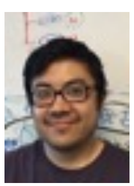
Light Cone Conference
Mumbai, India, Sep. 20, 2017

Towards a universal QCD analysis of PDFs and fragmentation functions

Wally Melnitchouk

Jefferson Lab

Nobuo Sato



Connecticut / JLab

Jacob Ethier

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JLab Angular Momentum collaboration

CTEQ-Jefferson Lab collaboration

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- ***PRD 93, 114017 (2016)***
- ***PRD 93, 074005 (2016)***
- ***PRD 94, 114004 (2016)***
- ***arXiv:1705.05889, PRL (2017)***

Outline

- *Aim*: understand quark/gluon flavor & spin structure of nucleon

- *Method*: extract parton distribution functions (PDFs) from global QCD analysis

Highlights:

- Constraints from recent Fermilab, JLab and LHC data on unpolarized (valence and sea quark) PDFs

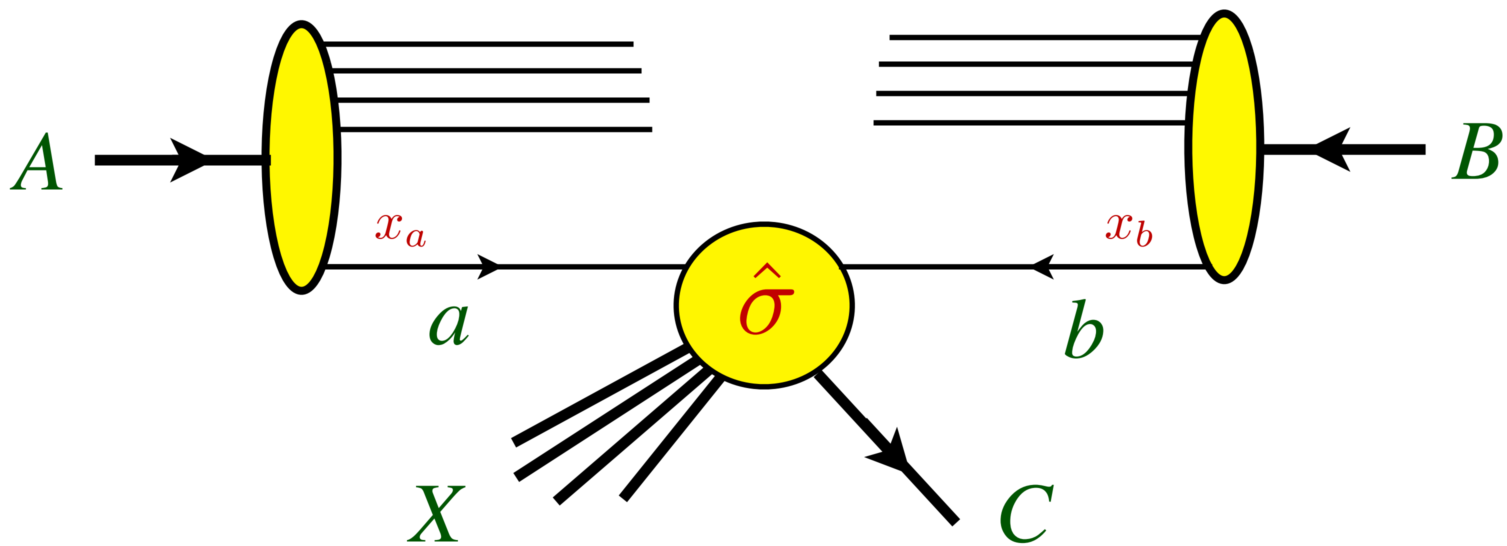
- First MC extraction of fragmentation functions (FFs) from e^+e^- single-inclusive annihilation (SIA) data

- First combined analysis of polarized DIS + SIDIS + SIA data, with simultaneous extraction of PDFs & FFs

  $\longrightarrow$ resolves strange quark polarization puzzle

Parton distributions in hadrons

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



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

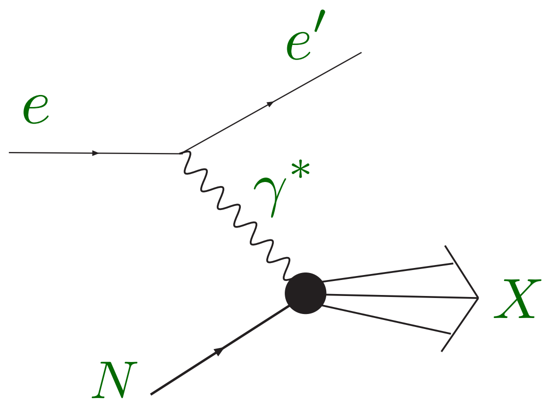
“factorization”

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

$\longrightarrow$ 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)

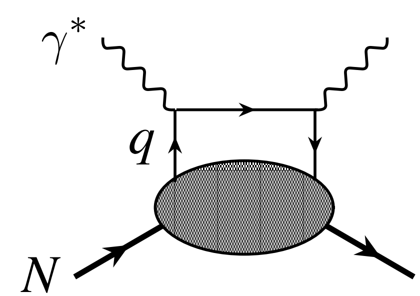


$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

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

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

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



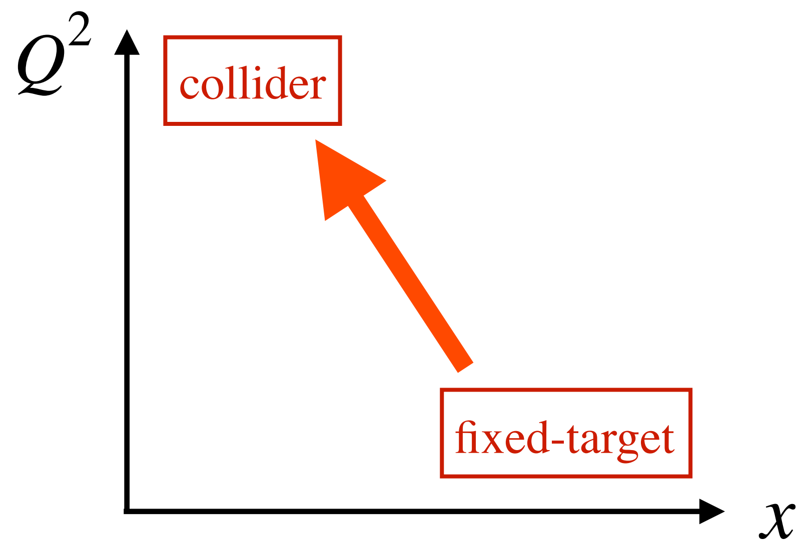
Global PDF analysis

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

  $\longrightarrow$ parametrizations of spin-averaged $(f = f^\uparrow + f^\downarrow)$ and spin-dependent $(\Delta f = f^\uparrow - f^\downarrow)$ PDFs

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

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



Global PDF analysis

- Analysis of data requires estimating expectation values and variances of observables $\mathcal{O}$ (= PDFs, FFs)

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

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

$\longrightarrow$ probability distribution

$$\mathcal{P}(\vec{a}|\text{data}) \;\propto\; \mathcal{L}(\text{data}|\vec{a}) \; \pi(\vec{a})$$

Bayes' theorem

priors

$\longrightarrow$ likelihood function

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

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

Global PDF analysis

- Standard method for evaluating E, V is "maximum likelihood"

  $\longrightarrow$ maximize probability distribution

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

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

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

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

  $\longrightarrow$ need more robust approach ($e.g.$ Monte Carlo)

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

Global PDF analysis

- Use traditional functional form for input distribution shape

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

but sample significantly larger parameter space than possible in single-fit analyses

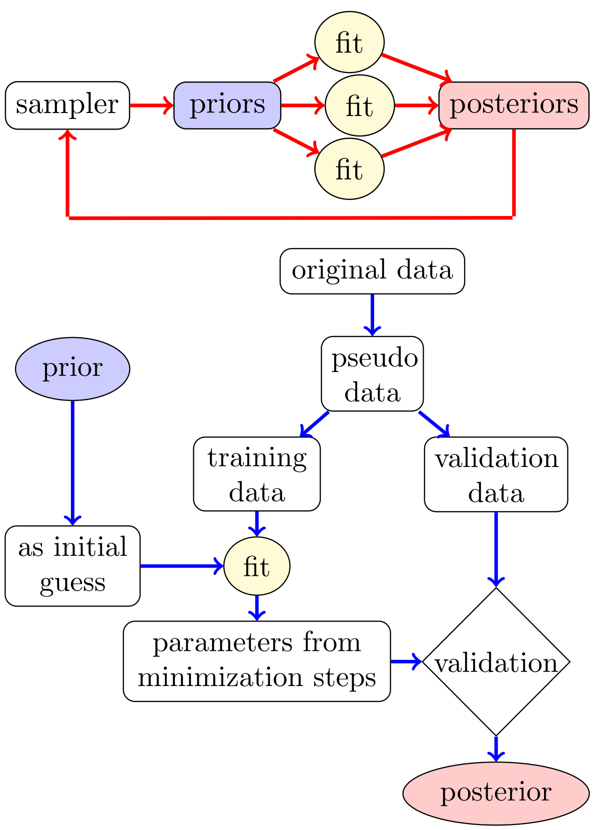
$\longrightarrow$ no assumptions for exponents

$\longrightarrow$ cross-validation to avoid overfitting

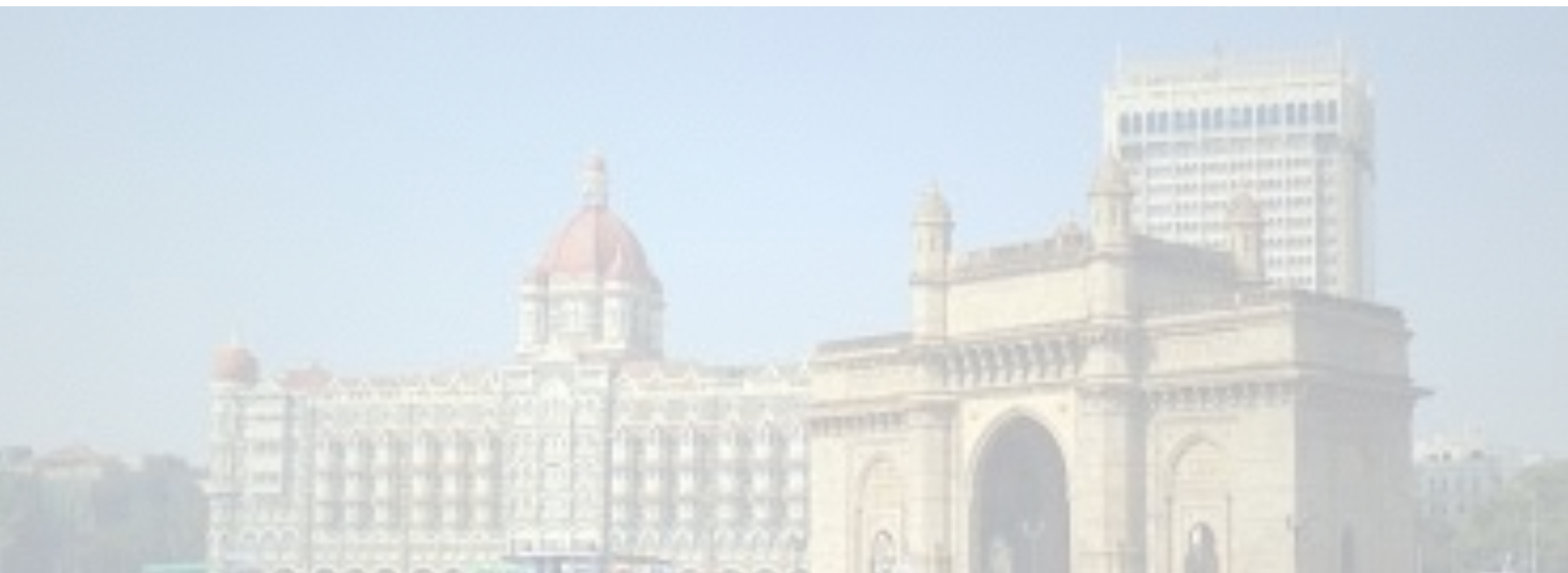
$\longrightarrow$ iterate until convergence criteria satisfied

$\longrightarrow$ robust determination of PDF uncertainties!

