Charm production with SMOG at LHCb

Running LHCb in a fixed-target mode

Heavy flavor production in Heavy Ion collisions

F. Fleuret on behalf of the LHCb collaboration
LHCb detector

- Designed for heavy flavor physics
- Single arm spectrometer, fully instrumented in $2 < y < 5$

Excellent vertex, IP and decay time resolution
\[ \sigma(\text{IP}) = 20 \mu\text{m} \]

Very good momentum resolution
\[ \frac{\Delta p}{p} \approx 0.5 \text{--} 1\% \text{ for } 0 < p < 200 \text{ GeV/c} \]

Particle identification
\begin{align*}
\varepsilon_{K \rightarrow K} & \approx 95\% \text{ for } \varepsilon_{\pi \rightarrow K} \approx 5\% \text{ up to } 100 \text{ GeV/c} \\
\varepsilon_{\mu \rightarrow \mu} & \approx 97\% \text{ for } \varepsilon_{\pi \rightarrow \mu} \approx 1\text{--}3\% 
\end{align*}

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022
SMOG (System for Measuring Overlap with Gas)

- Injecting gas in LHCb Vertex Locator (VELO) region
  - Primary role: luminosity measurement
  - Can be used as an internal gas target
  - Allows measurement of p-gas and ion-gas interactions

Noble gas only:
(very low chemical reactivity)

He, Ne, Ar, Kr, Xe
A = 4, 20, 40, 84, 131

Gaz pressure:
$10^{-7}$ to $10^{-6}$ mbar
Fixed-target program

\[ \sqrt{s_{NN}}^{SPS} \approx 20 \text{ GeV} \]
\[ \sqrt{s_{NN}}^{RHIC} = 200 \text{ GeV} \]
\[ \sqrt{s_{NN}}^{LHC} = 5 \text{ TeV} \]

Colliding mode (forward rapidity)

<table>
<thead>
<tr>
<th>( E_{\text{beam}}(p) )</th>
<th>pp</th>
<th>p-SMOG</th>
<th>p-Pb/Pb-p</th>
<th>Pb-SMOG</th>
<th>Pb-Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50 GeV</td>
<td>0.90 TeV</td>
<td>6.9 GeV</td>
<td>5. TeV</td>
<td>54 GeV</td>
<td>5.02 TeV</td>
</tr>
<tr>
<td>1.38 TeV</td>
<td>2.76 TeV</td>
<td>7 TeV</td>
<td>87 GeV</td>
<td>8.2 TeV</td>
<td>69 GeV</td>
</tr>
<tr>
<td>2.5 TeV</td>
<td>5 TeV</td>
<td>69 GeV</td>
<td>8.8 TeV</td>
<td>72 GeV</td>
<td>5.5 TeV</td>
</tr>
<tr>
<td>3.5 TeV</td>
<td>7 TeV</td>
<td>87 GeV</td>
<td>8.8 TeV</td>
<td>72 GeV</td>
<td>5.5 TeV</td>
</tr>
<tr>
<td>4.0 TeV</td>
<td>8 TeV</td>
<td>87 GeV</td>
<td>8.8 TeV</td>
<td>72 GeV</td>
<td>5.5 TeV</td>
</tr>
<tr>
<td>6.5 TeV</td>
<td>13 TeV</td>
<td>110 GeV</td>
<td>8.2 TeV</td>
<td>69 GeV</td>
<td>5.5 TeV</td>
</tr>
<tr>
<td>7.0 TeV</td>
<td>14 TeV</td>
<td>115 GeV</td>
<td>8.8 TeV</td>
<td>72 GeV</td>
<td>5.5 TeV</td>
</tr>
</tbody>
</table>

Fixed-target mode (backward rapidity)

At \( \sqrt{s_{NN}} = 110 \text{ GeV} \) \( y^* = y_{lab} - 4.77 \)

Give access to the target large Bjorken-\( x \) region

LHCb rapidity coverage in the center-of-mass system
Nucleus-Nucleus collisions

- **Physics case**
  - 2.75 TeV Pb beam on fixed target $\Rightarrow \sqrt{s_{NN}} \sim 71$ GeV (close to the 17 GeV regime reached at SPS)
    - Investigate the **Quark Gluon Plasma (QGP) phase transition**
    - Thanks to unique capabilities, LHCb offers new opportunities in the charm sector: $J/\psi$, $\psi'$, $\chi_c$, $D^0$, $D^{+/−}$, $D^*$, $\Lambda_c$... (in the 90’s the NA50/SPS experiment measured only $J/\psi$ and $\psi'$ in PbPb @ 17 GeV)

