The role of neutron data in polarized PDF analysis

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Jefferson Lab Angular Momentum Collaboration

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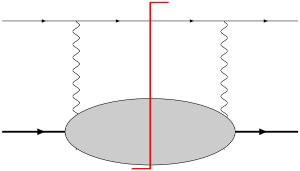
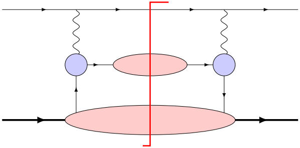
What can we learn from (un)polarized DIS?





$$\frac{d\sigma}{dxdQ^2} = H \otimes f(x, Q^2) + O\left(\frac{m^2}{Q^2}\right)$$

$$\frac{d\Delta\sigma}{dxdQ^2} = \Delta H \otimes \Delta f(x, Q^2) + O\left(\frac{m^2}{Q^2}\right)$$

- **collinear factorization**
+ valid up to corrections of $O\left(m^2/Q^2\right)$
+ it works when x is not too small or not too large and Q^2 not too small
+ H, ΔH are calculable in expansion of α_S
+ non-perturbative field theoretic objects f and Δf can be extracted from data
+ extensions of collinear factorization are needed to understand where the power corrections are not suppressed. Not clear if existing treatments have controlled errors

What can we learn from (un)polarized DIS?

- **comments**

+ factorization only holds in a limited region of $x \in [0, 1]$
+ at present it is not clear what are the boundaries in x, Q^2
+ however $f(\xi), \Delta f(\xi)$ are well defined quantities in the region $\xi \in [0, 1]$, where $\xi = k^+/P^+$
+ The bayesian inference of $f(\xi), \Delta f(\xi)$ from data is limited by the applicability of collinear factorization
+ In order to access to $\xi \to 1$ or $\xi \to 0$ we need other tools:
  - data that probes small and large x at large $Q \to$ EIC
  - improved factorization theorems to address regions where collinear factorization is not applicable
  - complementary approach using lattice QCD, e.g. quasi PDFs, pseudo PDFs
+ inclusive DIS cannot resolve fully the flavor dependence $\to$ additional observables (justified by collinear factorization) are needed: e.g. PVDIS, SIDIS, Jets, DY, W

What can we learn from polarized DIS?

- **polarized structure function g_1 at leading twist (τ_2)**

$$g_1^{p,n(\tau_2)}(x) = \frac{1}{2}\sum_q e_q^{2(p,n)} \left[H_q \otimes \Delta q^+(x) + 2H_g \otimes \Delta g(x)\right]$$

$$\overset{n_f=3}{=} \frac{1}{12}\left[H_{\rm NS} \otimes \left(\pm a_3 + \frac{1}{3}a_8\right)(x) + H_S \otimes \frac{4}{3}\Delta\Sigma(x)\right]$$

$$+ \frac{2}{3}H_g \otimes \Delta g(x)$$

$$g_1^{p-n(\tau_2)}(x) = \frac{1}{12}H_{\rm NS} \otimes a_3(x)$$

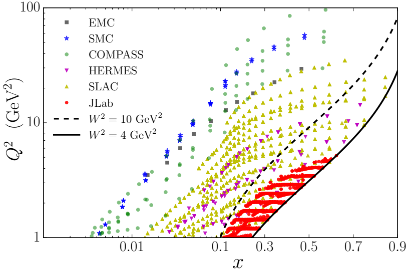
$$\Delta q^+ = \Delta q + \Delta\bar{q}$$
$$a_3 = \Delta u^+ - \Delta d^+$$
$$a_8 = \Delta u^+ + \Delta d^+ - 2\Delta s^+$$
$$\Delta\Sigma = \Delta u^+ + \Delta d^+ + \Delta s^+$$

+ p and n data "can" constrain a_3.
+ recall that $a_3^{(1)} \equiv \int_0^1 dx a_3(x) = g_A$
+ to constrain a_8 one needs other observables: PVDIS, ΔSIDIS
+ in the absence of PVDIS or ΔSIDIS, values for $a_{3,8}^{(1)}$ from hyperon beta decays are used $\rightarrow$ constrains only the normalization of Δf

What can we learn from polarized DIS?

