Light-flavor parton distributions for new physics searches

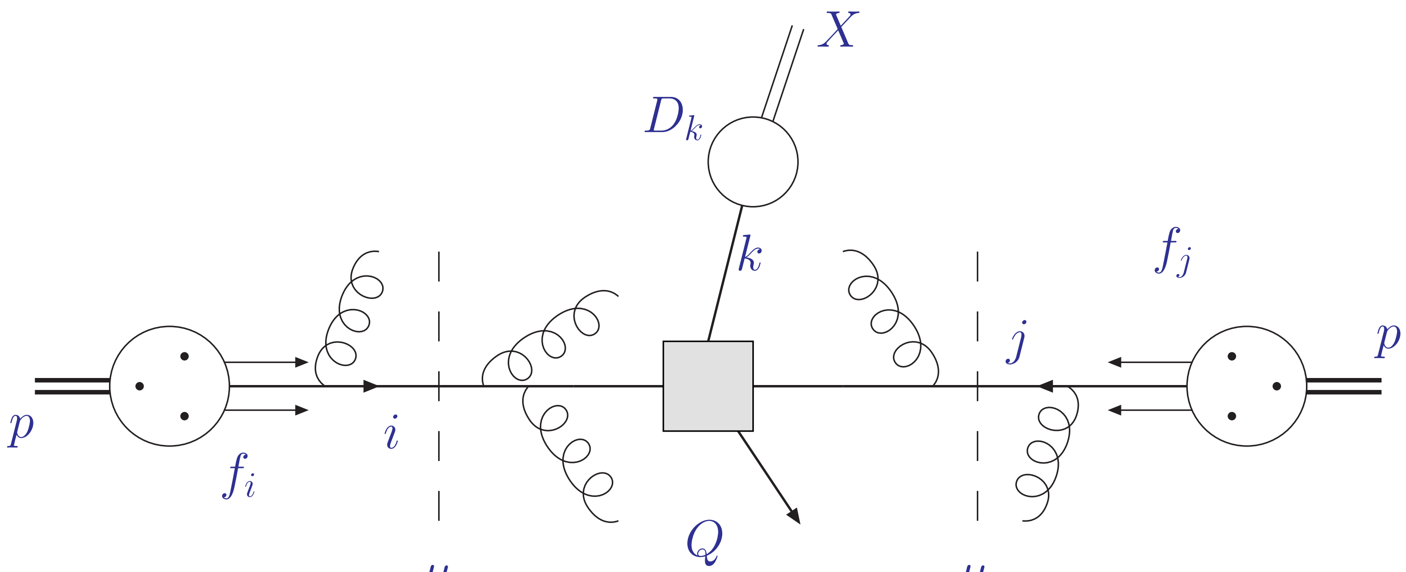
Sven-Olaf Moch

Universität Hamburg

Based on work done in collaboration with:

- *Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC*
  A. Anataichuk, O. Zenaiev, S. M., et. al. work in progress
- *Impact of SeaQuest data on PDF fits at large x*
  S. Alekhin, M.V. Garzelli, S. Kulagin and S. M. `arXiv:2306.01918`
- *Z′-boson dilepton searches and the high-x quark density*
  J. Fiaschi, F. Giuli, F. Hautmann, S. M. and S. Moretti `arXiv:2211.06188`
- *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`
- Many more papers of ABM and friends . . .
  `2008 - ...`

QCD factorization

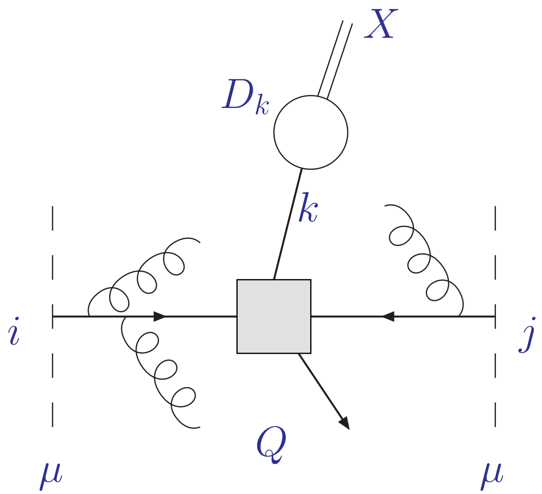


$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- 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

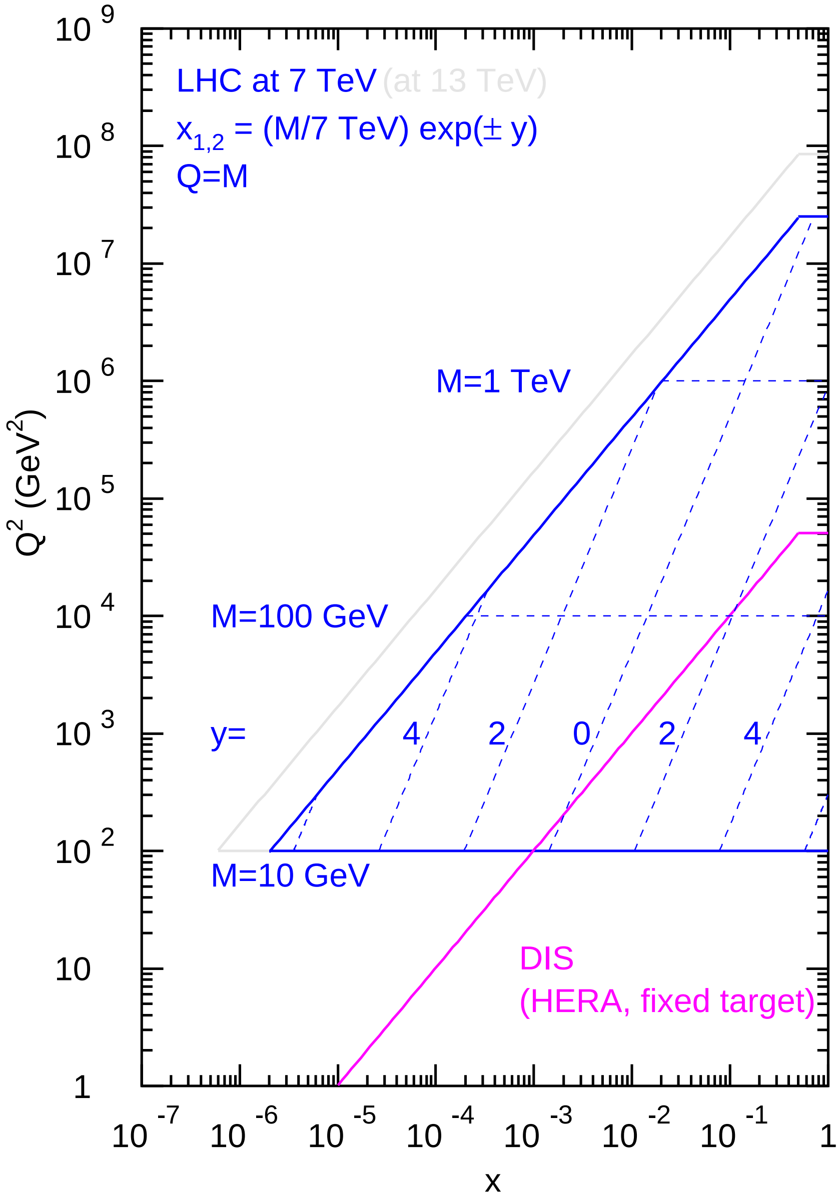
- Cross section depends on parton distributions f_i

