Nature of Hadron Mass and Quark-Gluon Confinement
from JLab Experiments in the 12-GeV Era

APCTP, Pohang, Korea, July 1, 2018

Parton distributions in hadrons: nucleon and pion

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JLab Angular Momentum collaboration **CTEQ-Jefferson Lab collaboration**

Outline

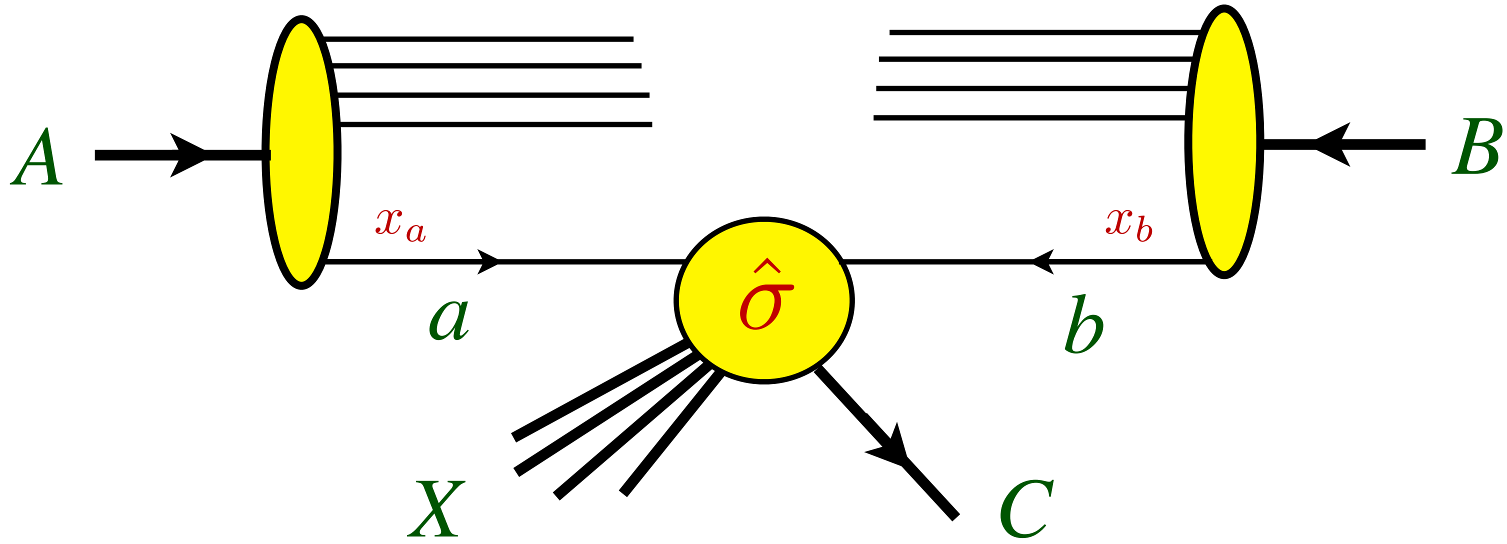
- *Aim*: understand internal quark-gluon structure of hadrons
- *Method*: extract parton distribution functions (PDFs) from global QCD analysis, using new Monte Carlo-based methods

Recent highlights:

- Constraints from Fermilab & JLab data on unpolarized PDFs at high x
- 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
- First extraction of pion PDFs from Drell-Yan and HERA leading neutron production data

Parton distributions in hadrons

- Generic process: inclusive particle production $A\,B \to C\,X$



$$\sigma_{AB\to CX}(p_A, p_B) = \sum_{a,b} \int dx_a\, dx_b\, f_{a/A}(x_a, \mu)\, f_{b/B}(x_b, \mu)$$

"factorization"

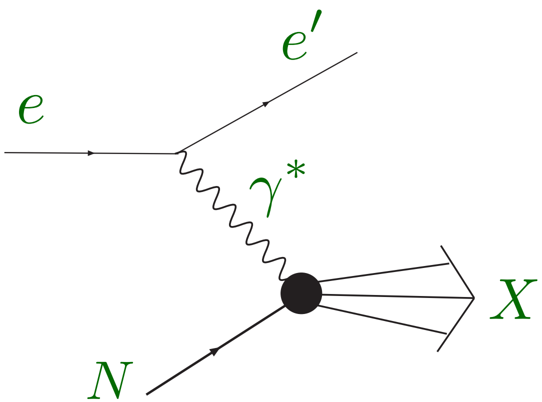
$$\times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}(x_a p_A, x_b p_B, Q/\mu)$$

Collins, Soper, Sterman (1980s)

⟶ universal functions $f_{a/A}$ characterize internal structure of bound state A

Parton distributions in hadrons

- Most information on parton distribution functions obtained from inclusive deep-inelastic scattering (DIS)



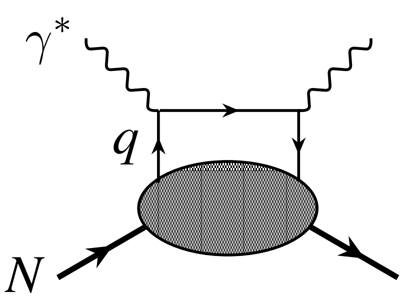
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$\nu = E - E'$$
$$Q^2 = \vec{q}^{\,2} - \nu^2$$
$$W^2 = M^2 + Q^2\frac{(1-x)}{x}$$

$$x = \frac{Q^2}{2M\nu}$$

- At leading order (LO) in pQCD, structure functions given in terms of charge-weighted sums of PDFs

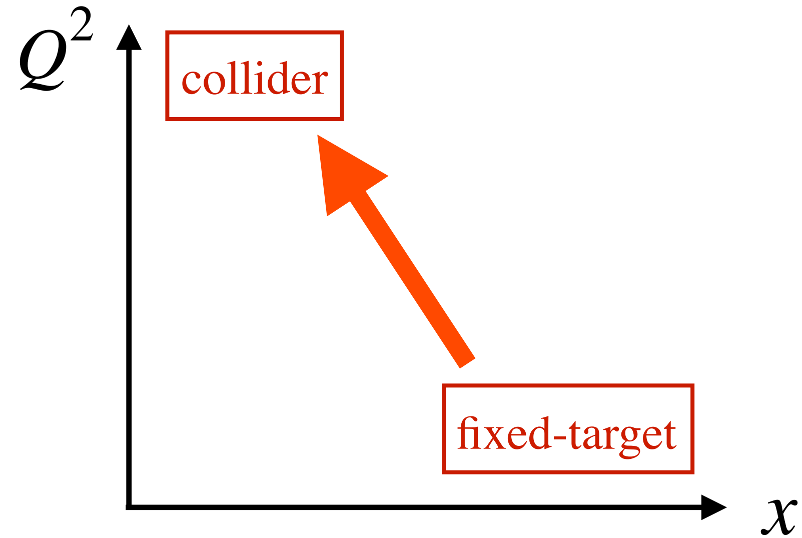
$$F_2(x, Q^2) = x\sum_q e_q^2\, q(x, Q^2)$$



Parton distributions in hadrons

- Precision PDFs needed to
  (1) understand basic structure of QCD bound states
  (2) compute backgrounds in searches for BSM physics

$\rightarrow$ Q^2 evolution feeds
low x, high Q^2 ("LHC")
from high x, low Q^2 ("JLab")



