Collinear polarised PDFs:
recent results on helicity and transversity extractions

5th International Workshop on Transverse Polarization Phenomena in Hard Processes

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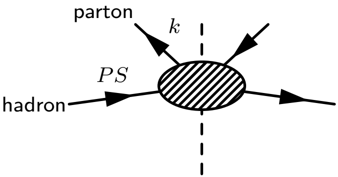
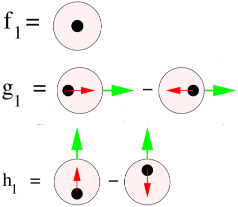
Foreword: (collinear) leading twist PDF map

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Foreword: (collinear) leading twist PDF map





$$\phi_{ij}(k;P,S) = 2\pi \sum_X \int \frac{d^3\mathbf{P}_X}{2E_X} \delta^4(P-k-P_X) \langle P,S|\bar{\psi}_j(0)|X\rangle\langle X|\psi_i(0)|P,S\rangle$$

$$\boxed{\phi(x,S) = \frac{1}{2}\left[\mathbf{f_1}(x)\not{n}_+ + S_L g_1(x)\gamma^5\not{n}_+ + h_1 i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]}$$

In this talk $\mathbf{f_1} \to f$, $g_1 \to \Delta f$ and $h_1 \to h_1$

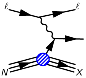
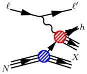
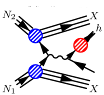
$$f(x) = \frac{1}{4\pi}\int dy^- e^{-ixP^+y^-}\langle P,S|\bar{\psi}_f(0,0,\mathbf{0}_\perp)\gamma^+\mathcal{P}\psi_f(0,y^-,\mathbf{0}_\perp)|P,S\rangle$$

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

$$h_1(x) = \frac{1}{4\pi}\int dy^- e^{-ixP^+y^-}\langle P,S|\bar{\psi}_f(0,0,\mathbf{0}_\perp)i\sigma^{1+}\gamma^5\mathcal{P}\psi_f(0,y^-,\mathbf{0}_\perp)|P,S\rangle$$

1. Collinear helicity

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	$0.05\lesssim x\lesssim 0.4$	$1\lesssim p_T^2\lesssim 200$

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

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

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

Coefficient functions are known up to NNLO for DIS and up to NLO for SIDIS and pp
Splitting functions known up to NNLO [NP B889 (2014) 351]

Available determinations of polarised PDFs

More than 20 years of NLO studies of polarised PDFs

Gehrmann, Stirling [PRD 53 (1996) 6100], Altarelli, Ball, Forte, Ridolfi [APP B29 (1998) 1145], de Florian, Sassot [PRD 57 (1998) 5803], Glück, Reya, Stratmann, Vogelsang [PRD 63 (2001) 094005] ...

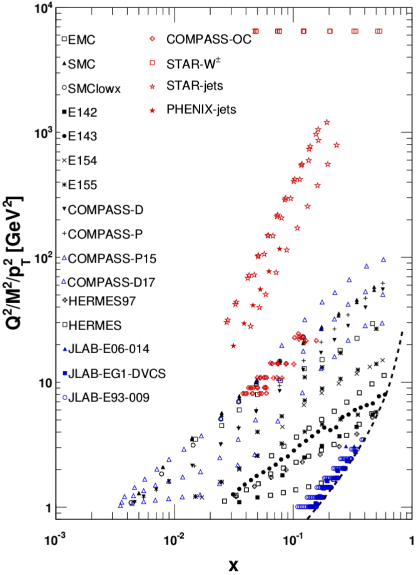
Key players over recent years (all use ZM-VFN scheme and $\overline{\text{MS}}$)

	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
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

Complementary insights from *less global* studies

Leader, Stamenov, Sidorov [PRD 82 (2010) 114018], Blümlein, Böttcher [NPB 841 (2010) 205], Hirai, Kumano [NPB 813 (2009) 106], Bourrely, Buccella, Soffer [NPA 941 (2015) 307], Khanpour et al. (DIS only, NNLO) [PR D93 (2016) 114024], ...

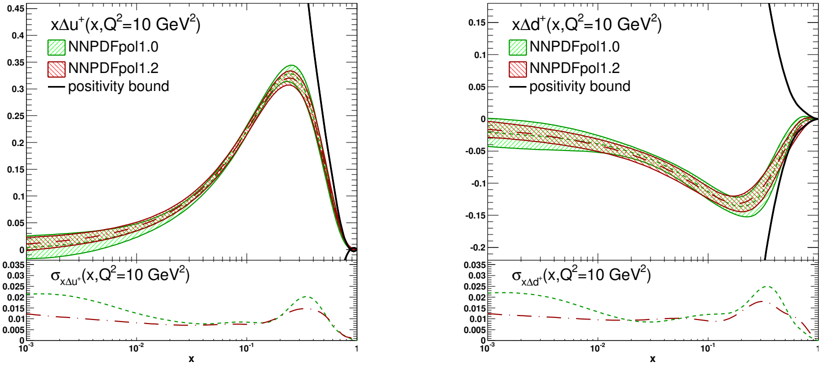
Kinematic coverage and fit quality (from NNPDF)



	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

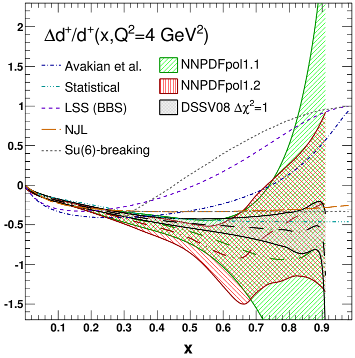
Global fits: total up and down (from NNPDF)



