The unique opportunities of PVDIS at high energy

Mark Dalton

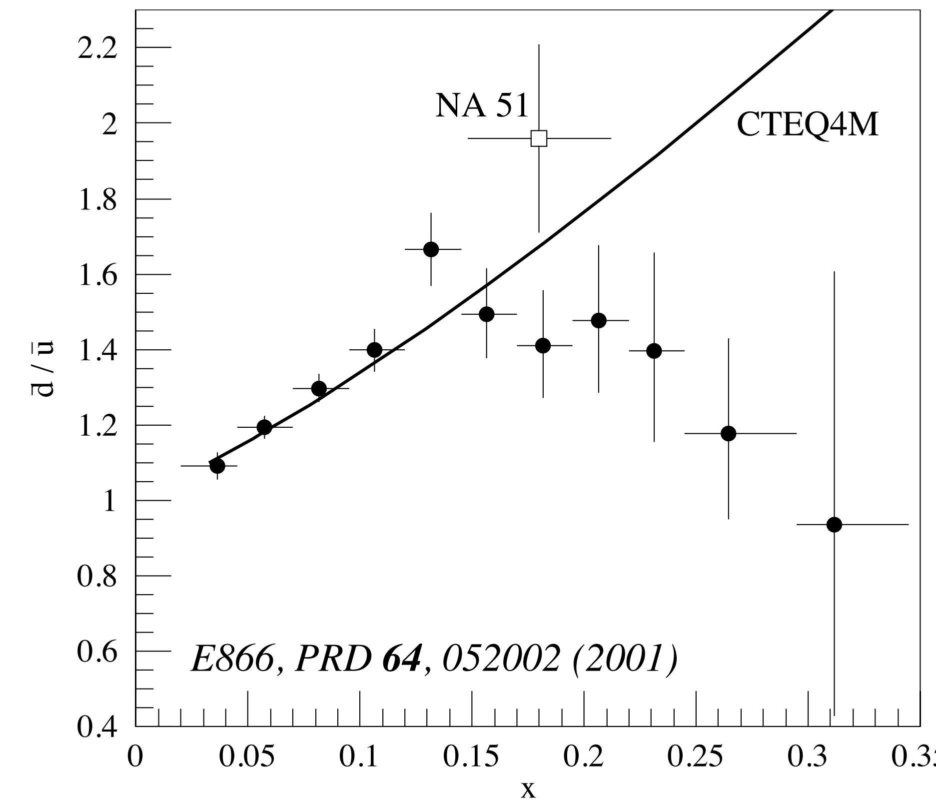
Acknowledgements to Nobuo Sato for huge contributions

Jefferson Lab

Importance of Strange Quarks

- Fundamental interest, is the sea SU(3) symmetric?

- What is the origin of the non-perturbative sea?
  non-zero $\bar{d} - \bar{u}$ cannot be generated perturbatively from gluon radiation
    chiral symmetry breaking?
    hadronic fluctuations (pion, kaon cloud)?
  Knowledge of the strange distributions is a vital component of understanding the effect.



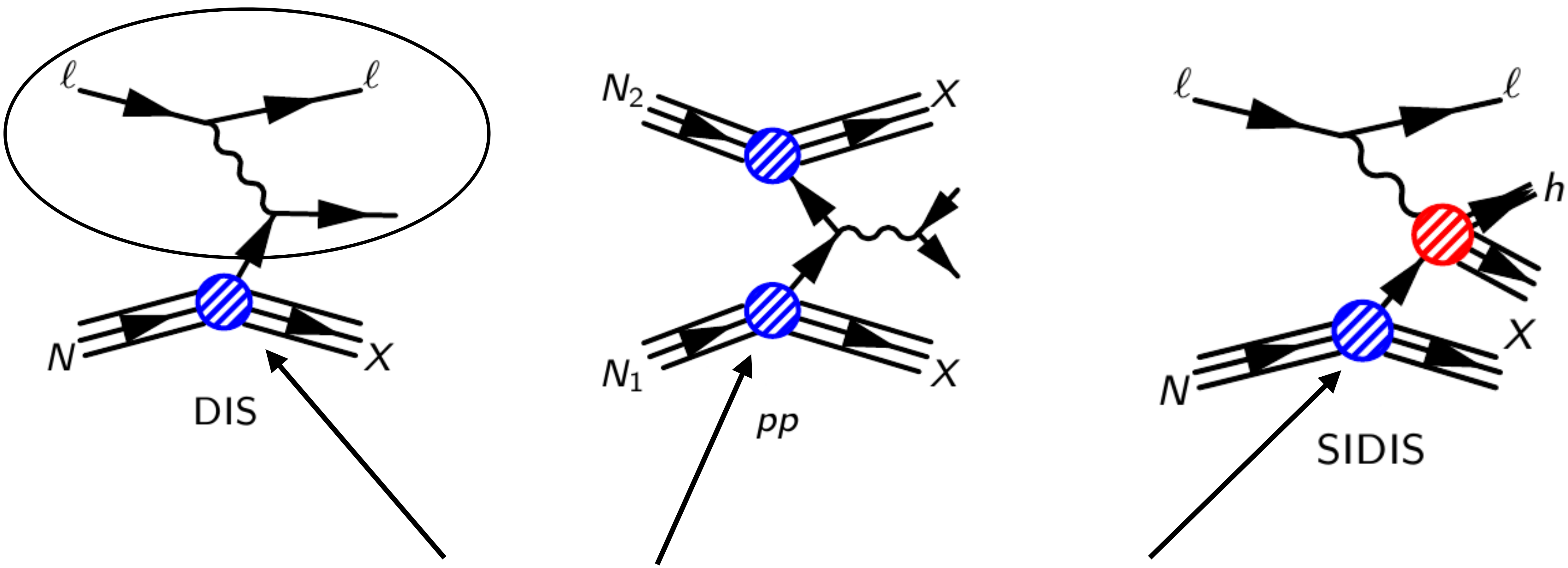
- Proton spin puzzle: a large negative contribution made by strange quarks?
  The polarized strange distribution (largely still unknown) constrained by the strange distribution.

$$|\Delta f(x, Q^2)| < f(x, Q^2)$$

- TMDs: Theoretical descriptions of transverse momentum distributions, central to the JLab 12 program, require precise input of the sea distribution.

Factorization

hard, calculable part



process-independent non-perturbative part, "universal" PDF

different processes probe different parts of the distributions

PDF Global Analysis

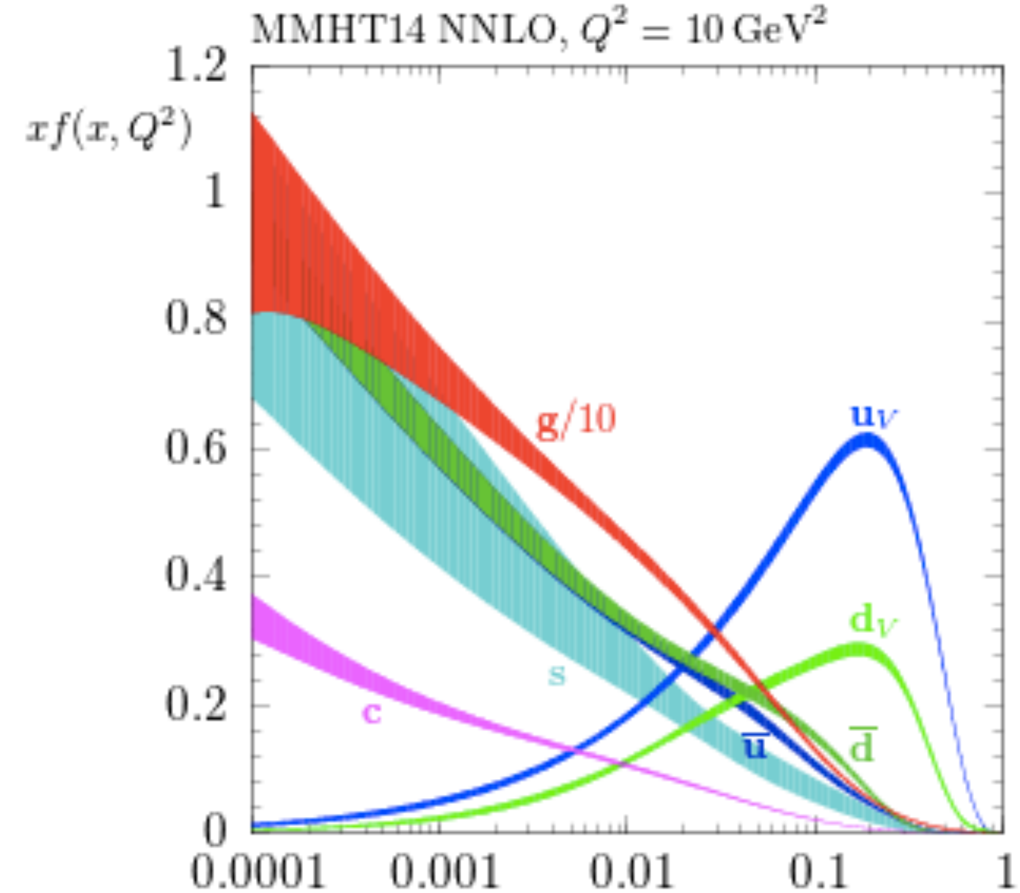
PDF: probability densities of the longitudinal momentum fraction x of quarks and gluons relative to their parent hadron momentum

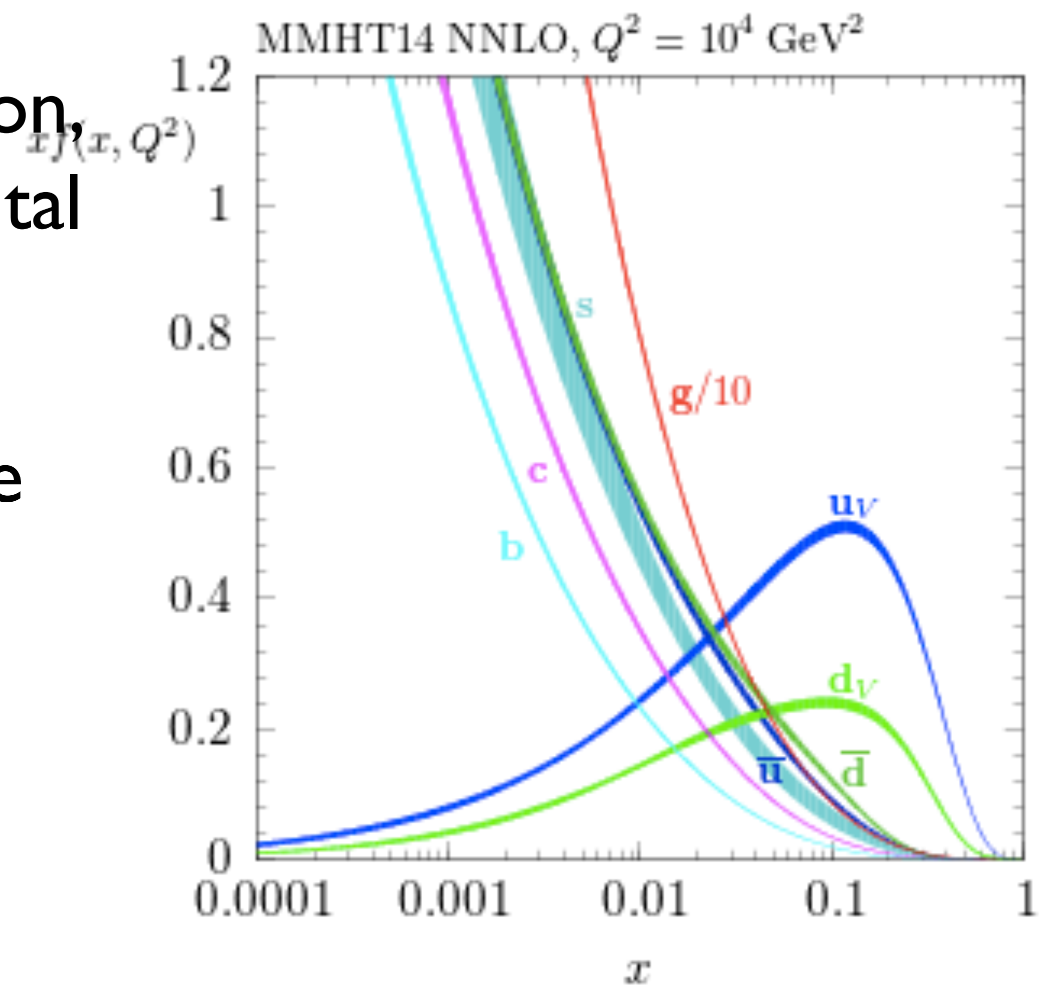
- Experimental data (~ 4k data points)
- QCD factorization: PDF (same for PPDF, FF)
- Global analysis

global analyses differ in: input data, parameterization, treatment of heavy quarks, value of αs, experimental errors treatment, theoretical error estimation.

