Charge symmetry violation in moments of the nucleon PDFs

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Outline

Charge symmetry violation in nucleon structure

- Warm-up: neutron–proton mass splitting

CSV in moments of parton distributions

- Use hyperon moments from lattice QCD to determine CSV
- Chiral extrapolation of octet baryon matrix elements
- Implications for the NuTeV Standard Model test

CSV in nucleon structure

Proton–neutron symmetry. Exact if:

up–down quark masses degenerate $m_u = m_d$

quark electromagnetic charges equal $Q_u = Q_d$

In reality:

$$\frac{M_n - M_p}{M_p} \sim 0.14\%$$

Quark masses

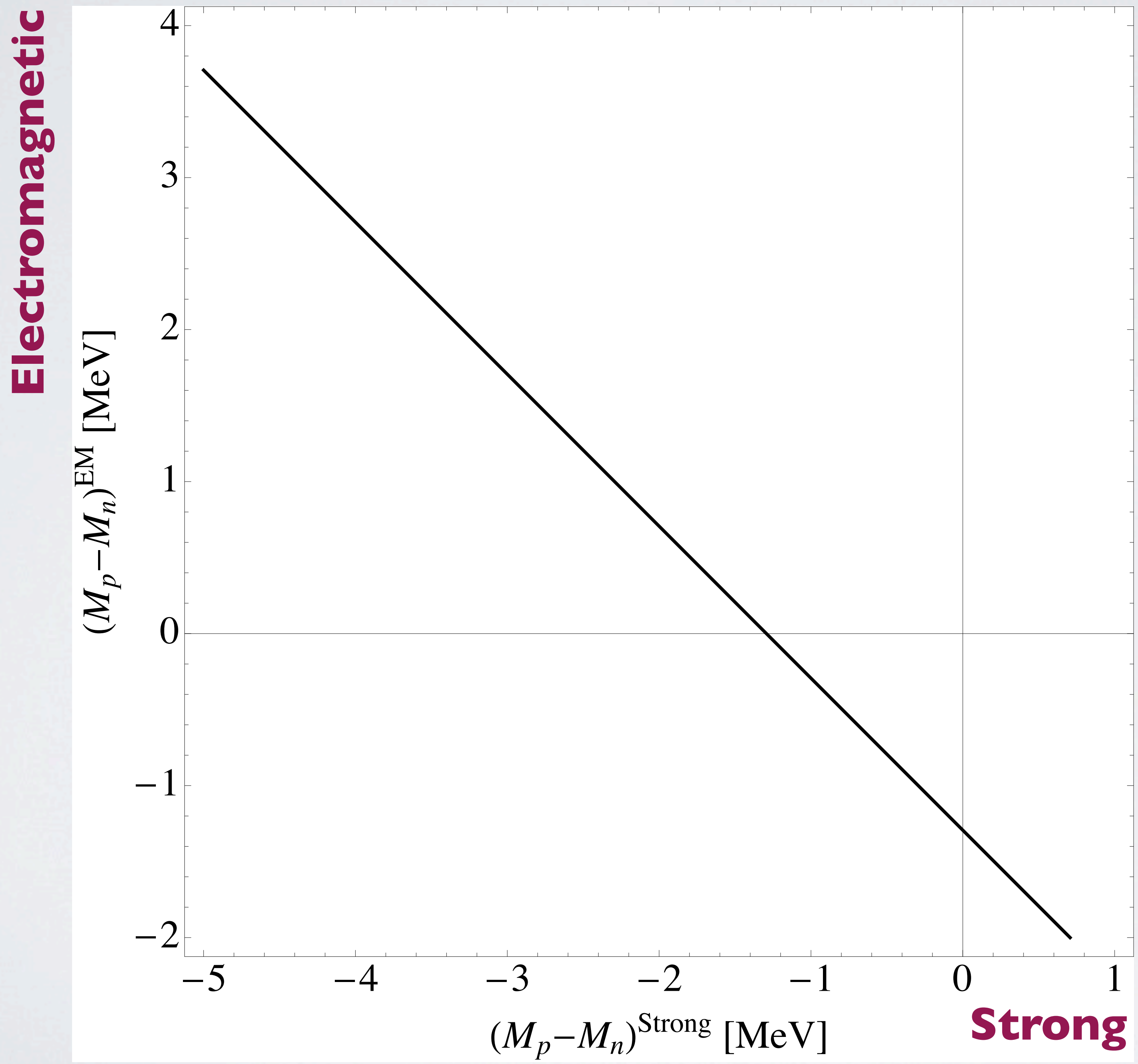
$$\frac{m_d - m_u}{M_p} \sim 0.5\%$$

Electromagnetic corrections $Q_u \neq Q_d$

$$\mathcal{O}(\alpha) \sim 1\%$$

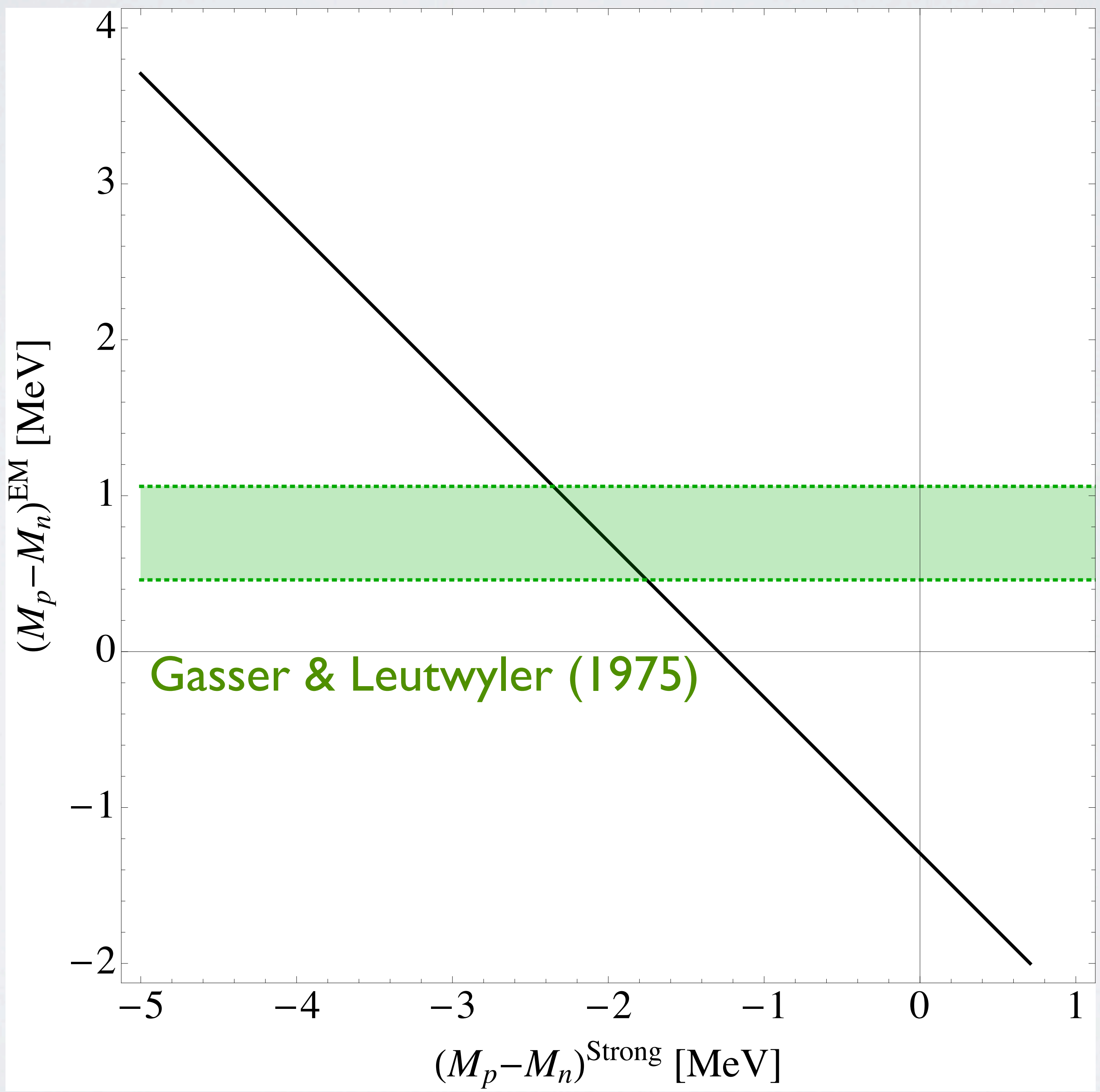
Experimental Constraint

Experiment: $M_p - M_n = -1.2933322(4)\,\mathrm{MeV}$



Cottingham Formula

Dispersion relation: electromagnetic self-energy written in terms of electron scattering observables



