JAM: Update on universal QCD analysis

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thanks to Wally Melnitchouk for slides

Overview

- JAM (Jefferson Lab Angular Momentum) collaboration aims to study the parton structure of hadrons through extraction of "quantum probability distributions" (PDFs, FFs, TMDs) via global QCD analysis using Monte Carlo-based methods

- Methodology is based on Bayesian statistics and Monte Carlo sampling of the parameter space

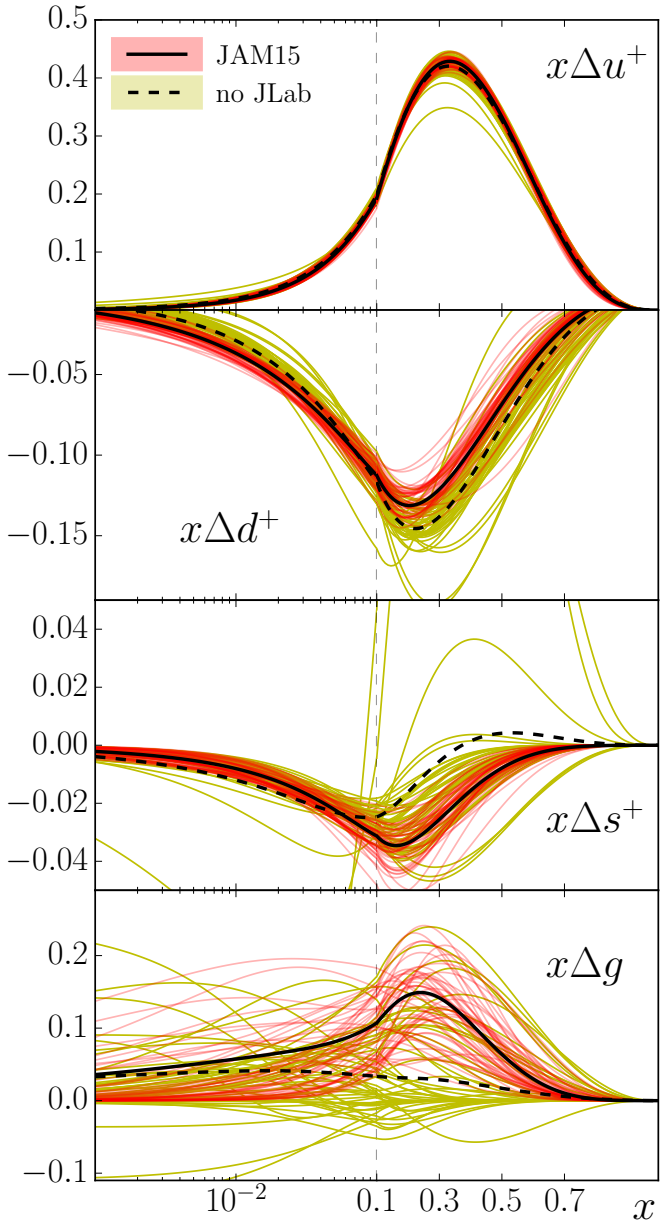
  → existence of multiple solutions — "inverse problem"

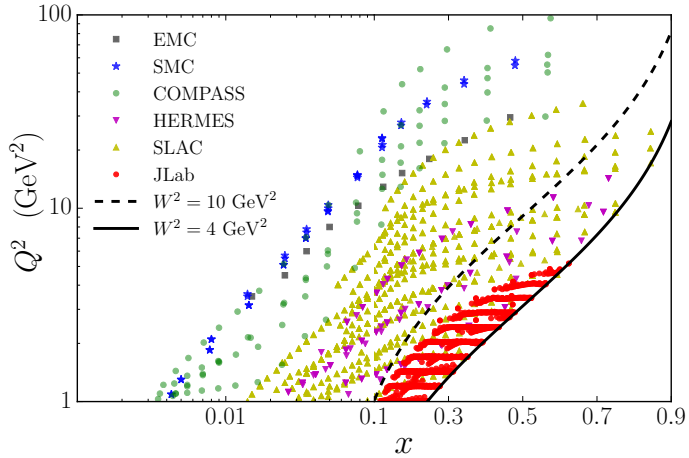
  → robust determination of PDF uncertainties

- Inter-dependence of observables on distributions requires simultaneous extraction of unpolarized and polarized PDFs & fragmentation functions

First application of IMC — spin structure

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





Sato, Melnitchouk, Kuhn, Ethier, Accardi (2016)

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

→ reduced uncertainty in Δs^+, Δg through Q^2 evolution

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

First application of IMC — spin structure

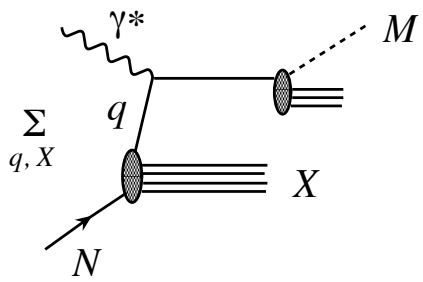
- Inclusive DIS data cannot distinguish between q and $\bar{q}$

