

# Towards Highly Precise Values of $\alpha_s(M_Z^2)$ in DIS

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[arXiv:1202.2700 and in preparation]

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# References

- Collaboration with: S. Alekhin, H. Böttcher, and S.-O. Moch
- ABKM09: S. Alekhin, JB, S. Klein, S.-O. Moch [arXiv:0908.2766](#)
- ABM10: S. Alekhin, JB, S.-O. Moch [arXiv:1007.3657](#)
- ABM11: S. Alekhin, JB, S.-O. Moch [arXiv:1202.2281](#)
- JB and H. Böttcher in preparation.

References below will mostly be used in terms of acronyms, like "MSTW08" etc.



# Introduction

- $\alpha_s$  is one of the fundamental couplings in the SM. It has to be known very precisely for an enormous host of processes.  $\implies$  Key question:  
**Unification of Forces: How and Where ?**
- Precision determinations of **parton distribution functions** (PDFs) and  $\alpha_s(M_Z^2)$  are currently being performed at **NNLO**,  $O(\alpha_s^3)$ .
- NLO fits suffer from scale uncertainties being **too large**.
- The **heavy flavor corrections** are available in NLO + threshold corrections and the calculation of the NNLO corrections is making progress.
- Sensitive data, capable to constrain the known PDFs better, have to be selected, rather than performing global analyses using data with problematic systematics.
- Current data: DIS World data (including H1+ZEUS combined); Di-muon data ( $s$ ); Drell-Yan data ( $\bar{d} - \bar{u}$ );  $pp$ -jet data: LHC data will take over very soon; Likewise:  $W^\pm, Z$  off-resonance Drell-Yan at LHC.



# Introduction

- $\alpha_s$  and HT terms have to be fitted along with the non-pert. parameters of the PDFs.
- Heavy flavor treatment: BMSN-interpolation from threshold to asymptotia; observe all relations implied by the RGE [Bierenbaum, JB, Klein, 2009](#).
- Deuteron wave function corrections and Target Mass corrections are mandatory.
- Characterize the fit publishing the covariance matrices.
- **Soft Resummation:** heavy flavor threshold; NS Wilson coefficients beyond 3-loop; Effect on the HT-terms.
- We will compare most of the results with those obtained by other fitting groups.
- What do we know about  $\alpha_s$  by June 2012 and what are the subtleties in hard processes ?
- What can be improved in the near future ?
- What are the hopes, if LHeC delivered data ?



# The Data: ABM11 analysis

	Experiment	NDP	$\chi^2(\text{NNLO})$	$\chi^2(\text{NLO})$
DIS inclusive	H1&ZEUS	486	537	531
	H1	130	137	132
	BCDMS	605	705	695
	NMC	490	665	661
	SLAC-E-49a	118	63	63
	SLAC-E-49b	299	357	357
	SLAC-E-87	218	210	219
	SLAC-E-89a	148	219	215
	SLAC-E-89b	162	133	132
	SLAC-E-139	17	11	11
Drell-Yan	FNAL-E-605	119	167	167
	FNAL-E-866	39	52	55
DIS di-muon	NuTeV	89	46	49
	CCFR	89	61	62
Total		3036	3391	3378

Tabelle 2: The value of  $\chi^2$  obtained in the NNLO and NLO fits for different data sets.



