

# Modern trends in PDFs' determination

S.Alekhin (*Univ. of Hamburg & IHEP Protvino*)

- Factorization and scheme dependence: FFNS and (G)MFNS
- Recent data: HERA, Tevatron and LHC: DIS and Drell-Yan complementarity
- Heavy-quark masses: cross-check of the factorization ansatz
- Interplay of  $\alpha_s$  and t-quark mass: vacuum stability
- Intrinsic charm

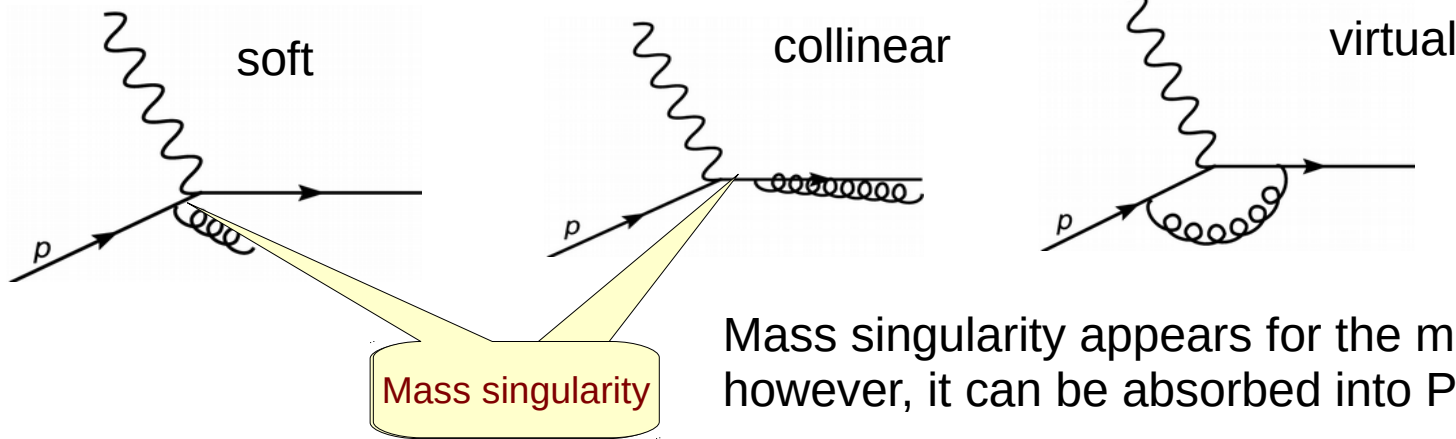
# Theory reminder: factorization

QPM: electro-production inclusive structure function

$$F_2(x, Q^2) = \sum_q e_q^2 p_q(x)$$

$p_q(x)$  – parton probability distributions (PDFs)

QCD radiative corrections:



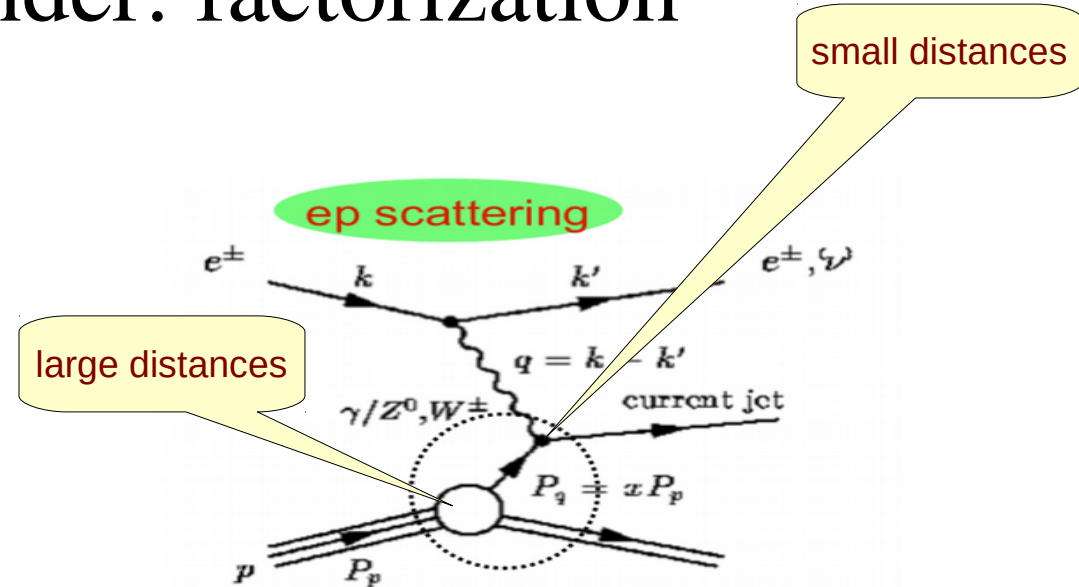
Mass singularity appears for the massless partons, however, it can be absorbed into PDFs  $\Rightarrow$  PDF evolution

State-of-art:

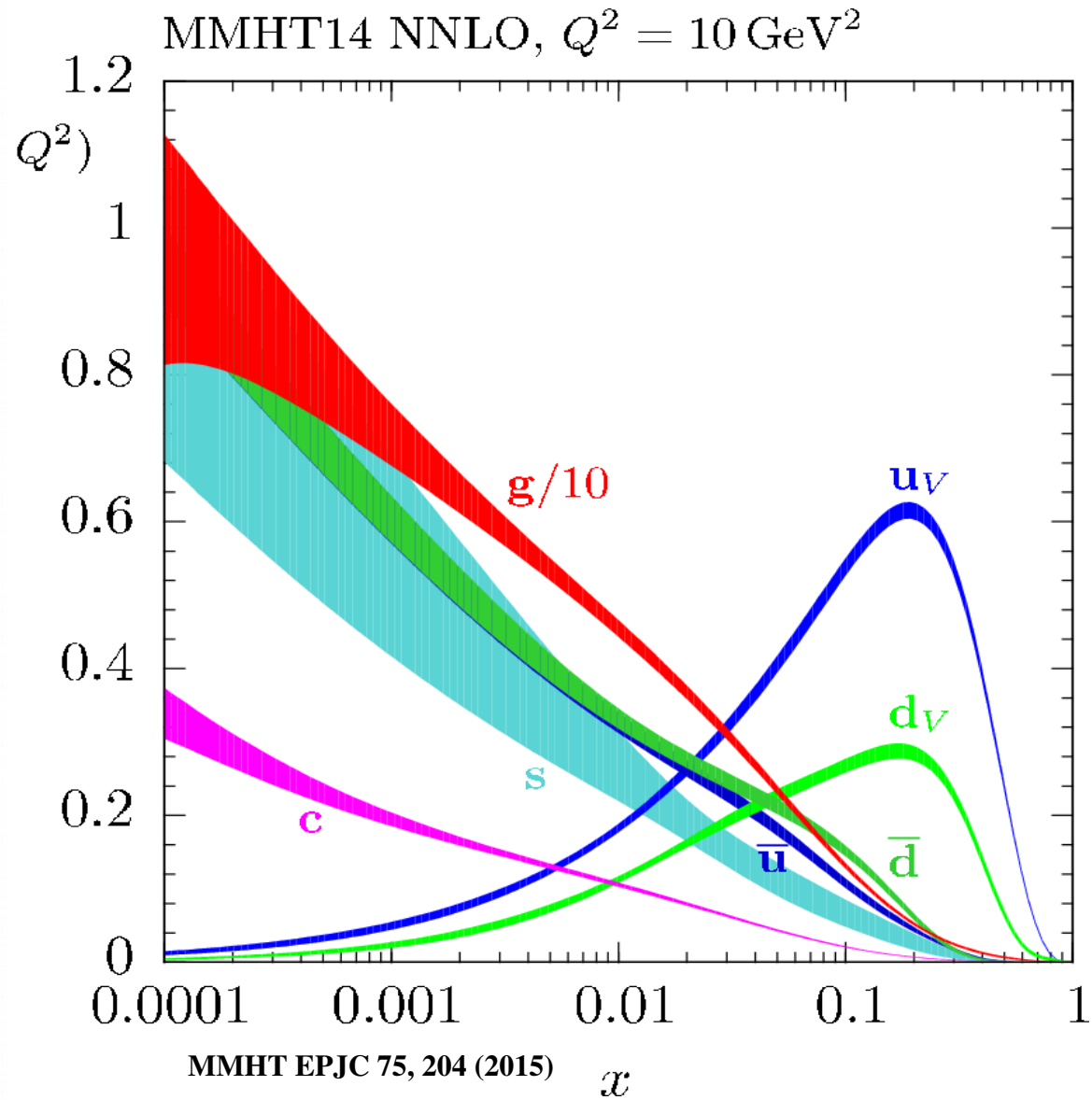
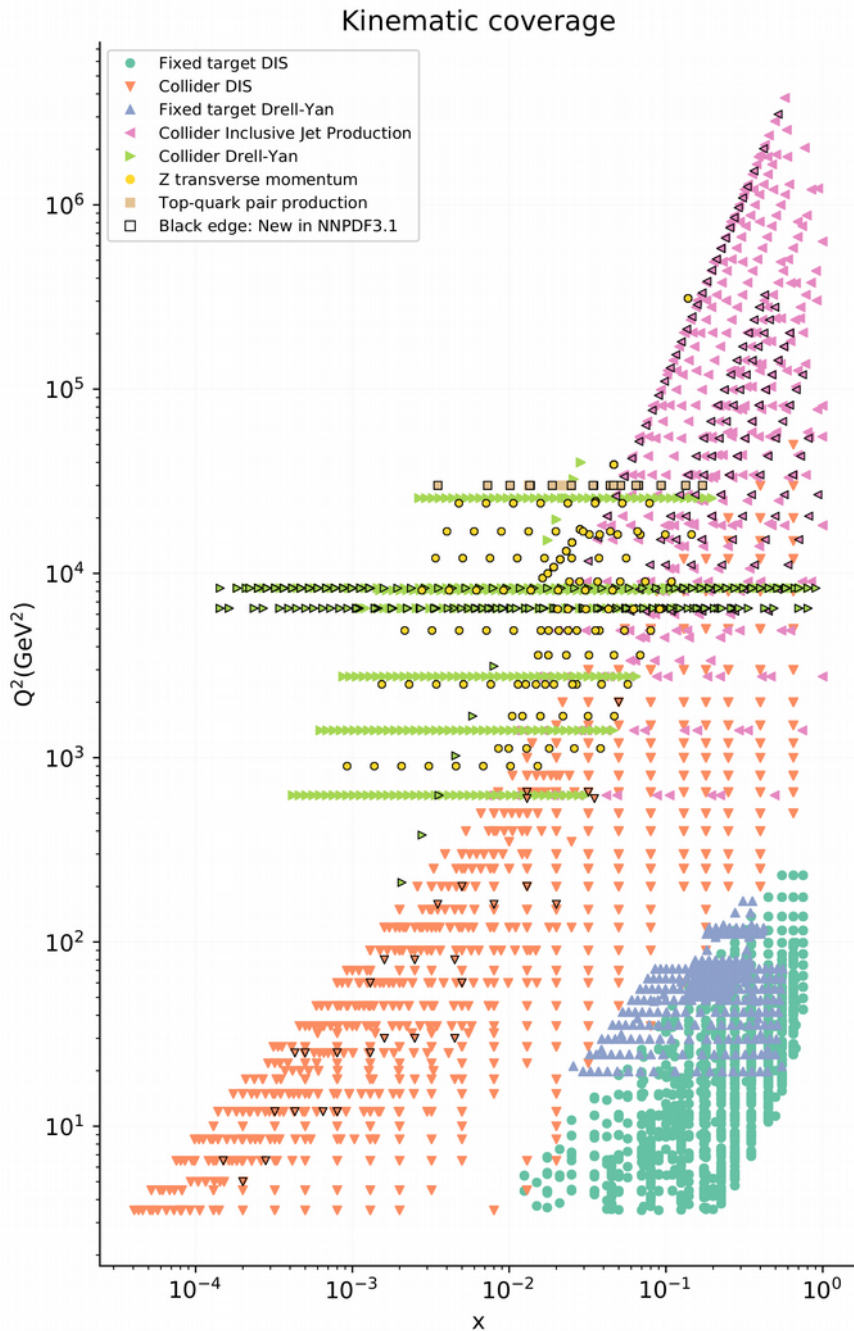
Better theoretical accuracy / Scheme dependence of PDFs

NNLO Moch, Vermaseren Vogt NPB 688, 101 (2004); NPB 691, 129 (2004)

N3LO Moch et al. hep-ph/1707.08315; Velizhanin hep-ph/1411.1331; Baikov, Chetyrkin NPPS 160, 76 (2006)



# Global PDF fits



# Anatomy of PDF fit (ABMP16)

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  $Q \gg m_c$

– running mass

NNLO exclusive DY (FEWZ 3.1)

NNLO inclusive  $t\bar{t}$  production ( pole / running mass )

Relaxed form of  $(d\bar{d}-u\bar{u})$  at small  $x$

DATA:

DIS NC/CC inclusive (HERA I+II added)

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

sa, Blümlein, Moch, Plačákytė PRD 96, 014011 (2017)

.....

# Heavy-quark electro-production with FFN and VFN

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

sa, Moch, Blümlein PRD 96, 014011 (2017)

- limited set of the NNLO Mellin moments

Ablinger et al. NPB 844, 26 (2011)

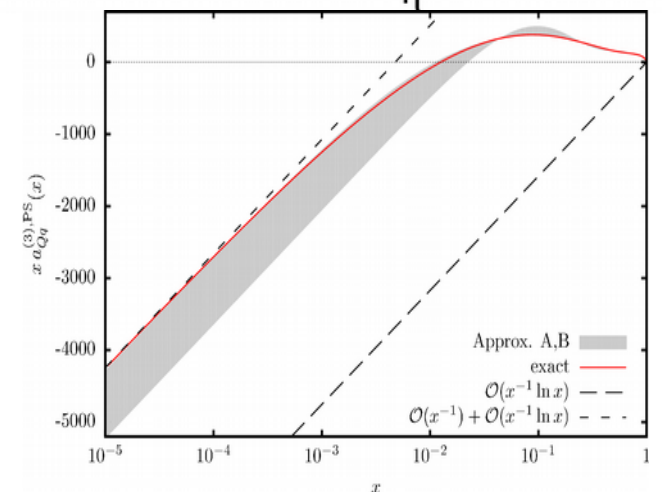
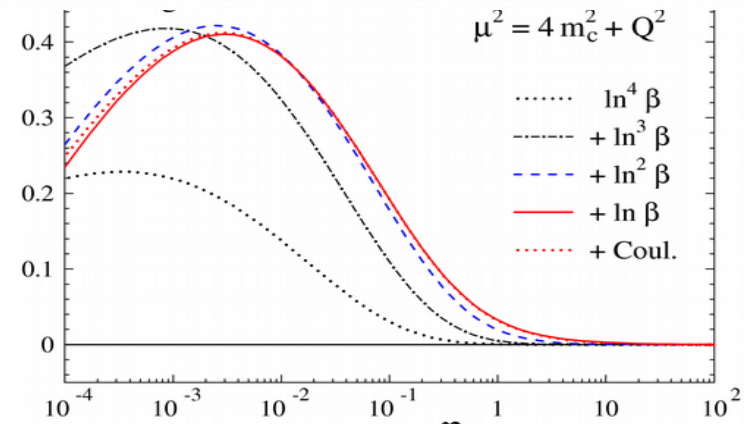
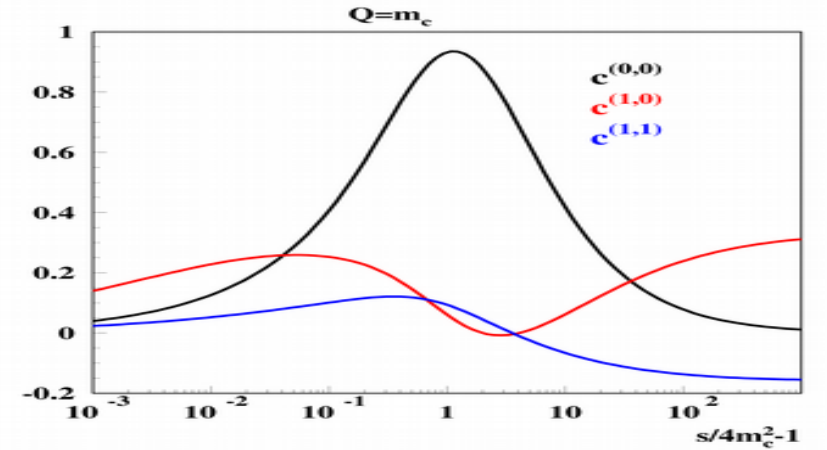
Bierenbaum, Blümlein, Klein NPB 829, 417 (2009)

Ablinger et al. NPB 890, 48 (2014)

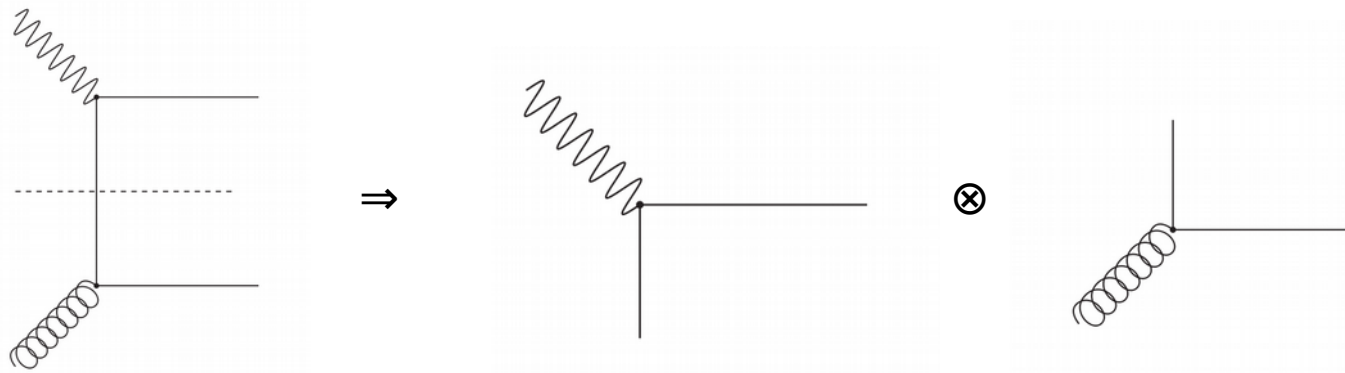
- At large  $Q$  the leading-order coefficient  $\rightarrow \ln(Q/m_h)$  and may be quite big despite the suppression by factor of  $\alpha_s$  and should be resummed

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

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



# FFN and VFN schemes



Collins, Tung NPB 278, 934 (1986)

$$H_{g,2}^{\text{asympt}} = a_s(N_f) A_{hg}^{(1)} \quad \text{Asymptotic 3-flavor coefficient function}$$

LO  $A_{ij}^{(1)}\left(z, \frac{m_h^2}{\mu^2}\right) = a_{ij}^{(1,1)}(z) \ln\left(\frac{\mu^2}{m_h^2}\right) \quad \text{Massive operator matrix elements (OMEs)}$

$$h^{(1)}(x, \mu^2) = a_s(N_f + 1, \mu^2) \left[ A_{hg}^{(1)}\left(\frac{m_h^2}{\mu^2}\right) \otimes G^{(2)}(N_f, \mu^2) \right](x) \quad \text{Matching condition for the heavy-quark PDFs}$$

$$F_{g,2}^{\text{asympt}} = e_h^2 x h^{(1)}(x, \mu^2)$$

NLO ...

Buza, Matiounine, Smith, van Neerven EPJC 1, 301 (1998)

$$A_{ij}^{(2)}\left(z, \frac{m_h^2}{\mu^2}\right) = a_{ij}^{(2,2)}(z) \ln^2\left(\frac{\mu^2}{m_h^2}\right) + a_{ij}^{(2,1)}(z) \ln\left(\frac{\mu^2}{m_h^2}\right) + a_{ij}^{(2,0)}(z)$$

NNLO

Blümlein, et al., work in progress

- The VFN scheme works well at  $\mu \gg m_h$  (W,Z,t-quark production,....)
- Problematic for DIS  $\Rightarrow$  additional modeling of power-like terms required (ACOT, BMSN, FONLL, RT....)

# Modeling NNLO massive coefficients

small  $s$

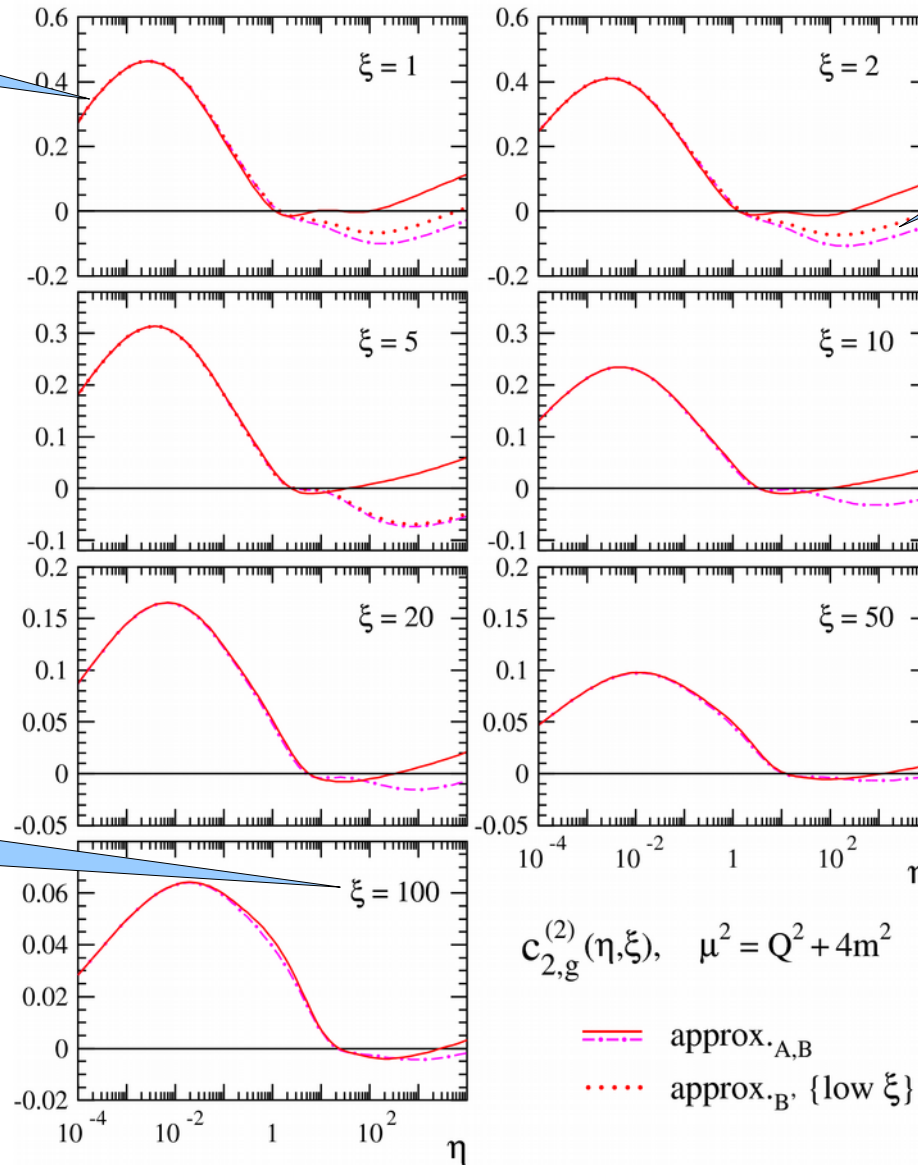
small  $x$

$s$

$$\xi = Q^2/m^2$$

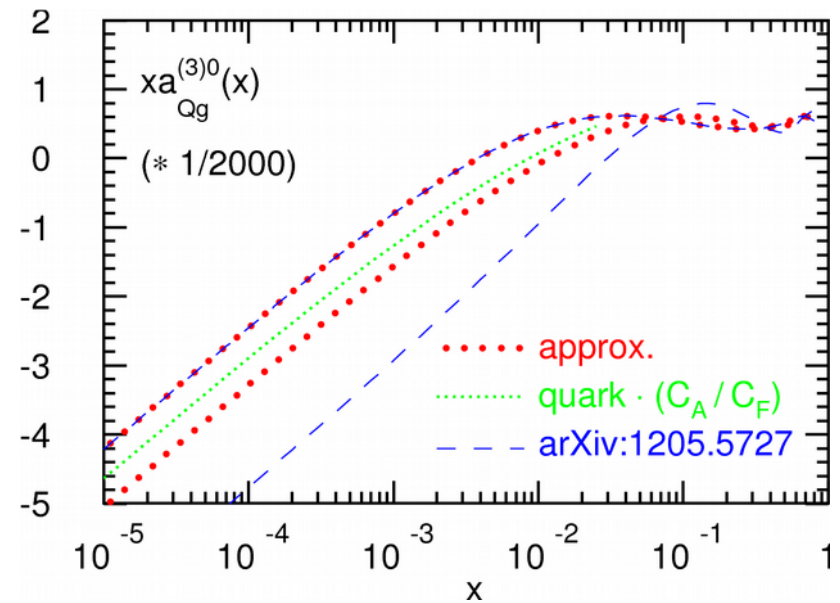
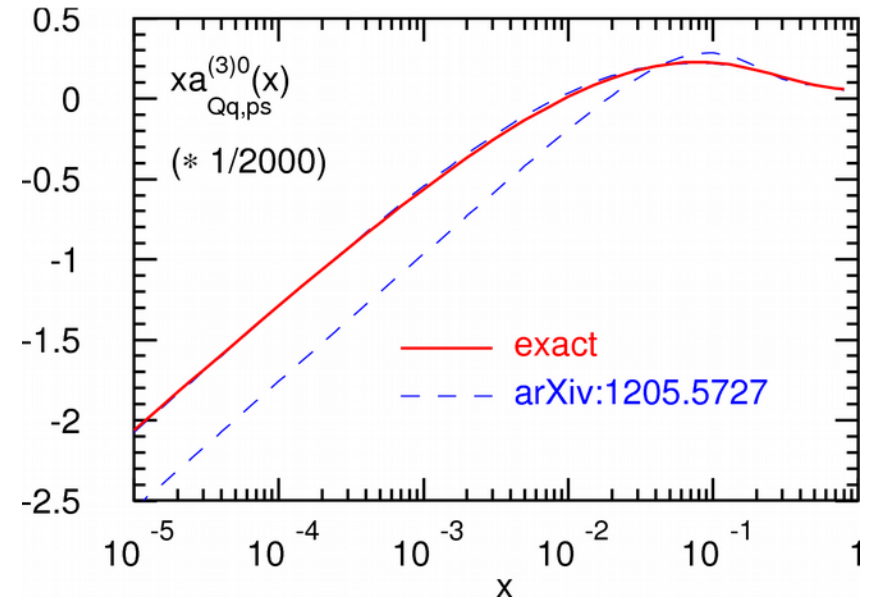
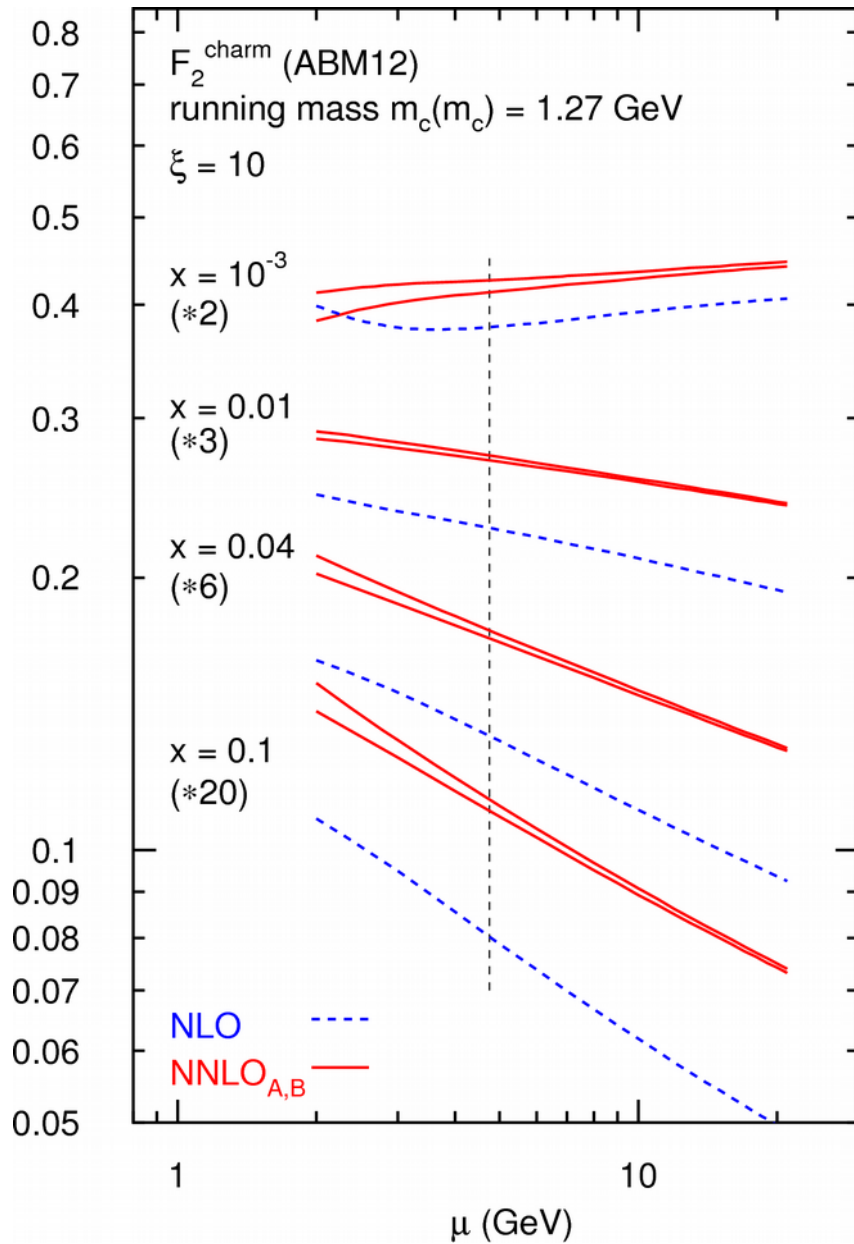
$$\eta = s/4m^2 - 1$$

large  $Q^2$



Combination of the threshold corrections (small  $s$ ), high-energy limit (small  $x$ ), and the NNLO massive OMEs (large  $Q^2$ )

