*Hall C Collaboration Meeting, Jefferson Lab*
*January 29, 2020*

# Parton distribution functions at Jefferson Lab

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— Jefferson Lab —

**JLab Angular Momentum (JAM) Collaboration** https://www.jlab.org/jam

**CTEQ-Jefferson Lab (CJ) Collaboration** https://www.jlab.org/cj

# Overview

- Introduction to parton distribution functions (PDFs)

- Methodology of global QCD analysis
  — maximum likelihood *vs*. Monte Carlo sampling

- Historical focus at JLab
  — large-$x$ PDFs, DIS-resonance transition ("CJ15")

- Current analyses focus on simultaneous extraction of unpolarized and polarized PDFs & fragmentation functions using Bayesian MC methods ("JAM19" …)
  — impact of SIDIS data on strange quark PDF
  — simultaneous analysis of polarized & unpolarized PDFs
  — combined analysis of experiment + lattice QCD data
  — MC analysis of pion PDFs

# Parton distributions in hadrons

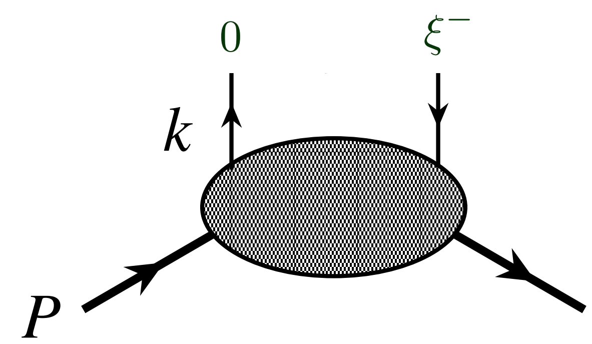
- Parton distribution functions (PDFs) are light-cone correlation functions

$$q(x) = \int_{-\infty}^{\infty} d\xi^- e^{-ixP^+\xi^-} \langle P | \overline{\psi}(\xi^-) \gamma^+ \mathcal{W}(\xi^-, 0) \psi(0) | P \rangle$$

$\longrightarrow$ light cone momentum fraction $x = \dfrac{k^+}{P^+}$

$\longrightarrow$ Wilson line (gauge invariance)

$$\mathcal{W}(\xi^-, 0) = \exp\left\{ -ig \int_0^{\xi^-} d\eta^- \mathcal{A}^+(\eta^-) \right\}$$




- In $\mathcal{A}^+ = 0$ gauge, in fast-moving frame PDF has a probabilistic interpretation as a particle density

$$\int_{-1}^{1} dx\, q(x) \;=\; \langle P | \overline{\psi}(0) \gamma^+ \psi(0) | P \rangle \;\approx\; \langle P | \psi^\dagger(0) \psi(0) | P \rangle$$

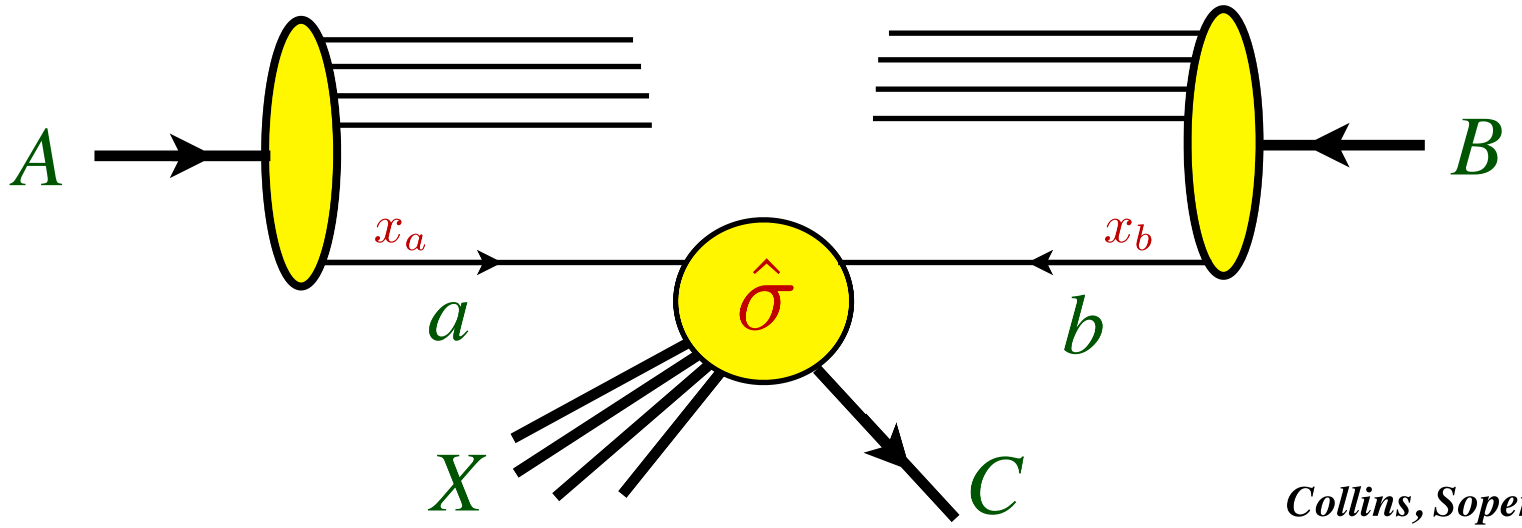
number density

$\overline{\psi} \gamma^0 \psi \approx \overline{\psi} \gamma^z \psi$

number operator

# Parton distributions in hadrons

- Inclusive high-energy particle production $A\,B \to C\,X$




*Collins, Soper, Sterman (1980s)*

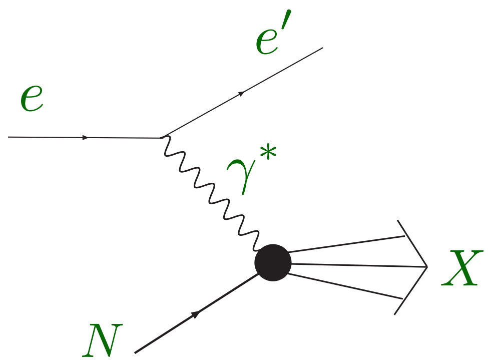
$\longrightarrow$ QCD factorization: separation of hard (perturbative, calculable) from soft (nonperturbative, parametrized) physics

$$\sigma_{AB\to CX}(p_A,p_B) = \sum_{a,b}\int dx_a\, dx_b\, f_{a/A}(x_a,\mu)\, f_{b/B}(x_b,\mu) \times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}\,(x_a p_A, x_b p_B, Q/\mu)$$

$\longrightarrow$ process-independent parton distribution functions $f_{a/A}$ characterizing structure of bound state $A$

# Parton distributions in hadrons

- Most information on PDFs obtained from lepton-hadron deep-inelastic scattering (DIS)



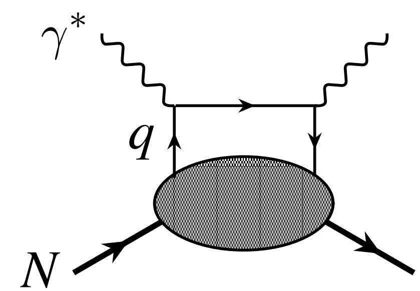

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$x_B = \frac{Q^2}{2M\nu} \qquad \begin{aligned} Q^2 &= \vec{q}^{\,2} - \nu^2 \\ \nu &= E - E' \end{aligned}$$

$\longrightarrow$ structure function given as convolution of hard Wilson coefficient with PDF

$$F_2(x_B, Q^2) = x_B \sum_q e_q^2 \int_{x_B}^1 \frac{dx}{x} C_q\left(\frac{x_B}{x}, \alpha_s\right) q(x, Q^2)$$

$$\longrightarrow x_B \sum_q e_q^2\, q(x_B, Q^2)$$



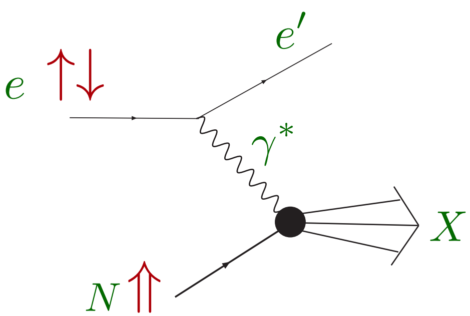

for leading order approximation $C_q \longrightarrow \delta\left(1 - \frac{x_B}{x}\right)$

# Parton distributions in hadrons

- Spin-dependent PDFs are defined similarly

$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$
$$= \int_{-\infty}^{\infty} d\xi^- e^{-ixP^+\xi^-} \langle P \,|\, \overline{\psi}(\xi^-)\, \gamma^+\gamma_5\, \mathcal{W}(\xi^-,0)\, \psi(0) \,|\, P \rangle$$

$\longrightarrow$ measured in polarized lepton-nucleon DIS




$$A_{\parallel} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} = D\,(A_1 + \eta\, A_2)$$

$$A_1 \approx \frac{2x_B\, g_1(x_B, Q^2)}{F_2(x_B, Q^2)}$$

$\longrightarrow$ polarized structure function in terms of spin-dependent PDFs

$$g_1(x_B, Q^2) = \frac{1}{2} \sum_q e_q^2 \int_{x_B}^{1} \frac{dx}{x}\, \Delta C_q\left(\frac{x_B}{x}, \alpha_s\right) \Delta q(x, Q^2)$$

$$\rightarrow \frac{1}{2} \sum_q e_q^2\, \Delta q(x_B, Q^2)$$ at leading order

# Global QCD analysis

- Universality of PDFs allows data from many different processes (DIS, SIDIS, weak boson/jet production in $pp$, Drell-Yan $\ldots$) to be analyzed simultaneously

$\longrightarrow$ $\ell\, N \to \ell'\, X$ $$d\sigma^{\rm DIS} \sim \sum_q e_q^2\, q(x)$$

$\longrightarrow$ $\ell\, N \to \ell'\, h\, X$ $$d\sigma^{\rm SIDIS} \sim \sum_q e_q^2\, q(x)\, D_q^h(z)$$

$\longrightarrow$ $\ell\, \bar{\ell} \to h\, X$ $$d\sigma^{\rm SIA} \sim \sum_q e_q^2\, D_q^h(z)$$

- Extraction of PDFs is challenging because usually there exist multiple solutions — "inverse problem"

$\longrightarrow$ PDFs are not directly measured, but inferred from observables involving convolutions with other functions

# Global QCD analysis

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

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

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

"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 likelihood function $\mathcal{L}$ and priors $\pi$

# Global QCD analysis

- Likelihood function

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

is a Gaussian form in the data, with $\chi^2$ function

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

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

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

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

# Global QCD analysis

- Standard method for evaluating $E, V$ via maximum likelihood

$\longrightarrow$ maximize probability distribution

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

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

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

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

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

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

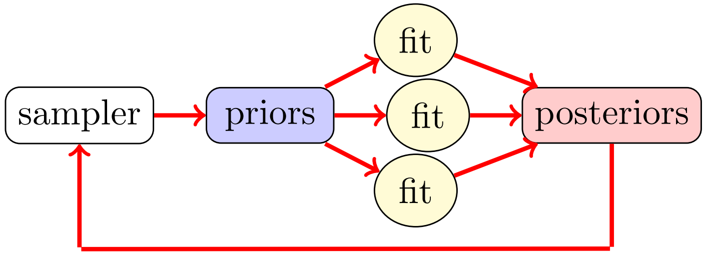
# Global QCD analysis

- JAM — iterative, multi-step Monte Carlo

→ traditional functional form for distributions

polynomial, neural net, …

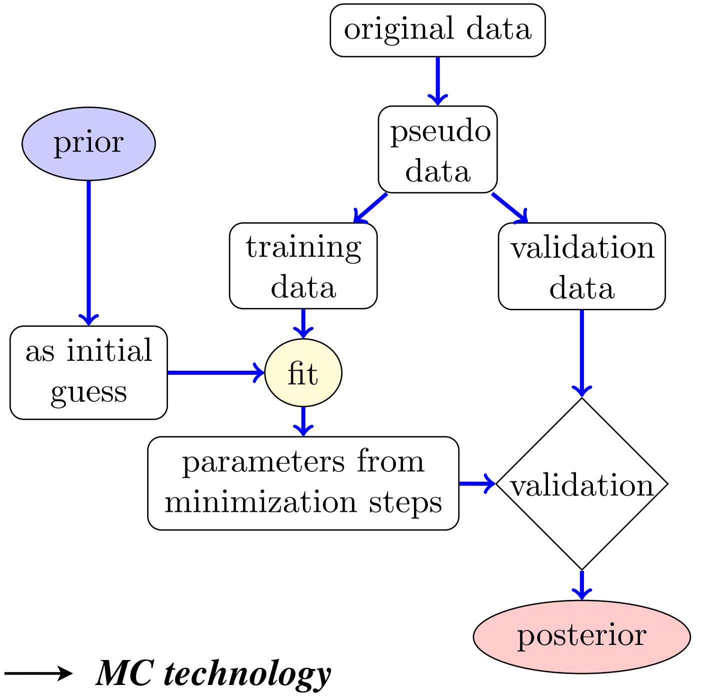
$$f(x) = N\, x^{\alpha}(1-x)^{\beta}\, P(x)$$




but sample large parameter space

→ iterate until convergence
(posteriors = priors)

