LHCb: Recent results on heavy ions

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Implications of LHCb measurements and future prospects
19th October 2018
LHCb heavy ion modes

- **pp collider:** 2010-2018, $\sqrt{s_{NN}} = 2.76, 5, 7, 8, 13$ TeV, $L \approx 9$ fb$^{-1}$
- **pPb collider:** 2013 and 2016, $\sqrt{s_{NN}} = 5 \& 8.16$ TeV, $L \approx 2 \& 34$ nb$^{-1}$
- **PbPb collider:** 2015, $\sqrt{s_{NN}} = 5$ TeV, $L \approx 10 \mu$b$^{-1}$. Next run: end 2018

### Timeline

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- **Fixed target mode:**
  - parasitic to collider mode,
  - inject noble gas into VELO,
  - use non-colliding bunches

![Graph showing proton on target (10^2) for different energies and years]

![Beam Energy Graph]

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LHCb heavy ion recent results

• Antiproton production in fixed-target configuration

• Charm production in fixed-target configuration

• Heavy flavour production in $pPb$ collisions
  • $D^0@5.02\text{TeV}$: LHCb-PAPER-2017-015, JHEP (2017) 090
  • $\Lambda_{c^+}@5.02\text{TeV}$: LHCb-PAPER-2018-021, arXiv:1809.01404
  • $J/\psi@8.16\text{TeV}$: LHCb-PAPER-2017-014, PLB774 (2017) 159
  • $B^+, B^0, \Lambda_{b^0}@8.16\text{TeV}$: LHCb-CONF-2018-004
  • $\Upsilon(nS)@8.16\text{TeV}$: LHCb-PAPER-2018-035, arXiv:1810.07655

• Exclusive photonuclear $J/\psi$ production in ultra-peripheral PbPb collisions @5TeV
  • LHCb-CONF-2018-003, see Paolo’s talk on Wednesday
Fixed-target mode setups at LHCb

- Noble gas injected in VELO = $^4$He, $^{20}$Ne, $^{40}$Ar, ...
- Access: $\sqrt{s_{NN}}$ in [69, 110] GeV, backward rapidity
- Fills the gap between SPS and RHIC energies

$$\sqrt{s_{NN}}^{SPS} \sim 20\text{GeV}, \sqrt{s_{NN}}^{LHCb-FT} \in [69,110]\text{GeV}, \sqrt{s_{NN}}^{RHIC} = 200\text{GeV}, \sqrt{s_{NN}}^{LHC} = 5\text{TeV}$$
$ar{p}$ production in fixed-target $p$He collisions

- Antiproton/proton ratio known with great precision in cosmic rays
  - AMS02 (PRL 117, 091103 (2016))
  - PAMELA (JETP Letters 96 (2013) 621)
- Hint for a possible excess
- Flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross-sections uncertainties
  - Need to reduce uncertainty
    - $p$He scattering cross-section results can serve as external input
- $\bar{p}$-production in $p$He collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics

\[\frac{\Phi_\bar{p}}{\Phi_p}\]

\[\text{Kinetic energy } T \text{ [GeV]}\]

\[\text{Uncertainty from: Cross-sections, Propagation, Primary slopes, Solar modulation}\]
$\bar{p}$ production in fixed-target $p$He collisions

- Data collected in 2016 in $p$He collisions at $\sqrt{s_{NN}} = 110$ GeV
- Counting antiproton in $(p, p_T)$ bins
- Access to range $12 \text{ GeV}/c < p < 110 \text{ GeV}/c$, $p_T > 0.4 \text{ GeV}/c$
- PID with 2 RICH detectors
- Account for background by residual gas
- Luminosity from $pe^-$ elastic scattering
\( p \) production in fixed-target \( pHe \) collisions

- Compared with EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4. ICRC ’17: difference summary by T. Pierog

- Uncertainties smaller than model spread

- EPOS LHC tuned on LHC collider data underestimates \( \bar{p} \)-production

- Unique and precise:
  - decisive contribution to shrink background uncertainties in dark matter searches in space

\[ \text{LHCb} \]
\[ pHe \rightarrow \bar{p} X \quad 0.4 < p_T < 0.7 \text{ GeV/c} \]
\[ \sqrt{s} = 110 \text{ GeV} \]

\[ \text{LHCb} \]
\[ pHe \rightarrow \bar{p} X \quad 0.7 < p_T < 1.2 \text{ GeV/c} \]
\[ \sqrt{s} = 110 \text{ GeV} \]

\[ \text{LHCb} \]
\[ pHe \rightarrow \bar{p} X \quad 1.2 < p_T < 2.8 \text{ GeV/c} \]
\[ \sqrt{s} = 110 \text{ GeV} \]
Charm production in fixed-target \( p-A \) collisions