- 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)

Global fits: total up and down at large x

Playground for models

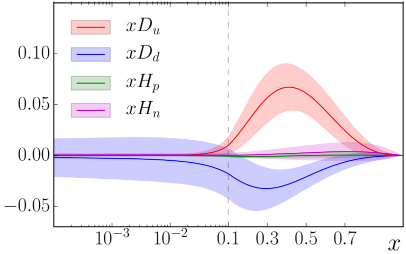


Model	$\Delta d^+/d^+$	Model	$\Delta d^+/d^+$
SU(6)	$-1/3$	NJL	-0.25
RCQM	$-1/3$	DSE (*realistic*)	-0.26
QHD ($\sigma_{1/2}$)	1	DSE (*contact*)	-0.33
QHD (ψ_ρ)	$-1/3$	pQCD	1

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]



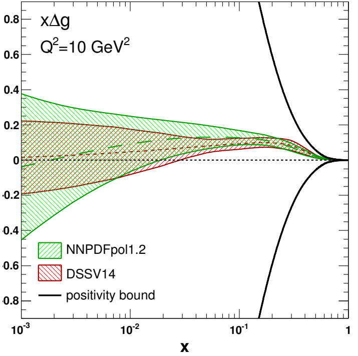
$g_1^{\tau=3} \propto D$ and $g_1^{\tau=4} = H/Q^2$

nonzero twist-3 quark distributions

twist-4 quark distributions compatible with zero

Global fits: gluon polarisation

High-p_T jet production
first evidence of a sizeable, positive gluon polarization in the proton

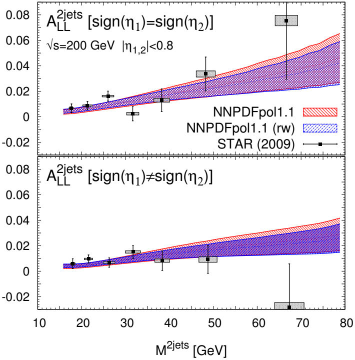


$$\langle x_{1,2}\rangle \simeq \frac{2p_T}{\sqrt{s}}e^{-\eta/2} \approx [0.05, 0.2]$$

NNPDF and DSSV results well compatible

$$\int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = +0.23\pm0.15$$

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 $x \sim 0.01$

$$\int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\mathrm{GeV}^2) = +0.32\pm0.13$$

Global fits: gluon polarisation

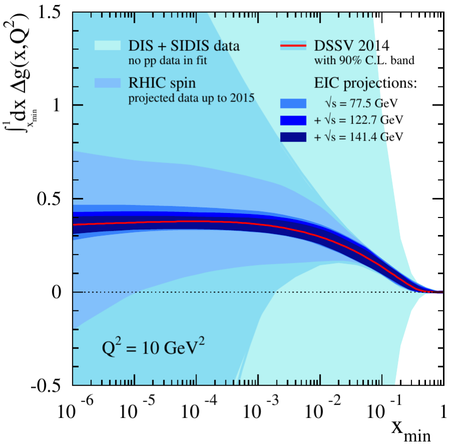
More data available: PHENIX π^0 run 12-13 at 510 GeV [PRD 93 (2016) 011501]
STAR dijets run 12 at 510 GeV [PoS(DIS2016)231]

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

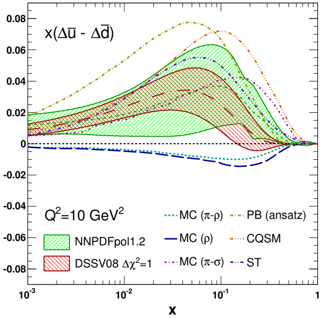
510 GeV forward rapidity data will have sensitivity down to few x 10^{-3}

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

Global fits: 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



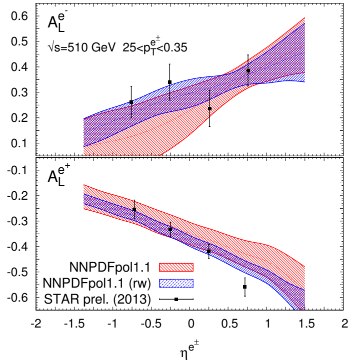
$$\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$$

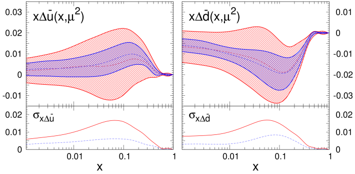
$$\Delta\bar{u} > 0 > \Delta\bar{d},\ |\Delta\bar{d}| > |\Delta\bar{u}|$$

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

$$\rightarrow +0.07 \pm 0.01$$

Preliminary 2013 data [arXiv:1702:02927]

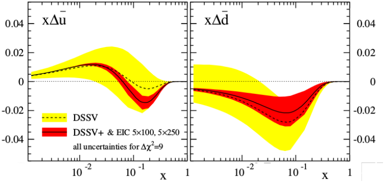


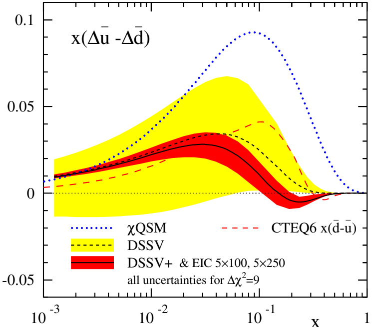


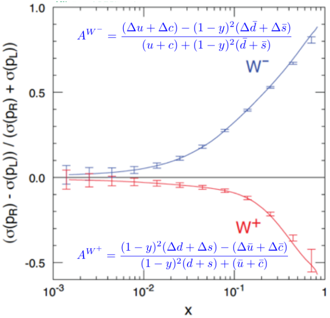
Global fits: sea quark polarisation $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$

