PDFs, α_s and Heavy-Quark Masses

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(in collaboration with J.Blümlein, S.Moch, and R.Plačakytė)

- HERA I+II data: $\alpha_s(M_Z)$, m_c, and m_b
- Drell-Yan data from the LHC and Tevatron: Isospin asymmetry and d/u at large x

sa, Blümlein, Moch, Plačakytė PRD 94, 114038(2016)

- t-quark data: m_t and gluon distribution
- Charm production data from NOMAD and CHORUS: strange sea

sa, Blümlein, Caminada, Lipka, Lohwasser,
Moch, Petti, Plačakytė PRD 91, 094002 (2015)

sa, Blümlein, Moch, Plačakytė, hep-ph/1701.05838

SM@LHC2017, Amsterdam, 3 *May 2017*

The fit ingredients

QCD:

- NNLO evolution
- NNLO massless DIS and DY coefficient functions
- NLO+ massive DIS coefficient functions (**FFN scheme**)
  - NLO + NNLO(approx.) corrections for NC
  - NNLO CC at Q>> m_c
  - running mass
- NNLO exclusive DY (FEWZ 3.1)
- NNLO inclusive ttbar production (pole / running mass)
- Relaxed form of (dbar-ubar) at small x

DATA:

- DIS NC/CC inclusive (HERA I+II added, no deuteron data included)
- DIS NC charm production (HERA)
- DIS CC charm production (HERA, NOMAD, CHORUS, NuTeV/CCFR)
- fixed-target DY
- LHC DY distributions (ATLAS, CMS, LHCb)
- t-quark data from the LHC and Tevatron
- deuteron data are excluded

Power corrections:

- target mass effects
- dynamical twist-4 terms

Heavy-quark electro-production in the FFNS

- Only 3 light flavors appear in the initial state
- The dominant mechanism is photon-gluon fusion
- The coefficient functions are known up to the NLO

Witten NPB 104, 445 (1976)

Laenen, Riemersma, Smith, van Neerven NPB 392, 162 (1993)

- Involved high-order calculations:
  - NNLO terms due to threshold resummation

    Laenen, Moch PRD 59, 034027 (1999)

    Lo Presti, Kawamura, Moch, Vogt [hep-ph 1008.0951]
  - limited set of the NNLO Mellin moments

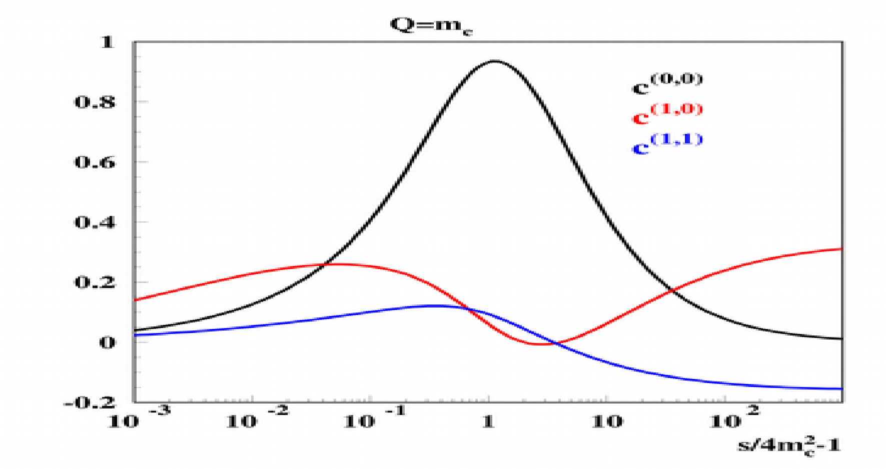
    Ablinger at al. NPB 844, 26 (2011)

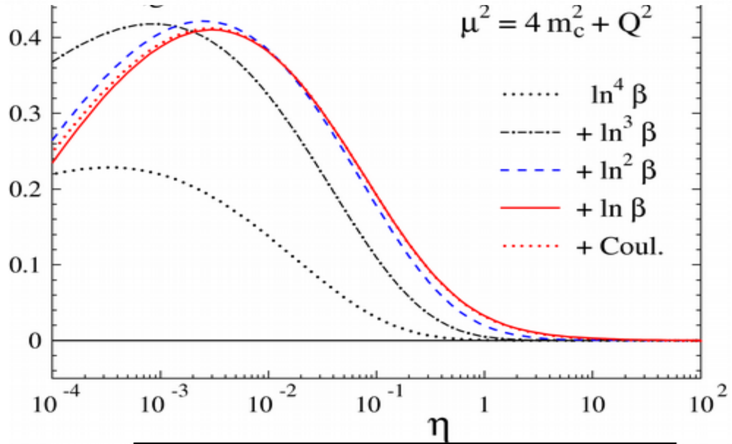
    Bierenbaum, Blümlein, Klein NPB 829, 417 (2009)

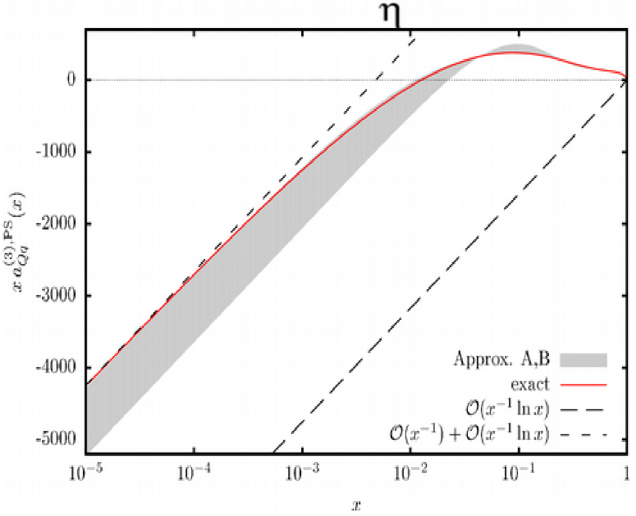
- At large Q the leading-order coefficient → $ln(Q/m_h)$ and may be quite big despite the suppression by factor of α_s and should be resummed

Shifman, Vainstein, Zakharov NPB 136, 157 (1978)

→ a motivation to derive the VFN scheme matched to the FFNS (ACOT...., RT..., FONLL....)

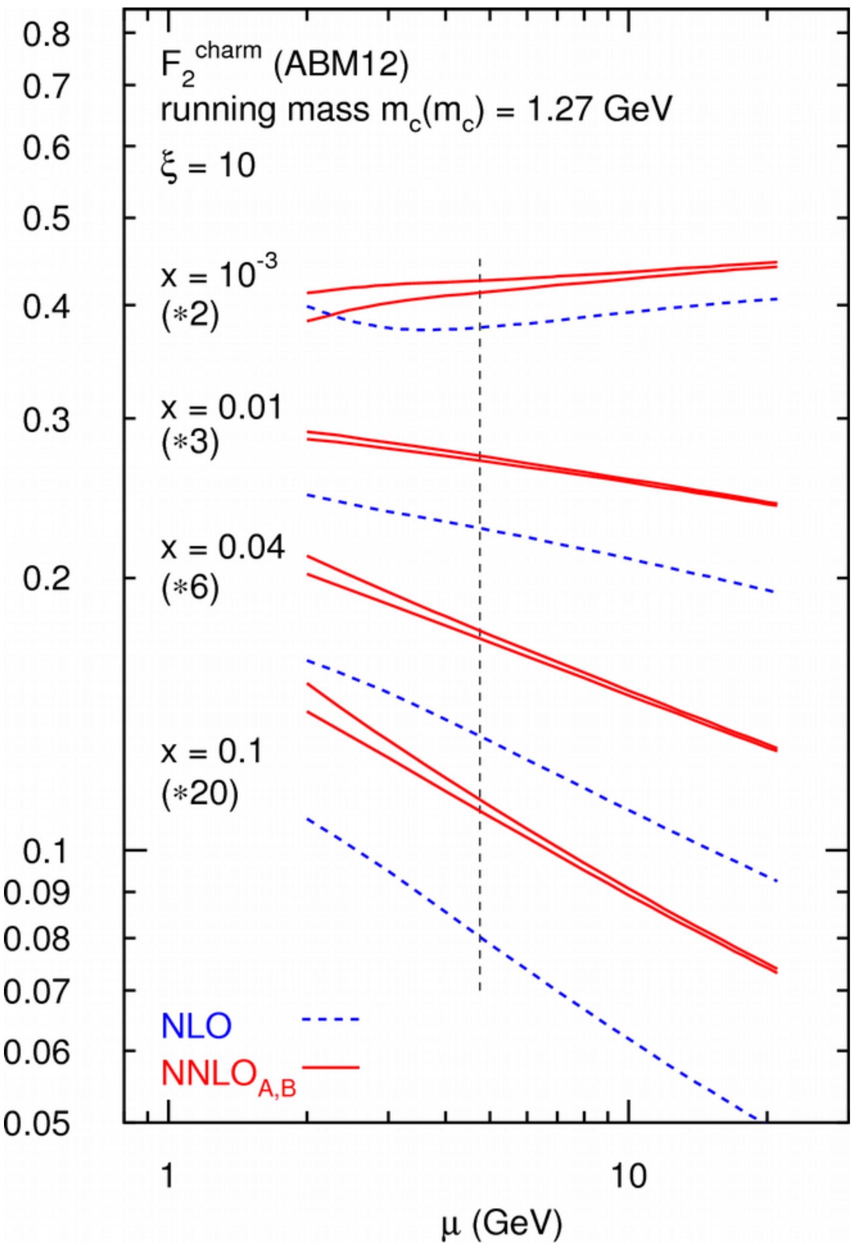






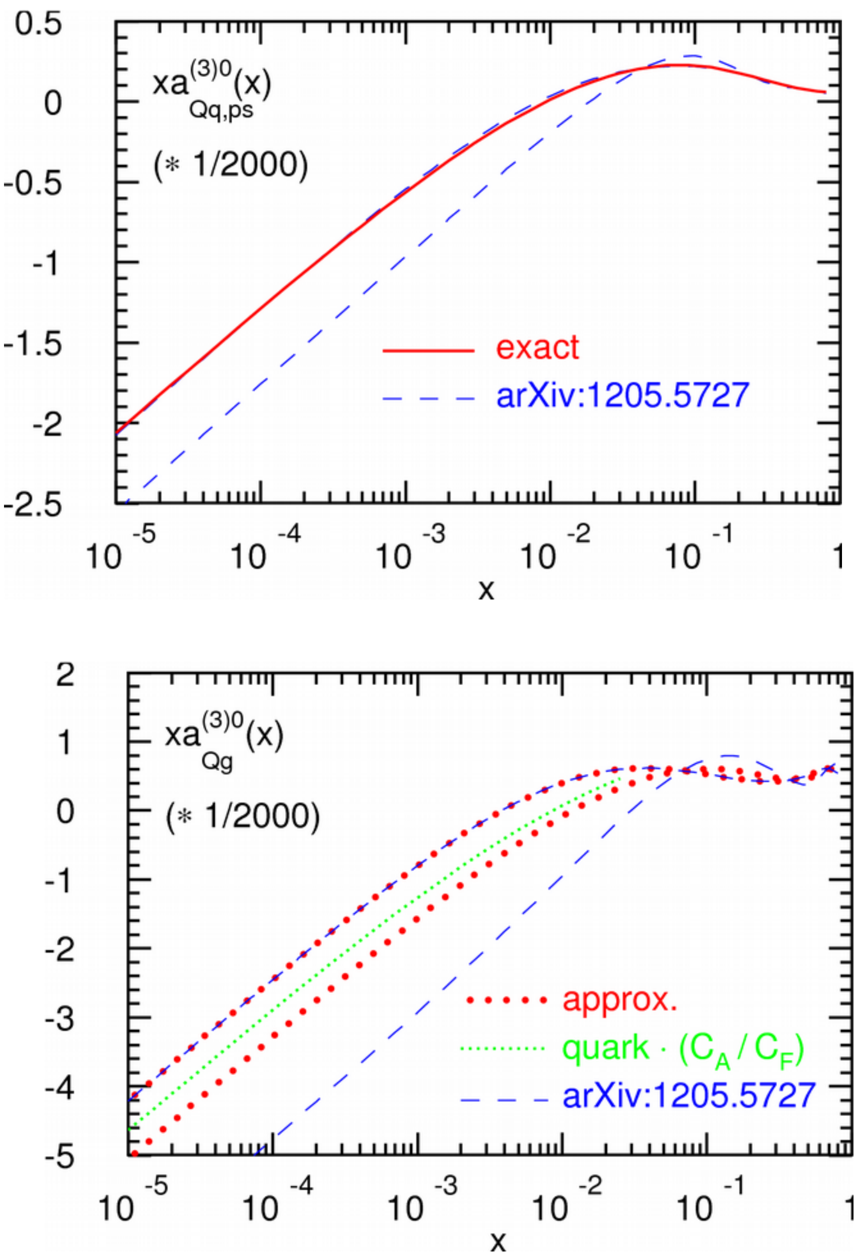
Ablinger et al. NPB 890, 48 (2014)

Progress in the massive DIS coefficients



Combination of the threshold corrections, high-energy limit, and the NNLO massive OMEs

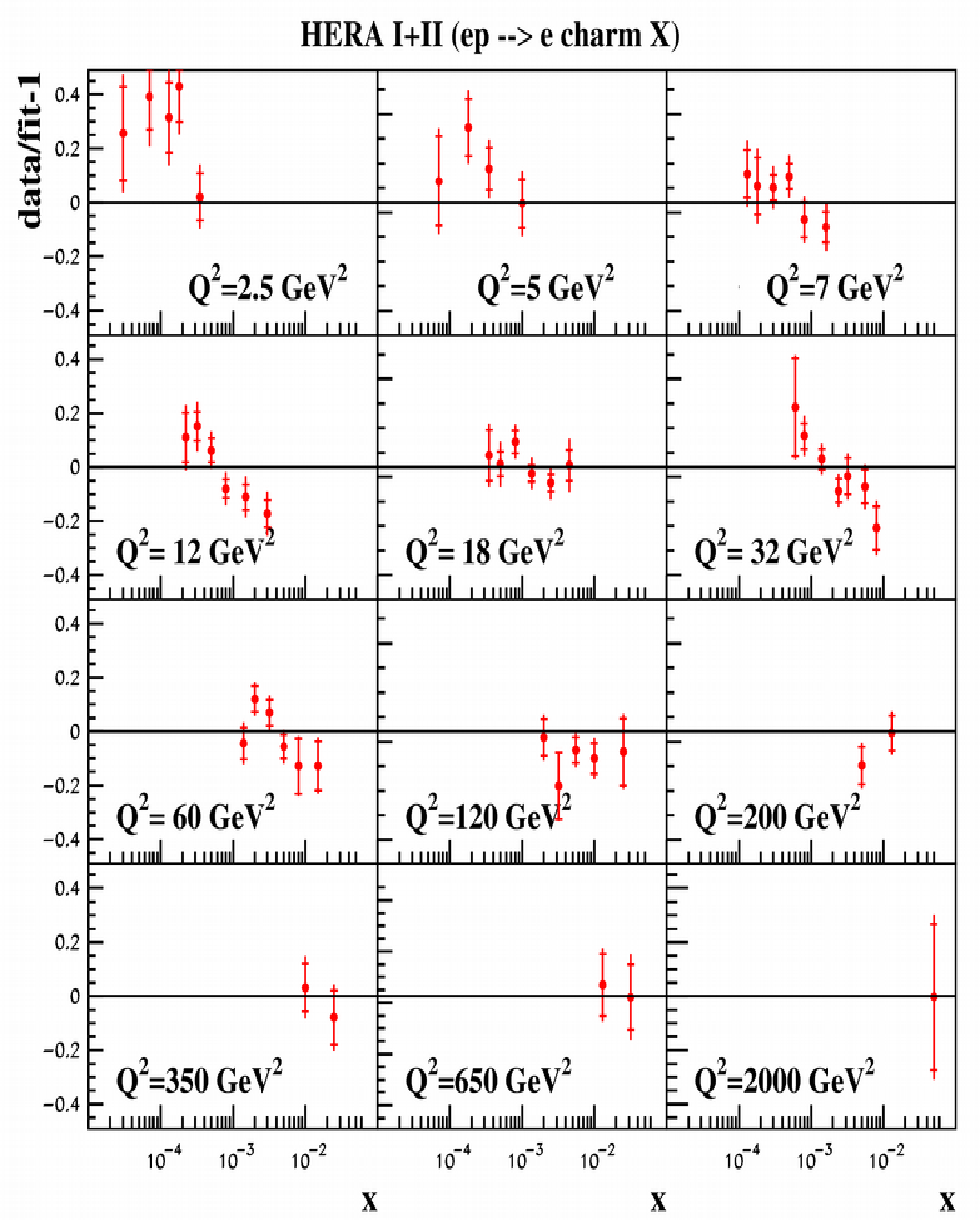
Kawamura, Lo Presti, Moch, Vogt NPB 864, 399 (2012)



Update with the pure singlet massive OMEs
→ improved theoretical uncertainties

HERA charm data and $m_c(m_c)$

H1/ZEUS ZPC 73, 2311 (2013)



- Running-mass definition of m_c → better perturbative stability

X^2/NDP=66/52
$m_c(m_c)$=1.252±0.018(exp.) GeV ABMP16
$m_c(m_c)$=1.24±0.03(exp.) GeV ABM12
m_c(pole)~1.9 GeV (NNLO)

Marquard et al. PRL 114, 142002 (2015)

- RT optimal
  X^2/NDP=82/52 NNLO
  m_c(pole)=1.25 GeV **MMHT14 EPJC 75, 204 (2015)**
- F0NLL
  X^2/NDP=60/47 NNLO
  m_c(pole)=1.275 GeV **NNPDF3.0 JHEP 504, 040 (2015)**
- S-ACOT-χ
  X^2/NDP=59/47 NNLO
  m_c(pole)=1.3 GeV **CT14 hep-ph 1506.07443**

Accardi, et al. EPJC 76, 471 (2016)

$m_c(m_c)$=1.246±0.023 (h.o.) GeV NNLO

Kiyo, Mishima, Sumino hep-ph/1510.07072

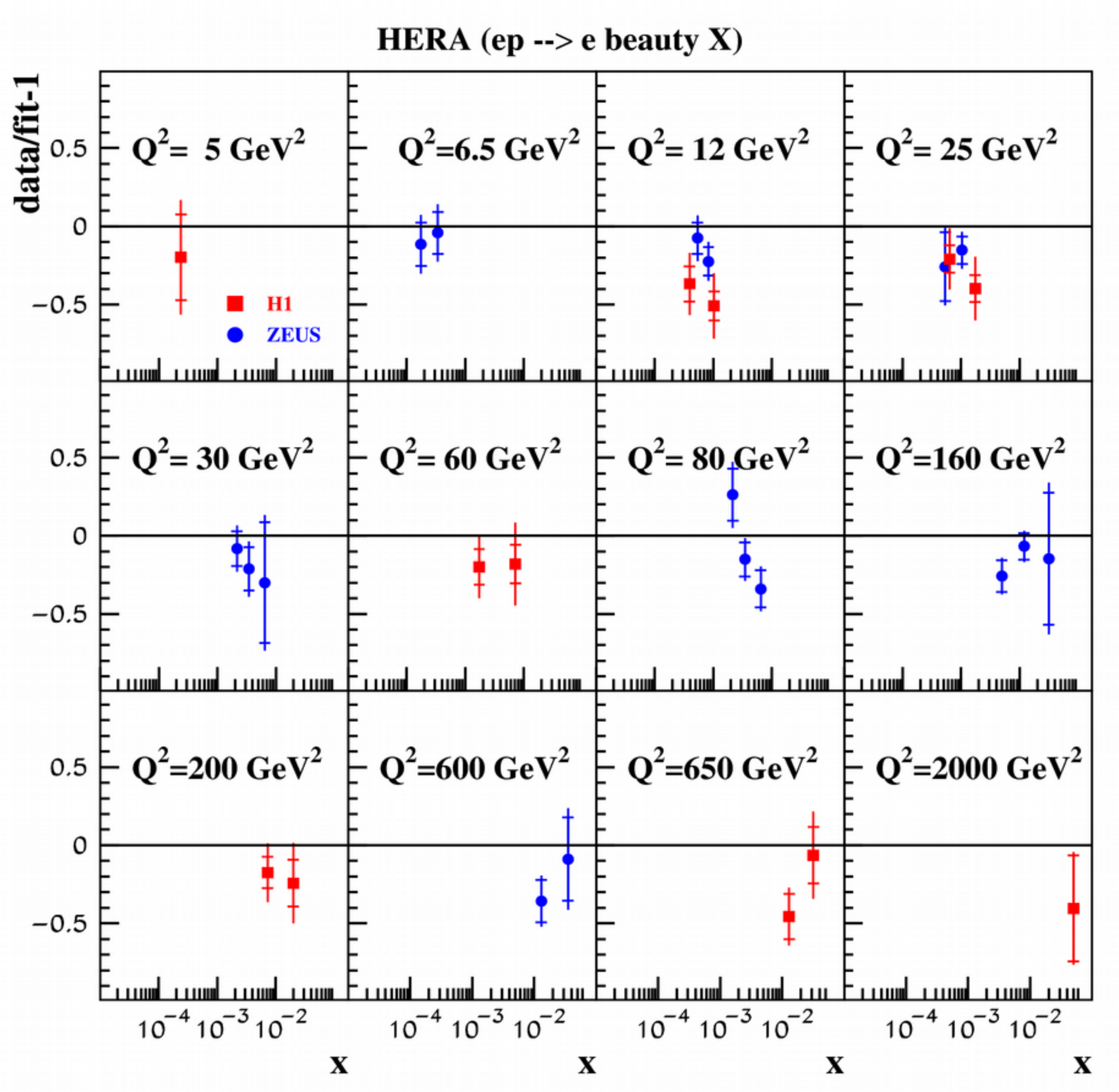
Charm quark mass and the Higgs cross section

MMHT

- "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 $\sigma^{c\bar{c}}$)	$\sigma(H)^{\text{NNLO}}$ [pb] best fit $\alpha_s(M_Z)$	$\sigma(H)^{\text{NNLO}}$ [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)

