Polarized PDFs from the NNPDF perspective

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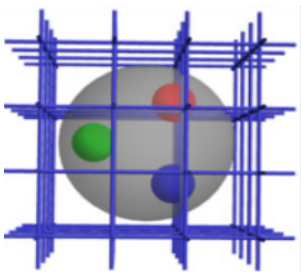
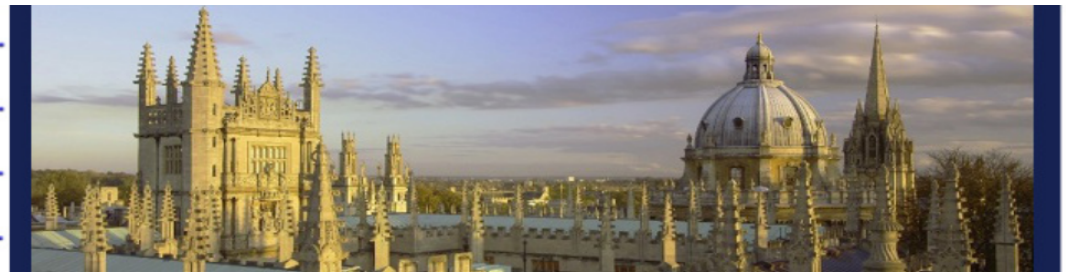
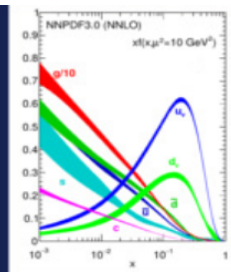
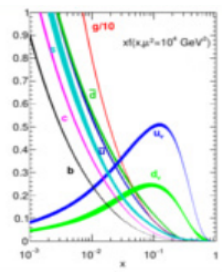
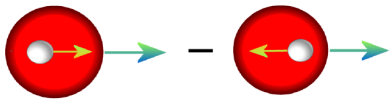
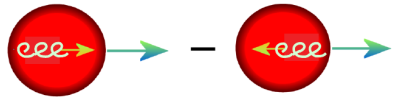






Polarized PDFs in a nutshell [See Werner's talk]

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
3. Guiding principle: (leading-twist) factorization and evolution
4. Combining theory and data with a suitable methodology

Theoretical constraints

positivity (PDFs must lead to positive cross sections): at LO, $|\Delta f(x,Q^2)| \leq f(x,Q^2)$

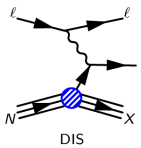
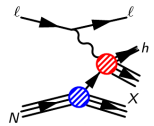
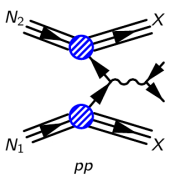
integrability (the nucleon matrix element of the axial current for each flavor is finite)

SU(2) and SU(3) flavor symmetries (related to the baryon octet β-decay constants)

$$a_3 = \int_0^1 dx\, \Delta T_3 = 1.2701 \pm 0.0025(\pm 0.176) \qquad a_8 = \int_0^1 dx\, \Delta T_8 = 0.585 \pm 0.025$$

$$\Delta T_3 = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} \qquad \Delta T_8 = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s})$$

