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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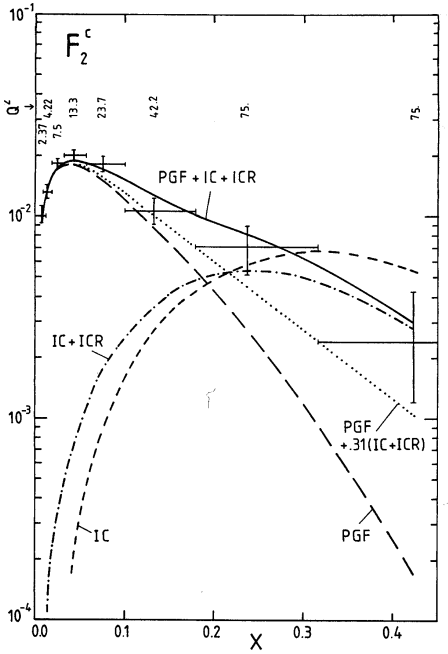
- Parametrization
- Numerical results from our fits with IC contribution
- Results and conclusions

What is our motivation?

European Muon Collaboration (EMC) Measurement of Charm Structure Function

First Evidence for Intrinsic Charm

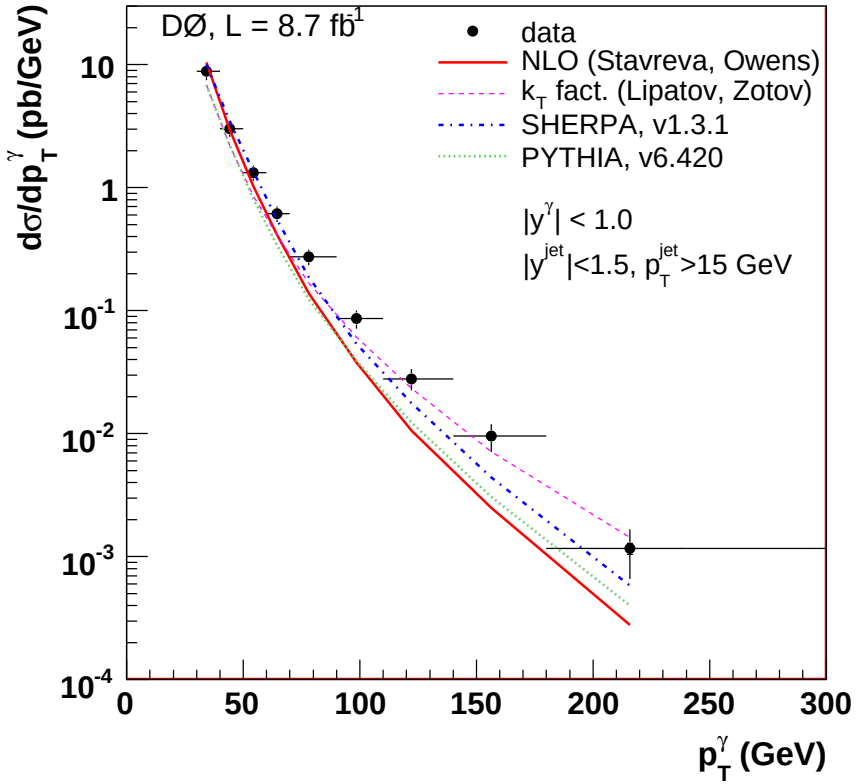
- J.J. Aubert, et al. [EMC], Nucl. Phys. B **213**, 31 (1983)



- The first experimental evidence of intrinsic heavy quarks came from the EMC measurement of the large x charm structure function.

Another evidence for IC

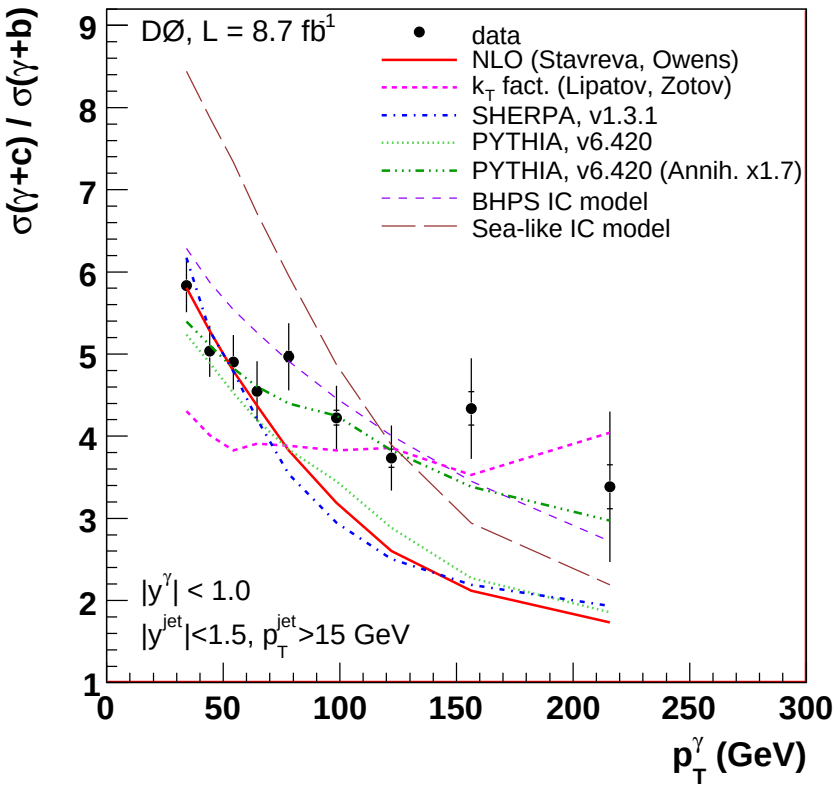
The $p\bar{p} \to \gamma + c$-jet differential production cross sections as a function of transverse momentum p_T^γ.[1]



[1] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **719**, 354 (2013).

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^γ. [2]



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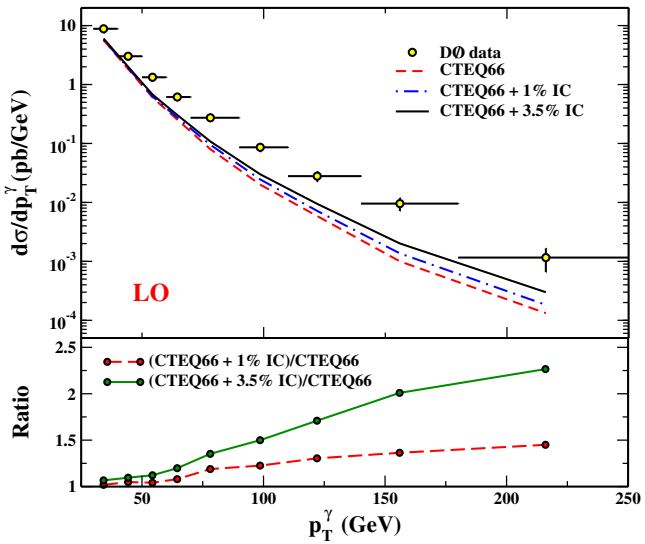
Another evidence: D0 data and the prompt photon production in association with charm quark jet

