Heavy-ion physics and strong interactions at LHCb

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Moriond QCD
27 March to 3 April 2021
General purpose single-arm forward spectrometer

- Acceptance
  - $2 < \eta < 5$ with particle identification
  - $0.1 < p_T / \text{GeV} c^{-1} < 10$
- Very good momentum and vertex resolution
  - Very good discrimination of prompt charm & beauty
- Very accurate luminosity (world record for $p-p$ 7 TeV)
- PID optimal for $\mu$, $\rho$, $K$, $\pi$
- Flexible software trigger
Overview

• $p$-$p$ $\sqrt{s} = 13$ TeV
  • Prompt charged particles New

• $p$-$Pb$ $\sqrt{s_{NN}} = 8.16$ TeV
  • Cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ New
  • Charm pair production

• Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
  • $J/\psi$ photo-production in hadronic Pb-Pb collisions New
Muons Puzzle in air showers

- Air showers are hadronic cascades driven by soft-QCD interactions
- Muon Puzzle: \( \mu \) deficit in simulated showers starting at \( \sqrt{S_{NN}} \approx 8 \) TeV
- Muon production quantitatively linked to forward hadron production and hadron composition — Ulrich et al. PRD 83 (2011) 054026 Baur et al. arxiv:1902.09265
- Nuclear effects in target important, large interest in p+O

Example event from Pierre Auger Observatory


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Prompt charged particles

LHCb-PAPER-2021-010-001, to be submitted to JHEP

- First double-differential forward charged particle spectrum at 13 TeV
- Fundamental measurement for (soft-)QCD, generator tuning, and astroparticle physics

\[
\frac{d^2 \sigma}{d \eta \, d p_T} \equiv \frac{n}{\mathcal{L} \, \Delta \eta \, \Delta p_T}
\]

Control study on fake track probability

- Loose candidate selection with high efficiency
- Total efficiency from data-adjusted simulation
- Backgrounds subtracted using data-adjusted simulation; e.g. fake tracks, tracks from material interactions
- Analysis written completely in Python
  - Numerical code accelerated with Numba
  - Python scientific stack + Scikit-HEP tools
Prompt charged particles

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- Uncertainty (2.3 to 15) %
- Fake tracks < 9.5 %
- Material interactions < 12 %
- Tracking efficiency < 5.1 %

- Full covariance matrix will be published for first time for charge particle analysis in LHCb
- Comparison with QCD generators
  - Generators mostly overestimate forward density
  - Charge density: Best agreement with EPOS-LHC
  - Charge ratio: Best agreement with Pythia-8.3

- Outlook: Extend to p-Pb and identified hadron spectra

Outlook: reduce each with improved techniques

\( \eta = [2.0, 2.5] \)
\( \eta = [4.5, 4.8] \)
Cross-section ratio \( \sigma(\chi_{c2})/\sigma(\chi_{c1}) \)

\[ p\text{-}Pb @ 8.16 \text{ TeV} \ 35/\mu b \]

- First measurement of prompt \( \chi_{c1} \) and \( \chi_{c2} \) production in \( p\text{-}Pb \) at TeV scale
  - \( \chi_{c1} \) with \( J=0,1,2 \) triplet of orbitally excited charmonia
  - \( \chi_{c1} \) and \( \chi_{c2} \) small difference in binding energy, study final state effects with cross-section ratio

- Reconstruction via \( \chi_{c1} \rightarrow J/\psi \ gamma \) followed by \( J/\psi \rightarrow \mu \mu \); two photon classes
  - Converted photons in material upstream of magnet (high momentum resolution)
  - Calorimetric photons (larger sample)

\[ \Delta M = M(\mu^+\mu^-) - M(\mu^+\mu^-) \]

**Figure 1:** Mass-distribution of resonances and combinatorial background (dashed black line).

**Figure 2:** Mass-distribution of converted candidates in material upstream of magnet (high momentum resolution).

**Figure 3:** Mass-distribution of calorimetric photons (larger sample).

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Cross-section ratio \( \sigma(\chi_{c2})/\sigma(\chi_{c1}) \)

**p-Pb @ 8.16 TeV 35/\mu b**

- Selection of prompt \( \chi_{c1} \) via pseudo decay-time \( t_z \)
- Efficiencies taken from simulation (EPOS-LHC + Pythia-8.1)

\[
t_z = \frac{(z_{\text{decay}} - z_{\text{PV}}) \times M_{\chi_{c1}}}{p_z}
\]

\[
\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}} \varepsilon_{\chi_{c1}} B(\chi_{c1} \to J/\psi \gamma)}{N_{\chi_{c1}} \varepsilon_{\chi_{c2}} B(\chi_{c2} \to J/\psi \gamma)}
\]

- Cross-section ratios compatible with unity
  - Forward and backward ratios consistent
  - Similar final state effects for \( \chi_{c1} \) and \( \chi_{c2} \)

- Ratio compared to \( pp \) 7 TeV
  - Double ratio consistent with 1 within uncertainties (deviation < 2\( \sigma \))

\[
R = \frac{\sigma(\chi_{c2})/\sigma(\chi_{c1})}{\sigma(\chi_{c2})/\sigma(\chi_{c1})} \bigg|_{p-Pb} = 1.41 \pm 0.21 \pm 0.18
\]

\[
R = \frac{\sigma(\chi_{c2})/\sigma(\chi_{c1})}{\sigma(\chi_{c2})/\sigma(\chi_{c1})} \bigg|_{pp} = 1.44 \pm 0.24 \pm 0.25
\]