- **Accessing similar energy density regime (than SPS): operate PbAr@71 GeV**
  - Particle multiplicity is related to event centrality and center-of-mass energy
  - Particle multiplicity can be used to compare different A+B collisions at different $\sqrt{s_{NN}}$

<table>
<thead>
<tr>
<th>System \ centrality</th>
<th>60 – 100%</th>
<th>50 – 60%</th>
<th>40 – 50%</th>
<th>30 – 40%</th>
<th>20 – 30%</th>
<th>10 – 20%</th>
<th>0 – 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbNe – 71 GeV</td>
<td>108.6</td>
<td>254.4</td>
<td>392.5</td>
<td>588.0</td>
<td>814.5</td>
<td>1086.0</td>
<td>1494.9</td>
</tr>
<tr>
<td>PbAr – 71 GeV</td>
<td>123.6</td>
<td>308.8</td>
<td>496.5</td>
<td>806.6</td>
<td>1228.3</td>
<td>1711.9</td>
<td>2372.7</td>
</tr>
<tr>
<td>PbKr – 71 GeV</td>
<td>196.9</td>
<td>533.6</td>
<td>919.1</td>
<td>1451.2</td>
<td>2205.5</td>
<td>2986.6</td>
<td>4084.3</td>
</tr>
<tr>
<td>PbPb – 17 GeV</td>
<td>124.2</td>
<td>331.6</td>
<td>605.9</td>
<td>919.6</td>
<td>1338.7</td>
<td>2035.8</td>
<td>2980.5</td>
</tr>
</tbody>
</table>

- PbAr @ 71 GeV multiplicity $\equiv$ PbPb@17 GeV multiplicity
  $\Rightarrow$ PbAr @ 71 GeV is a good starting point to compare with NA50 (SPS)
Proton-Nucleus collisions

- Serve as a **baseline** for nucleus-nucleus collisions
- **Specific proton-nucleus physics program:**
  - Precision cross-section measurement for cosmic ray physics (see G. Graziani’s talk)
  - Nuclear parton distribution function (nPDF), saturation, energy loss, nuclear absorption, ...

- With SMOG, LHCb offers a large rapidity coverage (~3 rapidity units) at **large Bjorken-x** $x_2$
  - Give access to nPDF **anti-shadowing** region and **intrinsic charm** content in the nucleon

PDF in a Pb nucleus/PDF in a single nucleon

<table>
<thead>
<tr>
<th>x</th>
<th>10^{-4}</th>
<th>10^{-3}</th>
<th>10^{-2}</th>
<th>10^{-1}</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPPS16</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&gt;</td>
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<tr>
<td>EPS09</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
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<td>DSSZ</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
</tr>
</tbody>
</table>

Charm quark distributions

- With **Intrinsic charm**
- With no **Intrinsic charm**

$C, \bar{C}$ at $\mu = 2$ GeV

Bjorken-$x$ = fraction of the nucleon momentum carried by a parton
LHCb fixed-target mode

- **Data recorded**
  - Gas pressure in the VELO: \( \sim 1 - 2 \times 10^{-7} \) mbar

<table>
<thead>
<tr>
<th>System</th>
<th>Duration</th>
<th>CMS energy</th>
<th>Protons on target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2015</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pHe</td>
<td>7h</td>
<td>110 GeV</td>
<td>2 \times 10^{21}</td>
</tr>
<tr>
<td>pNe</td>
<td>12h</td>
<td>110 GeV</td>
<td>1 \times 10^{21}</td>
</tr>
<tr>
<td><strong>pAr</strong></td>
<td>17h</td>
<td><strong>110 GeV</strong></td>
<td><strong>4 \times 10^{22}</strong></td>
</tr>
<tr>
<td>pAr</td>
<td>11h</td>
<td>69 GeV</td>
<td>2 \times 10^{20}</td>
</tr>
<tr>
<td>PbAr (To be analyzed)</td>
<td>100h</td>
<td>69 GeV</td>
<td>2 \times 10^{20}</td>
</tr>
<tr>
<td><strong>2016</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pHe (see G. Graziani’s talk)</td>
<td>18h</td>
<td>110 GeV</td>
<td>3 \times 10^{21}</td>
</tr>
<tr>
<td>pHe (to be analyzed)</td>
<td>87h</td>
<td>87 GeV</td>
<td>4 \times 10^{22}</td>
</tr>
</tbody>
</table>

