Helicity PDFs: status and prospects

Precision QCD Predictions for ep Physics at the EIC

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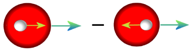
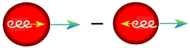
Helicity-dependent PDFs and the proton spin

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

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

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

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

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

$$G^{\alpha}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^{abc}A^b_\mu A^c_\nu$$

A realisation of the total proton angular momentum decomposition

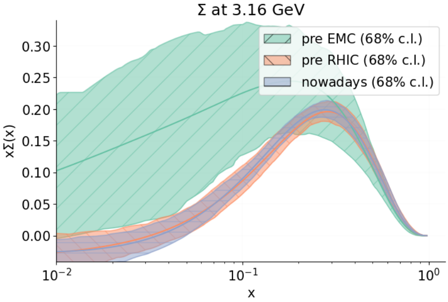
$$\mathcal{S}(\mu^2) = \sum_f \left\langle P;S|\hat{J}^z_f(\mu^2)|P;S\right\rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu^2) + \Delta G(\mu^2) + \mathcal{L}_q(\mu^2) + \mathcal{L}_g(\mu^2)$$

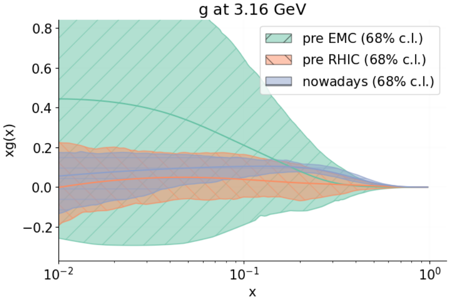
$$\Delta\Sigma(\mu^2) = \sum_{q=u,d,s}\int_0^1 [\Delta q(x,\mu^2) + \Delta\bar{q}(x,\mu^2)] \qquad \Delta G(\mu^2) = \int_0^1 dx \Delta g(x,\mu^2)$$

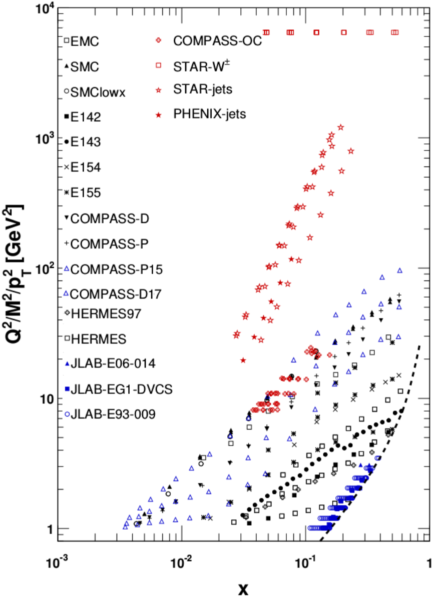
$$a_0 = \left\langle P;S|\hat{J}^z_\Sigma(\mu^2)|P;S\right\rangle \xrightarrow{\text{naive p.m.}} 2\langle S_z^{q+\bar{q}}\rangle \simeq 1 \qquad \text{EMC 1988 } \mathrm{a}_0 = 0.098 \pm 0.076 \pm 0.113$$

$$a_0 = \left\langle P;S|\hat{J}^z_\Sigma(\mu^2)|P;S\right\rangle \overset{\overline{\text{MS}}}{=} \Delta\Sigma(\mu^2) - n_f\frac{\alpha_s(\mu^2)}{2\pi}\Delta G(\mu^2) \qquad \Delta G(\mu^2) \propto \left[\alpha_s(\mu^2)\right]^{-1}$$

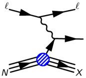
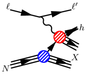
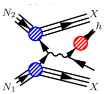
Looking back at 1988 with hindsight







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

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

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

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

Dependence of PDFs on μ is determined by DGLAP equations

[See S. Moch's, F. Petriello, and I. Pedron's talks on perturbative accuracy of coefficient and splitting functions]

1. Where we stand: global QCD analyses

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 simultaneus fit
latest updates	DSSV08 PRD 80 (2009) 034030 DSSV14 PRL 113 (2014) 012001	NNPDFpol1.0 NPB 874 (2013) 36 NNPDFpol1.1 NPB 887 (2014) 276	JAM17 PRL 119 (2017) 132001 +... [See N. Sato's talk]

A prescription to propagate uncertainties

$$E[\mathcal{O}] = \int \mathcal{D}\Delta f \mathcal{P}(\Delta f|data)\mathcal{O}(\Delta f)$$

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

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

A set of theoretical constraints

$$\int dx[\Delta u^+ - \Delta d^+] = a_3$$

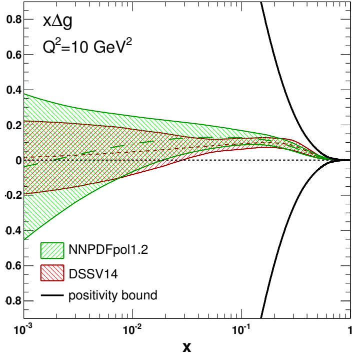
$$\int dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+] = a_8$$

from SU(2) and SU(3) symmetries
with a_3 and a_8 determined from baryon decays
$$|\Delta f| \leq f$$
from LO positivity

Gluon helicity

High-p_T jet production

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



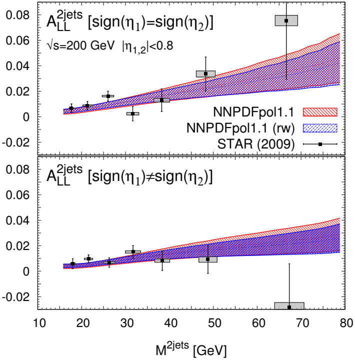
$$\langle x_{1,2}\rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$$

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 polarisation in the proton



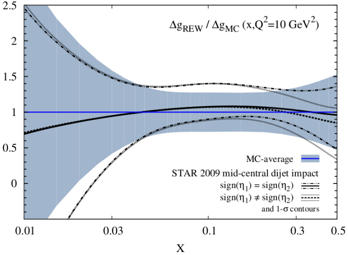
$$\langle x_{1,2}\rangle \simeq \frac{p_T}{\sqrt{s}} (e^{\pm\eta_1 \pm\eta_2}) \approx [0.01, 0.2]$$

