Polarized parton distributions from the NNPDF perspective

Future Physics with HERA data for current and planned experiments

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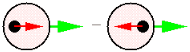
Foreword



$$\Delta f(x, Q^2) = f^{\Rightarrow\rightarrow}(x, Q^2) - f^{\Rightarrow\leftarrow}(x, Q^2)$$

How do quarks (including sea quarks) and gluons carry the proton spin

$$\mathcal{S}(\mu) = \frac{1}{2} = \sum_f \left\langle P; S | \hat{J}_f^z(\mu) | P; S \right\rangle = \frac{1}{2}\int_0^1 dx \Delta\Sigma(x, \mu) + \int_0^1 dx \Delta g(x, \mu) + L_z$$

All quantities depend on factorization scheme and scale μ

Spin decomposition is not unique [arXiv:1309.4235]

Very little of the proton spin is carried by quarks

$$\int_0^1 dx \Delta\Sigma = \int_0^1 dx \sum_{q=u,d,s} (\Delta q + \Delta\bar{q}) \sim 30\%$$

Quark and gluon longitudinal contributions $\Longleftrightarrow$ longitudinal spin-dependent PDFs

Outline

1. Introduction
2. Current status of polarized PDFs
   - Highlights from `NNPDFpol1.1` and `DSSV++`
   - Impact of new data and achievements of global QCD analyses
3. The path forward
   - Open issues in our knowledge of polarized PDFs
   - Interplay with current/future experiments
4. Conclusions

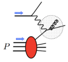
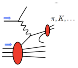
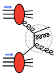
Mostly focus on HERMES
Apologies for some overlap with Elke's talk

1. Introduction

Probes of nucleon helicity structure

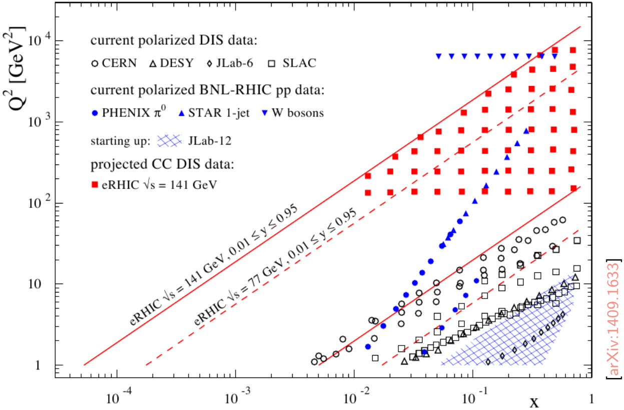
Guiding principle: FACTORIZATION

e.g. DIS $\quad d\Delta\sigma = \sum_{q,\bar{q},g} \Delta f(x,Q^2) \otimes d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2)) \qquad d\Delta\hat{\sigma}_{\gamma^* f} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{4\pi}\right)^n d\Delta\hat{\sigma}^{(n)}_{\gamma^* f}$

	Reaction	Partonic subprocess	PDF probed	x	Q^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	$\vec{p}\,\vec{p} \to jet(s)X$	$gg \to qg$ $qg \to qg$	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	$0.05 \lesssim x \lesssim 0.4$	$1 \lesssim p_T^2 \lesssim 200$

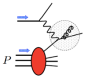
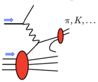
Different processes constrain different PDFs, factorization is successful

Available & projected experimental data



- Limited (x, Q^2) kinematic coverage
  $\rightarrow$ difficult to get Δg from scaling violations
  $\rightarrow$ need to use data down to $Q^2 = 1$ GeV^2
- No neutrino DIS data
  $\rightarrow$ no Δq - $\Delta\bar{q}$ separation in inclusive DIS
  $\rightarrow$ SIDIS or W production in pp collisions

