The longitudinal spin structure of the proton: a theory overview

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Mark Chadwick, *Abstract Spin Painting 21*, Acrylic on canvas (2010)

Foreword

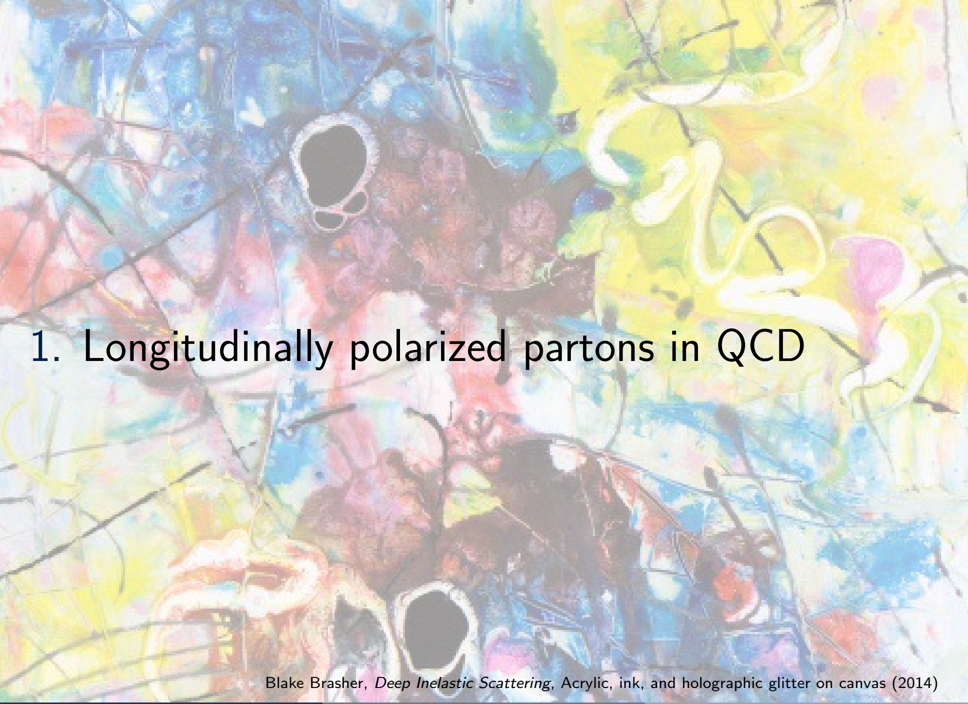
Thanks to all the speakers in the Nucleon Helicity Session

SPIN [from A. Prokudin]

- is a fundamental quantum degree of freedom
- contributes to the basic structure of fundamental interactions
- provides a complete test of QCD
- is a unique opportunity to probe the inner structure of a composite system

Outline

1. Longitudinally polarized partons in QCD
   - Parton distributions, factorization, evolution
2. A global determination of polarized Parton Distribution Functions
   - The art of parton fitting: data, theoretical progress, open issues/limiting factors
3. The path forward
   - Opportunities at JLAB, RHIC and at a future polarized EIC
4. Drawing conclusions



1. Longitudinally polarized partons in QCD

Blake Brasher, *Deep Inelastic Scattering*, Acrylic, ink, and holographic glitter on canvas (2014)

Where does the proton angular momentum come from?

$$a_0 = \left\langle P; S | \hat{J}^z_\Sigma(\mu^2) | P; S \right\rangle \xrightarrow{\text{naive p.m.}} 2\langle S_z^{q+\bar{q}} \rangle \simeq 1$$

($a_0 \sim 0.6$ including relativistic effects [NPB 337 (1990) 509])

$\mathrm{EMC\ 1988\ a_0} = 0.098 \pm 0.076 \pm 0.113$ [PLB 206 (1998) 364; NPB 328 (1989) 1]

An anomalous gluon contribution to the singlet axial charge [PLB 212 (1988) 391]

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

The gluon does not decouple in the asymptotic limit

A realization of the proton's total angular momentum decomposition [NPB 337 (1990) 509]

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

The decomposition is not unique

What should be the decompositions that lead to gauge-invariant, physically meaningful terms (and in which sense these are measurable) are discussed in [Phys.Rept. 541 (2014) 163]

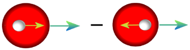
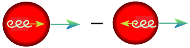
Here I focus on $\Delta\Sigma$ and Δg

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

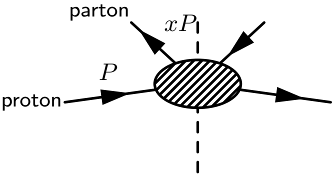
Polarized PDFs on the light-cone [Rev.Mod.Phys. 67 (1995) 157]

1. The momentum densities of partons with spin (↑) or (↓) *w.r.t* the nucleon

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

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

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
[Helicity+Lattice joint session, see also H.-W. Lin's talk]

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

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

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

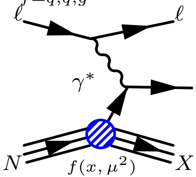
Factorization of physical observables [Adv.Ser.Direct.HEP 5 (1988) 1]

1. A variety of sufficiently inclusive processes allow for a factorized description

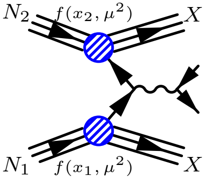
short-distance part		long-distance part
hard interaction of partons	$\xleftrightarrow[\text{scheme \& scale } \mu]{\text{factorization}}$	nucleon structure
process-dependent kernels		universal parton distributions