  → 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 Δq & $\Delta\bar{q}$

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

fragmentation functions



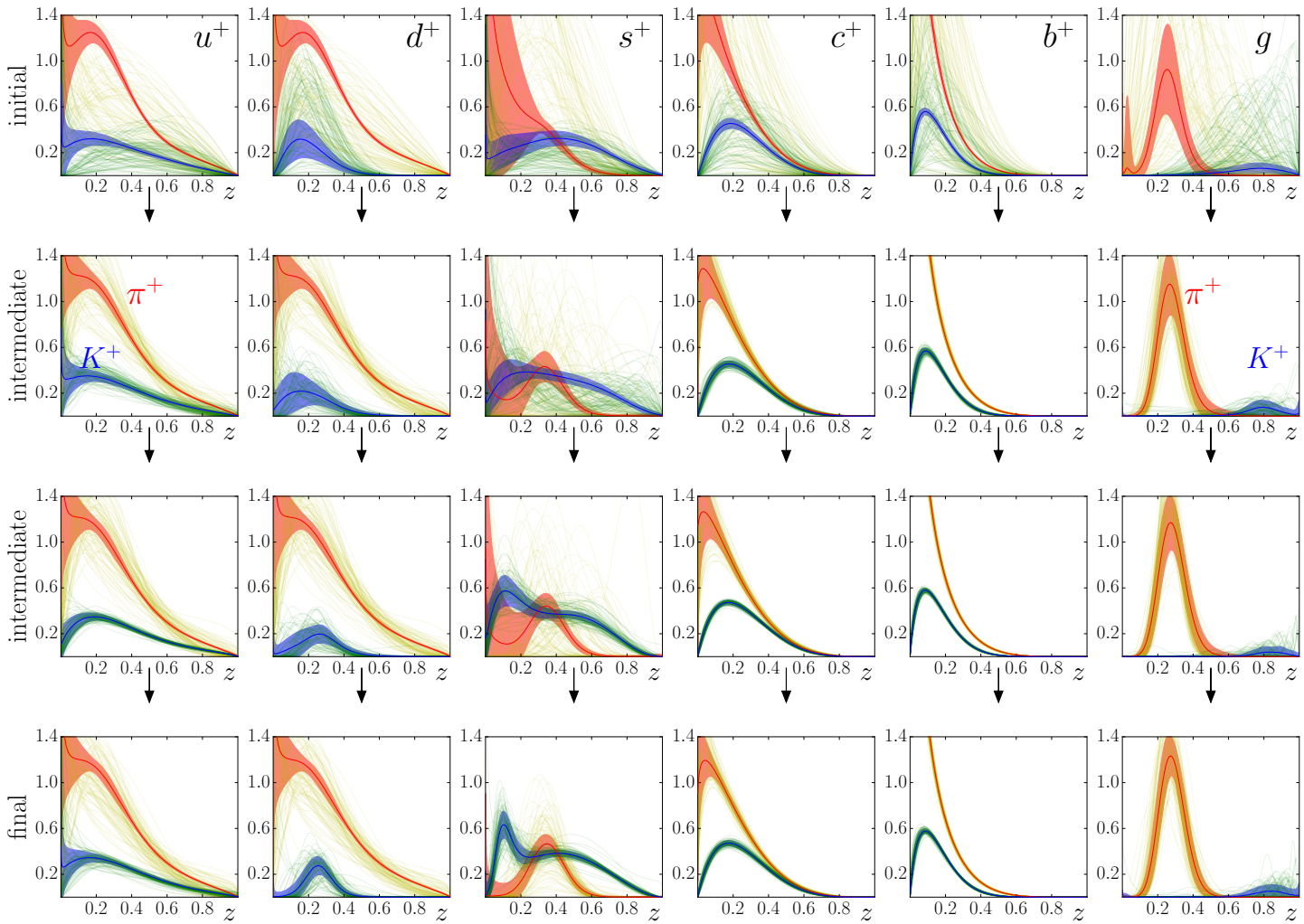
- Global analysis of DIS + SIDIS data gives different *sign* for strange quark polarization for different fragmentation functions!

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

  → need to understand origin of differences in fragmentation functions

IMC analysis of fragmentation functions

- Analysis of single-inclusive e^+e^- annihilation data for π, K production from $Q \sim 10$ GeV to Z boson pole



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

single-inclusive annihilation (SIA)

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

→ convergence after ~ 20 iterations

IMC analysis of fragmentation functions

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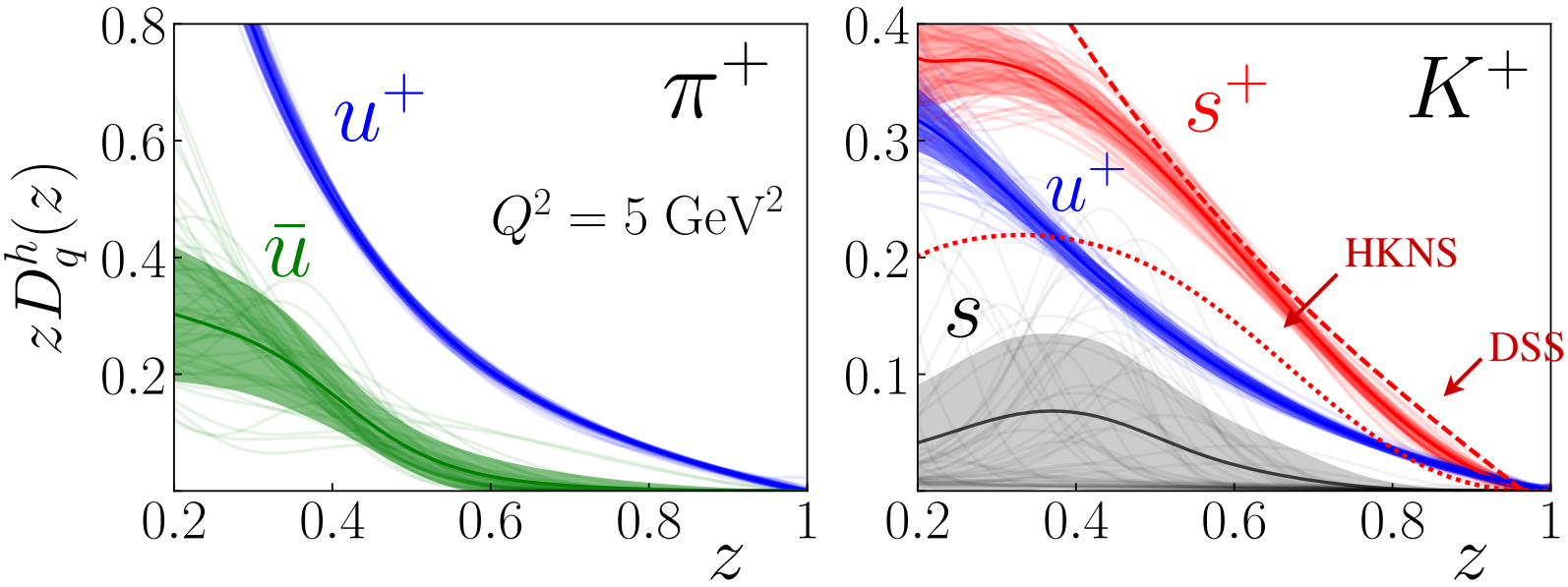


