ISOSPIN BREAKING EFFECTS ON NUCLEON STRUCTURE FROM FULLY DYNAMICAL QCD+QED

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QCDSF Collaboration

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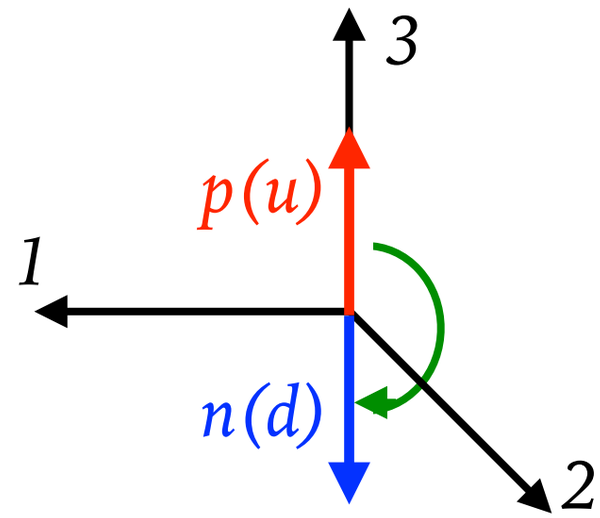
- H. Stüben (Hamburg)
- R. Young (Adelaide)

CHARGE SYMMETRY

u quarks in the proton $\equiv$ *d* quarks in the neutron

- Explicitly: *invariance of strong interaction under a rotation of 180° about the '2' axis in isospin space.*



- For form factors:

$$G_{E/M}^{p,u} = G_{E/M}^{n,d}$$

$$G_{E/M}^{p,d} = G_{E/M}^{n,u}$$

CHARGE SYMMETRY

Decompose form factors into their flavour contributions

$$p = e^u u^p + e^d d^p + \mathcal{O}_N$$

$$n = e^d d^n + e^u u^n + \mathcal{O}_N$$

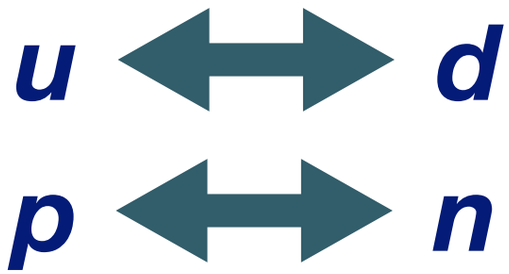
total *p/n* form factor

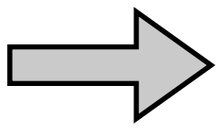
connected *d*-quark contribution to *n* FF

total disconnected contribution

$$\mathcal{O}_N = \frac{2}{3}\ell G^u - \frac{1}{3}\ell G^d - \frac{1}{3}\ell G^s$$

Under charge symmetry:





$$p = e^u u^p + e^d d^p + \mathcal{O}_N$$

$$n = e^d u^p + e^u d^p + \mathcal{O}_N$$

CHARGE SYMMETRY

u quarks in the proton $\equiv$ *d* quarks in the neutron

- Experimental determinations of $G^s_{E,M}(Q^2)$ rely on charge symmetry
- (As does the inclusion of neutron data for Qweak)
- EM and weak interactions give access to different combinations of $G^{p,(u/d/s)}$

$$G^{p,\gamma} = \frac{2}{3}G^{p,u} - \frac{1}{3}\left(G^{p,d} + G^{p,s}\right)$$

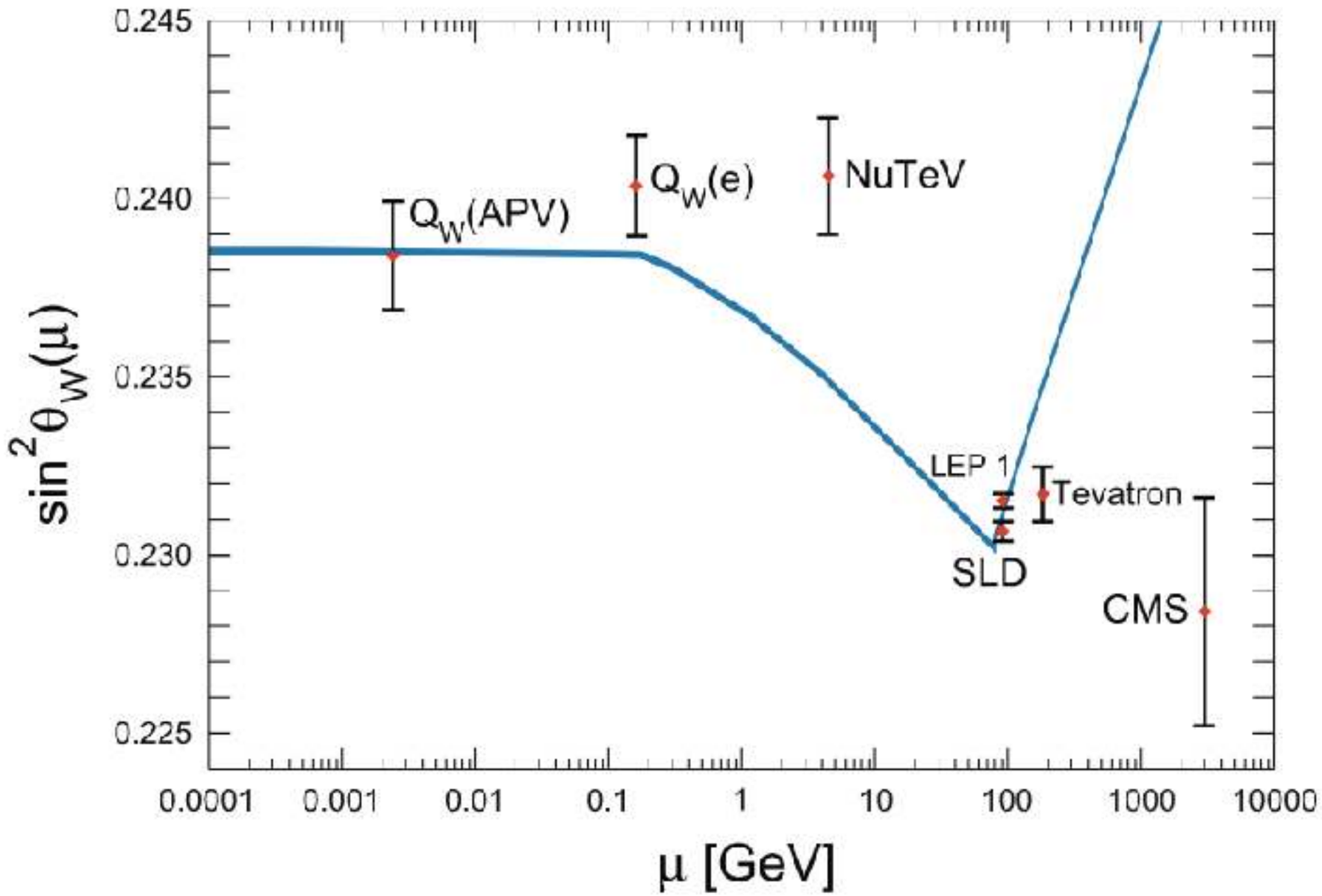
$$G^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G^{p,u} - \left(1 - \frac{4}{3}\sin^2\theta_W\right)\left(G^{p,d} + G^{p,s}\right)$$

- Assume charge symmetry $\left(G^{p,u} = G^{n,d}, \quad G^{p,d} = G^{n,u}, \quad G^{p,s} = G^{n,s}\right)$

$$\Rightarrow \left(G^{p,s}_{E/M} = \left(1 - 4\sin^2\theta_W\right)G^{p,\gamma}_{E/M} - G^{n,\gamma}_{E/M} - G^{p,Z}_{E/M}\right.$$

NUTEV & $SIN^2\Theta_W$

- NuTeV report a 3-sigma discrepancy from the Standard Model



Relies on assumption that CSV is negligible

CSV IN PDFS

- Under charge symmetry $u^p(x) = d^n(x)$, $d^p(x) = u^n(x)$
- Many experiments make this assumption (e.g. NuTeV)
- Use Lattice simulations to constrain the violation of charge symmetry

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

- Lattice, however, can only access (the lowest couple of) moments

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

- E.g. second moment of spin-independent

$$\delta u = \langle x \rangle_u^p - \langle x \rangle_d^n$$
$$\delta d = \langle x \rangle_d^p - \langle x \rangle_u^n$$

- or first moment of spin-dependent

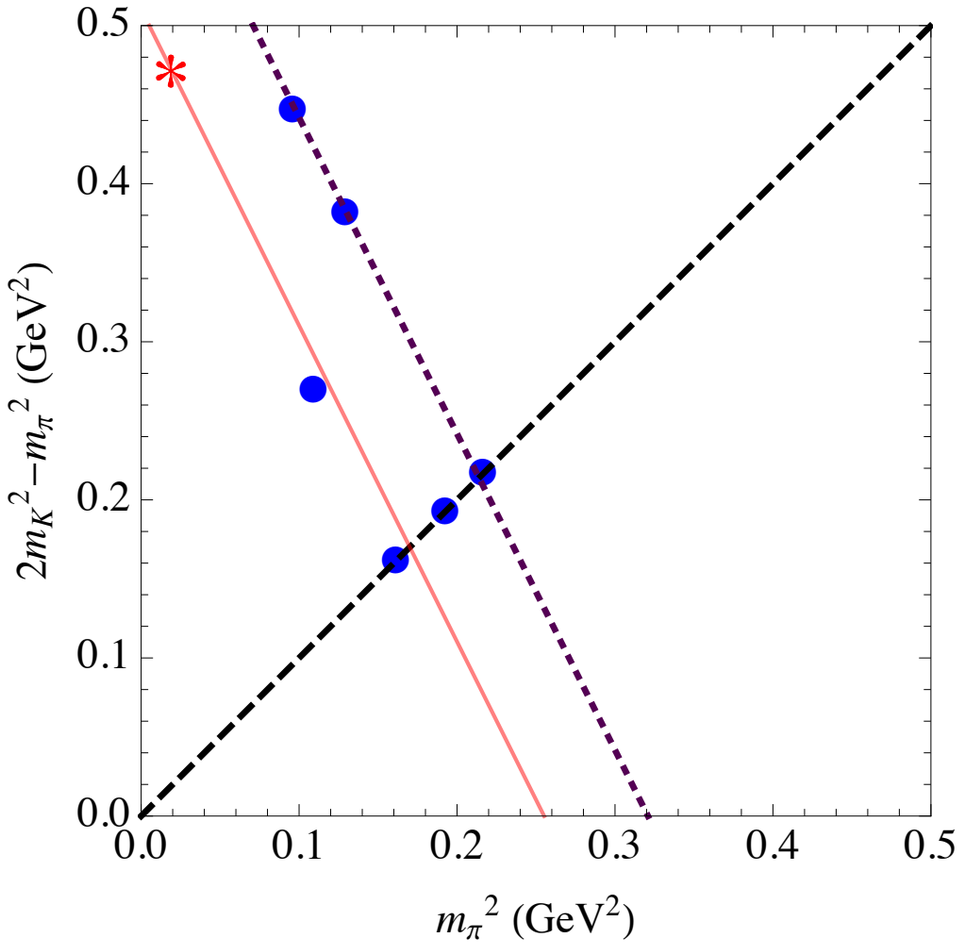
$$\delta\Delta u = \Delta u_p - \Delta d_n$$
$$\delta\Delta d = \Delta d_p - \Delta u_n$$

