Helicity PDFs: status and prospects

The 11th Workshop on Hadron Physics in China
and Opportunities Worldwide

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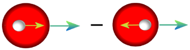
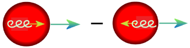
MARIE CURIE ACTIONS

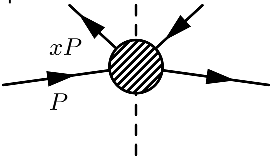
Foreword: parton distributions on the light cone

1. The momentum densities of partons with spin $(^{\uparrow})$ or $(^{\downarrow})$ *w.r.t.* the nucleon

$$\Delta f(x) \equiv f^{\uparrow}(x) - f^{\downarrow}(x)\,, \qquad f = u, \bar{u}, d, \bar{d}, s, \bar{s}, g$$

$\Delta q(x) =$  $\Delta g(x) =$ 

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

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

$$\Delta g(x) = \frac{1}{4\pi x P^{+}}\int dy^{-} e^{-iy^{-}xP^{+}} \langle P,S|G^{+\alpha}(0,y^{-},\mathbf{0}_{\perp})\tilde{G}^{+}_{\alpha}(0)|P,S\rangle$$

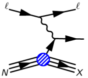
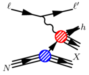
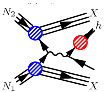
with light-cone coordinates and QCD field-strength tensor G ($A^{+}=0$ gauge)

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

$$G^{\alpha}_{\mu\nu} = \partial_{\mu}A^{a}_{\nu} - \partial_{\nu}A^{a}_{\mu} + f^{abc}A^{b}_{\mu}A^{c}_{\nu}$$

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

Experimental probes

Process	Reaction	Subprocess	PDFs probed	x	$Q^2/p_T^2/M^2$ [GeV^2]
	$\ell^\pm\{p,d,n\}\to\ell^\pm X$	$\gamma^* q\to q$	$\Delta q+\Delta\bar{q}$ Δg	$0.003\lesssim x\lesssim 0.8$	$1\lesssim Q^2\lesssim 70$
	$\ell^\pm\{p,d\}\to\ell^\pm hX$	$\gamma^* q\to q$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$ Δg	$0.005\lesssim x\lesssim 0.5$	$1\lesssim Q^2\lesssim 60$
	$\ell^\pm\{p,d\}\to\ell^\pm DX$	$\gamma^* g\to c\bar{c}$	Δg	$0.06\lesssim x\lesssim 0.2$	~ 10
	$\vec{p}\,\vec{p}\to jet(s)X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.2$	$30\lesssim p_T^2\lesssim 800$
	$\vec{p}\,p\to W^\pm X$	$u_L\bar{d}_R\to W^+$ $d_L\bar{u}_R\to W^-$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$	$0.05\lesssim x\lesssim 0.4$	$\sim M_W^2$
	$\vec{p}\,\vec{p}\to\pi X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.4$	$1\lesssim p_T^2\lesssim 200$

$$\text{DIS}:\qquad g_1=\frac{\sum_q^{n_f} e_q^2}{2n_f}\left(C_{\rm NS}\otimes\Delta q_{\rm NS}+C_{\rm S}\otimes\Delta\Sigma+2n_f C_g\otimes\Delta g\right)$$

$$\text{SIDIS}:\qquad g_1^h=\sum_{q,\bar{q}} e_q^2\left[\Delta q\otimes C_{qq}^{1,h}\otimes D_q^h+\Delta q\otimes C_{gq}^{1,h}\otimes D_g^h+\Delta g\otimes C_{qg}^{1,h}\otimes D_q^h\right]$$

$$pp:\qquad \Delta\sigma=\sigma^{(+)+}-\sigma^{(+)-}=\sum_{a,b,(c)}\Delta f_a\otimes(\Delta)f_b(\otimes D_c^h)\otimes\Delta\hat{\sigma}_{ab}^{(c)}$$

Cs: NNLO for DIS [NPB 889 (2014) 351; arXiv:1908.03779]; NLO for SIDIS and pp
Ps: NNLO [NP B889 (2014) 351]