# Recent progress in massive DIS coefficients

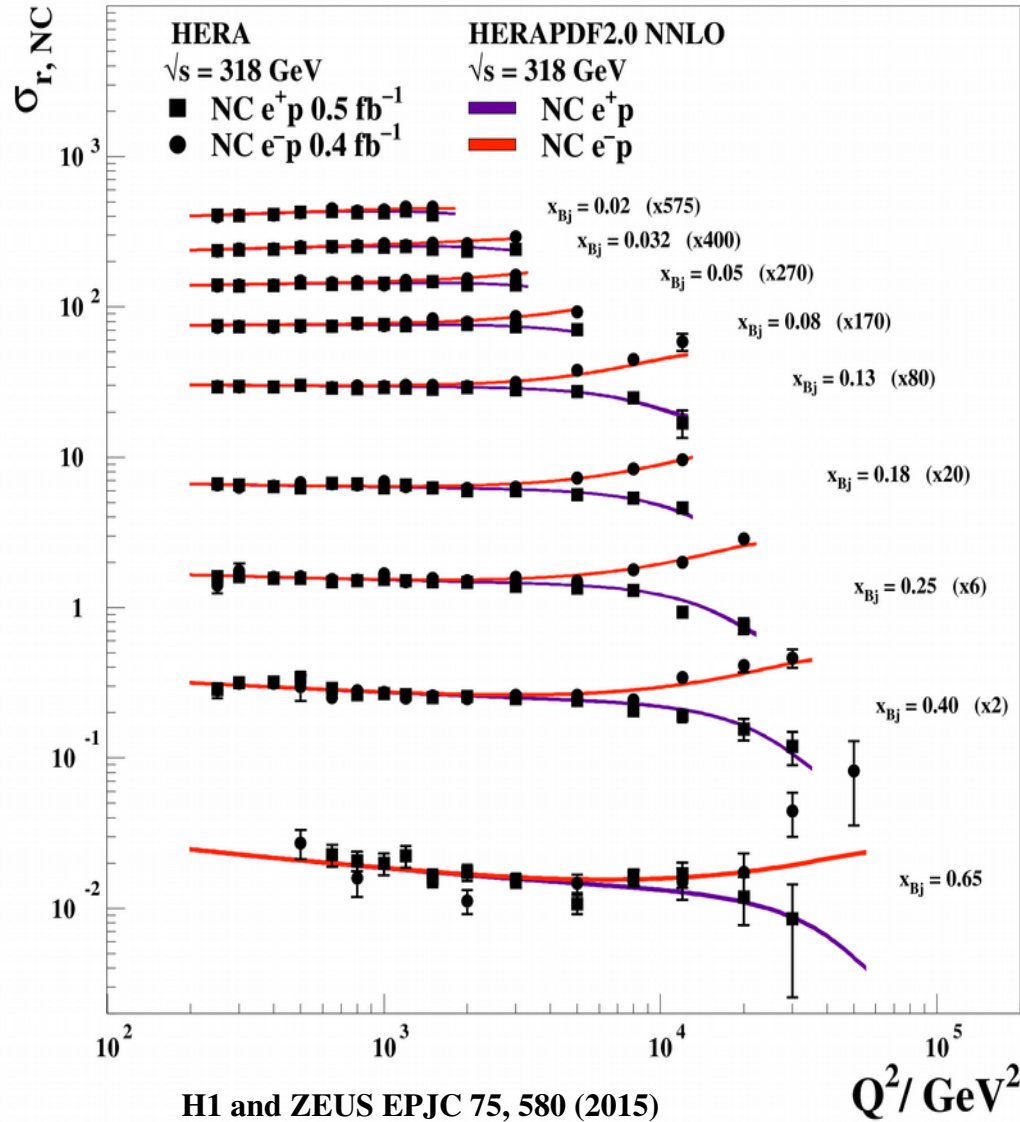


Update with the pure singlet massive OMEs  $\rightarrow$  improved theoretical uncertainties

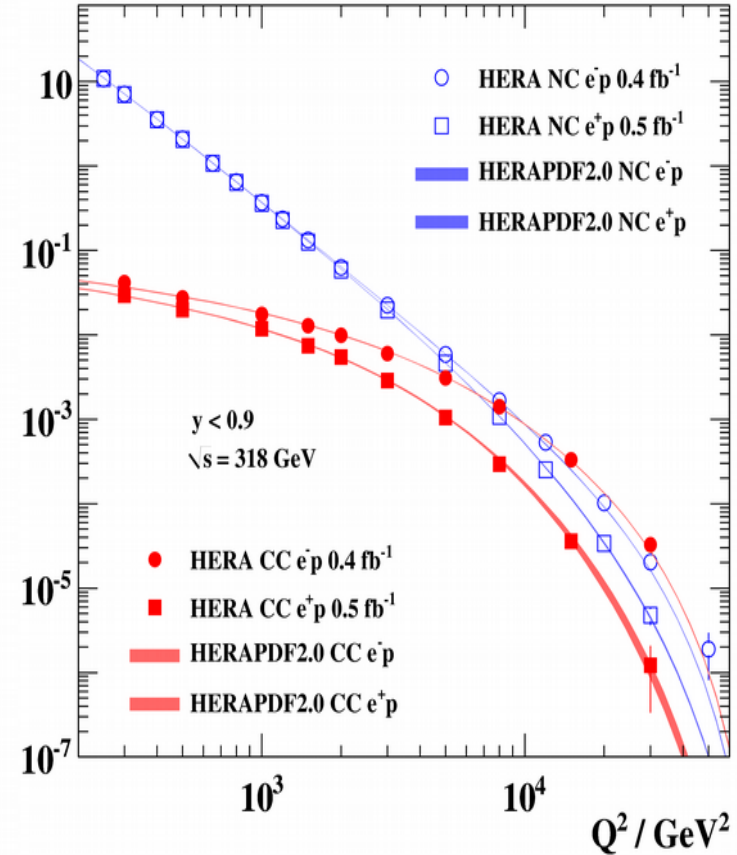


# Comined Run I+II HERA data

## H1 and ZEUS

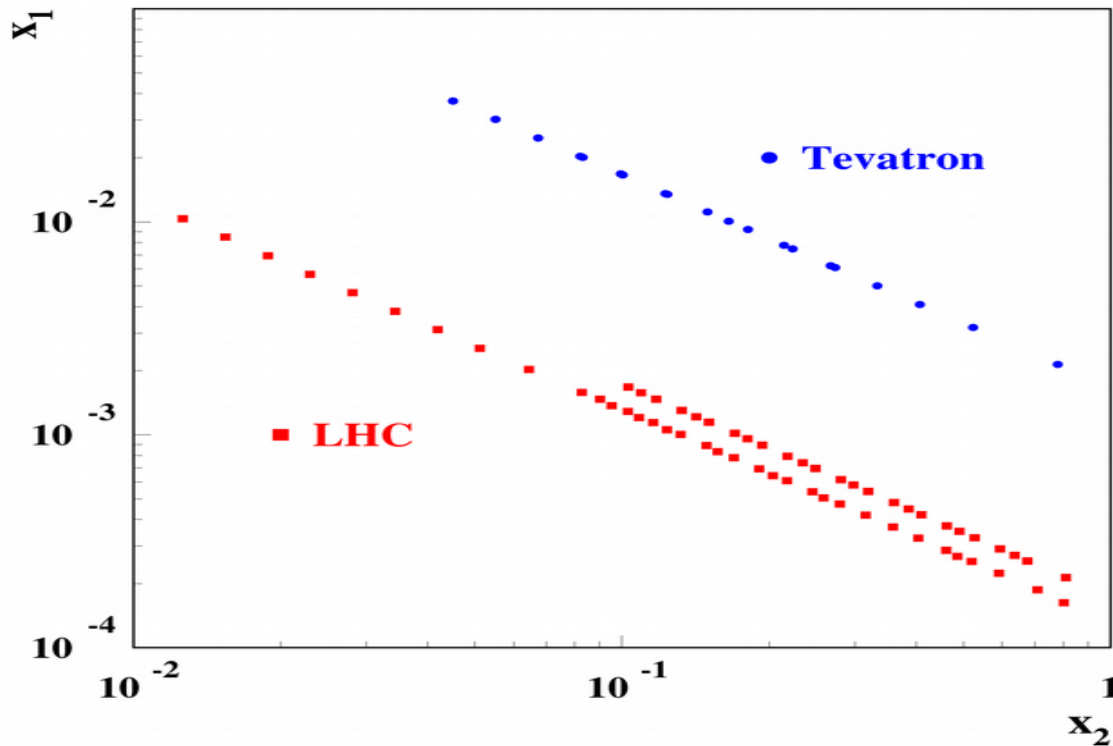


## H1 and ZEUS



- $\sigma(\text{DIS}) \sim q_u^2 u(x) + q_d^2 d(x) + q_s^2 s(x) \Rightarrow$  poor separation of the quark species
- The deuteron fixed-target data (SLAC, BCDMS NMS) are needed to disentangle d- and u-distributions by using transmutation  $u \leftrightarrow d$

# Forward DY kinematics at Tevatron and the LHC



In the forward region  $x_2 \gg x_1$

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

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

$$\sigma(Z) \sim Q_u^2 u(x_2) \text{ubar}(x_1) + Q_d^2 d(x_2) \text{dbar}(x_1)$$

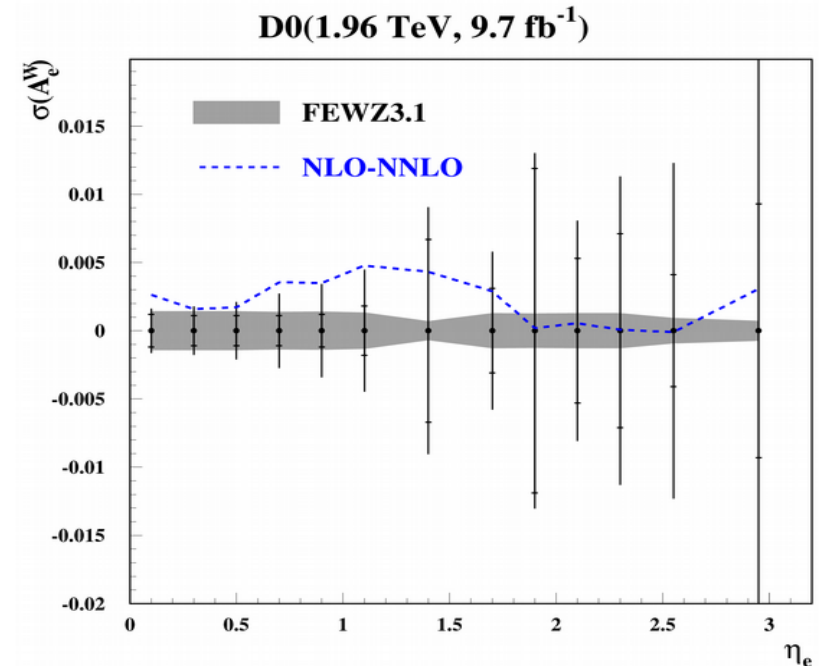
$$\sigma(\text{DIS}) \sim q_u^2 u(x_2) + q_d^2 d(x_2)$$

*Forward W&Z production probes small/large  $x$  and is complementary to the DIS  $\Rightarrow$  good quark disentangling*

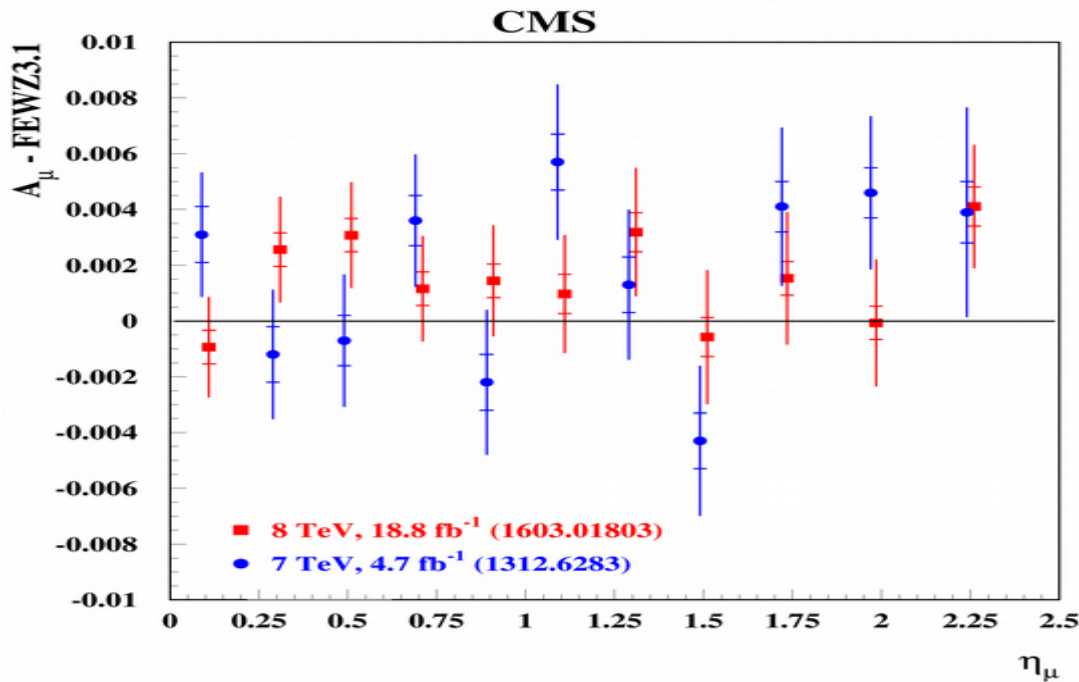
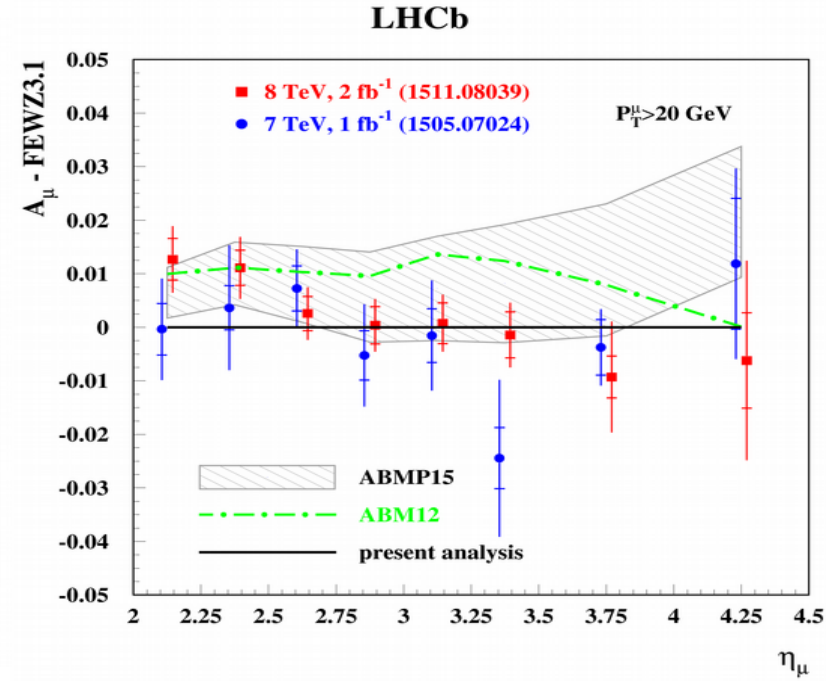
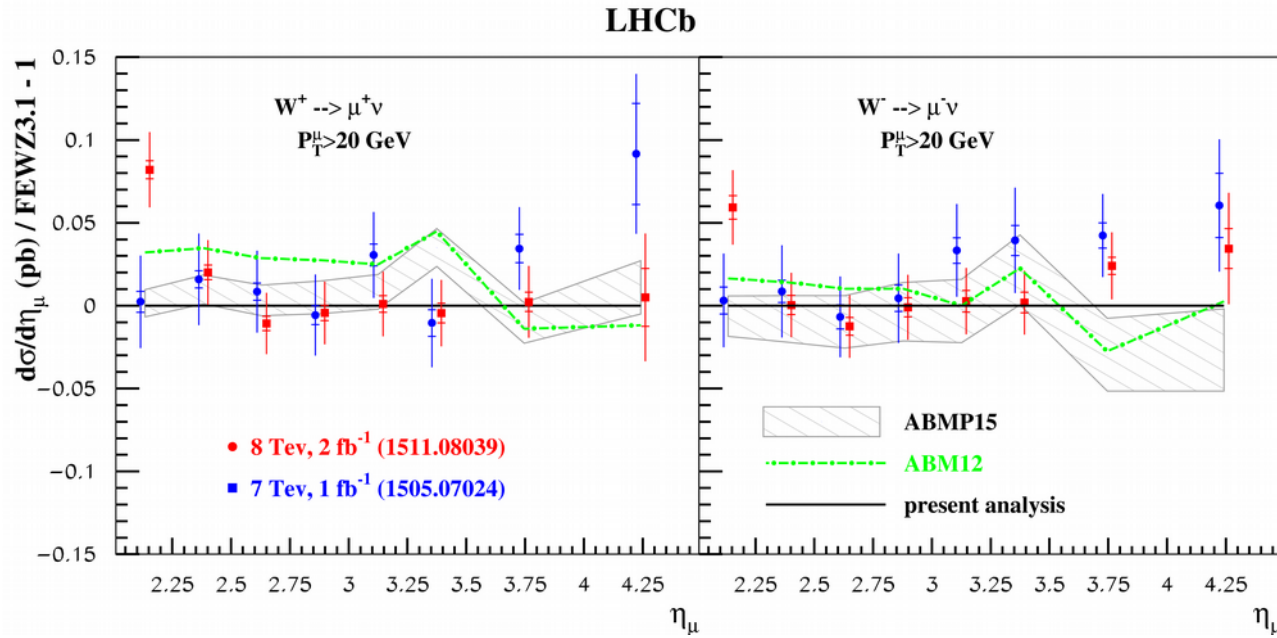
- Fully differential kinematics; existing NNLO codes, DYNNLO and FEWZ require huge computing resources to achieve the promille accuracy required
- DYNNLO-FEWZ difference not fully resolved

Salam ATLAS SM workshop 2014

Yannick Ulrich, Bachelor thesis, Univ. of Hamburg 2015



# Most recent DY inputs

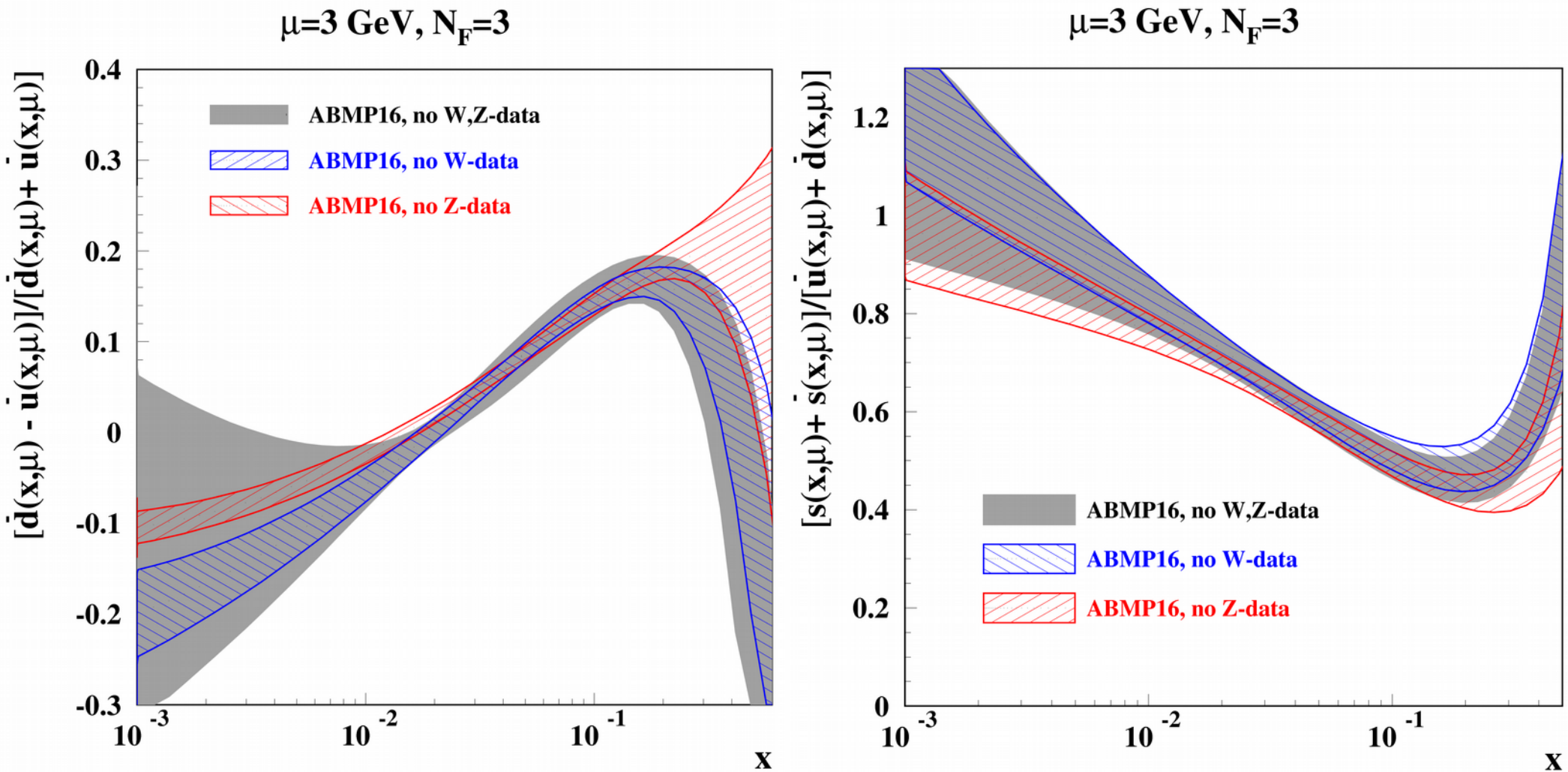


Filtering of the LHCb data has been performed:

- 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)