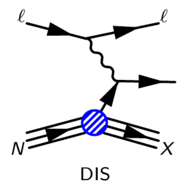
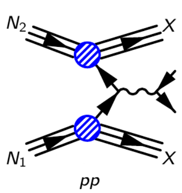
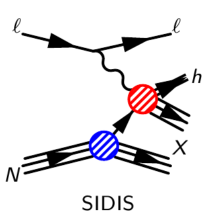
Fits have been done for 3 decades but the strange remains poorly determined

Momentum sum rule is important constraint





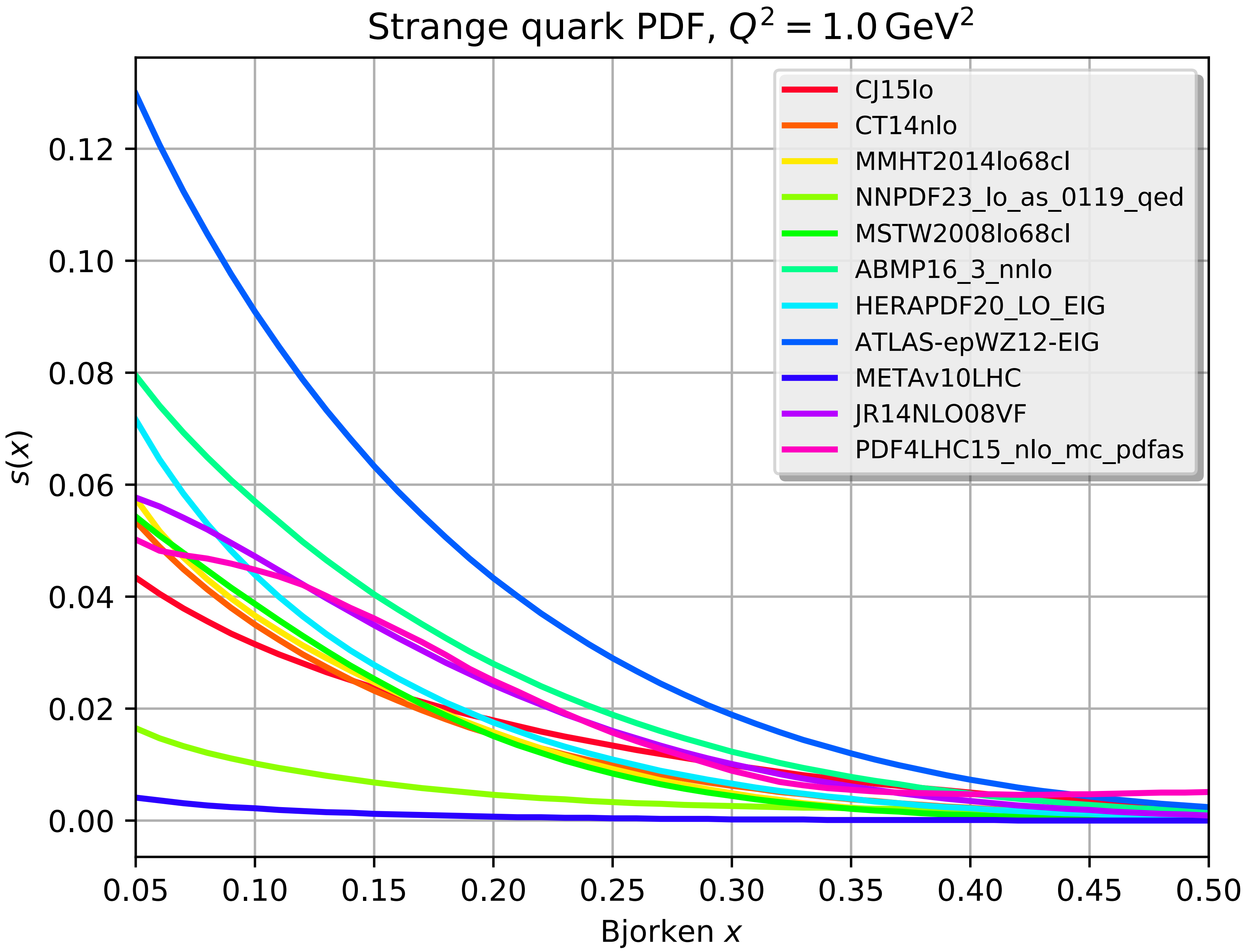
Nucleons in the initial state: Parton Distribution Functions

Process	Reaction	Subprocess	PDFs probed	x
	$\ell^\pm\{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.1$
	$e^\pm p \to jet(s) + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
	$\overrightarrow{\ell}^\pm\{\overrightarrow{p}, \overrightarrow{d}, \overrightarrow{n}\} \to \ell^\pm + X$	$\gamma^* q \to q$	$\Delta q + \Delta\bar{q}, \Delta g$	$0.003 \lesssim x \lesssim 0.8$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$p\bar{p}(pp) \to jet(s) + X$	$gg, qg, qq \to 2jets$	g, q	$0.005 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm\nu) + X$	$ud \to W^+$, $\bar{u}\bar{d} \to W^-$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$pp \to (W^\pm \to \ell^\pm\nu) + X$	$u\bar{d} \to W^+$, $d\bar{u} \to W^-$	$u, d, \bar{u}, \bar{d}, (g)$	$x \gtrsim 0.001$
	$p\bar{p}(pp) \to (Z \to \ell^+\ell^-) + X$	$uu, dd(u\bar{u}, d\bar{d}) \to Z$	$u, d(g)$	$x \gtrsim 0.001$
	$pp \to (W + c) + X$	$gs \to W^- c$, $g\bar{s} \to W^+\bar{c}$	$s, \bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \sim 0.01$
	$\overrightarrow{p} p \to W^\pm + X$	$u_L\bar{d}_R \to W^+$, $d_L\bar{u}_R \to W^-$	$\Delta u\ \Delta\bar{u}\ \Delta d\ \Delta\bar{d}$	$0.05 \lesssim x \lesssim 0.4$
	$\overrightarrow{p}\overrightarrow{p} \to \pi + X$	$gg \to qg$, $qg \to qg$	Δg	$0.05 \lesssim x \lesssim 0.4$
	$\overrightarrow{\ell}^\pm\{\overrightarrow{p}, \overrightarrow{d}\} \to \ell^\pm h + X$	$\gamma^* q \to q$	$\Delta u\ \Delta\bar{u}\ \Delta d\ \Delta\bar{d}$ Δg	$0.005 \lesssim x \lesssim 0.5$
	$\overrightarrow{\ell}^\pm\{\overrightarrow{p}, \overrightarrow{d}\} \to \ell^\pm D + X$	$\gamma^* g \to c\bar{c}$	Δg	$0.06 \lesssim x \lesssim 0.2$

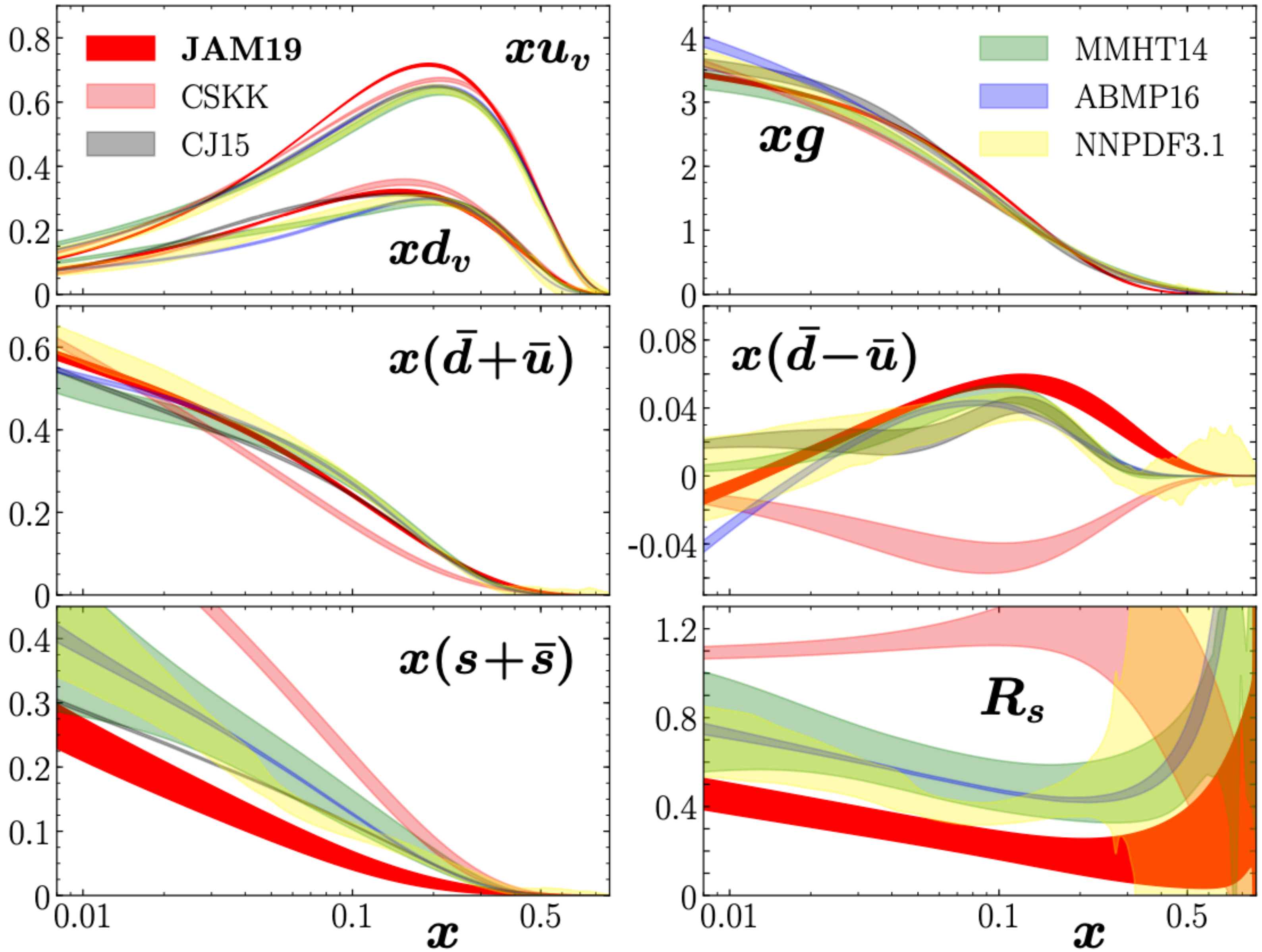
Strange PDF

Various extractions differ by more than and order of magnitude
Many fits not focusing on strange contribution

Results depend on parameterizations and assumptions in global fit.



