Towards a universal QCD analysis of PDFs and fragmentation functions

Wally Melnitchouk

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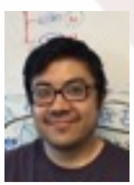
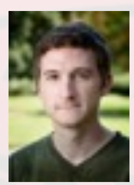


Connecticut / JLab

Jacob Ethier



William & Mary

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Hampton / JLab

Jeff Owens

Florida State U

CTEQ-Jefferson Lab collaboration

JLab Angular Momentum collaboration

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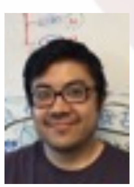

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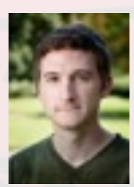

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- ***PRD 93, 114017 (2016)***
- ***PRD 93, 074005 (2016)***
- ***PRD 94, 114004 (2016)***
- ***arXiv:1705.05889***

Outline

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

- Extraction of structure information from global QCD analysis

  $\longrightarrow$ single-fit (Hessian) approach vs. Monte Carlo approaches
  (Bayesian determination of PDF errors)

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

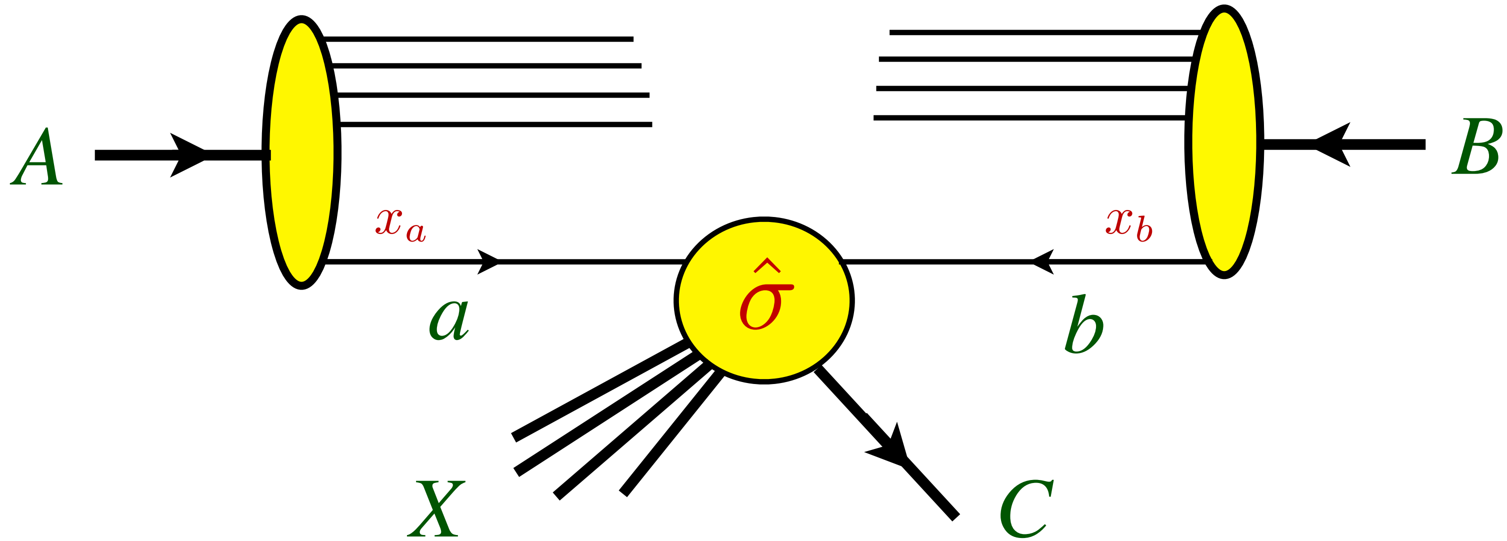
- First MC extraction of fragmentation functions (FFs)
  from e^+e^- single-inclusive annihilation (SIA) data

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

  $\longrightarrow$ resolves strange quark polarisation puzzle

Parton distributions in hadrons

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



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

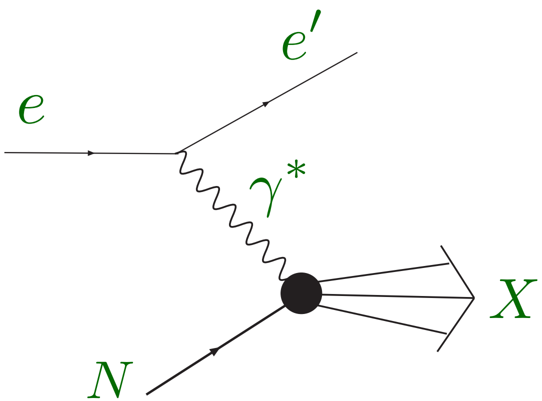
$$\times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}\,(x_a p_A, x_b p_B, Q/\mu)$$

$\boxed{\text{“factorisation”}}$

$\longrightarrow$ universal functions $f_{a/A}$ characterise internal structure of bound state A

Parton distributions in hadrons

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

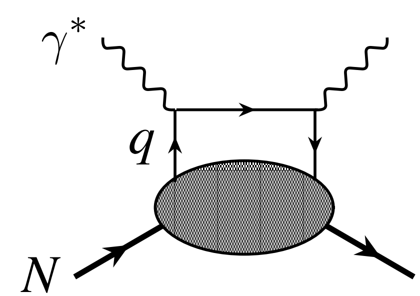


$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

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

- 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 $\ldots$) to be analysed simultaneously

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

- Typically parametrised as

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

with polynomial $e.g.$ $P(x) = 1 + \epsilon\sqrt{x} + \eta \, x$

Global PDF analysis

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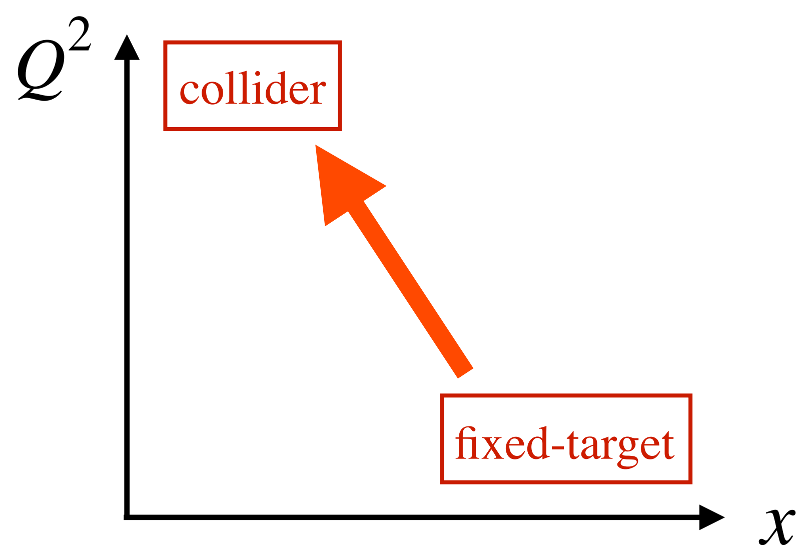
  $\longrightarrow$ parametrisations of spin-averaged $(f = f^{\uparrow} + f^{\downarrow})$ and spin-dependent $(\Delta f = f^{\uparrow} - f^{\downarrow})$ PDFs

- 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

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

Bayes' theorem

$\longrightarrow$ 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"

$\longrightarrow$ maximise probability distribution

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

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

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

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

$\longrightarrow$ need more versatile 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, but sample significantly larger parameter space than possible in single-fit analyses

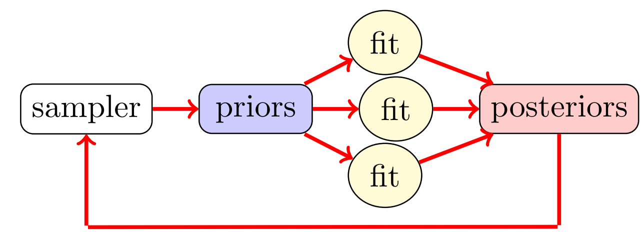
<u>Iterative Monte Carlo (IMC)</u>

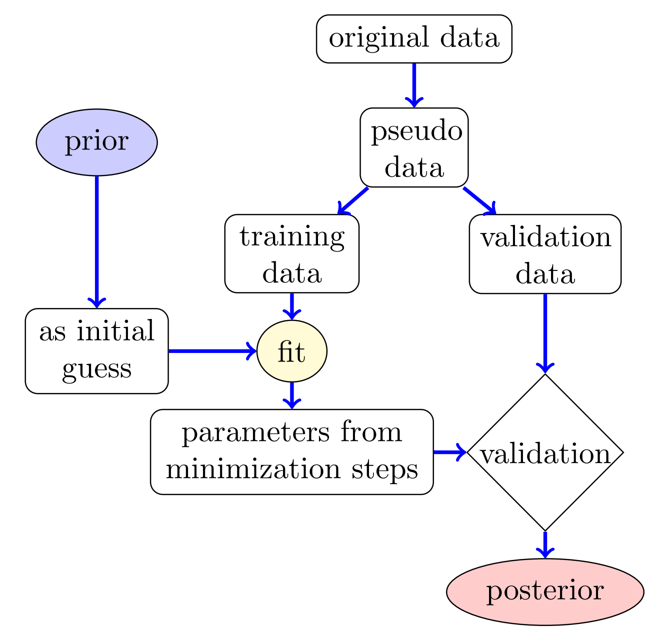
→ no assumptions for exponents

→ cross-validation to avoid overfitting

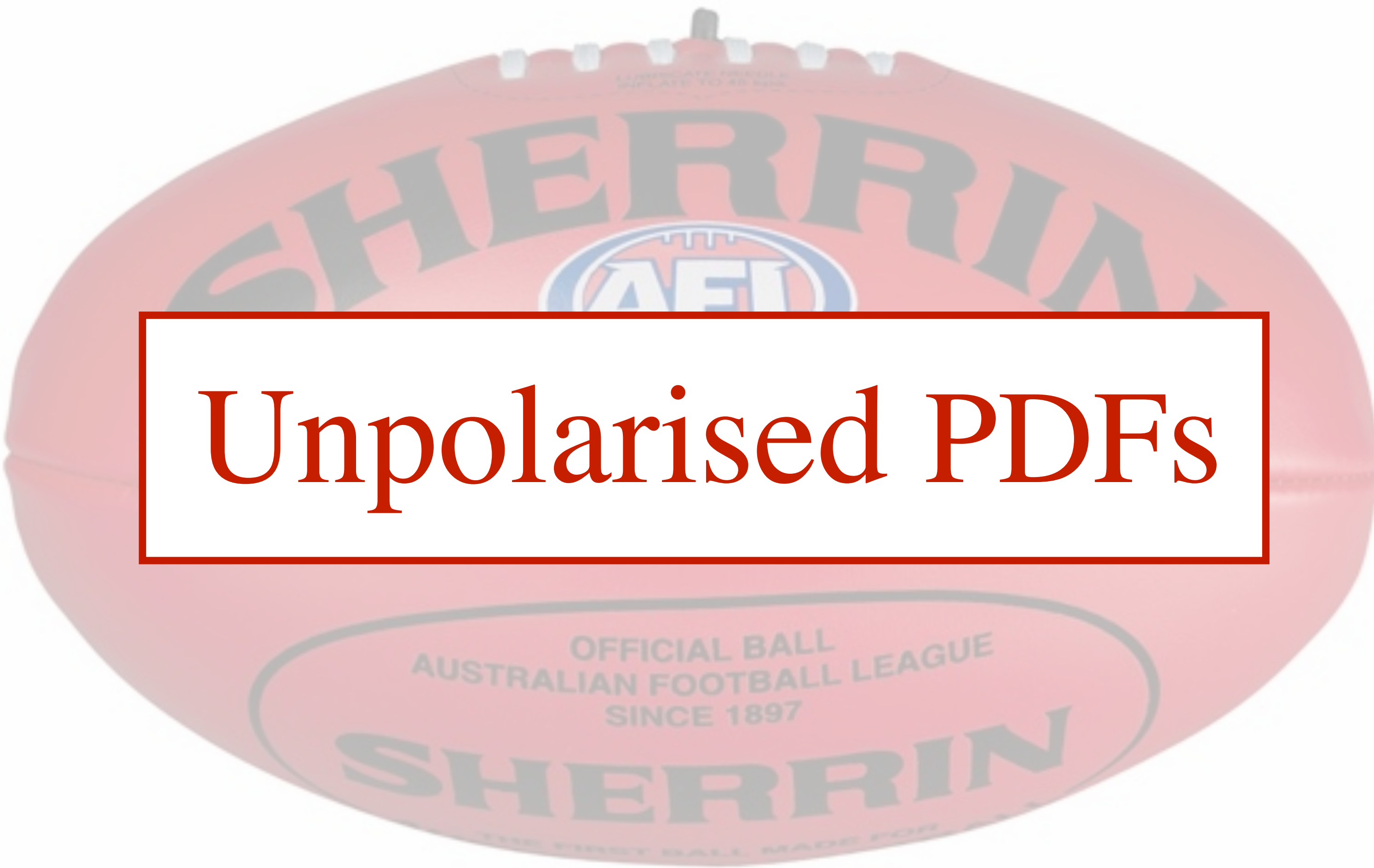
→ iterate until convergence criteria satisfied

→ robust determination of PDF uncertainties!