- Access to intrinsic charm via backward rapidity coverage
- Cover large Bjorken-\( x \) in the target

Valence-like intrinsic charm content in the nucleon

nPDF anti-shadowing region

Bjorken-\( x \) = fraction of the nucleon momentum carried by a parton
Charm production in fixed-target $p$-A collisions

- Data collected in 2016 in $p$He collisions at $\sqrt{s_{NN}} = 86.6$ GeV
- Cross sections measured with $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ decays
Charm production in fixed-target $p$-A collisions

- **$J/\psi$ and $D^0$ inclusive cross sections in $pHe$ @86.6 GeV**

$$\sigma_{J/\psi}^{86.6 \text{ GeV}} = 1225.6 \pm 62.0(\text{stat.}) \pm 81.6(\text{syst.}) \text{ nb/nucleon}$$

$$\sigma_{D^0}^{86.6 \text{ GeV}} = 156.0 \pm 4.6(\text{stat.}) \pm 12.3(\text{syst.}) \text{ \mu b/nucleon}$$

- **Scaling the $D^0$ cross-section with the global fragmentation ratio**

$$f(c \to D^0) = 0.542 \pm 0.024$$

$c\bar{c}$ production cross section can be obtained:

$$\sigma_{c\bar{c}}^{86.6 \text{ GeV}} = 287.8 \pm 8.5(\text{stat.}) \pm 25.7(\text{syst.}) \text{ \mu b/nucleon}$$

- **LHCb results in good agreement with NLO NRQCD fit ($J/\psi$, left) and NLO pQCD predictions ($c\bar{c}$, right) and other measurements**
Charm production in fixed-target $p$-$A$ collisions

- $J/\psi$ differential yields ($p$Ar@110GeV) and cross-section ($p$He@86.6GeV)

- HELAC-ONIA [EPJC 77:1 (2017)] predictions for $pp$ (blue line) and $pA$ (Green box) overlaid with measurement. HELAC-ONIA underestimate the $J/\psi$ cross section ($p$He) by a factor 1.78.

- Plain and dashed red lines: phenomenological parametrization [JHEP 1303(2013)122]. Good shape agreement with phenomenological predictions.
Charm production in fixed-target $p$-$A$ collisions

- $D^0$ differential yields ($p$Ar@110GeV) and cross-section ($p$He@86.6GeV)

- HELAC-ONIA [EPJC 77:1 (2017)] predictions for $pp$ (blue line) and $pA$ (Green box) overlaid with measurement. HELAC-ONIA underestimate the $D^0$ cross section ($p$He) by a factor 1.44.

- Good agreement in rapidity shapes between data and predictions

- No evidence of substantial valence-like intrinsic charm contribution
Proton-lead modes setups at LHCb

Ion = $^{208}_{82}$Pb

Forward region:
- $y^* = y_{lab} - 0.465$
- $p$Pb: $1.5 < y < 4.0$

Backward region:
- $y^* = -(y_{lab} + 0.465)$
- Pb$p$: $-5.0 < y < -2.5$

2013 data taking: $\sqrt{s_{NN}} = 5.02$ TeV
- $1.1 \text{nb}^{-1}$ (Fwd), $0.5 \text{nb}^{-1}$ (Bwd)

2016 data taking: $\sqrt{s_{NN}} = 8.16$ TeV
- $13.6 \text{nb}^{-1}$ (Fwd), $20.8 \text{nb}^{-1}$ (Bwd)
Proton-lead collisions

• Allow us to study QGP in a barely explored regime
• Study of cold nuclear matter effects and their disentangling from QGP effects
• Nuclear effects quantified by nuclear modification factor:

\[
R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_Tdy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_Tdy^*}, \quad A = 208
\]

where pp cross-sections at 5 TeV are from pp 5 TeV measurements, and pp cross-sections at 8.16 TeV are from interpolations with pp 2.76, 5, 7, 8, 13 TeV data
Prompt $D^0$ production in $pPb$ at 5.02 TeV

- Reconstructed through $D^0 \rightarrow K^- \pi^+$ decays
- Simultaneous 2D fit to $D^0$ mass and impact parameter (IP)

