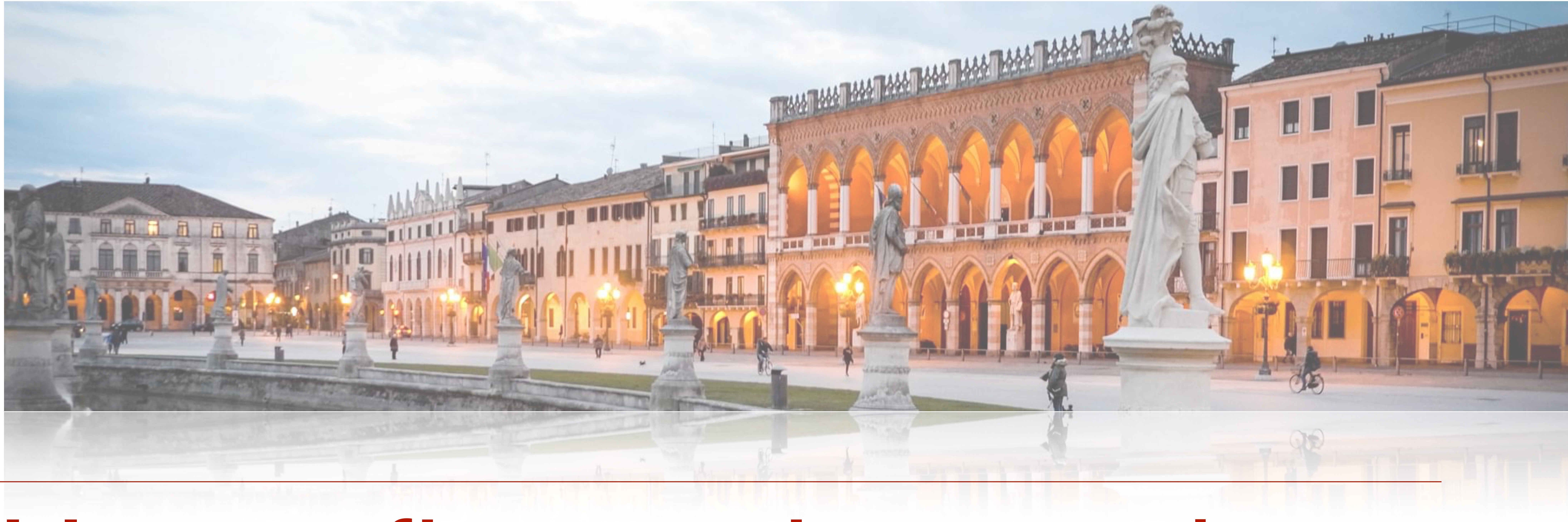
Terzo Incontro di Fisica con Ioni Pesanti alle Alte Energie 2021



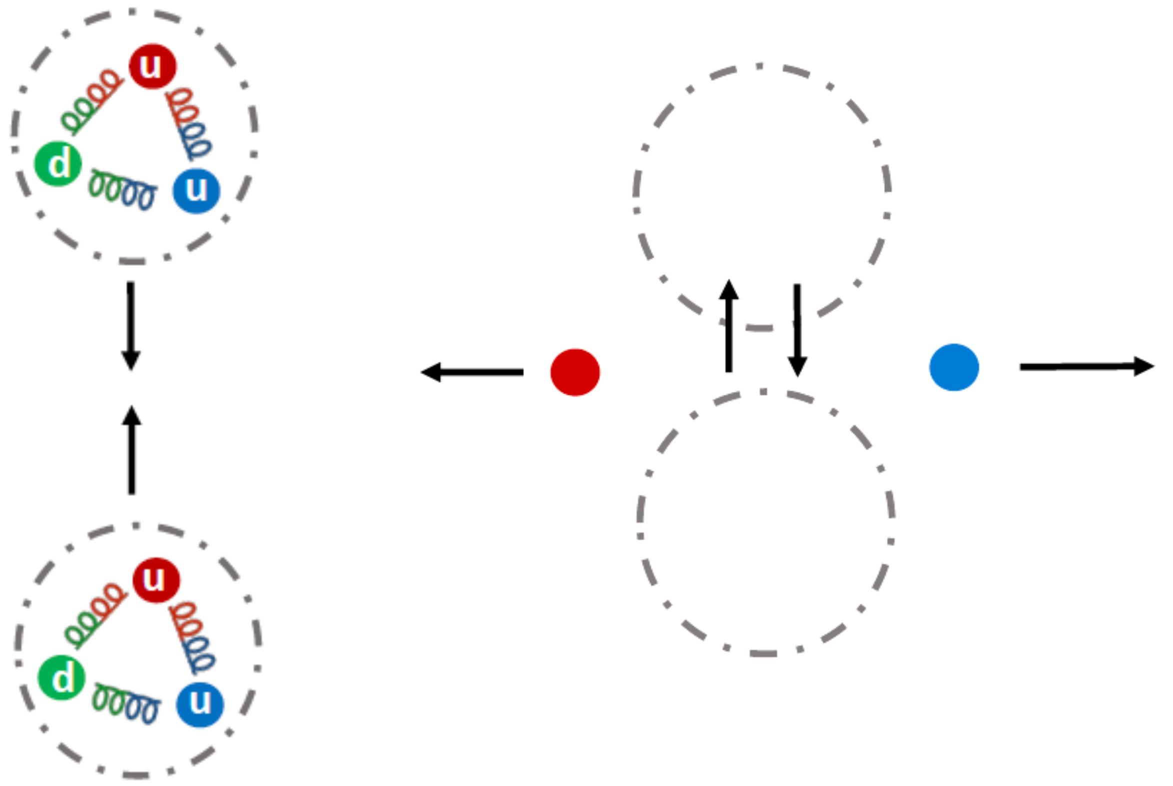
Heavy flavour jets and correlations

Marianna Mazzilli, CERN

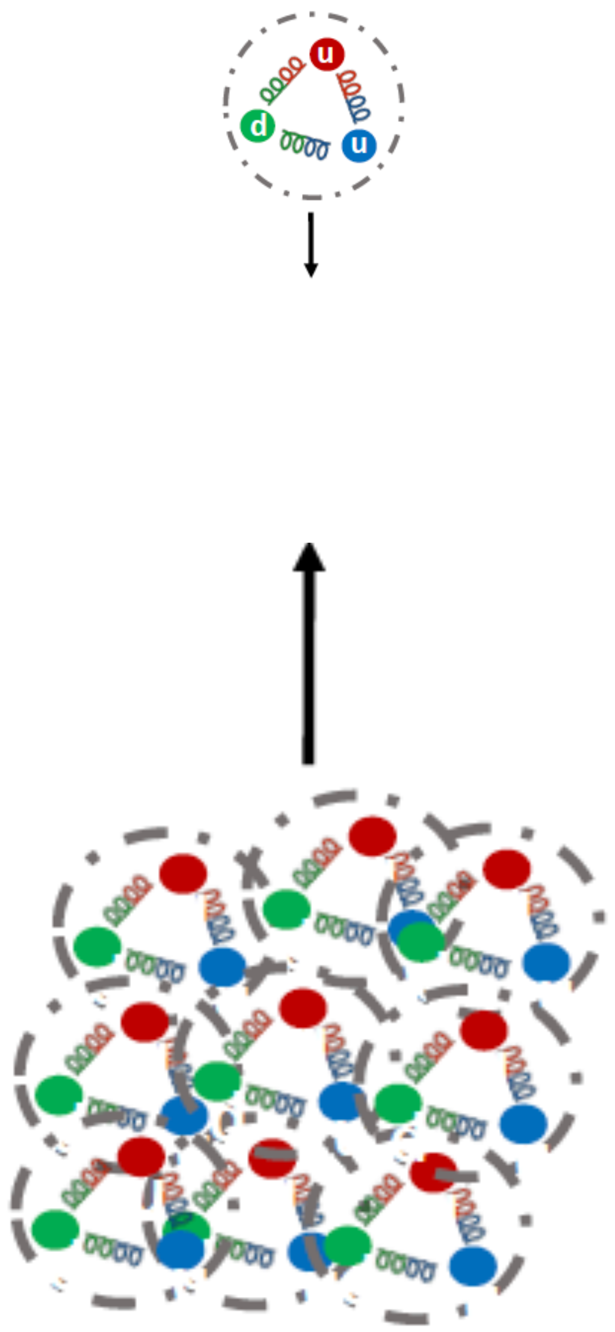
25/11/2021 PADOVA

Physics motivations

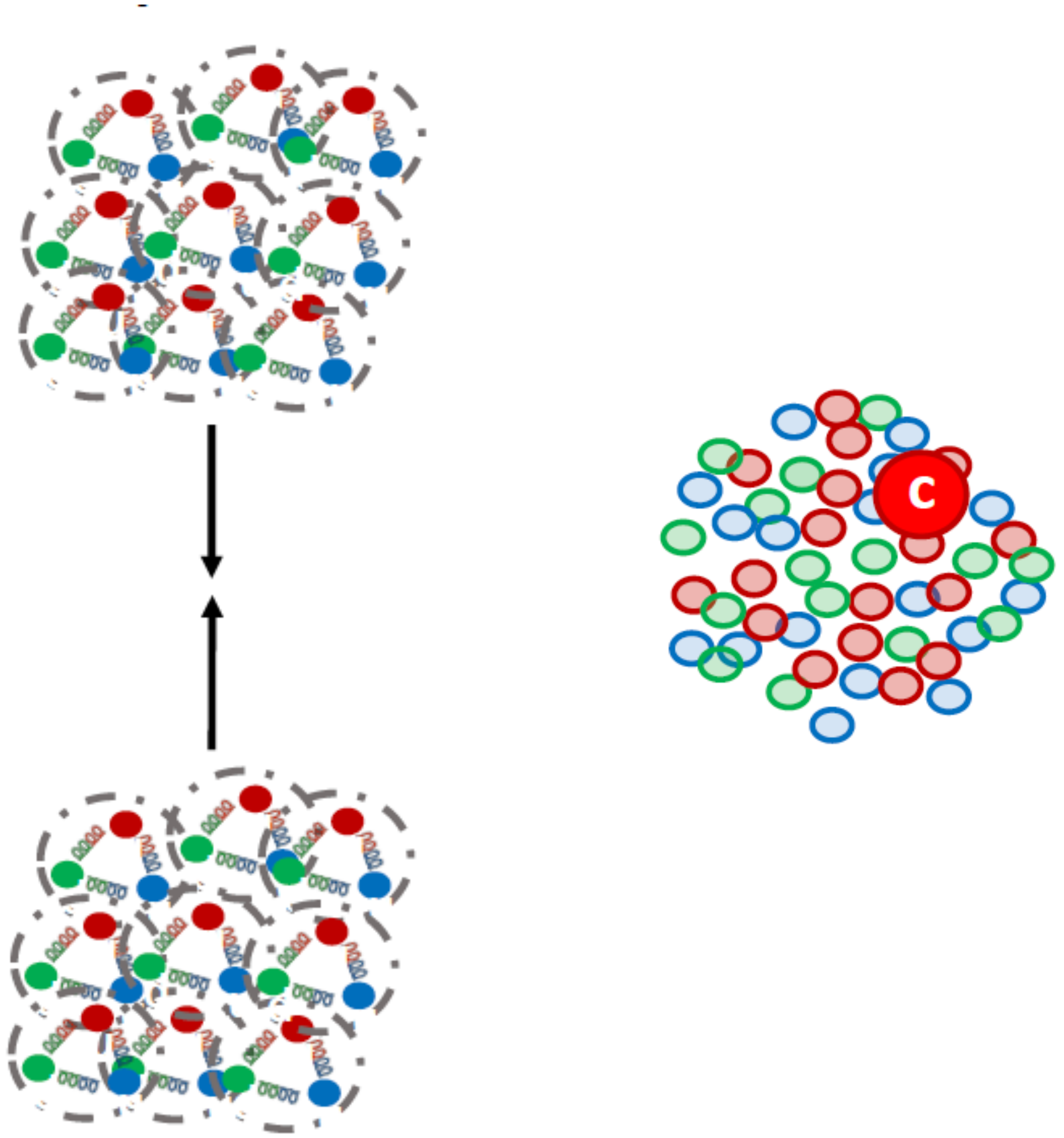
HF-jets and HF-correlations can provide additional information than single hadron studies:
→direct access to the parton kinematics



- Test pQCD
- Insights in to fragmentation and hadronisation
- Reference system

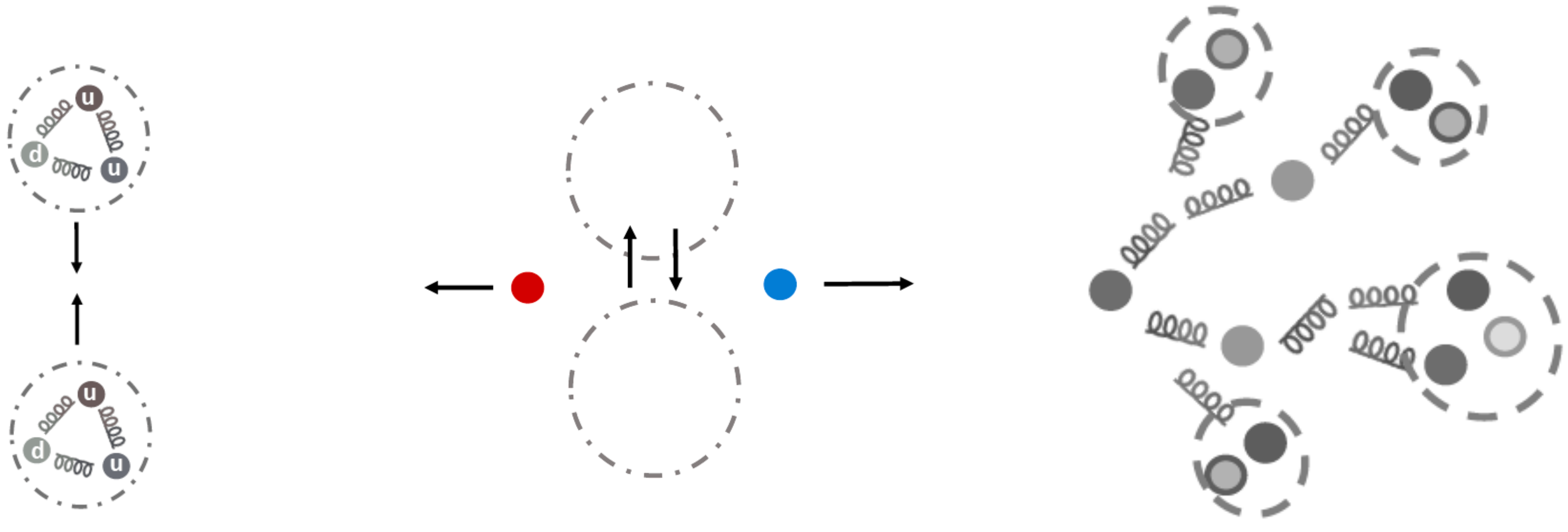


- Cold nuclear matter effects?
- Collectivity?



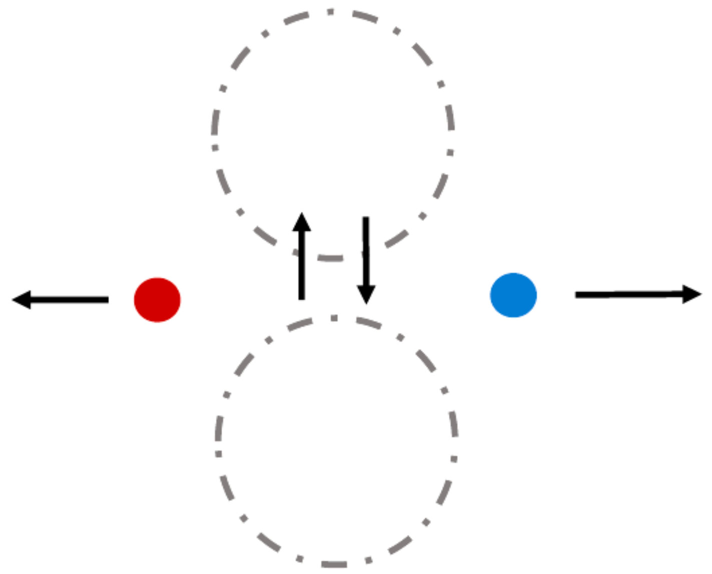
How fragmentation and hadronisation are modified in the medium?

Hard scattering and production mechanisms:



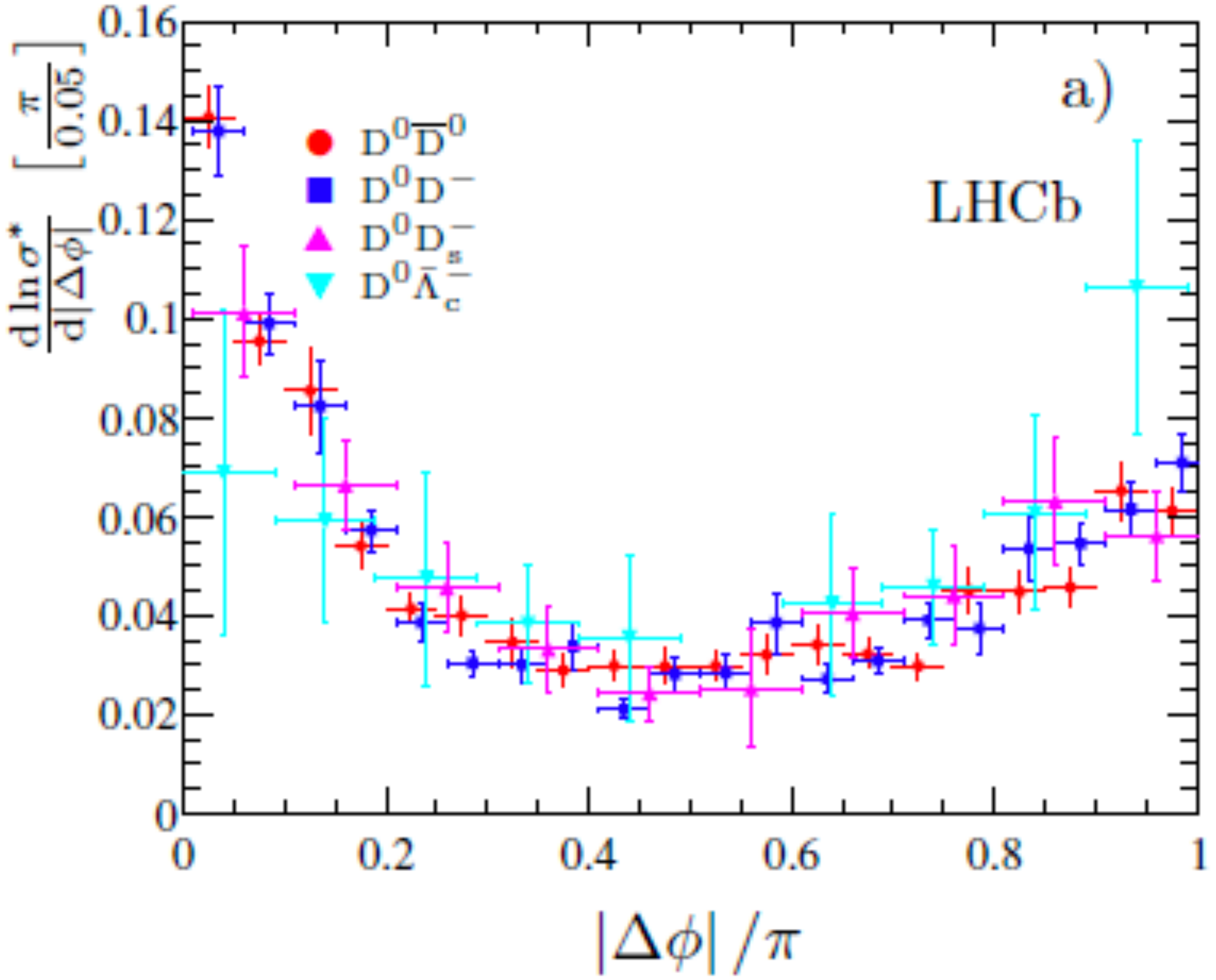
Production mechanism: HF correlations

- HF-HF correlation:
  - direct access to heavy quarks and the initial parton kinematics
  - allows for probing the HQ production mechanisms



- Opposite sign charm (beauty) hadron correlations in pp collisions by LHCb, forward rapidity

LHCb, JHEP 06 (2012) 141



- Charm correlations:
  - comparison with same charge correlations highlights the partonic hard-scattering features (new results also in p-Pb)
  - excess at $\Delta\varphi \sim 0$ point towards important **gluon splitting** contribution (collimated at high p_T)

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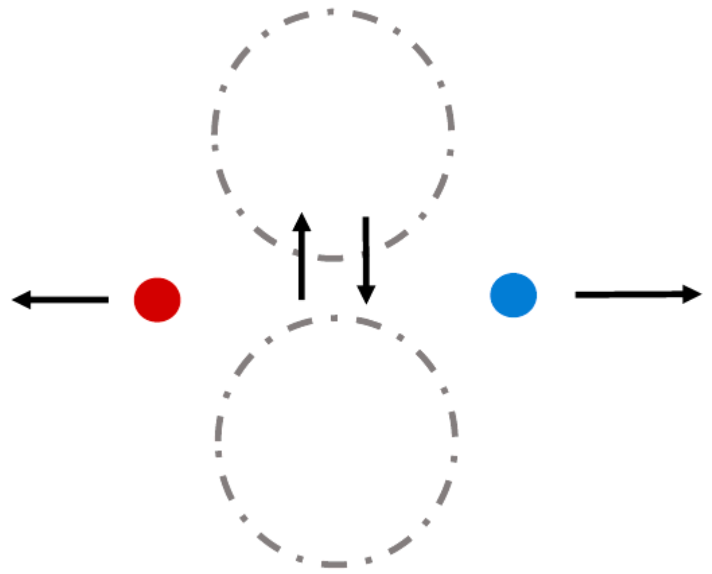

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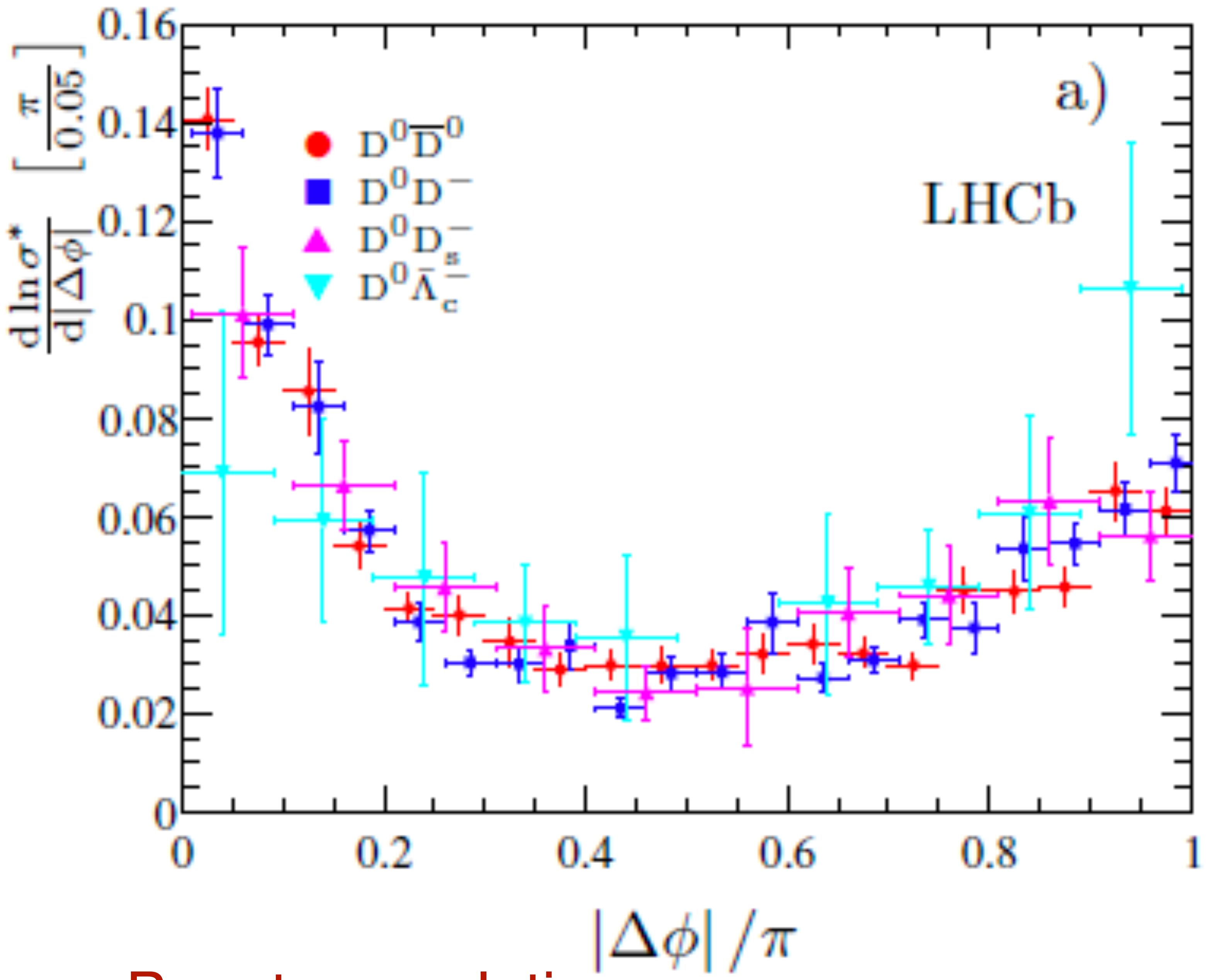
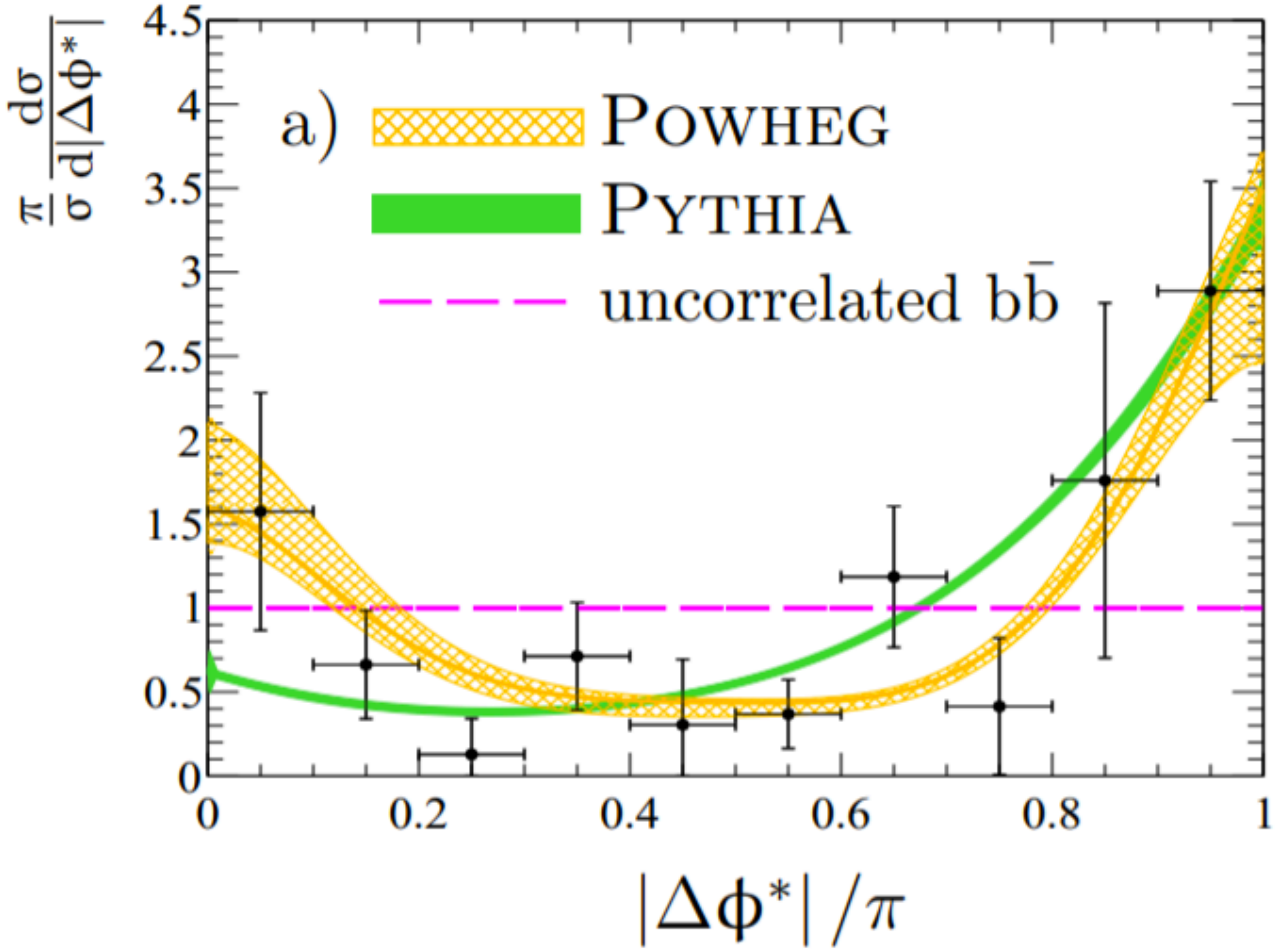


