Higgs boson cross section predictions at the LHC and the strong coupling constant

Sven-Olaf Moch

Universität Hamburg

MITP workshop *Determination of the Fundamental Parameters in QCD*, Mainz, Mar 07, 2016

Based on work done in collaboration with:

- *Recommendations for PDF usage in LHC predictions*
  A. Accardi, S. Alekhin, M. Botje, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. M., R. Plačakytė, J.F. Owens, E. Reya, N. Sato, A. Vogt and O. Zenaiev `DESY 16-041, to appear`

- *Iso-spin asymmetry of quark distributions and implications for single top-quark production at the LHC*
  S. Alekhin, J. Blümlein, S. M. and R. Plačakytė `arXiv:1508.07923`

- *Determination of Strange Sea Quark Distributions from Fixed-target and Collider Data*
  S. Alekhin, J. Blümlein, L. Caminada, K. Lipka, K. Lohwasser, S. M., R. Petti, and R. Plačakytė `arXiv:1404.6469`

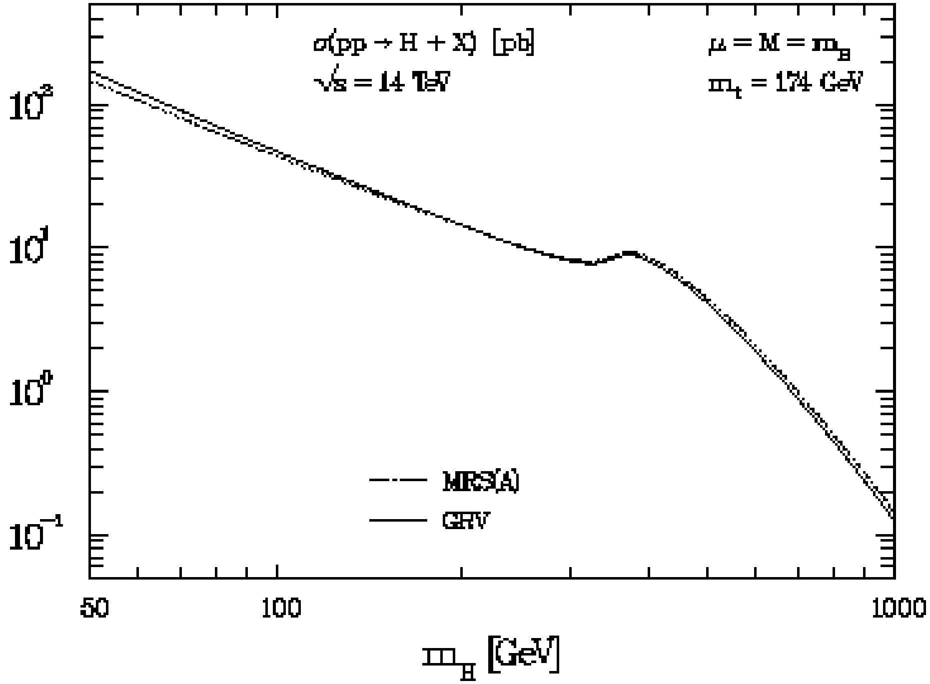
- *The ABM parton distributions tuned to LHC data*
  S. Alekhin, J. Blümlein and S. M. `arXiv:1310.3059`

- Many more papers of ABM and friends . . .
  `2008 - ...`

Higgs boson production

Higgs cross section (1995)

NLO QCD corrections



MRS(A): Martin, Roberts and Stirling, Phys. Rev. D50 (1994) 6734

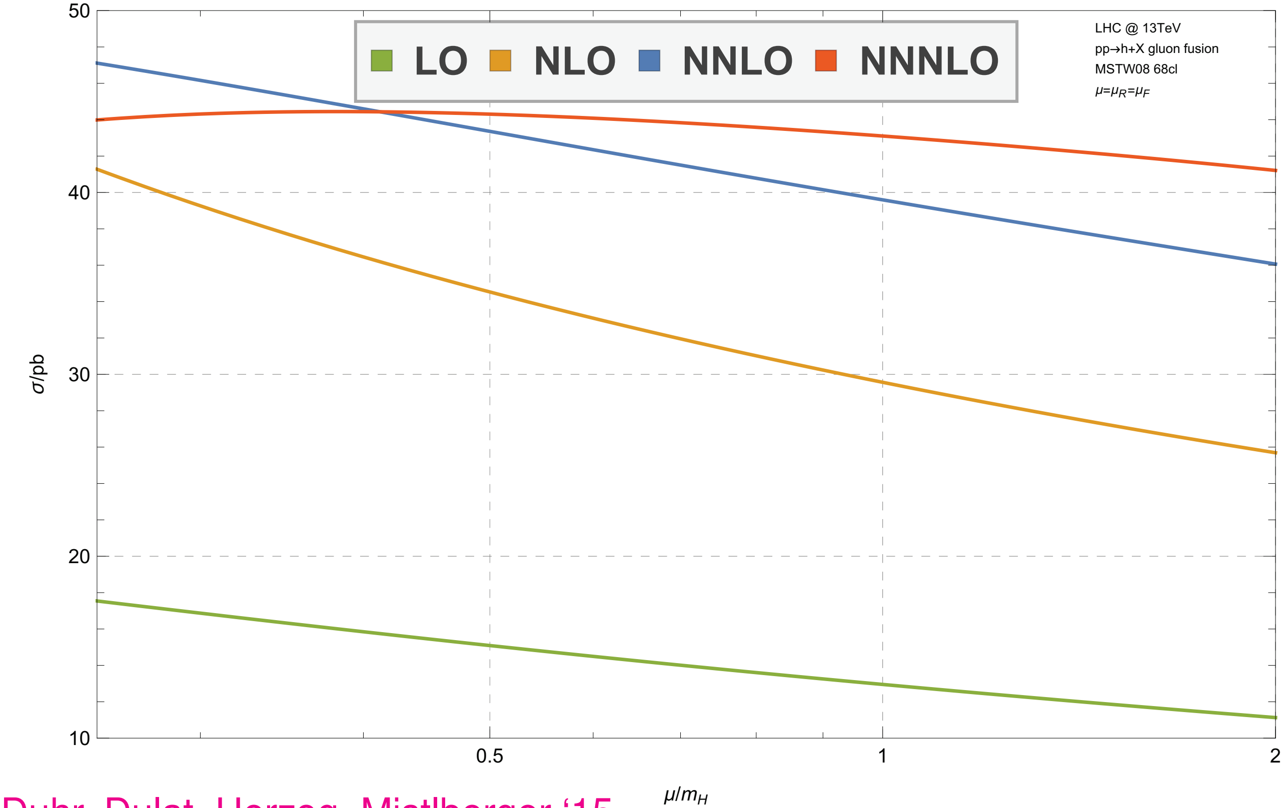
GRV: Glück, Reya and Vogt, Z. Phys. C53 (1992) 127

One of the main uncertainties *in the prediction of the Higgs production cross section is due to the* **gluon density***. [. . .] Adopting a set of representative parton distributions [. . .], we find a* **variation of about 7%** *between the maximum and minimum values of the cross section for Higgs masses above* $\sim$ *100 GeV.*

Spira, Djouadi, Graudenz, Zerwas (1995)
hep-ph/9504378

Higgs cross section (2016)

Exact N^{3}LO QCD corrections

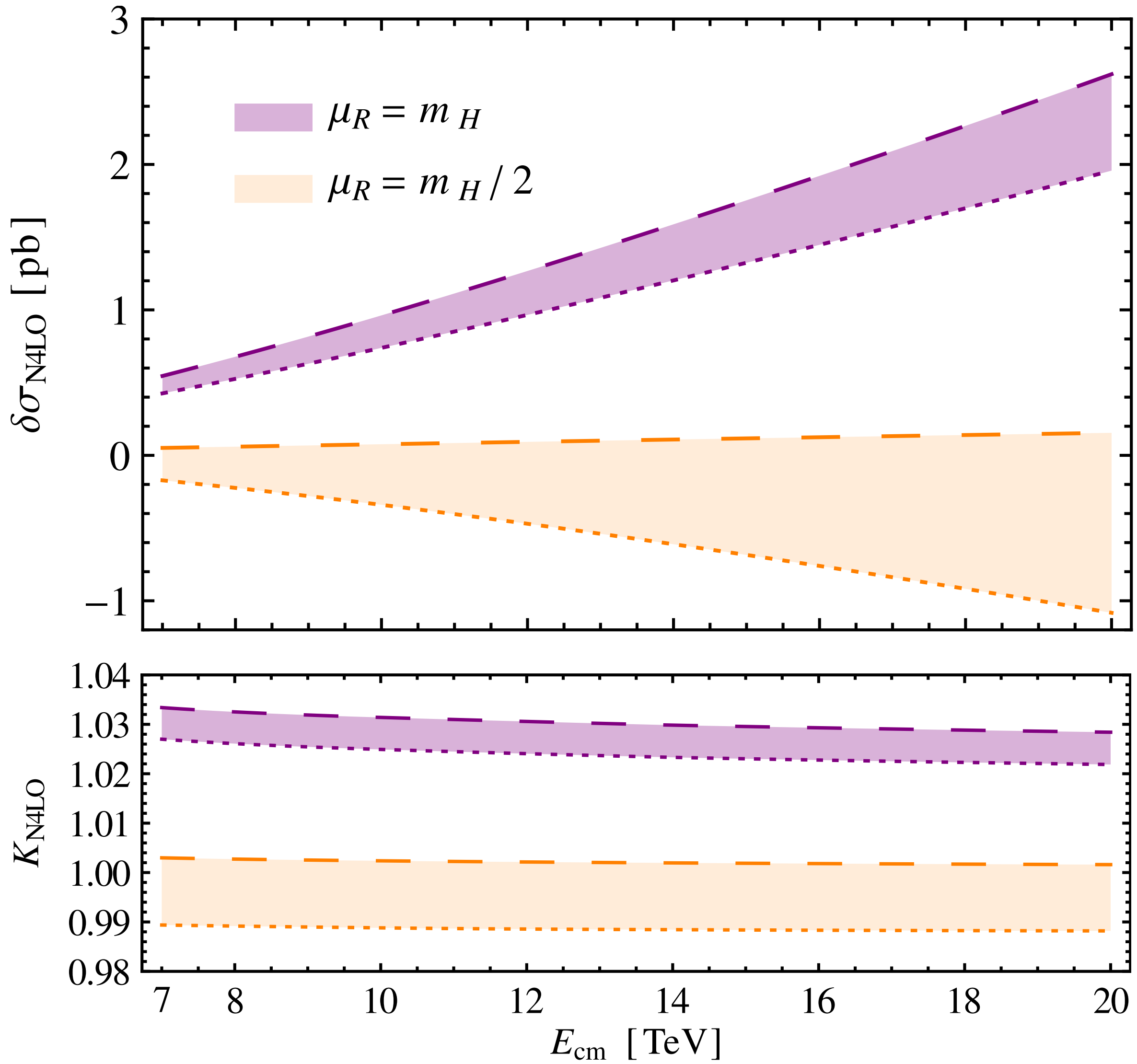


Anastasiou, Duhr, Dulat, Herzog, Mistlberger ‘15

- Apparent convergence of perturbative expansion
- Scale dependence of exact N^{3}LO prediction with residual uncertainty 3%
- Minimal sensitivity at scale $\mu = m_H/2$