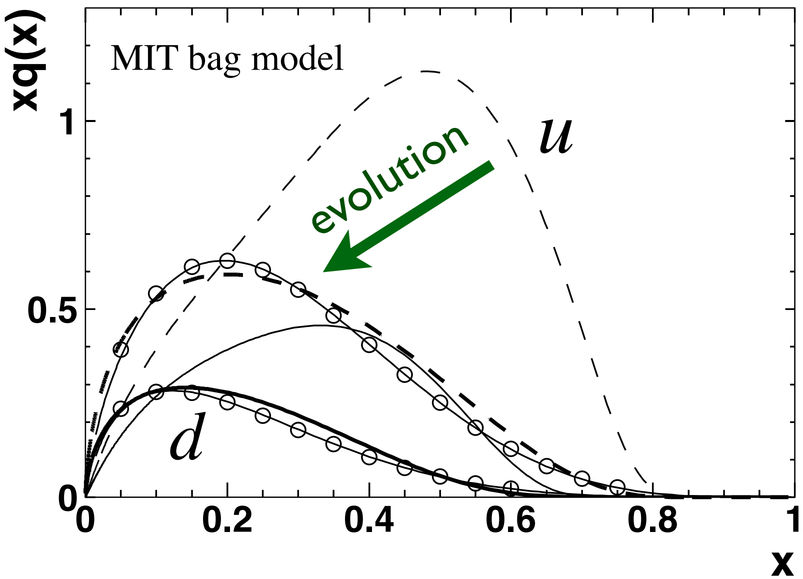
- Information on PDFs obtained from
  (1) nonperturbative approaches (low-energy models, DSE, χEFT)
  (2) lattice QCD
  (3) global QCD analysis

Parton distributions in hadrons

- Compute matrix element of leading twist operator at a low scale μ; evolve PDF to higher Q^2 using DGLAP

$$q(x,\mu) = \frac{M}{(2\pi)^3} \sum_n \int d^3p_n \left| \langle n | \gamma_- \gamma_+ \psi(0) | N \rangle \right|^2 \delta\left((1-x)M - p_n^+ \right)$$

Jaffe (1975, 1983)
Parisi, Petronzio (1976)



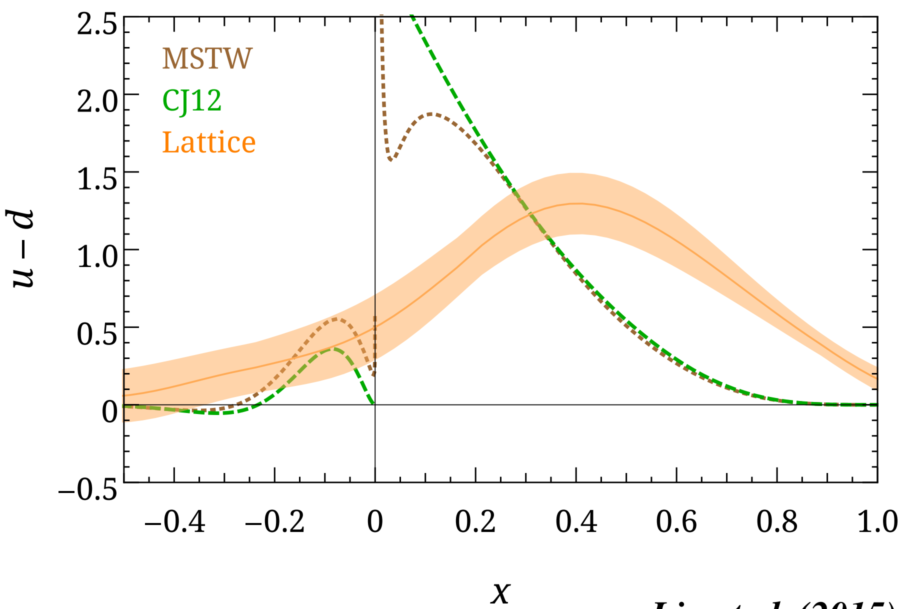
Boros, Thomas (1999)

$\longrightarrow$ reasonable phenomenology, but evolution (questionable at low scales $\sim 0.1\text{–}0.5\ \text{GeV}^2$??) "washes out" many differences between models

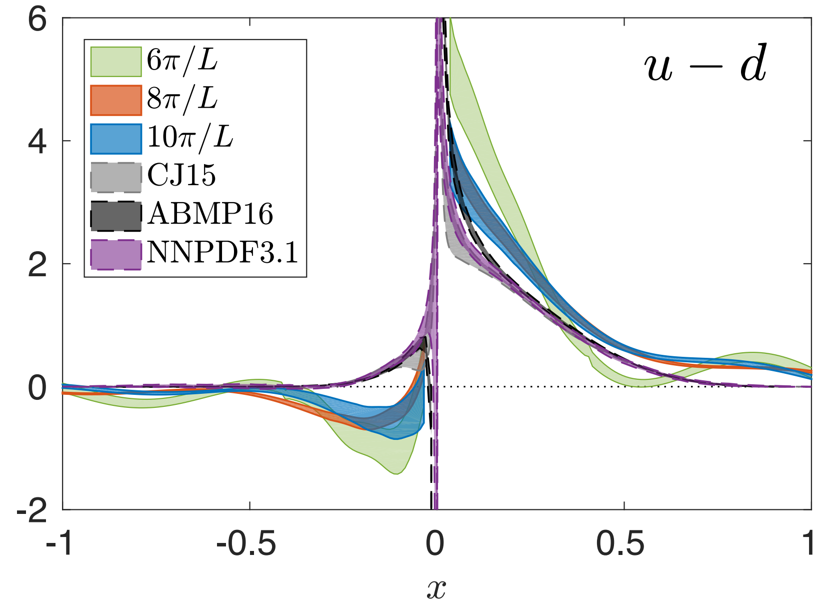
Parton distributions in hadrons

- More recently, significant progress made towards computing x dependence of PDFs directly on lattice

X. Ji (2013); Ma, Qiu (2014)
Radyushkin (2017)



Lin et al. (2015)



Alexandrou et al. (2018)

$$q(x,\mu) = \int_{-\infty}^{\infty} \frac{d\xi}{|\xi|}\, C(\xi, \mu/xP_z)\, \tilde{q}(x/\xi, \mu, P_z)$$

$$\tilde{q}(x,P) = \int \frac{dz}{4\pi} e^{-ixPz} \langle P|\bar{\psi}(0,z)\gamma_z W(z)\, \psi(0,0)|P\rangle$$

"quasi-PDF"

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

  → CTEQ, MRS/MMHT, HERAPDF, DSSV, ...
  use standard maximum likelihood methods (χ^2 minimization)

  → NNPDF, JAM
  use Monte Carlo 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, ...

