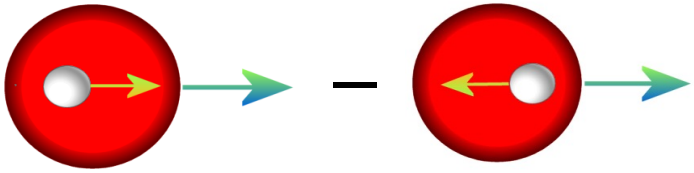
Nucleon Spin from global QCD analysis

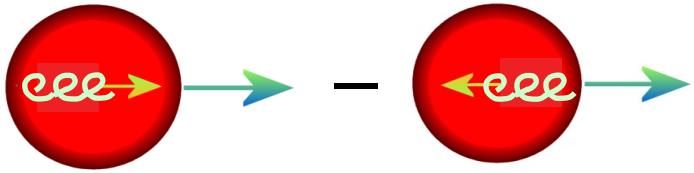
Werner Vogelsang

MIT, 09/23/2022

$$\Delta q(x) =$$

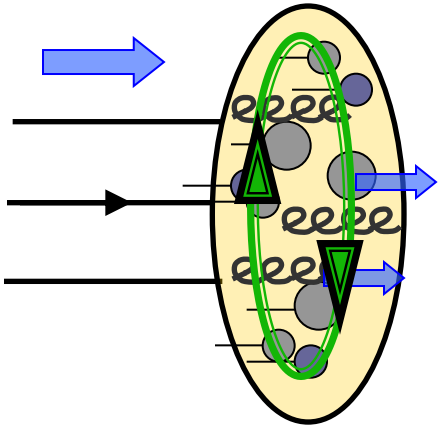


$$\Delta g(x) =$$



proton spin

Jaffe, Manohar; …



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

$$\Delta\Sigma = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x) \quad \ll 1$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

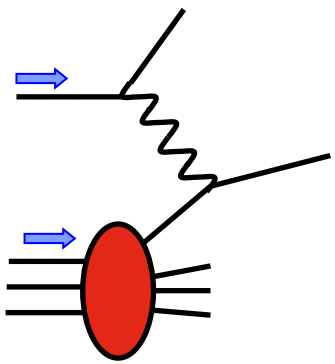
Outline:

- Global analysis of helicity PDFs: status
- EIC opportunities
- Where do we go from here? Preparing for the EIC
- Concluding remarks

* thanks to my colleagues **R. Sassot**, M. Stratmann, I. Borsa, E. Nocera, N. Sato

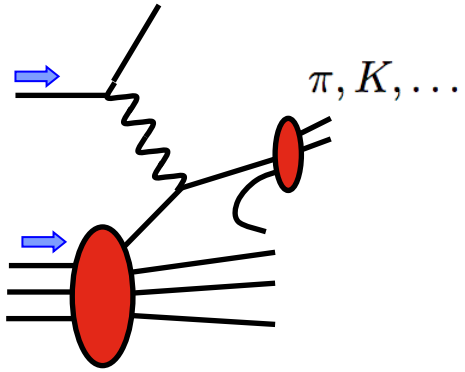
Global analysis: status

Helicity PDFs accessible in polarized high-energy scattering:

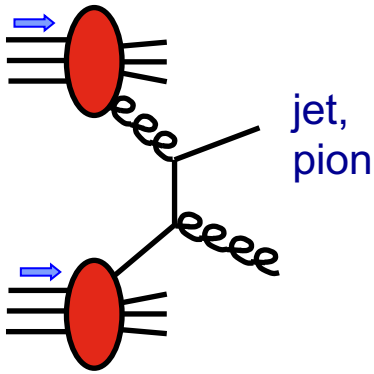


DIS

EMC, SMC, COMPASS,
E142, E143, E154, E155,
HERMES, CLAS, HALL-A

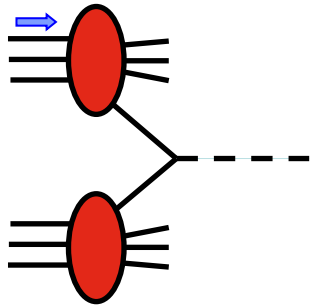


SIDIS



pp high-p_T

PHENIX, STAR



W bosons

$$\Delta\sigma_{\rm pp} = \sum_{a,b=q,\bar{q},g} \Delta f_a(x_a,\mu) \otimes \Delta f_b(x_b,\mu) \otimes \Delta\hat{\sigma}_{ab}$$

$$\Delta\hat{\sigma}_{ab} = \Delta\hat{\sigma}_{ab}^{\rm LO} + \frac{\alpha_s}{\pi}\Delta\hat{\sigma}_{ab}^{\rm NLO} + \left(\frac{\alpha_s}{\pi}\right)^2 \Delta\hat{\sigma}_{ab}^{\rm NNLO} + \ldots$$

Key players over recent years (all at NLO ($\overline{\text{MS}}$)):

DSSV
(2008 –)

NNPDF
(2013 –)

(2013 –)

- differences in methodology:

