Production of open heavy flavours and quarkonia in pp collisions with ALICE

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for the ALICE Collaboration
Physics Motivation

Heavy Flavours (HF) in ALICE

D-meson production (arXiv:1605.07569)


Azimuthal correlations between D mesons and charged particles (arXiv:1605.06963)


Summary and conclusions

pp collisions, 13 TeV, 20.05.2015
Heavy Flavours in pp collisions

- Heavy quark \((c, m_c = 1.275 \text{ GeV}/c^2, b, m_b = 4.18 \text{ GeV}/c^2 (\ast))\) pairs are produced in the hard scattering processes at the initial stages of the collisions with large \(Q^2\)
  - Open HF production cross section can be calculated with perturbative QCD
  - Quarkonium production related to a non-perturbative process

\[
\text{Differential cross section vs } p_T
\]

\(\text{pp, } \sqrt{s} = 7 \text{ TeV}\)

\(\checkmark\) Important test of (p)QCD, production mechanisms, constraints on PDFs

\(\checkmark\) Needed reference for p-A and A-A collisions
The ALICE detector

Heavy-Ion experiment
Coverage:
- $|\eta| < 0.9$
- $-4 < \eta < -2.5$
- $-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$

TOF: hadron PID

ITS: vertexing, tracking, PID

ITS SPD: multiplicity, MB trigger

V0 (A,C): multiplicity, MB trigger

TPC: tracking, hadron PID

MUON spectrometer: $\mu$ reconstruction, trigger

TPC:
- hadron PID

ITS:
- vertexing
- tracking
- PID

ITS SPD:
- multiplicity
- MB trigger

V0:
- (A,C)
- multiplicity
- MB trigger

TOF:
- hadron PID

Heavy-Ion experiment
Coverage:
- $|\eta| < 0.9$
- $-4 < \eta < -2.5$
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HF measurements in ALICE

- **Hadronic decays**
  - $D^0 \rightarrow K^- \pi^+$
  - $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
  - $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

- **μ channel**
  - $J/\psi \rightarrow \mu^+ \mu^-$
  - $\Psi(2S) \rightarrow \mu^+ \mu^-$
  - $Y(1S) \rightarrow \mu^+ \mu^-$
  - $Y(2S) \rightarrow \mu^+ \mu^-$
  - $Y(3S) \rightarrow \mu^+ \mu^-$

- **Semi-leptonic decays**
  - $D, B \rightarrow e + X$
  - $D, B \rightarrow \mu + X$

- **e channel**
  - $B \rightarrow J/\psi \rightarrow e^+ e^-$
  - $J/\psi \rightarrow e^+ e^-$

**Quarkonia**

- **pp, 2.76 TeV**
  - $L(MB) \sim 1.1 \text{ nb}^{-1}$, $L(MUON) \sim 20 \text{ nb}^{-1}$, $L(EMCAL) \sim 14.9 \text{ nb}^{-1}$

- **pp, 7 TeV**
  - $L \approx 5 \text{ nb}^{-1}$ (MB), $L(MUON) \sim 1.35 \text{ pb}^{-1}$, $L(EMCAL) \sim 2 \text{ nb}^{-1}$

- **pp, 8 TeV**
  - $L \approx 5 \text{ pb}^{-1}$ (MUON)

**Open HF**

- $pp \rightarrow 2.76 \text{ TeV (4 pub): } L(MB) \sim 1.1 \text{ nb}^{-1}$, $L(MUON) \sim 20 \text{ nb}^{-1}$, $L(EMCAL) \sim 14.9 \text{ nb}^{-1}$

- $pp \rightarrow 7 \text{ TeV (13 pub): } L \approx 5 \text{ nb}^{-1}$ (MB), $L(MUON) \sim 1.35 \text{ pb}^{-1}$, $L(EMCAL) \sim 2 \text{ nb}^{-1}$

- $pp \rightarrow 8 \text{ TeV (1 pub): } \sim 1.3 \text{ pb}^{-1}$ (MUON)
D mesons

- D-meson analysis based on the reconstruction of the secondary vertex
  - Displacement of decay product tracks from primary vertex
  - Separation of primary and secondary vertices
  - Pointing of the D-meson momentum to the primary vertex

→ Not suitable at low $p_T$ due to lower resolution of the track impact parameter and small Lorentz boost

\[
\begin{align*}
D^0 \rightarrow K^-\pi^+ : & \text{ BR } = 3.88\pm0.05\%, \ c\tau \approx 123 \ \mu m \\
D^+ \rightarrow K^-\pi^+\pi^+ : & \text{ BR } = 9.13\pm0.19\%, \ c\tau \approx 312 \ \mu m \\
D^{\ast}(2010)^+ \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+ : & \text{ BR of } 2.62 \pm 0.05\%, \\
D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+ : & \text{ BR } = 2.24\pm0.10\%, \ c\tau \approx 150 \ \mu m
\end{align*}
\]
**D⁰-meson production down to p_T = 0**

