Precise parton distributions for the LHC in Run II

Sven-Olaf Moch

Universität Hamburg

KITP workshop *LHC Run II and the Precision Frontier*, Santa Barbara, May 11, 2016

Based on work done in collaboration with:

- *Recommendations for PDF usage in LHC predictions*
  A. Accardi, S. Alekhin, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. M., J.F. Owens, R. Plačakytė, E. Reya, N. Sato, A. Vogt and O. Zenaiev `arXiv:1603.08906`

- *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 - ...`

PDF landscape

- Significant number of active groups ABM12, CJ15, CT14, HERAPDF2.0, JR14, MMHT14, NNPDF3.0
  - PDFs accurate to NNLO except for CJ15 (NLO)
  - different procedures ($\Delta\chi^2$ criterium)
  - data table from review arXiv:1603.08906

PDF sets	$\Delta\chi^2$ criterion	data sets used in analysis
ABM12 arXiv:1310.3059	1	incl. DIS, DIS charm, DY
CJ15 arXiv:1602.03154	100	incl. DIS, DY (incl. $p\bar{p} \to W^{\pm}X$), $p\bar{p}$ jets, γ+jet
CT14 arXiv:1506.07443	100	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets
HERAPDF2.0 arXiv:1506.06042	1	incl. DIS, DIS charm, DIS jets
JR14 arXiv:1403.1852	1	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, DIS jets
MMHT14 arXiv:1510.02332	$2.3 \ldots 42.3$ (dynamical)	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$
NNPDF3.0 arXiv:1410.8849	1	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$, $W+$charm

Recommendations (I)

PDF4LHC recommendations for LHC Run II

- Recommendations by CT14, MMHT14, NNPDF3.0
- PDFs averaged in set PDF4LHC15
  - to be used for Higgs cross sections, in seaches, for PDF uncertainties and for Monte Carlo simulations

PDF4LHC recommendations for LHC Run II

Jon Butterworth[1], Stefano Carrazza[2,4], Amanda Cooper-Sarkar[3], Albert De Roeck[4,5], Joël Feltesse[6], Stefano Forte[2], Jun Gao[7], Sasha Glazov[8], Joey Huston[9], Zahari Kassabov[2,10], Ronan McNulty[11], Andreas Morsch[4], Pavel Nadolsky[12], Voica Radescu[13], Juan Rojo[14] and Robert Thorne[1].

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Abstract:

Recommendations (II)

Recommendations for PDF usage in LHC predictions

- Shortcomings in PDF4LHC recommendations addressed
- Recommendations by ABM12, CJ15, HERAPDF2.0, JR14

Recommendations for PDF usage in LHC predictions

A. Accardi[a,b], S. Alekhin[c,d], J. Blümlein[e], M.V. Garzelli[c], K. Lipka[f], W. Melnitchouk[b], S. Moch[c], R. Plačakytė[f], J.F. Owens[g], E. Reya[h], N. Sato[b], A. Vogt[i] and O. Zenaiev[f]

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Recommendations (II)

Recommendations for PDF usage in LHC predictions

- Shortcomings in PDF4LHC recommendations addressed
- Recommendations by ABM12, CJ15, HERAPDF2.0, JR14

(i) Precision theory predictions

Recommendation: Use the individual PDF sets ABM12, CJ15, CT14, HERAPDF2.0, JR14, MMHT14, NNPDF3.0 (or as many as possible), together with the respective uncertainties for the chosen PDF set, the strong coupling $\alpha_s(M_Z)$ and the heavy quark masses m_c, m_b and m_t.

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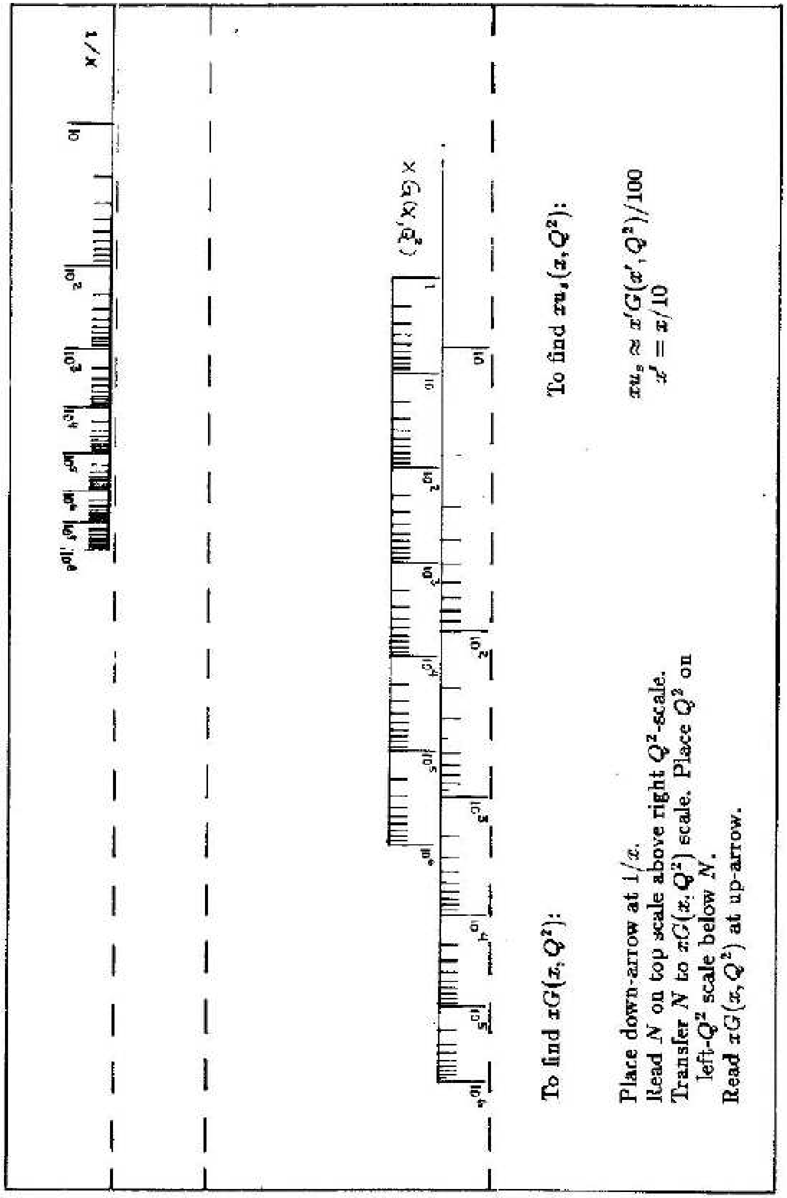
(ii) Other theory predictions

Recommendation: Use any one of the PDF sets listed in LHAPDF(v6).

Pocket partonometer

Volume 172, number 3,4 PHYSICS LETTERS B 22 May 1986



Volume 172, number 3,4 PHYSICS LETTERS B 22 May 1986

for t- or heavier particle distributions one must model thresholds numerically such as done in ref. [4] ‡4. However, departures from a symmetrically distributed sea, which complicate the boundary conditions, can be reproduced by the ratios $u_s \approx d_s \approx s_s \approx 2c_s \approx 2b_s$.

The analytic gluon solution (3), boundary conditions included, is calculated by the partonometer (fig. 2). The scales automate the logarithms of certain functions of $1/x$ and Q^2 left to the reader. In systematic testing the accuracy of the gizmo is at the 10–20% level depending on the operator's ability to read logarithmic scales. It is much better than interpolating between graphs such as fig. 1a. The speed is even faster than adding a new card ‡4 to an existing program that runs.

Gluon distributions are read off directly; see the example below. Quark sea distributions can be evaluated using the identity

$$xu_s(x, Q^2) = (2/b)\partial xG(x, Q^2)/\partial y, \qquad (7)$$

and evaluating the derivative numerically. But wait! To minimize reading errors, one finds that the derivative above and the normalization change are roughly represented by

$$xu_s(x, Q^2) \approx x'G(x', Q^2)/100, \quad x' = x/10. \qquad (8)$$

This estimate is actually quite close to the re-scaled $xu_s(x, Q^2)$ of ref. [5] and is not too bad a match to

‡4 Private communication with well known phenomenologist.

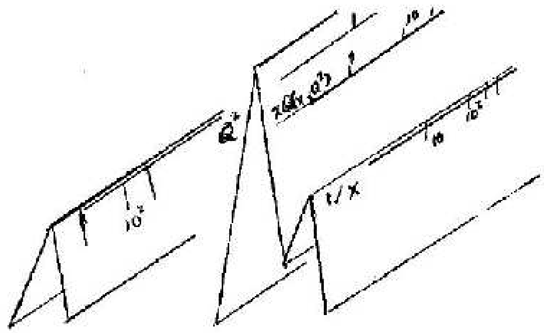
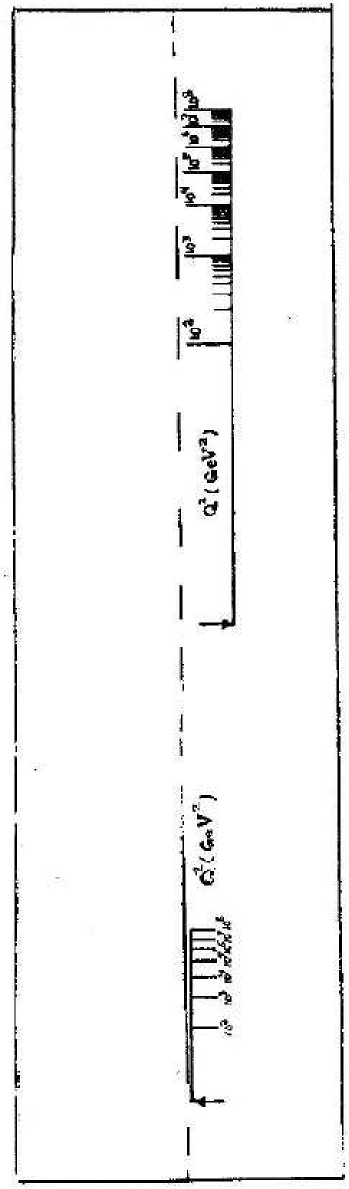


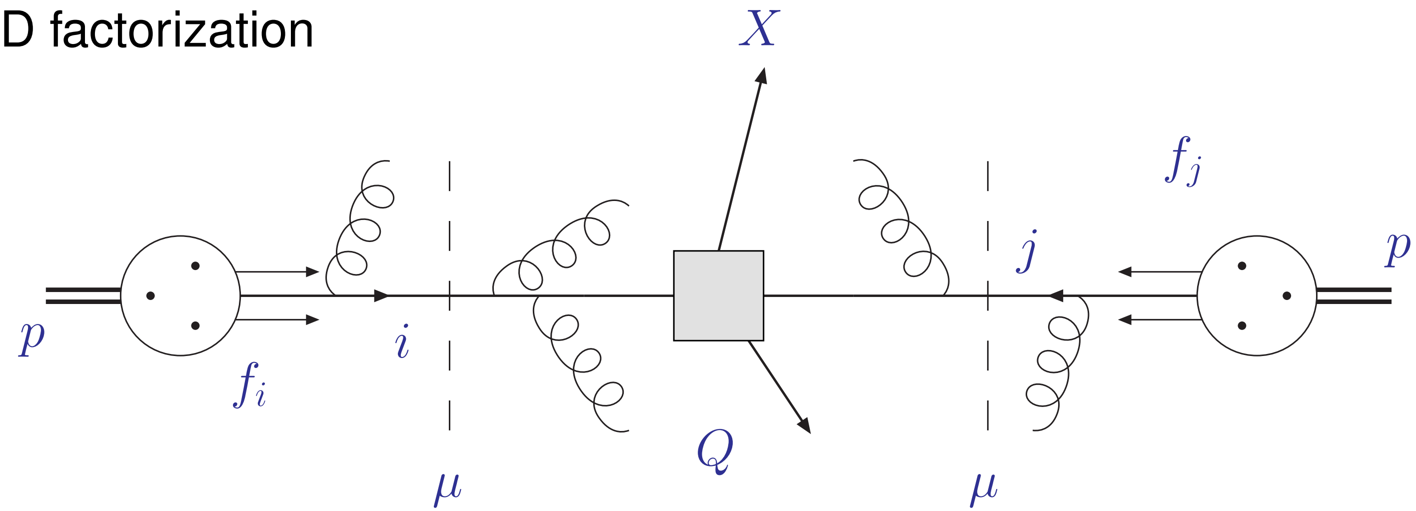
Fig. 2. The partonometer. To assemble: cut on solid lines, fold on dotted lines.



QCD factorization

QCD factorization

- QCD factorization



$$\sigma_{pp\to X} \quad = \quad \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \underbrace{\hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)}$$

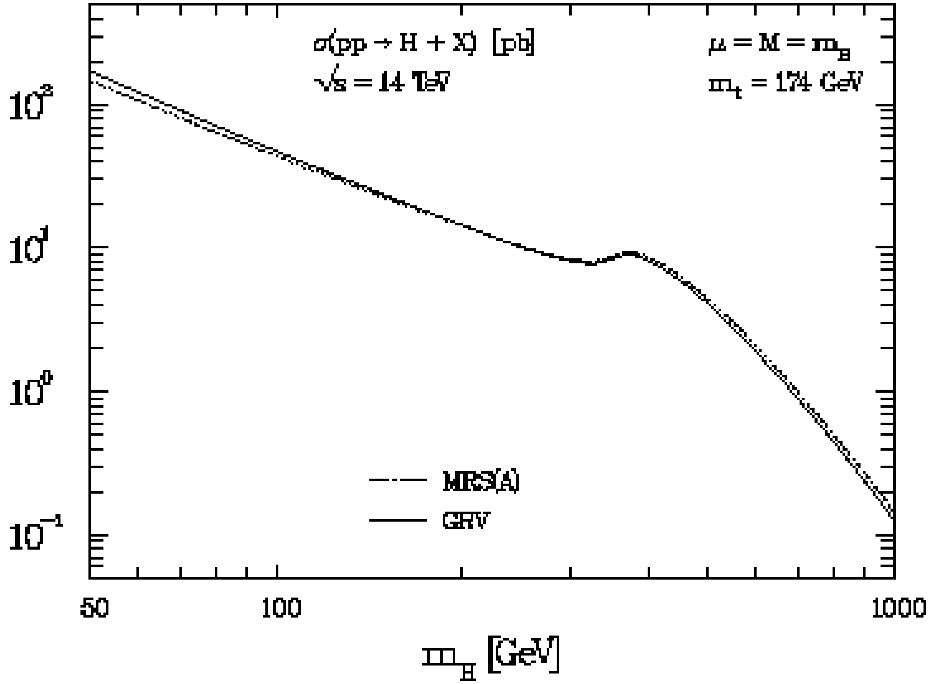
$$= \hat{\sigma}^{(0)}_{ij\to X} + \alpha_s\, \hat{\sigma}^{(1)}_{ij\to X} + \alpha_s^2\, \hat{\sigma}^{(2)}_{ij\to X} + \ldots$$

- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - known to NLO, NNLO, ... ($\mathcal{O}(\text{few}\%)$ theory uncertainty)
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, ...

Higgs boson production

Higgs cross section (1995)

NLO QCD corrections



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

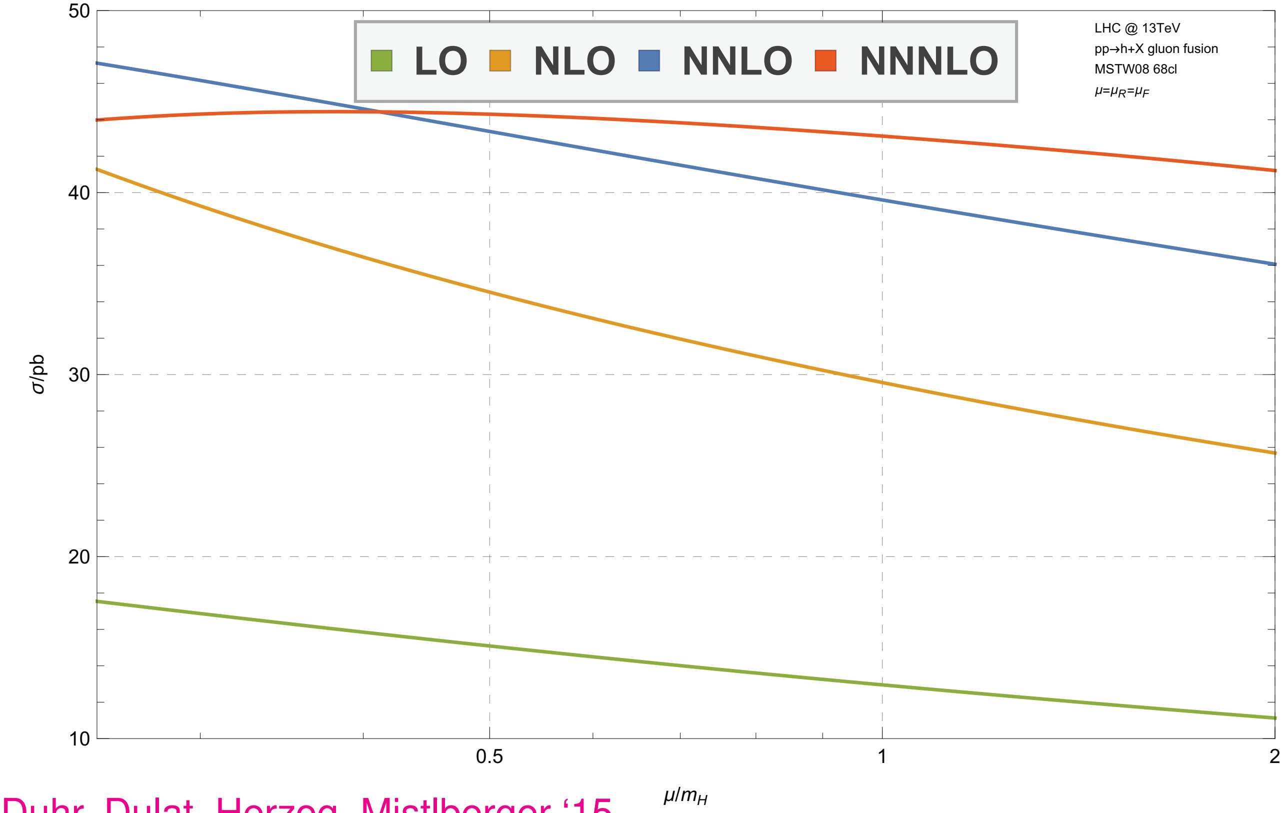
GRV: Glück, Reya and Vogt, Z. Phys. C53 (1992) 127

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^3LO QCD corrections

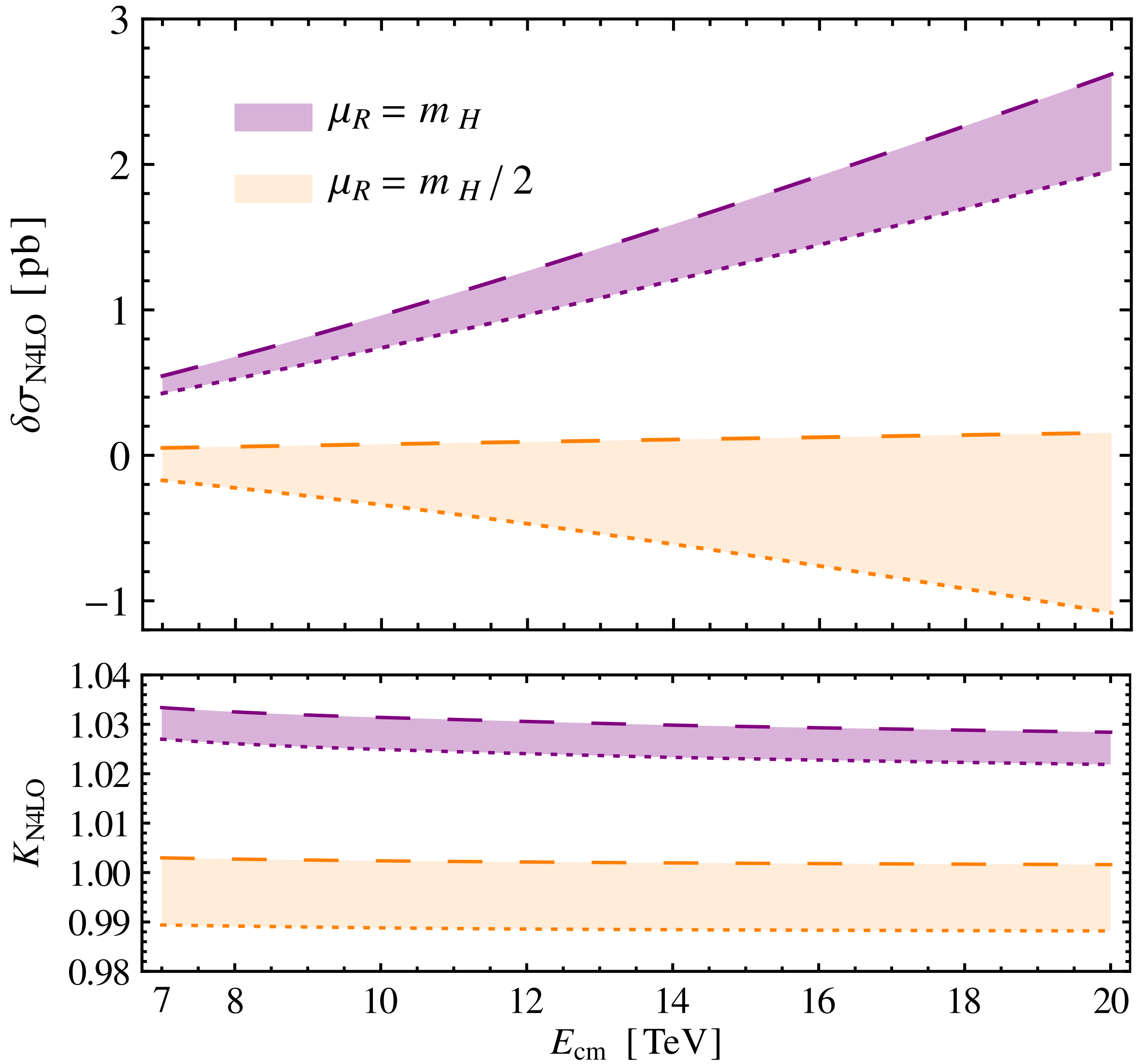


Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

- 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: $\sigma(H) + \Delta\sigma(\text{PDF} + \alpha_s)$ for $m_H = 125.0$ GeV at $\sqrt{s} = 13$ TeV with $\mu_R, \mu_F = m_H$ and nominal α_s

