

Hadron structure from JAM global QCD analysis

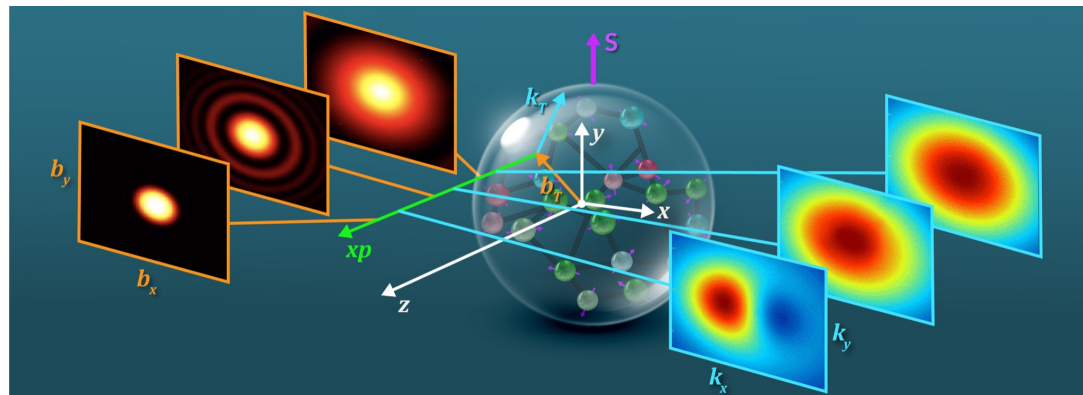
Wally Melnitchouk



Global QCD analysis with JAM

■ Jefferson Lab Angular Momentum (JAM) collaboration uses QCD theory and data analysis tools to determine internal quark & gluon structure of hadrons from experimental data

- analyse data using modern MC techniques & uncertainty quantification to simultaneously extract partonic quantum correlation functions (QCFs)
 - parton distribution functions (PDFs)
 - fragmentation functions (FFs)
 - transverse momentum dependent (TMD) distributions
 - generalised parton distributions (GPDs)
- use lattice QCD data (judiciously) to supplement global analysis in the absence of experimental constraints



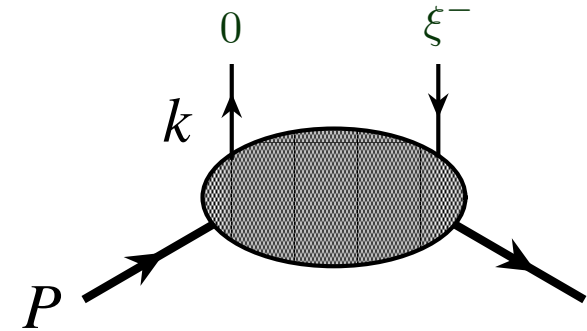
Parton distribution functions

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

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

- parton light-cone momentum fraction $x = \frac{k^+}{P^+}$
- Wilson line (for gauge invariance)

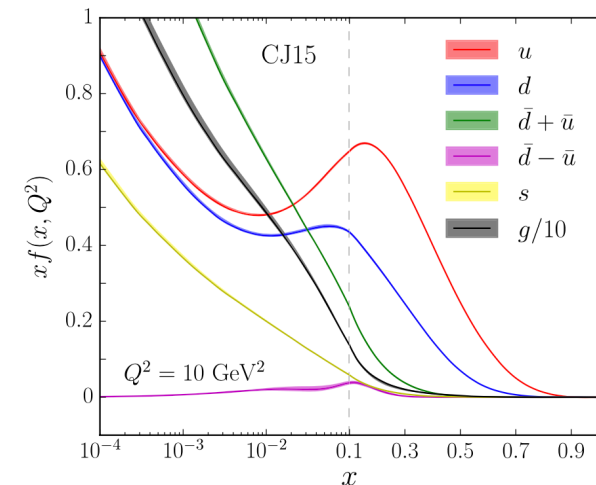
$$\mathcal{W}(\xi^-, 0) = \exp \left\{ -ig \int_0^{\xi^-} d\eta^- \mathcal{A}^+(\eta^-) \right\}$$



- In $\mathcal{A}^+ = 0$ gauge, in fast-moving frame PDF has a simple probabilistic interpretation as a particle density

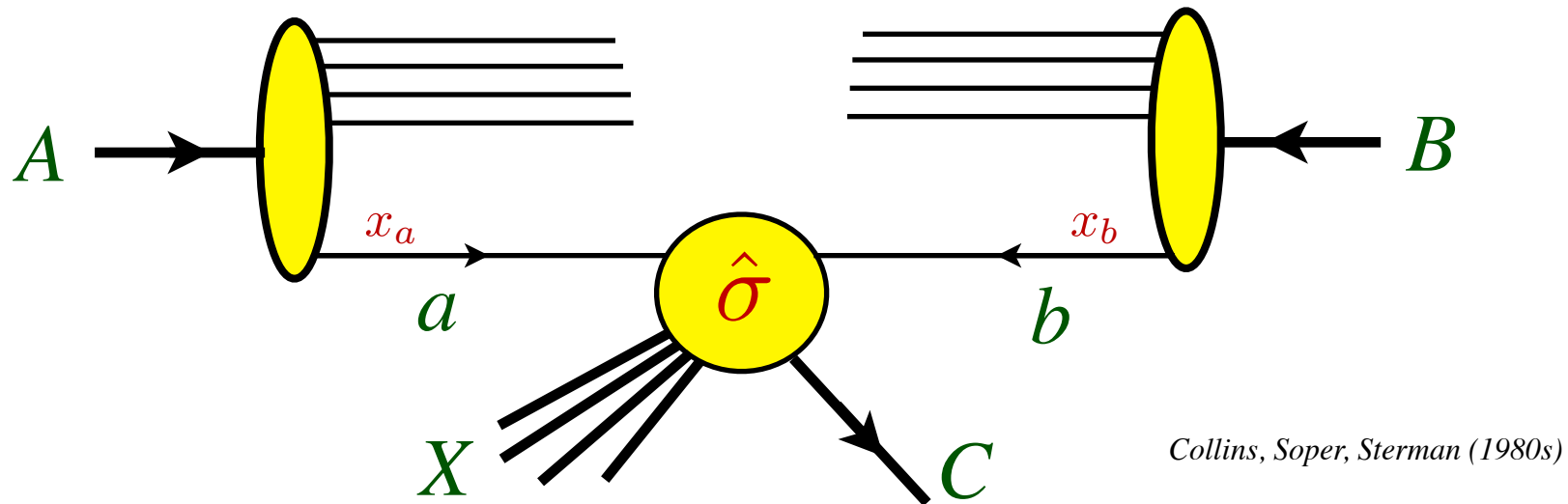
$$\int_{-1}^1 dx q(x) = \langle P | \bar{\psi}(0) \gamma^+ \psi(0) | P \rangle \approx \langle P | \psi^\dagger(0) \psi(0) | P \rangle$$

↑
number density
↑
number operator



Parton distribution functions

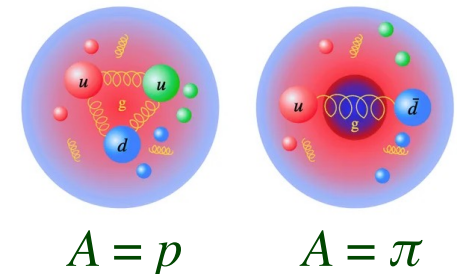
- High-energy scattering process $AB \rightarrow CX$



- QCD factorisation: systematic separation of hard (perturbative, process-dependent) from soft (nonperturbative, process-independent) physics

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

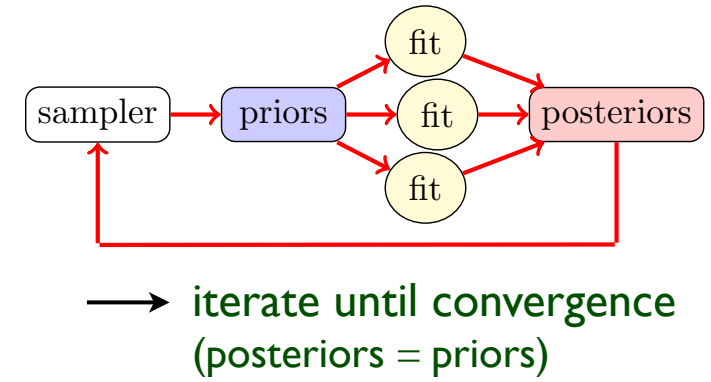
- process-independent parton distribution functions $f_{a/A}$ characterise structure of bound state A



JAM methodology

■ Theoretical framework

- collinear factorisation
- iterative Monte Carlo with data resampling
- Bayesian sampling of parameter space
- uncertainty quantification from replica ensembles



■ Traditional functional form for PDFs

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

↑
polynomial, neural net, ...

■ Bayesian formulas for expectation values and variances for $\mathcal{O}$ with parameters $\vec{a}$

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

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

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

likelihood function

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

prior distribution

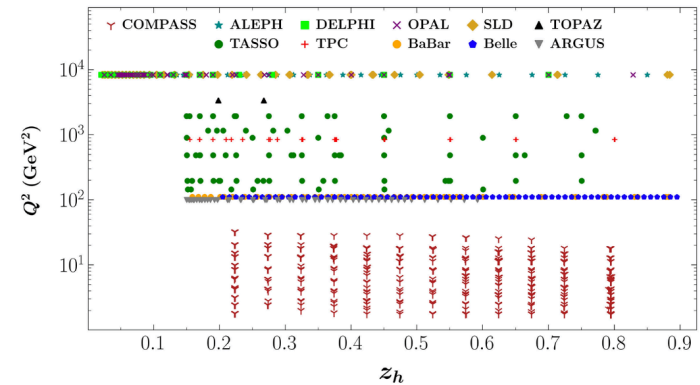
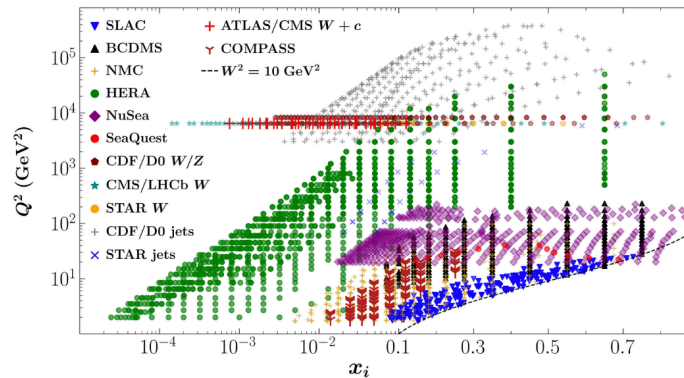
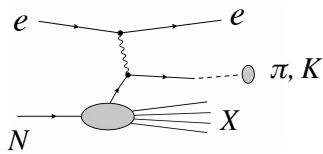


$$P(A|B) = \frac{P(B|A) P(A)}{P(B)}$$

Unpolarised proton PDFs

- Simultaneously extract PDFs and fragmentation functions from inclusive DIS, SIDIS, Drell-Yan, W/Z boson and jet production, $W+c$ production, single-inclusive e^+e^- annihilation

- DIS, Drell-Yan, W/Z /jet production $\rightarrow$ PDFs $f(x)$
- SIA (single-inclusive e^+e^- annihilation $e^+e^- \rightarrow h X$) $\rightarrow$ FFs $D^h(z)$
- SIDIS (semi-inclusive DIS $\ell N \rightarrow \ell h X$) $\rightarrow$ PDFs & FFs $f(x) \otimes D^h(z)$



