Light-flavor parton distributions from collider data

Sven-Olaf Moch

Universität Hamburg

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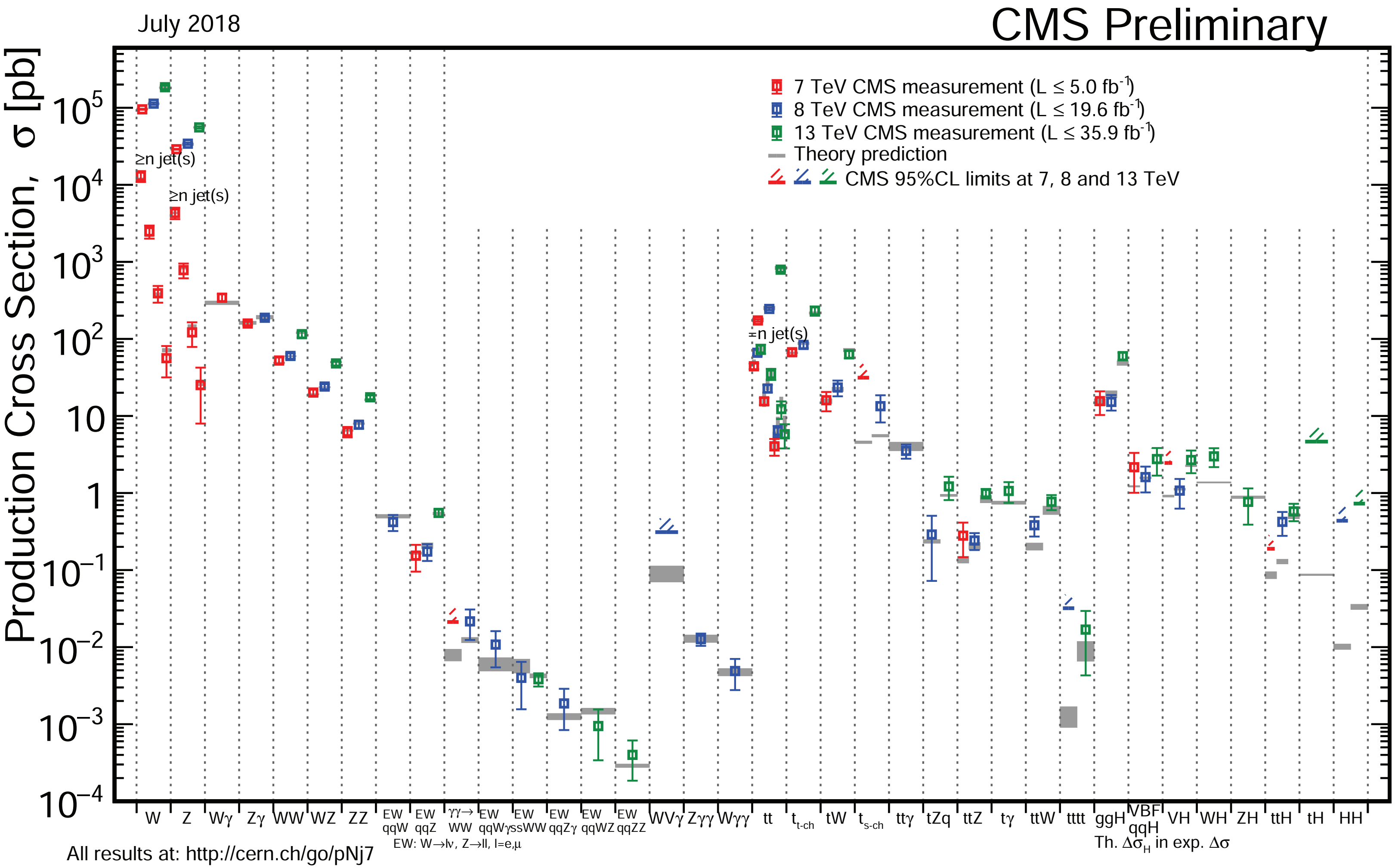
Based on work done in collaboration with:

- *NLO PDFs from the ABMP16 fit*
  S. Alekhin, J. Blümlein and S. M. arXiv:1803.07537
- *Strange sea determination from collider data*
  S. Alekhin, J. Blümlein and S. M. arXiv:1708.01067
- *Parton distribution functions, α_s, and heavy-quark masses for LHC Run II*
  S. Alekhin, J. Blümlein, S. M. and R. Plačakytė arXiv:1701.05838
- *A Critical Appraisal and Evaluation of Modern PDFs*
  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
- Many more papers of ABM and friends . . .
  2008 - ...

Standard Model cross sections

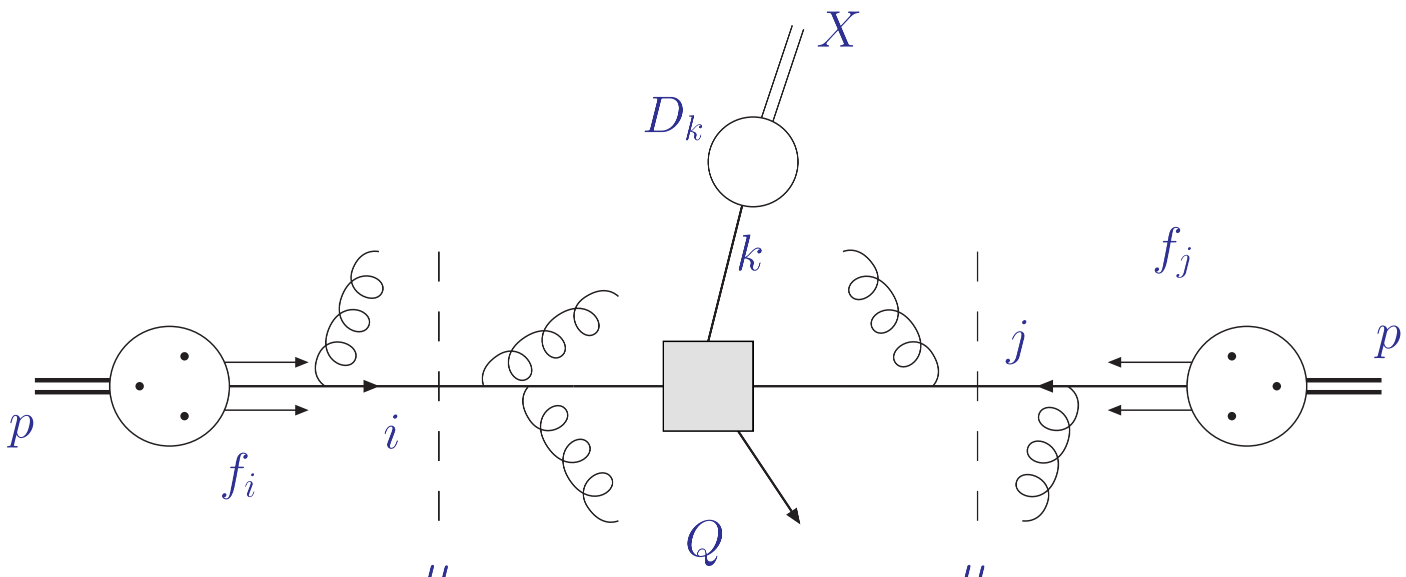
Cross sections for Standard Model processes at the LHC

- Hadroproduction of top-quarks (+ jets) and single-tops CMS coll. '18



QCD factorization

QCD factorization

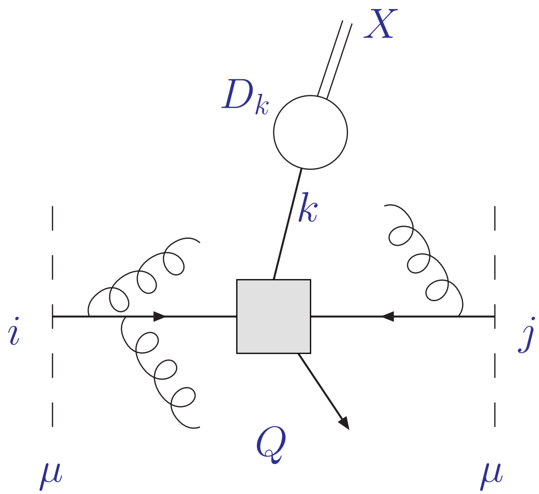


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Factorization at scale μ
  - separation of sensitivity to dynamics from long and short distances
- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- 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, . . .

Hard scattering cross section

- Parton cross section $\hat{\sigma}_{ij\to k}$ calculable pertubatively in powers of α_s
  - known to NLO, NNLO, ... ($\mathcal{O}(\text{few}\%)$ theory uncertainty)



- Accuracy of perturbative predictions
  - LO (leading order) ($\mathcal{O}(50-100\%)$ unc.)
  - NLO (next-to-leading order) ($\mathcal{O}(10-30\%)$ unc.)
  - NNLO (next-to-next-to-leading order) ($\lesssim$ $\mathcal{O}(10\%)$ unc.)
  - N^3LO (next-to-next-to-next-to-leading order)
  - ...

Parton luminosity

- Long distance dynamics due to proton structure

- Cross section depends on parton distributions f_i

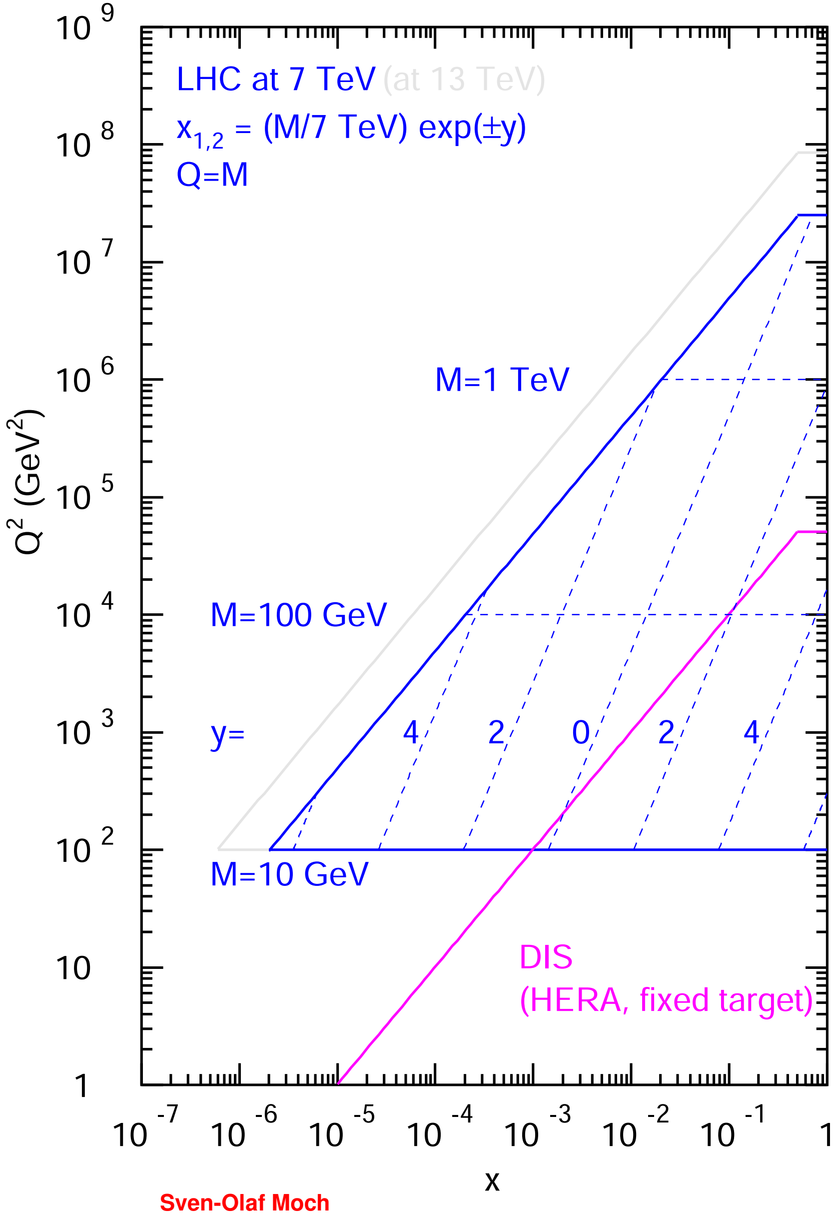
$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \left[\dots \right]$$

- Parton distributions known from global fits to exp. data
  - available fits accurate to NNLO
  - information on proton structure depends on kinematic coverage

Parton content of the proton

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 $x_{1,2} = M/\sqrt{S}\mathrm{e}^{\pm y}$
  - 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

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

Evolution equations

- Parton distribution functions $q_i(x,\mu^2)$, $\bar{q}_i(x,\mu^2)$ and $g(x,\mu^2)$ for quarks, antiquarks of flavour i and gluons
- Flavor non-singlet combinations with $2n_f - 1$ scalar evolution equations

$$q^{\pm}_{\mathrm{ns},ik} = (q_i \pm \bar{q}_i) - (q_k \pm \bar{q}_k) \quad \text{and} \quad q^{\mathrm{v}}_{\mathrm{ns}} = \sum_{i=1}^{n_f} (q_i - \bar{q}_i)$$

with $$\frac{d}{d\ln\mu^2}\, q^{\pm,\mathrm{v}}_{\mathrm{ns}} = P^{\pm,\mathrm{v}}_{\mathrm{ns}} \otimes q^{\pm,\mathrm{v}}_{\mathrm{ns}}$$

  - splitting functions $P^{\pm}_{\mathrm{ns}}$ and $P^{\mathrm{v}}_{\mathrm{ns}} = P^{-}_{\mathrm{ns}} + P^{\mathrm{s}}_{\mathrm{ns}}$

- Flavor singlet (2×2 matrix) evolution equations

$$\frac{d}{d\ln\mu^2} \begin{pmatrix} q_{\mathrm{s}} \\ g \end{pmatrix} = \begin{pmatrix} P_{\mathrm{qq}} & P_{\mathrm{qg}} \\ P_{\mathrm{gq}} & P_{\mathrm{gg}} \end{pmatrix} \otimes \begin{pmatrix} q_{\mathrm{s}} \\ g \end{pmatrix} \quad \text{and} \quad q_{\mathrm{s}} = \sum_{i=1}^{n_f} (q_i + \bar{q}_i)$$

  - quark-quark splitting function $P_{\mathrm{qq}} = P^{+}_{\mathrm{ns}} + P_{\mathrm{ps}}$

- Perturbative expansion of splitting functions up to N^{3}LO

$$P_{ij} = \alpha_s P^{(0)}_{ij} + \alpha_s^2 P^{(1)}_{ij} + \alpha_s^3 P^{(2)}_{ij} + \alpha_s^4 P^{(3)}_{ij} + \ldots$$

PDF landscape

- Significant number of active groups ABMP16, CJ15, CT14, HERAPDF2.0, JR14, MMHT14, NNPDF3.1
  - PDFs accurate to NNLO in QCD, except for CJ15 (NLO)
  - different choices of data sets
  - different fitting procedures ($\Delta\chi^2$ criterium)

PDF sets	$\Delta\chi^2$ criterion	data sets used in analysis
ABMP16 arXiv:1701.05838	1	incl. DIS, DIS charm, DY, $t\bar{t}$, single t
CJ15 arXiv:1602.03154	1	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	$2.3 \dots 42.3$ (dynamical)	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$
NNPDF3.1 arXiv:1706.00428	n.a.	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$, $W +$ charm, $Z p_T$

Data in global PDF fits

Data sets considered in ABMP16 analysis

- Analysis of world data for deep-inelastic scattering, fixed-target data for Drell-Yan process and collider data ($W^{\pm}$-, Z-bosons, top-quarks)
  - inclusive DIS data HERA, BCDMS, NMC, SLAC ($NDP = 2155$)
  - semi-inclusive DIS charm-, bottom-quark data HERA ($NDP = 81$)
  - Drell-Yan data (fixed target) E-605, E-866 ($NDP = 158$)
  - neutrino-nucleon DIS (di-muon data) CCFR/NuTeV, CHORUS, NOMAD ($NDP = 232$)
  - $W^{\pm}$-, Z-boson production data D0, ATLAS, CMS, LHCb ($NDP = 172$)
  - inclusive top-quark hadro-production CDF&D0, ATLAS, CMS ($NDP = 24$)

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 PDFs, strong coupling $\alpha_s(M_Z)$ and heavy quark masses m_c, m_b, m_t,

Theory considerations in PDF fits

Theory considerations in ABMP16

- 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
- PDF parameters, α_s, m_c, m_b and m_t sensitive to
  - radiative corrections at higher orders
  - chosen scheme (e.g. ($\overline{MS}$ scheme)
  - renormalization and factorization scales μ_R, μ_F
  - . . .

