Unbiased helicity-dependent Parton Distributions with polarized collider data

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Outline

1. Introduction
2. Including collider data in a global PDF determination
    - Experimental data sets and new observables
    - Some details on the methodology
3. The NNPDFpol1.1 parton set
    - Comparison with `NNPDFpol1.0` and `DSSV`
    - The spin content of the proton
4. Conclusions and outlook

1. Introduction

Motivation

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

1. Understand the spin content of the proton
   - what are the patterns of up, down and strange quark and antiquark polarizations?
   - how do gluons contribute to the proton spin?

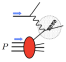
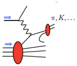
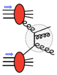
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta\Sigma = \int_0^1 dx \sum_{i=u,d,s} (\Delta q_i + \Delta\bar{q}_i) \qquad \Delta G = \int_0^1 dx\, \Delta g$$

2. Describe processes with polarized hadrons in initial states
   - explore QCD beyond the helicity-averaged case
   - beyond SM studies at a polarized Future Circular Collider [arXiv:1403.2383]

The goal is to provide a statistically sound determination of polarized parton distributions and their uncertainties

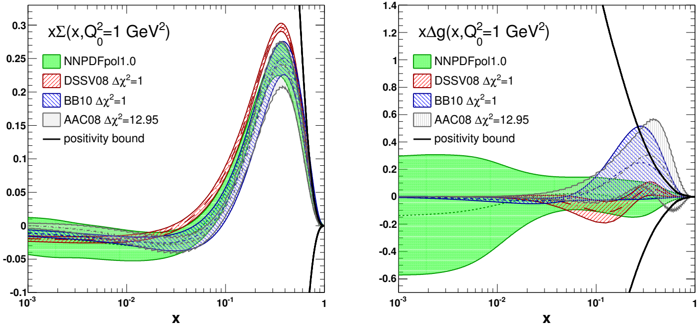
Spin-dependent PDF analyses in a nutshell

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

Fit	Data sets	Parton Distributions	Uncertainties	Latest update
`AAC08`	DIS, π^0	Δu^+, Δd^+, Δs^+, Δg	Hessian $\Delta\chi^2 = 12.95$	[arXiv:0808.0413]
`BB10`	DIS	Δu^-, Δd^-, $\Delta\bar{q}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1005.3113]
`LSS10`	DIS, SIDIS	Δu^+, Δd^+, $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta\bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1010.0574]
`DSSV`	DIS, SIDIS, π^0, Jets	Δu^+, Δd^+, $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta\bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$ Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	[arXiv:0904.3821] [arXiv:1404.4293]
`JAM13`	DIS	Δu^+, Δd^+, $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta\bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1310.3734]
`NNPDFpol1.0`	DIS	Δu^+, Δd^+, Δs^+, Δg	Monte Carlo	[arXiv:1303.7236]

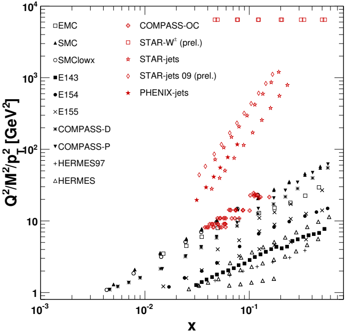
The NNPDFpol1.0 parton set in a nutshell [arXiv:1303.7236]

1. Monte Carlo error propagation by generation of $N_{\rm rep}$ replicas of experimental data
   - ⟶ results are delivered as statistical ensembles of equally probable PDF replicas
   - ⟶ expectation values and uncertainties are computed as means and standard deviations
   - ⟶ no need to rely on linear propagation of errors (not always adequate)
2. Neural Network parametrization of each PDF replica
   - ⟶ only requires smoothness of PDFs, reduce the bias due to the parametrization
   - ⟶ genetic algorithm for Neural Network training + cross-validation for stopping
3. Only DIS data included
   - ⟶ where no data or theoretical constraints are available, uncertainties are large
   - ⟶ gluon largely uncertain; no handle on Δq and $\Delta\bar{q}$ separation



2. Including collider data in a global PDF determination

Old and *new* experimental data set



- Include the experimental information from:
  → jet and W production data (collider)
  STAR, PHENIX
- Limited kinematic coverage at low-x
- Large Q^2 reached by collider data
- New data sets are included in `NNPDFpol1.0` (DIS-only fit) via Bayesian reweighting

REACTION	PARTONIC SUBPROCESS	PDF PROBED	x	Q^2 [GeV^2]
$\ell^\pm\{p,d,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$\Delta q + \Delta\bar{q}$ Δg	$0.003 \lesssim x \lesssim 0.8$	$1 \lesssim Q^2 \lesssim 70$
$\ell^\pm\{p,d\} \to \ell^\pm DX$	$\gamma^* g \to c\bar{c}$	Δg	$0.06 \lesssim x \lesssim 0.2$	$Q^2 \sim 10$
$\vec{p}\,\vec{p} \to jet(s)X$	$gg \to qg$ $qg \to qg$	Δg	$0.05 \lesssim x \lesssim 0.2$	$30 \lesssim p_T^2 \lesssim 800$
$\vec{p}\,p \to W^\pm X$	$u_L\bar{d}_R \to W^+$ $d_L\bar{u}_R \to W^-$	$\Delta u\ \Delta\bar{u}$ $\Delta d\ \Delta\bar{d}$	$0.05 \lesssim x \lesssim 0.4$	$\sim M_W^2$

Bayesian reweighting in a nutshell [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 σ_{ij}) in a prior ensemble of PDF replicas $\{f_k\}$, $k = 1, \dots, N_{\mathrm{rep}}$
- 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

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

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

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

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

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

- Loss of efficiency: $N_{\mathrm{eff}} \equiv \exp\left[-\sum_{k=1}^{N_{\mathrm{rep}}} p_k \log p_k\right]$ with $p_k = w_k/N_{\mathrm{rep}}$
  $0 < N_{\mathrm{eff}} < N_{\mathrm{rep}}$; N_{eff} must not be too low $\Rightarrow$ increase the number of replicas in the prior

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

Construction of the prior PDF ensemble: our strategy

New data sets are included in the DIS-only fit, `NNPDFpol1.0`, via Bayesian reweighting