LHCb, JHEP 1711 (2017) 030



- Beauty correlations:
  - predominant **away side** peak at large p_T
  - larger back-to-back production
  - NLO contribution less relevant than for charm

- POWHEG (NLO): higher peak for higher p_T, catch better the data

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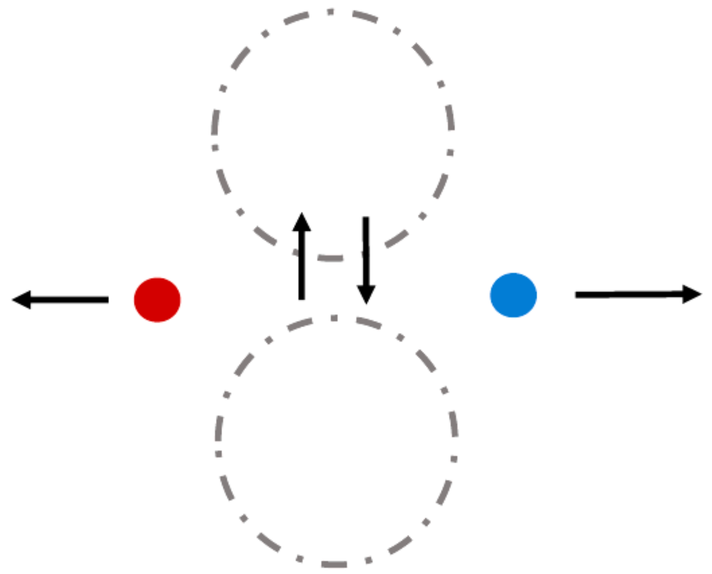

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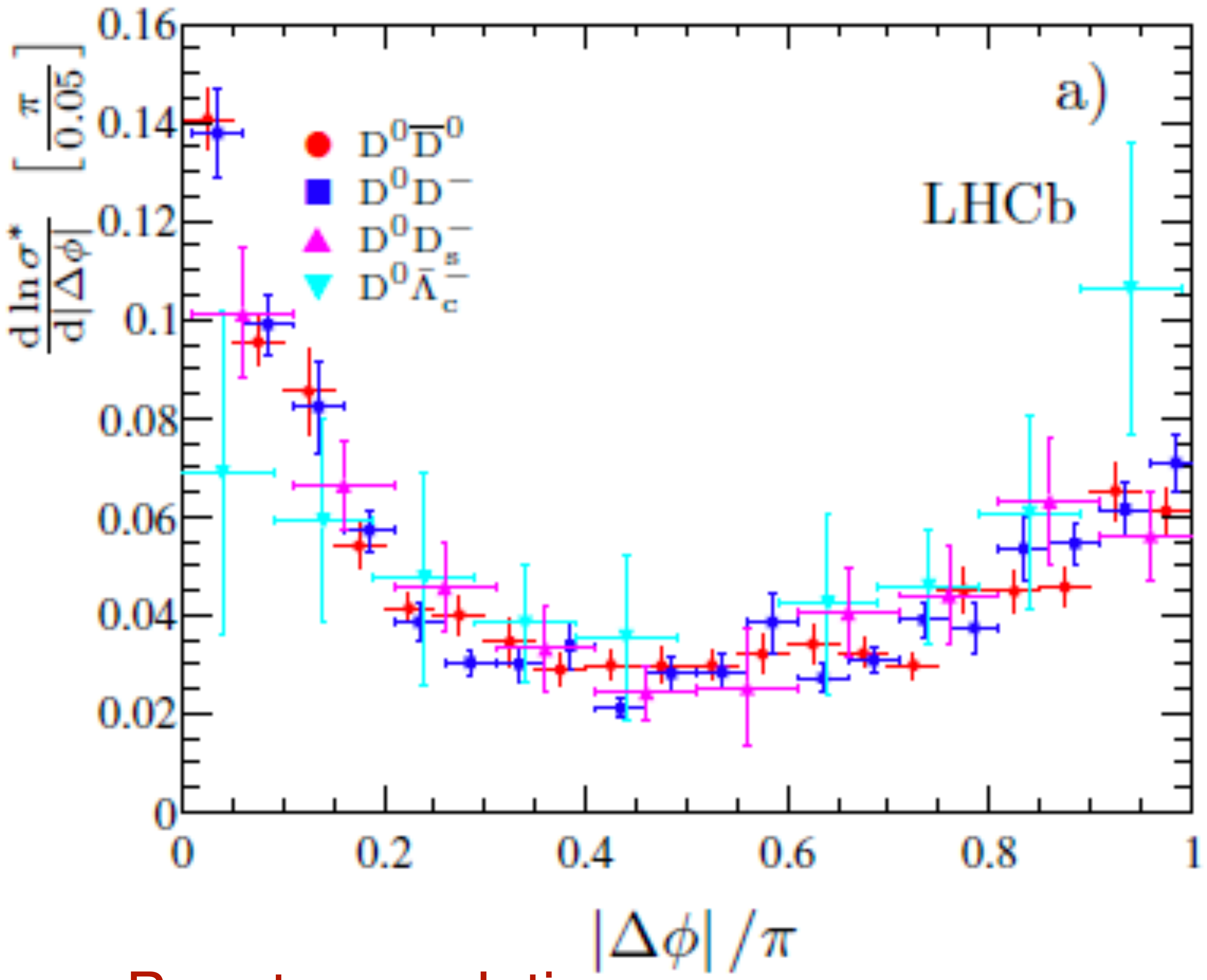

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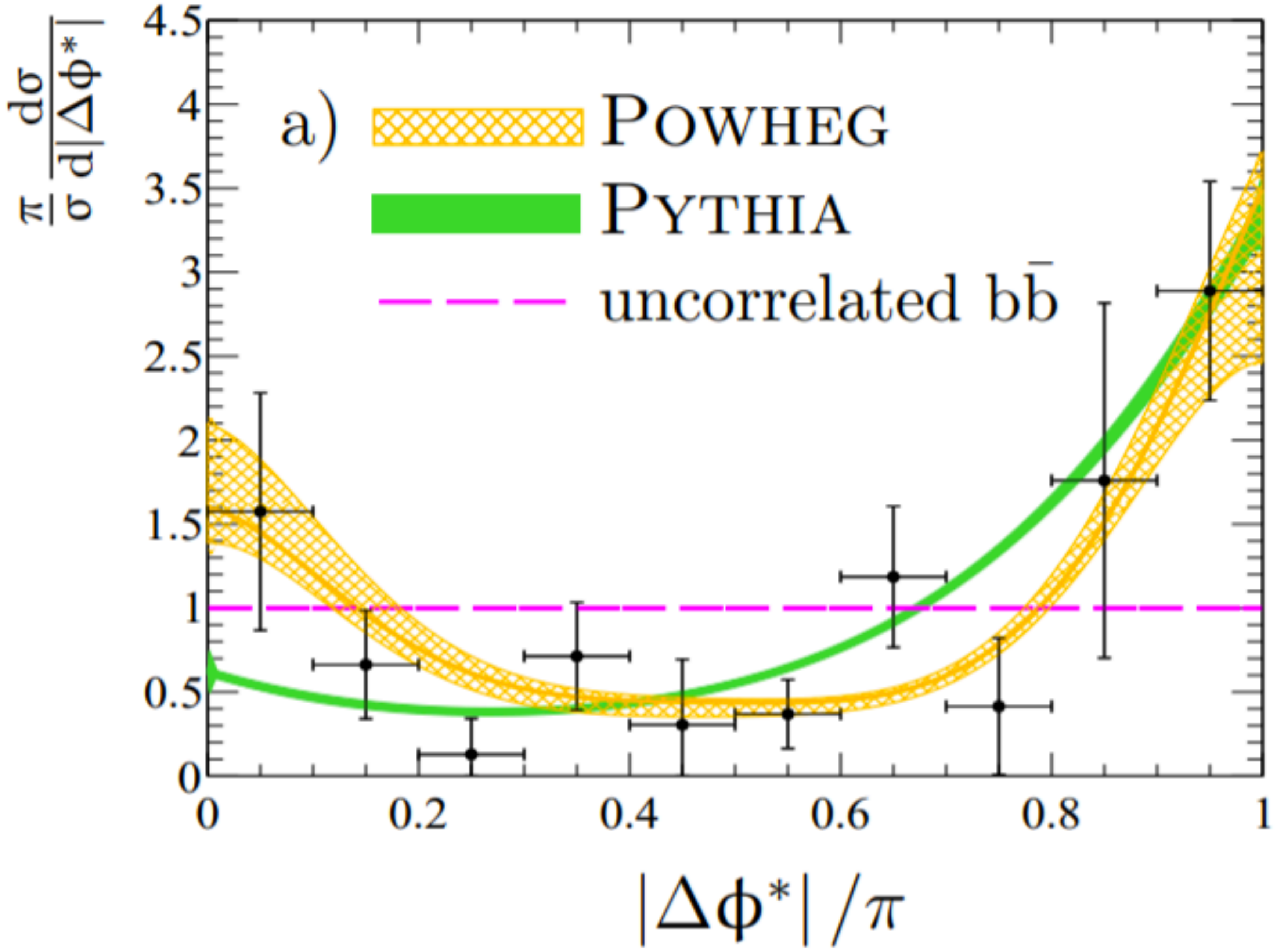
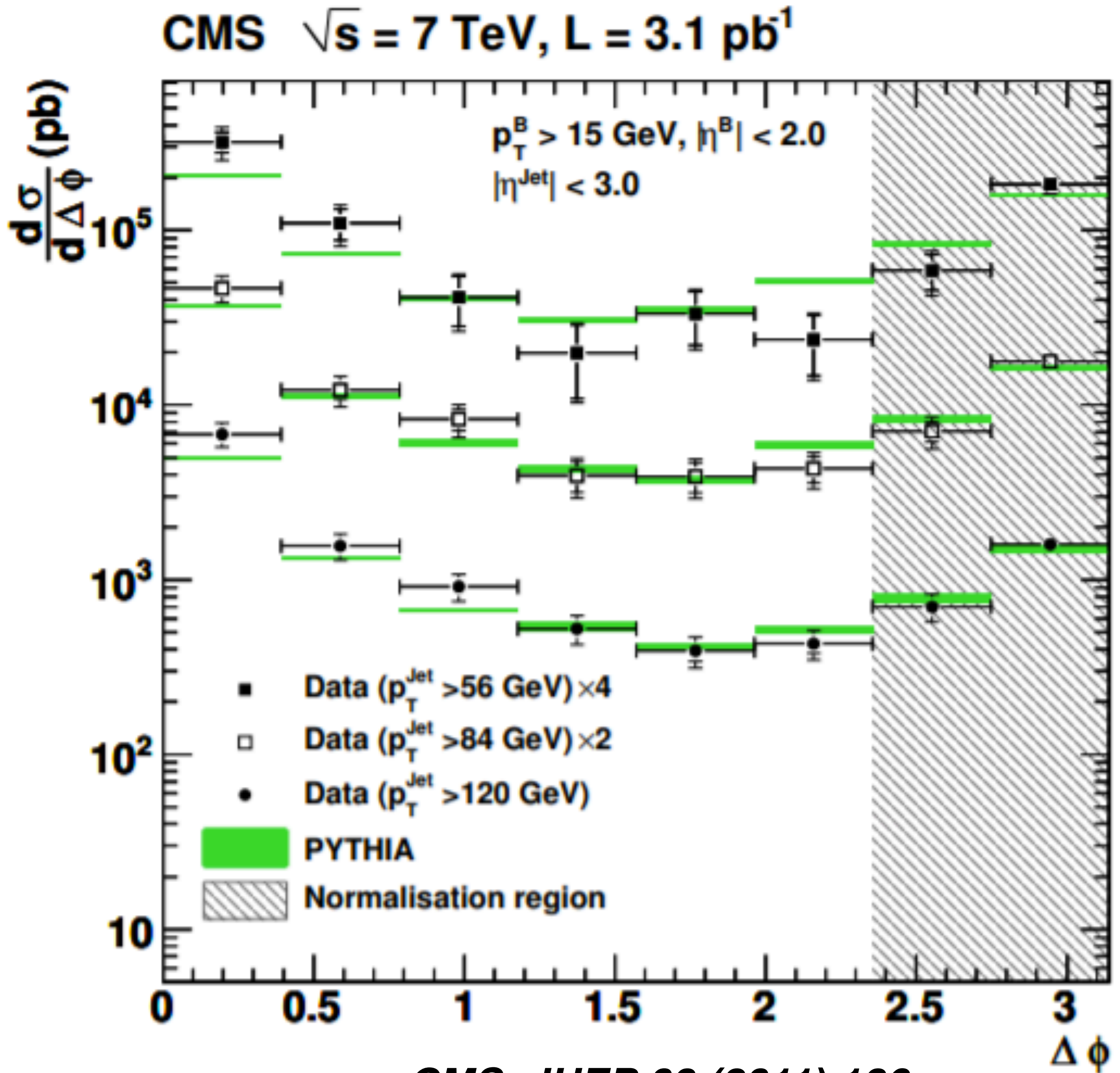


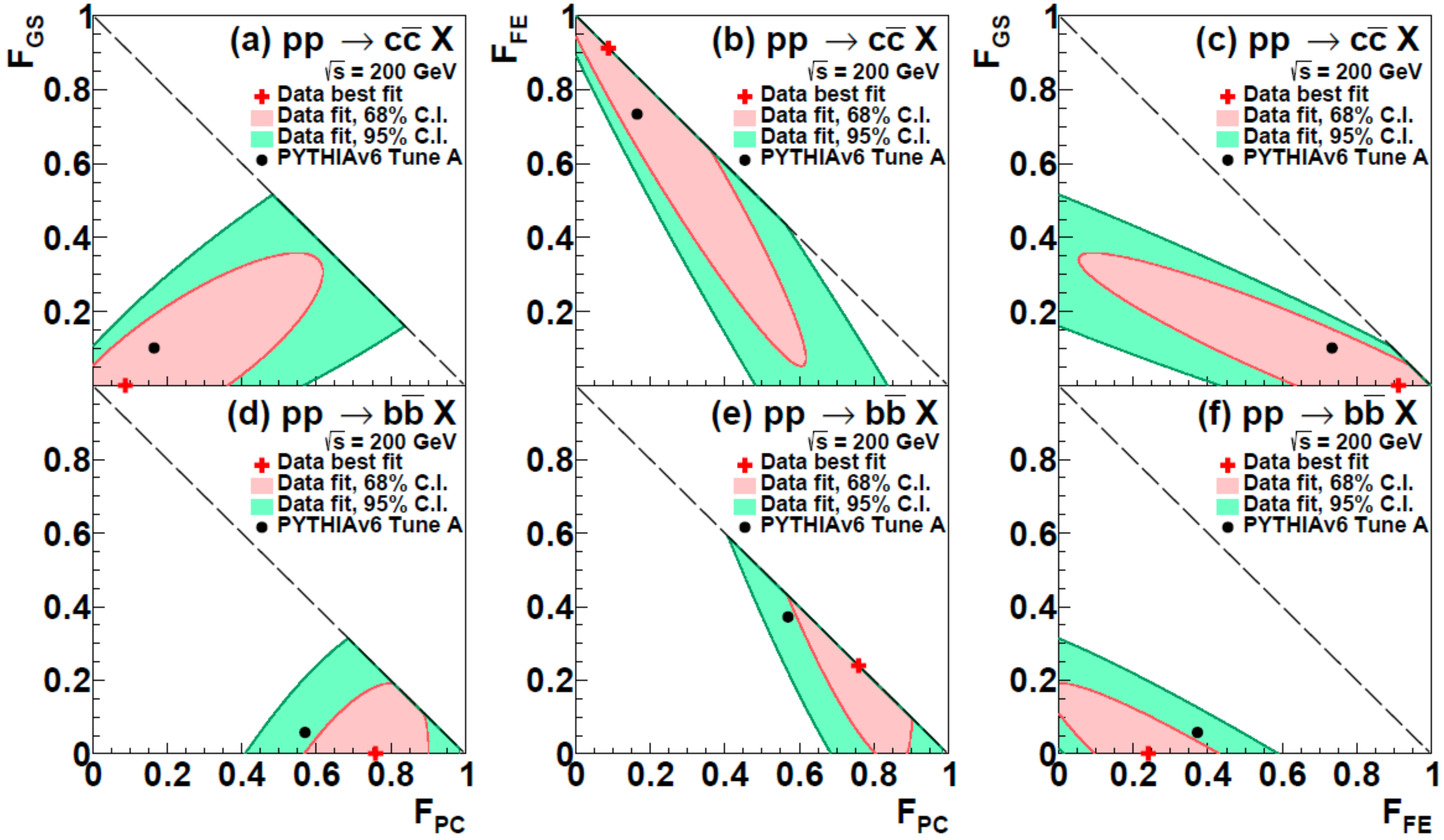


CMS, JHEP 03 (2011) 136

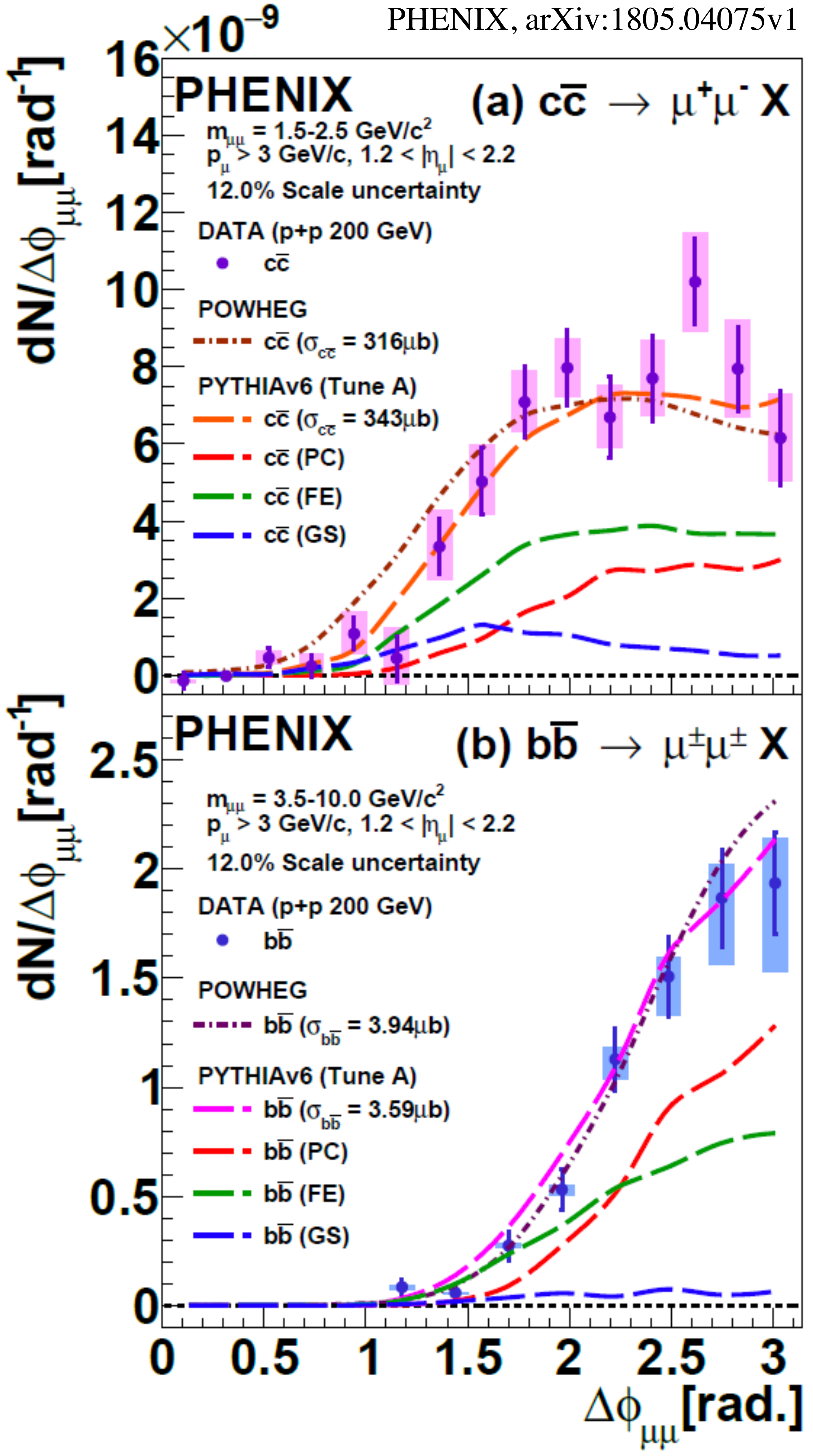
- Beauty correlations:
  - predominant **away side** peak at large p_T
  - larger back-to-back production
  - NLO contribution less relevant than for charm
- POWHEG (NLO): higher peak for higher p_T, catch better the data
- CMS (midrapidity) measurement: relevant fraction of BB pairs produced at small angular distance

Production mechanism: HF correlations

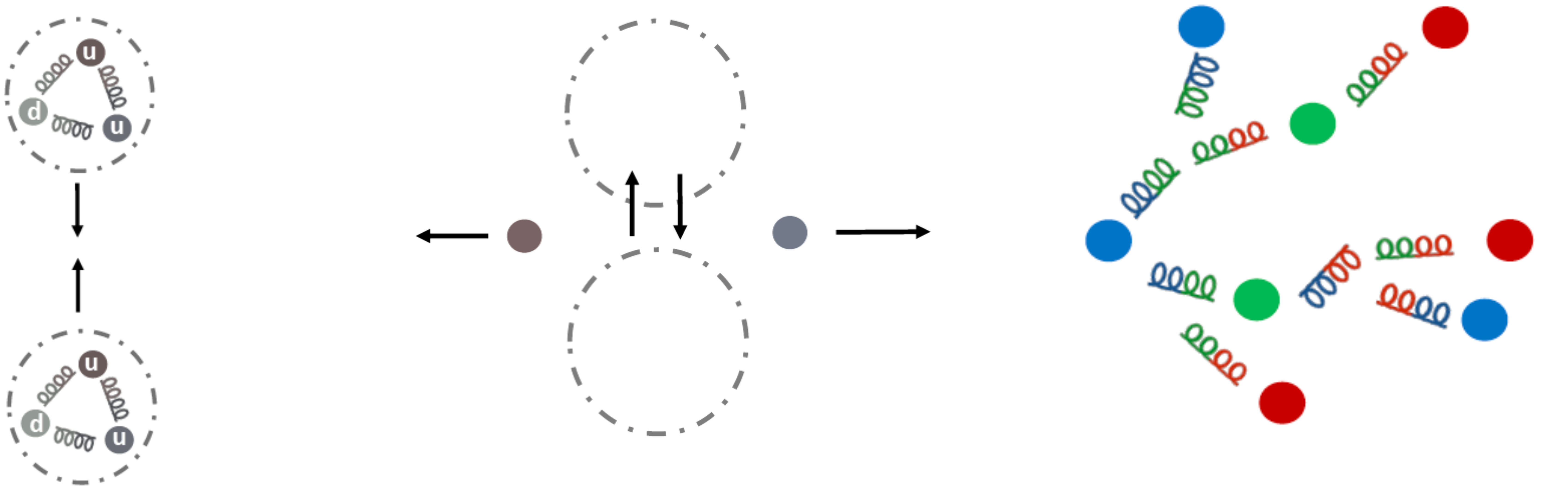
- HF lepton pair azimuthal correlation, PHENIX, lower energy (200 GeV)
- Large back to back contribution observed, in particular $b\bar{b}$
- Simultaneous shape allow to constrain GS/FE/PP fractions : NLO relevant for charm correlations
- Smaller NLO contributions for $b\bar{b}$