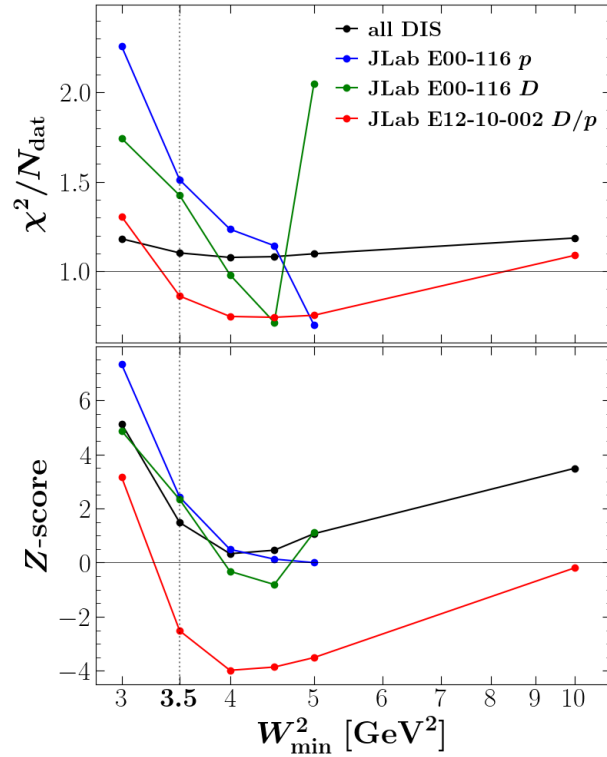
Process	N_{dat}	Baseline	χ^2_{red} (Z-score)		JAM
			+SIDIS	+W-charm	
DIS					
fixed target [39–42]	1495	1.07(+1.95)	1.08(+2.23)	1.07(+1.92)	1.08(+2.25)
HERA [43]	1185	1.16(+3.64)	1.18(+4.22)	1.15(+3.57)	1.18(+4.22)
Drell-Yan [2,3]	205	1.15(+1.50)	1.17(+1.69)	1.14(+1.43)	1.17(+1.69)
W-lepton asymmetry [19–21,23,46,47,50]	70	0.88(−0.69)	0.91(−0.50)	0.87(−0.72)	0.91(−0.52)
W charge asymmetry [48,49]	27	0.91(−0.24)	1.00(+0.08)	0.91(−0.25)	1.00(+0.08)
Z rapidity [51,52]	56	1.18(+0.98)	1.22(+1.15)	1.24(+1.25)	1.24(+1.24)
Inclusive jets [53–55]	198	1.02(+0.27)	0.94(−0.56)	1.04(+0.41)	0.94(−0.54)
W + charm [25–27]	37	...	...	0.57(−2.10)	0.59(−1.99)
SIDIS					
$\pi^\pm$ [44]	498	...	0.91(−1.42)	...	0.89(−1.74)
$K^\pm$ [45]	494	...	0.91(−1.50)	...	0.88(−1.96)
$h^\pm$ [44]	498	...	0.90(−1.65)	...	0.86(−2.22)
SIA					
$\pi^\pm$ [56–62,64–68]	403	0.73(−4.30)	0.82(−2.77)	0.73(−4.30)	0.82(−2.67)
$K^\pm$ [56–61,63–68]	377	0.65(−5.55)	0.78(−3.20)	0.65(−5.55)	0.79(−3.04)
$h^\pm$ [59,61,63,66,68–72]	310	0.76(−3.29)	0.73(−3.73)	0.76(−3.29)	0.73(−3.69)
Total	5853	1.00(+0.11)	1.00(−0.09)	1.00(−0.06)	0.99(−0.51)

Anderson, WM, Sato, PRD **112**, 094011 (2025)

Cocuzza, WM, Sato, Thomas, arXiv:2605.00666

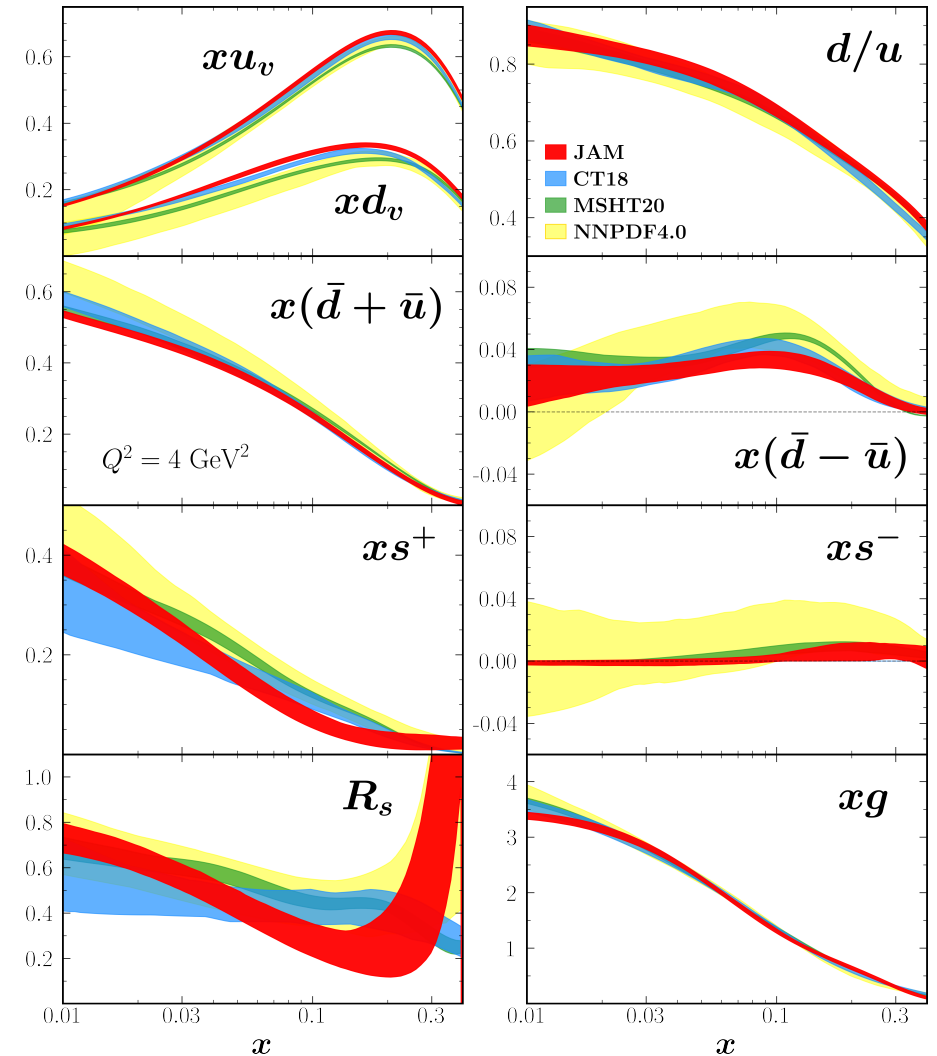
Unpolarised proton PDFs

- Simultaneously extract PDFs and fragmentation functions from inclusive DIS, SIDIS, Drell-Yan, W/Z boson and jet production, $W+c$ production, single-inclusive e^+e^- annihilation



Cocuzza, WM, Sato, Thomas, arXiv:2605.00666

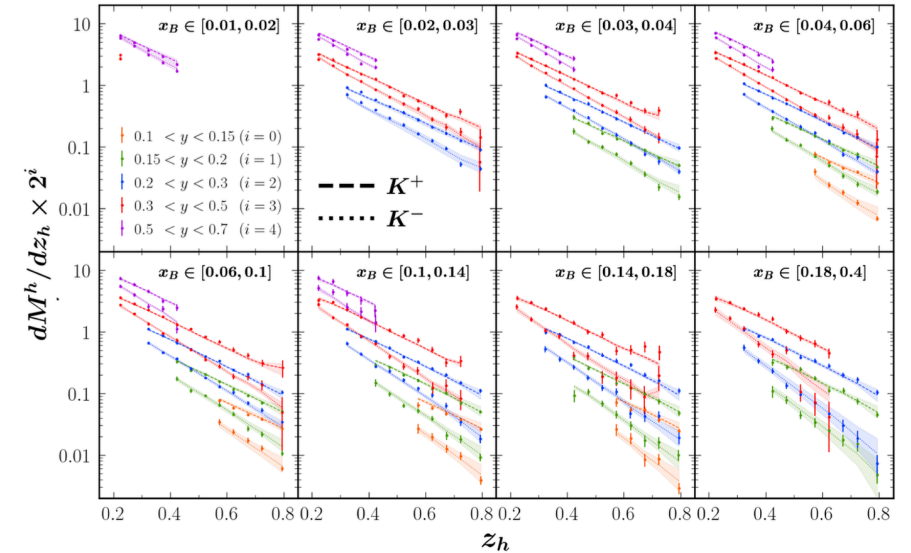
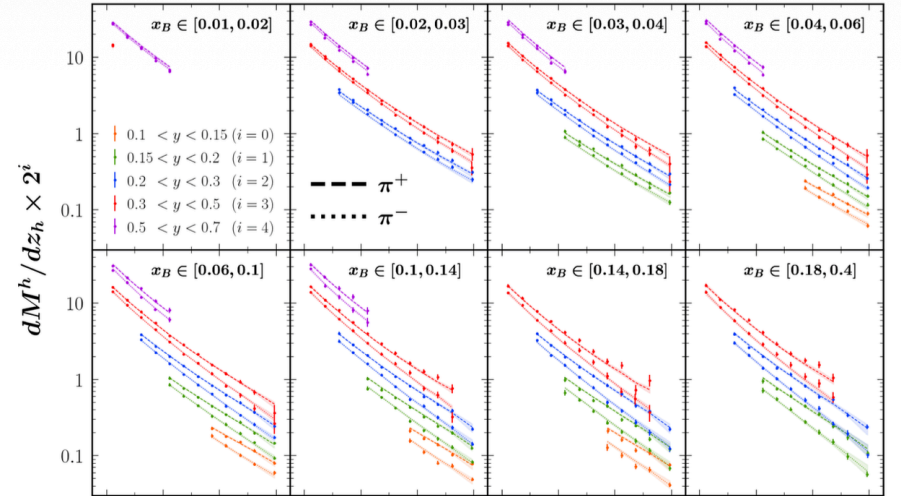
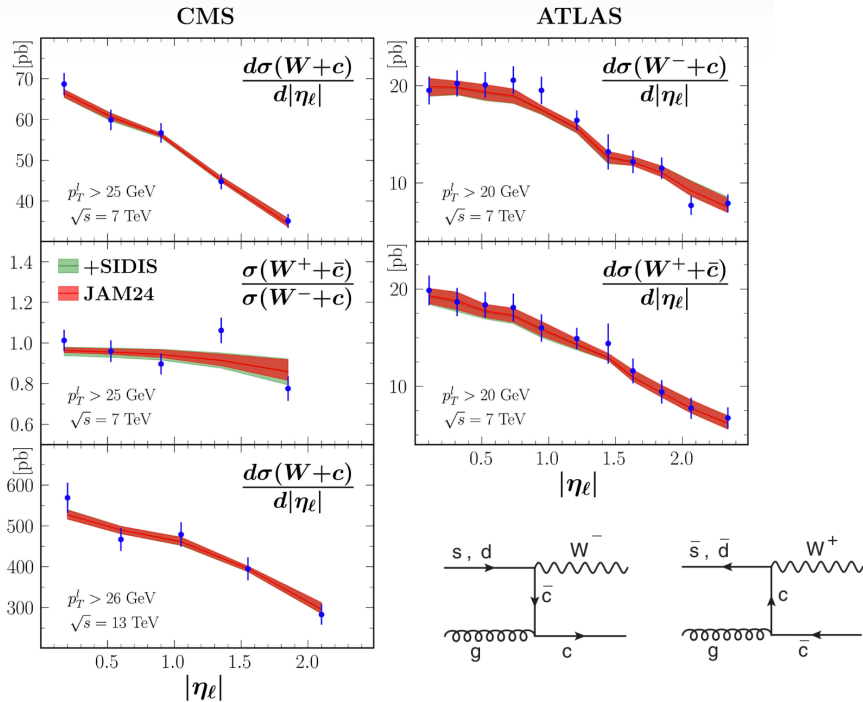
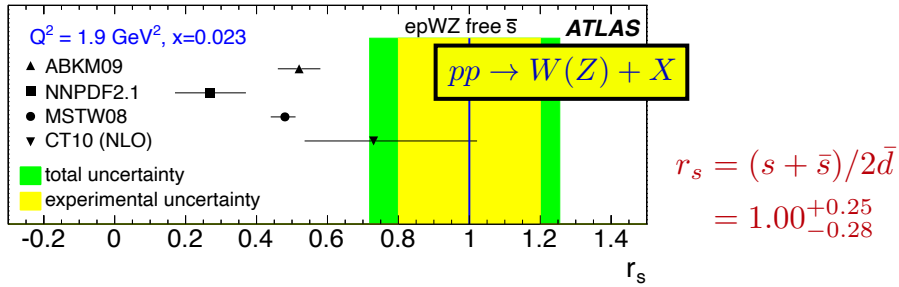
→ stability of fits down to $W^2 = 3.5 \text{ GeV}^2$