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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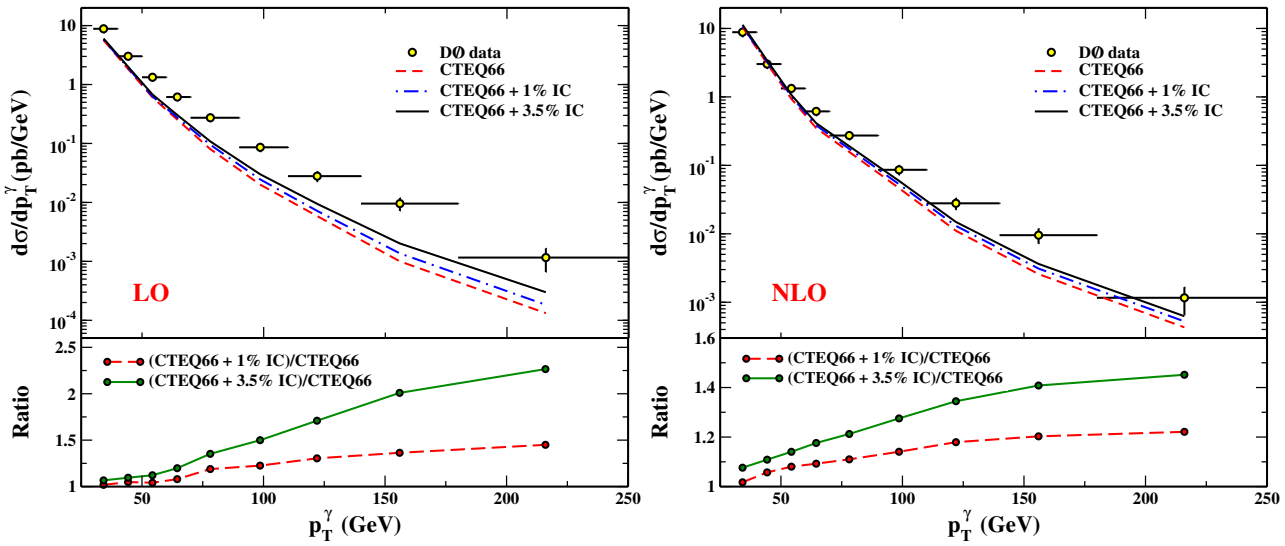


D0 Collaboration, Physics Letters B 719 (2013) 354361
S. Rostami, A. Khorramian, A. Aleedaneshvar, J. Phys. G **43**, no. 5, 055001 (2016)

A. Vafaee, A. Khorramian, S. Rostami and A. Aleedaneshvar, Nucl. Part. Phys. Proc. **270-272**, 27 (2016).

IC distribution and BHPS model

- L. Rottoli, arXiv:1606.09289 [hep-ph].
- S. Rostami, A. Khorramian, A. Aleedaneshvar, J. Phys. G **43**, no. 5, 055001 (2016)
- S. Duan, C. S. An and B. Saghai, Phys. Rev. D **93**, no. 11, 114006 (2016), [arXiv:1606.02000 [hep-ph]].
- A. V. Lipatov, G. I. Lykasov, Y. Y. Stepanenko and V. A. Bednyakov, arXiv:1606.04882 [hep-ph].
- S. Duan, C. S. An and B. Saghai, Phys. Rev. D **93**, no. 11, 114006 (2016).
- R. D. Ball *et al.* [NNPDF Collaboration], arXiv:1605.06515 [hep-ph].
- S. J. Brodsky, A. Kusina, F. Lyonnet, I. Schienbein, H. Spiesberger and R. Vogt, Adv. High Energy Phys. **2015**, 231547 (2015) [arXiv:1504.06287 [hep-ph]].
- ...

BHPS Model

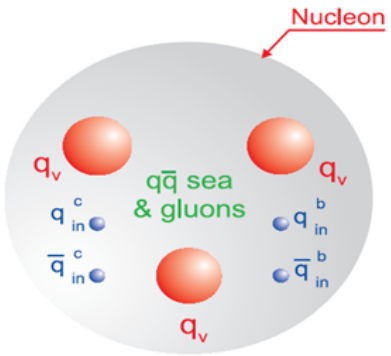
- In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS) suggested the existence of "intrinsic" charm in the nucleon.

  J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, Phys. Lett. B **93**, 451 (1980).

  S. J. Brodsky, C. Peterson, and N. Sakai, Phys. Rev. D **23**, 2745 (1981).

$$|p\rangle = \mathscr{P}_{3q}|uud\rangle + \mathscr{P}_{5c\bar{c}}|uudc\bar{c}\rangle + \dots .$$

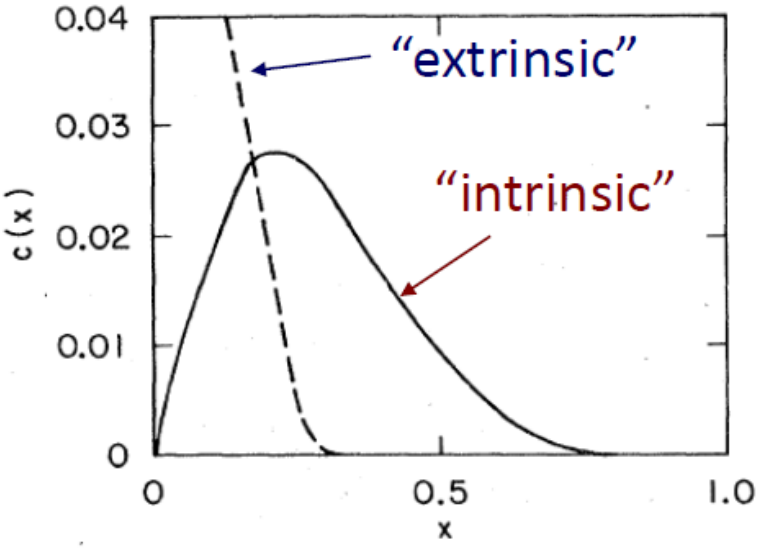
The $\mathscr{P}_{5c\bar{c}}$ is probability for the $|uudc\bar{c}\rangle$ five-quark Fock state in the proton.



Schematic presentation of a nucleon consisting of valence, sea quarks, gluons, and pairs of the intrinsic charm and bottom quarks.

Intrinsic and Extrinsic charm distribution

- 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

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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.

- 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.