  → *multiple local minima* present in the χ^2 function

  → thoroughly scan over sufficiently large parameter space

Global PDF analysis

- A major challenge has been to characterize PDF *uncertainties*, especially in the presence of *tensions* among data sets

- Previous attempts sought to address tensions in data sets by introducing

  $\longrightarrow$ "tolerance" factors (artificially inflating PDF errors)

  $\longrightarrow$ "neural net" parametrization (instead of polynomial parametrization), together with MC techniques

- However, to address the problem in a more statistically rigorous way, one requires going *beyond* the standard χ^2 minimization paradigm

  $\longrightarrow$ utilize modern techniques based on Bayesian statistics

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

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

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

"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 $\mathcal{L}$

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

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

$\longrightarrow$ 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 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

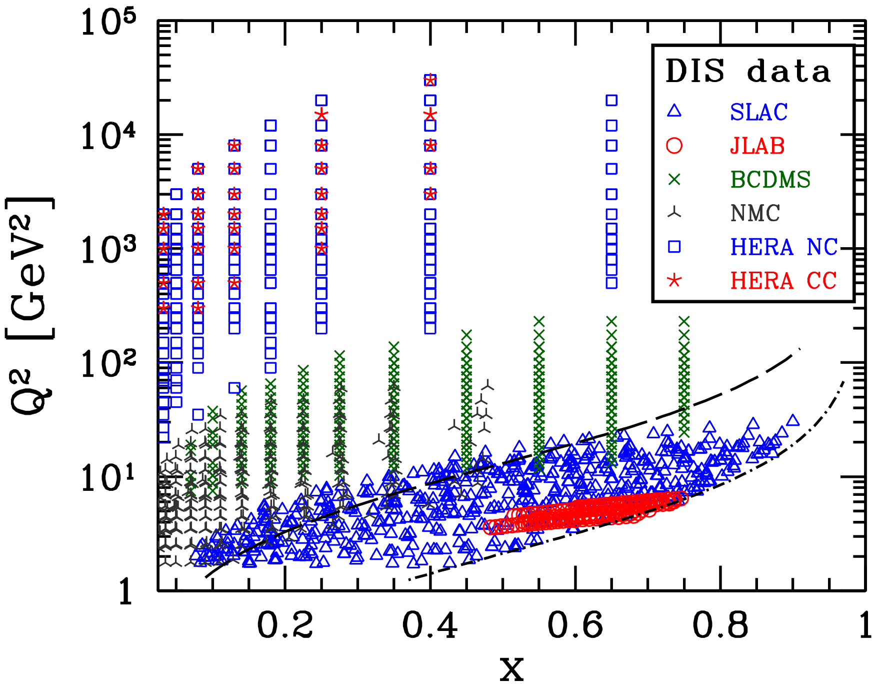
Gbedo, Mangin-Brinet (2017)

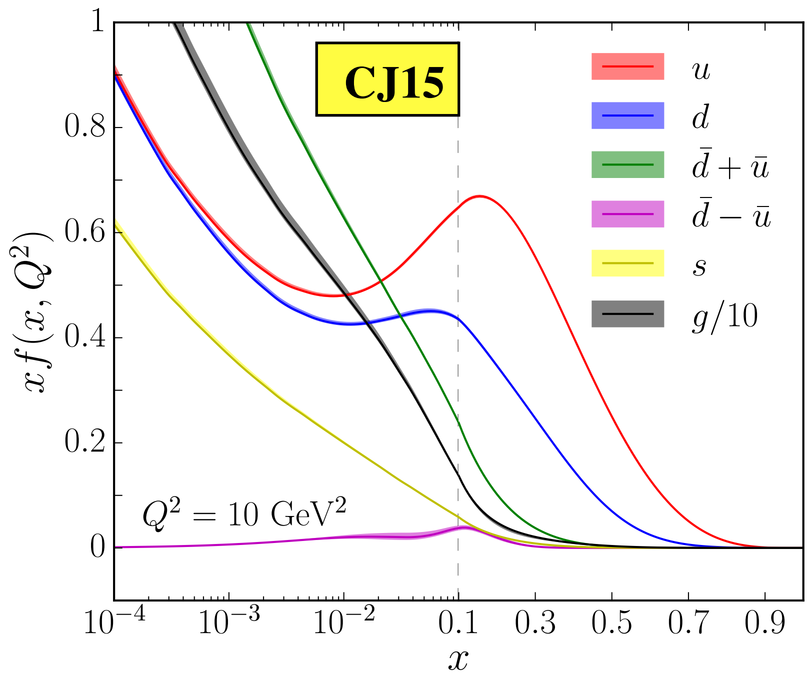
- Nested sampling (NS) — computes integrals in Bayesian master formulas (for E, V, Z) explicitly *Skilling (2004)*

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

Unpolarized PDFs

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

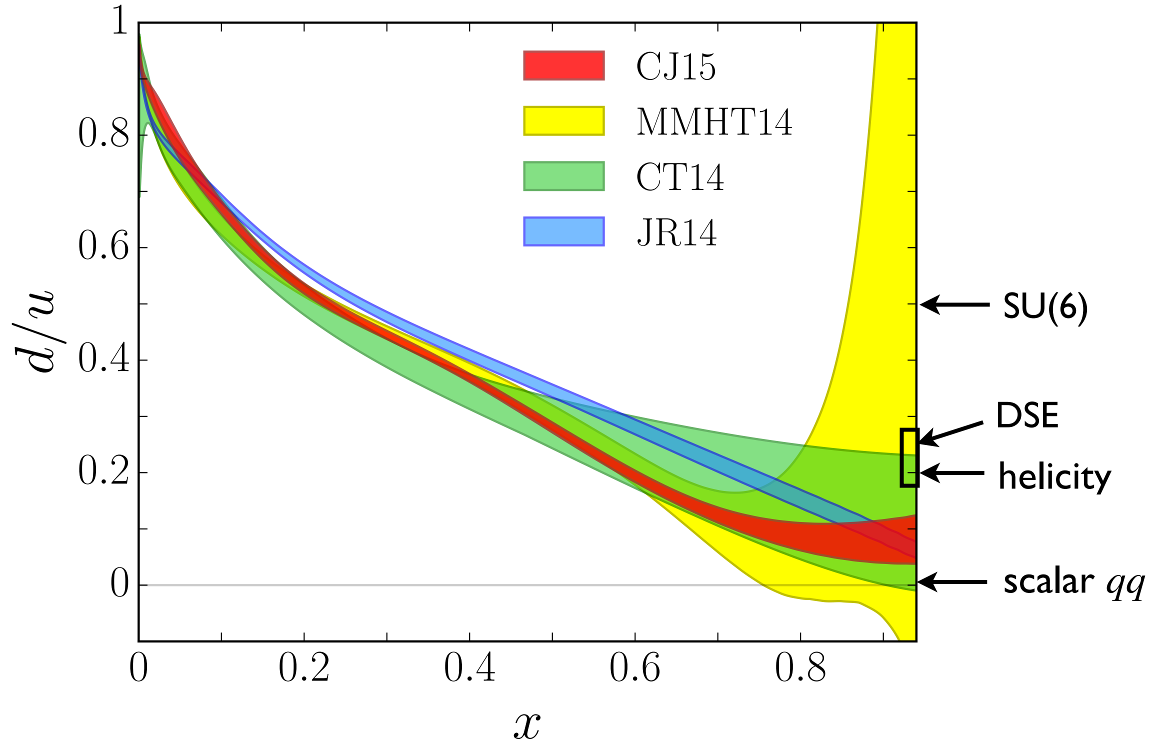
→ testing ground for nucleon models in $x \to 1$ limit

- $d/u \to 1/2$
  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!)