  DSSV and JAM: Mellin moment techniques

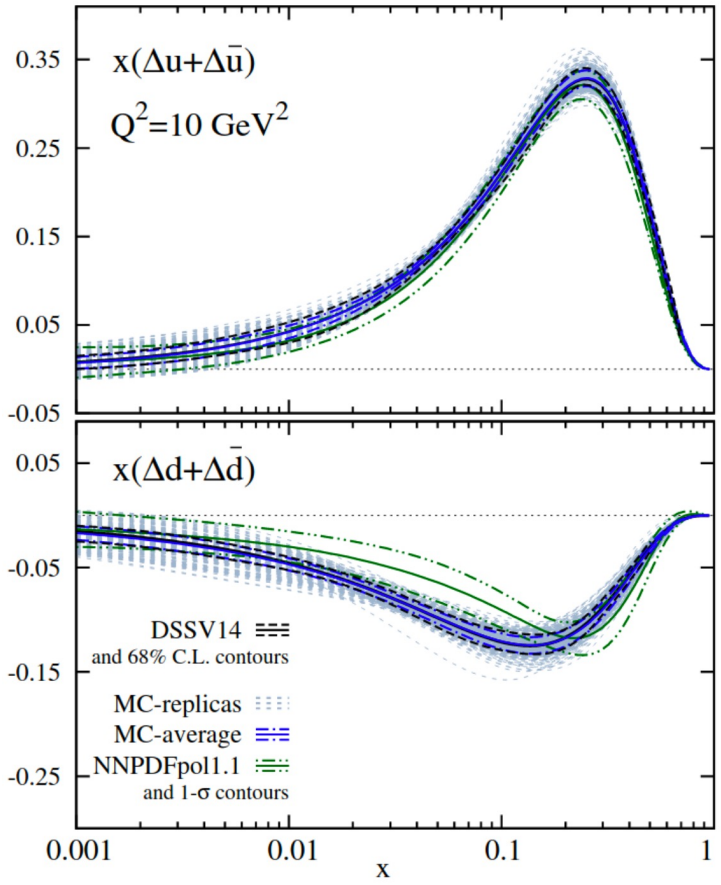
  NNPDF: neural-network technique, x-space

- mature analysis frameworks with robust assessment of uncertainties

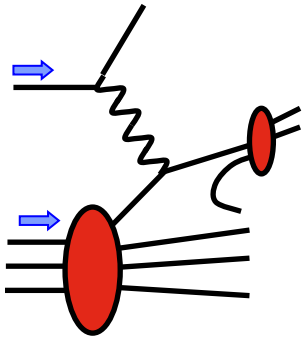
Total up and down polarizations:

$\Delta u + \Delta \bar{u}$

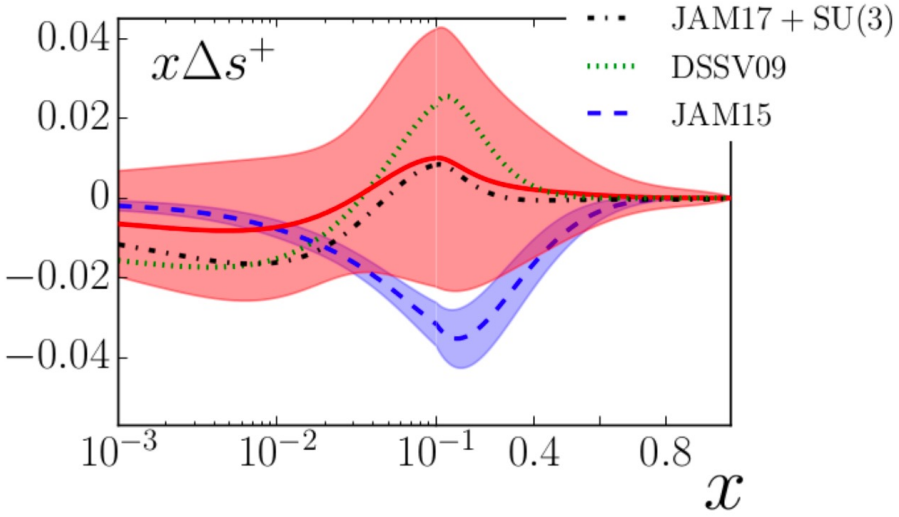
$\Delta d + \Delta \bar{d}$



strangeness $\Delta s + \Delta\bar{s}$:



→ little trace of strangeness



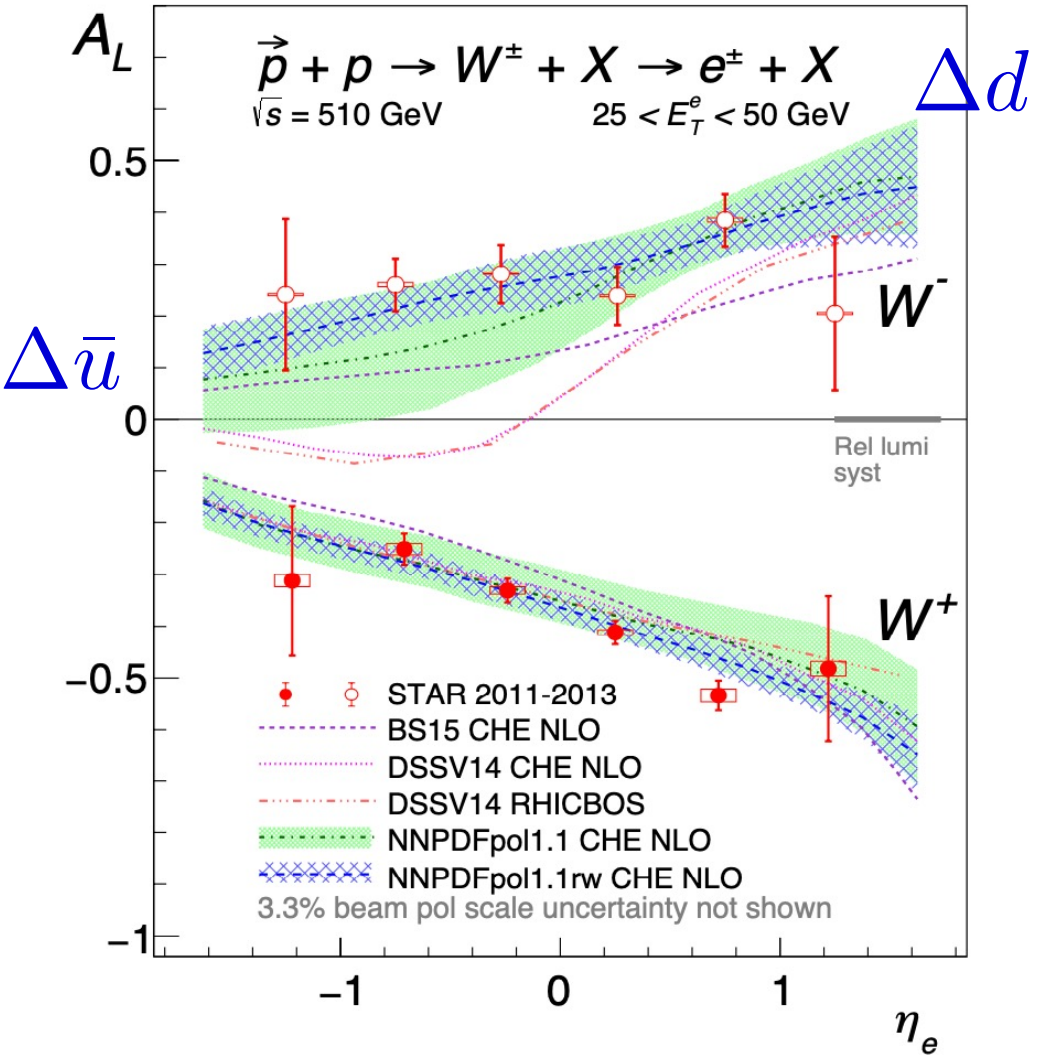
JAM'17:

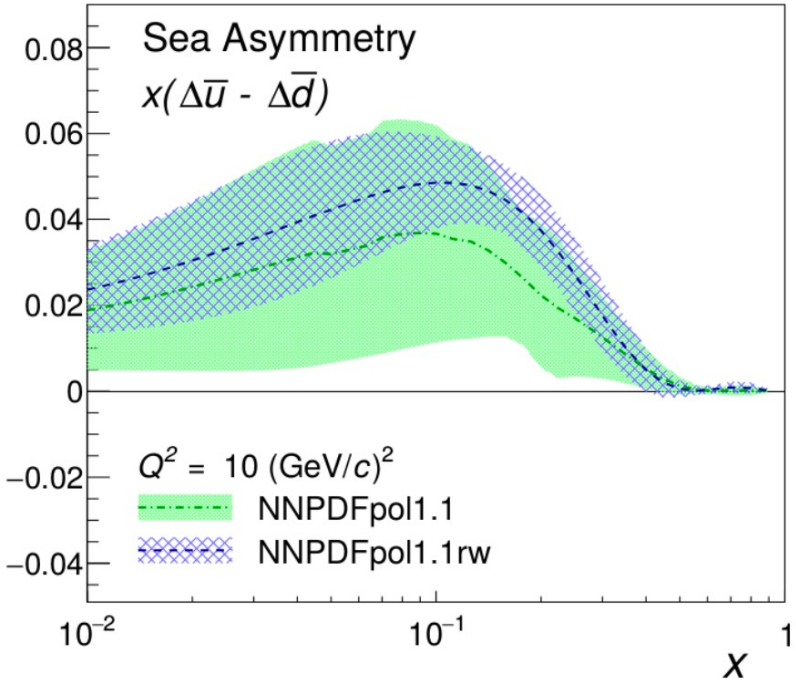
$$\int_0^1 dx(\Delta s + \Delta\bar{s}) = -0.03 \pm 0.10$$

SU(3): $$\int_0^1 dx\,\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s})\right) = 0.58 \pm 0.03$$

→ sizable negative $\int(\Delta s + \Delta\bar{s}) \sim -0.1$

Light sea quarks:



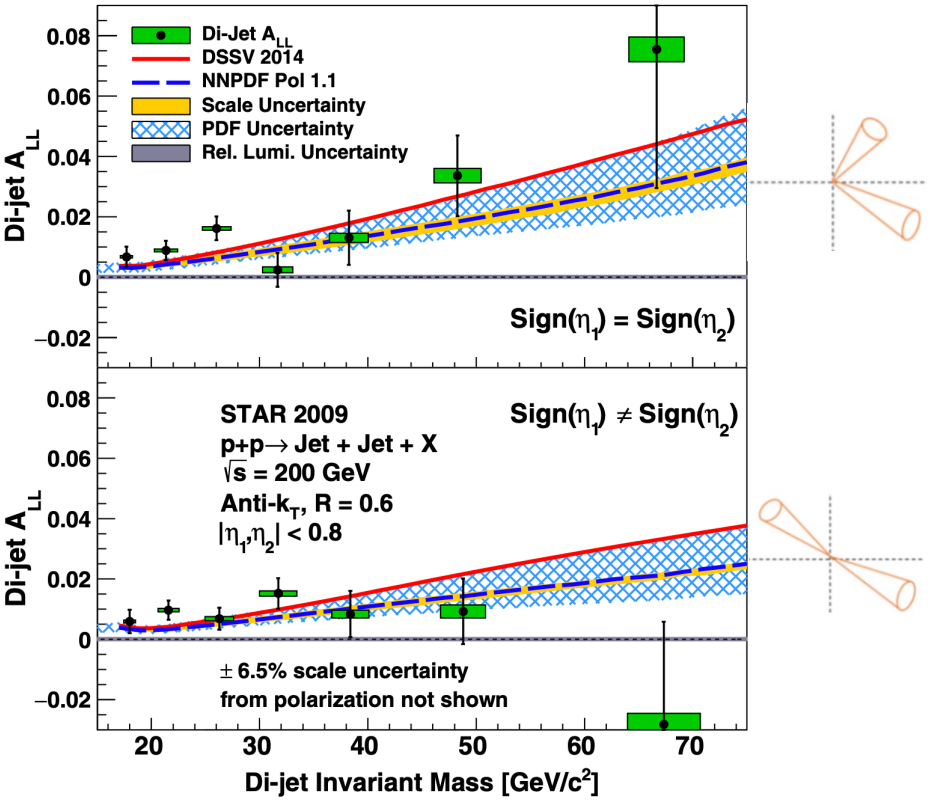


(consistent w/ SIDIS)