The data

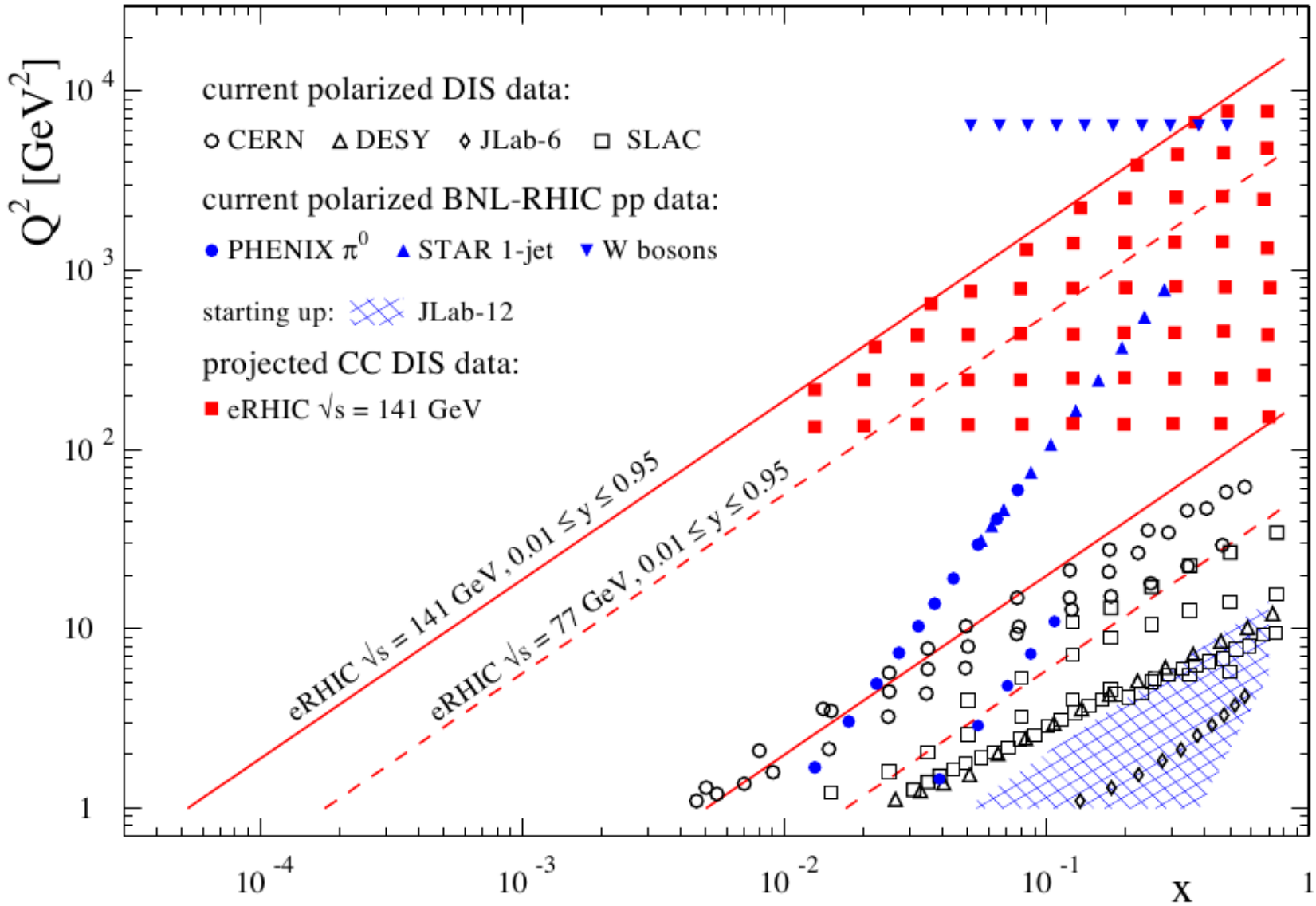
Process	Reaction	Subprocess	PDFs probed	x	$Q^2/p_T^2/M^2$ [GeV^2]
 DIS	$\ell^\pm\{p,d,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$\Delta q + \Delta\bar{q}$ Δg	$0.003 \lesssim x \lesssim 0.8$	$1 \lesssim Q^2 \lesssim 70$
 SIDIS	$\ell^\pm\{p,d\} \to \ell^\pm hX$	$\gamma^* q \to q$	$\Delta u\ \Delta\bar{u}$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

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

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

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

Kinematic coverage



[Figure taken from EPJA 52 (2016) 268]

Evolution of NNPDFpol fits

NNPDFpol1.0 [NP B874 (2013) 36]

- inclusive DIS data from CERN, SLAC and DESY on $g_1^{p,d,n}$

$$g_1(x,Q^2) = \underbrace{\frac{\sum_q^{n_f} e_q^2}{2n_f}\Big(\mathcal{C}_{\rm NS}\otimes\Delta q_{\rm NS} + \mathcal{C}_{\rm S}\otimes\Delta\Sigma + 2n_f\mathcal{C}_g\Delta g\Big)}_{\text{leading-twist factorization}} + \underbrace{\frac{h^{\rm TMC}}{Q^2} + \frac{h^{\rm HT}}{Q^2} + \mathcal{O}\Big(\frac{1}{Q^4}\Big)}_{\text{power-suppressed TMCs and HT}}$$

- kinematic cut $W^2 \geq 6.25$ GeV^2 to remove sensitivity to dynamical HTs [arXiv:0807.1501]
- inflated uncertainty on a_8 (up to 30% of its exp value) to allow for SU(3) violation
- NLO perturbative accuracy, $\overline{\rm MS}$ renormalization scheme, ZM-VFN scheme

NNPDFpol1.1 [NP B887 (2014) 276]

- + new collider data from RHIC, included via reweighting:

→ jet production: STAR [PRD 86 (2012) 032006, PRL 115 (2015) 092002], PHENIX [PRD 84 (2011) 012006]

→ W-boson production from STAR [PRL 11 (2014) 072301]

- + open-charm production: COMPASS [PRD 87 (2013) 052018], included via reweighting

NNPDFpol1.2 [in preparation]

- + new inclusive DIS data, included via a complete refit:

→ COMPASS [PLB 753 (2016) 18] (p) [arXiv:1612.00620] (d)

→ JLAB [PLB 641 (2006) 11, PRC 90 (2014) 025212, PLB 744 (2015) 309, arXiv:1505.07877] (p,d)

