Current status of spin-dependent parton distributions

Nobuo Sato
ODU/JLab

27th Workshop on Deep-Inelastic Scattering
and Related Subjects
DIS 2019
Turin, Italy

AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

- "*Proton has spin 1/2 because it's a fermion. Why need more explanation?* " Hatta

- "*Proton has spin 1/2 because it's a fermion. Why need more explanation?* " Hatta

- "*Spin crisis in the late 80's*"
  - Quark model of nucleon $\rightarrow$ 3 massive quarks
  - Nucleon is in the ground state (s-state) $\rightarrow$ no OAM
  - Quarks expected to carry most of the nucleon's spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

- "*Proton has spin 1/2 because it's a fermion. Why need more explanation?* " Hatta

- "*Spin crisis in the late 80's*"
  - Quark model of nucleon $\rightarrow$ 3 massive quarks
  - Nucleon is in the ground state (s-state) $\rightarrow$ no OAM
  - Quarks expected to carry most of the nucleon's spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

But $\Delta\Sigma \simeq 0.28(4)$ **JAM15**

- "*Proton has spin 1/2 because it's a fermion. Why need more explanation?* " Hatta

- "*Spin crisis in the late 80's*"
  - Quark model of nucleon $\rightarrow$ 3 massive quarks
  - Nucleon is in the ground state (s-state) $\rightarrow$ no OAM
  - Quarks expected to carry most of the nucleon's spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

But $\Delta\Sigma \simeq 0.28(4)$ **JAM15**

- Ok ... QCD is more complicated: "*Spin ~~crisis~~ challenge*"

- In terms of total angular momentum (GPDs):

$$\frac{1}{2} = J_q + J_g$$

- In terms of total angular momentum (GPDs):

$$\frac{1}{2} = J_q + J_g$$

- In terms of spin (PDFs) and OAM:

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

- In terms of total angular momentum (GPDs):

$$\frac{1}{2} = J_q + J_g$$

- In terms of spin (PDFs) and OAM:

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

Moments of helicity distributions

A big community working on the challenge

Small x asymptotics using large N_c

$$\Delta q(x, Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^q}$$

$$\Delta G(x, Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^G}$$

Small x asymptotics using large N_c

$$\Delta q(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^q}$$

$$\Delta G(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^G}$$

$$\alpha_h^q = \frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s\, N_c}{2\pi}} \approx 2.31\sqrt{\frac{\alpha_s\, N_c}{2\pi}}$$

$$\alpha_h^G = \frac{13}{4\sqrt{3}}\sqrt{\frac{\alpha_s\, N_c}{2\pi}} \approx 1.88\sqrt{\frac{\alpha_s\, N_c}{2\pi}}$$

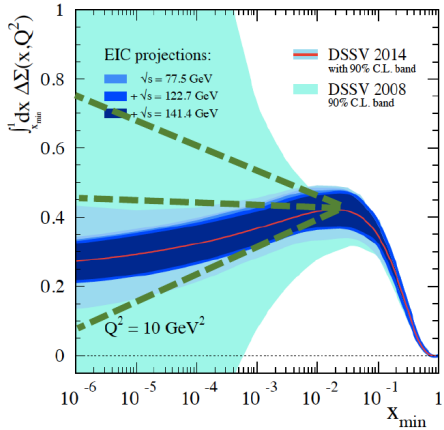
Small x asymptotics using large N_c

$$\Delta q(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^q}$$

$$\Delta G(x,Q^2) \sim \left(\frac{1}{x}\right)^{\alpha_h^G}$$

$$\alpha_h^q = \frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s\, N_c}{2\pi}} \approx 2.31\sqrt{\frac{\alpha_s\, N_c}{2\pi}}$$

$$\alpha_h^G = \frac{13}{4\sqrt{3}}\sqrt{\frac{\alpha_s\, N_c}{2\pi}} \approx 1.88\sqrt{\frac{\alpha_s\, N_c}{2\pi}}$$



Kovchegov, Sievert, Pitonyak ('17)