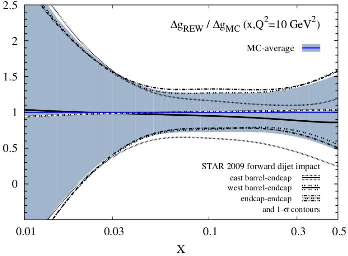
x sensitivity extended down to $x \sim 0.01$

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

Gluon helicity

High-p_T di-jets [PRD 100 (2019) 114027]

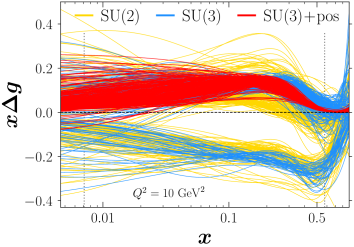




Slight distortion of the central value, consistent with a positive polarisation

High-p_T jets (unp & pol) [PRD 105 (2022) 074022]

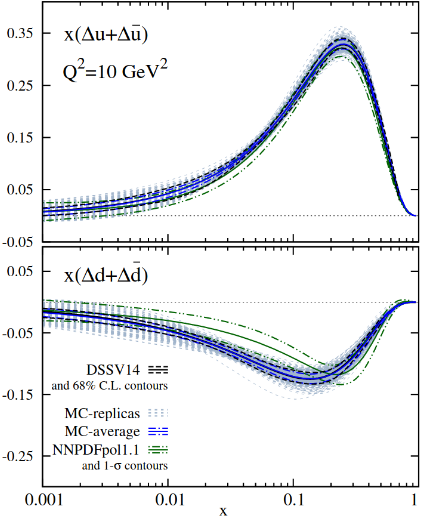
Data	N_{dat}	χ^2_{red}		
		SU(2)	**SU(3)**	**SU(3)+pos**
Unpolarized DIS	2680	$1.20^{(1.20)}_{(1.20)}$	$1.20^{(1.20)}_{(1.21)}$	1.20
Drell-Yan (*pp*, *pD*)	250	$1.06^{(1.05)}_{(1.06)}$	$1.06^{(1.06)}_{(1.06)}$	1.10
Jets				
D0 ($p\bar{p}$)	110	$0.89^{(0.89)}_{(0.89)}$	$0.89^{(0.89)}_{(0.89)}$	0.88
CDF ($p\bar{p}$)	76	$1.11^{(1.11)}_{(1.11)}$	$1.11^{(1.11)}_{(1.11)}$	1.11
STAR 2003 (*pp*)	3	$0.04^{(0.04)}_{(0.04)}$	$0.04^{(0.04)}_{(0.04)}$	0.04
STAR 2004 (*pp*)	9	$1.06^{(1.06)}_{(1.05)}$	$1.06^{(1.06)}_{(1.05)}$	1.06
Polarized DIS	365	$0.92^{(0.92)}_{(0.94)}$	$0.92^{(0.92)}_{(0.95)}$	0.96
Jets in polarized $\vec{p}\vec{p}$				
STAR	81	$0.82^{(0.83)}_{(0.86)}$	$0.81^{(0.82)}_{(0.85)}$	0.84
PHENIX	2	$0.38^{(0.38)}_{(0.39)}$	$0.38^{(0.38)}_{(0.39)}$	0.38
Total	**3576**	**1.14**	**1.14**	**1.15**

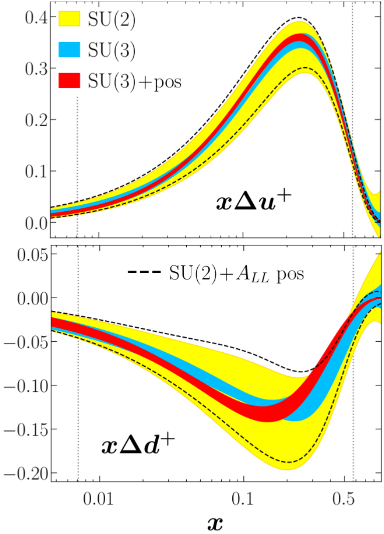


Simultaneous analysis of unp & pol jets consistent with a positive polarisation

Total up and down helicities

Mostly from DIS [PRD 100 (2019) 114027; PRD 105 (2022) 074022; NPB 887 (2014) 276]

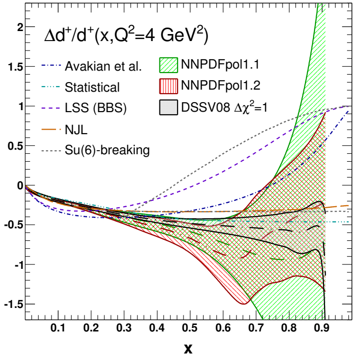




Overall good agreement across DSSV, JAM and NNPDF parton sets

Total up and down helicities at large x

Playground for models [PLB 742 (2015) 117]

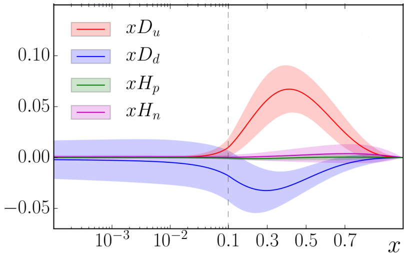


Model	$\Delta d^+/d^+$	Model	$\Delta d^+/d^+$
SU(6)	$-1/3$	NJL	-0.25
RCQM	$-1/3$	DSE (*realistic*)	-0.26
QHD ($\sigma_{1/2}$)	1	DSE (*contact*)	-0.33
QHD (ψ_ρ)	$-1/3$	pQCD	1

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]

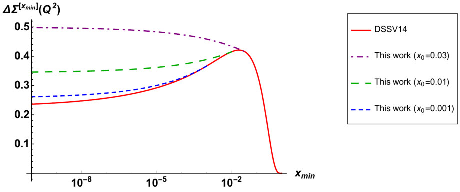


$g_1^{\tau=3} \propto D$ and $g_1^{\tau=4} = H/Q^2$

nonzero twist-3 quark distributions

twist-4 quark distributions compatible with zero

Quark singlet helicity at small x [See talk by Y. Kovchegov]



