Fixed-target physics at LHCb

Émilie Maurice on behalf of the LHCb collaboration

The 5th Annual Conference on Large Hadron Collider Physics
18th May 2017, Shanghai
LHCb detector and the fixed-target system

LHCb was designed for heavy flavor physics but is now a general purpose detector

Fully instrumented in $2 < y < 5$

Excellent performance:

✓ Vertex, IP and decay time resolution
✓ Momentum resolution
✓ Particle identification

$\epsilon_{K \rightarrow K} \approx 95\%$, $\epsilon_{\pi \rightarrow K} \approx 5\%$
$\epsilon_{\mu \rightarrow \mu} \approx 97\%$, $\epsilon_{\pi \rightarrow \mu} \approx 1\%-3\%$

Unique capability at LHC: Injecting noble gas (He, Ne, Ar) in the Vertex Locator

▶ Primary role: beam-gas imaging for luminosity measurement
▶ Can be used as an internal gas target ($\approx 10^{-7}$ mbar)
▶ Allows measurement of $p$-gas and ion-gas interactions

Access to the kinematic region: $\sqrt{s_{NN}} \in [69, 115]$ GeV and backward rapidity
LHCb fixed target: data taking

Data recorded with gas pressure in the VELO

- Parasitic to the collider mode
- Gas spreads in the beam pipe up to ±20m around LHCb
- Use non-colliding bunches

<table>
<thead>
<tr>
<th>System</th>
<th>Duration</th>
<th>$\sqrt{s_{NN}}$</th>
<th>Protons on target</th>
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<tbody>
<tr>
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First production measurements in fixed-target mode are presented here:

1. Antiproton production in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV
2. Heavy flavor production with $p$Ar collisions at $\sqrt{s_{NN}} = 110$ GeV
3. First look at the $p$He collisions at $\sqrt{s_{NN}} = 87$ GeV
Fixed target data for cosmic rays?

Fixed target data at 100 GeV provides inputs to MC models describing underlying event: Important for modeling cosmic ray showers in the atmosphere.

AMS02 measurement of $\bar{p}/p$ ratio in cosmic rays shows hints of excess at high energies.

$\bar{p}/p$ predictions from spallation of primary cosmic rays on interstellar medium (H or He):

- Limitation from uncertainties on $\bar{p}$ production cross-sections
- No previous measurement in $p$He
- Predictions from soft QCD models vary within a factor 2

**LHCb in fixed-target mode is well suited to measure $\bar{p}$ production cross section in $p$He**
$\bar{p}$ cross section measurement in $p$He collisions — LHCb-CONF-2017-002

**Measurement of antiproton production in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV**

Analysis of data collected in May 2016, with 6.5 TeV proton beam: **count antiprotons**
- Minimum bias trigger, fully efficiency on candidate events
- Exploit excellent LHCb PID capabilities
- In $(p, p_T)$ bins within the range: $12 < p < 110$ GeV/$c$, $p_T > 0.4$ GeV/$c$

Background: gas impurity measurement $(0.6 \pm 0.2)\%$
- Residual vaccum in LHC: $\sim 10^{-9}$ mbar
- Measurement in data before He injection

Normalization: use $p - e^-$ elastic scattering to evaluate the luminosity
- Cross section very well known
- Distinct signature with single low-$p$ and very low $p_T$ electron track, nothing else

$\rightarrow \mathcal{L} = 0.443 \pm 0.011 \pm 0.027$ nb$^{-1}$
$\bar{p}$ cross section measurement in $p$He collisions — LHCb-CONF-2017-002

LHCb measured the total inelastic cross section
$$\sigma_{\text{inel}}^{\text{LHCb}} = (140 \pm 10) \text{ mb}$$

The EPOS LHC prediction: 118 mb

→ Ratio is $1.19 \pm 0.08$

Result for prompt production compared to EPOS LHC predictions:

