

# Progress on Parton Distribution Functions from NNPDF

## The 4th International Workshop on Nucleon Structure at Large Bjorken $x$

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# Outline

- ① The NNPDF methodology
- ② Unpolarized PDFs: NNPDF3.0
- ③ Polarized PDFs: NNPDFpol1.1
- ④ Conclusions

# 1. The NNPDF methodology

# Foreword

## FACTORIZATION

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

## DGLAP EVOLUTION

$$\mu^2 \frac{\partial f(x, \mu^2)}{\partial \mu^2} = \int_z^1 \frac{dz}{z} P(z) f\left(\frac{x}{z}, \mu^2\right)$$

## SOURCES OF UNCERTAINTIES

- ➊ the underlying data, affected by statistical and (correlated) systematic errors
- ➋ the theory used to describe them, based on the truncation of a perturbative series
- ➌ the procedure used to extract PDFs from data

Available PDF sets are all based on item 2, but may differ significantly for items 1 and 3

# The NNPDF methodology: the idea

- ① Monte Carlo sampling of experimental data
  - generate experimental data replicas assuming multi-Gaussian probability distribution
  - validate against experimental data to determine the sample size ( $N_{\text{rep}} \sim 100$ )

⇒ no need to rely on linear error propagation, no tolerance needed
- ② Fit a set of PDFs parametrizing each replica with Neural Networks
  - redundant and flexible parametrization,  $\mathcal{O}(200)$  parameters
  - fit to each data replica by optimizing  $\chi^2$  (genetic algorithm + cross-validation)

⇒ reduce the theoretical bias due to the parametrization

PDF replicas are equally probable members of a statistical ensemble which samples the probability density  $\mathcal{P}[f_i]$  in the space of PDFs

$$\langle \mathcal{O} \rangle = \int \mathcal{D}f_i \mathcal{P}[f_i] \mathcal{O}[f_i]$$

Expectation values for observables are Monte Carlo integrals

$$\langle \mathcal{O}[f_i(x, Q^2)] \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} \mathcal{O}[f_i^{(k)}(x, Q^2)]$$

# The NNPDF methodology: reweighting

[arXiv:1012.0836] [arXiv:1108.1758]

- We would like to assess the impact of including a **new data set**  $\{y\} = \{y_1, \dots, y_n\}$  (delivered with  $\sigma_{ij}$ ) in a **prior ensemble** of PDF replicas  $\{f_k\}$ ,  $k = 1, \dots, N_{\text{rep}}$
- We can apply **Bayes theorem** to determine the conditional probability of PDF upon inclusion of the new data and update the probability density in the space of PDFs

$$\mathcal{P}_{\text{new}} = \mathcal{N}_\chi \mathcal{P}(\chi_k^2 | \{f_k\}) \mathcal{P}_{\text{old}}(\{f_k\}) \quad \mathcal{P}(\chi_k^2 | \{f_k\}) = [\chi_k^2(\{y\}, \{f_k\})]^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2(\{y\}, \{f_k\})}$$

$$\chi_k^2(\{y\}, \{f_k\}) = \sum_{i,j}^n \{y_i - y_i[f_k]\} \sigma_{ij} \{y_j - y_j[f_k]\}$$

- Replicas are **no longer equally probable**. Expectation values are given by

$$\langle \mathcal{O}[f_i(x, Q^2)] \rangle_{\text{new}} = \sum_{k=1}^{N_{\text{rep}}} w_k \mathcal{O}[f_i^{(k)}(x, Q^2)]$$

$$w_k \propto [\chi_k^2(\{y\}, \{f_k\})]^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2(\{y\}, \{f_k\})} \quad \text{with} \quad N_{\text{rep}} = \sum_{k=1}^{N_{\text{rep}}} w_k$$

**Reweighting** allows to incorporate new datasets **without** need of **refitting**

Validation and optimization of fitting strategy  
performed on closure test with known underlying physical law

- ① Set the theory (e.g. NLO pQCD)
- ② Set the fitting methodology (e.g. genetic algorithm, cross-validation)
- ③ Set the underlying *true* physical law (e.g. input PDFs from MSTW08)
- ④ Generate pseudodata and perform the fit with given theory and methodology
- ⑤ Validate the resulting PDF set
  - reproduce the underlying law (both central value and uncertainties)
  - check the consistency of expected values of  $\chi^2$
  - check that PDF reweighting is equal to PDF refitting (Bayesian inference)

level 0: fluctuations on pseudodata ; Monte Carlo replica generation

level 1: fluctuations on pseudodata ; Monte Carlo replica generation

level 2: fluctuations on pseudodata ; Monte Carlo replica generation

Full control of procedural uncertainties

## 2. Unpolarized PDFs: NNPDF3.0

[arXiv:1410.8849]

# Motivation

Precision physics at LHC and BSM searches

## PDFs

PDFs are an essential ingredient for LHC phenomenology

PDF uncertainties are crucial for LHC phenomenology  
often being the limiting factor in the accuracy of theoretical predictions  
both SM and BSM

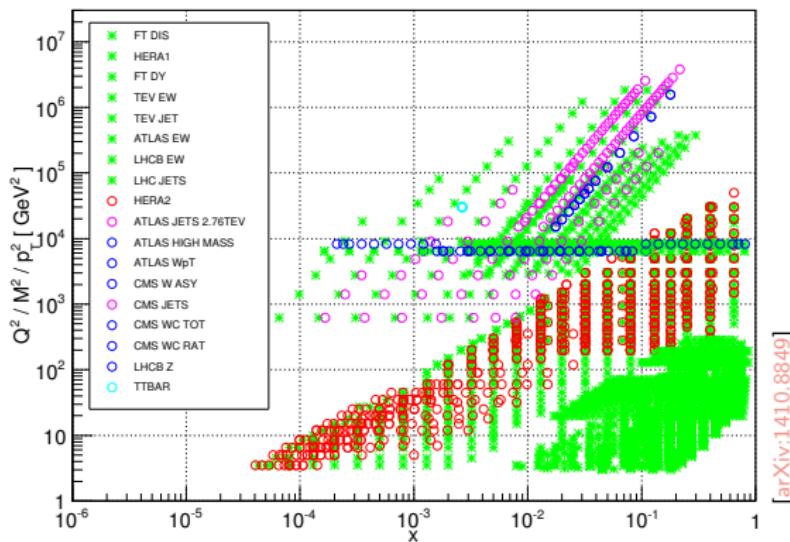


## LHC

Exploit the power of precise LHC data  
to reduce PDF uncertainties and discriminate among PDF sets

# Data set, theory, methodology

## NNPDF3.0 NLO dataset



NNPDF2.3

HERAII

→ structure functions from H1 and ZEUS  
new LHC EW

→ CMS muon asymmetries (2011)  
→ LHCb Z rapidity distributions (2011)

→ CMS  $W + c$  production data  
→ ATLAS & CMS DY production  
→ ATLAS  $W_{pT}$  distribution

