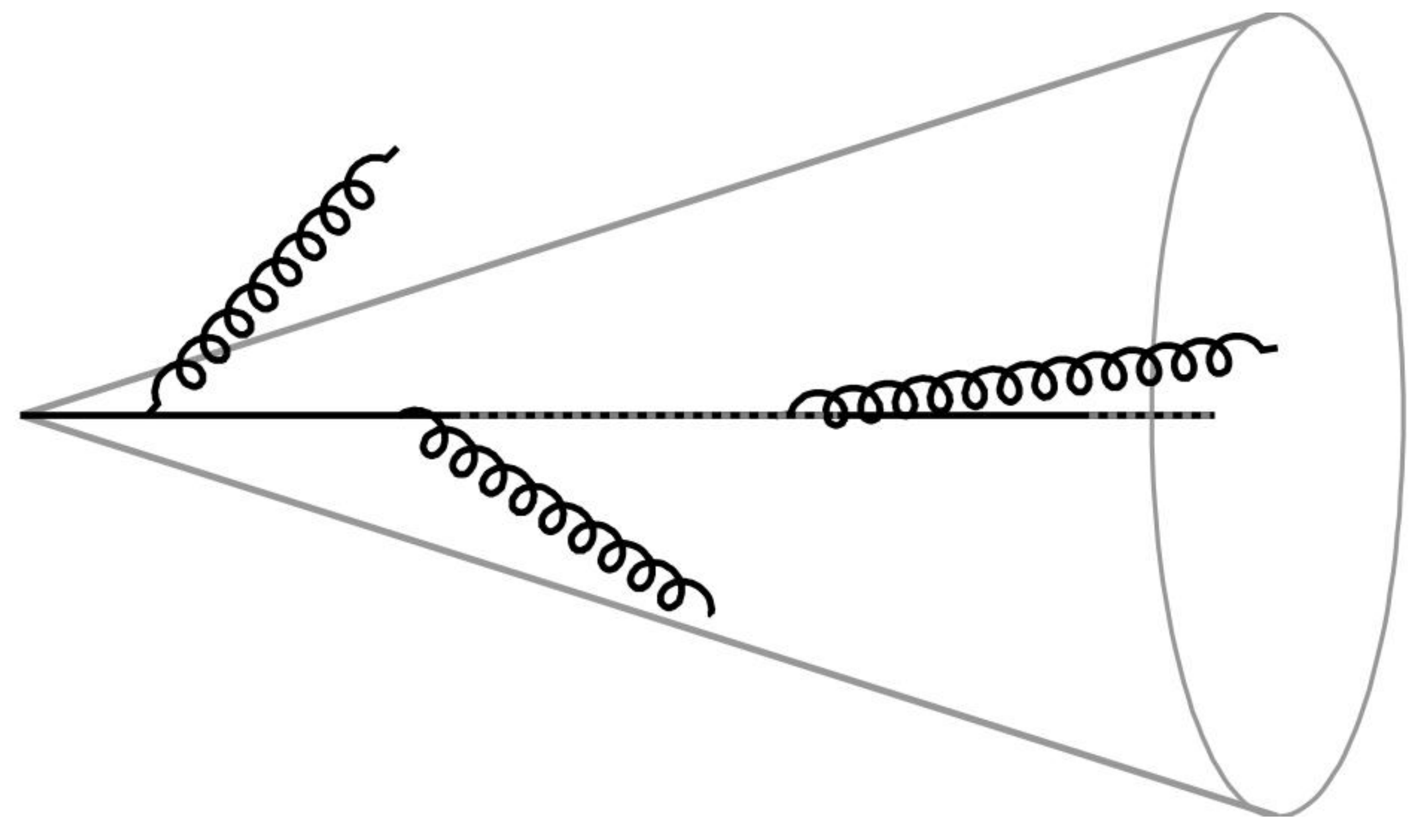
The European Physical Society Conference on High Energy Physics 2021

Introduction

Jet shower in vacuum

Evolution of highly virtual parton via gluon radiation

- Precise understanding in pQCD
- Reference process for nucleus collisions



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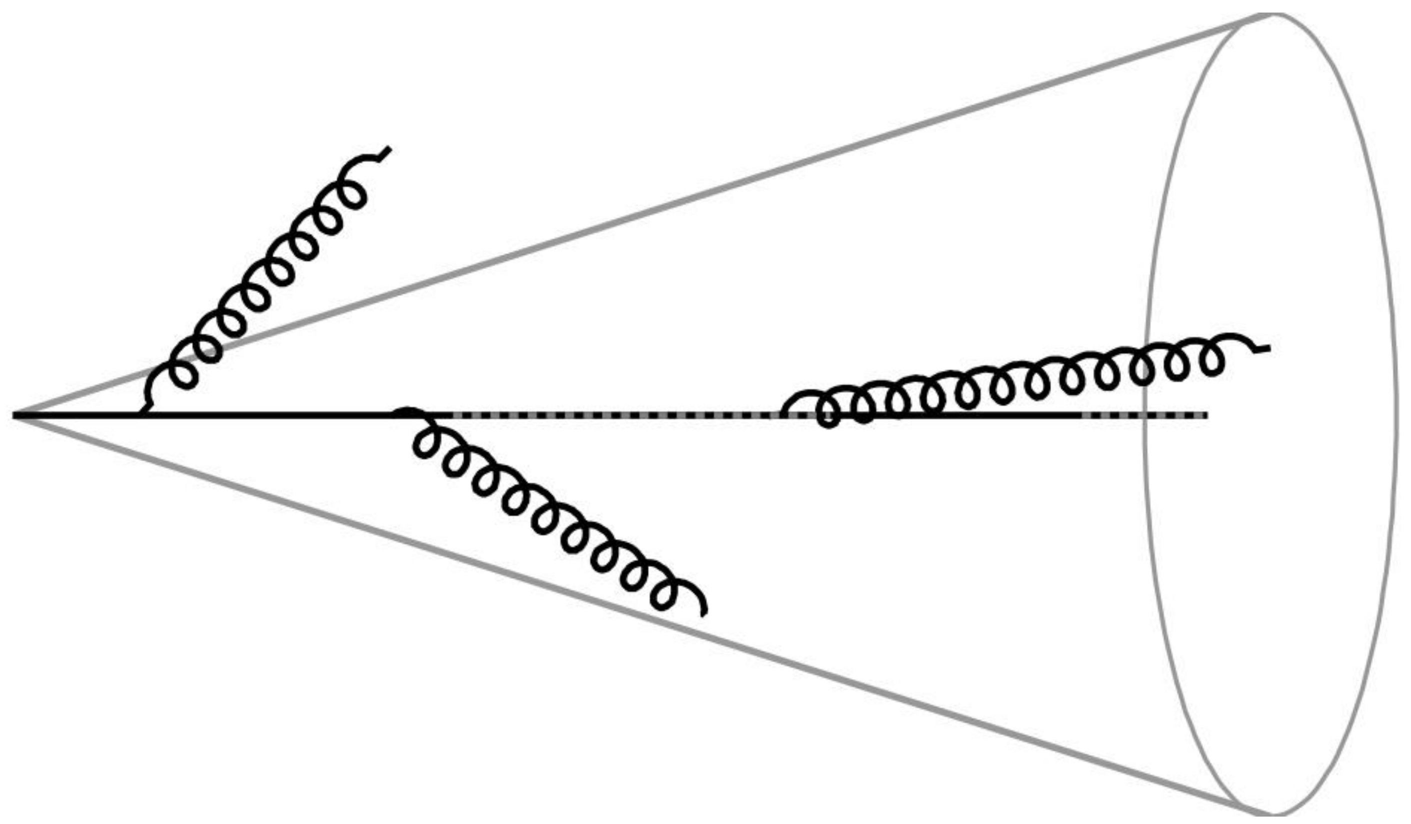
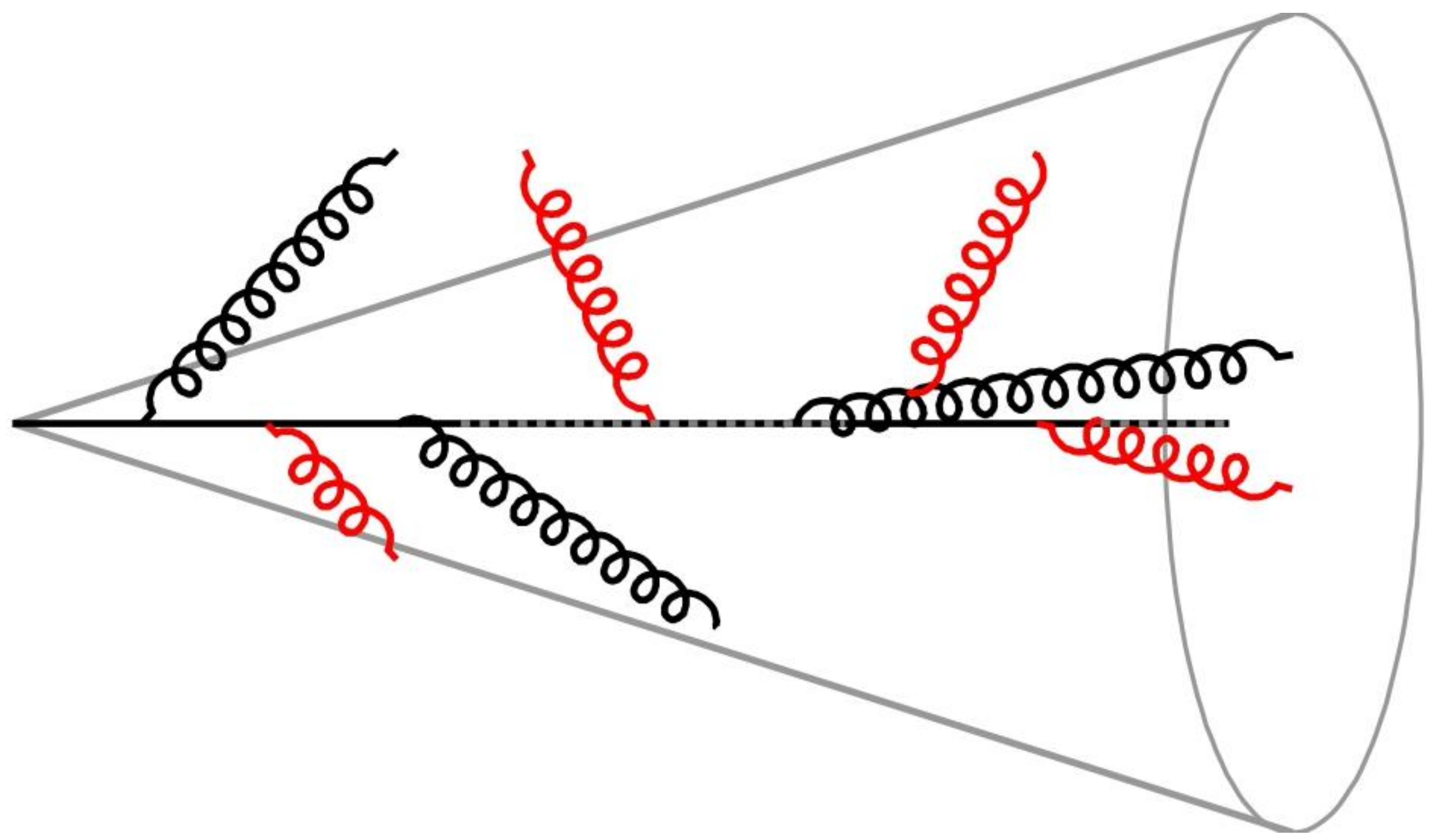


Jet shower in-medium

- Parton energy loss via medium-induced gluon radiation and elastic collisions → **jet quenching**
- Consequences of jet quenching:
  1. Yield suppression of high-p_T hadrons and jets
  2. Modification of jet substructure
  3. **Medium-induced acoplanarity** → semi-inclusive measurements

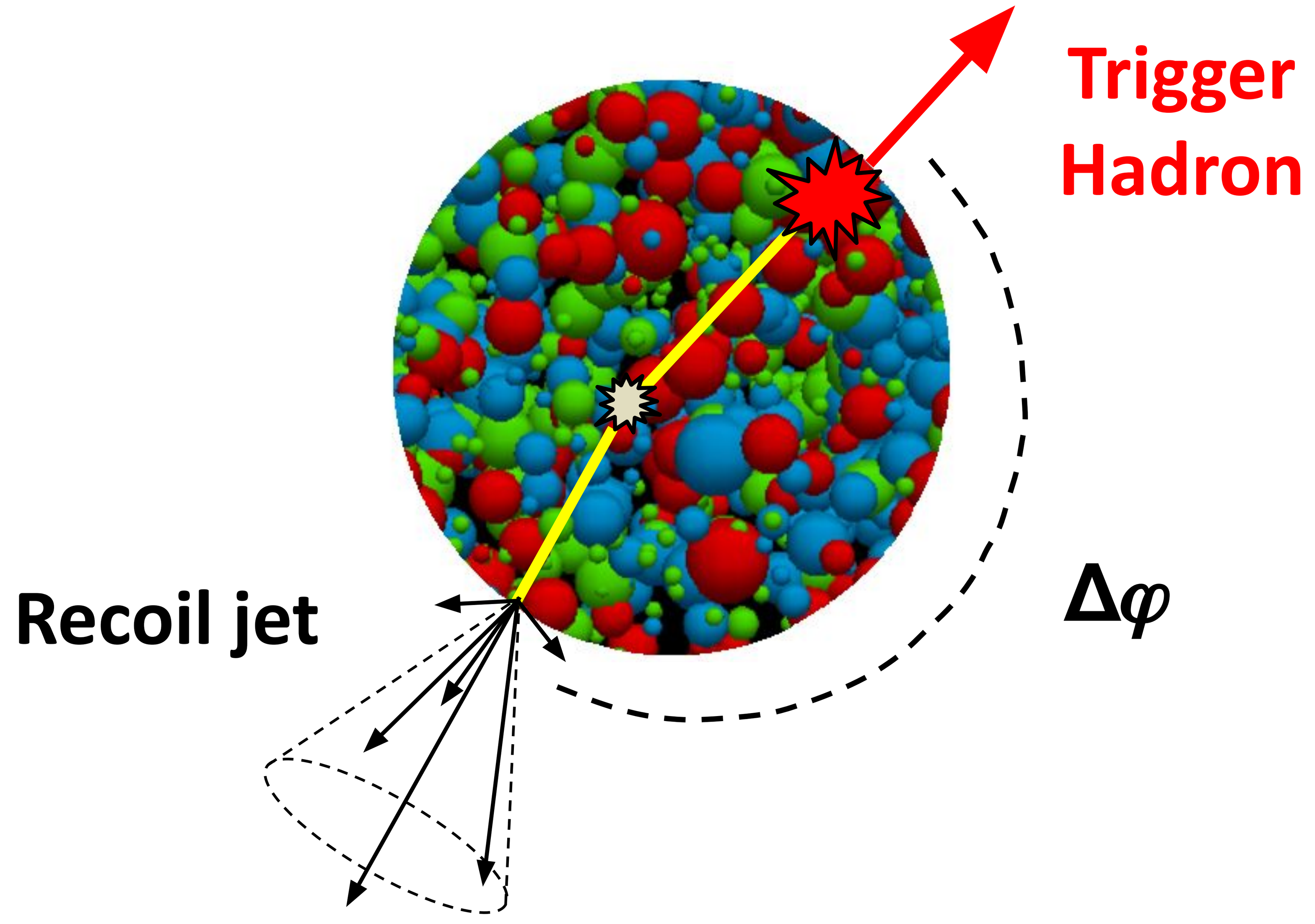
  of **trigger-jet acoplanarity** (trigger: **high-p_T hadron,** γ or Z)



Regions of interest

1. Small $|\Delta\varphi - \pi|$

- Hadron-jet acoplanarity broadening: **vacuum (Sudakov) radiation and multiple scatterings in medium** (L. Chen et al, Phys. Lett. B773 (2017) 672)
- Direct estimation of **jet transport coefficient** $\boldsymbol{q}$
- Negative radiative correction ⟶ **reduction of broadening** (B. G. Zakharov, arxiv:2003.10182)