OAM as a next-to-eikonal effect

$$L_g(x) \approx -\Delta G(x) + \cdots$$

OAM as a next-to-eikonal effect

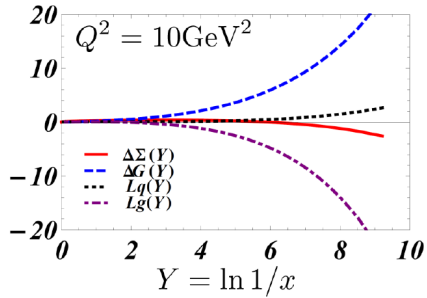
$$L_g(x) \approx -\Delta G(x) + \cdots$$

$$\frac{d}{d\ln Q^2}\begin{pmatrix} L_q(x) \\ L_g(x) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} \hat{P}_{qq}(z) & \hat{P}_{qg}(z) & \Delta\hat{P}_{qq}(z) & \Delta\hat{P}_{qg}(z) \\ \hat{P}_{gq}(z) & \hat{P}_{gg}(z) & \Delta\hat{P}_{gq}(z) & \Delta\hat{P}_{gg}(z) \end{pmatrix}\begin{pmatrix} L_q(x/z) \\ L_g(x/z) \\ \Delta q(x/z) \\ \Delta G(x/z) \end{pmatrix}$$

OAM as a next-to-eikonal effect

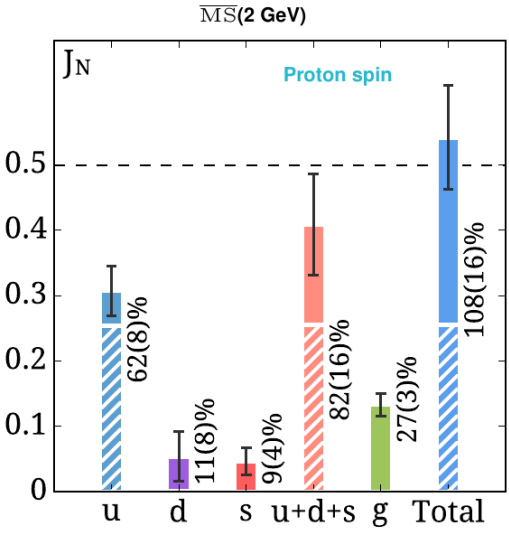
Hatta, Nakagawa, Xiao, Yuan, Zhao ('17)

$$L_g(x) \approx -\Delta G(x) + \cdots$$



$$\frac{d}{d\ln Q^2}\begin{pmatrix} L_q(x) \\ L_g(x) \end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} \hat{P}_{qq}(z) & \hat{P}_{qg}(z) & \Delta\hat{P}_{qq}(z) & \Delta\hat{P}_{qg}(z) \\ \hat{P}_{gq}(z) & \hat{P}_{gg}(z) & \Delta\hat{P}_{gq}(z) & \Delta\hat{P}_{gg}(z) \end{pmatrix}\begin{pmatrix} L_q(x/z) \\ L_g(x/z) \\ \Delta q(x/z) \\ \Delta G(x/z) \end{pmatrix}$$

Lattice QCD



Alexandrou et al.,(ETMC) ('17)

$$\frac{1}{2} = J_q + J_g$$

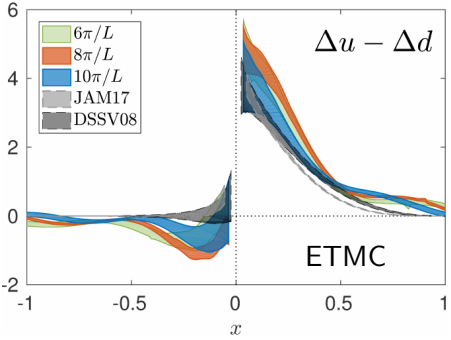
- Striped segments:
  $\rightarrow$ connected contributions
- Solid segments:
  $\rightarrow$ disconnected contributions

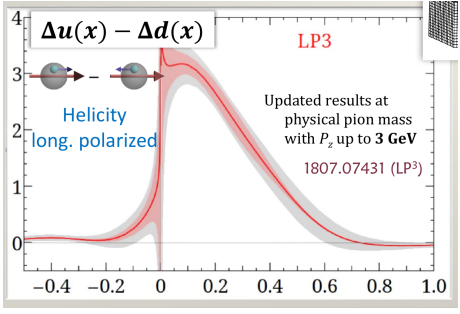
Lattice QCD: quasi-PDF

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) \boldsymbol{q(y,\mu)} + \mathcal{O}\left(M_N^2/P_z^2\right) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$