Approximate N^{4}LO QCD corrections

- Consistency check with approximate N^{4}LO corrections at two scales $\mu = m_H$ and $\mu = m_H/2$
- K-factor $\simeq 1\%$ for $\mu = m_H/2$ with at $\sqrt{s} = 13$ TeV
  de Florian, Mazzitelli, S.M., Vogt '14



Dependence of cross section on parton luminosity

- Cross section $\sigma(H)$ at NNLO with uncertainties: $\sigma(H) + \Delta\sigma(\mathrm{PDF} + \alpha_\mathrm{s})$ for $m_H = 125.0$ GeV at $\sqrt{s} = 13$ TeV with $\mu_R = \mu_F = m_H$ and nominal α_s

ABM12 Alekhin, Blümlein, S.M. '13	39.80 ± 0.84 pb
CJ15 (NLO) Accardi, Brady, Melnitchouk et al. '16	$45.45\ {}^{+\,0.17}_{-\,0.11}$ pb
CT14 Dulat et al. '15	$42.33\ {}^{+\,1.43}_{-\,1.68}$ pb
HERAPDF2.0 H1+Zeus Coll.	$42.62\ {}^{+\,0.35}_{-\,0.43}$ pb
JR14 (dyn) Jimenez-Delgado, Reya '14	38.01 ± 0.34 pb
MMHT14 Martin, Motylinski, Harland-Lang, Thorne '14	$42.36\ {}^{+\,0.56}_{-\,0.78}$ pb
NNPDF3.0 Ball et al. '14	42.59 ± 0.80 pb
PDF4LHC15 Butterworth et al. '15	42.42 ± 0.78 pb

- Large spread for predictions from different PDFs $\sigma(H) = 38.0 \dots 42.6$ pb
- PDF and α_s differences between sets amount to up to 11%
  - significantly larger than residual theory uncertainty due to N^{3}LO QCD corrections

How to explain the differences ?

Strong coupling constant

Strong coupling constant (1992)

	$\alpha_s(\mathrm{M_Z^2})$
R_τ	$0.117\ {}^{+\ 0.010}_{-\ 0.016}$
DIS	0.112 ± 0.007
Υ Decays	0.110 ± 0.010
$R_{e^+e^-}(s < 62\text{GeV})$	0.140 ± 0.020
$p\bar{p} \to W + jets$	0.121 ± 0.024
$\Gamma(Z \to \text{hadrons})/\Gamma(Z \to l\bar{l})$	0.132 ± 0.012
Jets at LEP	0.122 ± 0.009
Average	0.118 ± 0.007

G. Altarelli (1992)
in *QCD - 20 Years Later,*
CERN-TH-6623-92

Essential facts

- World average 1992 $\alpha_s(M_Z) = 0.118 \pm 0.007$
- Central value at NLO QCD
  - still right, but for very different reasons
- Error at NLO QCD
  - now down to $\sim 0.0050 - 0.0040$ (theory scale uncertainty)

Strong coupling constant (2016)

Measurements at NNLO

- Values of $\alpha_s(M_Z)$ at NNLO from PDF fits

SY	0.1166 ± 0.013	F_2^{ep}	Santiago, Yndurain '01
	0.1153 ± 0.063	$xF_3^{\nu N}$ (heavy nucl.)	
A02	0.1143 ± 0.013	DIS	Alekhin '01
MRST03	0.1153 ± 0.0020		Martin, Roberts, Stirling, Thorne '03
BBG	$0.1134\,^{+\,0.0019}_{-\,0.0021}$	valence analysis, NNLO	Blümlein, Böttcher, Guffanti '06
GRS	0.112	valence analysis, NNLO	Glück, Reya, Schuck '06
A06	0.1128 ± 0.015		Alekhin '06
JR08	0.1128 ± 0.0010	dynamical approach	Jimenez-Delgado, Reya '08
	0.1162 ± 0.0006	including NLO jets	
ABKM09	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$	Alekhin, Blümlein, Klein, S.M. '09
	0.1129 ± 0.0014	HQ: BSMN	
MSTW	0.1171 ± 0.0014		Martin, Stirling, Thorne, Watt '09
Thorne	0.1136	[DIS+DY, HT*] (2013)	Thorne '13
$\mathrm{ABM11}_J$	$0.1134 \ldots 0.1149 \ \pm 0.0012$	Tevatron jets (NLO) incl.	Alekhin, Blümlein, S.M. '11
NN21	0.1173 ± 0.0007	(+ heavy nucl.)	NNPDF '11
ABM12	0.1133 ± 0.0011		Alekhin, Blümlein, S.M. '13
	0.1132 ± 0.0011	(without jets)	
CT10	0.1140	(without jets)	Gao et al. '13
CT14	$0.1150\,^{+\,0.0060}_{-\,0.0040}$	$\Delta\chi^2 > 1$ (+ heavy nucl.)	Dulat et al. '15
MMHT	0.1172 ± 0.0013	(+ heavy nucl.)	Martin, Motylinski, Harland-Lang, Thorne '15

Strong coupling constant (2016)

Other measurements of α_s at NNLO

- Values of $\alpha_s(M_Z)$ at NNLO from measurements at colliders

3-jet rate	0.1175 ± 0.0025	Dissertori et al. 2009	arXiv:0910.4283
e^+e^- thrust	$0.1131 {}^{+\,0.0028}_{-\,0.0022}$	Gehrmann et al.	arXiv:1210.6945
e^+e^- thrust	0.1140 ± 0.0015	Abbate et al.	arXiv:1204.5746
C-parameter	0.1123 ± 0.0013	Hoang et al.	arXiv:1501.04111
CMS	0.1151 ± 0.0033	$t\bar{t}$	arXiv:1307.1907
NLO Jets ATLAS	$0.111 {}^{+\,0.0017}_{-\,0.0007}$		arXiv:1312.5694
NLO Jets CMS	0.1148 ± 0.0055		arXiv:1312.5694

$\alpha_s(M_Z)$ in Higgs cross sections

PDF sets	$\alpha_s(M_Z)$	method of determination
ABM12 Alekhin, Blümlein, S.M. '13	0.1132 ± 0.0011	fit at NNLO
CJ15 Accardi, Brady, Melnitchouk et al. '16	0.118 ± 0.002	fit at NLO
CT14 Dulat et al. '15	0.118	assumed at NNLO
HERAPDF2.0 H1+Zeus Coll.	$0.1183\ ^{+0.0040}_{-0.0034}$	fit at NLO
JR14 Jimenez-Delgado, Reya '14	0.1136 ± 0.0004	dynamical fit at NNLO
	0.1162 ± 0.0006	standard fit at NNLO
MMHT14 Martin, Motylinski, Harland-Lang, Thorne '14	0.118	assumed at NNLO
	0.1172 ± 0.0013	best fit at NNLO
NNPDF3.0 Ball et al. '14	0.118	assumed at NNLO
PDF4LHC15 Butterworth et al. '15	0.118	assumed at NLO
	0.118	assumed at NNLO

- Values of $\alpha_s(M_Z)$ often assumed and not fitted (no correlations)
- Large spread of fitted values at NNLO: $\alpha_s(M_Z) = 0.1132 \ldots 0.1172$
- PDF4LHC: order independent recommendation
  - use $\alpha_s(M_Z) = 0.118$ at NLO and NNLO

Differences in α_s determinations

Why α_s values from MSTW and NNPDF are large

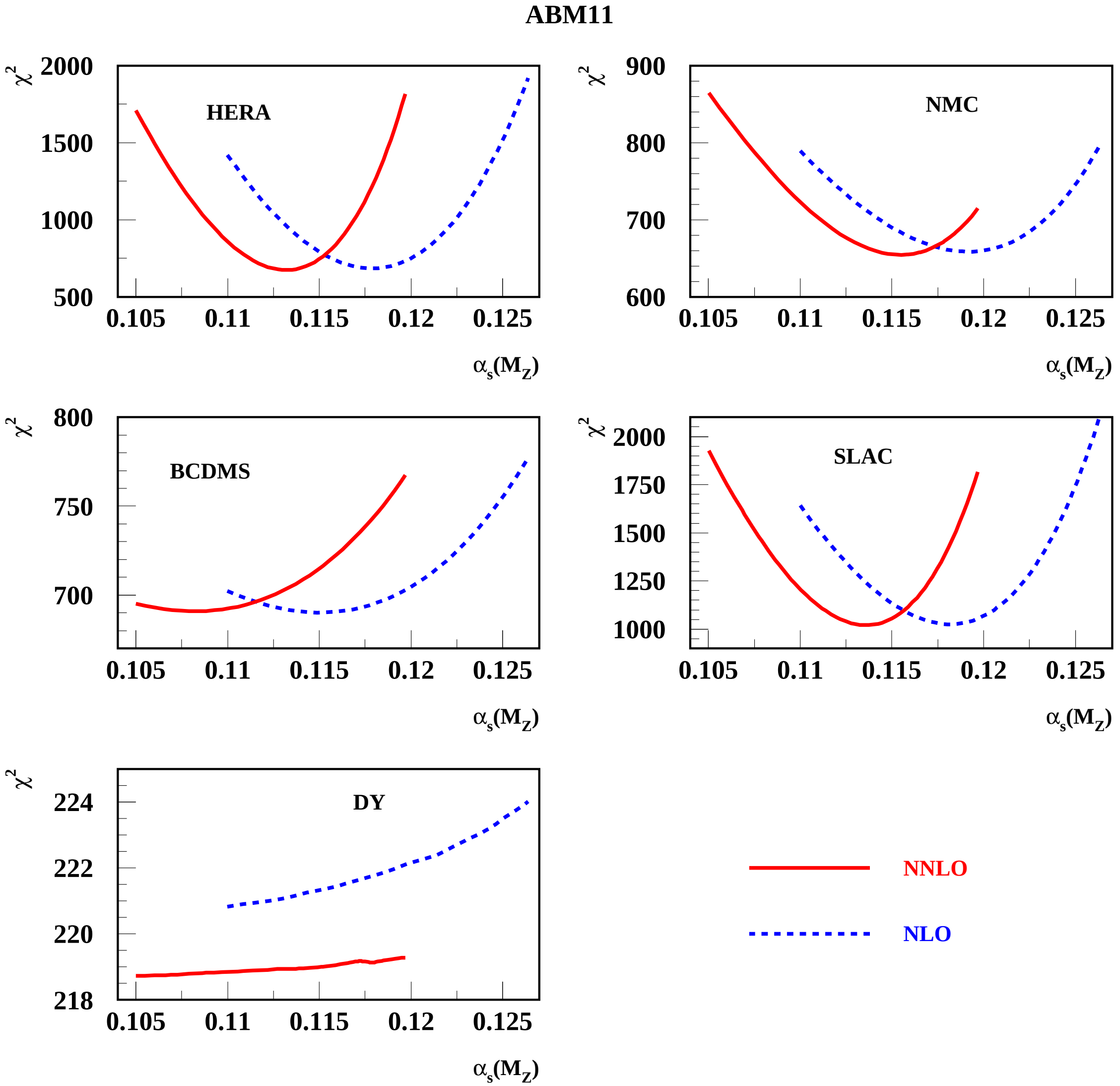
- Differences result from different physics models and analysis procedures
- Fits of DIS data
  - target mass corrections (powers of nucleon mass M_N^2/Q^2)
  - higher twist $F_2^{\rm ht} = F_2 + ht^{(4)}(x)/Q^2 + ht^{(6)}(x)/Q^4 + \dots$
  - correlation of errors among different data sets