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







$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d}+\bar{s})}$$

$$A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u}+\bar{c})}$$

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

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

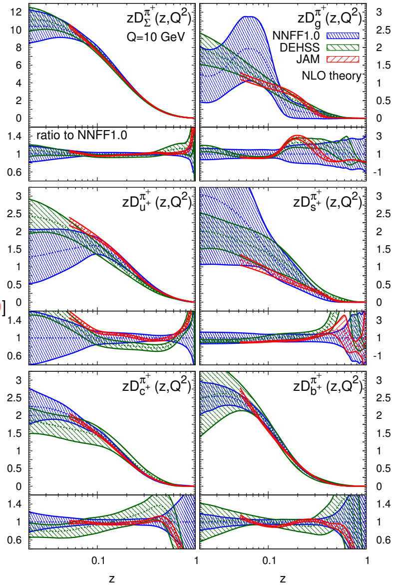
$$A_L^{W^+,p} \xrightarrow[y\to 1]{\text{LO}} \frac{\Delta u}{u}$$

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

Global fits: SIDIS and Fragmentation Functions [see also A. Vossen talk]

	DHESS	JAM	NNFF
SIA	☑	☑	☑
SIDIS	☑	☒	☒
PP	☑	☒	☒
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 [see also A. Vossen talk]

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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]
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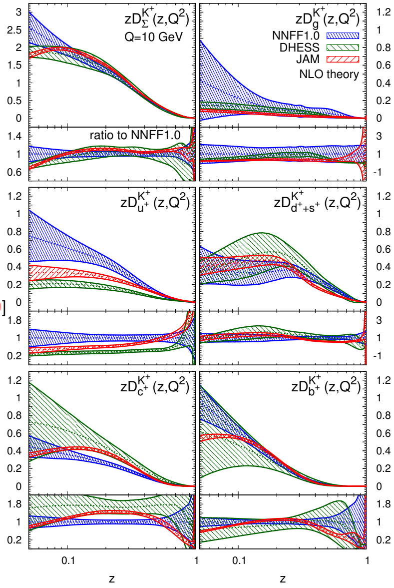
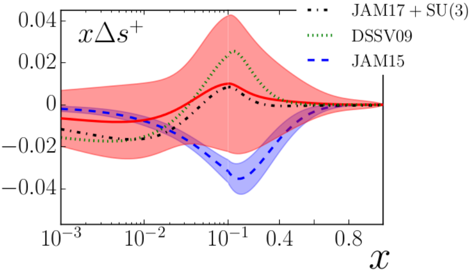
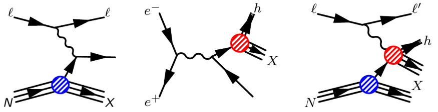
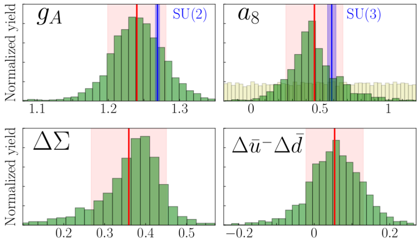


Simultaneous fits: Δs from JAM17 [PRL 119 (2017) 132001, more in J. Ethier talk]







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 $\sim 2\%$

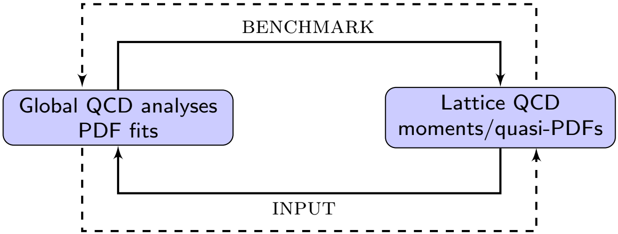
$\sim 20\%$ SU(3) breaking $\pm 20\%$

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

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

See [PR D96 (2017) 094020] for a simultaneous fit of FFs and the unpolarised strange via reweighting

Lattice QCD and (helicity) PDFs [arXiv:1709.01511; arXiv:1711.07916]



Define a mutually agreed conventional notation
for relevant PDF-related quantities, such as PDF moments.

Assess the sources of systematic uncertainties in lattice-QCD calculations.

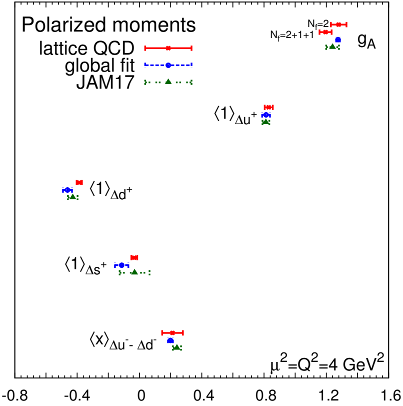
Identify a best-set of quantities
to benchmark lattice-QCD calculations against global-fit determinations.

Set precision targets for lattice-QCD calculations
with respect to global-fit determinations.

Assess the impact of lattice-QCD calculations
on global-fit determinations within their current/projected precision.

The PDFLattice2017 workshop, Balliol College, Oxford, 22-24 March 2017
http://www.physics.ox.ac.uk/confs/PDFlattice2017/index.asp

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 [arXiv:1711.07916]

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

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

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

Which precision shall we require to lattice QCD?