LATTICE QCD SET-UP

- $N_f = 2+1$ $O(a)$-improved Clover fermions ("SLiNC" action)
- Tree-level Symanzik gluon action (plaq + rect)
- Novel method for tuning the quark masses
  - keep the singlet quark mass fixed

$$\overline{m}^R = \frac{1}{3}(2m_l^R + m_s^R)$$

  - at its physical value $\overline{m}^{R*}$
- Multiple V, a, m_q



FORM FACTOR CSV

[CSSM/QCDSF PRD91 (2015) 113006]

- Determine the degree to which charge symmetry is violated in EM form factors by:
  - Combining χPT fits to isospin-averaged Lattice QCD hyperon FFs
  - Input m_u/m_d from experiment (or FLAG)

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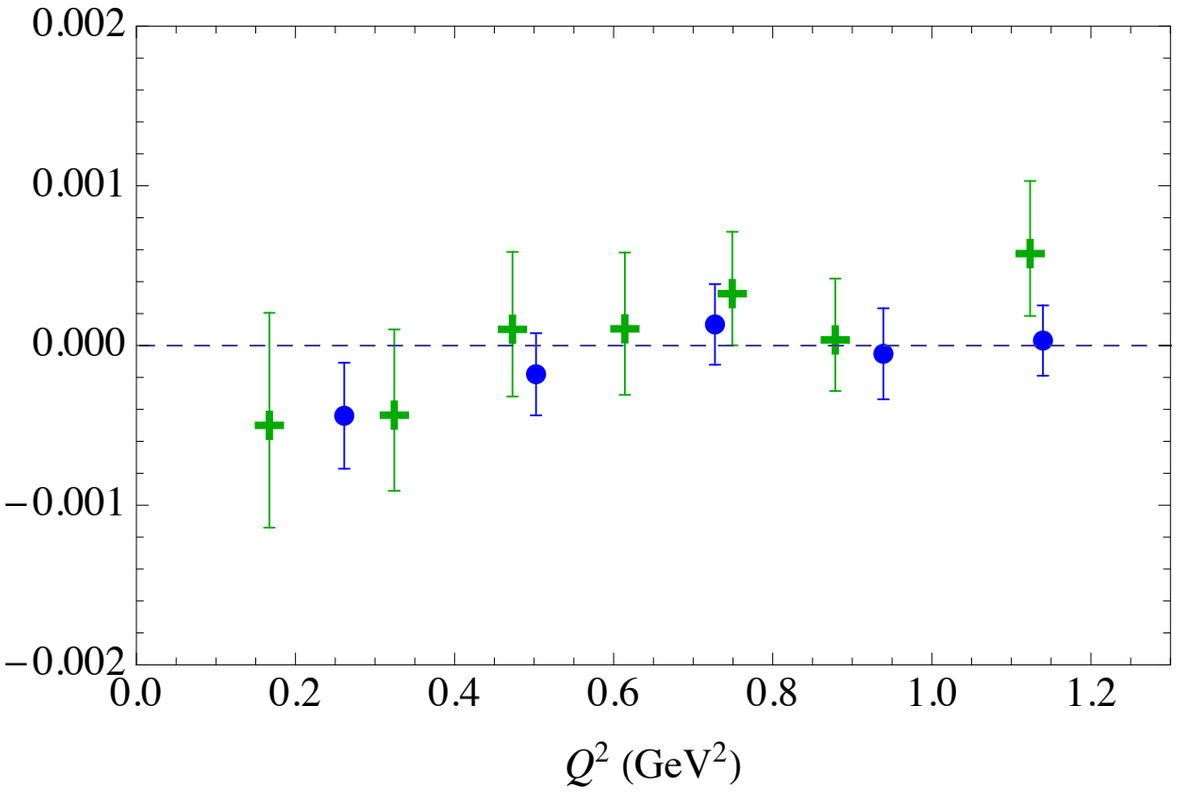