→ robust determination of
PDF uncertainties




→ ***MC technology developed by Nobuo Sato***

# Spin-averaged nucleon PDFs

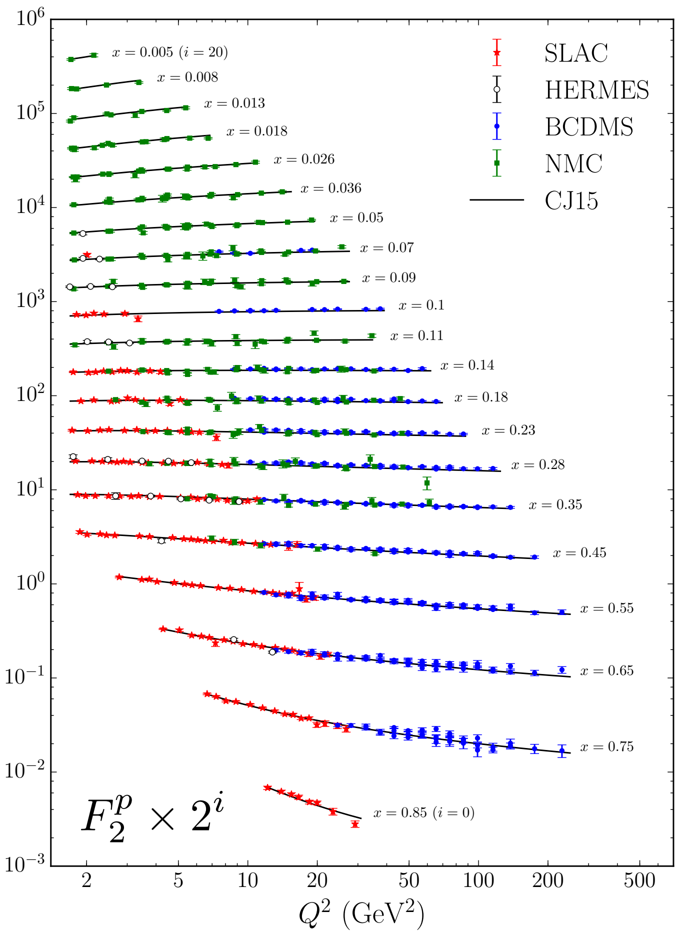
- Collaboration between JLab and CTEQ started $\sim 2008$ with initiative from Thia Keppel & Tony Thomas to fund postdoc position ( $\longrightarrow$ Alberto Accardi ) to analyze impact of JLab data on global QCD analysis — using established fitting technology ( $\longrightarrow$ Jeff Owens)

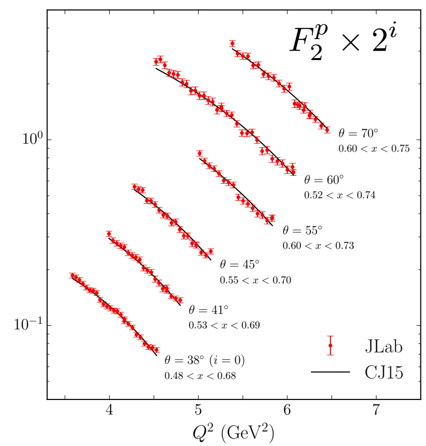
- Importance of high-precision data in high-$x$, low-$W$ region for constraining $x \to 1$ PDFs

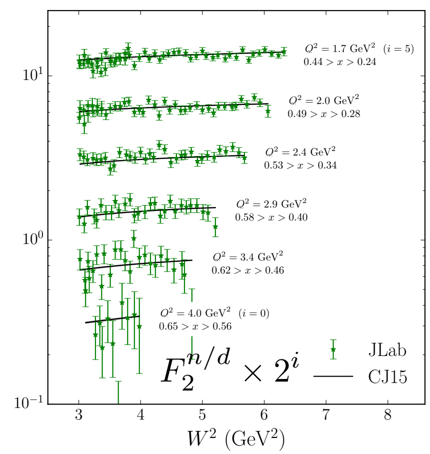
- A lot of data, a lot of phenomenological experience
$\longrightarrow$ single-fit technology usually sufficient for finding $\chi^2$ minima

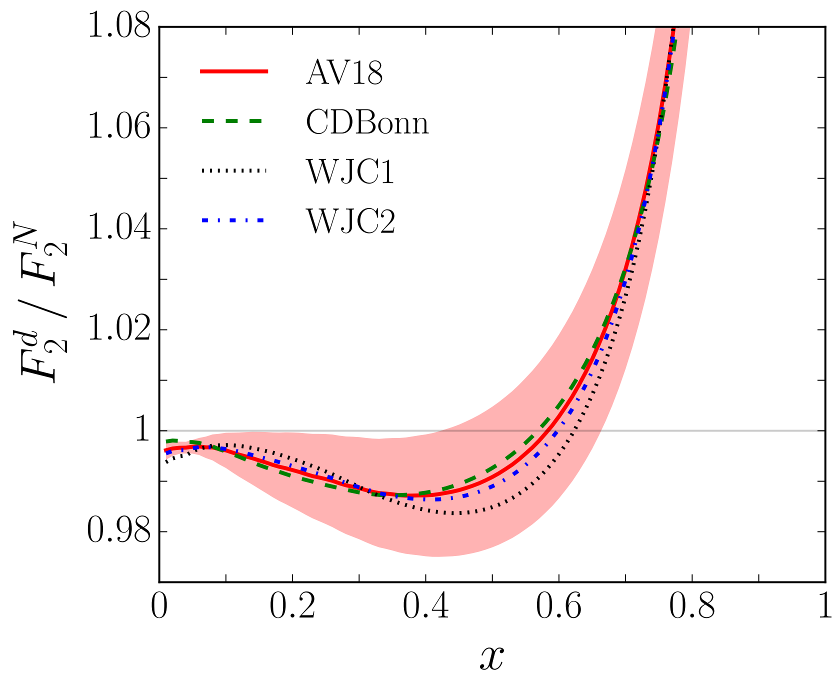
# Spin-averaged PDFs in CJ15

- Ubiquity of proton $F_2$ data $(\mathrm{SLAC, BCDMS, NMC, HERA, JLab}, \ldots)$ provides strong constraints on $u$-quark PDF over large $x$ range




$\longrightarrow$ nuclear EMC effect in deuterium??

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

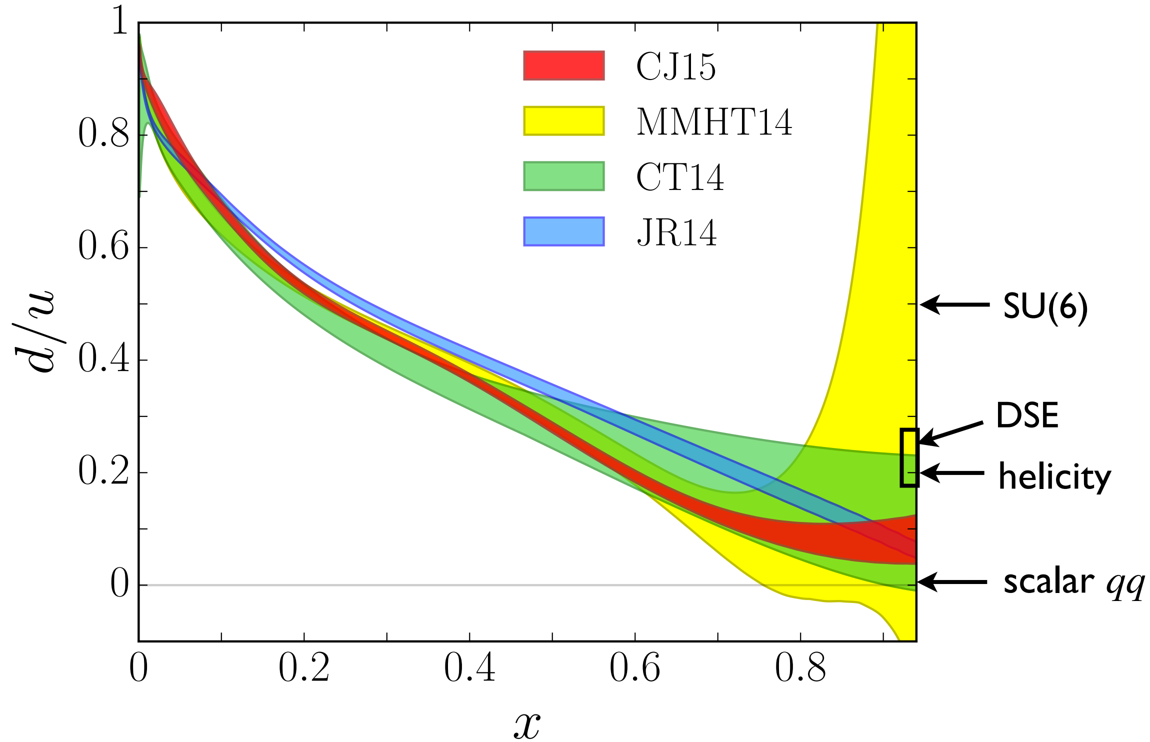
$\longrightarrow$ nuclear effects in deuterium obscure free-neutron structure

# Spin-averaged PDFs in CJ15

- 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!)

$$F_2^d(x,Q^2) = \int_x dy\ f(y,\gamma)\ F_2^N(x/y,Q^2)$$

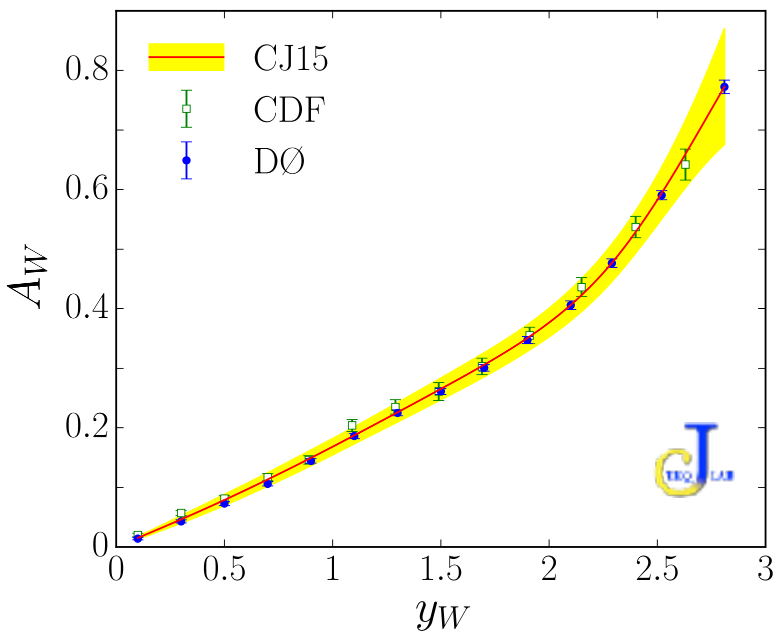
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\ |\psi_d(p)|^2\ \delta\left(y-1-\frac{\varepsilon+\gamma p_z}{M}\right)\times\frac{1}{\gamma^2}\left[1+\frac{\gamma^2-1}{y^2}\left(1+\frac{2\varepsilon}{M}+\frac{\vec{p}^{\,2}}{2M^2}(1-3\hat{p}_z^2)\right)\right]$$

# Spin-averaged PDFs in CJ15

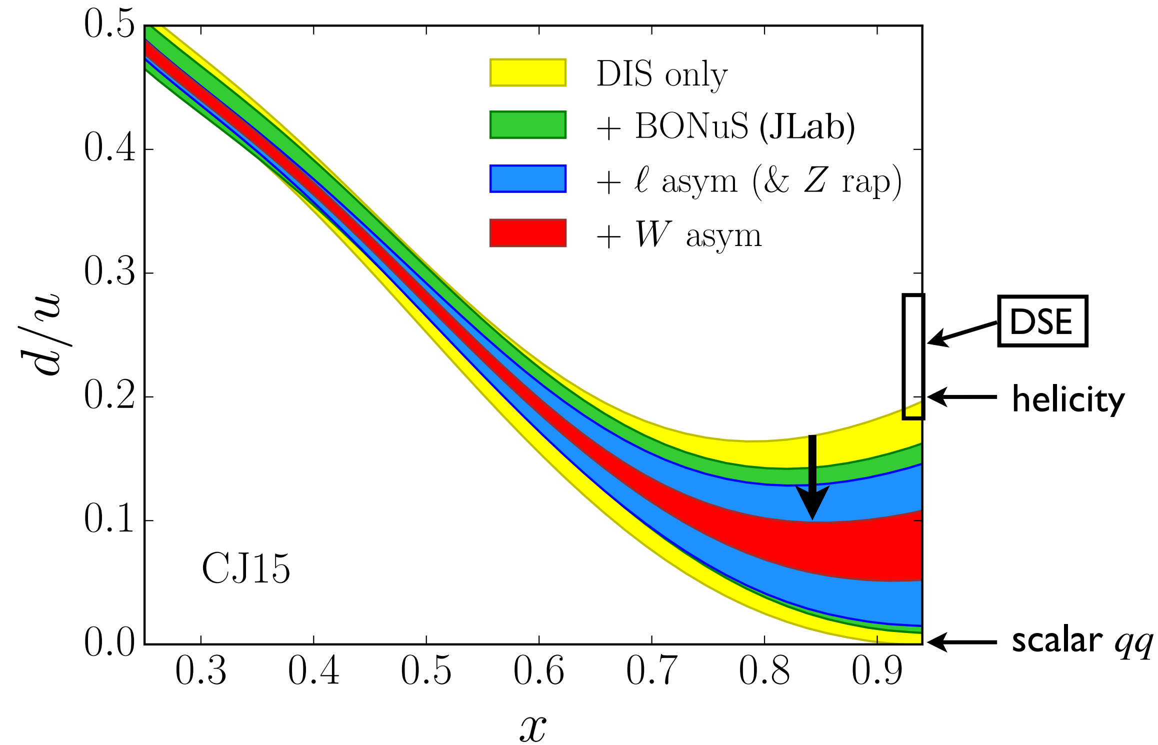
- Valence $d/u$ ratio at high $x$ of particular interest