Iterative Monte Carlo (IMC)

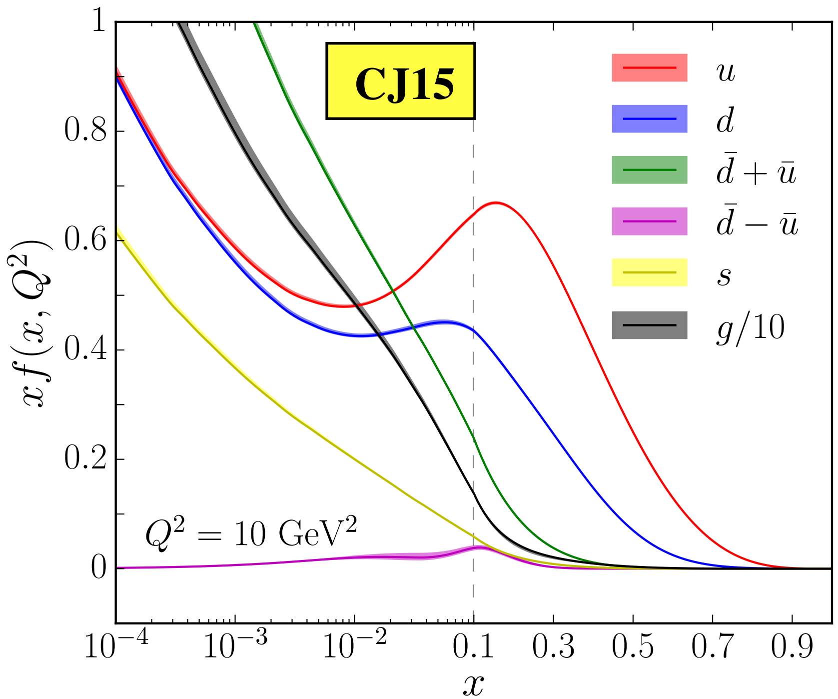


Unpolarized PDFs

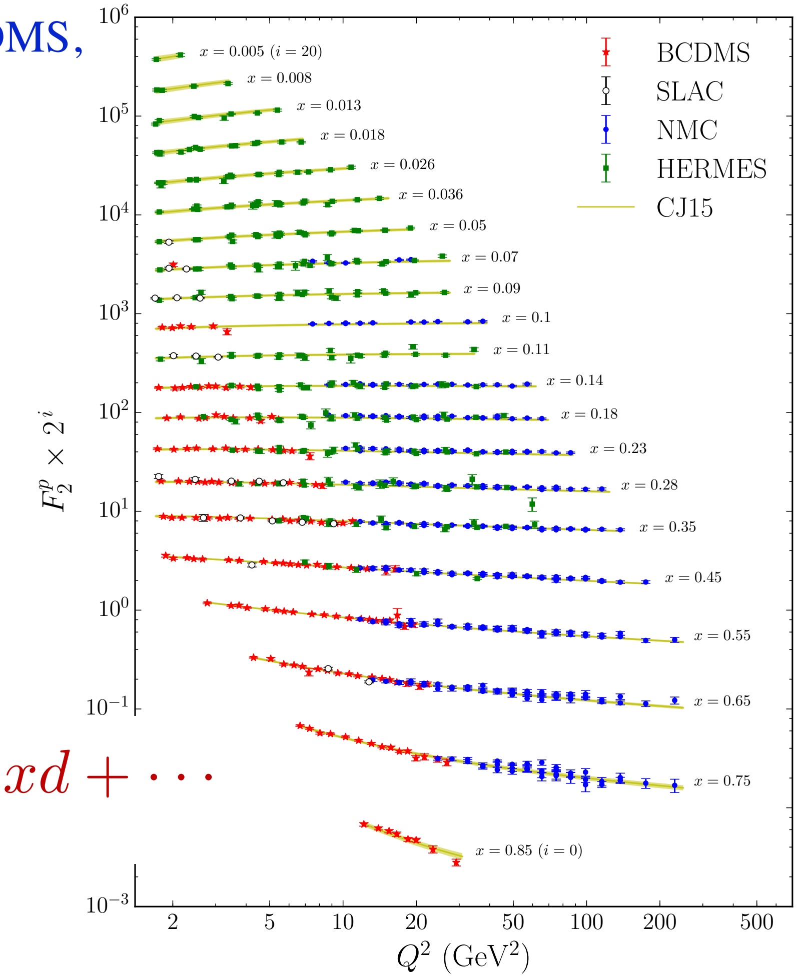


Unpolarized PDFs

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



$$F_2^p \sim \frac{4}{9}xu + \frac{1}{9}xd + \cdots$$



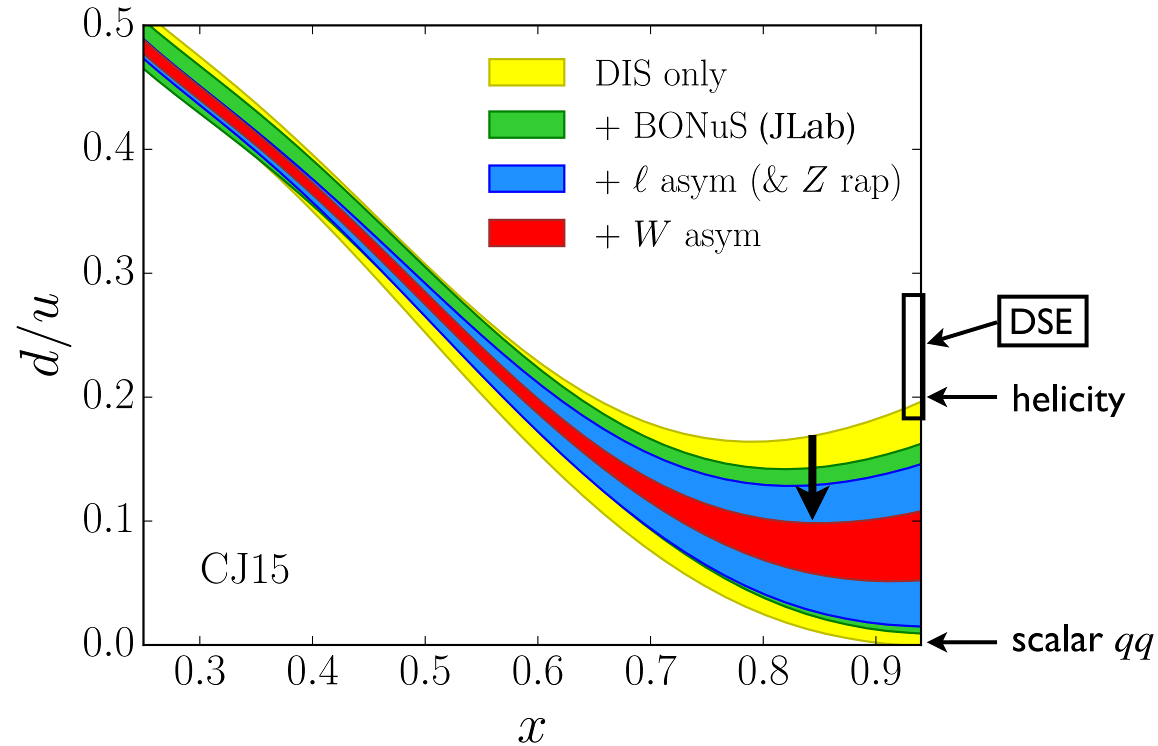
- Absence of free-neutron data and smaller $|e_q|$ of d quarks limit precision of d-quark PDF, especially at high x

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

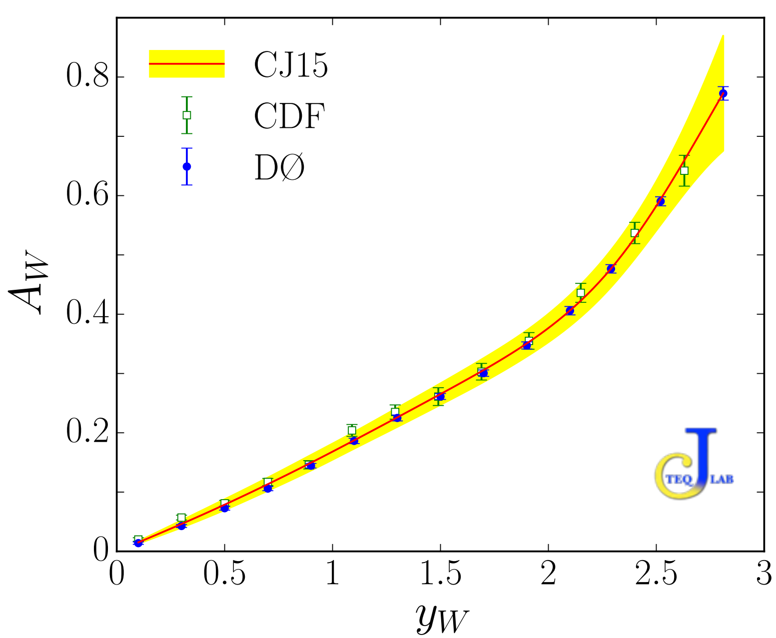
Valence quark PDFs

- 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 $x = 1$

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

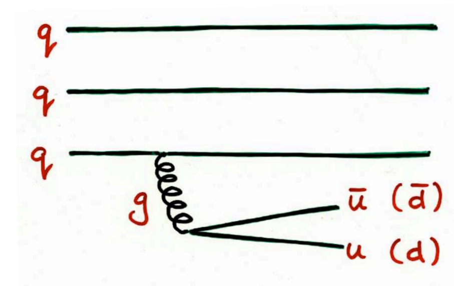
does not match any model…

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

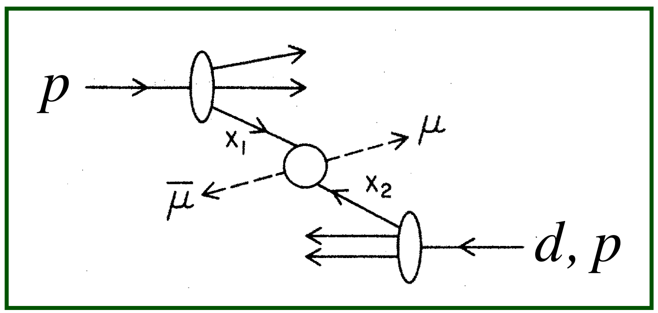
Light quark sea

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

$$\boxed{\bar{d} = \bar{u}}$$

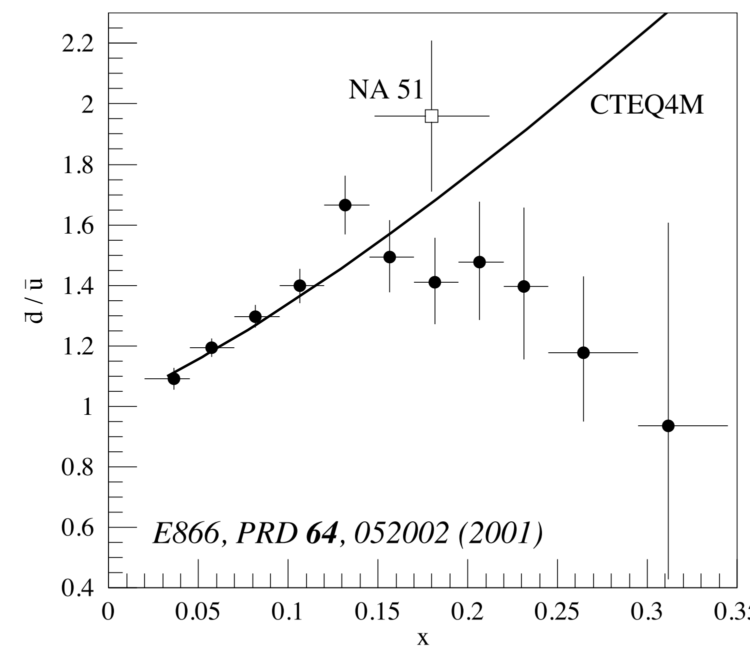


- x dependence of $\bar{d} - \bar{u}$ asymmetry established in Fermilab E866 pp/pd Drell-Yan experiment



