Measurements of the heavy-flavour nuclear modification factor in p-Pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV with ALICE at the LHC

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Outline

- Motivation
- Heavy-flavour measurements with ALICE
- Production cross section and nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
  - D mesons
  - Heavy-flavour decay electrons
  - Heavy-flavour decay muons
- Conclusion
Heavy flavours in p-Pb collisions: motivation

- Heavy quarks (charm and beauty) produced in initial hard scatterings and experience the full evolution of the medium

- Control experiment for Pb-Pb measurements

- Cold nuclear matter effects
  - nuclear modification of Parton Distribution Functions
    - shadowing / gluon saturation at low Bjorken-x
      

  - energy loss

  - multiple collisions

- Investigation by means of the nuclear modification factor

\[
R_{pA} = \frac{1}{\langle T_{pA} \rangle} \frac{dN_{pA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}
\]

K. J. Eskola et al., JHEP 0904 (2009) 65
F. Dominguez et al., arXiv:1109.1250 [hep-ph]
F. Arleo et al., arXiv:1204.4609 [hep-ph]
C. Lourenco et al., JHEP 0902 (2009) 014
## Data samples

<table>
<thead>
<tr>
<th>Observable</th>
<th>Data sample</th>
<th>Integrated luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>D mesons</td>
<td>p-Pb 5.02 TeV</td>
<td>48.6 µb⁻¹ (MB trigger), mid-rapidity</td>
</tr>
<tr>
<td>Heavy-flavour decay electrons</td>
<td></td>
<td>48.6 µb⁻¹ (MB trigger), mid-rapidity</td>
</tr>
<tr>
<td>Heavy-flavour decay muons</td>
<td></td>
<td>196 µb⁻¹ (low $p_T$ trigger, forward rapidity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4.9 \times 10^3$ µb⁻¹ (high $p_T$ trigger, forward rapidity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>254 µb⁻¹ (low $p_T$ trigger, backward rapidity)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5.8 \times 10^3$ µb⁻¹ (high $p_T$ trigger, backward rapidity)</td>
</tr>
</tbody>
</table>

- Rapidity shift of the center-of-mass of 0.465 units in the p direction
- pp reference: obtained by a pQCD-based energy scaling of the $p_T$-differential cross sections measured at $\sqrt{s} = 7$ TeV and extrapolated to higher $p_T$ by using pQCD calculations when no measurement is available

ALICE heavy-flavour results in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV shown also in **posters**:

- D mesons: A. Festanti (F-15), C. Jena (F-20) and G. Luparello (F-31)
- Heavy-flavour decay electrons: C. Jahnke (F-19), M. Kim/S. Cho (F-24), Y. Pachmayer (F-42), and J. Wagner (F-60)
- Charm baryon, $\Lambda_c$: R. Romita (M-23) and C. Zampolli (F-67)

D mesons in ALICE

- Fully reconstructed hadronic decays displaced from the interaction vertex
  \[ \begin{align*}
  D^0 &\rightarrow K^-\pi^+ \quad \text{BR} = 3.88\% \\
  D^+ &\rightarrow K^-\pi^+\pi^+ \quad \text{BR} = 9.13\% \\
  D^{*+} &\rightarrow D^0\pi^+ \quad \text{BR} = 67.7\% \\
  D_s^+ &\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+ \quad \text{BR} = 2.28\%
  \end{align*} \]

- \(|\eta|<0.9\)
  ITS: tracking, vertexing
  TPC: tracking, PID
  TOF: PID

- Signal yield from fit to the D-meson candidate invariant mass distribution
D mesons: \( p_T \)-differential cross sections in p-Pb collisions

- \( p_T \)-differential production cross sections measured for \( D^0 \), \( D^+ \), \( D^{*+} \) and \( D_s^+ \) in minimum-bias collisions over a wide \( p_T \) range
- The relative abundances of D mesons in p-Pb collisions are compatible within uncertainties with those measured in pp collisions

D mesons: $p_T$-differential $R_{pPb}$

- $R_{pPb}$ measured for $D^0$, $D^+$, $D^{*+}$ and $D_s^+$
- $R_{pPb}$ consistent with unity within uncertainties for all D-meson species
- No significant dependence on $p_T$ within uncertainties in the measured $p_T$ range
Comparison with models and $R_{AA}$

D-meson $R_{pPb}$ can be described by Color Glass Condensate (CGC) calculations, perturbative QCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and $k_T$-broadening.