Unpolarised PDFs

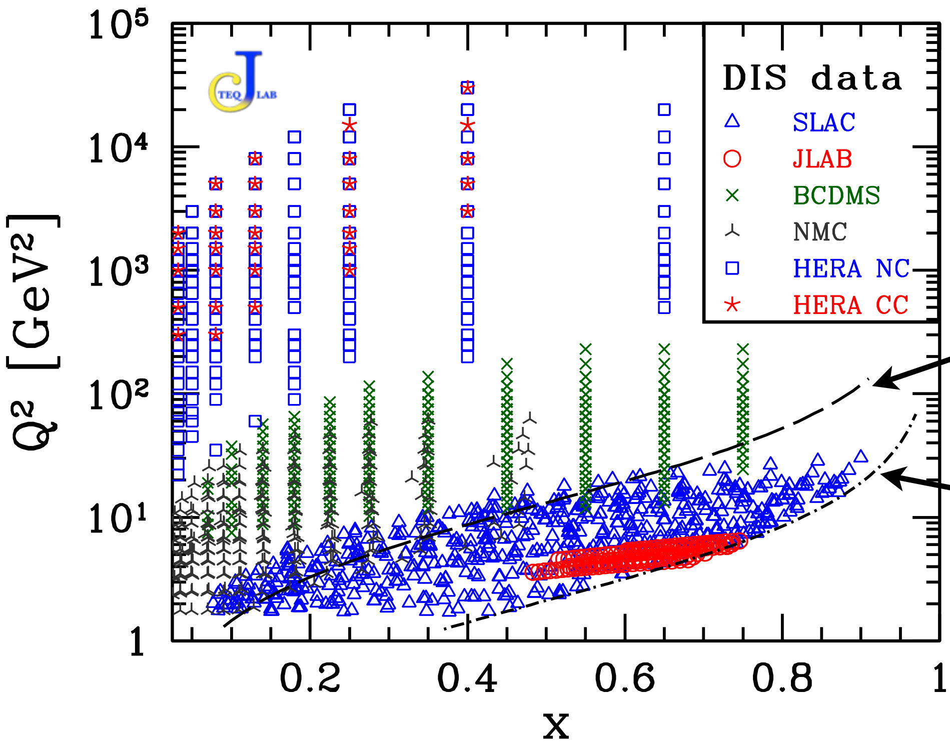


Unpolarised PDFs

- "CJ" (CTEQ-JLab) analysis of world's proton & deuteron data

  $\longrightarrow$ include high-x region ($x > 0.5$)

- High-x region requires use of data at lower W & Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

strong cut:
$Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

weak cut:
$Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

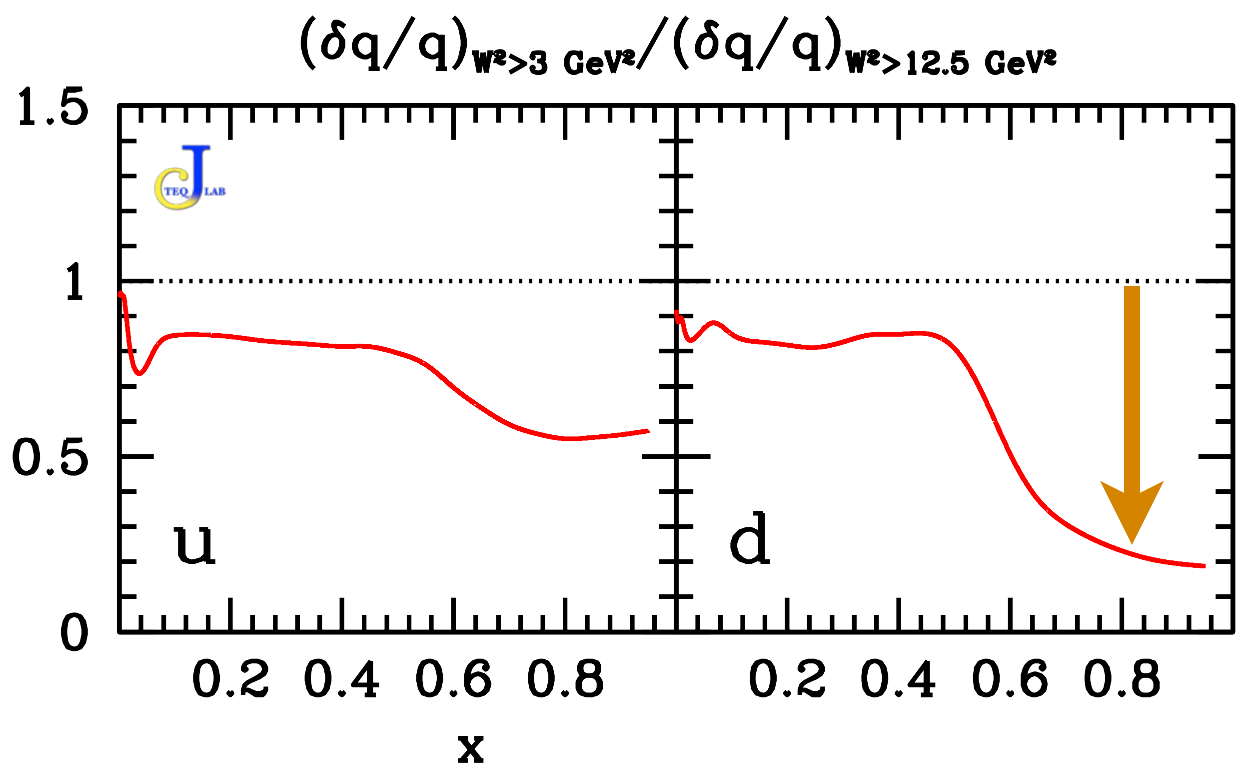
$\longrightarrow$ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) $\rightarrow$ weak cut

Unpolarised PDFs

- "CJ" (CTEQ-JLab) analysis of world's proton & deuteron data

  $\longrightarrow$ include high-x region ($x > 0.5$)

- High-x region requires use of data at lower W & Q^2



$\longrightarrow$ significant error reduction at high x

- data sets used in fit

Observable	Experiment	# points	χ^2 LO	NLO	NLO (OCS)	NLO (no nucl)	NLO (no nucl/D0)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440	427
	BCDMS (d) [81]	254	297	**292**	289	301	301
	SLAC (p) [82]	564	488	**434**	435	441	440
	SLAC (d) [82]	582	396	**376**	380	507	466
	NMC (p) [83]	275	431	**405**	404	405	403
	NMC (d/p) [84]	189	179	**172**	173	174	173
	HERMES (p) [86]	37	56	**42**	43	44	44
	HERMES (d) [86]	37	51	**37**	38	36	37
	Jefferson Lab (p) [87]	136	166	**166**	167	177	166
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219	219
DIS σ	HERA (NC e^-p) [85]	159	325	**241**	240	247	244
	HERA (NC e^+p 1) [85]	402	966	**580**	579	588	585
	HERA (NC e^+p 2) [85]	75	184	**94**	94	94	93
	HERA (NC e^+p 3) [85]	259	307	**249**	249	248	248
	HERA (NC e^+p 4) [85]	209	348	**228**	228	228	228
	HERA (CC e^-p) [85]	42	44	**48**	48	45	49
	HERA (CC e^+p) [85]	39	56	**50**	50	51	51
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143
	E866 (pd) [29]	129	207	**145**	143	158	157
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14
	DØ (μ) [17]	10	37	**20**	19	29	28
	DØ (e) [18]	13	20	**29**	29	14	14
	CDF (W) [89]	13	16	**16**	16	14	14
	DØ (W) [19]	14	39	**14**	15	82	—
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26	26
	DØ (Z) [91]	28	25	**16**	16	16	16
jet	CDF (run 2) [92]	72	33	**15**	15	23	25
	DØ (run 2) [93]	110	23	**21**	21	14	14
γ+jet	DØ 1 [94]	16	17	**7**	7	7	7
	DØ 2 [94]	16	34	**16**	16	17	17
	DØ 3 [94]	12	34	**25**	25	24	25
	DØ 4 [94]	12	76	**13**	13	13	13
total		4542	5894	**4700**	4702	4964	4817
total + norm			6022	**4708**	4710	4972	4826
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07

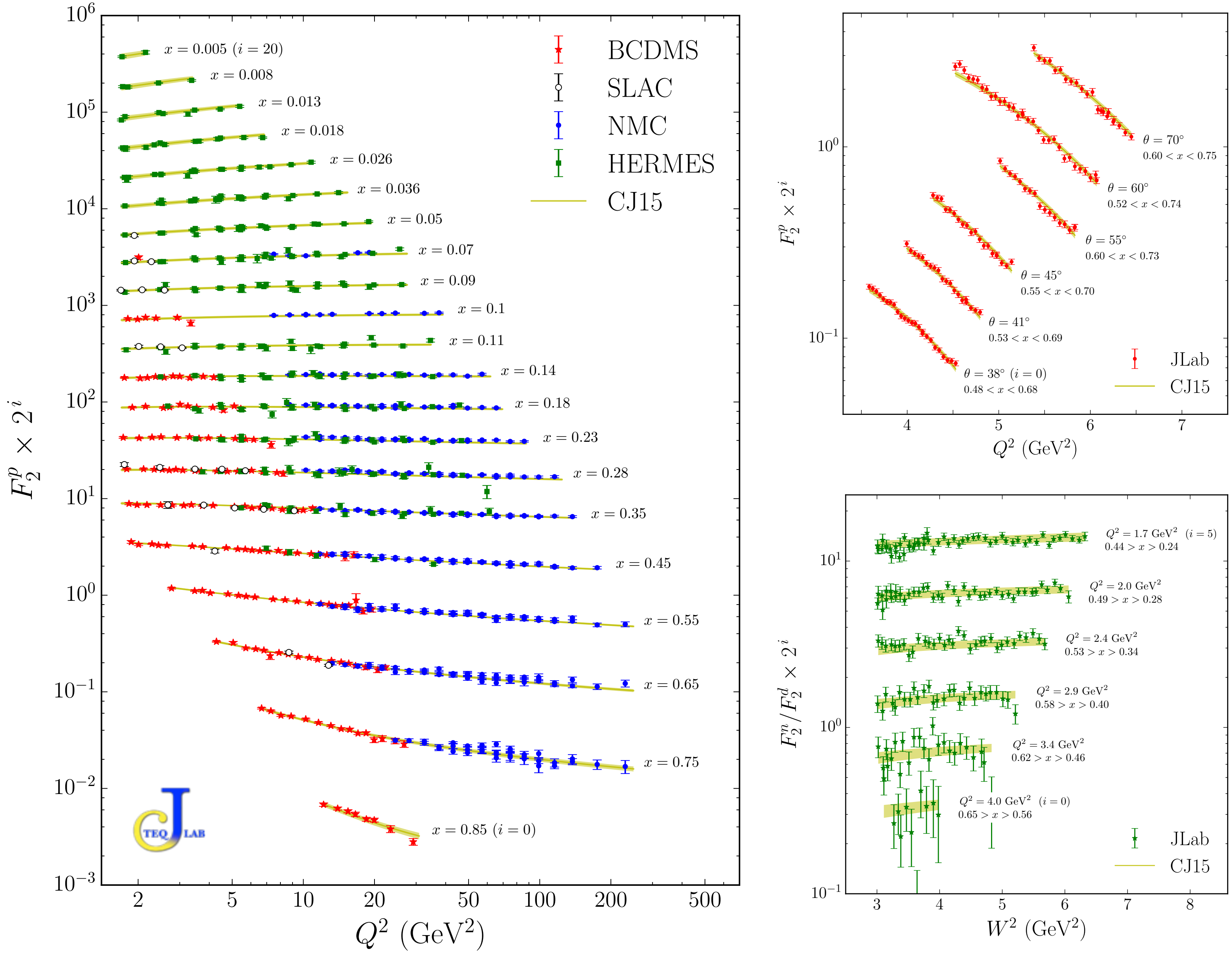
$\longleftarrow$ BONuS F_2^n/F_2^d

$\longleftarrow$ D0 A_l

$\longleftarrow$ D0 A_W

$\rightarrow$ ~ 4500 data points, with χ^2 per datum = 1.04

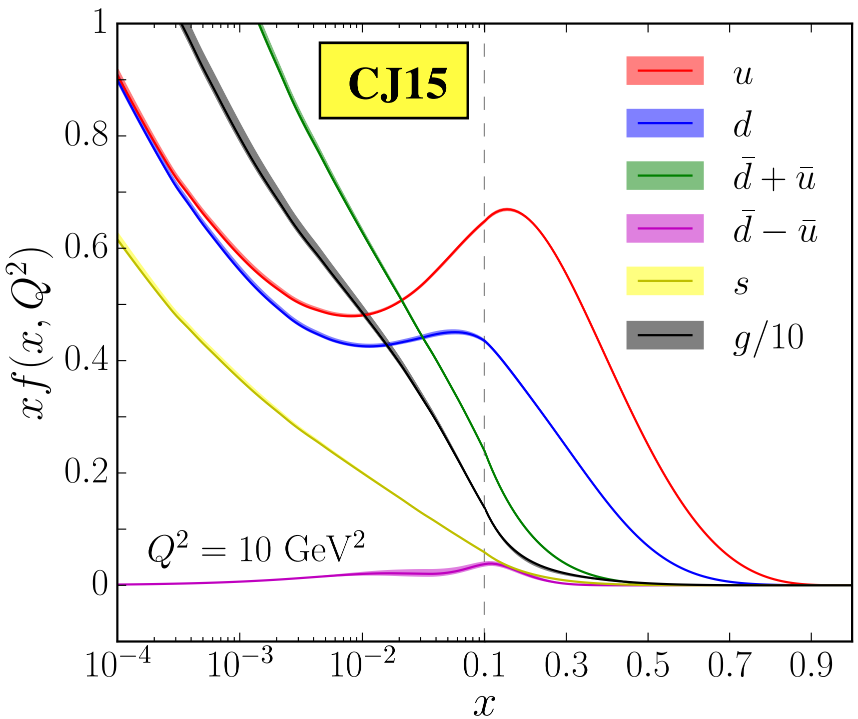
Unpolarised PDFs



$\longrightarrow$ excellent description over orders of magnitude in x and Q^2

Unpolarised PDFs

- Ubiquity of proton F_2 data (SLAC, EMC, 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

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

  - $d/u \to 1/2$

    SU(6) symmetry

  - $d/u \to 0$

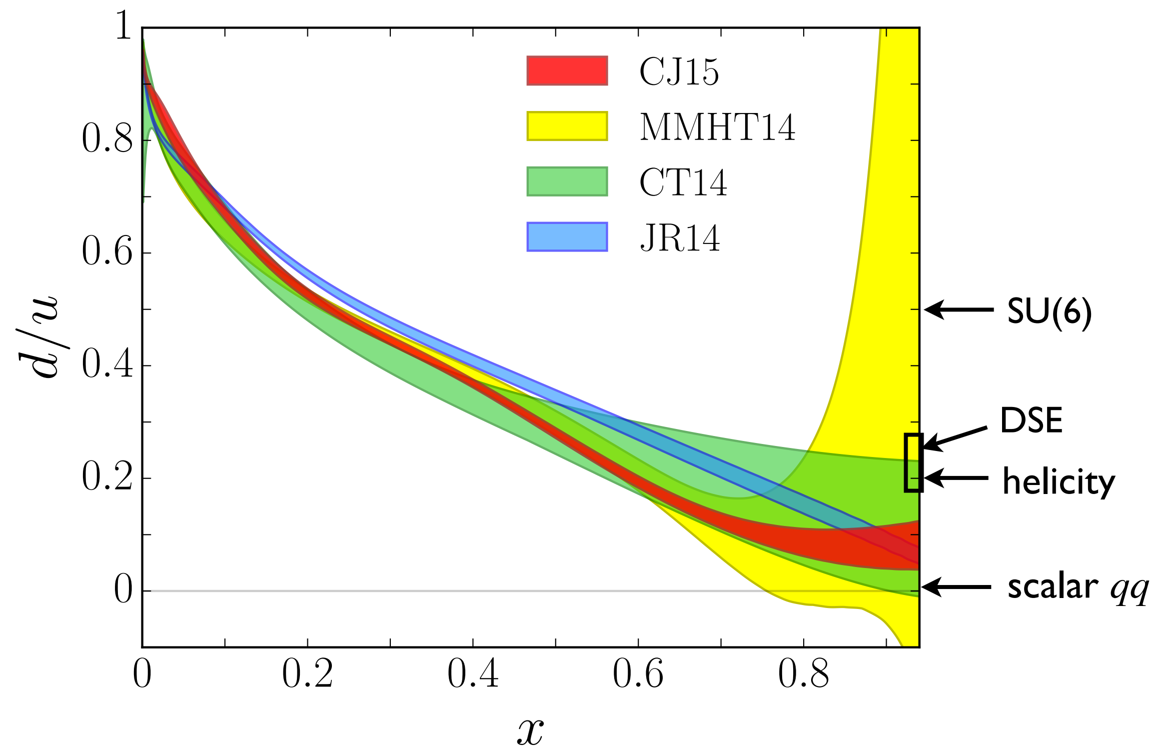
    $S = 0$ qq dominance
    (color-hyperfine interaction)

  - $d/u \to 1/5$

    $S_z = 0$ 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!)

