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

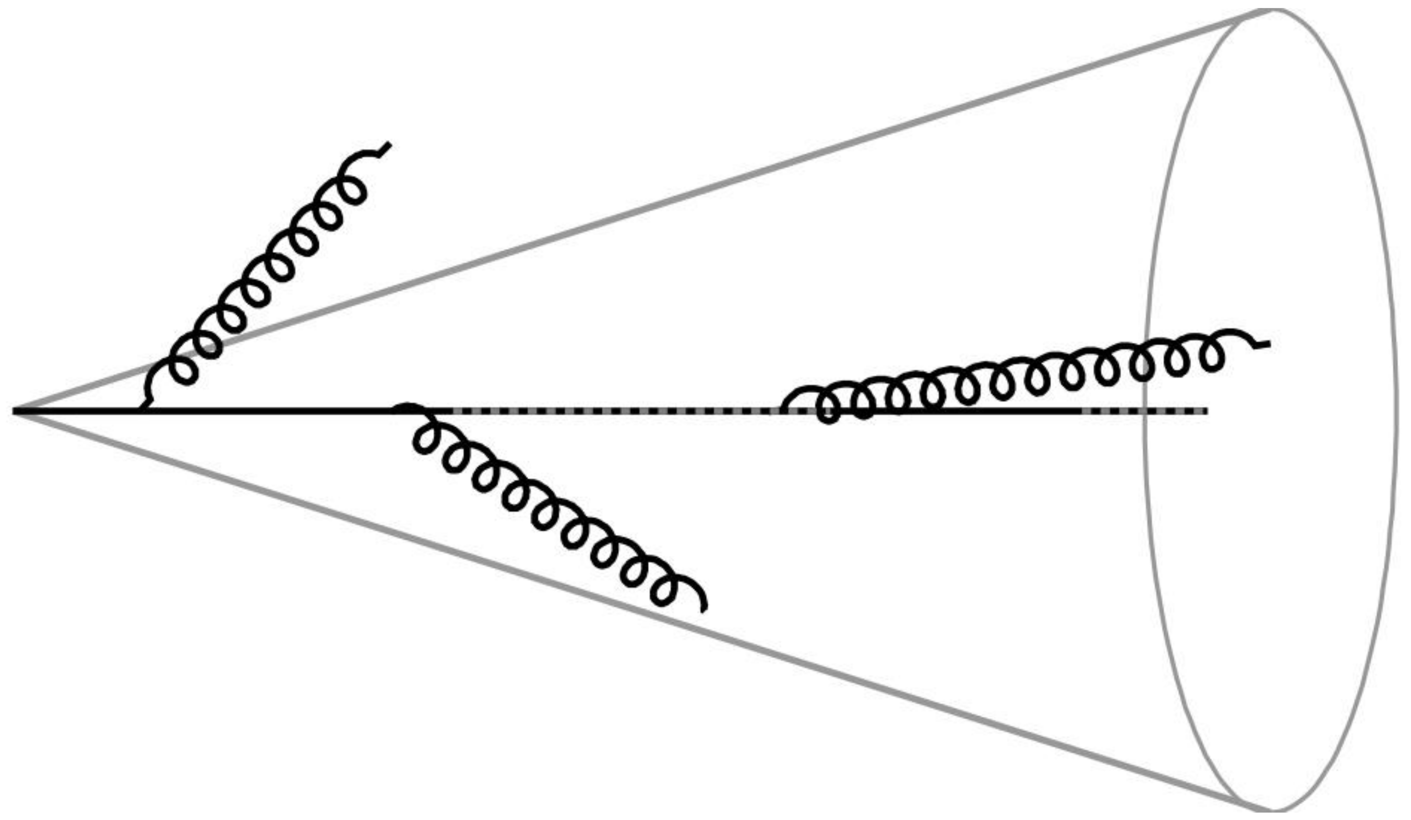
ALICE

Introduction

Jet shower in vacuum

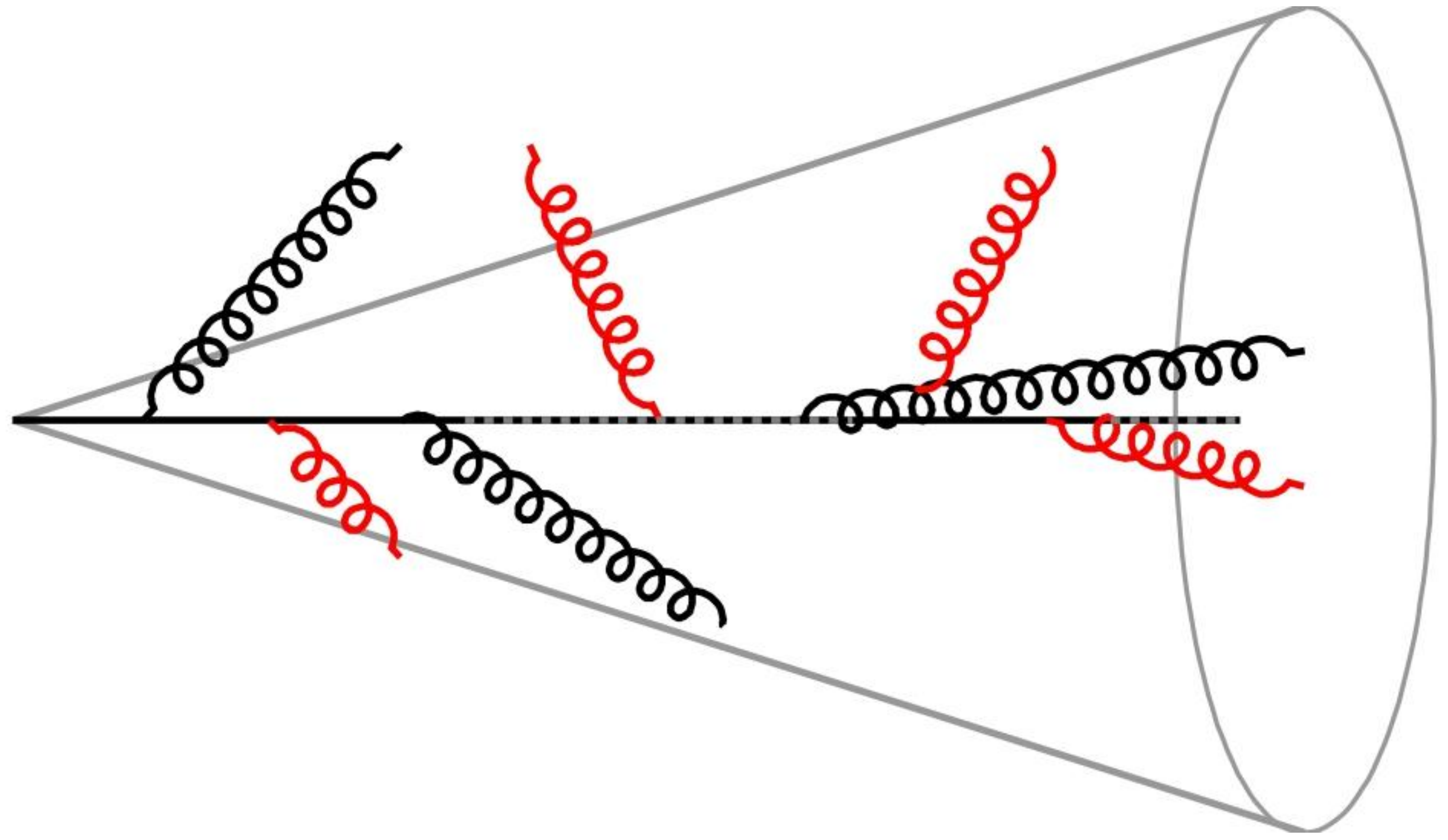
Evolution of highly virtual parton via gluon radiation

- Precise understanding in pQCD
- Reference process for nucleus collisions



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)



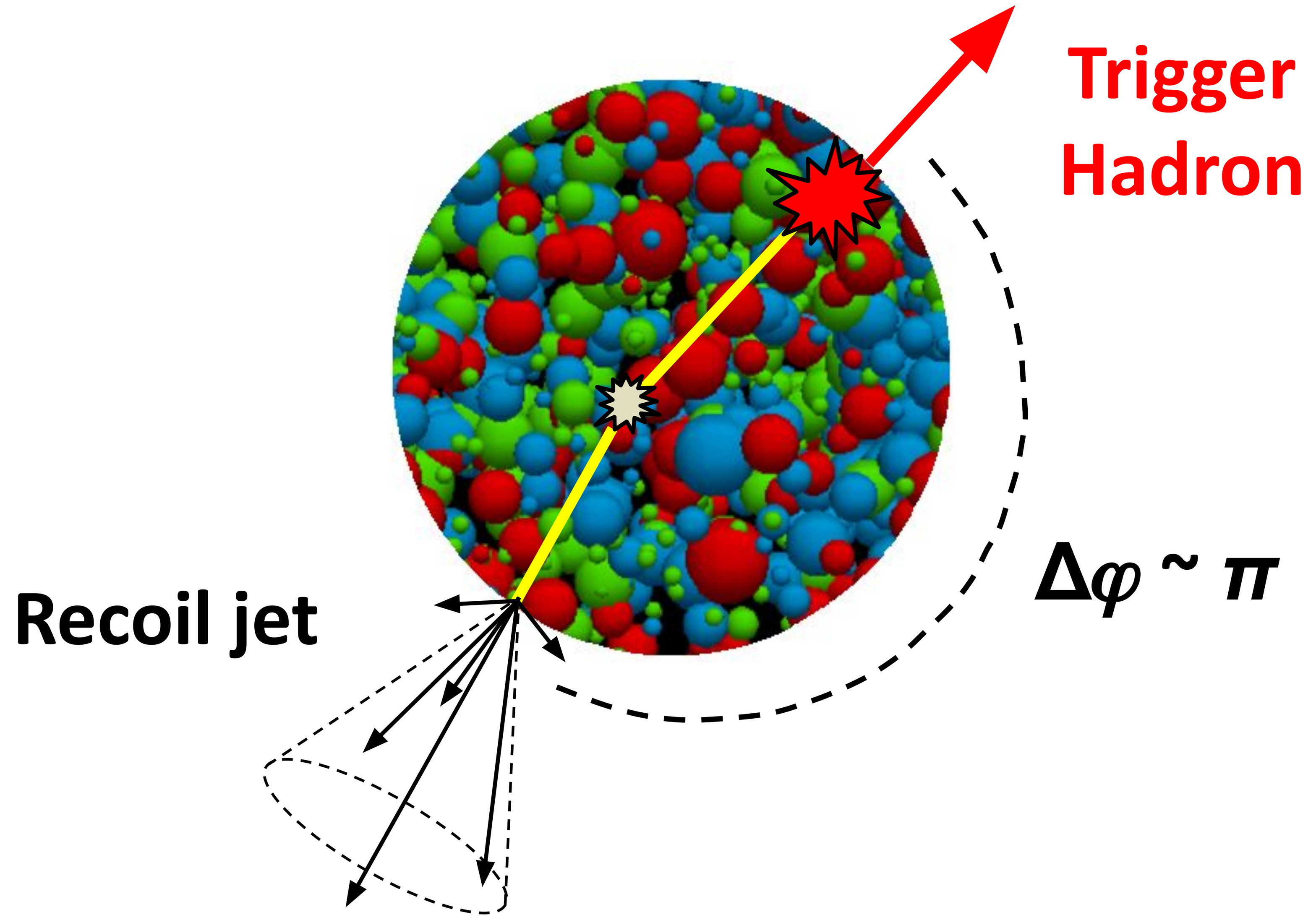
Hadron-jet acoplanarity

Regions of interest

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

- Acoplanarity broadening → **vacuum (Sudakov) radiation and multiple scatterings in medium** (L. Chen et al, Phys. Lett. B773 (2017) 672)
- Measurement of medium-induced broadening → direct estimation of **jet transport coefficient *q***
- Negative radiative correction to $\langle p^2{}_\perp \rangle$ → **reduction of broadening**