First error: stat. Second error: sys.
Charm pair production and DPS scattering


- First measurement of charm pair production in p-Pb at 8.16 TeV
  - Sensitive to double parton scattering (DPS)
  - Sensitive probe of nPDF
  - Test universality of $\sigma_{\text{eff}}$ in DPS cross-section

$$\sigma_{\text{DPS}}^{AB} = \frac{1}{1 + \delta_{AB}} \frac{\sigma^A \sigma^B}{\sigma_{\text{eff}}}$$  \(\text{inclusive prod. cross-sections for } A, B\)

\(\text{effective cross-section, independent of final state}\)

- Single parton scattering (SPS)
  - Produced hadrons correlated
  - Cross-section scales roughly with mass number $A$
- Double parton scattering (DPS)
  - Correlated and uncorrelated hadrons
  - Cross-section scaling enhanced, about factor $3$ in p-Pb wrt SPS
- Analysis of kinematic distributions of $D_1D_2$ and $J/\psi D$ pairs ($D = D^0, D^+, D_s^+$)
  - Opposite-sign pair, e.g. $D^0\bar{D}^0$ **SPS enhanced**
  - Like-sign pair, e.g. $D^0D^0$ **DPS enhanced**

**p-Pb 8.16 TeV 30.8/nb**

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  - Produced hadrons correlated
  - Cross-section scales roughly with mass number $A$
- Double parton scattering (DPS)
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Analysis of kinematic distributions of $D_1D_2$ and $J/\psi D$ pairs ($D = D^0, D^+, D_s^+$)

- Opposite-sign pair, e.g. $D^0\bar{D}^0$ **SPS enhanced**
- Like-sign pair, e.g. $D^0D^0$ **DPS enhanced**
Charm pair production and DPS scattering


\( p\text{-}Pb \ 8.16 \text{ TeV} \ 30.8/\text{nb} \)

- Cross-sections for all \( D_1D_2 \) and \( J/\psi D \) pairs given in the paper, here:
  - \( D^0\bar{D}^0 \) SPS enhanced (opposite-sign)
  - \( D^0D^0 \) DPS enhanced (like-sign)
- Two-charm invariant mass \( m_{DD} \)
  - \( D^0\bar{D}^0 \) good agreement with Pythia8
  - \( D^0D^0 \) shape different 2-3σ
- Relative azimuthal angle \( \Delta \phi \)
  - \( D^0\bar{D}^0 \) enhanced at 0 as expected but stronger than Pythia-8.1 predictions
- Effective cross-section \( \sigma_{\text{eff}} \) consistent with expected factor 3 enhancement

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Pairs} & -5 < y(H_c) < -2.5 & 1.5 < y(H_c) < 4 & pp \text{ extrapolation} \\
\hline
D^0\bar{D}^0 & 0.99 \pm 0.09 \pm 0.09 & 1.41 \pm 0.11 \pm 0.10 & 4.3 \pm 0.5 \\
J/\psi D^0 & 0.64 \pm 0.10 \pm 0.06 & 0.92 \pm 0.22 \pm 0.06 & 3.1 \pm 0.3 \\
\hline
\end{array}
\]

First error: stat.
Second error: sys.

assuming SPS scaling with \( A \)
**J/ψ photo-production in hadronic collisions**

LHCb-PAPER-2020-043, to be submitted to PRL

**Pb-Pb 5.02 TeV 210/µb**

- **First LHCb measurement in Pb-Pb**: Prompt J/ψ yields at very low p_T
  - Excess of J/ψ at very low p_T observed by ALICE in Pb-Pb at 2.76 TeV and STAR in Au-Au at 0.2 TeV
  - Coherently photo-produced J/ψ in hadronic heavy-ion collisions?

- **Analysis in centrality classes**
  - Centrality based on deposit in electromagnetic calorimeter and Glauber calculation
  - UPC rejected by requiring minimal deposit in ECAL
  - Reject beam-gas interactions with cut on primary vertex location
  - Prompt J/ψ selection with cut on pseudo-decay time t_z

- **Photo-produced J/ψ extracted via fit to background-subtracted di-muon p_T spectrum**
- **Efficiency obtained from data-adjusted simulations (EPOS-LHC + Pythia-8.1 + STARlight)**

![Graphs showing invariant-mass distribution and differential yield](image)

\[
\frac{dY_{J/\psi}^i}{dy} = \frac{N_{J/\psi}^i}{B N_{MB}^i \varepsilon^{tot}_i \Delta y}
\]

\[
\frac{d^2Y_{J/\psi}^i}{dp_T dy} = \frac{dY_{J/\psi}^i}{dy} \times \frac{1}{\Delta p_T}
\]
J/ψ photo-production in hadronic collisions

LHCb-PAPER-2020-043, to be submitted to PRL

Pb-Pb 5.02 TeV 210/µb

- Most precise results to date in $p_T$
- Photo-produced J/ψ confirmed as source of ALICE excess
- Results compared to predictions with and without nuclear overlap based on


- Shape reproduced, but not scale
Summary

• LHCb has developed full heavy-ion program with measurements in all collision systems

• $p-p \sqrt{s_{NN}} = 13$ TeV
  • Prompt charged particles New LHCb-PAPER-2021-010-001
    • First measurement of double differential cross-section in forward region at 13 TeV
    • Important input for the Muon Puzzle in astroparticle physics

• $p$-Pb $\sqrt{s_{NN}} = 8.16$ TeV
  • Cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ New arxiv:2103.07349
    • First measurement of $\chi_{c1}, \chi_{c2}$ in p-Pb at TeV scale
  • Charm production via double parton scattering PRL 125 (2020) 212001
    • First measurement of charm pair production in p-Pb at 8.16 TeV

• Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
  • J/ψ photo-production in hadronic Pb-Pb collisions New LHCb-PAPER-2020-043
    • First Pb-Pb measurement by LHCb
    • Most precise results in $p_T$