HERA bottom data and $m_b(m_b)$



ZEUS JHEP 1409, 127 (2014)

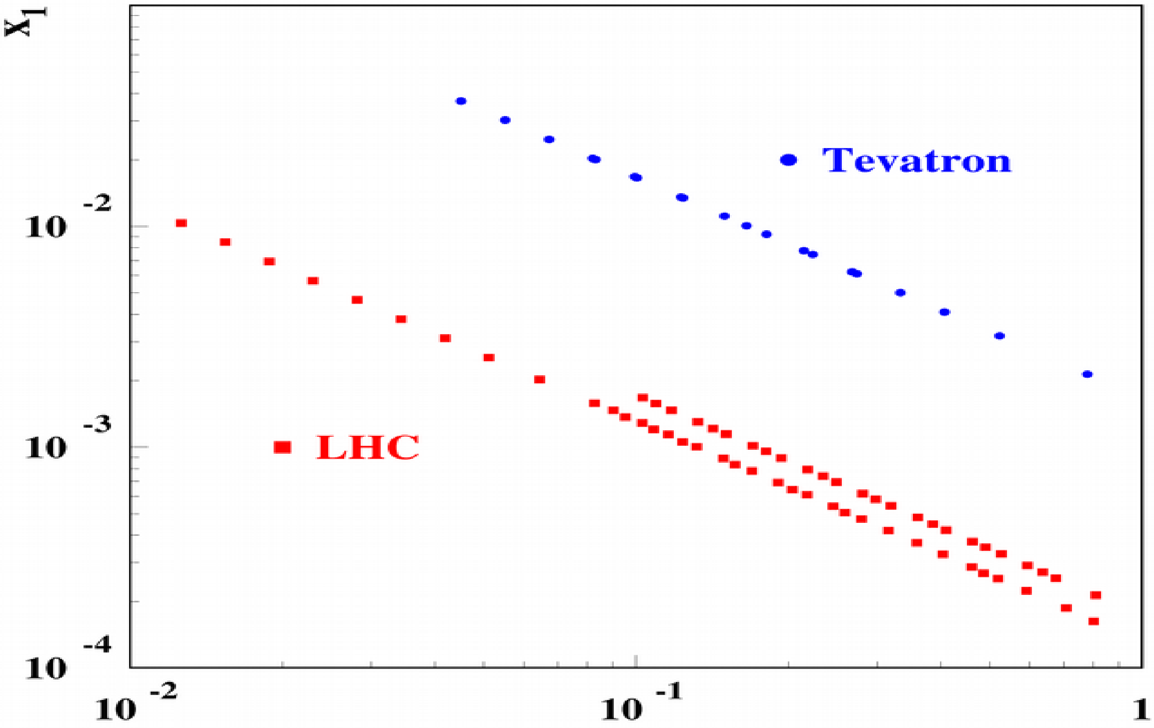
χ^2/NDP=16/17

H1 EPJC 65, 89 (2010)

χ^2/NDP=5/12

$m_b(m_b)$=3.83±0.12(exp.) GeV

Forward DY kinematics



In the forward region $x_2 >> x_1$

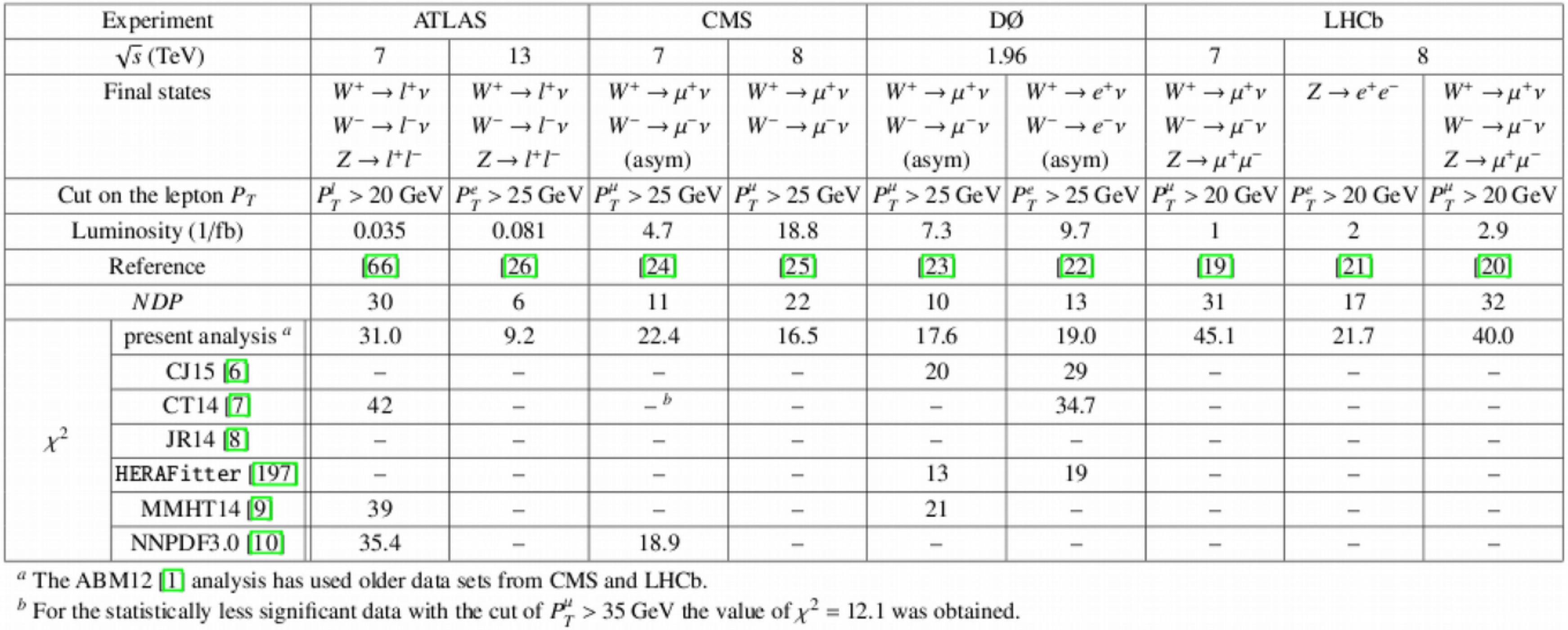
$\sigma(W^+) \sim u(x_2)\ \mathrm{dbar}\ (x_1)$

$\sigma(W^-) \sim d(x_2)\ \mathrm{ubar}(x_1)$

$\sigma(Z) \sim Q_U^2 u(x_2)\ \mathrm{ubar}\ (x_1) + Q_D^2 d(x_2)\ \mathrm{dbar}(x_1)$

$\sigma(DIS) \sim q_u^2 u(x_2) + q_d^2 d(x_2)$

Forward W&Z production probes small/large x and is complementary to the DIS → good quark disentangling

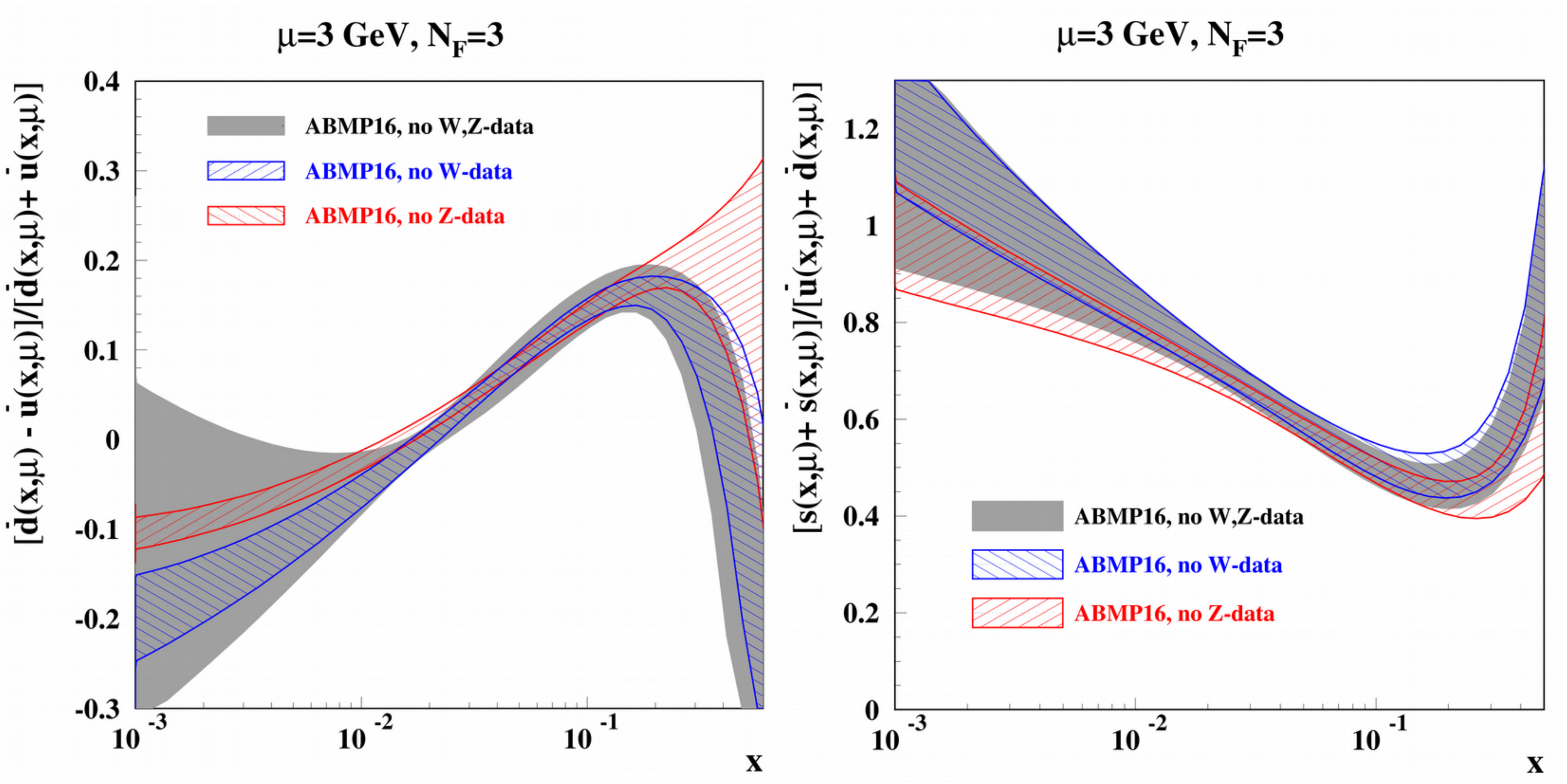


Experiment		ATLAS		CMS		DØ		LHCb		
$\sqrt{s}$ (TeV)		7	13	7	8	1.96		7	8	
Final states		$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to l^+\nu$ $W^- \to l^-\nu$ $Z \to l^+l^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ (asym)	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ (asym)	$W^+ \to e^+\nu$ $W^- \to e^-\nu$ (asym)	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$	$Z \to e^+e^-$	$W^+ \to \mu^+\nu$ $W^- \to \mu^-\nu$ $Z \to \mu^+\mu^-$
Cut on the lepton P_T		$P_T^l > 20$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^\mu > 25$ GeV	$P_T^e > 25$ GeV	$P_T^\mu > 20$ GeV	$P_T^e > 20$ GeV	$P_T^\mu > 20$ GeV
Luminosity (1/fb)		0.035	0.081	4.7	18.8	7.3	9.7	1	2	2.9
Reference		[66]	[26]	[24]	[25]	[23]	[22]	[19]	[21]	[20]
NDP		30	6	11	22	10	13	31	17	32
χ^2	present analysis [a]	31.0	9.2	22.4	16.5	17.6	19.0	45.1	21.7	40.0
	CJ15 [6]	–	–	–	–	20	29	–	–	–
	CT14 [7]	42	–	– [b]	–	–	34.7	–	–	–
	JR14 [8]	–	–	–	–	–	–	–	–	–
	`HERAFitter` [197]	–	–	–	–	13	19	–	–	–
	MMHT14 [9]	39	–	–	–	21	–	–	–	–
	NNPDF3.0 [10]	35.4	–	18.9	–	–	–	–	–	–

[a] The ABM12 [1] analysis has used older data sets from CMS and LHCb.

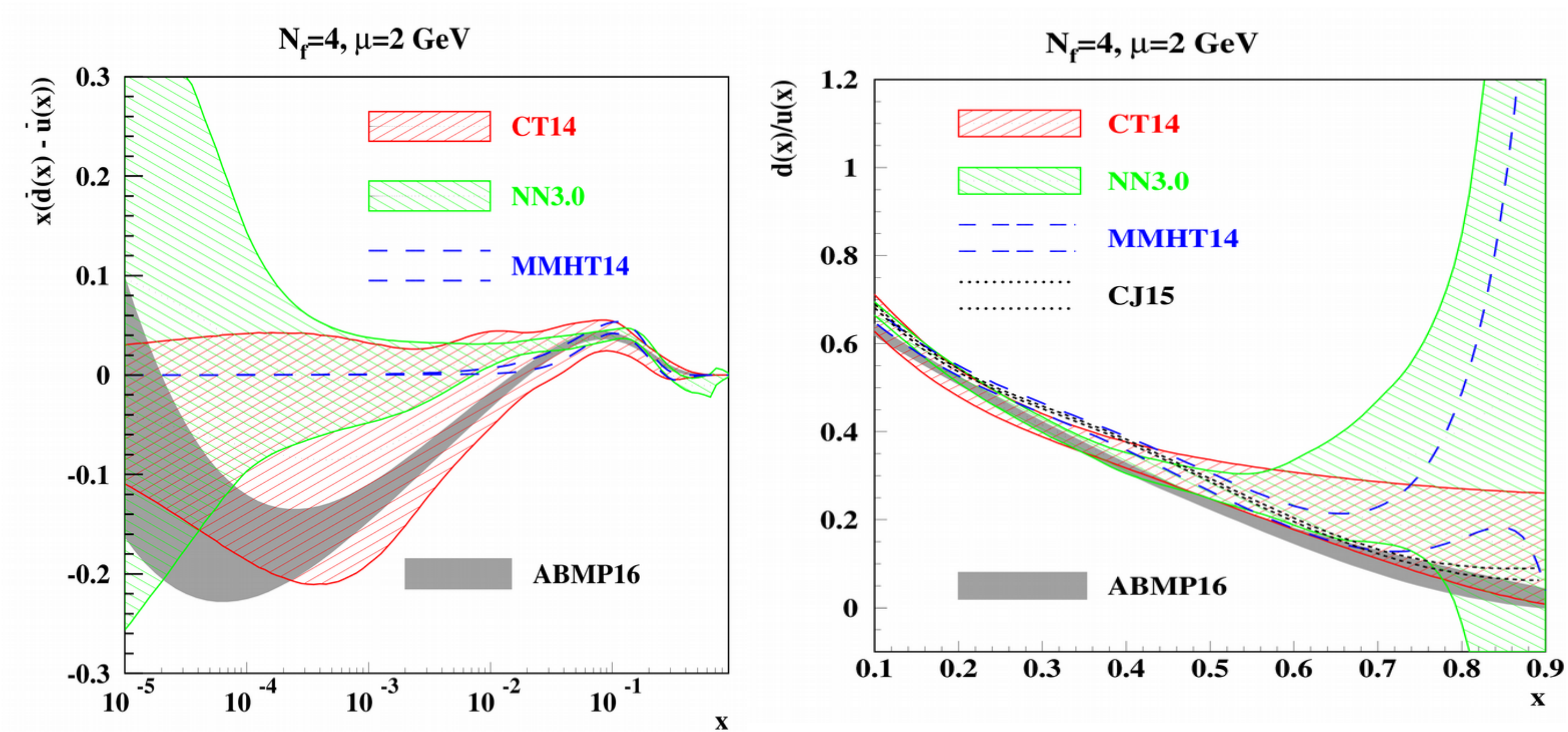
[b] For the statistically less significant data with the cut of $P_T^\mu > 35$ GeV the value of $\chi^2 = 12.1$ was obtained.

Impact of the W-, Z-data



W-, Z-data really control quark disentangling

Comparison with other PDF fits

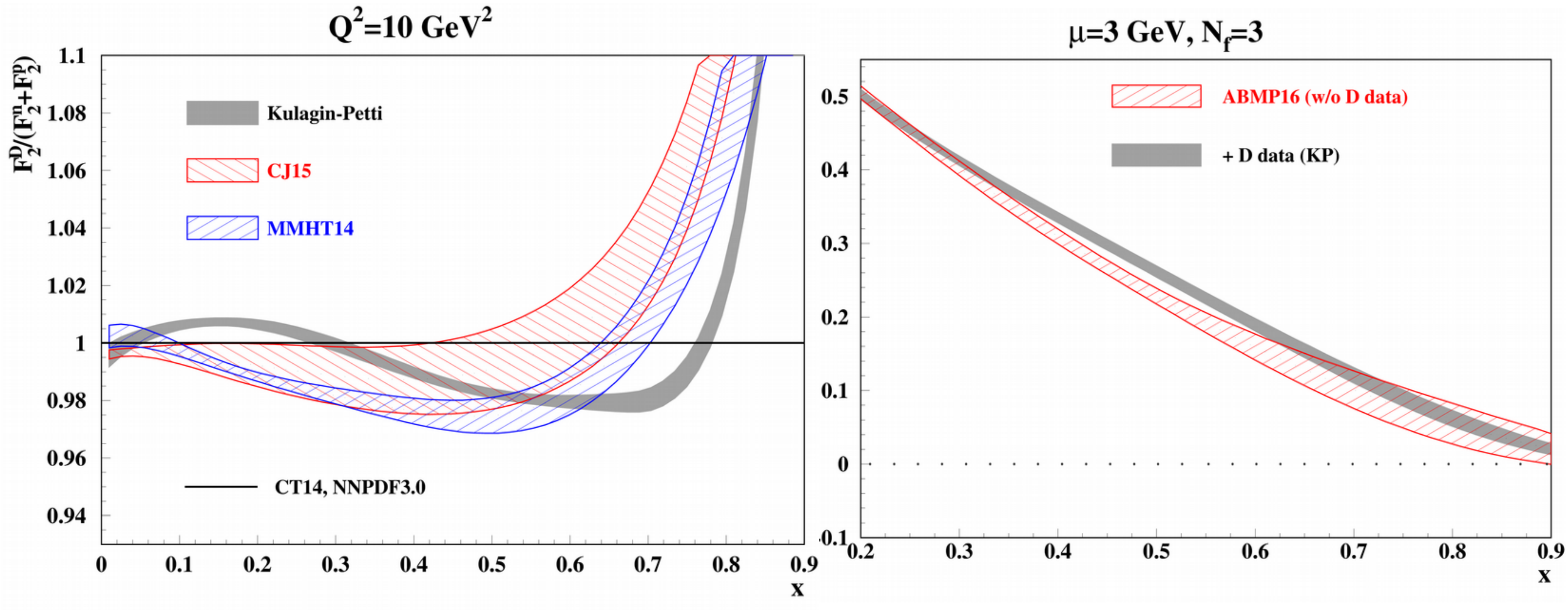


- Relaxed form of the sea iso-spin asymmetry I(x) at small x; Regge-like behaviour is recovered only at $x \sim 10^{-6}$; at large x it is still defined by the phase-space constraint

- Good constraint on the d/u ratio w/o deuteron data → independent extraction of the deuteron corrections **Accardi, Brady, Melnitchouk, Owens, Sato hep-ph/1602.03154;**

- Big spread between different PDF sets, up to factor of 30 at large x → poor control of the background to BSM effects without constraints from the DY data

