*Computing in High Energy & Nuclear Physics (CHEP2019)*
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# MC methods for global QCD analysis of PDFs
## — *a new "simultaneous" paradigm* —

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— Jefferson Lab —

**JLab Angular Momentum Collaboration**

https://www.jlab.org/jam

# Overview

- JAM collaboration studies the parton structure of hadrons through extraction of "quantum probability distributions" (PDFs, FFs, TMDs) via global QCD analysis using MC-based methods

- Methodology is based on Bayesian statistics and Monte Carlo sampling of parameter space to account for multiple solutions

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

# Parton distributions in hadrons

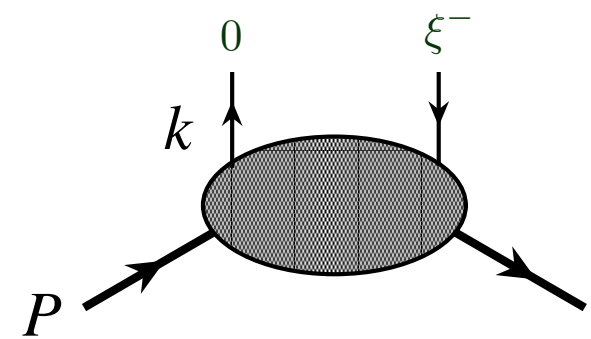
- Parton distribution functions (PDFs) are light-cone correlation functions

