Intrinsic charm and new PDFs using EMC charm structure function and LHC data

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In collaboration with:
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Proton and photon-induced nuclear collisions at the LHC
6-8 July 2016
Outline

- Measurement of Charm Structure Function
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- BHPS Model
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- $Q^2$ dependent of intrinsic heavy quarks
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- **BHPS Model**
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- Intrinsic and Extrinsic charm distribution
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- Numerical results from our fits with IC contribution
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- Results and conclusions
What is our motivation?
The first experimental evidence of intrinsic heavy quarks came from the EMC measurement of the large $x$ charm structure function.

Another evidence for IC

The $p\bar{p} \rightarrow \gamma + c$-jet differential production cross sections as a function of transverse momentum $p_T^\gamma$.\(^1\)

\[ \text{data} \]

DØ, $L = 8.7 \text{ fb}^1$

NLO (Stavreva, Owens)

$k_T$ fact. (Lipatov, Zotov)

SHERPA, v1.3.1

PYTHIA, v6.420

$|y| < 1.0$

$|y^{\text{jet}}| < 1.5$, $p_T^{\text{jet}} > 15 \text{ GeV}$

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Another evidence for IC

The ratio of $\gamma + c$-jet and $\gamma + b$-jet production cross sections for data together with theoretical predictions as a function of $p_T$.  

$\gamma \gamma$ production cross sections for data together with theoretical predictions as a function of $p_T$.

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Another evidence: D0 data and the prompt photon production in association with charm quark jet

Recent years, the prompt photon and heavy quark jet production in $p\bar{p}$ collisions at the Tevatron have been investigated that this process can be very useful for testing the possible existence of intrinsic quarks in the nucleon.
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D0 Collaboration, Physics Letters B 719 (2013) 354361
IC distribution and BHPS model


...
In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of ”intrinsic” charm in the nucleon.


\[
|p\rangle = \mathcal{P}_3q|uud\rangle + \mathcal{P}_5c\bar{c}|uudc\bar{c}\rangle + \ldots .
\]

The \( \mathcal{P}_5c\bar{c} \) is probability for the \( |uudc\bar{c}\rangle \) five-quark Fock state in the proton.

Schematic presentation of a nucleon consisting of valence, sea quarks, gluons, and pairs of the intrinsic charm and bottom quarks.
The intrinsic charm originating from the five-quark Fock state is to be distinguished from the extrinsic charm produced in the splitting of gluons into $c\bar{c}$, which is well described by QCD.
Intrinsic heavy quark content of the nucleon

The existence of a nonperturbative intrinsic heavy quark component in the nucleon is a rigorous prediction of Quantum Chromodynamics (QCD).
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- In the standard approach employed by almost all global analyses of PDFs, the heavy quark distributions are generated *radiatively*, according to DGLAP evolution equations, starting with a perturbatively calculable boundary condition at a scale of the order of the heavy quark mass.
Intrinsic heavy quark content of the nucleon

The existence of a nonperturbative intrinsic heavy quark component in the nucleon is a rigorous prediction of Quantum Chromodynamics (QCD).

- In the standard approach employed by almost all global analyses of PDFs, the heavy quark distributions are generated radiatively, according to DGLAP evolution equations, starting with a perturbatively calculable boundary condition at a scale of the order of the heavy quark mass.

- There are no free fit parameters associated to the heavy quark distribution and it is entirely related to the gluon distribution function at the scale of the boundary condition.

Intrinsic heavy quark content of the nucleon

- "Extrinsic quark" contributions: arise from gluon splitting in perturbative QCD.
  Extrinsic quarks are most important at low $x$ and depend logarithmically on the heavy quark mass $M_Q$. 

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Intrinsic heavy quark content of the nucleon

- "Extrinsic quark" contributions: arise from gluon splitting in perturbative QCD. Extrinsic quarks are most important at low $x$ and depend logarithmically on the heavy quark mass $M_Q$.