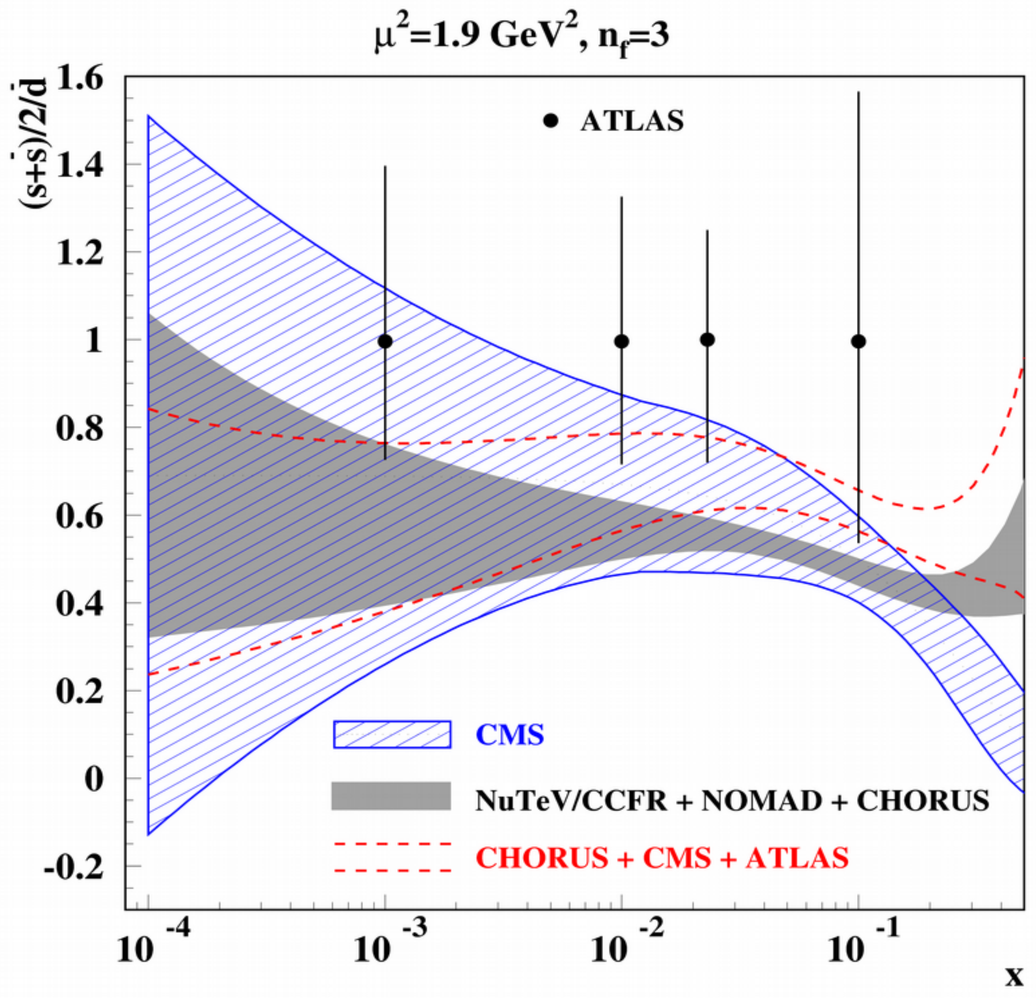
Deuteron corrections in the PDF fits

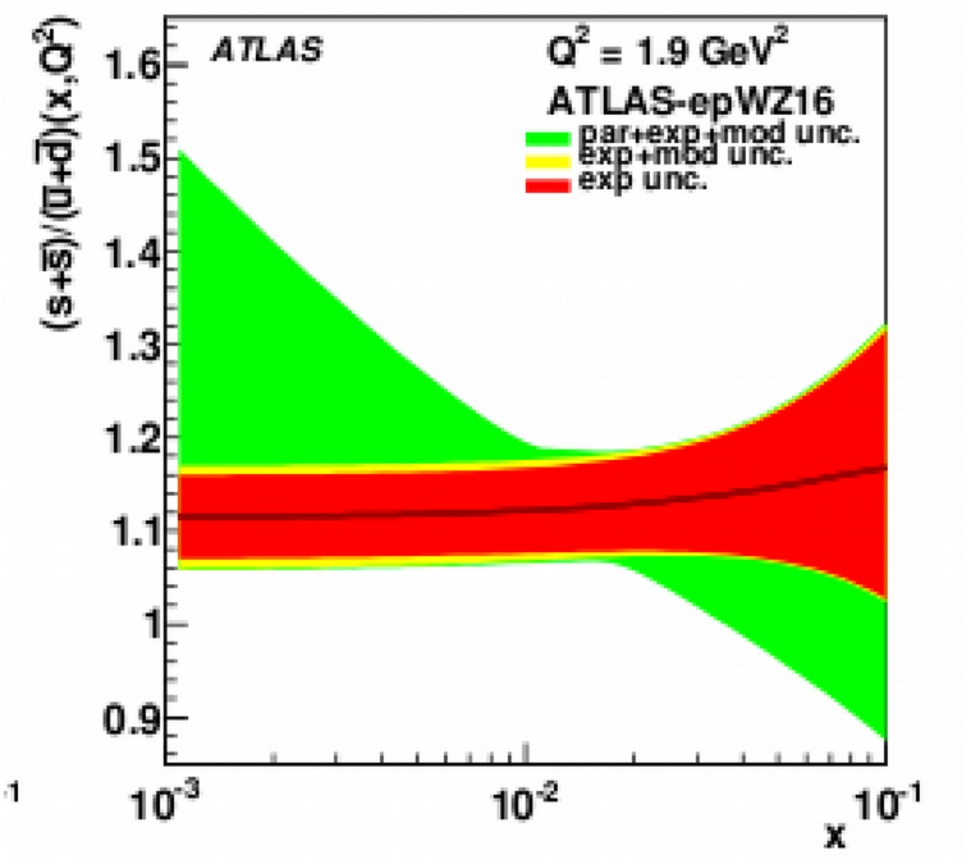


Spread between different deuteron models O(%); quite big for the purposes of precision measurements

DY data help to keep accuracy of the PDF determination avoiding uncertainty due to the modeling of nuclear effects

ATLAS strange sea determinations





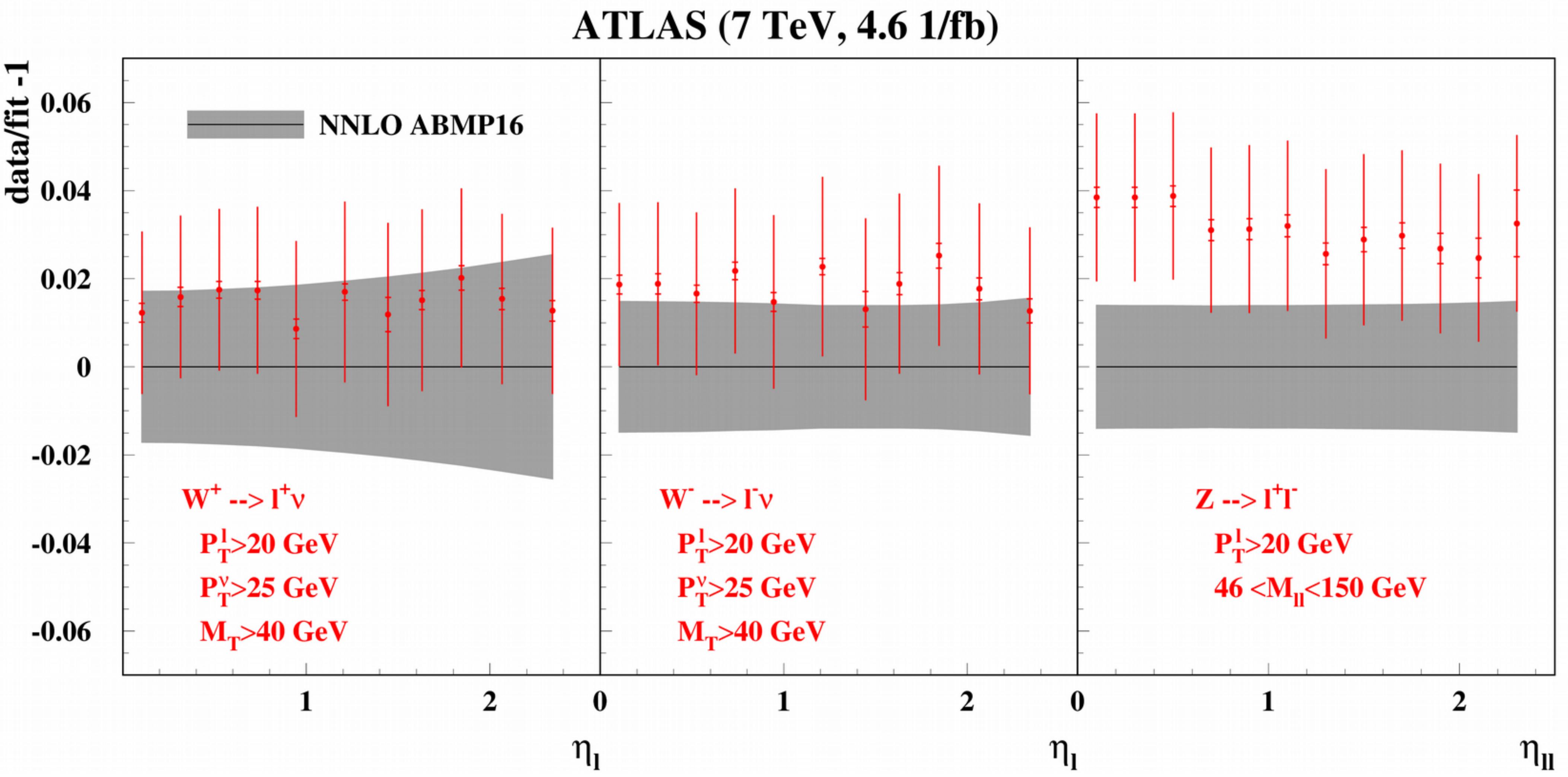
ATLAS arXiv:1612.03016

- ABM12 update (NuTeV/CCFR+NOMAD+CHORUS) demonstrate good agreement with the CMS result

- The ATLAS(2011) strange-sea in enhanced, however it is correlated with the d-quark sea suppression → disagreement with the FNAL-E-866 data

The result is confirmed with improved accuracy → disagreement with the neutrino-beam results??

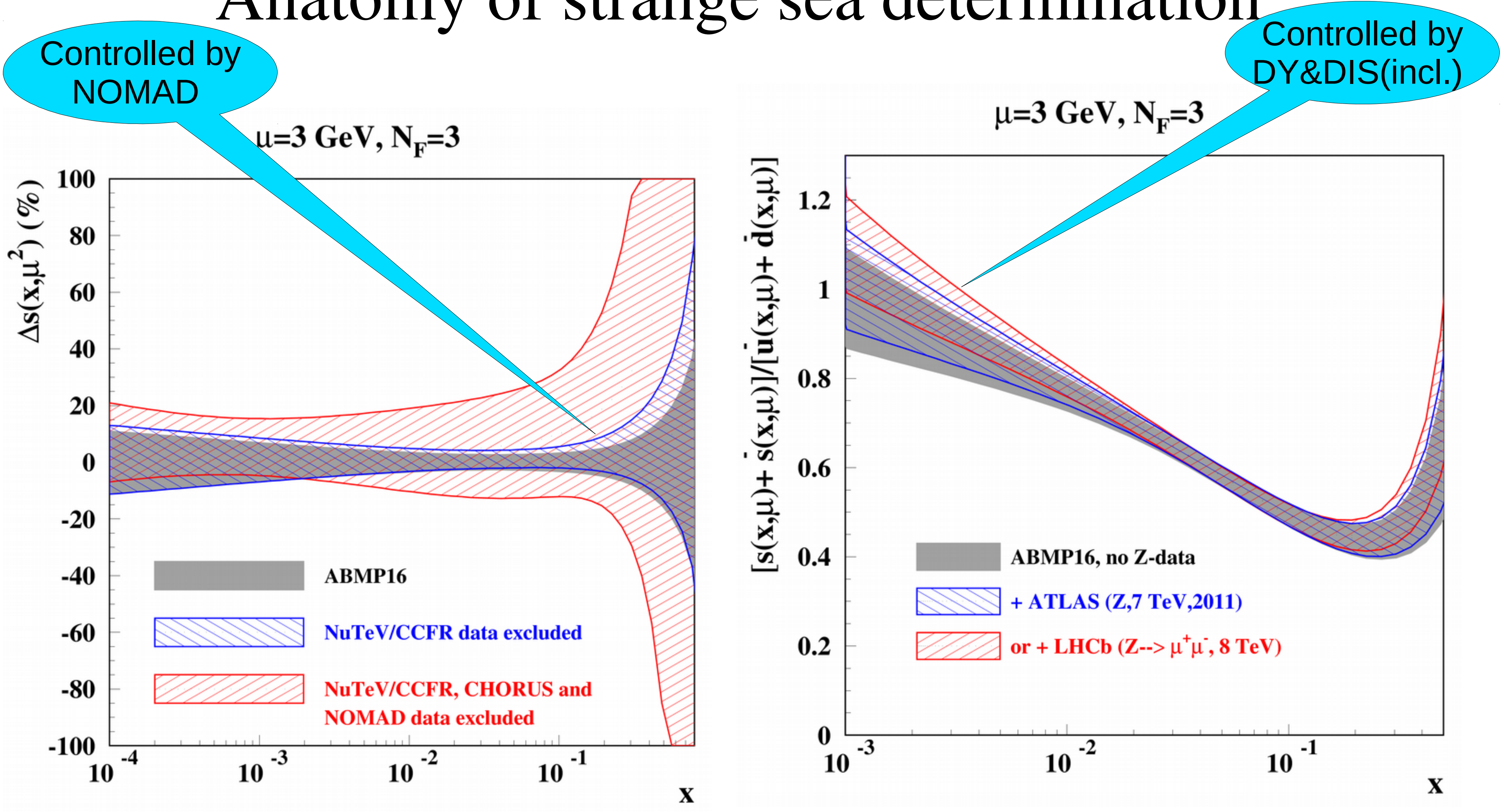
ATLAS data in the ABMP16 fit



W data are in agood agreement

Z data overshoot predictions → tension with our data sets

Anatomy of strange sea determination

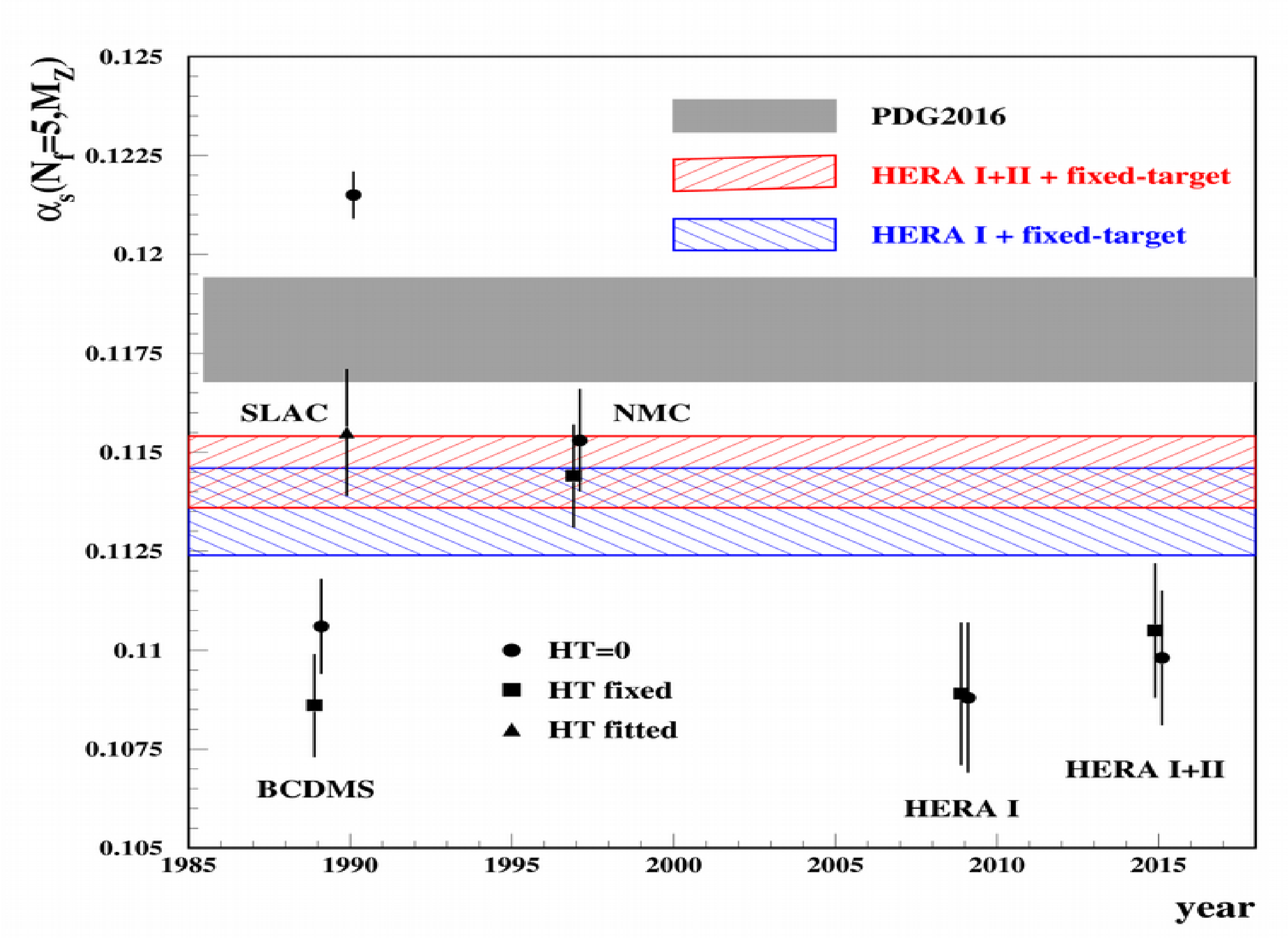


Controlled by NOMAD

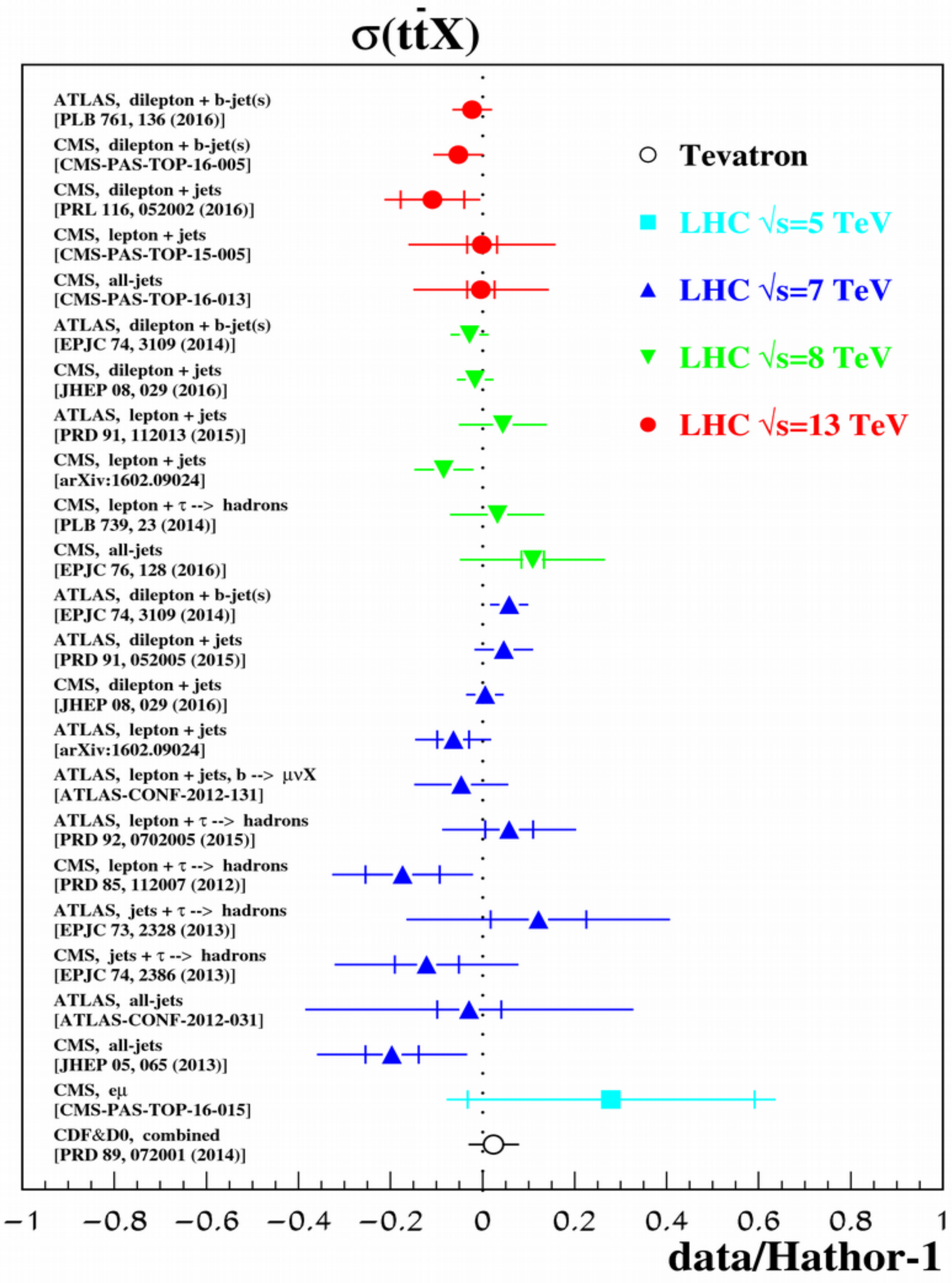
Controlled by DY&DIS(incl.)

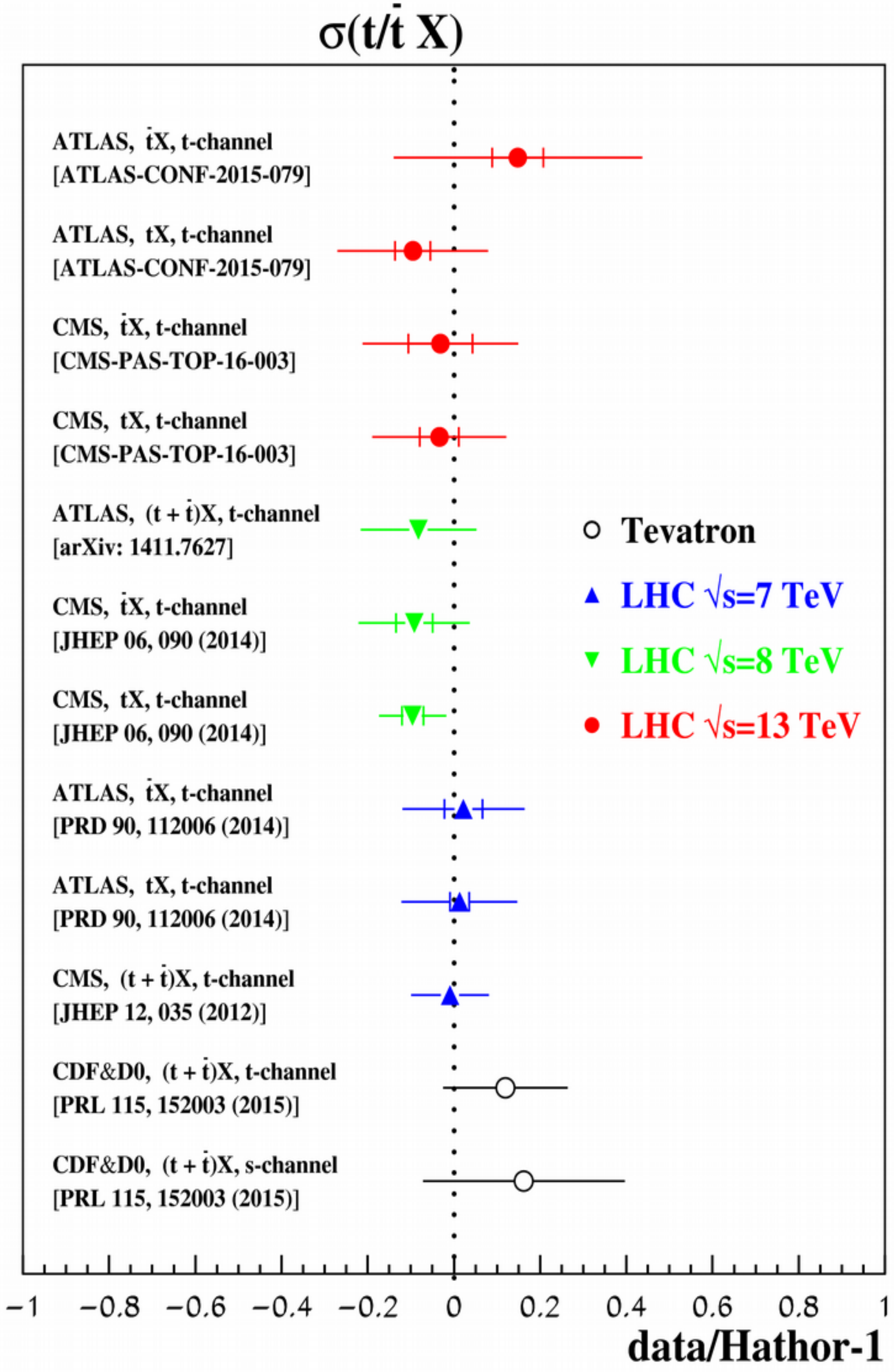
- Uncertainty of ~5% is achieved at x around 0.1
- NuTeV/CCFR data play no essential role → impact of the nuclear corrections is greatly reduced (NOMAD and CHORUS give the ratio CC/incl.)

