Prompt charged particle production in heavy-ion collisions

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LHCb Implications Workshop

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Motivation: hadron production

- Hadron production in $pp$ and $pA$ collisions not well understood
- Most production driven by non-perturbative soft-QCD interactions: hadronization, DPS, …
- Predictions of Monte-Carlo generators largely disagree in LHCb acceptance

Impact in cosmic-ray physics:
- generators used to study the evolution of hadronic cascades from high-energy cosmic rays
- uncertainties limited by quality of generators
- unexplained excess in the number of muons that reach the Earth surface (arXiv:2105.06148v1)

Figure: CMS-TOTEM, $\sqrt{s} = 8$ TeV, $L = 45 \mu$b$^{-1}$
Motivation: CNM effects

- Charged hadron production in $pA$ collisions influenced by cold nuclear matter (CNM) effects
- Baseline to study $AA$ collisions and quark gluon plasma effects
- Perturbative QCD ($p$QCD) calculations are only possible for high $p_T$ charged particles:
  - Description of shadowing/antishadowing in nuclear PDFs (nPDFs)
  - Study saturation of gluon density $\rightarrow$ constrains in Color Glass Condensate (CGC) models
  - Are additional CNM effects not described by nPDFs?

Nuclear modification factor $\rightarrow R_{ppb}(\eta, p_T) = \frac{1}{A} \frac{d^2\sigma_{ppb}(\eta, p_T)/dp_Td\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_Td\eta}$, $A = 208$
The LHCb detector

- Only LHC detector fully instrumented in $2 < \eta < 5$
- Minimum-bias datasets of $pp$ and $pPb$ collisions at different centre-of-mass energies
- Reverse beam directions in $pPb$:

$p$ — Pb

Forward $\eta > 0$

Pb — $p$

Backward $\eta < 0$

Boost of nucleon-nucleon cms system: $\eta = \eta_{lab} - 0.465$

Figure from arXiv:2105.06148v1
LHCb \((x, Q^2)\) coverage

- Nuclear effects depend on \((x, Q^2)\) of the probed Pb parton

\[ Q^2 \approx m^2 + p_T^2, \quad x \approx \frac{Q}{\sqrt{s_{NN}}} e^{-\eta} \]

\[ m = 256 \text{ MeV}/c^2 \]

- LHCb can probe unprecedented Bjorken-\(x\) range:
  - forward, \(10^{-6} \lesssim x \lesssim 10^{-4}\)
  - backward, \(10^{-3} \lesssim x \lesssim 10^{-1}\)

- Possible access to saturation region in perturbative scale \(p_T > 1.5 \text{ GeV}/c\)

- Backward acceptance overlaps with \((x, Q^2)\) at central BRAHMS \((dAu)\) and backward PHENIX \((Au p)\)

Saturation region:

\[ Q_{x,Pb}^2 \approx 0.26 A^{1/3} (x_0/x)^\lambda \text{ GeV}^2 \]

\[ \lambda = 0.288 \]

\[ x_0 = 3 \cdot 10^{-4} \]

\[ A = 208 \]
Prompt charged particle production in $p$Pb and $pp$.

Nuclear modification factor $\rightarrow R_{p$Pb$}(\eta, p_T) = \frac{1}{A} \frac{d^2\sigma_{p$Pb$}(\eta, p_T)/dp_Td\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_Td\eta}$, $A = 208$

- Prompt charged particles: long-lived particles (lifetime $< 30$ ps)
  - produced in primary interaction or without long-lived ancestors

- Long-lived charged particles: $\pi^-, K^-, p, e^-, \mu^-, \Xi^-, \Sigma^+, \Sigma^-, \Omega^-(+cc.)$

- Datasets at $\sqrt{s_{NN}} = 5$ TeV

- Measure $R_{p$Pb$}$ in common $\eta$ range

<table>
<thead>
<tr>
<th>Beam</th>
<th>Acceptance</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>$2 &lt; \eta &lt; 4.8$</td>
<td>$3.49 \pm 0.07$ nb$^{-1}$</td>
</tr>
<tr>
<td>$p$Pb</td>
<td>$1.6 &lt; \eta &lt; 4.3$</td>
<td>$42.73 \pm 0.98$ µb$^{-1}$</td>
</tr>
<tr>
<td>Pbp</td>
<td>$-5.2 &lt; \eta &lt; -2.5$</td>
<td>$38.71 \pm 0.97$ µb$^{-1}$</td>
</tr>
</tbody>
</table>
Analysis overview

- $N_{\text{ch}}$ measured with long tracks, covering $p > 2 \text{ GeV/c}$, $0.2 < p_T < 8 \text{ GeV/c}$

- $N_{\text{ch}} = N_{\text{candidates}} \frac{P}{\varepsilon_{\text{reco}} \varepsilon_{\text{sel}}}$
  - $N_{\text{candidates}}$: selected long tracks
  - $P$: signal purity
  - $\varepsilon_{\text{reco}}$: reconstruction efficiency
  - $\varepsilon_{\text{sel}}$: selection efficiency

- **Background contributions:**
  - **Fake tracks**, reconstruction artifacts not produced by charged particles
  - **Secondary particles**: particles from
    - interactions with the detector material ($e^-$ from $\gamma$ conversions and hadrons from hadronic interactions)
    - daughters of long-lived particles ($\Lambda^0$, $K_S^0$, $\Sigma^+$ . . .)