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

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

Parton kinematics at LHC

- Information on proton structure depends on kinematic coverage



- LHC run at $\sqrt{s}$ = 7/8 TeV ($\sqrt{s}$ = 13 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

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

Data in global PDF fits (I)

Data sets considered in ABMP16 analysis

Alekhin, Blümlein, S.M., Placakyte '17

- 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,

Data in global PDF fits (II)

DY data in ABMP16 analysis

- High precision experimental data from LHC ATLAS, CMS, LHCb and Tevatron D0 useful for determinations of parton distributions
  - statistically significant $NDP = 172$ in ABMP16
- Differential distributions in decay lepton pseudo-rapidity extend kinematics 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 $\sigma(W^-) \simeq d(x_2)\bar{u}(x_1)$;

    $\sigma(Z) \simeq Q_u^2 u(x_2)\bar{u}(x_1) + Q_d^2 d(x_2)\bar{d}(x_1)$
  - cf. DIS: $\sigma(\mathrm{DIS}) \simeq q_u^2 u(x) + q_d^2 d(x)$

ABMP16 PDF ansatz

- PDFs parameterization at scale $\mu_0 = 3\mathrm{GeV}$ in scheme with $n_f = 3$

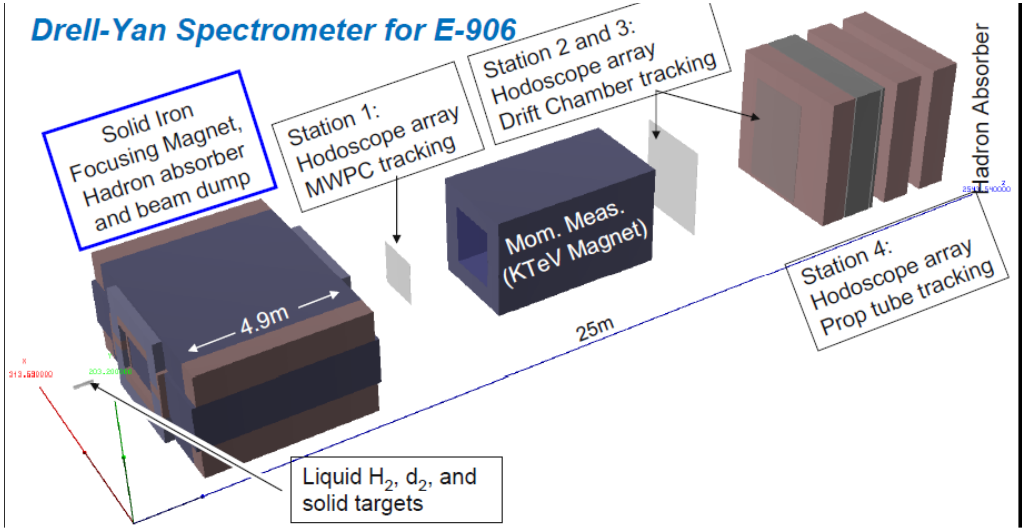
  Alekhin, Blümlein, S.M., Placakyte '17

  - ansatz for valence-/sea-quarks, gluon

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

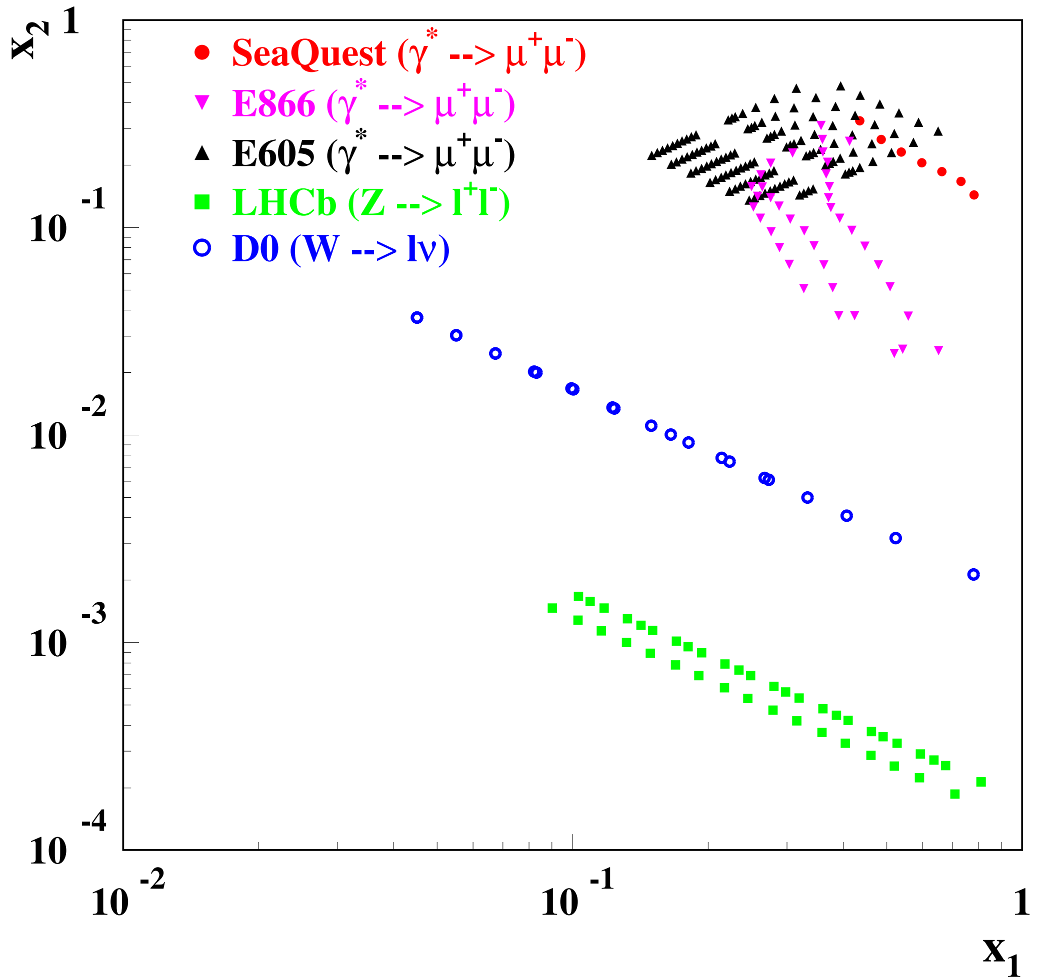
  - strange quark is taken in charge-symmetric form
  - function $P_p(x) = (1+\gamma_{-1,p}\ln x)\left(1+\gamma_{1,p}x+\gamma_{2,p}x^2+\gamma_{3,p}x^3\right)$,
  - 29 parameters in fit including $\alpha_s^{(n_f=3)}(\mu_0 = 3$ GeV), m_c, m_b and m_t
  - simultaneous fit of higher twist parameters (twist-4)
- Ansatz provides sufficient flexibility; no additional terms required to improve the quality of fit
- Large x part of all PDFs $\sim (1-x)^b$, where $b_{u_v} = 3.443 \pm 0.064$, $b_{d_v} = 4.47 \pm 0.55$, $b_{u_s} = 7.75 \pm 0.39$, $b_{d_s} = 8.41 \pm 0.34$, ...