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

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

→ 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

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

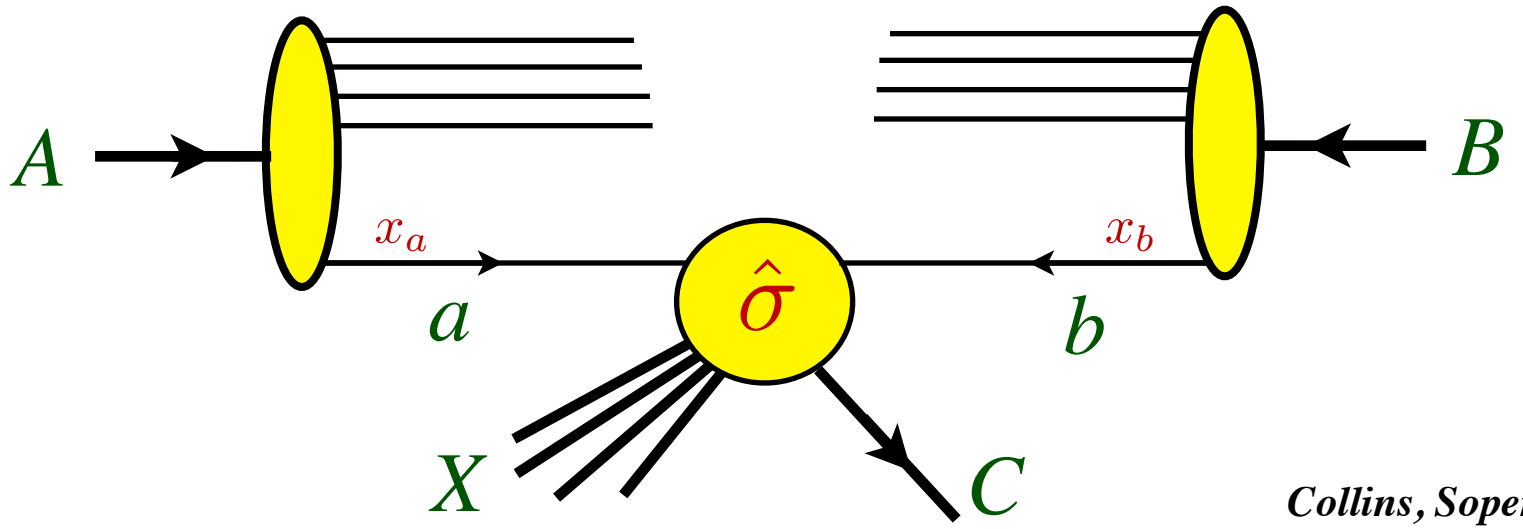
number density

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

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

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

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

# Global PDF analysis

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

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

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

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

- 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

