Charge symmetry violation

Phiala Shanahan, MIT

Image Credit: 2018 EIC User's Group Meeting

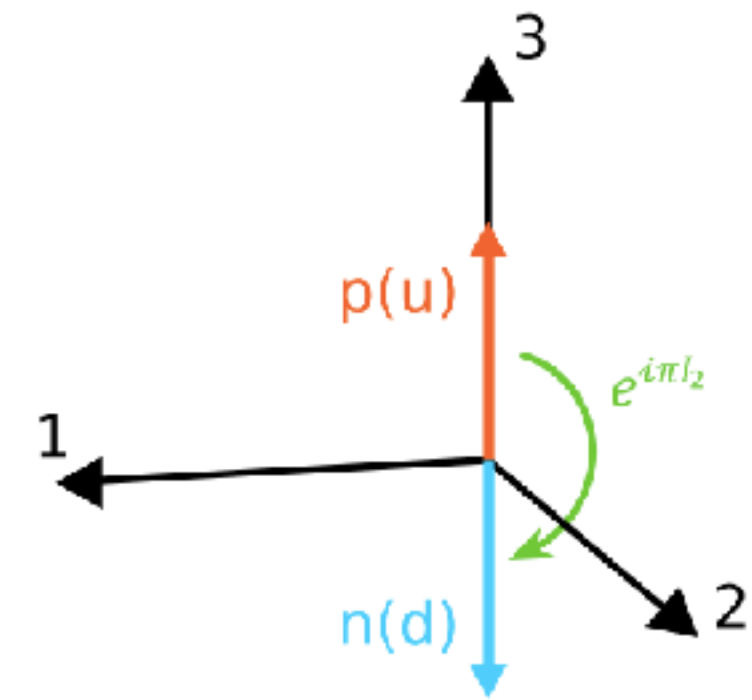
Massachusetts Institute of Technology

Charge symmetry violation

Charge symmetry

180° rotation about the '2' axis in isospin space

$$P_{CS} = e^{i\pi T_2}$$



Partonic charge symmetry relations

$$\begin{aligned} u^p(x,Q^2) &= d^n(x,Q^2) \\ d^p(x,Q^2) &= u^n(x,Q^2) \\ s^p(x,Q^2) &= s^n(x,Q^2) \\ c^p(x,Q^2) &= c^n(x,Q^2) \end{aligned}$$

Analogous for antiquark PDFs

Charge symmetry violation

Charge symmetry is not a symmetry of nature

$m_u \neq m_d$

Strong → quark masses

$Q_u \neq Q_d$

QED → photon radiation

Define "CSV" PDF combinations

$$\delta u(x) \equiv u^p(x) - d^n(x) \qquad \delta d(x) \equiv d^p(x) - u^n(x)$$

Consider CSV in

- Valence quark PDFs

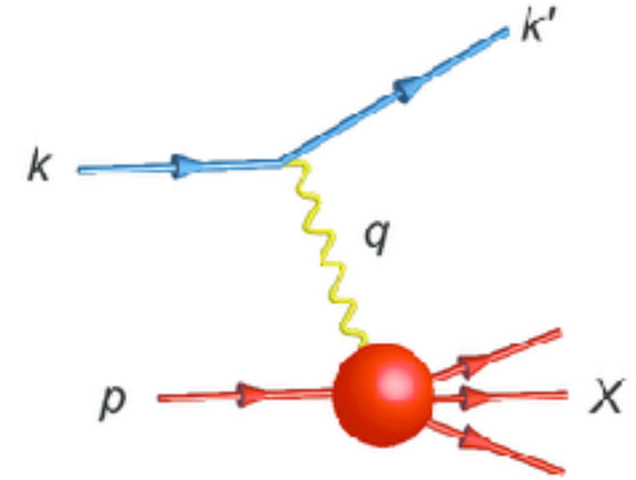
$$u_{\mathrm{v}}(x) \equiv u(x) - \bar{u}(x)$$
$$d_{\mathrm{v}}(x) \equiv d(x) - \bar{d}(x)$$

- Sea quark PDFs ↔ gluon PDF

$$\bar{u}(x) \quad \bar{d}(x)$$
$$\delta g(x) = g^p(x) - g^n(x)$$

Implications of CSV at the EIC

(SI)DIS cross-sections at the EIC



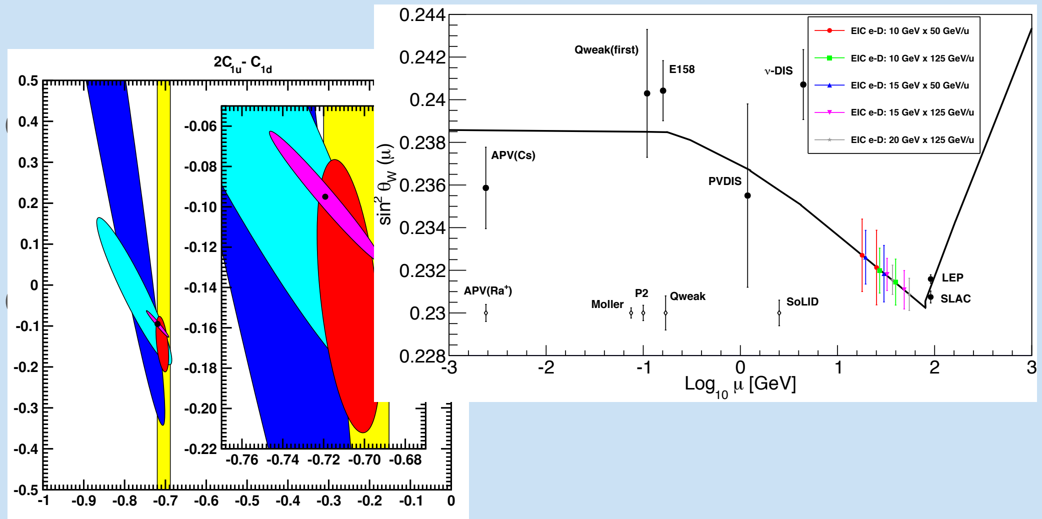
Constraints on nucleon and nuclear PDFs

Disentangle contributions from

- CSV
- Heavy flavour
- Sea quarks
- Gluons
- Nuclear effects

Tests of the SM

via precision measurements of electroweak parameters

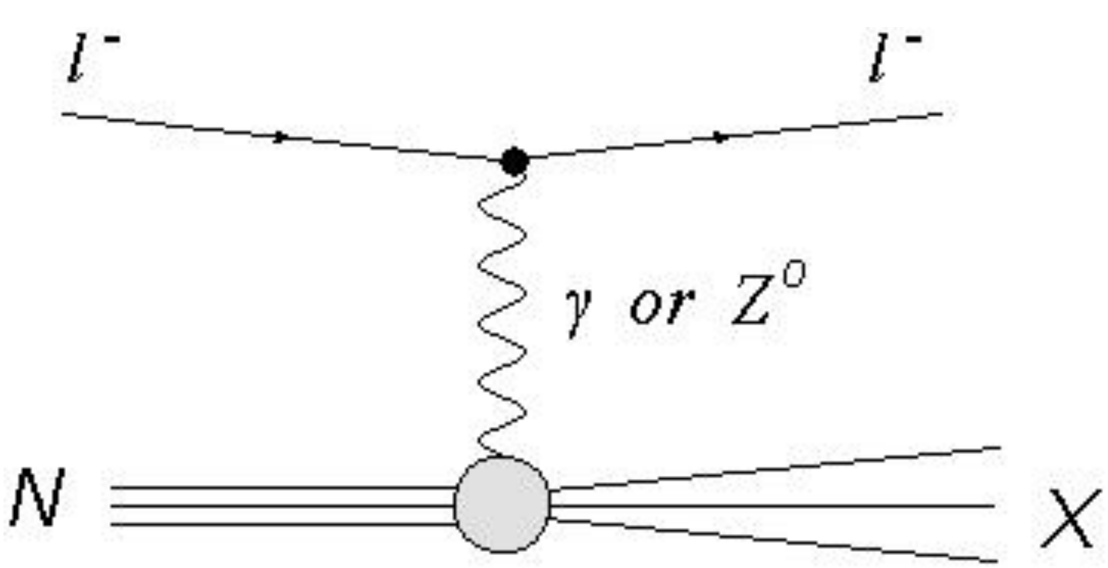


CSV in DIS cross-sections

Drop assumption of CSV

➡ chase through CSV terms in all structure functions

Neutral current interactions



$$\frac{d^2\sigma_{NC}^{L,R}}{dx\,dy} = \frac{4\pi\alpha^2 s}{Q^4}\Bigg(\Big[xy^2 F_1^\gamma(x,Q^2)$$
$$+\ f_1(x,y) F_2^\gamma(x,Q^2)\Big] - \frac{Q^2}{(Q^2+M_Z^2)}\frac{v_\ell \pm a_\ell}{2\sin\theta_W\cos\theta_W}$$
$$\times\ \Big[xy^2 F_1^{\gamma Z}(x,Q^2) + f_1(x,y) F_2^{\gamma Z}(x,Q^2)$$
$$\pm\ f_2(y) x F_3^{\gamma Z}(x,Q^2)\Big] + \left(\frac{Q^2}{Q^2+M_Z^2}\right)^2$$
$$\times\ \frac{v_\ell \pm a_\ell}{2\sin\theta_W\cos\theta_W}\Big[xy^2 F_1^Z(x,Q^2)$$
$$+\ f_1(x,y) F_2^Z(x,Q^2) \pm f_2(y) x F_3^Z(x,Q^2)\Big]\Bigg).$$

e.g., for isoscalar target N_0

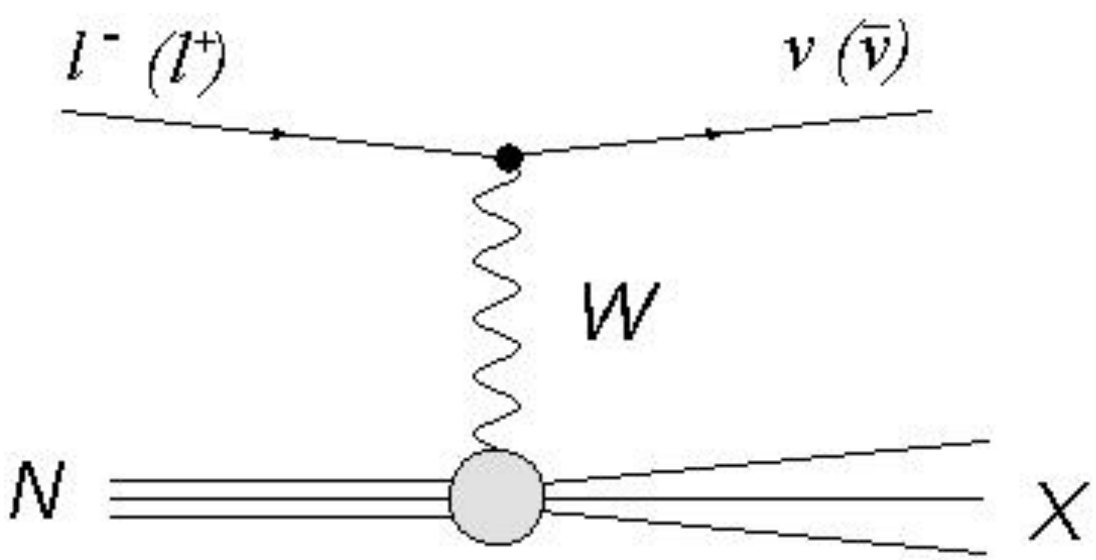
$$36 F_1^{\gamma N_0}(x,Q^2) = 5\,[u^+(x) + d^+(x)]$$
$$+\ 2s^+(x) + 8c^+(x) - 4\delta d^+(x) - \delta u^+(x).$$

Careful! Nuclear vs nucleon PDFs (even for deuteron)

CSV in DIS cross-sections

Drop assumption of CSV
chase through CSV terms in all structure functions

Charged current interactions



$$\frac{d^2\sigma_{CC}^{l^+(l^-)}}{dx\,dy} = \frac{\pi s}{2}\left(\frac{\alpha}{2\sin^2\theta_W(M_W^2+Q^2)}\right)^2$$
$$\times\left[xy^2 F_1^{W^\pm}(x,Q^2) + f_1(y) F_2^{W^\pm}(x,Q^2)\right.$$
$$\left.\mp f_2(y) x F_3^{W^\pm}(x,Q^2)\right].$$

e.g., for isoscalar target N_0

$$2F_1^{W^+N_0}(x,Q^2) \to u^+(x) + d^+(x) + 2s(x) + 2\bar{c}(x) - \delta u(x) - \delta\bar{d}(x)$$

Note: CSV contributions aren't purely valance

Charge symmetry violation

How large is CSV in parton distribution functions?

