EIC User Group Meeting
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Flavor decomposition of collinear PDFs and FFs

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Outline

- Unravel flavor (and spin) structure of hadrons by extracting parton distribution functions and fragmentation functions using global QCD analysis with Monte Carlo-based methods

Recent highlights:

- Constraints from Fermilab & JLab data on unpolarized PDFs at high x
- First extraction of pion PDFs from Drell-Yan and HERA leading neutron production data
- First combined analysis of polarized DIS + SIDIS + SIA data, with *simultaneous* extraction of PDFs & fragmentation functions
- First MC analysis of nucleon's transversity PDFs + lattice QCD

Global PDF analysis

- Universality of PDFs allows data from different processes (DIS, SIDIS, jet production, Drell-Yan …) to be analyzed simultaneously

- Several dedicated global efforts to extract PDFs using factorization theorems + pQCD at a given order in α_s

  $\longrightarrow$ CTEQ, MRS/MMHT, HERAPDF, DSSV, …
  use standard <u>maximum likelihood</u> methods (χ^2 minimization)

  $\longrightarrow$ NNPDF, JAM
  use <u>Monte Carlo</u> methods (neural networks, nested sampling)

- Typically PDF parametrizations are nonlinear functions of PDF parameters, *e.g.* $xf(x,\mu) = Nx^{\alpha}(1-x)^{\beta}\,P(x)$ where P is a polynomial, neural net, …

  $\longrightarrow$ *multiple local minima* present in the χ^2 function

  $\longrightarrow$ thoroughly scan over sufficiently large parameter space

Bayesian approach to global analysis

- Analysis of data requires estimating expectation values E and variances V of "observables" $\mathcal{O}$ (functions of PDFs) which are functions of parameters

$$\boxed{\begin{aligned} E[\mathcal{O}] &= \int d^n a\, \mathcal{P}(\vec{a}|\text{data})\, \mathcal{O}(\vec{a}) \\ V[\mathcal{O}] &= \int d^n a\, \mathcal{P}(\vec{a}|\text{data})\, \left[\mathcal{O}(\vec{a}) - E[\mathcal{O}]\right]^2 \end{aligned}}$$

"Bayesian master formulas"

- Using Bayes' theorem, probability distribution $\mathcal{P}$ given by

$$\mathcal{P}(\vec{a}|\text{data}) = \frac{1}{Z}\, \mathcal{L}(\text{data}|\vec{a})\, \pi(\vec{a})$$

in terms of the <u>likelihood function</u> $\mathcal{L}$

Bayesian approach to global analysis

- Likelihood function

$$\mathcal{L}(\text{data}|\vec{a}) = \exp\left(-\frac{1}{2}\chi^2(\vec{a})\right)$$

is a Gaussian form in the data, with χ^2 function

$$\chi^2(\vec{a}) = \sum_i \left(\frac{\text{data}_i - \text{theory}_i(\vec{a})}{\delta(\text{data})}\right)^2$$

with priors $\pi(\vec{a})$ and "evidence" Z

$$Z = \int d^n a\, \mathcal{L}(\text{data}|\vec{a})\, \pi(\vec{a})$$

$\longrightarrow$ Z tests if $e.g.$ an n-parameter fit is statistically different from $(n+1)$-parameter fit

Bayesian approach to global analysis

- Standard method for evaluating E, V via maximum likelihood

  $\longrightarrow$ maximize probability distribution

$$\mathcal{P}(\vec{a}|\text{data}) \;\rightarrow\; \vec{a}_0$$

  $\longrightarrow$ if $\mathcal{O}$ is linear in parameters, and if probability is symmetric in all parameters

$$E[\mathcal{O}(\vec{a})] = \mathcal{O}(\vec{a}_0)\,, \quad V[\mathcal{O}(\vec{a})] \rightarrow \text{Hessian} \qquad H_{ij} = \frac{1}{2}\frac{\partial\chi^2(\vec{a})}{\partial a_i \partial a_j}\Big|_{\vec{a}=\vec{a}_0}$$

- In practice, since in general $E[f(\vec{a})] \neq f(E[\vec{a}])$, maximum likelihood method often fails

  $\longrightarrow$ need more robust (Monte Carlo) approach

$$E[\mathcal{O}] \;\approx\; \frac{1}{N}\sum_k \mathcal{O}(\vec{a}_k)\,, \qquad V[\mathcal{O}] \;\approx\; \frac{1}{N}\sum_k \left[\mathcal{O}(\vec{a}_k) - E[\mathcal{O}]\right]^2$$

Monte Carlo methods

- First group to use MC for global PDF analysis was NNPDF, using neural network to parametrize $P(x)$ in *Forte et al. (2002)*

$$f(x) = N\, x^{\alpha}(1-x)^{\beta}\, P(x)$$

— α, β are fitted "preprocessing coefficients"

- Iterative Monte Carlo (IMC), developed by JAM Collaboration, variant of NNPDF, tailored to non-neutral net parametrizations

N. Sato et al. (2016)

- Markov Chain MC (MCMC) / Hybid MC (HMC)
— recent "proof of principle" analysis, ideas from lattice QCD

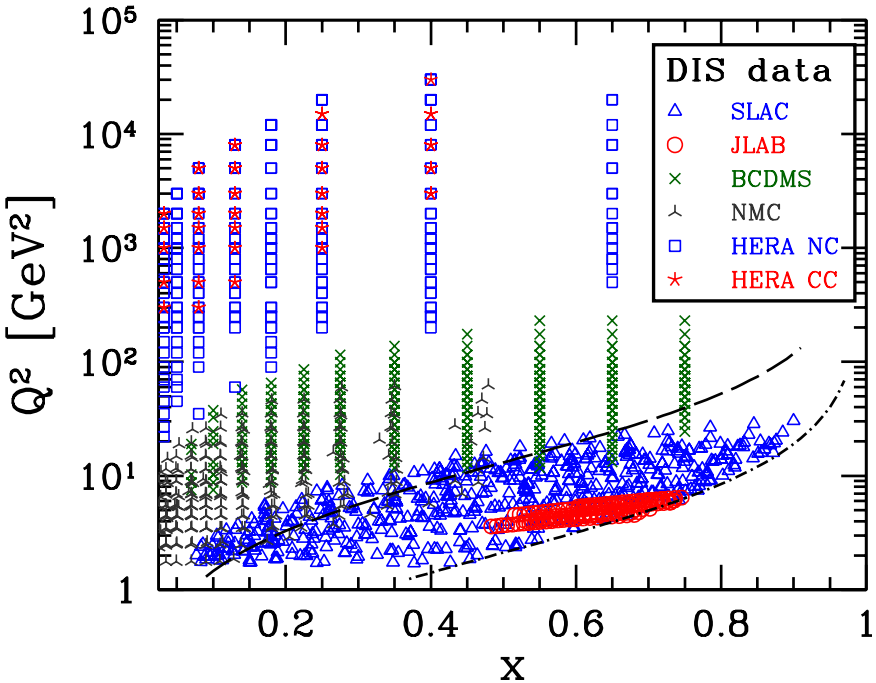
Gbedo, Mangin-Brinet (2017)

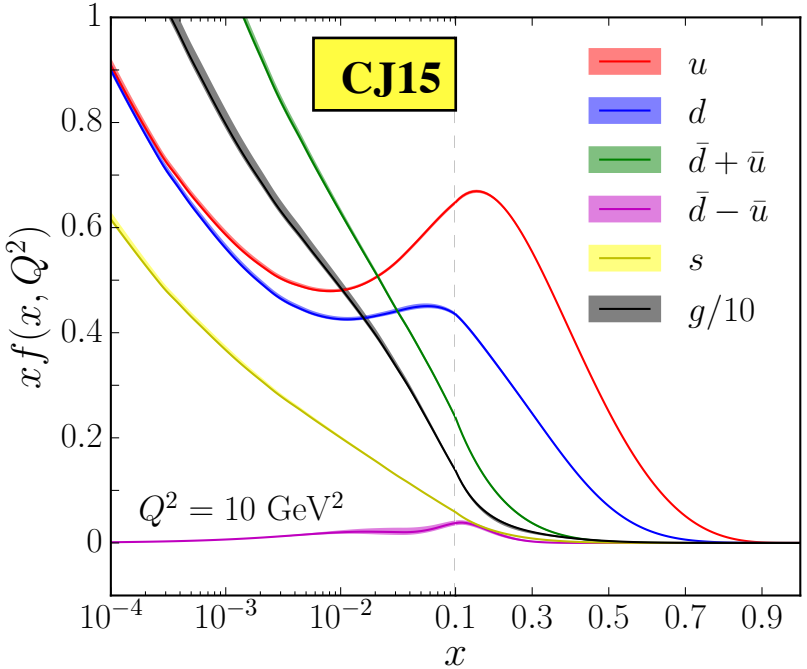
- Nested sampling (NS) — computes integrals in Bayesian master formulas (for $E,\ V,\ Z$) explicitly *Skilling (2004)*