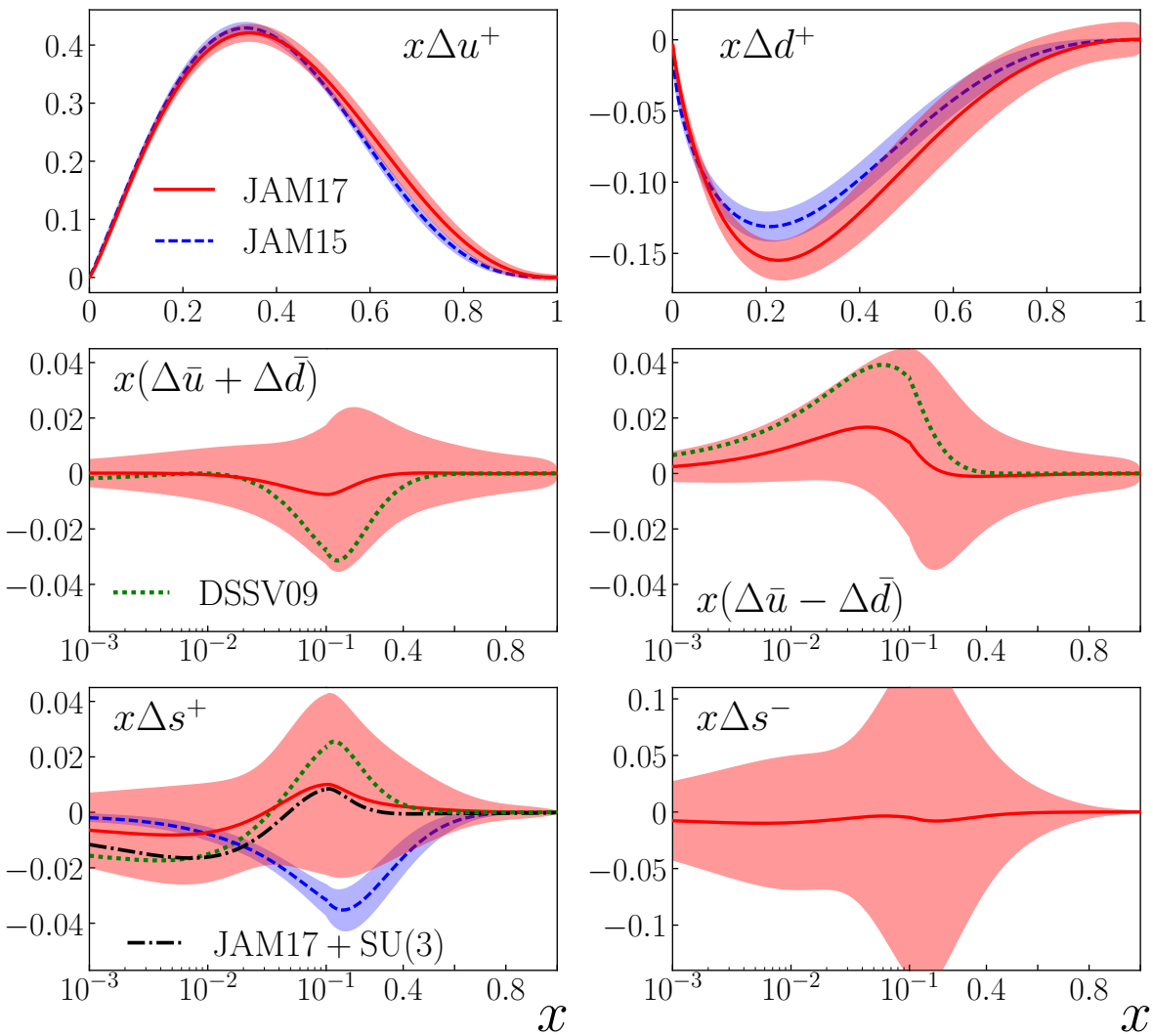
Ethier, Sato, Melnitchouk (2017)

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

→ larger $s \to K$ fragmentation *cf.* HKNS suggests less negative Δs

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

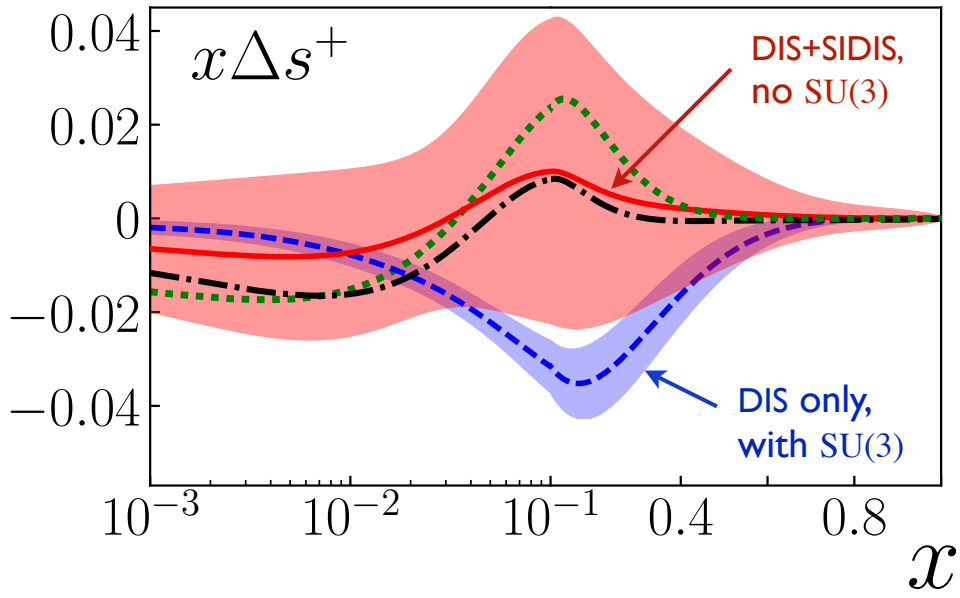
→ Δs slightly > 0 at high x, consistent with zero

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

Ethier, Sato, Melnitchouk (2017)

Simultaneous spin PDF + FF analysis

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



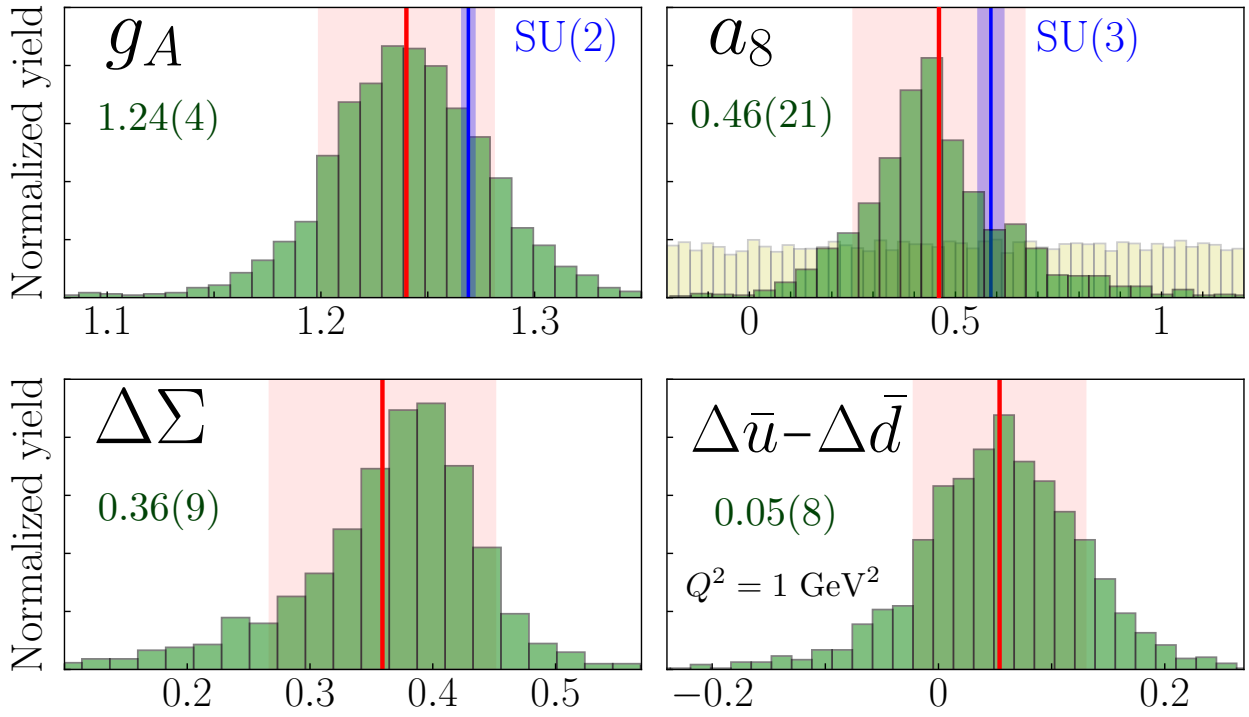
→ weak sensitivity to Δs^+ from DIS data & evolution