	α_s	NNLO	target mass corr.	higher twist	error correl.
ABM12	0.1132 ± 0.0011	**yes**	**yes**	**yes**	**yes**
NNPDF21	0.1173 ± 0.0007	**(yes)**	**yes**	**no**	**yes**
MSTW	0.1171 ± 0.0014	**(yes)**	**no**	**no**	**no**
MMHT	0.1172 ± 0.0013	**(yes)**	**no**	**no**	–

- Effects for differences are understood
  - variants of ABM with no higher twist etc. reproduce larger α_s values
    Alekhin, Blümlein, S.M. '11

Zooming in on ABM

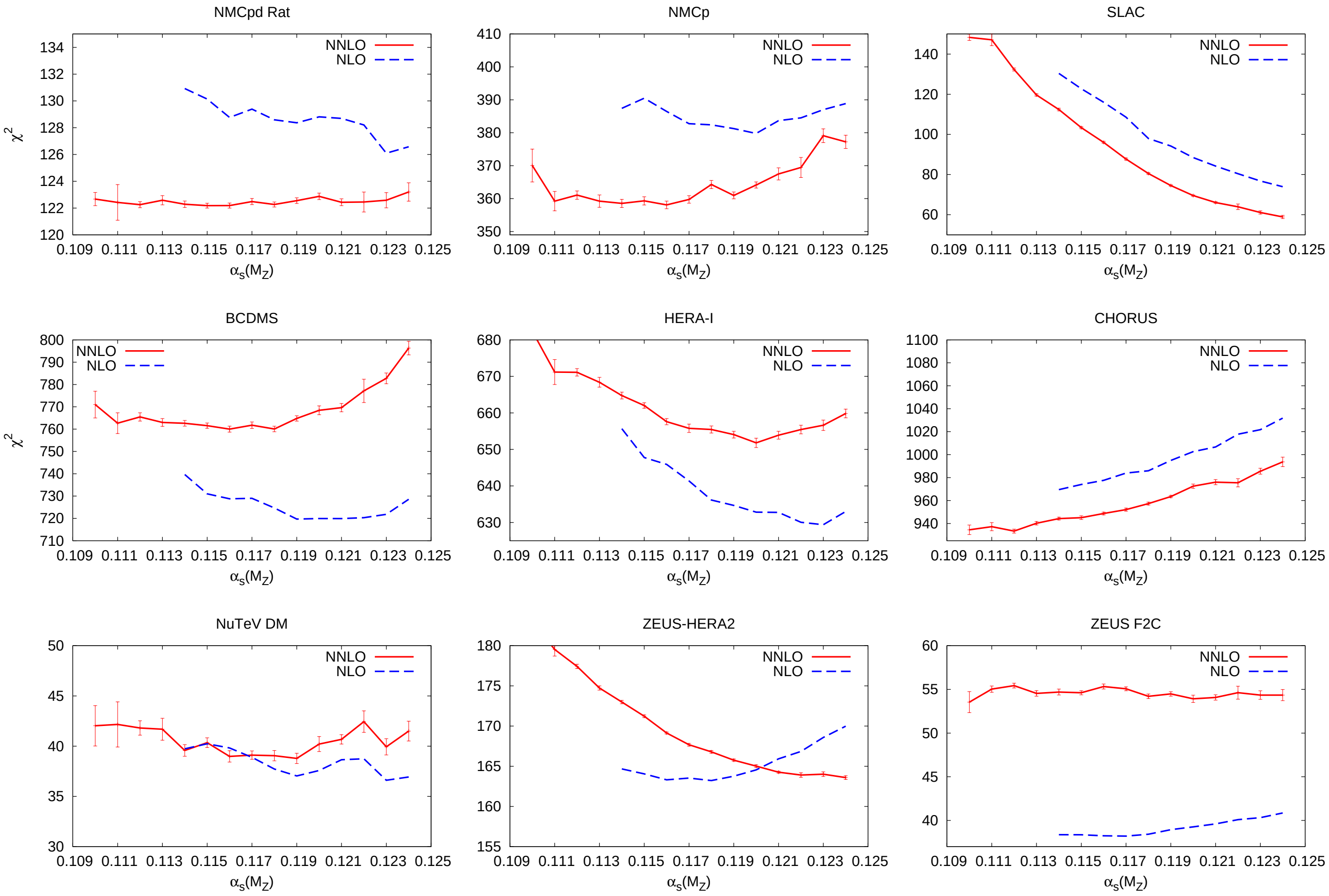
α_s from DIS and PDFs



- Profile of χ^2 for different data sets in ABM11 PDF fit Alekhin, Blümlein, S.M. '12

Zooming in on NNPDF

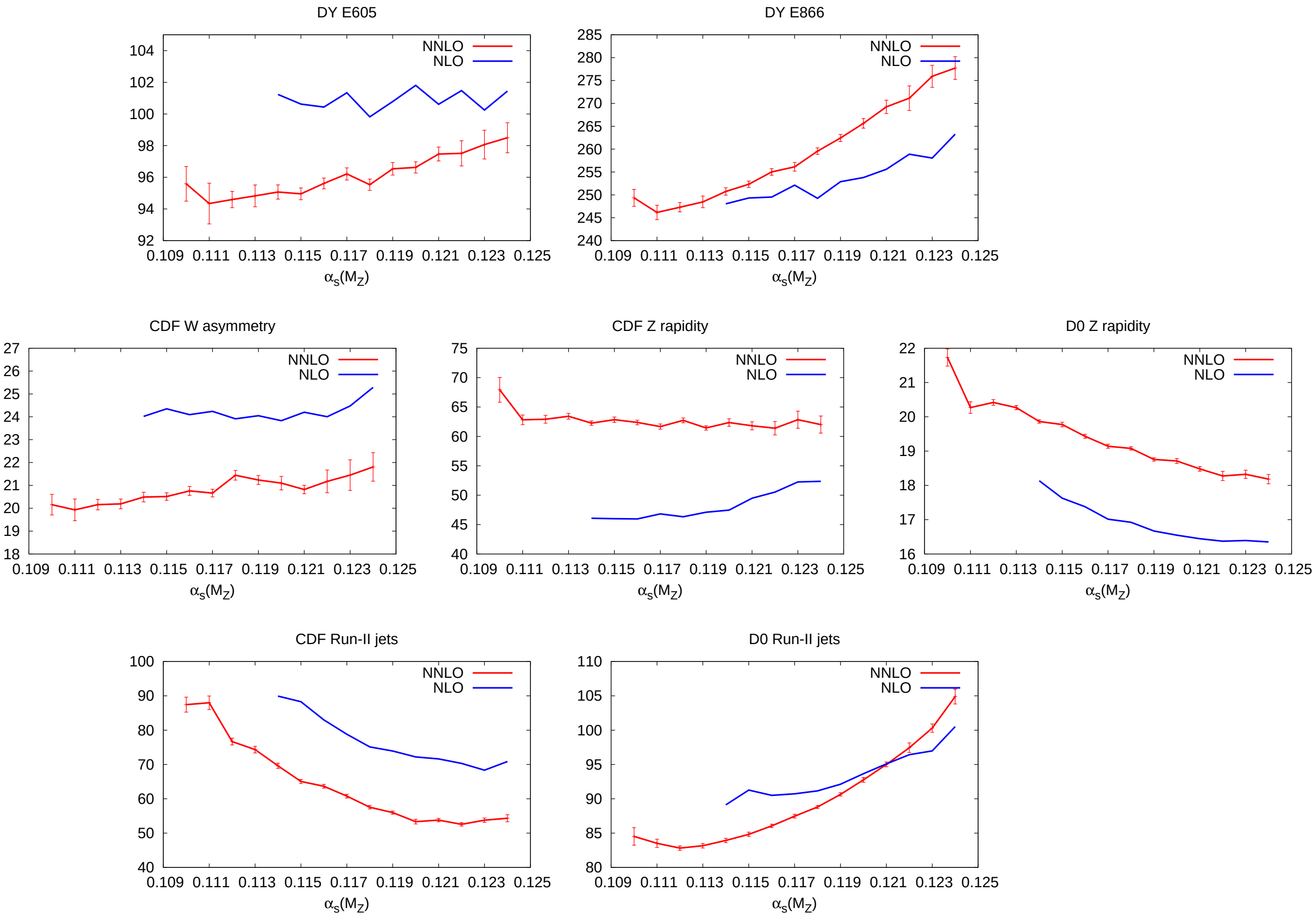
α_s *from DIS and PDFs*



- Profile of χ^2 for different data sets in NNPDF21 fit Ball et al. '11

Zooming in on NNPDF

α_s *from DIS and PDFs*



- Profile of χ^2 for different data sets in NNPDF21 fit Ball et al. '11

Parton content of the proton

Data in global PDF fits

Data sets considered in ABM12 analysis

- Analysis of world data for deep-inelastic scattering and fixed-target data for Drell-Yan process
  - inclusive DIS data HERA, BCDMS, NMC, SLAC $(NDP = 2699)$
  - semi-inclusive DIS charm production data HERA $(NDP = 52)$
  - Drell-Yan data (fixed target) E-605, E-866 $(NDP = 158)$
  - neutrino-nucleon DIS (di-muon data) CCFR/NuTeV $(NDP = 178)$
  - LHC data for $W^{\pm}$- and Z-boson production ATLAS, CMS, LHCb $(NDP = 60)$