General quark model arguments:

Quark mass differences ~1-5MeV

Fractional partonic CSV

$$\frac{\delta q}{q} \sim \frac{\delta m}{\langle M \rangle}$$

Effective mass of system w/ quark removed

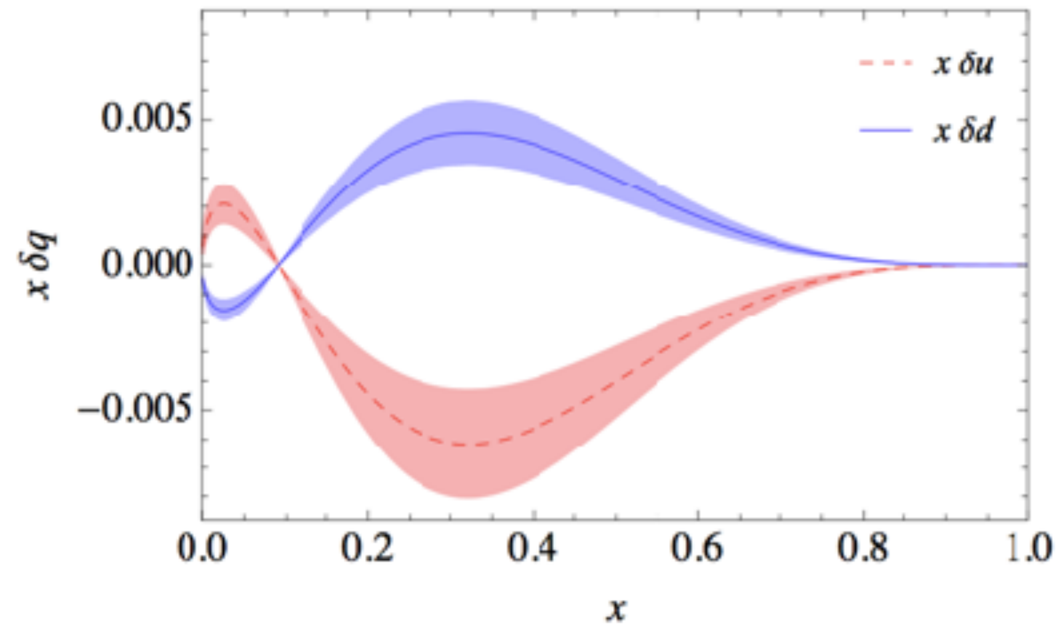
- Valence quark: ~500MeV
- Sea quark ~1.3GeV

Expectation: CSV in **valence** quark PDFs $>$ CSV in **sea** quark PDFs

Charge symmetry violation

How large is CSV in the parton distribution functions?

- Partonic CSV not directly resolved in experiment: bounds at few%-10% [Indirect evidence: global fits accommodate CSV]
- **Theory and lattice QCD calculations suggest ~1% level in valence PDFs**
  - Lattice QCD → lowest moments
  - Models: for moderate x (x >~0.1) $|\delta u_{\mathrm{v}}(x)+\delta d_{\mathrm{v}}(x)| << |\delta u_{\mathrm{v}}(x)-\delta d_{\mathrm{v}}(x)|$
- **Small, BUT could explain significant fraction of NuTEV anomaly**



Young, PES, Thomas [arXiv:1312.4990]

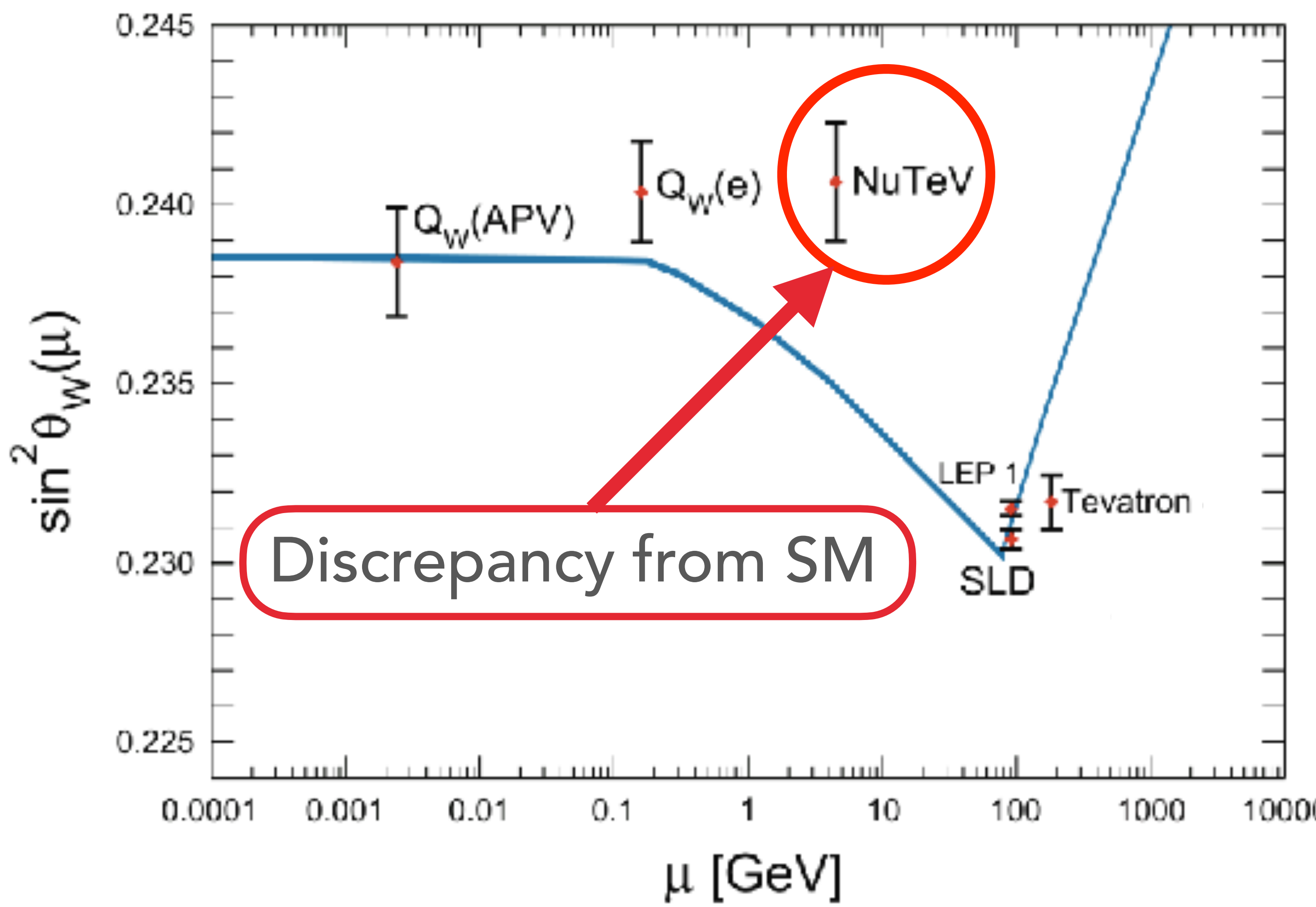
NuTeV experiment

Indirect measure of Paschos-Wolfenstein ratio:

$$R_{\mathrm{PW}} = \frac{\sigma_{NC}^{\nu\,A} - \sigma_{NC}^{\bar{\nu}\,A}}{\sigma_{CC}^{\nu\,A} - \sigma_{CC}^{\bar{\nu}\,A}} \overset{\bigstar}{\rightarrow} \frac{1}{2} - \sin^2\theta_W$$

This simplification ★ relies on assumptions:

- Exact charge symmetry
- Vanishing partonic strangeness $s(x) - \bar{s}(x)$
- Isoscalar nucleus with no nuclear effects
- No higher-twist effects



Implication CSV for NuTeV

Correction to the Paschos-Wolfenstein ratio from CSV

$$\Delta R_{\mathrm{PW}}^{\mathrm{CSV}} = \frac{1}{2}\left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x\rangle_{\delta u^-} - \langle x\rangle_{\delta d^-}}{\langle x\rangle_{u^-} + \langle x\rangle_{d^-}}$$

Extensive literature discussing further corrections incl. Non-isoscalar nucleus, strangeness

- Bentz, Cloet, Londergan & Thomas PLB(2010)
- Davidson, Forte, Gambino, Rius, Strumia JHEP 02 (2002) 037
- Londergan, Thomas Phys.Lett.B 558 (2003) 132
- Gluck, Jimenez-Delgado, Reya Phys.Rev.Lett. 95 (2005) 022002
- Diener KP, Dittmaier, Hollik, Phys.Rev. D72:093002 (2005),
- Hirai, Kumano, Nagai, Phys.Rev. D71:113007 (2005)
- Brodsky, Schmidt, Yang, Phys.Rev. D70:116003 (2004)
- …

Moments of PDFs

$$\langle x\rangle_q = \int x\, q(x)dx$$

Calculable in lattice QCD

CSV moments from lattice QCD

Indirect lattice QCD determination of first moment of CSV PDFs

[Shanahan, Thomas & Young, PRD(2013)094515]

- For small breaking in the u-d quark masses $m_\delta \equiv (m_d - m_u)$

$$\langle x \rangle_{\delta u} \simeq \frac{m_\delta}{2}\left[\left(-\frac{\partial \langle x \rangle_u^p}{\partial m_u} + \frac{\partial \langle x \rangle_u^p}{\partial m_d}\right) - \left(-\frac{\partial \langle x \rangle_d^n}{\partial m_u} + \frac{\partial \langle x \rangle_d^n}{\partial m_d}\right)\right]$$

Charge symmetry

$$\langle x \rangle_{\delta u} \simeq m_\delta \left[-\frac{\partial \langle x \rangle_u^p}{\partial m_u} + \frac{\partial \langle x \rangle_u^p}{\partial m_d}\right]$$

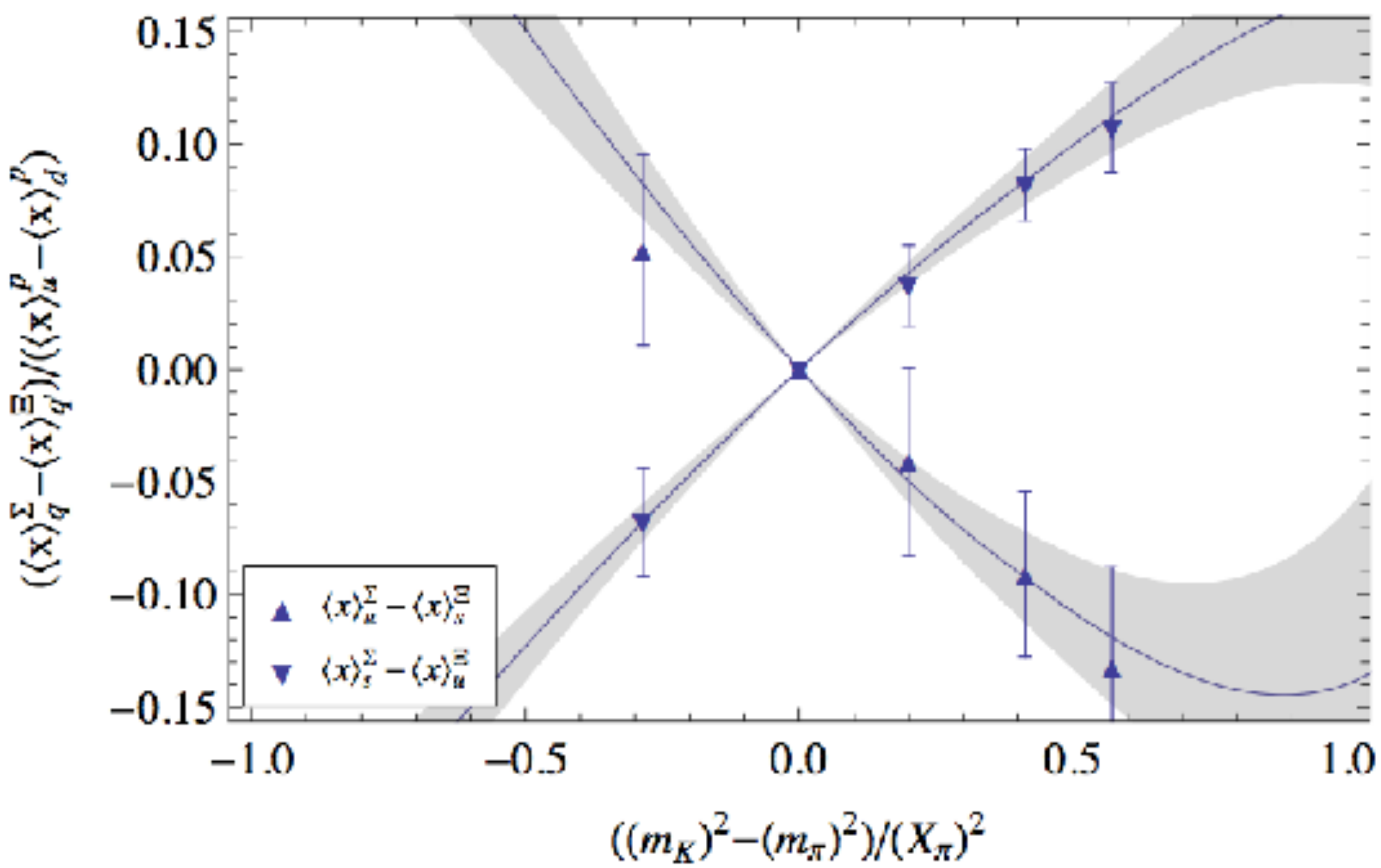
- SU(3) symmetry: fit isospin symmetric lattice results for hyperons (exploit use of non-physical quark masses in lattice QCD)

→ **Determines CSV parameters in EFT**

CSV moments from lattice QCD

Indirect lattice QCD determination of first moment of CSV PDFs

[Shanahan, Thomas & Young, PRD(2013)094515]