new LHC jets

→ CMS 7 TeV inclusive jets (2011)  
→ ATLAS 2.76 TeV jets

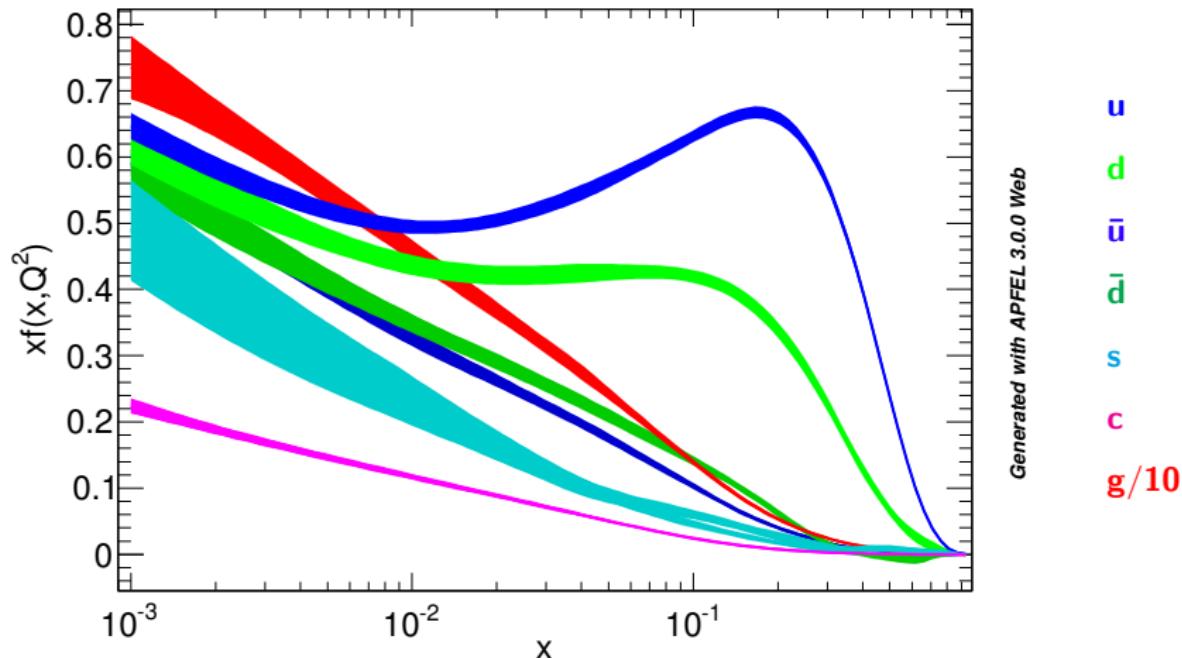
LHC  $t\bar{t}$

→ ATLAS & CMS  $t$  pair production

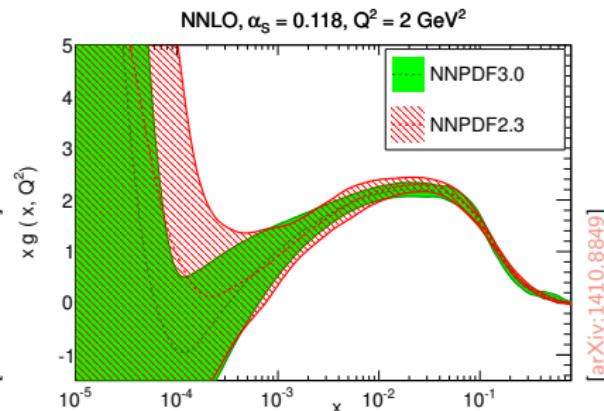
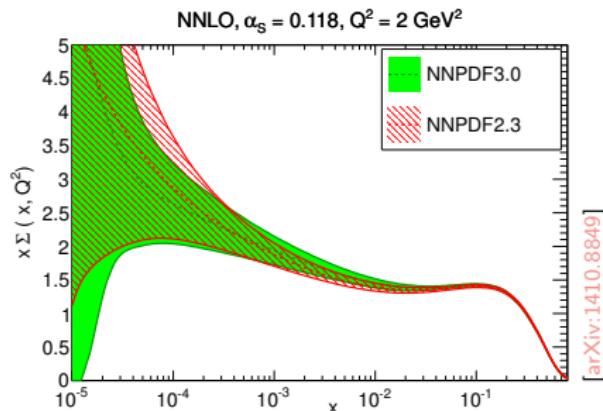
- Theory: LO, NLO, NNLO pQCD ( $K$ -factors for DY,  $t\bar{t}$  and inclusive jet production)
- Theory: EW corrections included for all neutral-current DY data sets
- Methodology: full characterization of procedural uncertainties through closure test
- Methodology: completely rewritten FORTRAN fitting code into C++ and PYTHON
- Methodology: genetic algorithm fitting efficiency largely improved

# The NNPDF3.0 set

NNPDF30 PDFs,  $Q^2=10 \text{ GeV}^2$

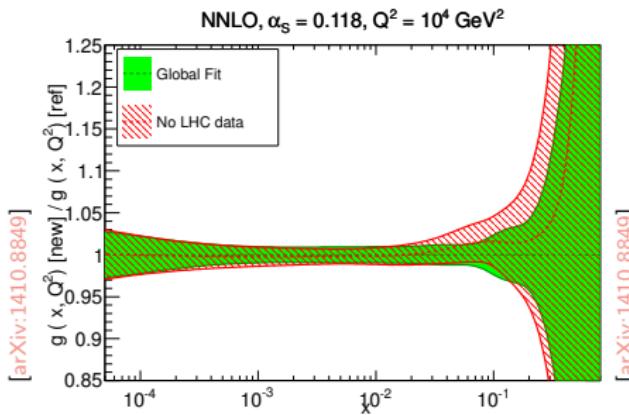
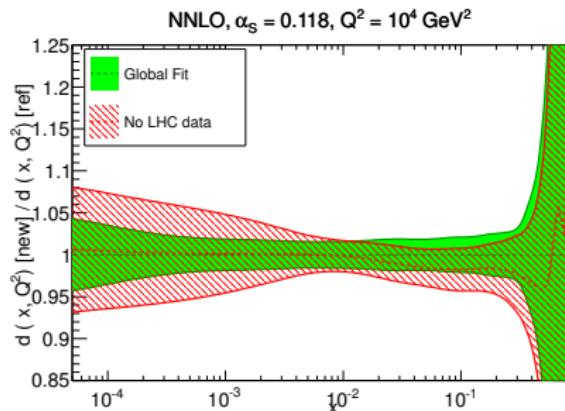


# Comparison with NNPDF2.3 and impact of LHC data



- Reasonable agreement between NNPDF3.0 and NNPDF2.3  
→ new HERA and LHC data already well described by NNPDF2.3
- Differences between PDFs at  $1 - \sigma$  level at most  
→ impact of new data and of updated theory and methodology
- PDF uncertainties are reduced in many cases  
→ small- $x$  gluon (but also down quarks and strangeness)

# Comparison with NNPDF2.3 and impact of LHC data

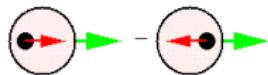


- PDF uncertainties on large- $x$  gluon is reduced  
→ thanks to top quark and jet production data
- PDF uncertainties on light quarks reduced  
→ thanks to DY and  $W + c$  data
- The description of all new LHC data is further improved in NNPDF3.0  
→ but already good in NNPDF2.3

### 3. Polarized PDFs: NNPDFpol1.1

[arXiv:1406.5539]

# Motivation



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

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

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

All quantities depend on factorization scheme and scale  $\mu$

Spin decomposition is not unique [arXiv:1309.4235]

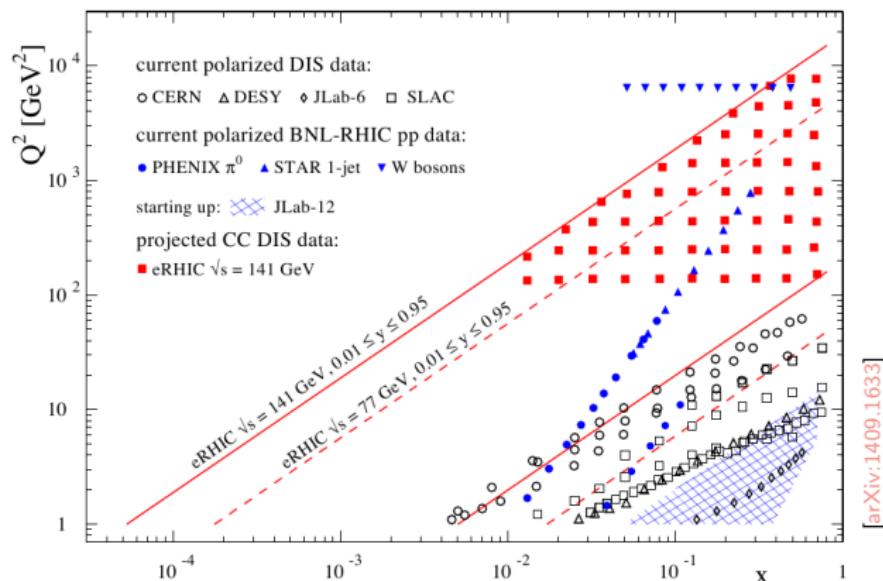
Very little of the proton spin is carried by quarks