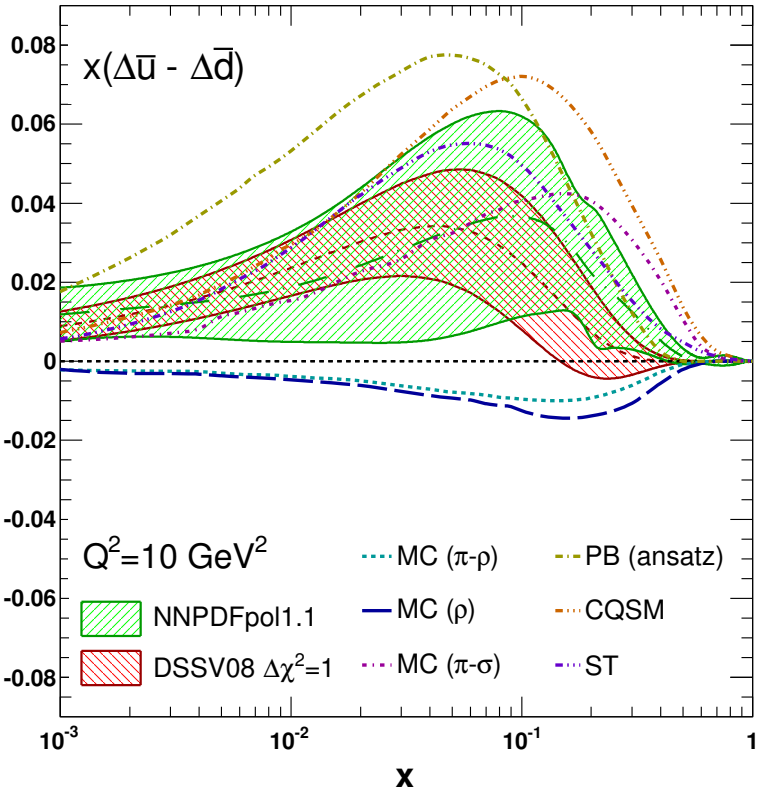
- + new collider data, included via reweighting:

→ di-jets [arXiv:1610.06616] and Ws from STAR, π^0 from PHENIX [PRD 83 (2016) 011501]

Impact of RHIC data: $\Delta\bar{u} - \Delta\bar{d}$ and Δg [NPB 887 (2014) 276]

$W^{\pm}$ boson production

first evidence of broken flavor symmetry for polarized light sea quarks

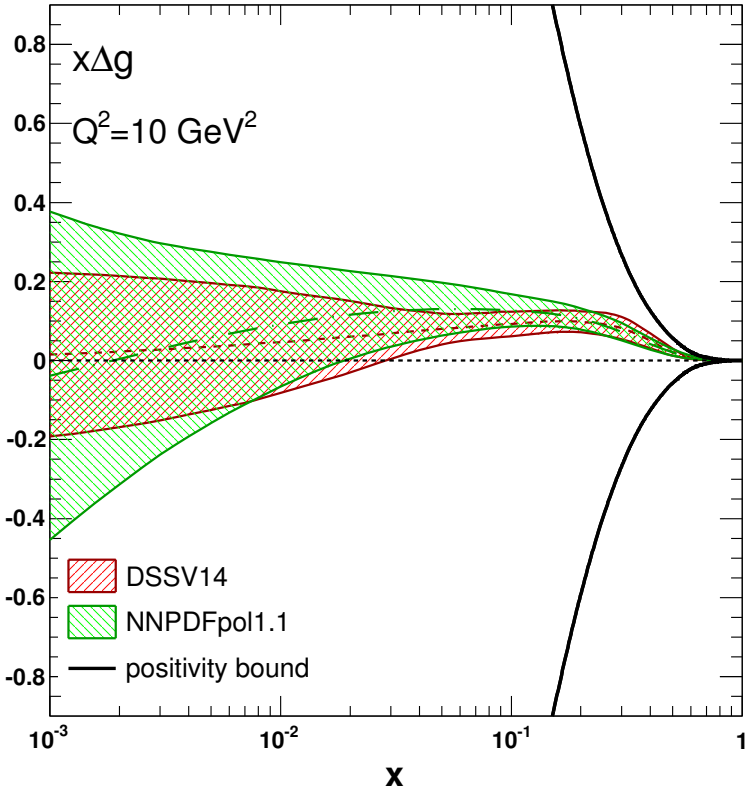


$$\langle x_{1,2}\rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$$

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

High-p_T jet production

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



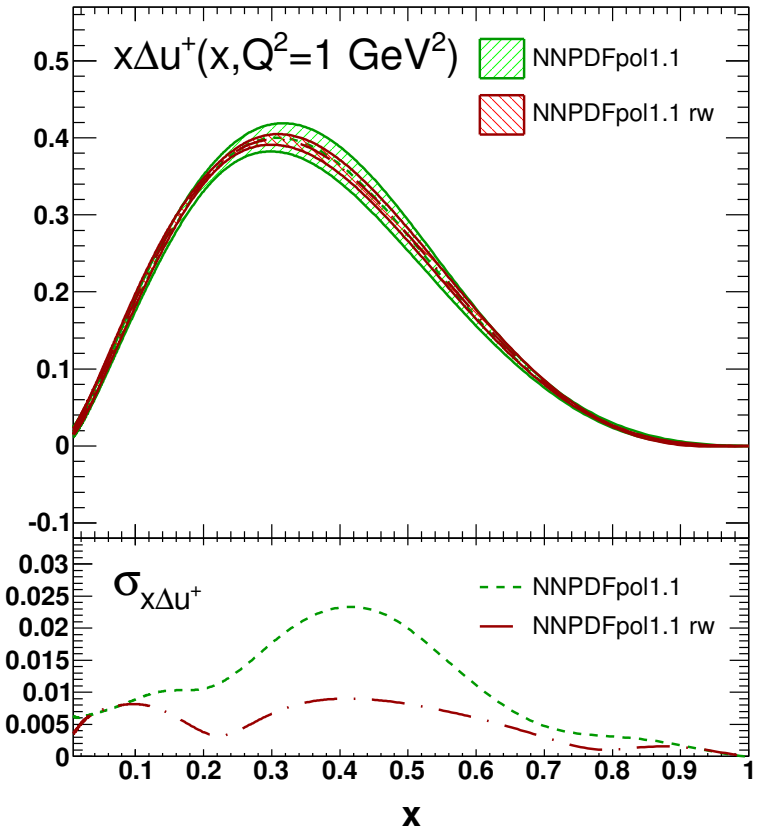
$$\langle x_{1,2}\rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$$