S. J. Brodsky, et. al arXiv:1504.06287 [hep-ph].

Intrinsic heavy quark content of the nucleon

- "Extrinsic quark" contributions: arise from gluon splitting in perturbative QCD.
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- "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

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

where N_n normalizes the n-particle Fock state probability.
In the heavy quark limit, $\widehat{m}_c, \widehat{m}_{\bar{c}} \gg m_h, \widehat{m}_q$,

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

So the intrinsic charm distribution is as followings:

$$x c_{int}(x) = x \int dx_1 \cdots dx_{\bar{c}} \frac{dP_{\rm IC}}{dx_i \cdots dx_{\bar{c}} dx_c} \, .$$

Five-quark $|uudQ\bar{Q}\rangle$ Fock state

According to the BHPS model the probability distribution for the five-quark $|uudQ\bar{Q}\rangle$ Fock state , can be written as

$$\mathrm{P}(\mathrm{x}_1,\ldots,x_5) = \mathscr{N}\delta(1-\textstyle\sum_{i=1}^{5} x_i)[M^2 - \textstyle\sum_{i=1}^{5} \frac{m_i^2}{x_i}]^{-2}$$

For the case that Q is a heavy quark:

$$\mathrm{P}(\mathrm{x}_1,\ldots,x_5) = \mathscr{N}_5\delta(1-\textstyle\sum_{i=1}^{5} x_i)\frac{x_4^2 x_5^2}{(x_4+x_5)^2},$$

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

$$\mathrm{P}(\mathrm{x}_5) = \mathscr{P}_5^{Q\bar{Q}} 1800 x_5^2 \left[\frac{(1-x_5)}{3}\left(1+10x_5+x_5^2\right) + 2x_5(1+x_5)\ln(x_5)\right].$$

Intrinsic heavy quark content of the nucleon

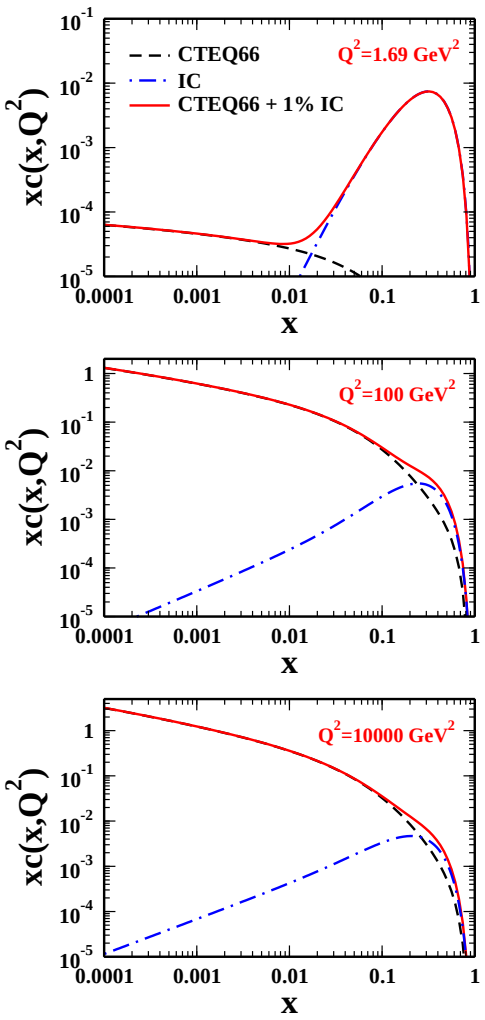
Definiteness: Two Components (separate evolution)

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

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

S. Rostami, A. Khorramian, A. Aleedaneshvar, J. Phys. G **43**, no. 5, 055001 (2016)

Q^2 dependent of intrinsic heavy quarks



M. Botje, Comput. Phys. Commun. **182**, 490 (2011)

S. Rostami, A. Khorramian, A. Aleedaneshvar, J. Phys. G **43**, no. 5, 055001 (2016)

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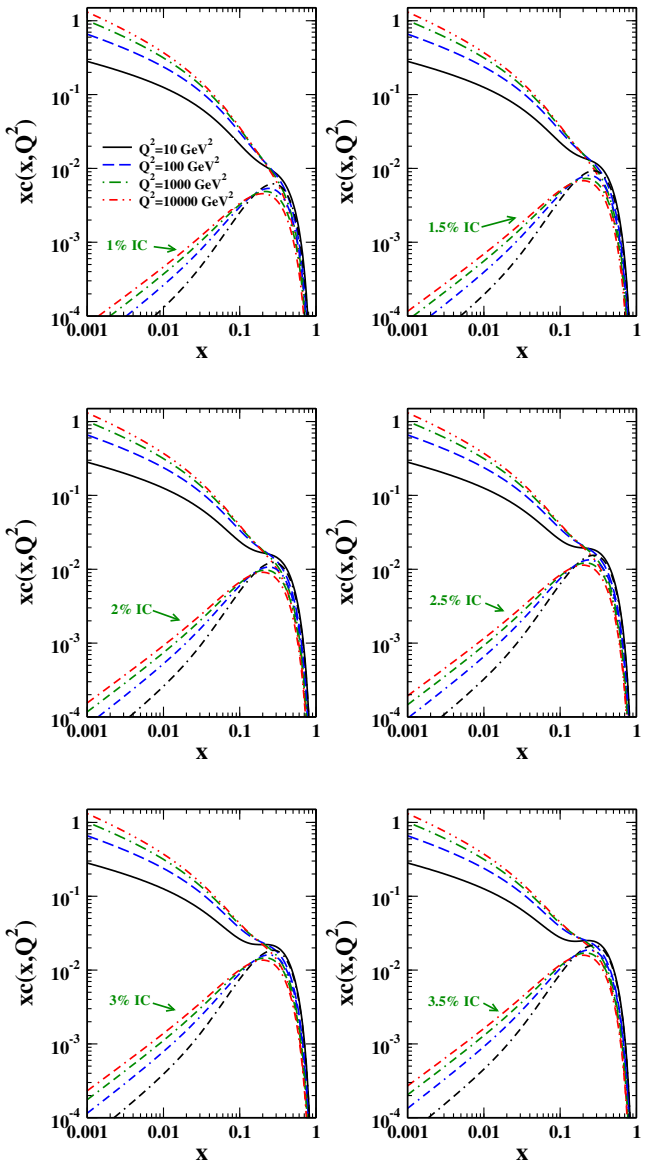