Iterative cycle of PDF fits

i) check of compatibility of new data set with available world data

ii) study of potential constraints due to addition of new data set to fit

iii) perform high precision measurement of the non-perturbative parameters

- parton distributions
- strong coupling $\alpha_s(M_Z)$
- heavy quark masses

ABM PDF ansatz

- PDFs parameterization at scale $\mu = 3\text{GeV}$ in scheme with $n_f = 3$
  Alekhin, Blümlein, S.M. '12
  - ansatz for valence-/sea-quarks, gluon with polynomial $P(x)$
  - strange quark is taken in charge-symmetric form
  - 24 parameters in polynomials $P(x)$
  - 4 additional fit parameters: $\alpha_s^{(n_f=3)}(\mu = 3$ GeV), m_c, m_b and deuteron correction
  - simultaneous fit of higher twist parameters (twist-4)

$$
\begin{aligned}
xq_v(x, Q_0^2) &= \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} x^{a_q}(1-x)^{b_q} x^{P_{qv}(x)} \\
xu_s(x, Q_0^2) = x\bar{u}_s(x, Q_0^2) &= A_{us} x^{a_{us}}(1-x)^{b_{us}} x^{a_{us}\, P_{us}(x)} \\
x\Delta(x, Q_0^2) = xd_s(x, Q_0^2) - xu_s(x, Q_0^2) &= A_\Delta x^{a_\Delta}(1-x)^{b_\Delta} x^{P_\Delta(x)} \\
xs(x, Q_0^2) = x\bar{s}(x, Q_0^2) &= A_s x^{a_s}(1-x)^{b_s}\,, \\
xg(x, Q_0^2) &= A_g x^{a_g}(1-x)^{b_g} x^{a_g\, P_g(x)}
\end{aligned}
$$

- Ansatz provides sufficient flexibility; no additional terms required to improve the quality of fit

Quality of fit

Statistical tests

- Goodness-of-fit estimator
  - χ^2 values compared to number of data points (typically a few thousand in global fit)

Covariance matrix

- Positive-definite covariance matrix
  - correlations for ABM11 PDF fit parameters (I)

    Alekhin, Blümlein, S.M. '12

	a_u	b_u	$\gamma_{1,u}$	$\gamma_{2,u}$	a_d	b_d	A_d	b_Δ	A_u	a_{us}	b_{us}	a_G	b_G
a_u	1.0000	0.9256	0.9638	-0.2527	0.3382	0.2922	0.1143	-0.4267	0.4706	0.3117	0.1422	0.0982	0.1127
b_u		1.0000	0.9574	-0.5608	0.1933	0.1200	0.1058	-0.3666	0.3712	0.2674	0.1537	0.0453	0.1878
$\gamma_{1,u}$			1.0000	-0.4504	0.2328	0.2329	0.0906	-0.3379	0.4106	0.2876	0.0812	0.0491	0.1627
$\gamma_{2,u}$				1.0000	0.3007	0.3119	-0.0242	-0.0118	0.0587	0.0026	-0.0305	0.0949	-0.1876
a_d					1.0000	0.8349	-0.2010	-0.3371	0.3786	0.2592	0.1212	-0.0377	0.1305
b_d						1.0000	-0.2669	-0.0599	0.2768	0.1941	-0.0698	-0.0926	0.2088
A_d							1.0000	-0.2132	0.0549	0.0245	0.2498	-0.0523	0.0614
b_Δ								1.0000	-0.1308	-0.0729	-0.7208	-0.0124	-0.0225
A_u									1.0000	0.9240	-0.0723	0.3649	-0.1674
a_{us}										1.0000	-0.0144	0.2520	-0.1095
b_{us}											1.0000	-0.1274	0.1808
a_G												1.0000	-0.6477
b_G													1.0000

Quality of fit

Statistical tests

- Goodness-of-fit estimator
  - χ^2 values compared to number of data points (typically a few thousand in global fit)

Covariance matrix

- Positive-definite covariance matrix
  - correlations for ABM11 PDF fit parameters (II)

    Alekhin, Blümlein, S.M. '12

	$\gamma_{1,G}$	$\alpha_s(3,3\text{ GeV})$	$\gamma_{1,\Delta}$	$\gamma_{1,us}$	$\gamma_{1,d}$	$\gamma_{2,d}$	A_s	b_s	a_s	a_Δ	m_c	m_b
a_u	-0.0727	-0.0611	0.3383	0.6154	0.2320	-0.0724	-0.0681	-0.0763	-0.0935	0.0026	0.0900	-0.0053
b_u	-0.1130	-0.1725	0.2992	0.4848	0.0849	0.0720	-0.0723	-0.0618	-0.0926	0.0049	0.0349	-0.0118
$\gamma_{1,u}$	-0.1106	-0.1338	0.2753	0.5638	0.1316	-0.0535	-0.0798	-0.0854	-0.1059	-0.0060	0.0817	0.0003
$\gamma_{2,u}$	0.1174	0.2195	-0.0210	0.0822	0.3712	-0.3310	0.0339	0.0143	0.0381	-0.0098	0.0430	-0.0004
a_d	-0.1631	-0.0208	0.0319	0.4974	0.9570	-0.4636	-0.0700	-0.0996	-0.0979	-0.2121	0.1066	-0.0150
b_d	-0.2198	-0.0913	-0.1775	0.4092	0.8985	-0.8498	-0.0533	-0.0669	-0.0806	-0.2252	0.0822	-0.0068
A_d	-0.0825	0.0188	0.8558	-0.0289	-0.2624	0.2852	-0.0075	-0.0189	-0.0180	0.9602	0.0420	0.0120
b_Δ	0.0530	-0.0801	-0.6666	-0.0904	-0.1981	-0.2532	-0.0022	0.0257	0.0048	-0.0260	-0.0166	-0.0056
A_u	0.2502	-0.0157	0.1265	0.7525	0.3047	-0.0668	-0.7064	-0.6670	-0.7267	0.0345	0.2137	0.0358
a_{us}	0.1845	-0.0216	0.0683	0.5714	0.2157	-0.0554	-0.8768	-0.8081	-0.8980	0.0145	0.0430	0.0074
b_{us}	-0.1619	-0.0715	0.5343	-0.3656	0.0293	0.2430	-0.0345	-0.0132	-0.0356	0.1527	-0.0899	-0.0058
a_G	0.8291	0.2306	-0.0260	0.3692	-0.0966	0.1496	0.0087	0.0007	0.0464	-0.0541	-0.0661	0.0417
b_G	-0.9184	-0.6145	0.0538	-0.2770	0.1990	-0.2552	0.0381	0.0616	-0.0468	0.0502	0.1847	0.0861

Quality of fit

Statistical tests

- Goodness-of-fit estimator
  - χ^2 values compared to number of data points (typically a few thousand in global fit)

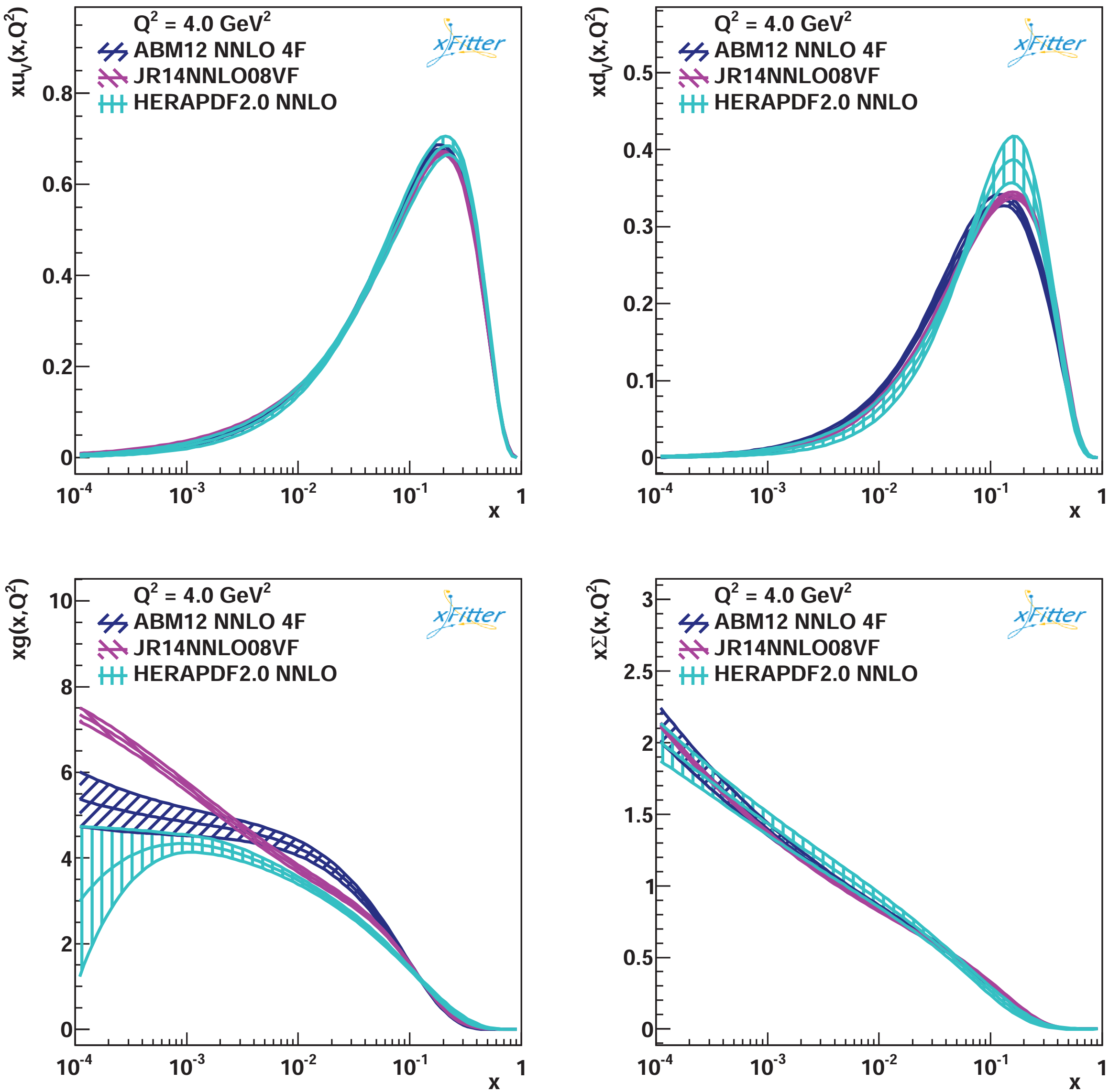
Covariance matrix

- Positive-definite covariance matrix
  - correlations for ABM11 PDF fit parameters (III)