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

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

Usually accessed in polarized inclusive and semi-inclusive DIS and  $p\bar{p}$  collisions

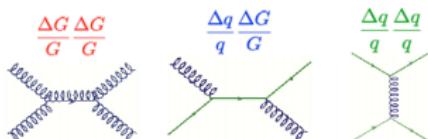
# Available & projected experimental data



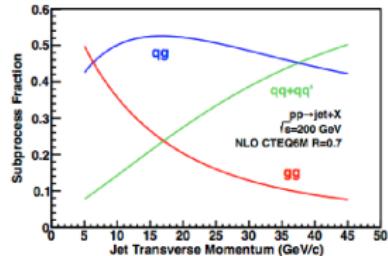
- Limited  $(x, Q^2)$  coverage
  - difficult to get  $\Delta g$  from scaling violations
  - need to use data down to  $Q^2 = 1 \text{ GeV}^2$
- No neutrino DIS data
  - no  $\Delta q - \Delta \bar{q}$  separation in inclusive DIS
  - SIDIS or  $W$  production in  $pp$  collisions

	DIS	SIDIS	OC	jets	$\pi$	$W^\pm$
NNPDFpol1.0	[arXiv:1303.7236]	☒	☒	☒	☒	☒
NNPDFpol1.1	[arXiv:1406.5539]	☒	☒	☒	☒	☒
DSSV++	[arXiv:1404.4293]	☒	☒	☒	☒	☒

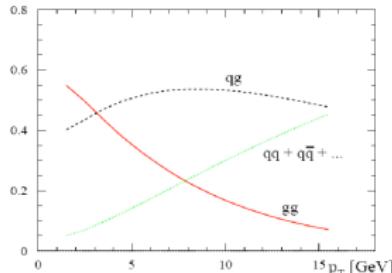
# New data from RHIC: jet and $\pi$ production



Jet production



$\pi$  production



## OBSERVABLE

The longitudinal double-spin asymmetry

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

## FEATURES

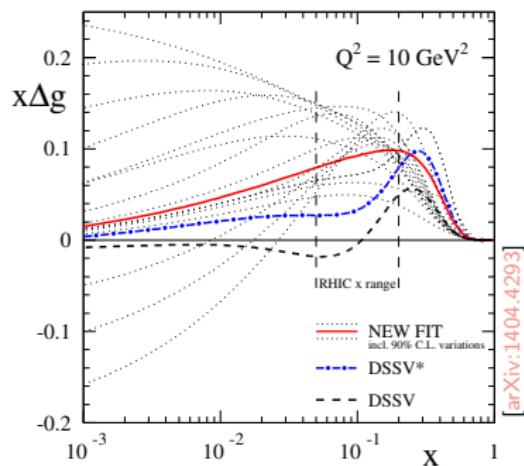
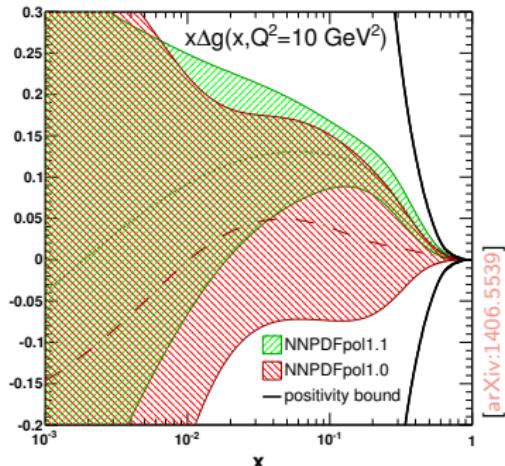
- at RHIC,  $\langle x_{1,2} \rangle \simeq \frac{2p_T}{\sqrt{s}} e^{-\eta/2} \approx [0.05, 0.2]$
- $qg$  and  $gg$  initiated subprocesses dominate (for most of the RHIC kinematics)
- $A_{LL}$  sensitive to gluon polarization
- cross sections are well described at NLO in pQCD

## MEASUREMENTS

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

# New data from RHIC: jet and $\pi$ production

## EFFECTS ON THE GLUON POLARIZATION $\Delta g$



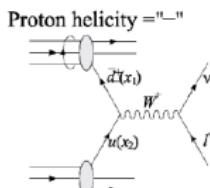
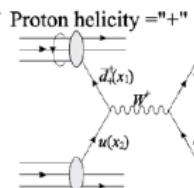
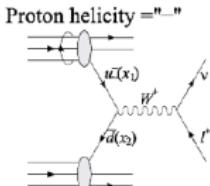
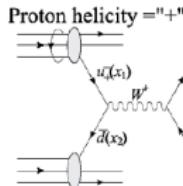
NNPDFpol1.0: jets  $\boxtimes$ ,  $\pi$   $\boxtimes$ ;

NNPDFpol1.1: jets  $\boxdot$ ,  $\pi$   $\boxtimes$ ;

DSSV++: jets  $\boxdot$ ,  $\pi$   $\boxdot$ ;

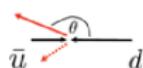
$Q^2 = 10 \text{ GeV}^2$	$\langle \Delta g(Q^2) \rangle^{[0,1]}$	$\langle \Delta g(Q^2) \rangle^{[0.001,1]}$	$\langle \Delta g(Q^2) \rangle^{[0.05,0.2]}$
NNPDFpol1.0	$-0.95 \pm 3.87$	$-0.06 \pm 1.12$	$+0.05 \pm 0.15$
NNPDFpol1.1	$-0.13 \pm 2.60$	$+0.31 \pm 0.77$	$+0.15 \pm 0.06$
DSSV08	—	$0.013^{+0.702}_{-0.314}$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

# New data from RHIC: $W^\pm$ production

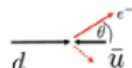


$$A_L^{W^-} \sim$$

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



backward lepton rapidity



forward lepton rapidity

## OBSERVABLE

Longitudinal single- and double-spin asymmetries

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

## FEATURES

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

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

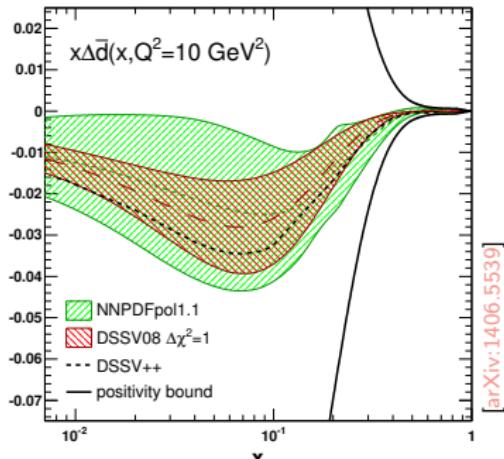
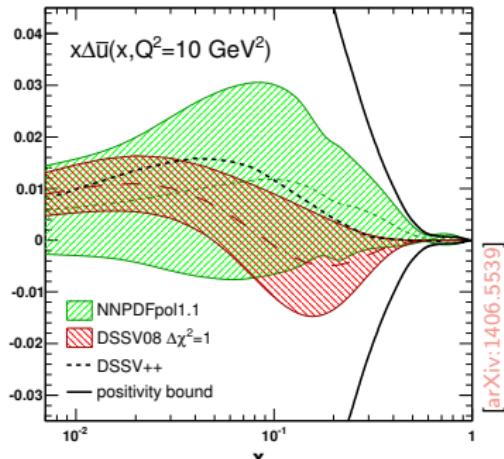
- no access to strangeness ( $W^\pm + c$  required)

