Nuclear PDF constraints from p+Pb collisions at the LHC
DIS2015

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Outline

- Introduction
  - Nuclear parton distribution functions
- New data from p+Pb at LHC
  - Hadron production
  - Dijet $\eta$ distributions
  - $W^\pm$ production
- Direct photon production
  - Production mechanisms
  - Sensitivity to small-$x$
  - Isolation cut
  - $R_{pPb}^\gamma$ at forward rapidities
- Summary & Conclusions

Mostly based on

with Kari J. Eskola and Hannu Paukkunen from U. of Jyväskylä
Parton distribution functions

Collinear factorization

\[ d\sigma^{p+p\rightarrow k+X} = \sum_{i,j,X'} f_i(x_1, Q^2) \otimes f_j(x_2, Q^2) \otimes d\hat{\sigma}^{ij\rightarrow k+X'} \]

- \( f_i(x, Q^2) \) are the parton distribution functions (PDFs) of proton
- \( d\hat{\sigma}^{ij\rightarrow k+X'} \) is the partonic cross section calculated from pQCD
Parton distribution functions

Collinear factorization

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Global DGLAP analysis

1. Parametrize \( f_i(x, Q^2) \) at chosen initial scale \( Q_0 \)

\[ f_i(x, Q_0^2) = N_i x^{a_i} (1 - x)^{b_i} F(x, c_i, \ldots) \]

2. Use DGLAP evolution equations to calculate \( f_i(x, Q^2) \) at \( Q > Q_0 \)

\[ \frac{\partial f_i(x, Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j P_{ij} \otimes f_j(x, Q^2) \]

3. Fit to wide range of data to obtain the values for parameters
Nuclear PDFs

The PDFs are modified in nuclear collisions:

\[ f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i(x, Q^2) \]

- \( R_i^A(x, Q^2) \) from global DGLAP-based analysis
- **Goal:** Test factorization and provide accurate pQCD baseline for \( A+A \)

Recent NLO analyses

- HKN07
- DSSZ
- nCTEQ
- EPS09  
  [JHEP 04 (2009) 065]

Data used in the fits

- Deep inelastic scattering (DIS)
- Drell-Yan dilepton production (DY)
- Pion production in d+Au collisions at RHIC

\[ \Rightarrow \text{Kinematic reach limited to } x > 0.001 \]
\[ \Rightarrow \text{Gluons not very well constrained} \]
nPDF uncertainties (from EPS09NLO)

\[ R_{Pb}^{i}(x, Q^2) \]

\[ Q^2 = Q_0^2 = 1.69 \text{ GeV}^2 \]

- Quarks well constrained, especially at \( x > 0.01 \)
- Large uncertainty for small-\( x \) gluons!

More constraints from p+Pb collisions at the LHC?

- Inclusive hadrons (ALICE, CMS, ATLAS)
- Dijet production (CMS)
- \( W^\pm \) production (CMS)
- Direct photons
Inclusive hadron production

Convolution of parton spectra and fragmentation function (FF)

\[ d\sigma_{p+Pb \rightarrow h+X} = \sum_{i,j,k,X'} f_i(x_1, Q^2) \otimes f_j^{Pb}(x_2, Q^2) \otimes d\hat{\sigma}^{ij \rightarrow k+X'} \otimes D^h_k(z, Q_{F}^2) \]

⇒ No direct connection between hadron \( p_T, \eta \) and parton \( x_2 \)

▶ Contribution from broad range of \( z \) (\( = p/q \))

▶ Sizable contribution from \( x_2 > 10^{-2} \) even at \( \eta = 4 \)
Inclusive hadron production

Charged hadron spectra in p+Pb:

\[ \frac{1}{N_{\text{evt}}} \frac{d^3N^h_{\text{pPb}}}{d^2p_T d\eta} \text{[GeV}^2 c^{-2}] \]

- KRE
- KKP
- DSS
- CT10+EPS09, \( \mu = Q = Q_F = p_T \)

\( \langle T_{pPb} \rangle = 0.0983 \pm 0.0035 \text{ mb}^{-1} \)