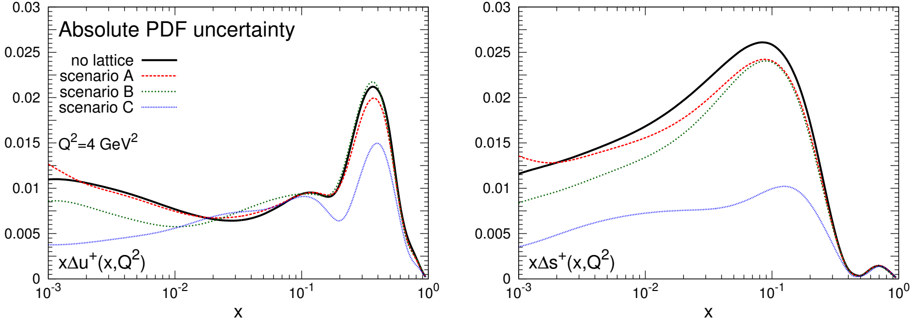
Generate lattice QCD pseudodata assuming NNPDFpol1.1 central values for

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

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



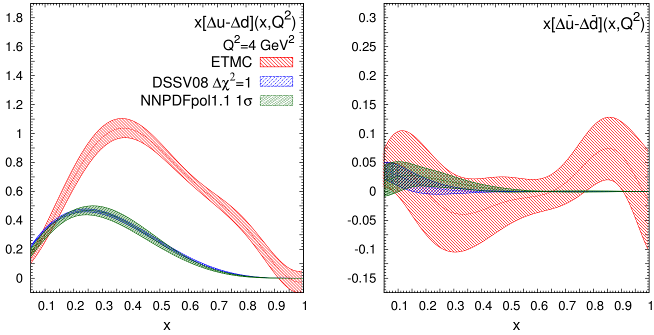
Comparing lattice QCD and global fit PDFs

Quasi-PDFs defined as momentum-dependent nonlocal static matrix elements for nucleon states at finite momentum, with an ultraviolet cut-off scale $\Lambda \sim 1/a$

$$\widetilde{q}(x,\Lambda,p_z) = \int \frac{dz}{4\pi} e^{-ixzp_z} \frac{1}{2}\sum_{s=1}^{2} \langle p,s|\, \bar{\psi}(z)\gamma_\alpha e^{ig\int_0^z A_z(z')dz'}\psi(0)\,|p,s\rangle$$

Must be related to the corresponding light-front PDF, usually within LaMET

$$\widetilde{q}(x,\Lambda,p_z) = \int_{-1}^{1} \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{p_z},\frac{\Lambda}{p_z}\right)_{\mu^2=Q^2} q(y,Q^2) + \mathcal{O}\left(\frac{\Lambda^2_{\text{QCD}}}{p_z^2},\frac{m^2}{p_z^2}\right)$$



[More in M. Constantinou and K. Orginos talks on Wednesday afternoon]

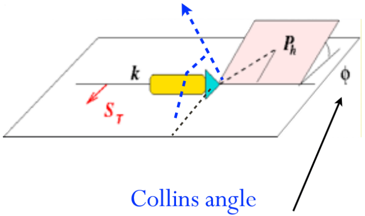
2. Collinear transversity

Experimental probes

The transversity is a chiral-odd function, two helicity flips are needed

Single hadron production

[NP B395 (1993) 161]



$$\mathbf{k}\times\mathbf{P}_h\cdot\mathbf{S_T}\propto\sin(\Phi+\Phi_S)$$

$$\mathbf{P}_h^T\neq 0$$

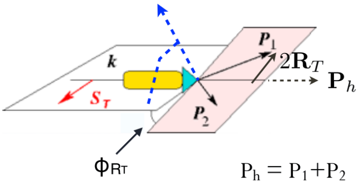
Transverse momentum of h required

Framework of TMD factorisation

$$A_{UT}^{\sin(\Phi+\Phi_S)}\propto\frac{\sum_q e_q^2 h_1^q\otimes H_1^{\perp q}}{\sum_q e_q^2 f_1^q\otimes D_1^q}$$

Di-hadron fragmentation

[NP B420 (1994) 565]



$$\mathbf{P}_h\times\mathbf{R}_T\cdot\mathbf{S_T}\propto\sin(\Phi_{R_T}+\Phi_S)$$

$$\mathbf{R}_T\neq 0 \qquad \mathbf{P}_h^T=0$$

The hadron pair is collinear

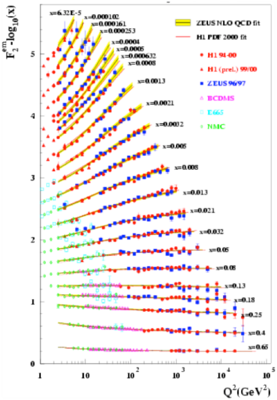
Framework of collinear factorisation

$$A_{UT}^{\sin(\Phi_{R_T}+\Phi_S)}\propto-\frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2 h_1^q H_1^{\sphericalangle}}{\sum_q e_q^2 f_1^q D_1^q}$$

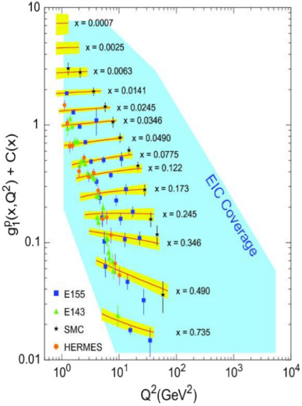
Kinematic coverage

On the experimental side, the history of transverse polarisation distributions is readily summarised: (almost) no measurements have been performed as yet. [Phys.Rept. 359 (2002) 1]