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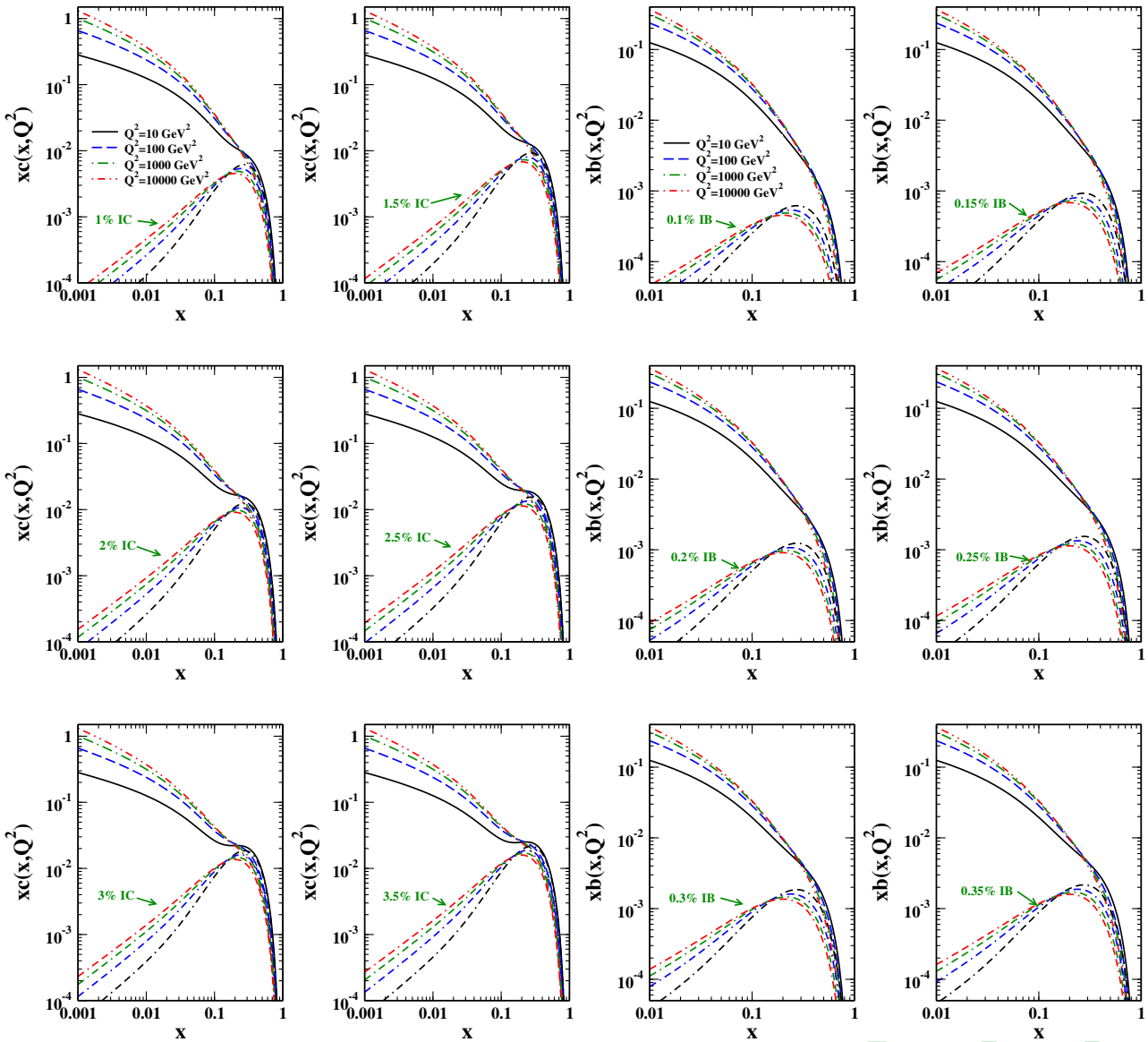

Parton distribution functions with IC

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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3-Calculate the cross section

- Various heavy flavor schemes FFNS, RT, ACOT, etc

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5-Minimize χ^2 with respect to PDF parameters:

- MINUIT, data driven regularisation

Our QCD fits

We choose the following functional form:

- PARAMITRIZATION

$$
\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}} (1 + D_{\bar{u}} x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}, \\
x\bar{s}(x) &= f_s x\bar{D}, \\
x\bar{d}(x) &= (1-f_s) x\bar{D}, \\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},
\end{aligned}
$$

The parameters A_{u_v}, A_{d_v} and A_g are fixed by the constraints from the number and momentum sum rules.
$x\bar{s} = f_s x\bar{D}$ 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

Data set	BASE	+EMC	+EMC **+Nucl. effect**	+LHC+IC **($W^2 \geq 15$)**
SLAC F_2^p	96/59	85/59	85/59	96/59
Charm H1-ZEUS combined	41/47	45/47	44/47	42/47
HERA1+2 CCep	48/39	54/39	56/39	45/36
HERA1+2 CCem	49/42	49/42	49/42	56/42
HERA1+2 NCem	238/159	240/159	239/159	240/159
HERA1+2 NCep	69/68	74/68	73/68	70/68
HERA1+2 NCep	434/363	463/363	458/363	448/363
HERA1+2 NCep 460	211/200	212/200	211/200	210/200
HERA1+2 NCep 575	219/249	221/249	221/249	219/249
EMC F_2^c	-	152/16	108/16	89/16
ATLAS Jet $0.0 \leq \lvert y \rvert < 0.3$	-	-	-	16/16
ATLAS Jet $0.3 \leq \lvert y \rvert < 0.8$	-	-	-	6.1/16
ATLAS Jet $0.8 \leq \lvert y \rvert < 1.2$	-	-	-	6.6/16
ATLAS Jet $1.2 \leq \lvert y \rvert < 2.1$	-	-	-	7.1/15
ATLAS Jet $2.1 \leq \lvert y \rvert < 2.8$	-	-	-	6.0/12
ATLAS Jet $2.8 \leq \lvert y \rvert < 3.6$	-	-	-	1.5/9
ATLAS Jet $3.6 \leq \lvert y \rvert < 4.4$	-	-	-	0.67/6
ATLAS Z rap.	-	-	-	8.1/8
ATLAS W+ lep. pseudorap.	-	-	-	22/11
ATLAS W- lep. pseudorap.	-	-	-	11/11
ATLAS low mass DY	-	-	-	11/8
ATLAS high mass DY	-	-	-	7.6/13
ATLAS DY mass ext.	-	-	-	8.0/6
CMS electon Asym. rap.	-	-	-	7.4/11
CMS Boson rap.	-	-	-	56/35
Total χ^2 / dof	1497/1212 **=1.235**	1695/1228 **=1.380**	1639/1228 **=1.334**	1804/1421 **=1.269**

D. de Florian, R. Sassot, P. Zurita and M. Stratmann, Phys. Rev. D **85**, 074028 (2012).

Numerical results

Parameter	**BASE**	**+EMC**	**+EMC (+Nucl. effect)**	**+LHC+IC**
B_{u_v}	0.684 ± 0.037	0.612 ± 0.038	0.615 ± 0.033	0.728 ± 0.022
C_{u_v}	4.542 ± 0.074	4.652 ± 0.071	4.635 ± 0.067	4.571 ± 0.071
E_{u_v}	13.0 ± 2.0	17.9 ± 2.9	17.4 ± 2.4	10.6 ± 1.1
B_{d_v}	0.800 ± 0.088	0.703 ± 0.082	0.731 ± 0.077	0.777 ± 0.053
C_{d_v}	3.95 ± 0.35	3.65 ± 0.38	3.79 ± 0.36	3.92 ± 0.23
$B_{\bar{u}}$	-0.181 ± 0.014	-0.140 ± 0.017	-0.150 ± 0.015	-0.151 ± 0.012
$C_{\bar{u}}$	8.16 ± 0.70	8.11 ± 0.59	7.93 ± 0.55	9.19 ± 0.79
$D_{\bar{u}}$	17.1 ± 3.8	12.9 ± 3.6	13.7 ± 3.3	12.3 ± 2.7
$A_{\bar{D}}$	0.125 ± 0.013	0.170 ± 0.021	0.158 ± 0.018	0.159 ± 0.014
$B_{\bar{D}}$	-0.181 ± 0.014	-0.140 ± 0.017	-0.150 ± 0.015	-0.151 ± 0.012
$C_{\bar{D}}$	4.7 ± 1.6	6.6 ± 1.6	7.8 ± 1.9	4.29 ± 0.81
B_g	-0.649 ± 0.064	-0.808 ± 0.022	-0.787 ± 0.023	-0.663 ± 0.043
C_g	3.55 ± 0.63	1.21 ± 0.18	1.31 ± 0.19	2.89 ± 0.35
A'_g	0.56 ± 0.11	0.249 ± 0.020	0.274 ± 0.023	0.464 ± 0.057
B'_g	-0.649 ± 0.059	-0.804 ± 0.021	-0.784 ± 0.022	-0.665 ± 0.039
C'_g	25.00	25.00	25.00	25.00

