Overview on recent open heavy-flavour correlation measurements

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Quark-Gluon Plasma Characterisation with Heavy Flavour Probes
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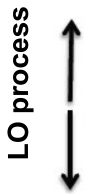
HF CORRELATIONS – INTRODUCTION

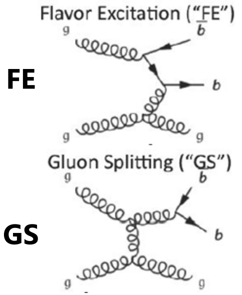
Ultra-relativistic hadronic collisions: from heavy-quark production to final state

Hard Scattering

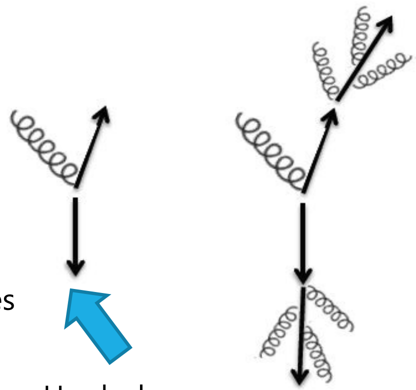
N.B. heavy quark production not always back-to-back...



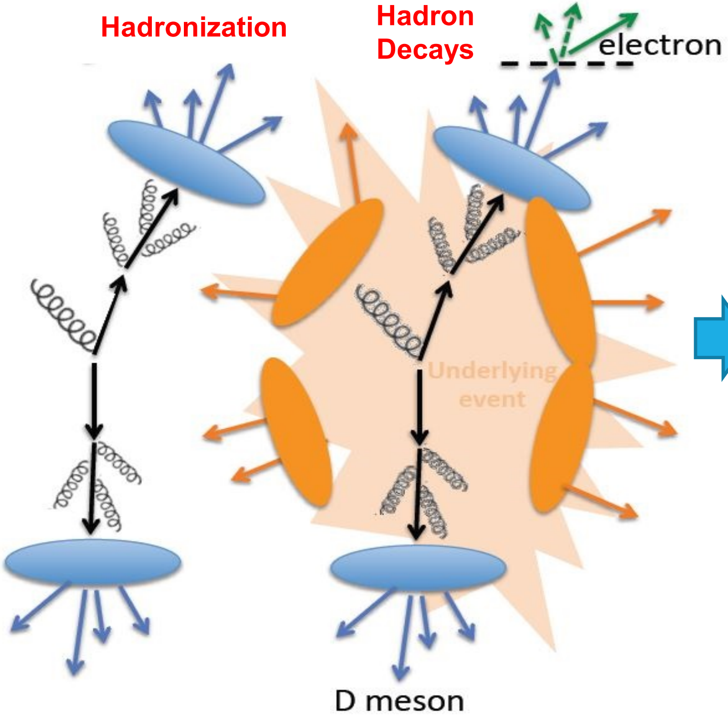
...due to NLO processes



Parton Shower

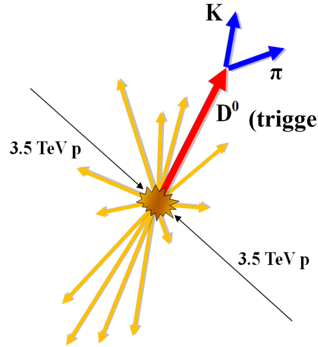


Hard-gluon radiation can also smear the back-to-back structure of HF jets in final state



This in vacuum. In Pb-Pb, this evolution happens inside a QGP medium

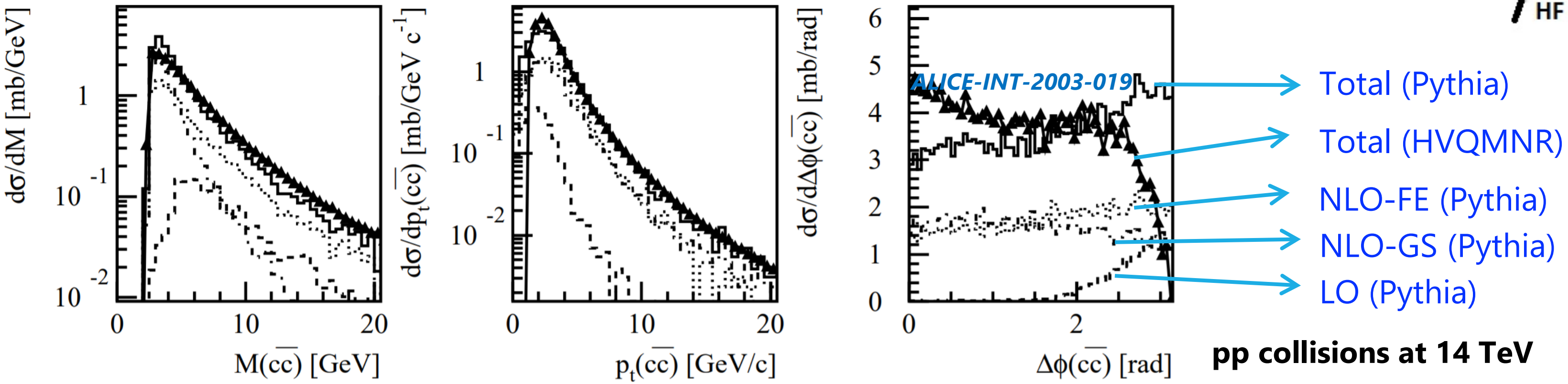
HF correlations allow to gain further insight on all these processes



PHYSICS MOTIVATIONS

pp collisions

- Multi-differential characterization of **HQ-induced jets**:
- Investigation of heavy-quark **fragmentation** and **hadronization** properties
- **Validation of Monte Carlo** models describing the above processes
- Characterisation of **strong interaction** via HQ with femtoscopy studies
- Sensitive to the relative contribution of different **LO** and **NLO** heavy-quark production processes

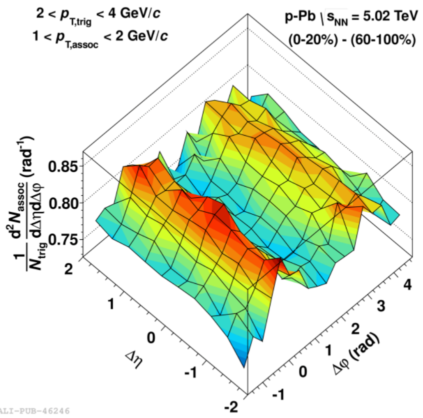


- **Reference** for p-Pb and Pb-Pb results

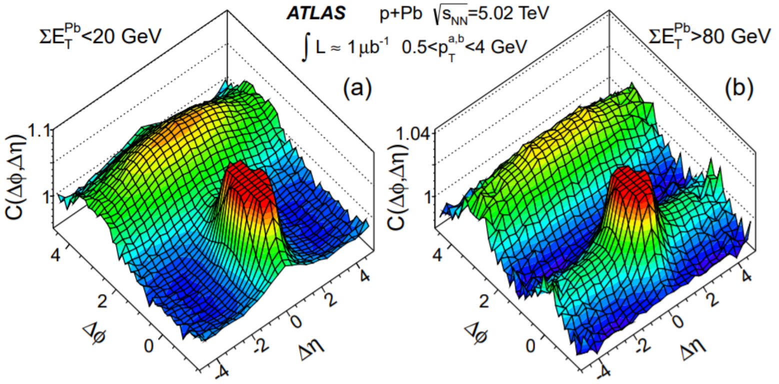
PHYSICS MOTIVATIONS

p-Pb collisions

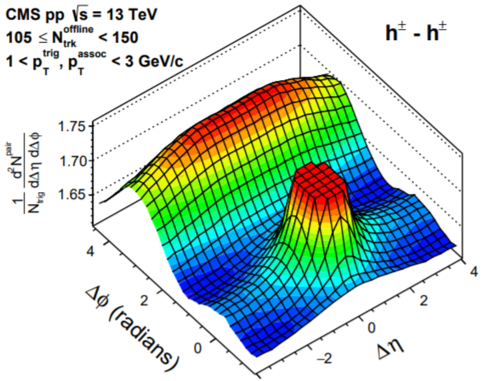
- Investigate possible modifications of angular correlations from **CNM effects**
- Search for **long-range ridge-like structures** (double ridge), observed in di-hadron correlations for high-multiplicity collisions, also in the heavy-flavour sector
  - Does **charm** and **beauty** experience collective effects?
  - What is the source of these effects? **Initial- or final-state**?



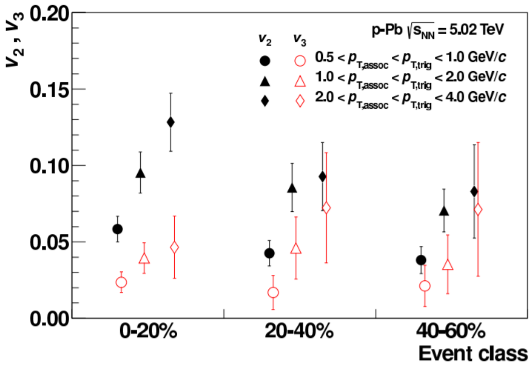
This holds also for HM pp collisions!



ATLAS, PRL 110 (2013) 182302



CMS, PLB 765 (2017) 193

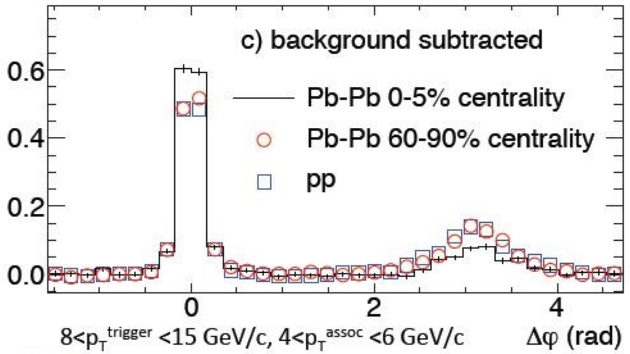


ALICE, PLB 709 (2013) 29

PHYSICS MOTIVATIONS

Pb-Pb collisions

- Probe the **QGP effects** on HQ via modifications of correlation distributions of heavy-flavour particles w.r.t. vacuum

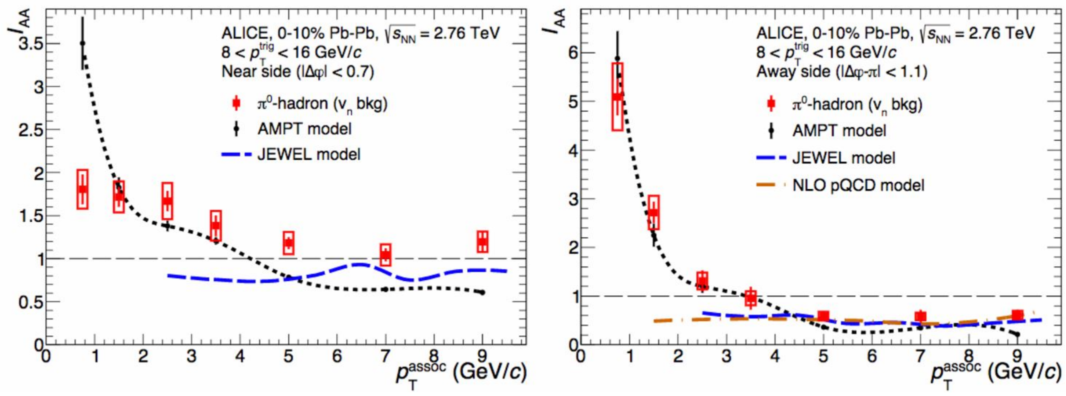


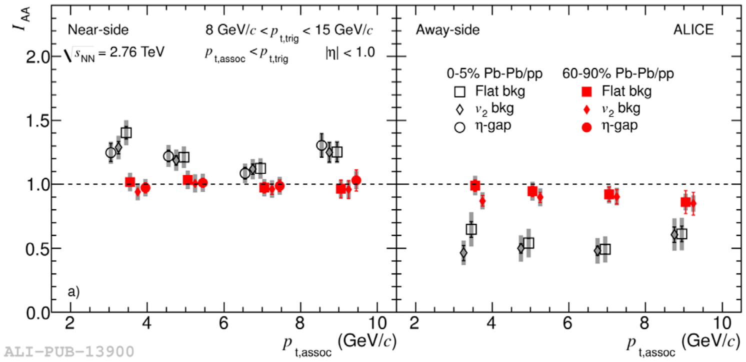
- In LF sector, we already observed:
  - **Away-side suppression at high p_T**
  - **Near side peak enhancement**

  what about HF?