## MEASUREMENTS

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

# New data from RHIC: $W^\pm$ production

## EFFECTS ON THE LIGHT QUARK SEA POLARIZATION $\Delta\bar{u}$ AND $\Delta\bar{d}$

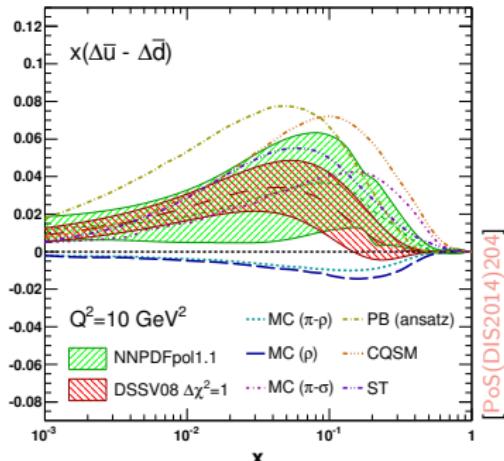
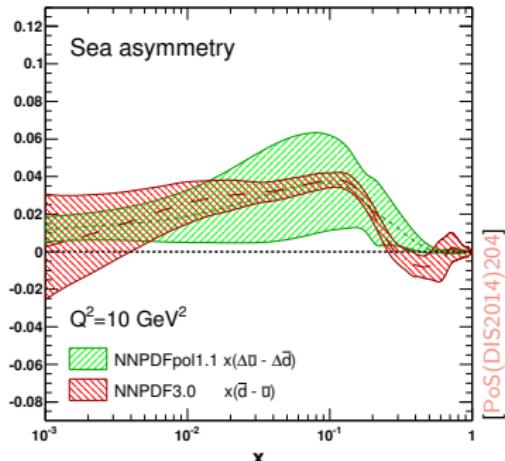


NNPDFpol1.1: SIDIS  $\blacksquare$ ,  $W^\pm$   $\blacksquare$ ; DSSV08: SIDIS  $\blacksquare$ ,  $W^\pm$   $\blacksquare$ ; DSSV++: SIDIS  $\blacksquare$ ,  $W^\pm$   $\blacksquare$ ;

$Q^2 = 10 \text{ GeV}^2$	$\langle \Delta f(Q^2) \rangle^{[0,1]}$		$\langle \Delta f(Q^2) \rangle^{[10^{-3},1]}$		
	NNPDFpol1.0	NNPDFpol1.1	NNPDFpol1.0	NNPDFpol1.1	DSSV08
$\Delta\bar{u}$	—	$+0.06 \pm 0.06$	—	$+0.04 \pm 0.05$	$+0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	—	$-0.11 \pm 0.06$	—	$-0.09 \pm 0.05$	$-0.089^{+0.090}_{-0.080}$
$\Delta\Sigma$	$+0.16 \pm 0.30$	$+0.18 \pm 0.21$	$+0.23 \pm 0.15$	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}$

# New data from RHIC: $W^\pm$ production

## EFFECTS ON THE FLAVOR ASYMMETRY $\Delta\bar{u} - \Delta\bar{d}$

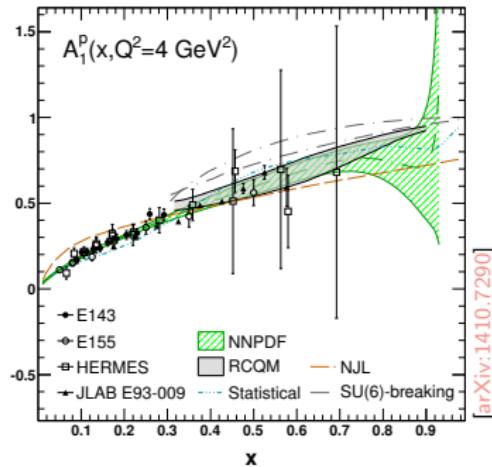
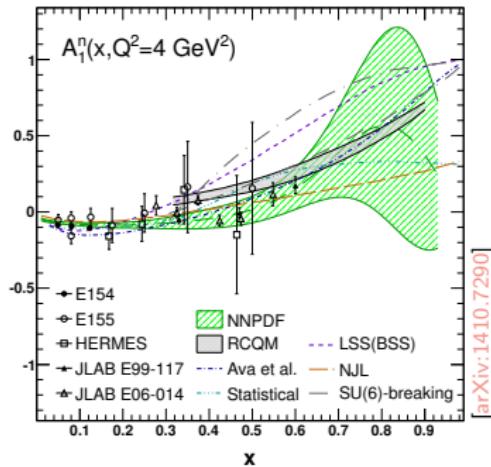


$I_\Delta$	MC ( $\pi$ -meson) $\equiv 0$	MC ( $\rho$ -meson) $< 0$	PB (bag-model) $\simeq 0.09$	PB $\simeq 0.2$	IN $\simeq 0.2$	DSSV08 $\Delta\chi^2 = 1$ $0.14 \pm 0.05$
$I_\Delta$	MC ( $\pi$ - $\rho$ inter.) $[-4 \cdot 10^{-3}, -0.033]$	MC ( $\pi$ - $\sigma$ inter.) $\simeq 0.12$	PB (ansatz) $\simeq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

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

# Large- $x$ behavior

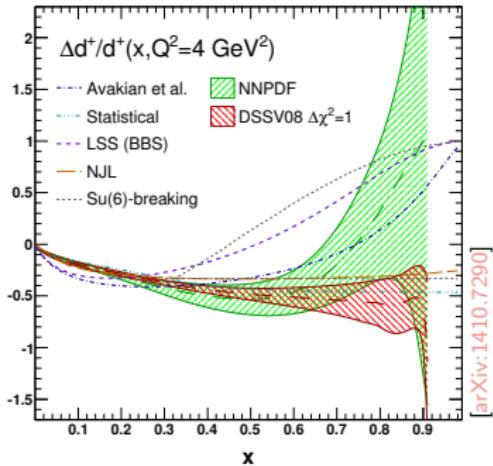
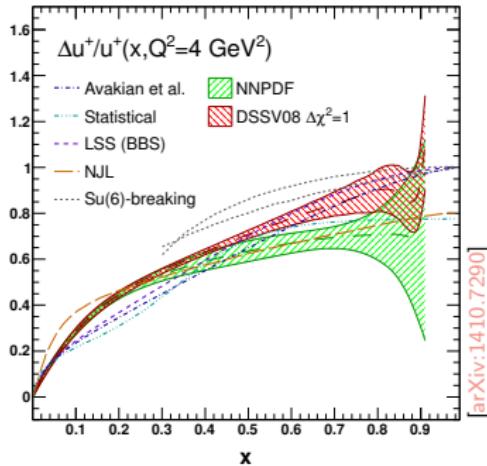
## VIRTUAL PHOTOABSORPTION ASYMMETRY IN INCLUSIVE DIS



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 ( <i>realistic</i> )	0.17	0.59
QHD ( $\sigma_{1/2}$ )	1	1	DSE ( <i>contact</i> )	0.34	0.88
QHD ( $\psi_\rho$ )	1	1	pQCD	1	1
NNPDF ( $x = 0.7$ )	$0.41 \pm 0.31$	$0.75 \pm 0.07$	NNPDF ( $x = 0.9$ )	$0.36 \pm 0.61$	$0.74 \pm 0.34$