PHENIX, arXiv:1805.04075v1

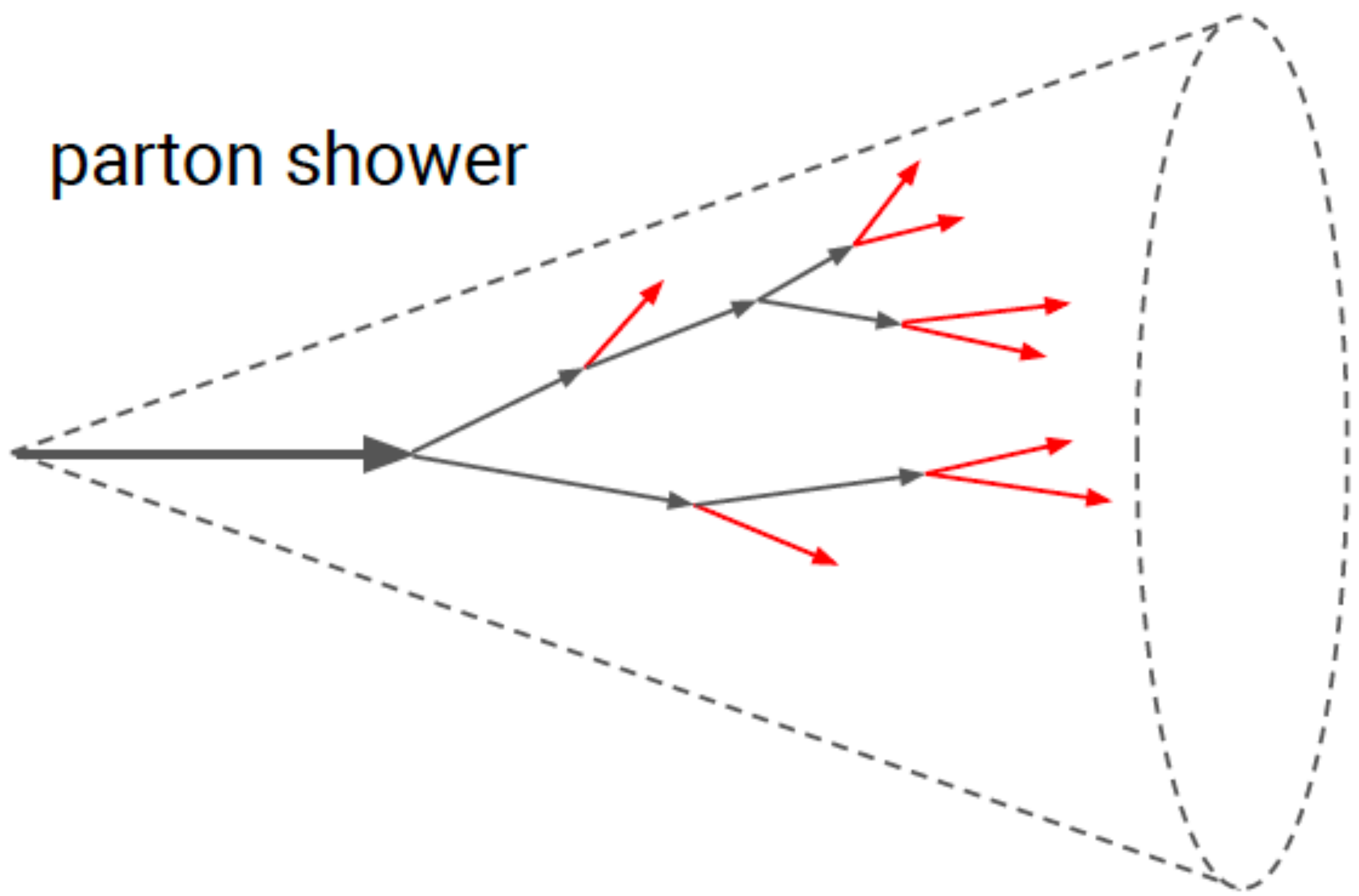


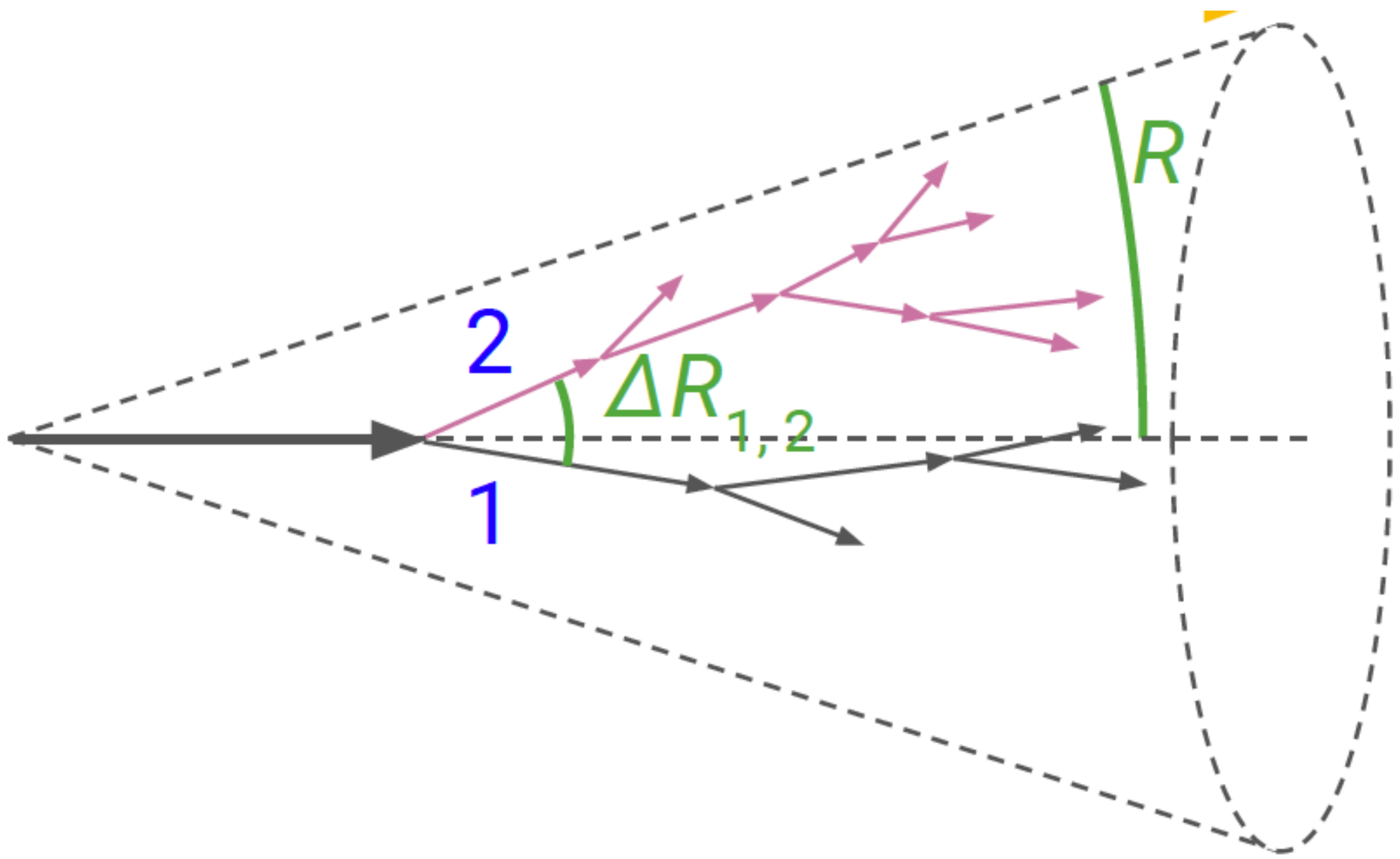
Looking in to the parton shower



Using jets to reconstruct the parton shower

Radiating heavy flavour survives the shower process



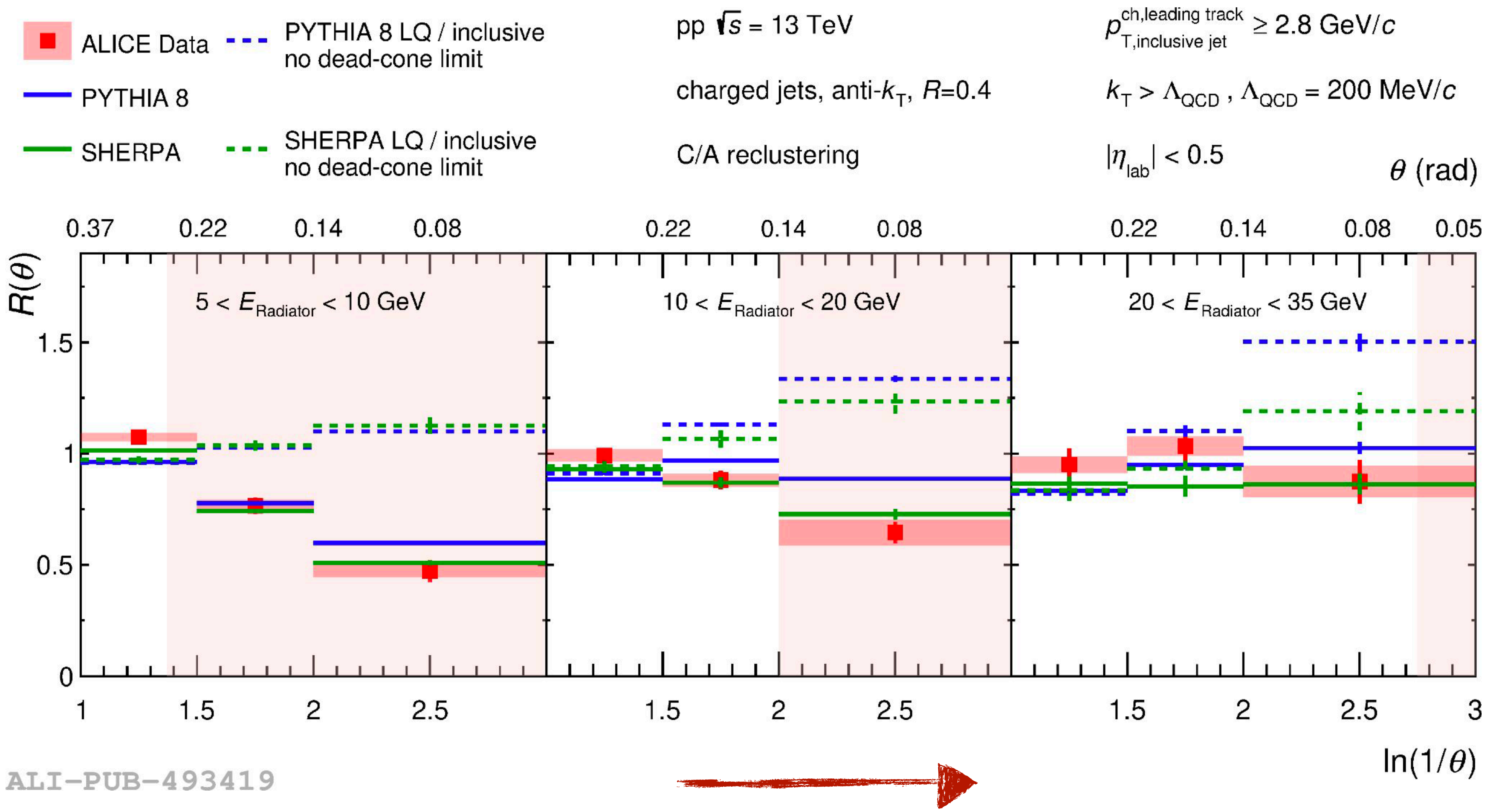


Jet algorithms can be used to cluster the final state hadrons originating from a scattered parton

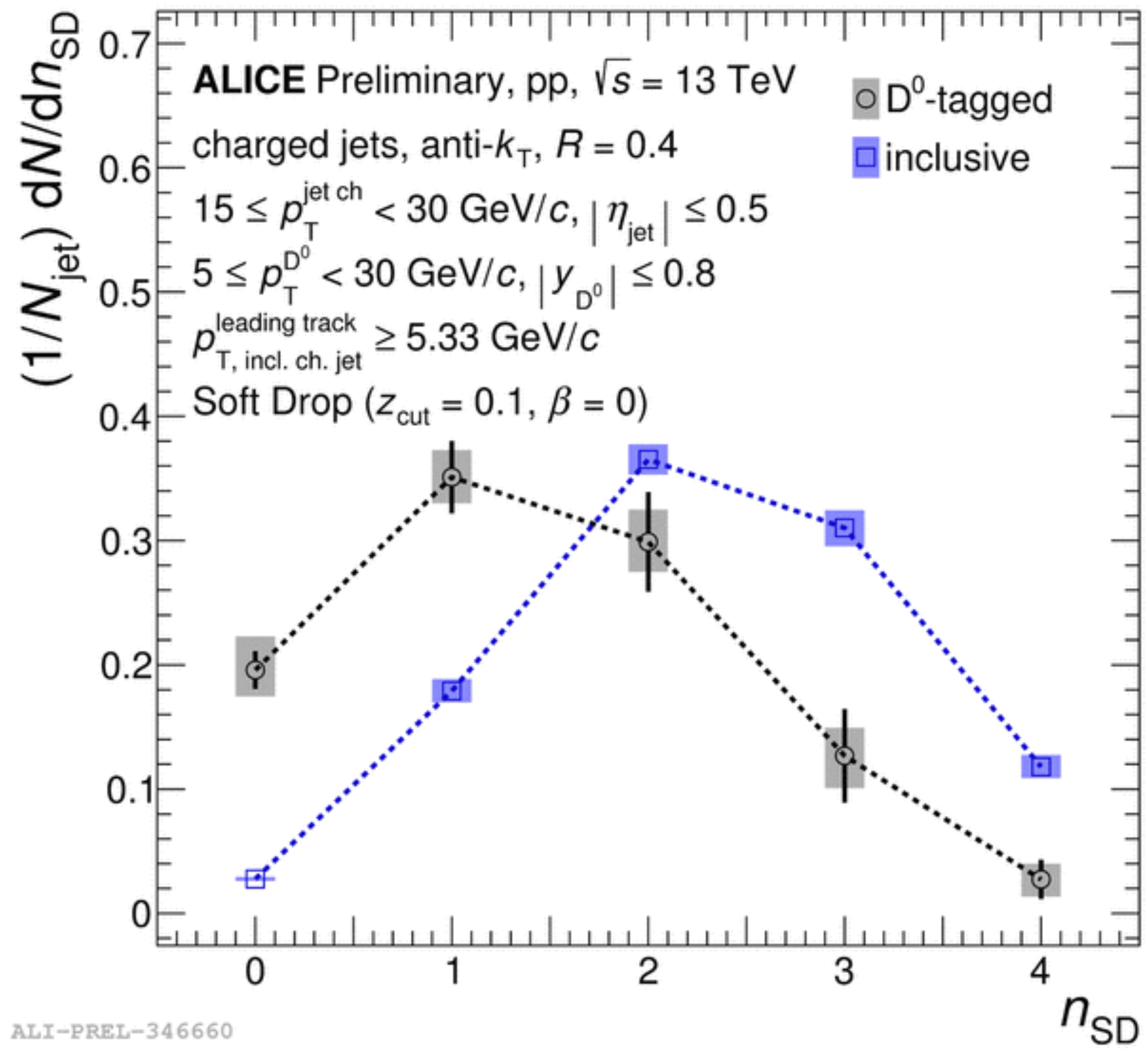
Fundamental QCD predictions for flavour dependence of strong interactions:

- **Casimir colour factors**: different fragmentation of quarks vs gluons
- **Dead-cone effect**: suppression of emission phase space $\boldsymbol{\theta} < \boldsymbol{\theta}_{DC} = m_q/E_q$, sizeable mass effect (heavy quarks vs light quarks)

Using jets to reconstruct the parton shower



Small angles

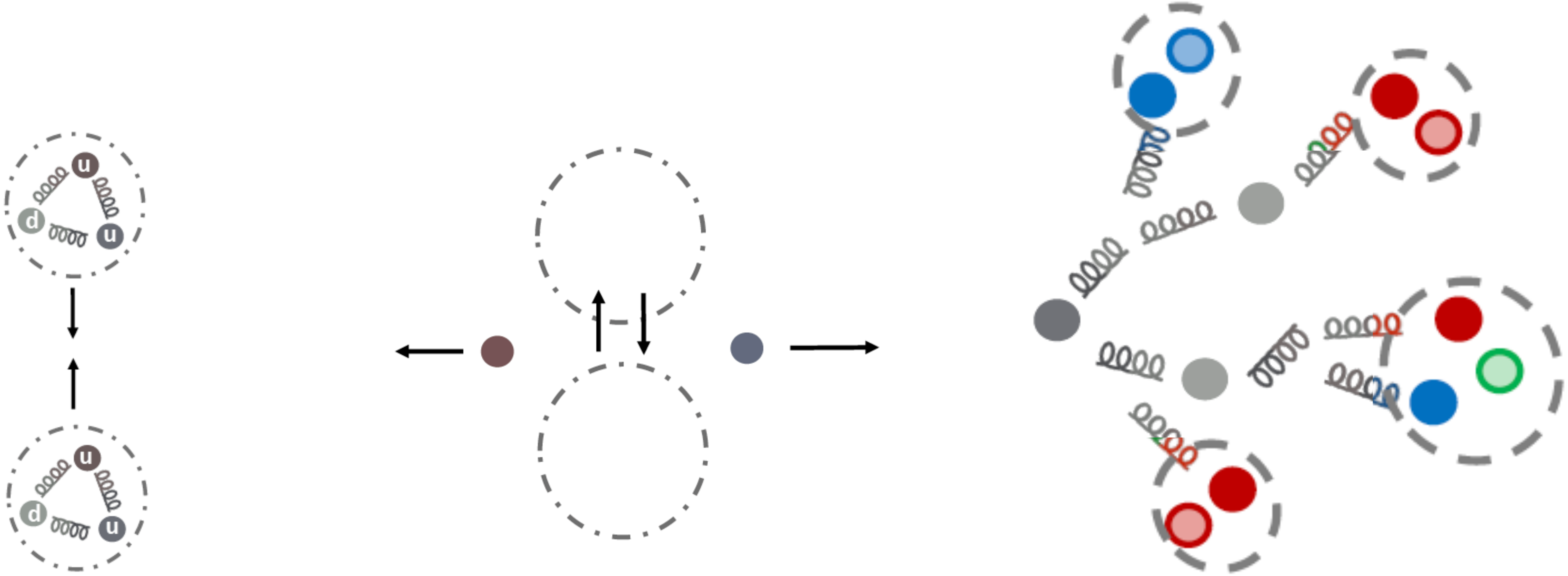


Ratio of Lund map projections for heavy-flavour jets and inclusive jets reveals the dead-cone effect.

- Significant suppression of small-θ splittings
- Dead cone closing with increasing $E_{Radiator}$

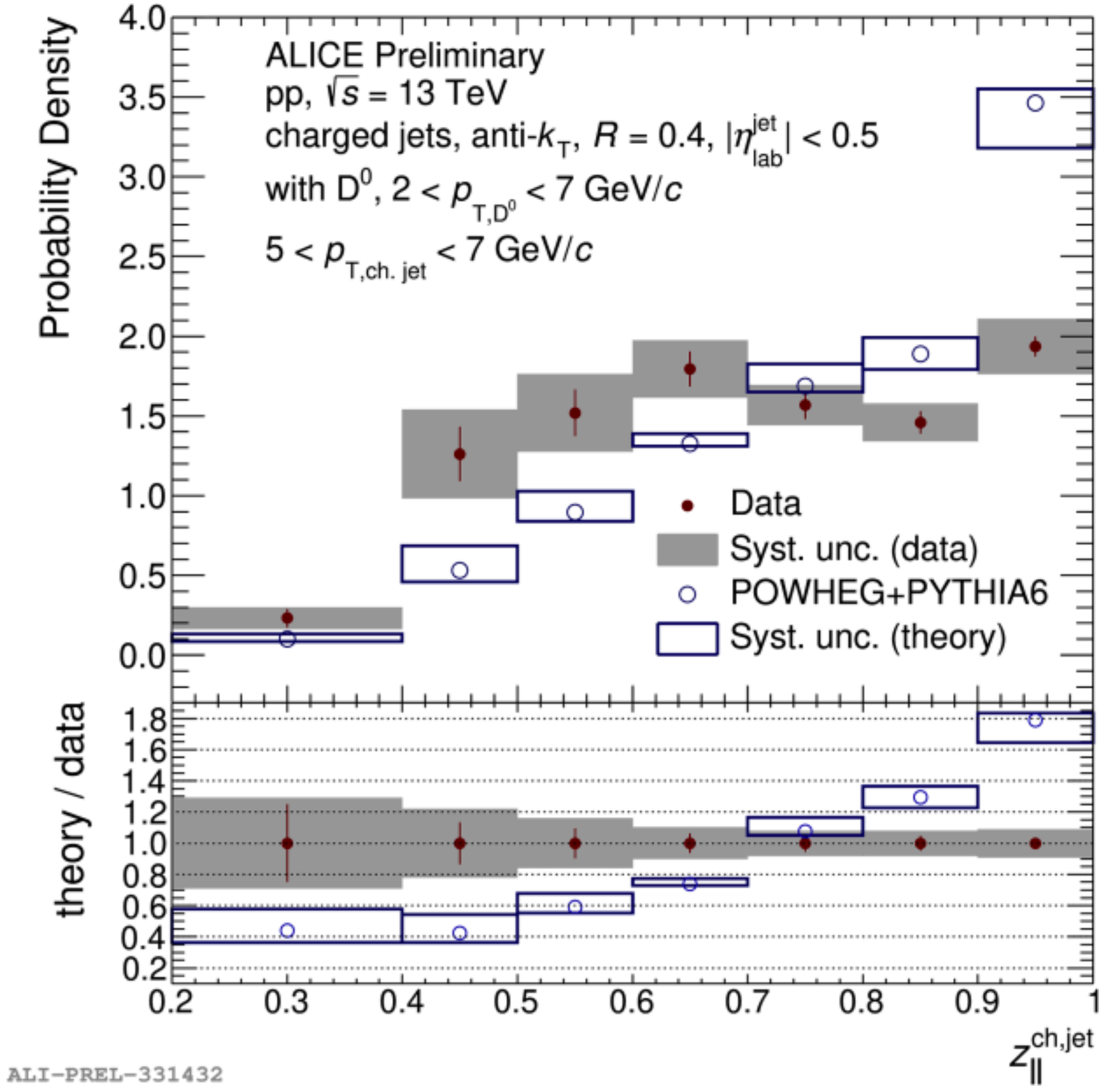
- **charm** jets have fewer "hard" splittings than **inclusive jets**
  - Low p_T region: strongest mass effect
- **described by PYTHIA**

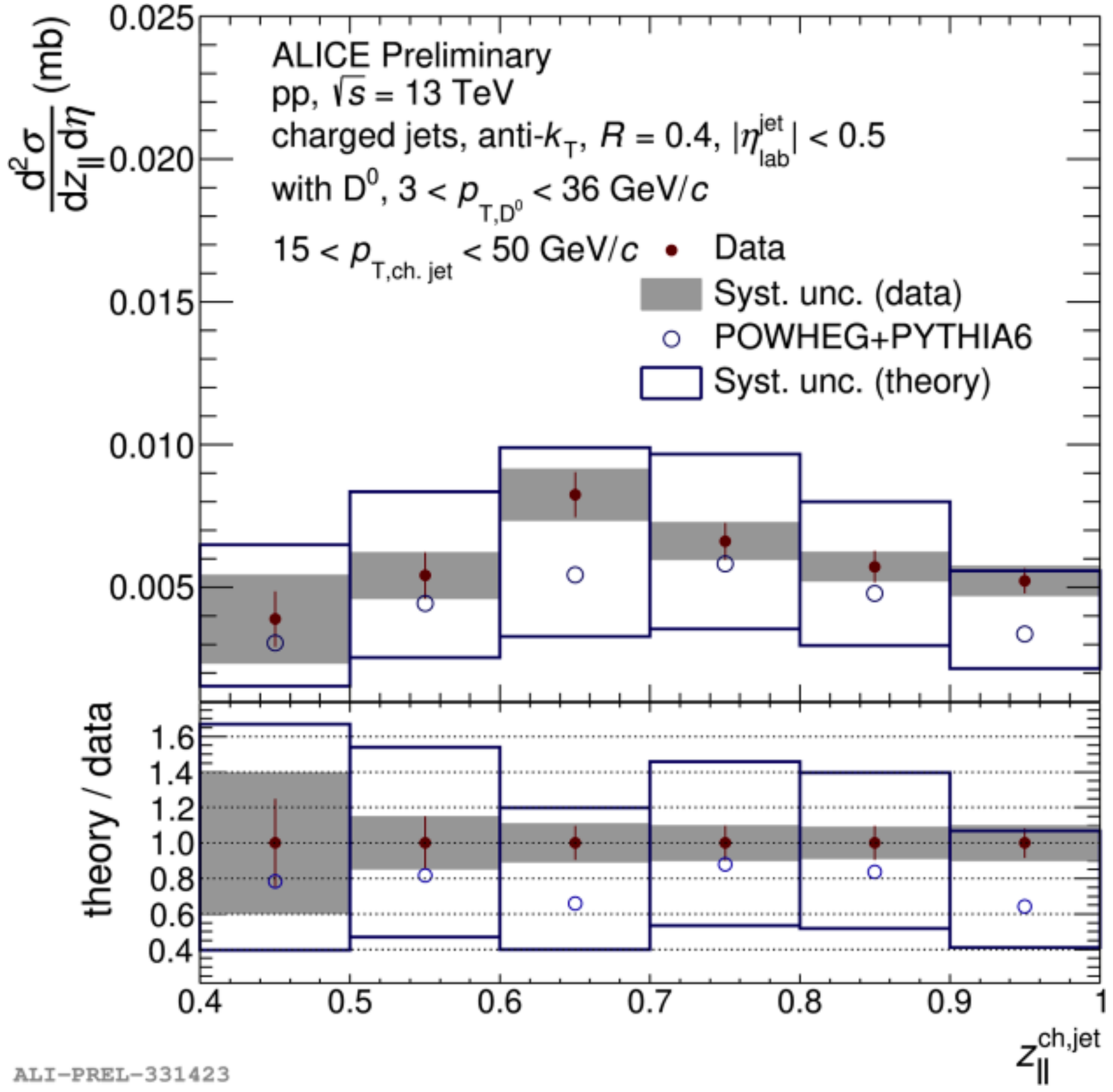
Hadronization

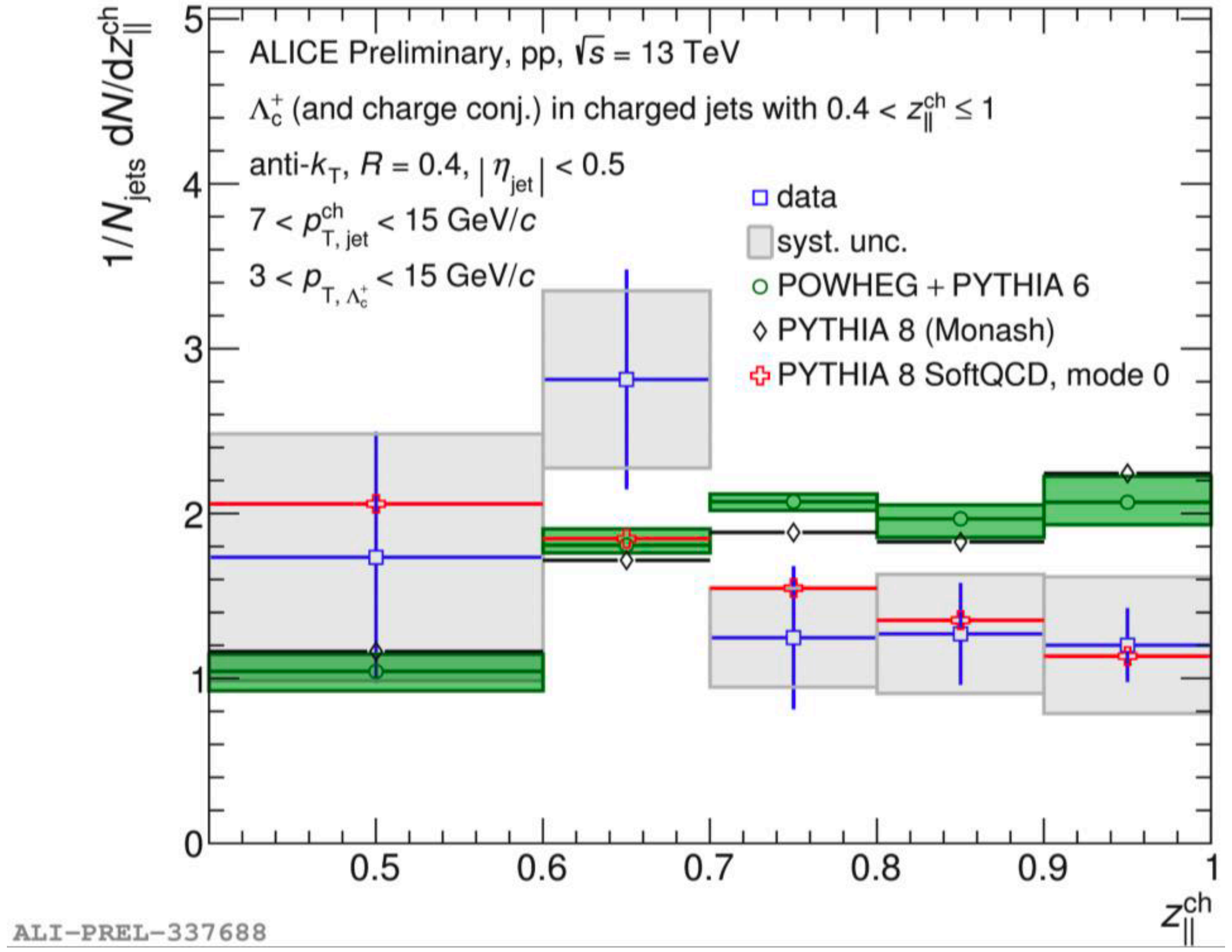


HF jets to look into hadronisation

HF-tagged jet provide a reference for the energy and direction of the initial charm quark