2. Physical observables are written as a convolution of coefficient functions and PDFs

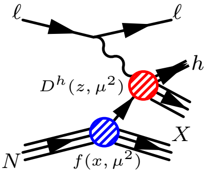
$$\mathcal{O}_I = \sum_{f=q,\bar{q},g} C_{If}(y, \alpha_s(\mu^2)) \otimes f(y, \mu^2) + \text{p.s. corrections} \qquad f \otimes g = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y)$$



DIS



DY



SIDIS

3. Coefficient functions allow for a perturbative expansion

$$C_{If}(y, \alpha_s) = \sum_{k=0} \left(\frac{\alpha_s}{4\pi}\right)^k C_{If}^{(k)}(y)$$

DIS (NNLO) [NPB 417 (1994) 61]
SIDIS (NLO) [PRD 57 (1998) 5811, EPJC 73 (2013) 2360]
PP (NLO) [NPB 539 (1999) 455,PRD 70 (2004) 034010]
[PRD 67 (2003) 054004,054005, PRD 81 (2010) 094020]

4. After factorization, all quantities (PDFs) depend on μ

Evolution of PDFs: DGLAP equations [NP B126 (1977) 298]

1. A set of $(2n_f+1)$ integro-differential equations, n_f is the number of active flavors

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

2. Often written in a convenient basis of PDFs

$$\Delta q_{\mathrm{NS};\pm} = (\Delta q_i \pm \Delta\bar{q}_i) - (\Delta q_j \pm \Delta\bar{q}_j) \quad \Delta q_{\mathrm{NS;v}} = \sum_i^{n_f}(\Delta q_i - \Delta\bar{q}_j) \quad \Delta\Sigma = \sum_i^{n_f}(\Delta q_i + \Delta\bar{q}_j)$$

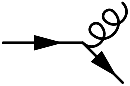
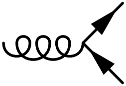
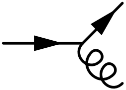
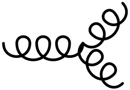
$$\frac{\partial}{\partial \ln \mu^2}\Delta q_{\mathrm{NS};\pm,v}(x,\mu^2) = \Delta P^{\pm,\mathrm{v}}(x,\mu_F^2)\otimes\Delta q_{\mathrm{NS};\pm,v}(x,\mu^2)$$

$$\frac{\partial}{\partial \ln \mu^2}\begin{pmatrix}\Delta\Sigma(x,\mu^2)\\ \Delta g(x,\mu^2)\end{pmatrix} = \begin{pmatrix}\Delta P^{qq} & \Delta P^{gq}\\ \Delta P^{qg} & \Delta P^{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta\Sigma(x,\mu^2)\\ \Delta g(x,\mu^2)\end{pmatrix}$$

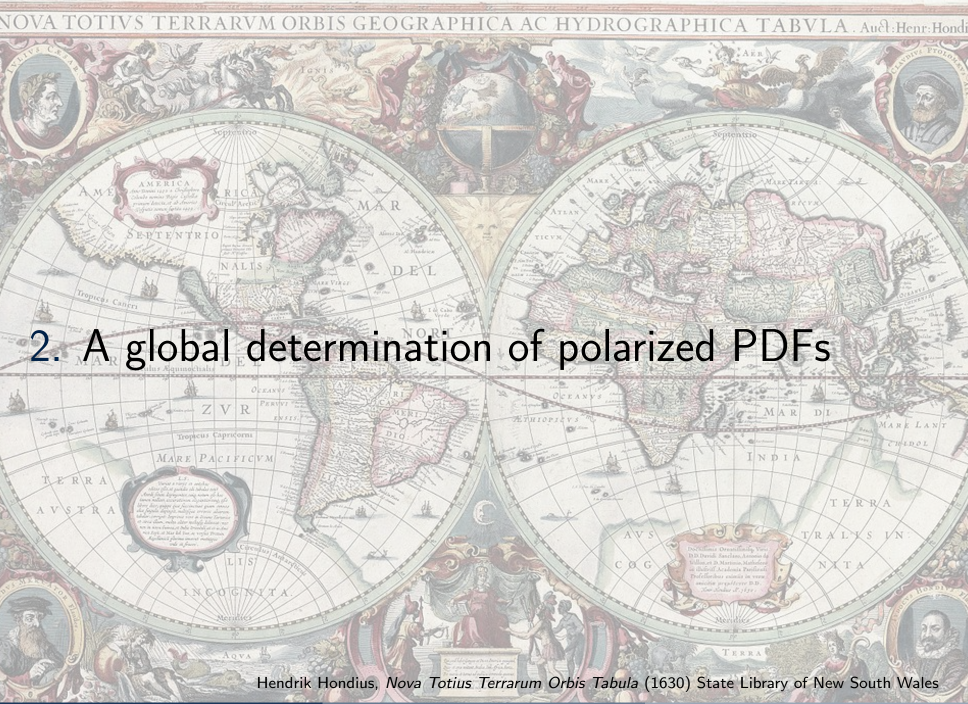
3. With perturbative computable splitting functions

$$\Delta P_{ji}(z,\alpha_s) = \sum_{k=0}\left(\frac{\alpha_s}{4\pi}\right)^{k+1}\Delta P_{ji}^{(k)}(z)$$

LO	[NPB 126 (1977) 298]
NLO	[ZPC 70 (1996) 637, PRD 54 (1996) 2023]
	[NPB 475 (1996) 47]
NNLO	[NPB 889 (2014) 351]

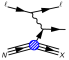
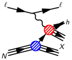
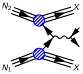
$\Delta P_{qq}^{(0)}$  $\Delta P_{gq}^{(0)}$  $\Delta P_{qg}^{(0)}$  $\Delta P_{gg}^{(0)}$ 