# Large- $x$ behavior

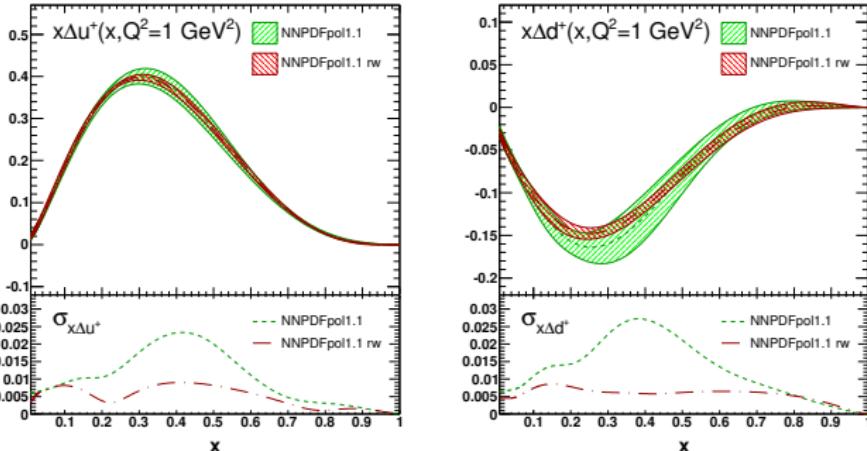
## POLARIZED TO UNPOLARIZED PDF RATIOS



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 ( <i>realistic</i> )	0.65	-0.26
QHD ( $\sigma_{1/2}$ )	1	1	DSE ( <i>contact</i> )	0.88	-0.33
QHD ( $\psi_\rho$ )	1	-1/3	pQCD	1	1
NNPDF ( $x = 0.7$ )	$0.07 \pm 0.05$	$-0.19 \pm 0.34$	NNPDF ( $x = 0.9$ )	$0.61 \pm 0.48$	$+0.85 \pm 6.55$

# Large- $x$ behavior

## POTENTIAL IMPACT OF JLAB DATA (INCLUSIVE DIS)



Experiment	Observable	Target	$N_{\text{dat}}$	$\chi^2/N_{\text{dat}}$	$\chi^2_{\text{rw}}/N_{\text{dat}}$	
JLAB E99-117	<a href="#">[nucl-ex/0405006]</a>	$A_1^n$	$\text{He}^3$	3	1.22	1.02
JLAB E93-009	<a href="#">[nucl-ex/0605028]</a>	$A_1^p$	$\text{NH}^3$	9	1.20	1.05
		$A_1^d$	$\text{ND}^3$	9	1.65	1.05
JLAB E06-014	<a href="#">[arXiv:1406.1207]</a>	$A_1^n$	$\text{He}^3$	6	4.31	1.32
				27	1.93	1.09

## 4. Conclusions

# Summary

- ① A new generation of unpolarized and polarized PDFs is now available
  - effort in including all recent experimental information from HERA, LHC and RHIC
  - effort in improving the fitting methodology: full control of procedural uncertainties
- ② The NNPDF parton sets (polarized and unpolarized) are available at
  - <http://lhapdf.hepforge.org/> (in a format compliant with LHAPDF5 and LHAPDF6)
  - <http://nnpdf.hepforge.org/> (with stand-alone Fortran/C++/*Mathematica* code)
- ③ Work in progress: a determination of a set of FFs ( $\pi^\pm$ ,  $K^\pm$ ,  $p/\bar{p}$ )
  - in view of a consistent fit of polarized PDFs to SIDIS and hadron production data
- ④ Long term project: a simultaneous fit of unpolarized/polarized PDFs and FFs
  - improvements of the methodology
  - new data to be included
  - theory progress (intrinsic charm, resummation effects, . . . )

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  - theory progress (intrinsic charm, resummation effects, . . . )

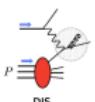
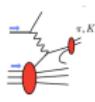
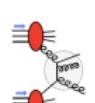
**Thank you for your attention**

## 5. Backup

# Probes of nucleon helicity structure

Guiding principle: FACTORIZATION

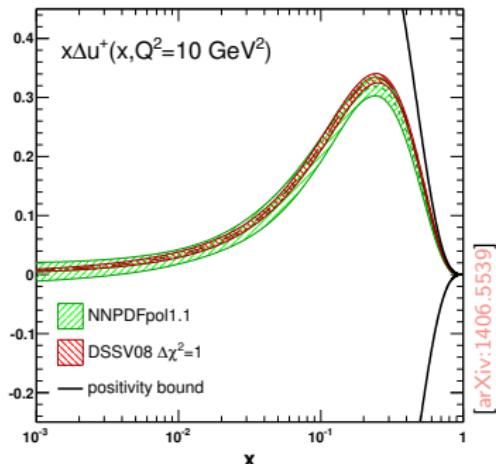
e.g. DIS     $d\Delta\sigma = \sum_{q, \bar{q}, g} \Delta f(x, Q^2) \otimes d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2))$      $d\Delta\hat{\sigma}_{\gamma^* f} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{4\pi}\right)^n d\Delta\hat{\sigma}_{\gamma^* f}^{(n)}$

	Reaction	Partonic subprocess	PDF probed	$x$	$Q^2$ [GeV $^2$ ]
	$\ell^\pm \{p, d, n\} \rightarrow \ell^\pm X$	$\gamma^* q \rightarrow q$	$\frac{\Delta q + \Delta \bar{q}}{\Delta g}$	$0.003 \lesssim x \lesssim 0.8$	$1 \lesssim Q^2 \lesssim 70$
	$\ell^\pm \{p, d\} \rightarrow \ell^\pm hX$	$\gamma^* q \rightarrow q$	$\frac{\Delta u + \Delta \bar{u}}{\Delta d + \Delta \bar{d}}$ $\Delta g$	$0.005 \lesssim x \lesssim 0.5$	$1 \lesssim Q^2 \lesssim 60$
	$\ell^\pm \{p, d\} \rightarrow \ell^\pm DX$	$\gamma^* g \rightarrow c\bar{c}$	$\Delta g$	$0.06 \lesssim x \lesssim 0.2$	$\sim 10$
	$\vec{p} \vec{p} \rightarrow jet(s)X$	$gg \rightarrow qg$ $qg \rightarrow qg$	$\Delta g$	$0.05 \lesssim x \lesssim 0.2$	$30 \lesssim p_T^2 \lesssim 800$
	$\vec{p} p \rightarrow W^\pm X$	$u_L \bar{d}_R \rightarrow W^+$ $d_L \bar{u}_R \rightarrow W^-$	$\Delta u + \bar{u}$ $\Delta d + \bar{d}$	$0.05 \lesssim x \lesssim 0.4$	$\sim M_W^2$
	$\vec{p} \vec{p} \rightarrow \pi X$	$gg \rightarrow qg$ $qg \rightarrow qg$	$\Delta g$	$0.05 \lesssim x \lesssim 0.4$	$1 \lesssim p_T^2 \lesssim 200$

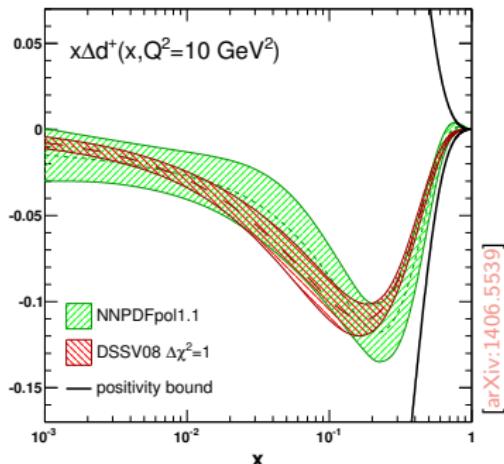
Different processes constrain different PDFs, factorization is successful