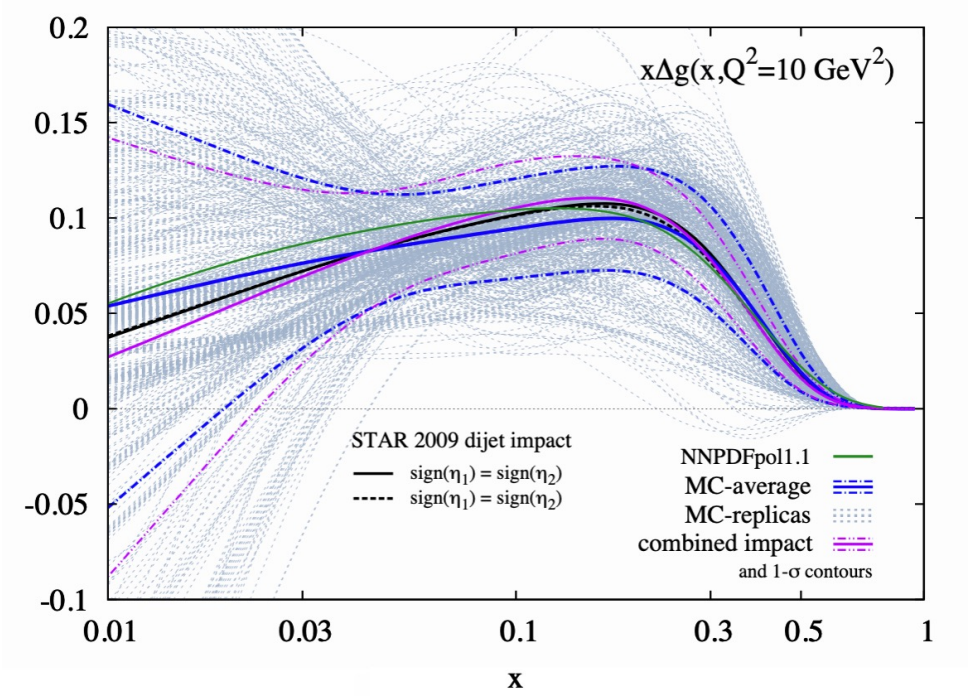
also JAM
(Cocuzza, Melnitchouk, Metz, Sato)

Gluon polarization: 2014 RHIC-discovery that $\Delta g > 0$

→ improvement and consolidation !