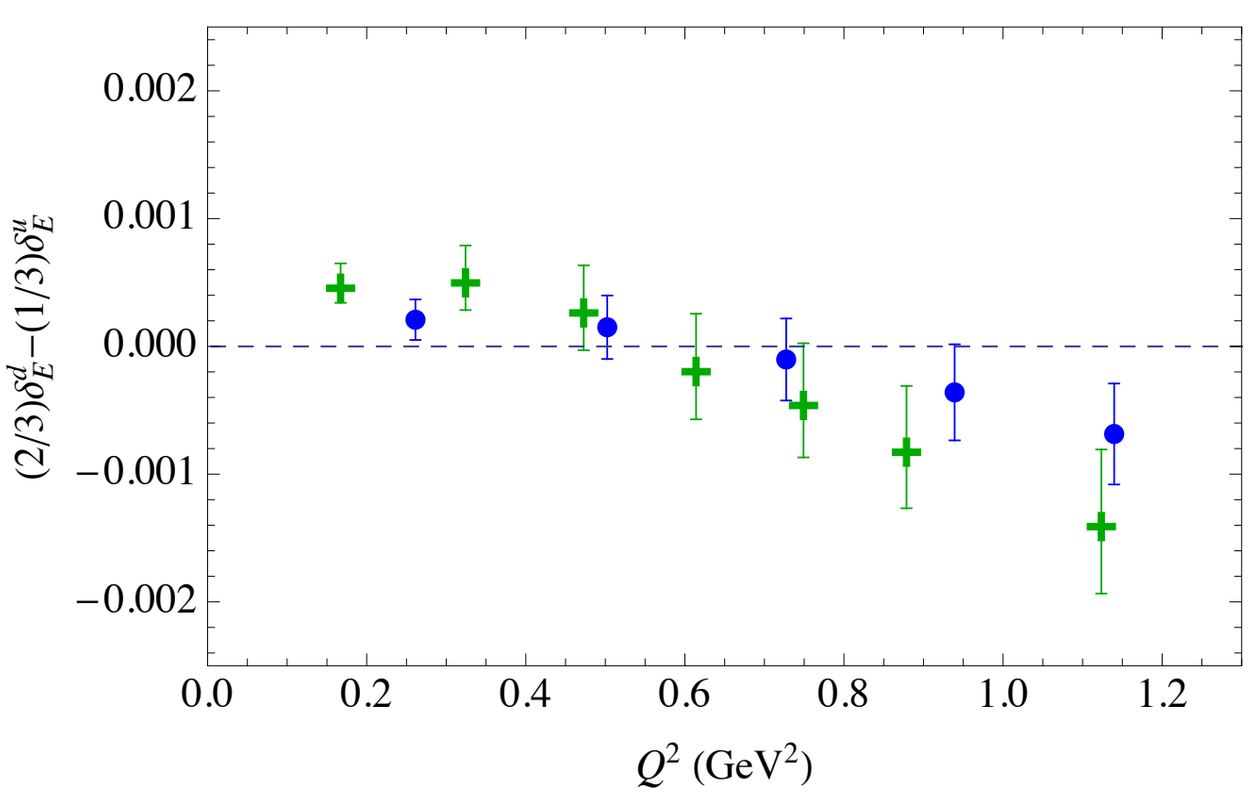

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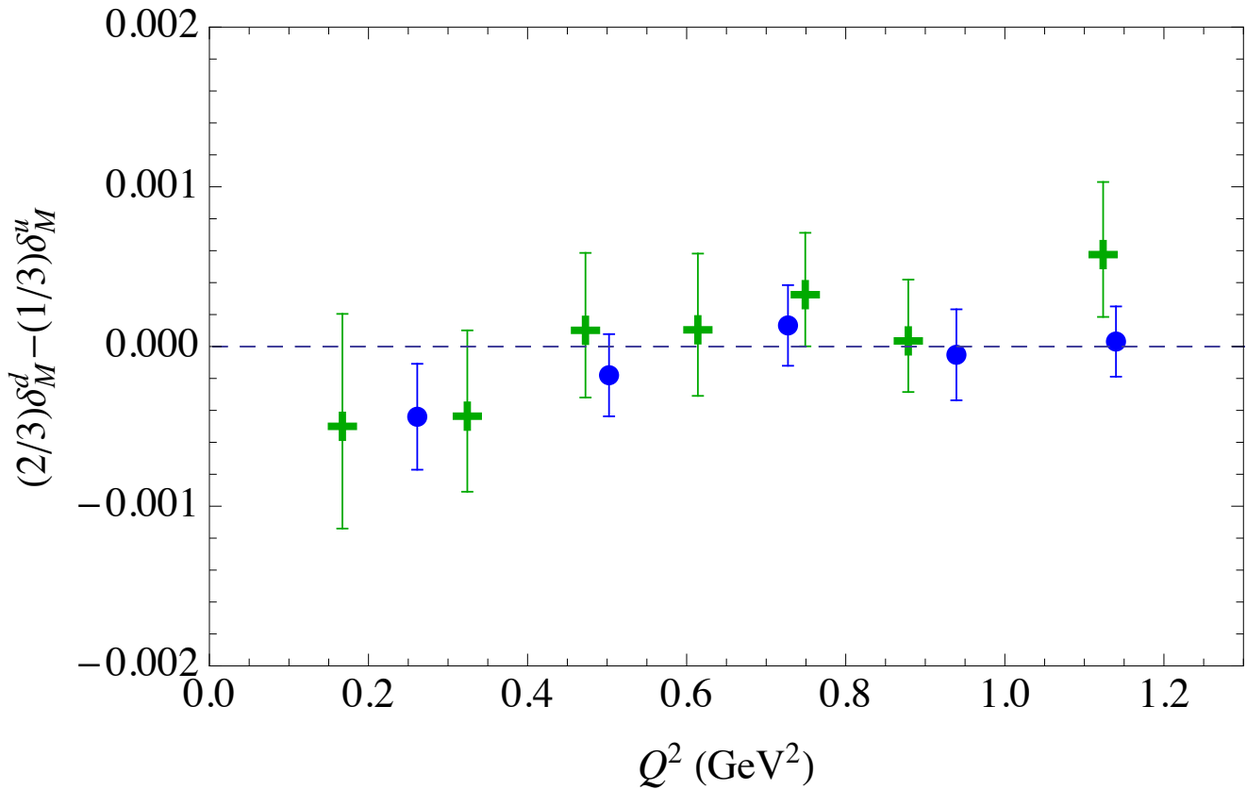
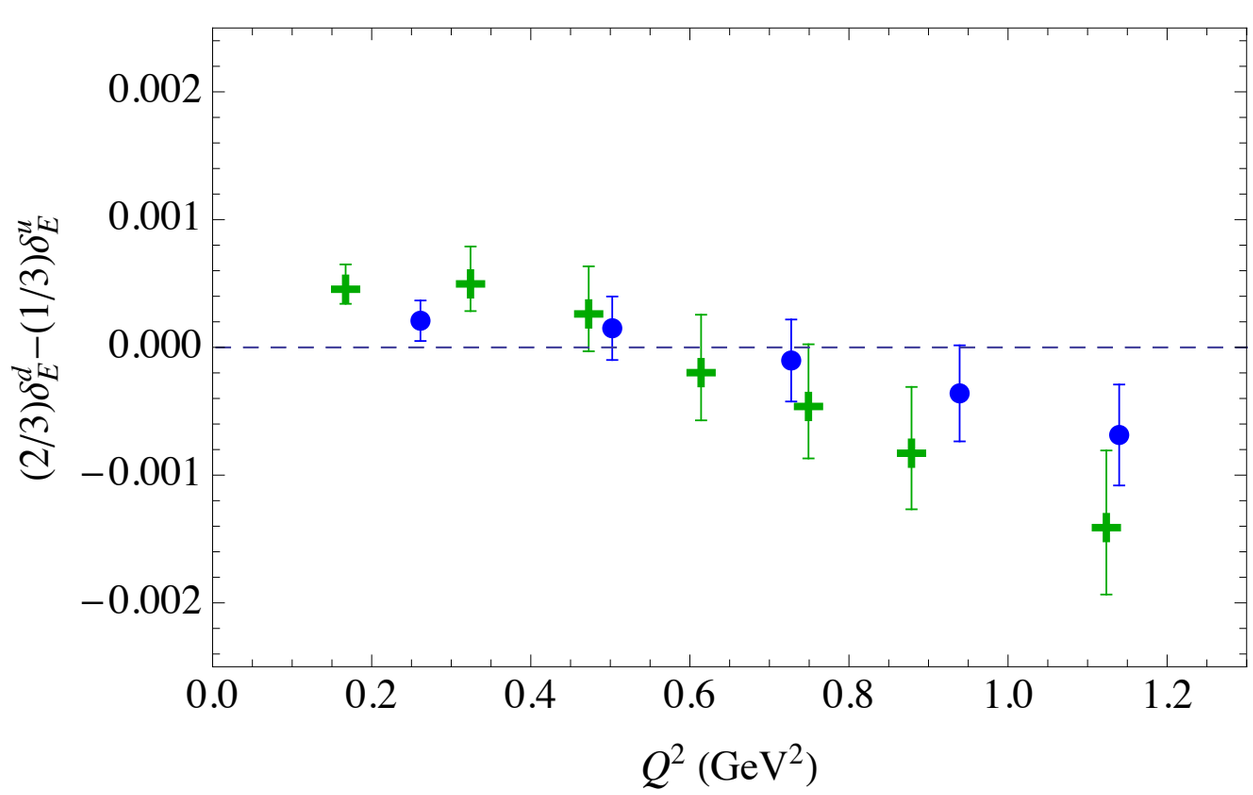




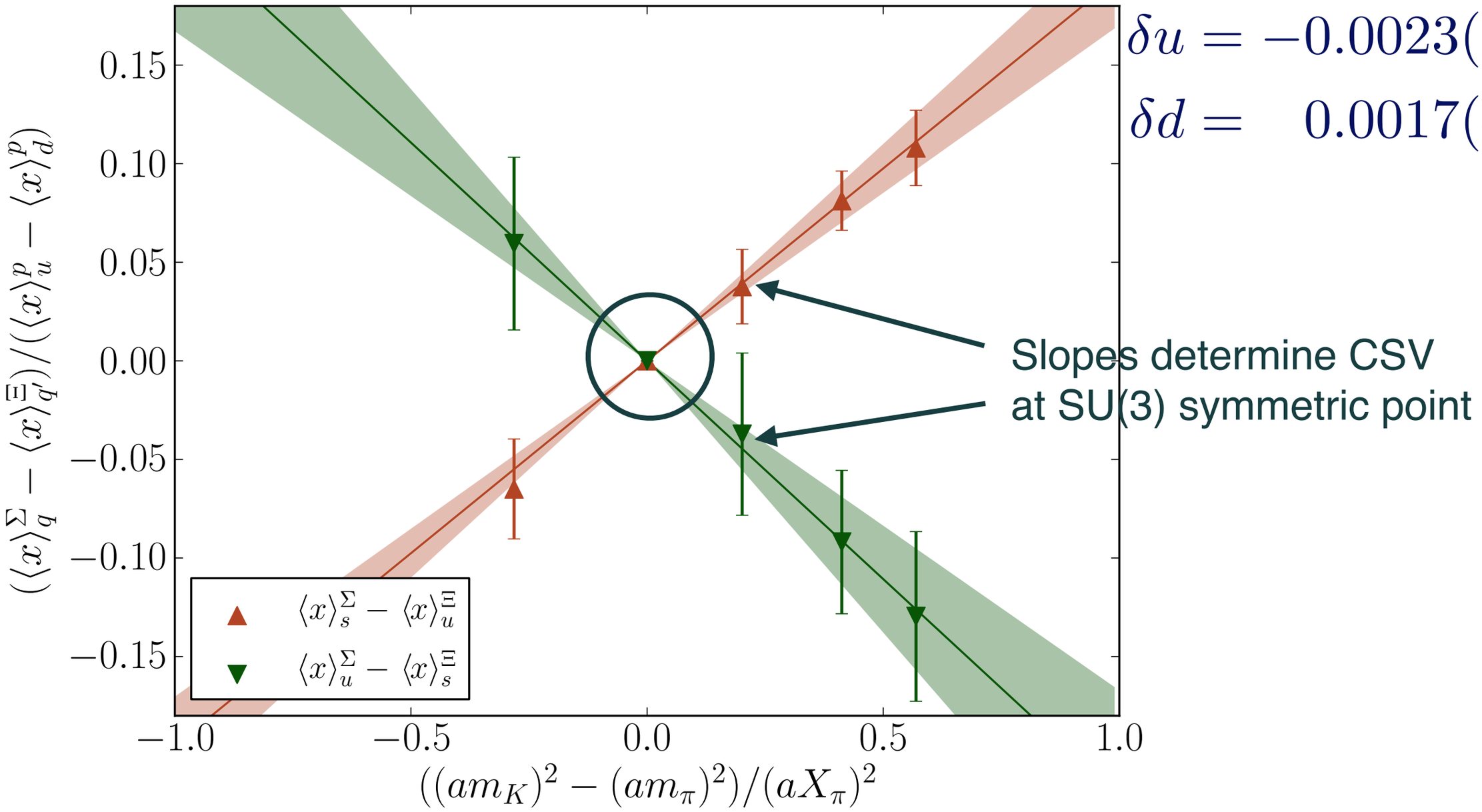
Charge symmetry satisfied to better than 0.2% (QCD)

Violations due to QED?

PDF CSV

[CSSM/QCDSF, 1012.0215 (PRD)]

Chiral corrections in **Shanahan, Thomas & Young, PRD(2013)094515**



- Reduce NuTeV Standard Model discrepancy by ~1 sigma

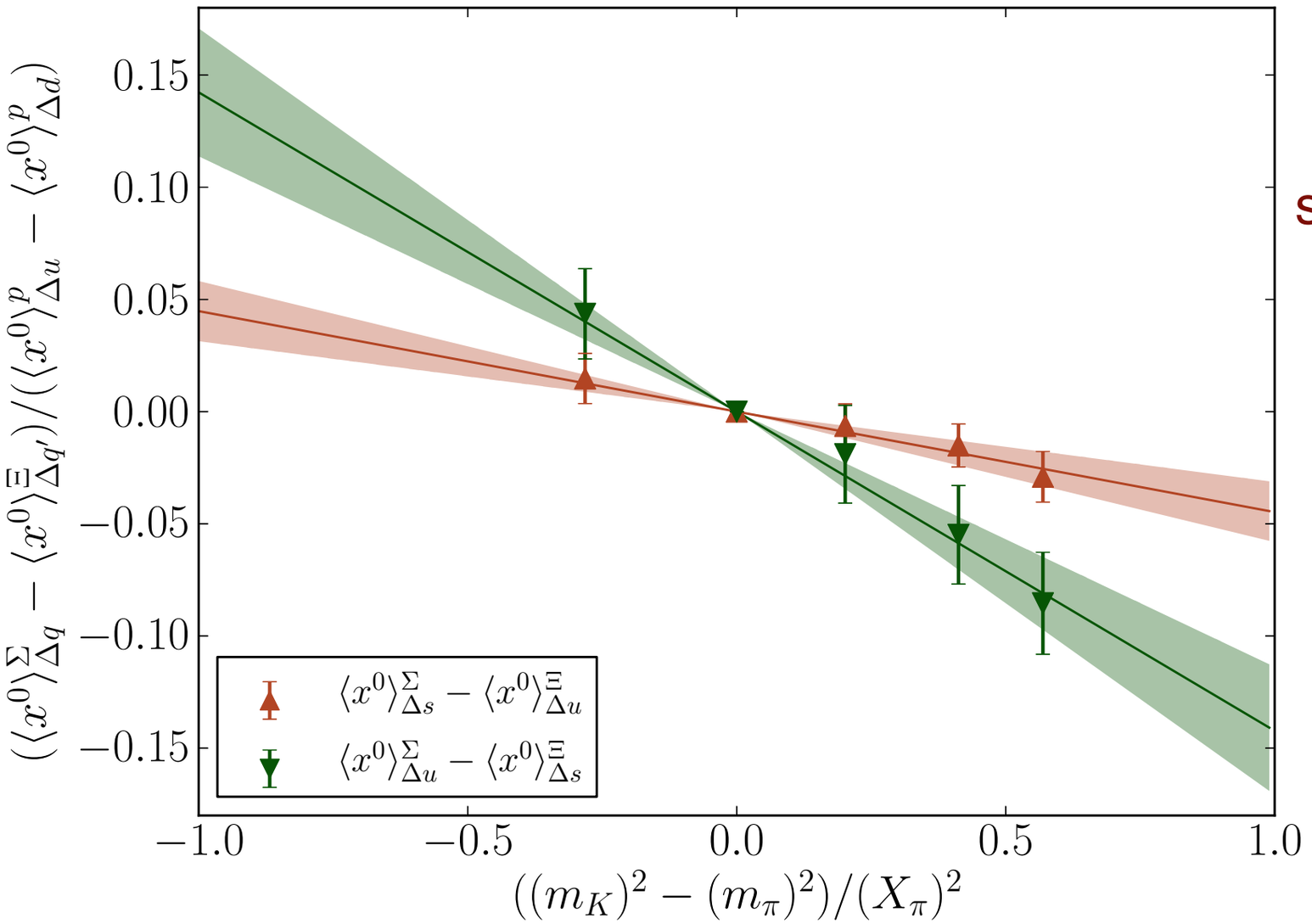
SPIN DEPENDENT CSV

[QCDSF, 1204.3492 (PLB)]

