More on ABMP16: ABMP16 + SeaQuest

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PDF@LHC meeting
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Constraints on PDFs at large x

* PDF uncertainties blow up at large x
* Loose constraints from HERA in the $0.1 < x < 1$ region
* While waiting for EIC,
  - fixed-target inclusive DIS experiments (SLAC, BCDMS, NMC, etc.)
  - semi-inclusive DIS experiments with ν beams (CCFR, NuTeV, CHORUS, NOMAD, etc.)
  - fixed-target DY experiments (CERN-NA51, FNAL-E605, FNAL-E866, etc.)
  - collider DY (+ jets) experiments (Tevatron, LHC)
  - collider single-top, $t\bar{t}$, inclusive jet and dijet production
* For sea-quark distributions: DY data $\leftarrow$ focus of this talk

The light-flavour sea isospin asymmetry

$*$ The light-flavour sea is isospin symmetric or asymmetric ? And why ?

$$\bar{u}(x) = \bar{d}(x) = \bar{s}(x) \text{ vs. } \bar{u}(x) \neq \bar{d}(x) \neq \bar{s}(x) \text{ ?}$$

$\Rightarrow$ models for the flavour structure of the nucleon sea
(see reviews, e.g. [Geeseman and Reimer, arXiv:1812.10372])

$*$ Using DY σ_{pd}/σ_{pp} to constrain $\bar{d}/\bar{u}$: [Ellis and Stirling, PLB 256 (1991) 258]

$$\frac{\sigma_{pd}}{2\sigma_{pp}} \simeq \frac{1}{2}\left(1 + \frac{\sigma_{pn}}{\sigma_{pp}}\right) \simeq \frac{1}{2}\left(1 + \frac{u_p(x_1)\bar{u}_n(x_2)}{u_p(x_1)\bar{u}_p(x_2)}\right) \simeq \frac{1}{2}\left(1 + \frac{\bar{d}_p(x_2)}{\bar{u}_p(x_2)}\right)$$

valid under condition $x_1 > x_2$ and of negligible nuclear effects, exploited in CERN NA51, FNAL-E866 (NuSea) and FNAL-E906 (SeaQuest) experiments.

SeaQuest dataset [arXiv:2212.12160]

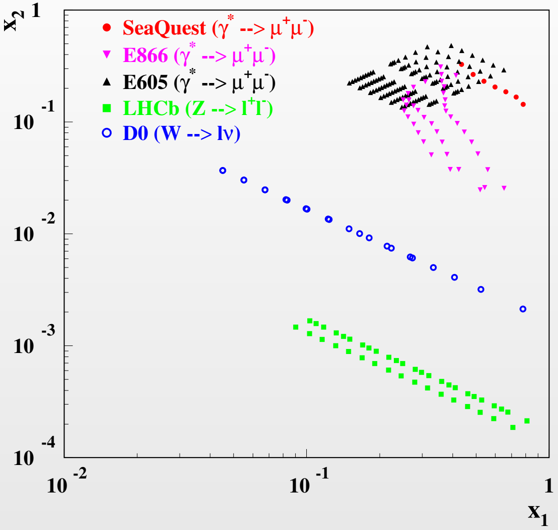
non-resonant $pd, pp \to \gamma^* \to \mu^+\mu^-$

x_F range	$\langle x_F \rangle$	$\langle x_1 \rangle$	$\langle x_2 \rangle$	$\langle P_T \rangle$ (GeV)	$\langle M_{\mu^+\mu^-} \rangle$ (GeV)	$\sigma^{pd}/2\sigma^{pp}$ MF
-0.100–0.200	0.124	0.435	0.327	0.674	5.624	$1.113 \pm 0.052 \pm 0.031$
0.200–0.300	0.255	0.486	0.266	0.714	5.340	$1.228 \pm 0.045 \pm 0.031$
0.300–0.400	0.352	0.538	0.232	0.704	5.242	$1.201 \pm 0.033 \pm 0.030$
0.400–0.500	0.449	0.598	0.206	0.719	5.201	$1.163 \pm 0.029 \pm 0.029$
0.500–0.600	0.546	0.663	0.186	0.717	5.192	$1.227 \pm 0.036 \pm 0.032$
0.600–0.700	0.644	0.730	0.167	0.707	5.146	$1.196 \pm 0.044 \pm 0.032$
0.700–0.800	0.721	0.781	0.144	0.665	4.946	$1.061 \pm 0.082 \pm 0.031$