Subtracted Dispersion Relation

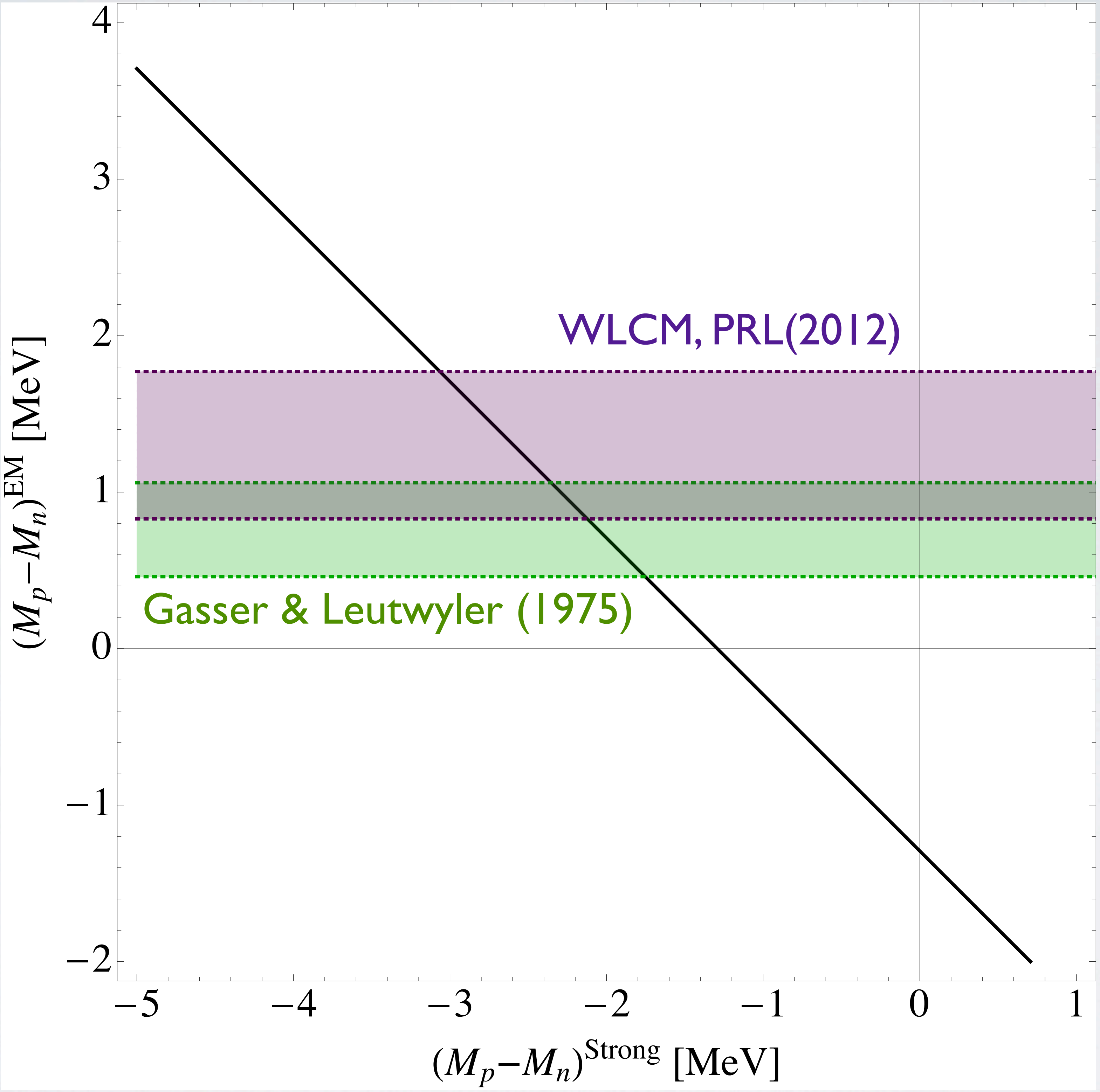
Walker-Loud, Carlson & Miller (WLCM), PRL(2012)

