

# xFitter project - a framework for QCD studies

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on behalf of the xFitter Developers' Team  
supported by the Polish Ministry under program Mobility Plus



QCD - Old Challenges and New Opportunities

WE-Heraeus Physics School, 24-30.09.2017, Bad Honnef

- Description of the xFitter project: methods, schemes and data used for PDF determination
- Selected results from xFitter (HERA, ATLAS, CMS)
- The main results for the foton PDF: [F.Guli](#) and [xFitter Developers' team](#)
- Dipole models in xFitter: sign of saturation of gluon density
  - Dipole model analysis of highest precision HERA data, including very low  $Q^2$ 's.



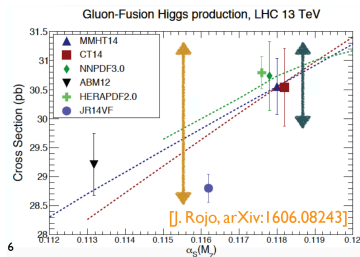
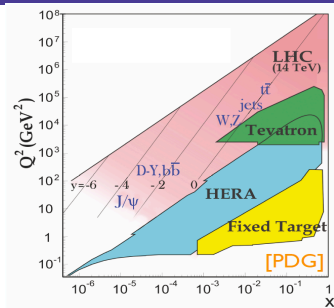
- The recent discovery of the **Higgs boson** and the extensive searches for signals of new physics in LHC pp collisions demand high-precision calculations to test the validity of the **Standard Model (SM)** and factorisation in **(QCD)**.
- The **factorisation theorem** for a hadronic cross section reads:

$$d\sigma_{had} = W_{ij} \otimes f_i \otimes f_j d\Phi$$

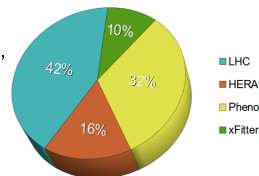
- **partonic cross section:**
  - Process dependent
  - High-energy dominated
  - Computable in perturbation theory
- **parton distribution functions:**
  - Universal (for a given hadronic species)
  - Low-energy dominated
  - Perturbation theory inapplicable
- The rapid flow of new data from the LHC has motivated the development of a tool to combine them together in a fast, efficient, open-source framework :  
**xFitter framework**
- How do we determine parton distribution functions **(PDFs)**?
- Presently, the most accurate and reliable way is through **fits to data**

# Fitting PDFs: Introduction

- **Data sets:**
  - as large and varied as possible
  - spanning a wide kinematic range
- Estimate of the **uncertainties:**
  - include full experimental uncertainties
  - ensure a faithful representation
- Choice of the **parametrisation:**
  - avoid parametrisation biases
- Theoretical inputs:
  - higher order corrections
  - Heavy-quarks mass effect
  - ...
- Different choices may lead to different results



- The xFitter project (former HERAFitter) is an **unique open-source QCD fit framework**
- GitLab (CERN) is now the main repository of the project:  
<https://gitlab.cern.ch/fitters/xfitter>  
(open access to download for everyone - read only)
- This code allows users to:
  - **extract PDFs** from a large variety of experimental data,
  - assess the impact of new data on PDFs,
  - check the consistency of experimental data,
  - test different theoretical assumptions
- Around 30 active developers between experimentalists and theorists
- LHC experiments provide the main developments and usage of the xFitter platform



- External xFitter's meeting in Oxford:
  - 33 participants
  - 2.5 days workshop with number of talks and many discussions

## Downloads of xFitter software package

📌 xFitter-2.0.0 release is publicly available.  
All the xFitter releases can be accessed [HERE](#).  
All the former (HERAFitter) releases can be accessed here:  
Description: 📄 <http://arxiv.org/abs/1410.4412>

## xFitter Meetings

📌 xFitter Meeting in Oxford 20-22 March 2017

- **User's Meetings:** meetings to enhance community
- **Developer's Meeting:** technical weekly meetings (restricted access)
- **Steering Group's Meeting** (restricted access)

## xFitter representation

- List of results
- List of collected talks

## Developers Info (restricted to developers)

- Internal Developments

## Organisation

Steering Group is composed of:

- **Conveners:** Voica Radescu, Ringale Placakyte
- **Release coordinator/Librarian** (revision of the code)
- **Contact Persons:** Crist Diaconu (H1), Klaus Reichle
- **DESY IT Contact:** Yves Kemp

## Getting help

## xFitter Meeting in Oxford, UK

19 - 22 March 2017  
St Hilda's College, Oxford, UK



# The xFitter Project - list of analysis

- More than 40 publications obtained using xFitter from the beginning of the project: <https://www.xfitter.org/xFitter/xFitter/results>

## List of analyses by xFitter

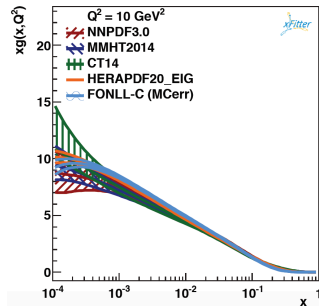
The link to the list of analyses using former HERAFitter can be accessed [here](#)