ABMP16 PDF ansatz

- PDFs parameterization at scale $\mu_0 = 3\mathrm{GeV}$ in scheme with $n_f = 3$
  Alekhin, Blümlein, S.M., Placakyte '17
  - ansatz for valence-/sea-quarks, gluon

$$
\begin{aligned}
xq_v(x,\mu_0^2) &= \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} x^{a_q}(1-x)^{b_q} x^{P_{qv}(x)} \\
xq_s(x,\mu_0^2) &= x\bar{q}_s(x,\mu_0^2) = A_{qs}(1-x)^{b_{qs}} x^{a_{qs} P_{qs}(x)} \\
xg(x,\mu_0^2) &= A_g x^{a_g}(1-x)^{b_g} x^{a_g P_g(x)}
\end{aligned}
$$

  - strange quark is taken in charge-symmetric form
  - function $P_p(x)$

$$
P_p(x) = (1 + \gamma_{-1,p} \ln x) \left(1 + \gamma_{1,p} x + \gamma_{2,p} x^2 + \gamma_{3,p} x^3\right) ,
$$

  - 29 parameters in fit including $\alpha_s^{(n_f=3)}(\mu_0 = 3$ GeV$)$, m_c, m_b and m_t
  - simultaneous fit of higher twist parameters (twist-4)
- 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 fit parameters of ABMP16 PDFs

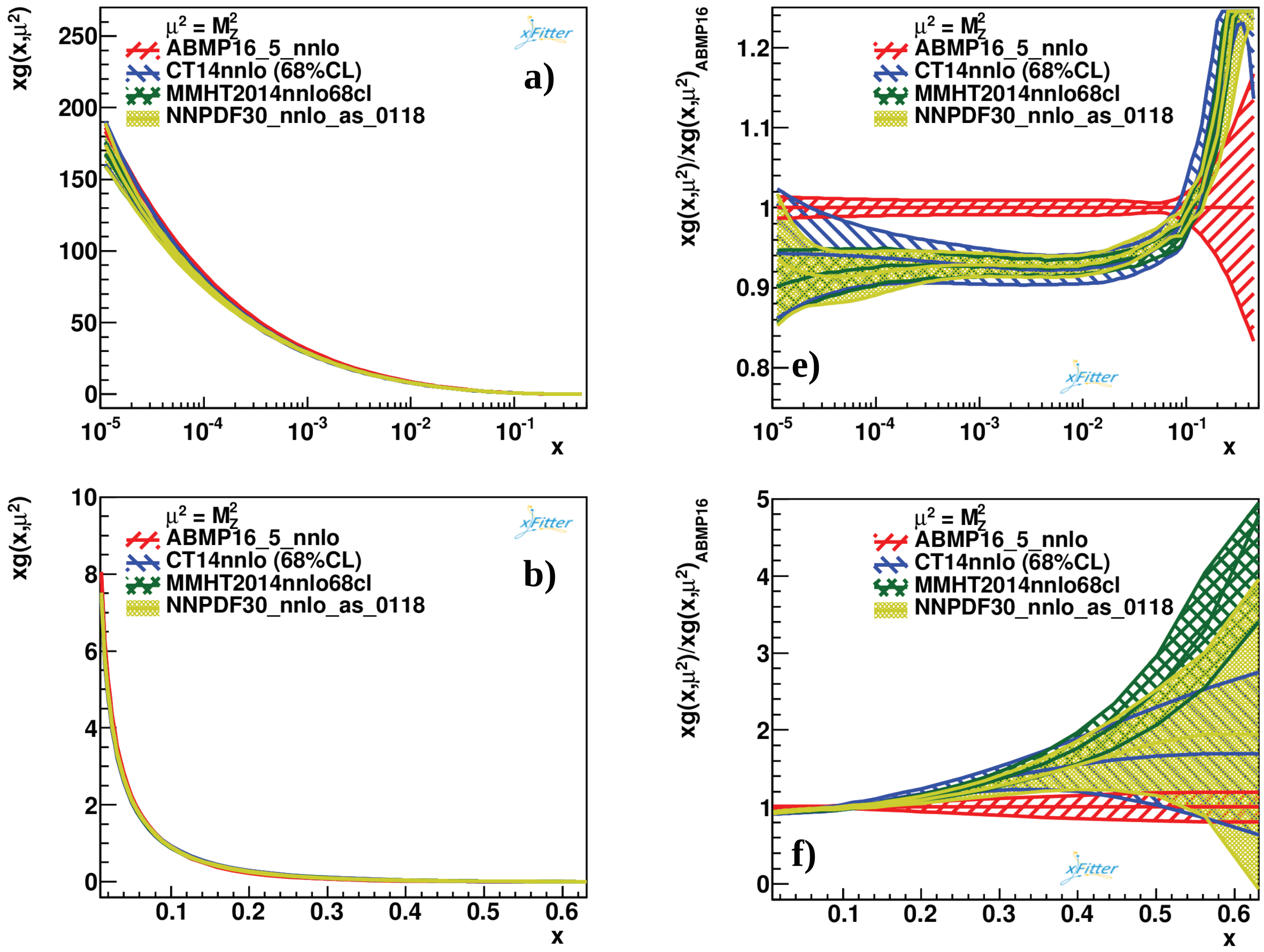
	a_u	b_u	$\gamma_{1,u}$	$\gamma_{2,u}$	$\gamma_{3,u}$	a_d	b_d	$\gamma_{1,d}$	$\gamma_{2,d}$	$\gamma_{3,d}$
a_u	1.0	0.7617	0.9372	-0.5078	0.4839	0.4069	0.3591	0.4344	-0.3475	0.0001
b_u	0.7617	1.0	0.6124	-0.1533	-0.0346	0.3596	0.2958	0.3748	-0.2748	0.0001
$\gamma_{1,u}$	0.9372	0.6124	1.0	-0.7526	0.7154	0.2231	0.2441	0.2812	-0.2606	0.0001
$\gamma_{2,u}$	-0.5078	-0.1533	-0.7526	1.0	-0.9409	0.2779	0.2276	0.2266	-0.1860	0.0
$\gamma_{3,u}$	0.4839	-0.0346	0.7154	-0.9409	1.0	-0.1738	-0.1829	-0.1327	0.1488	0.0
a_d	0.4069	0.3596	0.2231	0.2779	-0.1738	1.0	0.7209	0.9697	-0.6529	0.0001
b_d	0.3591	0.2958	0.2441	0.2276	-0.1829	0.7209	1.0	0.7681	-0.9786	-0.0001
$\gamma_{1,d}$	0.4344	0.3748	0.2812	0.2266	-0.1327	0.9697	0.7681	1.0	-0.7454	0.0002
$\gamma_{2,d}$	-0.3475	-0.2748	-0.2606	-0.1860	0.1488	-0.6529	-0.9786	-0.7454	1.0	-0.0002
$\gamma_{3,d}$	0.0001	0.0001	0.0001	0.0	0.0	0.0001	-0.0001	0.0002	-0.0002	1.0
a_{us}	-0.0683	-0.0081	-0.2094	0.3881	-0.3206	0.2266	0.1502	0.2000	-0.1293	0.0
b_{us}	-0.3508	-0.3089	-0.3462	0.0906	-0.0537	-0.1045	-0.2000	-0.2241	0.2798	0.0
$\gamma_{-1,us}$	0.2296	0.1387	0.3367	-0.4043	0.3474	-0.1171	-0.1127	-0.0810	0.0767	0.0
$\gamma_{1,us}$	-0.4853	-0.4119	-0.3844	-0.0365	0.0064	-0.4380	-0.3592	-0.4957	0.3771	-0.0001
A_{us}	0.0506	0.0807	-0.0949	0.3198	-0.2560	0.2527	0.1648	0.2350	-0.1509	0.0
a_{ds}	-0.0759	-0.0443	-0.0951	0.0263	-0.0382	-0.2565	-0.2541	-0.2666	0.2380	0.0
b_{ds}	0.0452	-0.0197	0.0345	-0.0589	0.0683	-0.2084	0.0190	-0.1841	-0.0522	0.0
$\gamma_{1,ds}$	-0.0492	-0.0809	0.0101	-0.1791	0.1309	-0.5576	-0.2029	-0.4584	0.0946	0.0
A_{ds}	-0.1980	-0.1262	-0.2349	0.1526	-0.1428	-0.1113	-0.2167	-0.1739	0.2407	0.0
a_{ss}	-0.2034	-0.1285	-0.2362	0.2328	-0.2080	0.0960	0.1596	0.0661	-0.1054	0.0
b_{ss}	-0.1186	-0.0480	-0.1532	0.1549	-0.1536	0.0486	0.1508	0.0267	-0.1161	0.0
A_{ss}	-0.1013	-0.0411	-0.1458	0.1802	-0.1625	0.1216	0.1678	0.0924	-0.1196	0.0
a_g	0.0046	-0.0374	0.1109	-0.1934	0.1653	-0.0288	-0.0122	0.0053	0.0059	0.0
b_g	0.2662	0.3141	0.1579	-0.0050	-0.0207	0.0973	0.0870	0.0646	-0.0666	0.0
$\gamma_{1,g}$	0.2008	0.2274	0.0706	0.0876	-0.0835	0.0919	0.0574	0.0493	-0.0364	0.0
$\alpha_s^{(n_f=3)}(\mu_0)$	0.1083	-0.0607	0.0848	-0.0250	0.0765	0.0763	-0.0306	0.0725	0.0243	0.0
$m_c(m_c)$	-0.0006	0.0170	-0.0104	0.0206	-0.0201	-0.0123	-0.0161	-0.0114	0.0108	0.0
$m_b(m_b)$	0.0661	0.0554	0.0605	-0.0367	0.0287	-0.0116	0.0029	-0.0074	-0.0051	0.0
$m_t(m_t)$	-0.1339	-0.2170	-0.0816	0.0081	0.0250	-0.0616	-0.0813	-0.0491	0.0736	0.0

	a_{us}	b_{us}	$\gamma_{-1,us}$	$\gamma_{1,us}$	A_{us}	a_{ds}	b_{ds}	$\gamma_{1,ds}$	A_{ds}	a_{ss}
a_u	-0.0683	-0.3508	0.2296	-0.4853	0.0506	-0.0759	0.0452	-0.0492	-0.1980	-0.2034
b_u	-0.0081	-0.3089	0.1387	-0.4119	0.0807	-0.0443	-0.0197	-0.0809	-0.1262	-0.1285
$\gamma_{1,u}$	-0.2094	-0.3462	0.3367	-0.3844	-0.0949	-0.0951	0.0345	0.0101	-0.2349	-0.2362
$\gamma_{2,u}$	0.3881	0.0906	-0.4043	-0.0365	0.3198	0.0263	-0.0589	-0.1791	0.1526	0.2328
$\gamma_{3,u}$	-0.3206	-0.0537	0.3474	0.0064	-0.2560	-0.0382	0.0683	0.1309	-0.1428	-0.2080
a_d	0.2266	-0.1045	-0.1171	-0.4380	0.2527	-0.2565	-0.2084	-0.5576	-0.1113	0.0960
b_d	0.1502	-0.2000	-0.1127	-0.3592	0.1648	-0.2541	0.0190	-0.2029	-0.2167	0.1596
$\gamma_{1,d}$	0.2000	-0.2241	-0.0810	-0.4957	0.2350	-0.2666	-0.1841	-0.4584	-0.1739	0.0661
$\gamma_{2,d}$	-0.1293	0.2798	0.0767	0.3771	-0.1509	0.2380	-0.0522	0.0946	0.2407	-0.1054
$\gamma_{3,d}$	0.0	0.0	0.0	-0.0001	0.0	0.0	0.0	0.0	0.0	0.0
a_{us}	1.0	-0.3156	-0.8947	-0.5310	0.9719	0.2849	0.0241	-0.0470	0.2983	0.4131
b_{us}	-0.3156	1.0	0.1372	0.8258	-0.3995	0.0467	-0.0221	-0.1190	0.1856	0.0291
$\gamma_{-1,us}$	-0.8947	0.1372	1.0	0.2611	-0.7829	-0.1695	0.0156	0.0501	-0.2117	-0.7191
$\gamma_{1,us}$	-0.5310	0.8258	0.2611	1.0	-0.6479	0.0086	0.0076	0.1460	0.0781	-0.0010
A_{us}	0.9719	-0.3995	-0.7829	-0.6479	1.0	0.2983	0.0515	-0.0404	0.3055	0.2811
a_{ds}	0.2849	0.0467	-0.1695	0.0086	0.2983	1.0	-0.1608	0.0719	0.9152	-0.2941
b_{ds}	0.0241	-0.0221	0.0156	0.0076	0.0515	-0.1608	1.0	0.7834	-0.3022	-0.0390
$\gamma_{1,ds}$	-0.0470	-0.1190	0.0501	0.1460	-0.0404	0.0719	0.7834	1.0	-0.1838	-0.1373
A_{ds}	0.2983	0.1856	-0.2117	0.0781	0.3055	0.9152	-0.3022	-0.1838	1.0	-0.1833
a_{ss}	0.4131	0.0291	-0.7191	-0.0010	0.2811	-0.2941	-0.0390	-0.1373	-0.1833	1.0
b_{ss}	0.2197	0.0643	-0.4479	0.1286	0.1193	-0.1579	-0.0260	0.0169	-0.0896	0.6522
A_{ss}	0.3627	0.0261	-0.6319	0.0102	0.2412	-0.2688	-0.0180	-0.0960	-0.1797	0.9280
a_g	-0.2570	0.0001	0.2196	0.0039	-0.2493	-0.2190	-0.0454	-0.1031	-0.2571	0.0626
b_g	-0.1419	0.1266	0.0694	0.2648	-0.1715	-0.0515	0.0917	0.2130	-0.0469	-0.0092
$\gamma_{1,g}$	-0.0241	0.0332	-0.0226	0.1296	-0.0489	-0.0137	0.0503	0.1409	0.0022	-0.0279
$\alpha_s^{(n_f=3)}(\mu_0)$	0.0954	-0.2866	-0.0341	-0.3493	0.1110	-0.0604	-0.1265	-0.1811	-0.1330	-0.0841
$m_c(m_c)$	0.0704	-0.0093	-0.0033	-0.0462	0.1182	0.0849	0.0547	0.0413	0.1193	-0.0728
$m_b(m_b)$	-0.0183	-0.0132	0.0044	0.0209	-0.0298	-0.0006	0.0332	0.0695	-0.0432	-0.0159
$m_t(m_t)$	0.0641	-0.1841	-0.0408	-0.2635	0.0755	-0.0573	-0.1067	-0.2003	-0.0869	0.0169