Unpolarized Nucleon PDFs

Unpolarized PDFs

- Ubiquity of proton F_2 data (SLAC, BCDMS, NMC, HERA, JLab, ...) provides strong constraints on u-quark PDF over large x range





- Absence of free-neutron data and smaller $|e_q|$ of d quarks limit precision of d-quark PDF, especially at high x

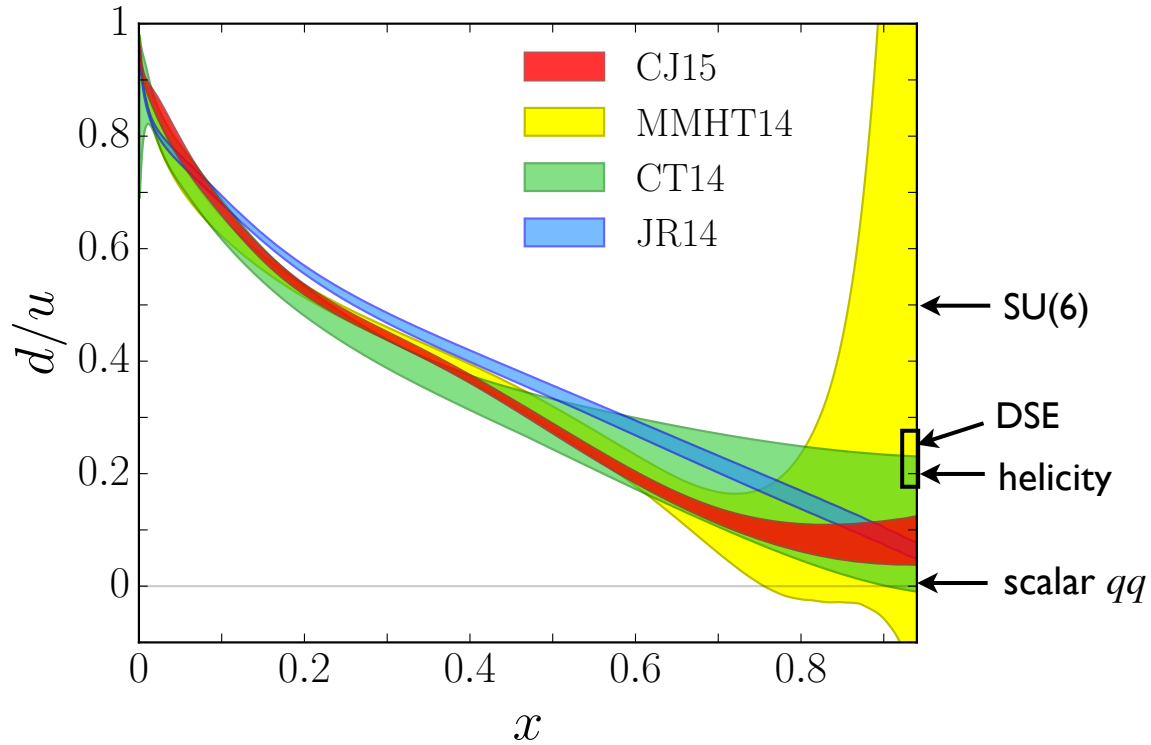
  $\longrightarrow$ nuclear effects in deuterium obscure free-neutron structure extracted from inclusive measurements

Unpolarized PDFs

- Valence d/u ratio at high x of particular interest

→ testing ground for nucleon models in $x \to 1$ limit

- $d/u \to 1/2$
  SU(6) symmetry
- $d/u \to 0$
  $S = 0$ qq dominance
  (color-hyperfine interaction)
- $d/u \to 1/5$
  $S_z = 0$ qq dominance
  (perturbative gluon exchange)
- $d/u \to 0.18 - 0.28$
  DSE with qq correlations

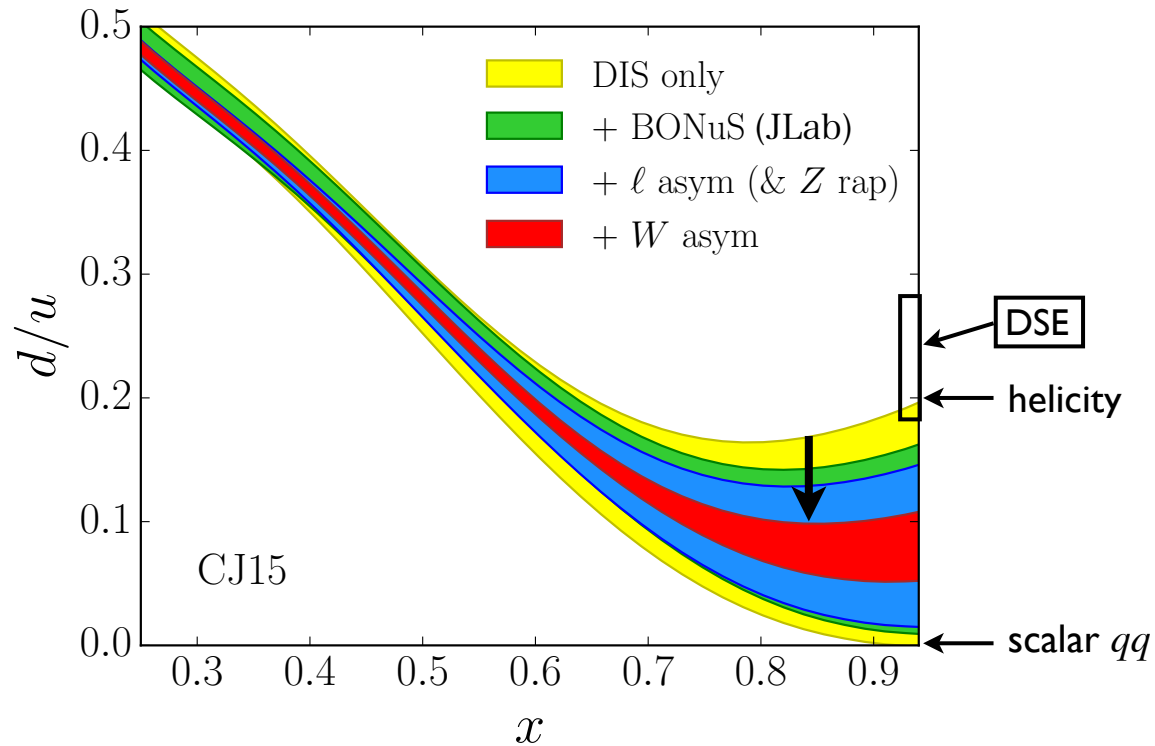


→ considerable uncertainty at high x from deuterium corrections (no free neutrons!)

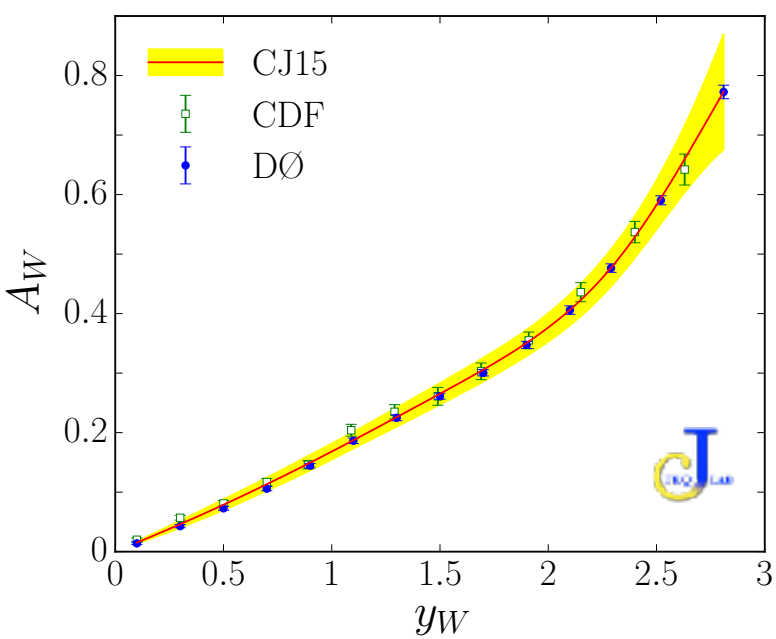
Unpolarized PDFs

- Valence d/u ratio at high x of particular interest

→ significant reduction of PDF errors with new JLab tagged neutron & FNAL W-asymmetry data



