OPEN HEAVY-FLAVOUR MEASUREMENTS WITH ALICE AT THE LHC

Fabio Colamaria, for the ALICE Collaboration

QCD@Work – Matera – 25/06/2018
HEAVY-FLAVOUR PRODUCTION

Open heavy flavour in Pb-Pb collisions

Heavy quarks experience the full evolution of the hot and dense medium produced in ultra-relativistic heavy-ion collisions → Excellent probes of the Quark-Gluon Plasma (QGP)

In particular, heavy quarks are expected to:

• Lose less energy w.r.t light quarks and gluons due to different Casimir factor and dead-cone effect
  ➢ Microscopic study of medium and characterisation of energy loss mechanisms

• Be influenced by the collective motion of the partons inside the medium
  ➢ Provide information on medium transport properties

• At low $p_T$, possibly hadronise also via coalescence:
  ➢ Modified momentum distribution of HF hadrons
  ➢ Enhanced $v_2$ of HF hadrons (light quark contribution)
  ➢ Modified hadrochemistry ($D_s^+, \Lambda_c^+$ enhancement)
HEAVY-FLAVOUR PRODUCTION

Studies of heavy-flavour production important also in smaller systems

**pp collisions**
- Test and set constraints on pQCD calculations for charm and beauty quark production
- Probe parton distribution function (especially for gluons) at low values of Bjorken $x$
- Reference for studies in p-Pb and Pb-Pb collisions

**p-Pb collisions**
- Heavy-flavour production and kinematic properties can be modified by:
  - Cold nuclear matter effects, like shadowing, gluon saturation, Cronin effect, possible energy loss mechanisms
  - "Collective-like" effects (e.g. elliptic flow), resembling what observed in heavy-ion collisions, which is ascribed to the hydrodynamic expansion of the system

In all collision systems, **more differential measurements** (as HF correlations, jets) can provide further information than single-particle studies, and a closer access to the heavy parton properties. 
HEAVY-FLAVOUR RECONSTRUCTION WITH ALICE

The ALICE Detector

- **V0**: trigger + centrality/multiplicity estimation + event characterization
- **ZDC**: centrality estimation
- **ITS**: tracking + vertexing
- **TPC**: tracking + PID
- **TOF**: PID
- **EMCAL**: high-$p_T$ trigger + electron ID
- **Forward muon spectrometer**: trigger + tracking

Open heavy flavour

Charmed hadrons ($|y| < 0.5$)
- $D^0 \rightarrow K^-\pi^+$
- $D^* \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+
- $D^{+}_s \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+
- \Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c \rightarrow pK^0_s, K^0_s \rightarrow \pi^+\pi^-
- \Lambda_c^+ \rightarrow e^+\Lambda\nu, \Lambda \rightarrow p\pi^-
- (\Xi_b \rightarrow) \Xi^0_c \rightarrow e^+\Xi^-\nu e, \Xi^- \rightarrow \pi^-\Lambda$

HF decay leptons
- $c,b \text{ hadrons} \rightarrow eX (|y| < 0.9)$
- $c,b \text{ hadrons} \rightarrow \mu X (2.5 < y < 4)$
- $b \rightarrow eX$ via impact parameter fit

Beauty-decay $J/\psi$ ($|y| < 0.9$)
- $b \text{ hadrons} \rightarrow J/\psi X, J/\psi \rightarrow e^+e^-$
- + open heavy-flavour jets, correlations, production vs multiplicity/centrality, ESE...
CROSS SECTIONS IN pp COLLISIONS

- $p_T$-differential production cross section of prompt D mesons and heavy-flavour decay leptons measured for several energies ($\sqrt{s} = 2.76, 5.02, 7, 8, 13$ TeV)
- Excellent constraints for charm (+beauty) production cross section over a wide $p_T$ interval
  - $D^0$ cross section down to $p_T = 0$
- All measurements are consistent with pQCD calculations, data always on upper part of FONLL uncertainty band (much larger than data uncertainties)
• $\Lambda_c^+/D^0$ ratios in pp and p-Pb collisions are compatible within uncertainties
  • Same $p_T$ trend as for light flavor baryon-to-meson ratio (see backup)
  • First $\Xi_c^0$ production measurement at the LHC
• Both $\Lambda_c^+/D^0$ and $\Xi_c^0/D^0$ ratios are **higher than MC expectation** (tuned on $e^+e^-$, $e^-p$ data)
  ➢ Enhanced color reconnection configuration of PYTHIA 8 is closer to data
  ➢ Theory bands on $\Xi_c^0$ due to the uncertainty on the branching ratio $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$
New preliminary results with better precision, due to reduction of uncertainties in the pp reference (2017 sample at 5 TeV)