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

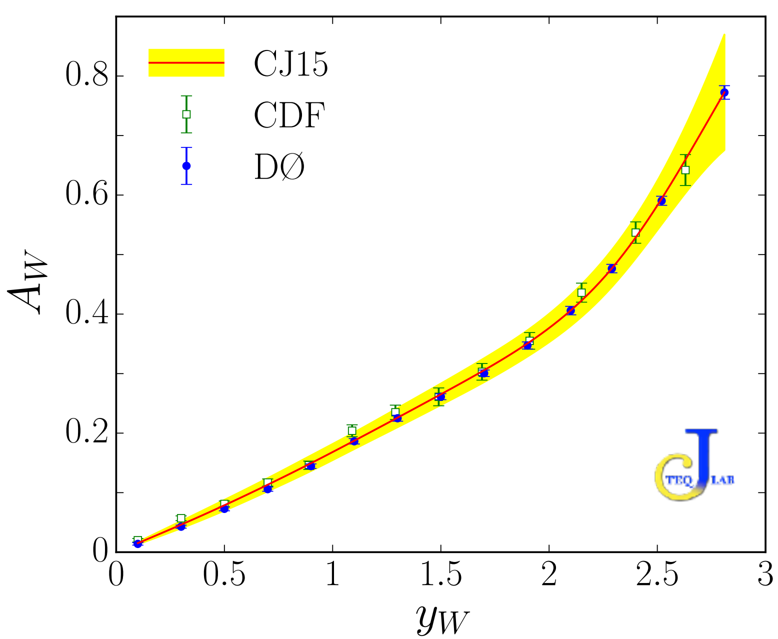
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\ |\psi_d(p)|^2\ \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big) \times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

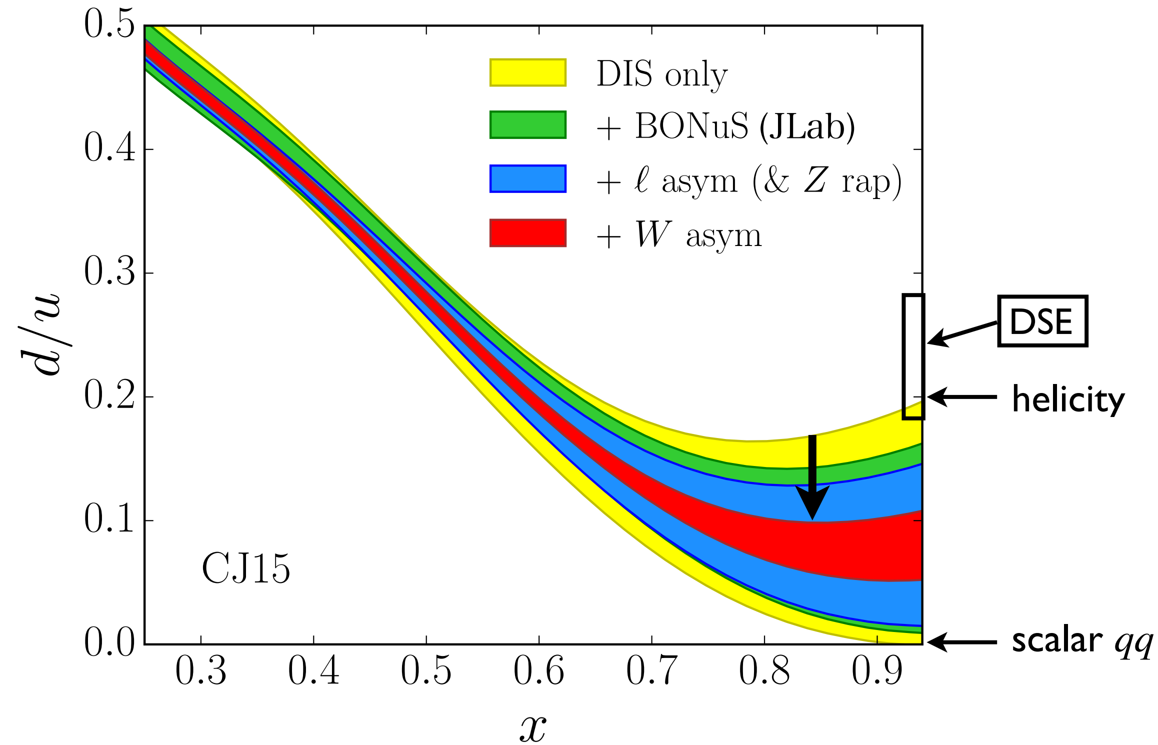
Unpolarized PDFs

- 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 $x \sim 0.85$

Nucleon
Helicity PDFs

Proton spin structure

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

→ in nonrelativistic quark model, spin of proton is carried entirely by quarks $\Delta\Sigma = \Delta u^+ + \Delta d^+ + \Delta s^+ = 1$ while early data suggested that

$\Delta q^+ \equiv \Delta q + \Delta\bar{q}$

$$\Delta\Sigma \approx 0\ ! \qquad \Delta s^+ \approx -(0.1 - 0.2)$$

EMC (1988)

→ proton spin sum requires

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

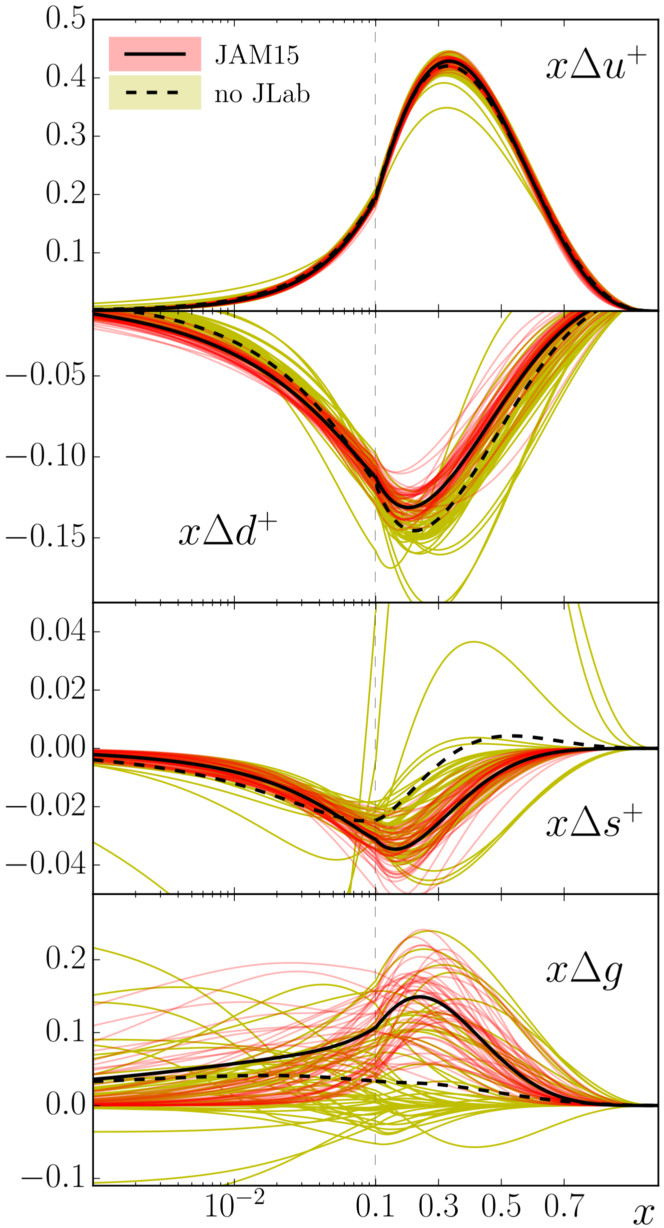
… does remaining spin come from large *gluon* polarization or *orbital* angular momentum?