6 07.2017	xFitter Developers	arXiv:1707.05343	● Impact of the heavy quark matching scales in PDF fits
5 01.2017	F. Giuli, xFitter Developers' team and M. Lisovsky	Eur.Phys.J. C77 (2017) no.6 400, arXiv:1701.08553	● The photon PDF from high-mass Drell-Yan data at the LHC
4 03.2016	xFitter and APFEL teams and A. Geiser	JHEP 1608 (2016) 050, arXiv:1605.01946	● A determination of $m_c(m_c)$ from HERA data using a matched heavy flavor scheme

## List of analyses using xFitter

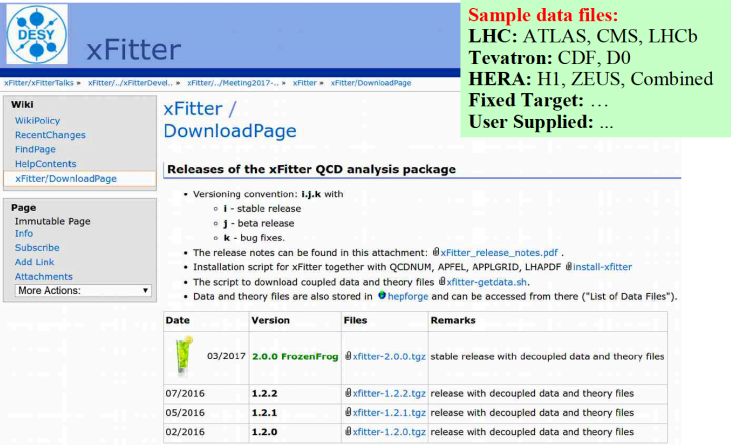
Number	Date	Group	Reference	Title
<b>2016</b>				
45	07.2017	Leszek Motyka et. al.	arXiv:1707.05992	● Evidence of quasi-partonic higher-twist effects in deep inelastic scattering at HERA at moderate Q <sup>2</sup> Q <sup>2</sup>
44	08.2017	A. Vafaei, A.N. Khorrarnian	Nucl.Phys. B921 (2017) 472	● The role of different schemes in the QCD analysis and determination of the strong coupling
43	05.2017	CMS	arXiv:1705.02628	● Measurement of the triple-differential dijet cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV and constraints on parton distribution functions
42	03.2017	CMS	arXiv:1703.01630, submitted to EPJC (TOP-14-013)	● Measurement of double differential cross sections for top quark pair production in pp collisions at 8 TeV and impact on PDFs
41	02.2017	A. Aleedaneshvara, M. Goharipour, S. Rostami	Chin Phys C 41, 2 (2017) 023101	● Uncertainty of parton distribution functions due to physical observables in a global analysis
40	01.2017	Y.G. Gbedo, M. Mangin-Brinet	arXiv:1701.07678	● Markov Chain Monte Carlo technics applied to PDF determination: proof of concept
39	01.2017	ABMP	arXiv:1701.05838	● Parton Distribution Functions, $\alpha_s$ and Heavy-Quark Masses for LHC Run II
38	12.2016	ATLAS	arXiv:1612.03636	● Measurements of top-quark pair to Z-boson cross-section ratios at $\sqrt{s} = 13; 8; 7$ TeV with the ATLAS detector
37	12.2016	ATLAS	arXiv:1612.03016	● Precision measurement and interpretation of inclusive W and Z production with the ATLAS detector
36	12.2016	A. Aleedaneshvara, M. Goharipour, S. Rostami	EPJA (2016) 52: 352	● The impact of intrinsic charm on the parton distribution functions
35	11.2016	CMS	CMS PAS SMP-16-011	● Measurement of triple-differential dijet cross sections at 8 TeV with the CMS detector and constraints on PDFs
34	11.2016	A. Luszczak and H. Kowalski	arXiv:1611.10100, PRD 95 (2017)014030	● Dipole model analysis of highest precision HERA data, including very low Q <sup>2</sup> 's

- **Parametrise PDFs at the initial scale:**
  - several functional forms available (“standard”, Chebyshev, etc.)
  - define parameters to be fitted
- **Evolve PDFs to the scales of the fitted data points:**
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- **Compute predictions for DIS and hadron colliders:**
  - several heavy quarks treatments are available in DIS (ZM-VFNS, ACOT, FONLL, RT, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions via  $\chi^2$  :**
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise the  $\chi^2$  w.r.t. the fitted parameters**
  - using MINUIT
- **Useful drawing tools**






- <https://www.xfitter.org/xFitter/xFitter/DownloadPage>



The screenshot shows the xFitter website's DownloadPage. The page title is "xFitter / DownloadPage". A sidebar on the left contains a "Wiki" section with links to WikiPolicy, RecentChanges, FindPage, HelpContents, and xFitter/DownloadPage. Below that is a "Page" section with links to Immutable Page, Info, Subscribe, Add Link, Attachments, and a "More Actions" dropdown. The main content area is titled "Releases of the xFitter QCD analysis package" and contains a bulleted list of release information:

- Versioning convention: **i,j,k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: @xFitter\_release\_notes.pdf .
- Installation script for xFitter together with QCDDNUM, APFEL, APPLGRID, LHAPDF @install-xfitter
- The script to download coupled data and theory files @xfitter-getdata.sh.
- Data and theory files are also stored in [hepforge](#) and can be accessed from there ("List of Data Files").