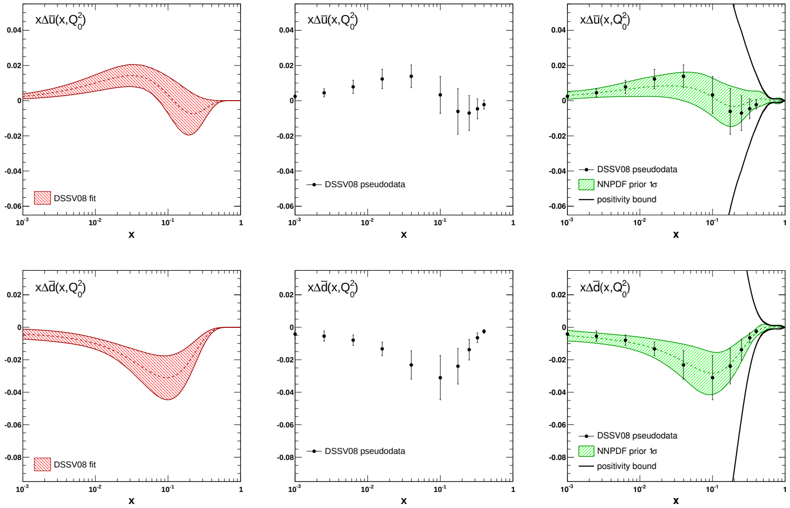
BUT

The computation of the new observables **requires** light **quark-antiquark separation**
The `NNPDFpol1.0` **fit does not provide separate** Δu, $\Delta\bar{u}$ **and** Δd, $\Delta\bar{d}$ PDFs
We need to make some assumption on $\Delta\bar{u}$, $\Delta\bar{d}$ and **construct a suitable unbiased prior**

1. Take a polarized parton set wich provides Δq and $\Delta\bar{q}$ PDFs (from SIDIS)
2. Sample their $\Delta\bar{u}$ and $\Delta\bar{d}$ distributions at a given reference scale
3. Perform a NN fit to these pseudodata
4. Supplement each replica in `NNPDFpol1.0` with $\Delta\bar{u}$ and $\Delta\bar{d}$ obtained in this way
5. Reweight PDFs and check that observables are properly reproduced

Check that reweighted results are stable upon the choice of different PDF priors: repeat the procedure from step 2, *e.g.* by increasing the nominal PDF uncertainty, until independence from the prior is reached

We consider four different priors: 1σ, 2σ, 3σ, 4σ corresponding to the different factors by which the DSSV08 nominal $\Delta\chi^2 = 1$ PDF uncertainty has been enlarged



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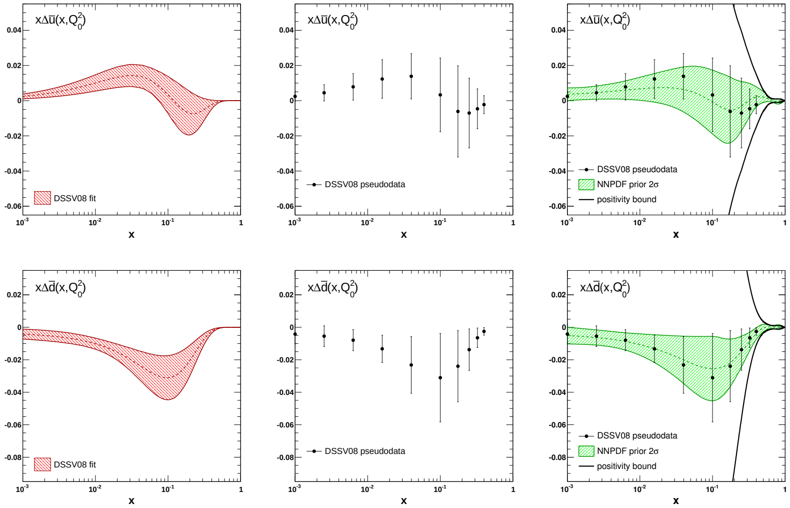

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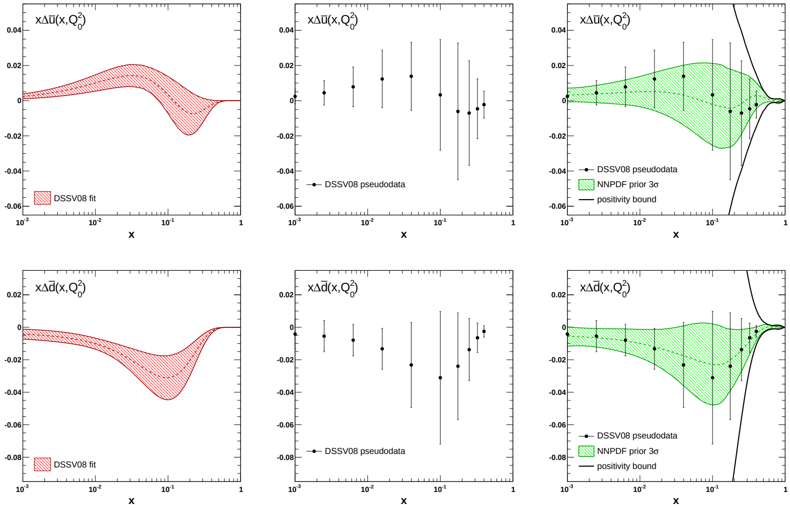

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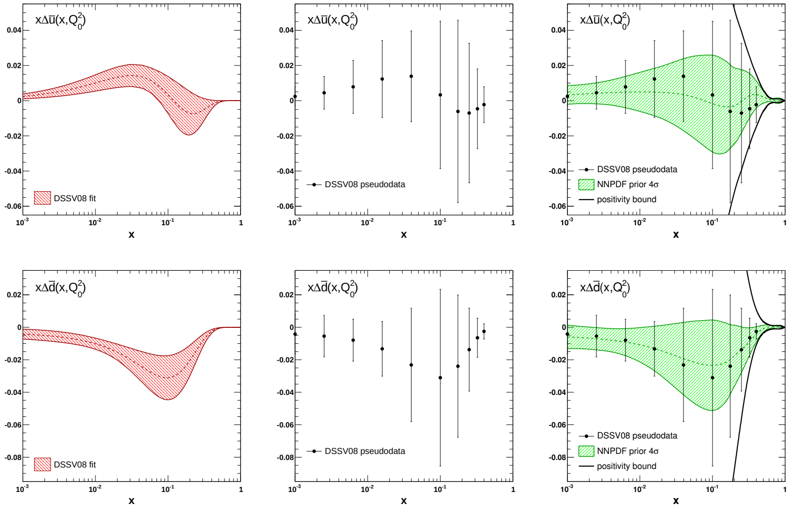


A) Reweighting with inclusive jet production at RHIC

Longitudinal double-spin asymmetry for single-inclusive jet production

[arXiv:hep-ph/9808262] [arXiv:hep-ph/0404057] [arXiv:1209.1785]

$$A_{LL}^{1jet} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

FEATURES

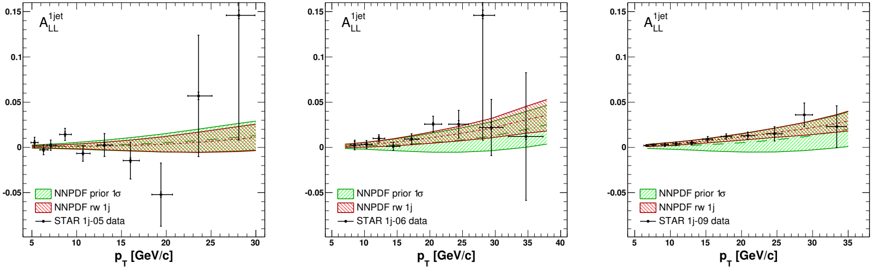
- sensitive to the polarized gluon Δg
  (receives leading contribution from $gq \to qg$ and $qg \to qg$ partonic subrocesses)