    Alekhin, Blümlein, S.M. '12

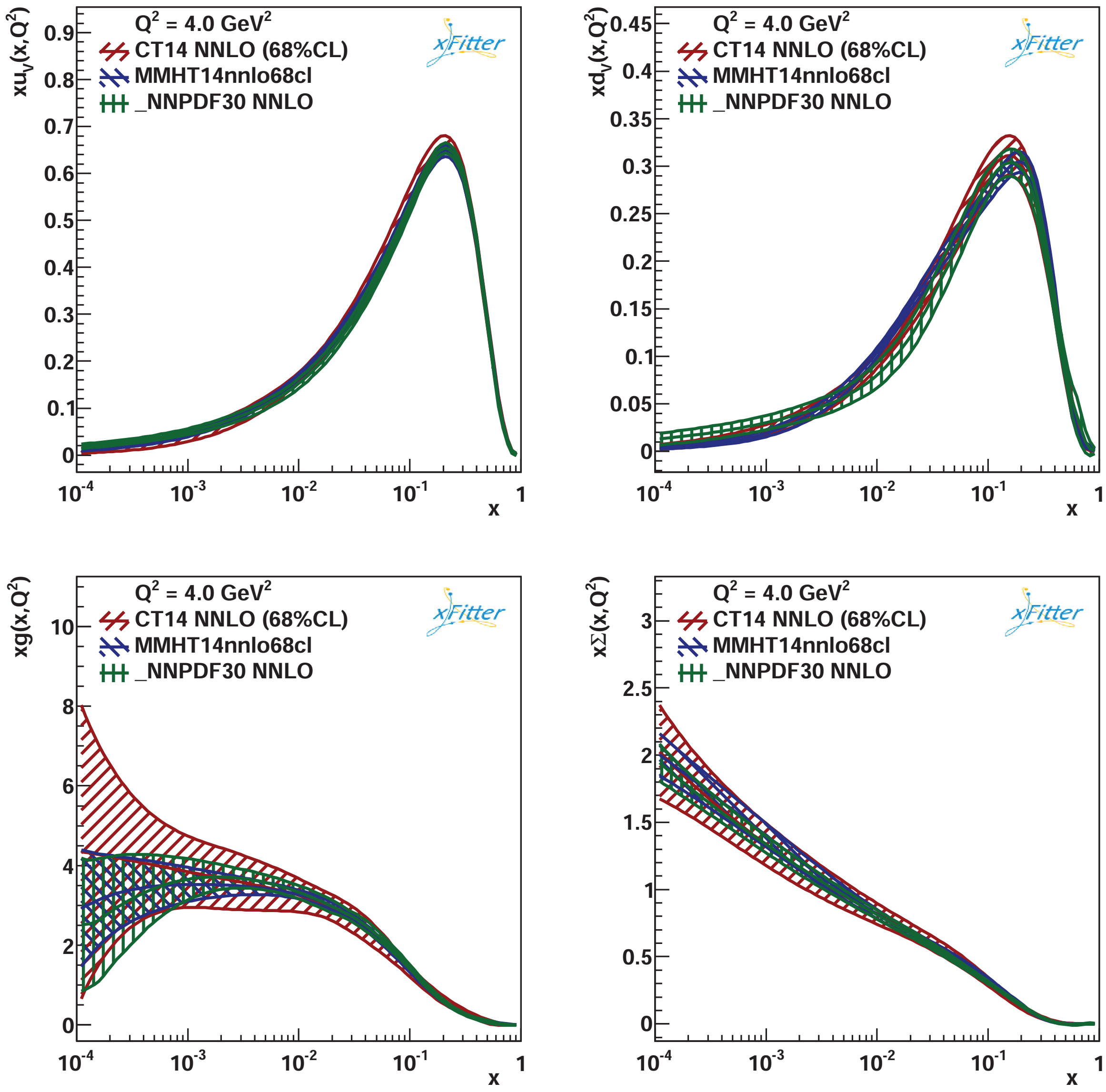
	$\gamma_{1,G}$	$\alpha_s(3,3\text{ GeV})$	$\gamma_{1,\Delta}$	$\gamma_{1,us}$	$\gamma_{1,d}$	$\gamma_{2,d}$	A_s	b_s	a_s	a_Δ	m_c	m_b
$\gamma_{1,G}$	1.0000	0.3546	-0.0876	0.2751	-0.2215	0.2410	-0.0539	-0.0634	0.0122	-0.0658	-0.1149	-0.0474
$\alpha_s(3,3\text{ GeV})$		1.0000	0.0601	0.1127	-0.0761	0.1534	-0.0176	-0.0121	0.0883	0.0022	-0.5641	-0.0526
$\gamma_{1,\Delta}$			1.0000	0.0699	-0.1081	0.3796	-0.0050	-0.0329	-0.0175	0.7098	0.0418	0.0113
$\gamma_{1,us}$				1.0000	0.4099	-0.1547	-0.2622	-0.3181	-0.2801	-0.0785	0.1870	0.0103
$\gamma_{1,d}$					1.0000	-0.6540	-0.0688	-0.0892	-0.0974	-0.2332	0.0999	-0.0093
$\gamma_{2,d}$						1.0000	0.0212	0.0128	0.0413	0.1876	-0.0396	-0.0049
A_s							1.0000	0.8584	0.9689	-0.0109	0.0596	0.0116
b_s								1.0000	0.8826	-0.0173	-0.0777	0.0003
a_s									1.0000	-0.0204	-0.0845	-0.0145
a_Δ										1.0000	0.0385	0.0085
m_c											1.0000	0.1451
m_b												1.0000

Results for parton distributions



- PDFs with 1σ uncertainty bands
- Comparison of ABM12, HERAPDF2.0, JR14
- Some interesting observations to be made . . .

Results for parton distributions



- PDFs with
  1σ uncertainty bands
- Comparison of
  CT14, MMHT14, NNPDF3.0
- Some interesting observations to be made
  . . .

Heavy quarks in deep-inelastic scattering

Treatment of heavy-quarks

Light quarks

- Neglect “light quark” masses $m_u, m_d \ll \Lambda_{QCD}$ and $m_s < \Lambda_{QCD}$ in hard scattering process
  - scale-dependent u, d, s, g PDFs from mass singularities

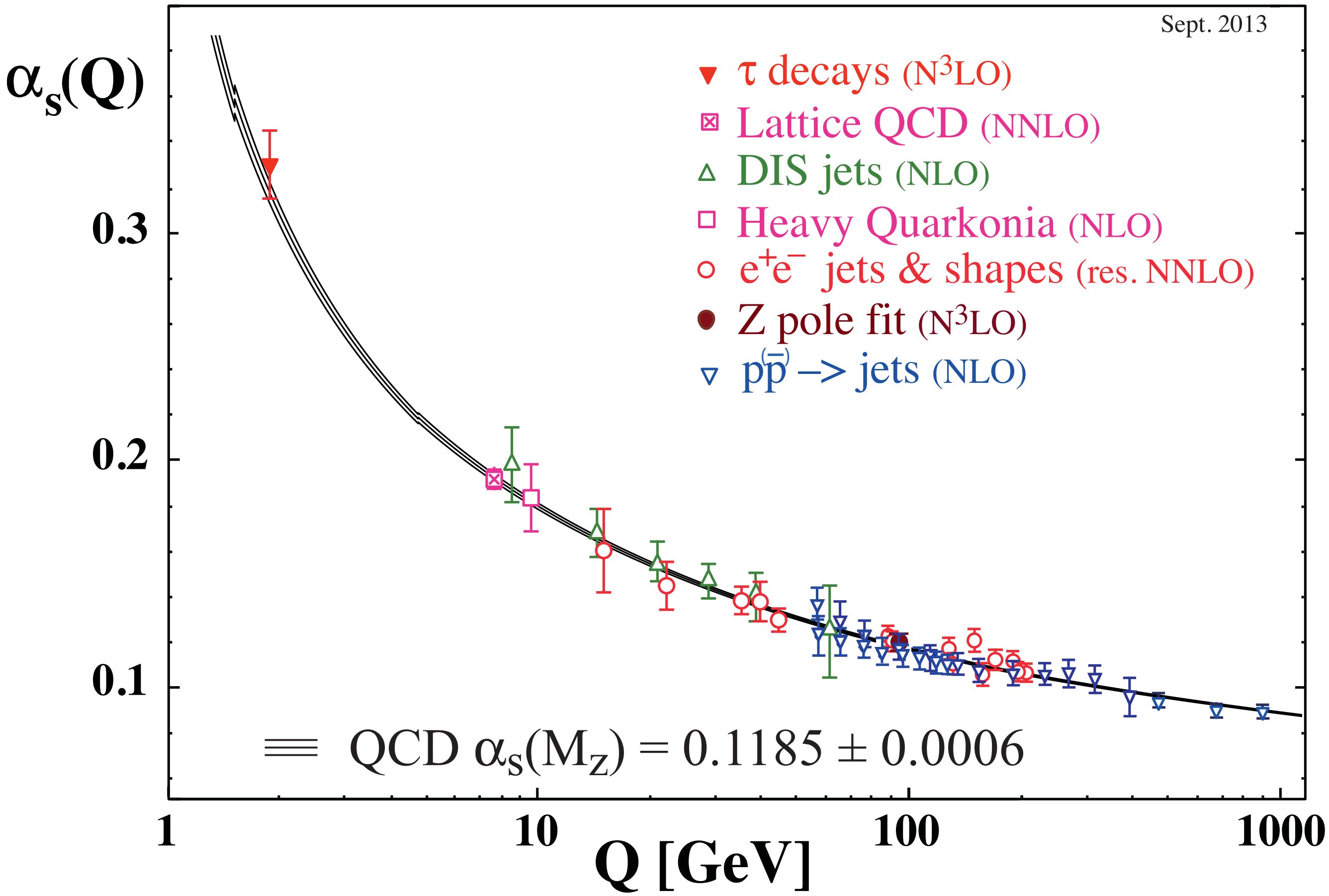
Heavy quarks

- No mass singularities for $m_c, m_b, m_t \gg \Lambda_{QCD}$, no (evolving) PDFs
  - c and b PDFs for $Q \ggg m_c, m_b$ generated perturbatively
  - matching of two distinct theories
    $\longrightarrow n_f$ light flavors + heavy quark of mass m at low scales
    $\longrightarrow n_f + 1$ light flavors at high scales