Forward

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<th>Candidates / (3 MeV/c^2)</th>
<th>$M(K^\pm \pi^\mp)$ [MeV/c^2]</th>
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<td>Data</td>
<td>Fit</td>
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Mass distribution:
Signal: Crystal Ball
Background: Linear

IP distribution:
Prompt signal: from simulation
$D^0$ from b: from simulation
Background: shape from sidebands
Prompt $D^0$ nuclear modification factor

- Strong suppression at forward rapidity ($\sim 30\%$),

- Backward rapidity: compatible with no suppression and hint of enhancement $\rightarrow$ different nuclear effect in forward and backward regions


- At forward rapidity region also consistent with Colour Glass Condensate (CGC) models [Phys. Rev. D91 (2015) 114005, arXiv:1706.06728], with a proper saturation scale
Prompt $D^0$ nuclear modification factor

- Compare with $J/\psi$ and $\psi(2S)$ results at 5 TeV
- Similar nuclear modification factor for $J/\psi$ to $D^0$, \[
\frac{R_{pPb}(J/\psi)}{R_{pPb}(D^0)} \sim 1
\]
- More suppressed for $\psi(2S)$ to $D^0$
Prompt $\Lambda_c^+$ production in $pPb$ at 5.02 TeV

- Reconstructed through $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays

- Similar analysis strategy as $D^0$
Prompt $\Lambda_c^+$ production in $pPb$ at 5.02 TeV

- $\Lambda_c^+/D^0$ similar in forward and backward directions
- Generally consistent with expectations from $pp$ data $\Lambda_c^+/D^0 \sim 0.3$,
**J/ψ production in pPb at 8.16 TeV**

- 2016 pPb collision data, 8.16 TeV
- Prompt J/ψ and J/ψ-from-b are extracted by simultaneous fit of mass and pseudo-proper time: $t_Z = (Z_{J/ψ} - Z_{PV}) \times M_{J/ψ} / p_Z$

**Mass distribution:**
- Signal: Crystal Ball
- Background: exponential

**tz distribution:**
- Signal: $\delta(t_z)$ for prompt J/ψ;
- Exponential for J/ψ-from-b.
- Background: empirical function from sideband

**Total yields:**
- Prompt Forward: $3.8 \times 10^5$; Backward: $5.6 \times 10^5$
- From-b Forward: $6.7 \times 10^4$; Backward: $7.1 \times 10^4$
$J/\psi$ differential cross-section

- The cross-sections as a function of $y^*$, integrated over the $p_T$
- Sizeable forward-backward asymmetry
Prompt $J/\psi$ nuclear modification factor

- In Fwd: suppression at low $p_T$ up to 50%, converging to unity at high $p_T$
- In Bwd: $R_{pPb}$ closer to unity. Intriguing low values in Bwd at low $p_T$
- Overall agreement with theoretical models. Compatible with $pPb$ 5 TeV results.

Models:
**J/ψ-from-b nuclear modification factor**

- In Fwd: suppression at low $p_T$ up to 30%, converging to unity at high $p_T$
- In Bwd: $R_{p\text{Pb}}$ slightly above unity
- Overall agreement with theoretical models. Compatible with $p\text{Pb}$ 5 TeV results.

**R_{p\text{Pb}} vs. $p_T$, Forward**

- **R_{p\text{Pb}} vs. $p_T$, Backward**

- **R_{p\text{Pb}} vs. $y^*$**

Model:

**b-hadron production in pPb at 8.16 TeV**

- **Exclusive decay modes:** $B^+ \rightarrow J/\psi K^+$, $B^+ \rightarrow D^0 \pi^+$, $B^0 \rightarrow D^- \pi^+$, $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$

\[
\begin{array}{|c|c|c|}
\hline
\text{Decay} & \text{pPb} & \text{Pbp} \\
\hline
B^+ \rightarrow D^0 \pi^+ & 1943 \pm 58 & 1824 \pm 64 \\
B^+ \rightarrow J/\psi K^+ & 883 \pm 32 & 905 \pm 33 \\
B^0 \rightarrow D^- \pi^+ & 1155 \pm 39 & 886 \pm 34 \\
\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- & 484 \pm 24 & 397 \pm 23 \\
\hline
\end{array}
\]
**b-hadron cross-sections**

- $B^+$ cross-section studied in $J/\psi K^+$ and $D^0 \pi^+$ modes. Both modes consistent. Weighted average shown here.