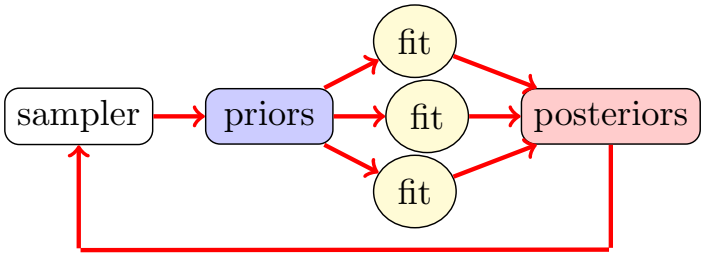
# JAM global QCD analysis

## Iterative, multi-step Monte Carlo

→ traditional functional form for distributions

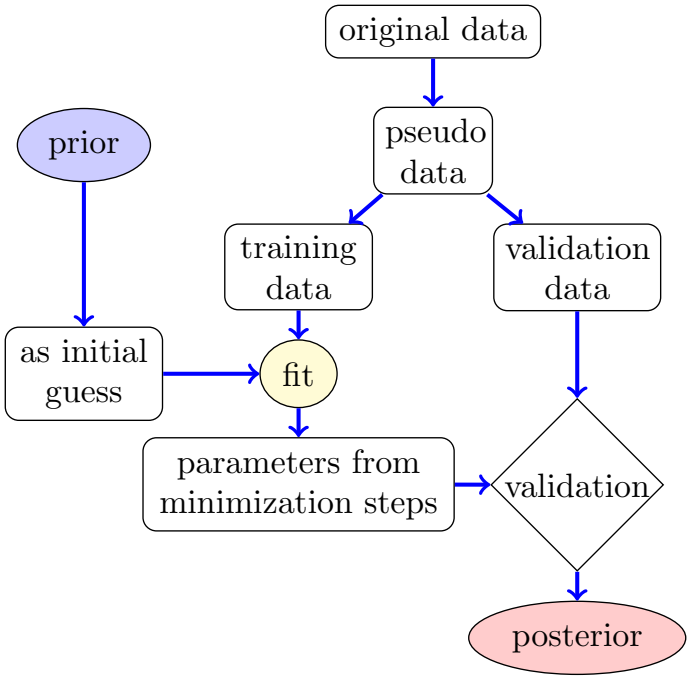
polynomial, neural net, …

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




but <u>sample large parameter space</u>

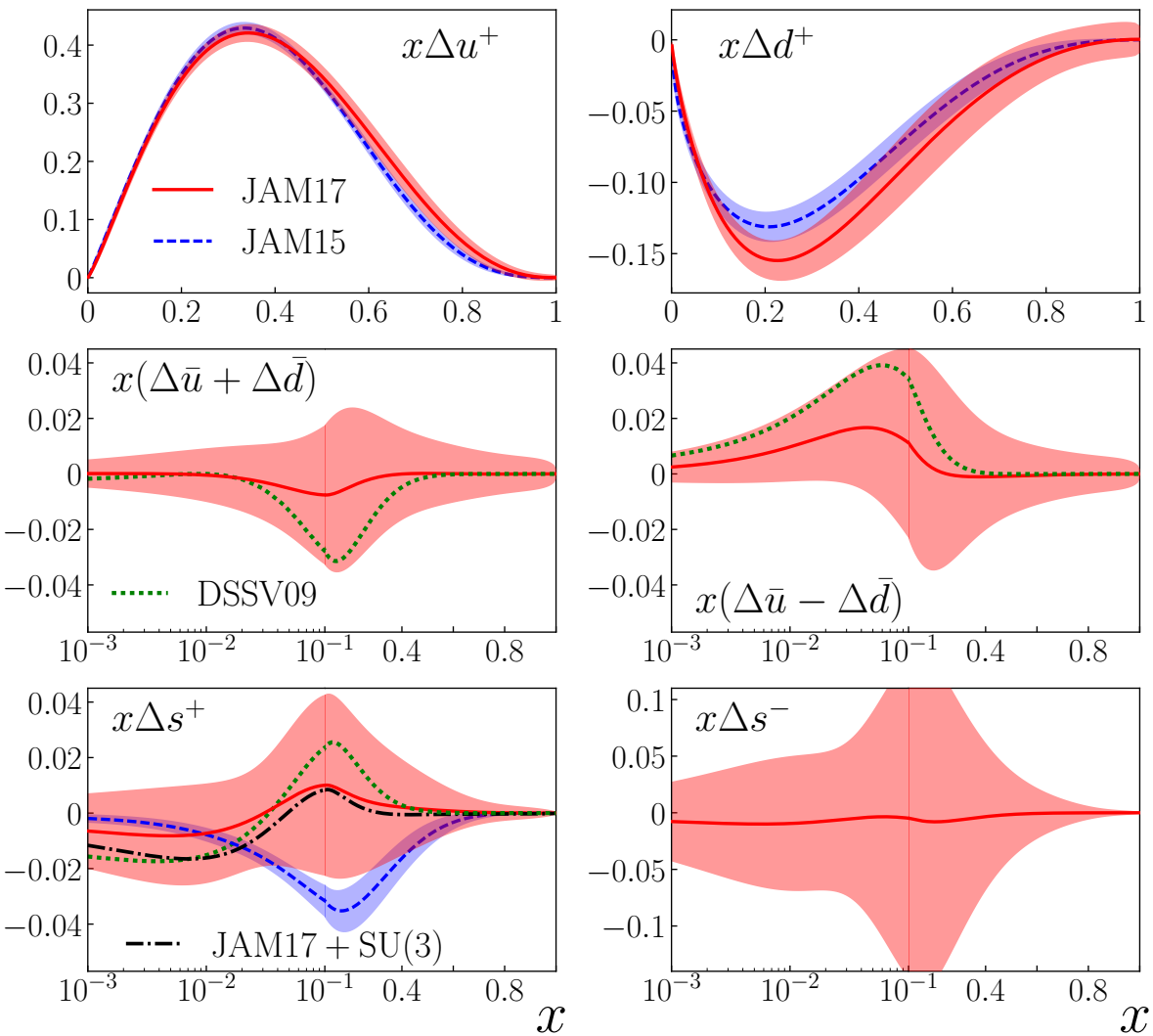
→ iterate until convergence
(posteriors = priors)




→ robust determination of
<u>PDF uncertainties</u>

# Simultaneous spin PDF + FF analysis

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




*Ethier, Sato, WM (2017)*

→ $s$-quark polarization *negative* from DIS alone

$$\Delta s \sim -0.1$$

(assuming SU(3) symmetry)

→ with SIDIS can relax SU(3) assumption

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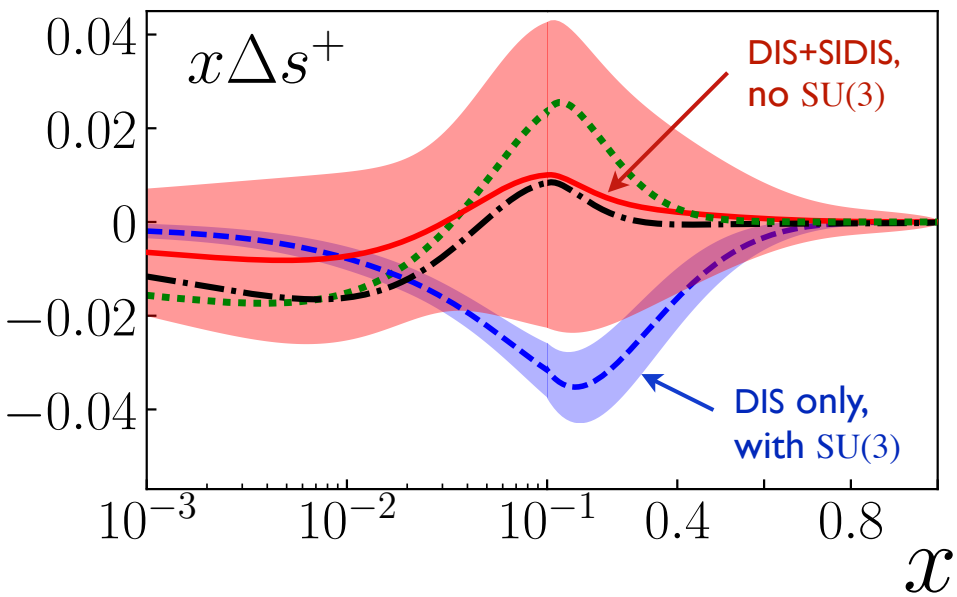