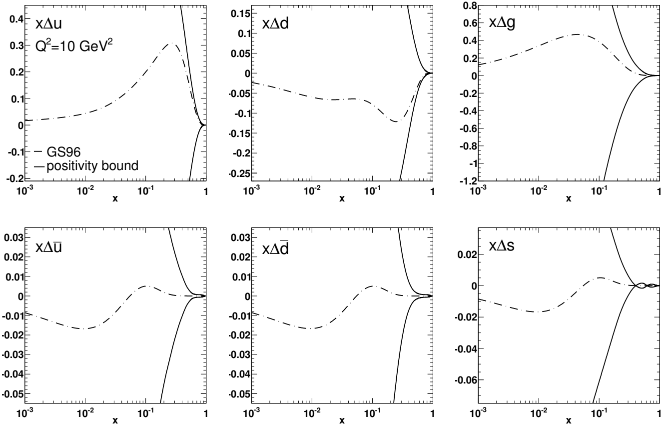
Experimental data from HERMES: DIS & SIDIS

	Observable	Target	Ref.	Probed quantity
	A_1	neutron (^{3}He)	[hep-ex/9703005]	$\Delta q + \Delta\bar{q}$, $q = u, d, s$
	g_1	proton (H)	[hep-ex/9807015]	
	A_1	proton, deuteron (H, ^{2}H)	[hep-ex/0609039]	
DIS	A_2	proton (H)	[arXiv:1112.5584]	
	$A_1^{h^\pm}$	proton, neutron (H, ^{3}He)	[hep-ex/9906035]	Δq, $\Delta\bar{q}$, $q = u, d, s$
	$A_1^{\pi^\pm}$, $A_1^{K^\pm}$	deuterium (^{2}H)	[hep-ex/0307064]	
	$A_1^{h^\pm}$, $A_1^{\pi^\pm}$	proton, deuteron (H, ^{2}H)	[hep-ex/0407032]	
	$A_1^{K^\pm}$	deuterium (^{2}H)	[hep-ex/0407032]	
SIDIS	$A_{\parallel}$	proton, deuteron (H, ^{2}H)	[hep-ex/9907020] [arXiv:1002.3921]	Δg
	mult. $\pi^\pm$, π^0	proton (H)	[hep-ex/0104004]	D_q^h, $q = u, d, s$
	mult. $\pi^\pm$, $K^\pm$	proton, deuteron (H, ^{2}H)	[arXiv:1212.5407]	$h = \pi^\pm, \pi^0, K^\pm$

Fragmentation Functions are needed to analyze SIDIS data
Fragmentation Functions are on the same footing as Parton Distribution Functions
and are an additional source of uncertainty

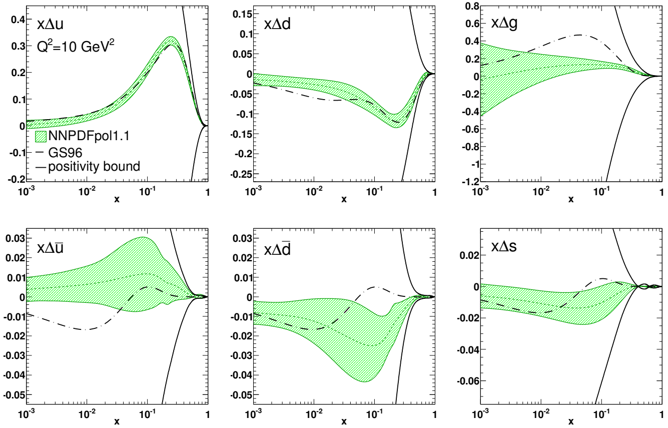
2. Status of polarized PDFs

1996 [arXiv:hep-ph/9512406]



Polarized PDFs took the first steps

2014 [arXiv:1406.5539]



Polarized PDFs are coming of *adult age* now

The latest determinations of polarized PDFs

The only PDF sets @ NLO accuracy which include data from polarized pp collisions

`NNPDFpol1.1` [arXiv:1406.5539]

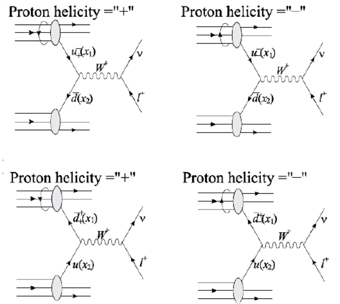
`DSSV++` [arXiv:1404.4293]