\( \sqrt{s_{NN}} = 5020 \text{ GeV} \)

\( |\eta| < 0.3 \)

Nuclear modification ratio

\[ R^h_{\text{pPb}}(p_T, \eta) = \frac{1}{208} \frac{d^2\sigma^h_{\text{pPb}}}{dp_T d\eta} / \frac{d^2\sigma^h_{pp}}{dp_T d\eta} \]

- FF differences cancel in ratio
- \( R^h_{\text{pPb}} \) not sensitive to FFs
- Enhancement in the data at \( p_T \sim 3 \text{ GeV/c} \)

- NLO calculations overshoot the data at \( p_T > 10 \text{ GeV/c} \)
Inclusive hadron production

ALICE $R_{pPb}$ for charged pions:

[Quark Matter 2014]

- No enhancement for mesons
- Some non-perturbative effects in baryon production
Inclusive hadron production

**ALICE $R_{pPb}$ for charged pions:**

![Graph showing $R_{pPb}$ for charged pions](ALICE preliminary)

- No enhancement for mesons
- Some non-perturbative effects in baryon production

**CMS result for charged hadron $R_{pPb}$**

![Graph showing CMS result for $R_{pPb}$](CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $L = 35$ nb$^{-1}$)

- Enhancement at $p_T > 20$ GeV/c
- Different $p+p$ baseline between ALICE and CMS?

[Quark Matter 2014]

[arXiv:1502.05387]
Dijets in p+Pb

Dijet pseudorapidity

\[ \eta_{dijet} = \frac{\eta_1 + \eta_2}{2} \]

- at \( \eta_{dijet} < 0 \) data sensitive to antishadowing region
- at \( \eta_{dijet} > 0 \) data sensitive to EMC effect
- Good description with EPS09

CMS pPb 35 nb⁻¹
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
\( p_T,1 > 120 \text{ GeV/c} \)
\( p_T,2 > 30 \text{ GeV/c} \)
\( \Delta\phi_{1,2} > 2\pi/3 \)
All \( E_T \) \( \geq 4 \)

**References**

[JHEP 1310 (2013) 213]
The impact of new data to nPDF fit can be studied by Hessian reweighting method.

Dijet data would improve gluon nPDFs at $x > 0.05$ (if given enough weight).

Supports gluon antishadowing and EMC suppression.

**Forward-backward asymmetry**

\[ \frac{N(\eta_{\text{lab}})}{N(-\eta_{\text{lab}})} \]

- Sum over \( W^+ \) and \( W^- \)
- \( \eta_{\text{lab}} = \eta + 0.465 \)
  where \( \eta \) pseudorapidity in nucleon-nucleon CMS frame
- Dominating processes:
  \( u\bar{d} \rightarrow W^+ \) and \( d\bar{u} \rightarrow W^- \)
- Sensitive to
  - \( \eta_{\text{lab}} > 0 \): \( 0.002 < x < 0.02 \)
  - \( \eta_{\text{lab}} < 0 \): \( 0.02 < x < 0.2 \)
- Good agreement with EPS09

**Graph**

- Data
- CT10
- CT10+EPS09

**References**

- [JHEP 03 (2011) 071]
- [arXiv:1503.05825]
Forward-backward asymmetry

\[ N(+\eta_{\text{lab}})/N(-\eta_{\text{lab}}) \]

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- Sensitive to
  - \( \eta_{\text{lab}} > 0: \ 0.002 < x < 0.02 \)
  - \( \eta_{\text{lab}} < 0: \ 0.02 < x < 0.2 \)
- Good agreement with EPS09

The gluon nPDFs at small-\( x \) remain badly constrained!
Direct $\gamma$ production

Two components in direct photon cross section

$$d\sigma_{pPb}^{\gamma+X} = d\sigma_{pPb}^{\text{prompt } \gamma+X} + d\sigma_{pPb}^{\text{fragmentation } \gamma+X}$$

Prompt photon production

e.g. Compton scattering

- Calculated from pQCD
- Sensitive to gluon PDFs

Fragmentation photon production

parton fragments into photon, e.g.

