Heavy-Ion and Fixed-Target Physics at LHCb

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Brief Introduction
LHCb Experiment Overview

- LHCb is a general purpose experiment covering the forward region at the LHC
- Physics program incorporates $pp$, $pA$, and $AA$ collisions, ultra-peripheral interactions, and a unique fixed target program
- 8 working groups, including Ions and Fixed Target (IFT)
- 699 physics papers published
- Top 4 most cited papers with 5,567 citations

Inspire HEP citation list (as of March 21, 2024)
LHCb Run 3 Detector Upgrade

**LHCb Run 3 Detector Upgrade**

**Runs 1 & 2**

- Designed for searches of new physics in beauty and charm hadron decays
  - Measures particles from $p_T > 0$ at forward pseudorapidity $2 < \eta < 5$

**Runs 3–4**

- LHCb tracking fully upgraded for Run 3 (2022–2026) *

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* See SMOG2 talk (QM2023)
LHCb Results Overview

Five recent LHCb analyses focus on the following collision systems and present the following measurements:

- **pp** collisions at $\sqrt{s} = 7, 13$ TeV
- **pPb** collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- **PbPb** collisions at $\sqrt{s_{NN}} = 5$ TeV

1. $\psi(2S)$ to $J/\psi$ ratio versus multiplicity in **pp** collisions
2. $\Lambda^0_b$ baryons in **pp** collisions
3. Prompt and nonprompt $\psi(2S)$ double ratio in **pPb** collisions
4. $\chi_c$ to $J/\psi$ ratio in **pPb** collisions
5. First $v_2$ and $v_3$ measurements in **PbPb** collisions
Ions and Fixed-Target Results
$\psi(2S)$ to $J/\psi$ Ratio
vs Multiplicity in $pp$ Collisions

- Normalised prompt and nonprompt $\psi(2S)$ to $J/\psi$ ratio vs multiplicity for different $p_T$
  - Suppression observed with increasing multiplicity at low $p_T$ for prompt production only
  - Consistent with final state effects, as initial state effects expected to largely cancel

| Variable     | mean value |
|--------------|------------|
| $N_{\text{tracks}}^{\text{PV}}$ | 25.88      |
| $N_{\text{fwd}}^{\text{PV}}$    | 16.14      |
| $N_{\text{bwd}}^{\text{PV}}$    | 9.74       |

Prompt $\sim$ Primary production
Nonprompt $\sim$ Secondary production

ArXiv: 2312.15201
Submitted 23 Dec 2023
**$\Lambda^0_b$ Baryons in High-Multiplicity $pp$ Collisions**

- $\sigma_{\Lambda^0_b}$ to $\sigma_{B^0}$ ratio in $pp$ collisions converges at low multiplicity with $e^+e^-$ results from LEP.
- Enhancement at low $p_T$ inconsistent with PYTHIA, well described by EPOS4HQ+coalescence.
  - $q\bar{q}$ pairs close in phase space can form mesonic or baryonic states, $\langle N^{\text{VELO}}_{\text{tracks}} \rangle_{\text{NB}} = 37.7$. 

![Graph showing $\sigma_{\Lambda^0_b}/\sigma_{B^0}$ ratio versus $N^{\text{VELO}}_{\text{tracks}}/\langle N^{\text{VELO}}_{\text{tracks}} \rangle_{\text{NB}}$.](image1)

![Graph showing $\sigma_{\Lambda^0_b}/\sigma_{B^0}$ ratio versus $p_T$.](image2)
Prompt & Nonprompt $\psi(2S)$ Production in $pPb$ Collisions

- Double ratio of prompt $\psi(2S)$ to $J/\psi$ cross section shows suppression (global errors cancel)
- Nonprompt double ratio in $pPb$ collisions with larger uncertainty, but consistent with unity
  - Suggests denser nuclear medium created in 8 TeV $pPb$ collisions vs 7 TeV $pp$ collisions
Fraction of $\chi_c$ to Prompt $J/\psi$ in $pPb$ Collisions

- Increasing ratio towards lower $p_T$ interpreted as suppression of the $\psi(2S)$
  → fewer $\psi(2S)$ available to decay to $J/\psi$

- Ratio of $\chi_c$ to $J/\psi$ versus $p_T$ in $pPb$ collisions similar to 7 TeV $pp$ collisions for $p_T > 3$ GeV/c
  - No additional nuclear effects seen for more loosely bound $\chi_c$ state with respect to $J/\psi$
Ratio of $\chi_c$ to $J/\psi$ versus $p_T$ in pPb collisions similar to 7 TeV pp collisions for $p_T > 3$ GeV/c
- No additional nuclear effects seen for more loosely bound $\chi_c$ state with respect to $J/\psi$
- Consistent with picture of co-moving nuclear medium as opposed to quark-gluon plasma
Charged Hadron Flow in PbPb Collisions

- First LHC measurements of flow harmonic coefficients $v_2$ and $v_3$ at forward rapidity in PbPb collisions

- Results compared with ALICE and ATLAS, show similar trends
  - All show rising $v_2$ and $v_3$ for $p_T < 2.5$ GeV/$c$ that fall approaching higher $p_T$
  - Possible nonflow effects in $v_2$ peripheral events