- D-meson analysis based on the reconstruction of the secondary vertex

\[ D^0 \text{ cross section at low } p_T \text{ (down to 0)} \text{ measured without vertexing with an} \]
\[ \text{invariant-mass analysis of UnLike-Sign K, } \pi \text{ pairs, relying on PID from TOF} \]
\[ \text{and TPC to reduce the background which was subtracted with (a) Like-Sign} \]
\[ \text{pairs, (b) event mixing, (c) track rotation, or (d) side band fits} \]

\[ \text{pp, } \sqrt{s} = 7 \text{ TeV} \]
Comparison to pQCD

From $D^0$ cross-section

$$
\sigma_{pp\,7\,\text{TeV}} = 8.18 \pm 0.67 \, \text{(stat.)} + 0.90_{-1.62}^{+0.90} \, \text{(syst.)} + 2.40_{-0.36}^{+0.40} \, \text{(extr.)} \pm 0.29 \, \text{(lumi.)} \pm 0.36 \, \text{(FF)} \, \text{mb}
$$

Smaller systematic and extrapolation errors than ALICE previous measurements

arXiv:1605.07569
Open charm vs multiplicity

- Investigate the interplay between the hard and the soft processes in particle production (initial hard scatterings + “soft” underlying event)
  - Investigate gluon radiation and Multiple-Parton Interactions (MPI)

Relative charged-particle multiplicity \( \langle dN_{ch}/d\eta \rangle, |\eta| < 1 \), from Eur. Phys. J. C68 (2010) 345-354
Open charm vs multiplicity

- Faster-than-linear increase at large multiplicity
- No dependence on $p_T$ within uncertainties

Self-normalized yields
- Some systematic uncertainties cancel out
- Comparison to other experiments/systems/models

Multiplicity dependence of HF production

- Faster-than-linear increase with multiplicity
  - Qualitatively in agreement with MPI; larger gluon radiation?
  - Similar increase with multiplicity of open and hidden HF
    - But: different $p_T$ and $\eta$ regions
  \[ \Rightarrow \] Multiplicity dependence determined by $c\bar{c}$ and $b\bar{b}$ production processes rather than hadronization

\[ \text{pp, 7 TeV} \]

**D**
Empty: $J/\psi \rightarrow ee$
Full: $J/\psi \rightarrow \mu\mu$

**D**
Non-prompt $J/\psi \rightarrow ee$

**D**
Prompt $J/\psi \rightarrow ee$

**HF vs multiplicity and models**

**Percolation calculations:**
- Mimic MPI

**EPOS 3 (with Hydro)**
- Number of MPI related to multiplicity

**PYTHIA 8**
- MPI
HF vs multiplicity and models

Percolation calculations:
- Mimic MPI

**EPOS 3 (with Hydro)**
- Number of MPI related to multiplicity

**PYTHIA 8**
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Qualitative agreement with models that include MPI
D mesons - charged particles azimuthal correlations

- To study heavy-flavour quark fragmentation and $c\bar{c}$ production

<table>
<thead>
<tr>
<th>$3 &lt; p_T^D &lt; 5 \text{ GeV/c}$</th>
<th>$5 &lt; p_T^D &lt; 8 \text{ GeV/c}$</th>
<th>$8 &lt; p_T^D &lt; 16 \text{ GeV/c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $D^0, D^+, D_s^+$ ALICE:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3 &lt; p_T^D &lt; 5 \text{ GeV/c}$, $p_T^{assoc} &gt; 0.3 \text{ GeV/c}$</td>
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</tbody>
</table>

Examples of simulation settings:
- *Pythia 6, Perugia 2009*
- *Pythia 6, Perugia 2010*
- *Pythia 6, Perugia 2011*
- *Pythia 8, Tune 4C*
- *Powheg+Pythia 6*

*pp, 7 TeV*

**Note:** The data points represent the ratio of the number of associated hadrons to the baseline, with error bars indicating the scale uncertainty. The figures show the distribution of azimuthal angles ($\Delta \phi$) for different $p_T$ ranges of the D meson and its associated hadrons.
D mesons - charged particles azimuthal correlations

- To study heavy-flavour quark fragmentation and $c\bar{c}$ production

**Good agreement with MC within uncertainties (after baseline subtraction)**

- PYTHIA6, Perugia 0
- PYTHIA6, Perugia 2010
- PYTHIA6, Perugia 2011
- PYTHIA8, Tune 4C
- POWHEG+PYTHIA6

