Parton Distributions today: needs, achievements and challenges

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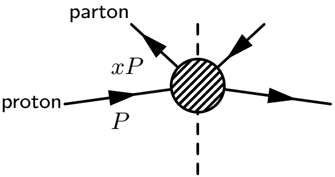
MARIE CURIE ACTIONS

Foreword: parton distributions on the light cone

1. The densities of partons $f = q, \bar{q}, g$ with momentum fraction x

$$f(x) \equiv f^{\uparrow}(x) + f^{\downarrow}(x) \qquad\qquad \Delta f(x) \equiv f^{\uparrow}(x) - f^{\downarrow}(x)$$

2. Allow for a proper field-theoretic definition as matrix elements of bilocal operators



collinear transition of a massles proton h
into a massless parton i
with fractional momentum x
local OPE $\Longrightarrow$ lattice formulation

$$q(x) = \frac{1}{4\pi}\int dy^- e^{-iy^- xP^+}\langle P|\bar{\psi}(0,y^-,\mathbf{0}_\perp)\gamma^+\psi(0)|P\rangle$$
$$\Delta q(x) = \frac{1}{4\pi}\int dy^- e^{-iy^- xP^+}\langle P,S|\bar{\psi}(0,y^-,\mathbf{0}_\perp)\gamma^+\gamma^5\psi(0)|P,S\rangle$$

with light-cone coordinates

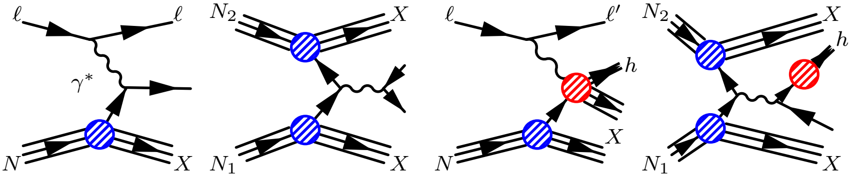
$$y = (y^+, y^-, \mathbf{y}_\perp)\,, \quad y^+ = (y^0 + y^z)/\sqrt{2}\,, \quad y^- = (y^0 - y^z)/\sqrt{2}\,, \quad \mathbf{y}_\perp = (v^x, v^y)$$

3. All these definitions have ultraviolet divergences which must be renormalized

Theoretical framework

1. Factorisation of physical observables

$$\mathcal{O}_I = \sum_{i=q,\bar{q},g} C_{Ii}(y,\alpha_s(\mu^2)) \otimes f_i(y,\mu^2) + \text{p.s. corrections} \qquad f\otimes g = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y)$$



$\ell + N \to \ell + X$ deep-inelastic scattering (DIS)	$N_1 + N_2 \to A + X$ (inclusive) production in proton-proton scattering (pp)	$\ell + N \to \ell' + h + X$ semi-inclusive deep-inelastic scattering (SIDIS)	$N_1 + N_2 \to h + X$ high-p_T hadron production in proton-proton collisions (pp)

2. Perturbative expansion of coefficient functions

$$C_{Ii}(y,\alpha_s) = \sum_{k=0} a_s^k C_{Ii}^{(k)}(y), \qquad a_s = \alpha_s/(4\pi)$$

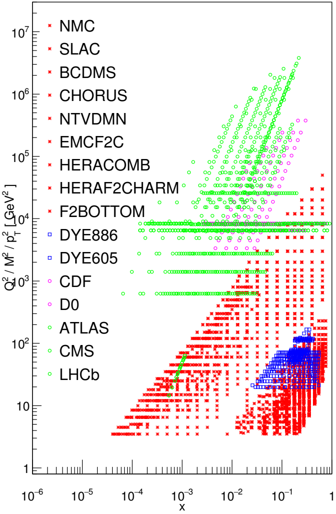
3. Perturbative (DGLAP) evolution of PDFs

$$\frac{\partial}{\partial \ln\mu^2} f_i(x,\mu^2) = \sum_j^{n_f} \int_x^1 \frac{dz}{z} P_{ji}\left(z,\alpha_s(\mu^2)\right) f_j\left(\frac{x}{z},\mu^2\right) \qquad P_{ji}(z,\alpha_s) = \sum_{k=0} a_s^{k+1} P_{ji}^{(k)}(z)$$

Unpolarised PDFs: NNPDF3.1 [EPJ C77 (2017) 663]

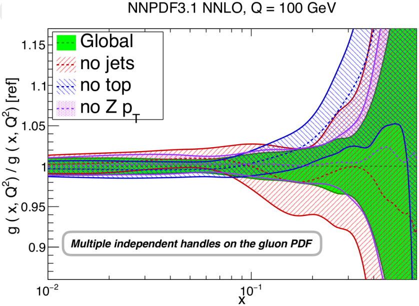
- Higgs boson characterisation
  PDF uncertainty often dominant
- Determination of SM parameters
  PDF uncertainty largest theoretical uncertainty in M_W determination
- Searches for BSM
  the larger the mass of the final state, the larger the PDF uncertainty