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

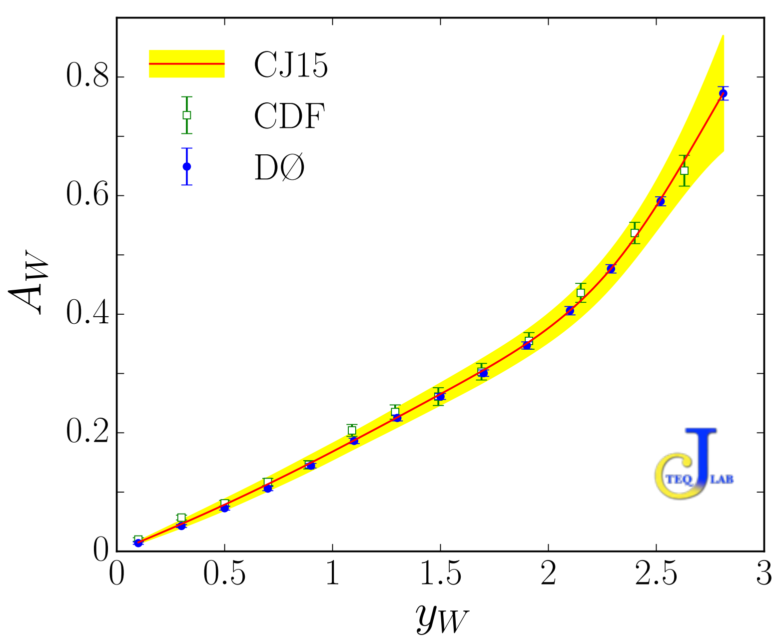
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\ |\psi_d(p)|^2\ \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big) \times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^{\,2}}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

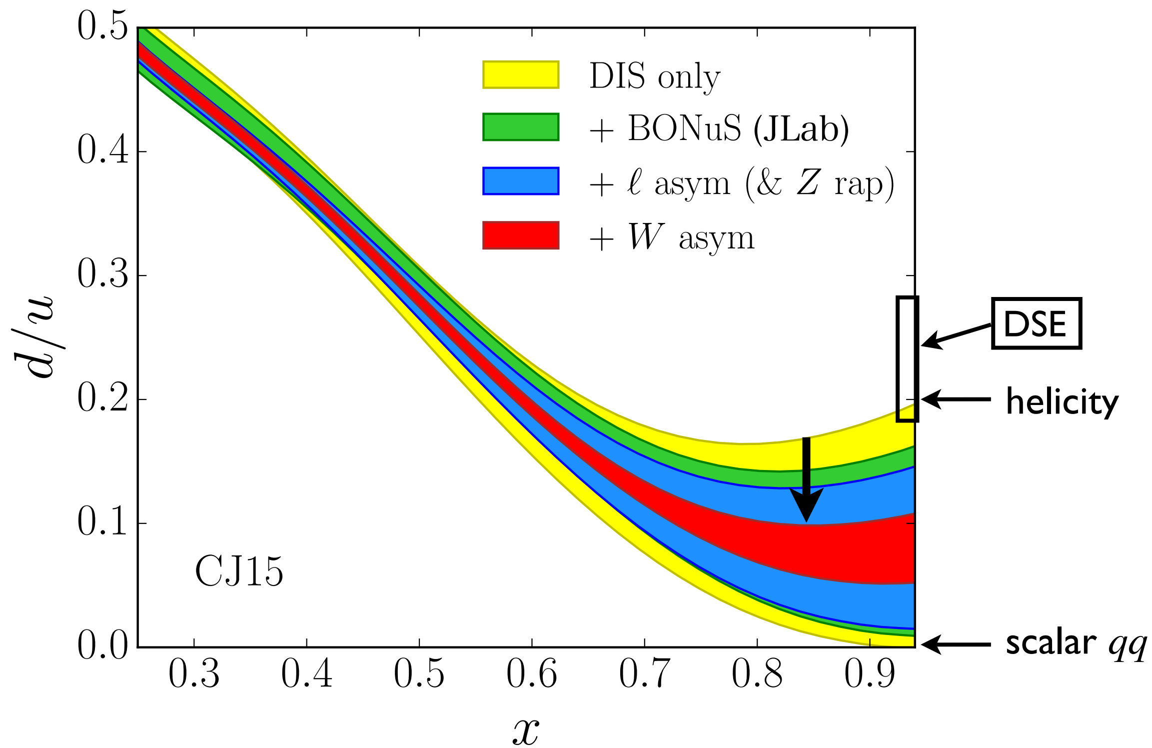
Valence quark PDFs

- 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 $x = 1$

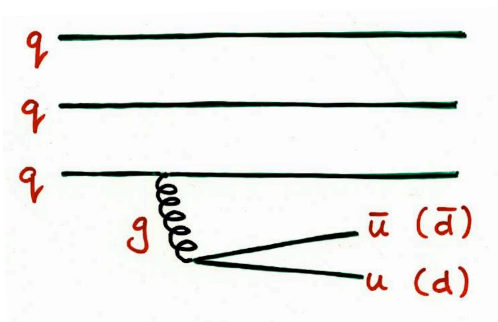
$$d/u \;\to\; 0.09 \pm 0.03$$

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

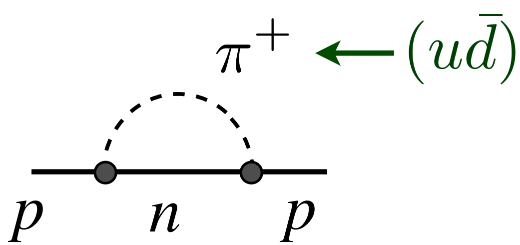
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



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

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

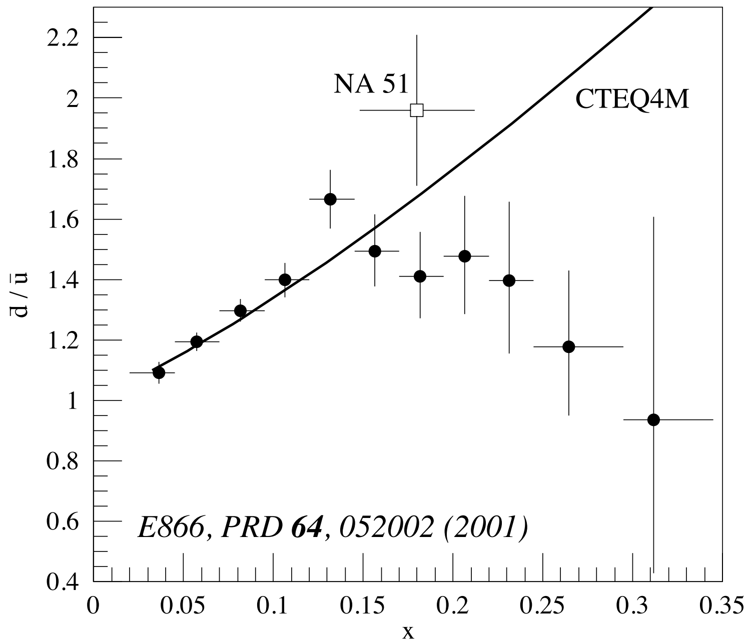
- In 1984 Tony Thomas made "audacious" suggestion that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

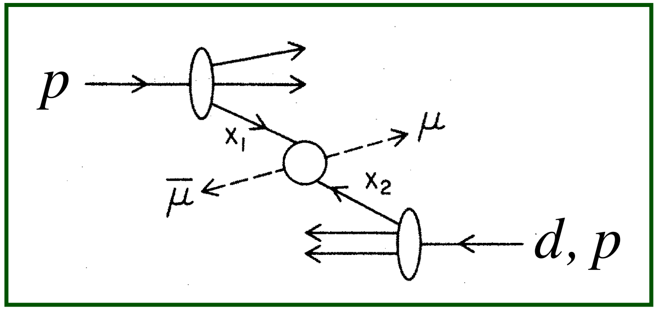


$\longrightarrow$ $\boxed{\bar{d} > \bar{u}}$

Light quark sea

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





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

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

$\longrightarrow$ suggested role of chiral symmetry and pion cloud

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

splitting function ↗ ↖ pion PDF

$\longrightarrow$ strong enhancement of $\bar{d}$ at $x \sim 0.1 - 0.2$, but intriguing behavior at large x hinting at possible sign change of $\bar{d} - \bar{u}$

Light quark sea

- Rigorous connection with QCD established via chiral EFT

$$\mathcal{L}_{\rm eff} = \frac{g_A}{2f_\pi}\,\bar\psi_N \gamma^\mu \gamma_5\, \vec\tau \cdot \partial_\mu \vec\pi\, \psi_N - \frac{1}{(2f_\pi)^2}\,\bar\psi_N \gamma^\mu\, \vec\tau \cdot (\vec\pi \times \partial_\mu \vec\pi)\, \psi_N$$

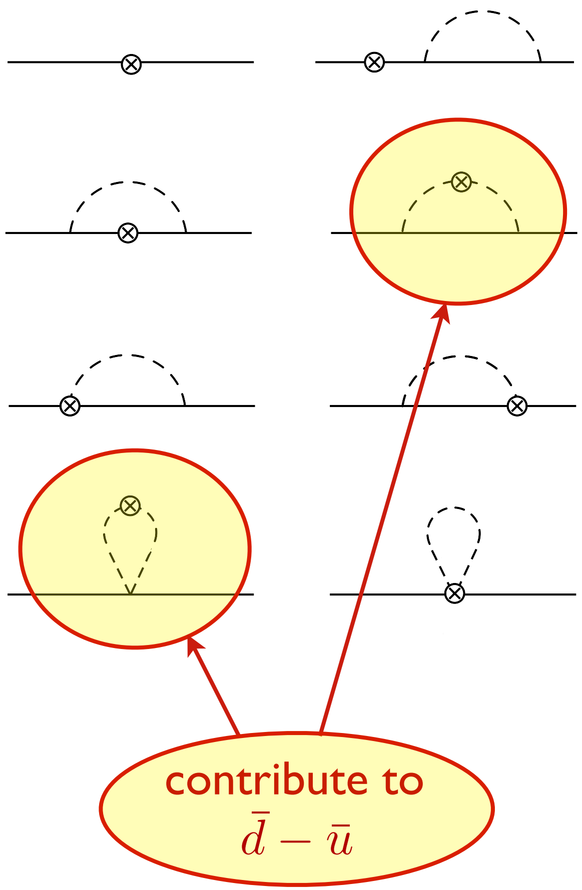
→ lowest order πN interaction includes pion rainbow and tadpole contributions

→ matching quark- and hadron-level operators

$$\mathcal{O}_q^{\mu_1 \cdots \mu_n} = \sum_h c_{q/h}^{(n)}\; \mathcal{O}_h^{\mu_1 \cdots \mu_n}$$

yields convolution representation

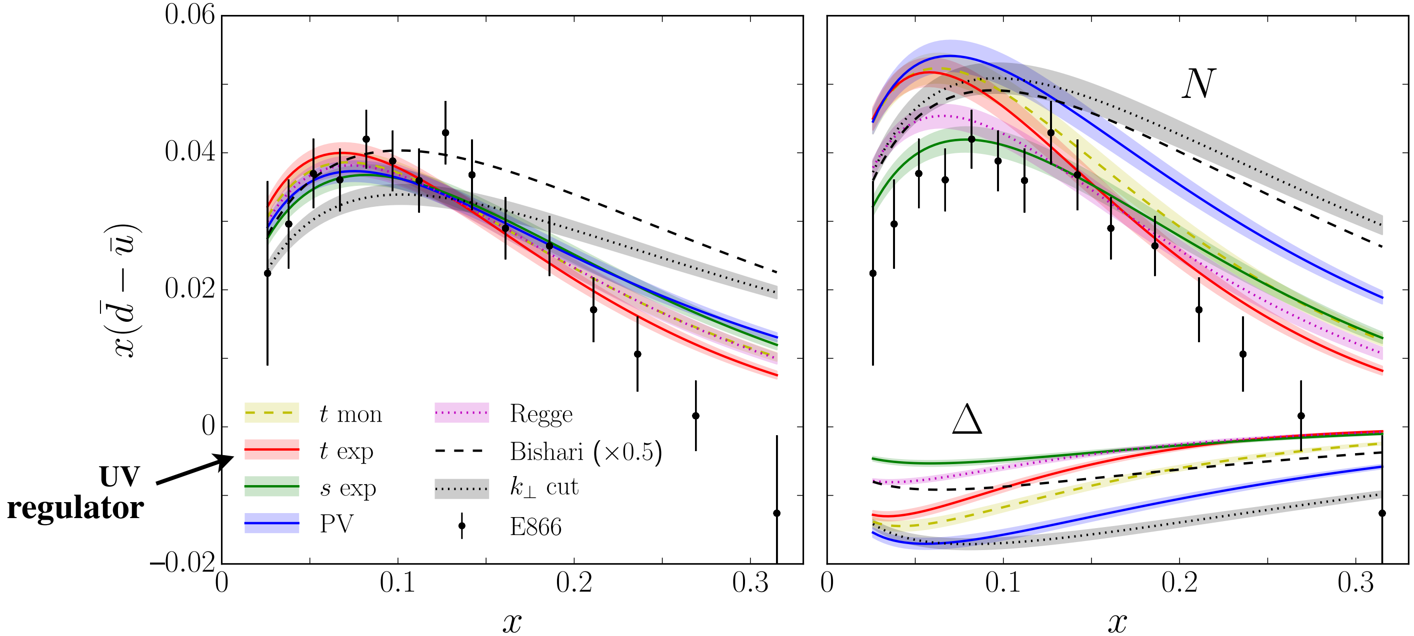
$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\, f_h(y)\, q_v^h(x/y)$$



C Ji, WM, Thomas (2013)

Light quark sea

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



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

McKenney et al.
PRD93, 054011 (2016)

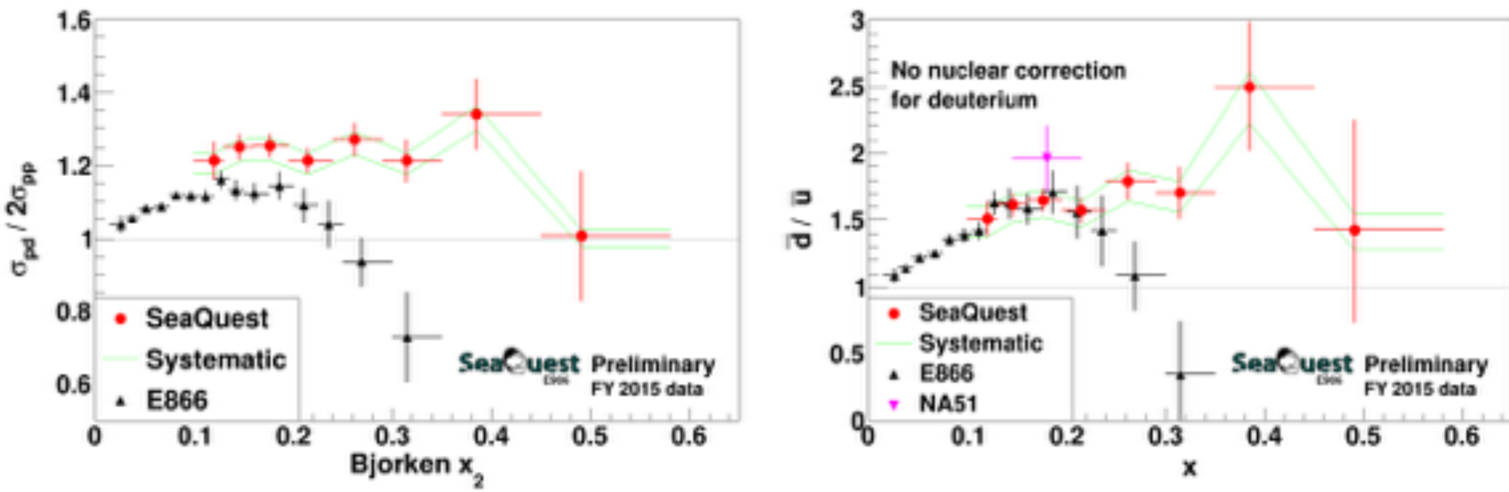
… but lingering question of possible sign change of $\bar{d}-\bar{u}$ at high x

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

$\longrightarrow$ evidence for other mechanisms?