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

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




*Accardi, Brady, WM, Owens, Sato (2016)*




→ extrapolated ratio at $x = 1$

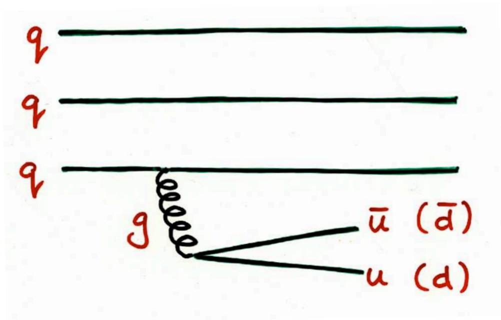
$$d/u \;\to\; 0.09 \pm 0.03$$

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 asymmetry

- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)

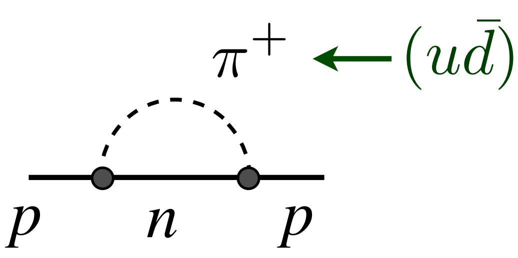



$\rightarrow$ since $u$ and $d$ quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

- From chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

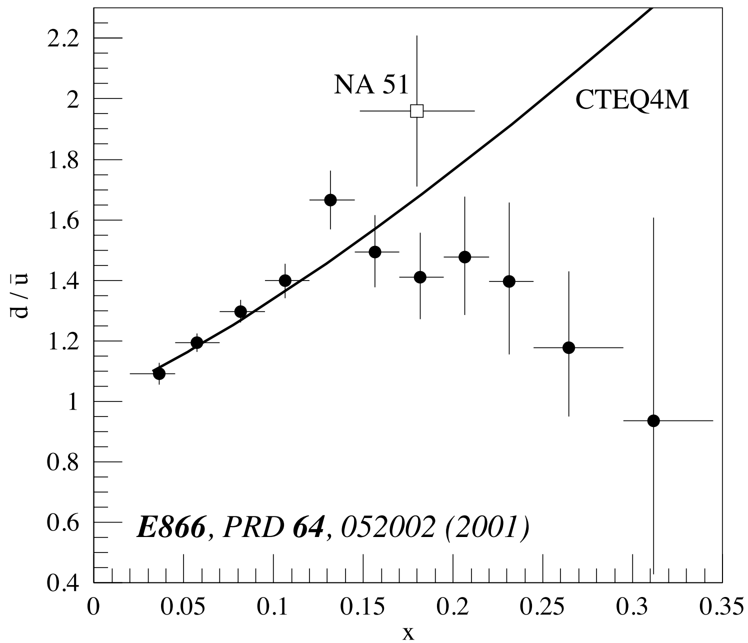
*A. Thomas (1984)*

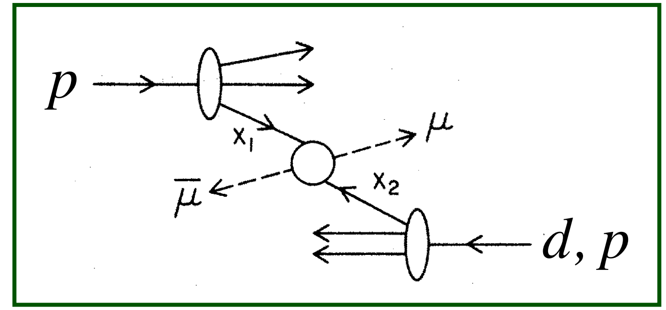



$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

# Light quark sea asymmetry

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments




$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \; + \; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

$\longrightarrow$ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

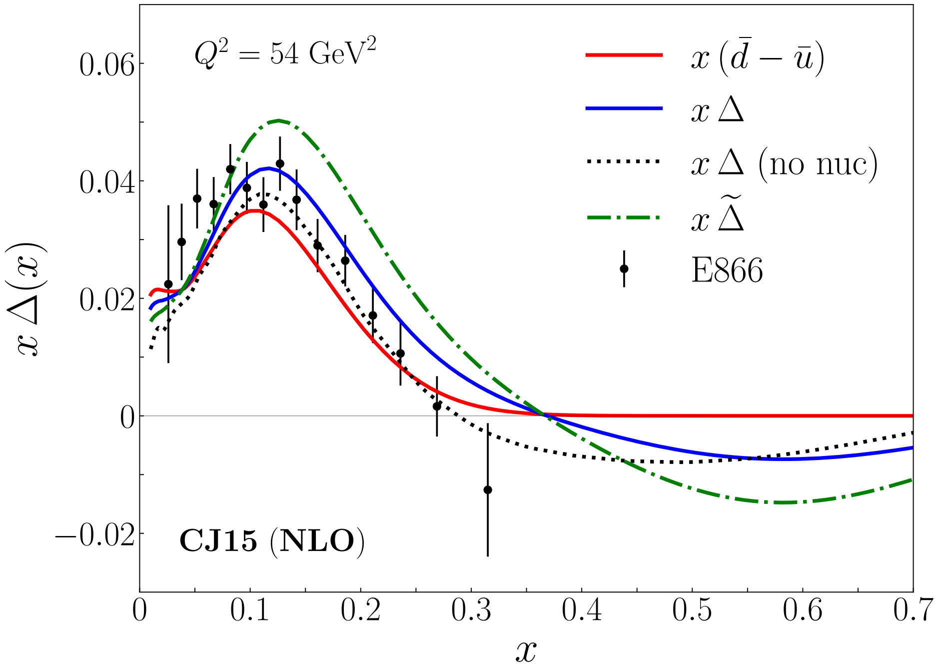
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution in nucleon

pion PDF

# Light quark sea asymmetry

- Intriguing suggestion of sign change in $\bar{d} - \bar{u}$ at high $x$




***Accardi, Keppel, S.Li, WM, Niculescu (x2), Owens (2020)***

$$\Delta \equiv \frac{1}{2}\left(u_v - d_v\right) - \frac{3}{2x}\left(F_2^p - F_2^n\right)$$

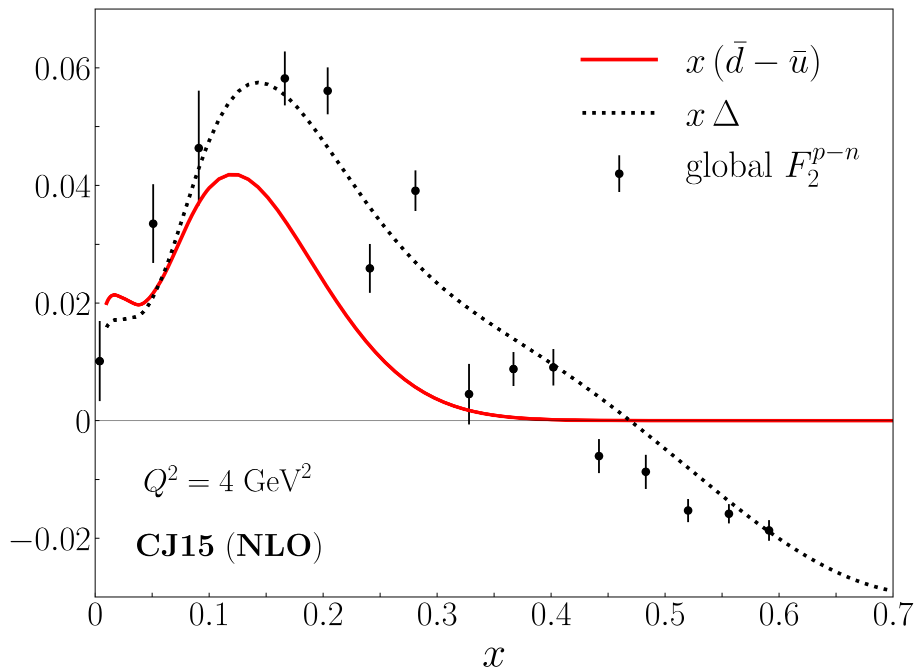
$$\xrightarrow{\text{LO}} \bar{d} - \bar{u}$$

alternative definition (equivalent at LO)

$$\widetilde{\Delta} \equiv u - d - \frac{3}{x}\left(F_2^p - F_2^n\right)$$

# Light quark sea asymmetry

- Intriguing suggestion of sign change in $\bar{d} - \bar{u}$ at high $x$




$$\Delta \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

$$\xrightarrow{\text{LO}} \bar{d} - \bar{u}$$

suggestion that $F_2^p - F_2^n$ data supports sign-change hypothesis

***Peng et al. (2014)***

$\longrightarrow$ global analysis shows that $F_2^p - F_2^n$ data can be well described with <u>no sign change</u> in $\bar{d} - \bar{u}$

$\longrightarrow$ apparent effect is due to higher-order (NLO) $\alpha_S$ corrections!

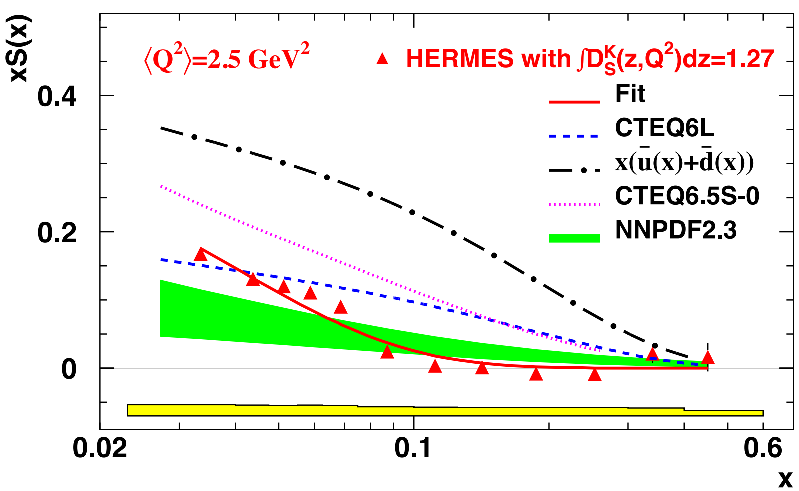
# Strange quarks

- Strange quark PDFs more difficult to constrain, since fewer observables directly sensitive to it

- Traditionally $s$-quark PDF extracted from dimuon production in (anti)neutrino-nucleus DIS $(W^+ s \to c \; / \; W^- \bar{s} \to \bar{c})$

  → but significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

  → tension with HERMES semi-inclusive $K$-production data




historically, strange to nonstrange ratio

$$\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 0.2 - 0.5$$

... but uncertainty from $K$ fragmentation functions?

# Strange quarks

- Since SIDIS depends on both PDFs and fragmentation functions, need to fit both kinds of distributions <u>simultaneously</u>!

  → JAM2019 analysis

  → unpolarized fixed-target DIS on $p, d$ (SLAC, BCDMS, NMC), HERA collider data (runs I & II)

  → Drell-Yan (Fermilab E866), jet production (CDF, D0)

  → SIDIS pion & kaon multiplicities for deuteron (COMPASS)

  → $e^+e^-$ annihilation (DESY, LEP/CERN, SLAC, KEK)

  PDFs

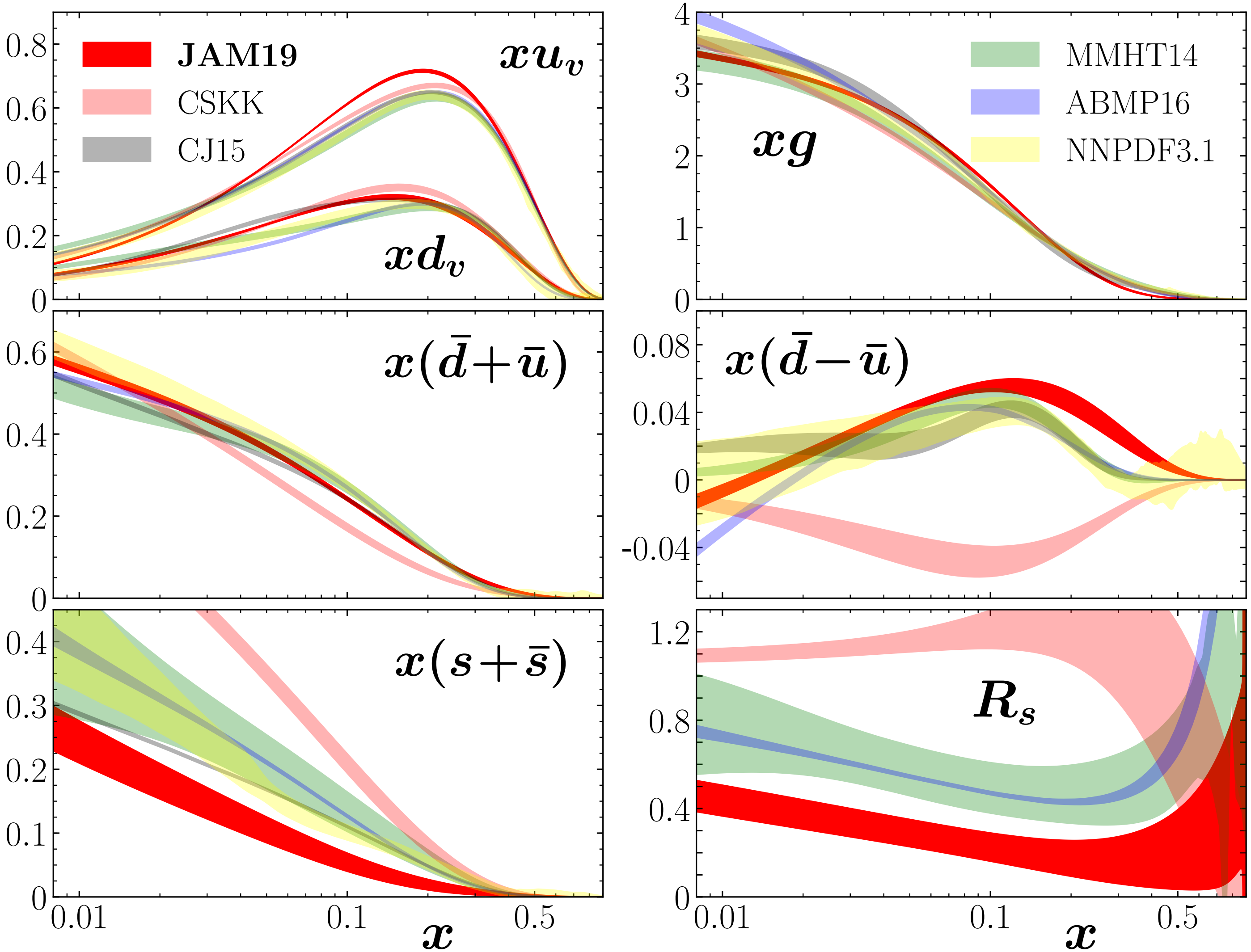
  FFs

- 52 shape parameters + 41 "nuisance" parameters for systematic uncertainties (data normalizations)