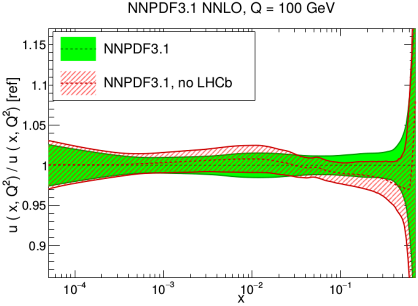
	$N_{\rm dat}$ (NNLO/NLO)	$\chi^2/N_{\rm dat}$ (NNLO)	$\chi^2/N_{\rm dat}$ (NLO)
FT DIS	1881/1881	1.15	1.20
HERA DIS	1211/1221	1.11	1.14
FT DY	189/189	1.25	0.96
Tevatron	150/156	1.08	1.06
ATLAS	360/358	1.09	1.37
CMS	409/397	1.06	1.20
LHCb	85/93	1.47	1.61
Total	4285/4295	1.148	1.168

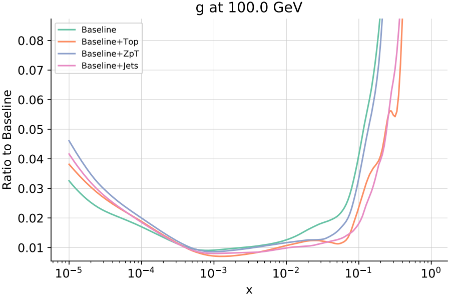


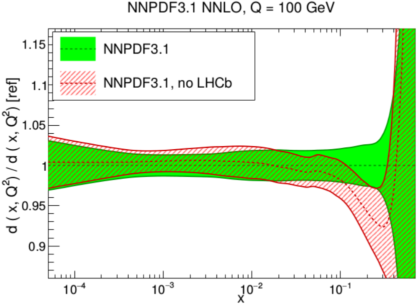
$\mathcal{O}(4000)$ data points after cuts
$Q^2_{\rm cut}$ few GeV^2 $W^2_{\rm cut} = 3 - 12.5$ GeV^2

Gluon and quark flavour separation

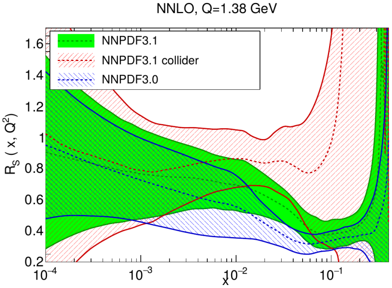


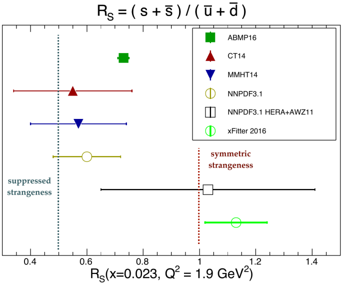






The strange PDF: neutrino DIS vs collider data





In most PDF fits the strange PDF is suppressed w.r.t up and down sea quark PDFs

effect mostly driven by neutrino dimuon data

A symmetric strange sea PDF is preferred by collider data

in particular by ATLAS W, Z rapidity distributions (2011) [EPJ C77 (2017) 367]

$$R_s(x, Q^2) = \frac{s(x,Q^2) + \bar{s}(x,Q^2)}{\bar{u}(x,Q^2) + \bar{d}(x,Q^2)} \begin{cases} \sim 0.5 \text{ from neutrino and CMS } W + c \text{ data} \\ \sim 1.0 \text{ from ATLAS } W, Z \end{cases}$$

The ATLAS data can be accommodated in the global fit

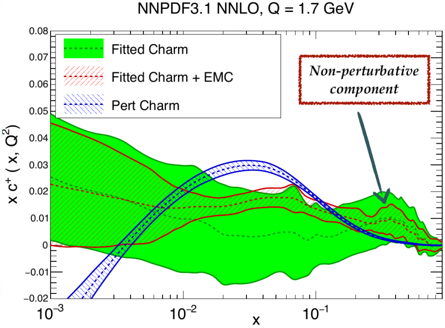
increased strangeness, though not as much as in a collider-only fit; slight tension remains

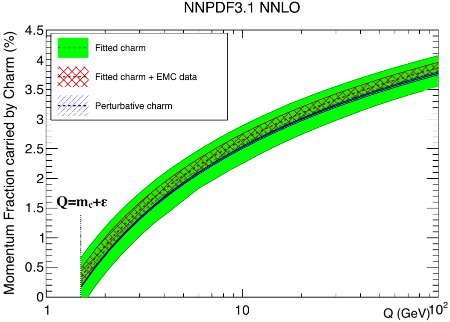
nuclear uncertainties in FT DIS? No [EPJ C79 (2019) 282]

massive CC coefficient functions at NNLO? Possibly [JHEP 1802 (2018) 026]

Suppressed strangeness confirmed by recent $W + c$ CMS analysis [CMS PAS SMP-17-014]

The charm PDF: perturbative vs fitted [EPJ C76 (2016) 647]





Parametrise the $c^+(x, Q_0^2)$, quark and gluon PDFs on the same footing

stabilise the dependence of LHC processes upon variations of m_c

quantify the nonperturbative charm component in the proton (BHPS? sea-like?)

take into account massive charm-initiated contribution to the DIS structure functions

Fitted charm found to differ from perturbative charm at scales $Q \sim m_c$ in NNPDF3.1

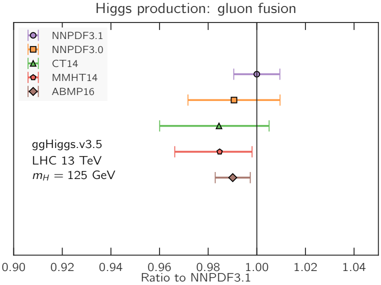
preference for a BHPS-like shape

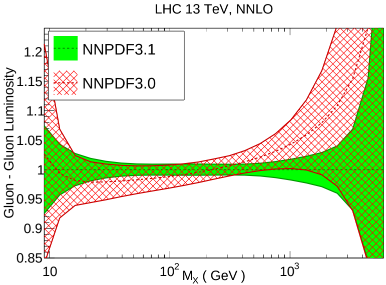
shape driven by LHCb W, Z data + EMC data