Standard Cottingham formula

- Two Lorentz equivalent decompositions of the $\gamma N \to \gamma N$ Compton amplitude produce inequivalent self-energies

WLCM: Use a subtracted dispersion relation to remove this ambiguity

New dispersive result



Precision limited by knowledge of real part of forward Compton amplitude

Lattice: "Strong"

Lattice QCD has a long history of describing quark mass dependence of observables

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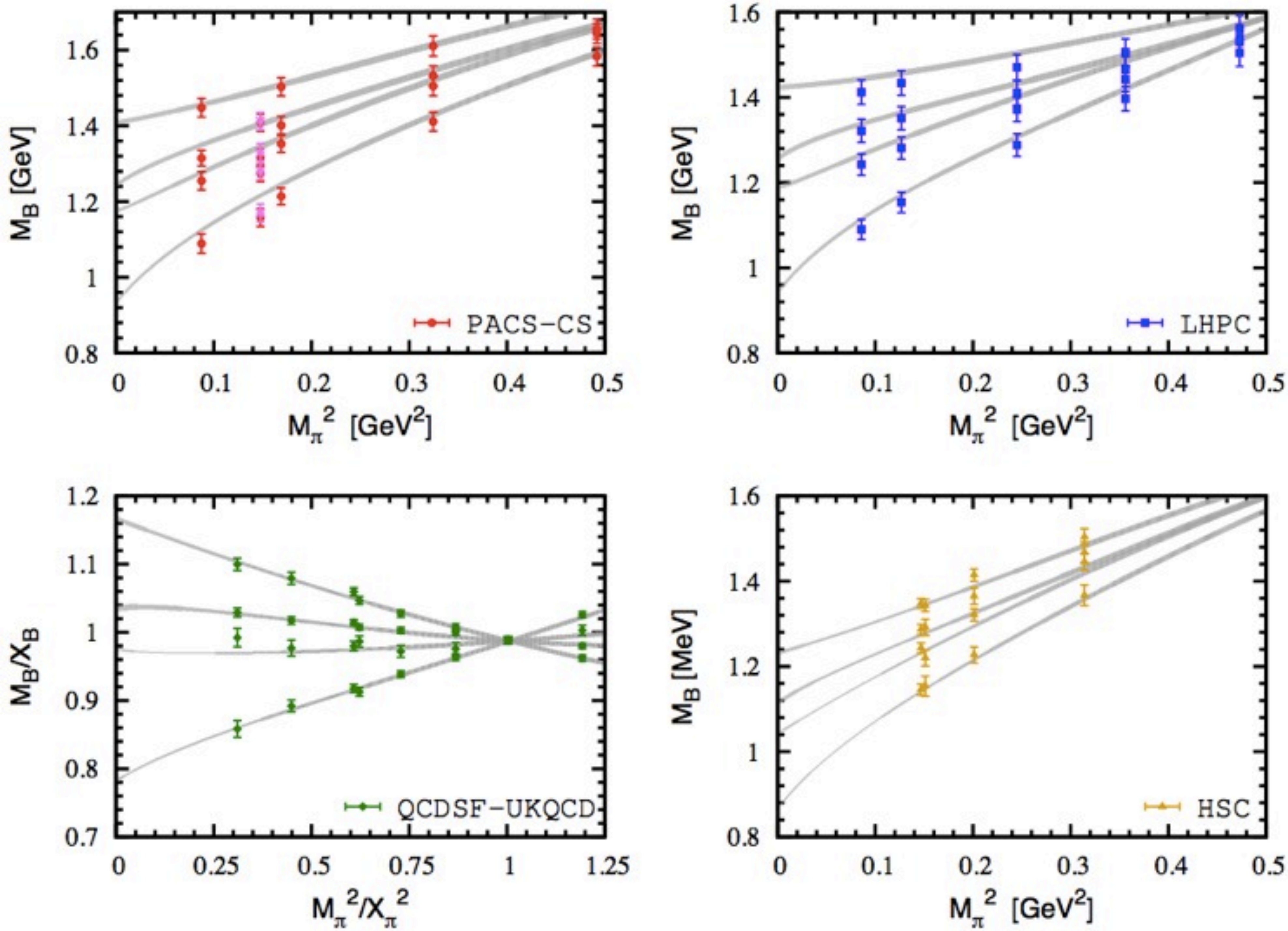