Recent determinations of polarised PDFs

	DSSV	NNPDF	JAM
DIS	☑	☑	☑
SIDIS	☑	☒	☑
pp	☑ (jets,π^0)	☑ (jets,$W^\pm$)	☒
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$ Monte Carlo	Monte Carlo	Monte Carlo
parametrization	polynomial (23 pars)	neural network (259 pars)	polynomial (10 pars)
features	global fit	minimally biased fit	large-x effects
latest updates	DSSV08 PRD 80 (2009) 034030 DSSV14 PRL 113 (2014) 012001	NNPDFpol1.0 NPB 874 (2013) 36 NNPDFpol1.1 NPB 887 (2014) 276	JAM15 PRD 93 (2016) 074005 JAM17 PRL 119 (2017) 132001

\+ simultaneous determination of PDF uncertainties (data, theory, methodology)

A matematically ill-posed problem: determine a set of functions from a finite set of data

$$E[\mathcal{O}] = \int \mathcal{D}\Delta f \mathcal{P}(\Delta f|data)\mathcal{O}(\Delta f) \qquad V[\mathcal{O}] = \int \mathcal{D}\Delta f \mathcal{P}(\Delta f|data)[\mathcal{O}(\Delta f) - E[\mathcal{O}]]^2$$

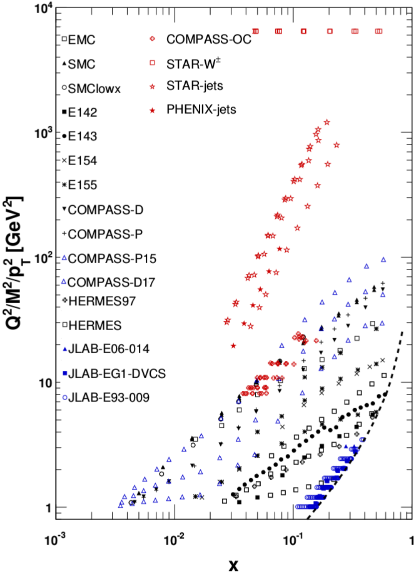
Monte Carlo (JAM, NNPDF, DSSV)

$$\mathcal{P}(\Delta f|data) \longrightarrow \{\Delta f_k\}$$
$$E[\mathcal{O}] \approx \frac{1}{N}\sum_k \mathcal{O}(\Delta f_k)$$
$$V[\mathcal{O}] \approx \frac{1}{N}\sum_k [\mathcal{O}(\Delta f_k) - E[\mathcal{O}]]^2$$

Maximum likelihood (DSSV, LSS, BB)

$$\mathcal{P}(\Delta f|data) \longrightarrow \Delta f_0$$
$$E[\mathcal{O}] \approx \mathcal{O}(\Delta f_0)$$
$$V[\mathcal{O}] \approx \text{Hessian}, \Delta\chi^2\text{envelope}, \ldots$$

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



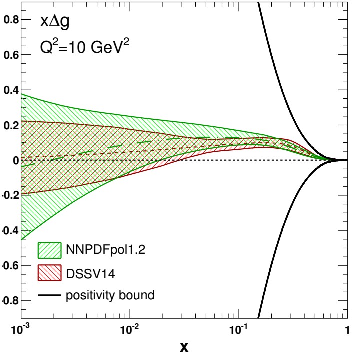
	EXPERIMENT	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ 1.0	1.1	1.2
	EMC	10	0.44	0.43	0.43
	SMC	24	0.93	0.90	0.92
	SMClowx	16	0.97	0.97	0.94
	E142	8	0.67	0.66	0.55
	E143	50	0.64	0.67	0.63
	E154	11	0.40	0.45	0.34
	E155	40	0.89	0.85	0.98
	COMPASS-D	15	0.65	0.70	0.57
	COMPASS-P	15	1.31	1.38	0.93
	HERMES97	8	0.34	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