$d + \bar{u} \to W^- \to \ell^- + \bar{\nu}$



→ extrapolated ratio at $x = 1$

$$d/u \;\to\; 0.09 \pm 0.03$$

does not match any model…

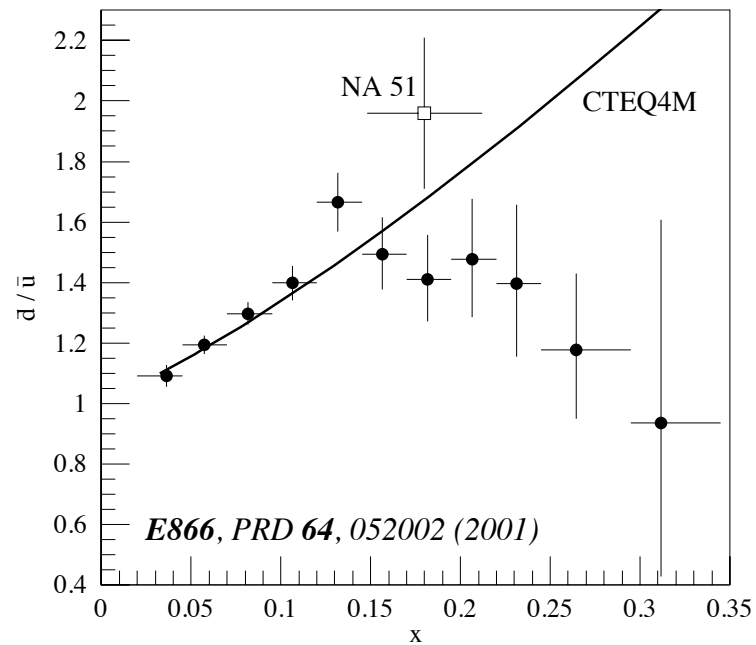
→ upcoming experiments at JLab (MARATHON, BONuS, SoLID) will determine d/u up to $x \sim 0.85$

Light quark sea

- From perturbative QCD expect $\approx$ symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs

Ross, Sachrajda (1979)

- x dependence of $\bar{d} - \bar{u}$ asymmetry established in FNAL E866 pp/pd Drell-Yan experiment



- A common explanation for flavor asymmetries in the nucleon $(\bar{d} - \bar{u},\ s - \bar{s}, \ldots)$ is meson "cloud"

Thomas (1984)

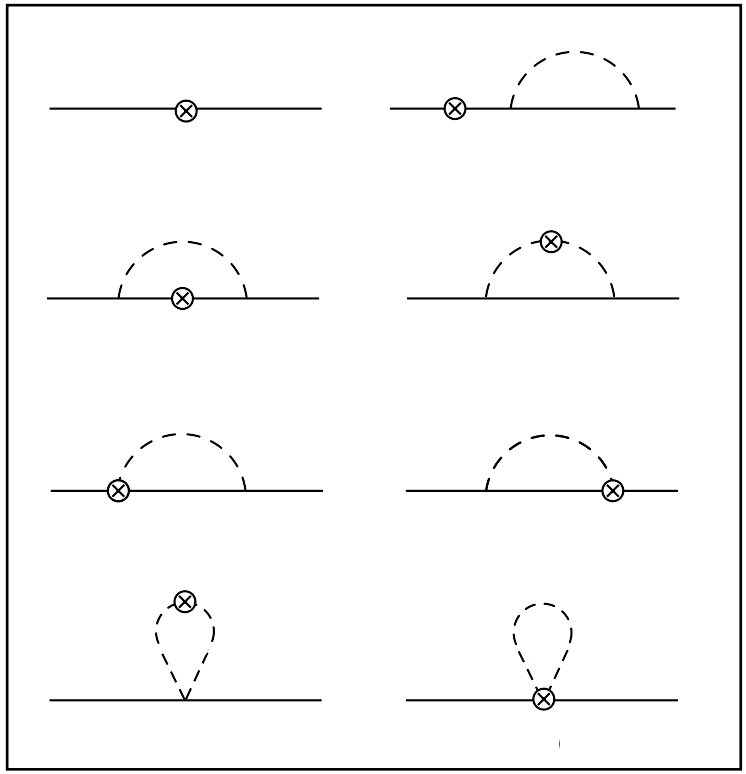
$\longrightarrow$ relatively successful phenomenology, but connection with QCD often unclear

Light quark sea

- Rigorous connection with QCD established via chiral EFT

$$\mathcal{L}_{\rm eff} = \frac{g_A}{2f_\pi}\,\bar\psi_N\gamma^\mu\gamma_5\,\vec\tau\cdot\partial_\mu\vec\pi\,\psi_N - \frac{1}{(2f_\pi)^2}\,\bar\psi_N\gamma^\mu\,\vec\tau\cdot(\vec\pi\times\partial_\mu\vec\pi)\,\psi_N + \ldots$$

- At leading order, gives rainbow, Kroll-Ruderman (for gauge invariance), and tadpole diagrams



- Matching of quark-level and hadron-level operators with same symmetries

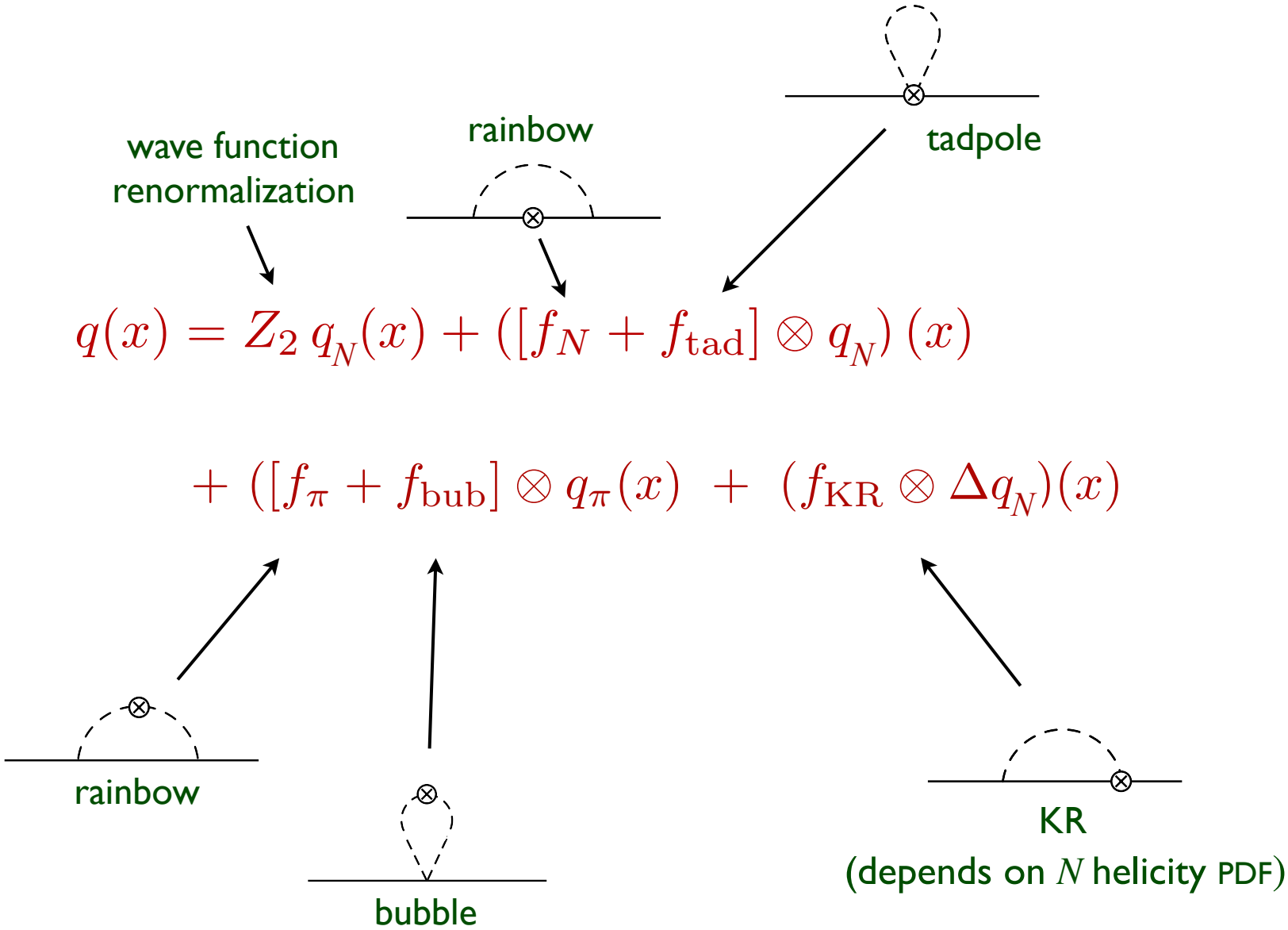
$$\mathcal{O}_q^{\mu_1\cdots\mu_n} = \sum_h c_{q/h}^{(n)}\,\mathcal{O}_h^{\mu_1\cdots\mu_n}$$