PDF sets	$\sigma(H)^{\text{NNLO}}$ [pb] nominal $\alpha_s(M_Z)$
ABM12 Alekhin, Blümlein, S.M. '13	39.80 ± 0.84
CJ15 Accardi, Brady, Melnitchouk et al. '16	$42.45\,^{+\,1.73}_{-\,1.12}$
CT14 Dulat et al. '15	$42.33\,^{+\,1.43}_{-\,1.68}$
HERAPDF2.0 H1+Zeus Coll.	$42.62\,^{+\,0.35}_{-\,0.43}$
JR14 (dyn) Jimenez-Delgado, Reya '14	38.01 ± 0.34
MMHT14 Martin, Motylinski, Harland-Lang, Thorne '14	$42.36\,^{+\,0.56}_{-\,0.78}$
NNPDF3.0 Ball et al. '14	42.59 ± 0.80
PDF4LHC15 Butterworth et al. '15	42.42 ± 0.78

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

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

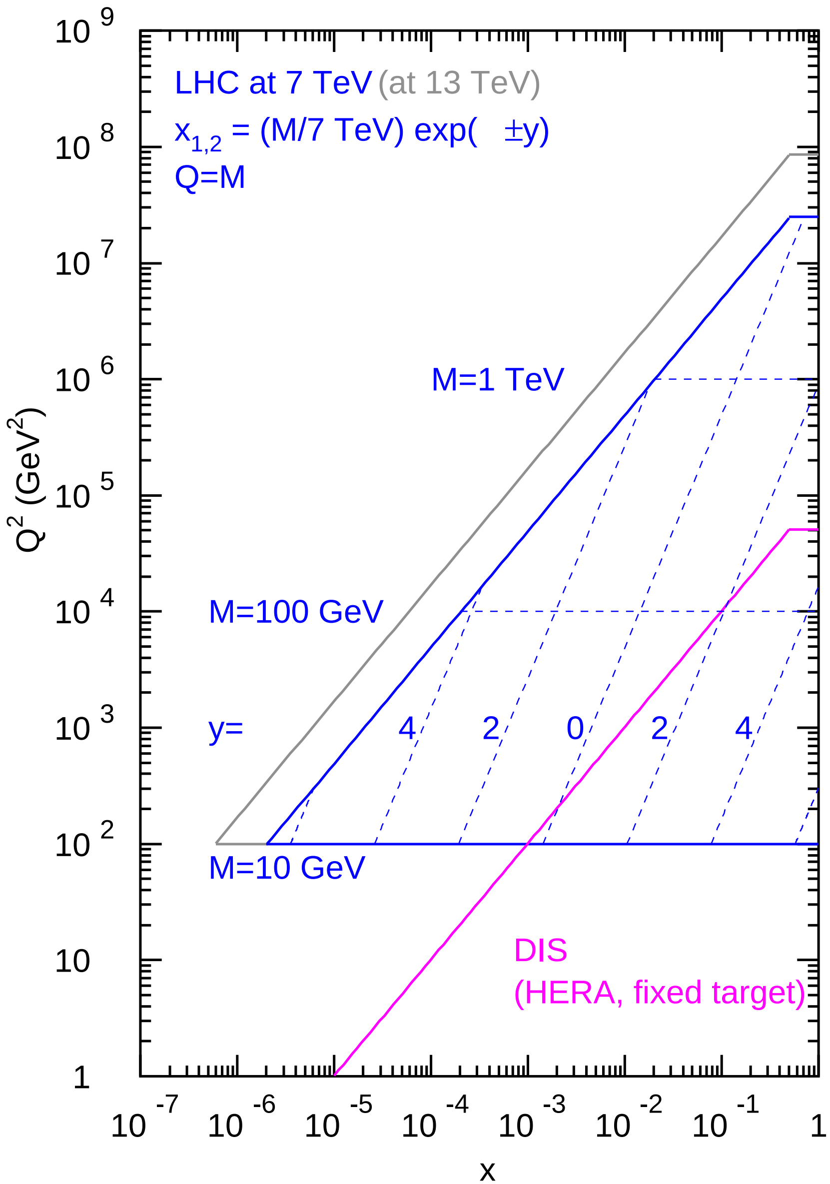
ii) study of potential constraints due to addition of new data set to fit

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

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

Parton kinematics at LHC

- Information on proton structure depends on kinematic coverage



- LHC run at $\sqrt{s}$ = 7/8 TeV
  - parton kinematics well covered by HERA and fixed target experiments
- Parton kinematics with $x_{1,2} = M/\sqrt{S}e^{\pm y}$
  - forward rapidities sensitive to small-x
- Cross section depends on convolution of parton distributions
  - small-x part of f_i and large-x PDFs f_j

$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \left[\ldots\right]$$

Theory considerations in PDF fits

Theory considerations

- Strictly NNLO QCD for determination of PDFs and α_s
- Consistent scheme for treatment of heavy quarks
  - $\overline{\mathrm{MS}}$-scheme for quark masses and α_s
  - fixed-flavor number scheme for $n_f = 3, 4, 5$
- Consistent theory description for consistent data sets
  - low scale DIS data with account of higher twist
- Full account of error correlations

Interplay with perturbation theory

- Accuracy of determination driven by precision of theory predictions
- Non-perturbative parameters sensitive to
  - radiative corrections at higher orders
  - chosen scheme (e.g. ($\overline{MS}$ scheme)
  - renormalization and factorization scales μ_R, μ_F
  - . . .

Benchmark measurements

DIS

- Structure functions for neutral and charged current known to $\mathcal{O}(\alpha_s^3)$
  - F_2, F_3, known N^{3}LO, F_L known NNLO S.M, Vermaseren, Vogt '04–'08
- Heavy-quark structure functions
  - asymptotic NNLO terms at large $Q^2 \gg m^2$ Bierenbaum, Blümlein, Klein '09; Behring, Bierenbaum, Blümlein, De Freitas, Klein, Wissbrock '14
  - approximate NNLO expressions for neutral and charged current Lo Presti, Kawamura, S.M., Vogt '12, Blümlein, A. Hasselhuhn, and T. Pfoh '14
- Dijet production in DIS
  - first results reported at NNLO Currie, Gehrmann, Niehues '16

LHC

- Complete NNLO QCD corrections available for
  - $W^{\pm}$- and Z-boson production Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02
  - hadro-production of top-quark pairs Czakon, Fiedler, Mitov '13
  - single top-quark production (t-channel) Brucherseifer, Caola, Melnikov '14
- Hadroproduction of jets
  - effort towards NNLO Gehrmann-De Ridder, Gehrmann, Glover, Pires '13

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

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    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

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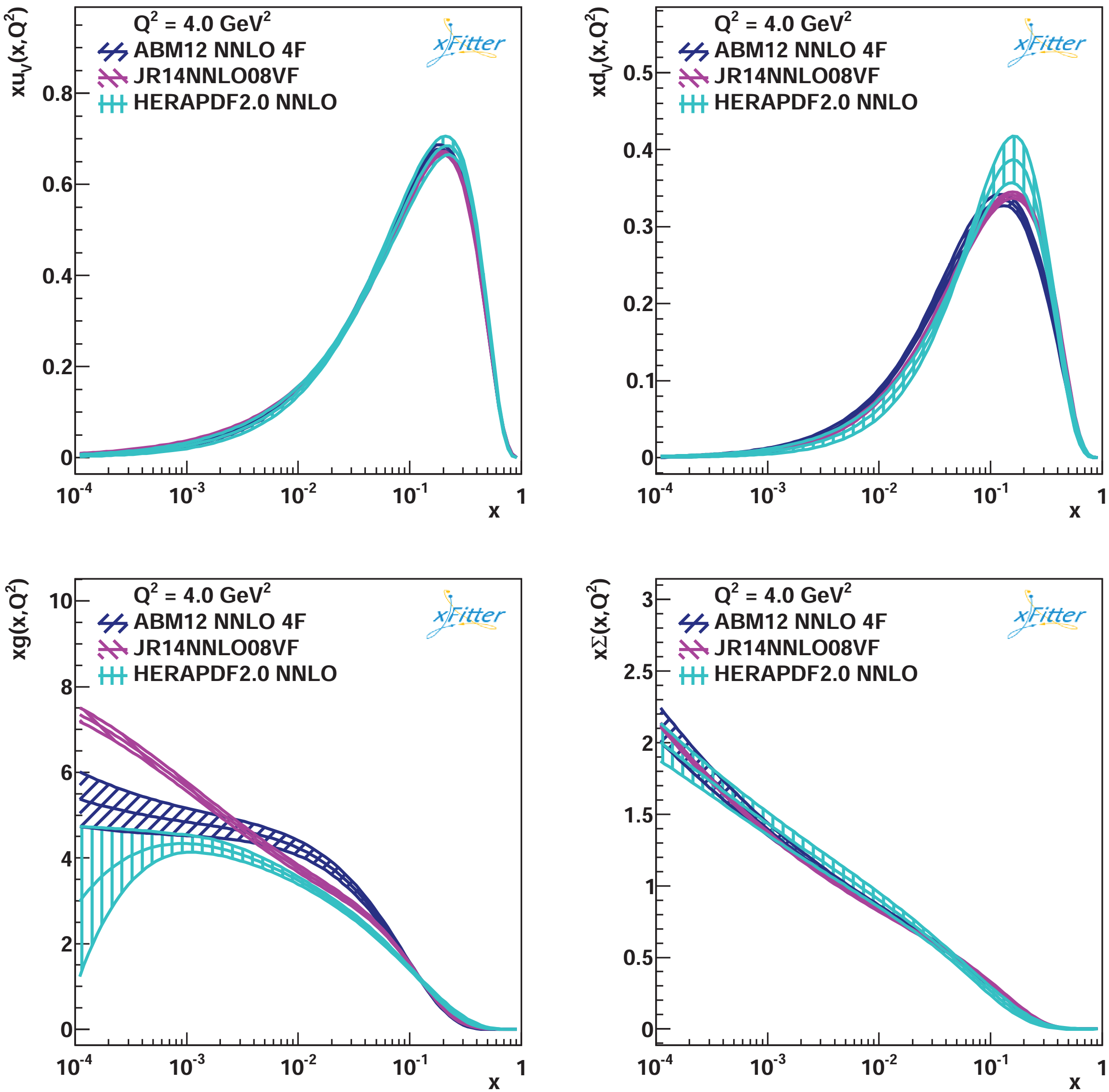
- Positive-definite covariance matrix
  - correlations for ABM11 PDF fit parameters (III)
    Alekhin, Blümlein, S.M. '12

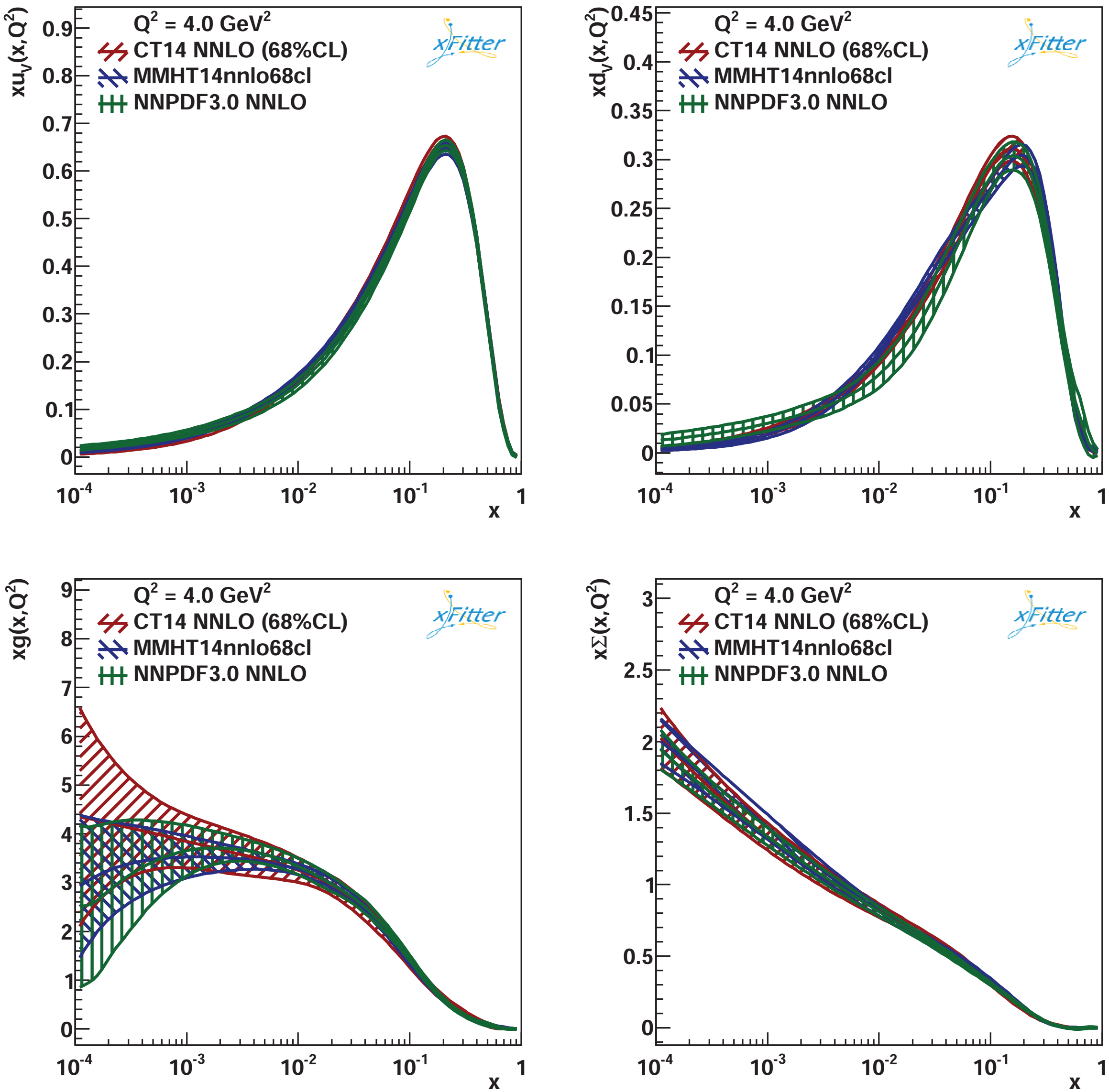
	$\gamma_{1,G}$	$\alpha_s(3,3\ \mathrm{GeV})$	$\gamma_{1,\Delta}$	$\gamma_{1,us}$	$\gamma_{1,d}$	$\gamma_{2,d}$	A_s	b_s	a_s	a_Δ	m_c	m_b
$\gamma_{1,G}$	1.0000	0.3546	-0.0876	0.2751	-0.2215	0.2410	-0.0539	-0.0634	0.0122	-0.0658	-0.1149	-0.0474
$\alpha_s(3,3\ \mathrm{GeV})$		1.0000	0.0601	0.1127	-0.0761	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

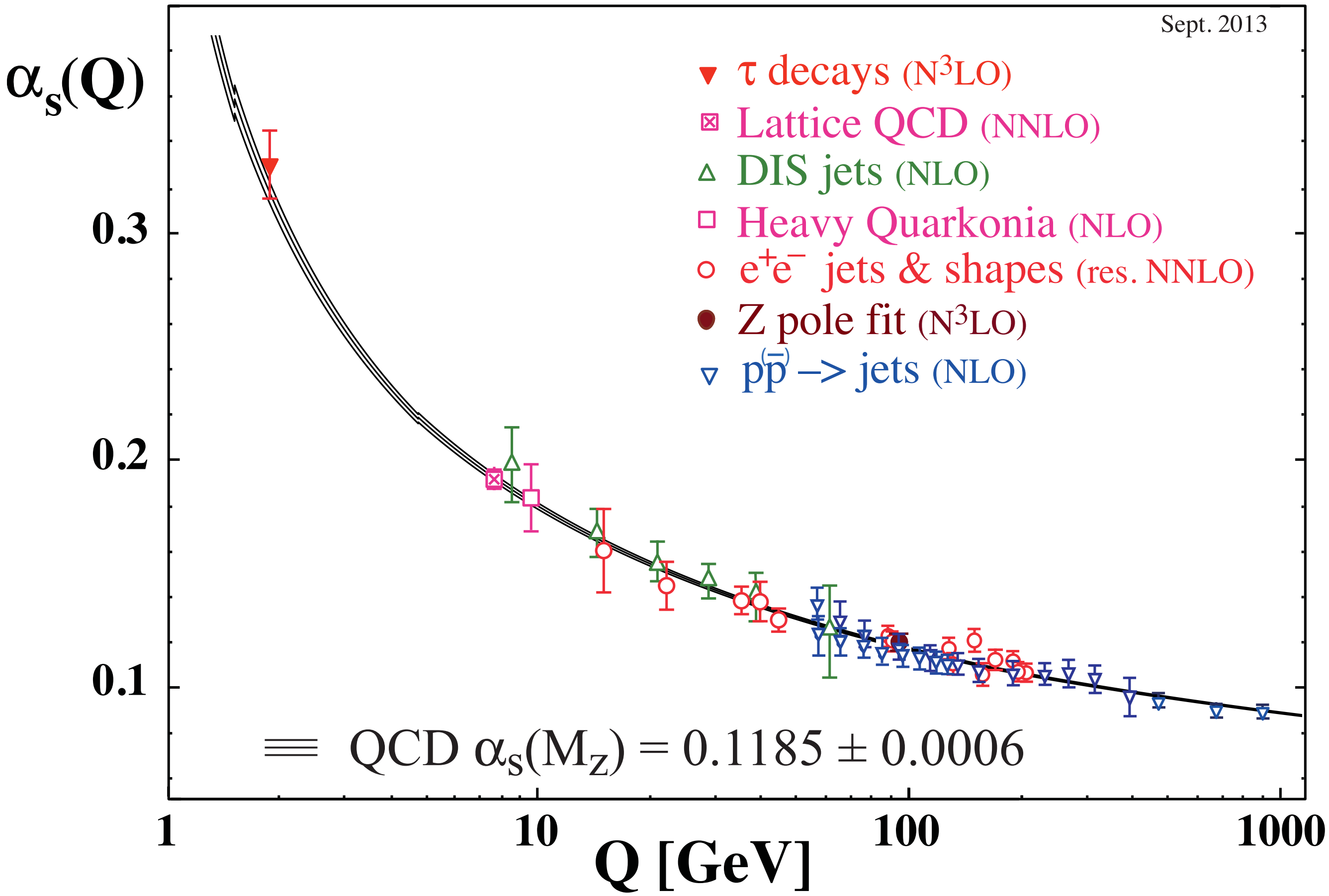
Heavy quarks

- 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

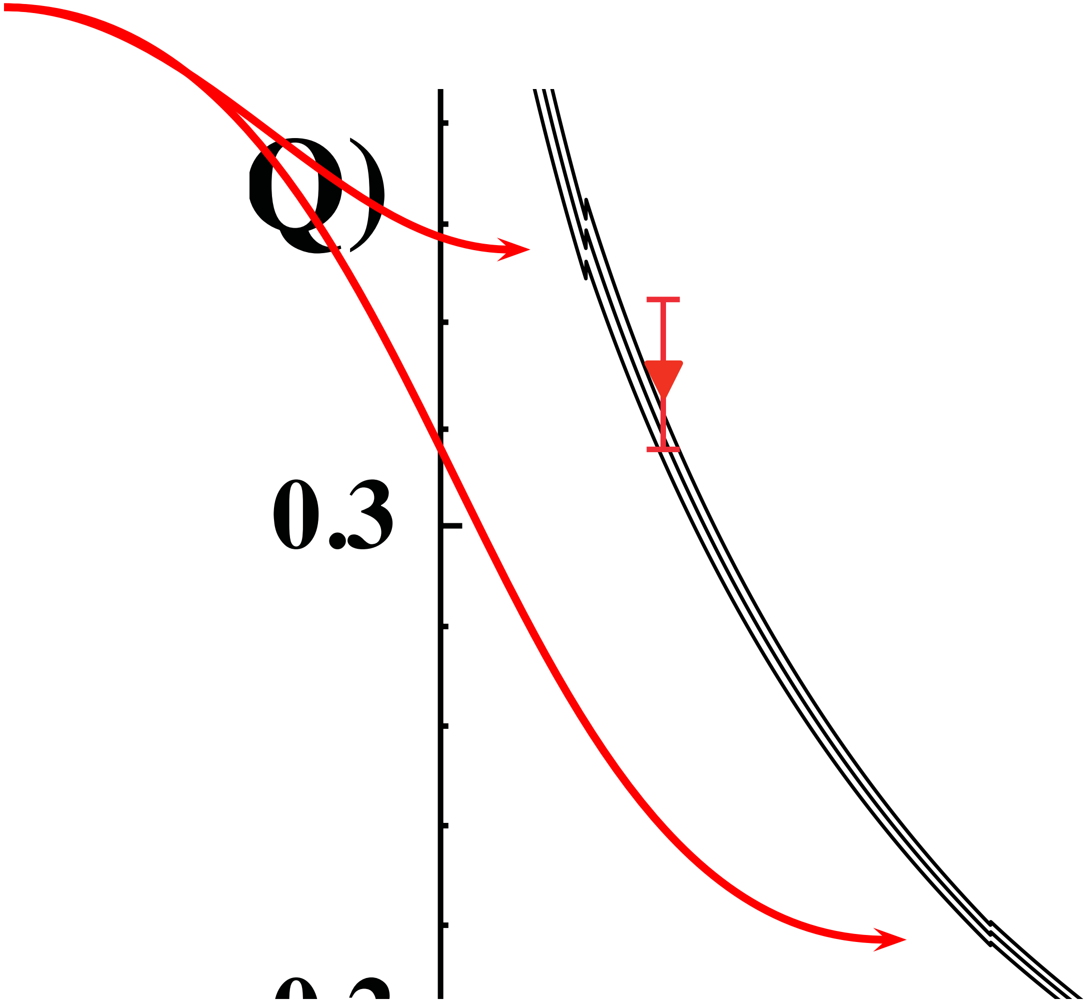
- Solution of QCD β-function for $\alpha_s^{n_l} \longrightarrow \alpha_s^{(n_l+n_h)}$
  - discontinuities for $n_f = 3 \rightarrow n_f = 4 \rightarrow n_f = 5$
- Big picture