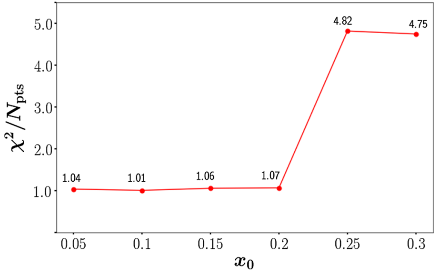
[JHEP 1601 (2016) 072; PRL 118 (2017) 052001]
[PLB 772 (2017) 136; JHEP 2207 (2022) 095]

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

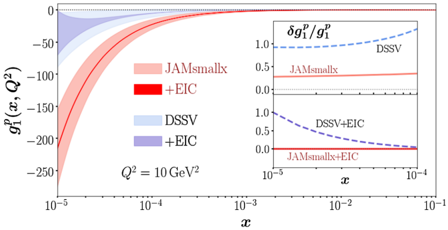
$$g_1 \sim \Delta\Sigma \sim \left(\frac{1}{x}\right)^{\alpha_h}, \qquad \alpha_h \sim 2.31\sqrt{\frac{\alpha_s N_C}{2\pi}}$$

Potential solid amount of spin at small x
attach $\Delta\hat{\Sigma}(x, Q^2) = N x^{-\alpha_h}$ at x_0 to DSSV
Should be tested at an EIC

How small is x_0?



Which precision to test small x?



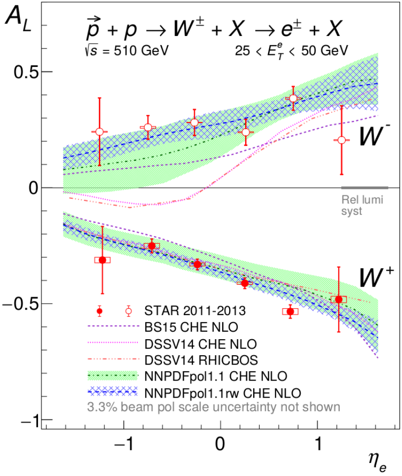
[PRD 104 (2021) L031501]

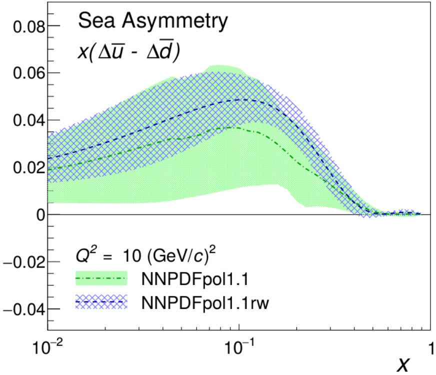
Sea quark helicity $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$ [arXiv:1702.05077]

$W^{\pm}$ boson production

first evidence of broken flavor symmetry for polarised light sea quarks

New 2013 data [PRD 99 (2019) 51102]





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

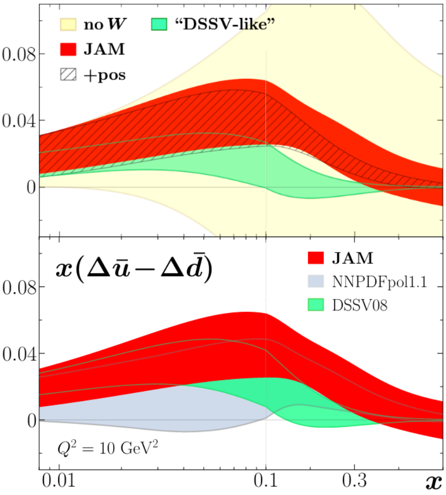
$$\Delta\bar{u} > 0 > \Delta\bar{d},\ |\Delta\bar{d}| > |\Delta\bar{u}|$$

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

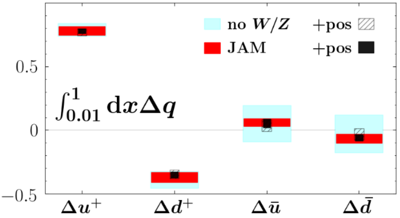
$$\to +0.07 \pm 0.01$$

Sea quark helicity $\Delta_s = \Delta\bar{u} - \Delta\bar{d}$ [arXiv:2202.03372]

$W^{\pm}$ boson production + SIDIS



process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
polarized		
inclusive DIS	365	0.93
inclusive jets	83	0.81
SIDIS (π^+, π^-)	64	0.93
SIDIS (K^+, K^-)	57	0.36
STAR $W^{\pm}$	12	0.53
PHENIX $W^{\pm}/Z$	6	0.63
total	**587**	**0.85**
unpolarized		
inclusive DIS	3908	1.11
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**4464**	**1.11**
SIA $(\pi^{\pm})$	231	0.85
SIA $(K^{\pm})$	213	0.49
total	**5495**	**1.05**



Significant impact of W measurements

Fair compatibility with DSSV08 (SIDIS)

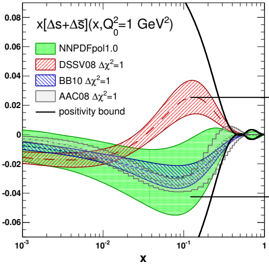
Strange helicity: DIS vs SIDIS

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

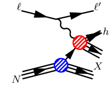
Lattice [PRL 108 (2012) 222001]
$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.020(10)(1)$

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

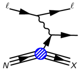
$a_8 = \int_0^1 dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+]$
$= 0.585 \pm 0.025$



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] [See R. Sassot's and I. Borsa's talks on FFs]

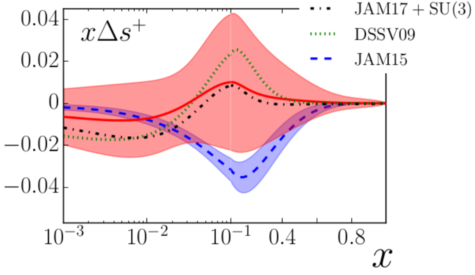
Tension between DIS and SIDIS data can be ficticious