Lattice QCD: quasi-PDF

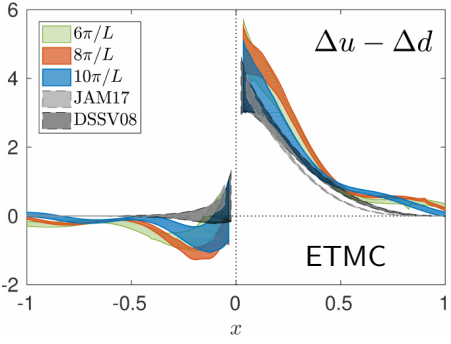
$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu) + \mathcal{O}\left(M_N^2/P_z^2\right) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$

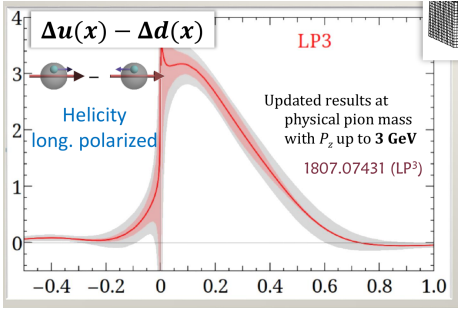




Lattice QCD: quasi-PDF

$$\tilde{q}(x,\mu,P_z) = \int_{-\infty}^{\infty} \frac{dy}{|y|} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) \boldsymbol{q(y,\mu)} + \mathcal{O}\left(M_N^2/P_z^2\right) + \mathcal{O}\left(\Lambda_{\mathrm{QCD}}^2/P_z^2\right)$$



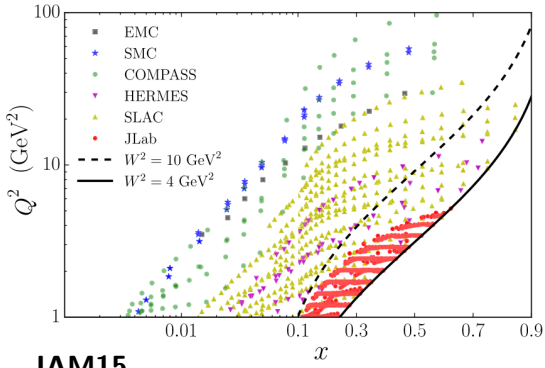


$\Delta\bar{d} < \Delta\bar{u}$

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

Global analyses

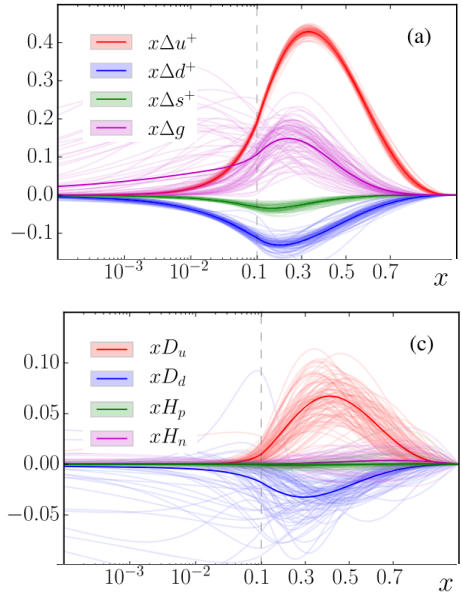
Valence polarization



JAM15

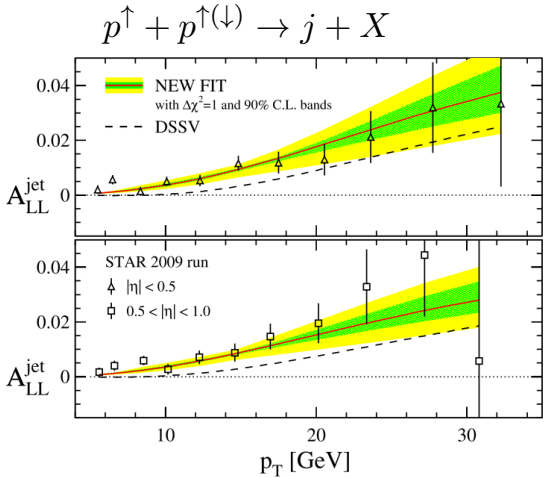
- MC sampling approach
- All ΔDIS data with $W^2 > 4\text{GeV}^2$
- Constraints on twist-3 distributions
- No sign of $\Delta d(x)/d(x) \to 1$

