Parton Distribution Functions and Physical Observables

Presentation: Majid Azizi

Semnan University

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Content:

- **Brief History**
- **Computational Frameworks**
- **Experimental Measurements**
- **Examples for Impact of Experimental Data on PDFs**
- **Conclusion**

Brief History

An open question from ancient age

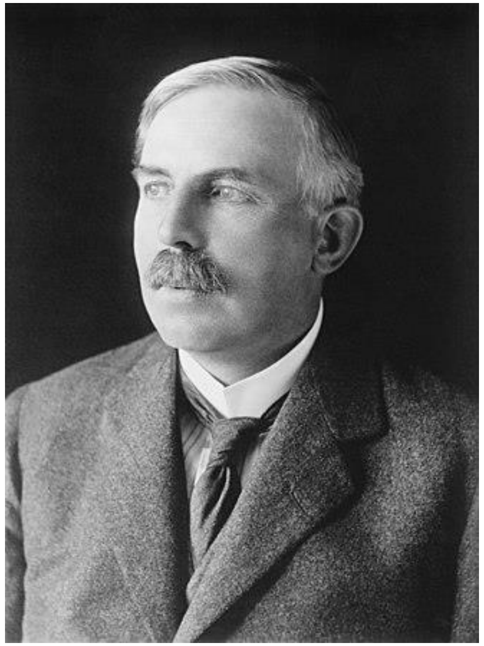
Democritus

Epicurus

The first descriptions of fundamental pieces of the world

An open question from ancient age

Thomson

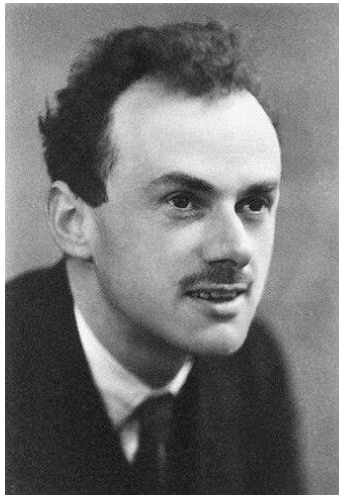


Rutherford

Bohr

The atoms are more complicated than they seem!