# Highlights from NNPDFpol1.1 & DSSV++: PDFs

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



NNPDFpol1.1: DIS

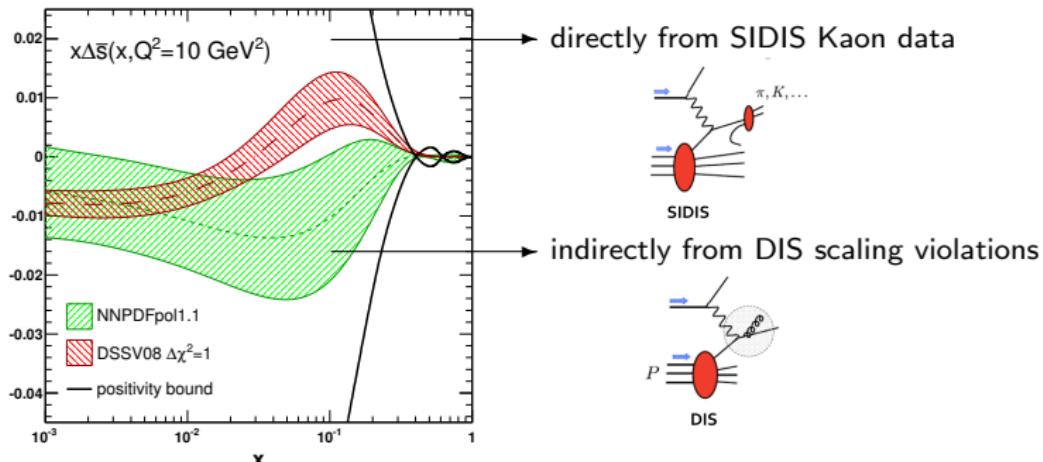


DSSV08: DIS

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

# Highlights from NNPDFpol1.1 & DSSV++: PDFs

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



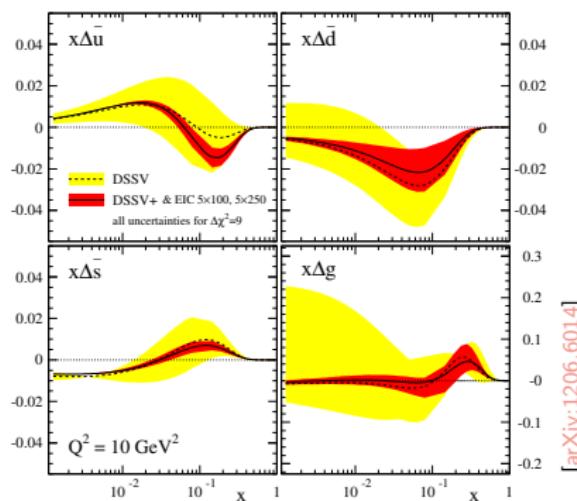
NNPDFpol1.1: DIS , SIDIS ( $K^\pm$ ) ;  
DSSV08: DIS , SIDIS ( $K^\pm$ ) ;

- DIS data  $\Rightarrow$  negative  $x\Delta\bar{s}$ ; SIDIS data  $\Rightarrow$  changing-sign  $x\Delta\bar{s}$
- 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](#)]

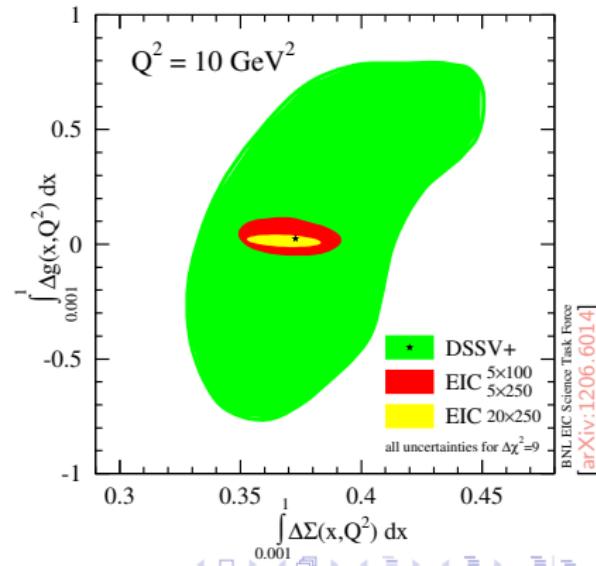
# Potential of a future polarized, high-energy EIC

## A FUTURE ELECTRON-ION COLLIDER

- Dramatic reduction of uncertainties of both PDFs and their moments
- Accurate determination of  $\Delta g$  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



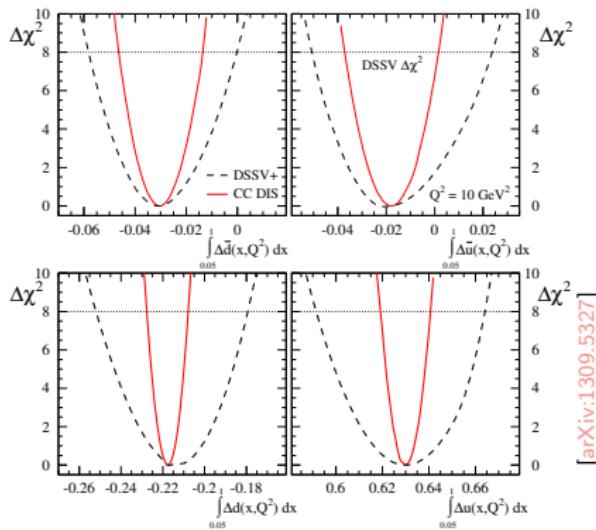
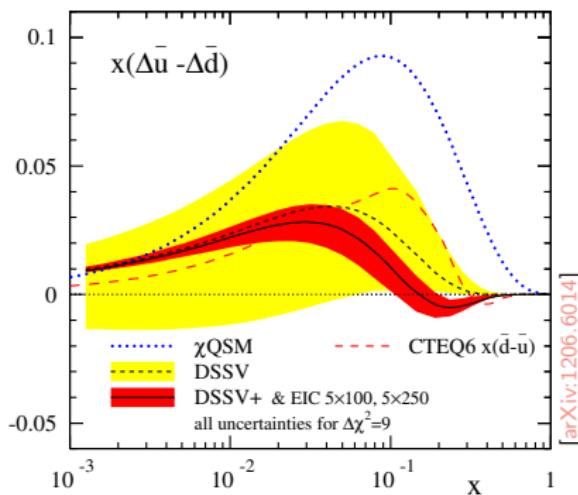
[arXiv:1206.6014]



# Potential of a future polarized, high-energy EIC

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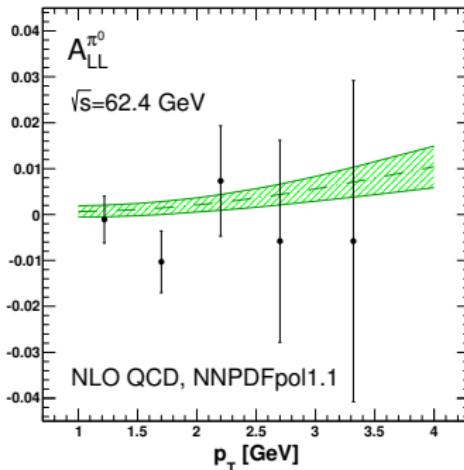
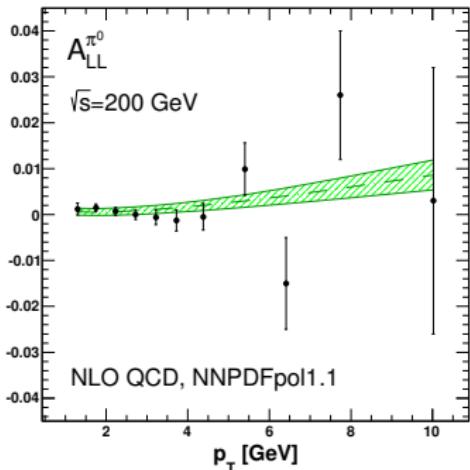
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# Predictions for single-hadron production asymmetry

$$A_{LL}^H = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \Delta\hat{\sigma}_{ab}^c}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \hat{\sigma}_{ab}^c}$$

PHENIX [arXiv:0810.0701] [arXiv:0810.0694] [arXiv:1402.6296] STAR [arXiv:1309.1800]