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

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

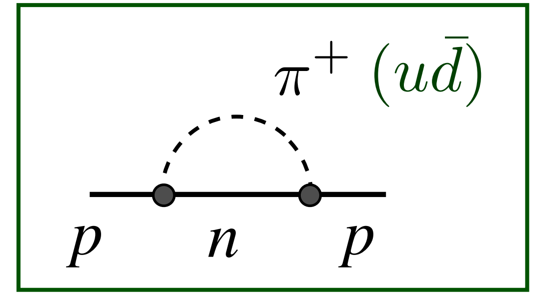


$$\boxed{\bar{d} > \bar{u}}$$

Light quark sea

- Asymmetry arises naturally from chiral symmetry breaking and pion cloud

Thomas (1984)



- Rigorous connection with QCD established via chiral EFT

→ lowest order πN interaction includes pion rainbow and tadpole contributions

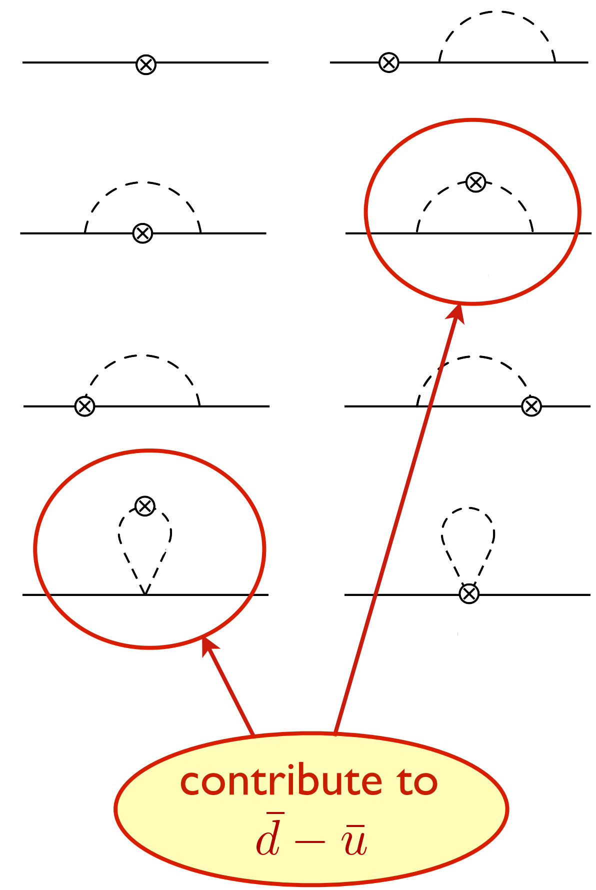
→ matching quark- and hadron-level operators yields convolution representation

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

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

$p \to \pi^+ n$ splitting function

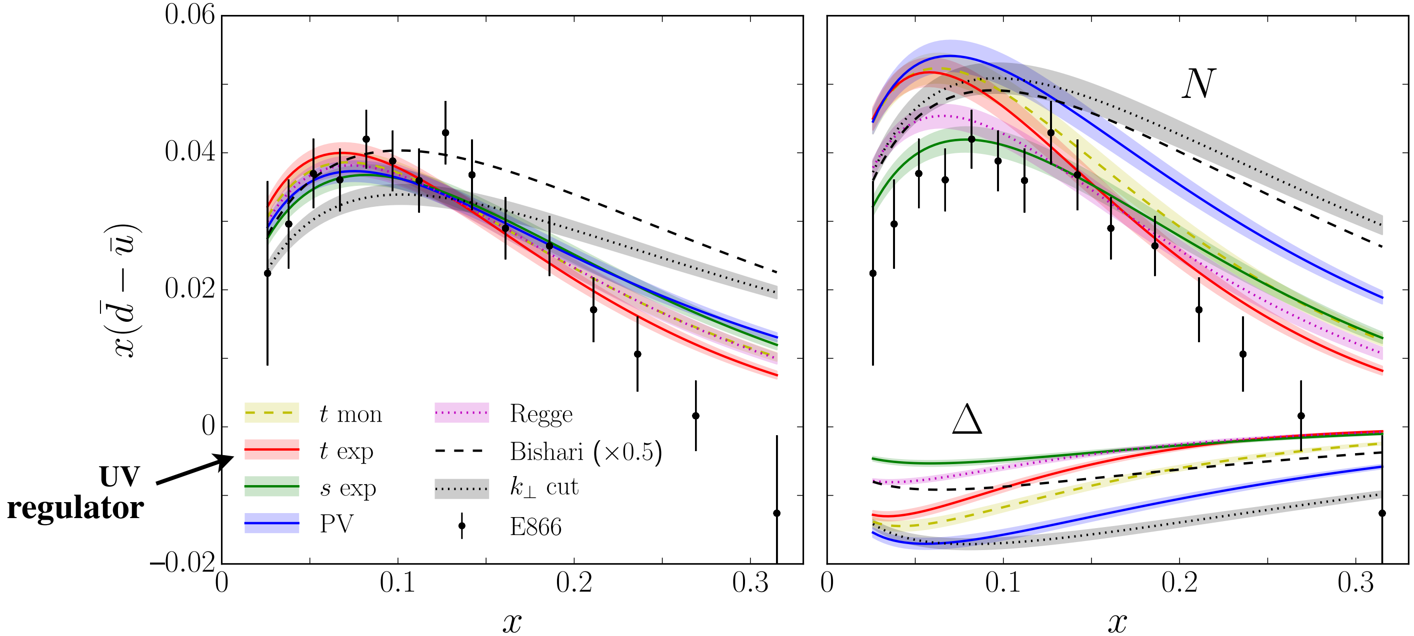
pion PDF



C Ji, WM, Thomas (2013)

Light quark sea

- E866 data have driven successful phenomenology through interplay of PDFs and chiral physics



$$f^{(\text{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2$$
$$\times \frac{y(k_\perp^2 + y^2 M^2)}{\left[k_\perp^2 + y^2 M^2 + (1-y) m_\pi^2\right]^2} \mathcal{F}^2$$

McKenney, Sato, WM, Ji (2016)

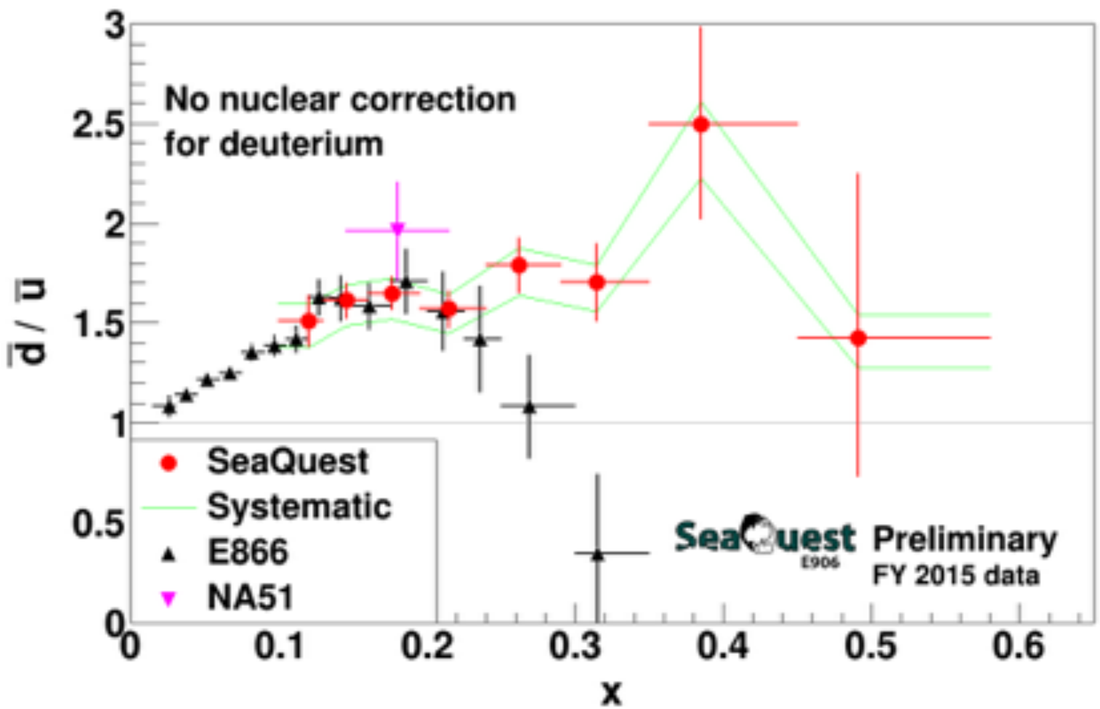
… but lingering question of possible <u>sign change</u> of $\bar{d}-\bar{u}$ at high x

$\longrightarrow$ sign change cannot be accommodated within chiral EFT framework since (negative) Δ contribution << (positive) N contribution

$\longrightarrow$ evidence for other mechanisms?