Gluon polarisation

High-p_T jet production

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



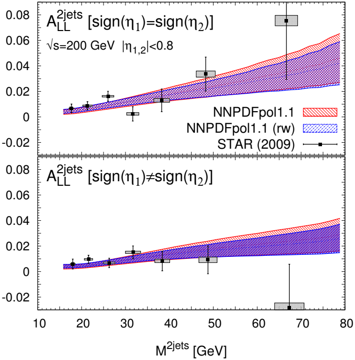
$$\langle x_{1,2}\rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$$

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

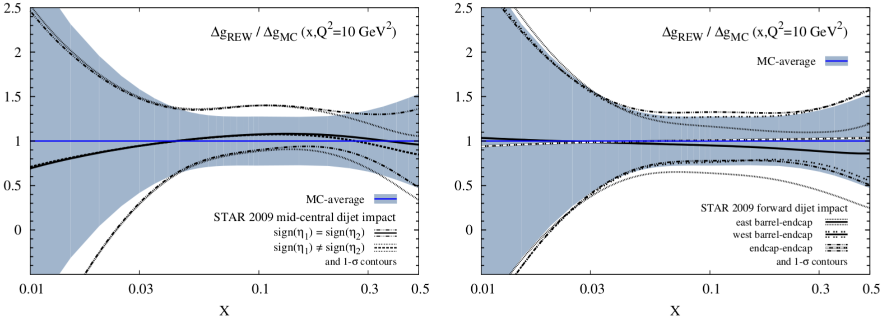


$$\langle x_{1,2}\rangle \simeq \frac{p_T}{\sqrt{s}} (e^{\pm\eta_1 \pm\eta_2}) \approx [0.01, 0.2]$$

x sensitivity extended down to $x \sim 0.01$

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

Gluon polarisation



New Monte Carlo version of the DSSV analysis [arXiv:1902.10548]

Effect of STAR high-p_T dijets at $\sqrt{s} = 200$ GeV similar to that observed in NNPDF

Uncertainty almost unaffected

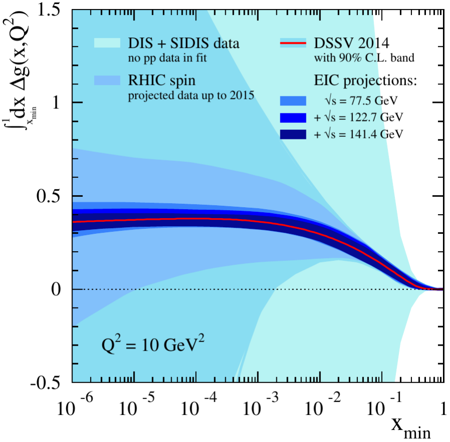
Slight distortion of the central value,
consistent with a positive polarisation, towards smaller values of x

Gluon polarisation

More data available: PHENIX π^0 run 12-13 at 510 GeV [PRD 93 (2016) 011501]
STAR jets and dijets run 12 at 510 GeV [arXiv:1906.02740]
More data to come: STAR dijets run 12-13 at 510 GeV, STAR jets run 12-13 at 510 GeV
Deep insight: a high-energy polarised Electron-Ion Collider [PRD 92 (2015) 094030]