2. A global determination of polarized PDFs



Hendrik Hondius, *Nova Totius Terrarum Orbis Tabula* (1630) State Library of New South Wales

Experimental data [More in A. Bazilevsky's talk]

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	$\ell^\pm\{p,d\}\to\ell^\pm hX$	$\gamma^* q\to q$	Δu $\Delta\bar{u}$ Δd $\Delta\bar{d}$ 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	$\vec{p}\,\vec{p}\to jet(s)X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.2$	$30\lesssim p_T^2\lesssim 800$
	$\vec{p}\,p\to W^\pm X$	$u_L\bar{d}_R\to W^+$ $d_L\bar{u}_R\to W^-$	Δu $\Delta\bar{u}$ Δd $\Delta\bar{d}$	$0.05\lesssim x\lesssim 0.4$	$\sim M_W^2$
	$\vec{p}\,\vec{p}\to\pi X$	$gg\to qg$ $qg\to qg$	Δg	$0.05\lesssim x\lesssim 0.4$	$1\lesssim p_T^2\lesssim 200$

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

[M. Wilfert, A. Deur, K. Klimaszewski]
[V. Andrieux, J. Zhang, C. Peng]

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

[N. Makke]
[G. Schnell]

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

[S. Ramachandran, H. Yu]
[T. Moon, Y. Wang]
[D. Gunarathne, S. Park]

Recent available determinations of polarized PDFs

	DSSV	NNPDF	JAM	LSS
DIS	☑	☑	☑	☑
SIDIS	☑	☒	☒	☑
pp	☑ (jets, π^0)	☑ (jets, $W^\pm$)	☒	☒
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	Monte Carlo	Monte Carlo	Hessian $\Delta\chi^2 = 1$
parametrization	polynomial (23 pars)	neural network (259 pars)	polynomial (10 pars)	polynomial (20 pars)
features	global fit	minimally biased fit	large-x effects	higher-twist effects
latest update	PRL 113 (2014) 012001	NPB 887 (2014) 276	PRD 93 (2016) 074005	PRD 82 (2010) 114018

+ 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) [see N. Sato's talk]

$$\mathcal{P}(\Delta f|data) \longrightarrow \{\Delta f_k\}$$

$$E[\mathcal{O}] \approx \frac{1}{N}\sum_k \mathcal{O}(\Delta f_k)$$

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

Maximum likelihood (DSSV, LSS, BB)

$$\mathcal{P}(\Delta f|data) \longrightarrow \Delta f_0$$

$$E[\mathcal{O}] \approx \mathcal{O}(\Delta f_0)$$

$V[\mathcal{O}] \approx$ Hessian, $\Delta\chi^2$envelope, ...

Impact of data: W production in pp collisions

Observable

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Features

- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$
- A_L sensitive to Δq, $\Delta \bar{q}$ at $Q \sim M_W$ (no need of fragmentation functions)

$$A_L^{W^-} \sim \frac{\Delta \bar{u}_{x_1} d_{x_2} (1-\cos\theta)^2 - \Delta d_{x_1} \bar{u}_{x_2} (1+\cos\theta)^2}{\bar{u}_{x_1} d_{x_2} (1-\cos\theta)^2 - d_{x_1} \bar{u}_{x_2} (1+\cos\theta)^2}$$

backward lepton rapidity   forward lepton rapidity

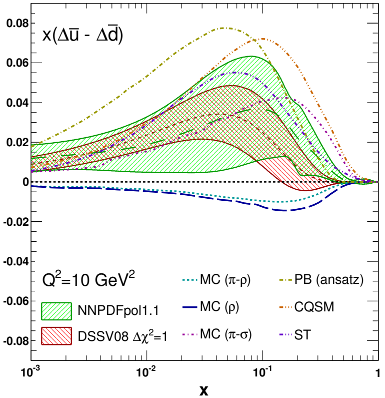
- for W^+, $d \longleftrightarrow u$ and $\Delta d \longleftrightarrow \Delta u$
- no access to strangeness ($W^\pm$ + c)

Measurements

- STAR [PRL 113 (2014) 072301]
- PHENIX [PRD 93 (2016) 051103]

Effects

First evidence of broken flavor symmetry for polarized light sea quarks



- $\Delta\bar{u} > 0 > \Delta\bar{d}$, $|\Delta\bar{d}| > |\Delta\bar{u}|$
- $|\Delta\bar{u} - \Delta\bar{d}| \sim |\bar{u} - \bar{d}|$
- some models are disfavored

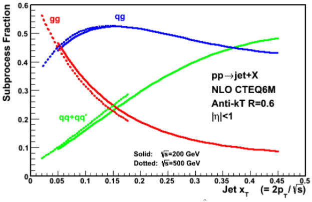
Impact of data: jet and π production

Observable

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

Features

- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$
- qg,gg initiated subprocesses dominate (for most of the RHIC kinematics)
- A_{LL} sensitive to Δg

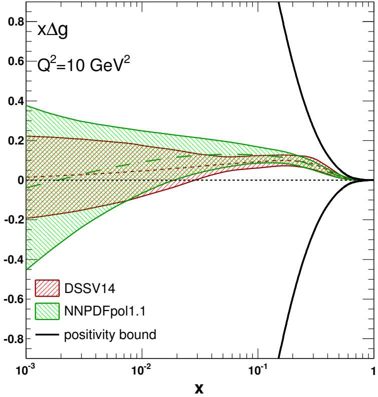


Measurements

- STAR (jets) [PRL 115 (2015) 092002]
- PHENIX (π) [PRD 90 (2014) 012007]