Below the text is a table with the following data:

Date	Version	Files	Remarks
 03/2017	<b>2.0.0 FrozenFrog</b>	@xfitter-2.0.0.tgz	stable release with decoupled data and theory files
07/2016	<b>1.2.2</b>	@xfitter-1.2.2.tgz	release with decoupled data and theory files
05/2016	<b>1.2.1</b>	@xfitter-1.2.1.tgz	release with decoupled data and theory files
02/2016	<b>1.2.0</b>	@xfitter-1.2.0.tgz	release with decoupled data and theory files

A green callout box on the right side of the screenshot contains the following text:

**Sample data files:**  
**LHC:** ATLAS, CMS, LHCb  
**Tevatron:** CDF, D0  
**HERA:** H1, ZEUS, Combined  
**Fixed Target:** ...  
**User Supplied:** ...

- By default, only final combined HERA I+II data are distributed
- **getter-xfitter.sh** script to download data with corresponding theory files
- in directory 'datasets' located all available files

- <http://xfitter.hepforge.org/data.html>

- <http://xfitter.hepforge.org/>



- Possibility to download data files (including theory)
- Updated automatically with new data added to svn
- Your feedback is welcome! (via email [xfitter-help@desy.de](mailto:xfitter-help@desy.de))

This page contains the list of publicly available experimental data sets (with corresponding theory grids if available) in the xFitter package. To download data set please click on the arXiv link (and open/save tar.gz file).

No	Collider	Experiment	Reaction	arXiv	Readme
1	fixedTarget	bcdms	inclusiveDis	<a href="#">cern-ep-89-06</a>	<a href="#">README</a>
2	hera	h1	beautyProduction	<a href="#">0907.2643</a>	
3	hera	h1	inclusiveDis	<a href="#">1012.4355</a>	
4	hera	h1	jets	<a href="#">0706.3722</a>	<a href="#">README</a>
5	hera	h1	jets	<a href="#">0707.4057</a>	<a href="#">README</a>
6	hera	h1	jets	<a href="#">0904.3870</a>	<a href="#">README</a>
7	hera	h1	jets	<a href="#">0911.5678</a>	<a href="#">README</a>
8	hera	h1	jets	<a href="#">1406.4709</a>	<a href="#">README</a>
9	hera	h1zeusCombined	charmProduction	<a href="#">1211.1182</a>	
10	hera	h1zeusCombined	inclusiveDis	<a href="#">0911.0884</a>	
11	hera	h1zeusCombined	inclusiveDis	<a href="#">1506.06042</a>	
12	hera	zeus	beautyProduction	<a href="#">1405.6915</a>	
13	hera	zeus	diffractiveDis	<a href="#">0812.2003</a>	
14	hera	zeus	jets	<a href="#">0208037</a>	
15	hera	zeus	jets	<a href="#">0608048</a>	
16	hera	zeus	jets	<a href="#">1010.6167</a>	
17	lhc	atlas	drellYan	<a href="#">1305.4192</a>	
18	lhc	atlas	drellYan	<a href="#">1404.1212</a>	
19	lhc	atlas	jets	<a href="#">1112.6297</a>	

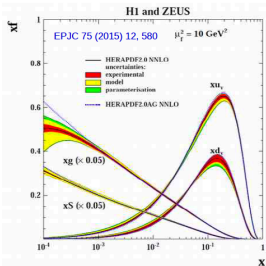
- [www.xfitter.org/xfitter/tutorials](http://www.xfitter.org/xfitter/tutorials)



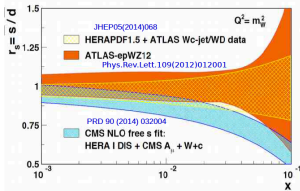
- A list of educational examples are provided in the package - prepared for the CTEQ summer school 2016:
- **Exercise 1:** PDF fit
  - learn the basic settings of a QCD analysis, based on HERA data only
- **Exercise 2:** Simultaneous PDF fit and  $\alpha_s$ :
  - learn the basic of an  $\alpha_s$  extraction using H1 jet data
- **Exercise 3:** LHAPDF analysis
  - how to estimate impact of a new data without fitting
  - profiling and reweighting techniques
- **Exercise 4:** Plotting LHAPDF files
  - direct visualisation of PDFs from LHAPDF6 using simple python scripts

# Results obtained with xFitter: Examples (1)

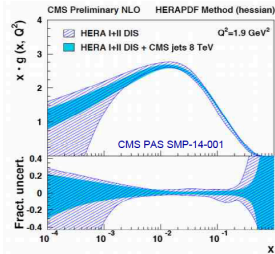
- DIS inclusive processes



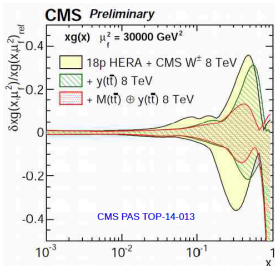
- Drell-Yan processes  
(strange quark density determination)