Anderson, WM, Sato, PRD 112, 094011 (2025)

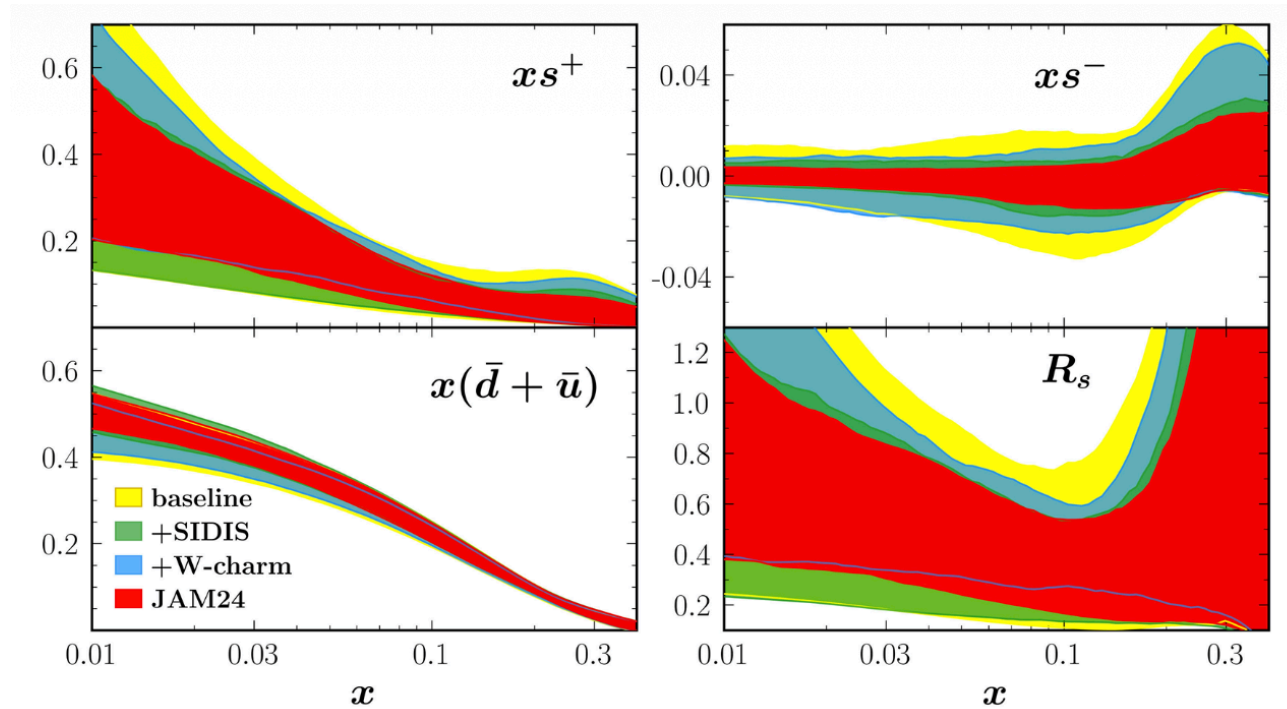
Strange quark PDF

- First analysis to include SIDIS multiplicity and $p + p \rightarrow W + c + X$ cross section data, with enhanced sensitivity to strange quarks



Adolph et al. (COMPASS)
 Phys. Lett. B **764**, 1 (2017)

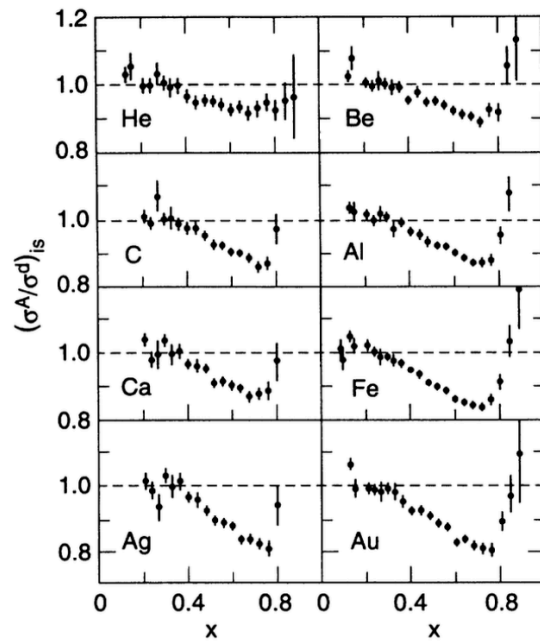
Strange quark PDF



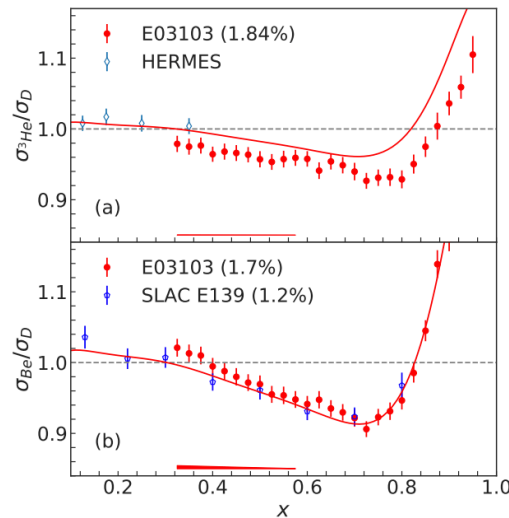
- SIDIS data have slight preference for smaller strangeness
- $W+c$ data have slight preference for larger strangeness
- strange/nonstrange ratio compatible with SU(3) at $x < 0.02$, suppressed at higher x ... **still relatively large uncertainty**

Nuclear EMC effect

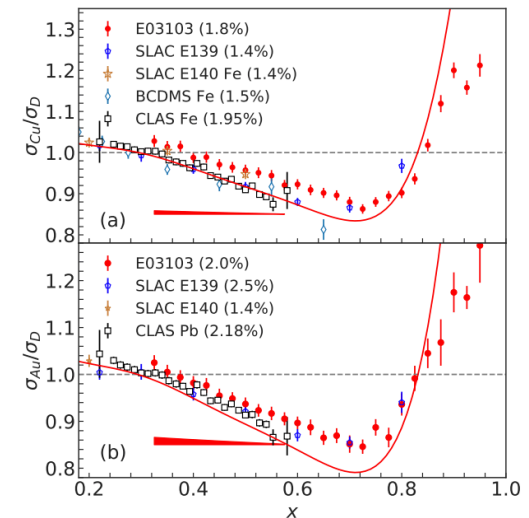
■ Ratios of cross sections of nuclei to “isoscalar nucleon” (often deuteron)



Gomez et al., PRD **49**, 4348 (1994)



Arrington et al., PRC **104**, 065203 (2021)



- systematic deviation of nuclear to nucleon ratios away from 1
... evidence of nuclear medium modification of quark structure

European Muon Collaboration (EMC)
PLB **123**, 275 (1983)

- similar general shape observed for all nuclei from ^4He to ^{208}Pb

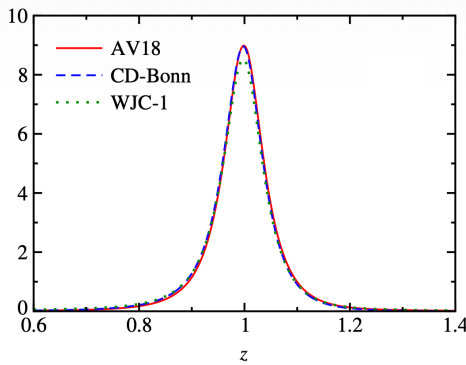
Nuclear EMC effect

■ Scattering from individual nucleons in the nucleus

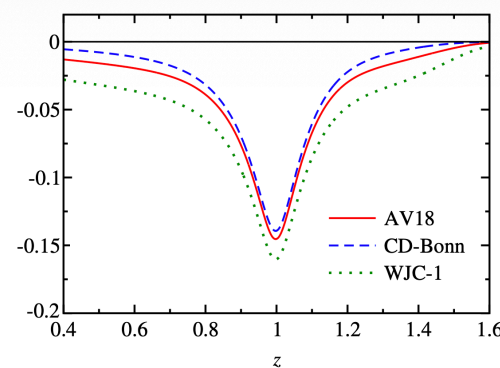
→ nuclear and nucleon structure related via generalised convolution

$$F_2^A(x_B, Q^2) = \sum_N \left[f_{N/A}^{(\text{on})} \otimes F_2^N + f_{N/A}^{(\text{off})} \otimes \delta F_2^{N/A} \right] (x_B, Q^2)$$

on-shell smearing function



off-shell smearing function



$$[f_{N/A} \otimes F_2](x_B, Q^2) \equiv \int_{x_B}^{M_A/M} dy f_{N/A}(y, \rho) F_2\left(\frac{x_B}{y}, Q^2\right)$$

$$\rho^2 = 1 + 4M^2 x_B^2 / Q^2$$

→ nucleon-level structure

$$F_2^N(x_B, Q^2) = x_B \sum_q e_q^2 [C_q \otimes q_N^+](x_B, Q^2) + \dots$$

on-shell proton PDF
(fitted to world proton data,
generally well constrained)

$$\delta F_2^{N/A}(x_B, Q^2) = x_B \sum_q e_q^2 [C_q \otimes \delta q_{N/A}](x_B, Q^2) + \dots$$

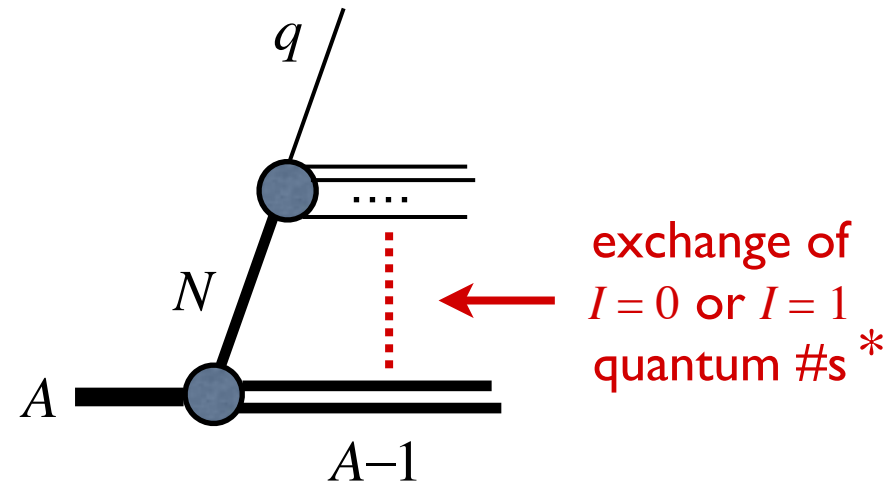
off-shell PDF
(fitted to nuclear data,
not well understood)