# Deuteron Corrections

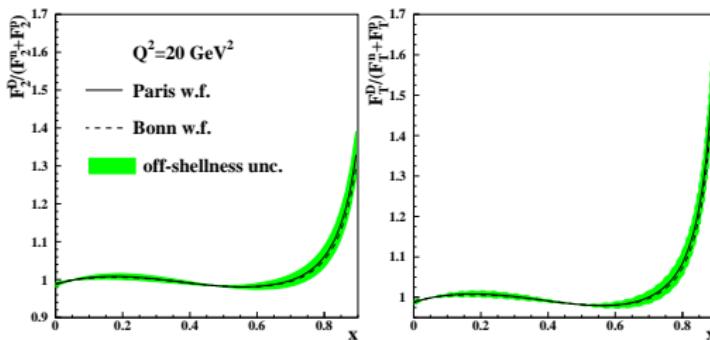


Figure 1: The ratio of the deuteron structure function  $F_2$  (left) and  $F_T$  (right) with account of the Fermi-motion and off-shellness effects of [Kulagin 2004] calculated for the Paris potential of (solid) and the Bonn potential (dashes) at the momentum transfer of  $20 \text{ GeV}^2$  to the sum of those for free proton and neutron versus  $x$ . The shaded area around the solid line gives the uncertainty due to a variation of the off-shell effects by 50%. The calculations are performed at NNLO QCD accuracy using the PDFs and the twist-4 terms obtained by ABKM.

# Higher Twist Contributions

ABM11:

$$F_i(x, Q^2) = F_i^{TMC, \tau=2}(x, Q^2) + \frac{H_i^4(x)}{Q^2} + \frac{H_i^6(x)}{Q^4} + \dots$$

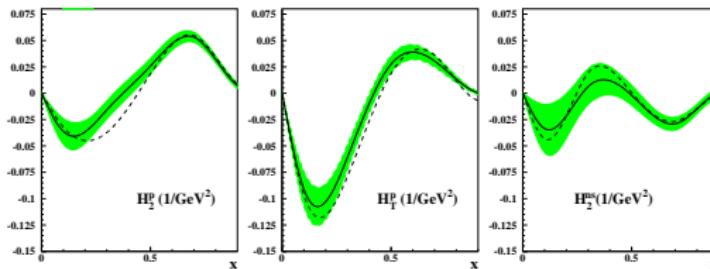


Figure 10: The central values (solid line) and the  $1\sigma$  bands (shaded area) for the coefficients of the twist-4 terms of the inclusive DIS structure functions obtained from our NNLO fit (left panel:  $F_2$  of the proton, central panel:  $F_T$  of the proton, right panel: non-singlet  $F_2$ ). The central values of the twist-4 coefficients obtained from our NLO fit are shown for comparison (dashes).



# Higher Twist Contributions

ABM11 :

To completely remove the HT-terms the cut  $W^2 > 12.5 \text{ GeV}^2$ ,  $Q^2 > 10 \text{ GeV}^2$  is necessary!

	$H_2^p(x)/\text{GeV}^2$	$H_2^{\text{ns}}(x)/\text{GeV}^2$	$H_T^p(x)/\text{GeV}^2$
$x = 0.1$	$-0.036 \pm 0.012$	$-0.034 \pm 0.023$	$-0.091 \pm 0.017$
$x = 0.3$	$-0.016 \pm 0.008$	$0.006 \pm 0.017$	$-0.061 \pm 0.012$
$x = 0.5$	$0.026 \pm 0.007$	$-0.0020 \pm 0.0094$	$0.0276 \pm 0.0081$
$x = 0.7$	$0.053 \pm 0.005$	$-0.029 \pm 0.006$	$0.031 \pm 0.006$
$x = 0.9$	$0.0071 \pm 0.0026$	$0.0009 \pm 0.0041$	$0.0002 \pm 0.0015$

Tabelle 3: The parameters of the twist-4 contribution to the DIS structure functions in for the fit to NNLO accuracy in QCD.