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ATLAS Jet $1.2 \leq \lvert y \rvert < 2.1$	-	-	7.1/15	7.7/15
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ATLAS Jet $3.6 \leq \lvert y \rvert < 4.4$	-	-	0.67/6	0.75/6
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ATLAS W+ lep.	-	-	22/11	18/11
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C_g	3.55 ± 0.63	1.31 ± 0.19	3.24 ± 0.35	2.89 ± 0.35
$A'g$	0.56 ± 0.11	0.274 ± 0.023	0.471 ± 0.059	0.464 ± 0.057
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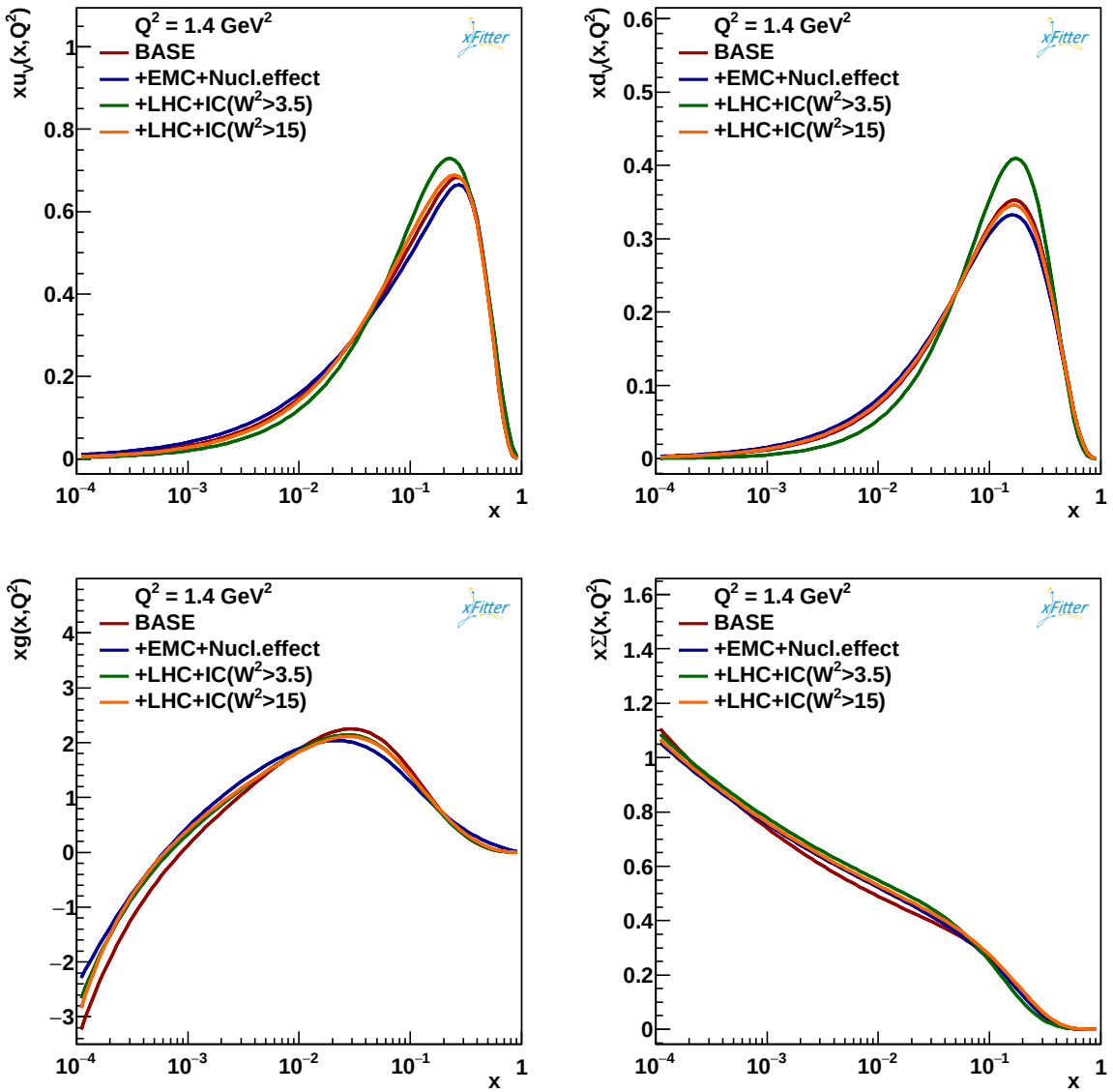
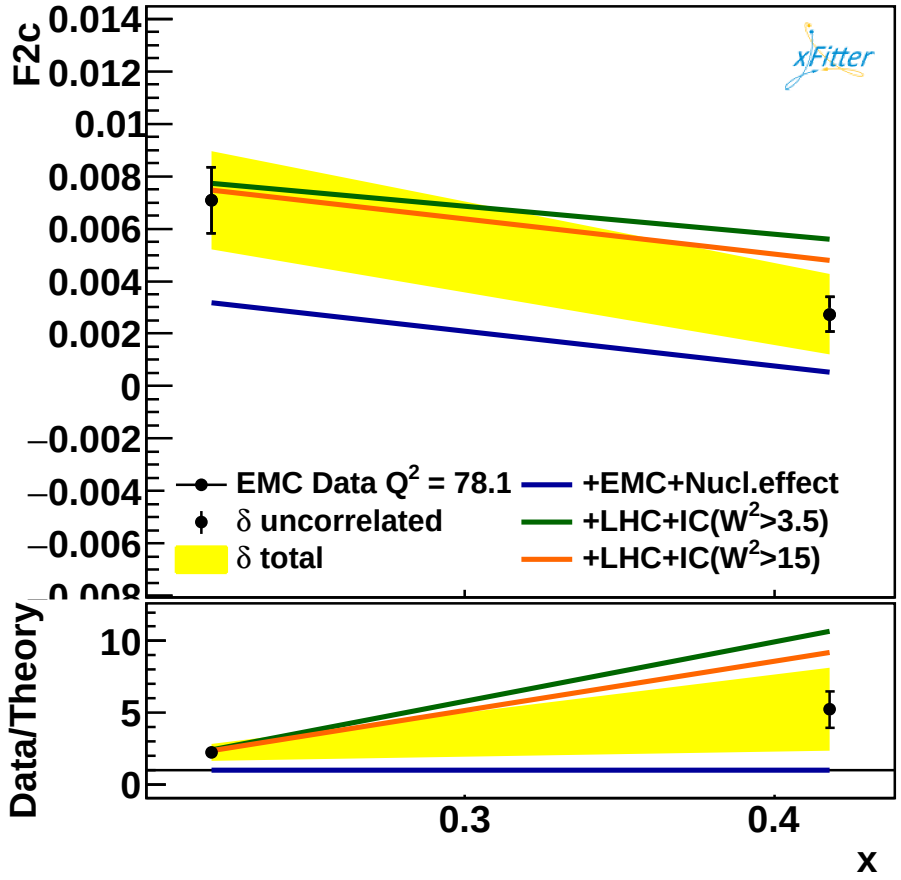
$C'g$	25.00	25.00	25.00	25.00