Non-strange D meson $R_{pPb}$ is **compatible with unity** within uncertainties

- Described by models including cold nuclear-matter effects and, at low $p_T$, by those assuming QGP formation

- Hint for D-meson “central-to-peripheral” ratio ($Q_{CP}$) $> 1$ with $1.5\sigma$ in $2 < p_T < 8$ GeV/c

  Initial- or final-state effect? Need theory models for its interpretation
D-h CORRELATIONS IN pp AND p-Pb

- Azimuthal correlation distributions of D mesons (average of $D^0$, $D^+$, $D^{**}$ mesons) with charged particles in pp and p-Pb collisions
- Characterize charm **production mechanisms** and **fragmentation** into jets and study possible modifications due to cold-nuclear-matter or medium-like effects

- Near-side peak yield and width extracted with two Gaussian + baseline fit to the $\Delta \phi$ distributions
- **Similar correlation pattern** and **near-side peak properties** in pp and p-Pb

pp@7 TeV
pp@13 TeV
p-Pb@5.02 TeV
D-TAGGED JETS IN pp AND p-Pb COLLISIONS

- **$p_T$-differential cross section** of charged jets with a reconstructed $D^0$ meson inside the jet cone in pp and p-Pb collisions
  - Allow a closer access to charm parton kinematics
- **POWHEG+PYTHIA** predictions (NLO pQCD) describe well the measured cross section
  - Theory uncertainties larger than data ones
Azimuthal correlations of heavy-flavour decay electrons with charged particles in HM (high multiplicity, 0-20%) and LM (low multiplicity, 60-100%) p-Pb collisions

- $v_2$ extracted from Fourier decomposition of HM – LM correlation distribution
- Positive $v_2$ for heavy-flavour decay electrons (5σ effect for $1.5 < p_T^e < 4$ GeV/c)
  - Strength of $v_2$ comparable with charged-particles measurement (but different $p_T$ ranges of original partons) and with muons (but different rapidities)
- Initial-state effect or final-state, collective effect? Need model predictions!
• Large suppression at high $p_T$ in Pb-Pb collisions (factor $\approx 4$ around 10 GeV/c)
  ➢ No deviations from unity observed in $R_{p\text{Pb}}$ → Final-state effect induced by in-medium energy loss of hard partons
• Suppression of heavy-flavour decay muons at forward rapidity is similar to that of heavy-flavour decay electrons
**BEAUTY $R_{AA}$ MEASUREMENTS**

- Nuclear modification factor of beauty-decay electrons in 0-10% Pb-Pb collisions at 5.02 TeV
  - Hint of a smaller suppression for $b$-origin electrons than for ($c+b$)-origin electrons at the same electron $p_T$
  - Large contribution to systematic uncertainties from the rescaled pp cross section, may be reduced with direct measurement of beauty-electron production in pp at 5.02 TeV
- Models implementing **mass-dependent** energy loss mechanisms provide a good description of data within uncertainties

F. Colamaria – QCD@Work 2018  Matera, 25/06/2018
CHARM HADRONS $R_{AA}$ AND $v_2$

- Possible hierarchy for $R_{AA}(\Lambda_c^+, 0-80\%) > R_{AA}(D_s^+, 0-10\%) > R_{AA}(D^0,D^+,D^{*+}, 0-10\%)$
  - From hadronisation via coalescence?
- At low $p_T$, $R_{AA}$ (non-strange D) > $R_{AA}(\pi)$
  - To be interpreted with care: different fragmentation functions, initial parton $p_T$ spectrum, radial flow contribution, $N_{coll}$ scaling violation at low $p_T$ for charged pions, ...
- Positive D-meson $v_2$ for $p_T > 2$ GeV/c, with hints of $v_2(D) < v_2(\pi^\pm)$ for $p_T < 4$ GeV/c
  - Supports the idea of charm thermalization and participation to collective motion
A simultaneous description of complementary observables ($R_{AA}$ and $v_2$) over a wide $p_T$ range is a challenging task: measurements allow us to set strong constraints to models

- Models in which charm quarks pick up collective flow via recombination or subsequent elastic collisions in expanding medium better describe $v_2$ at low $p_T$. Adding radiative energy loss improves the $R_{AA}$ description at high $p_T$ but gives too low $v_2$ at low $p_T$.