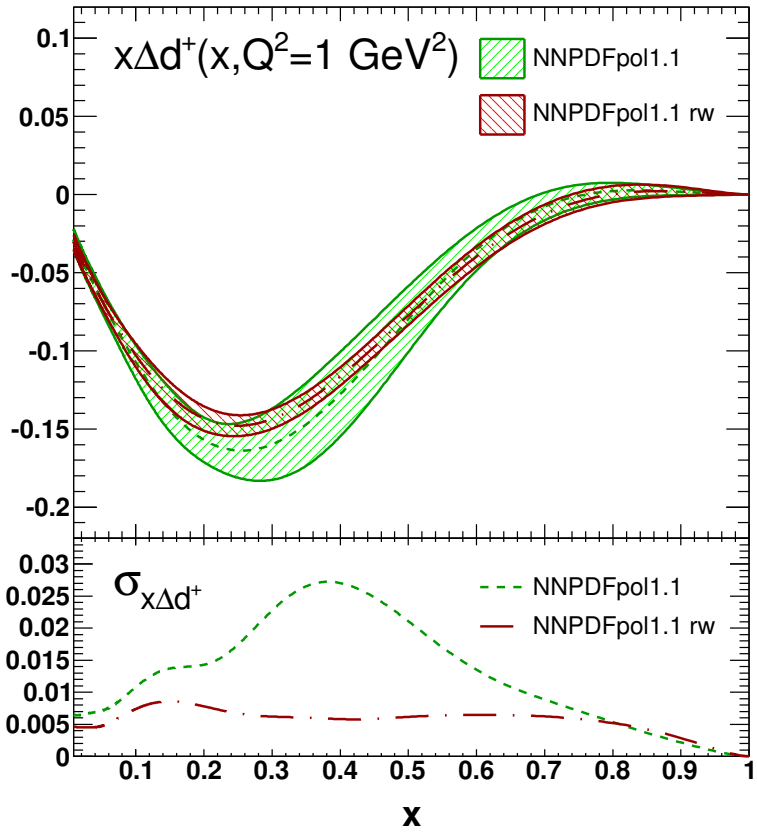
NNPDF and DSSV results well compatible

$$\int_{0.04}^{0.4} dx\, \Delta_{sea}(x, Q^2 = 10\,\text{GeV}^2) = +0.06 \pm 0.03 \qquad \int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\text{GeV}^2) = +0.23 \pm 0.23$$

Impact of JLAB data: total Δu^+ and Δd^+ [JPCS 678 (2016) 012030]

Inclusive DIS





conservative kinematic cut on the invariant mass of the final state

$$W^2 = m_p^2 \frac{1-x}{x} Q^2 \geq 6.25\,\mathrm{GeV}$$

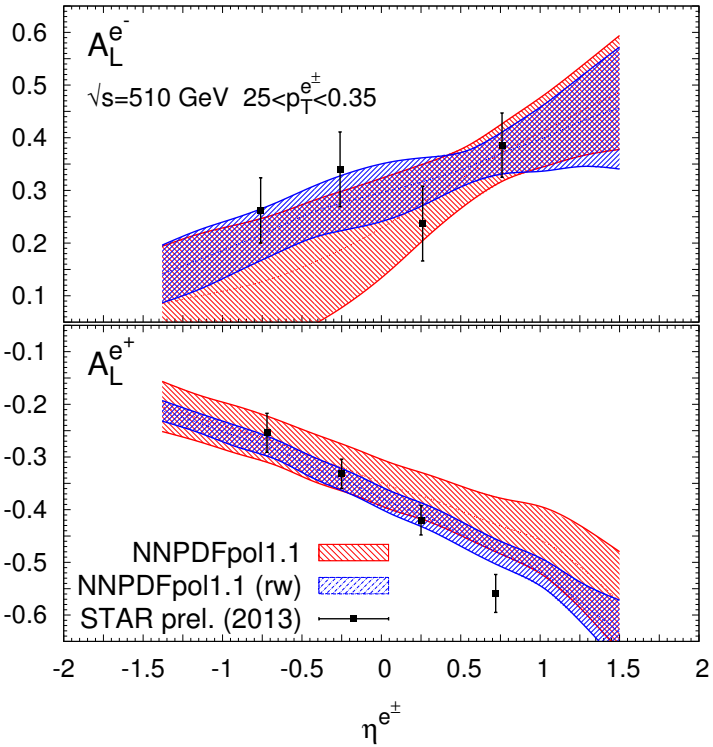
in order to remove sensitivity to dynamical higher twist

PDF uncertainty reduced up to 50%

Impact of new RHIC data: $\Delta\bar{u} - \Delta\bar{d}$ and Δg [arXiv:1702.05077]