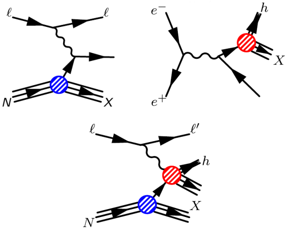
$SU(3)$ may be broken [PRD 58 (1998) 094028, Ann.Rev.Nucl.Part.Sci. 53 (2003) 39], but how much?
$\longrightarrow$ in `NNPDFpol`, the nominal uncertainty on a_8 in inflated by 30% of its value to allow for a $SU(3)$ symmetry violation ($a_8 = 0.585 \pm 0.025 \longrightarrow a_8 = 0.585 \pm 0.176$)
$\longrightarrow$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

Opportunities at an EIC

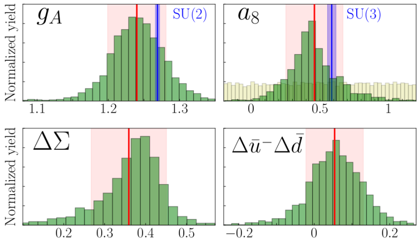
one could study kaon multiplicities in SIDIS $\longrightarrow$ further constraint on kaon FFs
one could study CC charm production $W^+ s \to c$ in DIS $\longrightarrow$ direct handle on s, $\bar{s}$
(handle on s-$\bar{s}$ asymmetry also from three-loop evolution [PRD 99 (2019) 054001])

Strange helicity: DIS vs SIDIS [PRL 119 (2017) 132001]





process	target	N_{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**



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

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

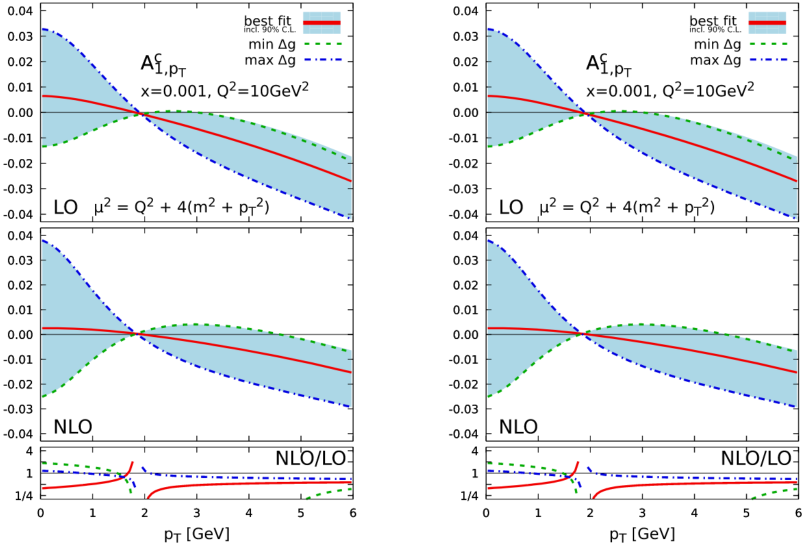
$\sim 20\%$ SU(3) breaking $\pm 20\%$

2. Where we are going: the theory front

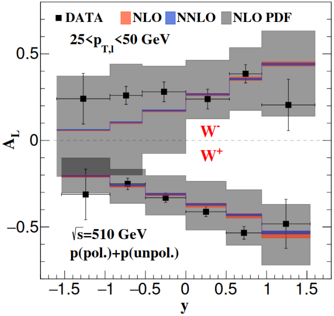
Heavy flavour production at NLO

First calculation of the heavy flavor contribution to the differential g_1^Q at NLO,

[PRD 98 (2018) 014018; ibid. 104 (2021) 016033]



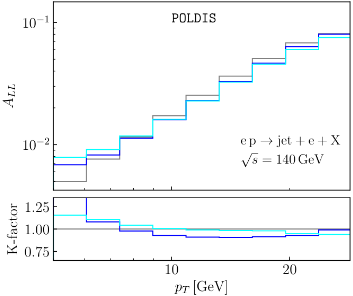
Progress on NNLO computations

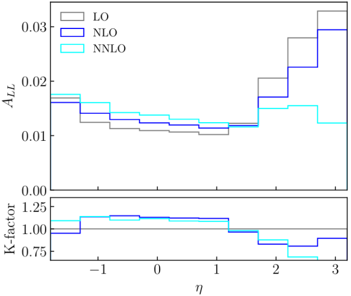


$W^{\pm}$ **boson production** [PLB 817 (2021) 136333]
computation based on
the N-jettiness method
[See talk by F. Petriello]

DIS+jet [PRL 125 (2020) 082001]
computation based on
the Projection-to-Born method
[See talk by I. Pedron]

SIDIS [PRD 104 (2021) 094046]
approximate corrections
from threshold resummation





The spin budget at NNLO and beyond

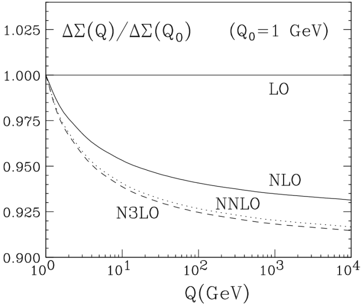
[PRD 99 (2019) 054001]

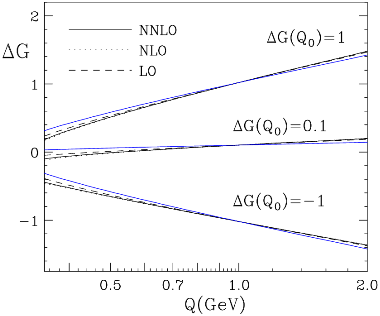
Splitting functions known at NNLO

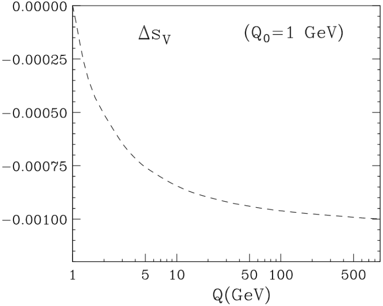
Computation of the evolution of $\Delta\Sigma$ at N^{3}LO and of ΔG at NNLO