Hadron-jet acoplanarity

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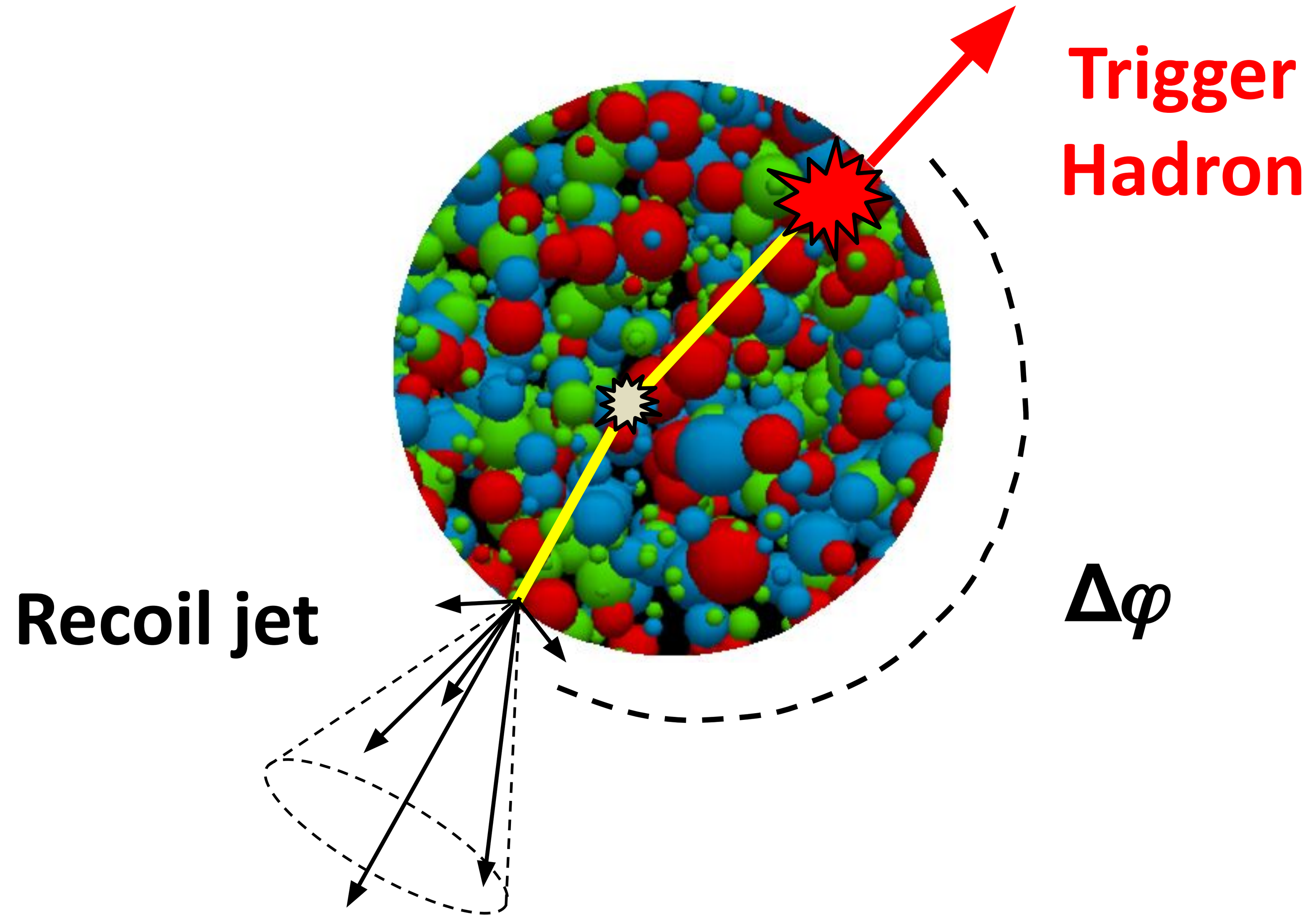
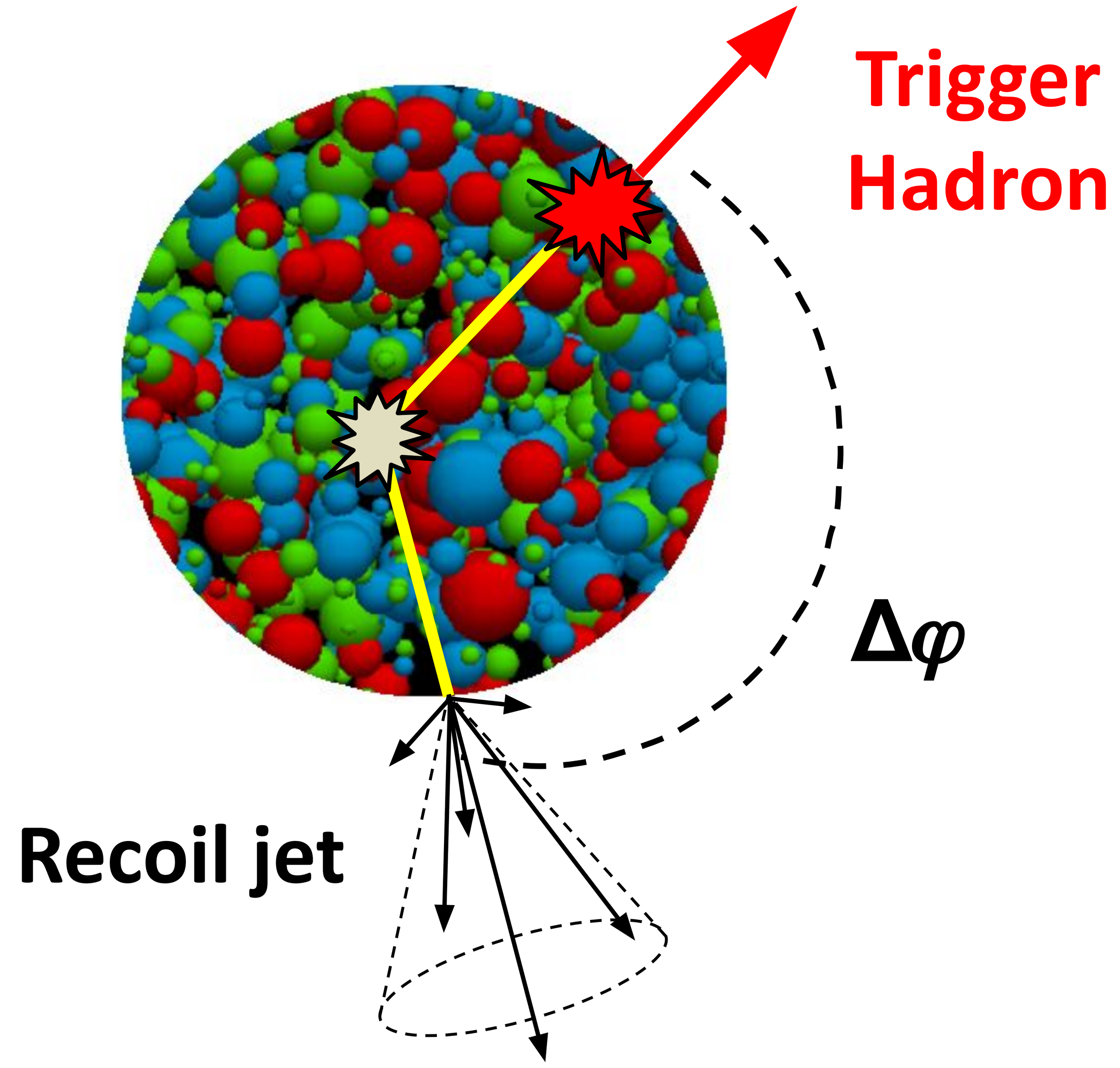


2. Large $|\Delta\varphi - \pi|$

- **Single hard scattering** → large angle scattering of parton on QGP quasi-particles
- Probe short distance quasi-particle structure of QGP (F. D'Eramo, Rajagopal, Y. Yin, JHEP 01 (2019) 172)



Hadron-jet acoplanarity via semi-inclusive measurements

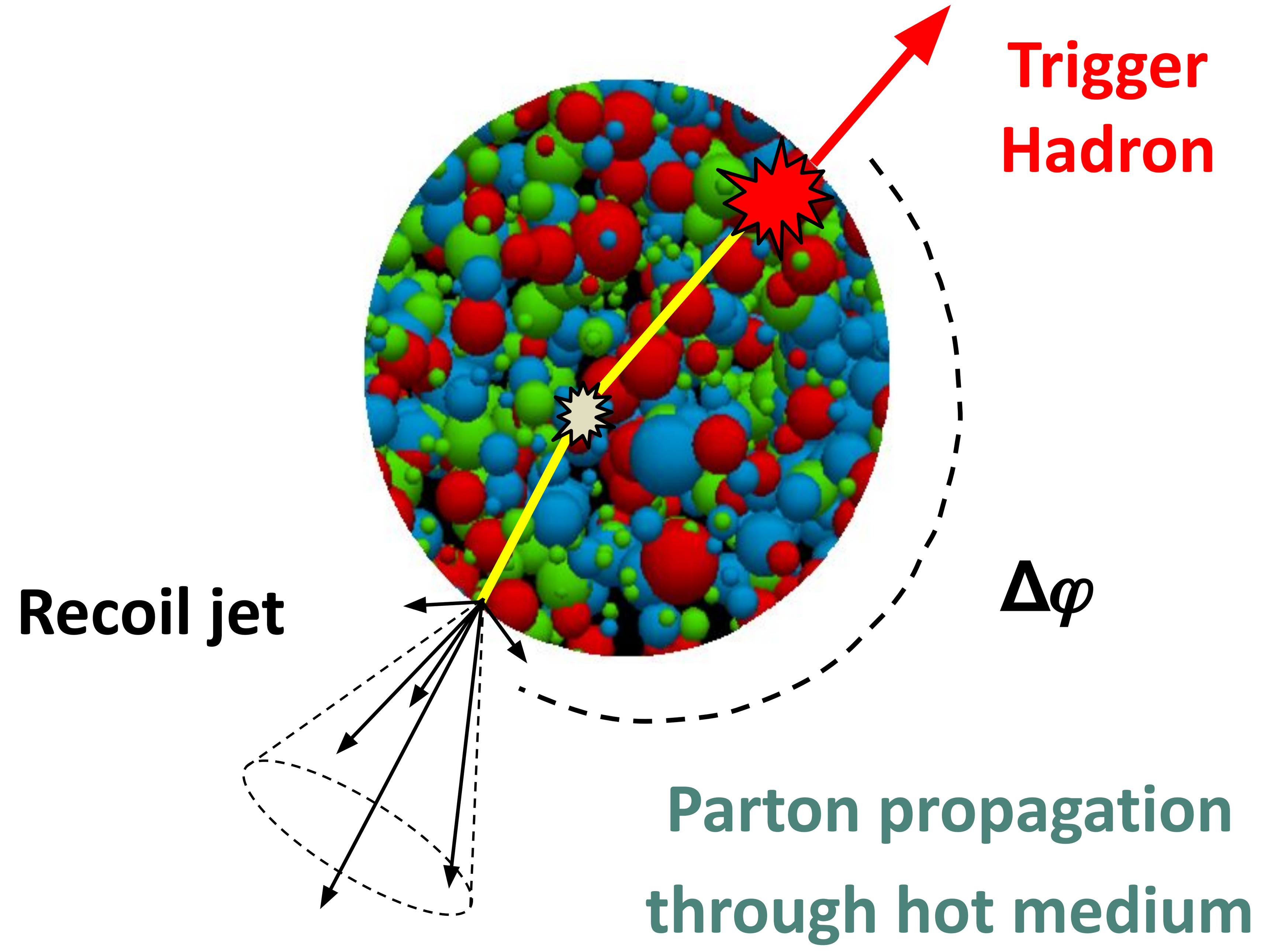
Per trigger normalized yield of jets recoiling from high-p_T hadron

$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{d^2 N_{\rm jet}^{\rm AA}}{dp_{\rm T,jet}^{\rm ch} d\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in {\rm TT}} = \left(\frac{1}{\sigma^{\rm AA \rightarrow h+X}} \cdot \frac{d^2 \sigma^{\rm AA \rightarrow h+jet+X}}{dp_{\rm T,jet}^{\rm ch} d\eta_{\rm jet}} \right)\Bigg|_{p_{\rm T,h}\in {\rm TT}}$$

→ Calculable in pQCD

Cross section for trigger hadron production

Differential cross section for coincidence production of trigger hadron and recoil jet



Semi-inclusive measurements provide:

- Unbiased jet population
- Access to **low p_T jets** → **more sensitive to medium-induced broadening**
- **Data driven approach for removal of uncorrelated background yield**

  → essential for precise acoplanarity measurements

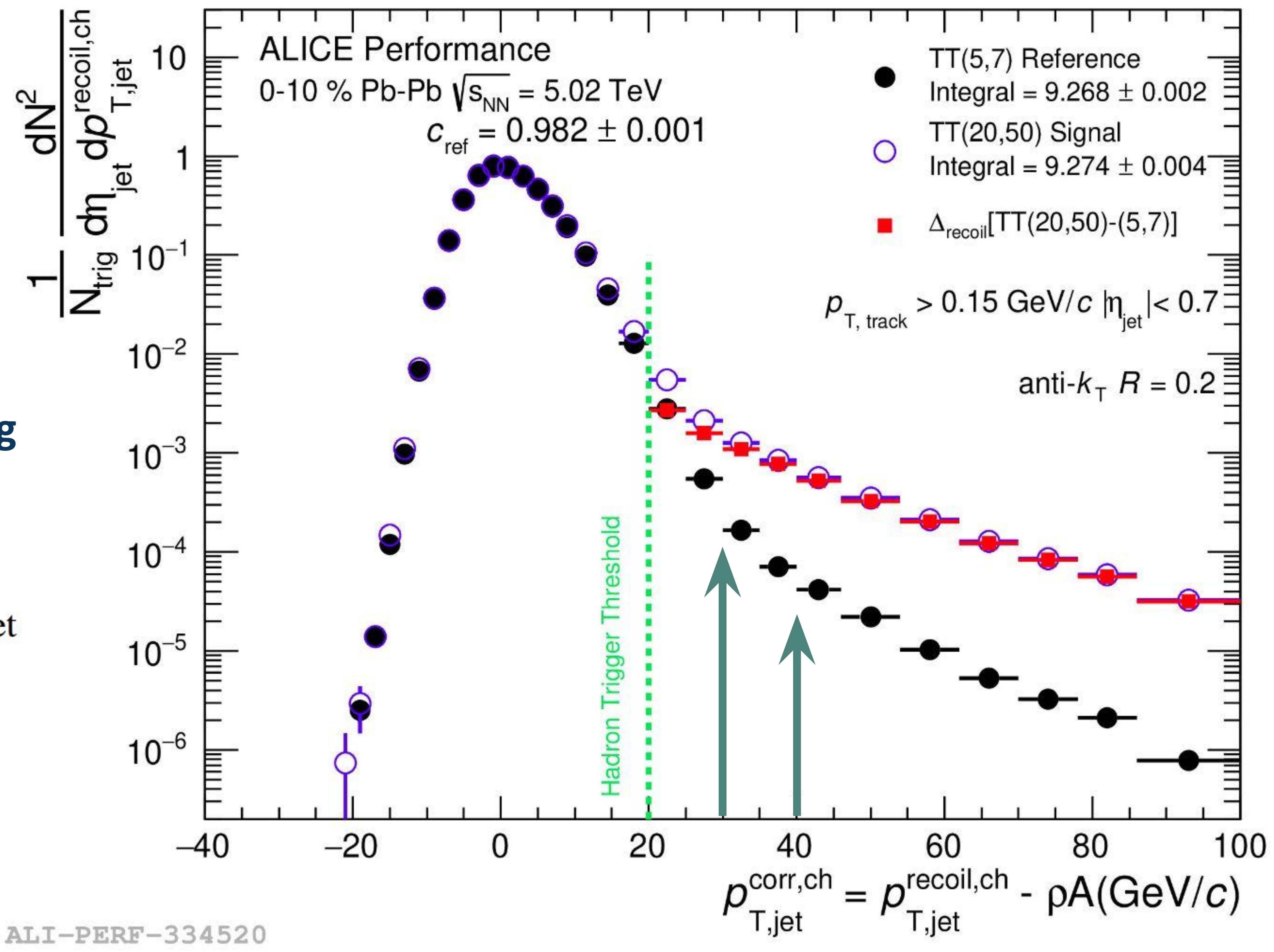
Hadron-jet acoplanarity: Δ_{recoil} observable

TT_{Sig}: $20 < p_T < 50$ GeV/c

TT_{Ref}: $5 < p_T < 7$ GeV/c

Jet p_T corrected for **underlying event density ρ**

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



- Jets recoiling from a high-p_T trigger hadron
- Data-driven approach to **remove uncorrelated background yield**

$$\Delta_{recoil} = \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}^{AA}}{dp_{T,jet}^{ch} d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}^{AA}} \frac{d^2N_{jet}^{AA}}{dp_{T,jet}^{ch} d\eta_{jet}}\Bigg|_{p_{T,trig}\in TT_{Ref}}$$