— SU(3) pulls Δs^+ to generate moment ~ -0.1

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

Simultaneous spin PDF + FF analysis

- Statistical distribution of lowest moments (axial charges)



Ethier, Sato, Melnitchouk (2017)

→ triplet charge g_A consistent with SU(2) value

→ hint of SU(3) breaking in octet charge a_8 ***Bass, Thomas (2010)***

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

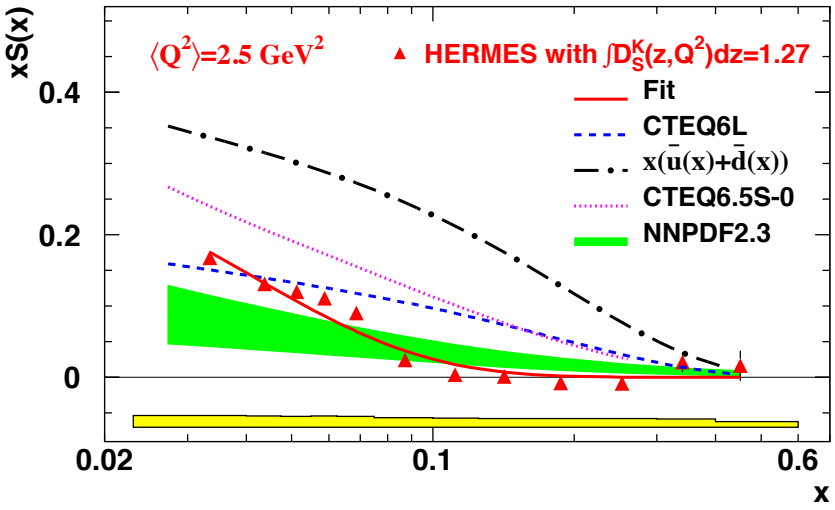
Simultaneous spin PDF + FF analysis

- What impact does unpolarized strange PDF have on the extraction of polarized strange?

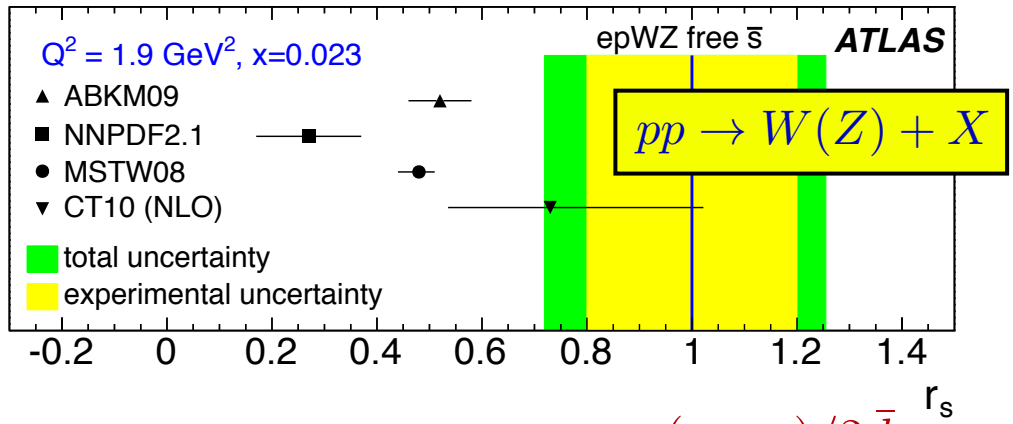
  → only systematic way is to fit unpolarized PDFs, polarized PDFs and fragmentation functions simultaneously…

- Shape of unpolarized strange PDF is interesting (and controversial) in its own right!

  → historically, strange to nonstrange ratio $R_s = \dfrac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 0.4$



HERMES, PRD 89 (2014) 097101



ATLAS
PRL 109 (2012) 012001

$r_s = (s+\bar{s})/2\bar{d}$
$= 1.00^{+0.25}_{-0.28}$

JAM 2019 analysis

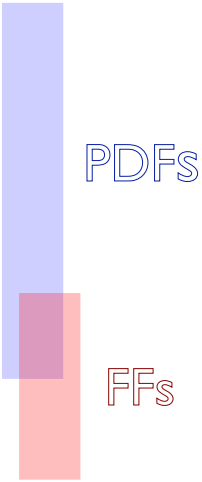
- Study the impact of SIDIS data on unpolarized PDFs

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

  → Drell-Yan (Fermilab E866)

  → SIDIS pion & kaon multiplicities for deuteron (COMPASS)