Knowledge of PDFs

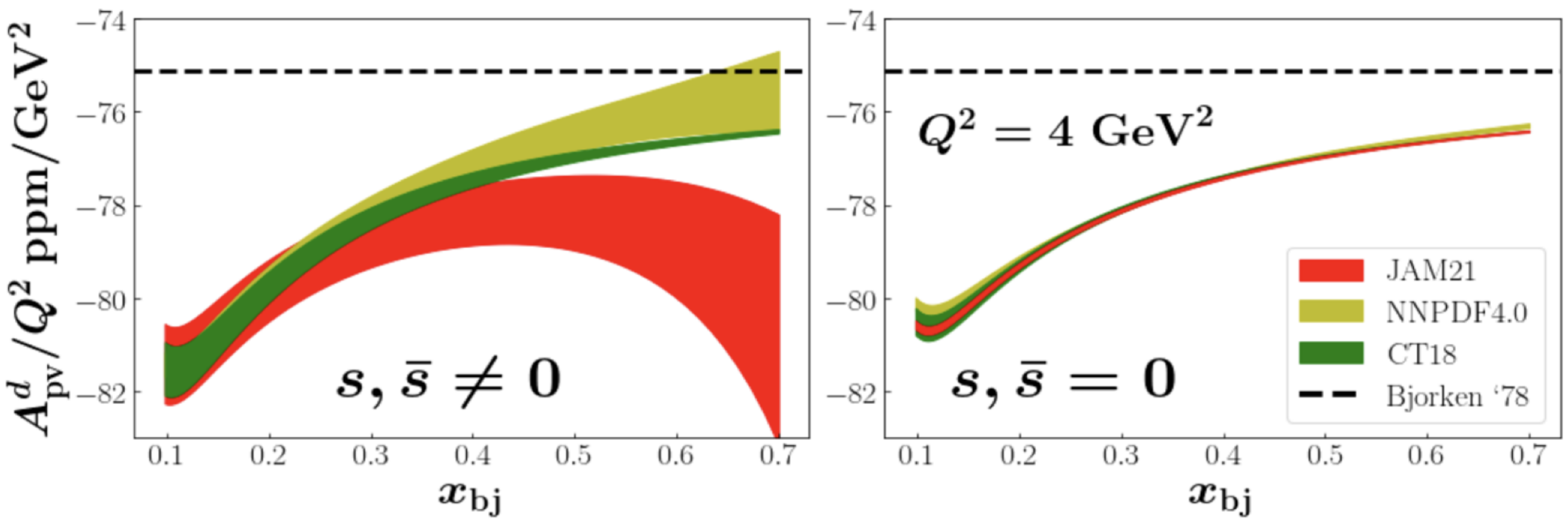


Strange quark uncertainties largest

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

"Strange quark suppression"
Size of strange

Compare PV asymmetry with and without strange quarks.



Parity violating electron scattering

usually small

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\mathrm{em}}}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

$$a_2(x) = -2\,g_A^e\,\frac{F_2^{\gamma Z}(x)}{F_2^{\gamma}(x)} = \frac{2\sum_q e_q g_V^q\, q^+(x)}{\sum_q e_q^2\, q^+(x)}$$

$$a_3(x) = -2\,g_V^e\,\frac{F_3^{\gamma Z}(x)}{F_2^{\gamma}(x)} = -4\,g_V^e\,\frac{\sum_q e_q\, g_A^q\, q^-(x)}{\sum_q e_q^2\; q^+(x)}$$

$$g_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W$$

$$g_V^d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$$

$$g_A^e = -\frac{1}{2}$$

$$g_V^e = -\frac{1}{2} + 2\sin^2\theta_W$$

$$g_A^u = -\,g_A^d = \frac{1}{2}$$

$$q^+(x) = q(x) + \bar{q}(x)$$

$$q^-(x) = q(x) - \bar{q}(x)$$

Brady, PHYSICAL REVIEW D 84, 074008 (2011)

Isolating the 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 in QCD

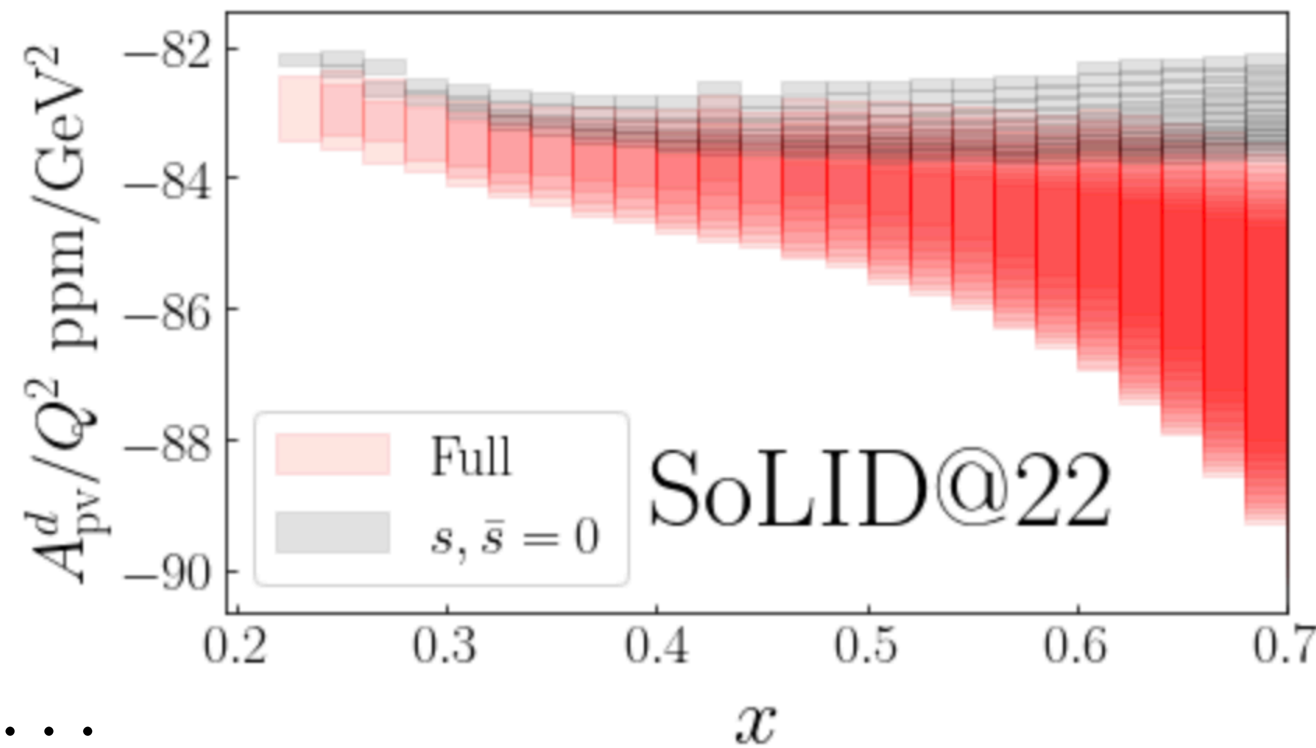
$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

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

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

$$+(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W)x(d+\bar{d}+s+\bar{s}) + \cdots$$

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



Compare PV asymmetry with and without strange quarks for SOLID kinematics in JAM framework.

3 equations with 3 unknowns

$$s+\bar{s} = 3(5F_2^{\gamma Zp} - F_2^{\gamma p} - F_2^{\gamma n})$$

Parity violating electron scattering

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\mathrm{em}}}\left[a_2(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

Beam energy dependence gives access to $a_3(x)$

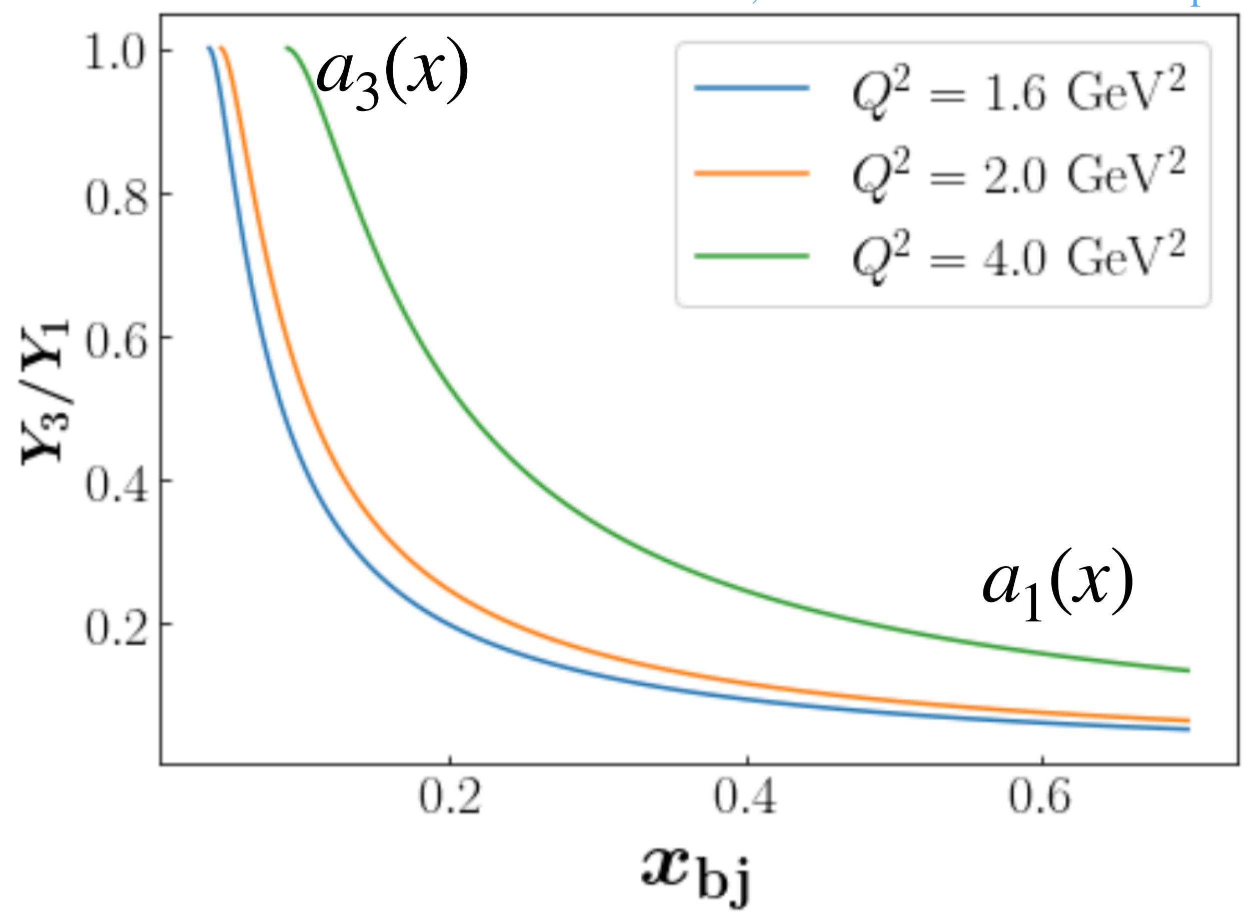
$$a_2(x) = -2\,g_A^e\,\frac{F_2^{\gamma Z}(x)}{F_2^{\gamma}(x)} = \frac{2\sum_q e_q\,g_V^q\,q^+(x)}{\sum_q e_q^2\;q^+(x)}$$

$$a_3(x) = -2\,g_V^e\,\frac{F_3^{\gamma Z}(x)}{F_2^{\gamma}(x)} = -4\,g_V^e\,\frac{\sum_q e_q\,g_A^q\,q^-(x)}{\sum_q e_q^2\;q^+(x)}$$

$$q^+(x) = q(x) + \bar{q}(x)$$
$$q^-(x) = q(x) - \bar{q}(x)$$

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

Sato, Science at Mid x Workshop



Not a new idea!