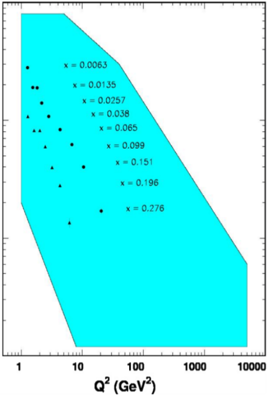
World data for F_2^p



World data for g_1^p



World data for **h_1**



f_1 from fits of **thousands** data

g_1 from fits of **hundreds** data

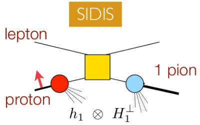
h_1 from fits of **tens** data

[H. Montgomery, QCDevolution 2016]

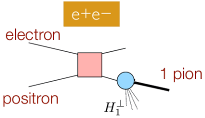
Experimental data

[See talks by A. Bressan, C. Van Hulse, Z.-E. Meziani, E. Aschenauer, A. Vossen, G. Schnell, B. Surrow, . . .]

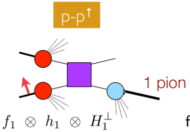
Collins fragmentation



HERMES [PRL 94 (2005) 012002; PL B693 (2010) 11]
COMPASS [PL B673 (2009) 127; PL B744 (2015) 250]
JLab [PRL 107 (2011) 072003]

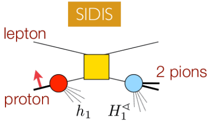


BELLE [PRL 96 (2006) 232002; PRD D78 (2008) 032011]
BABAR [PRD 90 (2014) 052003]

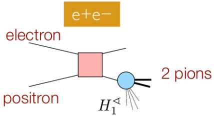


factorisation(?)

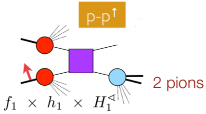
Di-hadron fragmentation



HERMES [JHEP 0806 (2008) 017]
COMPASS [PL B713 (2012) 10; EPJ WC 85 (2015) 02018]

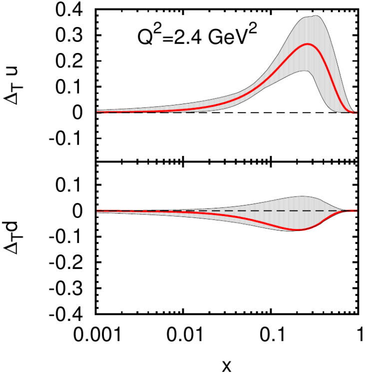


BELLE [PRL 107 (2011) 072004]



STAR [PRL 115 (2015) 242501]

Transversity from Collins effect [Anselmino at al., specifically PRD 92 (2015) 114023]



Experiment	χ^2	n. points	χ^2/points
Belle-z_1z_2 A_0^{UL}	14.0	16	0.88
Belle-z_1z_2 A_0^{UC}	13.6	16	0.85
BaBar-z_1z_2 A_0^{UL}	37.3	36	1.04
BaBar-z_1z_2 A_0^{UC}	13.0	36	0.36
BaBar-P_{1T} A_0^{UL}	5.6	9	0.63
BaBar-P_{1T} A_0^{UC}	3.1	9	0.35
Total A_0	86.7	122	0.71
HERMES p	31.6	42	0.75
COMPASS p	40.2	52	0.77
COMPASS d	58.5	52	1.12
Total SIDIS	130.3	146	0.89
Total	217.0	268	$\chi^2_{\rm d.o.f.} = 0.84$

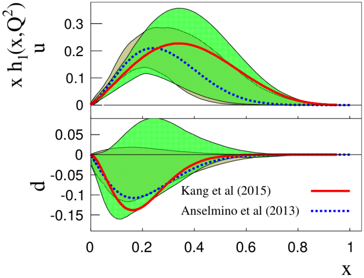
$$h_1^q(x,k_\perp,Q^2) = h_1^q(x,Q^2)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T} \qquad h_1^q(x,Q_0^2) = \mathcal{N}_q^T(x,Q_0^2)\,\frac{1}{2}\left[q(x,Q_0^2)+\Delta q(x,Q_0^2)\right]$$

$$\mathcal{N}_q^T(x) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha\beta^\beta} \qquad (q = u_v, d_v)$$

Simple, LO, phenomenological model with DGLAP evolution

Mild dependence of h_1 on TMD evolution, almost canceled out in asymmetry ratios

Transversity from Collins effect [PR D93 (2016) 014009]



Experiment	Observable	dependence	# ndata	χ^2	$\chi^2/ndata$
BELLE [12]	A_0^{UL}	z	16	13.02	0.81
BELLE [12]	A_0^{UC}	z	16	11.54	0.72
BABAR[98]	A_0^{UL}	z	36	34.61	0.96
BABAR[98]	A_0^{UC}	z	36	15.17	0.42
BABAR[98]	A_0^{UL}	$P_{h\perp}$	9	9.09	1.01
BABAR[98]	A_0^{UC}	$P_{h\perp}$	9	4.33	0.48
			122	87.76	0.72