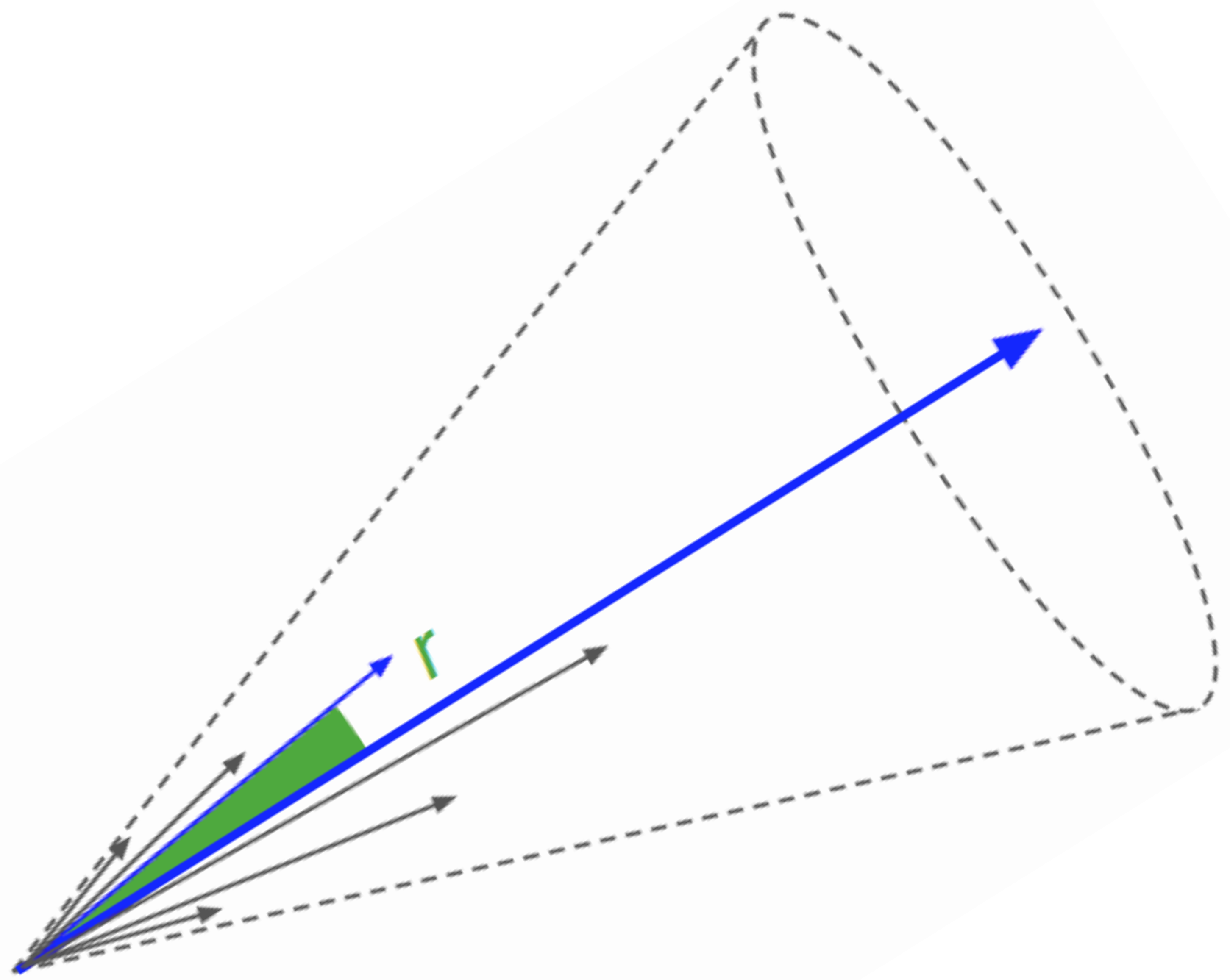


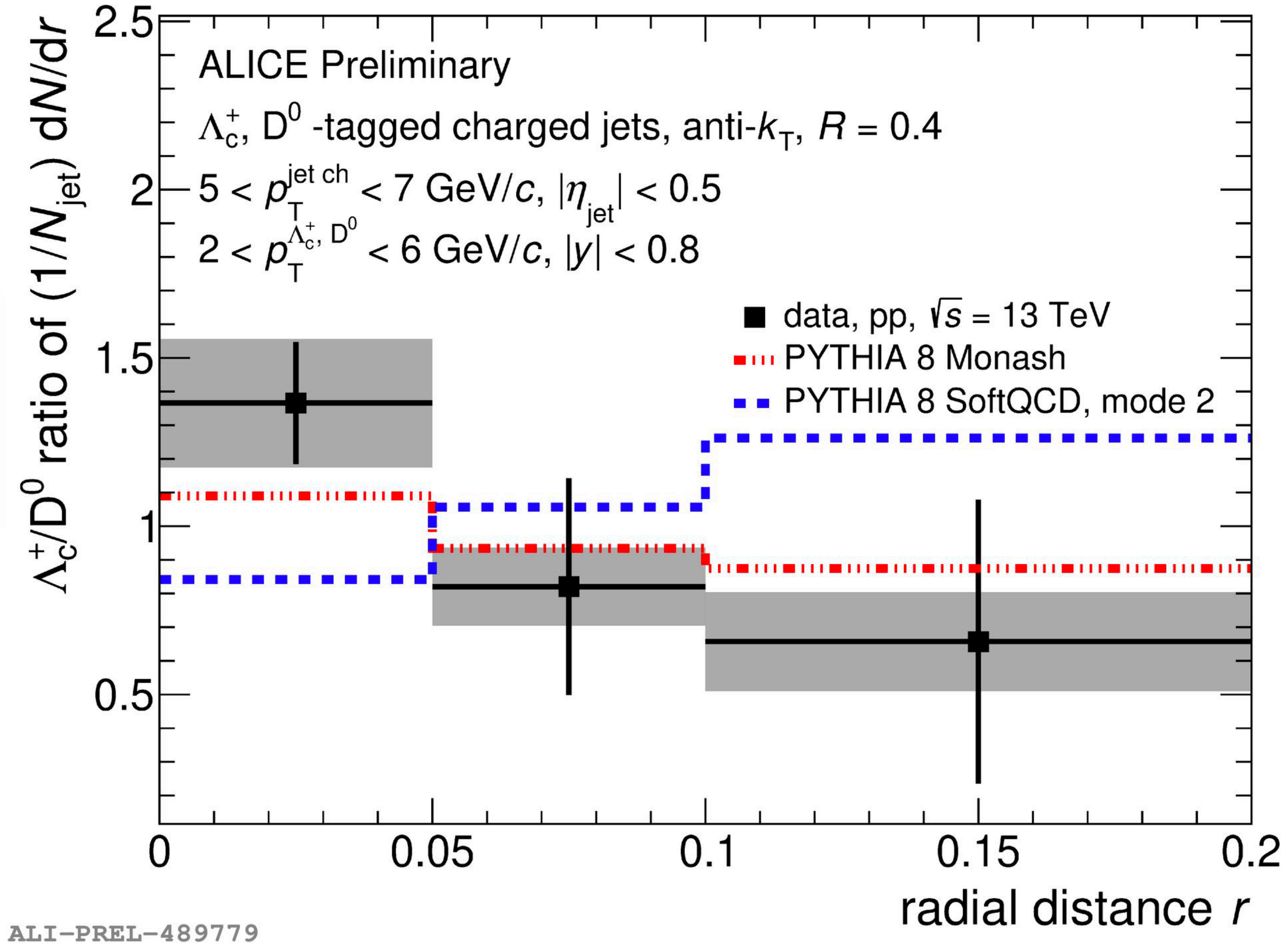
Parallel momentum fraction: $z^{ch}_{//} = \dfrac{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm HF}}{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm ch\ jet}}$

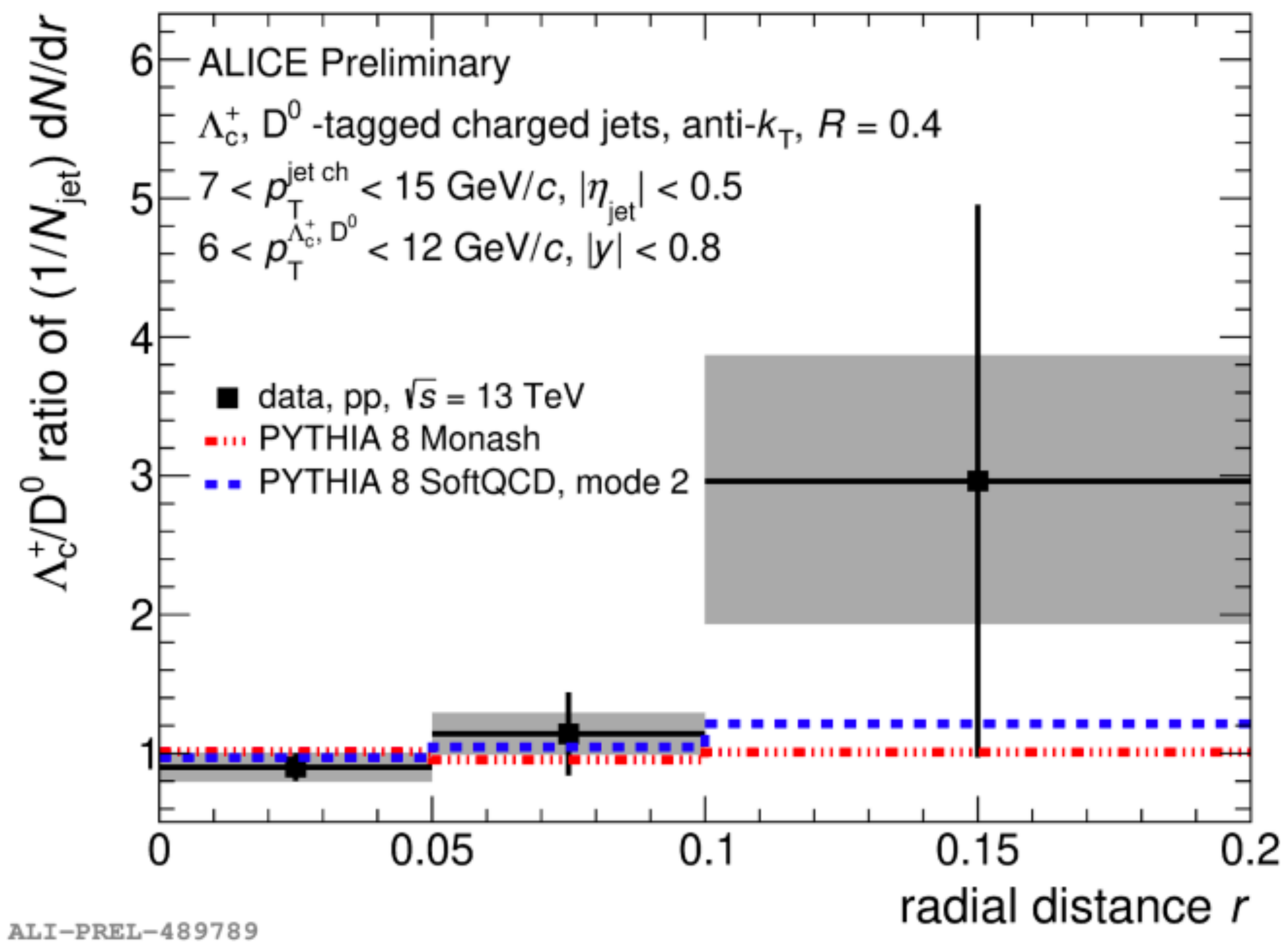
Comparison with models: data point toward a softer fragmentation at small $z_{//}$ and small p_T^{HF} and in the low $p_{T,\text{ch-jet}}$ range

More compatible at larger p_T (D^0) at larger $p_{T,\text{ch jet}}$

HF jets to look into hadronisation







Addressing possible modifications of the charm hadronisation through the radial angular distance of a hadron from the jet axis

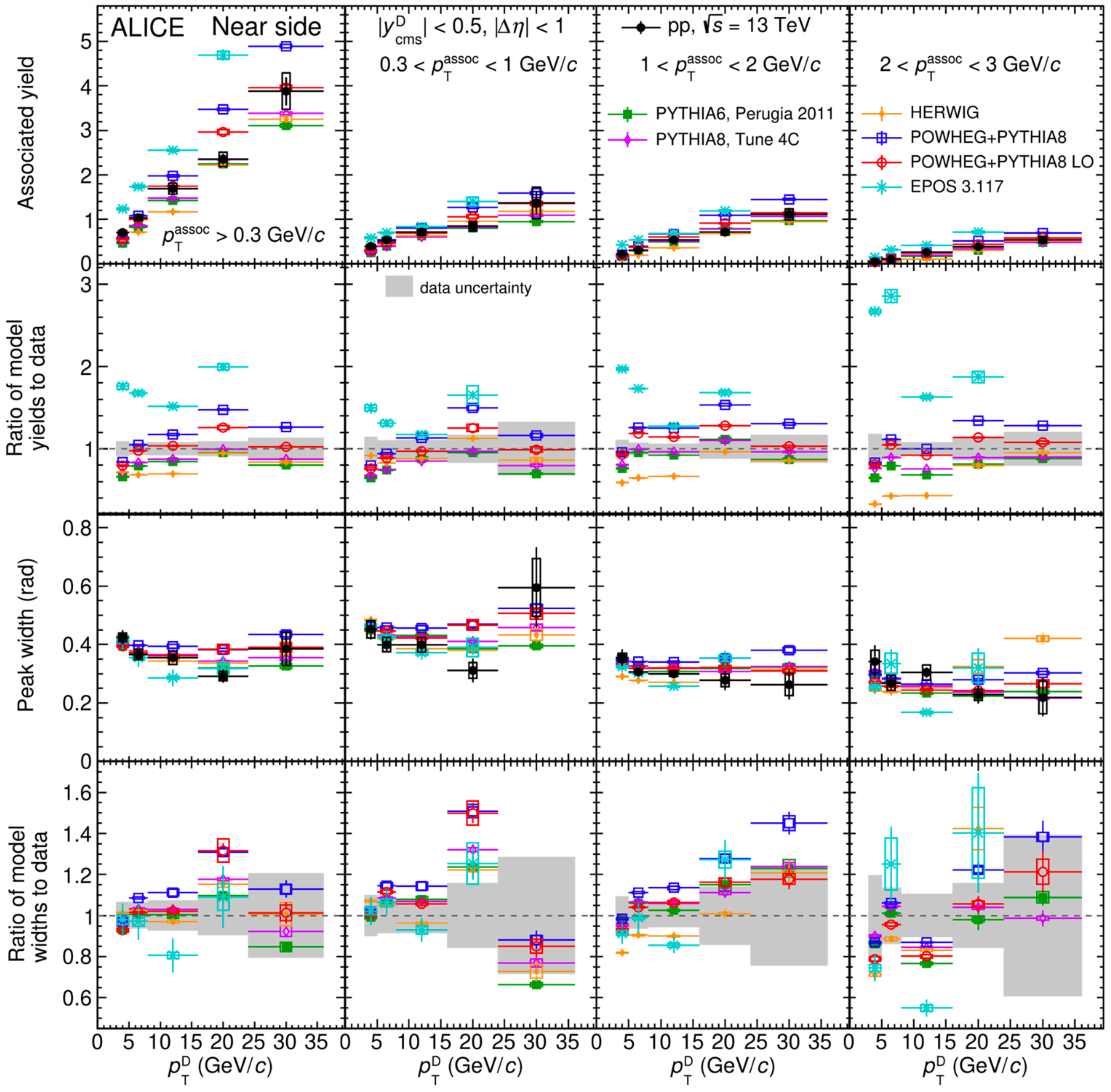
Radial distance $r = \sqrt{(\phi_{\text{jet}} - \phi_{\text{tag}})^2 + (\eta_{\text{jet}} - \eta_{\text{tag}})^2}$

Angular dependence of baryon–meson ratio of heavy-flavour hadrons

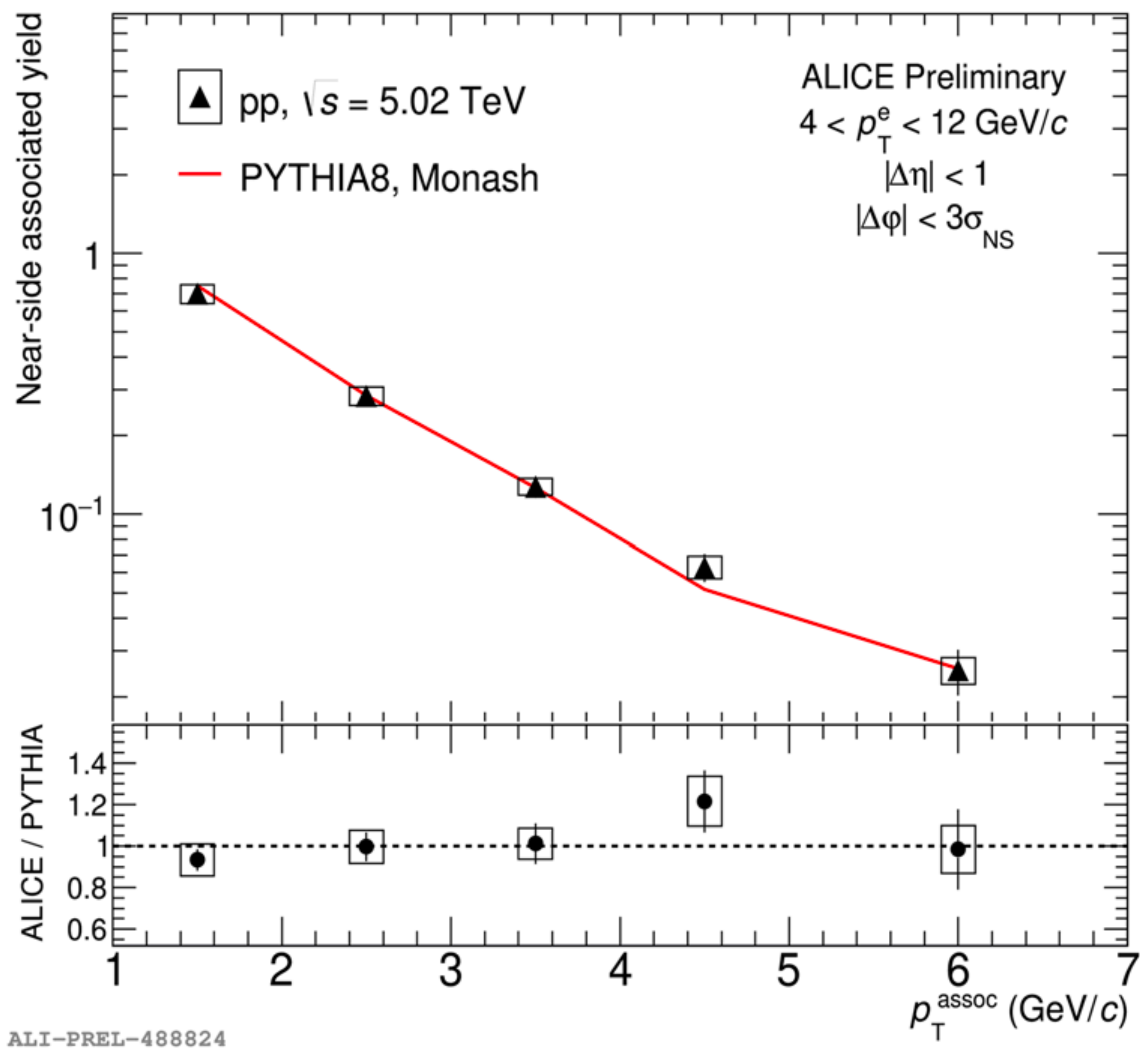
Is there a dependence of the Λ_c/D^0 as function of the radial distance?

- **Are baryons produced less collimated than mesons w.r.t. the direction of the jet?**
- **More precise results with Run3**

HF correlations into HQ fragmentation



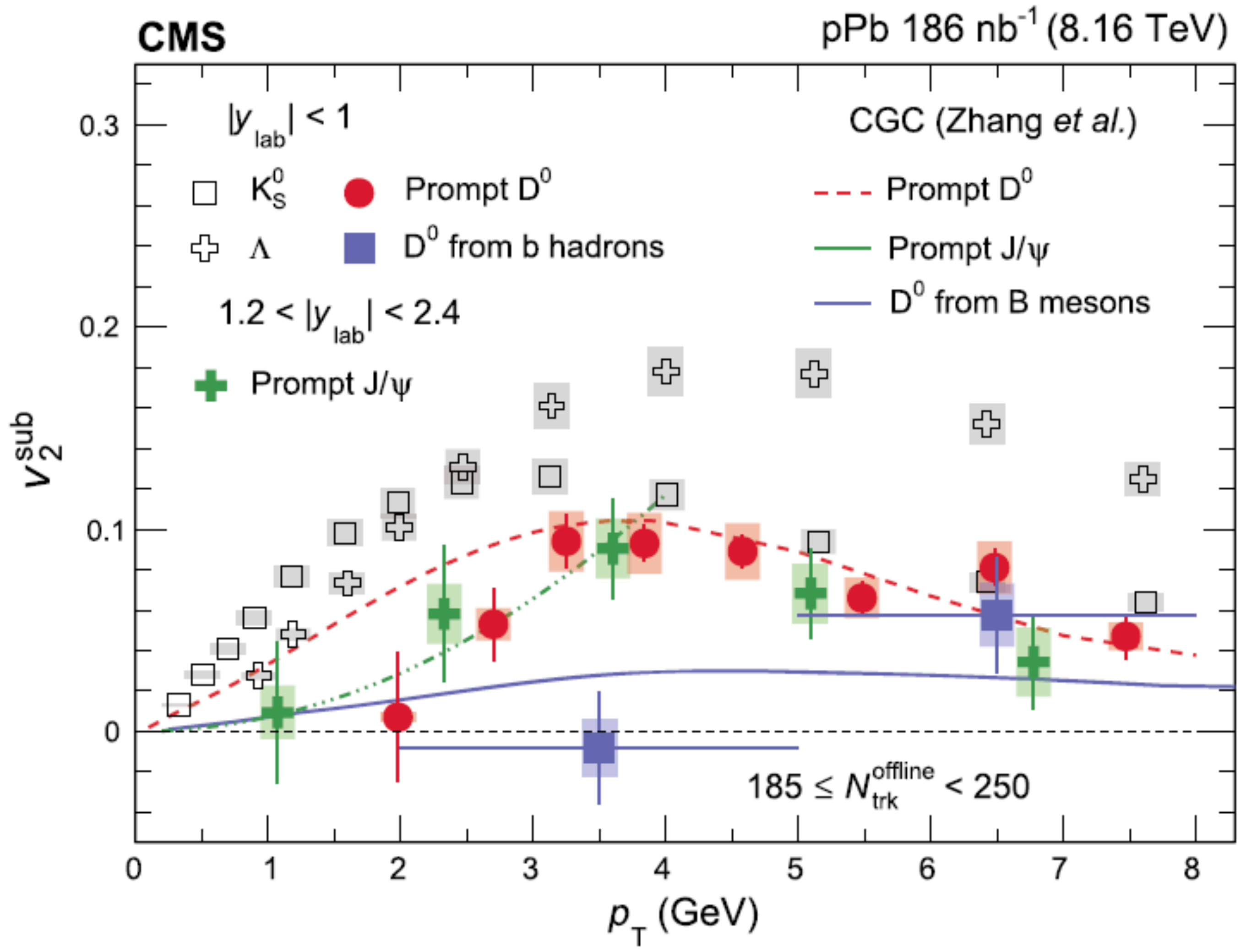
- Comparison of NS yields and widths with several model predictions
  - Different shower ordering, hadronisation approach, MPI treatment, UE description
  - All the models describe the peak yield and width within uncertainties, with PYTHIA and POWHEG+PYTHIA providing the best description
- Additional insight on HQ fragmentation from HF semi-leptonic decay-electron correlation measurements -> gives access also to beauty

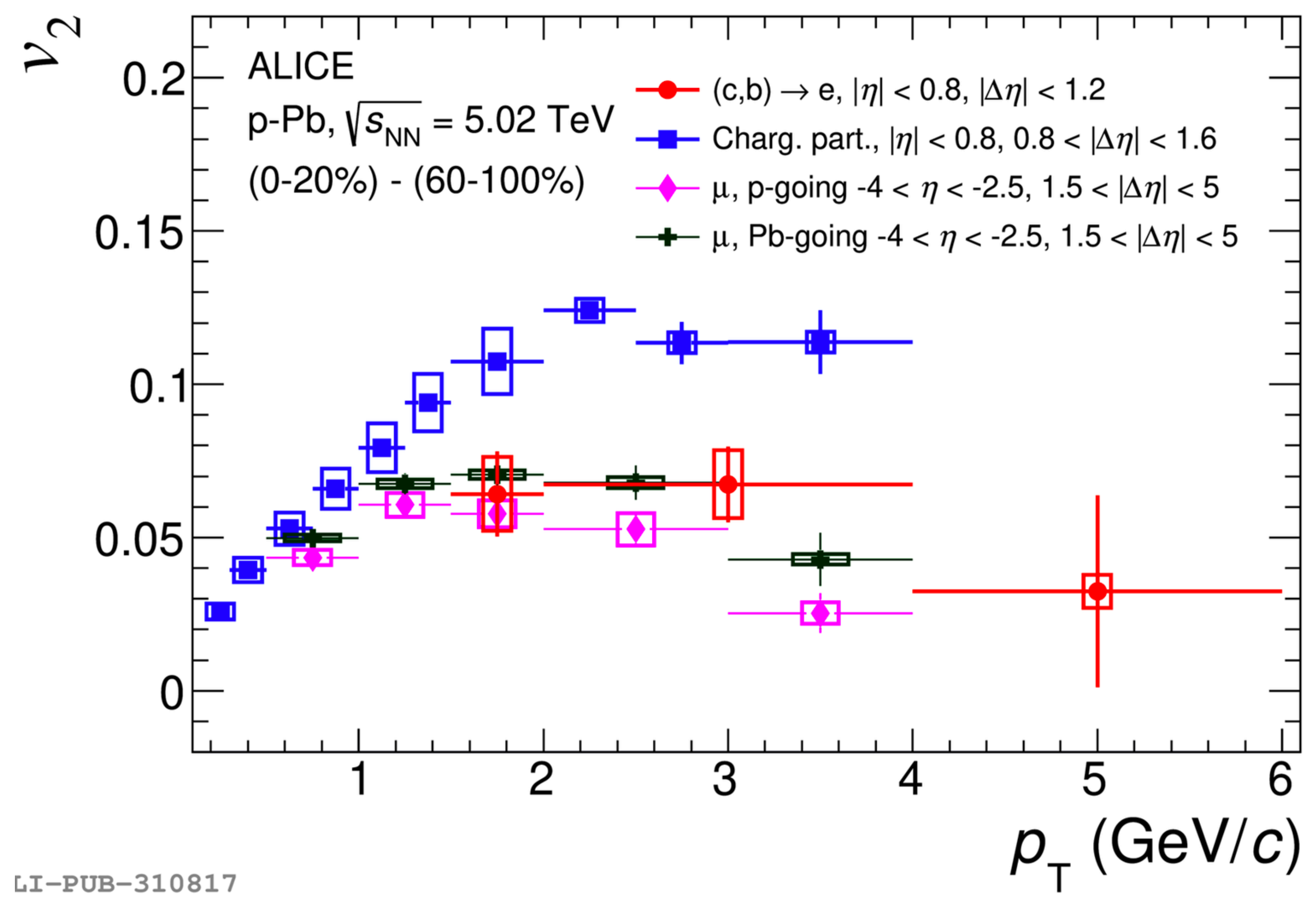


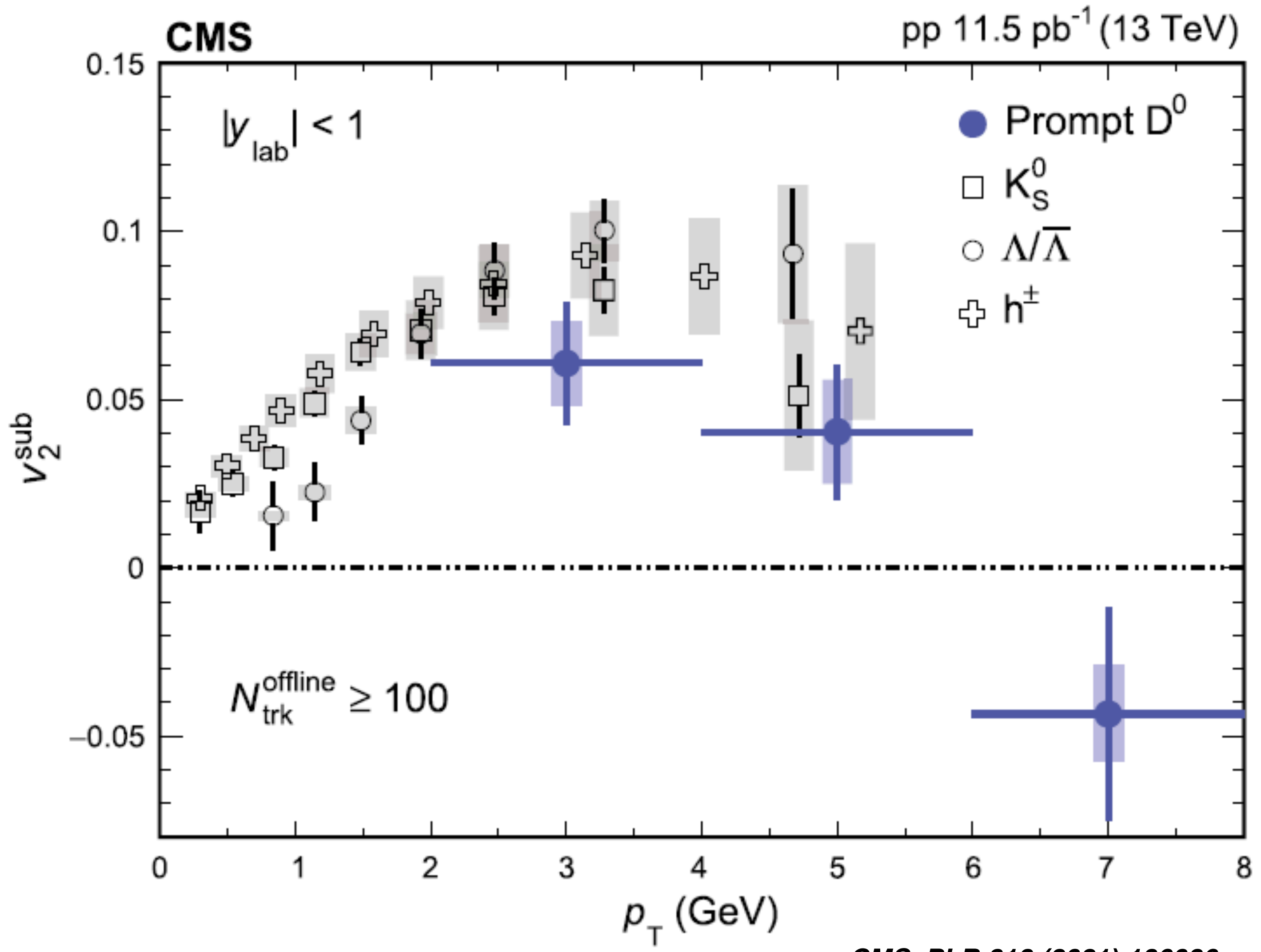
Larger systems: collectivity? Fragmentation modification?