# $\alpha_s(M_Z^2)$

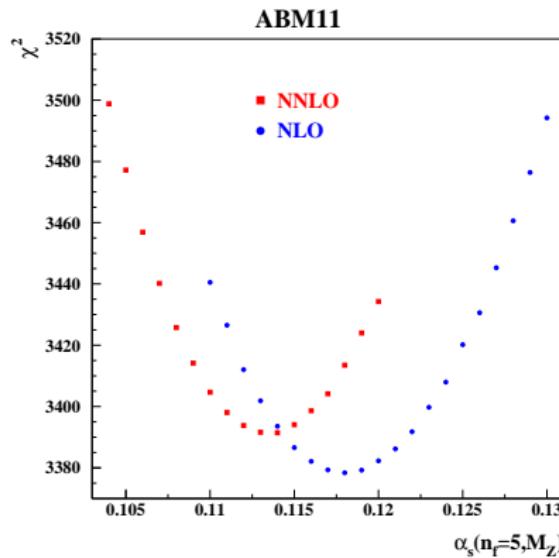


Figure 17: The  $\chi^2$ -profile as a function of  $\alpha_s(M_Z)$  in the present analysis. At NLO (circles) and NNLO (squares).



# $\alpha_s(M_Z^2)$

ABM11

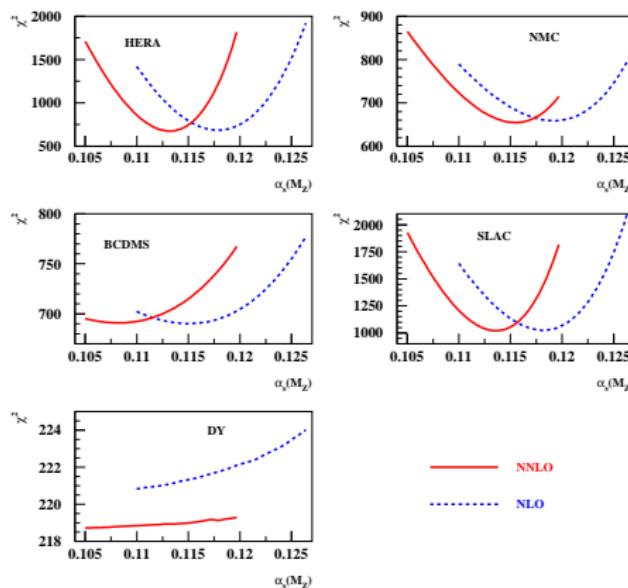


Figure 19: The  $\chi^2$ -profile versus the value of  $\alpha_s(M_Z)$  for the data sets used, all calculated with the PDF and HT parameters fixed at the values obtained from the fits with  $\alpha_s(M_Z)$  released (solid lines: NNLO fit, dashes: NLO one).



# $\alpha_s(M_Z^2)$

ABM11

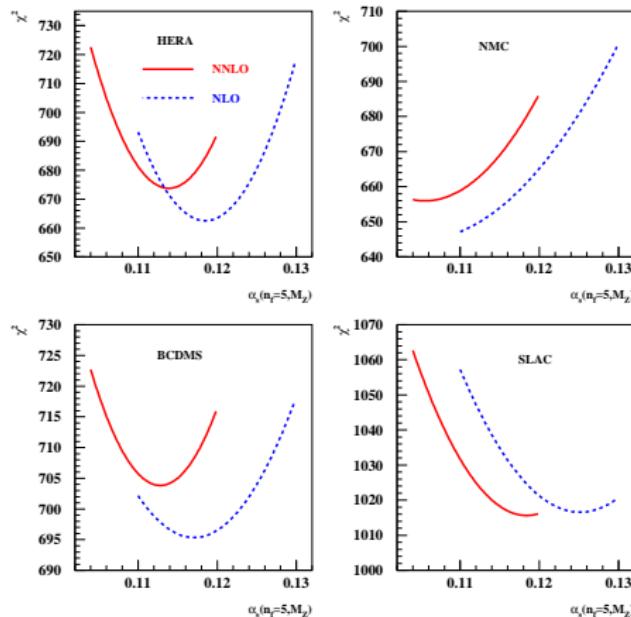


Figure 18: The  $\chi^2$ -profile versus the value of  $\alpha_s(M_Z)$  for the data sets used all obtained in variants of the present analysis with the value of  $\alpha_s$  fixed and all other parameters fitted (solid lines: NNLO fit, dashes: NLO fit).



