Hard probes production in $p$Pb collisions at LHCb

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• Introduction

• LHCb detector and datasets

• Results in $p$Pb collisions at LHCb
  • Prompt charm pair production at 8.16 TeV
    [PHYSICAL REVIEW LETTERS 125, 212001 (2020)]
  • Prompt $D^0$ meson production at 8.16 TeV
    [LHCb-CONF-2019-004]
  • Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at 8.16 TeV New!
    [LHCb-PAPER-2020-048-001]
  • Z boson production cross section at 8.16 TeV
    [LHCb-CONF-2019-003]

• Summary and outlook
Introduction

- Cold nuclear matter effects (CNM) are assumed to be dominant in $p$Pb collisions.
  - Modification of nuclear PDF (nPDFs).
  - Other initial/final state effects.
- Open heavy flavors, quarkonium, W/Z bosons are used to probe CNM and constrain nPDFs at small-$x$ and mid-$x$ region in LHCb $p$Pb collisions.

\[ R_i^{Pb}(x, Q^2) = \frac{f_i^{Pb}(x, Q^2)}{A_i^{Pb}(x, Q^2)}, i = g, q, \bar{q} \]
LHCb detector

- A single-arm forward spectrometer, covering the pseudo-rapidity range of $2 < \eta < 5$.
- Designed for studying particles containing $b$ or $c$ quarks.
Datasets

- \( pPb \) data is taken in 2016 (\( \sqrt{s_{NN}} = 8.16 \text{ TeV} \)), two collision configurations.

\[ pPb \text{ system boosted in laboratory frame:} \]
\[ y^* = y_{lab} - 0.465. \]

\[ \text{Rapidity acceptance:} \]
\[ pPb: 1.5 < y^* < 4.0 \]
\[ Pbp: -5.0 < y^* < -2.5 , \]
common region: \( 2.5 < |y^*| < 4.0 \)

\[ \text{Luminosity:} \]
\[ pPb: 13.6 \text{ nb}^{-1} + Pbp: 20.8 \text{ nb}^{-1}. \]
Prompt charm pair production at 8.16 TeV
Prompt charm pair production at 8.16 TeV
- The first measurement of charm pair production in pPb at 8.16 TeV.
- Single parton scattering (SPS) vs. double parton scattering (DPS).
- DPS is expected to be enhanced in heavy-ion collisions.
- Like-sign (LS) ($D^0$–$\bar{D}^0$)
  - Assumed to be produced dominantly by DPS.
  - Uncorrelated if no parton correlation.
- Opposite-sign (OS) ($D^0$–$\bar{D}^0$)
  - Produced from a $c\bar{c}$ pair via SPS.
  - SPS generally correlated.

[PHYSICAL REVIEW LETTERS 125, 212001 (2020)]
Correlation variables

- Double charm hadron invariant mass $m_{DD}$
  - Hints a difference between LS($D^0 - D^0$) and OS($D^0 - \bar{D}^0$) pairs.
  - OS pairs are consistent with Pythia8 simulation.

- Azimuthal angle between the charm hadron pair $\Delta \phi$
  - Obvious difference between LS and OS pairs.
  - OS pairs favor values $\Delta \phi \sim 0$.
  - LS pairs are compatible with being flat.
  - Both show inconsistency with Pythia8 simulation.

- Distributions of the pair transverse momentum $p_T(D_1 D_2)$ and the two-charm relative rapidity $\Delta y(D_1 D_2)$ are found to be compatible in OS data, LS data, and Pythia8 simulation.
Double charm pair production in $pPb$

- LS/OS ratios $R^\sigma$ are enhanced in $pPb$ compared to $pp$.
- DPS effective cross-sections $\sigma_{\text{eff}}$ are compatible with extrapolation from $pp \sim 0.9b$.
  - Suggesting DPS/SPS enhanced by a factor 3 in $pPb$ compared to $pp$.
- $\sigma_{\text{eff}}$ using $J/\psi - D^0$ are smaller than $D^0 - D^0$, similar to the case in $pp$ data, possibly due to SPS contamination or DPS enhancement in $J/\psi - D^0$ production.
- $\sigma_{\text{eff}}$ for $pPb$ data is larger than $Pbp$ data, suggesting a suppression of DPS signal in $pPb$ data compared to $Pbp$.