- **in practice (e.g. JAM15)**

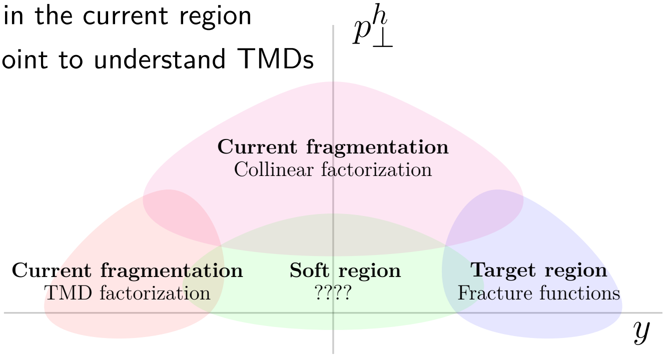
+ targets: proton, deuteron, 3He
+ $W^2 > 4\text{GeV}^2$, $Q^2 > 1\text{GeV}^2$
+ sensitivity:
  - $a_3 = \Delta u^+ - \Delta d^+$
  - $a_8 = \Delta u^+ + \Delta d^+ - 2\Delta s^+$



+ assumptions:
  - $a_{3,8}^{(1)}$ extracted from hyperon beta decays is imposed
  - data at very high x are measured at low $Q^2 \to$ requires treatment of power corrections. e.g. TMC, HT
  - high x deuteron and 3He data requires to add nuclear effects
+ beyond leading twist (from low Q^2 and high x):
  - twist 3 distribution can be isolated from data, under assumptions of factorization
  - determination of d_2 matrix element $\to$ color forces

Additional observables

- **ΔSIDIS**
  + $\pi^{\pm}$: can discriminate $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}$
  + $K^{\pm}$: can discriminate $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s, \Delta\bar{s}$
  + requires simultaneus extraction of FFs (along with SIA data)
  + assumes that the reaction is given by current fragmentation
  + at present, it is not clear that data sets from COMPASS and HERMES are in the current region
  + this is a key point to understand TMDs



Additional observables

- $\vec{p} + p \to W^{\pm} + X$
  - can discriminate $\Delta\bar{u}$ from $\Delta\bar{d}$
  - it depends on the knowledge of unpolarized $\bar{u}$ and $\bar{d}$.
  - a simultaneous extraction with upolarized PDFs (E866 DY data and tevatron $W + l$ asymmetry) is needed
- $\vec{p} + \vec{p} \to j + X$
  - constrains Δg
  - the asymmetry depends on $p + p \to j + X$
  - the denominator is not constrained at RHIC energies, hence it is an extrapolation from Tevatron/LHC single jet production
  - fits to unpolarized jets at RHIC energies is needed
  - ... then a combined analysis with the polarized jet data is needed

What we would like to learn from Δf:

+ precise determination of g_A, $\Delta g^{(1)}$
+ the flavor dependence $\rightarrow$ non perturbative sea asymmetries
+ helicity decomposition $(\Delta) f(x) = f^{\uparrow}(x) \pm f^{\downarrow}(x)$
+ test spectator counting rules in pQCD

$$\lim_{x \to 1} \frac{\Delta q(x)}{q(x)} = \lim_{x \to 1} \frac{q^{\uparrow}(x)}{q^{\uparrow}(x)} = 1$$

+ understand proton spin decomposition

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma^{(1)} + \Delta g^{(1)} + \mathcal{L}$$

+ despite the efforts, these questions are still not well understood

How do we extract (△)PDFs?

- **likelihood analysis using Bayesian stat.**

+ Bayes theorem:

$$\mathcal{P}(f|data) = \frac{1}{Z}\mathcal{L}(data|f)\pi(f)$$

+ The likelihood function *Gaussian likelihood*

$$\mathcal{L}(data|f) = \exp\left[-\frac{1}{2}\sum_i\left(\frac{d_i - \mathrm{model}_i(f)}{\delta d_i}\right)^2\right]$$

+ The prior function to restrict unphysical regions of f. e.g.

$$\pi(f) = \begin{cases} 1 & \mathrm{condition}(f) == \mathrm{True} \\ 0 & \mathrm{condition}(f) == \mathrm{False} \end{cases}$$

Bayesian perspective for global fits

- In practice f needs to be parametrized e.g

$$f(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx+...)$$
$$f(x) = Nx^a(1-x)^b\mathrm{NN}(x;\{w_i\})$$
$$f(x) = \mathrm{NN}(x;\{w_i\}) - \mathrm{NN}(1;\{w_i\})$$