→ $s$-quark polarization *negative* from DIS alone

$$\Delta s \sim -0.1$$

(assuming SU(3) symmetry)

→ with SIDIS can relax SU(3) assumption

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

$$\Delta s = -0.03(10)$$

→ gives larger total helicity

$$\Delta\Sigma = 0.36(9)$$

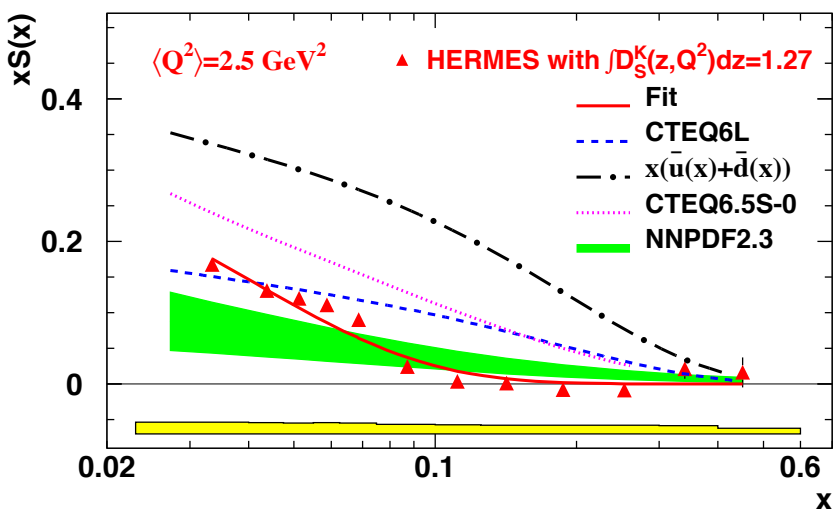
# Simultaneous spin PDF + FF analysis

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

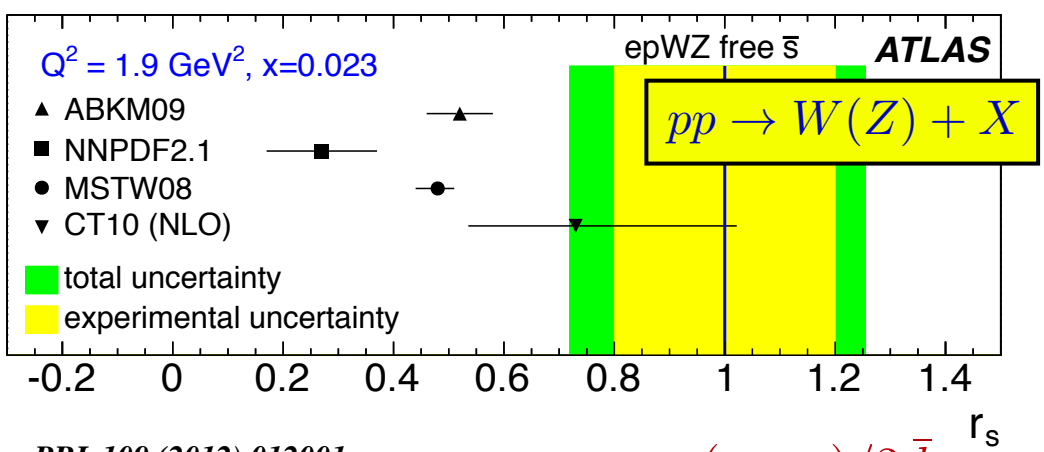
  → only systematic way is to fit unpolarized PDFs, polarized PDFs and fragmentation functions simultaneously

- Shape of unpolarized strange PDF is also controversial!