Light quark sea

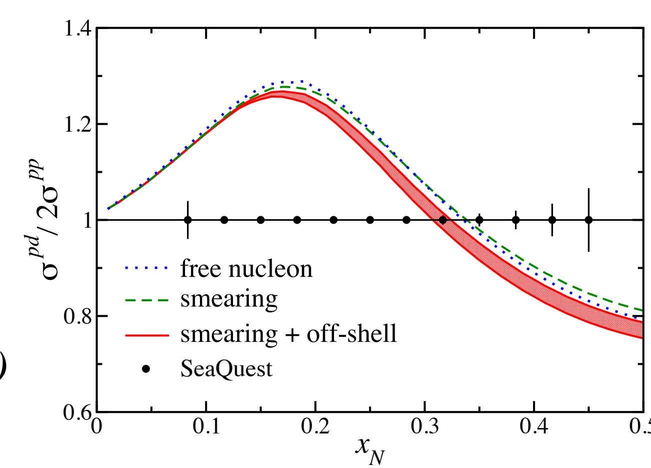
- Preliminary data from SeaQuest (E906) Drell-Yan experiment at Fermilab shows no evidence for sign change



P. Reimer (2016)

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

$\longrightarrow$ results not significantly affected if include nuclear corrections



Ehlers, Accardi, Brady, WM (2014)

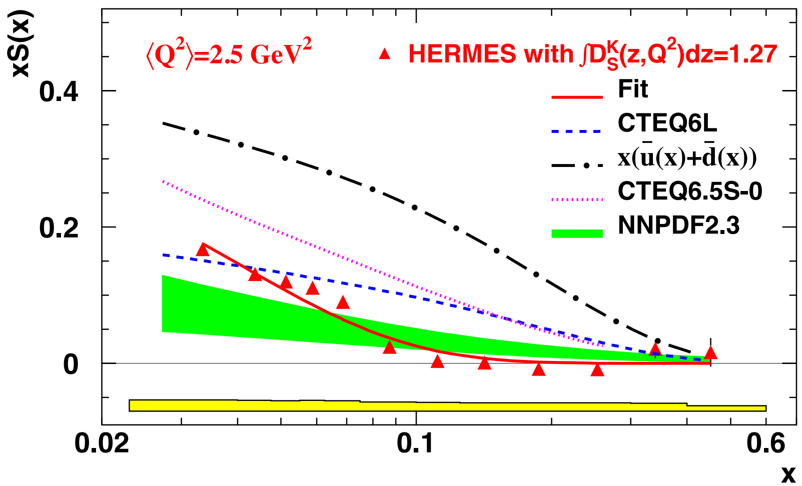
Strange quarks

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

→ but significant uncertainties from nuclear corrections, semileptonic branching ratio, and D meson propagation through the nucleus

→ 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

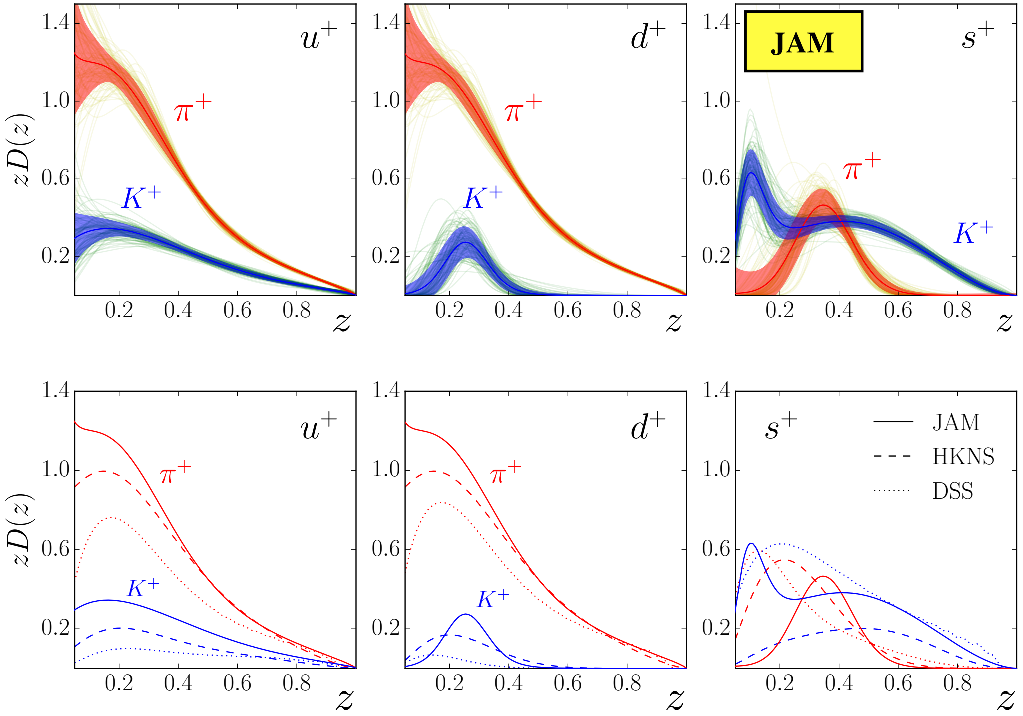
$$\kappa = \frac{s + \bar{s}}{\bar{u} + \bar{d}} \sim 0.2 - 0.5$$

... but uncertainty from K fragmentation functions $D(z)$

Strange quarks

- Fragmentation functions determined from single-inclusive meson production in e^+e^- annihilation

→ new "iterative Monte Carlo" (IMC) global analysis suggests differences with previous extractions

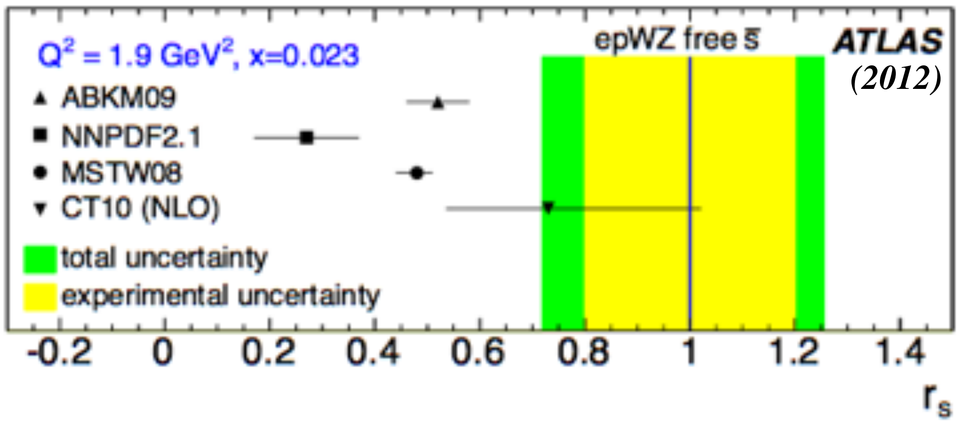


N. Sato et al.
PRD 94, 114004 (2016)

→ SIDIS data also constrain fragmentation functions, but require simultaneous PDF + FF fit

Strange quarks

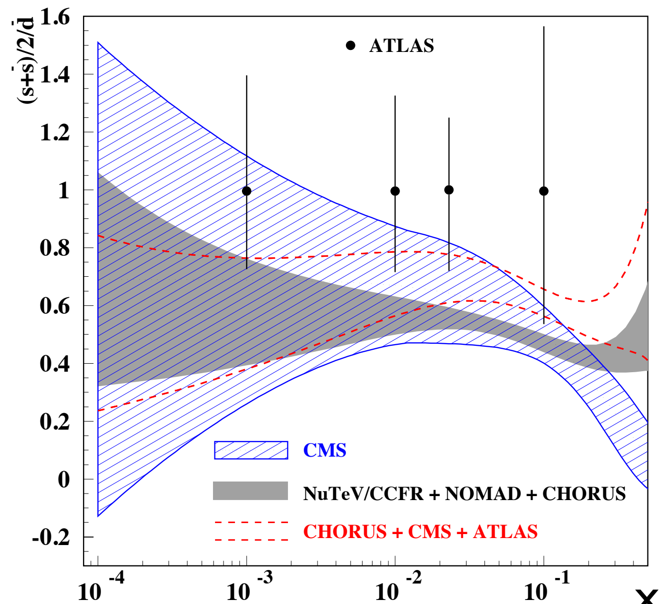
- Alternatively, probe strange PDF in W/Z production at LHC
  $pp \to W(Z) + X$ free of nuclear effects



→ surprisingly large strangeness

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

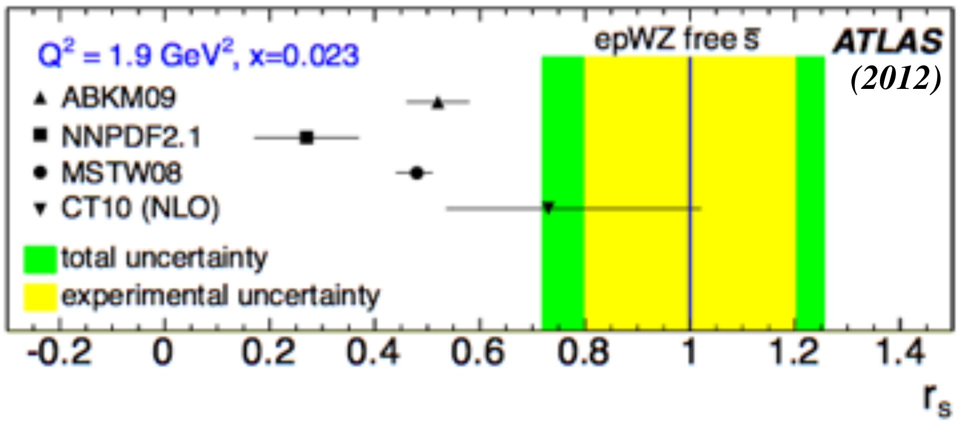
→ more recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF



Alekhin et al. (2015)

Strange quarks

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

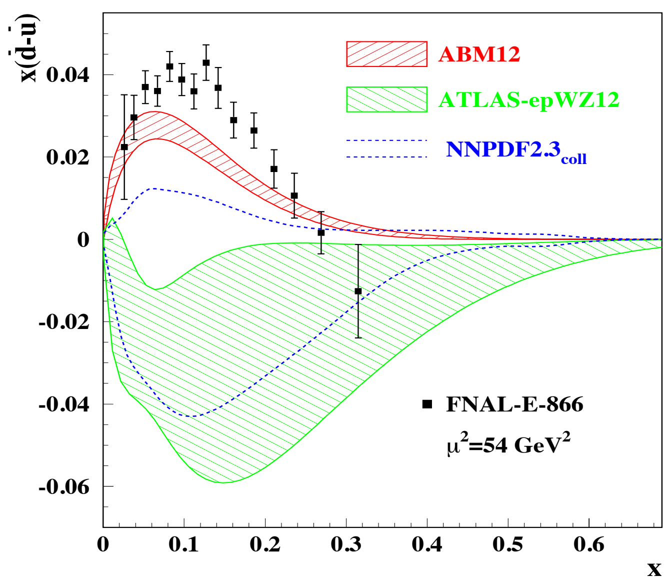


→ surprisingly large strangeness

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

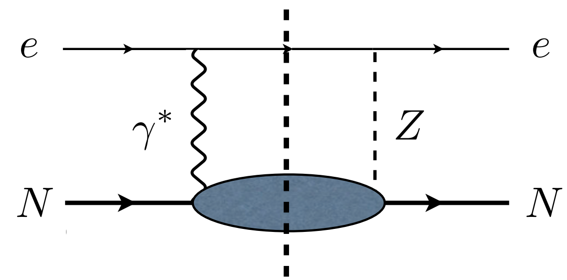
→ more recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF

→ 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



$\longrightarrow$ at leading order

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

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

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

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

$\longrightarrow$ 3 equations with 3 unknowns;
order of magnitude greater sensitivity of γZ to strange PDF

