Parton charge symmetry violation

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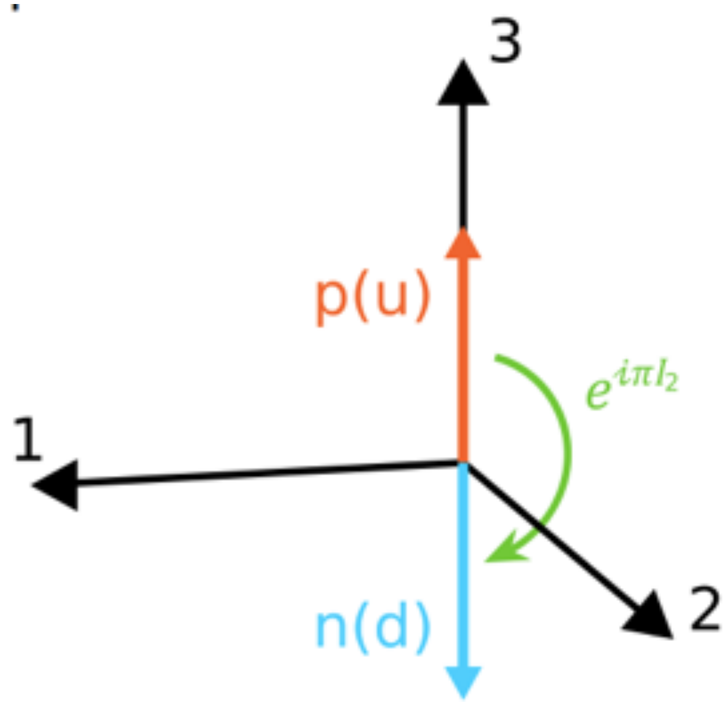
“Large (non-small) *x* at the EIC”,
4 October 2016
Jefferson Lab

Almost everything we know about the *up–down* flavour structure of the nucleon has used charge symmetry

Charge symmetry in partons

- Partonic charge symmetry relations

$$u^p(x) = d^n(x)$$
$$d^p(x) = u^n(x)$$



- Example:
  - Nucleon spin structure (quark-parton model):

$$\int_0^1 dx\, g_1^p(x) = \frac{1}{2}\int_0^1 \left[\frac{4}{9}\Delta u(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta s(x)\right]$$
$$\overset{\text{CS}}{\Longrightarrow} \int_0^1 dx\, g_1^n(x) = \frac{1}{2}\int_0^1 \left[\frac{1}{9}\Delta u(x) + \frac{4}{9}\Delta d(x) + \frac{1}{9}\Delta s(x)\right]$$

$$\Delta d^{(n)} \overset{\text{CS}}{=} \Delta u^{(p)} \equiv \Delta u, \text{ etc.}$$

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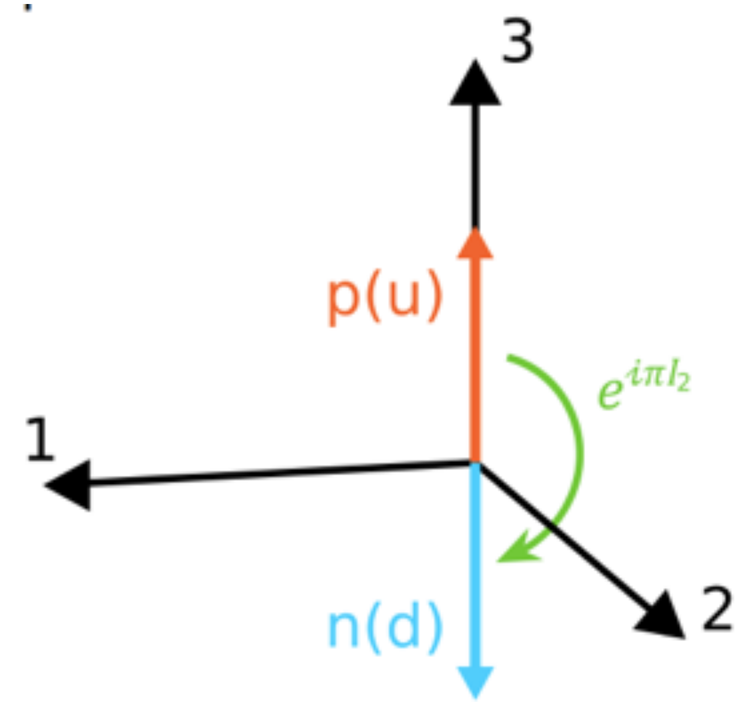

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$$\Delta d^{(n)} \stackrel{\text{CS}}{=} \Delta u^{(p)} \equiv \Delta u, \text{ etc.}$$

Further flavour separation from e.g. hyperon beta decay

Charge symmetry **violation** in partons

- Define CSV terms:

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

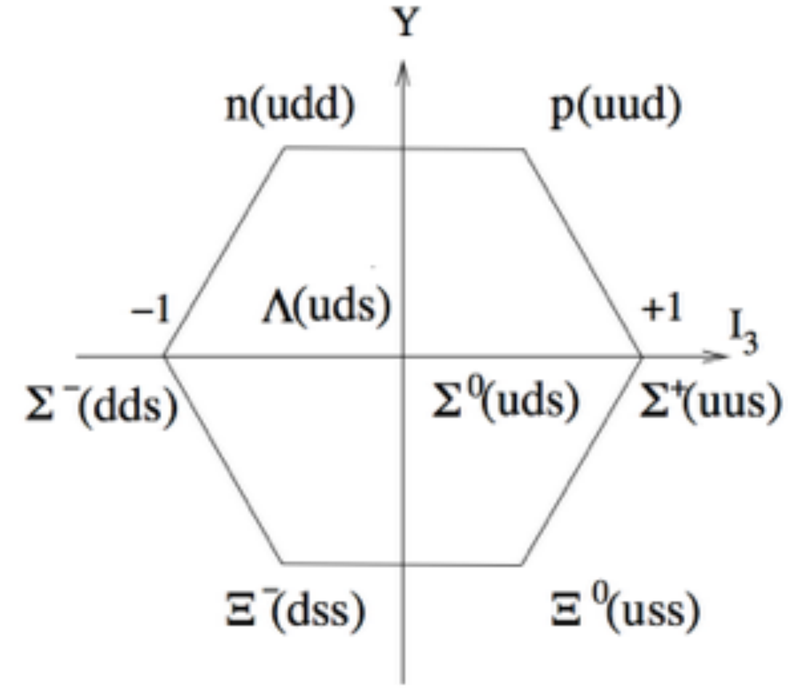
- Two dominant sources of CSV:

$$m_u \neq m_d \qquad\qquad Q_u \neq Q_d$$

Quark masses → Lattice

QED → photon radiation

Hyperon PDF moments



- Start from **exact** SU(3) symmetric point

$$\langle x \rangle_u^p = \langle x \rangle_u^{\Sigma^+} = \langle x \rangle_s^{\Xi^0}$$

- Determine small perturbations

$$\frac{\partial \langle x \rangle_u^p}{\partial m_u} \simeq \frac{\langle x \rangle_s^{\Xi^0} - \langle x \rangle_u^p}{m_s - m_l}, \qquad \frac{\partial \langle x \rangle_u^p}{\partial m_d} \simeq \frac{\langle x \rangle_u^{\Sigma^+} - \langle x \rangle_u^p}{m_s - m_l}$$

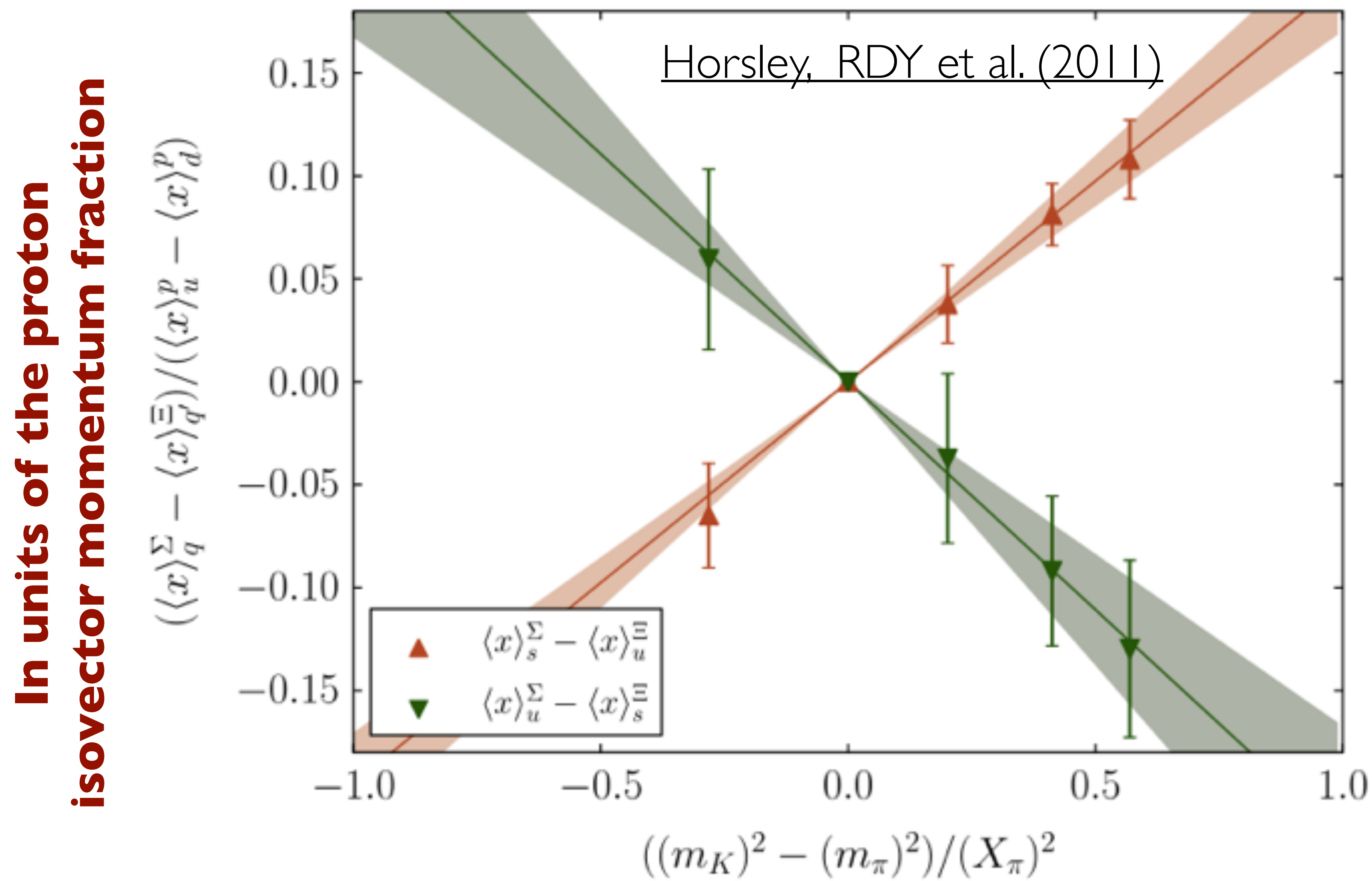
$$\Rightarrow \ \langle x \rangle_{\delta u} \simeq m_\delta \left[-\frac{\partial \langle x \rangle_u^p}{\partial m_u} + \frac{\partial \langle x \rangle_u^p}{\partial m_d} \right] \simeq m_\delta \frac{\langle x \rangle_u^{\Sigma^+} - \langle x \rangle_s^{\Xi^0}}{m_s - m_l}$$