- The pdf for f becomes

$$\boldsymbol{a} = (N,a,b,c,d,...)$$
$$\mathcal{P}(\boldsymbol{a}|d) = \frac{1}{Z}\mathcal{L}(d|\boldsymbol{a})\pi(\boldsymbol{a})$$
$$\mathcal{L}(d|\boldsymbol{a}) = \exp\left[-\frac{1}{2}\sum_i\left(\frac{d_i - \mathrm{model}_i(\boldsymbol{a})}{\delta d_i}\right)^2\right]$$
$$\pi(\boldsymbol{a}) = \prod_i \theta(a_i - a_i^{min})\theta(a_i^{max} - a_i)$$

$$\mathcal{P}(f|d) = \frac{1}{Z}\mathcal{L}(d|f)\pi(f)$$
$$\downarrow$$
$$\mathcal{P}(\boldsymbol{a}|d) = \frac{1}{Z}\mathcal{L}(d|\boldsymbol{a})\pi(\boldsymbol{a})$$

Bayesian perspective for global fits

- Having the pdf for f we can compute

$$\mathrm{E}[\mathcal{O}] = \int d^n a \ \ \mathcal{P}(\boldsymbol{a}|data) \ \ \mathcal{O}(\boldsymbol{a})$$

$$\mathrm{V}[\mathcal{O}] = \int d^n a \ \ \mathcal{P}(\boldsymbol{a}|data) \ \ (\mathcal{O}(\boldsymbol{a}) - \mathrm{E}[\mathcal{O}])^2$$

- $\mathcal{O}$ is any function of $\boldsymbol{a}$. e.g

$$\mathcal{O}(\boldsymbol{a}) = f(x;\boldsymbol{a})$$

$$\mathcal{O}(\boldsymbol{a}) = \int_x^1 \frac{d\xi}{\xi} C(\xi) f\left(\frac{x}{\xi};\boldsymbol{a}\right)$$

- How do we compute $\mathrm{E}[\mathcal{O}], \mathrm{V}[\mathcal{O}]$?
  - Maximum likelihood + (Hessian, Lagrange multipliers)
  - Monte Carlo sampling

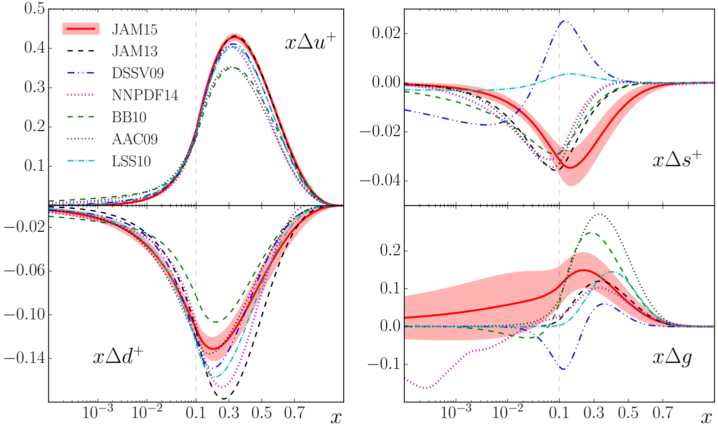
Global analyses

- **JAM15**:
  - extraction of ΔPDFs and τ_3 distributions
  - data sets: ΔDIS($p, d,$ ^{3}He),
  - focus: polarized twist 3 distributions
  - $W^2 > 4\text{GeV}^2$ and $Q^2 > 1\text{GeV}^2$
  - Iterative MC sampling
- **JAM17**:
  - simultaneous extraction of ΔPDFs, FF
  - data sets: ΔDIS(p, d), ΔSIDIS(p, d), SIA($\pi^\pm, K^\pm$)
  - focus: determination of Δs without a_3, a_8
  - $W^2 > 10\text{GeV}^2$ and $Q^2 > 1\text{GeV}^2$
  - Iterative MC sampling
- **JAM18**(in progress):
  - simultaneous extraction of PDFs, ΔPDFs, FF
  - data sets: (Δ)DIS(p, d), (Δ)SIDIS(p, d), SIA($\pi^\pm, K^\pm$), DY(p, d)
  - focus: determination of $s, \Delta s$
  - $W^2 > 10\text{GeV}^2$ and $Q^2 > 1\text{GeV}^2$
  - Nested Sampling