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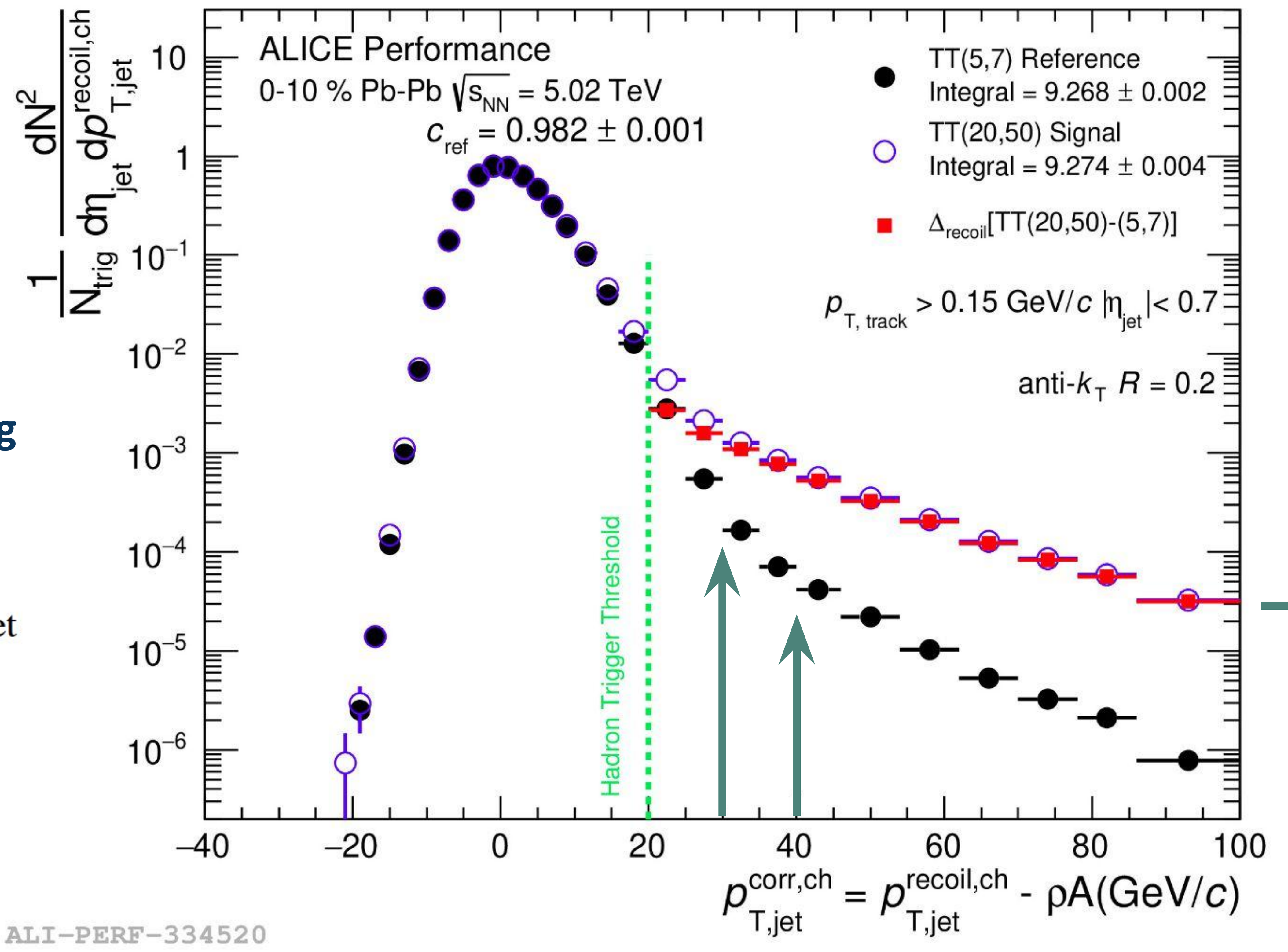
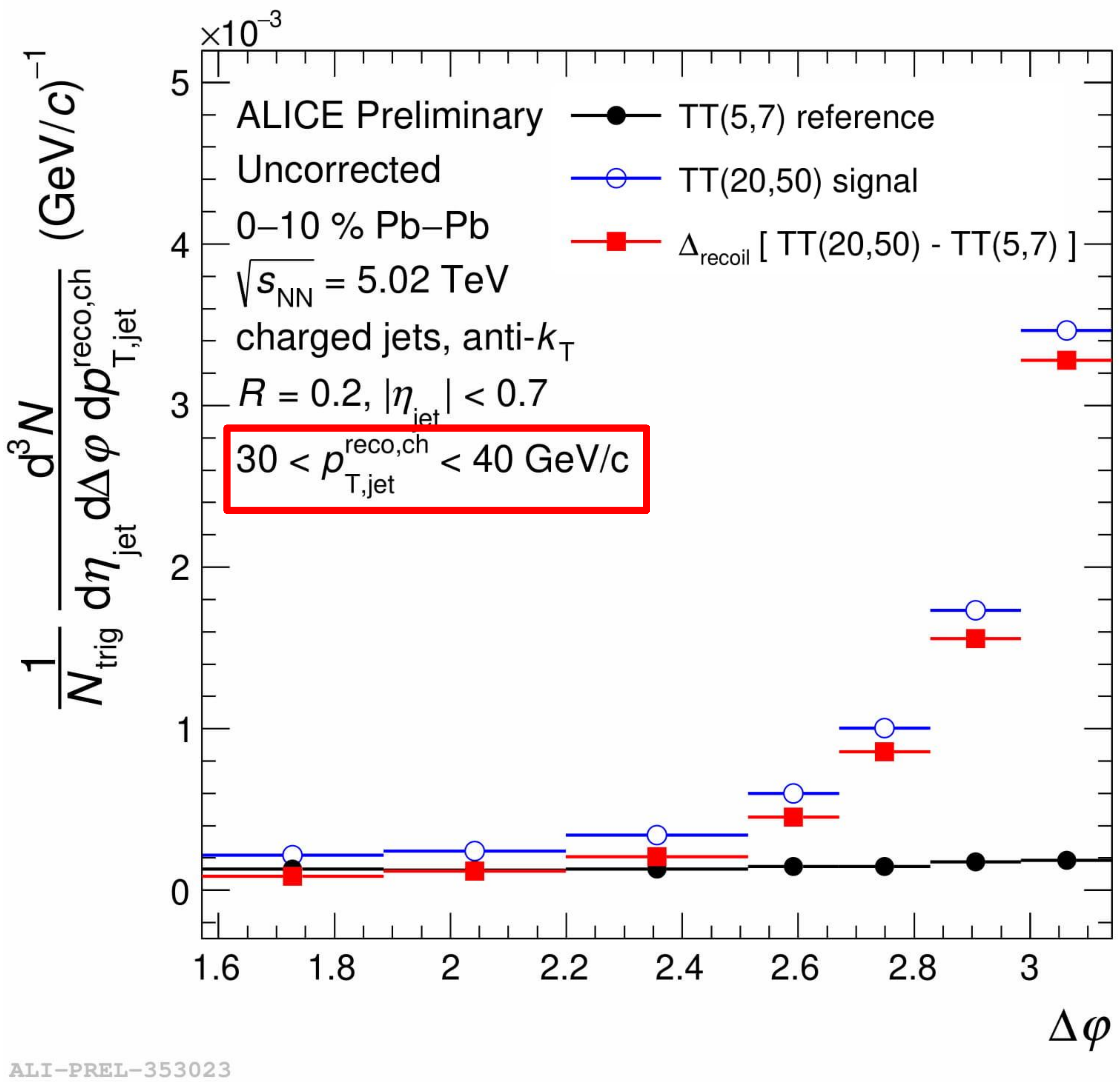


Δ_{recoil} as function of TT-jet opening angle



- Jets recoiling from a high-p_T trigger hadron
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$$\Delta_{recoil} = \frac{1}{\mathrm{N}_{trig}^{AA}} \frac{\mathrm{d}^2\mathrm{N}_{jet}^{AA}}{\mathrm{d}p_{T,jet}^{ch}\,\mathrm{d}\eta_{jet}}\Bigg|_{p_{T,trig}\in \mathrm{TT_{Sig}}} - c_{\mathrm{Ref}} \cdot \frac{1}{\mathrm{N}_{trig}^{AA}} \frac{\mathrm{d}^2\mathrm{N}_{jet}^{AA}}{\mathrm{d}p_{T,jet}^{ch}\,\mathrm{d}\eta_{jet}}\Bigg|_{p_{T,trig}\in \mathrm{TT_{Ref}}}$$

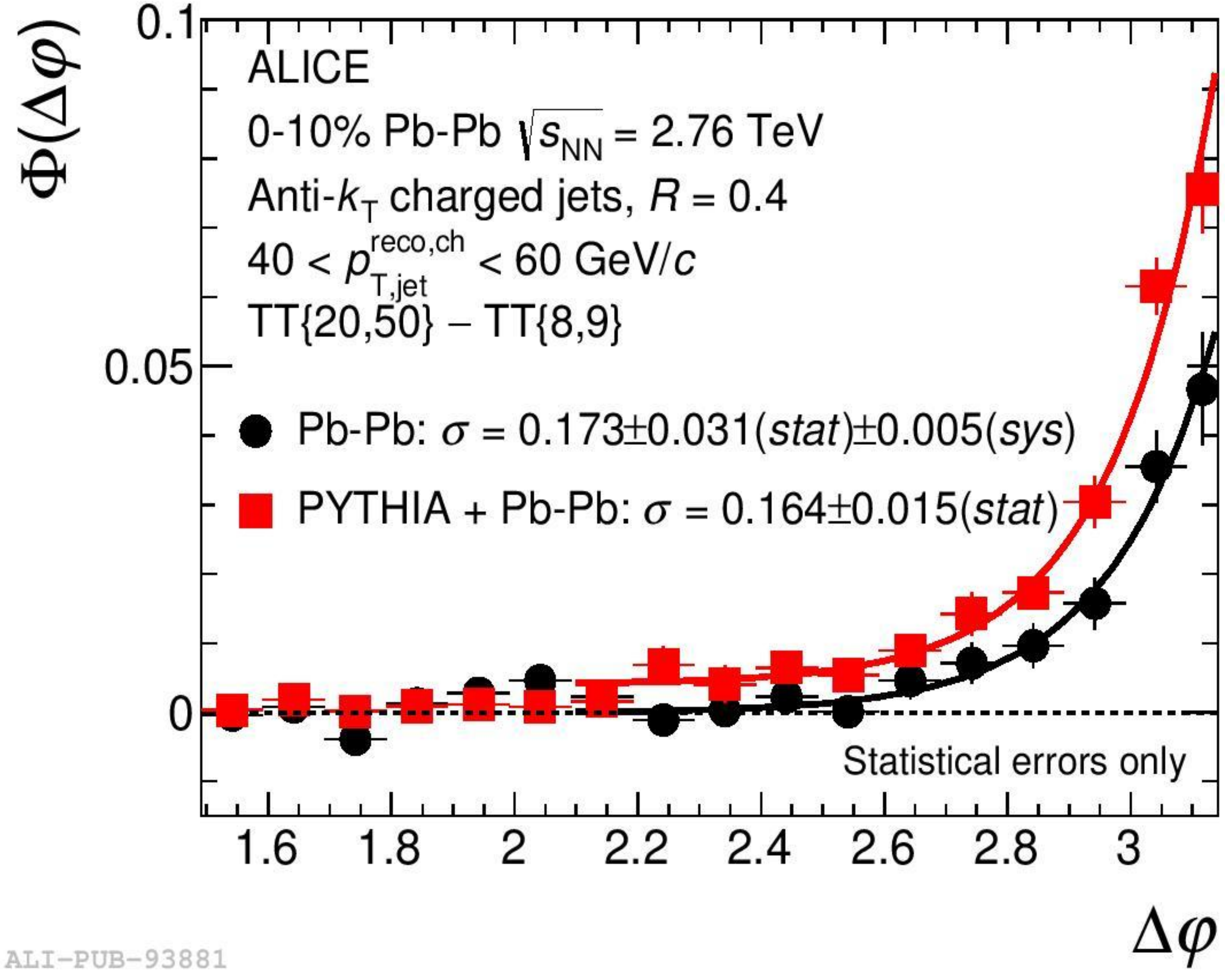
Results: Run 1 Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

- Limited statistics
- **Uncorrected for p_T and angular smearing**
- Anti-k_T charged-particle jets R = 0.4 with $p_T \in$ (40, 60) GeV/c
- Fit function:

$$\boxed{f(\Delta\varphi) = p_0 \times e^{(\Delta\varphi - \pi)/\sigma} + p_1}$$

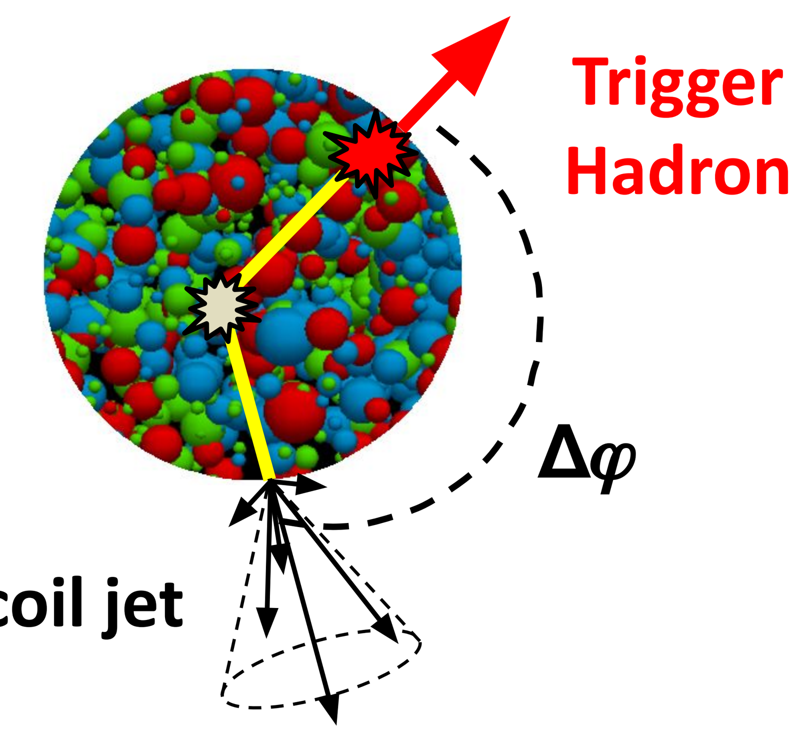
- Suppression of Pb-Pb data comparing to PYTHIA pp
- **No evidence for medium-induced acoplanarity within uncertainties**

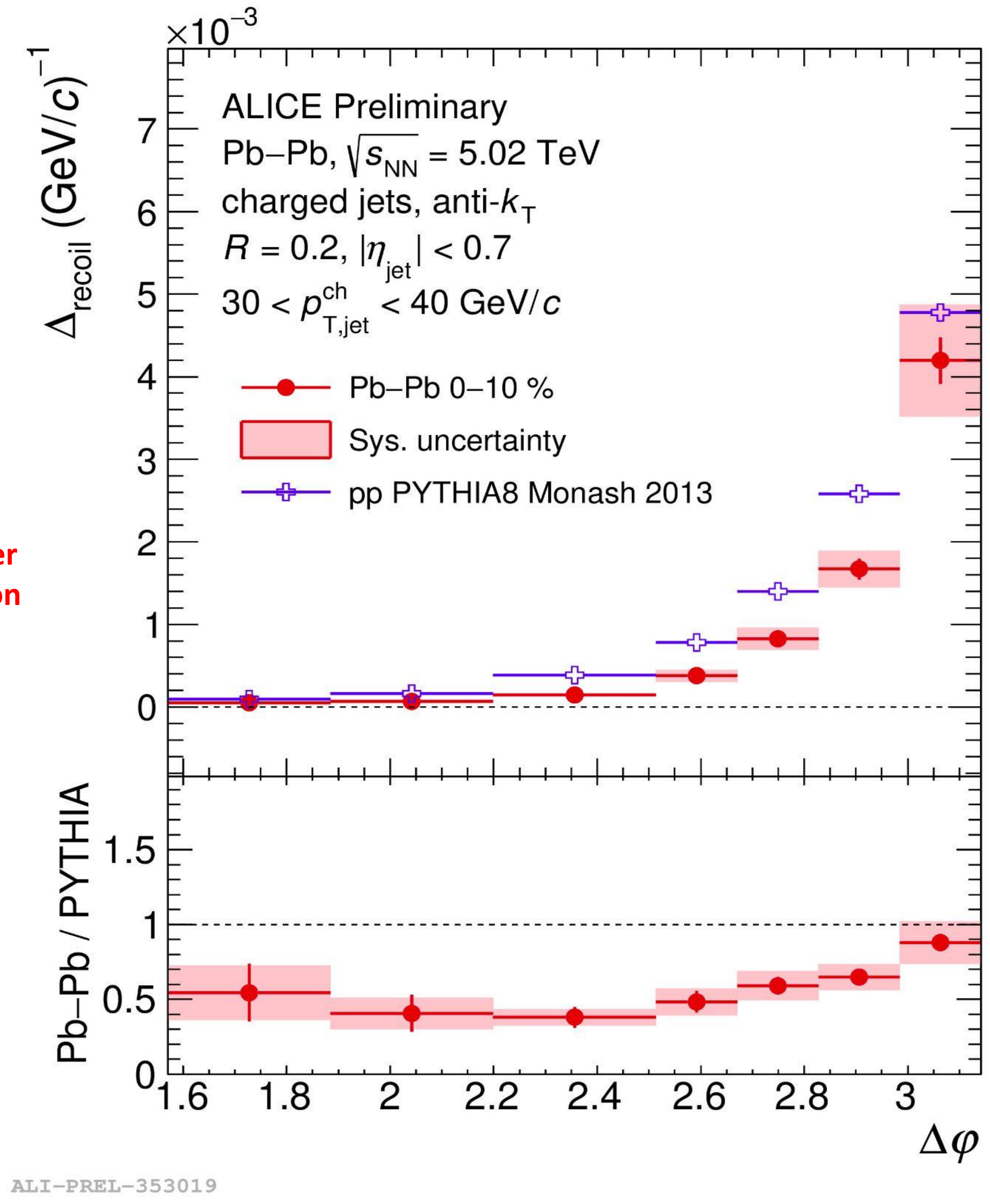
JHEP 09 (2015) 170 (arxiv:1506.03984)



Results: Run 2 Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

- $\Delta\varphi \sim \pi$: multiple soft momentum exchanges
- $\Delta\varphi \ll \pi$: Rutherford-like scattering off QGP quasi-particles





- **x9 larger statistics** with respect to Run 1 data
- Anti-k_T charged-particle jets R = 0.2 with $p_T \in$ (30, 40) GeV/c
- Fully corrected hadron-jet $\Delta\varphi$ distribution

- Recoil jet yield suppressed compared to pp PYTHIA data
- **Indication of narrowing of acoplanarity distribution in 30 < $p^{ch}_{T,\,jet}$ < 40 GeV/c**

Radiative corrections?