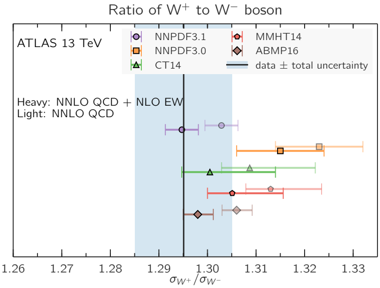
At $Q = 1.65$ GeV charm carry 0.26 ± 0.42 % of the proton momentum

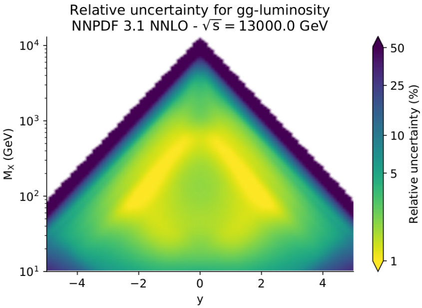
but it is affected by large uncertainties, especially if no EMC data are included

Standard candles and luminosities









Theoretical uncertainties in PDF fits [arXiv:1801.04842]

Experimental uncertainties propagated to PDFs via minimisation of figure of merit

$$\chi^2 = \sum_{i,j}^{N_{\rm dat}} (D_i - T_i)({\rm cov}_{\rm exp})^{-1}_{ij}(D_j - T_j)$$

Assuming that theory uncertainties are (a) Gaussian and (b) independent from experimental uncertainties, modify this to account for (a wide range of) theory errors

$$\chi^2 = \sum_{i,j}^{N_{\rm dat}} (D_i - T_i)({\rm cov}_{\rm exp} + {\rm cov}_{\rm th})^{-1}_{ij}(D_j - T_j)$$

Problem reduced to estimate the th. cov. matrix, *e.g.* in terms of nuisance parameters

$$({\rm cov}_{\rm th})_{ij} = \frac{1}{N}\sum_{k}^{N} \Delta_i^{(k)}\Delta_j^{(k)} \qquad \Delta_i \equiv T_i^{(k)} - T_i$$

Example 1: Nuclear uncertainties $\Delta_i^{(k)} = T_i^N[f_N^{(k)}] - T_i^N[f_p^{(k)}]$

Example 2: MHO uncertainties $\Delta_i^{(k)} = T_i(\mu_R, \mu_F) - T_i(\mu_{R,0}, \mu_{F,0})$

choices of scale combinations, range of scale variation, process categorisation

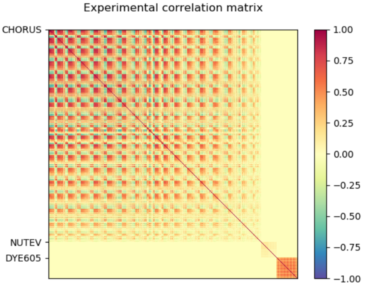
same process, 3pt $({\rm cov})_{ij} = \frac{1}{2}\left\{\Delta_i(+,+)\Delta_j(+,+) + \Delta_i(-,-)\Delta_j(-,-)\right\}$

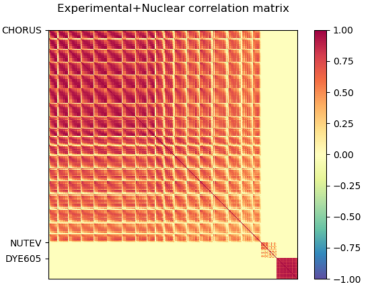
different process, 3pt $({\rm cov})_{ij} = \frac{1}{4}\left\{\left[\Delta_i(+,+) + \Delta_i(-,-)\right]\left[\Delta_j(+,+) + \Delta_j(-,-)\right]\right\}$

$$\Delta_i(+,+) = T_i(\mu_R = 2Q, \mu_F = 2Q) - T_i(\mu_R = Q, \mu_F = Q)$$

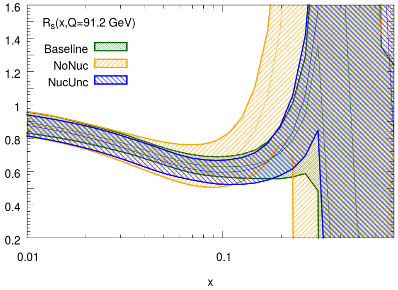
$$\Delta_i(-,-) = T_i(\mu_R = Q/2, \mu_F = Q/2) - T_i(\mu_R = Q, \mu_F = Q)$$

Example 1: nuclear uncertainties in PDF fits [EPJ C79 (2019) 282]





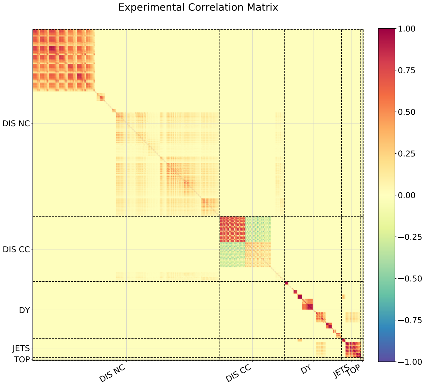
nuclear uncertainties determined by averaging over Monte Carlo replicas from three nuclear PDF sets: DSSZ12, nCTEQ15 and EPPS16