- Best $v_2$ description by models with diffusion coefficient $2\pi D_s(T)$ in the range 1.5-7 at $T_c$, with a corresponding thermalisation time $\tau_{charm} \sim 3-14 \text{ fm/c}$
**D-TAGGED JETS IN Pb-Pb COLLISIONS**

- Strong suppression of production cross section in 0-20% Pb-Pb collisions over full $p_T$(jet) range
- Comparison with inclusive jets difficult due to non-overlapping $p_T$ ranges, but hint of lower $R_{AA}$ for D jets in $5 < p_T$(jet) < 20 GeV/c than inclusive jets with $p_T > 50$ GeV/c
  - Can address different quark/gluon jet ratio and collisional/radiative energy loss fractions
- $R_{AA}$ comparable with single D-meson measurement: jet $R_{AA}$ dominated by leading particle energy loss? Or a coincidence? Yet not apple-to-apple comparison (jet vs. hadron $p_T$ scale)
CONCLUSIONS

Large set of measurements of open heavy-flavour particles in pp ($\sqrt{s} = 2.76, 5, 7, 8$ and $13\text{ TeV}$), p-Pb ($\sqrt{s_{NN}} = 5.02$ and $8.16\text{ TeV}$) and Pb-Pb ($\sqrt{s_{NN}} = 2.76$ and $5.02\text{ TeV}$) collisions.

**pp and p-Pb collisions**

- Precise $p_T$-differential cross section measurements of heavy-flavour particles set strong constraints for pQCD calculations.
- $R_{pPb}$ of non-strange D-mesons, $D_s^+$ meson and $\Lambda_c^+$ all compatible with unity. Other observables, as $Q_{CP}$ of D mesons or HF-decay electron $v_2$, point anyway to non-negligible nuclear effects.
- Measurements of D-h correlations and D-tagged jets are well described by model predictions within uncertainties.

**Pb-Pb collisions**

- Large suppression of open heavy-flavour particles in central collisions, due to heavy-quark energy loss in the QGP.
- Positive $v_2$ observed for open heavy-flavour hadrons and decay leptons: charm quarks undergo strong interaction with the QCD medium and participate to system collective motion.
- Enhanced $\Lambda_c^+$ (and possibly $D_s^+$) production in Pb-Pb: coalescence in strangeness-rich environment.
- Hints of smaller suppression for beauty-decay electrons from $p_T > 2\text{ GeV}/c$.
- First measurement of $D^0$-tagged jets in Pb-Pb: large suppression observed in 0-20% collisions.

**Higher precision** on current observables and more differential measurement expected with 2018 Pb-Pb run and in the next runs after the ALICE upgrade.
BACKUP SLIDES
Open heavy flavour in Pb-Pb collisions

- Heavy quarks experience the full evolution of the hot and dense medium produced in ultra-relativistic heavy-ion collisions → Excellent probes of the QGP

In particular, heavy quarks are expected to:

- Lose less energy w.r.t light quarks and gluons due to different Casimir factor and dead-cone effect
  - Microscopic study of medium and characterisation of energy loss mechanisms

- Participate to some extent to the collective motion inside the medium
  - Provide information on medium transport properties → F. Grosa’s contribution

- At low $p_T$, possibly hadronise also via coalescence:
  - Modified momentum distribution of HF hadrons (radial flow «bump»)
  - Enhance $v_2$ of HF hadrons (light quark contribution)
  - Modify hadrochemistry, enhancing $D_s^+, \Lambda_c^+$ production
Studies of heavy-flavour production important also in smaller systems

**pp collisions**
- Test and set constraints on production mechanisms
  - Production cross section can be treated perturbatively due to the large $Q^2$ involved
  - pQCD-based calculations describe reasonably well open charm and beauty production at the LHC
- Probe parton distribution function (especially for gluons) at low values of Bjorken $x$
- Reference for studies in p-Pb and Pb-Pb collisions

**p-Pb collisions**
- Heavy-flavour production and kinematic properties can be modified by:
  - Cold nuclear matter effects, like shadowing, gluon saturation/color glass condensate, Cronin effect, possible energy loss mechanisms
  - "Collective-like" effects (e.g. elliptic flow), resembling what observed in heavy-ion collisions, which is ascribed to the hydrodynamic expansion of the system
HEAVY-FLAVOUR CORRELATIONS

**HF correlations**: allow to gain further insight w.r.t. single-particle observables, by relating heavy-flavour particles to:

- The other tracks from the fragmentation of the same heavy quark
- The fragmentation particles from the other heavy quark in the event
- The underlying event (soft particle production)

**pp collisions**

- Investigate heavy-flavour quark fragmentation properties and characterize heavy-flavour jets
- Sensitivity to modeling of HQ production processes
- Reference for p-Pb and Pb-Pb results

**p-Pb collisions**

- Investigate possible modifications of angular correlation pattern from cold nuclear matter effects
- Search for long-range ridge-like structures (double ridge), observed in di-hadron correlations, also in the heavy-flavour sector, possibly due to initial- (e.g. CGC) or final-state effects (e.g. hydrodynamics)

ALICE, PLB 719 (2013) 29-41

F. Colamaria – QCD@Work 2018

Matera, 25/06/2018
HEAVY-FLAVOUR CORRELATIONS

**Pb-Pb collisions**

-Probe the QGP effects on heavy quarks by studying how correlation distributions of heavy-flavour particles are modified w.r.t. vacuum

---

For light flavour correlations:

- **Away-side suppression at high** $p_T$
  - Path-length dependence of energy loss
- **Near-side peak enhancement**: interplay of
  - Modification to quark/gluon ratio
  - Bias in partons $p_T$ spectrum due to energy loss in medium
  - Modified parton fragmentation

**Note - Different fragmentation, energy loss in medium, kinematic bias between heavy and light quarks! $I_{AA}$ not directly comparable!**

---

**For light flavour correlations:**

**Pb-Pb @ 2.76 TeV**

LO process only

→ Initial distribution: $\Delta \phi = \pi$

---

ALICE, PRL 108 (2012) 092301

ALICE, PRL 108 (2012) 092301


F. Colamaria – QCD@Work 2018

Matera, 25/06/2018
HEAVY-FLAVOUR JETS

Complementary information w.r.t. correlations, seeing the parton fragments as a single object instead of as a particle ensemble

Tight connection with HF correlations also for some goals, with alternative approach:

- Spatial distribution of energy lost in the medium by heavy quarks → differences with respect to light flavour/gluon jets?

- Jets tagged by HF hadron (D-jets, b-jets, ...): study of jet momentum fraction taken by the particle and its modification in a QGP medium

- Studies important also in pp and p-Pb (reference for Pb-Pb measurements, impact of cold-nuclear-matter effects)
HEAVY-FLAVOUR JETS

• Comparison of b-jet $R_{AA}$ with inclusive jet to investigate mass effect on medium-induced $\Delta E$
  ✓ Mass effects relevant for $p_T < 75$ GeV/c, dead-cone effect not negligible
  ✓ Measurements vs opening radius $R$ to characterize energy dissipation and possibly separate collisional and radiative energy loss
  ✓ Energy loss in gluon splitting cases (high $p_T$): b-pair seen by medium as massive gluon?
  ✓ Addressing the jet momentum sharing (via “soft drop declustering” technique) could probe the QGP-induced modifications of the heavy-flavour $1\rightarrow2$ jet splitting function

Vitev et al., PLB 726 (2013) 251

Li, Vitev, arXiv:1801.00008
HEAVY QUARK PRODUCTION


Parton Distribution Functions in CTEQ 4L parametrization, for $Q^2 = 5 \text{ GeV}^2$
Models: low and high $p_T$ regimes

In a oversimplified scheme we can identify two “regimes”:

**High $p_T$:**
- region **dominated by radiative energy loss**
- Quantum interferences in multiple scattering important (LPM effect) \( \langle k_T^2 \rangle \)
- Relevant parameter: \( \hat{q} = \frac{\langle k_T^2 \rangle}{\lambda} \)

**pQCD-based models** provide a fair description

**Low $p_T$:**
- Region **dominated by “collisional” energy loss**
- Heavy quarks undergo many soft and incoherent elastic collisions ~Brownian motion
- Goal: study how and if HQ reach the equilibrium with the medium
- Relevant parameter: **spatial diffusion coefficient, $D_s$**

Injecting a particle at $x=0$ and $t=0$, the mean squared position at time $t$ is: \( \langle x^2(t) \rangle = 6D_st \)

Strong coupling with the system $\rightarrow$ small $D_s$
FURTHER D-MESON $R_{AA}$ RESULTS

**ALICE**

Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Average $D^0$, $D^+$, $D^{*+}$, $|y|<0.5$