best fit prefers ΔG of about 0.36
70-75% of 1/2

but large uncertainties

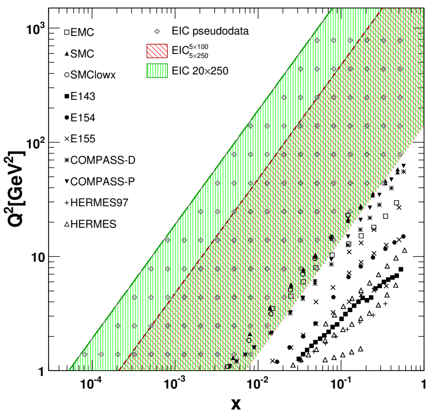


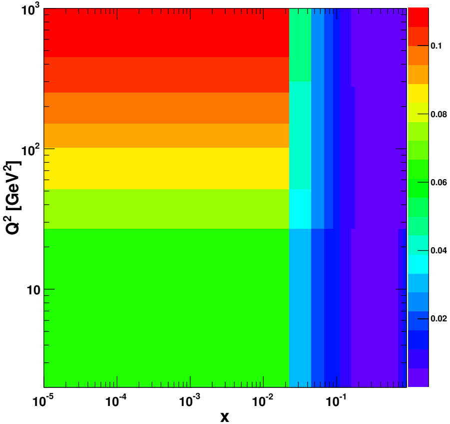
including jet and π^0 RHIC data $\leq$ 2015

510 GeV forward rapidity data will have sensitivity down to few x 10^{-3}

Small-x behaviour can be modified by small-x evolution [JHEP 1601 (2016) 072, JHEP 1710 (2017) 198, ...]

Gluon polarisation and charm





Heavy flavour contribution to g_1, specifically from charm

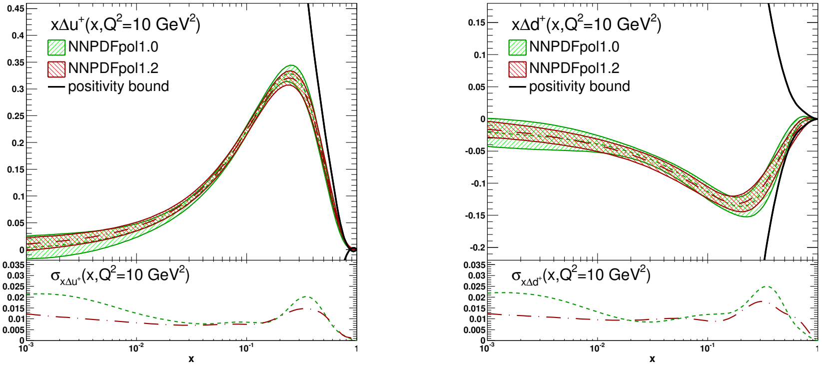
irrelevant ($\ll 1\%$) so far in fixed-target DIS, relevant at an EIC depending on Δg

small Δg (DSSV07) $\Rightarrow g_1^c$ negligible; $A_1^c \sim \mathcal{O}(10^{-5})$ too small to be measured

large Δg (GRSV) $\Rightarrow g_1^c \sim 10 - 15\%$ of g_1 at $x = 10^{-3}$, $Q^2 \simeq 10$ GeV^2; $A_1^c \sim \mathcal{O}(10^{-3})$

charm not massless at the EIC kinematics: relevant NLO corrections are needed

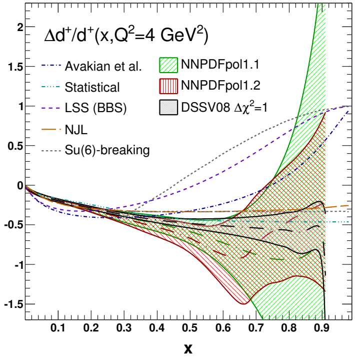
Total up and down polarisations [JPCS 678 (2016) 012030]



- 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)

Total up and down at large x [PLB 742 (2015) 117]

Playground for models

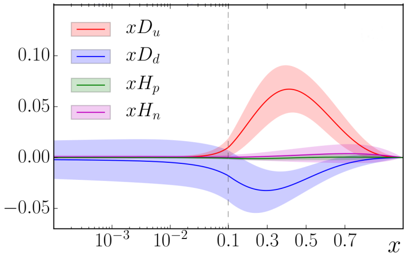


Model	$\Delta d^+/d^+$	Model	$\Delta d^+/d^+$
SU(6)	$-1/3$	NJL	-0.25
RCQM	$-1/3$	DSE (*realistic*)	-0.26
QHD ($\sigma_{1/2}$)	1	DSE (*contact*)	-0.33
QHD (ψ_ρ)	$-1/3$	pQCD	1