Shanahan, Thomas & Young, PRD(2013)094515

Our result

$$\langle x\rangle_{\delta u} = -0.0023(7)$$
$$\langle x\rangle_{\delta d} = 0.0017(4)$$

This result + CSV from QED parton evolution

NuTeV anomaly reduced by ~1σ

$\text{Sin}^2\theta_W$ at the EIC

Constrain $\sin^2\theta_W$ using parity-violating e-D scattering

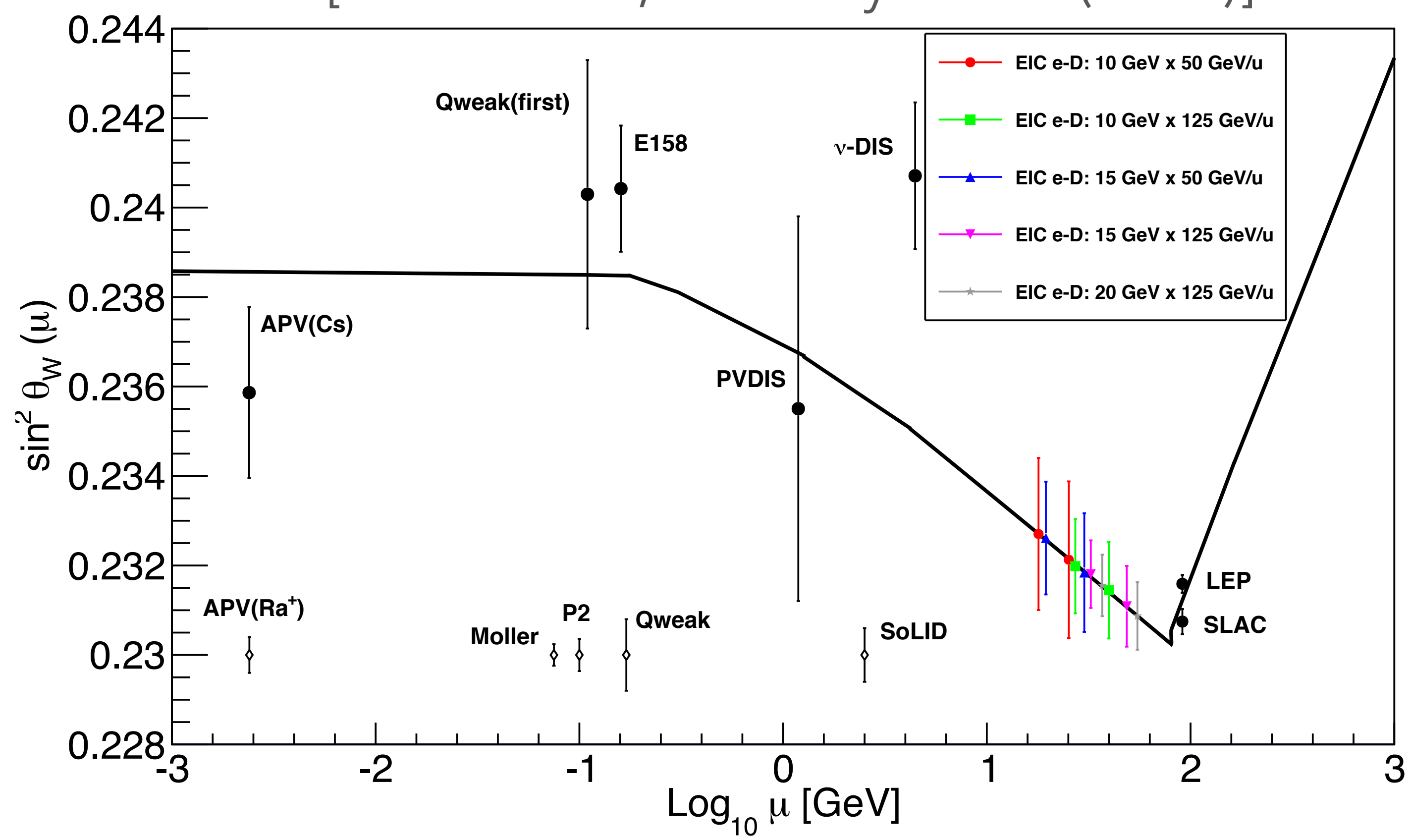
$$A_{PV}^{eD}(x,y) = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1^d + f(y)a_3^d\right]$$

$$= -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\left(1-\frac{20}{9}\sin^2\theta_W\right)+\left(1-4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

Assumptions:

- CSV negligible
- Impulse approximation in scattering
- No higher-twist contributions
- Sea quarks negligible

[Zhao et al., Eur. Phys. J. A (2017)]



$\sin^2\theta_W$ at the EIC

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$$A_{PV}^{eD}(x,y) = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1^d + f(y) a_3^d\right]$$

CSV terms contribute to both couplings

$$a_1^d \rightarrow a_1^{d(0)} + \delta^{(CSV)} a_1^d \qquad a_3^d \rightarrow a_3^{d(0)} + \delta^{(CSV)} a_3^d$$

$$\frac{\delta^{(CSV)} a_1^d}{a_1^{d(0)}} = \left[-\frac{3}{10} + \frac{2g_V^u + g_V^d}{2(2g_V^u - g_V^d)}\right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

$$\frac{\delta^{(CSV)} a_3^d}{a_3^{d(0)}} = \left[-\frac{3}{10} + \frac{2g_A^u + g_A^d}{2(2g_A^u - g_A^d)}\right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

x-dependent CSV PDFs, not just moments

- Lattice QCD calculation was first moment only

→ Model x-dependence

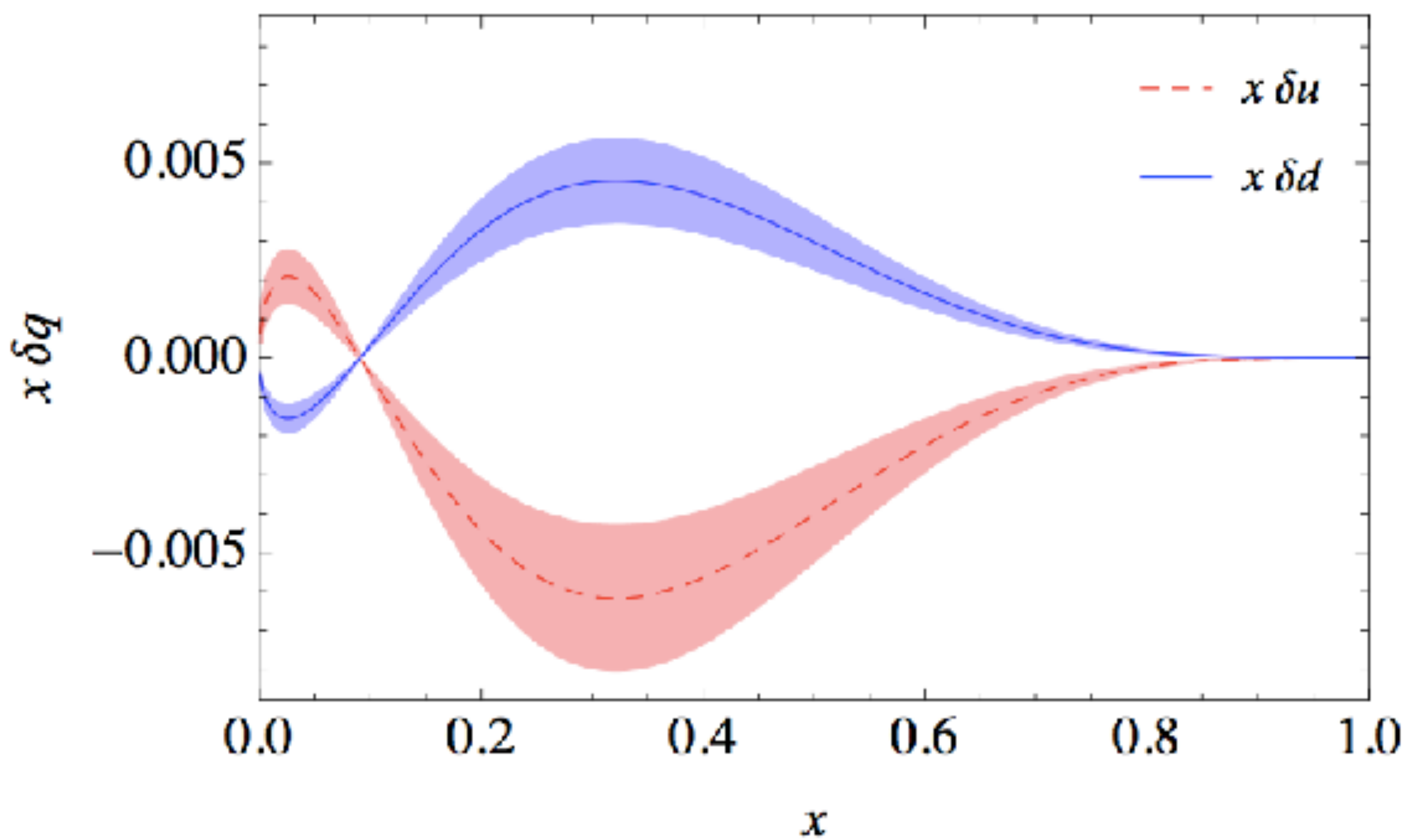
$\mathrm{Sin}^2\theta_W$ at the EIC

Only first moment from lattice QCD calculation

Constrain simple parameterisation of x-dependence

[MRST Eur.Phys.J.C35,2004]

