Studies of the cold nuclear matter (nPDFs)

Óscar Boente García, on behalf of the LHC collaborations
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QCD@LHC, Orsay
boente@llr.in2p3.fr
Introduction

- **Cold Nuclear Matter (CNM) effects**: modifications of particle production yields in ion collisions with respect to \( pp \) that are not due to formation of a deconfined medium, including:
  - Final state effects
  - **Initial state effects**

- Crucial to set the baseline to study AA collisions
- Collinear factorisation approach in pQCD:

\[
\frac{d\sigma^{AB\to k+X}(Q^2)}{d\Omega} = \sum_{i,j,x'} f_{i/A}(x_1, Q^2) \otimes f_{j/B}(x_2, Q^2) \otimes d\hat{\sigma}^{ij\to k+X'}(Q^2), \quad \text{for } Q^2 \gg \Lambda_{\text{QCD}}
\]

- Nuclear Parton Distribution Functions (nPDFs)

\[
R_i^A(x, Q^2) = \frac{f_{i/A}(x, Q^2)}{A f_{i/p}(x, Q^2)}; \quad i = u, d, s, c, \ldots
\]

- Fitted with global analyses considering different processes
- Validity of collinear factorisation approach needs to be constantly monitored

Figure from *Eur.Phys.J.C 82 (2022) 5, 413*
Constraining nPDFs with LHC data

- A variety of LHC datasets have potential to be used to constrain nPDFs:
  - $p$Pb collisions
  - $\gamma$Pb collisions (UPC PbPb)
  - fixed target collisions (Wed 14:00 K. Mattioli talk, parallel A)
- Many channels of interest:
  - Dijets
  - Z and W boson
  - Drell-yan
  - Charm hadrons
  - Light hadrons
  - Direct photons
  - diffractive processes
- Observables: production cross-sections, $R_{pA}$, $R_{FB}$, di-particle(jet) correlations...
- Need to keep open many channels simultaneously to understand well the interplay between CNM effects and to extend ($x, Q^2$) coverage
- Run1 and Run 2 LHC data included in several recent nPDF analyses:
  - EPPS21 (EPJ C82 (2022) 5, 413), nNPDF3.0 (EPJ C82 (2022) 6, 50), nCTEQ15WZSIH (PR D104 (2021) 094005), TUJU21 (PR D105 (2022) 9, 9)
LHC experiment comparison

- Very good complementarity between the four LHC experiments

ATLAS JINST 3 (2008) S08003
CMS JINST 3 (2008) S08004
ALICE JINST 3 (2008) S08002
LHCb JINST 3 (2008) S08005

• Track reconstruction down to $p_T = 0$.
• Excellent $p_T$ and mass resolution.
• Excellent particle identification.
• Precision vertex reconstruction.
Dijet production in $pPb$ collisions

- Dijet production in $pPb$ and $pp$ at 5 TeV
  - Using $\mathcal{L}_{pPb} = 35 \pm 1 \text{ nb}^{-1}$ and $\mathcal{L}_{pp} = 27.4 \pm 0.6 \text{ pb}^{-1}$
  - $\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2$
  - Precision from 2% to 20%
  - Suppression even at large Bjorken-$x$ ($x \sim 10^{-1}$) (EMC effect)
- Data included in EPPS21 and nNNPDF3.0
  - Important reduction of nPDF uncertainties! [EPJ C82 (2022) 6, 507, EPJ C82 (2022) 5, 413]

- Future: triple-differential ($y^*, y^b, p_T^{\text{ave}}$) dijets?
  - See $pp$ result at 8 TeV ([EPJ C77 (2017) 11, 746] with 19.7 fb$^{-1}$

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**CMS**

$pPb$ ($35 \text{ nb}^{-1}$), $pp$ ($27.4 \text{ pb}^{-1}$) \( \sqrt{s_N} = 5.02 \text{ TeV} \)

- Anti-$k_T$, $R = 0.3$ jets
- $p_{T,1} > 90 \text{ GeV}$, $p_{T,2} > 20 \text{ GeV}$
- $\Delta \phi_{1,2} > 2\pi/3$

- pp NLO pQCD: CT14

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**Studies of the cold nuclear matter (nPDFs)**

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Dijet correlations in \( pPb \) collisions

- Dijet correlations and yields from ATLAS
  (PR C100 (2019) 034903)
  - Using \( \mathcal{L}_{pPb} = 0.36 \text{ nb}^{-1} \) and
  \( \mathcal{L}_{pp} = 25 \text{ pb}^{-1} \) at 5 TeV
  - Jets of \( R = 0.4 \) and in \( |y^*| < 4 \)
  - Observables:
    \[
    C_{12}(p_{T,1}p_{T,2}, y^*_1, y^*_2) = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi}
    \]
    \[
    \rho^p_{W} = \frac{W_{pp}}{W_{12}}, \text{ with } W_{12} = \text{RMS}(C_{12})
    \]
    \[
    \rho^p_{I} = \frac{I_{pp}}{I_{12}}, \text{ with } I_{12} \text{ dijet conditional yields}
    \]
  - \( \rho^p_{I} \) suppressed for forward dijets pairs, (shadowing region \( x \lesssim 10^{-3} \))
  - No modification for backward-forward jets
  - Ratio of correlation functions RMS \( \rho^p_{W} \) does not show modification