→ yields convolution representation for PDFs

$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\,f_h(y)\,q_v^h(x/y)$$

Light quark sea

- More specifically, contributions to quark PDF from different diagrams can be organized as:



$$q(x) = Z_2\, q_N(x) + ([f_N + f_{\rm tad}] \otimes q_N)\,(x)$$

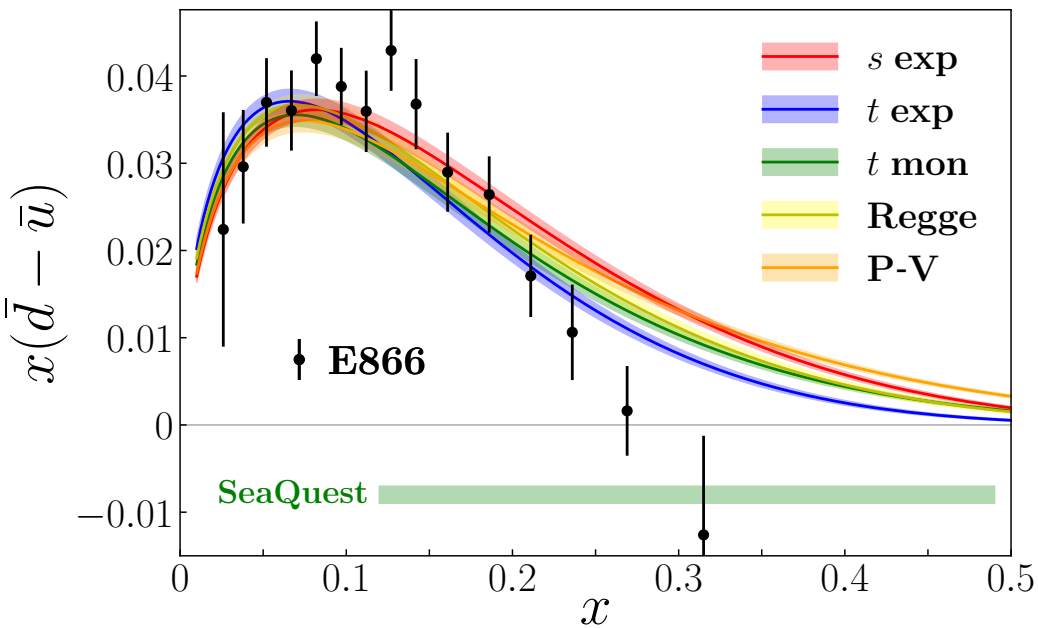
$$+\ ([f_\pi + f_{\rm bub}] \otimes q_\pi(x)\ +\ (f_{\rm KR} \otimes \Delta q_N)(x)$$

Ji, WM, Thomas (2015)

Light quark sea

- E866 $\bar{d} - \bar{u}$ data can be well described within chiral EFT framework

$$\bar{d} - \bar{u} = \left[f_\pi^{(\mathrm{rbw})} + f_\pi^{(\mathrm{bub})} \right] \otimes \bar{q}_v^\pi$$

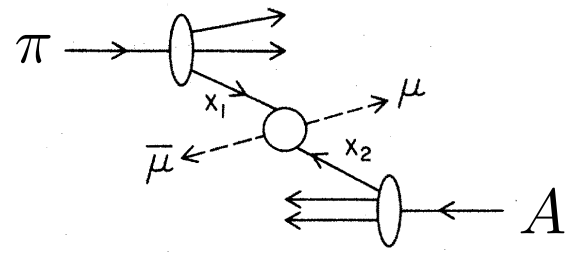


Barry, Sato, WM, C.-R. Ji (2018)

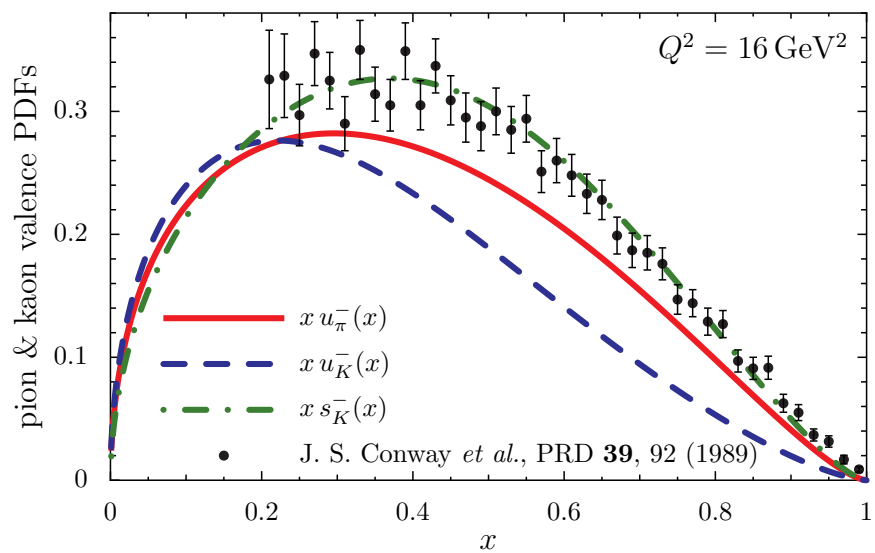
→ depends also on pion PDF … which can be fit simultaneously!

PDFs in the pion

- Most information on pion PDFs has come from pion-nucleus Drell-Yan data (CERN, Fermilab)



→ constrains valence PDFs at $x \gg 0$ (uncertainty from gluon resummation)

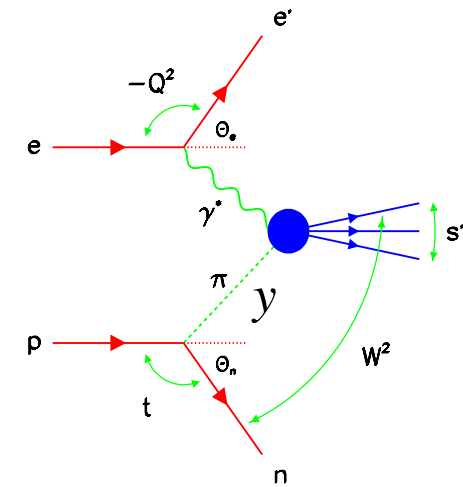


Hutauruk, Cloet, Thomas (2016)

→ pion sea quark & gluon PDFs at small x mostly unconstrained

PDFs in the pion

- Recent new (Monte Carlo-based) global analysis used chiral effective field theory to include also leading neutron electroproduction from HERA

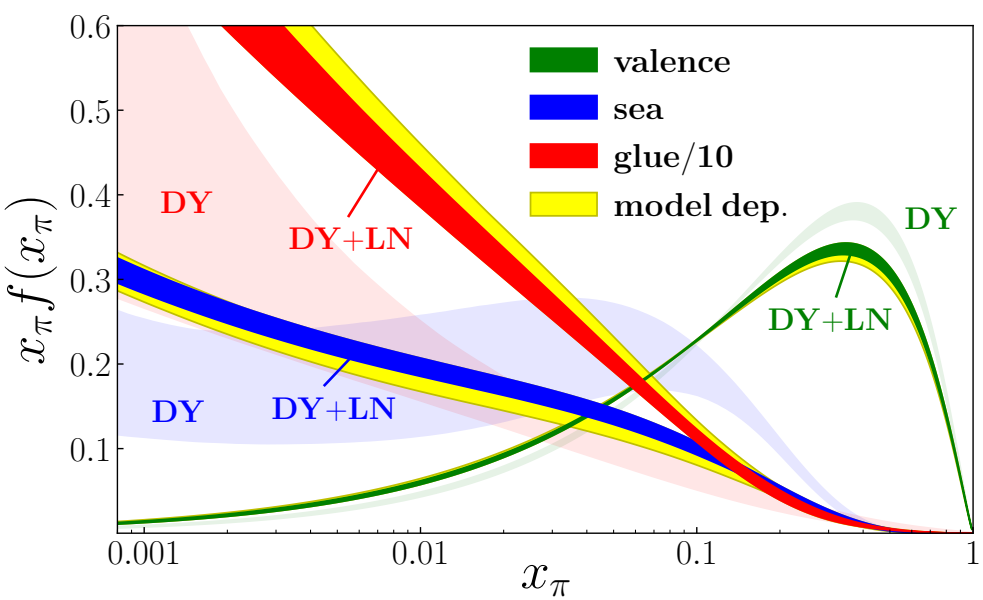


$$\frac{d^3\sigma^{\rm LN}}{dx\,dQ^2\,dy} \sim 2 f_{\pi/N}(y)\, F_2^{\pi}(x_\pi, Q^2)$$