- 953 fits to 4366 data points (2680 DIS, 992 SIDIS, 250 DY, 444 SIA)

  → such an analysis has never been attempted before…

# JAM 2019 analysis



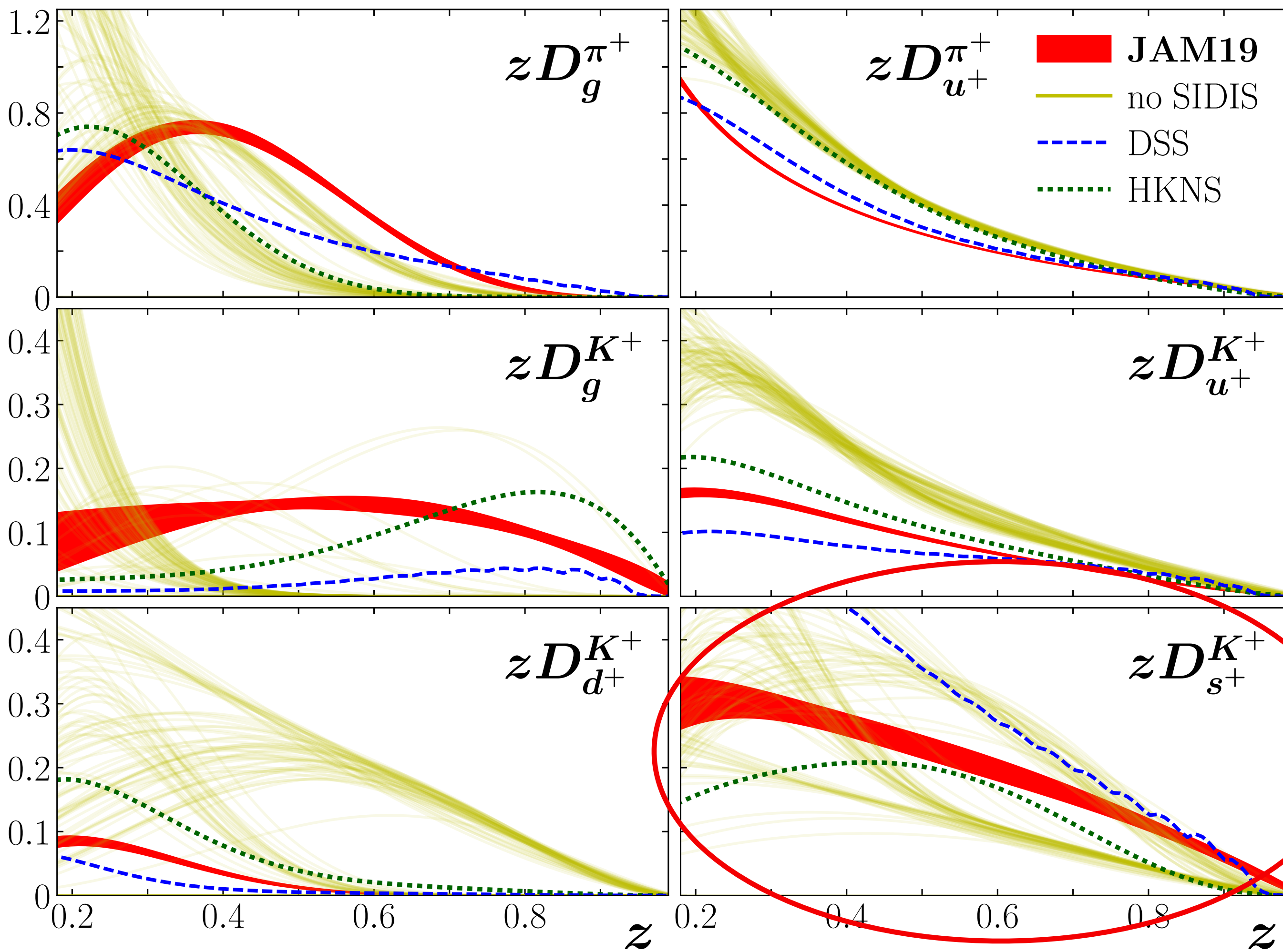

mean reduced
$\chi^2 = 1.3$
for all data

*Sato, Andres, Ethier, WM (2019)*

$\longrightarrow$ valence & light sea quark broadly in agreement with other groups

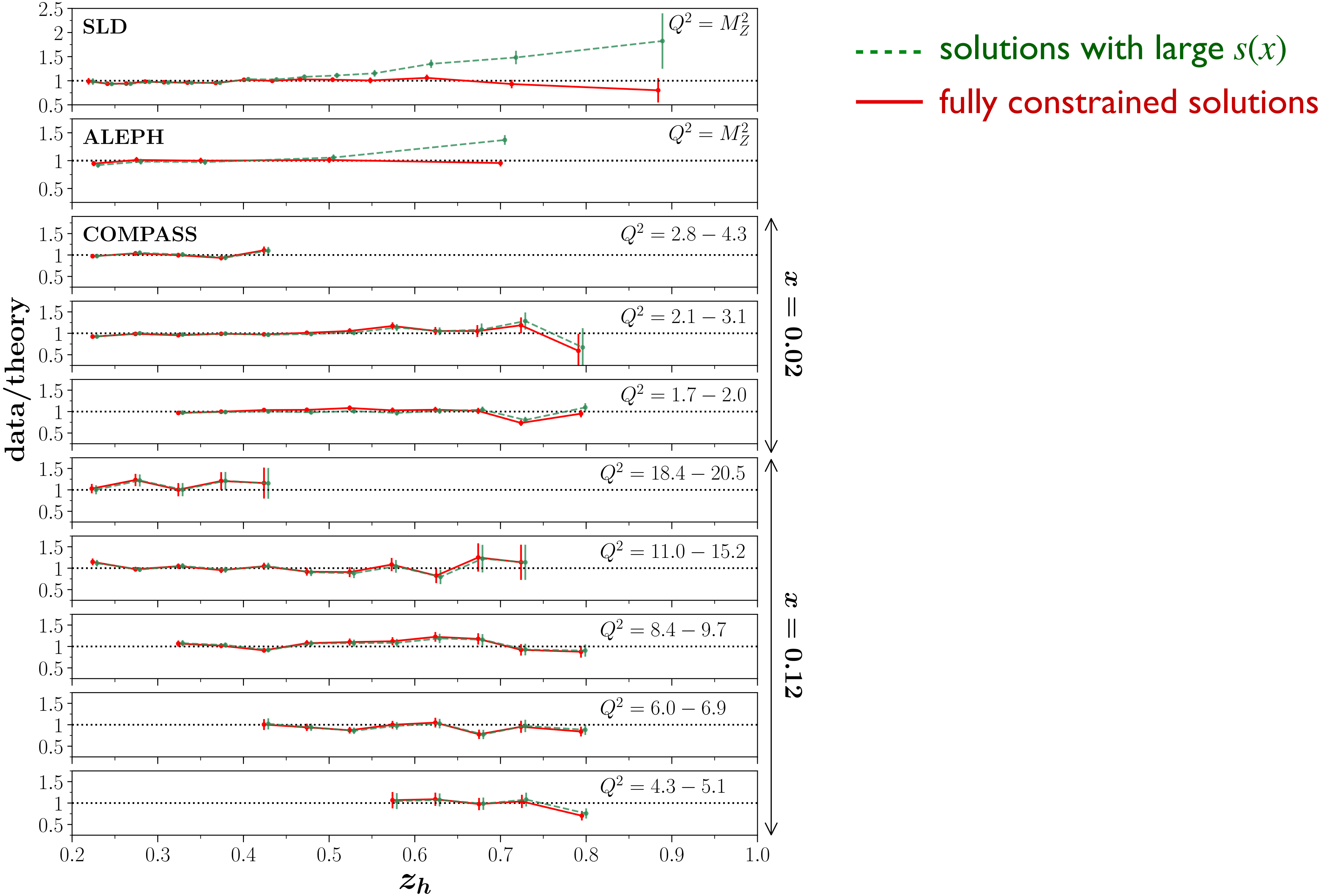
$\longrightarrow$ <u>suppression of strange</u> PDF compared to other extraction