ALICE, PLB 763 (2016) 238

π^0-h correlations





ALICE PRL 108 (2012) 092301

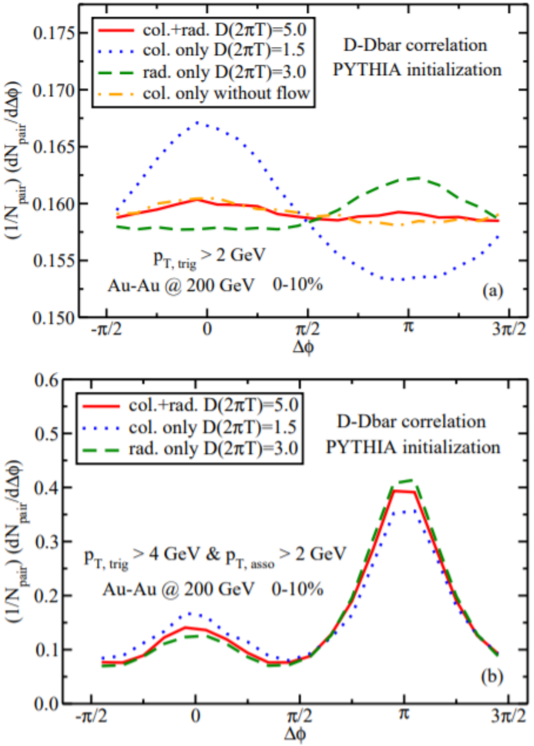
h-h correlations

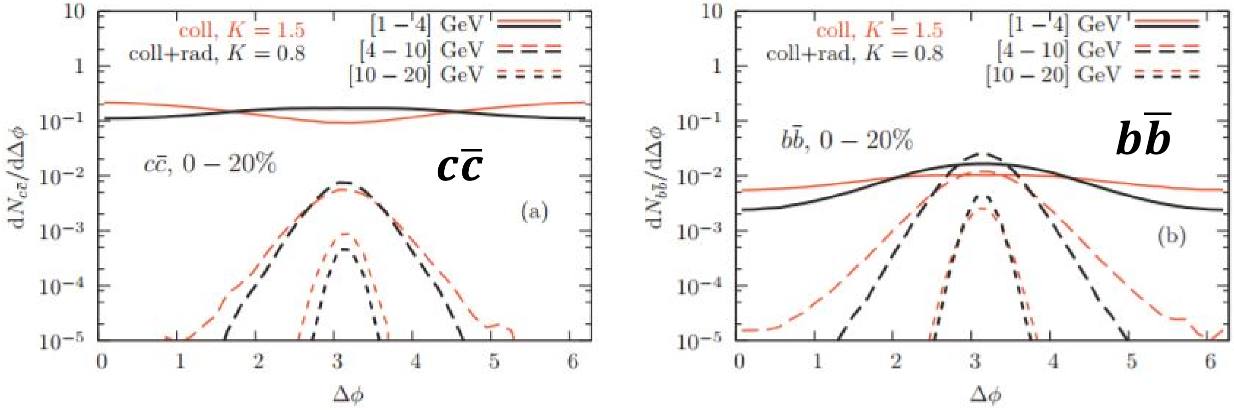
PHYSICS MOTIVATIONS

Pb-Pb collisions

- **Characterise energy-loss** of heavy quarks in QGP medium, with sensitivity to specific ΔE mechanisms
  - ➢ D-Dbar correlations sensitive to parton-level initial angular correlation
- Study **degree of HQ thermalisation** probing low-p_T angular decorrelation from quarks to hadrons

Au-Au @ 200 GeV
→ Initial distrib. From PYTHIA8





Nahrgang et al., Phys. Rev. C 90 (2014) 024907

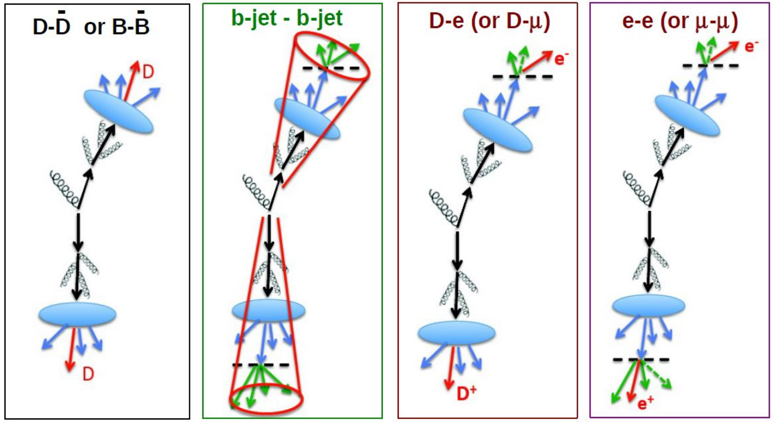
Pb-Pb @ 2.76 TeV, LO only
→ Initial distrib.: Δφ=π

Cao et al, Phys. Rev. C 92, 054909 (2015)

CHOICE OF OBSERVABLES

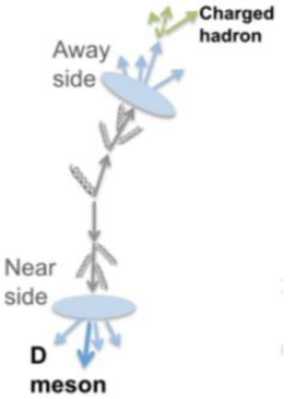
No direct access to heavy quarks:

- ➢ Two kinds of observables, with different feasibility and goals



- **Observables directly tracking $Q\overline{Q}$ angular correlations**:
  - ➢ D–D, Λ_c–Λ_c, B–B, …
  - ➢ c/b jet – c/b jet
  - ➢ HFe/μ – HFe/μ (or mixed hadron-lepton)

    - ✓ Close access to parton kinematics
    - ✓ Huge statistics is needed (possibly w/ dedicated triggers)
    - ✓ More suited for **production mechanism** and **HQ dynamics** studies



- **Observables relating one heavy-flavour particle to the rest of the event**:
  - ➢ D/B/Λ_c – hadron (or identified particle)
  - ➢ HF (e/μ) – hadron (or identified particle)

    - ✓ Access to $Q\overline{Q}$ angular correlations is more indirect and "washed out"
    - ✓ Increased feasibility of the analyses, less statistics required
    - ✓ Better suited for **HQ fragmentation** and **HF jet characterisation** studies

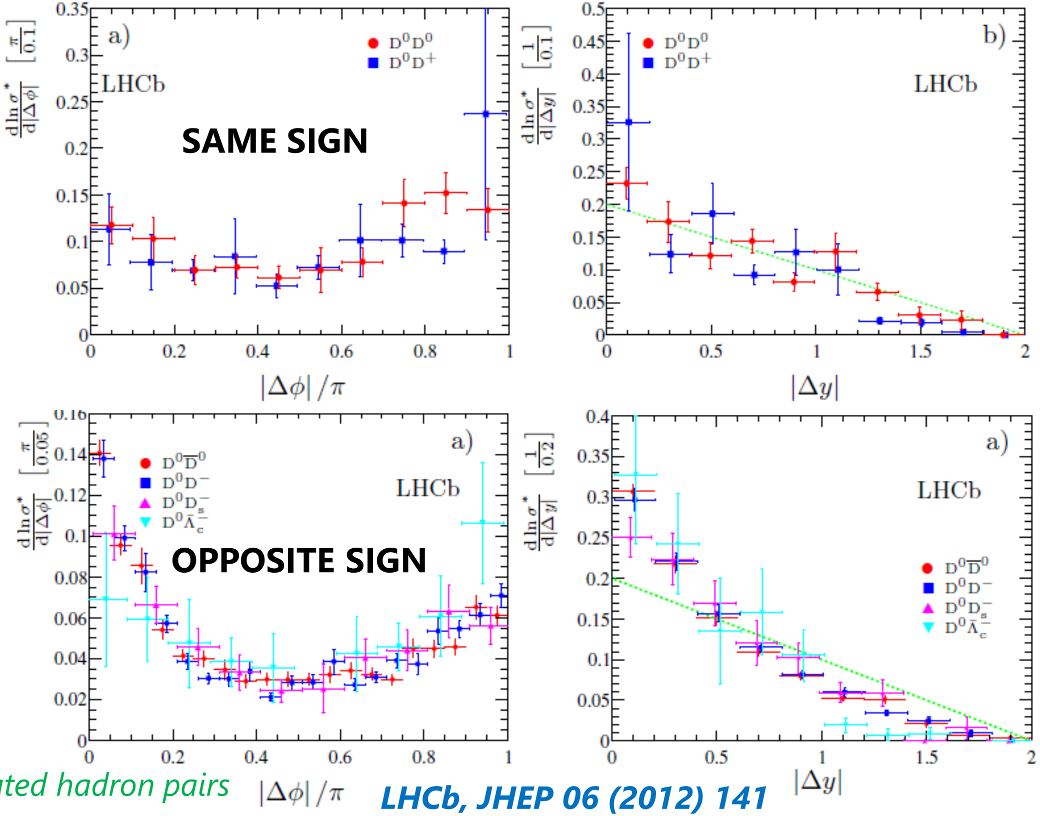
Insights on heavy-quark production mechanisms

HF-HF CORRELATION STUDIES – CHARM

Opposite-sign **charm-hadron correlations** in pp collisions at 7 TeV by LHCb

- Allows for probing the **charm production mechanism**
- Comparison with same-charge correlations highlights the **partonic hard-scattering features**
- Peak at $\Delta\varphi \approx \pi$ from back-to-back production…
- … but also **excess at ≈0** for both $\Delta\varphi$ and $\Delta\eta$ distributions
  - ➢ Points toward important **gluon-splitting** contribution (collimated at high p_T)

D mesons: $2 < y < 4$, $3 < p_T < 12$ GeV/c



Dashed line: expectation for uncorrelated hadron pairs

LHCb, JHEP 06 (2012) 141

HF-HF CORRELATION STUDIES – BEAUTY (FORWARD)