- Repeat procedure for

$$\delta\Delta u^m = \int_0^1 dx\ x^m[\Delta u^p(x) - \Delta d^n(x)]$$

$$\delta\Delta d^m = \int_0^1 dx\ x^m[\Delta d^p(x) - \Delta u^n(x)]$$



same sign for $\delta\Delta u$ and $\delta\Delta d$

~1% correction to Bjorken sum rule

LATTICE QCD+QED SET-UP

JHEP 1604, 093 (2016);
J.Phys. G43 no.10, 10LT02 (2016)

- Non-compact QED
- Gauge coupling corresponding to α_{QED}=0.1
- Quark masses tuned to $\mathrm{SU}(3)_{\mathrm{sym}}$ point via the *"Daschen Scheme"*

$$m_\pi^{u\bar{u}} = m_\pi^{d\bar{d}} = m_\pi^{s\bar{s}}$$

- Zero modes?

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- Zero modes?

  - Eliminated by additional gauge-fixing of Uno & Hayakawa (2008) — on valence quarks
- Finite volume effects? Not yet

LATTICE QCD+QED SET-UP

$V=32^3x64$, $a=0.068fm$

- Simulate with 3 different valence quark charges
  - $u: +2/3$ $\quad m_\pi^{n\bar{n}} = 408(3)$ MeV
  - $d: -1/3$ $\quad m_\pi^{d\bar{d}} = 409(1)$ MeV
  - $n: 0$ $\quad m_\pi^{u\bar{u}} = 407(3)$ MeV

Daschen:

$$m_\pi^{u\bar{u}} = m_\pi^{d\bar{d}} = m_\pi^{n\bar{n}}$$

- Construct baryons

flavour	Q	flavour	Q	flavour	Q
uuu	*+2*	*ddu*	*0*	*nnu*	*+2/3*
uud	*+1*	*ddd*	*-1*	*nnd*	*-1/3*
uun	*+4/3*	*ddn*	*-2/3*	*nnn*	*0*

- Isolate individual quark contributions, e.g.

u^{uud} u quark in (uud)

d^{ddn} n quark in (ddn)

FORM FACTORS

[Unrenormalised]

- Z_V depends on the charge of the active quark

[Also observed in Boyle et al., 1706.05293 (today!)]