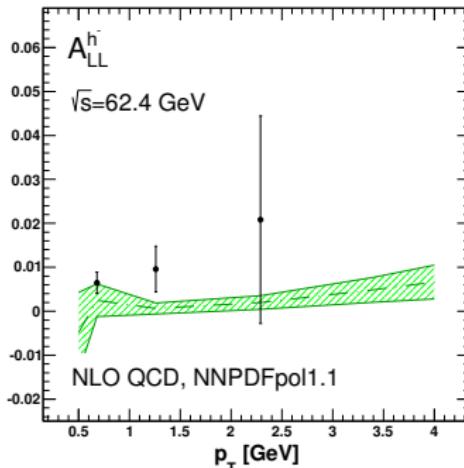
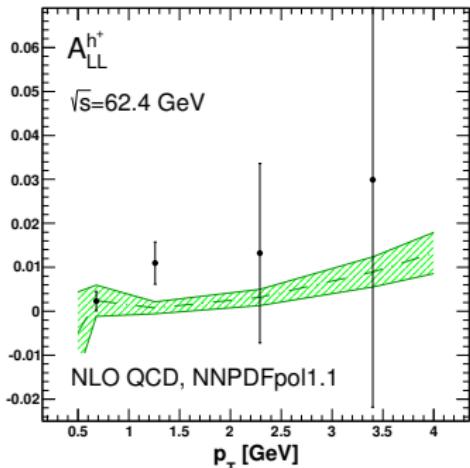


- Good agreement between experimental data and theoretical predictions
- Experimental uncertainties are larger than those of the corresponding predictions
- We expect a slight impact on the gluon PDF from these data

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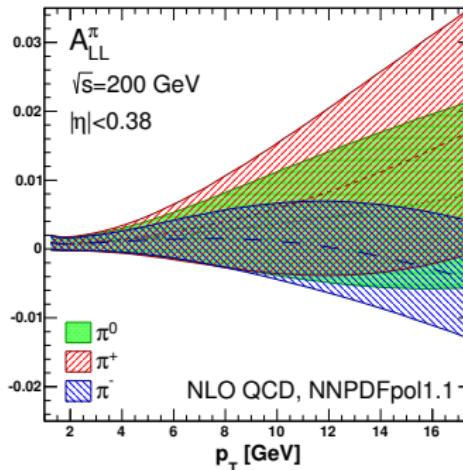
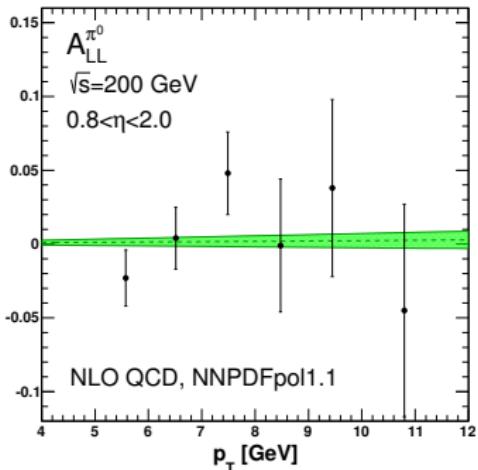


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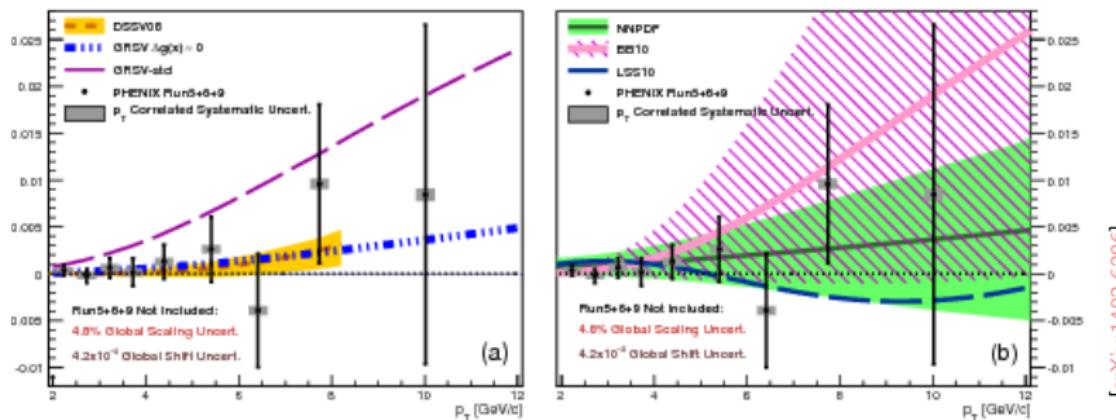


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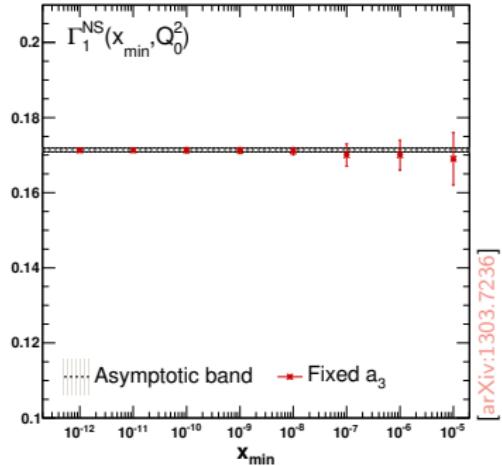
$$A_{LL}^H = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \Delta\hat{\sigma}_{ab}^c}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes D_c^H \otimes \hat{\sigma}_{ab}^c}$$

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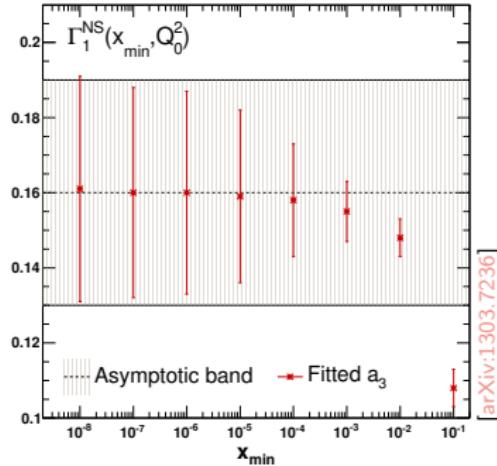


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# The Bjorken sum rule



$$\text{fixed } a_3 = 1.2701 \pm 0.0025$$

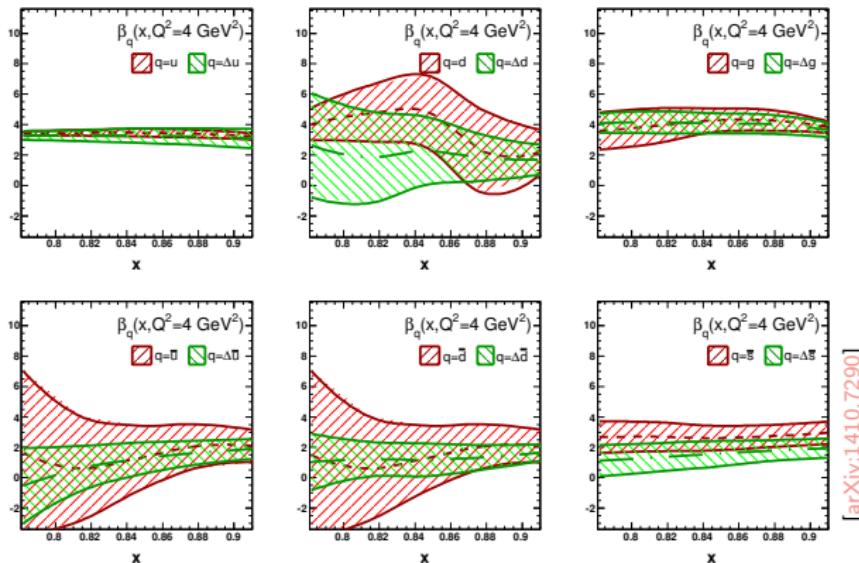


$$\text{fitted } a_3 = 1.19 \pm 0.22$$

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

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

## Asymptotic exponents at large- $x$



[arXiv:1410.7290]

PDF set	$u$	$\bar{u}$	$d$	$\bar{d}$	$\bar{s}$	$g$
NNPDF3.0	$3.23 \pm 0.21$	$2.09 \pm 1.07$	$2.20 \pm 1.46$	$2.09 \pm 1.07$	$2.95 \pm 0.74$	$3.82 \pm 0.37$
NNPDFpol1.1	$3.08 \pm 0.64$	$1.65 \pm 0.55$	$1.69 \pm 0.99$	$1.89 \pm 0.66$	$1.95 \pm 0.63$	$3.64 \pm 0.47$

