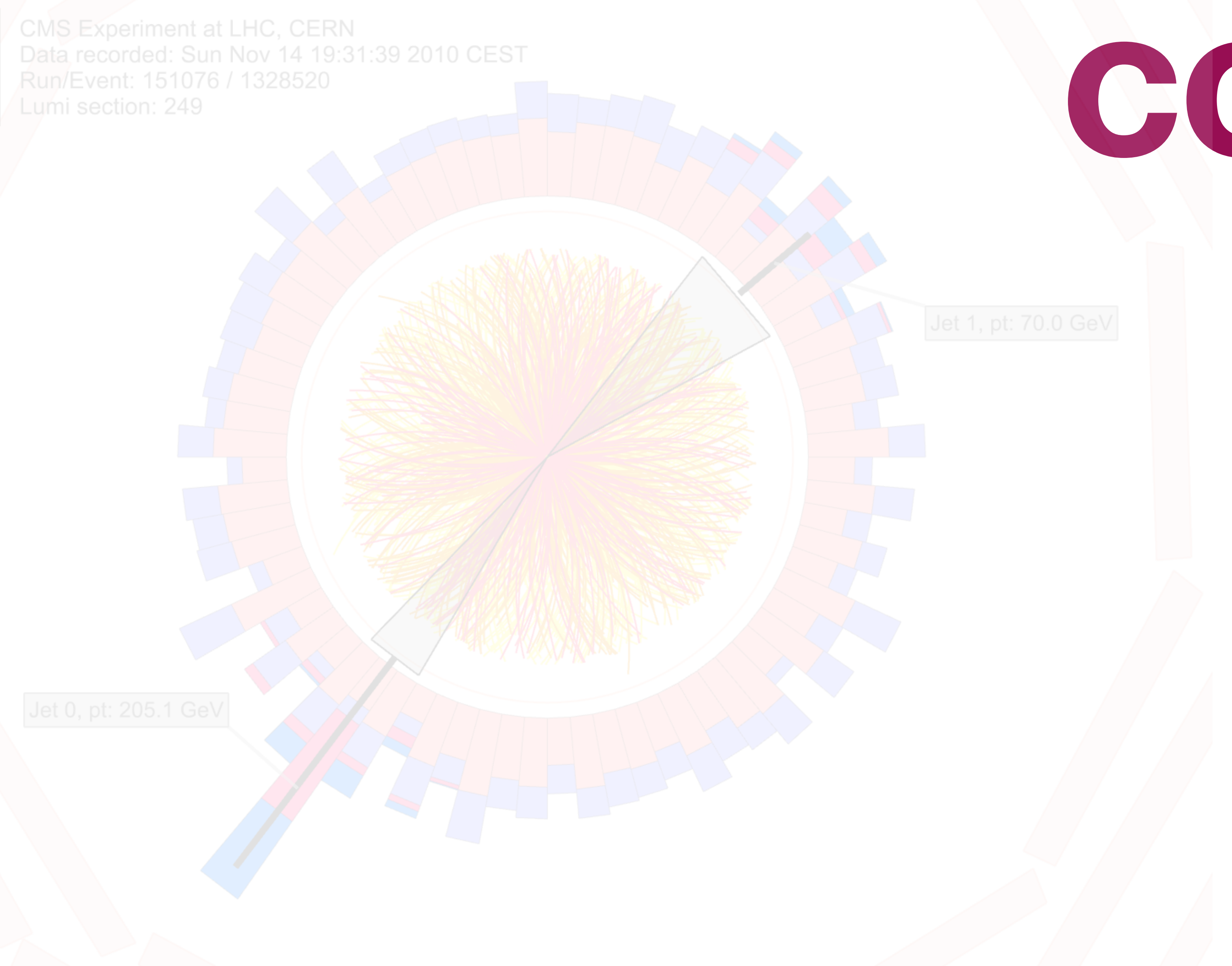
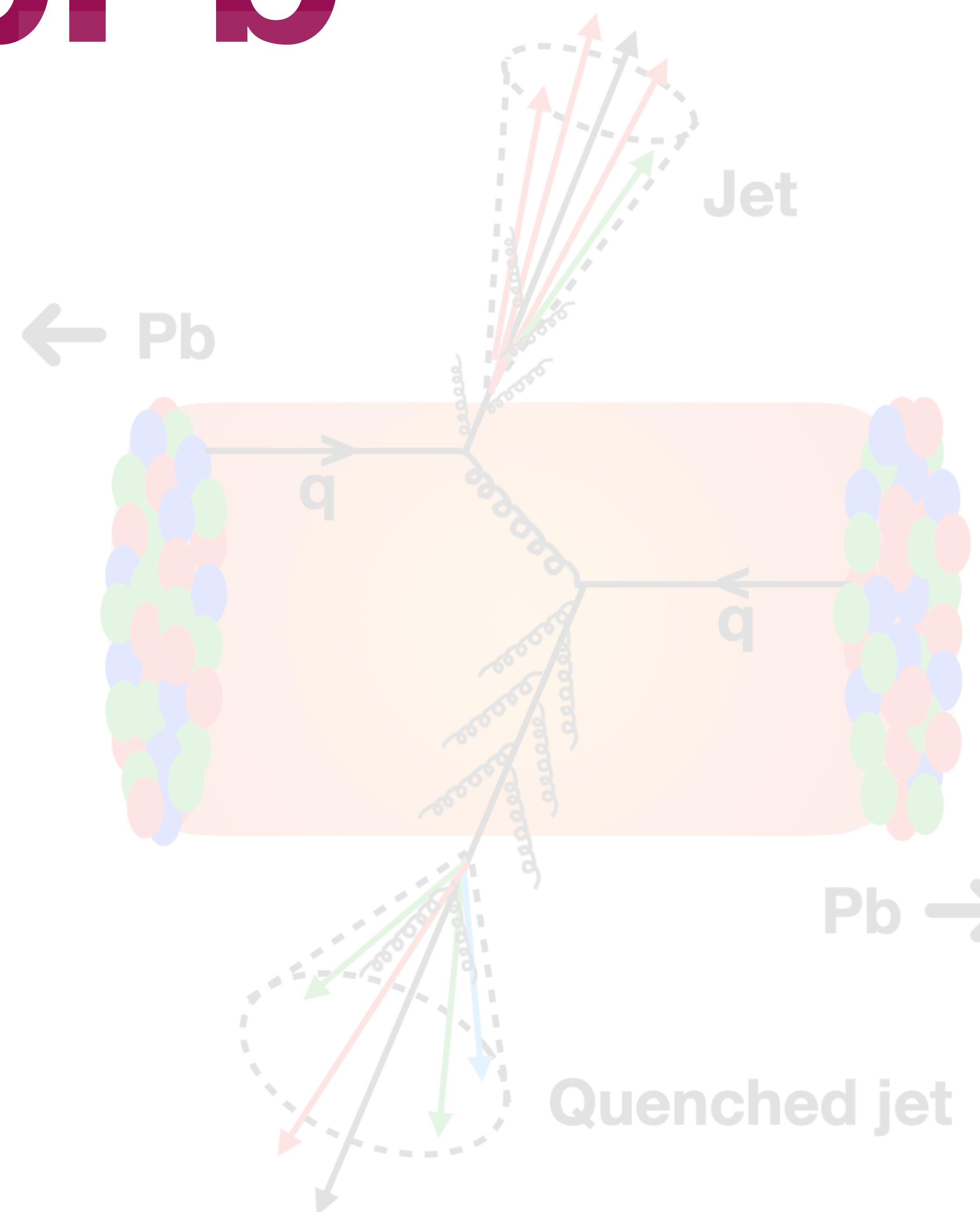
Constraining the color-charge effects of energy loss with jet axis-based substructure studies in PbPb collisions at 5.02 TeV





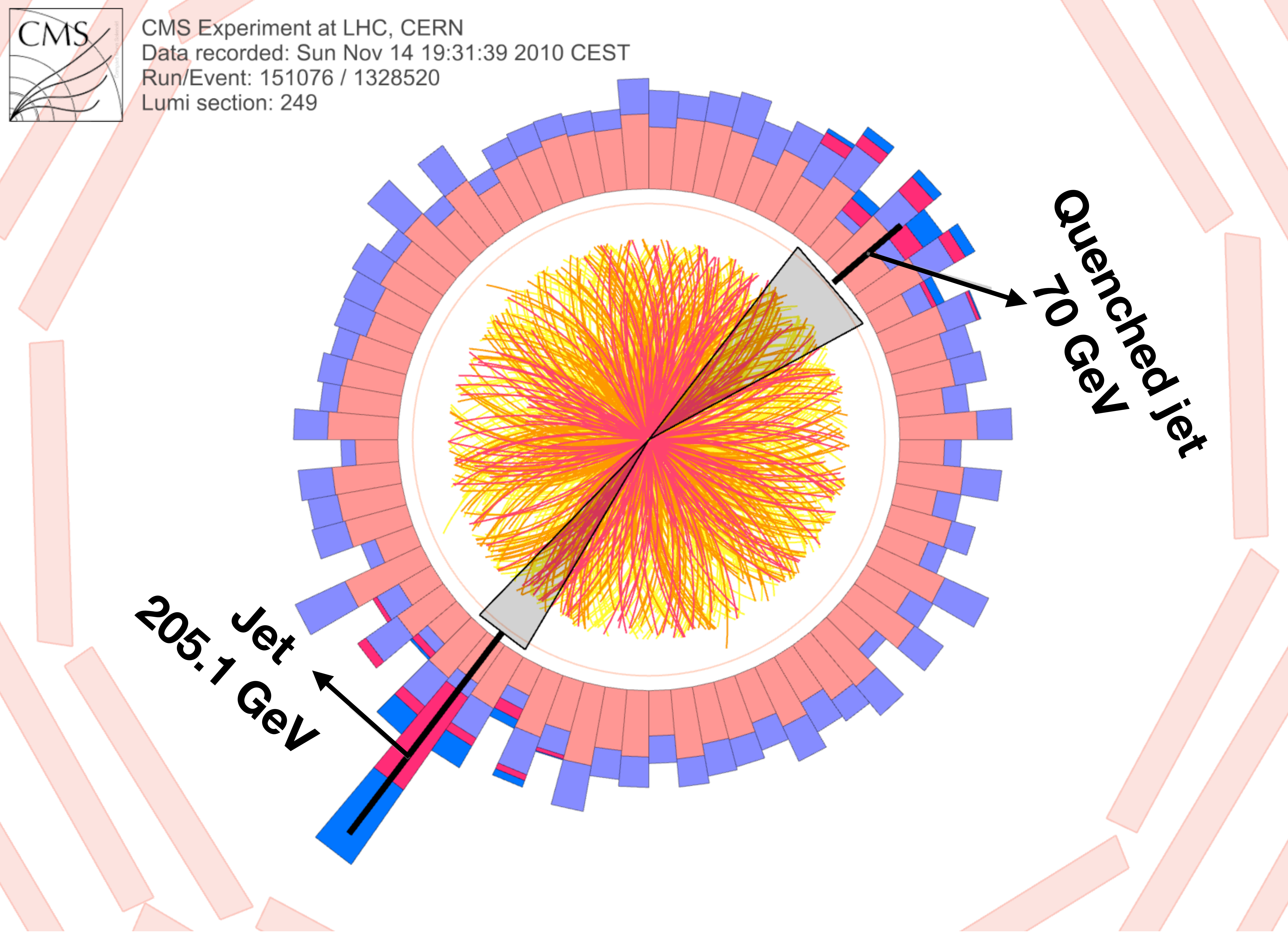
Raghunath Pradhan
for the CMS collaboration

University of Illinois, Chicago

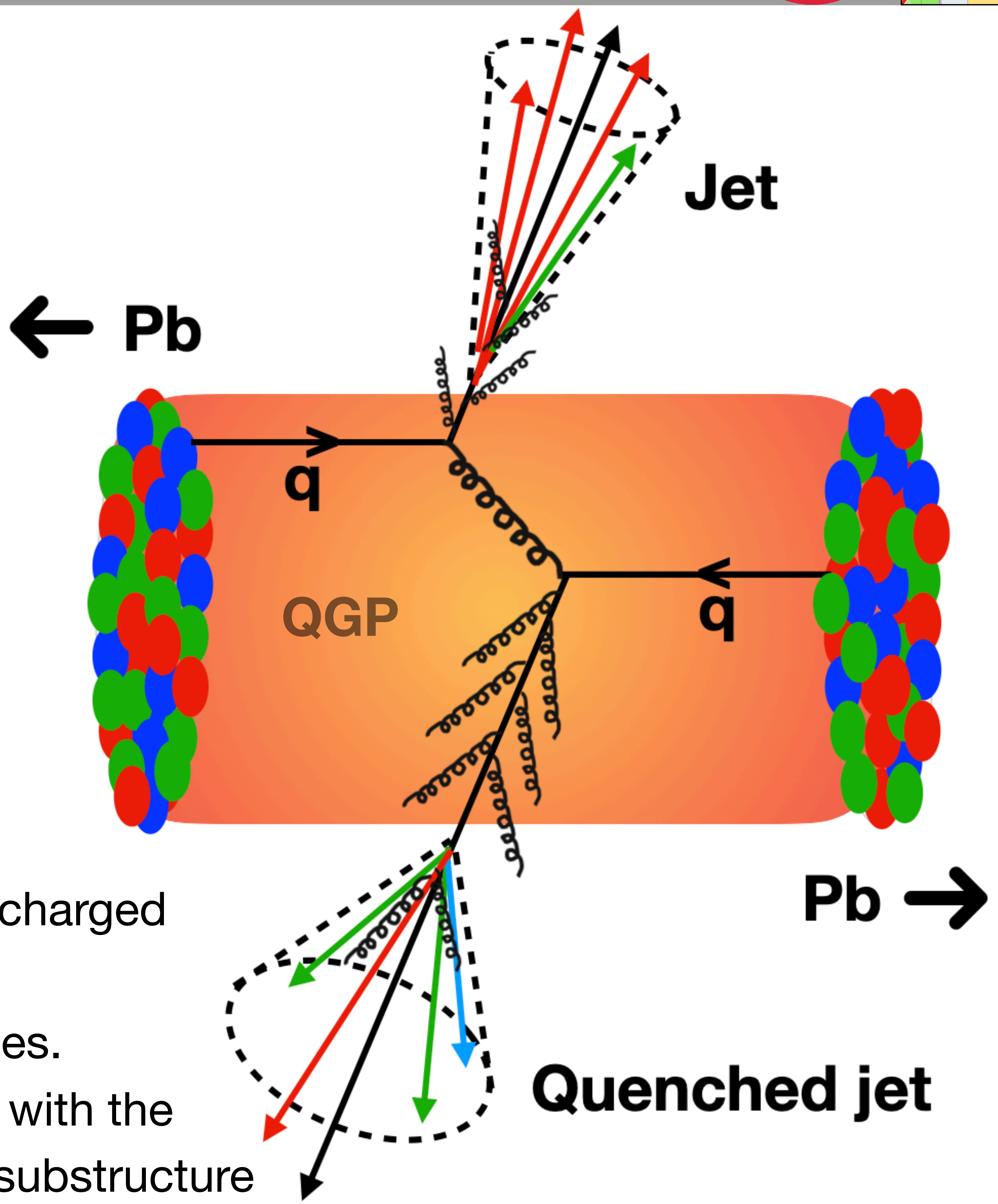
Date: 23/09/2024

HP2024
NAGASAKI

Introduction: QGP and jet quenching



[Link]



- **Quark-Gluon Plasma (QGP):** A thermally equilibrated, deconfined color-charged state formed during the collision of two heavy nuclei.
- **Jet:** A collimated stream of particles produced in hard scattering processes.
- **Jet quenching:** The phenomenon where a jet loses energy as it interacts with the Quark-Gluon Plasma (QGP), leading to modifications in its structure and substructure

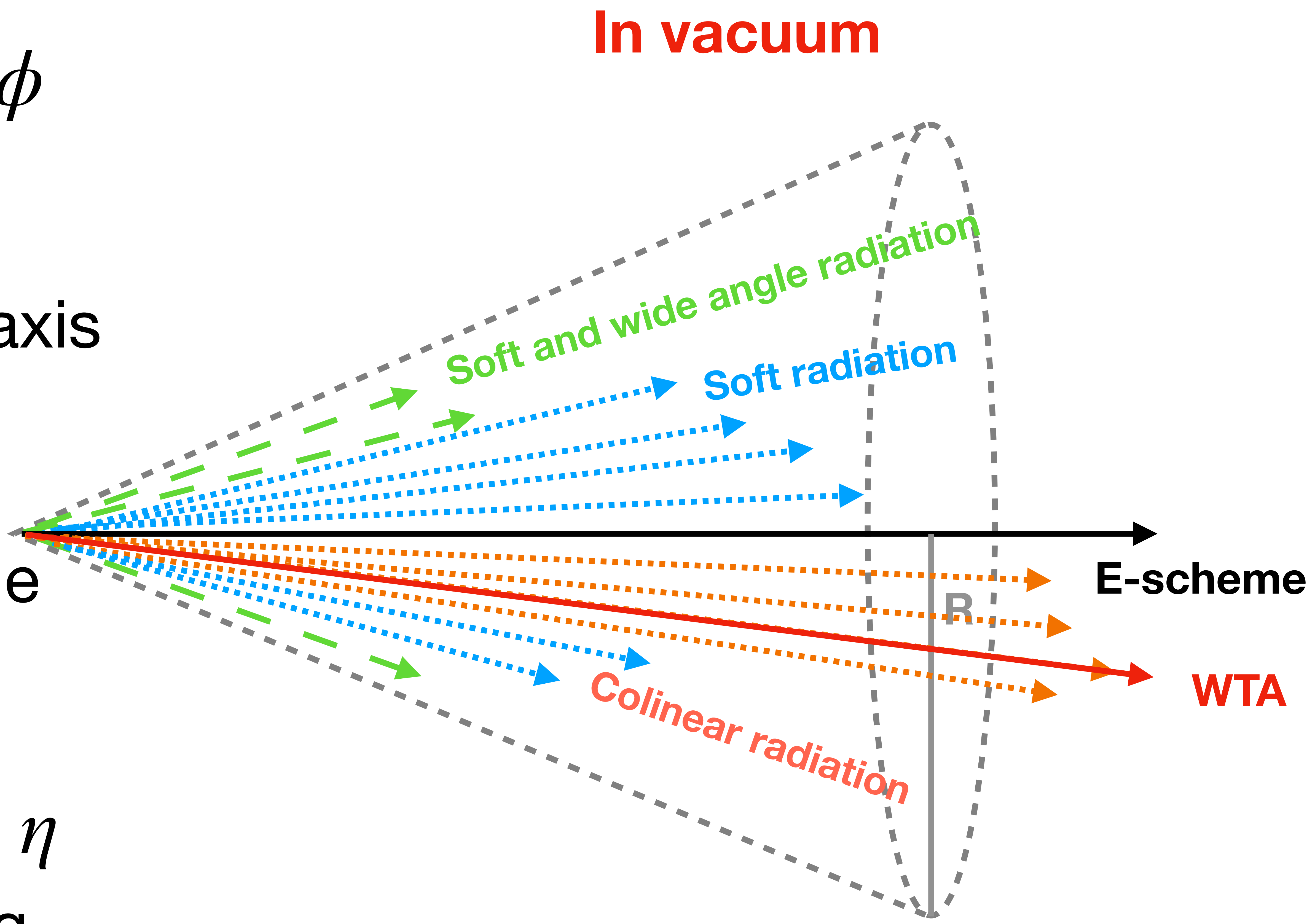
Introduction: jet axis

- Jet axis represents the direction of jet in η and ϕ coordinates

- This analysis focused on **E-scheme** and **WTA** axis

  - **E-scheme axis :** Coordinates in η and ϕ determined by the energy-weighted sum of the particle 4-momenta within a jet