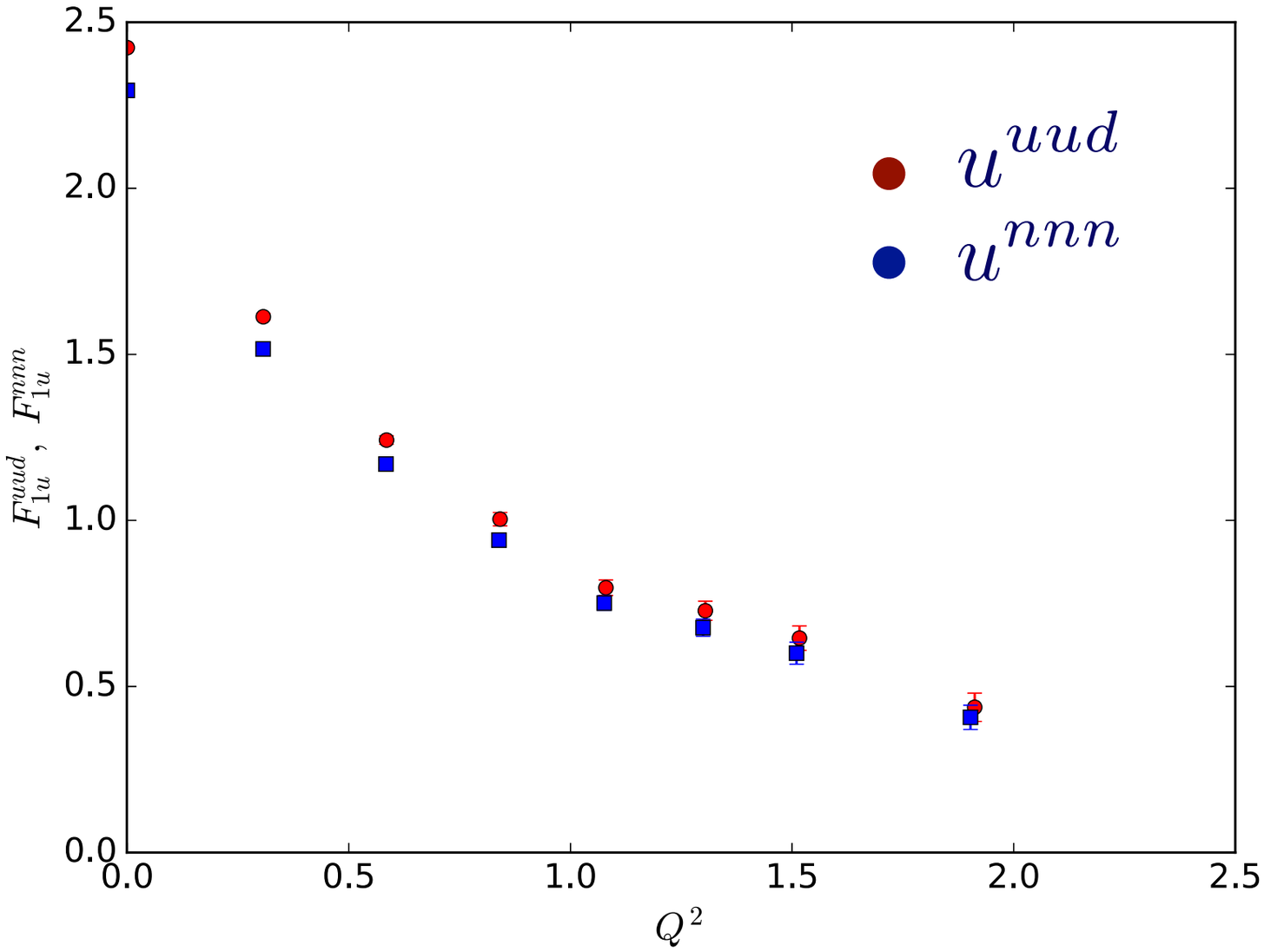
- From dipole fits

$$r_{1u}^{nnn} = 0.575(6)$$

$$r_{1u}^{uud} = 0.570(6)$$

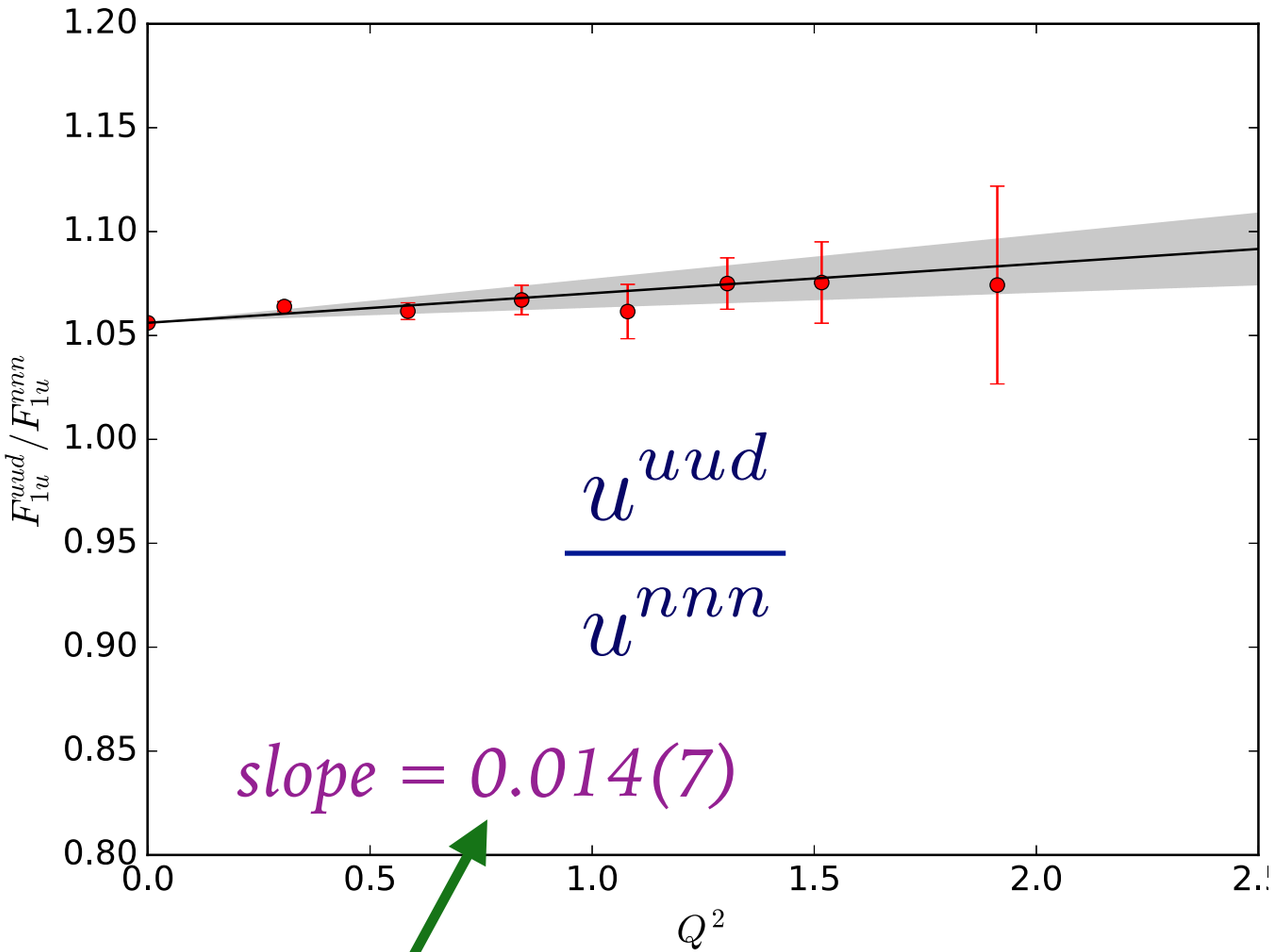
- Form factor shapes similar

➡ distinguish via ratios

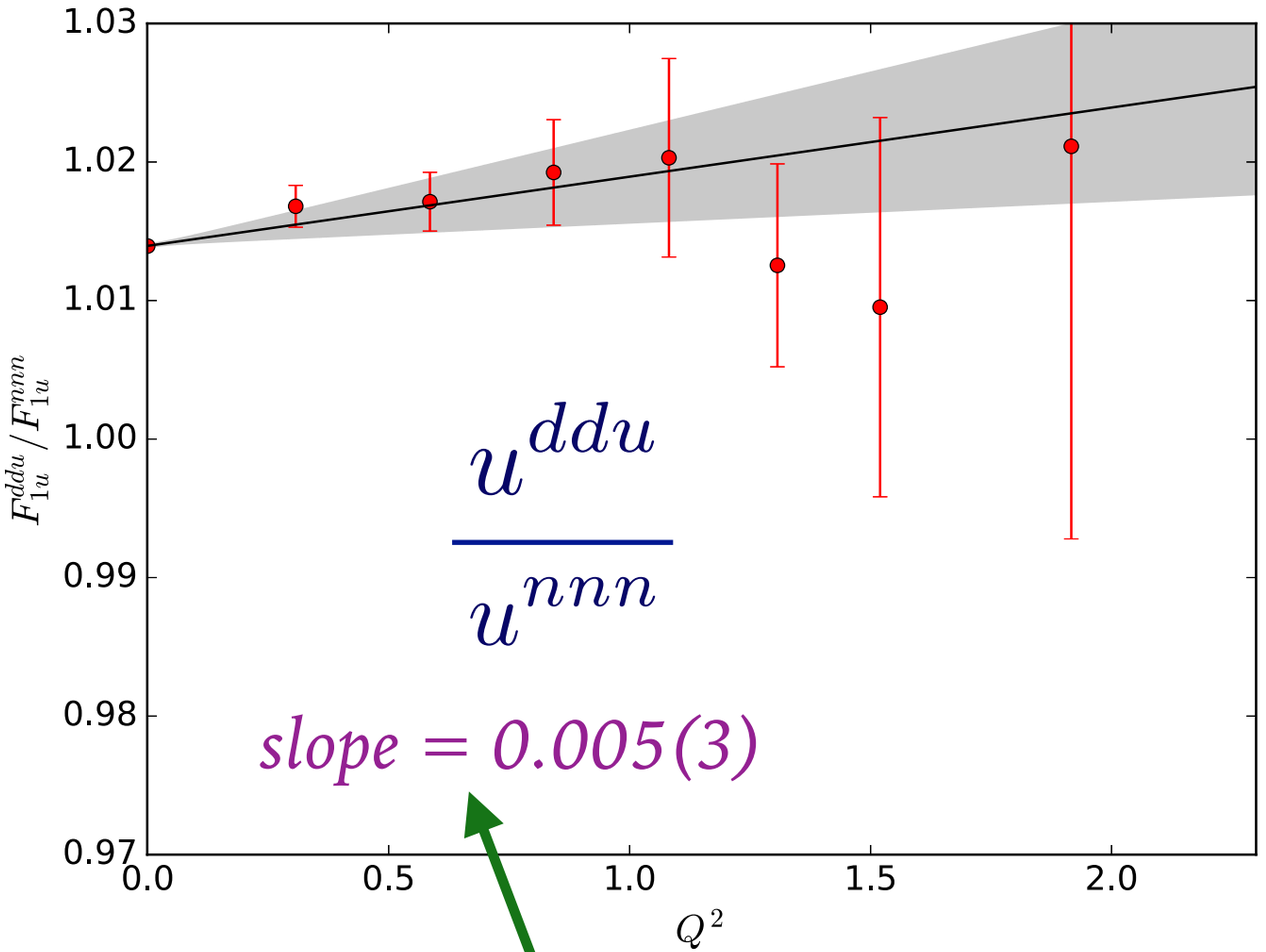


FORM FACTORS – DOUBLY REPRESENTED QUARK

- Coulomb attraction/repulsion, expect smaller/faster fall-off with Q^2



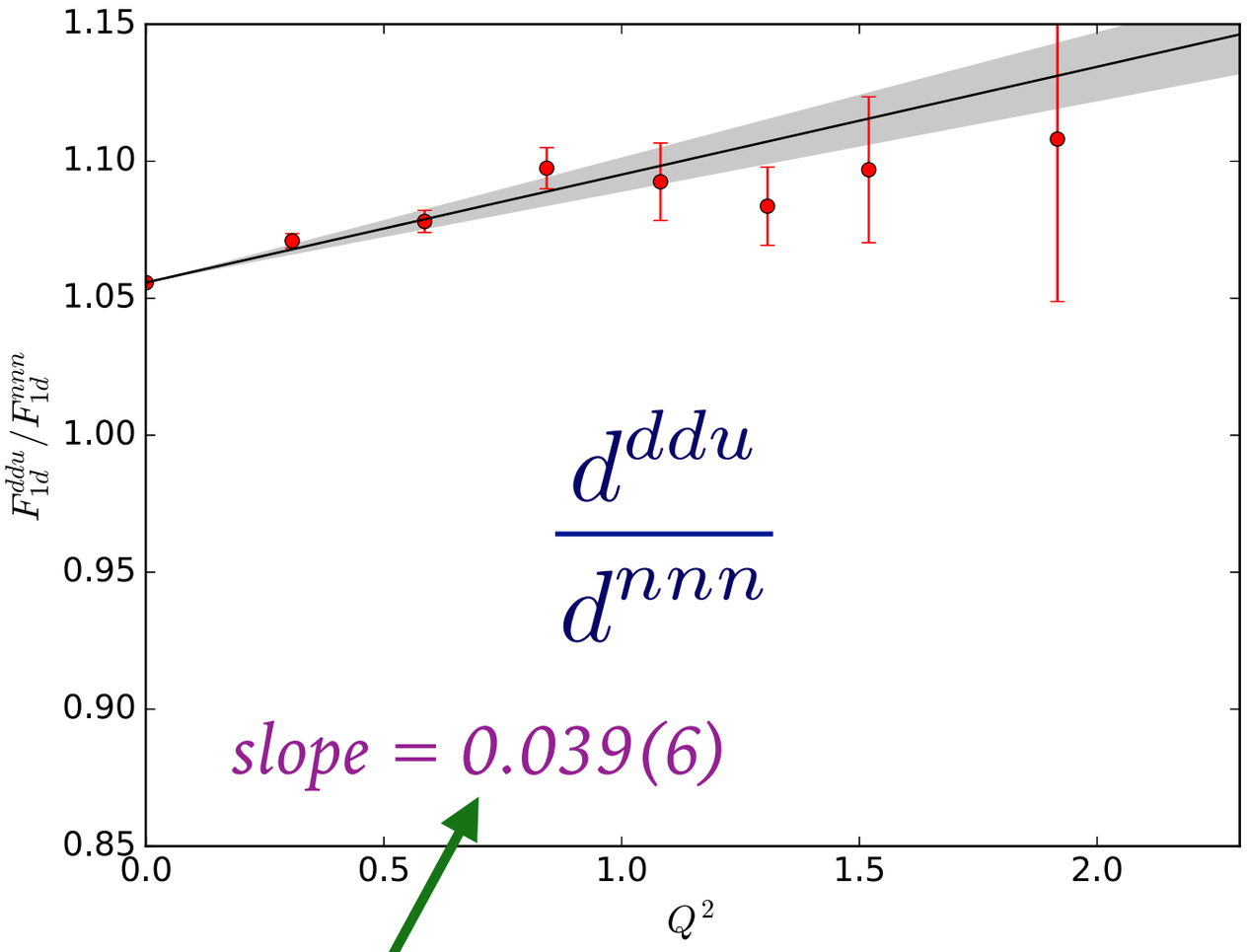
Counterintuitive? FV effect?