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




*PRD 89 (2014) 097101*




*PRL 109 (2012) 012001*

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

# JAM 2019 analysis

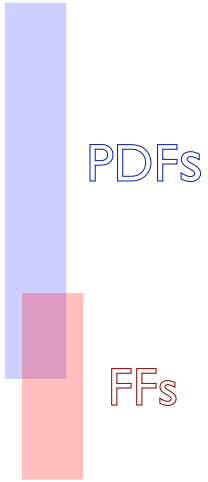
- Study the impact of SIDIS data on <u>unpolarized</u> PDFs

  → 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)

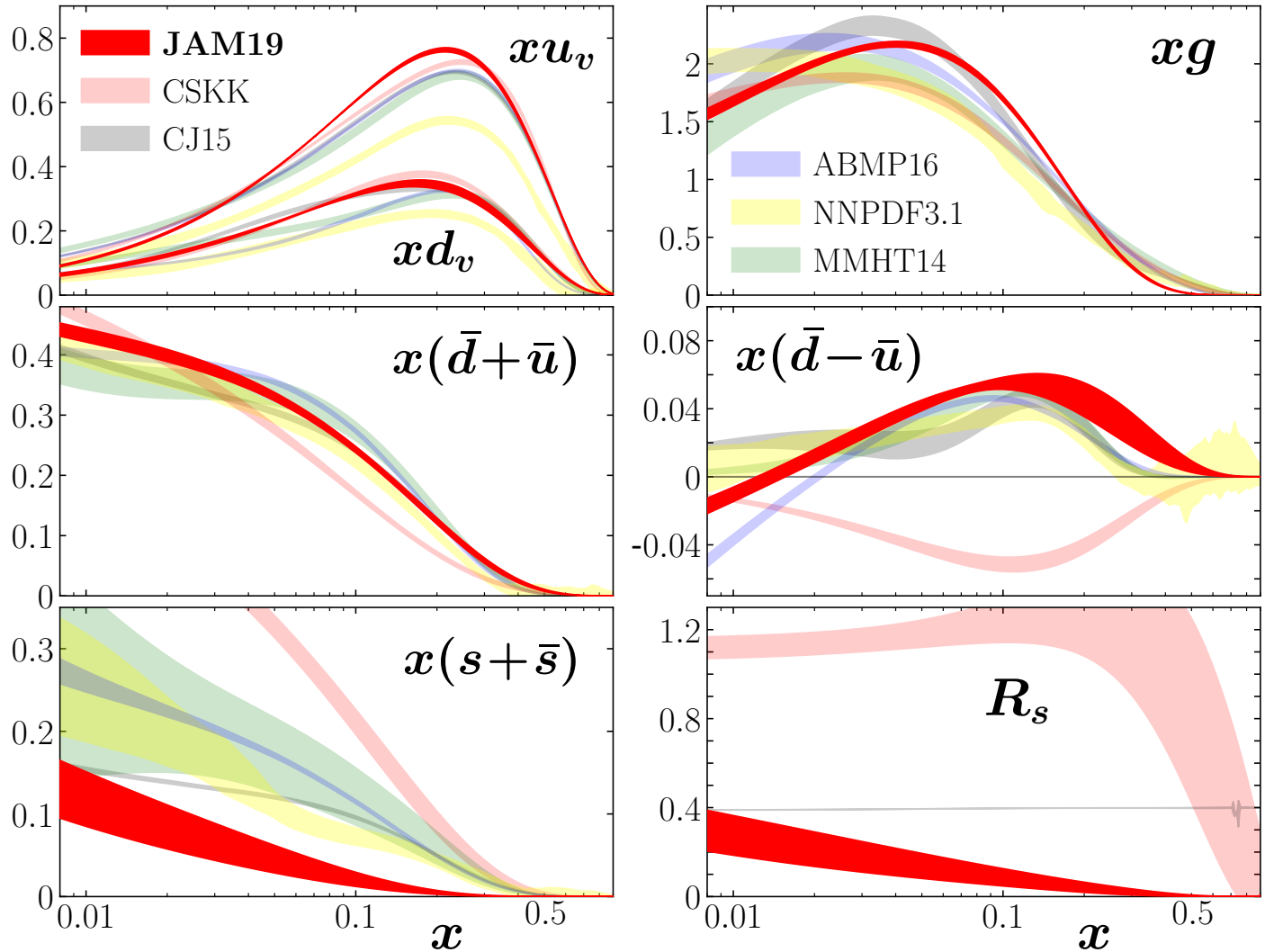



- 52 shape parameters + 41 "nuisance" parameters for systematic uncertainties (data normalizations)