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

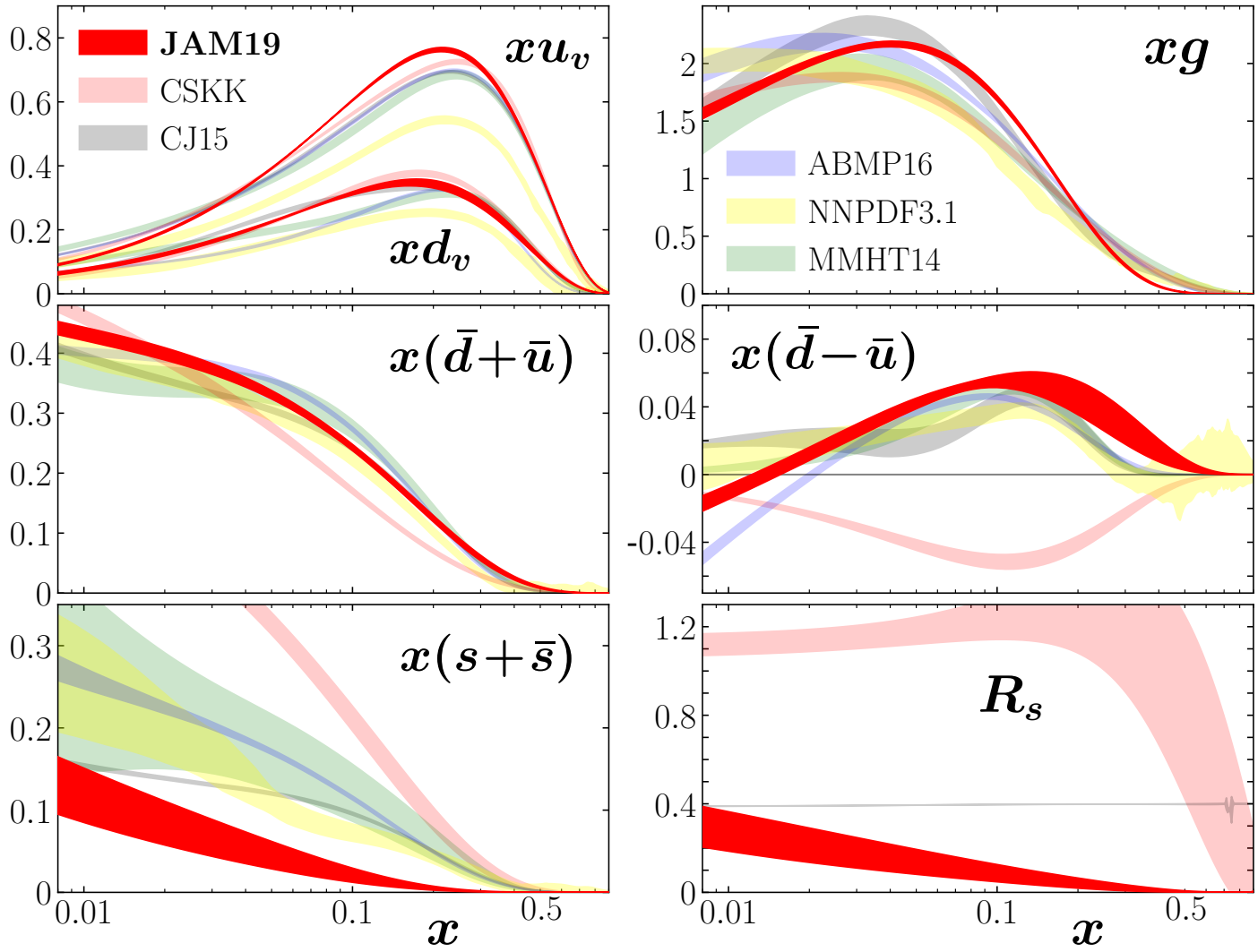


- 52 shape parameters + 41 "nuisance" parameters for systematic uncertainties (data normalizations)

- 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



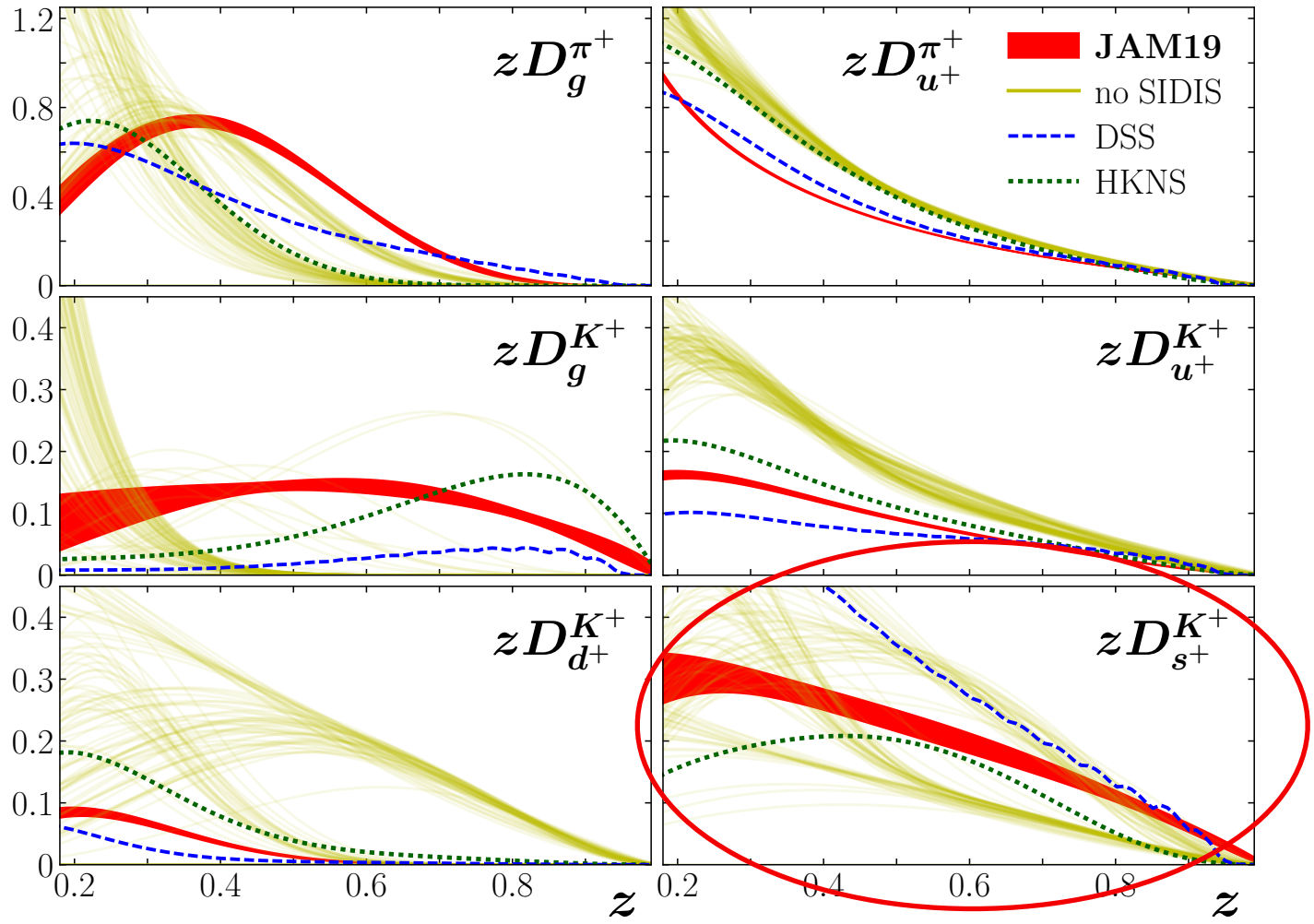
mean reduced
$\chi^2 = 1.3$
for all data

Sato, Andres, Ethier, Melnitchouk (2019)