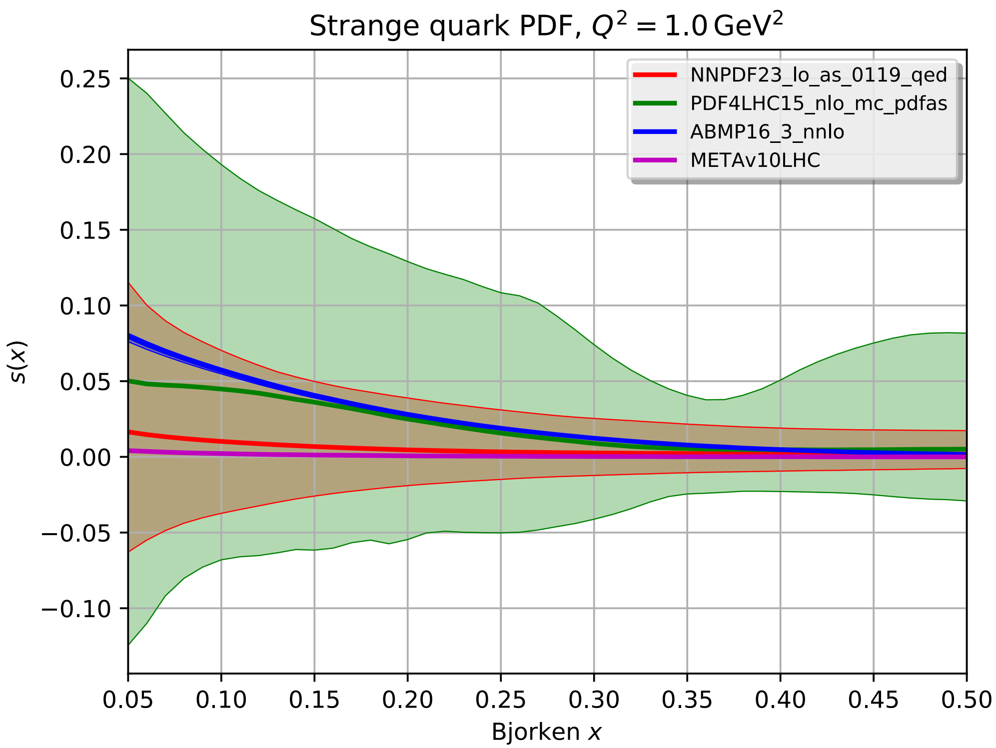
$\longrightarrow$ V x A term also sensitive to $s - \bar{s}$

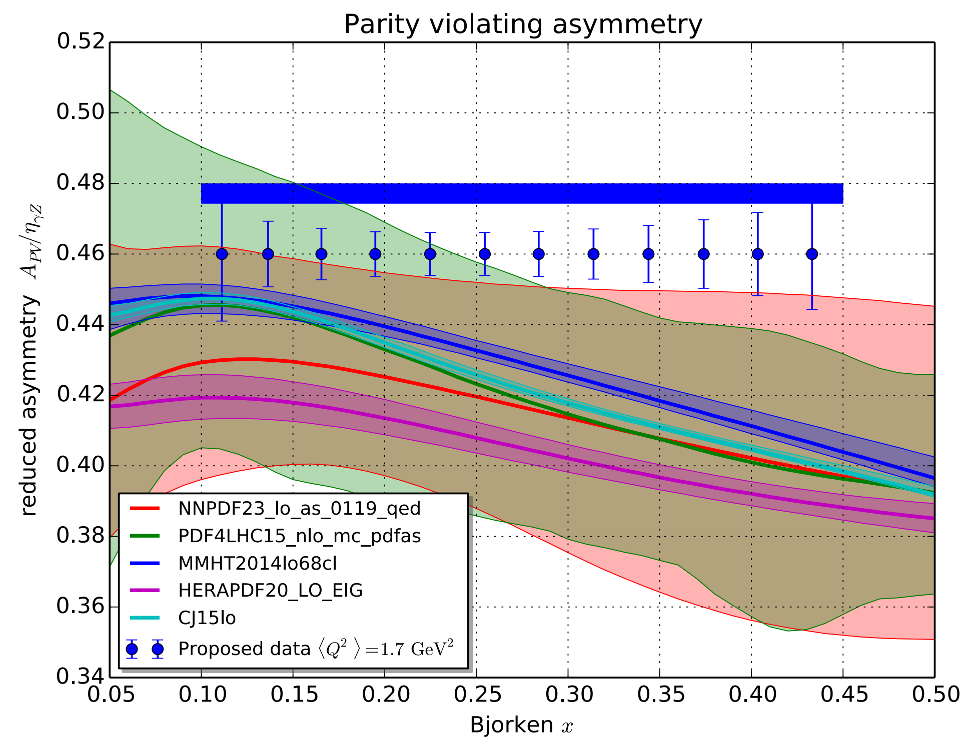
$$F_3^{\gamma Z,p} = \frac{2}{3}(u-\bar{u}) + \frac{1}{3}(d-\bar{d}+s-\bar{s}) + \cdots$$

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

→ PVDIS asymmetry $A_{\rm PV} \propto g_A^e\, Y_1 \dfrac{F_1^{\gamma Z}}{F_1^{\gamma}} + \dfrac{g_V^e}{2}\, Y_3 \dfrac{F_3^{\gamma Z}}{F_1^{\gamma}}$





M. Dalton et al.
JLab PAC45 proposal (2017)

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

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

$\longrightarrow$ 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 flavours measured in polarised 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

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

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 polarisation?

— orbital angular momentum?

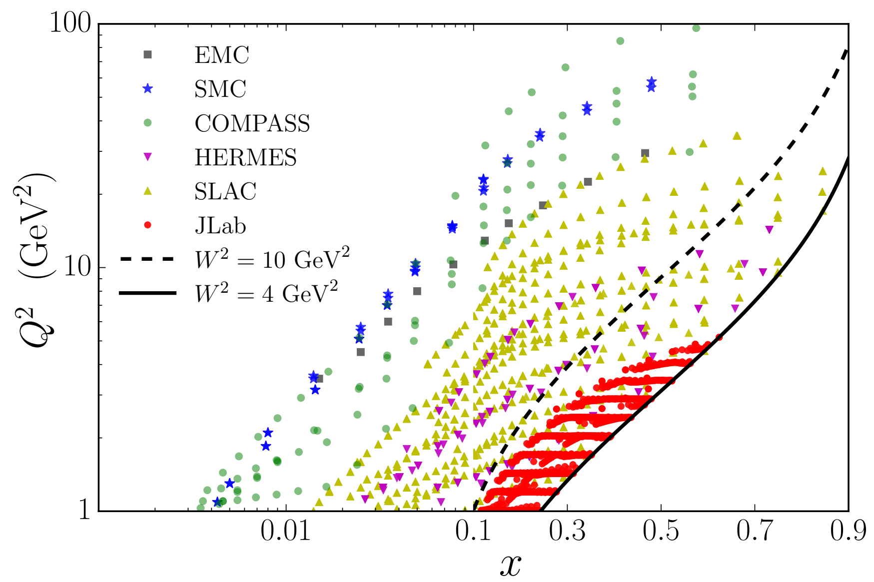
$\longrightarrow$ stimulated many advances in theory, experiment & data analysis

Inclusive DIS global analysis

- For x dependence of spin PDFs, fit experimental asymmetries (longitudinal & transverse) rather than derived structure functions

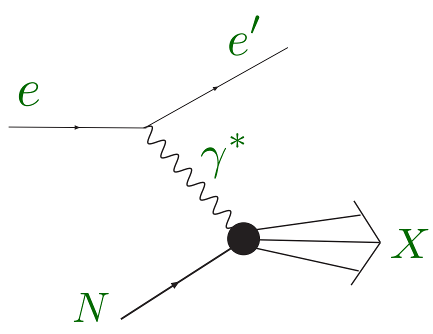
$$A_{\|} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} = D\,(A_1 + \eta\, A_2)$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\uparrow\Leftarrow}} = d\,(A_2 - \zeta\, A_1)$$



where $$A_1 = (g_1 - \gamma^2 g_2)\frac{2x}{(1+\gamma^2)F_2 - F_L}$$

$$A_2 = \gamma(g_1 + g_2)\frac{2x}{(1+\gamma^2)F_2 - F_L}$$



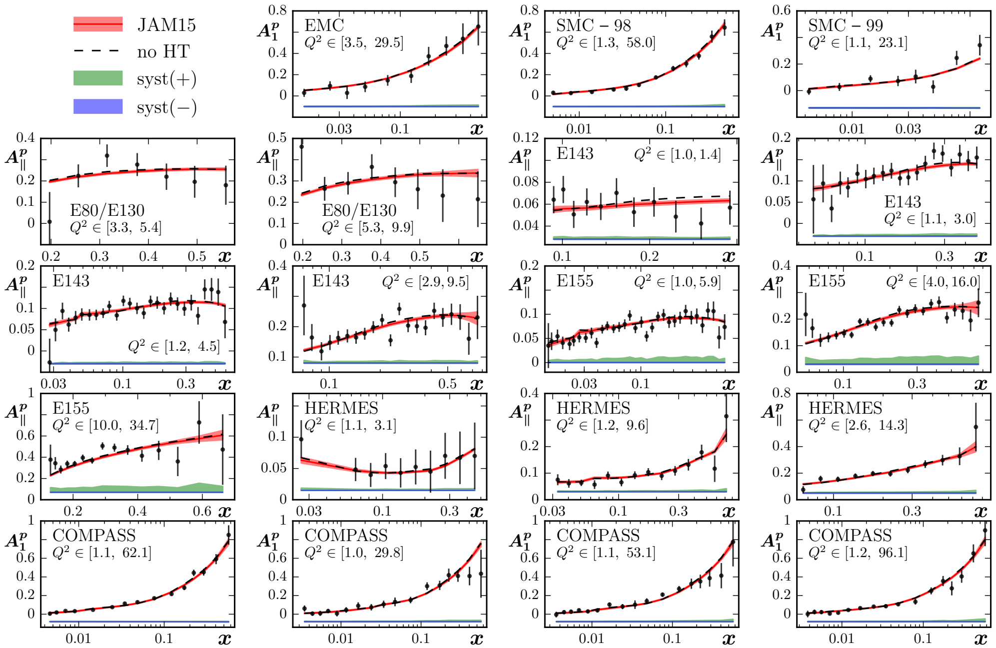
$$\gamma^2 = \frac{4M^2x^2}{Q^2} \qquad x = \frac{Q^2}{2M(E_i - E_f)} \qquad F_2 \overset{\text{LO}}{=} \sum_q e_q^2\; x(q + \bar{q})$$

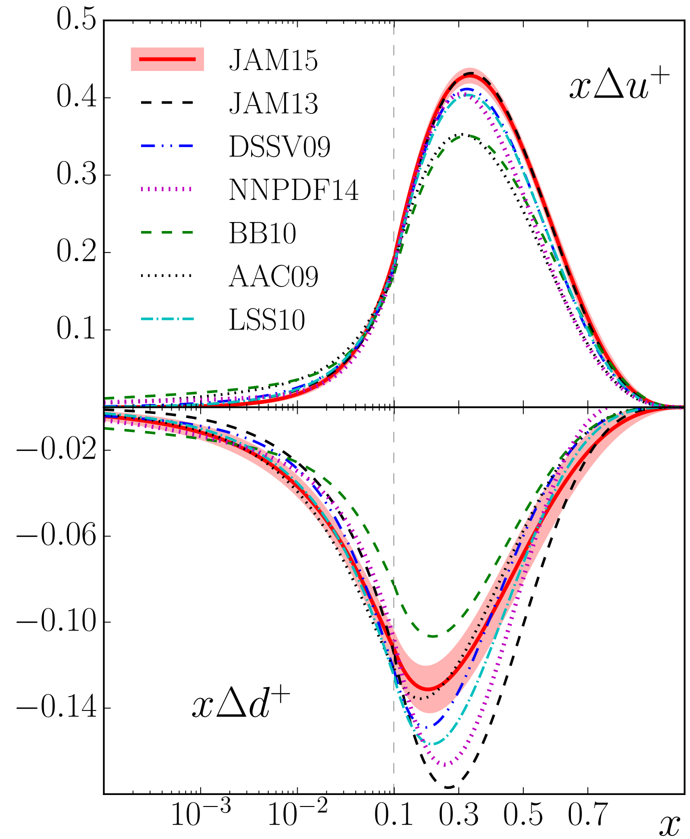
$\longrightarrow$ remove assumptions about $R = \sigma_L/\sigma_T$ ratio

Spin-dependent PDFs

- Polarized DIS data on protons similarly constrain Δu PDF

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



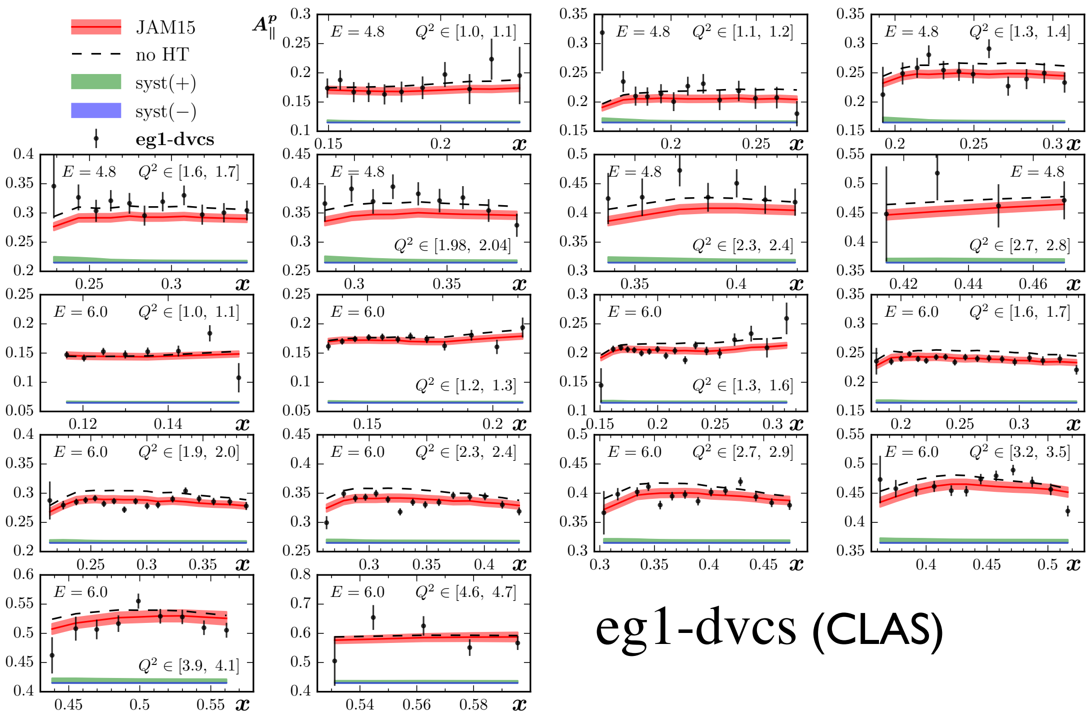


- Polarized deuterium & ^{3}He data more sensitive to Δd PDF

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

Spin-dependent PDFs

Impact of JLab 6 GeV data



eg1-dvcs (CLAS)

$$g_1 = g_1^{\tau 2(\mathrm{TMC})} + g_1^{\tau 3(\mathrm{TMC})} + g_1^{\tau 4}$$

$$g_2 = g_2^{\tau 2(\mathrm{TMC})} + g_2^{\tau 3(\mathrm{TMC})}$$

$$g_1^{\tau 3} = (\rho^2 - 1)\left[g_2^{\tau 3} - 2\int_x^1 \frac{dy}{y}\, g_2^{\tau 3}\right]$$