$R_{AA}$: suppression by a factor of 4-5 at $p_T \sim 10$ GeV/c in the 20% most central collisions

Suppression observed in central Pb-Pb collisions is a hot medium effect

Heavy-flavour decay electrons in ALICE

- $D, B, \Lambda_c \rightarrow e + X$
- $|\eta| < 0.9$
  - ITS: tracking, vertexing
  - TPC: tracking, PID
  - TOF, EMCal, TRD: e-ID

- Two methods for subtraction of electrons from non-HF sources
  - **Cocktail**: background calculation based on measured $\pi$ cross sections
  - **Invariant mass**: background reconstructed from low-mass $e^+e^-$ pairs

- Separation of electrons from beauty-hadron decays
  - Exploit long lifetime of beauty hadrons ($c\tau \sim 500 \, \mu m$)
    - Electrons from beauty hadrons displaced from the primary vertex $\rightarrow$ wide impact parameter, $d_0$, distribution
  - Impact parameter cut to select beauty decay electrons
  - Remaining background subtracted via simulations based on measured $\pi$ and D-meson cross sections
Heavy-flavour decay electrons: $p_T$-differential cross section in p-Pb collisions

- $p_T$-differential cross section measured in $0.5 < p_T < 12$ GeV/c for electrons from heavy-flavour decays in minimum-bias collisions
- $p_T$-differential cross section measured in $1.2 < p_T < 7$ GeV/c for electrons from beauty-hadron decays in minimum-bias collisions
Heavy-flavour decay electrons: $p_T$-differential $R_{pPb}$

- $R_{pPb}$ of electrons from heavy-flavour decays consistent with unity within uncertainties
- $R_{pPb}$ of electrons from beauty-hadron decays consistent with unity within uncertainties
Comparison with model and $R_{AA}$: heavy-flavour decay electrons

- $R_{pPb}$ data described by perturbative QCD calculations with EPS09 parameterization of shadowing within uncertainties
- $R_{AA}$: suppression by a factor $\sim 3$ in $4<p_T<10$ GeV/$c$ in the 10% most central collisions
- Suppression observed in central Pb-Pb collisions is a hot medium effect

Comparison with $R_{AA}$: beauty-hadron decay electrons

- $R_{pPb}$: results consistent with unity
- $R_{AA} < 1$ for $p_T > 3$ GeV/c in the 20% most central collisions
- Hint for a suppression of electrons from beauty-hadron decays in central Pb-Pb collisions
Heavy-flavour decay muons at forward rapidity in ALICE

- $D, B, \Lambda_c \rightarrow \mu + X$
- Muon spectrometer
  - acceptance and geometrical cuts
  - matching between tracking and trigger chambers
  - correlation between momentum and distance of closest approach (DCA) to remove further background

- Rapidity shift of the center-of-mass of 0.465 units in the p direction
- Data-based cocktail for background (mainly from $\pi^\pm$ and $K^\pm$ decays) estimated at forward rapidity ($p$-going direction, $2.03 < y_{\text{cms}} < 3.53$)
Heavy-flavour decay muons at backward rapidity in ALICE

- $D, B, \Lambda_c \rightarrow \mu + X$
- Muon spectrometer
  - acceptance and geometrical cuts
  - matching between tracking and trigger chambers
  - correlation between momentum and distance of closest approach (DCA) to remove further background
- Rapidity shift of the center-of-mass of 0.465 units in the $p$ direction
- Data-tuned Monte-Carlo cocktail for background (mainly from $\pi^\pm$ and $K^\pm$ decays) estimated at backward rapidity ($Pb$-going direction, $-4.46 < y_{\text{cms}} < -2.96$)
**Heavy-flavour decay muons:**

\[ p_T \]-differential cross sections measured for heavy-flavour decay muons at forward and backward rapidities in \( 2<p_T<16 \) GeV/c.