Effects

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

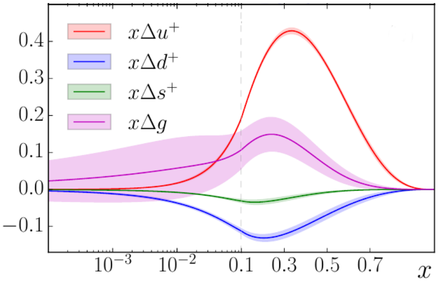


$Q^2 = 10$ GeV^2	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

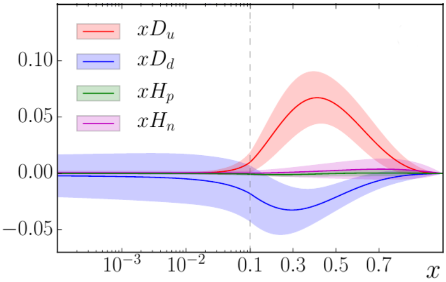
Higher twist corrections to g_1 [N. Sato's talk]

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

Helicity PDFs (DIS only) including TMCs and HT (up to $\tau = 4$) [PRD 93 (2016) 074005]



LT PDFs (contributing to $g_1^{\rm LT}$)



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

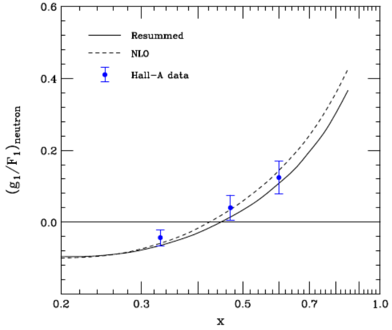
remarkably accuracy of all distributions (except the gluon)

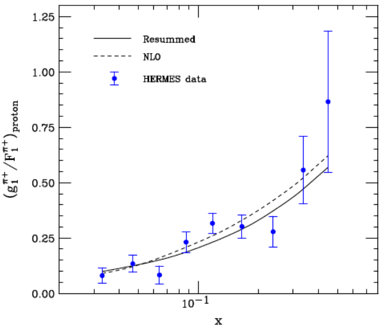
nonzero twist-3 quark distributions

twist-4 quark distributions compatible with zero

Threshold resummation for polarized processes [F. Ringers' talk]

DIS: Hall A data [PRC 70 (2004) 065207] SIDIS: HERMES data [PRD 71 (2005) 012003]





resummation of large logarithm corrections (NLO+NNLL) to spin asymmetries in DIS and SIDIS

asymmetries are rather insensitive to the inclusion of resummed higher-order terms

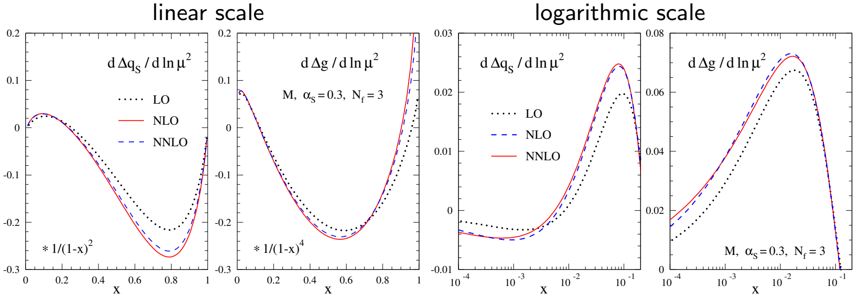
modest decrease of spin asymmetries at fairly high x values, more pronounced for SIDIS

most relevant for JLAB kinematics, important for future high statistic JLAB12

threshold resummation also performed for high-p_T hadron production [PRD 92 (2015) 094029]
(but effects are smaller than the experimental uncertaity of the data)

threshold resummation also performed for W production in polarized pp [PRD 73 (2006) 074005]
(but effects cancel out when asymmetries are considered)

Higher-order computations ($\overline{\mathrm{MS}}$ scheme) [NPB 889 (2014) 351]



NNLO (three-loop) corrections to spin-dependent splitting functions have been computed

NNLO corrections to the splitting functions are small outside the region of small x

corrections to the evolution of the PDFs can be unproblematic down to $x \approx 10^{-4}$

QCD analyses of polarized PDFs are now feasible up to NNLO accuracy [H. Khanpour's talk]
only including DIS data (coefficient functions are know at NNLO only for DIS)

may be needed at a future EIC

Helicity evolution at small x [Y. Kovchegov's talk, JHEP 1601 (2016) 072]

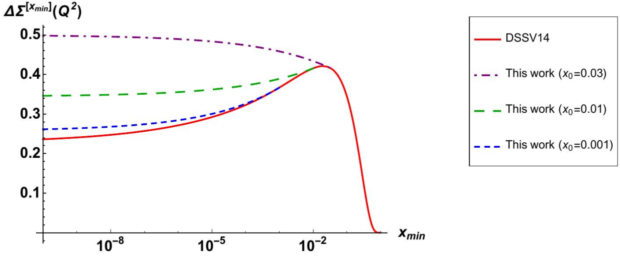
small-x evolution equations to calculate quark and anti-quark helicity PDFs and the g_1

they resum powers of $\alpha_s \ln^2(1/x)$ in the polarization-dependent evolution
along with the powers of $\alpha_s \ln(1/x)$ in the unpolarized evolution

these equations become closed in the large N_C and large N_C and n_f limits

a solution of the flavor-singlet evolution equations at large N_C is

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



poor-man solution: attach a $\Delta\hat{\Sigma}(x,Q^2) = N x^{-\alpha_h}$ factor to the existing polarized PDFs at x_0

potentially solid amount of spin at small x (but detailed phenomenology needed)