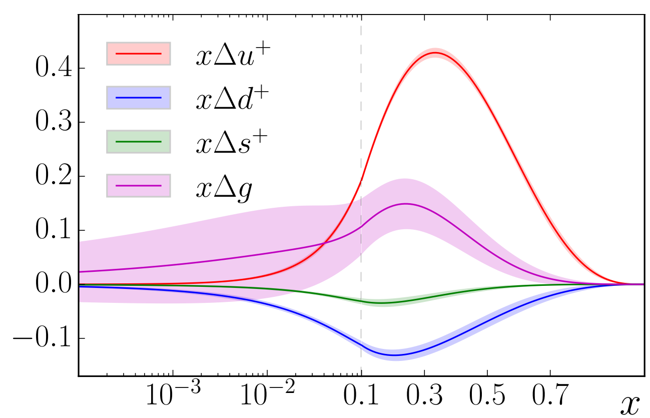
$$D^{\tau 3}(x) = N x^a (1-x)^b (1 + c\, x)$$

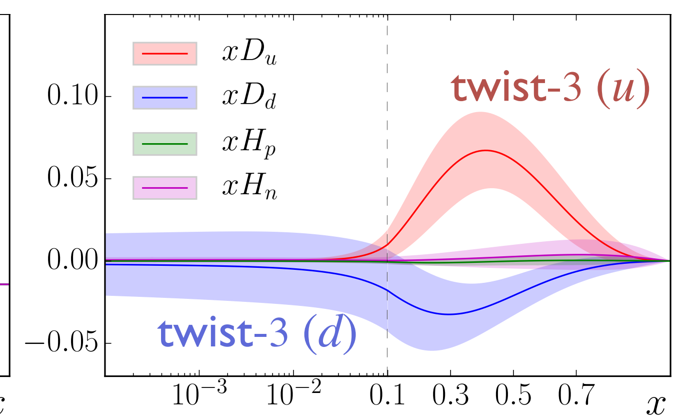
$$g_1^{\tau 4} = N' x^{a'} (1-x)^{b'} (1 + \gamma' x)\, \frac{1}{Q^2}$$

$\longrightarrow$ signal for higher twist

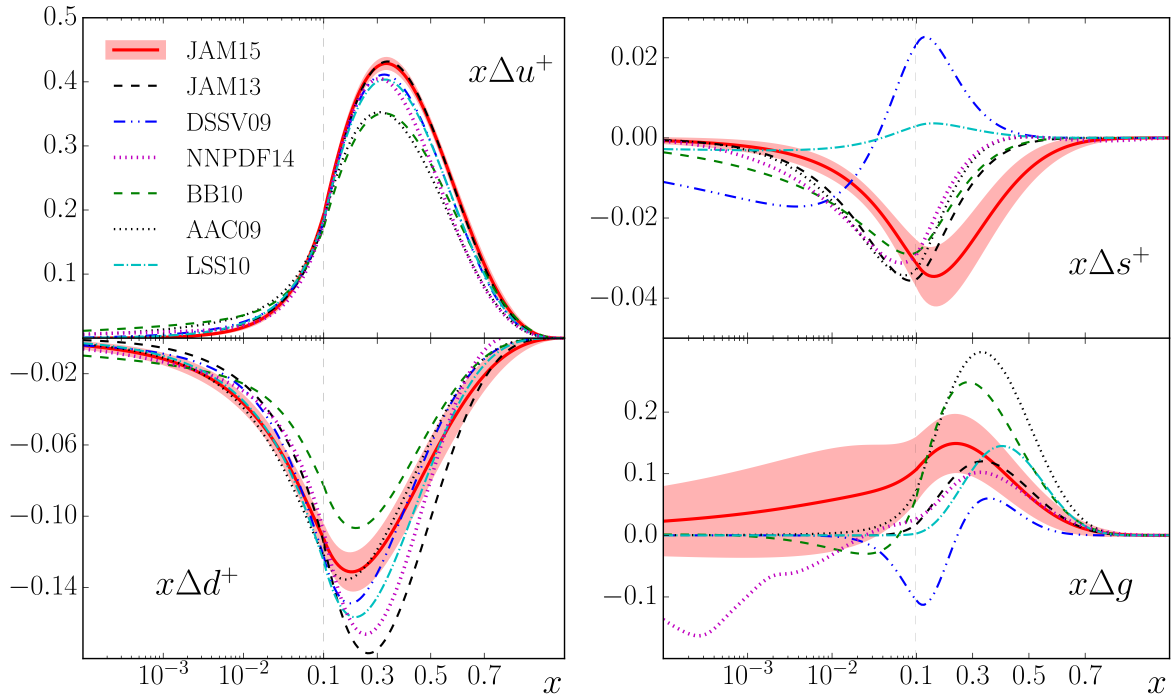
$\longrightarrow$ twist-3 PDFs large, same sign as twist-2

$\longrightarrow$ twist-4 negligible





Comparison with other analyses



→ u and d polarisation similar to earlier results
— uncertainties on d still larger because $|\Delta d| \ll |\Delta u|$

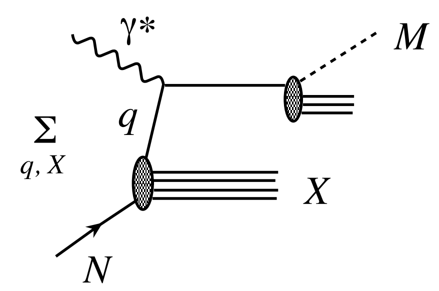
→ s-quark polarisation *negative*

→ gluon polarisation similar to recent DSSV fits
— moment unconstrained

Polarisation 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!

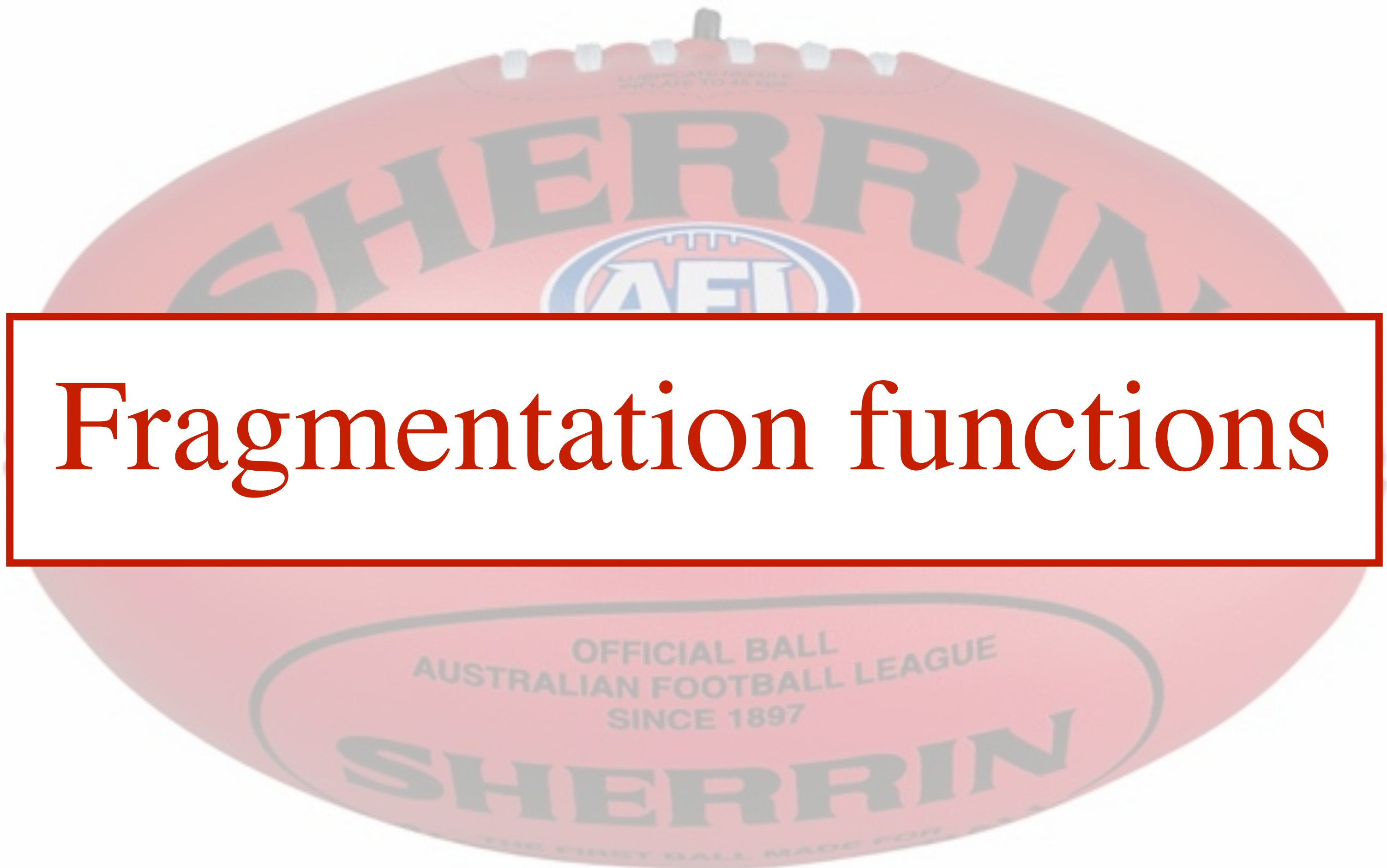
- Global analysis of DIS + SIDIS data gives different *sign* for strange quark polarisation for different fragmentation functions!

$\longrightarrow$ $\Delta s > 0$ for "DSS" parametrisation *de Florian et al., PRD75, 094009 (2007)*

$\Delta s < 0$ for "HKNS" parametrisation *Hirai et al., PRD75, 114010 (2007)*

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

Fragmentation functions



IMC analysis of fragmentation functions

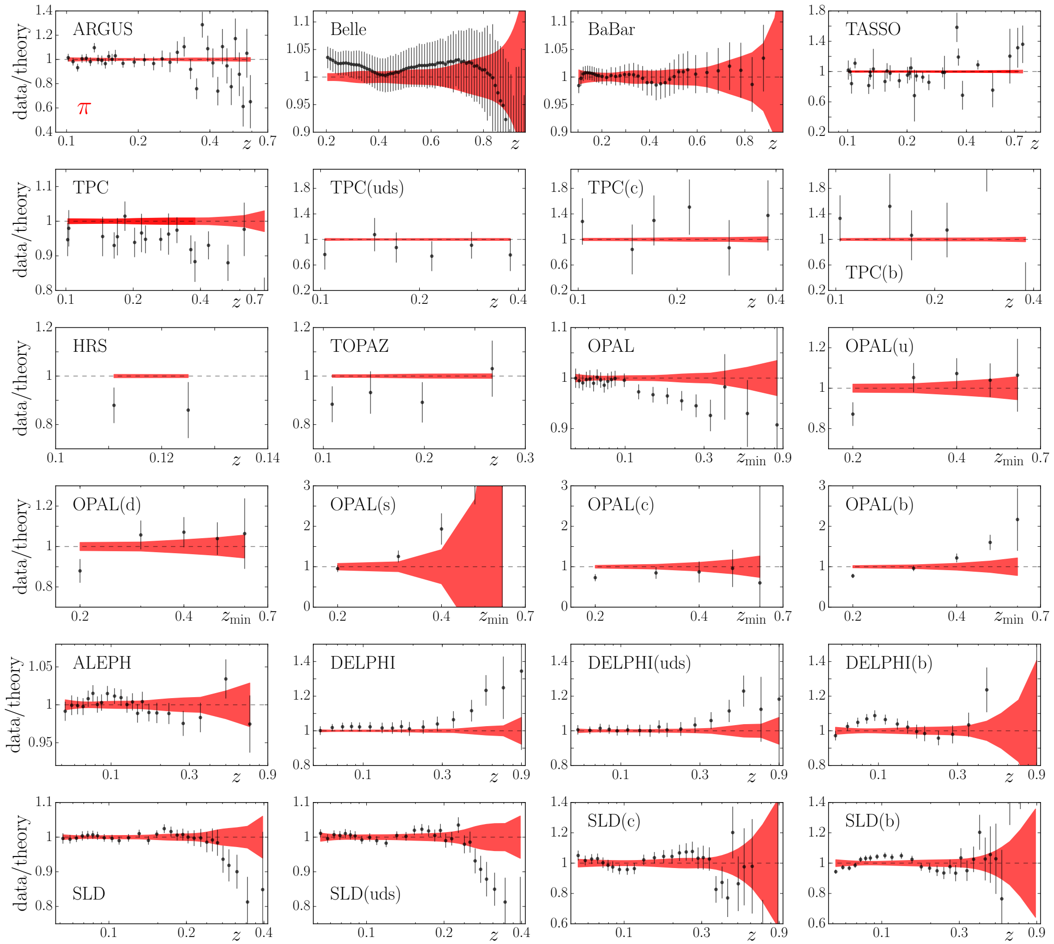
- Analyse single-inclusive e^+e^- annihilation data for pion & kaon production from DESY, CERN, SLAC & KEK from $Q \sim 10$ GeV to Z-boson pole

prompt (conventional)

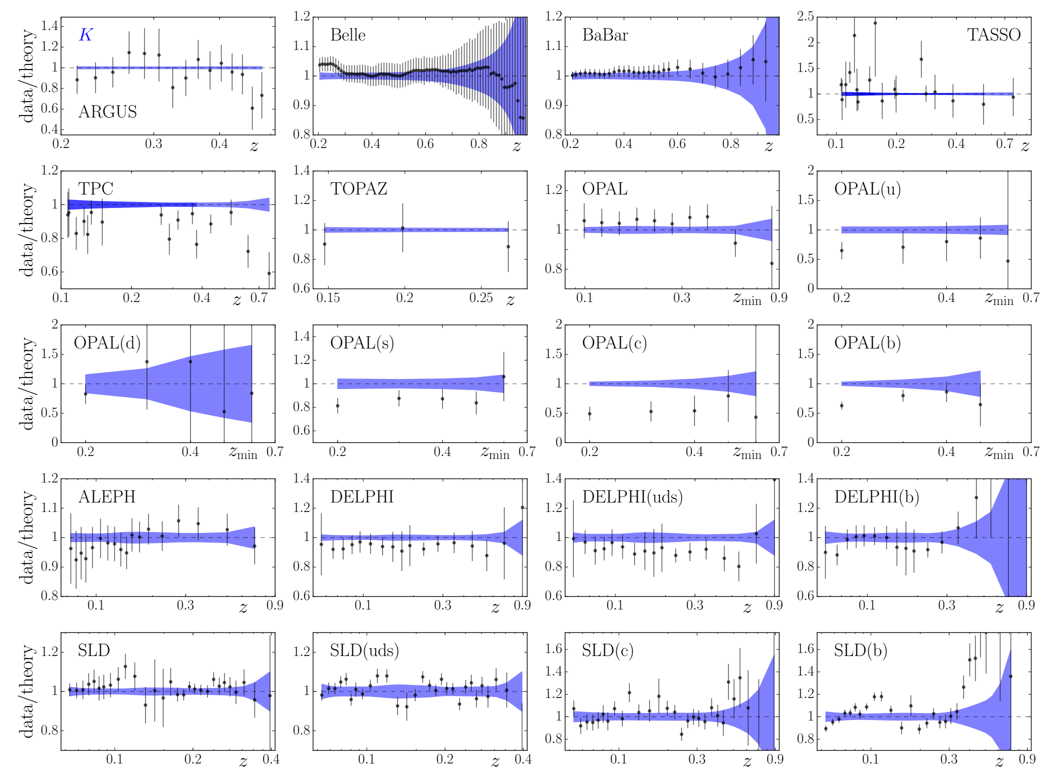
Experiment	Ref.	Observable	Q (GeV)	Pions N_{dat}	Pions norm.	Pions χ^2	Kaons N_{dat}	Kaons norm.	Kaons χ^2
ARGUS	[26]	Inclusive	9.98	35	1.024 (1.058)	51.1 (55.8)	15	1.007	8.5
Belle	[38,39]	Inclusive	10.52	78	0.900 (0.919)	37.6 (21.7)	78	0.988	10.9
BABAR	[40]	Inclusive	10.54	39	0.993 (0.948)	31.6 (70.7)	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
					$\chi^2/N_{\mathrm{dat}} = 1.31\ (1.46)$				$\chi^2/N_{\mathrm{dat}} = 1.01$