- Jet production

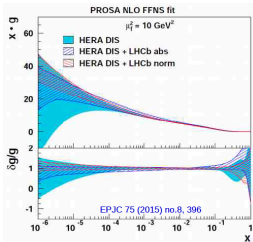


- Top-quark production

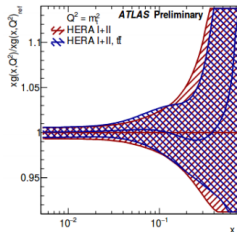


# Results obtained with xFitter: Examples (2)

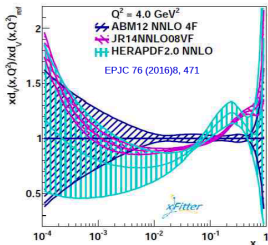
- Heavy quark production



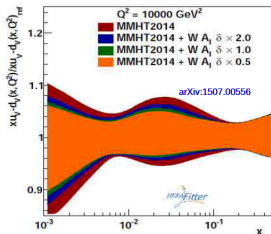
- The ratio of the fitted gluon PDF with and without  $t\bar{t}$  data included



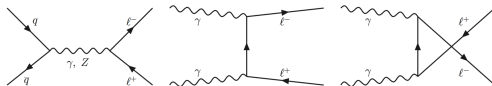
- Evolution of modern PDFs (benchmarking)



- PDF4LHC report (benchmarking)



- Interpretation of the LHC data requires theoretical calculations that include not only QCD corrections, but also the EW effects for the TeV region:
  - pure weak corrections
  - QED corrections → photon PDF published in [EPJC 77 \(2017\) 400](#)
- **Drell-Yan data** at LHC provide direct handle on the **photon PDF**:

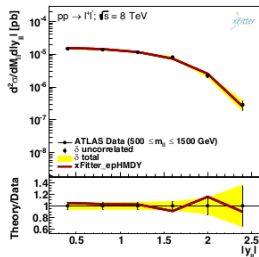
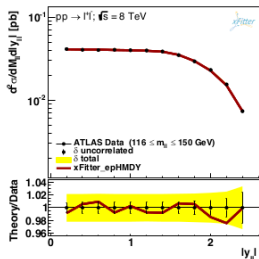


ATLAS high mass Drell Yan at 8 TeV: JHEP 1608 (2016) 009

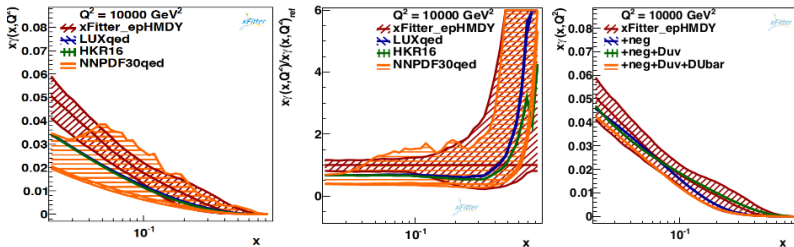
- Presented as  $d\sigma/dm_{ll}$ ,  $d^2\sigma/dm_{ll}d\Delta|\eta_{ll}|$  and  $d^2\sigma/dm_{ll}dy_{ll}$  (expected to provide most sensitivity to PDFs)
- PDF evolution and DIS cross sections via APFEL program:
  - Accurate up to NNLO in QCD + NLO in QED
  - Includes relevant mixed QCD + QED correction (NOVELTY)
  - FONLL general-mass scheme
- LHC hmDY cross sections calculated via Madgraph5.aMC@NLO
- NNLO QCD + NLO QED corrections to DY obtained using FEWZ3.1

- Good description of the dataset (remarkably, for DY data  $\chi^2/N_{data} = 48/48$ )

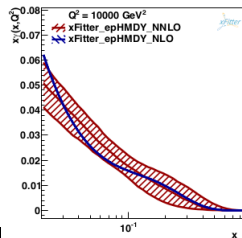
Dataset	$\chi^2/N_{dat}$
HERA I+II	1236/1056
high-mass DY $116 \text{ GeV} \leq m_{ll} \leq 150 \text{ GeV}$	9/12
high-mass DY $150 \text{ GeV} \leq m_{ll} \leq 200 \text{ GeV}$	15/12
high-mass DY $200 \text{ GeV} \leq m_{ll} \leq 300 \text{ GeV}$	14/12
high-mass DY $300 \text{ GeV} \leq m_{ll} \leq 500 \text{ GeV}$	5/6
high-mass DY $500 \text{ GeV} \leq m_{ll} \leq 1500 \text{ GeV}$	4/6
Correlated (high-mass DY) $\chi^2$	1.17
Log penalty (high-mass DY) $\chi^2$	-0.12
Total (high-mass DY) $\chi^2/N_{dat}$	<b>48/48</b>
Combined HERA I+II and high-mass DY $\chi^2/N_{dof}$	1284/1083