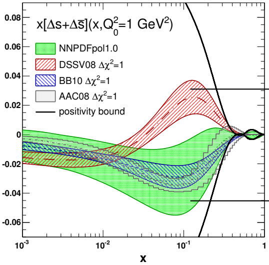
Open issues: SU(3) breaking and strangeness [E. Leader's talk]

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

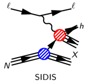
Lattice [PRL 108 (2012) 222001]
$\int_0^1 dx[\Delta s + \Delta\bar{s}] = -0.020(10)(1)$

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

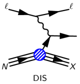
$a_8 = \int_0^1 dx[\Delta u^+ + \Delta d^+ - 2\Delta s^+] = 0.585 \pm 0.025$



directly from SIDIS Kaon data



indirectly from DIS + SU(3)



All PDF determinations based only on DIS data (+ SU(3)) find a negative Δs^+
PDF determinations based on DIS+SIDS data (+SU(3)) find a negative or a postive Δs^+ depending on the K FF set

Is there mounting tension between DIS and SIDIS data?

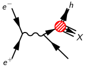
$SU(3)$ may be broken [PRD 58 (1998) 094028, Ann.Rev.Nucl.Part.Sci. 53 (2003) 39], but how much?
$\longrightarrow$ in NNPDFpol, the nominal uncertainty on a_8 in inflated by 30% of its value to allow for a $SU(3)$ symmetry violation ($a_8 = 0.585 \pm 0.025 \longrightarrow a_8 = 0.585 \pm 0.176$)
$\longrightarrow$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

No neutrino DIS data so far, but MicroBooNE will measure the ratio of neutral-current elastic to charged-current quasi-elastic events at low Q^2 [K. Woodruff's talk]

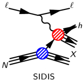
Inclusion of SIDIS data requires the knowledge of the fragmentation $s \rightarrow K$
$\longrightarrow$ how well do we know the kaon fragmentation function?

Open issues: fragmentation functions

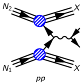
1. Progress on global determinations of Fragmentation Functions



$e^+ + e^- \to h + X$
single-inclusive annihilation (SIA)



$\ell + N \to \ell' + h + X$
semi-inclusive deep-inelastic scattering (SIDIS)



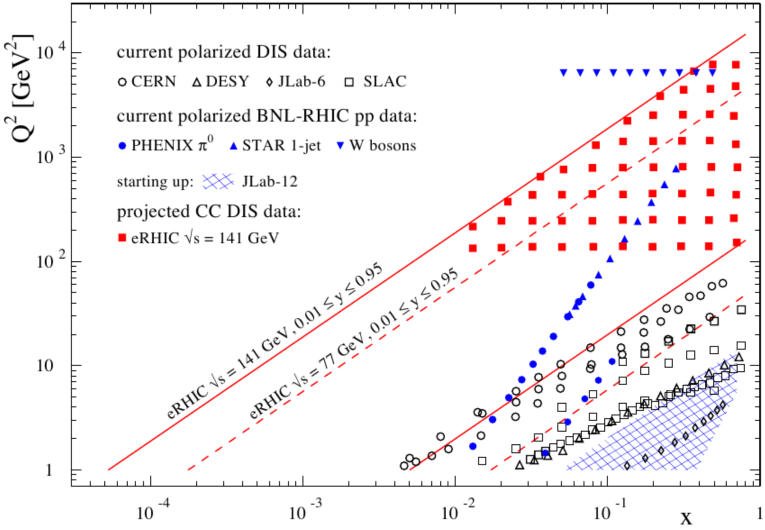
$N_1 + N_2 \to h + X$
high-p_T hadron production in pp collisions (PP)

Process	DSS	HKNS	JAM [N. Sato's talk]	NNPDF [ERN's talk]
SIA	✓	✓	✓	✓
SIDIS	✓	✗	✗	✗
PP	✓	✗	✗	✗
statistical treatment	Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	Hessian $\Delta\chi^2 = 15.94$	Monte Carlo	Monte Carlo
hadron species	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$	$\pi^\pm$, $K^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$
latest update	PRD 91 (2015) 014035	arXiv:1608.04067	arXiv:1609.00899	in progress

a truly global analysis is needed to determine all the aspects of FFs (fav./unf., gluon)

2. Experimental data
final COMPASS multiplicities for charged pions, kaons and unidentified hadrons
[N. Makke's talk + arXiv:1604.02695 + arXiv:1608.06760]
internal inconsistency of HERMES $[x, z]$ and $[Q^2, z]$ projections of pion multiplicities
HERMES $[Q^2, z]$ and COMPASS $[x, y, z]$ π multiplicities compatible in global analyses

Open issues: need for data [From the EIC White Paper]



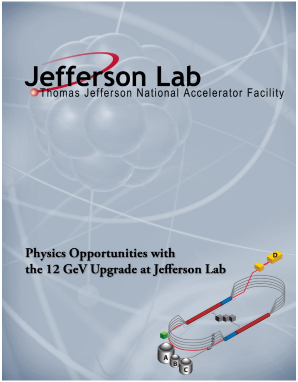
main culprit: lack of covergae at small-x + limited Q^2 lever arm

3. The path forward

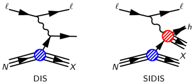
Luiza Vizali, *Path through the sky*, Acrylic, metallic acrylic, stretched canvas (2008)