# Effects of open-charm production at COMPASS

Virtual photon-nucleon asymmetry for open-charm production

[arXiv:1212.1319]

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

## FEATURES

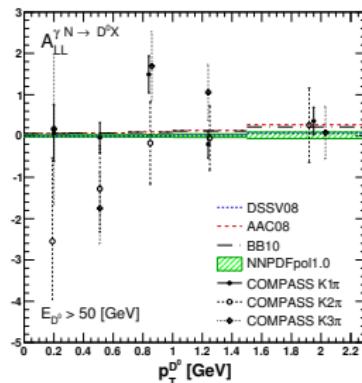
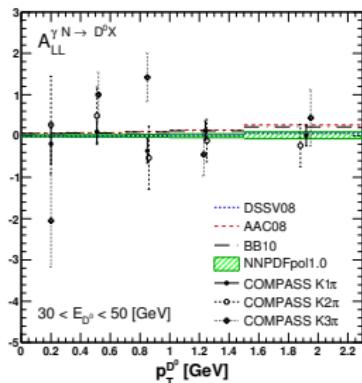
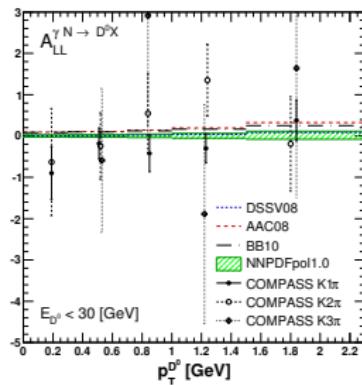
- $\Delta g$  is probed *directly* through the photon-gluon fusion process  
(in DIS  $\Delta g$  is mostly probed through scaling violations instead)
- the fragmentation functions for heavy quarks are computable in perturbation theory  
(and only introduce a very moderate uncertainty in the fit)

## EXPERIMENTAL MEASUREMENT

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

Experiment	Set	$N_{\text{dat}}$	NNPDFpol1.0	$\chi^2/N_{\text{dat}}$	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	

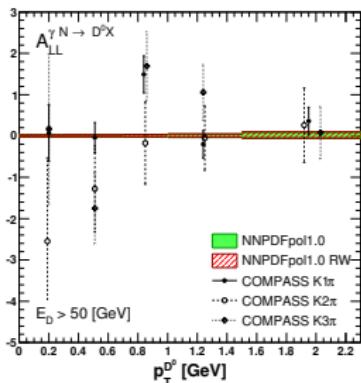
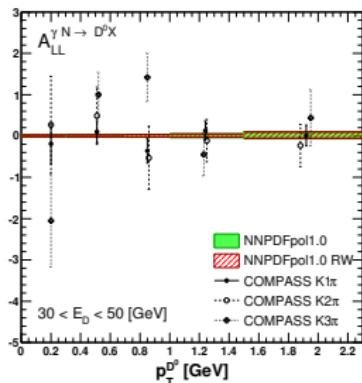
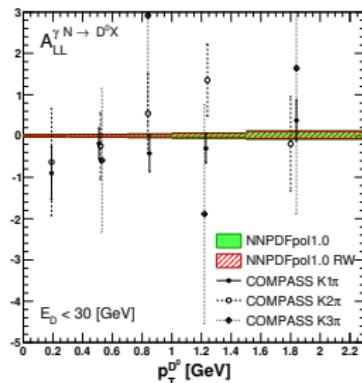
# Effects of open-charm production at COMPASS



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

Experiment	Set	$N_{\text{dat}}$	NNPDFpol1.0	$\chi^2/N_{\text{dat}}$	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	
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# Effects of open-charm production at COMPASS

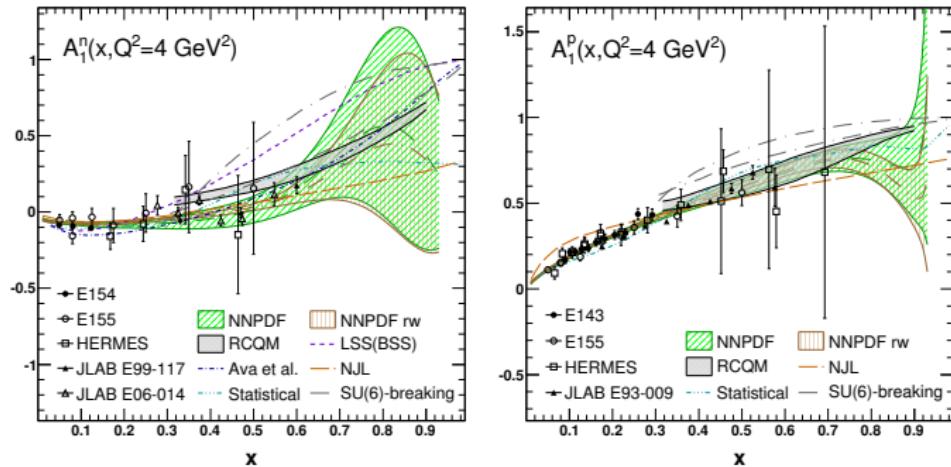


The impact of open-charm data from COMPASS is mostly negligible, as we notice from the value of the  $\chi^2/N_{\text{ndat}}$  and the reweighted observable

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

# Large- $x$ behavior

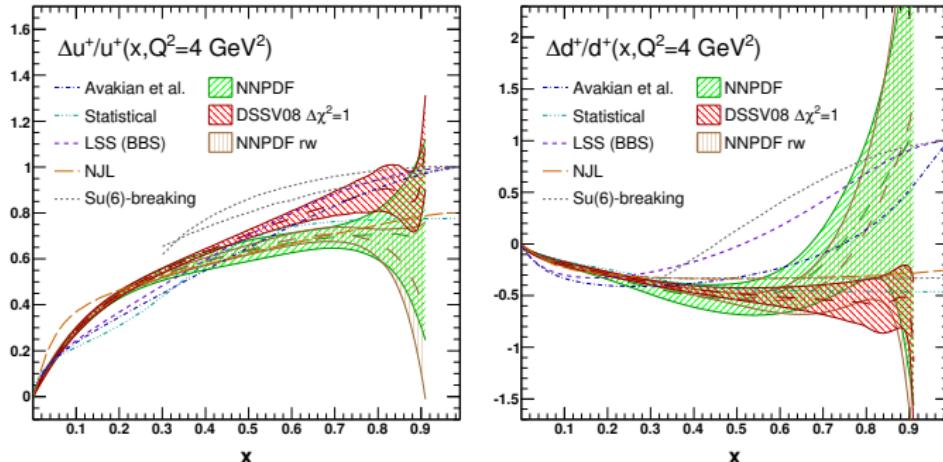
## VIRTUAL PHOTOABSORPTION ASYMMETRY IN INCLUSIVE DIS



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 ( <i>realistic</i> )	0.17	0.59
QHD ( $\sigma_{1/2}$ )	1	1	DSE ( <i>contact</i> )	0.34	0.88
QHD ( $\psi_\rho$ )	1	1	pQCD	1	1
NNPDF ( $x = 0.9$ )	$0.36 \pm 0.61$	$0.74 \pm 0.34$	NNPDF rw ( $x = 0.9$ )	$0.34 \pm 0.60$	$0.53 \pm 0.30$

# Large- $x$ behavior

## POLARIZED TO UNPOLARIZED PDF RATIOS



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 ( <i>realistic</i> )	0.65	-0.26
QHD ( $\sigma_{1/2}$ )	1	1	DSE ( <i>contact</i> )	0.88	-0.33
QHD ( $\psi_\rho$ )	1	-1/3	pQCD	1	1
NNPDF ( $x = 0.9$ )	$0.61 \pm 0.48$	$+0.85 \pm 6.55$	NNPDF rw ( $x = 0.9$ )	$0.33 \pm 0.46$	$+0.89 \pm 6.49$