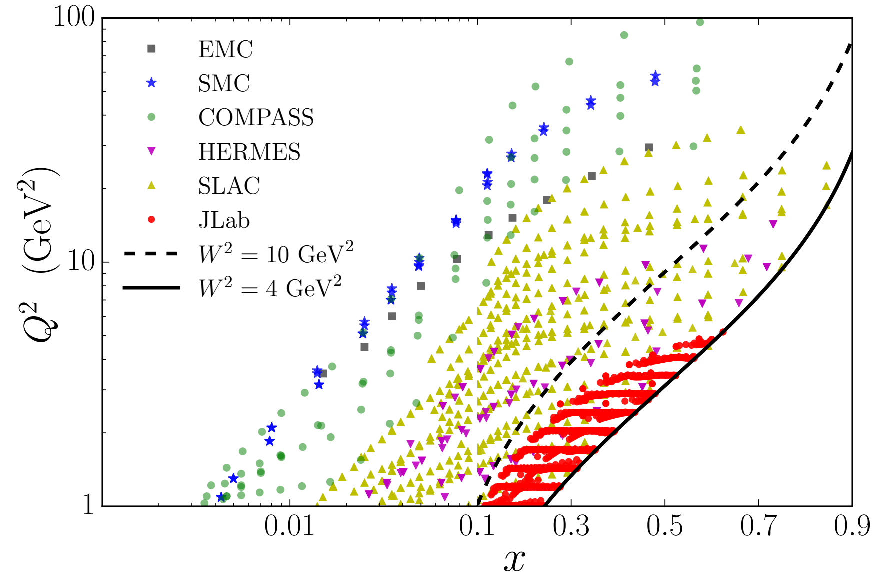
→ stimulated many advances in theory, experiment & analysis

→ recent JAM global analyses, including JLab 6 GeV data

Proton spin structure

Impact of JLab data





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

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

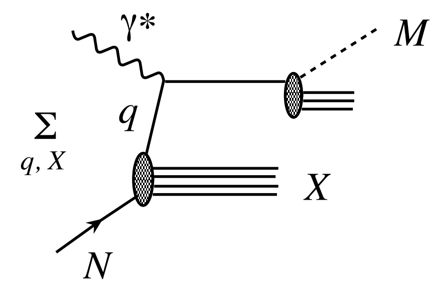
→ s-quark polarization *negative* from inclusive DIS data (assuming SU(3) symmetry)

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!

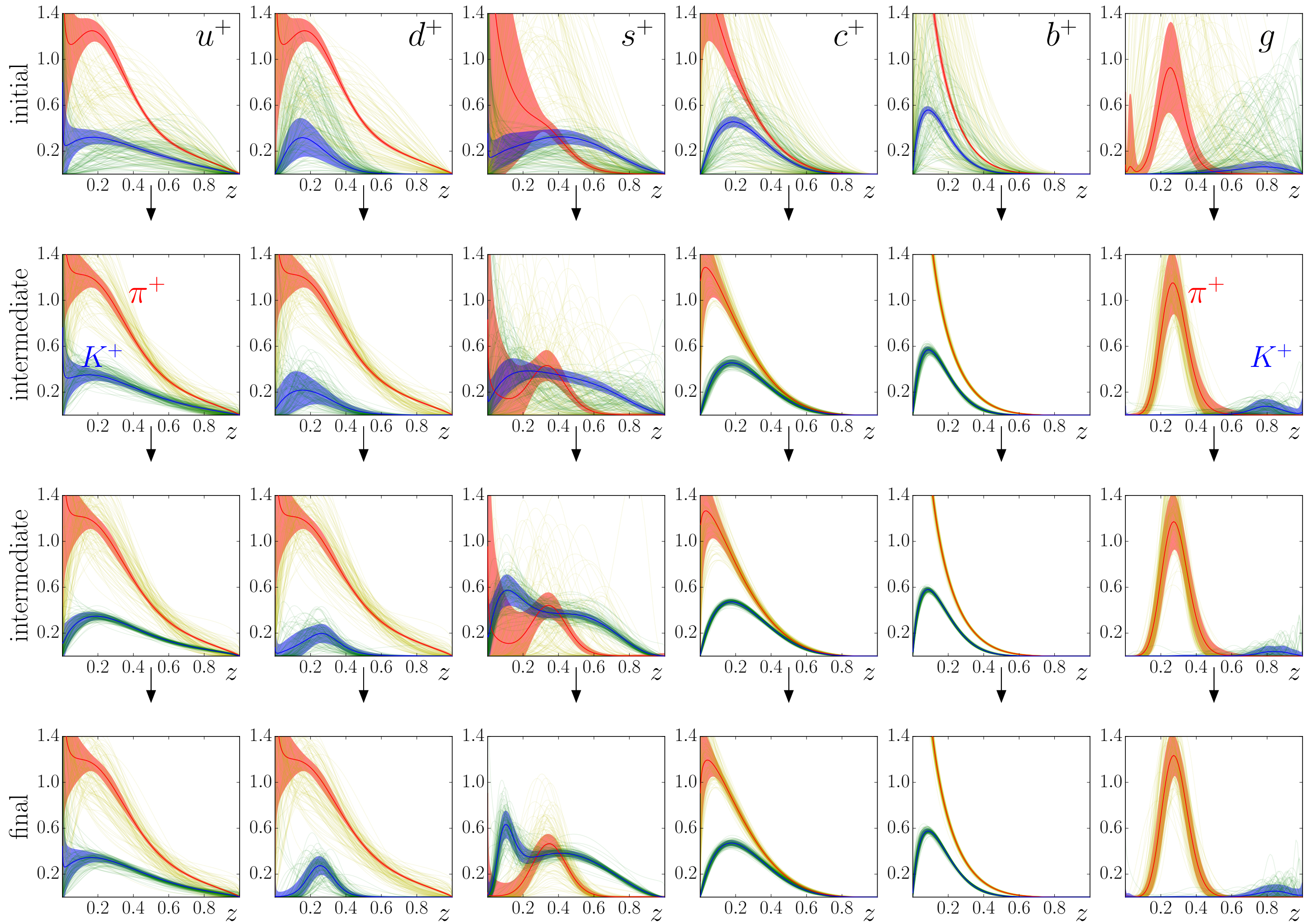
→ $\Delta s > 0$ for "DSS" FFs *de Florian et al. (2007)*

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

→ need to understand origin of differences in fragmentation!

Polarization of quark sea?