Beauty-hadron pair correlation distributions in pp collisions at 7 TeV at forward *y* by LHCb

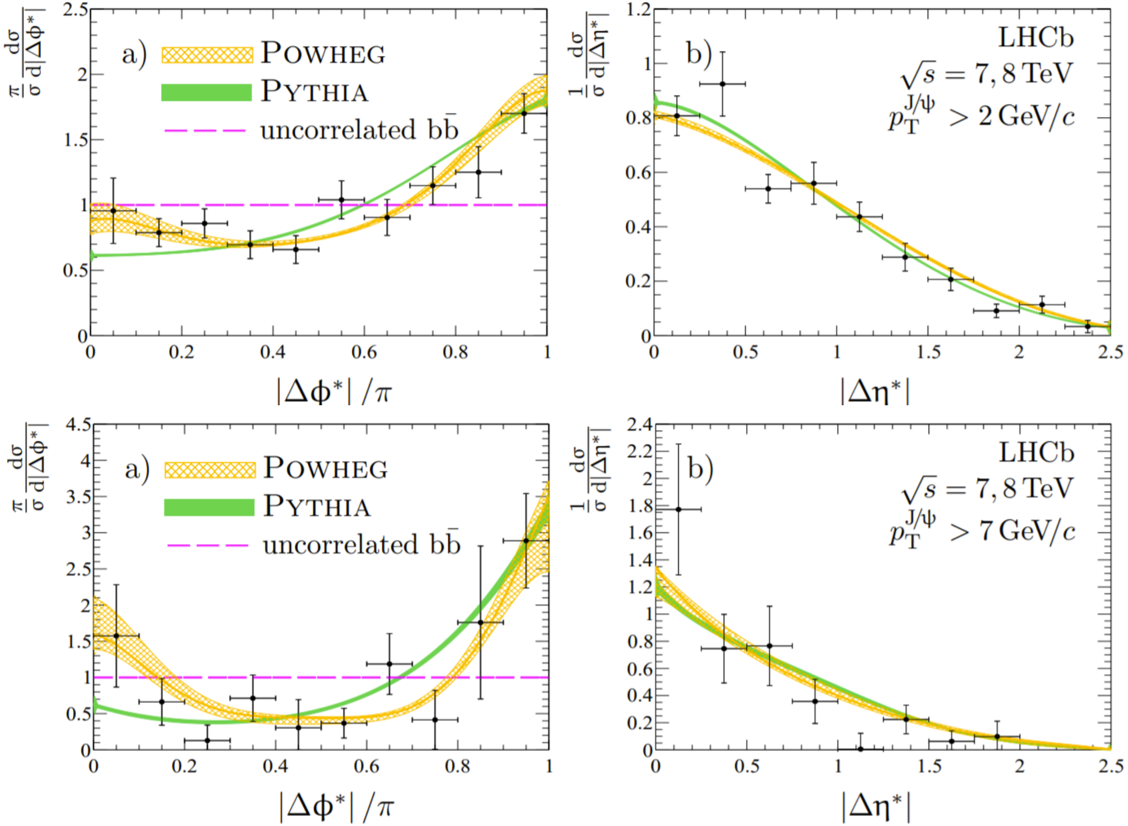
- ➢ From b->J/Ψ+X channel

- 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 (e.g. LHCb, JHEP 06 (2012) 141)
  - ➢ NLO contributions **less relevant for beauty** than for charm production

- Results are described by POWHEG (NLO) and PYTHIA (LO matrix elements) generators within uncertainties
  - ➢ Larger NS contribution by POWHEG, but difference significant only at high p_T

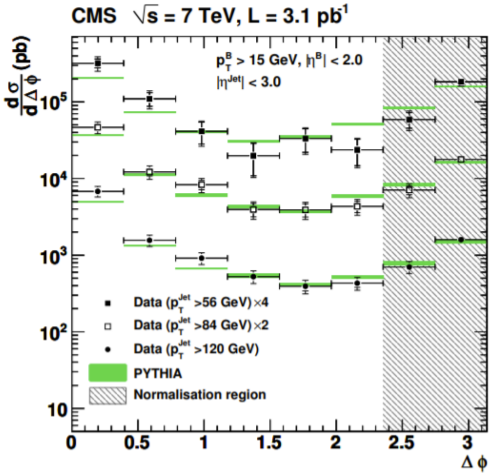
LHCb, JHEP 1711 (2017) 030

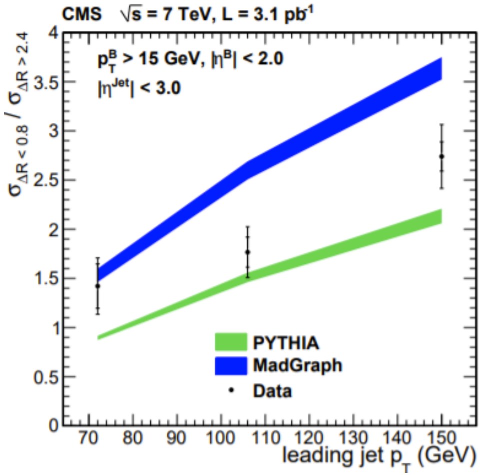


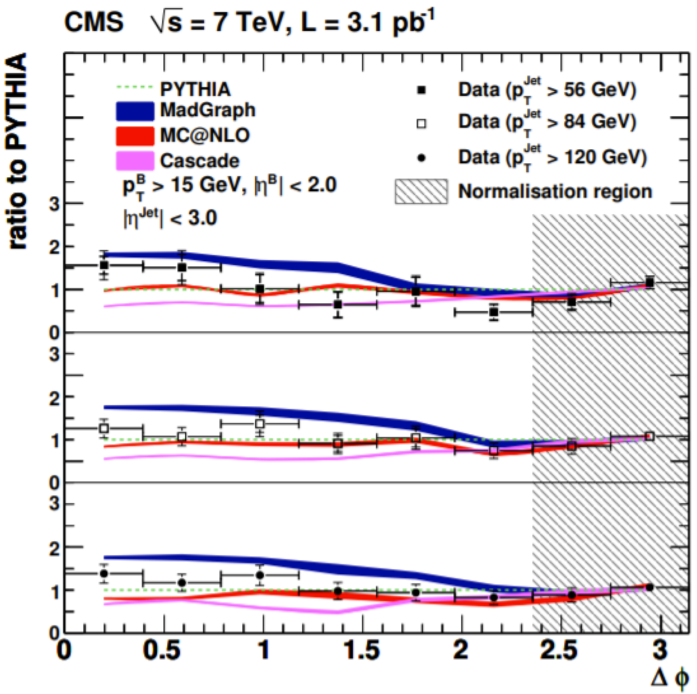
HF-HF CORRELATION STUDIES – BEAUTY (CENTRAL RAP.)

beauty-hadron pairs also measured by CMS in pp at 7 TeV, at midrapidity, from secondary vertex reconstruction

- Relevant fraction of $B\bar{B}$ pairs produced with **small angular distance**
  - ➢ Differently from LHCb, but different rapidity and much larger p_T
- Fraction of collinear production **increases with p_T(jet)**
  - ➢ More ‘room’ for *g* radiation, also confirmed by models/calculations
- Data lie in-between MadGraph and MC@NLO predictions

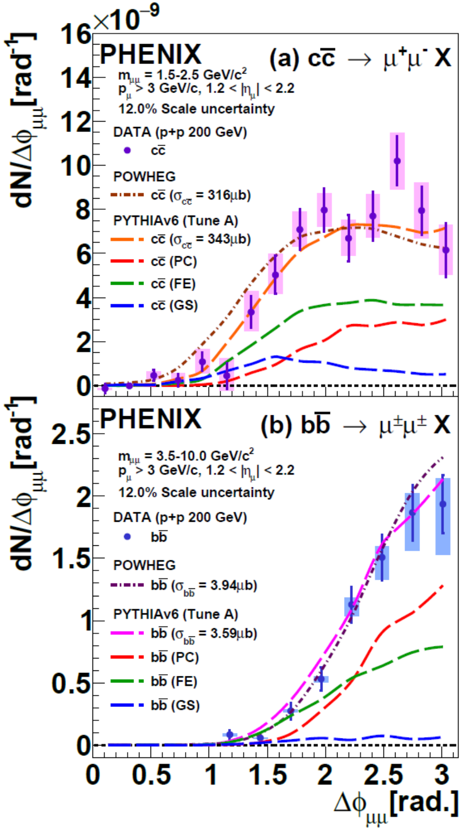






CMS, JHEP 03 (2011) 136

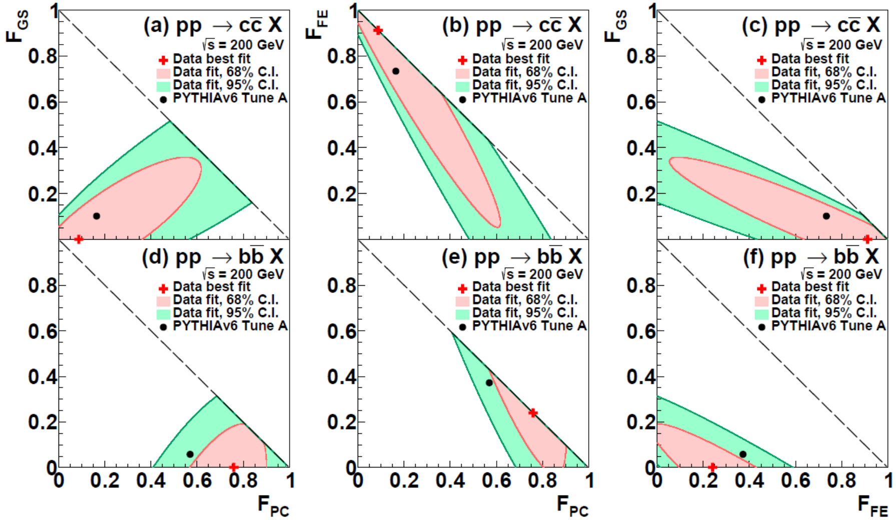
HF-HF CORRELATION STUDIES – HF LEPTONS



PHENIX, arXiv:1805.04075

Complementary view, at lower $\sqrt{s}$, from **HF lepton pair** azimuthal correlations by PHENIX

- For muons (forward η), also beauty/charm origin separation via LS/ULS combinations
- Large **back-to-back contribution** observed, in particular for $b\bar{b}$
- Fitting with PYTHIA8 templates for different $c\bar{c}$, $b\bar{b}$ prodution mechanism



- Simultaneous shape analysis of all result sets allows for constraining **GS/FE/PP fractions**
  - NLO mechanisms **are relevant for $c\bar{c}$** (FE dominates)
  - **Smaller for $b\bar{b}$** at this energy (24%, mainly FE)