NNPDFpol1.1 ($x = 0.9$) -0.74 ± 3.57
NNPDFpol1.2 ($x = 0.9$) -0.23 ± 1.06

Beyond leading-twist factorisation

Fit of higher twist terms (up to $\tau = 4$) in JAM15 [PRD 93 (2016) 074005]

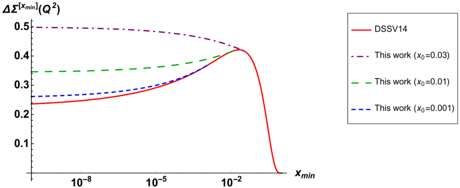


$g_1^{\tau=3} \propto D$ and $g_1^{\tau=4} = H/Q^2$

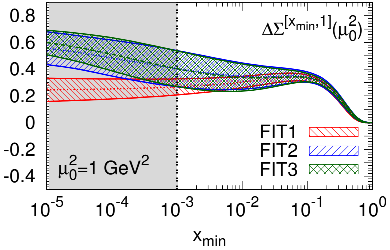
nonzero twist-3 quark distributions

twist-4 quark distributions compatible with zero

Small-x asymptotics of the quark helicity



[JHEP 1601 (2016) 072]



[arXiv:1611.07980]

Small-x evolution equations for g_1

based on the dipole model

resum powers of $\alpha_s \ln^2(1/x)$

become closed for N_C, n_f large

a solution for the flavor-singlet is

$$g_1 \sim \Delta\Sigma \sim \left(\frac{1}{x}\right)^{\alpha_h}, \qquad \alpha_h \sim 2.31\sqrt{\frac{\alpha_s N_C}{2\pi}}$$

Potential solid amount of spin at small x

attach $\Delta\hat{\Sigma}(x,Q^2) = Nx^{-\alpha_h}$ at x_0 to DSSV

detailed phenomenology needed

Should be tested at an EIC

FIT1: $\Delta T_3 = 1.2701 \pm 0.0025$
$\Delta T_8 = 0.585 \pm 0.176$

FIT2: $\Delta U^+ = +1.098 \pm 0.220$
$\Delta D^+ = -0.417 \pm 0.084$
$\Delta S^+ = -0.005 \pm 0.001$

FIT 3 $\Delta U^+ = +1.132 \pm 0.226$
$\Delta D^+ = -0.368 \pm 0.074$
$\Delta S^+ = 0$

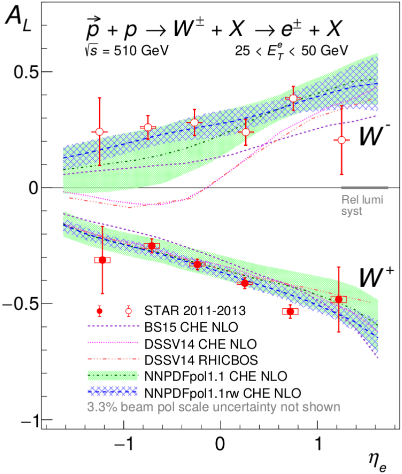
	FIT1	FIT2	FIT3
$\chi^2_{\rm dat}$	0.74	0.76	0.79
$\Delta\Sigma$	$+0.23 \pm 0.09$	$+0.64 \pm 0.14$	$+0.73 \pm 0.16$

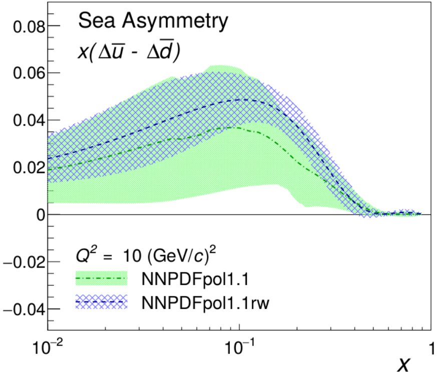
Sea quark polarisation $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$ [arXiv:1702.05077]

