New Heavy Flavor Results in Heavy Ion Collisions from LHCb

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The LHCb experiment

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for $p < 200$ GeV/c
- Particle ID: Excellent capabilities to select exclusive decays

Some unique features attractive for heavy ion physics:

- Excellent detector performance for heavy flavor
- Forward acceptance
- Possibility to run in fixed-target mode
Key feature: Forward acceptance

- Sensitivity to small parton momentum fraction $x$ (down to $\sim 10^{-5}$)
- Rapidity dependence can disentangle nuclear effects
- Nicely complements other LHC experiments
**Key feature: Fixed-target capabilities**

“Fixed-target-like” geometry well suited for . . . fixed-target physics!

- System for Measuring Overlap with Gas (SMOG) allows injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. **Turns LHCb into a fixed-target experiment!** Luminosity up to $10^{30}$ cm$^{-2}$ s$^{-1}$

- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{\text{beam}}M_p}$
  - 41-110 GeV for $E_{\text{beam}} = 0.9$-6.5 TeV
  - Between SPS and (main) RHIC energies

- At $\sqrt{s_{NN}} = 110$ GeV, c.m. rapidity is $-2.8 < y^* < 0.2$ **backward** detector with access to large $x$ value in target for different nuclear targets
  - Study nuclear PDFs in antishadowing/EMC region
**pPb data sets**

**Forward region:**
- \( y^* = y_{lab} - 0.465 \)
- pPb: \( 1.5 < y^* < 4.0 \)

**Backward region:**
- \( y^* = -(y_{lab} + 0.465) \)
- Pbp: \(-5.0 < y^* < -2.5\)

**2013:** \( \sqrt{s_{NN}} = 5.02 \) TeV
- 1.1 nb\(^{-1}\) (fwd), 0.5 nb\(^{-1}\) (bwd)

**2016:** \( \sqrt{s_{NN}} = 8.16 \) TeV
- 13.6 nb\(^{-1}\) (fwd), 20.8 nb\(^{-1}\) (bwd)
**Bottomonia in pPb at 8 TeV: $R_{pPb}^{Y(nS)}$**

- Clean separation of Y(nS) resonances

- Model including interactions between Y and comoving particles predicts large final-state effects, larger for excited states and in backward direction
  - Ferreiro and Lansberg, JHEP 10, 094 (2018)
- Consistent with patterns observed in data . . .
Bottomonia in pPb at 8 TeV: Double ratio

Double ratio, \( Y(nS)/Y(1S) \) in pPb with respect to pp

Additional suppression seen for \( Y(3S) \), in particular in backwards region. Consistent with comovers model.

Understanding this effect is crucial to interpretation of sequential quarkonium suppression observed in PbPb by CMS! (arXiv:1805.09215)
**Bottomonia in pPb at 8 TeV: $R_{\bar{p}p\bar{b}}^{Y(nS)}$**

Rising $p_T$ dependence, not observed in the calculations

- No interactions with comovers included—$p_T$ dependence not available

\[ R_{\bar{p}p\bar{b}} \text{ vs. } p_T, \quad Y(1S) \]

\[ R_{\bar{p}p\bar{b}} \text{ vs. } p_T, \quad Y(2S) \]
Bottomonia in $pPb$ at 8 TeV: $R_{FB}$

- Rising $p_T$ dependence
- Hint of rising $|y^*|$ dependence
- Compared to calculations using HELAC-Onia
Bottomonia in pPb at 8 TeV: $R_{Y(2S)}^{Y(2S)}$

Hint of less agreement for backward production suggests comover interactions could be relevant?
Charmed baryons in pPb at 5 TeV: Prompt $\Lambda_c^+$

- Contribution from $b$ decays subtracted using impact parameter distribution

- Single- and double-differential cross sections measured for forward (pPb) and backward (Pbp)

\[ \sigma(y^*, p_T) \]
Charmed baryons in pPb at 5 TeV: $R_{\Lambda_c/D}$

- $\Lambda_c^+/D^0$ ratio important input to hadronization phenomenology: crucial comparison with other collision systems
  - In ratio most nPDF uncertainties cancel
- Baryon enhancement expected from production via coalescence in nuclear collisions, also affected by thermal properties of nuclear medium
  - Large charmed baryon enhancement observed in central AuAu collisions by STAR
  - But no enhancement seen in pPb collisions by ALICE