Excluding weak decays of hyperons

Cross section data larger by a factor $\sim 1.5$ wrt EPOS LHC

LHCb plans:

Measure $\bar{p}$ from strange decays

Analyze $p$He data, $\sqrt{s_{NN}} = 87$ GeV
Fixed target heavy flavour program at LHCb

Unique opportunity to perform fixed-target heavy ion physics at LHC:

▶ Forward measurement of open and hidden charm production ($J/\psi, D^0$...)
▶ Measurement down to low $p_T$
▶ Large rapidity coverage (≈ 3 rapidity units) at large Bjorken-$x$

Access to nPDF anti-shadowing region

Access to intrinsic charm content in the nucleon

Proton-nucleus collisions provide reference for heavy ions studies
Charm production analysis in pAr collisions — LHCb-CONF-2017-001

Study the $J/\psi$ and $D^0$ production in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV

Analysis of data collected in 2015, with 6.5 TeV proton beam on argon gaseous target

- Reconstructed collision vertices extended over $\sim 1$ m
- $J/\psi$ and $D^0$ selected with $Z_{\text{vertex}}$ inside the Vertex Detector, $[-200, +200]$ mm, extracted with Crystal Ball functions

\begin{align*}
\sim 500 & \ J/\psi \rightarrow \mu^+\mu^- \\
\sim 6500 & \ D^0 \rightarrow K^\mp\pi^\pm
\end{align*}

- Split data in 4 rapidity bins: [2, 3], [3, 3.5], [3.5, 4], [4, 4.6]
- Split data in 4 $p_T$ bins: [0, 600], [600, 1200], [1200, 1800], [1800, 8000] MeV/c

\begin{align*}
&N_{J/\psi} = 482 \pm 23 \\
&\sigma \sim 14 \text{ MeV}/c^2 \\
&N_{D^0} = 6451 \pm 90 \\
&\sigma \sim 8 \text{ MeV}/c^2
\end{align*}
Yield corrections and uncertainties — LHCb-CONF-2017-001

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

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

\[ \epsilon = \epsilon_{\text{acc}} \times \epsilon_{\text{trig}} \times \epsilon_{\text{sel}} \times \epsilon_{\text{reco}} \times \epsilon_{\text{PID}} \]

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 ) y</th>
<th>( J/\psi ) ( p_T )</th>
<th>( D^0 ) y</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>
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\( J/\psi \) uncertainties are dominated by statistical uncertainties
**J/ψ corrected yields – LHCb-CONF-2017-001**

**J/ψ traverse momentum and rapidity distributions**

Box: quadratic sum of all uncertainties

Red area: Monte Carlo

- Pythia8-CT09MCS/NRQCD
- Overall MC yields normalized to overall data yields
Comparison with phenomenological parametrization — LHCb-CONF-2017-001

Phenomenological parametrizations based on

MC and phenomenological distributions are normalized to data

Phenomenological parameters

Extracted from linear and logarithmic interpolations between 41.5 GeV and 200 GeV measurements

→ No strong difference observed within uncertainties
$D^0$ corrected yields — LHCb-CONF-2017-001

$D^0$ traverse momentum and rapidity distributions

- **Box:** quadratic sum of all uncertainties
- **Red area:** Monte Carlo
  - Pythia8-CT09MCS
  - Overall MC yields normalized to overall data yields

LHCb preliminary
$\sqrt{s_{NN}} = 110$ GeV $pAr$

Transverse momentum $p_T$ [MeV/c]

Rapidity $y$

E. Maurice (LAL, LLR) Fixed-target physics at LHCb LHCP 2017
Comparison between $J/\psi$ and $D^0$ cross sections — LHCb-CONF-2017-001