An open question from ancient age



Dirac

Pauli

Feynman

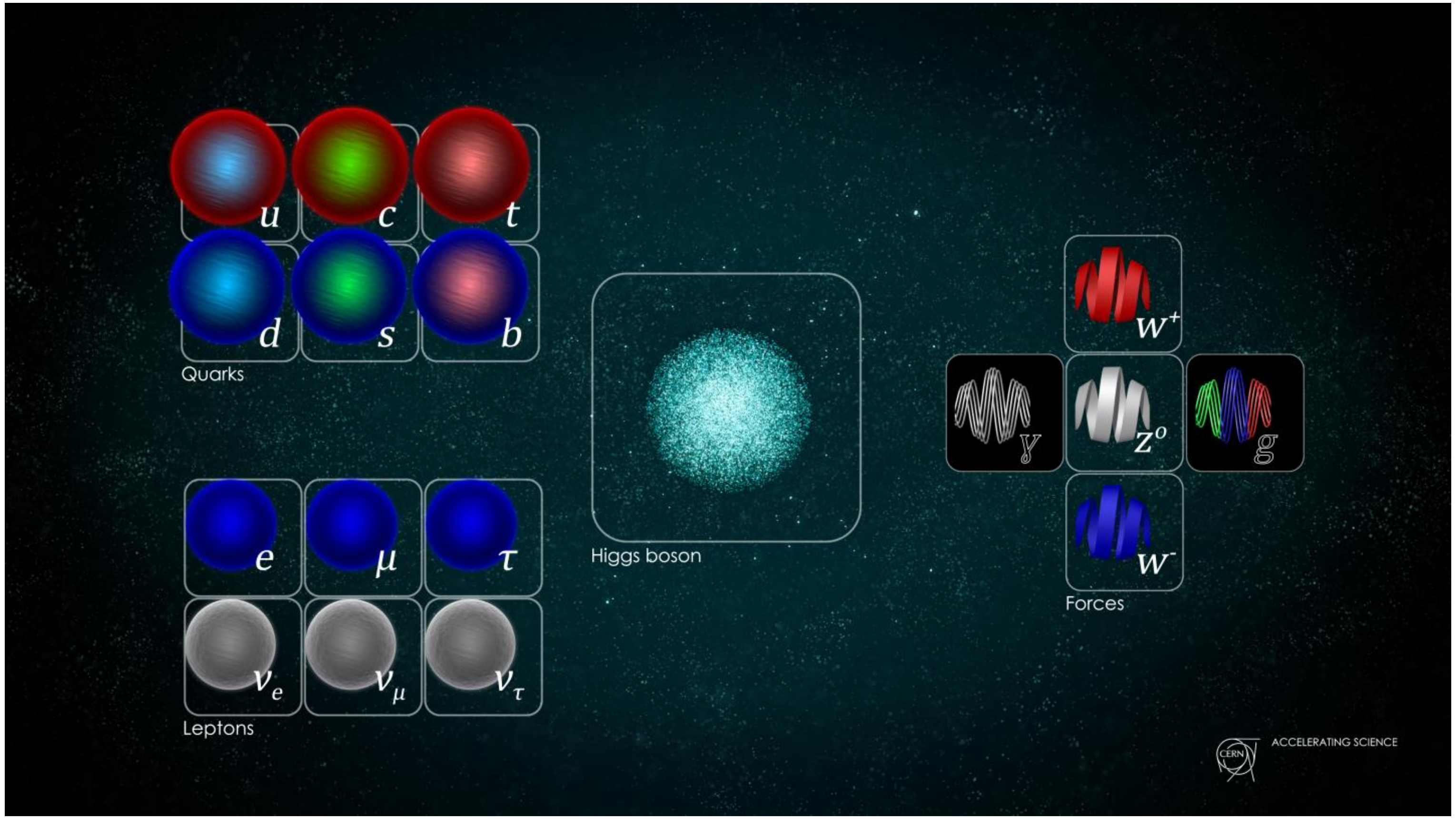
Weinberg

Gell-Mann

The unfinished journey

Standard Model

The most successful theory in physics



Particle Physics Laboratories

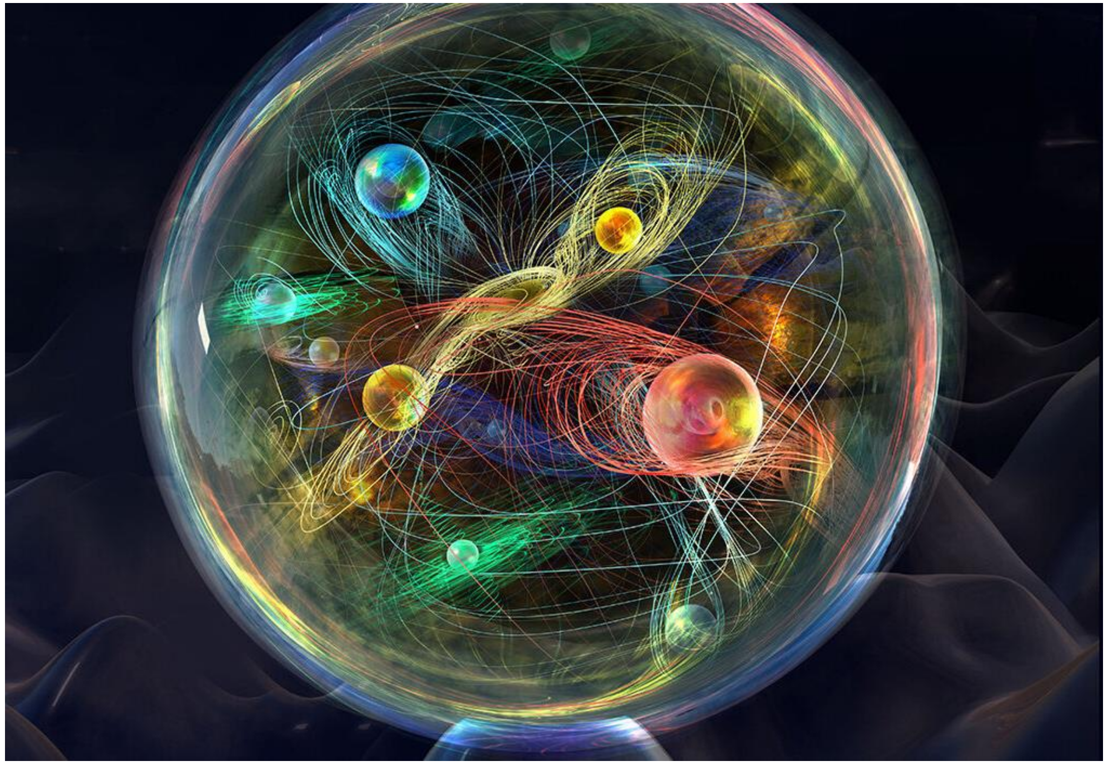
CERN

Fermilab

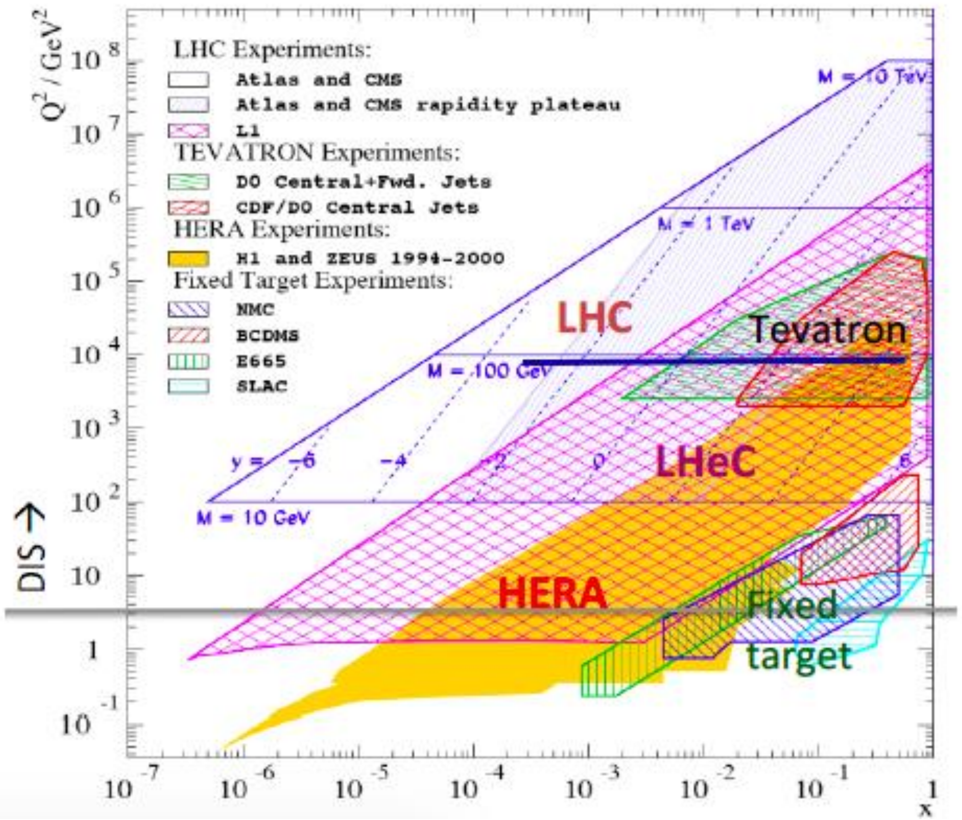
Also DESY and Jlab

Proton as a probe

- Stable
- Easy to access



Recent experimental constraints on proton structure



Q^2 – virtuality of the exchange photon

$$Q^2 = -q^2 = (k - k')^2$$

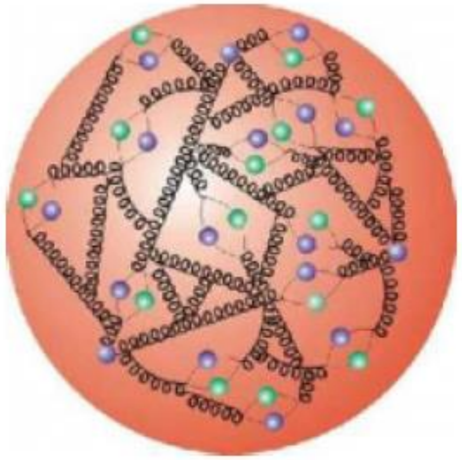
x – Bjorken scaling variable

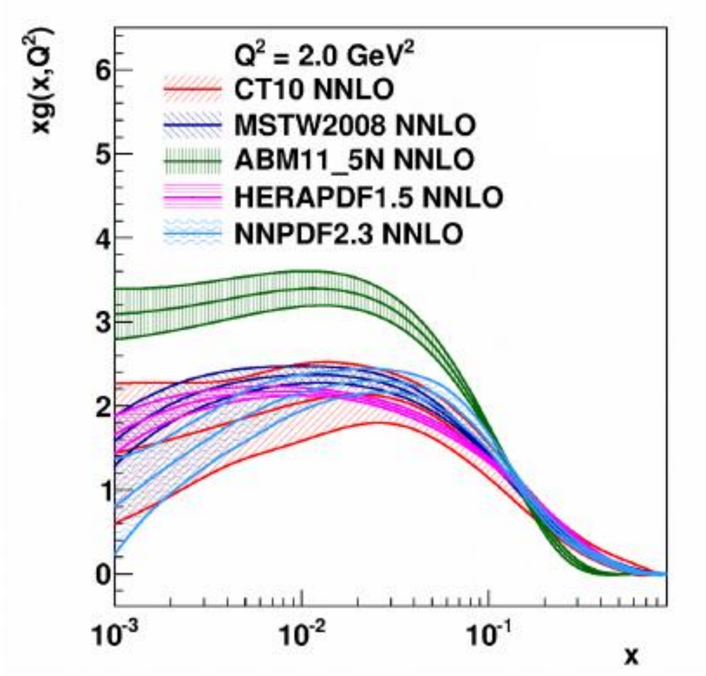
$$x = \frac{Q^2}{2P_p.q}$$

What is our motivation?