EXPERIMENTAL MEASUREMENT

- STAR 2005, 2006 [arXiv:1205.2735], 2009 (prel.) [arXiv:1303.0543]
- PHENIX [arXiv:1009.4921] at RHIC

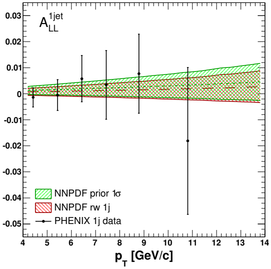
Data set	$N_{\rm dat}$	jet-algorithm	R	$[\eta_{\rm min}, \eta_{\rm max}]$	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]
STAR 1j-05	10	midpoint-cone	0.4	$[+0.20, +0.80]$	200	2.1
STAR 1j-06	9	midpoint-cone	0.7	$[-0.70, +0.90]$	200	5.5
STAR 1j-09 (prel.)	11	anti-kt	0.6	$[-0.50, +0.50]$	200	25
	11	anti-kt	0.6	$[-1.00, -0.50] \cup [+0.50, +1.00]$	200	25
PHENIX 1j	6	seeded-cone	0.3	$[-0.35, +0.35]$	200	2.1

A) Reweighting with inclusive jet production at RHIC



Experiment	Set	N_{dat}	χ^2/N_{dat}				χ^2_{rw}/N_{dat}			
			1σ	2σ	3σ	4σ	1σ	2σ	3σ	4σ
STAR		41	1.19	1.19	**1.20**	1.20	0.79	0.79	**0.79**	0.79
	STAR 1j-05	10	1.04	1.04	**1.04**	1.04	1.01	1.02	**1.02**	1.01
	STAR 1j-06	9	0.75	0.75	**0.75**	0.76	0.59	0.59	**0.59**	0.59
	STAR 1j-09	22	1.69	1.69	**1.70**	1.71	1.02	1.02	**1.03**	1.04
PHENIX										
	PHENIX 1j	6	0.24	0.24	**0.24**	0.24	0.24	0.24	**0.24**	0.24

A) Reweighting with inclusive jet production at RHIC



Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$				$\chi^2_{\rm rw}/N_{\rm dat}$			
			1σ	2σ	3σ	4σ	1σ	2σ	3σ	4σ
STAR		41	1.19	1.19	**1.20**	1.20	0.79	0.79	**0.79**	0.79
	STAR 1j-05	10	1.04	1.04	**1.04**	1.04	1.01	1.02	**1.02**	1.01
	STAR 1j-06	9	0.75	0.75	**0.75**	0.76	0.59	0.59	**0.59**	0.59
	STAR 1j-09	22	1.69	1.69	**1.70**	1.71	1.02	1.02	**1.03**	1.04
PHENIX										
	PHENIX 1j	6	0.24	0.24	**0.24**	0.24	0.24	0.24	**0.24**	0.24

A) Reweighting with inclusive jet production at RHIC

Overall good description of all data sets after they are included in the fit via reweighting
Reweighted results are stable upon the choice of different prior PDF ensembles
since we are looking at an observable which is mostly sensitive to Δg

Different data sets have different power in constraining Δg
Significant redution of the uncertainty of the gluon PDF in the measured region

Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$				$\chi^2_{\rm rw}/N_{\rm dat}$			
			1σ	2σ	3σ	4σ	1σ	2σ	3σ	4σ
STAR		41	1.19	1.19	**1.20**	1.20	0.79	0.79	**0.79**	0.79
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PHENIX										
	PHENIX 1j	6	0.24	0.24	**0.24**	0.24	0.24	0.24	**0.24**	0.24

B) Reweighting with $W^\pm$ production at RHIC

Longitudinal single-spin asymmetry for $W^\pm$ boson production
[arXiv:1003.4533]

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

$$A_L^{W^+} \sim \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \qquad A_L^{W^-} \sim \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

FEATURES

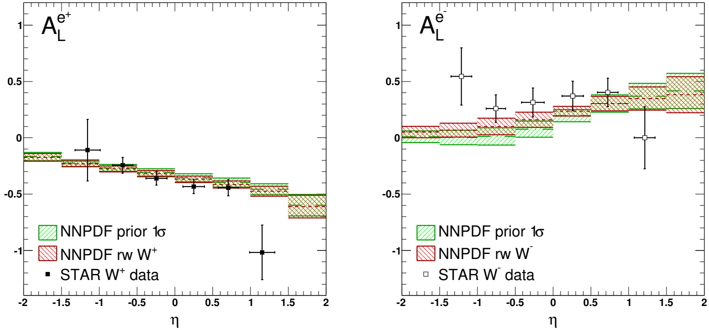
- sensitive to individual quark and antiquark flavours $(\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d})$
  (purely weak process coupling q_L with $\bar{q}_R$ at partonic level, $u_L\bar{d}_R \to W^+$ or $d_L\bar{u}_R \to W^-$)
- no need for fragmentation functions (instead of SIDIS)

EXPERIMENTAL MEASUREMENT

- STAR and PHENIX at RHIC [arXiv:1009.0326] [arXiv:1009.0505]
  (only preliminary measurements from STAR (2012) [arXiv:1302.6639] will be considered here)

Data set	$N_{\rm dat}$	$[p_{T,\rm min}, p_{T,\rm max}]$ [GeV]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]
STAR-W^+ (prel.)	6	[25, 50]	510	72
STAR-W^- (prel.)	6	[25, 50]	510	72

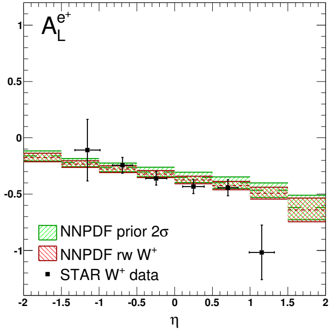
B) Reweighting with $W^{\pm}$ production at RHIC

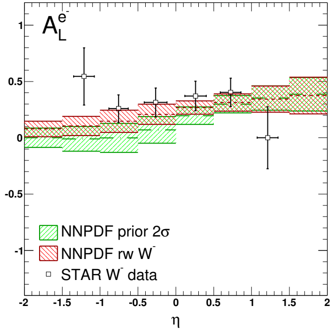


Experiment	Set	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$				$\chi^2_{\rm rw}/N_{\rm dat}$			
			1σ	2σ	3σ	4σ	1σ	2σ	3σ	4σ
STAR		12	1.93	1.97	**1.97**	1.91	1.43	1.12	**1.03**	1.02
	STAR-W^+	6	1.15	1.14	**1.22**	1.25	1.04	1.01	**1.02**	1.01
	STAR-W^-	6	2.71	2.80	**2.59**	2.43	1.78	1.25	**1.04**	1.02

Overall good description of both data sets after they are included in the fit via reweighting
Stability of reweighted results reached starting from 3σ prior