# JAM 2019 analysis

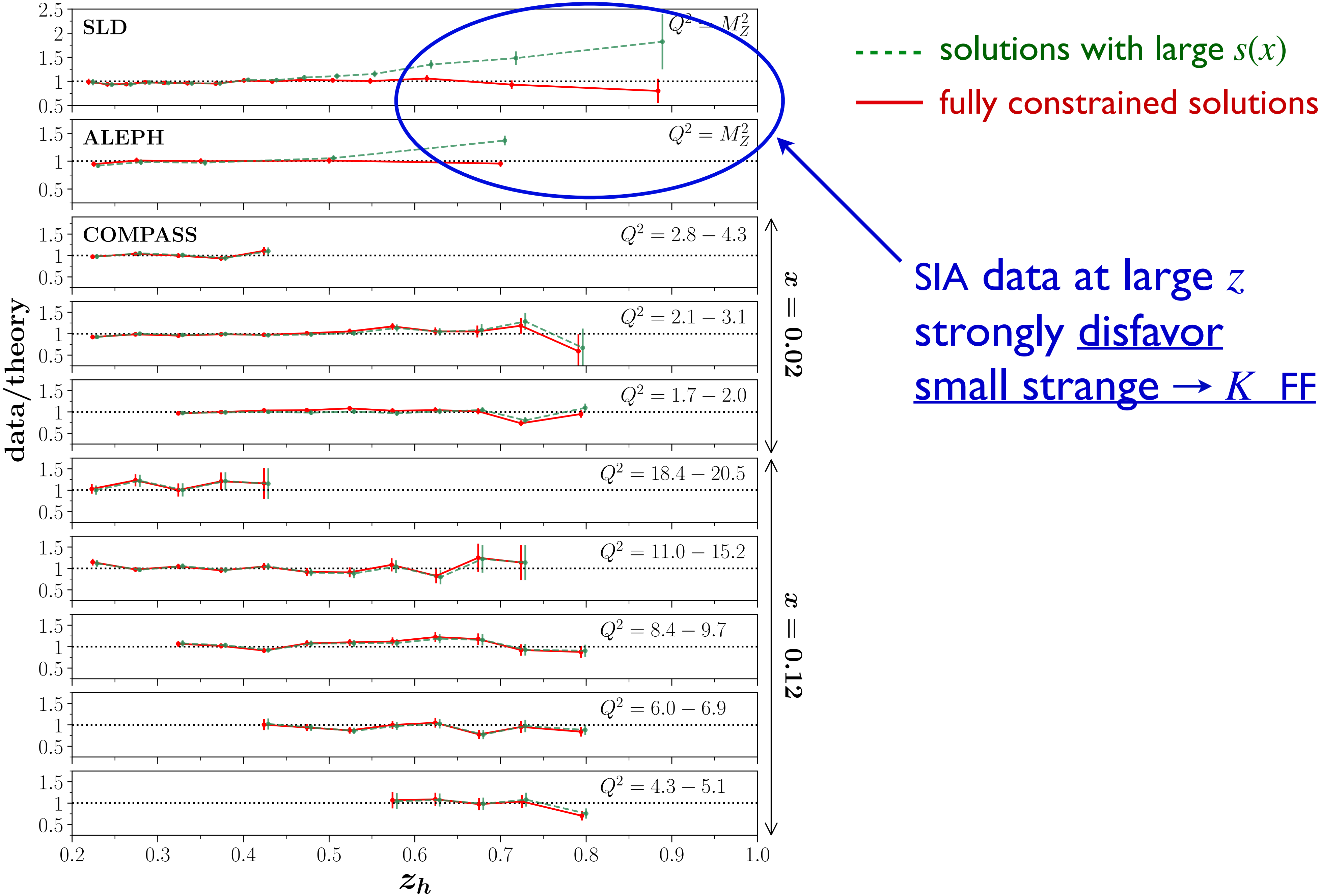



⟶ SIDIS + SIA data force strange to kaon FF to be larger

# JAM 2019 analysis

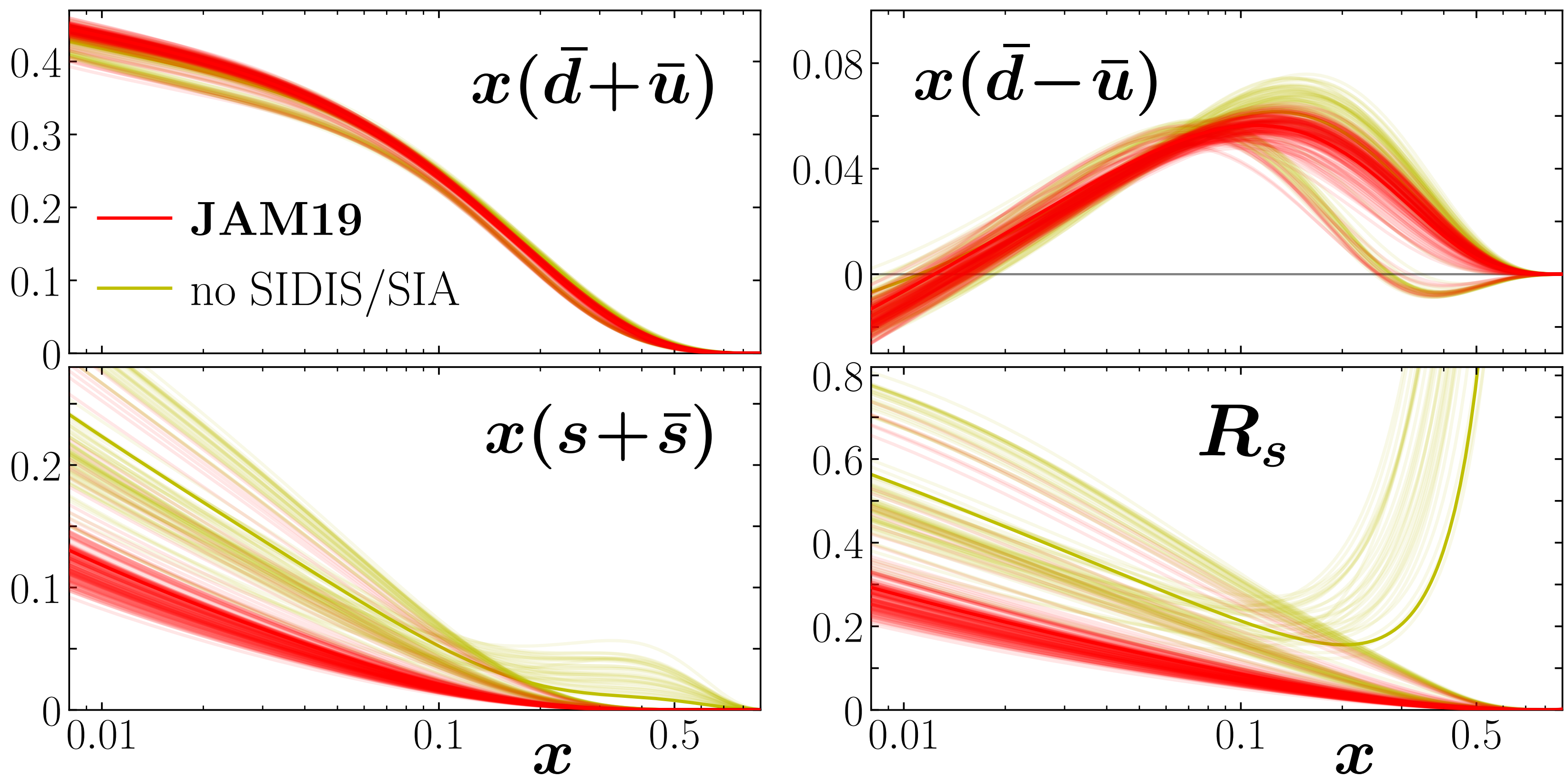


# JAM 2019 analysis




SIA data at large $z$ strongly disfavor small strange → $K$ FF

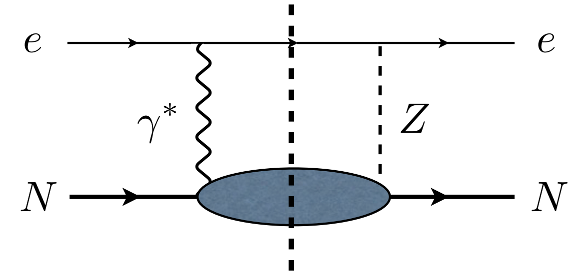
# JAM 2019 analysis




→ vital role played by SIDIS + SIA data in constraining strange PDF

# Strange quarks

- Parity-violating DIS measurements (*e.g.* SoLID at JLab12) will allow strange contribution to be isolated, when combined with e.m. $p$ and $n$ DIS data at low/intermediate $x$




→ at leading order

$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma n} = \frac{4}{9}x(d+\bar{d}) + \frac{1}{9}x(u+\bar{u}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma Z,p} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right)x(u+\bar{u}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(d+\bar{d}+s+\bar{s}) + \cdots$$

$$\approx \frac{1}{9}x(u+\bar{u}+d+\bar{d}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

→ 3 equations with 3 unknowns;
order of magnitude greater sensitivity of $\gamma Z$ to strange PDF

→ $V$ x $A$ term also sensitive to $s - \bar{s}$

$$F_3^{\gamma Z,p} = \frac{2}{3}(u-\bar{u}) + \frac{1}{3}(d-\bar{d}+s-\bar{s}) + \cdots$$

# Nucleon helicity PDFs

- Jefferson Lab Angular Momentum Collaboration began $\sim 2013$ as an attempt to coordinate JLab spin structure function analysis across Halls A, B & C

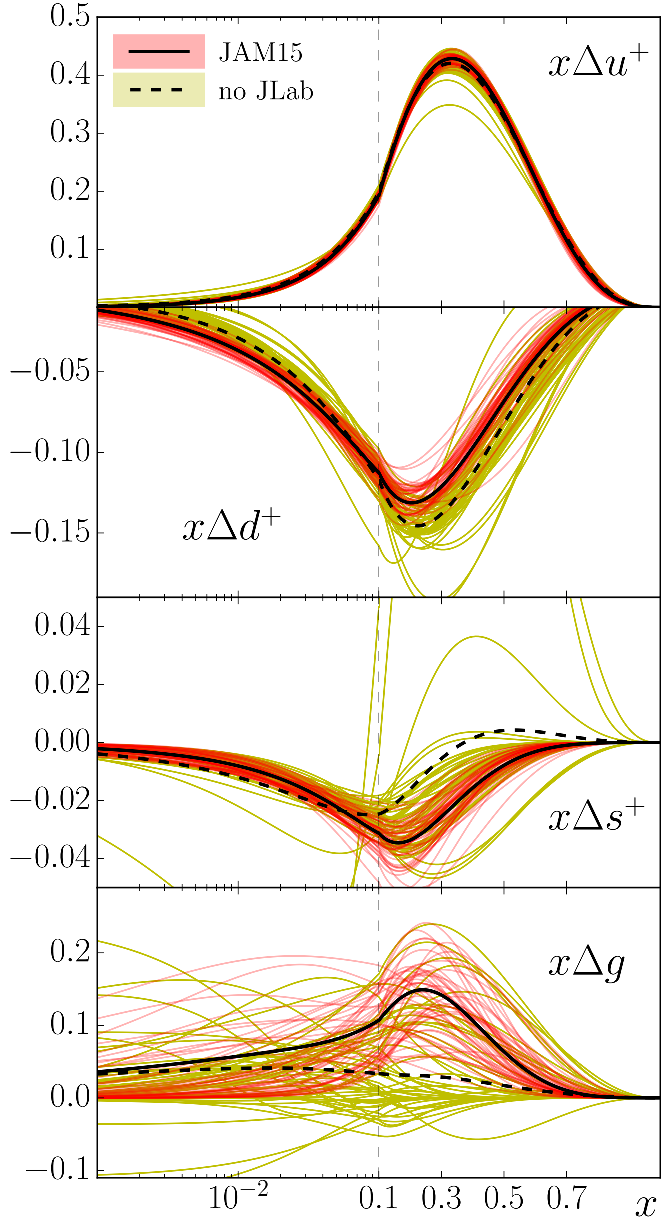
- With fewer data and smaller kinematic reach, soon realized that a Monte Carlo sampling approach was needed

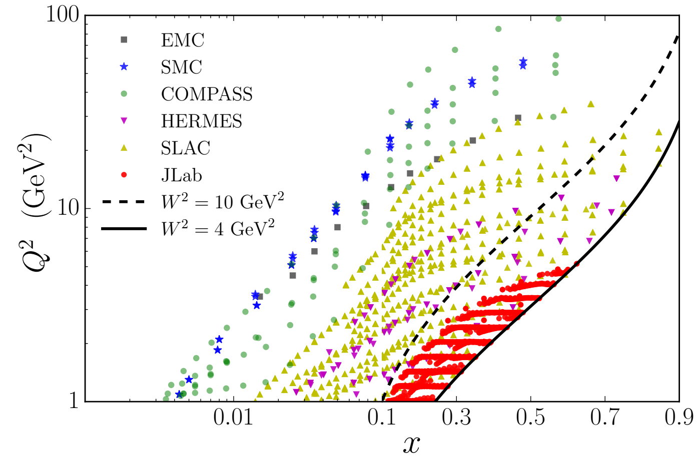
  $\longrightarrow$ de-correlate starting and final fit parameters, avoid getting stuck in local $\chi^2$ minima

  $\longrightarrow$ MC analysis spearheaded by Nobuo Sato

# First application of JAM MC — spin structure

- First JAM MC analysis studied impact of JLab data on spin structure of the nucleon




***Sato, WM, Kuhn, Ethier, Accardi (2016)***

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

→ reduced uncertainty in $\Delta s^+$, $\Delta g$ through $Q^2$ evolution

→ <u>$s$-quark polarization *negative*</u> from inclusive DIS data (assuming SU(3) symmetry)

# First application of JAM MC — spin structure

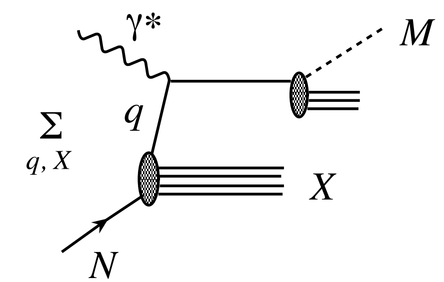
- Inclusive DIS data cannot distinguish between $q$ and $\bar{q}$

  → $2$ observables $(g_1^p,\ g_1^n)$ can determine up to $2$ unknowns, $e.g.$ $\Delta u + \Delta\bar{u},\ \Delta d + \Delta\bar{d}$ — sea quarks from $Q^2$ dependence

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

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

fragmentation functions



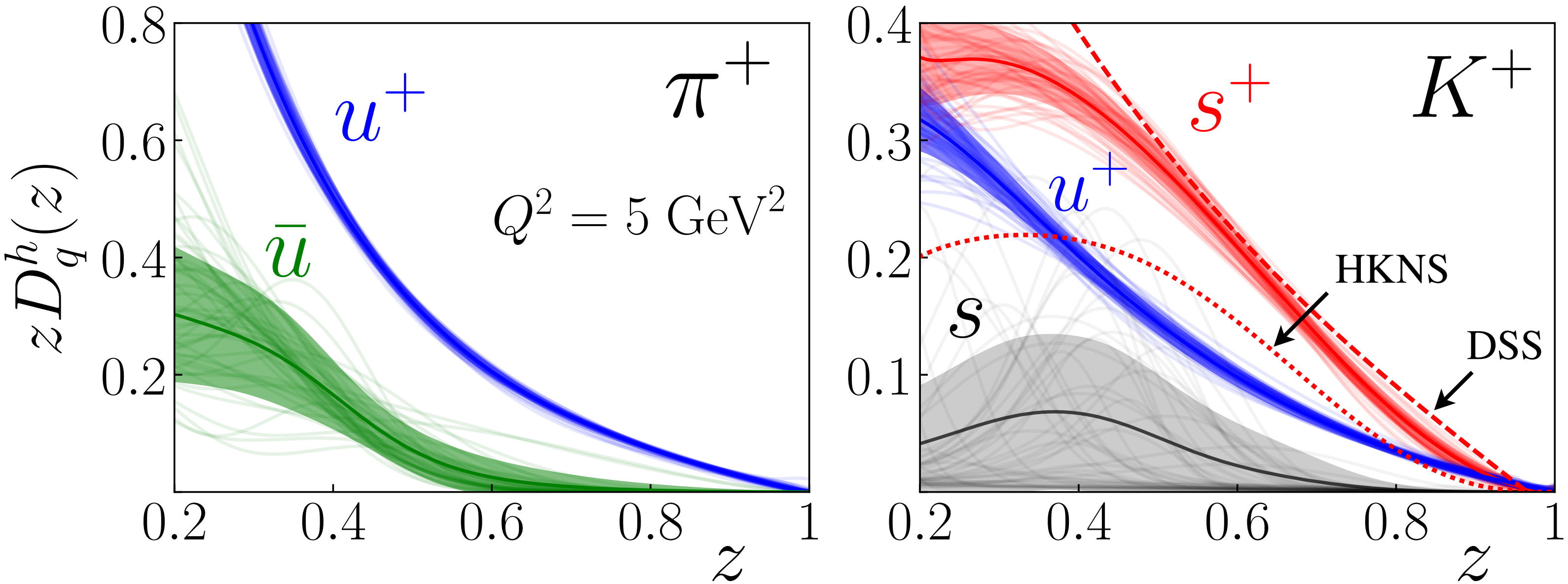

- Global analysis of DIS + SIDIS data gives different *sign* for strange quark polarization for different fragmentation functions!