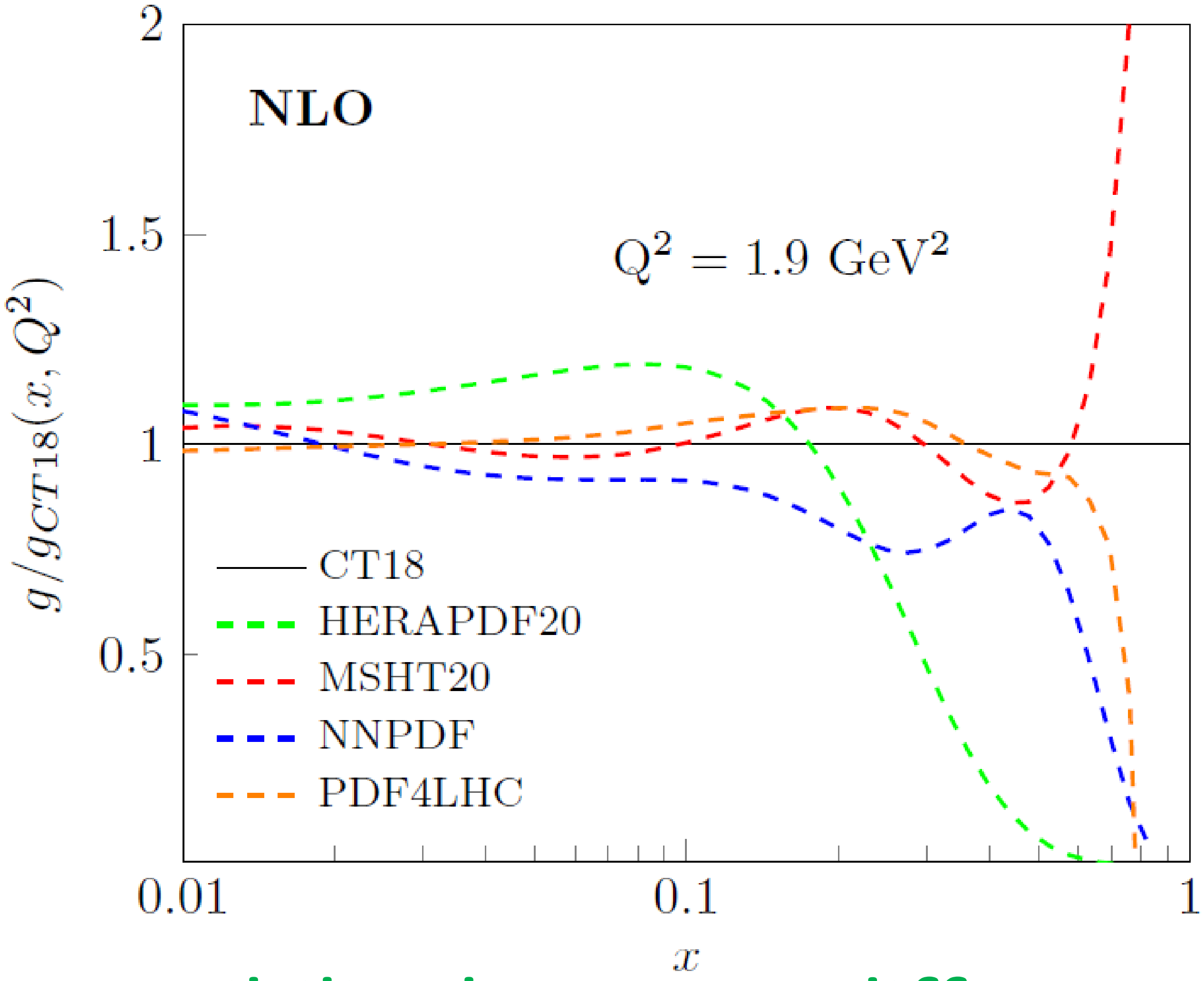
PDFs → Cross Sections → Testing Theory

More Accurate PDF → More Accurate Theoretical Predictions





Gluon distributions behavior at high-x



Incompatibility between different models

Deep-Inelastic Scattering

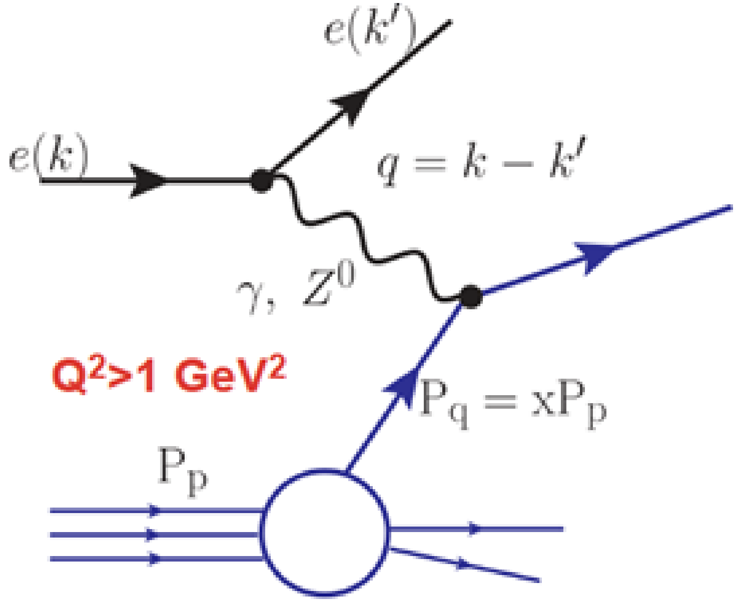
$$\frac{d^2\sigma^{e^{\pm}P}}{dxdQ^2} = \frac{2\pi\alpha}{xQ^4}\left[Y_+F_2(x,Q^2) \mp Y_-F_3(x,Q^2) - y^2F_L(x,Q^2)\right]$$