B) Reweighting with $W^{\pm}$ production at RHIC





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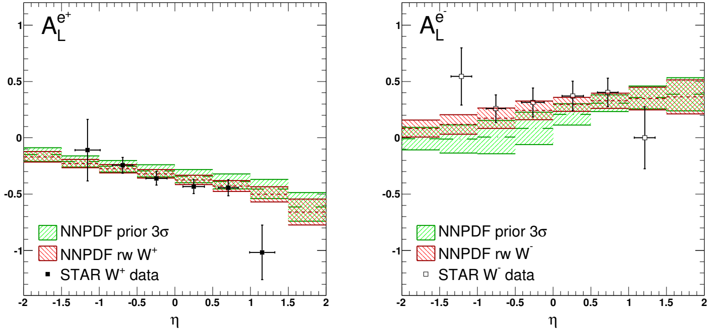
B) Reweighting with $W^{\pm}$ production at RHIC



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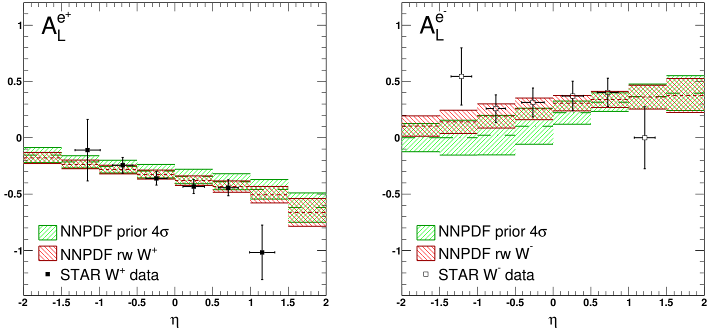

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Overall good description of both data sets after they are included in the fit via reweighting
Stability of reweighted results reached starting from 3σ prior

C) Global reweighting

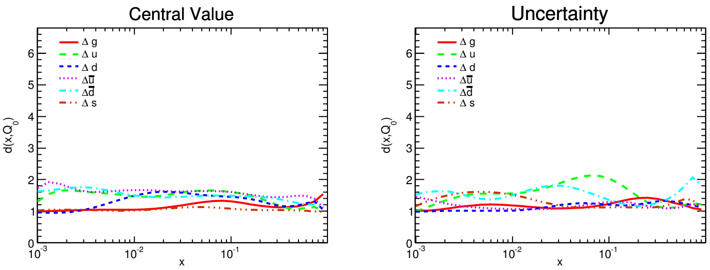
GLOBAL REWEIGHTING $N_{\rm dat} = 74$	1σ	2σ	3σ	4σ
$\chi^2/N_{\rm dat}$	1.22	1.25	**1.25**	1.24
$\chi^2_{\rm rw}/N_{\rm dat}$	1.07	1.04	**1.02**	1.02
$N_{\rm eff}$	224	197	**177**	176

$\chi^2_{\rm rw}/N_{\rm dat} = 1.02$ Good overall description of new data

$N_{\rm eff} \sim 180$ The loss of efficiency of the reweighted replicas is under control

$d \sim 2$ Results do not depend on the choice of either the 3σ or 4σ prior

Reweighted NNPDFpol1.1 3σ vs 4σ



3. The NNPDFpol1.1 parton set

Constructing the NNPDFpol1.1 parton set

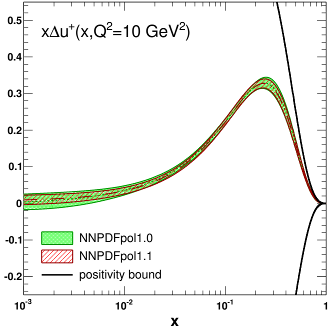
The NNNPDFpol1.1 parton set, made of $N_{\mathrm{rep}} = 100$ equally probable replicas, is obtained by unweighting the result from global reweighting.
The idea is to select (possibly more than once) replicas carrying relatively hight weight and discard replicas carrying relatively small weight.
The unweighted ensemble is statistically equivalent to the reweighted ensemble.

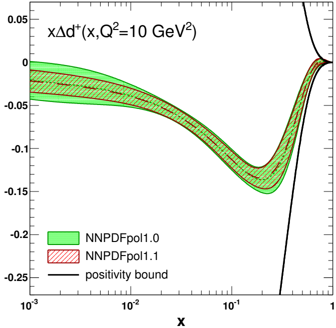
Experiment	NNPDFpol1.0 χ^2/N_{dat}	NNPDFpol1.1 χ^2/N_{dat}
EMC	0.44	0.43
SMC	0.93	0.90
SMClowx	0.97	0.97
E143	0.64	0.67
E154	0.40	0.45
E155	0.89	0.85
COMPASS-D	0.65	0.70
COMPASS-P	1.31	1.38
HERMES97	0.34	0.34
HERMES	0.79	0.82

Similar (good) description of inclusive DIS data in both NNPDF parton sets
How are PDFs affected by the inclusion of polarized collider data sets?

Comparison with NNPDFpol1.0

Δu^+ and Δd^+

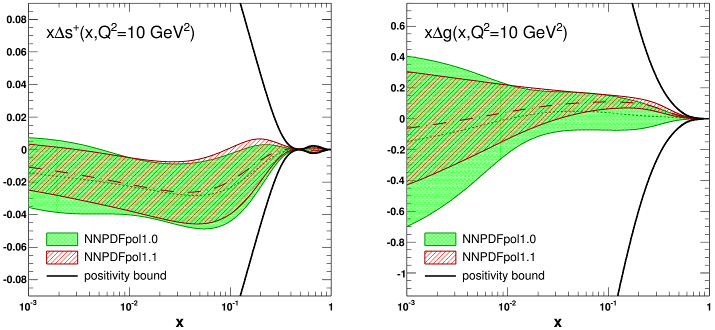




- $\Delta q^+ \equiv \Delta q + \Delta\bar{q}$, $q = u, d$ are statistically equivalent in the two parton sets
- Δs^+ is almost unaffected by W data (unlike in the unpolarized case)
- the underlying probability distributions for Δg in the two determinations differ up to one sigma in the region covered by jet data, $0.05 \lesssim x \lesssim 0.2$
- Δg from NNPDFpol1.1 is definitely positive in the data region and its uncertainty is reduced up to a factor three w.r.t. NNPDFpol1.0

Comparison with NNPDFpol1.0

Δs^+ and Δg



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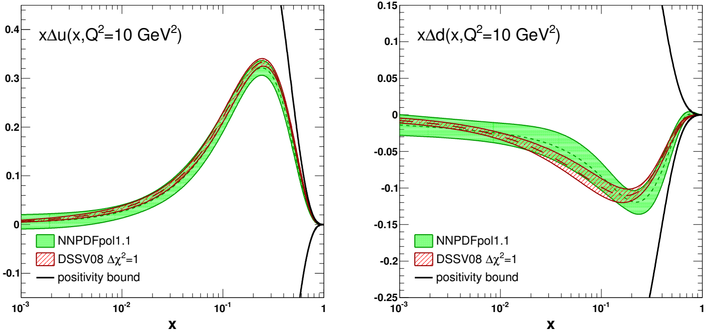
Comparison with DSSV