- Data sets

	DIS	SIDIS	OC	jets	π	$W^{\pm}$
`NNPDFpol1.1`	☑	☒	☑	☑	☒	☑
`DSSV++`	☑	☑	☒	☑	☑	☒

- Methodology

	Uncertainty estimate	PDF parametrization
`NNPDFpol1.1`	Monte Carlo replicas	Neural Network
`DSSV++`	Hessian $\Delta\chi^2 = 1$ Lagr. mult. $\Delta\chi/\chi = 2\%$	Functional form



$$A_L^{W^-} \sim$$

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

backward lepton rapidity | **forward lepton rapidity**

Longitudinal single- and double-spin asymmetries

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

FEATURES

- quark/antiquark separation at $Q \sim M_W$
- no need of fragmentation functions
- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{s}} e^{-\eta_l/2} \approx [0.04, 0.4]$
- for W^+, $d \longleftrightarrow d$ and $\Delta d \longleftrightarrow \Delta u$
- non-trivial positivity bound [arXiv:1104.2920]

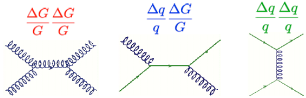
$$1 \pm A_{LL}(y_W) > |A_L(y_W) \pm A_L(-y_W)|$$

- no access to strangeness ($W^{\pm}$ + c required)

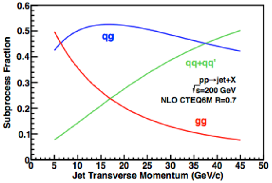
MEASUREMENTS

- STAR [arXiv:1404.6880] + PHENIX [PoS(DIS2014)205]
- much more to come from ongoing RHIC run

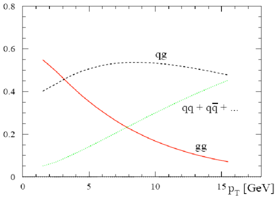
New data from RHIC: jet and π production



Jet production



π production



Longitudinal double-spin asymmetry

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

FEATURES

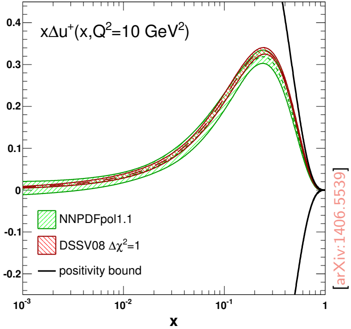
- at RHIC, $\langle x_{1,2} \rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$
- qg and gg initiated subprocesses dominate (for most of the RHIC kinematics)
- A_{LL} sensitive to gluon polarization
- cross sections are well described at NLO in pQCD

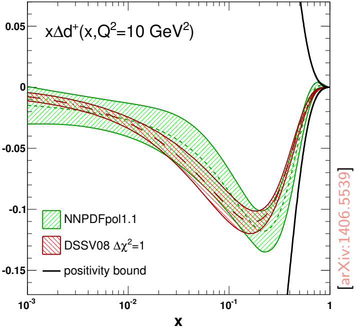
MEASUREMENTS

- STAR (jets) [arXiv:1405.5134]
- PHENIX (π) [arXiv:1402.6296] [arXiv:1409.1907]
- much more to come from ongoing RHIC run
  → gaining precision
  → di-jet measurements

Highlights from NNPDFpol1.1 & DSSV++: PDFs

$\Delta u^+ = \Delta u + \Delta \bar{u}$ and $\Delta d^+ = \Delta d + \Delta \bar{d}$

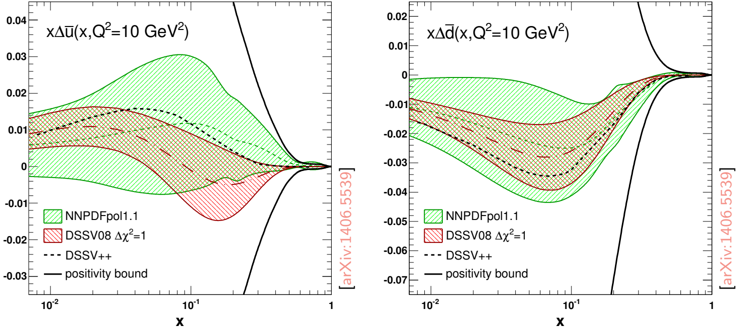




NNPDFpol1.1: DIS ☑; DSSV08: DIS ☑;