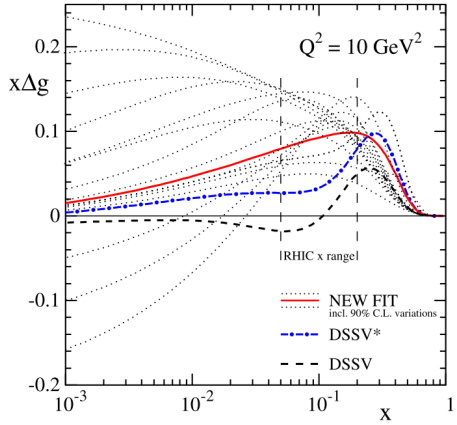
NS, Melnitchouk, Kuhn, Ethier, Accardi ('15)



Gluon polarization

De Florian, Sassot, Stratmann, Vogelsang ('14)



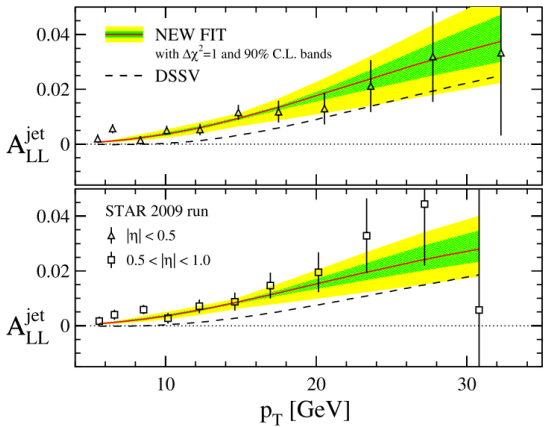


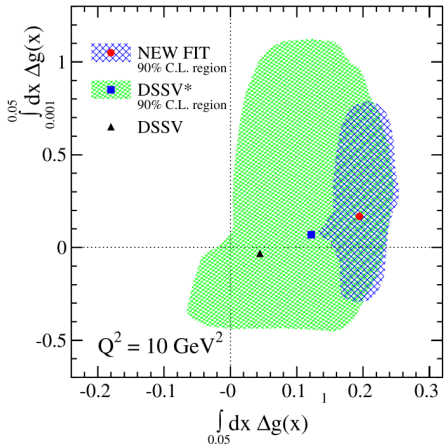
- Single fit method + Lagrange

Gluon polarization

De Florian, Sassot, Stratmann, Vogelsang ('14)