	b_{ss}	A_{ss}	a_g	b_g	$\gamma_{1,g}$	$\alpha_s^{(n_f=3)}(\mu_0)$	$m_c(m_c)$	$m_b(m_b)$	$m_t(m_t)$
a_u	-0.1186	-0.1013	0.0046	0.2662	0.2008	0.1083	-0.0006	0.0661	-0.1339
b_u	-0.0480	-0.0411	-0.0374	0.3141	0.2274	-0.0607	0.0170	0.0554	-0.2170
$\gamma_{1,u}$	-0.1532	-0.1458	0.1109	0.1579	0.0706	0.0848	-0.0104	0.0605	-0.0816
$\gamma_{2,u}$	0.1549	0.1802	-0.1934	-0.0050	0.0876	-0.0250	0.0206	-0.0367	0.0081
$\gamma_{3,u}$	-0.1536	-0.1625	0.1653	-0.0207	-0.0835	0.0765	-0.0201	0.0287	0.0250
a_d	0.0486	0.1216	-0.0288	0.0973	0.0919	0.0763	-0.0123	-0.0116	-0.0616
b_d	0.1508	0.1678	-0.0122	0.0870	0.0574	-0.0306	-0.0161	0.0029	-0.0813
$\gamma_{1,d}$	0.0267	0.0924	0.0053	0.0646	0.0493	0.0725	-0.0114	-0.0074	-0.0491
$\gamma_{2,d}$	-0.1161	-0.1196	0.0059	-0.0666	-0.0364	0.0243	0.0108	-0.0051	0.0736
$\gamma_{3,d}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
a_{us}	0.2197	0.3627	-0.2570	-0.1419	-0.0241	0.0954	0.0704	-0.0183	0.0641
b_{us}	0.0643	0.0261	0.0001	0.1266	0.0332	-0.2866	-0.0093	-0.0132	-0.1841
$\gamma_{-1,us}$	-0.4479	-0.6319	0.2197	0.0694	-0.0226	-0.0341	-0.0034	0.0044	-0.0408
$\gamma_{1,us}$	0.1286	0.0102	0.0039	0.2648	0.1296	-0.3493	-0.0462	0.0209	-0.2635
A_{us}	0.1193	0.2412	-0.2493	-0.1715	-0.0489	0.1110	0.1182	-0.0298	0.0755
a_{ds}	-0.1579	-0.2688	-0.2190	-0.0515	-0.0137	-0.0604	0.0849	-0.0006	-0.0573
b_{ds}	-0.0260	-0.0180	-0.0454	0.0917	0.0503	-0.1265	0.0547	0.0332	-0.1067
$\gamma_{1,ds}$	0.0169	-0.0960	-0.1031	0.2130	0.1409	-0.1811	0.0413	0.0695	-0.2003
A_{ds}	-0.0896	-0.1797	-0.2571	-0.0469	0.0022	-0.1330	0.1193	-0.0432	-0.0869
a_{ss}	0.6522	0.9280	0.0626	-0.0092	-0.0279	-0.0841	-0.0728	-0.0159	0.0169
b_{ss}	1.0	0.6427	-0.0179	0.1967	0.1164	-0.2390	-0.0965	0.0169	-0.1675
A_{ss}	0.6427	1.0	-0.0211	0.1403	0.0997	-0.1385	0.0216	0.0072	-0.1109
a_g	-0.0179	-0.0211	1.0	-0.5279	-0.8046	0.1838	-0.2829	0.0076	0.3310
b_g	0.1967	0.1403	-0.5279	1.0	0.8837	-0.5124	0.1438	0.1255	-0.7275
$\gamma_{1,g}$	0.1164	0.0997	-0.8046	0.8837	1.0	-0.2511	0.1829	0.0814	-0.5180
$\alpha_s^{(n_f=3)}(\mu_0)$	-0.2390	-0.1385	0.1838	-0.5124	-0.2511	1.0	-0.1048	0.0423	0.6924
$m_c(m_c)$	-0.0965	0.0216	-0.2829	0.1438	0.1829	-0.1048	1.0	0.0328	-0.1577
$m_b(m_b)$	0.0169	0.0072	0.0076	0.1255	0.0814	0.0423	0.0328	1.0	-0.0900
$m_t(m_t)$	-0.1675	-0.1109	0.3310	-0.7275	-0.5180	0.6924	-0.1577	-0.0900	1.0

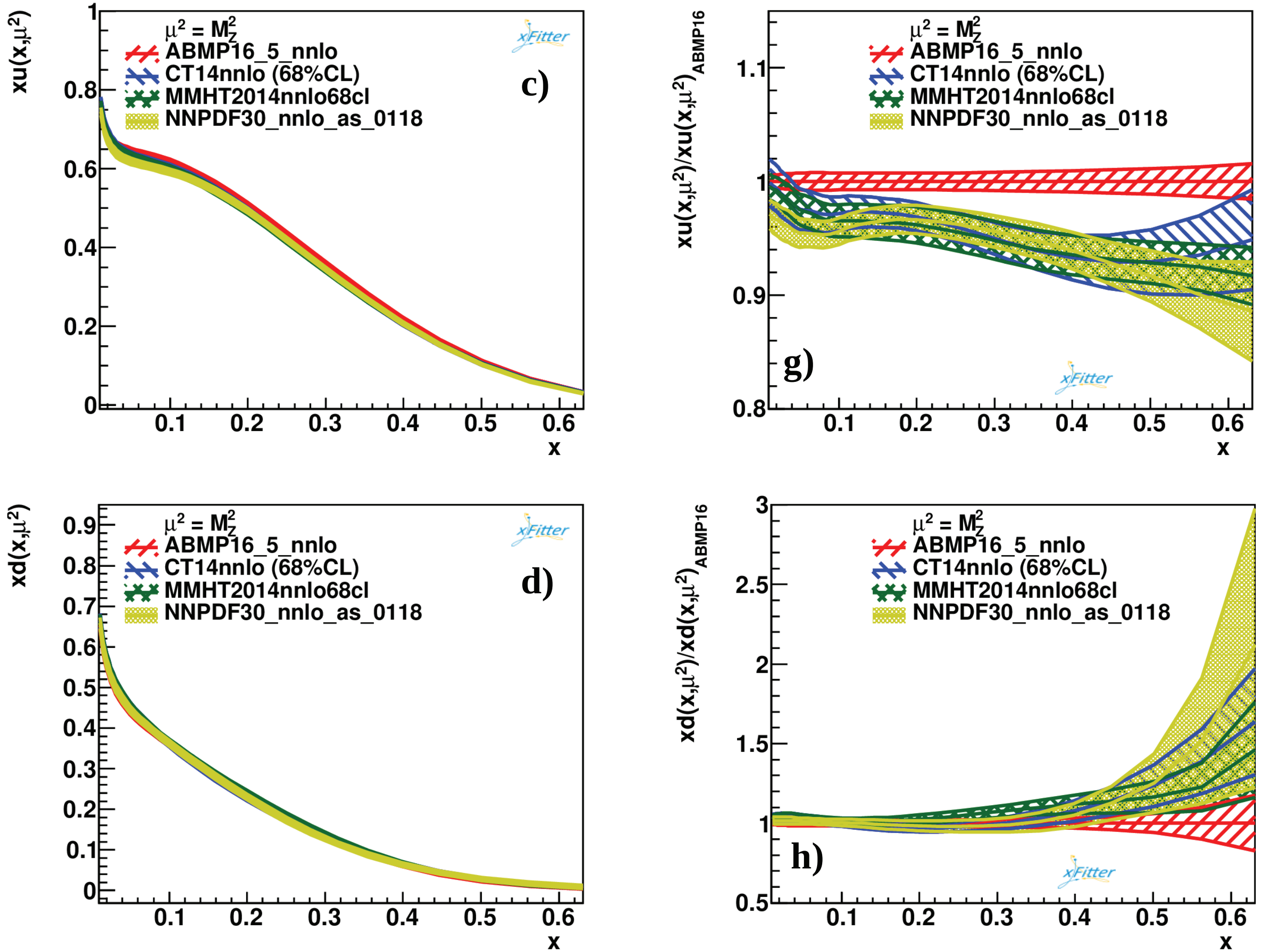
Results for parton distributions (I)

- PDFs with 1σ uncertainty bands; compare ABMP16, CT14, MMHT14 NNPDF3.0
- Gluon $g(x)$



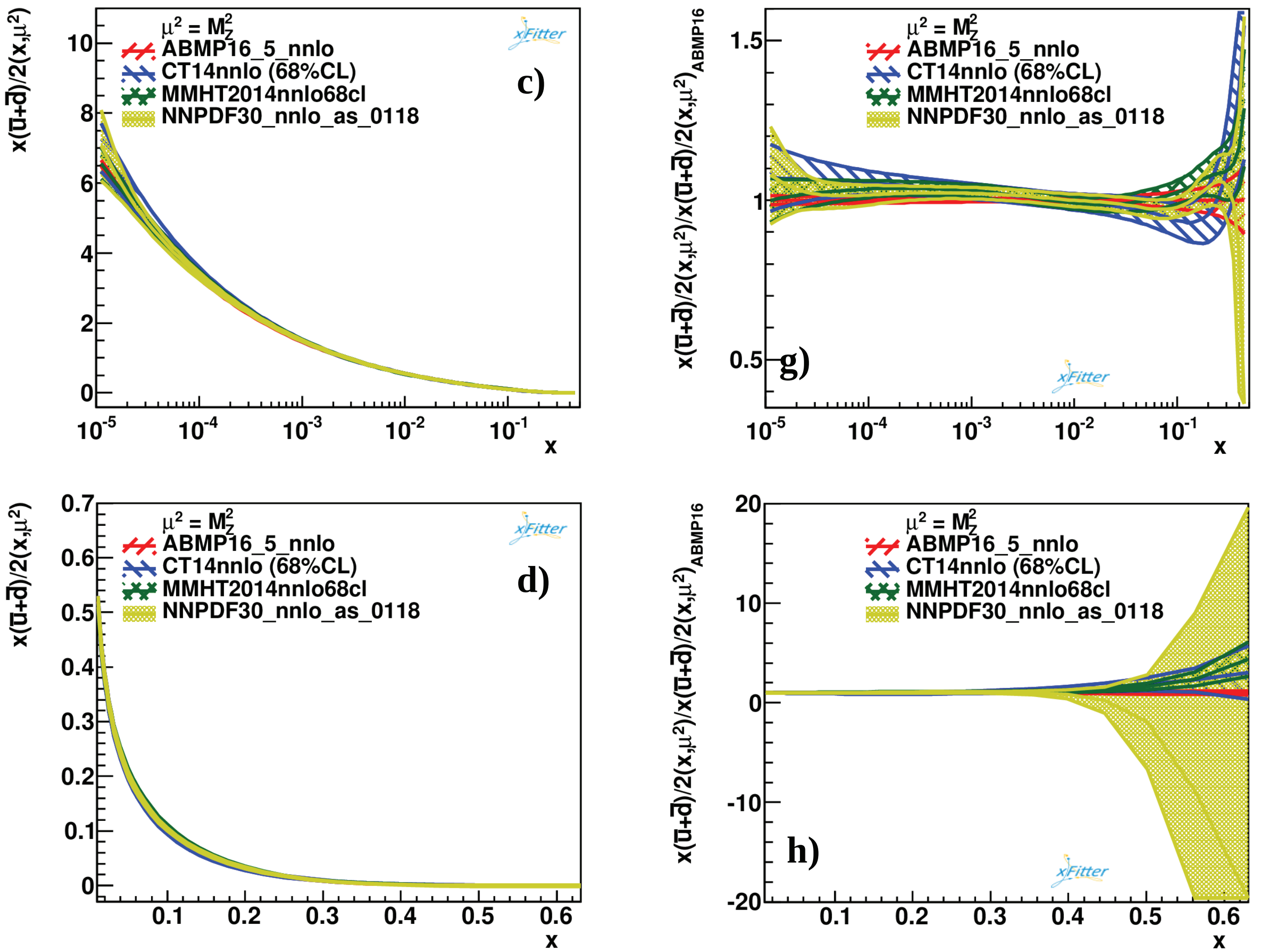
Results for parton distributions (II)

- PDFs with 1σ uncertainty bands; compare ABMP16, CT14, MMHT14 NNPDF3.0
- Light valence quarks $u(x)$, $d(x)$



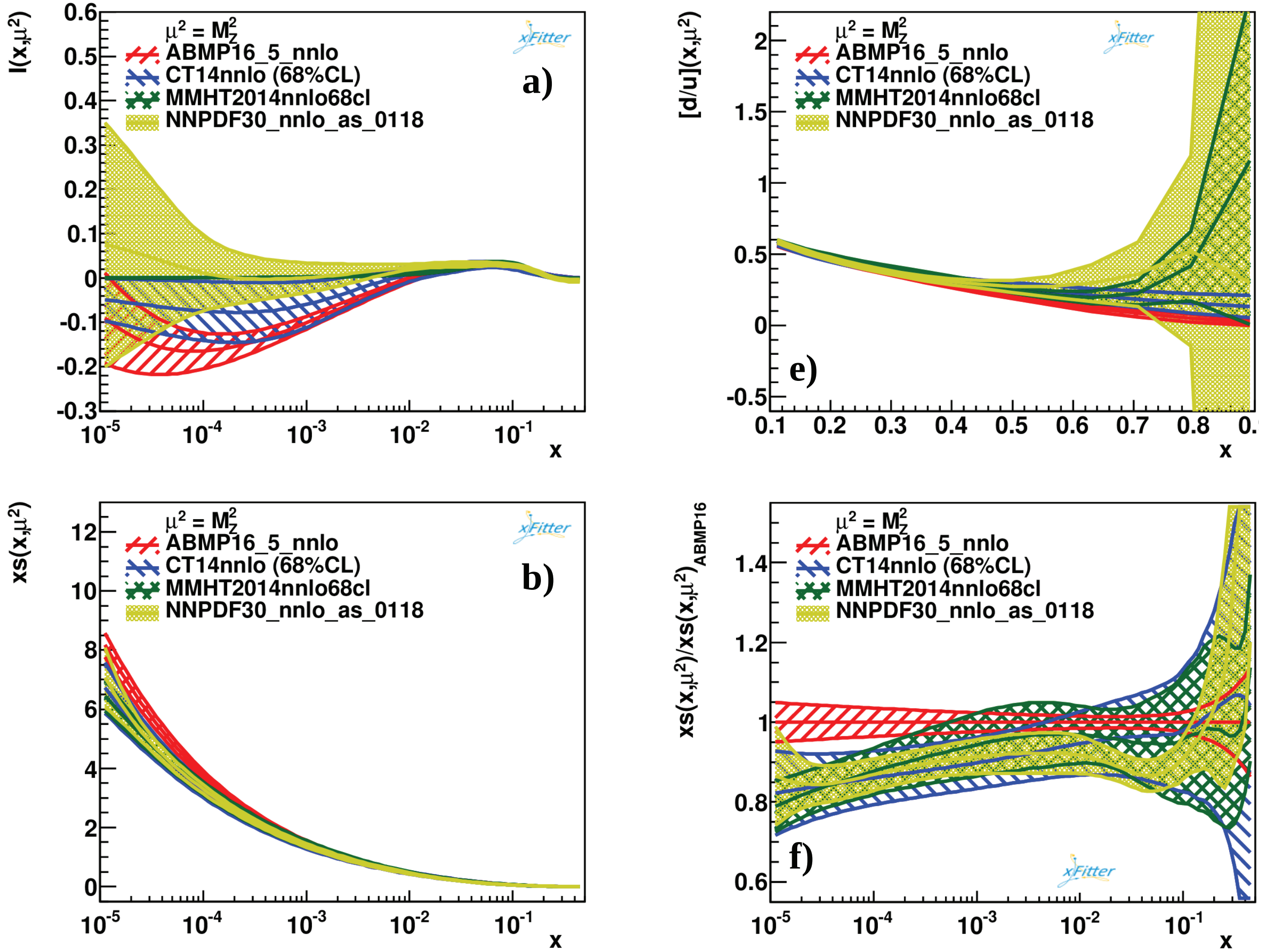
Results for parton distributions (III)

- PDFs with 1σ uncertainty bands; compare ABMP16, CT14, MMHT14 NNPDF3.0
- Sea quarks $\bar{u}(x) + \bar{d}(x)$



Results for parton distributions (IV)