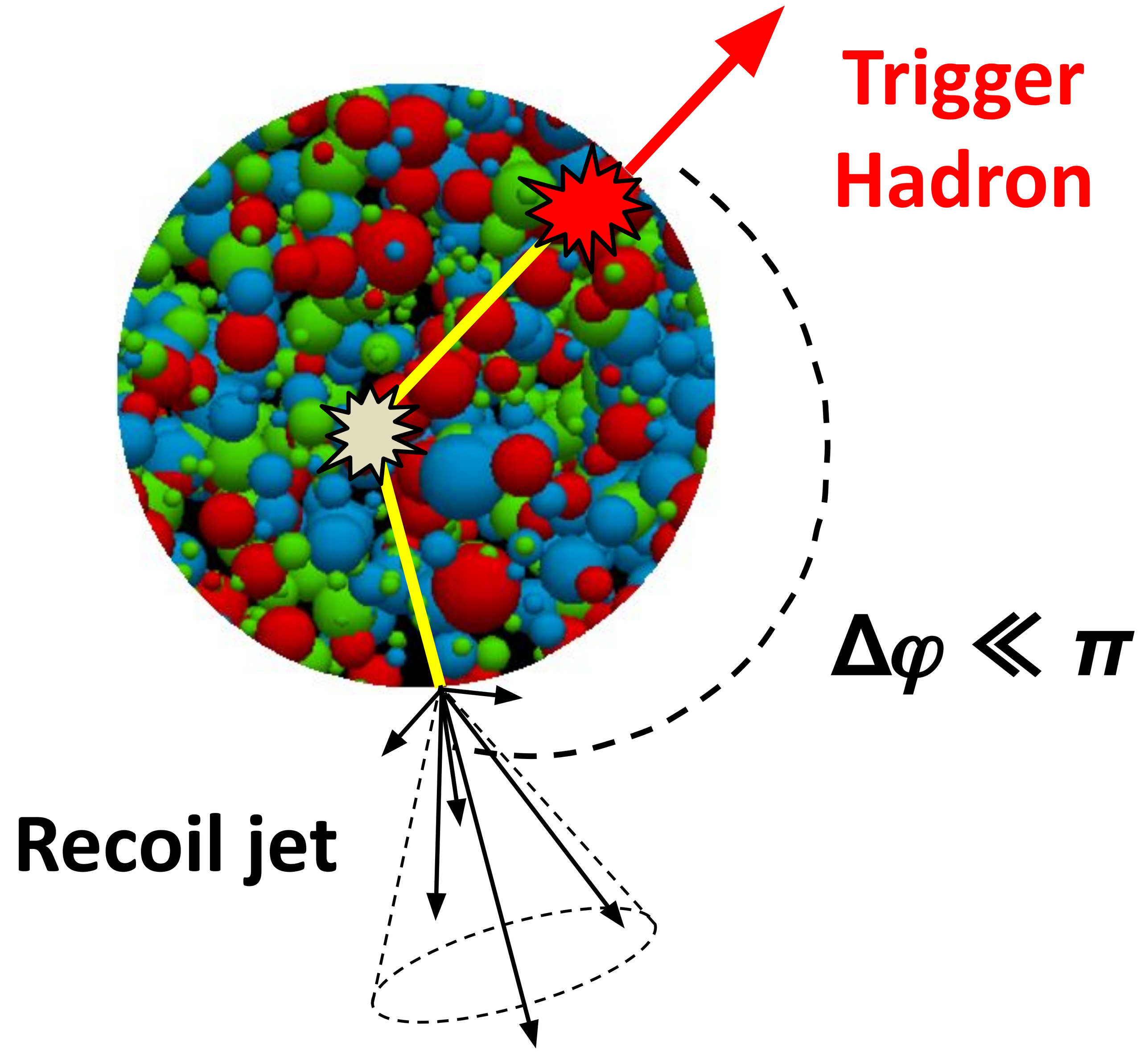
  (B. G. Zakharov, arxiv:2003.10182)



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

- 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)