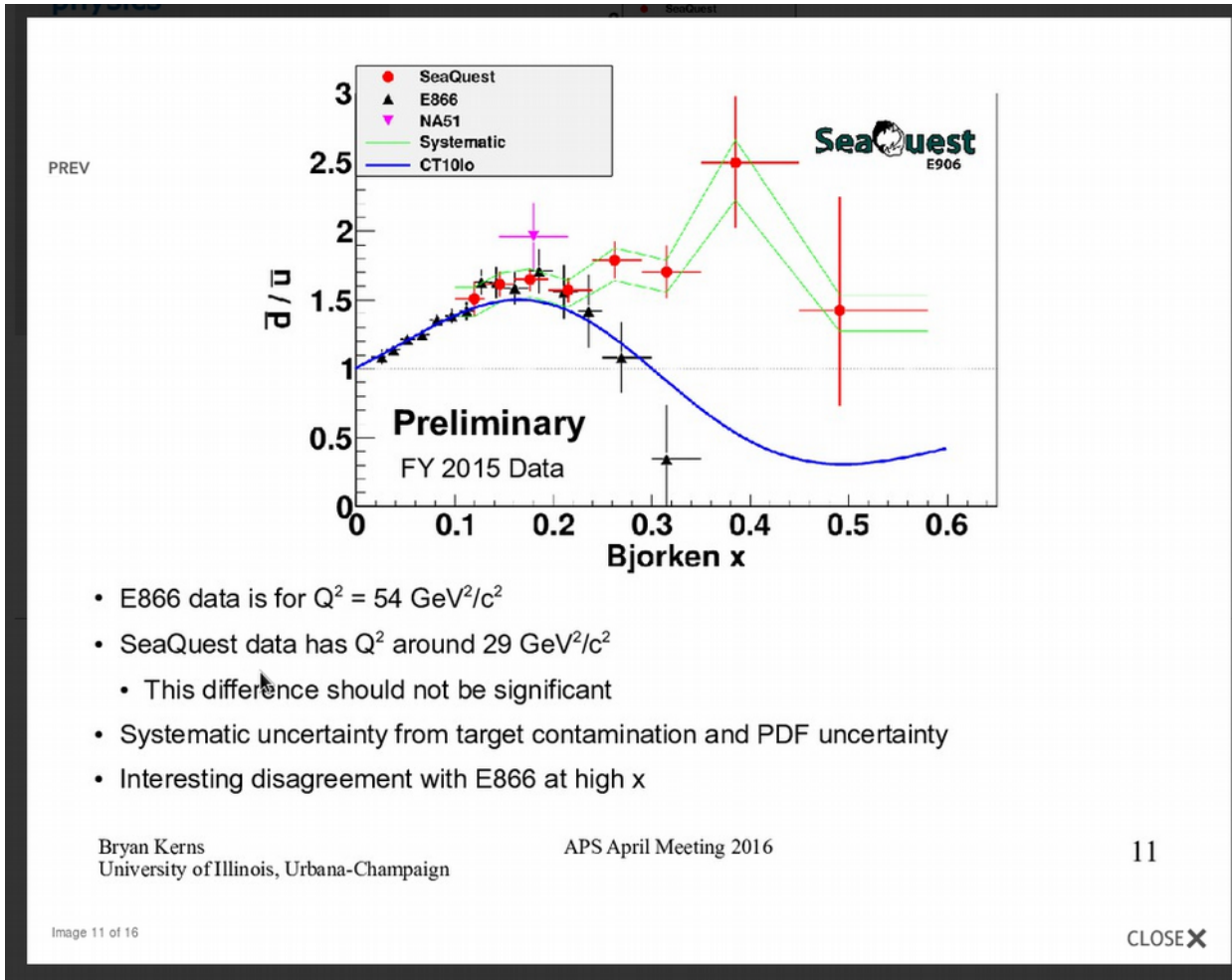
The CMS data at 8 TeV are much smoother than the ones at 7 TeV:  
 $\chi^2=17/22$  versus  $22/11$

# Impact of the W-, Z-data in ABMP16 fit

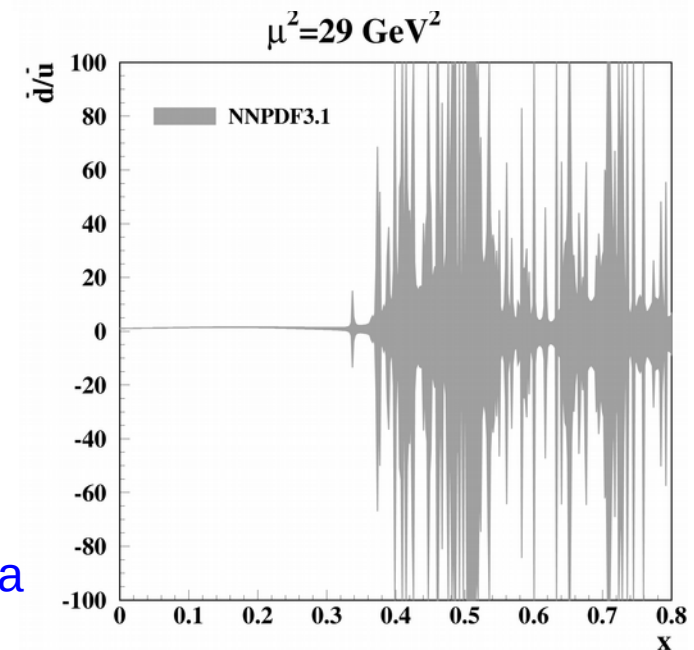
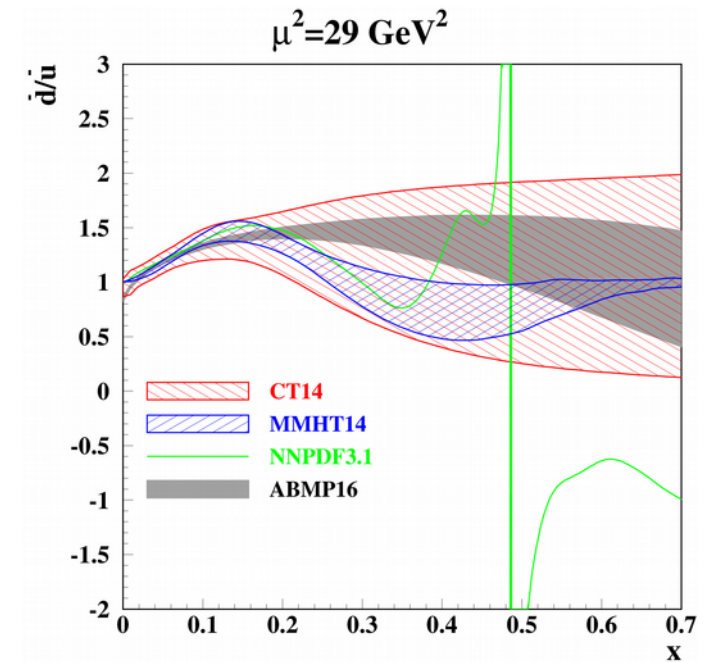


W-, Z-data really control quark disentangling at small x

# SeaQuest (FNAL-E906) prospects



- E906 confirms the E866 results at  $x \sim 0.1$  and continues the positive trend in the sea iso-spin asymmetry at bigger  $x$
- The existing PDF sets can be consolidated with the E906 data

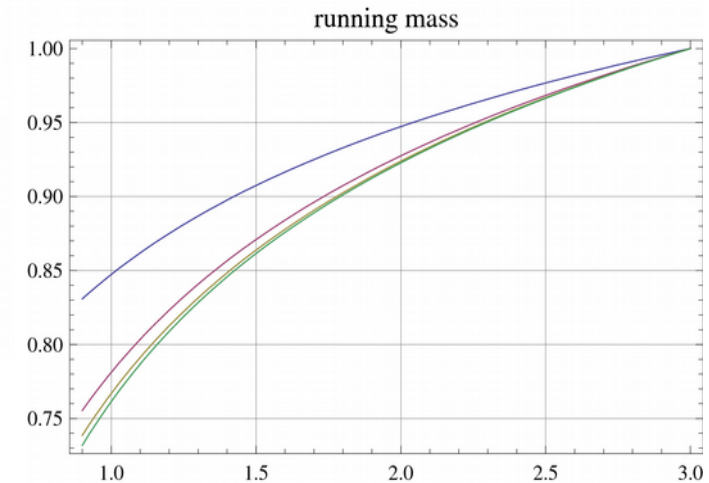
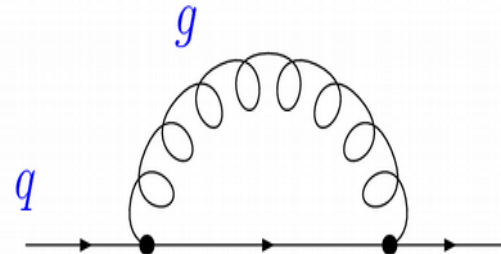


# Running mass in DIS

The pole mass is defined for the free (*unobserved*) quarks as a the QCD Lagrangian parameter and is commonly used in the QCD calculations

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{\text{flavors}} \bar{q} (i\not{D} - m_q) q$$

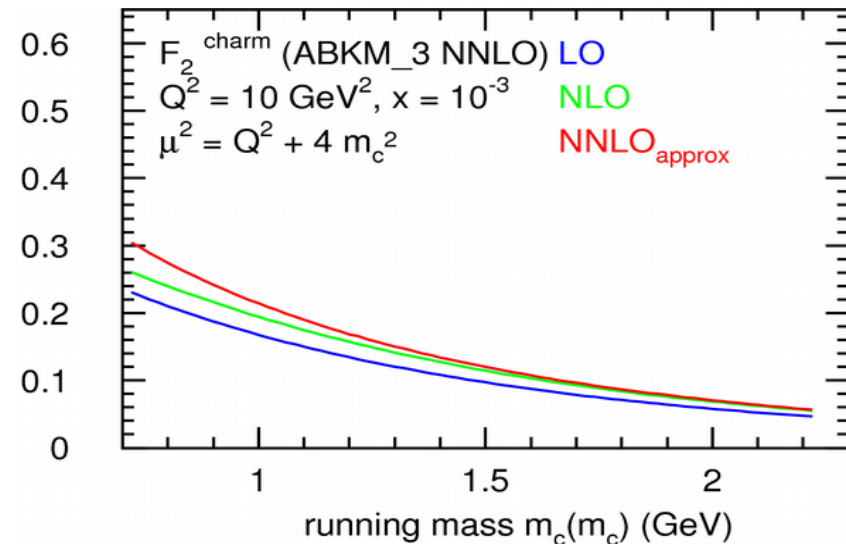
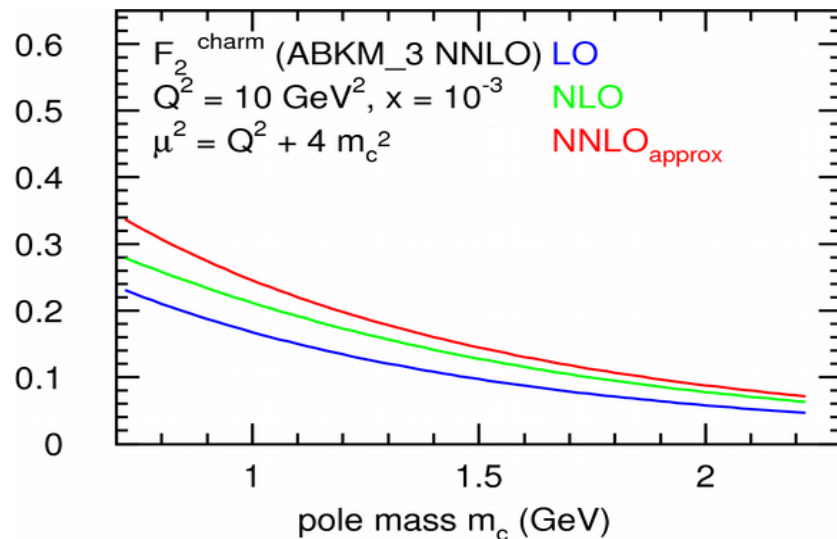
$$\not{p} - m_q - \Sigma(p, m_q) \Big|_{p^2=m_q^2}$$



The quantum corrections due to the self-energy loop Integrals receive contribution down to scale of  $O(\Lambda_{\text{QCD}})$

→ sensitivity to the high order corrections, particularly at the production threshold

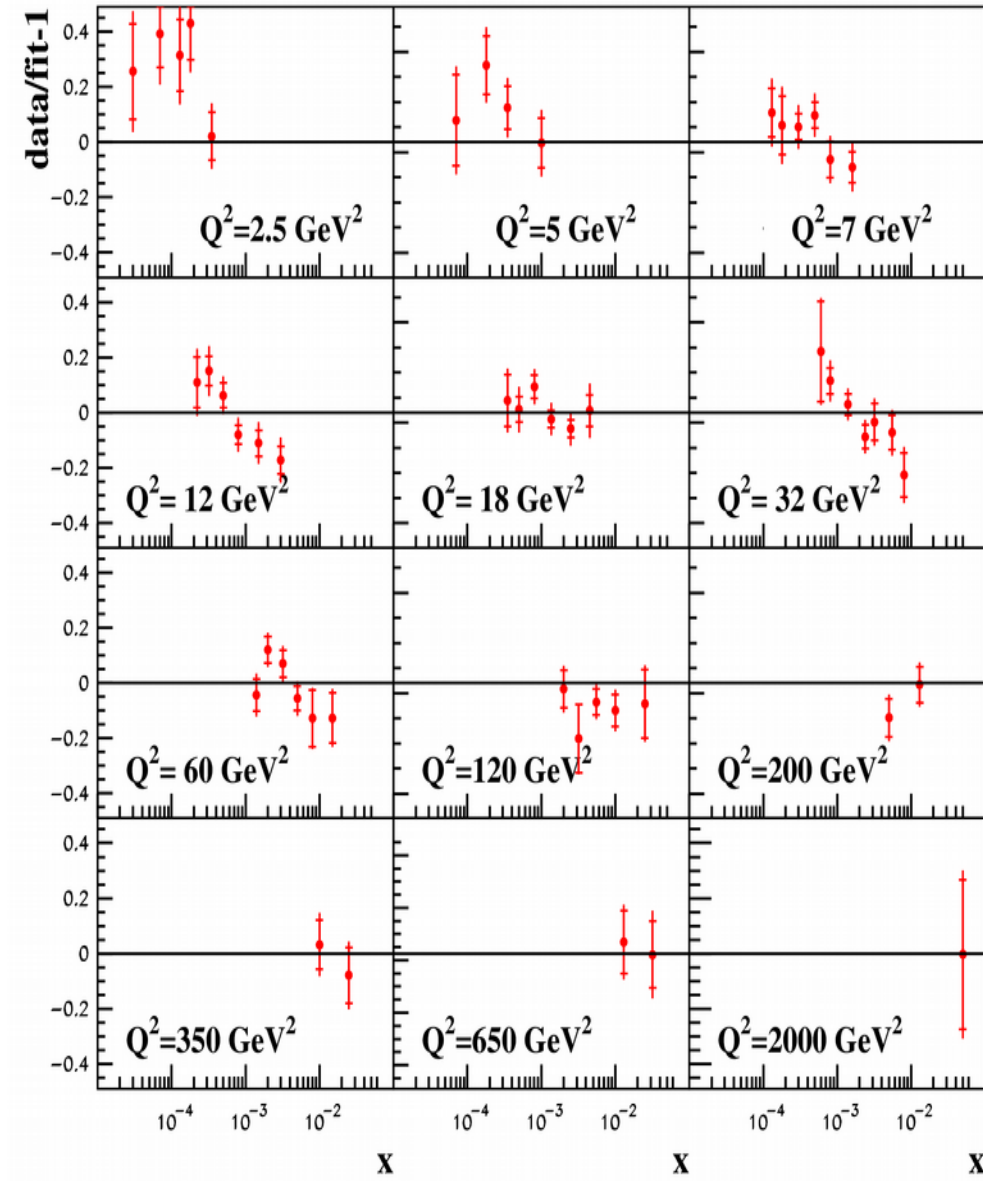
$$\mu^2 \frac{d}{d\mu^2} m(\mu) = \gamma(\alpha_s) m(\mu)$$



# HERA charm data and $m_c(m_c)$

H1/ZEUS ZPC 73, 2311 (2013)

HERA I+II (ep  $\rightarrow$  e charm X)



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

Kiyo, Mishima, Sumino PLB 752, 122 (2016)

$X^2/NDP=66/52$

$m_c(m_c)=1.252\pm 0.018$ (exp.)-0.01(th.) GeV

ABMP16

$m_c(m_c)=1.24\pm 0.03$ (exp.) GeV ABM12

$m_c(\text{pole})\sim 1.9$  GeV (NNLO)

Marquard et al. PRL 114, 142002 (2015)

• RT optimal

$X^2/NDP=82/52$

$m_c(\text{pole})=1.25$  GeV

NNLO

MMHT14 EPJC 75, 204 (2015)

• S-ACOT- $\chi$

$X^2/NDP=59/47$

$m_c(\text{pole})=1.3$  GeV

NNLO

CT14 PRD 93, 033006 (2016)

• FONLL

$X^2/NDP=60/47$

$m_c(\text{pole})=1.275$  GeV

NNLO

NNPDF3.0 JHEP 504, 040 (2015)

• FONLL

$X^2/NDP=54/37$

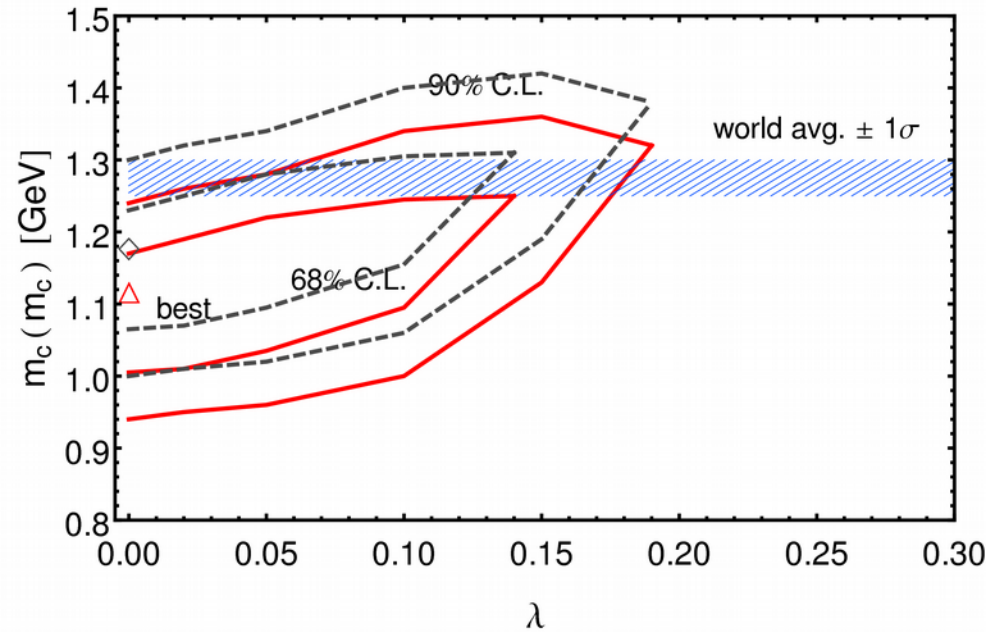
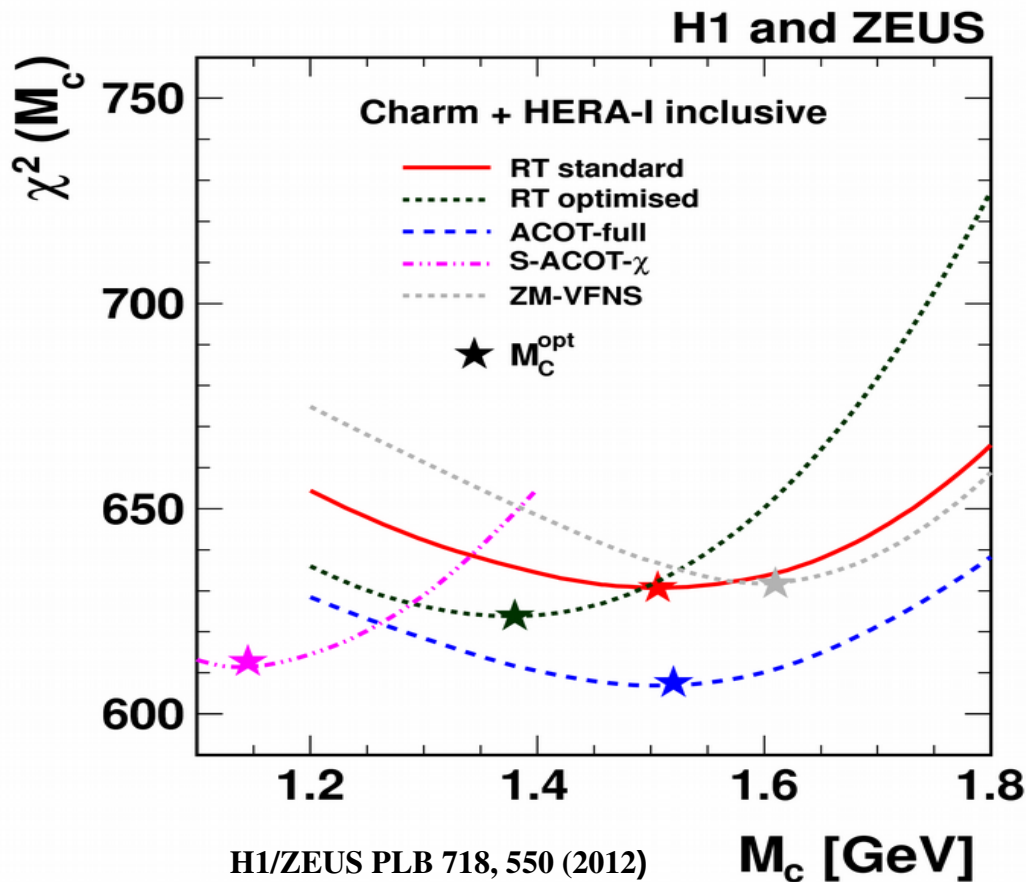
$m_c(\text{pole})=1.51$  GeV, intrinsic charm included

NNLO

NNPDF3.1 hep-ph/1706.00428

# c-quark mass in the CMVFN schemes

The values of pole mass  $m_c$  used by different groups and preferred by the PDF fits are systematically lower than the PDG value



$m_c(m_c) = 1.19^{+0.08}_{-0.15}$  GeV ACOT....  
Gao, Guzzi, Nadolsky EPJC 73, 2541 (2013)

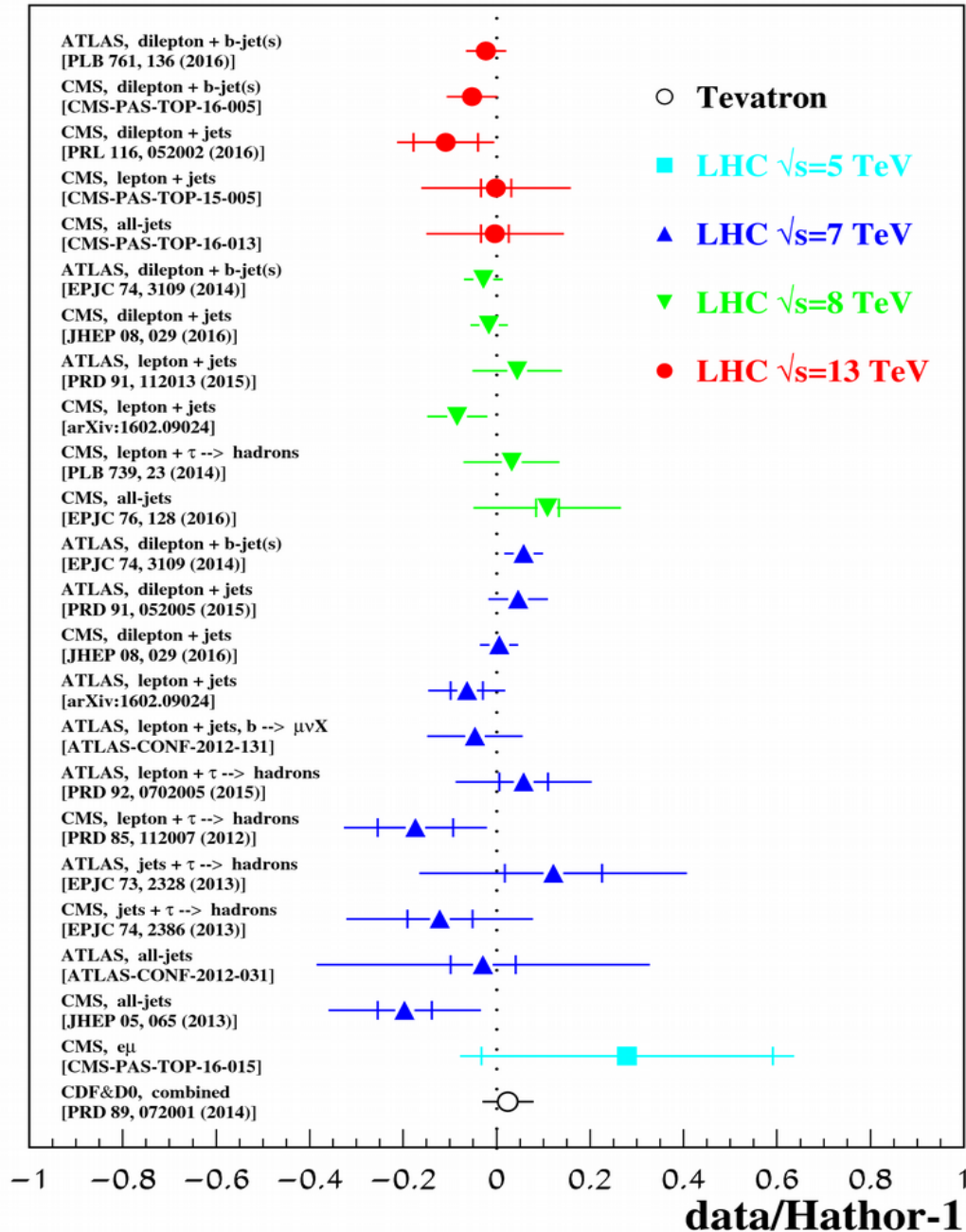
$m_c(m_c) = 1.34^{+0.04}_{-0.01}$  GeV FONLL  
Bertone et. al JHEP 1608, 050 (2016)

Wide spread of the  $m_c$  obtained in different version of the GMVFN schemes  $\rightarrow$  quantitative illustration of the GMVFNs uncertainties