- Calculated by convoluting with parton-to-photon FFs

- At NLO the decomposition ambiguous (scale dependent)
- More sensitivity to small-$x$ physics than hadrons?
Sensitivity to small-$x$

- The contribution from different $x_2$ values to NLO cross section
- Calculated with JETPHOX [JHEP 0205 (2002) 028] ($Q = p_T$)

- Prompt component very sensitive to small values of $x_2$
- Fragmentation component have contribution also from larger $x_2$'s
- Total cross section not sensitive only to small values of $x_2$
- The relative sensitivity still larger than for hadrons
Sensitivity to small-$x$

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<table>
<thead>
<tr>
<th>p+Pb, $\sqrt{s} = 8.8$ TeV</th>
<th>5 &lt; $p_T^\gamma$ &lt; 20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 &lt; $\eta^\gamma$ &lt; 5</td>
<td></td>
</tr>
</tbody>
</table>

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Isolated photons

Isolation cut

- Reject photons that have \( \Sigma E_T > E_T^{max} \), where
  \[
  \Sigma E_T = \sum_i E_T^i \theta(R - R_i), \quad \text{and} \quad R_i = \sqrt{(\eta_\gamma - \eta_i)^2 + (\phi_\gamma - \phi_i)^2}
  \]
  Sum runs over all hadrons \( i \).
Isolated photons

Isolation cut

- Reject photons that have $\Sigma E_T > E_T^{max}$, where
  
  $$\Sigma E_T = \sum_i E_T^i \theta(R - R_i), \text{ and } R_i = \sqrt{(\eta_\gamma - \eta_i)^2 + (\phi_\gamma - \phi_i)^2}$$

  Sum runs over all hadrons $i$.

- Isolation cut suppresses the fragmentation component
- Increase the sensitivity to smaller values of $x_2$
Isolation and $x_2$ sensitivity

- The contribution from different $x_2$ values to NLO cross section

- Only the sum of two components physical observable
Isolation and $x_2$ sensitivity

- The contribution from different $x_2$ values to NLO cross section

![Graph showing the distribution of $x_2$ values for different categories: Prompt, Fragmentation, Isolated.]

- Only the sum of two components physical observable
- Isolation cut with $\Sigma E_T < 4\text{ GeV}$ suppresses fragmentation component
  ⇒ Decrease contribution from larger values of $x_2$
Isolation and $x_2$ sensitivity

- The contribution from different $x_2$ values to NLO cross section

![Graph showing the contribution from different $x_2$ values to NLO cross section.]

- Only the sum of two components physical observable
- Isolation cut with $\Sigma E_T < 4$ GeV suppresses fragmentation component
  $\Rightarrow$ Decrease contribution from larger values of $x_2$
- Tighter isolation cut ($\Sigma E_T < 2$ GeV) further suppresses the fragmentation component but small effect to total distribution
Nuclear modification factor

- $R_{pPb}^\gamma$ for inclusive and isolated direct photons using
  - CTEQ6.6M proton PDFs with EPS09 nuclear modifications
  - BFGII parton-to-photon FFs
  - Scale choice $\mu = Q = Q_F = p_T$

- Suppression in $R_{pPb}^\gamma$ due to shadowing in the nPDFs
- Slightly stronger suppression with isolation at small $p_T$
- Uncertainty due to nPDFs of the order 10%
Yield asymmetry $Y_{pPb}^{asym}$

Accuracy of $R_{pPb}$ measurement

- If no $p+p$ run at the given energy interpolation required
- If no luminosity measurement in $p+Pb$ glauber modeling required
  ⇒ Can cause uncertainties $\gtrsim 10\%$

Yield asymmetry between forward and backward rapidities

$$Y_{pPb}^{asym}(p_T, \eta) \equiv \frac{d^2\sigma_{pPb}}{dp_T d\eta} \bigg|_{\eta \in [\eta_1, \eta_2]} / \frac{d^2\sigma_{pPb}}{dp_T d\eta} \bigg|_{\eta \in [-\eta_2, -\eta_1]}$$