- 0–10%
- 30–50%
- 60–80%

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference

**ALICE Preliminary**

Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

- Average $D^0$, $D^+$, $D^{*+}$, $|y|<0.5$
- $a^2$, $|y|<0.5$
- Charged particles, $|y|<0.8$

arXiv:1802.09145

**ALICE**

0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

$|y|<0.5$

- Average $D^0$, $D^+$, $D^{*+}$

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference

**ALICE**

0–10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV

$|y|<0.5$

- Average $D^0$, $D^+$, $D^{*+}$

Filled markers: pp rescaled reference
Open markers: pp $p_T$-extrapolated reference
D-MESON $R_{AA}$ - MODELS

**MC@sHQ+EPOS2**: PR C89 (2014) 014905
Coll+Rad Eloss, recombination, EPOS-expansion

**PHSD**: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906
Parton-Hadron-String Dynamics transport, coalescence

**Xu, Cao, Bass**: PR C88 (2013) 044907
Langevin with Coll+Rad Eloss, recombination+hydro

**SCETM, G NLO**: arXiv: 1610.02043
Soft Collinear Effective Theory, Bjorken expansion

**Djorkevic**: PR C92 (2015) 024918
Coll+Rad Eloss, recombination, finite-size hydro


Temperature dependence of the spatial diffusion coefficient $D_{s2\pi T}$

Langevin transport, Coll Eloss, recombination, hydrodynamics

**Ads/CFT**: JHEP 1411 (2014) 017; PR D91 (2015) 8, 085019;
Ads/CFT correspondence, Langevin Eloss + fluctuations, hydro

Boltzmann transport, Coll. Eloss, expansion

**TAMU**: PL B735 (2014) 445-450
Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

**ALICE**

$0-10%$ Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

| $|y|<0.5$ |
|---|
| **Average $D^0$, $D^+$, $D^{**}$** |

**Filled markers**: pp rescaled reference

**Open markers**: pp $p_T$-extrapolated reference

F. Colamaria – Jets and Heavy Flavour Workshop
Santa Fe, 29/01/2018
## Prospects of Models (Predicting $R_{AA}$ & $v_2$)

<table>
<thead>
<tr>
<th>Transport Models</th>
<th>Collisonal Energy Loss</th>
<th>Radiative Energy Loss</th>
<th>Coalescence</th>
<th>Hydro</th>
<th>nPDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBT arXiv:1703.00822</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PHSD PRC 93 (2016) 034906</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>POWLANG EPJC 75 (2015) 121</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MC@αsHQ+EPOS PRC 89 (2014) 014905</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pQCD Eloss Models</th>
<th>Collisonal Energy Loss</th>
<th>Radiative Energy Loss</th>
<th>Coalescence</th>
<th>Hydro</th>
<th>nPDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUJET3.0 JHEP 02 (2016) 169</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Djordjevic PRC 92 (2015) 024918</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>SCET JHEP 03 (2017) 146</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
</tbody>
</table>
CHARMED BARYONS – ADDITIONAL PLOTS

arXiv:1712.09581

ALICE Preliminary

p–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
$\Lambda_c^+$, $|y|<0.5$

$R_{AA}$

ALICE Preliminary

0–80% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
$\Lambda_c^+$, $|y|<0.5$

Data from arXiv:1712.09581

Catania, fragm. in pp

Catania, fragm.+coal. in pp
• $\Lambda_c^+/D^0$ ratios in pp and p-Pb collisions are compatible within uncertainties
  • p-Pb: decreasing values from $p_T > 4$ GeV/c, as for light flavor baryon-to-meson ratio
• First $\Xi_c^0$ production measurement at LHC
• Both $\Lambda_c^+/D^0$ and $\Xi_c^0/D^0$ ratios are **higher than MC expectation** (tuned on $e^+e^-$, $e^-p$ data)
 ➢ Enhanced color reconnection configuration of PYTHIA 8 is closer to data
 ➢ Theory bands on $\Xi_c^0$ due to the uncertainty on the branching ratio $\Xi_c^0 \rightarrow e^+\Xi^-\nu_e$
• Hint of **enhanced** $D_s^+$ production compared to non-strange D mesons in Pb-Pb collisions
  ➢ No evidence of centrality dependence within uncertainties
• In Pb-Pb collisions, $Λ_c^+/D^0$ ratio shows hint of **enhancement** w.r.t. pp and p-Pb
  ➢ Underestimated by model predictions