  → $\Delta s > 0$ for "DSS" FFs, <u>but</u> $\Delta s < 0$ for "HKNS" FFs

  → necessity to fit fragmentation functions simultaneously with PDFs…

# First application of JAM MC — spin structure

- Analysis of single-inclusive $e^+e^-$ annihilation data for $\pi$, $K$ production (from DESY, CERN, SLAC & KEK) from $Q \sim 10$ GeV to $M_Z$



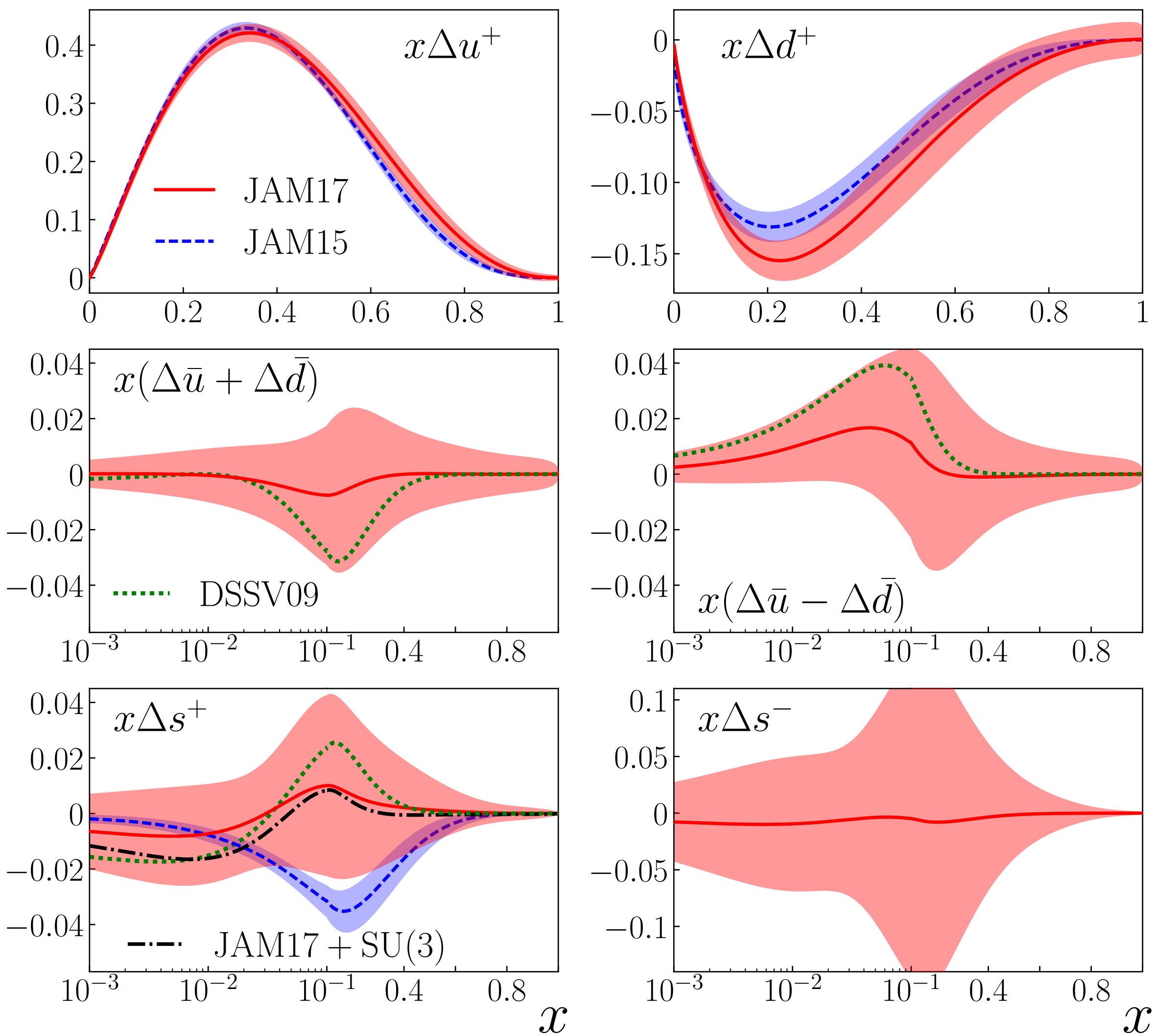

*Ethier, Sato, WM (2017)*

→ favored $u^+ = u + \bar{u}$ & $s^+ = s + \bar{s}$ FFs well constrained

→ larger $s \to K$ fragmentation *cf*. HKNS suggests <u>less negative $\Delta s$</u>

# Simultaneous spin PDF + FF analysis

- First simultaneous extraction of spin PDFs and FFs, fitting polarized DIS + SIDIS (HERMES, COMPASS) and SIA data




→ no assumption of SU(3) symmetry

$$\Delta u^+ - \Delta d^+ \stackrel{?}{=} g_A \equiv F + D$$

$$\Delta u^+ + \Delta d^+ - 2\Delta s^+ \stackrel{?}{=} a_8 \equiv 3F - D$$

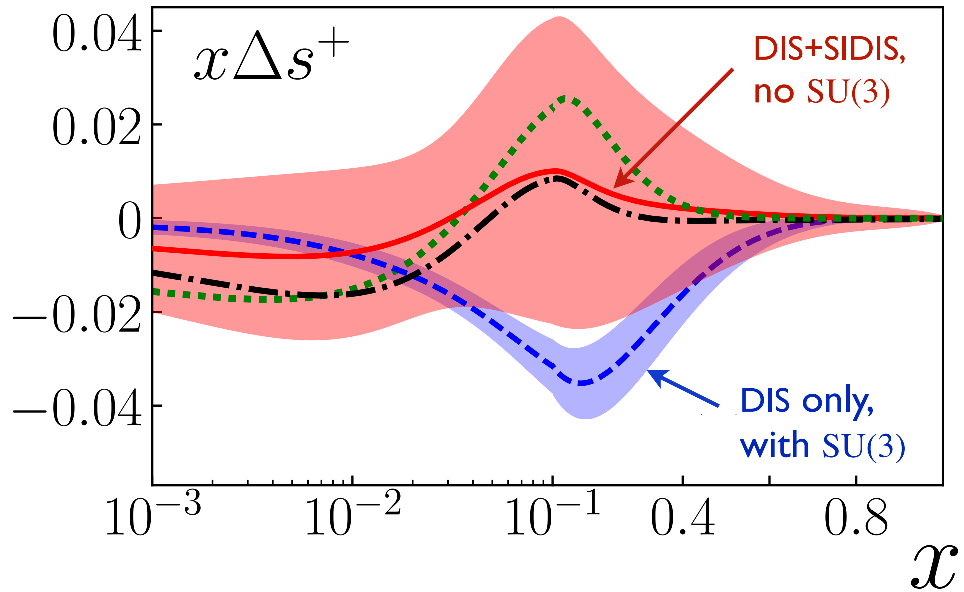
→ $\Delta s$ slightly > 0 at high $x$, consistent with zero

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

***Ethier, Sato, WM (2017)***

# Simultaneous spin PDF + FF 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)*

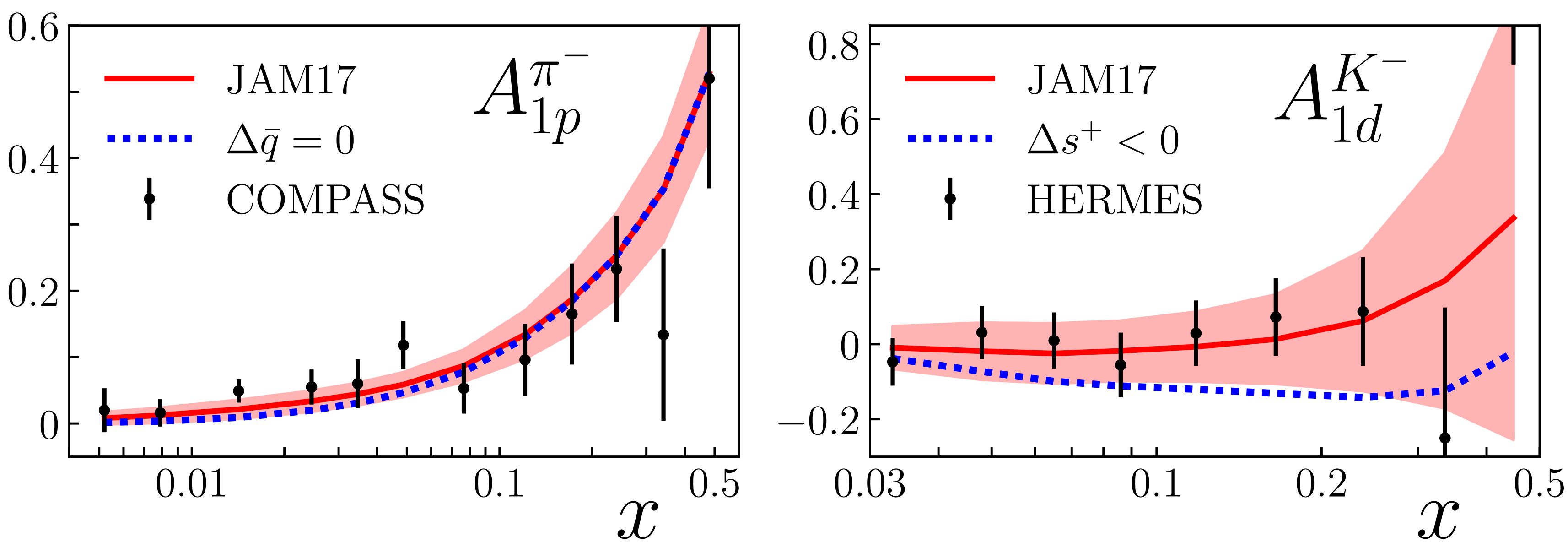
→ weak sensitivity to $\Delta s^+$ from DIS data & evolution

— $\mathrm{SU(3)}$ pulls $\Delta s^+$ to generate moment $\sim -0.1$

— negative peak at $x \sim 0.1$ induced by fixing $b \sim 6 - 8$

# Simultaneous spin PDF + FF analysis

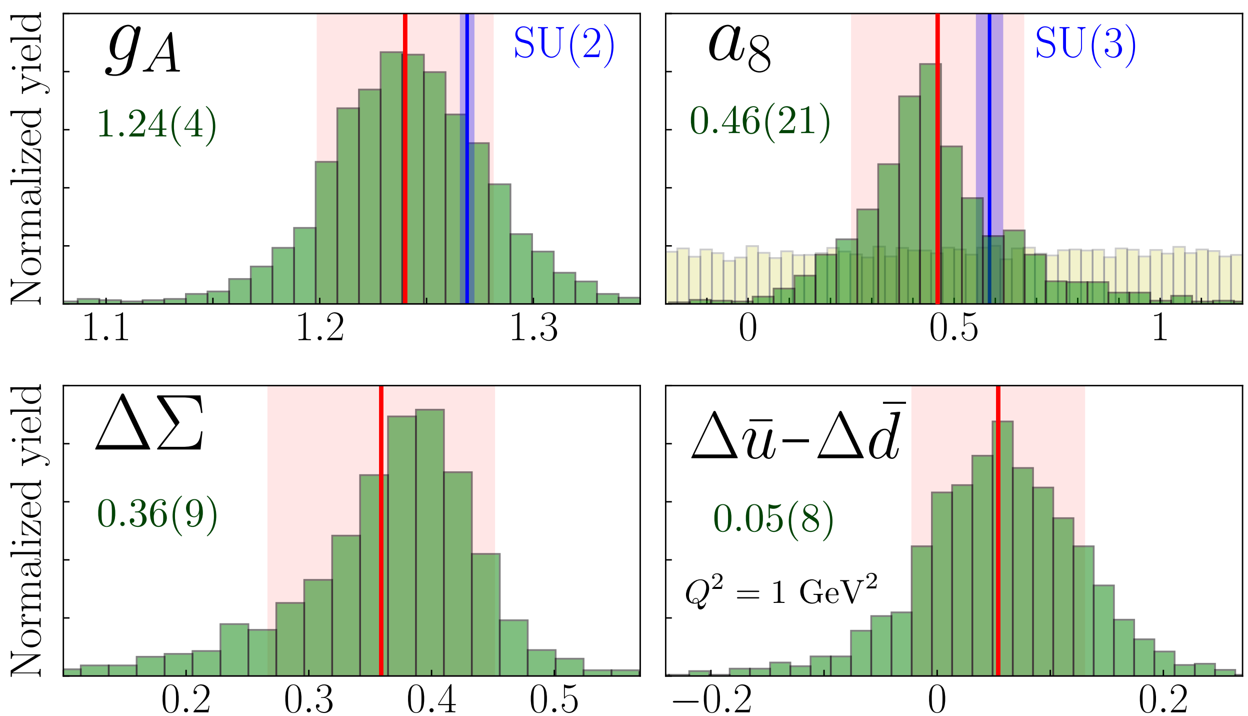
- SIDIS data, especially for $K$ production, clearly prefer a less negative $\Delta s$




***Ethier, Sato, WM (2017)***

# Simultaneous spin PDF + FF analysis

- Statistical distribution of lowest moments (axial charges)




***Ethier, Sato, WM (2017)***

$\longrightarrow$ triplet charge $g_A$ consistent with $\mathrm{SU}(2)$ value

$\longrightarrow$ hint of $\mathrm{SU}(3)$ breaking in octet charge $a_8$ ***Bass, Thomas (2010)***

$\longrightarrow$ less negative $\Delta s = -0.03(10)$ gives larger total helicity $\Delta\Sigma = 0.36(9)$

# JAM-lattice

# PDFs in lattice QCD

- Recent progress in extracting $x$ dependence of PDFs in lattice QCD from matrix element of nonlocal operator

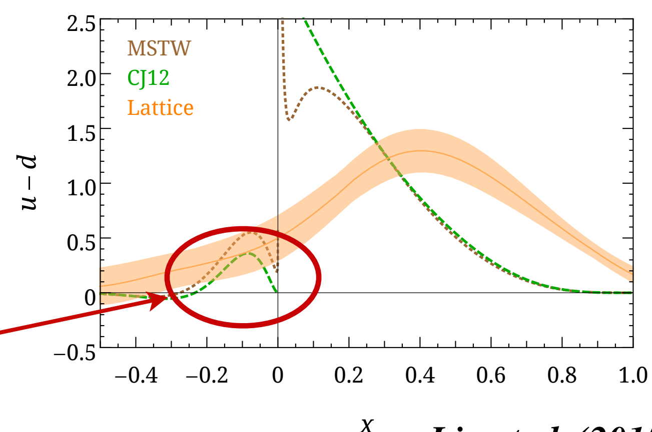
$$h(z,P_z) = \langle\, P \,|\, \overline{\psi}(0,z)\, \gamma_z \mathcal{W}(z,0)\, \psi(0,0) \,|\, P \,\rangle$$
$$= \int_{-\infty}^{\infty} dy\; e^{iyP_z z}\; \widetilde{q}(y,P_z)$$