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

2018 Pb-Pb data sample

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

V0 arrays

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

Inner tracking system $|\eta| < 0.9$

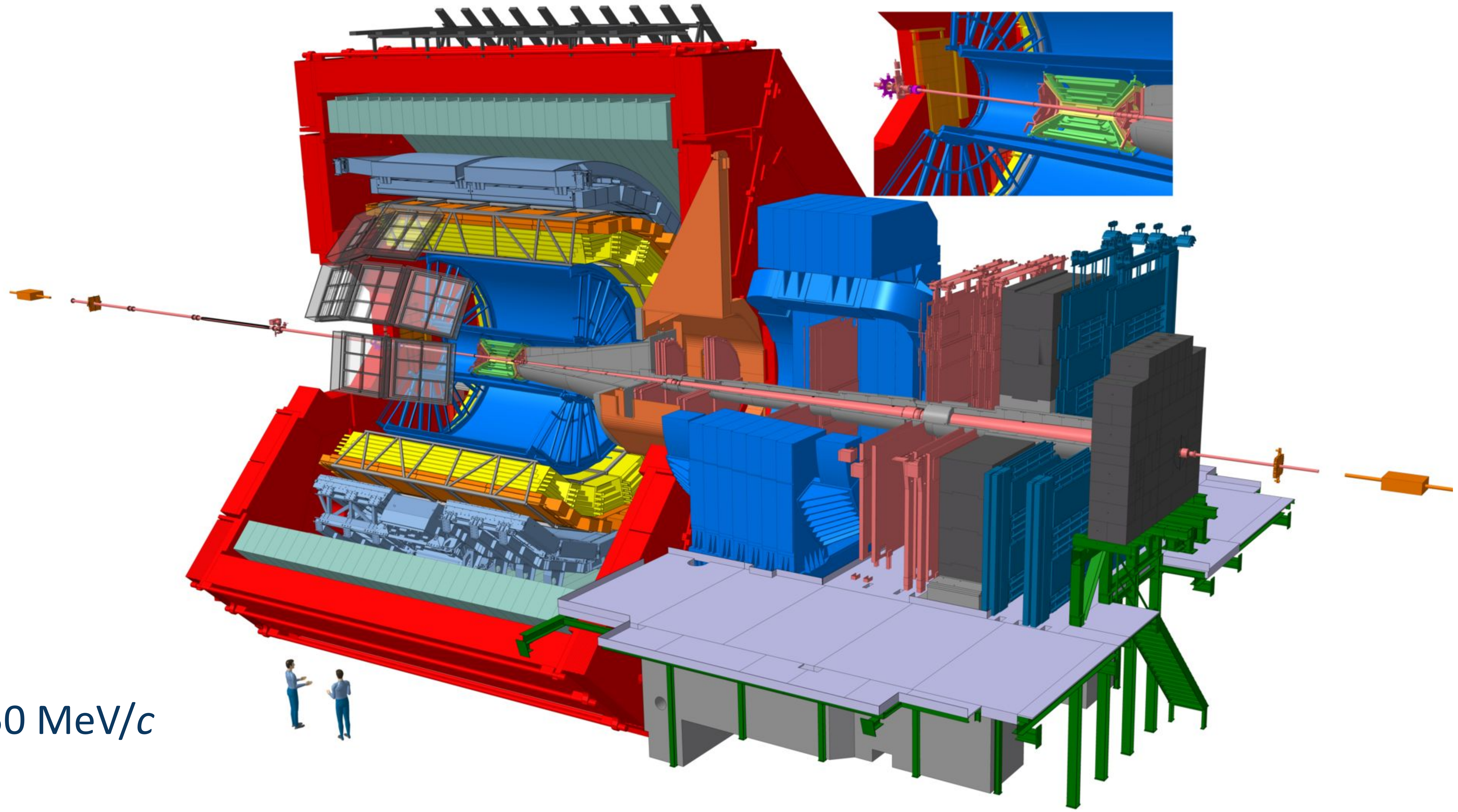
- Tracking and vertexing

Time projection chamber $|\eta| < 0.9$

- Tracking

Jet reconstruction

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



Hadron-jet acoplanarity via semi-inclusive measurements

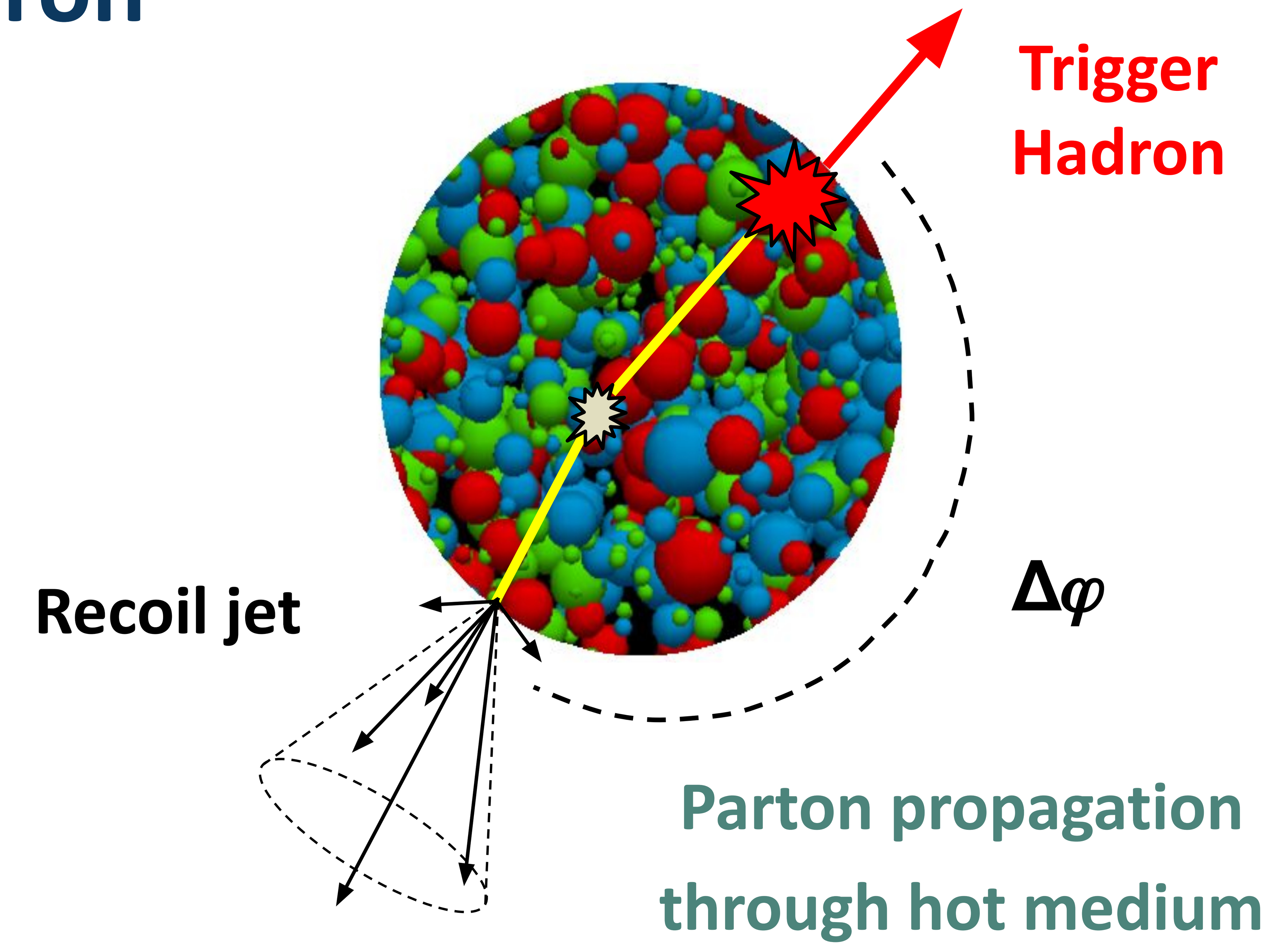
Per trigger normalized spectrum of jets recoiling from high-p_T hadron

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

→ 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:

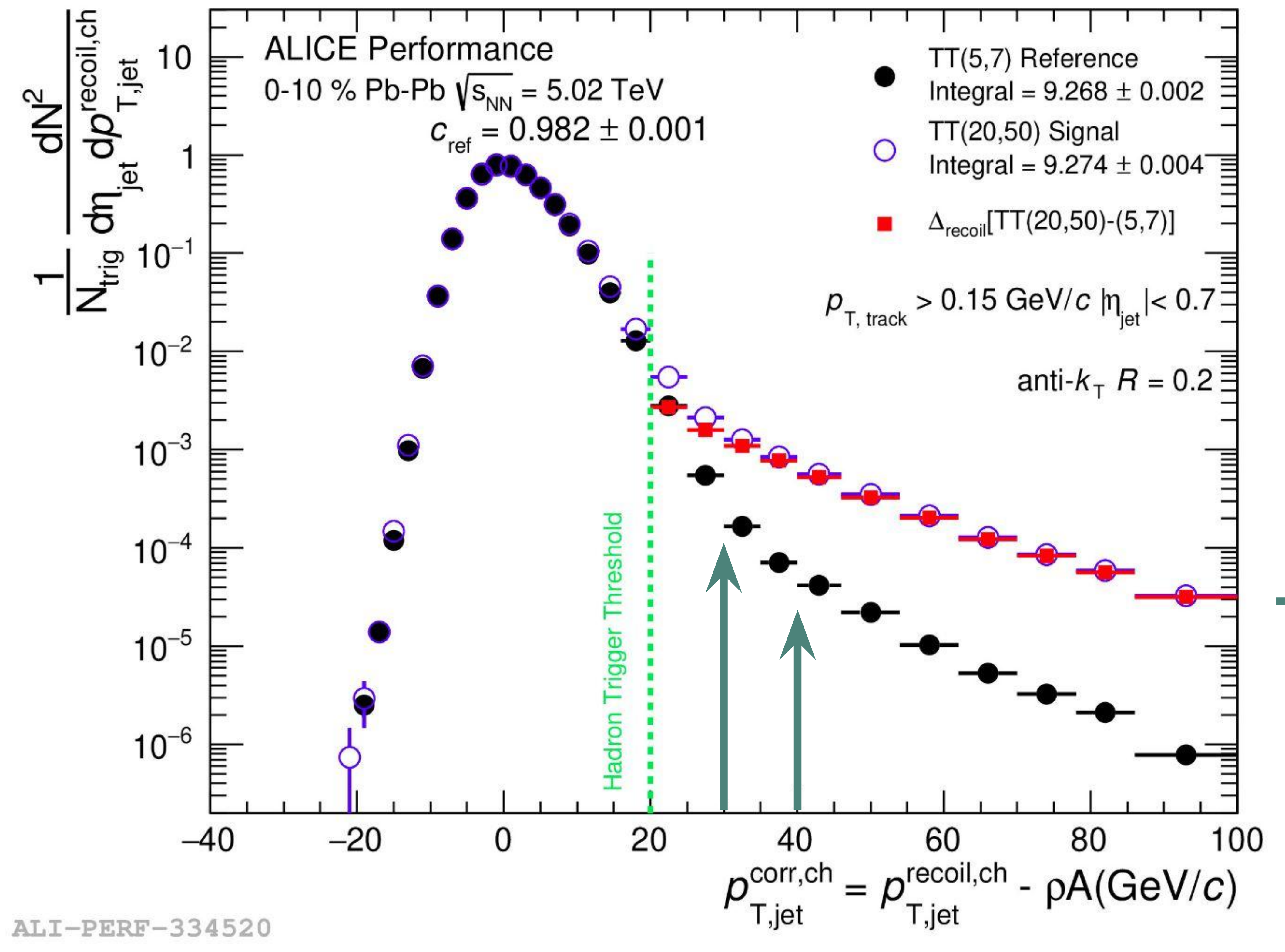
- Unbiased jet population
- Access to **low p_T jets → more sensitive to medium-induced broadening**
- **Data driven approach for removal of uncorrelated background yield**

  → essential for precise acoplanarity measurements

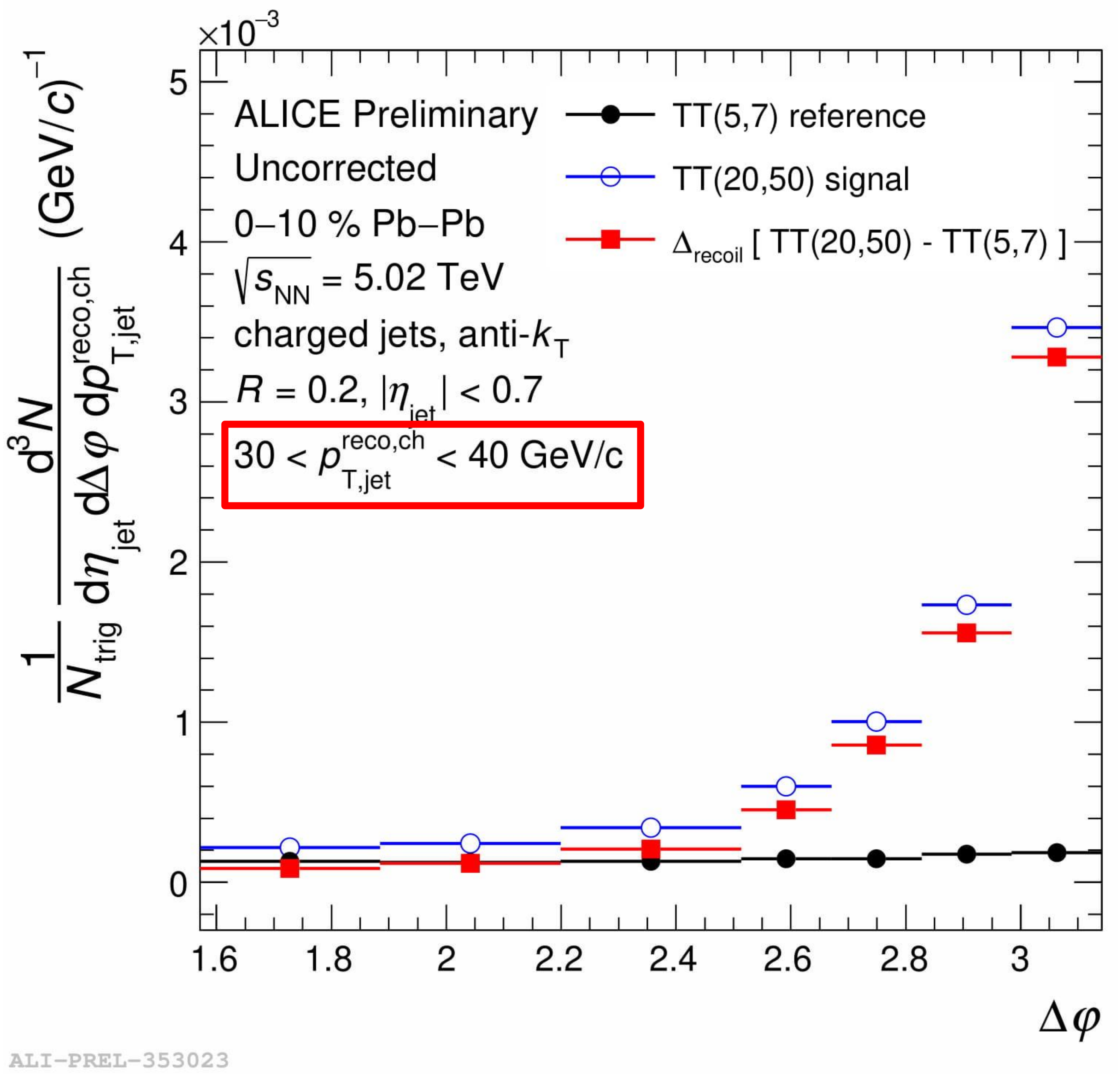
Hadron-jet acoplanarity: Δ_{recoil} observable

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

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



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



- Jet p_T corrected for **underlying event density ρ**
- Data-driven approach to **remove uncorrelated background yield**