Seaquest experiment



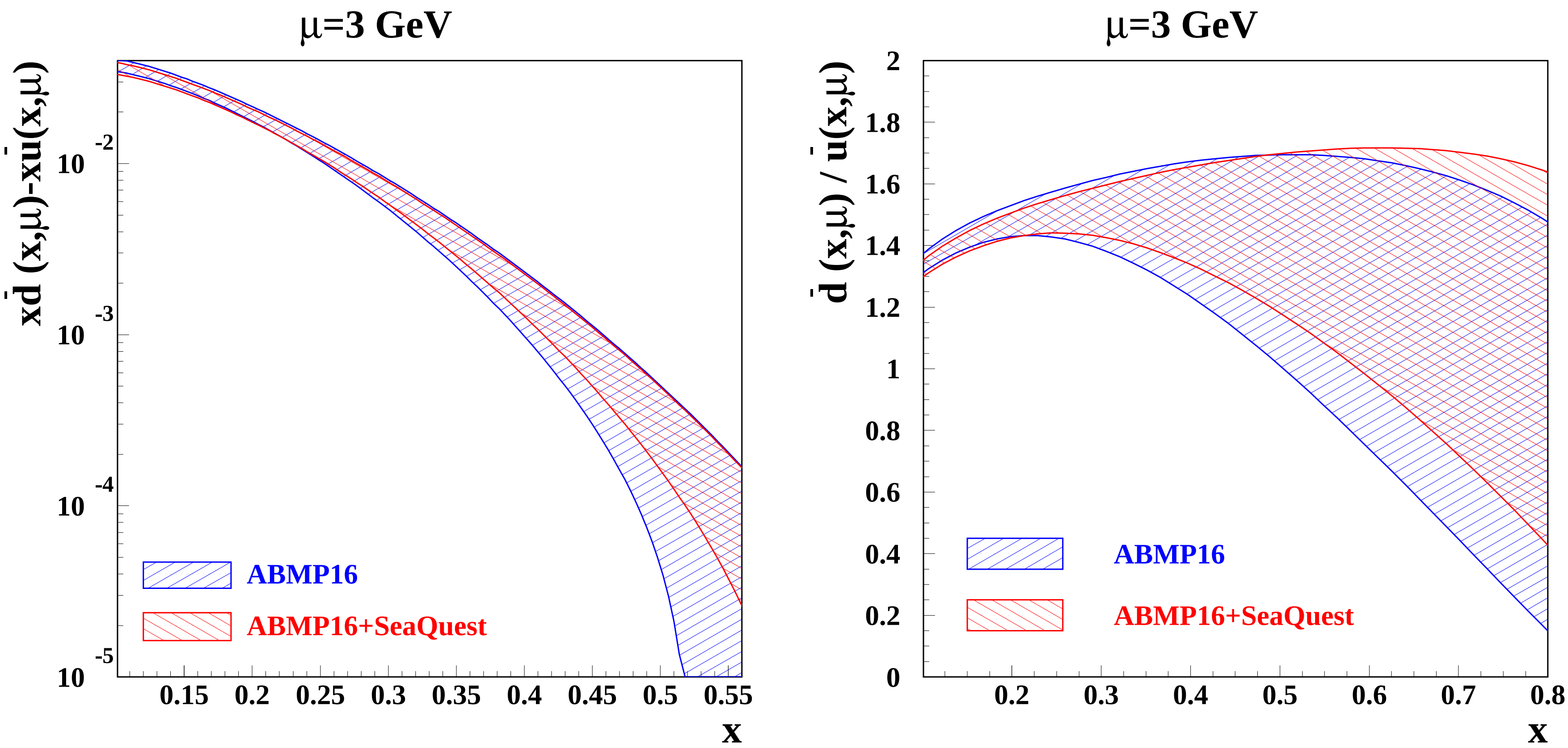
- Fermilab E-906/SeaQuest experiment is part of series of fixed target DY experiments
- Measurements of proton beam on deuterium target
- Invariant mass of observed γ^* decay products fixed to approximately $M_{\gamma^*} \sim 5$ GeV

Seaquest parton kinematics



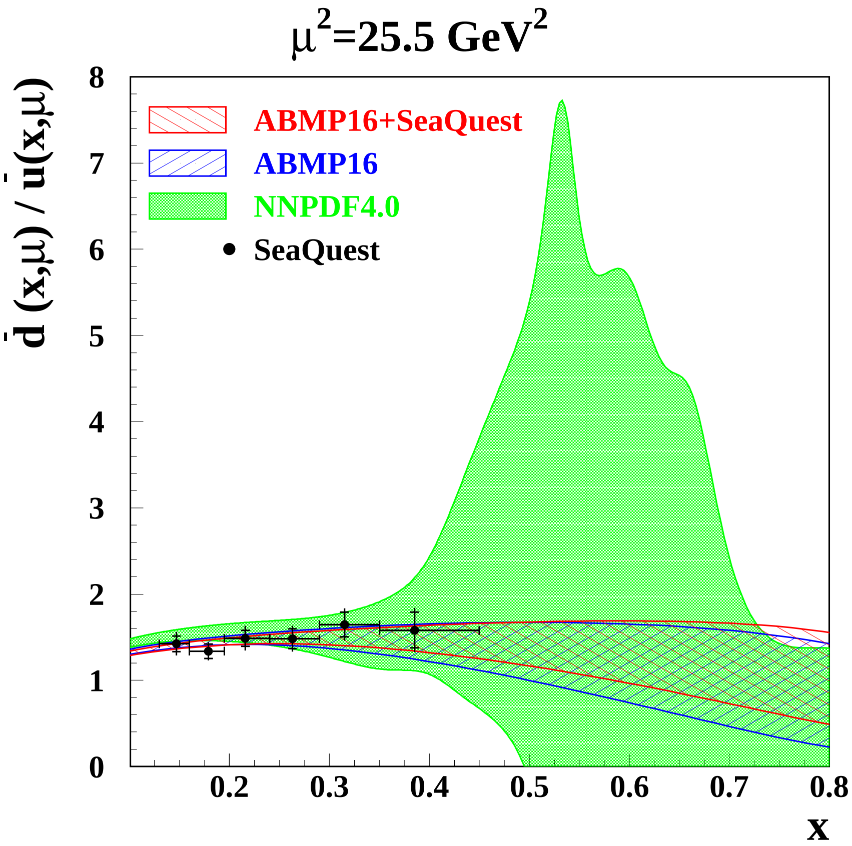
- Coverage of (x_1, x_2) plane by SeaQuest   Alekhin, Garzelli, Kulagin, S.M. '23
- DY data sets used in ABMP16 PDF fits extending to high (x)
  - Fermilab fixed-target experiment E866, E605
  - LHCb Z-boson rapidity distribution
  - D0 charged-lepton rapidity distribution