$J/\psi / D^0$ cross sections ratio vs transverse momentum and rapidity

- Luminosity cancel out in the cross section ratio: $\frac{\sigma(J/\psi)}{\sigma(D^0)} = \frac{Y(J/\psi)}{\mathcal{L}} \times \frac{\mathcal{L}}{Y(D^0)}$
- $\frac{\sigma(J/\psi)}{\sigma(D^0)}$ ratio increases with transverse momentum
- No significant dependence of $\frac{\sigma(J/\psi)}{\sigma(D^0)}$ with rapidity

→ Need theoretical predictions
Bjorken-\(x\) distribution — LHCb-CONF-2017-001

Bjorken-\(x\) definition:
\[
x_2 = \frac{M}{\sqrt{s_{NN}}} \exp(-y^*), \text{ with rapidity in CMS } y^* = y - 4.77
\]

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
Other charmed hadrons in $p$Ar data — LHCb-CONF-2017-001

- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+$
- $D_{s}^{*-} \rightarrow K^- K^+ \pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$

Data from LHCb, $\sqrt{s} = 110$ GeV $p$Ar.
First look at \( p\text{He} \) data, \( \sqrt{s_{NN}} = 87 \text{ GeV} \)

Data taken in November 2016

Very clean signal and low background

\[
J/\psi \rightarrow \mu^+ \mu^-
\]

\[
D^0 \rightarrow K^\mp \pi^\pm
\]

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More heavy flavour and cosmic ray results to come
Conclusion

First measurements of heavy-flavour and antiproton production in fixed-target mode

LHCb: unexpected contributor to cosmic ray physics

- $\bar{p}$ production measurement in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV
- Expected to narrow down the uncertainty on the $\bar{p}/p$ prediction for cosmic rays
- LHCb will also measure the detached component

Heavy flavour production

- Measure $\sim 500$ $J/\psi$ and $\sim 6500$ $D^0$ in $p$Ar collisions at $\sqrt{s} = 110$ GeV
- Access nPDF anti-shadowing region and intrinsic charm content in the nucleon
- Demonstrate the feasibility of a heavy-flavor fixed-target program with LHCb
- LHCb can also measure other charmed hadrons: $D^+, D^{*+}, D_s^+, \Lambda_c^+$ and $\psi(2S), \chi_c$ with future larger data samples

Outlook

- Work on luminosity for cross-section measurements
- Promising $p$He sample at $\sqrt{s_{NN}} = 87$ GeV
- Take additional fixed-target data in 2017
Extra slides
LHCb detector

Single arm spectrometer in the forward region, fully instrumented in $2 < \eta < 5$

→ LHCb can operate in fixed-target mode
# Antiproton cross section measurement in $p$He collisions

## Final relative uncertainties

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<tr>
<td>Statistical</td>
<td></td>
</tr>
<tr>
<td>Yields in data/PID calibration</td>
<td>0.7 - 10.8 (&lt; 3 for most bins)</td>
</tr>
<tr>
<td>Normalization</td>
<td>2.5</td>
</tr>
<tr>
<td>Correlated systematic</td>
<td></td>
</tr>
<tr>
<td>Normalization</td>
<td>6.0</td>
</tr>
<tr>
<td>GEC and PV cut</td>
<td>0.3</td>
</tr>
<tr>
<td>PV reco</td>
<td>0.8</td>
</tr>
<tr>
<td>Tracking</td>
<td>2.2</td>
</tr>
<tr>
<td>Residual Vacuum Background</td>
<td>0.1</td>
</tr>
<tr>
<td>Non-prompt background</td>
<td>0.3 - 0.7</td>
</tr>
<tr>
<td>PID</td>
<td>1.2 - 5.0</td>
</tr>
<tr>
<td>Uncorrelated systematic</td>
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<tr>
<td>Tracking</td>
<td>3.2</td>
</tr>
<tr>
<td>IP cut efficiency</td>
<td>1.0</td>
</tr>
<tr>
<td>PID</td>
<td>0 - 26 (&lt; 10 for most bins)</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.8 - 15 (&lt; 4 for $p_T &lt; 2$ GeV/c)</td>
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