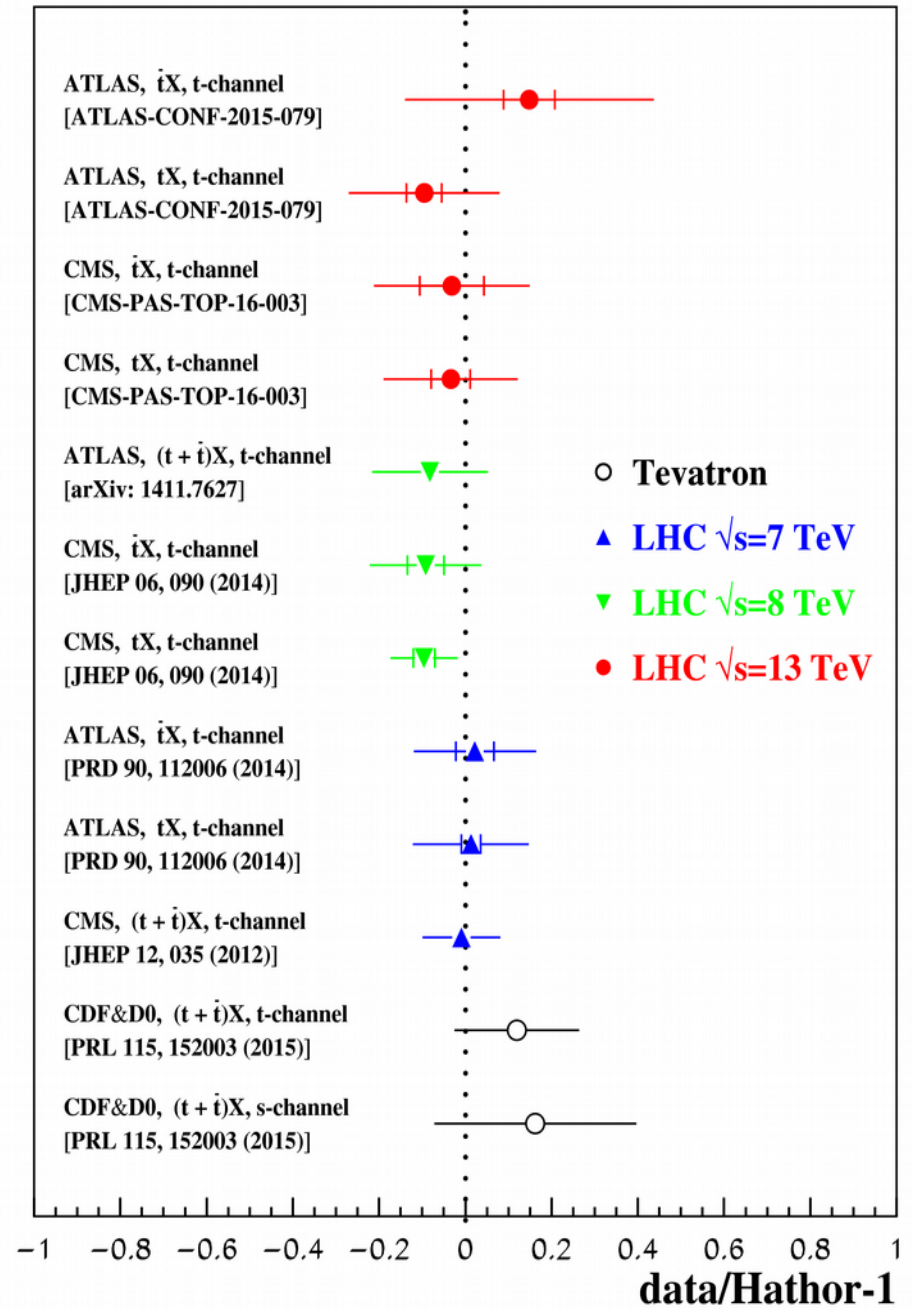


# t-quark production

$\sigma(ttX)$



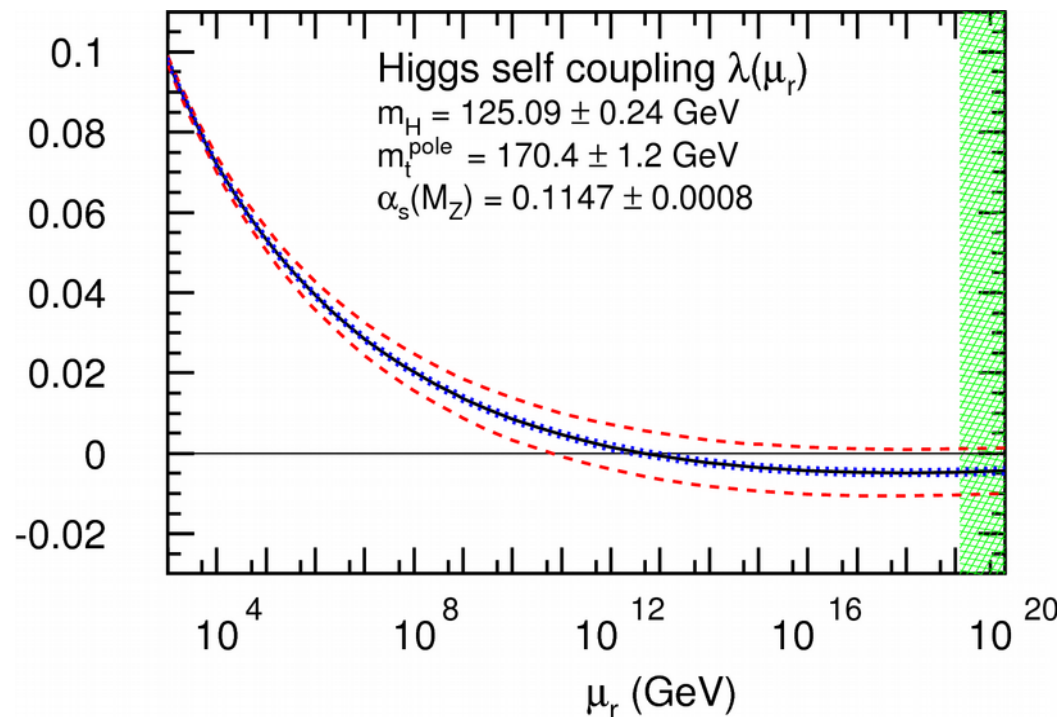
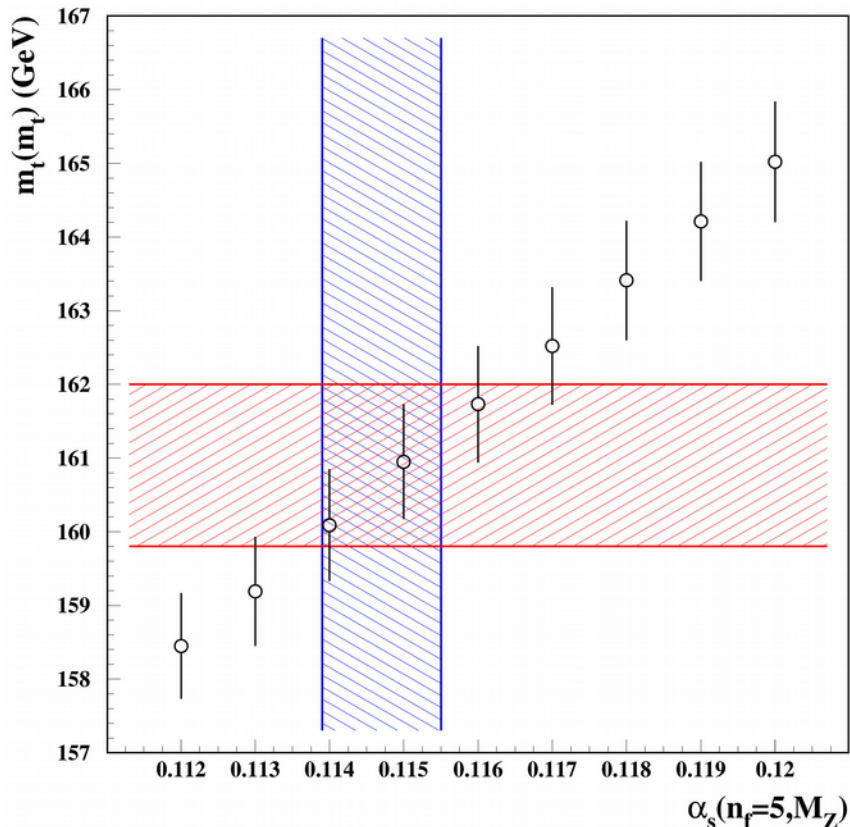
$\sigma(t/\bar{t} X)$



# Electroweak vacuum stability

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

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



nr: Kniehl, Pikelner, Veretin CPC 206, 84 (2016)

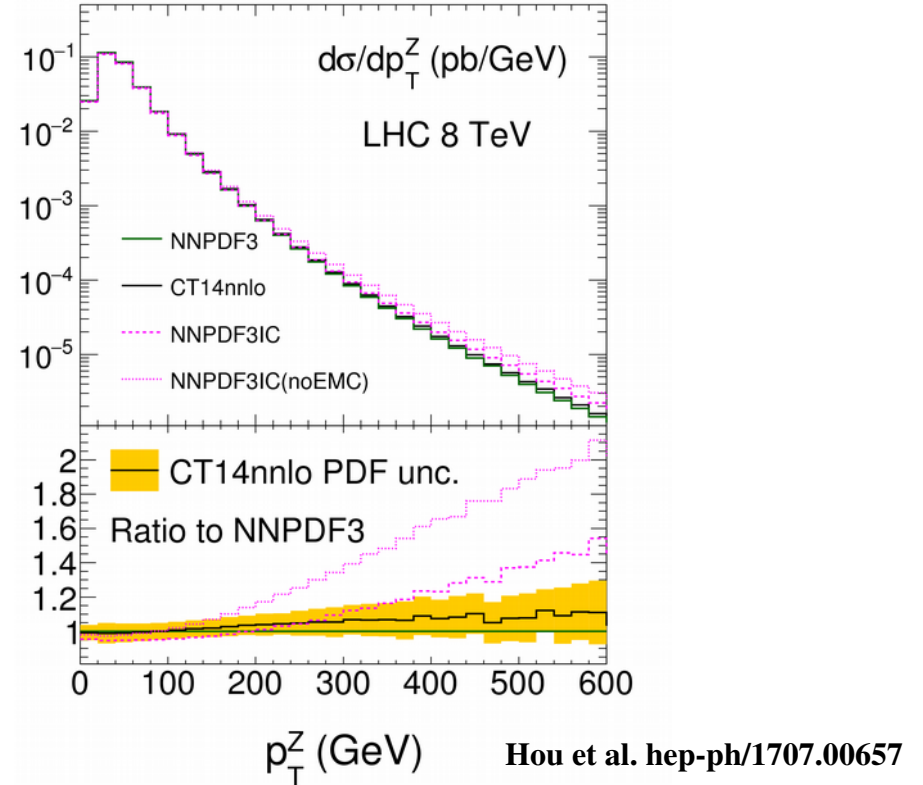
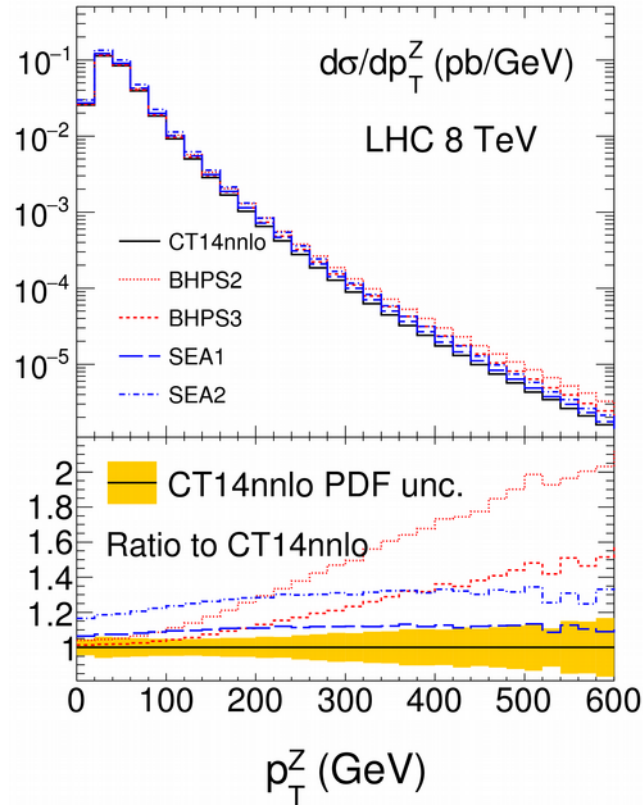
$$m_t(m_t) = 160.9 \pm 1.1 (\text{exp.}) \text{ GeV}$$

$$m_t^{\text{pole}} = 170.4 \pm 1.2 (\text{exp.}) \text{ GeV}$$

$$\alpha_s(M_Z) = 0.1147(8) \quad \text{NNLO}$$

*Vacuum stability is quite sensitive to the  $t$ -quark mass; stability is provided up to Planck-mass scale*

# Intrinsic charm in the CT and NNPDF fits



- The intrinsic-charm (IC) component is evolved starting from the small scale with the collinear DGLAP
- The value of  $m_c(\text{pole})=1.31$  (CT) and  $1.51$ (NNPDF) GeV is used
- Several IC shapes are considered by CT: BHPS, SEA,...; free form by NNPDF
- An agreement with the Z+charm LHC data might be improved

# new/ongoing global analyses

Hobbs, INT workshop, Seattle 12017

- **NNPDF3**: not anchored to specific parametrizations/models

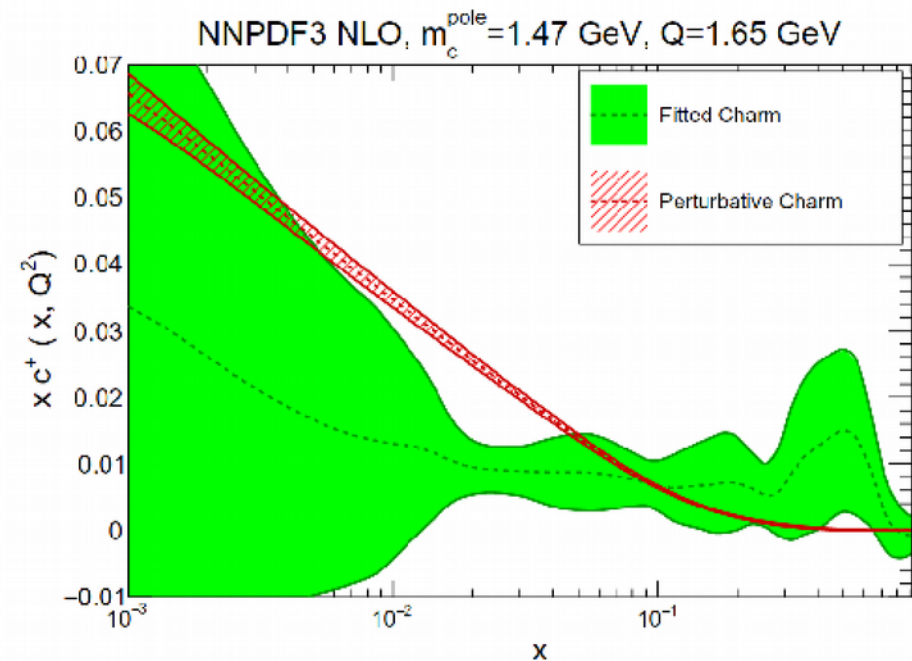
see: Ball *et al.* Eur. Phys. J. **C76** (2016) no.11, 647

- *included* EMC:

$$\langle x \rangle_{\text{IC}} = 0.7 \pm 0.3\% \text{ at } Q \sim 1.5 \text{ GeV}$$

→ drove a **very hard**  $c(x) = \bar{c}(x)$  distribution

- peaked at  $x \sim 0.5$
- AND, required a *negative* IC component to describe EMC  $F_2^{c\bar{c}}$ !



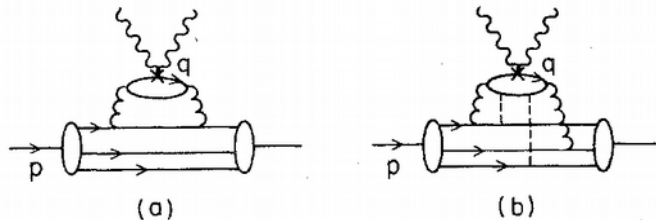
- complementary analyses for possible intrinsic **bottom**

see: Lyonnet *et al.* JHEP07 (2015) 141.

→ would be negligible based on the analysis presented here...

# Intrinsic charm: pitfalls

- **No mass singularities** for massive partons  $\Rightarrow$  collinear QCD evolution does not work
- The mass singularities  $\sim \ln(\mu/m_h)$  appear at  $\mu \gg m_h$  and the evolution restores. New charm(bottom) quark distribution may be introduced, however, extrapolation to smaller scales is still problematic
- Intrinsic charm is often introduced within the VFN framework  $\Rightarrow$  interplay with the “standard” VFN modeling of power-like terms
- Original formulation of the intrinsic charm implies its power-like behavior;



Brodsky, Peterson, Sakai PRD 23, 2745 (1981)

FIG. 7. (a) Example with contribution to the deep-inelastic structure functions from an extrinsic quark  $q$ ; (b) from an intrinsic quark  $q$ .

strong constraint on such terms was obtained from analysis of the EMC data on charm production

Jimenez-Delgado, Hobbs, Londergan, Melnitchouk PRL 114, 082002 (2015)

# Summary

- We have steady improvement in disentangling quark distributions at small  $x$  due to complementarity of the DIS and (forward) Drell-Yan data
- The HERA inclusive and semi-inclusive data allow to distinguish between the FFN and VFN factorization schemes in description of DIS. The FFN scheme provides nice agreement with existing DIS data and

$$m_c(m_c) = 1.252 \pm 0.018(\text{exp.}) - 0.01(\text{th.}) \text{ GeV},$$

which is in agreement with other precision determinations.

- The values

$$\alpha_s(M_Z) = 0.1147(8)$$

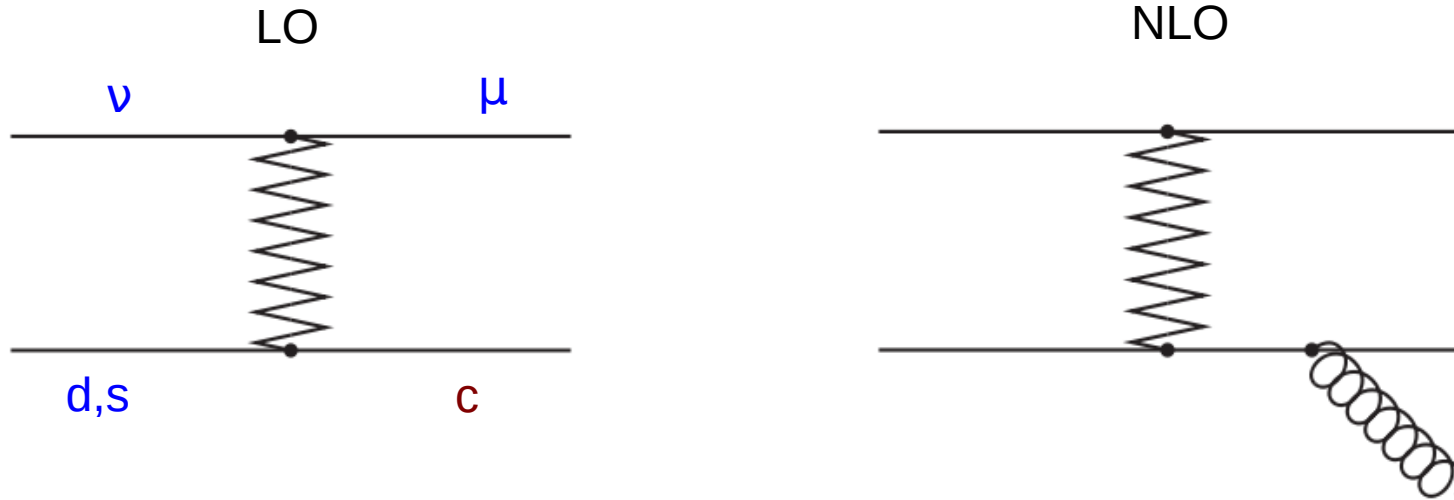
$$m_t(m_t) = 160.9 \pm 1.1 \text{ GeV} / m_t(\text{pole}) = 170.4 \pm 1.2 \text{ GeV}$$

obtained simultaneously with the PDFs provide vacuum stability up to the Planck-mass scale

- Intrinsic charm provides a new window for phenomenology, however, solid theoretical footing is still needed

**EXTRAS**

# Strange sea from the $\nu N$ DIS



Two decay modes of  $c$ -quark are used: hadronic (emulsion experiments) and semi-leptonic (electronic experiments)

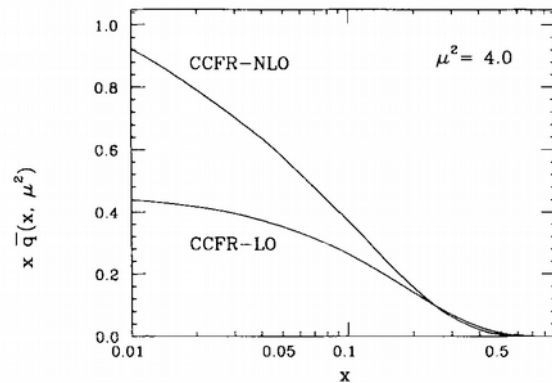


Fig. 3. The quark sea distribution  $x \bar{q}(x, \mu^2 = 4.0 \text{ GeV}^2/c^2)$  determined at next-to-leading order and leading order

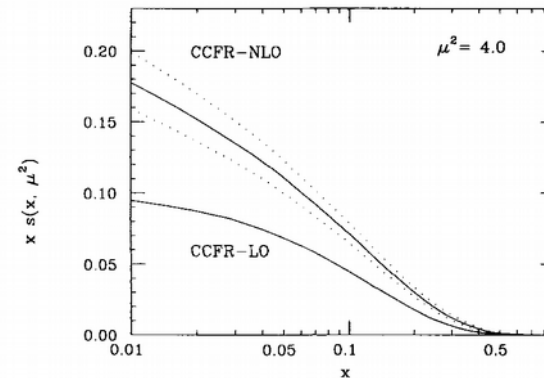


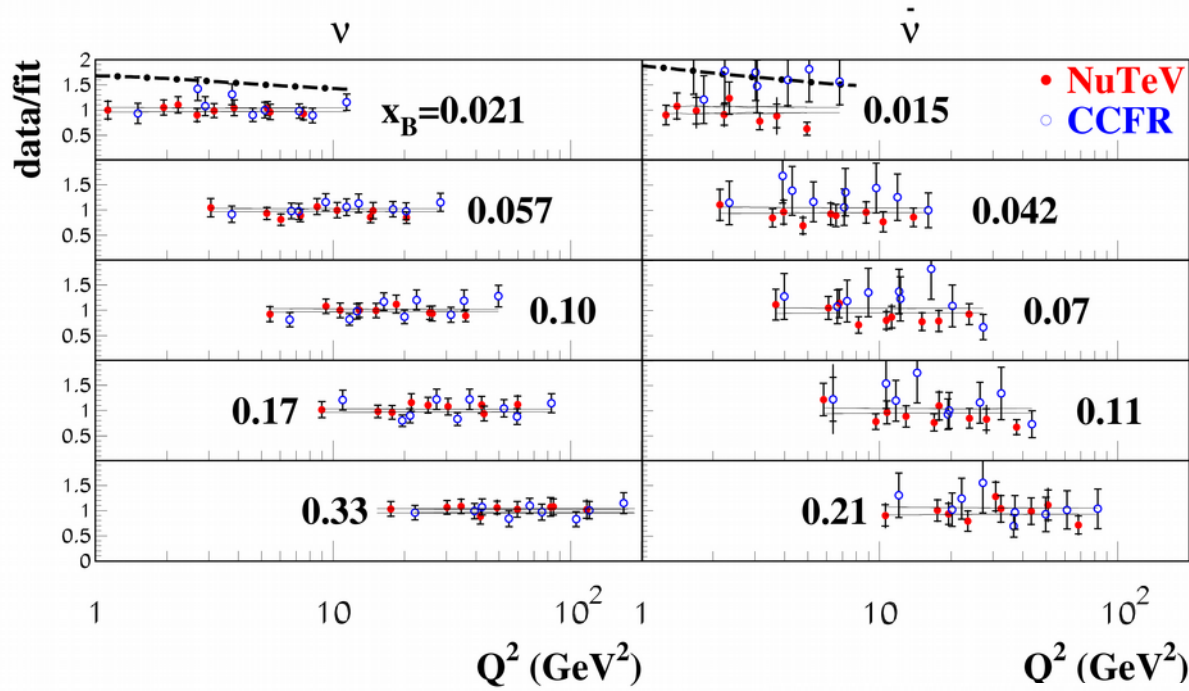
Fig. 4. The strange quark distribution  $x s(x, \mu^2 = 4.0 \text{ GeV}^2/c^2)$  determined at next-to-leading order (described in section 4.1) and leading order. The band around the NLO curve indicates the  $\pm 1\sigma$  uncertainty in the distribution

CCFR ZPC 65, 189 (1995)

Primary source for the strange sea was for a long time neutrino-induced charm production measured by CCFR/NuTeV at Fermilab preferring a suppression of  $\sim 0.5$  w.r.t. non-strange sea



# NuTeV/CCFR data in the PDF fit framework

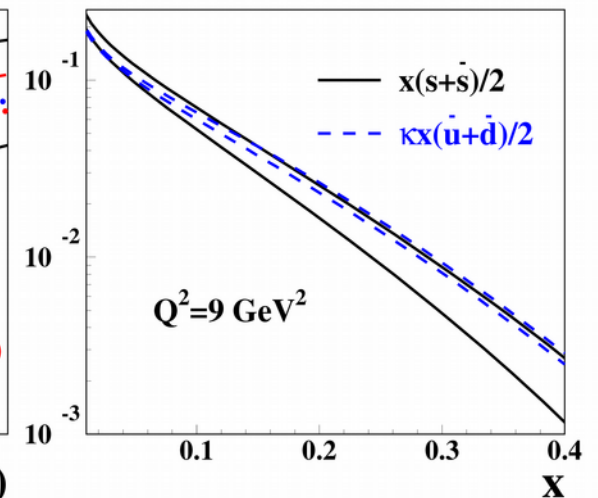
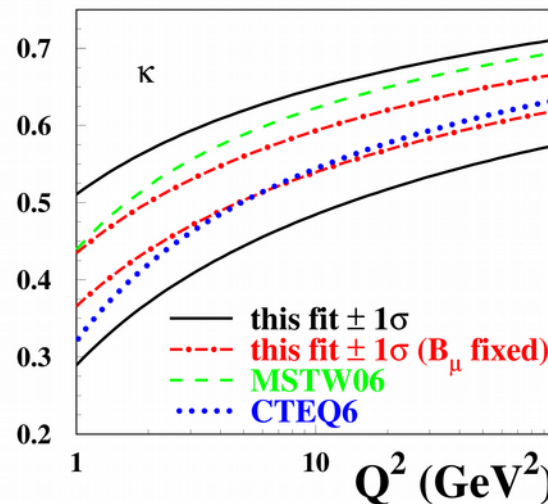


- CCFR and NuTeV are in a good agreement
- Charge asymmetry in the strange sea is consistent with 0 within uncertainties