Light flavor PDFs from Seaquest data



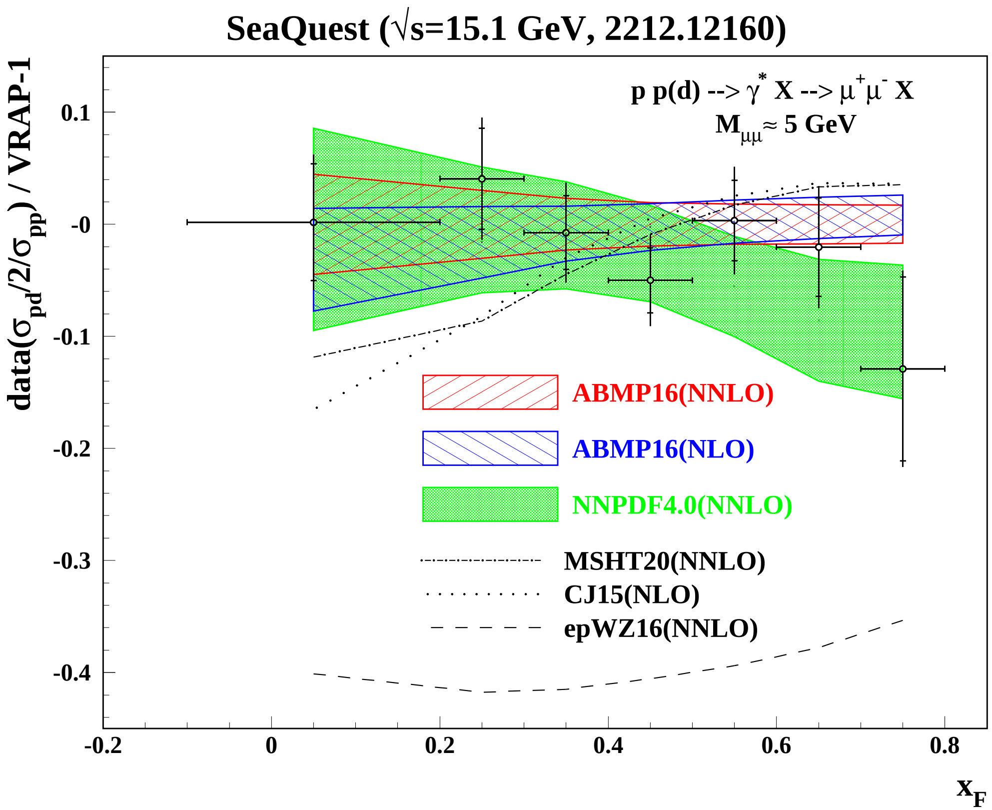
- 1σ bands for sea distributions in PDF fit with Seaquest data compared to ABMP16 fit Alekhin, Garzelli, Kulagin, S.M. '23
  - left: $n_f = 3$-flavor isospin asymmetry $x(\bar{d} - \bar{u})(x)$
  - right: ratio $\bar{d}/\bar{u}$ as a function of x

$\bar{d}/\bar{u}$ ratio from SeaQuest



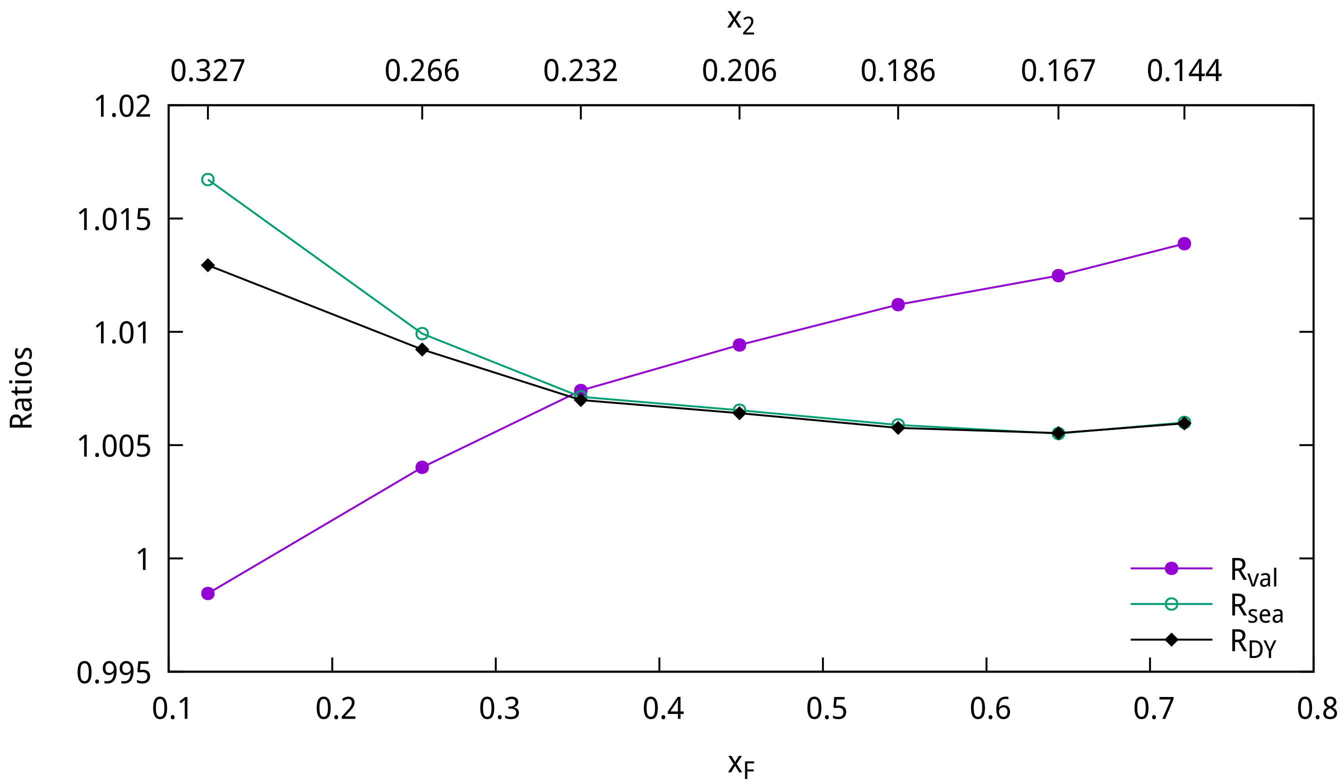
- 1σ bands for $\bar{d}/\bar{u}$ ratio at scale $\mu^2 = 25.5$ GeV^2 with comparison to SeaQuest extraction Alekhin, Garzelli, Kulagin, S.M. '23
  - SeaQuest data has been included in NNPDF4.0 NNLO PDF fit

Cross section ratio



- Pulls for SeaQuest data on ratio of pd and pp DY distributions over $x_F = P_L/P_{L,\max}$
  - theory predictions with code VRAP Anastasiou, Dixon, Melnikov, Petriello ‘03 and NNLO ABMP16 PDFs
- Comparison to different PDFs
  - NLO ABMP16 PDFs, NLO CJ15, NNLO MSHT20, NNLO NNPDF4.0, NNLO epWZ16 (based on $SU(3)$-symmetric quark sea model)

Deuteron nuclear corrections



- Valence quark PDFs $R_{\text{val}} = u_{\text{val}/d}/(u_{\text{val}/p} + u_{\text{val}/n})$
- Antiquark PDFs $R_{\text{sea}} = \overline{u}_d/(\overline{u}_p + \overline{u}_n)$
- DY cross sections $R_{\text{DY}} = \sigma_{pd}/(\sigma_{pp} + \sigma_{pn})$
  - plot with lower horizontal axis over $x_F = P_L/P_{L,\max}$, upper horizontal axis over x values of deuteron target (x_2)
- Nuclear effects in deuteron are small $\mathcal{O}(1\%)$ Alekhin, Garzelli, Kulagin, S.M. '23