Dominate, sensitive to gluon and sea quark

sensitive to gluon, relevant at high y

sensitive to valence quarks, relevant at high Q^2

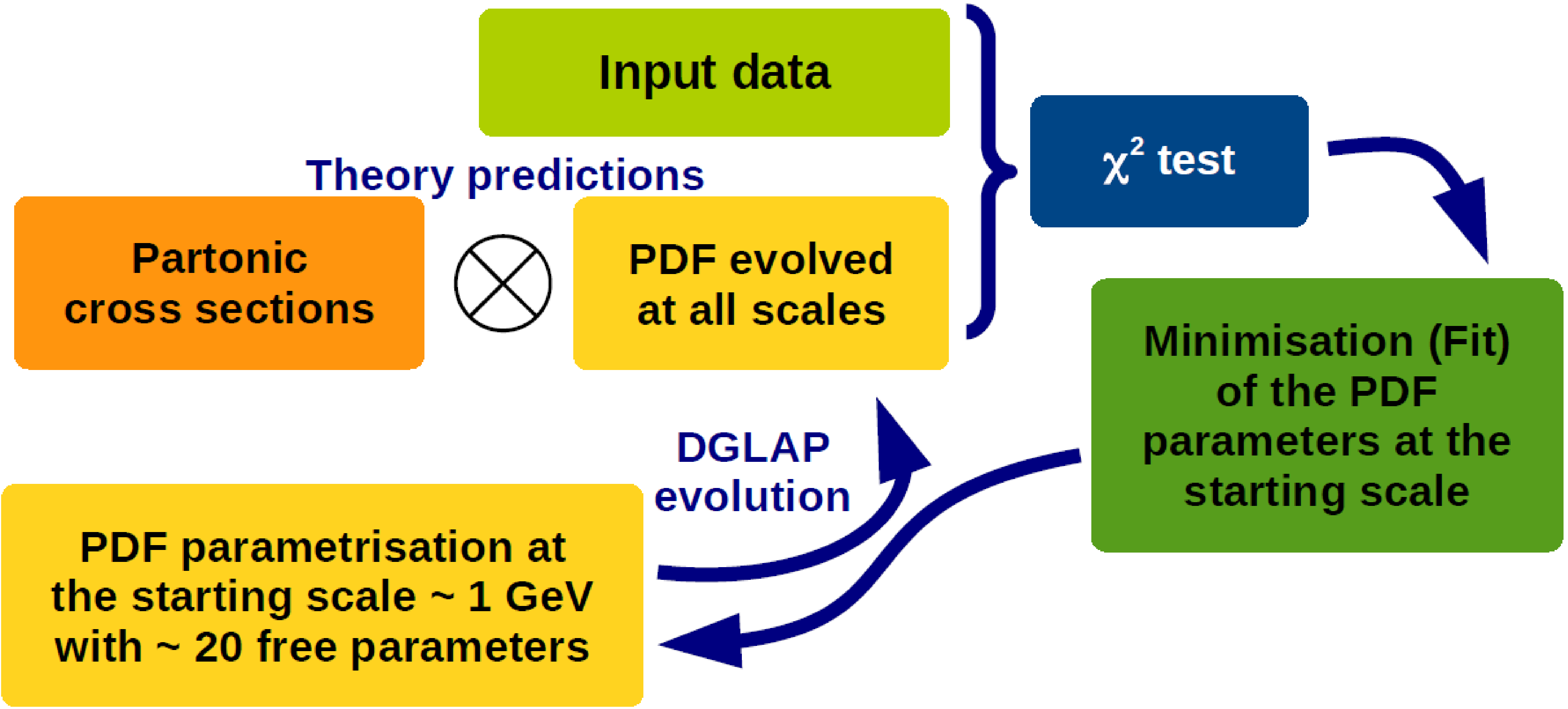
$$Y_{\pm} = 1 \pm (1-y^2) \qquad \boldsymbol{y} = \frac{\boldsymbol{P_p.q}}{\boldsymbol{2P_p.k}}$$



Neutral Current (Z/γ exchange)

Computational Frameworks

PDFs Extraction Procedure



PDF parametrization at the starting scale

$$xg(x) = A_g x^{B_g}(1 - \mathrm{x})^{C_g} - A'_g x^{B'_g}(1 - \mathrm{x})^{C'_g}$$

Gluon

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1 - \mathrm{x})^{C_{u_v}}(1 + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1 - \mathrm{x})^{C_{d_v}}$$

Valence quarks

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1 - \mathrm{x})^{C_{\bar{U}}}$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1 - \mathrm{x})^{C_{\bar{D}}}$$

Sea quarks

Computational Packages

- QCDNUM DGLAP Evolution

  M. Botje, Comput.Phys.Commun. 182 (2011) 490-532, [arXiv:1005.1481].

- APPLGRID Jet Cross Section Calculation

  T. Carli et al., Eur. Phys. J. C66, 503 (2010), [arXiv:0911.2985].

- Hathor Top Quark Cross Section Calculation

  S. Moch, Comput. Phys. Commun , 1034-1046 (2011), [arXiv:1007.1327].

- MINUIT Minimizer

  F. James and M. Roos, Comput.Phys.Commun. 10 (1975) 343-367.

- xFitter Fit Framework

  S. Alekhin et al., Eur. Phys. J. C 75, no. 7, 304 (2015) [arXiv:1410.4412].

New guys in town

- NNPDF Neural Network

R. D. Ball, Eur. Phys. J. C (2021), [arXiv:2109.02671].

- ePump PDFs update

T. J. Hou, Phys. Rev. D (2019), [arXiv:1907.12177].

Experimental Measurements

HERA I+II

Experiment	no. of points	x	Q^2 [GeV^2]
HERA1+2 CC e^+p	39	$8.0\times10^{-3} < x < 0.4$	$300 < Q^2 < 30000$
HERA1+2 CC e^-p	42	$8.0\times10^{-3} < x < 0.65$	$300 < Q^2 < 30000$
HERA1+2 NC e^-p	159	$8.0\times10^{-4} < x < 0.65$	$60 < Q^2 < 50000$
HERA1+2 NC e^-p 460	195	$3.48\times10^{-5} < x < 0.65$	$1.5 < Q^2 < 800$
HERA1+2 NC e^-p 575	243	$3.48\times10^{-5} < x < 0.65$	$1.5 < Q^2 < 800$
HERA1+2 NC e^+p 820	66	$6.21\times10^{-7} < x < 0.4$	$0.045 < Q^2 < 30000$
HERA1+2 NC e^+p 920	348	$5.02\times10^{-6} < x < 0.65$	$1.5 < Q^2 < 30000$

H. Abramowicz ,Eur. Phys. J. C 75, no.12, 580 (2015) [arXiv:1506.06042].

Experimental measurements:

- W, Z
- W + c
- Drell-Yan
- W, Z + jets
- Jets
- Top pair

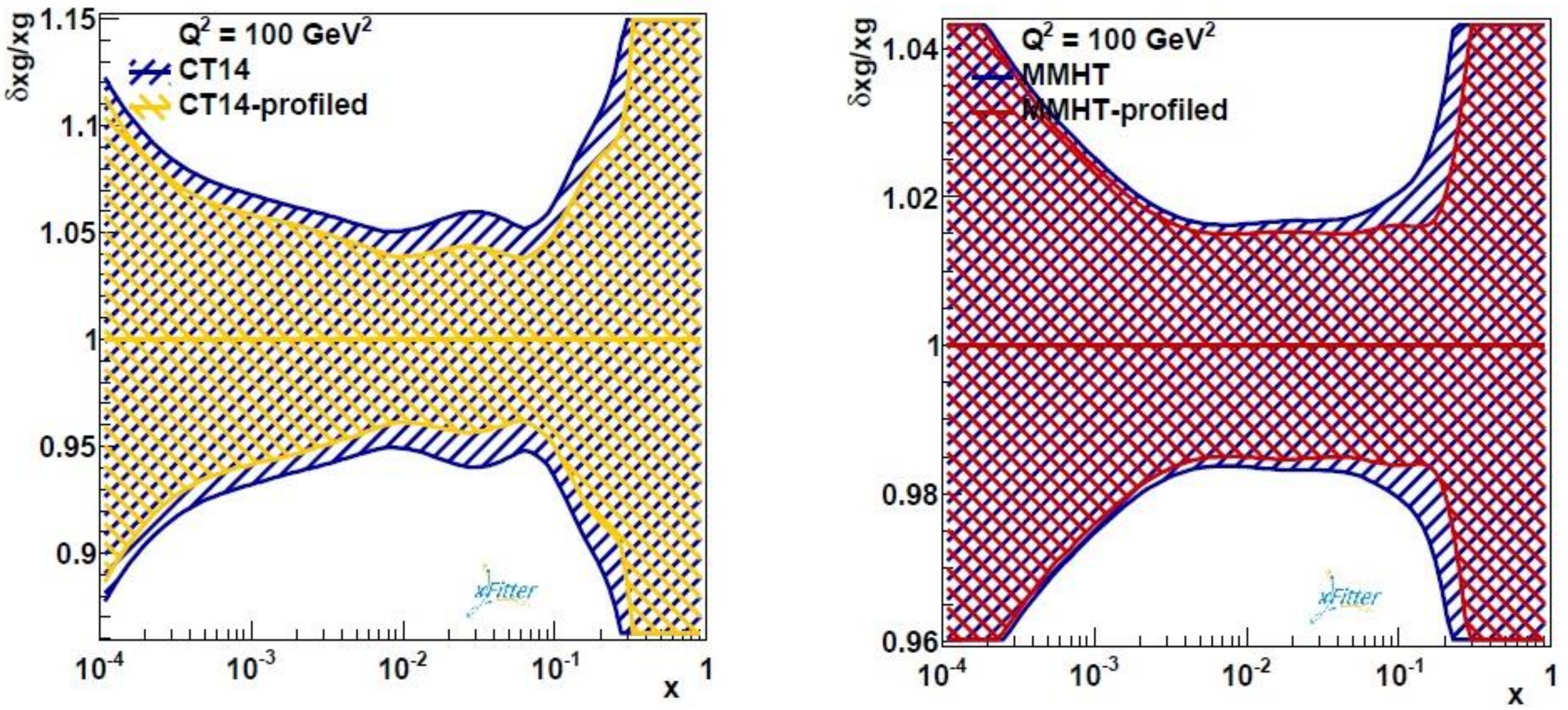
Impacts on PDFs:

- Valence quarks
- Strange quark
- Sea quarks
- Gluon mid-x
- Gluon and α_s
- Gluon

H. Abramowicz ,Eur. Phys. J. C 75, no.12, 580 (2015) [arXiv:1506.06042].

Examples for Impact of Experimental Data on PDFs

Profiling



Int. J. Mod. Phys. A 33, no.24, 1850142 [arXiv:1810.12063].

Experimental Data

Data set	Process	Experiment
HERA I+II		
DIS σ	$e^{\pm}p \rightarrow \overset{(-)}{\nu} X$	HERA I+II CC $e^{+}p$
		HERA I+II CC $e^{-}p$
	$e^{\pm}p \rightarrow e^{\pm}X$	HERA I+II NC $e^{-}p$
		HERA I+II NC $e^{-}p$ 460
		HERA I+II NC $e^{-}p$ 575
		HERA I+II NC $e^{+}p$ 820
		HERA I+II NC $e^{+}p$ 920
Non-LHC		
DIS heavy-quarks	$e^{\pm}p \rightarrow e^{\pm}cX$	H1-ZEUS Charm
	$e^{\pm}p \rightarrow e^{\pm}bX$	H1-ZEUS Beauty
Lepton-Hadron Jet	$e^{\pm}p \rightarrow jX$	H1 65.4 pb^{-1}
		H1 395 pb^{-1}
		H1 43.5 pb^{-1}
		H1 351 pb^{-1}
	$e^{\pm}p \rightarrow 2\text{-}jX$	H1 dijets
	$e^{\pm}p \rightarrow 3\text{-}jX$	H1 trijets
		ZEUS 300 GeV
	$e^{\pm}p \rightarrow jX$	ZEUS 318 GeV
	$e^{\pm}p \rightarrow 2\text{-}jX$	ZEUS dijet
Hadron-Hadron Jet	$hh \rightarrow jX$	CDF
		DØ
Hadron-Hadron Top	$hh \rightarrow t\bar{t}$	DØ-CDF (total)
		DØ (total)
LHC		
Hadron-Hadron Jet	$hh \rightarrow jX$	CMS
		ATLAS
		ATLAS
Hadron-Hadron Top	$hh \rightarrow t\bar{t}$	CMS (total)
		CMS (differential)
		ATLAS (total)
		ATLAS (differential)

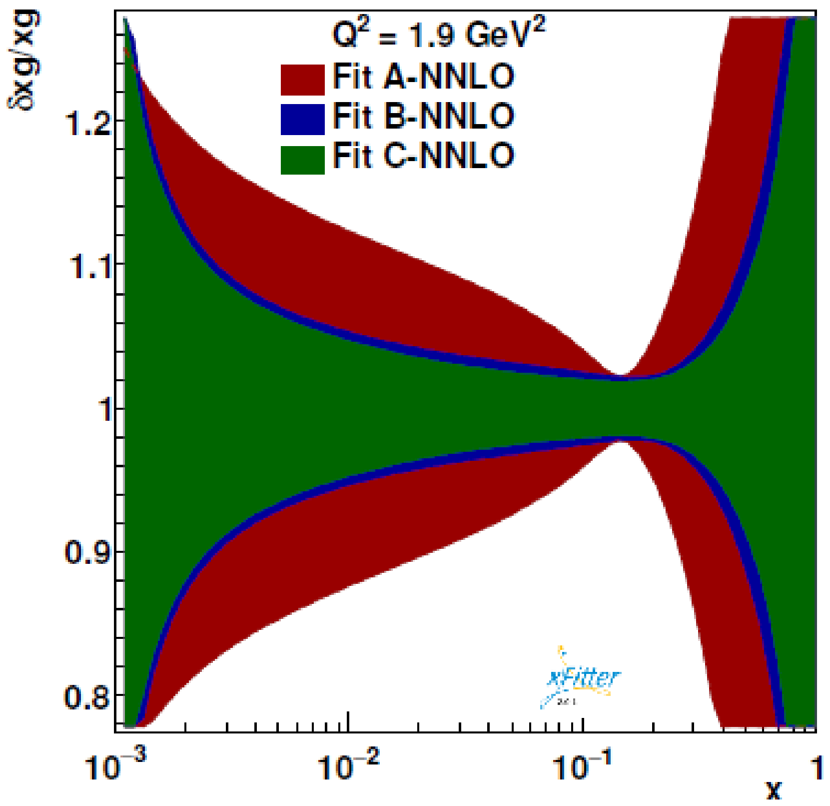
Phys. Rev. D 106, no.11, 114042 [arXiv:2212.07243].