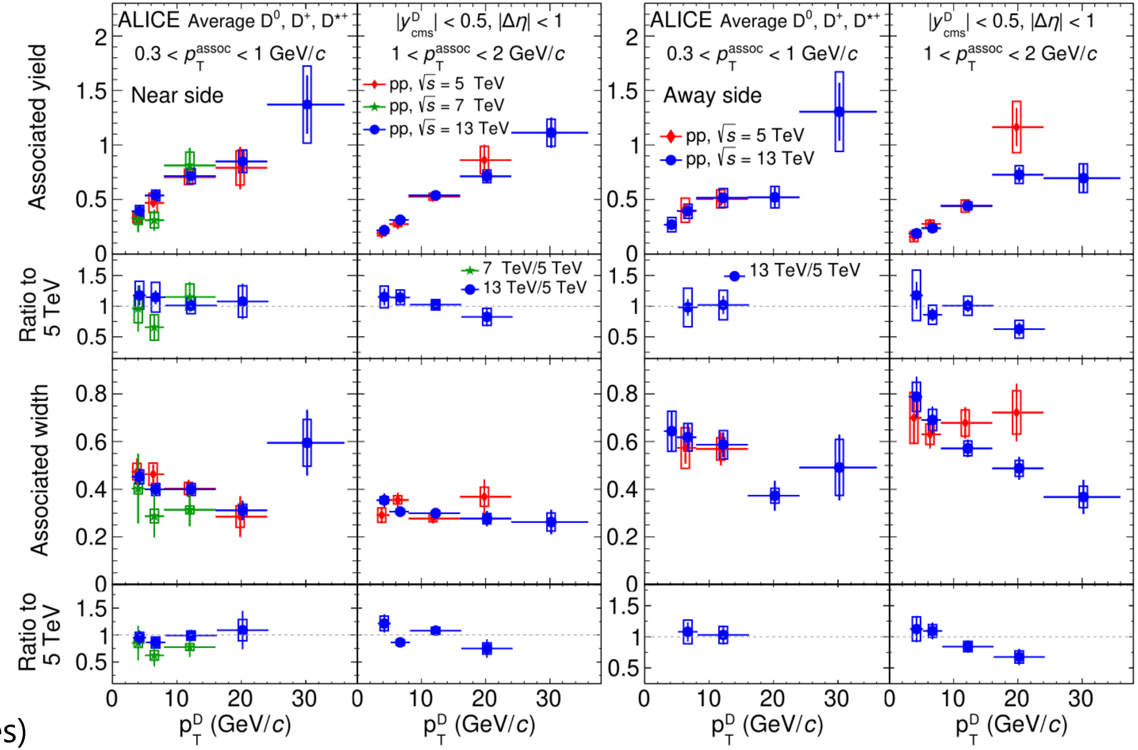
Characterisation of heavy-quark fragmentation and hadronisation

D MESON – HADRON CORRELATIONS IN pp

Main focus on **charm fragmentation** by studying features of near-side (NS) region
Away-side (AS) studies provide info on **production processes** and **hard-gluon radiations**

ALICE, arXiv:2110.10043v1

Comparison of peak features vs cms energy, from results at √s = 5.02, 7, 13 TeV



General features

With increasing p_T^D :

- **More energetic parton** → more phase space for other fragmenting particles
  - ➢ Complementary to D^0-jets $z_{//}$ softening at increasing $p_{T,jet}$
- Larger heavy-quark boost
  - ➢ Increased **peak collimation**

No sizable energy dependence within total uncertainties

- Confirmed by studies with PYTHIA8 and POWHEG+PYTHIA8 (10-15% max differences)

D MESON – HADRON CORRELATIONS IN pp

Comparison of NS (and AS) yields and widths with several model predictions

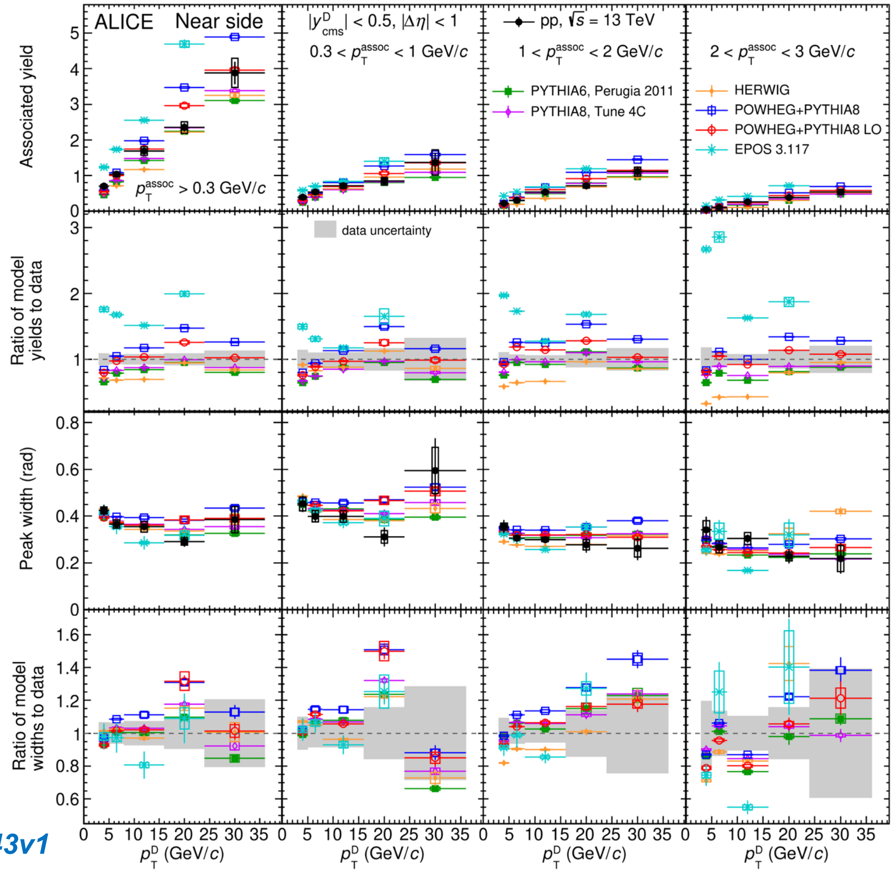
- ➢ Different shower ordering, hadronisation approach, MPI treatment, UE description

NS yields:

- PYTHIA8 and POWHEG+PYTHIA8 both provide an overall good description
  - ➢ POWHEG+PYTHIA8 > PYTHIA8, data lying in-between
- HERWIG tends to underestimate the NS yields at low p_T(D) and at high p_T(assoc)
- EPOS overestimates the yields in the addressed p_T range

NS widths:

- Overall, all models describe the peak width within uncertainties



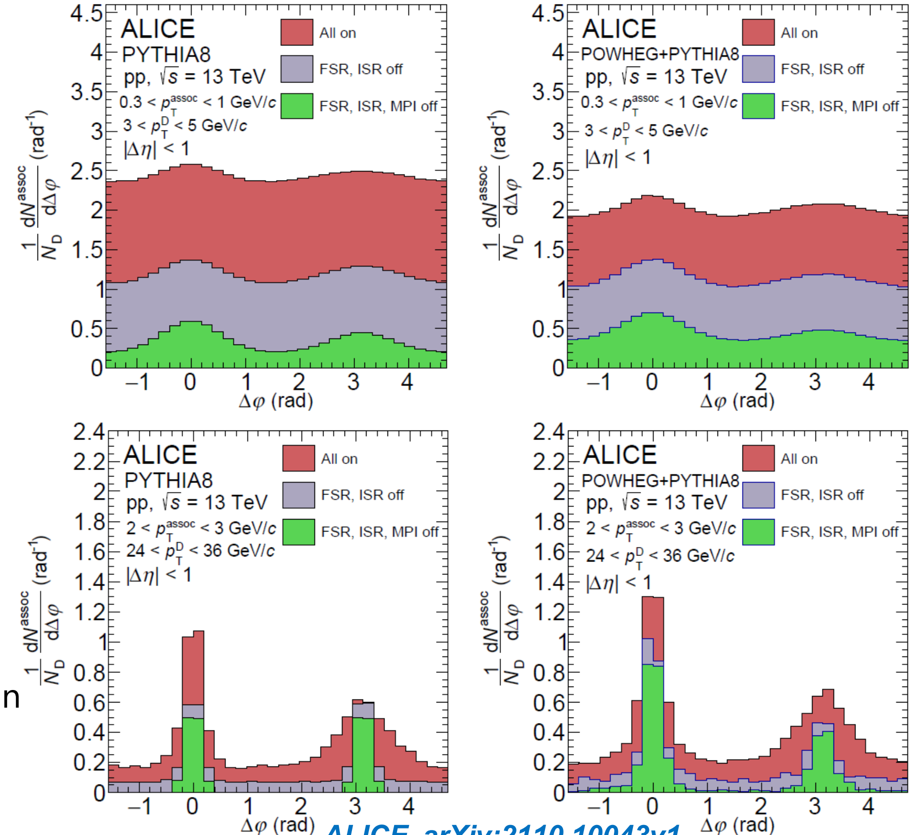
ALICE, arXiv:2110.10043v1

PARTON-LEVEL STUDIES

Breakdown of D-h correlation with parton-level processes sequentially suppressed, to understand how the step-by-step correlation function builds up in MC generators

All on → PYTHIA standard configuration
FSR, ISR off → without parton shower
FSR, ISR, MPI off → direct focus on hard-scattering products (+ hadronisation & decays)

- **Larger (and wider) NS peak** + higher "HS baseline" region from pure-NLO generator (POWHEG) in **FSR,ISR,MPI off**
- PYTHIA8 showering reconciles the differences for the widths, and partially for the yields
- **FSR+ISR off**: suppressed radiation from opposite-side parton
  - ➢ **AS cone smaller**, especially for Pythia8

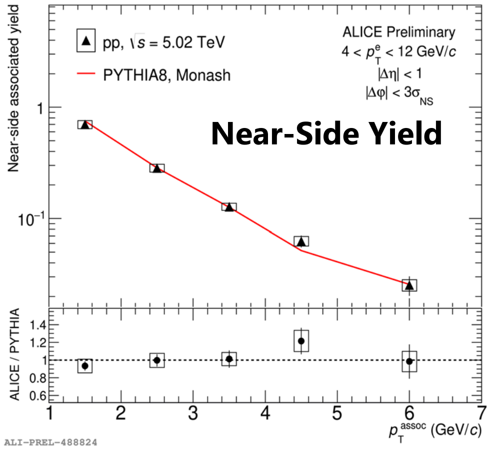


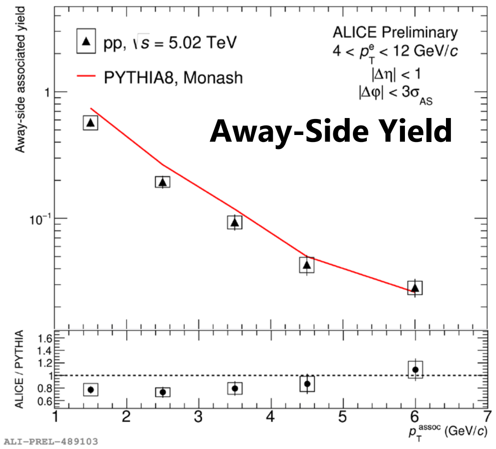
ALICE, arXiv:2110.10043v1

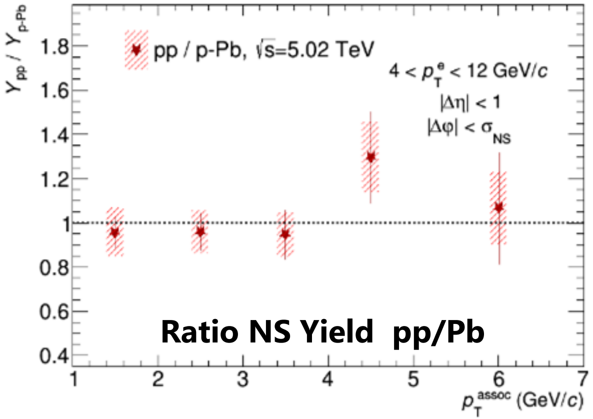
HFe – HADRON CORRELATIONS IN SMALL SYSTEMS

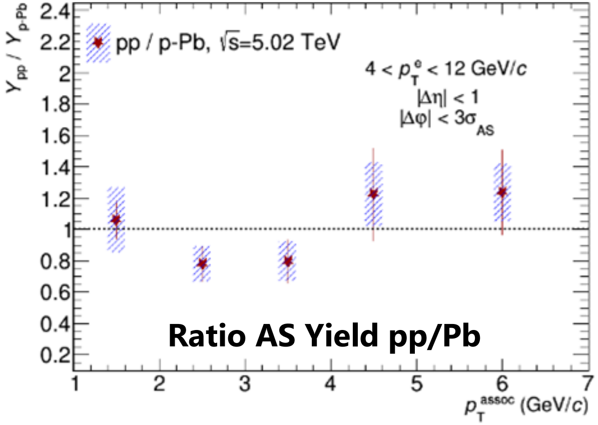
Additional insight on HQ fragmentation from **HF semileptonic-decay electron** correlation measurements.