Strong coupling constant



- Combination of the DY data (disentangle PDFs) and the DIS ones (constrain α_s)
- Run-II HERA data pull α_s up by 0.001
- 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



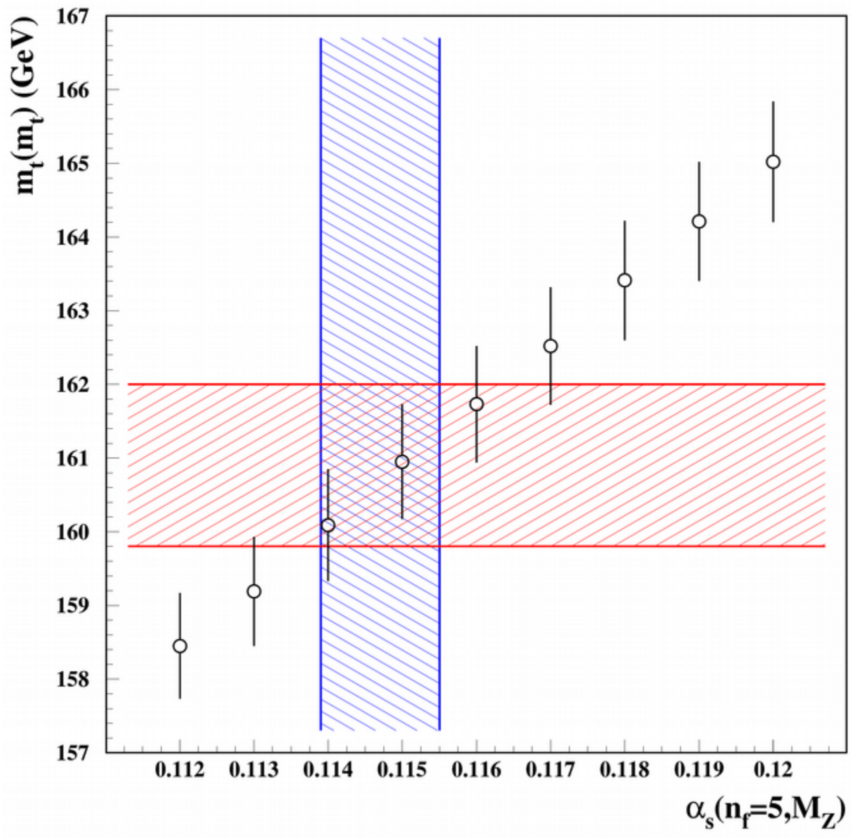


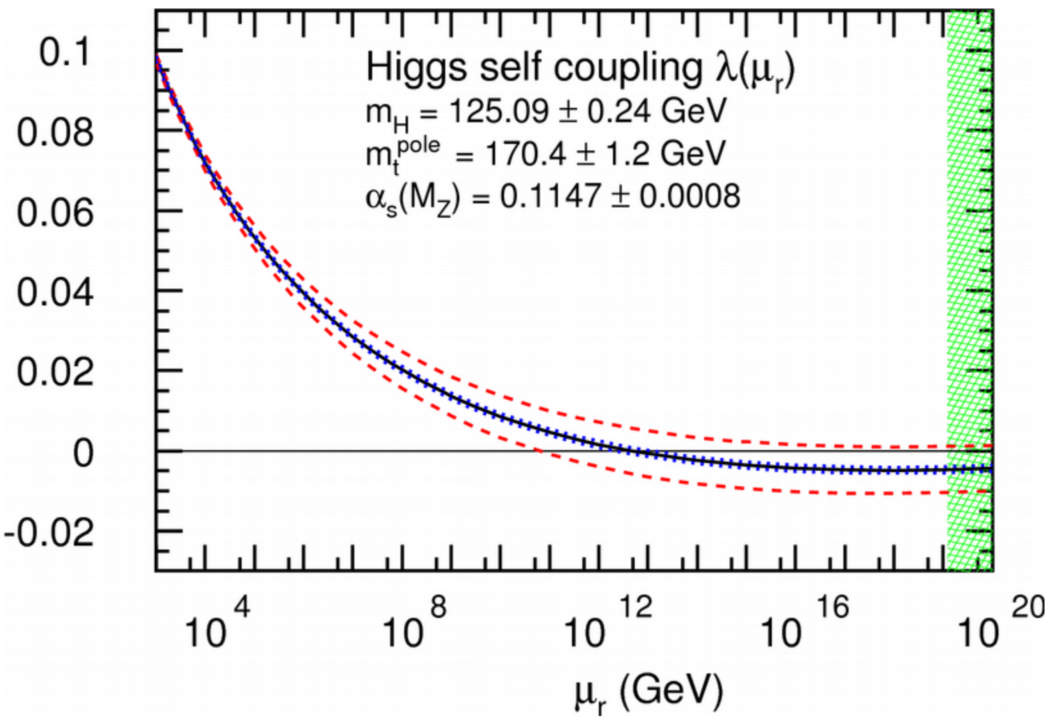
$m_t(m_t)$=160.9±1.1 GeV

Electroweak vacuum stability

$$m_H = 129.6\,\mathrm{GeV} + 1.8 \times \left(\frac{m_t^{\mathrm{pole}} - 173.34\ \mathrm{GeV}}{0.9} \right) - 0.5 \times \left(\frac{\alpha_s^{(n_f=5)}(M_Z) - 0.1184}{0.0007} \right) \mathrm{GeV} \pm 0.3\ \mathrm{GeV},$$

Buttazzo et al., JHEP 12, 089 (2013)

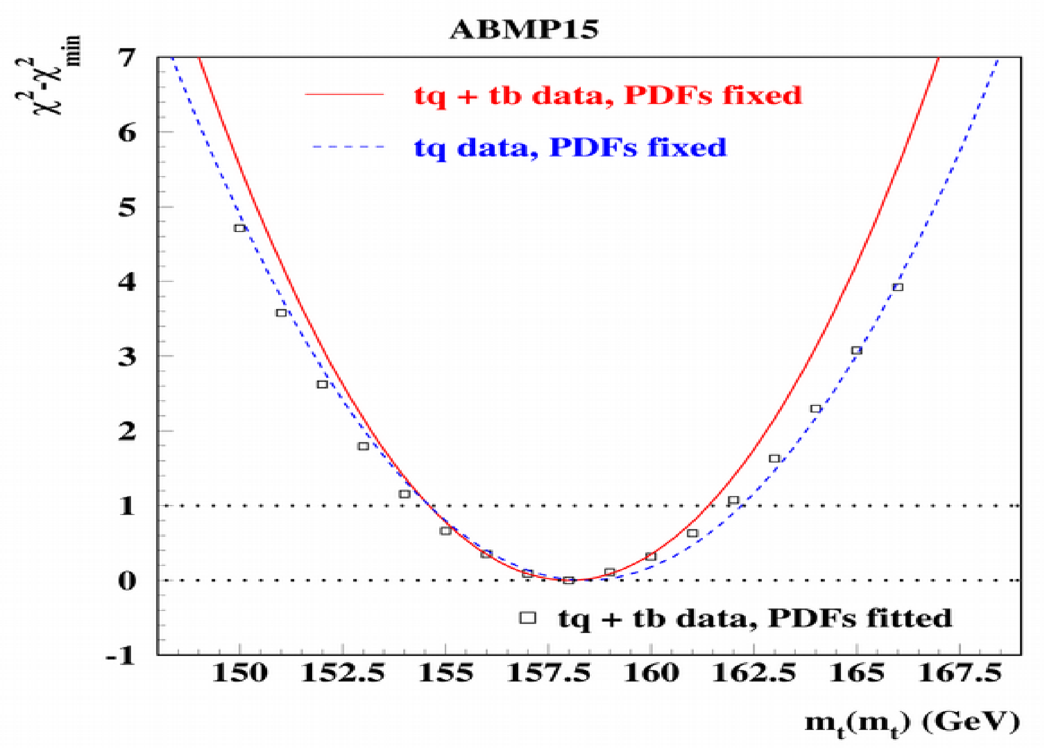




mr: **Kniehl, Pikelner, Veretin CPC 206, 84 (2016)**

Vacuum stability is quite sensitive to the t-quark mass; strong correlation m_t and α_s extracted from the ttbar data

t-quark mass from the single-top data



PDFs fixed:

- Different PDFs prefer value of

  $m_t(m_t)$ ~160± 3.5 GeV

NNPDF goes higher by 3 GeV.

- The CT14 and MMHT14 go higher by 3 GeV with the ttbar channel

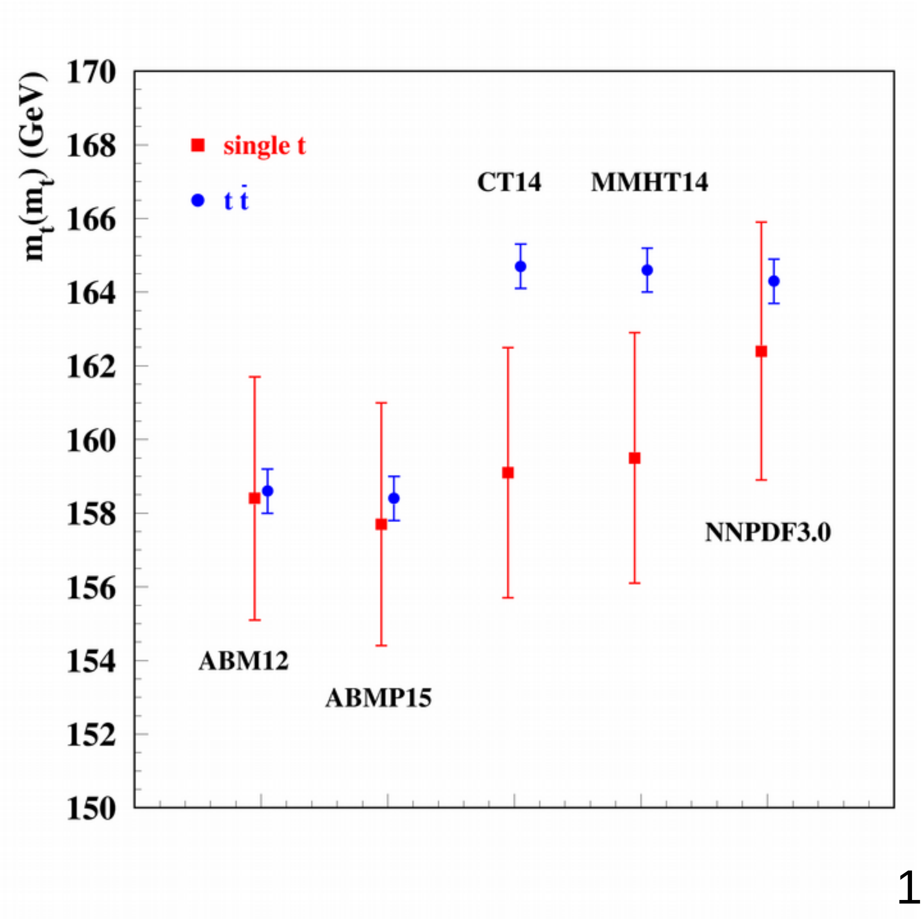
- Electroweak production → reduced impact of α_s and the PDF umcertainties
- HATHOR framework

  t-channel: NNLO

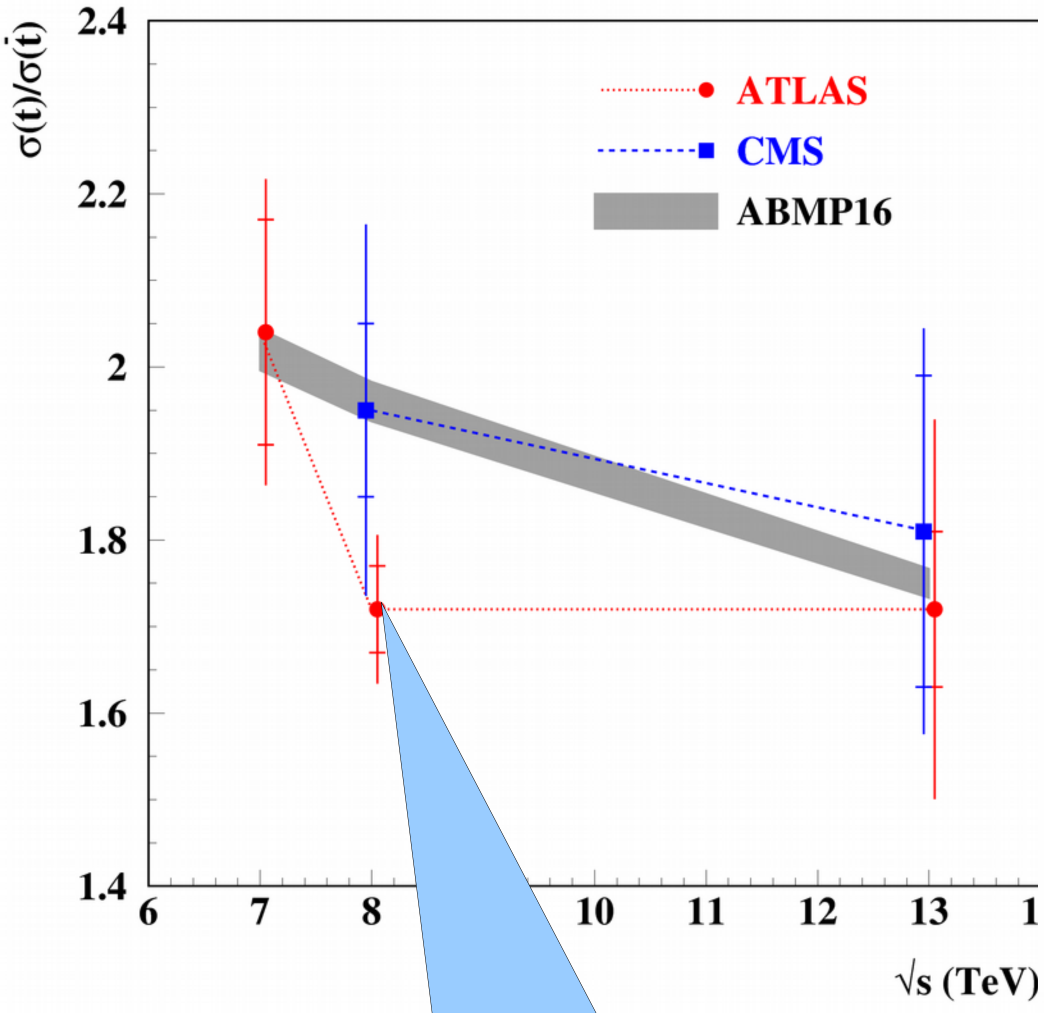
  Brucherseifer, Caola, Melnikov PLB 736, 58 (2014)

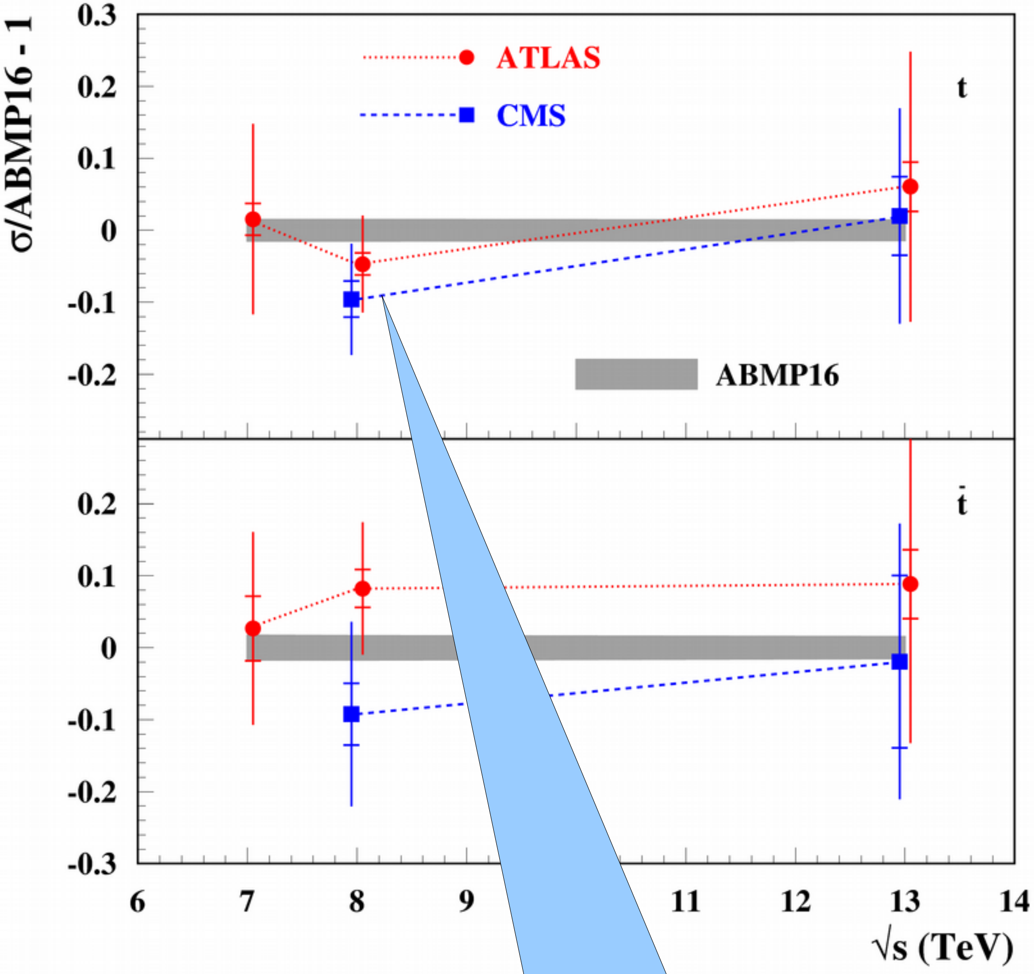
  s-channel: NNLO threshold. resum.

  sa, Moch, Thier PLB 763, 341 (2016)



Single-top: c.m.s. energy dependence





The errors in ATLAS data are much smaller: prefect cancellation of the errors in ratio

The trend in ATLAS data is different for t and tbar samples

Summary

The improvements summarized in the new PDF set:

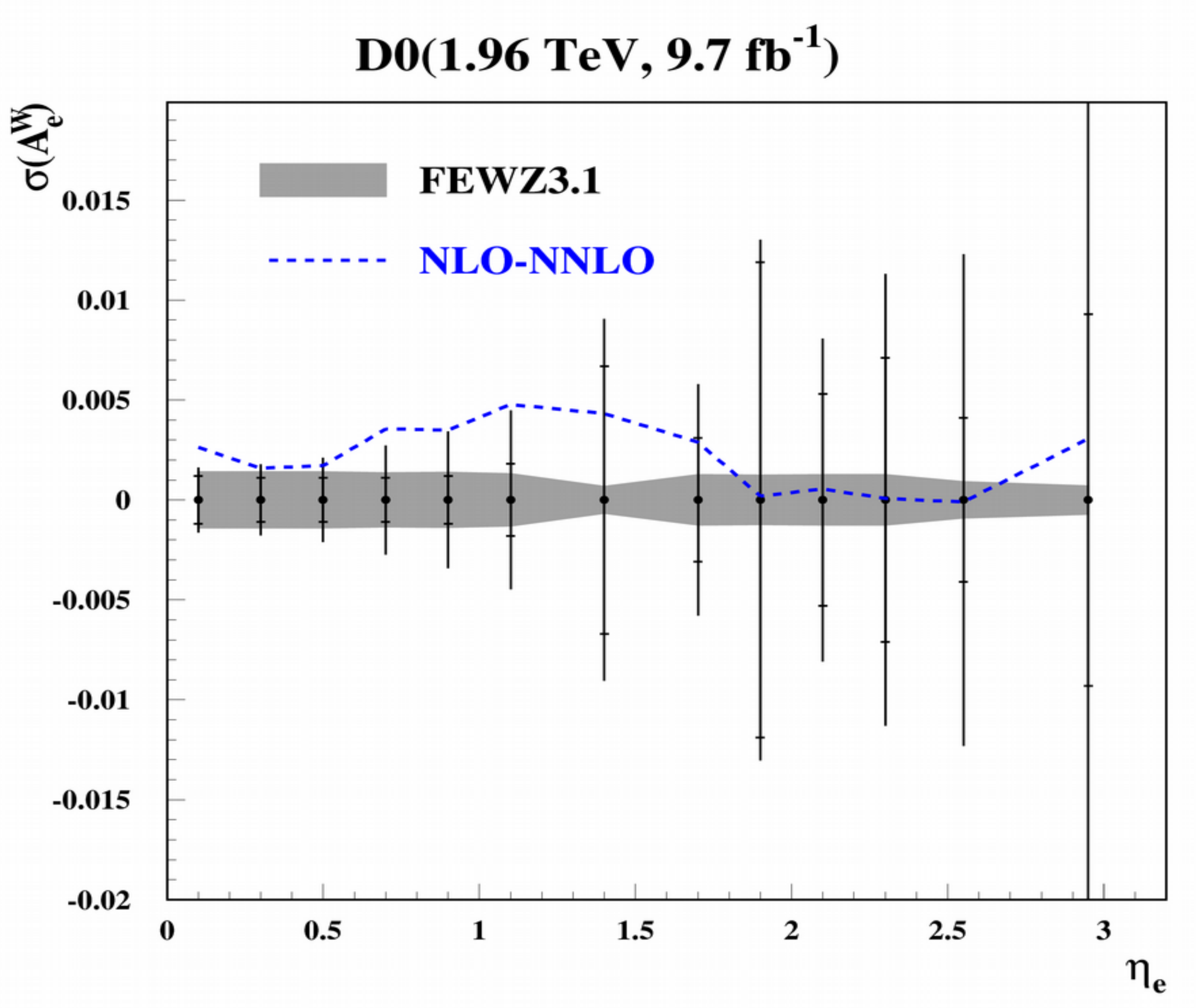
- deuteron data are replaced by the Drell-Yan ones from the LHC and Tevatron → reduced theoretical uncertainties in PDFs, in particular in d/u at large x
- the small-x iso-spin sea asymmetry is relaxed and turns negative at $x \sim 10^{-3}$; an onset of the Regge asymptotics still may occur at $x < 10^{-5}$
- improved strange sea determination, particularly at large x
- moderate increase in the large-x gluon distribution due to impact of the ttbar data
- HERA I+II data included → improved determination of $m_c(m_c)$;

$m_c(m_c) = 1.252 \pm 0.018$ GeV
$m_b(m_b) = 3.83 \pm 0.12$ GeV
$m_t(m_t) = 160.9 \pm 1.1$ GeV

$\alpha_s(M_Z) = 0.1145(9)$ DIS
$\alpha_s(M_Z) = 0.1147(8)$ DIS+ttbar

EXTRAS

Computation accuracy



- Accuracy of O(1 ppm) is required to meet uncertainties in the experimental data → O(10^4 h) of running FEWZ 3.1 in NNLO

- An interpolation grid a la FASTNLO is used

NNLO DY corrections in the fit

The existing NNLO codes (DYNNLO, FEWZ) are quite time-consuming →
fast tools are employed (FASTNLO, Applgrid,.....)