New physics searches

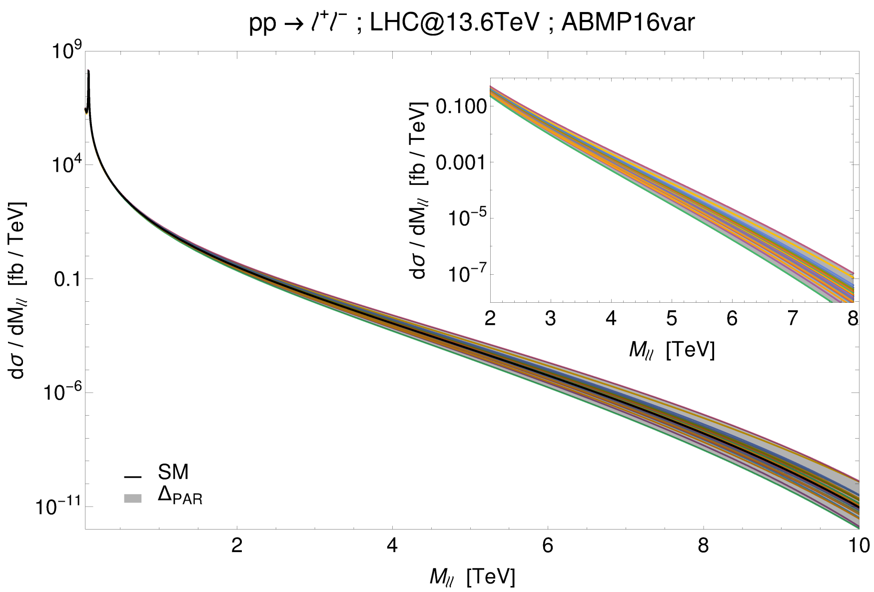
Searches at high scales

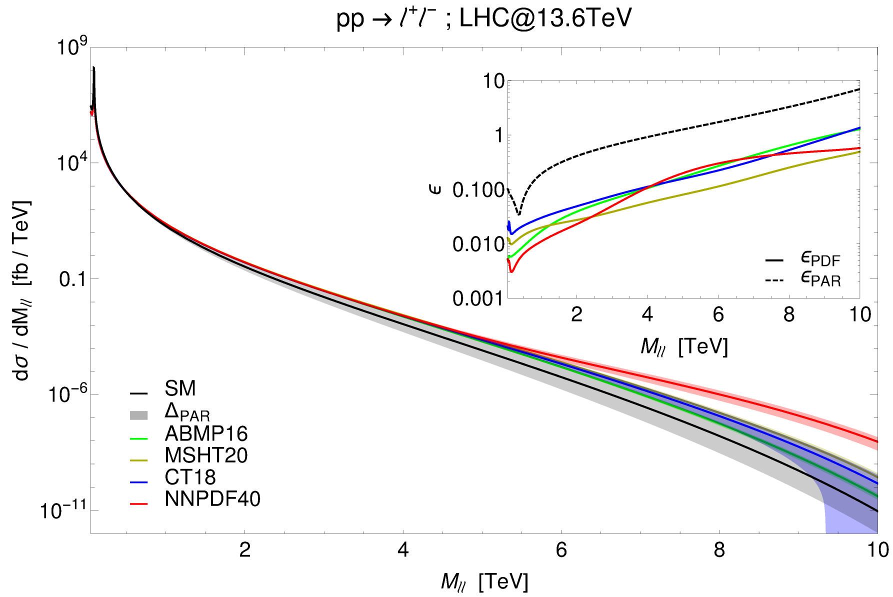
- Explore TeV region for deviations from Standard Model predictions
- Different theory approaches
  - parametrization of cross sections within the Standard Model as effective theory (SMEFT)

$$\mathcal{L} = \mathcal{L}^{(\mathrm{SM})} + \frac{1}{\Lambda^2} \sum_{j=1}^{N_6} C_j^{(6)}\, \mathcal{O}_j^{(6)} \,,$$

  - direct searches, e.g. new Z'-gauge boson
- Theory predictions depended on parton kinematics at high x
  - PDF uncertainty at high x can easily dominate overall error budget
  - estimates beyond measured kinematic range needed

Z-boson production at high invariant mass



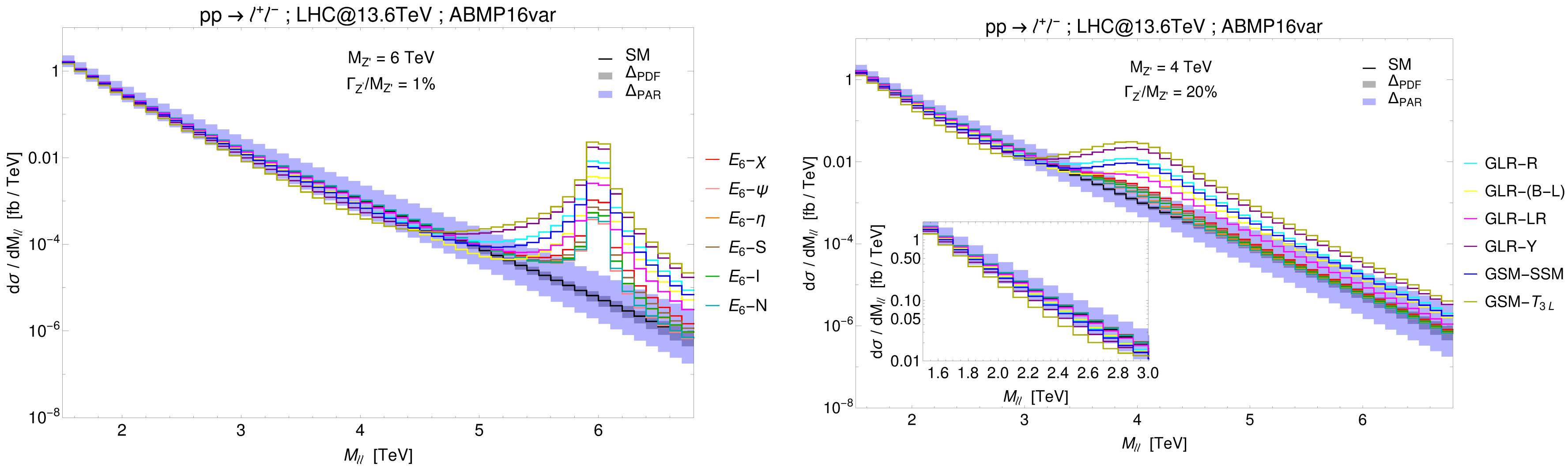


- ABMP16 NNLO PDFs, but large x part of u and d modified

  Fiaschi, Giuli, Hautmann, S. M., Moretti '22

  - parametrization $\sim (1-x)^b$ with variation of exponent $b \pm 0.3$ and 0.5 (recall $b \sim 3 \ldots 8$) $\longrightarrow$ ABMP16var
  - keep vanishing $\bar{d}/\bar{u}$ as $x \to 1$
- Differential cross section for Z-boson production in M_{ll} at LHC with $\sqrt{s}$ = 13.6 TeV
  - left: results for all ABMP16var members
  - right: comparison with results from standard PDF sets