Octet baryon masses: NNNLO ChPT

X.-L. Ren et al., JHEP 12 (2012) 073

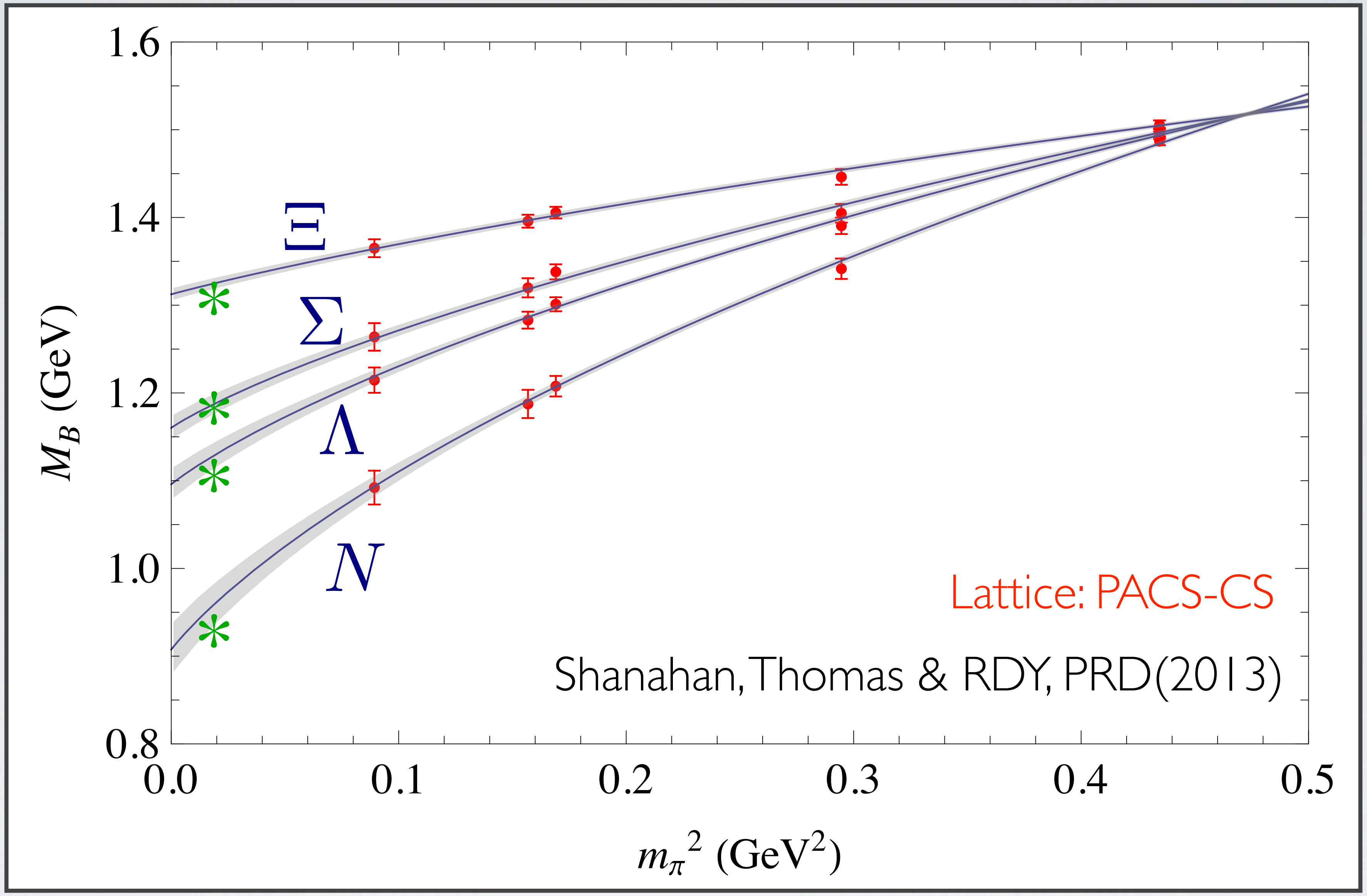
Lattice: "Strong"