Figure from *JINST 10 (2015) 02, P02007*
Analysis overview

Background description

- Background from fake tracks *specially important*
  - Increases with event occupancy, large contribution in Pb$p$
  - Contribution rises strongly with $p_T$

- Remove most background with a **tight track selection**

- **Selection efficiency** measured on data using a calibration sample of $\phi(1020) \rightarrow K^+K^-$ decays

- Remaining **background** estimated with simulation and corrected with data
  - use background-enriched proxy samples

Relative particle composition

- Reconstruction efficiency depends on **relative particle composition**

- **Charged particle composition** not yet measured in LHCb acceptance for $p$Pb → use EPOS-LHC simulation validated with ALICE data ([Phys. Lett. B760 (2016) 720](https://doi.org/10.1016/j.physletb.2016.06.013))
Systematic uncertainties

- Measurement dominated by systematic uncertainties:
  - particle composition in $p$Pb for most bins
  - tracking efficiency and signal purity in boundary ($\eta, p_T$) bins

- Total uncertainty shown in the table:
  - down to 2.8% in $d^2\sigma/d\eta dp_T$
  - down to 4.2% in $R_{pPb}$

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$p$Pb [%] (forward)</th>
<th>$p$Pb [%] (backward)</th>
<th>$pp$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-finding efficiency</td>
<td>1.5 – 5.0</td>
<td>1.5 – 5.0</td>
<td>1.6 – 5.3</td>
</tr>
<tr>
<td>Detector occupancy</td>
<td>0.0 – 2.8</td>
<td>0.6 – 2.9</td>
<td>0.1 – 1.6</td>
</tr>
<tr>
<td>Particle composition</td>
<td>0.4 – 4.1</td>
<td>0.4 – 4.6</td>
<td>0.3 – 2.4</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.7 – 2.2</td>
<td>0.7 – 3.0</td>
<td>1.0 – 1.7</td>
</tr>
<tr>
<td>Signal purity</td>
<td>0.1 – 1.8</td>
<td>0.1 – 1.17</td>
<td>0.1 – 5.8</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.3</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.0 – 0.6</td>
<td>0.0 – 1.0</td>
<td>0.0 – 1.1</td>
</tr>
<tr>
<td>Total (in $d^2\sigma/d\eta dp_T$)</td>
<td>3.0 – 6.7</td>
<td>3.3 – 14.5</td>
<td>2.8 – 8.7</td>
</tr>
<tr>
<td>Total (in $R_{pPb}$)</td>
<td>4.2 – 9.2</td>
<td>4.4 – 16.9</td>
<td>–</td>
</tr>
</tbody>
</table>
Double-differential cross-sections at 5 TeV

\[ \frac{d^2\sigma}{dp_Td\eta} \bigg|_{p_{\text{Pb}, pp}} = \frac{1}{\mathcal{L}} \cdot \frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta \eta} \]

- \( pp \) result compared with measurement at \( \sqrt{s} = 13 \) TeV (arXiv:2107.10090)
- cross-section at 13 TeV from 5 TeV increases a factor 1 – 3 depending on \( p_T \), consistent with expectations
Results of $R_{p\text{Pb}}$: forward region

- **Nuclear modification factor:**
  \[ R_{p\text{Pb}}(\eta, p_T) = \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}(\eta, p_T)/dp_Td\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_Td\eta}, \quad A = 208 \]

- **Strong suppression** at forward $\eta$, down to $\sim 0.3$ at low $p_T$ and most forward rapidity

- Discrepancy at low $p_T$ with CGC calculation

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**Models:**
- EPPS16+DDS: I. Helenius et. al. JHEP09(2014) 138
- CGC: T. Lappi et. al. PR D88, 114020

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**Graph:**

- **LHCb $\sqrt{s_{NN}}$=5 TeV**
- **Prompt charged particles**
- **Data**
- **EPPS16+DDS**
- **CGC**
Results of $R_{pPb}$: backward region

- **Nuclear modification factor:**
  \[
  R_{pPb}(\eta, p_T) = \frac{1}{A} \frac{d^2\sigma_{pPb}(\eta, p_T)/dp_Td\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_Td\eta}, \quad A = 208
  \]