  - **Winner-takes-all (WTA) axis :** Coordinates in η and ϕ representing the direction of the leading energy flow in a jet. Align with hard-collinear core of the jet



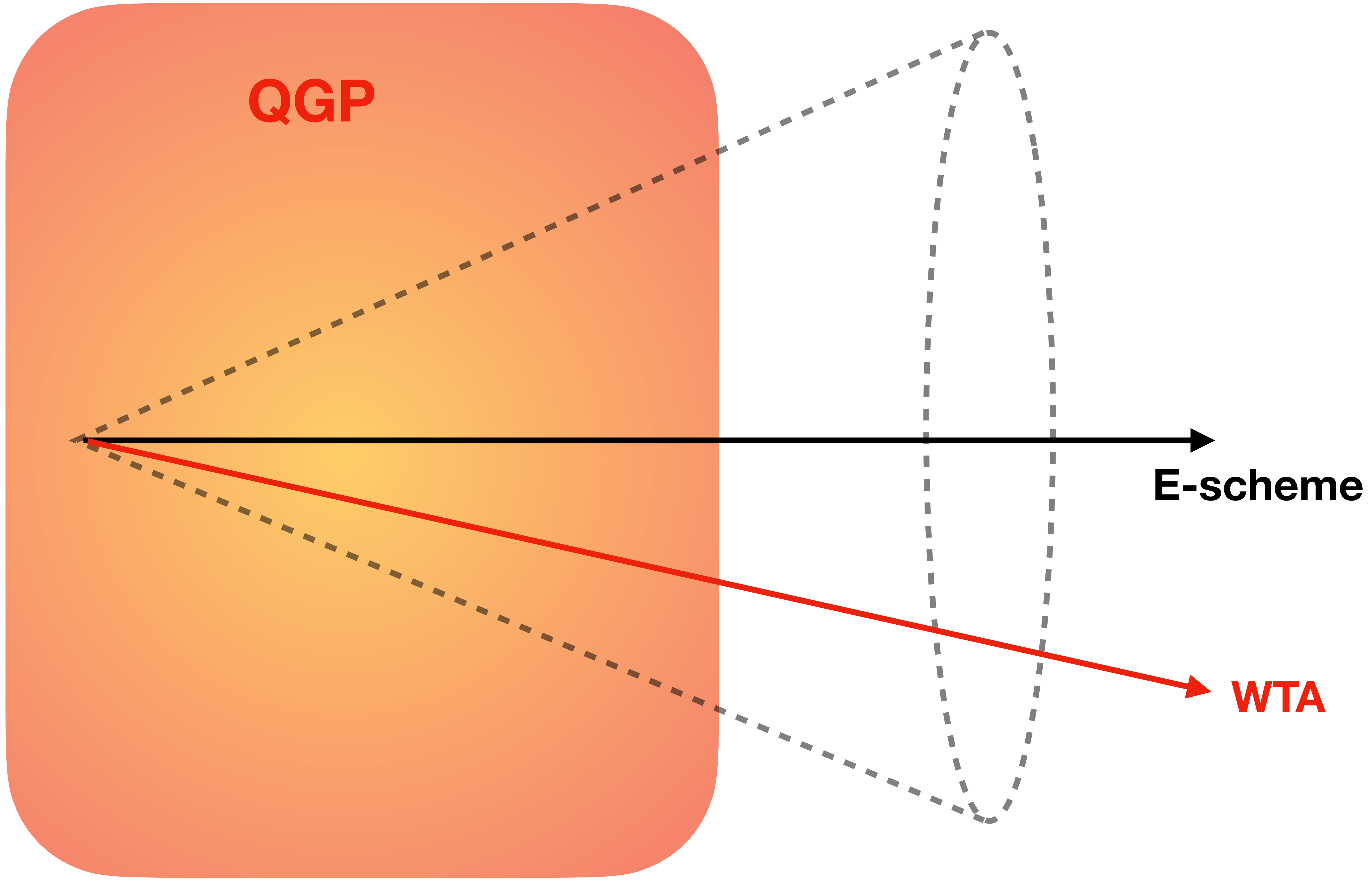
Introduction: jet axis

How the jet axes get modified in presence of medium?

For example:

- In medium gluon radiation can influencing the direction of **E-scheme axis**
- However, the **WTA axis** might be more susceptible to direction changes compared to the E-scheme axis if deflections of different jet partons go in random directions.

In the presence of a medium



Introduction: angle between jet axis

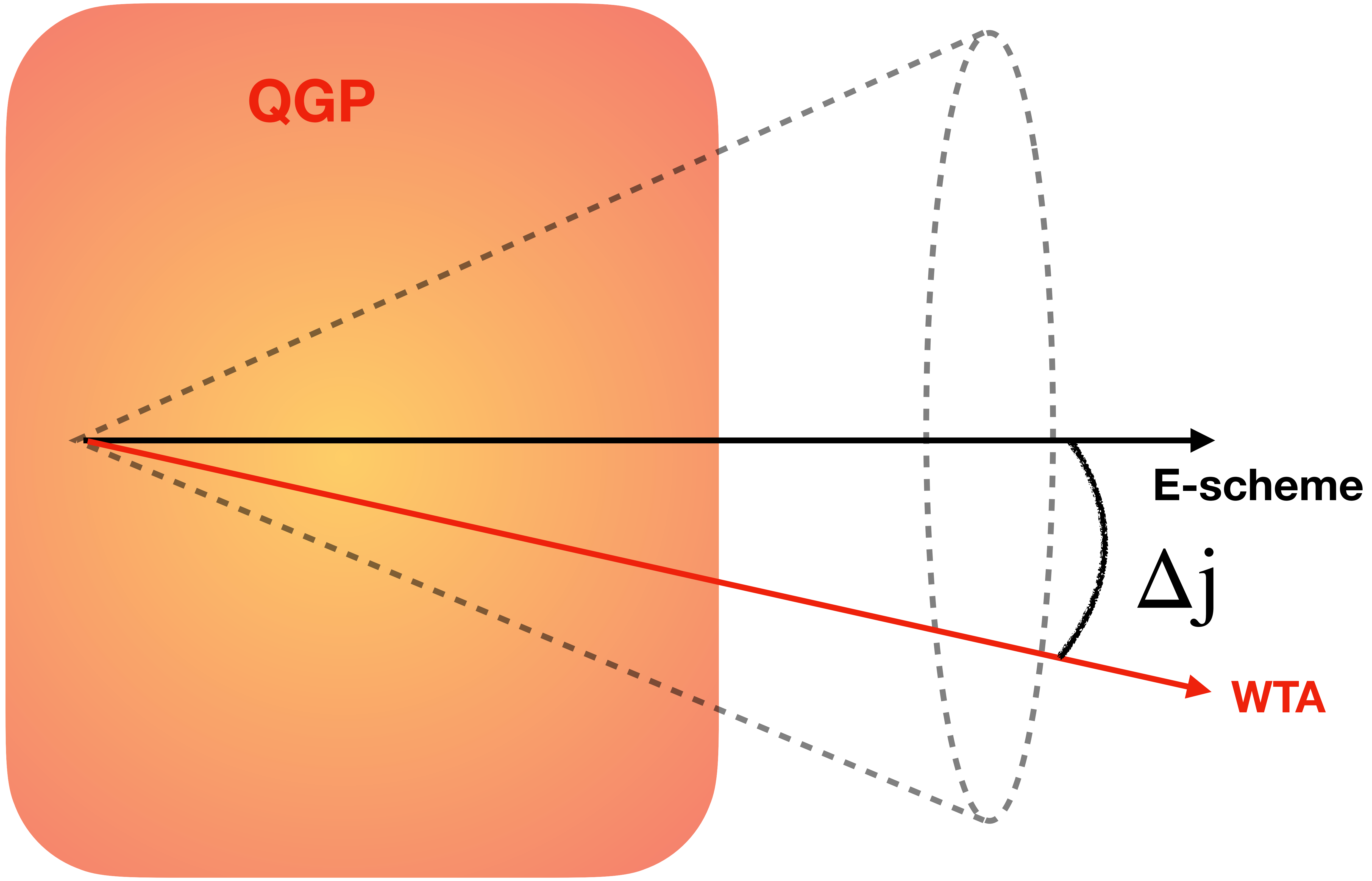
How the jet axes get modified in presence of medium?

For example:

- In medium gluon radiation can influencing the direction of **E-scheme axis**
- However, the **WTA axis** might be more susceptible to direction changes compared to the E-scheme axis if deflections of different jet partons go in random directions.

JHEP04(2020)211

In the presence of a medium



Jet substructure observable $\Delta j = \sqrt{(\eta^{E-scheme} - \eta^{WTA})^2 + (\phi^{E-scheme} - \phi^{WTA})^2}$

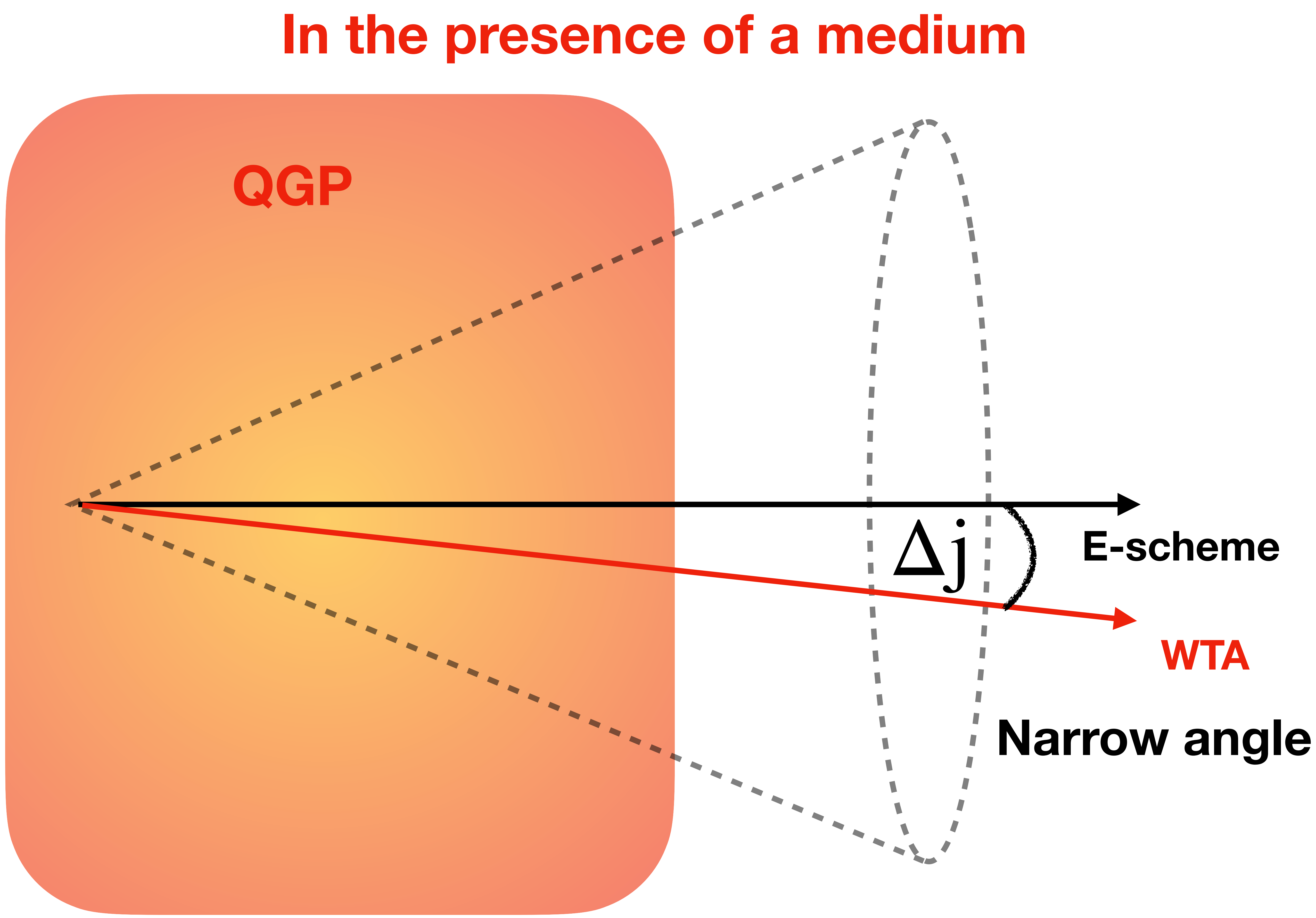
Introduction: angle between jet axis

How the jet axes get modified in presence of medium?

For example:

- In medium gluon radiation can influencing the direction of **E-scheme axis**
- However, the **WTA axis** might be more susceptible to direction changes compared to the E-scheme axis if deflections of different jet partons go in random directions.

JHEP04(2020)211



Jet substructure observable $\Delta j = \sqrt{(\eta^{E-scheme} - \eta^{WTA})^2 + (\phi^{E-scheme} - \phi^{WTA})^2}$

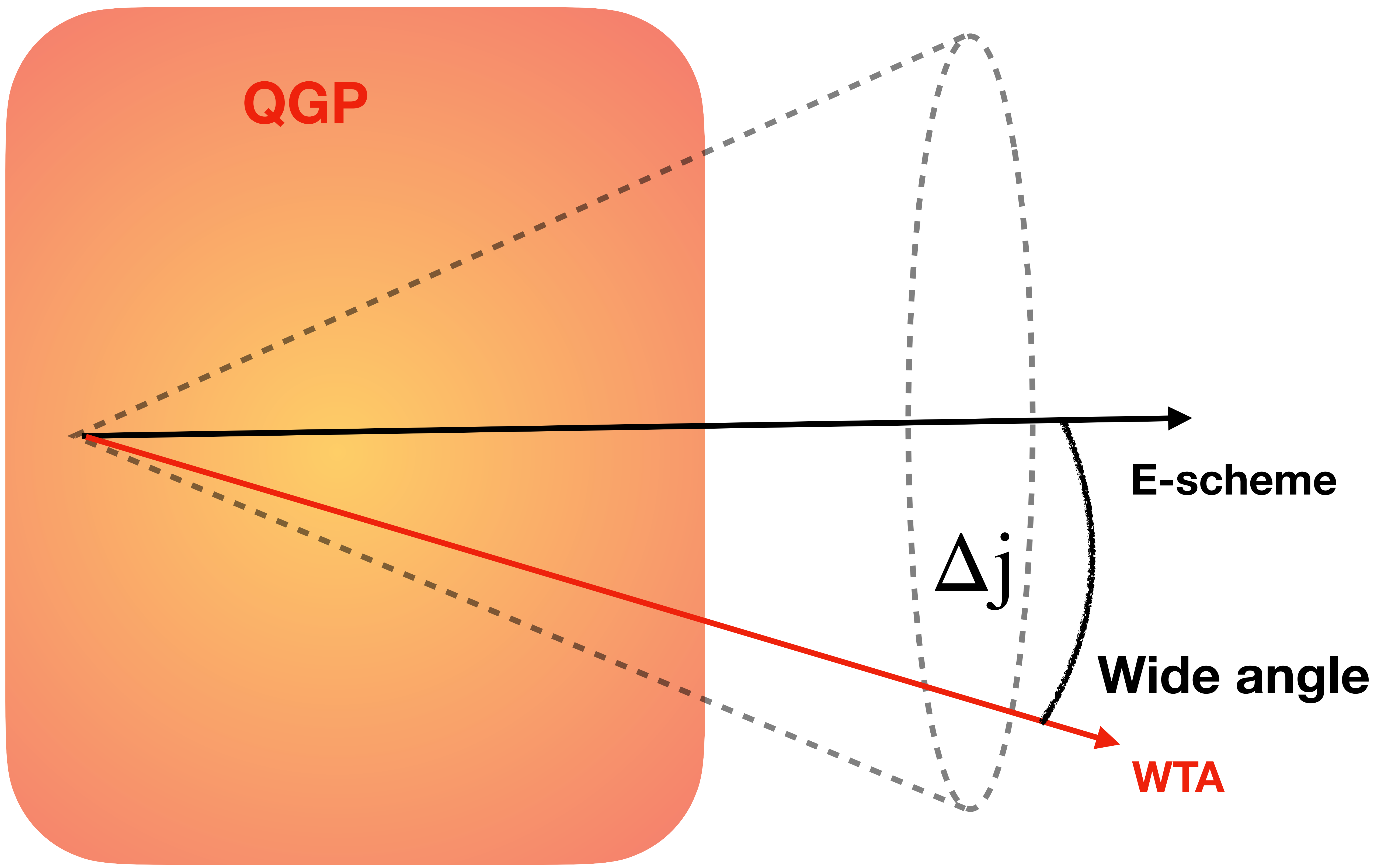
Introduction: angle between jet axis

How the jet axes get modified in presence of medium?

For example:

- In medium gluon radiation can influencing the direction of **E-scheme axis**
- However, the **WTA axis** might be more susceptible to direction changes compared to the E-scheme axis if deflections of different jet partons go in random directions.