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 $n_f = 3 \rightarrow n_f = 4 \rightarrow n_f = 5$
- Zoom



PDFs with flavor thresholds (I)

- 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

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

  - likewise light-quark PDFs $l_i^{(n_f)} \to l_i^{(n_f+1)}$ and gluon and the quark singlet PDFs $(\Sigma^{(n_f)}, g^{(n_f)}) \to (\Sigma^{(n_f+1)}, g^{(n_f+1)})$
- Perturbative expansion of OME A_{hg}

$$A_{hg}^{(1)}(x) \quad = \quad \underbrace{a_{hg}^{(10)}}_{=0} + \ln\left(\frac{\mu^2}{m^2}\right) P_{qg}^{(0)}$$

  - charm density at leading order with matching $c(x,\mu^2 = m_c^2) = 0$

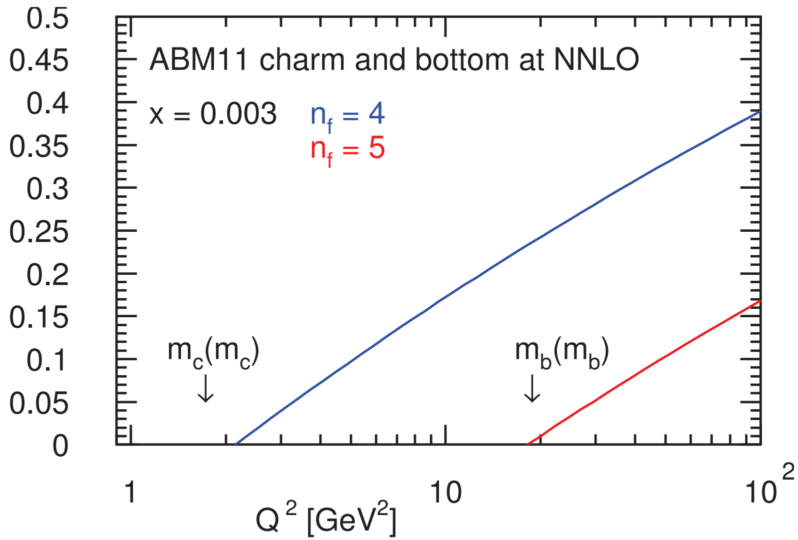
$$c(x,\mu^2)\Big|_{\rm LO} \quad = \quad a_s(\mu^2) \int_x^1 \frac{dz}{z} \ln\left(\frac{\mu^2}{m_c^2}\right) P_{qg}^{(0)}(z)\, g\left(\frac{x}{z},\mu^2\right)$$

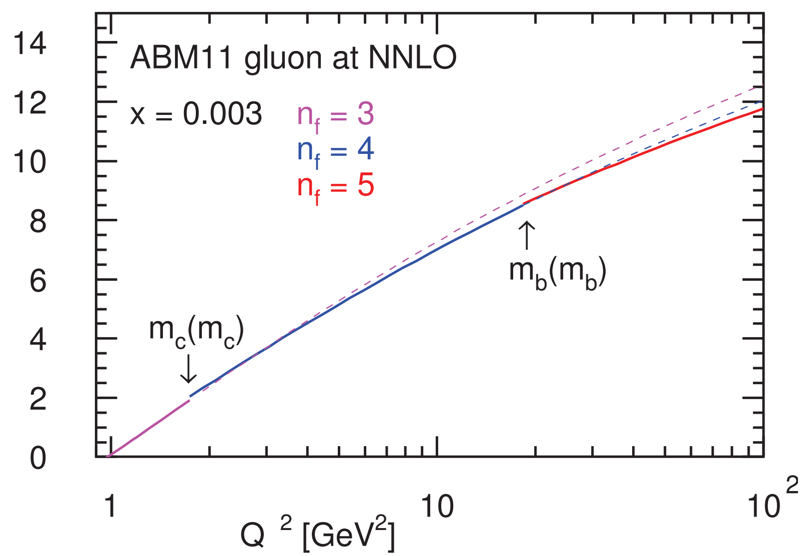
  - higher order matching $c(x,\mu^2 = m_c^2) \neq 0$

$$A_{hg}^{(2)}(x) \quad = \quad \underbrace{a_{hg}^{(20)}}_{\neq 0} + \ln\left(\frac{\mu^2}{m^2}\right) a_{hg}^{(21)} + \ln^2\left(\frac{\mu^2}{m^2}\right) a_{hg}^{(22)}$$

PDFs with flavor thresholds (II)

- Solution of evolution equations between thresholds for $n_f \longrightarrow (n_f + 1)$ with fixed $n_f = 3 \to n_f = 4 \to n_f = 5$
  - discontinuities in PDFs across flavor thresholds
  - matching conditions known to NLO; $A_{hg}^{(3)}$ currently unknown





Cross sections with flavor thresholds

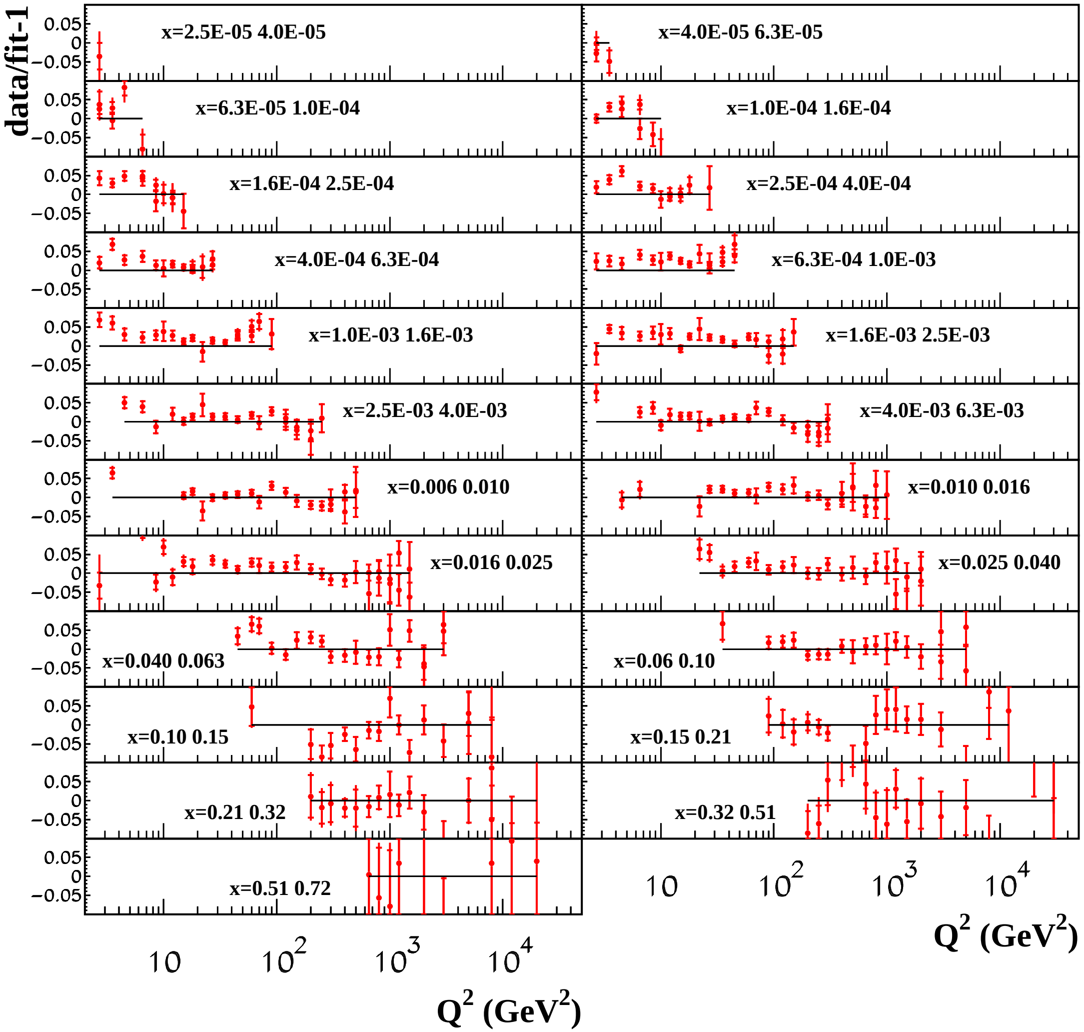
Fixed flavor number scheme (FFNS) ("fixed order $\ln(Q^2/m^2)$")

- 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

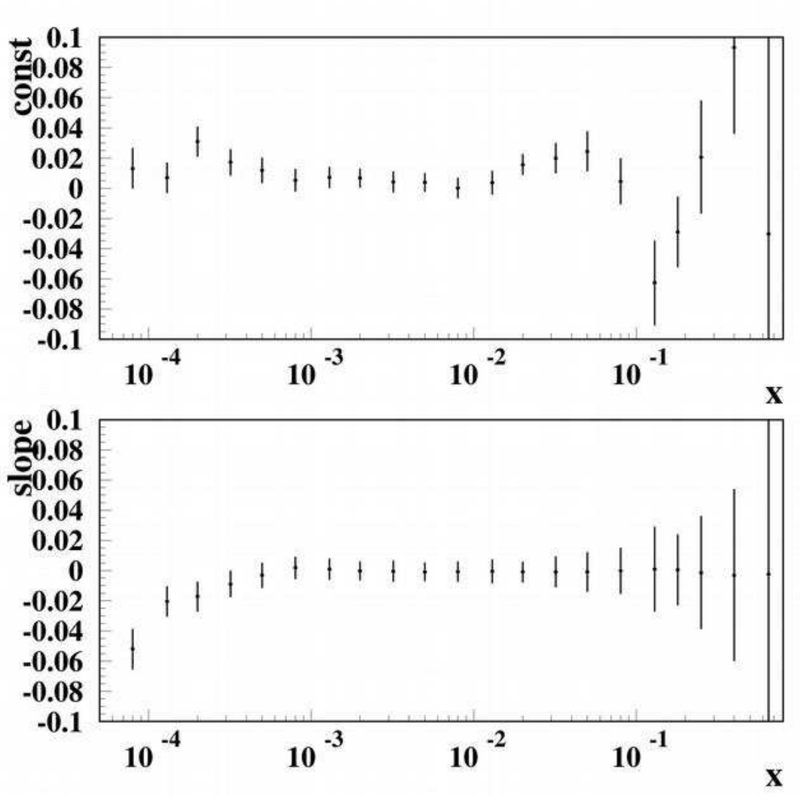
Variable flavor number scheme (VFNS) ("resum $\ln(Q^2/m^2)$")

- (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, FONLL Forte, Laenen, Nason, Rojo '10
  - model assumptions in matching conditions
  - details of implementation matter in global fits

Statistical check of big logarithms



$Q^2_{\rm min}$ (GeV^2)	χ^2/NDP
10	366/324
100	193/201
1000	95/83



- Parametrization of pulls in ABM12

  $$\text{pulls} = \text{const} + \text{slope} \ln\left(\frac{Q^2}{Q_0^2}\right)$$

- No indications for big logarithms

GM-VFNS implementation

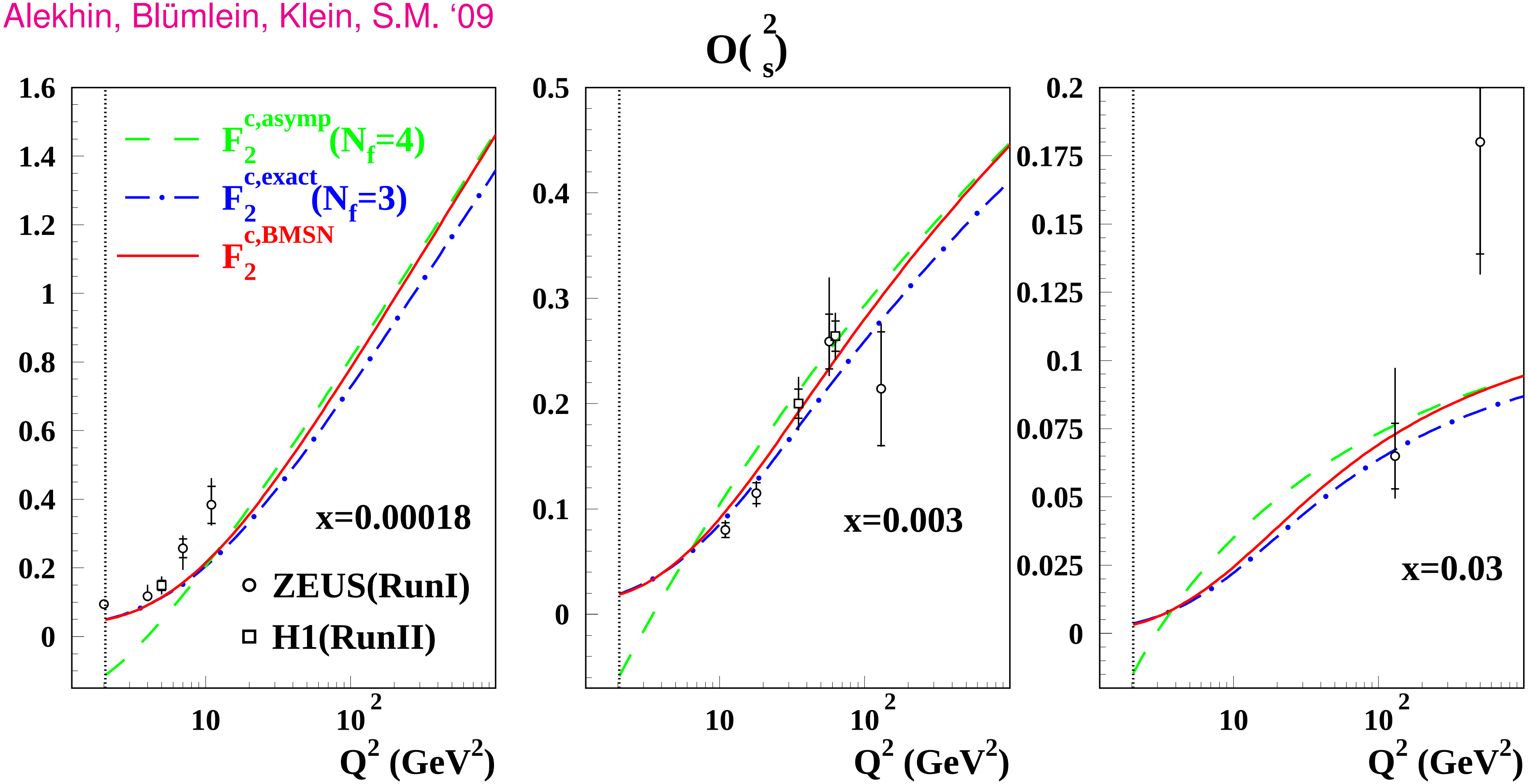
- GM-VFNS implementation using BSMN
  Buza, Matiounine, Smith, van Neerven '98
  - other variant: FONLL Cacciari, Greco, Nason '98; Forte, Laenen, Nason, Rojo '10
- DIS structure function F_2^h for heavy-quark h

$$F_2^{h,\mathrm{BMSN}}(N_f+1,x,Q^2) =$$

$$= \quad F_2^{h,\mathrm{exact}}(N_f,x,Q^2) + \left\{ F_2^{h,\mathrm{ZMVFN}}(N_f+1,x,Q^2) - F_2^{h,\mathrm{asymp}}(N_f,x,Q^2) \right\}$$

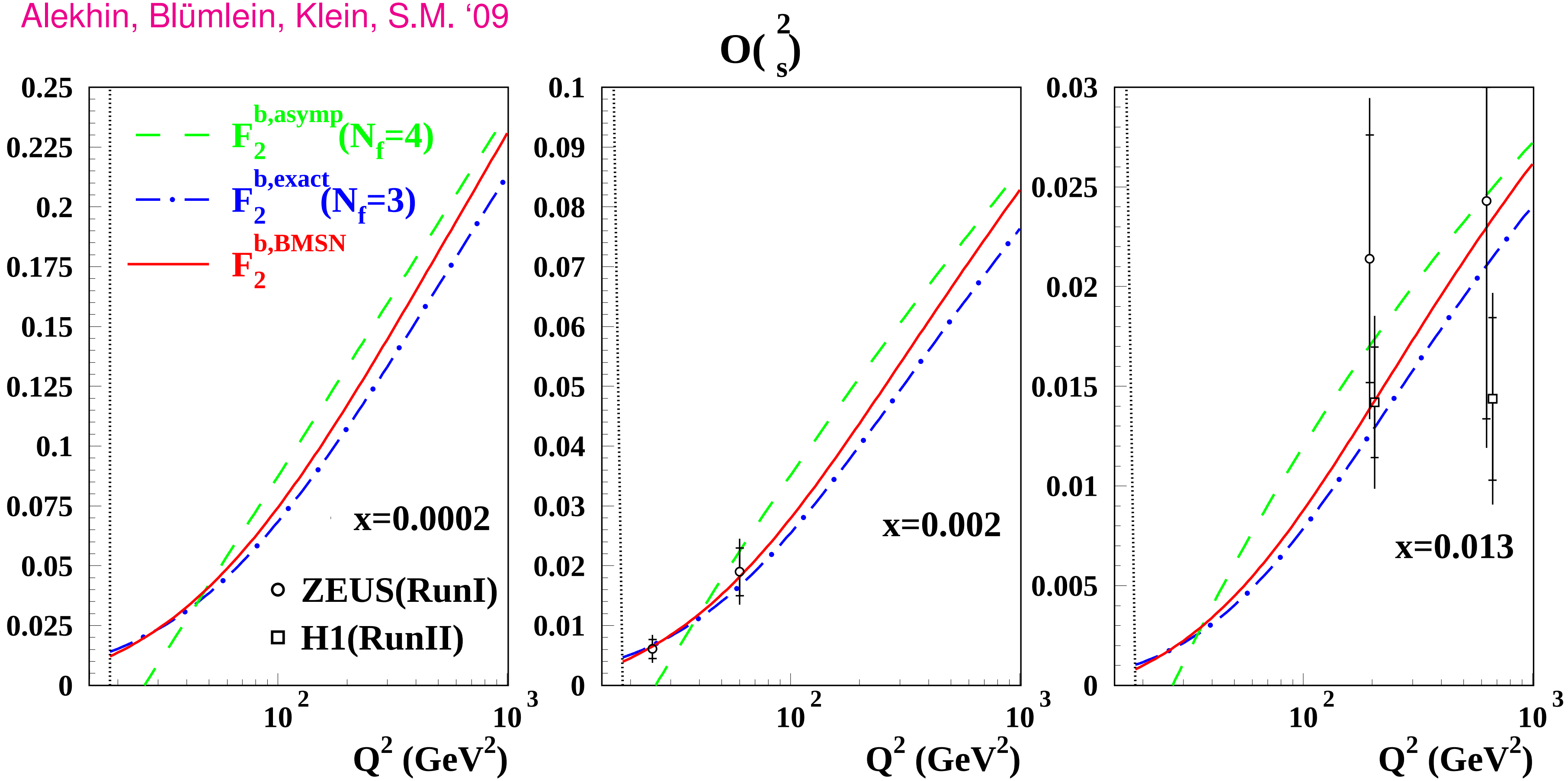
  - $F_2^{h,\mathrm{exact}}$: massive heavy-quark structure function ($m \neq 0$)
  - $F_2^{h,\mathrm{ZMVFN}}$: DIS structure function with zero mass ($m = 0$)
  - $F_2^{h,\mathrm{asymp}}$: asymptotic expansion of heavy-quark structure function (logarithms $\ln(Q^2/m^2)$)
- Difference $\{\dots\}$ has to vanish at threshold $Q \simeq m$
  - details differ for other GM-VFNS implementations:
    ACOT: S-ACOT-χ for slow rescaling $x \to \chi(x) = x\left(1 + \frac{4m^2}{Q^2}\right)$
    FONLL: suppression of $\{\dots\}$ with damping factor $\left(1 + \frac{m^2}{Q^2}\right)^2$
    RT: continuity of physical observables in threshold region

Alekhin, Blümlein, Klein, S.M. ‘09



- F_2^c in different schemes compared to H1- and ZEUS-data
  - GMVFN scheme in BMSN prescription (solid lines)
  - 3-flavor scheme (dash-dotted lines)
  - 4-flavor scheme (dashed lines)
  - charm-quark mass $m_c = 1.43 \text{ GeV}$ (vertical dotted line)