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

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

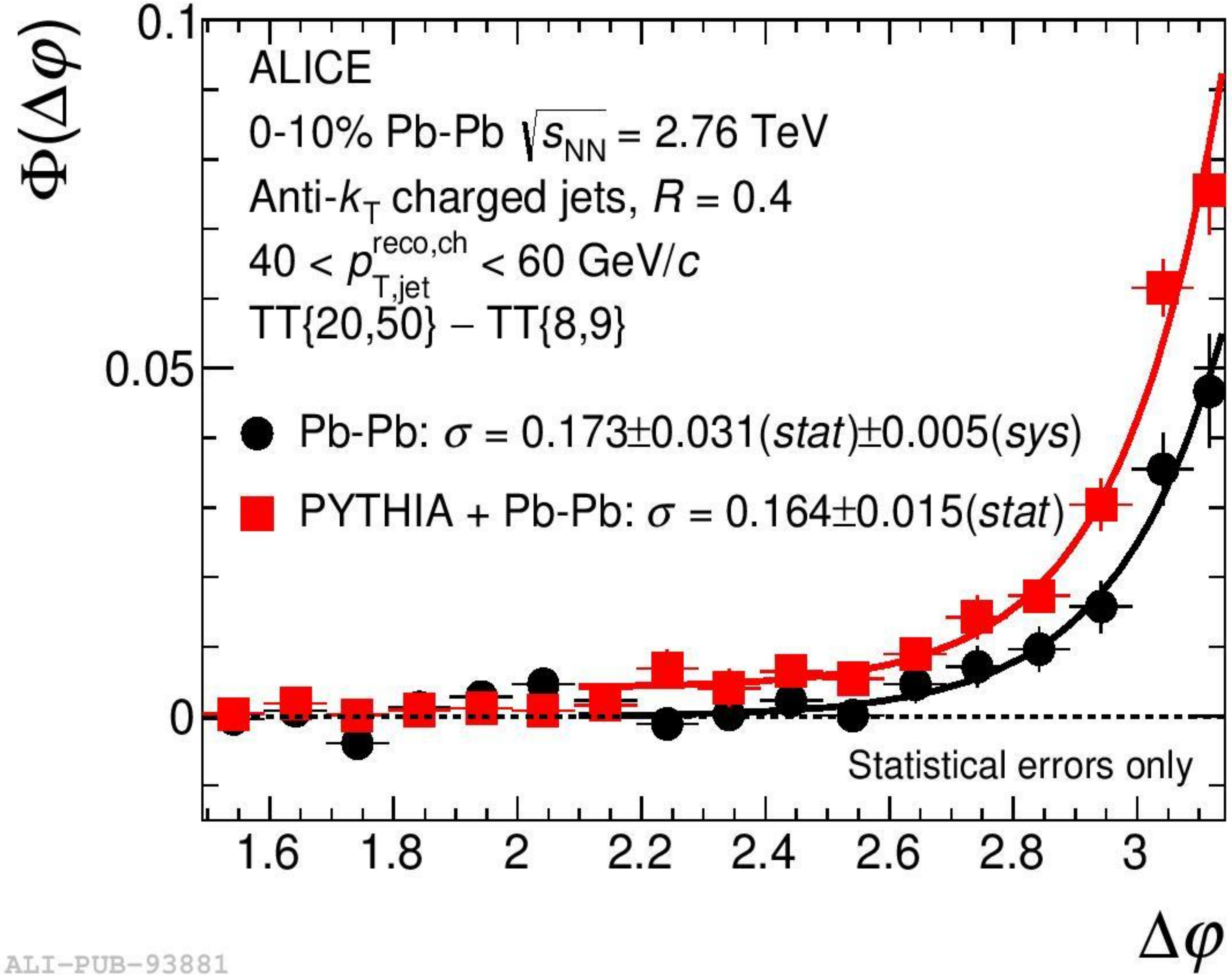
Run 1 data

- 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:

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

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

JHEP 09 (2015) 170 (arxiv:1506.03984)



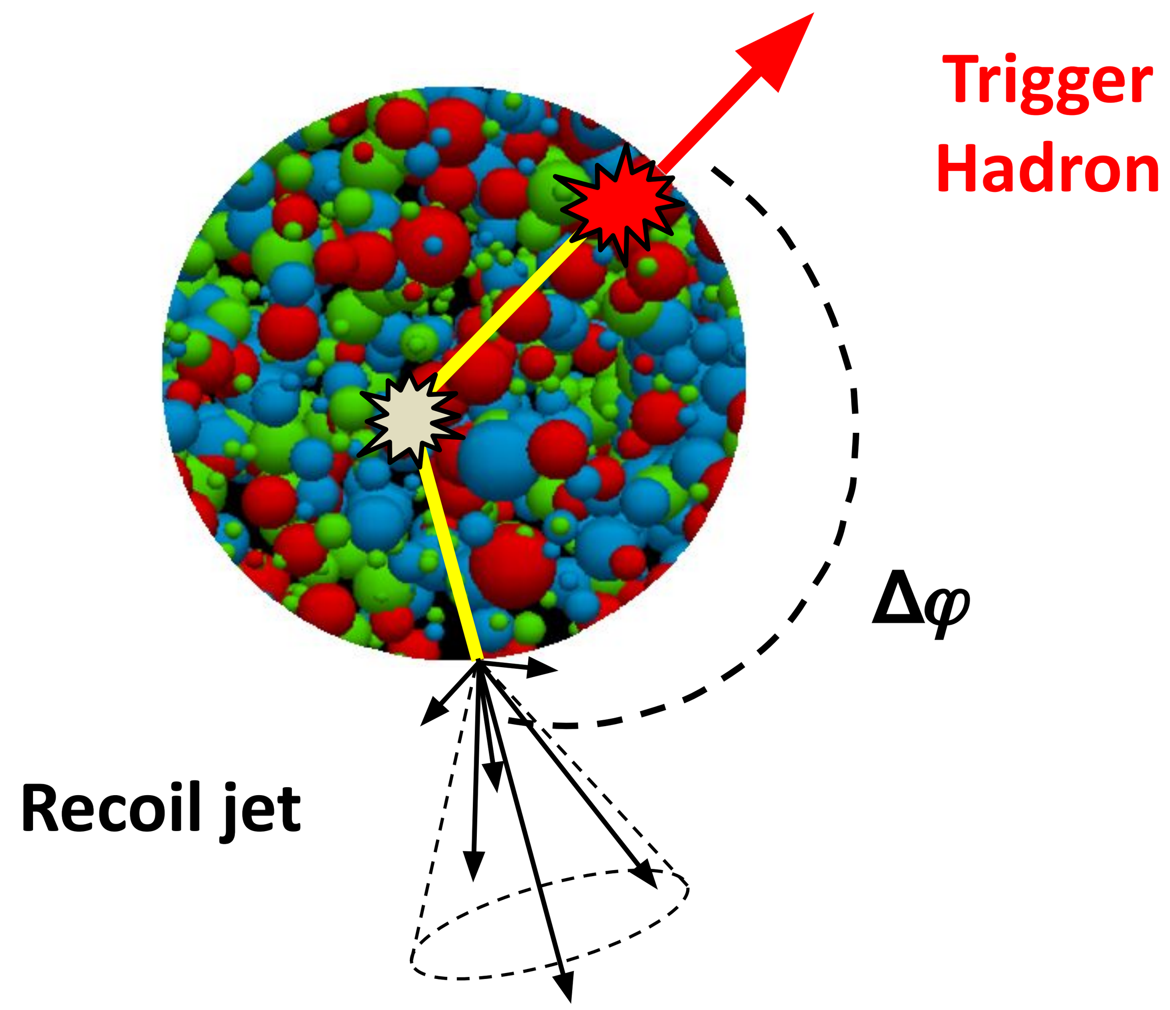
Acoplanarity measurement: Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

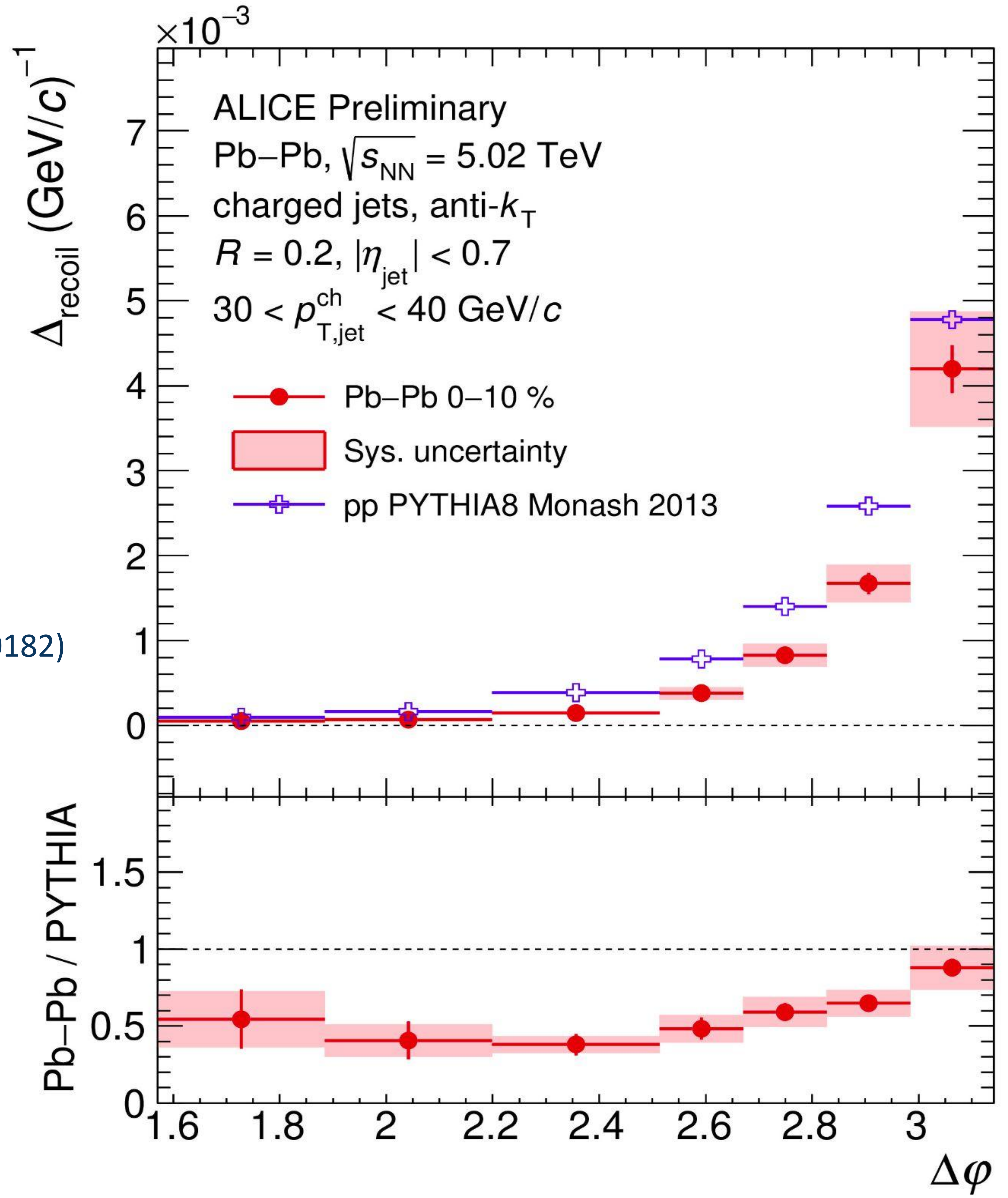
- **Run 2 data: x9 larger statistics** with respect to Run 1 data
- Anti-k_T charged-particle jets R = 0.2 with $p_T \in (30, 40)$ GeV/c
- Fully corrected hadron-jet $\Delta\varphi$ distribution

