Jefferson Lab

Positron Working Group Workshop (GWU)
March 19, 2024

Parton structure from electroweak processes with positrons

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— Jefferson Lab —

Overview

- Availability of positron beams could open up an entire new frontier for hadron structure (& BSM) studies at JLab

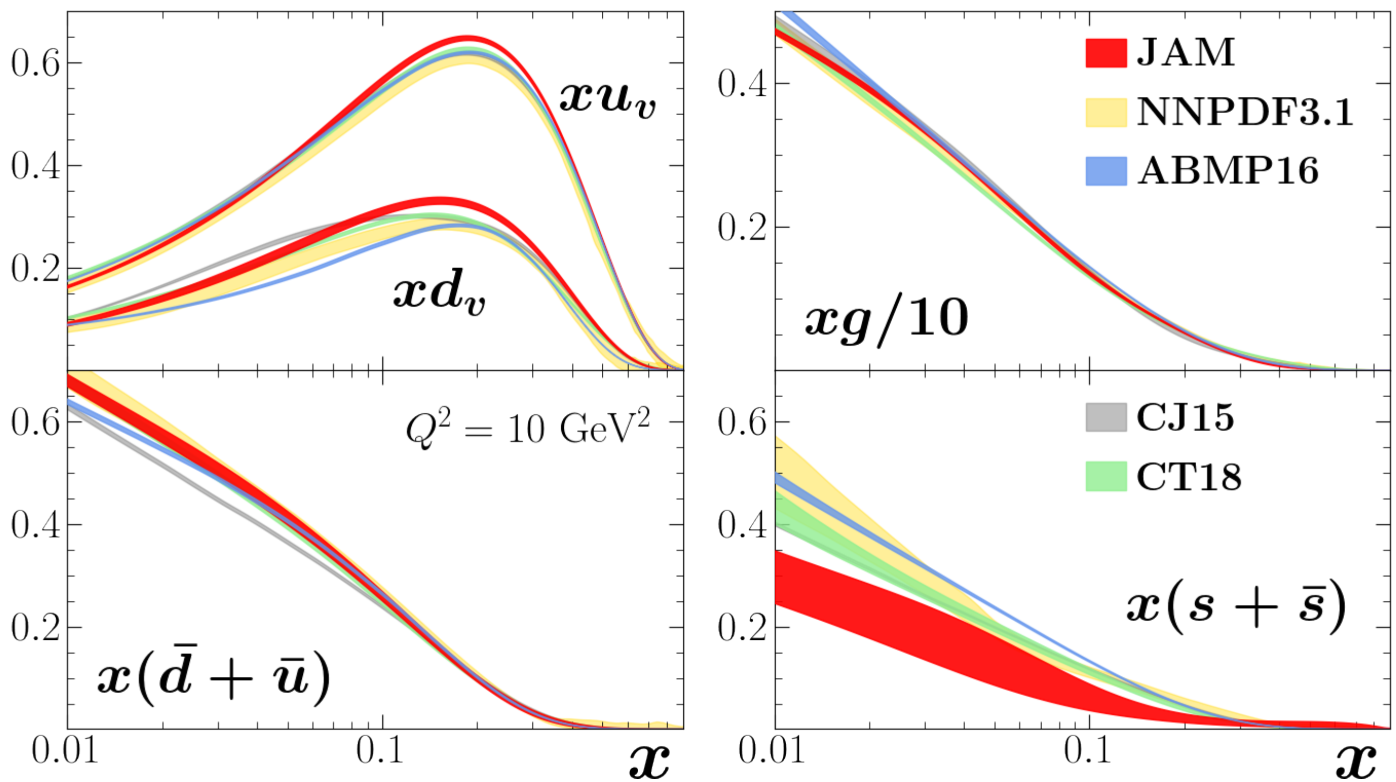
- Flavor separation of parton distribution functions (PDFs) in inclusive & semi-inclusive neutral current (NC) and charged current (CC) deep-inelastic scattering (DIS)

  → unpolarized proton PDFs

  → pion PDFs

  → reference: recent global QCD analyses by JAM Collaboration
  www.jlab.org/jam

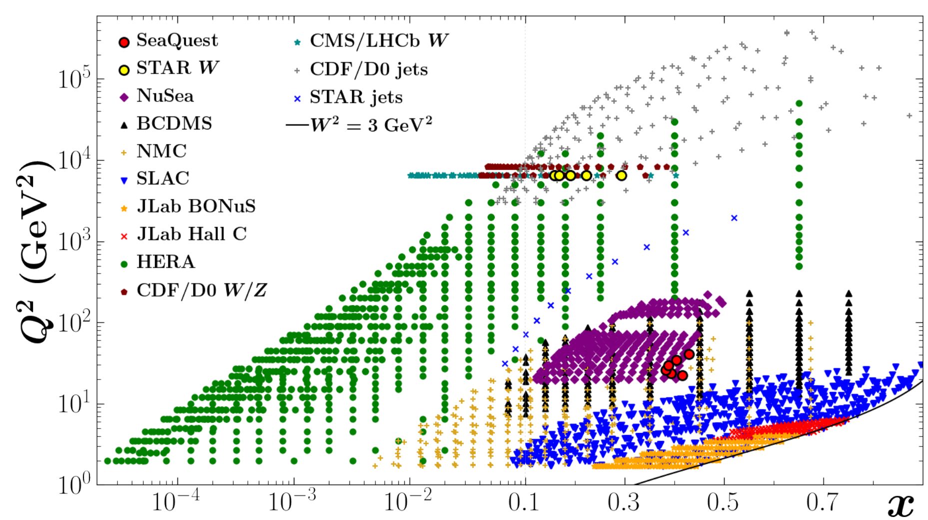
Unpolarized proton PDFs



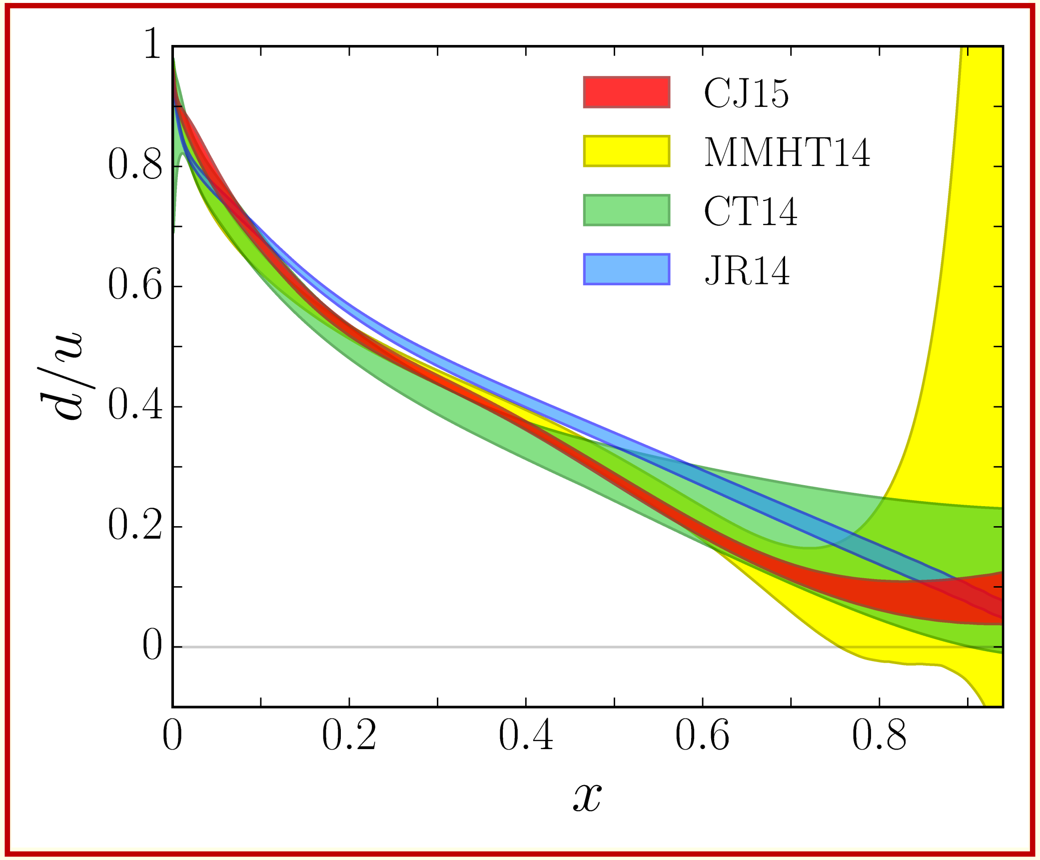
→ from recent JAM analysis

Cocuzza et al., PRD 104, 074031 (2021)