<table>
<thead>
<tr>
<th>Models</th>
<th>System energy</th>
<th>$Λ_c^+/D^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oh et al.</td>
<td>Au-Au (central) 200 GeV</td>
<td>~0.35 ($p_T = 6$ GeV/c)</td>
</tr>
<tr>
<td>Ghosh et al.</td>
<td>RHIC and LHC</td>
<td>0.15-0.2 ($p_T = 9$ GeV/c)</td>
</tr>
<tr>
<td>Das et al.</td>
<td>Pb-Pb (0-20%) 5.5 TeV</td>
<td>~0.2 ($p_T = 9$ GeV/c)</td>
</tr>
<tr>
<td>Plumari et al.</td>
<td>Pb-Pb (0-20%) 2.76 TeV</td>
<td>0.1-0.2 ($p_T = 8$ GeV/c)</td>
</tr>
</tbody>
</table>
• Hint of enhanced $D_s^+$ production compared to non-strange $D$ mesons in Pb-Pb collisions
  - No evidence of centrality dependence within uncertainties
• In Pb-Pb collisions, $\Lambda_c^+/D^0$ ratio shows hint of enhancement w.r.t. pp and p-Pb
  - Underestimated by model predictions
HF ELECTRON $R_{AA}$ AT LOW $p_T$

- Low-$p_T$ data help to better constrain the total HF production cross section (less extrapolation needed) and to test initial-state effects.
- Suppression better described by models including shadowing via nPDF (EPS09).
HF LEPTONS IN Xe-Xe

• Similar $R_{AA}$ is observed in Xe-Xe and Pb-Pb for similar $<dN/d\eta>$.
• Comparison of Pb-Pb and Xe-Xe collisions at different $N_{\text{part}}$ or may add sensitivity to probe the path-length dependence of energy loss.

• A similar suppression is observed for HF decay electrons at mid-rapidity and HF decay muons from at forward rapidity.
D-h CORRELATIONS: pp VS MODELS

Comparison of near-side peak yield and width from data and Monte Carlo predictions

$p_T(D)$ ranges
3-5, 5-8, 8-16 GeV/c

$p_T(\text{assoc})$ ranges
>0.3, 0.3-1, >1 GeV/c

- New results at 13 TeV confirm good description of data features by PYTHIA6,8, POWHEG predictions
  - Good observable to study the charm jet fragmentation modification in the QGP
- Analysis of the away-side ongoing with a x4 larger data sample
D-h CORRELATIONS: p-Pb VS MODELS

Comparison of near-side and away-side peak yields and widths to Monte Carlo predictions

Near-side
- Best description of away-side yields given by POWHEG. Some tension with the other models at high \( p_T(D) \). POWHEG seems anyway to overpredict the peak widths.

Away-side
- Reversed hierarchy for predictions of yield and width w.r.t near-side peak. Observables sensitive to modelling production processes
Charm jet fragmentation does not show modifications as a function of centrality above the current uncertainties.

- Possible flow in central p-Pb events taken into account as systematic uncertainty.
- No sensitivity to extract $v_2$ via HM – LM subtraction with available statistics.

Comparison of near-side peak properties versus event centrality:

- $p_T(D)$ ranges: 3-5, 5-8, 8-16, 24 GeV/c
- $p_T(assoc)$ ranges: $>0.3$, 0.3-1, $>1$ GeV/c
- Centrality classes: 0-20%, 20-60%, 60-100% (ZNA estimator)
HF ELECTRON CORRELATIONS IN Pb-Pb

- Near-side yields from integration of correlation distribution in $|\Delta\phi|<1$
- At low $p_T^{assoc}$, hints of a hierarchy appear between central Pb-Pb, peripheral Pb-Pb and p-Pb, despite large uncertainties
- Similar feature observed in h-h (see backup), interesting to have predictions from models
D-JETS: ANALYSIS STRATEGY

- Charged jets tagged by the presence of a reconstructed D-meson candidate inside the cone
  - Jet finder algorithm (Fastjet, anti-\(k_T\)) run for each D-meson candidate, after substituting the daughter tracks with the D-meson particle

- Invariant mass study to extract D-jet raw yield
  - Background spectrum from the sidebands

- Spectrum corrected for D-jet efficiency and for beauty feed-down, exploiting folded POWHEG+PYTHIA predictions

- Corrected D-jet spectrum unfolded for detector effects and background fluctuations (in p-Pb and Pb-Pb)
• **Charged-jet momentum fraction** carried by $D^0$ meson compared to PYTHIA+POWHEG predictions, for two $p_T^{\text{jet}}$ ranges in pp collisions

• Overall, good description of data. Hint of softer fragmentation at high $p_T$ in data w.r.t. prediction? Uncertainties are anyway still too large to conclude