$N \to N + \pi$
splitting function
(computed from χEFT)

pion structure function

$x_\pi = x/y$

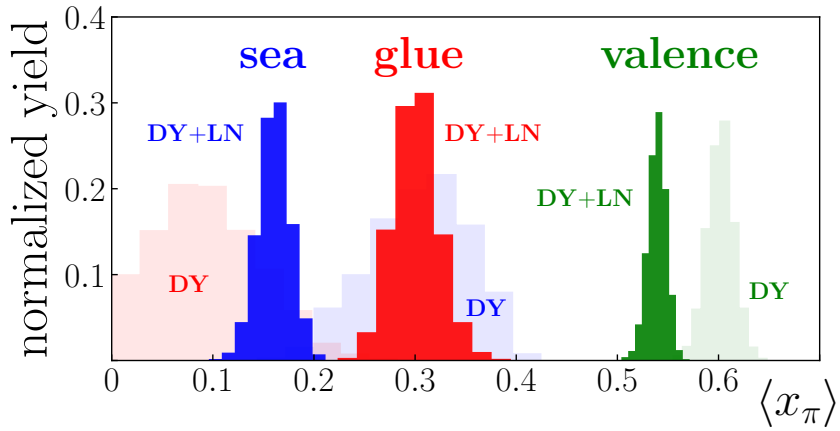


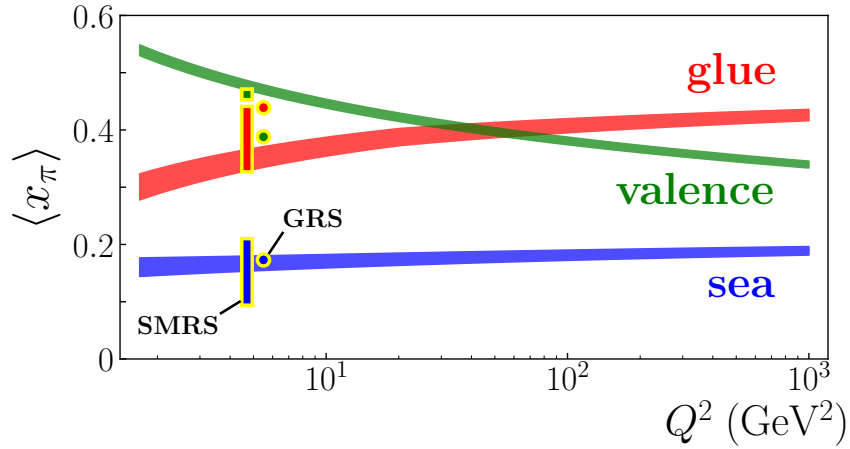
Barry, Sato, WM, C.-R. Ji (2018)

→ first constraints on pion PDFs at low x

PDFs in the pion

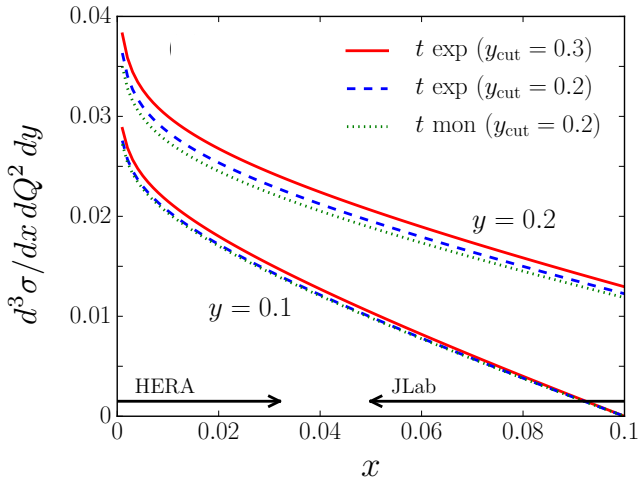
- Larger gluon fraction in the pion than without LN constraint

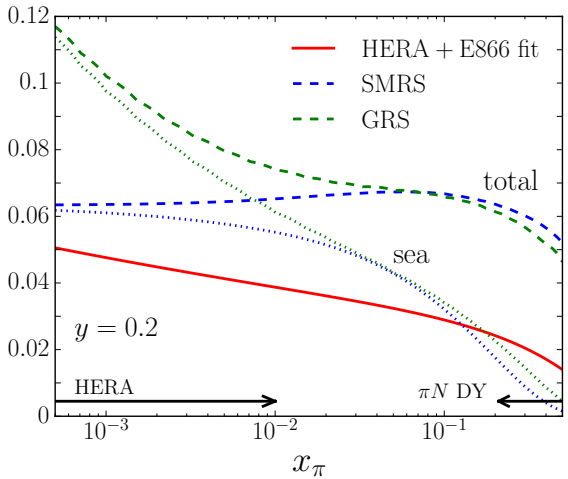




Barry, Sato, WM, C.-R. Ji (2018)

- Tagged DIS experiment at JLab $(e\,n \to e'\,p\,X)$ will probe pion structure at intermediate x values (between DY and LN)





→ extension to hyperon final state could probe kaon structure

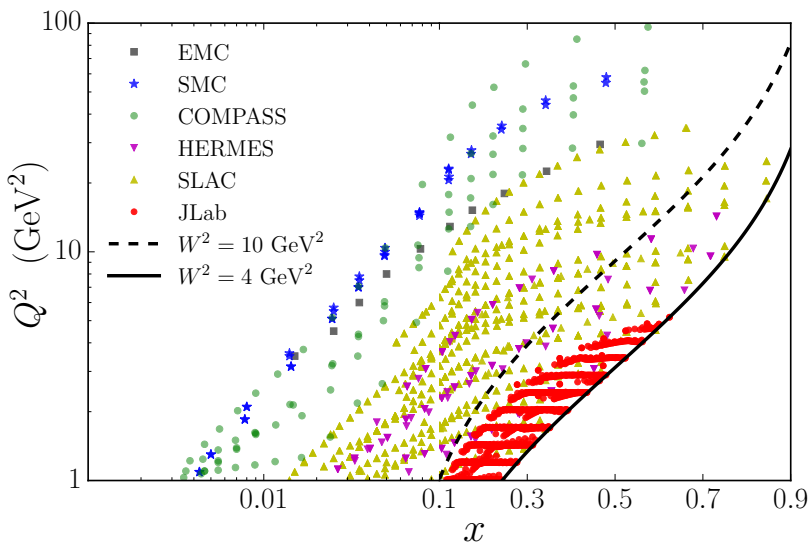
→ LN (p beam) and LP (d beam) at EIC!