$$p^{\uparrow} + p^{\uparrow(\downarrow)} \to j + X$$



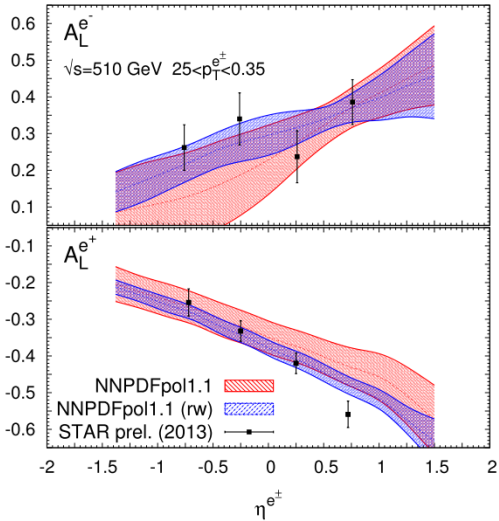


$$\int_{0.001}^{1} dx \Delta g(x) = 0.013 + 0.702 - 0.314$$

- Single fit method + Lagrange

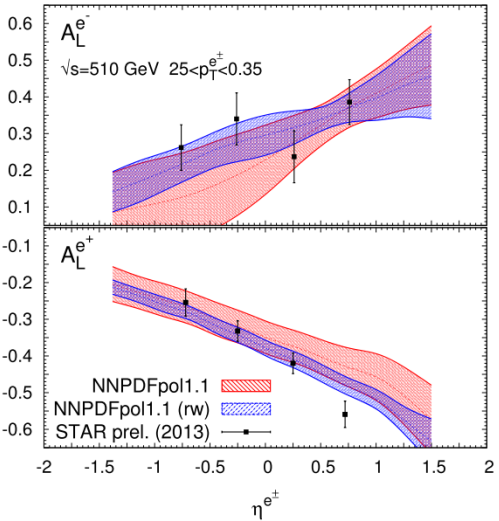
Light sea polarization

$$p^{\uparrow} + p \to W^{\pm} \to e^{\pm} + \nu + X$$

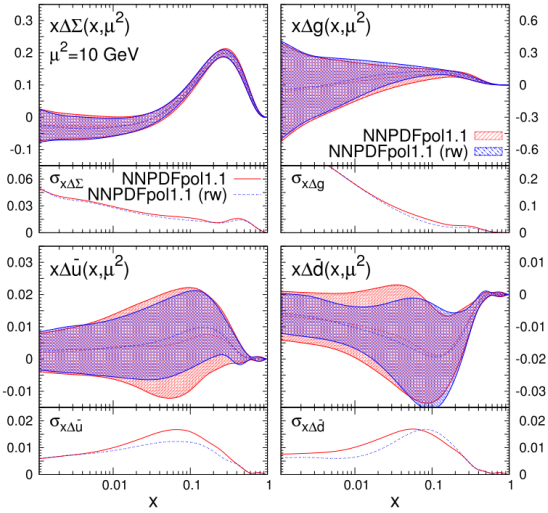


Light sea polarization

$$p^{\uparrow} + p \to W^{\pm} \to e^{\pm} + \nu + X$$

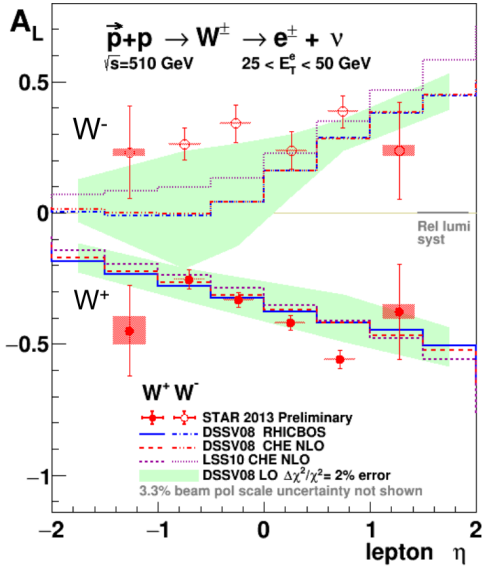


Nocera ('17)