Off-shell nucleon PDFs

- Off-shell nucleon PDF depends on the nucleon species, and on the specific nucleus in which the nucleon is bound

$$\delta q_{N/A} = \delta q_{N/A}^{(0)} + \delta q_{N/A}^{(1)}$$

- depends also on the nature of interaction between spectator partons (“diquark”) and residual (A-1) nuclear system



- normalisation condition (valence quark number the same in free & bound nucleon)

$$\int_0^1 dx \delta q_{N/A}^{(0)}(x) = 0 = \int_0^1 dx \delta q_{N/A}^{(1)}(x)$$

- assume isospin symmetry for all (on-shell and off-shell) PDFs

$$\delta u_{n/A} = \delta d_{p/A^*}$$

- for $A = D$, only the isoscalar $u + d$ combination enters (not to be confused with isospin of exchanged state $*$)

EMC effect in ^3He and ^3H

- First ever measurement of ratio of $^3\text{H}/D$ and $^3\text{He}/D$ (and $^3\text{He}/^3\text{H}$) cross sections in MARATHON experiment

→ original motivation was extraction of ratio of neutron to proton structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\text{He}}/F_2^{^3\text{H}}}{2F_2^{^3\text{He}}/F_2^{^3\text{H}} - \mathcal{R}} \leftarrow \mathcal{R} \equiv \mathcal{R}_{^3\text{He}/^3\text{H}} = \frac{R_{^3\text{He}}}{R_{^3\text{H}}} \leftarrow \begin{cases} R_{^3\text{He}} = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n} \\ R_{^3\text{H}} = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n} \end{cases}$$

and determination of d/u PDF ratio

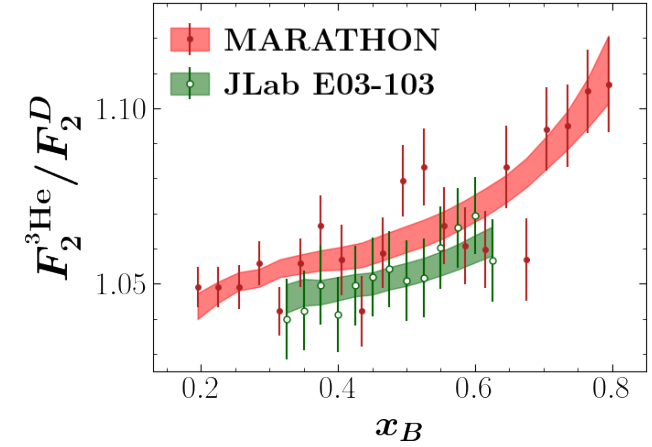
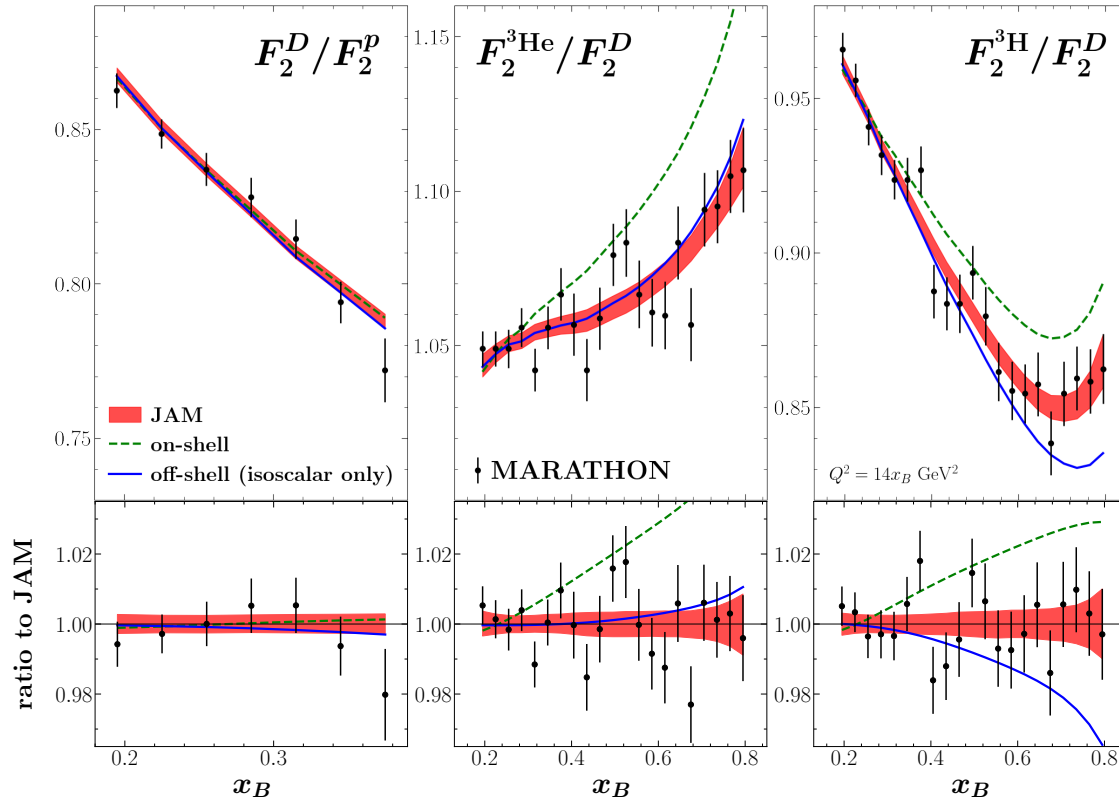
... assuming knowledge of nuclear effects

- Can we learn about *both* on-shell proton PDFs *and* off-shell functions (nuclear effects)?

→ JAM framework ideally suited to such (simultaneous) analysis

Global QCD analysis with MARATHON data

MARATHON data versus theory comparisons

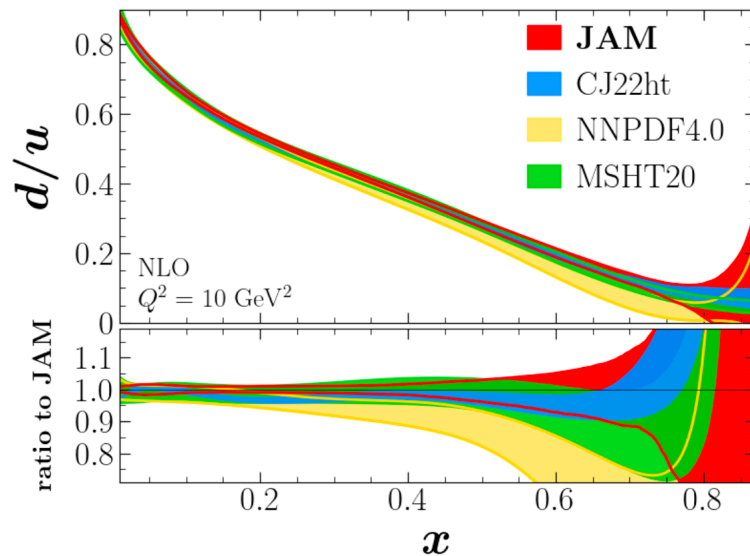
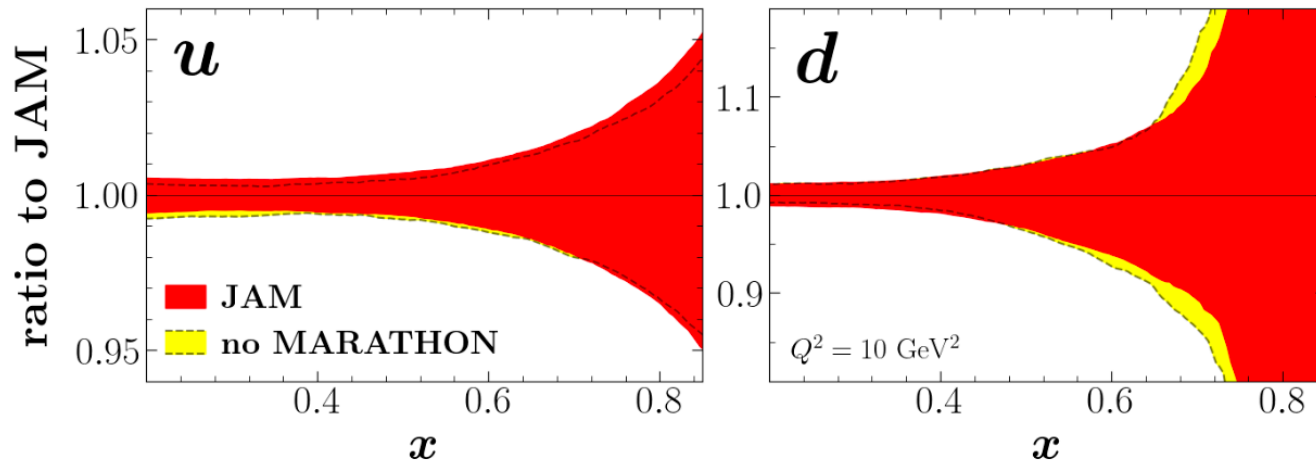


→ good agreement between data
(including MARATHON and E03-103)
and theory in global fit

Process	N_{dat}	χ^2_{red}	
		on-shell fit	full fit
DIS			
MARATHON D/p [30]	7	0.68	0.70
MARATHON $^3\text{He}/D$ [31]	21	5.10	1.04
MARATHON $^3\text{H}/D$ [31]	21	2.20	0.83
JLab E03-103 $^3\text{He}/D$ [48]	13	0.33	0.22
other fixed target	2793	0.99	0.99
HERA	1185	1.17	1.16
Drell-Yan	205	1.18	1.18
W -lepton asymmetry	70	0.82	0.82
W charge asymmetry	27	1.03	1.03
Z rapidity	56	1.10	1.11
jet	200	1.12	1.10
Total	4598	1.07	1.04