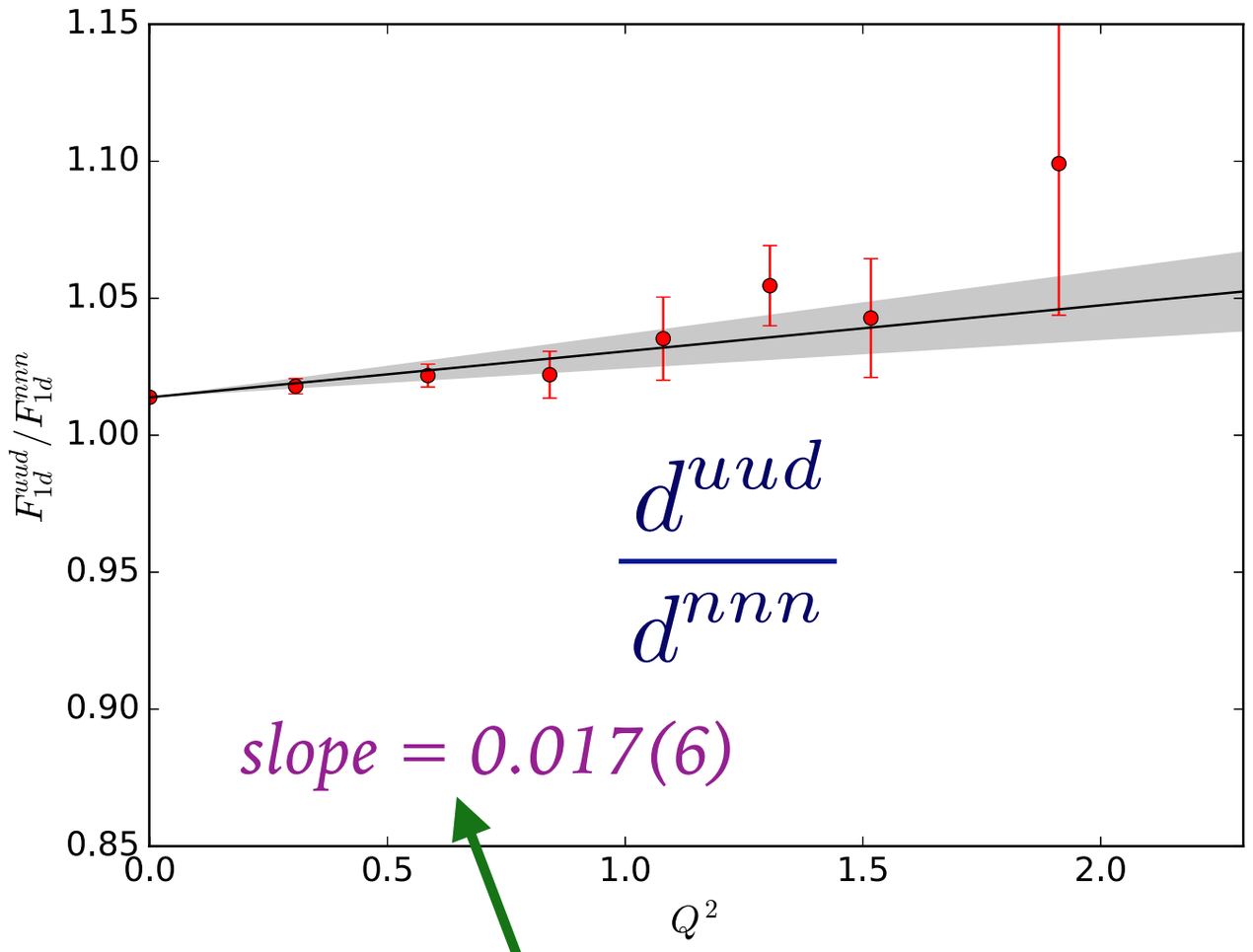
Competing effects? Perhaps ok?

FORM FACTORS – SINGLY REPRESENTED QUARK

- Coulomb attraction/repulsion, expect smaller/faster fall-off with Q^2



Signature for Coulomb attraction?

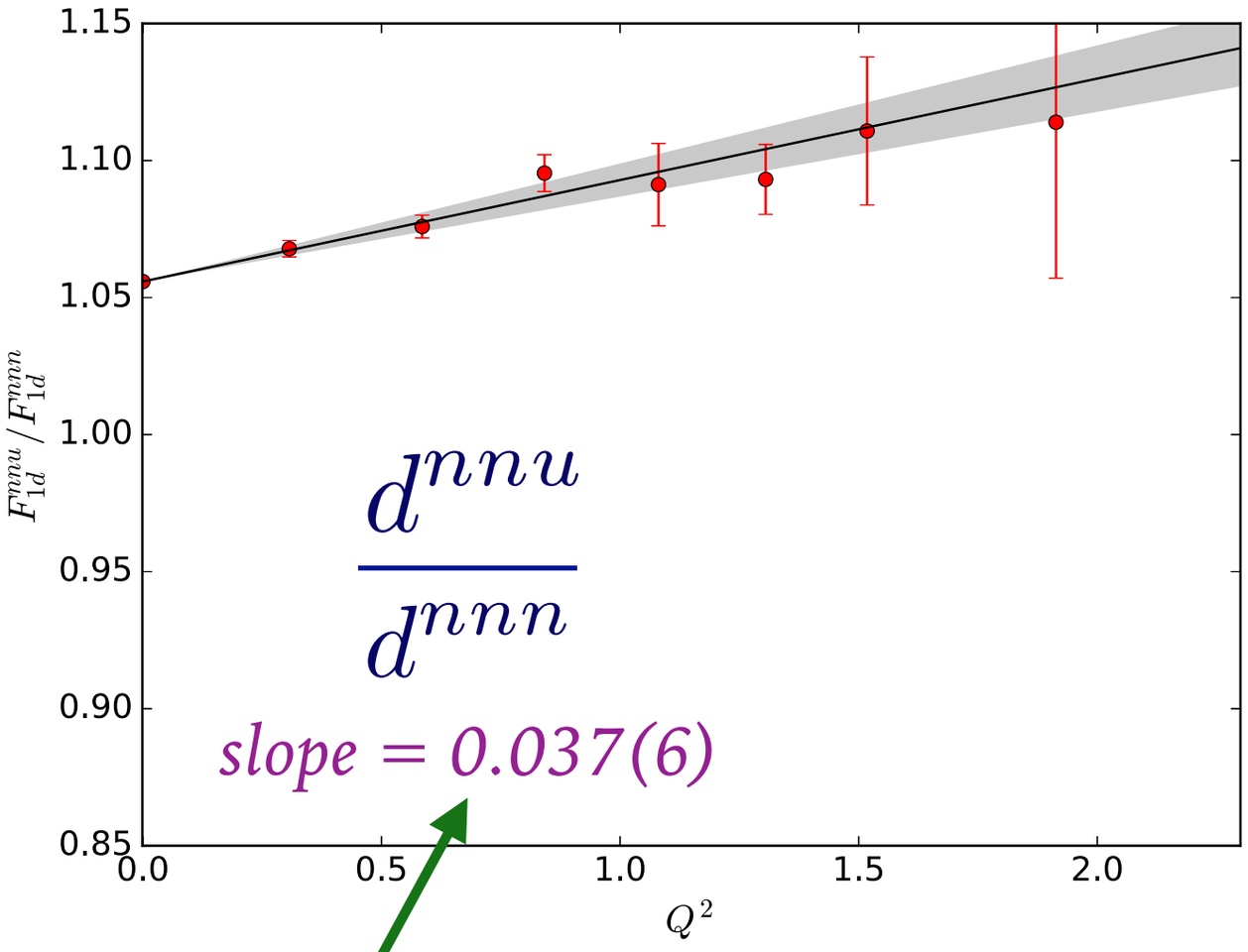


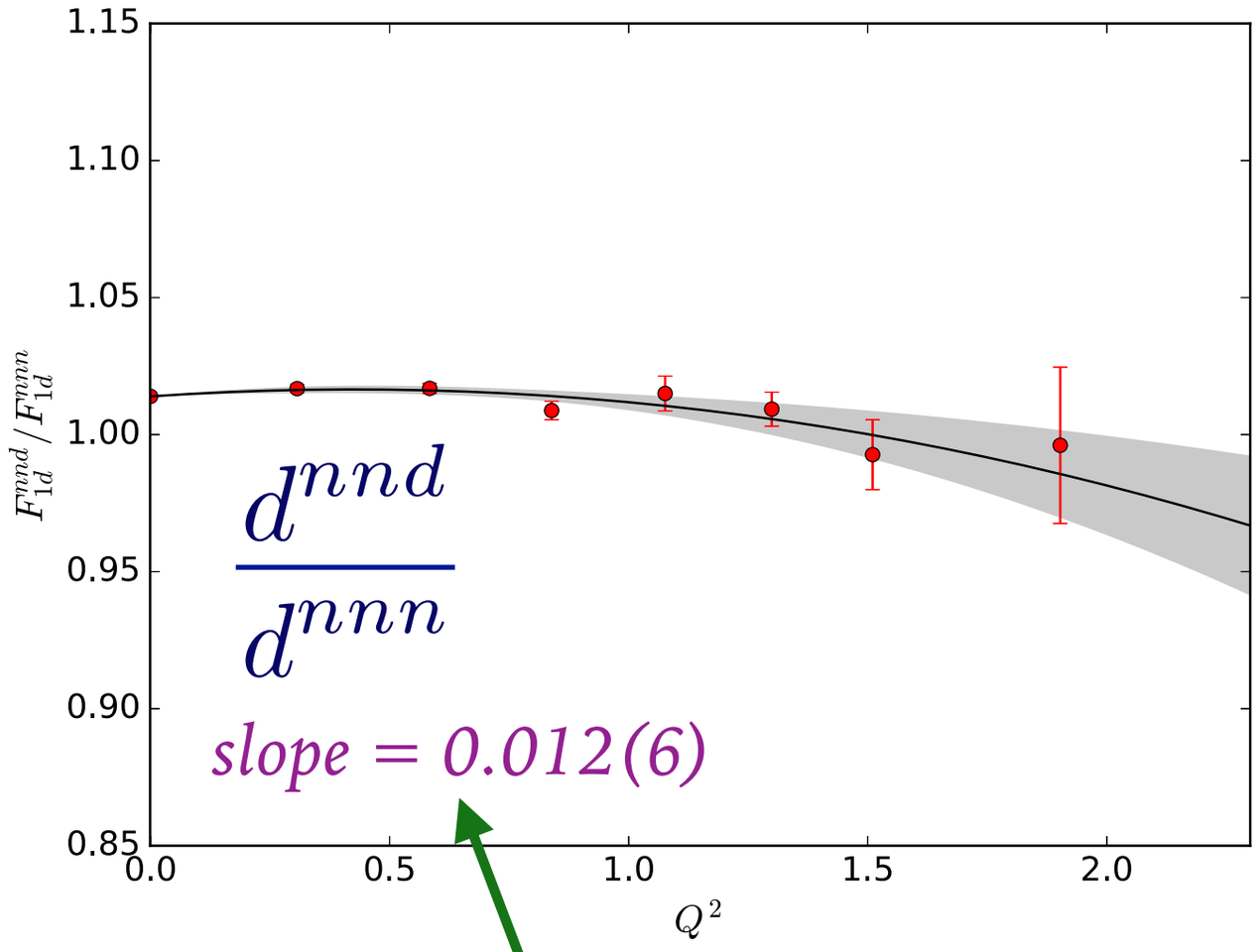
Expect similar Coulomb attraction.

FV effect due to $Q_{uud} = +1$?

FORM FACTORS

- Construct combination that should have no Coulomb effects (naive QM)





Umm..