- Recoil jet yield suppressed compared to pp PYTHIA data
- **Indication of narrowing of acoplanarity distribution**

  → effect of negative radiative corrections? (B. G. Zakharov, arxiv:2003.10182)

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





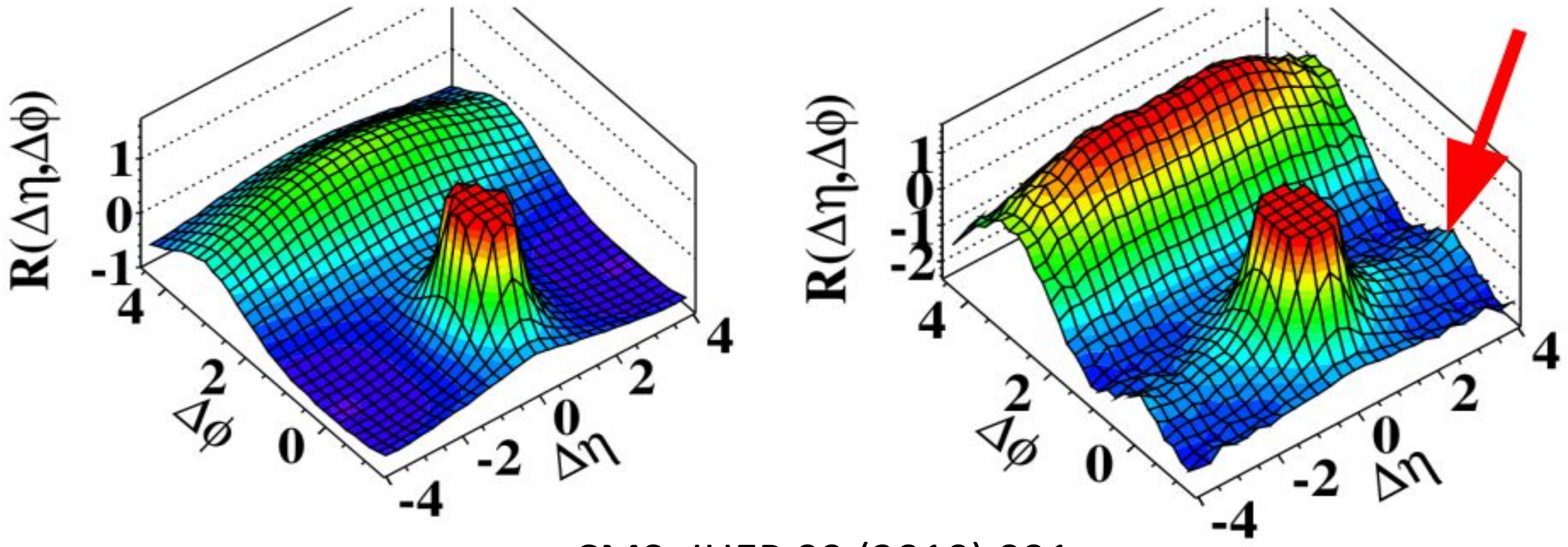
High-particle multiplicity pp collisions

Quark-gluon plasma formation in small collision systems?

Collective flow

Azimuthal correlation between two particles pp 7 TeV

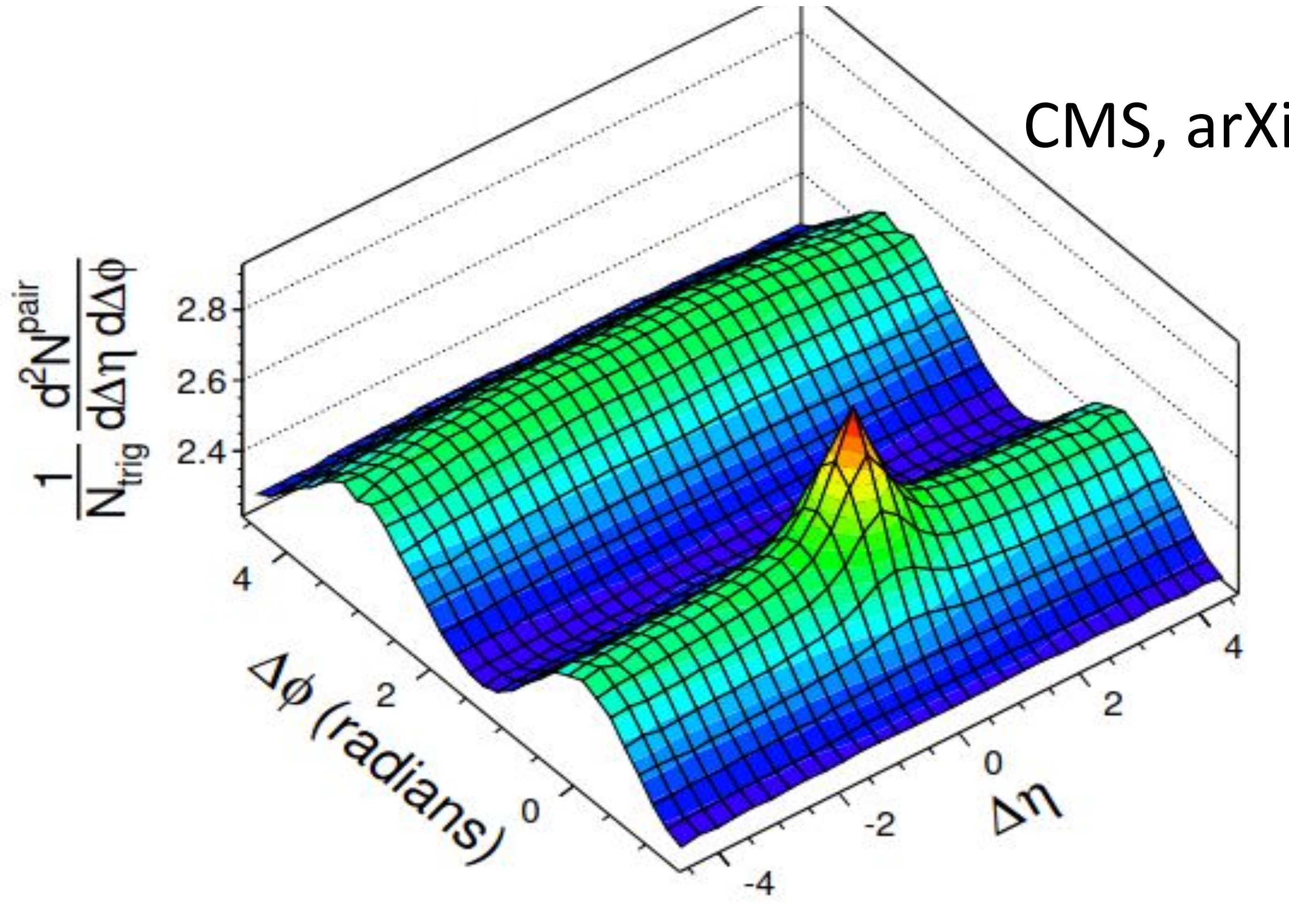
Minimum bias events   High-multiplicity events



CMS, JHEP 09 (2010) 091

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

CMS, arXiv:1305.0609v3



Jet quenching in high particle multiplicity pp collisions

R_{AA} nuclear modification factor measurements

$$R_{AA} = \frac{d^2N_{AA}/dy dp_T}{\langle T_{AA}\rangle d^2\sigma_{pp}^{INEL}/dy dp_T}$$