$$\delta_q(x) = \kappa_q x^{-1/2}(1-x)^4(x-1/11)$$



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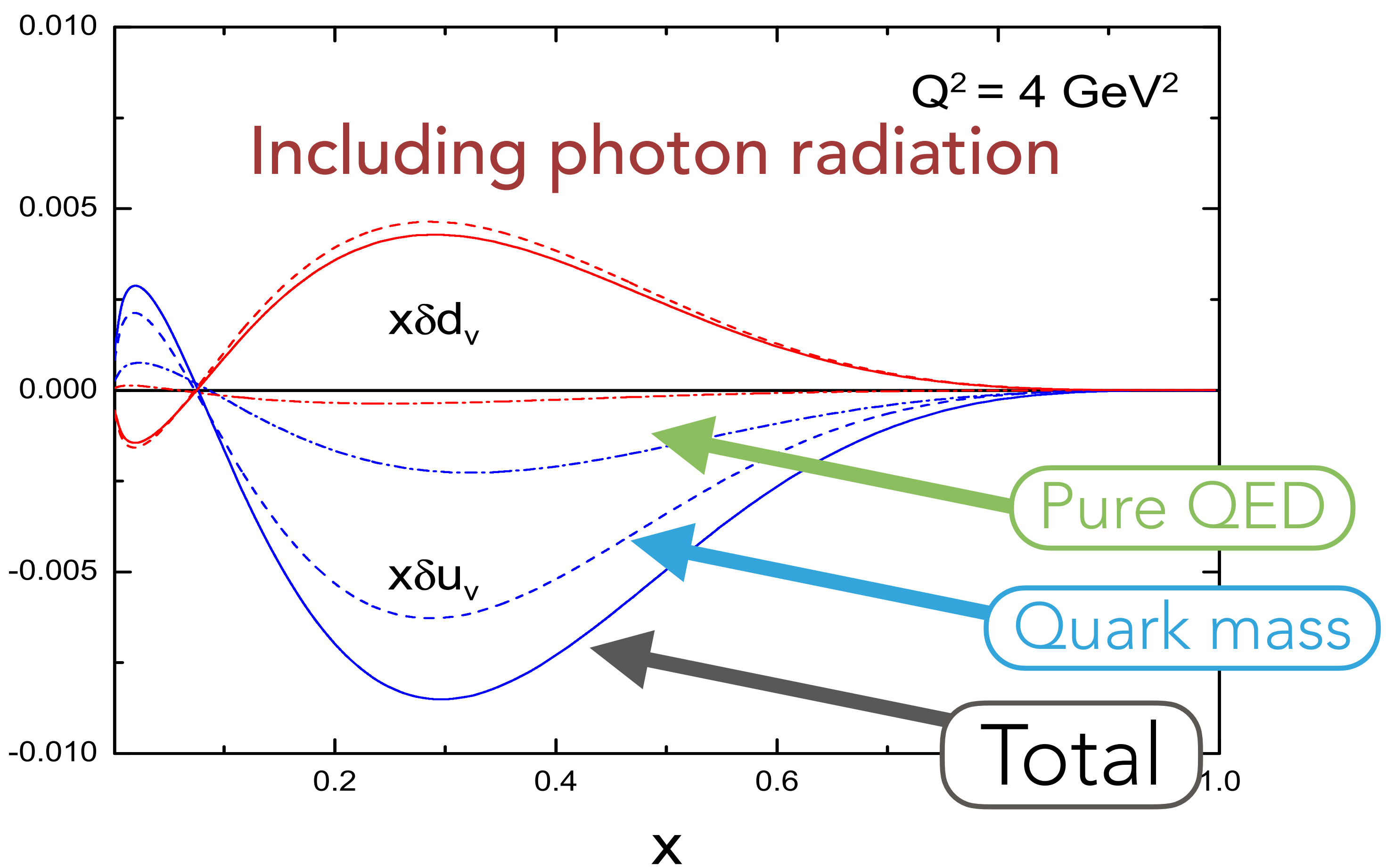
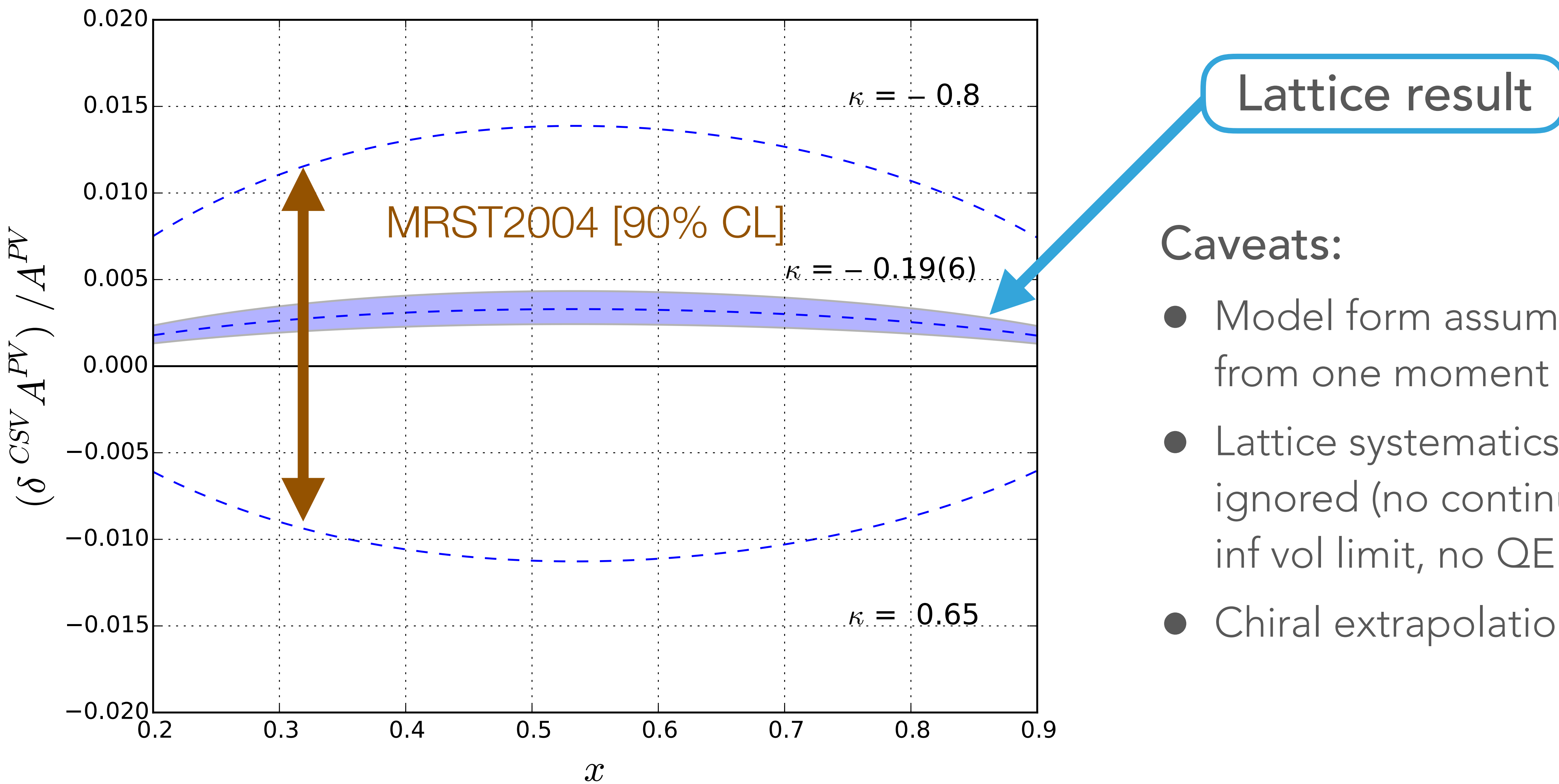


Wang, Thomas, Young, PLB(2016)

$\sin^2\theta_W$ at the EIC

CSV contribution to parity-violating asymmetry is at the **sub-percent level**



Caveats:

- Model form assumed, fit from one moment
- Lattice systematics ignored (no continuum, inf vol limit, no QED)
- Chiral extrapolation used

CSV in WNC couplings from e-D DIS

Note that CSV affects couplings a_1^d , a_3^d in the same way (x-dep)

$$\frac{\delta^{(CSV)} a_1^d}{a_1^{d(0)}} = \left[-\frac{3}{10} + \frac{2g_V^u + g_V^d}{2(2g_V^u - g_V^d)}\right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

$$\frac{\delta^{(CSV)} a_3^d}{a_3^{d(0)}} = \left[-\frac{3}{10} + \frac{2g_A^u + g_A^d}{2(2g_A^u - g_A^d)}\right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

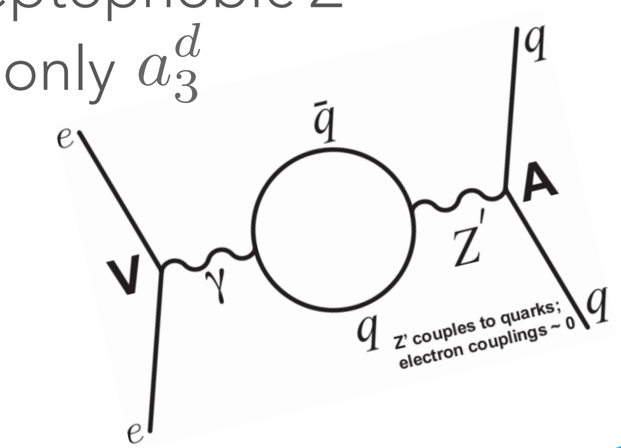
Use this to distinguish CSV effects on WNC couplings from possible new physics signatures in couplings

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left[\bar{e}\gamma^\mu\gamma_5 e \left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e \left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\right)\right]$$

$$a_1^d = \frac{6}{5}(2C_{1u} - C_{1d})[1 + (\mathrm{CSV}) + (\mathrm{new}) + (\mathrm{sea}) + (\mathrm{TMC}) + (\mathrm{HT})]$$

$$a_3^d = \frac{6}{5}(2C_{2u} - C_{2d})[1 + \ldots]$$

e.g., Leptophobic Z′ affects only a_3^d



CSV in WNC couplings from e-D DIS

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$$\frac{\delta^{(CSV)} a_1^d}{a_1^{d(0)}} = \left[-\frac{3}{10} + \frac{2g_V^u + g_V^d}{2(2g_V^u - g_V^d)}\right] \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

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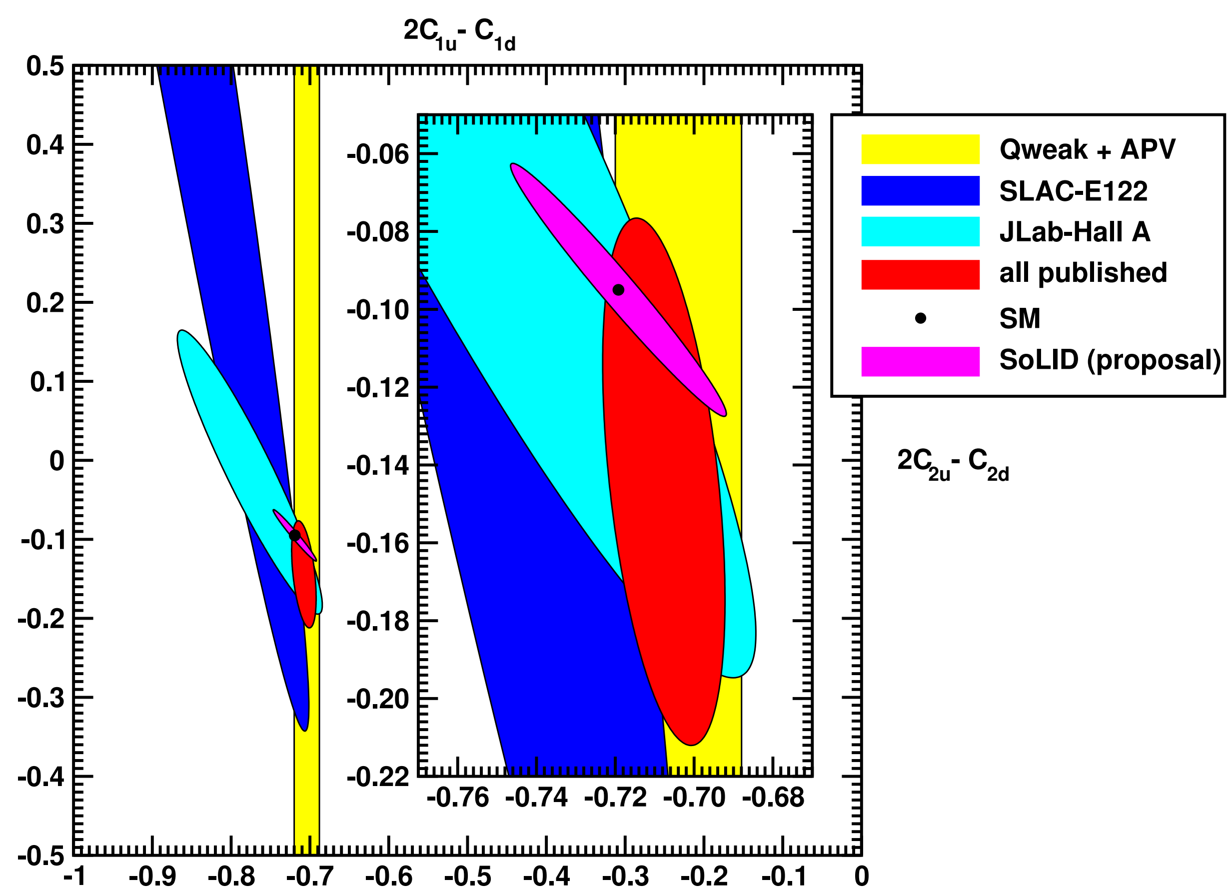
$$a_3^d = \frac{6}{5}(2C_{2u} - C_{2d})[1 + \ldots]$$

Theory/ lattice QCD suggests CSV contributions to the couplings is at the **sub-percent level**



[Y.X.Zhao (SoLID Collaboration)]

How can we constrain CSV?

- Strongest upper limit by comparing F_2 in charged current reactions induced by neutrinos with F_2 for charged lepton DIS, on isoscalar targets

- **Coupled knowledge of heavy quark PDFs and CSV**

→ Sea quark contributions suppressed at larger x, more sensitive to CSV

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

$$R_c(x) \approx 1 + \frac{3\left(\delta u^+(x) - \delta d^+(x)\right)}{10\sum_j q_j^+(x)}\ .$$

- Neutral current structure function at EIC
- Charged current structure function at EIC with sufficiently high beam intensity?

Also: **neutrino-nucleon DIS on heavy targets**:

$$\begin{aligned}\Delta x F_3(x) &= x F_3^{W^+}(x) - x F_3^{W^-}(x)\ ; \\ \Delta x F_3^{N_0}(x) &\rightarrow x\Big[2\big(s^+(x) - c^+(x)\big) \\ &\quad + \delta d^+(x) - \delta u^+(x)\Big].\end{aligned}$$

- Role for EIC: precise nuclear correction factors

Semi-inclusive pion production

Lepton DIS on isoscalar nuclear targets

$$\frac{1}{\sigma_N(x)}\frac{d\sigma_N^h(x,z)}{dz} = \frac{N^{Nh}(x,z)}{\sum_i e_i^2 q_i^N(x)}$$

Yield of hadron h per scattering from nucleon N

$$R^{\Delta}(x,z) \equiv \frac{8\left(\frac{N^{D\pi^-}(x,z)}{1+4\Delta(z)} - \frac{N^{D\pi^+}(x,z)}{4+\Delta(z)}\right)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}$$

$$= C^{\Delta}(z)\left[R_{CS}(x) + R_{SV}(x,z)\right]$$

CSV

Sea-valence interference term, less important at large x

- Requires that factorisation be valid to a few percent

$$R_{CS}(x) = \frac{4(\delta d_{\mathrm{v}}(x) - \delta u_{\mathrm{v}}(x))}{3(u_{\mathrm{v}}(x) + d_{\mathrm{v}}(x))}$$

- CSV terms substantial for x>0.4
- Determine CSV via measurement of x-dep of R for fixed z