$\longrightarrow$ quasi-PDF $\widetilde{q}$ related to light-cone PDF via matching kernel $\widetilde{C}$

$$q(x,\mu) = \int_{-\infty}^{\infty} \frac{dy}{|y|}\; \widetilde{C}\Big(\frac{x}{y}, \mu, P_z\Big)\; \widetilde{q}(y,P_z,\mu)$$

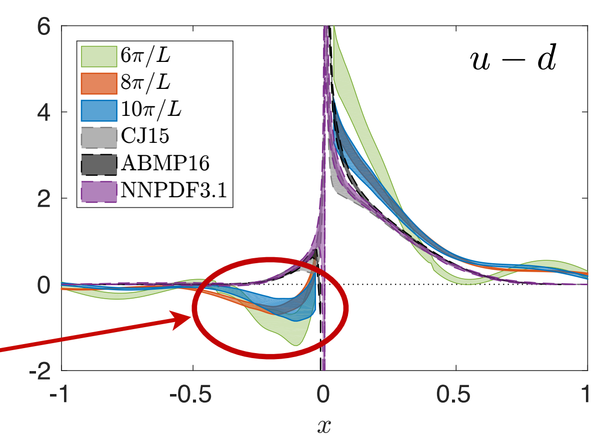
- Conflicting results on sign of $\bar{d}-\bar{u}$ asymmetry

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




*Lin et al. (2015)*

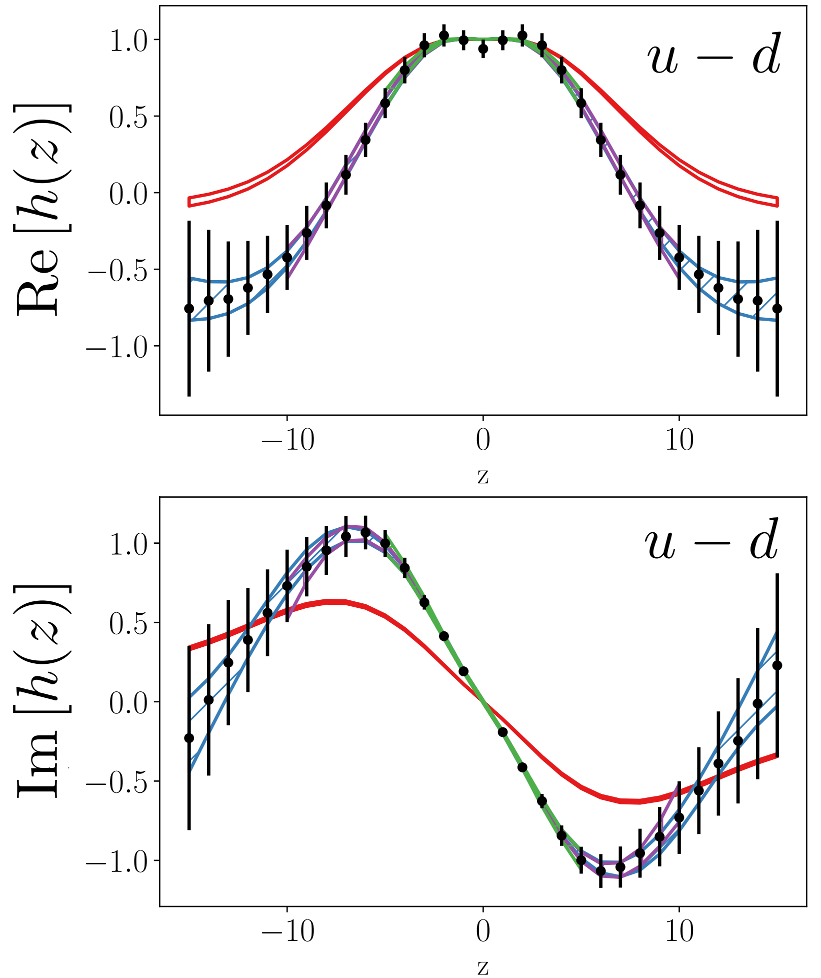
$\bar{d} < \bar{u}$

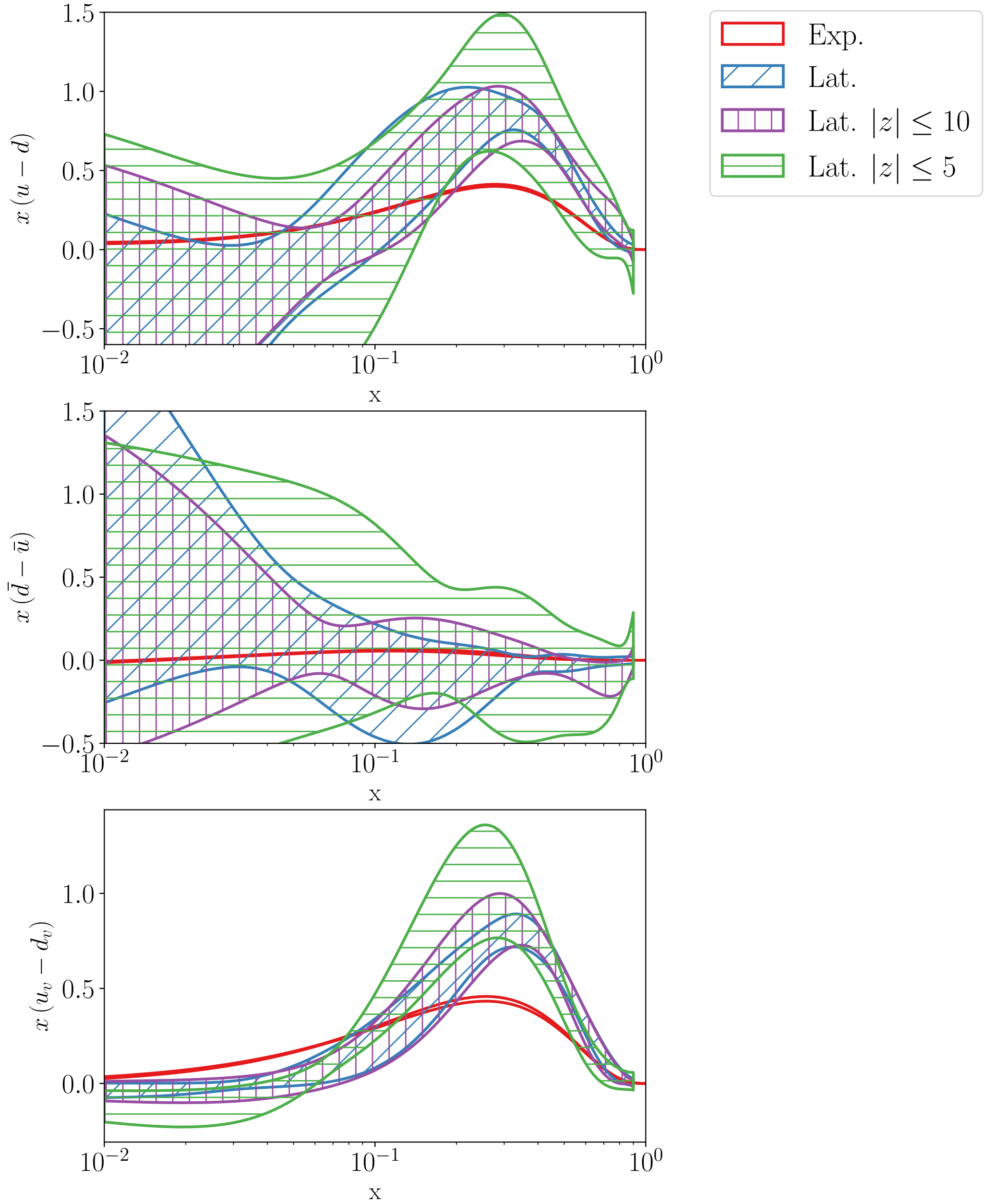



*Alexandrou et al. (2018)*

# PDFs in lattice QCD

- Fit lattice observable directly within JAM framework



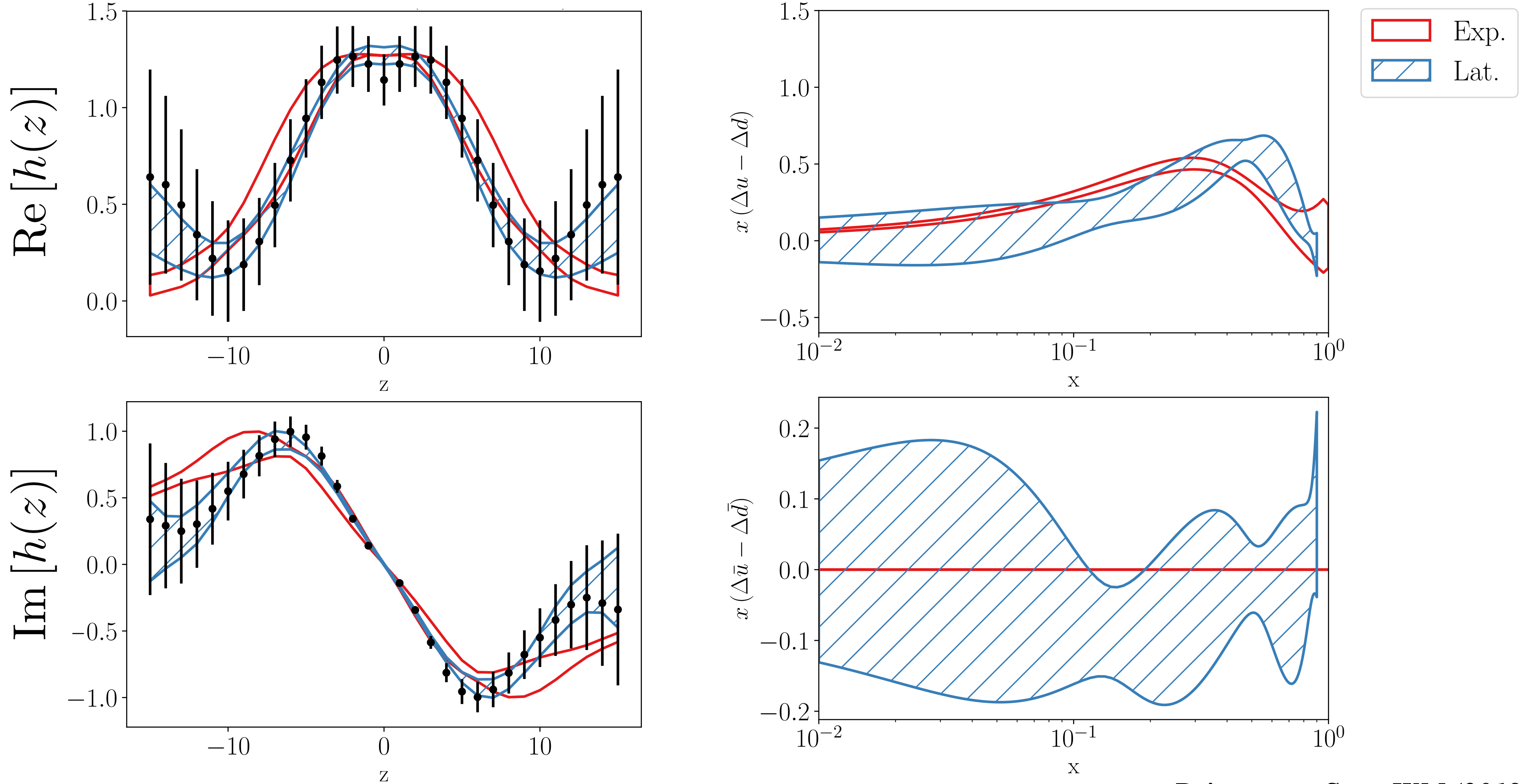




→ cannot determine $\bar{d}-\bar{u}$ from present lattice data

*Bringewatt, Sato, WM (2019)*

# PDFs in lattice QCD

- Fit lattice observable directly within JAM framework



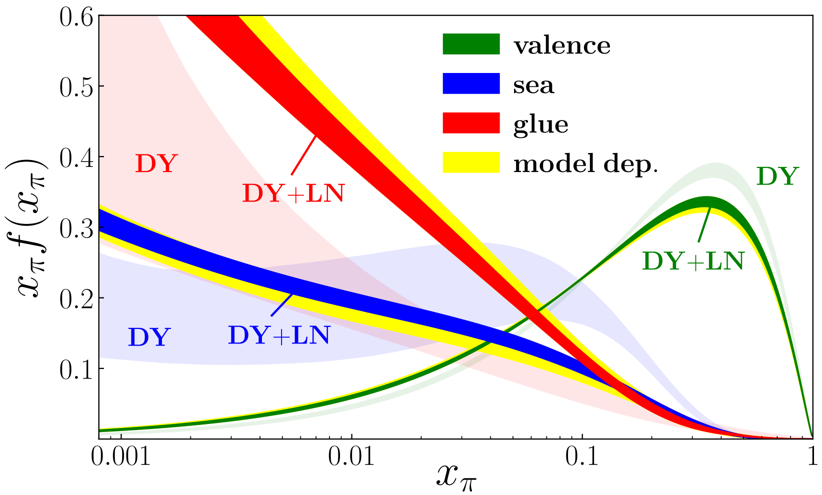

*Bringewatt, Sato, WM (2019)*

$\longrightarrow$ better agreement between lattice and experiment for polarized PDFs (within larger uncertainties)