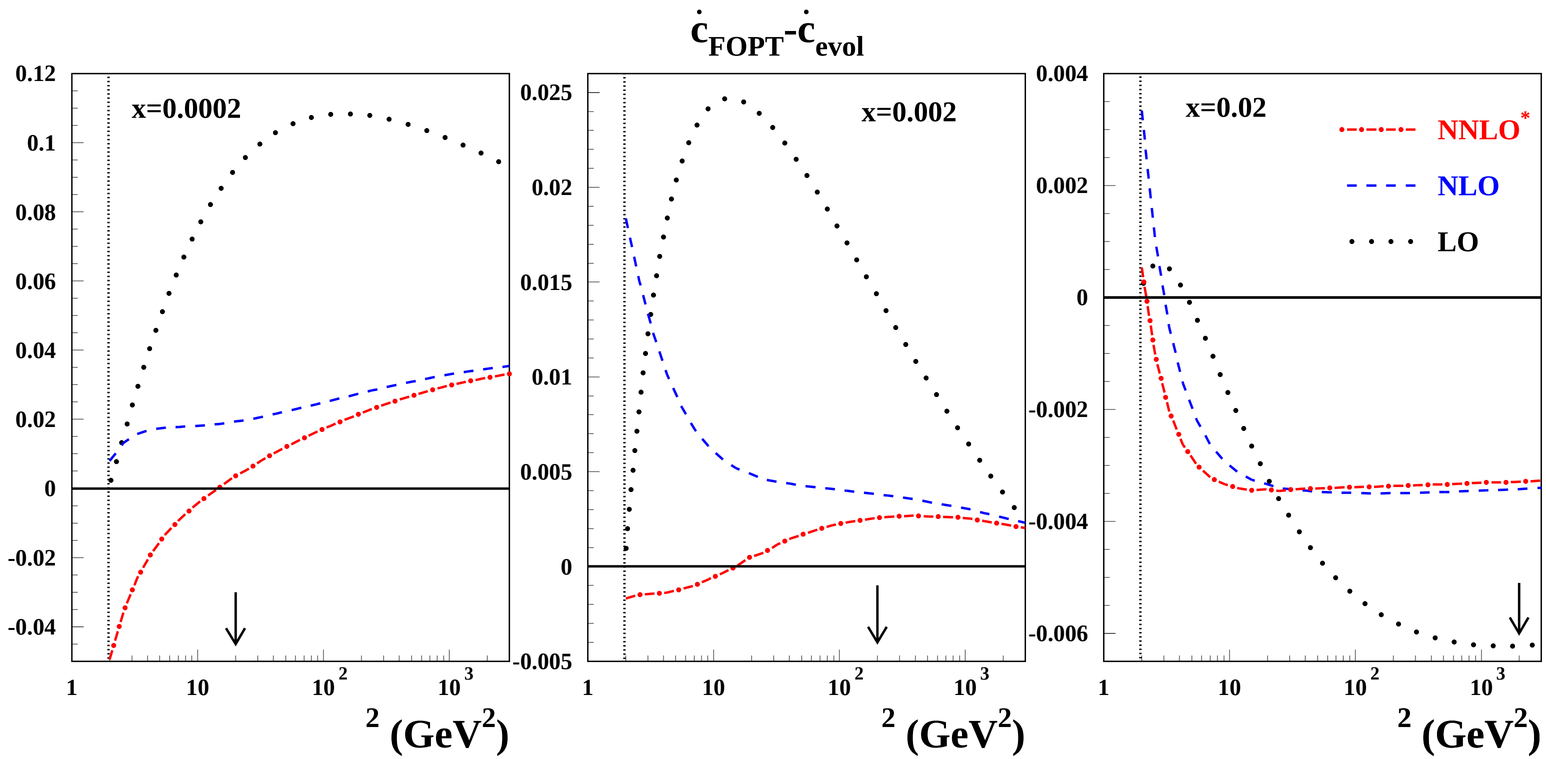
Alekhin, Blümlein, Klein, S.M. '09



- F_2^b in different schemes compared to H1- and ZEUS-data
  - GMVFN scheme in BMSN prescription (solid lines)
  - 3-flavor scheme (dash-dotted lines)
  - 4-flavor scheme (dashed lines)
  - bottom-quark mass $m_b = 4.30$ GeV (vertical dotted line)

Uncertainties in GM-VFNS

Alekhin, Blümlein, S.M. '13



- Derivative of c-quark PDF $\dot{c}(x,\mu^2) \equiv \frac{dc(x,\mu^2)}{d\ln\mu^2}$; difference between fixed order perturbation theory (FOPT) and evolution (massless $n_f = 4$-flavors)
  - check impact of resummation of large logarithms $\ln(Q^2/\mu^2)$
- Uncertainties due to truncation of perturbative expansion
  - **LO**: LO OMEs A_{ji}, LO evolution
    NLO: NLO OMEs A_{ji}, NLO evolution
    NNLO*: NLO OMEs A_{ji}, NNLO evolution (inconsistent)

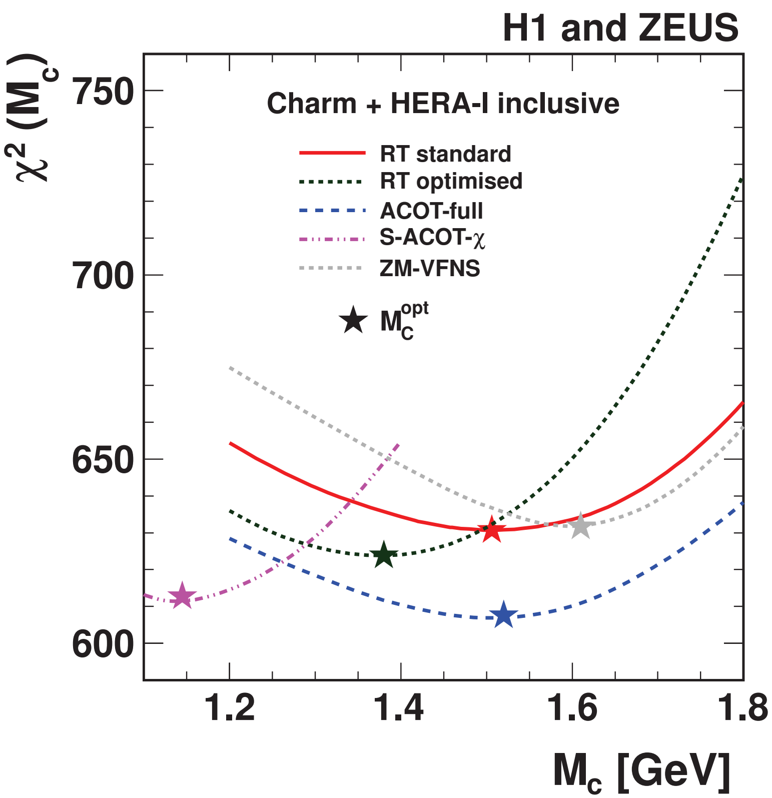
Charm quark mass vs. data

- Data on F_2^c at HERA has correlation of m_c, $\alpha_S(M_Z)$, gluon PDF

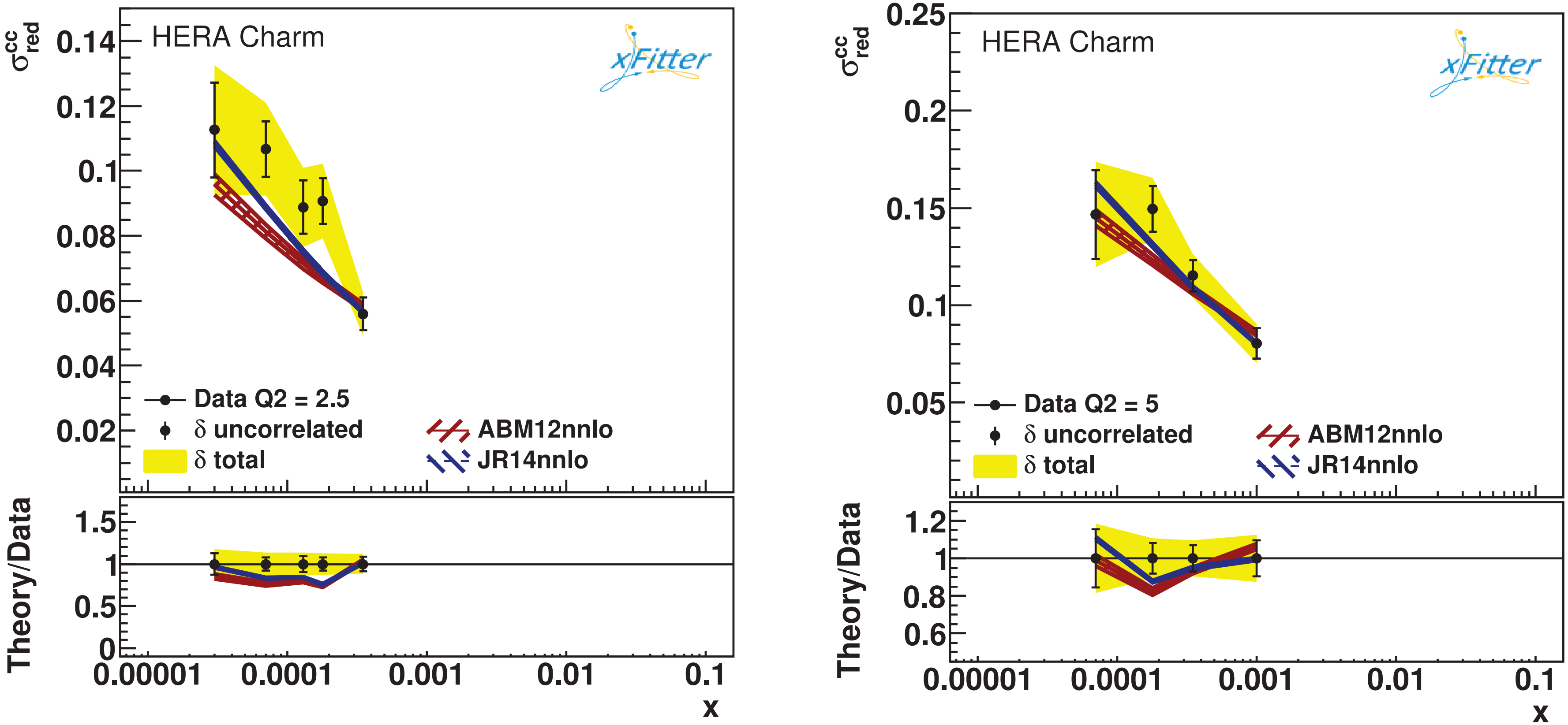
  $\sigma_{c\bar{c}} \sim \alpha_s \, m_c^2 \, g(x)$

- Comparison of measured data with predictions in various VFNS schemes
  - data shows very good sensitivity to value of m_c
  - fit of value of m_c strongly dependent on particular choice of VFNS

    H1 coll. arxiv:1211.1182

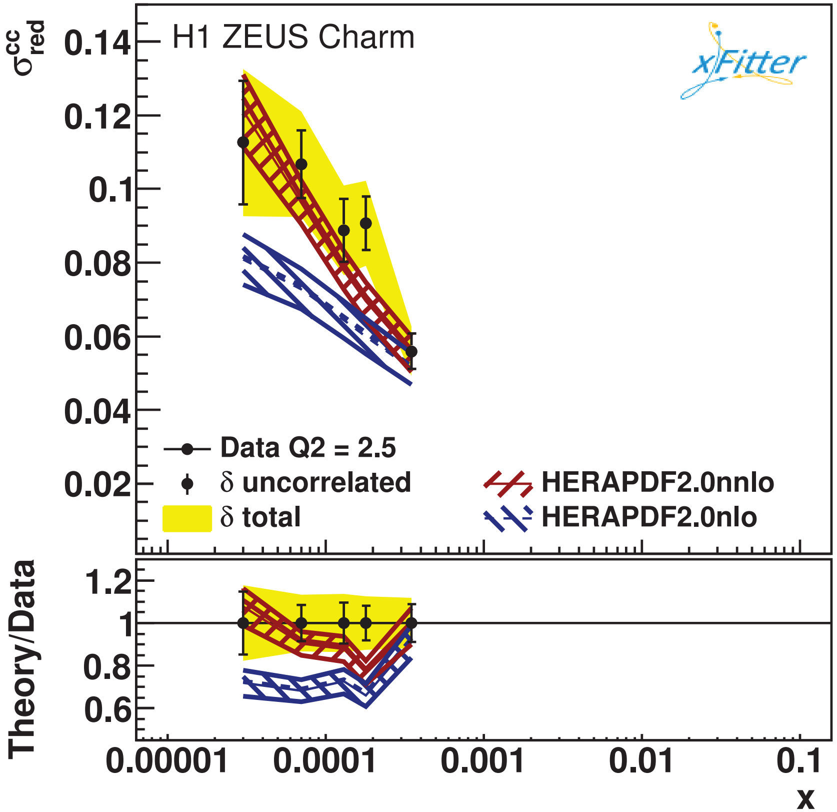


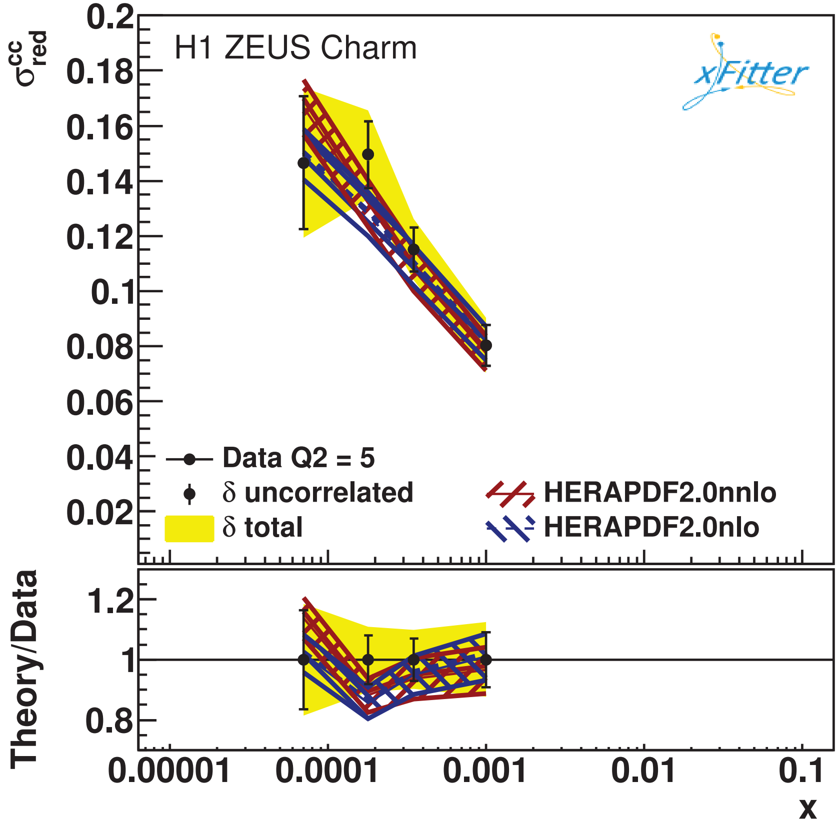
Comparision to data



- 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

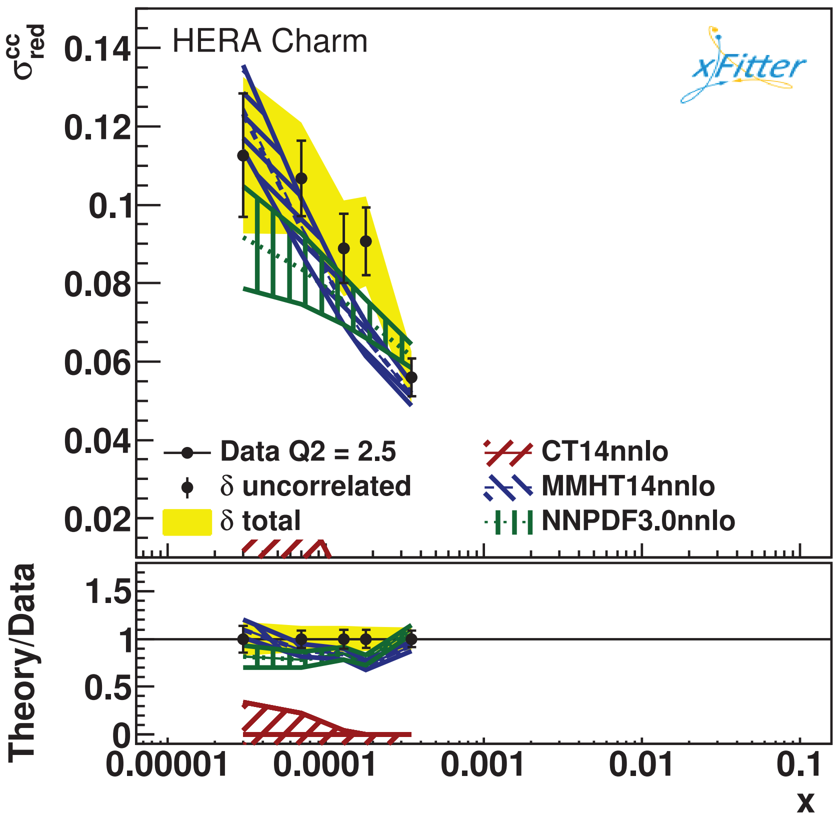
Comparision to data

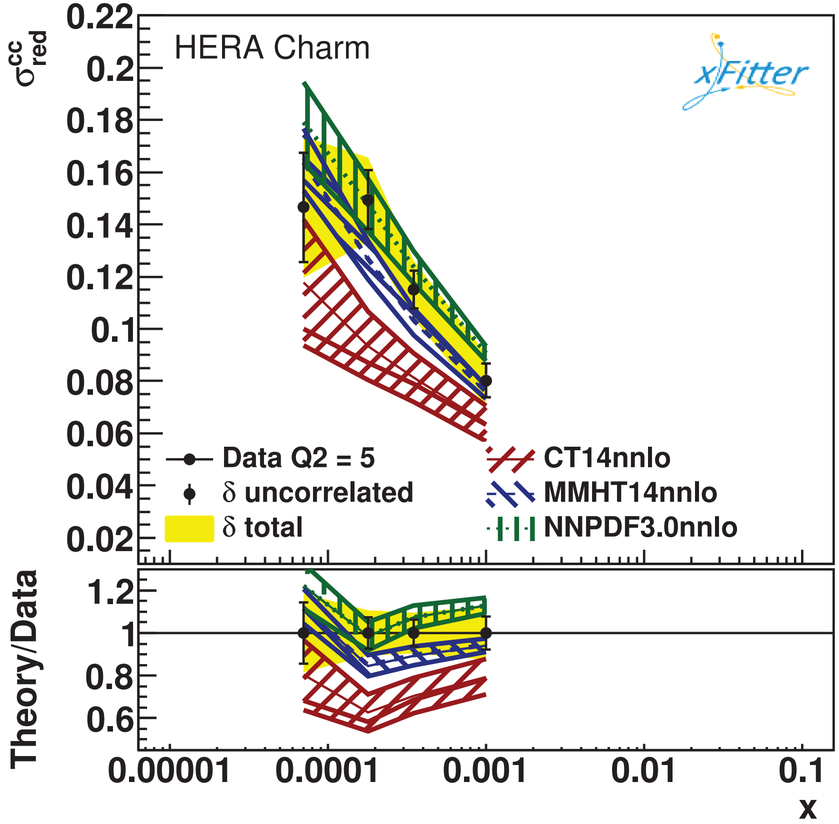




- Comparision of theory predictions for the DIS pair-production of charm quarks to the combined HERA data H1 & ZEUS coll. arXiv:1211.1182
  - HERAPDF2.0 using the RT optimal GM-VFNS scheme

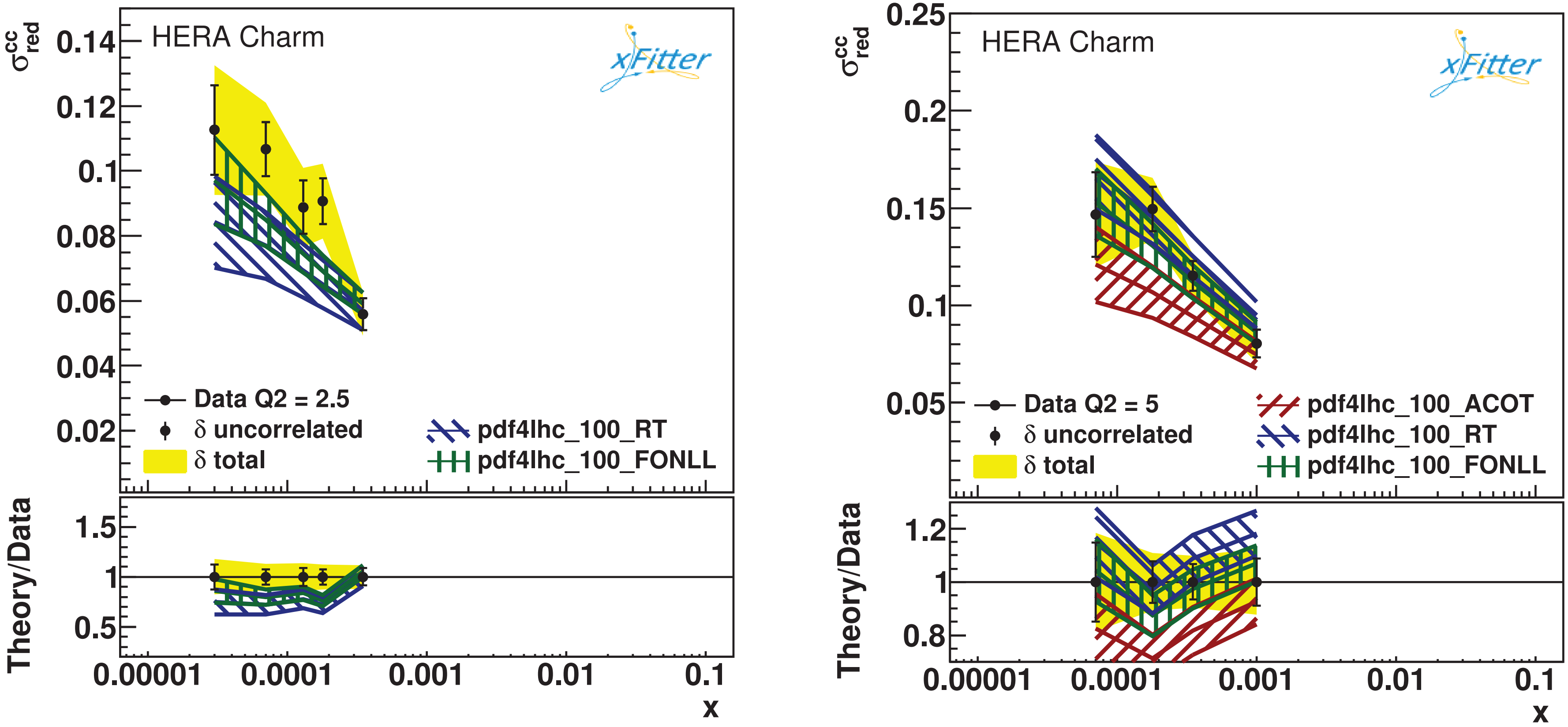
Comparision to data





- 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	$1.24\ ^{+\ 0.05}_{-\ 0.03}$	$m^{\overline{MS}}$	65/52	FFNS($n_f = 3$)	**yes**
CT14 arXiv:1506.07443	1.3 (assumed)	m^{pole}	582/52 (64/47)	S-ACOT-χ	**no**
MMHT arXiv:1510.02332	1.25	m^{pole}	75/52	RT optimal	**no**
NNPDF3.0 arXiv:1410.8849	1.275 (assumed)	m^{pole}	67/52	FONLL-C	**no**
PDF4LHC15 arXiv:1510.03865	-	-	58/52	FONLL-B	-
	-	-	71/52	RT optimal	-
	-	-	51/47	S-ACOT-χ	-

