Probing CSV with Deuteron Beams at the EIC

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Electroweak and BSM physics at the EIC, CFNS workshop May 7- 8, 2020

Charge Symmetry (CS) is a form of Iso-spin Symmetry (IS)

CS operation is a isospin rotation by 180^0 about the "2" axis (y-axis)

Isospin describes protons and neutrons as two states of one particle the "nucleon" (analogous to spin).

The strong force is isospin independent

(invariant under all rotations in isospin space)

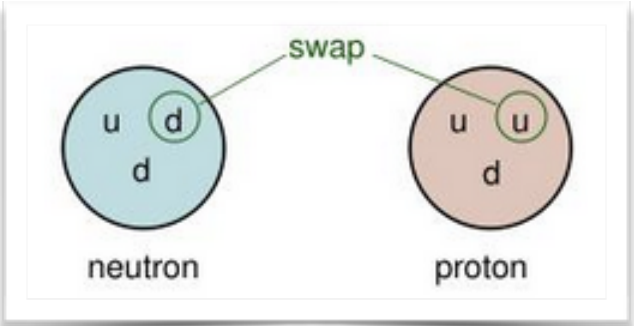
IS is a stronger symmetry than CS

CS $\Rightarrow$ protons & neutrons have same properties

(in the nucleon-meson picture CS operator swaps n-p)

In terms of the quarks and gluons of QCD

CS interchanges up and down quarks $P_{cs}|d\rangle = |u\rangle$, $P_{cs}|u\rangle = -|d\rangle$



assuming equal mass up-down quarks

(strong processes do not depend on the swap of up-down quarks)

$$\Rightarrow u^p(x,Q^2) = d^n(x,Q^2),\ d^p(x,Q^2) = u^n(x,Q^2),\ s^p(x,Q^2) = s^n(x,Q^2)\ \ldots\ldots$$

At low energies there are several direct measurements of charge symmetry and its violation (CSV).

CS appears broken at the level <1%

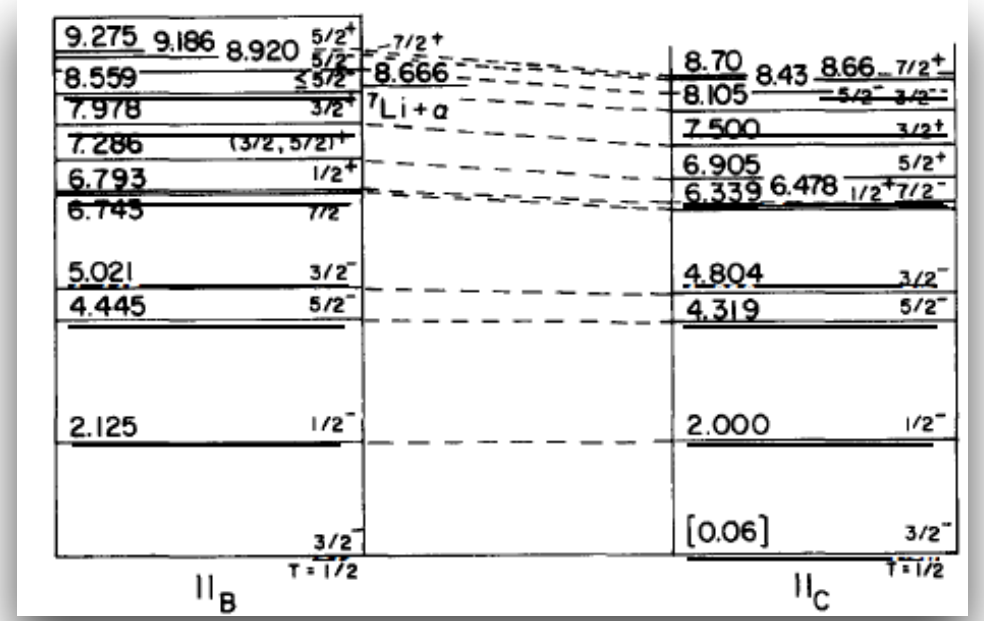
mass splitting within isospin multiplets of particles and nuclei

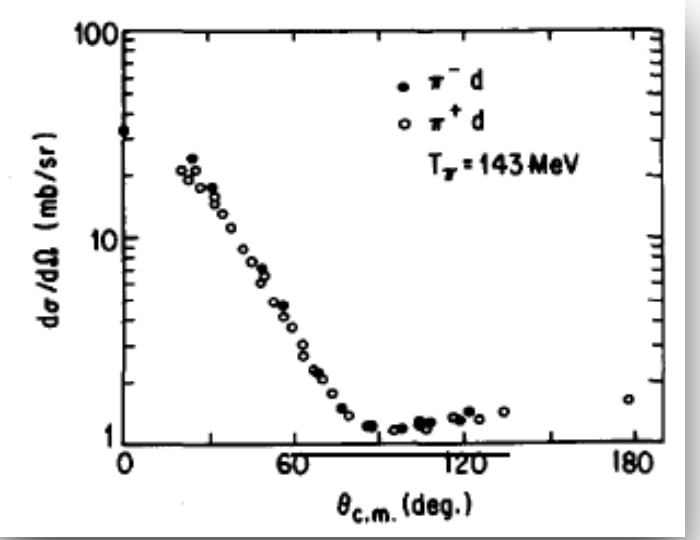
$m_p = m_n$ (to 1%)

***pp* and *nn* scattering lengths are equal to within 1%**

Binding energies of ^{3}H and ^{3}He are equal to 1%

Energy levels in mirror nuclei are equal to 1% (corrected for EM interactions)





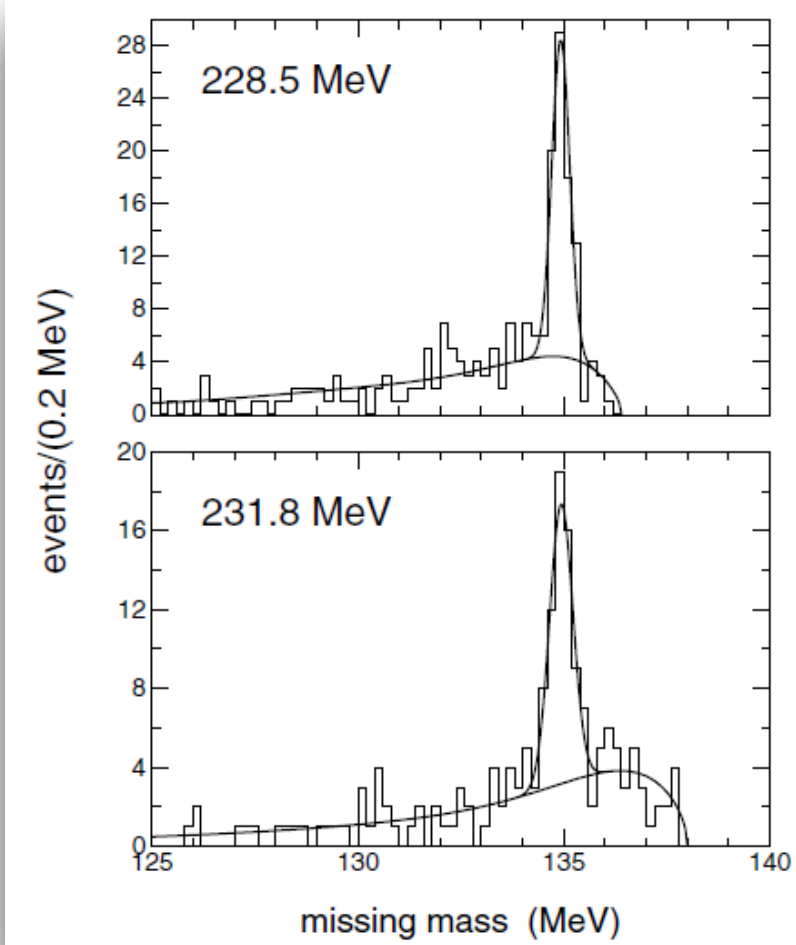
$d\sigma(\pi^+ d \rightarrow \pi^+ d) \approx d\sigma(\pi^- d \rightarrow \pi^- d)$ to 1%

At low energies there are several direct measurements of charge symmetry and its violation (CSV).