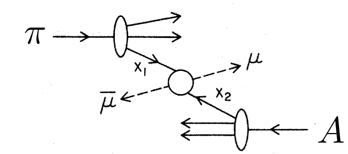
# JAM-pion

# PDFs in the pion

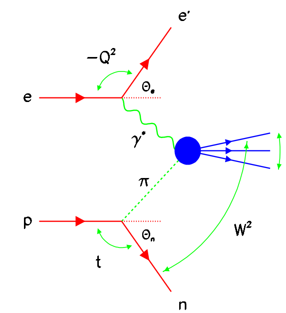
- MC analysis combining pQCD with chiral EFT to fit $\pi N$ Drell-Yan + leading neutron electroproduction data from HERA




DY = $\pi N$ Drell-Yan data (medium/high $x$)

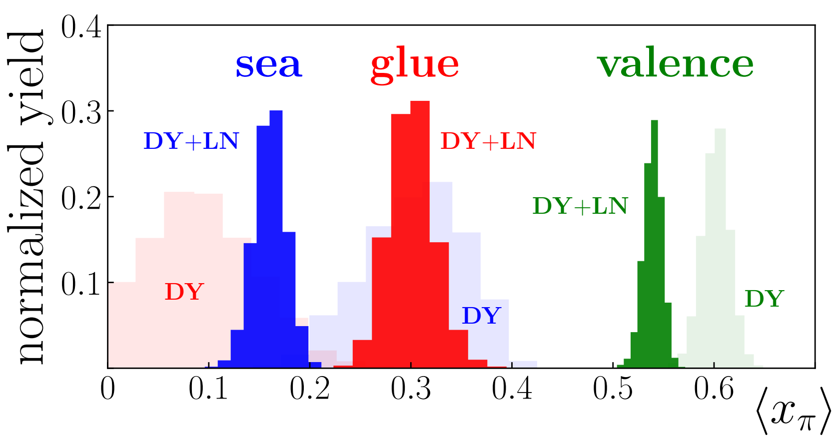



LN = leading neutron electroproduction (low $x$)

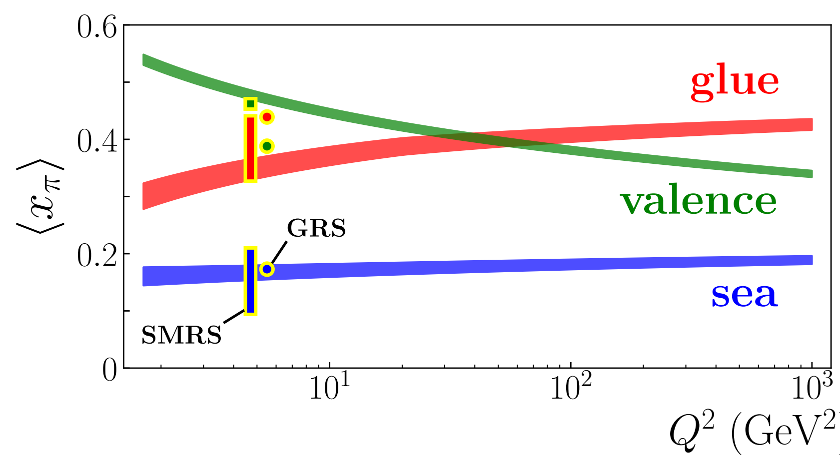



$\longrightarrow$ TDIS!

- Larger gluon fraction in the pion than without LN constraint

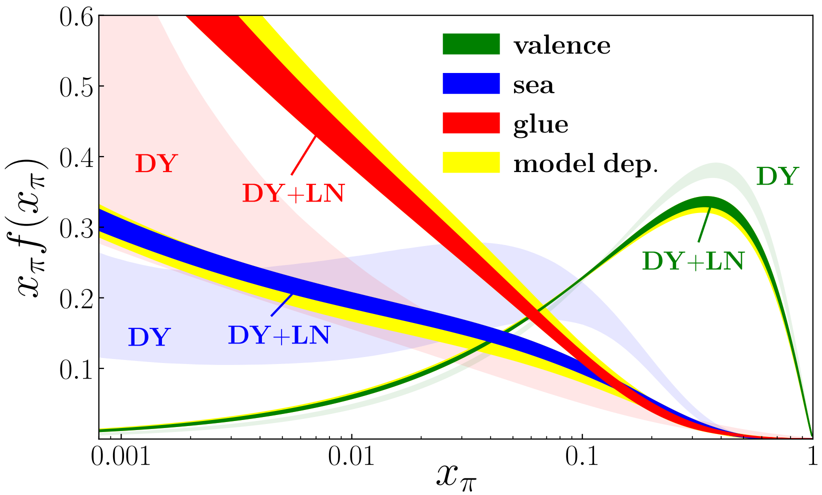



*Barry, Sato, WM, C.-R. Ji (2018)*

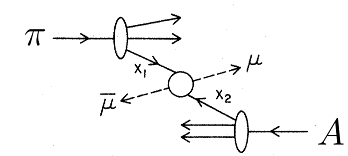


# PDFs in the pion

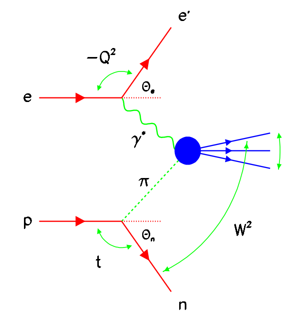
- MC analysis combining pQCD with chiral EFT to fit $\pi N$ Drell-Yan + leading neutron electroproduction data from HERA




DY = $\pi N$ Drell-Yan data (medium/high $x$)

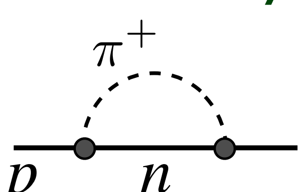



LN = leading neutron electroproduction (low $x$)

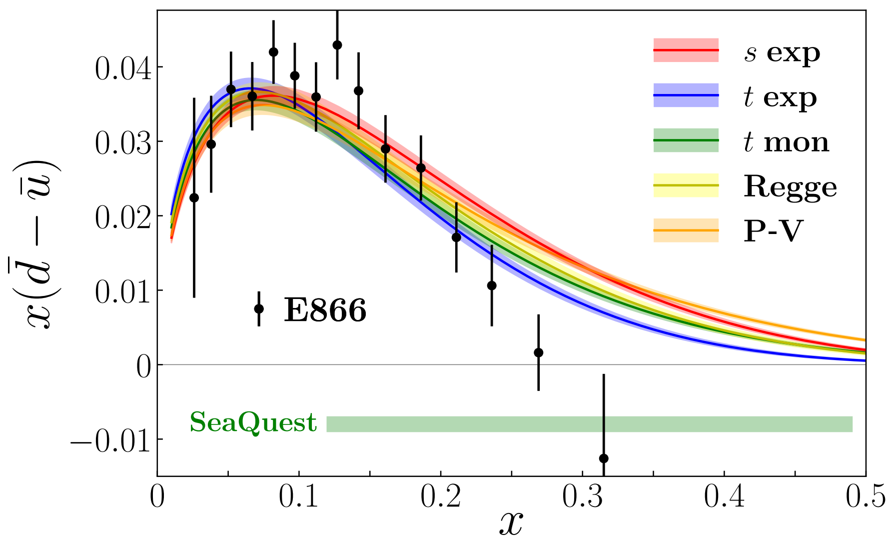



- Provides new insights into the origin of the $\bar{d} - \bar{u}$ asymmetry in the proton

⟶ chiral effective theory relates asymmetry to structure of pion



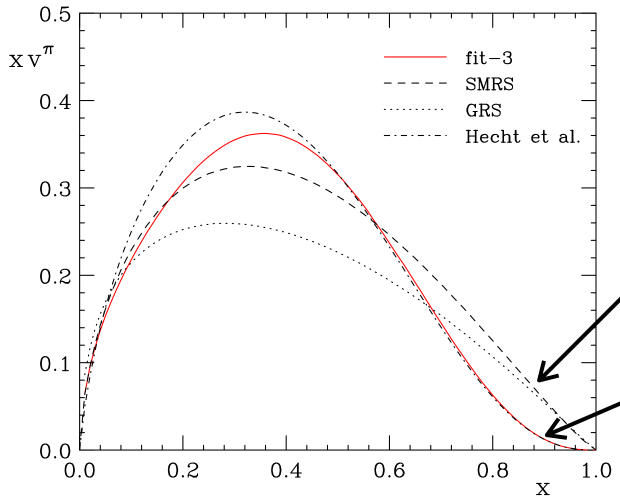

$$(\bar{d} - \bar{u})(x) = \int \frac{dy}{y} f_{\pi^+ n}(y)\, \bar{q}^\pi(x/y)$$




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

# PDFs in the pion

- $x \rightarrow 1$ behavior of pion PDF is controversial: $\sim (1-x)$ or $(1-x)^2$ ?

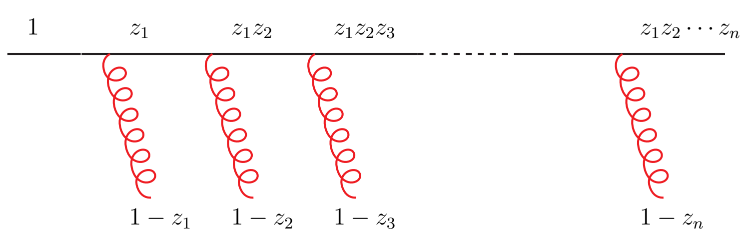


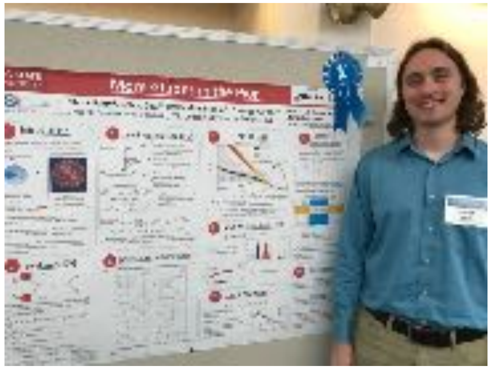

*Aicher, Schafer, Vogelsang (2010)*

no resummation: more consistent with $\sim (1-x)$

with resummation: more consistent with $\sim (1-x)^2$

- Hard scattering coefficient function kinematically enhanced when $z \rightarrow 1$ because of gluon emissions



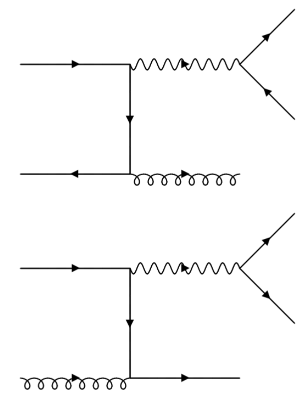
*Patrick Barry et al. (2019)*

$\longrightarrow$ effect of resummation on phenomenology?

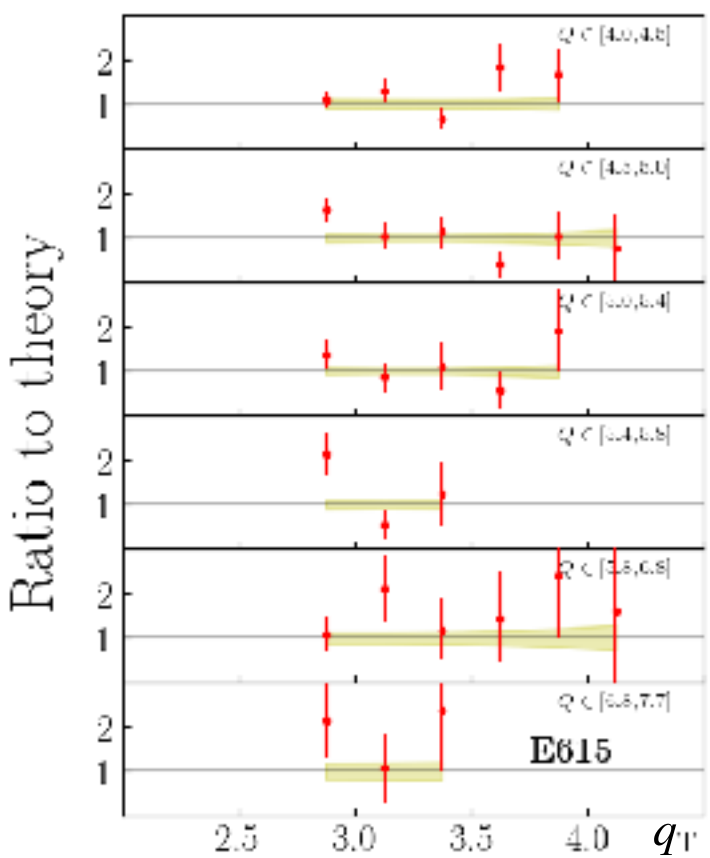
# PDFs in the pion

- New analysis examines whether large-$q_T$ DY data can be simultaneously described with $q_T$-integrated DY + HERA LN data

→ large-$q_T$ photon requires hard gluon to recoil against — sensitivity to <u>gluon PDF</u> in pion at <u>large $x$</u>!



*Nina Cao et al. (2019)*




→ first time that one has been able to describe $q_T$ spectra $(q_T > 2.9\ \mathrm{GeV})$ spectra in terms of collinear PDFs!

# Outlook

- New paradigm in global analysis — <u>simultaneous</u> determination of collinear distributions (unpolarized & polarized PDFs and FFs) using Monte Carlo sampling of parameter space

- Technology developed in collinear sector will be applied to global QCD analysis of transverse momentum dependent (TMD) distributions — map out full 3-d image of nucleon

- Incorporate new tools/technologies, e.g., machine learning — LDRD ("Empirically Trained Hadronic Event Regenerator") and CNF ("QCD theory and machine learning for global analysis") projects — collaboration with computer science/AI researchers