→ valence & light sea quark broadly in agreement with other groups

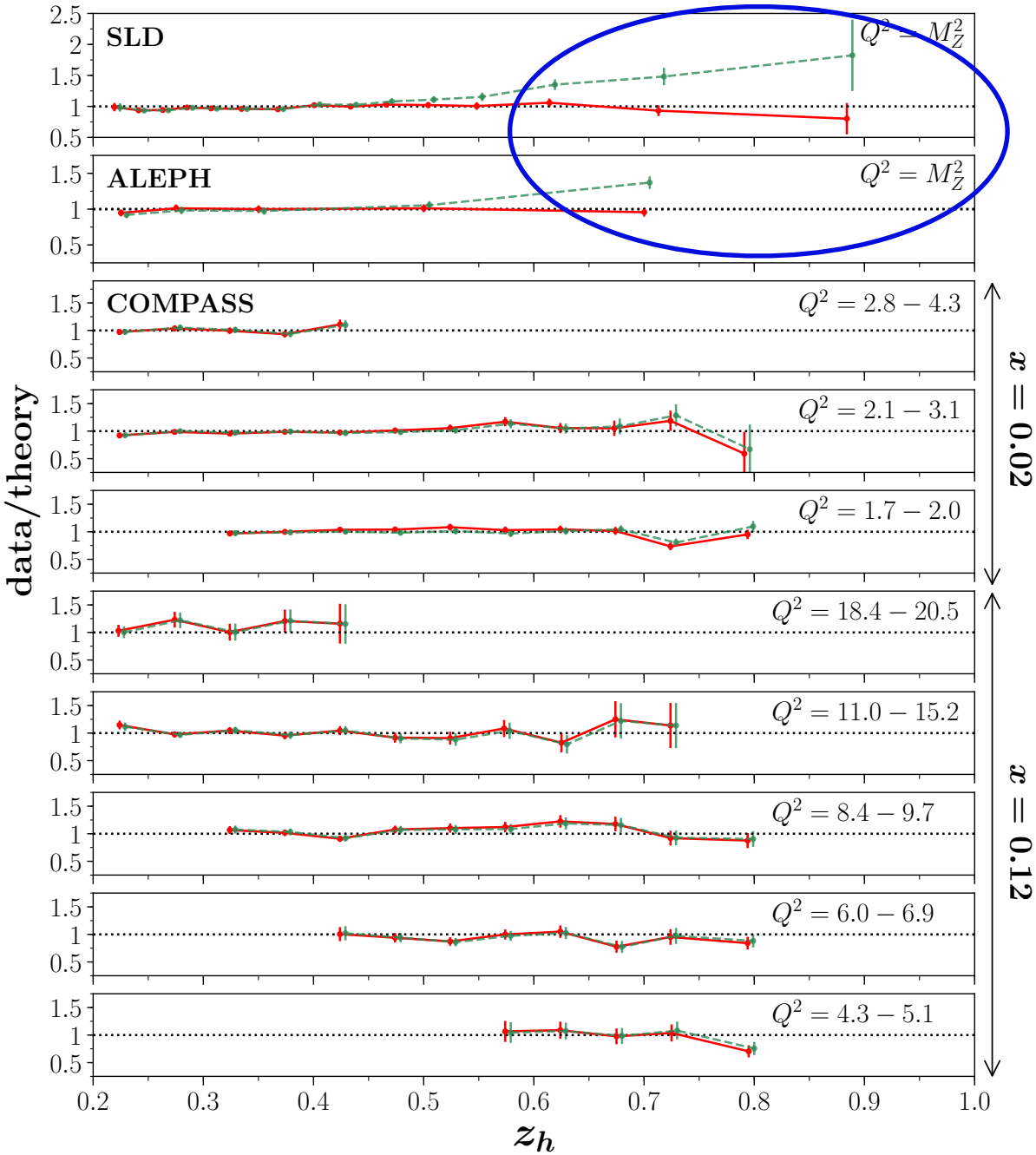
→ striking <u>suppression of strange</u> PDF compared to ATLAS extraction

JAM 2019 analysis



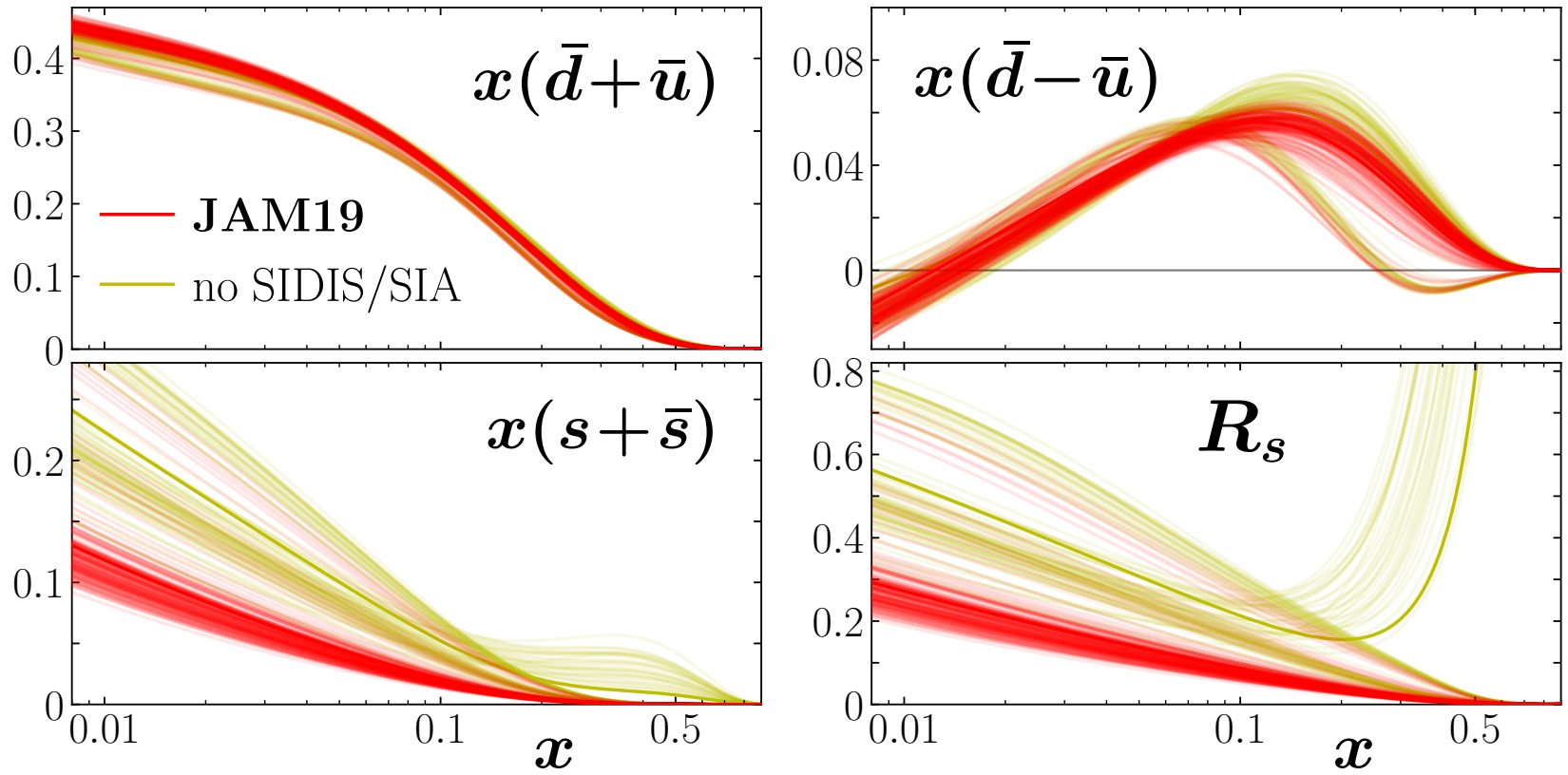
→ SIDIS + SIA data force strange to kaon FF to be larger