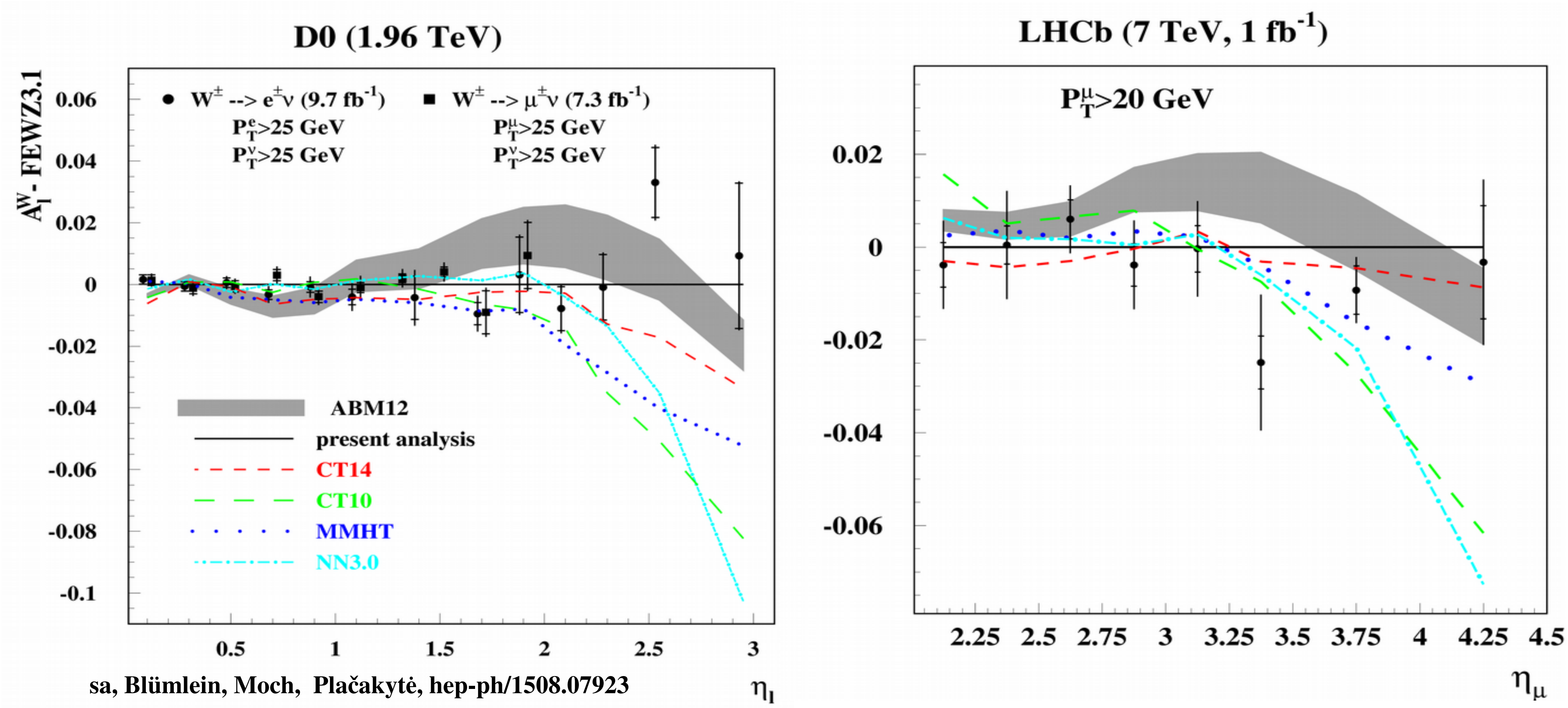
- the corrections for certain basis of PDFs are stored in the grid
- the fitted PDFs are expanded over the basis
- the NNLO c.s. in the PDF fit is calculated as a combination of expansion coefficients with the pre-prepared grids

The general PDF basis is not necessary since the PDFs are already constrained by the data, which do not require involved computations → *use as a PDF basis the eigenvalue PDF sets obtained in the earlier version of the fit*

$\mathbf{P_0} \pm \Delta\mathbf{P}_0$ – vector of PDF parameters with errors obtained in the earlier fit
E – error matrix
P – current value of the PDF parameters in the fit

- store the DY NNLO c.s. for all PDF sets defined by the eigenvectors of **E**
- the variation of the fitted PDF parameters ($\mathbf{P} - \mathbf{P}_0$) is transformed into this eigenvector basis
- the NNLO c.s. in the PDF fit is calculated as a combination of transformed ($\mathbf{P} - \mathbf{P}_0$) with the stored eigenvector values

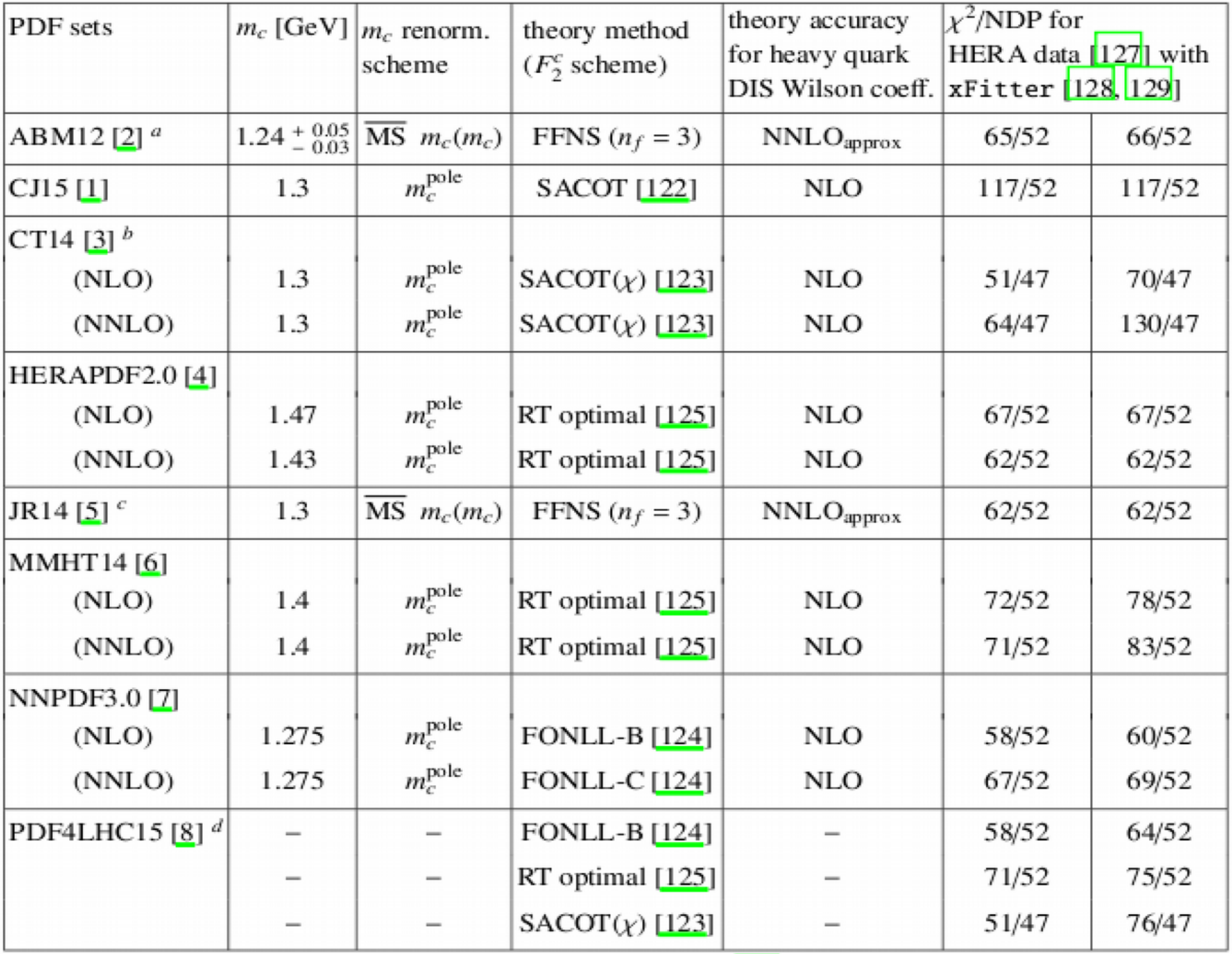
DY at large rapidity



sa, Blümlein, Moch, Plačakytė, hep-ph/1508.07923

- The data can be evidently used for consolidation of the PDFs, however, unification of the theoretical accuracy is also needed

ABM	CT	MMHT	NNPDF
Interpolation of accurate NNLO grid (a la FASTNLO)	NNLL (ResBos)	NLO + NNLO K-factor	NLO + NNLO C-factors (y-dependent K-factors)

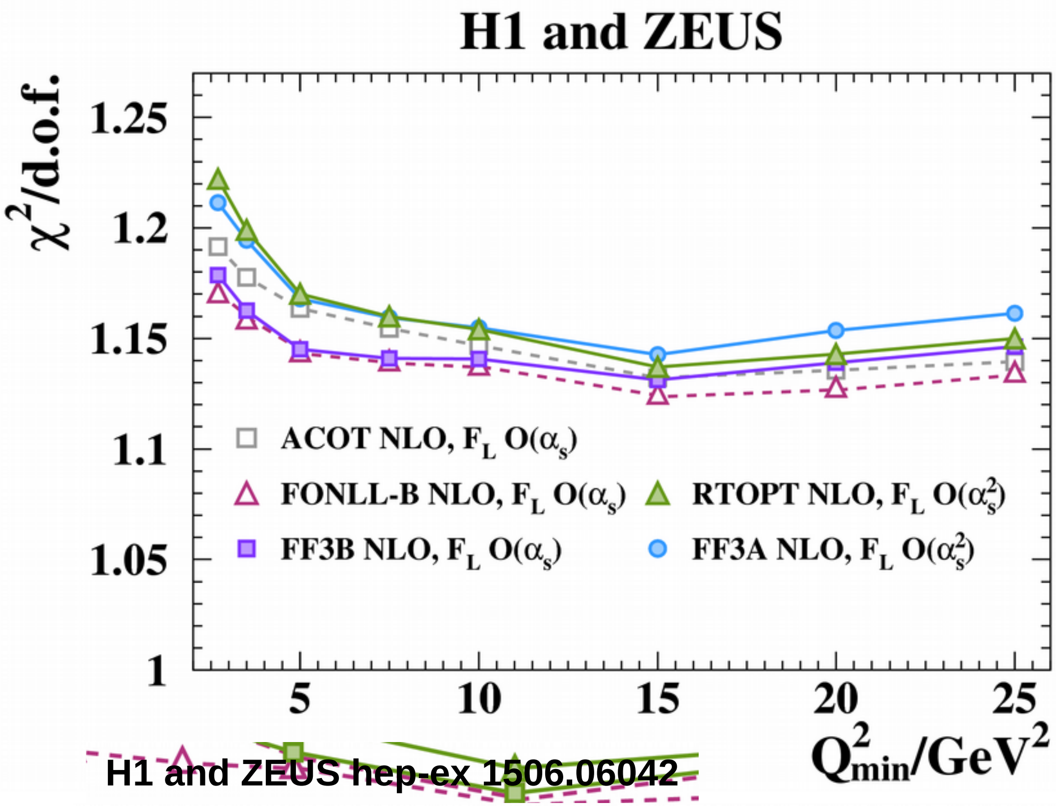


PDF sets	m_c [GeV]	m_c renorm. scheme	theory method (F_2^c scheme)	theory accuracy for heavy quark DIS Wilson coeff.	χ^2/NDP for HERA data [127] with `xFitter` [128, 129]	
ABM12 [2] [a]	$1.24^{+0.05}_{-0.03}$	$\overline{\text{MS}}$ $m_c(m_c)$	FFNS ($n_f = 3$)	$\text{NNLO}_{\text{approx}}$	65/52	66/52
CJ15 [1]	1.3	m_c^{pole}	SACOT [122]	NLO	117/52	117/52
CT14 [3] [b]						
(NLO)	1.3	m_c^{pole}	SACOT(χ) [123]	NLO	51/47	70/47
(NNLO)	1.3	m_c^{pole}	SACOT(χ) [123]	NLO	64/47	130/47
HERAPDF2.0 [4]						
(NLO)	1.47	m_c^{pole}	RT optimal [125]	NLO	67/52	67/52
(NNLO)	1.43	m_c^{pole}	RT optimal [125]	NLO	62/52	62/52
JR14 [5] [c]	1.3	$\overline{\text{MS}}$ $m_c(m_c)$	FFNS ($n_f = 3$)	$\text{NNLO}_{\text{approx}}$	62/52	62/52
MMHT14 [6]						
(NLO)	1.4	m_c^{pole}	RT optimal [125]	NLO	72/52	78/52
(NNLO)	1.4	m_c^{pole}	RT optimal [125]	NLO	71/52	83/52
NNPDF3.0 [7]						
(NLO)	1.275	m_c^{pole}	FONLL-B [124]	NLO	58/52	60/52
(NNLO)	1.275	m_c^{pole}	FONLL-C [124]	NLO	67/52	69/52
PDF4LHC15 [8] [d]	–	–	FONLL-B [124]	–	58/52	64/52
	–	–	RT optimal [125]	–	71/52	75/52
	–	–	SACOT(χ) [123]	–	51/47	76/47

Accardi, et al. hep-ph/1603.08906

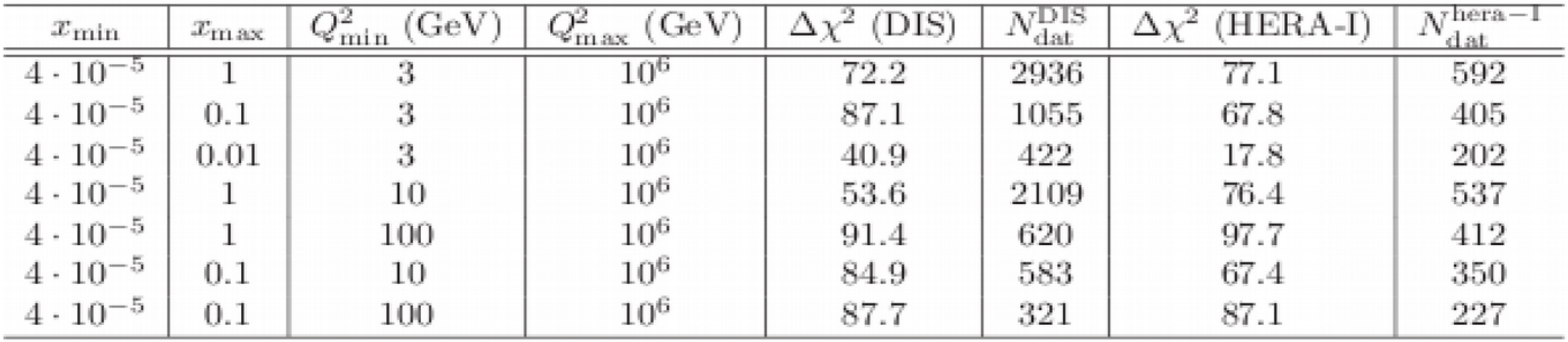
No advantage of the GMVFN schemes: the VFN χ^2 values are systematically bigger than the FFN ones

Factorization scheme benchmarking



H1 and ZEUS hep-ex 1506.06042

- Data allow to discriminate factorization schemes
- FFN scheme works very well in case of correct setting (running mass definition and correct value of m_c) → no traces of big logs due to resummation



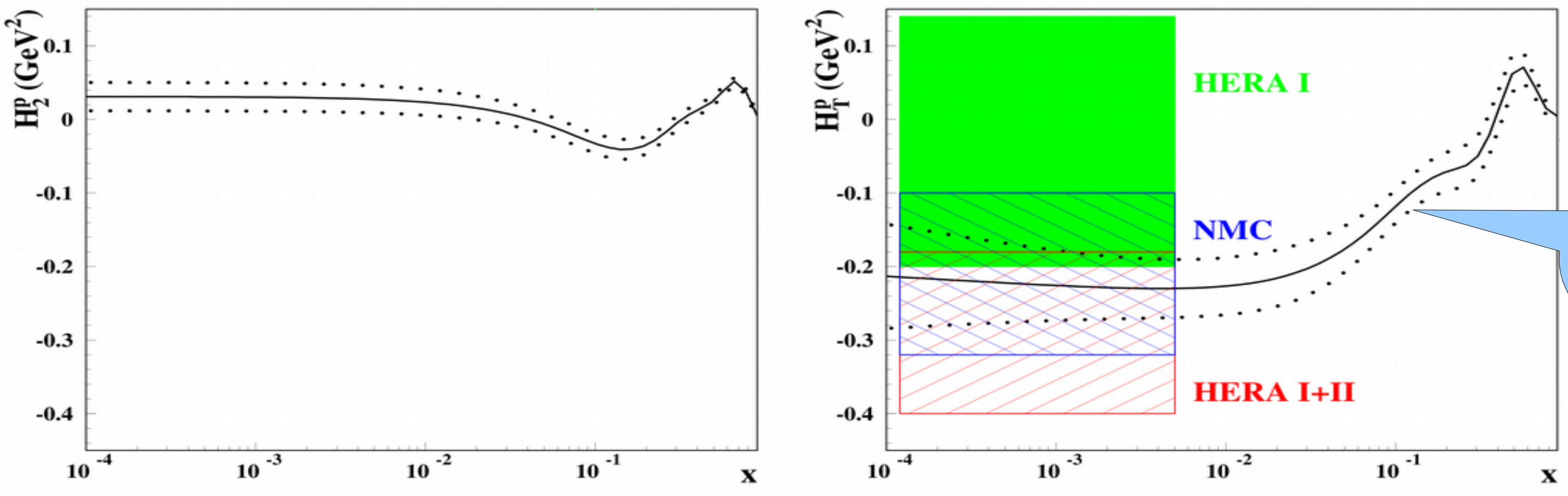
$x_{\min}$	$x_{\max}$	$Q^2_{\min}$ (GeV)	$Q^2_{\max}$ (GeV)	$\Delta\chi^2$ (DIS)	$N^{\mathrm{DIS}}_{\mathrm{dat}}$	$\Delta\chi^2$ (HERA-I)	$N^{\mathrm{hera-I}}_{\mathrm{dat}}$
$4\cdot10^{-5}$	1	3	10^6	72.2	2936	77.1	592
$4\cdot10^{-5}$	0.1	3	10^6	87.1	1055	67.8	405
$4\cdot10^{-5}$	0.01	3	10^6	40.9	422	17.8	202
$4\cdot10^{-5}$	1	10	10^6	53.6	2109	76.4	537
$4\cdot10^{-5}$	1	100	10^6	91.4	620	97.7	412
$4\cdot10^{-5}$	0.1	10	10^6	84.9	583	67.4	350
$4\cdot10^{-5}$	0.1	100	10^6	87.7	321	87.1	227

We conclude that the FFN fit is actually based on a less precise theory, in that it does not include full resummation of the contribution of heavy quarks to perturbative PDF evolution, and thus provides a less accurate description of the data

NNPDF PLB 723, 330 (2013)

High twists at small x

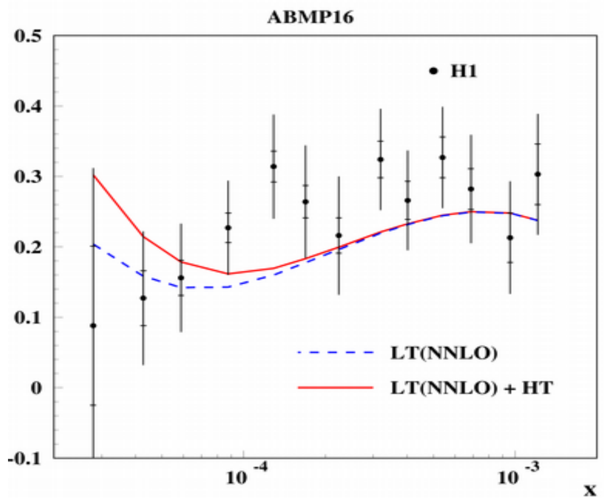
$F_{2,L}=F_{2,L}(\text{leading twist}) + H_{2,L}(x)/Q^2$ $H(x)=x^{h}P(x)$