Larger systems: collectivity?

- D^0 v_2 in pp and p-Pb collisions via two particle correlations with $|\Delta\eta|<1$
  - Prompt D^0: positive v_2 in p-Pb and in high multiplicity pp
  - Slightly smaller v_2 w.r.t. LF hadron, similar to J/Psi
- Positive v_2 for HFe
  - Consistent with HF muon measurement (at forward rapidity)
  - Compatible with $v_2(D^0)$ by CMS





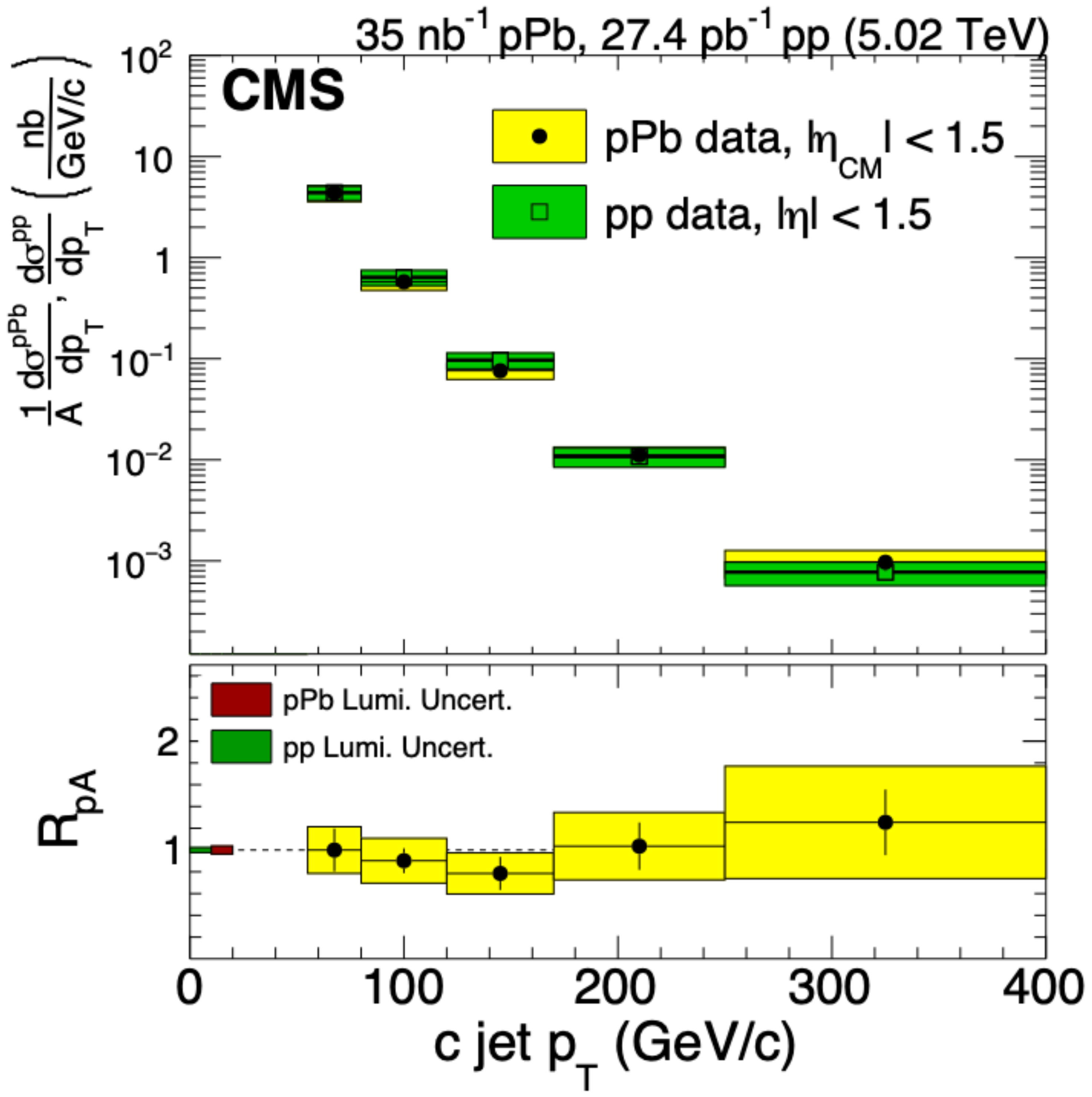


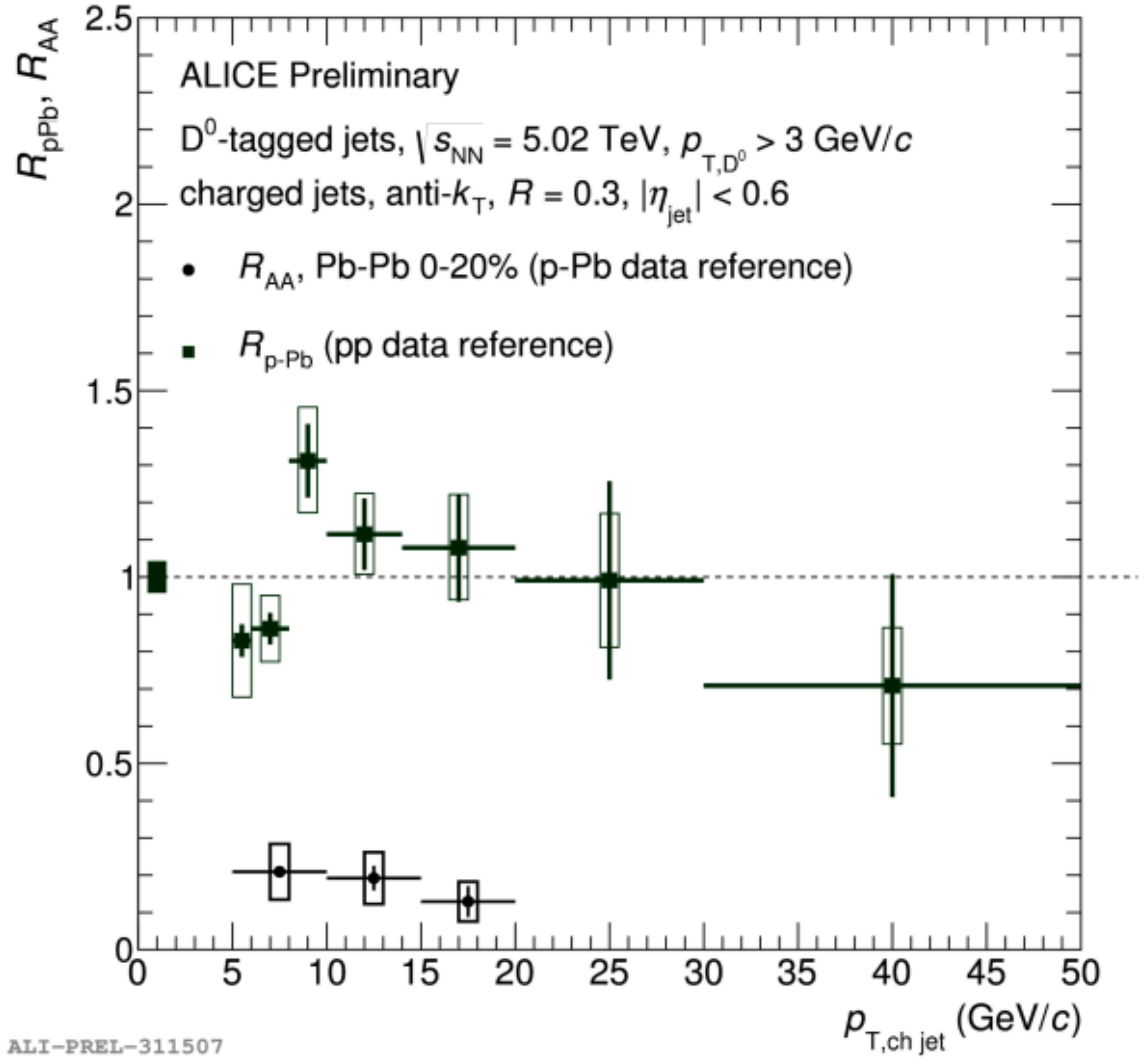
CMS, PLB 813 (2021) 136036

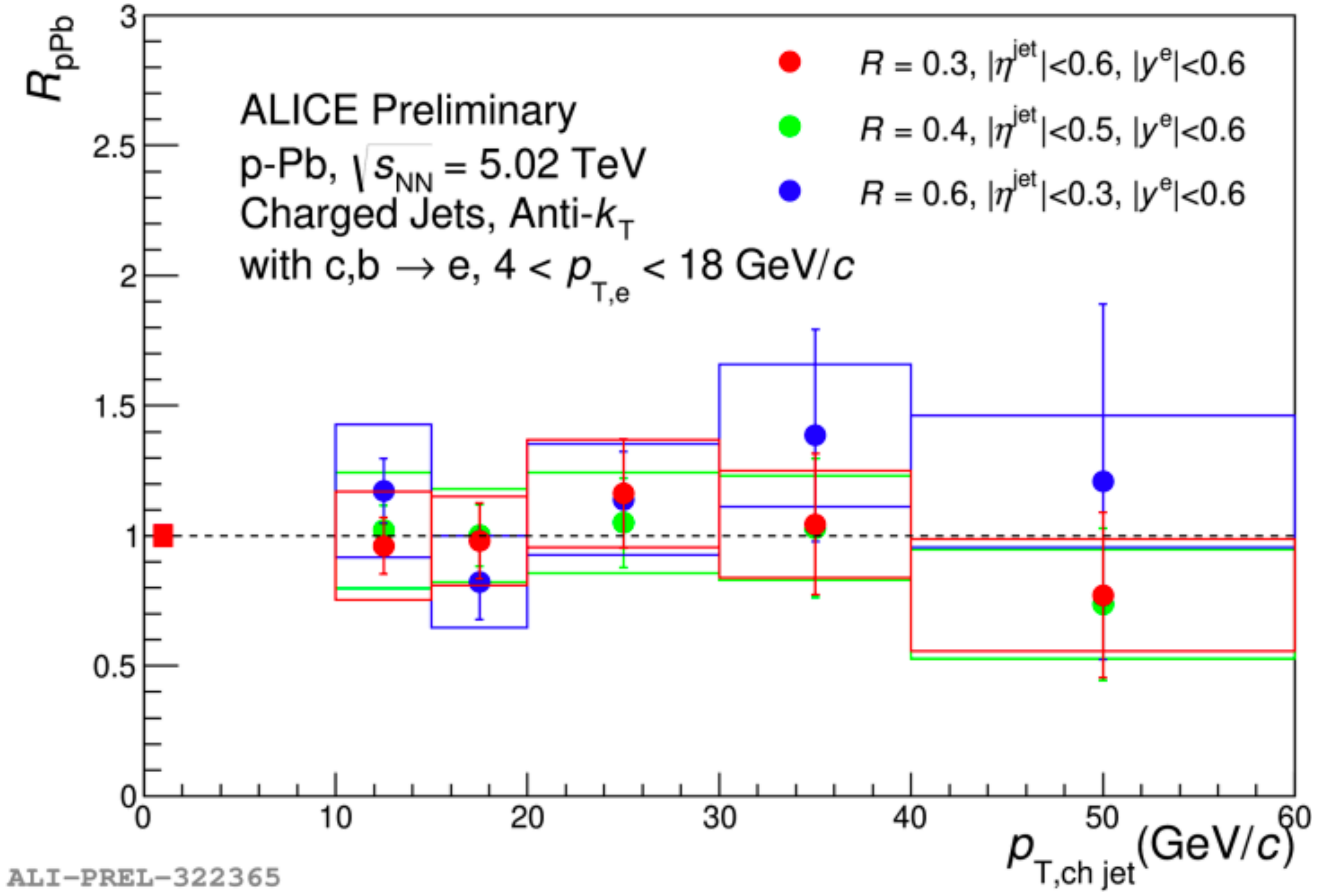
Final state effects (QGP droplets) or collective motion in HM collisions?

Or related to initial state effects (e.g. gluon saturation in CGC framework)?

Larger systems: collectivity?

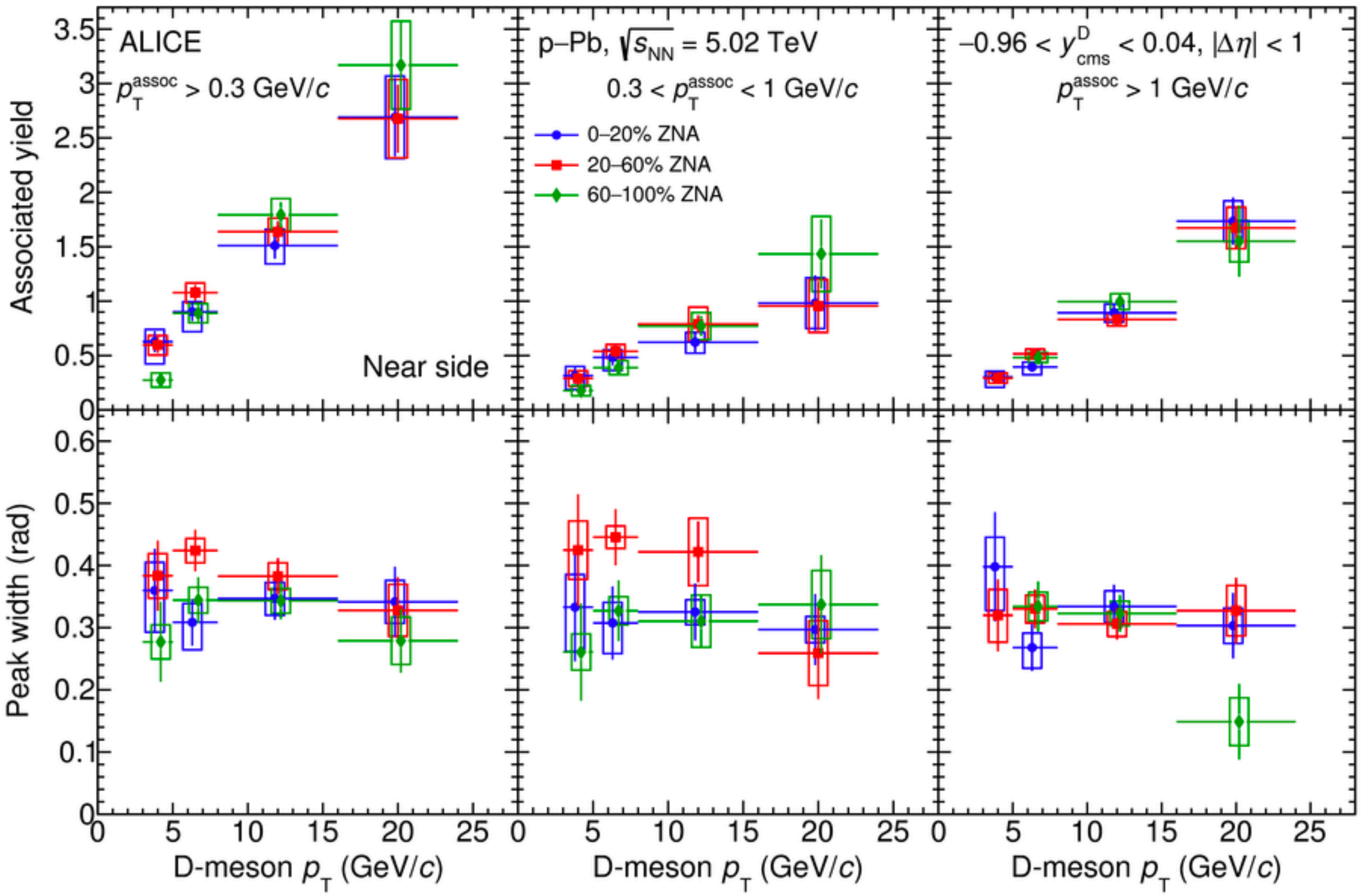


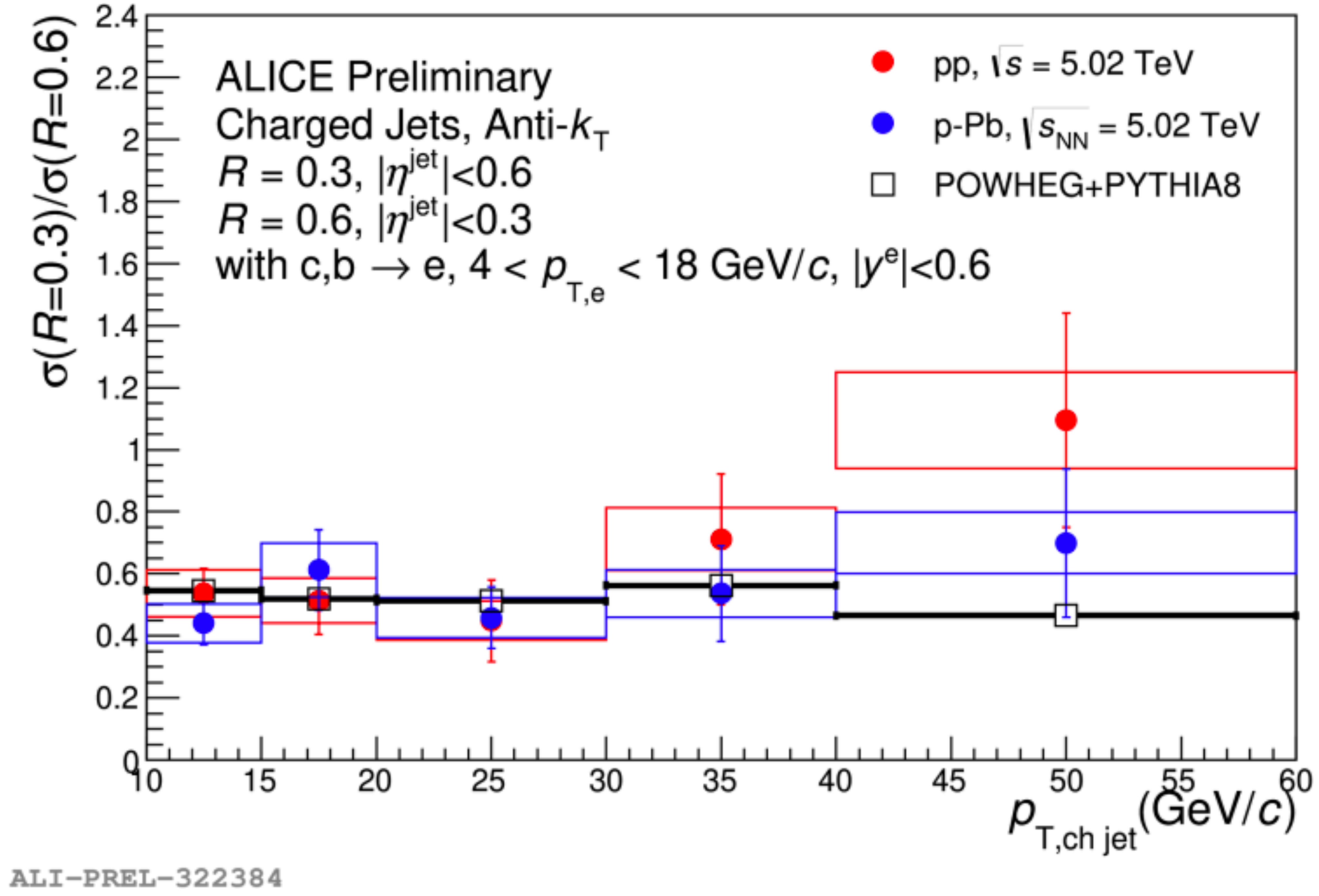




- Investigating the nuclear modification in larger systems:
  - R_{pPb} compatible with unity in the HF jet cross sections —> not compatible with the QGP droplets hypothesis
  - No jet suppression/broadening as a function of the resolution parameters (looking at R_{pPb} as a function of the cone size)

Larger systems: fragmentation modification?

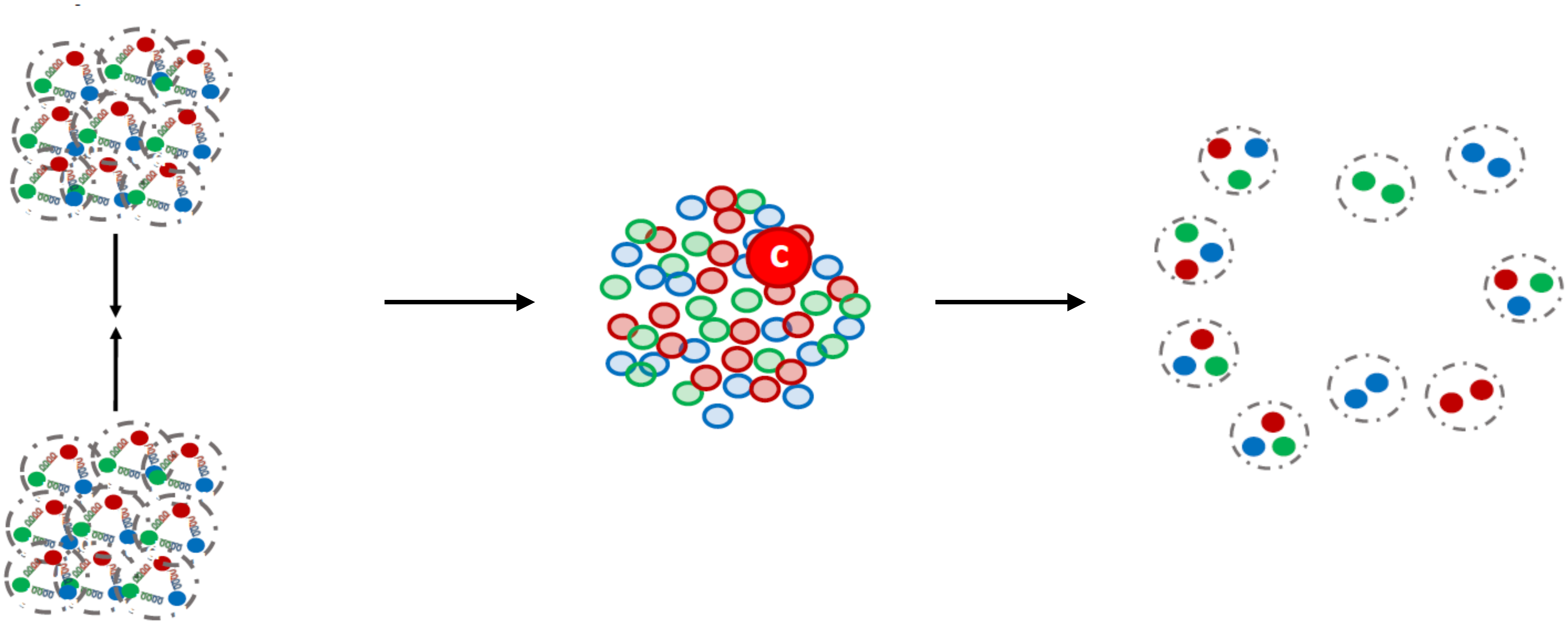




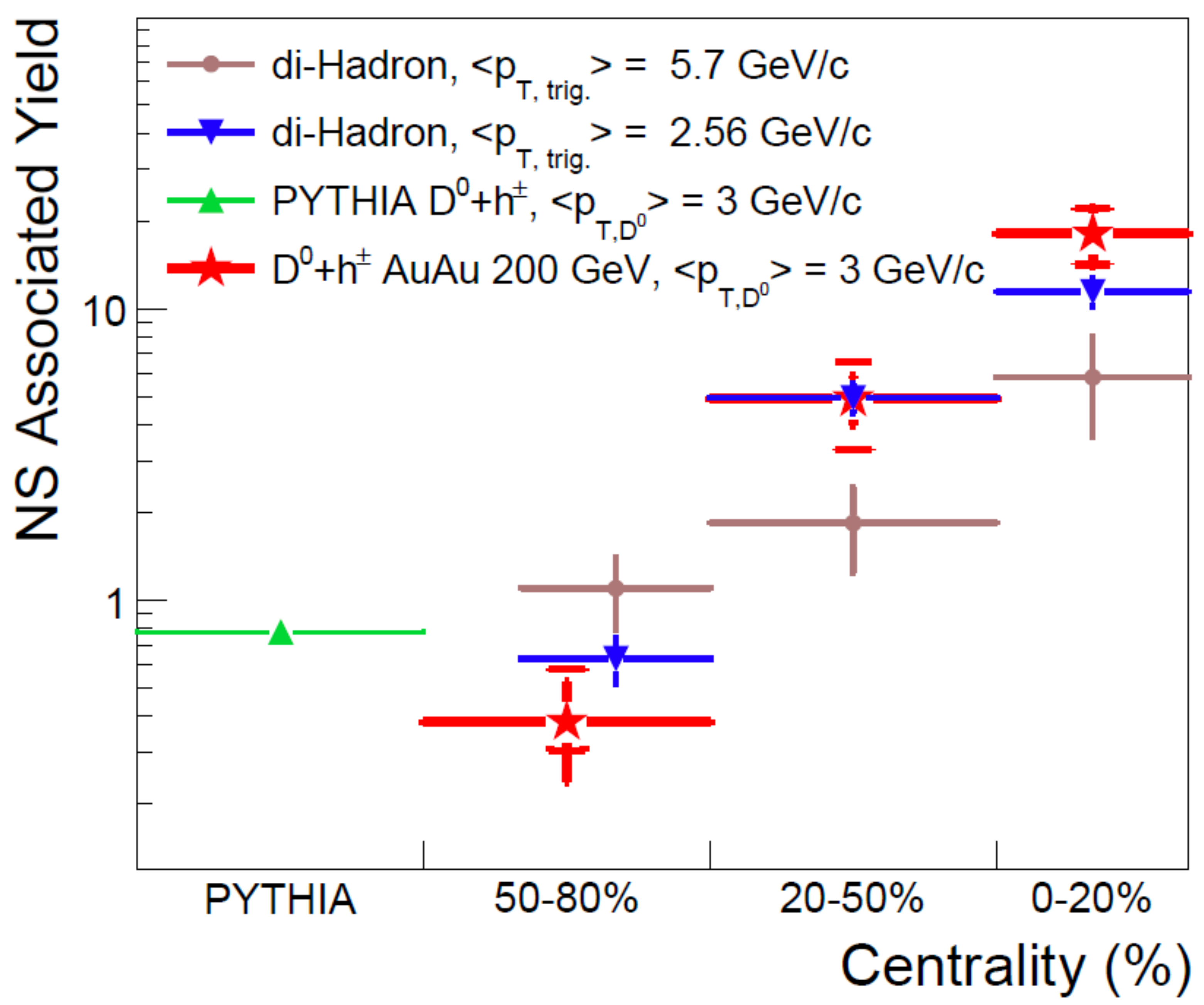
- In p-Pb, possible modification to the jet shape or spectrum could evidence cold nuclear matter effects.