- Good description of the dataset (remarkably, for DY data  $\chi^2/N_{data} = 48/48$ )



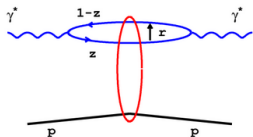
- Agreement within uncertainties for all determinations for  $x \geq 0.1$  ( $1\sigma$  level)
- For  $x \geq 0.1$  LUXqed and HKR16 are softer than xFitter.epHMDY (agreement at ( $2\sigma$  level))
- Smaller uncertainty as compared to NNPDF3.0qed ( $\sim 30\%$  below  $x = 1$ ) the only other direct determination
- Direct determination not competitive with theoretical calculations, but fully consistent with them
- Robustness of the fit and his perturbative stability studied (NLO vs NNLO)





- **Motivation:** Investigation of the [gluon density](#) with so-called [BGK dipole model](#), as an alternative to the [PDF approach](#). BGK dipole model, uses a very similar evolution scheme as PDFs, i.e. DGLAP evolution in the kt factorization scheme (in contrast to the collinear factorization for PDFs).
- The precise knowledge of the [gluon density](#) is mandatory to fully exploit the LHC physics potential - because gluon density determines the Higgs production rate.
- We analyse, within a dipole model, the final, inclusive HERA DIS cross section data in the [low  \$x\$](#)  region, using fully correlated errors.
- We show, that these highest precision data are very well described within the dipole model framework starting from very [low  \$Q^2\$](#)  values of [0.3 GeV<sup>2</sup>](#) to the highest values of  [\$Q^2 = 250 \text{ GeV}^2\$](#) .
- We discuss the saturation question and the properties of the gluon density obtained in this way.
- The analysis was done in the [xFitter](#), published in [Phys.Rev.D 95, 2017](#).

- Dipole picture of DIS at small  $x$  in the proton rest frame



$r$  - dipole size

$z$  - longitudinal momentum fraction of the quark/antiquark

- Factorization: dipole formation + dipole interaction

$$\sigma^{\gamma P} = \frac{4\pi^2 \alpha_{em}}{Q^2} F_2 = \sum_f \int d^2r \int_0^1 dz |\Psi^\gamma(r, z, Q^2, m_f)|^2 \hat{\sigma}(r, x)$$

- Dipole-proton interaction

$$\hat{\sigma}(r, x) = \sigma_0 (1 - \exp\{-\hat{r}^2\}) \quad \hat{r} = r/R_s(x)$$

- GBW (Golec-Biernat-Wüsthoff) parametrization with heavy quarks:  
 $f = u, d, s, c$

$$\hat{\sigma}(r, x) = \sigma_0 (1 - \exp(-r^2/R_s^2)), \quad R_s^2 = 4 \cdot (x/x_0)^\lambda \text{ GeV}^2$$

- The dipole scattering amplitude in such a case reads

$$\hat{N}(\mathbf{r}, \mathbf{b}, x) = \theta(b_0 - b) (1 - \exp(-r^2/R_s^2))$$

where

$$\hat{\sigma}(r, x) = 2 \int d^2b \hat{N}(\mathbf{r}, \mathbf{b}, x)$$

- Parameters  $b_0$ ,  $x_0$  and  $\lambda$  from fits of  $\hat{N}$  to  $F_2$  data

$$\lambda = 0.288 \quad x_0 = 4 \cdot 10^{-5} \quad 2\pi b_0^2 = \sigma_0 = 29 \text{ mb}$$

- BGK (Bartels-Golec-Kowalski) parametrization

$$\hat{\sigma}(r, x) = \sigma_0 \left\{ 1 - \exp \left[ -\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2) / (3\sigma_0) \right] \right\}$$

- $\mu^2 = C/r^2 + \mu_0^2$  is the scale of the gluon density
- $\mu_0^2$  is a starting scale of the QCD evolution.  $\mu_0^2 = Q_0^2$
- gluon density is evolved according to the LO or NLO DGLAP eq.
- soft gluon:

$$xg(x, \mu_0^2) = A_g x^{\lambda_g} (1-x)^{C_g}$$

- soft + hard gluon:

$$xg(x, \mu_0^2) = A_g x^{\lambda_g} (1-x)^{C_g} (1 + D_g x + E_g x^2)$$

- The total cross section for a small  $q\bar{q}$  dipole to pass through a dilute gluon cloud is proportional to the dipole area, the strong coupling constant, and the number of gluons in the cloud

$$\sigma_{q\bar{q}} = \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2),$$

- where  $xg(x, \mu^2)$  is gluon density at some scale  $\mu^2$ . Now imagine that the density of gluons in the target is not small. Divide the target into thin slices of thickness  $dz$ . The probability that a dipole at impact parameter  $b$  does not suffer an inelastic interaction passing through one slice of the proton is:

$$P = 1 - \frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2) \rho(z) dz.$$