Global QCD analysis with MARATHON data

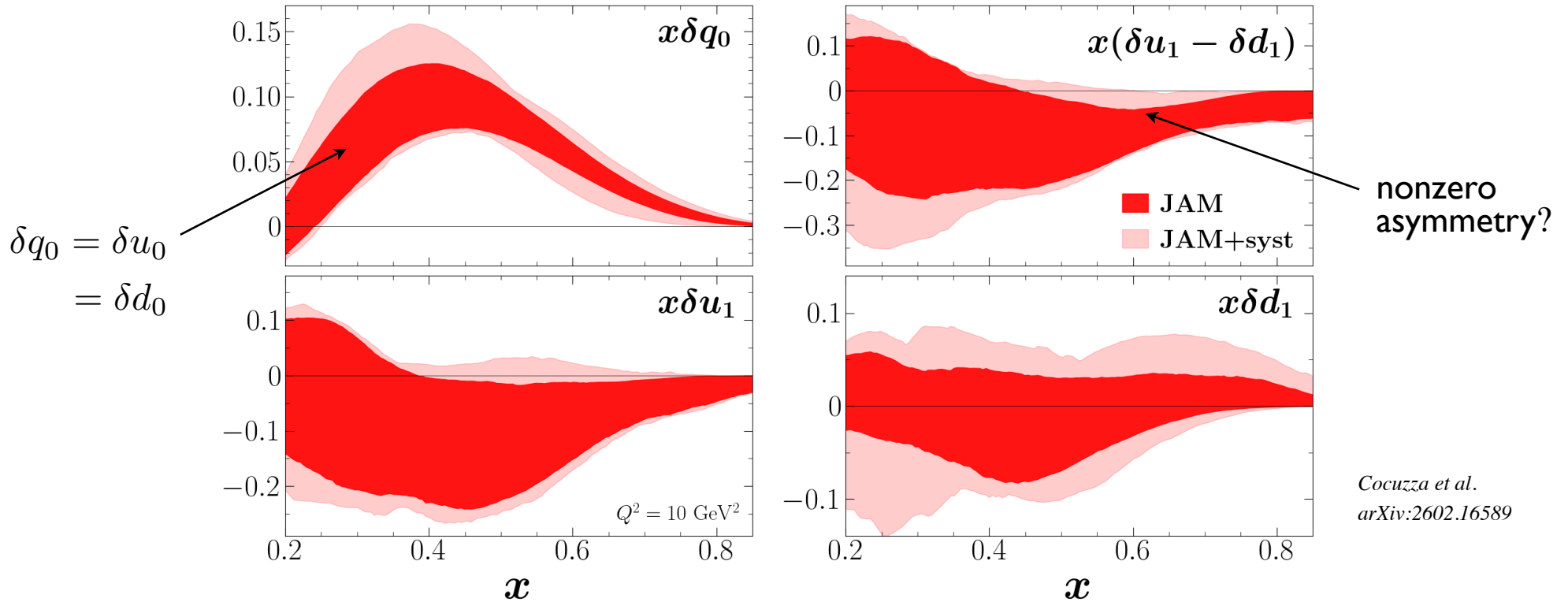
Impact of MARATHON data on u and d PDFs in the proton



→ relatively small effect on u and d PDFs
... already constrained by global dataset

Global QCD analysis with MARATHON data

- First ever extraction of flavor dependence of off-shell PDFs



→ large nonzero isoscalar off-shell PDF

→ hint of flavour asymmetric isovector off-shell PDF

$$\delta u_{p/3\text{He}}^{(0)} = \delta u_{p/3\text{H}}^{(0)} = 2\delta u_{p/D}^{(0)} \equiv \delta u_0$$

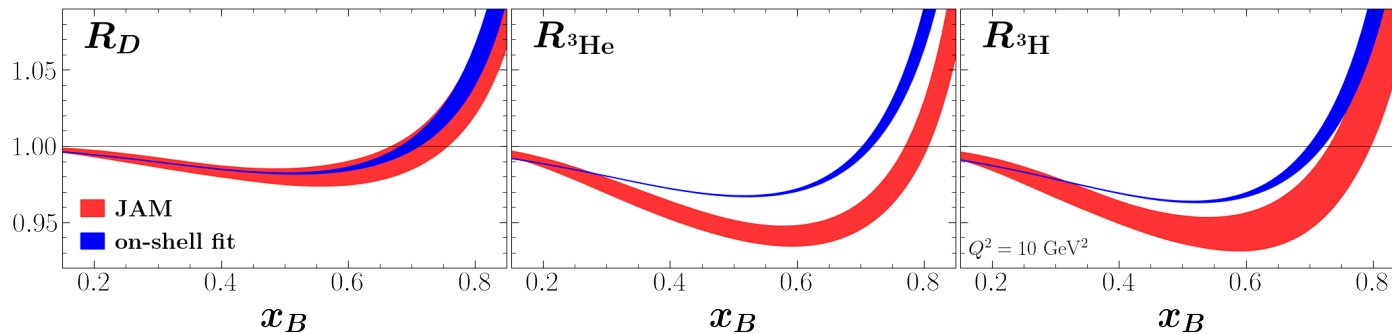
$$\delta d_{p/3\text{He}}^{(0)} = \delta d_{p/3\text{H}}^{(0)} = 2\delta d_{p/D}^{(0)} \equiv \delta d_0.$$

$$\delta u_{p/3\text{He}}^{(1)} = 0, \quad \delta u_{p/3\text{H}}^{(1)} = 2\delta u_{p/D}^{(1)} \equiv \delta u_1$$

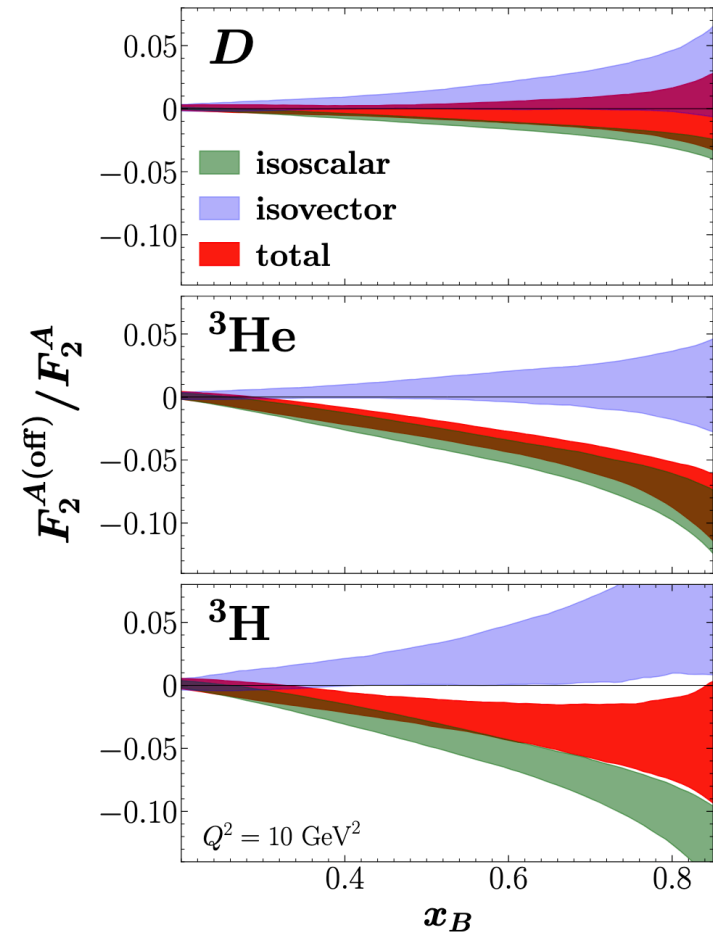
$$\delta d_{p/3\text{He}}^{(1)} = 0, \quad \delta d_{p/3\text{H}}^{(1)} = 2\delta d_{p/D}^{(1)} \equiv \delta d_1$$

EMC effect in ^3He and ^3H

- Shape of EMC ratio depends on sign and magnitude of off-shell effects



- D : cancellation of small isovector (> 0) and isoscalar (< 0) contributions
- ^3He : almost no contribution from isovector; entire effect from isoscalar
- ^3H : large isoscalar, partially cancelling smaller isovector



Summary

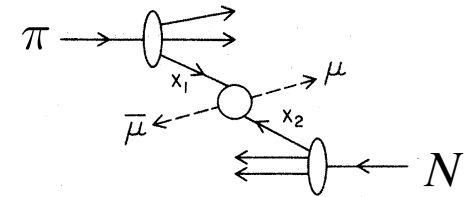
- Nucleon off-shell contributions to PDFs essential to describe $A=3$ data
- Sizable isoscalar off-shell corrections, hint of isovector effect
- First information on flavor dependence on EMC effect in light nuclei

→

Tyler Hague

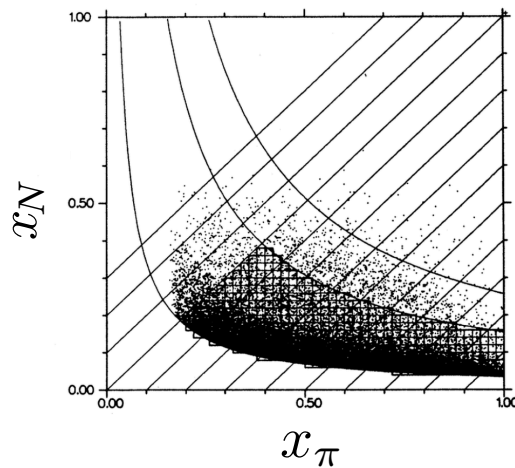
PDFs in the pion — Drell-Yan

- Understanding differences between PDFs in different hadrons can give insights into how hadrons are built from quarks & gluons, and nature of nonperturbative QCD
- Proton structure studied intensively for $> 1/2$ century — in contrast, much less is known about parton structure of the pion
- Historically, PDFs in the pion extracted from pion-nucleon (tungsten) Drell-Yan data (CERN, FNAL)



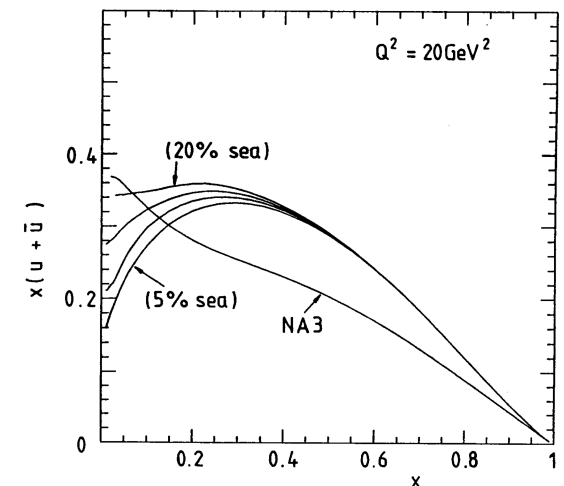
→ **constrains valence PDFs at $x \gg 0$...**

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9Q^2} \sum_{ij} [C_{ij} \otimes f_i^\pi \otimes f_j^N] (x_1, x_2, \mu^2)$$



Conway et al., PRD 39, 92 (1989)

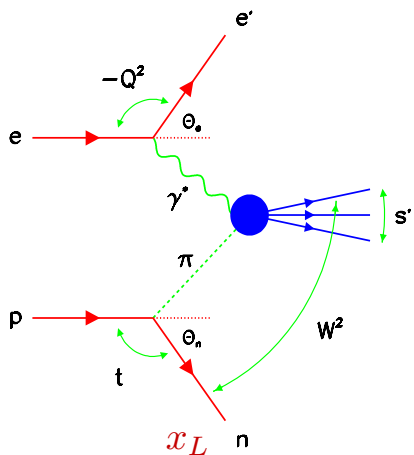
... but sea quark & gluon PDFs at small x unconstrained



Sutton et al., PRD 45, 2349 (1992)

PDFs in the pion — leading neutrons

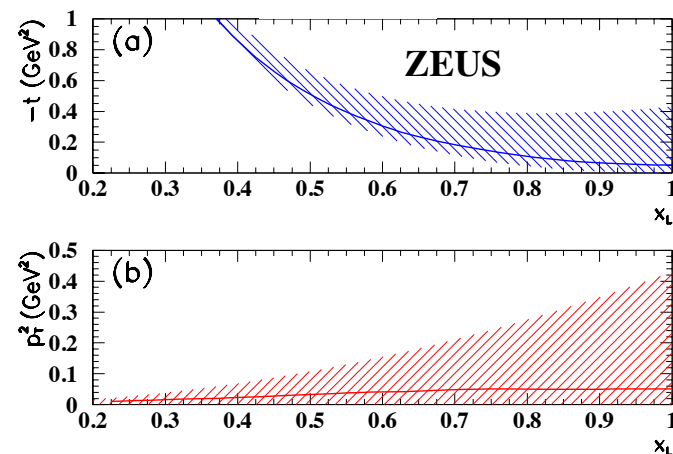
- ZEUS & H1 collaborations at HERA measured spectra of “leading neutrons” (LN) ($ep \rightarrow enX$) produced at very forward angles



$$\begin{aligned} x_L &= \frac{p_n \cdot q}{p \cdot q} \\ &\equiv 1 - y \end{aligned}$$