- Best constrained polarized PDFs from inclusive DIS data
- NNPDFpol1.1 and DSSV08 distributions are qualitatively similar
- NNPDFpol1.1 uncertainties are typically slightly larger

$\Delta\bar{u}$ and $\Delta\bar{d}$

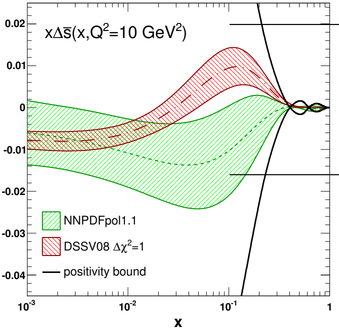


NNPDFpol1.1: SIDIS ☒, $W^\pm$ ☑; DSSV08: SIDIS ☑, $W^\pm$ ☒; DSSV++: SIDIS ☑, $W^\pm$ ☑;

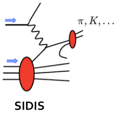
- Start to test of what we know about light sea quarks from SIDIS with pions
- Looming (mild) tension between $W^\pm$ and SIDIS data?
- Are fragmentation function uncertainties underestimated?

Highlights from NNPDFpol1.1 & DSSV++: PDFs

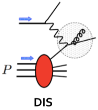
$\Delta\bar{s}$ (assuming $\Delta s = \Delta\bar{s}$, which may not be true [hep-ph/0505153])



directly from SIDIS Kaon data



indirectly from DIS scaling violations

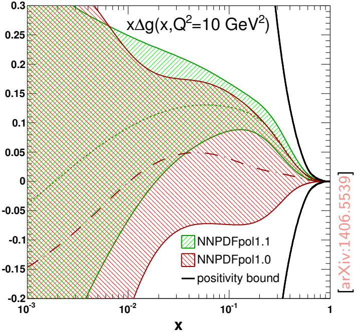


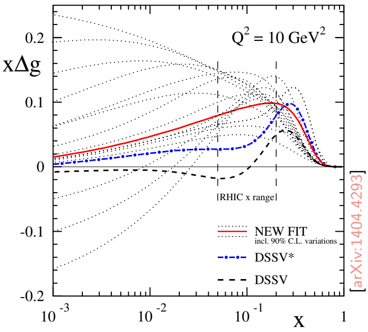
NNPDFpol1.1: DIS ☑, SIDIS ($K^{\pm}$) ☒;   DSSV08: DIS ☑, SIDIS ($K^{\pm}$) ☑;

- DIS data ⇒ negative $x\Delta\bar{s}$; SIDIS data ⇒ 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]

Highlights from NNPDFpol1.1 & DSSV++: PDFs

Δg

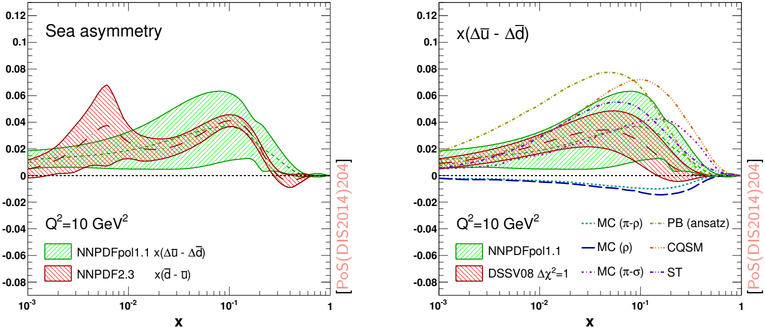




NNPDFpol1.0: jets ☒, π ☒; NNPDFpol1.1: jets ☑, π ☒; DSSV++: jets ☑, π ☑;