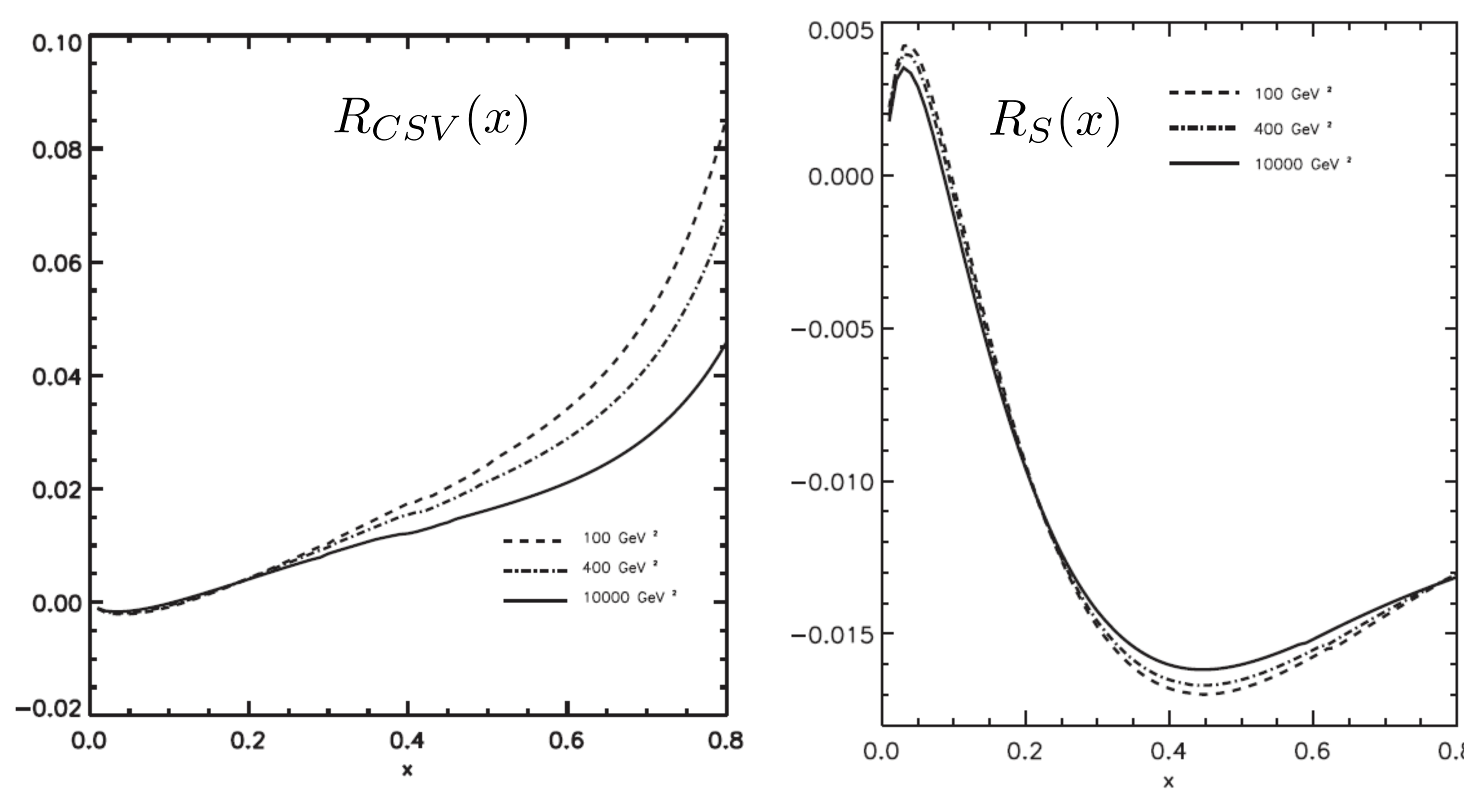
Test of weak current relation

Compare charge-changing interactions from electron/positron scattering on isospin-0 nucleus

$$
\begin{aligned}
R_W(x) &\equiv \frac{2\left(F_2^{W^+D}(x) - F_2^{W^-D}(x)\right)}{F_2^{W^+D}(x) + F_2^{W^-D}(x)} \\
&\approx \frac{\delta d_{\rm v}(x) - \delta u_{\rm v}(x) + 2(s^-(x) - c^-(x))}{\sum_j q_j^+(x)} \\
&\equiv R_{CSV}(x) + R_S(x)\ .
\end{aligned}
$$

Theory calculations suggest

- Opposite sign $\delta d_v(x), \delta u_v(x)$
  ➡ effects add in magnitude
- x-dep of CSV and strange is different (note strange must have node)



Londergan, Braendler, Thomas, Phys. Lett. B424 (1998) 185

Sea quark CSV: sum rules

Expectation: CSV in **valence** quark PDFs $>$ CSV in **sea** quark PDFs

- First moments of valence quark CSV vanish by quark normalisation conditions

$$\int_0^1 \delta u_{\rm v}(x)\,dx = \int_0^1 \delta d_{\rm v}(x)\,dx = 0$$

➡ Sum rules in moments isolate sea quark CSV

- Note: sea quark CSV ↔ gluon CSV via evolution

e.g., **Gottfried sum rule**

- CSV vs sea quark flavour asymmetry

$$\begin{aligned} S_G \;&\equiv\; \int_0^1 dx\,\frac{\left[F_2^{\ell p}(x) - F_2^{\ell n}(x)\right]}{x} \\ &= \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,\left[\bar{d}^p(x) - \bar{u}^p(x)\right] \\ &+ \frac{2}{9}\int_0^1 dx\,\left[4\delta\bar{d}(x) + \delta\bar{u}(x)\right]\ . \end{aligned}$$

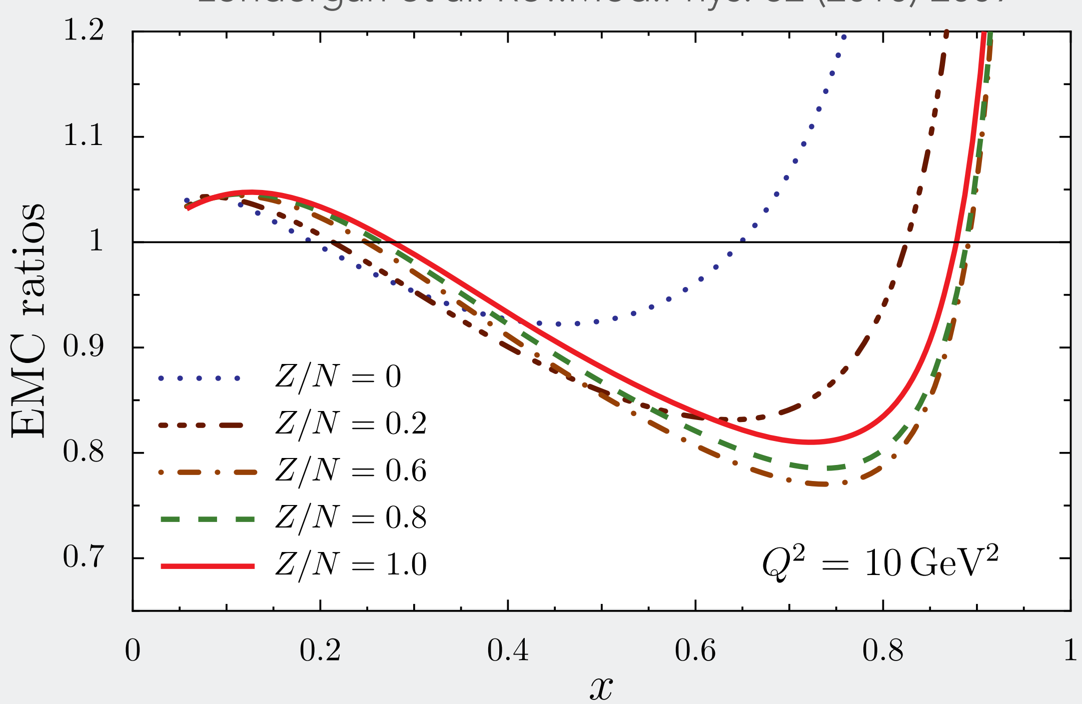
"pseudo-CSV" EMC effect

- **Isovector EMC effect** for nuclei with N≠Z

$$R_{N,Z}(x) = \frac{F_2^{(N,Z)}(x)}{F_2^{(d)}(x)}$$

- Isovector EMC has similar signature to CSV → "pseudo-CSV"

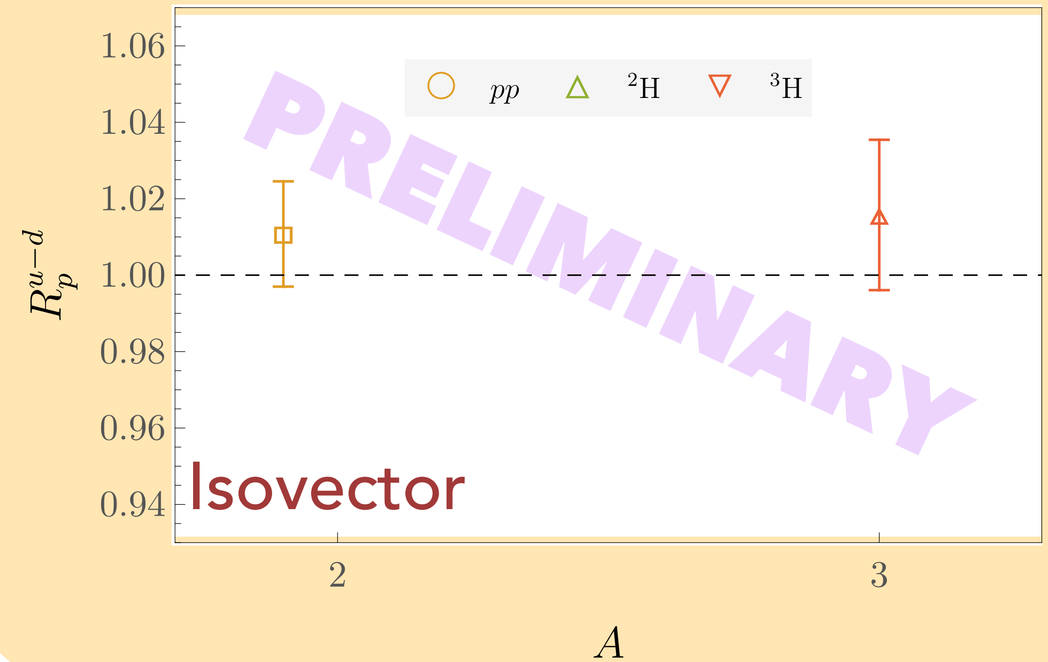
Londergan et al. Rev.Mod.Phys. 82 (2010) 2009



- **Full flavour dependence** of EMC effects

$$R^{(3)}_{N,Z}(x) = \frac{u_{N,Z}(x) - d_{N,Z}(x)}{u_d(x) + d_d(x)}$$

  - Challenging in experiment (eg MINERvA)
  - Moments accesible in LQCD



Parton physics from Lattice QCD

Precision Era

Fully-controlled w/ few-percent errors within ~5y

- Static properties of nucleon incl. spin, flavour decomp.
- Mellin moments of PDFs, GPDs

Early Era

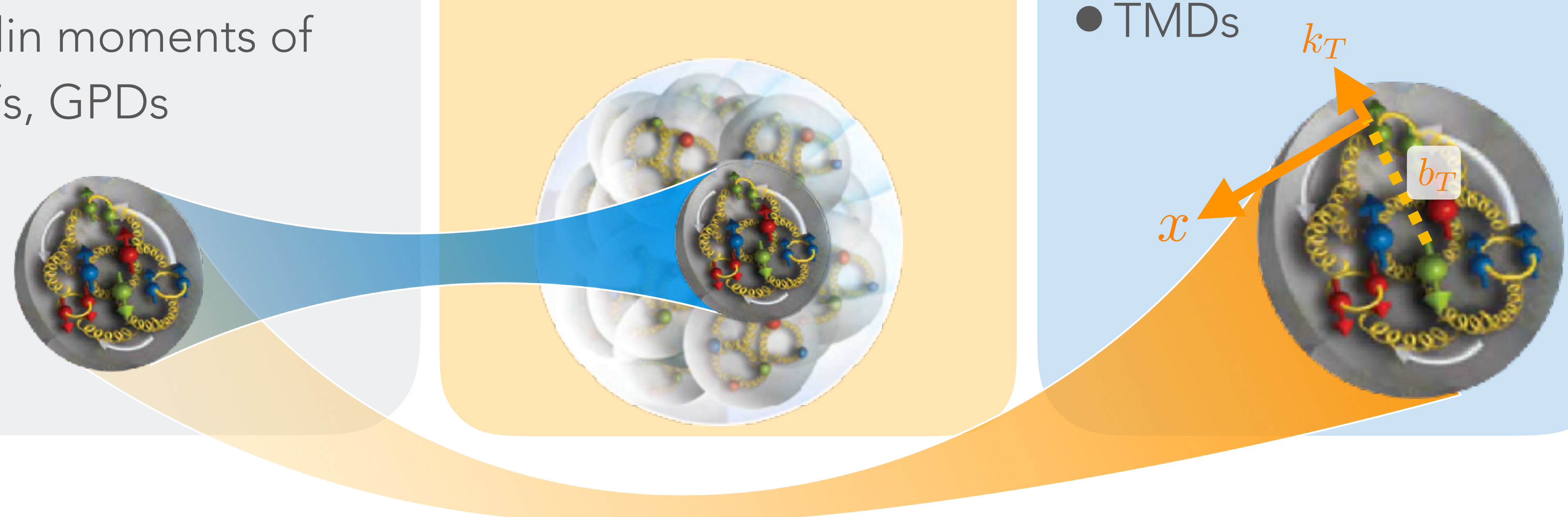
Fully-controlled w/ ~15—percent errors within ~5y