SLAC-PROPOSAL E149 *bis*
May 4, 1993

DIS-PARITY

Parity Violation in Deep Inelastic Electron Scattering

R. G. Arnold, P. E. Bosted (spokesman), S. E. Rock, Z. M. Szalata, J. L. White
The American University, Washington D.C. 20016

P. Degtyarenko, S. Shuvalov
Institute for Theoretical and Experimental Physics, Moscow, Russia

L. Elouadrhiri, R. S. Hicks, R. A. Miskimen,
G. A. Peterson, J. Button-Shafer, K. Wang
University of Massachusetts, Amherst, MA 01003

T. E. Chupp
University of Michigan, Ann Arbor, MI 48109

A. K. Thompson
N.I.S.T., Gaithersburg, Md 20899

S. Kuhn
Old Dominion University, Norfolk, VA 23529

K. Griffioen
University of Pennsylvania, Philadelphia, PA 19104

P. Decowski
Smith College, Northampton, MA 01063

R. Gearhart, S. Rokni, S. St. Lorant, L. Stuart, M. Woods
Stanford Linear Accelerator, Stanford, CA 94309

D. Day, R. W. Lourie, O. Rondon-Aramayo
University of Virginia, Charlottesville, VA 22901

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ABSTRACT

We propose to measure the parity-violating interference between electromagnetic and weak coupling in deep-inelastic electron scattering from hydrogen and deuterium. The primary physics goals are to test the electro-weak Standard Model and to determine the flavor content of the quark sea. The experiment will determine the Z−quark coupling to an equivalent precision in $\sin^2(\theta_w)$ of approximately 0.003 (1.2%), and will be quite sensitive to the possible existence of certain types of new physics beyond the Standard Model. The experiment will also measure two new combinations of quark distribution functions with errors of about 0.05. The deuterium case is particularly interesting because it directly isolates the strange sea quark contributions.

The experiment consists of scattering polarized electrons from long liquid hydrogen and deuterium targets in End Station A. The scattered electrons are detected in two large solid angle magnetic spectrometers centered around scattering angles of 4.25 and 6.5 degrees for an incident beam energy of 29.1 GeV. At E = 48.6 GeV, the 6.5° spectrometer is moved to 2.75°. The spectrometers are entirely made up of existing magnets. The detectors consist primarily of lead glass arrays that can be made from the surplus ASP pieces. The beam is required to have a polarization of 80% or more, and high current (4×10^{11} e^- per beam pulse at 120 Hz non-SLED, 2×10^{11} SLED). The combination of higher beam polarization, higher beam energy, and larger spectrometer solid angle provides a factor of eight greater sensitivity than the original SLAC experiment on deuterium. The addition of hydrogen allows more sensitive studies of the flavor content of the quark sea.

A total of twelve weeks of running time is requested for an initial run at 29.1 GeV, of which one third will be used for checkout, calibrations, and background studies, and two thirds for data taking. A subsequent run of ten weeks at 48.6 GeV is also requested. In a relatively modest running time, this experiment will provide significantly improved precision on electroweak physics at low Q^2 and on the flavor content of the quark sea. We emphasize that this experiment can only be undertaken at SLAC.

Experimental Overview

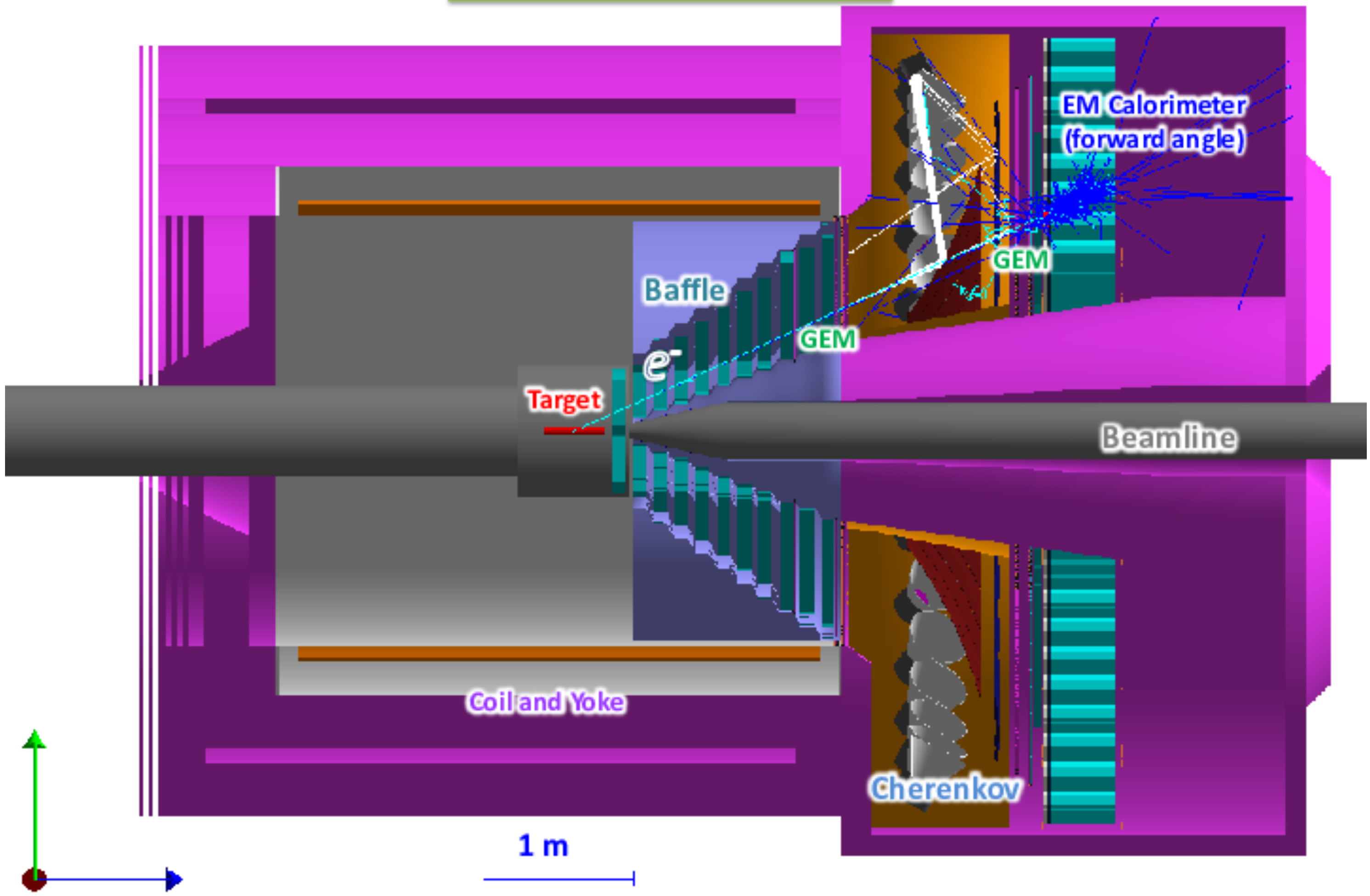
Beam: 40 uA @ 22 GeV.
40 cm liquid H_2 or D_2
100 days of running

Luminosity (instantaneous)
4.3×10^{38} cm^{-2}s^{-2}

Luminosity (integrated)
4.5×10^{6} fb^{-1}

cf EIC Yellow Report
proton ~ 100 fb^{-1}
deuteron ~ 10 fb^{-1}

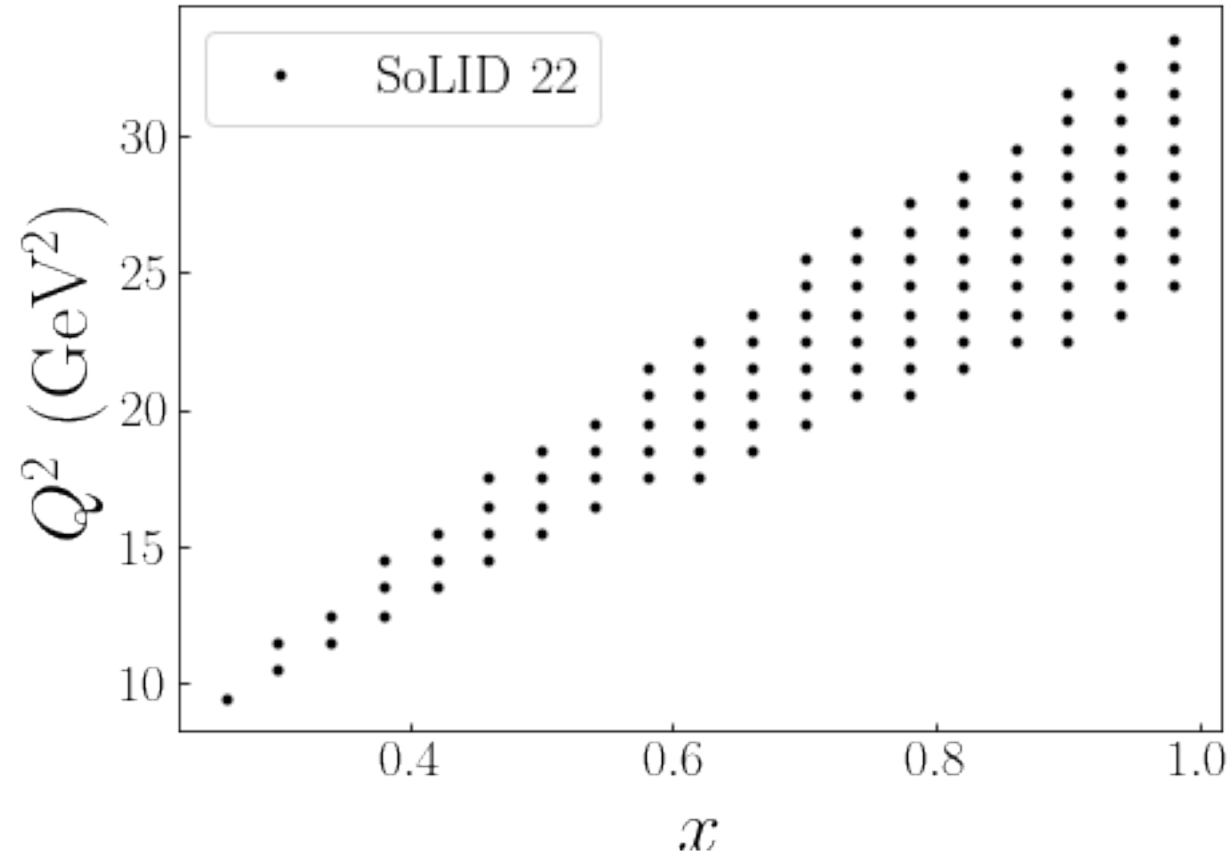
SoLID (PVDIS)



SoLID spectrometer and detectors optimized for PVDIS experiment:
high luminosity, small systematics, polarimetry, beam quality and control