Strong coupling with flavor thresholds

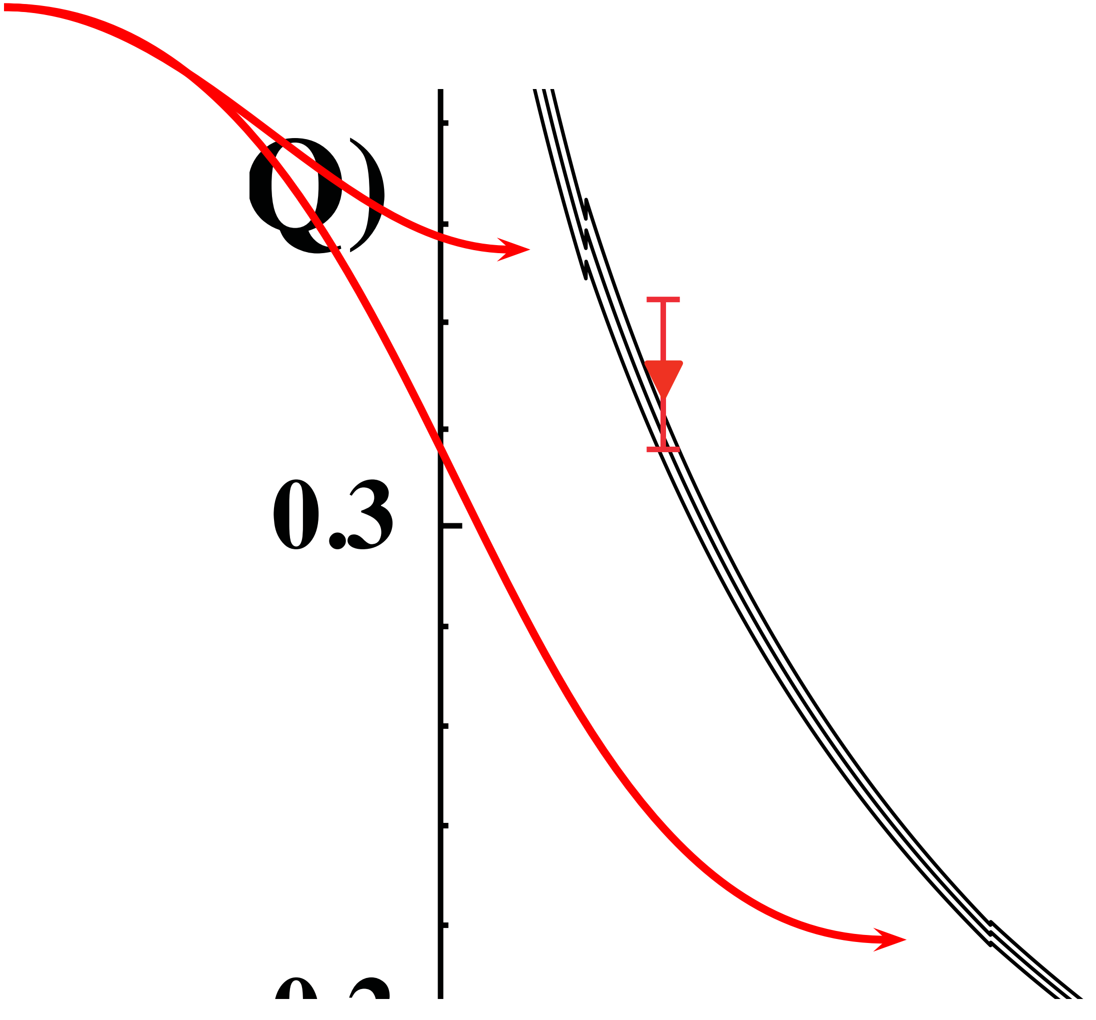
- Solution of QCD β-function for $\alpha_s^{n_l} \longrightarrow \alpha_s^{(n_l+n_h)}$
  - discontinuities for $n_f = 3 \rightarrow n_f = 4 \rightarrow n_f = 5$
- Big picture

Bethke for PDG 2014



Strong coupling with flavor thresholds

- Solution of QCD β-function for $\alpha_s^{n_l} \longrightarrow \alpha_s^{(n_l+n_h)}$
  - discontinuities for $n_f = 3 \to n_f = 4 \to n_f = 5$
- Zoom

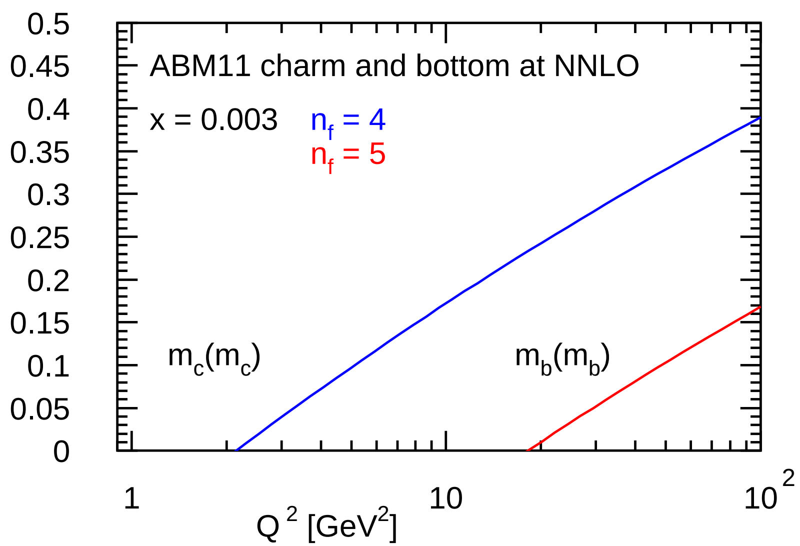


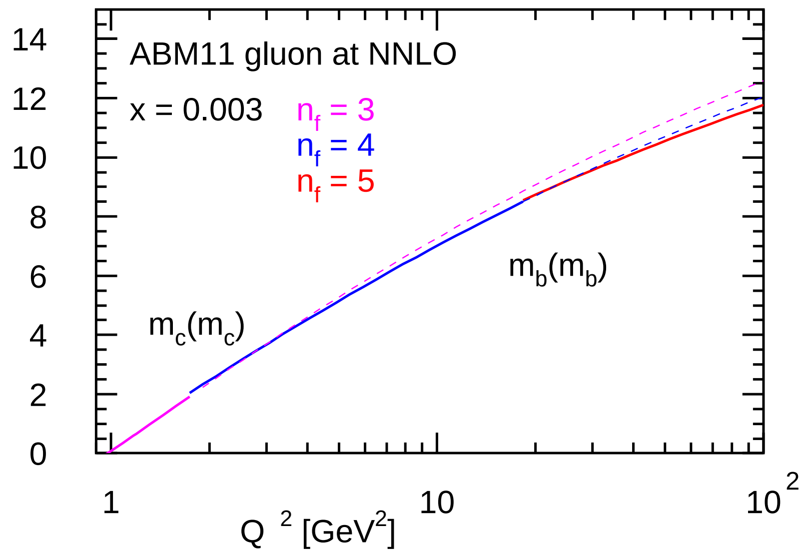
PDFs with flavor thresholds

- Generate heavy-quark PDFs $h^{(n_f+1)}$ from light-flavor PDFs
  - heavy-quark operator matrix elements (OMEs) A_{ji} at three loops
    Bierenbaum, Blümlein, Klein '09; Ablinger, Behring, Blümlein, De Freitas, von Manteuffel, Schneider '14

$$h^{(n_f+1)}(x,\mu) + \bar{h}^{(n_f+1)}(x,\mu) = A_{hq}(x) \otimes \Sigma^{(n_f)}(x,\mu) + A_{hq}(x) \otimes g^{(n_f)}(x,\mu)$$

  - likewise light-quark PDFs $l_i^{(n_f)} \to l_i^{(n_f+1)}$ and gluon and the quark singlet PDFs $(\Sigma^{(n_f)}, g^{(n_f)}) \to (\Sigma^{(n_f+1)}, g^{(n_f+1)})$
- Solution of evolution equations between thresholds for $n_f \longrightarrow (n_f+1)$ with fixed $n_f = 3 \to n_f = 4 \to n_f = 5$





Cross sections with flavor thresholds

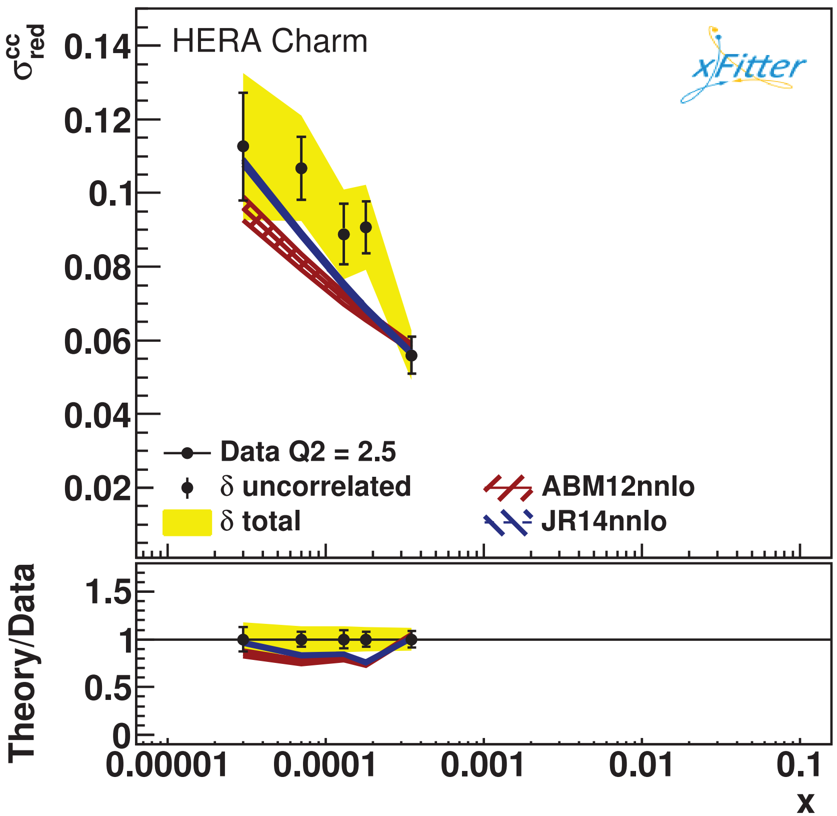
Fixed flavor number scheme (FFNS) (“do nothing”)

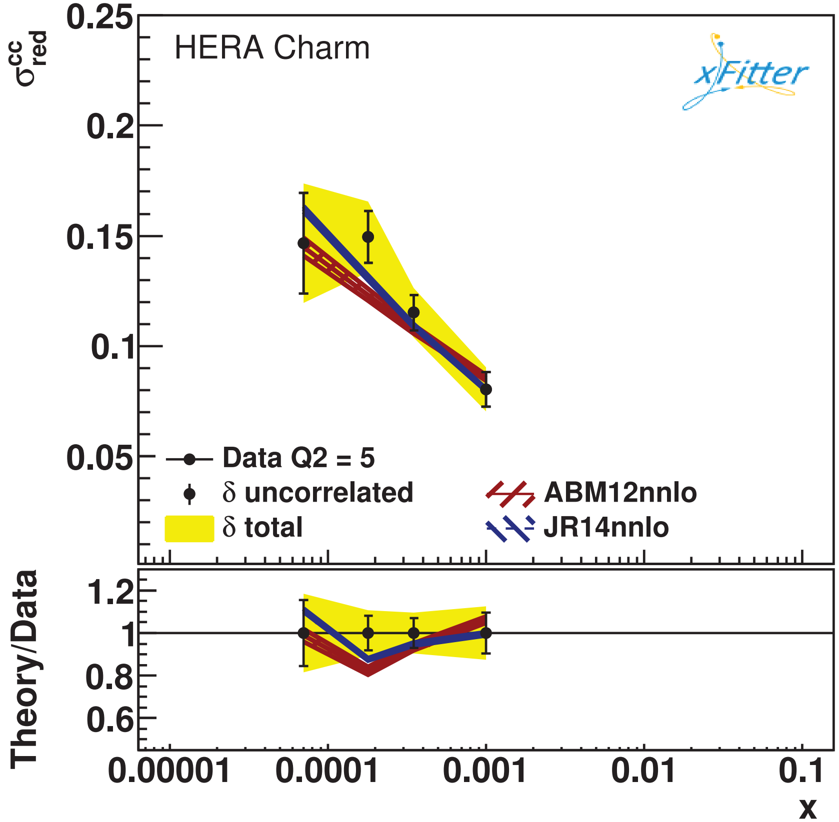
- Cross section with massive quarks at scales $Q \not\gg m_c$
  - top-quark hadro-production ($t\bar{t}$ pairs, single top in 4FS or 5FS, . . .]
- F_2^c at HERA with u, d, s, g partons and massive charm coeff. fcts.
  - complete NLO predictions Laenen, Riemersma, Smith, van Neerven ‘92
  - approximations at NNLO Bierenbaum, Blümlein, Klein ‘09; Lo Presti, Kawamura, S.M., Vogt ‘12; Behring, Bierenbaum, Blümlein, De Freitas, Klein, Wissbrock ‘14