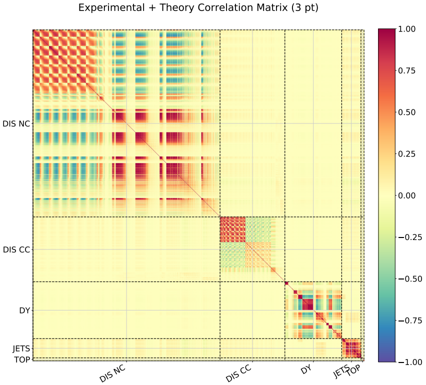


Experiment	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ (bas.)	$\chi^2/N_{\rm dat}$ (nucl.)
CHORUS (ν)	416	1.29	0.97
CHORUS ($\bar{\nu}$)	416	1.20	0.78
NUTEV (ν)	37	0.41	0.31
NUTEV ($\bar{\nu}$)	39	0.90	0.62
DYE605	85	1.18	0.85
	4285	1.18	1.07

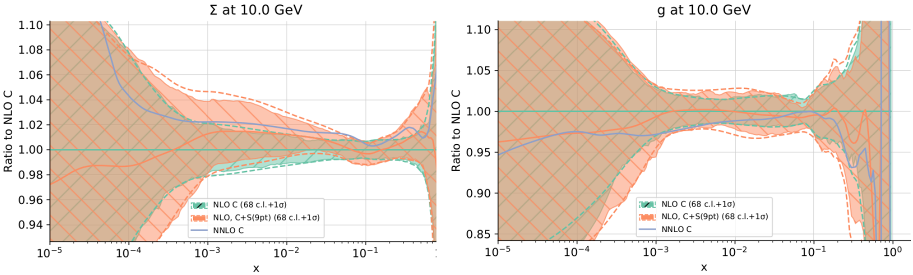
Example 2: MHO uncertainties in PDF fits [arXiv:1906.10698]

μ_F variations are correlated across all processes (PDF evolution)
μ_R variations are correlated by process (hard cross section)
vary scales in $\frac{1}{2} \leq \frac{\mu_F}{\mu_{F,0}}, \frac{\mu_R}{\mu_{R,0}} \leq 2$; consider 3-, 7- or 9-point variations
average over flat distribution of points; consider different correlation treatments
validate the NLO theory covariance matrix over the NLO-NNLO shift





Example 2: MHO uncertainties in PDF fits [arXiv:1906.10698]



PDF uncertainty increase encapsulates NLO-NNLO shift

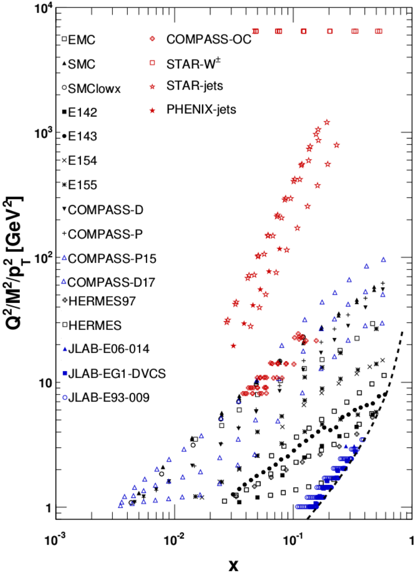
Overall (rather small) increase in uncertainties

Increase in PDF uncertainties due to replica generation
is counteracted by extra correlations in fitting minimisation

Tensions relieved: improvement in χ^2
exp only: $\chi^2/N_{\rm dat} = 1.139$ exp+th: $\chi^2/N_{\rm dat} = 1.110$

Data whose theoretical descrition is affected by large scale uncertainties
are deweighted in favour of more perturbatively stable data

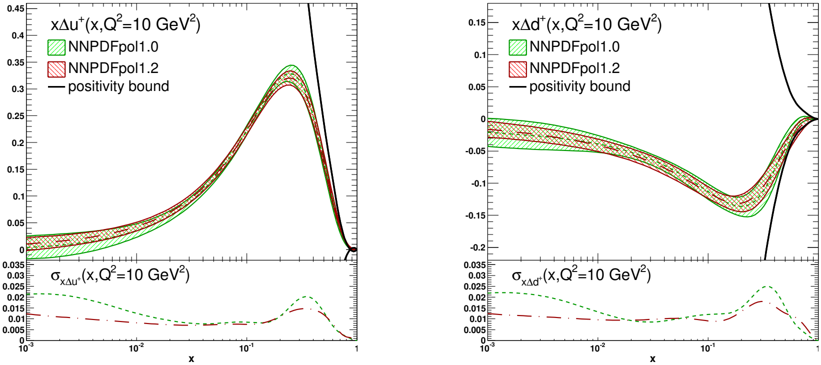
Polarised PDFs: NNPDFpol1.x [Nucl.Phys. B887 (2014) 276]