Light quark sea

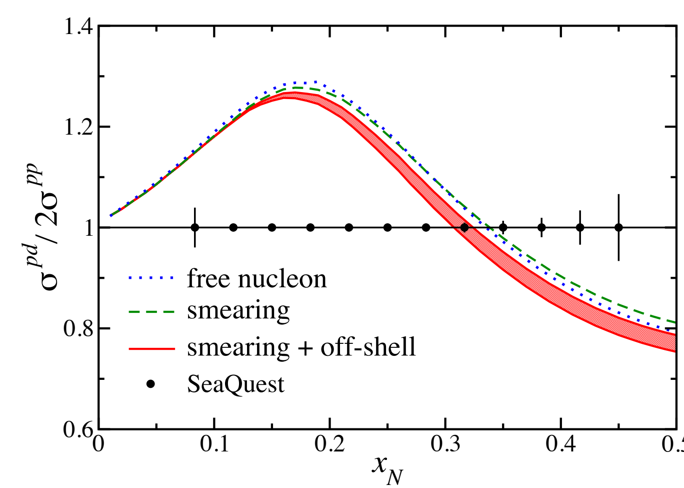
- Preliminary data from SeaQuest (E906) Drell-Yan experiment at Fermilab shows no evidence for sign change



→ SeaQuest consistent with E866 data up to $x \sim 0.2$, remains above unity up to $x \sim 0.5$

→ results not significantly affected if include nuclear corrections

Ehlers, Accardi, Brady, WM (2014)



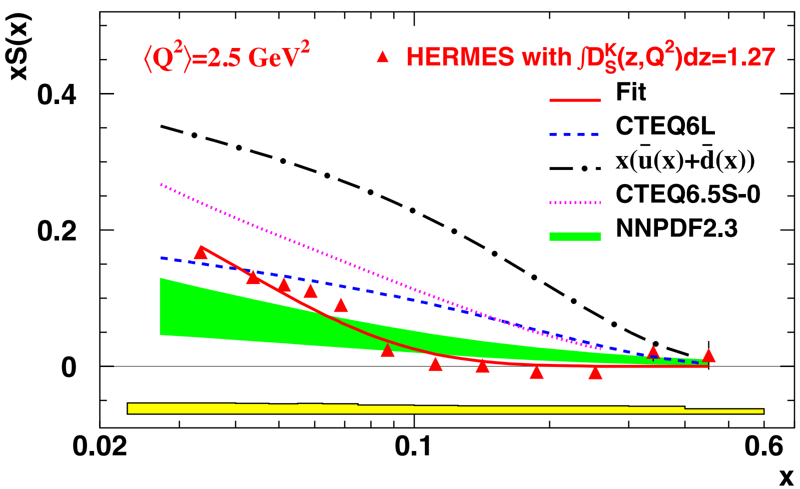
Strange quarks

- Strange quark PDFs most directly determined from dimuon production in neutrino-nucleus DIS $(W^+ s \to c\ /\ W^- \bar{s} \to \bar{c})$

  $\longrightarrow$ but significant uncertainties from nuclear corrections, semileptonic branching ratio, and D meson propagation through nucleus

  $\longrightarrow$ also, tension with (HERMES) semi-inclusive K-production data?

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



historically, strange to nonstrange ratio

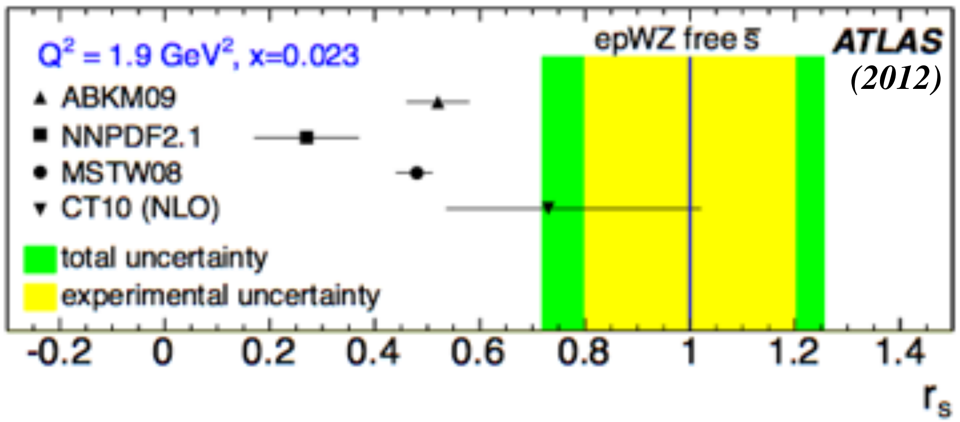
$$\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

$$\sim\ 0.2 - 0.5$$

... however, uncertainty from K fragmentation functions $D(z)$

Strange quarks

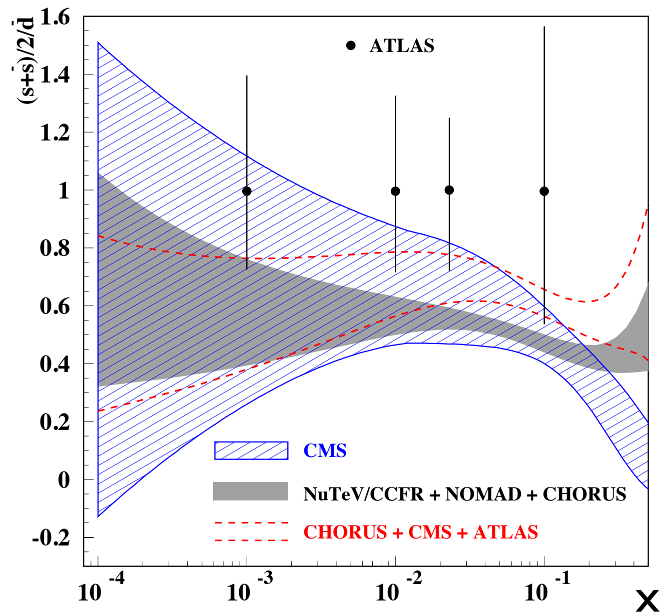
- Alternatively, probe strange PDF in W/Z production at LHC
  $pp \to W(Z) + X$ free of nuclear effects



→ surprisingly large strangeness

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

→ more recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF



Alekhin et al. (2015)

Strange quarks

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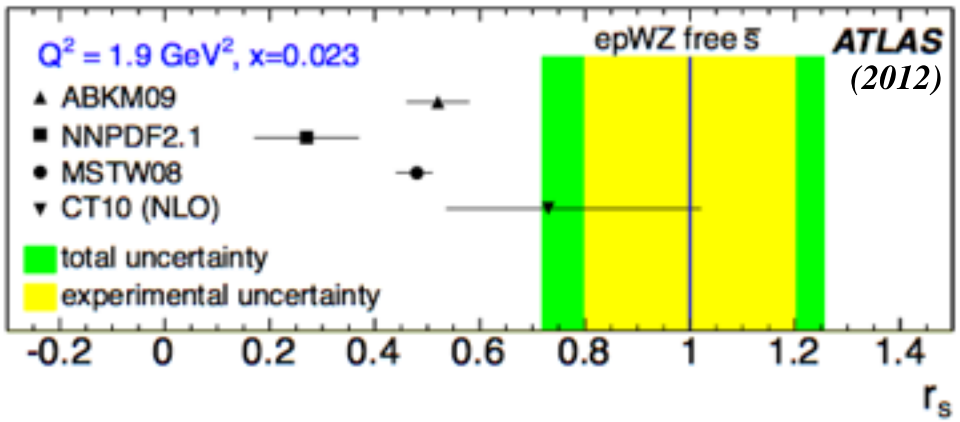

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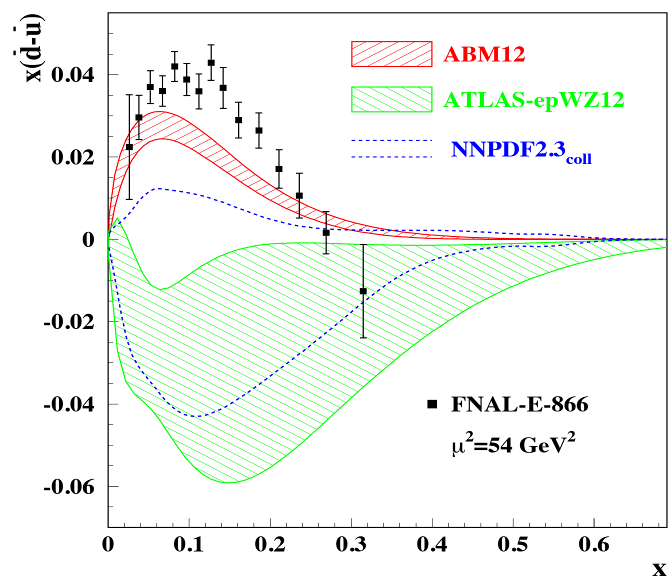
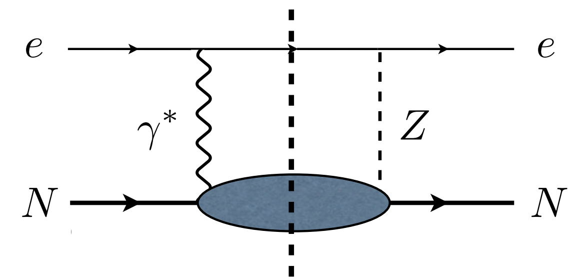
$\longrightarrow$ effect could be related to underestimated $\bar{d}$ PDF from collider data?



Strange quarks

- Parity-violating DIS allows 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 γZ to strange PDF

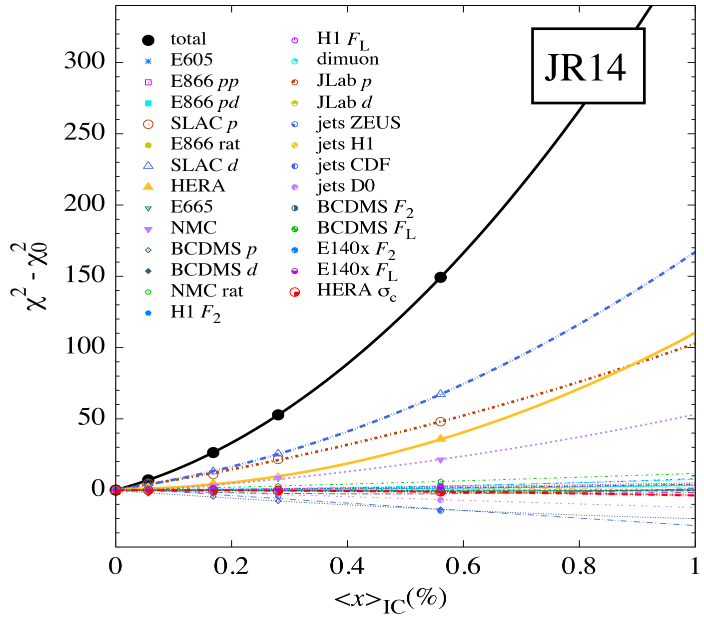
→ V x A term also sensitive to $s - \bar{s}$

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

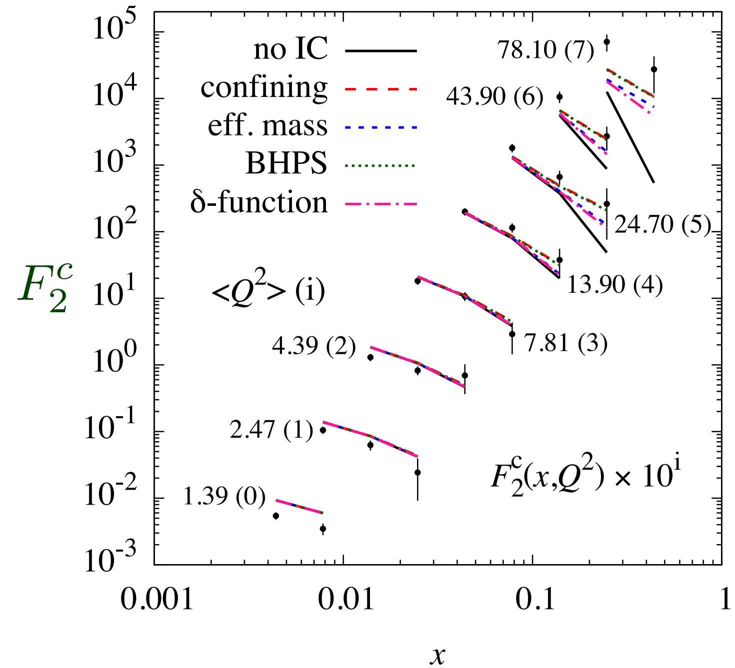
Dalton et al., JLab PAC45 proposal (2017)

Charm in the nucleon

- Is there a large "intrinsic charm" (IC) component in the nucleon?