- More diluted connection to HQ pair (due to decay kinematics + parton-hadron p_T scale), but better statistical precision + higher p_T reach
- Gives access also to **beauty** (dominant above 5-6 GeV/c)







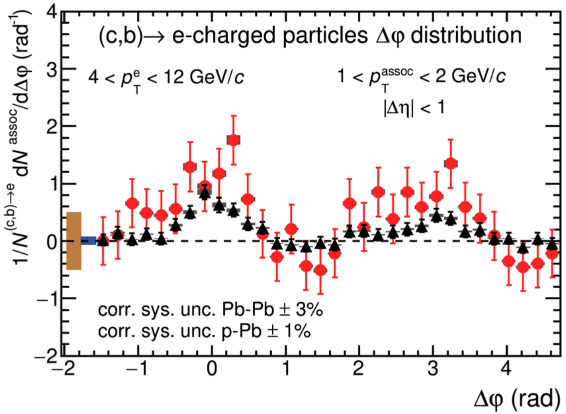


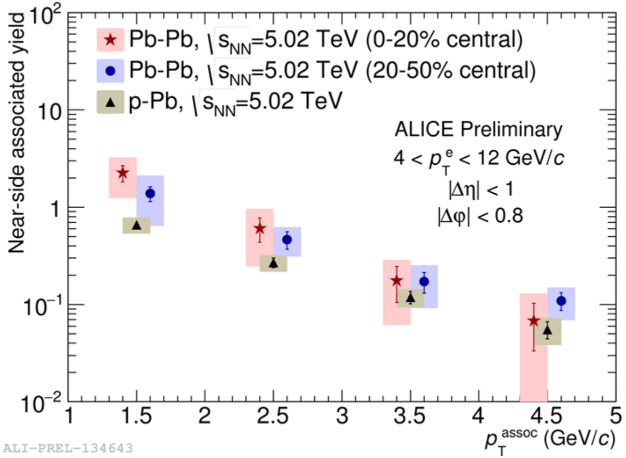
- Pythia8 predictions provide a consistent description of pp results
- **I_{AA} of both peaks compatible with unity:** No clear evidences of CNM effects

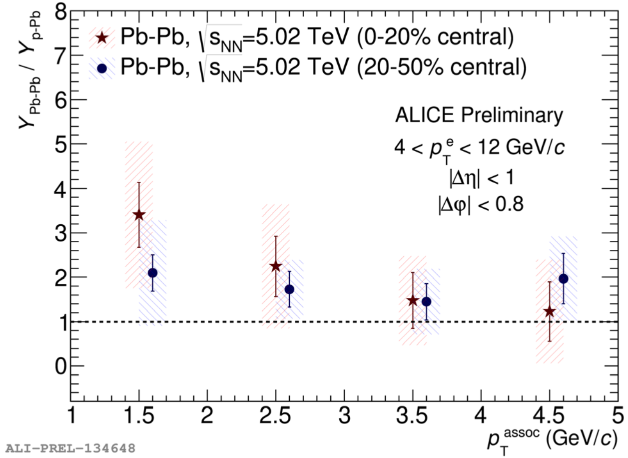
HFe – HADRON CORRELATIONS IN Pb-Pb

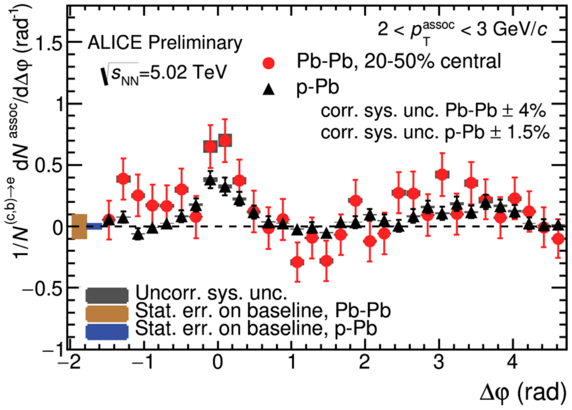
Study yield modifications to HFe-h from in-medium effects

- Hints of **NS yield hierarchy** among collision systems, at **low p_T^{assoc}**, though with large uncertainties
- **Similar features** for HF and LF quarks, but different fragmentation, energy loss in medium, kinematic bias! **I_{AA} not directly comparable**
  - ➢ Model predictions would be very helpful as a link to parton dynamics







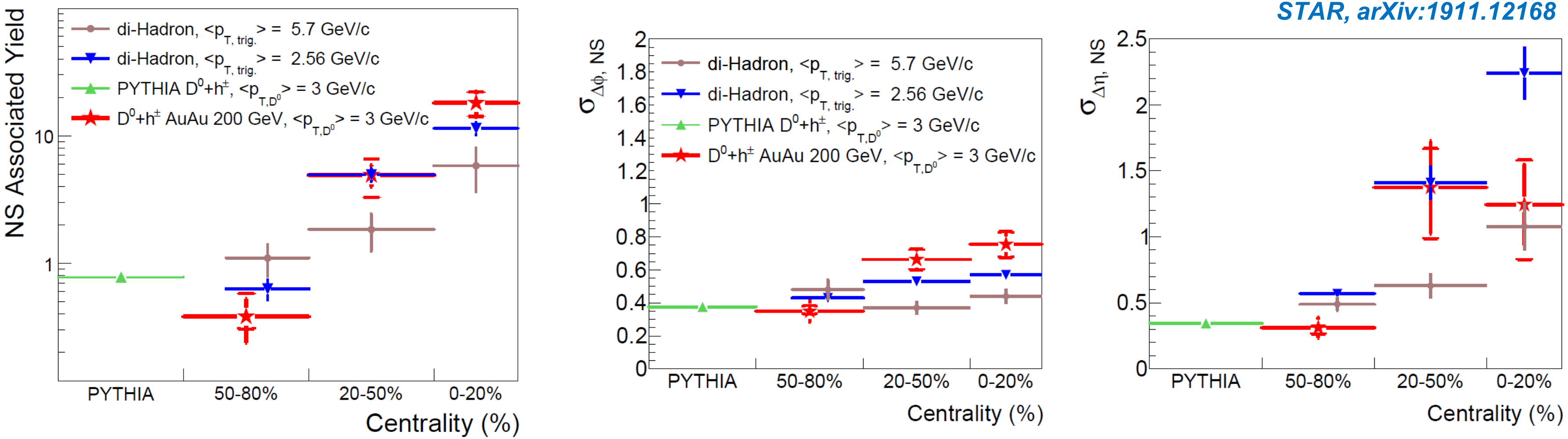


D^0 – HADRON CORRELATIONS IN Pb-Pb

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

- NY yields consistent with PYTHIA for peripheral events, then **large enhancement** in more central events, though with large uncertainties (qualitatively similar to ALICE HFe-h)
- NS enhancement **consistent with di-hadron results** in similar p_T range (smaller increase at higher p_T for LF)
- **Broadening of NS peak** observed for increasing centrality

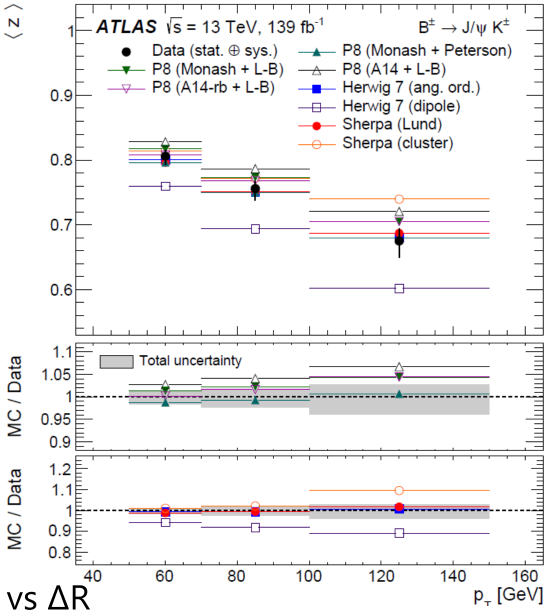
STAR, arXiv:1911.12168



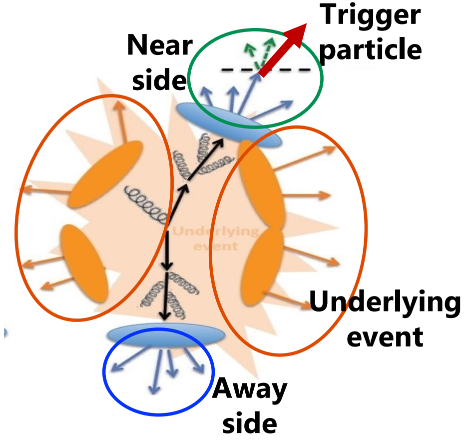
FURTHER IDEAS AND POSSIBLE DEVELOPMENTS

LHC Run3 will pave the way for **b-hadron vs charged-particle** correlation studies

- Investigation of **beauty-quark fragmentation** into final-state jet
  - ➢ Additional insight on measured larger <z> of b-hadrons w.r.t. parton
- If Pb-Pb system is also accessible
  - ➢ Alternate approach for **mass dependence** of **partonic energy loss** w.r.t. R_{AA}



ATLAS, arXiv:2108.11650



Complete **characterization of charm fragmentation** (+ away-side peak studies) via D-h correlations

- Extension of p_T reach and improved precision
- Bidimensional (Δφ, Δη)-dependent analysis + studies vs ΔR
  - ➢ Complementary observable to radial displacement of D-jets
- Perform analysis in **Pb-Pb** at LHC energies
  - ➢ Probe peak modifications and compare to light-flavour
  - ➢ Study **spatial redistribution** of energy lost by the charm quark

FURTHER IDEAS AND POSSIBLE DEVELOPMENTS

In Run2, observed **enhanced Λ_c^+ production** w.r.t. D^0 in pp + hint of more radially displaced Λ_c^+ from jet axis, compared to D^0