	EXPERIMENT	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ 1.0	1.1	1.2
	EMC	10	0.44	0.43	0.43
	SMC	24	0.93	0.90	0.92
	SMClowx	16	0.97	0.97	0.94
	E142	8	0.67	0.66	0.55
	E143	50	0.64	0.67	0.63
	E154	11	0.40	0.45	0.34
	E155	40	0.89	0.85	0.98
	COMPASS-D	15	0.65	0.70	0.57
	COMPASS-P	15	1.31	1.38	0.93
	HERMES97	8	0.34	0.34	0.23
	HERMES	56	0.79	0.82	0.69
new	COMPASS-P-15	51	0.98*	0.99*	0.65
new	COMPASS-D-17	15	1.32*	1.32*	0.80
new	JLAB-E93-009	148	1.26*	1.23*	0.94
new	JLAB-EG1-DVCS	18	0.45*	0.59*	0.29
new	JLAB-E06-014	2	2.81*	3.20*	1.33
	COMPASS (OC)	45	1.22*	1.22	1.22
	STAR (jets)	41	—	1.05	1.06
	PHENIX (jets)	6	—	0.24	0.24
	STAR-$A_L^{W^\pm}$ (2012)	24	—	1.05	1.05
	STAR-$A_{LL}^{W^\pm}$	12	—	0.95	0.94
new	STAR-$A_L^{W^\pm}$ (2013)	8	—	2.76*	1.34
new	STAR (dijets)	14	—	1.34*	1.00
	TOTAL		0.77	1.05	1.01

* data set not included in the corresponding fit

Total up and down polarisations [JPCS 678 (2016) 012030]

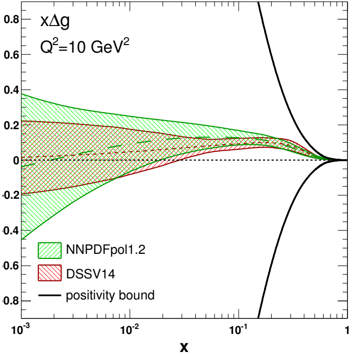


- Improved accuracy at small x: new COMPASS data
  (+ improved unpolarized F_L and F_2 from NNPDF3.1)
- Improved accuracy at large x: new JLAB data
  (also note that the positivity bound is slightly different)
- A lower cut on W^2 will allow for exploiting the full potential of JLAB data
  (if we replace $W^2 \geq 6.25$ GeV^2 with $W^2 \geq 4.00$ GeV^2 the χ^2 deteriorates significantly)
  (need to include and fit dynamic higher twists, in progress)

Gluon polarisation

High-p_T jet production

first evidence of a sizeable, positive gluon polarization in the proton



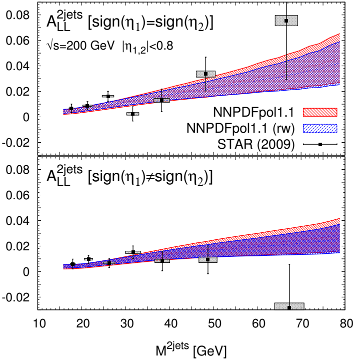
$$\langle x_{1,2}\rangle \simeq \frac{2p_T}{\sqrt{s}}e^{-\eta/2} \approx [0.05, 0.2]$$

NNPDF and DSSV results well compatible

$$\int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = +0.23 \pm 0.15$$

High-p_T di-jets [PRD 95 (2017) 071103]

confirm a positive gluon polarization in the proton



$$\langle x_{1,2}\rangle \simeq \frac{p_T}{\sqrt{s}}(e^{\pm\eta_1 \pm\eta_2}) \approx [0.01, 0.2]$$

x sensitivity extended down to $x \sim 0.01$

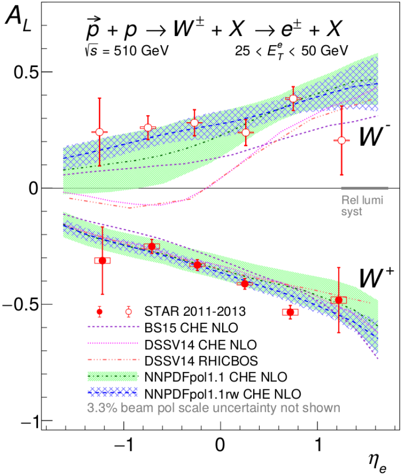
$$\int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = +0.32 \pm 0.13$$

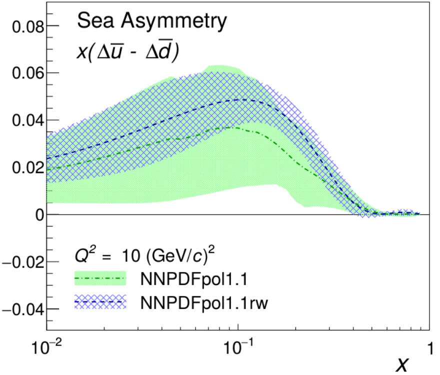
Sea quark polarisation $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$ [arXiv:1702.05077]

$W^{\pm}$ boson production

first evidence of broken flavor symmetry
for polarized light sea quarks

New 2013 data [PRD 99 (2019) 51102]





$$\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$$

$$\Delta\bar{u} > 0 > \Delta\bar{d}, \; |\Delta\bar{d}| > |\Delta\bar{u}|$$

$$\int_{0.04}^{0.4} dx \, \Delta_s(x, Q^2 = 10\,\text{GeV}^2) = +0.06 \pm 0.03$$

$$\rightarrow +0.07 \pm 0.01$$

[See also Jinlong Zhang's talk]

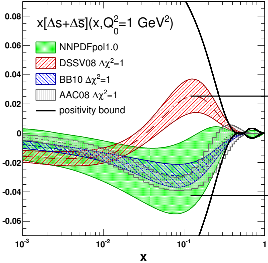
SU(3) breaking and strangeness

NNPDFpol1.0 [NPB 874 (2013) 36]
$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.13 \pm 0.09$