→ ~ 4,400 data points from many different processes (DIS, DY, *W*/*Z*, jets)



d/u ratio shows significant variations between various PDF sets



- Some is due to parametrization bias
- Some is due to Q and W cuts that effectively limit x to $x \sim 0.7$ so the large x region is an extrapolation
- Some is due to different treatments of nuclear corrections

d/u ratio

Need a way to constrain the d PDF in the absence of nuclear corrections

Classic solution is to use neutrino DIS. Again, at lowest order at large values of x

$$F_2^{\nu p} = 2x(d + s + \bar{u} + \bar{d}) \xrightarrow[x \to 1]{} 2xd$$

and

$$F_2^{\bar{\nu} p} = 2x(u + c + \bar{d} + \bar{s}) \xrightarrow[x \to 1]{} 2xu$$

so that at large values of x

$$F_2^{\nu p} / F_2^{\bar{\nu} p} = d/u$$

d/u ratio

However

- Data on proton targets from early bubble chamber experiments had low statistics and provided little constraint on d/u at large values of x
- High statistics experiments used nuclear targets
  - Results give information on *nuclear* PDFs
  - Need to account for nuclear model dependent corrections to extract d/u for the proton
  - Highly unlikely to get data from a hydrogen target using modern high intensity neutrino beams due to safety concerns

d/u ratio

Another solution - use the line-reversed DIS processes, again for large x

$$e^+p \to \bar{\nu} + X \qquad F_2^{e^+p,cc}(x,Q) \propto xd$$

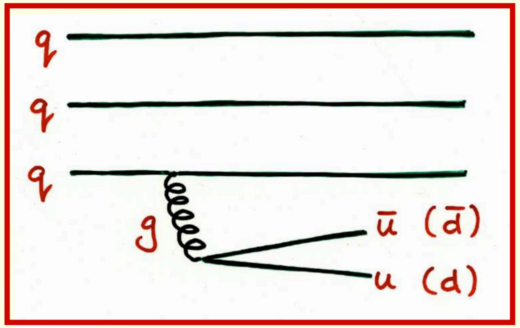
and

$$e^-p \to \nu + X \qquad F_2^{e^-p,cc}(x,Q) \propto xu$$

- Allows direct extraction of d/u at large values of x
- These processes have been measured at HERA out to $x \simeq 0.4$
- Need good statistics at larger x values if one wants to extract d/u directly

Light sea quark asymmetry

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

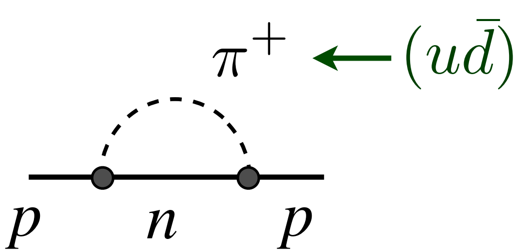


→ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

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

- From chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

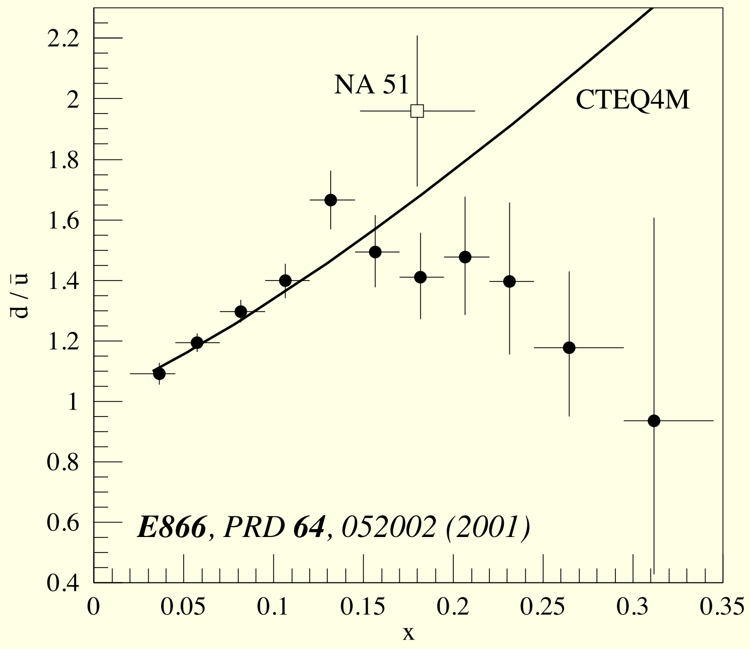
Thomas (1984)

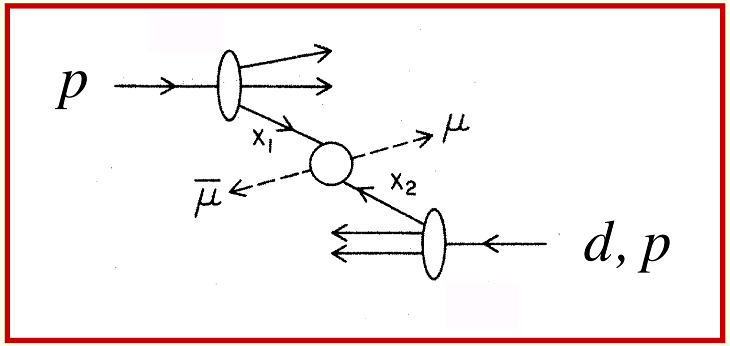


$\rightarrow$ $\bar{d} > \bar{u}$

Light sea quark asymmetry

- Asymmetry spectacularly confirmed in high-precision DIS (NMC) and Drell-Yan (FNAL E866) experiments





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

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

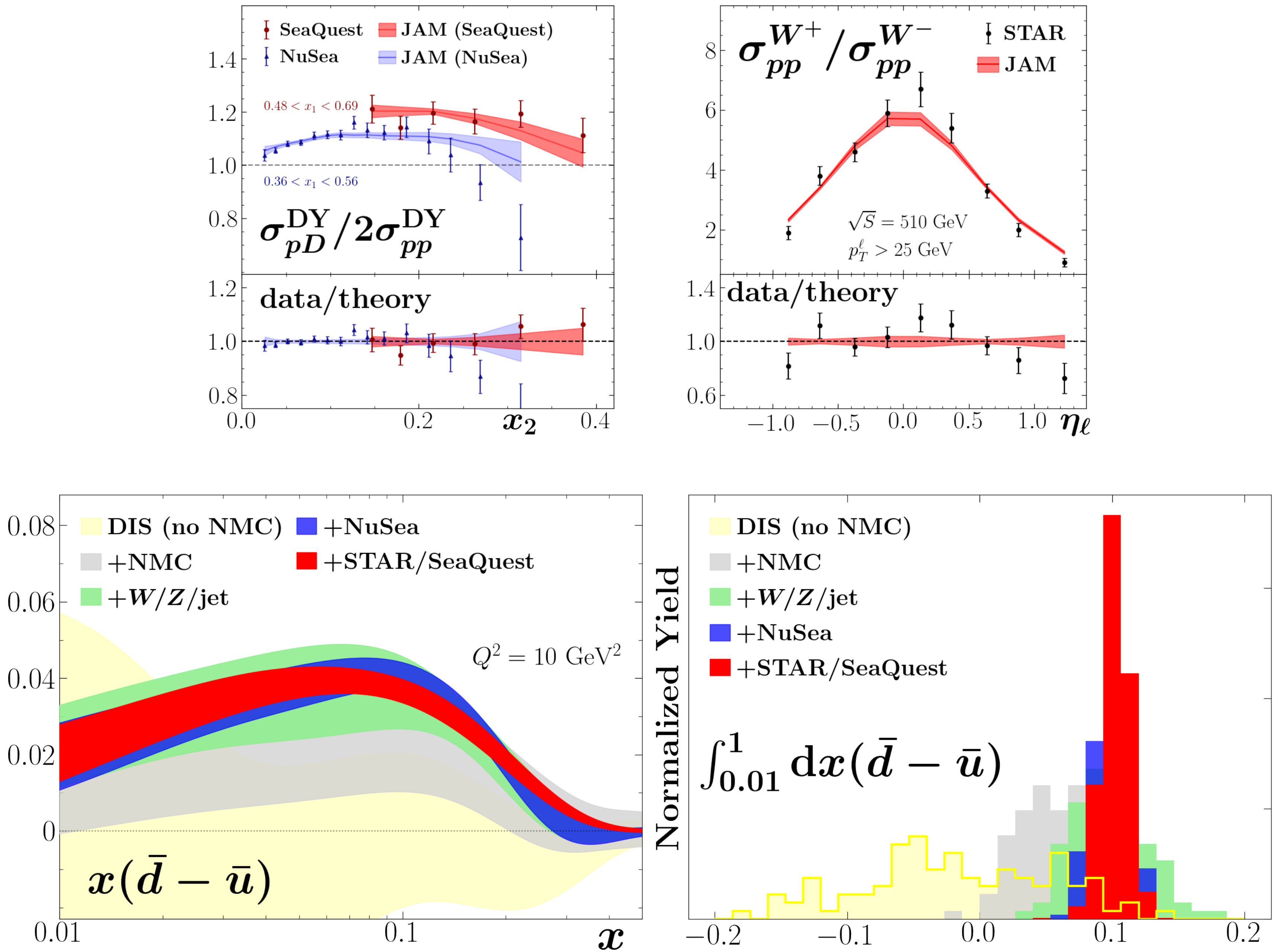
$\longrightarrow$ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