Jimenez-Delgado et al. (2015)



- with standard fitting technology momentum carried by "IC" $\langle x \rangle_{\rm IC} < 0.1\%$ at 5σ CL

- difficult to accommodate both low-x and high-x EMC F_2^c data

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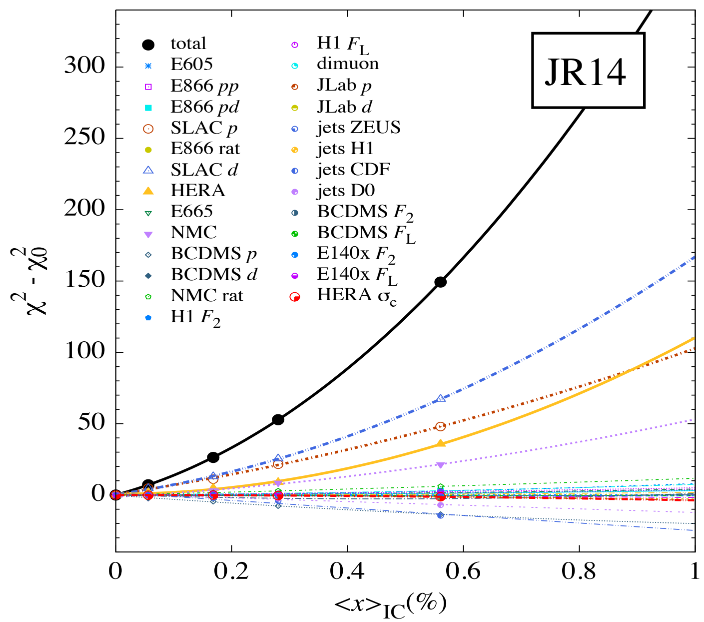

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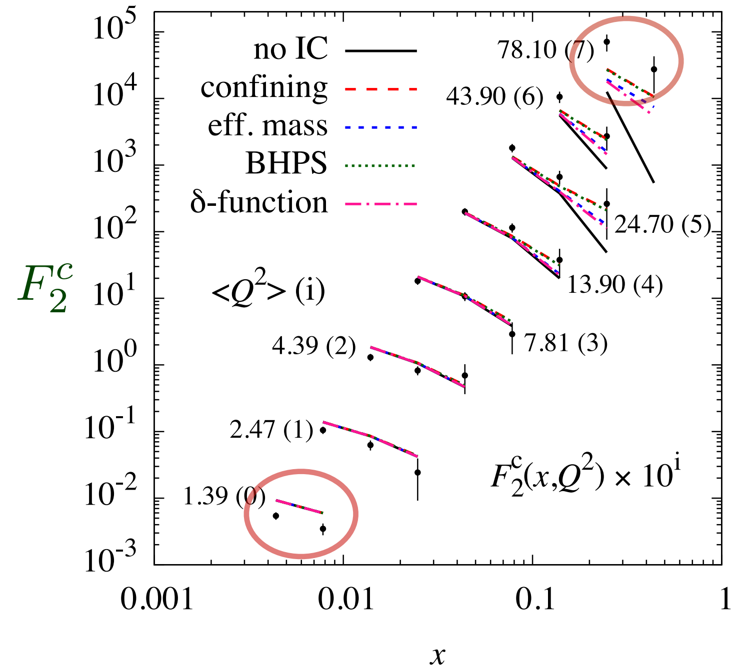

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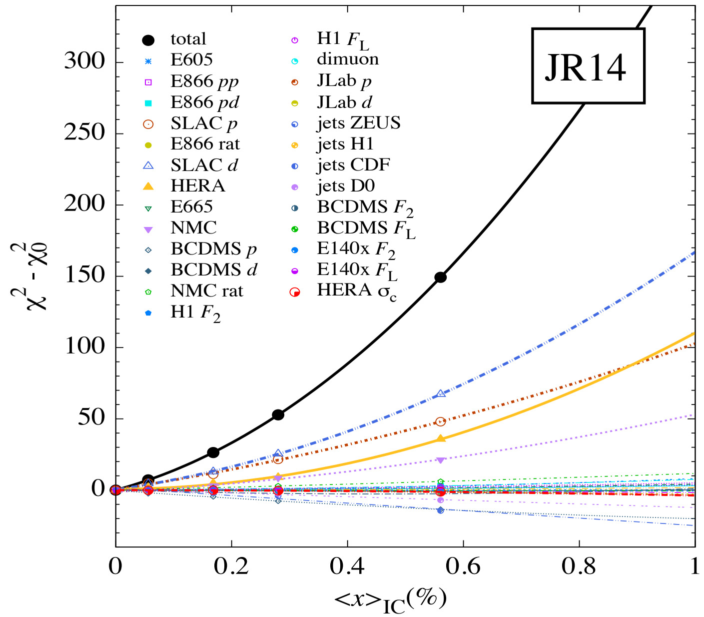

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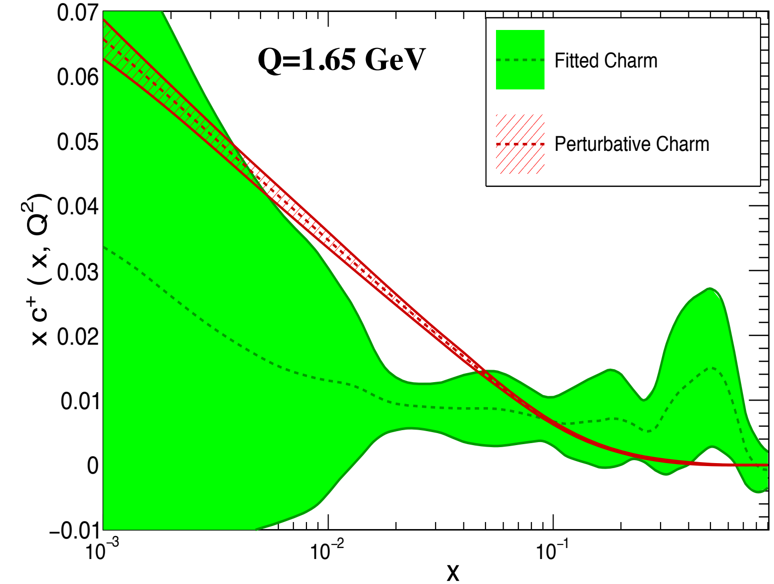


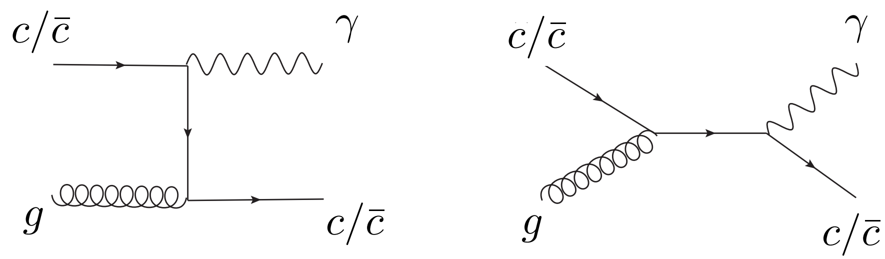
NNPDF (2016)

- with standard fitting technology momentum carried by "IC" $\langle x \rangle_{\rm IC} < 0.1\%$ at 5σ CL
- recent "neural network" analysis $\langle x \rangle_{\rm IC} < 1\%$ at 1σ CL, but can go < 0 at low x to fit EMC F_2^c data

$\longrightarrow$ no evidence for "large" IC, but exact limits subject to treatment of perturbative & nonperturbative QCD effects

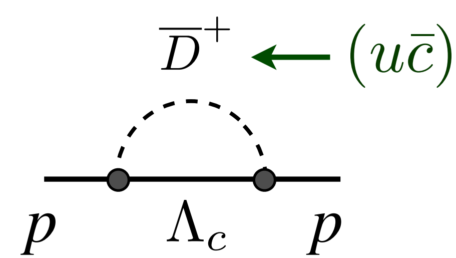
Charm in the nucleon

- Associated prompt photon + charm production
  $pp \to \gamma + c/\bar{c} + X$ may reveal "intrinsic" charm component



$\longrightarrow$ "smoking gun" would be observation of asymmetric distributions $c(x) \neq \bar{c}(x)$

$\longrightarrow$ arises naturally in hadronic models with $p \to \overline{D} + \Lambda_c$ dissociation



Spin-dependent PDFs

Proton spin structure

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

$\longrightarrow$ in nonrelativistic quark model, spin of proton is carried entirely by quarks

$$\Delta\Sigma = \Delta u^+ + \Delta d^+ + \Delta s^+ = 1 \qquad \Delta q^+ \equiv \Delta q + \Delta\bar{q}$$

$\longrightarrow$ experimentally, from hadron weak decays have

$$\Delta u^+ - \Delta d^+ = g_A = 1.269(3) \qquad \text{[SU(2) symmetry]}$$

$$\Delta u^+ + \Delta d^+ - \Delta s^+ = a_8 = 0.586(31) \qquad \text{[SU(3) symmetry]}$$

$\longrightarrow$ third combination of flavors measured in polarized DIS

$$\int_0^1 dx\, g_1 = \frac{1}{18}\left(4\Delta u^+ + \Delta d^+ + \Delta s^+\right)$$

Proton spin structure

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

$\longrightarrow$ solving system of equations, early indications were that

$$\Delta\Sigma \approx 0\,! \qquad\qquad \Delta s^+ \approx -(0.1 - 0.2)$$ ***EMC (1988)***

$\longrightarrow$ since proton spin sum requires

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

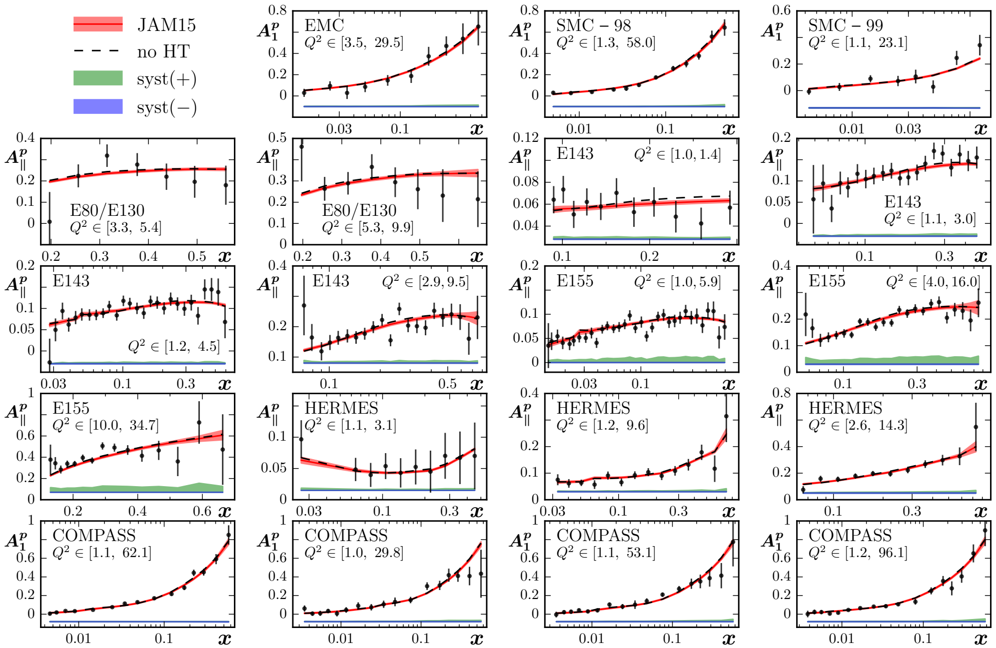
does remaining spin come from large gluon polarization? orbital angular momentum?