CS appears broken at the level <1%

Difference in the analyzing powers $A_n - A_p$ in elastic n-p scattering.

PRL 56, 2571 (1986), PRL 75, 1711 (1995), PRL 66, 1410 (1991)



$d + d \rightarrow {}^4He + \pi^0$

(iso-spin violation & CSV)

PRL 91, 142302 (2003)

$$A_{fb} = [17.2 \pm 8.0(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-4}.$$

Forward-backward asymmetry in $n+p \rightarrow d\,\pi^0$

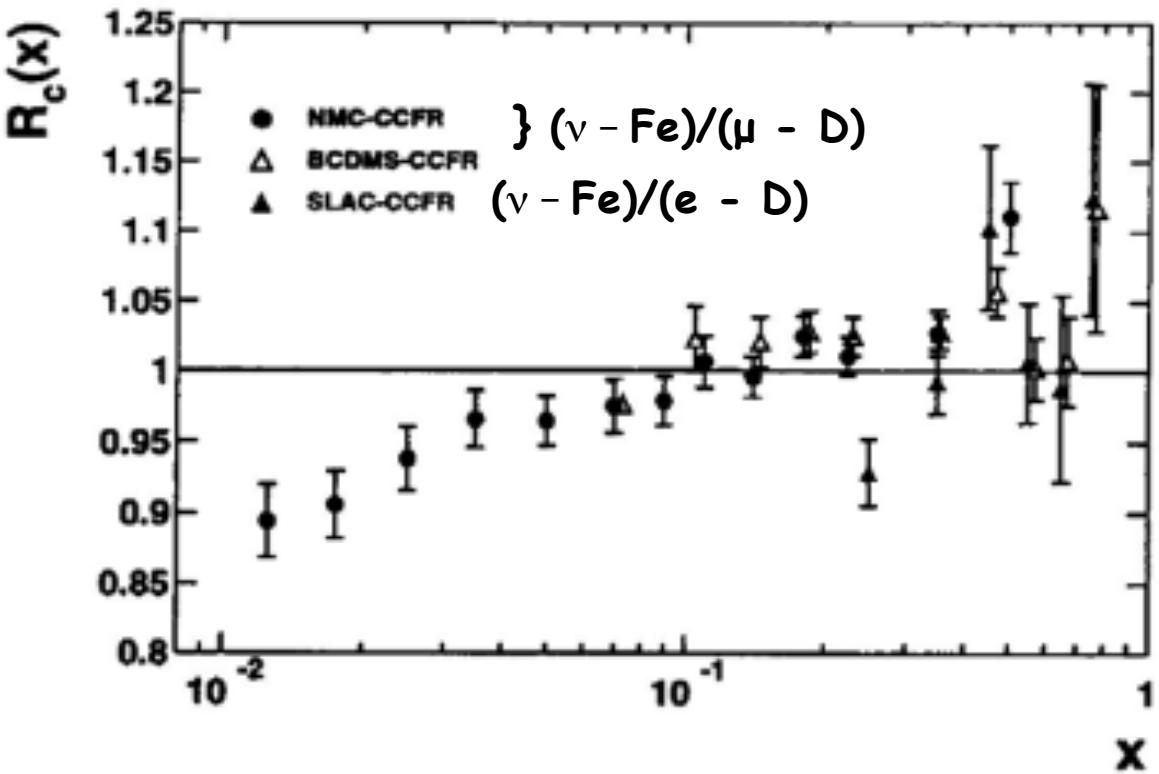
PRL 91 212302 (2003)

At high energies there are no direct measurements of partonic CSV.

Partonic CSV has not been directly observed

We only have upper limits on the magnitude of partonic CSV.

Comparing F_2 structure functions from (ν) vs (e, μ) DIS on N=Z targets



$$R_c(x) \equiv \frac{F_2^{\gamma N_0}(x) + x[s^+(x) + c^+(x)]/6}{5\bar{F}_2^{WN_0}(x)/18},$$

$0.1 \leq x \leq 0.4$:

9% upper limit for CSV effect!

In QCD the only sources of CSV are: mass difference between *u* and *d* quarks and the E&M interaction.

CS interchanges (equal mass) up and down quarks

$P_{cs}|d\rangle = |u\rangle$, $P_{cs}|u\rangle = -|d\rangle$

Naively, one expects that CSV would be of the order of $(m_d - m_u)/\langle M\rangle$

Where $\langle M\rangle$ = 1 GeV ,or a CSV effect of 1%

CSV is related to our understanding of the flavor dependence of the quark masses (one of the key unsolved problems in Physics – why is $m_d \sim m_u \neq m_s \neq m_c \neq m_b \neq m_t$)

CS has been universally assumed in parton distribution functions (PDFs)

this implies

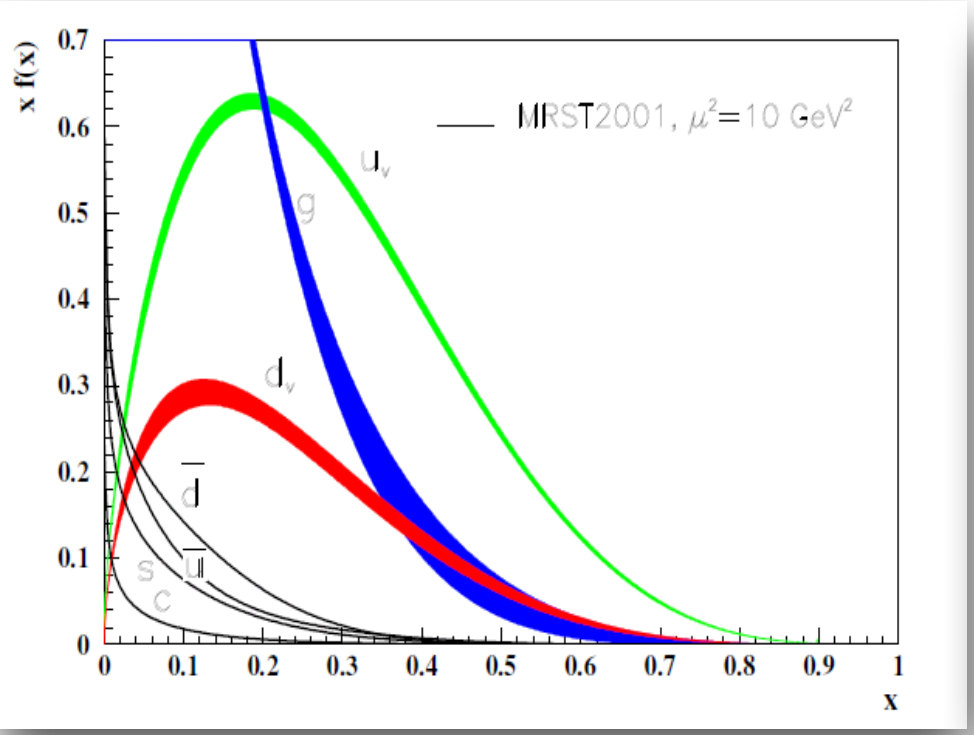
$u^p(x,Q^2) = d^n(x,Q^2)$,

$d^p(x,Q^2) = u^n(x,Q^2)$

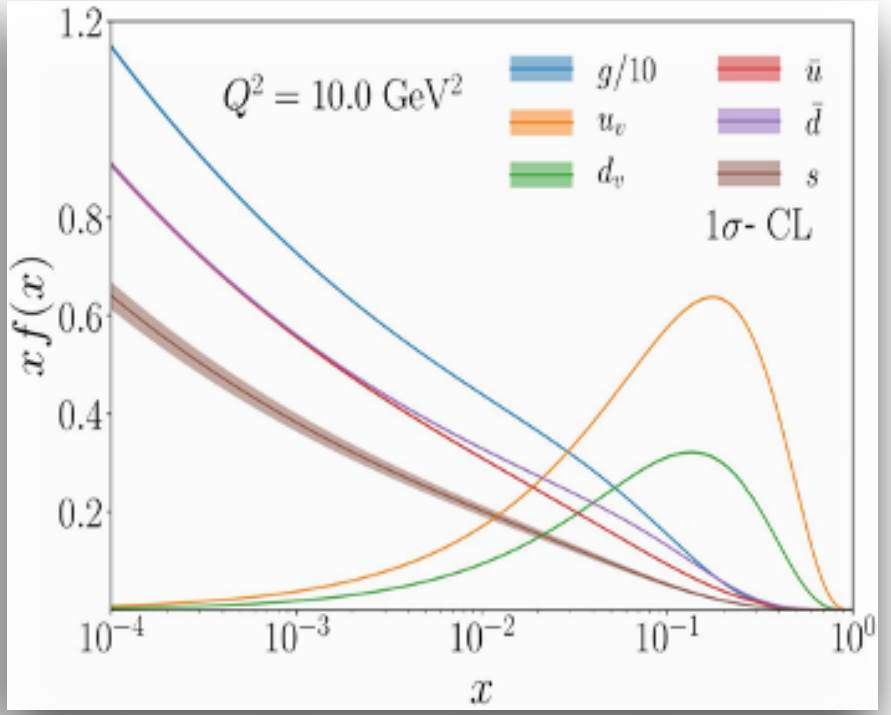
$s^p(x,Q^2) = s^n(x,Q^2)$ .....