JHEP04(2020)211



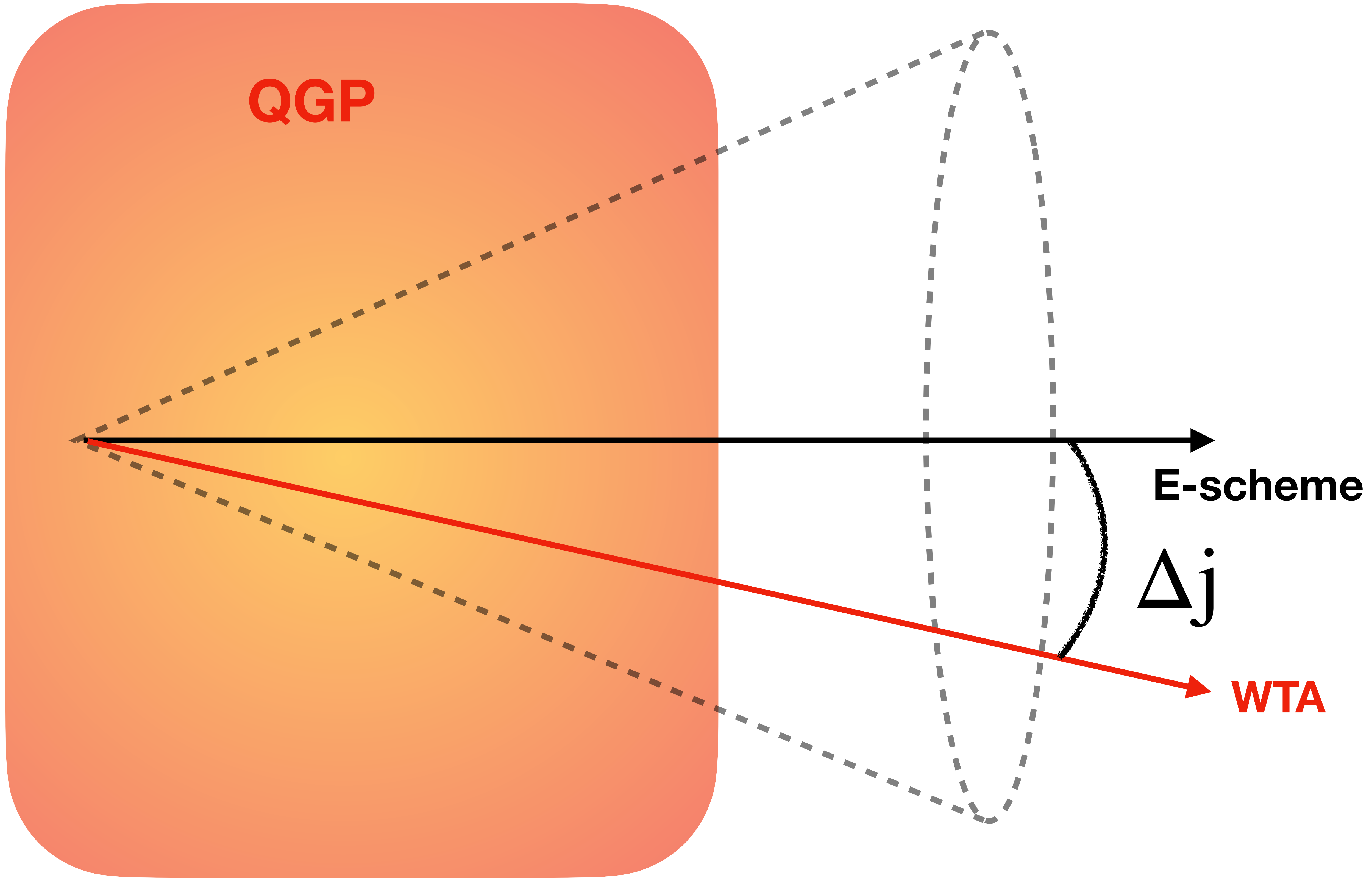
Jet substructure observable $\Delta j = \sqrt{(\eta^{E-scheme} - \eta^{WTA})^2 + (\phi^{E-scheme} - \phi^{WTA})^2}$

Motivation

Search for QGP induced jet substructure modification

- The correlation between **E-scheme** and **WTA axis** is used to access jet substructure
  - Boost invariant and analytical calculation possible (JHEP04(2020)211)
  - Could provide insights into radiative energy loss in QGP, as the E-scheme and WTA axis exhibit different sensitivities to soft radiation
  - Sensitive to various medium-induced effects

In the presence of a medium



Jet substructure observable

$$\Delta j = \sqrt{(\eta^{\mathrm{E-scheme}} - \eta^{\mathrm{WTA}})^2 + (\phi^{\mathrm{E-scheme}} - \phi^{\mathrm{WTA}})^2}$$

Analysis set up and CMS detector

2018 PbPb data at 5.02 TeV

- Centrality: 0-80%
- Centrality binning: {0, 10, 30, 50, 80}%
- Anti-k_T R = 0.4
- $|\eta^{\mathrm{jet}}| < 1.6$
- 120 < p_T^{jet} < 300 GeV
- p_T^{jet} binning: {120, 150, 190, 230, 300} GeV

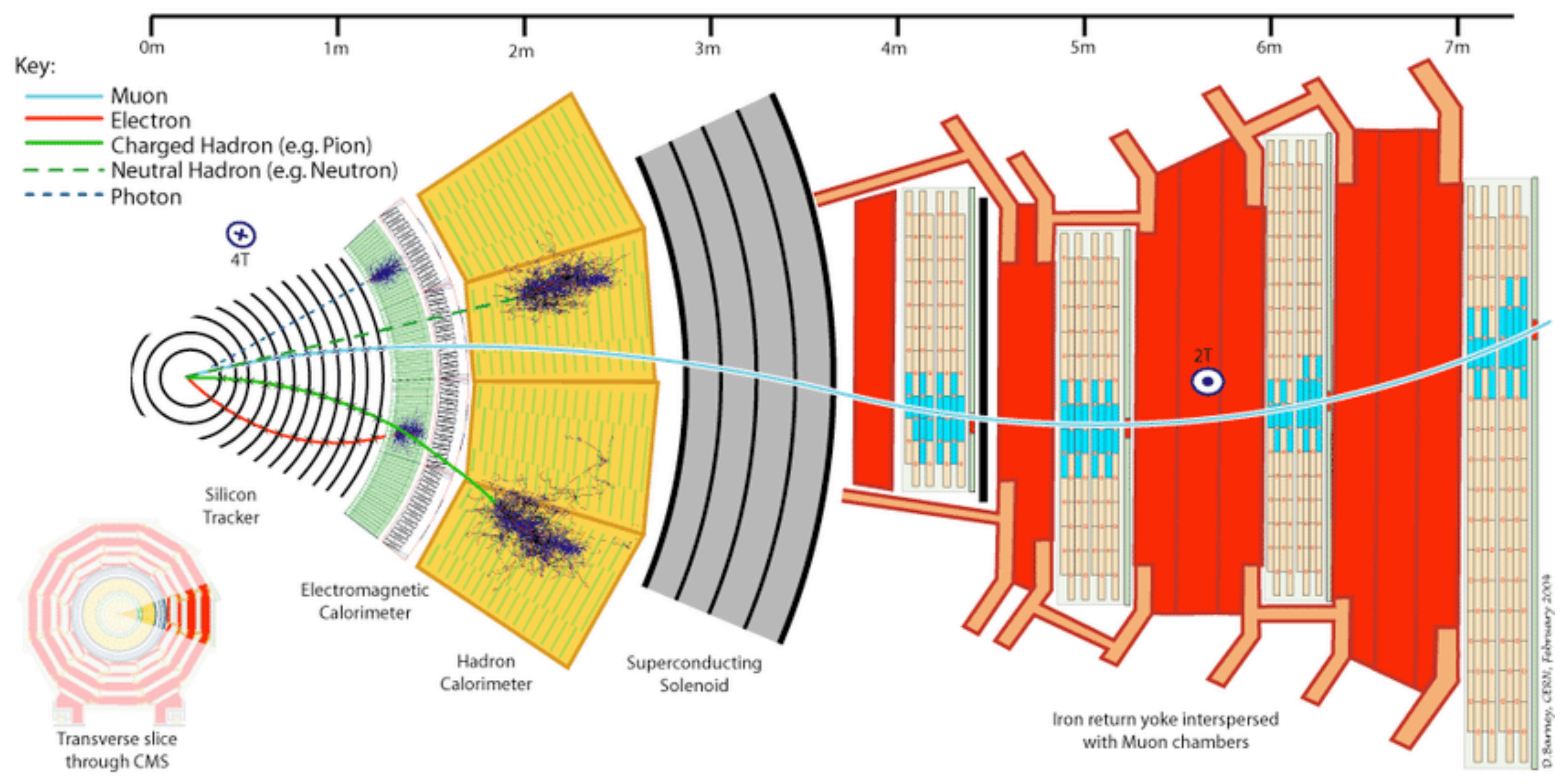
Analysis set up and CMS detector

2018 PbPb data at 5.02 TeV

- Centrality: 0-80%
- Centrality binning: {0, 10, 30, 50, 80}%
- Anti-k_T R = 0.4
- $|\eta^{jet}| < 1.6$
- 120 < p_T^{jet} < 300 GeV
- p_T^{jet} binning: {120, 150, 190, 230, 300} GeV

- **Particle flow candidates used to reconstruct jets** Link

Cross-sectional view of the CMS detector



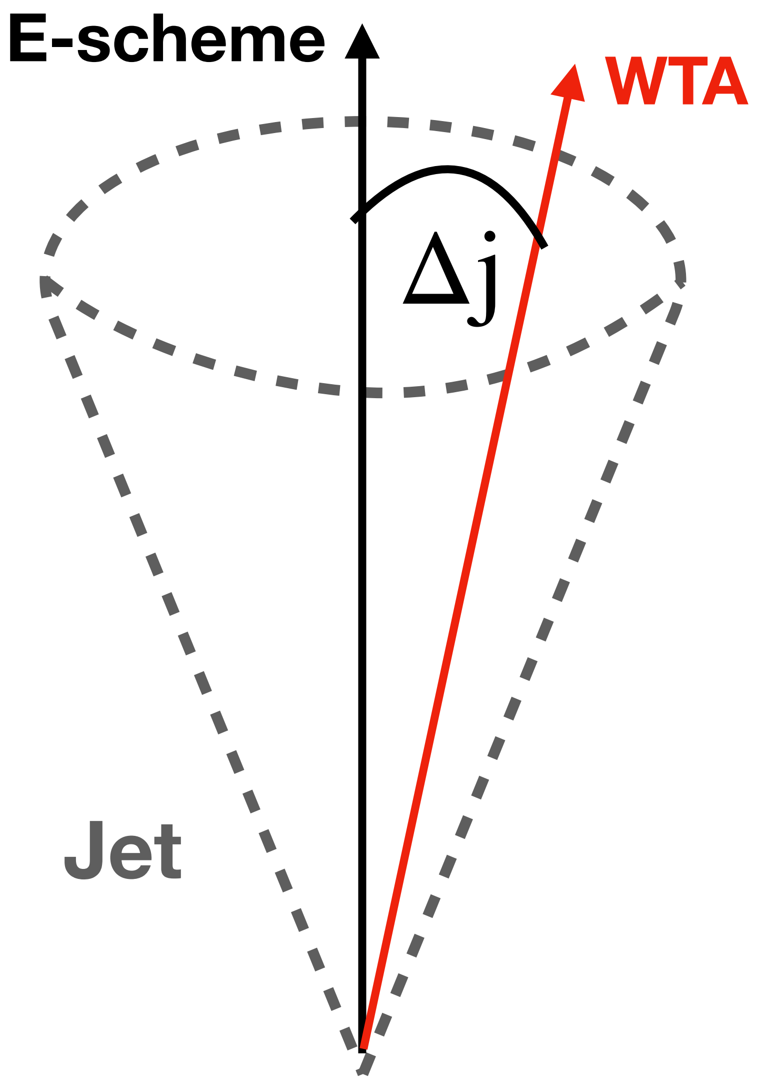
2018 PbPb data at 5.02 TeV

- Centrality: 0-80%
- Centrality binning: {0, 10, 30, 50, 80}%
- Anti-k_T R = 0.4
- $|\eta^{\text{jet}}| < 1.6$
- $120 < p_T^{\text{jet}} < 300$ GeV
- p_T^{jet} binning: {120, 150, 190, 230, 300} GeV

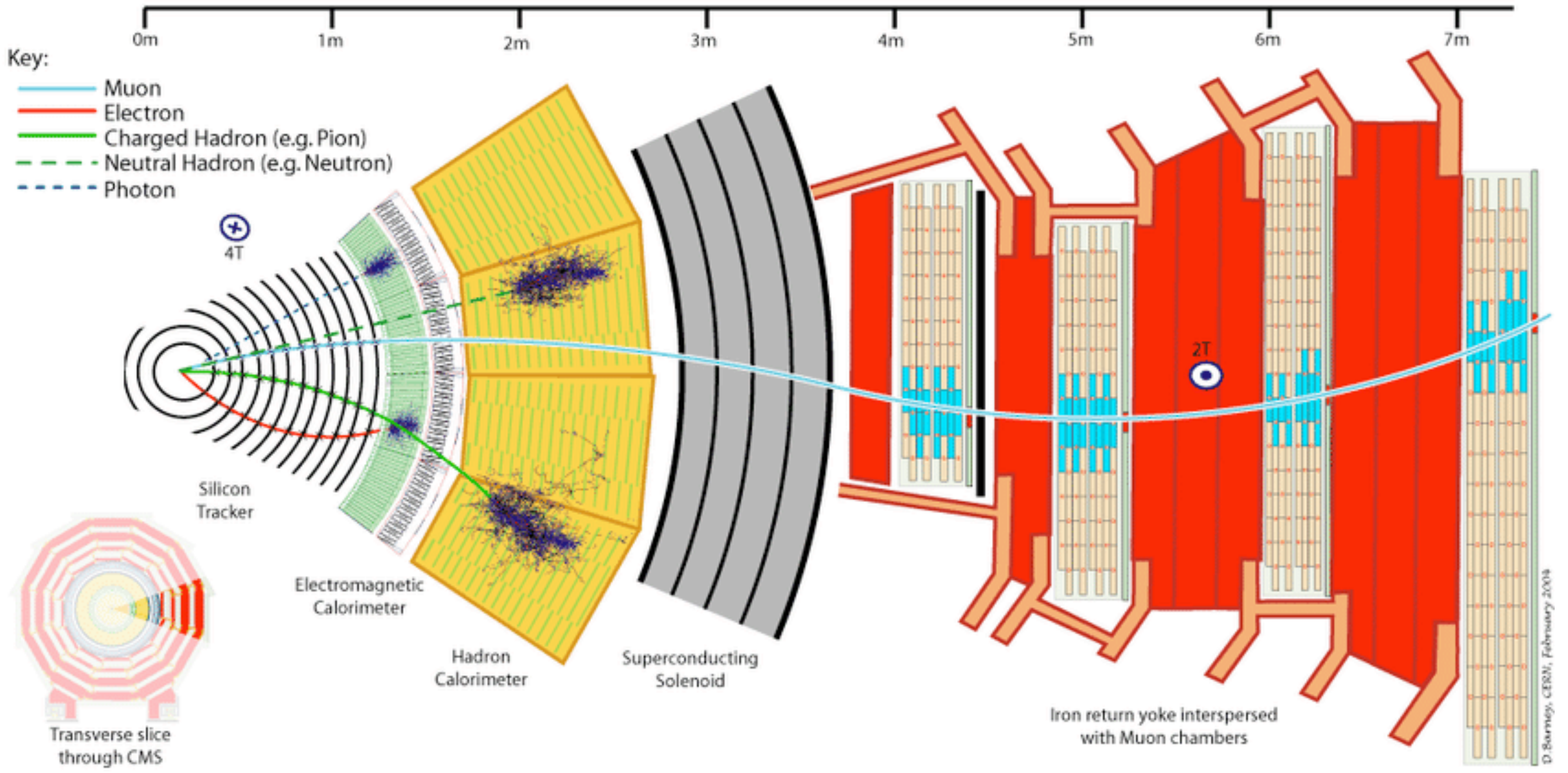
- **Particle flow candidates used to reconstruct jets** Link

Observable $\Delta j = \sqrt{(\eta^{\text{E-scheme}} - \eta^{\text{WTA}})^2 + (\phi^{\text{E-scheme}} - \phi^{\text{WTA}})^2}$

Normalised → $\frac{1}{N}\frac{dN}{d\Delta j}$, N = total number of jets



Cross-sectional view of the CMS detector



Analysis set up and CMS detector

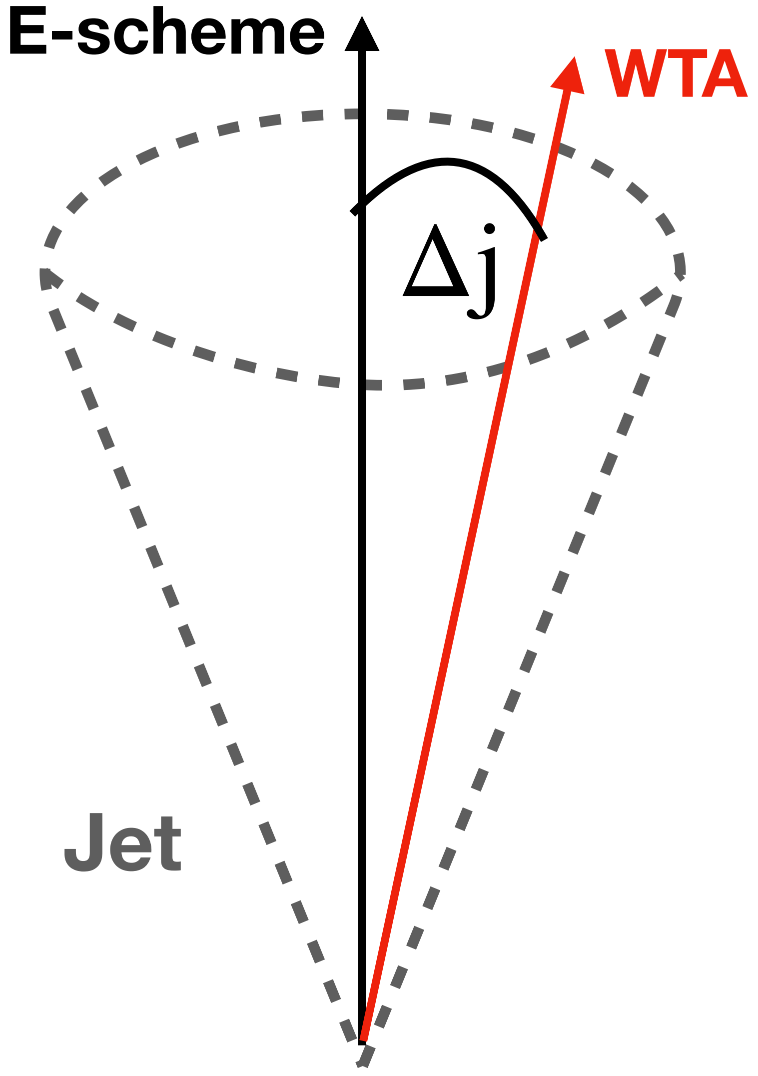
2018 PbPb data at 5.02 TeV

- Centrality: 0-80%
- Centrality binning: {0, 10, 30, 50, 80}%
- Anti-k_T R = 0.4
- $|\eta^{\text{jet}}| < 1.6$
- $120 < p_T^{\text{jet}} < 300$ GeV
- p_T^{jet} binning: {120, 150, 190, 230, 300} GeV