- **Enhancement** at backward for $p_T > 1.5$ GeV/$c$, as observed by PHENIX in Au$^+$p

- Observed a $\eta$ dependence of the enhancement

- **Models:**
  - EPPS16+DDS: I. Helenius et. al.  
    - does not reproduce enhancement
  - pQCD calculation with MS: Z. B. Kang et. al.
    - same calculation reproduces enhancement in Au$^+$p collisions at PHENIX
      
      | JHEP09(2014) 138 |
      | PL B740(2015) 23 |
      | PR C101 (2020) 034910 |

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**Graph:**

- EPPS16+DDS
- pQCD+MS

- $-3.0 < \eta < -2.5$
- $-3.5 < \eta < -3.0$
- $-4.0 < \eta < -3.5$
- $-4.5 < \eta < -4.0$
- $-4.8 < \eta < -4.5$

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**Prompt charged particles in heavy-ion collisions**

21/10/2021
Results of $R_{pPb}$: comparison with ALICE

- Continuous trend of $R_{pPb}$ from forward to backward $\eta$ rapidity, including CMS and ALICE results

Normalization uncertainties for LHCb and ALICE
Results of $R_{pPb}$: dependence with $(x_{exp}, Q_{exp}^2)$

$Q_{exp}^2 \equiv m^2 + p_T^2$ and $x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$

- experimental proxies for $(x, Q^2)$
- with $\eta$ and $p_T$ the center of each bin and $m = 256$ MeV/c$^2$
- indirect study of the evolution of $R_{pPb}$ with $x$ and $Q^2$

- Continuous evolution of $R_{pPb}$ with $x_{exp}$ at different $Q_{exp}^2$, between forward, central and backward $\eta$

- $LHCb$, $\sqrt{s_{NN}}=5$ TeV

- Prompt charged particles

- $0.75 < Q_{exp}^2 < 0.85$ GeV$^2$/c$^2$
- $3 < Q_{exp}^2 < 4$ GeV$^2$/c$^2$
- $7 < Q_{exp}^2 < 10$ GeV$^2$/c$^2$
- $45 < Q_{exp}^2 < 50$ GeV$^2$/c$^2$

- $\text{LHCb}$
- $\text{ALICE}$, $-1.3 < \eta < 0.3$
- $\text{CMS}$, $-1.0 < \eta < 1.0$

- $\text{LHCb}$
Conclusions

- First determination of $R_{pPb}$ for prompt charged particles in forward and backward regions at LHC
  - double-differential prompt charged particle cross-section in $pp$ and $pPb$ at $\sqrt{s_{NN}} = 5$ TeV
  - total uncertainty down to 4.2% in $R_{pPb}$
  - Study of cold nuclear matter effects over a wide range of $x$
  - Strong constrains to nuclear PDFs and saturation models at intermediate and very low $x$

- Prospects: exploit excellent $(\pi, K, p)$ PID at LHCb to measure cross-sections by species in $pp$ and $pPb$ collisions
  - Reduction of systematic uncertainty in this measurement
  - Input to understand enhancement in backward region
Backup slides
The LHCb detector

- Forward spectrometer at LHC fully instrumented in $2 < \eta < 5$
  - Tracking system with excellent momentum resolution
  - Identification of charged hadrons ($\pi, K, p$), neutrals ($\gamma, \pi^0$), and leptons ($\mu, e$)

- Resolution of $B$ and $D$ decay vertices from primary collision
- Highly flexible trigger, configured to measure very low $p_T$
- Accurate luminosity determination (uncertainty $\sim 2\%$, JINST 9 (2014) 12, P12005)
Previous results of $R_{pA,dA}$

**BRAHMS $R_{dAu}$**


**PHENIX $R_{pAu}$**


**CMS, ALICE $R_{pPb}$**

*JHEP 04* (2017) 039

*JHEP 1811* (2018) 013

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**Charged-particle spectra and nuclear modification factors**

ALICE Collaboration

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**Parameter value description**

- **$R_{pA}$**
  - $p+Au \rightarrow h^+ + X$, $|s_{NN}|=200$ GeV
  - 0%-100% centrality
  - $-2.2 < \eta < 1.2$ (Au-going)

**Model comparisons**

- EPPS16+PYTHIA
- CT10
- nCTEQ15+PYTHIA
- pQCD calculation

**Statistical errors**

- Shown with error bars.

**Systematic errors**

- Shown as boxes around data points.

**Normalization uncertainties**

- Consistent with data within 1 standard deviation.

**Parton energy loss**

- Violent collisions.

**Data-driven efficiency correction procedure**

- Contributed to the suppression at forward rapidity.

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