Global analyses

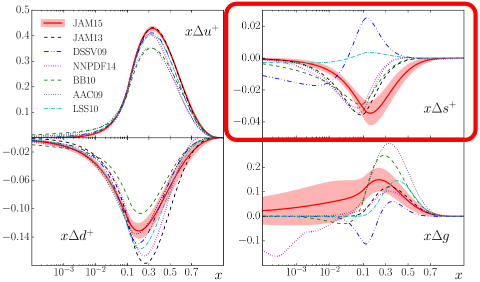
- **NNPDF14**
  - extraction of ΔPDFs only
  - data sets: ΔDIS(p, d, n), $\vec{p}, p \to W^{\pm}X$, $\vec{p}, \vec{p} \to jX$, ΔSIDIS$(p, d \to D)$
  - Extraction of twist 3 distributions
  - $W^2 > 10\mathrm{GeV}^2$ and $Q^2 > 1\mathrm{GeV}^2$
  - Reweighting
- **DSSV14**
  - extraction of ΔPDFs only
  - data sets: ΔDIS(p, d, n) $\vec{p}, p \to W^{\pm}X$, $\vec{p}, \vec{p} \to jX$, ΔSIDIS$(p, d \to \pi^{\pm}, K^{\pm})$, $\vec{p}, p \to \pi X$,
  - Extraction of twist 3 distributions
  - $W^2 > 10\mathrm{GeV}^2$ and $Q^2 > 1\mathrm{GeV}^2$
  - ML+Lagrange multipliers

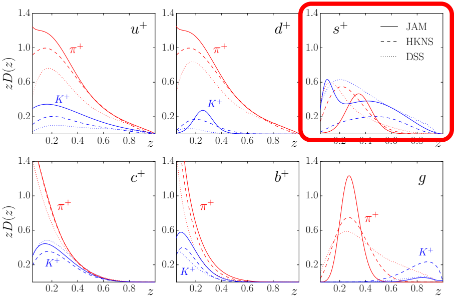
Global analyses



- Stability of Δu^+ and Δd^+ is mostly due to inclusion of $a_{3,8}$ from beta decays.
- "the strange puzzle" resolved in JAM17
- constraints on Δg are from scaling violations

The Δs^+ puzzle



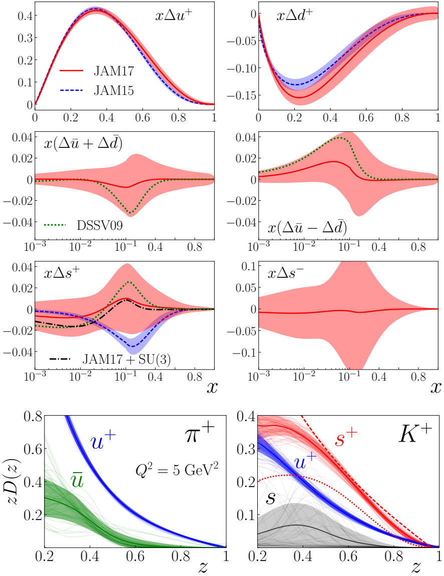


- **Constraints on Δs^+**
  - JAM: ΔDIS + SU3
  - DSSV: ΔDIS + SU3, ΔSIDIS
- **Note**
  - DSSV analysis shows no violation of SU3 due to penalties
  - In DSSV, FF is extracted independently from SIA, SIDIS and pp data
  - In JAM negative Δs^+ comes only from SU3
- **Questions**
  - What controls the sign of Δs^+?
  - What are the actual uncertainties on Δs^+ ?

Combined ΔPDF and FF: ΔDIS+ΔSIDIS+SIA

Ethier, NS, Melnitchouk (PRL 119, 132001)

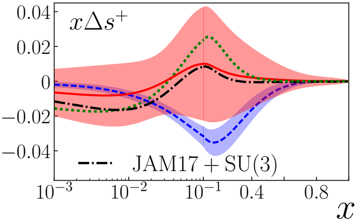
- **Setup**
  - Simultaneous extraction of polarized ΔPDFs and FFs
  - Data: ΔDIS,ΔSIDIS, SIA
  - No SU(3) constraints
- **Results**
  - Sea polarization consistent with zero
  - The current precision of ΔSIDIS data is not sufficient to determine the sea polarization
  - $D^K_{s^+}$ consistent with SIA only analysis

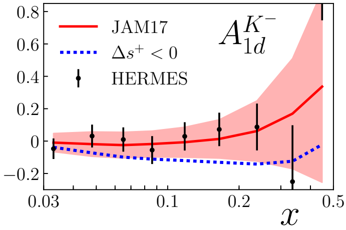


What determines the sign of Δs^+?