B. G. Zakharov, arxiv:2003.10182

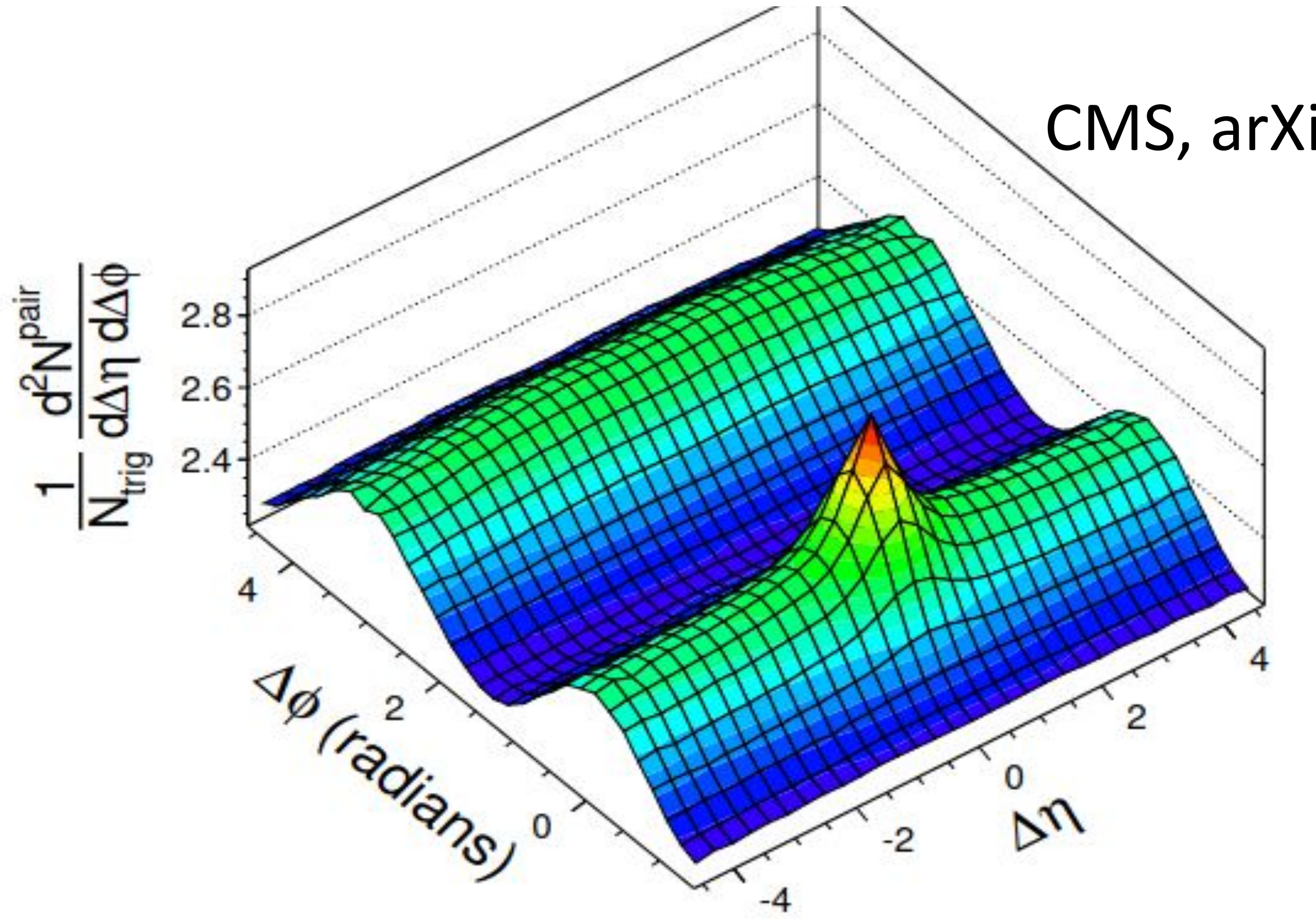
High-particle multiplicity pp collisions

Quark-gluon plasma formation in small collision systems?

Collective flow

Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

CMS, arXiv:1305.0609v3



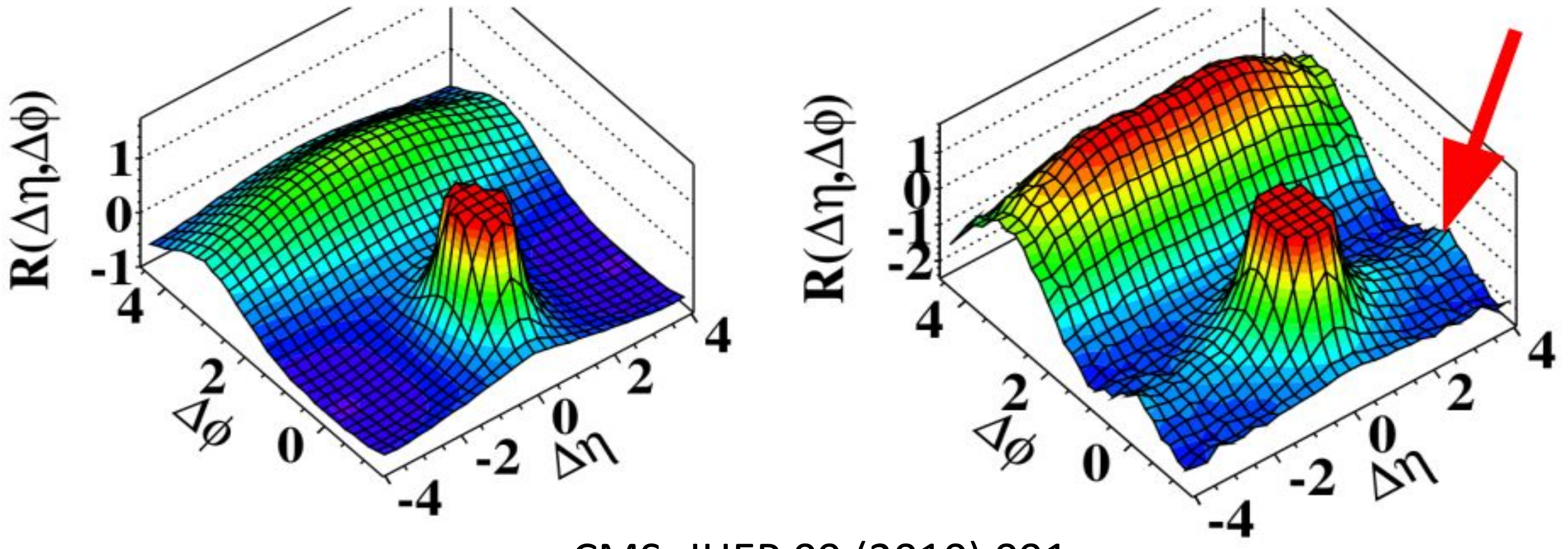
Quark-gluon plasma formation in small collision systems?

Collective flow

Azimuthal correlation between two particles pp 7 TeV

Minimum bias events

High-multiplicity events



CMS, JHEP 09 (2010) 091

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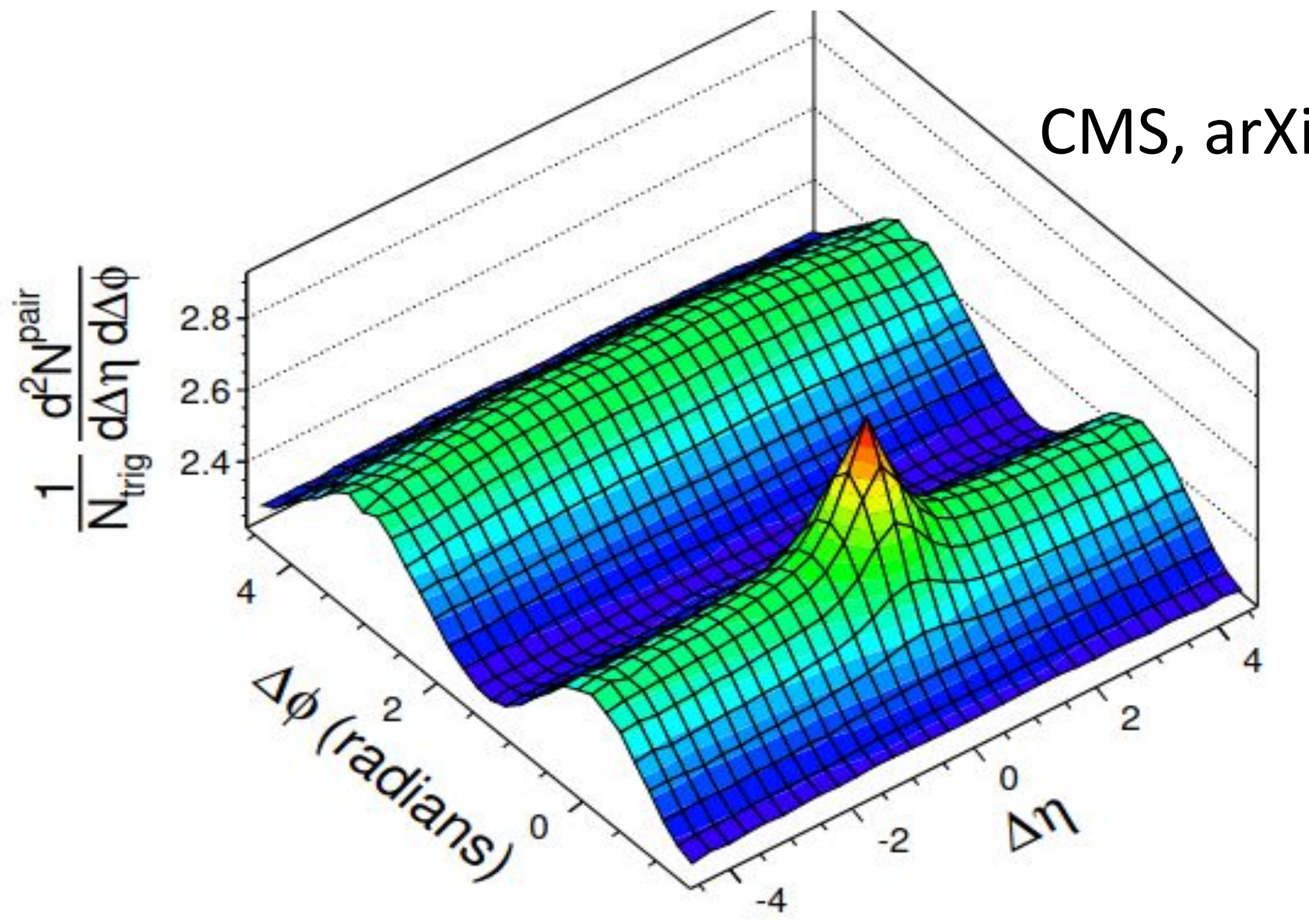
CMS, arXiv:1305.0609v3



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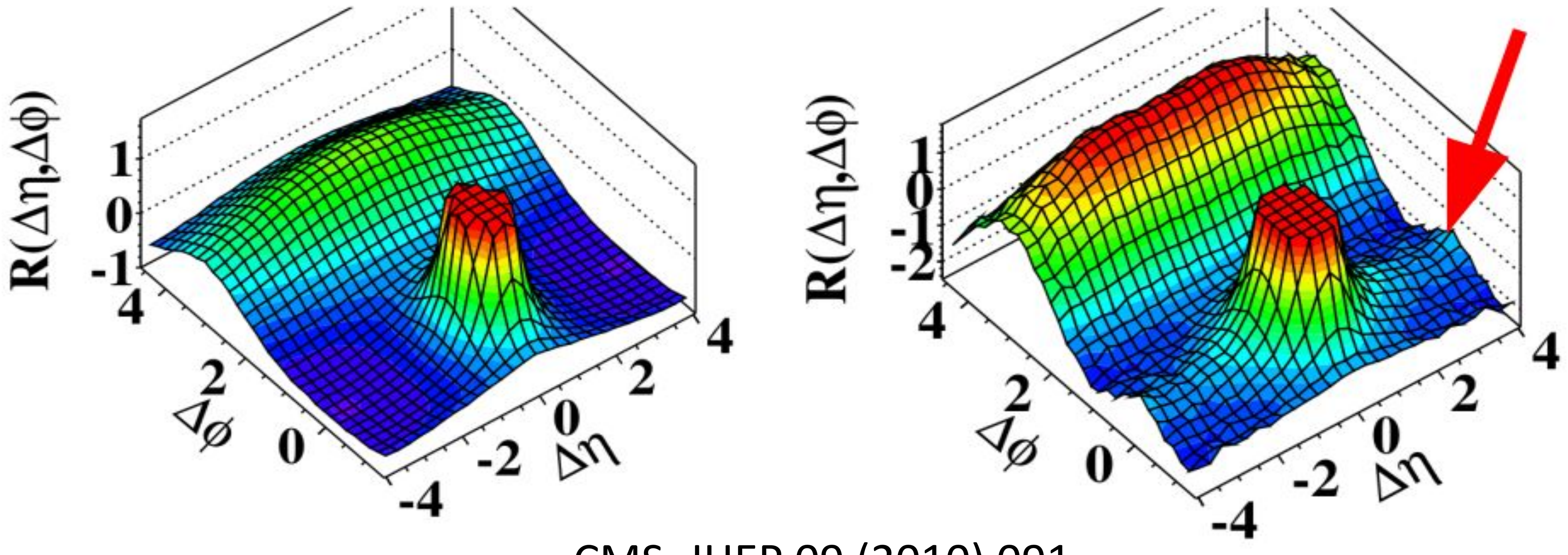

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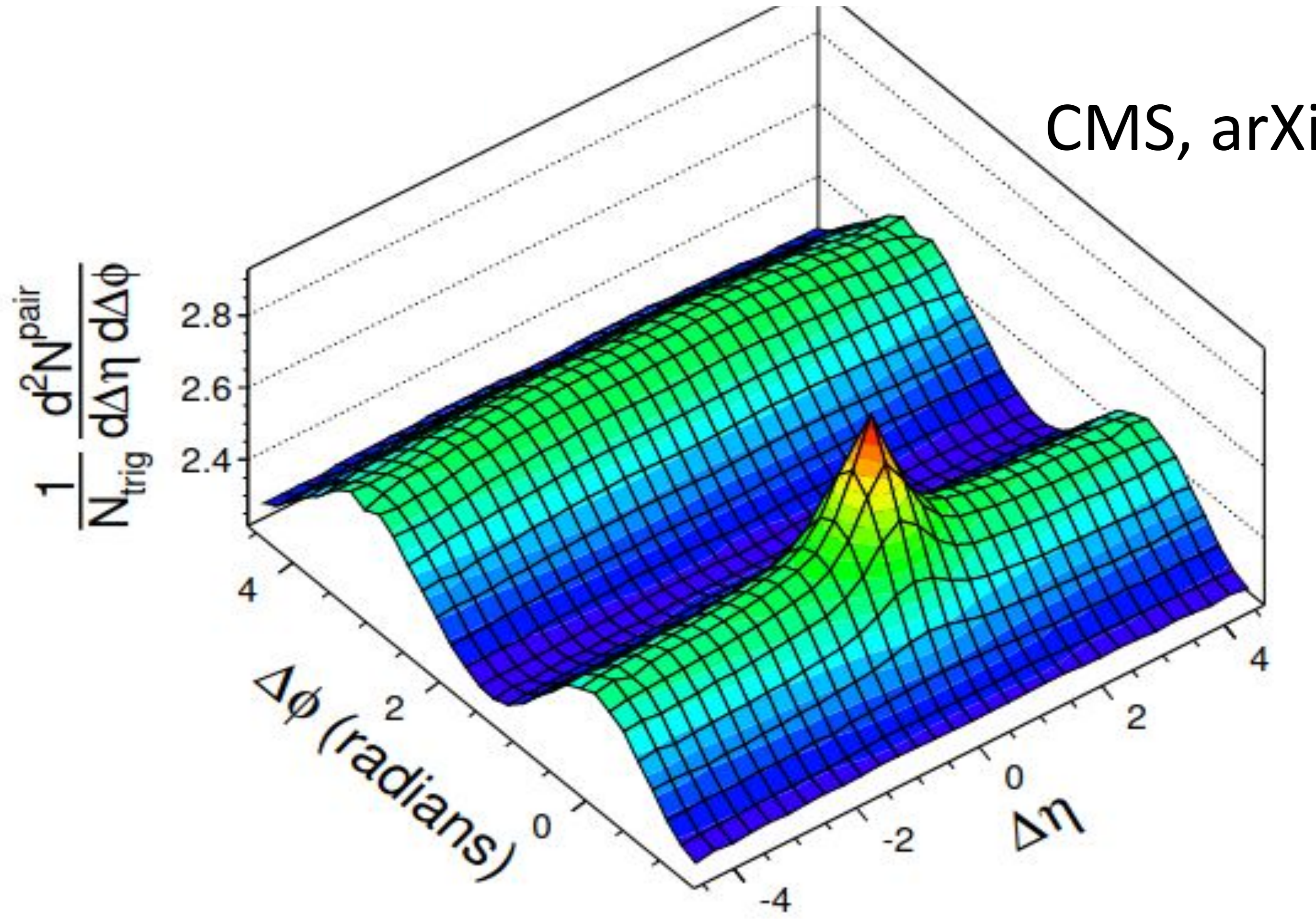