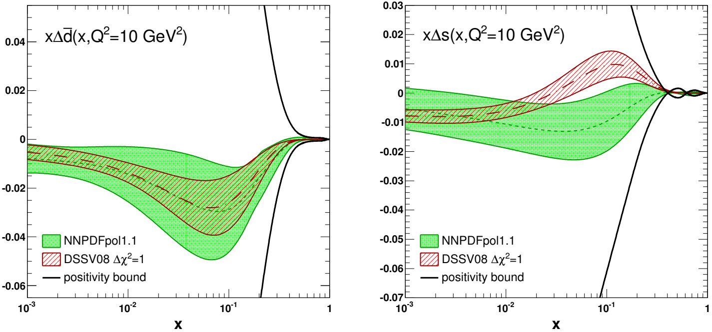
Δu and Δd



- Consistent results are found in the two parton determinations
- NNPDF uncertainties are slightly larger, especially at small-x values (where experimental data are lacking)

Comparison with DSSV

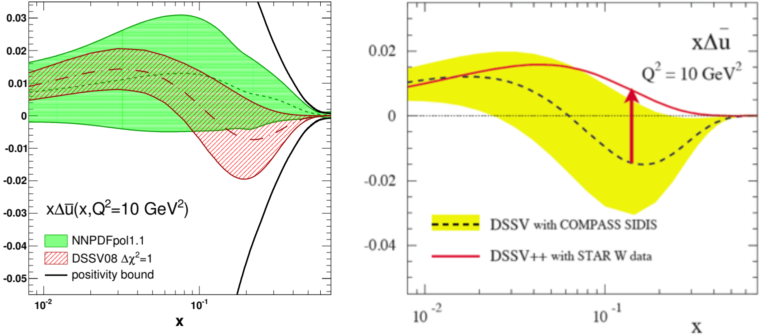
$\Delta\bar{d}$ and $\Delta s = \Delta\bar{s}$



- Good agreement for the $\Delta\bar{d}$ distribution, but with large uncertainty
- Discrepancy between NNPDF and DSSV determinations of Δs (bias from the kaon fragmentation function used to include SIDIS data?)

Comparison with DSSV

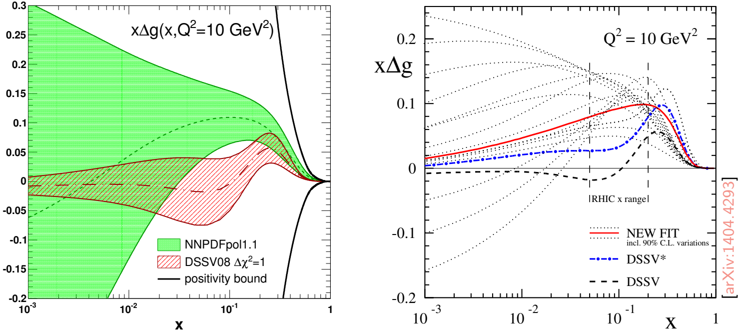
$\Delta\bar{u}$



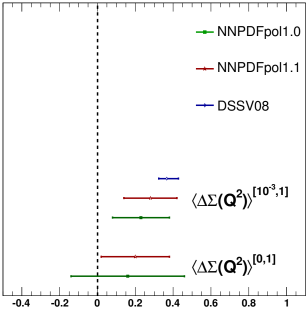
[Marco Stratmann, talk at DIS2013]

- Slight discrepancy for the $\Delta\bar{u}$ distribution at $x \gtrsim 3 \cdot 10^{-2}$
- Recall that $W^{\pm}$ data were not included in the DSSV08 analysis
- The $\Delta\bar{u}$ distribution was determined in DSSV08 from π production data in SIDIS (bias from the pion fragmentation function?)
- This discrepancy disappears when W data are included in the DSSV analysis

Δg



- For $x < 0.2$ the gluon has a node in `DSSV08`, while it is definitely positive in `NNPDFpol1.1`
- `NNPDFpol1.1` and `DSSV` are in perfect agreement once recent jet data are included
- First evidence of gluon polarization in the proton in the region covered by data, $x \gtrsim 0.2$
- The uncertainty of the gluon blows up in the unmeasured small-x region

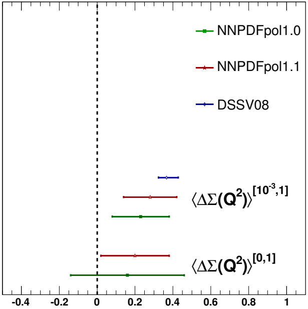


`NNPDFpol1.0` vs `NNPDFpol1.1`

- Moments obtained from `NNPDFpol1.0` and `NNPDFpol1.1` are consistent with each other
- The uncertainty in the region $x \in [0,1]$ reduces by a factor two, except for $\Delta\bar{s}$
- The relative contribution to the total momentum uncertainty from the extrapolation region is roughly a half in both parton sets

$Q^2 = 10$ GeV^2	$\langle\Delta f(Q^2)\rangle^{[0,1]}$		$\langle\Delta f(Q^2)\rangle^{[10^{-3},1]}$		
Δf	`NNDPFpol1.0`	`NNDPFpol1.1`	`NNDPFpol1.0`	`NNDPFpol1.1`	`DSSV08` ($\Delta\chi^2/\chi^2 = 2\%$)
$\Delta u + \Delta\bar{u}$	$+0.77 \pm 0.10$	$+0.79 \pm 0.06$	$+0.76 \pm 0.06$	$+0.76 \pm 0.03$	$+0.793^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.46 ± 0.10	-0.47 ± 0.06	-0.41 ± 0.06	-0.41 ± 0.04	$-0.416^{+0.035}_{-0.025}$
$\Delta\bar{u}$	—	$+0.06 \pm 0.05$	—	$+0.05 \pm 0.05$	$+0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	—	-0.12 ± 0.07	—	-0.10 ± 0.05	$-0.089^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.07 ± 0.06	-0.06 ± 0.05	-0.06 ± 0.04	-0.05 ± 0.04	$-0.006^{+0.028}_{-0.031}$
$\Delta\Sigma$	$+0.16 \pm 0.30$	$+0.20 \pm 0.18$	$+0.23 \pm 0.15$	$+0.25 \pm 0.10$	$+0.366^{+0.042}_{-0.062}$

The spin content of the proton: quarks and antiquarks



`NNPDFpol1.1` vs `DSSV08`

- Truncated moments are in perfect agreement, both central values and uncertainties
- Slight differences are found for $\Delta\bar{u}$ and $\Delta\bar{s}$ (according to the corresponding PDFs)