**pp, 7 TeV**
D mesons - charged particles azimuthal correlations

\[ f(\Delta \varphi) = b + \frac{A_{NS}}{\sqrt{2\pi} \sigma_{\text{fit,NS}}} e^{-\frac{(\Delta \varphi)^2}{2 \sigma_{\text{fit,NS}}^2}} + \frac{A_{AS}}{\sqrt{2\pi} \sigma_{\text{fit,AS}}} e^{-\frac{(\Delta \varphi - \varphi_0)^2}{2 \sigma_{\text{fit,AS}}^2}} \]

Fitting procedure to extract the properties of the near-side correlation peak (properties of the jet containing the D meson)

Good agreement with MC within uncertainties (after baseline subtraction)

PYTHIA6, Perugia 0
PYTHIA6, Perugia 2010
PYTHIA6, Perugia 2011
Pythia8, Tune 4C
POWHEG+PYTHIA6

\[ p_{\text{T}}^{\text{assoc}} > 0.3 \text{ GeV/c} \]

\[ 0.3 < p_{\text{T}}^{\text{assoc}} < 1 \text{ GeV/c} \]

\[ p_{\text{T}}^{\text{assoc}} > 1 \text{ GeV/c} \]
Quarkonium production

- Quarkonium production models
  - Color Evaporation Model
  - Color Singlet Model
  - Non-relativistic QCD

High precision measurements in pp collisions fundamental to constrain models ($p_T$ spectra, cross section, polarization)

ALICE measures down to $p_T = 0$
Quarkonium production

- Quarkonium production models
  - Color Evaporation Model
  - Color Singlet Model
  - Non-relativistic QCD

High precision measurements in pp collisions fundamental to constrain models
($p_T$ spectra, cross section, polarization)

Similar trend was already observed in pp, 7 TeV
Summary and Conclusions

- **ALICE** has a very diverse **Heavy Flavour** program in pp collisions
  - Not everything could be shown here
- Open heavy-flavour cross section (measured down to $p_T = 0$ for $D^0$) is in agreement with pQCD calculations
- HF (open and hidden) measurements as a function of **multiplicity** show an increase faster than linear with multiplicity and are qualitatively in agreement with models including MPI
- **Azimuthal correlations** between D mesons and charged particles (first measurement at the LHC!) in agreement with Monte Carlo generators
- **Quarkonium** production measured at $\sqrt{s} = 8$ TeV (down to $p_T = 0$) shows similar results as at $\sqrt{s} = 7$ TeV

✔ The Run2 data at higher energies (and multiplicities) will give us more statistics, more precise measurements, higher/lower $p_T$ reach
✔ Stay tuned: pp data at $\sqrt{s} = 5$ TeV and 13 TeV are being analyzed: they will help us to understand more of heavy-ion collisions
BACKUP
Heavy Flavours in pp collisions

- Heavy quark ($c, m_c = 1.275 \text{ GeV}/c^2$, $b, m_b = 4.18 \text{ GeV}/c^2$ (*)\) pairs are produced in the hard scattering processes at the initial stages of the collisions with large $Q^2$
  - Open HF production cross section can be calculated with perturbative QCD
  - Quarkonia production related to a non-perturbative process

- Important test of (p)QCD, production mechanisms, constraints on PDFs
  - Needed reference for pA and AA
Heavy Flavours in pp collisions

- Heavy Flavours (HF: $c$, $m_c = 1.275\, \text{GeV}/c^2$, $b$, $m_b = 4.18\, \text{GeV}/c^2$) pairs are produced in the hard scattering processes at the initial stages of the collisions with large $Q^2$
  - Production cross section can be calculated with perturbative QCD
  - HF production mechanism can be studied through more differential measurements (multiplicity dependence, azimuthal angular correlations)
- HF pairs have a formation time ($\tau = O(0.1)\, \text{fm}$) shorter than the life time of the QGP (HI collisions)
  - Experience the evolution of the medium and interact with it

✓ pp data are the needed reference in pA and AA collisions to study the medium-induced effects and its properties
HF measurements in ALICE

• Hadronic decays
  - $D^0 \rightarrow K^- \pi^+$
  - $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
  - $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

• Based on the displaced vertex topology of the decay
  - Vertex reconstruction and tracking (ITS + TPC)
  - $D^0$ with $p_T < 1 \text{ GeV}/c$

• Reducing the background with PID information
  - $K, \pi$ identification (TPC + TOF)
HF measurements in ALICE