Charge symmetry is universally assumed in PDFs extracted from fits to DIS data.

Assumed: $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$, $s^p(x,Q^2) = s^n(x,Q^2)$



A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C28 (2003) 455.



C. Andres, JAM Colaboration-2018 Jlab Users Group Meeting

PDFs extracted from fits to DIS data

The MRST group calculated the limits on CSV from the uncertainties in the PDFs extracted from DIS data.

- CSV parameterization $\delta u_v = -\delta d_v = \kappa(1-x)^4 x^{-0.5}(x-0.0909)$ matches the shape of the PDFs

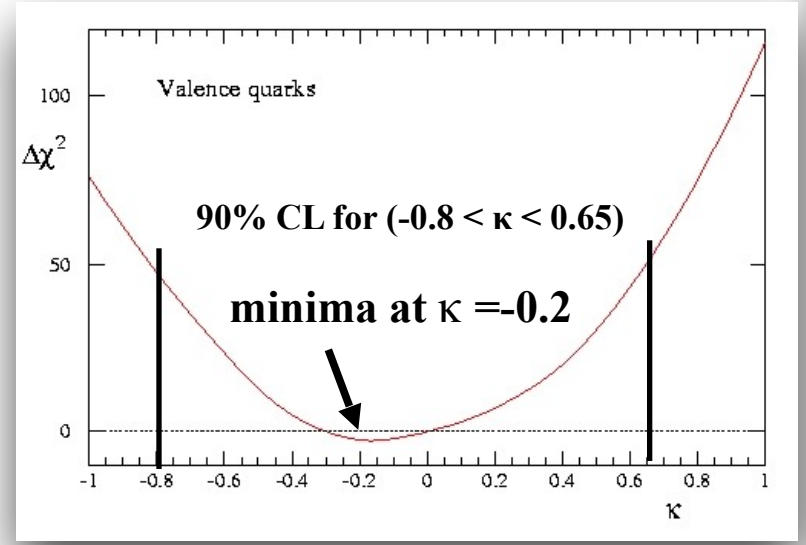
$$\delta d_v(x) = d^p(x) - u^n(x) \text{ and}$$
$$\delta u_v(x) = u^p(x) - d^n(x) \qquad C(x) = \delta d_v - \delta u_v \, (CSV)$$

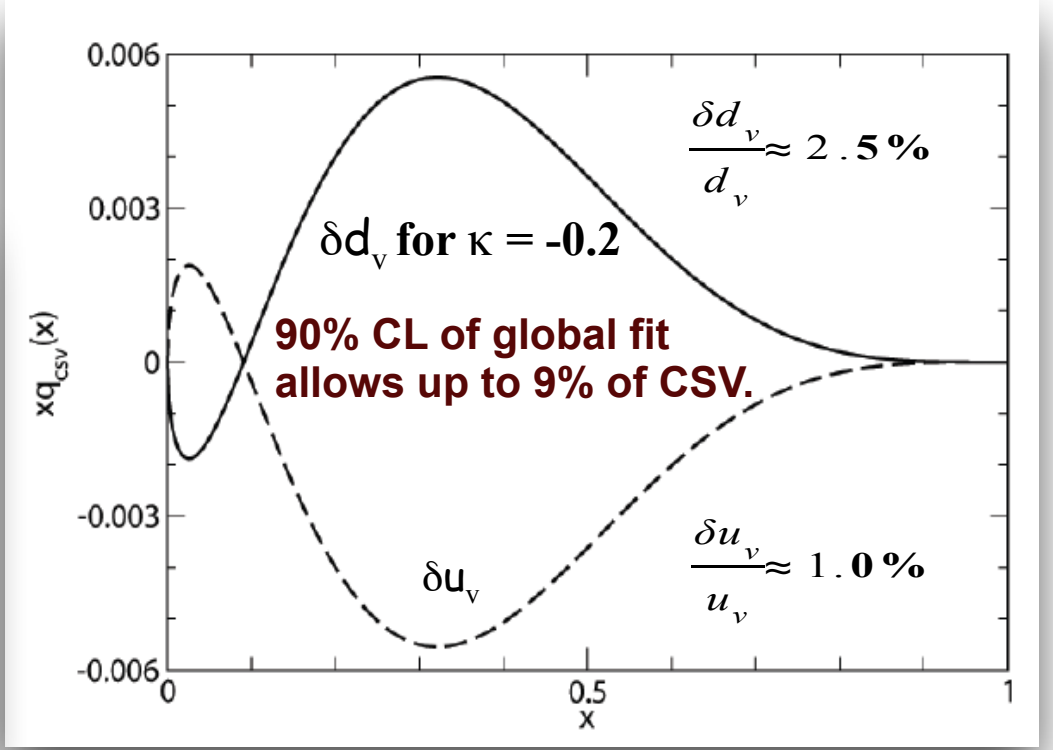
- κ was varied in the global fit: 90% CL obtained for $(-0.8 < \kappa < 0.65)$ minima at $\kappa = -0.2$

(Q^2 dependence of CSV was neglected)

- Must satisfy the normalization condition

$$\int_0^1 dx \delta d_v(x) = \int_0^1 dx \delta u_v(x) = 0$$





A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C28 (2003) 455.

There are also a few models in the market that predict CSV in the PDFs.

$$\delta q_V(x) \approx \frac{\partial q_V}{\partial m}\delta m + \frac{\partial q_V}{\partial M}\delta M$$

quark mass difference

nucleon mass difference

require $\langle \delta q_v \rangle = 0$ (valence quark normalization)

Based on the twist-2 PDF from Adelaide group

❖Model by Sather (PLB274(1992)433):