$W^{\pm}$ boson production

first evidence of broken flavor symmetry for polarized light sea quarks

New 2013 data [PRD 99 (2019) 51102]





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

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

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

$$\to +0.07 \pm 0.01$$

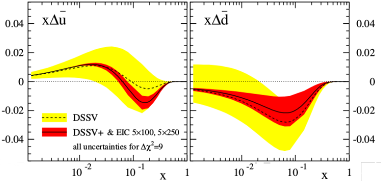
[See also M. Zurek's talk]

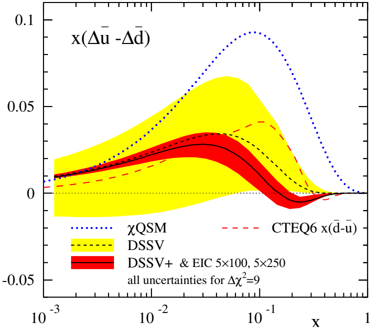
Sea quark polarisation $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$

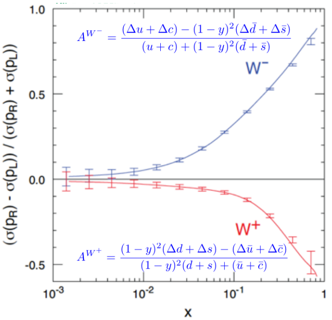
More data available: PHENIX W run 11-13 at 510 GeV [PRD 93 (2016) 051103]

Deep insight: a high-energy polarised Electron-Ion Collider [PRD 88 (2013) 114025]

accurate determination of $\Delta\bar{u}$ and $\Delta\bar{d}$ through CC DIS and SIDIS







$$A_L^{W^+,p} \xrightarrow[y\to 0]{\text{LO}} \frac{\Delta u - \Delta\bar{d}}{u+\bar{d}}$$

$$A_L^{W^+,p} \xrightarrow[y=1/2]{\text{LO}} \frac{4\Delta u - \Delta\bar{d}}{4u+\bar{d}}$$

$$A_L^{W^+,p} \xrightarrow[y\to 1]{\text{LO}} \frac{\Delta u}{u}$$

$\longleftrightarrow$ for $A_L^{W^-,n}$

SU(3) breaking and strangeness

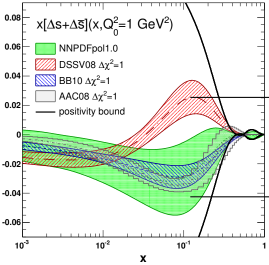
NNPDFpol1.0 [NPB 874 (2013) 36]
$\int_0^1 dx[\Delta s + \Delta \bar{s}] = -0.13 \pm 0.09$

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

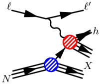
First moment constrained by

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

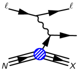
$a_8 = \int_0^1 dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+] = 0.585 \pm 0.025$



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+SIDIS 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, $\bar{s}$
(handle on s-$\bar{s}$ asymmetry also from three-loop evolution [PRD 99 (2019) 054001])

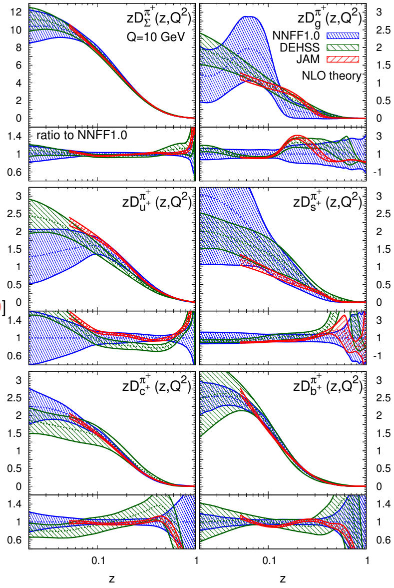
SIDIS and Fragmentation Functions [See A. Vossen's talk]