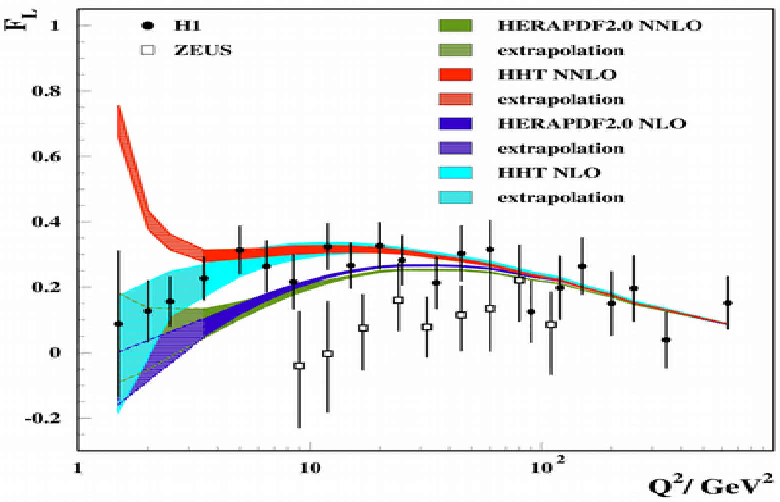
Controlled by SLAC and NMC data

sa, Blümlein, Moch
PRD 86, 054009 (2012)

- $H_T(x)$ continues a trend observed at larger x; $H_2(x)$ is comparable to 0 at small x
- h_T=0.05±0.07 → slow vanishing at x → 0
- $\Delta\chi^2 \sim -40$ **Harland-Lang, Martin, Motylinski, Thorne hep-ph/1601.03413**

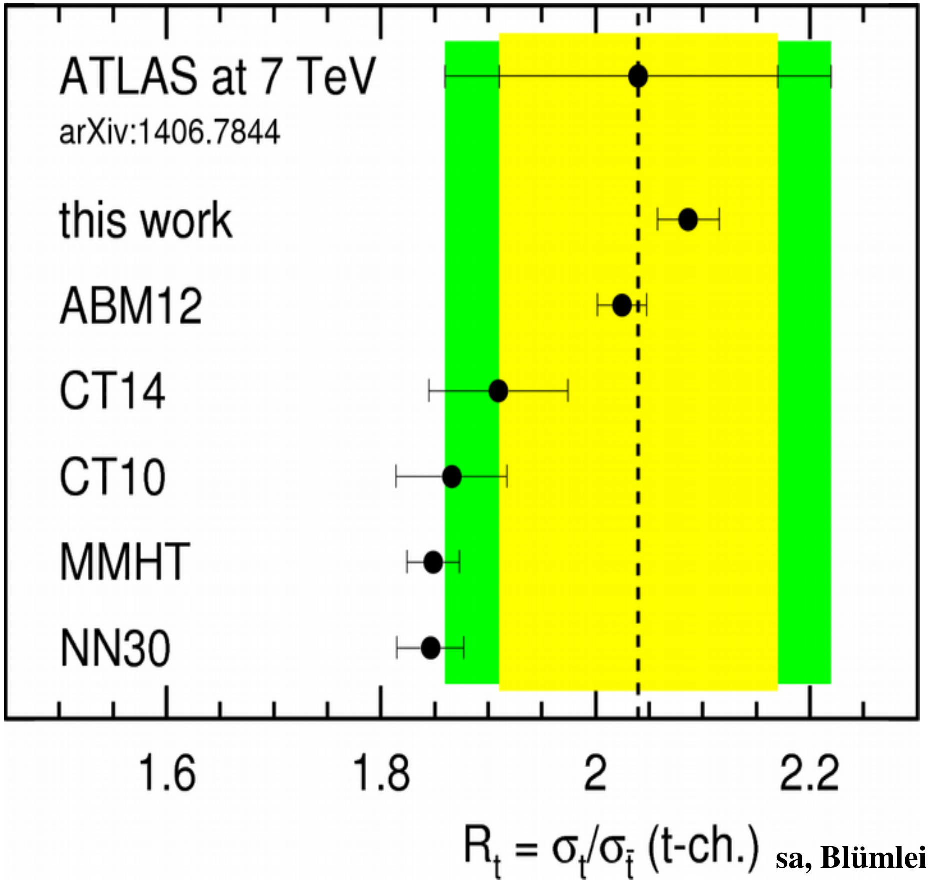


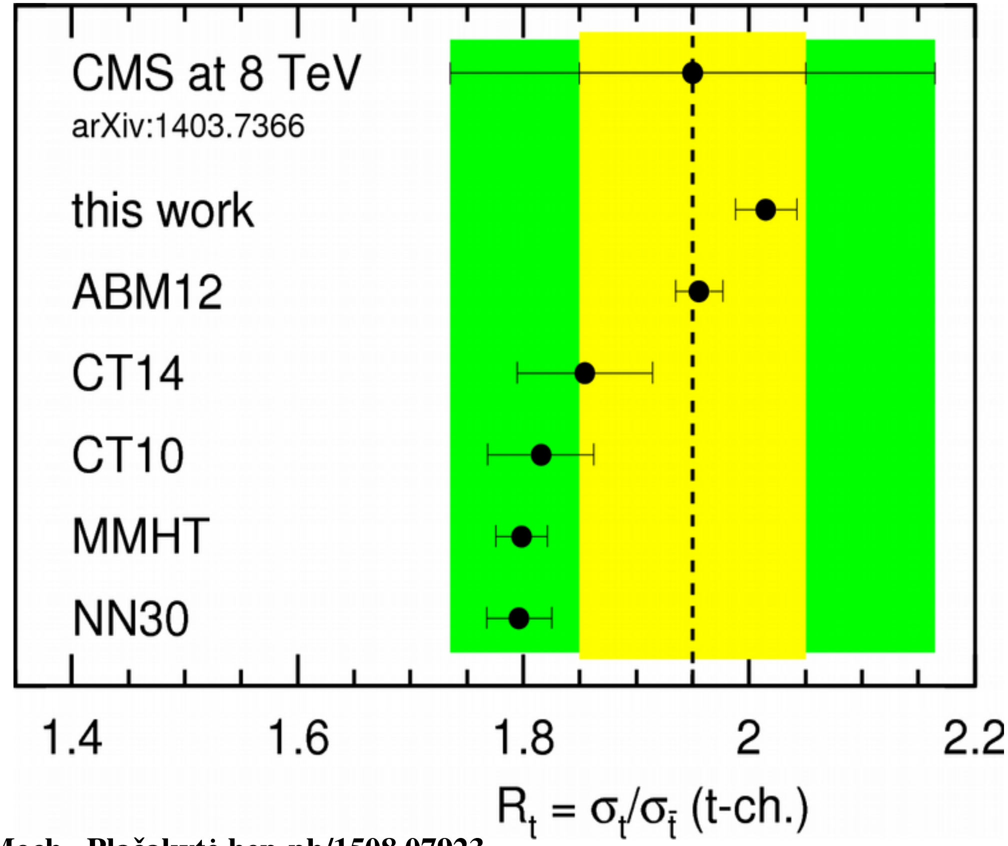
No dramatic increase of F_L at small x



Abt, et al. hep-ex/1604.02299

Implication for(of) the single-top production





sa, Blümlein, Moch, Plačakytė hep-ph/1508.07923

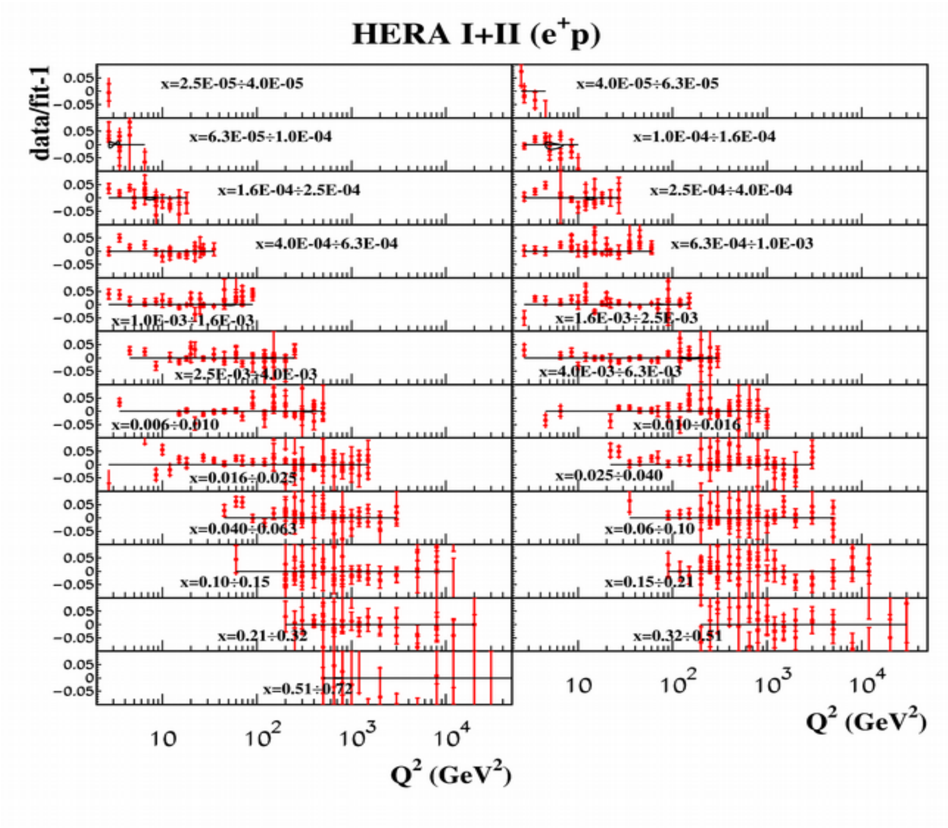
- ATLAS and CMS data on the ratio t/tbar are in a good agreement

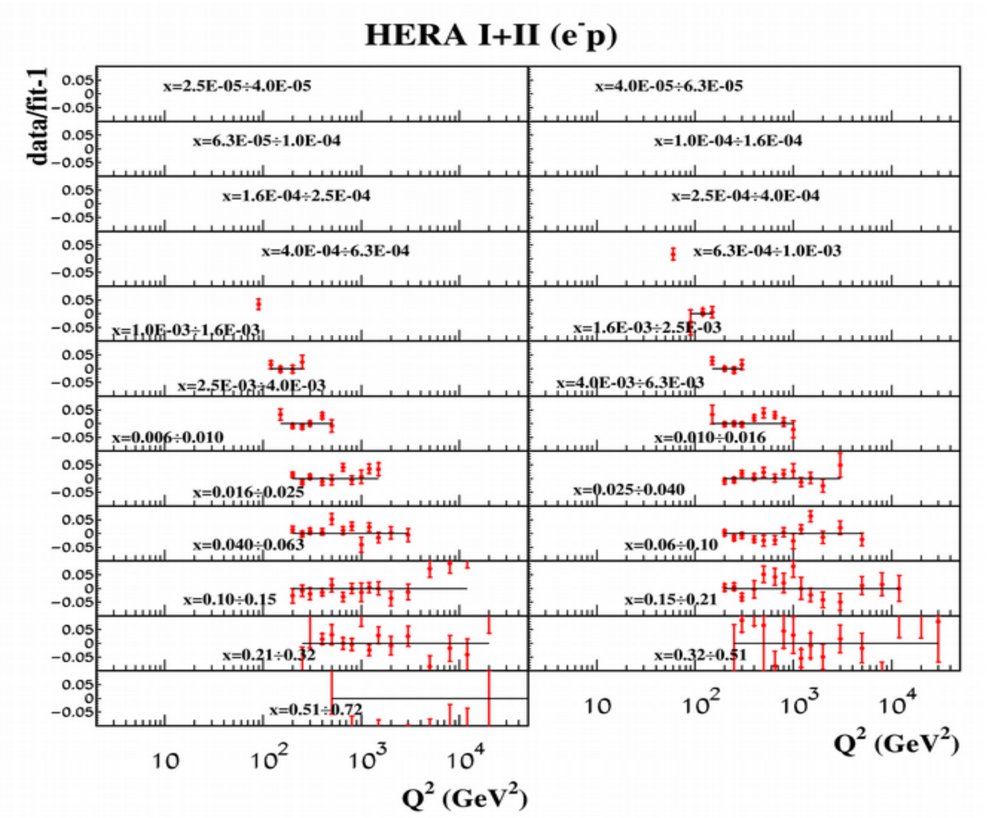
- The predictions driven by the froward DY data are in a good agreement with the single-top data (N.B.: ABM12 is based on the deuteron data → consistent deuteron correction was used) **talks by Petti at DIS2016**

Single-top production discriminate available PDF sets and can serve as a standard candle process

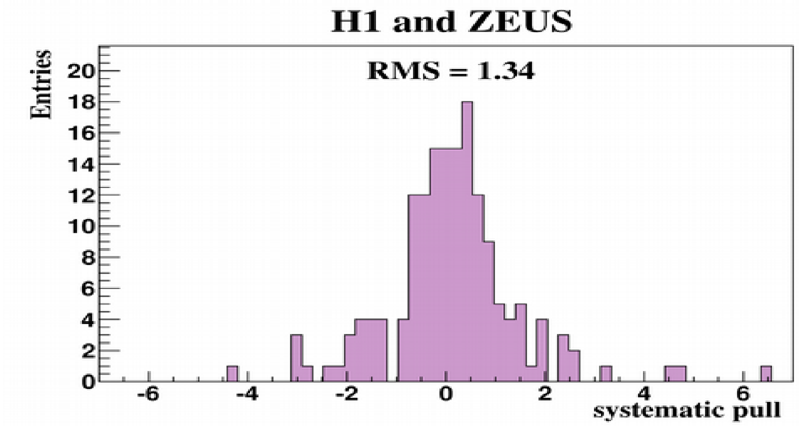
Inclusive HERA I+II data

H1 and ZEUS hep-ex/1506.06042





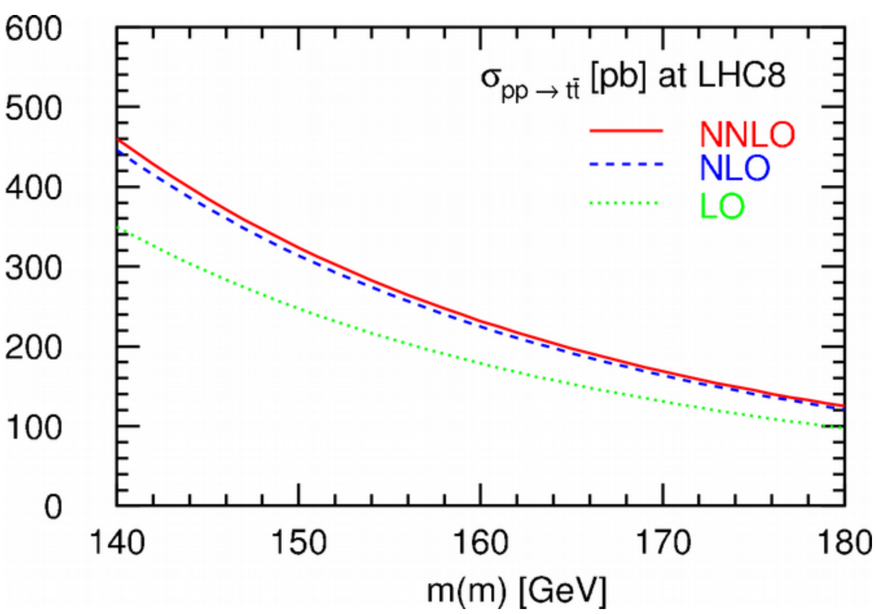
Q^2(HERA)	χ^2/NDP(HERA)
>2.5 GeV^2	1509/1168=1.29
>5 GeV^2	1354/1092=1.24
>10 GeV^2	1228/1007=1.22



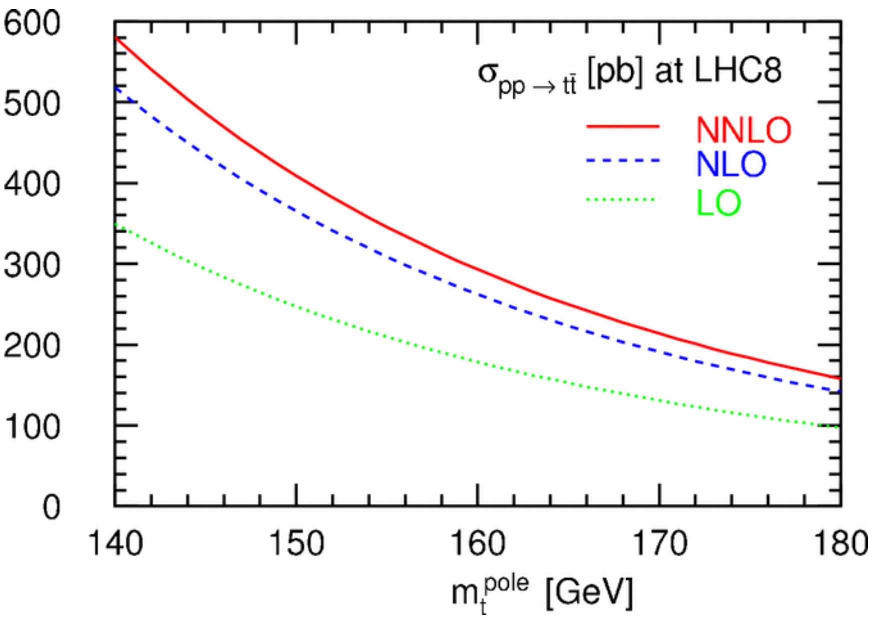
The value of χ^2/NDP is bigger than 1, however still comparable to the pull distribution width

ttbar production with pole and Msbar mass

MSbar



Pole

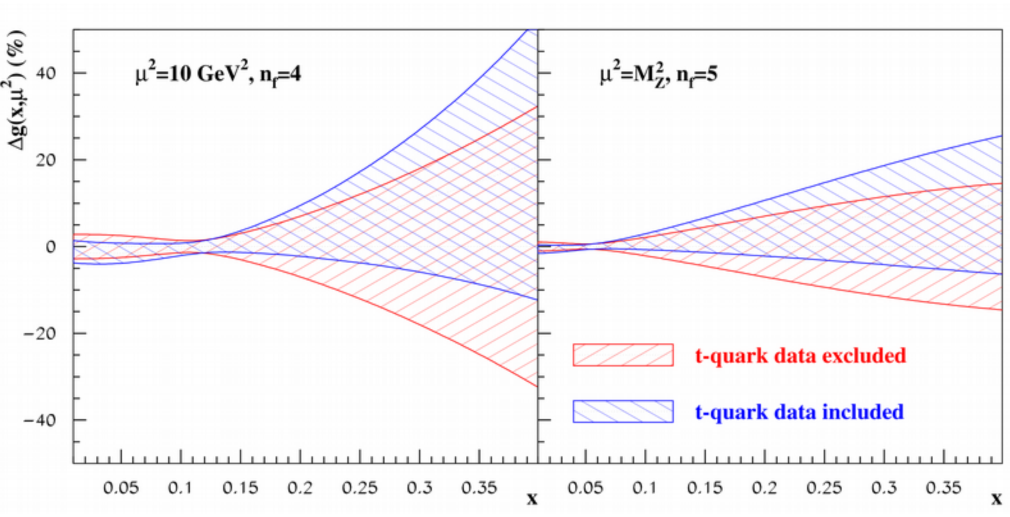


HATHOR (NNLO terms are checked with TOP++)

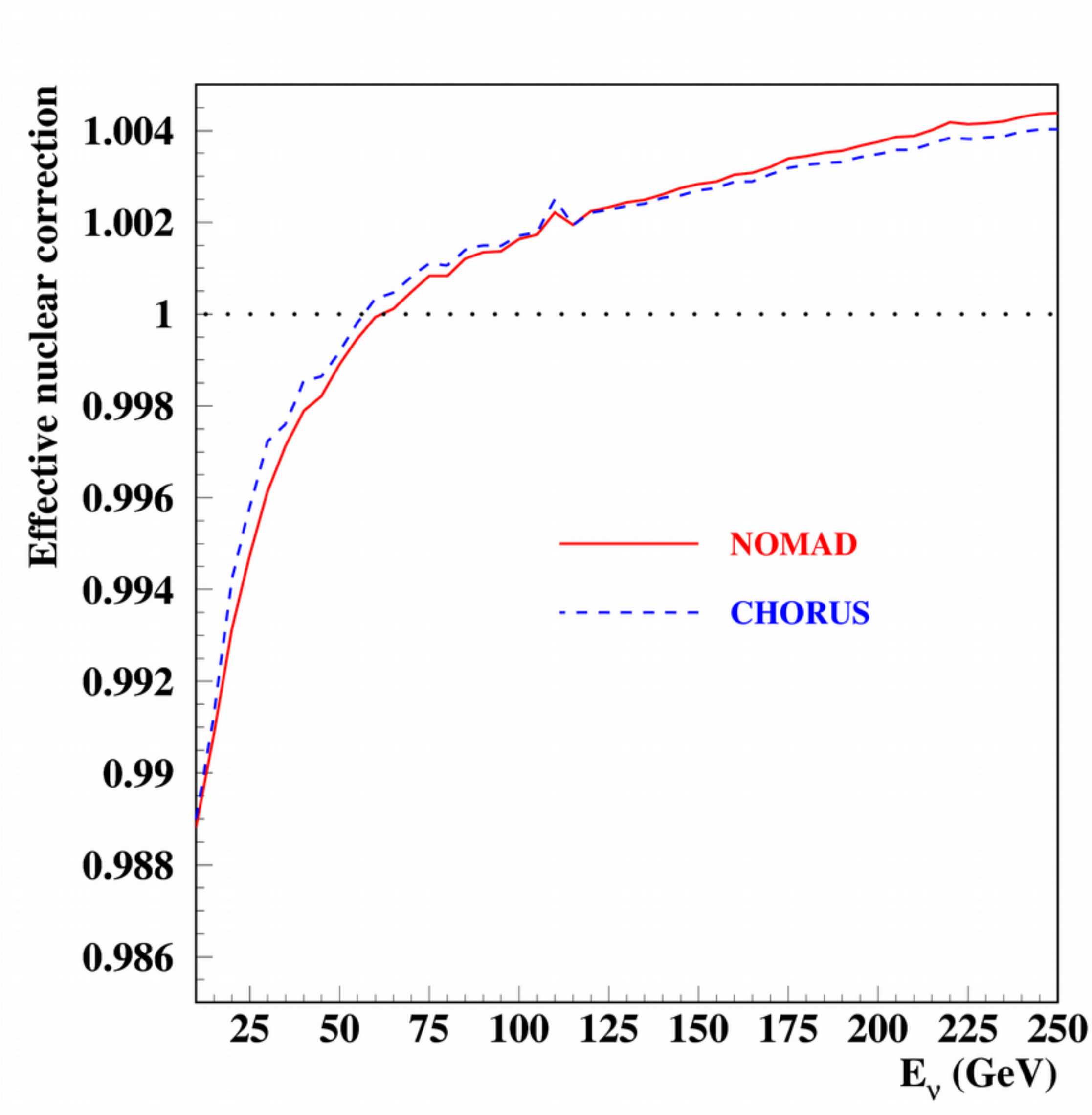
Langenfeld, Moch, Uwer PRD 80, 054009 (2009)