δd ~ 2-3% and δu ~ 1%

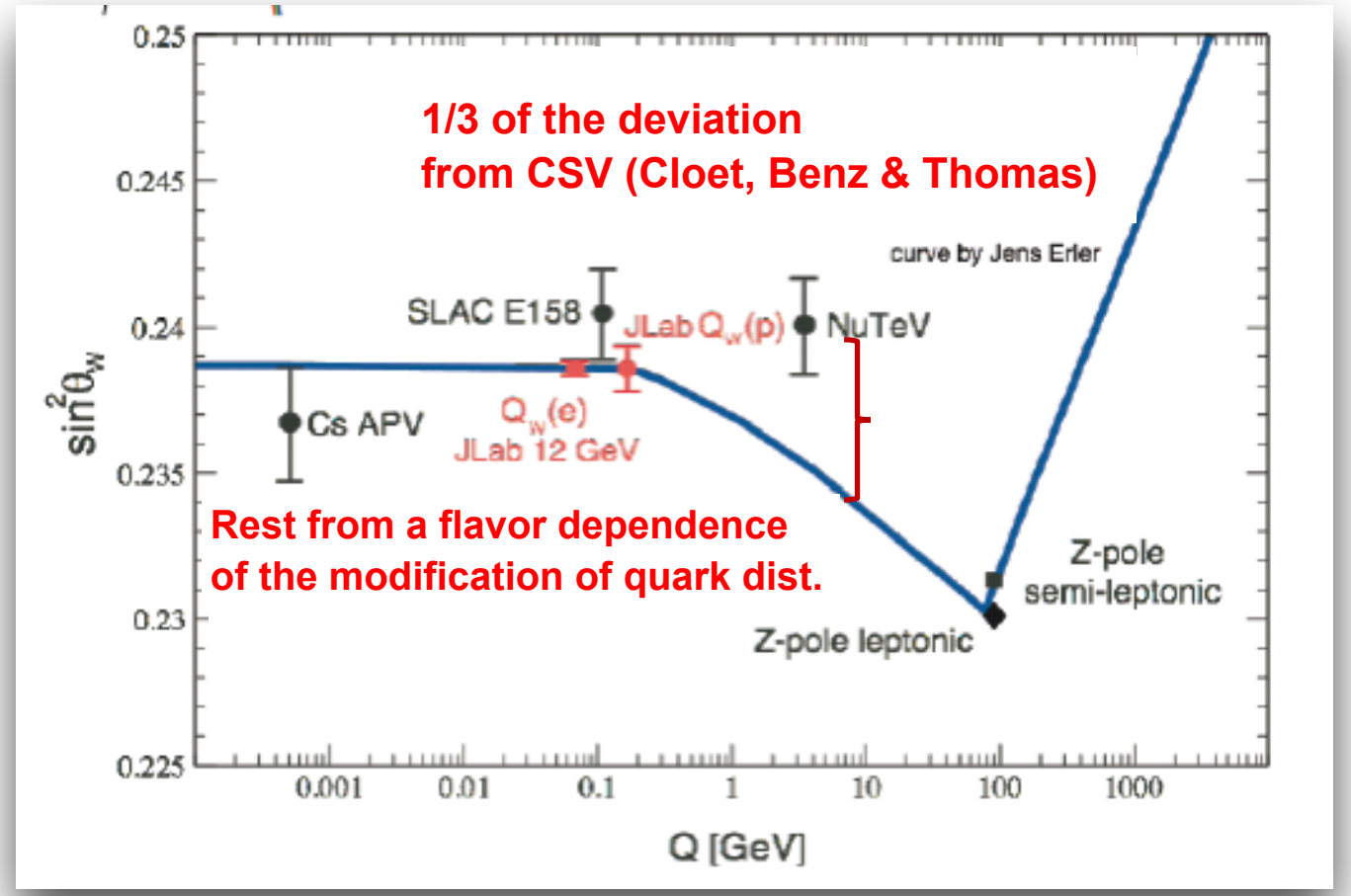
❖Model by Rodionov, Thomas and Londergan (Mod. PLA9(1994)1799):

including quark transverse momentum (neglected by Sather)

δd could reach up to 10% at high x

CSV has been suggested as a viable explanation for the anomalous value of the Weinberg angle extracted by the NuTeV experiment.

using ν DIS, measurement



$$R^- = \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar{\nu}}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar{\nu}}_{\rm CC}}.$$

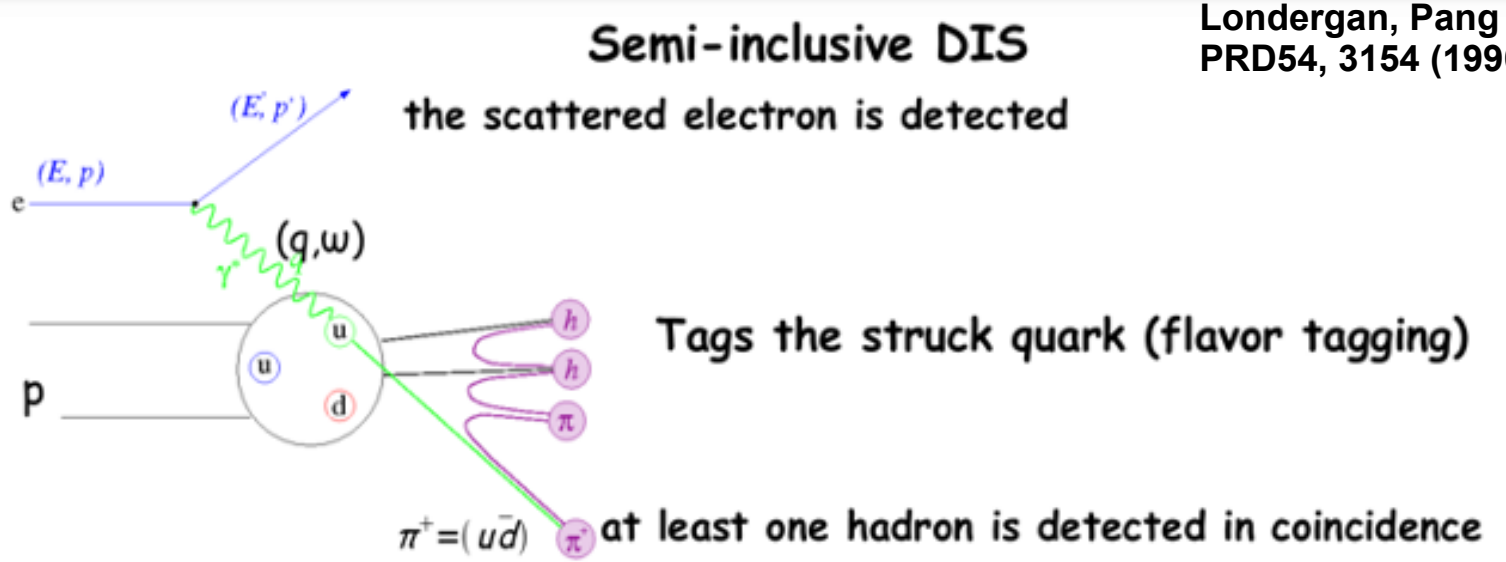
$$\approx \frac{1}{2} - \sin^2\theta_{\rm W},$$

There is ample motivation for direct measurement of CSV

- CSV measurements are important for a complete understanding of the strong force.
- The validity of charge symmetry of PDFs is a necessary condition for many relations between structure functions
- Flavor symmetry violation extraction ($\bar{u}^p(x) \neq \bar{d}^p(x)$) relies on the implicit assumption of charge symmetry (sea quarks)
- Charge symmetry violation could be a viable explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment

A leading-order formalism to quantify CSV in semi-inclusive deep inelastic scatter (SIDIS) was developed

Londergan, Pang and Thomas
PRD54, 3154 (1996)



Measure the ratio $R_Y(x,z)$ of π^+ to π^- yield from ^2H via SIDIS to get

$$R^D_{Meas}(x,z) = \frac{4 - R_Y(x,z)}{R_Y(x,z) - 1}$$

assuming factorization, and under impulse approximation

$$\boxed{D(z)R(x,z) + A(x)\,C(x) = B(x,z)}$$

ratio of fragmentation functions (FFs)

$$R^D_{Meas} + \frac{5}{2}$$

Function of valance quark PDFs

CSV parameter
$\delta d_v - \delta u_v$

Function of sea quark PDFs

A recent SIDIS experiment at the upgraded JLab has measured π^+ to π^- yield from ^{2}H to probe CSV.