- **Presented here** : **pAr @ 110 GeV (LHCb-CONF-2017-001)**
  - Preliminary results on heavy flavor production with SMOG
  - **Study \( J/\psi \) and \( D^0 \) production in \( \sqrt{s_{NN}} = 110 \) GeV proton-argon collisions**
    - Demonstration of feasibility of the heavy-flavor LHCb fixed-target program
Data sample

- pAr collisions @ 110 GeV

\[ R = \sqrt{X^2 + Y^2} \]

(R,Z) position of the Primary Vertex

- 17h of pAr collisions with 685 non-colliding bunches: \(~4\times10^{22}\) protons on target
- Select events with Beam 1 only at interaction point
- Apply topological cuts to remove possible residual proton-proton collisions (ghost charge)
- Select events with \(Z_{\text{vertex}}\) inside VELO \(Z_{\text{vertex}} \in [-20 \text{ cm}, 20 \text{ cm}]\)
Signal extraction

- **J/ψ and D⁰ signal**

  - Overall data (17h) : \(~500\ J/ψ \quad \sim6500\ D⁰\)

  - Very clear signal, very small background
J/\psi and D^0 differential production

- 4 $p_T$ bins $\in [0, 600] - [600, 1200] - [1200, 1800] - [1800, 8000]$ MeV/c
J/ψ and D⁰ differential production

Yield corrections and uncertainties

\[
Y = \frac{Y_{\text{measured}}}{\varepsilon}
\]

\(Y_{\text{measured}}\) extracted from mass fits are corrected for different efficiencies:

\[
\varepsilon = \varepsilon_{\text{acc}} \times \varepsilon_{\text{trig}} \times \varepsilon_{\text{sel}} \times \varepsilon_{\text{reco}} \times \varepsilon_{\text{PID}}
\]

geometrical acceptance, trigger, selection, reconstruction, particle identification

Corrections are computed using pAr simulation samples and pp 13 TeV data

<table>
<thead>
<tr>
<th>Source of uncertainties</th>
<th>(J/\psi)</th>
<th>(J/\psi p_T)</th>
<th>(D^0)</th>
<th>(D^0 p_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corr. between bins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal selection</td>
<td>1.4%</td>
<td>1.4%</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>2.3%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>2.7%</td>
</tr>
<tr>
<td><strong>Uncorr. between bins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC sample</td>
<td>(1.2 – 2.6)%</td>
<td>(0.9 – 1.4)%</td>
<td>(1.0 – 1.9)%</td>
<td>(1.0 – 1.5)%</td>
</tr>
<tr>
<td>Tracking</td>
<td>(2.2 – 3.7)%</td>
<td>(2.2 – 2.9)%</td>
<td>(2.7 – 3.4)%</td>
<td>(2.8 – 3.6)%</td>
</tr>
<tr>
<td>PID</td>
<td>(0.2 – 2.7)%</td>
<td>(0.1 – 2.0)%</td>
<td>(4.1 – 8.8)%</td>
<td>(4.8 – 6.9)%</td>
</tr>
<tr>
<td><strong>Stat. uncertainties</strong></td>
<td>(7.7 – 12.5)%</td>
<td>(7.8 – 13.6)%</td>
<td>(0.7 – 3.7)%</td>
<td>(0.6 – 3.4)%</td>
</tr>
</tbody>
</table>

\(J/\psi\) uncertainties are dominated by statistical uncertainties
J/ψ corrected yields

- J/ψ transverse momentum and rapidity distributions
  - Box = quadratic sum of all uncertainties

- Red boxes = MC
  - Pythia8-CT09MCS/NRQCD
  - Overall MC yields normalized to overall data yields
J/ψ yields compared to phenomenological parametrizations

- **Phenomenological parametrizations based on**
  - *MC and phenomenological distributions are normalized to data*

- **Phenomenological parameters**
  - extracted from linear (blue plain curve) and logarithmic (green dashed curve) interpolations between 41.5 GeV and 200 GeV measurements