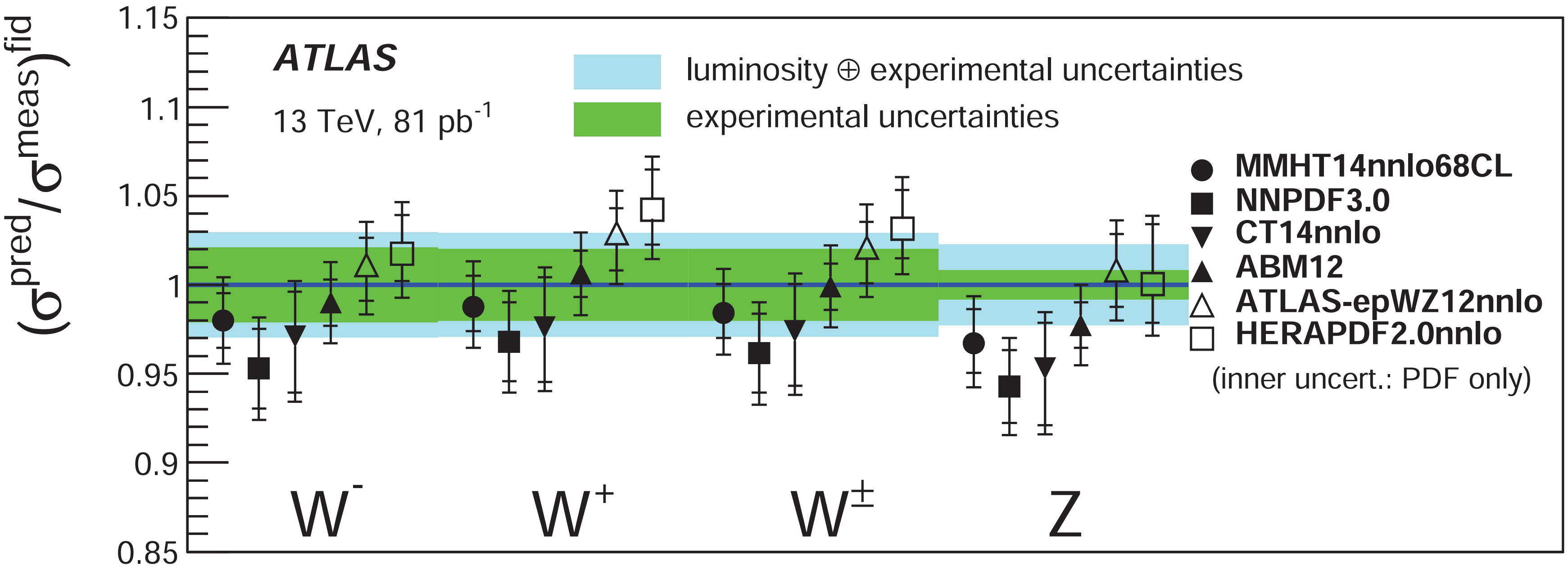
- PDFs with 1σ uncertainty bands; compare ABMP16, CT14, MMHT14 NNPDF3.0
- Iso-spin asymmetry $x(\bar{d}(x) - \bar{u}(x))$; ratio $d(x)/u(x)$; strange $s(x)$



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

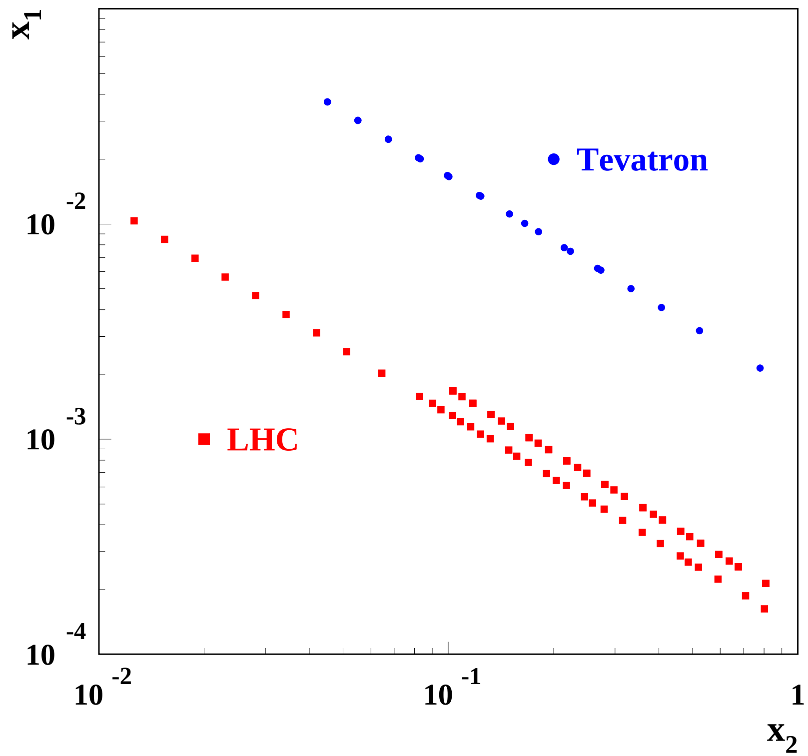
W- and *Z*-boson cross sections

- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$
  - statistically significant: $NDP = 172$ in ABMP16
- ATLAS measurement at $\sqrt{s} = 13$ TeV from arXiv:1603.09222



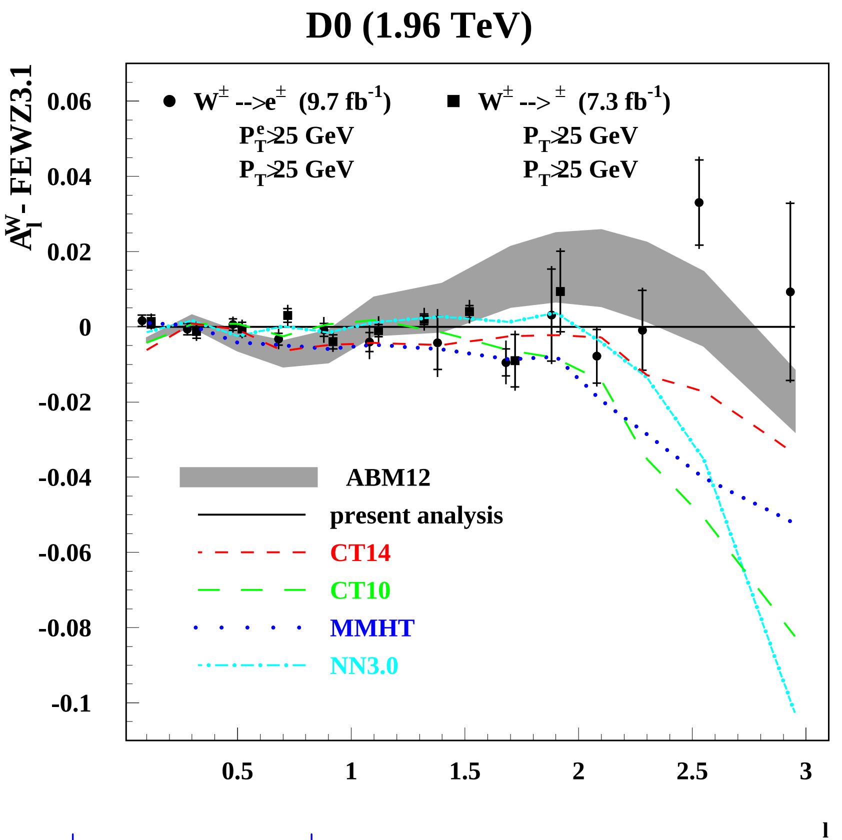
- Spread in predictions from different PDFs significantly larger than experimental precision

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



- High precision data from LHC ATLAS, CMS, LHCb and Tevatron D0
  - statistically significant $NDP = 172$
- Differential distributions extend to forward region
  - sensitivity to light quark flavors at $x \simeq 10^{-4}$
  - leading order kinematics with $\sigma(W^+) \simeq u(x_2)\bar{d}(x_1)$ and $\sigma(W^-) \simeq d(x_2)\bar{u}(x_1)$ and $\sigma(Z) \simeq Q_u^2 u(x_2)\bar{u}(x_1) + Q_d^2 d(x_2)\bar{d}(x_1)$
  - cf. DIS: $\sigma(\mathrm{DIS}) \simeq q_u^2 u(x) + q_d^2 d(x)$

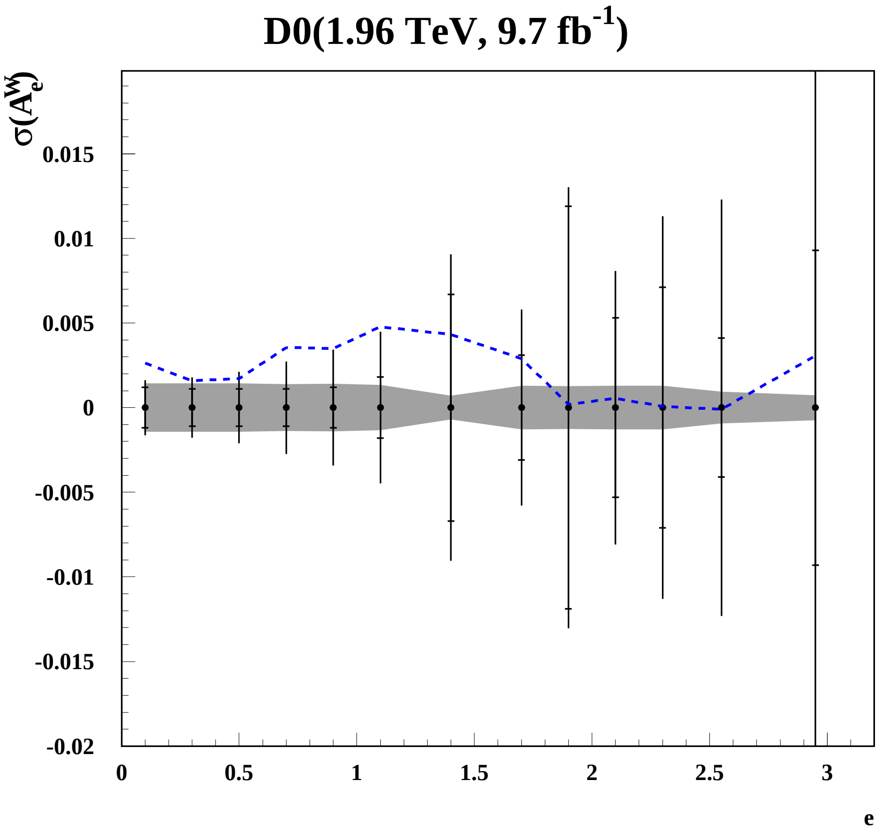
Tevatron charged lepton asymmetry



- 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

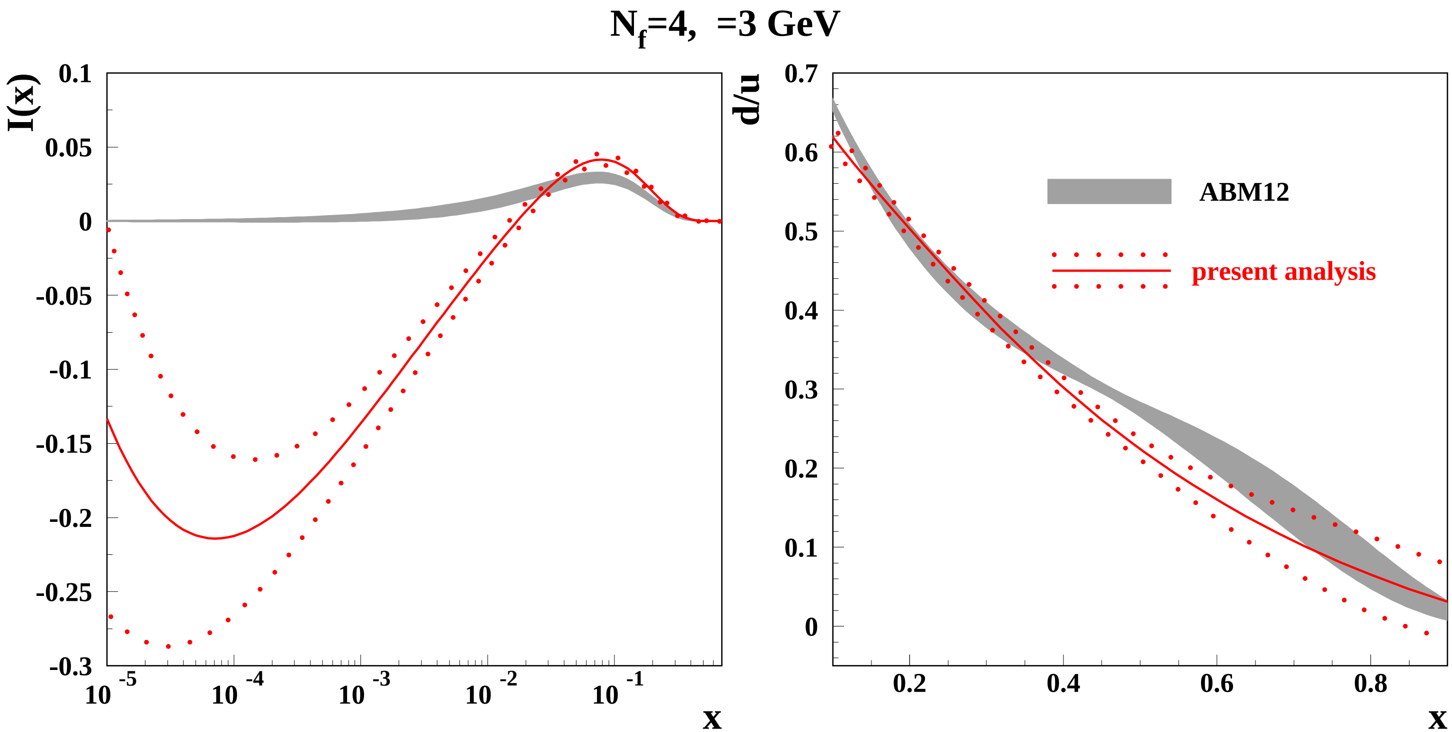
Theory issues

- Data on electron asymmetry with high precision at central rapidities D0
- NNLO corrections in coefficient functions not uniform in η_e (dashed curve)
- Numerical accuracy at NNLO (shaded area) obtained with FEWZ (v3.1)
- Accuracy of $\mathcal{O}(1 \text{ ppm})$ to meet uncertainties in experimental data requires $\mathcal{O}(10^4 \text{h})$ of running FEWZ (v3.1) at NNLO