IMC analysis of fragmentation functions

pion production



kaon production

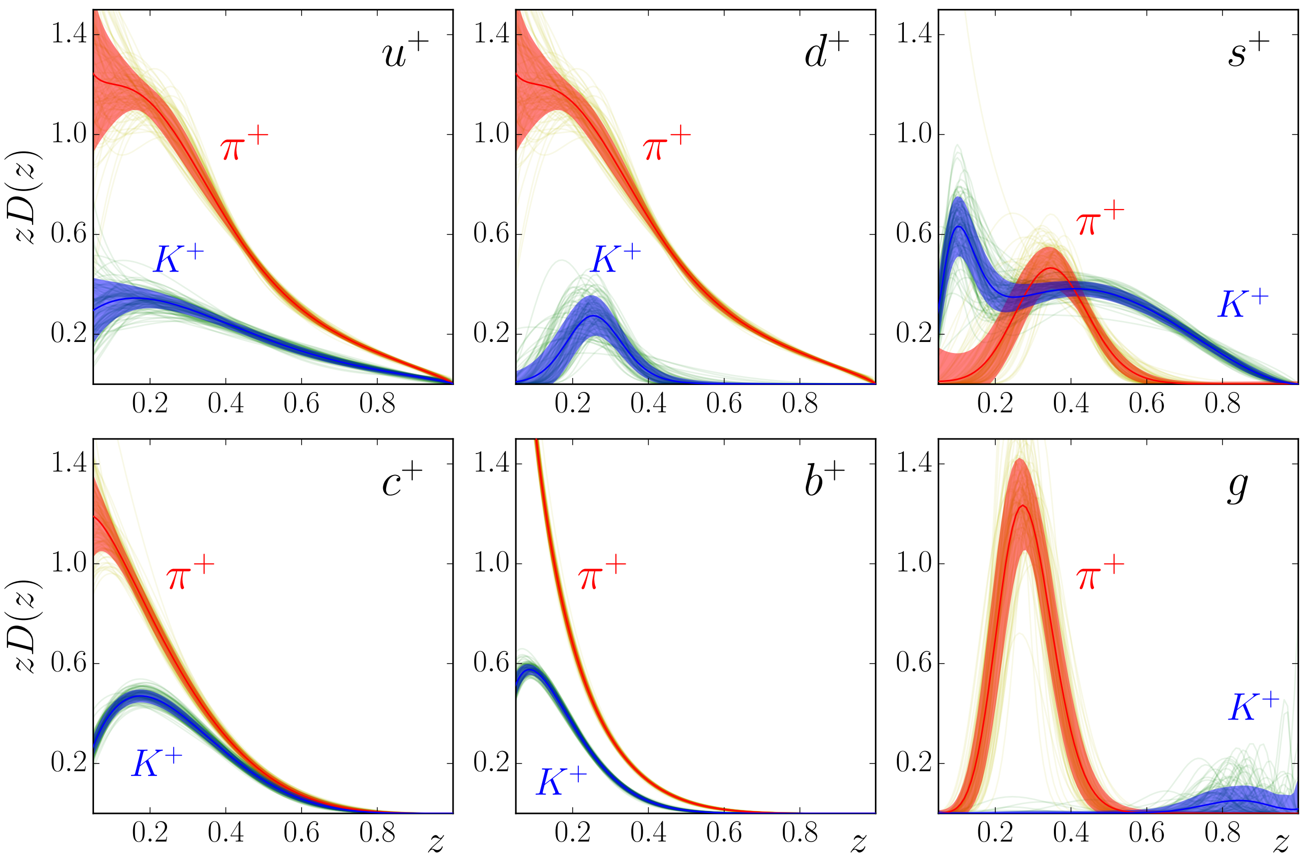


→ generally good agreement

→ some issues at high z

→ smaller χ^2 for K *cf.* π due to larger uncertainties

IMC analysis of fragmentation functions

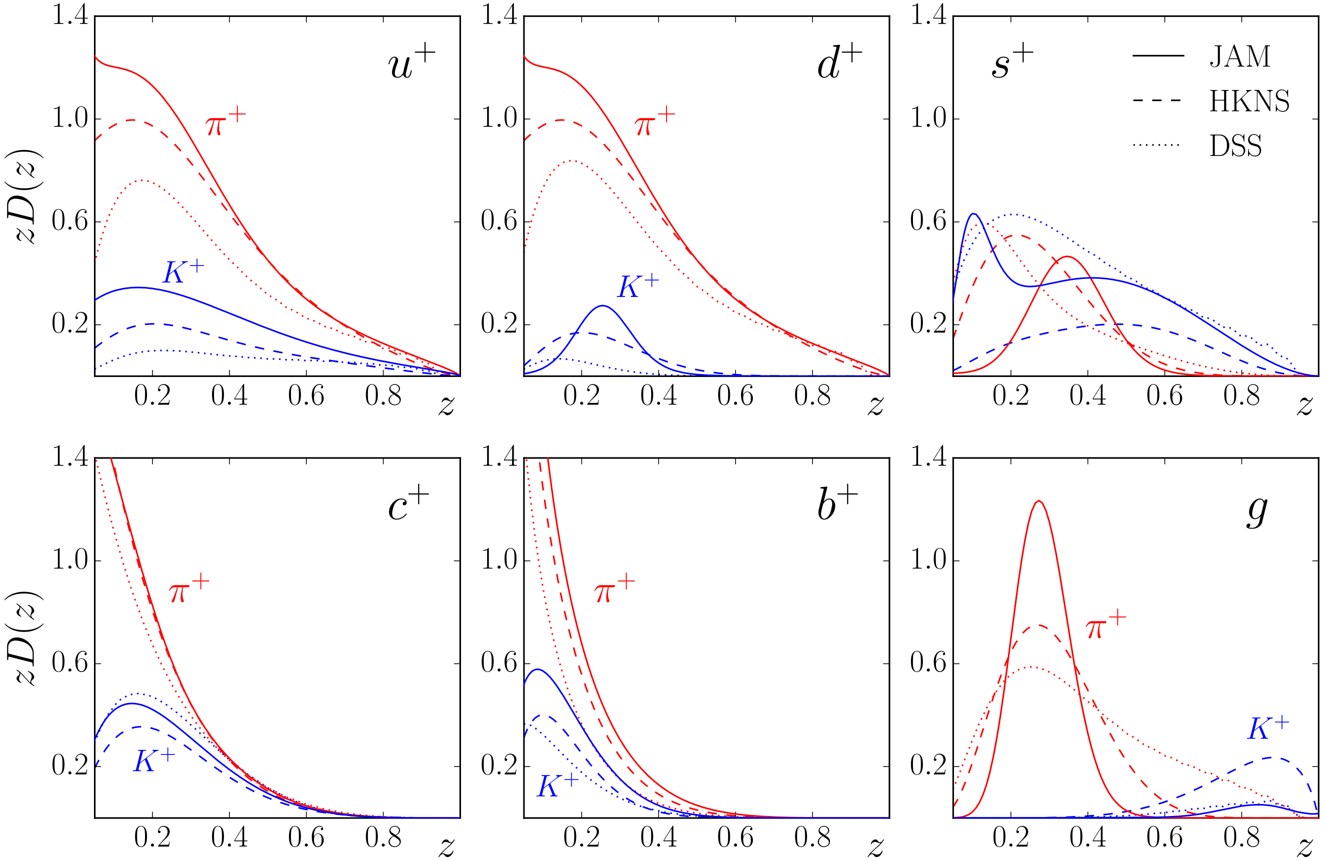


→ favoured FFs well constrained; unfavoured not as well…

→ nontrivial shape of $s \rightarrow K$ fragmentation

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

IMC analysis of fragmentation functions

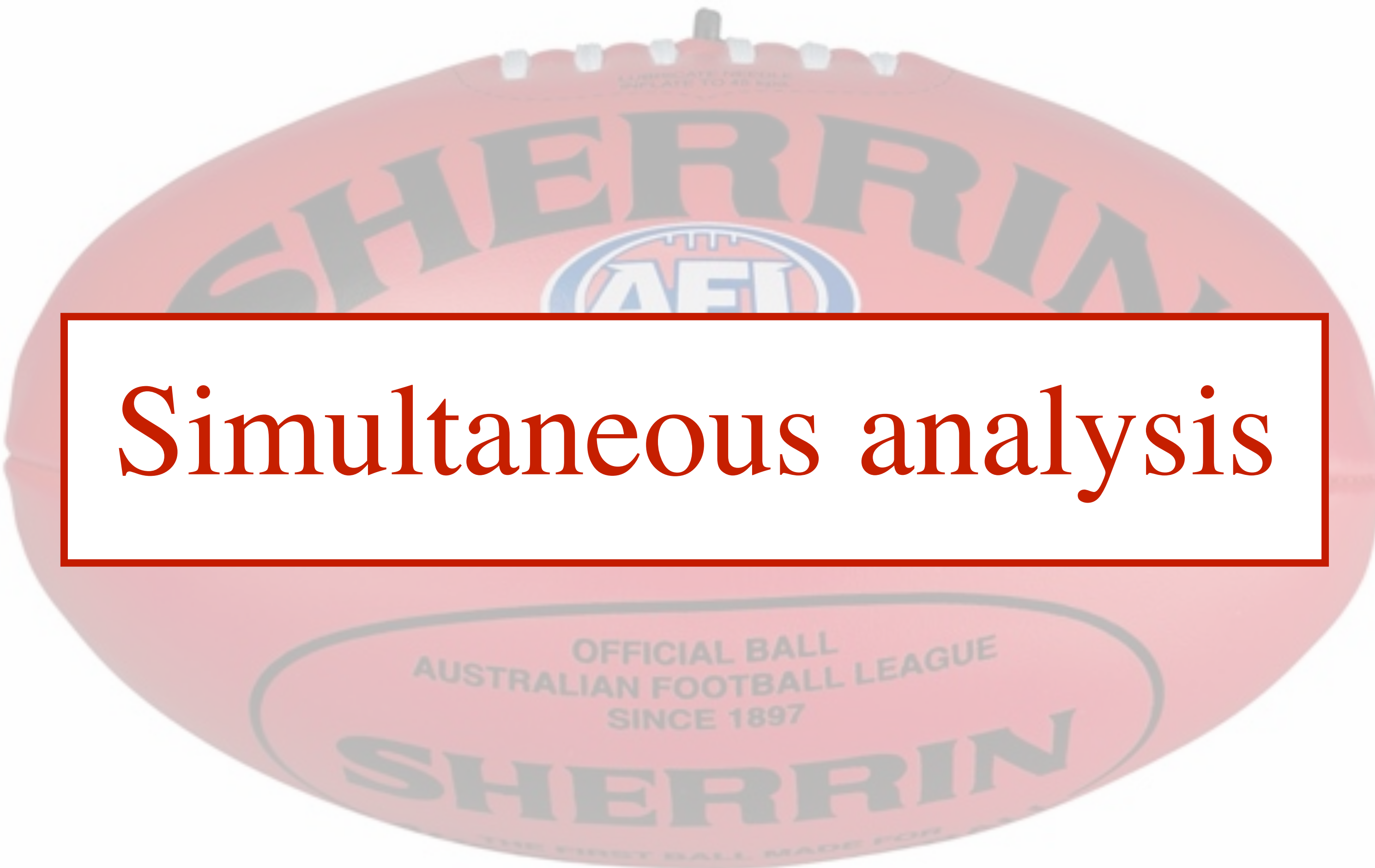


→ qualitatively similar behavior as in previous analyses

→ JAM strange FF closer to DSS parametrization

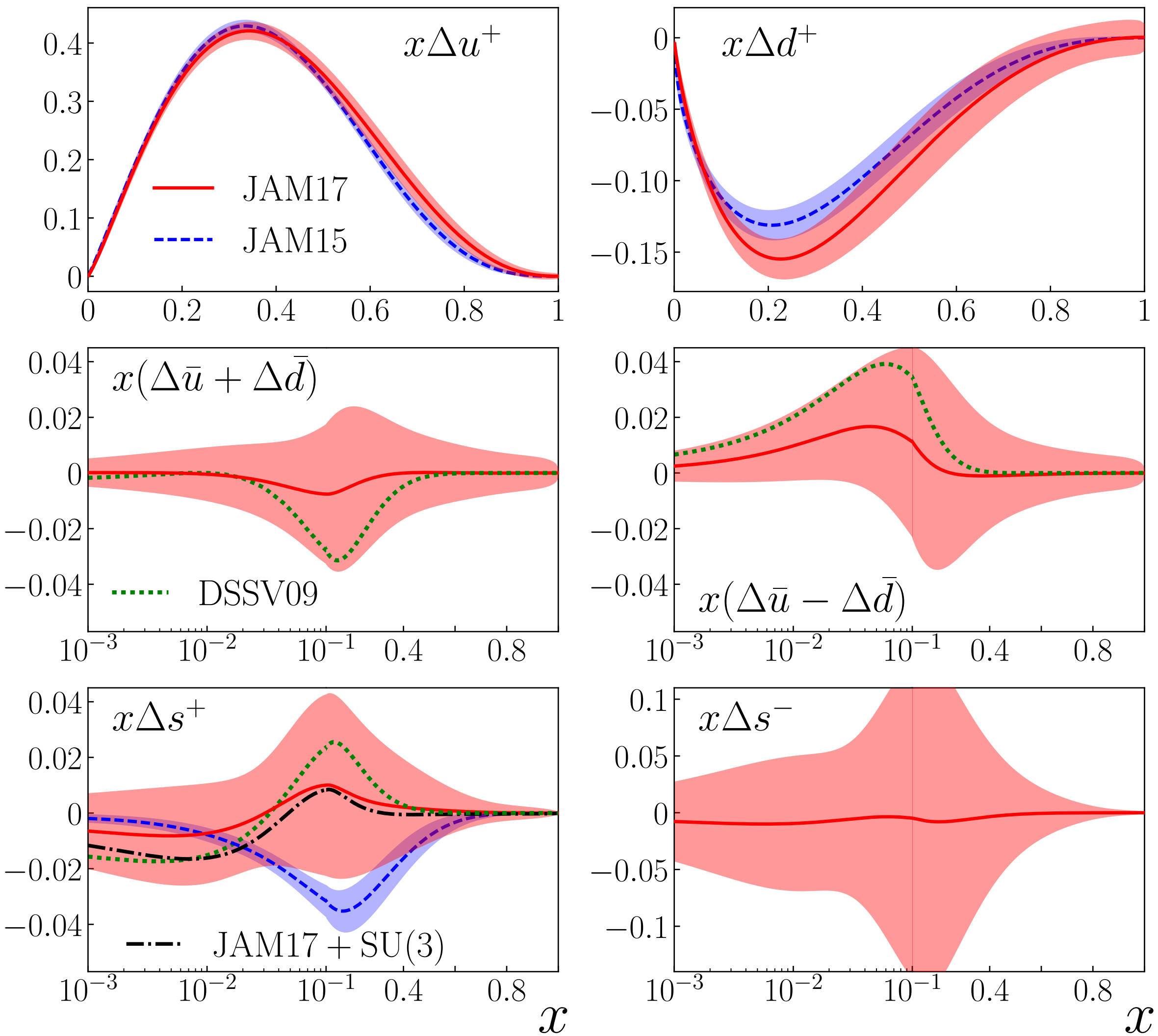
— impact on Δs^+ extraction??