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

pion distribution in nucleon

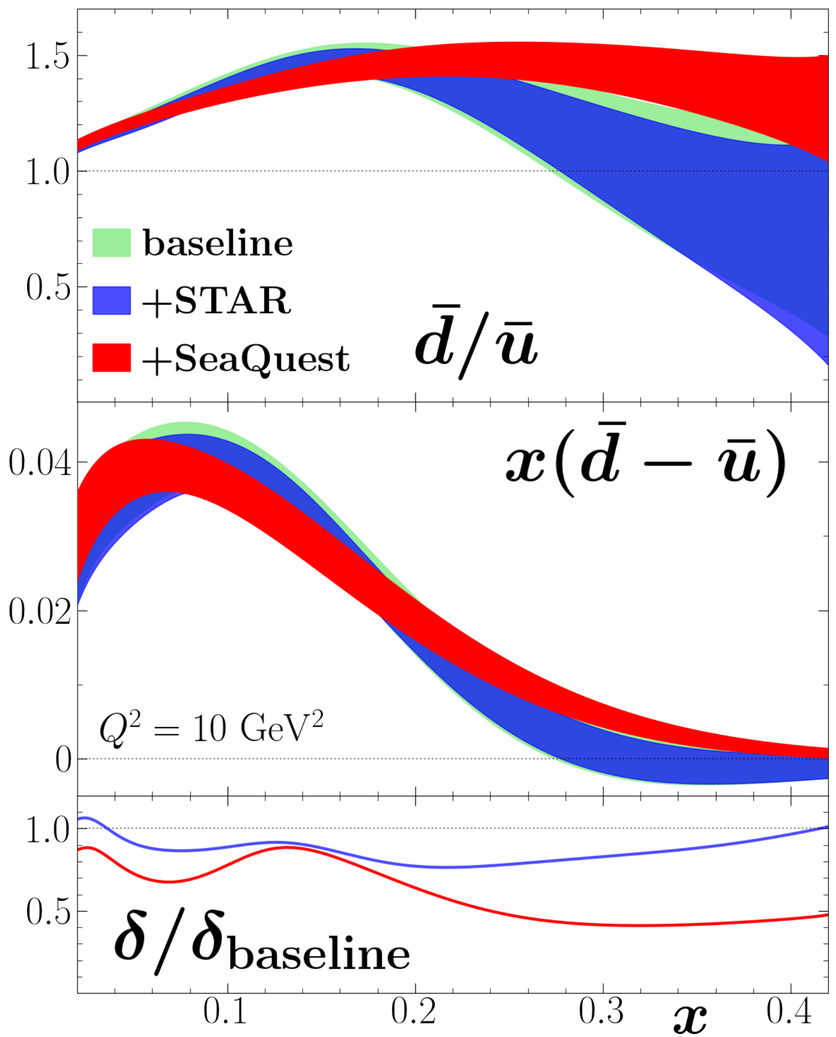
pion PDF

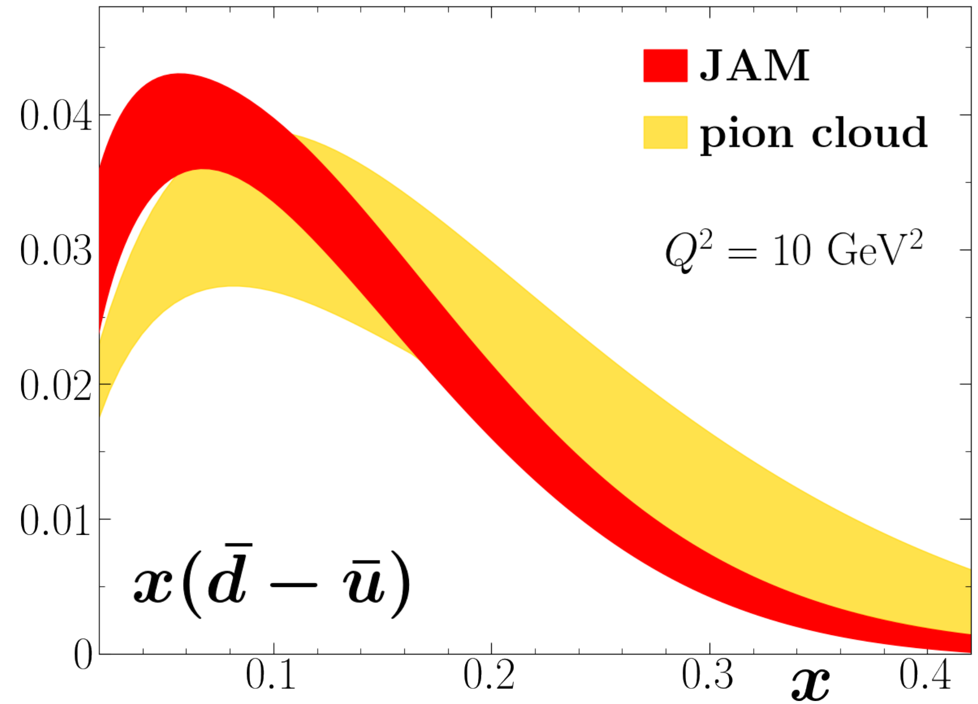
Light sea quark asymmetry



Cocuzza et al., PRD 104, 074031 (2021)

Light sea quark asymmetry





Cocuzza et al., PRD 104, 074031 (2021)

Light sea quark asymmetry

Again, consider the charged current structure functions in lowest order

$$F_2^{e^+p,cc}(x,Q) = \boxed{2x(d + s + \bar{u} + \bar{c})}$$

and

$$F_2^{e^-p,cc}(x,Q) = \boxed{2x(u + c + \bar{d} + \bar{s})}$$

- If $xF_3^{e^-p,cc} = 2(\underline{u - \bar{d} - \bar{s} + c})$ and $xF_3^{e^+p,cc} = 2(\underline{d - \bar{u} - \bar{c} + s})$ can be extracted, one can separate the quark and antiquark PDFs
- If the charm PDF is perturbative, *i.e.* there is no intrinsic charm, then $c = \bar{c}$
- Can get information on $\bar{d}/\bar{u}$

Strange quarks

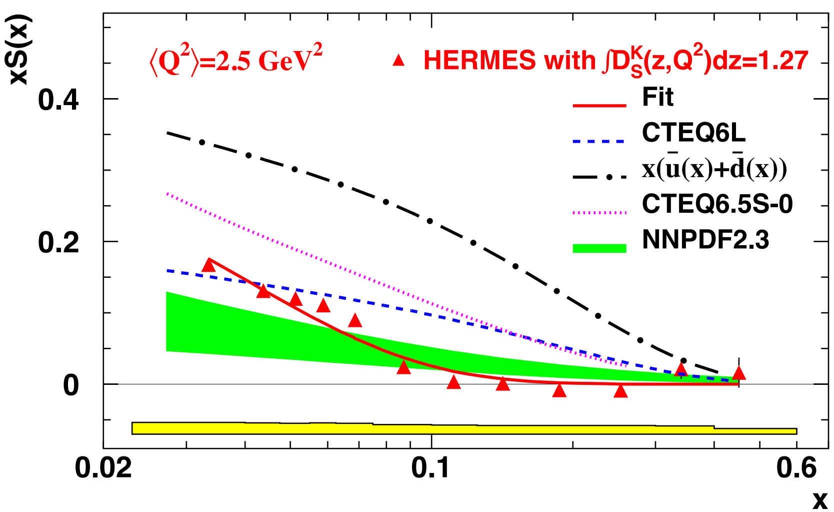
- Strange quark PDFs more difficult to constrain, since fewer observables directly sensitive to it

- Traditionally s-quark PDF extracted from dimuon production in (anti)neutrino-nucleus DIS $(W^+ s \to c \;/\; W^- \bar{s} \to \bar{c})$

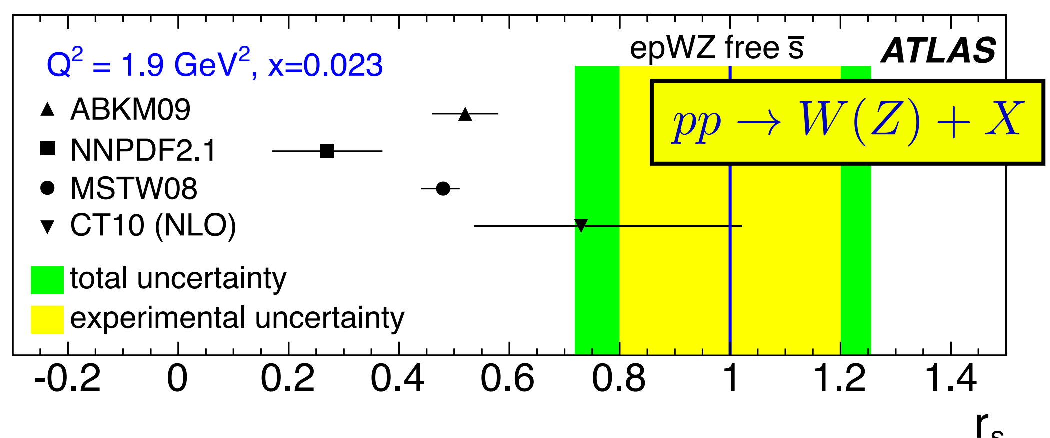
  → CCFR/NuTeV give strange/nonstrange ratio $R_s = \dfrac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 0.4$

  → but significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

  → tensions with HERMES K-production & ATLAS W-production data?