- First evidence of sizable gluon polarization
- NNPDFpol1.1 and DSSV++ results in perfect agreement
- Most significant constraints come from STAR jet data from 2009 run
- The gluon polarization remains largely uncertain outside the x-range probed by RHIC

The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$

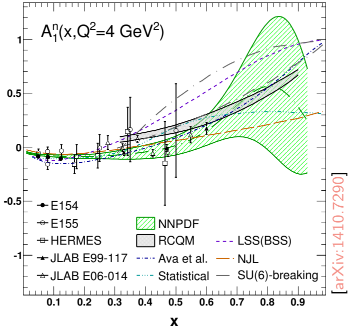


	MC (π-meson)	MC (ρ-meson)	PB (bag-model)	PB	IN	DSSV08 $\Delta\chi^2 = 1$
I_Δ	$\equiv 0$	< 0	$\simeq 0.09$	$\simeq 0.2$	$\simeq 0.2$	$\mathbf{0.14 \pm 0.05}$
	MC (π-ρ inter.)	MC (π-σ inter.)	PB (ansatz)	CQS	ST	NNPDFpol1.1
I_Δ	$[-4\cdot 10^{-3}, -0.033]$	$\simeq 0.12$	$\simeq 0.3$	0.31	> 0.12	$\mathbf{0.17 \pm 0.08}$

$$I_\Delta(Q^2) = \int_0^1 dx \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right], \quad Q^2 = 10\,\mathrm{GeV}^2$$

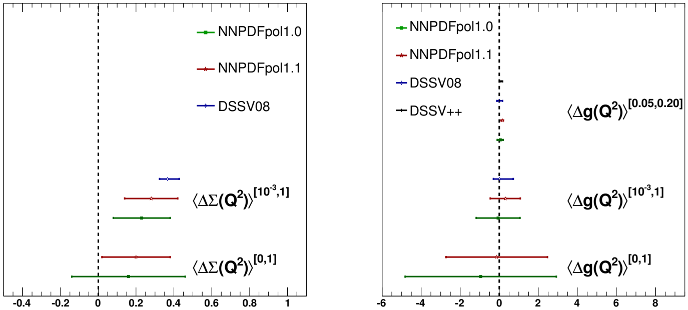
Highlights from NNPDFpol1.1 & DSSV++: outcomes

The large-x behavior



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

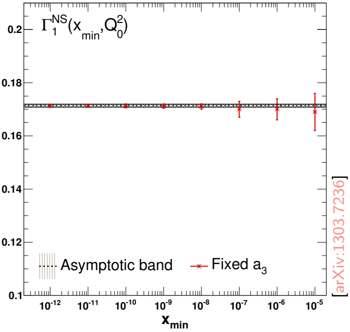
The spin content of the nucleon



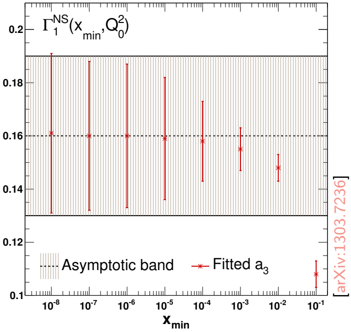
$Q^2 = 10$ GeV^2	$\langle\Delta\Sigma(Q^2)\rangle^{[0,1]}$	$\langle\Delta\Sigma(Q^2)\rangle^{[0.001,1]}$	$\langle\Delta g(Q^2)\rangle^{[0,1]}$	$\langle\Delta g(Q^2)\rangle^{[0.001,1]}$	$\langle\Delta g(Q^2)\rangle^{[0.05,0.2]}$
NNPDFpol1.0	$+0.16 \pm 0.30$	$+0.23 \pm 0.15$	-0.95 ± 3.87	-0.06 ± 1.12	$+0.05 \pm 0.15$
NNPDFpol1.1	$+0.18 \pm 0.21$	$+0.25 \pm 0.10$	-0.13 ± 2.60	$+0.31 \pm 0.77$	$+0.15 \pm 0.06$
DSSV08	—	$+0.366^{+0.042}_{-0.062}$	—	$0.013^{+0.702}_{-0.314}$	$0.005^{+0.129}_{-0.164}$
DSSV++	—	—	—	—	$0.10^{+0.06}_{-0.07}$