$*$ $x_F = (x_1 - x_2)$, forward $x_F \Rightarrow x_1 > x_2$.
$1 =$ projectile (proton), $2 =$ target (deuteron, proton),
largest x_2 for the smallest x_F.

$*$ x_2 is large, but not terribly large.... $x_{2,max} = 0.45$ in the extreme of the first bin, limited by the experimental coverage

(x_1, x_2) coverage of DY data in the ABMP fits



* Each point corresponds to one bin in the experimental data
* (x_1, x_2) correlation more evident for collider DY data than for fixed-target DY data, in relation to the mass interval of the off-shell boson propagator (Z, $W^\pm$ vs. γ^*)
* coverage of LHCb $W^\pm$ data not shown but similar to LHC Z ones.

How to infer x_1, x_2 ?

* x_1, x_2 are not observables.

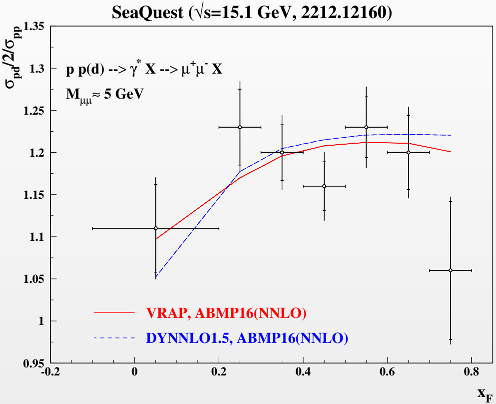
* SeaQuest uses $x_{1,2} = \frac{P_{1,2}\cdot Q}{P_{1,2}\cdot P}$, with $P_{1,2}=$ four-momenta of the projectile and target hadron, $P = P_1 + P_2$, $Q = p_{\mu^+} + p_{\mu^-}$.

* For E866, we use x_F, M, and p_T to build p_L and then E and then y, and then x_1, x_2 according to $p_L = x_F\, p_{L,\max} = x_F \sqrt{s}\,(1 - M^2/s)/2$, $E = \sqrt{p_L^2 + p_T^2 + M^2}$, $y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$, $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$.

* For E605 data and LHCb Z-boson data we use directlry the latter formula.

* For LHCb $W^\pm$-boson data we use $x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y_l}$.

DY theory predictions vs. SeaQuest exp. data



$*$ DYNNLO allows for exact computations of $d\sigma/dx_F$, with phase-space point by phase-space point information on p_T, M, etc.

$*$ VRAP allows to compute in a fast way rapidity distributions $d\sigma/dy$, by just a 2-dim integration. At this purpose the combination of $\langle x_F \rangle$, $\langle p_T \rangle$, $\langle M \rangle$ values corresponding to the center of each SeaQuest bin (see SeaQuest Table) is mapped to a y rapidity value.

$*$ Differences in the first bin, due to its extension, not significant for our fits, considering the big experimental errorbars.

Total χ^2 of the ABMP16 and ABMP16+SeaQuest fits

fit	NDP	χ^2	
		NLO	NNLO
ABMP16	2861	3428.9	3377.6
present analysis (ABMP16 + SeaQuest)	2868	3438.4	3384.7

$*$ χ^2 with/without SeaQuest data compatible among each other within statistical uncertainties.

$*$ χ^2 for NNLO fits better than for NLO fits
(better description of DY data at NNLO than at NLO).