# $\alpha_s(M_Z^2)$ : ABM11

Experiment	$\alpha_s(M_Z)$		
	$\text{NLO}_{exp}$	NLO	NNLO
BCDMS	$0.1111 \pm 0.0018$	$0.1150 \pm 0.0012$	$0.1084 \pm 0.0013$
NMC	$0.117 \pm 0.011$	$0.1182 \pm 0.0007$	$0.1152 \pm 0.0007$
SLAC		$0.1173 \pm 0.0003$	$0.1128 \pm 0.0003$
HERA comb.		$0.1174 \pm 0.0003$	$0.1126 \pm 0.0002$
DY		$0.108 \pm 0.010$	$0.101 \pm 0.025$
ABM11		$0.1180 \pm 0.0012$	$0.1134 \pm 0.0011$

Tabelle 4: Comparison of the values of  $\alpha_s(M_Z)$  obtained by BCDMS and NMC at NLO with the individual results of the fit in the present analysis at NLO and NNLO for the HERA data the NMC data the BCDMS data the SLAC data and the DY data.

# $\alpha_s(M_Z^2)$ : ABM11 + Tevatron jets

Experiment	$\alpha_s(M_Z)$		
	NLO <sub>exp</sub>	NLO	NNLO*
D0 1 jet	$0.1161^{+0.0041}_{-0.0048}$	$0.1190 \pm 0.0011$	$0.1149 \pm 0.0012$
D0 2 jet		$0.1174 \pm 0.0009$	$0.1145 \pm 0.0009$
CDF 1 jet (cone)		$0.1181 \pm 0.0009$	$0.1134 \pm 0.0009$
CDF 1 jet ( $k_\perp$ )		$0.1181 \pm 0.0010$	$0.1143 \pm 0.0009$
ABM11		$0.1180 \pm 0.0012$	$0.1134 \pm 0.0011$

Tabelle 5: Comparison of the values of  $\alpha_s(M_Z)$  obtained by D0 with the ones based on including individual data sets of Tevatron jet data into the analysis at NLO. The NNLO\* fit refers to the NNLO analysis of the DIS and DY data together with the NLO and soft gluon resummation corrections (next-to-leading logarithmic accuracy) for the 1 jet inclusive data.



# $\alpha_s(M_Z^2)$ : BBG/BB

Experiment	$\alpha_s(M_Z)$			
	NLO <sub>exp</sub>	NLO	NNLO	N <sup>3</sup> LO*
BCDMS	$0.1111 \pm 0.0018$	$0.1138 \pm 0.0007$	$0.1126 \pm 0.0007$	$0.1128 \pm 0.0006$
NMC	$0.117 \begin{array}{l} + 0.011 \\ - 0.016 \end{array}$	$0.1166 \pm 0.0039$	$0.1153 \pm 0.0039$	$0.1153 \pm 0.0035$
SLAC		$0.1147 \pm 0.0029$	$0.1158 \pm 0.0033$	$0.1152 \pm 0.0027$
BBG		$0.1148 \pm 0.0019$	$0.1134 \pm 0.0020$	$0.1141 \pm 0.0021$
BB		$0.1147 \pm 0.0021$	$0.1132 \pm 0.0022$	$0.1137 \pm 0.0022$

Tabelle 6: Comparison of the values of  $\alpha_s(M_Z)$  obtained by BCDMS and NMC at NLO with the results of the flavor non-singlet fits BBG and BB of the DIS flavor non-singlet world data, at NLO, NNLO, and N<sup>3</sup>LO\* with the response of the individual data sets, combined for the experiments BCDMS NMC SLAC.