Highlights from NNPDFpol1.1 & DSSV++: outcomes

The Bjorken sum rule



fixed $a_3 = 1.2701 \pm 0.0025$



fitted $a_3 = 1.19 \pm 0.22$

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

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

3. The path forward

Achievements & open issues

Achievements

- New data are improving our knowledge of polarized PDFs
- Evidence of a sizable gluon polarization, though in a limited x-region
- Evidence of a sizable polarized sea quark asymmetry

Open Issues

- Uncertainties coming from the unmeasured small-x region spoil PDF first moments
- The present accuracy of polarized PDF cannot discriminate between models at large-x
- What is the strange spin content of the proton?
- A better knowledge of fragmentation functions is needed to analyze SIDIS data
- Very little is known about the g_2 structure function in DIS
- Electroweak structure functions have never been accessed

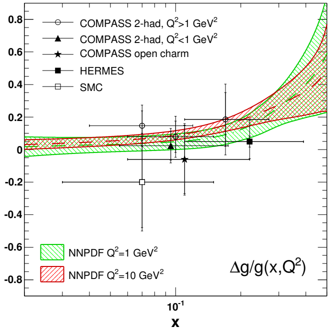
Open issues: interplay with future experiments

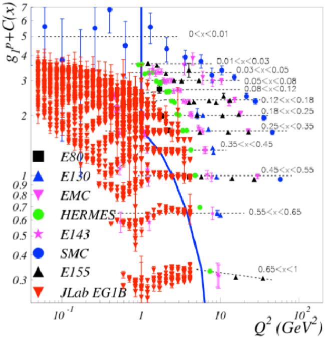
The Relativistic Heavy Ion Collider: STAR & PHENIX

- Open heavy-quark & pion production @ 500 GeV: Δg
- Further data on W production to come from the 2013 run: $\Delta\bar{u}$ and $\Delta\bar{d}$

Jefferson Lab: CLAS, Hall-A

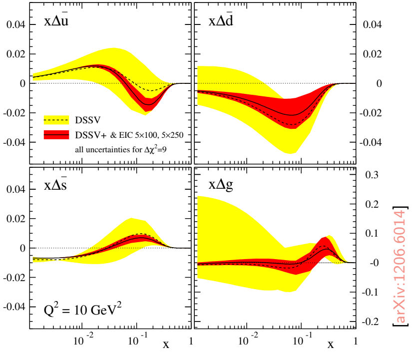
- Accurate determination of g_1 in inclusive DIS up to $x \sim 0.7$ and further insight into g_2

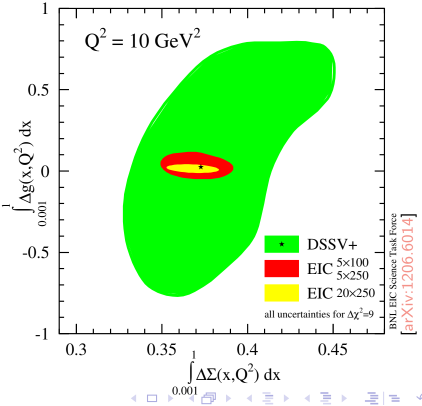




A future Electron-Ion Collider

- Dramatic reduction of uncertainties of both PDFs and their moments
- Accurate determination of Δg via scaling violations in DIS
- Accurate determination of $\Delta\bar{u}$, $\Delta\bar{d}$ via SIDIS and CC DIS
- Access to unknown electroweak structure functions