Variable flavor number scheme (VFNS) (“match something”)

- (Smooth) matching of two distinct theories:
  n_f light + heavy quark at low scales $\longrightarrow n_f + 1$ light flavors at high scales
  - Higgs boson production in $b\bar{b}$-annihilation (“Santander matching” Harlander, Krämer, Schumacher ‘11)
- F_2^c at HERA with ACOT Aivazis, Collins, Olness, Tung ‘94, BMSN Buza, Matiounine, Smith, van Neerven ‘98, RT Thorne, Roberts ‘98, FONNL Forte, Laenen, Nason, Rojo ‘10
  - model assumptions in matching conditions
  - details of implementation matter in global fits

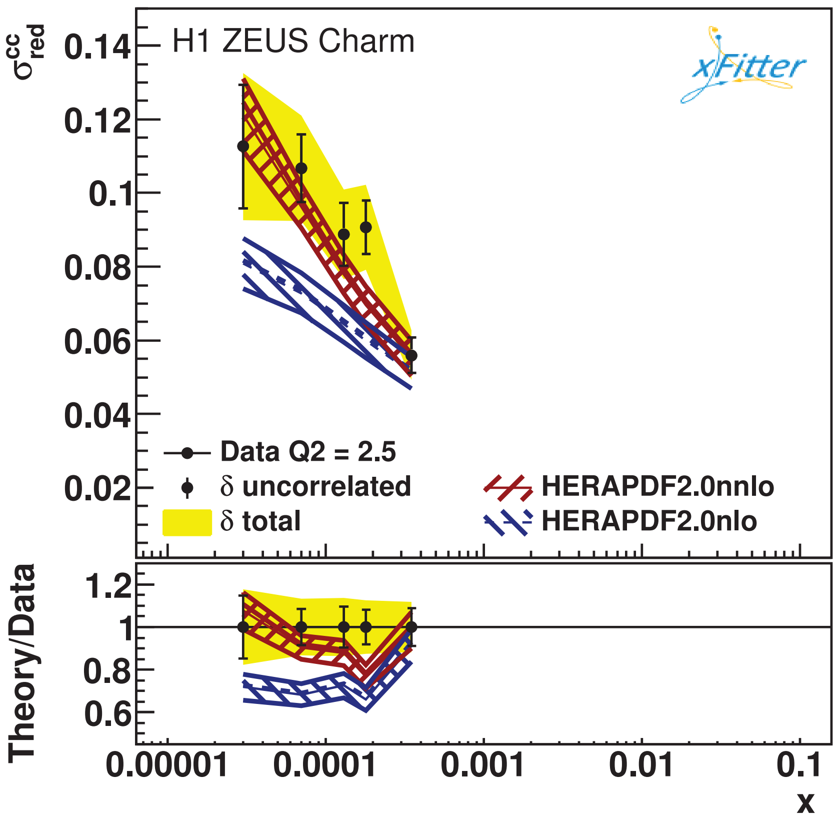
Comparision to data

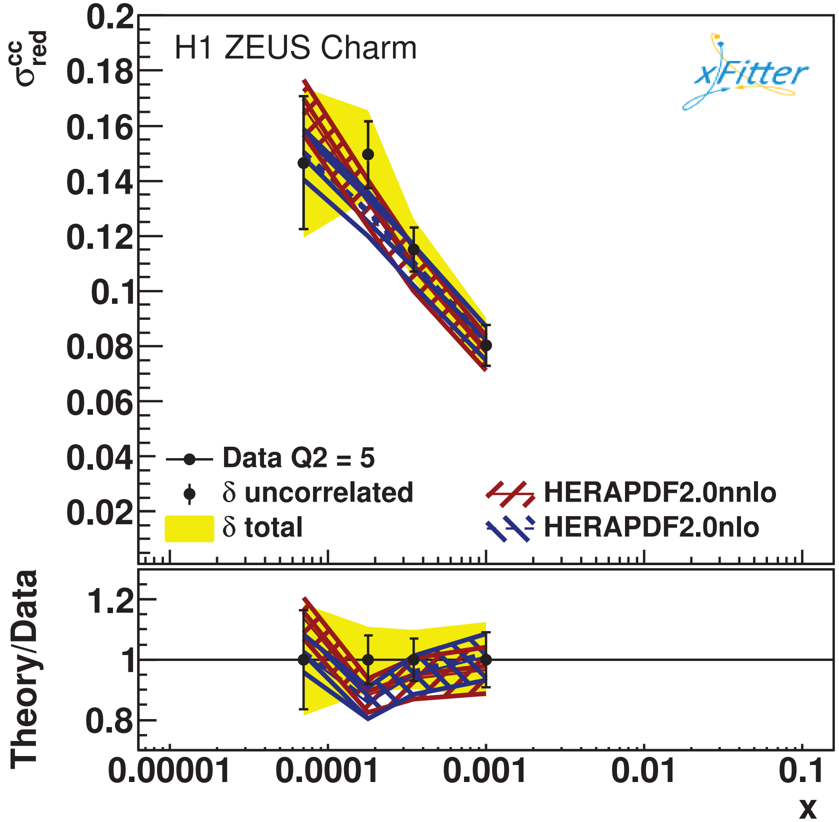




- Comparision of theory predictions for the DIS pair-production of charm quarks to the combined HERA data H1 & ZEUS coll. arXiv:1211.1182
  - ABM12 and JR14 using FFNS scheme