- Inclusive production measured at forward rapidity with the MUON spectrometer (-4 < η < -2.5)
  - Tracking, μ identification
  - Acceptance down to p_T = 0 GeV/c
  - Signal extracted with a Crystal Ball or pseudo Gaussian fit
    - Background also fitted

- μ channel
  - J/ψ → μ⁺ μ⁻
  - Ψ(2S) → μ⁺ μ⁻
  - Υ (1S) → μ⁺ μ⁻
  - Υ (2S) → μ⁺ μ⁻
  - Υ (3S) → μ⁺ μ⁻
HF measurements in ALICE

- Non-prompt J/ψ measured in \(|\eta| < 0.9\)
  - Simultaneous fit of invariant mass and pseudo-proper decay length
  - TPC PID used to select e

\[
L_{xy} = \left( \vec{L} \cdot \vec{p}_T \right) / p_T
\]

\[
x = \left( c \cdot L_{xy} \cdot m \right) / p_T
\]

- e channel
  - B \rightarrow J/ψ \rightarrow e^+ e^-
  - J/ψ \rightarrow e^+ e^-
HF measurements in ALICE

• Heavy flavour (HF) Single Electron spectrum extracted from
  a) “Cocktail” of background electrons sources (à la RHIC)
  • Photonic, dielectron decays of mesons, direct radiation, J/ψ, Υ
  b) Cut on impact parameter to select electrons, especially efficient for those from B
  • Analysis relies on e PID from TOF, TRD, TPC and EMCAL (in EMCAL triggered data)

• Semi-leptonic decays
  – D, B → e + X
  – D, B → μ + X

Phys. Rev. D 86, 112007
HF measurements in ALICE

- **Open HF**

- **Semi-leptonic decays**
  - $D, B \rightarrow e + X$
  - $D, B \rightarrow \mu + X$

- Heavy flavour (HF) Single Electron spectrum extracted from:
  a) “Cocktail” of background electrons sources (à la RHIC)
     - Photonic, dielectron decays of mesons, direct radiation, $J/\psi, \Upsilon$
  b) Cut on impact parameter to select electrons, especially efficient for those from $B$
     - Analysis relies on e PID from TOF, TRD, TPC and EMCAL (in EMCAL triggered data)

- HF from $\mu$ decays measured with the MUON spectrometer
  - Rejecting punch-through hadrons from tracking-trigger matching
  - Pile-up rejection
  - Background contamination subtracted using MC
HF measurements in ALICE

- Inclusive production measured at central rapidity ($|\eta| < 0.9$)
  - Signal extracted with bin counting
    - Background removed with like-sign/mixed events/fitting/track rotation
  - TPC PID used to select $e$

- **$\mu$ channel**
  - $J/\psi \to \mu \mu$
  - $\Psi(2S) \to \mu \mu$
  - $\Upsilon(1S) \to \mu \mu$

- **$e$ channel**
  - $J/\psi \to e e$
  - $B \to J/\psi \to e e$
HF measurements in ALICE

- Inclusive production measured at central rapidity (|\eta| < 0.9)
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- TPC PID used to select e
- Non-prompt J/\psi measured in |\eta| < 0.9
  - Simultaneous fit of invariant mass and pseudo-proper decay length
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\[ L_{xy} = \left( \vec{L} \cdot \vec{p}_T \right) / p_T \]
\[ x = \left( c \cdot L_{xy} \cdot m \right) / p_T \]

- e channel
  - J/\psi \rightarrow e^+ e^-
  - B \rightarrow J/\psi \rightarrow e^+ e^-
**D^0 meson production down to p_T = 0**

- **D-meson analysis** based on the reconstruction of the secondary vertex
- **D^0** cross section at low **p_T** (down to 0) measured without vertexing with an invariant-mass analysis of UnLike-Sign K, π pairs, relying on PID from TOF and TPC to reduce the background which was subtracted with (a) Like-Sign pairs, (b) event mixing, (c) track rotation, or (d) side band fits
- Not suitable at low **p_T** due to low resolution of the track impact parameter and small Lorentz boost

Very good agreement of cross sections obtained with and without vertex reconstruction