$$D(z)R(x,z) + A(x)\,C(x) = B(x,z)$$

ratio of fragmentation function

$$R^D_{Meas} + \frac{5}{2}$$

Function of valance quark PDFs

CSV parameter

$\delta d_v - \delta u_v$

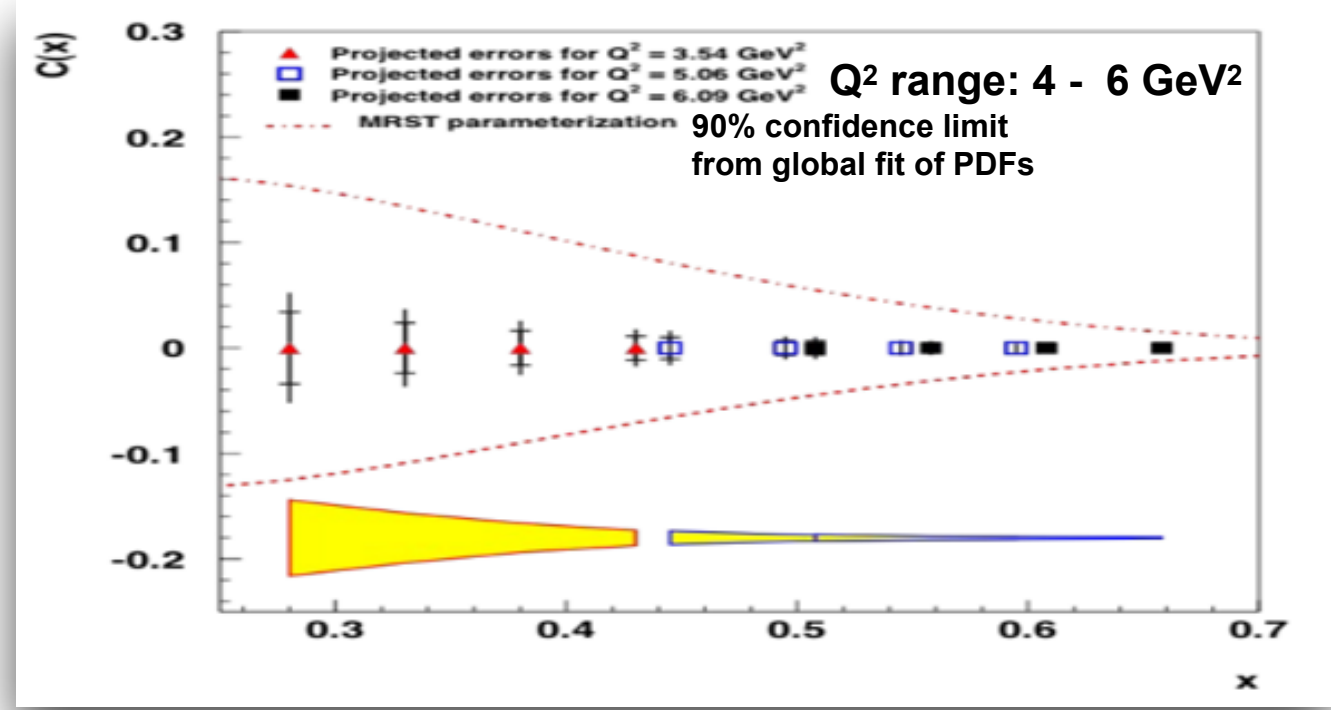
Function of sea quark PDFs

E12-09-002 measured R(x,z) at 16 (x, z) points at 3 fixed Q^2 values with the 11 GeV beam on a 10cm liquid deuterium, in order to extract C(x) and D(z)

electrons in the HMS and pions in the pions in the new SHMS

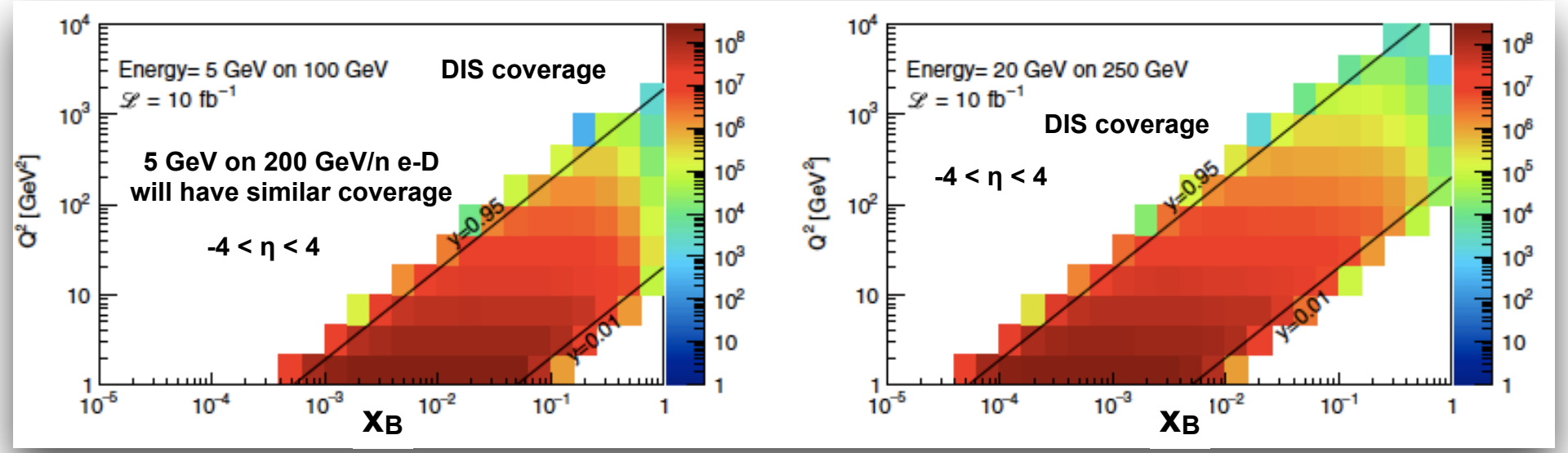
Projected uncertainties on the extracted CSV parameter.

Analysis in progress some results expected by early 2021.



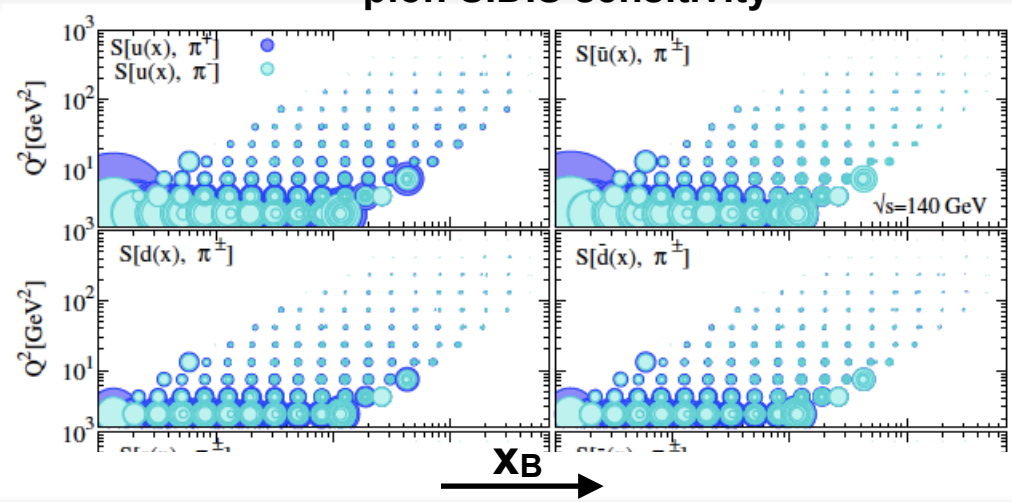
Can e-D collisions at the future EIC probe CSV?