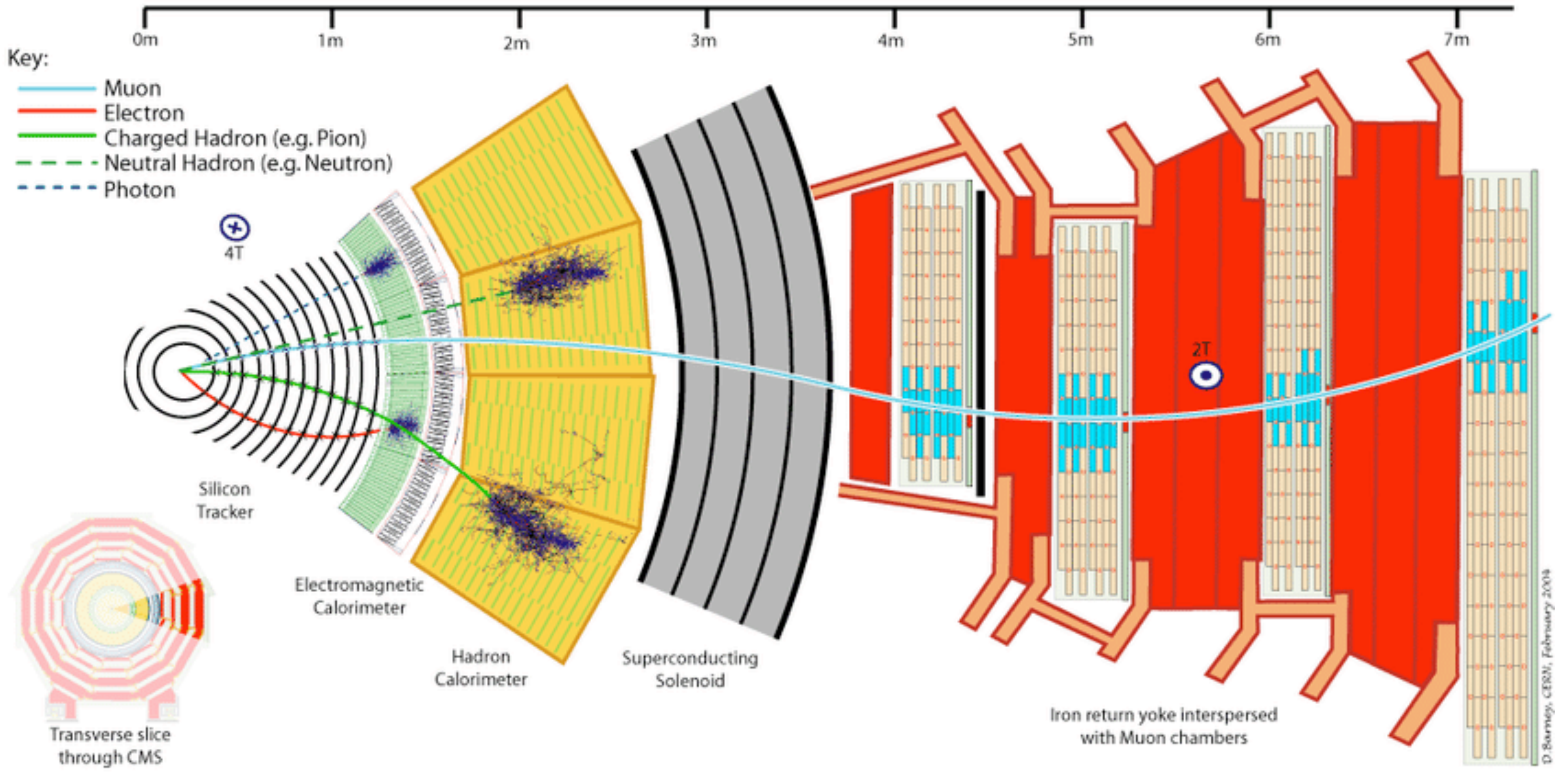
- **Particle flow candidates used to reconstruct jets** Link

Observable $\Delta j = \sqrt{(\eta^{\text{E-scheme}} - \eta^{\text{WTA}})^2 + (\phi^{\text{E-scheme}} - \phi^{\text{WTA}})^2}$

Normalised → $\frac{1}{N}\frac{dN}{d\Delta j}$, N = total number of jets



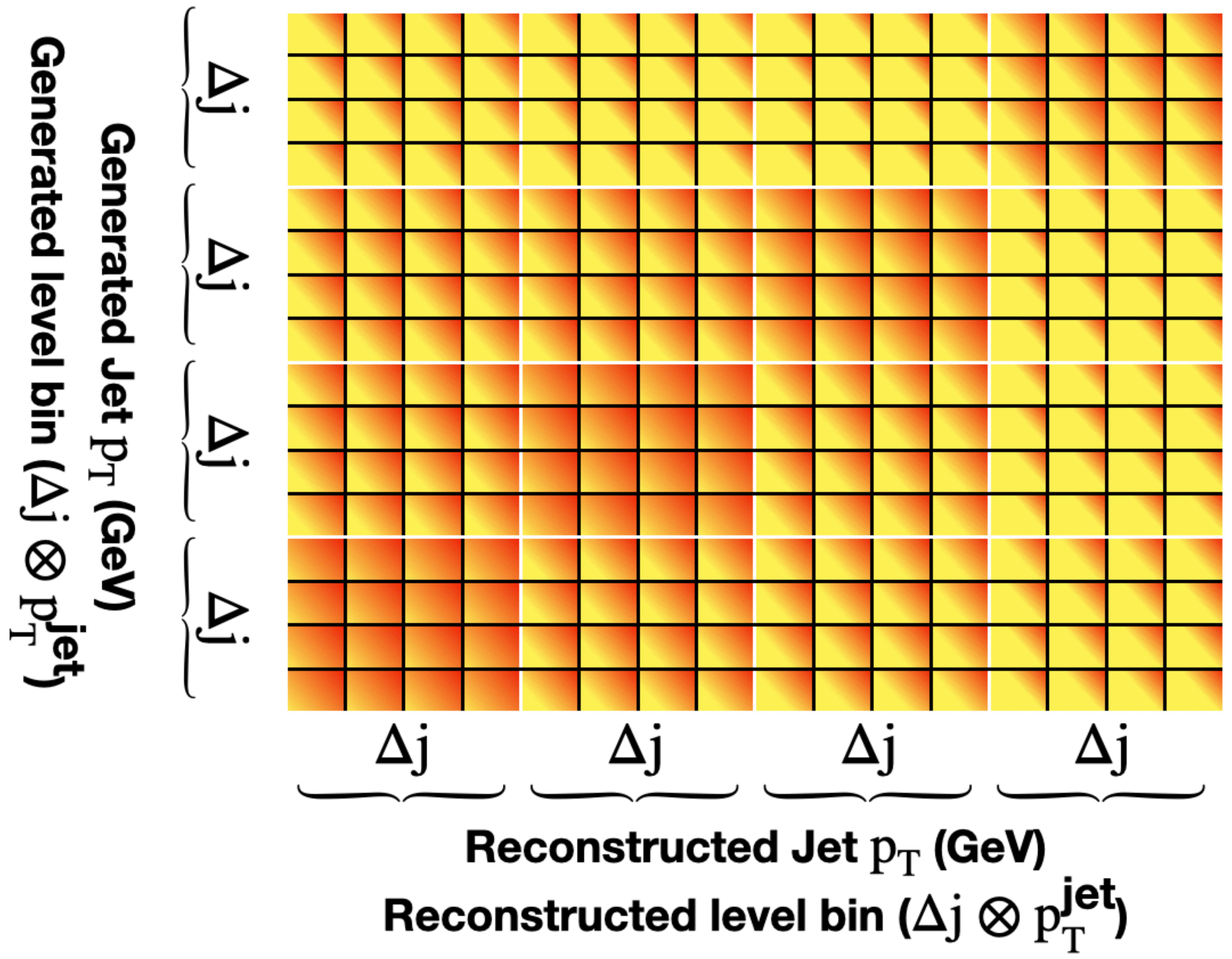
Cross-sectional view of the CMS detector



Unfolding procedure

- Method: D' Agostini iterative
- Unfold two-dimensionally in p_T^{jet} and Δj

Response matrix cartoon →



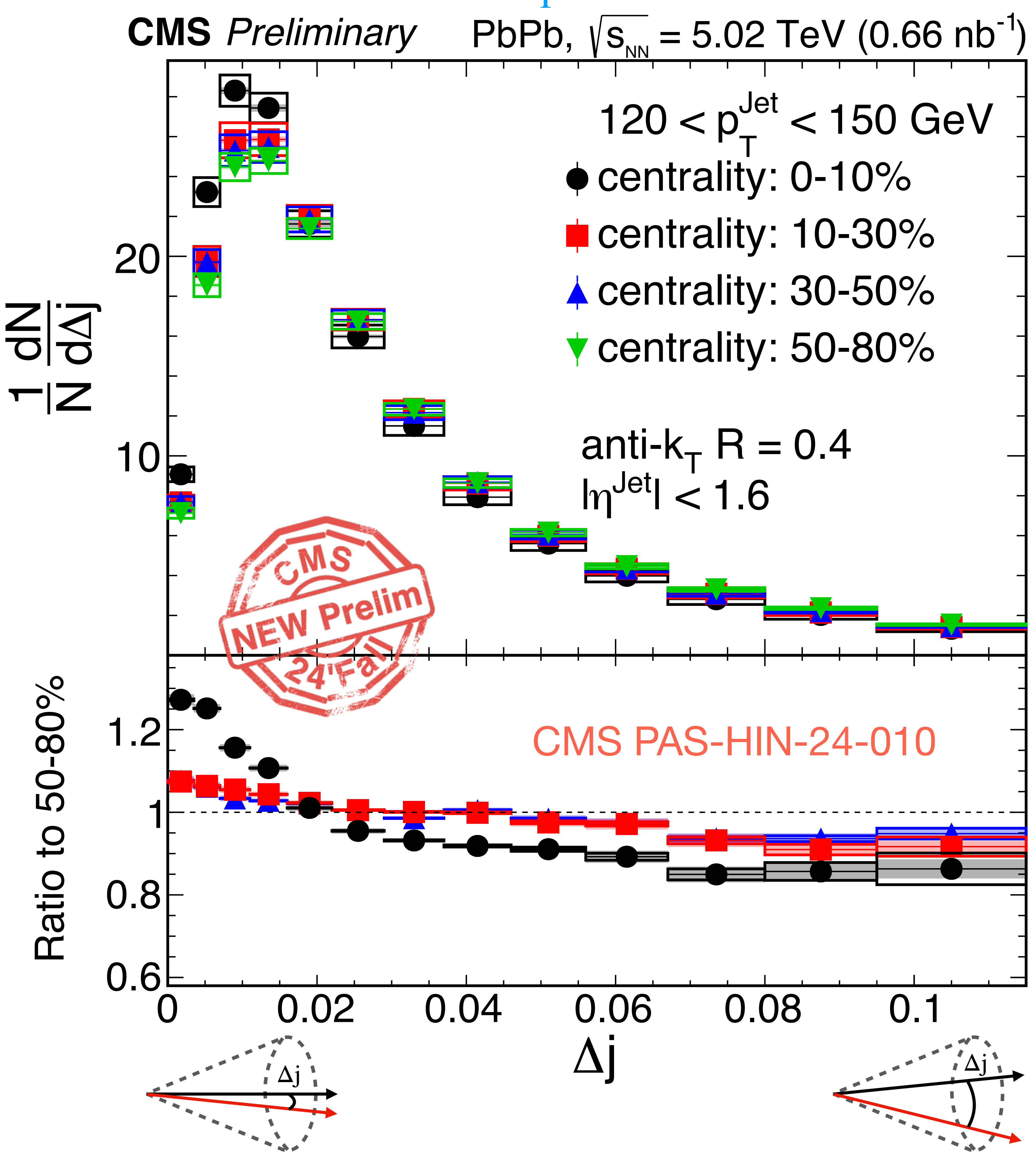
Results: unfolded Δj distributions

- Relative enhancement at lower Δj and suppression at higher Δj
- The Δj distributions in central collisions is narrower than peripheral collisions
- Applied cancelation of the correlated systematic error in the ratio

□ Correlated systematic error

■ Uncorrelated systematic error

120 < p_T^{jet} < 150 GeV



Results: in higher p_T bins

Increasing p_T^{jet}

$120 < p_T^{jet} < 150$ GeV | $150 < p_T^{jet} < 190$ GeV | $190 < p_T^{jet} < 230$ GeV | $230 < p_T^{jet} < 300$ GeV

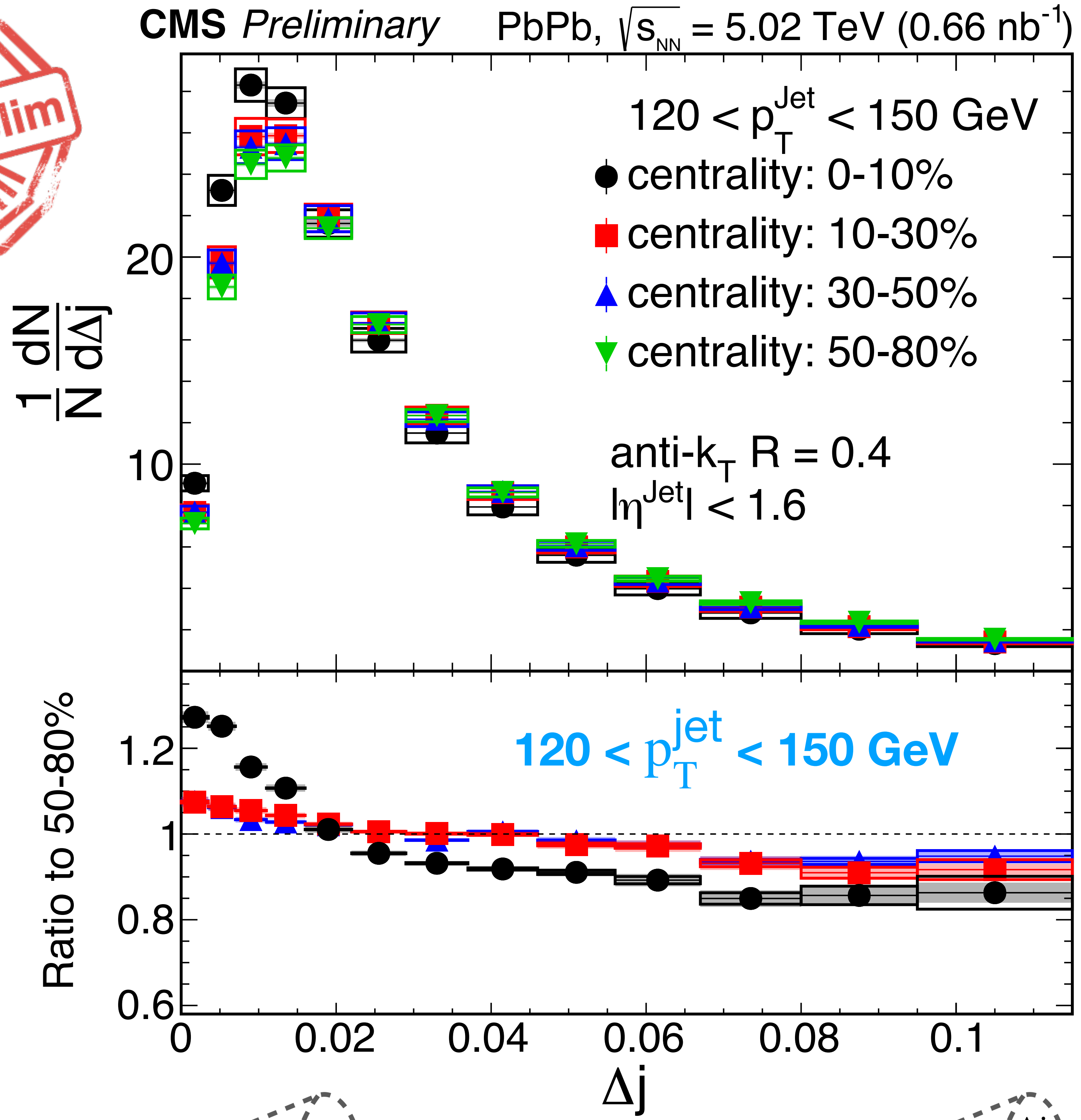
- Narrowing behaviour observed in all the p_T^{jet} bins studied in this analysis
  - modification of jet substructure and/or selection bias due to p_T^{jet} selection?