# $\alpha_s(M_Z^2)$ : NNPDF

Experiment	$\alpha_s(M_Z)$		
	NLO <sub>exp</sub>	NLO	NNLO
BCDMS	$0.1111 \pm 0.0018$	$0.1204 \pm 0.0015$	$0.1158 \pm 0.0015$
NMC <sub>p</sub>		$0.1192 \pm 0.0018$	$0.1150 \pm 0.0020$
NMC <sub>pd</sub>	$0.117 \pm 0.011$		$0.1146 \pm 0.0107$
SLAC		$> 0.124$	$> 0.124$
HERA I		$0.1223 \pm 0.0018$	$0.1199 \pm 0.0019$
ZEUS H2		$0.1170 \pm 0.0027$	$0.1231 \pm 0.0030$
ZEUS F2C		$0.1144 \pm 0.0060$	
NuTeV		$0.1252 \pm 0.0068$	$0.1177 \pm 0.0039$
E605		$0.1168 \pm 0.0100$	
E866		$0.1135 \pm 0.0029$	
CDF Wasy		$0.1181 \pm 0.0060$	
CDF Zrap		$0.1150 \pm 0.0034$	$0.1205 \pm 0.0081$
D0 Zrap		$0.1227 \pm 0.0067$	
CDF R2KT		$0.1228 \pm 0.0021$	$0.1225 \pm 0.0021$
D0 R2CON	$0.1161 \pm 0.0041$	$0.1141 \pm 0.0031$	$0.1111 \pm 0.0029$
NN21		$0.1191 \pm 0.0006$	$0.1173 \pm 0.0007$

Tabelle 7: Comparison of the values of  $\alpha_s(M_Z)$  obtained by BCDMS, NMC, and D0 at NLO with the results of NN21 for the fits to DIS and other hard scattering data at NLO and NNLO and the corresponding response of the different data sets analysed.



# $\alpha_s(M_Z^2) : \text{MSTW08/09}$

Experiment	$\alpha_s(M_Z)$		
	NLO <sub>exp</sub>	NLO	NNLO
BCDMS $\mu p, F_2$	0.1111 $\pm$ 0.0018	—	0.1085 $\pm$ 0.0095
BCDMS $\mu d, F_2$	0.1117 $\pm$ 0.011	0.1135 $\pm$ 0.0155	0.1117 $\pm$ 0.0093
NMC $\mu p, F_2$	0.117 $\pm$ 0.036	0.1275 $\pm$ 0.0105	0.1217 $\pm$ 0.0077
NMC $\mu d, F_2$		0.1265 $\pm$ 0.0115	0.1215 $\pm$ 0.0070
NMC $\mu n/\mu p$		0.1280	0.1160
E665 $\mu p, F_2$		0.1203	—
E665 $\mu d, F_2$		—	—
SLAC $ep, F_2$		0.1180 $\pm$ 0.0060	0.1140 $\pm$ 0.0060
SLAC $ed, F_2$		0.1270 $\pm$ 0.0090	0.1220 $\pm$ 0.0060
NMC, BCDMS, SLAC, $F_L$		0.1285 $\pm$ 0.0115	0.1200 $\pm$ 0.0060
ES86/NuSea $pp$ , DY %cite{Webb:2003bj}		—	0.1132 $\pm$ 0.0088
ES86/NuSea $pd/pp$ , DY		0.1173 $\pm$ 0.107	0.1140 $\pm$ 0.0110
NuTeV $\nu N, F_2$		0.1207 $\pm$ 0.0067	0.1170 $\pm$ 0.0060
CHORUS $\nu N, F_2$		0.1230 $\pm$ 0.0110	0.1150 $\pm$ 0.0090
NuTeV $\nu N, xF_3$		0.1270 $\pm$ 0.0090	0.1225 $\pm$ 0.0075
CHORUS $\nu N, xF_3$		0.1215 $\pm$ 0.0105	0.1185 $\pm$ 0.0075
CCFR		0.1190	—
NuTeV $\nu N \rightarrow \mu\mu X$		0.1150 $\pm$ 0.0170	—
H1 $ep$ 97-00, $\sigma_{NC}^{NC}$		0.1250 $\pm$ 0.0070	0.1205 $\pm$ 0.0055
ZEUS $ep$ 95-00, $\sigma_{NC}^{NC}$		0.1235 $\pm$ 0.0065	0.1210 $\pm$ 0.0060
H1 $ep$ 99-00, $\sigma_r^{CC}$		0.1285 $\pm$ 0.0225	0.1270 $\pm$ 0.0200
ZEUS $ep$ 99-00, $\sigma_r^{CC}$		0.1125 $\pm$ 0.0195	0.1165 $\pm$ 0.0095
H1/ZEUS $ep, F_2^{\text{charm}}$		—	0.1165 $\pm$ 0.0095
H1 $ep$ 99-00 incl. jets	0.1168 $\pm$ 0.0049	0.1127 $\pm$ 0.0093	
ZEUS $ep$ 96-00 incl. jets	0.1208 $\pm$ 0.0048	0.1175 $\pm$ 0.0055	
D0 $pp$ incl. jets	0.1161 $\pm$ 0.0044	0.1185 $\pm$ 0.0055	0.1133 $\pm$ 0.0063
CDF II $p\bar{p}$ incl. jets		0.1205 $\pm$ 0.0045	0.1165 $\pm$ 0.0025
D0 $W \rightarrow l\nu$ asym.		—	—
CDF II $W \rightarrow l\nu$ asym.		—	—
D0 II $Z$ rap.		0.1125 $\pm$ 0.0100	0.1136 $\pm$ 0.0084
CDF II $Z$ rap.		0.1160 $\pm$ 0.0070	0.1157 $\pm$ 0.0067
MSTW		0.1202 $\pm$ 0.0012	0.1171 $\pm$ 0.0014