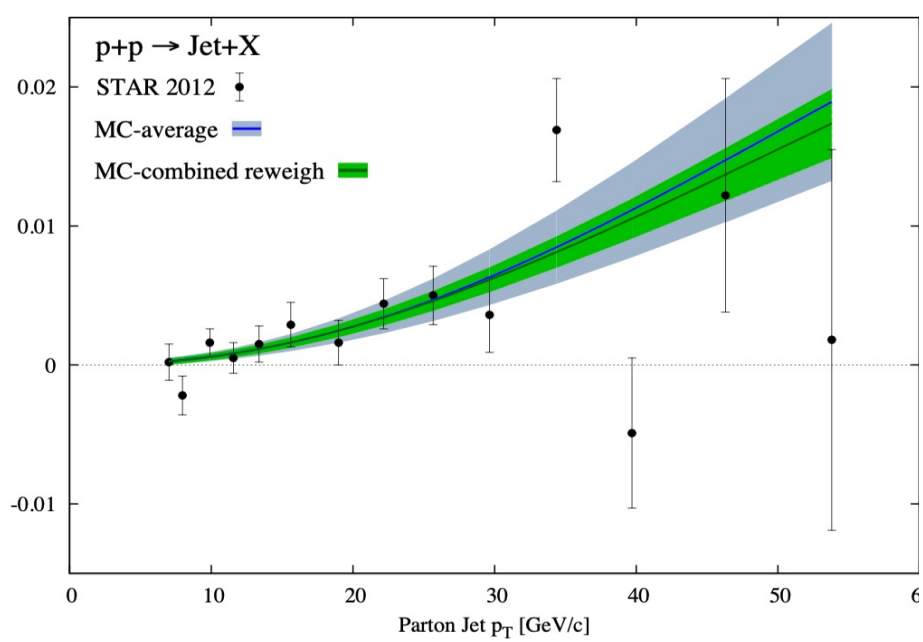


DSSV



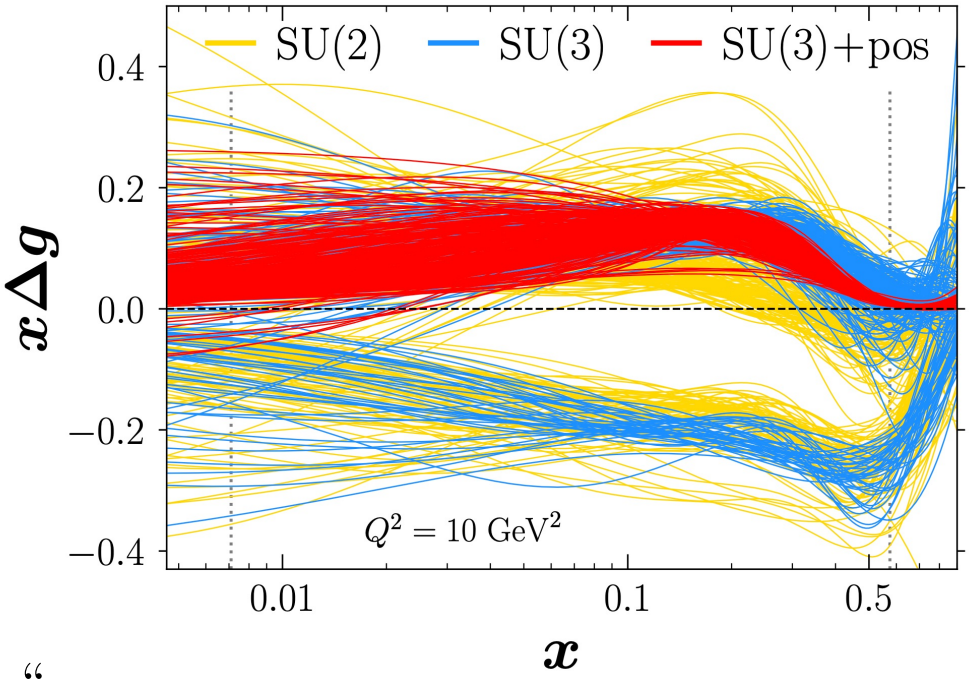
consistent w/ NNPDF

single jets @ 510 GeV

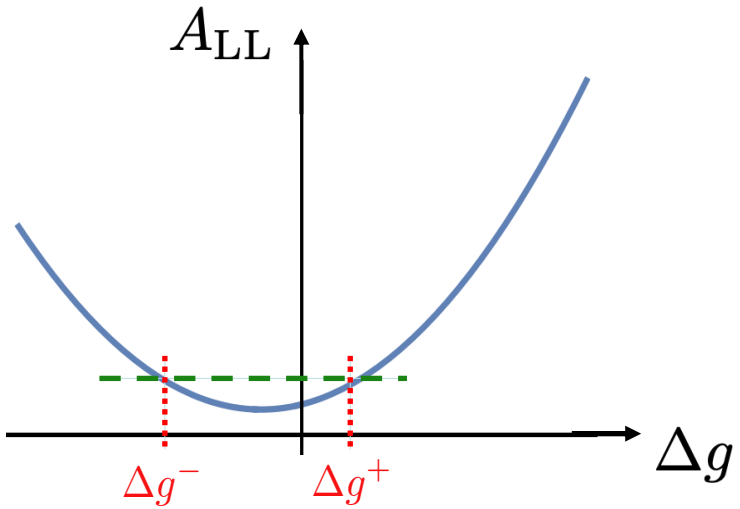


a recent little hiccup:

JAM



“ $A_{\mathrm{LL}} = a_{gg}\,(\Delta g)^2 + a_{qg}\,\Delta g + a_{qq}$ “

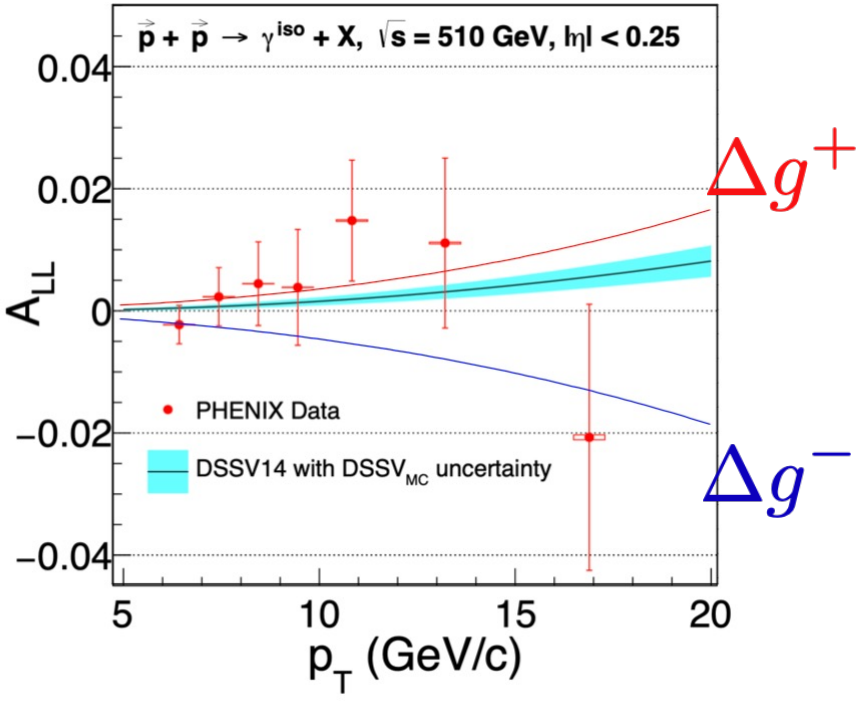


Jäger, Kretzer, Stratmann, WV 2004

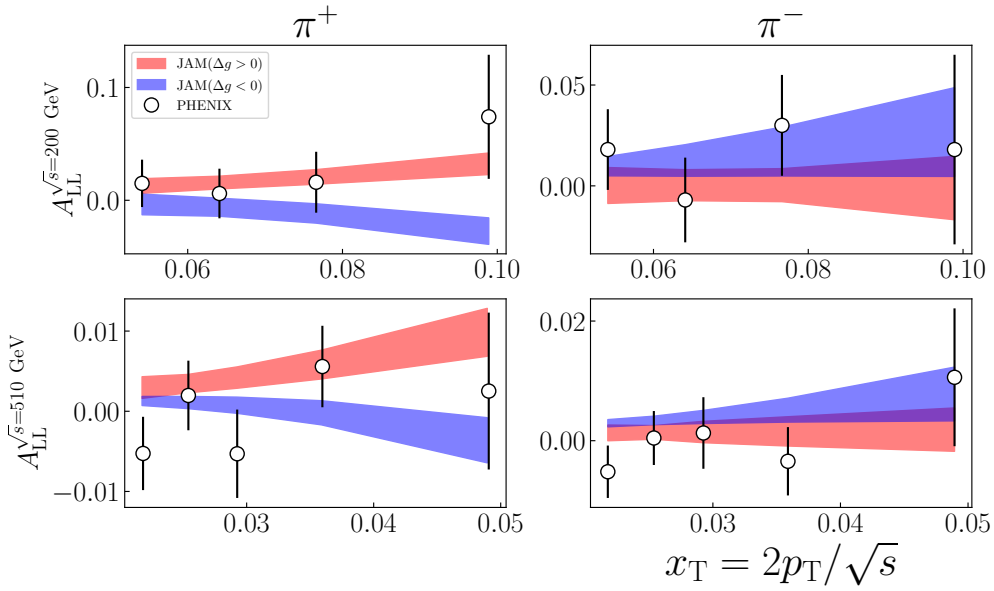
$$|\Delta g| > g$$

Phenix direct photons and charged hadrons:

$$qg \rightarrow \gamma q$$



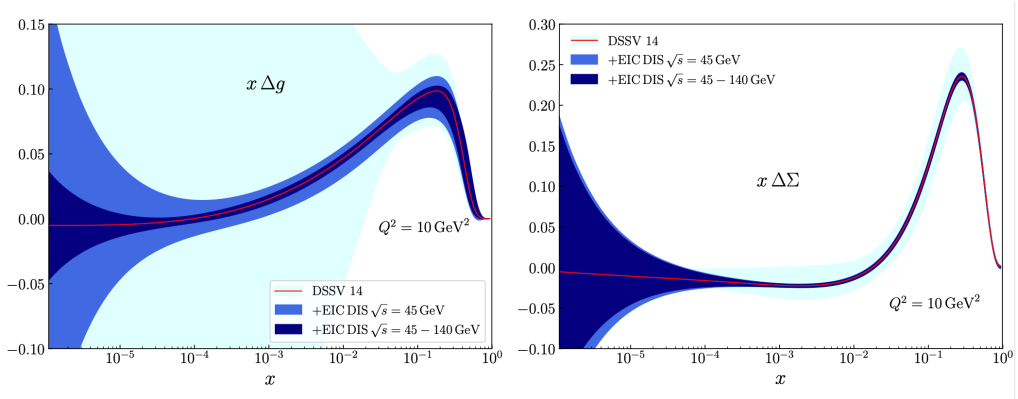
(courtesy N. Sato)



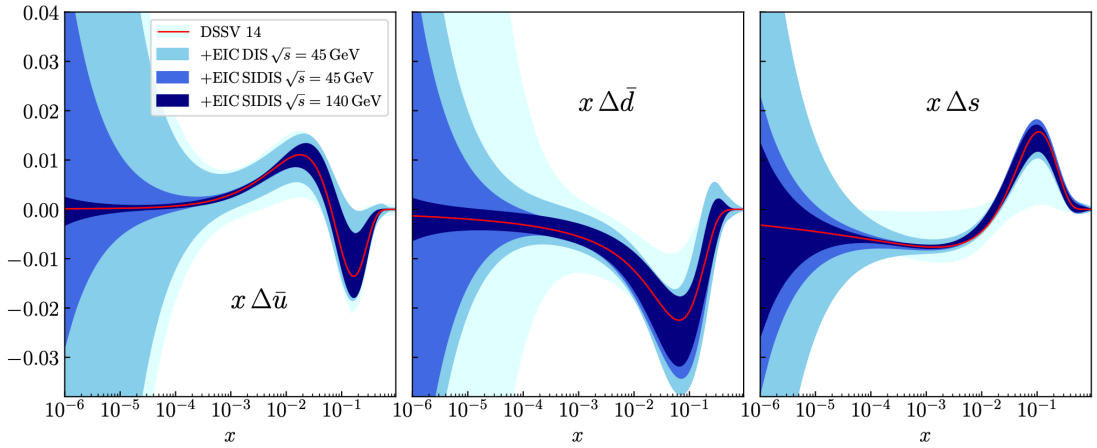
EIC opportunities

Aschenauer, Borsa, Lucero, Nunes, Sassot (YR)

DIS



SIDIS



plus: jet production, charged-current DIS, …

→ spin structure at low x: see talk Y. Kovchegov

Where do we go from here?
Preparing for the EIC

- ”RHIC legacy” analysis:
  STAR π^0 and jet/dijet asymmetries
  PHENIX π^0, $\pi^{\pm}$, η, γ, heavy flavor

- high-precision DIS and SIDIS data from JLab12

- continued impact studies for EIC

- precision era: the path to NNLO

$$\Delta\hat{\sigma}_{ab} = \Delta\hat{\sigma}_{ab}^{\rm LO} + \frac{\alpha_s}{\pi}\Delta\hat{\sigma}_{ab}^{\rm NLO} + \left(\frac{\alpha_s}{\pi}\right)^2 \Delta\hat{\sigma}_{ab}^{\rm NNLO} + \dots$$

PDF evolution

$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta P_{ij}^{\rm LO} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{\rm NLO} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta P_{ij}^{\rm NNLO} + \dots$$

Moch, Vogt, Vermaseren

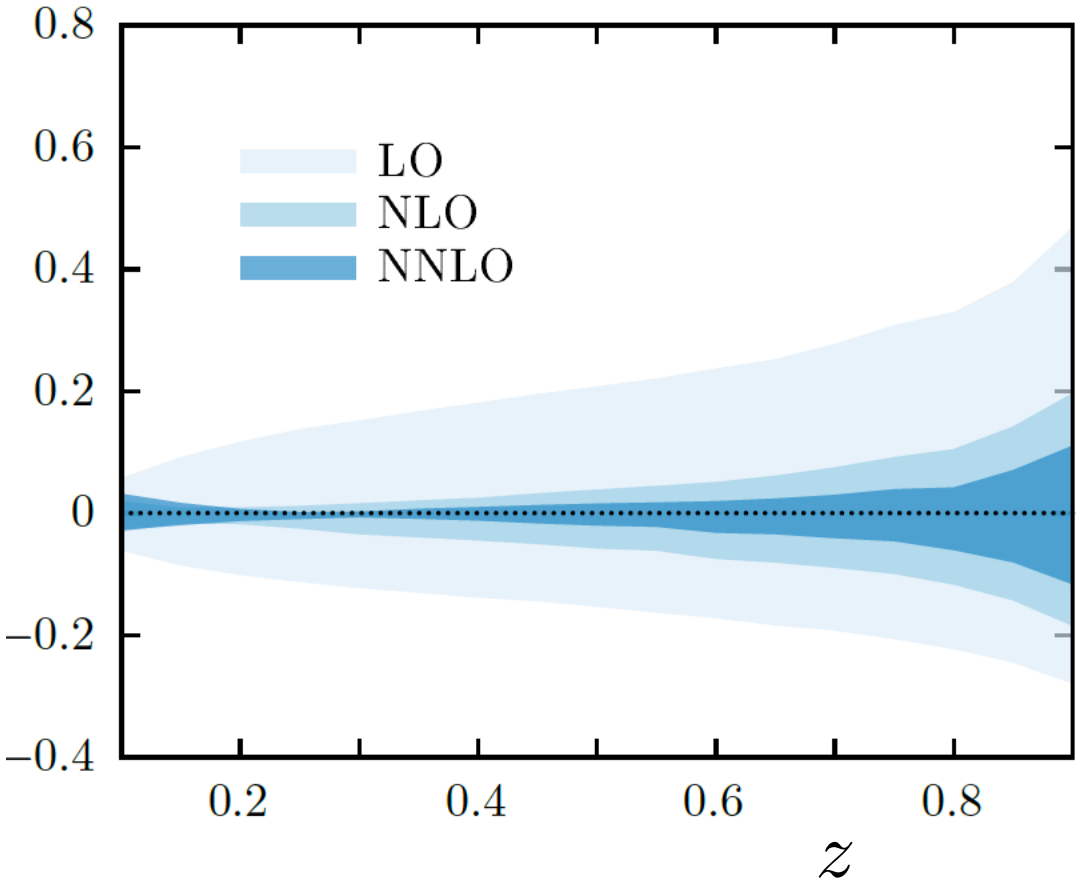
- NNLO available for some partonic cross sections:
  - DIS — van Neerven, Zilstra
  - DIS jets — Borsa, de Florian, Pedron; Boughezal, Petriello, Xing
  - W bosons in pp — Boughezal, Li, Petriello
  - SIDIS (approx.) — Abele, de Florian, WV