Running mass definition provides nice perturbative stability

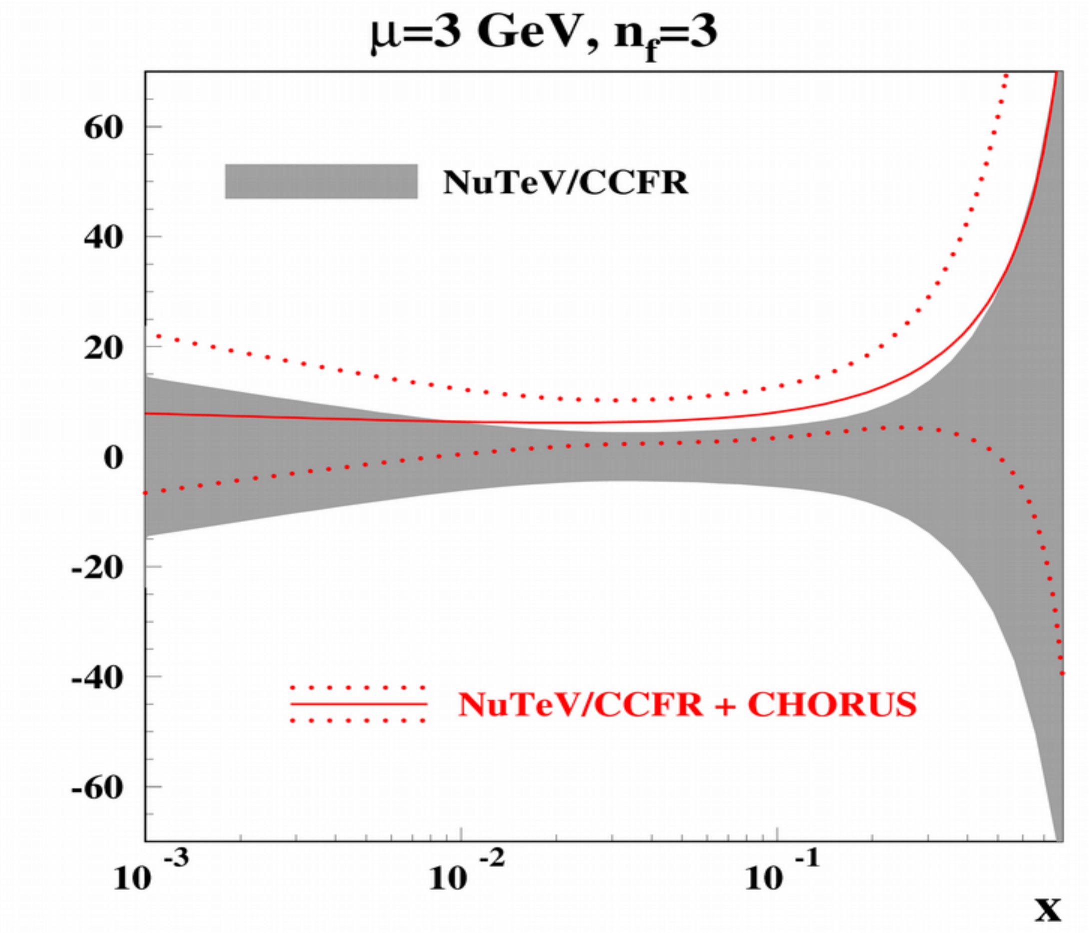
Czakon, Fiedler, Mitov hep-ph/1303.6254



- $m_t(m_t)$=160.9±1.1(exp.) GeV NNLO
- $\alpha_s(M_Z)$=0.1145(9) → 0.1147(8) NNLO
- moderate change in the large-x gluon distribution


Effective nuclear correction
1.004
1.002
1
0.998
0.996
0.994
0.992
0.99
0.988
0.986
25
50
75
100
125
150
175
200
225
250
E_ν (GeV)
NOMAD
CHORUS

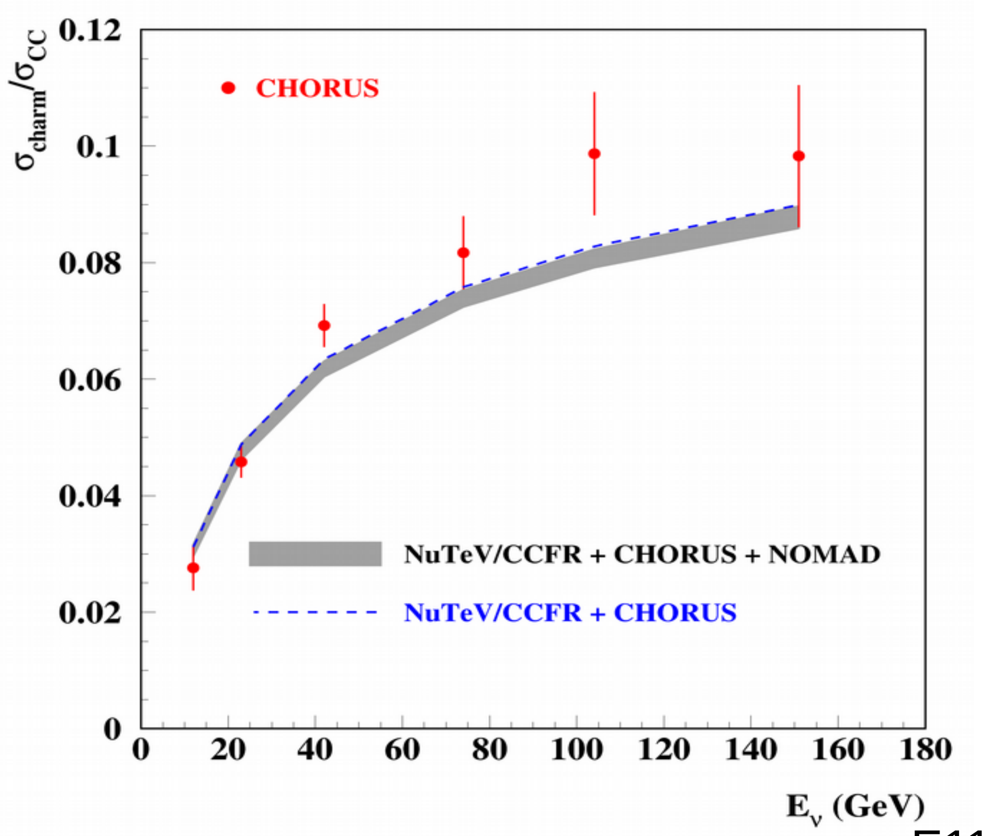
CHORUS charm data



Emulsion data on charm/CC ratio with the charmed hadron vertex measured

CHORUS NJP 13, 093002 (2011)

- full phase space measurements
- no sensitivity to B_μ
- low statistics (2013 events)

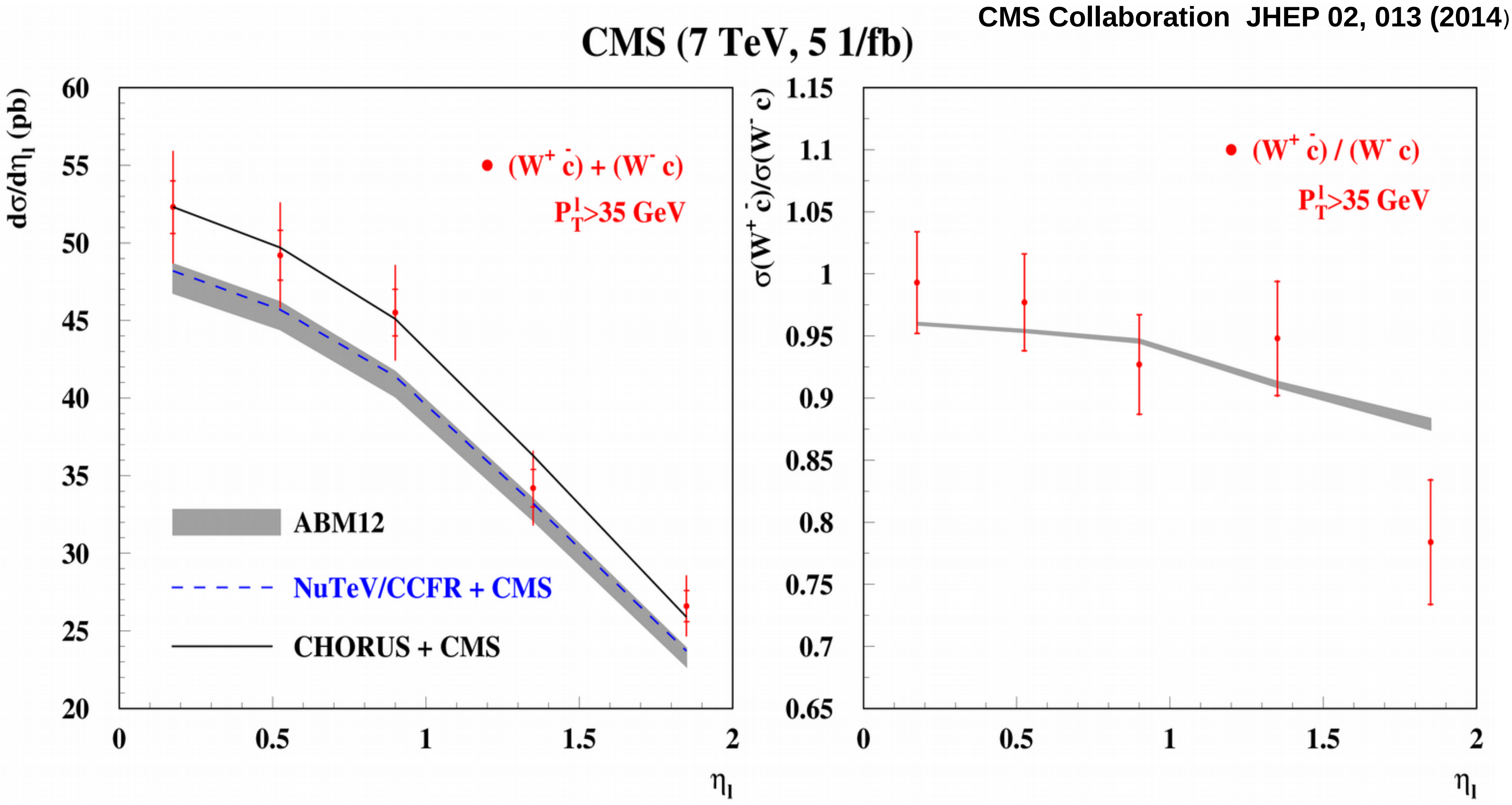


CHORUS data pull strangeness up, however the statistical significance of the effect is poor

sa, Blümlein, Caminadac, Lipka, Lohwasser, Moch, Petti, Placakyte hep-ph/1404.6469

CMS W+charm data

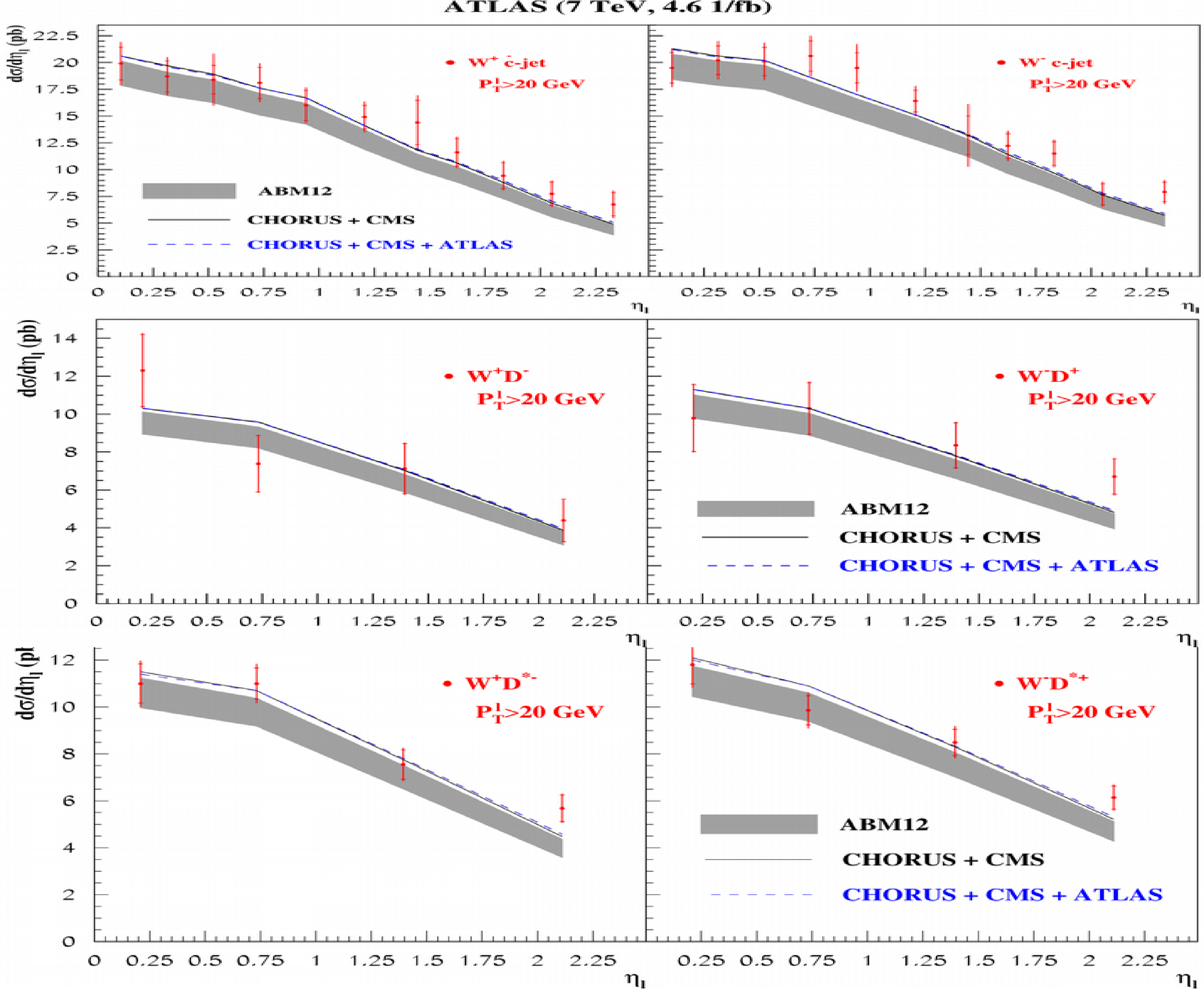
CMS Collaboration JHEP 02, 013 (2014)



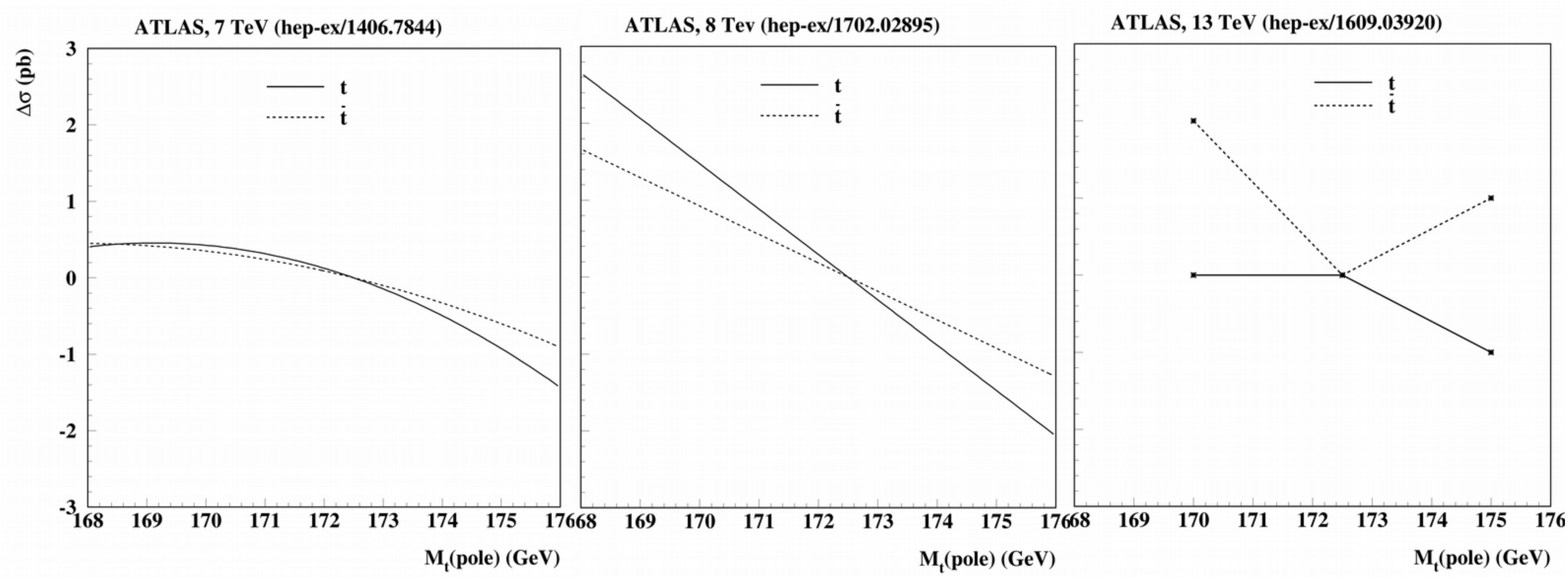
- CMS data go above the NuTeV/CCFR by 1σ; little impact on the strange sea
- The charge asymmetry is in a good agreement with the charge-symmetric strange sea
- Good agreement with the CHORUS data

ATLAS W+charm data

ATLAS arXiv:1402.6263



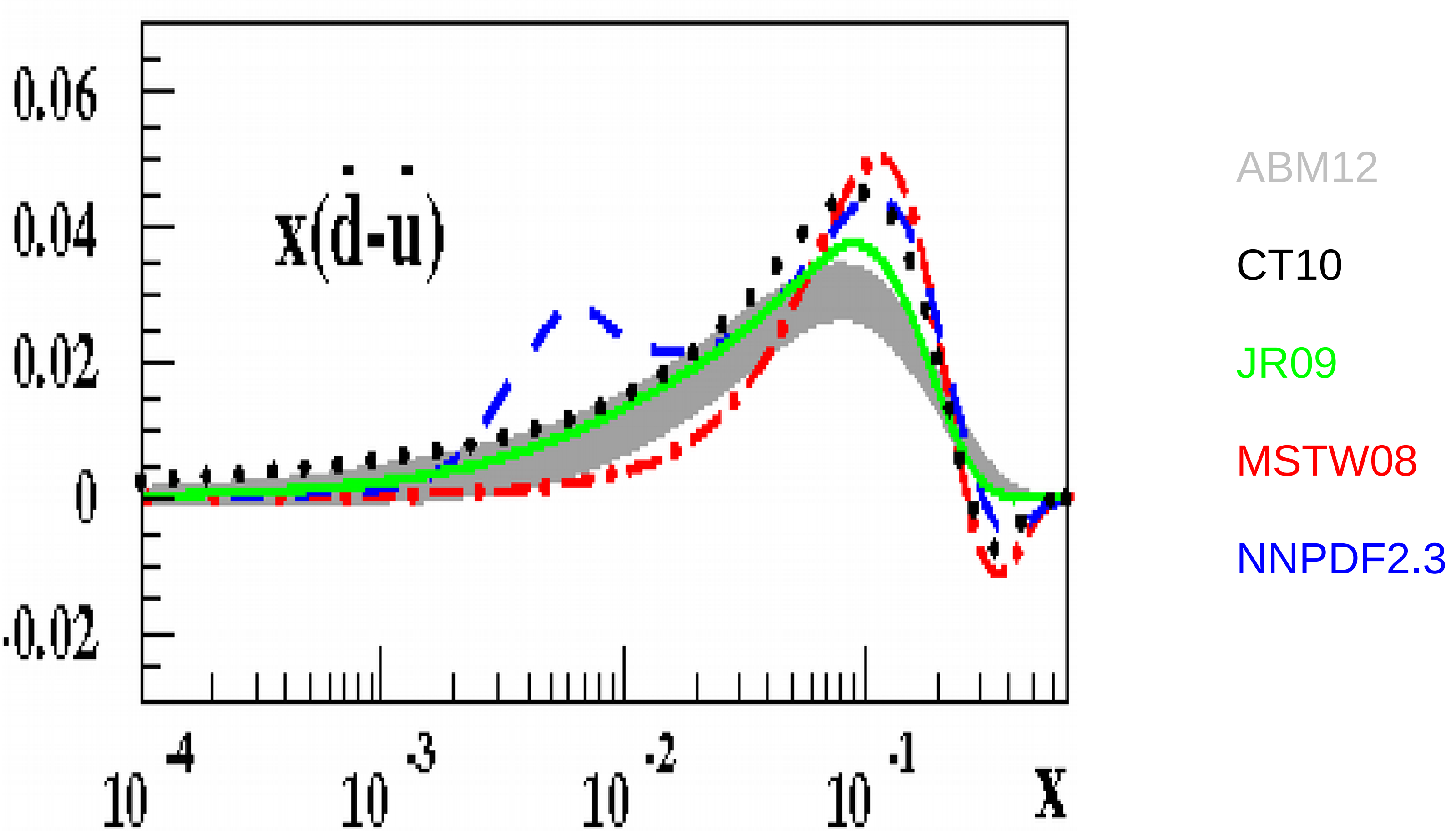
Single-top: mass dependence


ATLAS, 7 TeV (hep-ex/1406.7844)