Chekanov et al., NPB 637, 3 (2002)

Aaron et al., EPJC 68, 381 (2010)



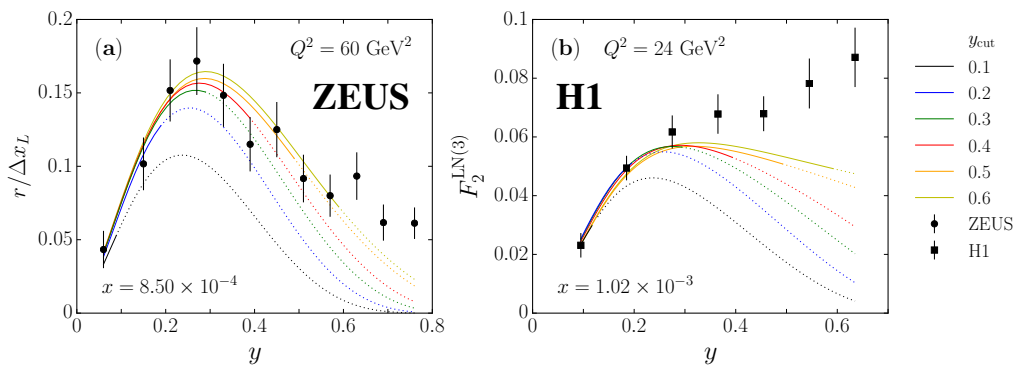
→ can data be described with Sullivan process (DIS from near on-shell pion)?

Thomas, PLB 126, 97 (1983)

- Measured LN differential cross section (integrated over p_T)

$$\begin{aligned} \frac{d^3 \sigma^{\text{LN}}}{dx dQ^2 dy} &\sim F_2^{\text{LN}(3)}(x, Q^2, y) \\ &\sim f_{\pi N}(y) F_2^\pi(x/y, Q^2) \end{aligned}$$

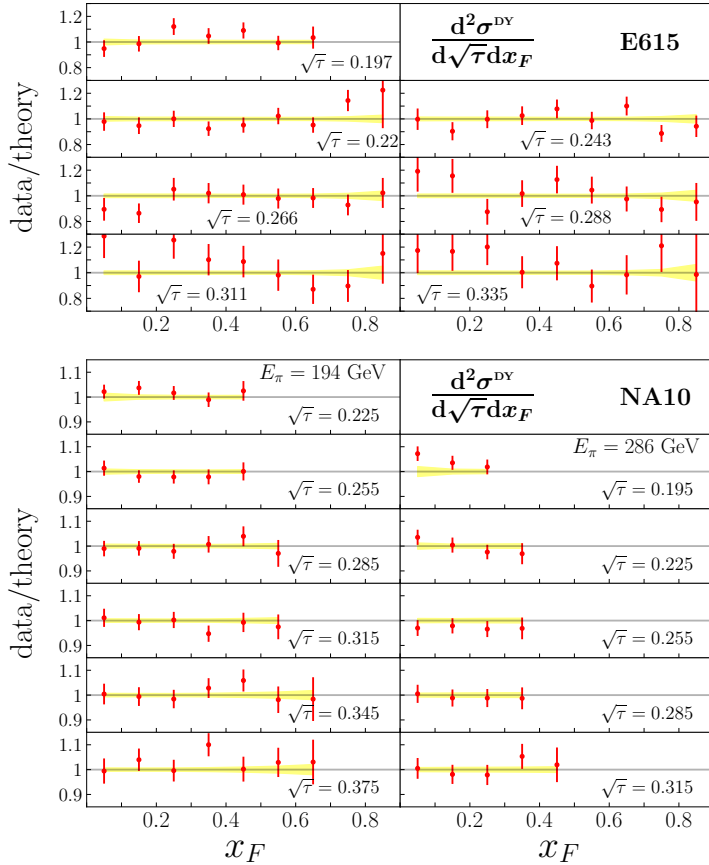
$p \rightarrow \pi N$ 
splitting function



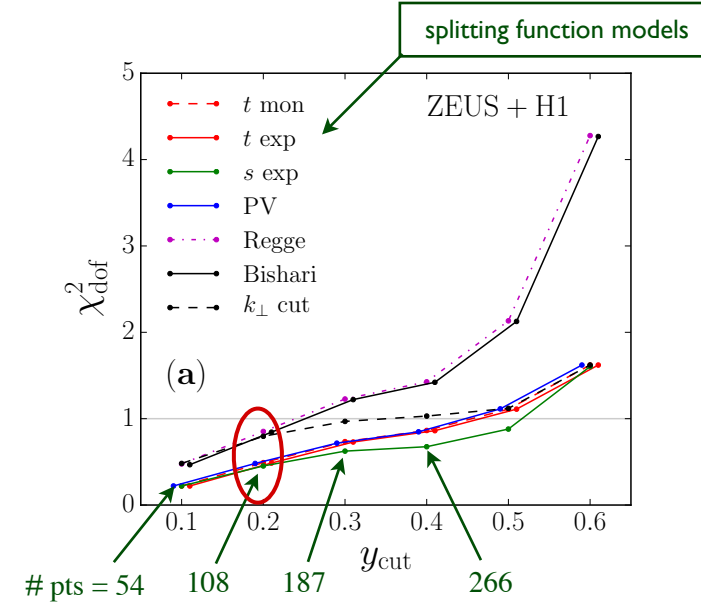
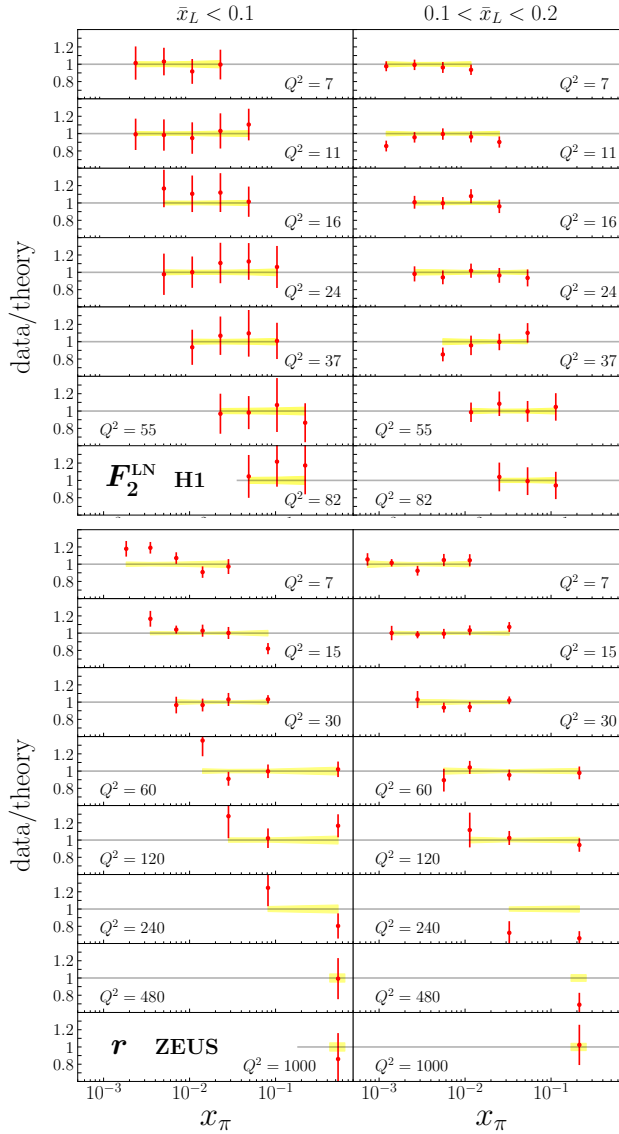
→ expect more non-pionic contributions at larger y

Simultaneous analysis of DY and LN

- First combined fit to HERA LN and Drell-Yan data, fitting both PDF and chiral splitting function parameters simultaneously



Barry, Sato, WM, Ji
PRL 121, 152001 (2018)



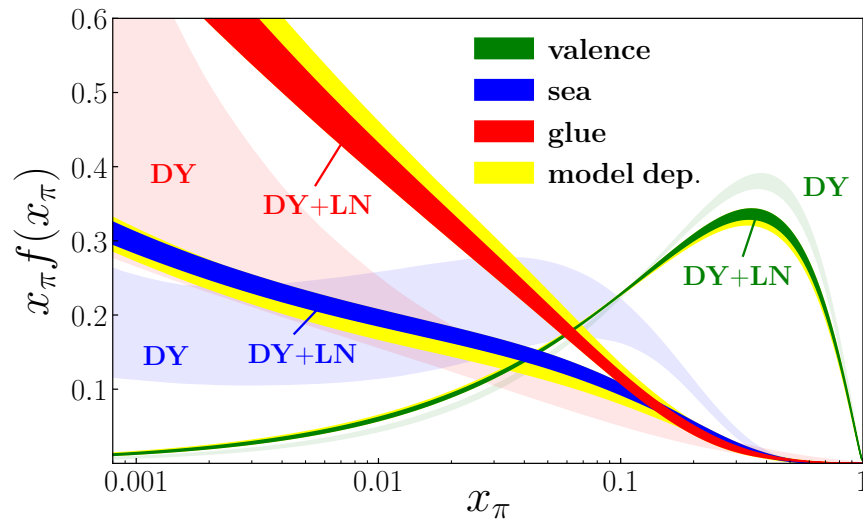
→ optimize χ^2_{dof} with maximum number of points that can be described

Process	Experiment (observables)	N_{dat}	χ^2_{dat}	n_e
DY	E615 (x_F, Q)	61	0.85	1.08
	NA10 (194 GeV) (x_F, Q)	36	0.52	0.88
	NA10 (286 GeV) (x_F, Q)	20	0.78	0.83
	E615 (Q, p_T)	34	1.08	0.83
	E615 (x_F, p_T)	49	0.85	0.50
LN	H1	58	0.38	1.26
	ZEUS	50	1.51	0.95
Total		308	0.85	

→ optimal cut choice $y < 0.2$

Simultaneous analysis of DY and LN

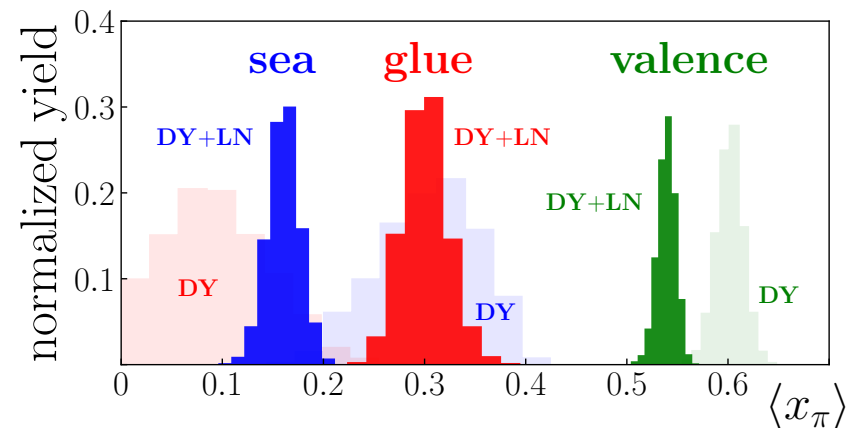
- First combined fit to HERA LN and Drell-Yan data, fitting both PDF and chiral splitting function parameters simultaneously