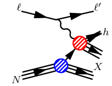
Lattice [PRL 108 (2012) 222001]
$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.020(10)(1)$

First moment constrained by
$a_3 = \int_0^1 dx[\Delta u^+ - \Delta d^+]$
$= 1.2701 \pm 0.0025$

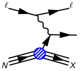
$a_8 = \int_0^1 dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+]$
$= 0.585 \pm 0.025$



directly from SIDIS Kaon data



indirectly from DIS + SU(3)



All PDF determinations based only on DIS data (+ SU(3)) find a negative Δs^+
PDF determinations based on DIS+SIDS data (+SU(3)) find a negative or a positive Δs^+
depending on the K FF set [PRD 91 (2015) 054017]

Tension between DIS and SIDIS data can be ficticious

$SU(3)$ may be broken [PRD 58 (1998) 094028, Ann.Rev.Nucl.Part.Sci. 53 (2003) 39], but how much?
$\longrightarrow$ in `NNPDFpol`, the nominal uncertainty on a_8 in inflated by 30% of its value to allow for a $SU(3)$ symmetry violation ($a_8 = 0.585 \pm 0.025 \longrightarrow a_8 = 0.585 \pm 0.176$)
$\longrightarrow$ but *e.g.* lattice finds a larger $SU(3)$ symmetry violation [PRL 108 (2012) 222001]

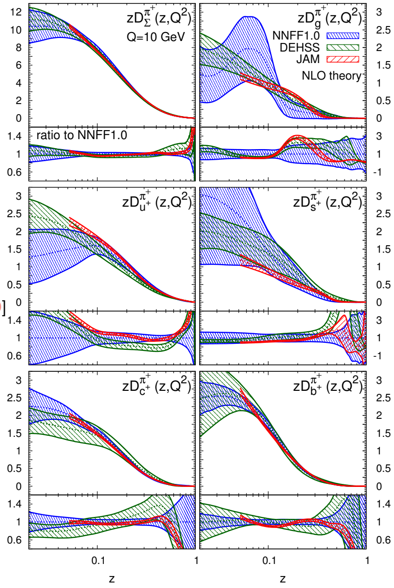
Opportunities at an EIC

one could study kaon multiplicities in SIDIS $\longrightarrow$ further constraint on kaon FFs
one could study CC charm production $W^+ s \to c$ in DIS $\longrightarrow$ direct handle on s, $\bar{s}$

Global fits: SIDIS and Fragmentation Functions

	DHESS	JAM	NNFF
SIA	✓	✓	✓
SIDIS	✓	✓	✗
PP	✓	✗	✓ $(h^{\pm})$
statistical treatment	Iterative Hessian 68% - 90%	Monte Carlo	Monte Carlo
parametrisation	standard	standard	neural network
pert. order	(N)NLO	NLO	up to NNLO
HF scheme	ZM(GM)-VFN	ZM-VFN	ZM-VFN

DEHSS $\pi^{\pm}$ [PRD 91 (2015) 014035] $K^{\pm}$ [PRD 95 (2017) 094019]
JAM $\pi^{\pm}$, $K^{\pm}$ [PRD 94 (2016) 114004]
NNFF $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ [EPJ C77 (2017) 516]



Focus on new data:
BELLE and BABAR SIA cross sections
COMPASS SIDIS multiplicities

Overall fair agreement among the three sets
(except flavour separation for $K^{\pm}$)
NNFF uncertainties usually larger
(especially for the gluon)
Note various shapes for the $\pi^{\pm}$ gluon

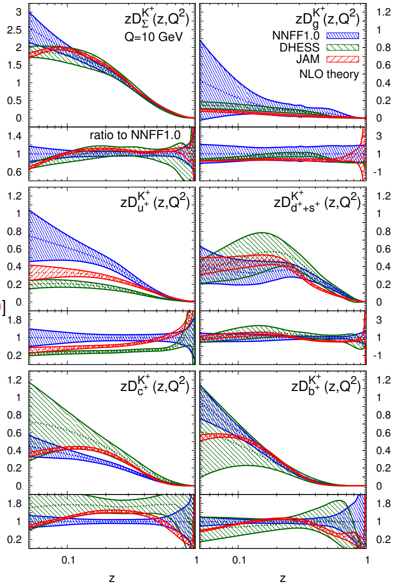
Global fits: SIDIS and Fragmentation Functions

	DHESS	JAM	NNFF
SIA	☑	☑	☑
SIDIS	☑	☑	☒
PP	☑	☒	☑ $(h^{\pm})$
statistical treatment	Iterative Hessian 68% - 90%	Monte Carlo	Monte Carlo
parametrisation	standard	standard	neural network
pert. order	(N)NLO	NLO	up to NNLO
HF scheme	ZM(GM)-VFN	ZM-VFN	ZM-VFN

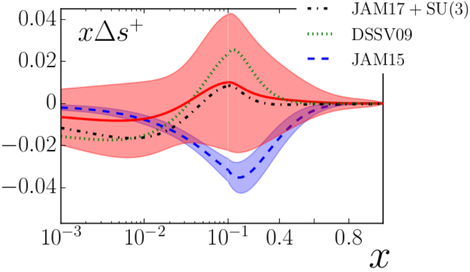
DEHSS $\pi^{\pm}$ [PRD 91 (2015) 014035] $K^{\pm}$ [PRD 95 (2017) 094019]
JAM $\pi^{\pm}$, $K^{\pm}$ [PRD 94 (2016) 114004]
NNFF $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ [EPJ C77 (2017) 516]