$$m_\delta \equiv (m_d - m_u)$$

Consider hyperon moments about SU(3) symmetric point

Partonic charge symmetry violation

- Lattice results for quark-mass dependence of hyperon momentum fractions

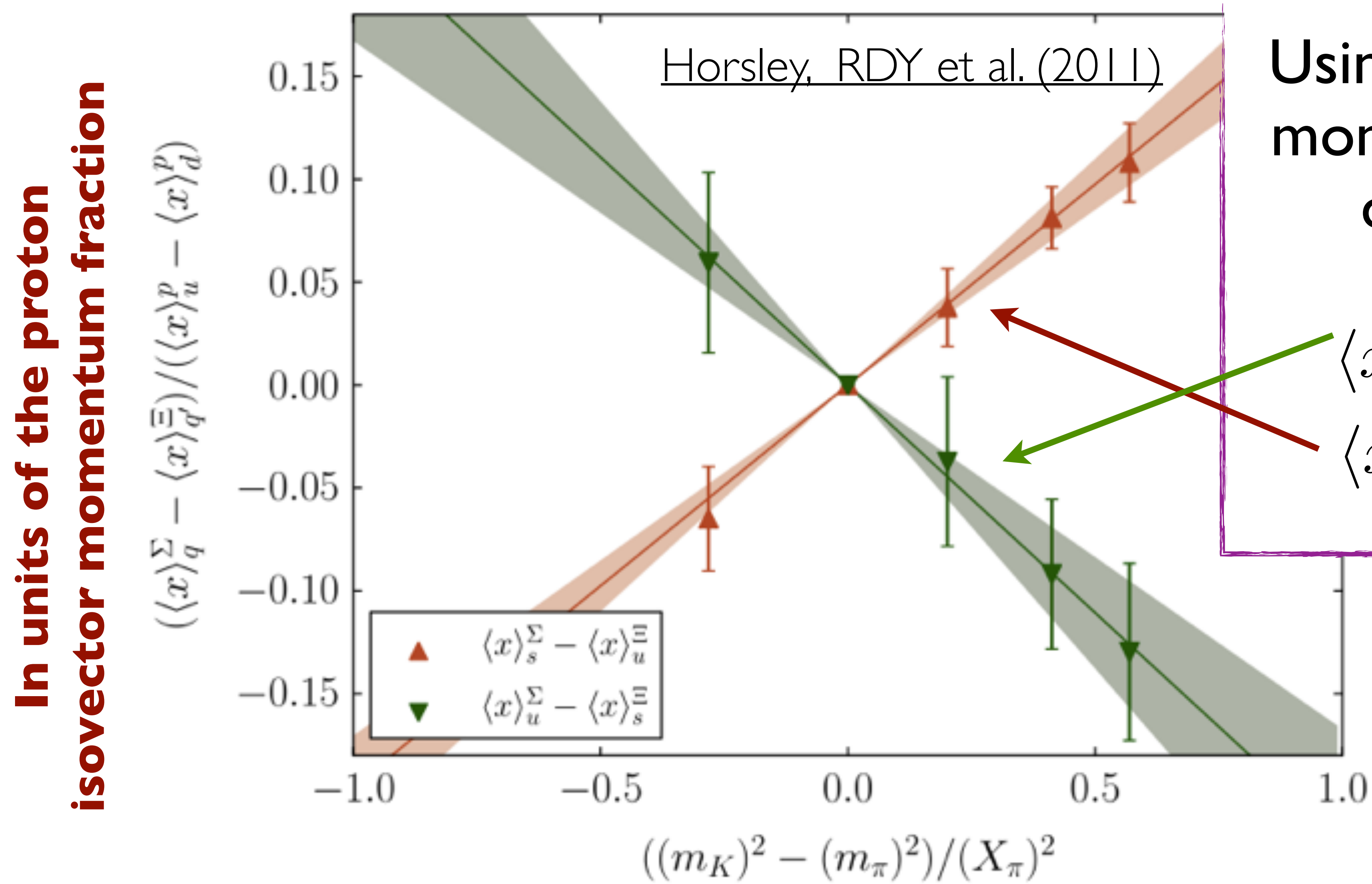


Slopes determine CSV at SU(3) symmetric point

Lattice: $\langle x^{m-1}\rangle_q = \int_0^1 dx\, x^{m-1}\,[q(x) + (-1)^m \overline{q}(x)]$

Partonic charge symmetry violation

- Lattice results for quark-mass dependence of hyperon momentum fractions



Using phenomenological momentum fraction and quark mass ratio:

$$\langle x\rangle_{\delta u} = -0.0012(3)$$

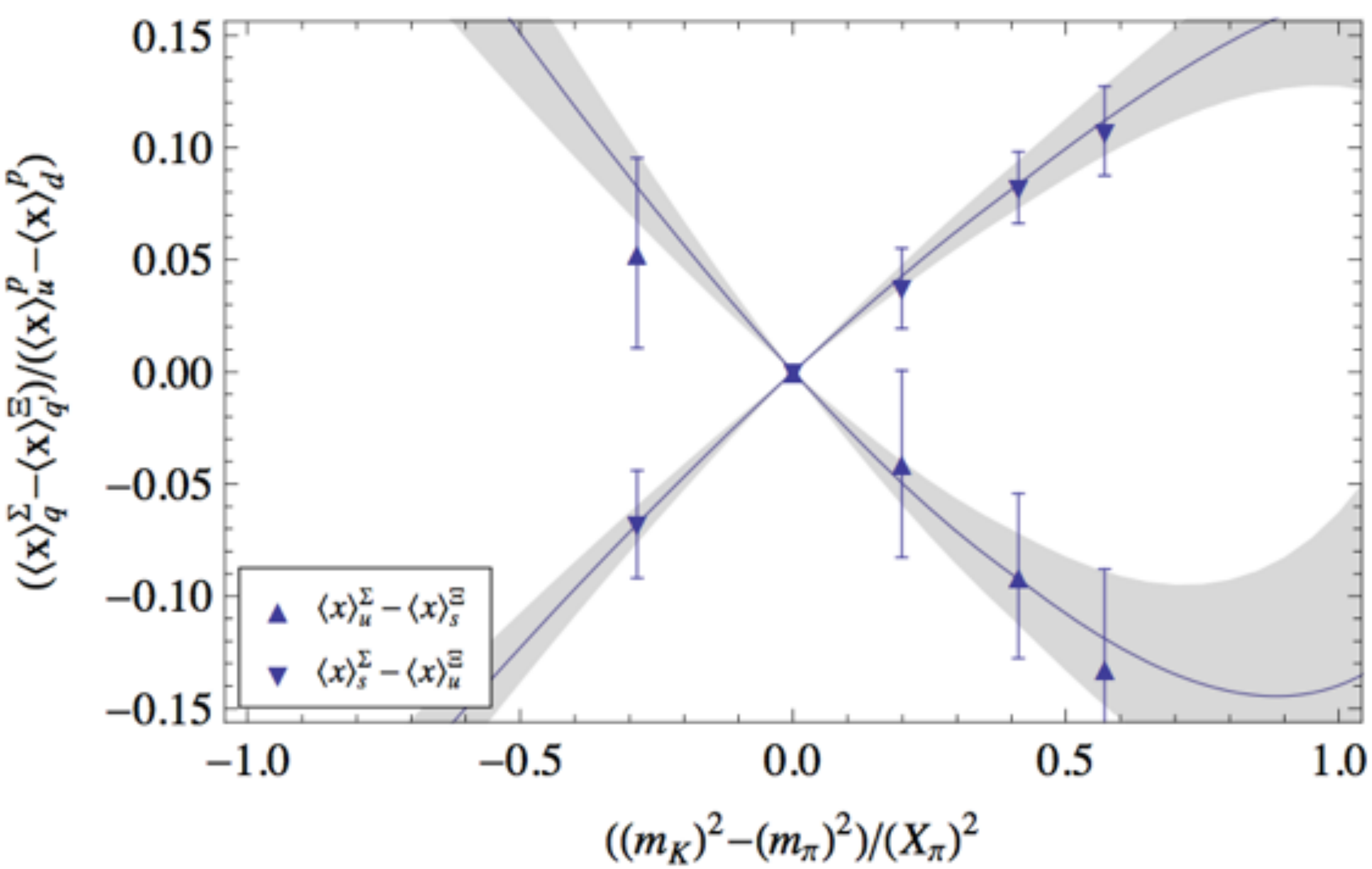
$$\langle x\rangle_{\delta d} = 0.0010(2)$$

Slopes determine CSV at SU(3) symmetric point

Lattice: $\langle x^{m-1}\rangle_q = \int_0^1 dx\, x^{m-1}\, [q(x) + (-1)^m \overline{q}(x)]$