- Nuclear structure A<5
- Spin, flavour decomp. of EMC-type effects

Exploratory Era

First calculations, timeline for controlled calculations unclear

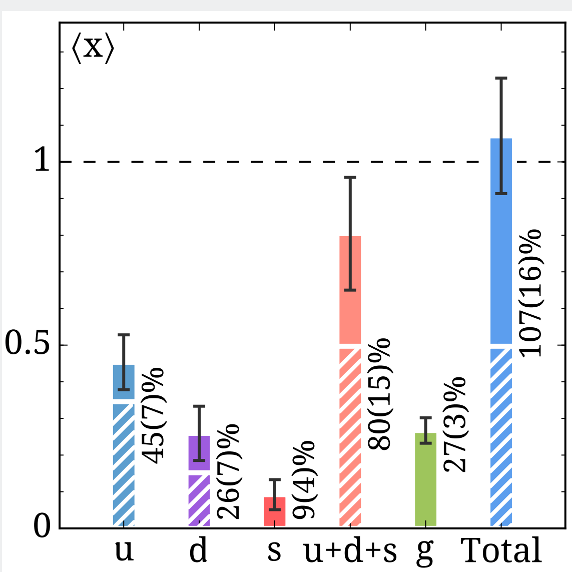
- x-dependence of PDFs
- TMDs



Prospects for CSV from Lattice QCD

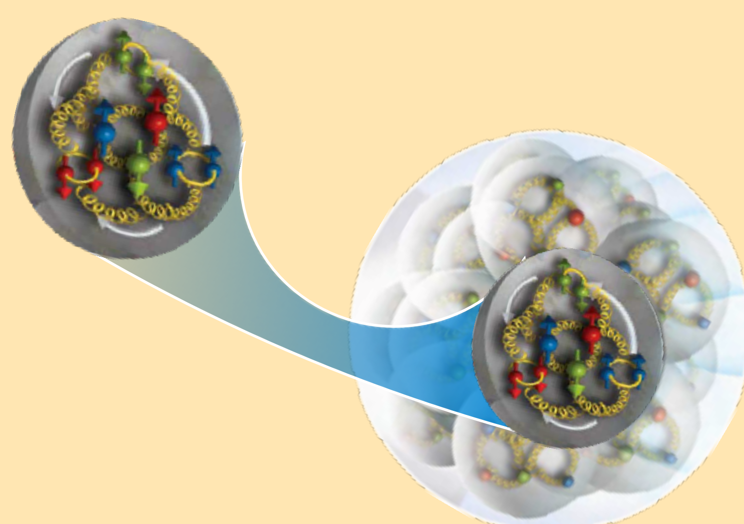
- State of the art lattice QCD calculations include QED and isospin breaking
  [M_n-M_p: Borsanyi *et al. Science* 347 (2015) 1452]
- On EIC timescale:

Low moments of CSV PDFs

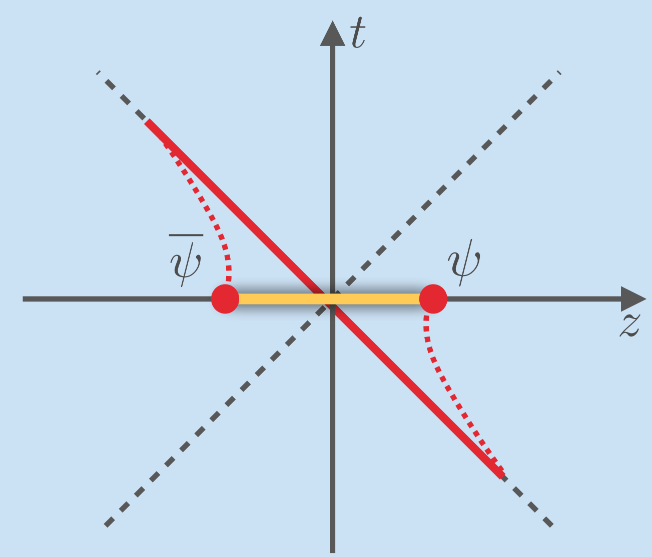


[C. Alexandrou et al., PRL 119 (2017)]

EMC effect in moments (isovector)



CSV PDFs including x-dependence



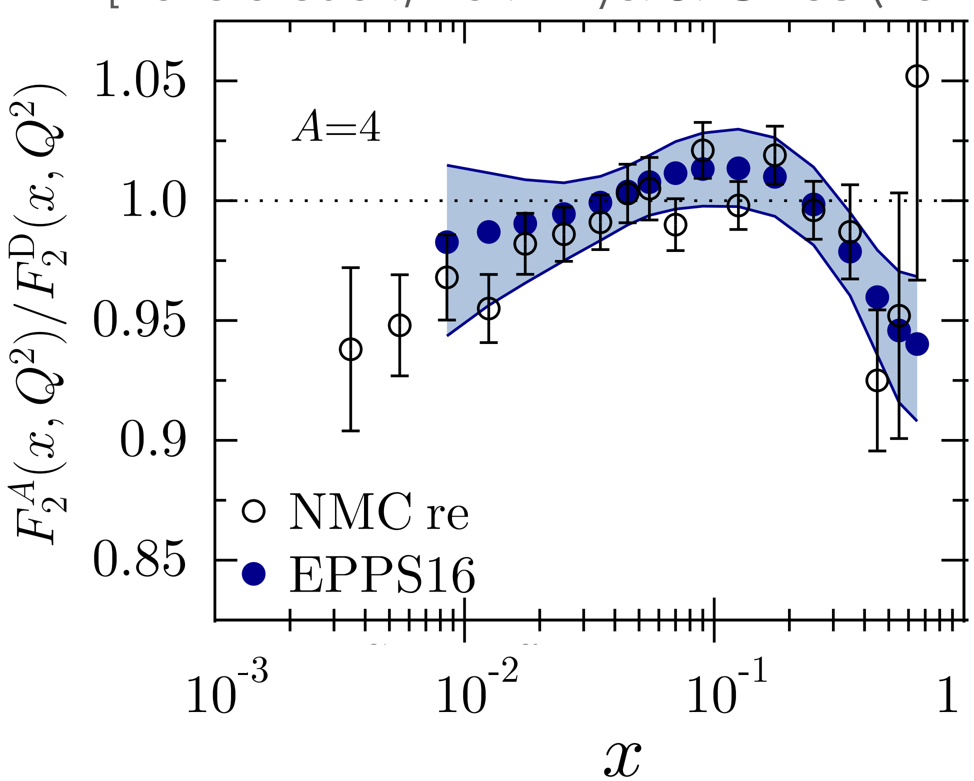
SPECULATIVE

EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- BUT EMC effects in moments are very small

[Eskola et al., Eur. Phys. J. C 163 (2017)]



Classic EMC effect is defined in F_2:

$$F_2(x,Q^2) = \sum_{q=u,d,s\ldots} x\, e_q^2 \left[q(x,Q^2) + \overline{q}(x,Q^2)\right]$$

Number density of partons of flavour q

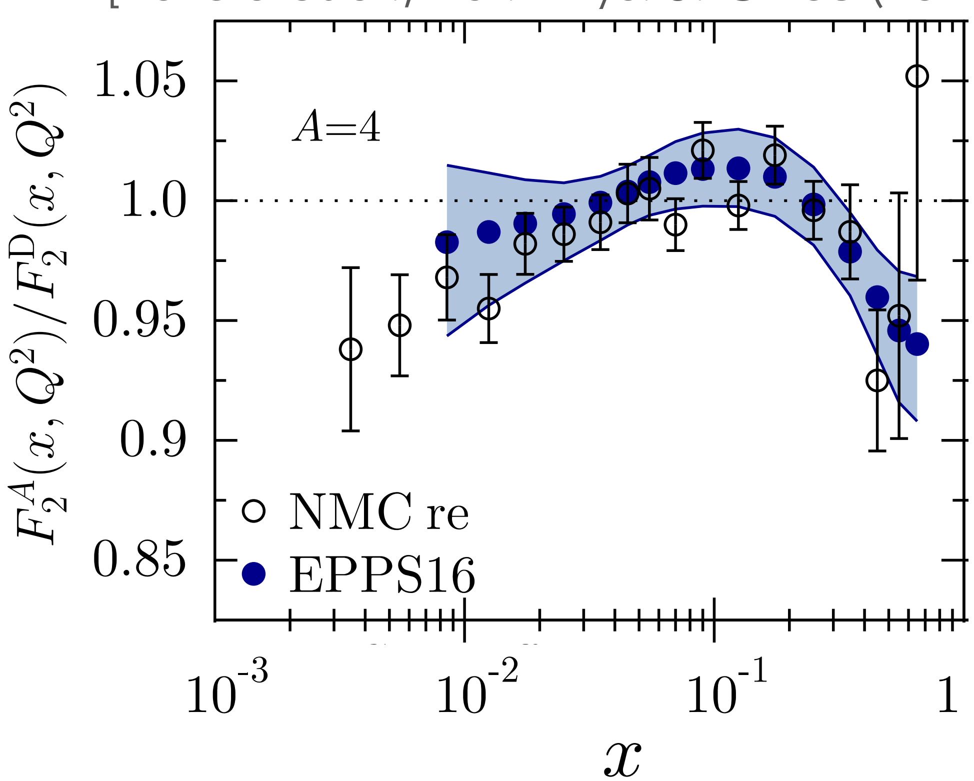
x-integrals of numerator and denominator $\int_0^1 dx\, x^n q(x,Q^2)$

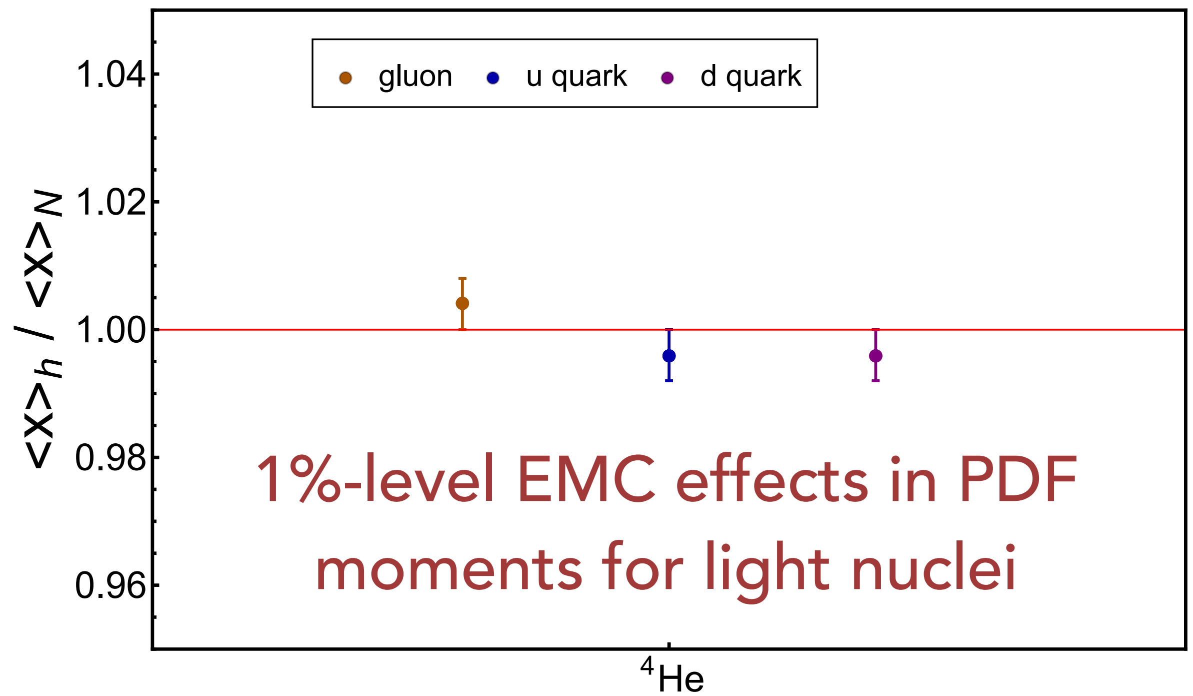
EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- BUT EMC effects in moments are very small

[Eskola et al., Eur. Phys. J. C 163 (2017)]