pion SIDIS will have large kinematic coverages at the forthcoming EIC



pion SIDIS sensitivity

E. C. Aschenauer et al., PRD 99, 094004 (2019)



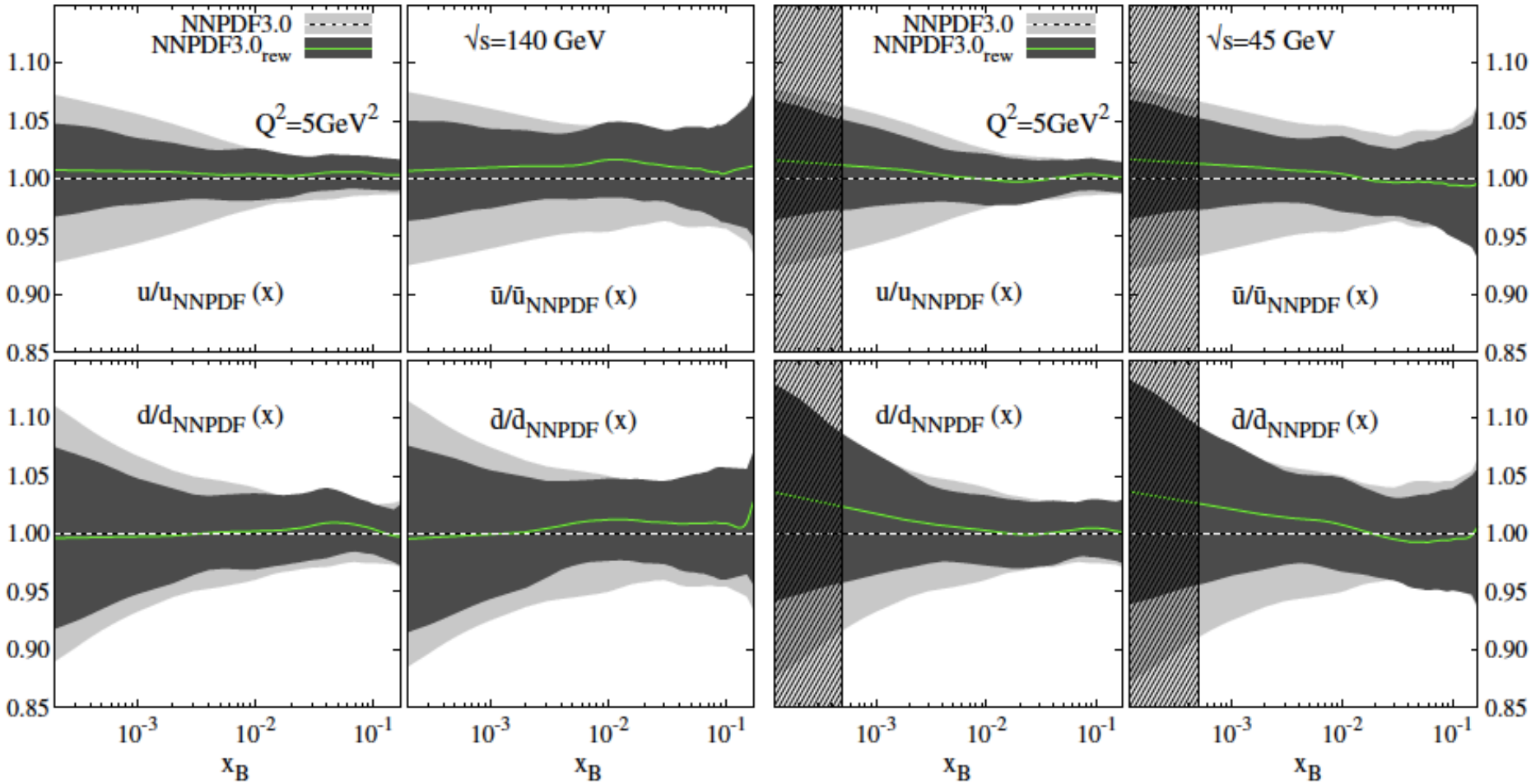
Weighted correlations or sensitivity (shown by the size of the circles)

EIC data will be most impactful for PDFs in $x_B < 0.01$ and $Q^2 < 100$ GeV^2 range relative to how well they are already known.

For valence quark CSV measurements $x_B > 0.01$ is the region of interest.

Can e-D collisions at the future EIC probe CSV?

EIC data will significantly reduce the uncertainty of the light quark PDFs
(as indicated by the reweighing of the NNPDF3.0 with EIC pseudodata)



E. C. Aschenauer et al., PRD 99, 094004 (2019)

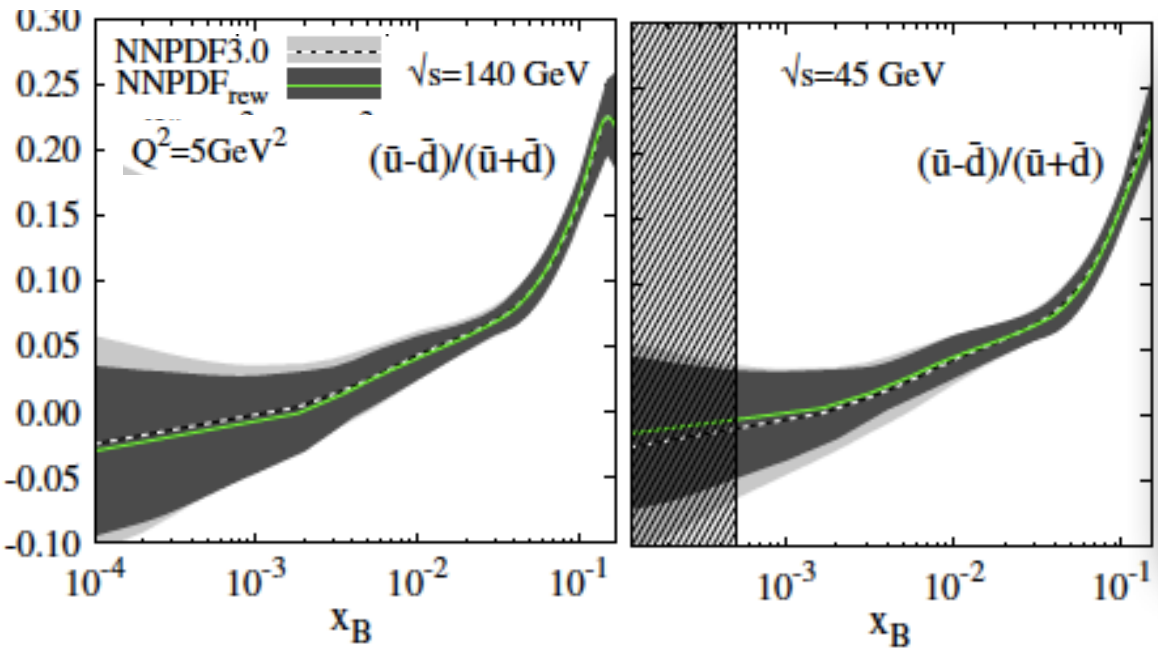
The impact on FFs will be even bigger

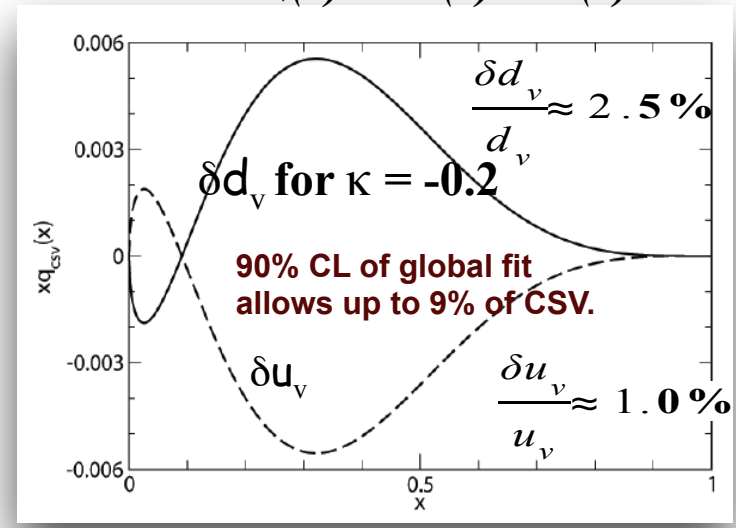
Can e-D collisions at the future EIC probe CSV?

EIC data will have little impact on the uncertainty for the PDF combinations that are sensitive to CSV and ISV
(as indicated by the reweighing of the NNPDF3.0 with EIC pseudodata)

E. C. Aschenauer et al., PRD 99, 094004 (2019)

$$\delta d_v(x) = d^p(x) - u^n(x)$$
$$\delta u_v(x) = u^p(x) - d^n(x)$$





This further makes a strong case for direct measurement

The factorization assumption should be more valid at the EIC energies

The limits on sea quark CSV were also calculated from the uncertainties in the PDFs.