Predictions for models with Z'-boson

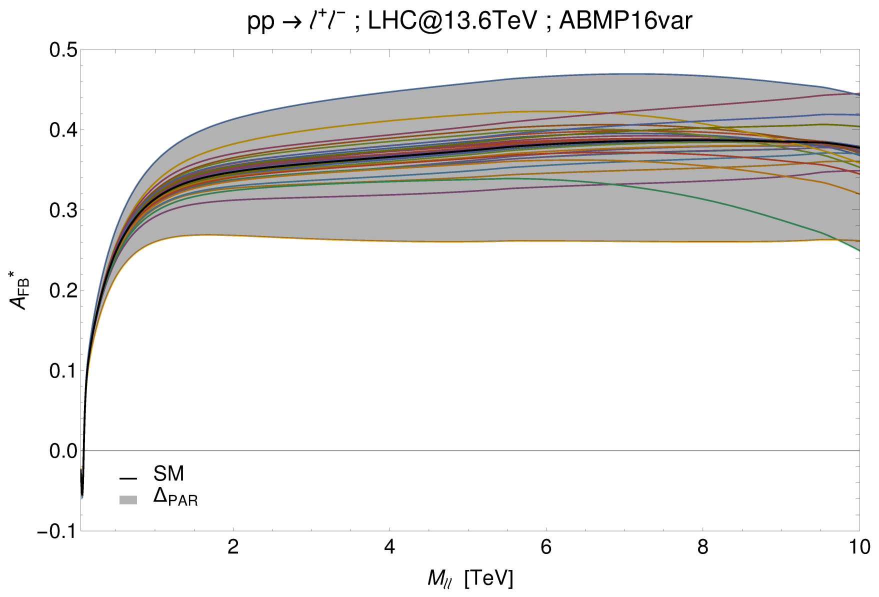


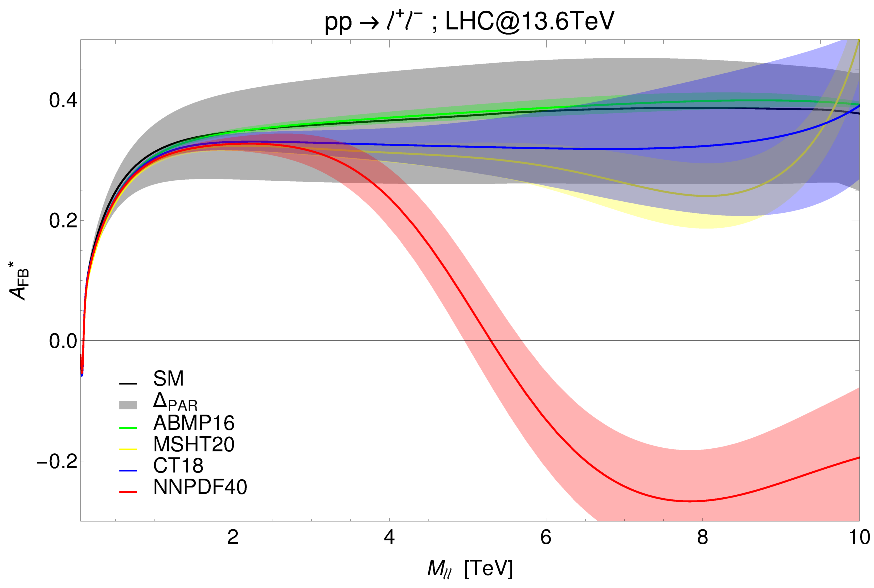
- Differential cross section in M_{ll} at LHC with $\sqrt{s}$ = 13.6 TeV for a series of single Z' benchmark models using ABMP16var PDFs

  Fiaschi, Giuli, Hautmann, S. M., Moretti '22

  - left: results for $M_{Z'} = 6$ TeV, $\Gamma_{Z'}/M_{Z'} =$ 1%
  - right:results for $M_{Z'} = 4$ TeV, $\Gamma_{Z'}/M_{Z'} =$ 20%

Forward-backward asymmetry





- Forward-backward asymmetry A_{FB}^*

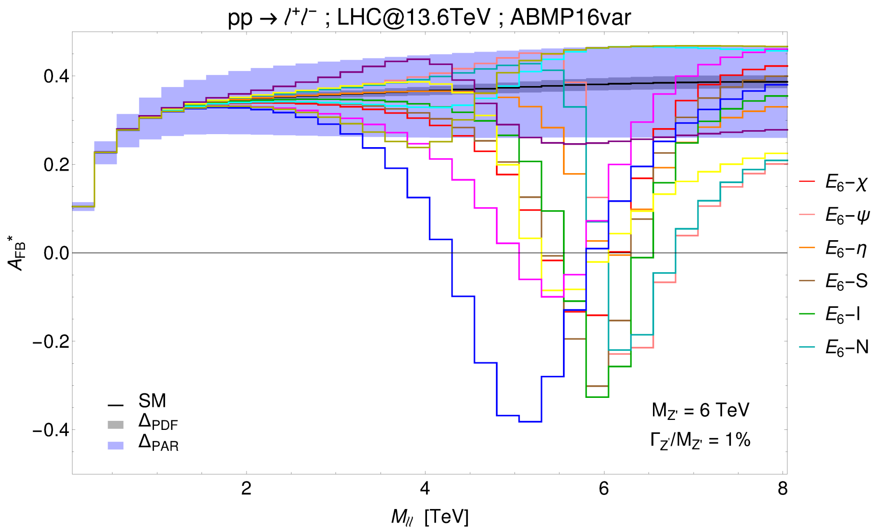
$$A_{\mathrm{FB}}^* = \frac{d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* > 0] - d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* < 0]}{d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* > 0] + d\sigma/(dM_{\ell\ell}dy_{\ell\ell})[\cos\theta^* < 0]}.$$

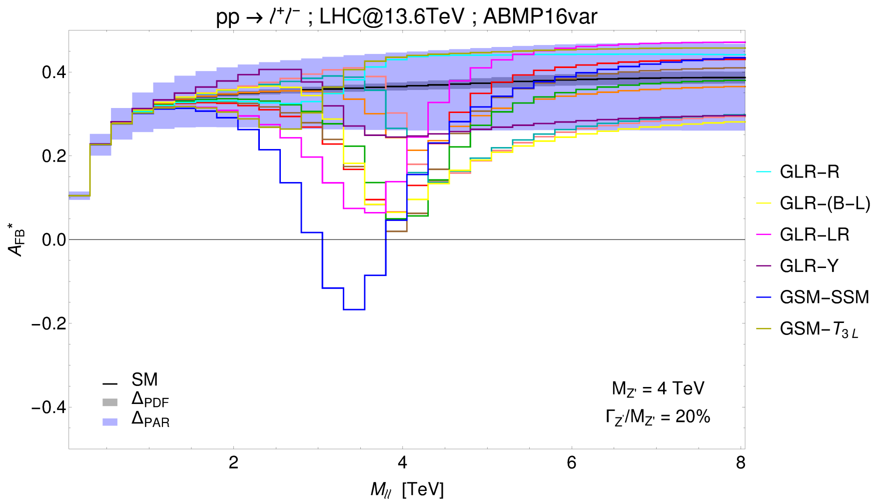
- Asymmetry A_{FB}^* in M_{ll} at LHC with $\sqrt{s}$ = 13.6 TeV