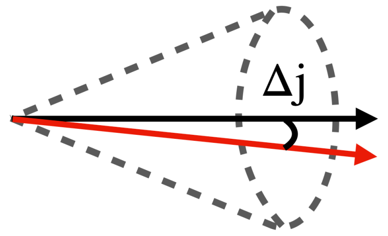
CMS PAS-HIN-24-010

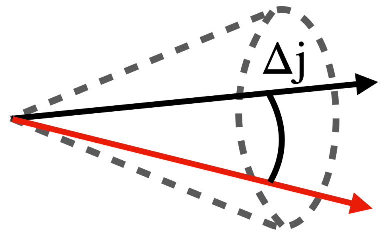
Comp. with previous measurements

CMS NEW Prelim 24'Fall

CMS PAS-HIN-24-010



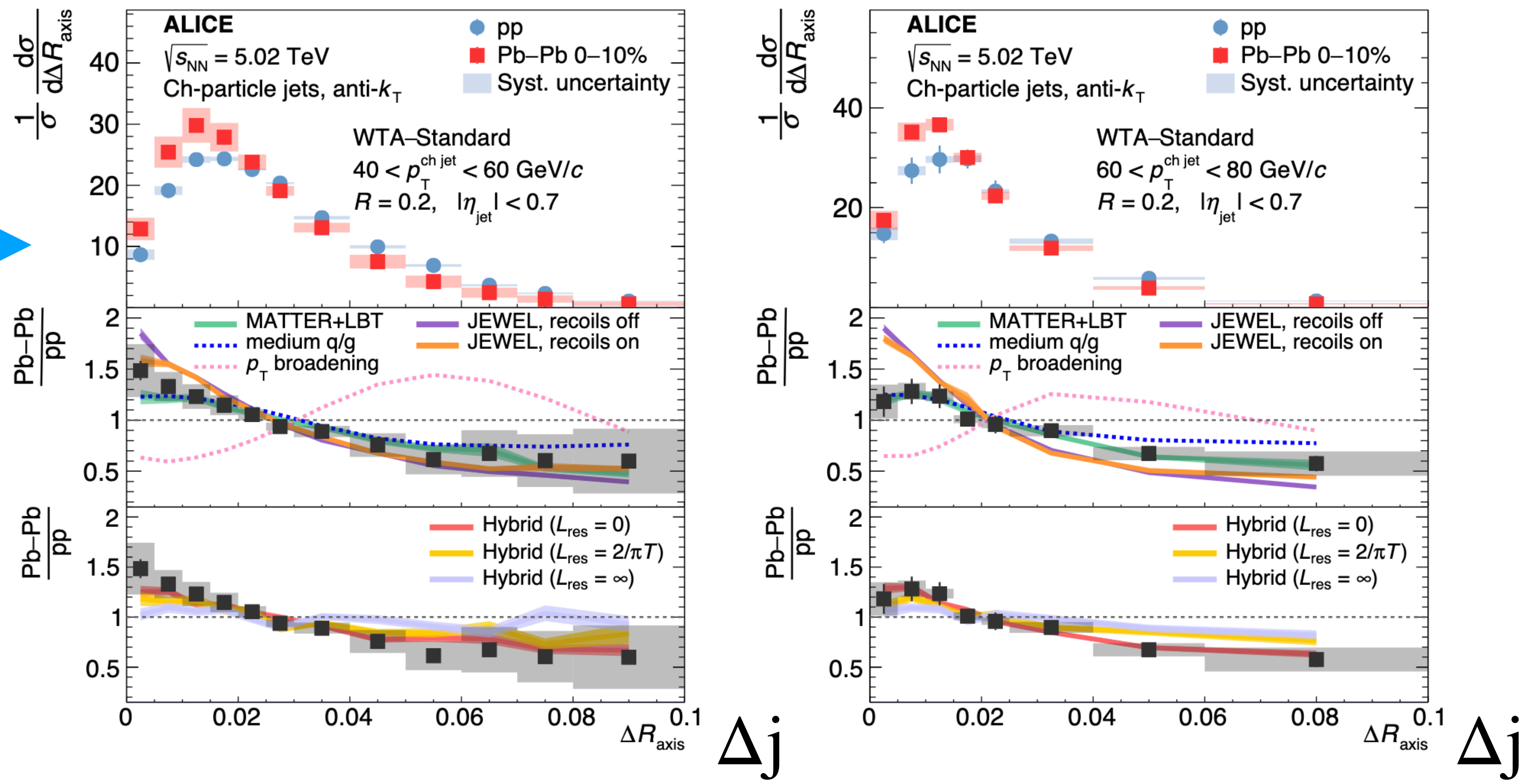




40 < p_T^{jet} < 80 GeV

arXiv:2303.13347

ALICE →

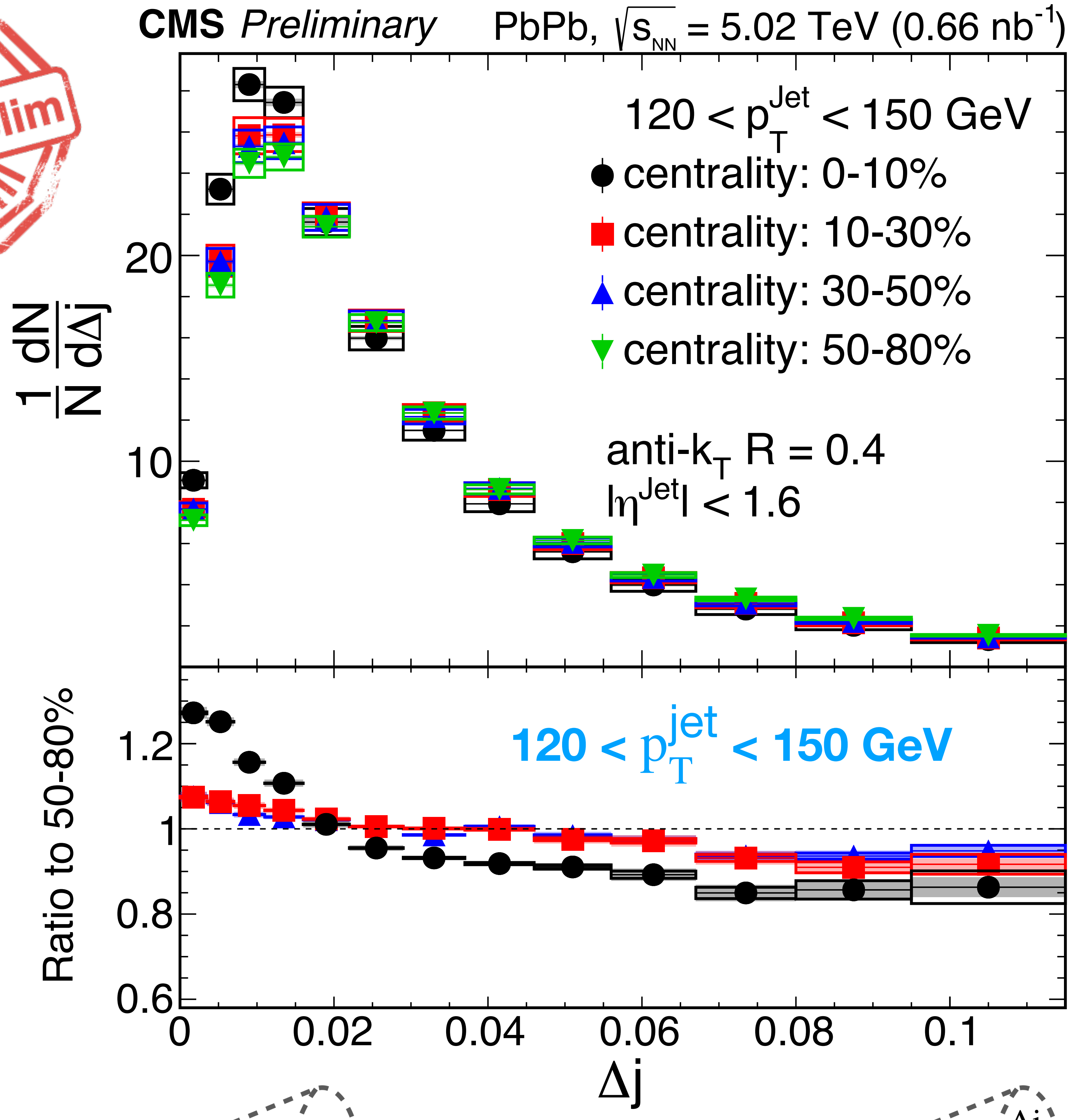


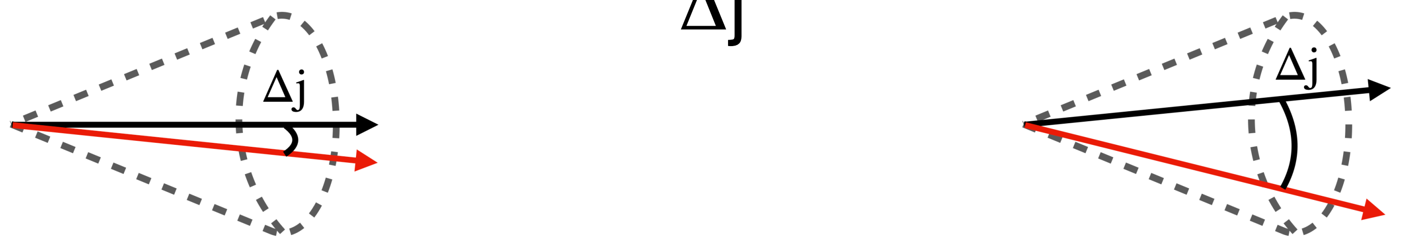
- Similar narrowing observed in ALICE inclusive measurement using charge jet

Comp. with previous measurements

CMS NEW Prelim 24'Fall

CMS PAS-HIN-24-010

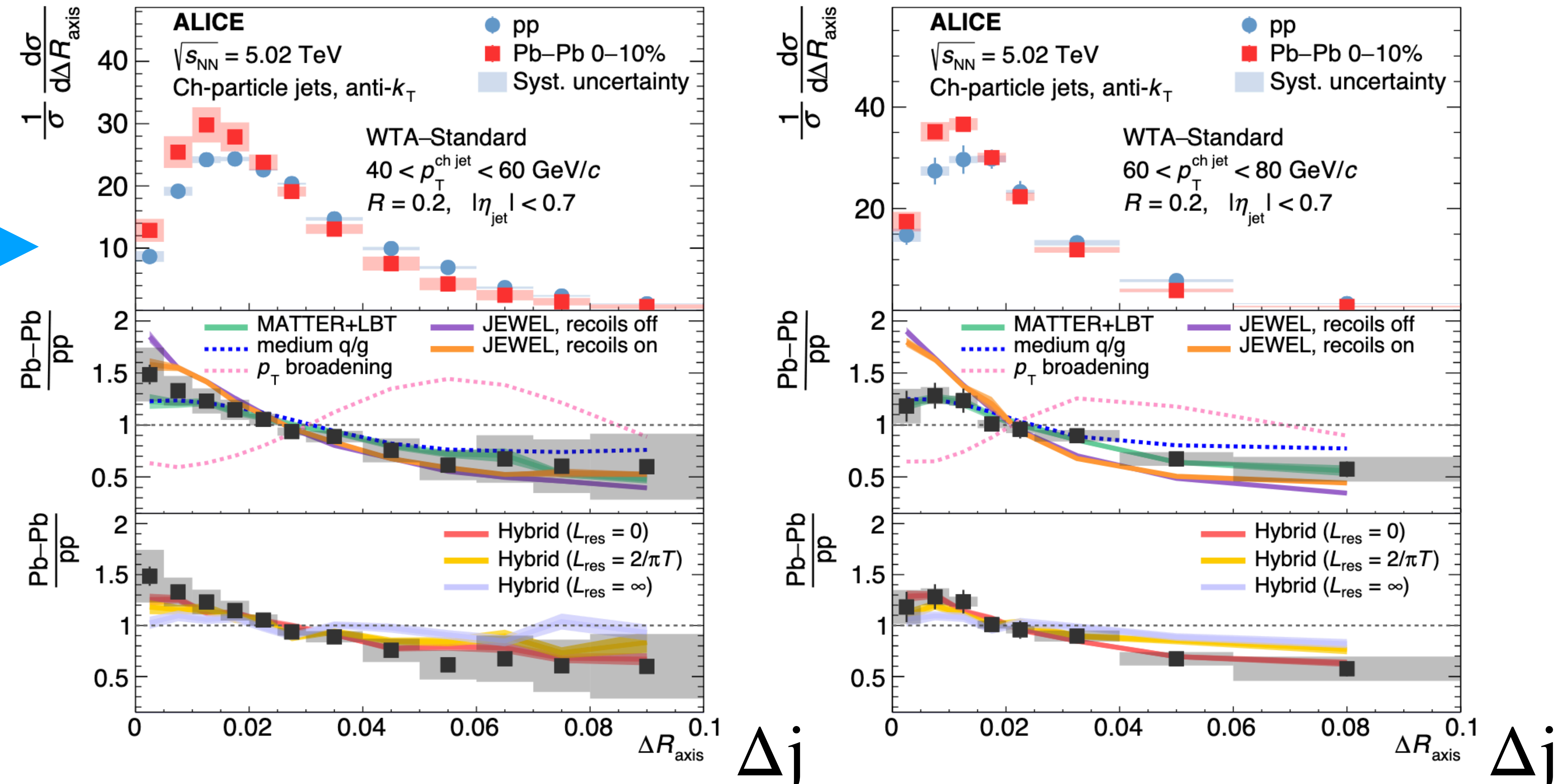




40 < p_T^{jet} < 80 GeV

arXiv:2303.13347

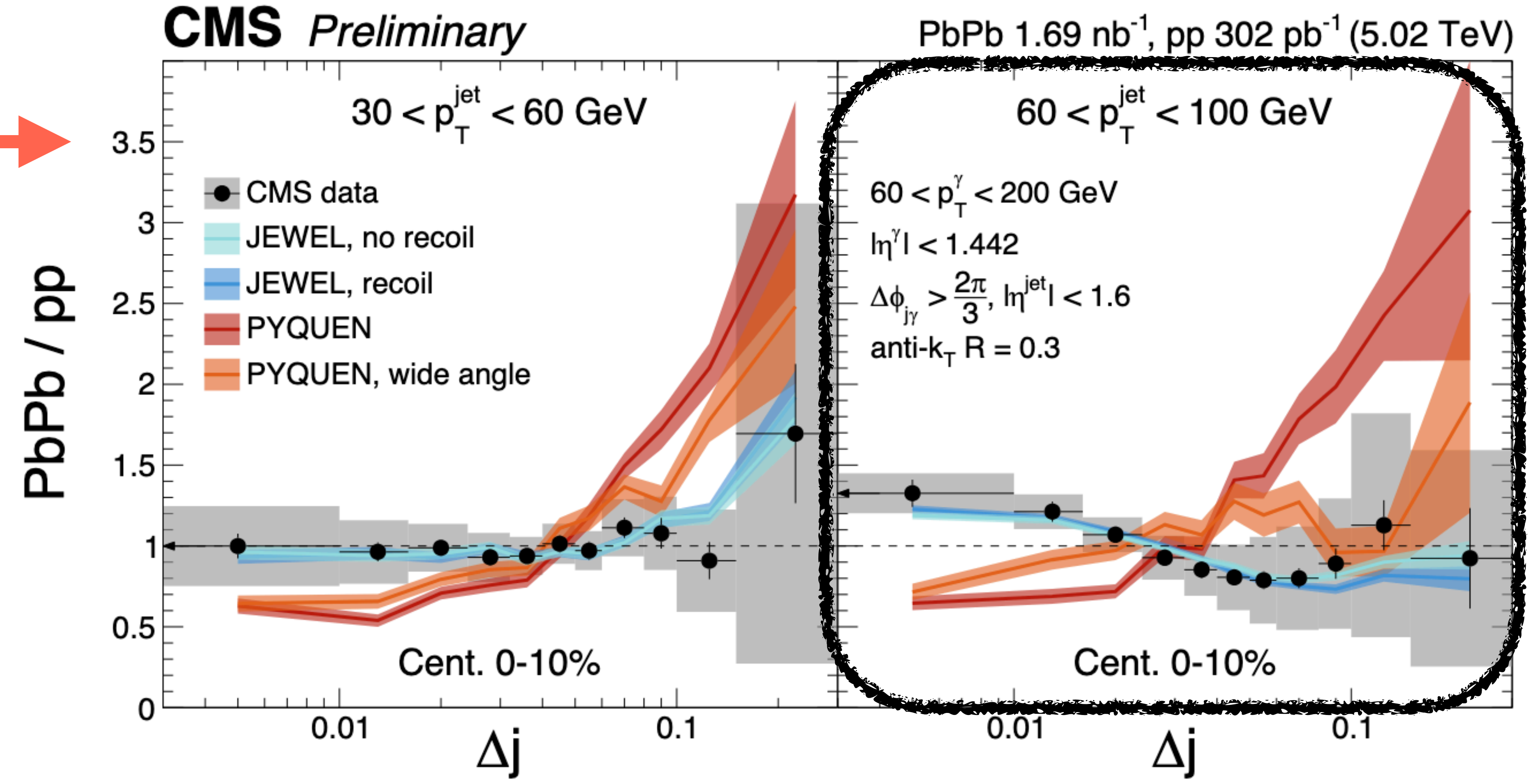
ALICE →



30 < p_T^{jet} < 100 GeV

CMS PAS-HIN-21-019

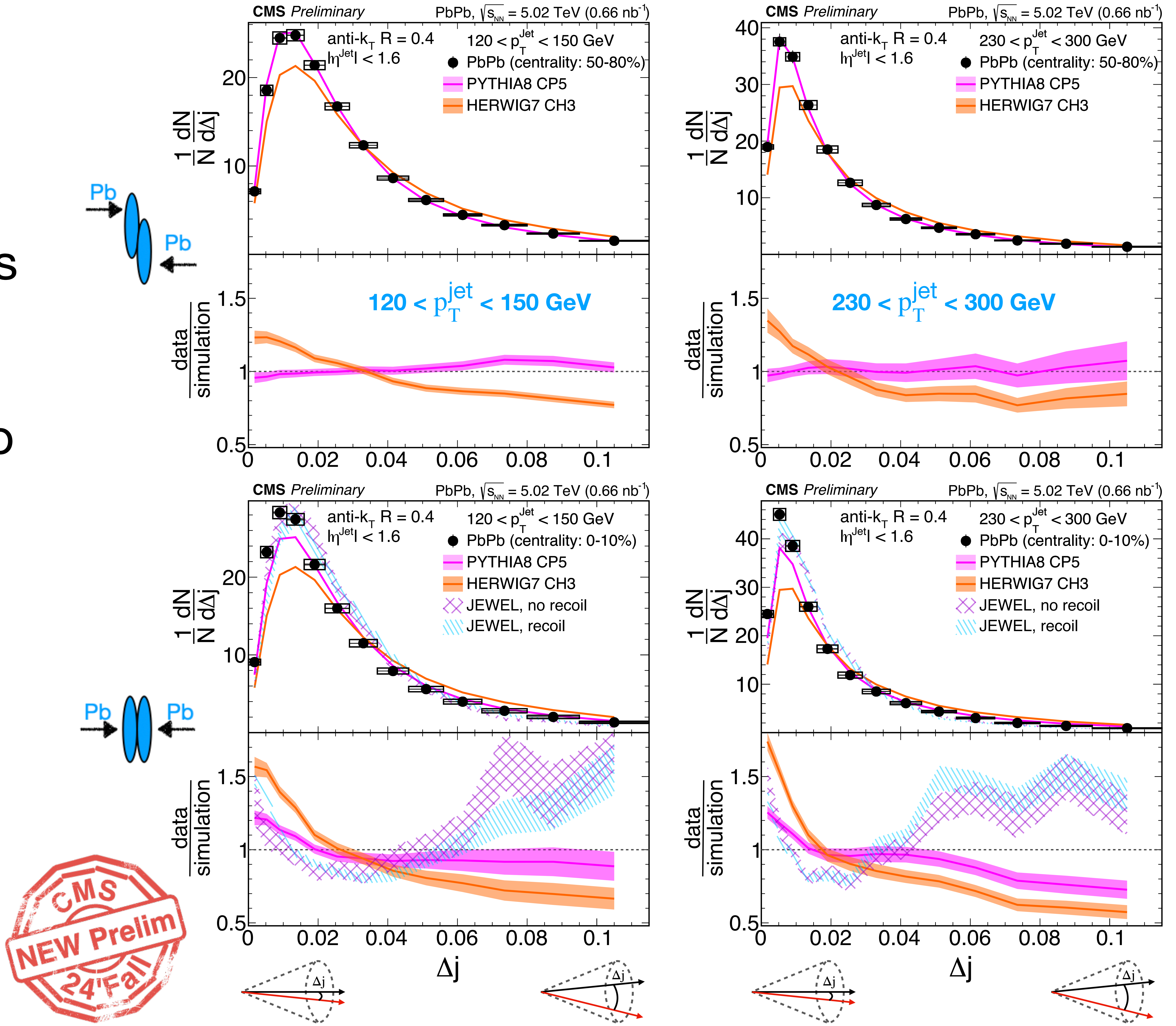
CMS: See Molly Park's talk →



- Similar narrowing observed in ALICE inclusive measurement using charge jet
- Using γ+jet, CMS also observed narrowing in 60 < p_T^{jet} < 100 GeV
- Not a apple to apple comparison, but physics observation is same