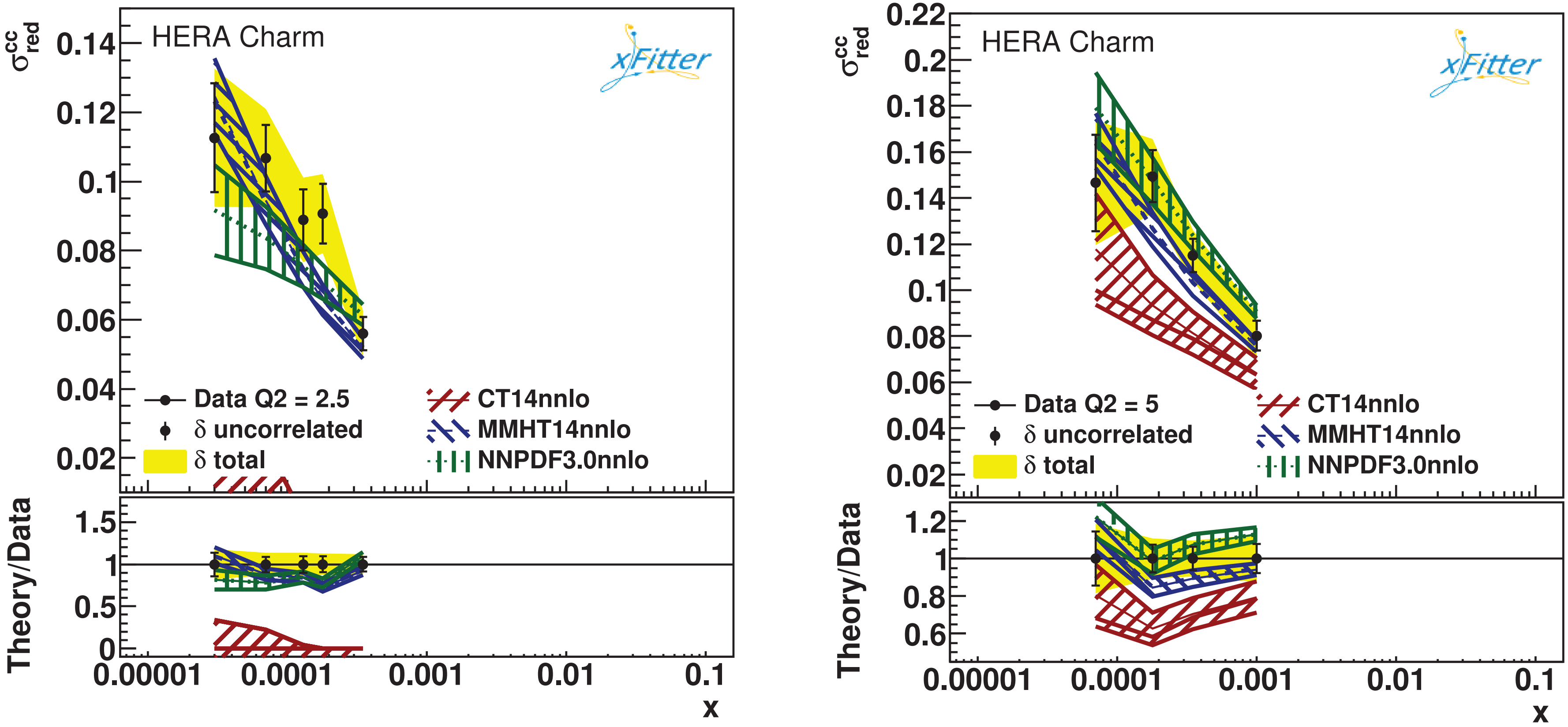
Comparision to data





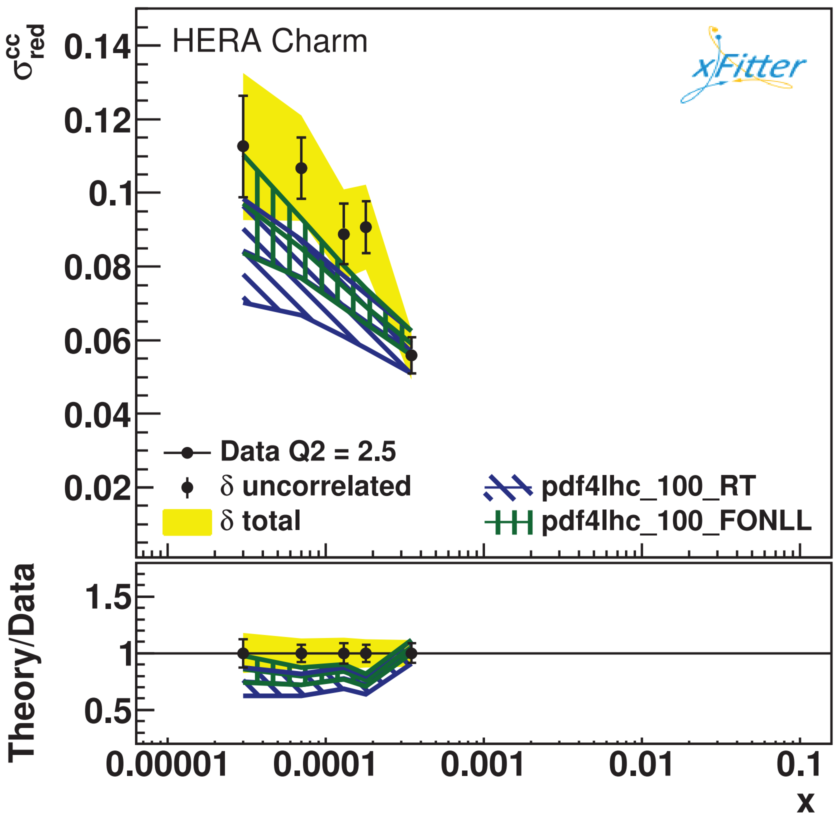
- Comparision of theory predictions for the DIS pair-production of charm quarks to the combined HERA data H1 & ZEUS coll. arXiv:1211.1182
  - HERAPDF2.0 using the RT optimal GM-VFNS scheme

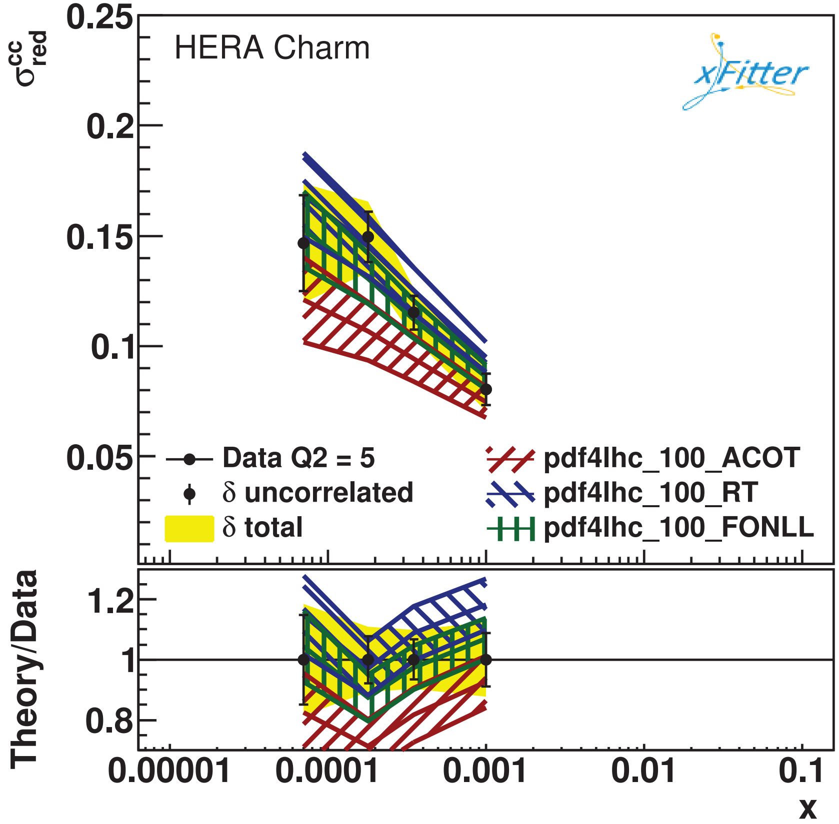
Comparision to data



- Comparision of theory predictions for the DIS pair-production of charm quarks to the combined HERA data H1 & ZEUS coll. arXiv:1211.1182
  - CT14, MMHT14 and NNPDF3.0 using FFNS scheme

Comparision to data





- Comparision of theory predictions for the DIS pair-production of charm quarks to the combined HERA data H1 & ZEUS coll. arXiv:1211.1182
  - ABM12 and JR14 using FFNS scheme

Charm quark mass in PDF fits

	m_c (GeV)	m_c scheme	χ^2/NDP (HERA data)	F_2^c scheme	NNLO Wilson coeff.
ABM12 arXiv:1310.3059	$1.24 \begin{smallmatrix} +\ 0.05 \\ -\ 0.03 \end{smallmatrix}$	$m^{\overline{MS}}$	65/52	FFNS($n_f = 3$)	**yes**
CT14 arXiv:1506.07443	1.3 (assumed)	$m^{\rm pole}$	582/52 (64/47)	S-ACOT-χ	**no**
MMHT arXiv:1510.02332	1.25	$m^{\rm pole}$	75/52	RT optimal	**no**
NNPDF3.0 arXiv:1410.8849	1.275 (assumed)	$m^{\rm pole}$	67/52	FONLL-C	**no**
PDF4LHC15 arXiv:1510.03865	-	-	58/52	FONLL-B	-
	-	-	71/52	RT optimal	-
	-	-	51/47	S-ACOT-χ	-

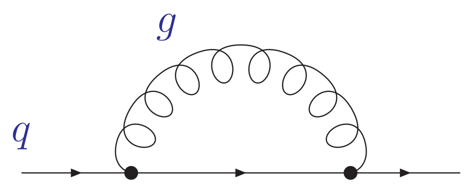
- PDG quotes running masses:
  charm: $m_c(m_c) = 1.27^{+0.07}_{-0.11}$ GeV, bottom: $m_b(m_b) = 4.20^{+0.17}_{-0.07}$ GeV
- Values of charm-quark pole mass for CT14, MMHT14 and NNPDF3.0 not compatible with world average of PDG

Quark mass renormalization

Pole mass

- Based on (unphysical) concept of heavy-quark being a free parton

$$\not{p} - m_q - \Sigma(p, m_q)\Big|_{p^2=m_q^2}$$



  - heavy-quark self-energy $\Sigma(p, m_q)$ receives contributions from regions of all loop momenta – also from momenta of $\mathcal{O}(\Lambda_{QCD})$
- Renormalon ambiguity in definition of pole mass of $\mathcal{O}(\Lambda_{QCD})$
  Bigi, Shifman, Uraltsev, Vainshtein '94; Beneke, Braun '94; Smith, Willenbrock '97

$\overline{MS}$ *mass*

- Free of infrared renormalon ambiguity
- Conversion between $m_{\rm pole}$ and $\overline{MS}$ mass $m(\mu_R)$ in perturbation theory known to four loops in QCD Marquard, Smirnov, Smirnov, Steinhauser '15
  - does not converge in case of charm quark

$$\begin{aligned} m_c(m_c) = 1.27\ \text{GeV} &\longrightarrow m_c^{\rm pole} = 1.47\ \text{GeV (one loop)} \\ &\longrightarrow m_c^{\rm pole} = 1.67\ \text{GeV (two loops)} \\ &\longrightarrow m_c^{\rm pole} = 1.93\ \text{GeV (three loops)} \\ &\longrightarrow m_c^{\rm pole} = 2.39\ \text{GeV (four loops)} \end{aligned}$$

Charm quark mass and the Higgs cross section

MMHT14

- "Tuning" Charm mass m_c parameter effects the Higgs cross section
  - linear rise in $\sigma(H) = 40.5 \ldots 42.6$ pb for $m_c = 1.15 \ldots 1.55$ GeV with MMHT14 PDFs Martin, Motylinski, Harland-Lang, Thorne '15

m_c^{pole} [GeV]	$\alpha_s(M_Z)$ (best fit)	χ^2/NDP (HERA data on $\sigma^{c\bar{c}}$)	$\sigma(H)^{\mathrm{NNLO}}$ [pb] best fit $\alpha_s(M_Z)$	$\sigma(H)^{\mathrm{NNLO}}$ [pb] $\alpha_s(M_Z) = 0.118$
1.15	0.1164	78/52	40.48	(42.05)
1.2	0.1166	76/52	40.74	(42.11)
1.25	0.1167	**75/52**	**40.89**	(42.17)
1.3	0.1169	76/52	41.16	(42.25)
1.35	0.1171	78/52	41.41	(42.30)
1.4	0.1172	**82/52**	41.56	**(42.36)**
1.45	0.1173	88/52	41.75	(42.45)
1.5	0.1173	96/52	41.81	(42.51)
1.55	0.1175	105/52	42.08	(42.58)

Charm quark mass and the Higgs cross section

NNPDF

- Same trend: lighter charm mass implies smaller Higgs cross section
  - fit range for m_c too small and no correlation with value of $\alpha_s(M_Z)$
  - best fits with NNPDF2.1 and NNPDF30 give range $\sigma(H) = 42.6 \ldots 44.2$ pb

PDF sets	m_c^{pole} [GeV]	$\alpha_s(M_Z)$ (fixed)	χ^2/NDP (HERA data on $\sigma^{c\bar{c}}$)	$\sigma(H)^{\text{NNLO}}$ [pb] fixed $\alpha_s(M_Z)$
NNPDF2.1 [arXiv:1107.2652]	$\sqrt{2}$	0.119	**65/52**	44.18 ± 0.49
	1.5	0.119	78/52	44.54 ± 0.51
	1.6	0.119	92/52	44.74 ± 0.50
	1.7	0.119	110/52	44.95 ± 0.51
NNPDF2.3 [arXiv:1207.1303]	$\sqrt{2}$	0.118	71/52	43.77 ± 0.41
NNPDF3.0 [arXiv:1410.8849]	1.275	0.118	**67/52**	42.59 ± 0.80

Summary

Parton distributions at the LHC

- Precision determinations of non-perturbative parameters is essential
  - parton content of proton (PDFs), strong coupling constant $\alpha_s(M_Z)$, quark masses m_c, m_b, m_t
- Experimental precision of $\lesssim 1\%$ makes theoretical predictions at NNLO in QCD mandatory

Higgs cross section

- Strong coupling constant $\alpha_s(M_Z)$
  - fixed value of $\alpha_s(M_Z)$ lacks correlation with parameters of PDF fits
  - $\alpha_s(M_Z) = 0.118$ at NNLO not preferred by data
- Uncertainties due model assumption in PDF fits neglected
  - implementations of variable flavor number schemes use charm-quark mass m_c to tune cross section
  - low value of pole mass $m_c^{\mathrm{pole}} \simeq 1.25$GeV in contradiction to world average