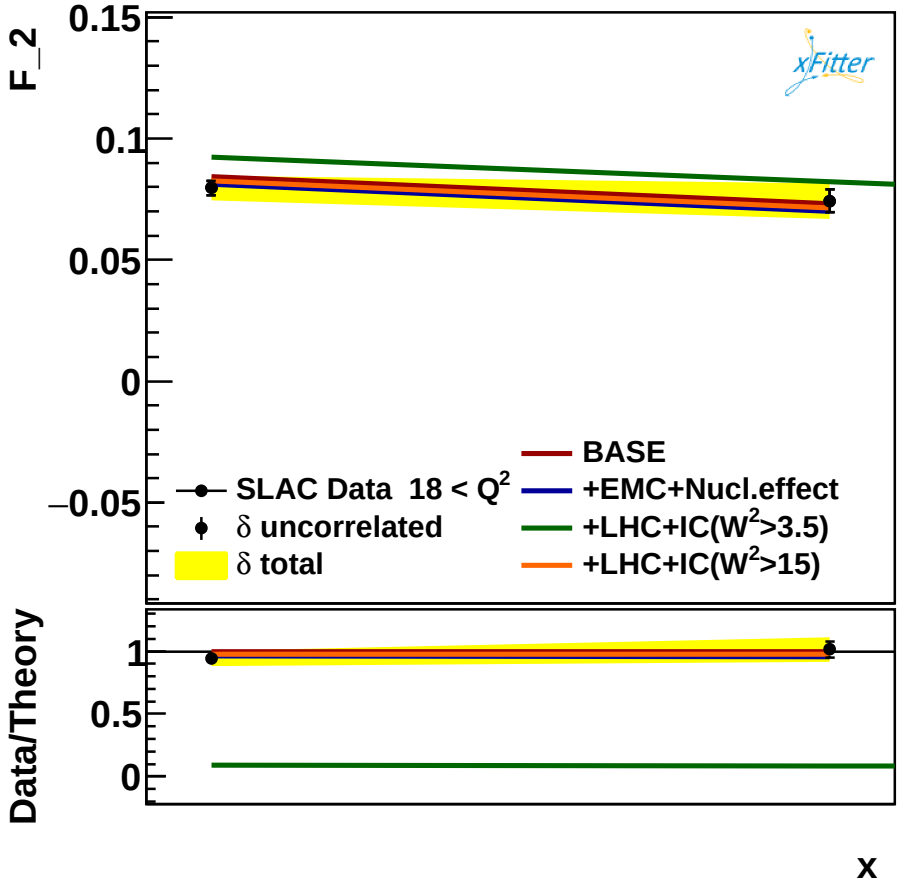
Parton distributions at the initial scale Q^2= 1.4 GeV^2



EMC data with IC contribution



SLAC data with IC contribution



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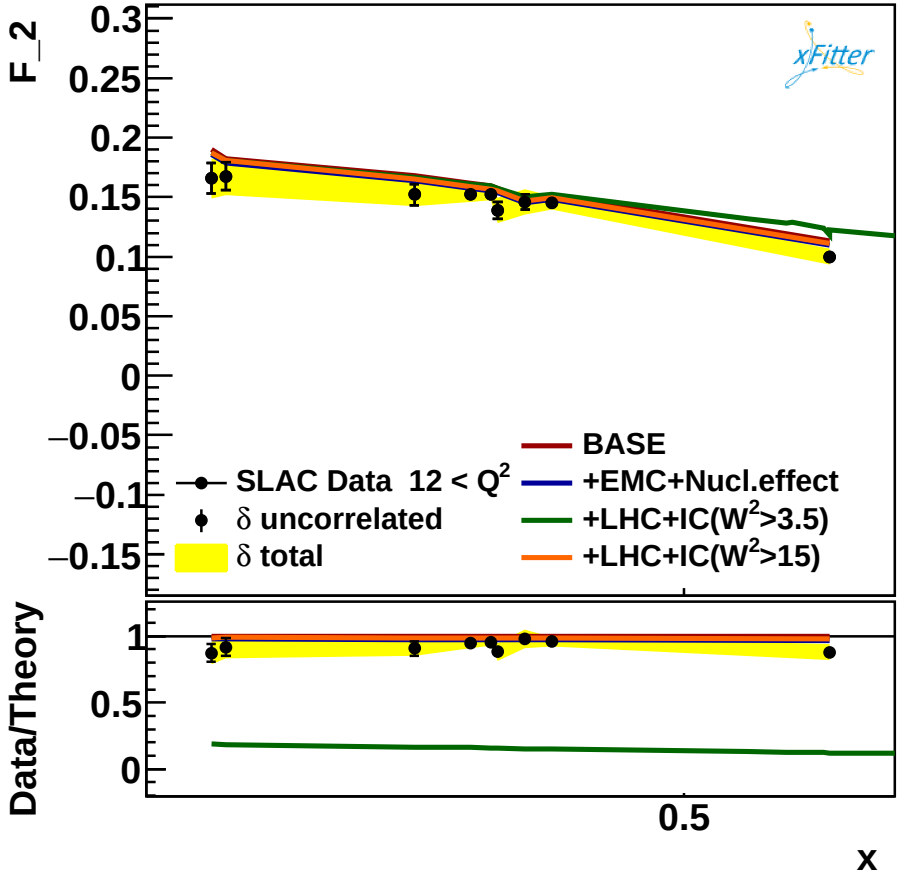


Figure : The SLAC data and our QCD fit result and for different values of $W^2 \geq 3.5$ and $W^2 \geq 15$.