$Q^2 = 10$ GeV^2	$\langle\Delta f(Q^2)\rangle^{[0,1]}$		$\langle\Delta f(Q^2)\rangle^{[10^{-3},1]}$		
Δf	`NNDPFpol1.0`	`NNDPFpol1.1`	`NNDPFpol1.0`	`NNDPFpol1.1`	`DSSV08` ($\Delta\chi^2/\chi^2 = 2\%$)
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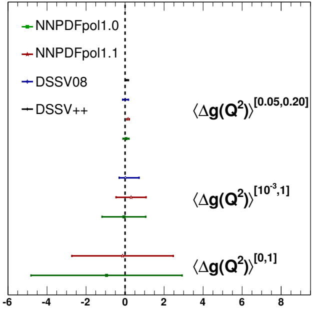
The spin content of the proton: the gluon



`NNPDFpol1.0` vs `NNPDFpol1.1`

- Reduction of the uncertainty thanks to jet data
  $\longrightarrow$ by a factor two for $x \in [0,1]$, $x \in [10^{-3},1]$
  $\longrightarrow$ by a factor three for $x \in [0.05, 0.2]$

`NNPDFpol1.1` *full* vs *truncated* moments

- The extrapolation uncertainty is still dominant
  $\longrightarrow$ 3 times the uncertainty in $x \in [10^{-3},1]$
  $\longrightarrow$ 40 times the uncertainty in $x \in [0.05, 0.2]$

`NNPDFpol1.1` vs `DSSV++` (same jet data sets)

- Results perfectly consistent for $x \in [0.05, 0.2]$

$Q^2 = 10$ GeV^2	$\langle\Delta g(Q^2)\rangle^{[0,1]}$	$\langle\Delta g(Q^2)\rangle^{[10^{-3},1]}$	$\langle\Delta g(Q^2)\rangle^{[0.05,0.2]}$
`NNPDFpol1.0`	-0.95 ± 3.87	-0.06 ± 1.12	$+0.05 \pm 0.15$
`NNPDFpol1.1`	-0.13 ± 2.60	$+0.31 \pm 0.77$	$+0.15 \pm 0.06$
`DSSV08` ($\Delta\chi^2/\chi^2 = 2\%$)	—	$0.013^{+0.702}_{-0.314}$	$0.005^{+0.129}_{-0.164}$
`DSSV++` ($\Delta\chi^2/\chi^2 = 2\%$)	—	—	$0.10^{+0.06}_{-0.07}$

4. Conclusions and outlook

Summary

1. The first unbiased global determination of polarized PDFs was presented
   - `NNPDFpol1.1`: inclusive DIS + open-charm (fixed-target) + jets + W (collider)
   - W data allows for a determination of $\Delta\bar{u}$ and $\Delta\bar{d}$ polarizations
   - jet data from STAR provide the first evidence of gluon polarization, $x \in [0.05, 0.2]$
   - outside this region, the polarized gluon is still largely uncertain
   - large values of the gluon first moment are not completely ruled out
2. The NNPDF parton sets (polarized and unpolarized) are available at

   http://nnpdf.hepforge.org/

   NNPDFs together with stand-alone `Fortran`/`C++`/*Mathematica* code
3. We plan to determine a set of pion and kaon fragmentation functions
   - in view of a full global analysis including SIDIS and hadron production data
4. Only an EIC would probe polarized PDFs at small-x values and higher Q^2
   - accurate determination of the longitudinal spin structure [arXiv:1206.6014] [arXiv:1310.0461]
   - quark-antiquark separation from charged-current DIS [arXiv:1309.5327]

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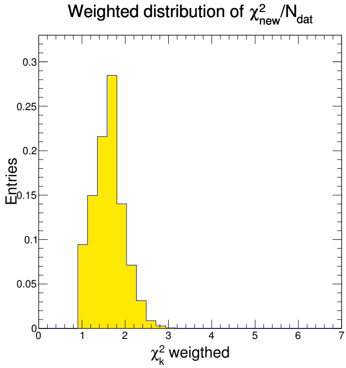
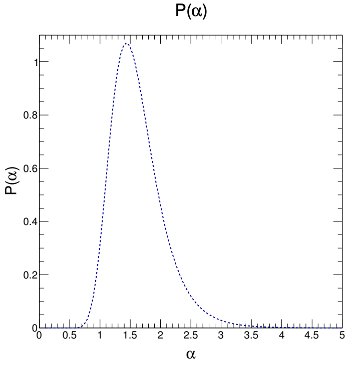
Thank you for your attention

5. Backup

$W^{\pm}$ production at RHIC





Experiment	Set	$N_{\rm dat}$	$\chi^2_{\rm rw}/N_{\rm dat}$				$\langle\alpha\rangle$			
			1σ	2σ	3σ	4σ	1σ	2σ	3σ	4σ
STAR		12	1.43	1.12	**1.03**	1.02	1.45	1.43	**1.40**	1.39
	STAR-W^+	6	1.04	1.01	**1.02**	1.01	1.11	1.13	**1.15**	1.14
	STAR-W^-	6	1.78	1.25	**1.04**	1.02	1.60	1.47	**1.38**	1.35

Overall good description of both data sets after they are included in the fit via reweighting
Stability of reweighted results reached starting from 3σ prior

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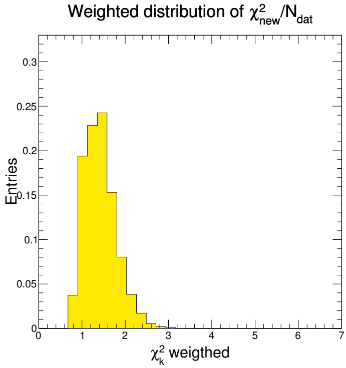

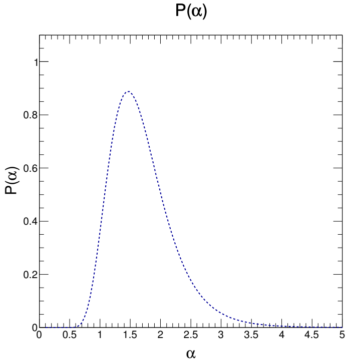

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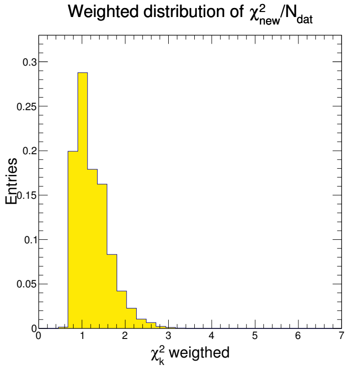