“Static” solutions for ΔG at every perturbative order that tend to an asymptotic limit ($\simeq 0.1$)

NNLO perturbative evolution predicts $\Delta s - \Delta\bar{s} < 0$, 1% of the total $\Delta s + \Delta\bar{s}$

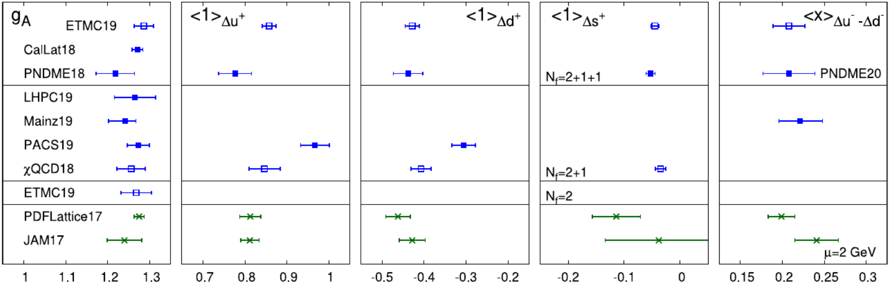






Comparing lattice QCD and global PDF fits: moments

PDFLattice studies [Prog.Part.Nucl.Phys. 100 (2018) 107; ibid. 121 (2021) 103908]



Moment	Lattice QCD	Global Fit	JAM17
g_A	1.179–1.309[a] 1.202–1.314[b] 1.268(36)[c,d]	1.258(28)	1.240(41)
$\langle 1\rangle_{\Delta u^+}$	0.738–0.875[a] 0.810–1.001[b]	0.813(25)	0.812(22)
$\langle 1\rangle_{\Delta d^+}$	−0.473–−0.403[a] −0.431–−0.278[b]	−0.462(29)	−0.428(31)
$\langle 1\rangle_{\Delta s^+}$	−0.0538–−0.0379[a] −0.0035(9)[b,d]	−0.114(43)	−0.038(96)
$\langle x\rangle_{\Delta u^- - \Delta d^-}$	0.174–0.239[a] $0.221(^{27}_{-25})$[b,d]	0.199(16)	0.241(26)

[a]$N_f = 2+1+1$. [b]$N_f = 2+1$. [c]$N_f = 2$. [d]Single lattice result.

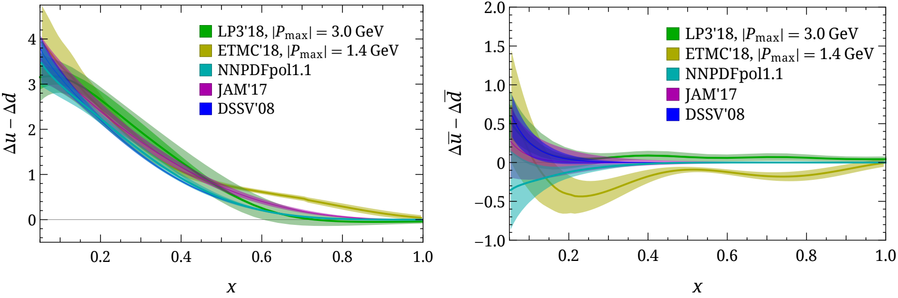
$$g_A = \langle 1\rangle_{\Delta u^+ - \Delta d^+} = \int_0^1 dx\,\left[\Delta u^+ - \Delta d^+\right](x,Q^2)$$

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

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

Comparing lattice QCD and global PDF fits: PDFs

PDFLattice studies [Prog.Part.Nucl.Phys. 100 (2018) 107; ibid. 121 (2021) 103908]



Ref.	Sea quarks	Valence quarks	$N_{\Delta t}$	method	$P_{\rm max}$ (GeV)	a (fm)	M_π (MeV)	$M_\pi L$
ETMC'20	2f twisted mass	twisted mass	4	pseudo-PDF	1.38	0.09	130	3.0
JLab/W&M	2+1 clover	clover	n/a	pseudo-PDF	3.29	0.09	172–358	5.08–5.47
ETMC'18	2f twisted mass	twisted mass	4	quasi-PDF	1.38	0.09	130	3.0
LP3'18	2+1+1f HISQ	clover	4	quasi-PDF	3	0.09	135	4.0
LP3'17	2+1+1f HISQ	clover	2	quasi-PDF	1.3	0.09	135	4.0

ETMC and LP3 determinations are both at the physical pion mass

Lattice determinations are qualitatively similar (among them) and similar to global fits

Nucleon momentum is limited by lattice spacing

Different procedures lead to slightly different behaviour in x

Which precision shall we require to lattice QCD?

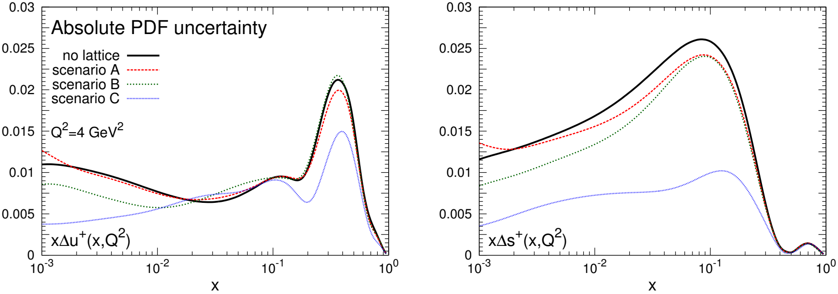
Generate lattice QCD pseudodata assuming NNPDFpol1.1 central values for

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

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



What if one includes lattice data in a global fit?