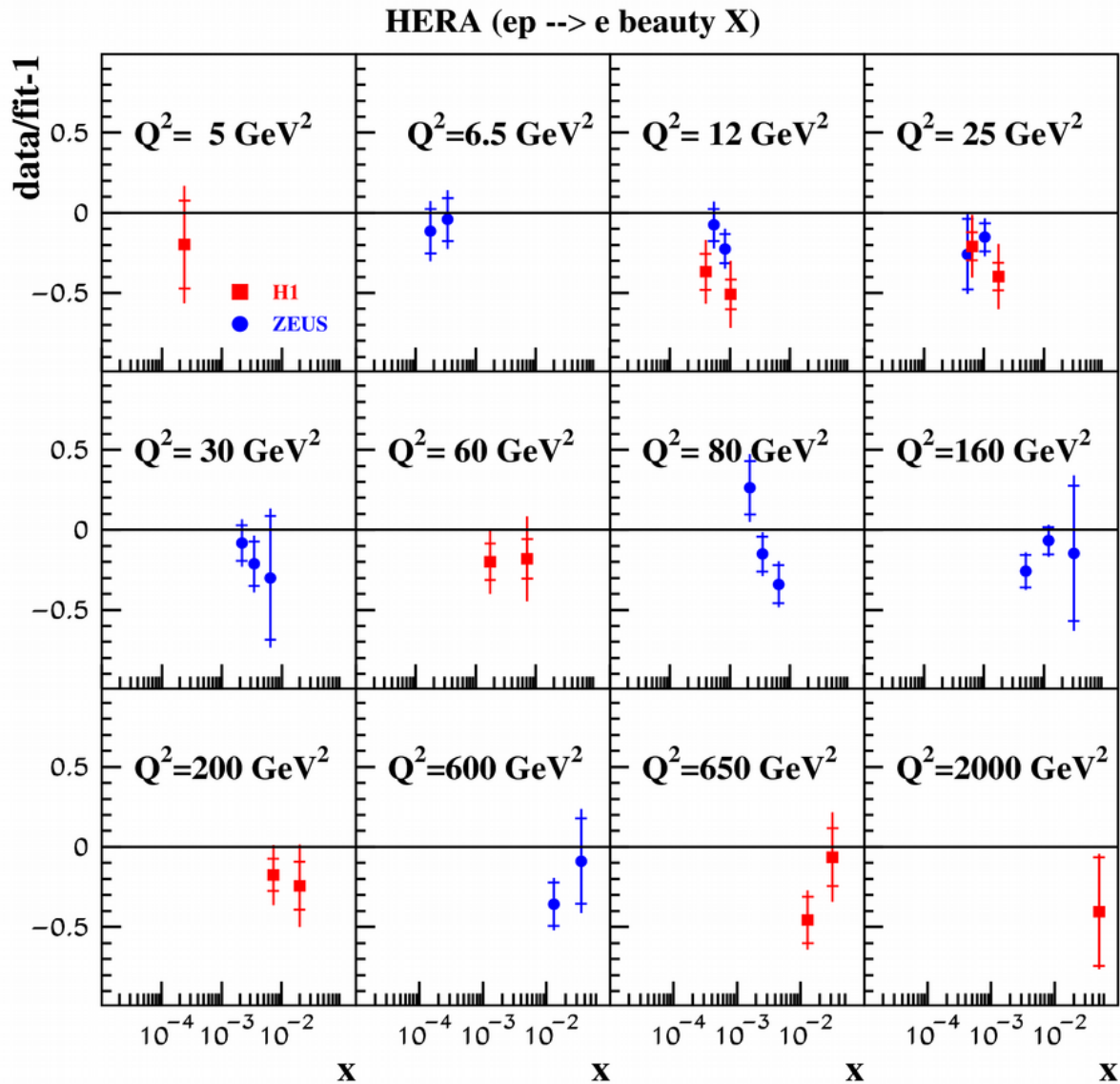
sa, Kulagin, Petti PLB 675, 433 (2009)

$$\kappa_s(\mu^2) = \frac{\int_0^1 x[s(x, \mu^2) + \bar{s}(x, \mu^2)]dx}{\int_0^1 x[\bar{u}(x, \mu^2) + \bar{d}(x, \mu^2)]dx},$$

*Integral suppression factor*  
 $K_s(20 \text{ GeV}^2) = 0.62 \pm 0.04$  is obtained



# HERA bottom data and $m_b(m_b)$



ZEUS JHEP 1409, 127 (2014)

$$\chi^2/\text{NDP} = 16/17$$

H1 EPJC 65, 89 (2010)

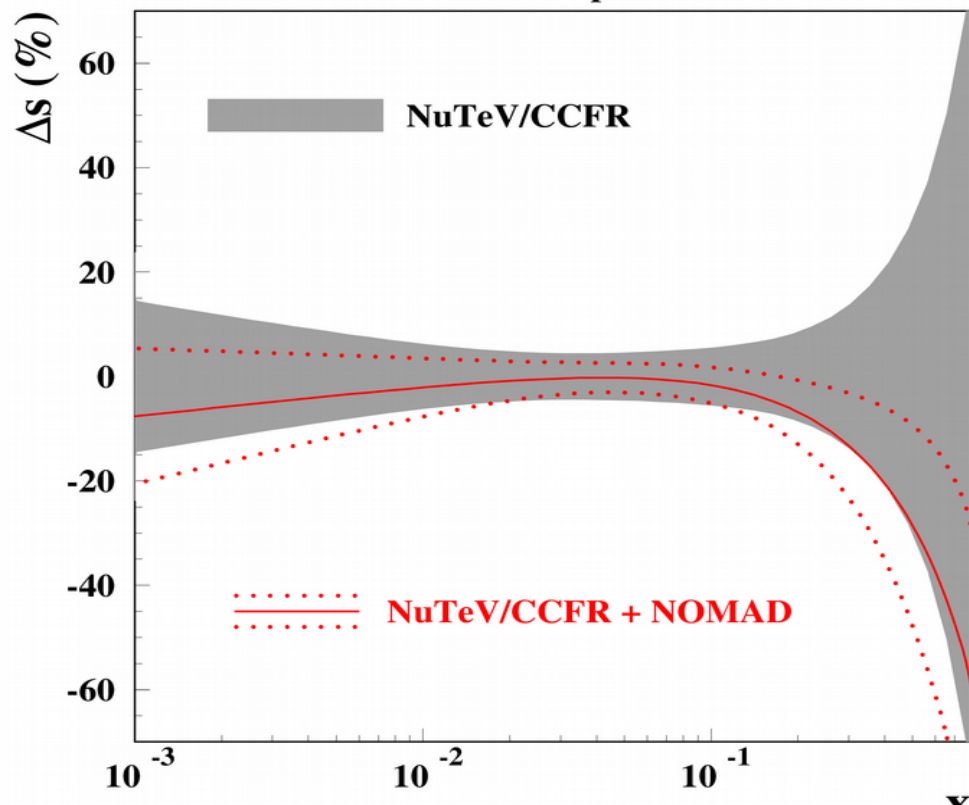
$$\chi^2/\text{NDP} = 5/12$$

$$m_b(m_b) = 3.83 \pm 0.12(\text{exp.}) - 0.1(\text{th.}) \text{ GeV}$$

# NOMAD charm data

$\mu=3 \text{ GeV}, n_f=3$

NOMAD NPB 876, 339 (2013)



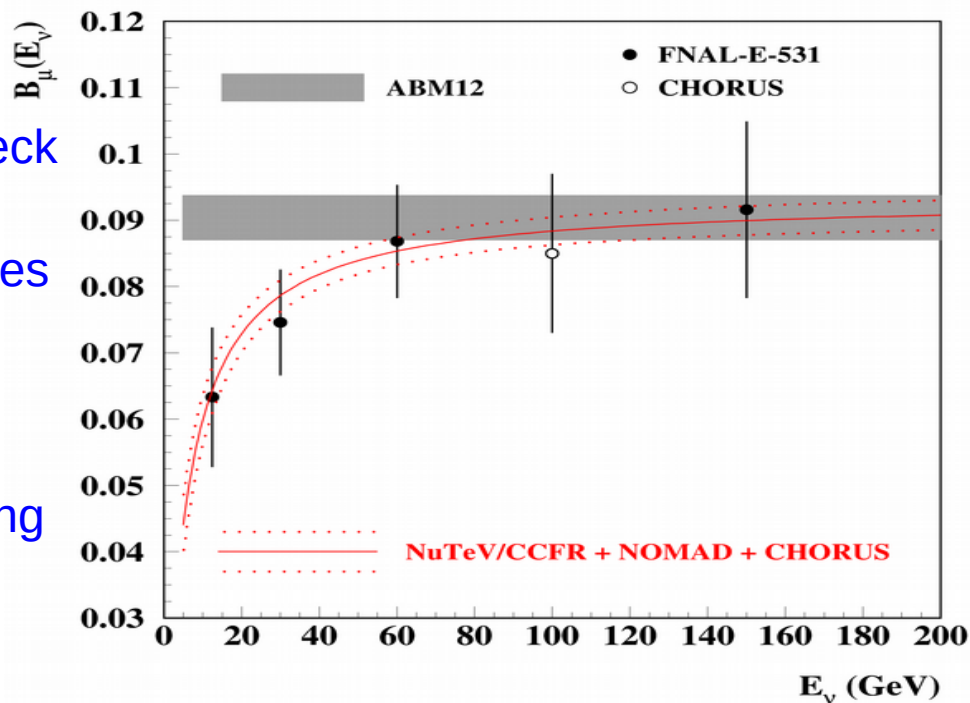
- The data on ratio  $2\mu/\text{incl. CC}$  ratio with the  $2\mu$  statistics of 15000 events (much bigger than in earlier CCFR and NuTeV samples).
- Systematics, nuclear corrections, etc. cancel in the ratio
- Pull down strange quarks at  $x > 0.1$  with a sizable uncertainty reduction

The semi-leptonic branching ratio  $B_\mu$  is a bottleneck

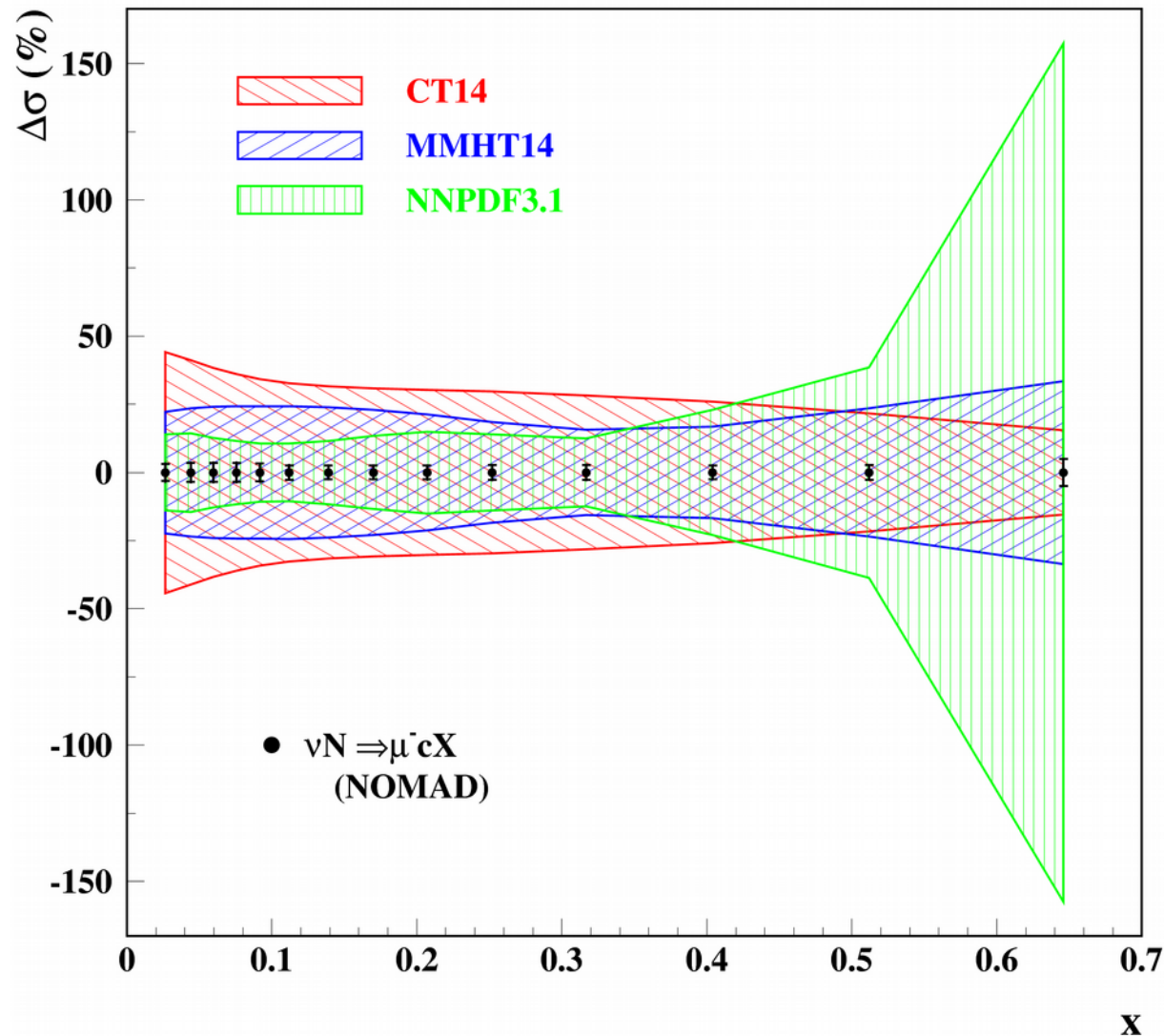
– weighted average of the charmed-hadron rates

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

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



# Impact of NOMAD data



- Evident room for the PDF improvement by adding NOMAD data to various PDF fits
- Big spread in the predictions  $\Rightarrow$  PDF4LHC averaging provides inefficient estimate

# 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

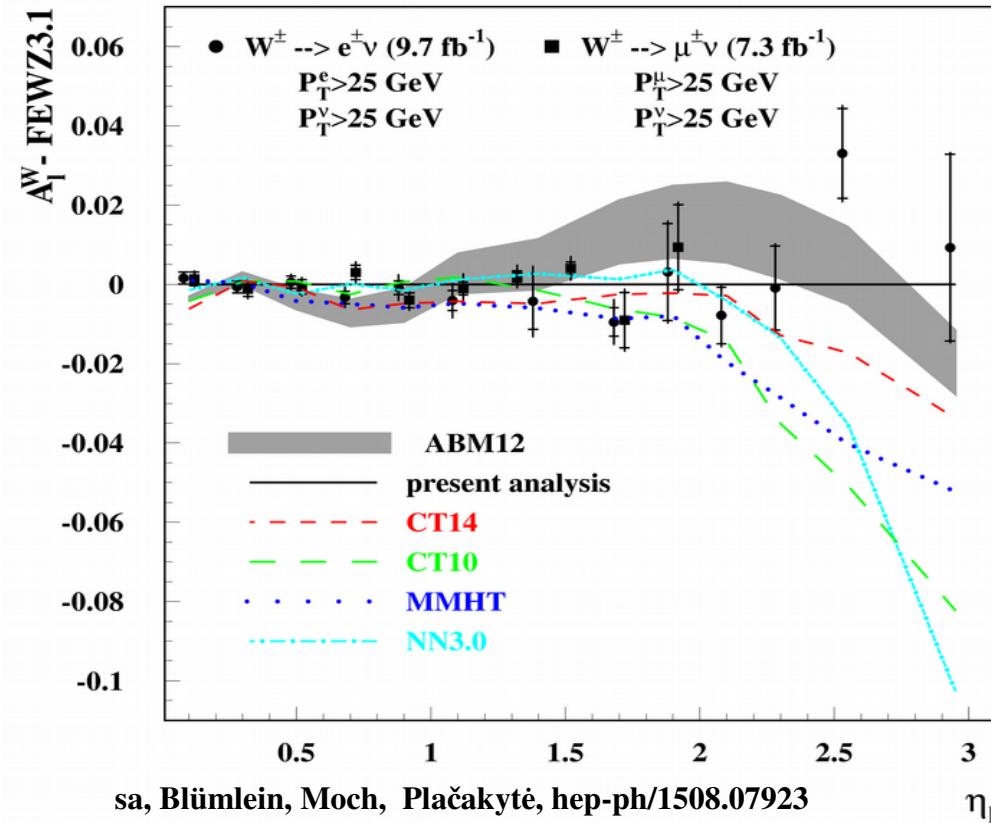
$\mathbf{E}$  – error matrix

$\mathbf{P}$  – current value of the PDF parameters in the fit

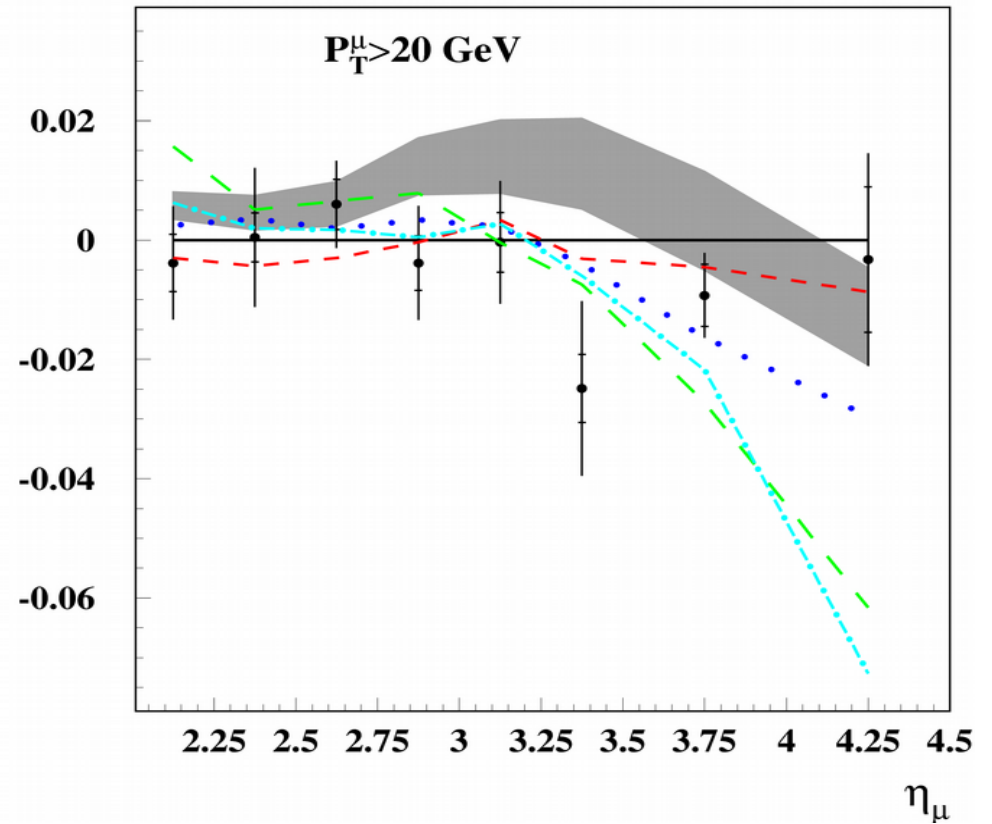
- store the DY NNLO c.s. for all PDF sets defined by the eigenvectors of  $\mathbf{E}$
- the variation of the fitted PDF parameters ( $\mathbf{P} - \mathbf{P}_0$ ) is transformed into this eigenvector basis
- the NNLO c.s. in the PDF fit is calculated as a combination of transformed ( $\mathbf{P} - \mathbf{P}_0$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

# DY at large rapidity

D0 (1.96 TeV)



LHCb (7 TeV,  $1 \text{ fb}^{-1}$ )



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

ABM

Interpolation of accurate NNLO grid (a la FASTNLO)

CT

NNLL (ResBos)

MMHT

NLO + NNLO K-factor

NNPDF

NLO + NNLO C-factors (y-dependent K-factors)

# DY data selection in the ABMP16 fit

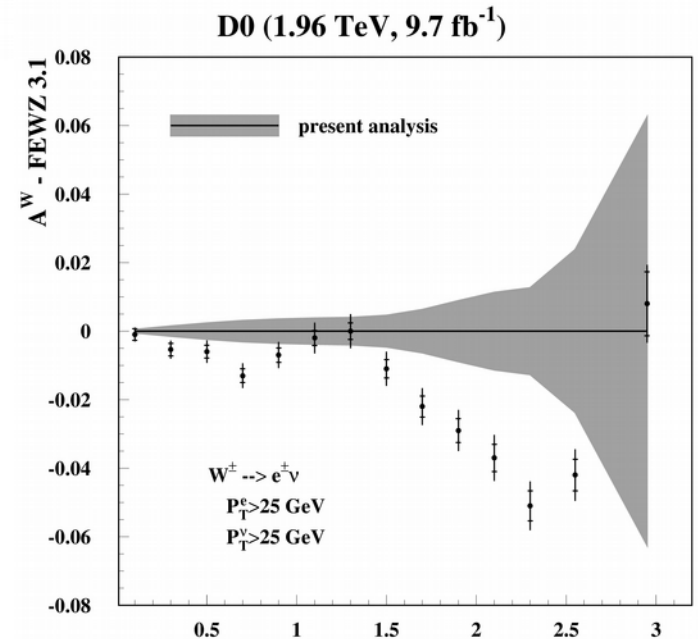
Experiment	ATLAS		CMS		DØ		LHCb			
$\sqrt{s}$ (TeV)	7	13	7	8	1.96		7	8		
Final states	$W^+ \rightarrow l^+ \nu$ $W^- \rightarrow l^- \nu$ $Z \rightarrow l^+ l^-$	$W^+ \rightarrow l^+ \nu$ $W^- \rightarrow l^- \nu$ $Z \rightarrow l^+ l^-$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ (asym)	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ (asym)	$W^+ \rightarrow e^+ \nu$ $W^- \rightarrow e^- \nu$ (asym)	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ $Z \rightarrow \mu^+ \mu^-$	$Z \rightarrow e^+ e^-$	$W^+ \rightarrow \mu^+ \nu$ $W^- \rightarrow \mu^- \nu$ $Z \rightarrow \mu^+ \mu^-$	
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	
NDP	30	6	11	22	10	13	31(33) <sup>a</sup>	17	32(34)	
	ABMP16	31.0	9.2	22.4	16.5	17.6	19.0	45.1(54.4)	21.7	40.0(59.2)
	CJ15	–	–	–	–	20	29	–	–	–
	CT14	42	–	– <sup>b</sup>	–	–	34.7	–	–	–
	HERAFitter	–	–	–	–	13	19	–	–	–
	MMHT16	39 <sup>c</sup>	–	–	21	21 <sup>c</sup>	26	(43)	29	(59)
	NNPDF3.1	29	–	19	–	16	35	(59)	19	(47)

<sup>a</sup> The values of NDP and  $\chi^2$  correspond to the unfiltered samples.

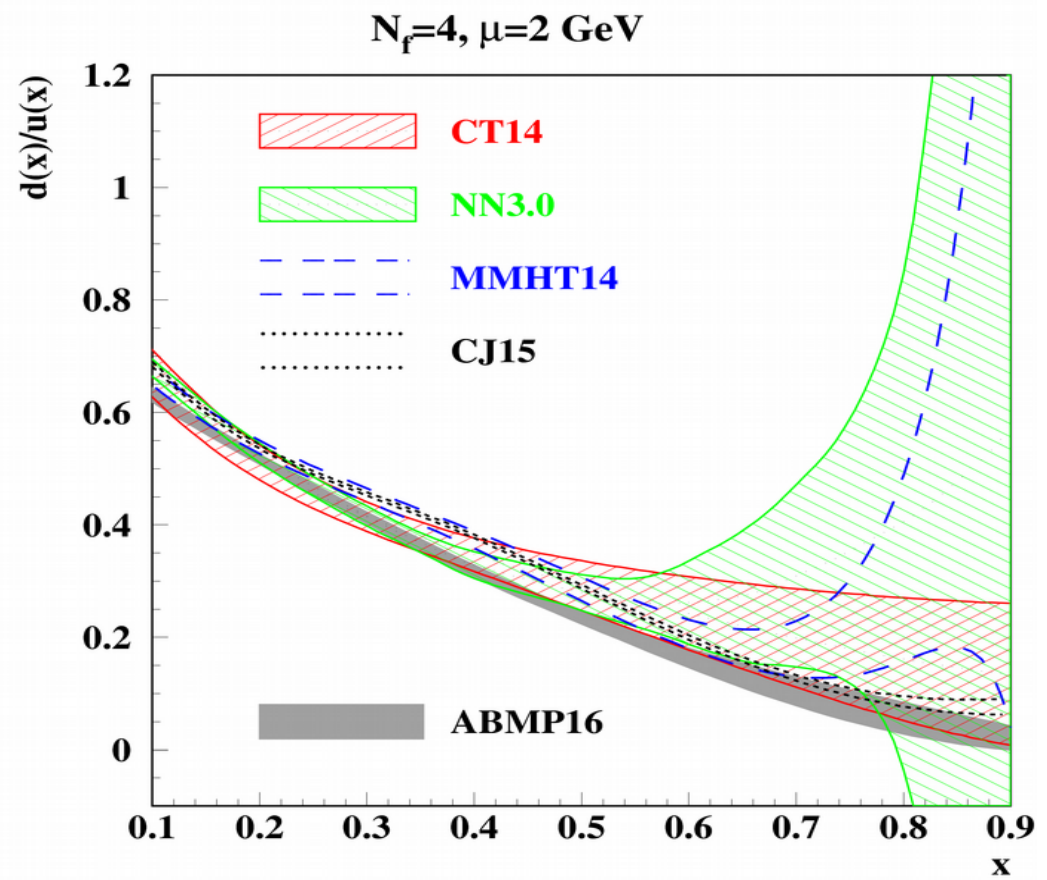
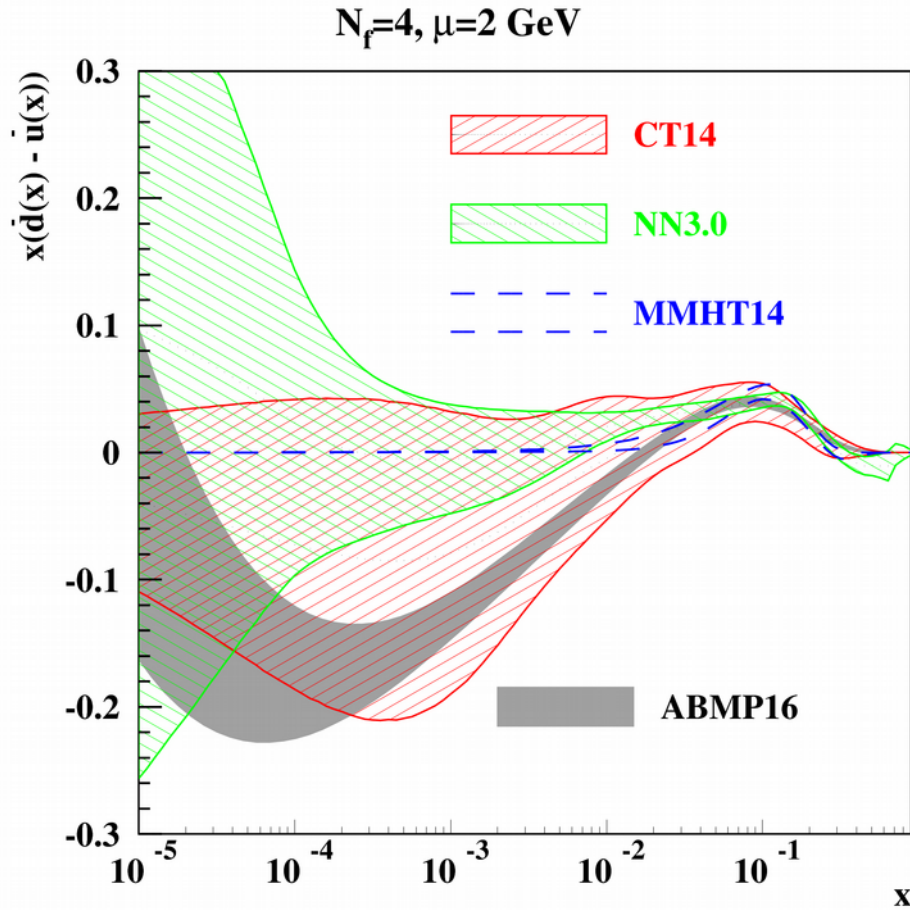
<sup>b</sup> For the statistically less significant data with the cut of  $P_T^\mu > 35$  GeV the value of  $\chi^2 = 12.1$  was obtained.