	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

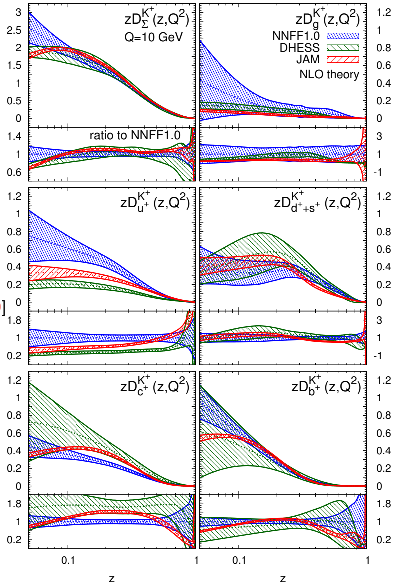
Overall fair agreement among the three sets
(except flavour separation for $K^{\pm}$)
NNFF uncertainties usually larger
(especially for the gluon)
Note various shapes for the $\pi^{\pm}$ gluon



SIDIS and Fragmentation Functions [See A. Vossen's talk]

	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)

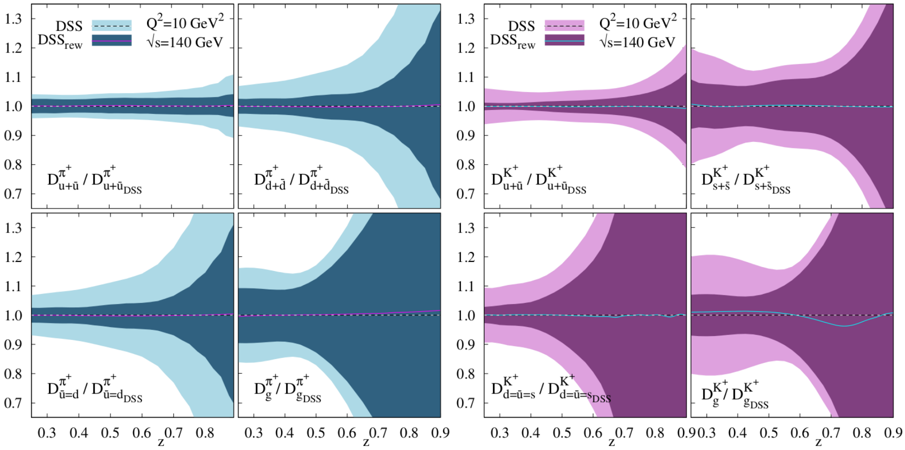
Note various shapes for the $\pi^{\pm}$ gluon

Fragmentation Functions at a future EIC [PRD 99 (2019) 094004]

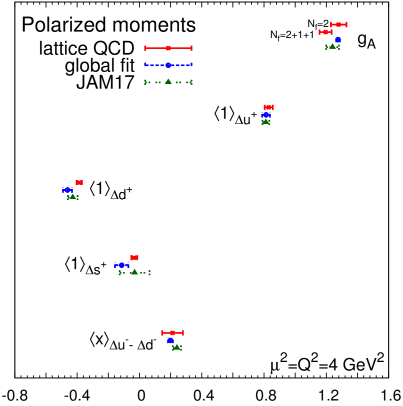
Assess the quantitative impact of simulated $\pi^\pm$ and $K^\pm$ DIS data at an EIC

Consider one kinematic scenario for the EIC ($\sqrt{s}$=140 GeV)

Appreciate the significant impact on all FFs



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?

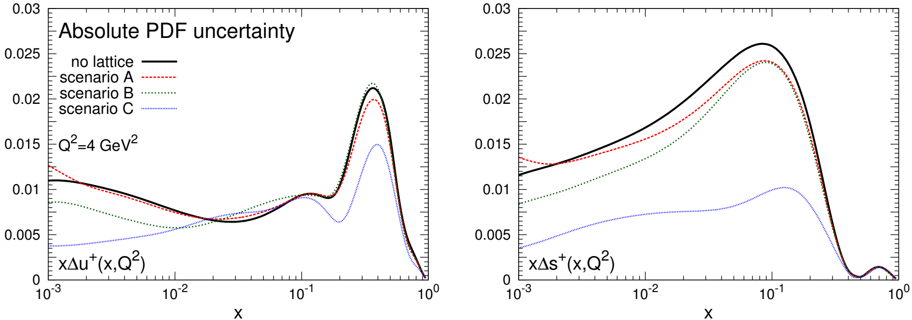
Generate lattice QCD pseudodata assuming NNPDFpol1.1 central values for