Use pseudo-pdf pseudodata [PRD 103 (2021) 016003]

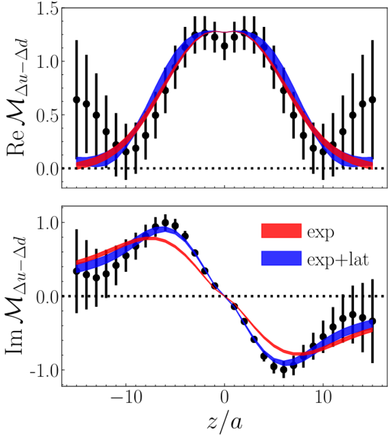
Define the matrix elements $\mathcal{M}$ on the light-cone

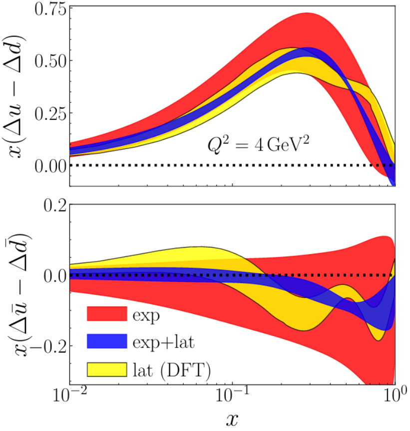
Relate them to light-front PDFs using LaMET

$$\mathrm{Re}\mathcal{M}_{\Delta u-\Delta d} = \mathcal{C}^{\mathrm{Re}}_{\Delta u-\Delta d} \otimes T_3$$

$$\mathrm{Im}\mathcal{M}_{\Delta u-\Delta d} = \mathcal{C}^{\mathrm{Im}}_{\Delta u-\Delta d} \otimes V_3$$

Observable	N_{pt}	χ^2_{pt} (exp)	χ^2_{pt} (exp+lat)
DIS ($A_1^{p,d}$)	651	1.1	—
ETMC Re$\mathcal{M}_{\Delta u-\Delta d}$	31	—	0.5
ETMC Im$\mathcal{M}_{\Delta u-\Delta d}$	30	—	0.3
Total (exp+lat)	712	—	1.0

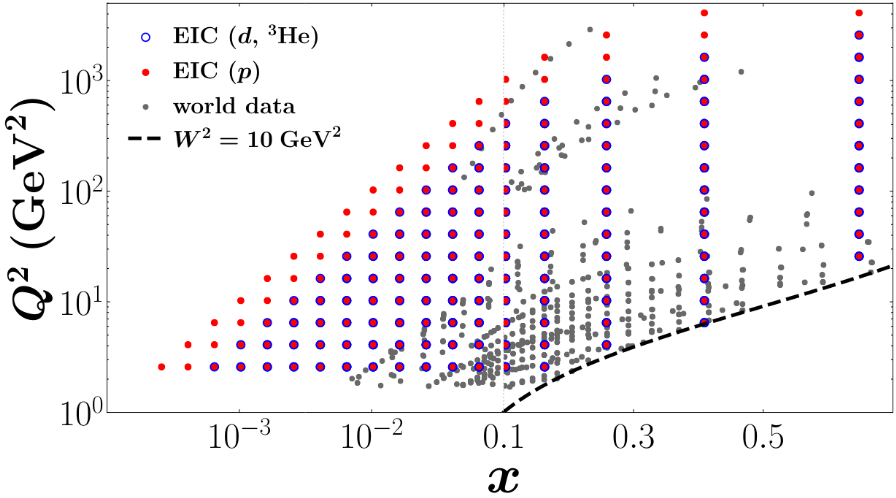




3. Where we aim to get: opportunities at the EIC

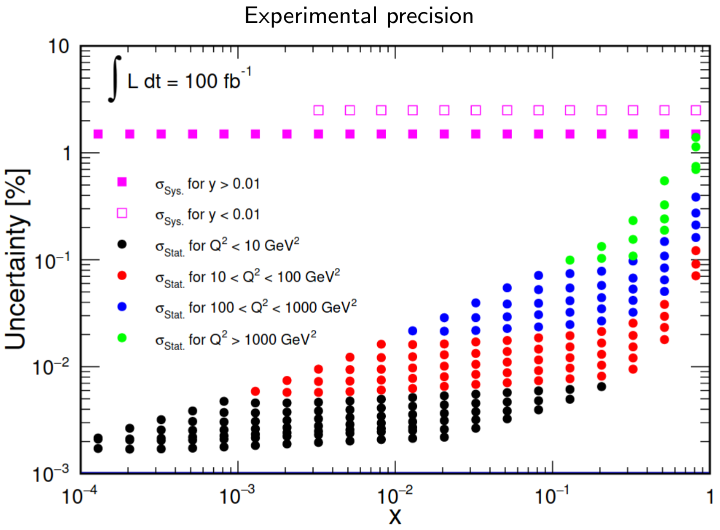
EIC measurements

Kinematic coverage



[Figure from PRD 104 (2021) 034028]

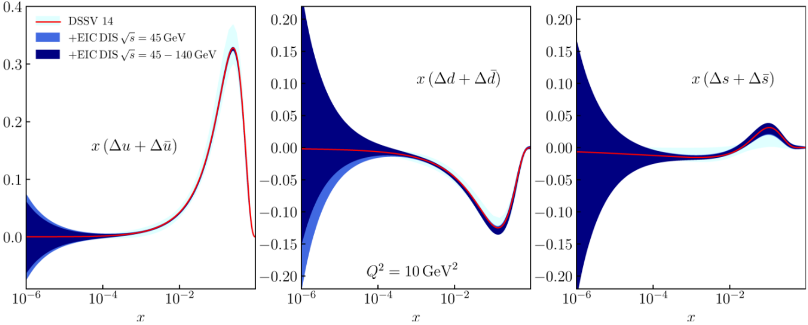
EIC measurements

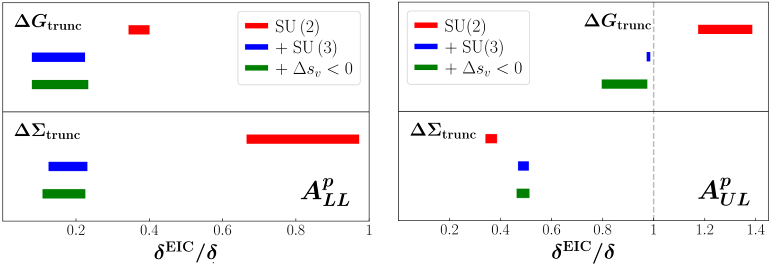


[Figure from the EIC Yellow Report arXiv:2103.05419]