- 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



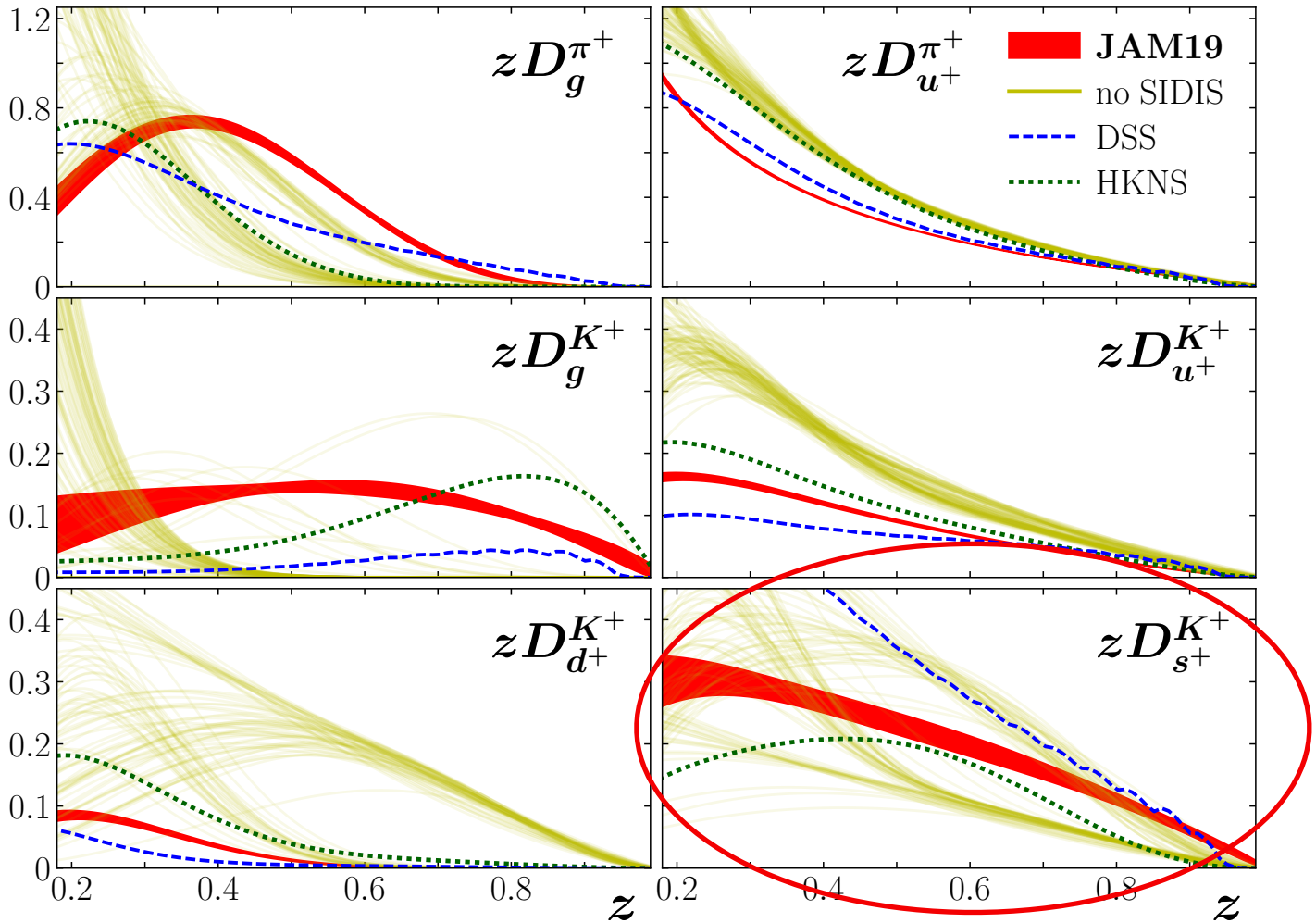

mean reduced $\chi^2 = 1.3$ for all data

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