**Forward rapidity:**

\[ p-\text{Pb} \ \text{at} \ s_{NN} = 5.02 \text{ TeV}, \ \mu^\pm \rightarrow c,b \ \text{decays} \]

\[ 2.5<y_{\text{cms}}<3.54 \]

**Backward rapidity:**

\[ p-\text{Pb} \ \text{at} \ s_{NN} = 5.02 \text{ TeV}, \ \mu^\pm \rightarrow c,b \ \text{decays} \]

\[ -4<y_{\text{cms}}<-2.96 \]

**ALICE Preliminary**

3.3% normalization uncertainty not included

3.1% normalization uncertainty not included
Heavy-flavour decay muons: $p_T$-differential $R_{pPb}$

- $R_{pPb}$ at forward rapidity: consistent with unity within uncertainties over the whole measured $p_T$ range.
- $R_{pPb}$ at backward rapidity: slightly larger than unity in $2<p_T<4$ GeV/c and close to unity at higher $p_T$.
- Within uncertainties, data can be described by perturbative QCD calculations with EPS09 parameterization of shadowing.

Heavy-flavour decay muons: \( p_T \)-differential \( R_{FB} \)

Forward-to-backward ratio

\[
R_{FB}(2.96 < |y_{cms}| < 3.54) = \frac{d\sigma/dp_T \ [\text{Forward}(2.96 < y_{cms} < 3.54)]}{d\sigma/dp_T[\text{Backward}(-3.54 < y_{cms} < -2.96)]}
\]

- \( R_{FB} \): systematically smaller than unity in \( 2<p_T<4 \) GeV/c and close to unity at higher \( p_T \)
- Within uncertainties, data can be described by perturbative QCD calculations with EPS09 parameterization of shadowing

New

Comparison with $R_{AA}$

- $R_{AA}$: suppression by a factor of 3-4 in $4<p_T<10$ GeV/c in the 10% most central collisions
- $R_{pPb}$: consistent with unity for $p_T>4$ GeV/c at both forward and backward rapidity
- **Suppression** observed in central Pb-Pb collisions is a **hot medium effect**
• **Cold nuclear matter effects** on heavy-flavour production assessed at mid-rapidity, forward and backward rapidity via the nuclear modification factor $R_{pPb}$

• $R_{pPb}$ compatible with unity in the measured $p_T$ range at mid-rapidity and at forward (= p-going) rapidity

• $R_{pPb}$ at backward rapidity compatible with unity for $p_T > 4$ GeV/c, slightly larger than unity in $2 < p_T < 4$ GeV/c

• Models implementing cold nuclear matter effects describe the data within uncertainties

• **Suppression** observed in central Pb-Pb collisions at mid-rapidity and forward rapidity is due to hot medium effect
Backup
D mesons ($D^0$): signal in p-Pb collisions

- The Invariant Mass distributions in each rapidity interval extracted after applying topological cuts and PID are fitted to obtain the raw yields.
- The fitting function includes the Gaussian term describing the signal and Exponential term for the background.

\[ \text{p-Pb, } \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ \text{100M events} \]
\[ D^0 \to K \pi^+ \text{ and charge conjugate} \]
\[ 2<p_T<5 \text{ GeV/c} \]
D mesons: $y$-differential cross sections

- Production cross section for $D^0$, $D^+$ and $D^{*+}$
- No significant dependence on $y$
D mesons ($D^0$): systematic uncertainty

- Yield extraction: vary fit range, background fit function, bin counting method, with and without fixed mean and sigma
- Selection Cuts: repeat analysis with different cut values
- PID strategy: repeat analysis with and without PID
- Tracking efficiency: different track selection criteria
- Branching ratio
- Simulated shape of D meson $p_T$ distribution: compare results obtained with different $p_T$ distribution: PYTHIA Perugia-0 vs. FONLL
Identification of electrons from heavy-flavour hadron decays

- Low $p_T$ electrons ($p_T < 6 \text{ GeV/c}$): identified with TOF and TPC
  - TOF: symmetric 3σ cut around electron hypothesis in order to reject kaons and protons
  - TPC: select tracks in the upper half of the electron Bethe-Bloch band (-0.5~3σ) for further hadron rejection

- High $p_T$ electrons ($p_T > 6 \text{ GeV/c}$): identified with TPC and EMCal
Identification of electrons from heavy-flavour hadron decays