Chiral extrapolation of CSV

- SU(3) chiral EFT formalism to extrapolate to physical quark masses



$\sim 0.7\text{–}1\%$

Shanahan, Thomas & RDY, PRD(2013)094515

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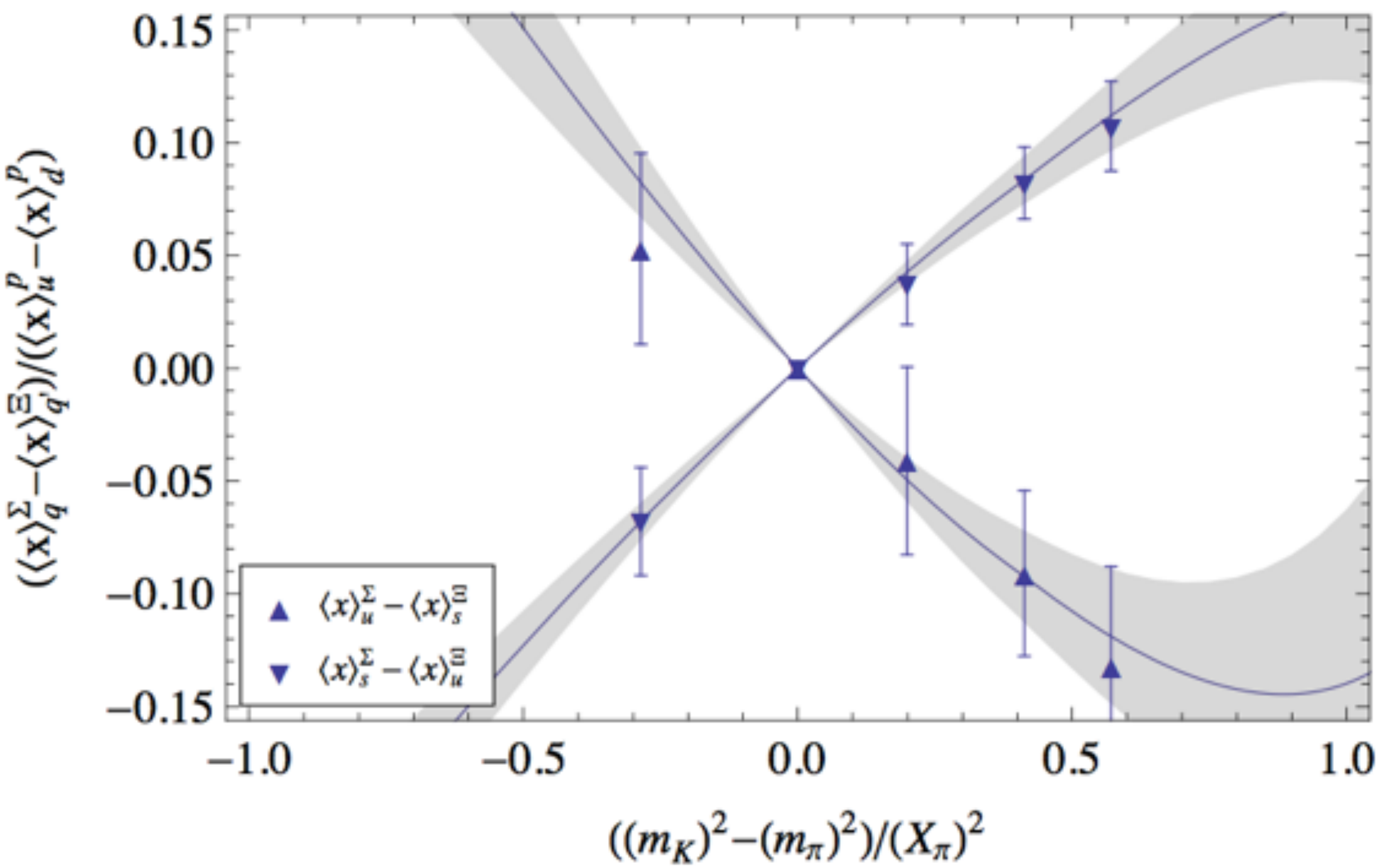


Our result

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

$$\langle x\rangle_{\delta d} = 0.0017(4)$$

$$\sim 0.7\text{–}1\%$$

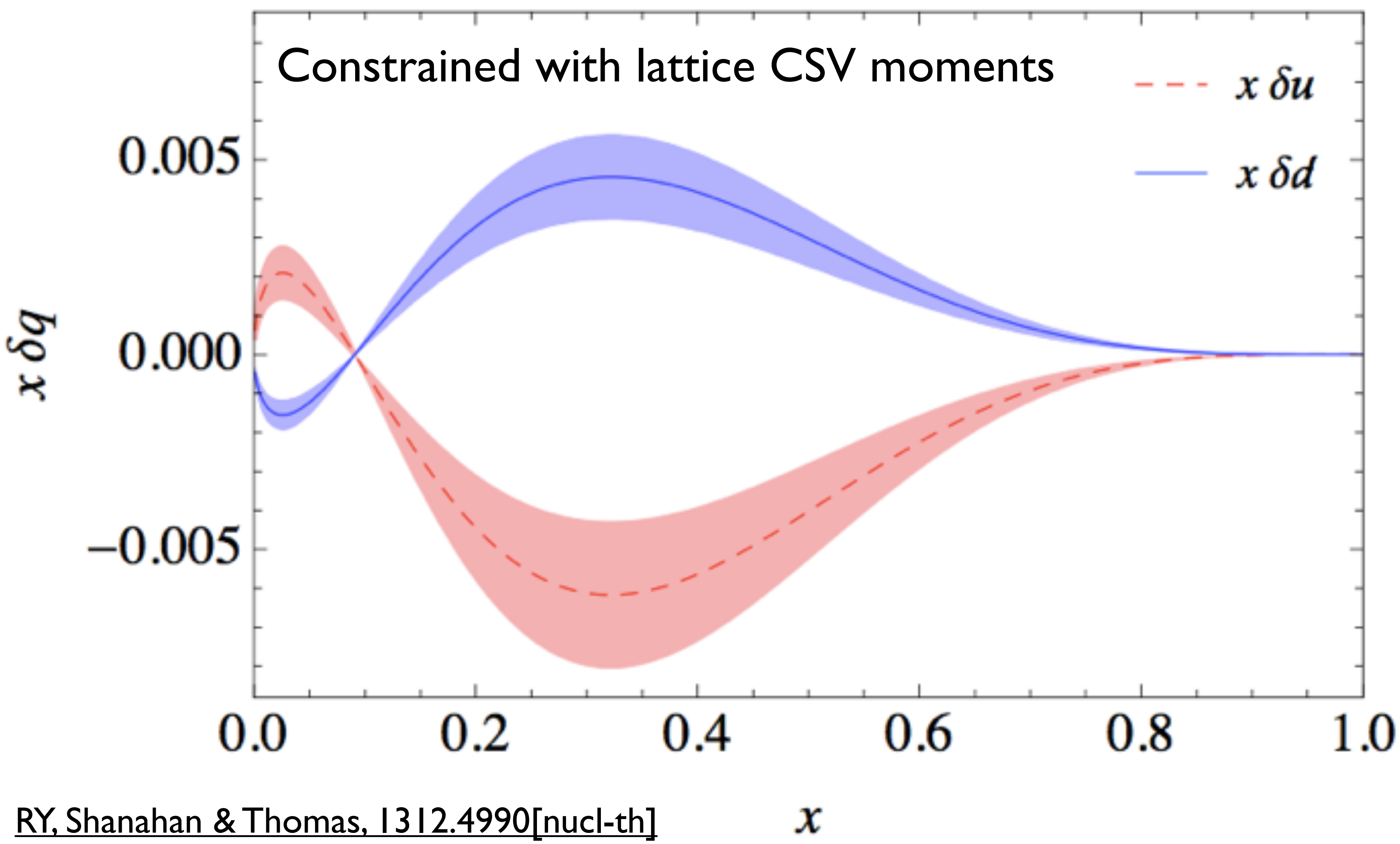
Shanahan, Thomas & RDY, PRD(2013)094515

CSV “distributions”

- We only have one moment from the lattice 

- Simple parameterisation: MRST2004

$$\langle x \rangle_{\delta q} = \kappa_q \, x^{-1/2} (1-x)^4 (x - 1/11)$$

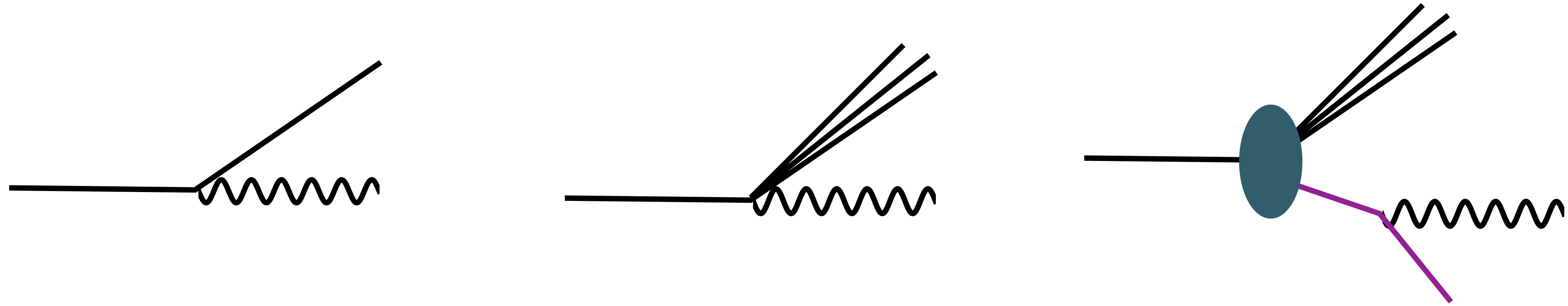


RY, Shanahan & Thomas, 1312.4990[nucl-th]

QED contribution & photon radiation?

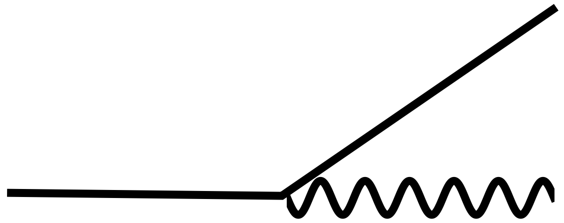
How bright is the proton?