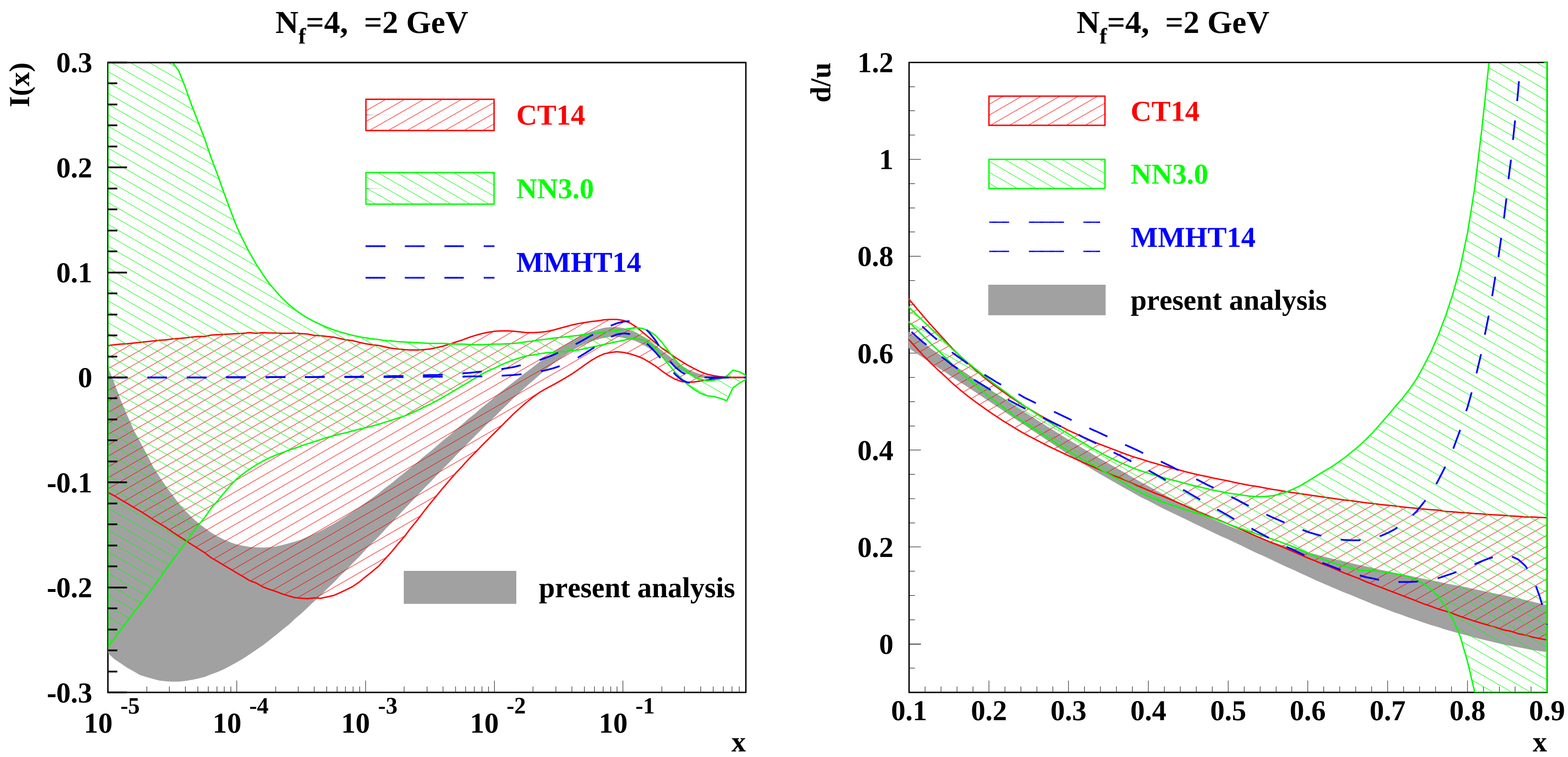
Sven-Olaf Moch

Light flavor PDFs



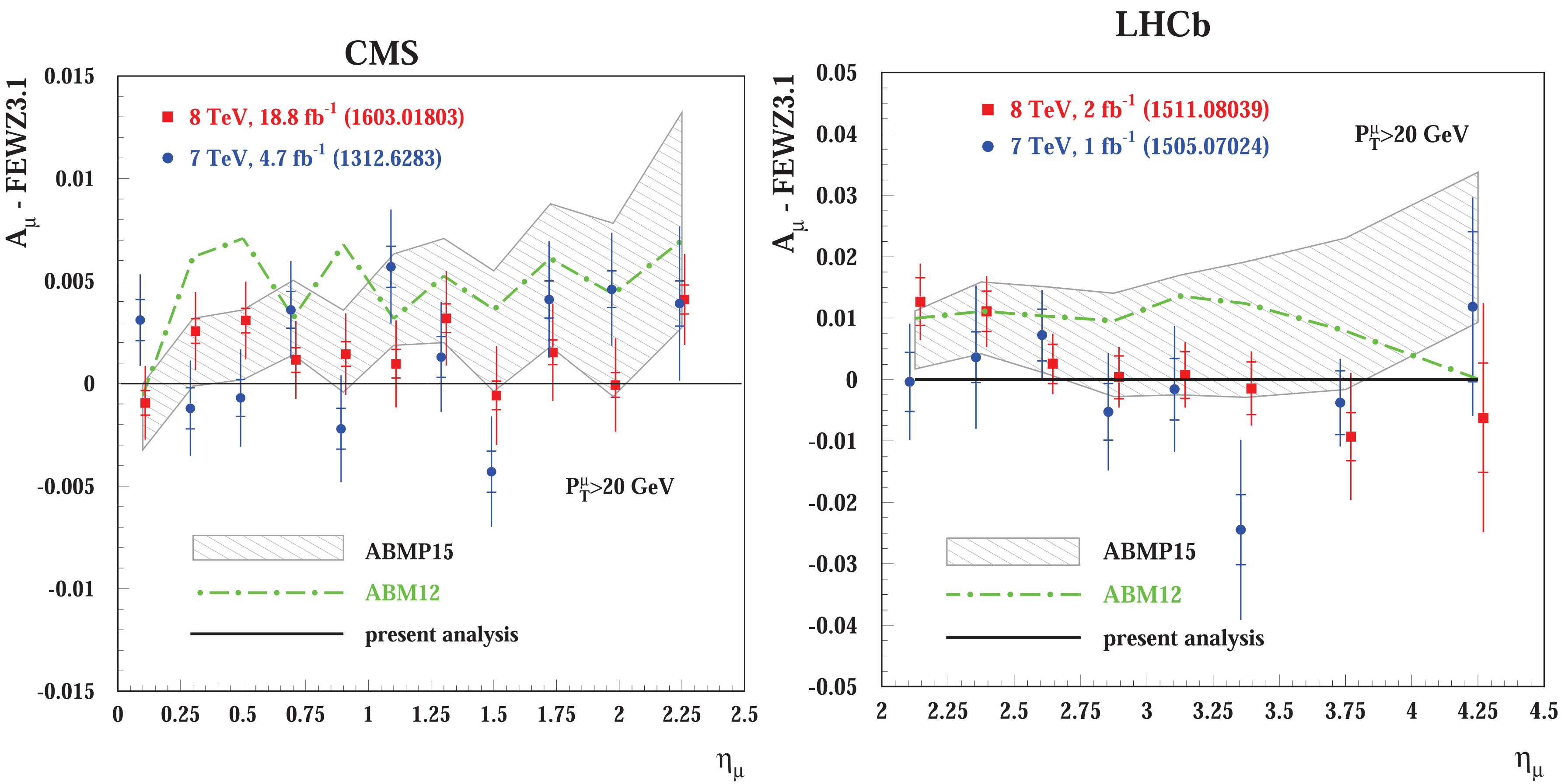
- Light flavor decomposition not well constrained in DIS data
  - ratio d/u at large x from fixed target Drell-Yan data E-605, E-866 at the price of modelling nuclear corrections
- Iso-spin asymmetry of sea $I(x) = \bar{d} - \bar{u}$
  - Regge theory arguments for small x predict $I(x) \simeq 0$
  -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



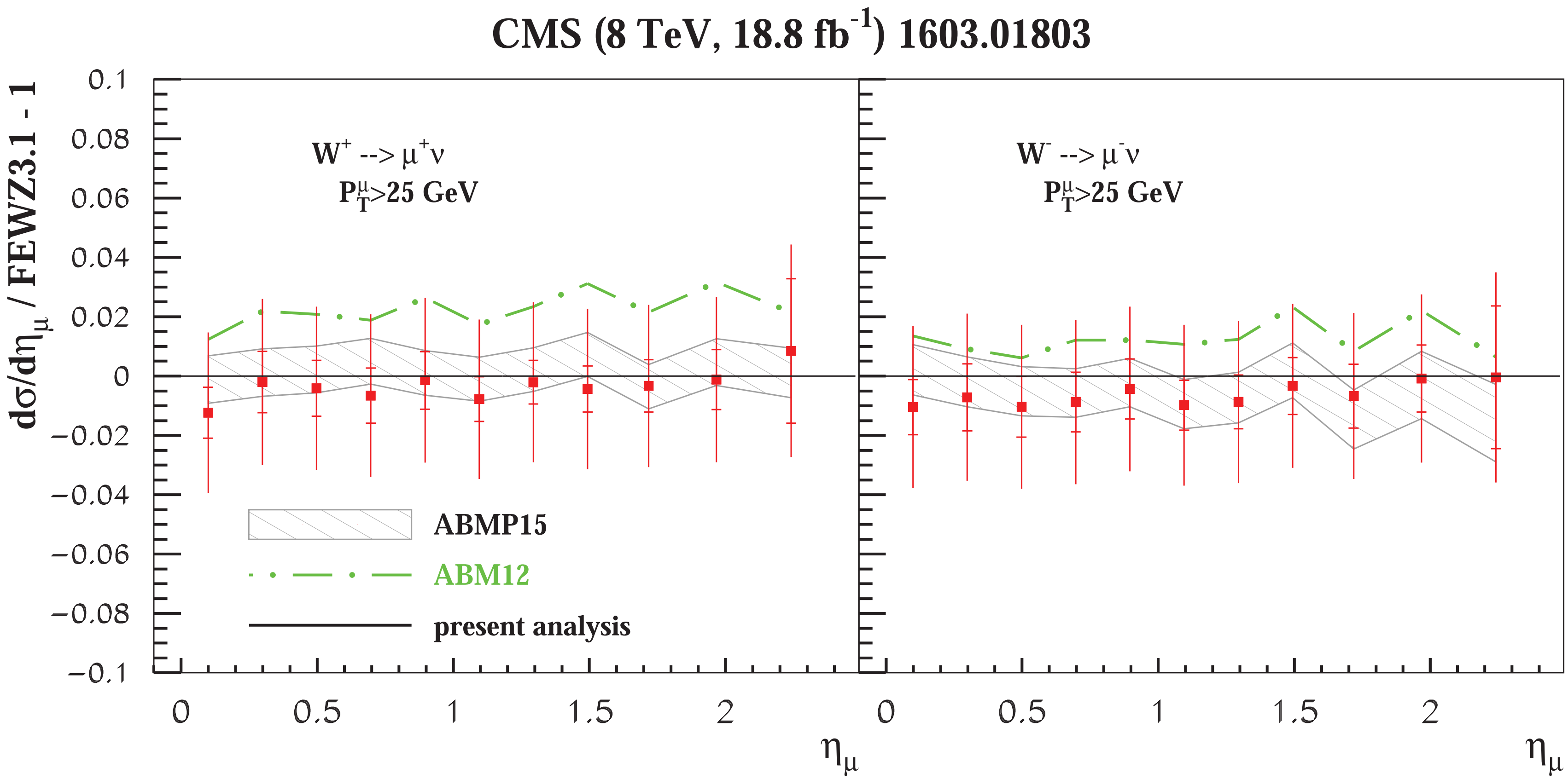
- Iso-spin asymmetry of sea $I(x)$ at small x and ratio d/u at large x with 1σ uncertainty band
- Comparison with CT14, MMHT14, NN3.0
  - CT14 finds non-vanishing $I(x)$ from fit to Tevatron charged lepton asymmetry (D0 data), but with large uncertainties

Muon charge asymmetry from LHC



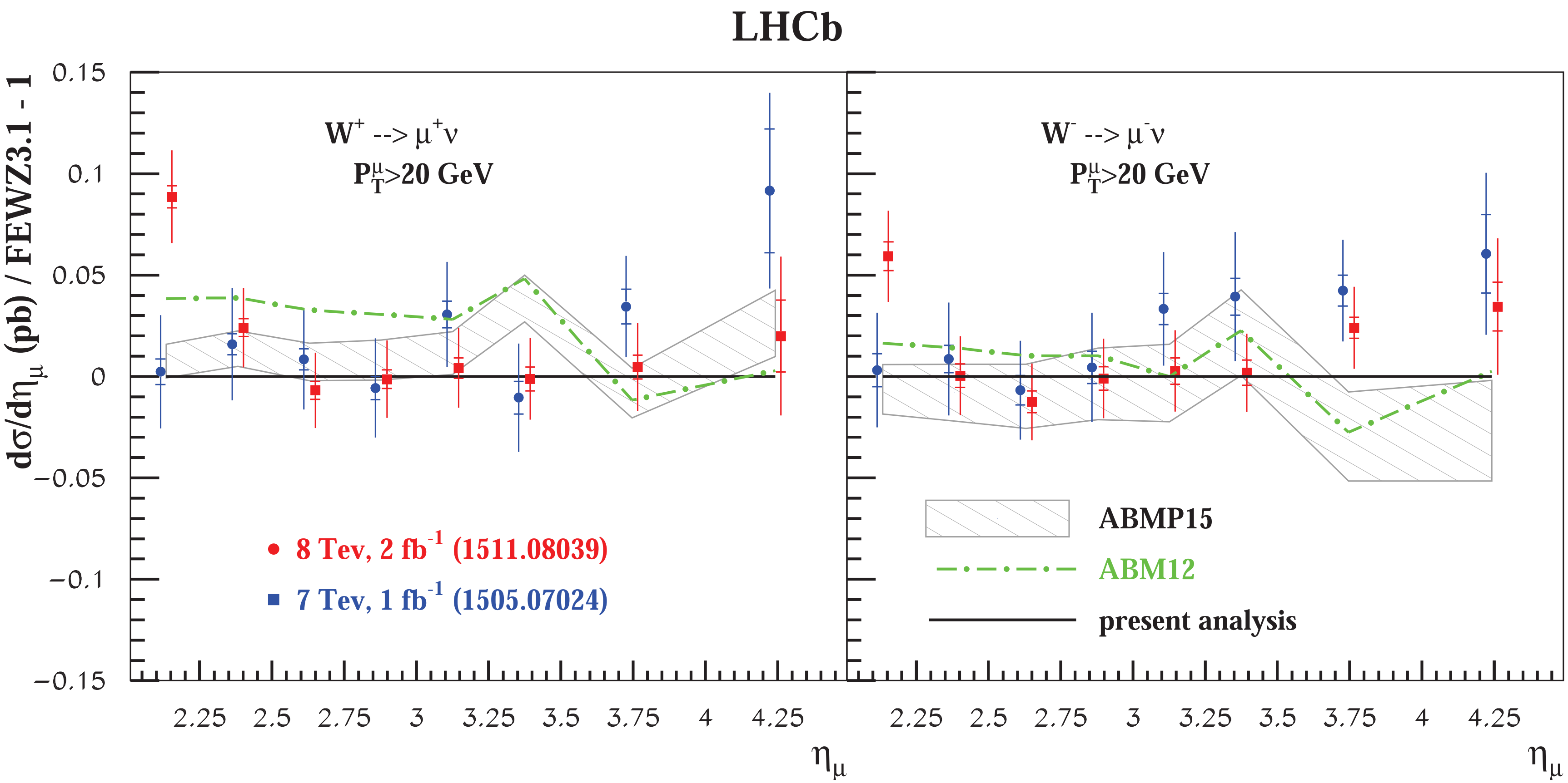
- CMS and LHCb data for $pp \to W^\pm + X \to \mu^\pm \nu + X$ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
  - comparison of ABM12, ABMP15 and ABMP16 fits
- Problematic data point at $\eta_\mu = 3.375$ for $\sqrt{s} = 7$ TeV in LHCb data are omitted in fit

$W^{\pm}$-boson production from LHC (I)



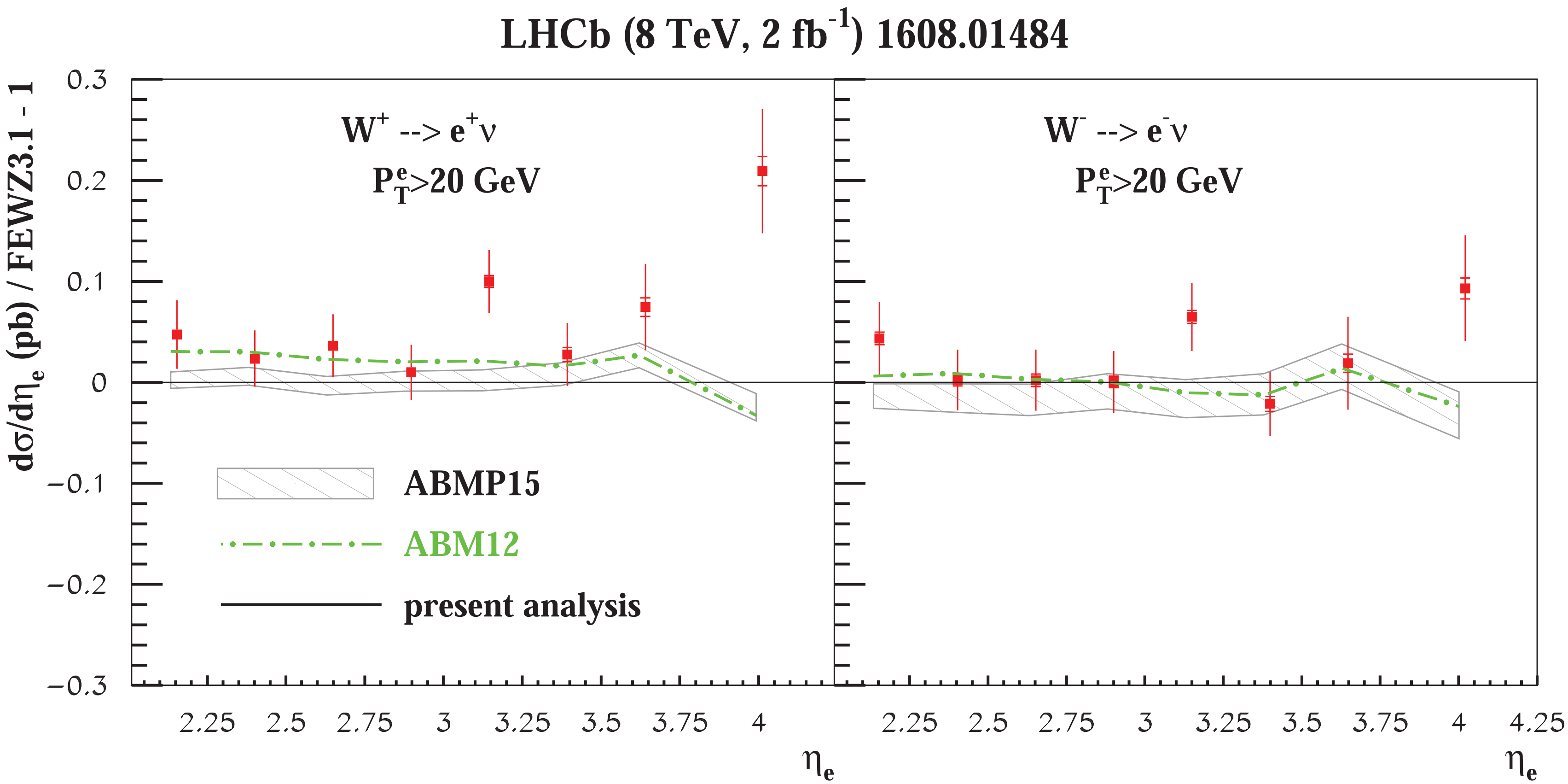
- CMS data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to \mu^{\pm}\nu$