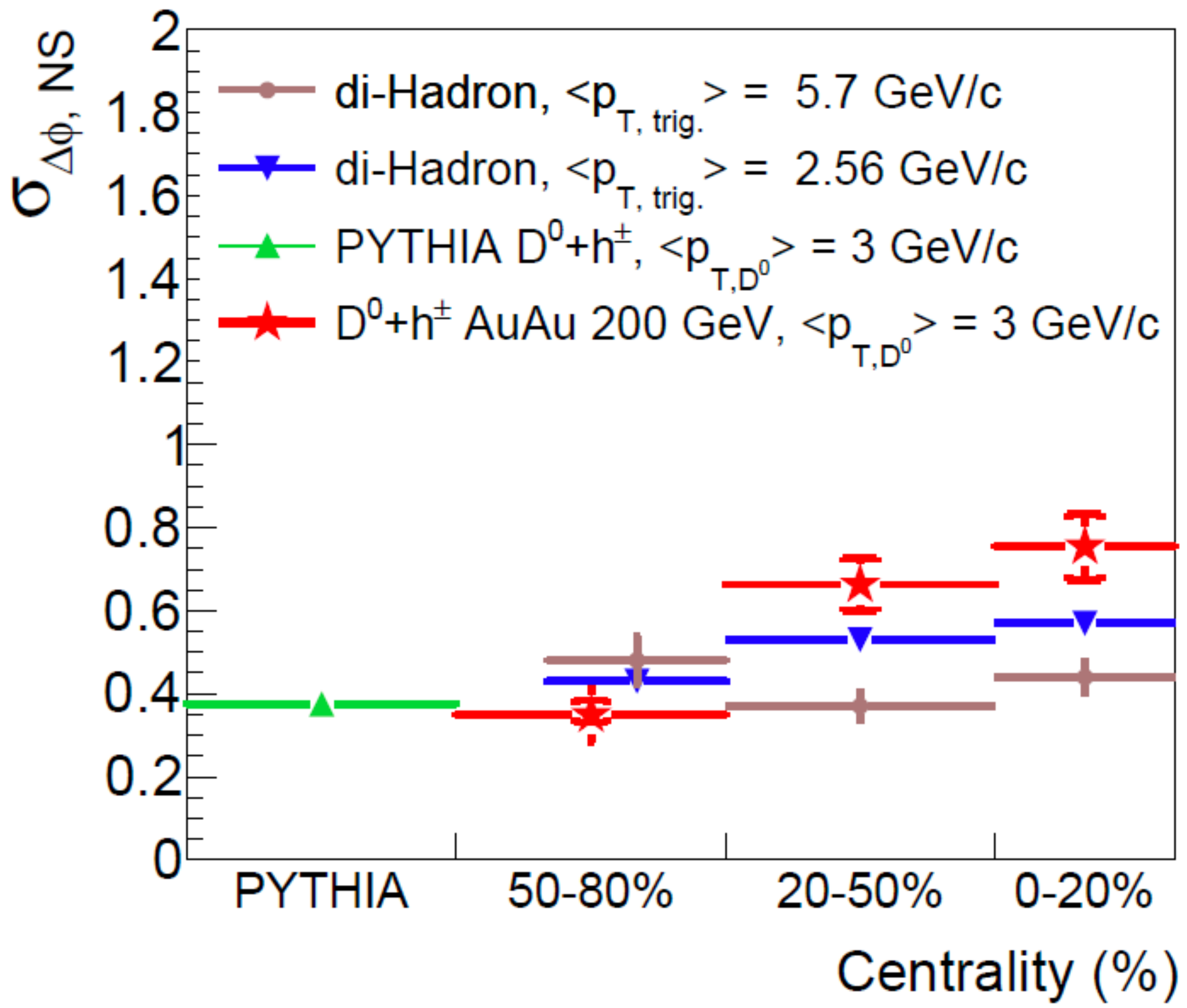
- No evident modification to the jet shape depending on the collision system

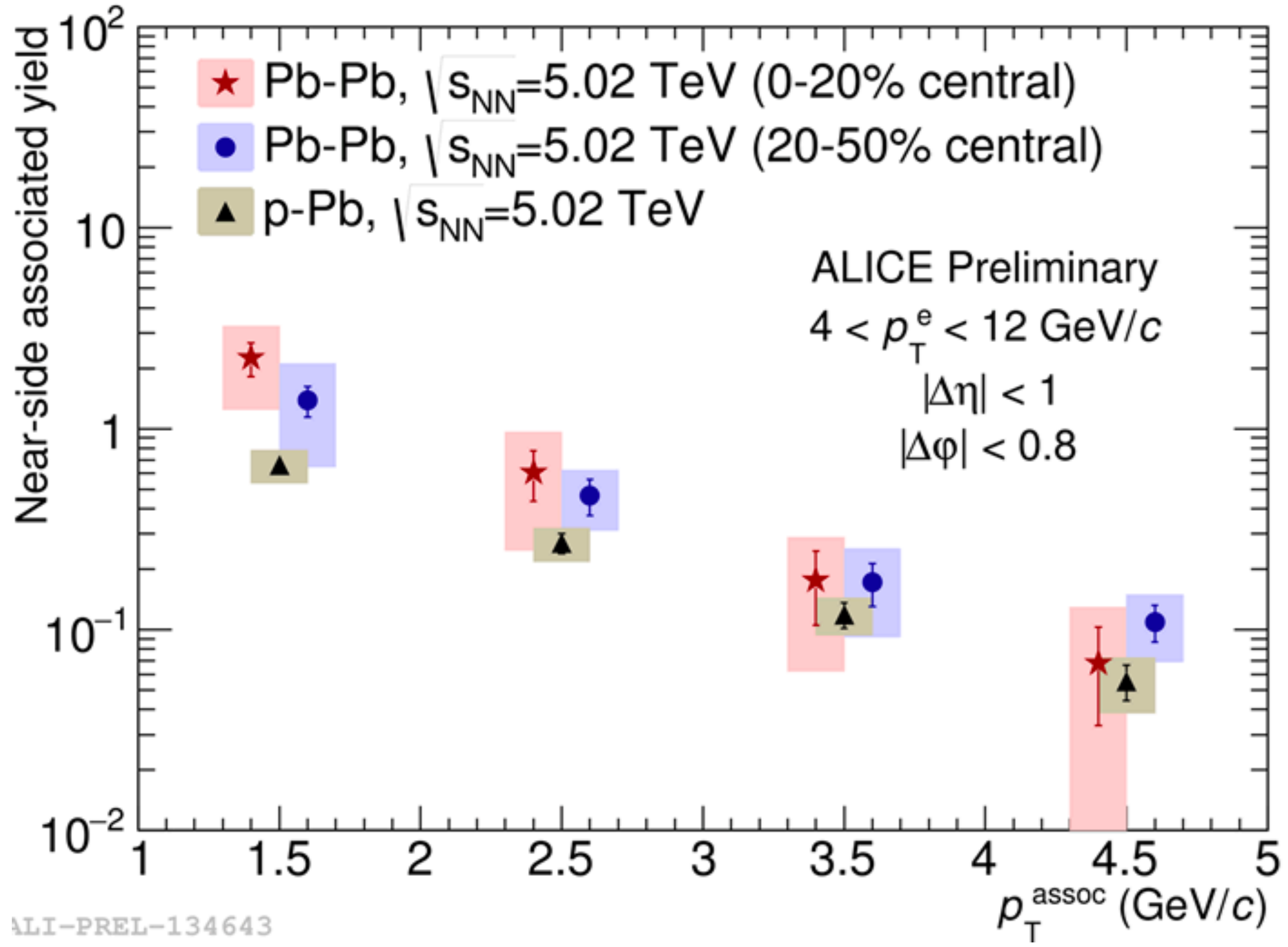
Medium effects



HF correlations in Pb-Pb







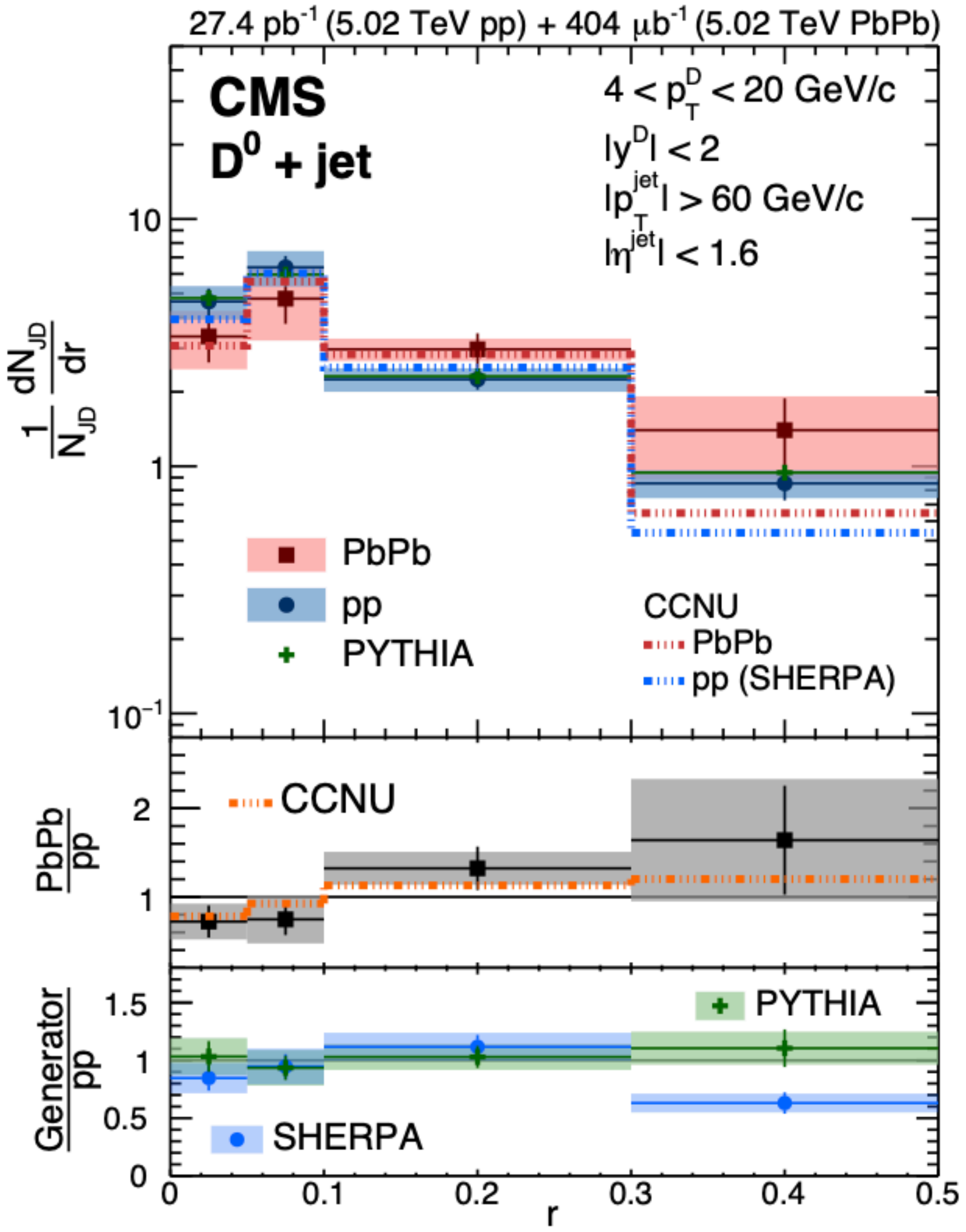
Yield modifications in Pb-Pb studied also for D-h correlations at lower energy and mass number by **STAR**

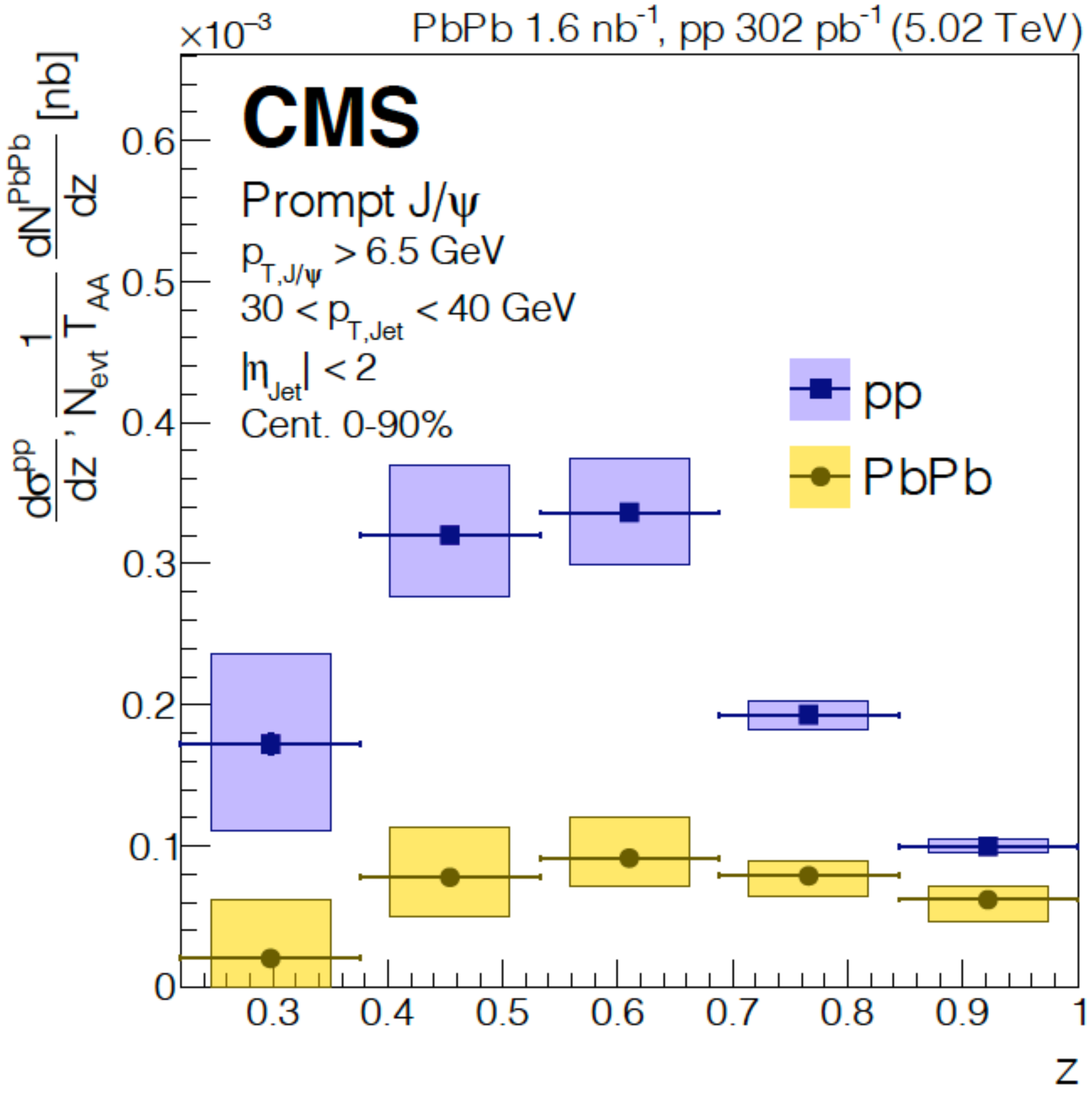
- NS yields consistent with PYTHIA for peripheral events, then large enhancement in more central events
- Broadening of NS peaks observed for increasing centrality

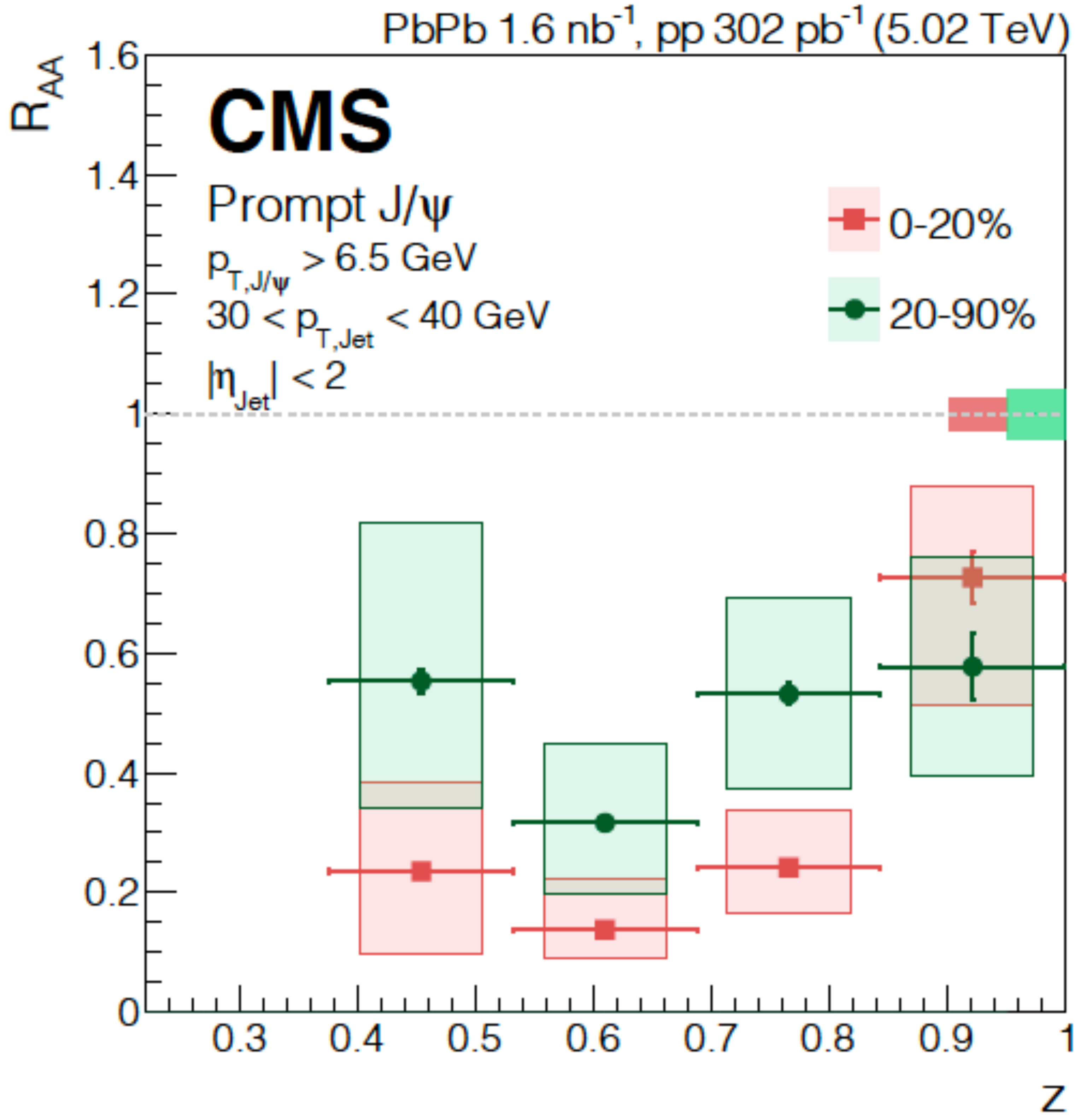
Study yield modifications to HFe-h from in-medium effects

- Hints of NS hierarchy among collision systems at low p_T of the associated tracks
- Similar features for HF and LF quarks but different fragmentation, energy loss in medium, kinematic bias

HF jets in Pb-Pb







- pp collisions: well-described by PYTHIA
- D^0 mesons at low p_T are farther away from the jet axis in PbPb compared to pp collisions
- Hint at a modification of the D^0 meson radial profile in PbPb collisions at low p_T(D) —> related to charm diffusion in the medium

- J/ψ R_{AA} as a function of z shows a rising trend
- Larger suppression in most central events:
  - J/ψ produced with a large surrounding jet activity are higher suppressed than those produced in association with fewer particles

Summary

HF-tagged jet and correlations provide a reference for the energy and direction of the initial charm quark: Powerful tool to constrain HQ hadronization and production mechanisms

Run3/4 plans:
Expand the successful pp program to study pQCD and hadronisation mechanisms in small systems:
- Higher statistics (x100) and improved DCA resolution in Run3
- More differential analyses vs multiplicities
- More precise results

Study of quenching, hadronisation and collectivity in central AA collisions will be the core ALICE activities:
- traditional observables (R_{AA}, v_2, particle ratios) for charm and beauty down to very low p_T
- HF-jet chemistry and HF-jet substructure from low to intermediate/high p_T

Backup

Production mechanism: HF correlations

- HF-HF correlation:
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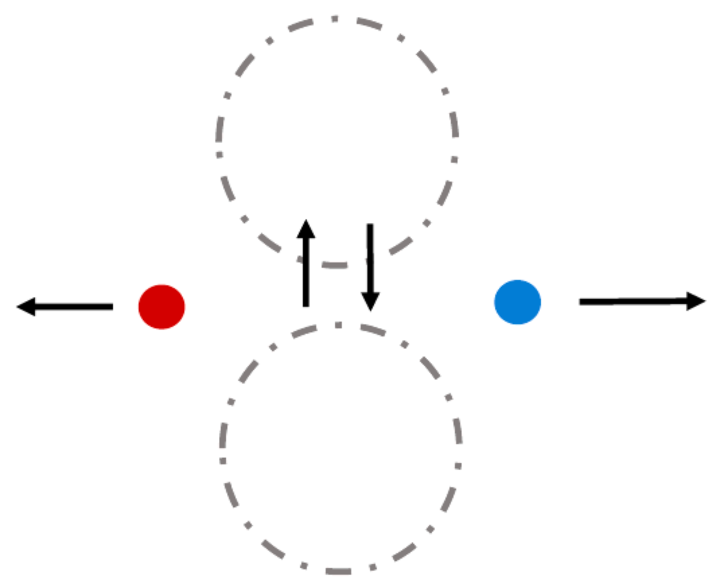