Models comparison

- Comparison with unquenched PYTHIA and HERWIG, and JEWEL
- PYTHIA describe well for peripheral 50-80% data, but fails to explain central 0-10% data as expected
- HERWIG has broader distribution compared to data
- JEWEL also fails to explain the central 0-10% data
- However, good to check the ratio between 0-10% and 50-80% in JEWEL (when it will available) and then compare the same in data



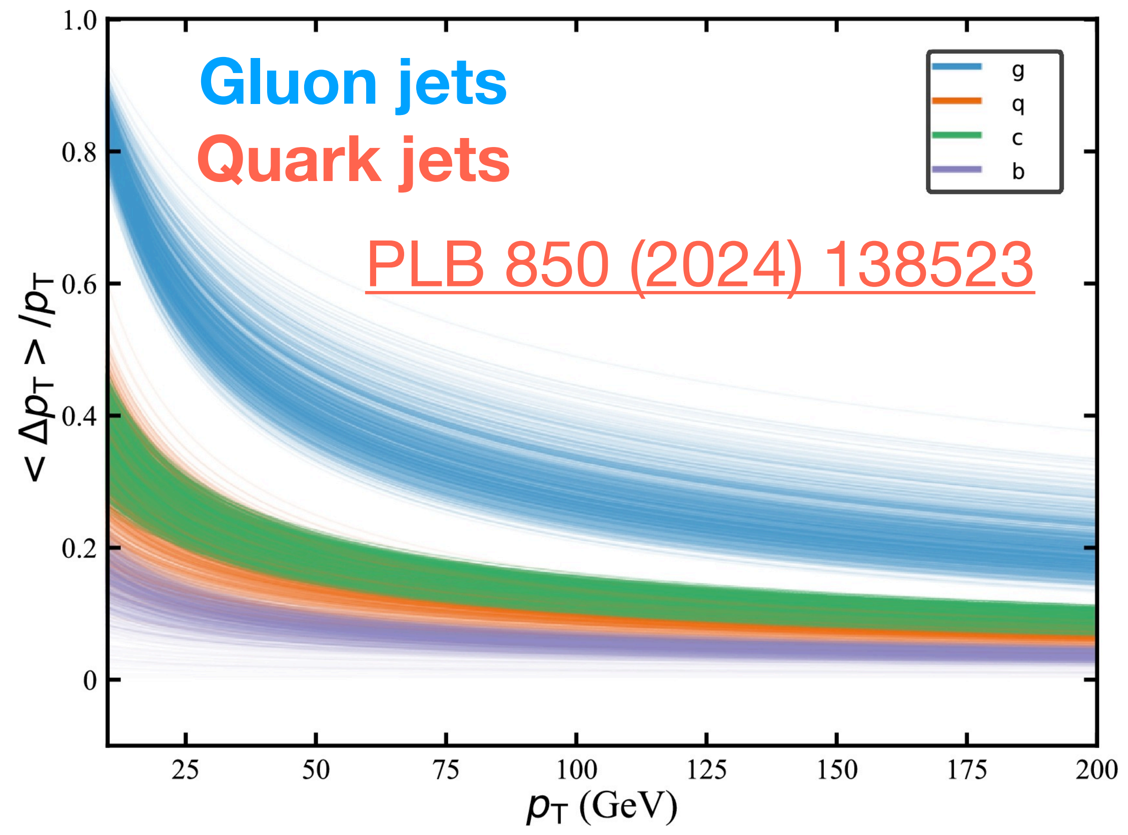
CMS PAS-HIN-24-010

Models comparison continue..

Modified quark/gluon fractions in presence of medium using modified jet function:
PRL 122 (2019) 252301

Medium q/g: Rewight the vacuum PYTHIA based on modified quark/gluon fractions

- Color charge dependent energy loss
  - gluon jet lose more energy than quark jet



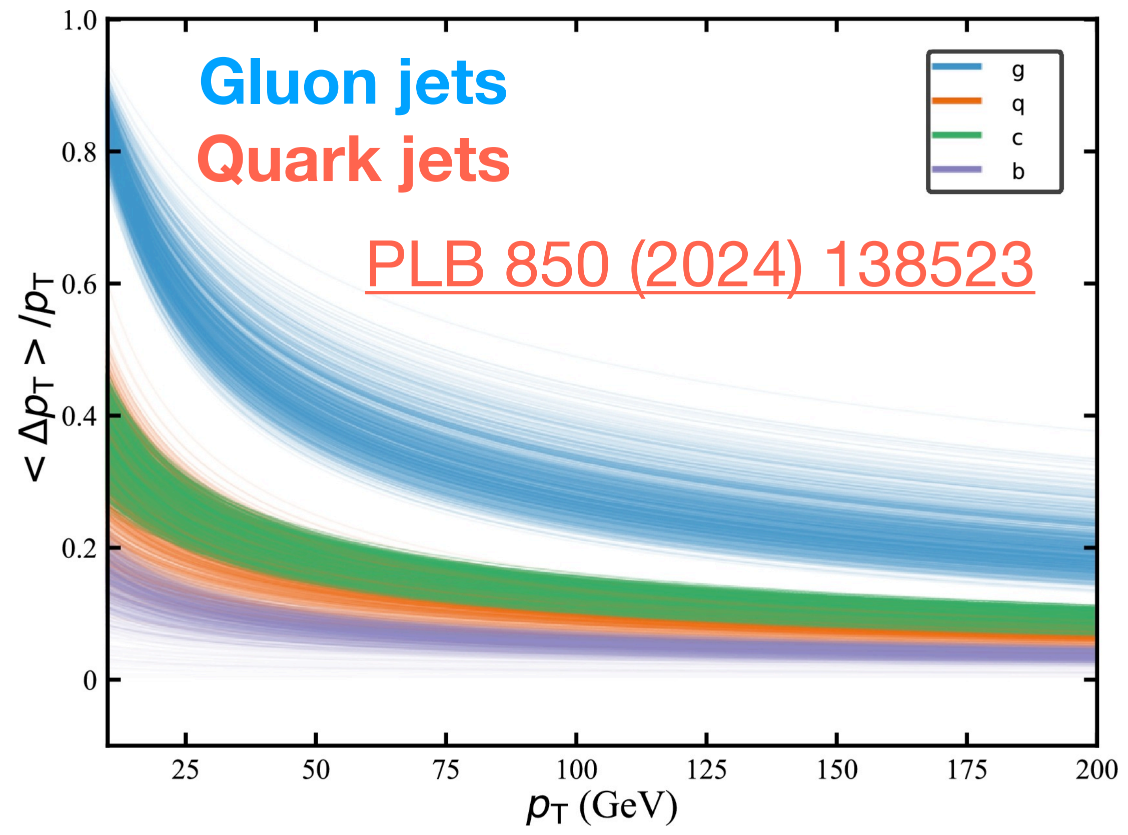
Models comparison continue..

Modified quark/gluon fractions in presence of medium using modified jet function:
PRL 122 (2019) 252301

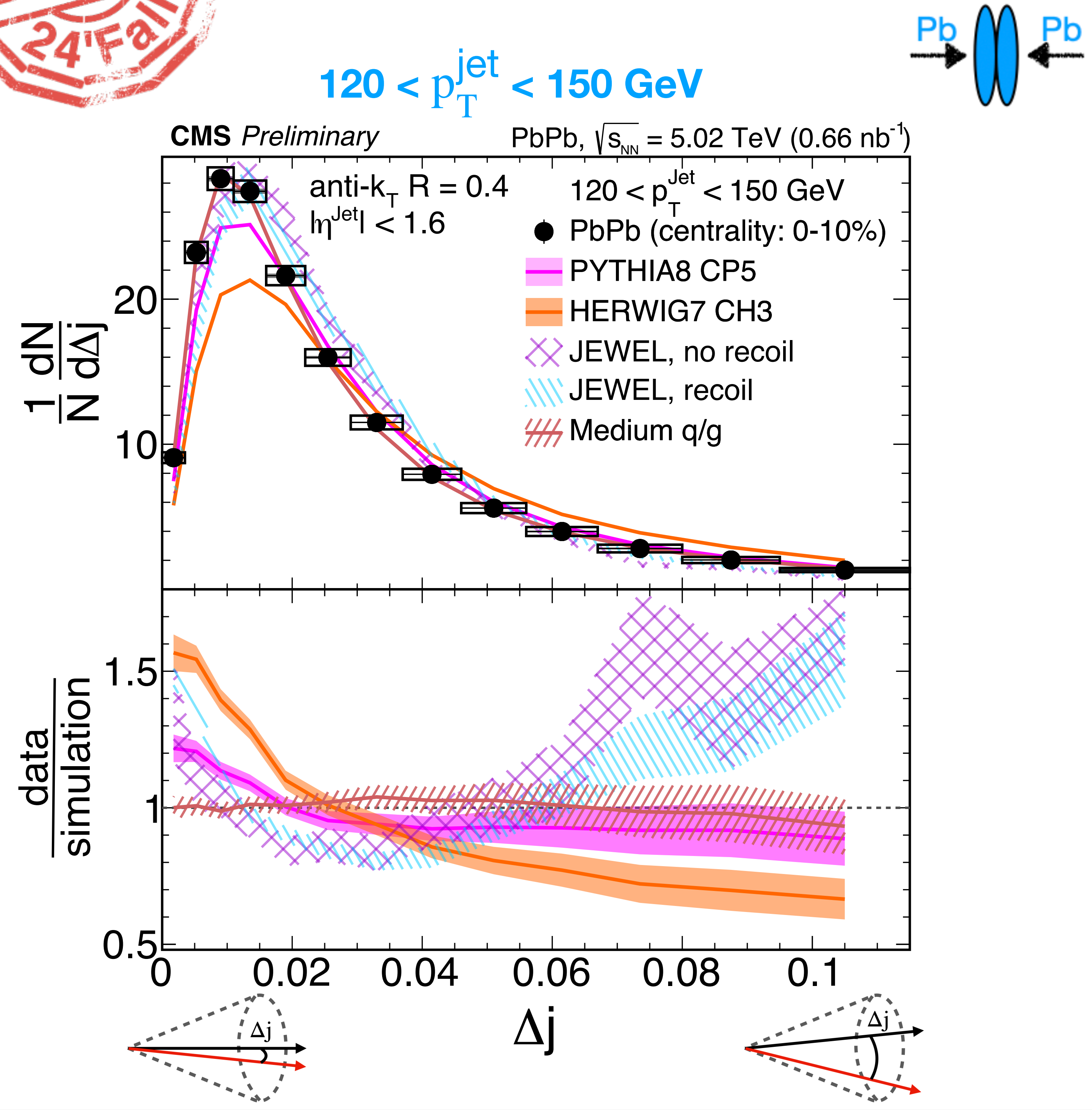
Medium q/g: Rewight the vacuum PYTHIA based on modified quark/gluon fractions

- Medium q/g describe well the low p_T central 0-10% data

- Color charge dependent energy loss
  - gluon jet lose more energy than quark jet



CMS PAS-HIN-24-010



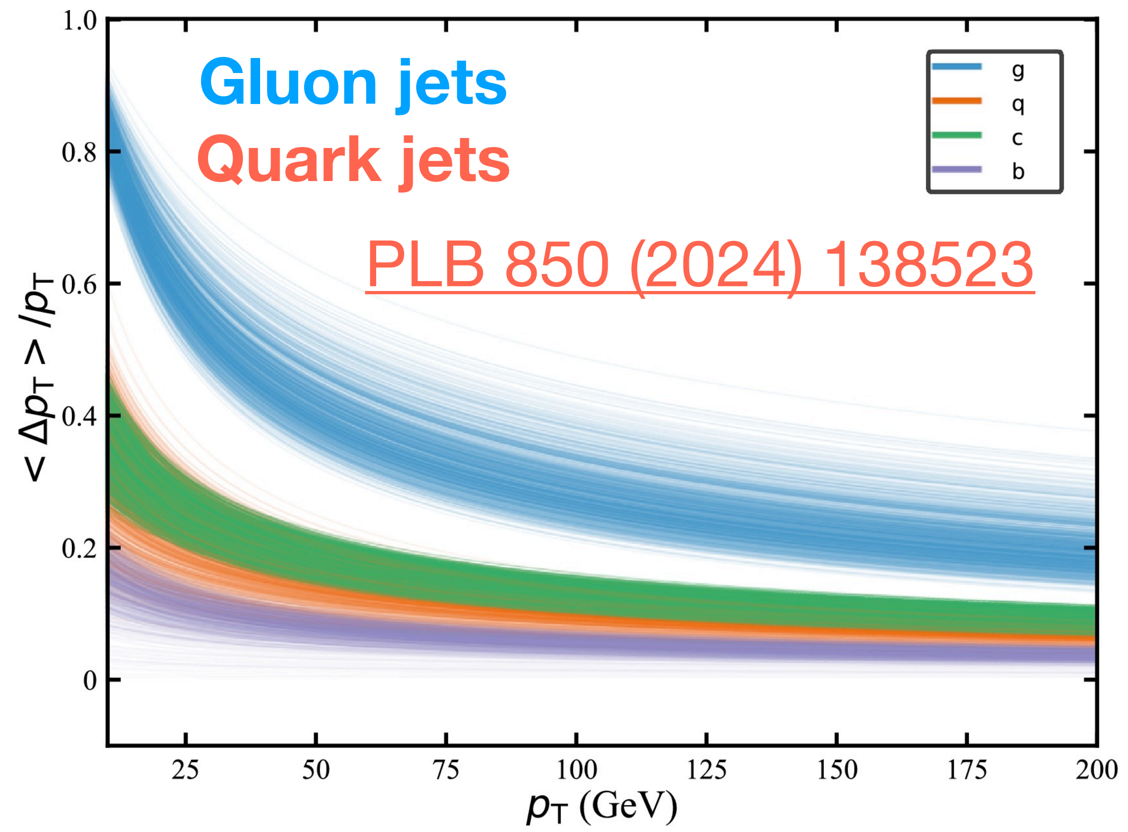
Models comparison continue..

Modified quark/gluon fractions in presence of medium using modified jet function: PRL 122 (2019) 252301

Medium q/g: Rewight the vacuum PYTHIA based on modified quark/gluon fractions

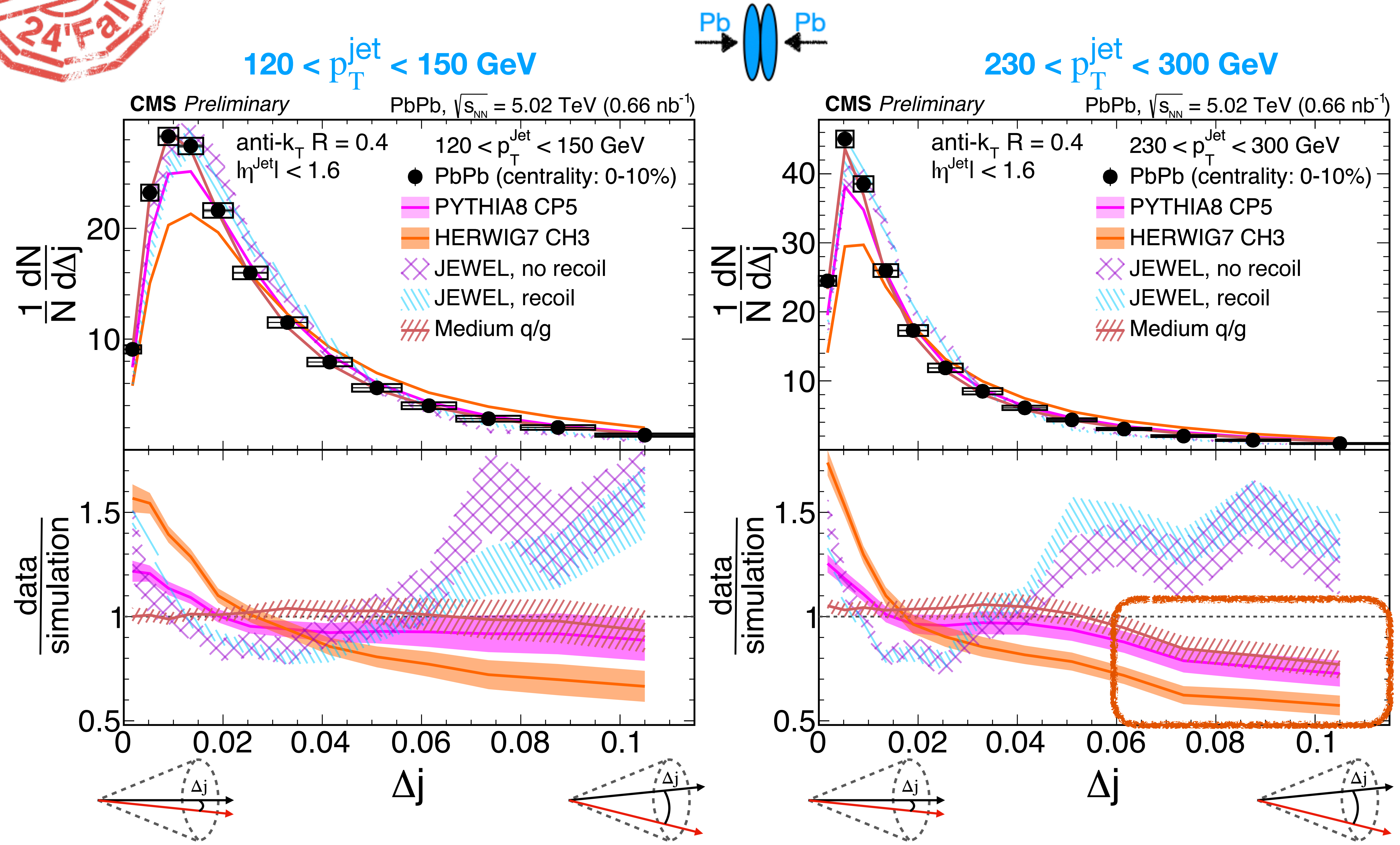
- Medium q/g describe well the low p_T central 0-10% data
- It fails to explain the high p_T central data, particularly towards high Δj
- I.e., only quark/gluon fractions change cannot explain this narrowing behaviour
  - ▸ Indicating the need to account for medium-induced substructure

- Color charge dependent energy loss
  - ▸ gluon jet lose more energy than quark jet