JAM 2019 analysis



← SIA data at large z strongly disfavor small strange to K FF

JAM 2019 analysis



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

PDFs in lattice QCD

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

$$h(z, P_z) = \langle\, P \,|\, \overline{\psi}(0, z)\, \gamma_z \mathcal{W}(z, 0)\, \psi(0, 0) \,|\, P \,\rangle$$

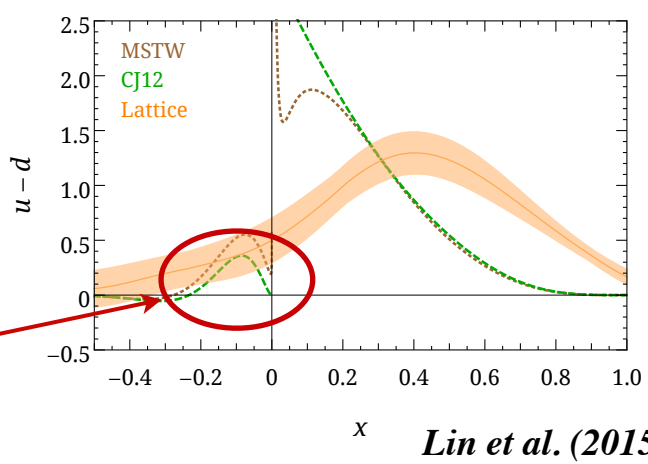
$$= \int_{-\infty}^{\infty} dy\; e^{iyP_z z}\; \widetilde{q}(y, P_z)$$

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

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

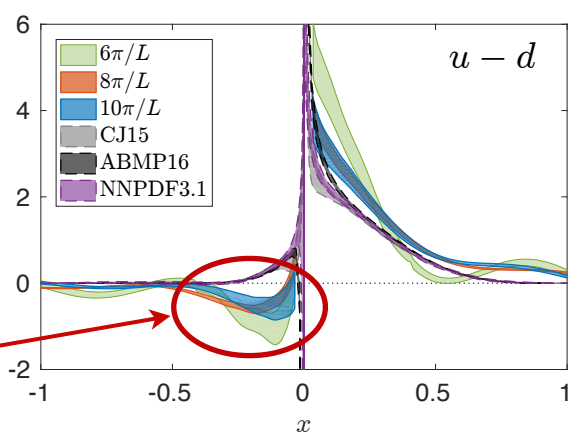
- Conflicting results on sign of $\bar{d} - \bar{u}$ asymmetry

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



Lin et al. (2015)

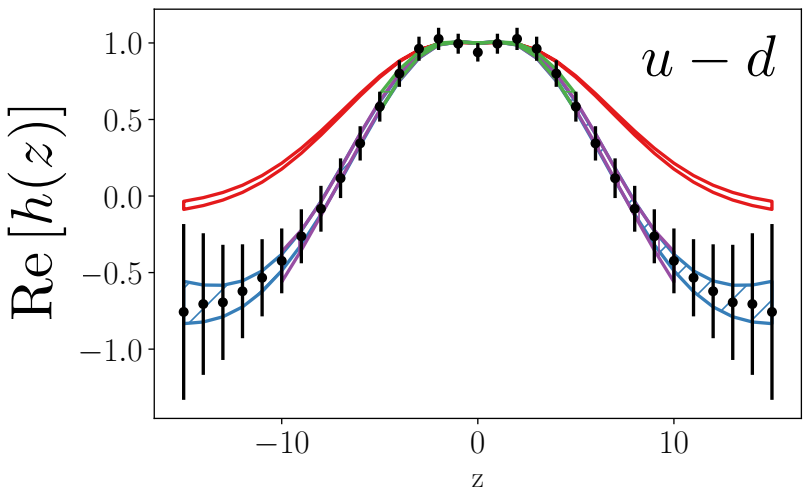
$\bar{d} < \bar{u}$

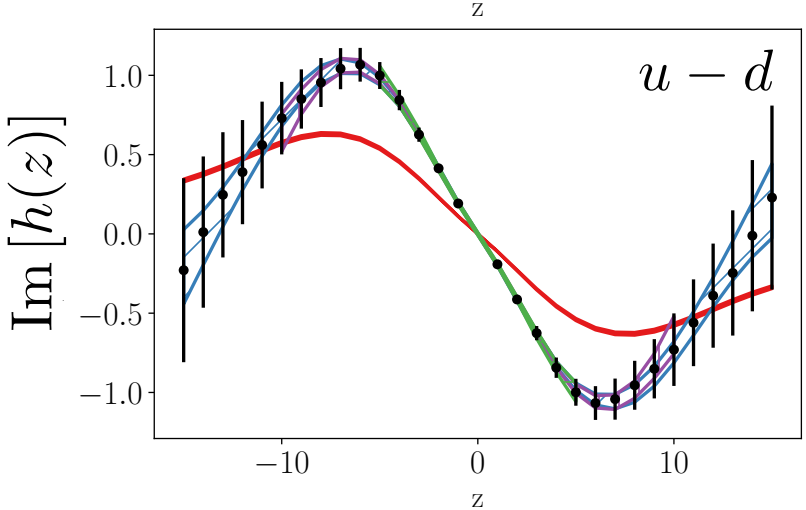


Alexandrou et al. (2018)