Jet quenching in high particle multiplicity pp collisions

R_{AA} nuclear modification factor measurements

$$R_{\mathrm{AA}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{INEL}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

undefined Glauber scaling factor for high particle multiplicity pp

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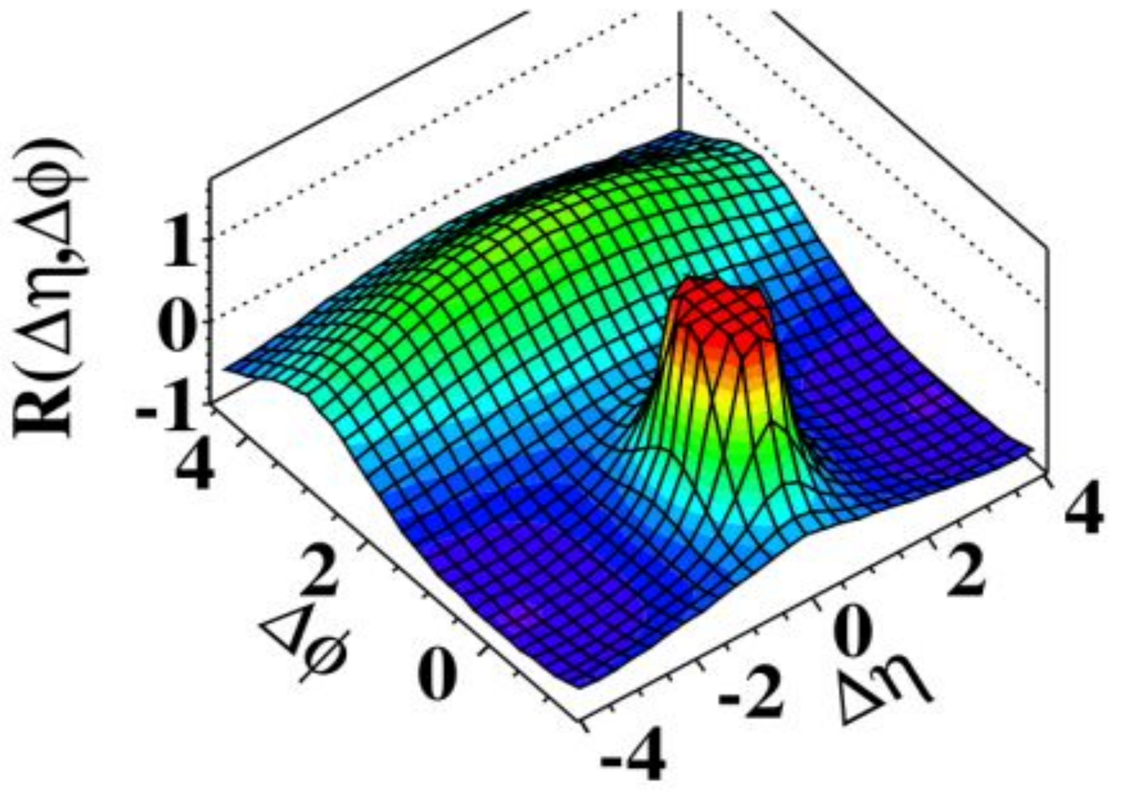
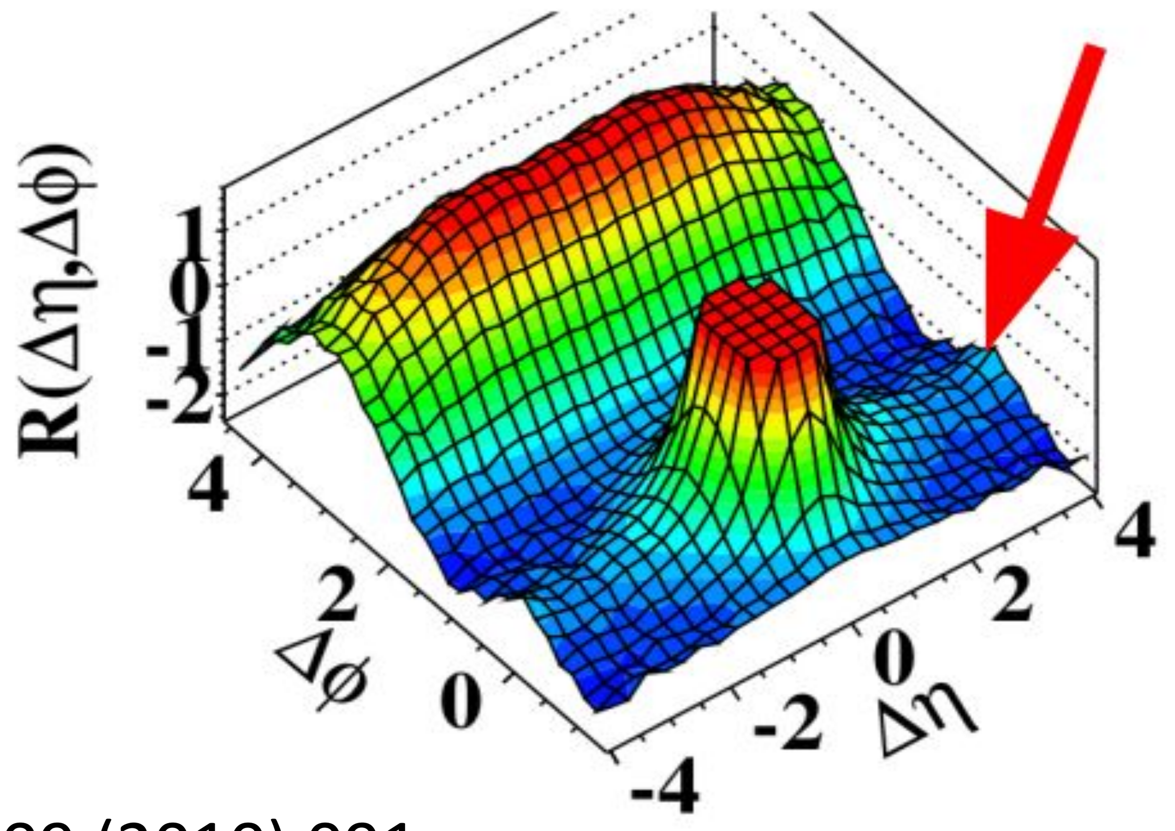


High-multiplicity events



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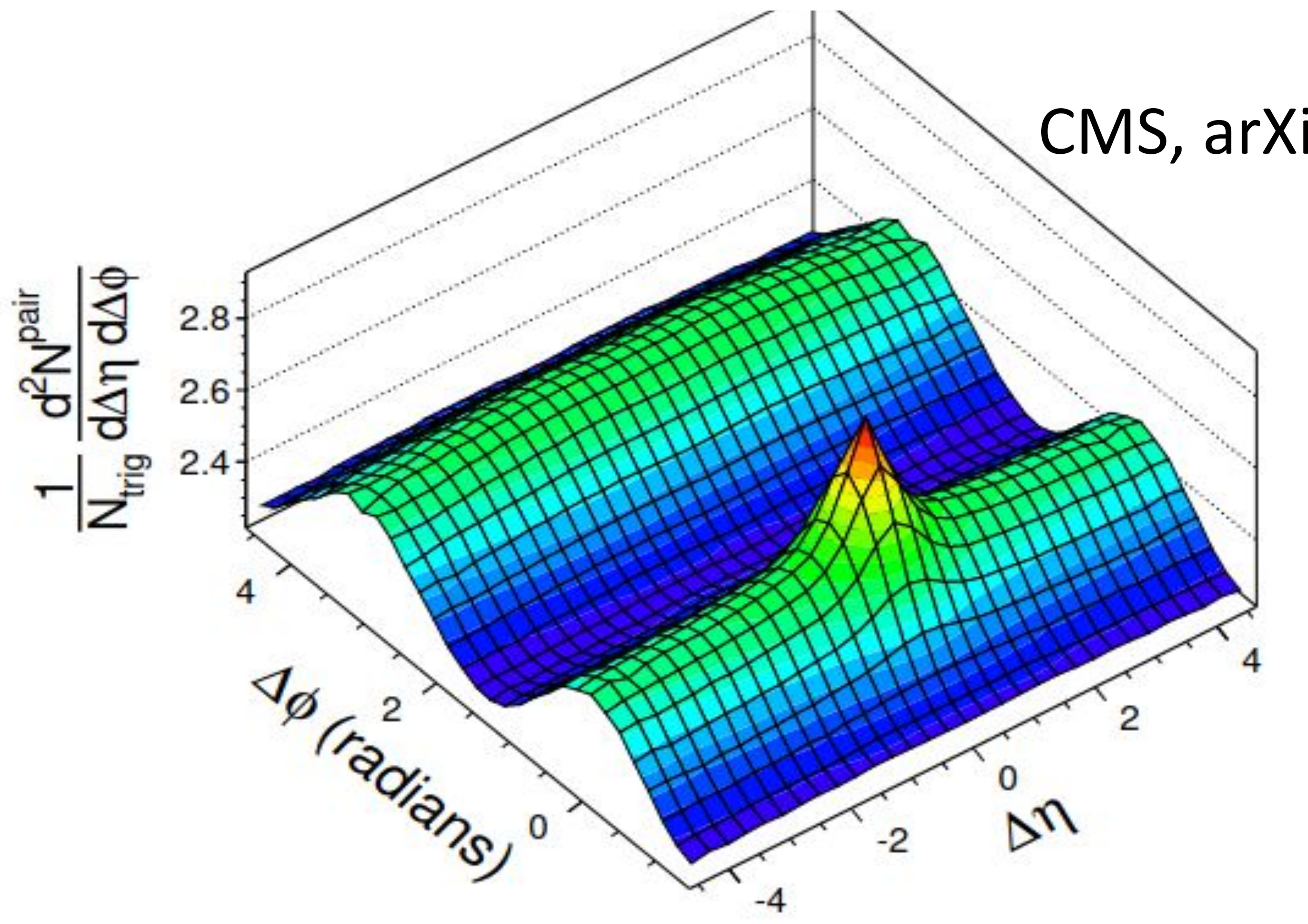

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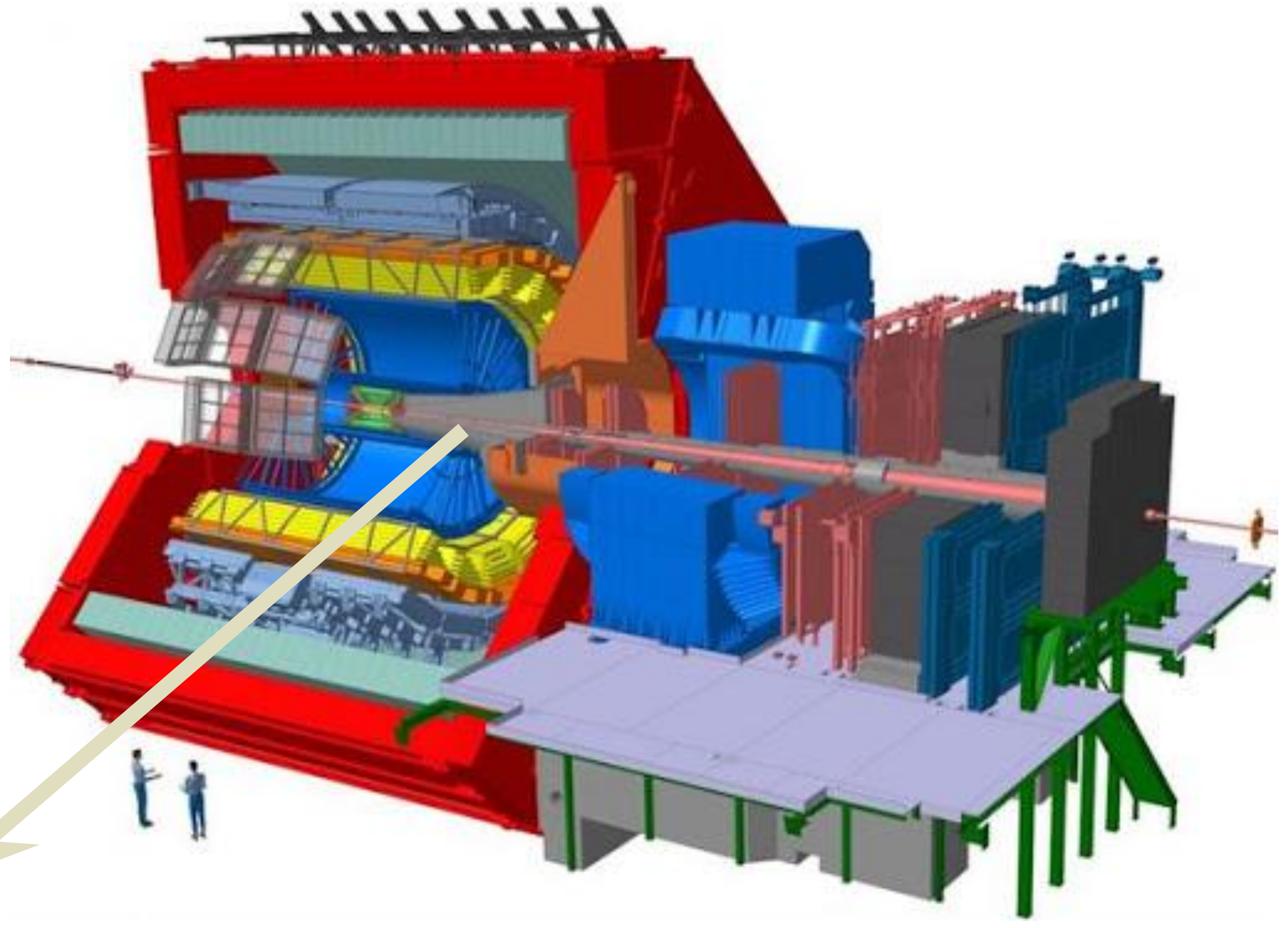
Semi-inclusive measurements

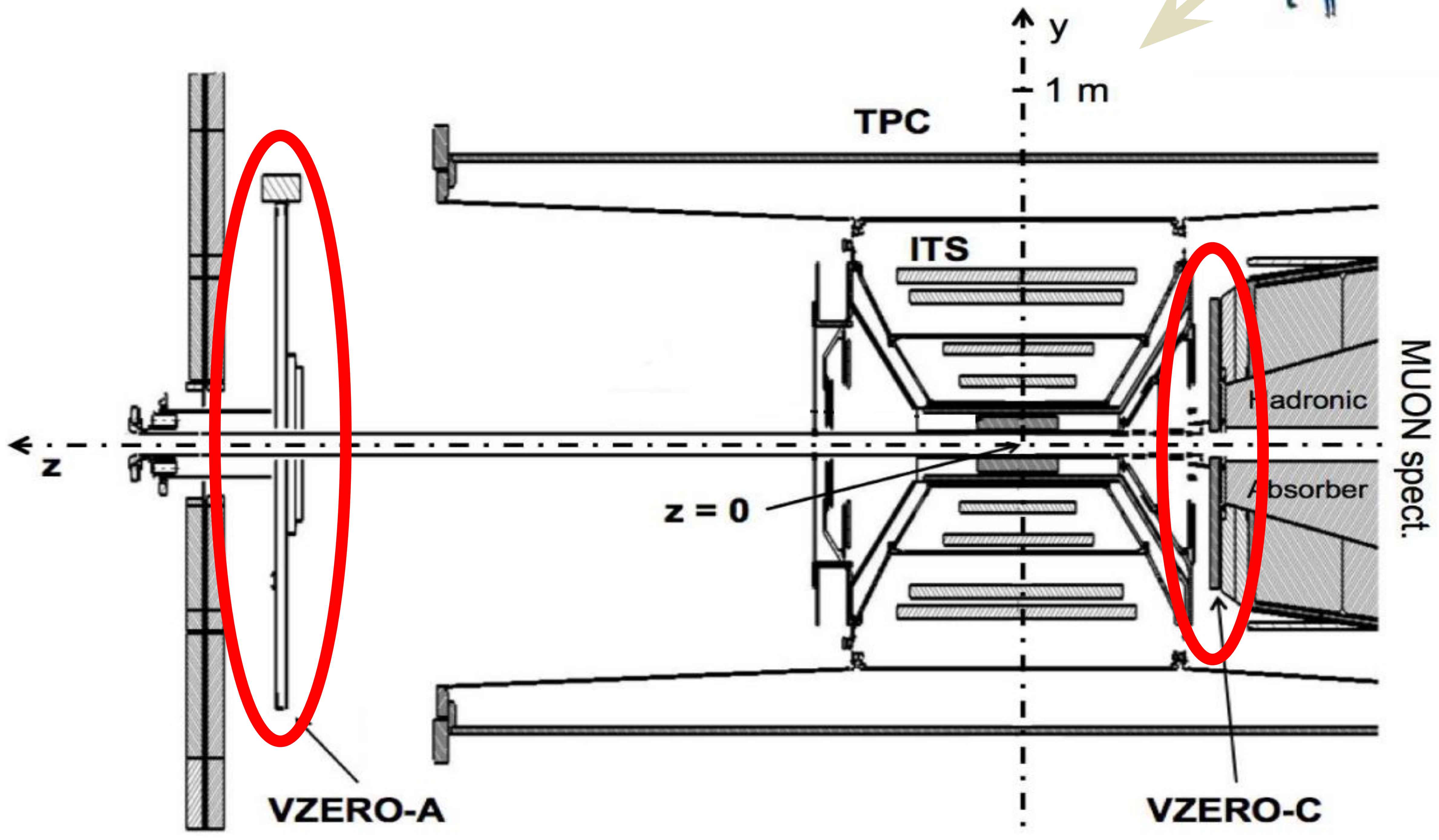
$$\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}} \frac{\mathrm{d}^2\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,\,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{\mathrm{h}\,\in\,\mathrm{TT}} = \frac{1}{\sigma^{\mathrm{pp}\to\mathrm{h+X}}} \frac{\mathrm{d}^2\sigma^{\mathrm{pp}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,\,jet}}^{\mathrm{ch}}\mathrm{d}\eta_{\mathrm{jet}}} \times \cancel{\frac{\langle T_{\mathrm{AA}}\rangle}{\langle T_{\mathrm{AA}}\rangle}}\Bigg|_{\mathrm{h}\,\in\,\mathrm{TT}}$$