Extracted parameters

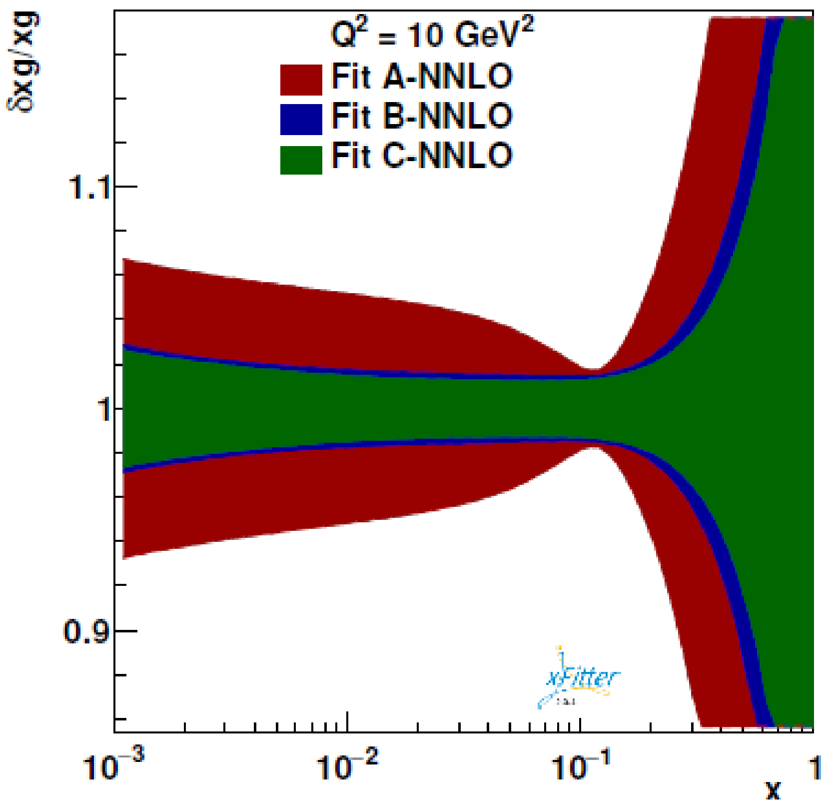
Parameter	Fit A	Fit B	Fit C
B_{uv}	0.731 ± 0.034	0.610 ± 0.016	0.631 ± 0.014
C_{uv}	4.898 ± 0.077	4.974 ± 0.072	4.982 ± 0.077
E_{uv}	11.3 ± 1.5	17.9 ± 1.4	15.9 ± 1.1
B_{dv}	0.869 ± 0.085	0.704 ± 0.066	0.663 ± 0.060
C_{dv}	4.60 ± 0.41	4.59 ± 0.38	4.13 ± 0.35
$C_{\bar{U}}$	5.01 ± 0.69	2.065 ± 0.078	1.972 ± 0.047
$A_{\bar{D}}$	0.231 ± 0.014	0.1784 ± 0.0069	0.1758 ± 0.0065
$B_{\bar{D}}$	-0.1271 ± 0.0091	-0.1597 ± 0.0061	-0.1624 ± 0.0058
$C_{\bar{D}}$	7.7 ± 1.6	4.77 ± 0.83	5.02 ± 0.80
f_s	0.31 (Fixed)	0.31 (Fixed)	0.31 (Fixed)
B_g	-0.38 ± 0.13	-0.239 ± 0.033	-0.249 ± 0.035
C_g	4.9 ± 1.4	3.57 ± 0.26	4.06 ± 0.20
A'_g	0.34 ± 0.20	0.096 ± 0.021	0.142 ± 0.028
B'_g	-0.526 ± 0.048	-0.582 ± 0.019	-0.546 ± 0.017
C'_g	25.00 (Fixed)	25.00 (Fixed)	25.00 (Fixed)
$\alpha_s(M_Z^2)$	0.1134 ± 0.0024	0.1187 ± 0.0007	0.1179 ± 0.0006

Phys. Rev. D 106, no.11, 114042 [arXiv:2212.07243].