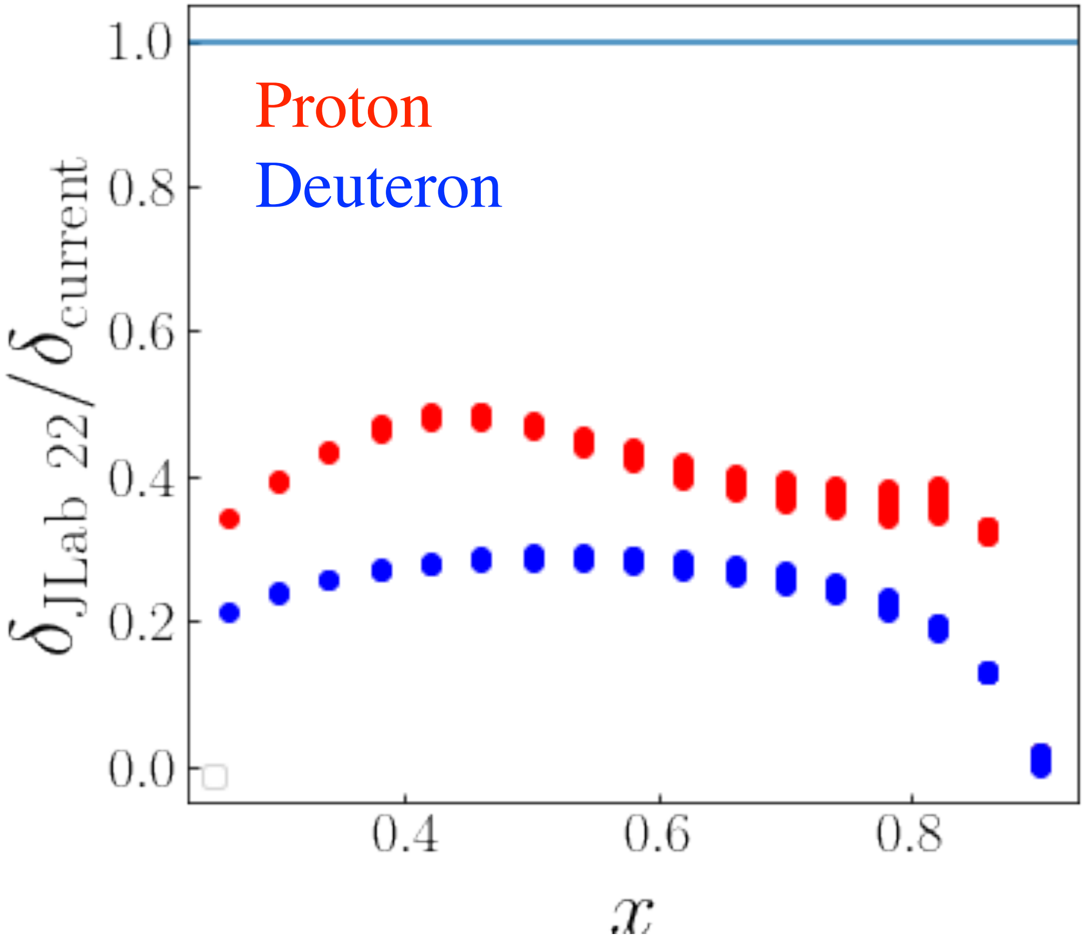
The only place in the world where this is possible.

SoLID 22 GeV

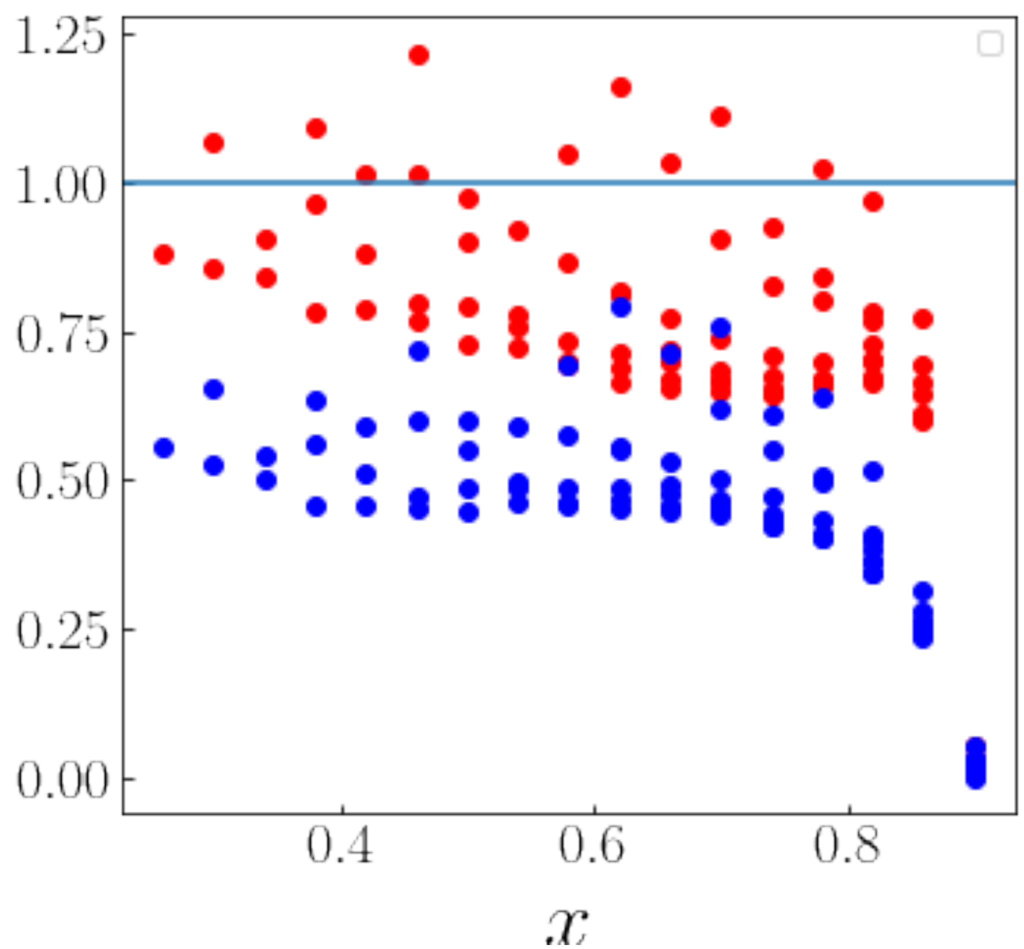


Ratio of statistical uncertainties to current PDF uncertainties (JAM) on APV.

100% acceptance



SoLID acceptance



The only place in the world where this is possible.

Corrections and Interpretation

Target Mass Corrections

$$\propto \frac{M^2}{Q^2}$$ ✓

Implemented in some PDF extractions

Higher Twist Corrections

non-pert. parton correlations

✓ $$\propto \frac{\Lambda^2}{Q^2} \qquad \Lambda \sim 0.1 - 1\text{GeV}$$

Implemented in some PDF extractions

Nuclear Corrections ?

binding, Fermi motion, off-shellness
calculations are largely model-dependent

QED

Recent recognition of this issue.
New formalism to include effects in global fit. ✓

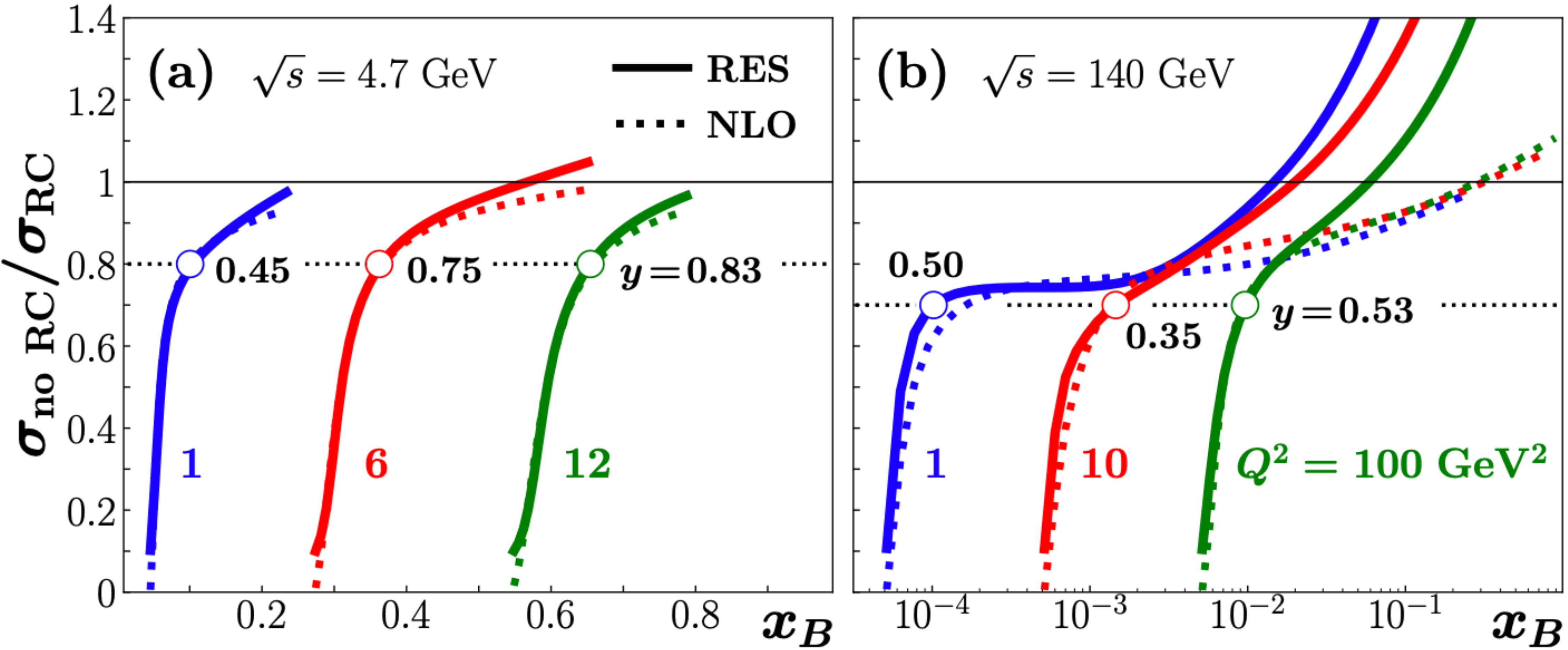
Final State Interactions

Inclusive ✓

Interpretation - QED effects

QED "corrections" depend on the input hadronic tensor
Not possible to construct model-independent QED RC corrections
Need to include QED in global analysis

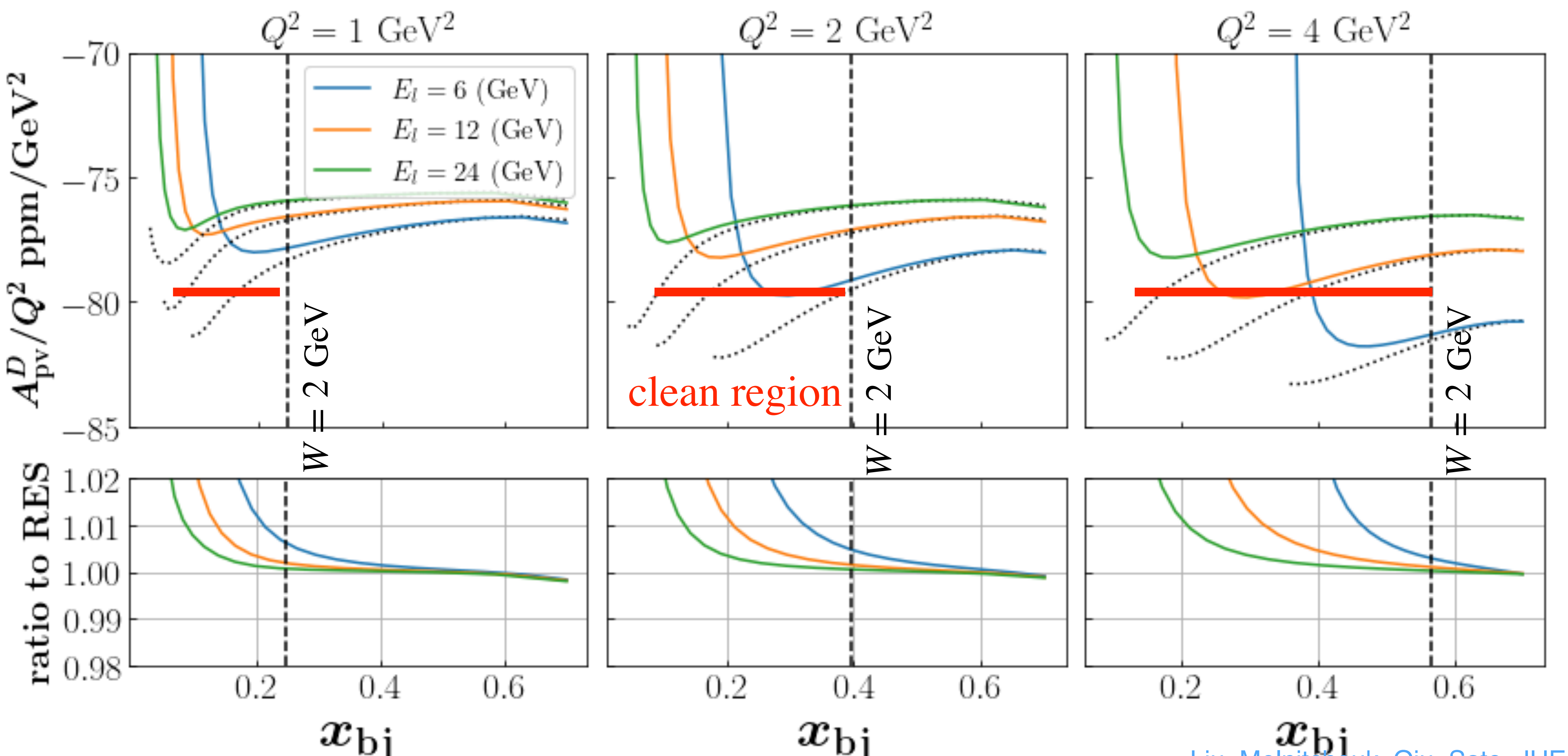
Size of RCs quickly become extremely large at small x