LHCb pPb:
- Substantial agreement with collinear factorization predictions based on pp data; no strong kinematic dependence observed
- Need update with 8 TeV data to determine dependence on event activity
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Open beauty in pPb at 8 TeV

Clean signals in exclusive decay modes:

\[ B^+ \rightarrow \bar{D}^0 \pi^+ , \ B^+ \rightarrow J/\psi K^+ , \ B^0 \rightarrow D^- \pi^+ , \ \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \]

- First measurement of \( \Lambda_b^0 \) in nuclear collisions
- First measurement of B mesons in nuclear collisions down to low \( p_T \) (< hadron mass)

Yields:

<table>
<thead>
<tr>
<th>Decay</th>
<th>pPb</th>
<th>PbP</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow \bar{D}^0 \pi^+ )</td>
<td>1943 ± 58</td>
<td>1824 ± 64</td>
</tr>
<tr>
<td>( B^+ \rightarrow J/\psi K^+ )</td>
<td>883 ± 32</td>
<td>905 ± 33</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^- \pi^+ )</td>
<td>1155 ± 39</td>
<td>886 ± 34</td>
</tr>
<tr>
<td>( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- )</td>
<td>484 ± 24</td>
<td>397 ± 23</td>
</tr>
</tbody>
</table>
Open beauty in pPb at 8 TeV: $R_{pPb}^{B^+}$

- Confirms suppression pattern observed in $J/\psi$ from b, consistent with nPDF effects
- Calculations consistent with data, without interactions with comovers—more relevant for quarkonium than open heavy flavor
- $\Lambda_b^0/B^0$ ratio also measured and found consistent with nPDF effects
**Ultraperipheral charmonium production in PbPb**

- First preliminary result by LHCb from PbPb collisions
- Goal is to study coherent J/ψ production in PbPb collisions at 5 TeV
- Hadron photo-production enhanced by photon flux ($\propto Z^2$) in PbPb
- Sensitive to gluon distribution down to $x \sim 10^{-5}$
- Integrated luminosity $\sim 10 \, \mu b^{-1}$
- J/ψ $p_T < 1$ GeV, rapidity $2.0 < y < 4.5$

- The collisions are either
  - Coherent, where the photon couples coherently to all nucleons
  - Or incoherent, where the photon couples to a single nucleon
Ultraperipheral charmonium production in PbPb

Coherent J/ψ cross section measured and compared to phenomenological models

Limited statistics, but precision of measurement demonstrated

Good prospects for 2018 data, with 20x more luminosity

STARlight MC used for templates:
Fixed-target samples

- First papers from the first samples collected in 2015 and 2016:
  - Antiproton production in pHe – PRL 121, 222001 (2018) (not shown here)
  - Charm production in pAr and pHe – arXiv:1810.07907
LHCb results in good agreement with world data,
  - and with NLO NRQCD calculation based on fit to other world data ($J/\psi$)
  - and with NLO pQCD predictions ($c\bar{c}$)
Charm production in fixed targets

\( \text{J/}\psi \)  \( \text{D}^0 \)

pHe  pAr

arXiv:1810.07907
Charm production in fixed targets

$J/\psi$  $D^0$

$pHe$  $pAr$

No evidence for sizable valence-like intrinsic charm contribution

$-2.53 < y^* < -1.73$

$0.12 < x_2 < 0.37$
Summary and outlook

- LHCb has developed a growing heavy ion program, with very specific capabilities and unique acceptance at a hadron collider
  

- Much more data from Run 2 still to be analyzed!
  - Manpower limited

- Substantial development of the program in the near future for Run 3
  - Upgraded spectrometer
    - Improved centrality reach for PbA, PbPb due to upgraded tracking
  - Target storage cell: Up to 2 orders of magnitude higher luminosity, improved lumi determination, reduced backgrounds, wider variety of target species: H$_2$, D$_2$, He, N$_2$, O$_2$, Ne, Ar, Kr, Xe

- Stay tuned for more results in the near future!
Extra
Bottomonia in pPb at 8 TeV

JHEP 1811, 194 (2018)
Bottomonia in pPb at 8 TeV

JHEP 1811, 194 (2018)
Bottomonia in pPb at 8 TeV

\[ \frac{\sigma(J/\psi)_{b \to b}}{\sigma(J/\psi)_{s \to q\bar{q}}} \]