- First MC analysis of fragmentation functions



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

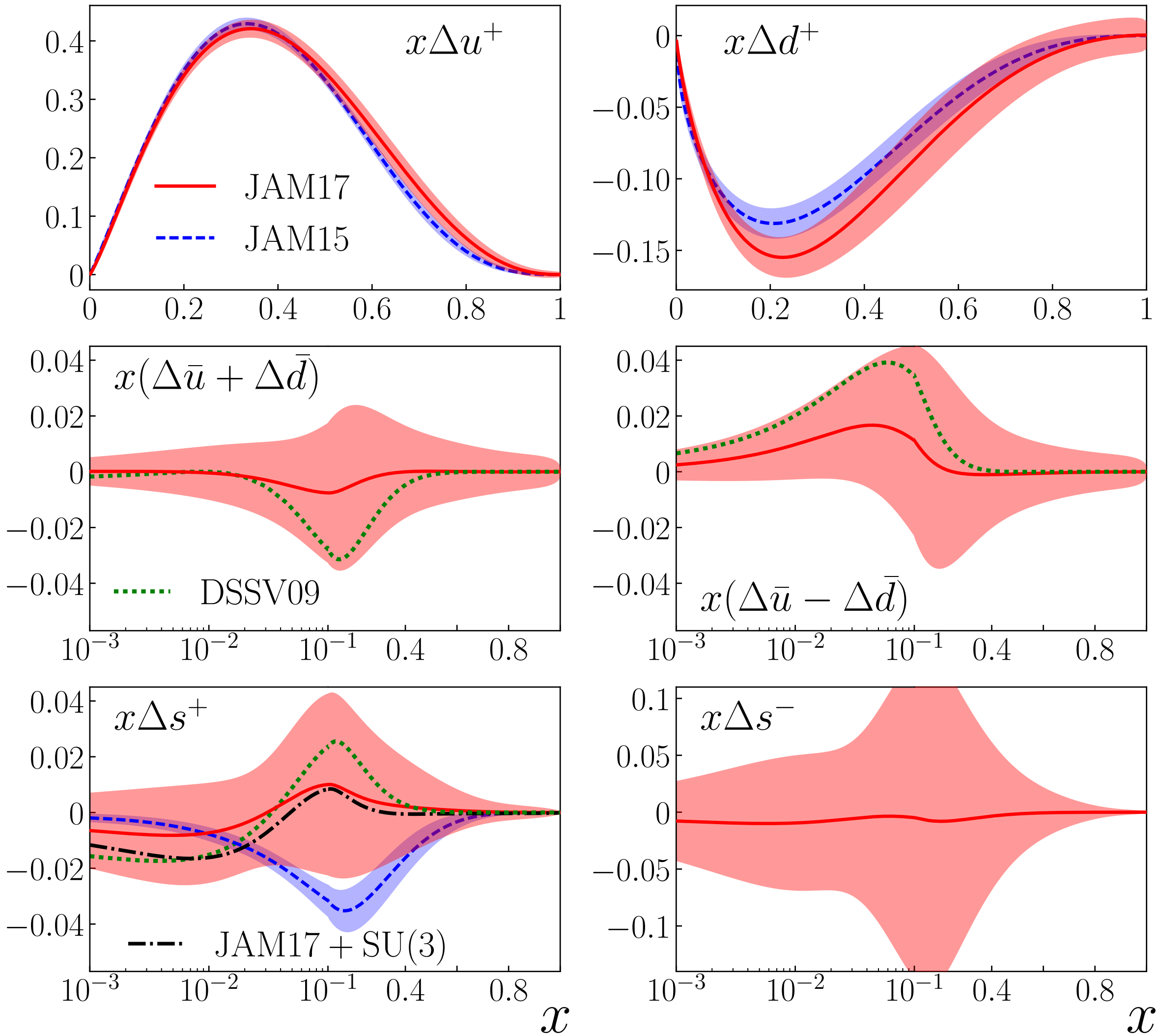
single-inclusive annihilation (SIA)

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

$\longrightarrow$ convergence after ~ 20 iterations

Polarization of quark sea?