- CSV parameterization for sea quarks

$$u^n_{\rm sea}(x) = d^p_{\rm sea}(x)(1+\kappa),$$

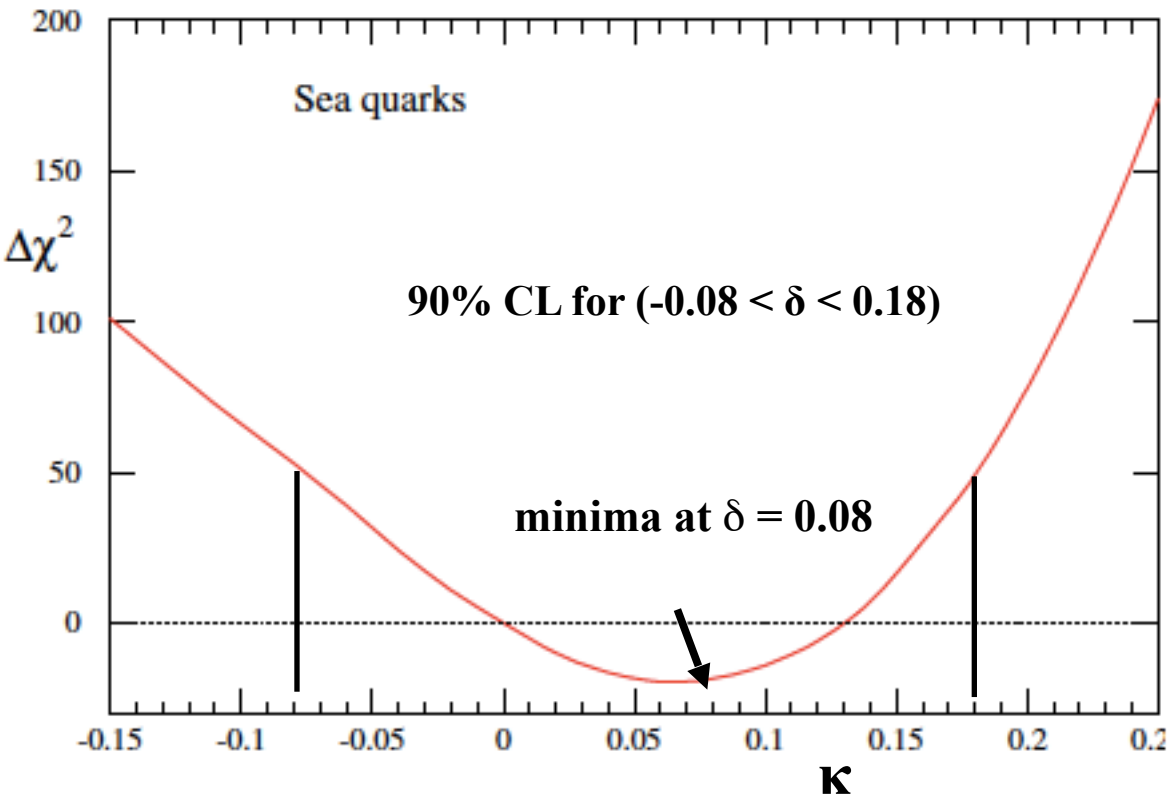
$$d^n_{\rm sea}(x) = u^p_{\rm sea}(x)(1-\kappa).$$

- Must satisfy the normalization condition

$$\int_0^1 \delta\bar{u}(x)\,dx = \int_0^1 \delta\bar{d}(x)\,dx = 0$$

- κ was varied in the global fit: 90% CL obtained for (-0.08 <κ< 0.18)

minima at $\kappa = 0.08$



assumes

$$\delta\bar{u}(x) + \delta\bar{d}(x) = -\kappa\,[\bar{d}(x) - \bar{u}(x)]\,.$$

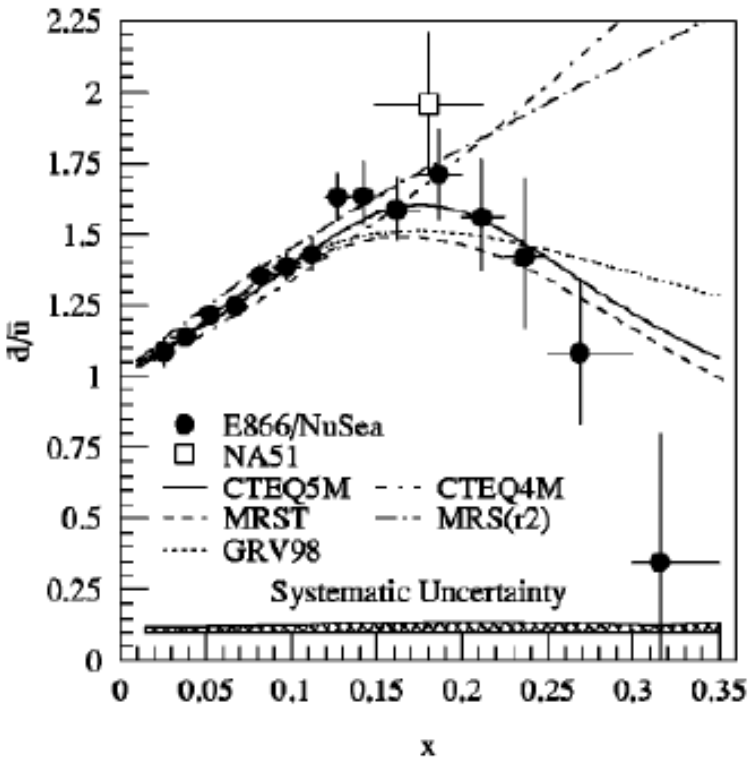
measured in Drell-Yan experiments and at HERMES

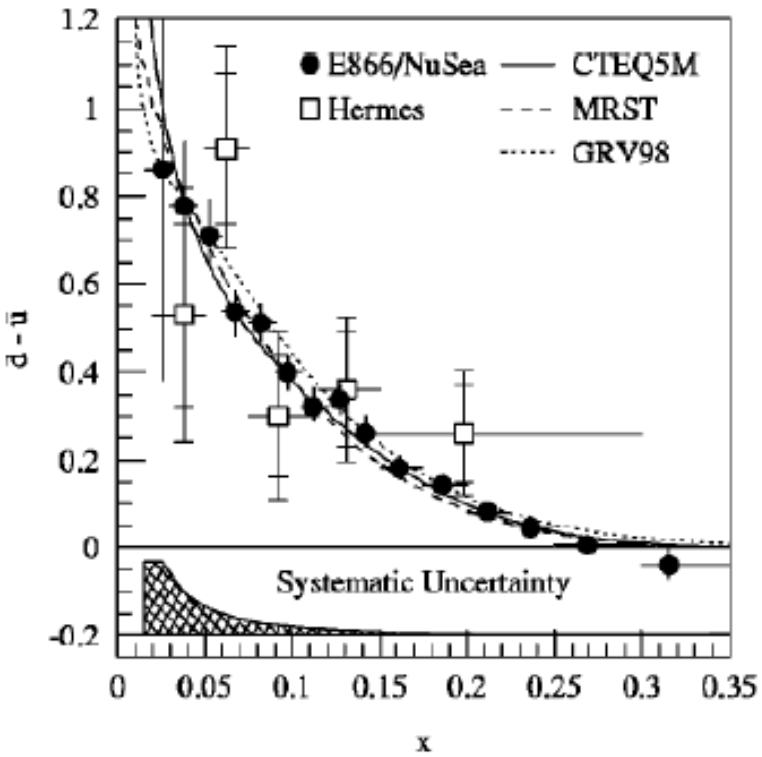
A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Eur. Phys. J. C28 (2003) 455.

Several DIS sum rules are sensitive to CSV of the sea but are difficult to separate from flavor symmetry violation.

Sum rules involving appropriate linear combination of first moments of structure functions help distinguish between sea quark and heavy quark CSV.

The observed sea quark flavor asymmetry can be due to a combination of CSV and flavor symmetry violations.





J. T. Londergan et al., Rev. Mod. Phys. 82, 2009 (2010).

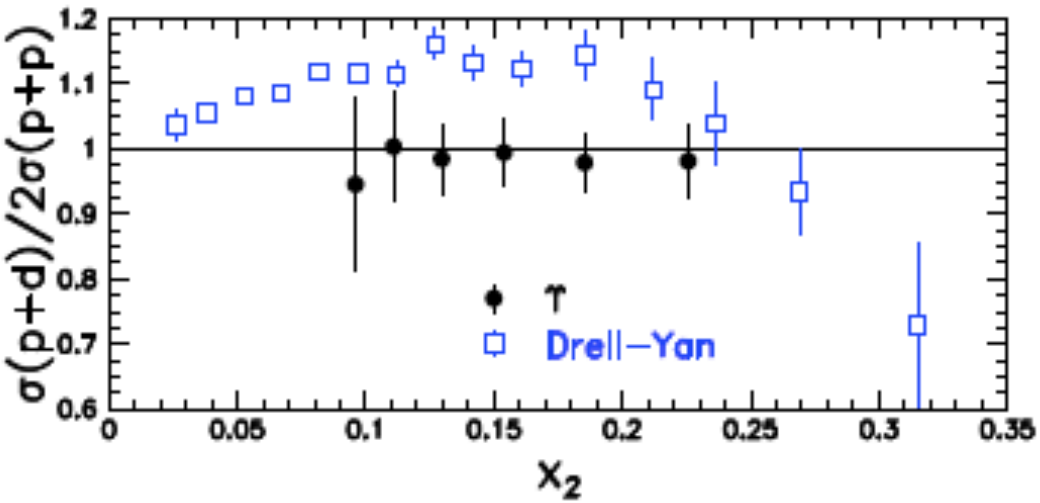
Experimental limits on CSV in the sea are also lacking.