Ongoing/planned/proposed experimental programs

Jefferson Laboratory



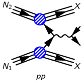
[arXiv:1208.1244]



large-x, high precision

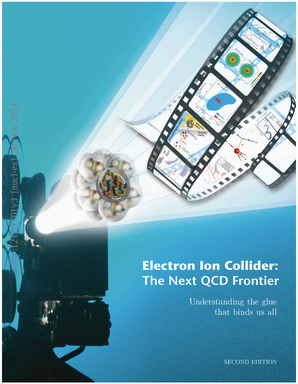
Relativistic
Heavy Ion Collider

[arXiv:1501.01220]

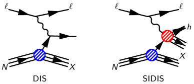


Δg, Δq, $\Delta\bar{q}$

A future
Electron-Ion Collider



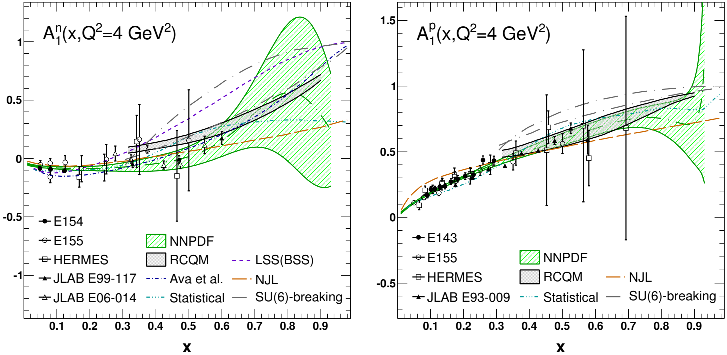
[arXiv:1212.1701]



small-x, high-Q^2

Opportunities at JLAB (towards 12 GeV upgrade)

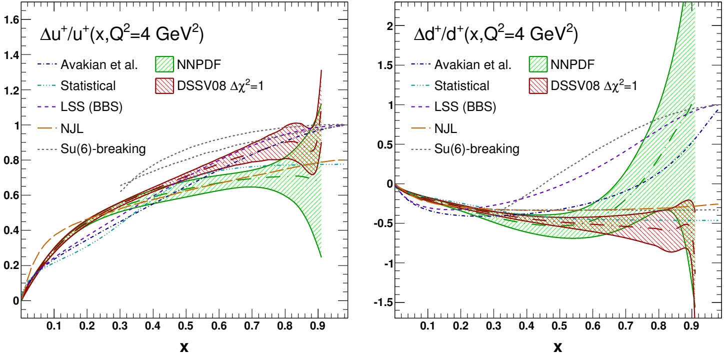
VIRTUAL PHOTOABSORPTION ASYMMETRY IN INCLUSIVE DIS [PLB 742 (2015) 117]



Model	A_1^n	A_1^p	Model	A_1^n	A_1^p
SU(6)	0	5/9	NJL	0.35	0.77
RCQM	1	1	DSE (*realistic*)	0.17	0.59
QHD ($\sigma_{1/2}$)	1	1	DSE (*contact*)	0.34	0.88
QHD (ψ_ρ)	1	1	pQCD	1	1
NNPDF ($x = 0.7$)	0.41 ± 0.31	0.75 ± 0.07	NNPDF ($x = 0.9$)	0.36 ± 0.61	0.74 ± 0.34

Opportunities at JLAB (towards 12 GeV upgrade)

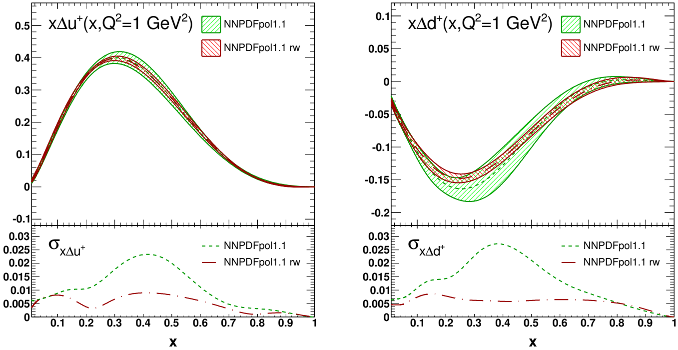
POLARIZED TO UNPOLARIZED PDF RATIOS [PLB 742 (2015) 117]



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	$+0.85\pm6.55$

Opportunities at JLAB (towards 12 GeV upgrade)

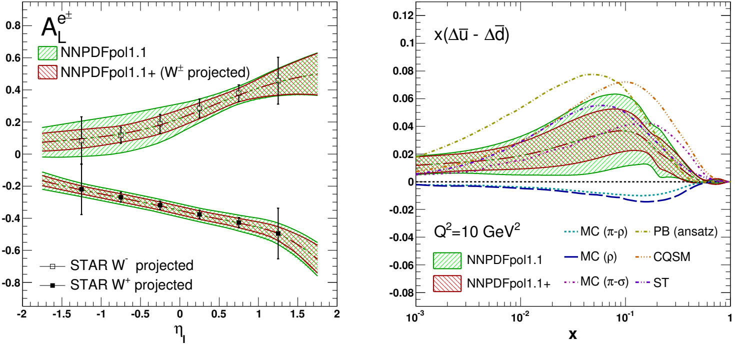
POTENTIAL IMPACT OF JLAB DATA (INCLUSIVE DIS) [JPCS 678 (2016) 012030]