Manohar *et al*. arXiv:1607.04266

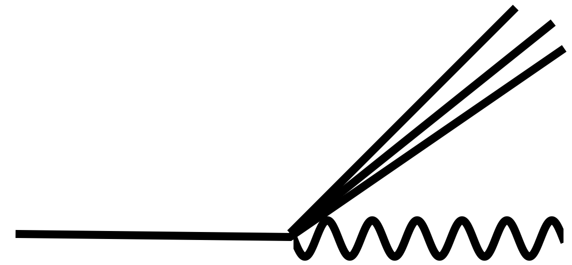


Elastic Inelastic Partonic

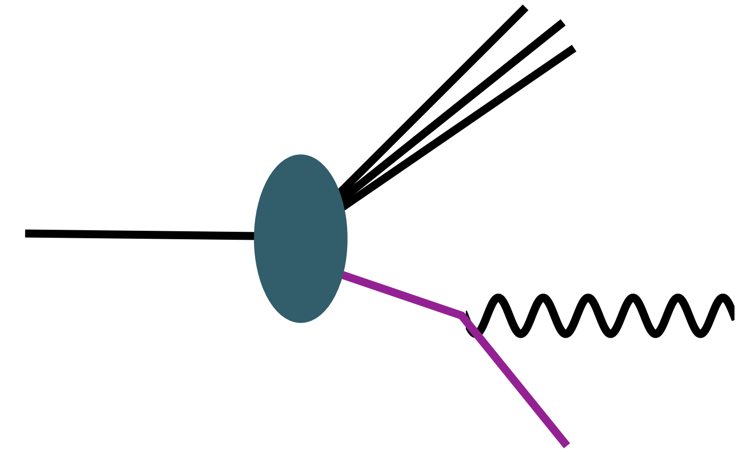
Manohar *et al*. arXiv:1607.04266



Elastic

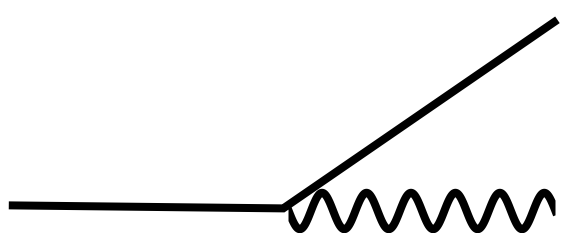


Inelastic

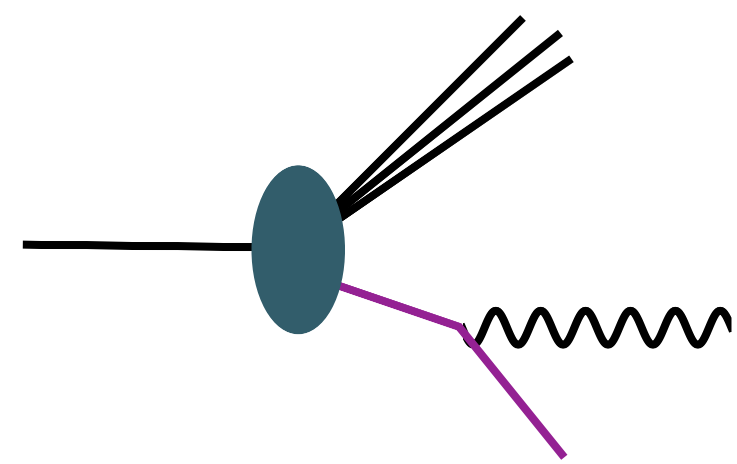


Partonic

Martin & Ryskin, EPJC(2014)



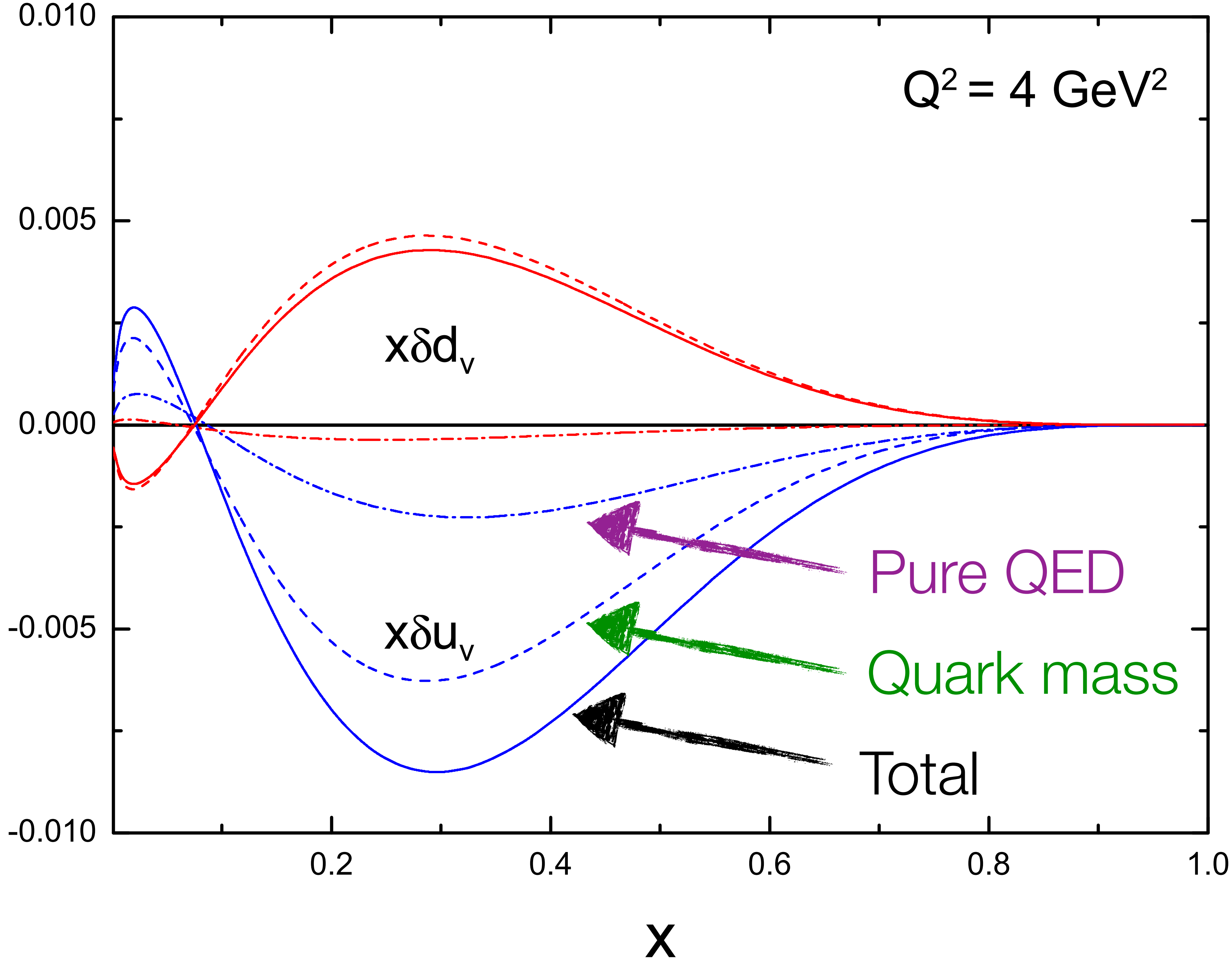
Elastic



Partonic

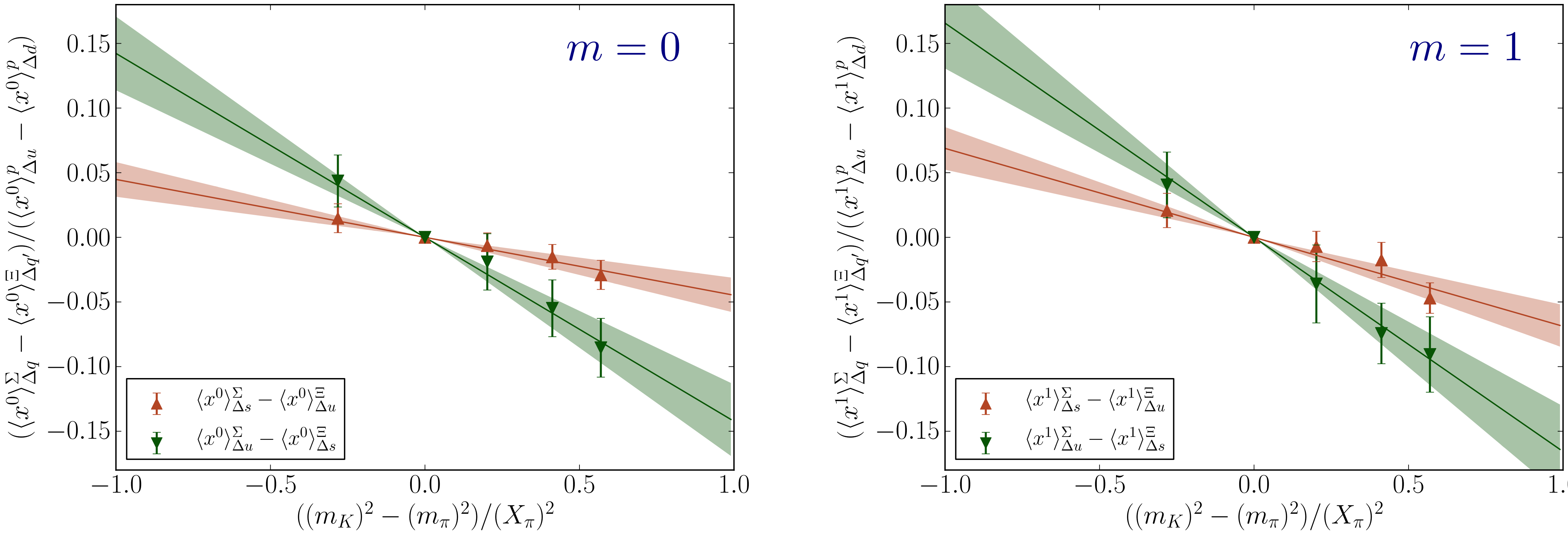
Including photon radiation in the quark CSV terms