CMS NEW Prelim '24 Fall

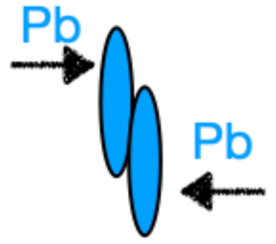
CMS PAS-HIN-24-010

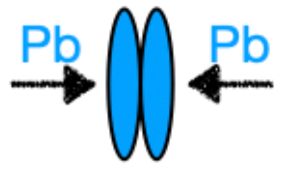


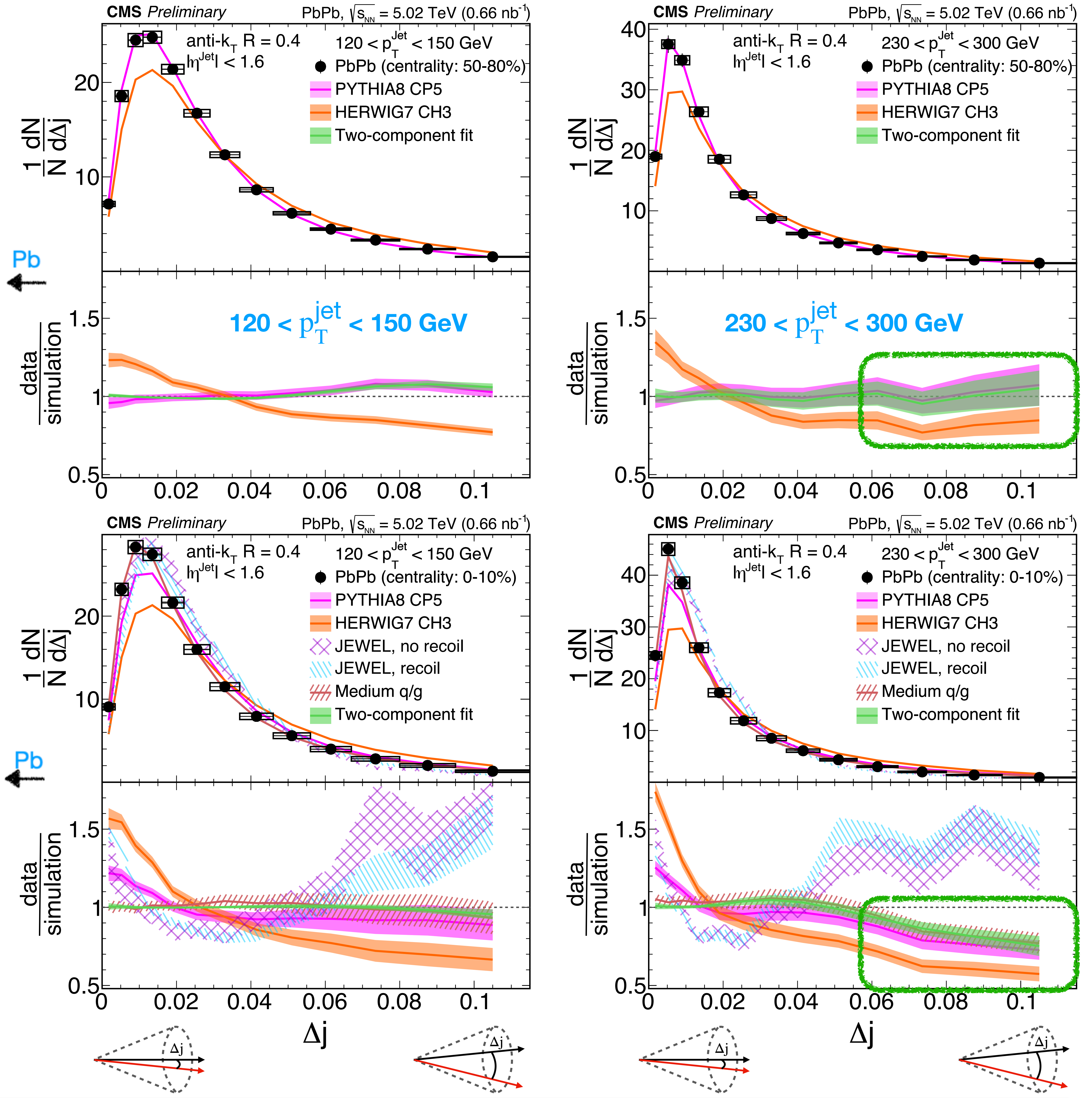
Models comparison continue..

Further test on modified quark/gluon fractions

- Two-component fit: fit to unfolded data using vacuum PYTHIA quark and gluon templates
- The obtained gluon fractions in peripheral 50-80% aligns with PYTHIA expectations
- For central 0-10%, it is in excellent agreement with the prediction from Medium q/g
- Similar to Medium q/g, Two-component fit describe well the low p_T central 0-10% data, but fails to explain the high p_T central data, particularly towards high Δj







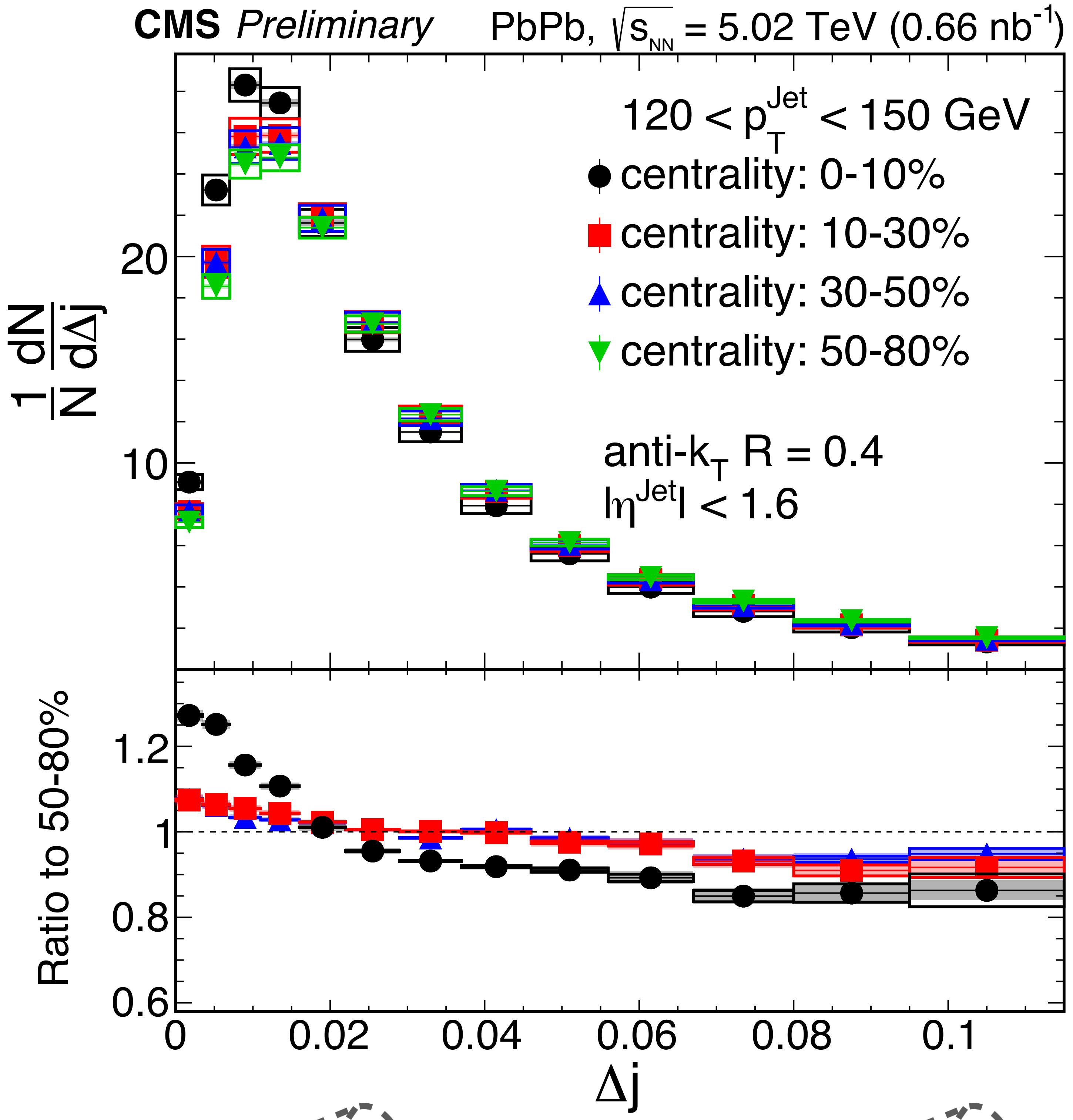
CMS PAS-HIN-24-010

CMS PAS-HIN-24-010

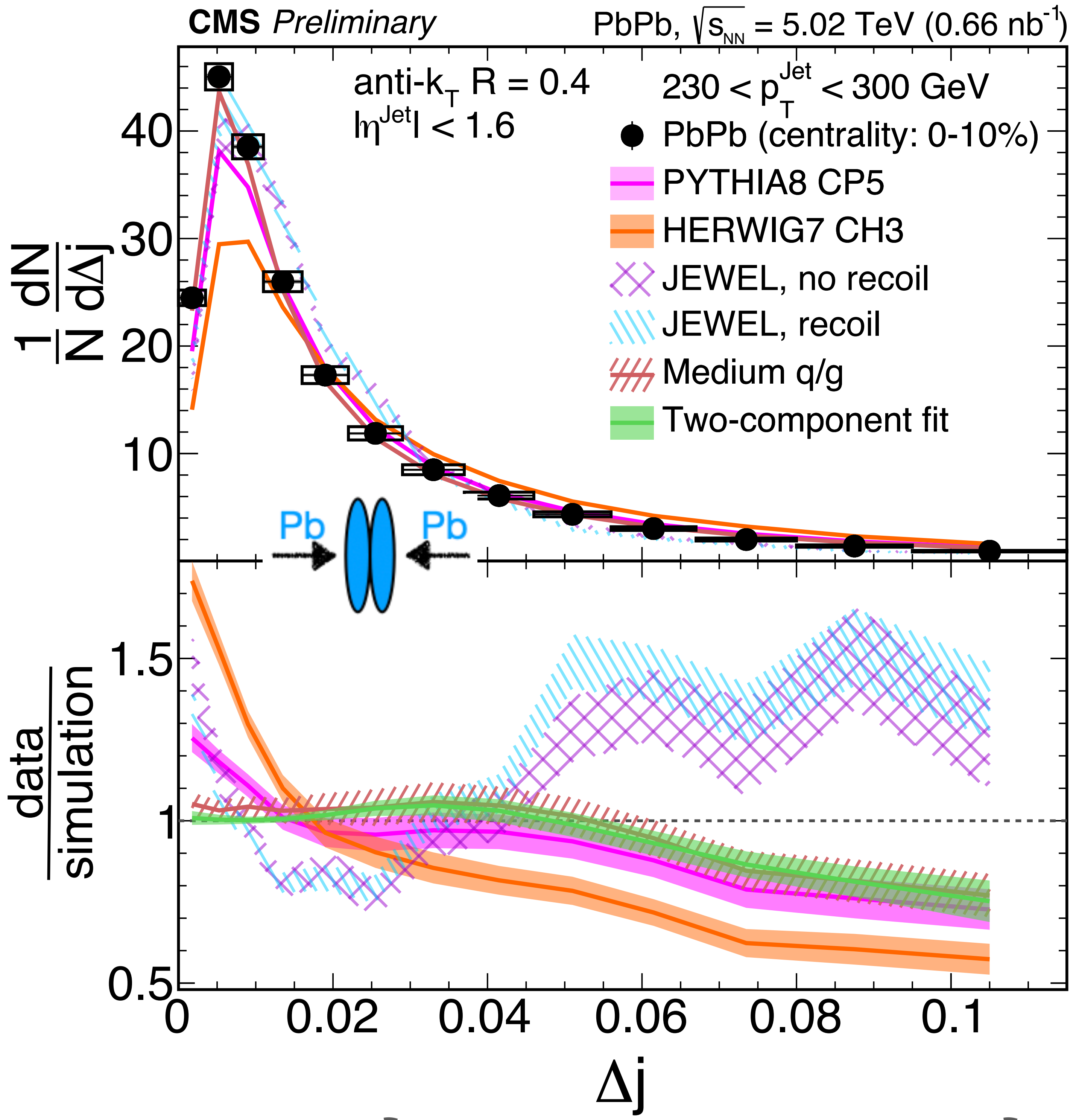
- The Δj distribution is narrower in central collisions than peripheral collisions in all the p_T^{jet} bins studied in this analysis

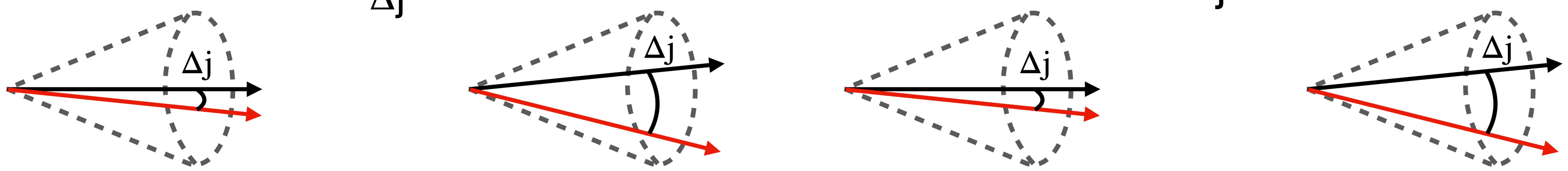
- Two energy loss models (Medium q/g and Two-component fit) fail to explain high Δj behaviour for high p_T^{jet} in the 0-10% central data
  - Indicates the need to account for medium-induced substructure modification

$120 < p_T^{jet} < 150$ GeV



$230 < p_T^{jet} < 300$ GeV





Thank you for your kind attention!

Backup

Systematic sources

JES uncertainty : up and down [(anti)correlated with Δj]
JER uncertainty : centrality independent (JER up and down), centrality dependent [(anti)correlated with Δj]

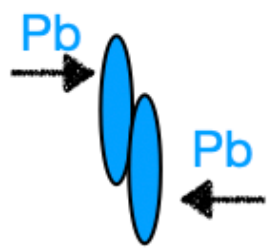
Background subtraction : akFlowPuCs4PF jets collection
Unfolding iteration : varied to 2 and 4
Response matrix statistics : using 50 toy response matrices
Modified template : reweight the response matrix and modify the quark gluon template based on the fraction extracted from raw data
Unfolding prior : generate new response matrix without pT reweight
Centrality variation : up and down

Correlated source

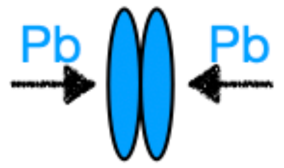
Uncorrelated source

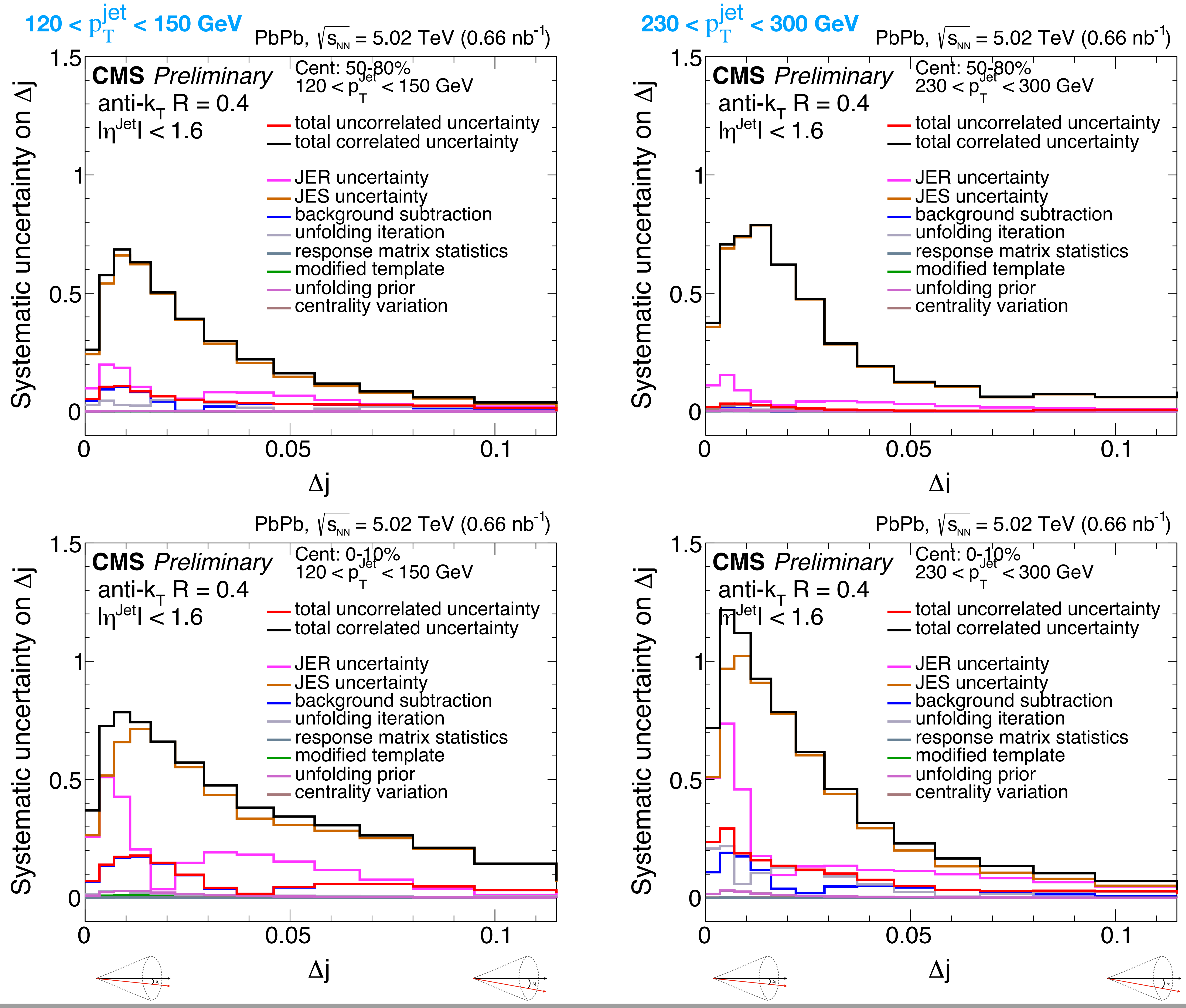
Systematic uncertainty for Δj

Absolute systematic uncertainty



- JES and JER are the dominant systematic for this analysis, which are also treated as correlated uncertainty
- Others are sub-dominant and teated as uncorrelated uncertainty