$W^{\pm}$-boson production from LHC (II)



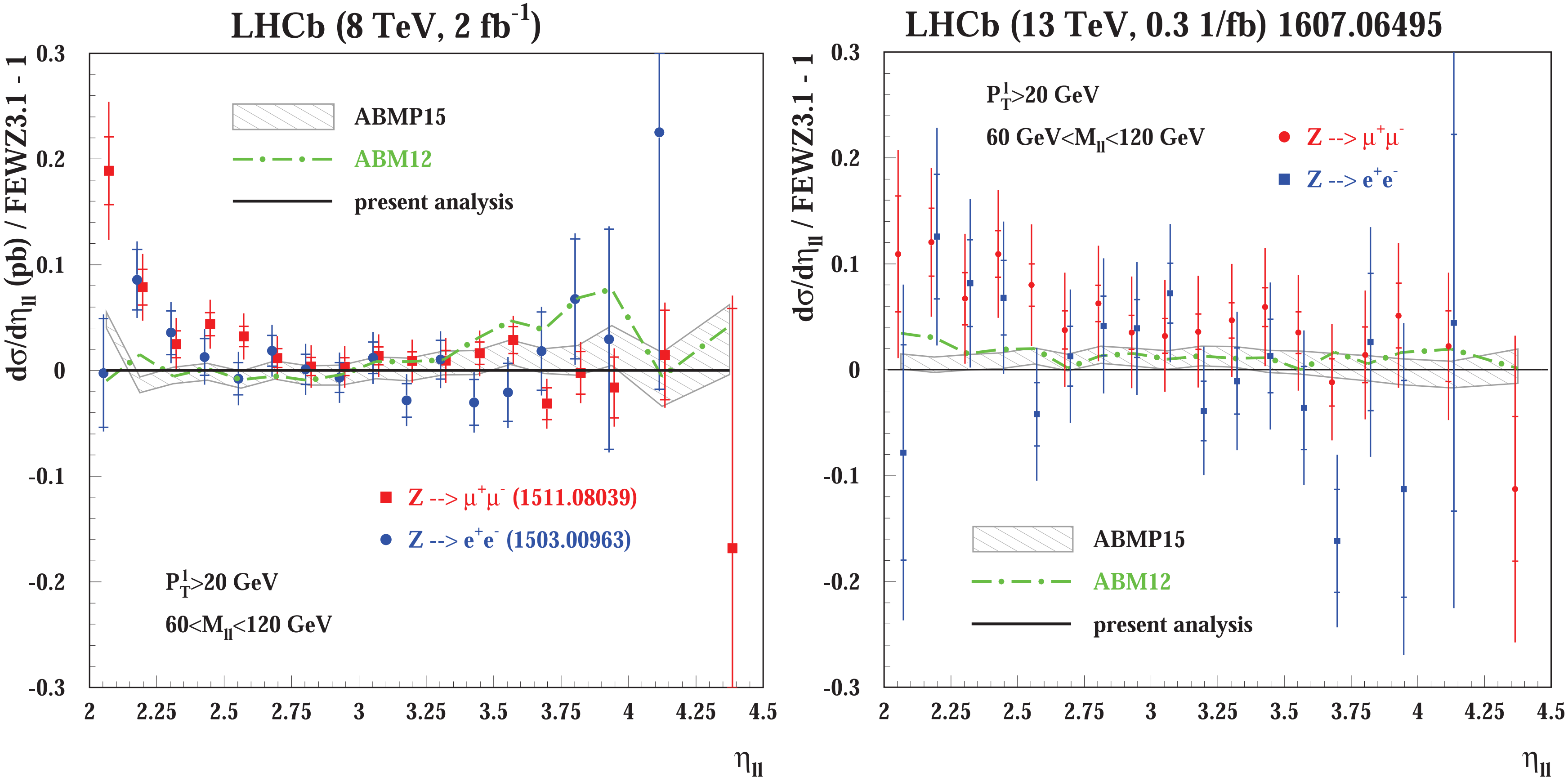
- LHCb data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to \mu^{\pm}\nu$
- Points at $\eta_{\mu} = 2.125$ for $\sqrt{s} = 8$ TeV are not used in fit

$W^{\pm}$-boson production from LHC (III)



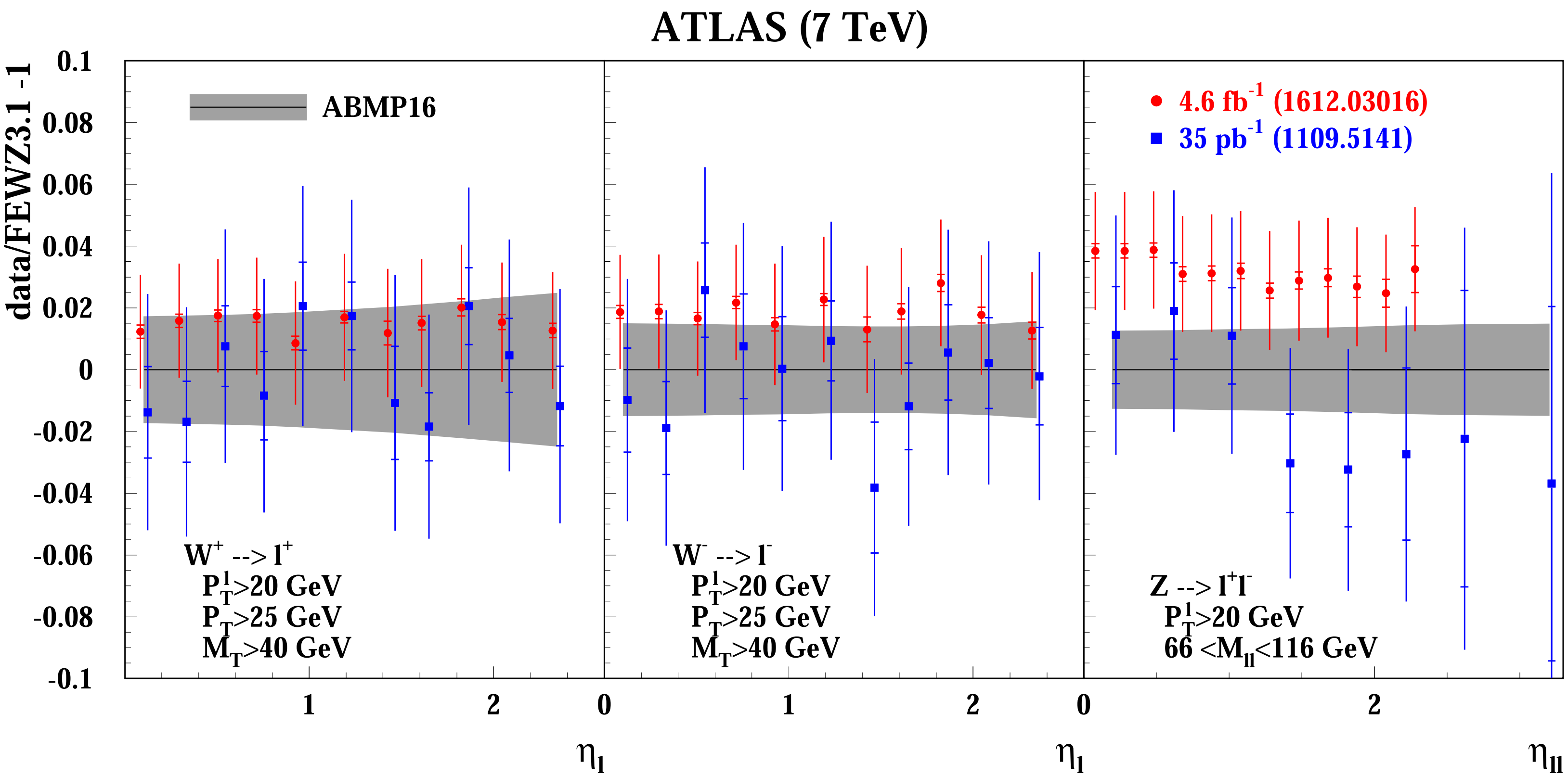
- LHCb data on cross section of inclusive $W^{\pm}$-boson production at $\sqrt{s} = 8$ TeV
  - channel $W^{\pm} \to e^{\pm}\nu$

Z-boson production from LHC



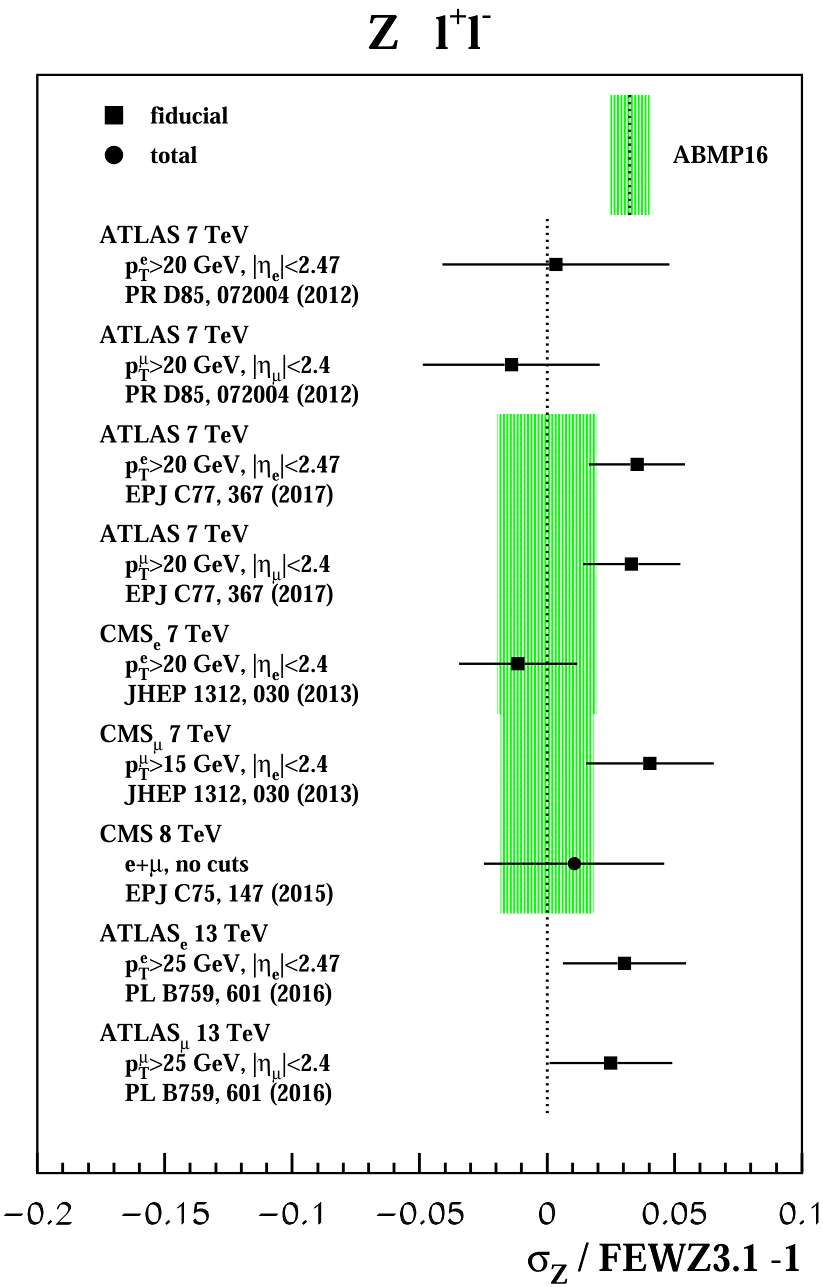
- LHCb data for $pp \to Z + X \to l\bar{l}$ at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV
  - channels $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$

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



- Pulls for ATLAS data for $pp \to W^{\pm} + X \to \mu^{\pm}\nu + X$ and $pp \to Z + X \to l\bar{l}$ at $\sqrt{s} = 7$ TeV compared to ABMP16
  - collected at luminosity of 35 pb^{-1} (2011) (blue squares)
  - collected at luminosity of 4.6 fb^{-1} (2016) (red circles)

Pulls of Z-boson production from LHC

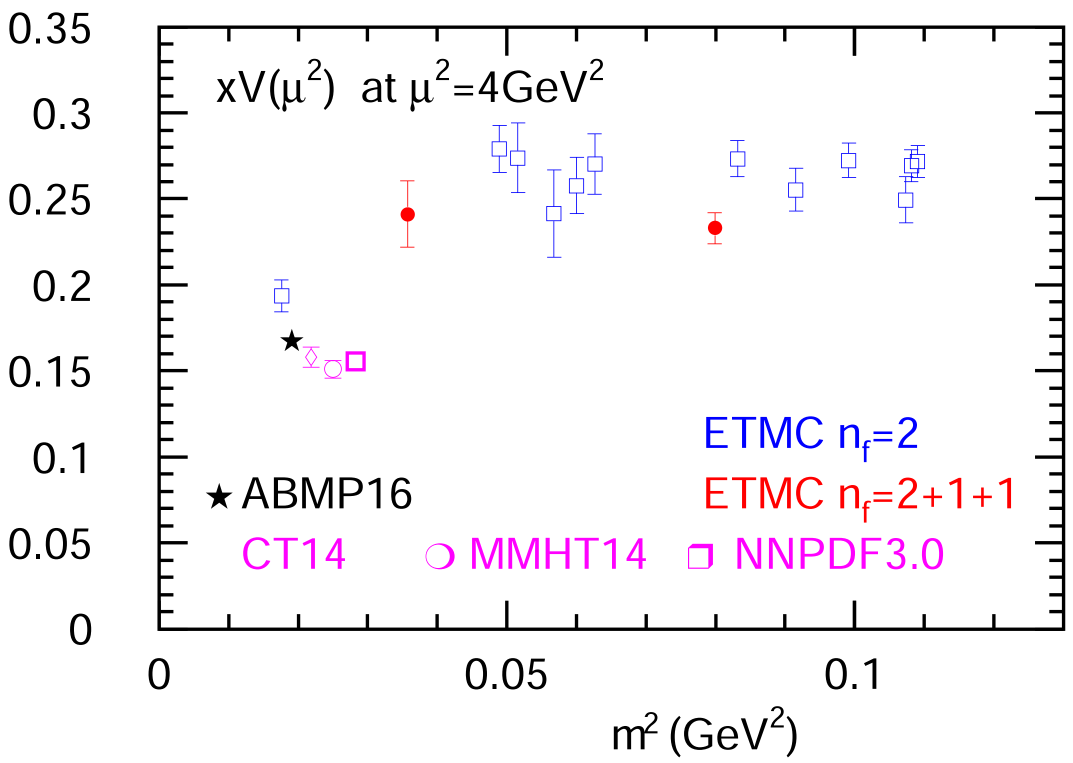


- Integrated cross sections of Z-boson production in proton-proton collisions in central-region measured by ATLAS and CMS in e- and μ-decay channels at different center-of-mass energies

Lattice results

- Moments of valence quark densities at NNLO at scale $Q^2 = 4\ \mathrm{GeV}^2$

$$\langle x \rangle_{u-d}(Q^2) \quad = \quad \int_0^1 dx\, x \left\{ \left[u(x,Q^2) + \bar{u}_s(x,Q^2) \right] - \left[d(x,Q^2) + \bar{d}_s(x,Q^2) \right] \right\}$$



Alekhin, Blümlein, S.M. ‘17

- Lattice QCD for $n_f = 2$ now down to nearly physical quark masses

Lattice results

- Moments of valence quark densities at NNLO at scale $Q^2 = 4\ \mathrm{GeV}^2$

$$\langle x \rangle_{u-d}(Q^2) = \int_0^1 dx\, x \left\{ \left[u(x,Q^2) + \bar{u}_s(x,Q^2) \right] - \left[d(x,Q^2) + \bar{d}_s(x,Q^2) \right] \right\}$$