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

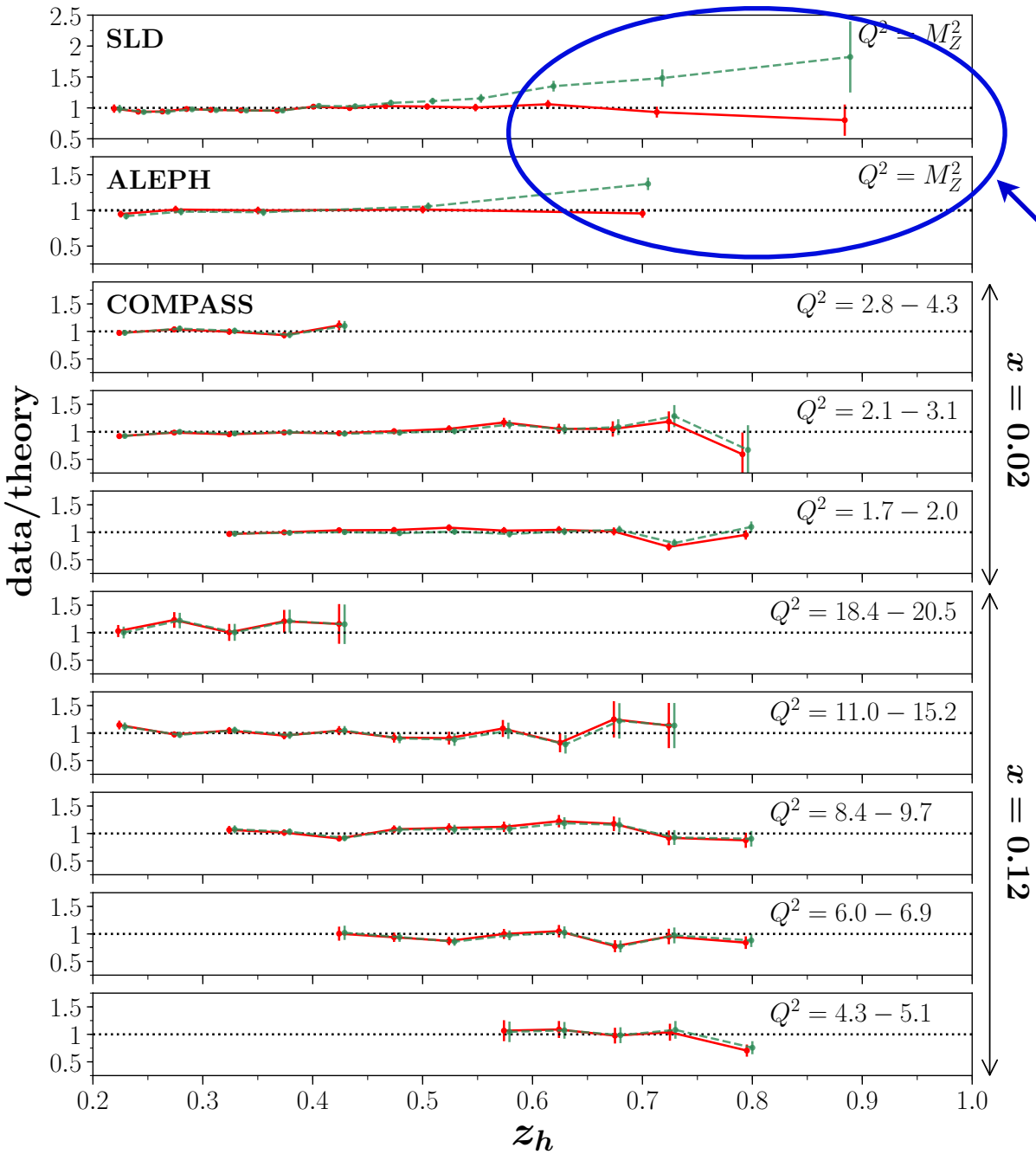
→ striking <u>suppression of strange</u> PDF compared to ATLAS extraction