Impact of neutral-current inclusive DIS

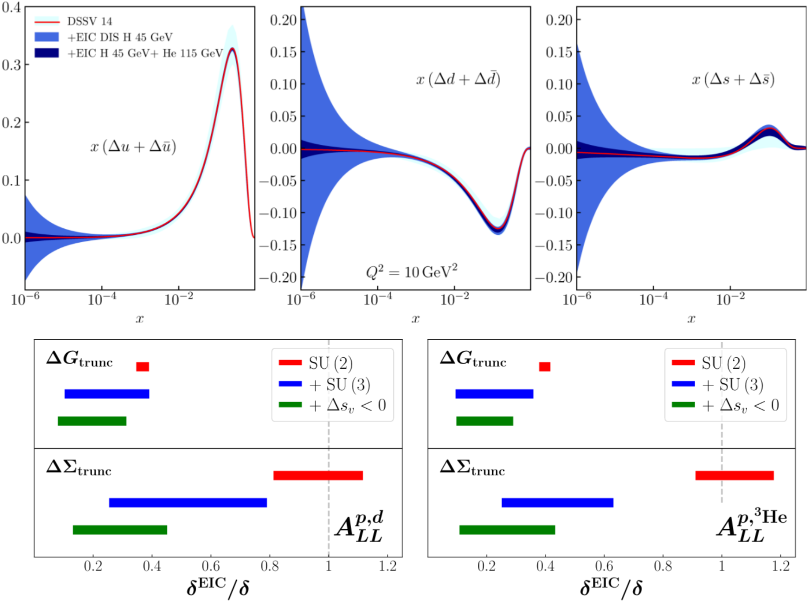
On proton [PRD 102 (2020) 094018; PRD 104 (2021) 034028]





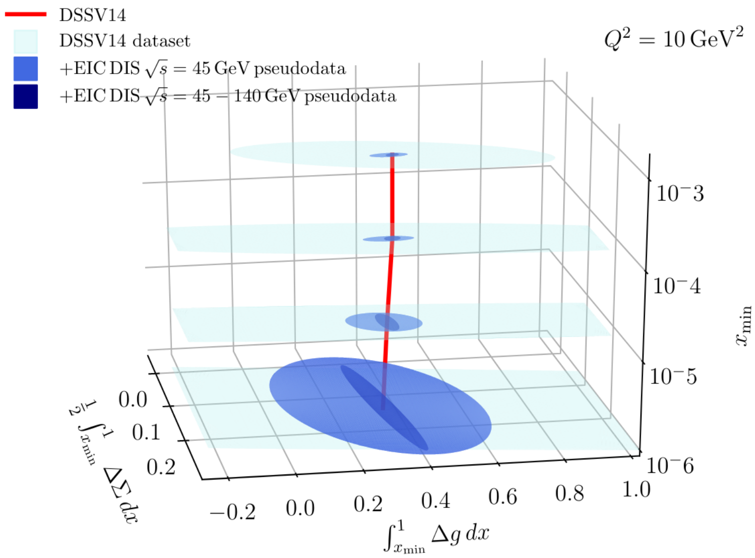
Impact of neutral-current inclusive DIS

On ^{3}He [PRD 102 (2020) 094018; PRD 104 (2021) 034028]



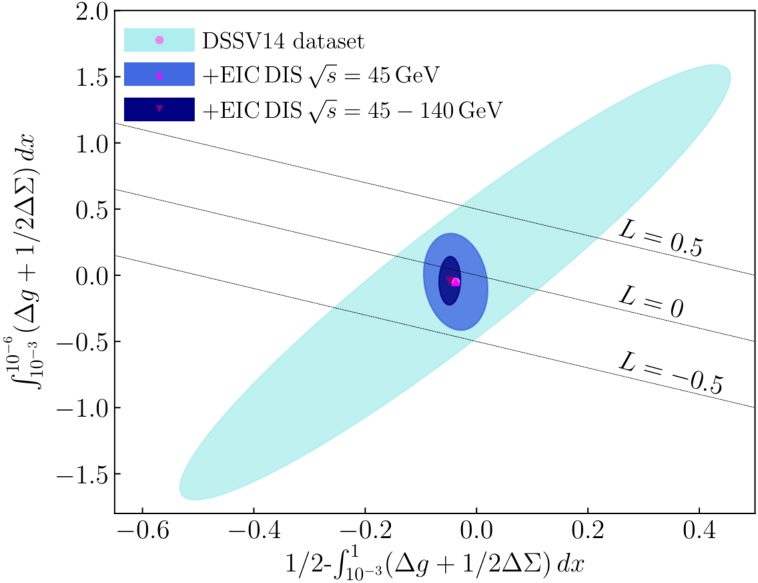
Impact of neutral-current inclusive DIS

Quark, gluon and orbital angolar momenta [PRD 88 (2013) 114025]



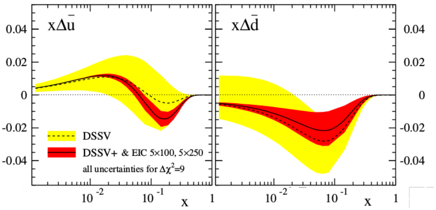
Impact of neutral-current inclusive DIS

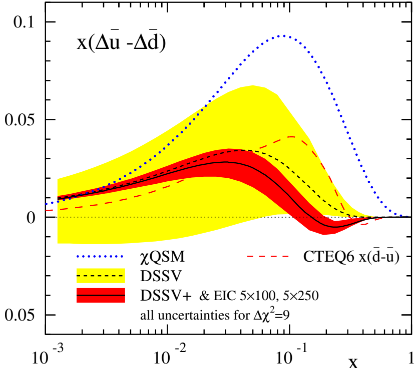
Quark, gluon and orbital angolar momenta [PRD 88 (2013) 114025]