ATLAS, 8 Tev (hep-ex/1702.02895)

ATLAS, 13 TeV (hep-ex/1609.03920)

Sea quark iso-spin asymmetry



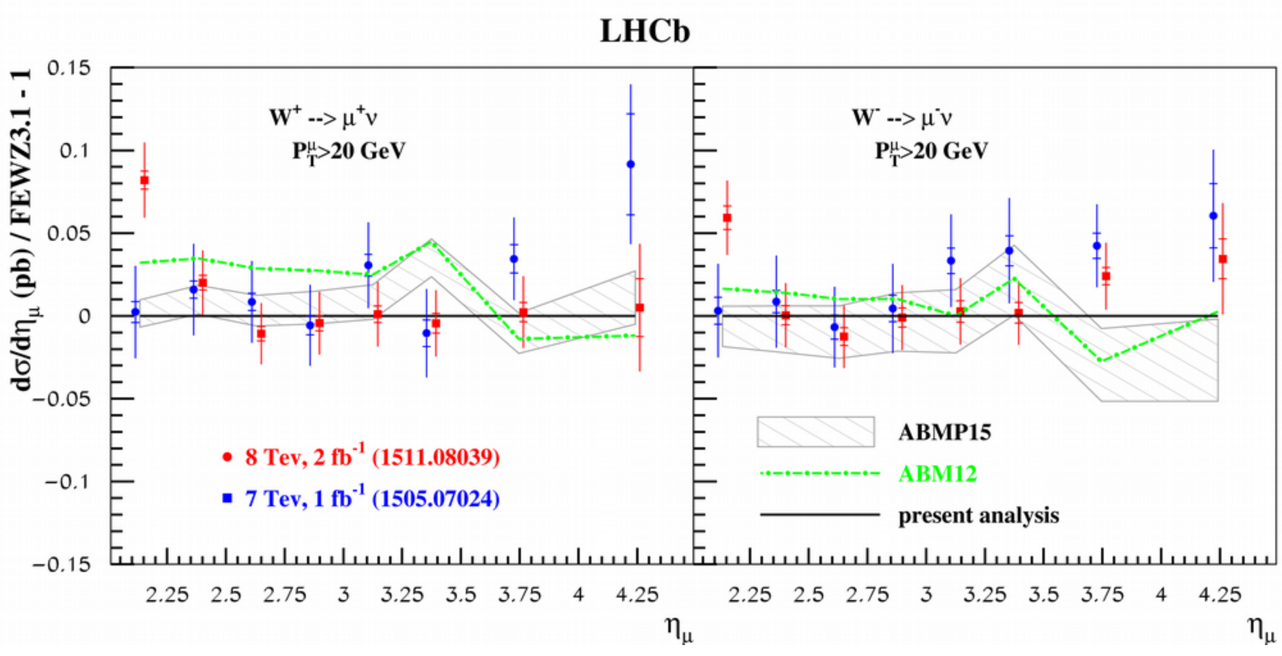
sa, Blümlein, Moch PRD 89, 054028 (2014)

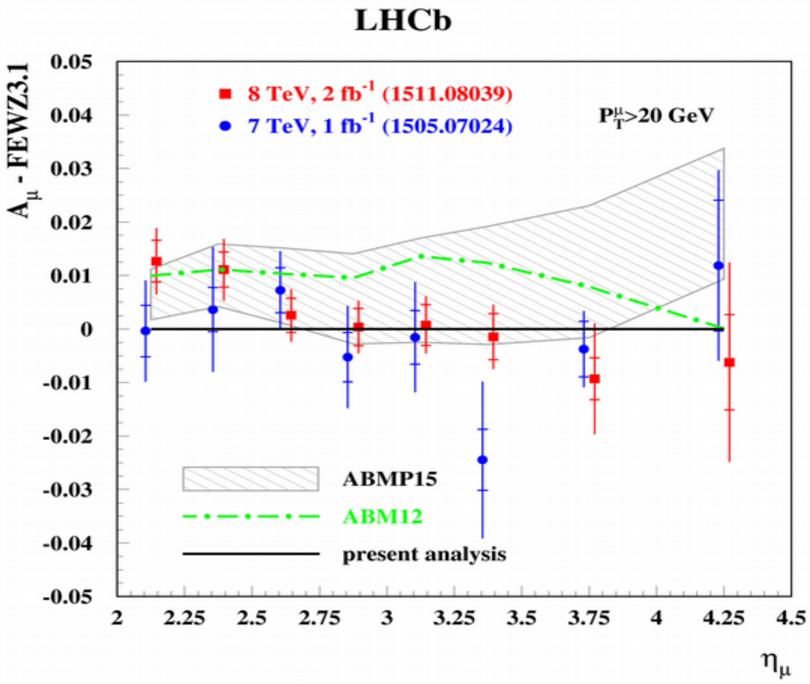
- At x~0.1 the sea quark iso-spin asymmetry is controlled by the fixed-target DY data (E-866), weak constraint from the DIS (NMC)

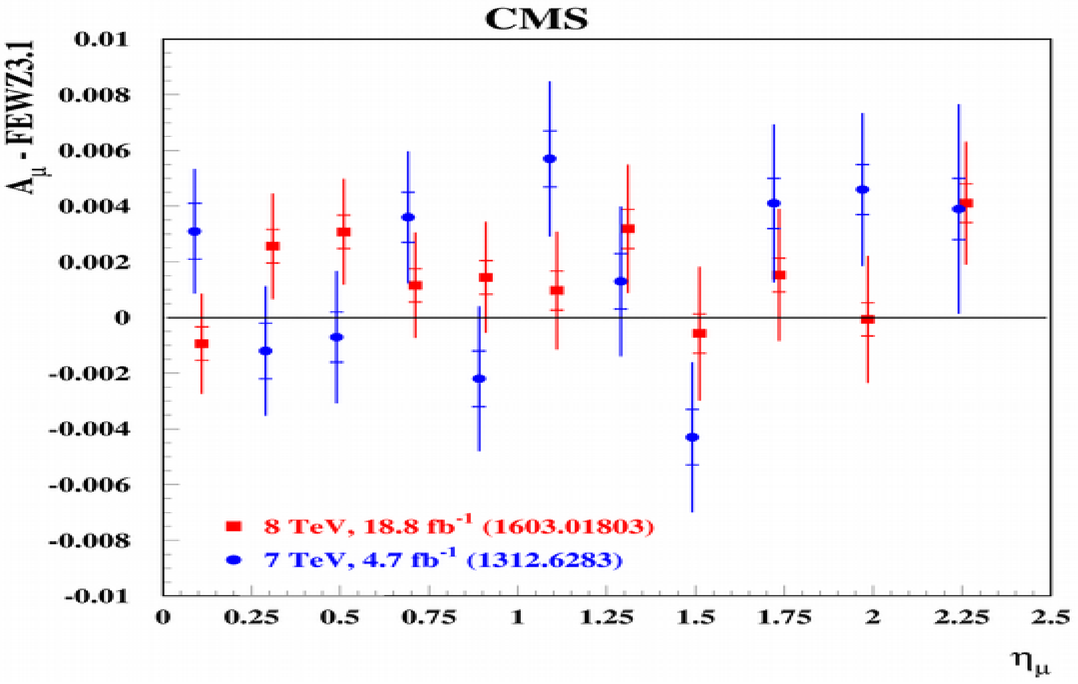
- At x<0.01 Regge-like constraint like $x^{(a-1)}$, with a close to the meson trajectory intercept; the “unbiased” NNPDF fit follows the same trend

Onset of the Regge asymptotics is out of control

Most recent DY inputs







cf. earlier data in sa, Blümlein, Moch, Plačakytė PRD 94, 114038 (2016)

Filtering of the LHCb data has been performed:

– a bump at 7 Tev and Y=3.275
(not confirmed by the LHCb data at 8 TeV)

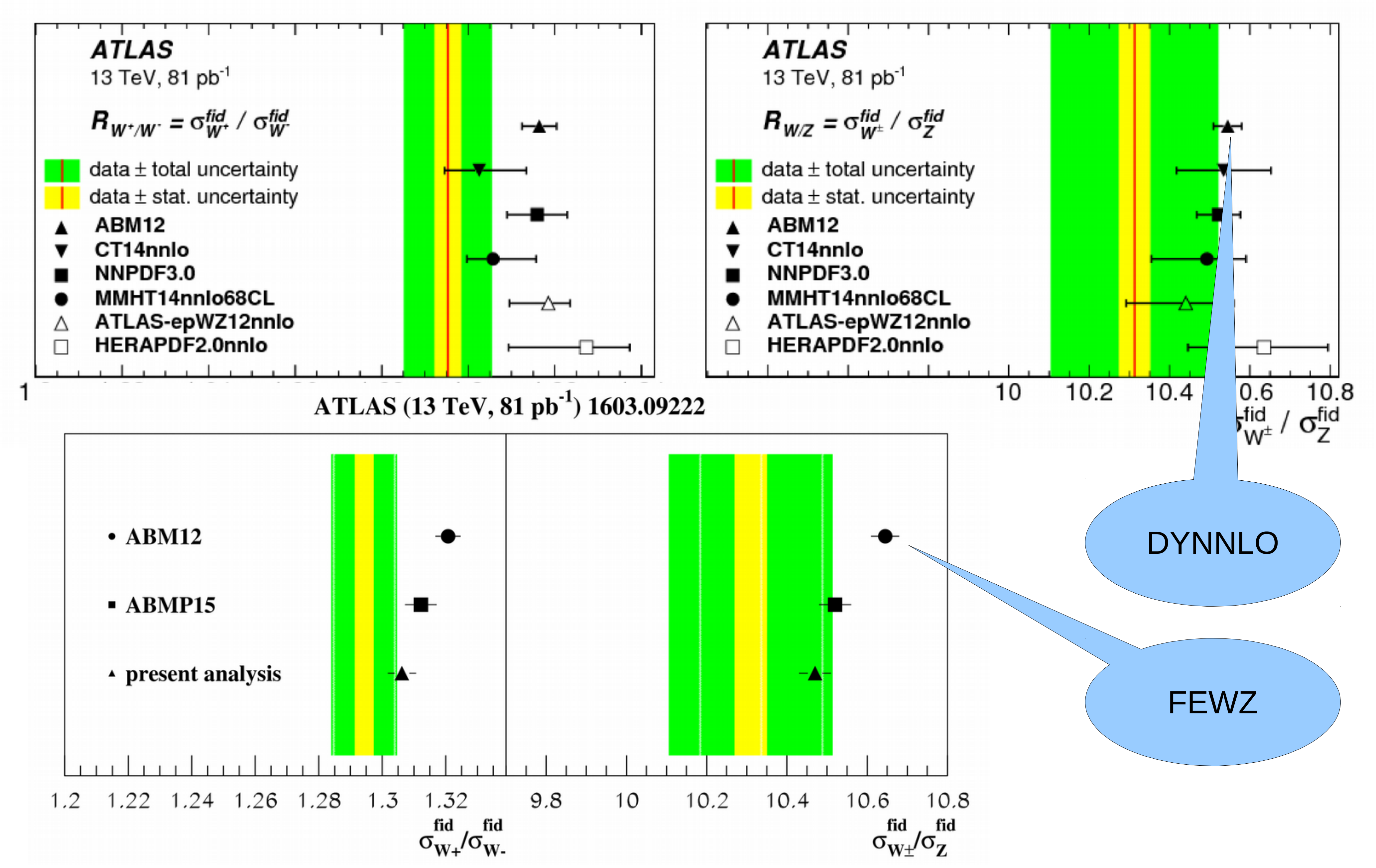
– and excess at 8 TeV and Y=2.125
(not confirmed by the CMS data at 8 TeV)

The CMS data at 8 TeV are much smoother than the ones at 7 TeV:

χ^2=17/22 versus 22/11

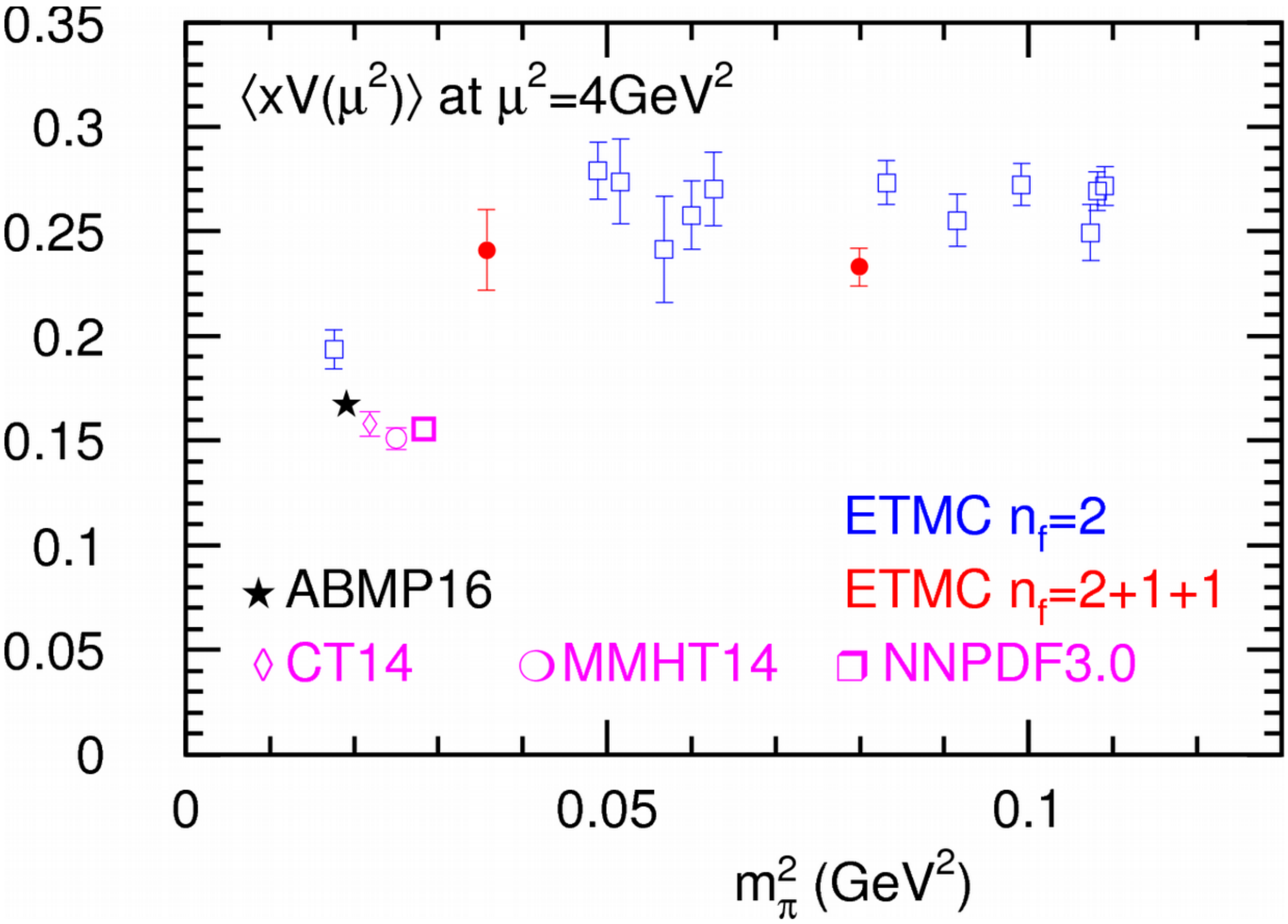
ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222

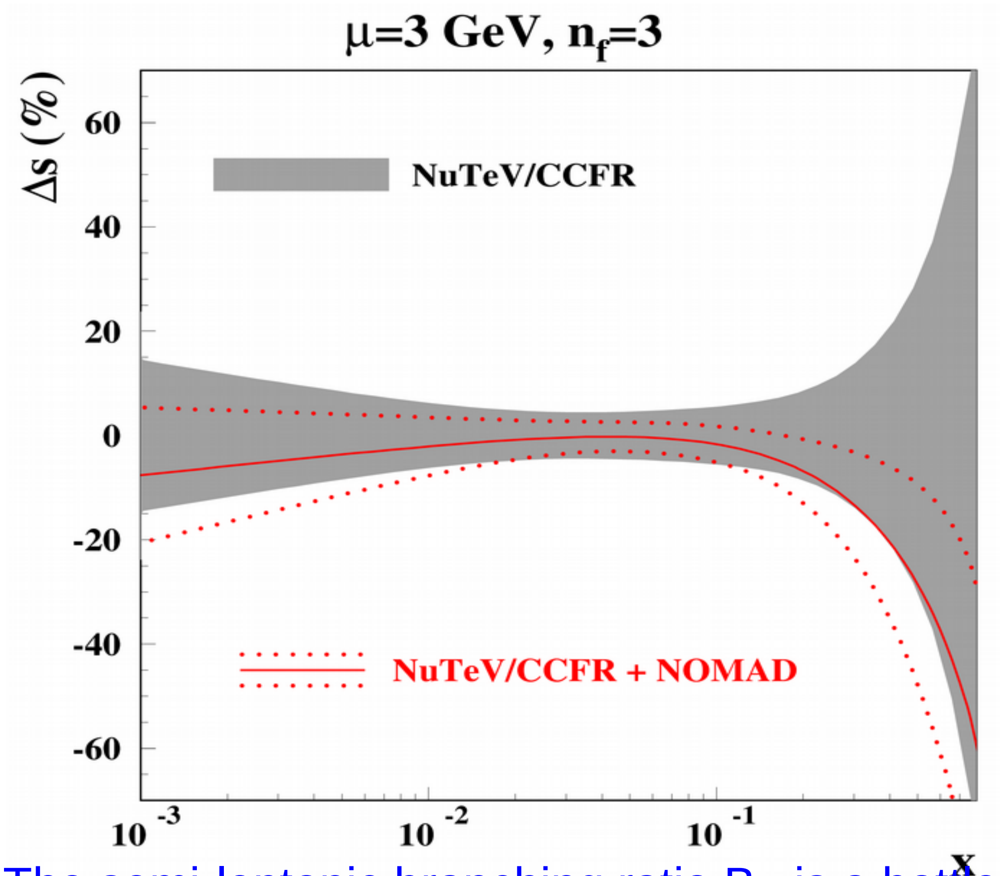


Data are well accommodated into the fit χ^2/NDP=9/6

Comparison with lattice results



NOMAD charm data



The data on ratio 2μ/incl. CC ratio with the 2μ statistics of 15000 events (much bigger than in earlier CCFR and NuTeV samples).

NOMAD NPB 876, 339 (2013)

Systematics, nuclear corrections, etc. cancel in the ratio

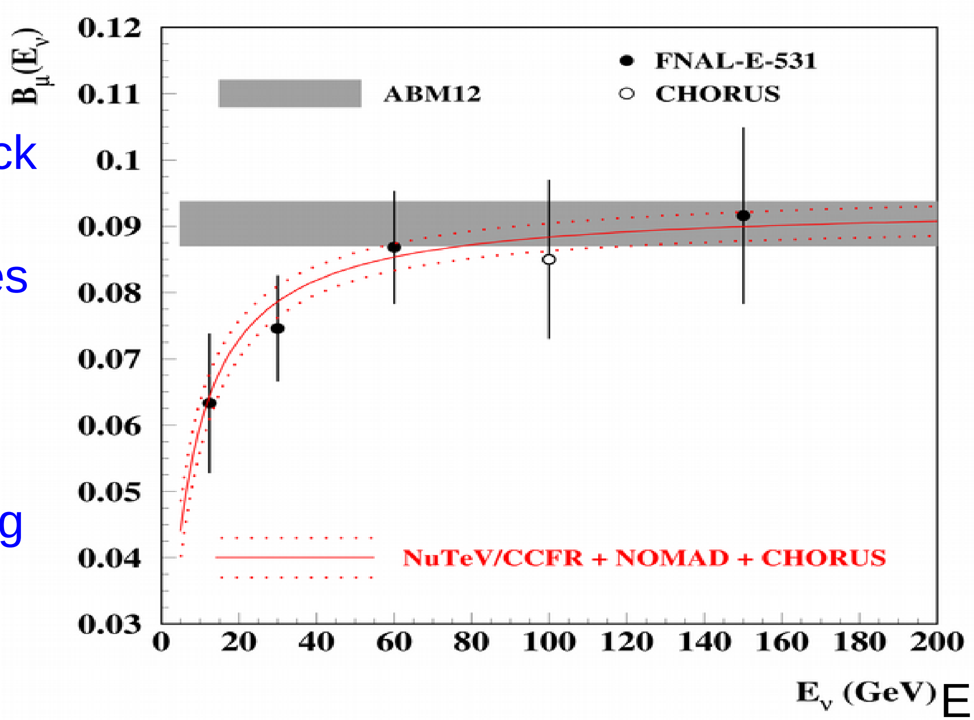
- pull down strange quarks at x>0.1 with a sizable uncertainty reduction
- $m_c(m_c)$=1.23±0.03(exp.) GeV is comparable to the ABM12 value

The semi-leptonic branching ratio B_μ is a bottleneck

- weighted average of the charmed-hadron rates

$$B_\mu(E_\nu)=\sum_h r^h(E_\nu)B^h_\mu = a/(1+b/E_\nu)$$

- fitted simultaneously with the PDFs, etc. using the constraint from the emulsion data



ttbar: c.m.s. energy dependence