Glauber scaling factors $\langle T_{AA}\rangle$ cancel identically

pp data $\sqrt{s}$ = 13 TeV

- Data from 2016 - 2018
- Online triggers based on V0 arrays:
  - **Minimum bias** (MB): 0.098 pb^{-1}
  - **High-multiplicity** (HM): 13 pb^{-1}





V0A: 2.8 < η < 5.1

V0C: -3.7 < η < -1.7

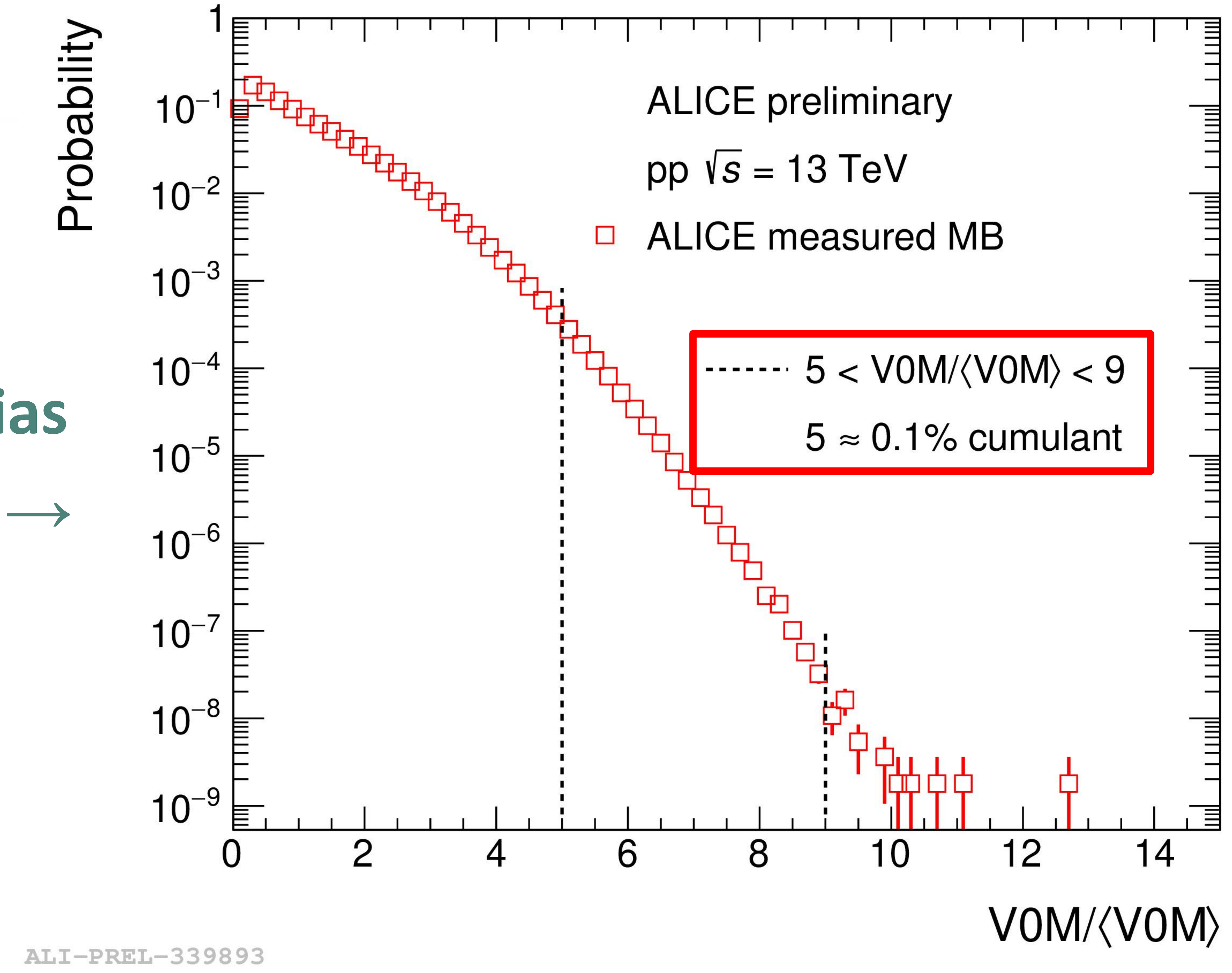
- **Offline event activity (EA) selection:**

  V0M = V0A + V0C → sum of signals

- **Scaled multiplicity V0M/⟨V0M⟩**

  ⟨V0M⟩ - mean of MB distribution

Minimum bias distribution →



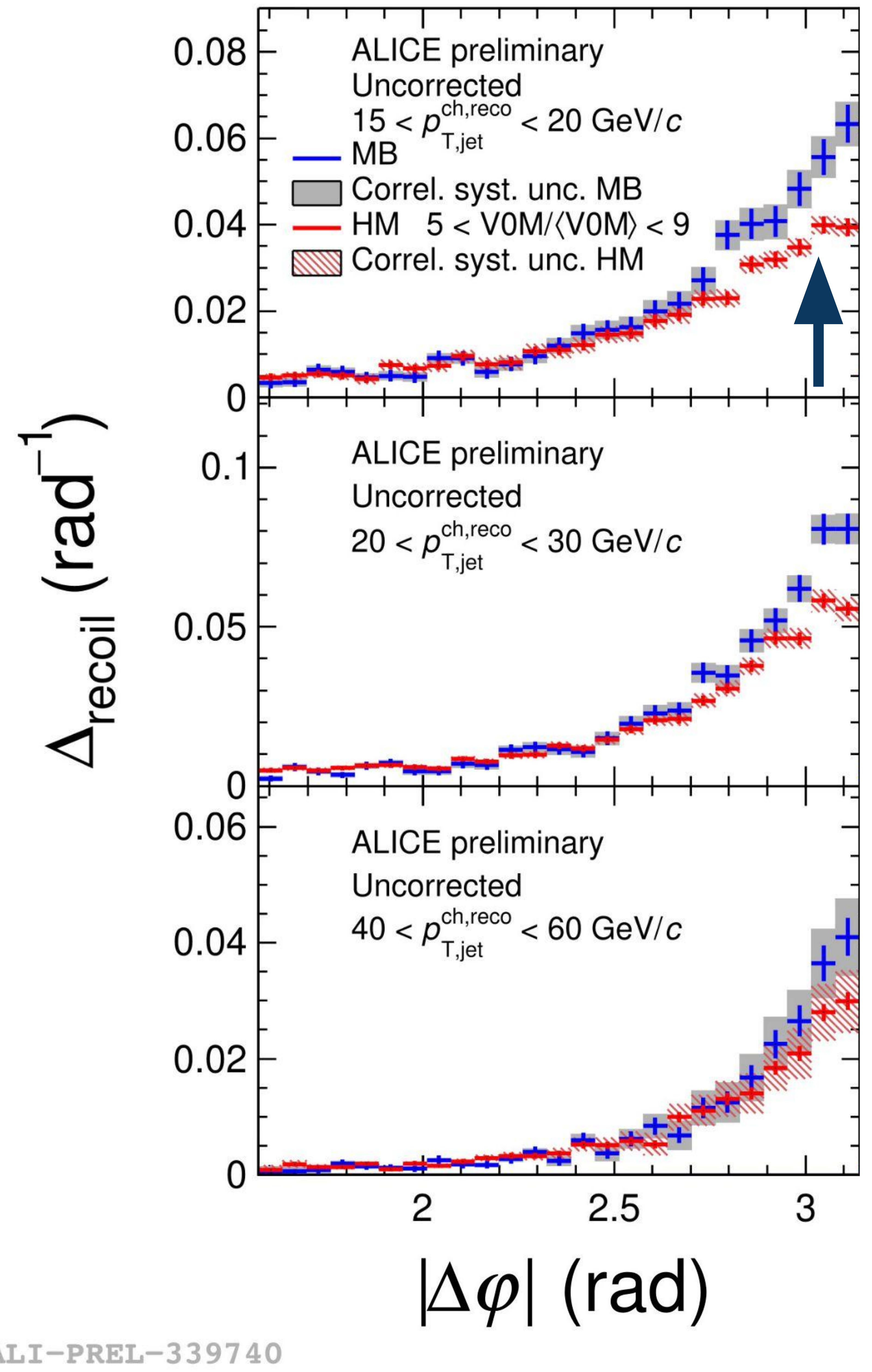
Acoplanarity versus event activity: uncorrected data and PYTHIA 8

- Anti-k_T R = 0.4 charged-particle recoil jets

Uncorrected data

- Estimated uncertainty from tracking efficiency
- **Significant suppression and broadening of HM data when compared to MB**

Uncorrected data



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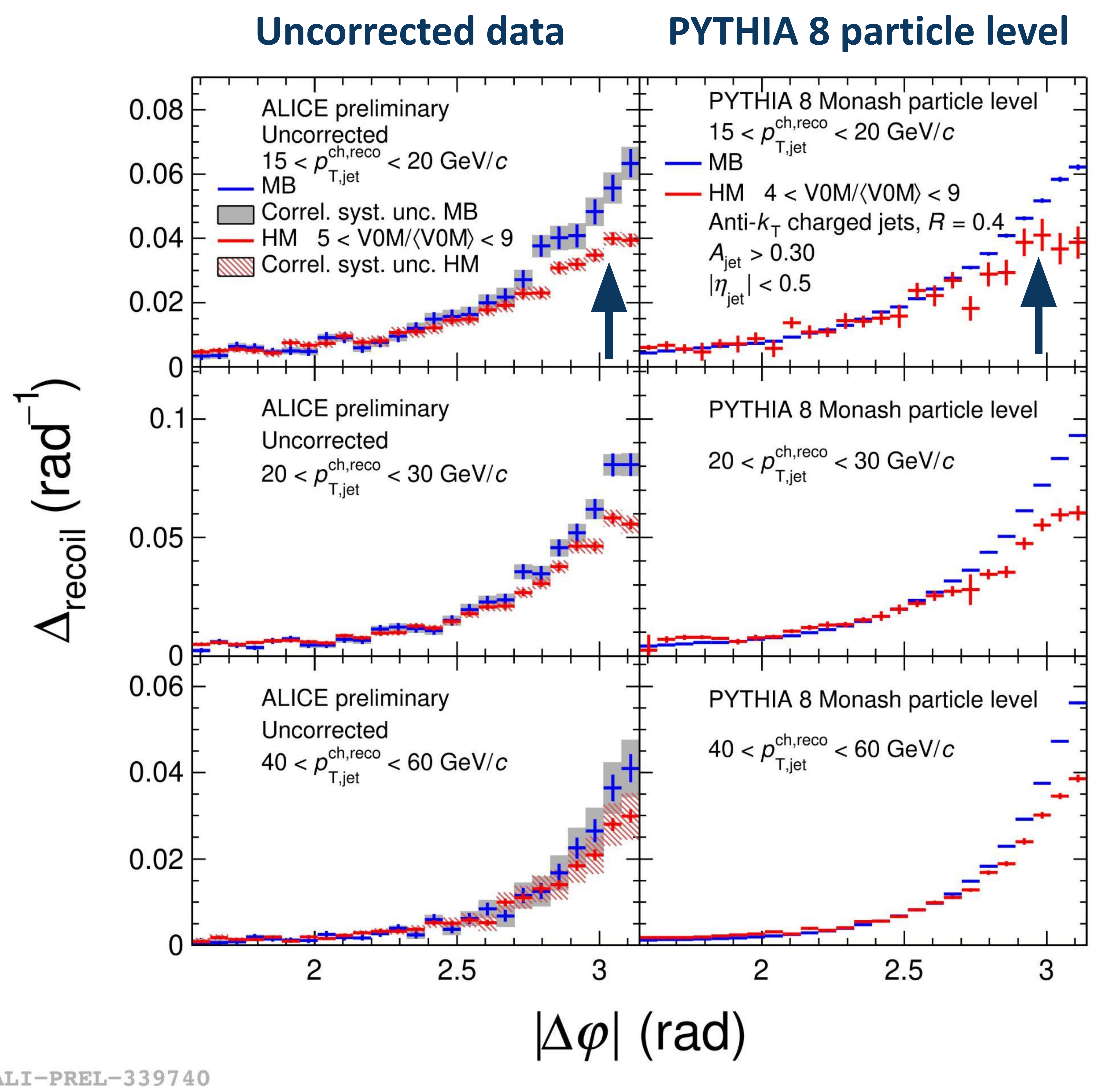
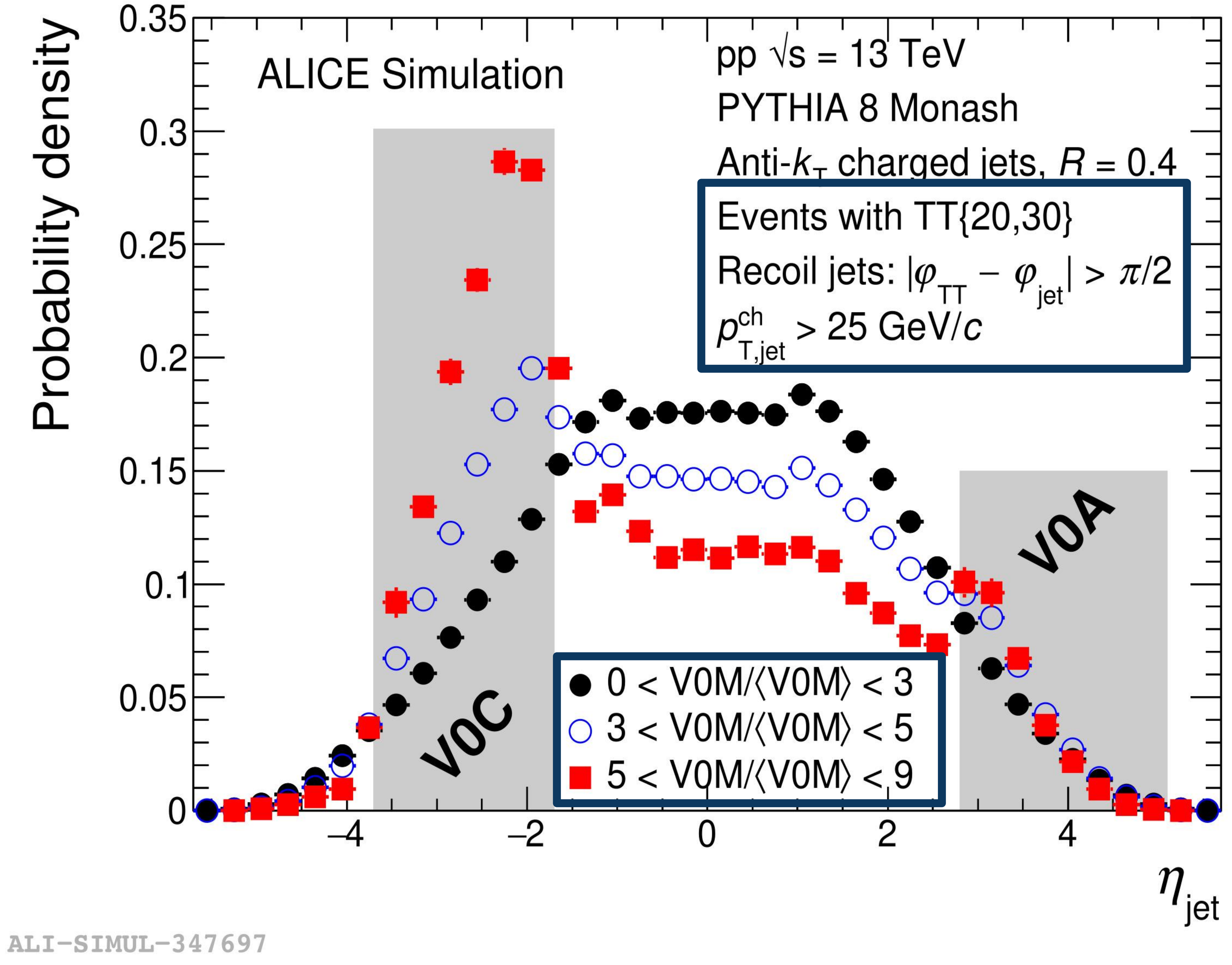
PYTHIA 8 simulation