Lattice QCD has a long history of describing quark mass dependence of observables

Just require splitting of up and down quark masses;
But, all dynamical lattice simulations have $m_u = m_d$

- Study mass variation with partially-quenched valence quarks
- Use SU(3) symmetry in relation to hyperon masses

SU(3) Finite-Range Regularisation

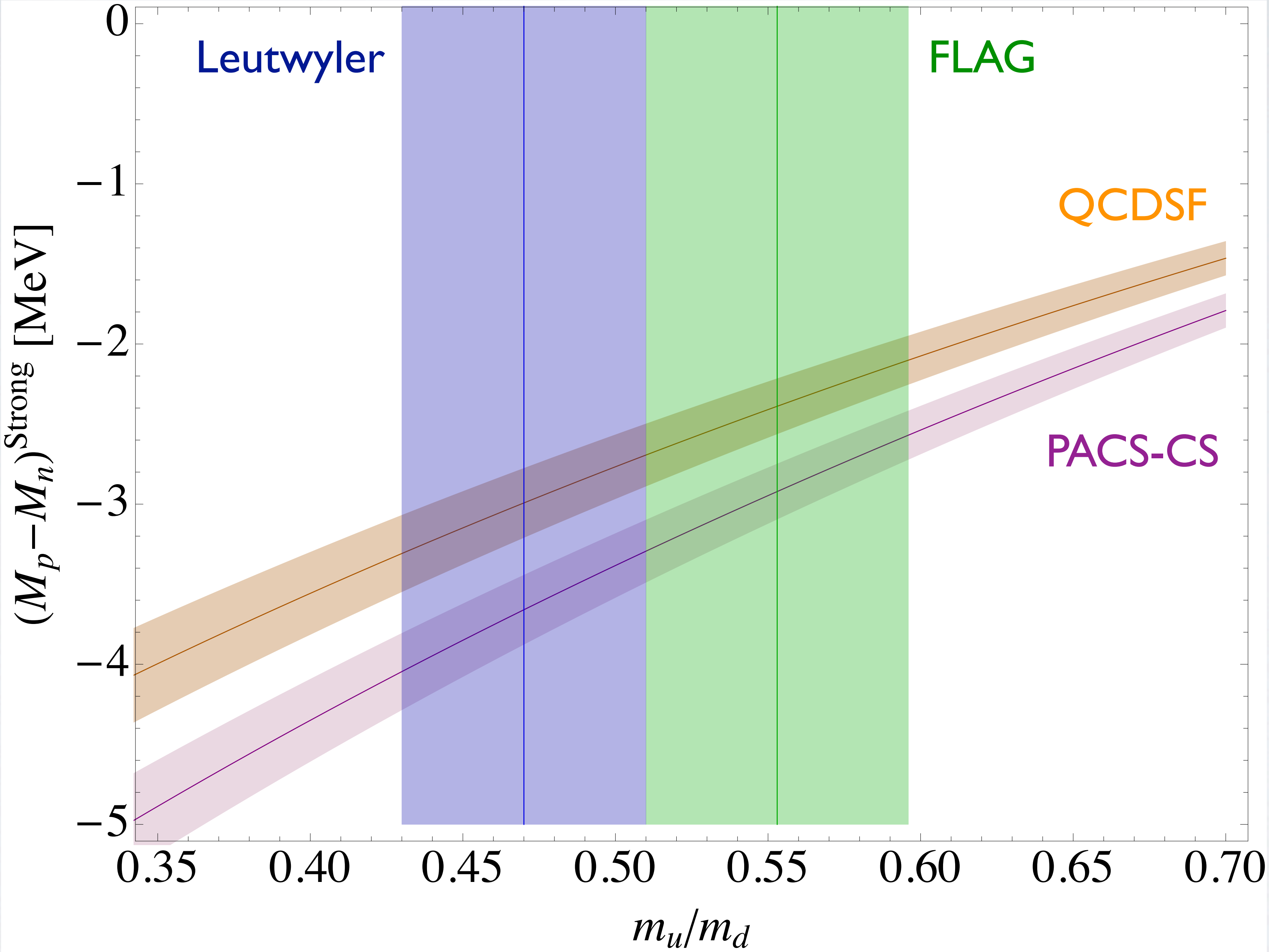


SU(2) symmetric simulation:

No new parameters in EFT to break SU(2)

Strong mass splitting

Sensitive to quark mass ratio

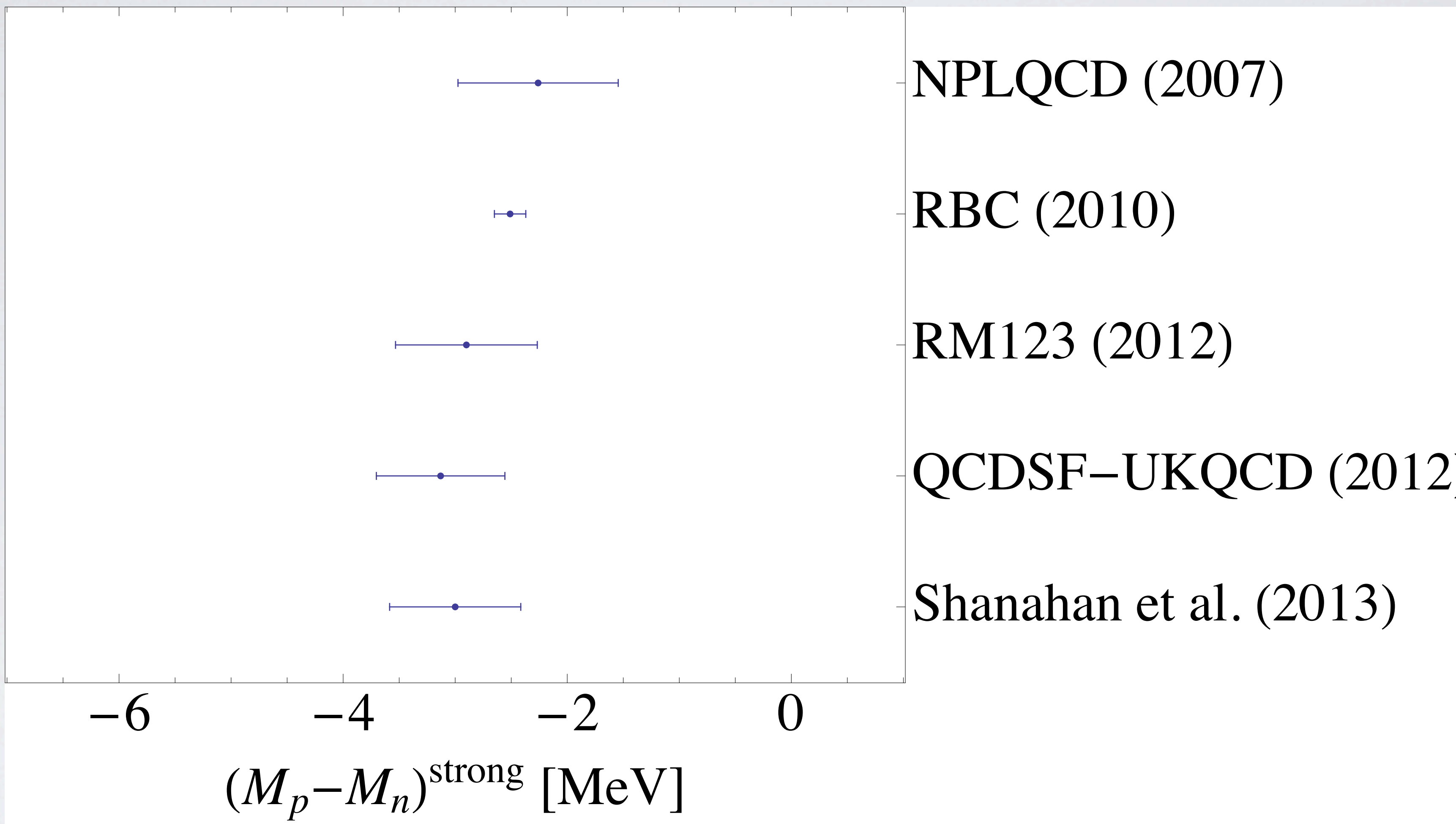


Our result $$(M_p - M_n)^{\text{strong}} = -3.0 \pm 0.6\,\text{MeV}$$

Shanahan, Thomas & RDY, PLB(2013)