$W^{\pm}$ boson production

first evidence of broken flavor symmetry
for polarized light sea quarks



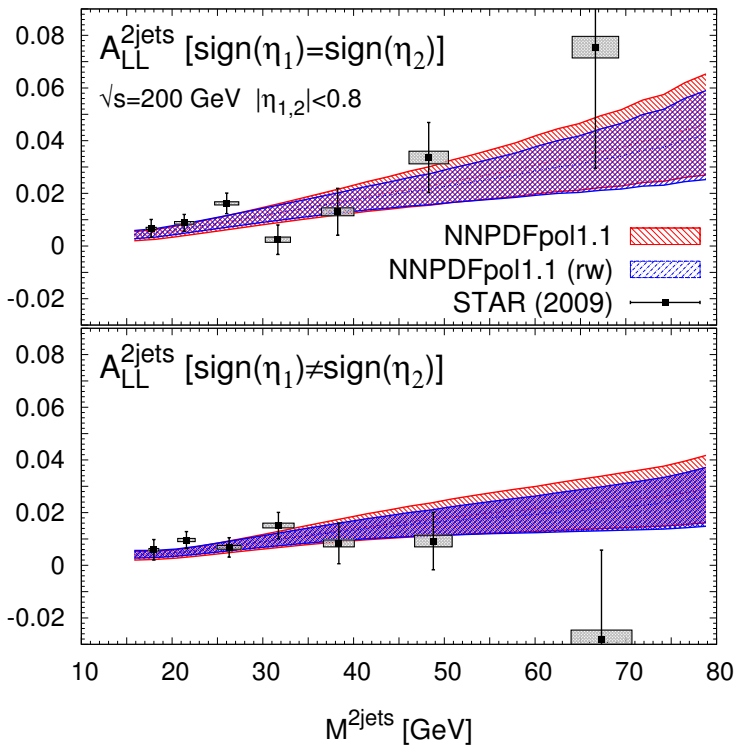
$$\langle x_{1,2}\rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$$

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

$$\int_{0.04}^{0.4} dx\, \Delta_{sea}(x, Q^2 = 10\,\text{GeV}^2) = +0.07 \pm 0.01$$

High-p_T di-jet production

confirm a positive
gluon polarization in the proton

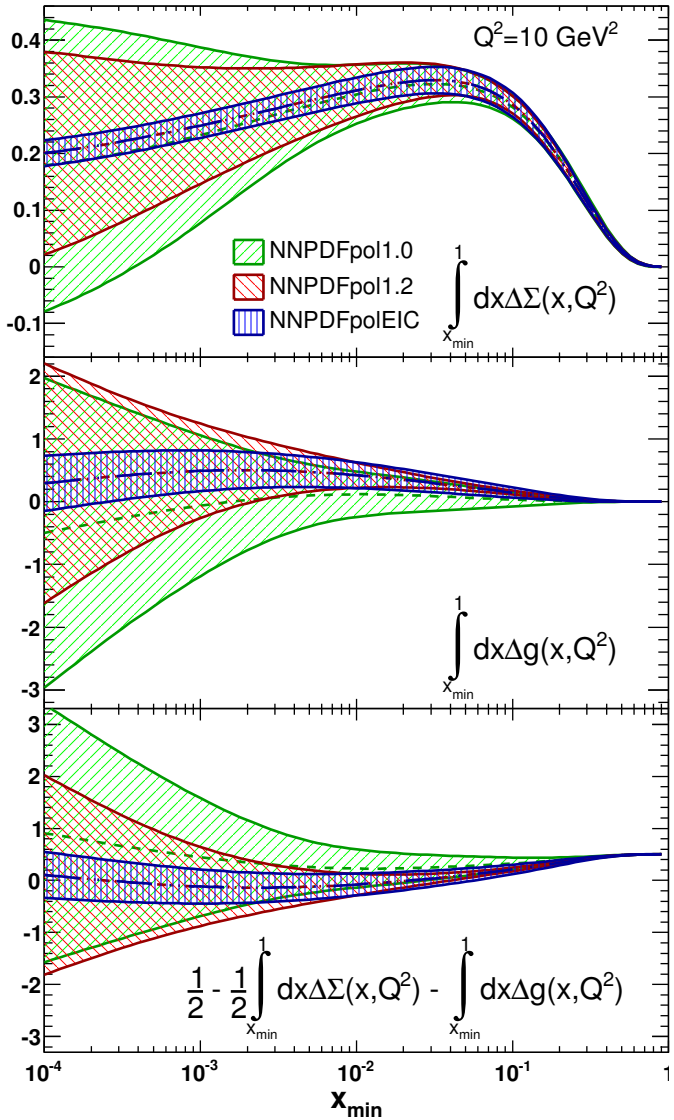


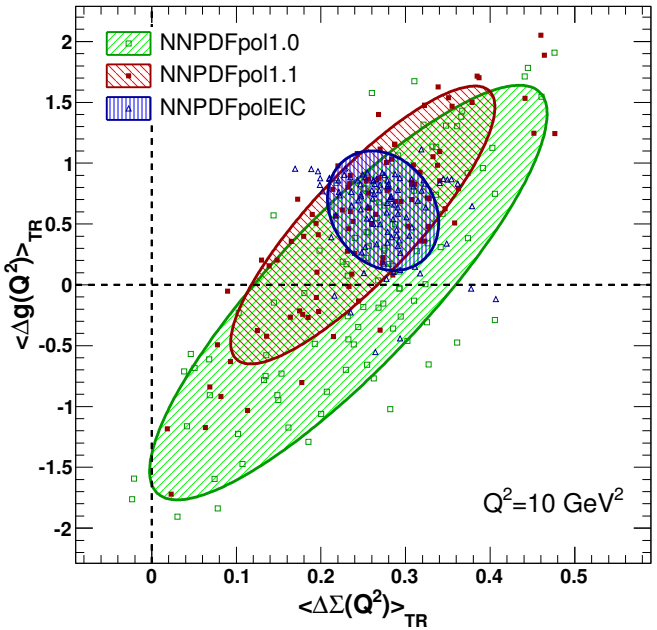
$$\langle x_{1,2}\rangle \simeq \frac{p_T}{\sqrt{s}} (e^{\pm\eta_3 \pm \eta_4}) \approx [0.01, 0.2]$$