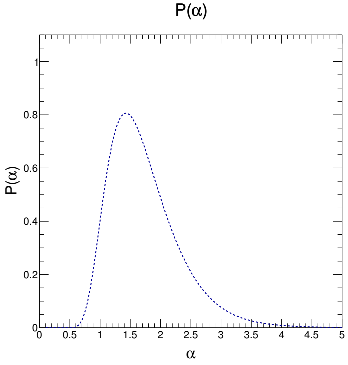

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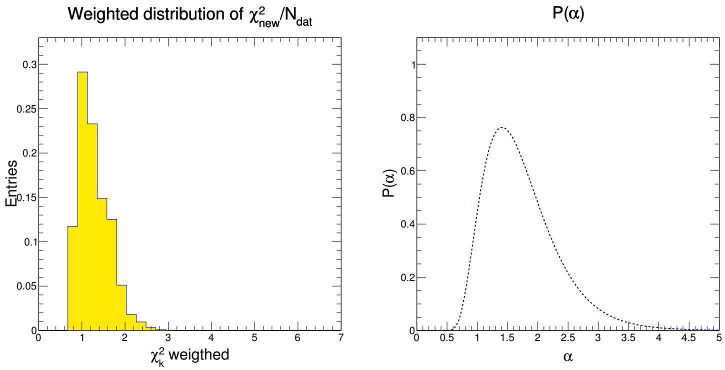

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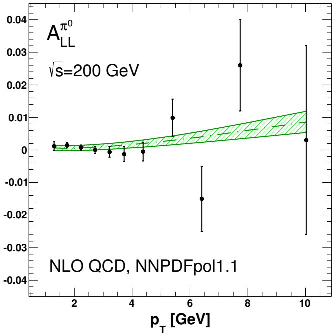
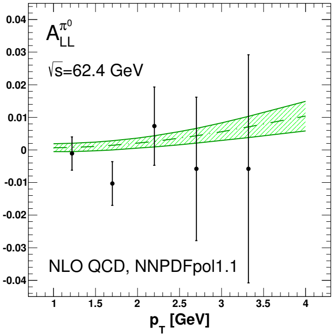
Predictions for single-hadron production asymmetry

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

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





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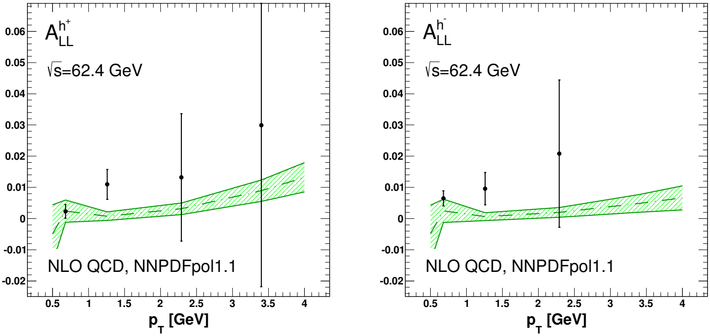

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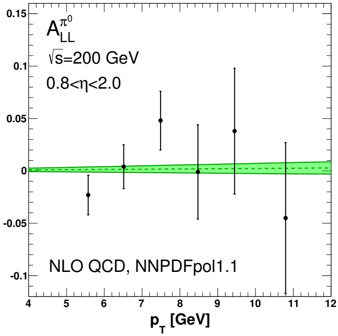

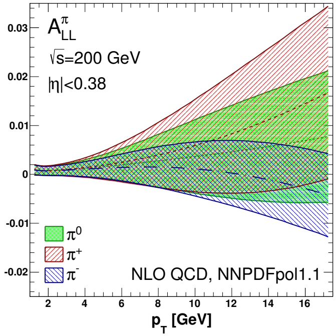

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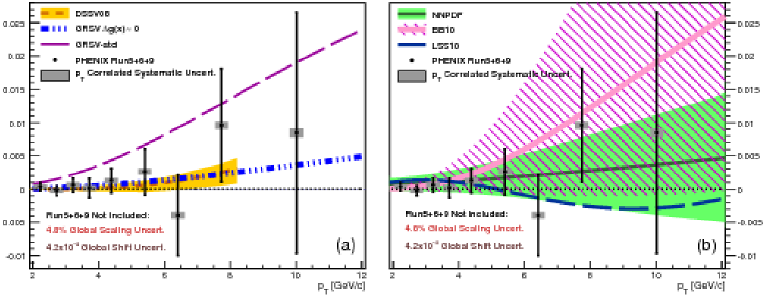

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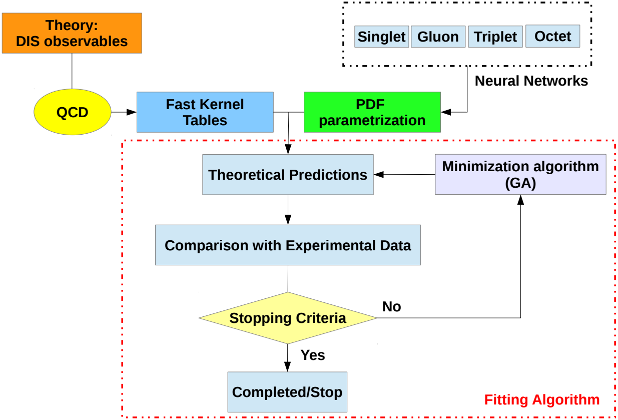
A general overview on the methodology



Ingredients:

Monte Carlo sampling and Neural Networks

Ingredient 1: Monte Carlo sampling of experimental data

MONTE CARLO SAMPLING

- Sample the probability density $\mathcal{P}[\Delta q]$ in the space of functions assuming multi-Gaussian data probability distribution

$$g_{1,p}^{(\mathrm{art}),(k)}(x,Q^2) = \left[1 + \sum_c r_{c,p}^{(k)}\sigma_{c,p} + r_{s,p}^{(k)}\sigma_{s,p}\right] g_{1,p}^{(\mathrm{exp})}(x,Q^2)$$

$\sigma_{c,p}$: correlated systematics $\sigma_{s,p}$: statistical errors (also uncorrelated systematics)

$r_{c,p}^{(k)}$, $r_{s,p}^{(k)}$: Gaussian random numbers

- Generate MC ensemble of N_{rep} replicas with the data probability distribution

MAIN FEATURES

- Expectation values for observables are Monte Carlo integrals

$$\langle\mathcal{O}[\Delta q]\rangle = \frac{1}{N_{\mathrm{rep}}}\sum_{k=1}^{N_{\mathrm{rep}}}\mathcal{O}[\Delta q_k]$$

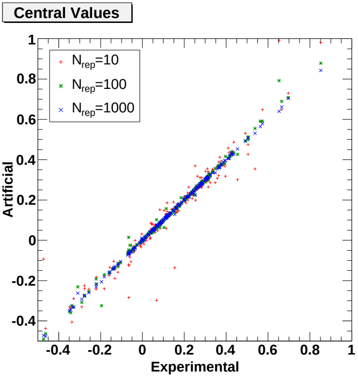
...and the same is true for errors, correlations etc.