Simultaneous analysis



Simultaneous analysis

- Using same IMC tools, new analysis attempted first ever simultaneous determination of spin PDFs and FFs, fitting to DIS, SIA and polarised 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

- Using same IMC tools, new analysis attempted first ever simultaneous determination of spin PDFs and FFs, fitting to DIS, SIA and polarised SIDIS (HERMES, COMPASS) data

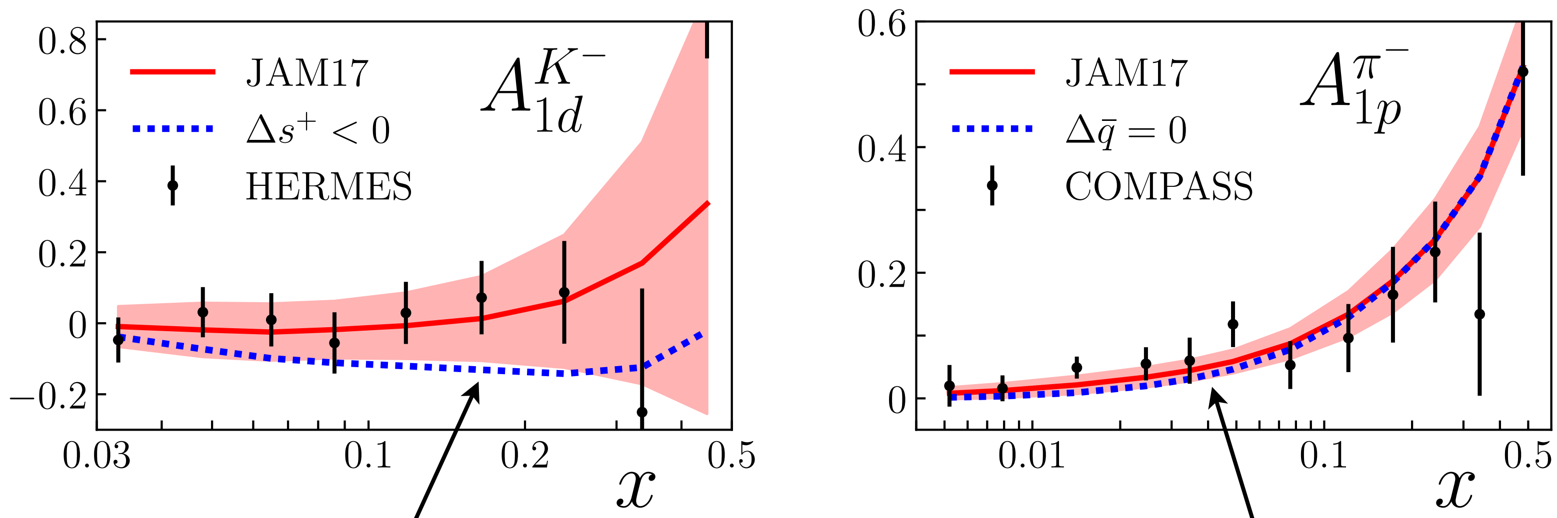
process	target	$N_{\rm dat}$	χ^2
DIS	$p, d, {}^3$He	854	854.8
SIA $(\pi^\pm, K^\pm)$		850	997.1
SIDIS $(\pi^\pm)$			
HERMES [15]	d	18	28.1
HERMES [15]	p	18	14.2
COMPASS [16]	d	20	8.0
COMPASS [17]	p	24	18.2
SIDIS $(K^\pm)$			
HERMES [15]	d	27	18.3
COMPASS [16]	d	20	18.7
COMPASS [17]	p	24	12.3
Total:		**1855**	**1969.7**

$\longrightarrow$ SIDIS data dwarfed by DIS & SIA

$\longrightarrow$ smaller χ^2 for K *cf.* π SIDIS due to larger errors

Simultaneous analysis

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

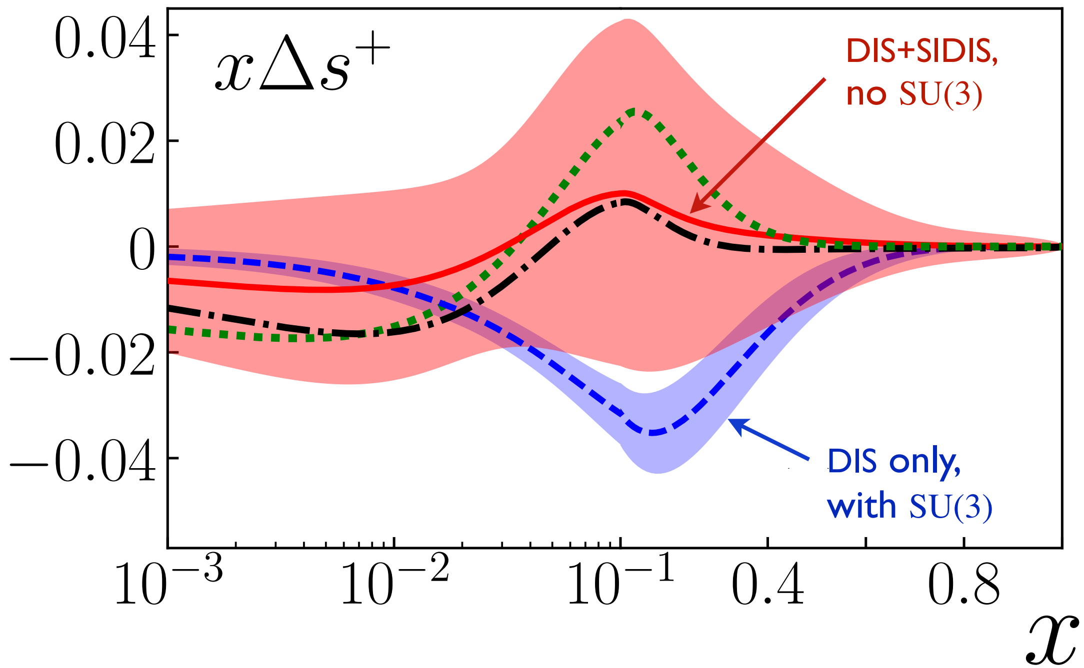


significantly worse fit using negative JAM15 Δs^+ (also for COMPASS and p data)

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

Simultaneous analysis

- Polarised strangeness in previous, DIS-only analyses (*e.g.* JAM15) was negative at $x \sim 0.1$, induced by SU(3) and parametrisation bias

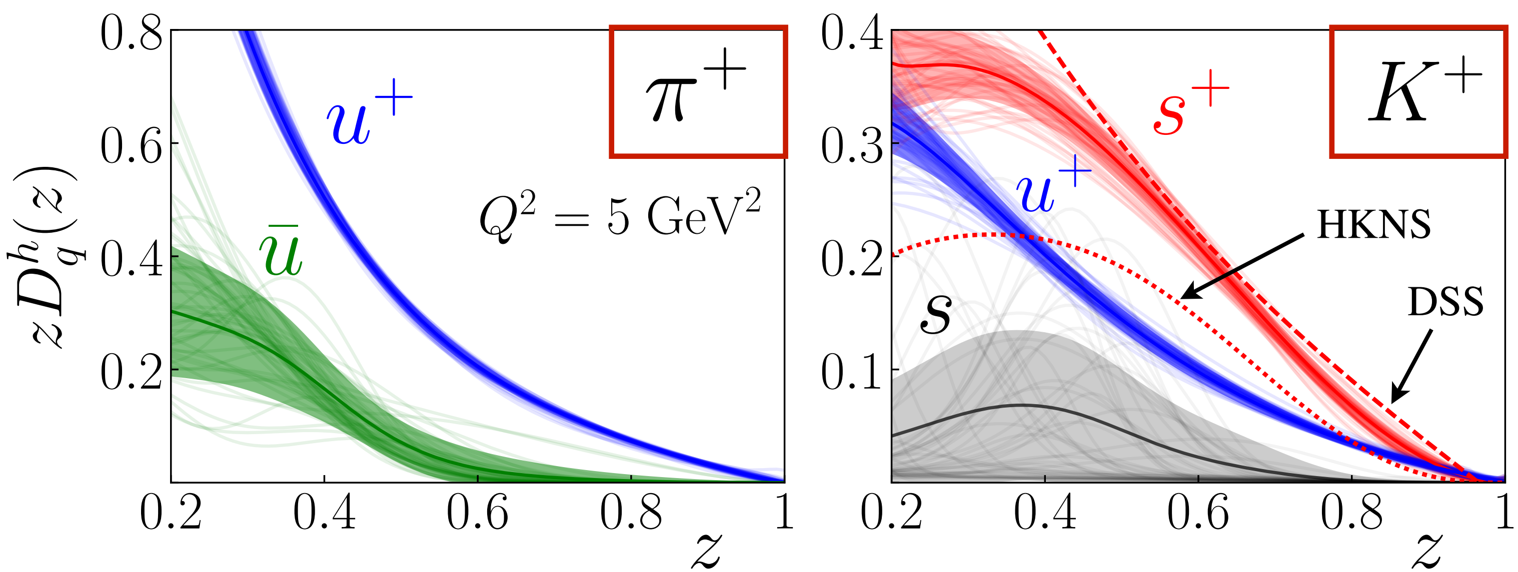


⟶ negligible sensitivity to Δs^+ from DIS data & evolution
— SU(3) pulls Δs^+ to generate moment ~ -0.1

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

Simultaneous analysis

- Fragmentation functions similar to previous SIA-only analysis



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

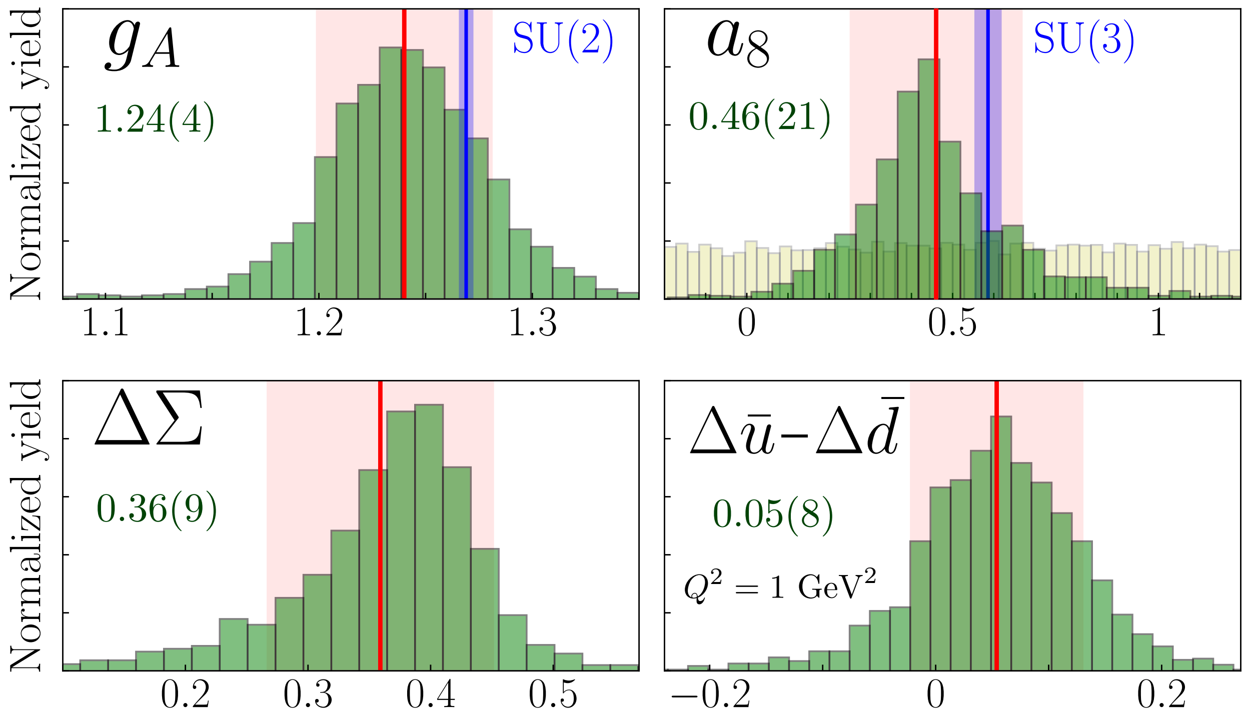
$\longrightarrow$ new result more consistent with DSS at moderate z

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

Matevosyan et al., PRD ***83****, 114010 (2011)*

Simultaneous analysis

- Statistical distribution of lowest moments (axial charges)



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

$\longrightarrow$ hint of SU(3) breaking in octet charge a_8 *cf. Bass, Thomas, PLB **684**, 216 (2010)*

$\longrightarrow$ 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 polarised DIS + SIDIS + SIA,
  with consistent extraction of spin PDFs and FFs
  without assuming $\mathrm{SU}(3)$ symmetry

  $\longrightarrow$ resolves strange quark polarisation puzzle: $\Delta s = -0.03(10)$
  (less negative than traditional $\mathrm{SU}(3)$ value $\Delta s \sim -0.1$)

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

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