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\( \rho^p_{W} \) with ATLAS data:
- 2015 \( pp \) data, 25 \( \text{ pb}^{-1} \)
- 2016 \( p+Pb \) data, 360 \( \mu\text{b}^{-1} \)

\( \rho^p_{I} \) with ATLAS data:
- 2015 \( pp \) data, 25 \( \text{ pb}^{-1} \)
- 2016 \( p+Pb \) data, 360 \( \mu\text{b}^{-1} \)
Production of $W$ bosons in $pPb$

- Charge asymmetry $A_{ch}$ helps to separate $u\bar{d}$ ($W^+$) and $\bar{u}d$ ($\bar{W}^-$) flavours
- Run 2 data from CMS and ALICE
- CMS data included in most nPDF fits
- ALICE $A_{ch}$ in forward bin not reproduced by models (more than $5\sigma$ discrepancy)
- $R_{pPb}$ of $W^-$ shows tension in backward region with models
- No variation of $\sigma_{pPb}^{W^\pm}$ with respect to centrality
Drell-Yan and $Z$ production in central region

- CMS measurement with Run2 data at 8.16 TeV
- Low-mass ($15 < m_{\mu\mu} < 60$ GeV/$c$) and high-mass ($60 < m_{\mu\mu} < 120$ GeV/$c$) regions
  - First measurement at LHC of low-mass in $pPb$ covering $-2.87 < |\eta_{lab}| < 1.93$
  - Measurement in $m_{\mu\mu}$, $y_{CM}$, $p_T$ and $\phi^*$, where $\phi^* = \tan\left(\frac{\pi - \Delta \phi}{2}\right)\sin(\theta^*_\eta)$ with $\cos(\theta^*_\eta) = \tanh(\Delta \eta/2)$
  - Correlation matrices of systematic uncertainties
- Forward-to-backward ratio shows more precision than EPPS16 and nCTEQW/Z
Z boson in forward and backward regions

- LHCb and ALICE measured $Z \rightarrow \mu^+\mu^-$ in the forward and backward regions with Run 2
  - LHCb measurement includes $p_T$, $y^*$ and $\phi^*$ dependance, $R_{FB}$ and $R_{pPb}$
  - correlation matrices of systematic uncertainties
- Can extend CMS constrains towards lower and higher $x$
- Both measurements in general agreement with EPPS16 and nCTEQ15 predictions
- ALICE data included in nNNPDF3.0 (EPJ C82 (2022) 6, 50), LHCb not yet

LHCb: arXiv:2205.10213

ALICE: JHEP 2009 (2020) 076
LHCb measured $D^0$ meson production with Run 1 data ($\mathcal{L}_{p\text{Pb}} \sim 1.5 \text{ nb}^{-1}$) in $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$

- Measure double-differential cross-sections, $R_{p\text{Pb}}$ and $R_{FB}$
- Data included in EPPS21 (EPJ C82 (2022) 5, 413) and nNNPDF3.0 (EPJ C82 (2022) 6, 50)
  - Drastic reduction of nPDF uncertainties down to $x \sim 10^{-6}$

**Figure 4.5.** Comparison of the nPDFs of lead nuclei at $Q = 10 \text{ GeV}$ between nNNPDF3.0 (no LHCb $D^0$) and nNNPDF3.0, normalised to the central value of the former.

**Figure 4.6.** Same as Fig. 4.5 now presented in terms of the terms of the nuclear modification ratios $R(\mathcal{A}) f(x, Q)$. Accounting for the correlations between proton and lead PDFs. In the case of the sea quark PDFs, the enhanced shadowing for $x \approx < 10^{-3}$ and the corresponding uncertainty reduction is qualitatively similar to that observed at the lead PDF level. The preference of the LHCb $D^0$-meson production measurements for a strong small-$x$ shadowing of the quark and gluon PDFs of lead is in agreement with related studies of the same process in the literature [86, 97, 98].

Whenever the nuclear ratios deviate from unity, $R(\mathcal{A}) f(x, Q) \neq 1$, the fit results favour non-zero nuclear modifications of the free-proton PDFs. However, such non-zero nuclear modifications will not be significant unless the associated nPDF uncertainties are small enough. In order to quantify the local statistical confidence, EPPS16, EPPS21 nuclear err., EPPS21 full err.
**$D^0$ meson production**

- New LHCb $D^0$ meson production measurement with Run 2 data ($\mathcal{L}_{pPb} \sim 30 \text{ nb}^{-1}$)
- Finer $y^*$ binning and extended range to $p_T \in [0,30] \text{ GeV}/c$
- Comparison with HELAC-Onia predictions with EPPS16 and nCTEQ15 weighted with Run1 $D^0$ data
  - Discrepancy in backward rapidity at high $p_T$ with reweighted nPDF predictions
  - Great potential for additional constrains