Experiment	Reference	Observable	Target	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$	$\chi^2_{\rm rw}/N_{\rm dat}$
JLAB E99-117	[PRC 70 (2004) 065207]	A_1^n	He^3	3	1.22	1.02
JLAB E93-009	[PRC 92 (2015) 055201]	A_1^p	NH^3	148	1.20	1.05
		A_1^d	ND^3	9	1.65	1.05
JLAB E06-014	[PLB 744 (2015) 309]	A_1^n	He^3	6	4.31	1.32
JLAB EG1-DVCS	[PRC 90 (2014) 025212]	A_1^p	NH^3	18	0.59	0.29
				184	1.93	1.09

Opportunities at RHIC

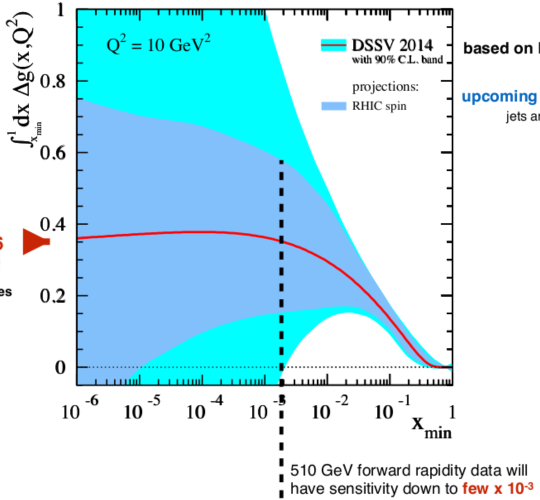
PINNING DOWN THE LIGHT POLARIZED SEA ASYMMETRY (new 2013 data)



	$\int_{10^{-3}}^{1} dx\Delta f(x,Q^2)$			$\int_{0.05}^{0.4} dx\Delta f(x,Q^2)$		
	cv	*unc* (pol1.1)	*unc* (pol1.1+)	*cv*	*unc* (pol1.1)	*unc* (pol1.1+)
Δu^+	$+0.764$	±0.035	±0.034	$+0.523$	±0.014	±0.013
Δd^+	-0.407	±0.037	±0.036	-0.231	±0.018	±0.018
$\Delta\bar{u}$	$+0.044$	±0.046	±0.030	$+0.019$	±0.023	±0.012
$\Delta\bar{d}$	-0.088	±0.067	±0.032	-0.037	±0.021	±0.013
Δ_{sea}	$+0.123$	±0.076	±0.038	$+0.056$	±0.030	±0.016

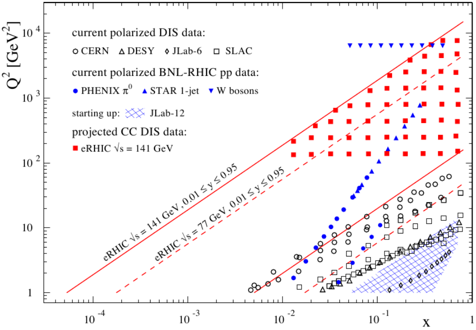
Opportunities at RHIC

PINNING DOWN THE GLUON POLARIZATION (combine jet and π^0 data leq 2015)



[E.C. Aschenauer's talk]

Opportunities at a future EIC [E.C. Aschenauer and B. Page talks]



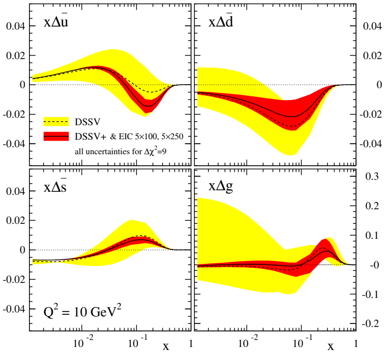
REQUIREMENTS & FEATURES

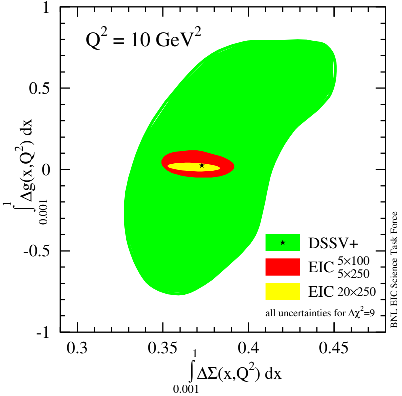
- large kinematic reach
  → high-energy collider
- precision of electromagnetic probes
  → electron beams
- spin
  → polarized hadron beams
- versatility
  → heavy ion beams

DELIVERABLES	OBSERVABLES	WHAT WE LEARN
Δg	scaling violations in DIS	gluon contribution to proton spin
Δq, $\Delta\bar{q}$	SIDIS for pions and kaons	quark contribution to proton spin; flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$; strangeness Δs
$g_1^{W^-}$, $g_5^{W^-}$	inclusive CC DIS at high Q^2	flavor separation at medium x and high Q^2

Opportunities at a future EIC

- Dramatic reduction of uncertainties of both PDFs and their moments [PRD 86 (2012) 054020]
- Accurate determination of Δg via scaling violations in DIS [PRD 86 (2012) 054020]
- Accurate determination of $\Delta\bar{u}$, $\Delta\bar{d}$ via SIDIS and CC DIS [PRD 88 (2013) 114025]
- Access to unknown electroweak structure functions [PRD 88 (2013) 114025]