(Martin & Ryskin model)



X.-G. Wang, Thomas & RDY, PLB(2016)

Spin dependent



Cloët, RDY et al., PLB(2012)

$$\langle x^m \rangle_{\Delta q} = \int_0^1 dx\, x^m \left[\Delta q(x) + (-1)^m \Delta\bar{q}(x)\right]$$

with chiral EFT analysis: Shanahan, RDY & Thomas, PRD(2013)

$$\delta\,\Delta u^{0+} = -0.0061(13)$$
$$\delta\,\Delta d^{0+} = -0.0018(6)$$
$$\delta\,\Delta u^{1-} = -0.0007(2)$$
$$\delta\,\Delta d^{1-} = -0.0002(1)$$

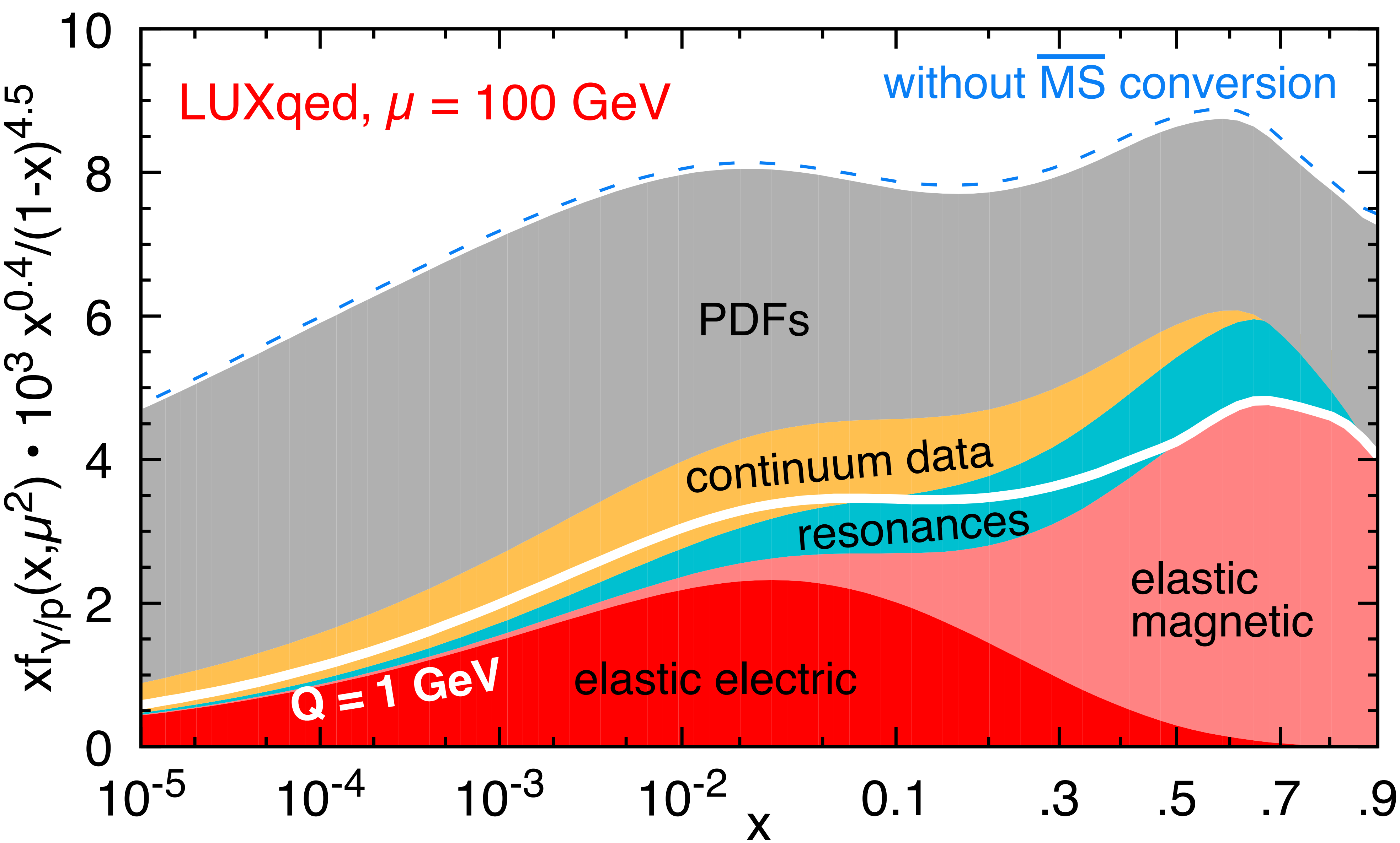
~0.5% correction to Bjorken sum rule

Questions?

- Lattice & the future?

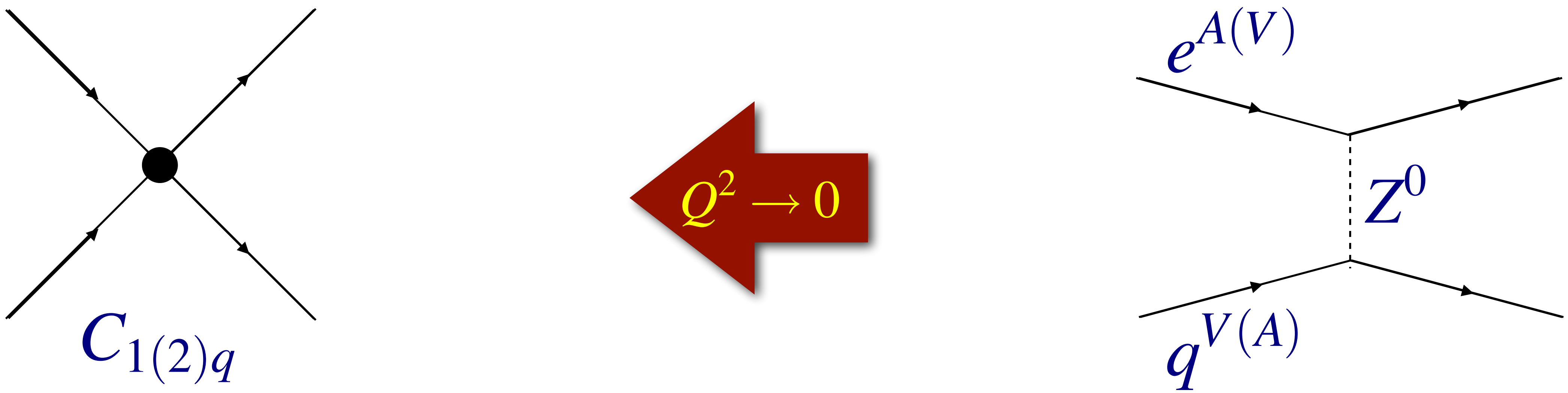
  lattice spacing; volume; quark mass

  - Another non-trivial moment (higher moments challenging)
  - QED effects in lattice simulations
    - we’re already attempting the photon momentum fraction!
- PVDIS @12GeV
  - What will be known/constrained by 12 GeV parity program?
  - Could we use e.g. moment normalisation from lattice QCD with parity measurements to constrain shape?
- Not small *x* @ EIC
  - Are there opportunities to isolate these effects?
  - Limitations of physics interpretation from CSV?

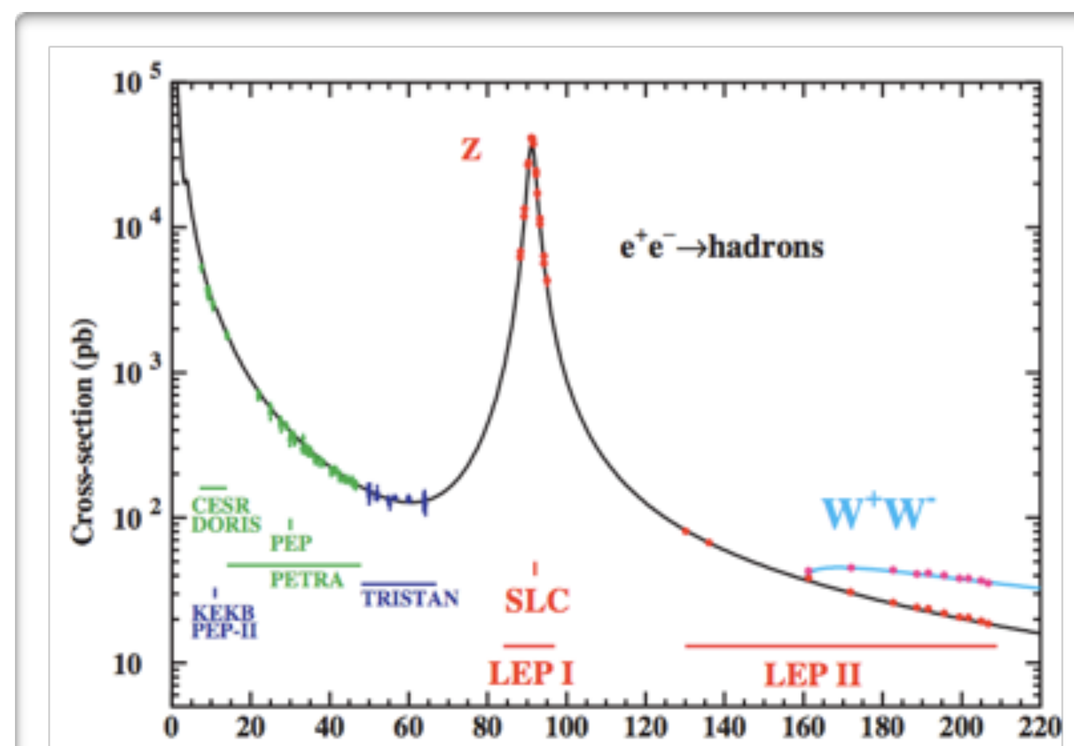


Photon PDF: Manohar *et al*. arXiv:1607.04266

Effective weak interaction



Precision *Z*-pole measurements [LEP]



ALEPH *et al.*, [2006]