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**$y^*$ integrated**

**in $y^*$ intervals**

![Graphs showing $R_{pPb}$ as a function of $p_T$ for different $y^*$ intervals.](image)
Hadrons: $\pi^0$ meson production

- Precise measurement $\pi^0$ spectrum from ALICE and LHCb Run 2 data
- Very wide phase-space coverage:
  - ALICE: $-0.3 < y < 1.3$ and $0.3 < p_T < 200$ GeV/$c$
  - LHCb: $2.5 < \eta_{CM} < 3.5$, $-4.0 < \eta_{CM} < -3.0$ and $1.5 < p_T < 10$ GeV/$c$
- Excess in backward region over nPDF predictions
  - ALICE data included in nCTEQ15WZSIH (PR D104, 094005)
  - Considers $\pi^\pm$, $K^\pm$ ALICE data (PL B760, 720 (2016))
  - Also new LHCb charged hadron result with wide $\eta$ coverage in $-5.3 < \eta < -2.5$ and $2.0 < \eta < 4.3$ (PRL 128 (2022) 142004)
Prompt photons in $pPb$

- Direct/prompt photons provide direct access to initial conditions of nuclei
- ATLAS measurement with Run2 data
  - Isolated photons in cone of $\Delta R = 0.4$
  - measured $d\sigma/E_T^\gamma$, $R_{pPb}$ and $R_{FB}$
  - large energy-loss contribution is not observed
  - compatible with expectations from EPPS16 and nCTEQ15
  - Included in nNNPDF3.0 fit (EPJ C82 (2022) 6, 50)
- Access to lower $\gamma$ energy?
  - Preliminary plot from ALICE
  - LHCb potential in forward & backward regions
  - ALICE FoCal detector in Run4: photons of $p_T > 2$ GeV/c in $3.4 < \eta < 5.8$

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**Link to repository**

**CERN-LHCC-2020-009**

**ALICE Preliminary**

$pPb$ fit is 5.02 TeV

$L_{\text{int}} = 4.96\text{n}b^{-1}$, $|\eta| < 0.67$

$R = 0.4$, $p_T^{\text{min}} < 1.5$ GeV/c

NLO JETPHOX $\times x^{10}$

NNPDF40 PDF, nNNPDF30 nPDF

BFG II FF

$R = 0.4$, $p_T^{\text{min}} < 2$ GeV/c

**Data/JETPHOX**

**Ratio with stat. unc.**

Systematic uncertainty

Theory scale uncertainty $p_T^{1/2} < \mu < 2x p_T^{1/2}$

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**ATLAS**

$\sqrt{s} = 8.16$ TeV $p+Pb$, 165 nb$^{-1}$

$-1.09 < \eta^* < 1.90$

$-1.84 < \eta^* < 0.91$

$-2.83 < \eta^* < -2.02$

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**EIC fit**

- no E-loss
- $\mu = 0.35$ GeV, $\lambda_q = 1.5$ fm
- $\mu = 0.35$ GeV, $\lambda_q = 1$ fm

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**EIC**

[32]

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**nNNPDF 1.0**

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**FOCAL fit**

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Constrains from $\gamma$Pb process

- CMS measured dijet azimuthal correlations in exclusive $\gamma$Pb processes
  - RAPGAP model overestimates strength of correlations \textit{CPC 86 (1995) 147}
  - soft gluon radiation calculation (Hatta et. al.) reproduces low $Q_T$ \textit{PRL 126 (2021) 142001}
  - information of gluon polarization in nuclei

- Preliminar ATLAS measurement of dijet production in $\gamma$Pb
  - ZDC tag events without nuclear break-up, results for results for $0nXn$ condition
  - Complementary ($x$, $Q^2$) coverage to $p$Pb dijets
  - expectations to increase precision in final result

- Exclusive quarkonia production in UPC → see Wed. 16:00, A. Matyja talk, parallel A

\textbf{ATLAS-CONF-2022-021}

\textbf{arXiv:2205.00045}
Conclusions and prospects

- **Huge progress of the understanding of CNM** in the recent years, with LHC data playing a major role
- **LHC pPb** data (dijets, $D^0$,...) sets unprecedented constraints to nPDF
- **Tensions with nPDF** predictions in several recent measurements not yet included in global analyses, such as:
  - $W^\pm$ production in forward/backward regions (ALICE)
  - $D^0$ production in backward region (LHCb)
- **γPb** interactions in UPCs provide a **unique source of information** (strength of gluon polarization)

- **Prospects for Run3/Run4:**
  - **great increase in statistics from a new pPb run**, several measurements now limited to $pp$ collisions would become possible
  - Future $pO$ run crucial do reduce nPDF uncertainties by setting constrains to a medium size nucleus

 OMB Some of the mentioned measurements can be performed with very limited statistics (i.e. light hadron production)
Backup