[PHYSICAL REVIEW LETTERS 125, 212001 (2020)]
Prompt $D^0$ meson production at 8.16 TeV
Prompt $D^0$ meson production at 8.16 TeV

- Charm hadron decay modes: $D^0 \rightarrow K^-\pi^+$ & c. c
- $D^0$ yields extracted from $K^+\pi^\pm$ mass fits.
- Prompt and non-prompt (from b-decay) $D^0$ are separated using fit to the impact parameter (IP) $\chi^2$ distribution.

Transverse momentum:
- $0 < p_T < 16 \text{ GeV}/c$

Rapidity:
- forward: $1.5 < y^* < 4.0$,
- backward: $-5.0 < y^* < -2.5$

$$\frac{d^2\sigma}{dp_T dy^*} = \frac{N_{\text{prompt}}}{\mathcal{L} \times \epsilon_{\text{tot}} \times \mathcal{B} \times \Delta p_T \times \Delta y^*}$$
Forward – backward ratio $R_{FB}$ at 8.16 TeV

$R_{FB}(p_T, y^*) = \frac{d^2\sigma_{pPb}(p_T, +|y^*|)/dp_Tdy^*}{d^2\sigma_{Pb}(p_T, -|y^*|)/dp_Tdy^*}$

- $R_{FB}$ increases with increasing $p_T$
  - Lower $p_T$: consistent with 5.02 TeV results and nPDF.
  - Higher $p_T$: above nPDF expectation.
- $R_{FB}$ decreases with increasing $y^*$
  - Consistent with nPDFs and 5.02 TeV measurement.

Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at 8.16 TeV  New!
\( \chi_{cJ} \rightarrow J/\psi + \gamma \) in \( p\text{Pb} \) collisions at 8.16 TeV  New!

- First ever measurement of P-wave charmonia in \( p\text{Pb} \) collisions at the LHC.

- \( \chi_{cJ} \) is a triplet charmonium state with masses between those of \( J/\psi \) and \( \psi(2S) \), the masses of the three states sequentially differ by \(< 100 \text{ MeV} \).

- Binding energy of \( \chi_{cJ} \) is between \( J/\psi \) and \( \psi(2S) \). Measuring the suppression of \( \chi_{cJ} \) in \( p\text{Pb} \) will add additional points on \( R_{p\text{Pb}} \) and binding energy axis.

- Working with two different samples:
  - **Converted photons**: photons converted into an electron-positron pair in the Vertex Locator and T station.
  - **Calorimetric photons**: non-converted photons reconstructed in calorimeter.

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[Graphs and tables showing data on \( \chi_{cJ} \) and \( \psi \) states in \( p\text{Pb} \) collisions at 8.16 TeV.]

**Converted \( \chi_{c1,2} \) candidates**

**Calorimetric \( \chi_{c1,2} \) candidates**

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[LHCb-PAPER-2020-048-001]
Cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at 8.16 TeV  New!

• Converted photons method ($3 < p_T < 15$ GeV/c):
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})(1.5 < y^* < 4.0) = 1.02 \pm 0.39$ (stat.) $\pm 0.12$ (syst.)
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})(-2.5 < y^* < 5.0) = 1.00 \pm 0.42$ (stat.) $\pm 0.16$ (syst.)

• Calorimetric photons method ($5 < p_T < 15$ GeV/c):
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})(1.5 < y^* < 4.0) = 1.10 \pm 0.16$ (stat.) $\pm 0.10$ (syst.)
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})(-2.5 < y^* < 5.0) = 1.05 \pm 0.21$ (stat.) $\pm 0.60$ (syst.)