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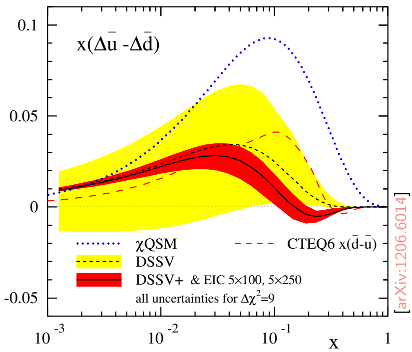
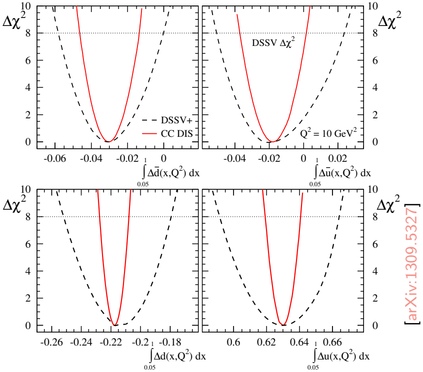
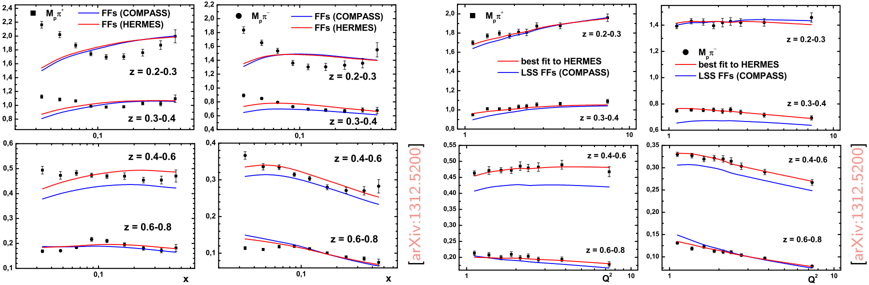




Detour: hadron multiplicities & fragmentation functions

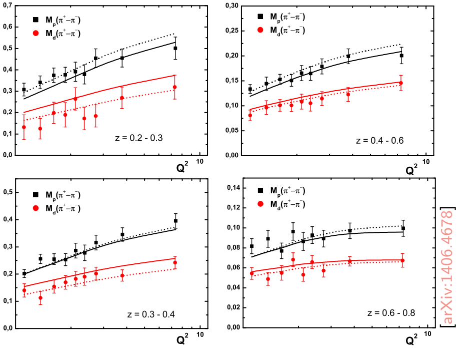
Multiplicities of $\pi^{\pm}$ and $K^{\pm}$ from SIDIS on proton and deuteron targets [arXiv:1212.5407]
Only $\pi^{\pm}$ data have been included in phenomenological analyses so far

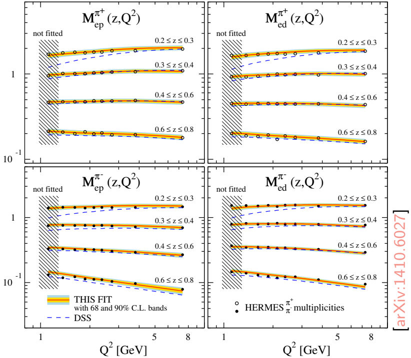


- Possible inconsistency between $[x, z]$ and $[Q^2, z]$ data analysis
- COMPASS (preliminary) and HERMES $[x, z]$ data are not consistent
- COMPASS (preliminary) and HERMES $[Q^2, z]$ data are consistent except
  → for π^+: the 3$^{\rm rd}$ z-bin
  → for π^-: the 2$^{\rm nd}$ and 3$^{\rm rd}$ z-bins

Detour: hadron multiplicities & fragmentation functions

Multiplicities of $\pi^{\pm}$ and $K^{\pm}$ from SIDIS on proton and deuteron targets [arXiv:1212.5407]
Only $\pi^{\pm}$ data have been included in phenomenological analyses so far





$$\chi^{2(p)}_{\pi^+-\pi^-} = 0.79,\ \chi^{2(d)}_{\pi^+-\pi^-} = 1.19;\ \chi^{2(p)}_{\pi^+} = 0.87,\ \chi^{2(p)}_{\pi^-} = 1.49,\ \chi^{2(d)}_{\pi^+} = 1.26,\ \chi^{2(d)}_{\pi^-} = 1.85$$