- "Intrinsic heavy quarks": charm, and bottom quarks are thus a fundamental property of the wave functions of hadronic bound states. Intrinsic heavy quarks are dominant at high $x$ and depend on $1/M_Q^2$. 
Intrinsic heavy quark content of the nucleon

The probability distribution as a function of $x$ in a general $n$–particle intrinsic $c\bar{c}$ Fock state is

$$\frac{dP_{IC}}{dx_i \cdots dx_n} = N_n \frac{\delta(1 - \sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n} (\hat{m}_i^2/x_i))^2},$$

where $N_n$ normalizes the $n$–particle Fock state probability.

In the heavy quark limit, $\hat{m}_c, \hat{m}_{\bar{c}} \gg m_h, \hat{m}_q$,

$$\frac{dP_{IC}}{dx_i \cdots dx_n} = N_n \frac{x_c^2 x_{\bar{c}}^2}{(x_c + x_{\bar{c}})^2} \delta\left(1 - \sum_{i=1}^{n} x_i\right),$$

So the intrinsic charm distribution is as followings:

$$x_c\text{int}(x) = x \int dx_1 \cdots dx_{\bar{c}} \frac{dP_{IC}}{dx_i \cdots dx_{\bar{c}} dx_c}.$$
According to the BHPS model the probability distribution for the five-quark $|uudQ\bar{Q}\rangle$ Fock state, can be written as

$$P(x_1, \ldots, x_5) = \mathcal{N} \delta(1 - \sum_{i=1}^{5} x_i) \left[ M^2 - \sum_{i=1}^{5} \frac{m_i^2}{x_i} \right]^{-2}$$

For the case that $Q$ is a heavy quark:

$$P(x_1, \ldots, x_5) = \mathcal{N}_5 \delta(1 - \sum_{i=1}^{5} x_i) \frac{x_4^2 x_5^2}{(x_4 + x_5)^2},$$

where $\mathcal{N}_5 = \mathcal{N} / m_{Q\bar{Q}}^4$ and $\mathcal{N}_5 = 3600 \mathcal{P}_5^{Q\bar{Q}}$. Finally, the probability distribution for the intrinsic heavy quark in the proton by integrating over $dx_1 \ldots dx_4$ is given by

$$P(x_5) = \mathcal{P}_5^{Q\bar{Q}} 1800 x_5^2 \left[ \frac{(1-x_5)}{3} (1 + 10x_5 + x_5^2) + 2x_5 (1 + x_5) \ln(x_5) \right].$$
Intrinsic heavy quark content of the nucleon

**Definiteness: Two Components (separate evolution)**

- $c_{\text{ext}}$: extrinsic charm
- $c_{\text{int}}$: intrinsic charm
- $c(x, Q^2) = c_{\text{ext}}(x, Q^2) + c_{\text{int}}(x, Q^2)$: full charm parton distribution

By using **DGLAP** evolution equations, we can obtain the extrinsic charm at any scale since the intrinsic component $c_{\text{int}}(x, Q)$ is governed (to a very good approximation) by a non-singlet evolution equation.

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Evidences for IC
Prompt photon production
BHPS Model
Intrinsic heavy quarks

\( Q^2 \) dependent of intrinsic heavy quarks

List of experimental data
Nuclear effects on EMC data
List of experimental data
Numerical results
Summarize

\[ xc(x, Q^2) \]

CTEQ66
IC
CTEQ66 + 1% IC

\( Q^2 = 1.69 \text{ GeV}^2 \)
\( Q^2 = 100 \text{ GeV}^2 \)
\( Q^2 = 10000 \text{ GeV}^2 \)


$Q^2$ dependent of intrinsic heavy quarks

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Summarize
Parton distribution functions with IC
Main Steps for a QCD fit

1-Parametrise PDFs at the starting scale

- Multiple options for functional forms
- Standard Polynomial, Chebyshev, etc
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1-Parametrise PDFs at the starting scale
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- DGLAP evolution
- QCDNUM, APFEL (x-space)
- PEGASUS (Mellin N-space)
## Main Steps for a QCD fit

### 1-Parametrise PDFs at the starting scale
- Multiple options for functional forms
- Standard Polynomial, Chebyshev, etc