- Here  $\rho(z)$  denotes density of the gluons within a proton and is normalized to 1,

$$\int dz \rho(z) = 1.$$

- Exponentiating this result, the probability that the dipole suffers no inelastic interactions passing through the entire proton is  $|S|^2$ ,

$$\int |S|^2 = \exp\left(-\frac{\pi^2}{N_c} r^2 \alpha_s(\mu^2) xg(x, \mu^2)\right).$$

- Dipole model BGK fit with fixed valence quarks

TABLE I. BGK fit with fixed valence quarks for  $\sigma_r$  for H1ZEUS-NC data in the range  $Q^2 \geq 3.5$  or  $8.5 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft gluon*.  $m_{uds} = 0.14$ ,  $m_c = 1.3 \text{ GeV}$ .  $Q_0^2 = 1.9 \text{ GeV}^2$ .

$Q_{\min}^2$ [GeV <sup>2</sup> ]	$\sigma_0$ [mb]	$A_g$	$\lambda_g$	$C_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
3.5	$87.0 \pm 8.9$	$2.32 \pm 0.009$	$-0.056 \pm 0.11$	$8.21 \pm 0.80$	534	551.1	1.03
8.5	$72.4 \pm 7.4$	$2.77 \pm 0.009$	$-0.042 \pm 0.123$	$6.54 \pm 0.632$	448	452.5	1.01

- Dipole model BGK fit with fitted valence quarks

TABLE II. BGK fit with fitted valence quarks for  $\sigma_r$  for H1ZEUS-NC data in the range  $Q^2 \geq 3.5 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft gluon*.  $m_{uds} = 0.14$ ,  $m_c = 1.3 \text{ GeV}$ .  $Q_0^2 = 1.9 \text{ GeV}^2$ .

$Q_{\min}^2$ [GeV <sup>2</sup> ]	$\sigma_0$ [mb]	$A_g$	$\lambda_g$	$C_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
3.5	$89.99 \pm 9.2$	$2.44 \pm 0.145$	$-0.079 \pm 0.099$	$7.24 \pm 0.61$	530	540.35	1.02

- Dipole model BGK fit without valence quarks

TABLE VI. BGK fit without valence quarks for  $\sigma_r$  for HIZEUS-NC data in the range  $Q^2 \geq 3.5 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft gluon*.  $m_{uds} = 0.14, m_c = 1.3 \text{ GeV}$ .  $Q_0^2 = 1.9 \text{ GeV}^2$ .

$Q_{\min}^2$ [GeV <sup>2</sup> ]	$\sigma_0$ [mb]	$A_g$	$\lambda_g$	$C_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
3.5	$105.20 \pm 12.234$	$2.4788 \pm 0.093$	$-0.066 \pm 30.004$	$6.9093 \pm 0.510$	534	554.68	1.04

- Parameters of valence quarks from HERAPDF fit

TABLE VIII. Parameters of valence quarks obtained in HERAPDF NLO fits for  $Q^2 > 3.5 \text{ GeV}^2$ .

No	$A_{uv}$	$B_{uv}$	$C_{uv}$	$E_{uv}$	$A_{dv}$	$B_{dv}$	$C_{dv}$
1	$4.073 \pm 0.123$	$0.713 \pm 0.016$	$4.841 \pm 0.214$	$13.405 \pm 0.921$	$3.151 \pm 10.121$	$0.806 \pm 0.056$	$4.079 \pm 0.301$

- HERAPDF fit with fitted valence quarks for  $x < 1$

TABLE VII. HERAPDF NLO fits to the same data set as for the dipole model but in the full  $x$  range.  $Q_0^2 = 1.9 \text{ GeV}^2$ .

No	$Q_{\min}^2$ [GeV <sup>2</sup> ]	Heavy flavors scheme	$Np$	$\chi^2$	$\chi^2/Np$
1	3.5	Roberts-Thorne	1131	1356.70	1.20
2	8.5	Roberts-Thorne	456	470.88	1.15

- HERAPDF fit with fitted valence quarks for  $x < 0.01$

TABLE IX. HERAPDF NLO fits with fixed valence quarks to the same data set as for the dipole model, but with  $x < 0.01$  range.  $Q_0^2 = 1.9 \text{ GeV}^2$ . No. 1, *soft gluon*; No. 2, *soft+hard gluon*.

No	$Q_{\min}^2$ [GeV <sup>2</sup> ]	Heavy flavors scheme	$Np$	$\chi^2$	$\chi^2/Np$
1	3.5	FONLL-B	534	539.3	1.01
2	3.5	FONLL-B	532	537.3	1.01



- HERAPDF fit with fitted valence quarks for  $x < 1$ , soft gluon

No	$Q^2$	HF Scheme	$Np$	$\chi^2$	$\chi^2/Np$
1	$Q^2 \geq 3.5$	RT	534	572.69	1.07

Table 1: HERAPDF NLO fits with fixed valence quarks to the same data set as for the dipole model, but with  $x < 0.01$  range.  $Q_0^2 = 1.9 \text{ GeV}^2$ .

