Heavy ion physics at LHCb

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On behalf of the LHCb collaboration

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Outline

• LHCb detector

• $p$Pb collisions: recent results
  • Open heavy flavor results
  • Hidden heavy flavor results

• PbPb collisions: work in progress

• Fixed target: first results
  • Heavy flavor in $p$Ar
  • Antiproton in $p$He
LHCb detector

- A single arm forward spectrometer designed for the study of particles containing $c$ or $b$ quark.
- Acceptance: $2 < \eta < 5$
- Vertex detector
  - IP resolution $\sim 20 \mu m$
- Tracking system
  - $\frac{\Delta p}{p} = 0.5\% - 1\%$ (5-200 GeV/c)
- RICH
  - $K/\pi/p$ separation
- Electromagnetic + hadronic Calorimeters
- Muon systems
**pPb datasets and recent results**

- **Rapidity Coverage**
  - $y^*$: rapidity in nucleon-nucleon cms
  - $y_{cms} = \pm 0.465$
  - Forward: $1.5 < y^* < 4.0$
  - Backward: $-5.0 < y^* < -2.5$
  - Common region: $2.5 < |y^*| < 4.0$

- $\sqrt{s_{NN}} = 5$ TeV (2013)
  - $pPb$ (1.06 nb$^{-1}$) + Pbp (0.52 nb$^{-1}$)
  - Open heavy flavor $D^0$ and $\Lambda_c^+$
  - Collectivity

- $\sqrt{s_{NN}} = 8$ TeV (2016)
  - $pPb$ (13.6 nb$^{-1}$) + Pbp (21.8 nb$^{-1}$)
  - Hidden heavy flavor $J/\psi$
Prompt $D^0$ measurement in $p$Pb at 5TeV

- Reconstructed through decay channel: $D^0 \rightarrow K^-\pi^+$
- Inclusive $D^0$ mesons from fitting invariant mass dist.:
  - Signal: Crystal Ball
  - Background: linear
- Prompt $D^0$ fraction extracted from fitting impact parameter dist.:
  - Prompt: simulation
  - $D^0$-from-$b$: simulation
  - Background: sideband in data

arXiv:1707.02750
Prompt $\Lambda_c^+$ measurement in $p$Pb at 5TeV

- Reconstructed through decay channel $\Lambda_c^+ \rightarrow pK^-\pi^+$

- Inclusive $\Lambda_c^+$ baryons from fitting invariant mass dist.:
  - Signal: Gaussian
  - Background: linear

Prompt $\Lambda_c^+$ fraction extracted from fitting impact parameter dist.:
  - Prompt: simulation
  - $\Lambda_c^+$-from-$b$: simulation
  - Background: sideband in data
Prompt $D^0$ at 5TeV
nuclear modification factor in $pPb$

$R_{pPb}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})}$, $A=208$

Updated since preliminary result:
Directly measured with prompt $D^0$ in $pp$ at $\sqrt{s} = 5$ TeV
arXiv:1610.02230

• Nuclear modification factor smaller at large rapidity
• Measurements consistent with theoretical calculations

arXiv:1707.02750
Prompt $D^0$ at 5TeV forward-backward production ratio

- $R_{FB} = \frac{d\sigma(+|y^*|,p_T)/dx}{d\sigma(-|y^*|,p_T)/dx}$

- $R_{FB}$ does not need results from $pp$ collisions.

- Compared to next-to-leading order NLO calculations with different nPDFs

- Consistent with theoretical calculations within uncertainty

arXiv:1707.02750

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Prompt $\Lambda^+_c$ at 5TeV forward-backward production ratio

- $R_{FB} = \frac{d\sigma(+|y^*,p_T)/dx}{d\sigma(-|y^*,p_T)/dx}$

- $R_{FB}$ does not need results from $pp$ collisions.

- Compared to next-to-leading order NLO calculations with different nPDFs

- Consistent with theoretical calculations within uncertainty


Charmed baryon/meson production ratio $R_{\Lambda_c^+ / D^0}$ at 5TeV

- $R_{\Lambda_c^+ / D^0} = \frac{\sigma_{\Lambda_c^+}(y^*,p_T)}{\sigma_{D^0}(y^*,p_T)}$

- EPS09LO & EPS09NLO gives similar predictions.
- nCTEQ15 slightly lower.

- Forward:
  - Consistent at lower $p_T$
  - Below theory at higher $p_T$
- Backward:
  - Consistent for all $p_T$

Charmed baryon/meson production ratio $R_{\Lambda_c^+/D^0}$ at 5TeV

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- EPS09LO & EPS09NLO gives similar predictions.
- nCTEQ15 slightly lower.

- Forward:
  - Consistent for all $|y^*|$

- Backward:
  - Consistent at lower $|y^*|$
  - Displays a rising trend with increasing $|y^*|$

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Prompt and nonprompt $J/\psi$ in $p$Pb at 8TeV

- Reconstructed through $J/\psi \rightarrow \mu^+\mu^-$
- Signal extraction with 2D simultaneous fit to mass and the pseudo proper decay time $t_z \equiv \frac{(Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}}{p_z}$
- Prompt and nonprompt (from-$b$-hadrons) separated
- Fraction from $b$ hadrons:
  - Increasing trend
  - Low $p_T$: cold nuclear matter effects different for the prompt and nonprompt

9/2/2017 PANIC2017
Prompt $J/\psi$ at 8TeV
nuclear modification factor in $pPb$

$$R_{pPb}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})}$$, $A=208$

- $pp$ reference: interpolation of LHCb measurements at 7, 8 and 13TeV
- Forward rapidity: suppression up to 50% at low $p_T$, decreasing with increasing $p_T$
- Backward rapidity: closer to unity
- Overall agreement with models with large uncertainties on the gluon PDFs at low $x$
- Compatible with 5TeV results