### 2-Evolve to the scale corresponding to data point
- DGLAP evolution
- QCDNUM, APFEL (x-space)
- PEGASUS (Mellin N-space)

### 3-Calculate the cross section
- Various heavy flavor schemes FFNS, RT, ACOT, etc
Main Steps for a QCD fit

4-Compare with data via $\chi^2$:

- Multiple forms to account for correlations
Main Steps for a QCD fit

4-Compare with data via $\chi^2$:
- Multiple forms to account for correlations

5-Minimize $\chi^2$ with respect to PDF parameters:
- MINUIT, data driven regularisation
Our QCD fits

We choose the following functional form:

- **PARAMETERIZATION**

\[
egin{align*}
x_u(x) &= A_u x^{B_u} (1 - x)^{C_u} (1 + E_u x^2), \\
x_d(x) &= A_d x^{B_d} (1 - x)^{C_d}, \\
x_u(x) &= A_u x^{B_u} (1 - x)^{C_u} (1 + D_u x), \\
x_D(x) &= A_D x^{B_D} (1 - x)^{C_D}, \\
x_s(x) &= f_s x_D, \\
x_d(x) &= (1 - f_s) x_D, \\
x_g(x) &= A_g x^{B_g} (1 - x)^{C_g} - A_g' x^{B_g'} (1 - x)^{C_g'},
\end{align*}
\]

The parameters \(A_u, A_d\) and \(A_g\) are fixed by the constraints from the number and momentum sum rules.
\[x_s = f_s x_D\] with the factor of \(f_s = 0.31\).

"HERAFitter, Open Source QCD Fit Project" By S. Alekhin at al., EPJC (2015), 75: 304, xfitter.org
### List of experimental data