	$\langle xu_v(x) \rangle$	$\langle xd_v(x) \rangle$	$\langle x[u_v - d_v](x) \rangle$	$\langle xV(x) \rangle$
ABM11 Alekhin, Blümlein, S.M. ‘12	0.2966 ± 0.0039	0.1172 ± 0.0050	0.1794 ± 0.0041	0.1652 ± 0.0039
ABM12 Alekhin, Blümlein, S.M. ‘13	0.2950 ± 0.0029	0.1212 ± 0.0016	0.1738 ± 0.0025	0.1617 ± 0.0031
ABMP16 Alekhin, Blümlein, S.M., Placakyte ‘17	0.2911 ± 0.0024	0.1100 ± 0.0031	0.1811 ± 0.0032	0.1674 ± 0.0037
CT14 Dulat et al. ‘15	$0.2887^{+0.0074}_{-0.0073}$	$0.1180^{+0.0053}_{-0.0041}$	$0.1707^{+0.0078}_{-0.0092}$	$0.1579^{+0.0095}_{-0.0117}$
MMHT14 Martin, Motylinski, Harland-Lang, Thorne ‘14	$0.2852^{+0.0052}_{-0.0034}$	$0.1202^{+0.0030}_{-0.0031}$	$0.1650^{+0.0047}_{-0.0034}$	$0.1509^{+0.0053}_{-0.0039}$
NNPDF3.0 Ball et al. ‘14	0.2833 ± 0.0042	0.1183 ± 0.0049	0.1650 ± 0.0054	0.1553 ± 0.0037
NNPDF3.1 Ball et al. ‘17	0.2888 ± 0.0042	0.1139 ± 0.0048	0.1749 ± 0.0047	0.1533 ± 0.0030

- Differences, even for low pion masses, between lattice measurements and experimental determination $\langle x \rangle_{u-d} = 0.1811$ ABM16

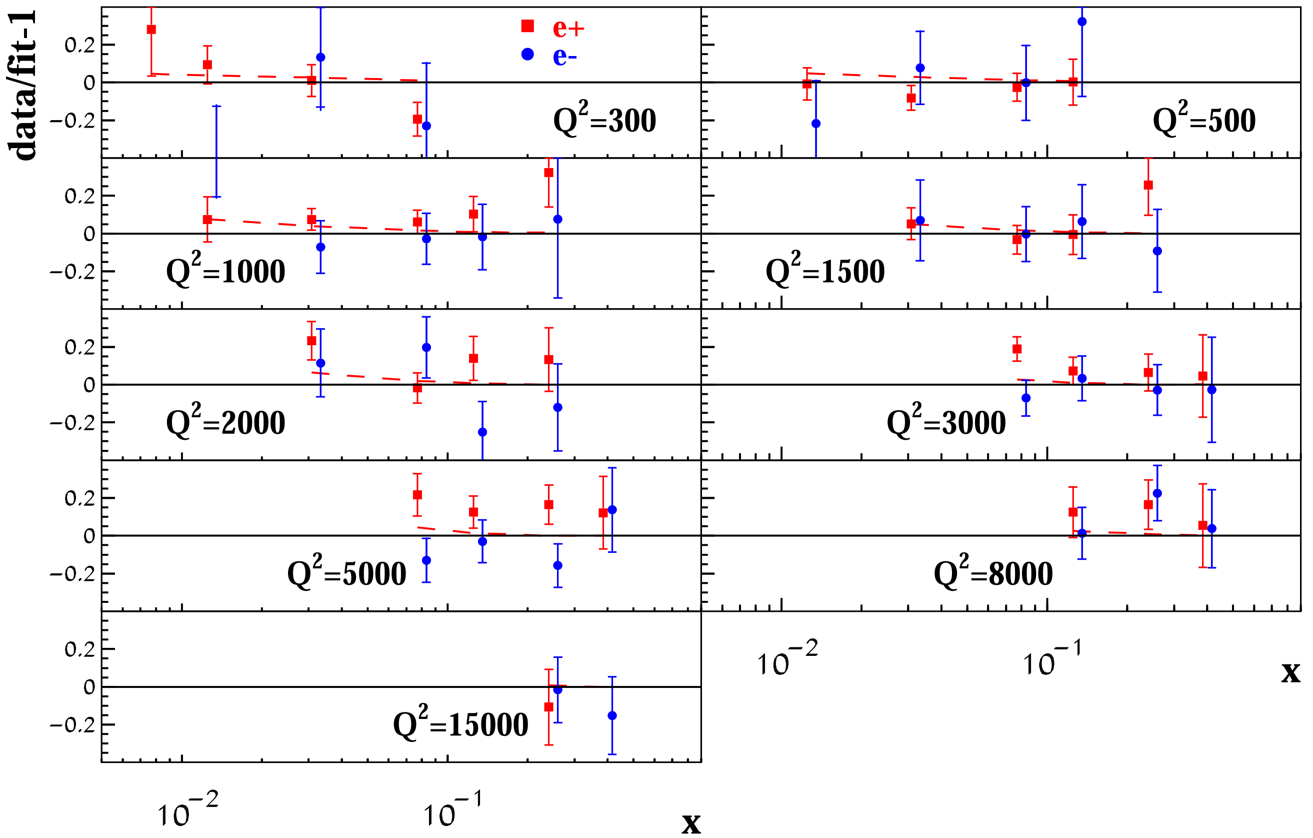
Strange sea in the proton

Strange sea determination

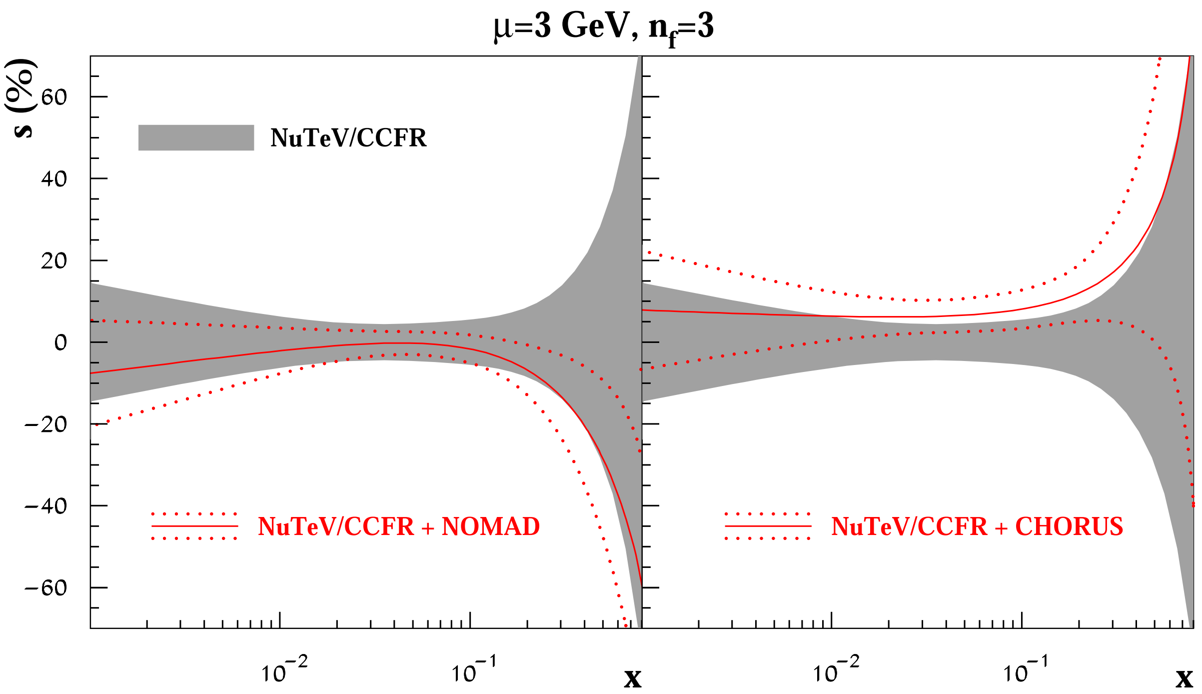
Charged current DIS

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

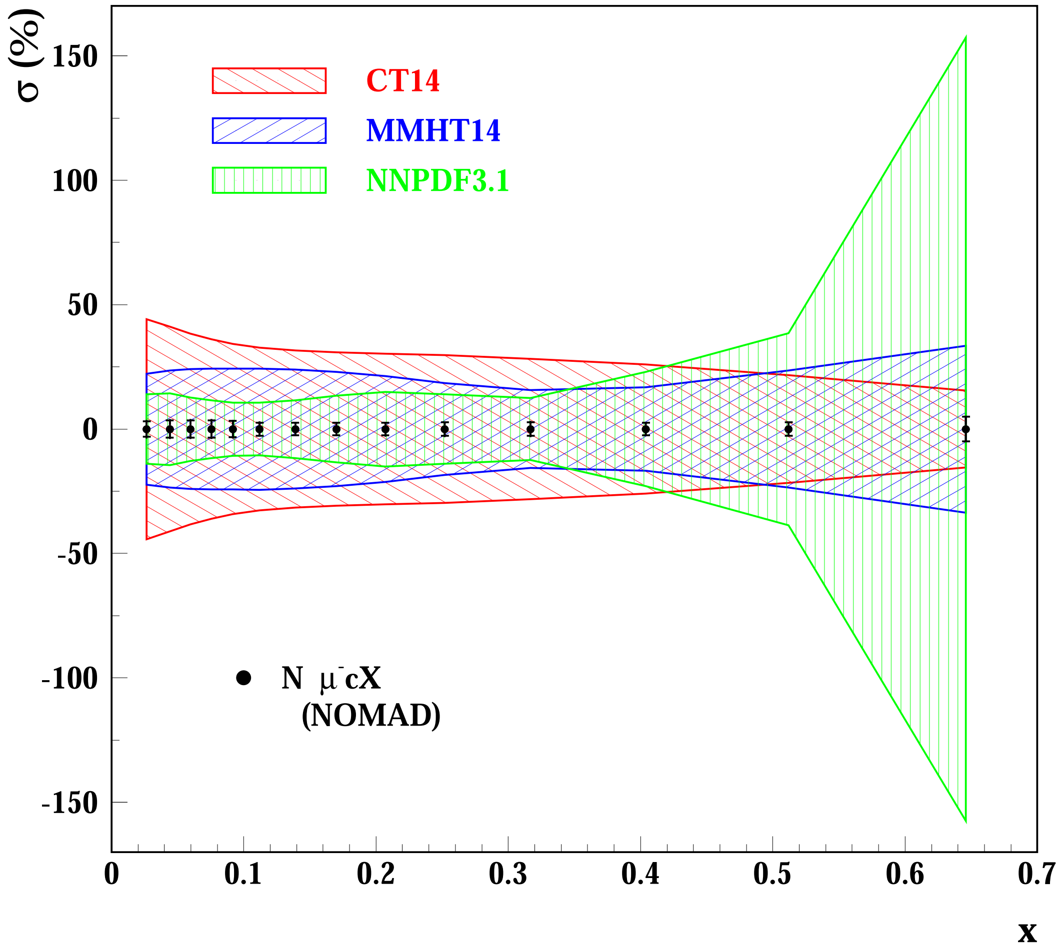


Strange sea from new fixed target data



- 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

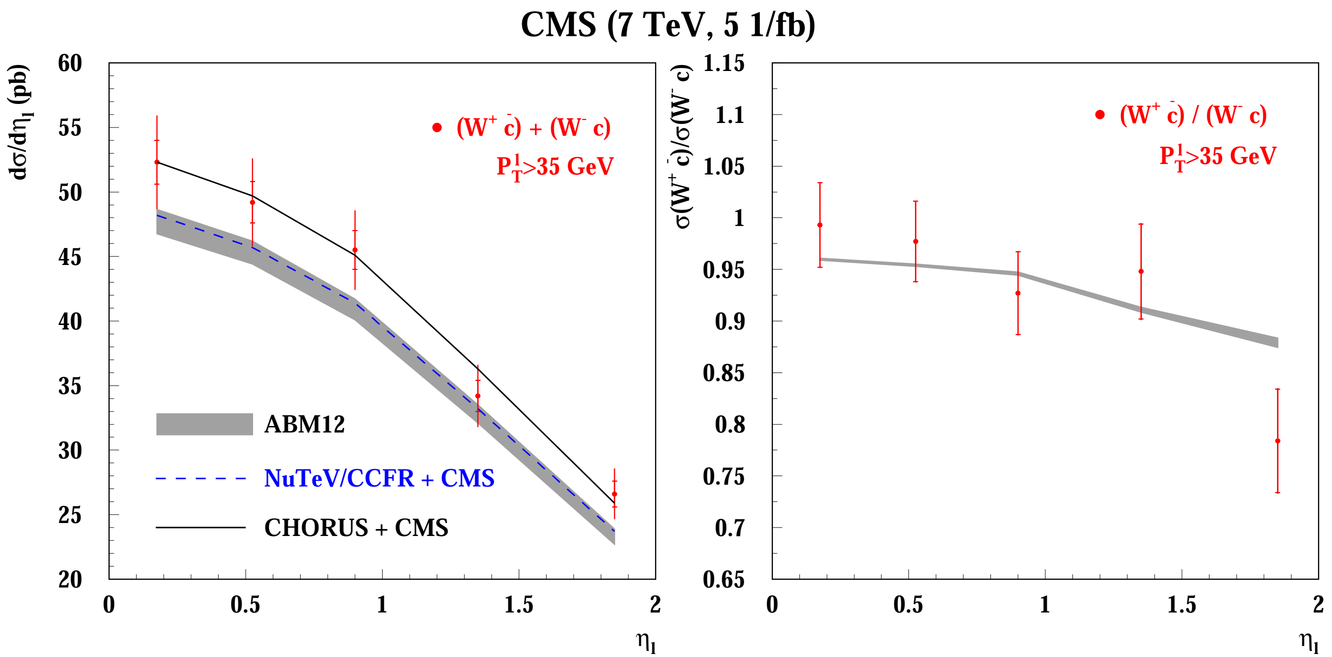
Constraints on the strange sea



- Uncertainties in NOMAD data for di-muons from incl. CC DIS versus Bjorken x in comparison to PDF predictions
  - CT14, MMHT14, NNPDF3.1 and ABMP16