- No need for the $p+p$ baseline
- Many experimental uncertainties cancel in the ratio
- Nuclear modifications at backward rapidities well constrained by DIS and DY data
Prediction for $Y_{\text{pPb}}^{\text{asym}} (p_T, \eta)$

- NLO prediction with CTEQ6.6M+EPS09 PDFs and BFGII FFs

**Yield asymmetry**

- Smaller charge density in nuclei $\Rightarrow$ Isospin effect
- nPDFs uncertainties mainly from small-$x$ 
  $\Rightarrow$ Provides further constraints to nPDFs
- Serves also as a test of factorization
### Summary

- New data from p+Pb collisions at the LHC
  - Inclusive hadron production (not an ideal observable)
  - Dijet data constraints gluon nPDFs at \( x \gtrsim 0.01 \)
  - \( W^\pm \) data provides constraints for quarks at \( x > 0.002 \)
  
  \[ \Rightarrow \text{Gluons remain weakly constrained at } x < 0.01 \]

### Conclusions

- Direct photons more sensitive to small-\( x \) than inclusive hadrons
- Isolation cut increases the sensitivity to smaller values of \( x \)
- If no accurate p+p baseline available, the yield asymmetry can be used
Backup
Data comparison

- **Isolated photons at the LHC**

  - $\sqrt{s_{NN}} = 7.0$ TeV
  - $|\eta| < 0.9$
  - $p+p$

  - CMS
  - $R = 0.4$
  - $\Sigma E_T < 5$ GeV
  - JETPHOX
  - CT10, BFG II
  - $\mu = Q = Q_F = p_T$

  - Data comparison
  - [Data: Phys.Rev. D84:052011 (2011)]

  - Very well described by NLO pQCD

  - Same holds also for inclusive jets

- **Charged hadrons at LHC**

  - $E d^3\sigma / d^3p\left[\text{mb GeV}^{-2}\text{c}^3\right]$

  - $\sqrt{s} = 7000$ GeV
  - $\sqrt{s} = 2760$ GeV
  - $\sqrt{s} = 900$ GeV

  - $|\eta| < 1.0$

  - $p_T$

  - [JHEP 1108 (2011) 086]

  - NLO pQCD with recent FFs overshoots the data by factor of 2!

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$p_T$ systematics

Inclusive: $2 < p_T^\gamma < 20$ GeV
$5 < p_T^\gamma < 20$ GeV
$10 < p_T^\gamma < 20$ GeV

Isolated, $R = 0.4$, $\Sigma E_T < 2$ GeV
$2 < p_T^\gamma < 20$ GeV
$5 < p_T^\gamma < 20$ GeV
$10 < p_T^\gamma < 20$ GeV

$\sqrt{s} = 8.8$ TeV
More sensitivity to small-$x$ than hadrons

Contribution also from quark initiated processes
The relative contributions to direct photon cross section with

- three scale choices ($\mu = Q = Q_F$)

In NLO the division depends on the scale choice

$\Rightarrow$ Meaningful observable only when both processes are included!

- At small $p_T$ the fragmentation component dominant
Relative contributions from quarks and gluons in the Pb-nucleus at mid- and forward rapidities

- At $\eta = 0$ similar contribution from gluons and quarks
- At $\eta = 4.5$ about 80% from gluons
Rapidity systematics of isolated photons

▶ Larger rapidities \( \sim \) smaller \( x_2 \)

▶ Weak \( x \) dependence in the EPS09 at \( x < 0.01 \)
  \( \Rightarrow R_{pPb} \) independent of rapidity at \( \eta > 2 \) for isolated photons

▶ Uncertainties similar in each rapidity bin

▶ Accurate measurements required!
  ▶ FoCal in ALICE?
  ▶ LHCb capabilities?
Isolated photons at backward rapidities

- At $\eta < -2$ cross section mainly sensitive to quarks at $x_2 > 0.01$
  ⇒ nPDFs well constrained by DIS and DY data:

  ![Graph showing $R_{pPb}(p_T, \eta)$ as a function of $p_T$ and $\eta$]

Isospin effect

- Nuclei consist of protons and neutrons
  ⇒ Smaller charge density than in protons
- Photons couple to electric charge
  ⇒ Suppression in the large $x$ region where valence quarks dominate
Uncertainties in proton PDFs

- Proton PDFs from CT10 analysis [Phys.Rev. D82 (2010) 074024]

- Large uncertainties also for gluon PDFs in proton at $x < 10^{-4}$

⇒ Further constraints would be welcome to here also
Charged hadron yield asymmetry

- No unexpected effects at $p_T > 10 \text{ GeV}/c$
- Enhancement in $R_{pPb}$ independent of rapidity
- Baseline/normalization effect?

CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}, L = 35 \text{ nb}^{-1}$

Charged particles, $0.3<|\eta_{CM}|<0.8$

- 0.8<|\eta_{CM}|<1.3
- 1.3<|\eta_{CM}|<1.8

Total systematic uncertainty

[arXiv:1502.05387]
Charged hadrons in p+Pb

New data for charged hadrons in p+Pb from ALICE

\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]
\[ |\eta| < 0.8 \]
\[ p+Pb \]

\[ \langle T_{pPb} \rangle = 0.0983 \pm 0.0035 \text{ mb}^{-1} \]
\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]
\[ |\eta| < 0.3 \]
\[ p+Pb \]

\[ \langle T_{pPb} \rangle = 0.0983 \pm 0.0035 \text{ mb}^{-1} \]

At \( p_T \gtrsim 10 \text{ GeV}/c \) the data/NLO ratios are flat for both p+p and p+Pb

\Rightarrow The ALICE baseline seems to be in control up to \( p_T = 40 \text{ GeV}/c \)
Charged hadrons in p+Pb

- New data for charged hadrons in p+Pb from CMS

\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]

\[ p+p \]

\[ p+Pb \]

\[ p_T \]

\[ 1/N_{\text{evt}} d^3N/d^3p \]

\[ [\text{GeV}^{-2} c^2] \]

\[ \text{Data/NLO} \]

\[ \text{INCNLO, CT10+EPS09} \]

Kretzer, \( \mu = Q = Q_F = p_T \)

ALICE, arXiv:1405:2737, \(|\eta| < 0.3\)

Interpolated

CMS, preliminary, \(|\eta| < 1.0\)

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\[ \text{Data/NLO} \]

- Disclaimer: CMS spectra read ”by eye” (from H. Paukkkunen)!
- Rise in CMS data/NLO ratio at \( p_T > 50 \text{ GeV/c} \) in both p+p and p+Pb
Charged hadron production in p+p at different $\sqrt{s}$

$\sqrt{s} = 7.0 \text{ TeV}$

$\sqrt{s} = 1960.0 \text{ GeV}$

$\sqrt{s} = 2760 \text{ GeV}$

$\sqrt{s} = 900 \text{ GeV}$

Charged pion cross section

Charged pions in p+p collisions

Data consistent within the uncertainties when using Kretzer FFs
With DSS and KKP calculation a factor two of above the ALICE data
Dijets in p+Pb

Comparison of different nPDF sets

$\sqrt{s} = 5.02$ TeV

$\mu = p_T, \text{average}/2$

$1/\sigma d\sigma/d\eta_{dijet}$

NLO/CT10

Relative uncertainty

$\eta_{dijet} = (\eta_1 + \eta_2)/2$

[\text{JHEP 1310 (2013) 213}]

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**$W^\pm$ production**

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**CMS**

$W^+ \to l^+ + \nu$

$p_T^l > 25$ GeV/c

$pPb \ 34.6$ nb$^{-1}$

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

- Data
- CT10
- CT10+EPS09

\[ N^+/(-\eta_{lab})/N^{-/\eta_{lab}} \]

\[ 0 \leq \eta_{lab} \leq 2.5 \]

[arXiv:1503.05825]