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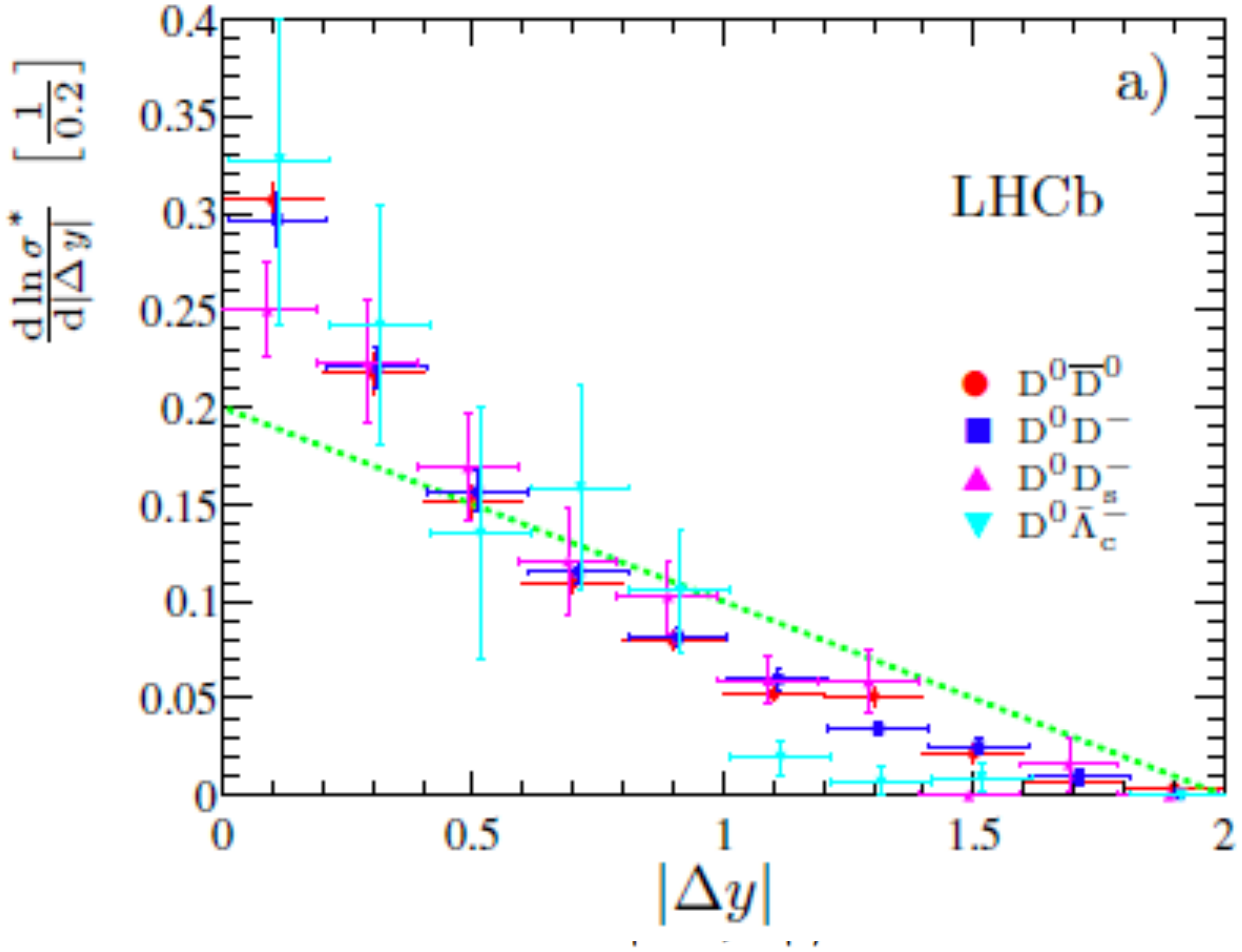
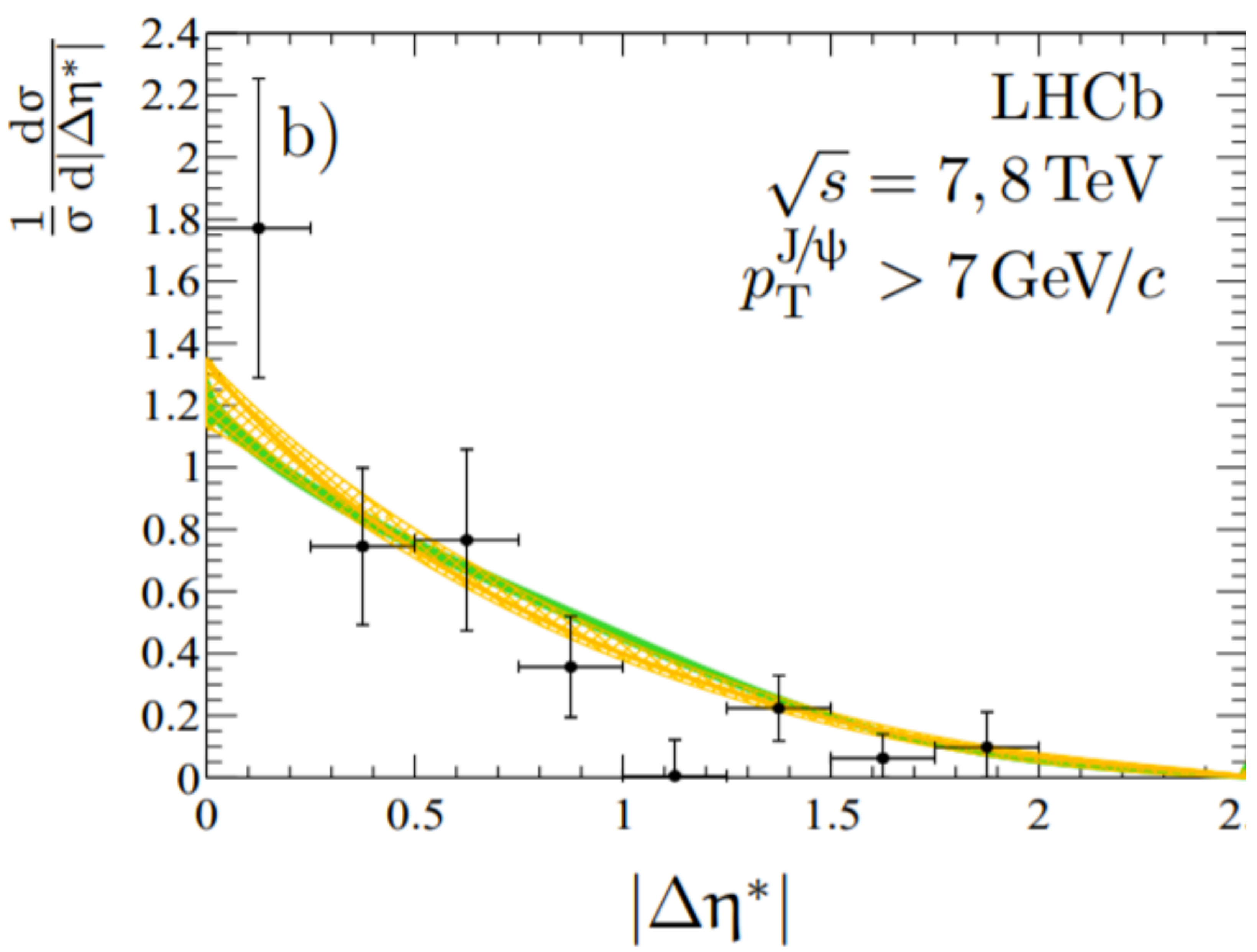
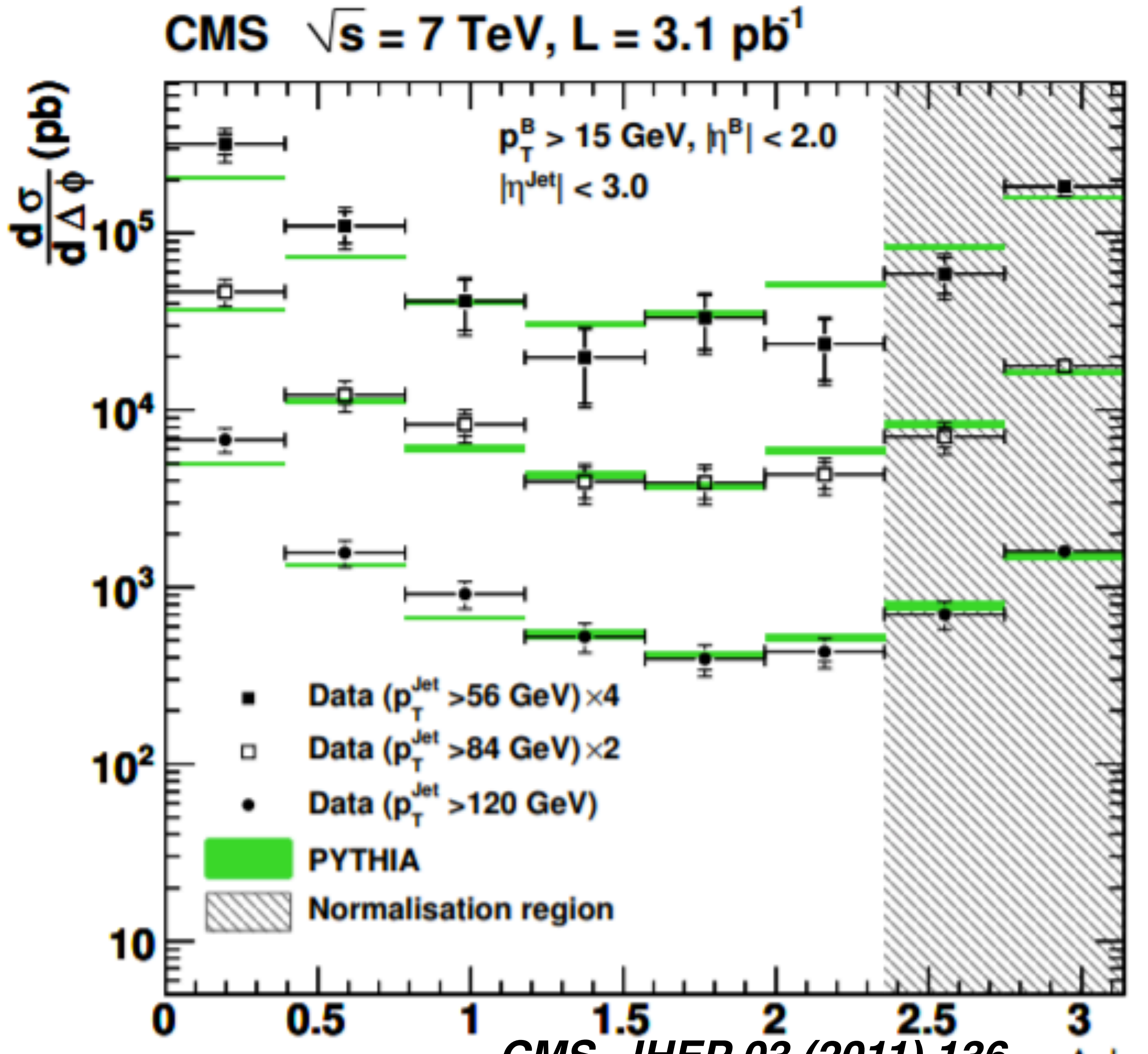


LHCb, JHEP 1711 (2017) 030





CMS, JHEP 03 (2011) 136

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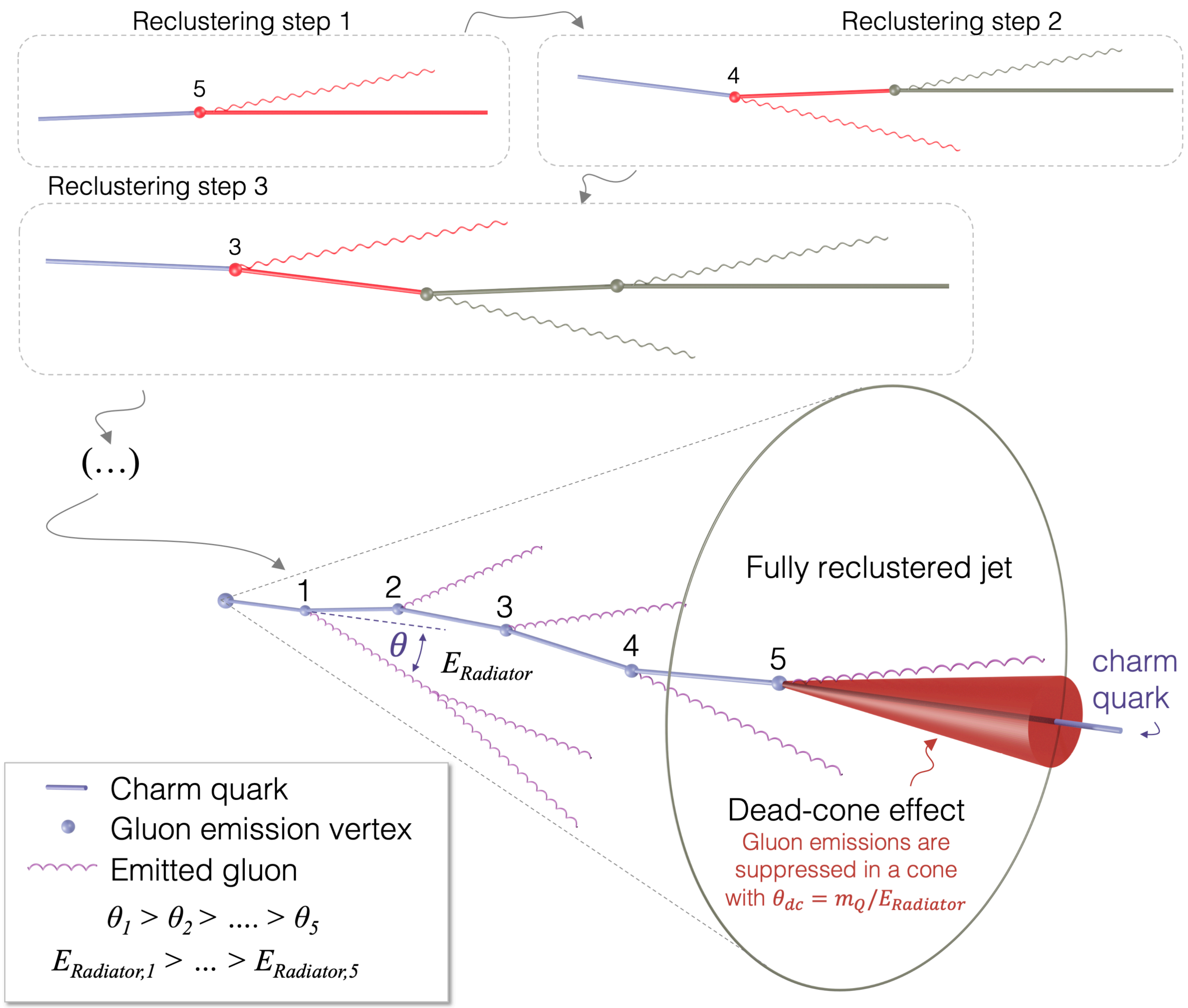
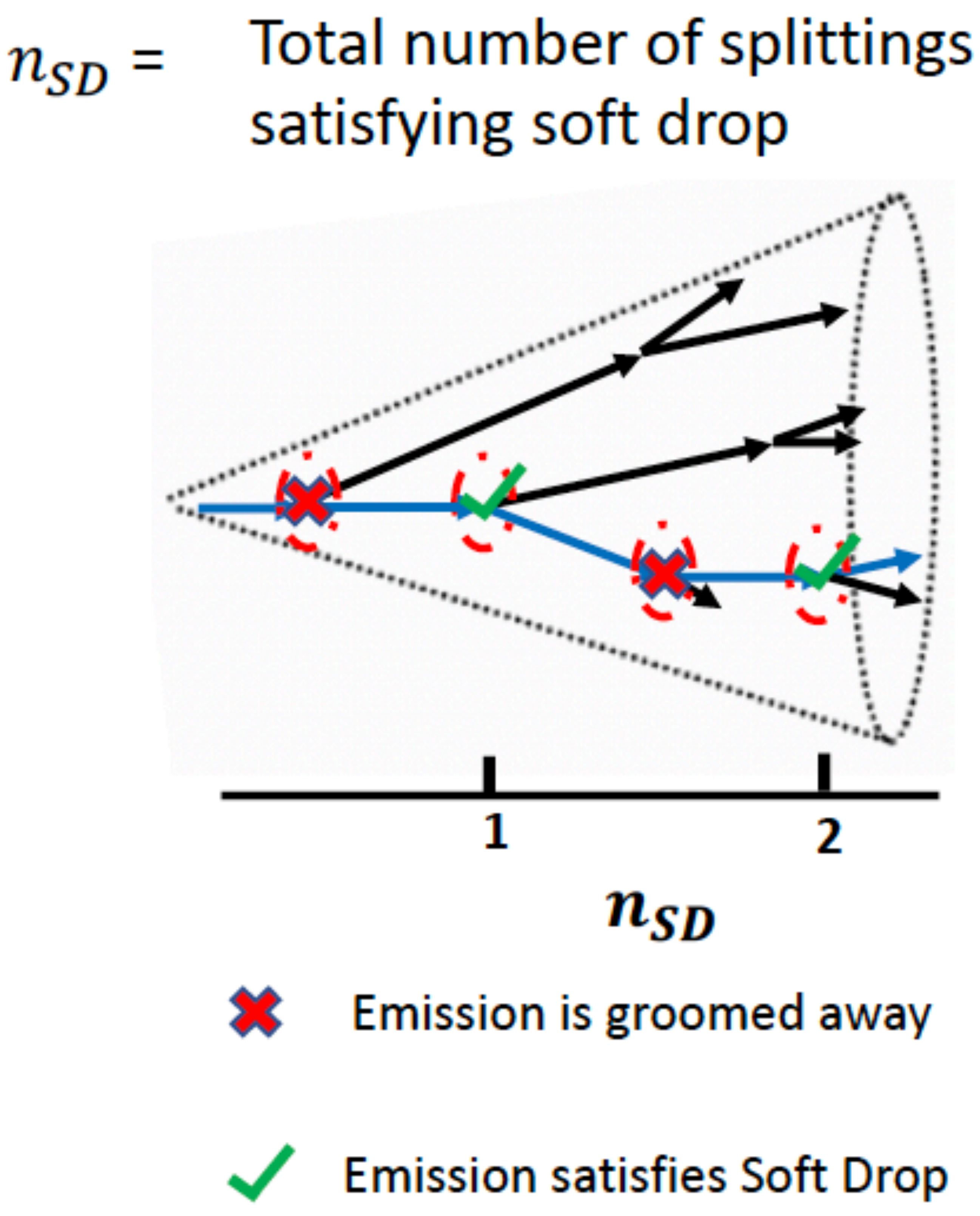


Reclustering step 1
5
Reclustering step 2
4
Reclustering step 3
3
(…)
1
2
3
4
5
θ
$E_{Radiator}$
Fully reclustered jet
charm quark
Dead-cone effect
Gluon emissions are suppressed in a cone with $\theta_{dc} = m_Q/E_{Radiator}$
Charm quark
Gluon emission vertex
Emitted gluon
$\theta_1 > \theta_2 > .... > \theta_5$
$E_{Radiator,1} > ... > E_{Radiator,5}$

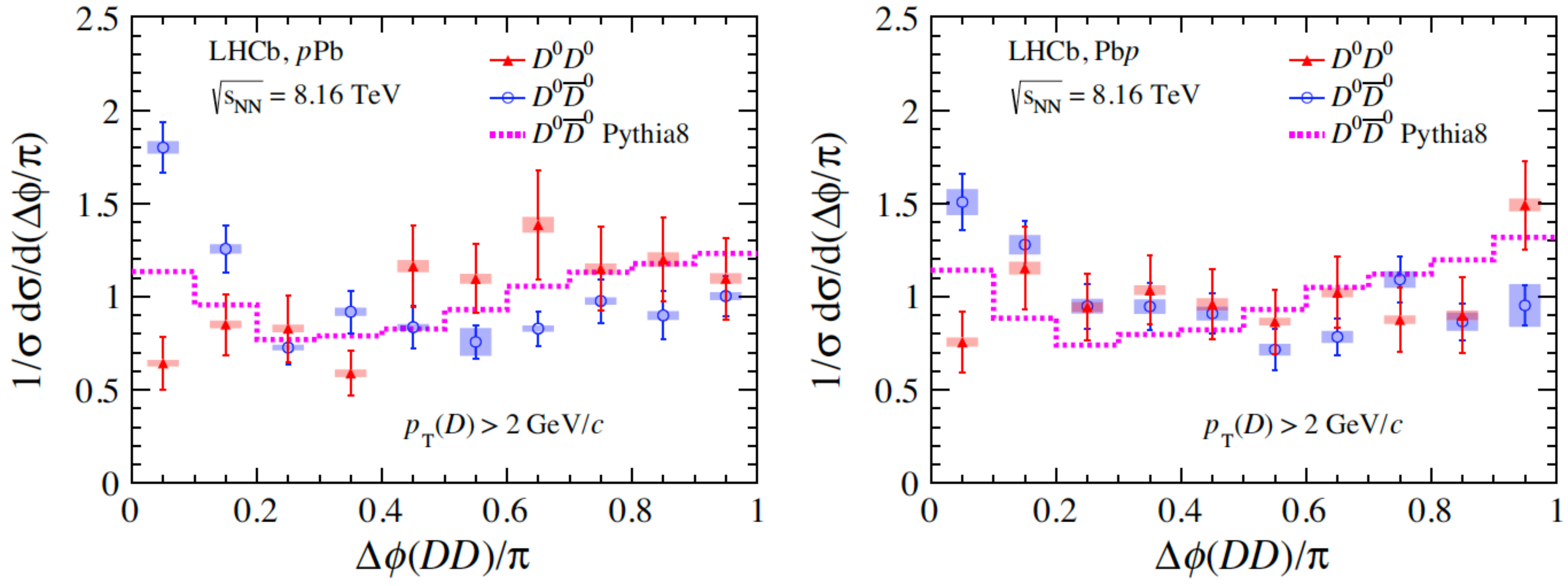
The Soft Drop groomer selects perturbative splittings in the jet shower

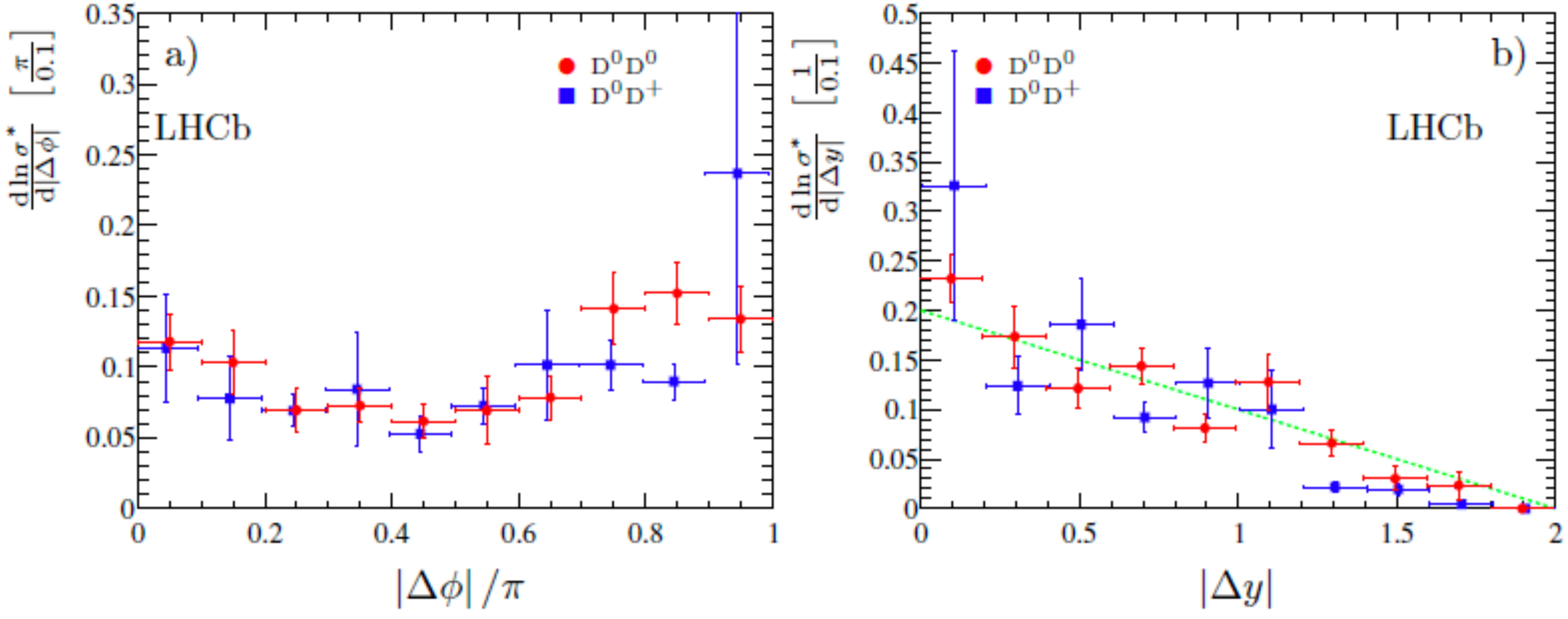


Number of Soft-Dropped splittings n_{SD}:

- sub-leading prong carries > 10% of splitting p_T

Larger systems: fragmentation modification?