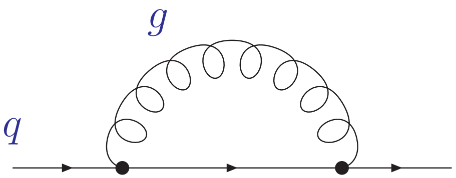
- PDG quotes running masses:
  charm: $m_c(m_c) = 1.27^{+0.07}_{-0.11}$ GeV, bottom: $m_b(m_b) = 4.20^{+0.17}_{-0.07}$ GeV
- Values of charm-quark pole mass for CT14, MMHT14 and NNPDF3.0 not compatible with world average of PDG

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

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

Charm quark mass and the Higgs cross section

MMHT14

- "Tuning" of 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

$m_c^{\rm pole}$ [GeV]	$\alpha_s(M_Z)$ (best fit)	χ^2/NDP (HERA data on $\sigma^{c\bar{c}}$)	$\sigma(H)^{\rm NNLO}$ [pb] best fit $\alpha_s(M_Z)$	$\sigma(H)^{\rm NNLO}$ [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

$W^{\pm}$- and Z-boson production

$W^{\pm}$- and Z-boson production

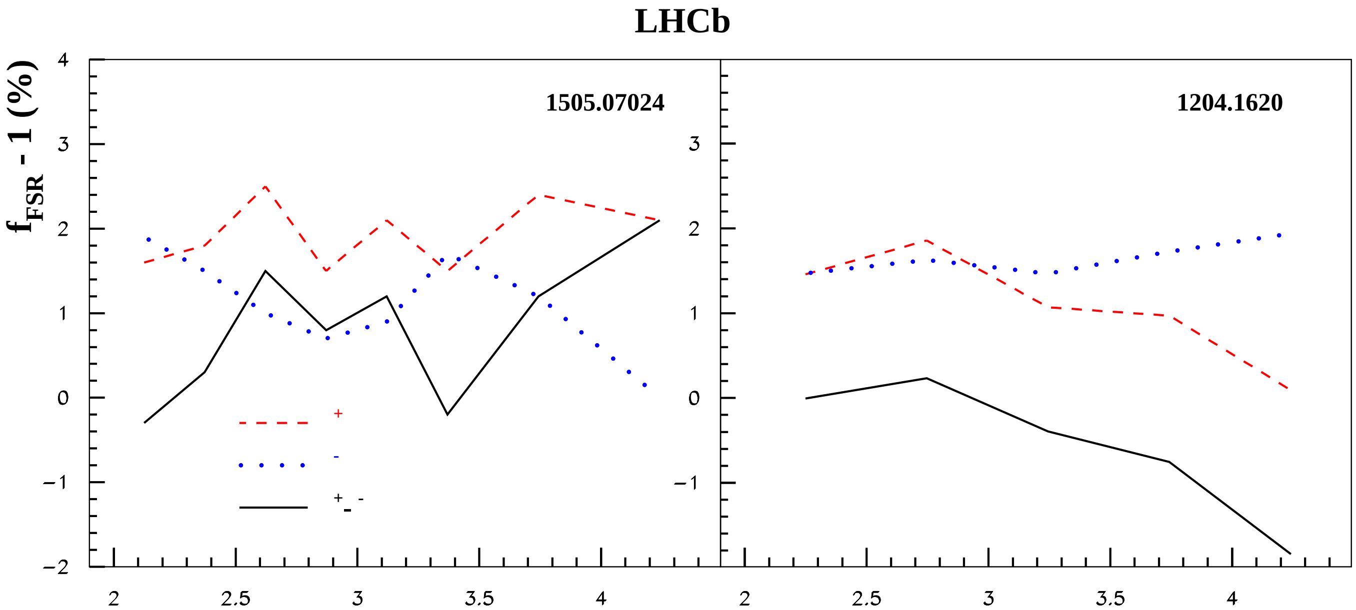
- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - statistically significant $NDP = 168$
  - differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$

Experiment	ATLAS	CMS		D0		LHCb		
$\sqrt{s}$ (TeV)	7	7	8	1.96		7	8	8
Final states	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$
Reference	1109.5141	1312.6283	1603.01803	1309.2591	1412.2862	1505.07024	1503.00963	1511.08039
Cut on the lepton P_T	$P_T^l > 20$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 20$ GeV	$P_T^\mu > 20$ GeV
Luminosity (1/fb)	0.035	4.7	18.8	7.3	9.7	1.	2.	1.
NDP	30	11	22	10	13	31	17	34

Theory issues (I)

Final-state-radiation effects

- QED corrections in $W^{\pm}$- and Z-boson decays applied to data of LHCb
  - left: FSR effects from mean of simulations with Herwig++ and Pythia8 with anomalous irregularity at $\eta_\mu = 3.375$
  - right: earlier analysis of LHCb with smooth FSR corrections from PHOTOS Monte Carlo Golonka, Was '05

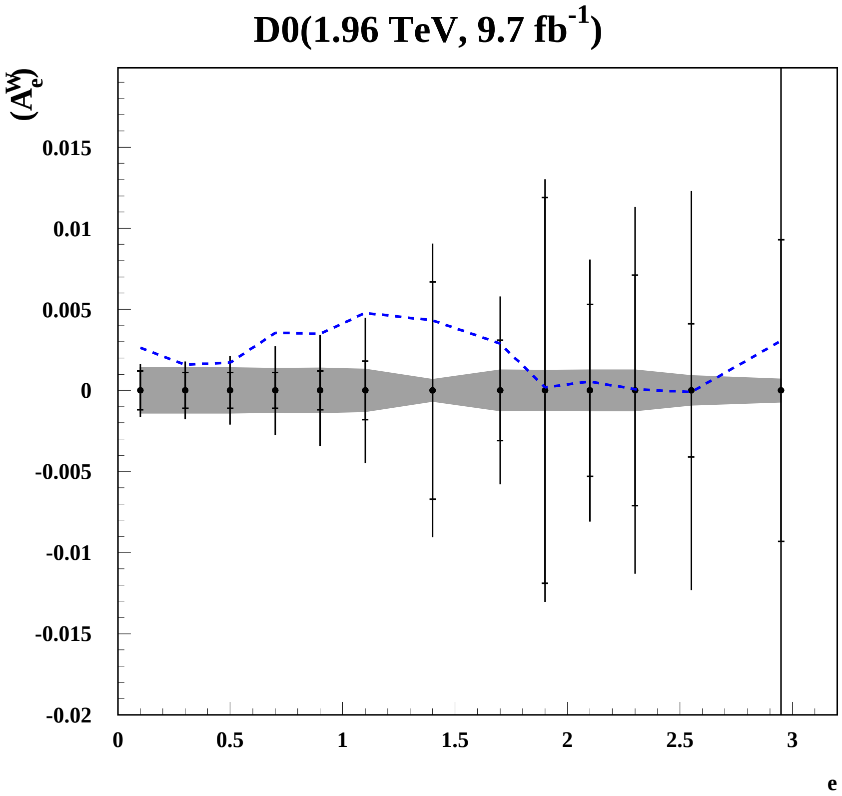


- Dropping problematic data points at $\eta_\mu = 3.375$ reduces χ^2 value by some 10 units

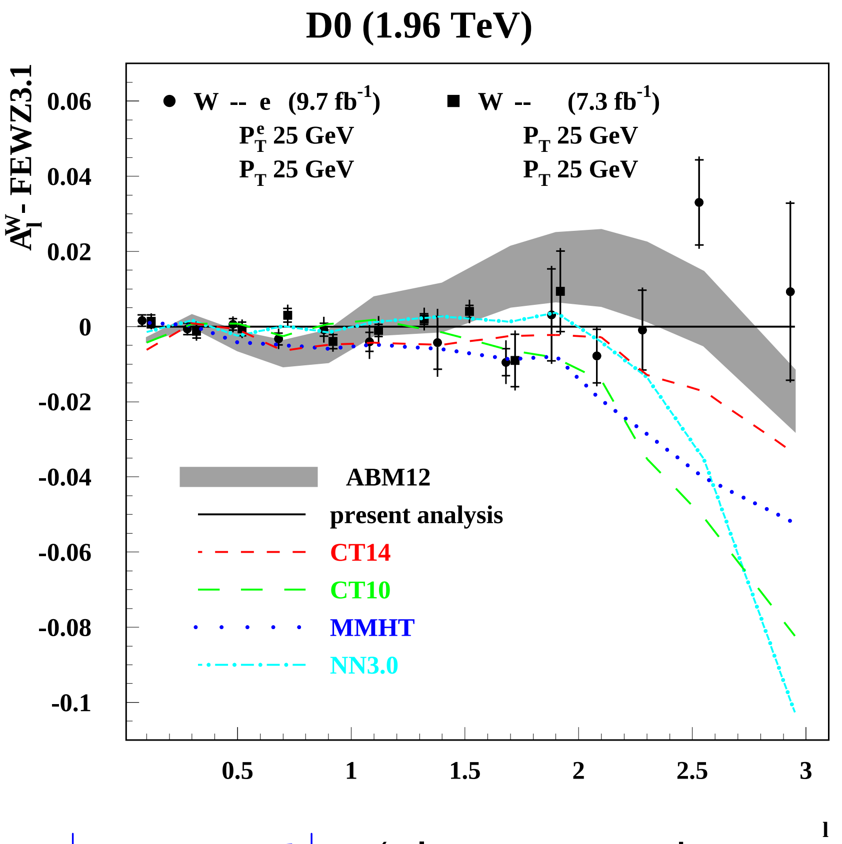
Theory issues (II)

NNLO QCD corrections

- Precision of experimental uncertainties challenges accuracy of numerical integration in QCD NNLO predictions
  - data on electron asymmetry with high precision at central rapidities D0
  - numerical accuracy of NNLO grids (shaded area) obtained with FEWZ
  - NNLO corrections in coefficient functions not uniform in η_e (dashed curve)

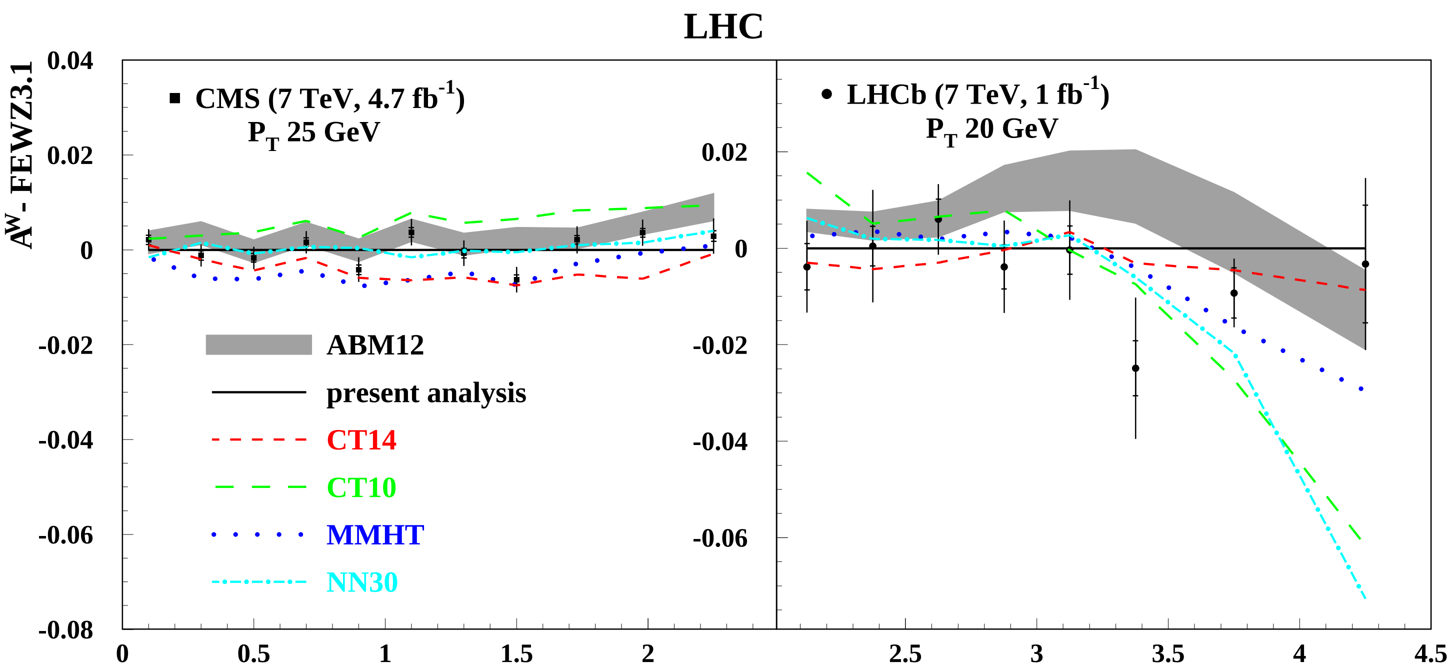


Tevatron charged lepton asymmetry



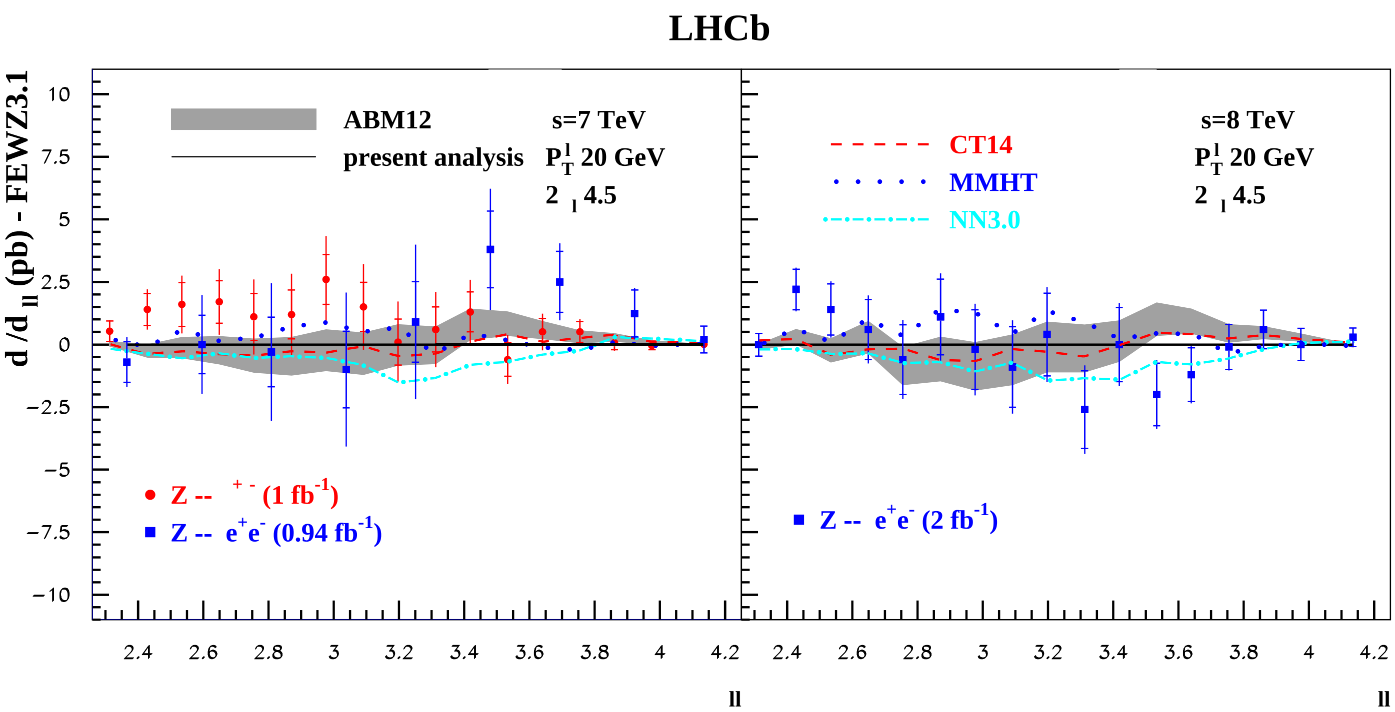
- D0 data for $p\bar{p} \to W^{\pm} + X \to l^{\pm}\nu$ (electrons and muons) at $\sqrt{s} = 1.96$ TeV
- Charged lepton asymmetry as function of pseudo-lepton rapidity η_l
- NNLO QCD predictions with FEWZ (version 3.1)
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT10, CT14, MMHT, and NN3.0

Muon charge asymmetry from LHC



- CMS and LHCb data for $pp \to W^{\pm} + X \to \mu^{\pm}\nu$ at $\sqrt{s} = 7$ TeV
- Problematic data points at $\eta_\mu = 3.375$ in LHCb data are omitted in fit

Z-boson production from LHC



- LHCb data for $pp \to Z + X \to l\bar{l}$ (muon and electron) at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
- Comparison with ABM12 (including combined PDF+α_s uncertainty), CT14, MMHT, and NNPDF3.0

Fit quality

Experiment		ATLAS	CMS	D0		LHCb	
$\sqrt{s}$ (TeV)		7	7	1.96		7	8
Final states		$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to e^+\nu$ $W^- \to e^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$
Reference		1109.5141	1312.6283	1309.2591	1412.2862	1505.07024	1503.00963
NDP		30	11	10	13	31	17
χ^2	ABMP15	29.8	22.5	16.9	18.0	44.1	18.2
	CJ15	–	–	20	29	–	–
	CT14	42	– [a]	–	34.7	–	–
	HERAFitter	–	–	13	19	–	–
	MMHT14	39	–	21	–	–	–
	NNPDF3.0	35.4	18.9	–	–	–	–

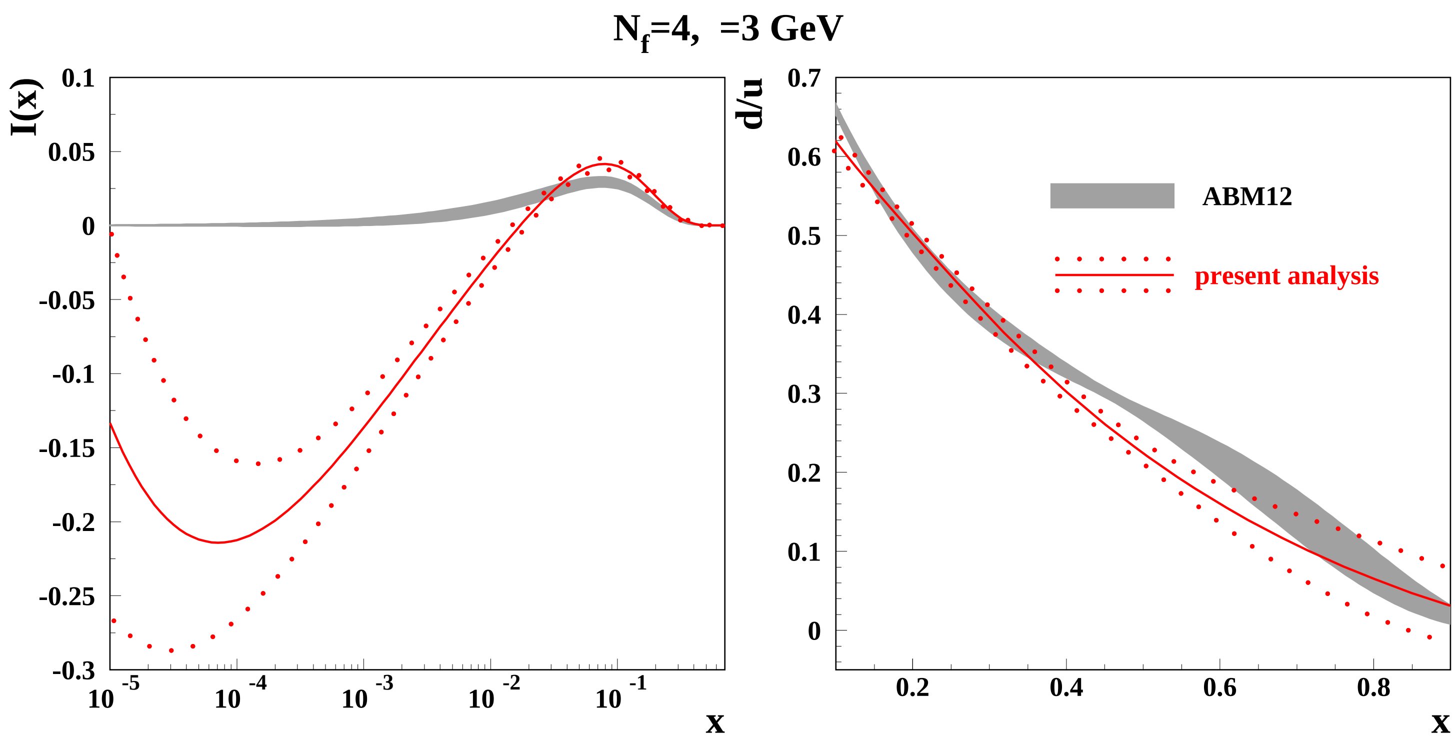
[a] Statistically less significant data with the cut of $P_T^\mu > 35$ GeV are used.