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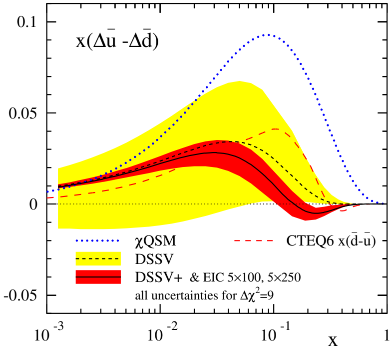
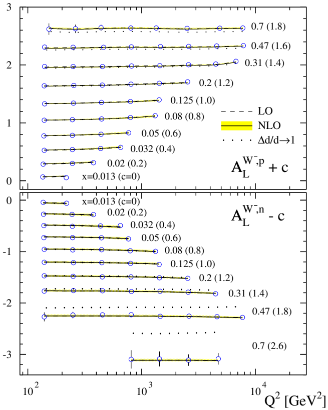
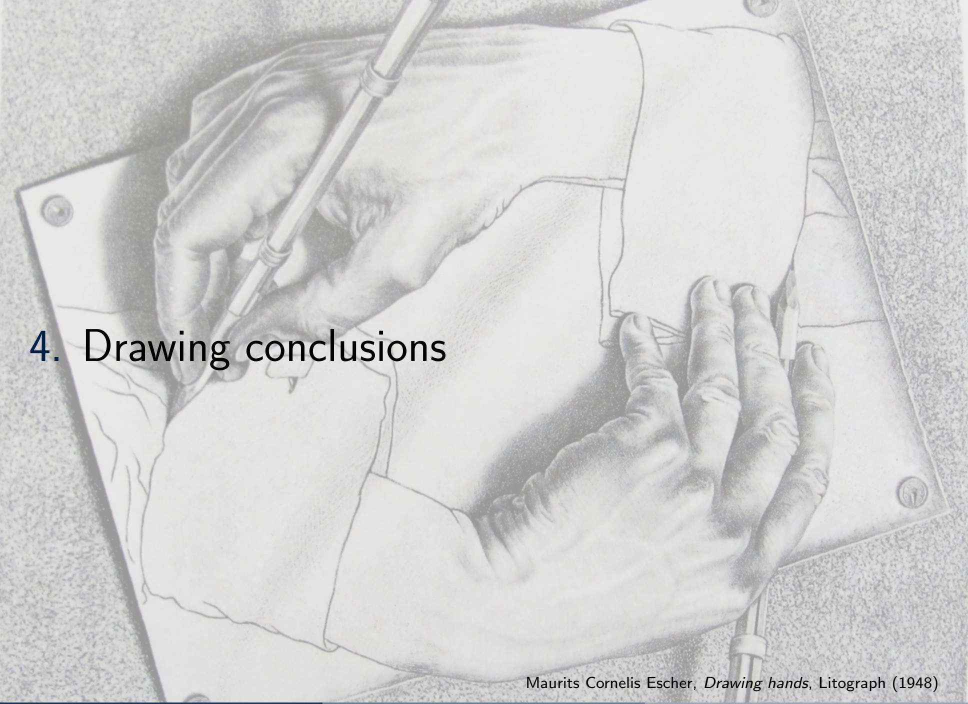


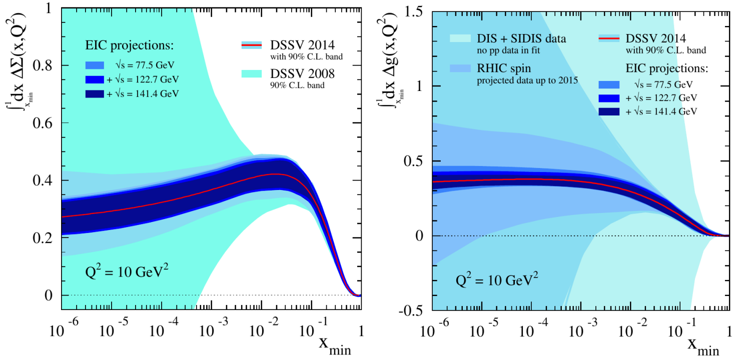




4. Drawing conclusions

Maurits Cornelis Escher, *Drawing hands*, Litograph (1948)

The ultimate spin content of the proton [PRD 92 (2015) 094030]



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, ...)
first evidence of gluon polarization and light sea symmetry in the proton
Theory efforts and global QCD analyses try to keep up

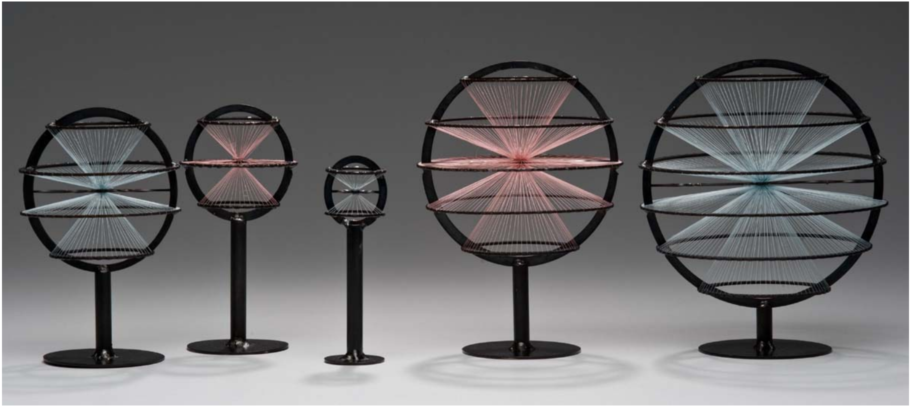
Only an EIC would be able to push forward our knowledge of the nucleon spin content

Thank you for your attention

Sin-Itiro Tomonaga, Nobel Prize for Physics, 1965

[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]



Julian Voss-Andreae, *Spin Family (Bosons and Fermions)*, Steel and silk (2009)