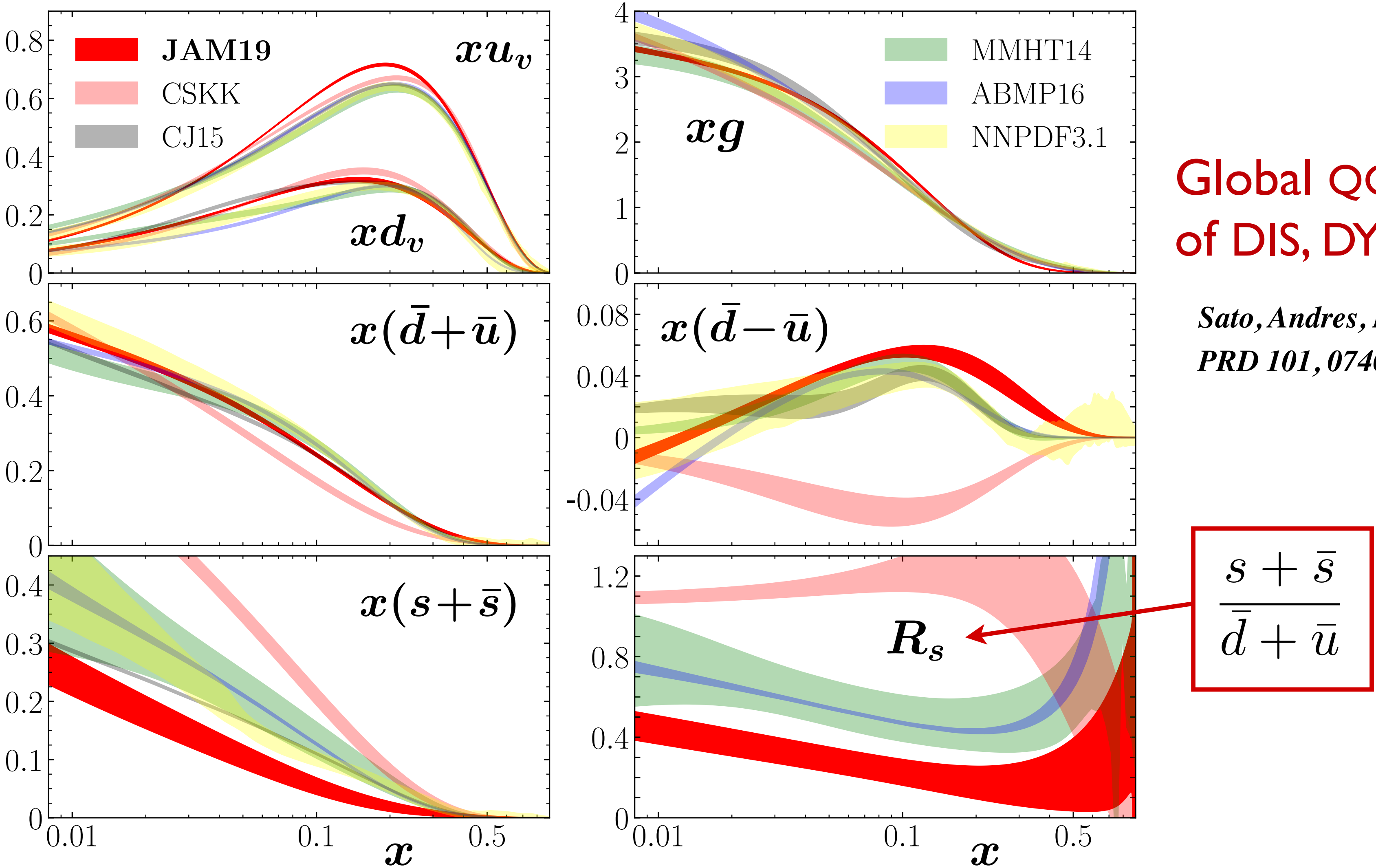
PRD 89 (2014) 097101



PRL 109 (2012) 012001

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

JAM 2019 simultaneous analysis

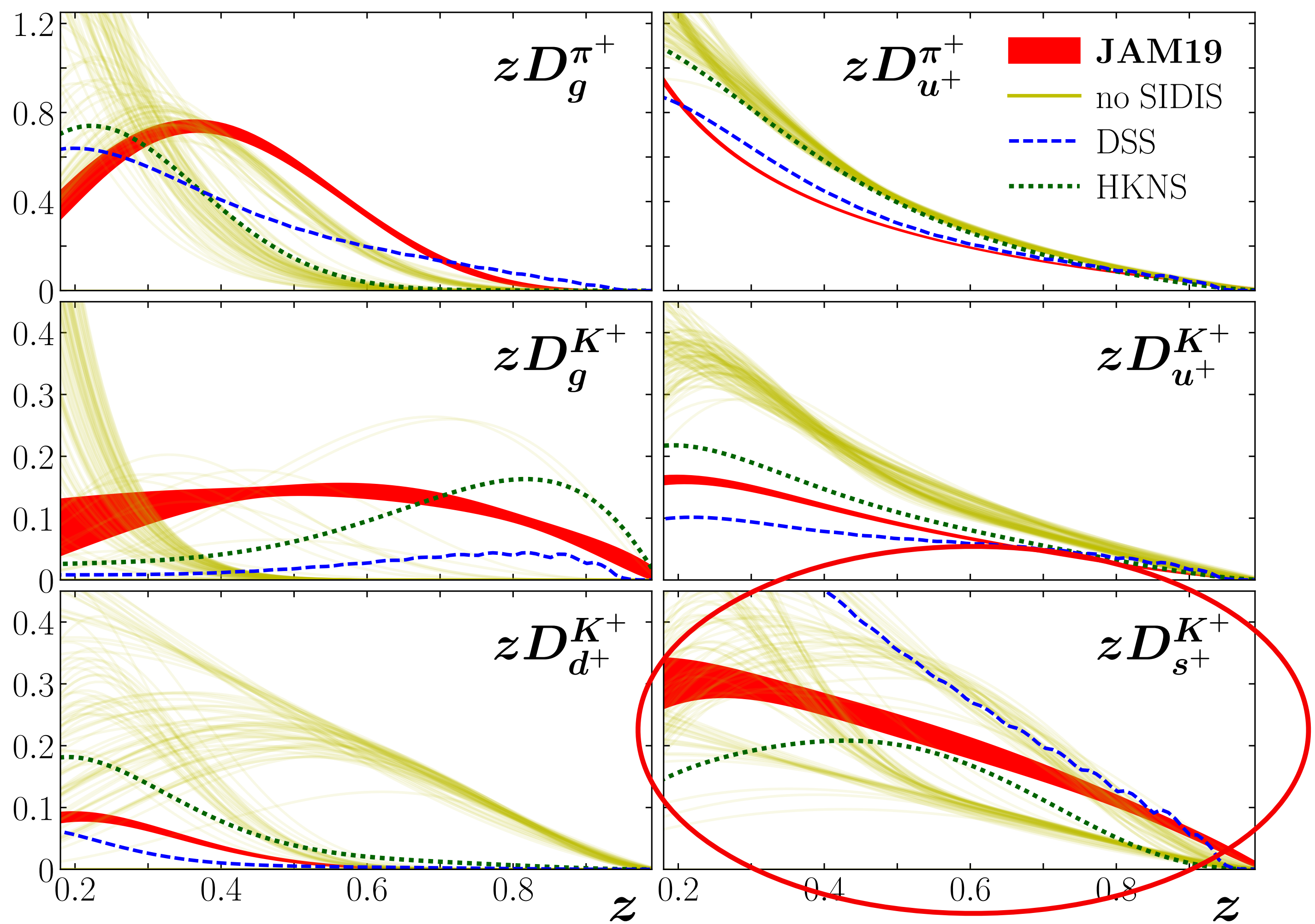


Global QCD analysis of DIS, DY, SIDIS, SIA

Sato, Andres, Ethier, WM
PRD 101, 074020 (2020)