Fit quality (zoom in)

ATLAS data at $\sqrt{s} = 7$ TeV $NDP = 30$			
PDF sets	χ^2	theory accuracy	theory method
this work	32.3	**NNLO**	FEWZ3.1
ABM12	34.5	**NNLO**	FEWZ3.1 and DYNNLO
CT14	42	**(NNLL)**	ResBos
MMHT14	39	**(NNLO)**	APPLGrid, NNLO K-factors (constant)
NN3.0	35.4	**NNLO**	APPLGrid, C-factors (kinematic dependence with FEWZ3.1)

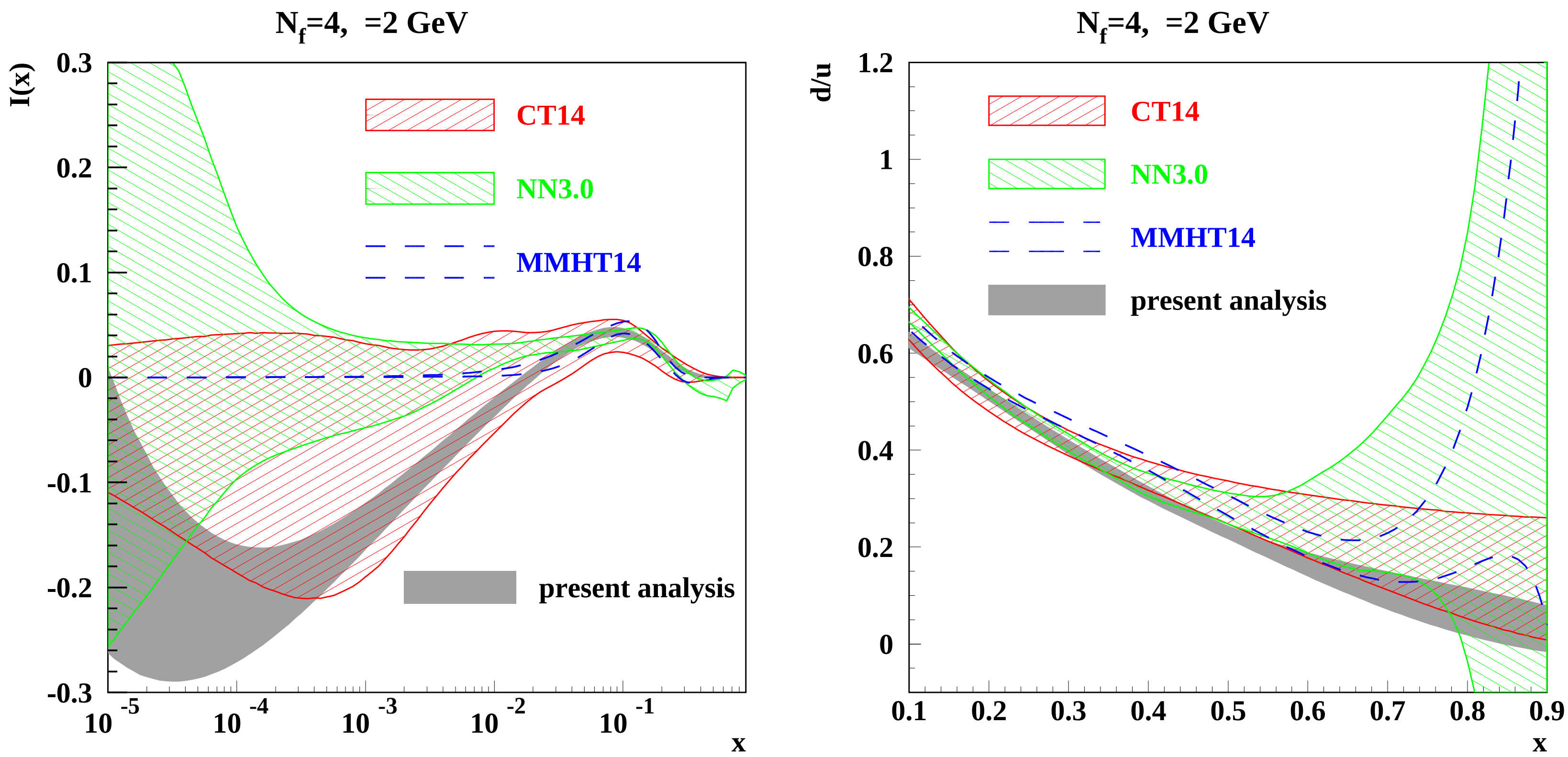
- Use of exact NNLO QCD results with full dependence on kinematics mandatory for goog fit quality
  - significantly deterioration in χ^2 values for CT14 and MMHT

Light flavor PDFs



- Light flavor decomposition not well constrained in DIS data
  - ratio d/u at large x from fixed target Drell-Yan data E-605, E-866 at the price of modelling nuclear corrections
- Iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
  - Regge theory arguments for small x predict $I(x) \simeq 0$
  - $I(x)$ at small x constrained by new Tevatron and LHC data
- Upshot: non-vanishing $I(x)$ at small $x \simeq 10^{-4}$

Comparision with other PDFs

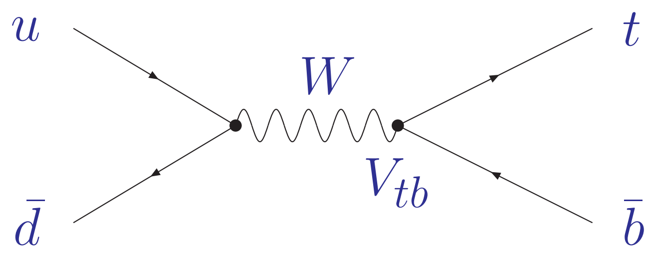


- Iso-spin asymmetry of sea $I(x)$ at small x and ratio d/u at large x with 1σ uncertainty band
- Comparison with CT14, MMHT14, NN3.0
  - CT14 finds non-vanishing $I(x)$ from fit to Tevatron charged lepton asymmetry (D0 data), but with large uncertainties

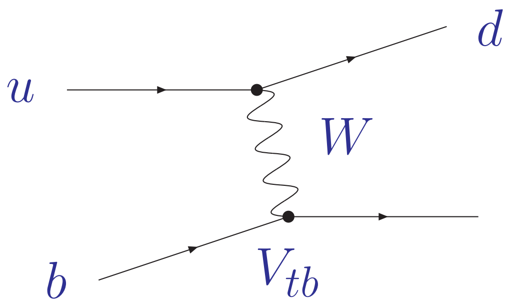
Single top-quark production

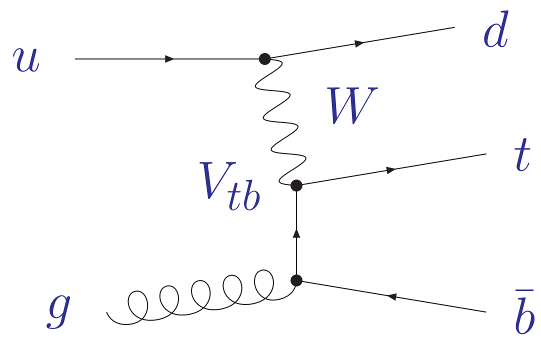
Single top-quark production

- Study of charged-current weak interaction of top quark
- s-channel production

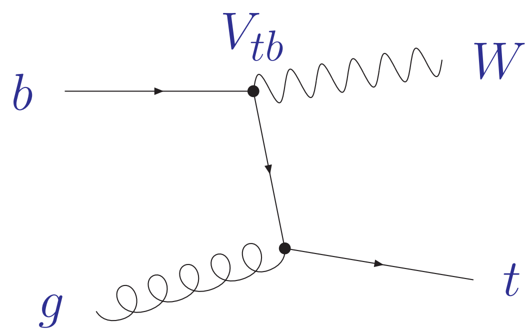


- t-channel production
  - sensitivity to light flavor PDFs
  - bg-channel at NLO enhanced by gluon luminosity

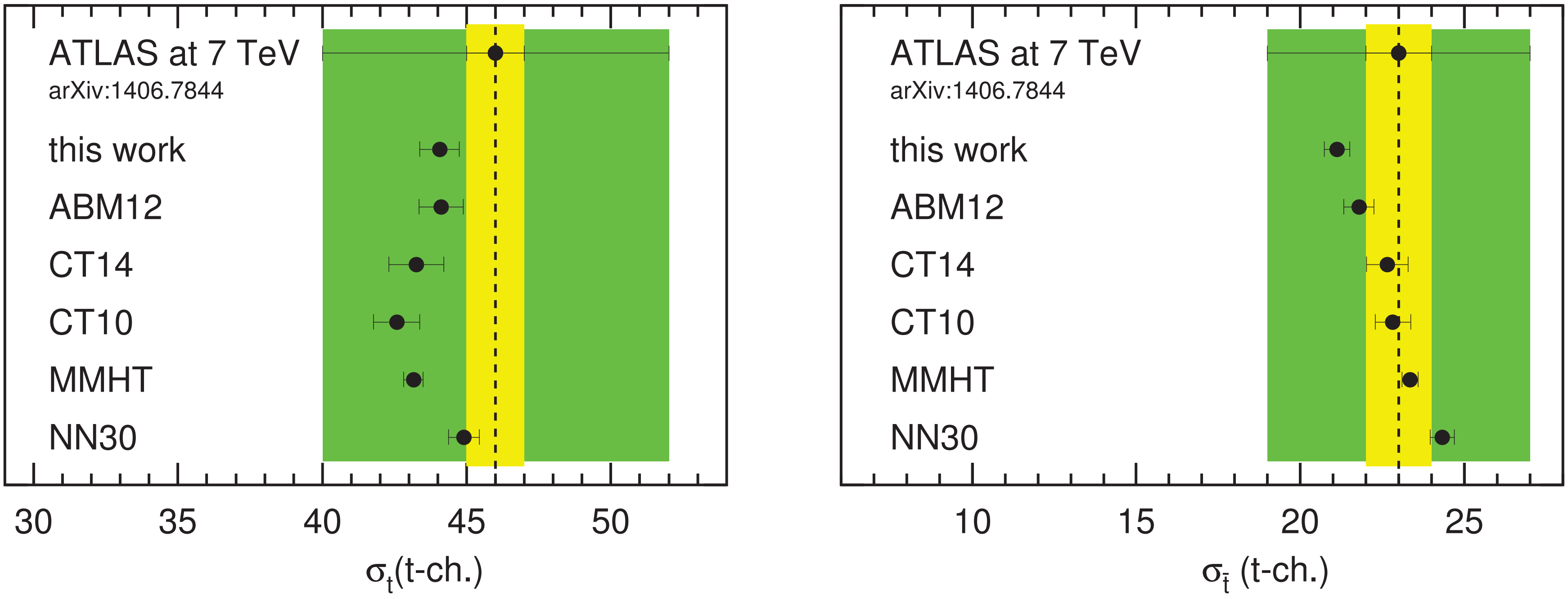




- Wt-production
  - contributes at LHC (small at Tevatron)

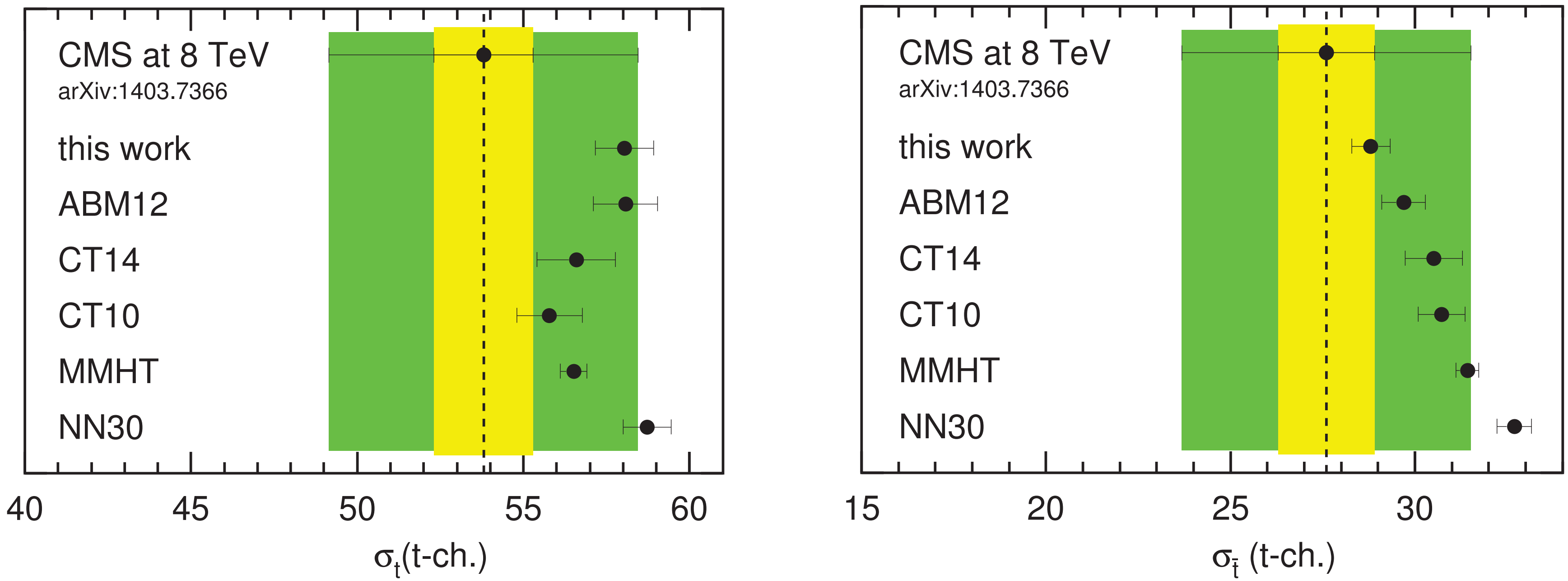


Inclusive cross sections (I)



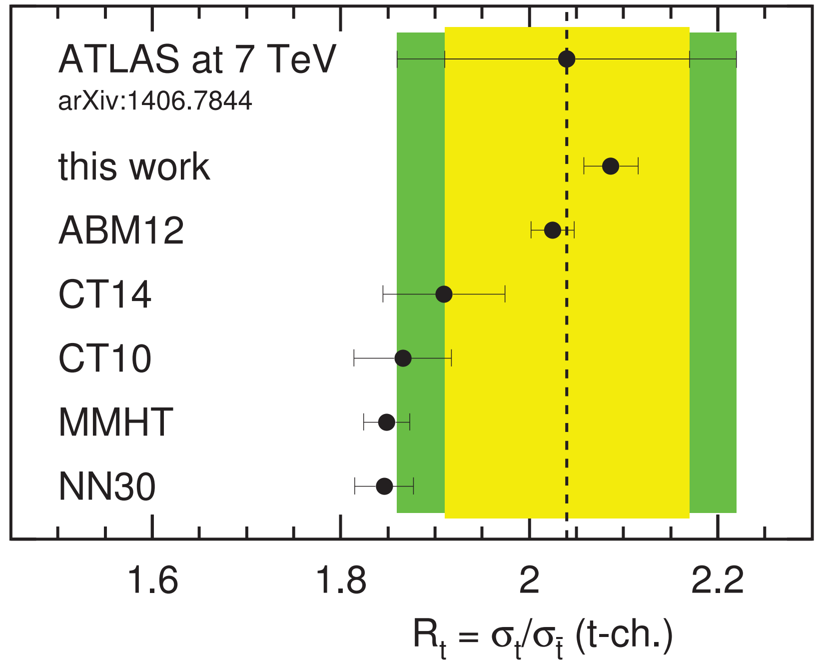
- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties Alekhin, Blümlein, S.M., Plačakytė '15
  - computation of hard cross section to NLO in QCD with Hathor for $\overline{\mathrm{MS}}$ mass $m_t(m_t) = 163$ GeV at scale $\mu_R = \mu_F = m_t(m_t)$
- Data at $\sqrt{s} = 7$ TeV from ATLAS
  - inner (yellow) band for statistical uncertainty and outer (green) band for combined statistics and systematics uncertainty

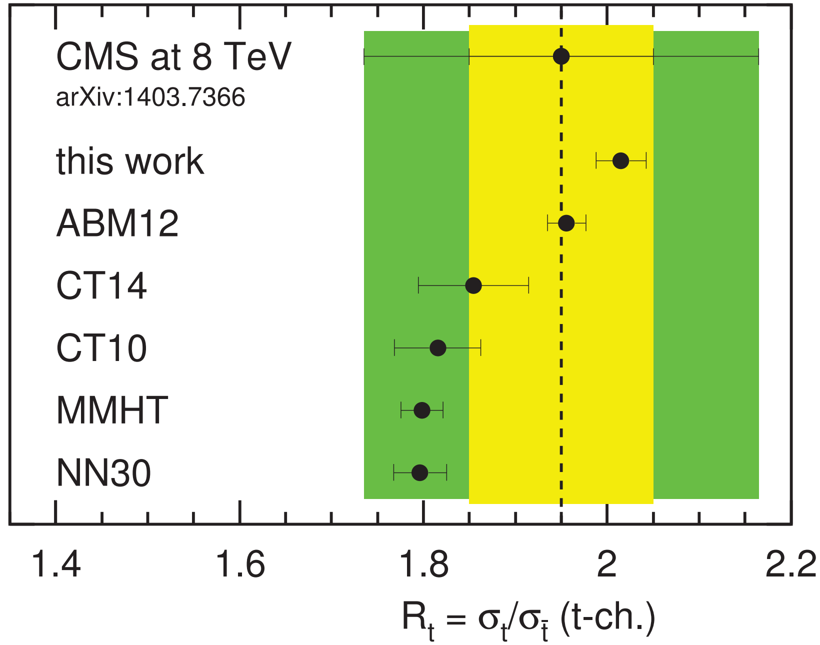
Inclusive cross sections (II)



- Cross sections for t-channel production of single (anti)top-quarks at LHC with 1σ PDF uncertainties Alekhin, Blümlein, S.M., Plačakytė '15
  - computation of hard cross section to NLO in QCD with Hathor for $\overline{\mathrm{MS}}$ mass $m_t(m_t) = 163$ GeV at scale $\mu_R = \mu_F = m_t(m_t)$
- Data at $\sqrt{s} = 8$ TeV from CMS
  - inner (yellow) band for statistical uncertainty and outer (green) band for combined statistics and systematics uncertainty

Cross section ratio





- Cross section ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ is very sensitive probe Alekhin, Blümlein, S.M., Plačakytė '15
  - data from ATLAS and CMS dominated by inner (yellow) band for statistical uncertainty, systematics largey cancel
- Theory predictions sensitive to ratio d/u of PDFs
  - 1σ PDF uncertainties in R_t small

Upshot

- Production of single top-quarks at LHC can serve as standard candle for the light quark flavor content of proton