- HERAPDF fit with fitted valence quarks for  $x < 0.01$ , soft+hard gluon

No	$Q^2$	HF Scheme	$Np$	$\chi^2$	$\chi^2/Np$
1	$Q^2 \geq 3.5$	RT	532	564.80	1.06

Table 2: HERAPDF NLO fits with fixed valence quarks to the same data set as for the dipole model, but with  $x < 0.01$  range.  $Q_0^2 = 1.9 \text{ GeV}^2$ .

- $m_{u,d,s} = 140 \text{ MeV}$ ,  $m_c = 1.3 \text{ GeV}$
- $\hat{\sigma}(r, x) = \sigma_0 \{ 1 - \exp [ -\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2) / (3\sigma_0) ] \}$  with saturation

TABLE IV. BGK fit with valence quarks for  $\sigma_r$  for H1ZEUS-NC data in the range  $Q^2 \geq 3.5$  or  $8.5 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft+hard gluon*.  $m_{uds} = 0.14, m_c = 1.3 \text{ GeV}$ .  $Q_0^2 = 1.9 \text{ GeV}^2$ .

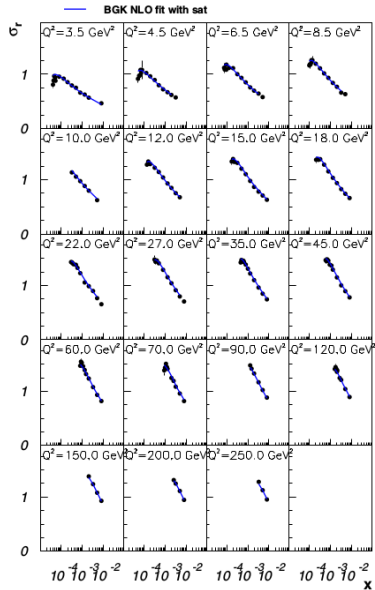
$Q_{\min}^2$ [GeV <sup>2</sup> ]	$\sigma_0$ [mb]	$A_g$	$\lambda_g$	$C_g$	$D_g$	$E_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
3.5	$77.6 \pm 18.6$	$2.62 \pm 0.16$	$-0.064 \pm 0.0087$	$37.1 \pm 5.06$	$3.06 \pm 6.51$	$1406.4 \pm 552.7$	532	534.2	1.00
8.5	$63.5 \pm 18.5$	$2.11 \pm 0.10$	$-0.054 \pm 0.0065$	$21.3 \pm 4.062$	$1.10 \pm 5.76$	$867.2 \pm 423.7$	448	439.0	0.98

- $\hat{\sigma}(r, x) = \sigma_0 [ \pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2) / (3\sigma_0) ]$  without saturation

TABLE X. BGK fit with valence quarks for  $\sigma_r$  for H1ZEUS-NC data in the range  $Q^2 \geq 3.5 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft+hard gluon*.  $m_{uds} = 0.14, m_c = 1.3 \text{ GeV}$ , nonsaturation ansatz.  $Q_0^2 = 1.9$  or  $1.1 \text{ GeV}^2$ .

$Q_{\min}^2$ [GeV <sup>2</sup> ]	$Q_0^2$ [GeV <sup>2</sup> ]	$A_g$	$\lambda_g$	$C_g$	$D_g$	$E_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
3.5	1.9	$2.33 \pm 0.10$	$-0.094 \pm 0.006$	$14.8 \pm 11.5$	$9.80 \pm 14.7$	$-99.5 \pm 74.830$	533	556.17	1.04
3.5	1.1	$3.80 \pm 0.22$	$0.10 \pm 0.01$	$32.5 \pm 1.6$	$-25.2 \pm 3.49$	$1868 \pm 252$	533	539.2	1.01

# Comparison with HERA+II data



- BGK dipole model fit for  $Q^2 \geq 0.35 \text{ GeV}^2$ , **saturation ansatz**

TABLE XI. BGK fit with valence quarks for  $\sigma_r$  for HIZEUS-NC data in the range  $Q^2 \geq 0.35 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft+hard gluon*.  $m_{uds} = 0.14, m_c = 1.3 \text{ GeV}$ , saturation ansatz.  $Q_0^2 = 1.9$  or  $1.1 \text{ GeV}^2$ .

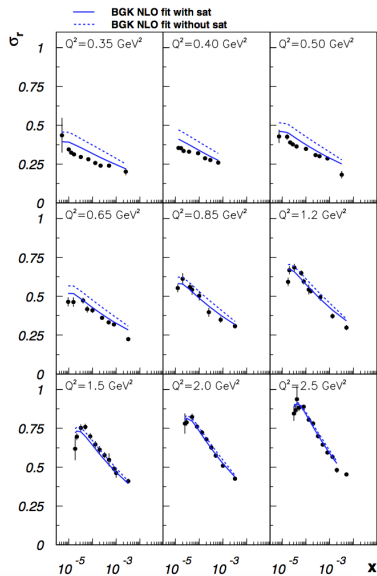
$Q_0^2$ [GeV <sup>2</sup> ]	$\sigma_0$ [mb]	$A_g$	$\lambda_g$	$C_g$	$D_g$	$E_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
1.9	$38.2 \pm 4.1$	$2.80 \pm 0.14$	$-0.063 \pm 0.006$	$46.3 \pm 4.58$	$12.1 \pm 6.00$	$1970.4 \pm 566.0$	653	790.4	1.21
1.1	$196.1 \pm 105$	$6.24 \pm 0.53$	$0.098 \pm 0.012$	$52.3 \pm 6.5$	$-22.0 \pm 10.64$	$2145.0 \pm 835.7$	653	894.1	1.37