• The cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is consistent with unity at both forward and backward rapidity regions.

• Ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is larger in $p$Pb than in $pp$, although they are consistent within statistical uncertainty.

• Result suggests that the final-state nuclear effects impact the $\chi_{c1}$ and $\chi_{c2}$ states similarly within the achieved precision.
Z boson production in $p$Pb collisions at 8.16 TeV
Z boson production in pPb collisions at 8.16 TeV

- The Z production in pPb collisions can be used to probe cold nuclear matter effects for Bjorken-x from $\sim 10^{-4}$ to $\sim 1$ at $Q^2 \sim 10^4$ GeV$^2$.

- 8 TeV luminosity: forward $(12.2 \pm 0.3$ nb$^{-1})$ / backward $(18.6 \pm 0.5$ nb$^{-1})$
  - yields: forward (268 events) / backward (167 events).

- 5 TeV luminosity: forward $(1.099 \pm 0.021$ nb$^{-1})$ / backward. $(0.521 \pm 0.011$ nb$^{-1})$
  - yields: forward (11 events) / backward (4 events). [JHEP09(2014)030]

- The much larger 8.16 TeV datasets leads to a significant improvement in precision.

- Efficiencies are estimated using MC and tag-and-probe data-driven corrections.
Z boson cross-section at 8.16 TeV

- Cross-section: \( \sigma_{Z \rightarrow \mu^+ \mu^-} = \frac{N_{\text{sig}}}{\mathcal{L} \times \varepsilon_{\text{tot}}} \).

- Cross-section results:
  - \( \sigma_{Z \rightarrow \mu^+ \mu^-} \) (forward):
    \[
    25.8 \pm 1.7 \, \text{(stat)} \pm 1.2 \, \text{(syst)} \pm 0.7 \, \text{(lumi)} \, \text{nb}
    \]
  - \( \sigma_{Z \rightarrow \mu^+ \mu^-} \) (backward):
    \[
    13.4 \pm 1.0 \, \text{(stat)} \pm 1.4 \, \text{(syst)} \pm 0.3 \, \text{(lumi)} \, \text{nb}
    \]

- Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with NNPDF3.1(PDF) for p and NNPDF3.1(PDF) for Pb.
  - EPPS16 (nPDF)
  - nCTEQ15 (nPDF)

- Results are compatible with previous 5 TeV results from various experiments.
Z boson forward-backward ratio at 8.16 TeV

• Forward-backward ratio: \( R_{FB}^{2.5<|y^*|<4.0} = \frac{\sigma_{Z\rightarrow \mu^+\mu^- , pPb}}{\sigma_{Z\rightarrow \mu^+\mu^- , Pbp}} \bigg|_{2.5<|y^*|<4.0} \).

• Measured \( R_{FB} \) at 8.16 TeV
  \( R_{FB}^{2.5<|y^*|<4.0} = 1.28 \pm 0.14\text{(stat)} \pm 0.14\text{(syst)} \pm 0.05\text{(lumi)}. \) [LHCb-CONF-2019-003]

• Compatible with theoretical predictions:
  \( R_{FB,NNPDF3.1}^{2.5<|y^*|<4.0} = 1.59 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.05\text{(PDF)}, \)
  \( R_{FB,NNPDF3.1+EPPS16}^{2.5<|y^*|<4.0} = 1.45 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.27\text{(PDF)}, \)
  \( R_{FB,NNPDF3.1+nCETQ15}^{2.5<|y^*|<4.0} = 1.44 \pm 0.10\text{(theo.)} \pm 0.01\text{(num.)} \pm 0.20\text{(PDF)}. \)
Summary and outlook

- LHCb has strong capabilities to study heavy flavor in heavy-ion collisions.

- Studied production of charm pair, $D^0, \chi_{c1,2}$ charmonia and Z boson at LHCb:
  - The first measurement of charm pair production in $p\text{Pb}$ collisions at 8.16 TeV: 
    observes 3 times DPS/SPS enhancement in $p\text{Pb}$ compared to $pp$ and 
    suggests a suppression of DPS in $p\text{Pb}$ data compared to Pb$p$.