Gluon Ratio

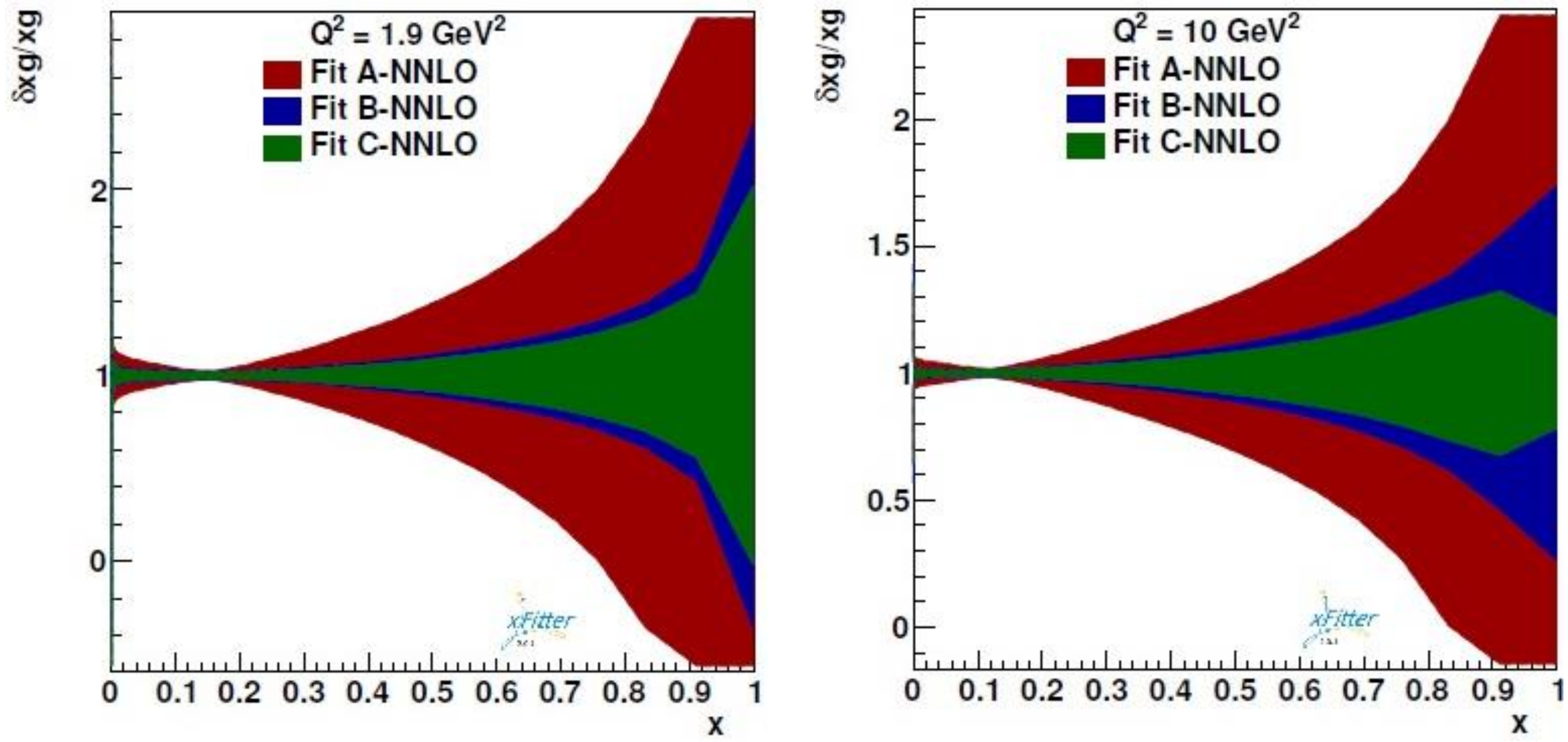


δxg/xg
$Q^2 = 1.9\ GeV^2$
Fit A-NNLO
Fit B-NNLO
Fit C-NNLO
1.2
1.1
1
0.9
0.8
10^{-3}
10^{-2}
10^{-1}
1
x
xFitter