<sup>c</sup> The value obtained in MMHT14 fit.

- Many early low-statistical Tevatron and LHC data are not included into the fit
- The D0 sample for the charge-lepton asymmetry is preferred as compared to the W-asymmetry: smaller sensitivity to the modeling details; might even introduce a bias due to data sets' discrepancy



# Comparison of various PDF fits

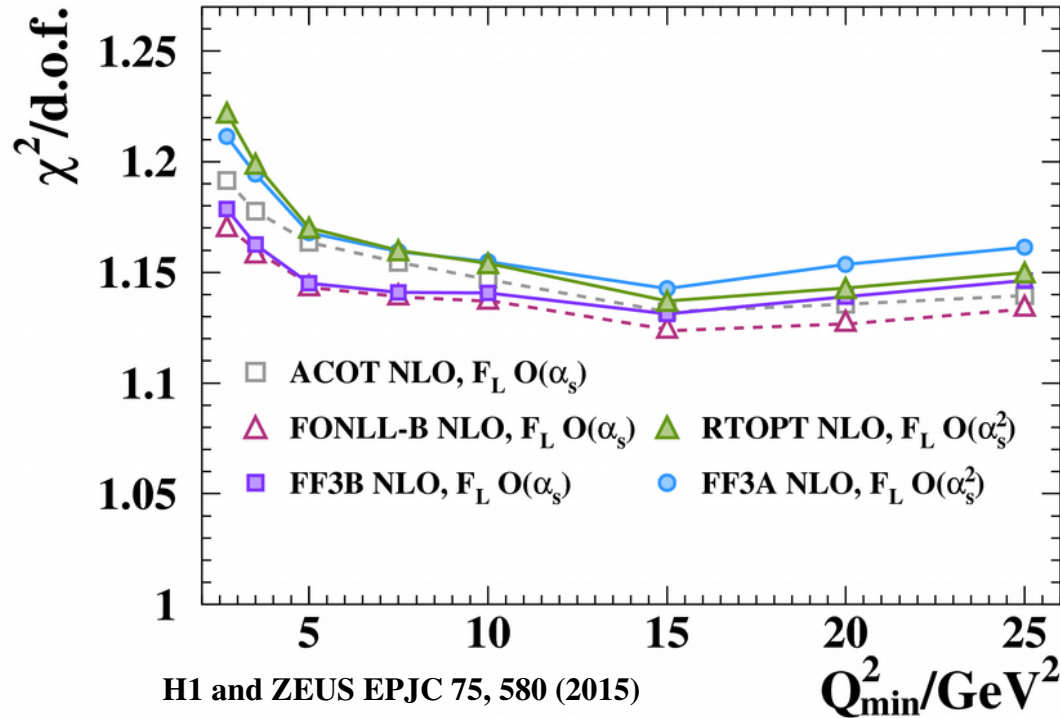


- Relaxed form of the sea iso-spin asymmetry  $I(x)$  at small  $x$ ; Regge-like behaviour is recovered only at  $x \sim 10^{-6}$ ; at large  $x$  it is still defined by the phase-space constraint
  - Big spread between different PDF sets, up to factor of 30 at large  $x$   $\rightarrow$  poor control of the BSM effects without constraints from the DY data
  - Good constraint on the  $d/u$  ratio w/o deuteron data  $\rightarrow$  independent extraction of the deuteron corrections
- Accardi, Brady, Melnitchouk, Owens, Sato PRD 93, 114017 (2016)



# Factorization scheme benchmarking

## H1 and ZEUS



- 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

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

PDF sets	$m_c$ [GeV]	$m_c$ renorm. scheme	theory method ( $F_2^c$ scheme)	theory accuracy for heavy quark DIS Wilson coeff.	$\chi^2$ /NDP for HERA data [127] with xFitter [128, 129]	
ABM12 [2] <sup>a</sup>	$1.24^{+0.05}_{-0.03}$	$\overline{\text{MS}}$ $m_c(m_c)$	FFNS ( $n_f = 3$ )	NNLO <sub>approx</sub>	65/52	66/52
CJ15 [1]	1.3	$m_c^{\text{pole}}$	SACOT [122]	NLO	117/52	117/52
CT14 [3] <sup>b</sup>	(NLO)	$m_c^{\text{pole}}$	SACOT( $\chi$ ) [123]	NLO	51/47	70/47
	(NNLO)	$m_c^{\text{pole}}$	SACOT( $\chi$ ) [123]	NLO	64/47	130/47
HERAPDF2.0 [4]	(NLO)	$m_c^{\text{pole}}$	RT optimal [125]	NLO	67/52	67/52
	(NNLO)	$m_c^{\text{pole}}$	RT optimal [125]	NLO	62/52	62/52
JR14 [5] <sup>c</sup>	1.3	$\overline{\text{MS}}$ $m_c(m_c)$	FFNS ( $n_f = 3$ )	NNLO <sub>approx</sub>	62/52	62/52
MMHT 14 [6]	(NLO)	$m_c^{\text{pole}}$	RT optimal [125]	NLO	72/52	78/52
	(NNLO)	$m_c^{\text{pole}}$	RT optimal [125]	NLO	71/52	83/52
NNPDF3.0 [7]	(NLO)	$m_c^{\text{pole}}$	FONLL-B [124]	NLO	58/52	60/52
	(NNLO)	$m_c^{\text{pole}}$	FONLL-C [124]	NLO	67/52	69/52
PDF4LHC15 [8] <sup>d</sup>	–	–	FONLL-B [124]	–	58/52	64/52
	–	–	RT optimal [125]	–	71/52	75/52
	–	–	SACOT( $\chi$ ) [123]	–	51/47	76/47

*No advantage of the GMVFN schemes: the VFN  $\chi^2$  values are systematically bigger than the FFN ones*

Accardi, et al. hep-ph/1603.08906

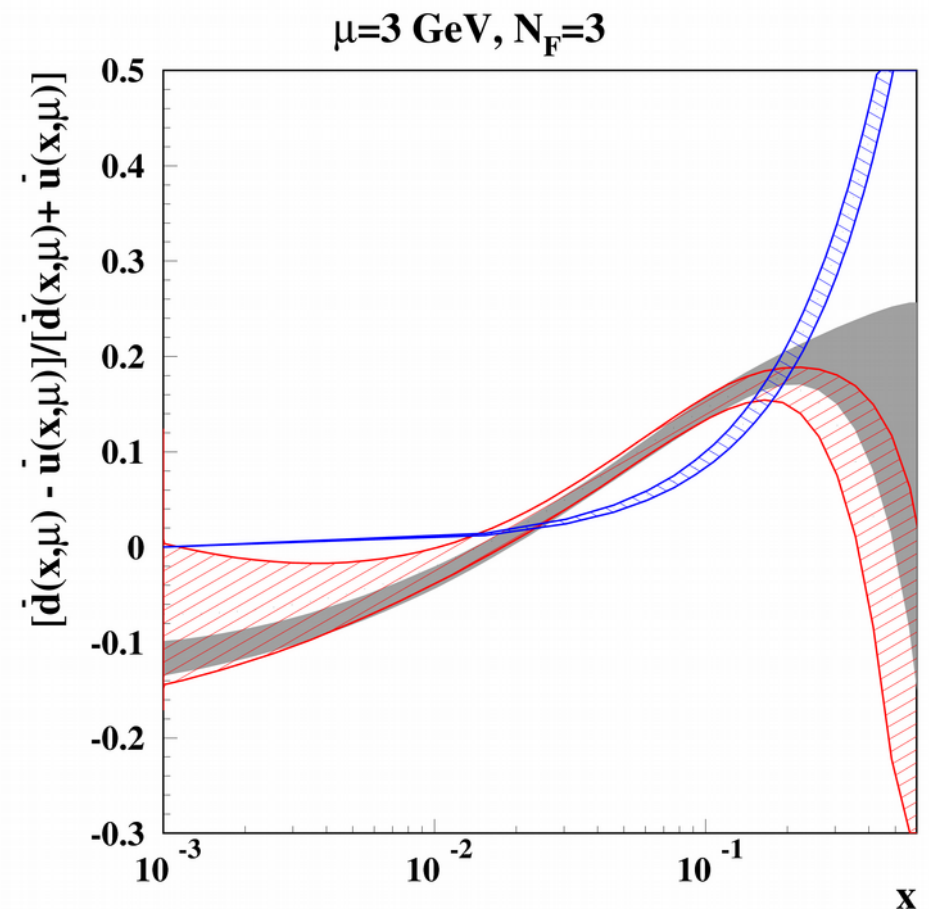
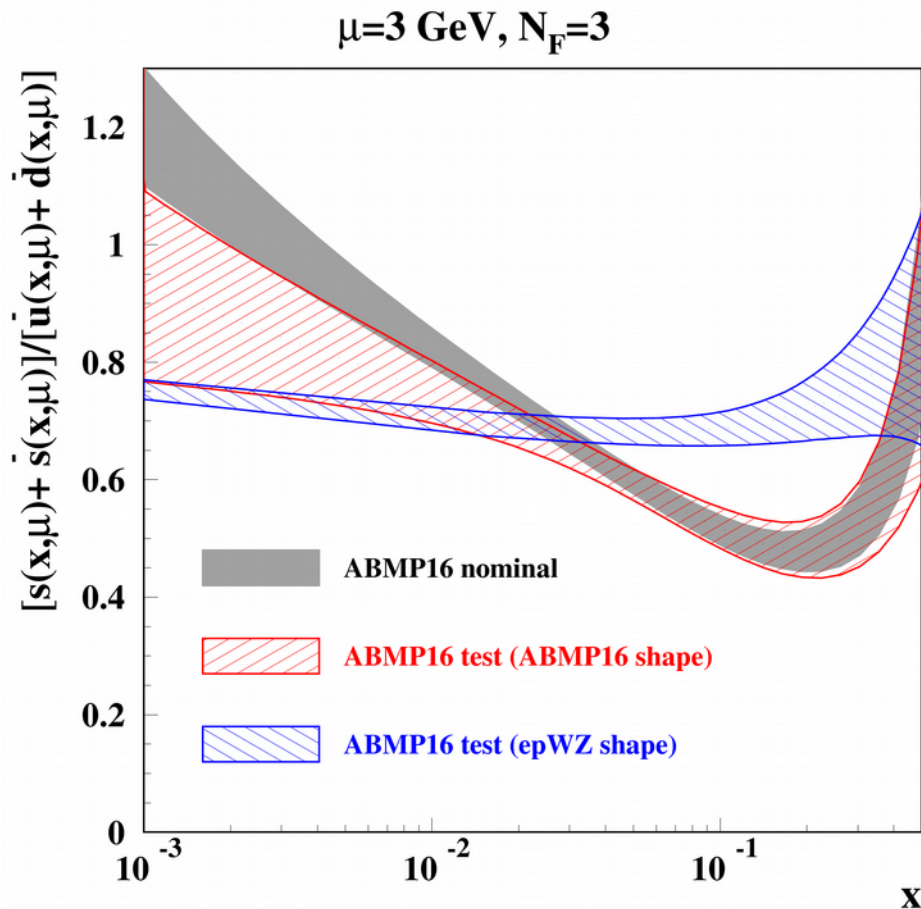
# Charm quark mass and the Higgs cross section

## MMHT

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

$m_c^{\text{pole}}$ [GeV]	$\alpha_s(M_Z)$ (best fit)	$\chi^2/\text{NDP}$ (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	<b>75/52</b>	<b>40.89</b>	(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	<b>82/52</b>	41.56	<b>(42.36)</b>
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)

# Test fit (the PDF shape comparison)



The data used in test fit: collider data discarded and replaced by the deuteron ones  
 (fit is consistent with the nominal ABMP16 at  $x > 0.01$ ) sa, Kulagin, Petti hep-ph/1704.00204

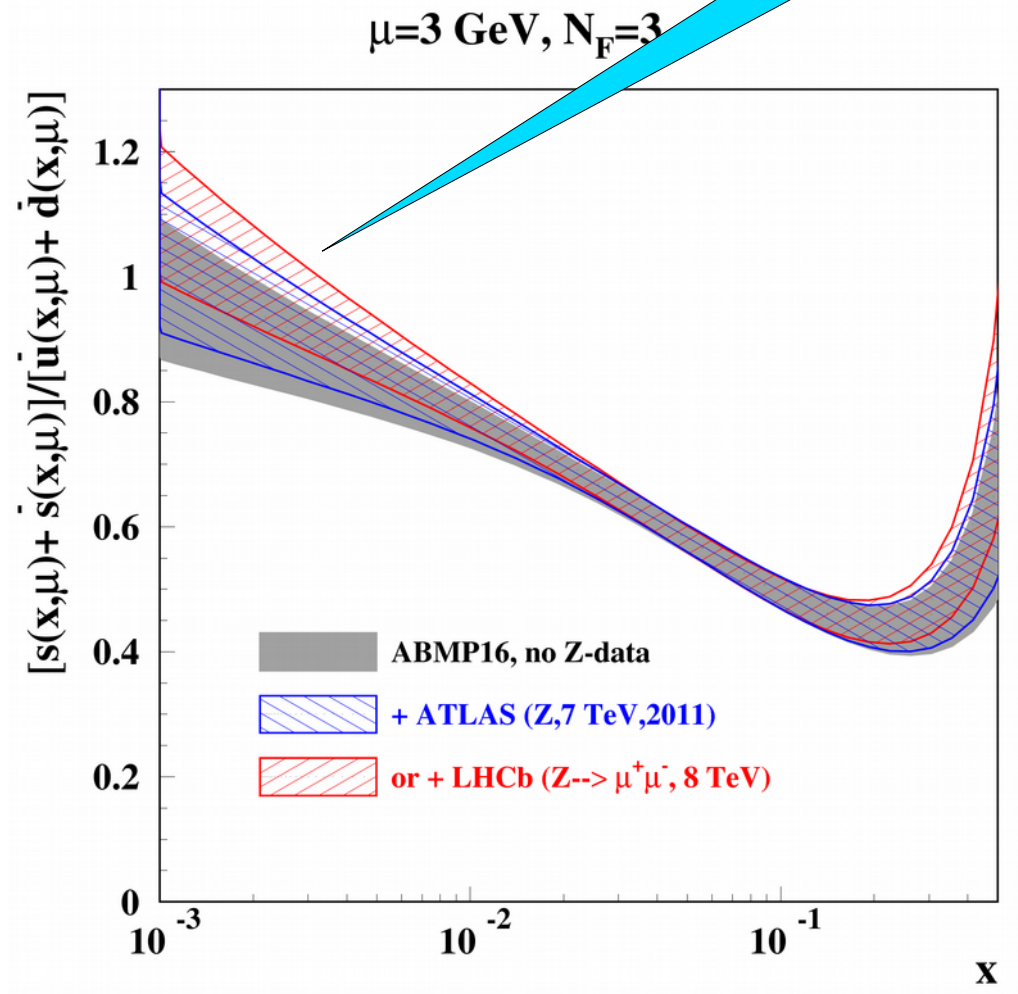
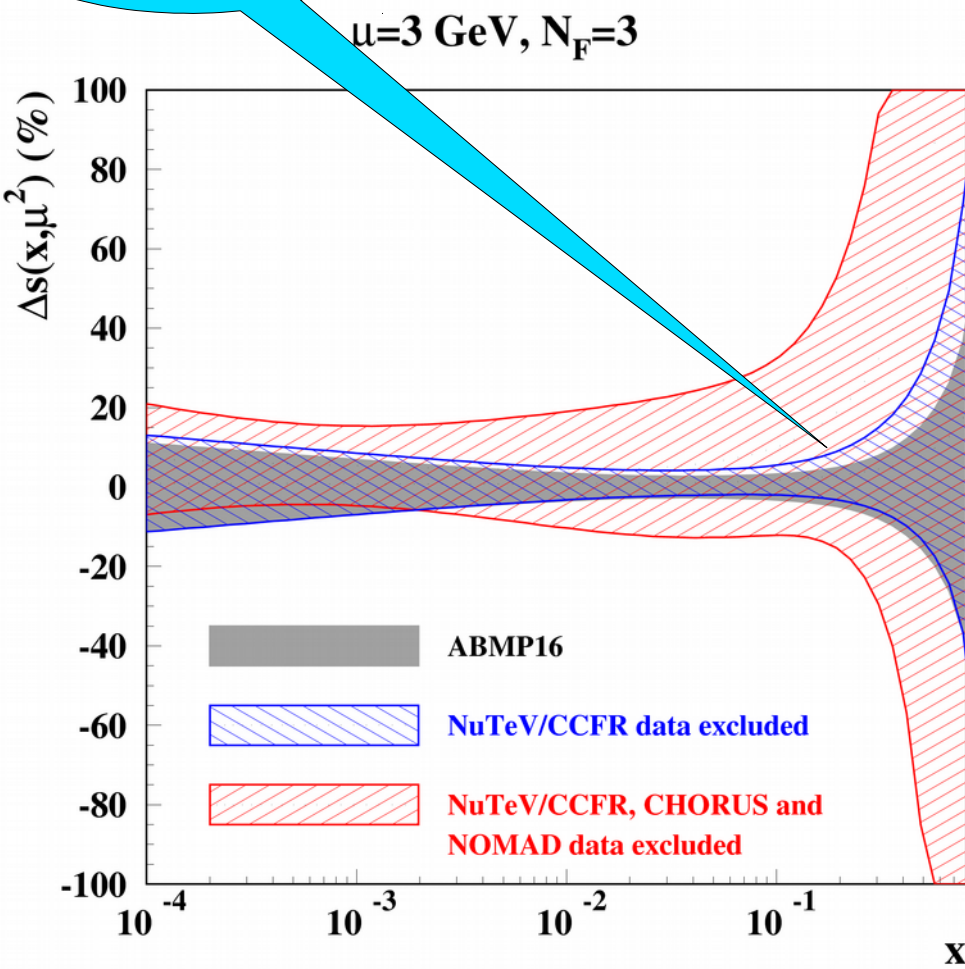
*The strange sea is enhanced for the epWZ shape despite the ATLAS data are not used. However, the dimuon data description is not deteriorated:  $\chi^2=167$  versus 161 for the ABMP shape  $\Rightarrow$  enhancement is achieved by the price of the d-quark sea suppression*

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

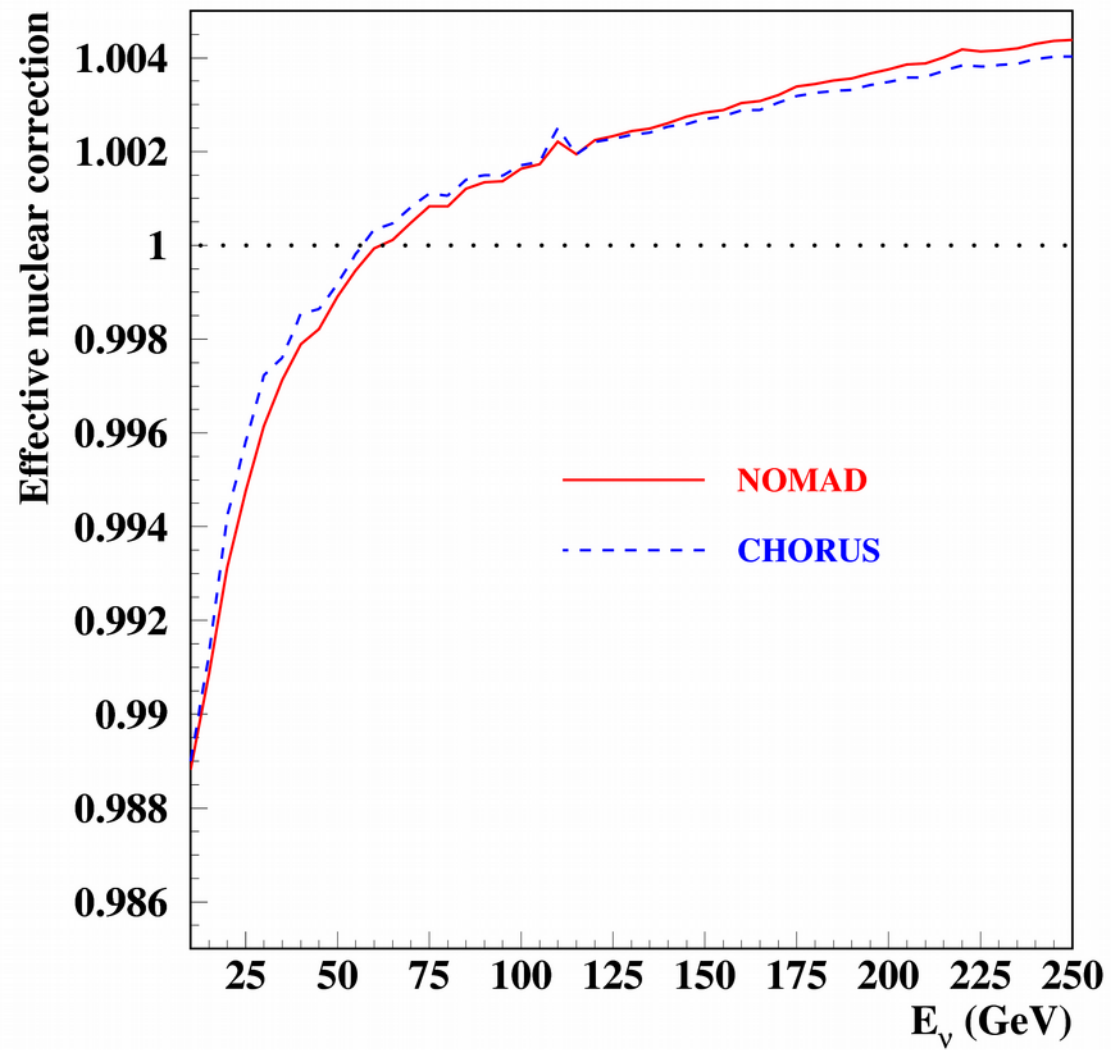
# Constraints on strange sea

Controlled by  
NOMAD

Controlled by  
DY&DIS(incl.)

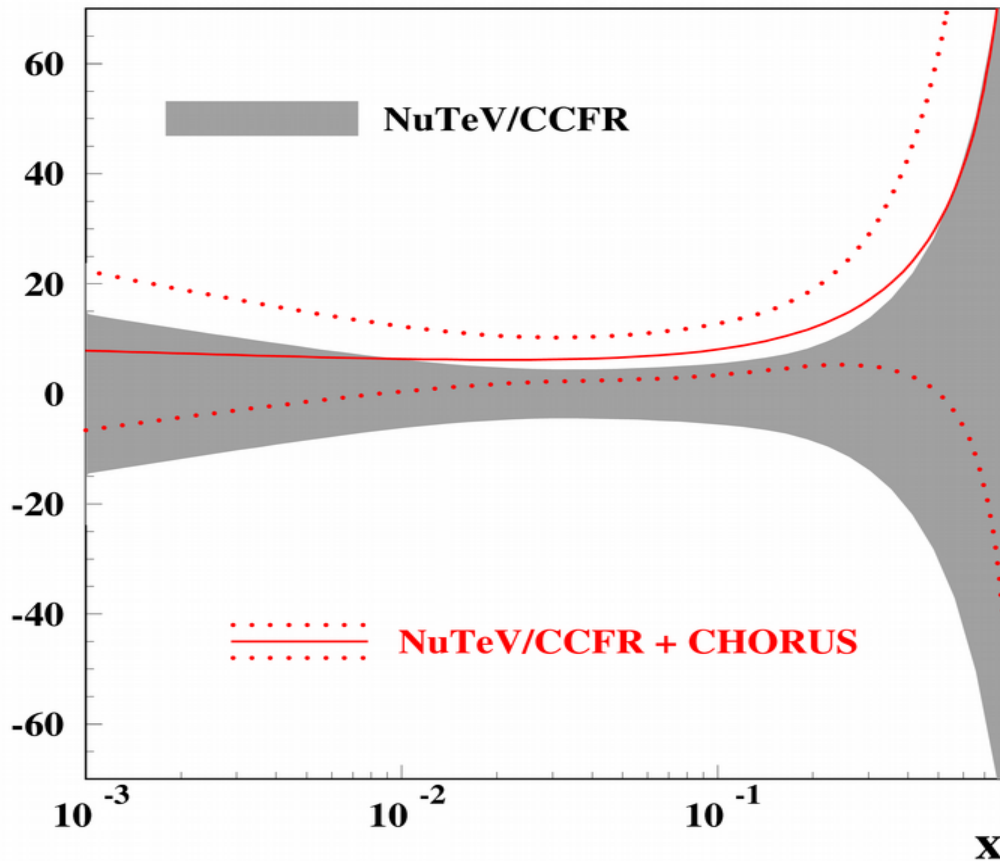


- Uncertainty of  $\sim 5\%$  is achieved at  $x$  around 0.1
- NuTeV/CCFR data play no essential role  $\rightarrow$  impact of the nuclear corrections is greatly reduced (NOMAD and CHORUS give the ratio CC/incl.)