  - Preliminary $D^0 R_{FB}$ at 8.16 TeV: 
    hints an increasing trend towards high $p_T$.

  - First measurement of prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in $p\text{Pb}$ collisions at the LHC: 
    the ratio is consistent with unity for forward and backward.

  - Z boson production in $p\text{Pb}$ collisions at 8.16 TeV: 
    constrains nPDF models for Bjorken-$x$ from $\sim10^{-4} - \sim1$.

- More production measurements in $p\text{Pb}$, PbPb and SMOG1/SMOG2 at LHCb:
  - Example: $D^+, D_s^+, D^{*+}, \Lambda_c^+, \Xi_c^+$ in $p\text{Pb}$ at 8.16 TeV ...
Thank you!
Back up
Prompt $D^0$ meson production at 8.16 TeV
nuclear PDFs (nPDFs)

\[ R_{g}^{\text{Pb}}(x, Q^2) = \frac{f_{g}^{\text{Pb}}(x, Q^2)}{(A f_{g}^{\text{P}}(x, Q^2))} \]

- **LHCb forward**: at small-\(x\) region, the most relevant effect on the PDFs is shadowing: a reduction of the parton densities at low \(x\).
- **LHCb backward**: at mid-\(x\) region (anti-shadowing).
- Shadowing, anti-shadowing, EMC effect, fermi motion.
- These effects can be described by means of phenomenological parametrisations of the PDF modifications, denoted as nuclear PDFs (nPDFs).

- In LHCb forward and backward region, the uncertainties on the \(R_{g}^{\text{Pb}}(x, Q^2)\) are large.
- Measurements of charm production cross-sections in LHCb pPb collisions are important tests of pQCD, and as the rapidity range available to LHCb is unique at the LHC, such measurements are complementary to those made by other experiments.

**LHCb forward**: \[ x_1 \sim m_T(e^{+y_1} + e^{+y_2})/\sqrt{s} \]

**LHCb backward**: \[ x_2 \sim m_T(e^{-y_1} + e^{-y_2})/\sqrt{s} \]

\[ m_T = \sqrt{m^2 + p_T^2} \]
Prompt charm pair production at 8.16 TeV

Figure 2. Example of a process which can be seen either as a DPS or as an SPS. If the hard process is defined by the black box, then it is a DPS with the two subprocesses $q\bar{q} \rightarrow A$ and $q\bar{q} \rightarrow B$. In the case where the hard process is defined by the green box, then one has the SPS $gg \rightarrow A + B$. The pieces which are not included within the boxes are integrated out inside the PDFs.

- Cross-section factorization in DPS:

$$\sigma^{AB}(p_T^A, y^A, p_T^B, y^B) = \kappa \sum_{i,j,k,l} \int \hat{\sigma}^A_{i,j}(x_1, x'_1; p_T^A, y^A) \hat{\sigma}^B_{k,l}(x_2, x'_2; p_T^B, y^B)$$

$$\times f^{i,k}_{h}(x_1, b_1, x_2, b_2; Q_1^2, Q_2^2) f^{j,l}_{h}(x'_1, b_1' - b', x'_2, b_2 - b'; Q_1^2, Q_2^2) dx_1 dx'_1 dx_2 dx'_2 d^2 b_1 d^2 b_2 d^2 b'$$

Impact parameter dependent double-parton distribution function (2-PDF)