W+charm production at LHC

- Cross check with LHC data for W+charm production

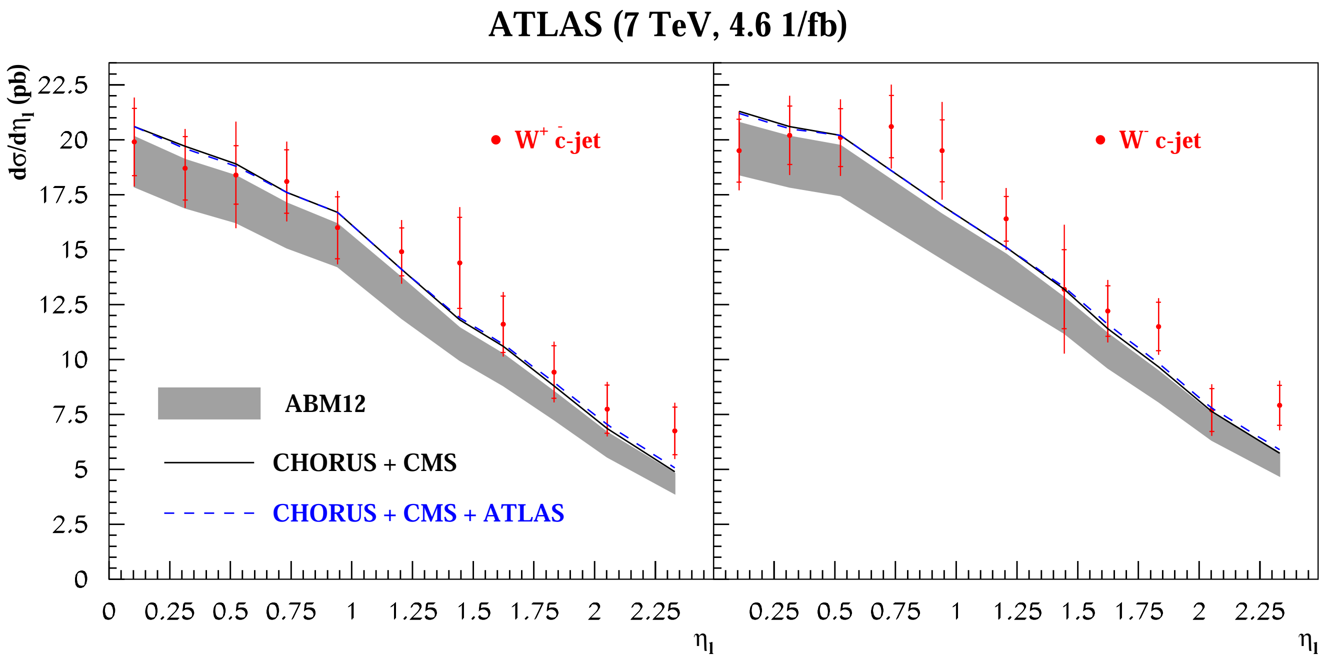


CMS

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

W+charm production at LHC

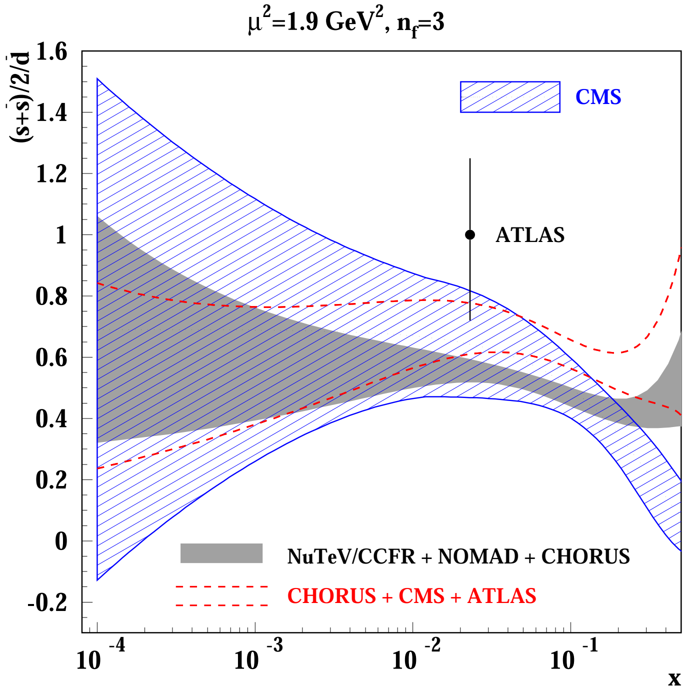
- Cross check with LHC data for W+charm production

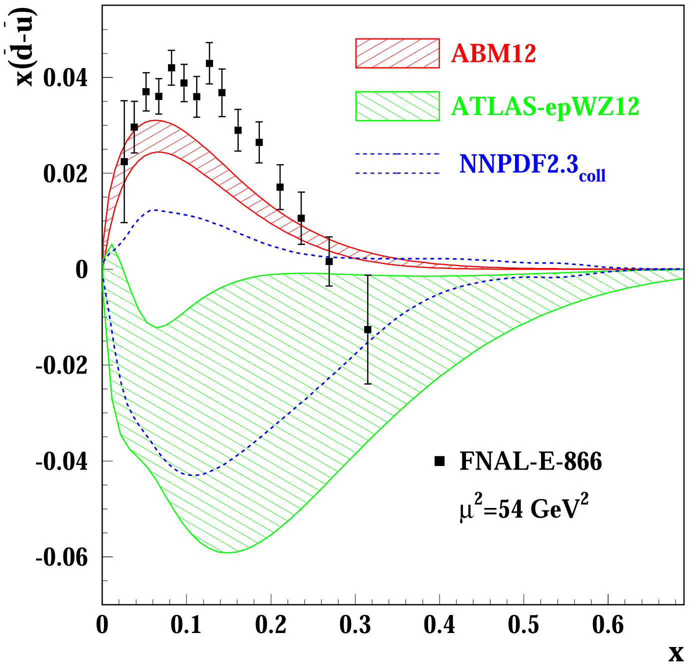


ATLAS

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

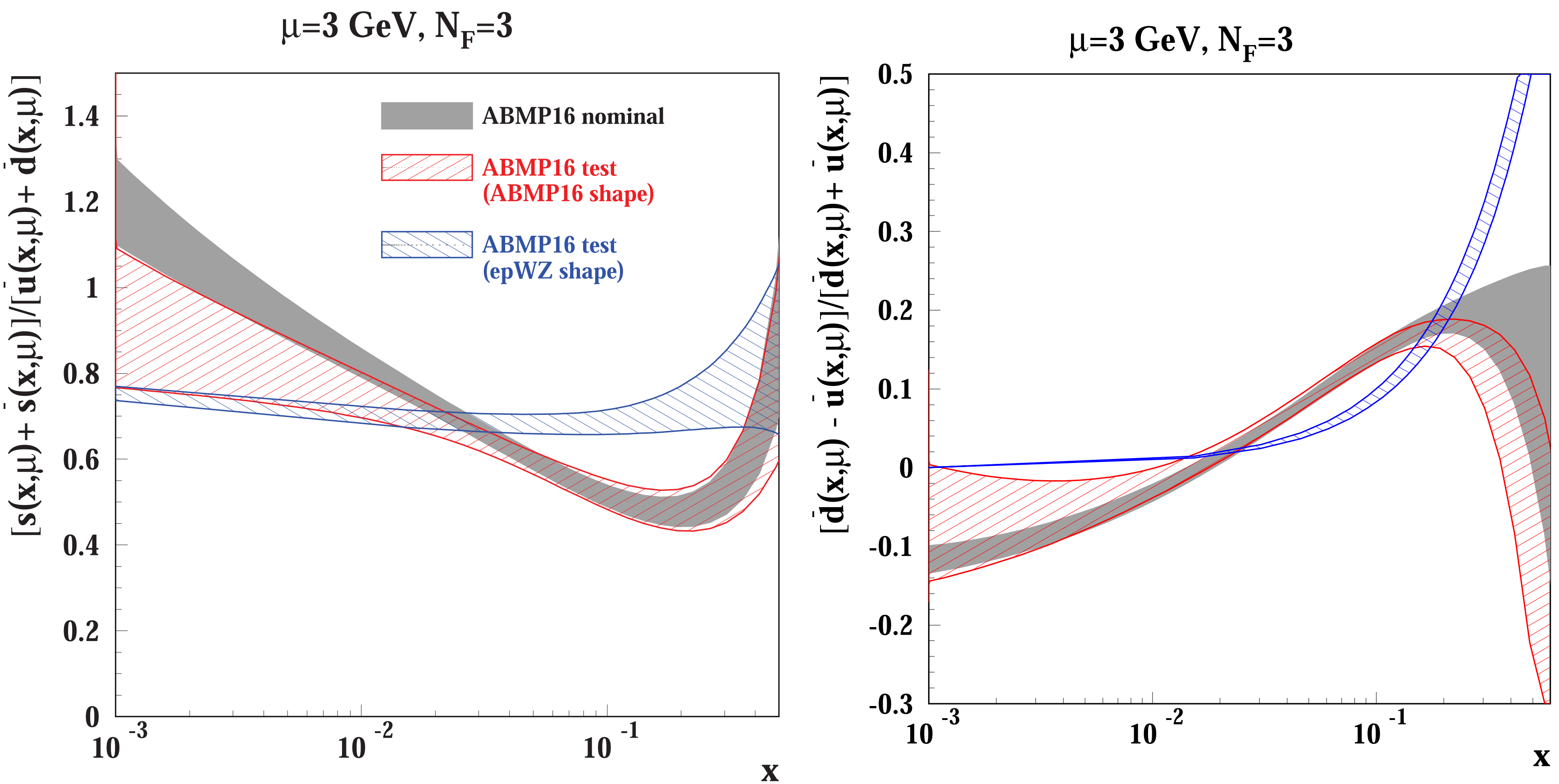
Comparision with earlier determinations





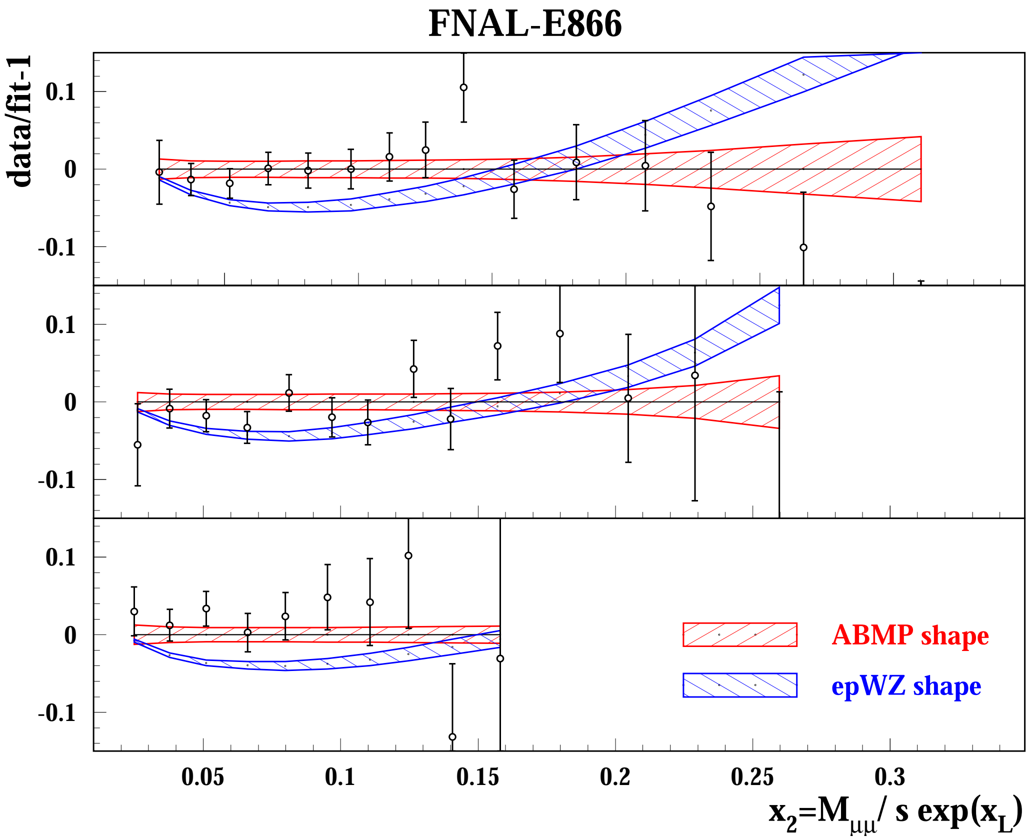
- ABM update (NuTeV/CCFR+NOMAD+CHORUS) in good agreement with CMS results
- ATLAS strange-sea in enhanced (epWZ12), but correlated with $\bar{d}$-quark sea suppression (disagreement with the FNAL-E866 data)
- Upper margin of ABM analysis (CHORUS+CMS+ATLAS) is lower than epWZ12 fit by ATLAS

Comparision with recent determinations (I)



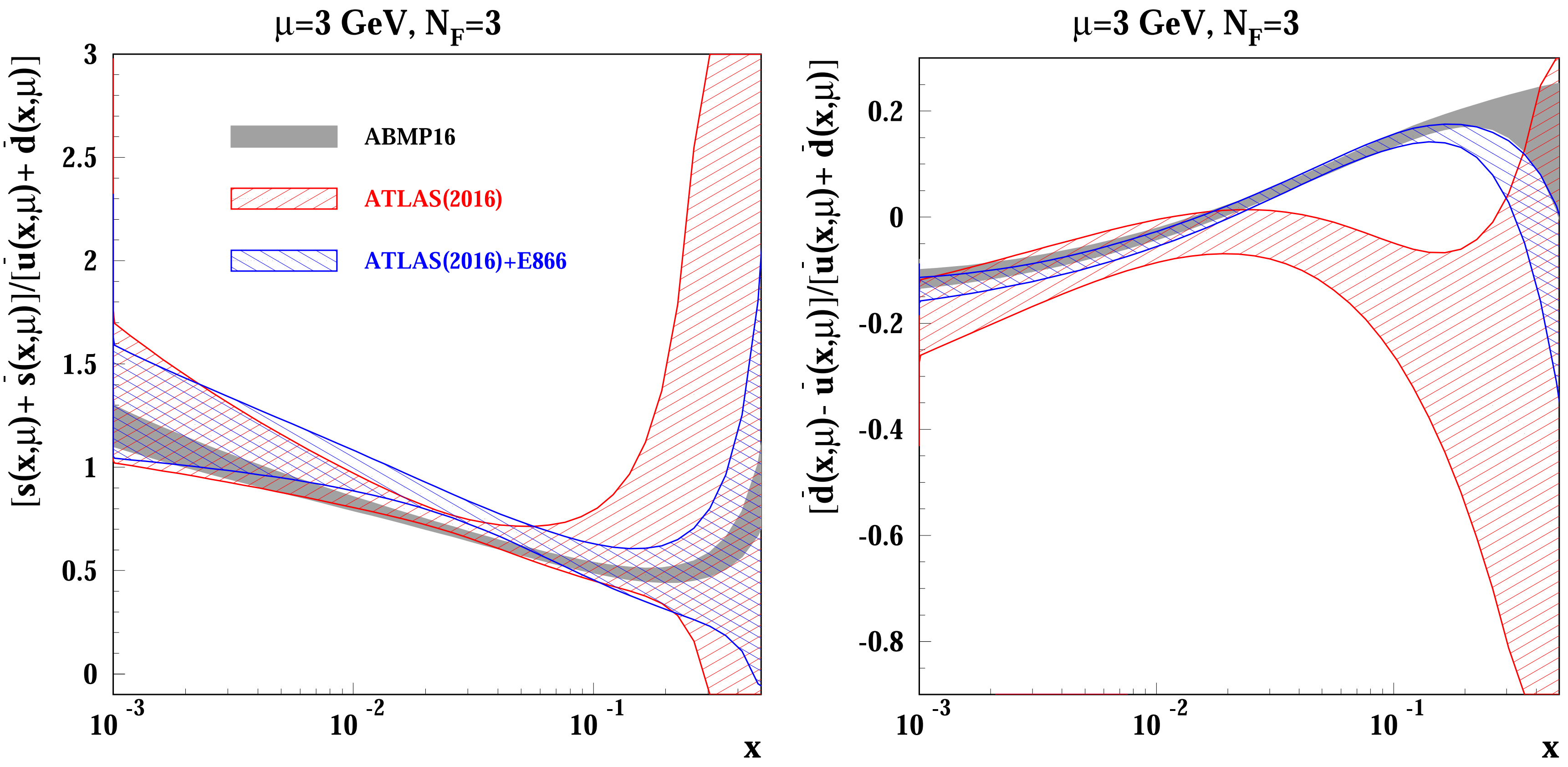
- Strangeness suppression factor $r_s(x,\mu^2) = \frac{s(x,\mu^2)+\bar{s}(x,\mu^2)}{\bar{d}(x,\mu^2)+\bar{u}(x,\mu^2)}$ (left) and sea-quark iso-spin asymmetry $I(x,\mu^2) = \frac{\bar{d}(x,\mu^2)-\bar{u}(x,\mu^2)}{\bar{d}(x,\mu^2)+\bar{u}(x,\mu^2)}$ (right)
- Use of ABMP16 or epWZ16 parametrization shape

Comparision with recent determinations (II)



- Pulls of the E866 data on inclusive di-muon production in proton-proton collisions for ABMP16 or epWZ16 parametrization shape

Comparision with recent determinations (III)



- Strangeness suppression factor $r_s(x,\mu^2) = \frac{s(x,\mu^2)+\bar{s}(x,\mu^2)}{\bar{d}(x,\mu^2)+\bar{u}(x,\mu^2)}$ (left) and sea-quark iso-spin asymmetry $I(x,\mu^2) = \frac{\bar{d}(x,\mu^2)-\bar{u}(x,\mu^2)}{\bar{d}(x,\mu^2)+\bar{u}(x,\mu^2)}$ (right)
- Use of ATLAS data with or withour E866 data

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
  - correlations are important and need to be taken into account
- LHC data for $W^\pm$- and Z-boson production provides valuable information on light flavor PDFs u, d and s over wide range of x
- Strange sea suppression is constrained by data from neutrino-nucleon DIS
  - Strange sea supenhancement in ATLAS analysis epWZ16 is consequence of parametrization bias
- Experimental precision of $\lesssim 1\%$ makes theoretical predictions at NNLO in QCD mandatory
  - efforts towards at N^{3}LO are under way