- Does not account for jet quenching
- **Exhibits qualitatively similar suppression effect as real data**



PYTHIA 8 simulation

Recoil jet pseudorapidity distribution vs. event activity

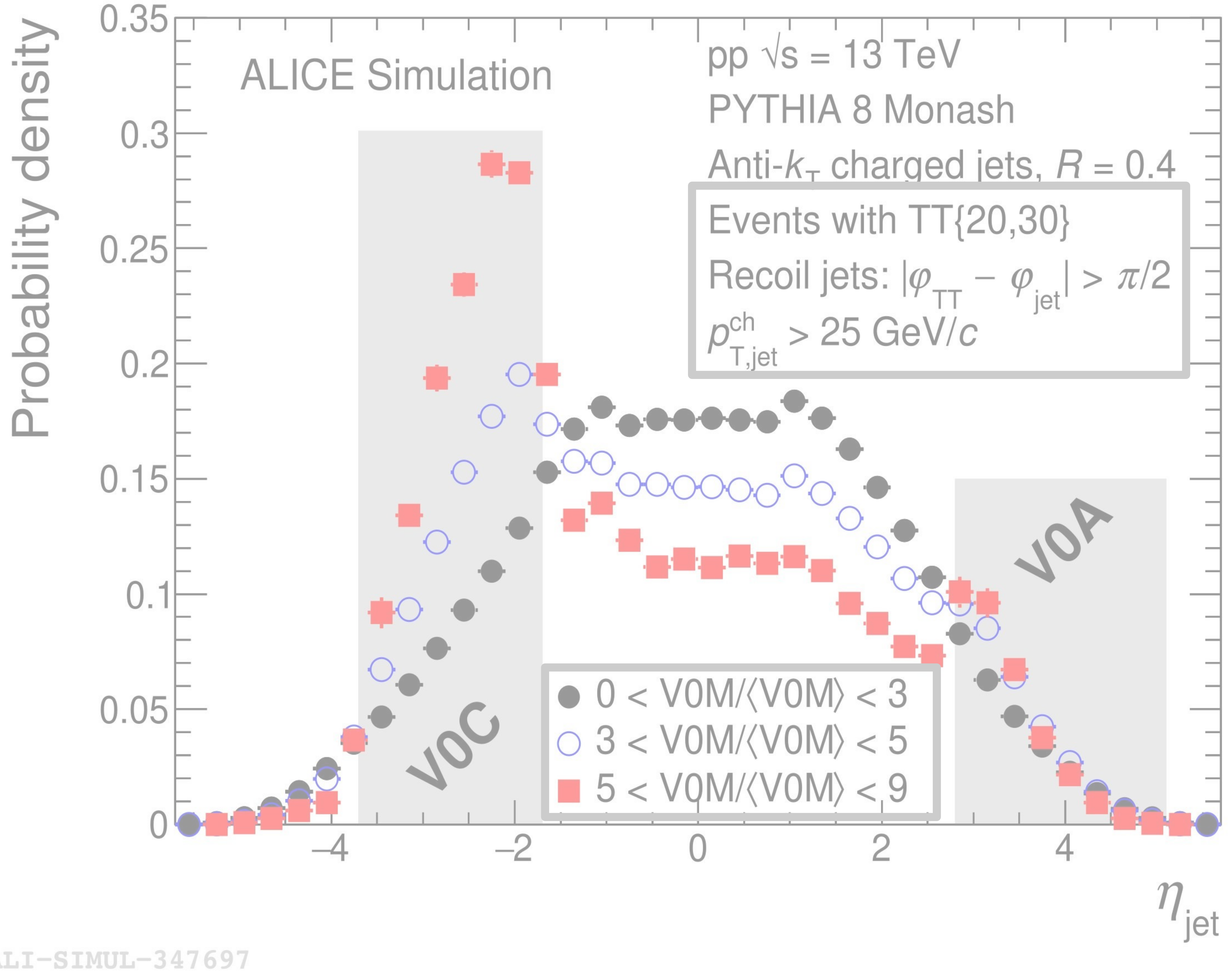


- HM bias imposed by V0M selection **enhances probability** to find a high-p_T recoil jet in V0
- Lower enhancement in V0A is caused by asymmetric coverage of V0 arrays
- **HM selection biases recoil jets**

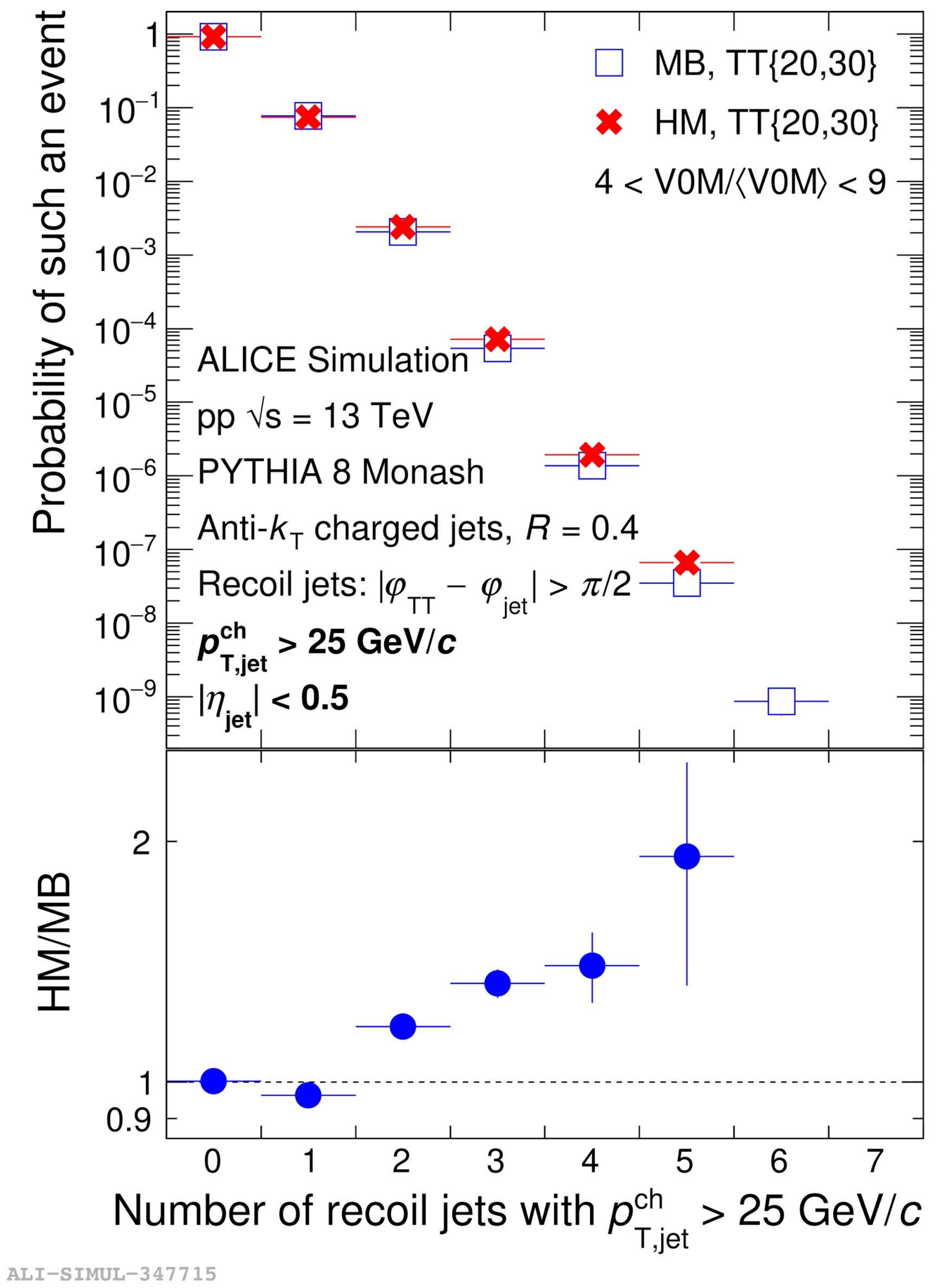
★ V0M is defined as the number of charged, final state particles within V0A & V0C acceptances

PYTHIA 8 simulation

Recoil jet pseudorapidity distribution vs. event activity



Number of high-p_T recoil jet vs. event activity



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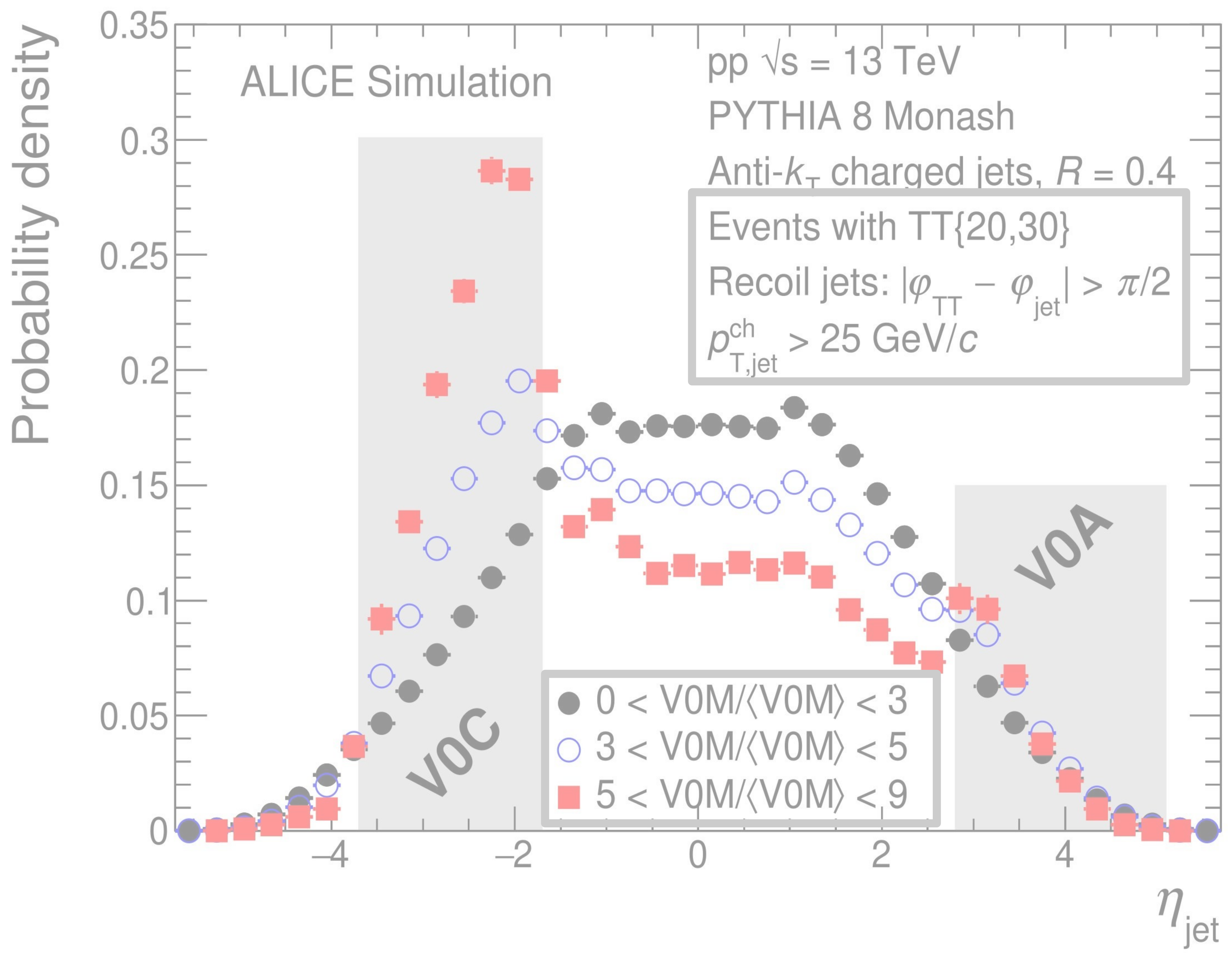
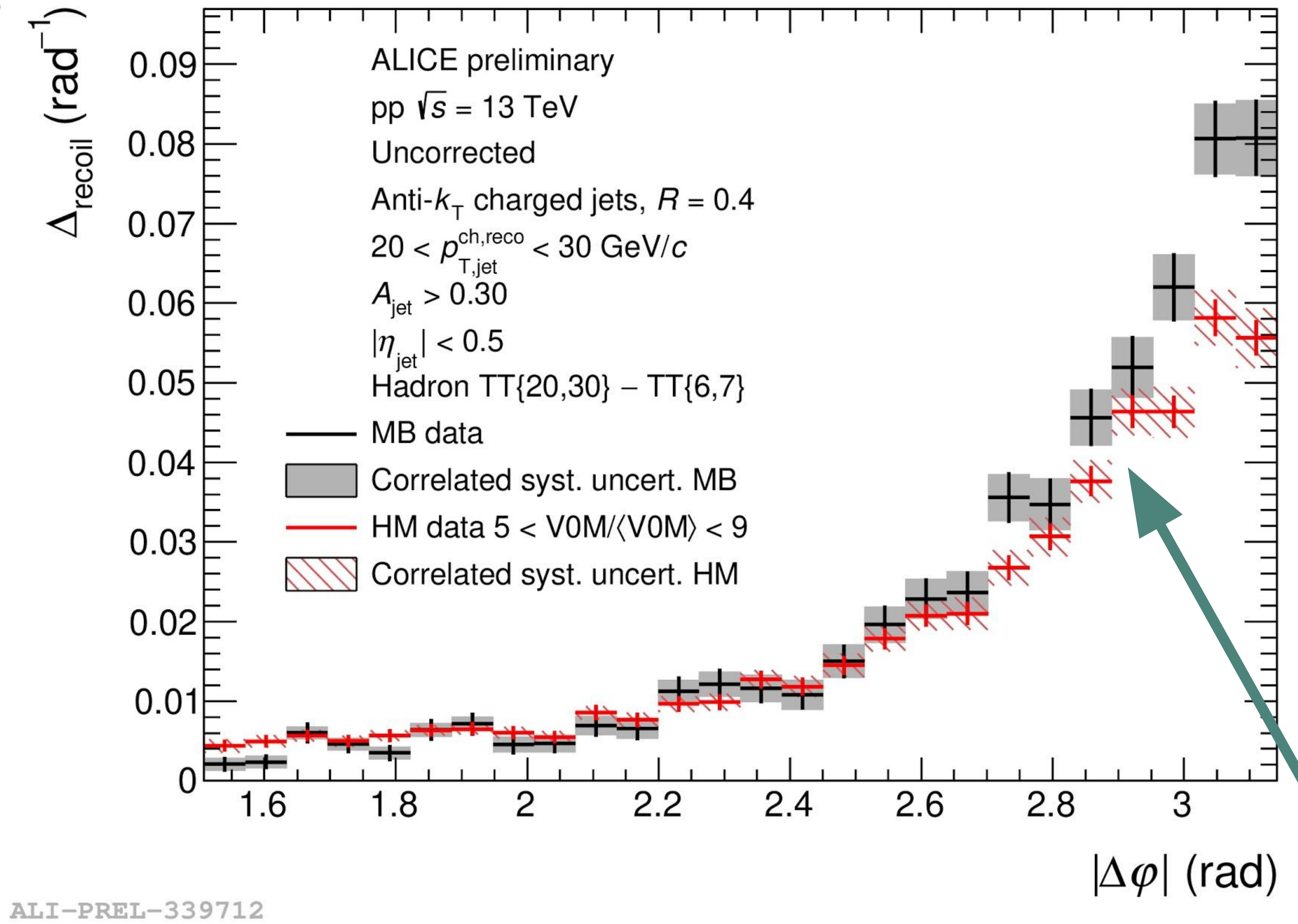