x sensitivity extended down to $x \sim 0.01$

$$\int_{0.01}^{0.2} dx\, \Delta g(x, Q^2 = 10\,\text{GeV}^2) = +0.32 \pm 0.21$$

Open issues: small-x extrapolation [PLB 728 (2014) 524]

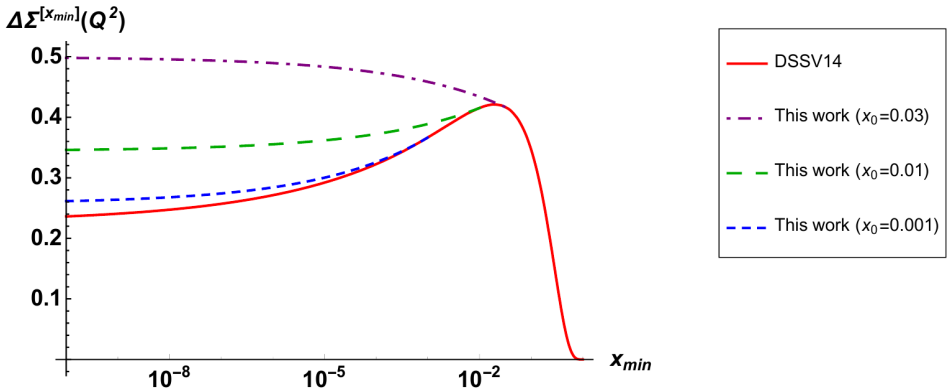




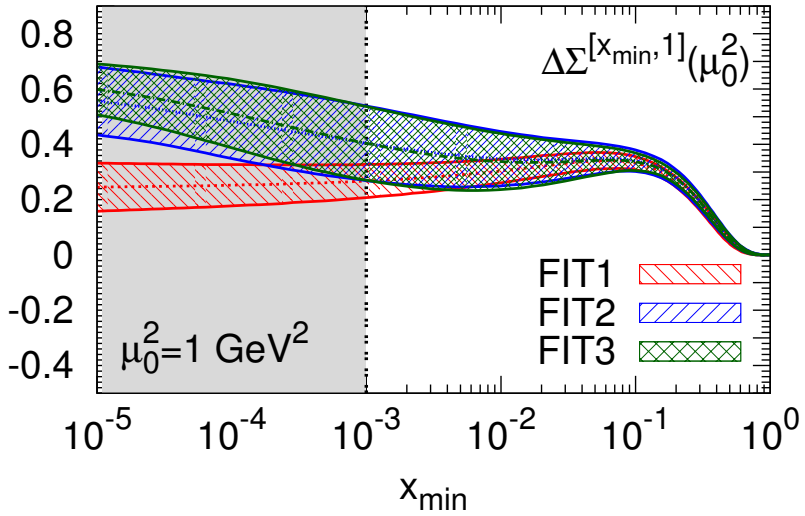
$Q^2 = 10$ GeV^2	$\int_{10^{-3}}^{1} dx\,\Delta\Sigma$	$\int_{10^{-3}}^{1} dx\,\Delta g$
NNPDFpol1.0	$+0.23 \pm 0.15$	-0.06 ± 1.12
NNPDFpol1.2	$+0.25 \pm 0.10$	$+0.49 \pm 0.75$
NNPDFpolEIC	$+0.24 \pm 0.04$	$+0.49 \pm 0.25$

quarks and antiquarks $\sim 20\% - 30\%$
gluons $\sim 70\%$
OAM $\sim 0\%$

Open issues: how much $\Delta\Sigma$ is there at small x? [arXiv:1611.07980]



[Figure taken from arXiv:1610.06188]



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: $\Delta T_3 = 1.270 \pm 0.003$
$\Delta T_8 = 0.585 \pm 0.176$