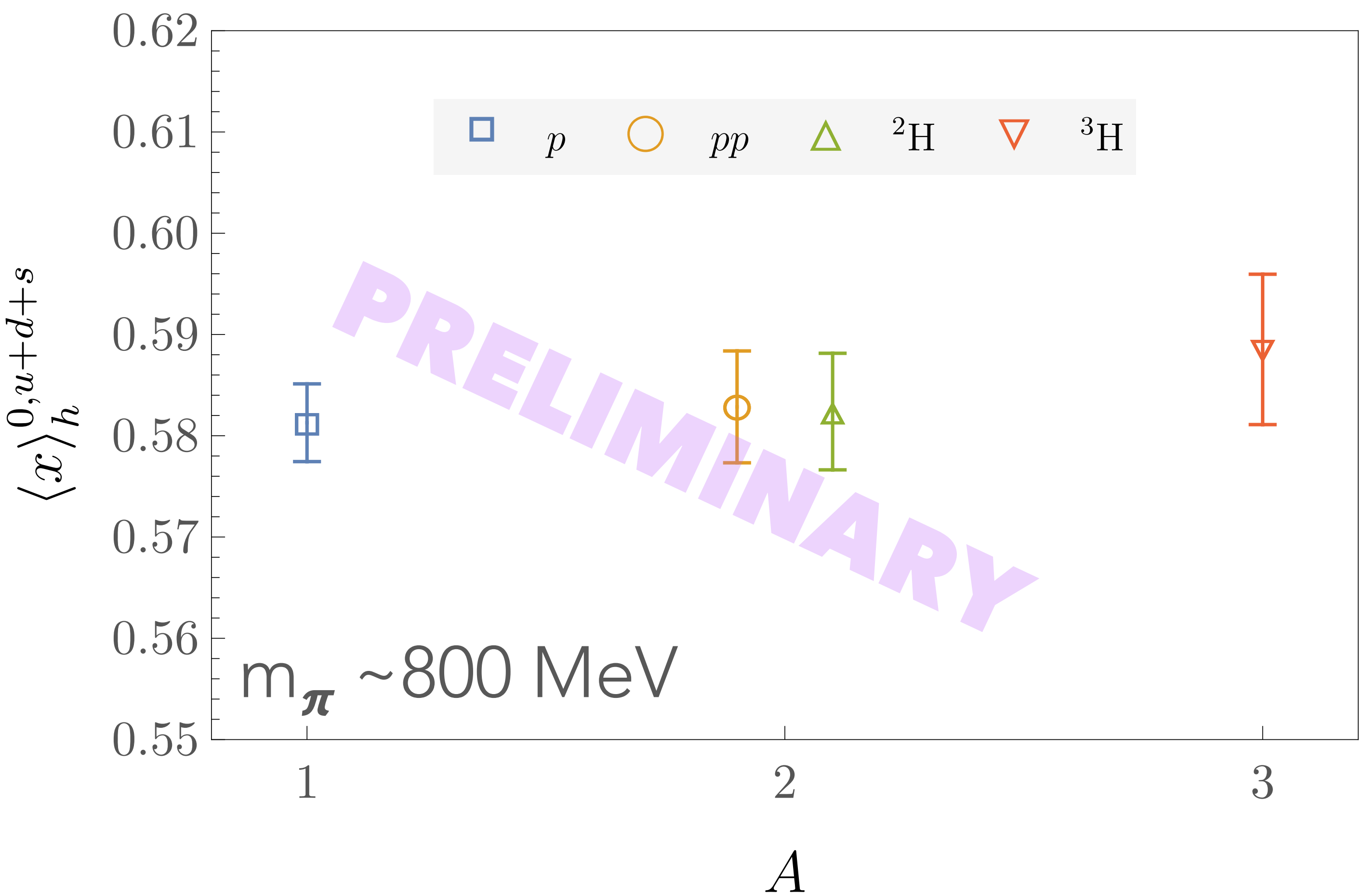
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

first QCD determination of momentum fraction of nuclei

- Few-percent determination of quark momentum fraction
  ~10% determination of strange quark contributions

Isoscalar
(BARE)

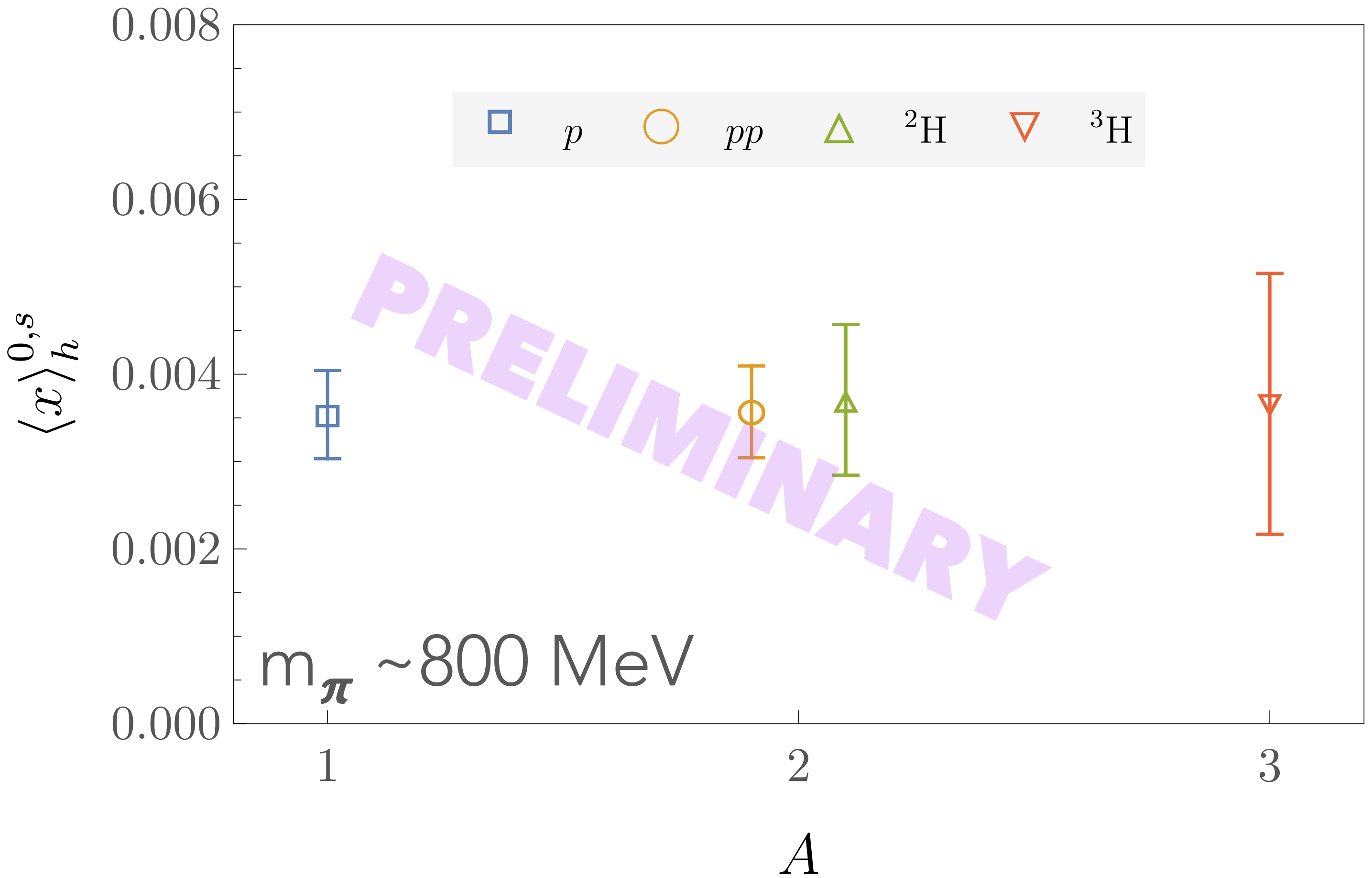


Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei
→ **first QCD determination of momentum fraction of nuclei**

- Few-percent determination of quark momentum fraction
  ~10% determination of strange quark contributions

Strange
(BARE)



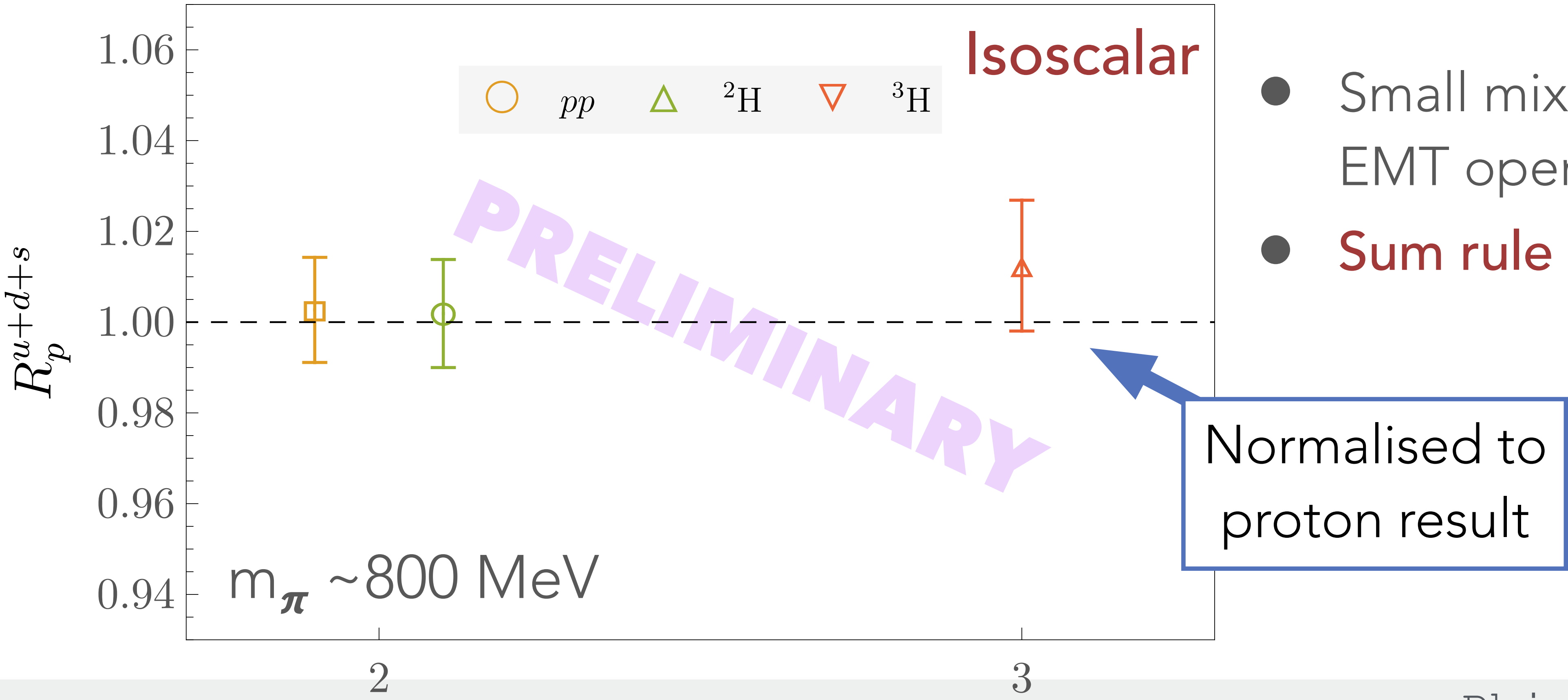
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

first QCD determination of momentum fraction of nuclei

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology

Ratio of quark momentum fraction in nucleus to nucleon



- Small mixing with gluon EMT operators (neglected)
- Sum rule constraint

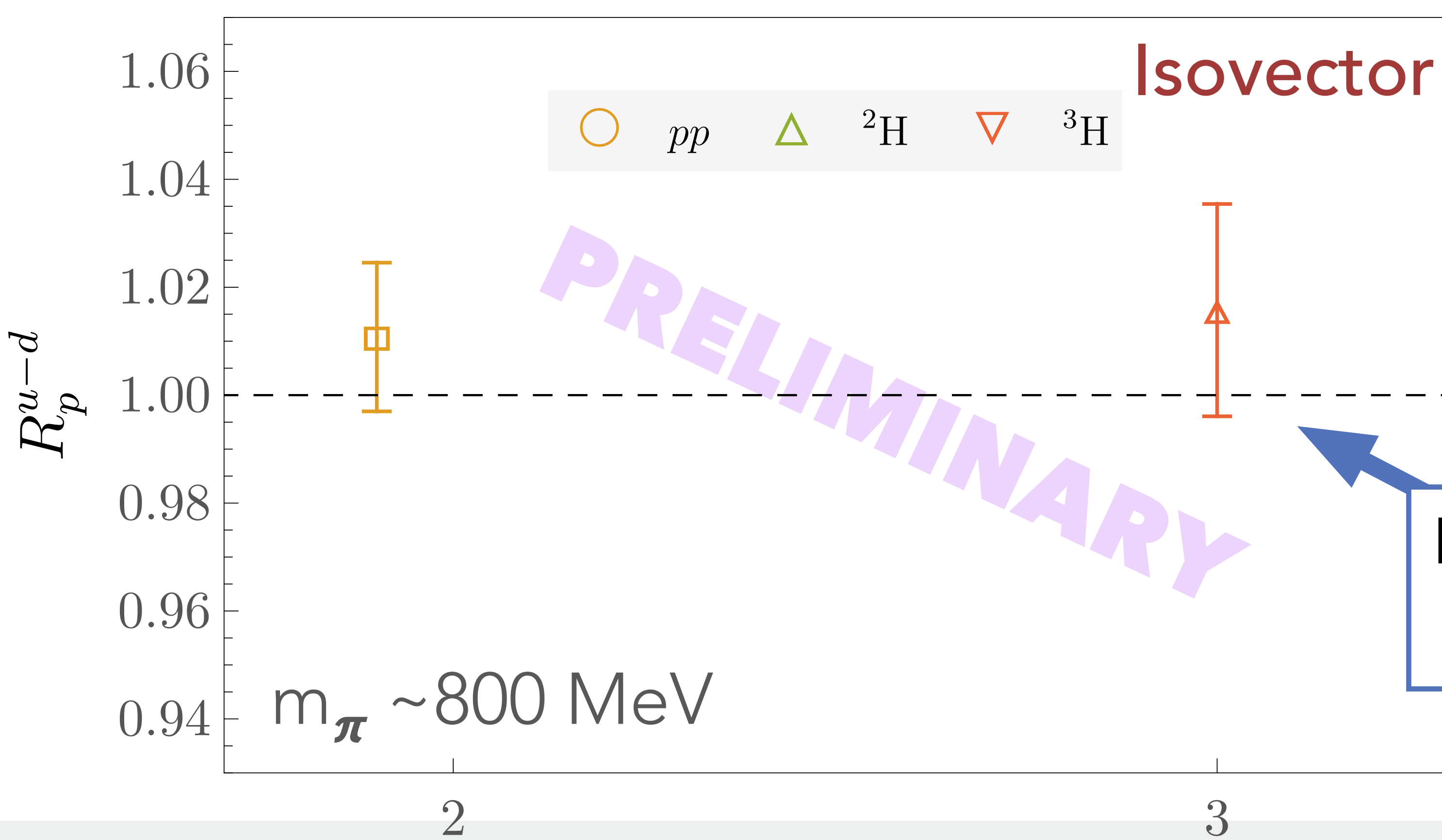
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