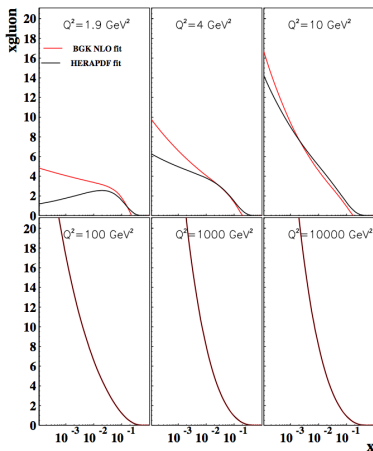
- BGK dipole model fit for  $Q^2 \geq 0.35 \text{ GeV}^2$ , **non saturation ansatz**

TABLE XII. BGK fit with valence quarks for  $\sigma_r$  for HIZEUS-NC data in the range  $Q^2 \geq 0.35 \text{ GeV}^2$  and  $x \leq 0.01$ . NLO fit. *Soft+hard gluon*.  $m_{uds} = 0.14, m_c = 1.3 \text{ GeV}$ , non-saturation ansatz.  $Q_0^2 = 1.9$  or  $1.1 \text{ GeV}^2$ .

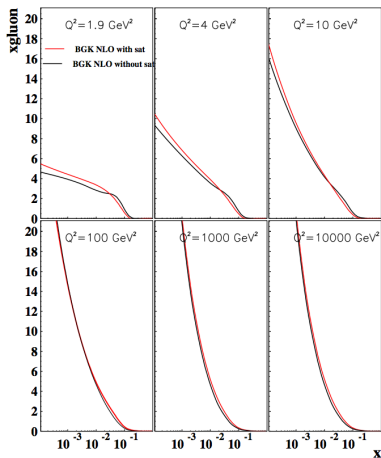
$Q_0^2$ [GeV <sup>2</sup> ]	$A_g$	$\lambda_g$	$C_g$	$D_g$	$E_g$	$N_{df}$	$\chi^2$	$\chi^2/N_{df}$
1.9	$3.05 \pm 0.092$	$-0.022 \pm 0.004$	$40.3 \pm 1.067$	$-32.3 \pm 3.02$	$3158.3 \pm 219.3$	654	1024.3	1.56
1.1	$5.62 \pm 0.13$	$0.158 \pm 0.001$	$43.320 \pm 0.15$	$-55.011 \pm 8.62$	$3791.6 \pm 187.7$	654	999.98	1.53

- The  $\chi^2/N_{df}$  in the region:  $0.3 < Q^2 < 250 \text{ GeV}^2$  is sizably higher than in the fits in the region  $3.5 < Q^2 < 250 \text{ GeV}^2$
- $\chi^2/N_{df} = 1.21$ , with the saturation ansatz and  $\chi^2/N_{df} = 1.52$  without the saturation ansatz.
- The fit in the whole  $Q^2$  region,  $0.3 < Q^2 < 250 \text{ GeV}^2$  is only slightly better than in the extrapolated case.
- The systematic overshoot of the fits over data remains





- The differences are disappearing at larger  $Q^2$ .



- The differences are disappearing at larger  $Q^2$ .

- BGK dipole fits (with saturation) describe the final, high precision HERA data with  $x < 0.01$ , very well:  $\chi^2/Np \rightarrow 1$ .
- Little sensitivity to valence quarks contribution observed.
- **Gluon density** from the BGK model is higher than the PDFs gluon at low  $Q^2$ .
- The extrapolation to the very low  $Q^2$  region shows a sizable overshoot. This indicates that at very low  $Q^2$  **saturation effects** of the eikonal approximation are too small.
- In the **lower  $Q^2 < 3.5 \text{ GeV}^2$**  range the **saturated ansatz** of the gluon density seems to be preferred.



- **xFitter** (former **HERAFitter**) is a unique **open-source** package oriented to fits of PDFs that provides a framework for the **interpretation** and the **analysis** of the experimental data.
- xFitter is presently widely used for many analyses of the **LHC data** to quantify the **constraints on PDFs**.
- **xFitter-2.0.0** is latest (recommended) release.
- Over 40 public results obtained using xFitter.
- The photon PDF from high-mass Drell-Yan data at the LHC is determined
- I have presented one of the many recent results obtained with xFitter:
  - Dipole model analysis of highest precision HERA data, including very low  $Q^2$ 's.

We welcome a new developers and ideas!

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