Liu, Melnitchouk, Qiu, Sato, JHEP11(2021)157
Liu, Melnitchouk, Qiu, Sato, PHYSICAL REVIEW D 104, 094033 (2021)

Interpretation - QED effects

RCs quickly become extremely large at small x, resonance region begins at higher x.
Limits range of useful data
Higher beam energy and higher Q^2 help a lot.



Liu, Melnitchouk, Qiu, Sato, JHEP11(2021)157
Liu, Melnitchouk, Qiu, Sato, PHYSICAL REVIEW D 104, 094033 (2021)

Summary

Strange PDF is the least well known

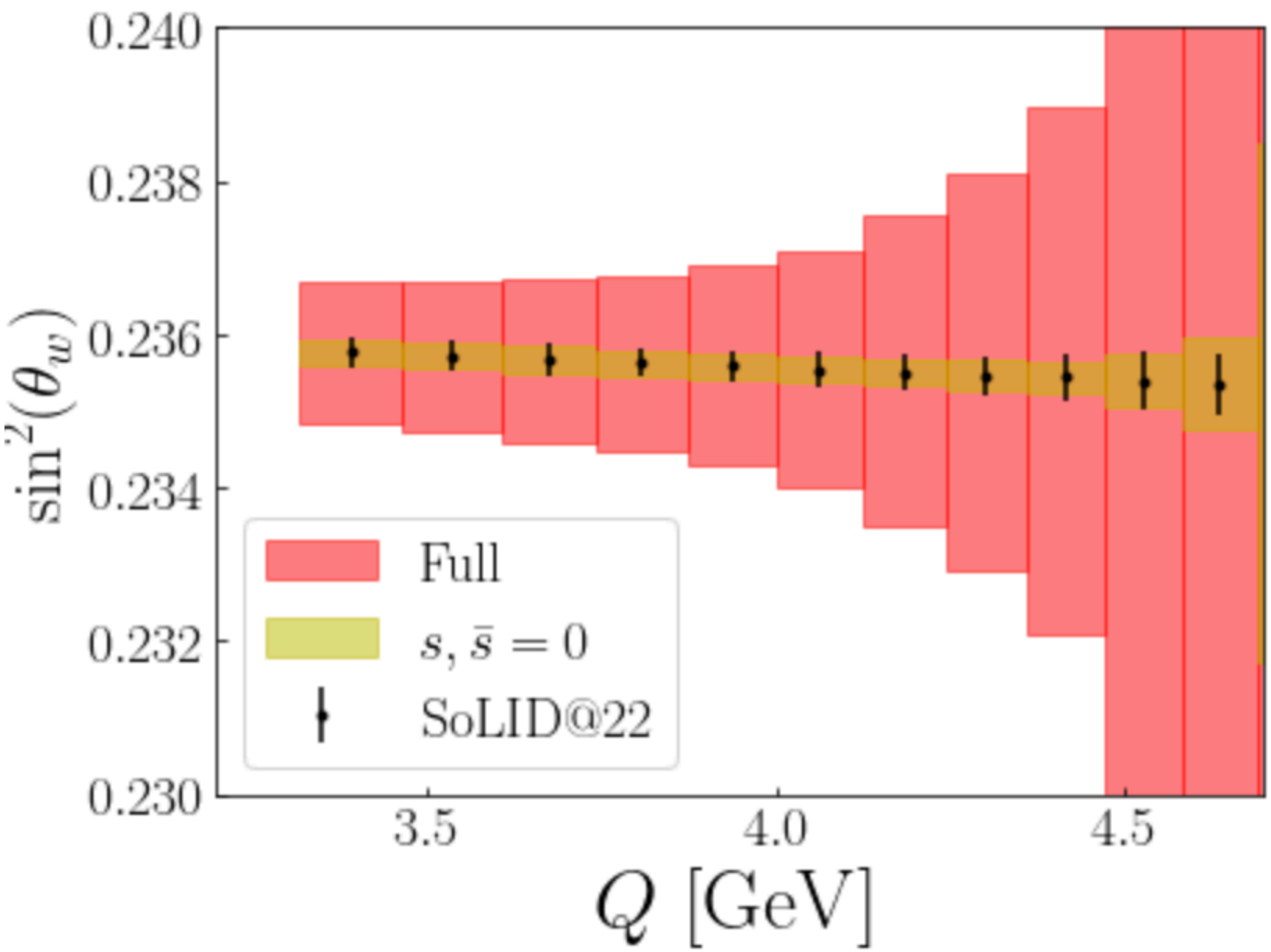
Parity Violating DIS provides a unique new combination of PDFs and has much greater sensitivity to the strange

SoLID @ 22 GeV with 100 days can provide a very strong constraint on $s + \bar{s}$.

The interpretation of data is easier at higher energies and Q^2.

Extras

Connection to $\sin^2\theta_W$



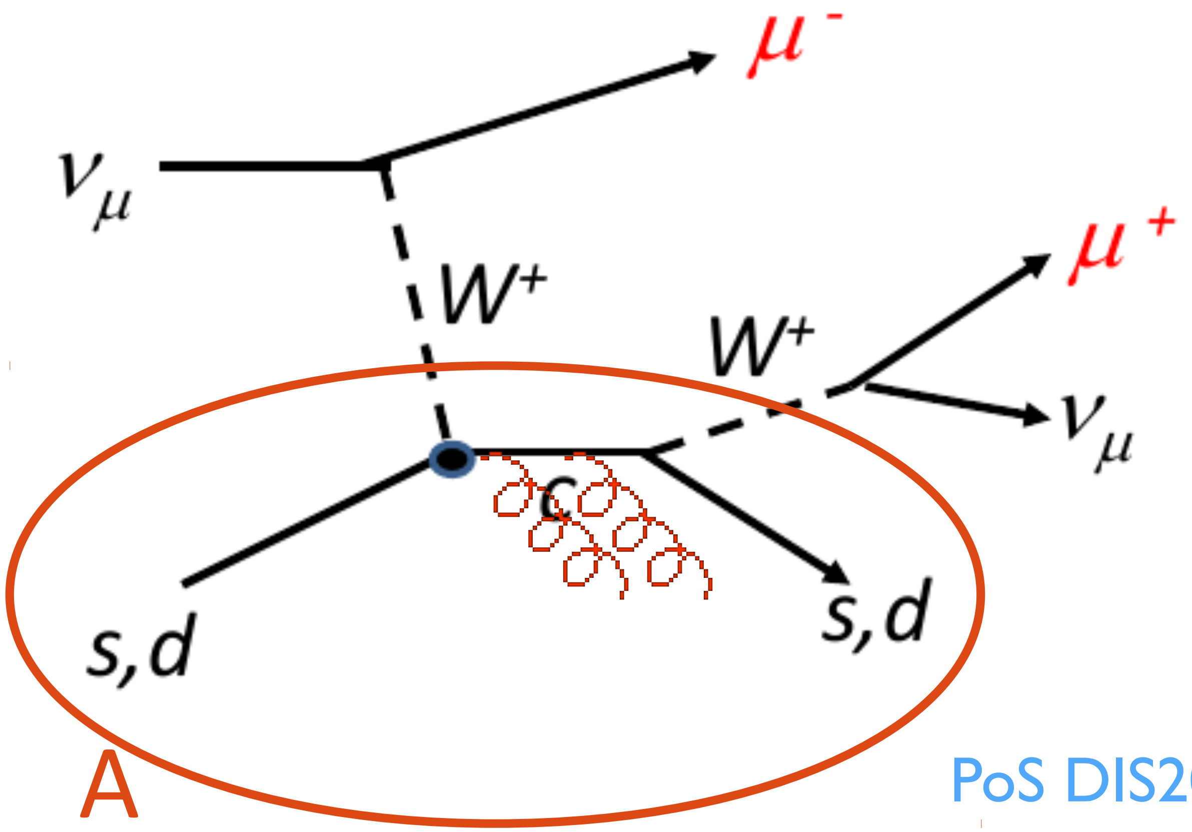
Accessing Strange Quarks

- di-muon production in neutrino-nucleus scattering $0.01 < x < 0.2$
- W and Z rapidity distributions $x >\sim 0.001$
- LHC W+c production $x \sim 0.01$
- Semi-inclusive K production: $0.02 < x < 0.6$
  not included in global fits (fragmentation)
- Parity Violating electron scattering $0.1 < x < 0.5$

It's still not clear whether the strange sea is as big as the up and down sea (k ~ 1) or half as big (k ~ 0.5)