→ significant reduction of glue and sea quark PDF uncertainties

→ larger gluon fraction than without LN constraint

→ gluons carry $\sim 30\%$ of pion's momentum



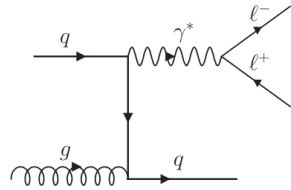
Barry, Sato, WM, Ji, PRL **121**, 152001 (2018)

(featured landmark paper in "50 years of QCD" in Physical Review)

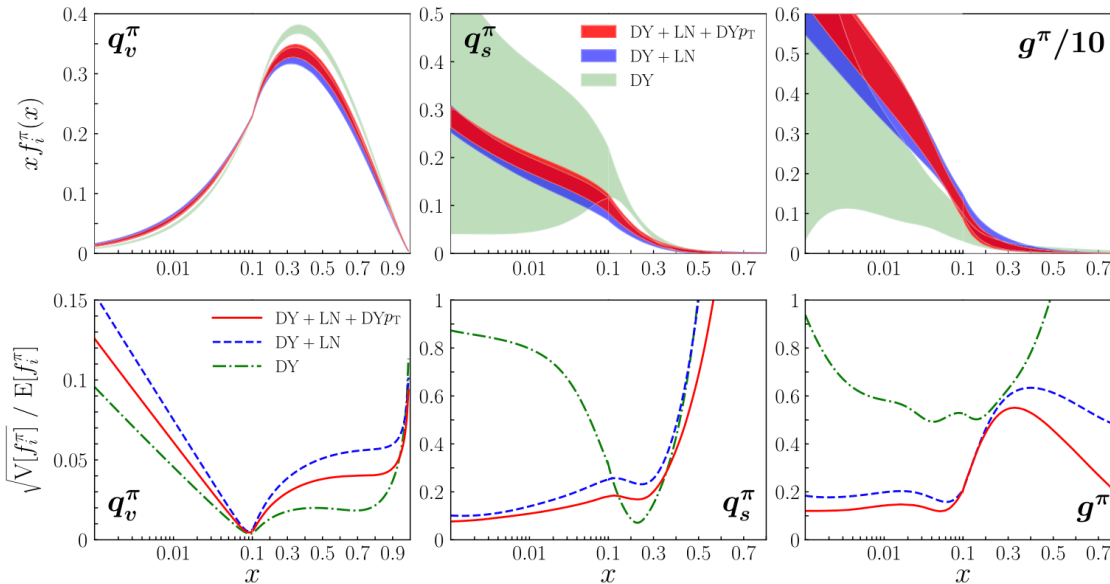
Gluons in the pion

- E615 also collected data differential in transverse momentum (never before included in global QCD analysis)

→ large- p_T photon requires hard gluon to recoil against, offering sensitivity to gluon PDF in pion at high x

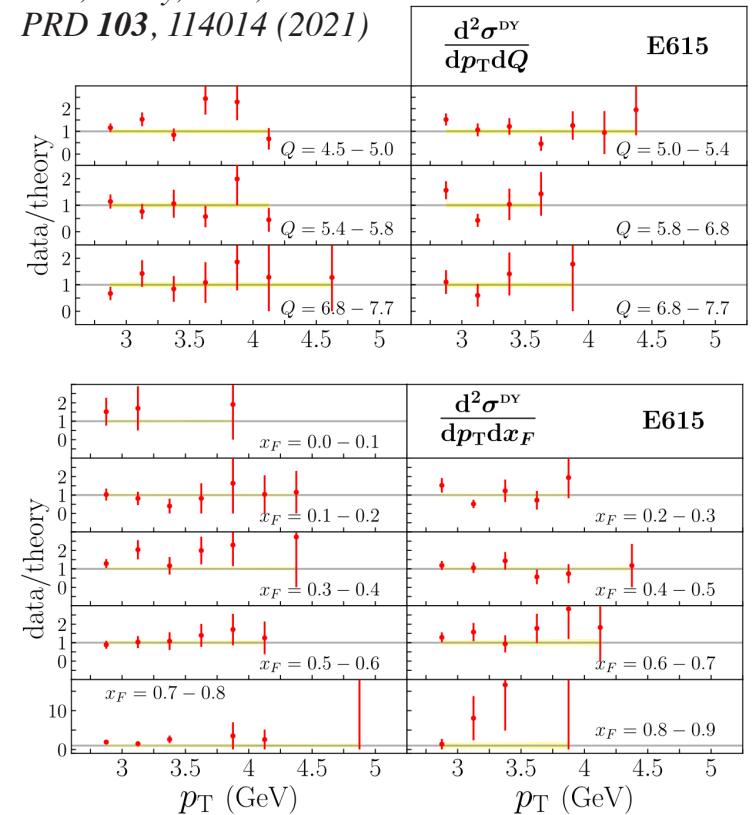


gluon contribution enters at same order as quark



→ some reduction of gluon PDF uncertainties at high x , but need higher precision data

Cao, Barry, Sato, WM
PRD 103, 114014 (2021)



→ first analysis combining p_T -integrated with p_T -differential data

Lattice matrix elements

Recent advances in calculation of reduced pseudo loffe-time distributions (RpITD) from lattice QCD

$$\mathcal{M}(\nu, z^2) = \frac{M(z, P_z)/M(z, 0)}{M(0, P_z)/M(0, 0)}$$

loffe time

$$\nu = zP_z$$

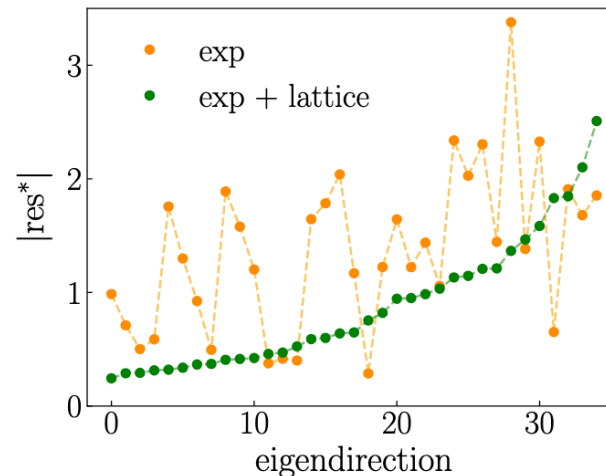
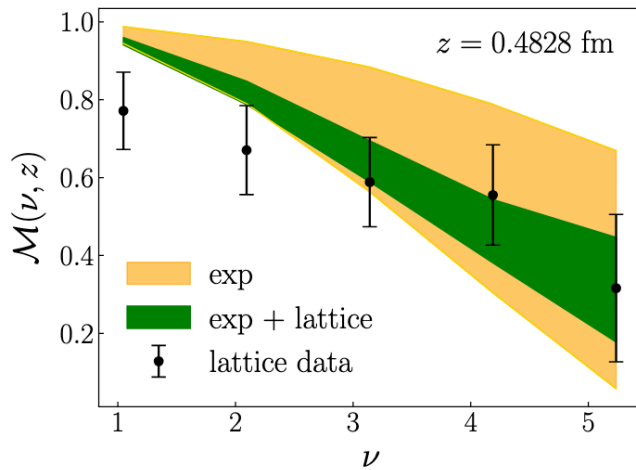
$$M(z, P_z) = \langle \pi(P_z) | O(z) | \pi(P_z) \rangle$$

gluonic operator

$$O^{\mu\nu}(z) = F_a^{\mu\alpha}(z) W(z, 0) F_{a,\alpha}^\nu(0)$$

$$\mathcal{M}(\nu, z^2) = \int_0^1 dx \frac{xg(x)}{\langle x_g \rangle} \left[R_{gg}(x\nu, z^2) + R_r(x\nu, z^2) \frac{\langle x_\Sigma \rangle}{\langle x_g \rangle} \right] + \int_0^1 dx \frac{x\Sigma(x)}{\langle x_g \rangle} R_{gq}(x\nu, z^2) + z^2 B_1(\nu) + \frac{1}{z} P_1(\nu)$$

perturbative kernel
power corrections
lattice spacing

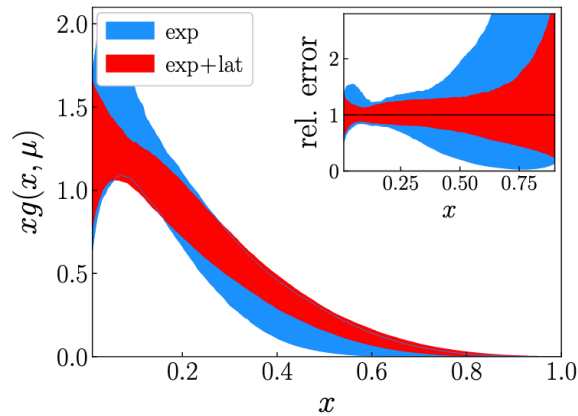


→ for 35 RpITD data inputs
(different z, P_z) $\chi_{\text{red}}^2 \approx 1.25$

→ significant reduction
of uncertainties with
LQCD data

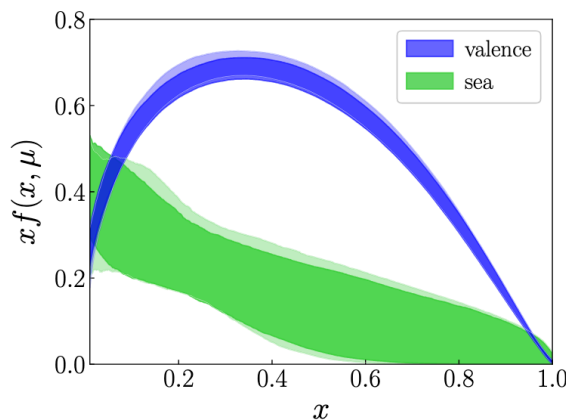
Simultaneous DY + LN + RpITD analysis

Reconstructed pion PDFs constrained by experimental and lattice RpITD data

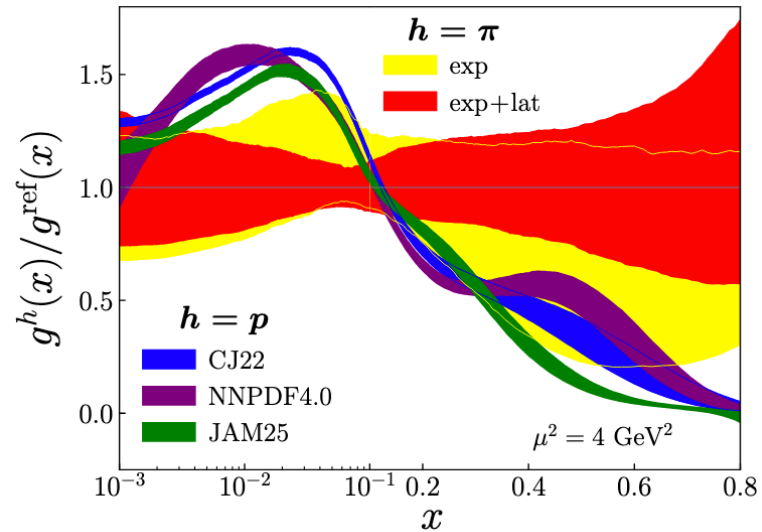


→ lattice data compatible with experimental (DY+LN) constraints

→ gluon PDFs clearly nonzero with reduced uncertainty



→ negligible impact on quark PDFs



→ comparison with proton PDFs shows enhancement of pion's gluon PDF at large x
— note total moments are similar

$$\langle x \rangle_g^\pi = 0.43(4) \quad \langle x \rangle_g^p = 0.40 - 0.42$$

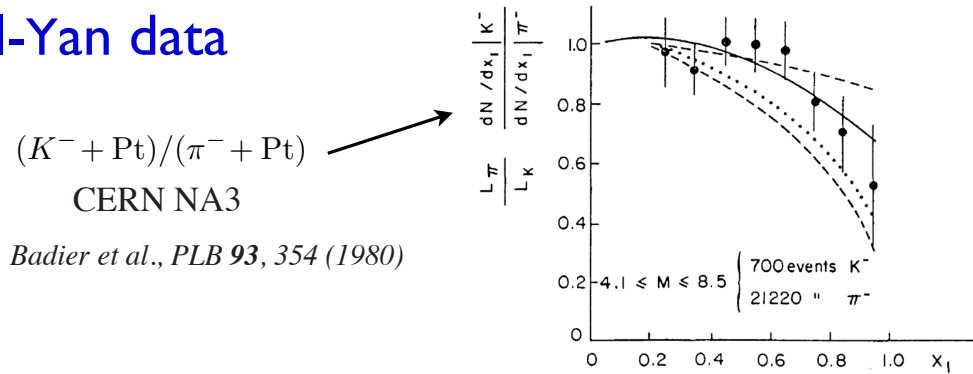
→ differences clearly resolved with addition of lattice data

Good, Barry, Lin, WM, NieMiera, Sato
arXiv:2507.22730

Kaon structure

■ How does switching $s \leftrightarrow u$ affect PDFs in kaon vs. pion?