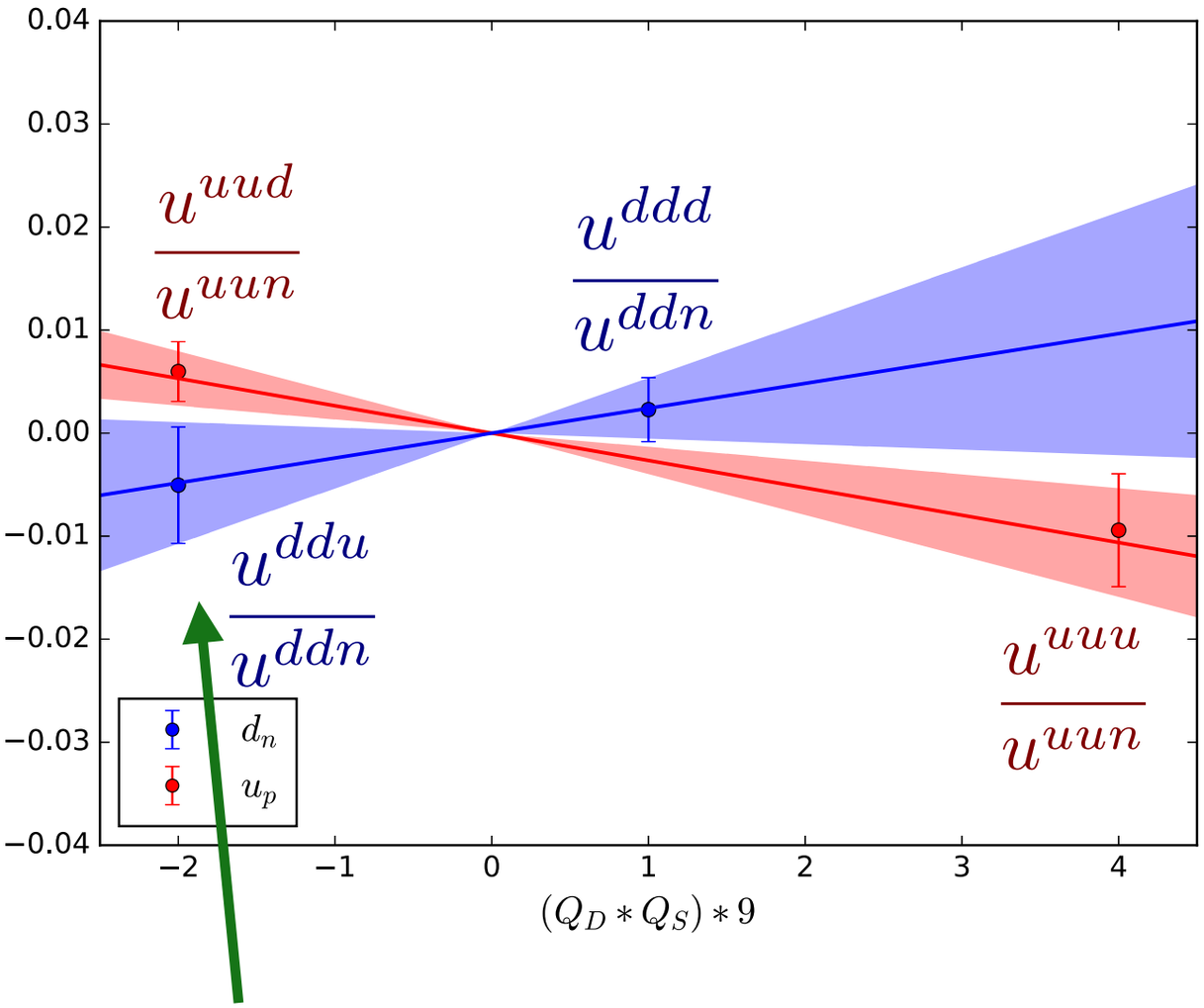
Beyond QM?

FV effect?

Similar effect, but smaller

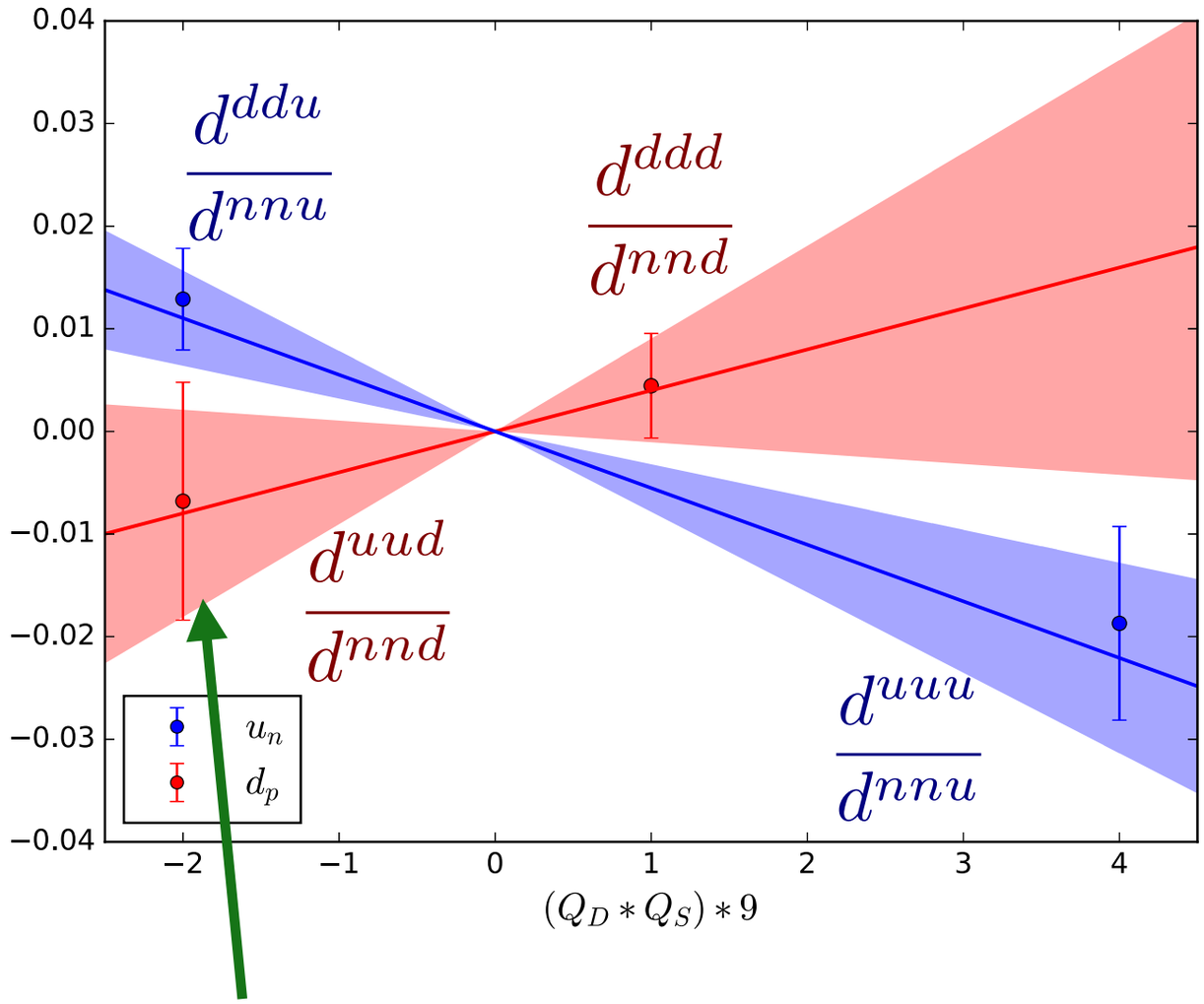
FORM FACTORS – CSV

- Attempt to gain insights into CSV through the following combinations



difference between these
2 points like

$$\delta u = u_p - d_n (\equiv u^{uud} - u^{ddu})$$



while difference here

$$\delta d = d_p - u_n (\equiv d^{uud} - d^{ddu})$$

AXIAL CHARGE

- To compute g_A, usual procedure is to assume isospin symmetry and compute

$$g_A = u^p - d^p \qquad \text{i.e.} \quad \langle p|\bar{u}\gamma_3\gamma_5 u - \bar{d}\gamma_3\gamma_5 d|p\rangle$$

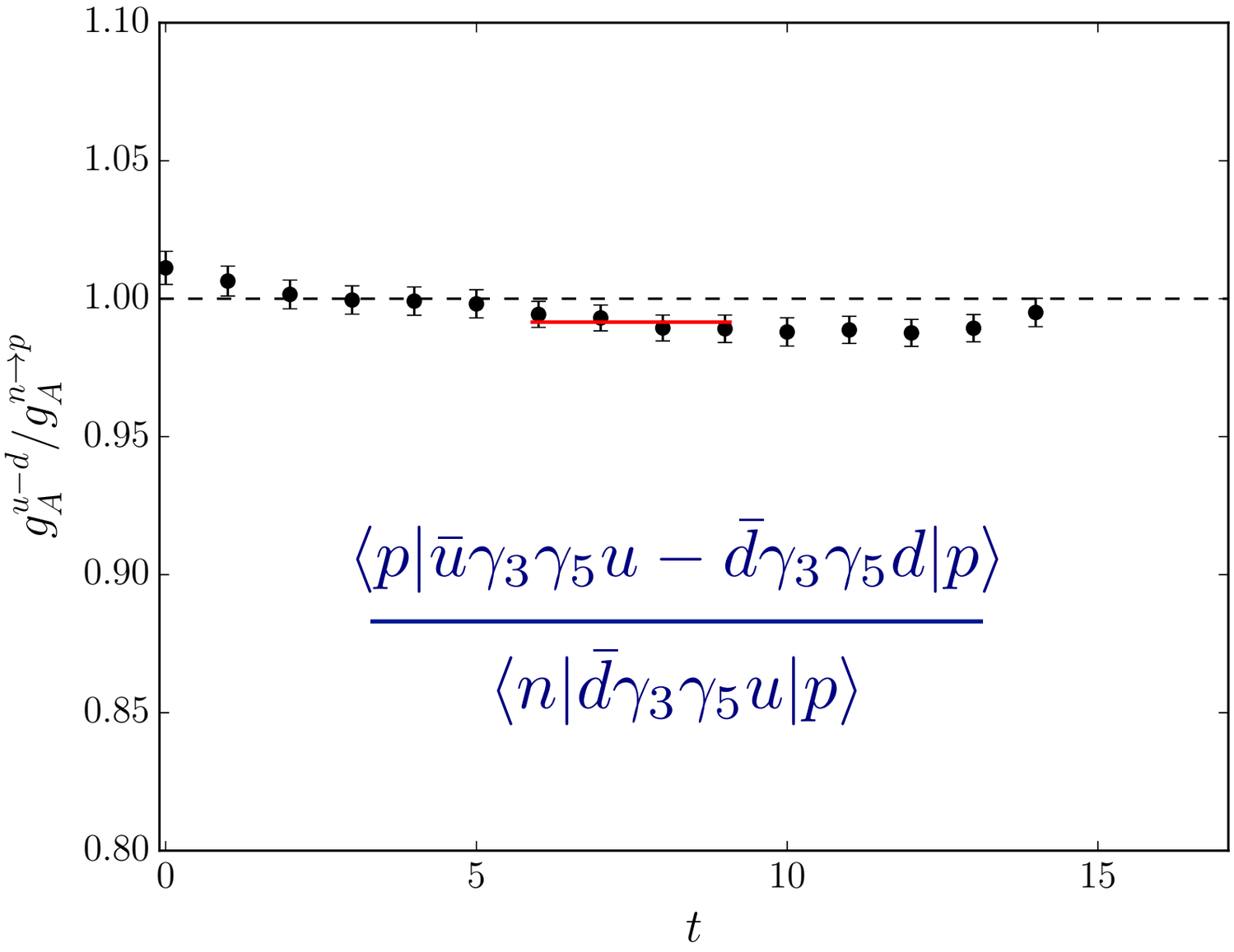
- Experimentally determined via $n \to pe^-\bar{\nu}$