Table 8: Comparison of the values of  $\alpha_s(M_Z)$  obtained by BCDMS, NMC, HERA-jet and D0 at NLO with the results of the MSTW fits to DIS and other hard scattering data at NLO and NNLO and the corresponding response of the different data sets analysed, cf. Figs. 7a and 7b in MSTW08. Entries not given correspond to  $\alpha_s(M_Z)$  central values below 0.110 or above 0.130; in case no errors are assigned these are larger than the bounds provided in form of the plots in MSTW08.

# $\alpha_s(M_Z^2)$ : Correlation with HT

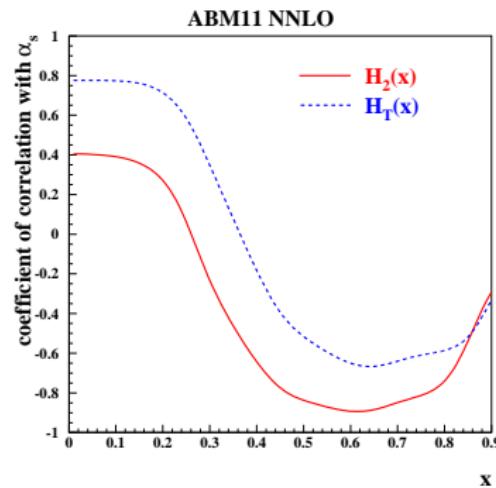


Figure 20: The correlation coefficient of  $\alpha_s(M_Z)$  with the nucleon twist-4 coefficients  $H_2$  (solid line) and  $H_T$  (dashes) versus  $x$  as obtained in our NNLO fit.