- Stronger flow observed for ALICE and ATLAS at mid-rapidity
Fixed Target Mode (SMOG2)

- SMOG: System for Measuring Overlap with Gas
- Run3 initial data for $D^0 \rightarrow K^- \pi^+$
- Run3 initial data for $J/\psi \rightarrow \mu^- \mu^+$
  - Only 18 minutes of $p$+Ar collisions data taking
- Future gas targets include: $^4$He, $^{20}$Ne, $^{40}$Ar, $^{84}$Kr, $^{132}$Xe, H$_2$, N$_2$, O$_2$
Summary
Conclusion

**Heavy-Ion Physics**

- New evidence for coalescence with $\Lambda_b^0$ to $B^0$ enhancement in high multiplicity $pp$ collisions (Phys. Rev. Lett. Featured in Physics)
- First-ever flow measurements in PbPb collisions from LHC at forward rapidity
- Many new results in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
  - Including prompt and nonprompt $\psi(2S)$ double ratios, $\chi_c$ production
- $\psi(2S)/J/\psi$ ratio shows suppression with increasing multiplicity in 13 TeV $pp$ collisions, consistent with final state effects

**Fixed Target Physics**

- SMOG2 results coming soon in $p$Ar collisions at $\sqrt{s_{NN}} = 113$ GeV
- Plans to run future fixed target mode with Nitrogen, Oxygen, Xenon and more
Back-Up
Call For Paper: [Symmetry] Special Issue - Recent Advances in High-Energy Physics: QCD from Heavy-Ion to Electron-Ion Colliders

- **Website:** [https://www.mdpi.com/journal/symmetry/special_issues/1OB695571H](https://www.mdpi.com/journal/symmetry/special_issues/1OB695571H)
- **Guest Editor:** Dr. Krista Lizbeth Smith
- **Deadline for manuscript submissions:** 31 July 2024

In this Special Issue, original research articles and reviews are welcome. Research areas may include (but are not limited to) the following:

- Heavy-ion collisions;
- Electron-ion collisions;
- Quark-gluon plasma;
- Quantum chromodynamics
Measured $\eta$ to $\pi^0$ cross-section ratios in the backward (left) and forward regions

PYTHIA8 generally describes the data well, while EPOS4 generally overestimates the ratio, especially at high $p_T$
$\psi(2S)$ to $J/\psi$ Ratio vs $pp$ Collision Energy
$J/\psi$ to $D^0$ Ratio in PbNe Collisions at LHC

- Data recorded in fixed-target mode at $\sqrt{s_{NN}} = 68.5$ GeV (regeneration effects minimal)
- $J/\psi$ to $D^0$ ratio shows strong dependence on $p_T$
- $J/\psi(D^0)$ cross section assumed to scale as $\langle N_{coll} \rangle^\alpha$ ($\langle N_{coll} \rangle$)
- Linear falling trend from $p$Ne to central PbNe indicates $J/\psi$ suppression inconsistent with QGP effects
Conclusions

- Heavy-ion physics in Run 3-4: QGP studies accessible in LHCb with increasing centrality reach.
  - Expecting great performances in pPb and in fixed-target.
  - PbPb physics accessible up to 30% centrality in Run 3 and 20-10% in Run 4.
- In Run 5 expected full centrality coverage:
  - MIGHTY tracker solves occupancy problem.
  - UT upgrade would solve upstream occupancy, ghost rate in Long Tracks and cope with the data rate (40 pp collisions per bunch crossing).
  - Studies still ongoing.
- The future of heavy-ion in LHCb is promising!

Thank you for your attention!
**B baryon enhancement**

- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Baryon/meson ratio shows significant multiplicity dependence
- Expected in scenario where b quarks coalesce with light quarks to form baryons

![Graph showing the dependence of $\sigma_{\Lambda_b}/\sigma_{B^0}$ on $p_T > 0$ in LHCb collisions at $\sqrt{s} = 13$ TeV.](image)

- $pp \rightarrow b\bar{b} + X$, global uncertainty: $^{+19%}_{-16%}$
- $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}$
**Quarkonium Level Scheme**

- $c\bar{c}$ states approximately non-relativistic and can be shown in spectroscopic notation $J^{PC}$, where $\bar{J} = \bar{L} + \bar{S}$
- Inclusive $J/\psi$ contributions
  - $\sim 60\%$ direct production
  - $\sim 30\%$ $\chi_c$ states
  - $\sim 10\%$ decays from $\psi(2S)$
- Vector mesons $J/\psi$ and $\psi(2S)$ can decay directly to dileptons via virtual photons

Phys. Letters B561 (2003), 61-72. Image Credit M. Teklishyn
Prog.Part.Nucl.Phys.61:455-511,2008
Cold Nuclear Matter Effects

1. **Gluon Shadowing/Anti-Shadowing:**
   Modification (suppression/enhancement) of heavy quark cross section due to modifications of the gluon nuclear parton distribution functions (nPDFs) in the target.