Nucleon Helicity PDFs

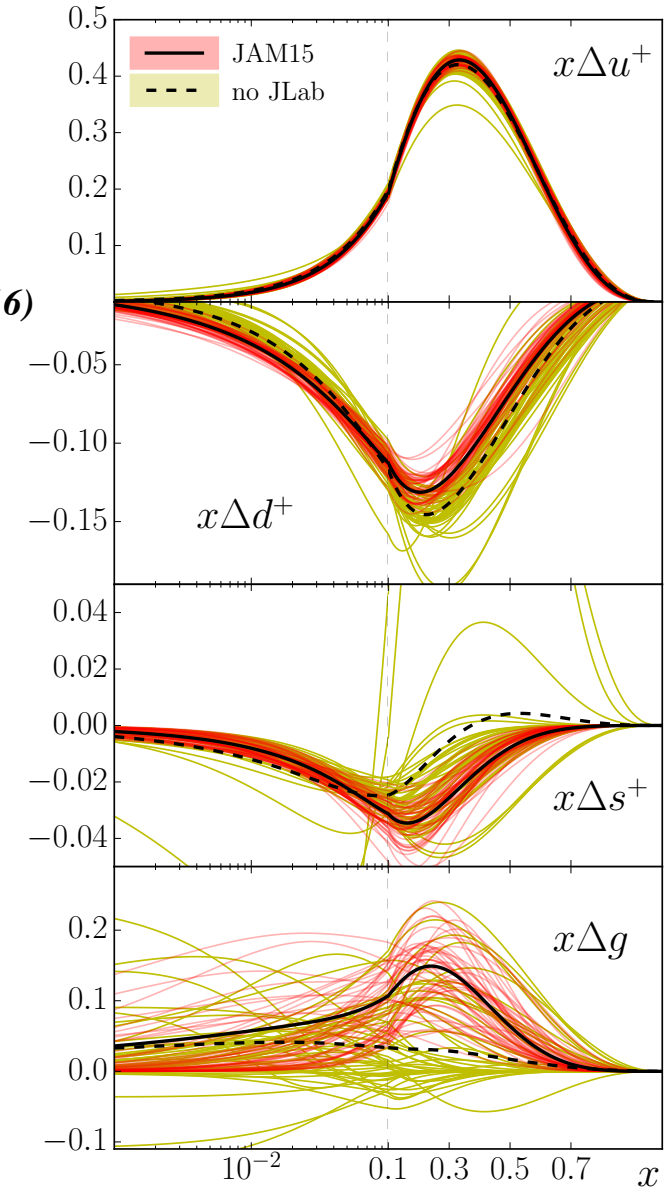
Proton spin structure

- Question of how proton spin decomposed into its q & g constituents has engrossed community for > 30 years

→ stimulated advances in theory, experiment & analysis



Sato et al (2016)



→ inclusion of JLab data increases # data points by factor ~ 2

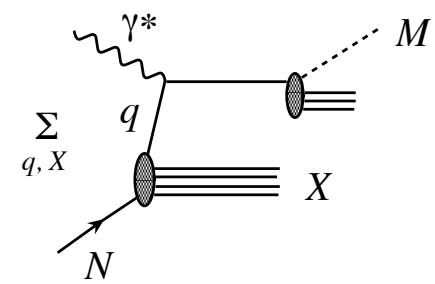
→ s-quark polarization *negative* from inclusive DIS data (assuming SU(3) symmetry)

Polarization of quark sea?

- Inclusive DIS data cannot distinguish between q and $\bar{q}$

  → semi-inclusive DIS sensitive to Δq & $\Delta\bar{q}$

$$\sim \sum_q e_q^2 \left[\Delta q(x)\, D_q^h(z) + \Delta\bar{q}(x)\, D_{\bar{q}}^h(z)\right]$$



$$z = \frac{E_M}{E_{\gamma^*}}$$

  → but need fragmentation functions!

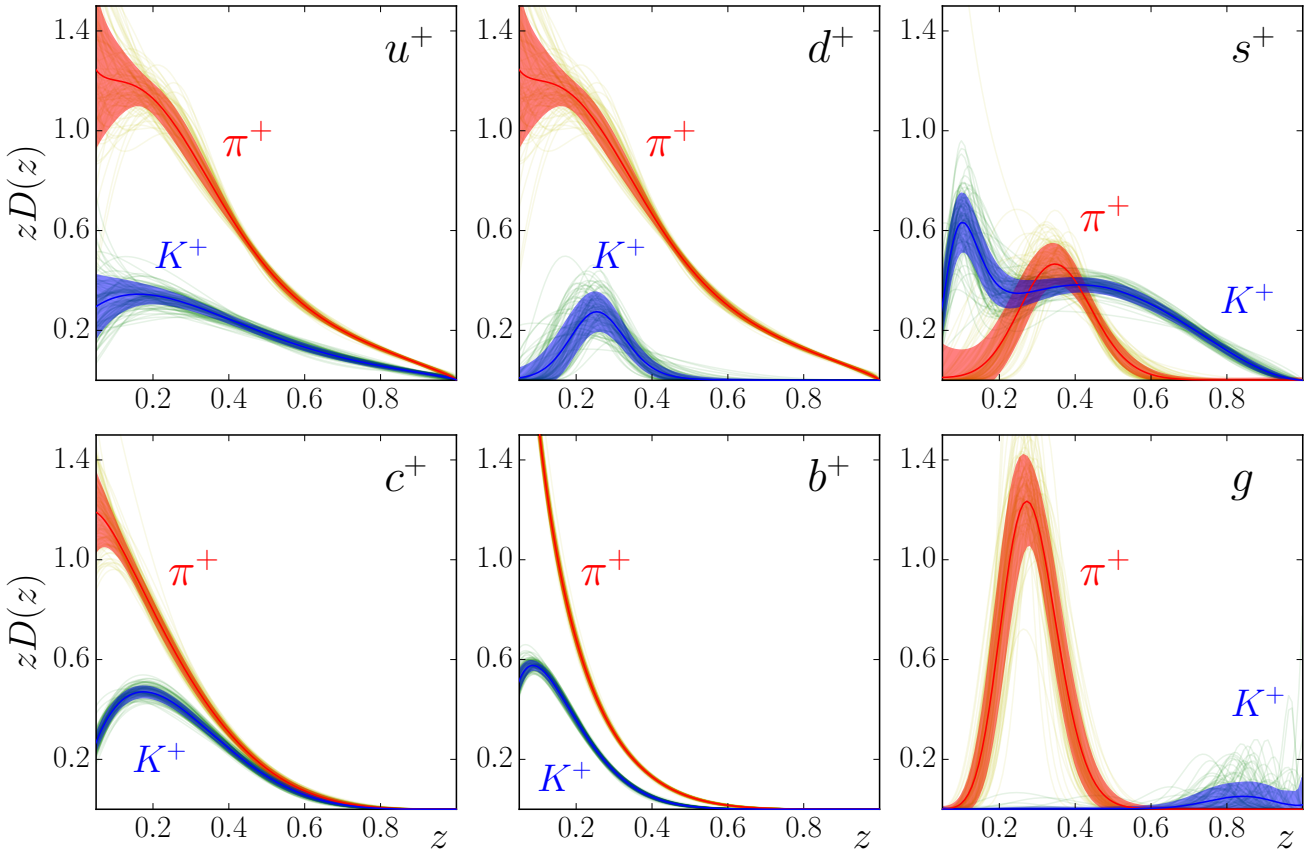
- Global analysis of DIS + SIDIS data gives different *sign* for strange quark polarization for different fragmentation functions!

  → $\Delta s > 0$ for "DSS" FFs *de Florian et al. (2007)*

  $\Delta s < 0$ for "HKNS" FFs *Hirai et al. (2007)*

  → need to understand origin of differences in fragmentation!

MC analysis of fragmentation functions



$$e^+e^- \to h\,X$$

single-inclusive annihilation (SIA)

Sato, Ethier, WM, Hirai, Kumano, Accardi (2016)

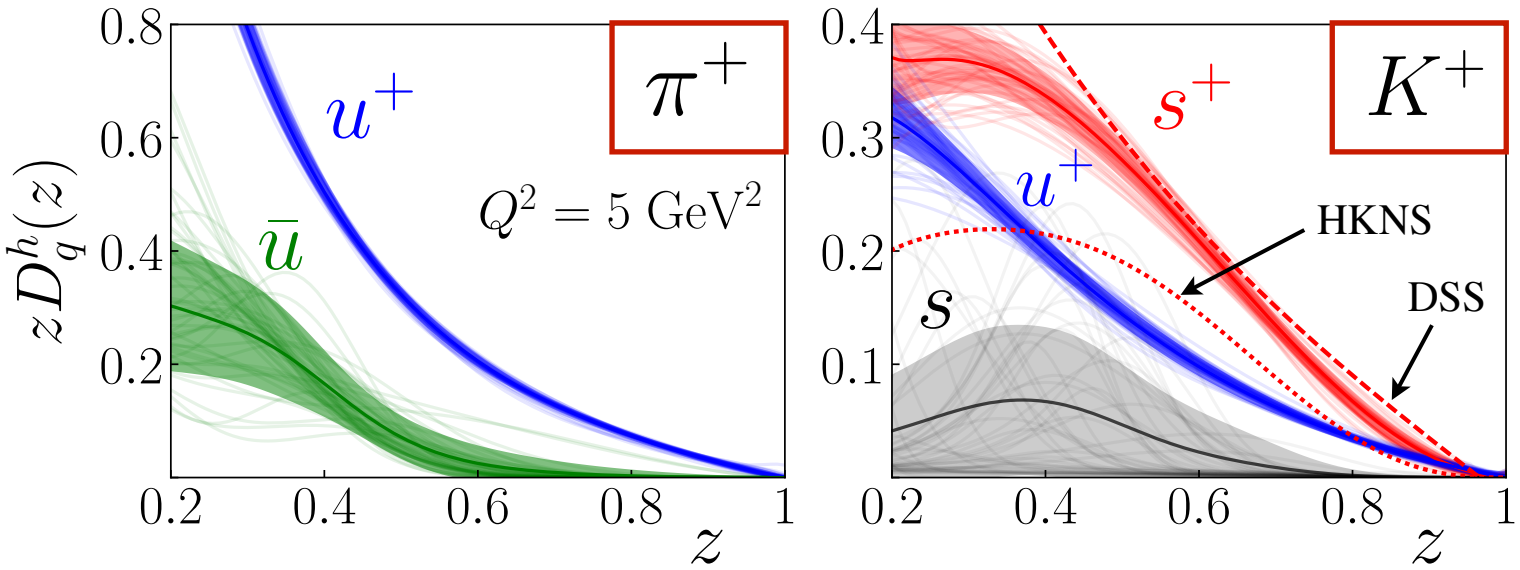
→ favored FFs well constrained; unfavored not as well…