Assuming 2-PDF factorizable into PDF: $f(x_i, b_i, x_j, b_j) = f(x_i)f(b_i)f(x_j)f(b_j)$

$$= \kappa \sum_{i,j} \int \hat{\sigma}^A_{i,j}(x_1, x'_1) f^{i}_{h}(x_1) f^{j}_{h}(x'_1) dx_1 dx'_1 \times \sum_{k,l} \int \hat{\sigma}^B_{k,l}(x_2, x'_2) f^{k}_{h}(x_2) f^{l}_{h}(x'_2) dx_2 dx'_2$$

$$\times \int d^2 b' \int f(b_1)f(b_1 - b') d^2 b_1 \times \int f(b_2)f(b_2 - b') d^2 b_2$$

$$\equiv \kappa \sigma^A \times \sigma^B \times \int T^2(b') d^2 b'$$

$T(b)$: overlapping integral at separation $b$
Prompt charm pair production at 8.16 TeV

- DPS cross-section factorized into product of single inclusive cross-section
  \[ \sigma^{AB} \propto \sigma^A \times \sigma^B \times \int T^2(b) db = \frac{\sigma^A \sigma^B}{\sigma_{\text{eff}}} \]

  Two-parton PDF factorizable \( \Rightarrow \sigma_{\text{eff}} \) is universal

- Studies of DPS probe correlations of partons and impact parameter dependent PDF

- Studies of associated production in \( pp(\bar{p}) \)
  \[ \sigma_{\text{eff}} = \kappa \frac{\sigma^A \times \sigma^B}{\sigma^{AB}} \sim 15 \text{ mb}, \text{ but not consistent} \]

- DPS is enhanced in heavy ion collisions
  \[ \sigma^{DPS}_{p\bar{p}b} \approx 600 \times \sigma^{DPS}_{pp}, \text{ while } \sigma^{\text{SPS}}_{p\bar{p}b} \approx 208 \times \sigma^{\text{SPS}}_{pp} \]

  arXiv:1708.07519

- \( D\bar{D} \) correlation probes nuclear matter
  \[ \Rightarrow \text{Nuclear PDF} \]
  \[ \Rightarrow \text{Parton saturation} \]
  \[ \Rightarrow \text{Final state modification} \]
Z boson production in $p$Pb collisions

- The theoretical predictions are calculated using FEWZ with the NNLO pQCD and NLO perturbative electroweak (pEW) theory.
- The FEWZ codes are modified so as to calculate the cross-sections using PDFs for the proton side and using nPDFs for the Pb side.
- The PDF sets used for these calculations are NNPDF3.1 PDFs, EPPS16+CT14NLO nPDFs, and nCTEQ15 nPDFs.
- In the calculations, the theoretical uncertainty is evaluated by varying the factorization and renormalization scales by up and down by two standard deviations around their central values. The PDF uncertainties for EPPS16 and nCTEQ15 are conservatively estimated using the same nPDF set for both p and Pb sides.
- This is due to technical limitations in the modified FEWZ codes when evaluating the PDF uncertainties using two different versions of PDF sets.
Introduction

- Hard and electroweak probes:
  - Heavy flavor hadrons, quarkonium, etc., are excellent hard probes of the cold and hot nuclear matter effects in heavy-ion collisions.
    - Bring information of the early stage.
    - $t_{\text{prod}} \ll t_{\text{QGP}}$: experience whole time evolution of collisions.
    - $m_Q \gg \Lambda_{\text{QCD}}$: allow perturbative calculations.
  - Photon and W/Z bosons, are used to probe nuclear effects and can be a reference for hard probes.
    - Decay before QGP formation.
    - Leptonic final states pass through the medium without being affected by the strong interaction.
Can operate both in pp/pPb/PbPb and fixed-target!

Principle of the SMOG2 system, consisting of a gas feed system, injecting into a pump (TP 301). With valve GV 302 open, the VELO vessel is filled with gas at low density, determined by the injected flow rate.

SMOG2: Standalone gas storage cell covering: $-500 < z < -300$ mm.
- Up to $\times 100$ higher gas density with same gas flow of current SMOG.
- Possibility to run in parallel of pp collisions and inject no noble Gaz.

Fixed-target mode: unique at LHC!
- Injecting gas in the LHCb VErtex LOcator (VELO) tank.
- Noble gas only: He, Ne, Ar
- Gas pressure: $10^{-7}$ to $10^{-6}$ mbar