$$k = \frac{2s}{(\bar{u} + \bar{d})}$$

Neutrino nucleus



PoS DIS2015 (2015) 001

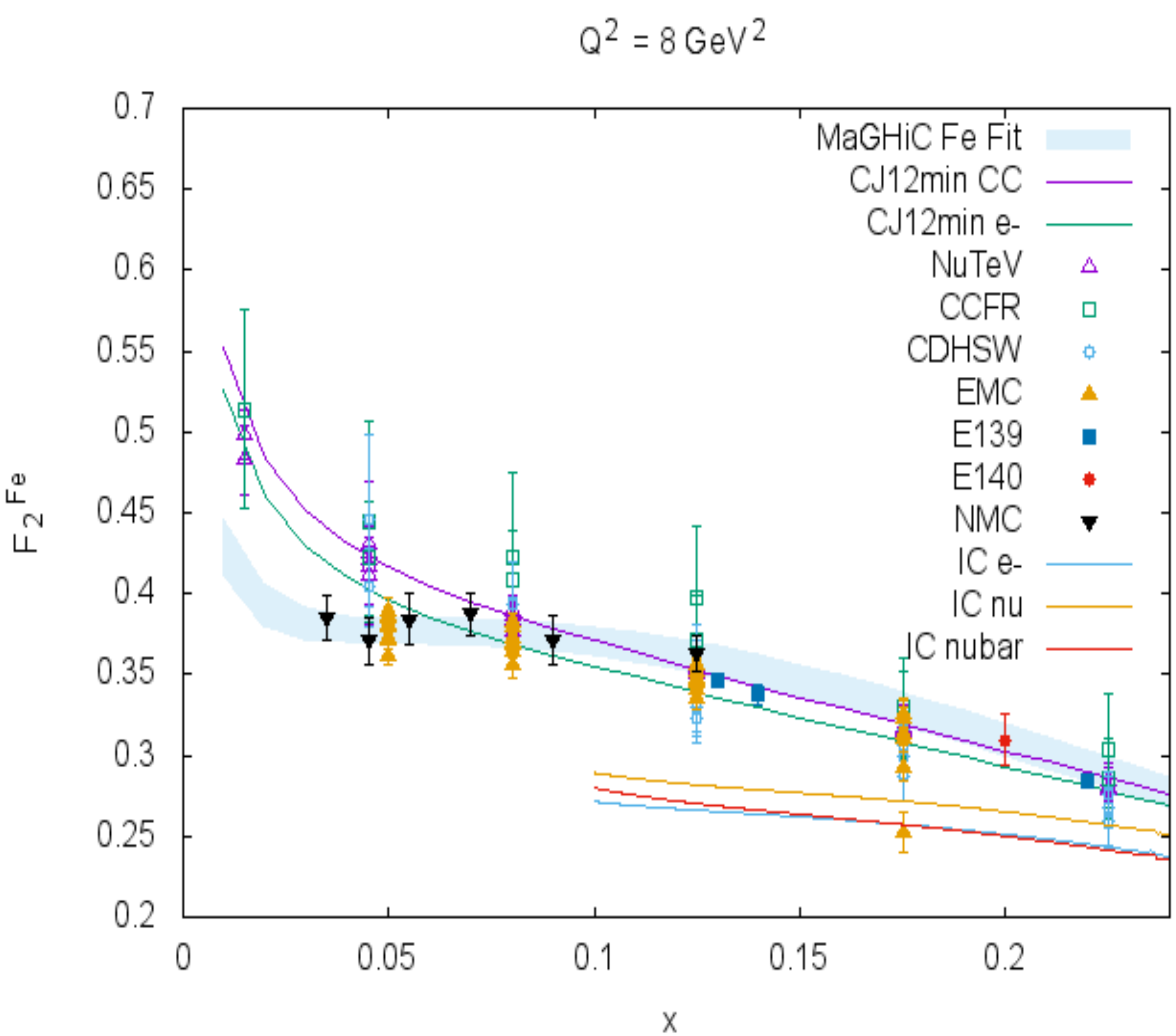
di-muon production in neutrino-nucleus scattering tags strangeness

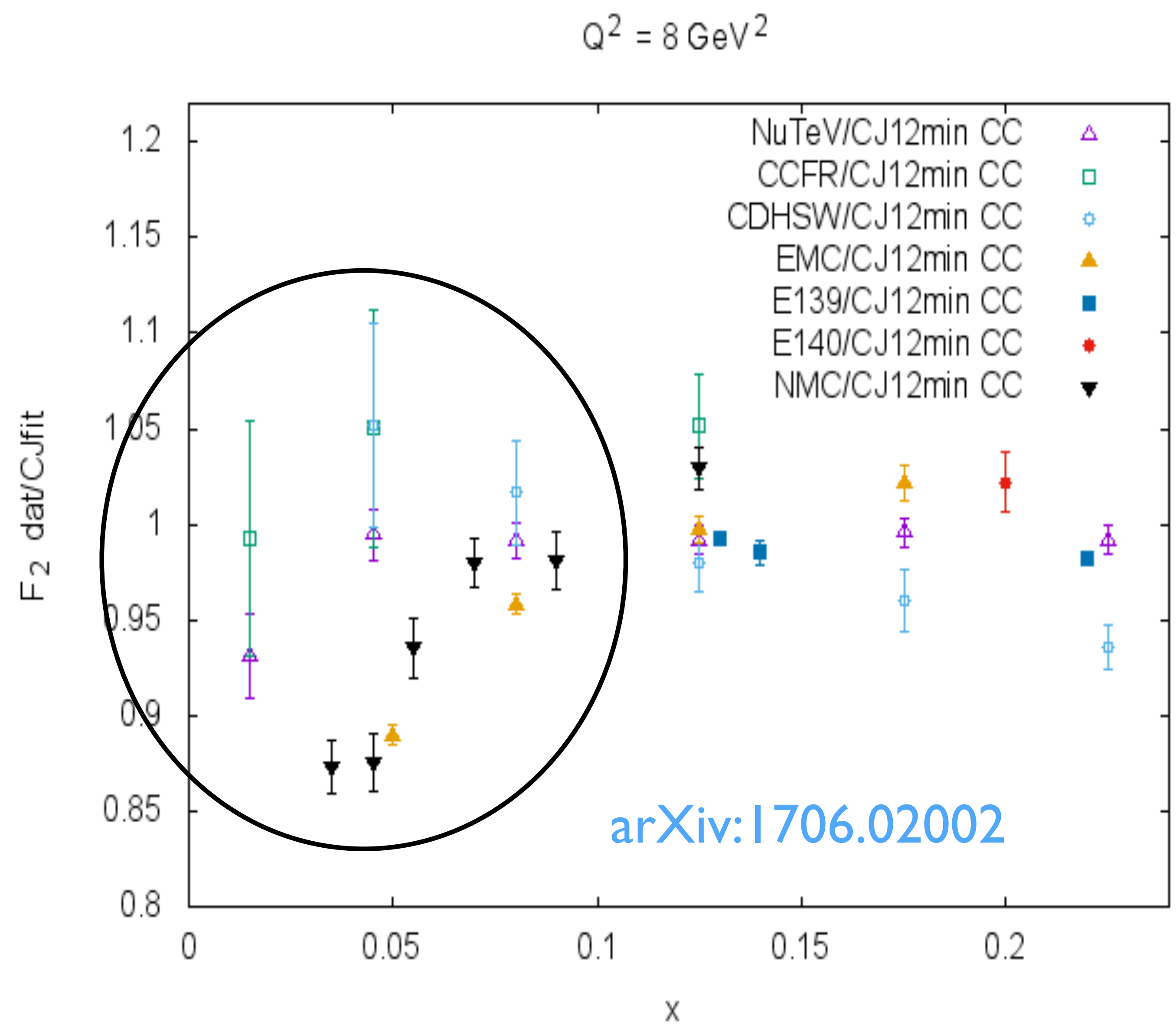
k ≈ 0.4

- initial state nuclear modifications of the PDFs themselves (partly under control—nuclear PDF fits)
- final state interactions
  - medium-induced gluon bremsstrahlung;
  - final state suppression of charm production (measured at RHIC significantly larger than perturbative calculations for QGP)

Neutrino nucleus

Neutrino and electron scattering data from iron do not agree below x~0.1
Sensitive to different nuclear effects?