$*$ Systematic uncertainties assumed correlated bin-by-bin. SeaQuest does not report exact information on the degree of correlation. When assumption of complete uncorrelation is done, the χ^2 slightly decreases.

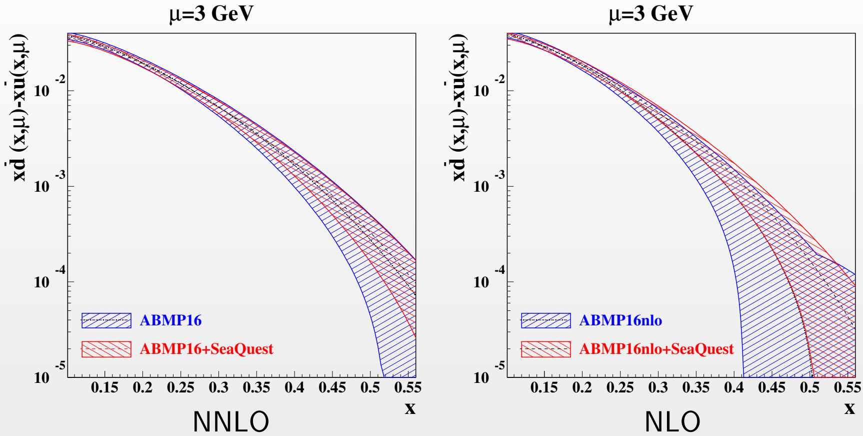
Partial χ^2 for variants of the ABMP16+SeaQuest fits

Experiment	Process	$\sqrt{s}$ (TeV)	Ref.	NDP	χ^2			
					I	II	III	IV
SeaQuest	$pp \to \gamma^* X \to \mu^+\mu^- X$ $pd \to \gamma^* X \to \mu^+\mu^- X$	0.0151	[24]	7	–	7.3	8.1	7.6
NuSea	$pp \to \gamma^* X \to \mu^+\mu^- X$ $pd \to \gamma^* X \to \mu^+\mu^- X$	0.0388	[25]	39	52.8	54.3	52.5	53.0
D0	$\bar{p}p \to W^\pm X \to \mu^\pm \overset{(-)}{\nu} X$	1.96	[45]	10	17.6	17.6	–	14.5
	$\bar{p}p \to W^\pm X \to e^\pm \overset{(-)}{\nu} X$	1.96	[39]	13	19.0	19.0	–	15.9
LHCb	$pp \to W^\pm X \to \mu^\pm \overset{(-)}{\nu} X$ $pp \to ZX \to \mu^+\mu^- X$	7	[33]	31	45.1	43.9	35.0	–
	$pp \to W^\pm X \to \mu^\pm \overset{(-)}{\nu} X$ $pp \to ZX \to \mu^+\mu^- X$	8	[34]	32	40.0	39.6	38.2	–
	$pp \to ZX \to e^+e^- X$	8	[46]	17	21.7	21.9	21.9	–

TABLE II: The values of χ^2 obtained for the data sets probing the large-x PDFs, which are included in various analyses (column I: NNLO ABMP16 PDF fit [32], column II: present analysis, column III: a variant of present analysis with D0 DY data excluded, column IV: a variant of present analysis with LHCb DY data excluded).

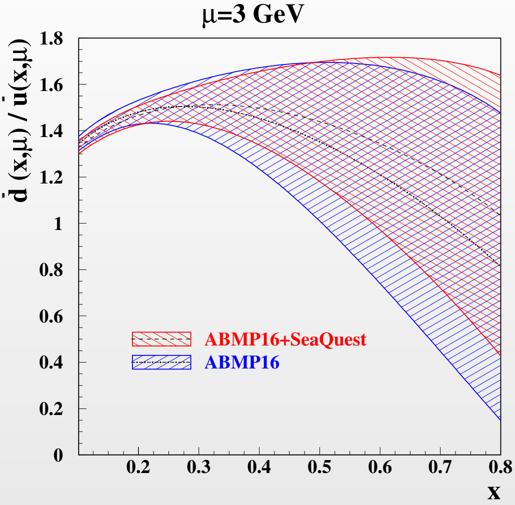
* χ^2 with/without SeaQuest data compatible within statistical uncertainties for all datasets (full compatibility of SeaQuest with all)
* Slight tension between D0 and LHCb data
* NuSea equally compatible with both.