# $\alpha_s(M_Z^2)$ : Global DIS Comparison

Data Set	ABM11	BBG	NN21	MSTW
BCDMS	$0.1048 \pm 0.0013$	$0.1126 \pm 0.0007$	$0.1158 \pm 0.0015$	$0.1101 \pm 0.0094$
NMC	$0.1152 \pm 0.0007$	$0.1153 \pm 0.0039$	$0.1150 \pm 0.0020$	$0.1216 \pm 0.0074$
SLAC	$0.1128 \pm 0.0003$	$0.1158 \pm 0.0034$	$> 0.124$	$\begin{cases} 0.1140 \pm 0.0060 & \text{ep} \\ 0.1220 \pm 0.0060 & \text{ed} \end{cases}$
HERA	$0.1126 \pm 0.0002$		$\begin{cases} 0.1199 \pm 0.0019 \\ 0.1231 \pm 0.0030 \end{cases}$	$0.1208 \pm 0.0058$
DY	$0.101 \pm 0.025$	—	—	$0.1136 \pm 0.0100$
	$0.1134 \pm 0.0011$	$0.1134 \pm 0.0020$	$0.1173 \pm 0.0007$	$0.1171 \pm 0.0014$

Table 9: Comparison of the pulls in  $\alpha_s(M_Z)$  per data set between the ABM11, BBG, NN21, MSTW analyses at NNLO.

Use:  $W^2 > 12.5 \text{ GeV}^2$ ,  $Q^2 > 2.5 \text{ GeV}^2$  and no HT:  $\alpha_s(M_Z^2) = 0.1191 \pm 0.0016$

Use:  $W^2 > 12.5 \text{ GeV}^2$ ,  $Q^2 > 10 \text{ GeV}^2$  and no HT:  $\alpha_s(M_Z^2) = 0.1134 \pm 0.0008$

MSTW08 and NNPDF: no HT corrections.

Taking into account error correlations is of importance.



# $\alpha_s(M_Z^2)$ : DIS & other NNLO Determinations

	$\alpha_s(M_Z)$	
BBG	$0.1134^{+0.0019}_{-0.0021}$	valence analysis, NNLO
BB	$0.1132 \pm 0.0022$	valence analysis, NNLO
GRS	0.112	valence analysis, NNLO
ABKM	$0.1135 \pm 0.0014$	HQ: FFNS $n_f = 3$
ABKM	$0.1129 \pm 0.0014$	HQ: BSMN-approach
JR	$0.1124 \pm 0.0020$	dynamical approach
JR	$0.1158 \pm 0.0035$	standard fit
ABM11	$0.1134 \pm 0.0011$	
MSTW	$0.1171 \pm 0.0014$	
NN21	$0.1173 \pm 0.0007$	
CT10	$0.118 \pm 0.005$	
Gehrman et al.	$0.1153 \pm 0.0017 \pm 0.0023$	$e^+e^-$ thrust
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	$e^+e^-$ thrust
3 jet rate	$0.1175 \pm 0.0025$	Dissertori et al. 2009
Z-decay	$0.1189 \pm 0.0026$	BCK 2008/12 ( $N^3\text{LO}$ )
$\tau$ decay	$0.1212 \pm 0.0019$	BCK 2008
$\tau$ decay	$0.1204 \pm 0.0016$	Pich 2011
$\tau$ decay	$0.1169 \pm 0.0025$	Boito et al. 2011
lattice	$0.1205 \pm 0.0010$	PACS-CS 2009 (2+1 fl.)
lattice	$0.1184 \pm 0.0006$	HPQCD 2010
lattice	$0.1200 \pm 0.0014$	ETM 2012 (2+1+1 fl.)
lattice	$0.1156 \pm 0.0022$	Brambilla et al. 2012 (2+1 fl.)
BBG	$0.1141^{+0.0020}_{-0.0022}$	valence analysis, $N^3\text{LO}(\ast)$
BB	$0.1137 \pm 0.0022$	valence analysis, $N^3\text{LO}(\ast)$
world average	$0.1184 \pm 0.0007$ $(2009)$	
	$0.1183 \pm 0.0010$ $(2011)$	

Table 10: Summary of recent NNLO QCD analyses of the DIS world data, supplemented by related measurements using other processes.