undefined Glauber scaling factor for high particle multiplicity pp

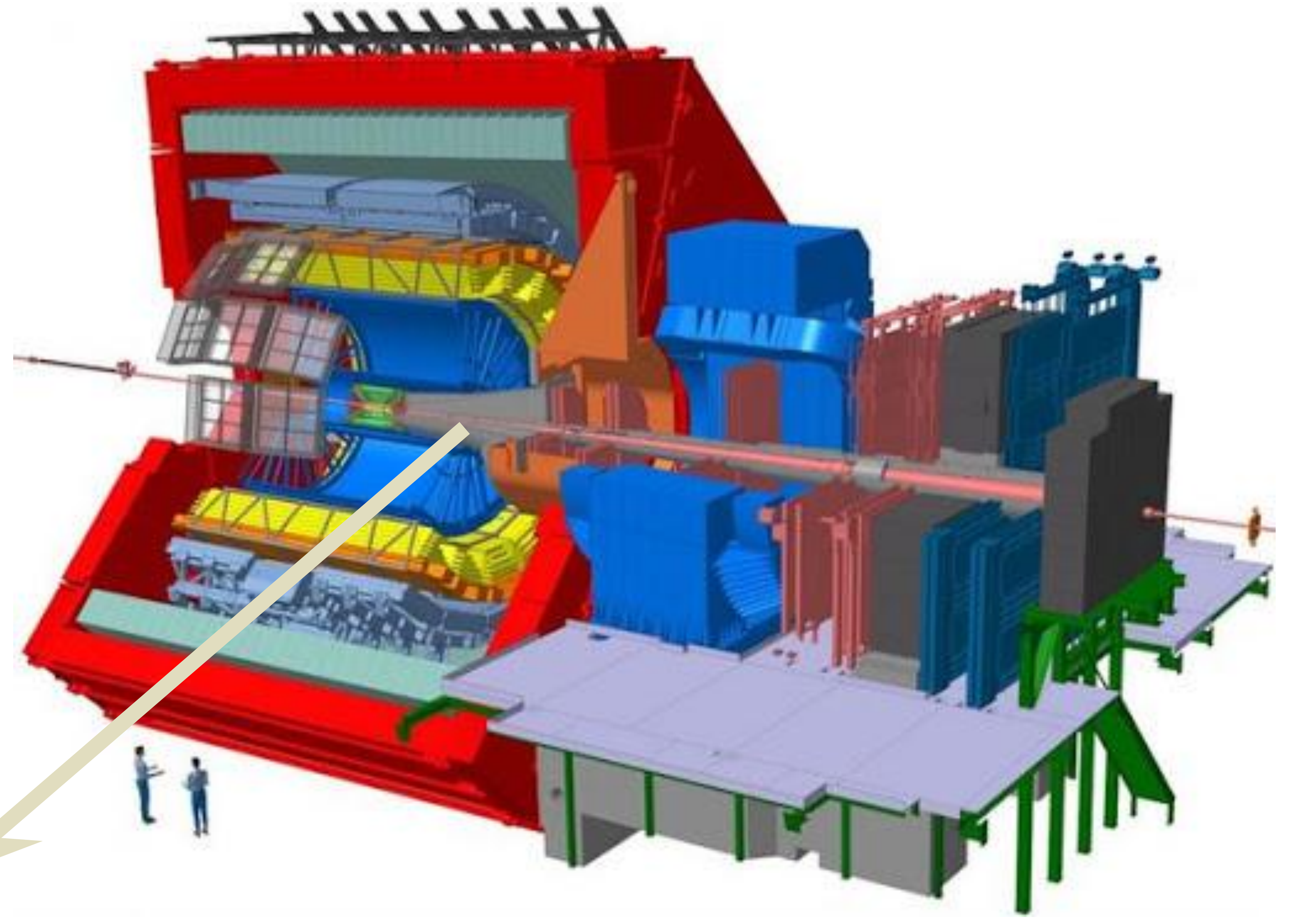
Semi-inclusive measurements

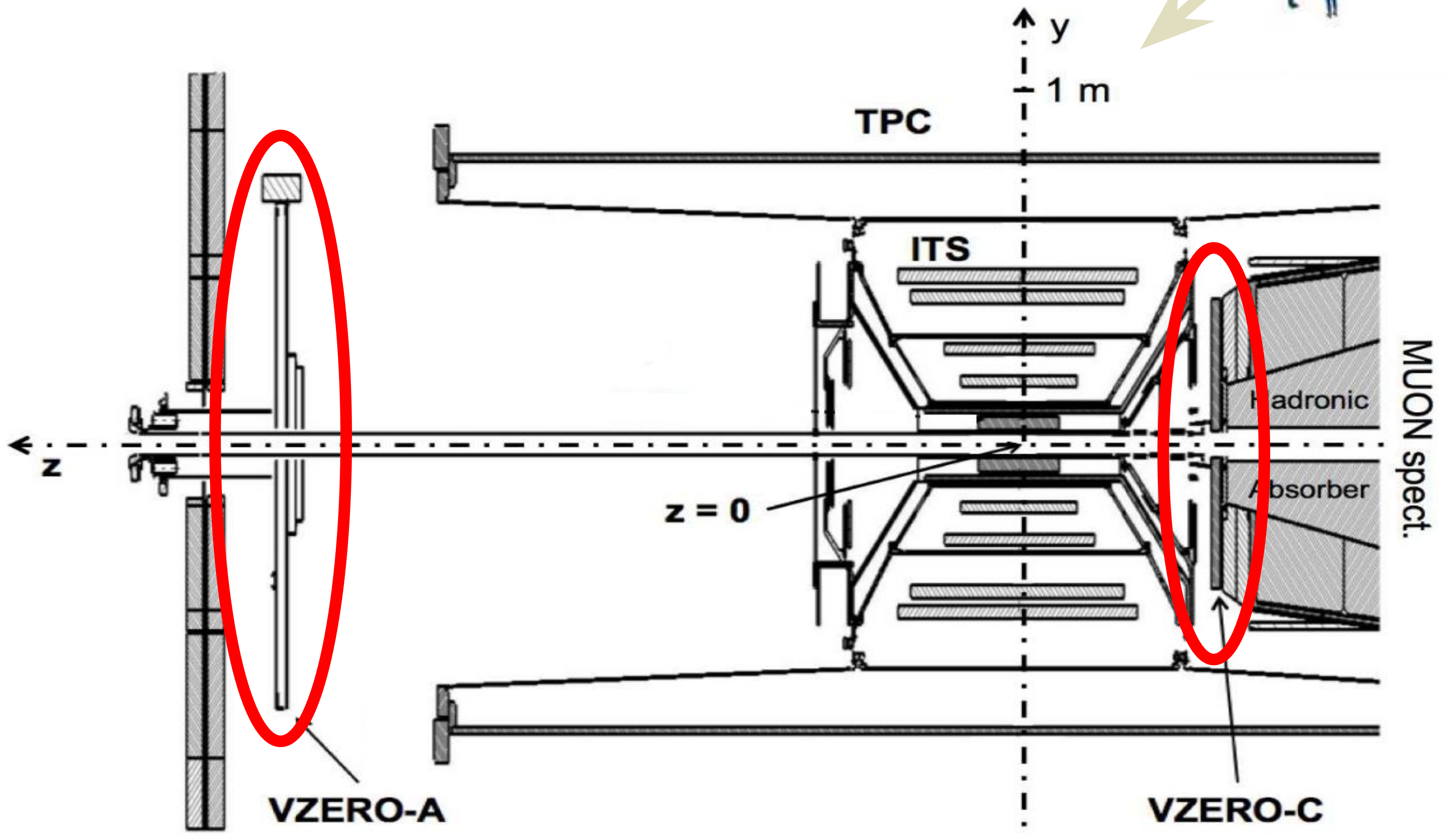
$$\left.\frac{1}{\sigma^{AA\to h+X}}\frac{d^2\sigma^{AA\to h+jet+X}}{dp_{T,jet}^{ch}d\eta_{jet}}\right|_{h\in TT} = \left.\frac{1}{\sigma^{pp\to h+X}}\frac{d^2\sigma^{pp\to h+jet+X}}{dp_{T,jet}^{ch}d\eta_{jet}}\times\frac{\langle T_{AA}\rangle}{\langle T_{AA}\rangle}\right|_{h\in TT}$$

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

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

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





V0A: $2.8 < \eta < 5.1$

V0C: $-3.7 < \eta < -1.7$

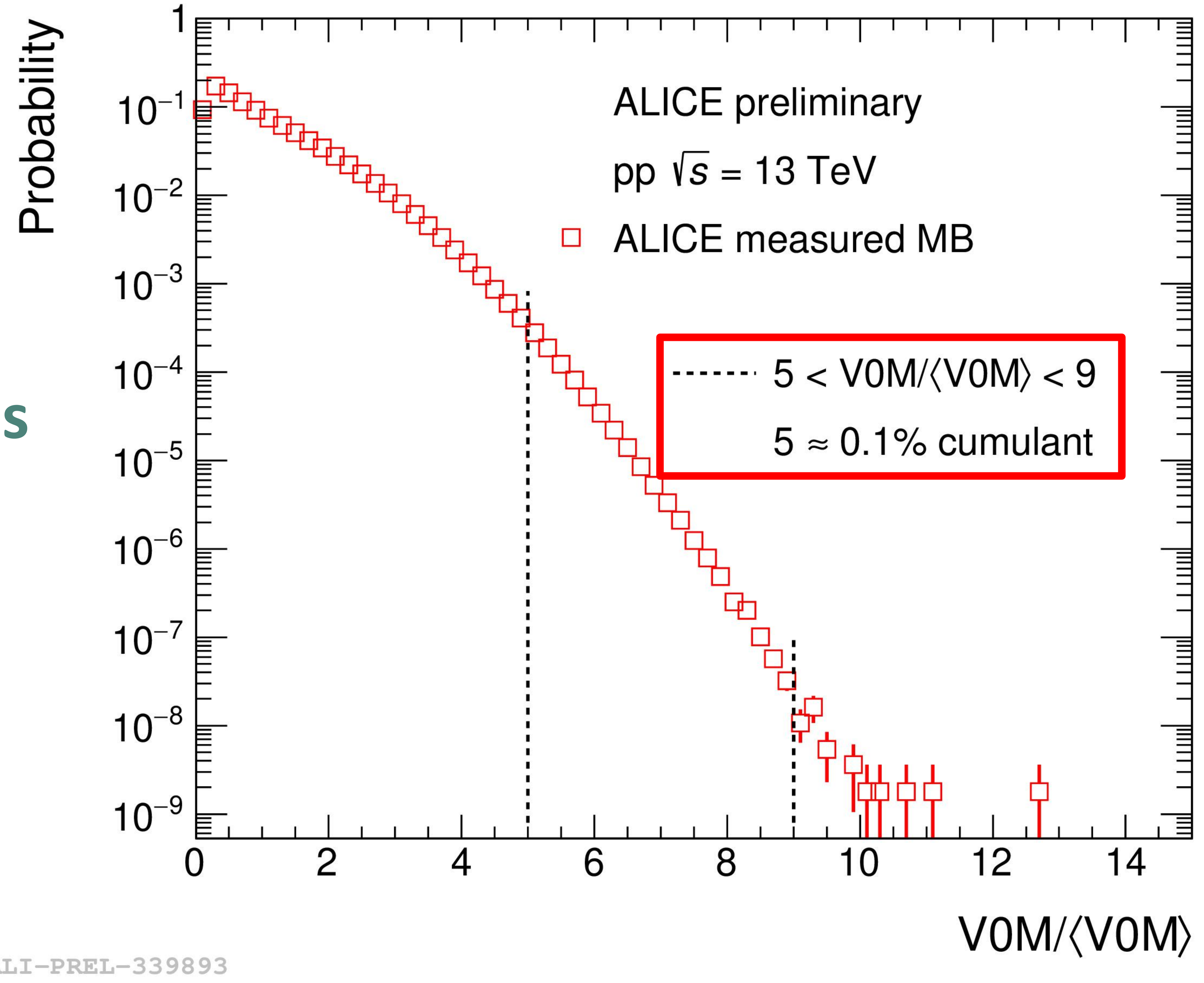
- **Offline event activity (EA) selection:**