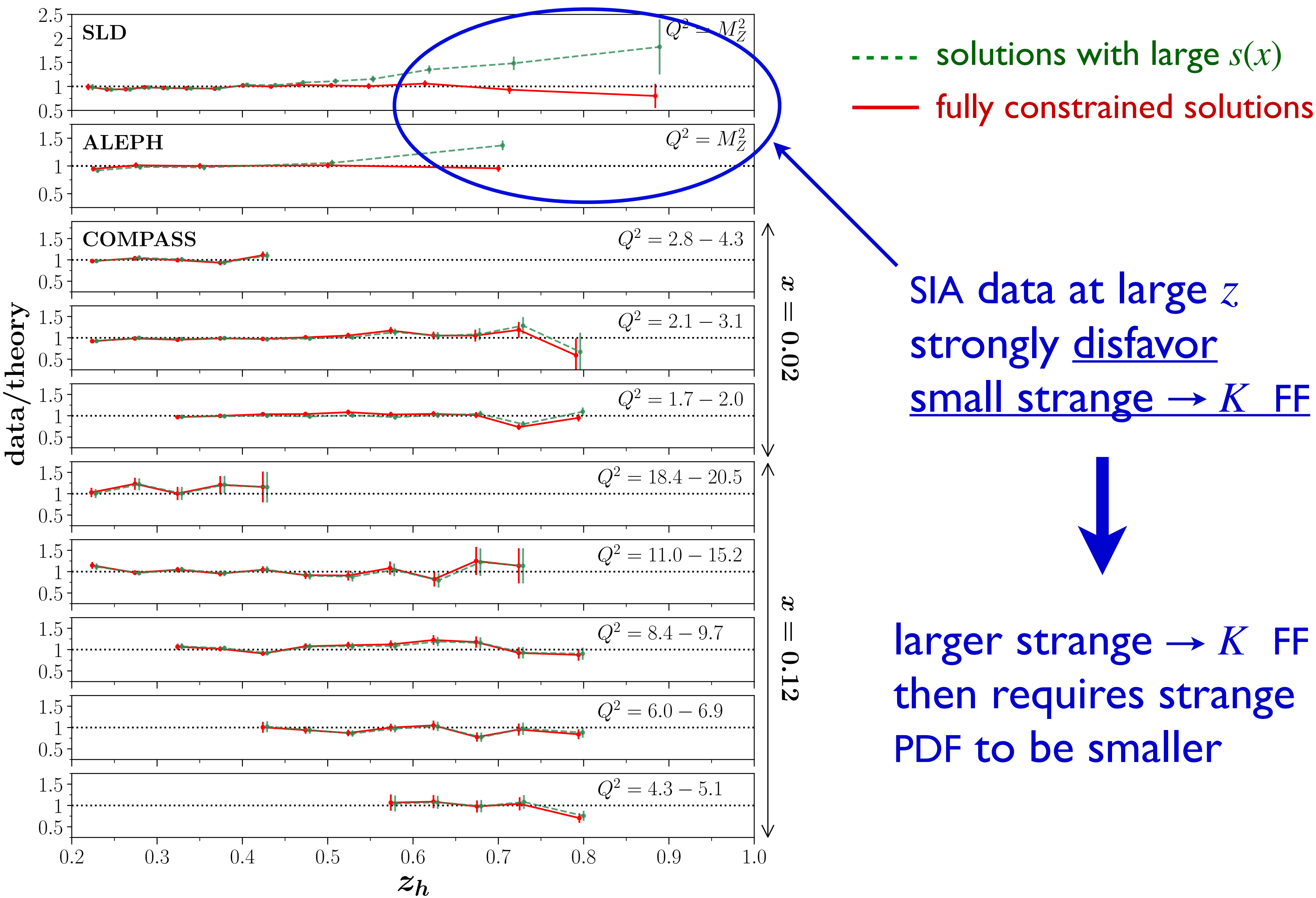
→ <u>suppression of strange</u> PDF compared to other extractions

JAM 2019 simultaneous analysis



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

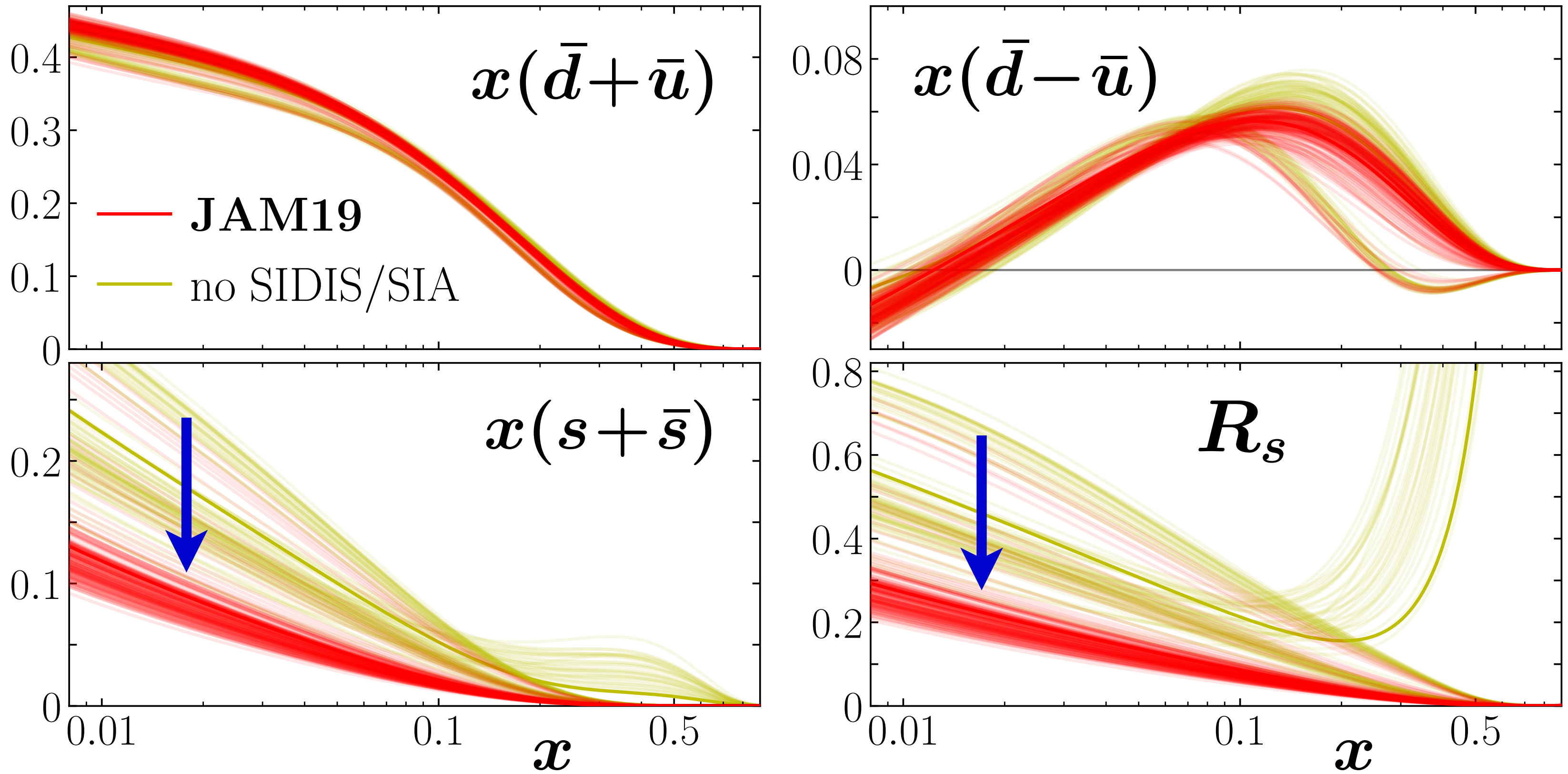
JAM 2019 simultaneous analysis



SIA data at large z strongly disfavor small strange → K FF

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

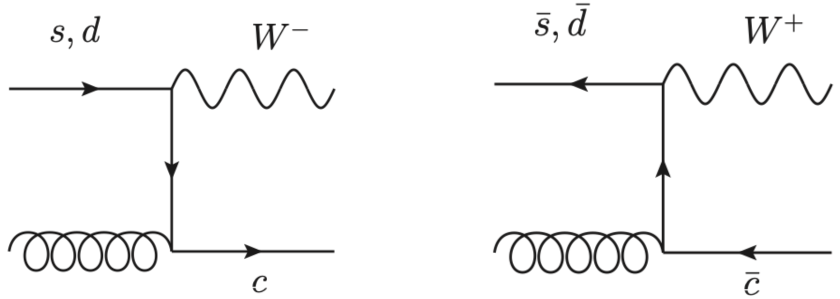
JAM 2019 simultaneous analysis

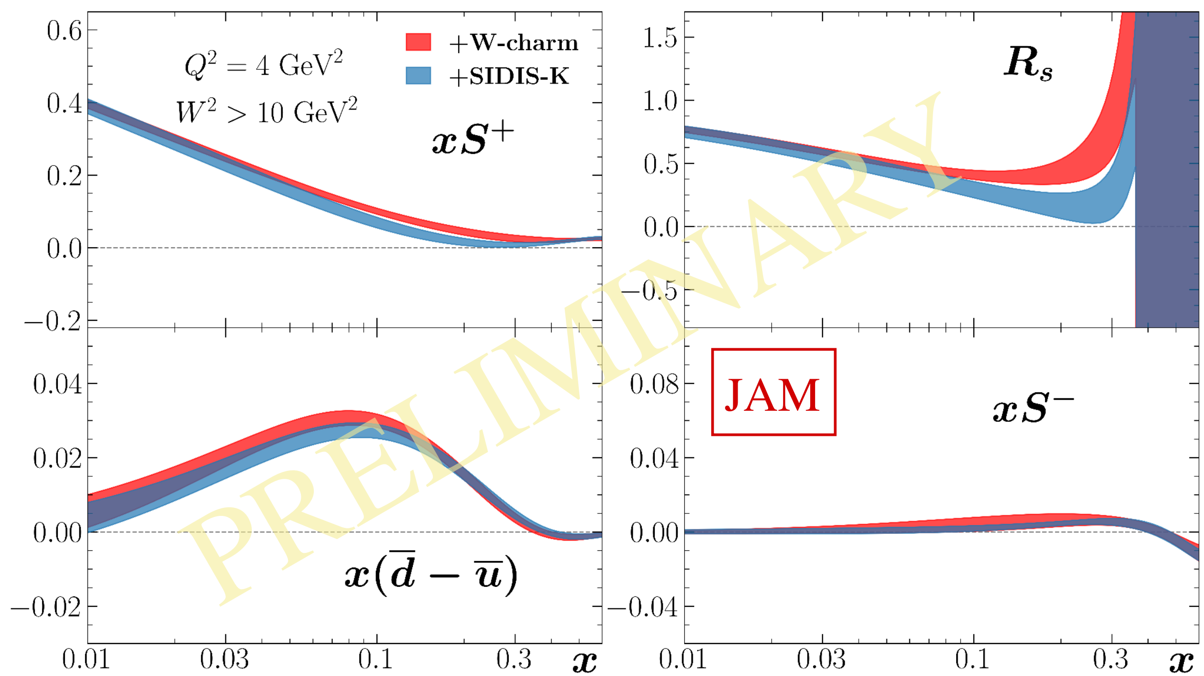


→ vital role played by SIDIS + SIA data in constraining strange PDF

Strange quarks

- It has been suggested that W+charm production in pp collisions could be sensitive to s-quark PDF in the proton