2. **Nuclear Absorption:**
   The break up of the bound $J/\psi$ (or precursor state) in collisions with other target nucleons passing through $J/\psi$ production point.

3. **Cronin Effect:**
   Modification of $J/\psi p_T$ distribution due to multiple elastic scattering off partons.

4. **Parton Energy Loss:**
   The projectile gluon experiences multiple scattering passing through the target prior to $J/\psi$ production.

5. **Comovers:**
   Final state break-up of the $J/\psi$ via interactions with produced partons.
### Publications of the Ions and Fixed Target Working Group

| TITLE | DOCUMENT NUMBER | JOURNAL | SUBMITTED ON |
|-------|-----------------|---------|--------------|
| Modification of $p_T(3872)$ and $\psi(2S)$ production in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV | PAPER-2023-026 arXiv:2402.14975 [PDF] | JHEP | 22 Feb 2024 |
| Prompt and nonprompt $\psi(2S)$ production in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV | PAPER-2023-024 arXiv:2401.11342 [PDF] | JHEP | 20 Jan 2024 |
| Multiplicity dependence of $\sigma_{p\bar{p}ll}/\sigma_{NN}$ in $pp$ collisions at $\sqrt{s} = 13$ TeV | PAPER-2023-035 arXiv:2312.15201 [PDF] | JHEP | 23 Dec 2023 |
| Measurement of forward charged hadron flow harmonics in peripheral $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the LHCb detector | PAPER-2023-031 arXiv:2311.09985 [PDF] | Phys. Rev. C | 16 Nov 2023 |
| Observation of strangeness enhancement with charmed mesons in high-multiplicity $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV | PAPER-2023-021 arXiv:2311.08490 [PDF] | PRL | 14 Nov 2023 |
| Fraction of $J/\psi$ decays in prompt $J/\psi$ production measured in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV | PAPER-2023-028 arXiv:2311.01562 [PDF] | Phys. Rev. Lett. 132 (2024) 102302 | 02 Nov 2023 |
| Production of $\eta$ and $\eta'$ mesons in $pp$ and $p\bar{p}$ collisions | PAPER-2023-030 arXiv:2310.17326 [PDF] | Phys. Rev. C 109 (2024) 024907 | 26 Oct 2023 |
| Enhanced Production of $ab0$ Baryons in High-Multiplicity $pp$ Collisions at $s=13$ TeV | PAPER-2023-027 arXiv:2310.12278 [PDF] | Phys. Rev. Lett. 132 (2024) 081901 | 18 Oct 2023 |
| Measurement of prompt $D^+$ and $D_s^+$ production in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV | PAPER-2023-006 arXiv:2309.14206 [PDF] | JHEP 01 (2024) 070 | 25 Sep 2023 |
| Study of the Bose-Einstein correlations of same-sign pions in proton-lead collisions | PAPER-2023-002 arXiv:2306.09755 [PDF] | JHEP 09 (2023) 172 | 16 Jun 2023 |
| Measurement of $\Xi^+$ production in $p\bar{p}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV at LHCb | PAPER-2022-041 arXiv:2305.06711 [PDF] | PRL | 11 May 2023 |

New LHCb heavy-ion and fixed target (IFT) results since Moriond 2023 (web link)
Quarkonia binding energies listed according to *J. Phys. G* 32 (2006) R25

- Note the binding energy of $\chi_{c1,2} >$ binding energy of $\psi(2S)$
Heavy Flavor: Charm & Bottom Quarks

| state     | $\eta_c$ | $J/\psi$ | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ | $\psi'$ |
|-----------|----------|----------|--------------|--------------|--------------|---------|
| mass [GeV]| 2.98     | 3.10     | 3.42         | 3.51         | 3.56         | 3.69    |
| $\Delta E$ [GeV] | 0.75 | 0.64 | 0.32 | 0.22 | 0.18 | 0.05 |

Table 1: Charmonium states and binding energies

| state     | $\Upsilon$ | $\chi_{b0}$ | $\chi_{b1}$ | $\chi_{b2}$ | $\Upsilon'$ | $\chi'_{b0}$ | $\chi'_{b1}$ | $\chi'_{b2}$ | $\Upsilon''$ |
|-----------|------------|--------------|--------------|--------------|-------------|--------------|--------------|--------------|-------------|
| mass [GeV]| 9.46       | 9.86         | 9.89         | 9.91         | 10.02       | 10.23        | 10.26        | 10.27        | 10.36       |
| $\Delta E$ [GeV] | 1.10 | 0.70 | 0.67 | 0.64 | 0.53 | 0.34 | 0.30 | 0.29 | 0.20 |

Table 2: Bottomonium states and binding energies

- Hadrons carrying single charm or bottom quarks, i.e. open heavy flavor
- Heavy quarkonia, bound states of charm or bottom quarks and their antiquarks, i.e. hidden charm or beauty
the amplitude are interpolated in mass between the fitted points. The resulting Argand diagram, shown in Fig. 9(a), is consistent with a rapid counter-clockwise change of the $P_c(4450)^+$ phase when its magnitude reaches the maximum, a behavior characteristic of a resonance. A similar study for the wider state is shown in Fig. 9(b); although the fit