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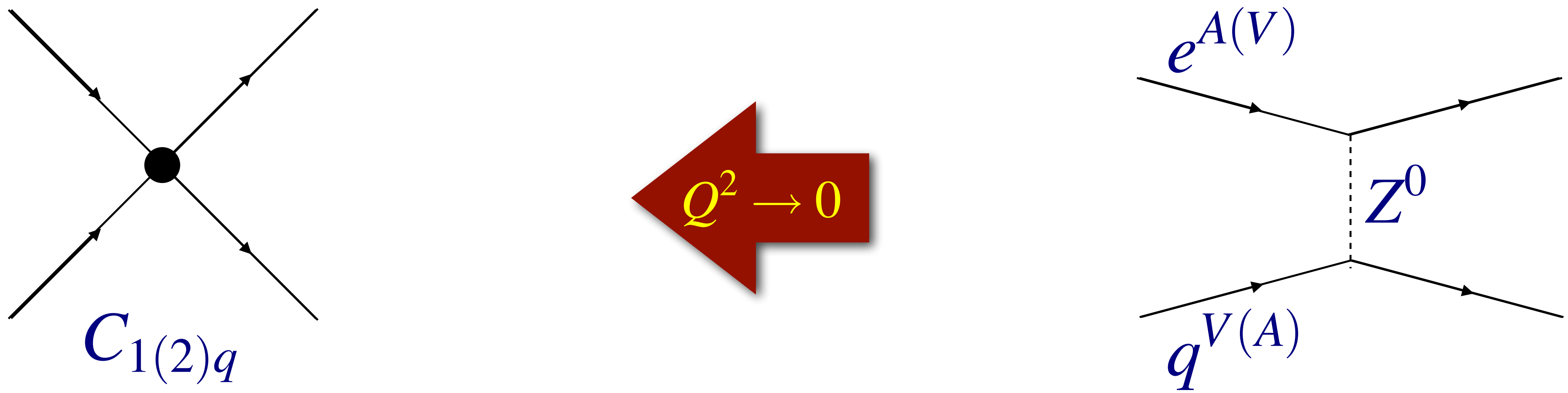

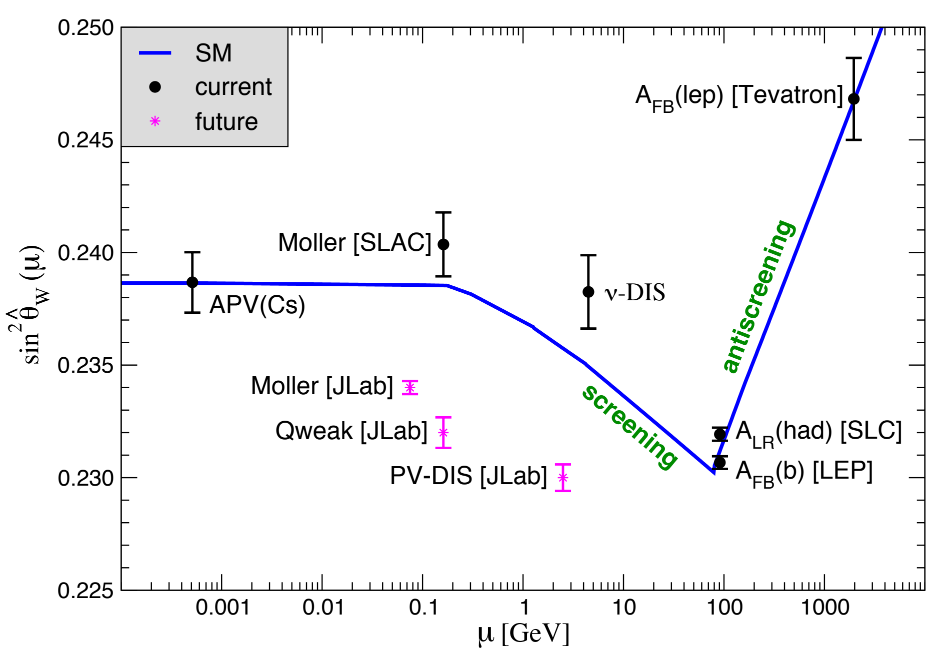

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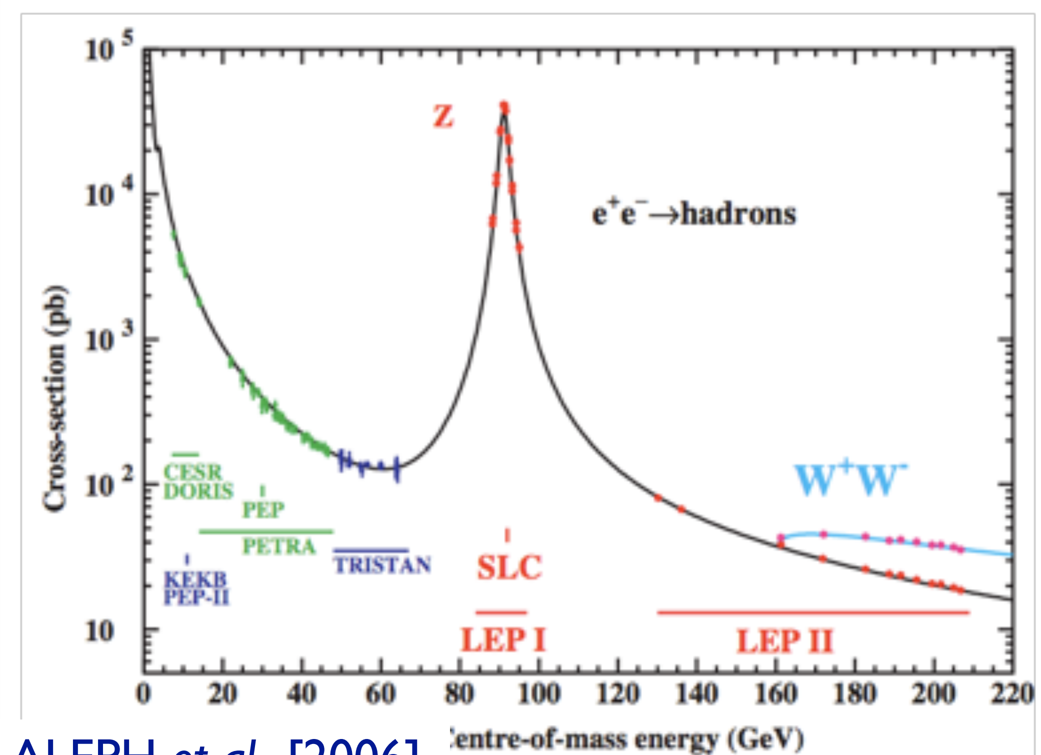

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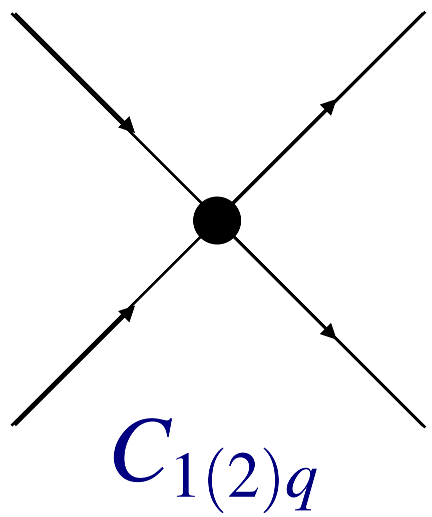
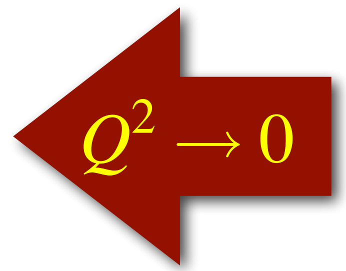
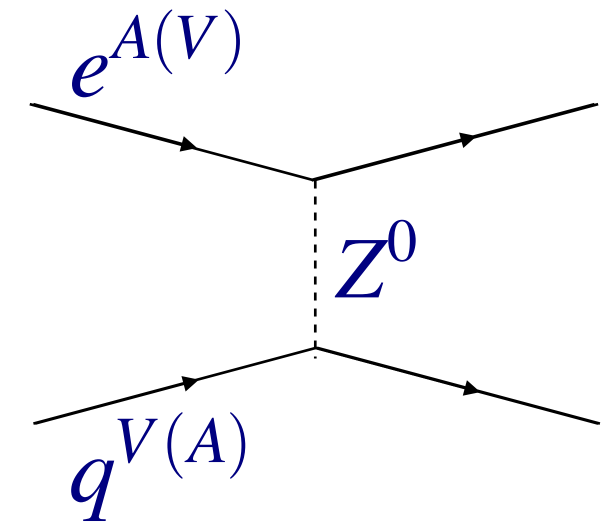
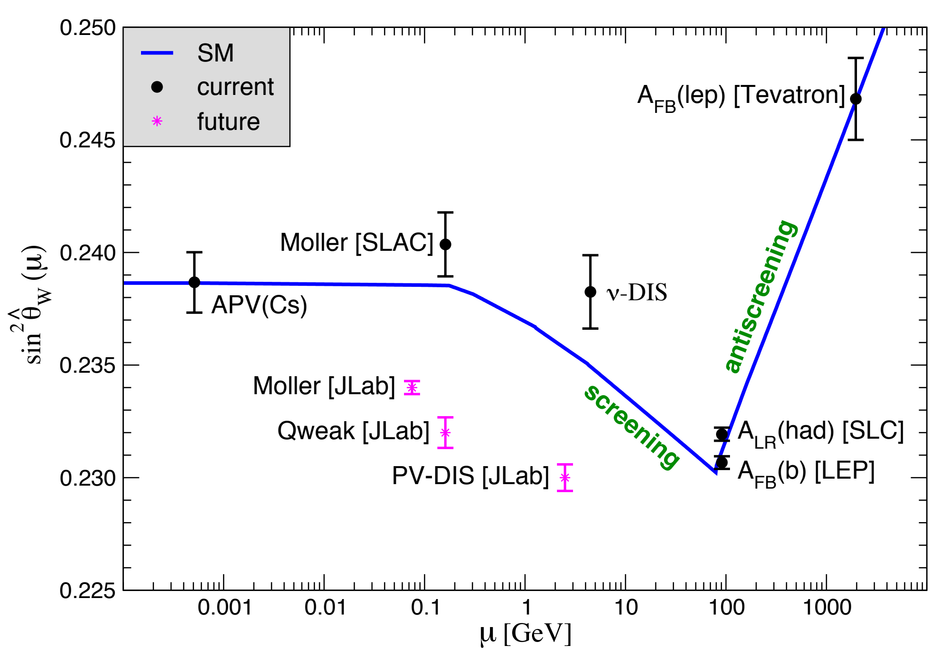






$$\mathcal{L}^{PV}_{(q)} = \frac{G_F}{\sqrt{2}}\left[C_{1q}\bar{q}\gamma^{\mu}q\,\bar{e}\gamma_{\mu}\gamma_5 e + C_{2q}\bar{q}\gamma^{\mu}\gamma_5 q\,\bar{e}\gamma_{\mu}e\right]$$