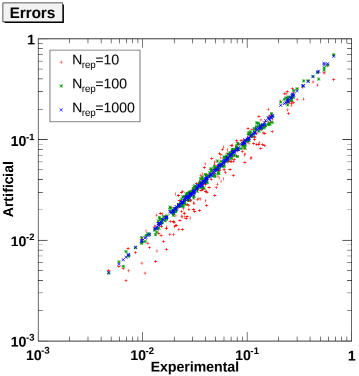
- No need to rely on linear propagation of errors
- Possibility to test for non-Gaussian behaviour in fitted PDFs

Ingredient 1: Monte Carlo sampling of experimental data

DETERMINING THE SAMPLE SIZE

- Require the average over the replicas reproduces central values and errors of the original experimental data to desired accuracy

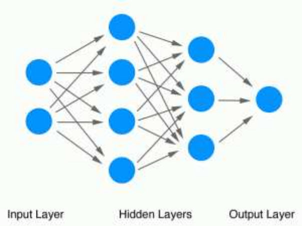




Accuracy of few % requires ∼ 100 replicas

Ingredient 2: Neural Networks

A convenient functional form
providing redundant and flexible parametrization
used as a generator of random functions in the PDF space



$$\xi_i^{(l)} = g\left(\sum_j^{n_l-1} \omega_{ij}^{(l-1)} \xi_j^{(l-1)} - \theta_i^{(l)}\right)$$

$$g(x) = \frac{1}{1+e^{-x}}$$

- made of neurons grouped into layers (define the architecture)
- each neuron receives input from neurons in preceding layer (feed-forward NN)
- activation determined by parameters (weights and thresholds)
- activation determined according to a non-linear function (except the last layer)

Distances

Compare two sets of $N_{\rm rep}^{(1)}$ and $N_{\rm rep}^{(1)}$ replicas coming from different fits
Do they have belong to the same underlying probability distribution?

MEAN VALUE

$$d^2\left(\langle q^{(k)}\rangle_{(1)},\langle q^{(k)}\rangle_{(2)}\right)=\frac{\left(\langle q^{(k)}\rangle_{(1)}-\langle q^{(k)}\rangle_{(2)}\right)^2}{\sigma^2\left[\langle q^{(k)}\rangle_{(1)}\right]+\sigma^2\left[\langle q^{(k)}\rangle_{(2)}\right]}$$

$$\langle q^{(k)}\rangle_{(i)}=\frac{1}{N_{\mathrm{rep}(i)}}\sum_{l=1}^{N_{\mathrm{rep}(i)}}q_l^{(k)}\qquad \sigma^2\left[\langle q^{(k)}\rangle_{(i)}\right]=\frac{1}{N_{\mathrm{rep}(i)}}\sigma^2\left[q_{(i)}^{(k)}\right]=\frac{1}{N_{\mathrm{rep}(i)}-1}\sum_{l=1}^{N_{\mathrm{rep}(i)}}\left(q_{l,(i)}-\langle q\rangle_{(i)}\right)^2$$

UNCERTAINTY

$$d^2\left(\sigma^2_{(1)},\sigma^2_{(2)}\right)=\frac{\left(\bar\sigma^2_{(1)}-\bar\sigma^2_{(2)}\right)}{\sigma^2\left[\sigma^2_{(1)}\right]+\sigma^2\left[\sigma^2_{(2)}\right]}$$

$$\bar\sigma^2_{(i)}\equiv\sigma^2\left[q_{(i)}^{(k)}\right]\qquad \sigma^2\left[\sigma^2_{(i)}\right]=\frac{1}{N_{\mathrm{rep}(i)}}\left[\frac{1}{N_{\mathrm{rep}(i)}}\sum_{l=1}^{N_{\mathrm{rep}(i)}}\left(q_{l,(i)}-\langle q\rangle_{(i)}\right)^4-\frac{N_{\mathrm{rep}(i)}-3}{N_{\mathrm{rep}(i)}-1}\left(\bar\sigma^2_{(i)}\right)^2\right]$$

By definition, the distances have a χ^2 probability distribution with one degree of freedom
mean $\langle d\rangle=1$ and $d\lesssim 2.3$ at 90% confidence level

Unweighting [arXiv:11081758]

Unweighting allows for constructing an ensemble of equally probable PDFs
statistically equivalent to a given reweighted set
Hence, the new set can be given without weights

IDEA

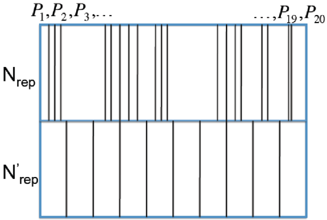
Given a weighted set of $N_{\rm rep}$ replicas, select (possibly more than once) replicas carrying relatively hight weight and discard replicas carrying relatively small weight

CONSTRUCTION OF THE UNWEIGHTED SET

1. Set the number of replicas $N'_{\rm rep}$ in the unweighted set (pointless to choose $N'_{\rm rep} > N_{\rm rep}$: no gain of information)
2. Compute, for the k-th replica of the reweighted set, the integer non negative number

$$w'_k = \sum_{j=1}^{N'_{\rm rep}} \theta\left(\frac{j}{N'_{\rm rep}} - P_{k-1}\right)\theta\left(P_k - \frac{j}{N'_{\rm rep}}\right), \quad P_k = \sum_{j=0}^{k}\frac{w_j}{N_{\rm rep}}, \quad \sum_{k=1}^{N_{\rm rep}} w'_k = N'_{\rm rep}$$

3. Construct the unweighted set taking w'_k copies of the k-th replica, for $k = 1, \ldots, N_{\rm rep}$



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C) Reweighting with 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

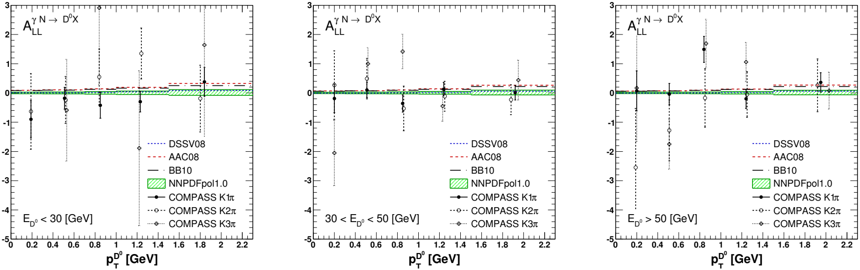
- Δg is probed *directly* through the photon-gluon fusion process (in DIS Δg is mostly probed through scaling violations instead)
- the fragmentation functions for heavy quarks are computable in perturbation theory (and only introduce a very moderate uncertainty in the fit)

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

C) Reweighting with 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

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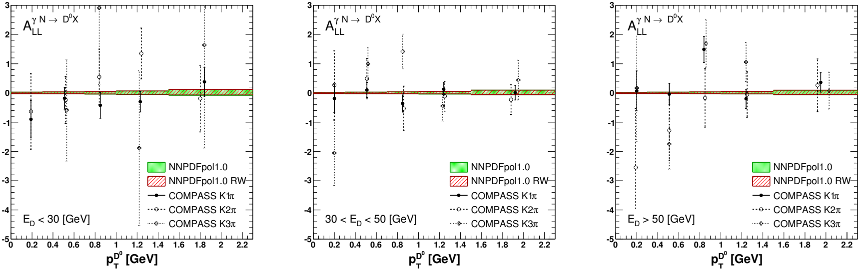

The impact of open-charm data from COMPASS is mostly negligible, as we notice from the value of the $\chi^2/N_{\rm ndat}$ and the reweighted observable

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