→ nontrivial shape of $s \to K$ fragmentation

→ hard $g \to K$ fragmentation? (robust feature!)

MC analysis of fragmentation functions

- Fragmentation functions from SIA and (polarized) SIDIS



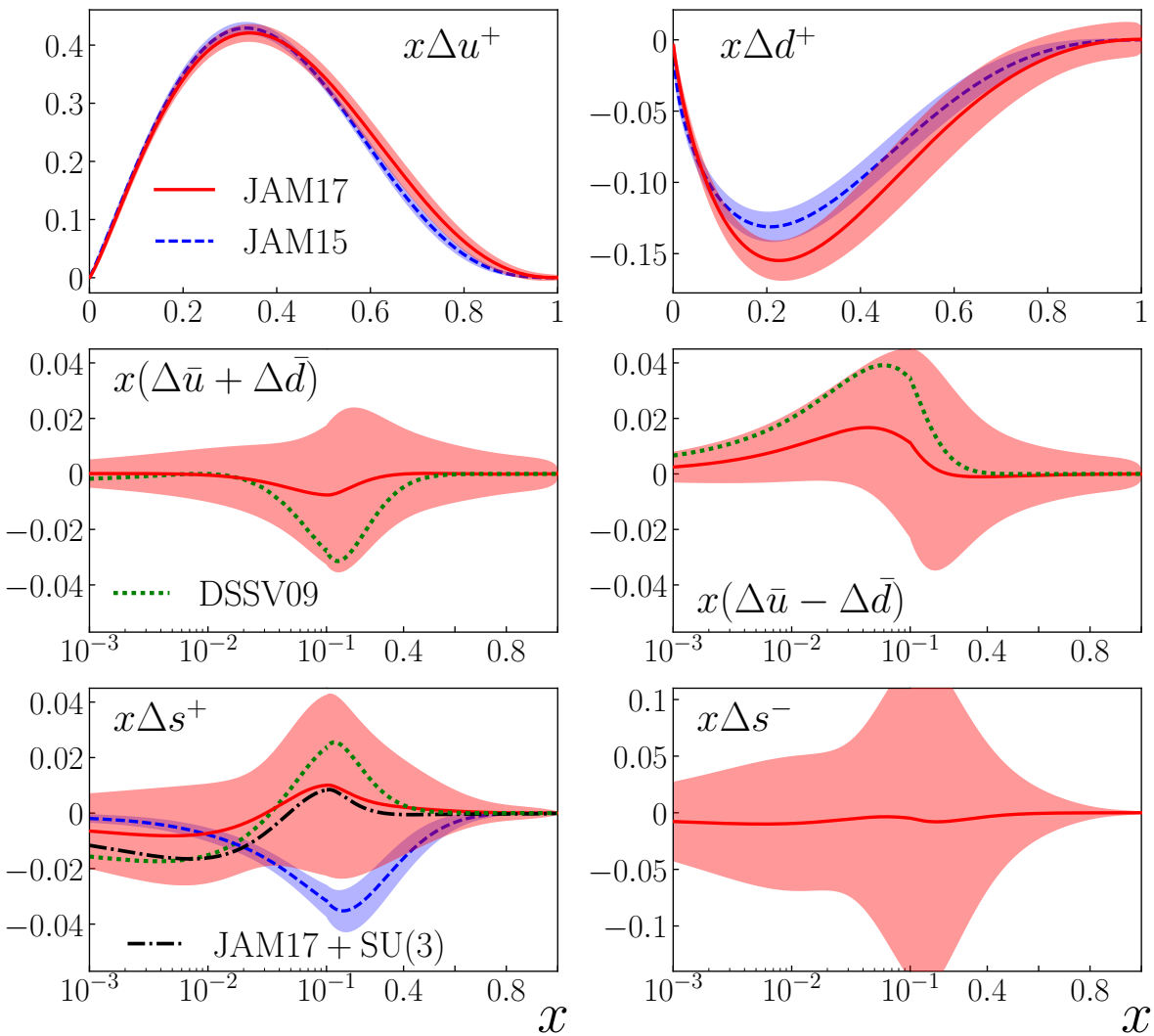
Ethier, Sato, WM (2017)

→ some constraint from SIDIS on unfavored FFs ($e.g.\ \ s \to K^+$), but uncertainties still large

→ new result more consistent with DSS at moderate z

Simultaneous analysis

- Simultaneous determination of spin PDFs and FFs, fitting to DIS, SIA and polarized SIDIS (HERMES, COMPASS) data



→ no assumption of SU(3) symmetry

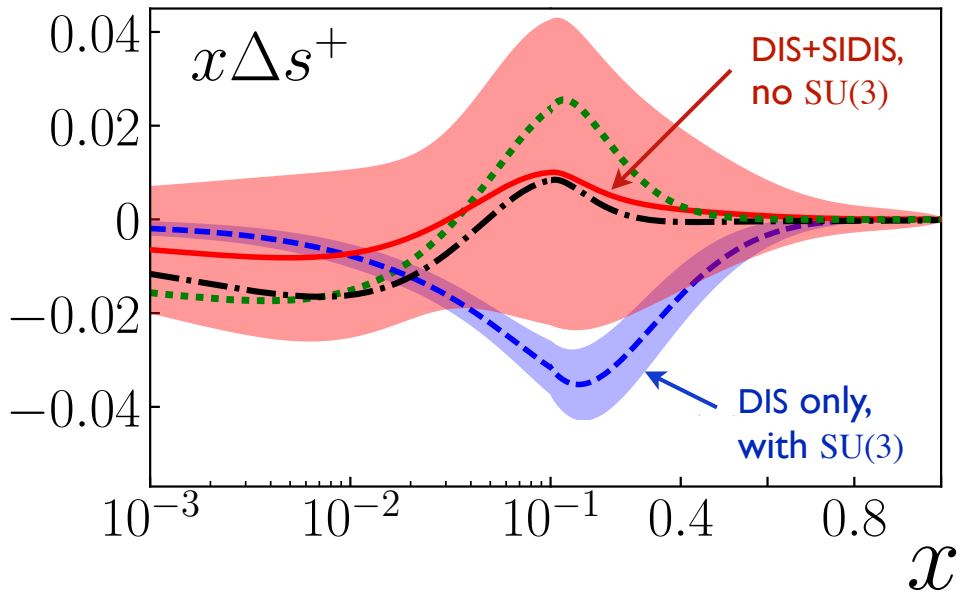
→ Δs slightly > 0 at high x, consistent with zero

→ $\Delta s - \Delta\bar{s}$ & $\Delta\bar{u} - \Delta\bar{d}$ consistent with zero

Ethier, Sato, WM (2017)

Simultaneous analysis

- Polarized strangeness in previous, DIS-only analyses was negative at $x \sim 0.1$, induced by $\mathrm{SU}(3)$ and parametrization bias



Ethier, Sato, WM (2017)