Experiment	hadron	Target	dependence	# ndata	χ^2	$\chi^2/ndata$
COMPASS [97]	π^+	LiD	x	9	11.16	1.24
COMPASS [97]	π^-	LiD	x	9	9.08	1.01
COMPASS [97]	π^+	LiD	z	8	3.26	0.41
COMPASS [97]	π^-	LiD	z	8	7.29	0.91
COMPASS [97]	π^+	LiD	$P_{h\perp}$	6	4.19	0.70
COMPASS [97]	π^-	LiD	$P_{h\perp}$	6	4.50	0.75
COMPASS [96]	π^+	NH_3	x	9	21.46	2.38
COMPASS [96]	π^-	NH_3	x	9	6.23	0.69
COMPASS [96]	π^+	NH_3	z	8	7.80	0.98
COMPASS [96]	π^-	NH_3	z	8	10.29	1.29
COMPASS [96]	π^+	NH_3	$P_{h\perp}$	6	3.82	0.64
COMPASS [96]	π^-	NH_3	$P_{h\perp}$	6	3.85	0.64
HERMES [95]	π^+	H	x	7	5.37	0.77
HERMES [95]	π^-	H	x	7	12.61	1.80
HERMES [95]	π^+	H	z	7	3.04	0.43
HERMES [95]	π^-	H	z	7	3.23	0.46
HERMES [95]	π^+	H	$P_{h\perp}$	6	1.60	0.27
HERMES [95]	π^-	H	$P_{h\perp}$	6	4.82	0.80
JLAB [9]	π^+	^{3}He	x	4	3.90	0.98
JLAB [9]	π^-	^{3}He	x	4	3.11	0.78
				140	130.65	0.93

at NLL with TMD evolution

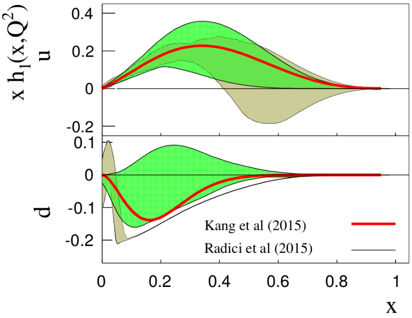
same parametrisation as in [PRD 92 (2015) 114023]

$$h_1(x,Q_0^2) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha \beta^\beta} \frac{1}{2}\left[q(x,Q_0^2) + \Delta q(x,Q_0^2)\right] \qquad (q = u_v, d_v)$$

Good consistency with Anselmino et al.

Mild dependence of h_1 on TMD evolution within the current precision of the data

Transversity from di-hadron fragmentation [JHEP 1505 (2015) 123]



χ^2/d.o.f.	$\alpha_s(M_Z^2) = 0.125$	$\alpha_s(M_Z^2) = 0.139$
rigid	1.42	1.46
flexible	1.65	1.71
extraflexible	1.97	2.07

Determine the DiFF from e^+e^- data

Use such a DiFF to extract h_1^q in SIDIS

Make use of Monte Carlo techniques to estimate the PDF uncertainty

Study the stability of the fit upon three parametrisations and two values of α_s

Mild dependence on these choices

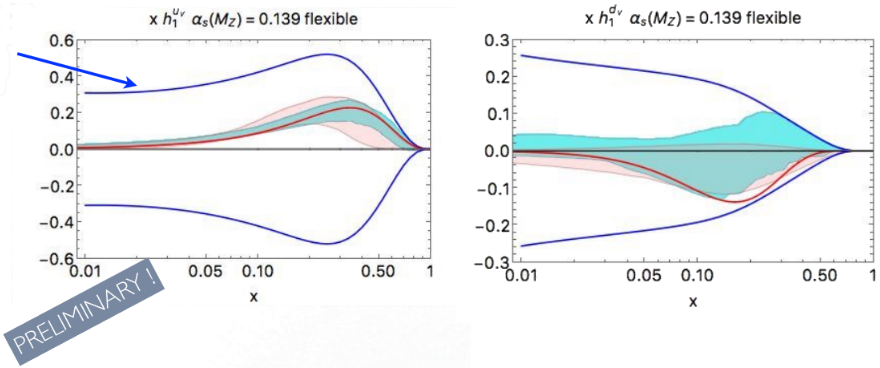
Agreement of $h_1^{u_V}$ with Kang et al. (and Anselmino et al.)

Saturation of the Soffer bound in $h_1^{d_V}$ driven by COMPASS deuteron bins 7-8 (more flexibility in the parametrisation)

$$xh_1^q(x,Q_0^2) = \tanh\left[x^{1/2}(A_q + B_q x + C_q x^2 + D_q x^3)\right] x \left[\mathrm{SB}^q(x,Q_0^2) + \mathrm{SB}^{\bar{q}}(x,Q_0^2)\right]$$

rigid $C_q = D_q = 0$ flexible $C_q = 0$ $D_q \neq 0$ extraflexible $C_q \neq D_q \neq 0$

Transversity from di-hadron fragmentation [See talk by M. Radici]



blue line: Soffer bound

red line: Kang et al. pink band: Anselmino et al. cyan band: Bacchetta et al. (prel.)