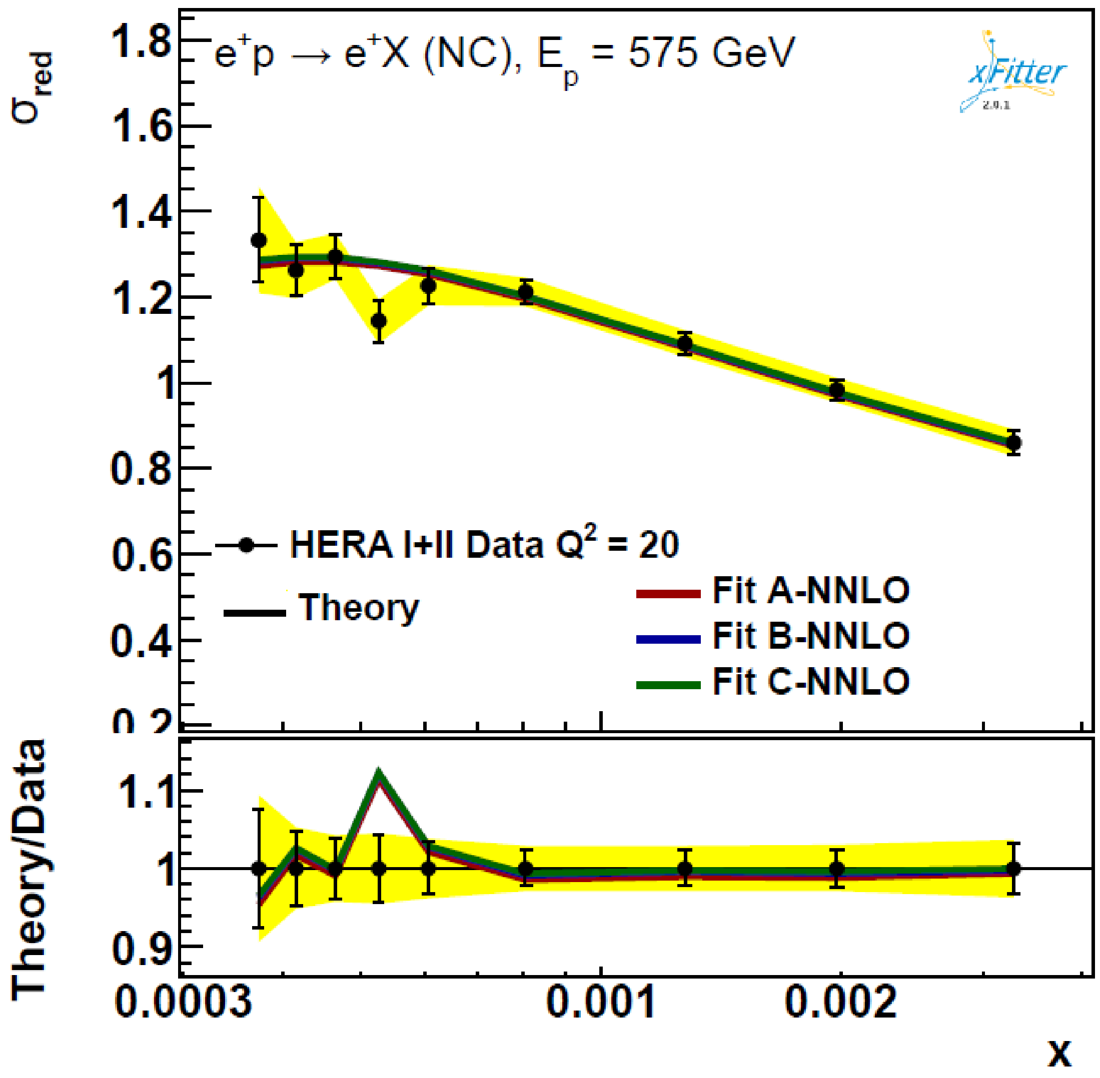


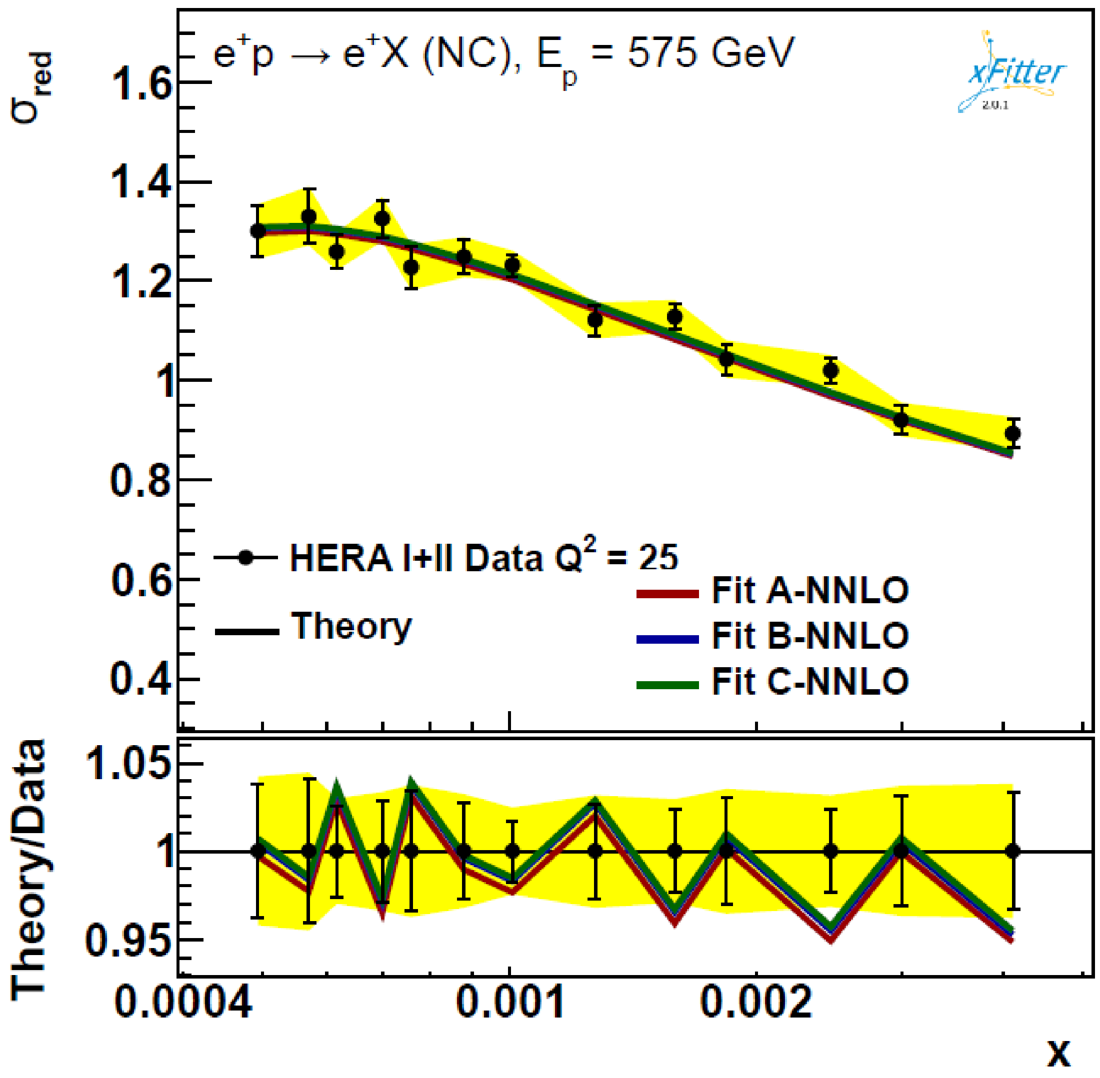
δxg/xg
$Q^2 = 10\ GeV^2$
Fit A-NNLO
Fit B-NNLO
Fit C-NNLO
1.1
1
0.9
10^{-3}
10^{-2}
10^{-1}
1
x
xFitter

Gluon Restricted Uncertainty at High-x

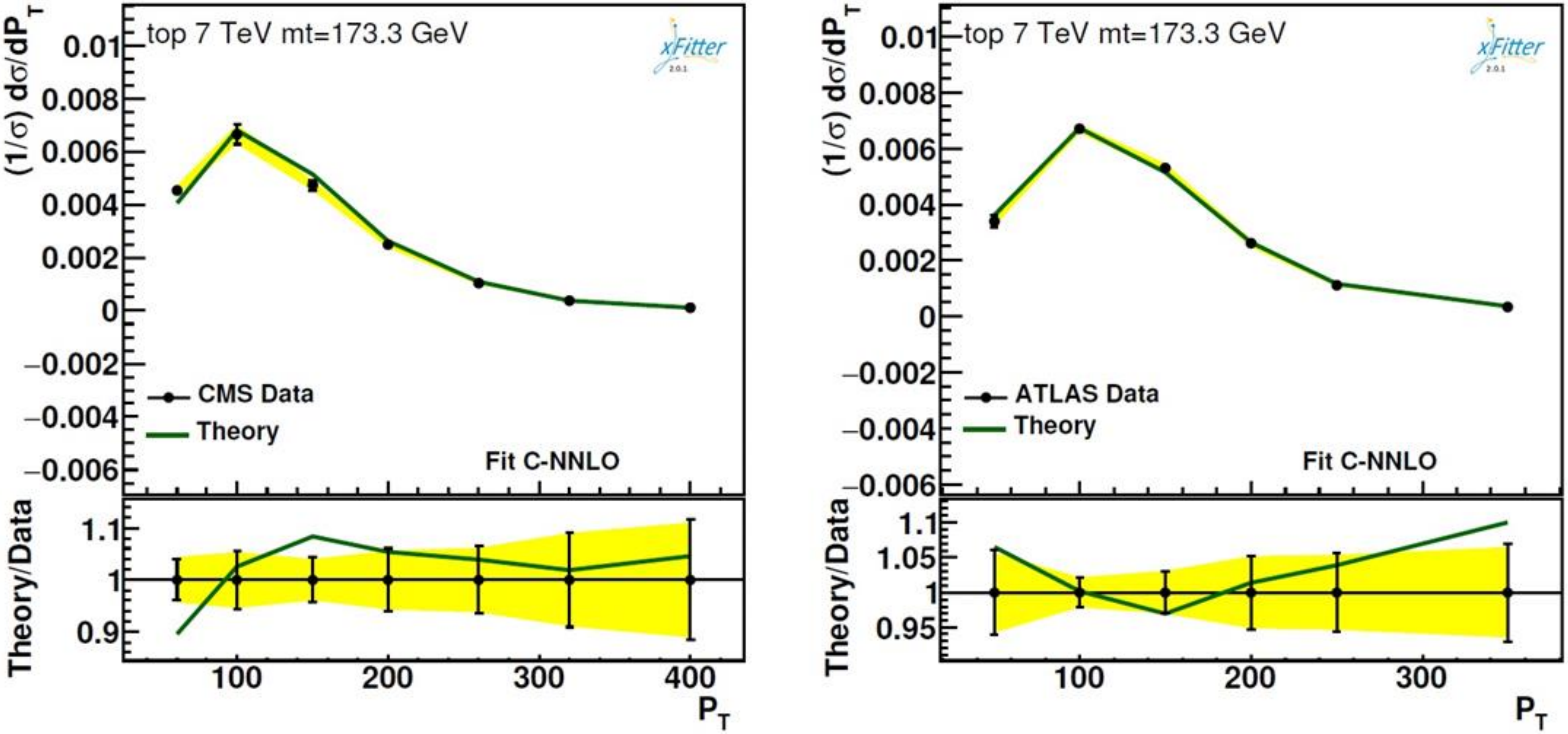


QCD Fit results





QCD Fit results



Conclusion

- The PDFs are essential inputs for calculating physical observable like cross-sections.
- With more accurate PDFs we are able to describe the experimental measurements more accurately
- The extracted values and uncertainties of observables such as $\boldsymbol{\alpha_s}$ are important for investigating the validity of results.

Thanks