  V0M = V0A + V0C → sum of signals

- **Scaled multiplicity V0M/⟨V0M⟩**

  ⟨V0M⟩ - mean of MB distribution

Minimum bias distribution



Acoplanarity vs. event activity: uncorrected data and PYTHIA 8

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

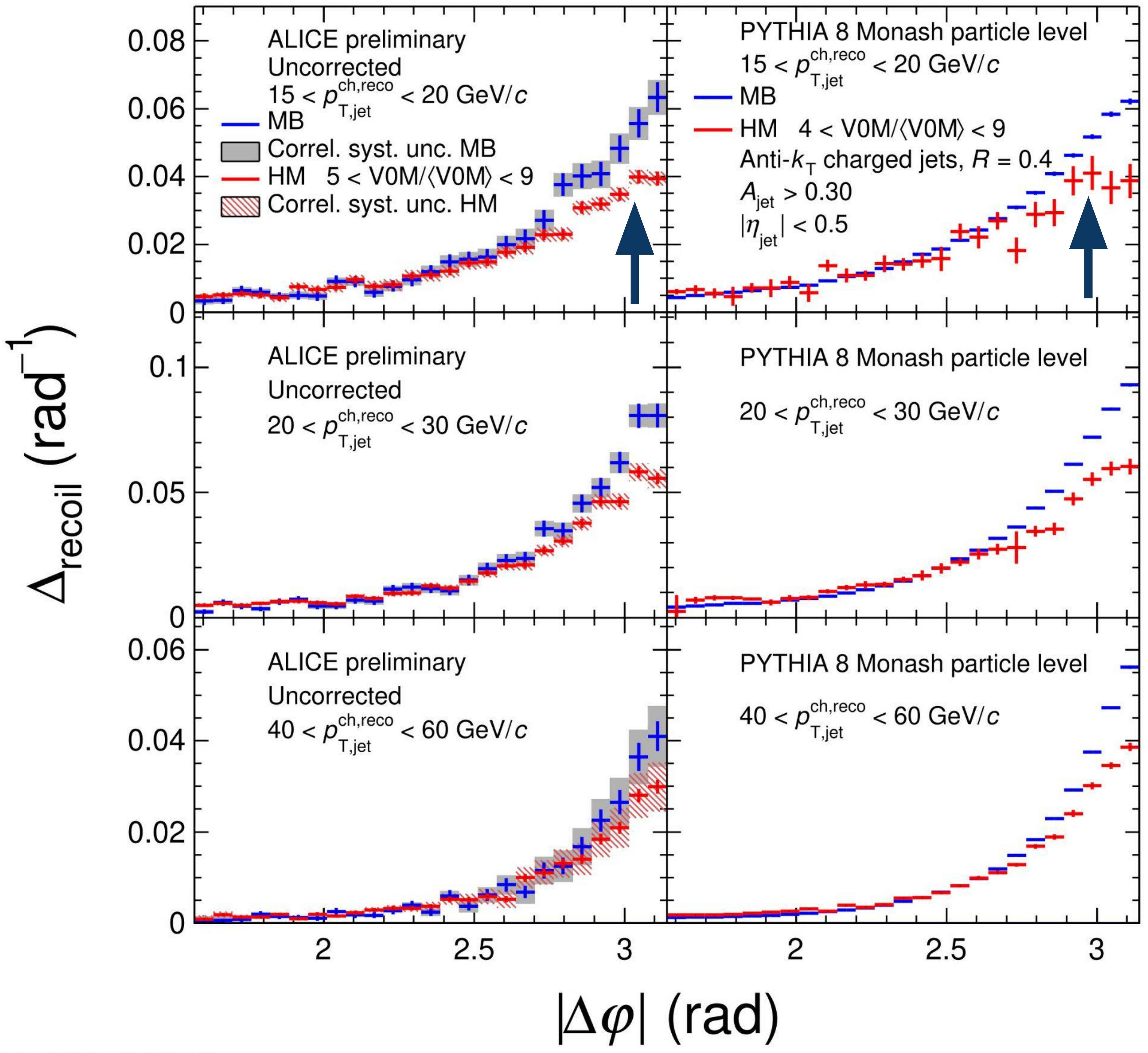
Uncorrected data

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

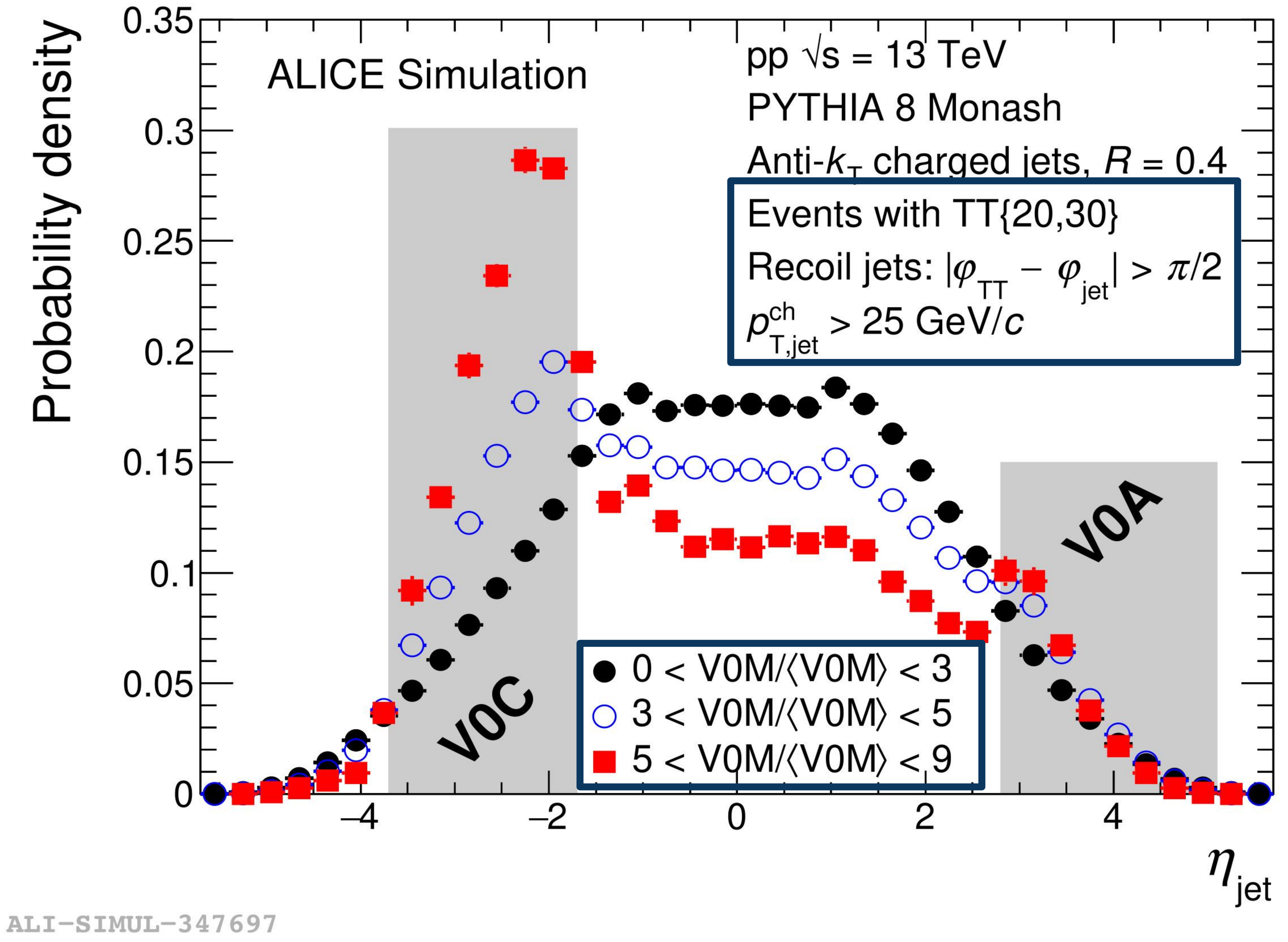
PYTHIA 8 simulation

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

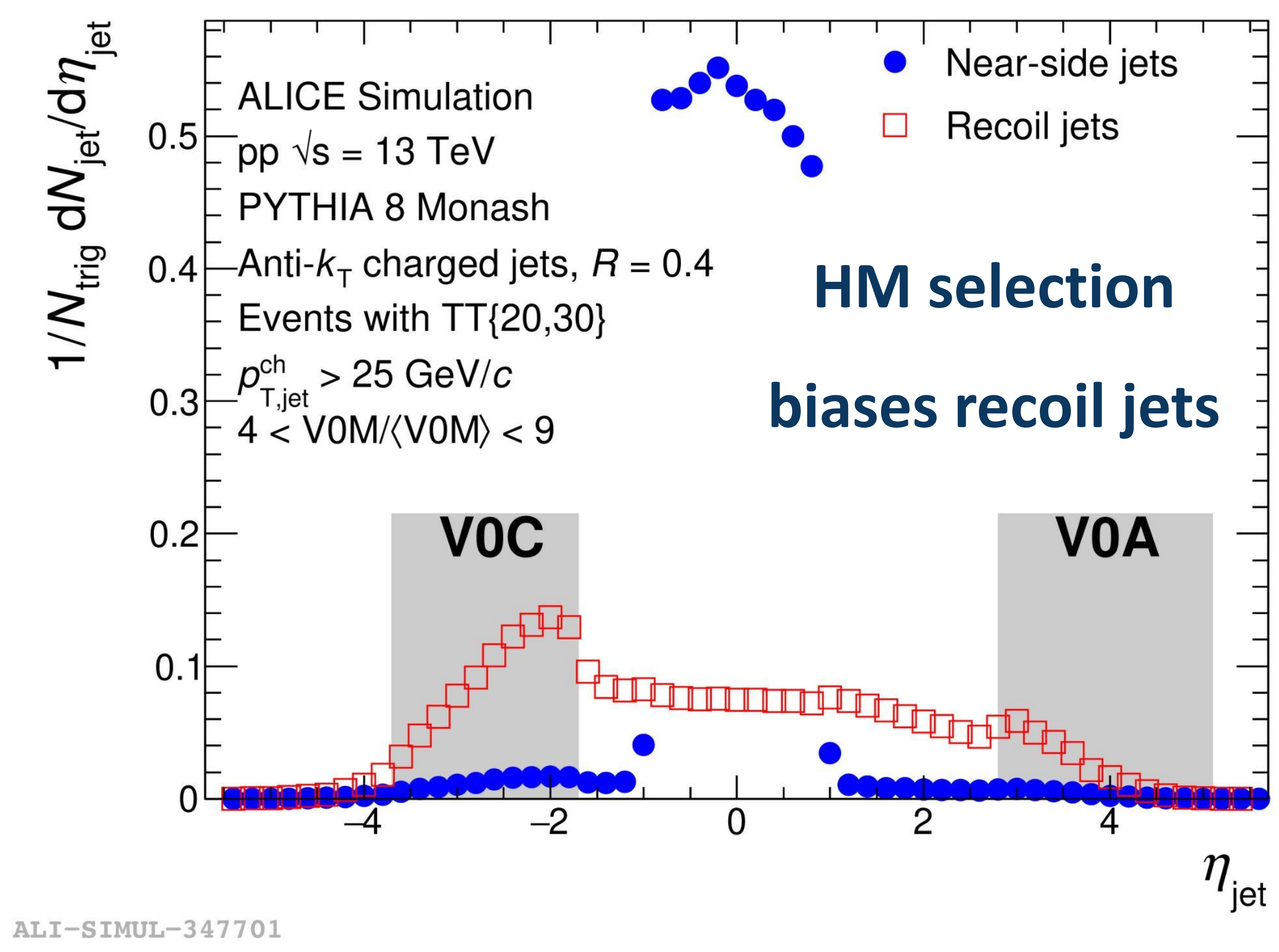
Uncorrected data **PYTHIA 8 particle level**