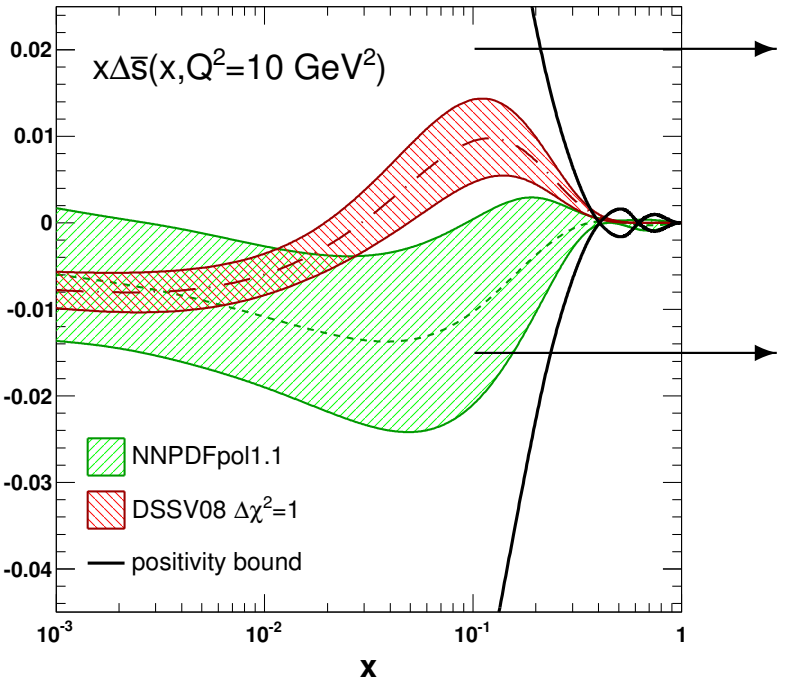
FIT2: $\Delta T_3 = 1.515 \pm 0.304$
$\Delta T_8 = 0.691 \pm 0.138$

FIT3: $\Delta T_3 = 1.444 \pm 0.289$
$\Delta T_8 = 0.684 \pm 0.137$

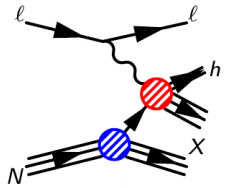
	FIT1	FIT2	FIT3
$\chi^2_{\rm dat}$	0.74	0.76	0.79
$\Delta\Sigma$	$+0.23 \pm 0.09$	$+0.64 \pm 0.14$	$+0.73 \pm 0.16$

Open issues: the strange content of the proton

$\Delta\bar{s}$ (assuming $\Delta s = \Delta\bar{s}$, which may not be true [hep-ph/0505153])

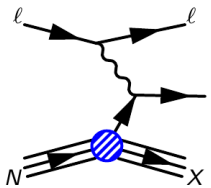


directly from SIDIS Kaon data



SIDIS

indirectly from DIS scaling violations

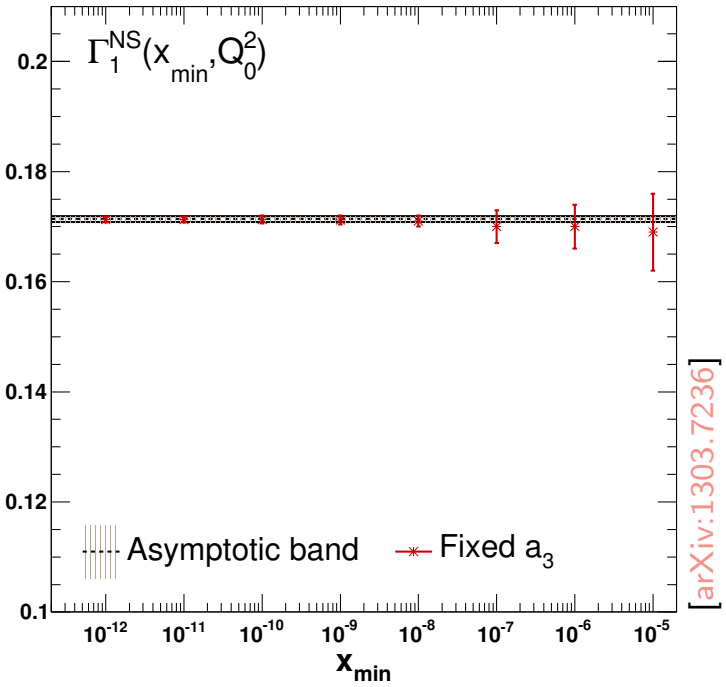


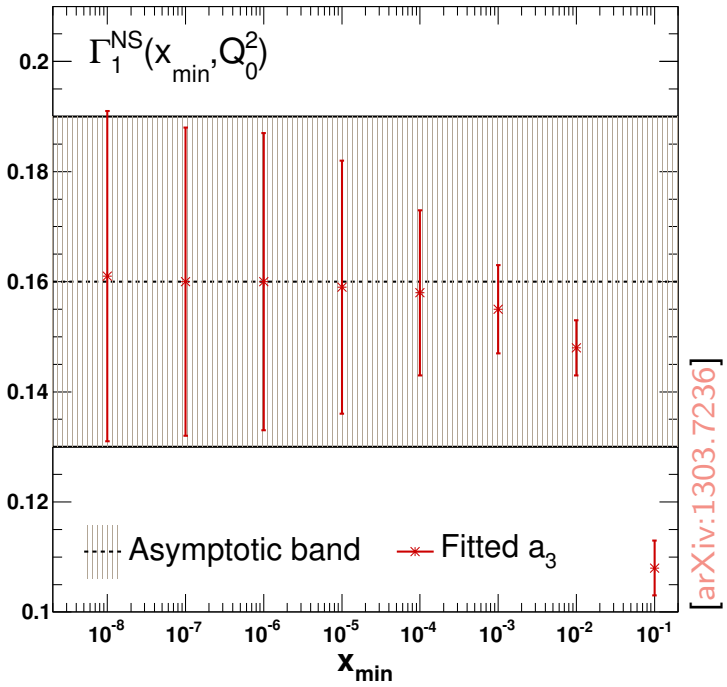
DIS

`NNPDFpol1.1`: DIS ☑, SIDIS ($K^{\pm}$) ☒; `DSSV08`: DIS ☑, SIDIS ($K^{\pm}$) ☑;