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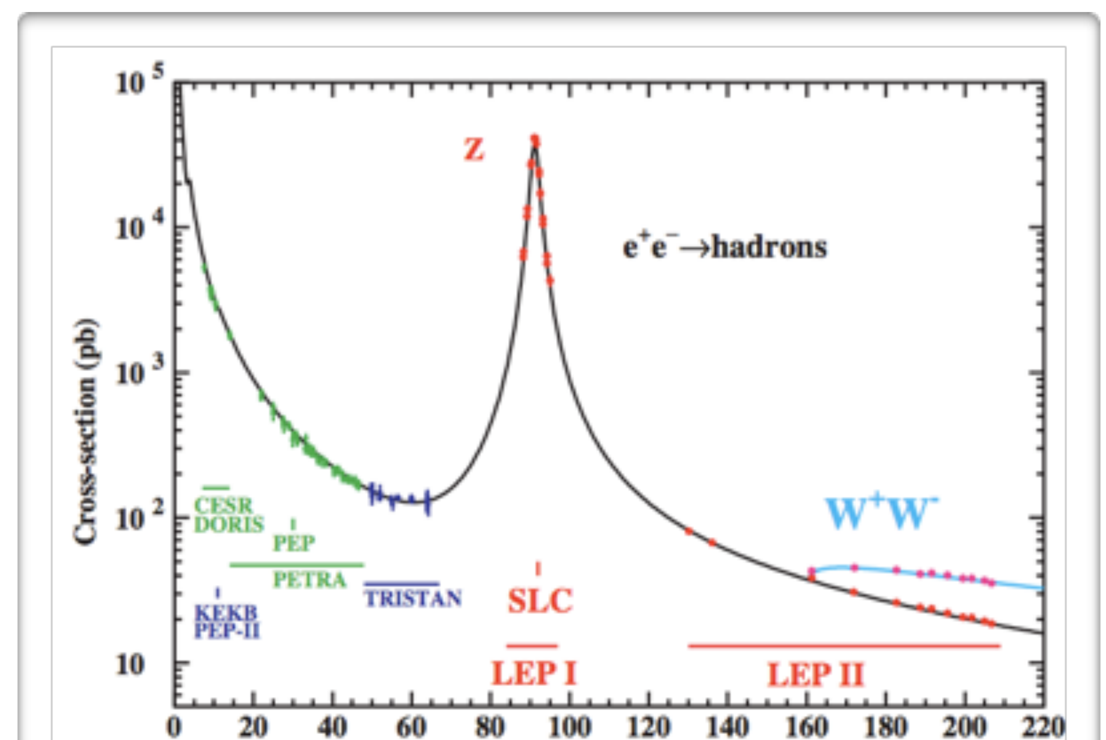

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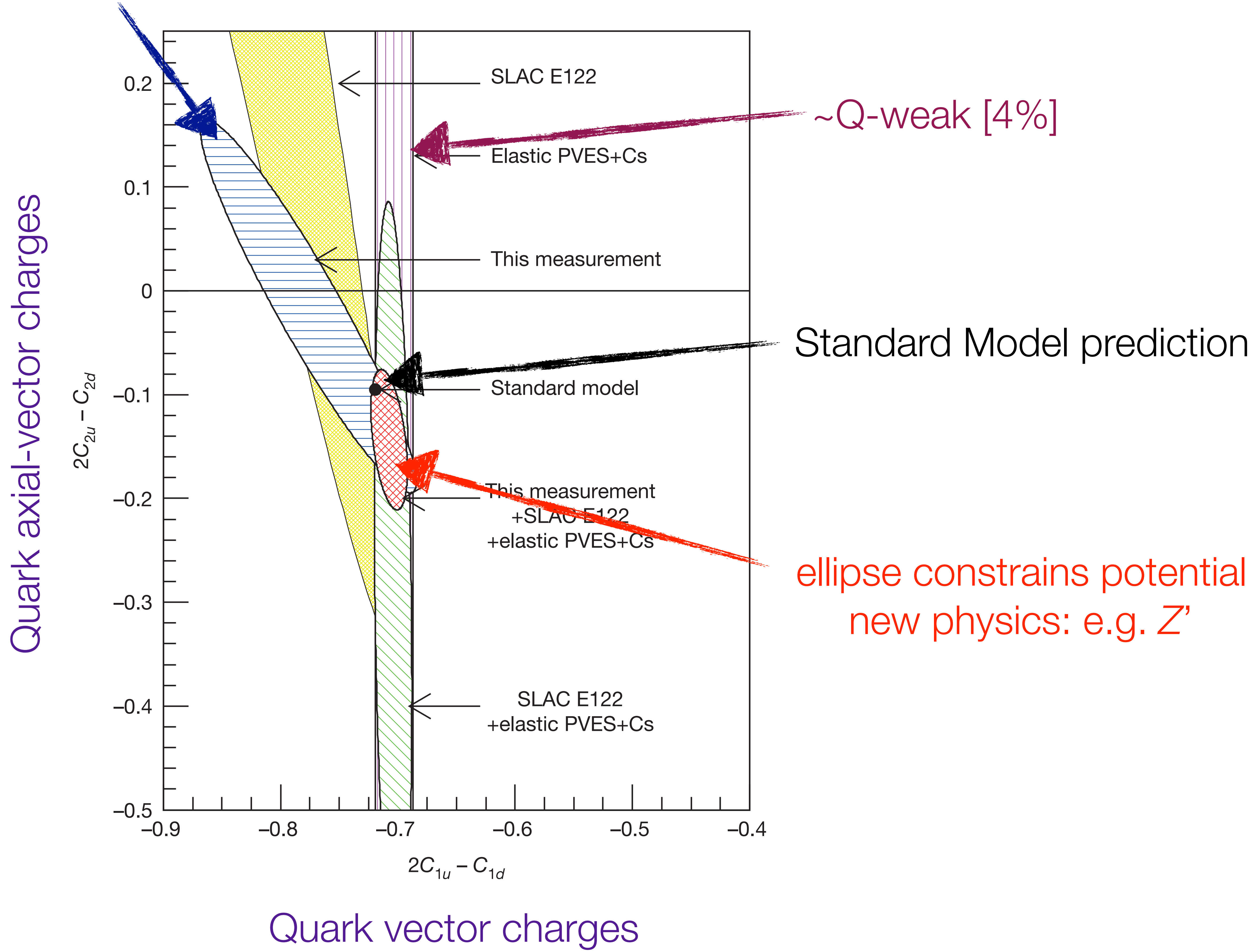
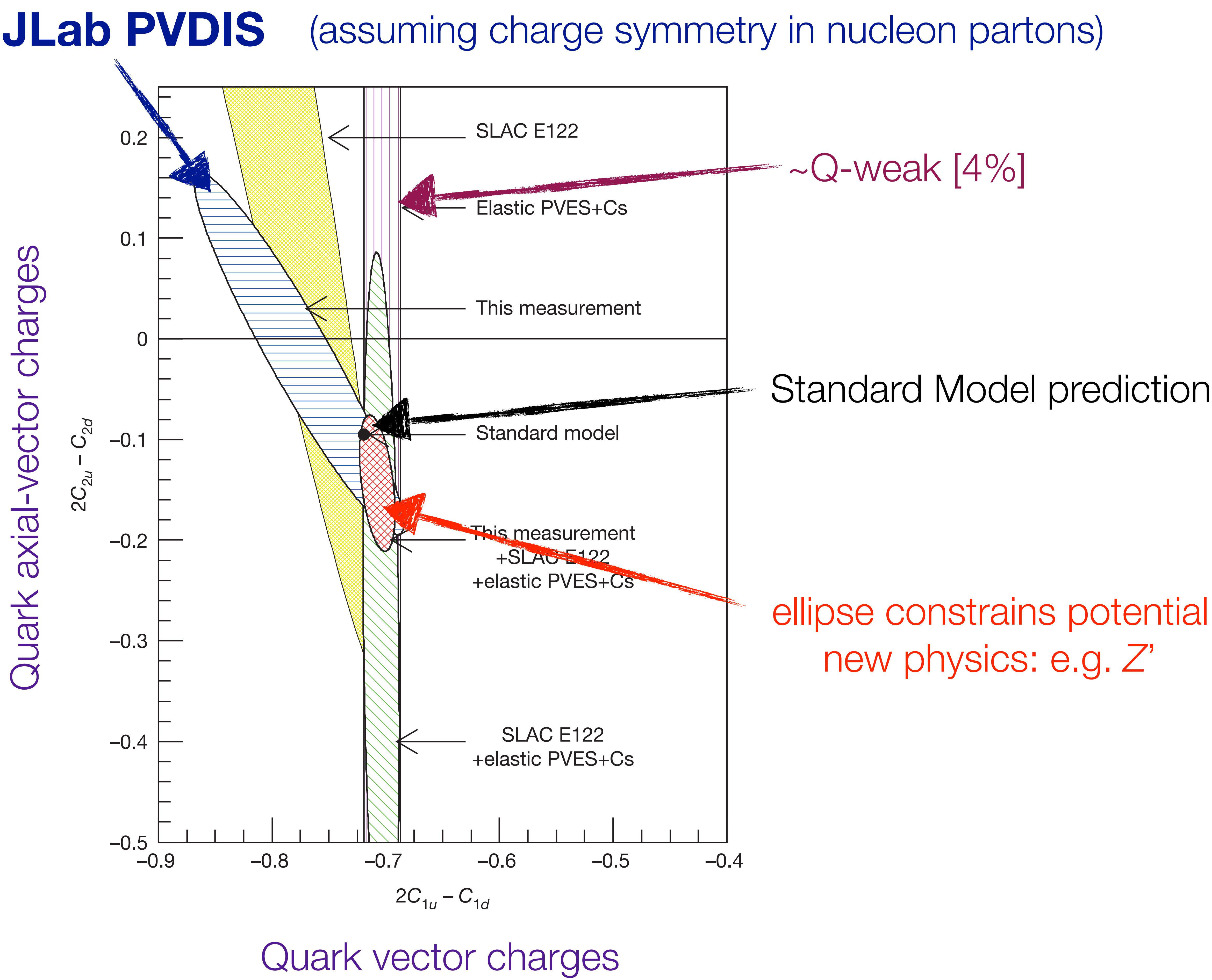
JLab PVDIS