first QCD determination of momentum fraction of nuclei

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology

Ratio of quark momentum fraction in nucleus to nucleon

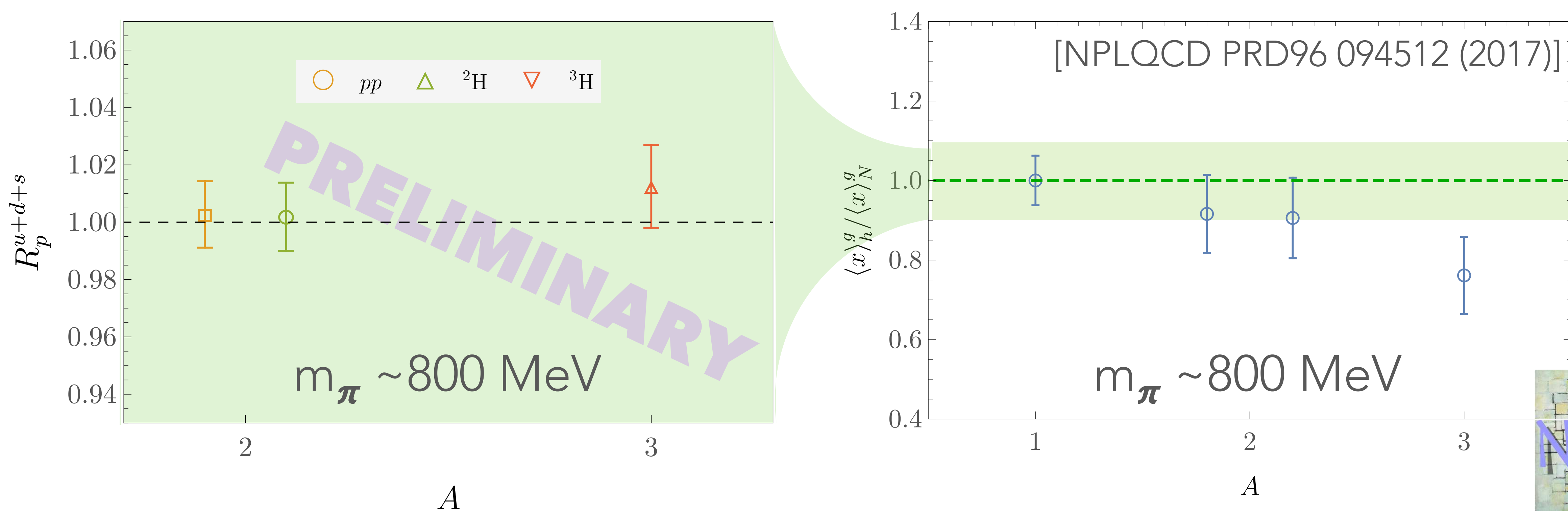


- No mixing
- No sum rule constraint

Normalised to proton result

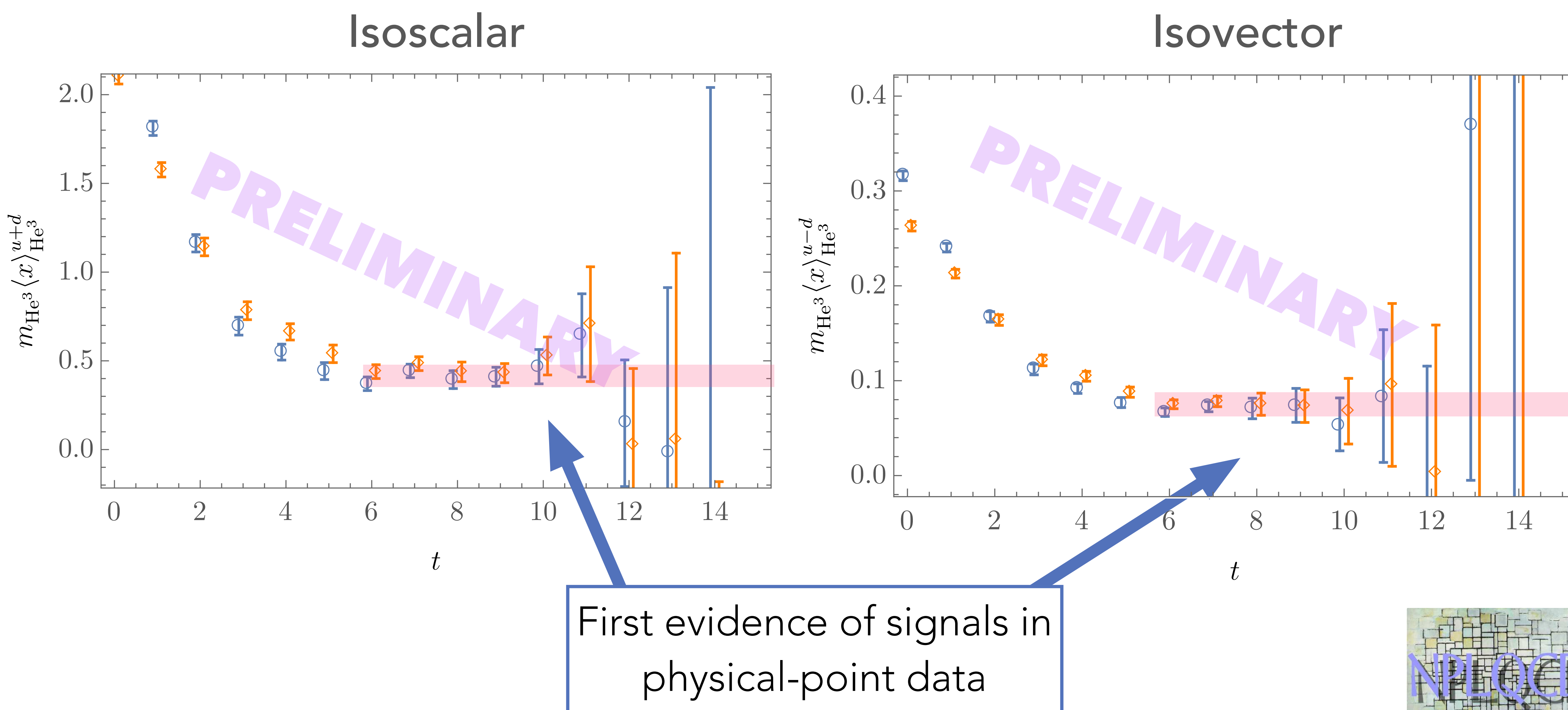
Momentum fractions of nuclei

- First determination of all components of momentum decomposition of light nuclei
- Small mixing between quark and gluon EMT operators neglected
- Constraint on either quark or gluon EMC in this quantity implies constraint on the other from sum rules:



Momentum fractions of nuclei

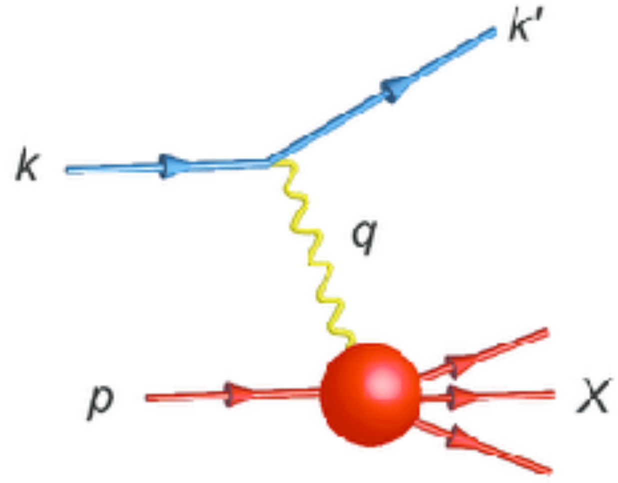
- Work in progress at close-to-physical values of the quark masses



NPLQCD

Implications of parton CSV at the EIC

(SI)DIS cross-sections at the EIC



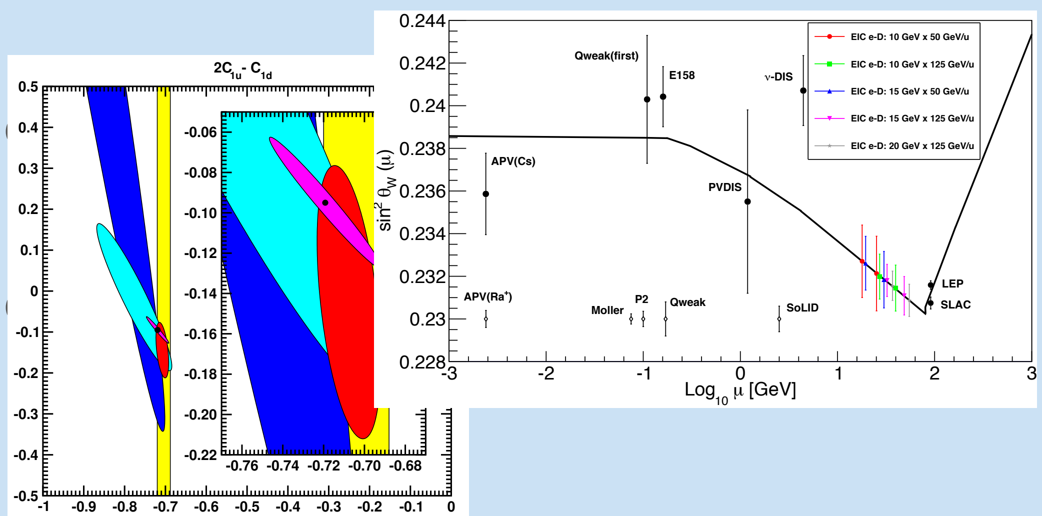
Constraints on nucleon and nuclear PDFs

Disentangle contributions from

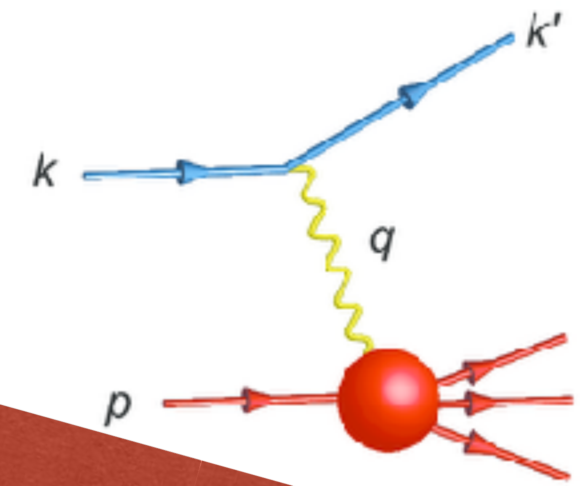
- CSV
- Heavy flavour
- Sea quarks
- Gluons
- Nuclear effects

Tests of the SM

via precision measurements of electroweak parameters



Implications of parton CSV at the EIC



ss-sections

CSV relevant in cross-sections/asymmetry measurements at the percent-level

Constr...

and nuclear PD...

Disentangle contributions from

- CSV
- Heavy flavour
- Sea quarks
- Gluons
- Nuclear effects

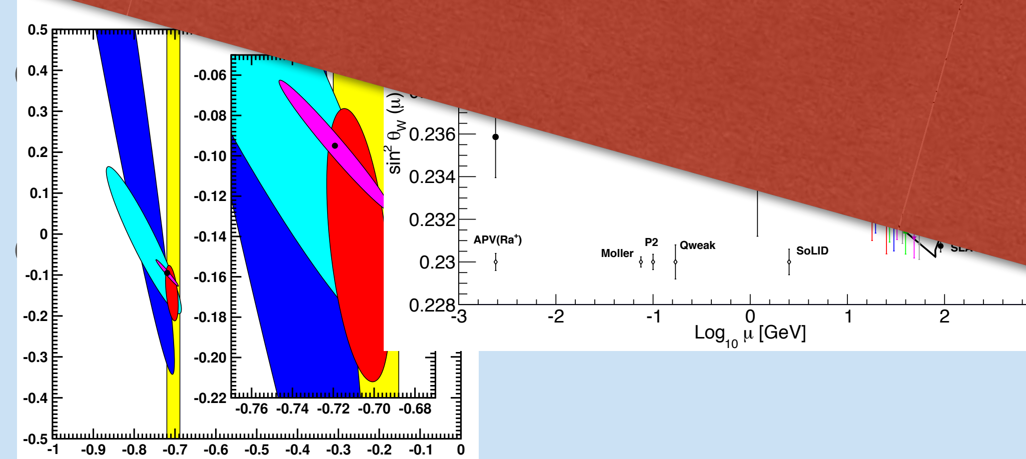


Image Credit: 2018 EIC User's Group Meeting