  Fiaschi, Giuli, Hautmann, S. M., Moretti '22

  - left: results for all ABMP16var members
  - right: comparison with results from standard PDF sets

Predictions for models with Z'-boson



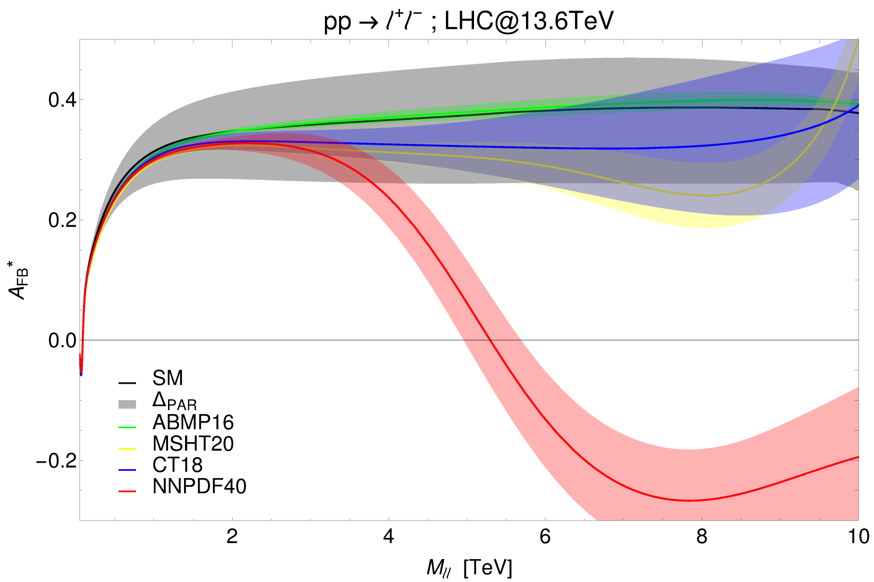


- Asymmetry $A^*_{\rm FB}$ in M_{ll} at LHC with $\sqrt{s}$ = 13.6 TeV for a series of single Z' benchmark models using ABMP16var PDFs

  Fiaschi, Giuli, Hautmann, S. M., Moretti ‘22

  - left: results for $M_{Z'} = 6$ TeV, $\Gamma_{Z'}/M_{Z'} = 1\%$
  - right:results for $M_{Z'} = 4$ TeV, $\Gamma_{Z'}/M_{Z'} = 20\%$

$A^*_{\rm FB}$ *at high invariant mass*

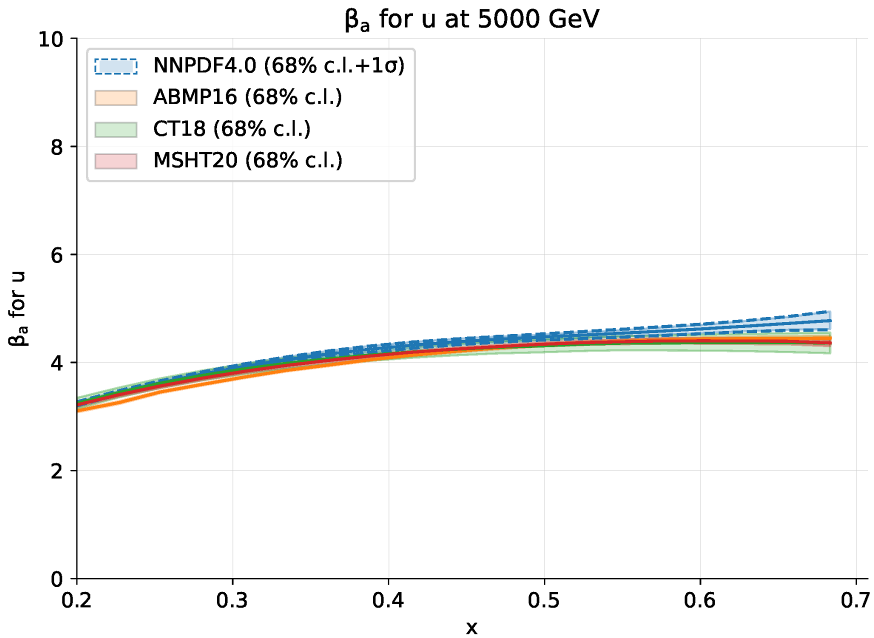


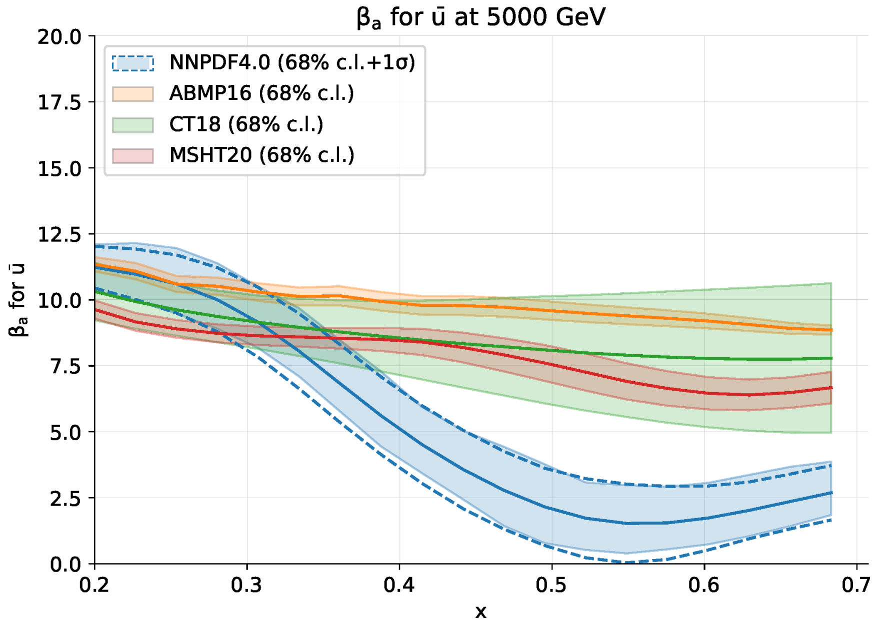
- Explaining the $A^*_{\rm FB}$ prediction by NNPDF4.0
- Recall leading order kinematics $\sigma(Z) \simeq Q_u^2 u(x_2)\bar{u}(x_1) + Q_d^2 d(x_2)\bar{d}(x_1)$
- Define slope of light quark PDFs $f_q(x,\mu^2) \sim (1-x)^{b_q}$

$$\beta_q(x) = \frac{\partial |x f_q(x,\mu^2)|}{\partial \ln(1-x)}$$

  - positive A_{FB} require light flavor sea PDFs ($\bar{u}$ and $\bar{d}$) to fall off faster at large-x than valence quarks (u and d)
  - $\beta_{\bar{u}}(x) > \beta_u(x)$ and $\beta_{\bar{d}}(x) > \beta_d(x)$ for all values of x

Light quark PDFs at high x





- Plot of $\beta_u(x)$, $\beta_{\bar{u}}(x)$ (similar situation for d flavor PDF)