SLAC E122
~Q-weak [4%]
Elastic PVES+Cs
This measurement
Standard Model prediction
Standard model
This measurement
+SLAC E122
+elastic PVES+Cs
ellipse constrains potential
new physics: e.g. Z'
SLAC E122
+elastic PVES+Cs
Quark axial-vector charges
$2C_{2u} - C_{2d}$
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
$2C_{1u} - C_{1d}$
Quark vector charges



JLab PVDIS
(assuming charge symmetry in nucleon partons)
SLAC E122
~Q-weak [4%]
Elastic PVES+Cs
This measurement
Standard Model prediction
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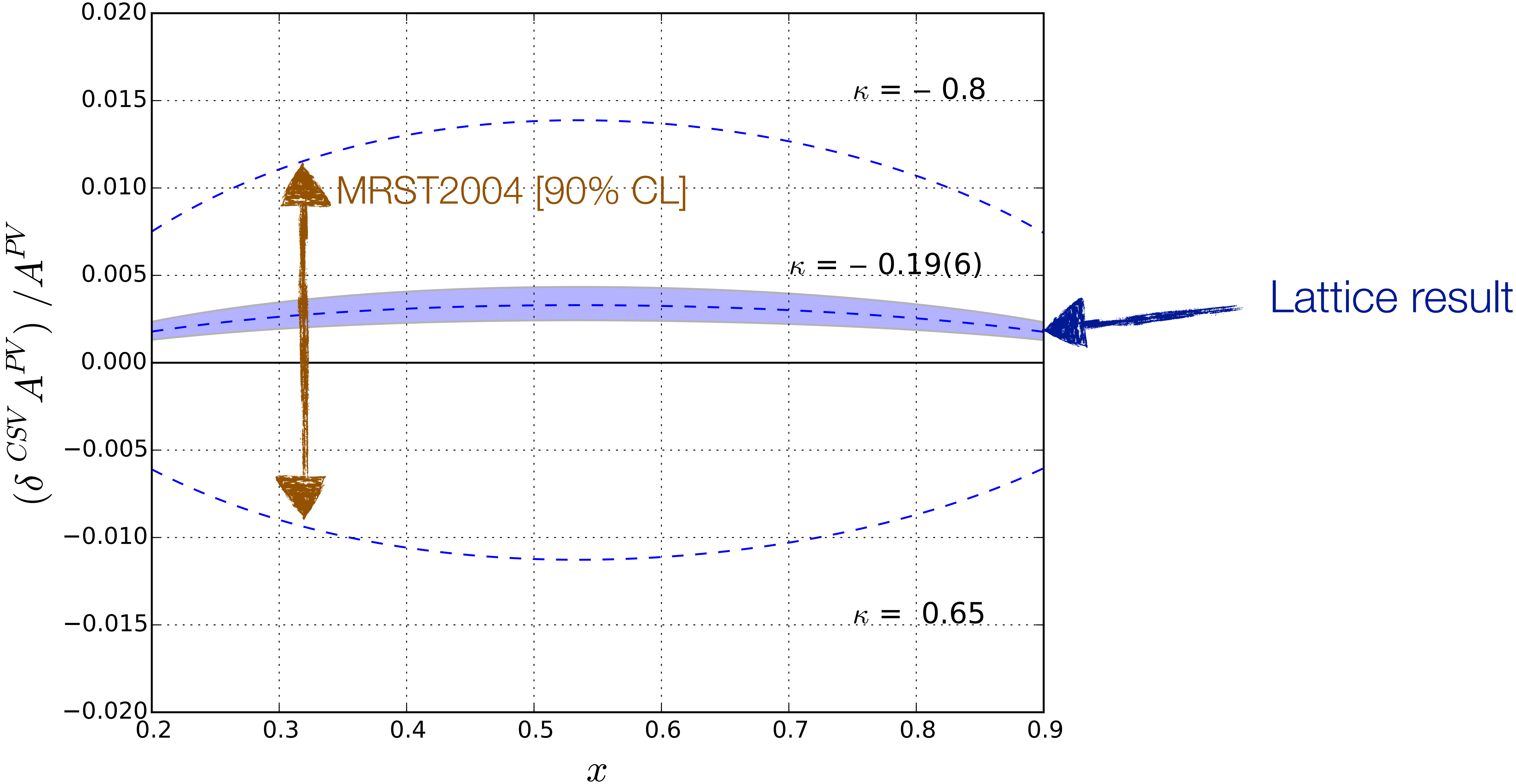
−0.5
−0.4



CSV is small compared to present experimental precision

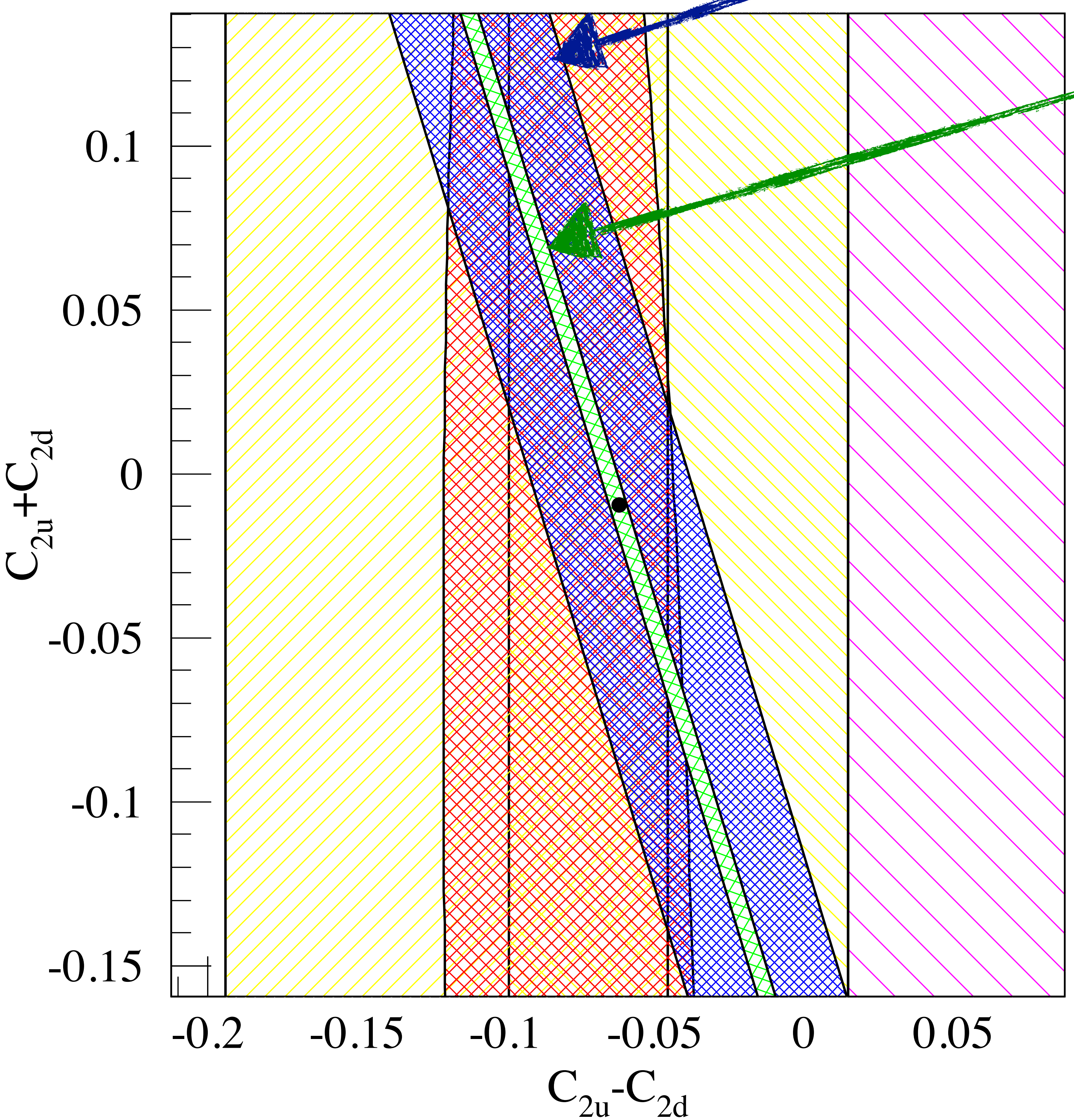
PVDIS@6GeV:

$$A_{\rm PV} = -91.1 \pm 3.1 \pm 3.0\,{\rm ppm}, \quad [Q^2 = 1.085\,{\rm GeV}^2, \overline{x} = 0.241];$$

$$A_{\rm PV} = -160.8 \pm 6.4 \pm 3.1\,{\rm ppm}, \quad [Q^2 = 1.901\,{\rm GeV}^2, \overline{x} = 0.295].$$

± 4–5%

Contact interactions



PVDIS @6GeV

Proposed order-of-magnitude improvement using SoLID @12GeV

Control of CSV will be essential for robust test of the Standard Model

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- "Local"
  - J. Crilly, P. Shanahan, A. Thomas, X-G. Wang, J. Zanotti
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