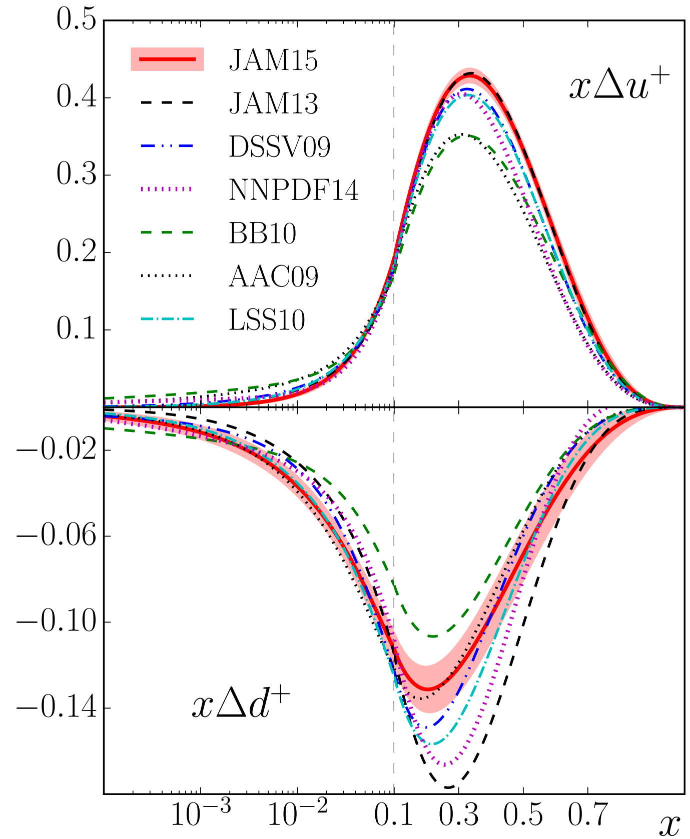
$\longrightarrow$ stimulated many advances in theory, experiment & data analysis $\rightarrow$ most recent "JAM15" global QCD analysis including JLab 6 GeV data

Spin-dependent PDFs

- Polarized DIS data on protons similarly constrain Δu PDF

$$g_1^p \sim \frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \cdots$$



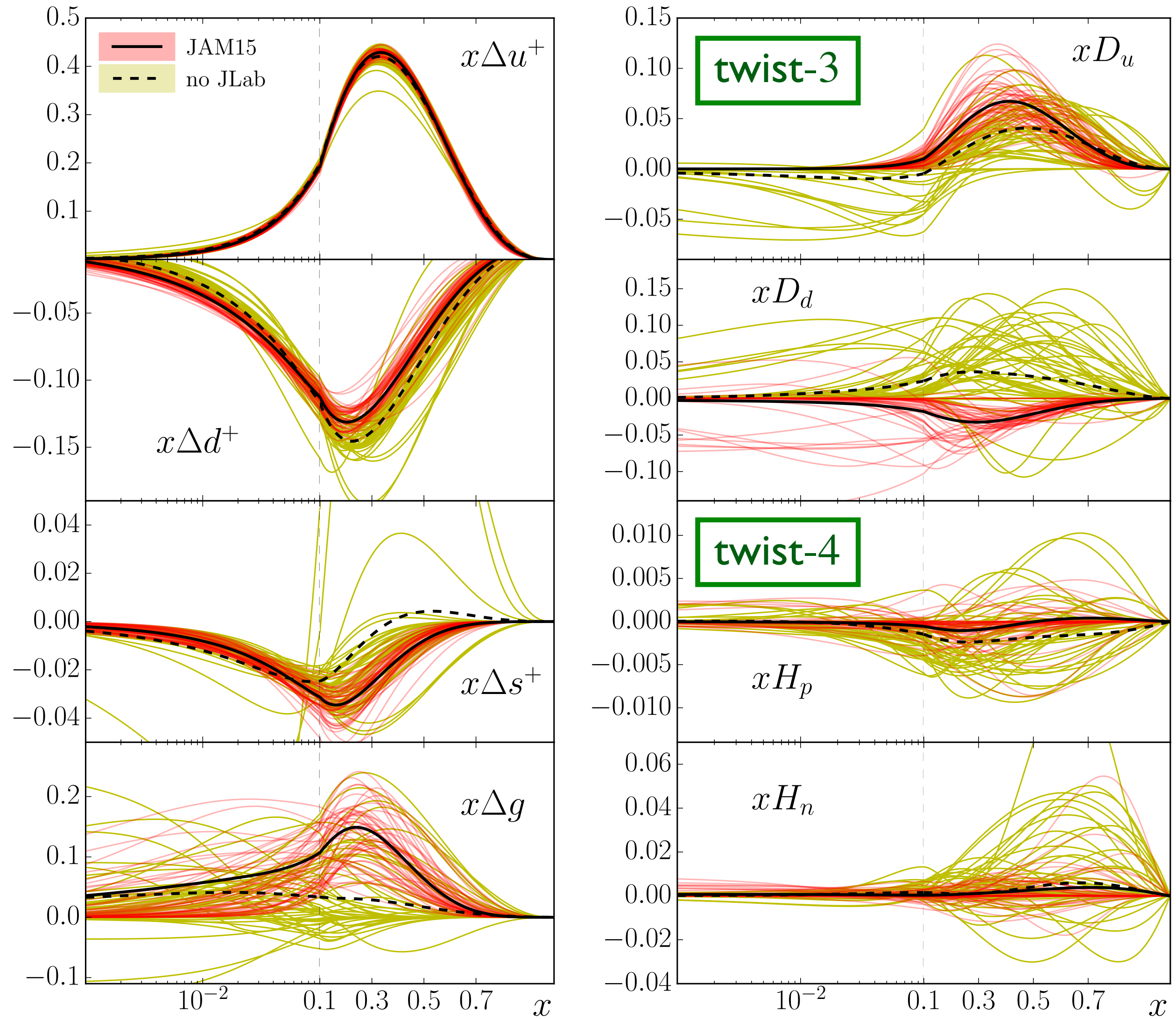


- Polarized deuterium & ^{3}He data more sensitive to Δd PDF

$\longrightarrow$ uncertainties still larger because $|\Delta d| \ll |\Delta u|$

Spin-dependent PDFs

Impact of JLab data



Sato et al. ***[JAM] (2016)***

→ reduced uncertainty in Δs^+, Δg

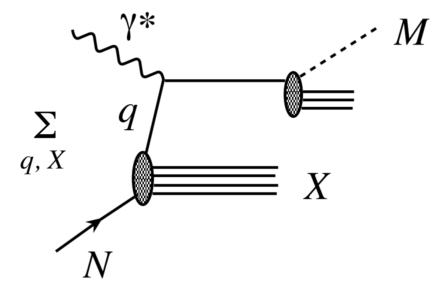
→ nonzero twist-3 contributions

→ s-quark polarization *negative* from inclusive DIS data

Polarization of quark sea?

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

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



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

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

$\longrightarrow$ but need fragmentation functions!

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

$\longrightarrow$ $\Delta s > 0$ for "DSS" parametrization *de Florian et al., PRD**75**, 094009 (2007)*

$\Delta s < 0$ for "HKNS" parametrization *Hirai et al., PRD**75**, 114010 (2007)*

$\longrightarrow$ need to understand origin of differences in fragmentation!

Fragmentation functions

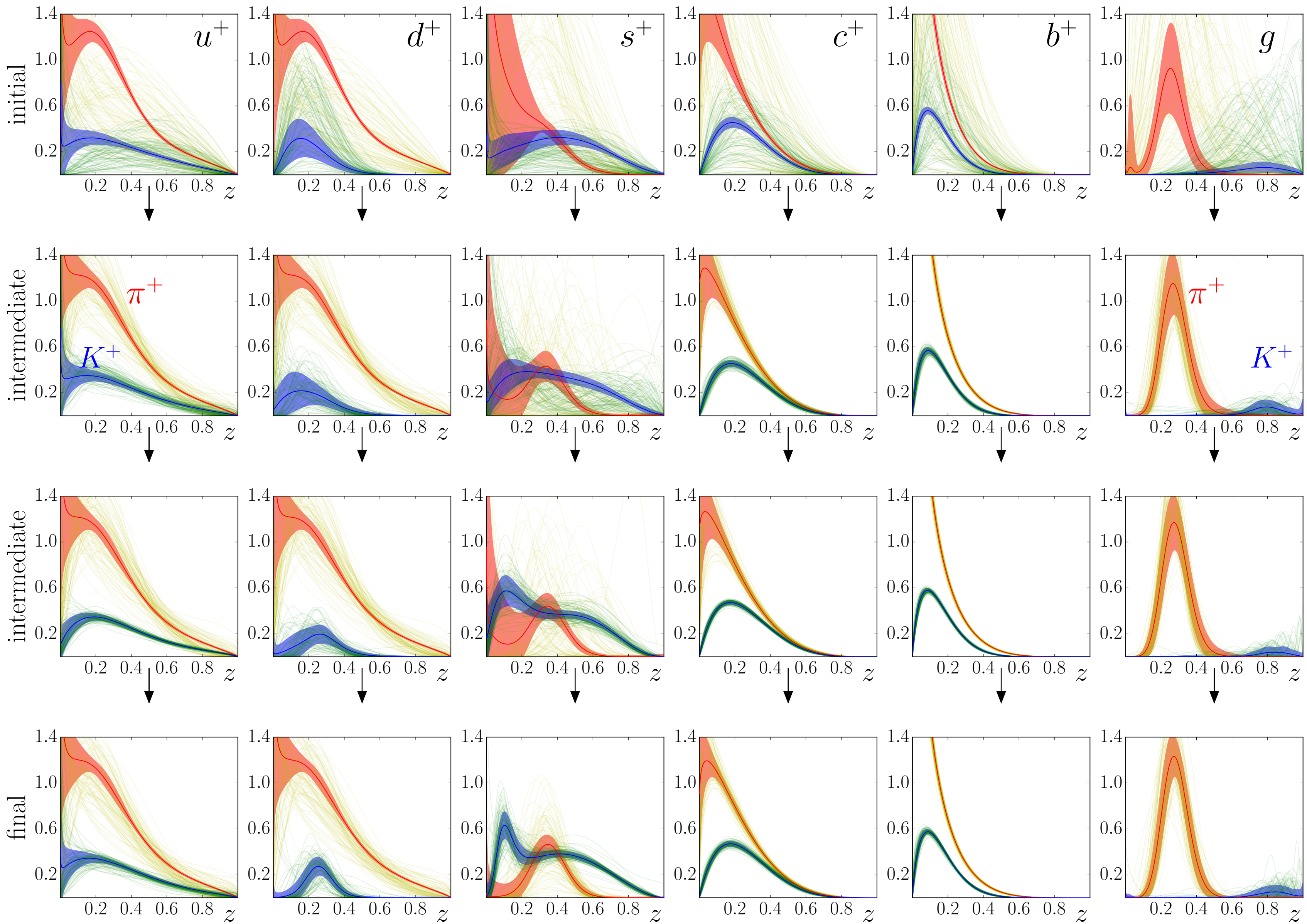
IMC analysis of fragmentation functions

- Analyze single-inclusive e^+e^- annihilation data for pion & kaon production from DESY, CERN, SLAC & KEK from $Q \sim 10$ GeV to Z-boson pole

prompt (conventional)