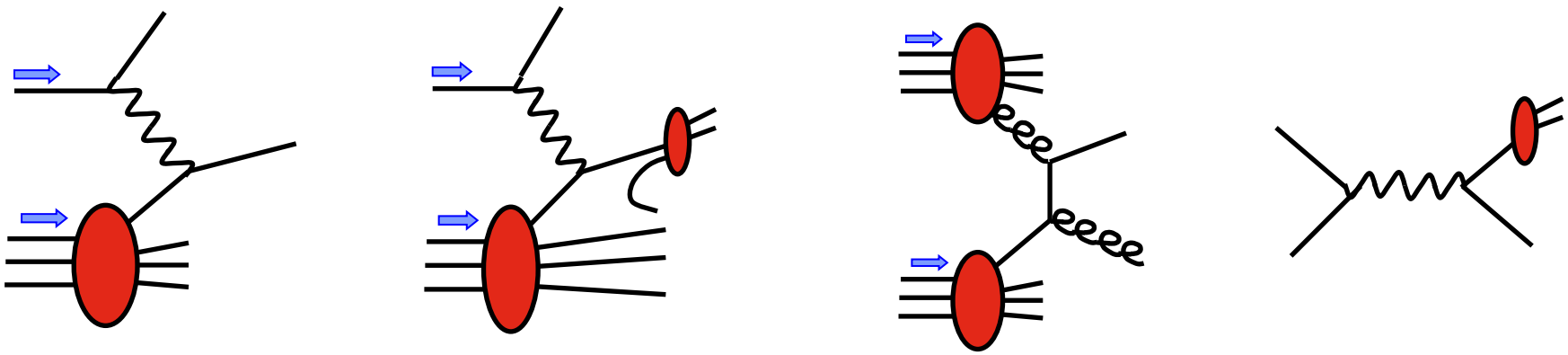
scale dependence in SIDIS at EIC:

$$Q^2 > 5\,\mathrm{GeV}^2$$

$$\frac{\sigma(\mu) - \sigma(Q)}{\sigma(Q)}$$

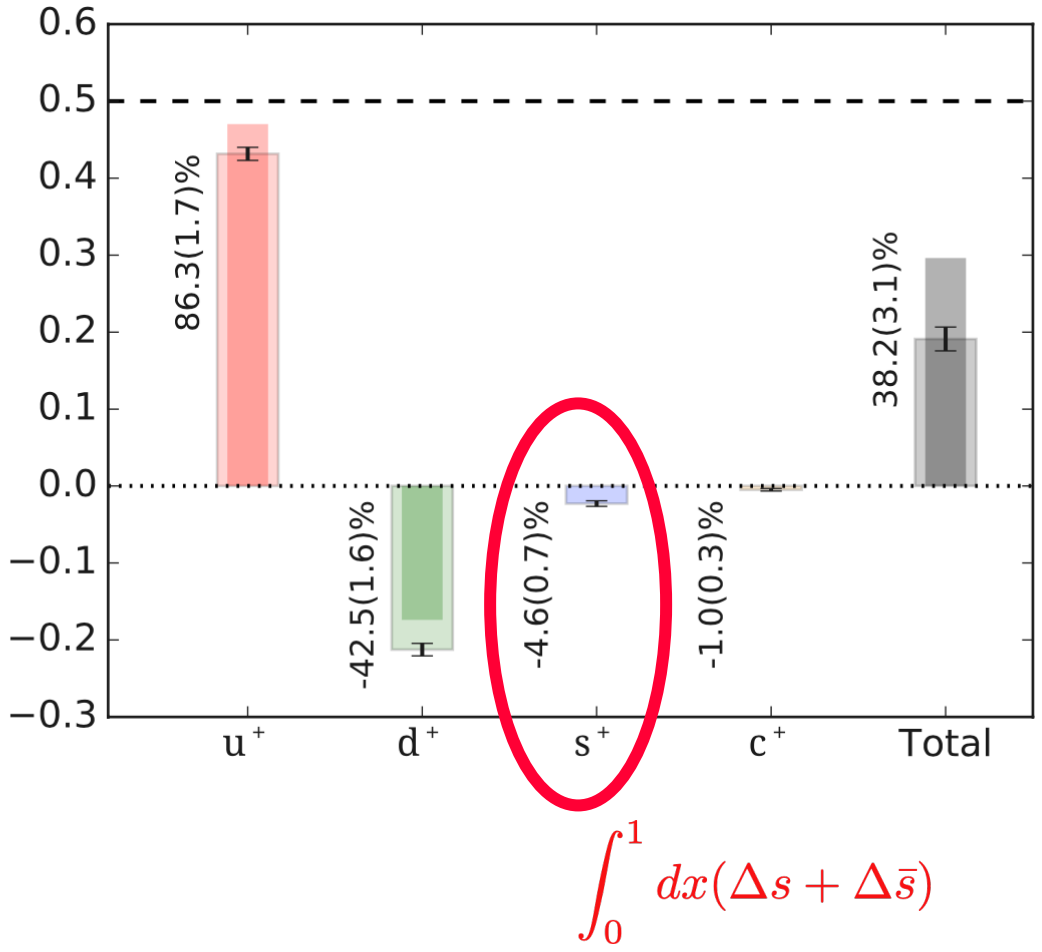
$$Q/2 \leq \mu_{R,F} \leq 2Q$$





- JAM has spearheaded efforts toward ”simultaneous global” analyses of PDFs/FFs

- synergy with lattice, for example



$$\int_0^1 dx(\Delta s + \Delta \bar{s})$$

Constantinou et al. (ETMC) 2021

Bali et al. 2012:

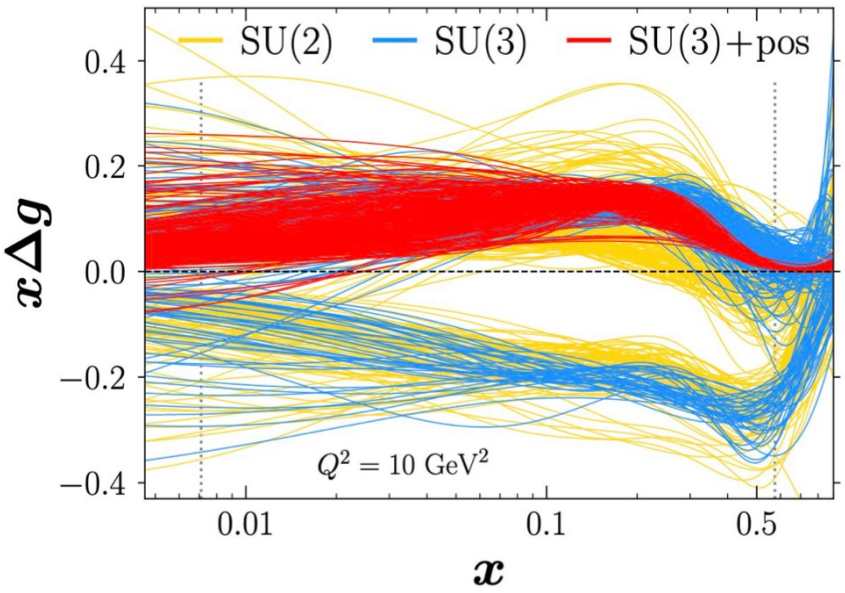
$$\int_0^1 dx(\Delta s + \Delta \bar{s}) = -0.02 \pm 0.01$$

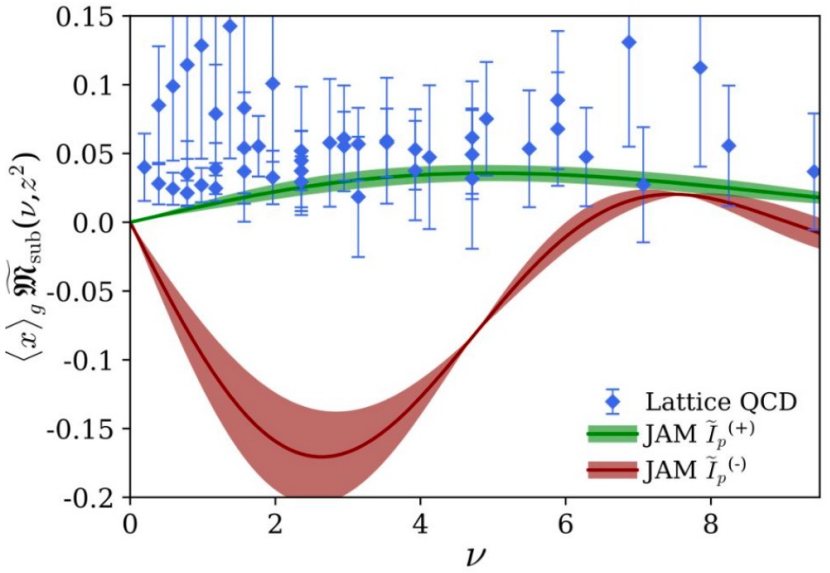
Lin et al. (PNDME) 2018:

$$\int_0^1 dx(\Delta s + \Delta \bar{s}) = -0.053 \pm 0.008$$

HadStruc collab.

Egerer et al ('22)





- emerging studies of x-dependence of pol. PDFs, and first inclusions in global analyses

Bringewatt, Sato, Melnitchouk, Qiu, Steffens, Constantinou

Concluding remarks:

- enormous progress on helicity PDFs over past ~decade

$$\int_{0.01}^{1} dx\, \Delta\Sigma(x,Q^2) = 0.43 \pm 0.08 \qquad \int_{0.01}^{1} dx\, \Delta g(x,Q^2) = 0.3 \pm 0.1 \qquad @\ 10\ \text{GeV}^2$$

- to move ahead will require to make qualitative steps forward:

  NNLO corrections & beyond
  low-x
  fully global analyses
  power corrections
  exploiting synergies with lattice

- will only be possible with strong, sustainable and diverse workforce in QCD phenomenology and global analysis, and with international collaborative efforts

CFNS workshop: EIC Theory in the next decade, Sep. 20-22, 2022, MIT
Organizers: Ian Cloët (ANL), Dmitri Kharzeev (Stony Brook University/BNL), Xiangdong Ji (University of Maryland), Peter Petreczky (BNL), Jianwei Qiu (JLab), Phiala Shanahan (MIT), Iain Stewart (MIT), Ivan Vitev (LANL), Feng Yuan (LBNL)
#participants: 65
https://indico.bnl.gov/event/16740/

Goal: review the needs and challenges for EIC theory including interdisciplinary aspects, 15 talks (5 by young faculty), 7 open mic discussion sessions

Resolution:

“We recommend the establishment of a national EIC theory alliance to enhance and broaden the theory community needed to advance EIC physics goals and the experimental program. This theory alliance will develop a diverse workforce through a competitive national EIC theory fellow program and tenure-track bridge positions, including appointments at minority serving institutions."