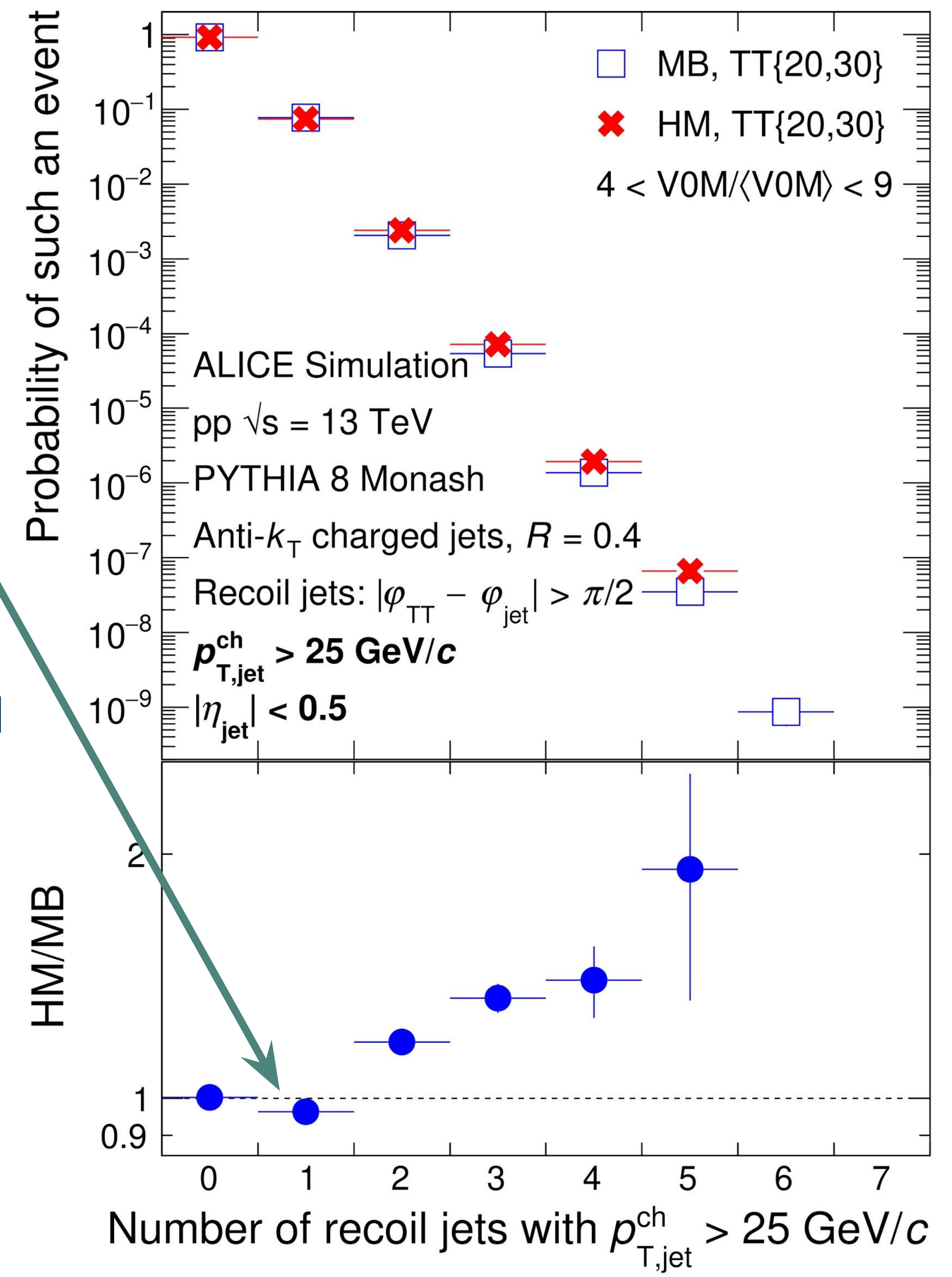
ALI-SIMUL-347697



ALI-PREL-339712

- HM events → **suppressed probability to have 1 hard recoil jet** in ALICE central barrel w.r.t. MB

Number of high-p_T recoil jet vs. event activity



ALI-SIMUL-347715

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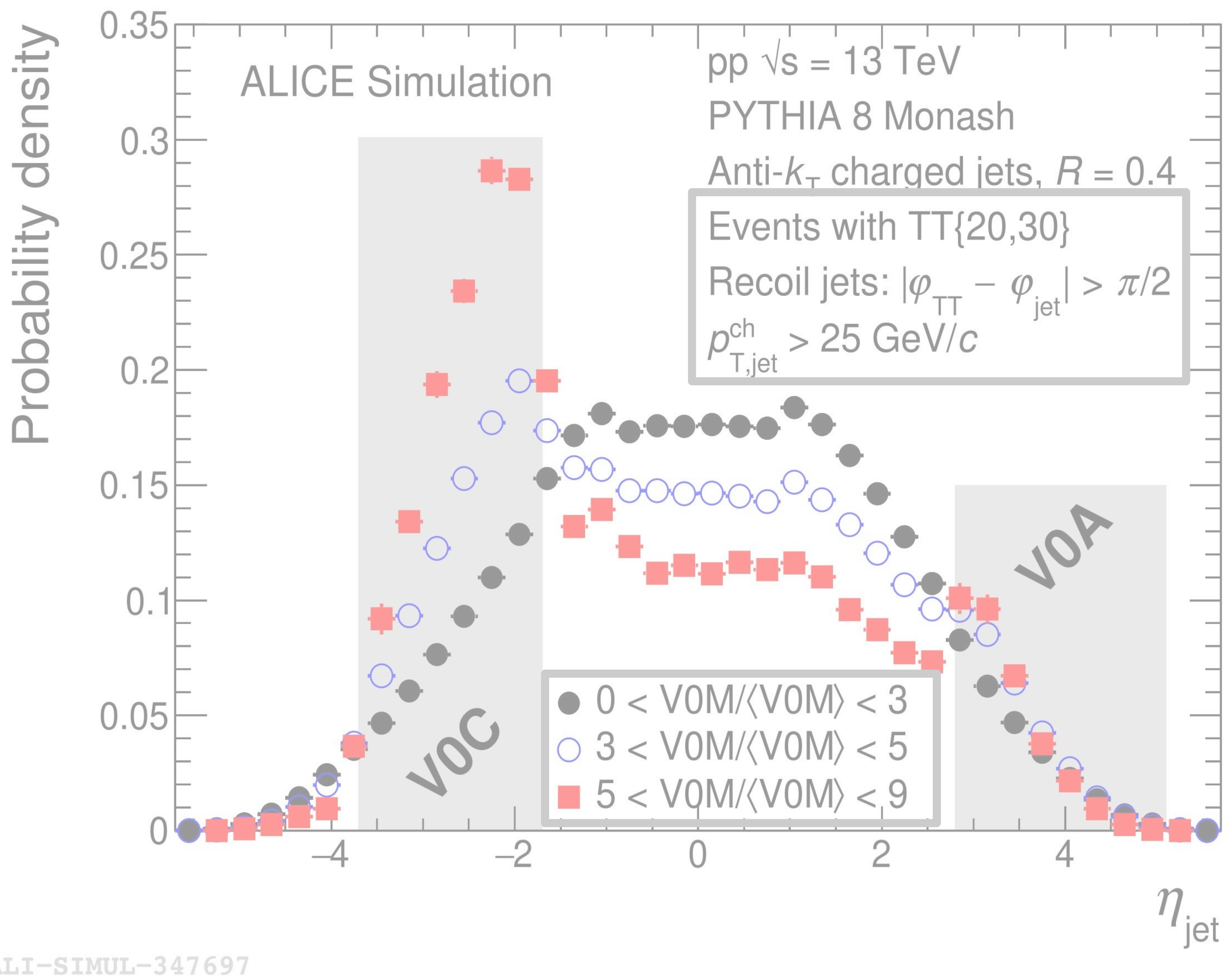
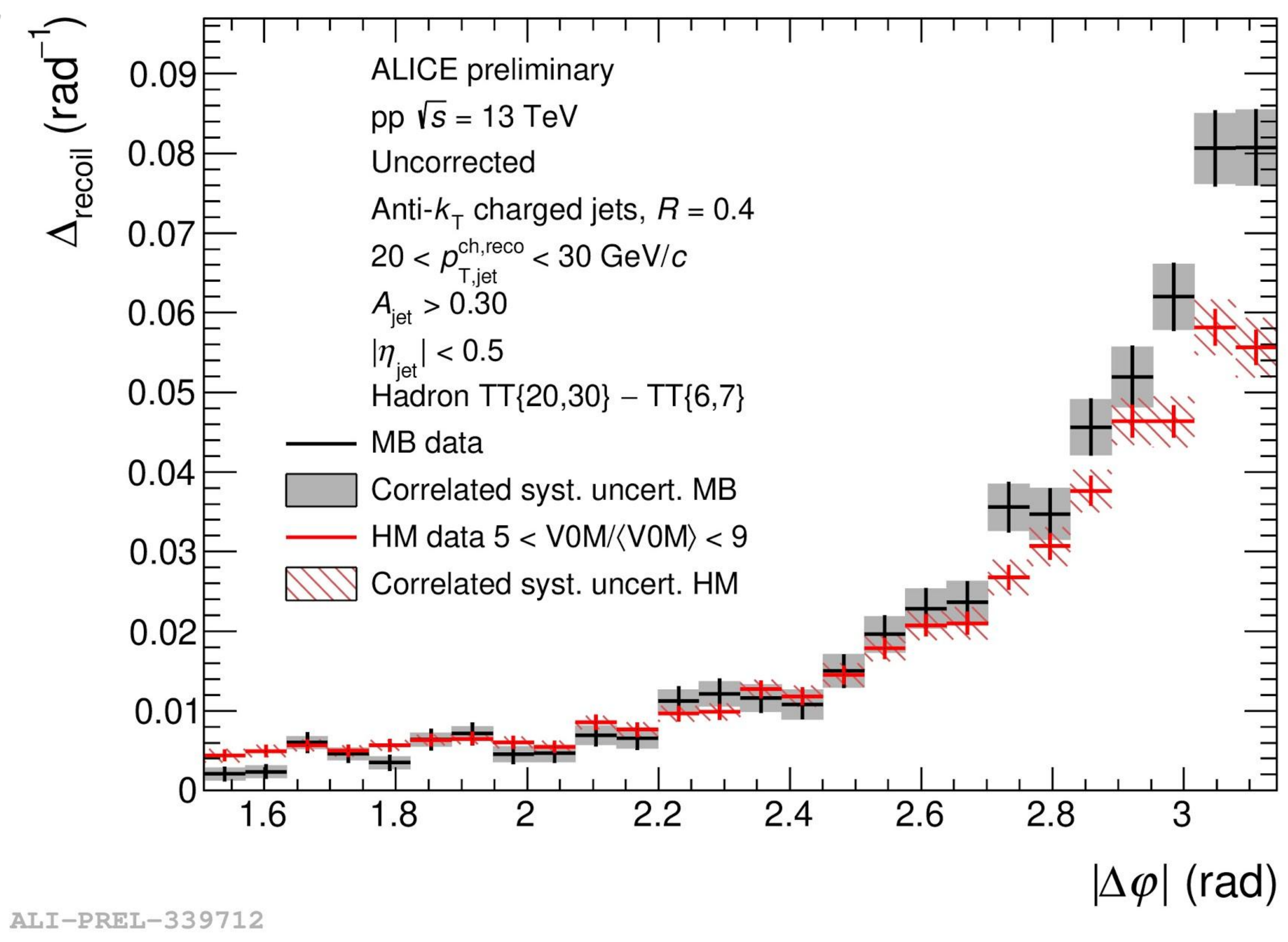
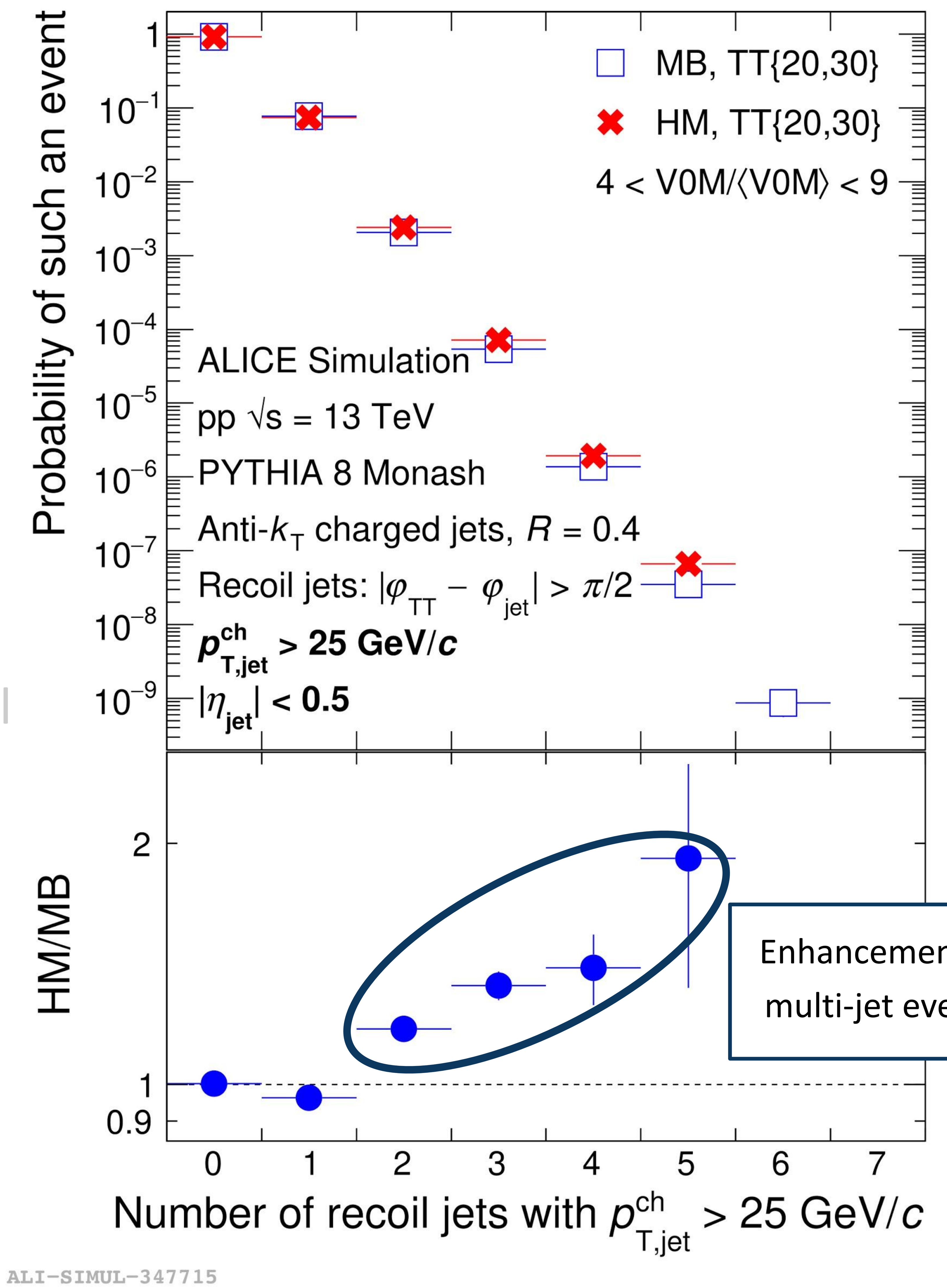




Number of high-p_T recoil jet vs. event activity



- HM events ⟶ **suppressed probability to have 1 hard recoil jet** in ALICE central barrel w.r.t. MB
- HM trigger ⟶ **bias towards multi-jet final states**

- HM bias imposed by V0M selection **enhances probability** to find a high-p_T recoil jet in V0
- Lower enhancement in V0A is caused by asymmetric coverage of V0 arrays
- **HM selection biases recoil jets**

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Summary

Pb-Pb collisions $\sqrt{s_{NN}} = 5.02$ TeV

- **Fully corrected hadron-jet $\Delta\varphi$ distribution** for $R = 0.2$ jets in $30 < p_{\mathrm{T\,jet}} < 40$ GeV/c
- Suppression with respect to PYTHIA pp data
- Observation of narrowing of $\Delta\varphi$ distribution with respect to pp $\rightarrow$ **signs of radiative corrections?**

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

- Significant suppression and broadening of **uncorrected high-particle multiplicity $\Delta_{recoil}(\Delta\varphi)$ distribution** with respect to minimum bias one

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

- Significant suppression and broadening of **uncorrected high-particle multiplicity $\Delta_{recoil}(\Delta\varphi)$ distribution** with respect to minimum bias one
- **Qualitatively similar** effects are observed in PYTHIA 8 events:
  - High-multiplicity bias → enhance probability to have high-pT recoil jet in V0 acceptance
  - Bias towards multi-jet final state induced by high-multiplicity trigger: increased acoplanarity due to standard QCD effect → **obscures possible jet quenching signal**
  - Multi-jet final state → generic bias for all measurements in small collision systems

Backup slides

Pb-Pb data $\sqrt{s_{NN}}$ = 5.02 TeV

2018 Pb-Pb data sample

- 133M most central events (0-10 %)

Inner tracking system $|\eta| < 0.9$

- Tracking and vertexing

Time projection chamber $|\eta| < 0.9$

- Tracking

V0 arrays

- Centrality determination
- **V0A:** $2.8 < \eta < 5.1$ & **V0C:** $-3.7 < \eta < -1.7$

Jet reconstruction

- Track $p_T > 150$ MeV/c
- Anti-k_T $R = 0.2$ charged-particle jets
- Fiducial cut $|\eta_{Jet}| < 0.7$