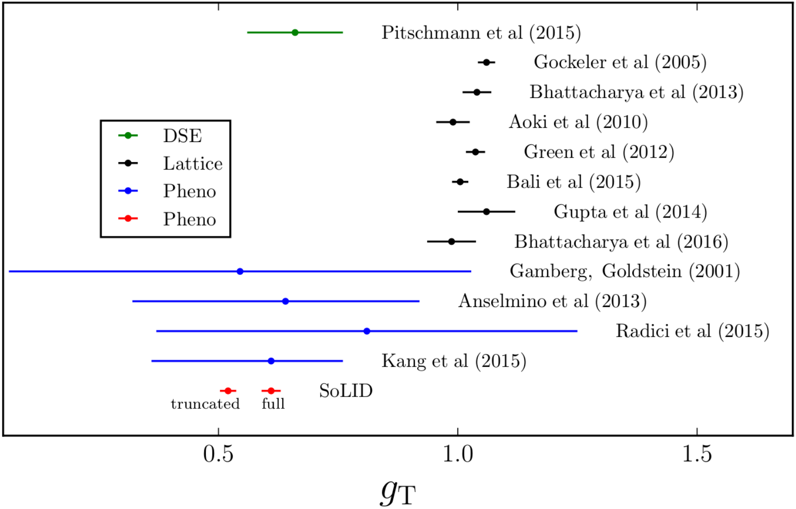
Extend the data set to DiFFs in transversely polarised collisions at RHIC

Include STAR 2006 run data [PRL 115 (2015) 242501]

Effect of the new data: higher precision and better compatibility

The isovector charge g_T and lattice [See also lattice talks on Wednesday afternoon]

$$g_T \equiv \delta u - \delta d \qquad \delta q \equiv \int_0^1 dx\,\left[h_1^q(x) - h_1^{\bar{q}}\right]$$



[PL B767 (2017) 91; see A. Prokudin talk for the projected uncertainties including SoLID pseudodata]

Is lattice in tension with phenomenology?

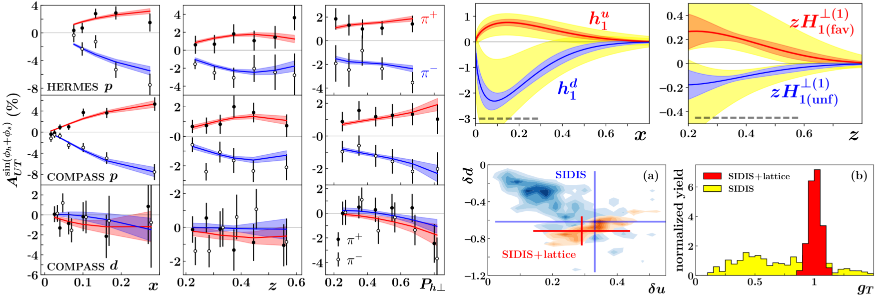
Simultaneous fit to the Collins asymmetry data from HERMES and COMPASS of

$$f_1^q(x,k_\perp^2) \qquad h_1^q(x,k_\perp^2) \qquad D_1^{h/q}(z,p_\perp^2) \qquad H_1^{\perp h/q}(z,p_\perp)$$

and to three lattice *data sets* with reliable estimate of systematic ucnertainties

PDNME [Bhattacharya et al. (2016)] RQCD [Bali et al. (2015)] LHPC [Green et al. (2012)]

using Monte Carlo techniques for the representation of uncertainties



[arXiv:1710.09858, see also J. Ethier]

Excellent description of the data with and without lattice results ($\chi^2/N_{\rm dat} = 0.65$)

Lattice results are compatible with measured asymmetries

Lattice results are able to reduce the uncertainty on h_1 and $H_1^\perp$ significantly

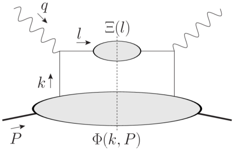
Transversity in inclusive DIS [PL B773 (2017) 632, see also A. Accardi talk]

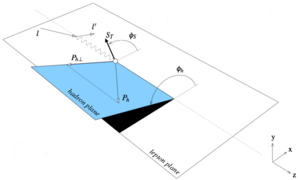
In DIS, on-shell quarks cannot be present in the final state, but they decay into hadrons
A nonperturbative spin-flip term associated with M_q couples to h_1

$$\Xi(l^-, \mathbf{l}_T) \equiv \int \frac{dl^2}{2l^-}\Xi(l) = \frac{\Lambda}{2l^-}\xi_1 \mathbf{1} + \xi_2 \frac{\not{n}^-}{2} + \text{h.t. terms}$$

$$\xi_1 = \int d\mu^2 \frac{\mu}{\Lambda} J_1(\mu^2) \equiv \frac{M_q}{\Lambda} \quad \xi_2 = \int d\mu^2 J_2(\mu^2) = 1 \quad \text{(quark spectral functions)}$$

from positivity $\quad 0 < M_q < \int d\mu^2 \mu J_2(\mu^2) \Longrightarrow M_q = \mathcal{O}(10 - 100\ \text{GeV}) \quad$ much larger than m_q





$$\frac{d\sigma}{dx_B\, dy\, d\Phi_S} \propto \left\{ F_T + \epsilon F_L + S_\parallel \lambda_e \sqrt{1-\epsilon^2} F_{LL} + |\mathbf{S}_T| \lambda_e \sqrt{2\epsilon(1-\epsilon)} \cos\Phi_S F_{LT}^{\cos\Phi_S} \right\}$$

$$F_T = x_B \sum_q e_q^2 f_1^q(x_B) \quad F_L = 0 \quad F_{LL} = x_B \sum_q e_q^2 g_1^q(x_B)$$

$$F_{LT}^{\cos\Phi_S} = -x_B \sum_q e_q^2 \frac{2M}{Q} \left(x_B g_T^q(x_B) + \frac{M_q - m_q}{M} h_1^q(x_B) \right)$$

3. Conclusions

Summary

1. Continuous effort in improving the existing determinations of collinear PDFs
   - Data: *global fits*

     $\longrightarrow$ inclusion of a variety of obervables, consistency of the QCD framework