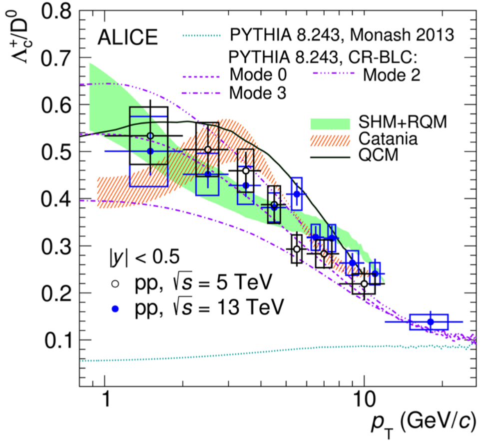
- Modification of the charm fragmentation and hadronisation with baryon production

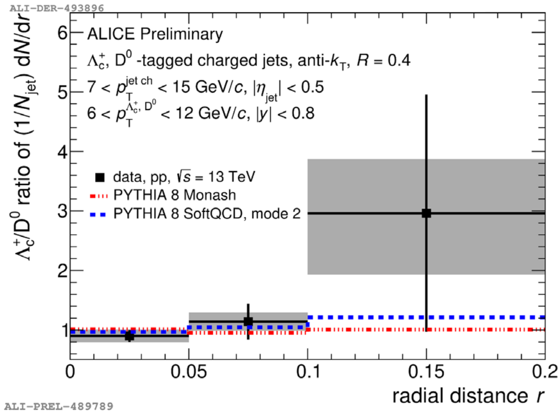
According to Catania, QCM models, **coalescence** mechanism (also) contributes to charm hadronisation **also in pp**, enhancing baryon production:

- Is the **final-state jet** modified by coalescence effects?
  - ➢ Naively expecting a reduced number of accompanying particles

Λ_c^+-h correlations should be **sensitive** to such aspects

- Perform measurement in pp and compare with fragmentation-only models
- Would be interesting to have **predictions** for Λ_c^+-h from coalescence models
- Ideally, measure is also very interesting in **Pb-Pb** to probe nuclear medium effects on fragmentation and hadronization (→ similar arguments hold for D_s^+-h)





EXTENSION TO HEAVY IONS FOR HF-HF OBSERVABLES

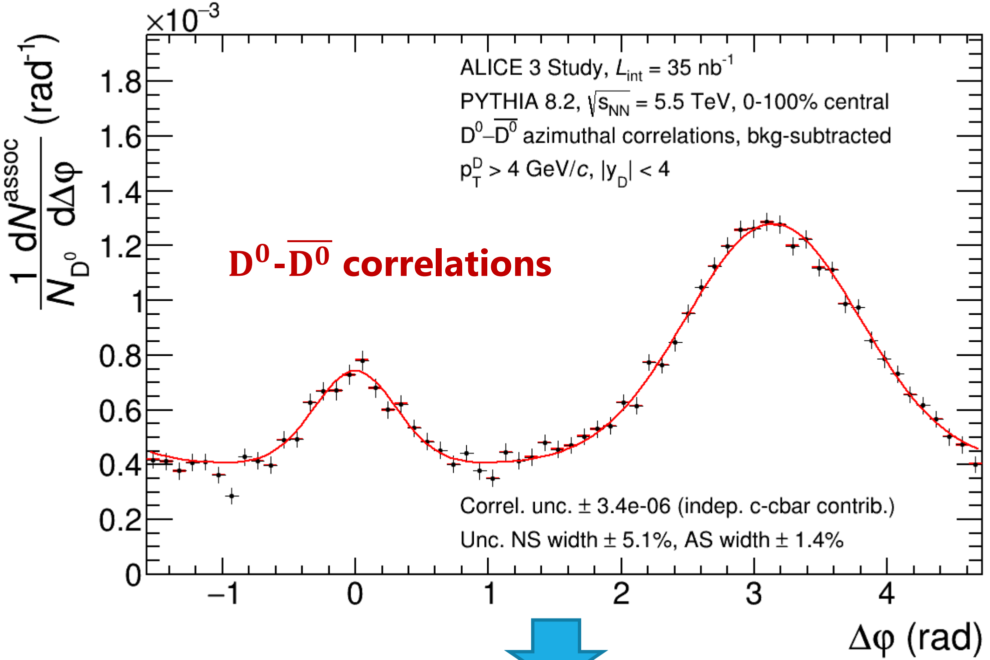
Extension of HF-HF measurements to **Pb-Pb collisions** is more challenging

- Rare probes + large combinatorial background + large contribution from uncorrelated $Q\bar{Q}$ pairs

Some results could be obtained already during LHC Run3+4, though good precision would be important

Longer-term timeline:

- Excellent capabilities from **ALICE 3 detector**, under proposal, to probe such observables
  - ➢ Very large η acceptance, possibly up to 8 units
  - ➢ Excellent low p_T tracking and secondary-vertex resolutions
  - ➢ Optimal PID capabilities for bkg rejection



Low-p_T reach crucial for:

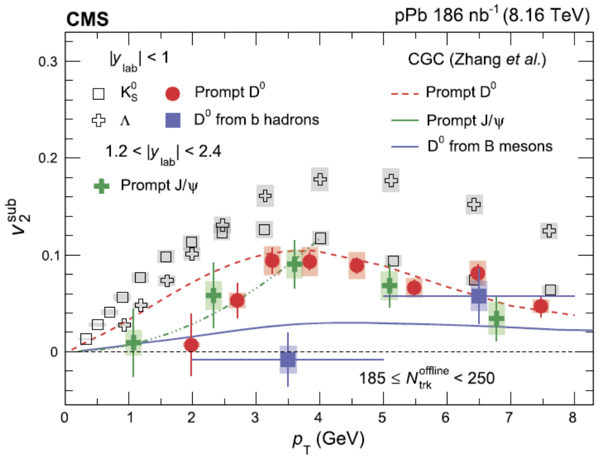
- Sensitivity to energy loss mechanisms,
- Strength of thermalization via pair decorrelation

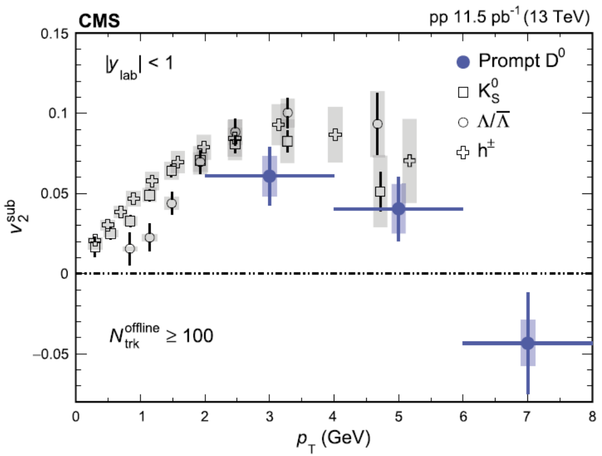
Collectivity in small systems

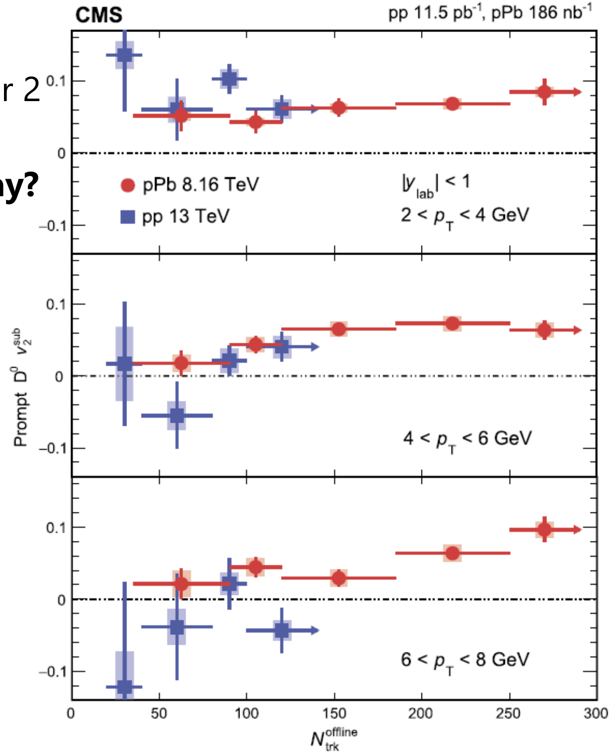
HF ELLIPTIC FLOW IN pp, p-Pb HM

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 (with decreasing trend in LM events), and in pp for $2 < p_T < 4$ GeV/c (significant for $N_{trk} > 100$)
  - ➢ Similar values and p_T trend in pp/p-Pb at same N_{trk}: **Same mechanism at play?**
  - ➢ Slightly smaller v_2 w.r.t LF hadrons
  - ➢ In p-Pb, **similar values as J/Ψ**: v_2 of D^0 not just driven by light quark
- **Non-prompt D^0**: results **consistent with no flow**, with large uncertainties







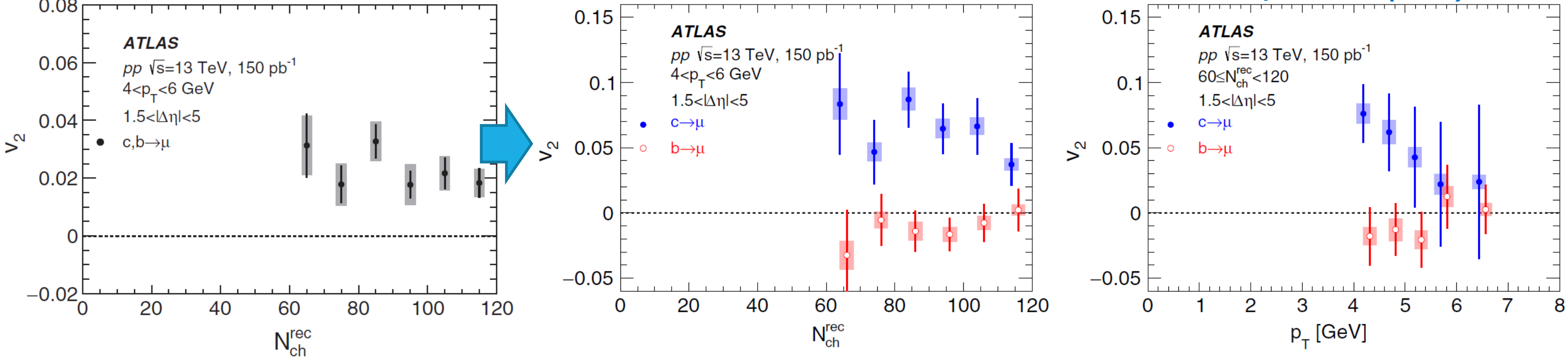
CMS, PLB 813 (2021) 136036

HF ELLIPTIC FLOW IN pp

Elliptic-flow coefficient of HF muons in pp collisions at 13 TeV, from long-range two particle correlations with $1.5 < |\Delta\eta| < 5$