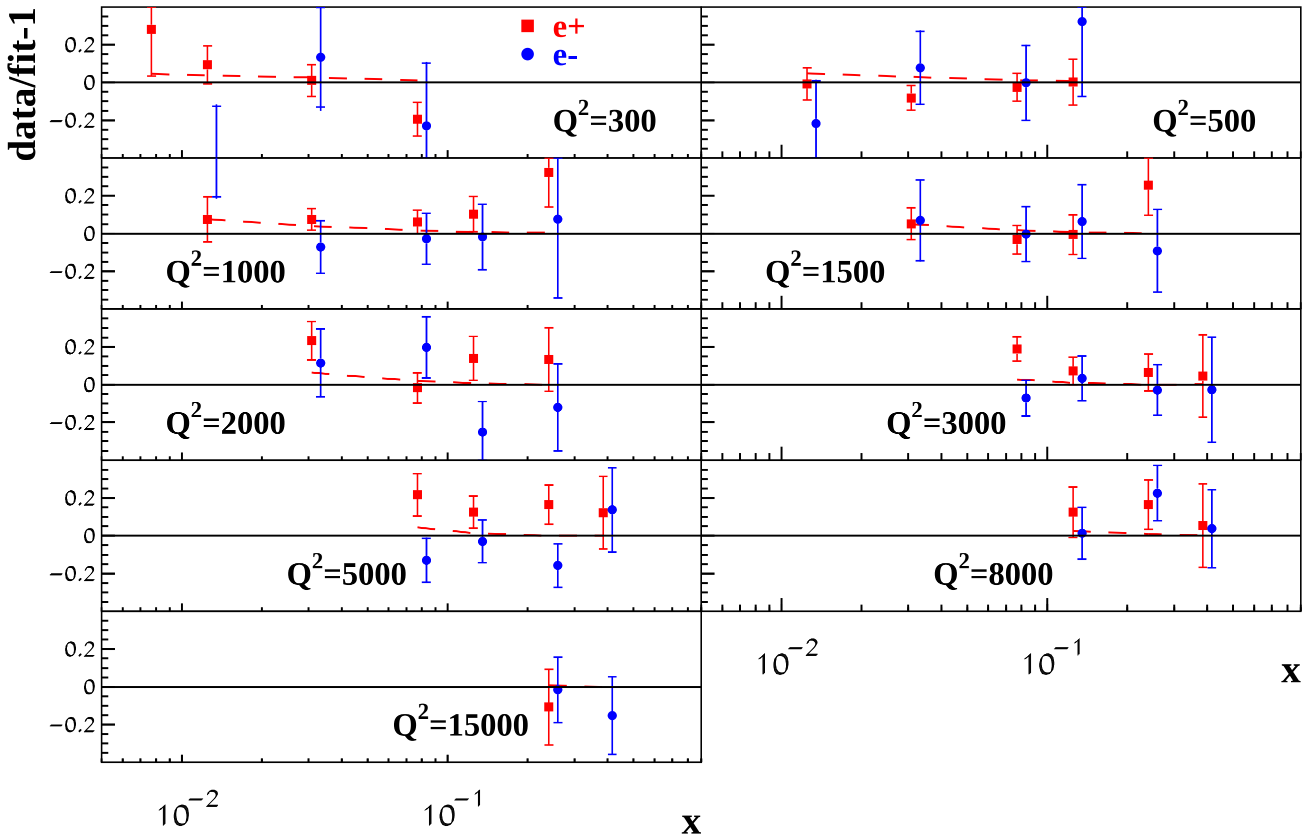
Strange sea in the proton

Strange sea determination

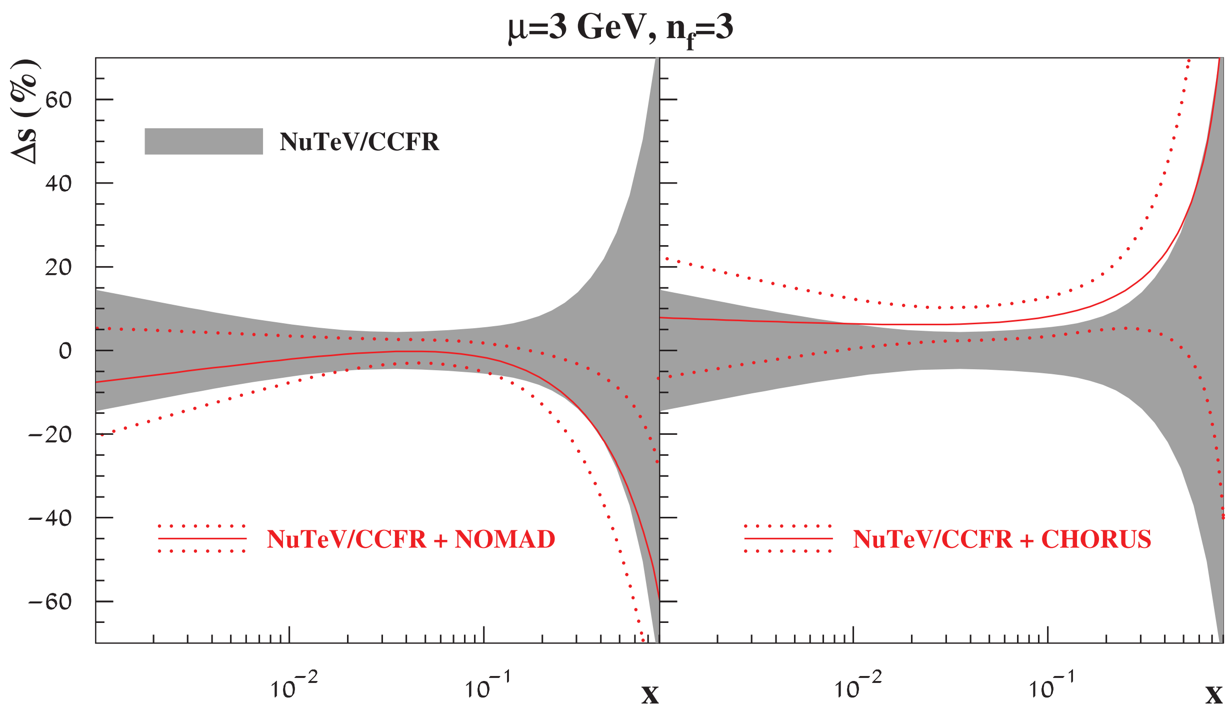
Charged current DIS

Alekhin, Bümlein, Caminada, Lipka, Lohwasser, S.M. Petti, Placakyte '14

- CC DIS inclusive data (HERA), CC DIS di-muon production data (NOMAD) and CC DIS charmed-hadron production data (CHORUS)
- Theory description with exact NLO QCD corrections and asymptotic NNLO terms at large $Q^2 \gg m^2$ Buza van Neerven '97



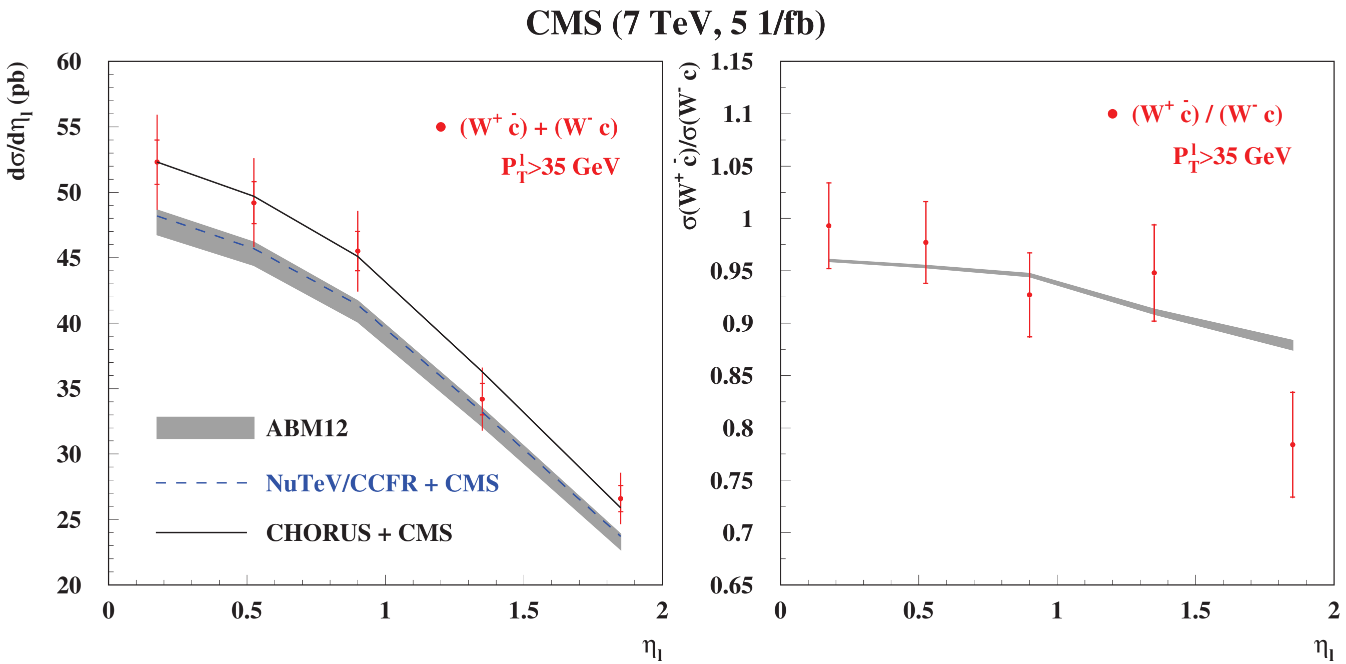
Strange sea from new fixed target data



- Nomad data on ratio of di-muon sample to incl. CC DIS with statistics of 15000 events (much more than CCFR and NuTeV samples)
  - systematics, nuclear corrections, etc. cancel in ratio
  - pull down strange quarks at $x > 0.1$; sizable reduction of uncertainty
  - $m_c(m_c) = 1.23 \pm 0.03(\text{exp.})\text{GeV}$
- Chorus data pull strangeness up
  - statistical significance of the effect is poor

W +charm production at LHC

- Cross check with LHC data for W+charm production

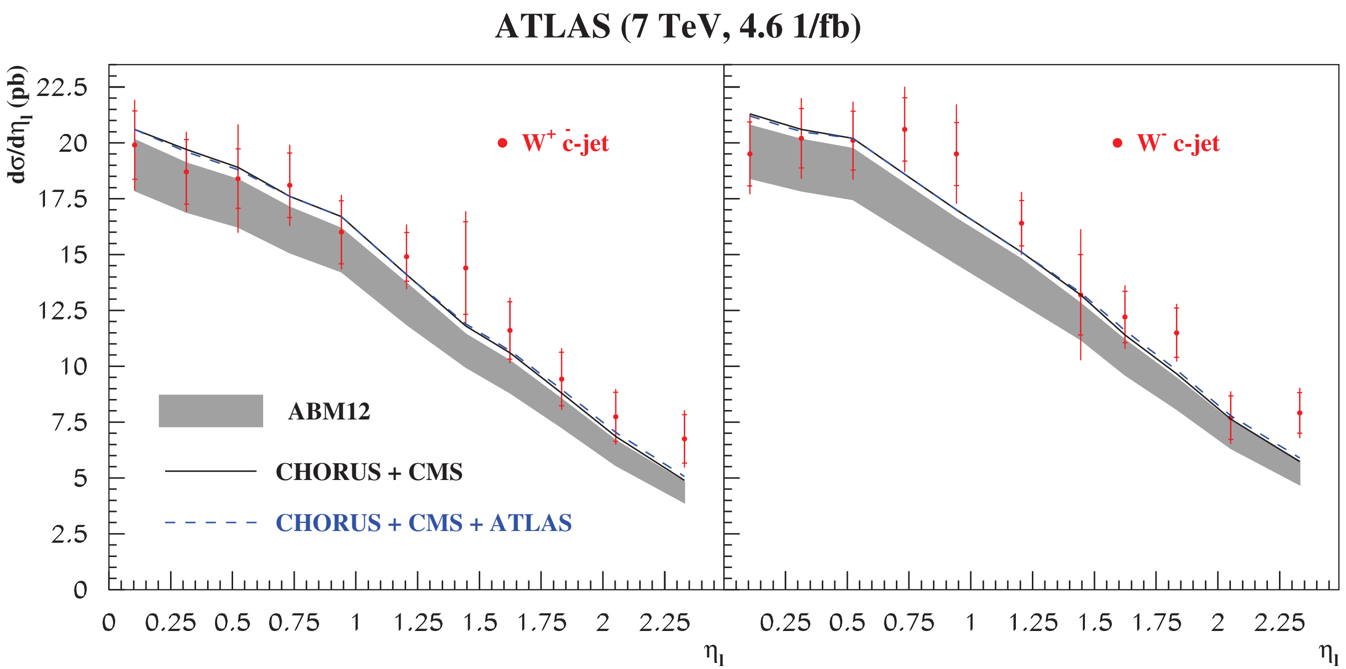


CMS

- CMS data above NuTeV/CCFR by 1σ
- Charge asymmetry in a good agreement with charge-symmetric strange sea

W+charm production at LHC

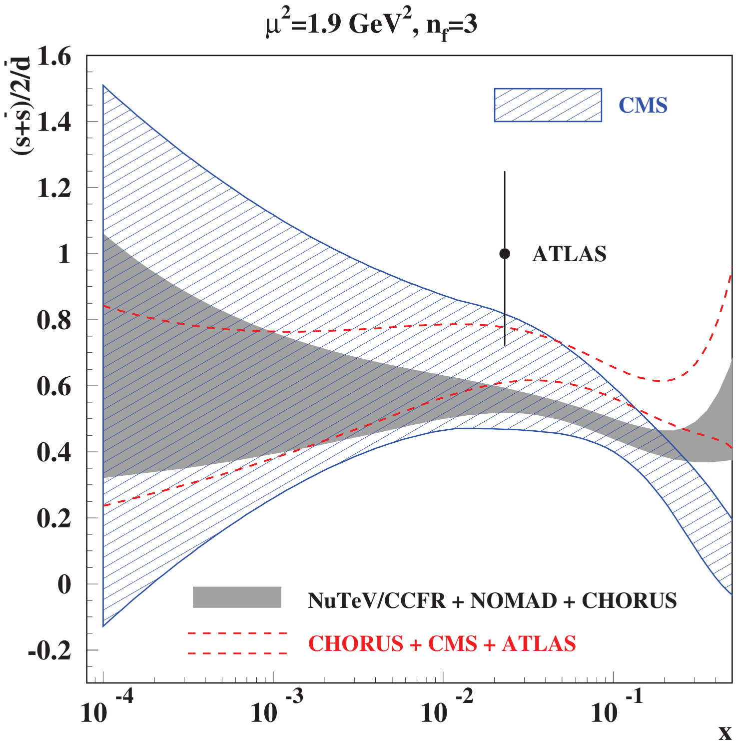
- Cross check with LHC data for *W*+charm production

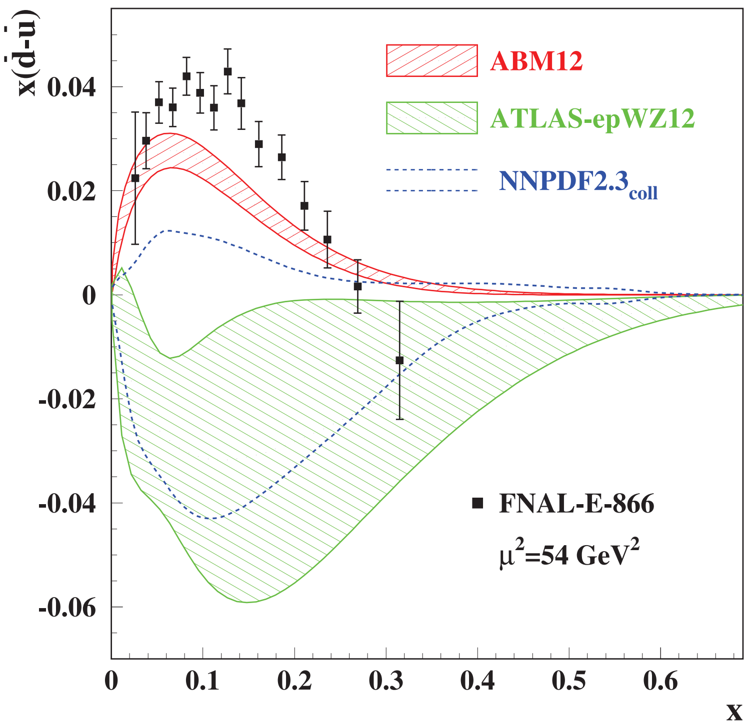


ATLAS

- ATLAS data in good agreement with NuTeV/CCFR
- Highest bin in η_l deviates

Comparision with earlier determinations



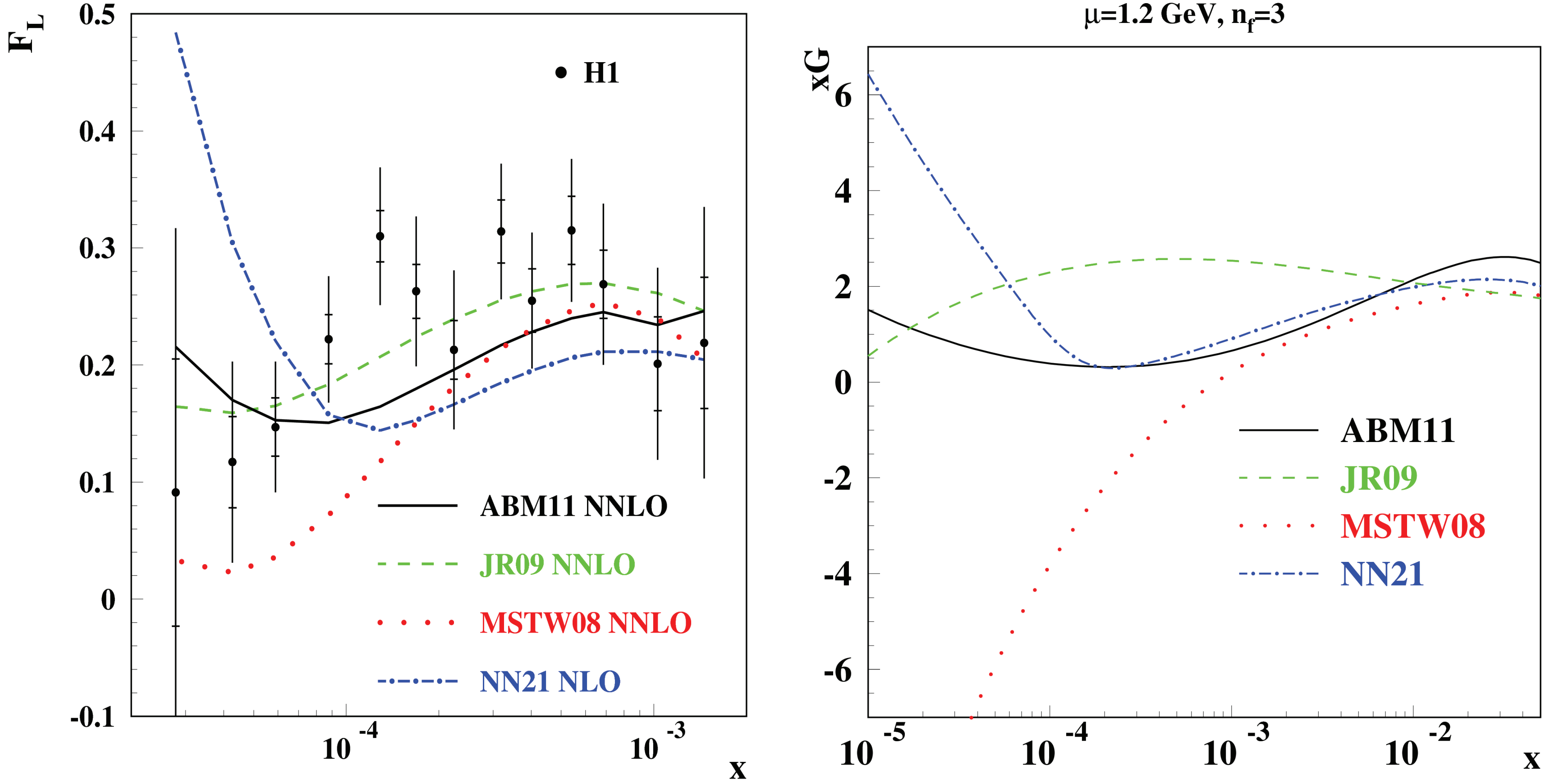


- ABM update (NuTeV/CCFR+NOMAD+CHORUS) in good agreement with CMS results
- ATLAS strange-sea in enhanced, but correlated with d-quark sea suppression (disagreement with the FNAL-E-866 data)
- Upper margin of ABM analysis (CHORUS+CMS+ATLAS) is lower than ATLAS

Gluon PDF at small x

Longitudinal structure function

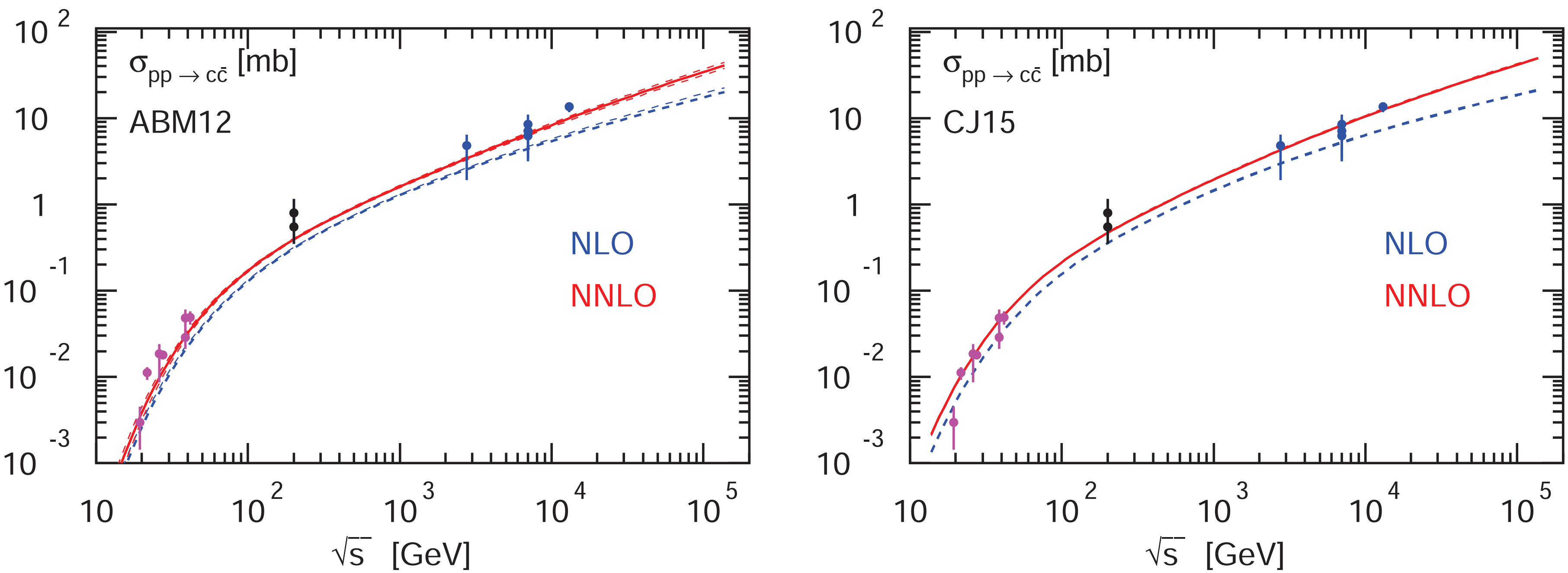
Discrimination of the small-x gluons



Slide from S. Alekhin

Charm quark hadro-production (I)