SeaQuest constraints on $\bar{d}(x) - \bar{u}(x)$



* Uncertainty bands at NNLO smaller than at NLO.
* SeaQuest data play a constraining role for $x \gtrsim 0.3$.
* The asymmetry becomes small at large x.

SeaQuest constraints on $\bar{d}(x)/\bar{u}(x)$ ratio

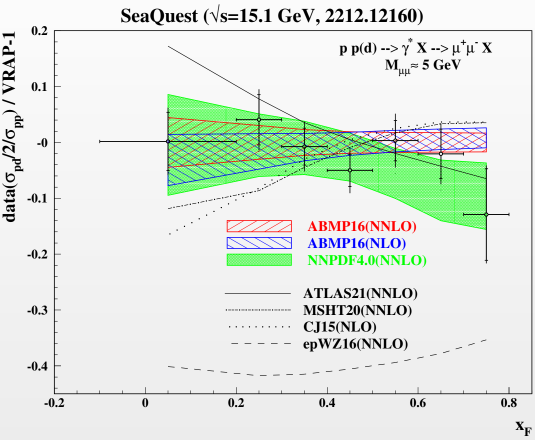


* $\bar{d}(x)/\bar{u}(x) > 1$ up to $x \lesssim 0.5 - 0.6$.

* $\bar{d}(x)/\bar{u}(x) < 1$ at both small (10^{-4}) (small x behaviour from LHCb DY) and very large x.

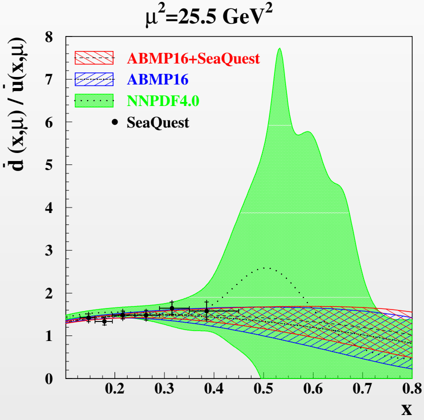
* SeaQuest data play a constraining role for $x \gtrsim 0.3$ (slight decrease of the uncertainties and modification of the central set).

Compatibility of SeaQuest data with different PDF fits



* NNPDF4.0 is the only one already including SeaQuest data in their nominal fit.
* See also separate analyses of SeaQuest data by the ATLAS, CT18, CJ15, and MSHT collaborations, partially ongoing.
* Symmetric sea ruled out.

SeaQuest constraints on $\bar{d}(x)/\bar{u}(x)$ ratio

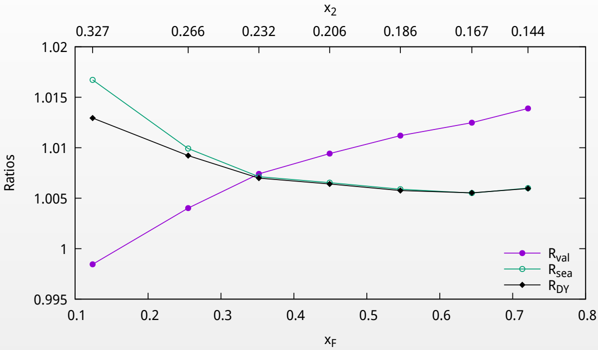


* NNPDF4.0 includes SeaQuest data, but its uncertainties in the region $0.3 < x < 0.45$ start to blow up (inefficiencies in the statistical estimators ? possible tension with other datasets ? too many parameters ?)