- **case 1**
  - ~ 5 COMPASS d data points at $x < 0.002$ favor small $\Delta s^+(x)$
  - To generate $\Delta s^{+(1)}(Q_0^2) \sim -0.1$ a peak at $x \sim 0.1$ is generated
- **case 2**
  - In the absence of $x < 0.002$ data, the negative $\Delta s^{+(1)}(Q_0^2) \sim -0.1$ is mostly generated at small x.
  - No need for negative $\Delta s^+(x)$ at $x \sim 0.1$
- **case 3**
  - $\Delta s^+(x \sim 0.1) < 0$ disfavored by HERMES $A_{1d}^{K^-}$
  - Smaller $\Delta s^{+(1)}(Q_0^2)$ but larger uncertainties

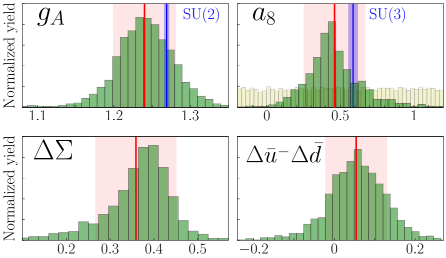
case	data	sign change	$\Delta s^{+(1)}(Q_0^2)$
1	ΔDIS+SU(3)	No	-0.1
2	ΔDIS+SU(3) ($x > 0.02$)	Possible	-0.1
3	ΔDIS+ΔSIDIS+FF	Possible	$-0.03(10)$





Updates on the moments

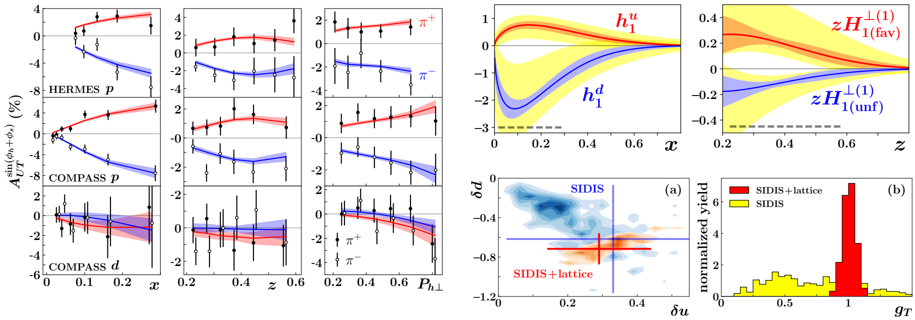
- We construct flat priors that gives flat a_8 in order to have an unbiased extraction of a_8
- Data prefers smaller values for $a_8 \to 25\%$ larger total spin carried by quarks.
- a_3 is in a good agreement with values from β decays within 2%.
- Data indicates possible $\Delta\bar{u} > \Delta\bar{d}$ consistent with measurements of $W^{\pm}(Z)$ asymmetries from PHENIX and STAR



obs.	JAM15	JAM17
g_A	$1.269(3)$	$1.24(4)$
g_8	$0.586(31)$	$0.46(21)$
$\Delta\Sigma$	$0.28(4)$	$0.36(9)$
$\Delta\bar{u} - \Delta\bar{d}$	0	0.05(8)

SIDIS+Lattice analysis of nucleon tensor charge

Lin, Melnitchouk, Prokudin, NS, Shows (arXiv:1710.09858)



+ Extraction of transversity and Collins FFs from SIDIS A_{UT}+Lattice g_T
+ In the absence of Lattice, SIDIS at present has no significant constraints on $g_T \rightarrow$ this will change with the upcoming JLab12 measurements

Summary and outlook

- **Why EIC's neutron data is important?**
  - existing ΔDIS, ΔSIDIS data is still not precise to determine g_A at the precision of hyperon beta decays
  - upcoming JLab12 measurements will constrain further the value of g_A
  - however, it is desirable to have pure neutron ΔDIS at large Q^2 in order to avoid assumptions about nuclear corrections and potential power corrections at low Q^2
  - yet, that won't be enough. PVDIS is required to really constrain the strange polarization
  - a complementary SIDIS program is also needed to make sure the data is in the current fragmentation region
- **from global analysis to "universal QCD analysis"**
  - the nature of PDF/ΔPDF/FFs extraction demands to constrain all the distribution simultaneously
  - this is only possible if the analysis is formulated via Bayesian statistics along with its proper MC sampling methods