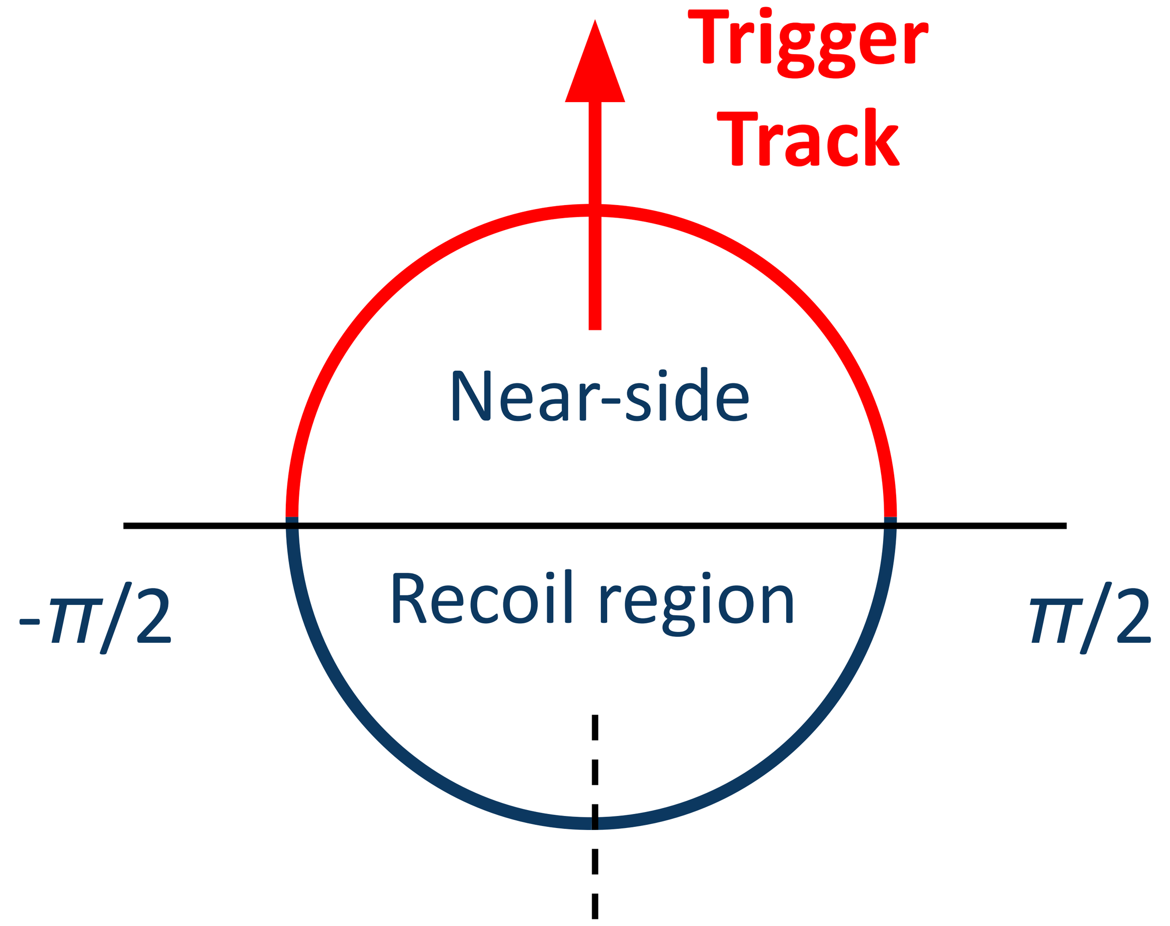


PYTHIA 8 simulation: Recoil jet pseudorapidity vs. event activity



Recoil jets vs. near-side jets

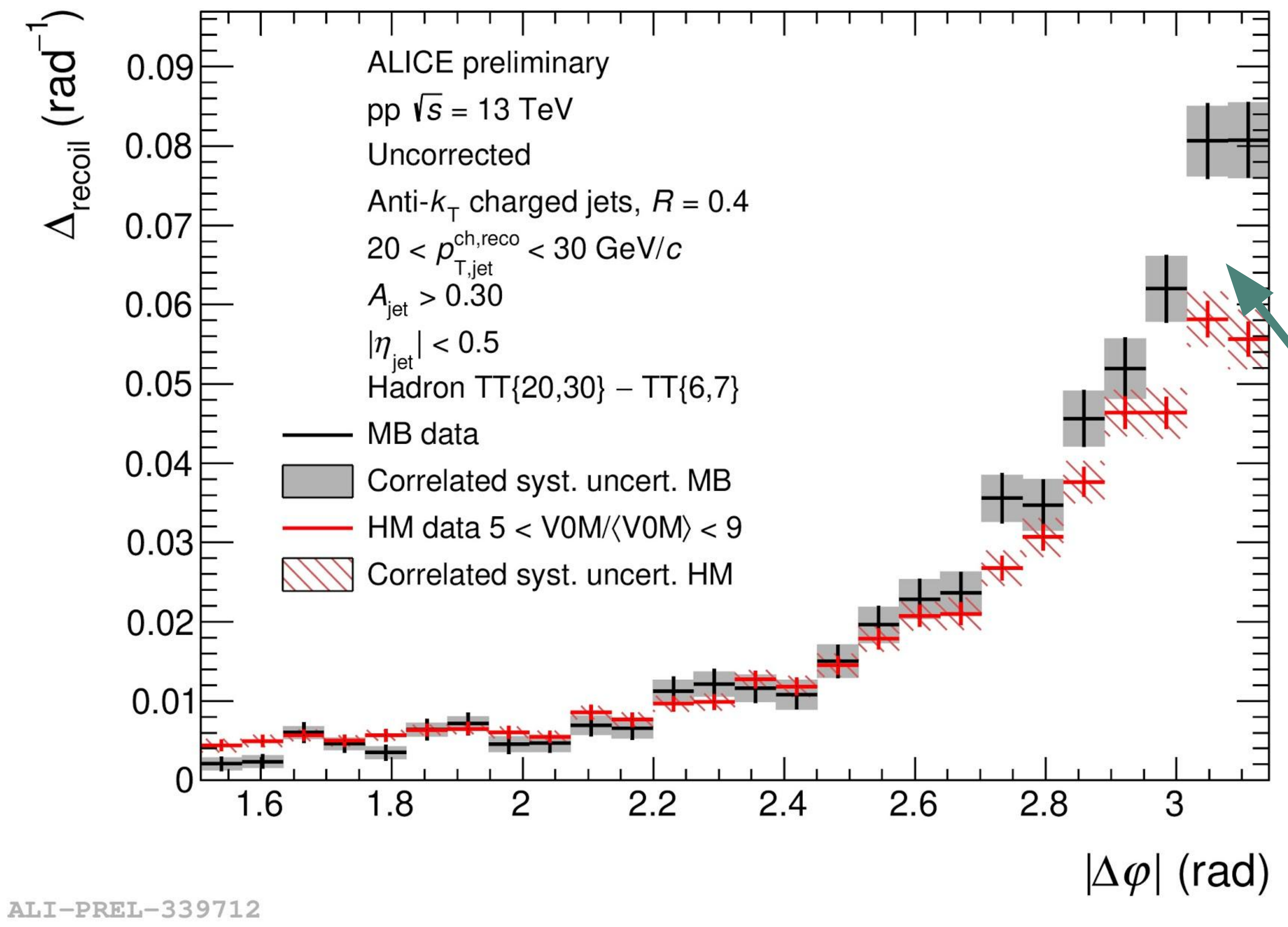


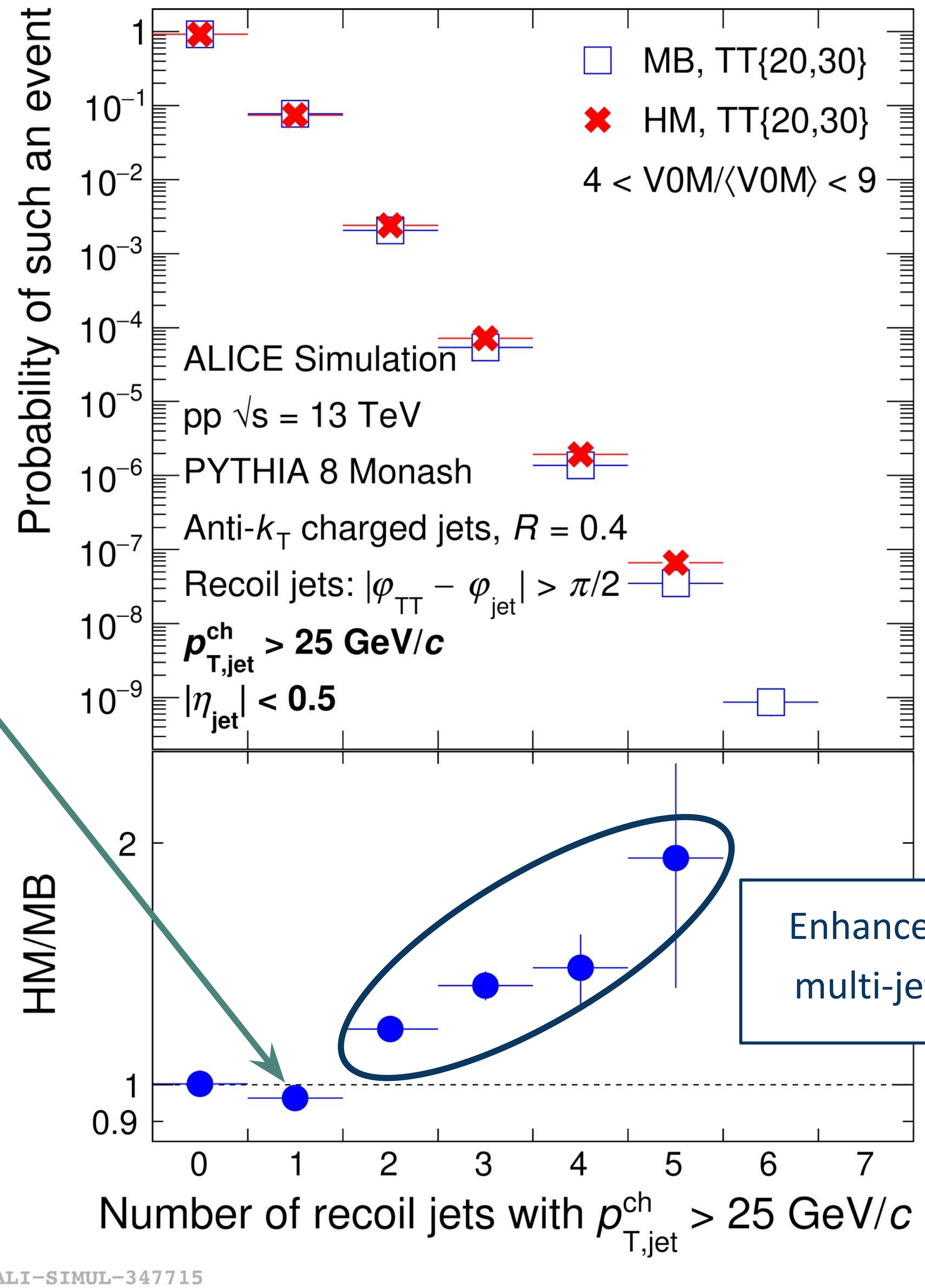


- HM bias imposed by V0M selection **enhances probability** to find high-p_T recoil jet in V0
- Lower enhancement in V0A is caused by asymmetric coverage of V0 arrays

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

PYTHIA 8 simulation: Number of high-p_T recoil jet vs. event activity





Enhancement of multi-jet events

- High-multiplicity data → **less probability to have 1 hard recoil jet** in ALICE central barrel compared to minimum bias events
- High-multiplicity trigger → **bias toward multi-jet final state**

Summary

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

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

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-p_T 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