     $\longrightarrow$ increasing experimental precision, extended kinematic range
   - Methodology: *simultaneous fits*

     $\longrightarrow$ non-trivial interplay between PDFs and FFs

     $\longrightarrow$ accompanied by an increased sophistication of the fitting techniques
   - Theory: *improved fits*

     $\longrightarrow$ refinement of the QCD details in the PDF analyses
2. Possible fruitful interplay between QCD fits and lattice QCD calculations
   - An extensive benchmark for helicity PDFs is now available

     $\longrightarrow$ competitive lattice QCD moments

     $\longrightarrow$ promising methods to determine the PDF x dependence
   - Studies of the impact of lattice QCD on trasversity are promising

     $\longrightarrow$ lattice QCD results on g_T pin down theh uncertainty on h_1 significantly
3. Combination of all the above will perfectly fit into the EIC program

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   - Studies of the impact of lattice QCD on trasversity are promising

     $\longrightarrow$ lattice QCD results on g_T pin down theh uncertainty on h_1 significantly
3. Combination of all the above will perfectly fit into the EIC program

Thank you

4. Additional material

From NNPDFpol1.0: SU(2) and SU(3)

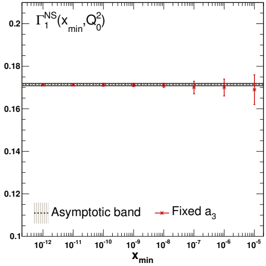
fixed

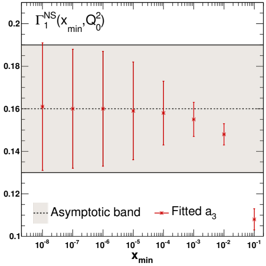
$$a3 = 1.2701 \pm 0.0025$$

fitted

$$a_3 = 1.19 \pm 0.22$$

$$\Gamma_1^{\rm NS}(x_{\rm min}, Q^2) \equiv \int_{x_{\rm min}}^1 dx [g_1^p(x, Q^2) - g_1^n(x, Q^2)] \xrightarrow{x_{\rm min}=0} \frac{1}{6} a_3(Q^2) \Delta C_{\rm NS}[\alpha_s(Q^2)]$$





NNPDFpol1.0 [NPB 874 (2013) 36]

$$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.13 \pm 0.09$$

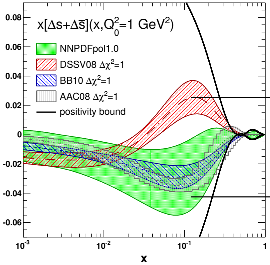
JAM17 [arXiv:1705.05889]

$$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.03 \pm 0.10$$

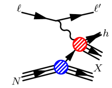
First moment constrained by

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

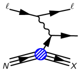
$$a_8 = \int_0^1 dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+] = 0.585 \pm 0.176$$



directly from SIDIS Kaon data



indirectly from DIS + SU(3)



JAM17, first moments fitted: $a_3 = 1.24 \pm 0.04$ $a_8 = 0.46 \pm 0.21$

Appraising lattice QCD calculations

Mom.	Collab.	Ref.	N_f	discretisation	quark mass	finite volume	renormalisation	excited states		Value
g_A	CalLat 17	[arXiv:1704.01114]	2+1+1	■	★	■	★	★	◇	1.278(21)(26)
	PNDME 16	[PRD 94 (2016) 054508]	2+1+1	○	★	○	★	★		1.195(33)(20)
	LHPC 14	[PLB 734 (2014) 290]	2+1	■	★	★	★	★		0.97(8)
	Mainz 17	[arXiv:1705.06186]	2	★	○	★	★	★		$1.278(68)(^{+0}_{-0.087})$
	ETMC 17	[arXiv:1705.03399]	2	■	★	■	★	★	*	1.212(33)(22)
	RQCD 15	[PRD 91 (2015) 054501]	2	○	○	○	★	○	‡	1.280(44)(46)
	QCDSF 14	[PLB 732 (2014) 41]	2	○	○	○	★	■	‡	1.29(5)(3)
$\langle 1\rangle_{\Delta u^+}$	ETMC 17	[arXiv:1706.02973]	2	■	★	■	★	★	*	$0.830(26)(4)$
$\langle 1\rangle_{\Delta d^+}$	ETMC 17	[arXiv:1706.02973]	2	■	★	■	★	★	*	$-0.386(16)(6)$
$\langle 1\rangle_{\Delta s^+}$	χQCD 17	[PRD 95 (2017) 114509]	2+1	■	○	○	★	★	†,◁	-0.0403(44)(78)
	Engelhardt 12	[PRD 86 (2012) 114510]	2+1	■	■	○	★	★	◁	-0.031(17)
	ETMC 17	[arXiv:1706.02973]	2	■	★	■	★	★	*	-0.042(10)(2)
$\langle x\rangle_{\Delta u^- - \Delta d^-}$	RBC/ UKQCD 10	[PRD 82 (2010) 014501]	2+1	■	■	★	★	■		0.256(23)/ 0.205(59)
	LHPC 10	[PRD 82 (2010) 094502]	2+1	■	■	○	○	■		0.1972(55)
	ETMC 15	[PRD 92 (2015) 114513]	2	■	★	■	★	★	*	0.229(33)

* Study employing a single physical pion mass ensemble.

‡ g_A is determined via the ratio g_A/f_π employing the physical value for f_π.

◇ Approach inspired by the Feynman-Hellmann method is employed.

† Partially quenched simulation with $m_\pi = 330$ MeV.

◁ Some parts of the renormalisation are estimated.