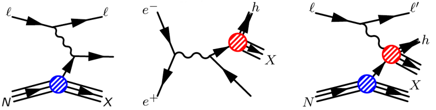
Focus on new data:
BELLE and BABAR SIA cross sections
COMPASS SIDIS multiplicities

Overall fair agreement among the three sets
(except flavour separation for $K^{\pm}$)
NNFF uncertainties usually larger
(especially for the gluon)
Note various shapes for the $\pi^{\pm}$ gluon

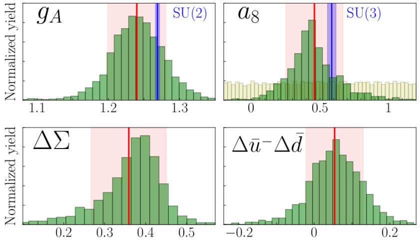


Simultaneous fits of (pol.) PDFs and FFs [PRL 119 (2017) 132001]





process	target	$N_{\rm dat}$	χ^2
DIS	$p, d, {}^3$He	854	854.8
SIA ($\pi^\pm, K^\pm$)		850	997.1
SIDIS ($\pi^\pm$)			
HERMES	d	18	28.1
HERMES	p	18	14.2
COMPASS	d	20	8.0
COMPASS	p	24	18.2
SIDIS ($K^\pm$)			
HERMES	d	27	18.3
COMPASS	d	20	18.7
COMPASS	p	24	12.3
Total:		**1855**	**1969.7**



$g_A = 1.24 \pm 0.04$ $\quad$ $a_8 = 0.46 \pm 0.21$

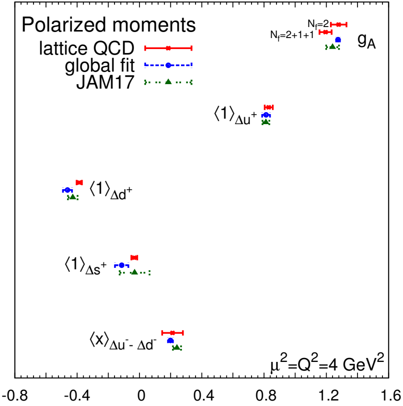
confirmation of SU(2) symmetry to $\sim 2\%$

$\sim 20\%$ SU(3) breaking $\pm 20\%$

$\Delta s^+ = -0.03 \pm 0.09$

$\Delta\Sigma = 0.36\pm0.09$ $\quad$ $\Delta u - \Delta d = 0.05\pm0.08$

Comparing lattice QCD and global fit PDF moments



Moment	Lattice QCD	Global Fit	JAM17
g_A	1.195(39)* 1.279(50)**	1.275(12)	1.240(41)
$\langle 1\rangle_{\Delta u+}$	0.830(26)†	0.813(25)	0.812(22)
$\langle 1\rangle_{\Delta d+}$	-0.386(17)†	-0.462(29)	-0.428(31)
$\langle 1\rangle_{\Delta s+}$	-0.052−-0.014	-0.114(43)	-0.038(96)
$\langle x\rangle_{\Delta u^- - \Delta d^-}$	0.146–0.279	0.199(16)	0.241(26)

* $N_f = 2$.
** $N_f = 2+1+1$.
† Single lattice result available [PRL 119 (2017) 142002].
$\Delta q^{\pm} + \Delta q \pm \Delta\bar{q}$, $q = u, d, s$; $Q = 2$ GeV.
For details, see [Prog.Part.Nucl.Phys. 100 (2018) 107]

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

$$\langle 1\rangle_{\Delta q^+} = \int_0^1 dx\, \Delta q^+(x,Q^2)$$

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

Which precision shall we require to lattice QCD?

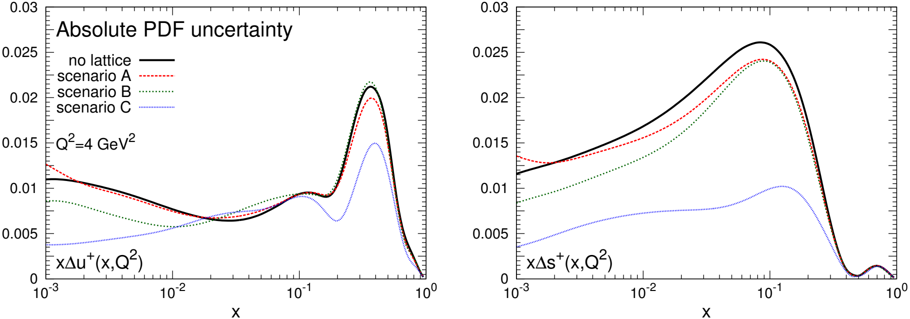
Generate lattice QCD pseudodata assuming NNPDFpol1.1 central values for

$$g_A \equiv \langle 1 \rangle_{\Delta u^+ - \Delta d^+},\ \langle 1 \rangle_{\Delta u^+},\ \langle 1 \rangle_{\Delta d^+},\ \langle 1 \rangle_{\Delta s^+},\ \langle x \rangle_{\Delta u^- - \Delta d^-}$$

Assume percentage uncertainties according to three scenarios

scenario	g_A	$\langle 1 \rangle_{\Delta u^+}$	$\langle 1 \rangle_{\Delta d^+}$	$\langle 1 \rangle_{\Delta s^+}$	$\langle x \rangle_{\Delta u^- - \Delta d^-}$
A	5%	5%	10%	100%	70%
B	3%	3%	5%	50%	30%
C	1%	1%	2%	20%	15%
current	3%	3%	5%	70%	65%