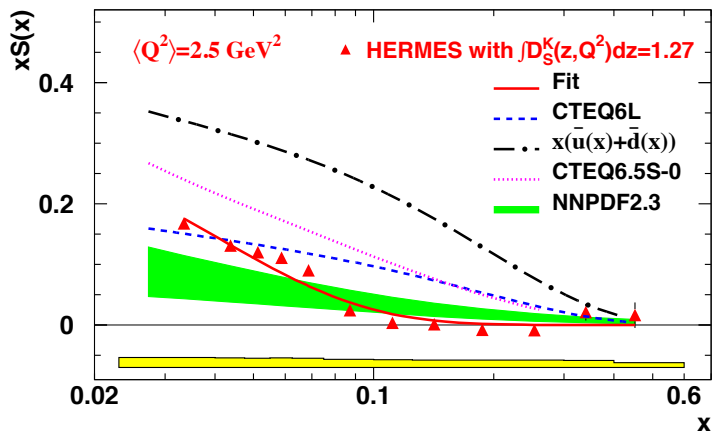
→ weak sensitivity to Δs^+ from DIS data & evolution
— $\mathrm{SU}(3)$ pulls Δs^+ to generate moment ~ -0.1
— negative peak at $x \sim 0.1$ induced by fixing $b \sim 6 - 8$

→ less negative $\boxed{\Delta s = -0.03(10)}$ gives larger total helicity $\Delta\Sigma = 0.36(9)$

Simultaneous analysis

- Simultaneous analysis of DIS (unpolarized + polarized), SIDIS (unpolarized + polarized), SIA under way

→ minimize uncertainty from unpolarized s & $\bar{s}$ PDFs



Andres, Ethier, Sato, WM (2018)

→ indication of $s - \bar{s}$ asymmetry from neutrino DIS data

$$S^- = \int_0^1 dx\, x(s - \bar{s}) = (2.0 \pm 1.4) \times 10^{-3}$$

NuTeV (2007)

→ from chiral SU(3) loops

$$S^- = (0.4 - 1.1) \times 10^{-3}$$

Salamu, C. Ji, WM, Thomas, Wang (2018)

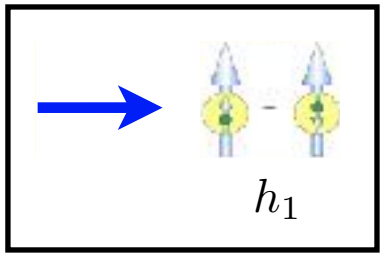
Nucleon Transversity PDFs

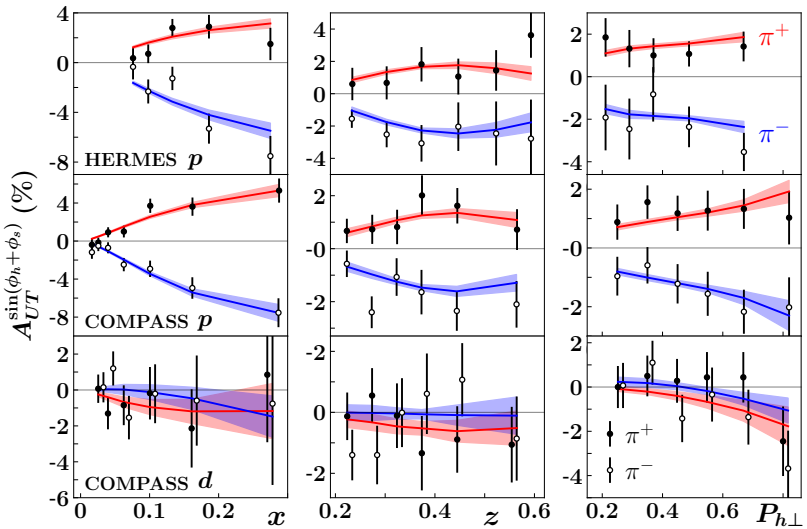
Transversity distributions

- Extraction of transversity (TMD) PDF from SIDIS data
  + isovector moment $g_T = \int dx\,(h_1^u - h_1^d)$ from lattice QCD

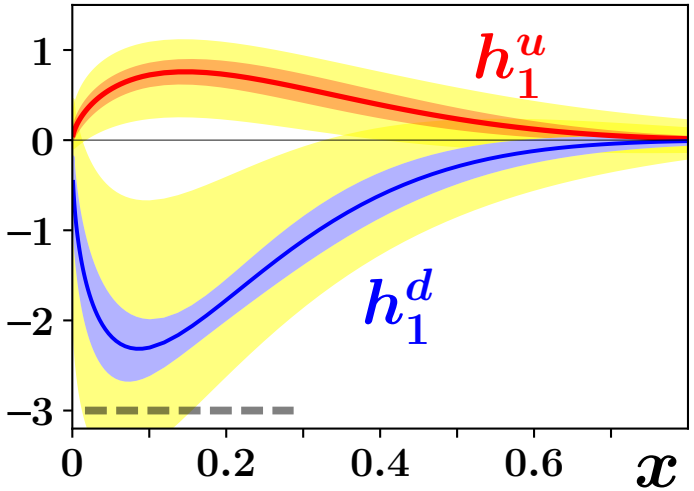
→ Collins asymmetry

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto \frac{h_1 \otimes H_1^\perp}{f_1 \otimes D_1}$$





$g_T^{\rm latt} = 1.01(6)$

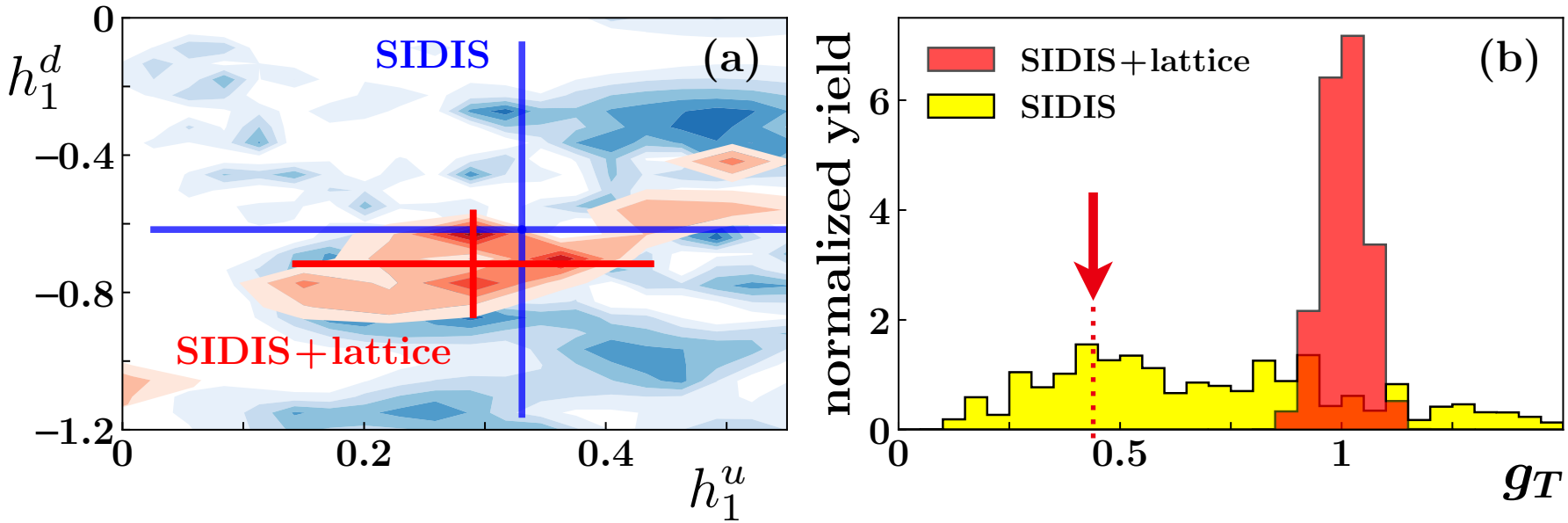


Lin, WM, Prokudin, Sato, Shows (2018)

→ significantly reduced uncertainties with lattice constraint

Transversity distributions

- Extraction of transversity (TMD) PDF from SIDIS data
  + isovector moment $g_T = \int dx\,(h_1^u - h_1^d)$ from lattice QCD



Lin, WM, Prokudin, Sato, Shows (2018)

→ distributions do not look very Gaussian!

→ MC analysis gives $g_T = 1.0 \pm 0.1$

→ maximum likelihood analysis would have given $g_T \approx 0.5$

Outlook

- New paradigm in global analysis — *simultaneous* determination of collinear distributions using MC sampling of parameter space

  ⟶ providing new & more reliable insights into quark/gluon structure of hadrons

- *Short-term*: "universal" QCD analysis of all observables sensitive to collinear (unpolarized & polarized) PDFs and FFs

- *Longer-term*: application to global analysis of transverse momentum dependent (TMD) distributions to map out full 3-d image of hadrons