* ABMP16 $\bar{d}(x)/\bar{u}(x)$ in agreement with the one extracted by SeaQuest (on the basis of CT18 PDFs, but robust).

* uncertainties for $x > 0.5$ driven by extrapolation (lack of data).

Effects of deuteron nuclear corrections

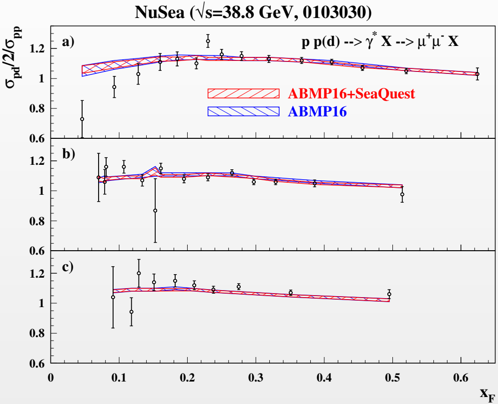


$R_{val} = u_{val,d}/(u_{val,p} + u_{val,n})$, $R_{sea} = \bar{u}_d/(\bar{u}_p + \bar{u}_n)$, $R_{DY} = \sigma_{pd}/(\sigma_{pp} + \sigma_{pn})$.

$*$ Sea quarks in the deuteron (instead of the nucleon) are subject to nuclear corrections effects, mainly due to Fermi motion, nuclear binding and off-shell modifications of bound nucleon PDFs

$*$ Nuclear effects on DY σ_{pd}/σ_{pp} ratio follows those on the sea quarks.

Compatibility of NuSea data with AMBP PDF fits



$*$ three different spectrometer settings, emphasizing the role of different dimuon invariant mass intervals.
$*$ NuSea data important for constraining $(\bar{d}/\bar{u})(x)$ for $0.015 < x < 0.12$, not covered by SeaQuest (complementarity).

$*$ Predictions diverge from ABMP16 or ABMP16+SeaQuest at large x_2, where however NuSea data uncertainties increase. Data still compatible with ABMP16(+ SeaQuest) PDF fits within $2\,\sigma$.

Second Mellin moments of combinations of quarks PDFs

$q(x, Q^2) = q_{\rm val}(x, Q^2) + q_{\rm sea}(x, Q^2)$, $\bar{q}(x, Q^2) = \bar{q}_{\rm sea}(x, Q^2)$

$\Rightarrow q^+ \equiv \; q + \bar{q}$ (total) and $q^- \equiv \; q - \bar{q}$ (valence) quark distrib. with n^{th} Mellin moment (also called $(n-1)^{th}$ x-moment)

$$\langle x^{n-1} \rangle_{q^\pm}(Q^2) \; = \int_0^1 dx \, x^{n-1} \, q^\pm(x, Q^2) \, ,$$

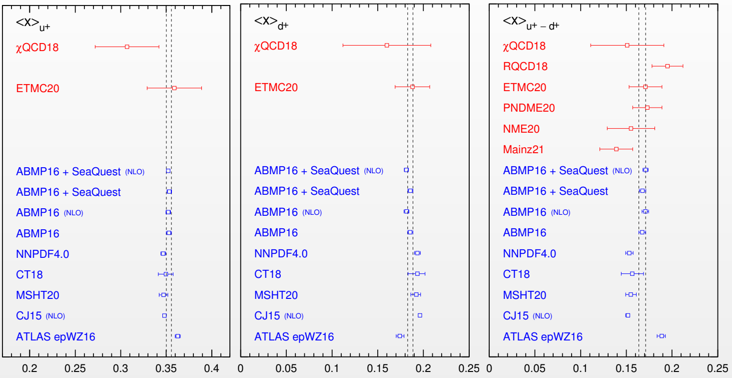
$*$ $\langle 1 \rangle_{q^-}$ correspond to the quark number sum rules, whereas $\langle 1 \rangle_{q^+}$ are divergent.