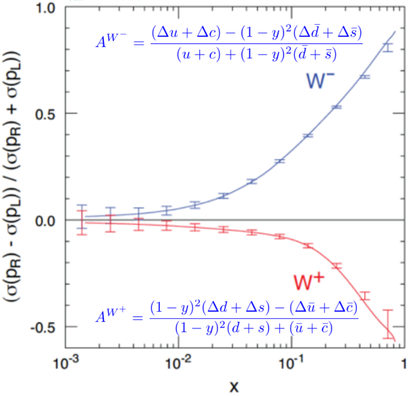


Impact of charged-current DIS

On proton [PRD 88 (2013) 114025]







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

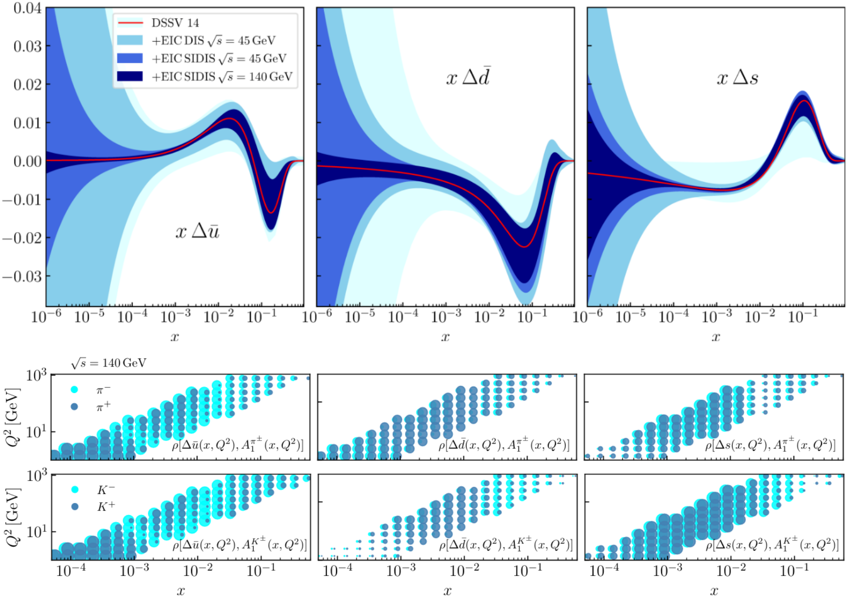
$$A_L^{W^+,p} \xrightarrow[y=1/2]{\text{LO}} \frac{4\Delta u - \Delta\bar{d}}{4u+\bar{d}}$$

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

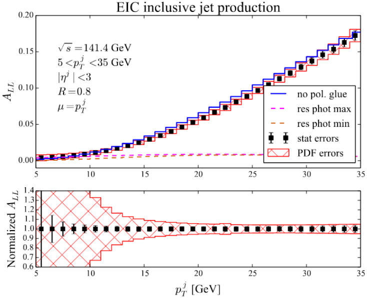
$\longleftrightarrow$ for $A_L^{W^-,n}$

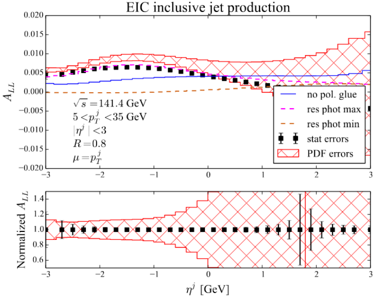
Impact of semi-inclusive DIS

With charged pions and kaons [PRD 102 (2020)]



Impact of DIS+jets



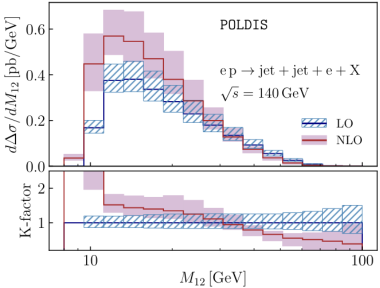


[PRD 98 (2018) 054031]

Include all relevant partonic contributions (direct and resolved photon contributions)

Intermediate-to-high tranverse momenta are sensitive to the polarised gluon PDF

Find that PDF errors are much larger than projected statistical errors

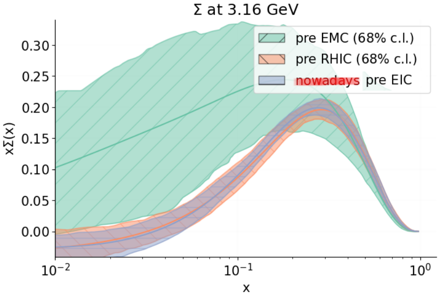


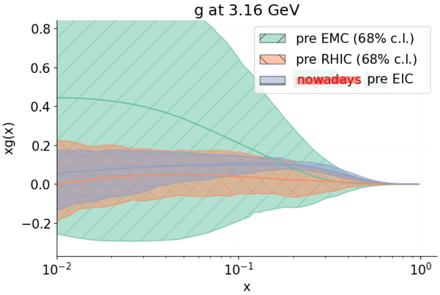
[PRD 103 (2021) 014008; ibid. 105 (2022) 074025]

Fully differential NLO corrections to di-jet production in NC and CC DIS

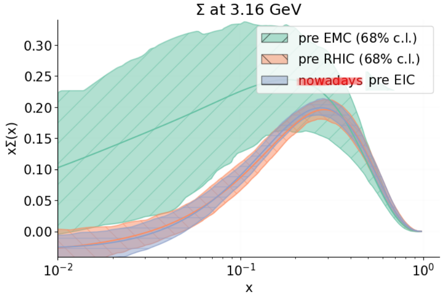
4. In summary

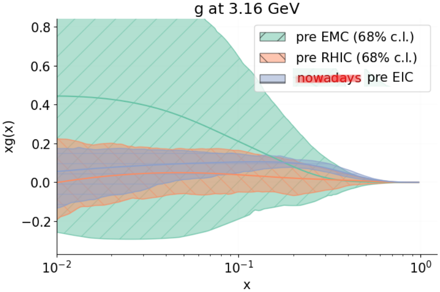
Looking ahead in light of 30 years of experience





Looking ahead in light of 30 years of experience





[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