# ATLAS Jet Data

NNLO: ABM11:  $\alpha_s(M_Z^2) = 0.1134(11)$

ABM11+ATLAS jets:  $\alpha_s(M_Z^2) = 0.1141(8)$

NLO: ATLAS:  $\alpha_s(M_Z^2) = 0.1151 \pm 0.0047(\text{exp}) \pm 0.0023(\text{pdfs})$

Malaescu/Starovoitov '12

$\mu=3 \text{ GeV}$

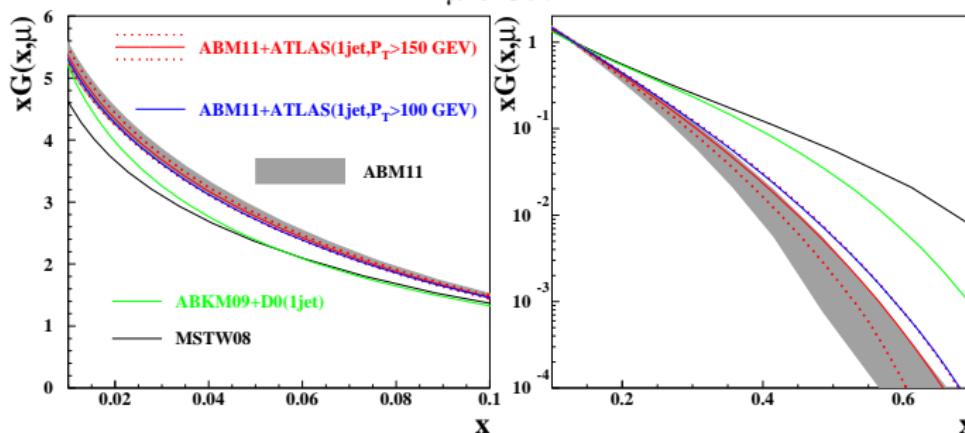


Figure 28: Gluon distribution obtained by including the ATLAS jet data into the ABM11 analysis.



# Future Challenges

- Precise high  $Q^2$  data from LHeC both for **protons** and **deuterons** with well controlled systematics are highly desireable.
- Try to perform non-singlet analyses, including charged current data.
- LHeC will have a rich host of heavy flavor data for dedicated QCD analyses.
- Higher Twist will be less important.
- Interesting other samples with more uniform systematics:  $ep \rightarrow jets$ .
- Constrain the Gluon from as many as possible precision measurements.
- Precision data from new facilities may finally evaluate whether the current high-precision data deliver a correct value of  $\alpha_s(M_Z^2)$ .



# Conclusions

- New ABM11: theory improvements, inclusion of jet data; predicts hadron collider data well
- NNLO:  $\alpha_s(M_Z^2) = 0.1134 \pm 0.0011$  vs ABKM09  
 $\alpha_s(M_Z^2) = 0.1135 \pm 0.0014$
- The different  $\alpha_s$ -values given by MSTW and NNPDF are understood.
- The correct inclusion of **systematic error correlations** and **higher twist effects** are important.
- ATLAS jet data analyzed  $\rightarrow \alpha_s(M_Z^2) = 0.1141 \pm 0.0008$ ; the gluon obtained is softer than that in case of Tevatron; Higgs production cross section almost unchanged.
- Inclusive top-cross section: still differences between the groups:  $\rightarrow \alpha_s, xg(x, Q^2)$
- LHC data start to constrain sea-quarks  $W^\pm, Z$ , off-resonance Drell-Yan
- LHC data start to constrain the gluon **LHC jets**: NNLO corrections needed.
- Need of continuous benchmarking



# Conclusions

- LHC may improve our understanding of  $\alpha_s$  during the next years.
- LHeC might play an important role in providing systematically well-controlled high  $Q^2$  data to be used to measure  $\alpha_s$  at a higher precision.
- The use of different targets is important:  $ep$  and  $ed$ .
- DIS still is one of the very clean processes to measure  $\alpha_s$ .