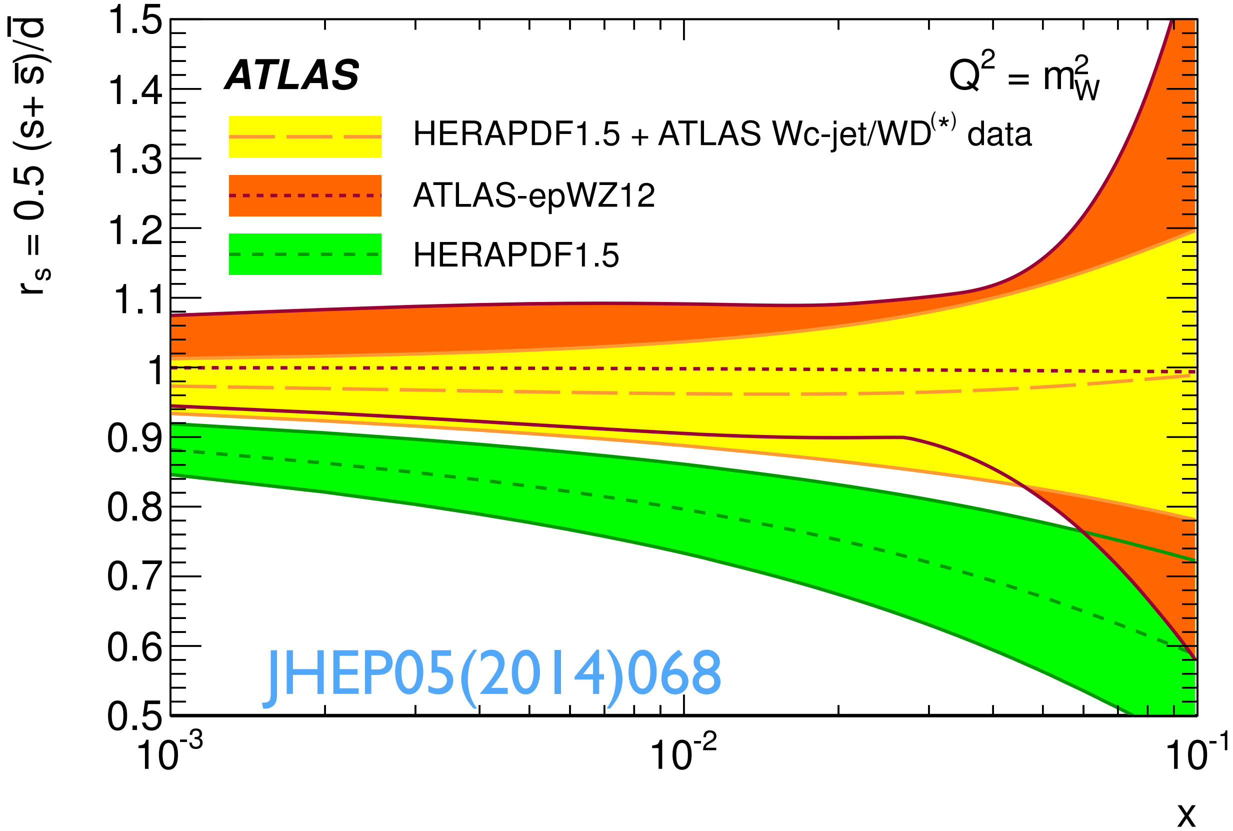




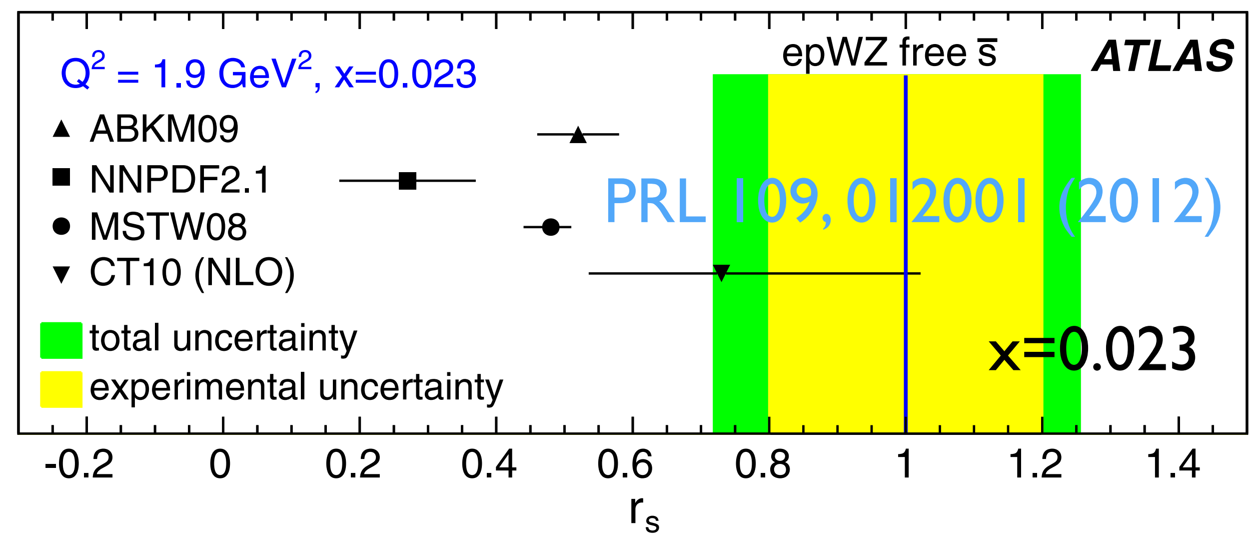
Proton — proton

ATLAS fits get k≈1 using collider only data

$$pp \to (W + c) + X$$

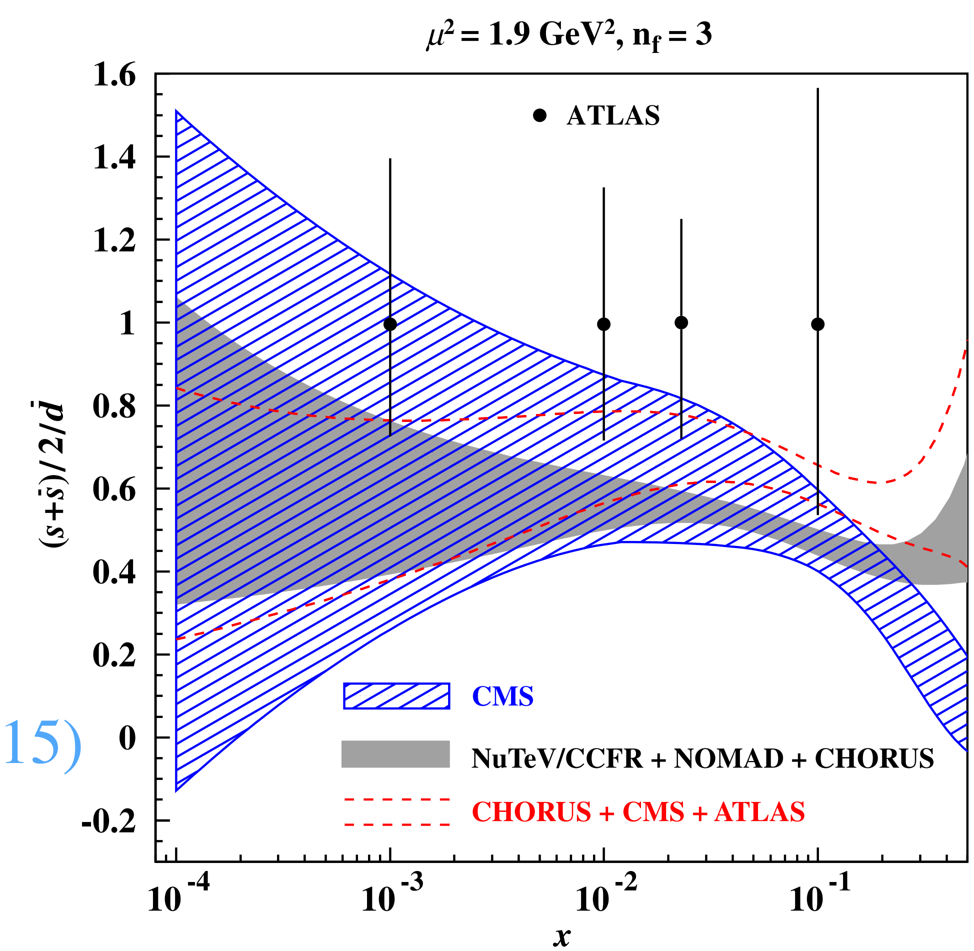


$$pp \to (W^{\pm} \to l^{\pm} + \nu, Z \to l^{+}l^{-}) + X$$



Quoted uncertainties depend on assumptions

$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$



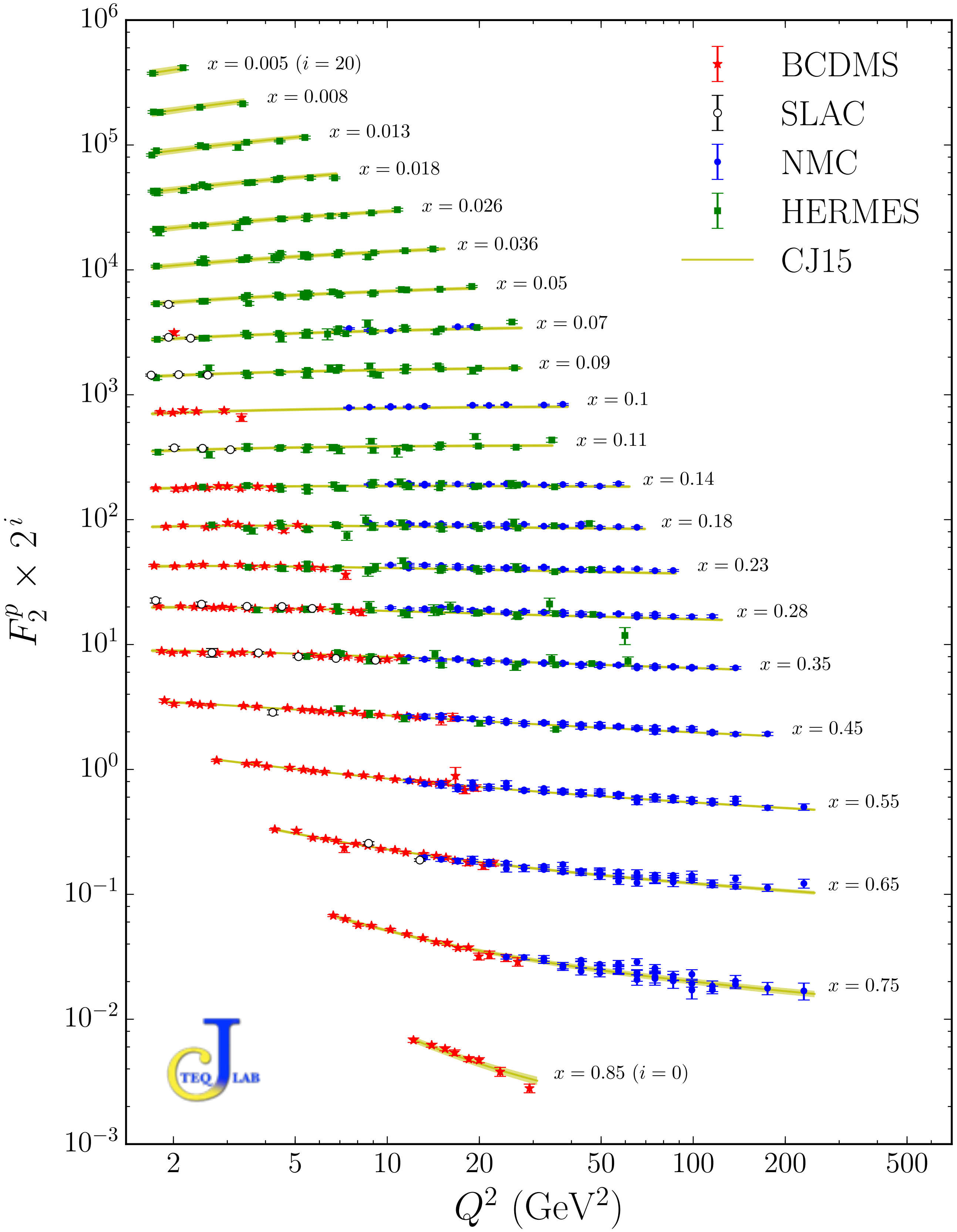
Tension with neutrino nucleus results

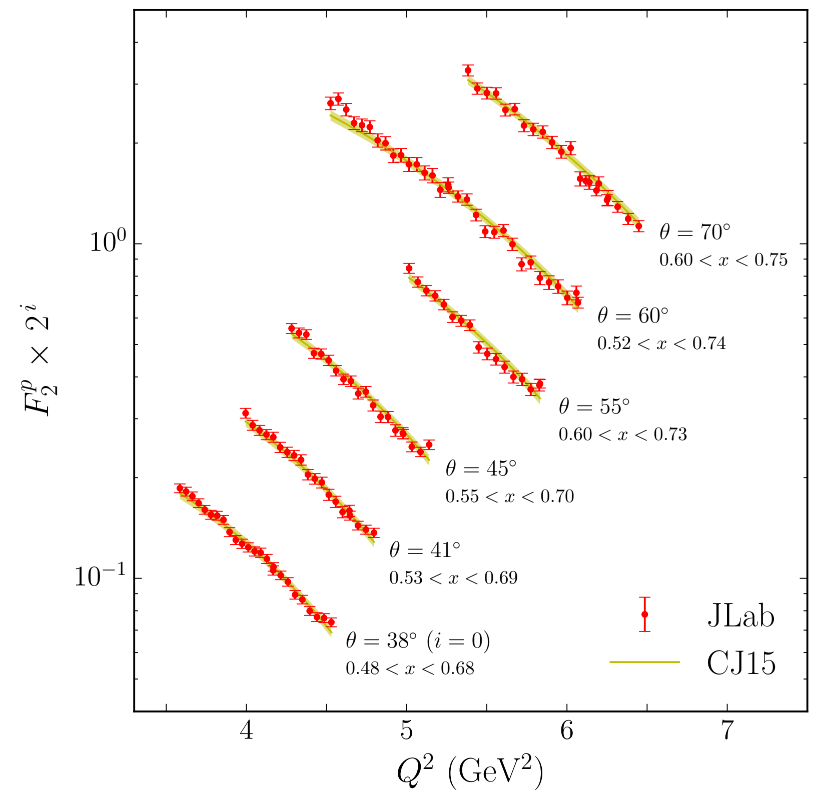
d distribution might be underestimated in collider-only fits.

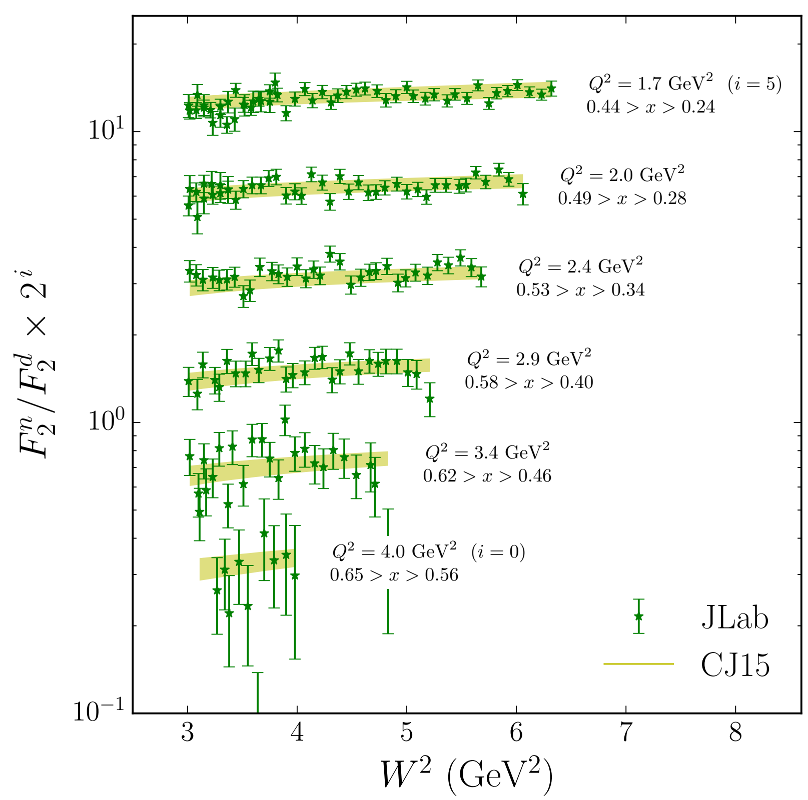
PRD 91, 094002 (2015)

Comparing data will expose final state effects

Proton F_2







Excellent description over orders of magnitude in x and Q^2

PhysRevD.93.114017 (2016)

SoLID acceptance