- **Cocktail of background electrons**
  - Dalitz-decay of light mesons ($\pi^0$, $\eta$ and $\eta'$)
  - Photon conversions
  - Di-electron decays of light vector mesons ($\rho$, $\omega$ and $\phi$)
  - Di-electron decays of heavy quarkonia, i.e. $J/\Psi$ and $\Upsilon$
  - Weak kaon decays ($K_{e3}$)
  - Direct real and virtual photon production via hard scattering processes

- **Sys. uncertainty (background contribution excluded)**

<table>
<thead>
<tr>
<th>Error source</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS clusters</td>
<td>2%</td>
</tr>
<tr>
<td>TPC clusters</td>
<td>2%</td>
</tr>
<tr>
<td>TPC PID clusters</td>
<td>2%</td>
</tr>
<tr>
<td>DCA</td>
<td>negligible</td>
</tr>
<tr>
<td>ITS-TPC matching [9]</td>
<td>2.5%</td>
</tr>
<tr>
<td>TOF matching</td>
<td>5%</td>
</tr>
<tr>
<td>TOF PID</td>
<td>2%</td>
</tr>
<tr>
<td>TPC PID ($p_T &lt; 6$ GeV/c)</td>
<td>5%</td>
</tr>
<tr>
<td>$\eta$ and charge</td>
<td>4%</td>
</tr>
<tr>
<td>MC sample</td>
<td>3%</td>
</tr>
<tr>
<td>total</td>
<td>( \approx 10% )</td>
</tr>
</tbody>
</table>
Identification of electrons from beauty-hadron decays

- **Track impact parameter cut**
  - Electron tracks from semi-leptonic beauty-hadron decays feature a broader $d_0$ distribution compared to that of background electrons => allows for separation
  - Minimum impact parameter cut optimised to maximise S/B is applied to reject misidentified $\pi^\pm$, $e^\pm$ from Dalitz decays, $\gamma$ conversions and charm meson decays

- **Background subtraction**
  - Background is estimated by weighting the relevant electron source yields in PYTHIA (electrons from charm hadron decays) and DPMJET (photonic electrons) to match the measured ones

- **Systematic uncertainty**
  - Electron background and minimum impact parameter cut are the dominant sources of systematic uncertainties
Heavy-flavour hadron decay muons: background subtraction

- **Forward rapidity** (p-going direction, $2.5<y_{CMS}<3.54$)
  - inputs: charged hadron spectra ($\pi^{\pm}$ and $K^{\pm}$) measured at mid-rapidity with ALICE
  - extrapolate the measured results to forward rapidity according to the $dN/dy$ shapes from Monte-Carlo generators
  - produce the $K^{\pm}/\pi^{\pm}$ decay muon background in Monte-Carlo via fast simulation of the decay kinematics and absorber effect

- **Backward rapidity** (Pb-going direction, $-4<y_{CMS}<-2.96$)
  - scale estimated charged hadron spectra at forward rapidity to backward rapidity based on CMS measurement of forward-backward asymmetry as a function of $p_T$ and Monte-Carlo generator predictions
**Heavy-flavour hadron decay muons: systematic uncertainty on $R_{pPb}$**

<table>
<thead>
<tr>
<th>Systematics</th>
<th>p-Pb (forward rapidity)</th>
<th>p-Pb (backward rapidity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{pA}$</td>
<td></td>
<td>3.6% (for 0-100%)</td>
</tr>
<tr>
<td>Normalization to Min. Bias</td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>32% maximum ($p_T&lt;12$ GeV/c)</td>
<td>40% maximum ($p_T&lt;12$ GeV/c)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1% (5%) for Low (High) $p_T$ Muon Events</td>
<td></td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>Matching efficiency</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Misalignment</td>
<td></td>
<td>1% x $p_T$</td>
</tr>
<tr>
<td>pp reference</td>
<td>$&lt; 15%$ (30%) maximum in $p_T&lt;12$ GeV/c ($p_T&gt;12$ GeV/c); $&lt; 3%$ for rapidity extrapolation</td>
<td></td>
</tr>
<tr>
<td>Additional uncertainty on signal</td>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>(no background in $p_T&gt;12$ GeV/c)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $K^{\pm}/\pi^{\pm}$ decay muon background and pp reference are the dominant sources of systematic uncertainties
Heavy-flavour hadron decay muons: $R_{pPb}$ within sub-rapidity bins

Within uncertainties, similar results in sub-rapidity bins for $R_{pA}$ at both forward and backward rapidity.