i.e. $\langle n|\bar{d}\gamma_3\gamma_5 u|p\rangle$

- Can we observe violations due to isospin breaking due to quark charges?
- Compute

$$\frac{\langle p|\bar{u}\gamma_3\gamma_5 u - \bar{d}\gamma_3\gamma_5 d|p\rangle}{\langle n|\bar{d}\gamma_3\gamma_5 u|p\rangle}$$

AXIAL CHARGE

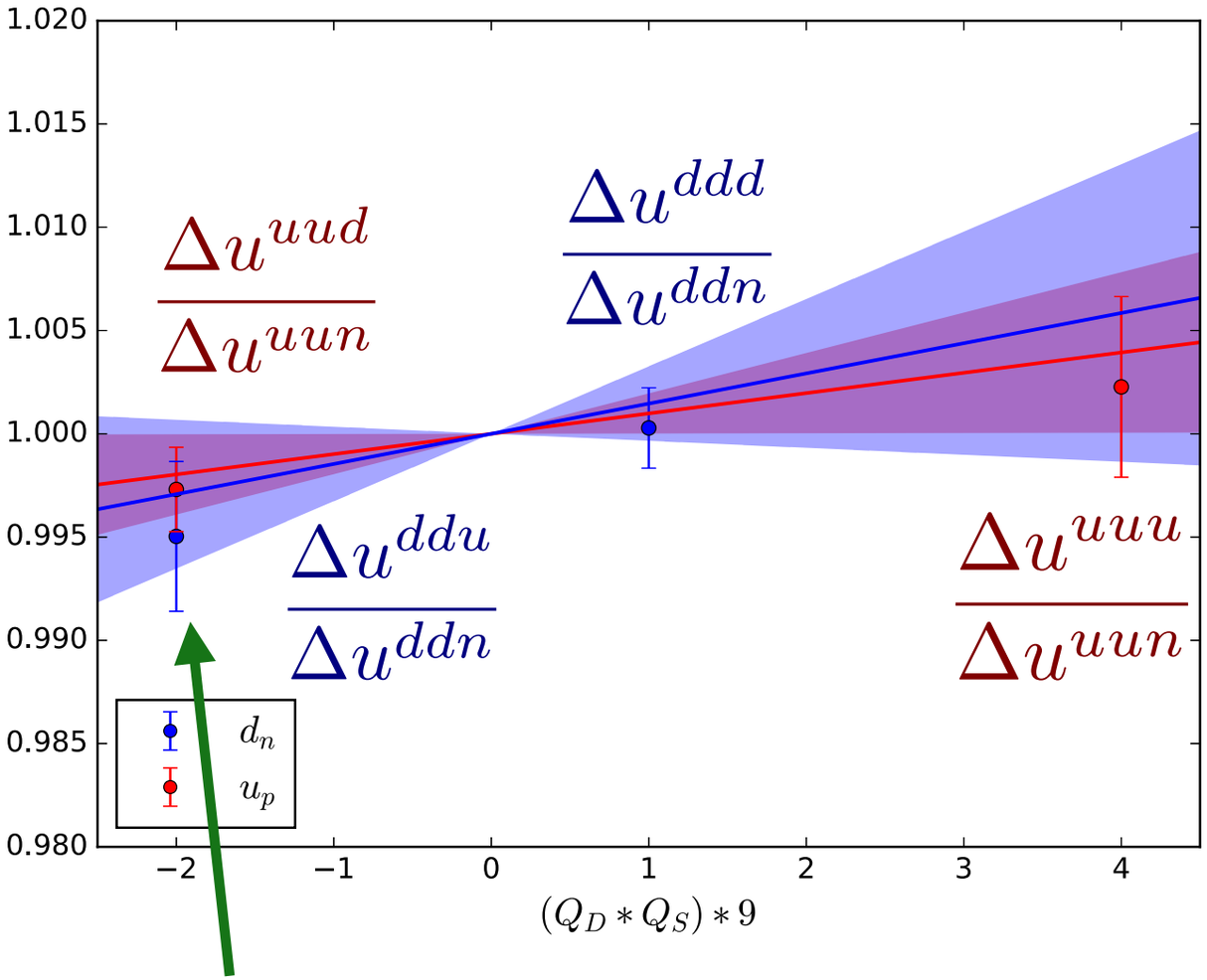


0.992(5)

- Need better treatment of excited states
- Evidence for ~ (0.5-1)/10 % effect

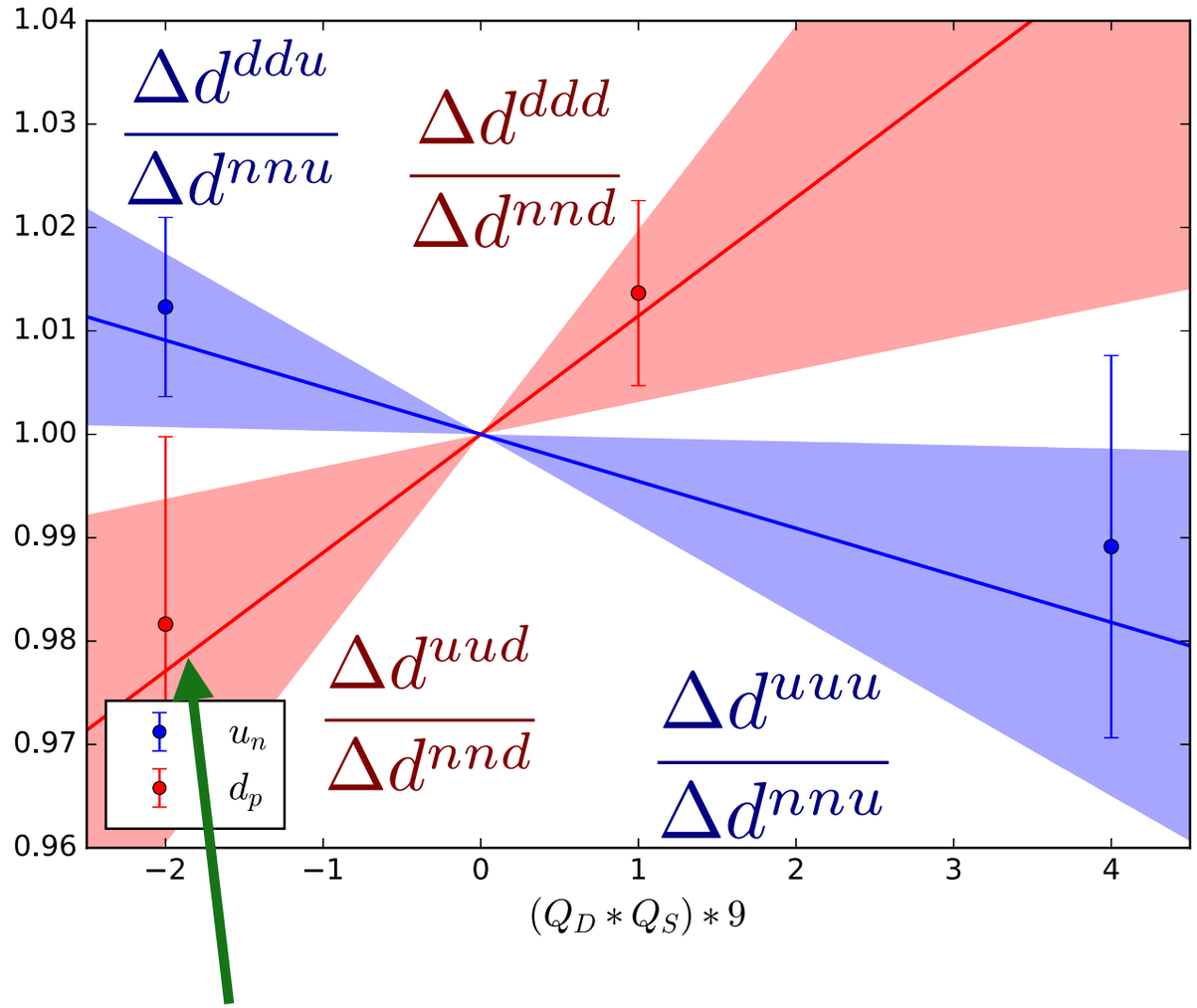
CSV IN SPIN-DEPENDENT PDFS $\delta\Delta u \quad \delta\Delta d$

- To cancel potentially charge-dependent Z_A
- Construct ratios and compare charged quark sectors



difference gives $\delta\Delta u = \Delta u_p - \Delta d_n$

Consistent with zero



while here $\delta\Delta d = \Delta d_p - \Delta u_n$

Evidence for ~ (3/10) %

SUMMARY AND OUTLOOK

- Had a first look at QED effects in nucleon matrix elements
- Form factors:
  - Evidence for Coulomb attraction for u quark in neutron
  - Hints at (small) CSV effects due to QED
- Axial charge:
  - Isospin-breaking effects due to quark charges appear to have <1% effect on $g_A = \Delta u - \Delta d$
  - Evidence for negligible CSV$^{\text{QED}}$ $\delta\Delta u$

    but non-zero $\delta\Delta d$
- Much work to be done on systematics, e.g. FV effects (including radiative corrections)