$*$ Lattice QCD computations have allowed to calculate the second Mellin moments $\langle x \rangle_{u^+ - d^+}$ (isovector combination) and $\langle x \rangle_{q^+}$ for all individual light quarks, together with the third Mellin moments $\langle x^2 \rangle_{u^- - d^-}$ and $\langle x^2 \rangle_{q^-}$.

$*$ Here we are interested in Mellin moments of

$u^+ = u_v + 2\bar{u}, \quad d^+ = d_v + 2\bar{d}, \quad u^+ - d^+ = (u_v - d_v) + 2(\bar{u} - \bar{d})$

Second Mellin moments of combinations of quarks PDFs



∗ Results of different PDFs not always compatible among each other but still compatible with lattice QCD results, that are characterized by larger uncertainties.

∗ The incorporation of SeaQuest data in the PDF fits plays little role on these moments, which involve both valence and sea quarks PDFs. They do not modify the central values, but they decrease the uncertainties.

∗ NLO and NNLO Mellin moments compatible: fast convergence because it is a rather inclusive quantity.

Conclusions

* SeaQuest $\sigma_{pd}/2\sigma_{pp}$ DY data relevant for constraining $(\bar{d}-\bar{u})(x)$ and $(\bar{d}/\bar{u})(x)$ at relatively large x target, $0.12 < x < 0.45$.
* Effects on the ABMP16 NNLO and NLO fits visible for $x \gtrsim 0.3$, mainly consisting in a reduction of uncertainties on these quantities.
* Better theoretical description of data at NNLO than NLO.
* PDF constraints from SeaQuest and NuSea DY data well compatible with those from LHC DY data.
* Complementarity of E866 and E906 $\sigma_{pd}/2\sigma_{pp}$ DY data, constraining $(\bar{d}/\bar{u})(x)$ ratio in different x regions.
* Tension in the region $0.24 < x < 0.35$ (last two bins of E866) is not significant for the AMBP16+SeaQuest fit, due to the large E866 uncertainty bands in that region.
* Mellin moments of different light-quark combinations from lattice QCD compatible with those from PDFs, but still too uncertain.
* So far, only $\sim 1/2$ of SeaQuest already collected data have been published.
* Therefore we are optimistic that data uncertainties $\sim 5\%$ can be decreased.
* (ABMP16 + SeaQuest) PDFs are going to be released in LHAPDF.

Forthcoming Workshop of possible interest for the PDF community:

indico.desy.de/event/41404/

Joint ECFA-NuPECC-APPEC Activity Workshop "Synergies between the EIC and the LHC"

14–15 dic 2023
DESY, Hamburg
Europe/Berlin fuso orario

- Sintesi
- Local Organizing Committee
- Programma scientifico
- Iscrizione
- Workshop fee
- Call for abstract
- Raccolta degli abstract
- Elenco dei relatori
- Timetable (still preliminary)
- Elenco partecipanti
- Workshop Venue
- Social dinner
- Accomodation
- Sponsors / co-organizers

ECFA European Committee for Future Accelerators — NuPECC — APPEC

A Joint ECFA-NuPECC-APPEC activity (http://www.nupecc.org/jenaa/) on the topic of exploring the synergies between the EIC and the LHC has recently started. For the Expression of Interest, see https://indico.ph.tum.de/event/7004

This Workshop, taking place in person, follows the kick-off meeting held at CERN in June 2022 (https://indico.ph.tum.de/event/7014/) and aims to continue the discussion and promote further fruitful exchanges between the theoretical and experimental communities involved in LHC, EIC, and astroparticle physics.

In the days before this Workshop, the XVI Meeting of the Physics at the Terascale Alliance will also take place in the same venue. For registrations to the latter, please visit https://indico.desy.de/event/41133/

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Forschungsgruppe FOR 2926/2 — Next Generation Perturbative QCD for Hadron Structure: Preparing for the Electron-Ion Collider — HRT