# CHORUS charm data

$\mu=3 \text{ GeV}, n_f=3$



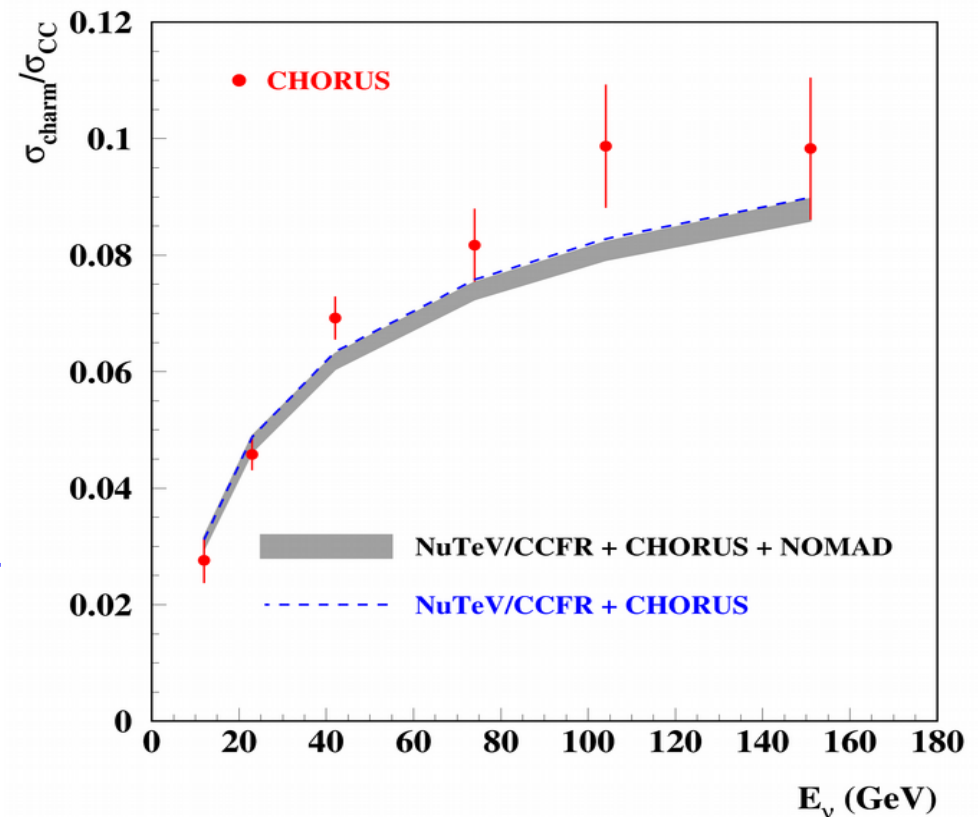
CHORUS data pull strangeness up, however the statistical significance of the effect is poor

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

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

CHORUS NJP 13, 093002 (2011)

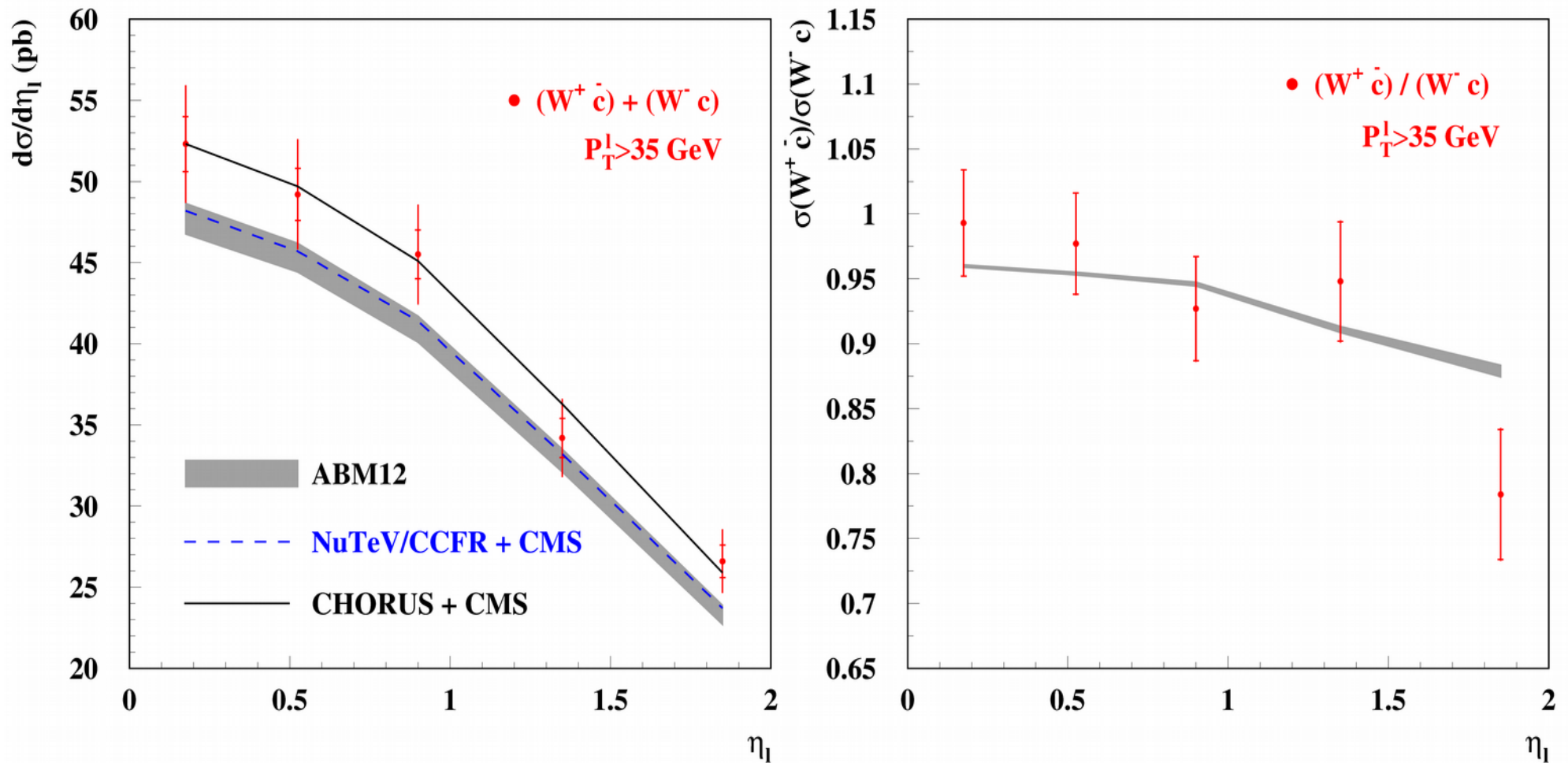
- full phase space measurements
- no sensitivity to  $B_\mu$
- low statistics (2013 events)



# CMS W+charm data

CMS Collaboration JHEP 02, 013 (2014)

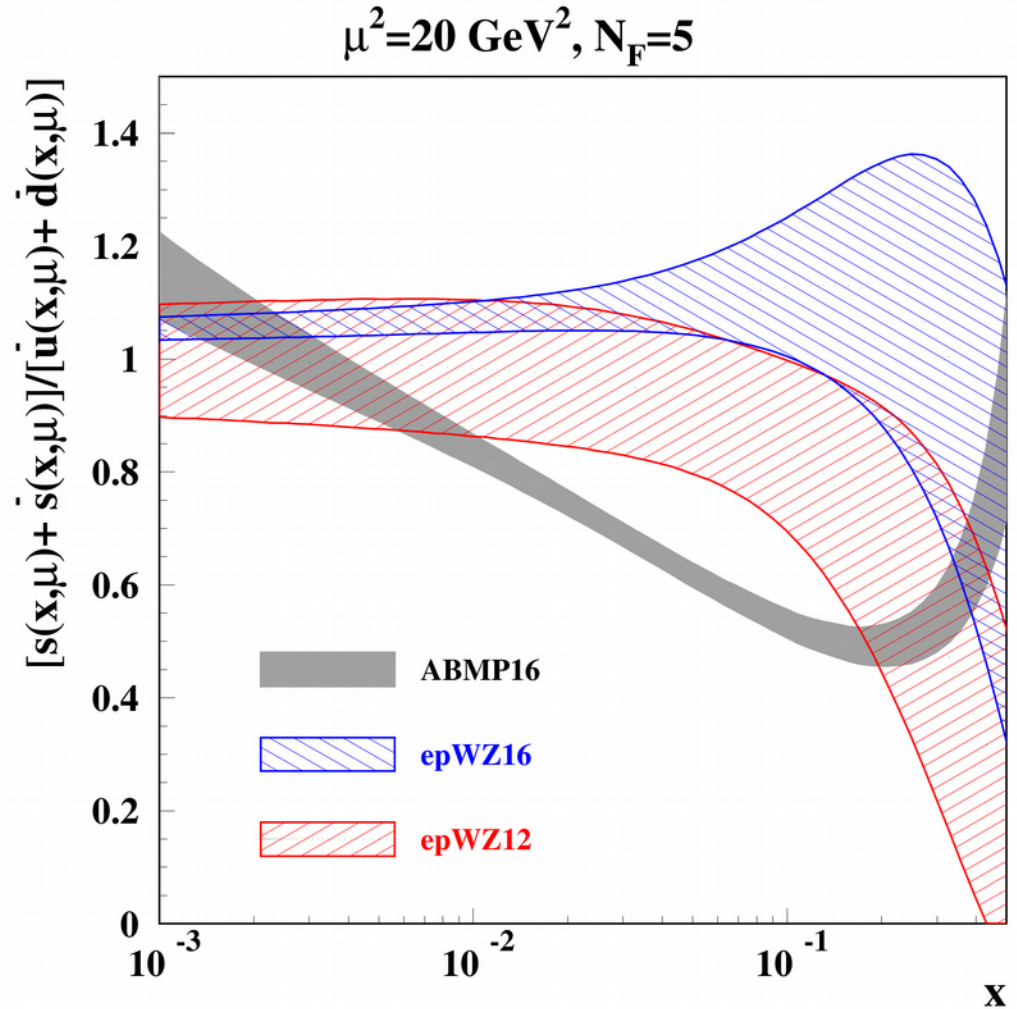
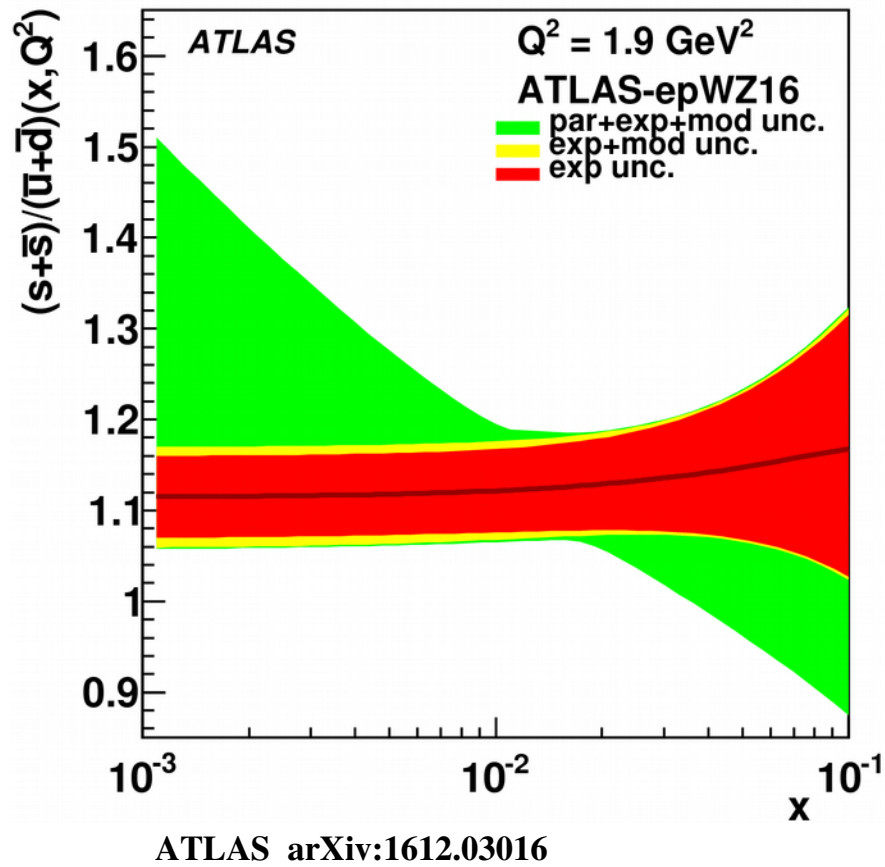
CMS (7 TeV, 5 1/fb)



- CMS data go above the NuTeV/CCFR by  $1\sigma$ ; 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 strange enhancement



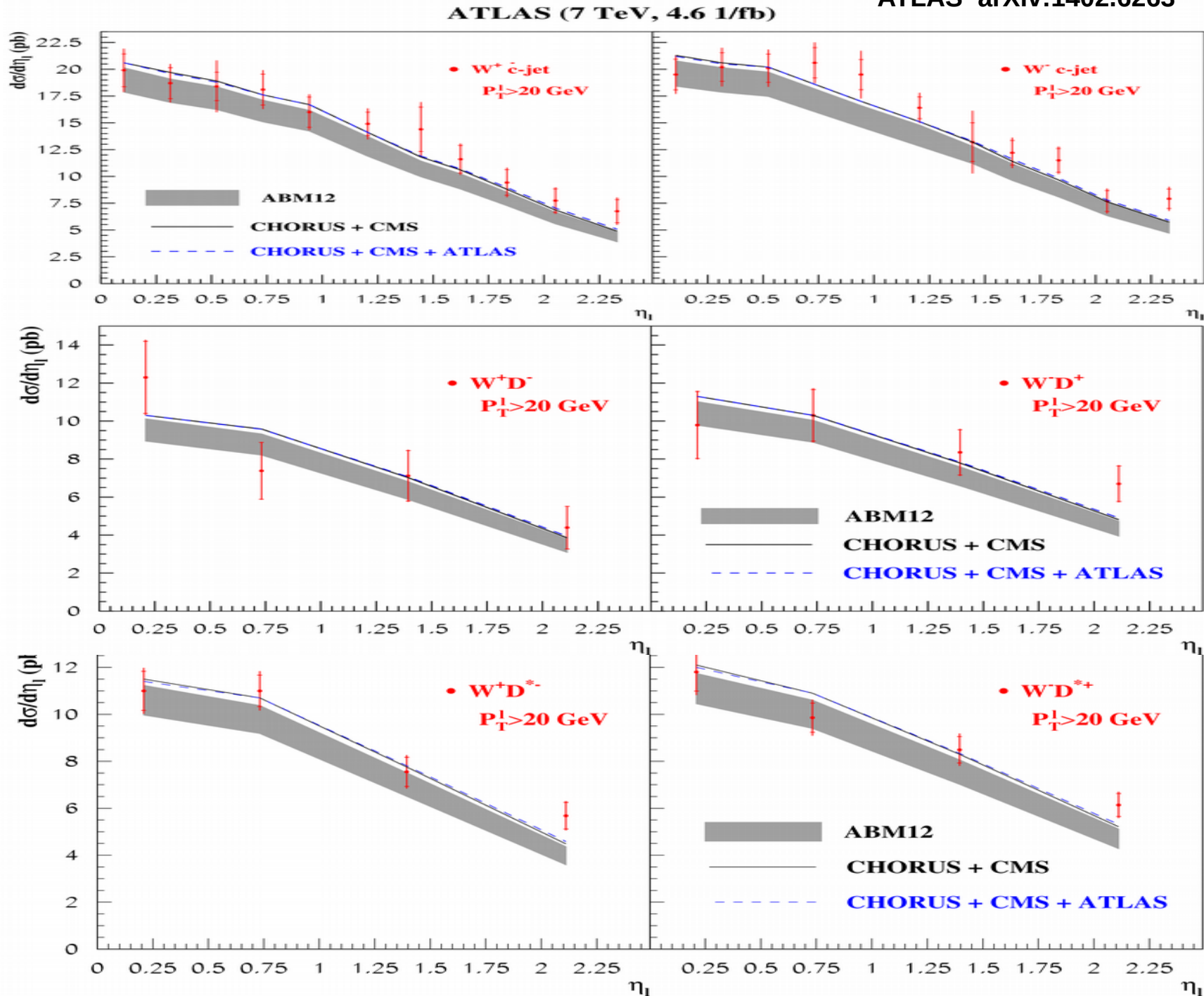
The epWZ16 strange-sea determined from analysis of the combined HERA-ATLAS data is enhanced as compared to other (earlier) determinations

ABM strange sea determination is in particular based on the dimuon neutrino-nucleon DIS production (NuTeV/CCFR and NOMAD) that gives a strange sea suppression  $\sim 0.5$  at  $x \sim 0.2$

- Disentangling  $d$ - and  $s$ - contribution?
- Impact of the nuclear corrections?
- .....?

# ATLAS W+charm data

ATLAS arXiv:1402.6263

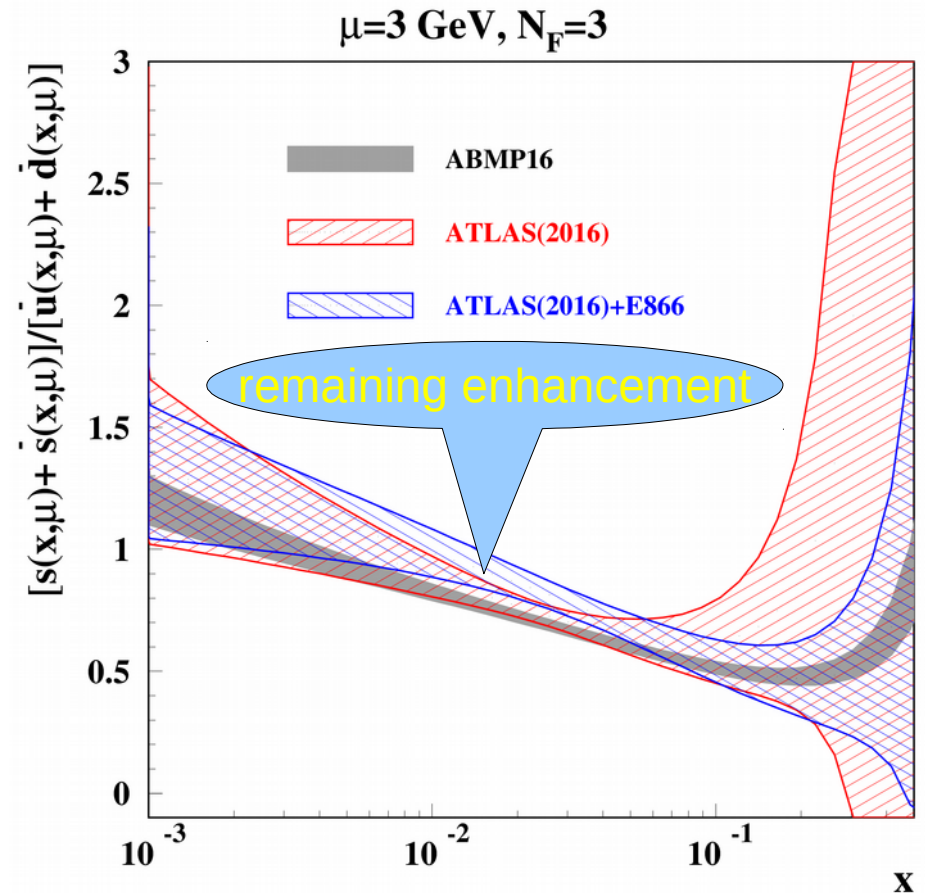


# Impact of ATLAS data with flexible PDF shape

	$\kappa_s(\mu^2=20 \text{ GeV}^2)$
HERA+ATLAS	0.81(18)
HERA+ATLAS+E866	0.72(8)
ABMP16(incl. NOMAD)	0.66(3)

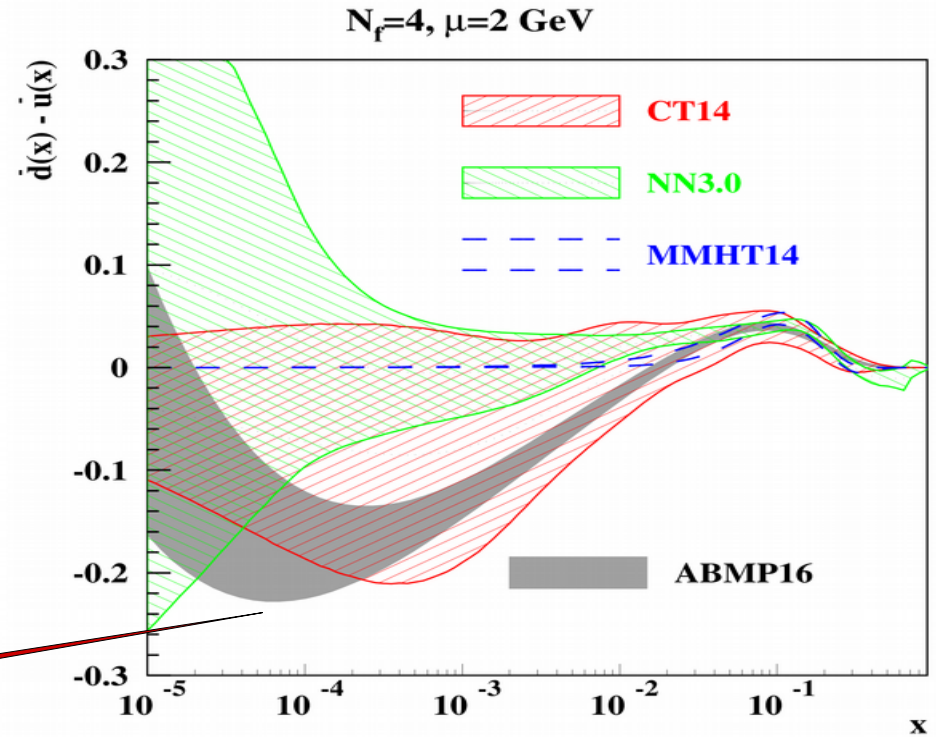
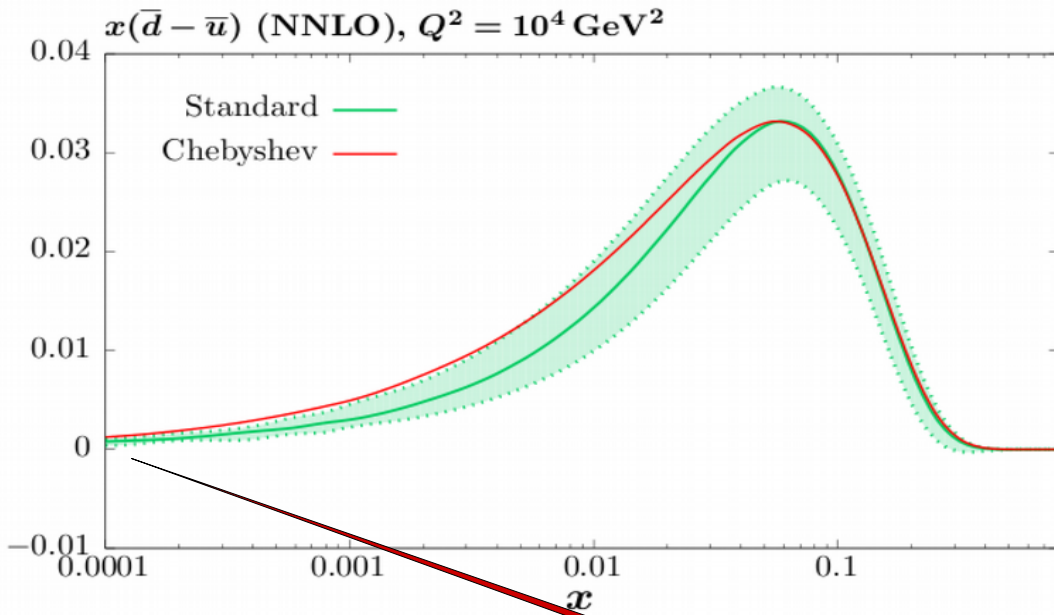
$\kappa_s$  is integral strange sea suppression factor:

$$\kappa_s(\mu^2) = \frac{\int_0^1 x[s(x, \mu^2) + \bar{s}(x, \mu^2)]dx}{\int_0^1 x[\bar{u}(x, \mu^2) + \bar{d}(x, \mu^2)]dx},$$



- For the flexible PDF shape the strangeness is in a broad agreement with the one extracted from the dimuon data
- The E866 data are consistent with the ATLAS(2016) set:  $\chi^2/\text{NDP}=48/39$  and  $40/34$ , respectively.

$$(\bar{d} - \bar{u})(x, Q_0^2) = A(1 - x)^{\eta_{sea} + 2} x^\delta (1 + \sum_{i=1}^4 a_i T_i(1 - 2x^{\frac{1}{2}})),$$



Thorne, this conference

	no. points	NLO $\chi^2_{pred}$	NLO $\chi^2_{new}$	NNLO $\chi^2_{pred}$	NNLO $\chi^2_{new}$
$\sigma_{t\bar{t}}$ Tevatron +CMS+ATLAS	18	19.6	20.5	14.7	15.5
LHCb 7 TeV $W + Z$	33	50.1	45.4	37.1	36.7
LHCb 8 TeV $W + Z$	34	77.0	58.9	76.1	67.2
LHCb 8TeV $e$	17	37.4	33.4	30.0	27.8
CMS 8 TeV $W$	22	32.6	18.6	57.6	29.4
CMS 7 TeV $W + c$	10	8.5	10.0	8.7	8.0
D0 $e$ asymmetry	13	22.2	21.5	27.3	22.9
total	3738/3405	4375.9	4336.1	3768.0	3739.3

$$x u_s(x, \mu_0^2) = \bar{u}_s(x, \mu_0^2) = A_{us}(1-x)^{\eta_{us}} x^{\delta_{us}} \chi^{\alpha_{us} + \beta_{us} x^{\gamma_{us}}},$$

$$x d_s(x, \mu_0^2) = \bar{d}_s(x, \mu_0^2) = A_{ds}(1-x)^{\eta_{ds}} x^{\delta_{ds}} \chi^{\alpha_{ds} + \beta_{ds} x^{\gamma_{ds}}},$$

$\bar{d} \neq \bar{u}$  at small  $x$   
(the same applies for CT14)

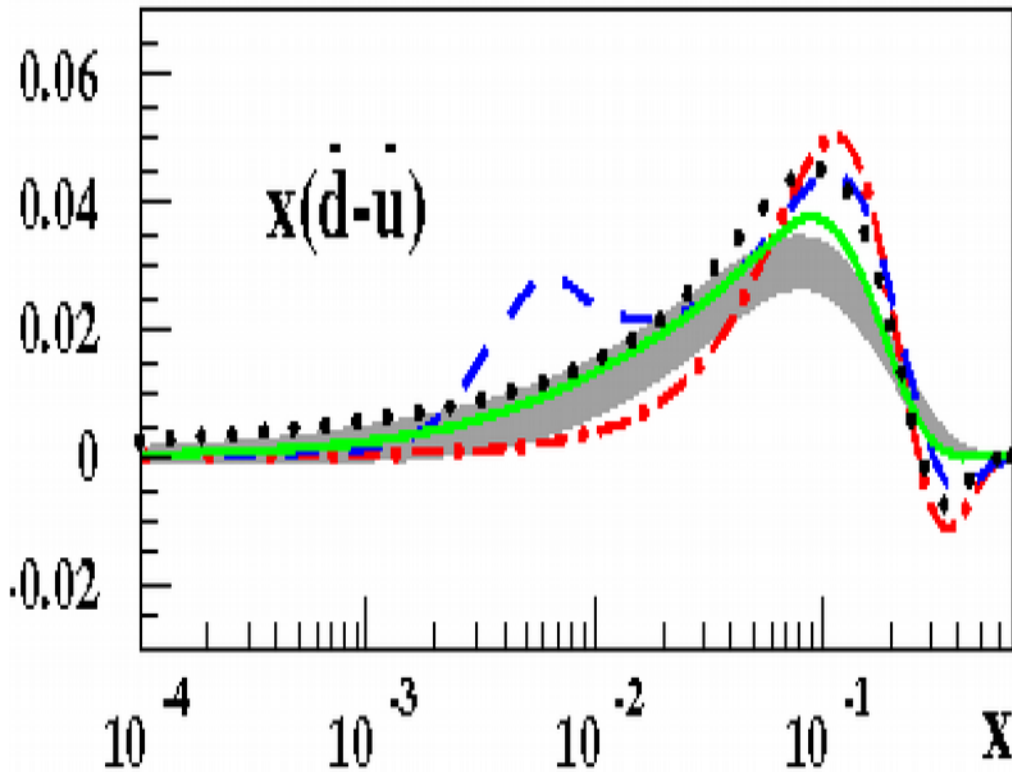
The sum of  $\chi^2/NDP$  for the DY data by LHCb, CMS, and D0 from the table:

184/119 (MMHT16)