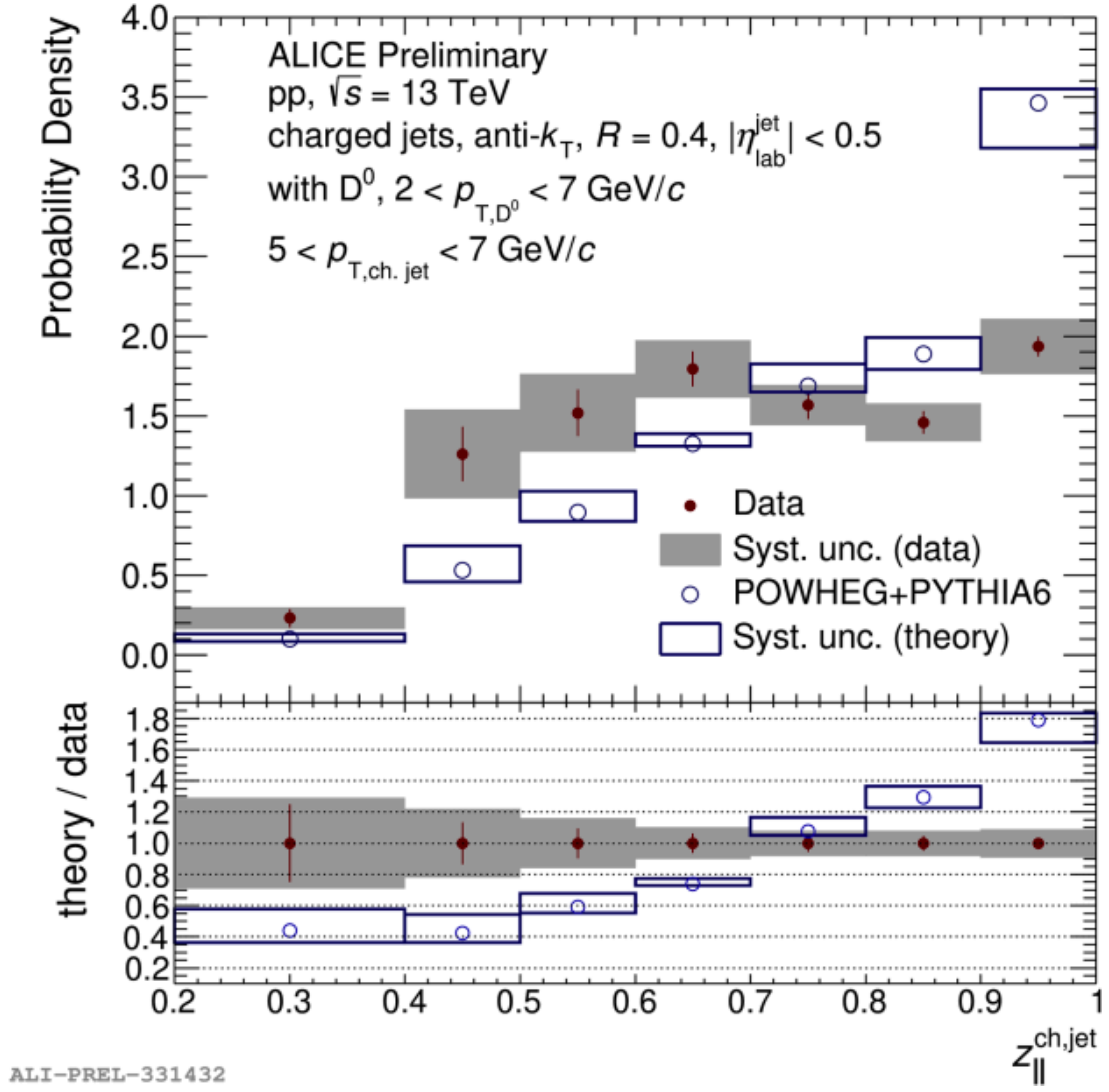


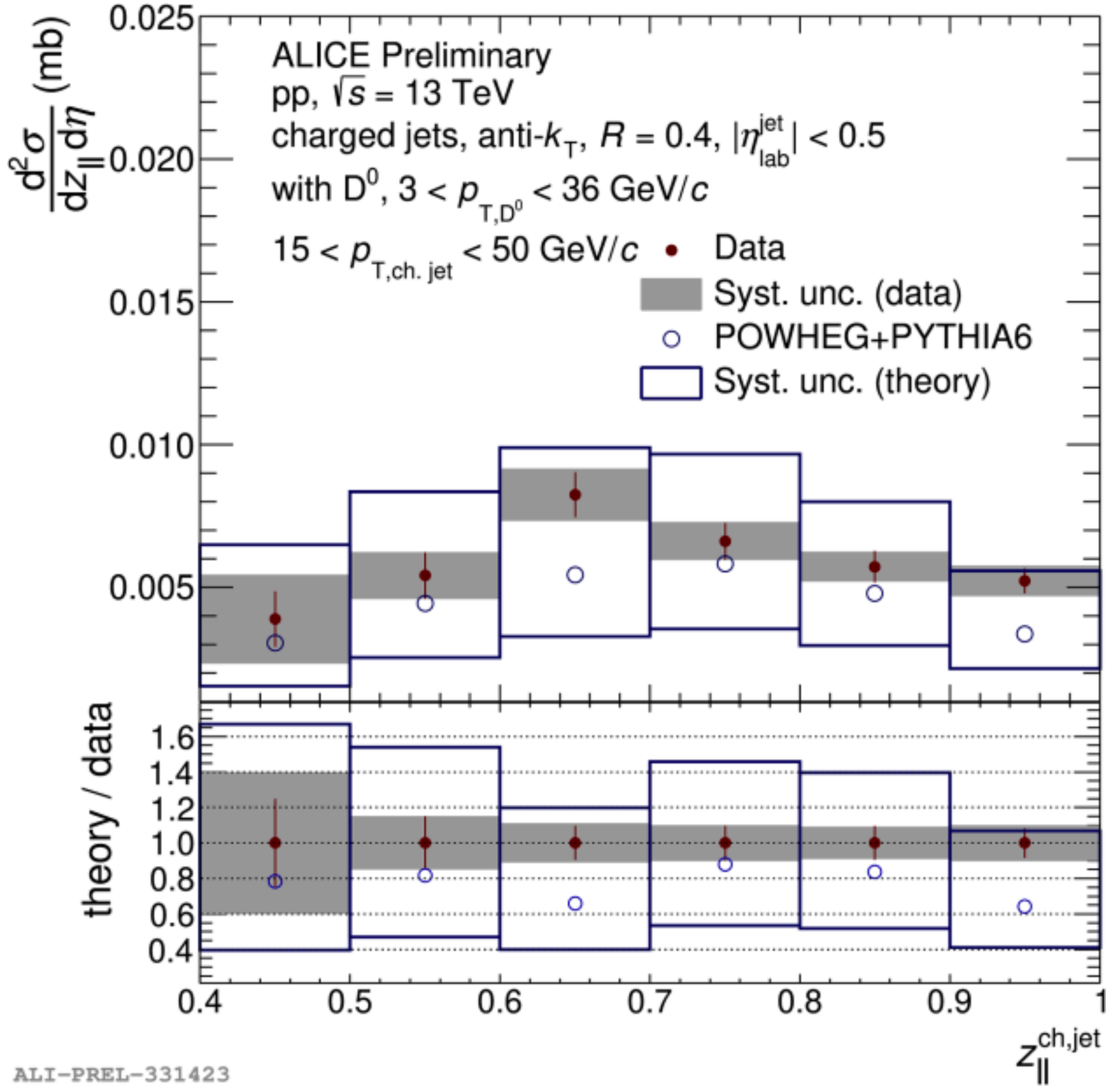


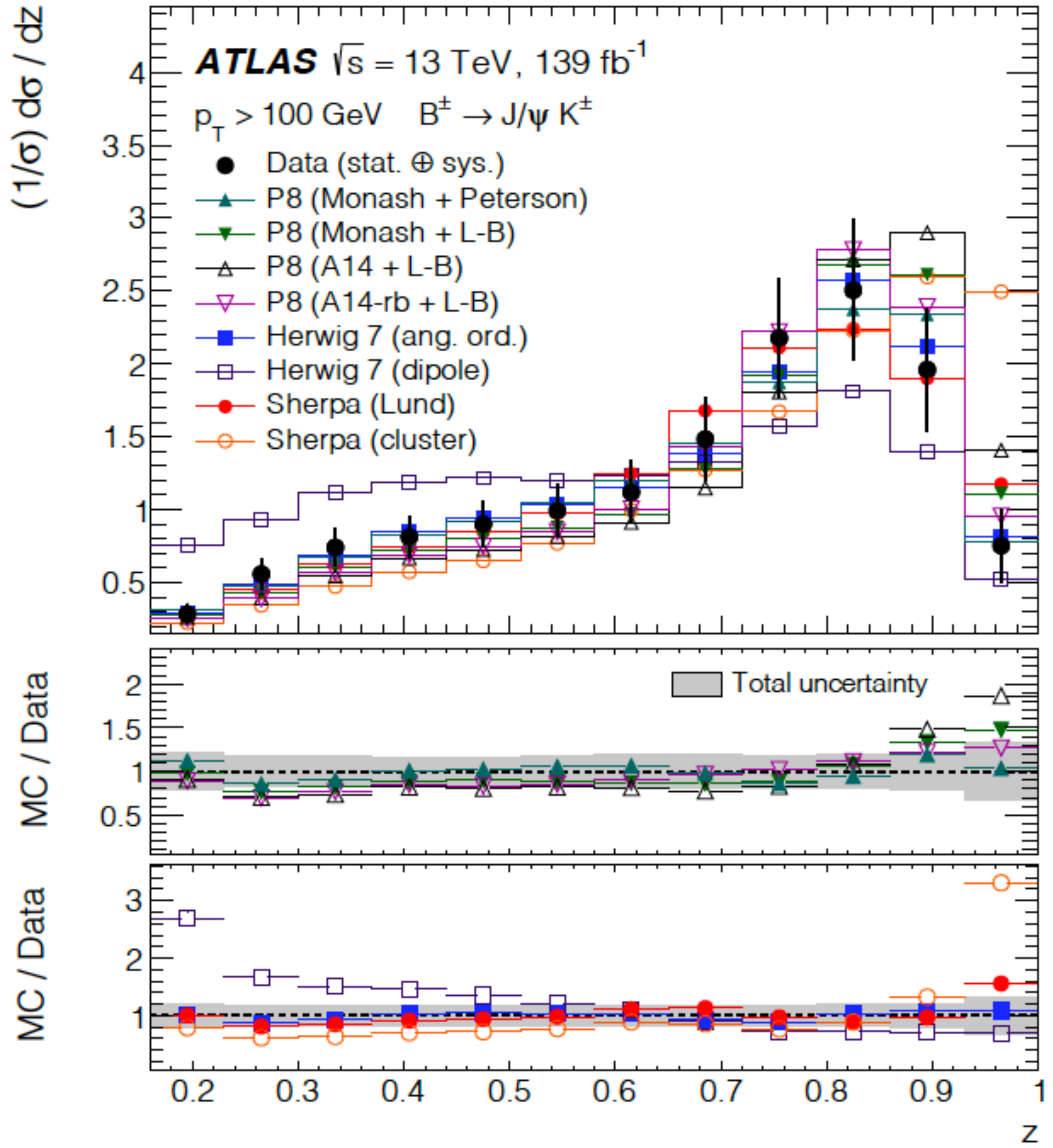
- The cross-section ratio between LS and OS pairs is found to be a factor of 3 higher than that in pp data.
- LS pairs exhibit a flat relative azimuthal angle distribution independent of charm hadron p_T.
- The effective cross-section and nuclear modification factor for J/ψ D^0 and D^0D^0 are in general compatible with the expected enhancement factor of 3 for DPS over SPS production ratio from pp to p-Pb collisions.
- First direct observation of such an enhancement using LS charm production in p-Pb data.

HF jets to look into hadronisation

HF-tagged jet provide a reference for the energy and direction of the initial charm quark





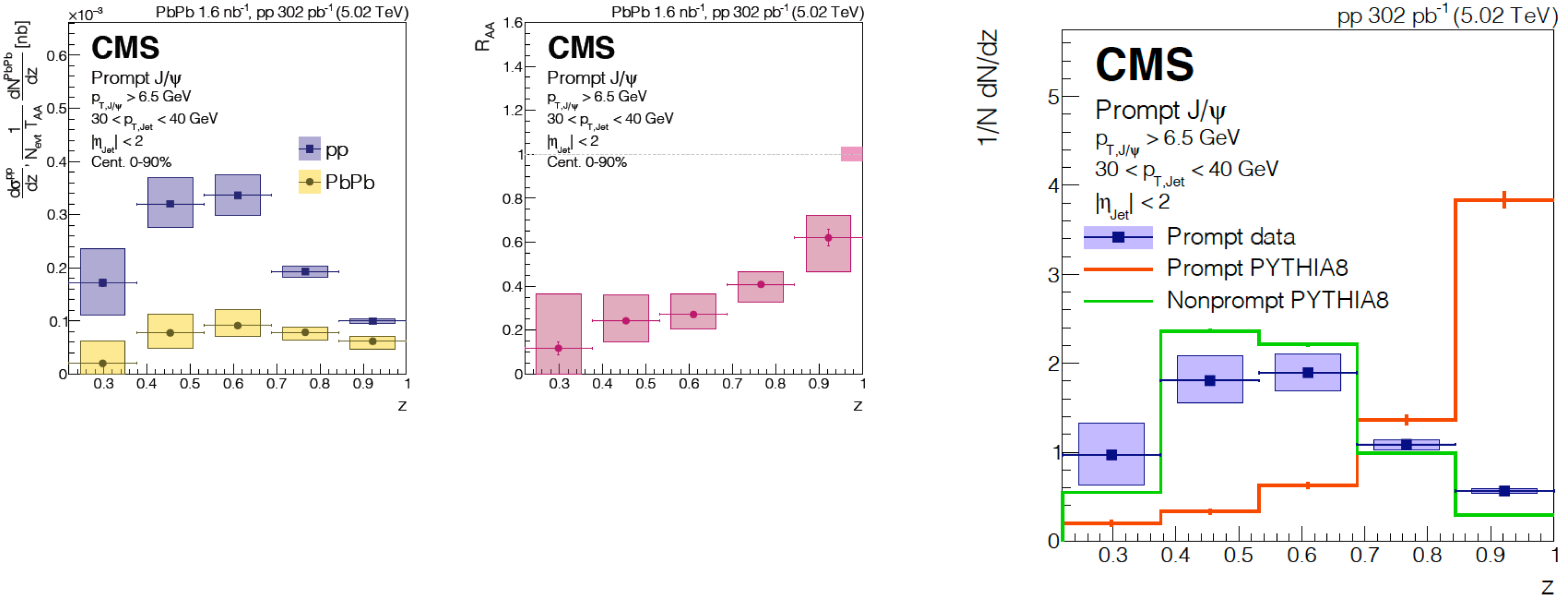


Parallel momentum fraction: $z_{//}^{ch} = \dfrac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$

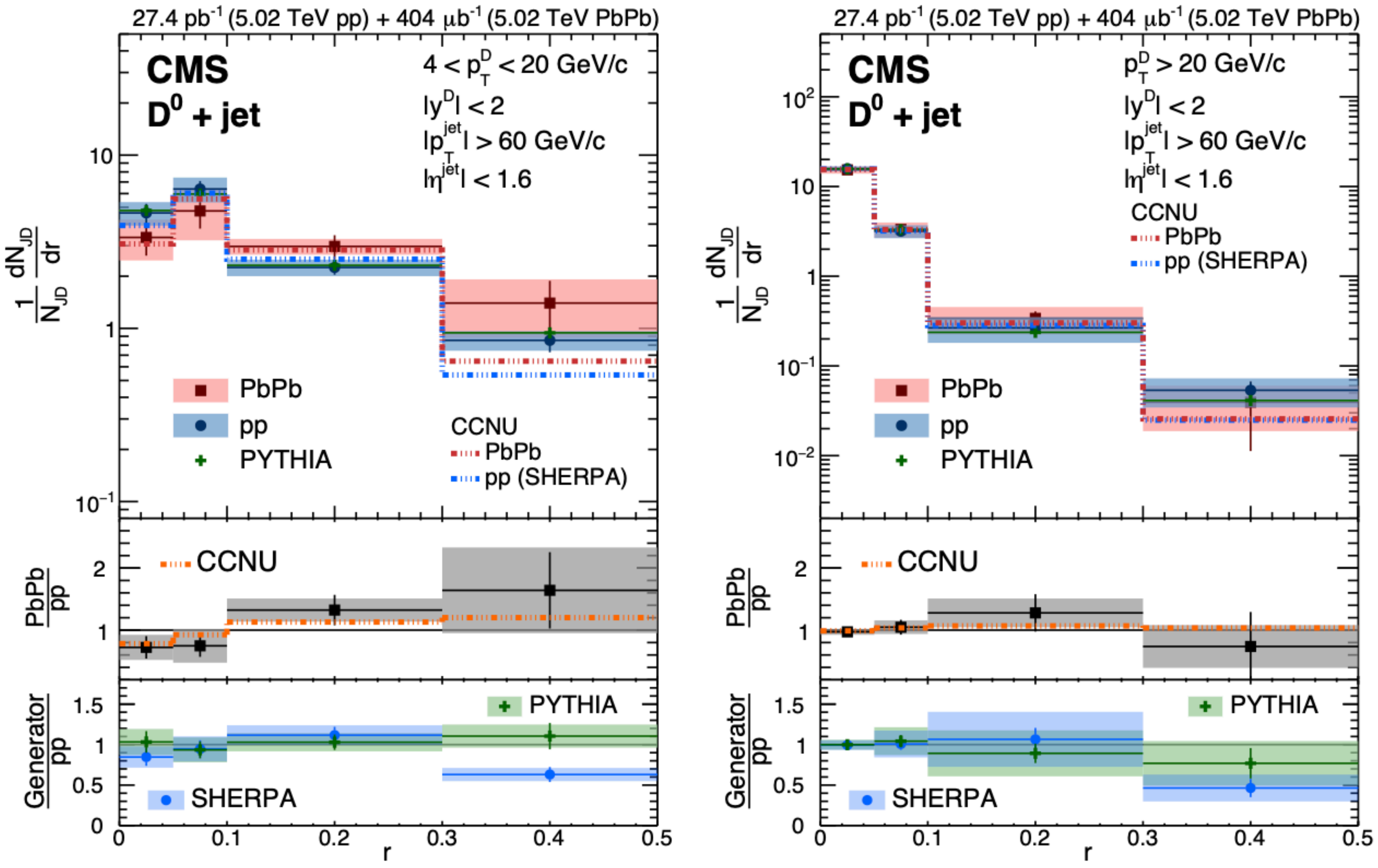
Comparison with models: data point toward a softer fragmentation at small $z_{//}$ and small p_T^{HF} and in the low $p_{T,\text{ch-jet}}$ range

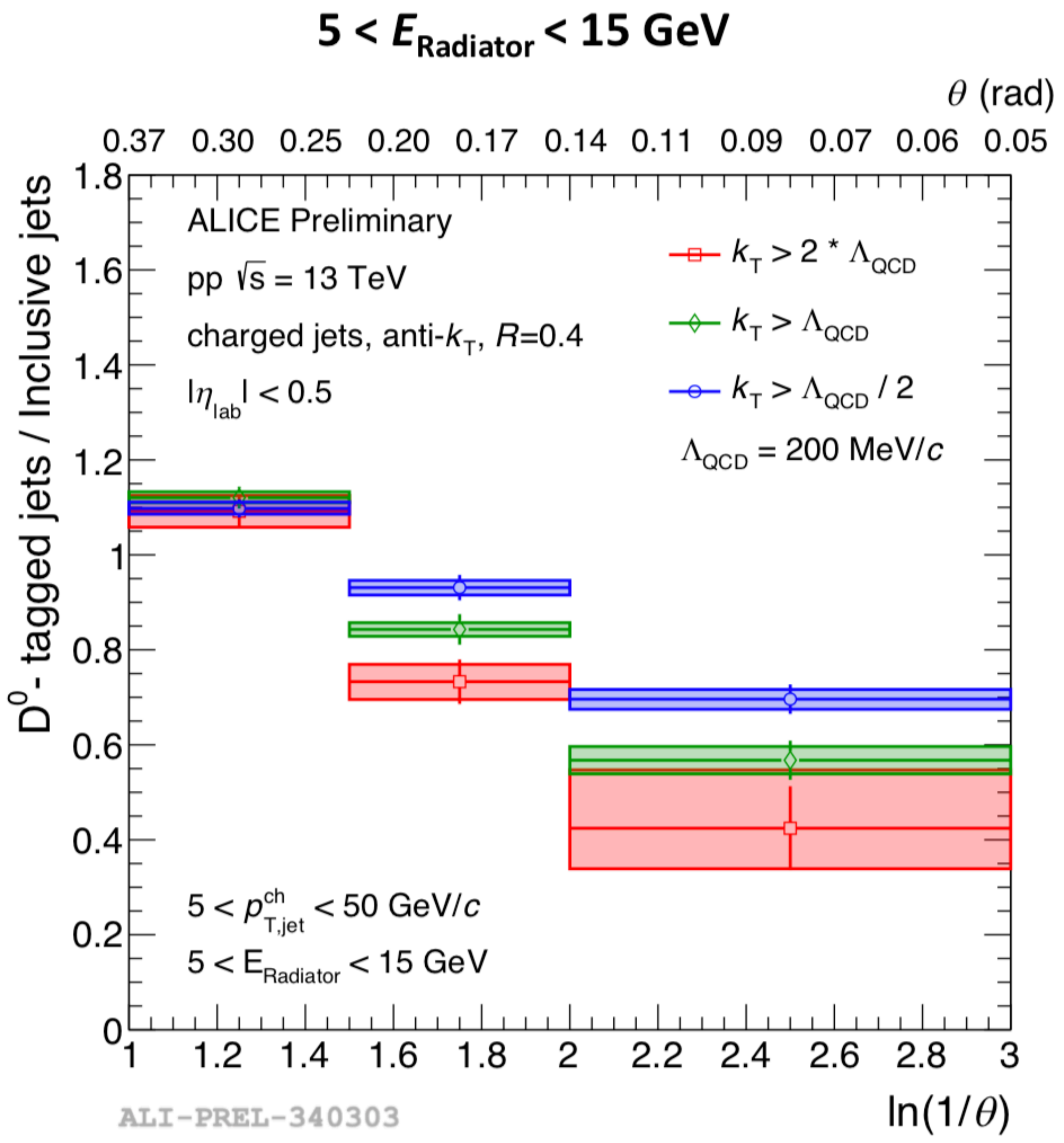
Hint of softer fragmentation also in ATLAS for b-jets —> explained as a gluon splitting consequence

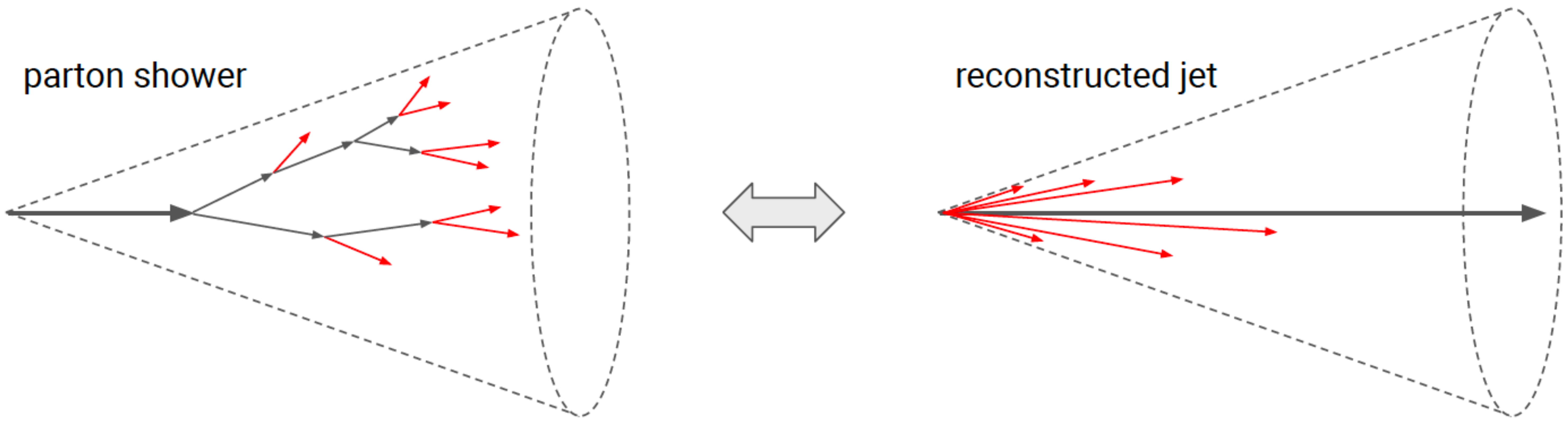
CMS fragm function

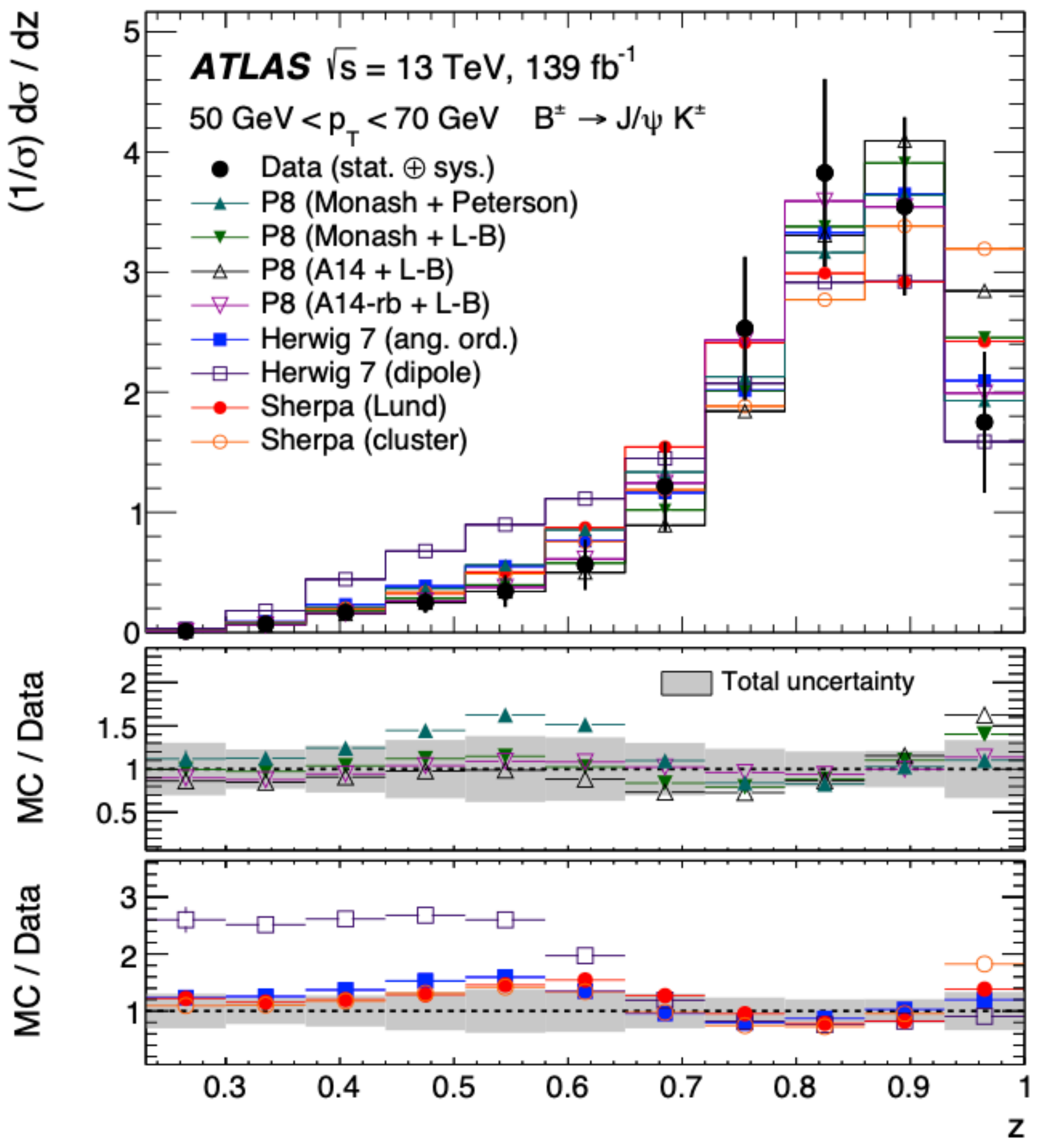


D0 meson radial distribution




5 < $E_{Radiator}$ < 15 GeV
θ (rad)
0.37 0.30 0.25 0.20 0.17 0.14 0.11 0.09 0.07 0.06 0.05
ALICE Preliminary
pp $\sqrt{s}$ = 13 TeV
charged jets, anti-k_T, R=0.4
$|\eta_{lab}| < 0.5$
$k_T > 2 * \Lambda_{QCD}$
$k_T > \Lambda_{QCD}$
$k_T > \Lambda_{QCD} / 2$
Λ_{QCD} = 200 MeV/c
$5 < p_{T,jet}^{ch} < 50$ GeV/c
$5 < E_{Radiator} < 15$ GeV
D^0- tagged jets / Inclusive jets
ln(1/θ)
ALI-PREL-340303


parton shower
reconstructed jet



ATLAS √s = 13 TeV, 139 fb-1
50 GeV < pT < 70 GeV B± → J/ψ K±
Data (stat. ⊕ sys.)
P8 (Monash + Peterson)
P8 (Monash + L-B)
P8 (A14 + L-B)
P8 (A14-rb + L-B)
Herwig 7 (ang. ord.)
Herwig 7 (dipole)
Sherpa (Lund)
Sherpa (cluster)
(1/σ) dσ / dz
Total uncertainty
MC / Data
MC / Data
z

Production mechanism: HF correlations

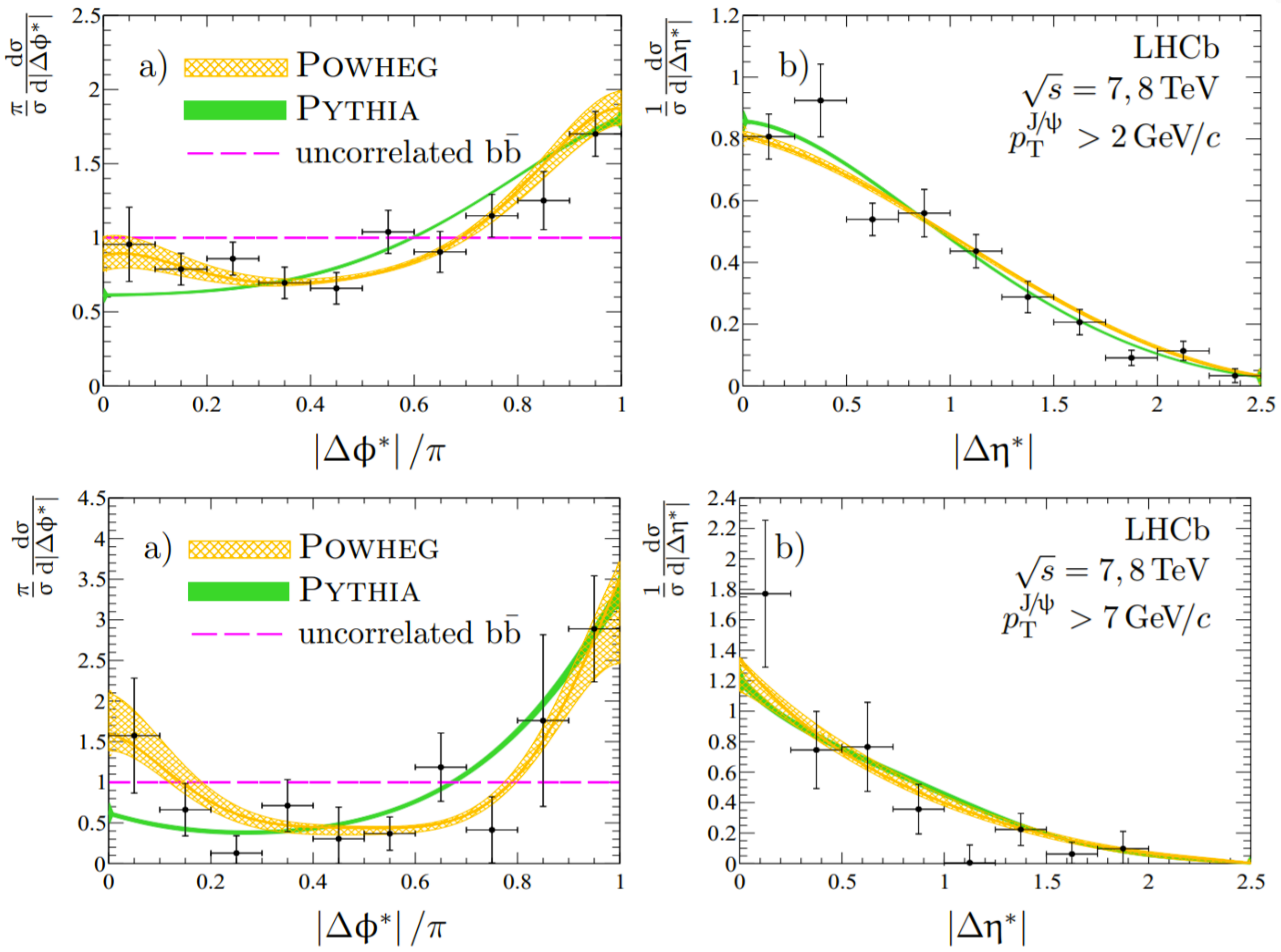
Beauty hadron pair correlations in pp collisions by LHCb, forward y

Predominant away side peak at large p_T, correlation pattern more diluted at lower p_T

Much larger back to back production than for charm

NLO contribution less relevant for beauty than for charm

- POWHEG (NLO) —> higher peak for higher pt, catch better the data



Production mechanism: HF correlations

- Beauty hadron pairs measured by CMS at 7 TeV, mid rapidity
- Relevant fraction of BB pairs produced at small angular distance (differently than LHCb, but different rapidity)
- Fraction of collinear production increases with p_T
  - Higher contribution from g radiation?