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



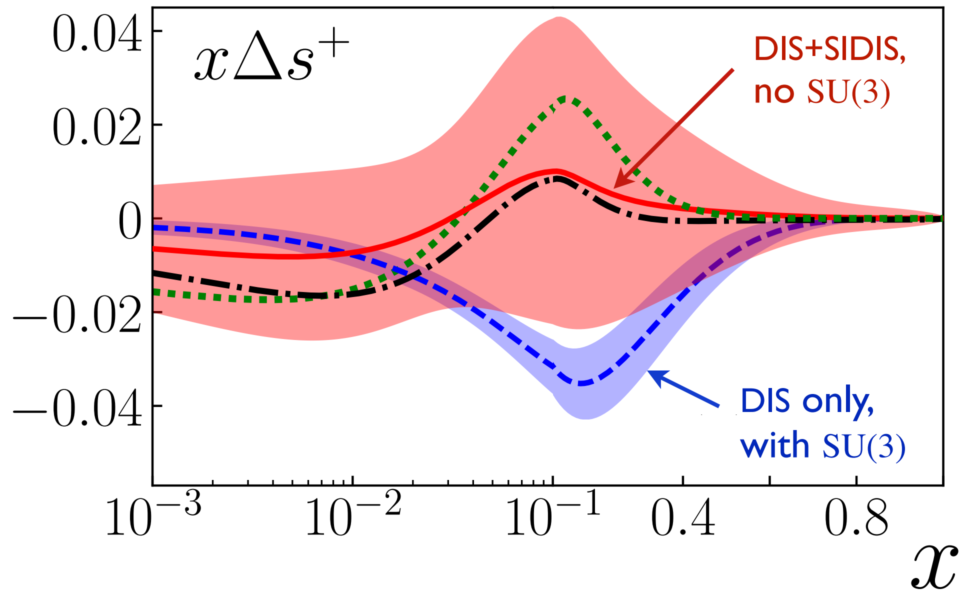
→ no assumption of SU(3) symmetry

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

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

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 $\Delta\Sigma = 0.36(9)$

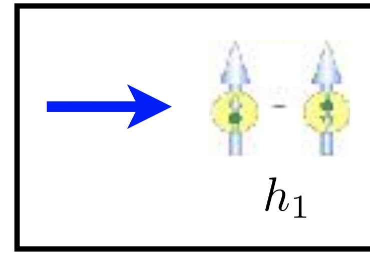
Nucleon Transversity PDFs

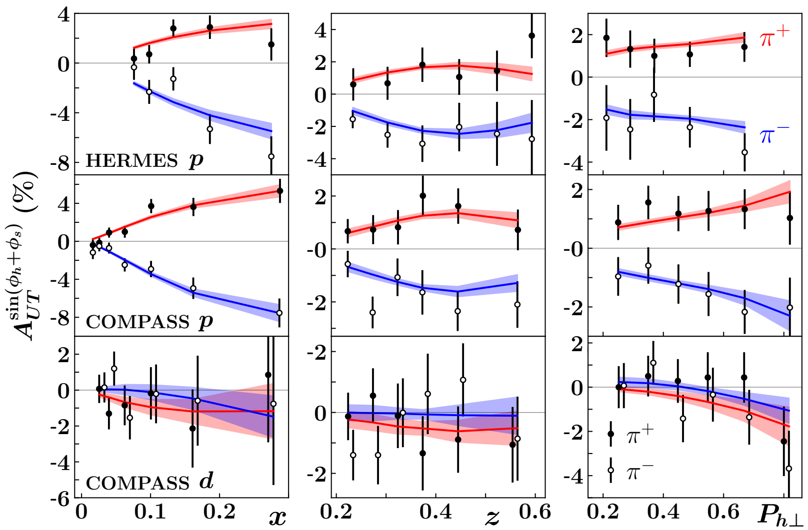
Transversity distributions

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

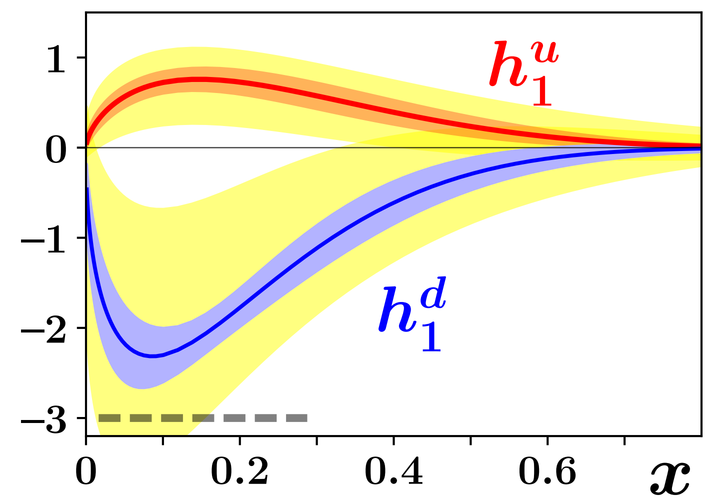
→ Collins asymmetry

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





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

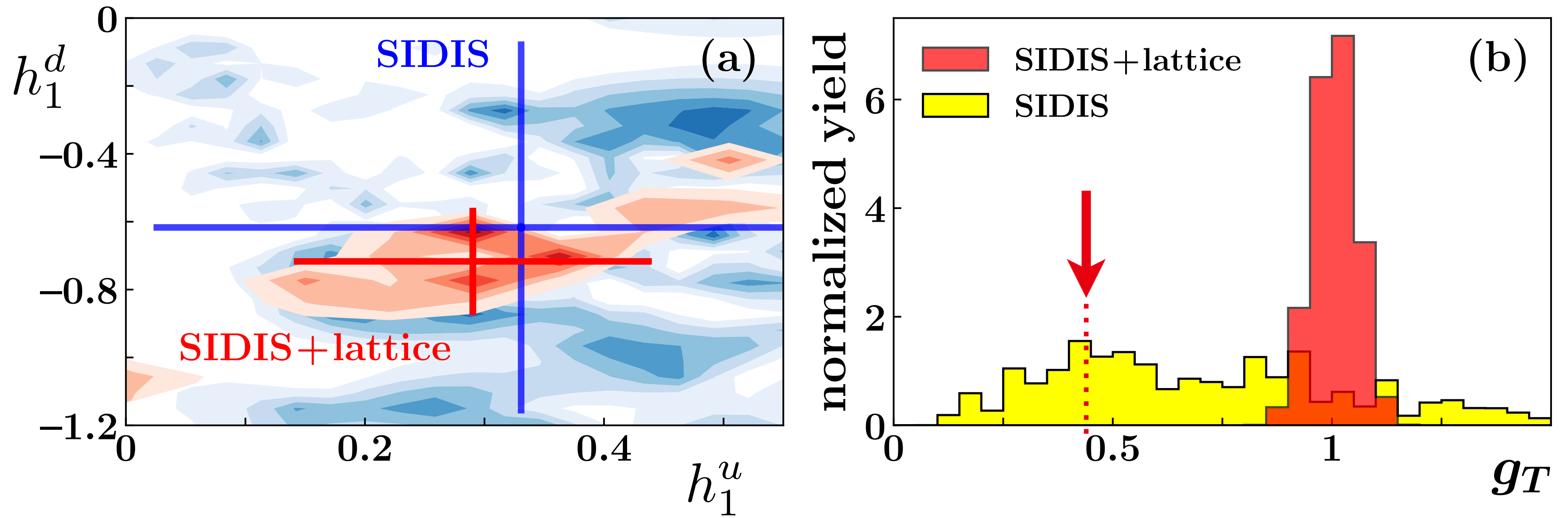


Lin, WM, Prokudin, Sato, Shows (2018)

→ 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 (PRL, 2018)

$\longrightarrow$ distributions do not look very Gaussian!

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

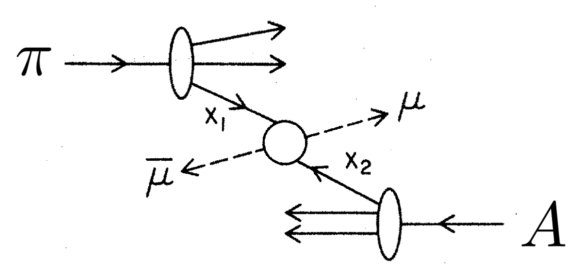
$\longrightarrow$ maximum likelihood analysis would have given $g_T \approx 0.5$

Pion PDFs

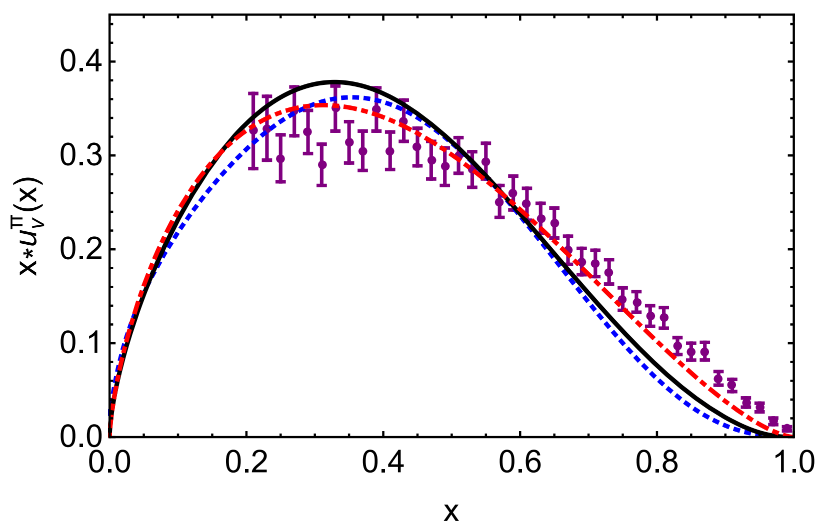
PDFs in the pion

- PDFs in the pion (in principle) simpler to compute than baryons, but are more difficult to study experimentally

→ most information has come from pion-nucleus (tungsten) Drell-Yan data (CERN, Fermilab)



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

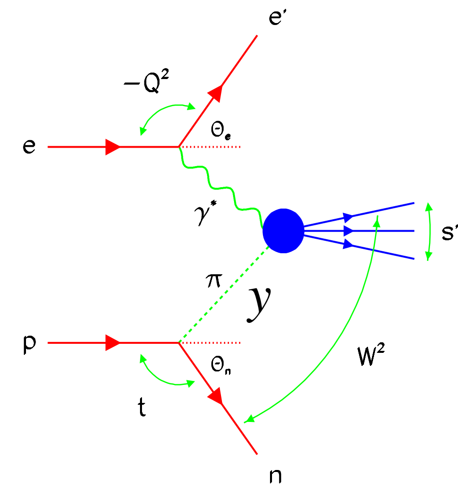


Shi, Mezrag, Zong (2018)