- **Charm-origin muons**: significant **non-zero v_2**
  - Decreasing with increasing muon $p_{T,}$ similar to CMS D^0 results, with different p_T scale
  - **Flat behaviour** vs event multiplicity (no signs of decrease down to $N_{ch,rec} = 60$)
- **Beauty-origin muons**: v_2 **consistent with zero**
  - No signs of collective-like effects for beauty in small systems (ATLAS + CMS results)
  - Different from Pb-Pb, where open beauty flows

ATLAS, PRL 124 (2020) 082301

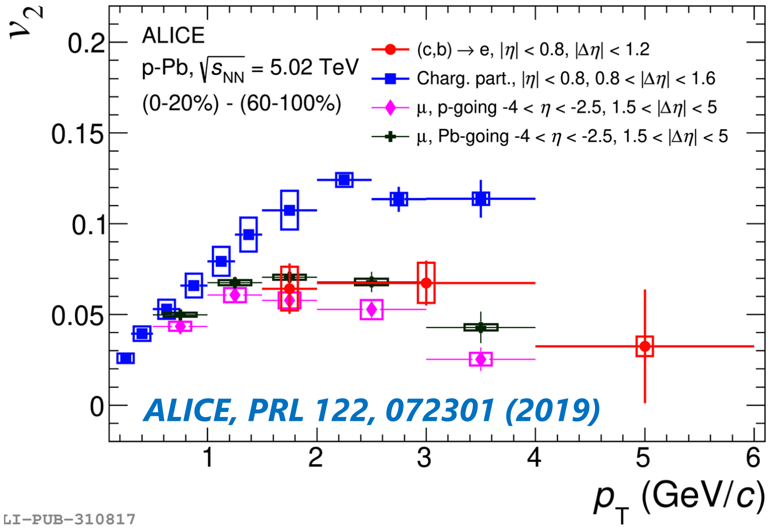


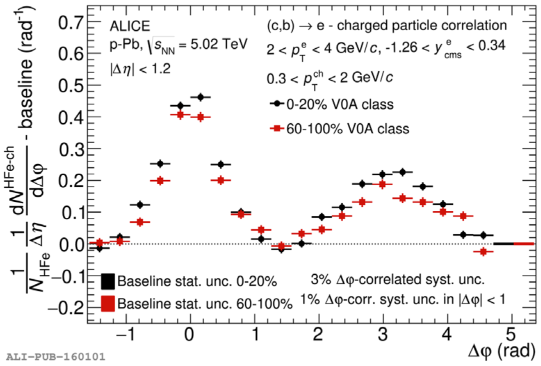
HF ELLIPTIC FLOW IN p-Pb

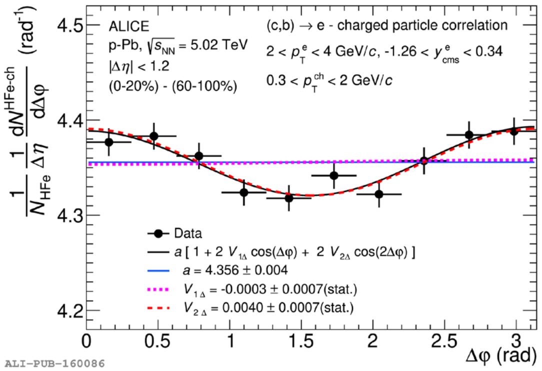
v_2 coefficient of heavy-flavour decay electrons with charged particles in 0-20% p-Pb collisions by ALICE

Positive v_2 for HFe (4.4σ effect for $1.5 < p_T^e < 4$ GeV/c)

- Results **consistent with HFμ** measurement (at forward rapidity)
- Strength of v_2 comparable or slightly lower than di-hadron results
  - ➢ Note: different parton-particle p_T scale + decay kinematics
  - ➢ Similar to CMS results for D^0 v_2







From collective motion in HM collisions due to **final state effects** (QGP droplet)?

Or related to **initial-state effects**, e.g. gluon saturation in CGC fremwork?

Puzzle still open!

SUMMARY

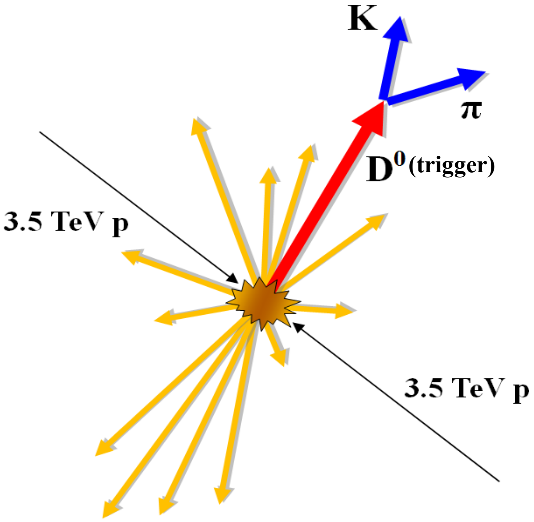
- HF correlations act as a more differential study for probing heavy quark **production**, **fragmentation** and **hadronisation**, and their modifications in a QGP environment
- HF-HF measurements at LHC energies point toward **relevant contribution of NLO processes** for charm, LO still the dominant production process for beauty
- Precise **characterisation of jet-induced correlation peak** in pp, from D-h, HFe-h studies
  - ➢ Complementary to HF-jet studies, allow to set contraints to model predictions
  - ➢ In Pb-Pb central events, signs of significant **ehancement of near-side peak**, similar to what observed for light flavours
- **Collective-like effects** in small systems at HM observed also for **charm**, no signs of it for beauty
  - ➢ Puzzle on its origin is still open
- Wealth of new results expected in **Run3+4** and beyond due to larger data samples and improved detectors
  - ➢ In particular for **heavy-ion collisions**, with peculiar sensitivity to microscopic HQ dynamics, quenching, and hadronisation modification
  - ➢ Useful to have **model predictions** on expected correlation observables!

Backup

HF CORRELATIONS – INTRODUCTION

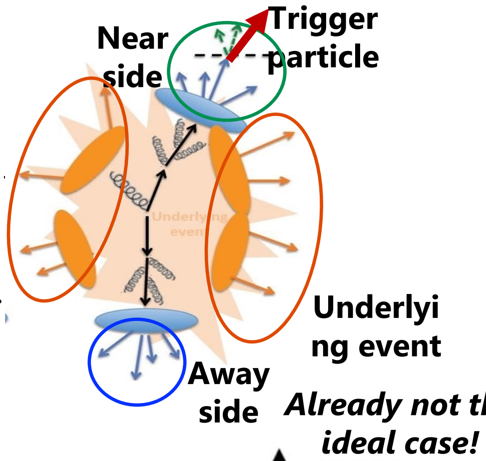
- **HF correlations**: allow to gain further insight on heavy quarks w.r.t. single particle studies, by relating heavy-flavour particles to the rest of the event:
  - The parent heavy quark and the other tracks from its fragmentation
  - The other heavy quark in the event, and its fragmentation particles
  - The underlying event (mainly softer particle production)

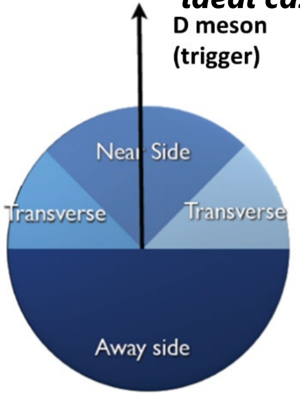
- Access to complementary information w.r.t. "standard" HF observables, in particular:
  - Heavy quark **production** mechanisms
  - Heavy quark **fragmentation** and jets
  - **Dynamics of HQ** and their interaction with the nuclear medium in heavy-ion collisions
  - Heavy quark **elliptic flow** in small systems via correlations with hadrons



ANGULAR CORRELATIONS - GENERAL FEATURES

- Select an heavy-flavour particle (*trigger particle*) and correlate it to other particles, specific or generic, in the event (*associated particles*)
  - i.e. «count» the number of associated particles vs $\Delta\varphi = \varphi_{trig} - \varphi_{assoc}$, $\Delta\eta = \eta_{trig} - \eta_{assoc}$
- Three main region can be identified in angular (azimuthal) correlation distributions.
- Ideal and simplest case: LO production (back-to-back), no gluon radiation from parton, negligible angular opening between HF quark and trigger particle. In this situation:
  - **Near-side region** (peak at $\Delta\varphi=0$) → tracks from the jet containing the trigger
  - **Away-side region** (peak at $\Delta\varphi=\pi$) → tracks from fragmentation of the other HF jet
  - Correlations to underlying event tracks (flattish in $\Delta\varphi$), produces a **pedestal** on top of which peaks develope





ANGULAR CORRELATIONS - GENERAL FEATURES

- Things are not so simple in reality… For example:
  - **NLO production processes** or **gluon radiation** from heavy quarks $\rightarrow$ broadening of away-side peak w.r.t. near-side (wider and lower AS peak)
  - **Gluon splitting process** $\rightarrow$ correlations with underlying event tracks have a **bump in the AS** (tracks from recoiling gluon). In addition, if the heavy quarks are collinear, near-side peak shape is altered
  - **Non-zero opening angle** between HF particles and heavy quarks smears the correlation peaks
  - Under the baseline also **correlations with HF tracks** are present (mainly from NLO processes)
  - **Partonic energy loss** in the medium can lead to **suppression of away side** (*surface bias*)

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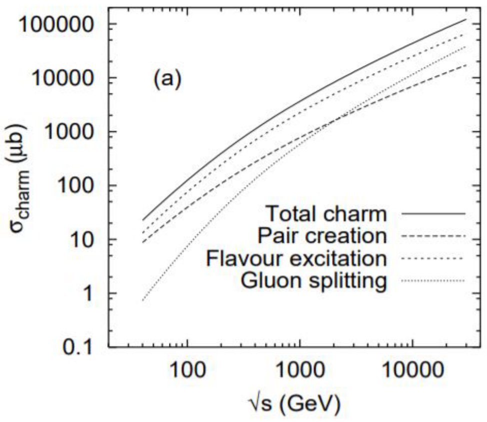
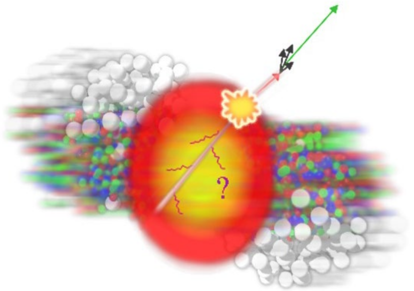
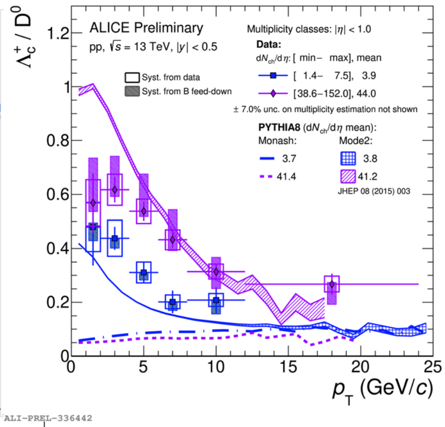