Reweight NNPDFpol1.1 with lattice pseudodata and look at the impact

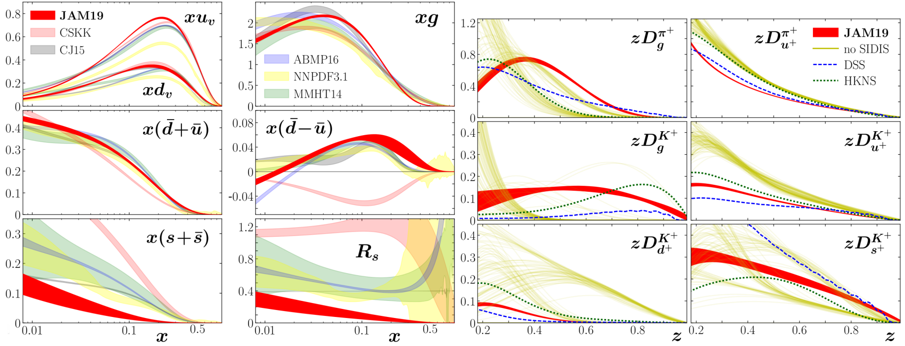


Simultaneous fits of (unp.) PDFs and FFs [arXiv:1905.03788]

Multi-step procedure

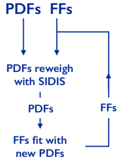
- sampling the posterior distributions from flat priors for fixed-target DIS data (BCDMS, SLAC, NMC)
- update these posteriors with collider DIS data (HERA I-II)
- update the resulting posteriors with DY data (E866)
- sampling the posterior distributions from flat priors for SIA data (DESY, SLAC, CERN, KEK)
- update the FF/PDF posteriors with SIDIS data (COMPASS)

Process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
DIS	2680	1.28
SIDIS	992	1.25
DY	250	1.67
SIA	444	1.27
Total	4366	1.30

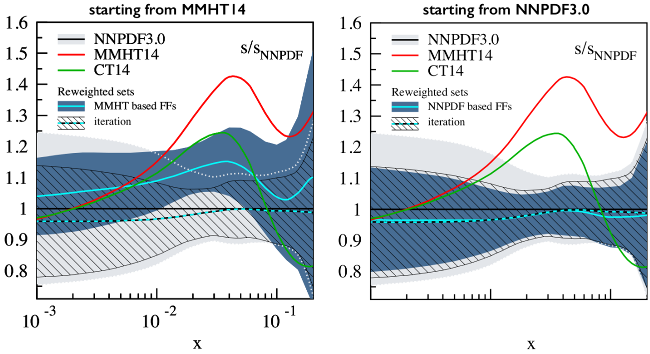


Simultaneous fits of (unp.) PDFs and FFs [PRD 96 (2017) 094020]

IDEA:
iterative reweighting of PDFs and fit of FFs
with kaon SIDIS data ($N_{\rm dat} = 906$)
HERMES [PRD 87 (2013) 074029]
COMPASS [PLB 767 (2017) 133]



**convergence?
and very fast!
robust!**



χ^2_{FF} = 1271.7 | 1041.3 | 1002.3 1017.2 | 1005.3 | 1000.6

similar results with CT14 replicas

Improvements in the NNPDF fit methodology [arXiv:1907.05075]

Current NNPDF methodology
is no longer state-of-the-art

Gradient-based optimisation of large NNs
Quality industry backed libraries available

New NNPDF methodology:
gradient descent techniques

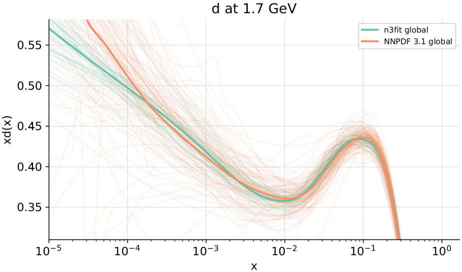
Implemented with Keras + TensorFlow
Performance increased by a factor $\sim$20
Allows to remove a lot of legacy code

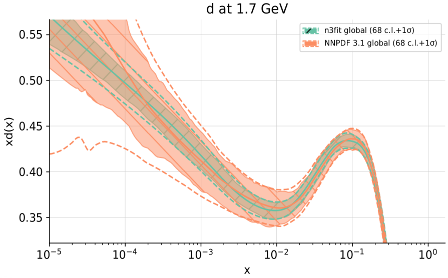
Central values and fit quality
remarkably stable

PDF uncertainties somewhat affected
comparable in the data region
significantly reduced outside

Fewer replicas for equal accuracy

Completely new classes of studies open up





Summary

1. The impact of the data
   - Extended experimental input, with a full control of experimental uncertainties

Unpolarised PDFs	Polarised PDFs
the gluon PDF at small and large x	the gluon PDF at small x
the strange-antistrange asymmetry	the individual quark-antiquark PDFs
fitting charm (photon PDF, resummation,...)	the strange PDF

2. The (limits of the) methodology
   - methodology must adapt accordingly
   - statistical analysis tools necessary to cope with data accuracy
   - PDF uncertainties are faithful, but not optimised
3. The theory frontier
   - theory must adapt accordingly
   - with the reduction of data uncertainties, theoretical uncertainties become relevant
   - a complete characterisation of theoretical uncertainties in PDF fits

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Thank you