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

PDFs in the pion

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



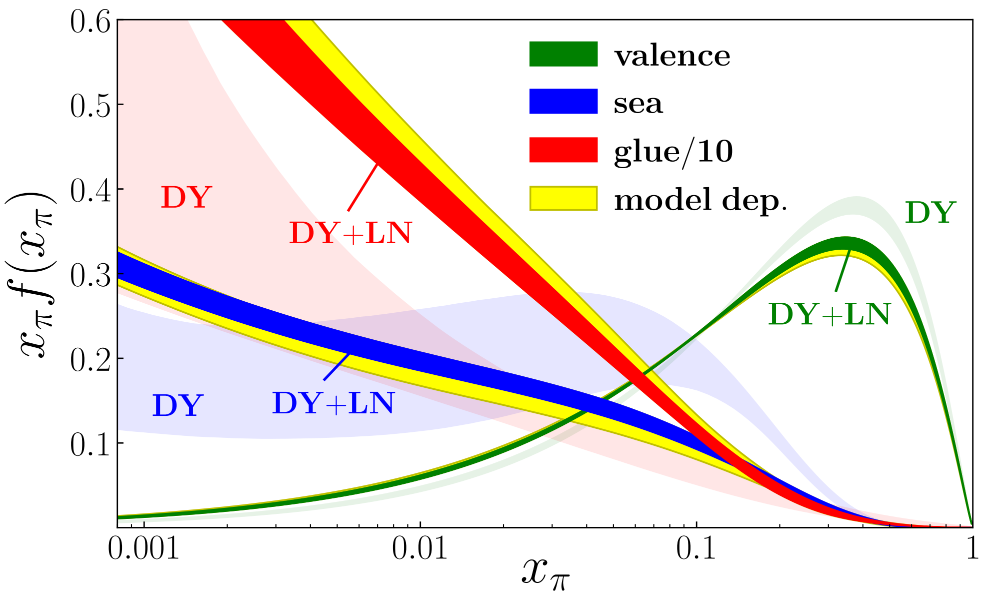
$$\frac{d^3\sigma^{\rm LN}}{dx\,dQ^2\,dy} \sim 2 f_{\pi/N}(y)\, F_2^\pi(x_\pi, Q^2)$$

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

pion structure function

$x_\pi = x/y$

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

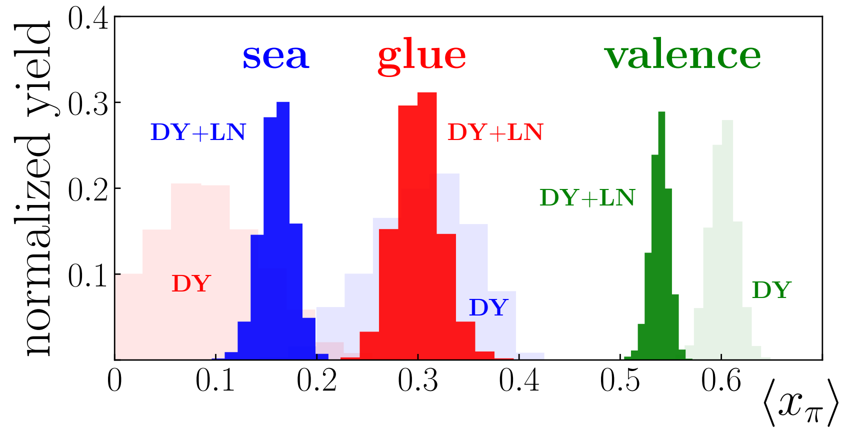


Barry, Sato, WM, C.-R. Ji (2018)

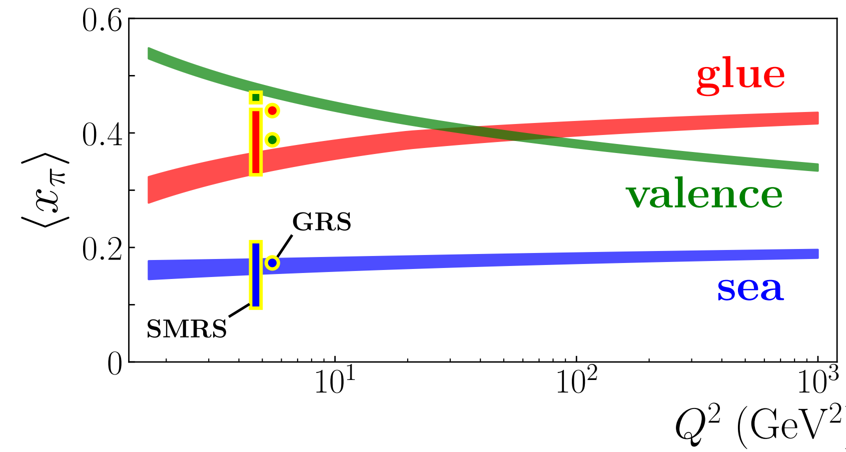
→ first constraints on pion PDFs at low x

PDFs in the pion

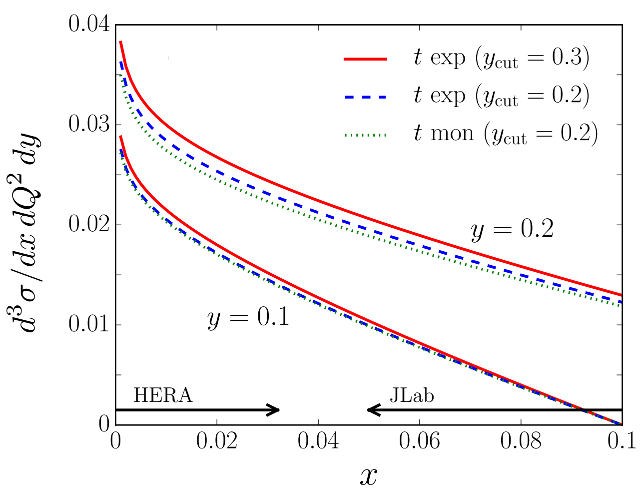
- Larger gluon fraction in the pion than without LN constraint

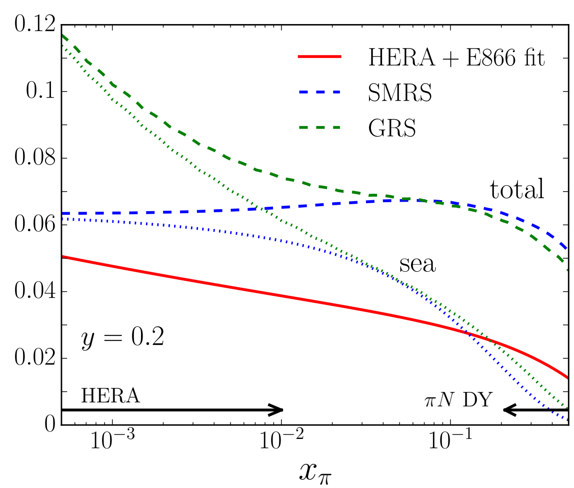


Barry, Sato, WM, C.-R. Ji (2018)



- 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 will probe kaon structure

Outlook

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

  → providing new 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*: technology developed will be applied to global analysis of transverse momentum dependent (TMD) distributions to map out full 3-d image of hadrons

  → vital interplay between theory & experiment at JLab

대단히 감사합니다.