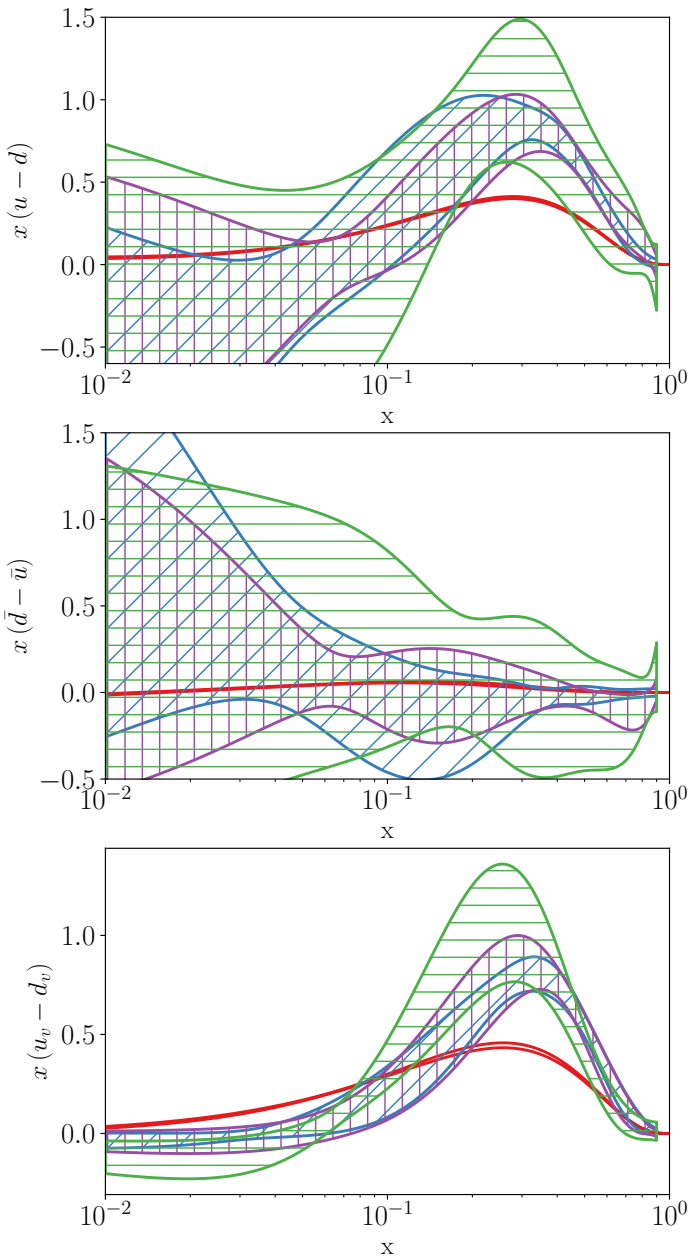
PDFs in lattice QCD

- Fit lattice observable directly within JAM framework





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



Bringewatt et al. (2019)

PDFs in lattice QCD

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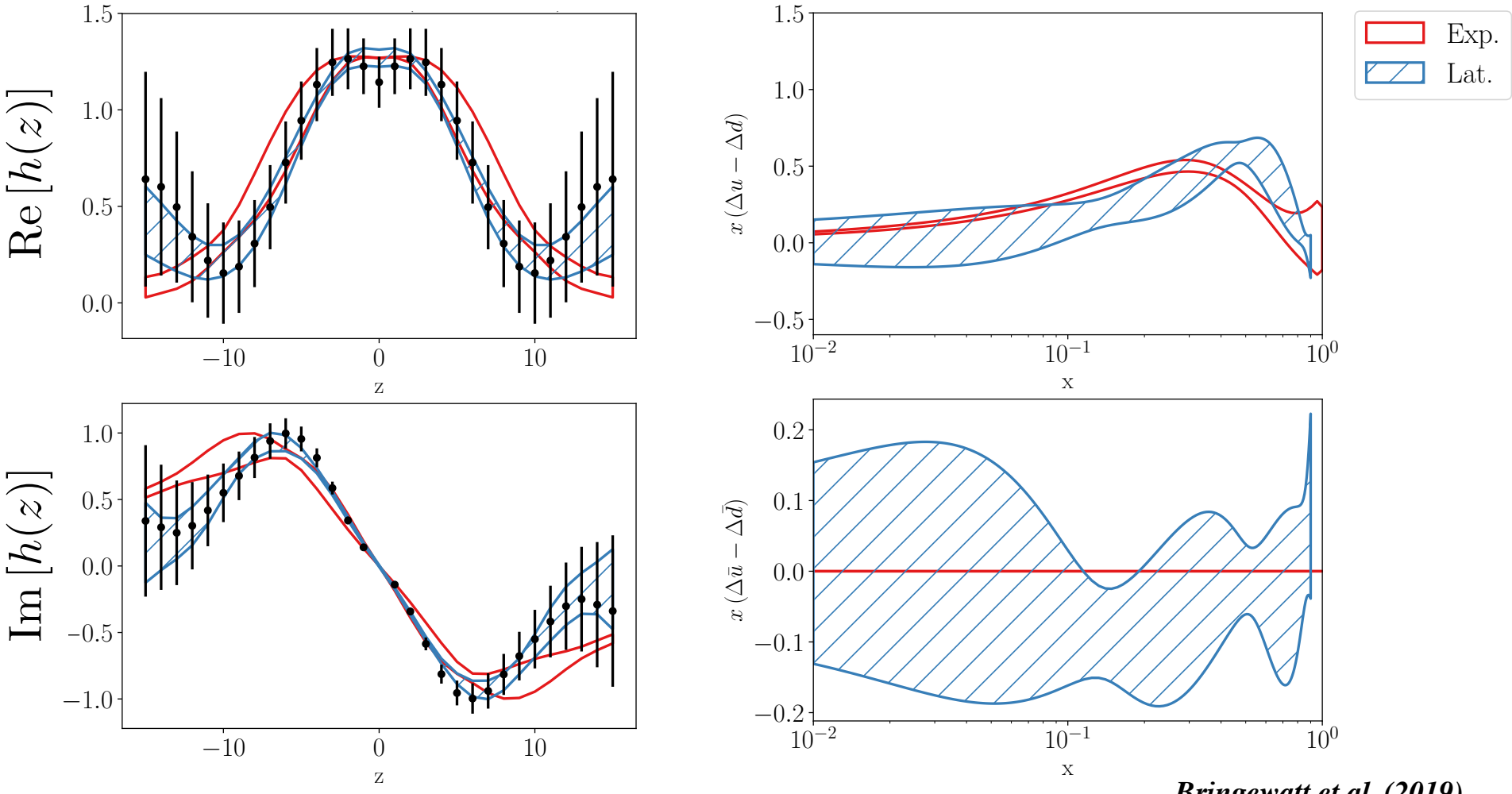

Bringewatt et al. (2019)

→ better agreement between lattice and experiment for polarized PDFs (within larger uncertainties)

Outlook

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

- Next steps: simultaneous analysis of all collinear distributions — unpolarized & polarized PDFs and FFs
  (including jet, W production, … data)

- Longer-term: technology developed here will be applied to global QCD analysis of transverse momentum dependent (TMD) distributions — map out full 3-d image of hadrons

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