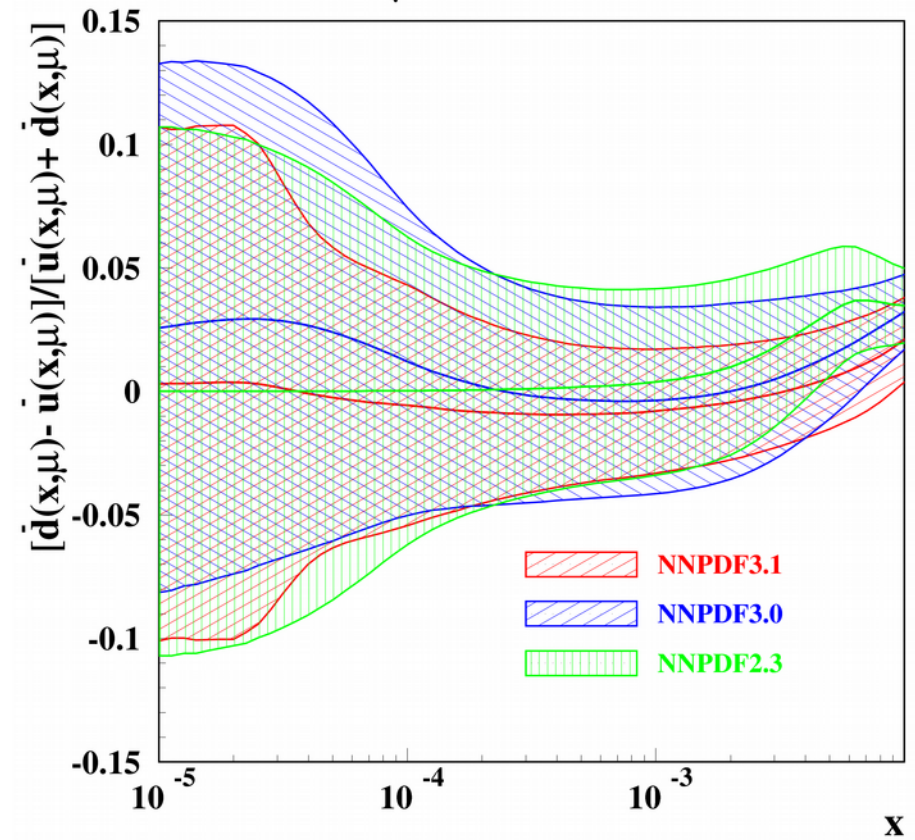
171/119 (ABMP16, no filtering), account of other DY data increases the difference

# Sea quark iso-spin asymmetry

$\mu=3 \text{ GeV}$



ABM12 CT10 JR09 MSTW08 NNPDF2.3



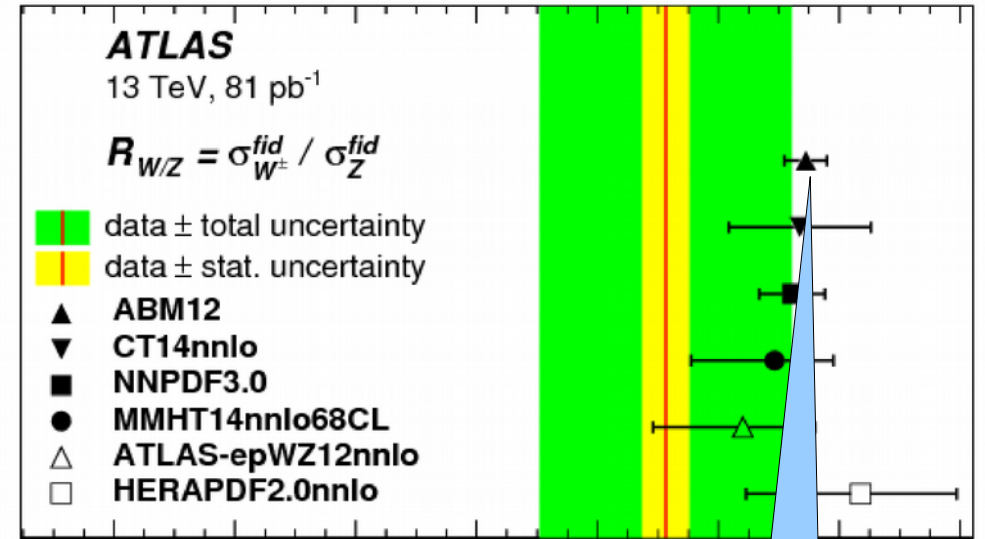
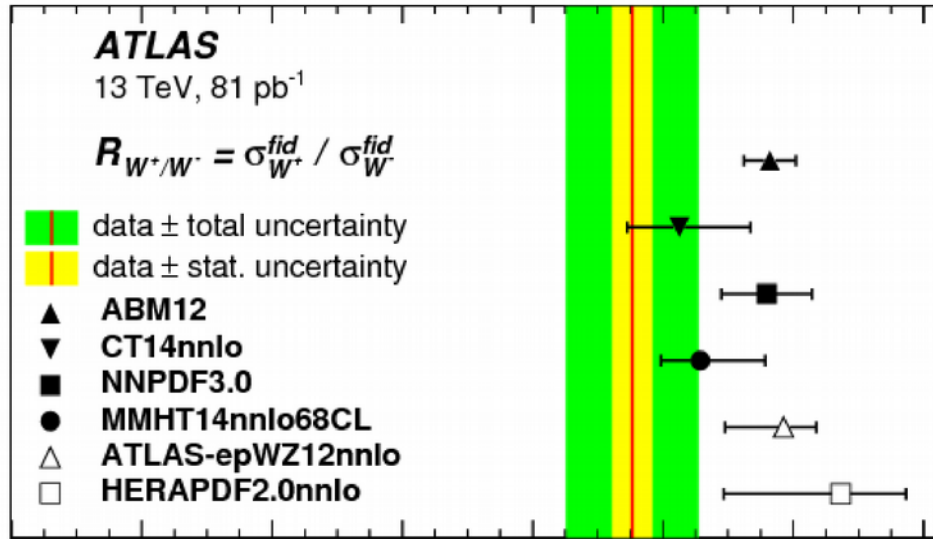
sa, Blümlein, Moch PRD 89, 054028 (2014)

- At  $x \sim 0.1$  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

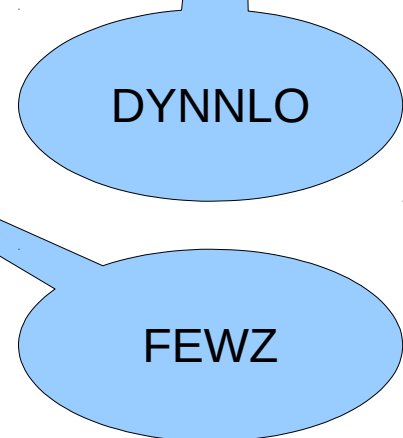
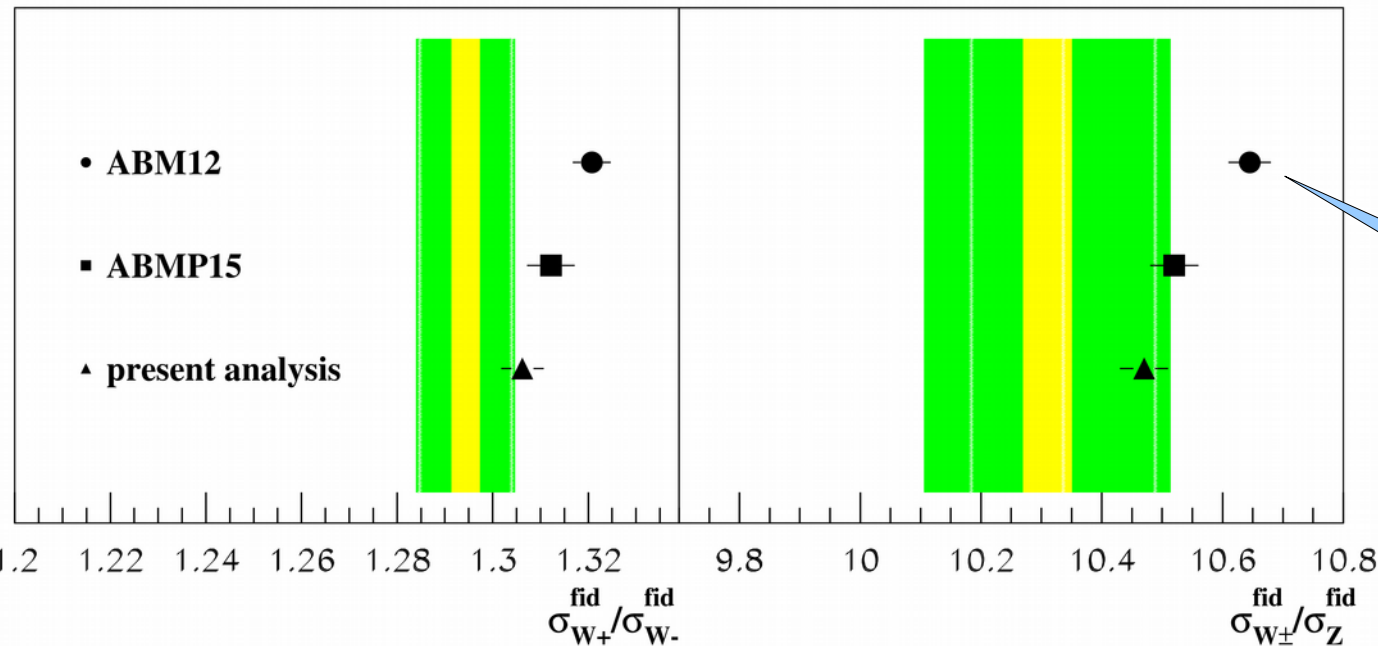
*Onset of the Regge asymptotics is out of control*

# ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222

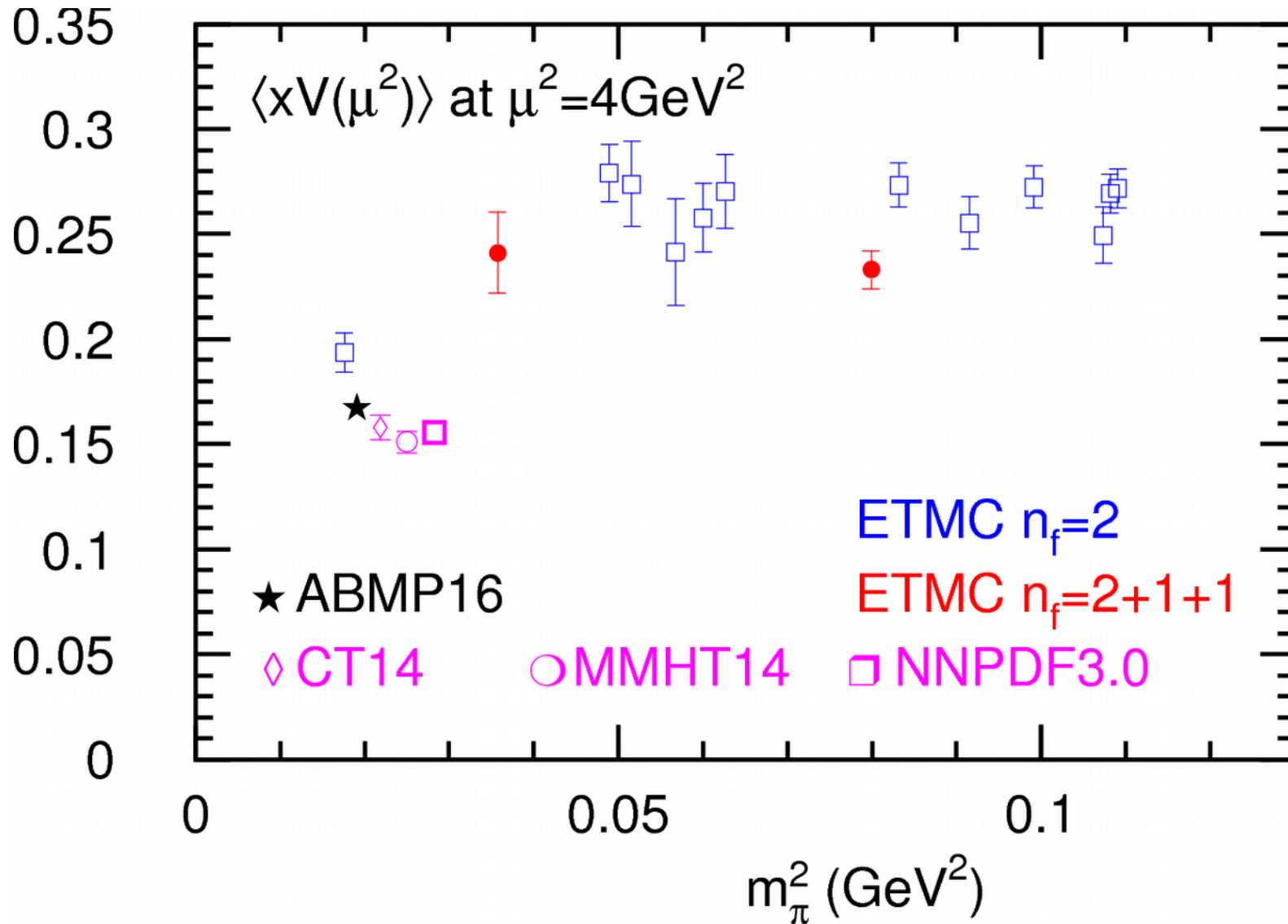


ATLAS (13 TeV, 81 pb<sup>-1</sup>) 1603.09222



Data are well accommodated into the fit  $\chi^2/NDP=9/6$

# Comparison with lattice results



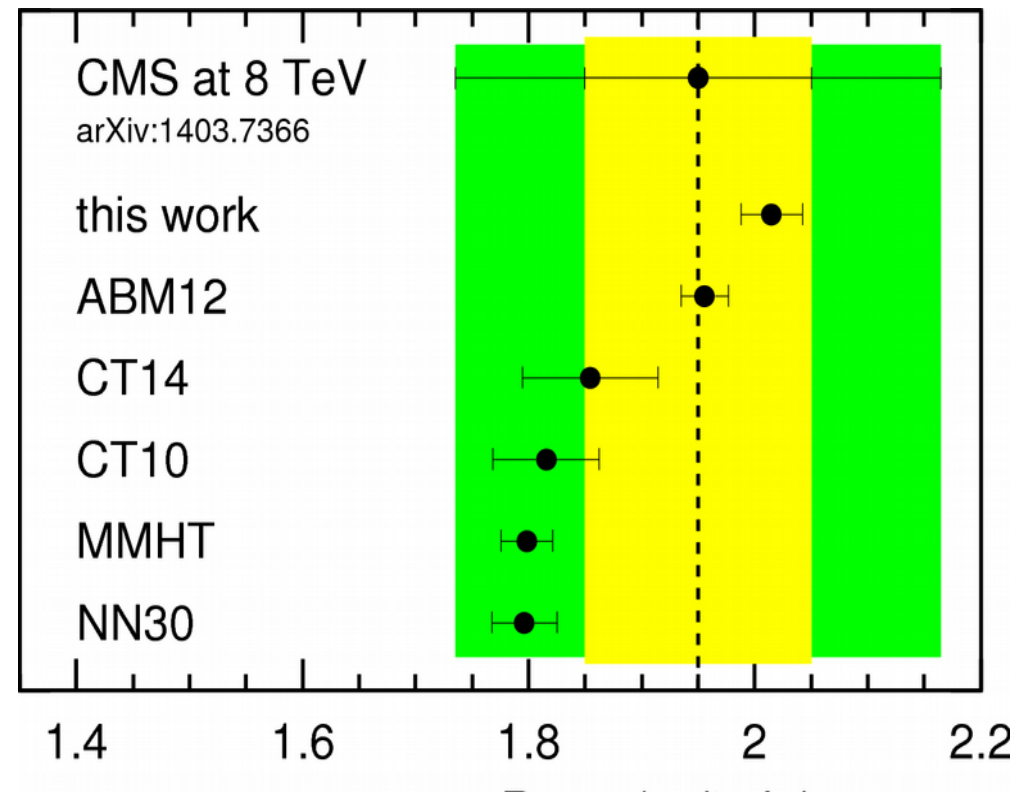
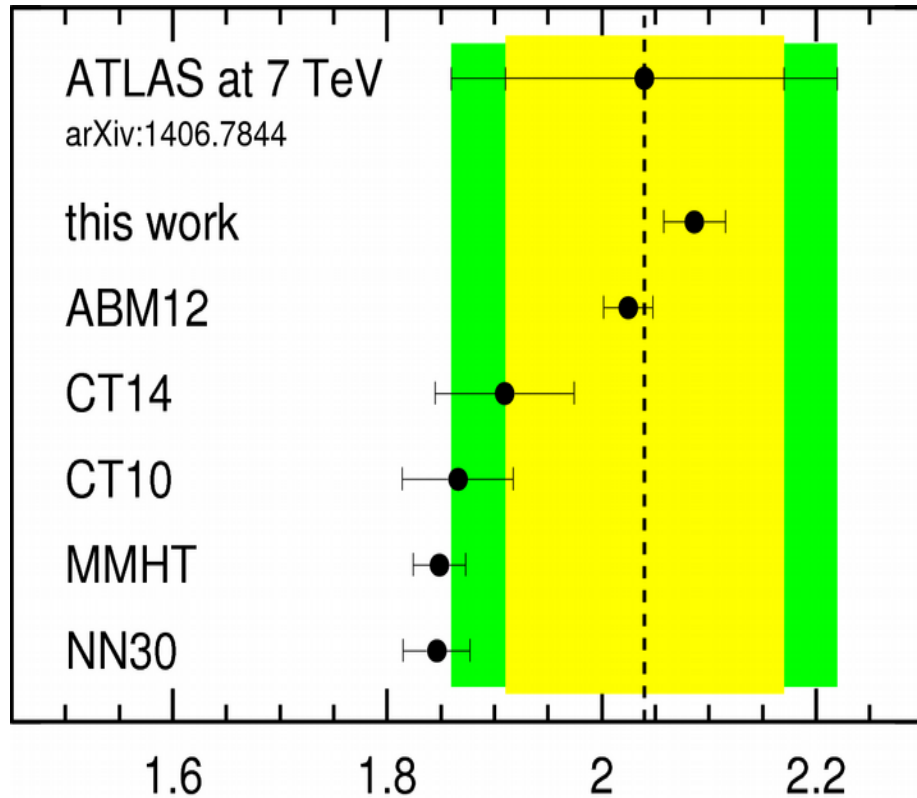
# Details of the epWZ and ABMP16 fits

	epWZ16	ABMP16
Data	HERA, ATLAS W&Z	HERA, LHC and Tevatron W&Z, fixed-target DIS and charm production, fixed-target DY, ....
PDF shape	$xu_v(x, \mu_0^2) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$ $xd_v(x, \mu_0^2) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$ $x\bar{u}(x, \mu_0^2) = A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}},$ $x\bar{d}(x, \mu_0^2) = A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}},$ $xg(x, \mu_0^2) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$ $x\bar{s}(x, \mu_0^2) = A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}},$ <p style="text-align: center;">15 free parameters</p>	$xq_v(x, \mu_0^2) = \frac{2\delta_{qu} + \delta_{qd}}{N_q^v} (1-x)^{b_{q^v}} x^{a_{q^v}} P_{q^v}(x),$ $xq_s(x, \mu_0^2) = A_{q_s} (1-x)^{b_{q_s}} x^{a_{q_s}} P_{q_s}(x),$ $xg(x, \mu_0^2) = A_g (1-x)^{b_g} x^{a_g} P_g(x),$ $P_p(x) = (1 + \gamma_{-1,p} \ln x) \left( 1 + \gamma_{1,p} x + \gamma_{2,p} x^2 + \gamma_{3,p} x^3 \right),$ <p style="text-align: center;">25 free parameters</p>

ABMP16 PDFs are selected more flexible in order to accommodate more data as compared to the EpWZ16 fit, which was evolved from the HERA data analysis



# Implication for(of) the single-top production



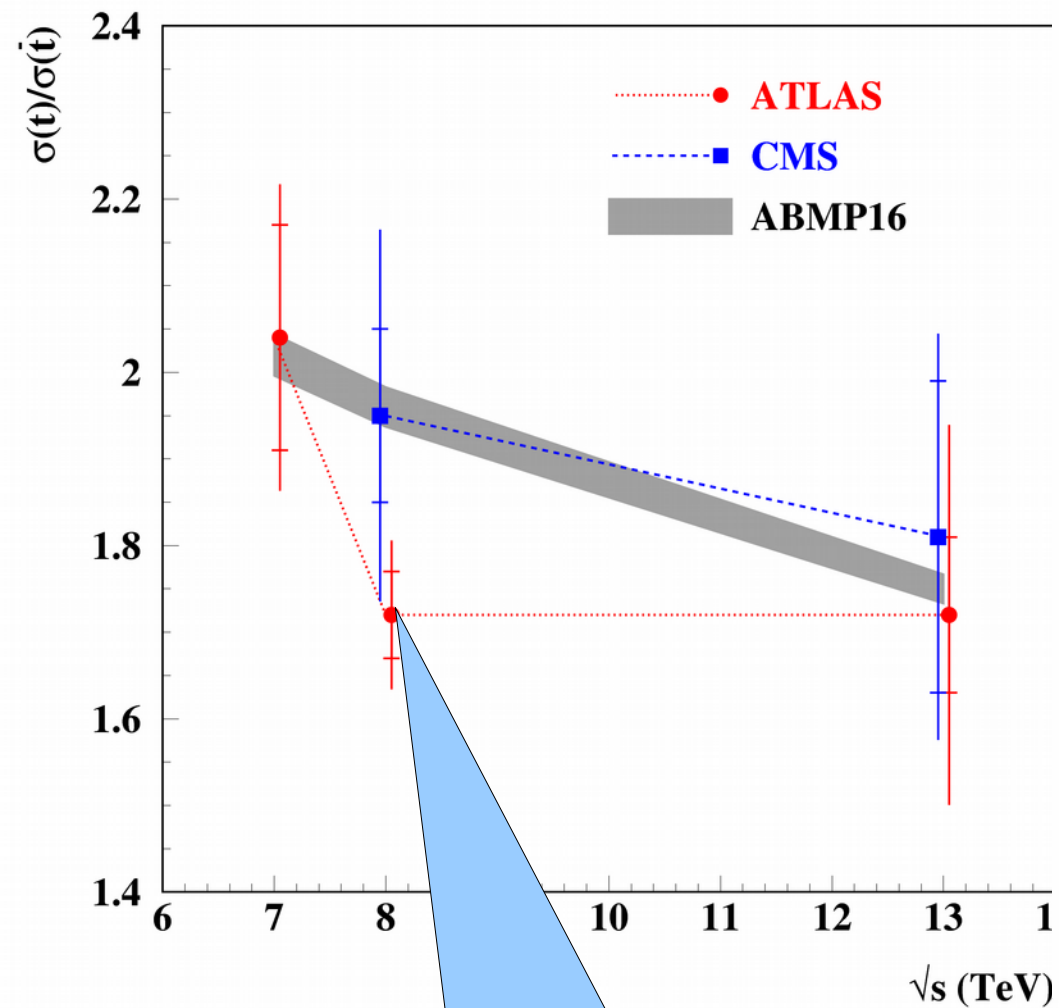
$$R_t = \sigma_t/\sigma_{\bar{t}} \text{ (t-ch.) } \text{ sa, Blümlein, Moch, Plačákytė hep-ph/1508.07923}$$

$$R_t = \sigma_t/\sigma_{\bar{t}} \text{ (t-ch.)}$$

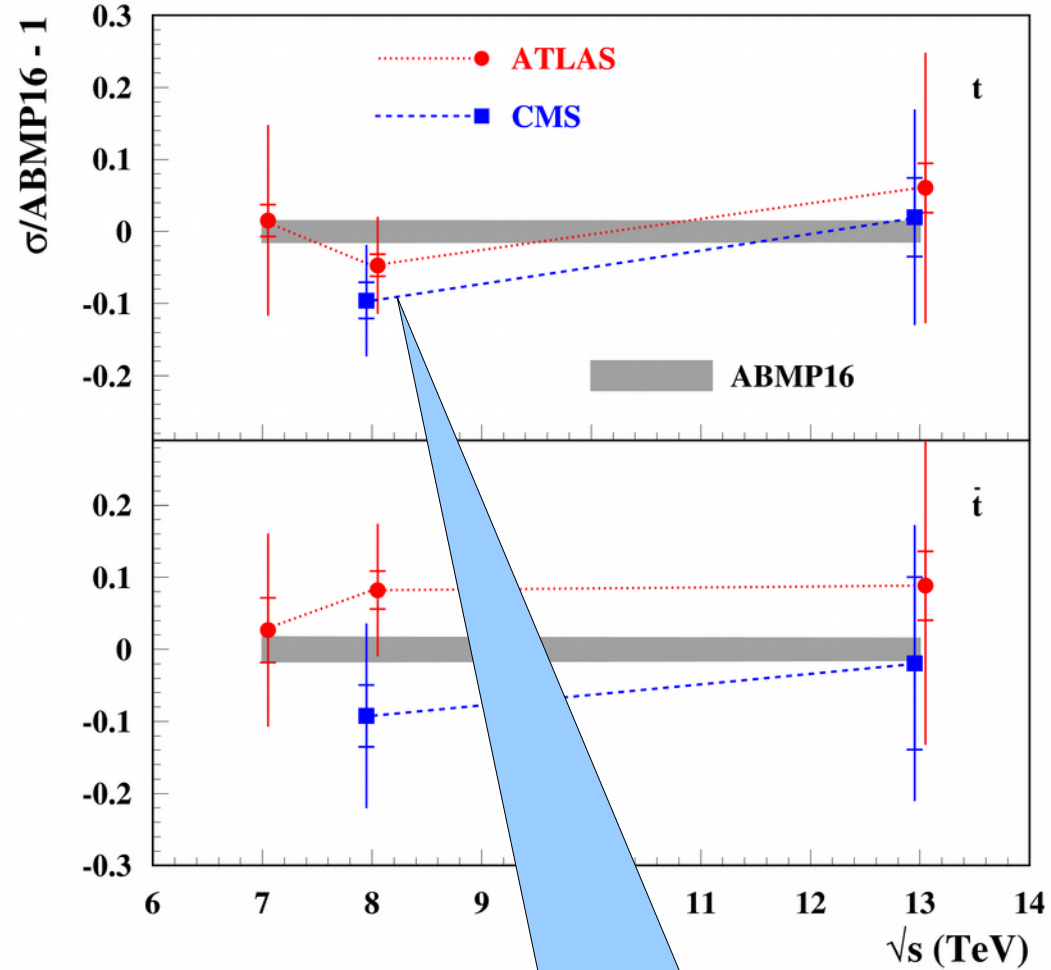
- ATLAS and CMS data on the ratio  $t/\bar{t}$  are in a good agreement
- The predictions driven by the forward DY data are in a good agreement with the single-top data (N.B.: ABM12 is based on the deuteron data → consistent deuteron correction was used) talks by Petti at DIS2016

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

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



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



The trend in ATLAS data is different for  $t$  and  $\bar{t}$  samples

# CJ15 results on the d/u ratio

Accardi, Brady, Melnitchouk, Owens, Sato PRD 93, 114017 (2016)

- NLO PDF fit including Tevatron data on W-asymmetry
- value of  $d/u \sim 0.07$  at large  $x$  is obtained
- NLO FEWZ predictions with CJ15 PDFs miss data (limitation of the K-factor approach used by CJ15?)