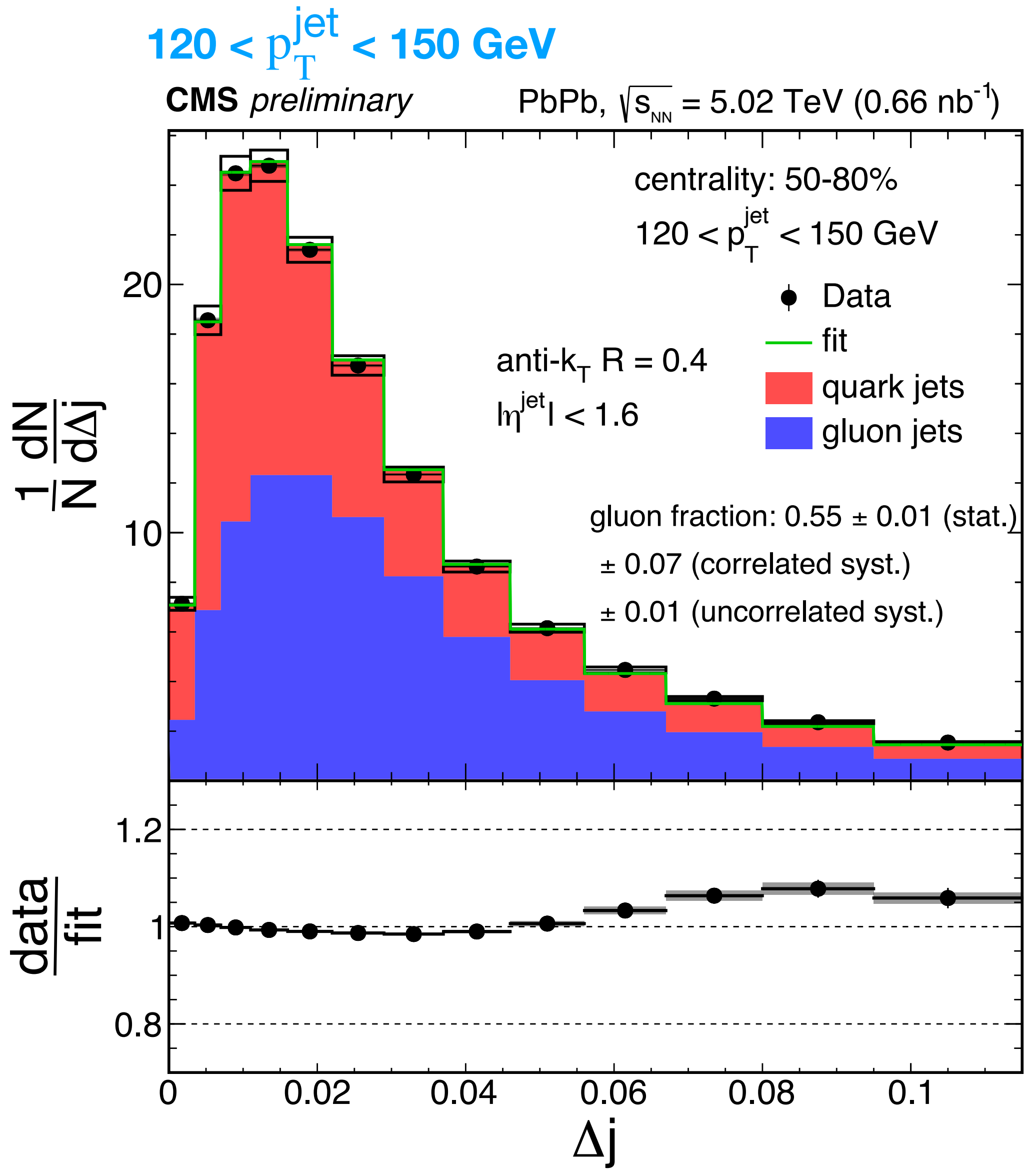


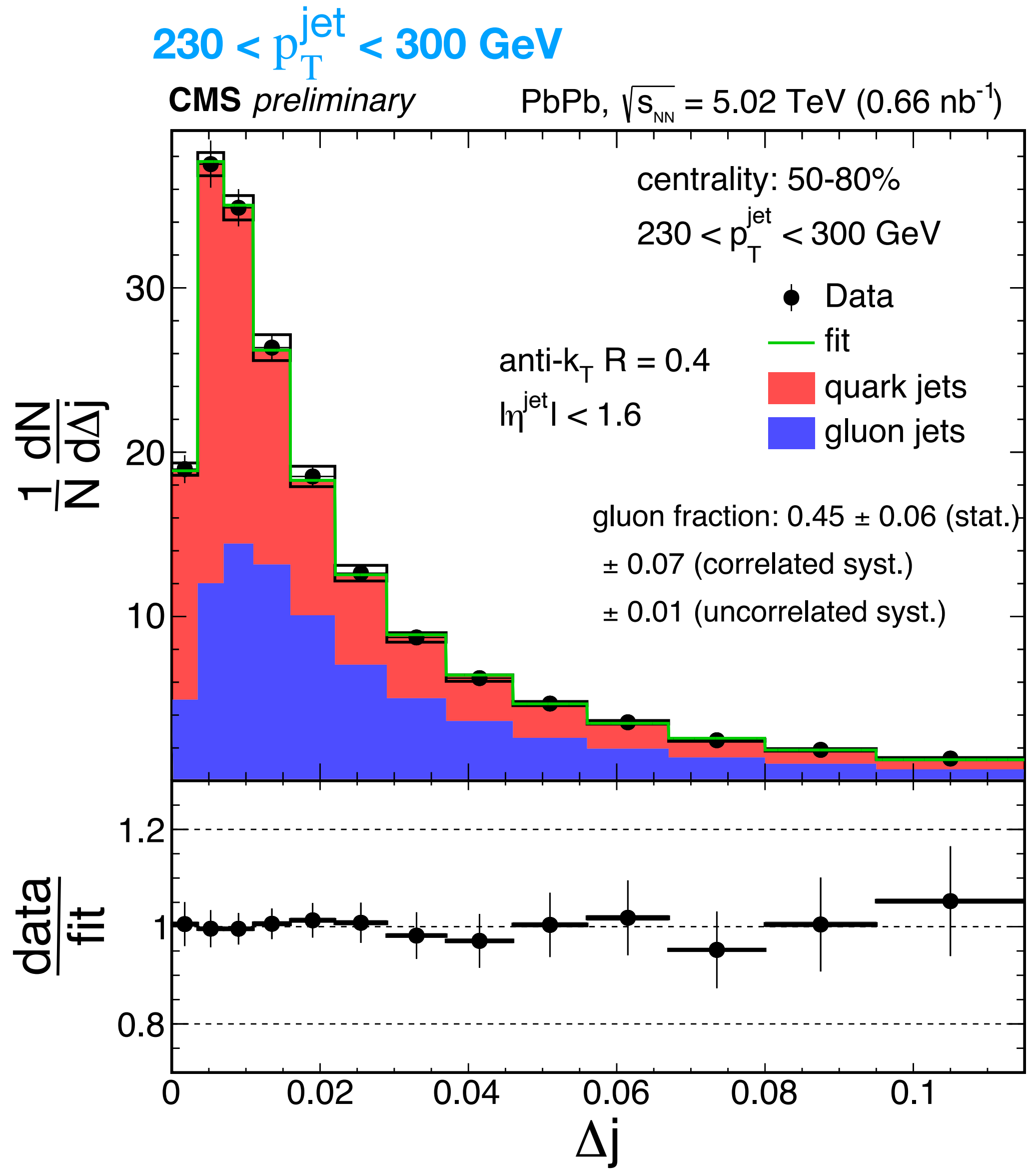


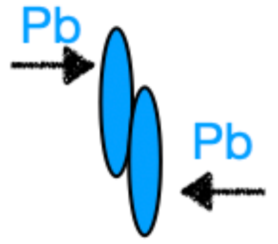
Template fit to data

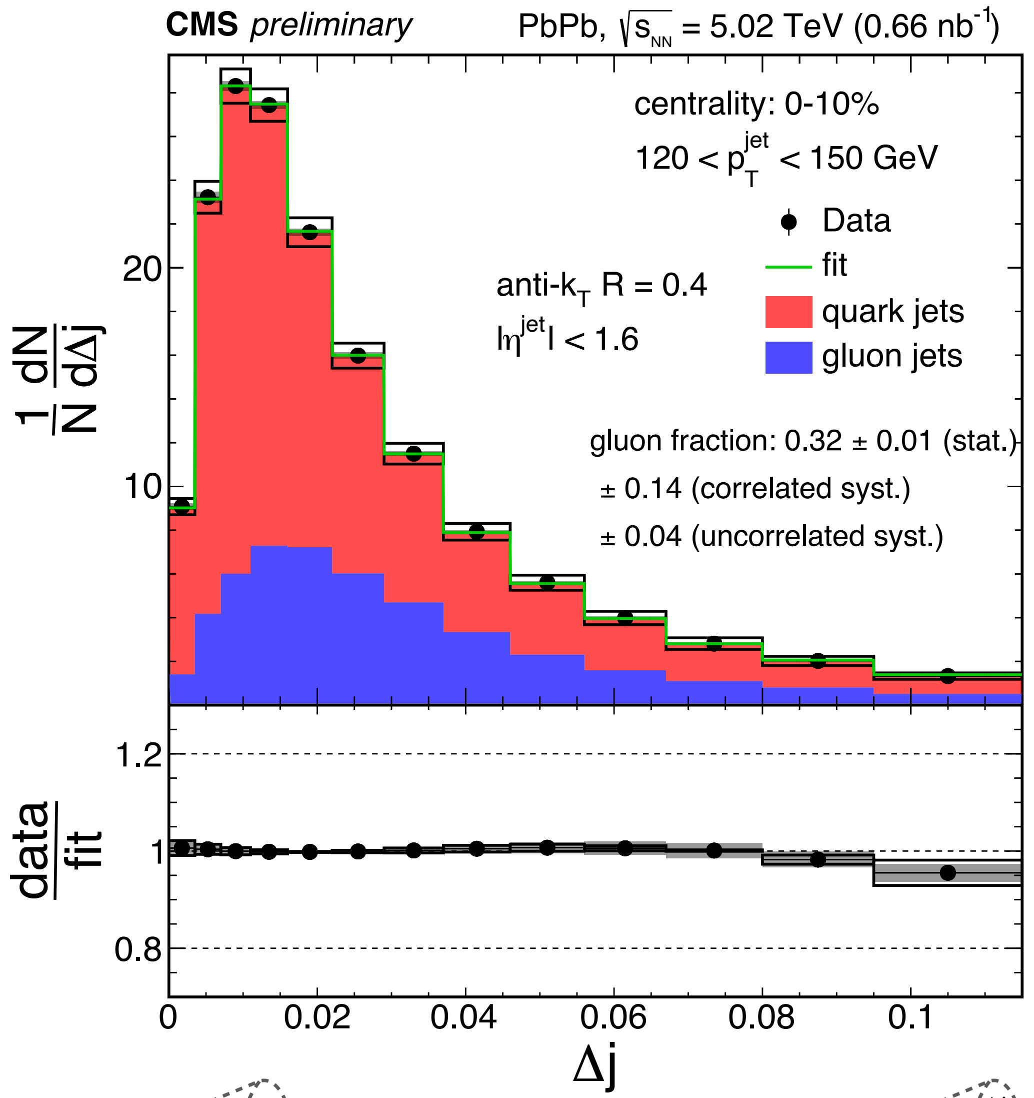
Using vacuum PYTHIA

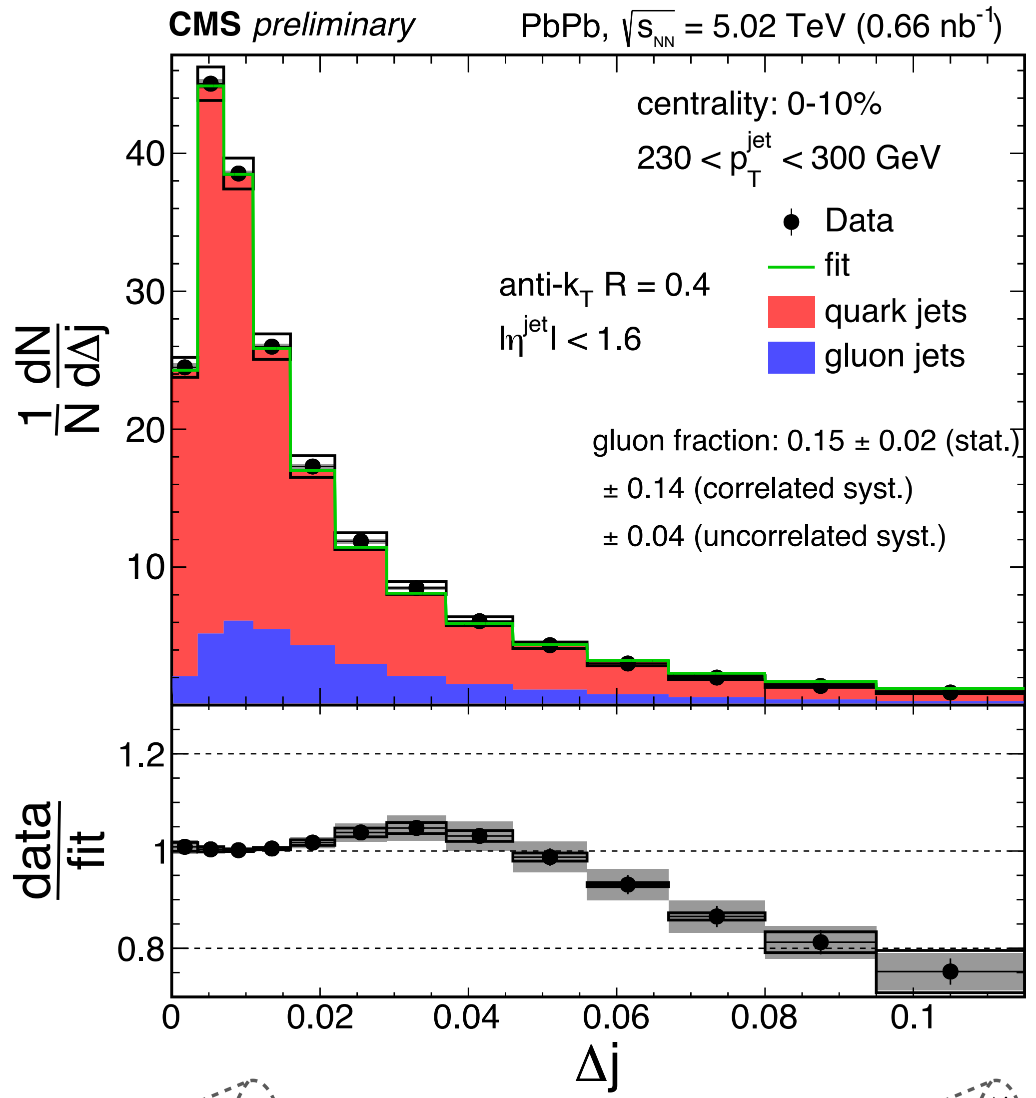
Δj is sensitive to parton flavour

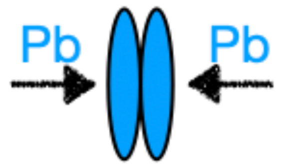


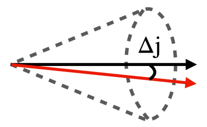
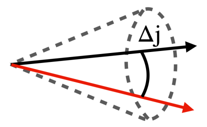
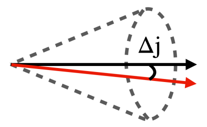
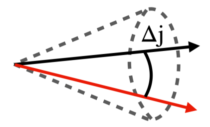


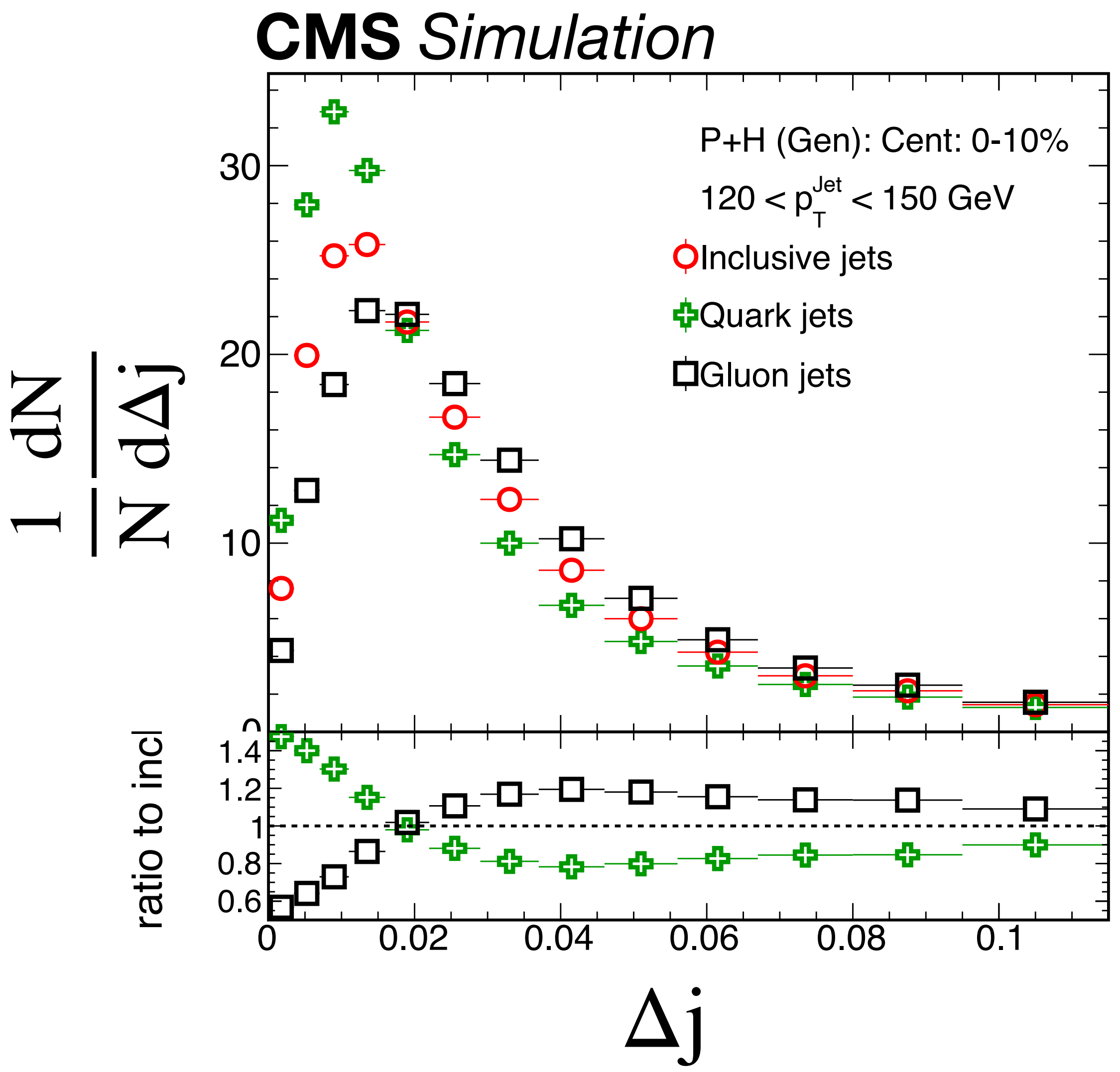










arXiv:2405.02737