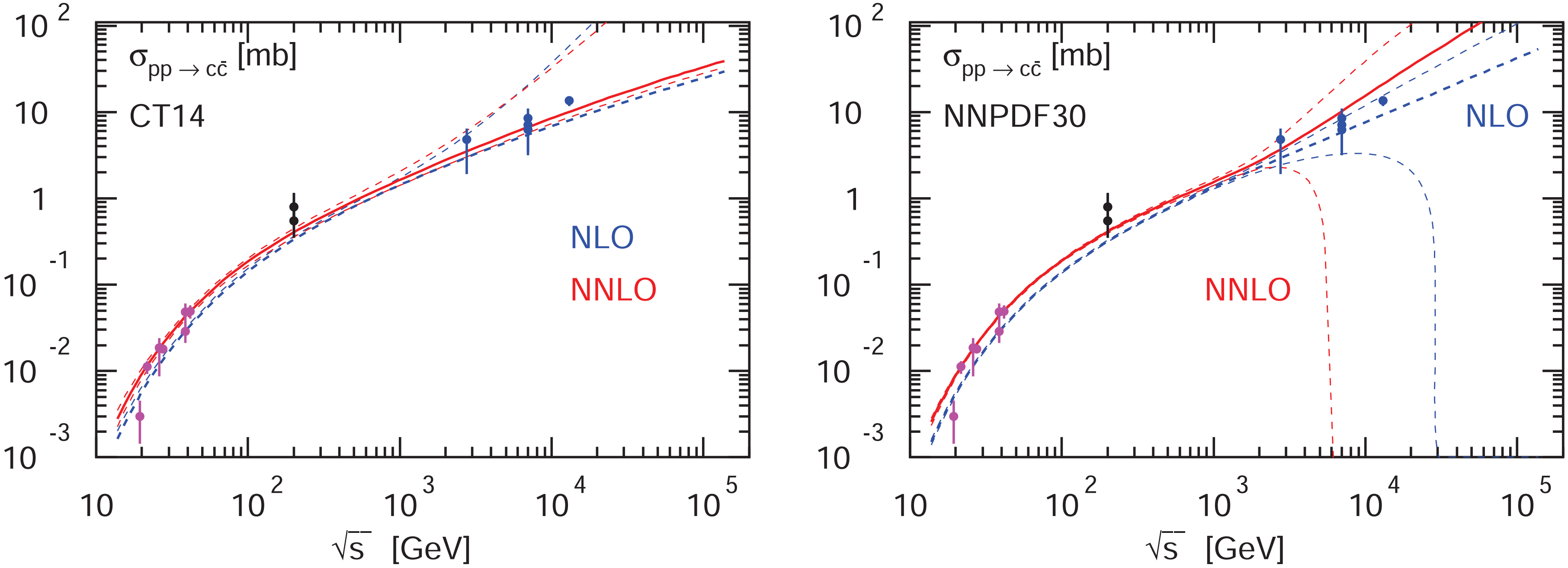
- Charm-quark hadro-production at high energies
  - quark-gluon parton luminosity dominates
- Gluon PDF at small-x
  - fits yield $xg(x) \simeq x^a$; e.g. $a \simeq -0.2$ in ABM12
  - kinematic coverage of data down to $x \simeq 10^{-5}$ (DIS structure function F_L)
- Predictions compatible with LHC measurements (Alice, ATLAS, LHCb)



Charm quark hadro-production (II)

Issues

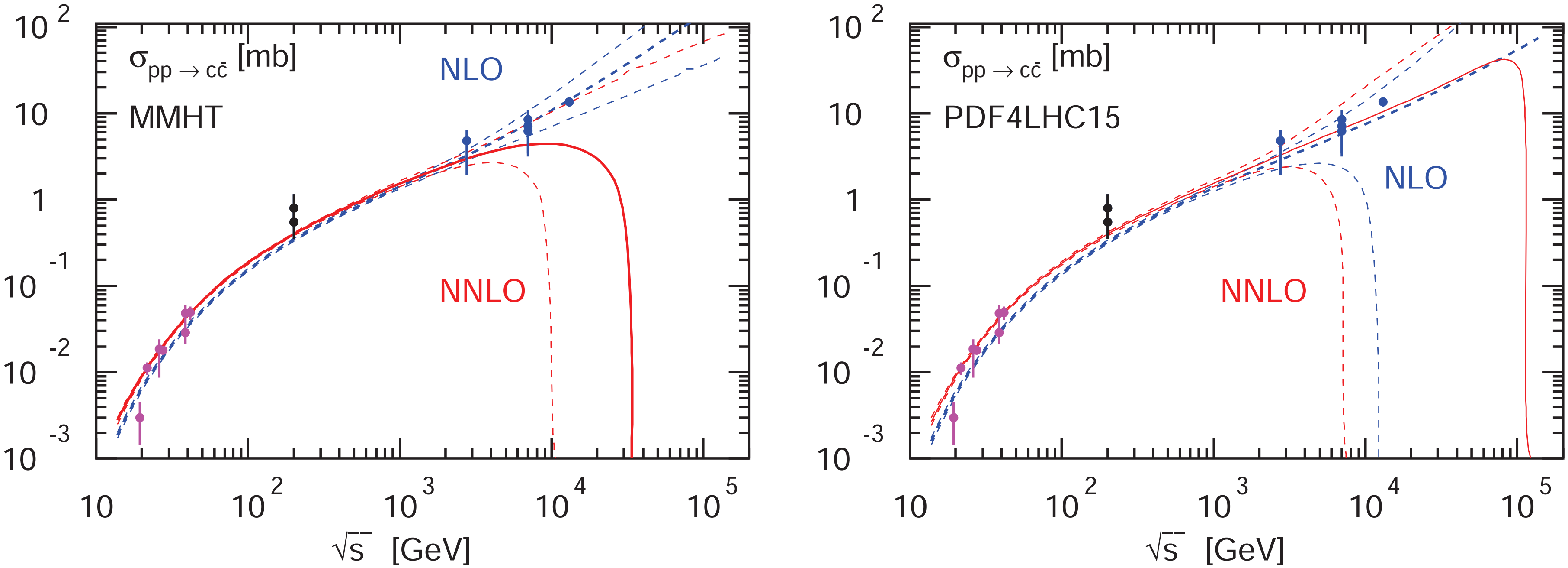
- Extrapolation of gluon PDF towards smaller x
  - some PDFs feature large uncertainities for extrapolation to unmeasured regions $\longrightarrow$ this invalidates predictive potential



Charm quark hadro-production (III)

More issues

- Some PDFs predict negative gluon PDF at small-x and low scales $\mu_F \simeq 2m_c$
  - negative cross section is unphysical; consequence of modelling in variable flavor number schemes applied and description of structure function F_L at NNLO
  - large differences between gluon PDFs fitted at NLO and NNLO



Strong coupling constant

Strong coupling constant (1992)

	$\alpha_s(\mathrm{M}_\mathrm{Z}^2)$
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: $\alpha_s(M_Z) = 0.1132 \dots 0.1172$
- 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

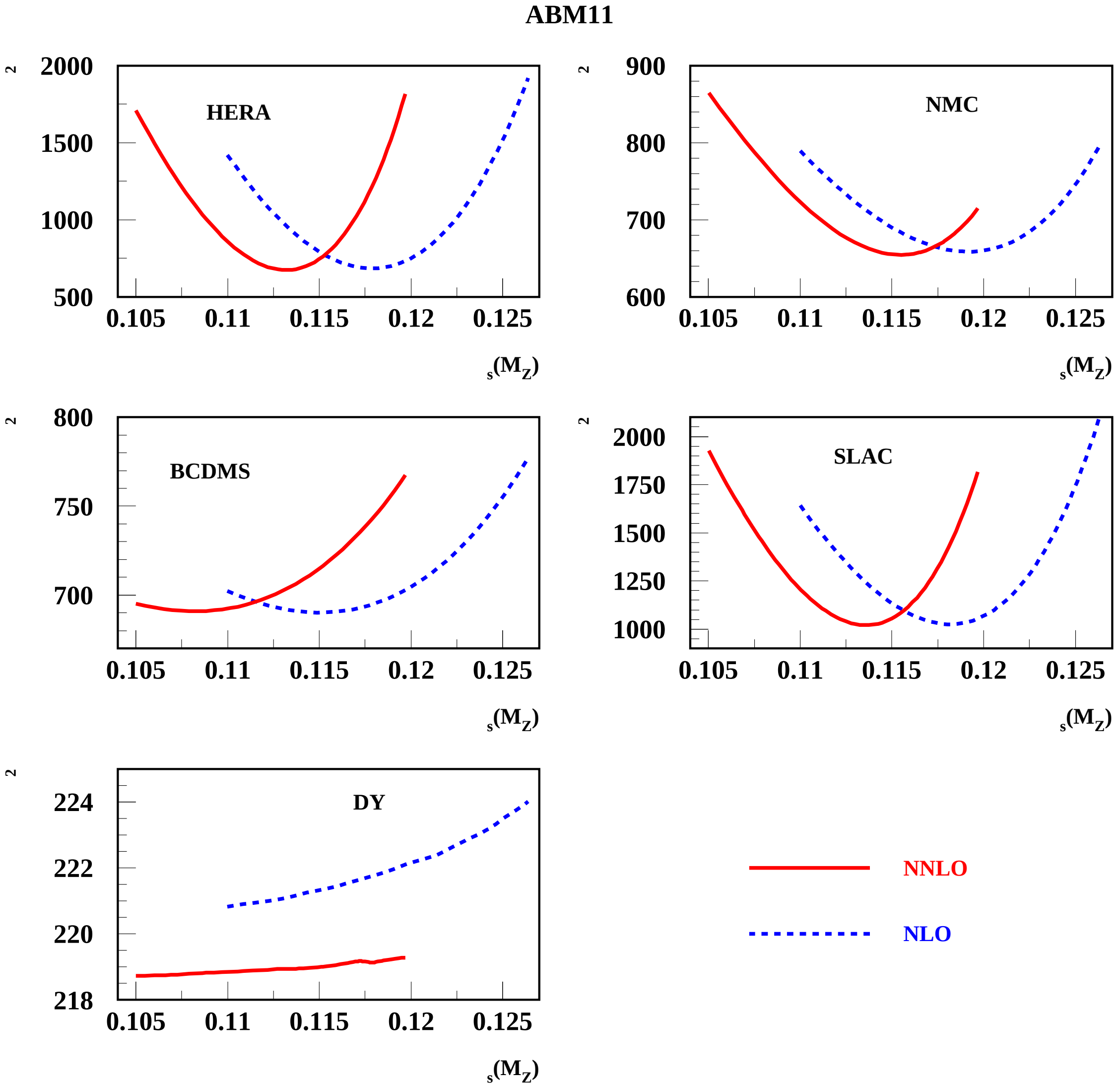
- Differences result from different physics models and analysis procedures
- Fits of DIS data
  - target mass corrections (powers of nucleon mass M_N^2/Q^2)
  - higher twist $F_2^{\rm ht} = F_2 + ht^{(4)}(x)/Q^2 + ht^{(6)}(x)/Q^4 + \dots$
  - correlation of errors among different data sets

	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

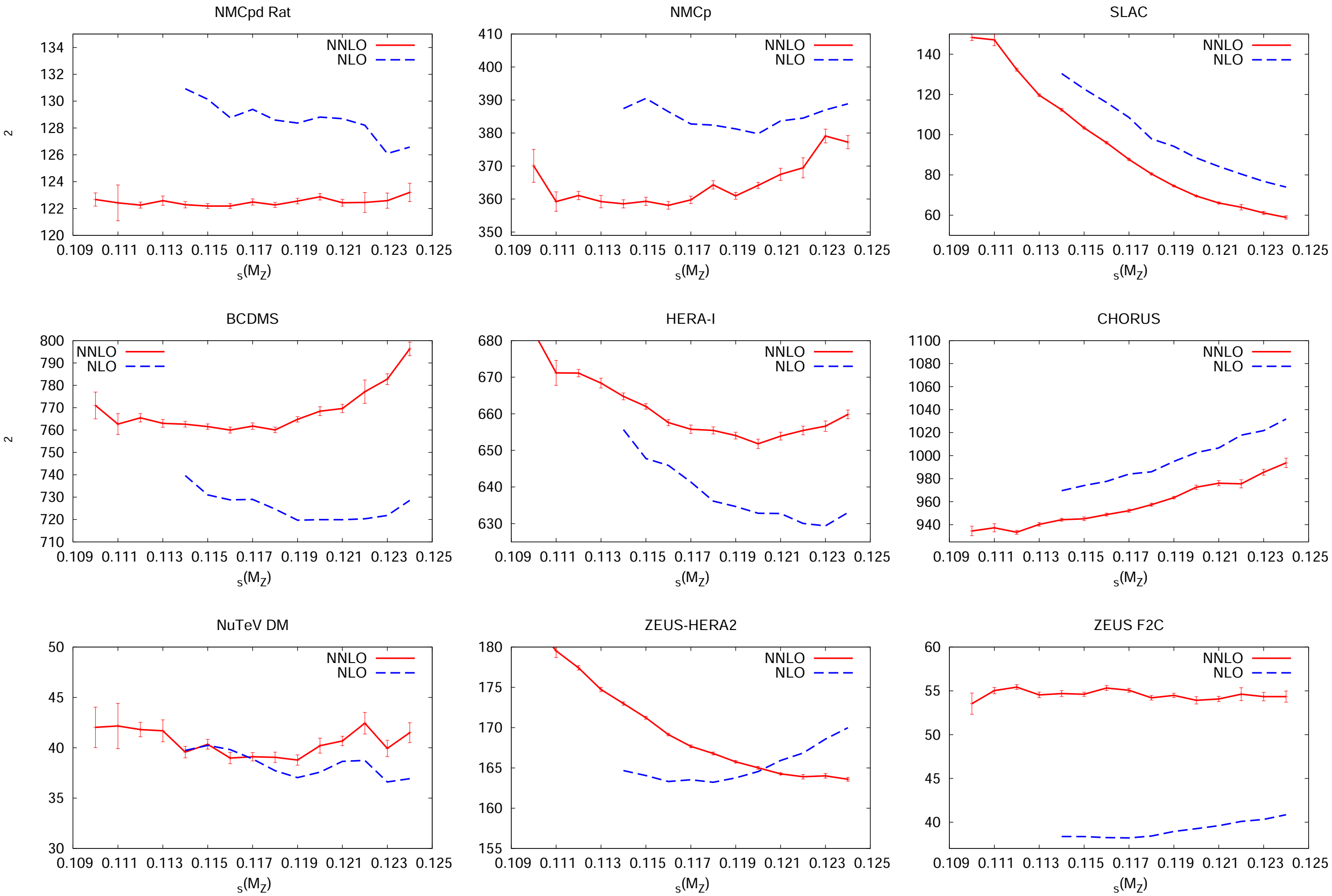
α_s from DIS and PDFs



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

Zooming in on NNPDF

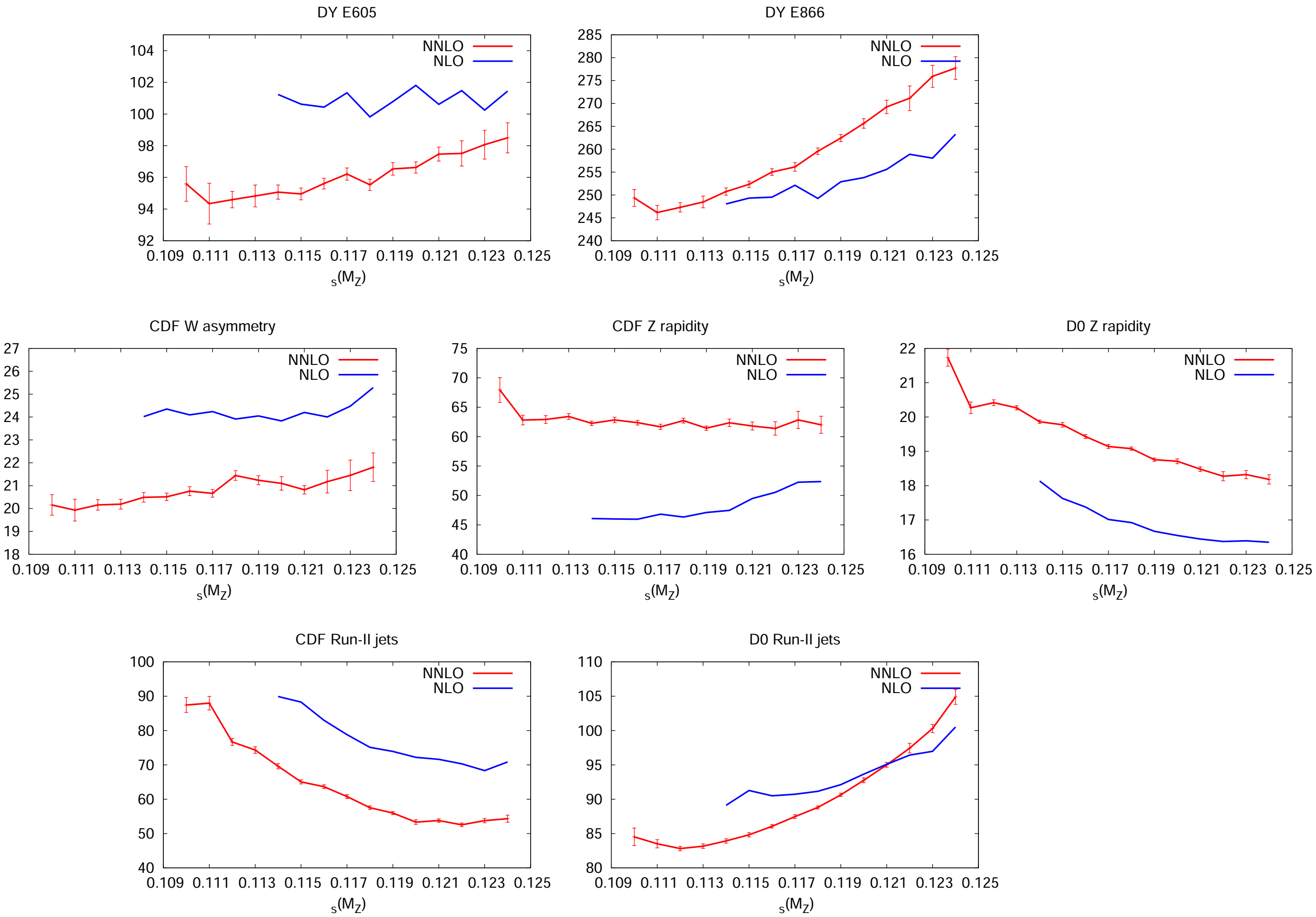
α_s from DIS and PDFs



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

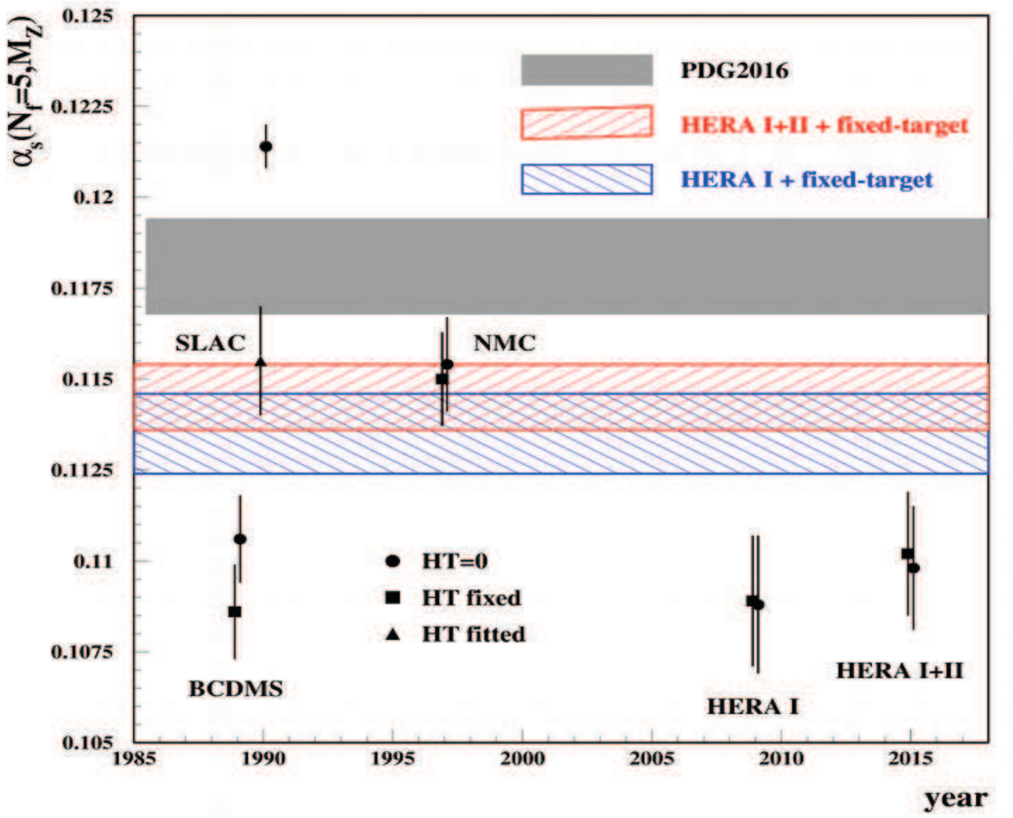
Zooming in on NNPDF

α_s *from DIS and PDFs*



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

Update of the α_s determination



Slide from S. Alekhin

- α_s goes up by 1σ with HERA I+II data
- the value of α_s is still lower than the PDG one: pulled up by the SLAC and NMC data; pulled down by the BCDMS and HERA ones
- only SLAC determination overlap with the PDG band provided the high-twist terms are taken into account

Summary

- Precision determination 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
- Uncertainties due model assumption in PDF fits often neglected
  - implementations of variable flavor number schemes use charm-quark mass m_c for tuning
  - low value of pole mass $m_c^{\rm pole} \simeq 1.25$GeV in contradiction to world average
- Values of $\alpha_s(M_Z)$ at NNLO from measurements at colliders lower than world average
  - $\alpha_s(M_Z) = 0.118$ at NNLO not preferred by data
  - data analysis with fixed value of $\alpha_s(M_Z)$ lacks correlation with parameters of PDF fits
- PDF4LHC recommendations introduce bias and inflated uncertainties
  - very difficult to quantify potential discrepancies between individual PDF sets