- **No strong difference observed within uncertainties**
• **D⁰ transverse momentum and rapidity distributions**
  – Box = quadratic sum of all uncertainties

  - Red boxes = MC
    - Pythia8-CT09MCS
    - Overall MC yields normalized to overall data yields

D⁰ corrected yields

\[ \text{LHCb preliminary} \]
\[ \sqrt{s_{NN}} = 110 \text{ GeV pAr} \]

\[ \Delta \text{N}^{D^0}/d\rho_T \]
Transverse momentum \( p_T [\text{MeV/c}] \)

\[ \Delta \text{N}^{D^0}/dy \]
Rapidity \( y \)

0 \rightarrow 8 \text{ GeV/c}
2 \rightarrow 4.5
\( \frac{\sigma(J/\psi)}{\sigma(D^0)} \) cross section ratio vs. \( p_T \) and rapidity

- Luminosity cancel out in the cross section ratio
  \[
  \frac{\sigma(J/\psi)}{\sigma(D^0)} = \frac{Y(J/\psi)}{Y(D^0)} \times \frac{L}{Y(D^0)}
  \]

- No significant dependence of \( \frac{\sigma(J/\psi)}{\sigma(D^0)} \) with rapidity

- \( \frac{\sigma(J/\psi)}{\sigma(D^0)} \) ratio increases with transverse momentum

- Need theoretical predictions!
Bjorken-x distributions

- **Definition used in this analysis:**
  \[
  x_2 = \frac{M}{\sqrt{s_{NN}}} e^{-y^*}
  \]

  - Overall MC yields normalized to overall data yields

- Bjorken-x range covered by the data
  - \( J/\psi \ x_2 \in [0.03, 0.45] \)
  - \( D^0 \ x_2 \in [0.02, 0.27] \)

- **Access Intrinsic charm regime**
  - *Need theoretical predictions!*

(Rapidity in CMS: \( y^* = y - 4.77 \))

(Pythia8 – CT09MCS)

- LHCb preliminary
  \( \sqrt{s_{NN}} = 110 \text{ GeV pAr} \)
  \[
  x_2 = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \exp(-y^*)
  \]

- **Charm quark distributions**
  - BHPS with CTEQ6.5
    - \( C, \bar{C} \) at \( \mu = 2 \text{ GeV} \)
  - *With no Intrinsic charm*

(PRD75 (2007), 054029)
Other charmed hadrons

- Other possible measurements: signals extracted from these pAr data

\[ \sim 1000 \]

LHCb preliminary
\[ t_s = 110 \text{ GeV pAr} \]
\[ D^+ \rightarrow K^- \pi^+ \pi^+ \]

\[ \sim 130 \]

LHCb preliminary
\[ t_s = 110 \text{ GeV pAr} \]
\[ D_s^+ \rightarrow K^- K^+ \pi^+ \]

\[ \sim 2300 \]

LHCb preliminary
\[ t_s = 110 \text{ GeV pAr} \]
\[ D_s^+ \rightarrow D^0 \pi^+ \]

\[ \sim 50 \]

LHCb preliminary
\[ t_s = 110 \text{ GeV pAr} \]
\[ \Lambda_c^+ \rightarrow p K^- \pi^+ \]
Conclusion

• **LHCb has been designed for heavy flavor studies**
  – Offers the capabilities to measure many charm hadrons in a wide rapidity range

• **LHCb is the only experiment at LHC capable of running in a fixed-target mode**
  – Operate at $\sqrt{s_{NN}} = 70$ GeV in lead-nucleus collisions
  – Operate at $\sqrt{s_{NN}} = 110$ GeV in proton-nucleus collisions

• **First measurement of heavy flavor production in fixed-target mode completed**
  – Measured $\sim$500 $J/\psi$ and 6500 $D^0$, other charm hadrons observed
  – Theoretical predictions needed for $J/\psi / D^0$ ratio (nPDF) and $D^0$ yield (Intrinsic Charm)
  – *Demonstrate the feasibility of a heavy-flavor fixed-target program with LHCb*

• **Future**
  – (Close) Analyse PbAr@69 GeV and pHe@87 GeV data samples
  – Record larger statistics (10 to 100 times) to access $\chi_c$ and $\psi'$ ($\psi'$ yield $\sim$2% $J/\psi$ yield)