■ Kaon Drell-Yan data



$$\frac{d^2\sigma}{dx_1 dx_2} \approx \frac{4\pi\alpha^2}{9Q^2} \bar{u}^{K^-}(x_1) u^A(x_2)$$

$$(x_2 \gg x_1)$$

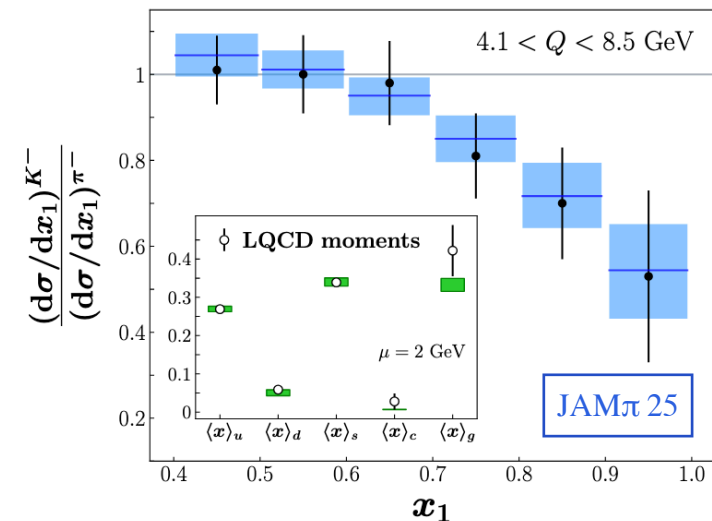
→ constrains (at most) $\bar{u}^{K^-}$ PDF

→ determining other flavours in kaon (valence s -quark, sea-quark, gluon) requires additional input, *e.g.*, lattice data

■ Combined fit to all pion DY+LN, kaon/pion DY, lattice moments $\langle x \rangle_q, \langle x^2 \rangle_q, \langle x^3 \rangle_q$

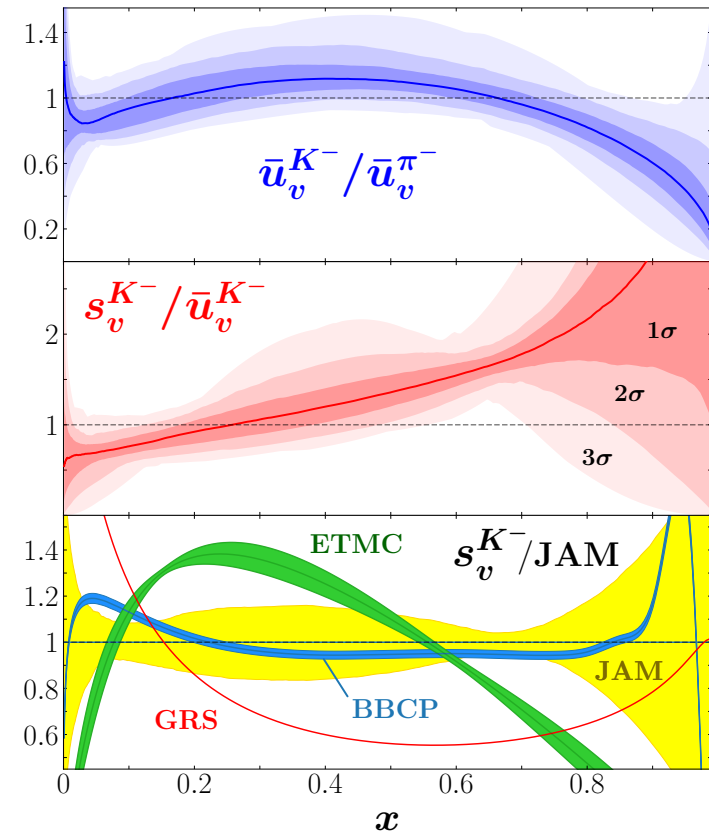
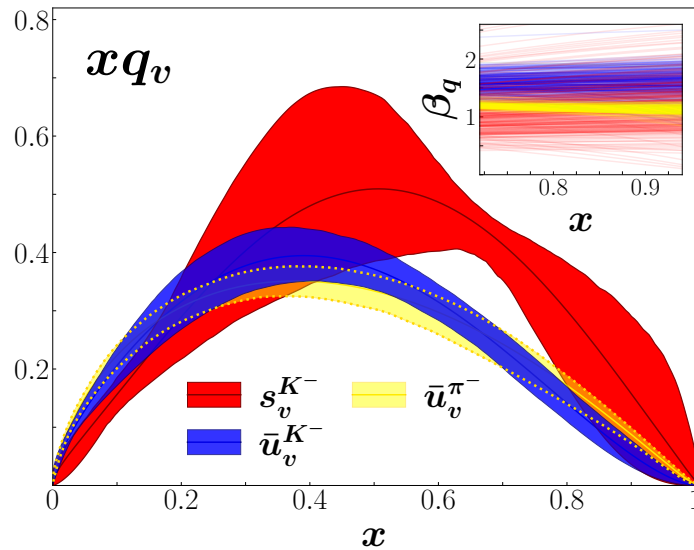
Moment	kaon		pion	
	ETMC	JAM	ETMC	JAM
$\langle x \rangle_u$	0.269(9)	0.269(7)	0.249(28)	0.256(10)
$\langle x \rangle_d$	0.059(9)	0.051(8)	0.249(28)	0.256(10)
$\langle x \rangle_s$	0.339(11)	0.340(11)	0.036(15)	0.040(10)
$\langle x \rangle_c$	0.028(21)	0.0071(3)	0.013(16)	0.0092(6)
$\langle x \rangle_g$	0.422(67)	0.333(17)	0.402(53)	0.439(28)
$\langle x^2 \rangle_u$	0.096(3)	0.089(4)	0.110(14)	0.090(4)
$\langle x^2 \rangle_s$	0.139(2)	0.137(4)	—	—
$\langle x^3 \rangle_u$	0.033(6)	0.050(3)	0.024(18)	0.052(2)
$\langle x^3 \rangle_s$	0.073(5)	0.082(5)	—	—

ETMC: Alexandrou et al., PRD **104**, 054504 (2021)



Kaon structure

Reconstructed valence quark s and u PDFs moments in kaon vs. pion?



Barry, Ji, WM, Sato, Steffens
arXiv:2510.11979

→ softer valence $\bar{u}$ in K than in π^-

→ harder valence s in K than $\bar{u}$ in K

→ first evidence of SU(3) flavour breaking in valence sector of K

→ smaller gluonic momentum fraction in K $\longrightarrow \langle x \rangle_g^K < \langle x \rangle_g^\pi$
 suggests $\approx 1/4$ of mass of K is gluonic in origin, compared to $\approx 1/3$ of π

Summary

■ First simultaneous global QCD analysis of pion (DY p_T -integrated & p_T -differential, LN, LQCD) and kaon (DY $K+\pi$, LQCD) PDFs

→ enhanced gluon PDF in pion at large x compared with proton

$$g^\pi \neq g^p$$

→ first data-driven evidence for flavor symmetry breaking in valence kaon PDFs

$$\bar{u}^{K^-} \neq s^{K^-}$$

■ Future experimental avenues

→ TDIS (Tagged DIS) experiment at JLab (“leading proton” in $eD \rightarrow eppX$)

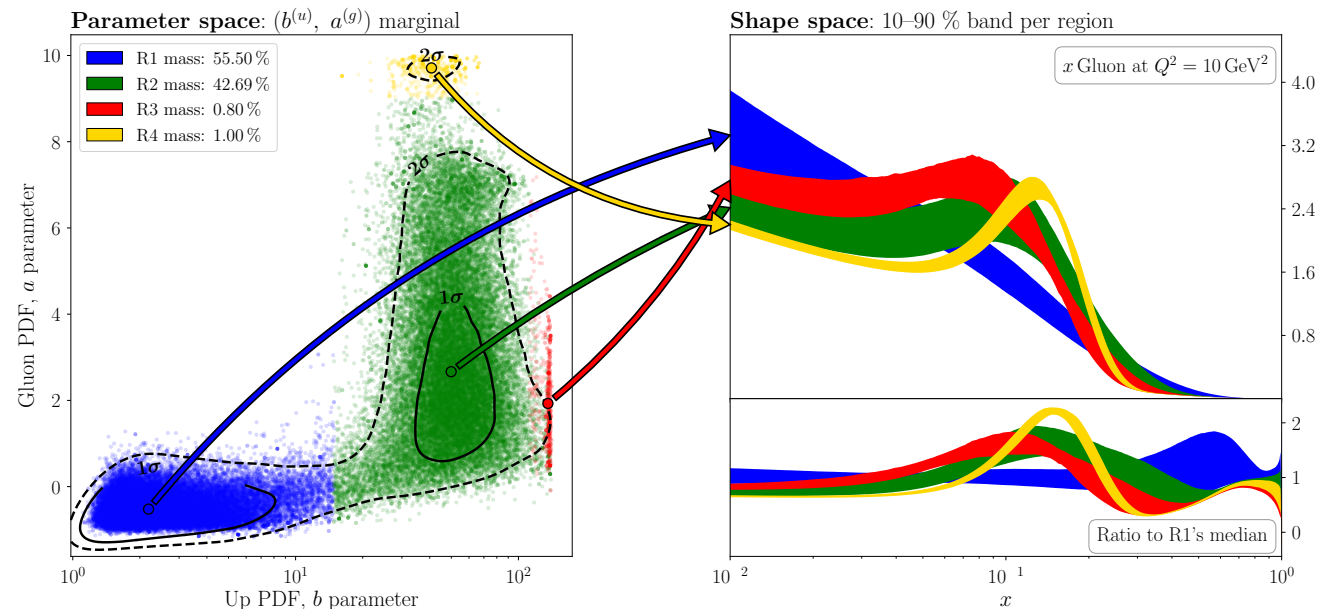
→ AMBER program at CERN (pion & kaon beams — esp. K^- and K^+)

Outlook

■ Future methodological improvement through use of Markov chain Monte Carlo (MCMC) in place of data resampling

- directly sample full posterior for fixed observed data
- capture non-Gaussian uncertainties & correlations

e.g., JAM pion PDFs with MCMC



Risse, WM, Sato (2026)

- more costly, however... requires AI tools such as normalizing flow for practical global QCD analysis