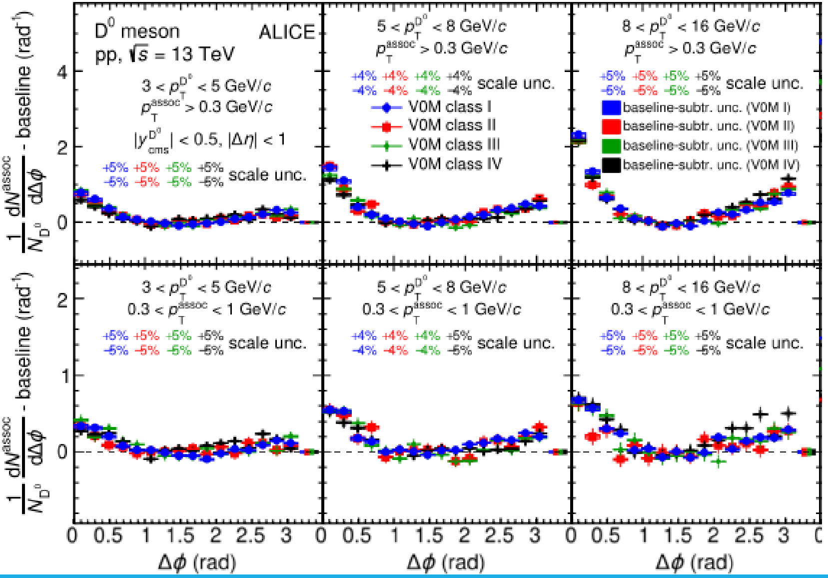
D-h: STUDIES VS MULTIPLICITY (pp)

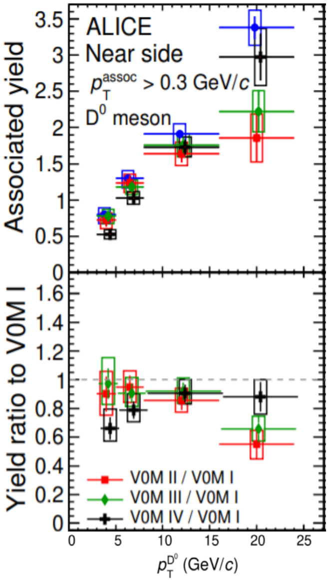
Observed **multiplicity-dependent effects** on HF production (e.g. self-norm-yields) and baryon/meson hadronisation (Λ_c/D^0 ratios).

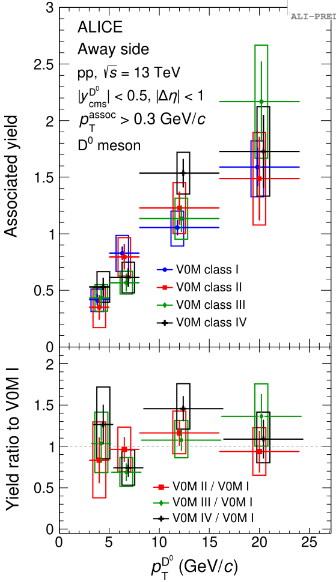


What about charm fragmentation and hadronisation into D mesons?

- ➢ From D-h studies, no clear modification of charm jet fragmentation vs multiplicity within uncertainties (at least when a D meson is produced)



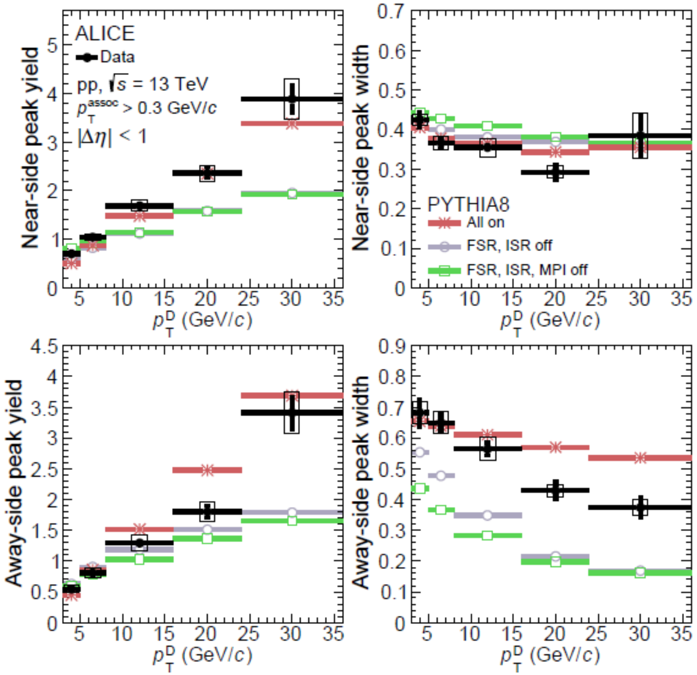




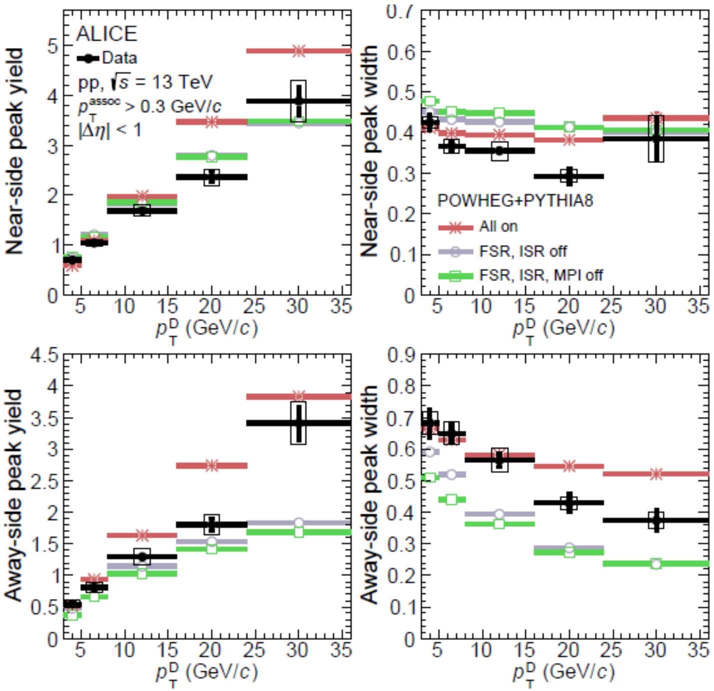
PARTON-LEVEL STUDIES

More quanitative view of previous results, as a function of trigger p_T

PYTHIA 8



POW+PYT 8



- At high p_T, larger HS+hadronisation contribution (over 50%) from POWHEG+PYTHIA8 in the NS w.r.t. PYTHIA8
- **FSR+ISR off**: suppressed radiation from opposite-side parton
  - **AS cone smaller**, especially for Pythia8
  - NS cone not significantly modified

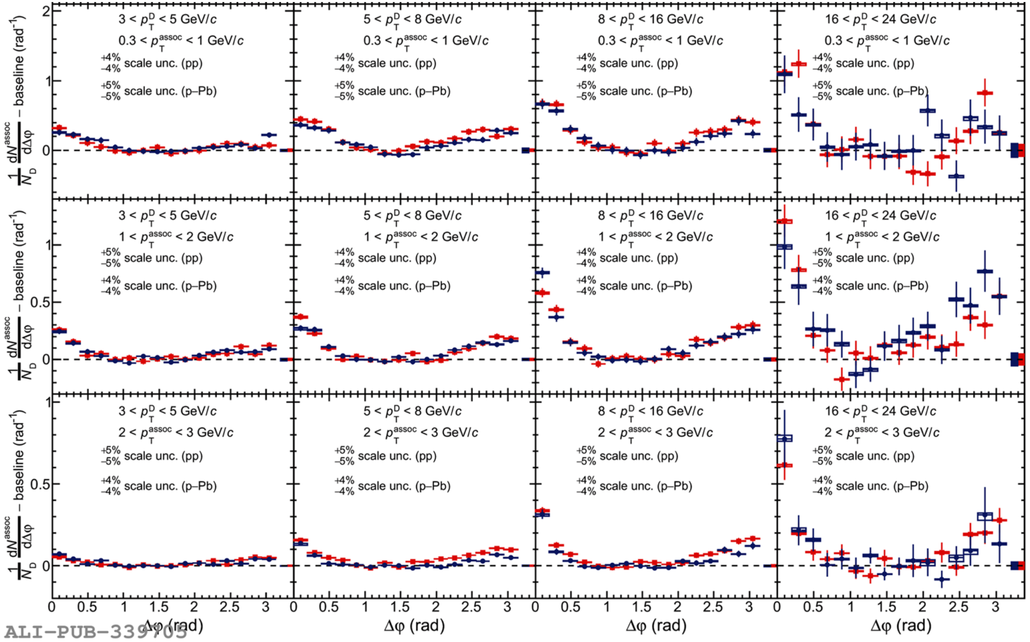
D MESON – HADRON CORRELATIONS IN p-Pb

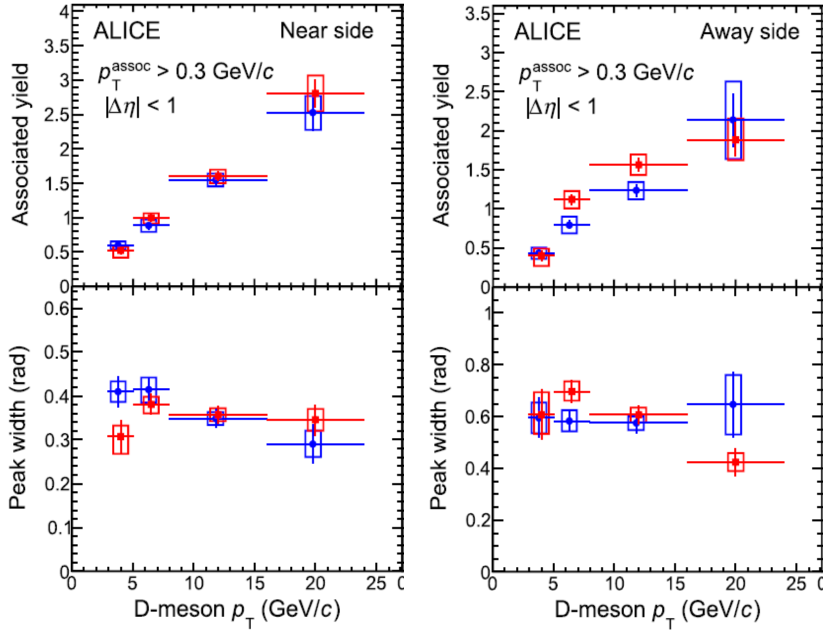
No significant modification of Δφ shape and peak observables from CNM effects

- Fragmentation of c quark into D meson + surrounding jet **consistent within uncertainties** in pp and p-Pb

pp @ 5.02 TeV **p-Pb @ 5.02 TeV**

ALICE, EPJ C 80 (2020) 979





Consistent features of correlation pattern and peaks observed also in **studies vs collision centrality** (not shown)

HF v2 WITH ALICE: FUTURE PERSPECTIVES

Anisotropic flow studies in small systems

- HFe-h: estimates on x170 larger p-Pb sample
  - ➢ Largely improved precision + extension of the measurement down to $p_T^e = 0$;
  - ➢ D-h measurement also in our plan → even in high-multiplicity pp if a sample of L_{int} = 200 pb^{-1} is taken
  - ➢ Is it possible to do the study also for charm baryons? Quantitative estimates not available yet
- Ideally, also perform a scan vs event multiplicity to study behaviour at lower multiplicities