Sea quark CSV should in principle lead to CSV in gluon distributions as the sea quark and gluon distributions are connected through QCD evolution equations

Upsilon production ratio of D and H is sensitive to gluon CSV

$$\frac{\sigma(p+D\to\Upsilon)}{2\sigma(p+p\to\Upsilon)} \to \left[1-\frac{\delta g(x_t)}{2g(x_t)}\right]$$

E866/NuSea results put a 10% upper limit on gluon CSV.



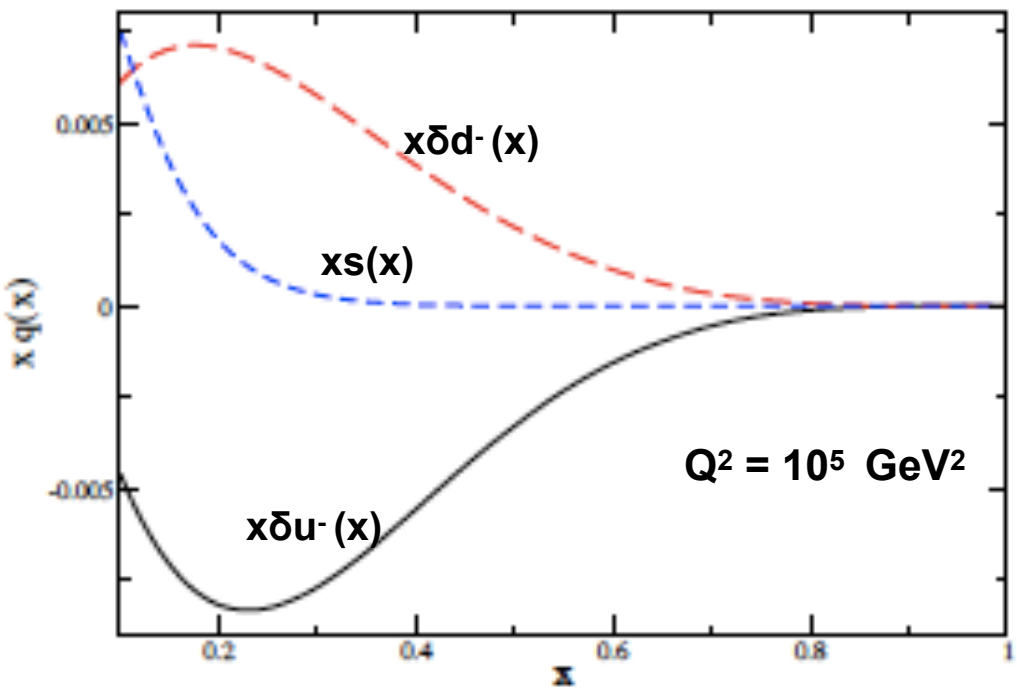
J. T. Londergan et al., Rev. Mod. Phys. 82, 2009 (2010).

The SIDIS pion ratios from e-D and e-P collisions with the formalism of Londergan et al. can be sensitive to sea quark CSV. They can be accessed at the EIC.

Charge current DIS with e^+ and e^- collisions with p and D has been shown to be sensitive to valence quark CSV.

Deep inelastic (e, ν) reaction with p and D beams can be used to measure the ratio:

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)} = \frac{x[-2s^-(x) + \delta u^-(x) - \delta d^-(x)]}{x[u^+(x) + d^+(x) + s^+(x) + 2c(x)]}$$



$$q^{\pm}(x) = x[q(x) \pm \bar{q}(x)] \; ;$$
$$\delta u(x) = u^p(x) - d^n(x) \; ;$$
$$\delta d(x) = d^p(x) - u^n(x) \; .$$

T. J. Hobbs et al., Phys. Lett. B698, 123 (2011)

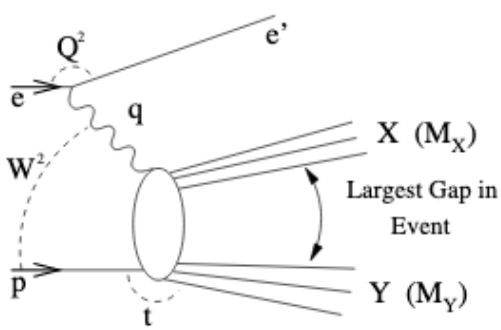
What are some of the requirements for successful CSV measurement at the EIC?

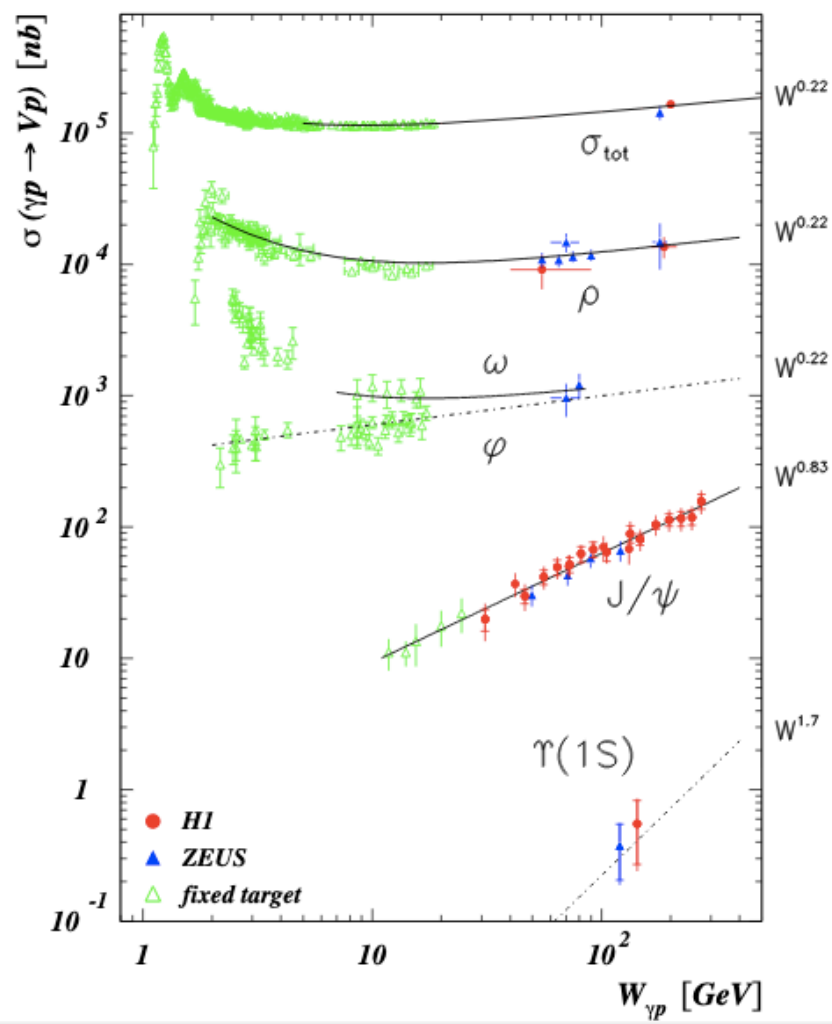
Needs high precision (% level) measurement of the pi+/pi- production ratio in e-D collisions for SIDIS kinematics.

Desirable to have the acceptance for pi+ and pi- as similar as possible.

A major source of background are the pions from diffractive rho production. Need ability to distinguish these pions from the SIDIS events.

For example: @ HERA it was found that ~10% of the DIS events were from diffractive events (characterized by large rapidity gap)





Summary

- Partonic CSV has not been directly measured, only upper limits based on uncertainties on PDFs exist (~ 9% - 10%).
- SIDIS pion production on ^{2}H can be used to directly measure CSV.
- A JLab experiment was recently completed and analysis is in progress.
- EIC will provide new opportunities to measure CSV for valence quarks and possibly for sea quarks as well.
- Detailed simulations are needed to demonstrate feasibility.