Trey Anderson, WM, Nobuo Sato (JAM, 2024)

Strange quarks

Measure charged current cross sections with a muon tag to select charm final states

$$e^+ s \to \bar{\nu} c \quad \text{followed by} \quad c \to s \mu^+ \nu_\mu$$

and

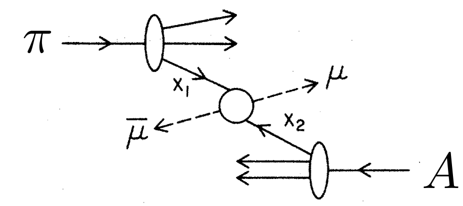
$$e^- \bar{s} \to \nu \bar{c} \quad \text{followed by} \quad \bar{c} \to \bar{s} \mu^- \bar{\nu}_\mu$$

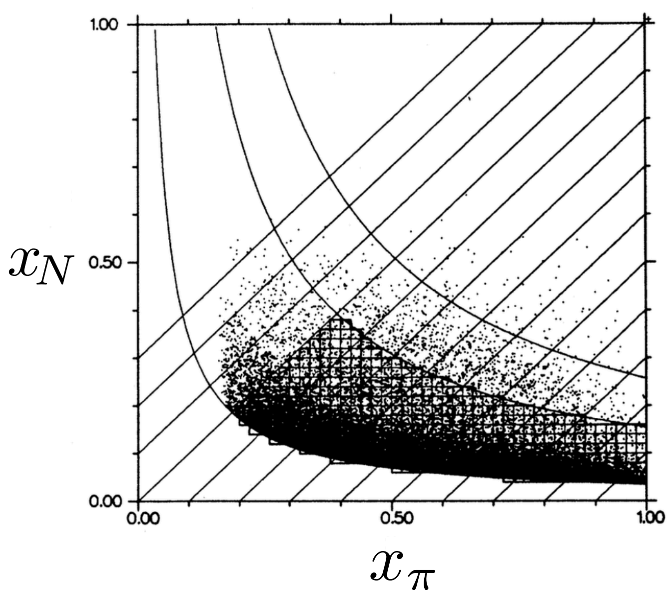
- Note that the sign of the muon is the same as the sign of initial state lepton
- Potentially capable of separating s from $\bar{s}$

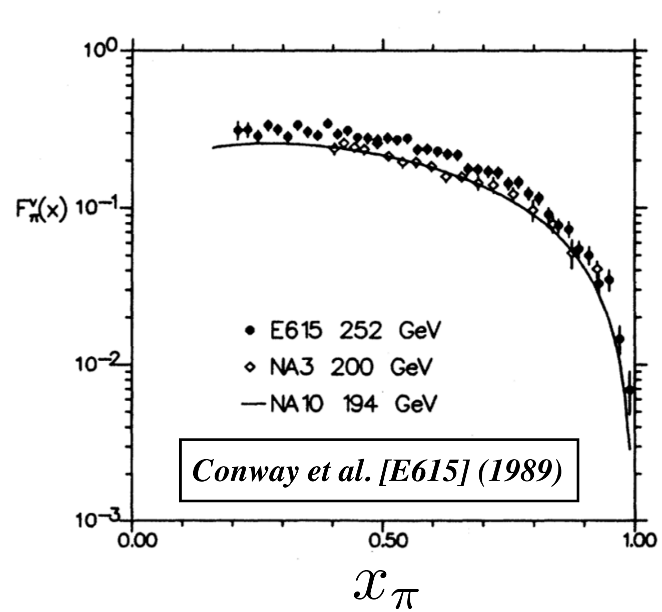
Pion PDFs

PDFs in the pion — Drell-Yan

- PDFs in the pion difficult to study experimentally
  - ⟶ most information has come from pion-tungsten Drell-Yan data (CERN, Fermilab)
  - ⟶ constrains valence PDFs at $x \gg 0$



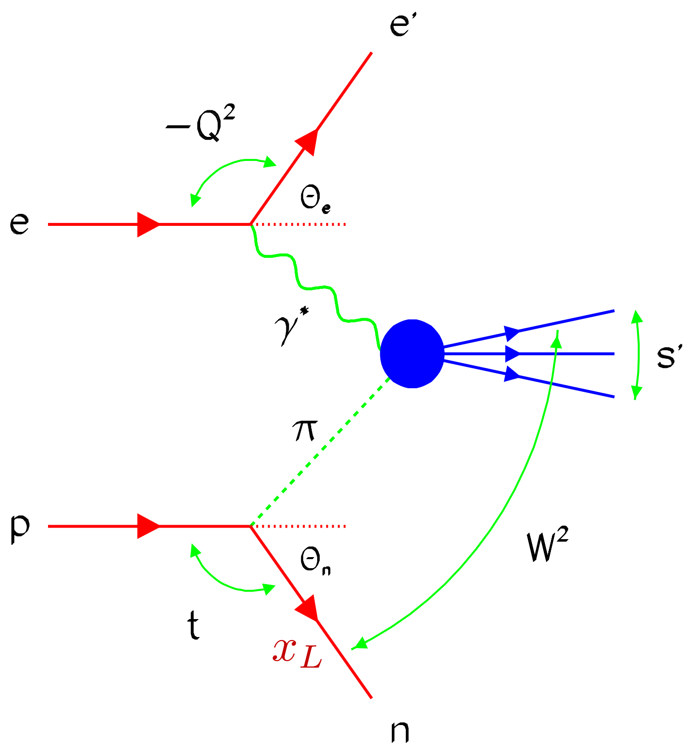


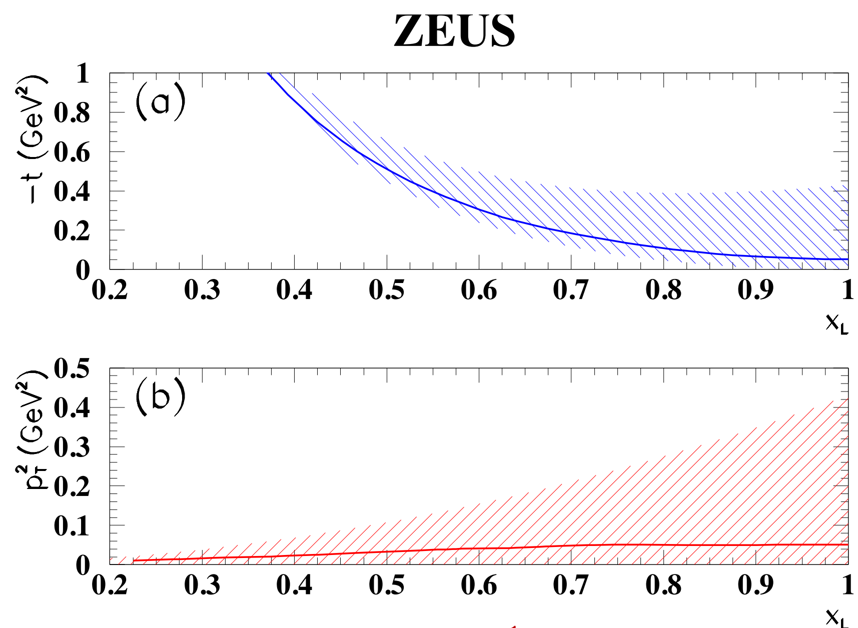


… but pion sea quark & gluon PDFs at small x unconstrained

PDFs in the pion — leading neutrons

- ZEUS & H1 collaborations at HERA measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8$ mrad