- Similar $p_T$ and $y$ distributions for $B^+, B^0$ and $\Lambda_b^0$ hadrons.
**b-hadron cross-section ratios**

- Probing relative $b$-quark fragmentation into different $b$-hadrons

- $B^0 / B^+$ ratio independent of $y$ and $p_T$, slightly above unity (isospin symmetry)

- $\Lambda_b^0 / B^0 \approx 40\%$, decreasing with $p_T$, no hint of strong rapidity dependence. Similar to results in LHCb $pp$ data [JHEP 08 (2014) 143]

- $\Lambda_b^0 / B^0$ ratio reaches LEP data at high $p_T$, $0.20 \pm 0.02$ [arXiv:1612.07233]
B⁺ nuclear modification factors

- Pattern consistent with $R_{pA}$ of $D^0$ hadron
- Significant suppression ($\approx 25\%$) in forward rapidity, suppression decreased at large $p_T$
- Consistent with unity at backward rapidity
$\Lambda_b^0$ and $B^0$ relative modification

• Ratio of $R_{pA}$ between $\Lambda_b^0$ and $B^0$ hadrons

Forward rapidity: consistent with unity in all kinematic bins $\rightarrow b$-quark fragmentation function at forward rapidity similar to $pp$

Backward rapidity: hint of stronger suppression for $\Lambda_b^0$ compared with $B^0$. Demanding more statistics for a firm conclusion.
$\Upsilon(nS)$ production in $p\text{Pb}$ at 8.16 TeV

- Quarkonium: QCD hydrogen atom $\rightarrow$ probe deconfinement in PbPb
- $\Upsilon(nS)$ suppression observed in PbPb by CMS and ALICE
- Observed additional suppression of $\Upsilon(2S,3S)$ at low-$p_T$ also in $p\text{Pb}/\text{Pb}$ by LHC collaborations in Run 1, but statistics limited

LHCb Run-2: Factor 20 more luminosity in 2016 than in Run 1
- Mass spectra are fitted with double crystal ball functions
- Clear $\Upsilon(3S)$ signal in both forward and backward rapidity
**ϒ(1S) and ϒ(2S) nuclear modification factor**

- **ϒ(1S):** forward: suppressed by ~30%
- **ϒ(1S):** backward: compatible with unity within nPDF uncertainties
- **ϒ(2S):** additional suppression confirmed
- Double ratio: shadowing cancels
- Consistent with comovers model

MODELS:
\( \mathcal{R}_{\Upsilon(3S)/\Upsilon(1S)}^{(pPb|Pbp)/pp} = \frac{R(\Upsilon(nS))_{pPb|Pbp}}{R(\Upsilon(nS))_{pp}} \)

- An even larger suppression for \( \Upsilon(3S) \) observed
- Consistent with comovers model
\[ \Upsilon(1S) \text{ to } J/\psi \text{-from-}b \text{ ratio} \]

- \( p_T \)-integrated \( \Upsilon(1S) \) to \( J/\psi \)-from-\( b \) similar in \( pp \) & in \( pPb/Pbp \):

- Small suppression indicate different suppression mechanism for quarkonia with different binding energies
Conclusions

- LHCb has strong capabilities to study heavy flavor in heavy ion collisions
- $\bar{p}$ production in fixed-target $p$He collisions
  - Valuable input to astrophysics community
- Charm production in fixed-target proton-nucleus collisions
  - No evidence of strong intrinsic charm contribution
- Heavy flavour production in $p$Pb collisions
  - Tested heavy-flavour bound state hadronisation & fragmentation down to low-$p_T$
  - Tested different suppression mechanism for quarkonia with different binding energies
  - Nuclear suppressions in $p$Pb forward: up to 50% at low-$p_T$ for charm and 20-30% for beauty
- Many studies are ongoing with current heavy-ion programmes and in view of future upgrades
Backups
LHCb 5 TeV quarkonium results - $J/\psi$, $\psi(2S)$ and $\Upsilon(1S)$

- Candidates fully reconstructed from well identified muons
- Prompt $J/\psi$, $\psi(2S)$ and those from $b$ decays separated using pseudo-proper decay time

**Prompt $J/\psi$, $\psi(2S)$**

- Significant suppression for $J/\psi$, even larger for $\psi(2S)$
- Modest suppression for non-prompt $J/\psi$, similar to $\Upsilon(1S)$

**Backward rapidity**

- No suppression for $J/\psi$ and $\Upsilon(1S)$
- Unexpected large suppression for $\psi(2S)$, not described by E.loss and shadowing

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