**pp, 7 TeV**

![Graphs showing cross section](image)
D meson cross section

Comparison to pQCD

pp, \( \sqrt{s}=7 \) TeV

Prompt \( D^0 \), |y|<0.5
ALICE, |y|<0.5

\( \frac{d^2\sigma}{dp_T dy} \) (\( \mu b \) GeV\(^{-1}\) c)

pp, 7 TeV

ALICE, pp, \( \sqrt{s}=7 \) TeV

Prompt \( D^0 \), |y|<0.5
ALICE, |y|<0.5

\( \frac{d^2\sigma}{dp_T dy} \) (\( \mu b \) GeV\(^{-1}\) c)

pp measurement needed to build the reference for pPb

pp, 7 TeV

arXiv:1605.07

\( \sigma_{pp7\text{TeV}} = 8.18 \pm 0.67 \) (stat.) \( \pm 1.62 \) (syst.) \( \pm 0.36 \) (extr.) \( \pm 0.29 \) (lumi.) \( \pm 0.56 \) (fit) \( \mu b \)
D meson cross section

Comparison to pQCD

\[ \sigma_{pp}^{D^0} = 8.18 \pm 0.67 \text{ (stat.)} + 0.90_{-1.62} \text{ (syst.)} + 2.40_{-0.36} \text{ (extr.)} + 0.29 \text{ (lumi.)} + 0.36 \text{ (FF) mb} \]

pp, 7 TeV

pp measurement needed to build the reference for pPb

ALI-PUB-106044

arXiv:1605.07569

pp, \( \sqrt{s} = 7 \text{ TeV} \)

Prompt \( D^0, |y| < 0.5 \)

ALICE

FONLL

GM-VFNS

LO \( k_T \) fact

\( R_{pPb} \)

pp, \( \sqrt{s} = 7 \text{ TeV} \)

Prompt \( D^0, |y| < 0.5 \)

\( p-Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

\(-0.96 < y_{\text{cms}} < 0.04\)

ALICE

ALICE extr. unc.

ATLAS (total unc.)

ATLAS extr. unc.

LHCb (total unc.)

STAR

PHENIX

NLO (MNR)

HERA-B (pA)

E653 (pA)

E743 (pA)

NA27 (pA)

NA16 (pA)

E769 (pA)
Faster than linear increase at high multiplicity
No dependence on $p_T$
Similar trend when adding rapidity gap between D meson and multiplicity region (avoid bias from including charm fragmentation particles and D decay products in multiplicity estimator)

Self-normalized quantities
- Some systematic uncertainties cancel out
- Comparison to other experiments/systems/models

Multiplicity measured at forward rapidity

Multiplicity dependence of HF production

- Linear increase with multiplicity
  - Qualitatively in agreement with MPI; larger gluon radiation?
  - Similar increase with multiplicity of open and hidden HF
    - But: different $p_T$ and $\eta$ regions
→ Multiplicity dependence determined by $c\bar{c}$ and $b\bar{b}$ production processes more than hadronization

arXiv:1602.07240

Similar behaviour seen in pPb!

C. Zampolli for ALICE - LHCP 2016
AlICE

Percolation calculations:

• Exchange of colour sources with finite extension that can interact → in high density environment, their effective number decreases → affects more soft sources (with larger transverse size \( \approx 1/m_T \)) and charged multiplicities → mimic MPI

**EPOS 3 (with Hydro)**

• Initial conditions that allow hydrodynamical evolution
• Number of MPI related to multiplicity

**PYTHIA 8**

• Soft QCD processes
• MPI
• Colour reconnection
• Diffractive processes
HF vs multiplicity and models

Percolation calculations:
- Exchange of colour sources with finite extension that can interact in high density environment, their effective number decreases affects more soft sources (with larger transverse size \(\approx 1/m_T\)) and charged multiplicities mimic MPI

EPOS 3 (with Hydro)
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PYTHIA 8
- Soft QCD processes
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- Colour reconnection
- Diffractive processes
D mesons - charged particles azimuthal correlations

- To study heavy-flavour quark fragmentation and $c\bar{c}$ production

**Corrections:**
- Background D-meson candidate in the **peak range** removed using the background candidates in the sidebands
D mesons - charged particles azimuthal correlations

- To study heavy flavour quark fragmentation and cc production
- Corrections:
  - Background D-meson candidate in the peak range removed using the background candidates in the sidebands
  - Limited detector acceptance and detector spatial inhomogeneities (with event mixing technique)
  - B feed-down contribution

Good agreement with MC within uncertainties (after baseline subtraction)

PYTHIA6, Perugia 0
PYTHIA6, Perugia 2010
PYTHIA6, Perugia 2011
PYTHIA8, Tune 4C
POWHEG+PYTHIA6

16/06/16
C. Zampolli for ALICE - LHCP 2016

pp, 7 TeV

arXiv:1605.06963
D mesons - charged particles azimuthal correlations

Fitting procedure to extract the properties of the near-side correlation peak (properties of the jet containing the D meson)

pp, 7 TeV

Same measurement in pPb

Good agreement with MC within uncertainties (after baseline subtraction)

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