- LHCb
  - pPb, PbP 8.16 TeV
  - pp 8 TeV

\[ p_T < 25 \text{ GeV}/c \]
Charmed baryons in $pPb$: Prompt $\Lambda_c^+$

- Single-differential cross sections
Charmed baryons in pPb: Prompt $\Lambda_c^+ R_{FB}$

- $R_{FB} < 1$, consistent with calculations (within large uncertainties)
Charmed baryons in pPb: $R_{\Lambda_c/D}$

$p_T$ dependence, 4 different bins in rapidity
LHCb entered PbPb data taking in 2015. About 10 μb recorded by LHCb.
Tracking performance studied: saturation occurs at about 50% centrality.
2018 PbPb run just finished, collected 210 μb.

Still interesting physics from peripheral collisions:
- J/ψ photoproduction (low-\(p_T\) “excess”)
- J/ψ/D^0 ratio and γ states vs centrality
- Flow for D^0
**XeXe Collisions @ 5.44 TeV**

- We started analysing the XeXe Run collected in 2017
- Collisions at 5.44 TeV and Luminosity 0.2-0.4 μb⁻¹
- We had a preliminary look at K+K- pairs: nice features appearing
- Preliminary plots, no background subtraction, etc.
- Very small Q² in the decay and is produced pretty much at rest

**Ultraperipheral \( \phi(1020) \) production**

![Graphs showing ultraperipheral \( \phi(1020) \) production](image-url)
HeRSCheL veto detector for coherent exclusive production

The HeRSCheL detector: high-rapidity shower counters for LHCb

JINST 13 (2018) P04017

- Forward detector installed for Run2: increase $\eta$ coverage
- Idea: scintillators in the tunnel where beampipe is accessible
- High Rapidity Shower Counters for LHCb: HERSCHEL
- Five planes of scintillators: 4 quadrants, 20mm thick
- Built in 2014 and installed at the beginning of 2015.
- Use same electronics of Preshower Detector
- Can be used to veto forward and backward activity
*New detector installed for Run2 → Increase \( \eta \) coverage in the forward region*

To get an idea on distances

To get an idea on the coverage

\[ \text{LHCb simulation} \]

\[ \text{Deposited energy [a. u.]} \]

\[ \text{Pseudorapidity of the parent particle} \]
D⁰ production in pPb collisions at 5.02 TeV

HF are unique probes in HI collision:
- \( m_\Lambda \gg \Lambda_{QCD} \) allows perturbative calculations
- \( t_{\text{prod}} \ll t_{\text{QGP}} \) experiences the whole time evolution of the collision

Both cross section (left) and Nuclear Modification Factor (right) are fairly described by nPDFs and Color Glass Condensate calculations

LHCb data already used to constrain nPDFs in the unexplored region at low-x (PRL 121 (2018) 052004)
J/ψ production in pPb collisions at 8.16 TeV

**Prompt production**

- strong suppression at forward rapidity: increasing from 0.5 at lowest $p_T$ reaching 1 at highest $p_T$
- nPDFs & Color Glass Condensate calculations account for observations
- for rapidity dependence (not shown here) also the coherent energy-loss accounts for observation

**Non-prompt production**

- first precise $b$-production measurement in pPb down to $p_T \sim 0$
- suppression at forward rapidity, modification factor close to 1 at backward rapidity
- crucial input for the HI phenomenology

Very valuable constraint of nPDFs in unexplored area at low-$x$  (PRL 121, 052004 (2018))
A real storage cell - **SMOG2** - will be installed during the LHC LS2 and start taking data from 2021.
HELAC-Onia: an automatic matrix element generator for heavy quarkonium physics


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ABSTRACT

By the virtues of the Dyson-Schwinger equations, we upgrade the published code HELAC to be capable to calculate the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization, which we dub HELAC-Onia. We rewrote the original HELAC to make the new program be able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Therefore, besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia (e.g. $h_{c,b}, \chi_{c,b}$) and P-wave color-octet intermediate states. To the best of our knowledge, it is a first general-purpose automatic quarkonium matrix elements generator based on recursion relations on the market.
Partonic momentum structure of nuclei: Not just superposed protons and neutrons

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction $x$
- Regions of both enhancement and depletion—only Fermi motion reasonably understood

$$R_A \equiv \frac{1}{A} \frac{F_{2A}}{F_{2N}} \neq 1$$

SLAC: Gomez et al PRD49, 4348 (1994)