LHC data with IC contribution

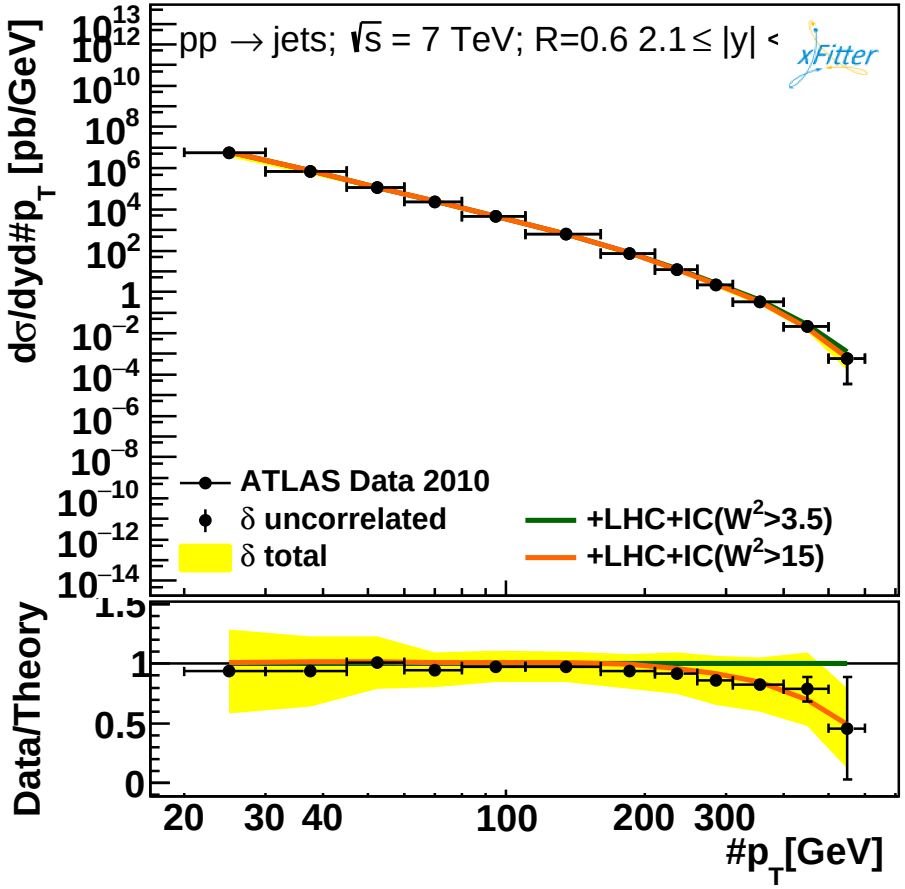
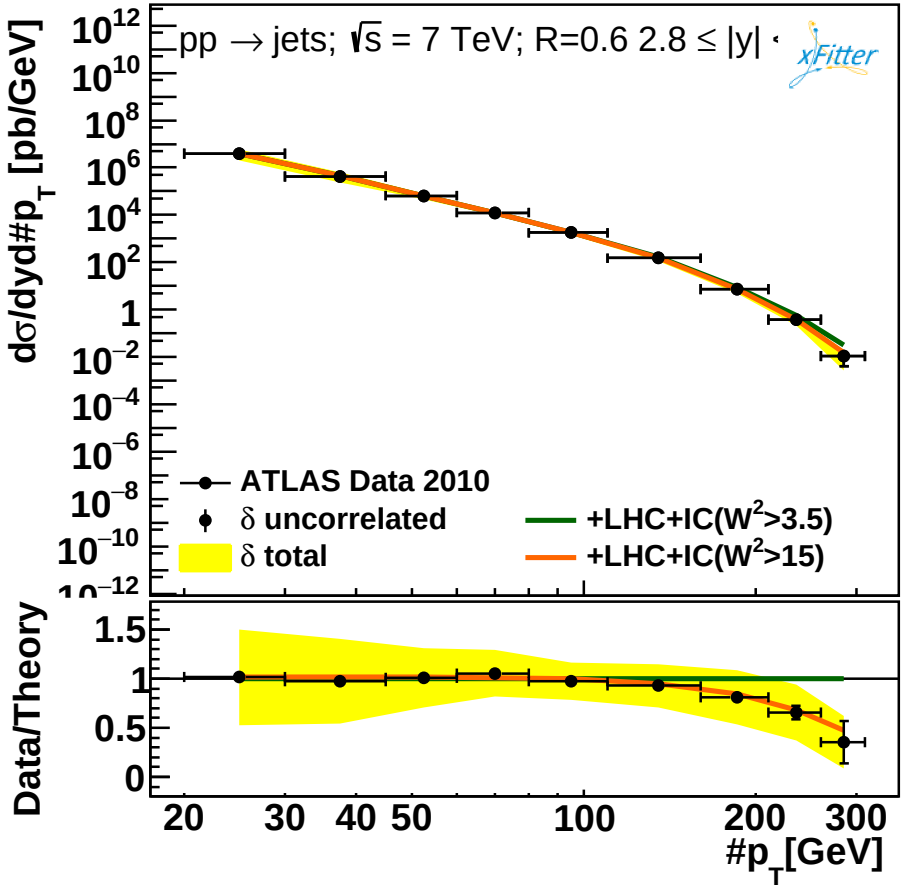


Figure : The LHC data with result of our fits with 1% IC contribution and for $W^2 \geq 15$.

LHC data with IC contribution



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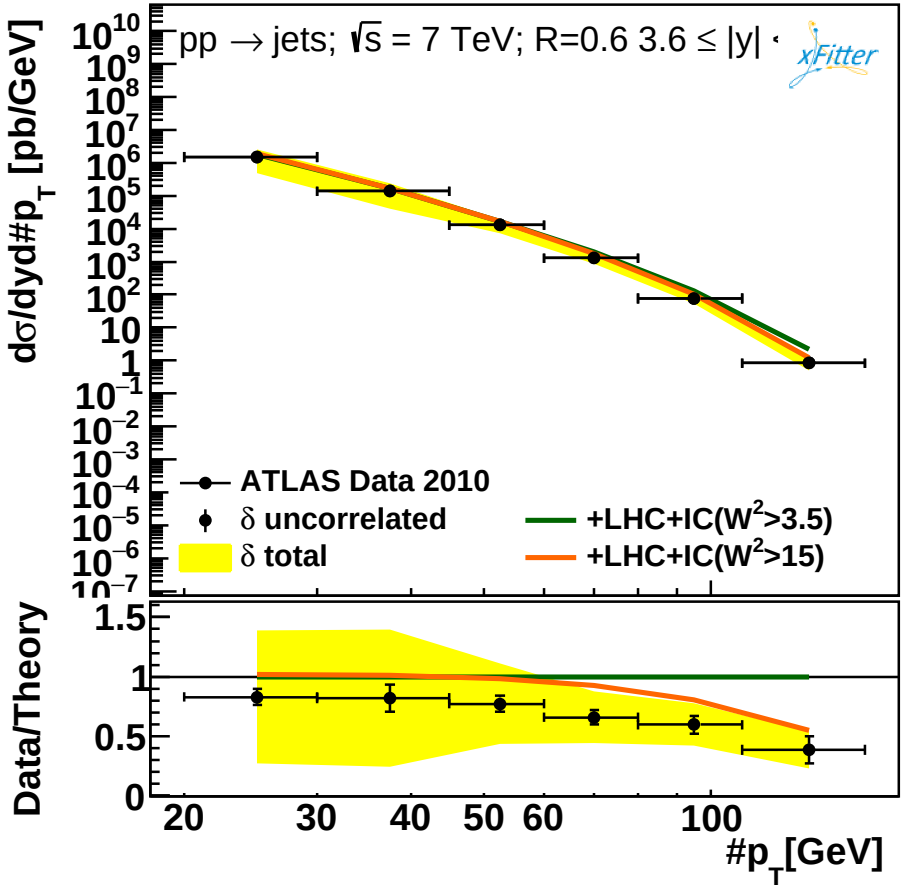
LHC data with IC contribution