#### Nuclear effects on EMC data

<table>
<thead>
<tr>
<th>Data set</th>
<th>BASE</th>
<th>+EMC</th>
<th>+EMC + Nucl. effect</th>
<th>+LHC+IC (W² ≥ 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC F₂^P</td>
<td>96/59</td>
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<td>49/42</td>
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<td>152/16</td>
<td>108/16</td>
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<td>ATLAS Jet 3.6 ≤</td>
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<td>ATLAS W+ lep. pseudorap.</td>
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<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>ATLAS W- lep. pseudorap.</td>
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<td>-</td>
<td>-</td>
<td>11/11</td>
</tr>
<tr>
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<td>-</td>
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<td>11/8</td>
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<tr>
<td>ATLAS high mass DY</td>
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<td>7.6/13</td>
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<td>-</td>
<td>7.4/11</td>
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<tr>
<td>CMS Boson rap.</td>
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<td>-</td>
<td>-</td>
<td>56/35</td>
</tr>
<tr>
<td>Total χ² / dof</td>
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<td>1695/1228</td>
<td>1639/1228</td>
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<td>=1.235</td>
<td>=1.380</td>
<td>=1.334</td>
<td>=1.269</td>
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### Numerical results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BASE</th>
<th>+EMC</th>
<th>+EMC (+Nucl. effect)</th>
<th>+LHC+IC</th>
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</thead>
<tbody>
<tr>
<td>$B_{uv}$</td>
<td>0.684 ± 0.037</td>
<td>0.612 ± 0.038</td>
<td>0.615 ± 0.033</td>
<td>0.728 ± 0.022</td>
</tr>
<tr>
<td>$C_{uv}$</td>
<td>4.542 ± 0.074</td>
<td>4.652 ± 0.071</td>
<td>4.635 ± 0.067</td>
<td>4.571 ± 0.071</td>
</tr>
<tr>
<td>$E_{uv}$</td>
<td>13.0 ± 2.0</td>
<td>17.9 ± 2.9</td>
<td>17.4 ± 2.4</td>
<td>10.6 ± 1.1</td>
</tr>
<tr>
<td>$B_{dv}$</td>
<td>0.800 ± 0.088</td>
<td>0.703 ± 0.082</td>
<td>0.731 ± 0.077</td>
<td>0.777 ± 0.053</td>
</tr>
<tr>
<td>$C_{dv}$</td>
<td>3.95 ± 0.35</td>
<td>3.65 ± 0.38</td>
<td>3.79 ± 0.36</td>
<td>3.92 ± 0.23</td>
</tr>
<tr>
<td>$B_{ü}$</td>
<td>−0.181 ± 0.014</td>
<td>−0.140 ± 0.017</td>
<td>−0.150 ± 0.015</td>
<td>−0.151 ± 0.012</td>
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<tr>
<td>$C_{ü}$</td>
<td>8.16 ± 0.70</td>
<td>8.11 ± 0.59</td>
<td>7.93 ± 0.55</td>
<td>9.19 ± 0.79</td>
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<tr>
<td>$D_{ü}$</td>
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<td>12.3 ± 2.7</td>
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<td>$A_{D}$</td>
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<td>$C_{D}$</td>
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<td>6.6 ± 1.6</td>
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<td>−0.808 ± 0.022</td>
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<td>−0.663 ± 0.043</td>
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<tr>
<td>$C_{g}$</td>
<td>3.55 ± 0.63</td>
<td>1.21 ± 0.18</td>
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<tr>
<td>$A'_{g}$</td>
<td>0.56 ± 0.11</td>
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<td>0.464 ± 0.057</td>
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<tr>
<td>$B'_{g}$</td>
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<td>−0.804 ± 0.021</td>
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<td>ATLAS low mass DY</td>
<td>-</td>
<td>-</td>
<td>11/8</td>
<td>11/8</td>
</tr>
<tr>
<td>ATLAS high mass DY</td>
<td>-</td>
<td>-</td>
<td>7.6/13</td>
<td>7.9/13</td>
</tr>
<tr>
<td>ATLAS DY mass ext.</td>
<td>-</td>
<td>-</td>
<td>8.0/6</td>
<td>7.8/6</td>
</tr>
<tr>
<td>CMS electron Asym. rap.</td>
<td>-</td>
<td>-</td>
<td>7.4/11</td>
<td>7.7/11</td>
</tr>
<tr>
<td>CMS Boson rap.</td>
<td>-</td>
<td>-</td>
<td>56/35</td>
<td>54/35</td>
</tr>
<tr>
<td>Total $\chi^2$ / dof</td>
<td>1497/1212</td>
<td>1639/1228</td>
<td>1804/1421</td>
<td>2896/1747</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=1.235</td>
<td>=1.334</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>=1.269</td>
<td>=1.657</td>
</tr>
</tbody>
</table>
### Numerical results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BASE</th>
<th>+EMC</th>
<th>+LHC+IC (W² ≥ 3.5)</th>
<th>+LHC+IC (W² ≥ 15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{uυ}</td>
<td>0.684 ± 0.037</td>
<td>0.615 ± 0.033</td>
<td>0.786 ± 0.014</td>
<td>0.728 ± 0.022</td>
</tr>
<tr>
<td>C_{uυ}</td>
<td>4.542 ± 0.074</td>
<td>4.635 ± 0.067</td>
<td>2.51 ± 0.12</td>
<td>4.571 ± 0.071</td>
</tr>
<tr>
<td>E_{uυ}</td>
<td>13.0 ± 2.0</td>
<td>17.4 ± 2.4</td>
<td>−0.50 ± 0.16</td>
<td>10.6 ± 1.1</td>
</tr>
<tr>
<td>B_{dυ}</td>
<td>0.800 ± 0.088</td>
<td>0.731 ± 0.077</td>
<td>1.028 ± 0.054</td>
<td>0.777 ± 0.053</td>
</tr>
<tr>
<td>C_{dυ}</td>
<td>3.95 ± 0.35</td>
<td>3.79 ± 0.36</td>
<td>4.90 ± 0.25</td>
<td>3.92 ± 0.23</td>
</tr>
<tr>
<td>B_{u}</td>
<td>−0.181 ± 0.014</td>
<td>−0.150 ± 0.015</td>
<td>−0.150 ± 0.012</td>
<td>−0.151 ± 0.012</td>
</tr>
<tr>
<td>C_{u}</td>
<td>8.16 ± 0.70</td>
<td>7.93 ± 0.55</td>
<td>13.97 ± 0.94</td>
<td>9.19 ± 0.79</td>
</tr>
<tr>
<td>D_{u}</td>
<td>17.1 ± 3.8</td>
<td>13.7 ± 3.3</td>
<td>23.0 ± 4.0</td>
<td>12.3 ± 2.7</td>
</tr>
<tr>
<td>A_{D}</td>
<td>0.125 ± 0.013</td>
<td>0.158 ± 0.018</td>
<td>0.163 ± 0.014</td>
<td>0.159 ± 0.014</td>
</tr>
<tr>
<td>B_{D}</td>
<td>−0.181 ± 0.014</td>
<td>−0.150 ± 0.015</td>
<td>−0.150 ± 0.012</td>
<td>−0.151 ± 0.012</td>
</tr>
<tr>
<td>C_{D}</td>
<td>4.7 ± 1.6</td>
<td>7.8 ± 1.9</td>
<td>5.26 ± 0.81</td>
<td>4.29 ± 0.81</td>
</tr>
<tr>
<td>B_{g}</td>
<td>−0.649 ± 0.064</td>
<td>−0.787 ± 0.023</td>
<td>−0.676 ± 0.039</td>
<td>−0.663 ± 0.043</td>
</tr>
<tr>
<td>C_{g}</td>
<td>3.55 ± 0.63</td>
<td>1.31 ± 0.19</td>
<td>3.24 ± 0.35</td>
<td>2.89 ± 0.35</td>
</tr>
<tr>
<td>A'_{g}</td>
<td>0.56 ± 0.11</td>
<td>0.274 ± 0.023</td>
<td>0.471 ± 0.059</td>
<td>0.464 ± 0.057</td>
</tr>
<tr>
<td>B'_{g}</td>
<td>−0.649 ± 0.059</td>
<td>−0.784 ± 0.022</td>
<td>−0.676 ± 0.037</td>
<td>−0.665 ± 0.039</td>
</tr>
<tr>
<td>C'_{g}</td>
<td>25.00</td>
<td>25.00</td>
<td>25.00</td>
<td>25.00</td>
</tr>
</tbody>
</table>
Intrinsic charm and new PDFs using EMC charm structure function and LHC data