  Ball, Candido, Forte, Hekhorn, Nocera, Rojo, Schwan '22

  - large variation of high x exponent for sea quark PDFs for NNPDF4.0
  - no predictive power for new physics searches

Outlook

Strategies for experimantal analyses

- New physics searches in TeV region need to minimize/cancel PDF depedence
  - data driven approaches
  - ratios with parton kinematics in control region, e.g. $M_{ll} \lesssim 1$ TeV
- Extension of study from single Z' benchmark models to SMEFT
  Anataichuk, Zenaiev, S. M., et. al.
  - fits to data within XFitter framework
- Account for constraints on light flavor PDFs from other sources
  - lattice QCD

Lattice results (I)

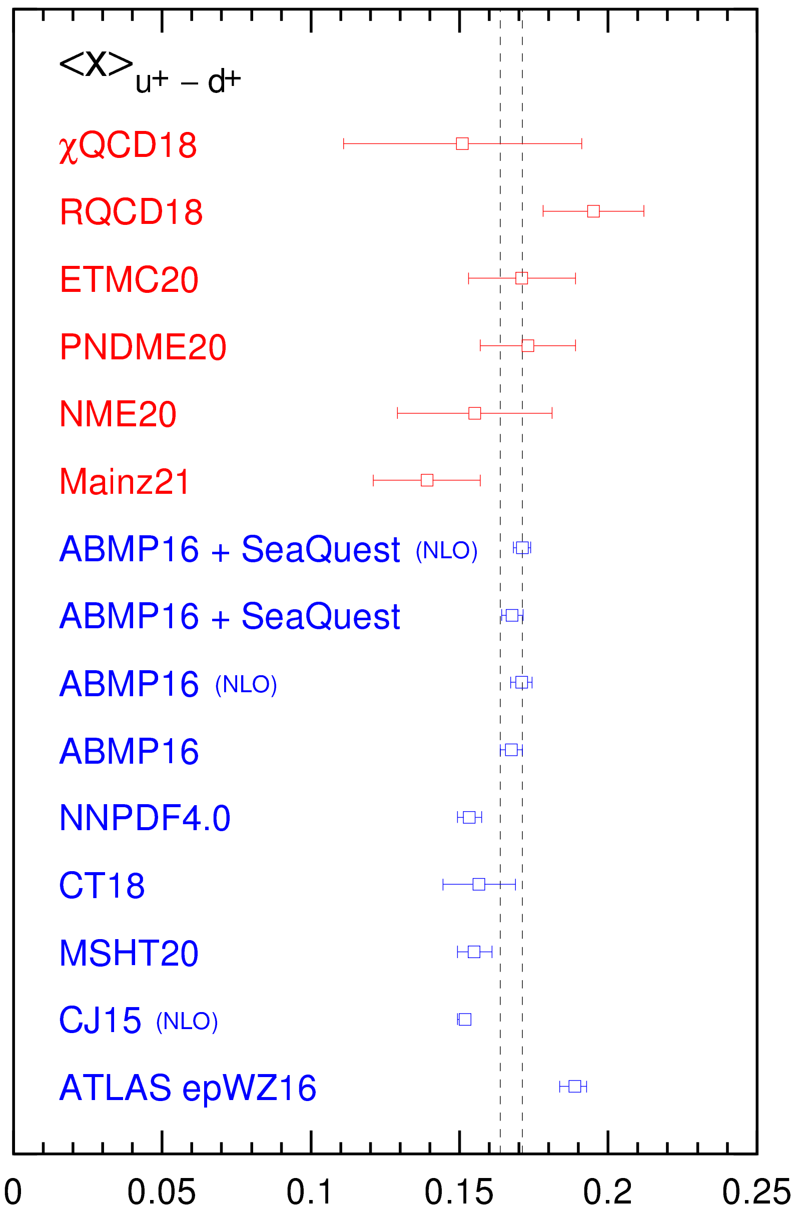
- Recall $q(x) = q_{\rm val}(x) + q_{\rm sea}(x)$, $\bar{q}(x) = \bar{q}_{\rm sea}(x)$
- n^{th} moment of the $q^{\pm} \equiv\ q \pm \bar{q}$ distribution at scale $Q^2 = 4\ \mathrm{GeV}^2$

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

PDF fit	$\langle x\rangle_{u^+}$	$\langle x\rangle_{d^+}$	$\langle x\rangle_{u^+-d^+}$
ABMP16 + SeaQuest NLO	0.3523 ± 0.0010	0.1813 ± 0.0023	0.1711 ± 0.0029
ABMP16 + SeaQuest NNLO	0.3535 ± 0.0026	0.1858 ± 0.0028	0.1677 ± 0.0036
ABMP16 NLO	0.3522 ± 0.0026	0.1814 ± 0.0027	0.1708 ± 0.0036
ABMP16 NNLO	0.3532 ± 0.0027	0.1858 ± 0.0029	0.1673 ± 0.0037
NNPDF4.0 NNLO	0.3468 ± 0.0026	0.1934 ± 0.0032	0.1533 ± 0.0041
CT18 NNLO	$0.3498\,^{+0.0078}_{-0.0085}$	$0.1934\,^{+0.0083}_{-0.0103}$	$0.1564\,^{+0.0123}_{-0.0120}$
MSHT20 NNLO	$0.3471\,^{+0.0048}_{-0.0048}$	$0.1923\,^{+0.0046}_{-0.0060}$	$0.1548\,^{+0.0062}_{-0.0056}$
CJ15 NLO	$0.3480\,^{+0.0009}_{-0.0012}$	$0.1962\,^{+0.0015}_{-0.0014}$	$0.1518\,^{+0.0019}_{-0.0024}$
epWZ16 NNLO	$0.3628\,^{+0.0027}_{-0.0028}$	$0.1741\,^{+0.0047}_{-0.0039}$	$0.1887\,^{+0.0041}_{-0.0050}$
lattice computation			
χQCD18 ($n_f = 2+1$)	0.307 ± 0.030 ± 0.018	0.160 ± 0.027 ± 0.040	0.151 ± 0.028 ± 0.029
RQCD18 ($n_f = 2$)	-	-	0.195 ± 0.007 ± 0.015
ETMC20 ($n_f = 2+1+1$)	0.359 ± 0.030	0.188 ± 0.019	0.171 ± 0.018
PNDME20 ($n_f = 2+1+1$)	-	-	0.173 ± 0.014 ± 0.007
NME20 ($n_f = 2+1$)	-	-	0.155 ± 0.017 ± 0.020
Mainz21 ($n_f = 2+1$)	-	-	0.139 ± 0.018 (stat)

Lattice results (II)

- Second Mellin moments of isovector combination $(u^+ - d^+)(x)$ and their uncertainties
  - comparison of several PDF fits and lattice QCD
  - vertical band denotes ABMP16 NNLO fit



Summary

- DY data from LHC and from fixed target experiments allow for good control of light flavor content in proton at high x
- Very good precision of experimental data leads to residual uncertainties in percent range in measured region
  - new Seaquest data compatible with u and d PDFs in ABMP16
- High x parton kinematics is important region for new physics searches
  - A_{FB} for Z-boson in the TeV range
- Dedicated analysis for new physics searches to control and reduce PDF uncertainities
- Future input on moments of PDFs from lattice QCD welcome