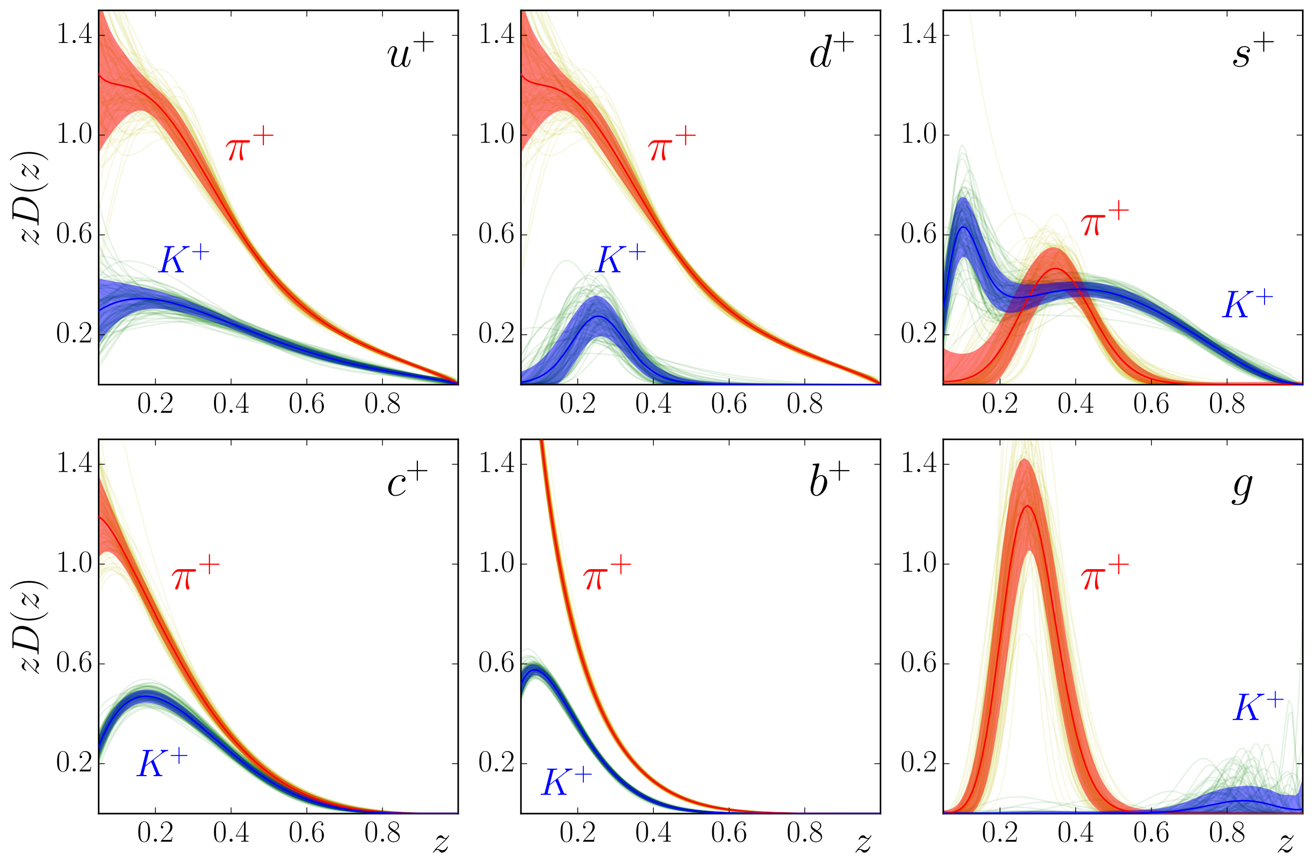
				Pions			Kaons		
Experiment	Ref.	Observable	Q (GeV)	N_{dat}	norm.	χ^2	N_{dat}	norm.	χ^2
ARGUS	[26]	Inclusive	9.98	35	1.024 (1.058)	51.1 (55.8)	15	1.007	8.5
Belle	[38,39]	Inclusive	10.52	78	0.900 (0.919)	37.6 (21.7)	78	0.988	10.9
BABAR	[40]	Inclusive	10.54	39	0.993 (0.948)	31.6 (70.7)	30	0.992	4.9
TASSO	[23–25]	Inclusive	12-44	29	(*)	37.0 (38.8)	18	(*)	14.3
TPC	[27–29]	Inclusive	29.00	18	1	36.3 (57.8)	16	1	47.8
		uds tag	29.00	6	1	3.7 (4.6)			
		b tag	29.00	6	1	8.7 (8.6)			
		c tag	29.00	6	1	3.3 (3.0)			
HRS	[30]	Inclusive	29.00	2	1	4.2 (6.2)	3	1	0.3
TOPAZ	[37]	Inclusive	58.00	4	1	4.8 (6.3)	3	1	0.9
OPAL	[32,33]	Inclusive	91.20	22	1	33.3 (37.2)	10	1	6.3
		u tag	91.20	5	1.203 (1.203)	6.6 (8.1)	5	1.185	2.1
		d tag	91.20	5	1.204 (1.203)	6.1 (7.6)	5	1.075	0.6
		s tag	91.20	5	1.126 (1.200)	14.4 (11.0)	5	1.173	1.5
		c tag	91.20	5	1.174 (1.323)	10.7 (6.1)	5	1.169	13.2
		b tag	91.20	5	1.218 (1.209)	34.2 (36.6)	4	1.177	10.9
ALEPH	[34]	Inclusive	91.20	22	0.987 (0.989)	15.6 (20.4)	18	1.008	6.1
DELPHI	[35,36]	Inclusive	91.20	17	1	21.0 (20.2)	27	1	3.9
		uds tag	91.20	17	1	13.3 (13.4)	17	1	22.5
		b tag	91.20	17	1	41.9 (42.9)	17	1	9.1
SLD	[31]	Inclusive	91.28	29	1.002 (1.004)	27.3 (36.3)	29	0.994	14.3
		uds tag	91.28	29	1.003 (1.004)	51.7 (55.6)	29	0.994	42.6
		c tag	91.28	29	0.998 (1.001)	30.2 (40.4)	29	1.000	31.7
		b tag	91.28	29	1.005 (1.005)	74.6 (61.9)	28	0.992	134.1
Total:				459		599.3 (671.2)	391		395.0
					$\boxed{\chi^2/N_{\text{dat}} = 1.31\ (1.46)}$				$\boxed{\chi^2/N_{\text{dat}} = 1.01}$

IMC analysis of fragmentation functions



$\longrightarrow$ convergence after ~ 20 iterations

IMC analysis of fragmentation functions



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

→ favored FFs well constrained; unfavored not as well…

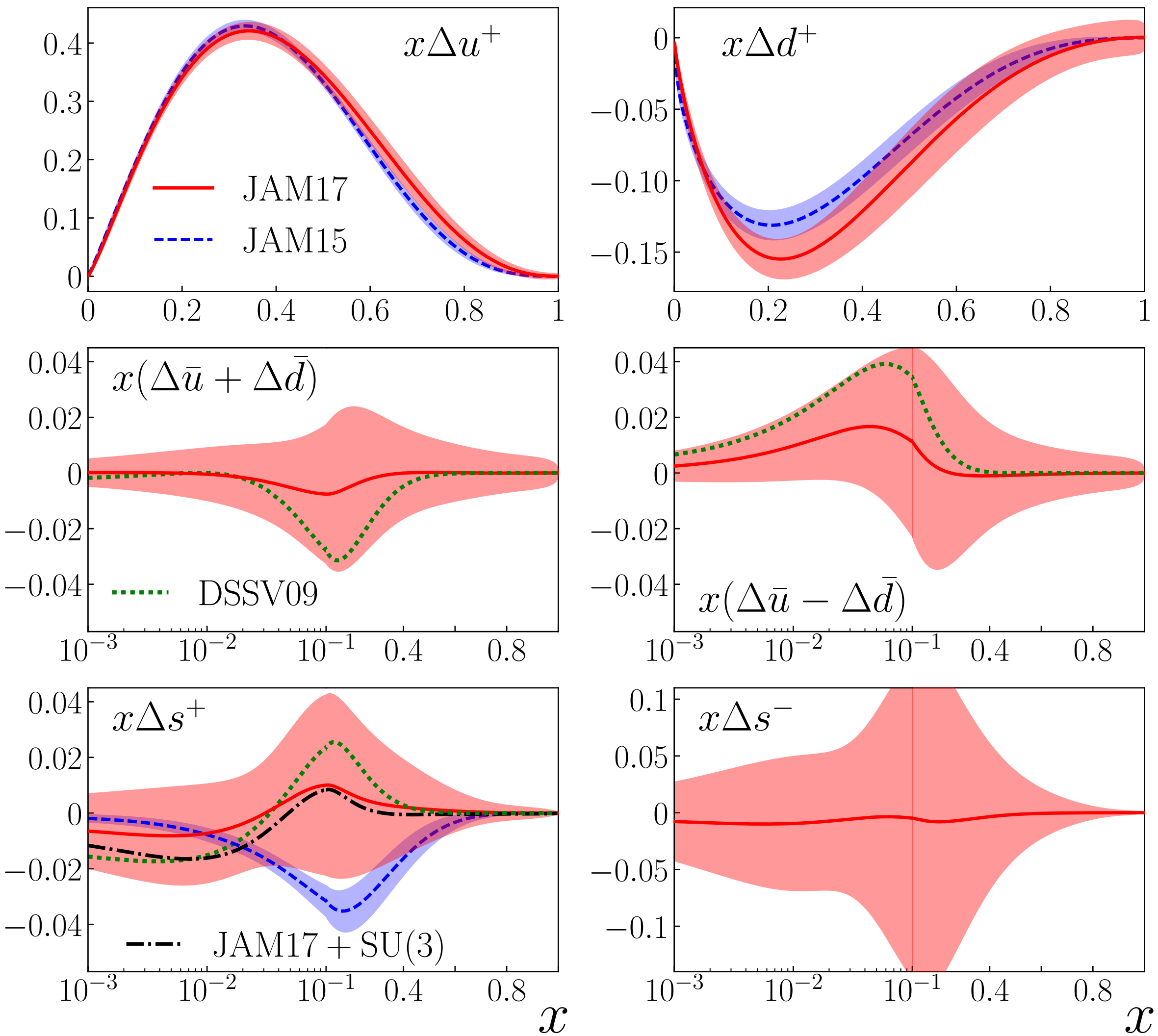
→ very hard $g \rightarrow K$ fragmentation? (robust feature!)

→ nontrivial shape of $s \rightarrow K$ fragmentation
— impact on Δs^+ extraction?