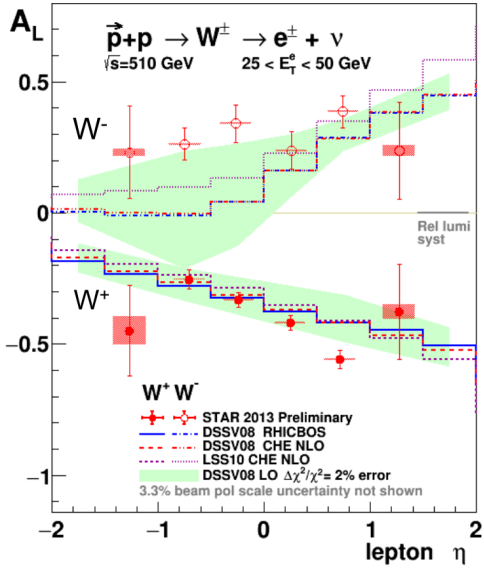


NNPDF Reweighting

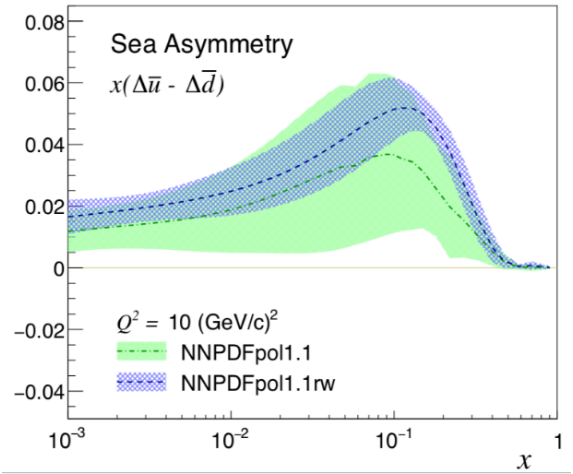
Light sea polarization



Light sea polarization



Xu (spin 18)

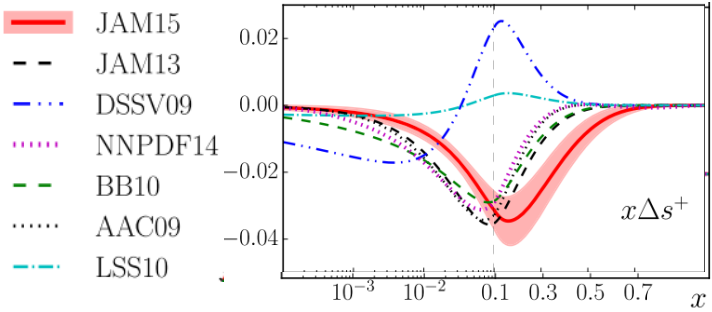


$$\Delta\bar{u} > \Delta\bar{d}$$

Strange polarization

Most of existing analysis on ΔPDFs used additional constraints

- Neutron decay $\rightarrow \int_0^1 dx\ (\Delta u^+ - \Delta d^+) = g_A$
- Hyperon decay $\rightarrow \int_0^1 dx\ (\Delta u^+ + \Delta d^+ - 2\Delta s^+) = g_8$

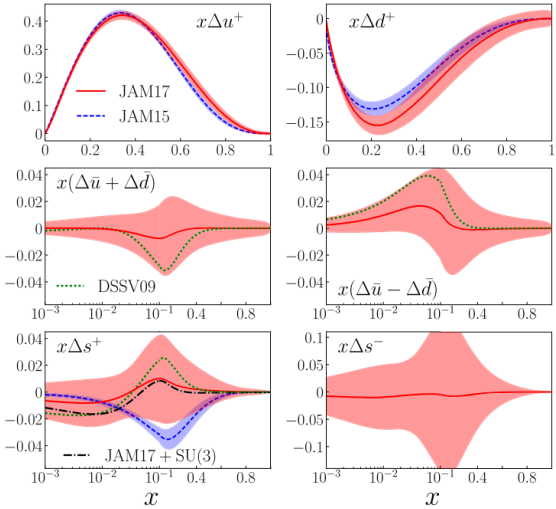


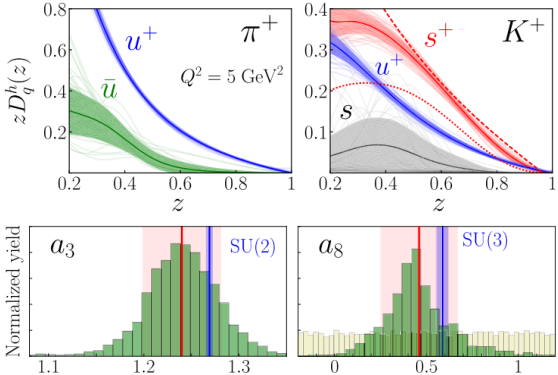
Δs^+ puzzle

- g_8?
- ΔSIDIS ($\bar{s} \rightarrow K$ FF)?
- fiction?

Strange polarization

Ethier, NS, Melnitchouk ('17)





- Current ΔSIDIS unable to discriminate strange polarization
- No conflict between the ΔDIS and ΔSIDIS
- A combined (Δ)PDF & FF is needed

Summary and outlook

- From spin crisis to spin challenge:
  $\rightarrow$ a growing community exploring QCD
- From global analysis to universal analysis:
  $\rightarrow$ TMDs, GPDs
- From single fits to MC methods:
  $\rightarrow$ a paradigm shift