# JAM 2019 analysis




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

# JAM 2019 analysis



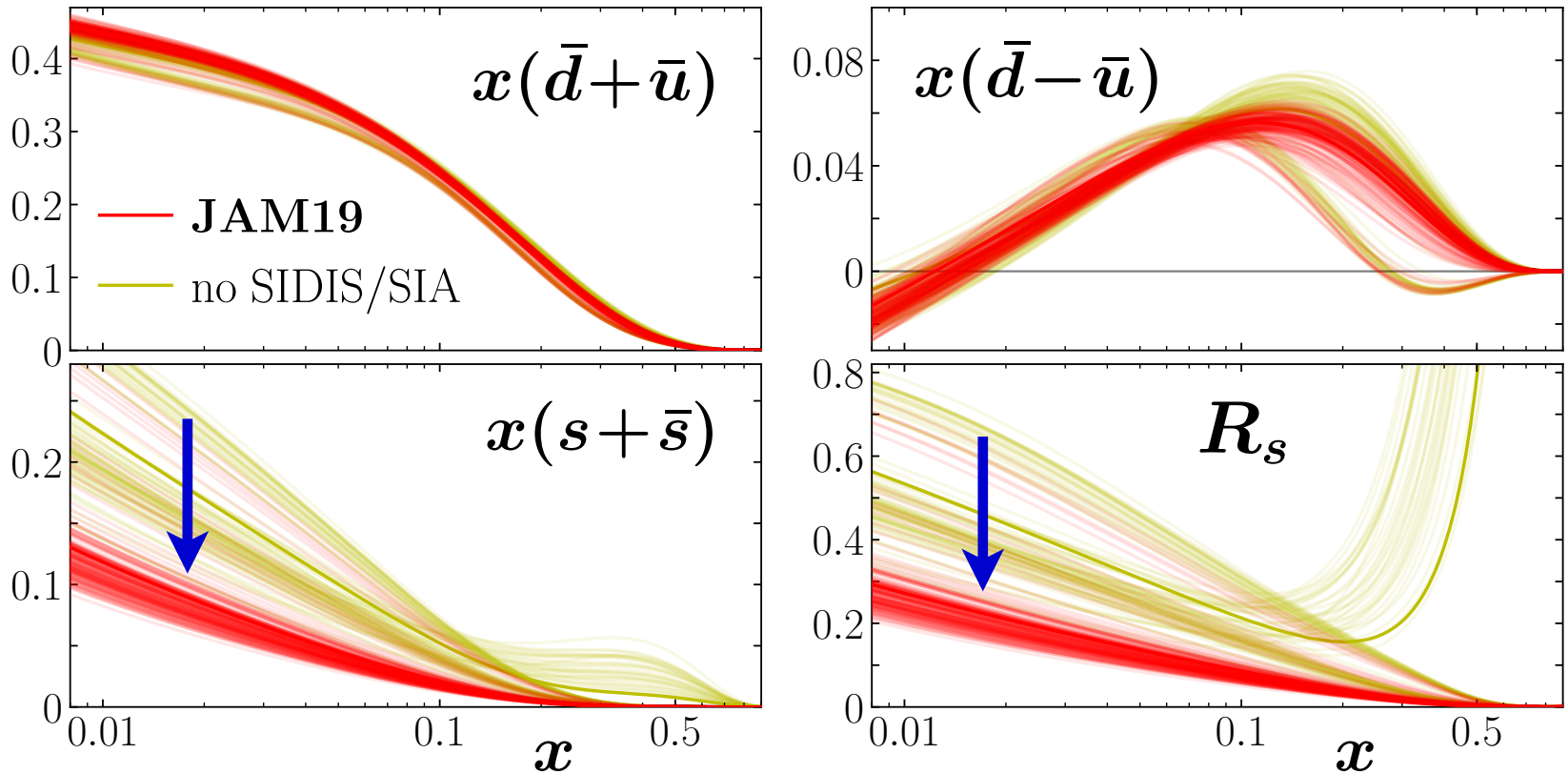

- - - - - solutions with large $s(x)$

——— fully constrained solutions

SIA data at large $z$ strongly <u>disfavor</u> <u>small strange → $K$ FF</u>

larger strange → $K$ FF then requires strange PDF to be smaller

# JAM 2019 analysis




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

→ could not have seen this without simultaneous MC analysis

# Outlook

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

  → JAM19 simultaneous analysis of unpolarized PDFs & FFs reveals significantly smaller strange quark PDF than reported by ATLAS

- Technology developed will be applied to global QCD analysis of transverse momentum dependent (TMD) distributions

  — map out full 3-d image of hadrons (JLab, Electron-Ion Collider)

- Longer term: global QCD analysis is ripe for application of machine learning techniques

  → solving "inverse problem" (Center for Nuclear Femtography)

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