- DIS data $\Rightarrow$ negative $x\Delta\bar{s}$; SIDIS data $\Rightarrow$ changing-sing $x\Delta\bar{s}$
- New, very precise, JLAB data (DIS) point to negative $x\Delta s$ [arXiv:1410.1657]
- Is there mounting tension between DIS and SIDIS data?
- How well do we know K fragmentation functions? [arXiv:1103.5979]

Open issues: the Bjorken sum rule





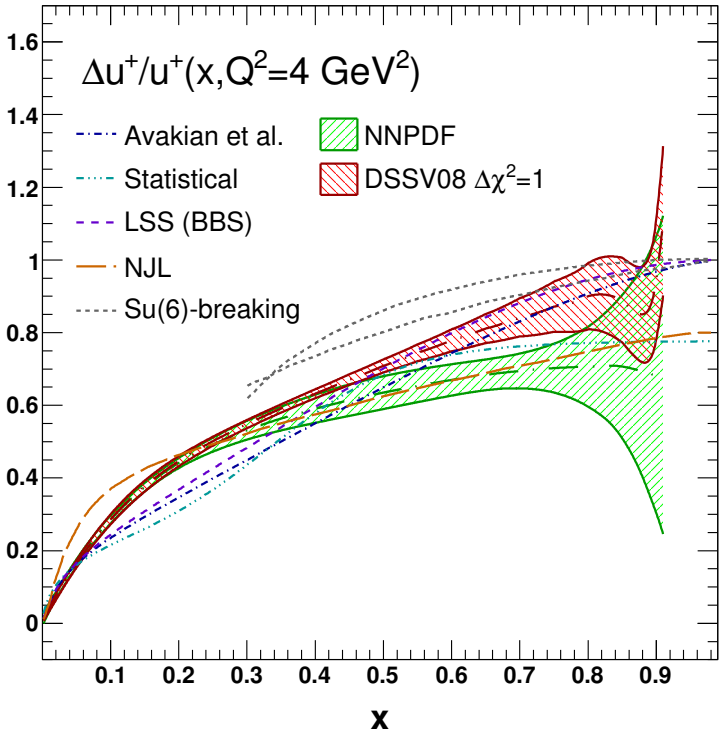
fixed $a_3 = 1.2701 \pm 0.0025$

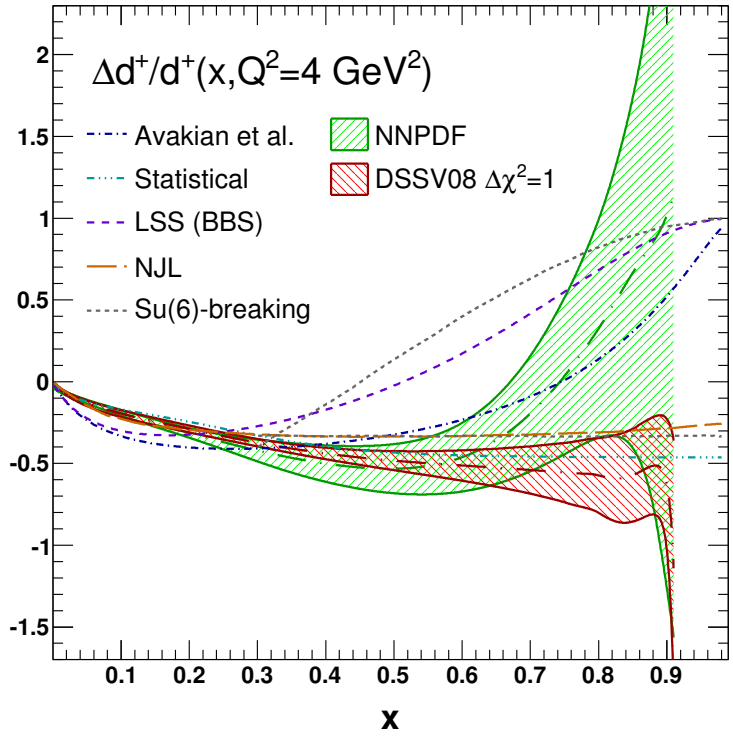
fitted $a_3 = 1.19 \pm 0.22$

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

$$a_3(Q^2) = \int_0^1 dx \left[\Delta u(x,Q^2) + \Delta\bar{u}(x,Q^2) - \Delta d(x,Q^2) - \Delta\bar{d}(x,Q^2)\right]$$

Open issues: polarized to unpolarized PDF ratios [PLB 742 (2015) 117]





Model	$\Delta u^+/u^+$	$\Delta d^+/d^+$	Model	$\Delta u^+/u^+$	$\Delta d^+/d^+$
SU(6)	$2/3$	$-1/3$	NJL	0.80	-0.25
RCQM	1	$-1/3$	DSE (*realistic*)	0.65	-0.26
QHD ($\sigma_{1/2}$)	1	1	DSE (*contact*)	0.88	-0.33
QHD (ψ_ρ)	1	$-1/3$	pQCD	1	1
NNPDF ($x=0.7$)	0.07 ± 0.05	-0.19 ± 0.34	NNPDF ($x=0.9$)	0.61 ± 0.48	$+0.85 \pm 6.55$