[Graphs showing $R_{pPb}$ for $pPb$ and $pPb$ at different rapidity regions]

arXiv:1706.07122
$J/\psi$-from-$b$-hadrons at 8TeV
nuclear modification factor in $pPb$

$$R_{pPb}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{pPb}(y^*, p_T, \sqrt{S_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{S_{NN}})}, \quad A=208$$

- $pp$ reference: interpolation of LHCb measurements at 7, 8 and 13TeV
- Forward rapidity: smaller suppression up to 30% at low $p_T$, reach unity at higher $p_T$
- Backward: compatible with unity
- FONLL with EPS09NLO consistent with data
- Compatible with 5TeV results

JHEP 04 (2009) 065
arXiv:1706.07122
Prompt $J/\psi$ at 8TeV
forward-backward production ratio

- $R_{FB} = \frac{d\sigma(+|y^*|, p_T)/dx}{d\sigma(-|y^*|, p_T)/dx}$
- $R_{FB}$ does not need results from $pp$ collisions.
- Prompt $J/\psi$:
  - Clear forward-backward asymmetry
  - Increasing trend with increasing $p_T$
- Nonprompt $J/\psi$:
  - Closer to unity
- Models for prompt $J/\psi$ only
- Consistent with 5TeV results

arXiv:1706.07122
PbPb collisions

- December 2015: first LHCb PbPb data taken
- $\sqrt{s_{NN}} = 5$ TeV (3-5 $\mu$b$^{-1}$)
- Event classification: total energy in the calorimeters (Ecal)
- Analyses limited by saturation in Vertex Locator (VELO)
- Track reconstruction: 50-100% event activity (~15k clusters)
Fixed target physics

- **LHCb**: only experiment at the LHC can operate in fixed-target mode
- **SMOG**: The System for Measuring Overlap with Gas
  - Unique feature
  - Noble gas (He, Ne, Ar...) injection inside the LHC beam close to the interaction point
  - Luminosity measurement
  - Internal gas target
- Allows p-gas and ion-gas collisions
- $\sqrt{s_{NN}}$ region between 20 GeV (SPS) and 200 GeV (RHIC)
- Access nPDF anti-shadowing region and intrinsic charm content in the nucleon
Charm production in $p$Ar collisions

• Dataset:
  • $\sqrt{s_{NN}} = 110$ GeV (2015)
  • 6.5 TeV proton beam on Ar gas target
  • Protons on target: $4 \times 10^{22}$
  • $\sim 500 \ J/\psi$ and $\sim 6500 \ D^0$

• Shapes consistent with PYTHIA and interpolation between HERA-B and PHENIX
Charm production in $p\text{Ar}$ collisions

- $J/\psi / D^0$ cross section ratio
  - Luminosity cancels
  - Increase with $p_T$
  - Little dependence on rapidity
- Demonstrate the feasibility of a heavy–flavor–fixed–target program at LHCb
- Theoretical calculations are welcome
Measurement of $\bar{p}$ production in $p$He collisions

• AMS-2: possible anti-proton excess at high energies
• $\bar{p}/p$ ratio predictions limited by uncertainties on $\bar{p}$ production cross-sections, particularly for $p$-He
• Prompt production at $\sqrt{s_{NN}} = 110$ GeV in $p$He collisions
• EPOS LHC prediction:
  • Data/MC $\sim 1.19 \pm 0.08$
Conclusion

• Heavy ion collisions
  • \( p\text{Pb} \) collisions at \( \sqrt{s_{NN}} = 5 \) and 8 TeV in 2013/2016
    • Open heavy flavor analyses: prompt \( D^0 \) and \( \Lambda_c^+ \)
    • Hidden heavy flavor: prompt and nonprompt \( J/\psi \)
    • Angular correlation measured (not included)
  • \( \text{PbPb} \) collisions at \( \sqrt{s_{NN}} = 5 \) TeV in 2015
    • Ongoing analyses on semi-central to peripheral collisions

• Fixed target collisions
  • SMOG: unique feature enabling a fixed target program in LHCb
  • First results on
    • \( D^0 \) and \( J/\psi \) production in \( p\text{Ar} \) collisions \( \sqrt{s_{NN}} = 110 \) GeV
    • \( \bar{p} \) production in \( p\text{He} \) collisions \( \sqrt{s_{NN}} = 110 \) GeV
backup
SMOG: Gas target in LHCb

- **SMOG:** System for Measuring Overlap with Gas
  - Inject noble gas (He, Ne, Ar...) into the LHC beam (~±20 m) around the LHCb collision region
  - Gas pressure ~ $2 \times 10^{-7}$ mbar
  - Primarily for measuring luminosity at LHC
  - Fixed target: use non-colliding bunches

- **Fixed target collisions:**
  - Covers mid to backward rapidity region:
    - $y^* = y - 4.77$

<table>
<thead>
<tr>
<th>$E_{\text{beam}(p)}$</th>
<th>$p$-SMOG</th>
<th>Pb-SMOG</th>
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<tbody>
<tr>
<td>2.5 TeV</td>
<td>69 GeV</td>
<td></td>
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<tr>
<td>6.5 TeV</td>
<td>110 GeV</td>
<td>69 GeV</td>
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<tr>
<td>7.0 TeV</td>
<td>115 GeV</td>
<td>72 GeV</td>
</tr>
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Charm signals in PbPb dataset

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

\[ D^0 \to K^- \pi^+ \]
Strange signals in PbPb dataset

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015
Ultraperipheral $J/\psi$ photo-production

- Selecting events containing only two muon tracks
Long-range near-side angular correlations

In high-activity events, a long-range correlation on the near side is observed in the pseudorapidity range $2.0 < \eta < 4.9$.