The smaller the values of z, the larger the values of W have to be
for a clean separation between quark and target fragmentation effects

4. Conclusions

Summary

HERMES has provided endless pioneering measurements
to understand the helicity structure of the proton

High impact results are being provided by ongoing experimental programs
(STAR, PHENIX, COMPASS, JLAB)

Theory efforts and global QCD fits try to keep up interesting physics questions
in gluon/sea quark regime

A brand new facility is needed to address open issues
in the longitudinal spin structure of the nucleon

A polarized, high-energy, Electron-Ion Collider

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Thank you for your attention

5. Backup

Effects of open-charm production at COMPASS

Virtual photon-nucleon asymmetry for open-charm production
[arXiv:1212.1319]

$$A^{\gamma N \to D^0 X} = \frac{\Delta g \otimes \Delta\hat{\sigma}_{\gamma g} \otimes D_c^H}{g \otimes \hat{\sigma}_{\gamma g} \otimes D_c^H}$$

FEATURES

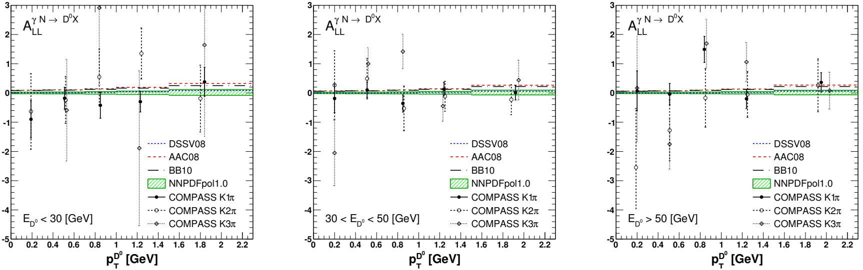
- Δg is probed *directly* through the photon-gluon fusion process
  (in DIS Δg is mostly probed through scaling violations instead)
- the fragmentation functions for heavy quarks are computable in perturbation theory
  (and only introduce a very moderate uncertainty in the fit)

EXPERIMENTAL MEASUREMENT

- COMPASS (2002-2007) [arXiv:1211.6849]

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$ NNPDFpol1.0	DSSV08	AAC08	BB10
COMPASS		45	1.23	1.23	1.27	1.25
	COMPASS $K1\pi$	15	1.27	1.27	1.43	1.38
	COMPASS $K2\pi$	15	0.51	0.51	0.56	0.55
	COMPASS $K3\pi$	15	1.90	1.90	1.81	1.82

Effects of open-charm production at COMPASS



Data are affected by large uncertainties w.r.t. the uncertainty due to PDFs
They do not show a clear trend

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$			
			NNPDFpol1.0	DSSV08	AAC08	BB10
COMPASS		45	1.23	1.23	1.27	1.25
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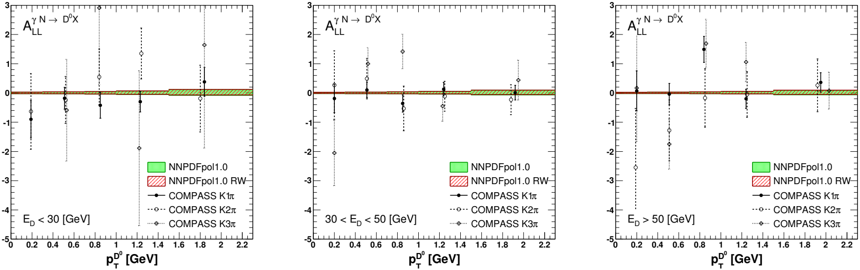

The impact of open-charm data from COMPASS is mostly negligible, as we notice from the value of the $\chi^2/N_{\rm ndat}$ and the reweighted observable

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$	$\chi^2_{\rm rw}/N_{\rm dat}$
COMPASS		45	1.23	1.23
	COMPASS $K1\pi$	15	1.27	1.27
	COMPASS $K2\pi$	15	0.51	0.51
	COMPASS $K3\pi$	15	1.90	1.89