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

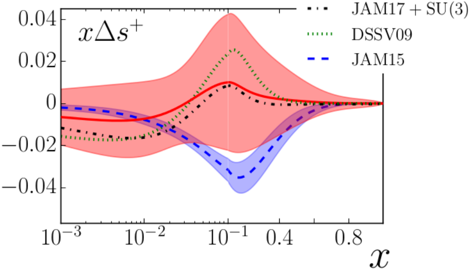
Assume percentage uncertainties according to three scenarios

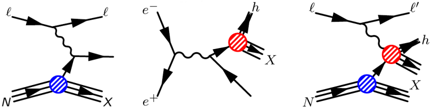
scenario	g_A	$\langle 1 \rangle_{\Delta u^+}$	$\langle 1 \rangle_{\Delta d^+}$	$\langle 1 \rangle_{\Delta s^+}$	$\langle x \rangle_{\Delta u^- - \Delta d^-}$
A	5%	5%	10%	100%	70%
B	3%	3%	5%	50%	30%
C	1%	1%	2%	20%	15%
current	3%	3%	5%	70%	65%

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

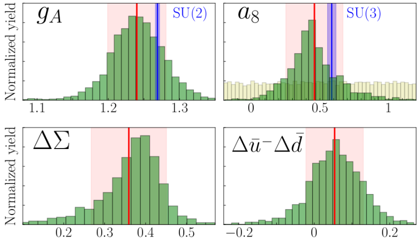


Simultaneous fits of (pol.) PDFs and FFs [PRL 119 (2017) 132001]





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 $\pm 20\%$

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

$\Delta\Sigma = 0.36 \pm 0.09$ $\quad \Delta u - \Delta d = 0.05 \pm 0.08$

Improvements in the NNPDF fit methodology [arXiv:1907.05075]

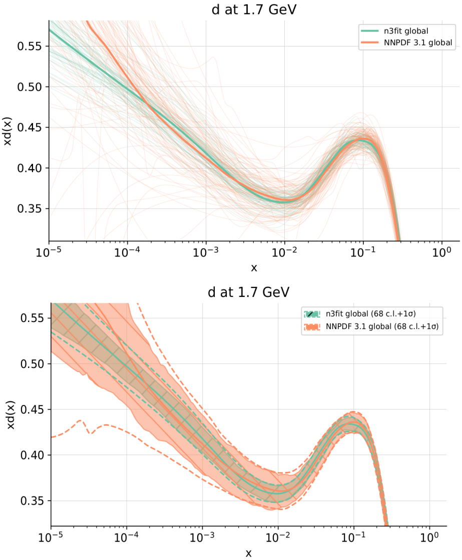
Current NNPDF methodology
is no longer state-of-the-art
Gradient-based optimisation of large NNs
Quality industry backed libraries available

New NNPDF methodology:
gradient descent techniques
Implemened 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



Summary

After three decades of experimental and theoretical activity,
we cannot really say we know $\Delta\Sigma$ and Δg
Main culprit: small-x behavior of polarized PDFs

Spin experiments continue to produce high impact results (RHIC, JLAB, COMPASS)
first evidence of gluon polarization and light sea symmetry in the proton

Theory efforts and global QCD analyses try to keep up

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[Spin] is a mysterious beast, and yet its practical effect prevails the whole of science. The existence of spin, and statistics associated with it, is the most subtle and ingenious design of Nature - without it the whole Universe would collapse.

S-I. Tomonaga, *The story of spin* 2nd ed., University of Chicago Press (1998) [from the preface]

Thank you