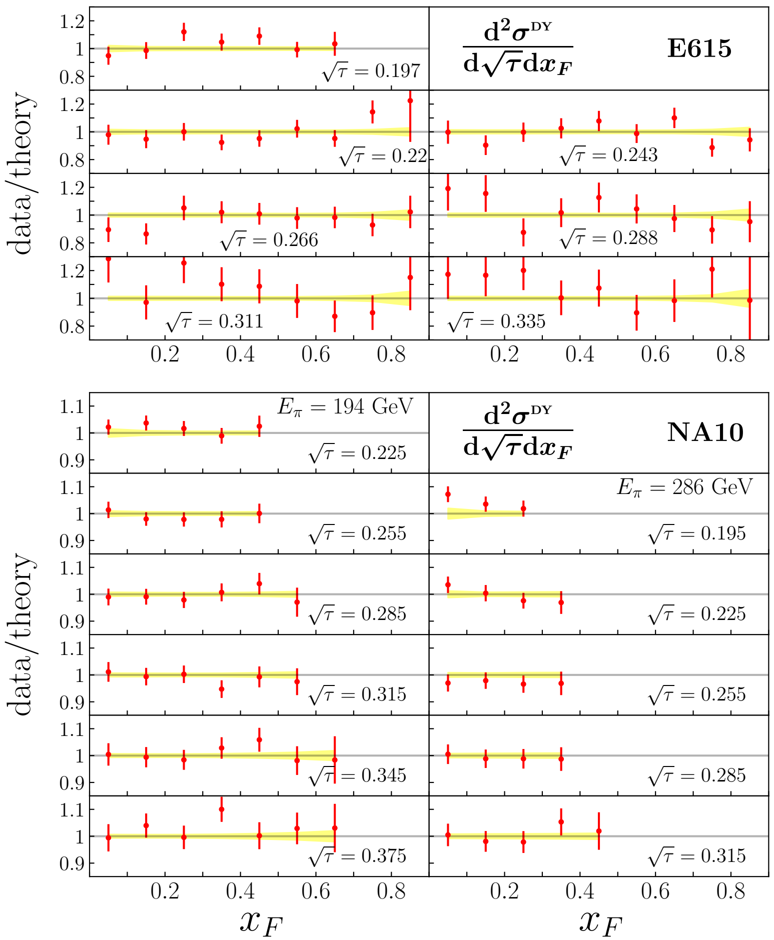


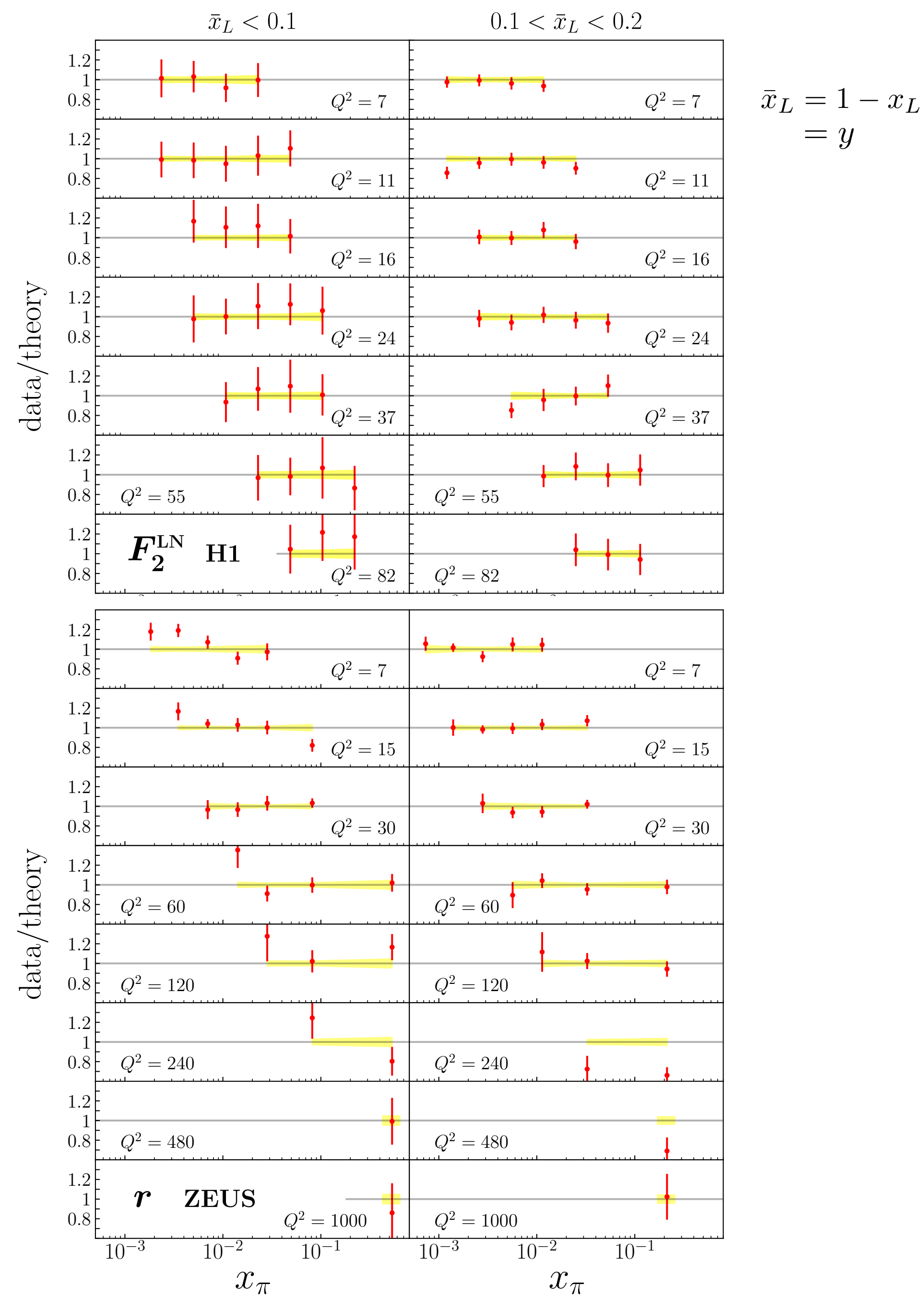
$x_L \approx 1 - y$

→ can data be described within Sullivan process?

→ first simultaneous fit performed by JAM Collaboration

Impact of leading neutrons

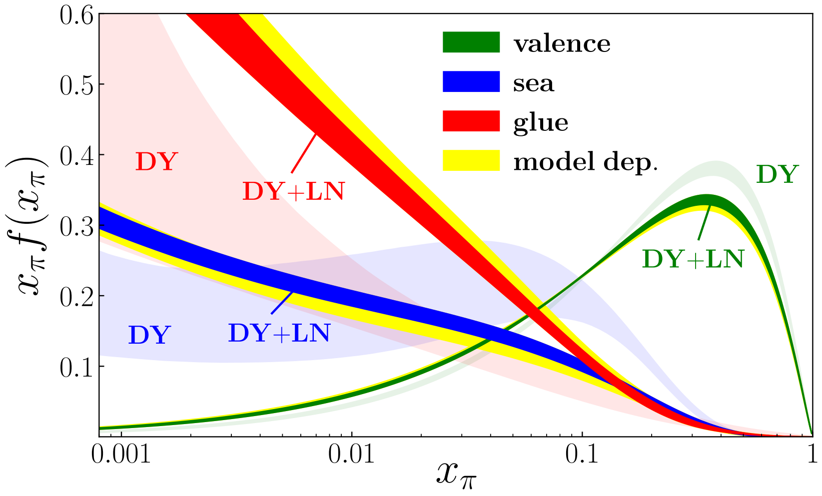




Process	Experiment (observables)	$N_{\rm dat}$	$\chi^2_{\rm dat}$	n_e
DY	E615 (x_F, Q)	61	0.85	1.08
	NA10 (194 GeV) (x_F, Q)	36	0.52	0.88
	NA10 (286 GeV) (x_F, Q)	20	0.78	0.83
	E615 $(Q, p_{\rm T})$	34	1.08	0.83
	E615 $(x_F, p_{\rm T})$	49	0.85	0.50
LN	H1	58	0.38	1.26
	ZEUS	50	1.51	0.95
Total		308	0.85	

Impact of leading neutrons

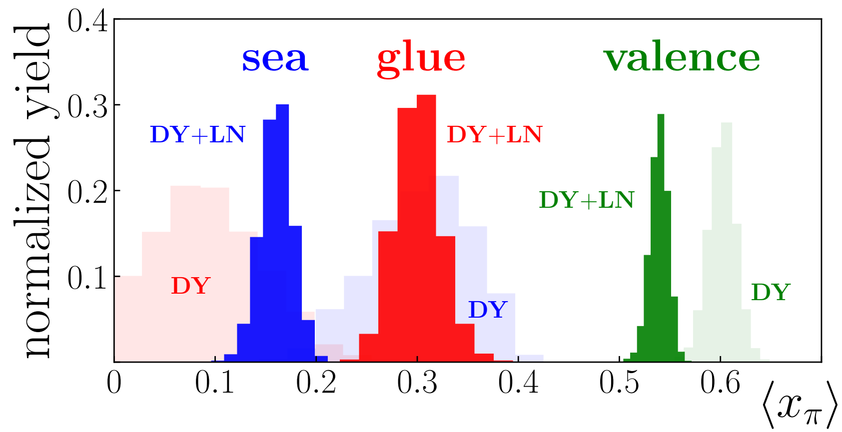
- MC analysis combining pQCD with chiral EFT to fit πN Drell-Yan + leading neutron electroproduction data from HERA



Barry, Sato, WM, C.-R. Ji
PRL 121, 152001 (2018)

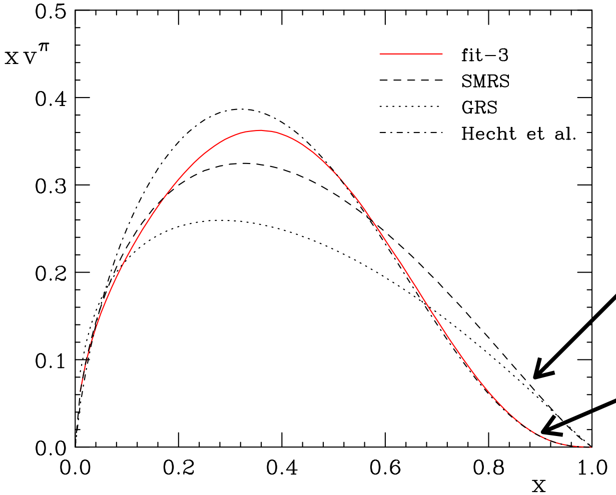
→ reduction of glue and sea quark PDF uncertainties

→ larger gluon fraction in the pion than without LN constraint



Pion PDFs with threshold resummation

- $x \to 1$ behavior of pion PDF is controversial: $\sim (1-x)$ or $(1-x)^2$?