Evidences for IC
Prompt photon production
BHPS Model
Intrinsic heavy quarks
$Q^2$ dependent of intrinsic heavy quarks
List of experimental data
Nuclear effects on EMC data
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Numerical results
Summarize

Parton distributions at the initial scale $Q^2 = 1.4 \, \text{GeV}^2$
EMC data with IC contribution

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SLAC data with IC contribution
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Figure: The SLAC data and our QCD fit result and for different values of $W^2 \geq 3.5$ and $W^2 \geq 15$. 
Figure: The LHC data with result of our fits with 1% IC contribution and for \( W^2 \geq 15 \).
Figure: The LHC data with result of our fits with 1% IC contribution and for $W^2 \geq 15$. 

LHC data with IC contribution

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LHC data with IC contribution

Figure: The LHC data with result of our fits with 1% IC contribution and for $W^2 \geq 15$. 
Parton distributions at the scale of $Q^2 = 10 \text{ GeV}^2$
Parton distributions at the scale of $Q^2 = 100 \text{ GeV}^2$

**Intrinsic charm and new PDFs using EMC charm structure function and LHC data**

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- A detailed study of the impact of EMC and LHC data on PDF with IC distribution is presented.
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We have considered nuclear effect in EMC data in our QCD fits.
A detailed study of the impact of EMC and LHC data on PDF with IC distribution is presented.

In this work, we extract PDFs with take into account the intrinsic charm from QCD global fits of the data.

We have considered nuclear effect in EMC data in our QCD fits.

This analysis shows that the $\chi^2$ value is depend on the different $W^2$ cut values, i.e. $W^2 \geq 3.5$ and $W^2 \geq 15$, especially for SLAC and EMC data.
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Summarize

Thank you.