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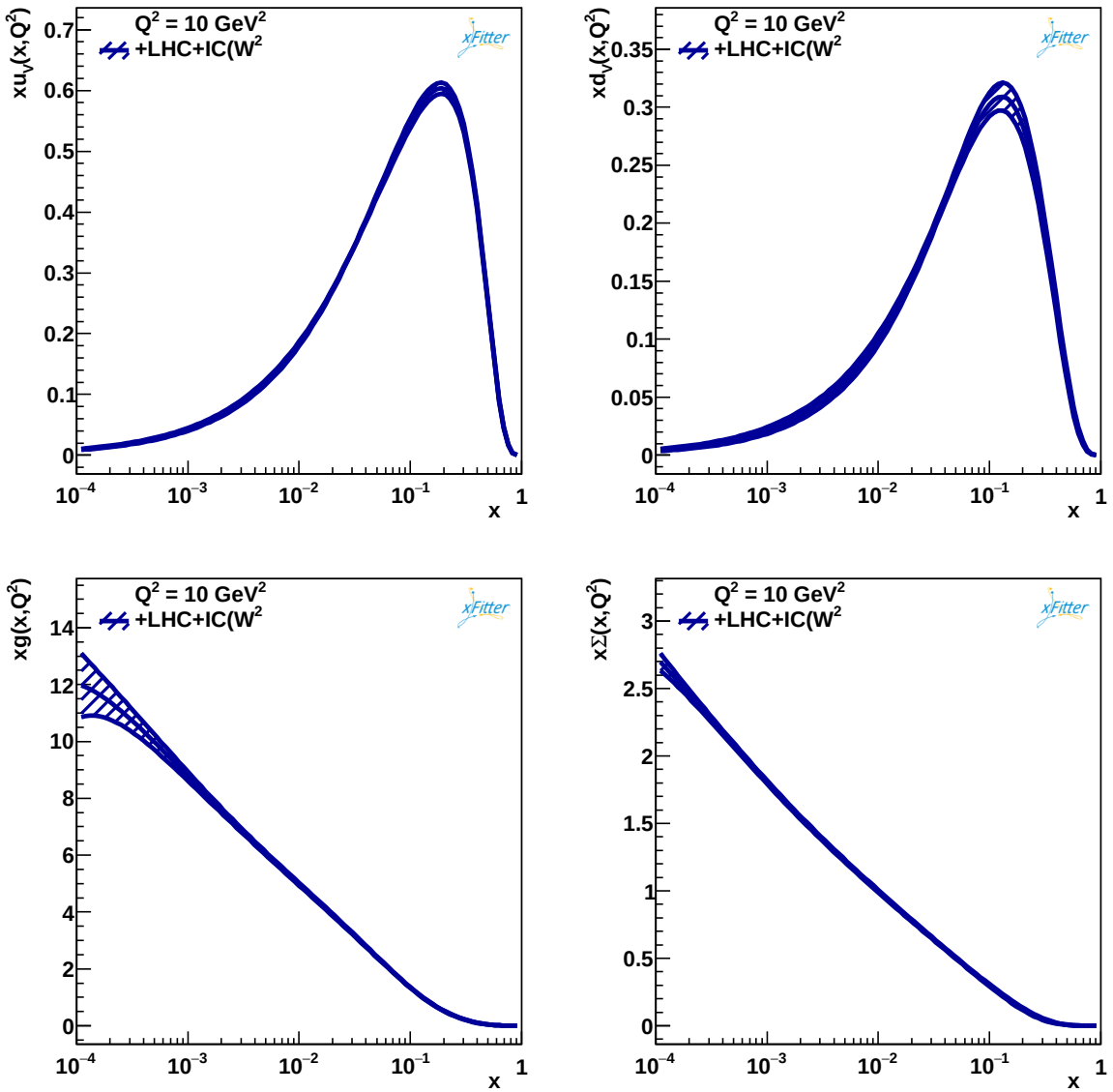
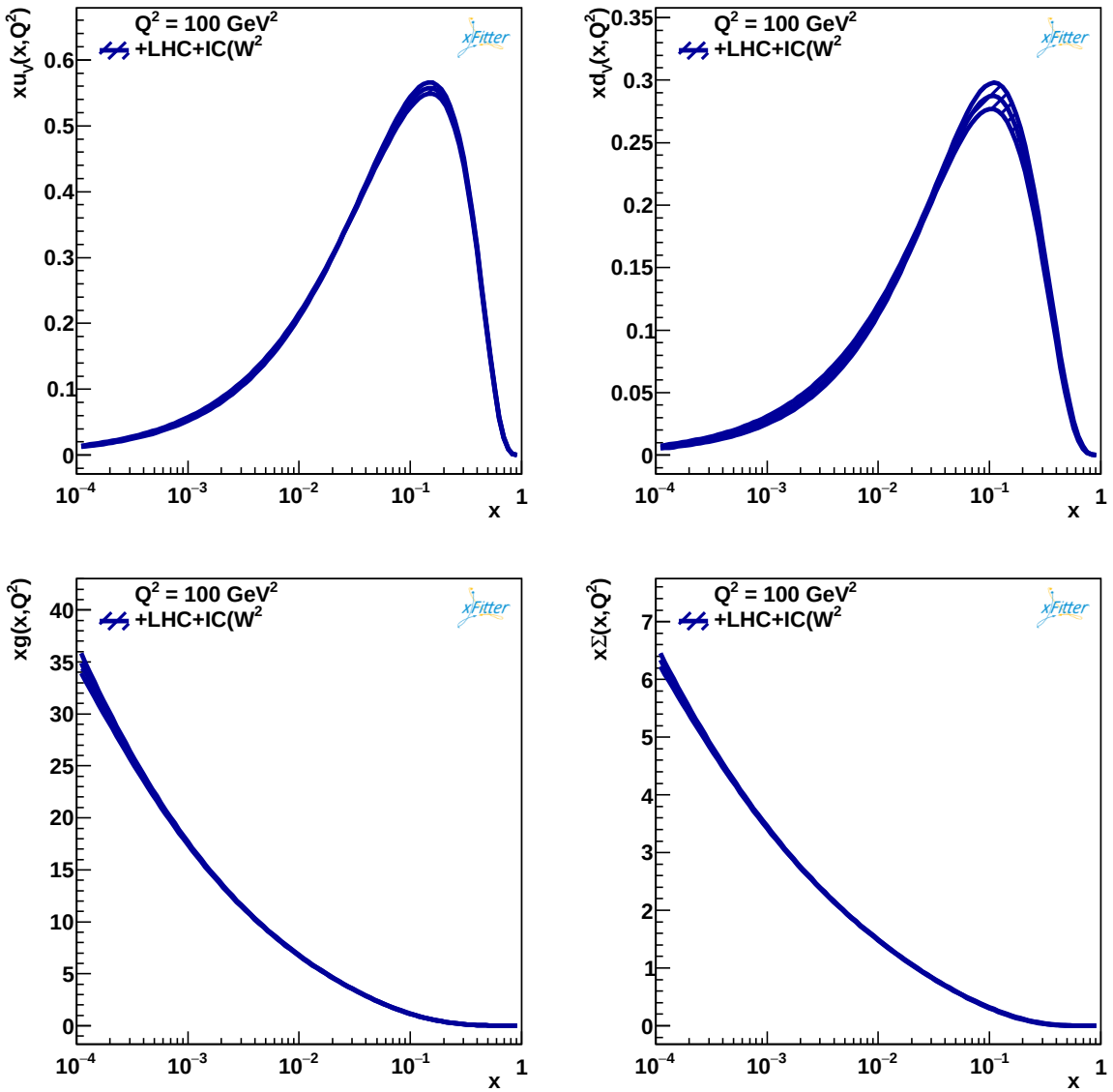
Parton distributions at the scale of Q^2= 10 GeV^2



Parton distributions at the scale of Q^2= 100 GeV^2



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- 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 χ^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.

Thank you.