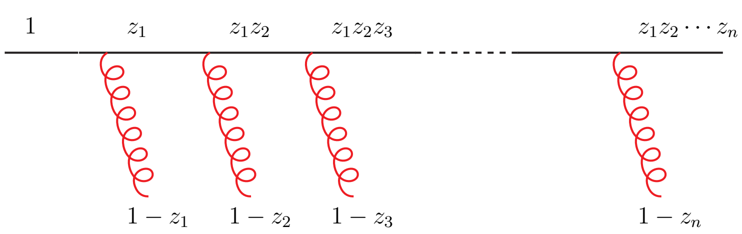


Aicher, Schafer, Vogelsang (2010)

no resummation: more consistent with $\sim (1-x)$

with resummation: more consistent with $\sim (1-x)^2$

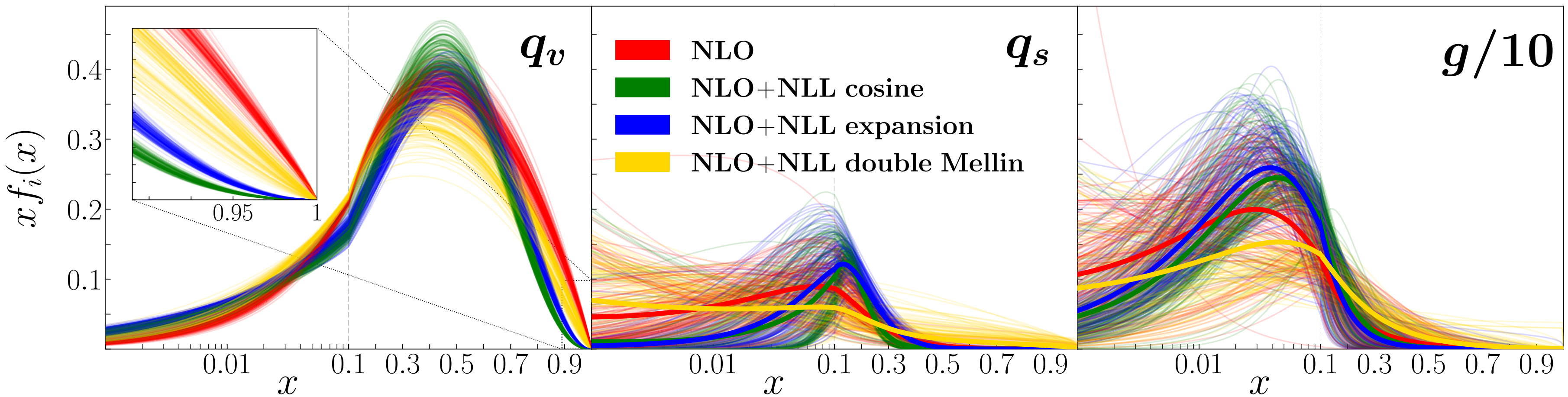
- Hard scattering coefficient function kinematically enhanced when $z \to 1$ because of (soft) gluon emissions



$\longrightarrow$ effect of resummation on phenomenology?

Pion PDFs with threshold resummation

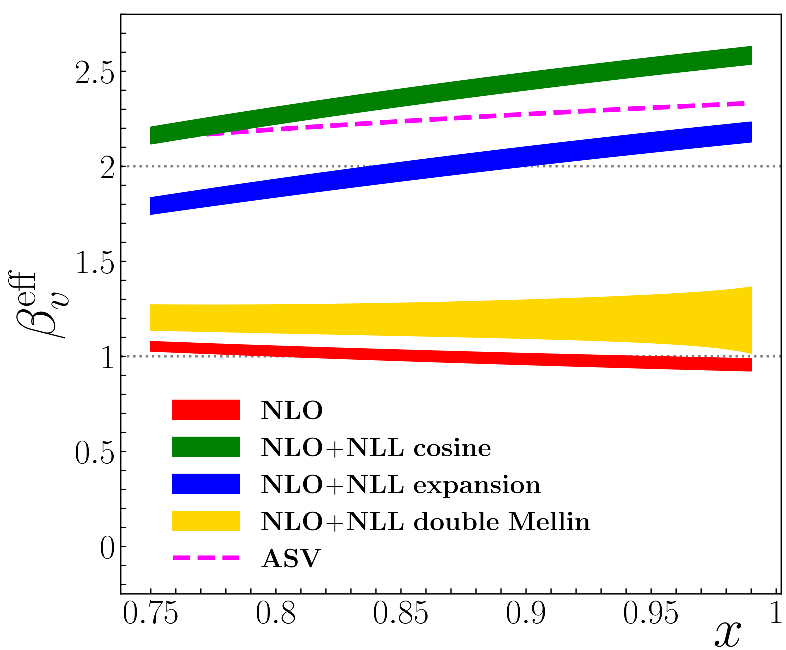
→ redistribution of x dependence



→ effective exponent

$$\beta_v^{\rm eff}(x,Q) = \frac{\partial \log |q_v(x,Q)|}{\partial \log(1-x)}$$

→ double Mellin method (theoretically preferred) gives similar results to fixed-order NLO — more consistent with $\beta_v^{\rm eff} \sim 1$

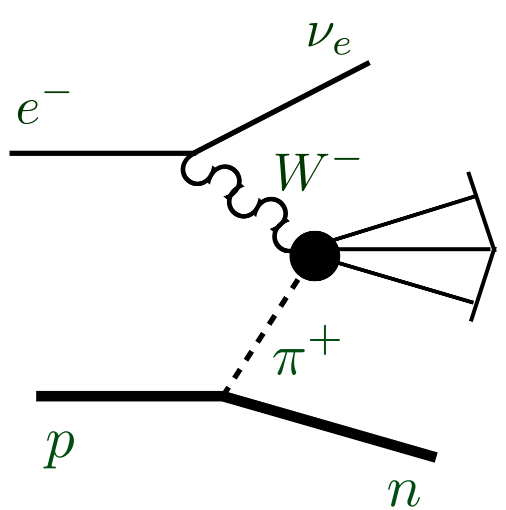


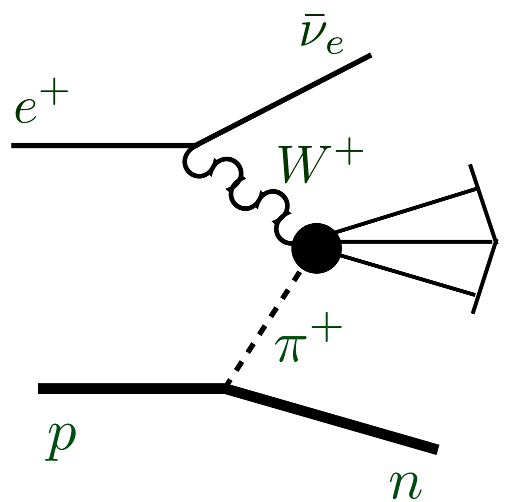
Barry, Ji, Sato, WM
PRL 127, 232001 (2021)

PDFs in the pion — leading neutrons with CC

- Leading neutron production with

$e^- p \to \nu_e n X$ or $e^+ p \to \bar{\nu}_e n X$





$W^- u \to d$

or

$W^- \bar{d} \to \bar{u}$

$W^+ \bar{u} \to \bar{d}$

or

$W^+ d \to u$

→ probes <u>valence</u> structure of π^+

→ probes <u>sea</u> quark structure of π^+

Outlook

- CC measurements in $e^{\pm}p$ DIS can provide novel information on flavor separation of PDFs

  $\longrightarrow$ clean determination of d/u ratio in the proton at large x

  $\longrightarrow$ complementary information on antiquark PDFs $\bar{d} - \bar{u}$ from P-even and P-odd structure functions

  $\longrightarrow$ extract $s - \bar{s}$ from inclusive charm production

  $\longrightarrow$ unique determination of valence and sea quark content of pion

- Can repeat this program for helicity-dependent proton PDFs with availability of polarized targets