Simultaneous analysis

Simultaneous analysis

- Using same IMC tools, new analysis performed first ever <u>simultaneous</u> determination of spin PDFs and FFs, fitting to DIS, SIA and polarized SIDIS (HERMES, COMPASS) data



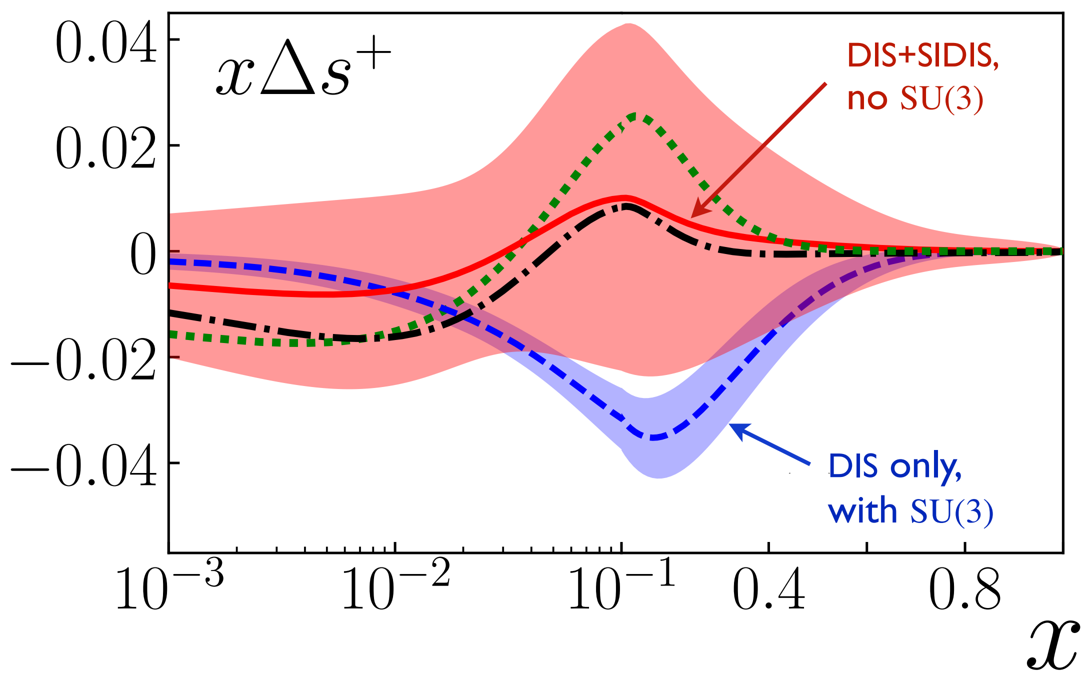
→ no assumption of SU(3) symmetry

→ 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 ($e.g.$ JAM15) was negative at $x \sim 0.1$, induced by SU(3) and parametrization bias

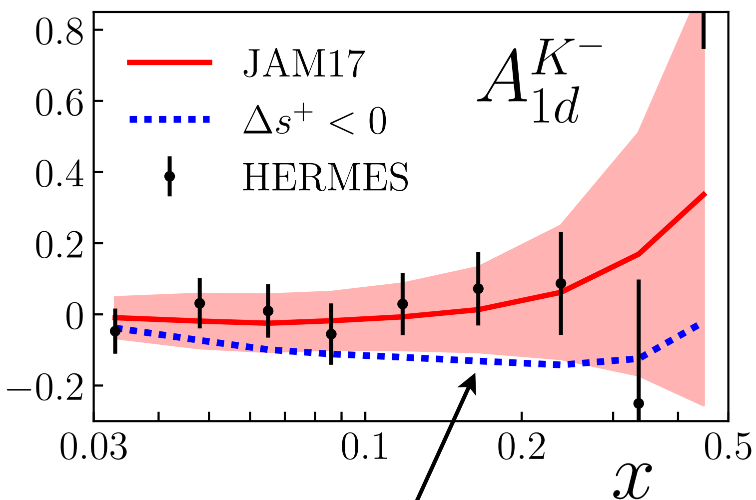


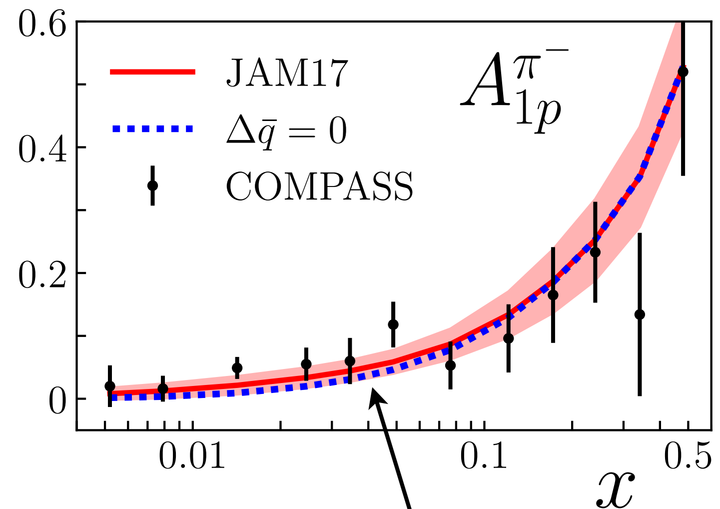
⟶ negligible sensitivity to Δs^+ from DIS data & evolution
— SU(3) pulls Δs^+ to generate moment ~ −0.1

⟶ negative peak at $x \sim 0.1$ induced by fixing b parameter to ~ 6 – 8

Simultaneous analysis

- Slightly positive Δs^+ at $x \sim 0.1$ attributed directly to deuteron K^- production data



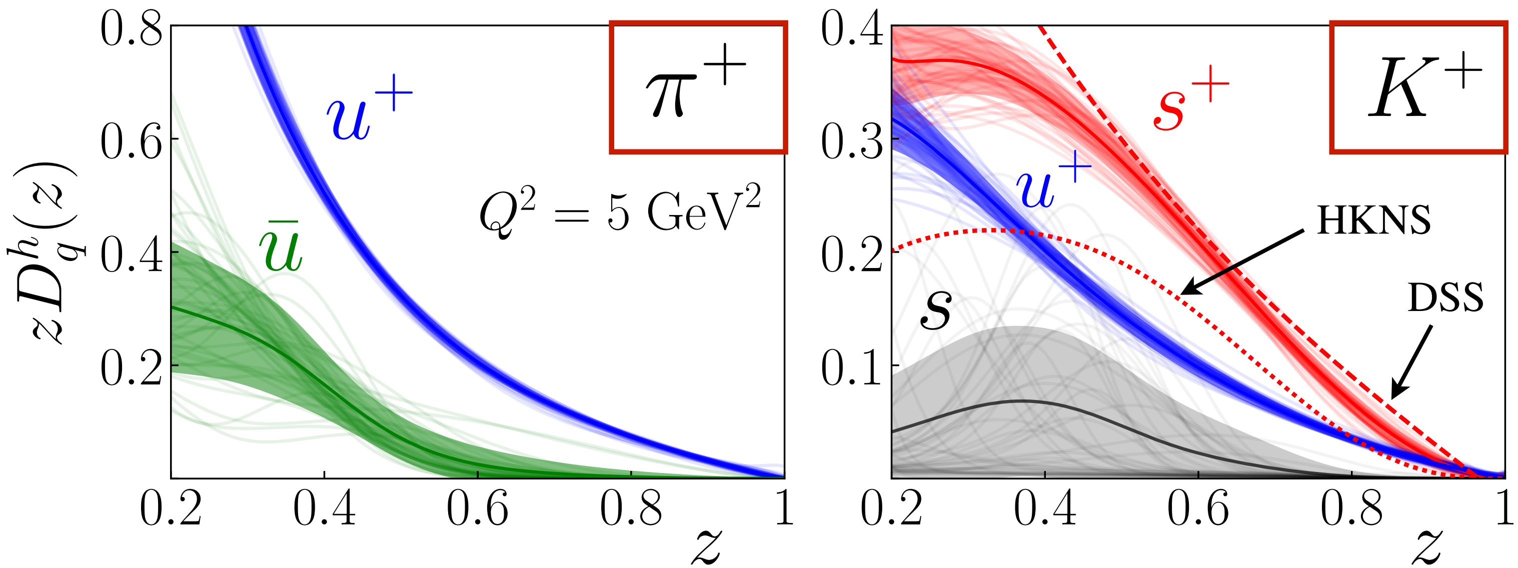


significantly worse fit using negative JAM15 Δs^+ (also for COMPASS and p data)

no such effect observed for pion data sensitive to $\Delta\bar{u}$ & $\Delta\bar{d}$

Simultaneous analysis

- Fragmentation functions similar to previous SIA-only analysis



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

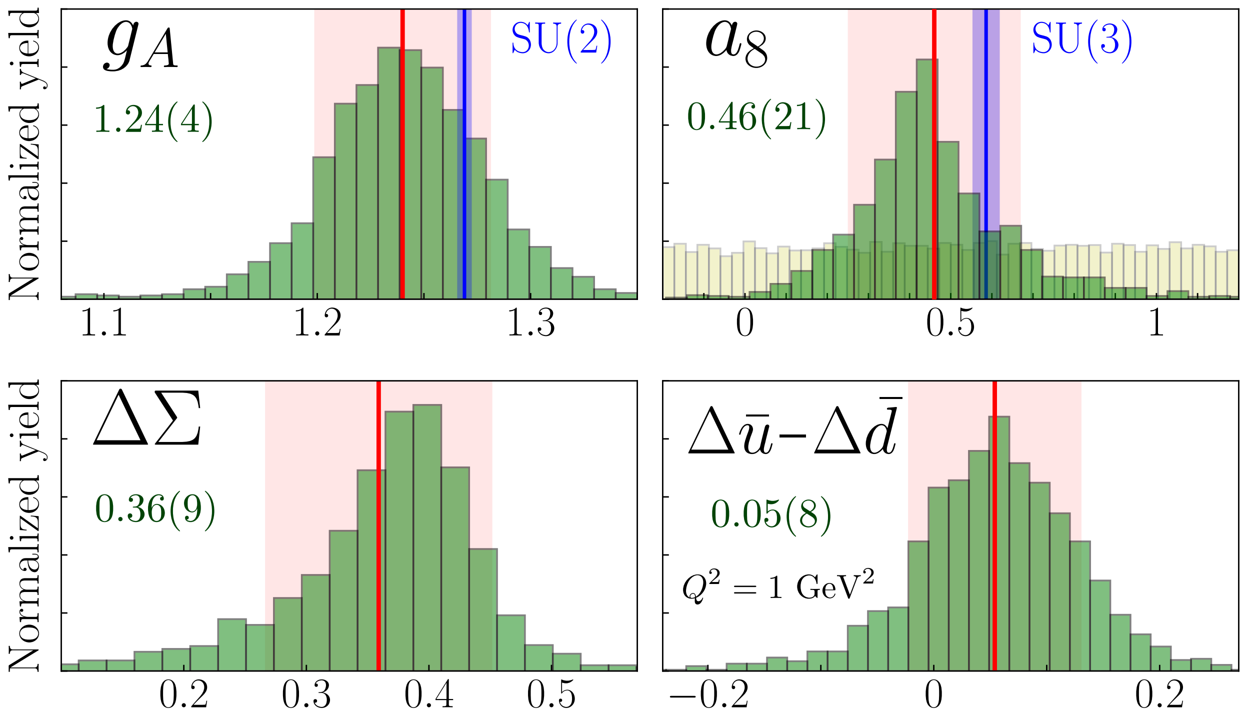
$\longrightarrow$ new result more consistent with DSS at moderate z

$\longrightarrow$ qualitatively similar to NJL-Jet model calculation

Matevosyan et al. (2011)

Simultaneous analysis

- Statistical distribution of lowest moments (axial charges)



Ethier, Sato, WM (PRL, to appear 2017)

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

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

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

Outlook

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

- First combined analysis of polarized DIS + SIDIS + SIA, with consistent extraction of spin PDFs and FFs without assuming SU(3) symmetry
  → resolves strange quark polarization puzzle: $\Delta s = -0.03(10)$
  (less negative than traditional SU(3) value $\Delta s \sim -0.1$)

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

- Longer−term: apply IMC technology to global QCD analysis of transverse momentum dependent (TMD) PDFs and FFs