Lattice Summary

Lattice estimates of "strong" part of mass splitting



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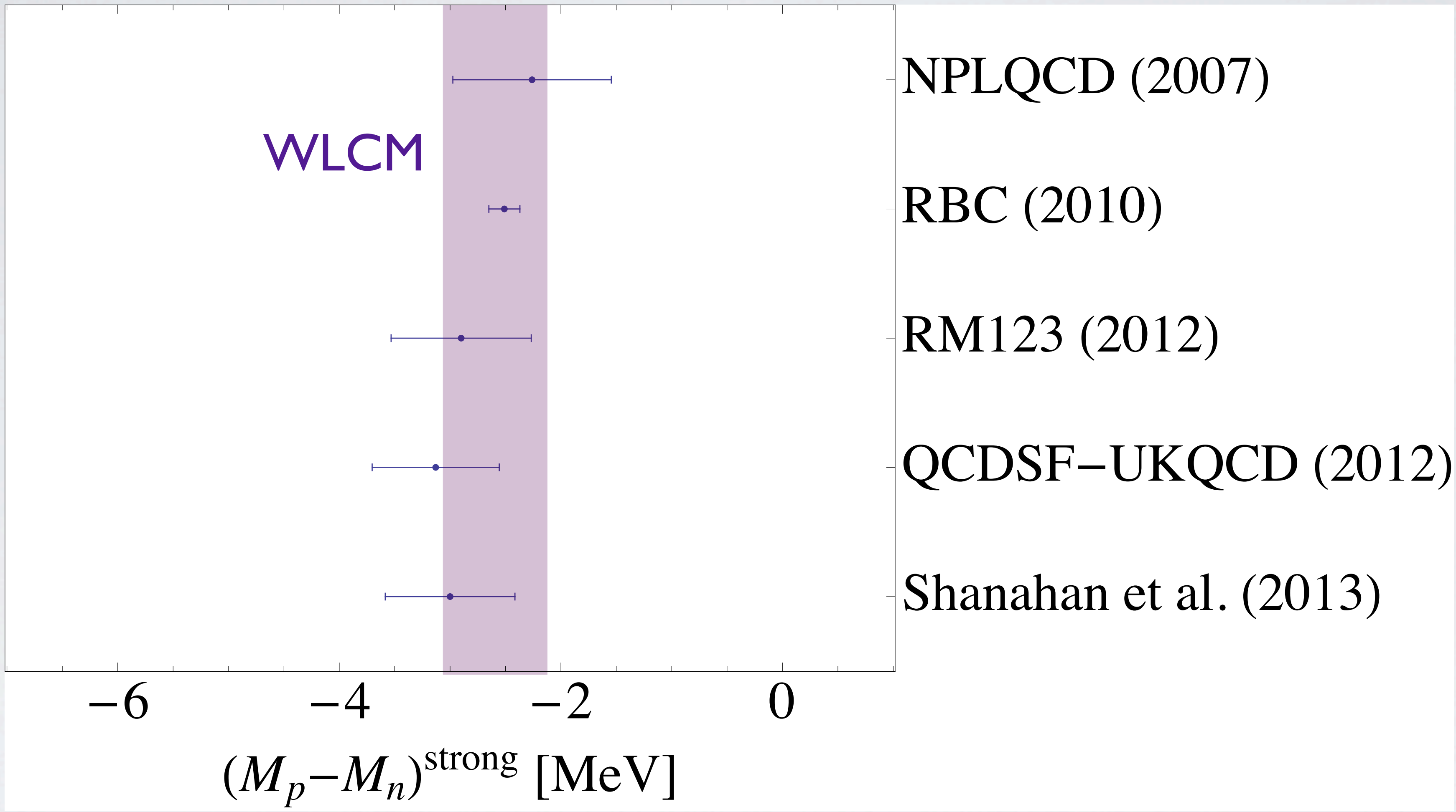

Consistent with dispersive estimate by WLCM

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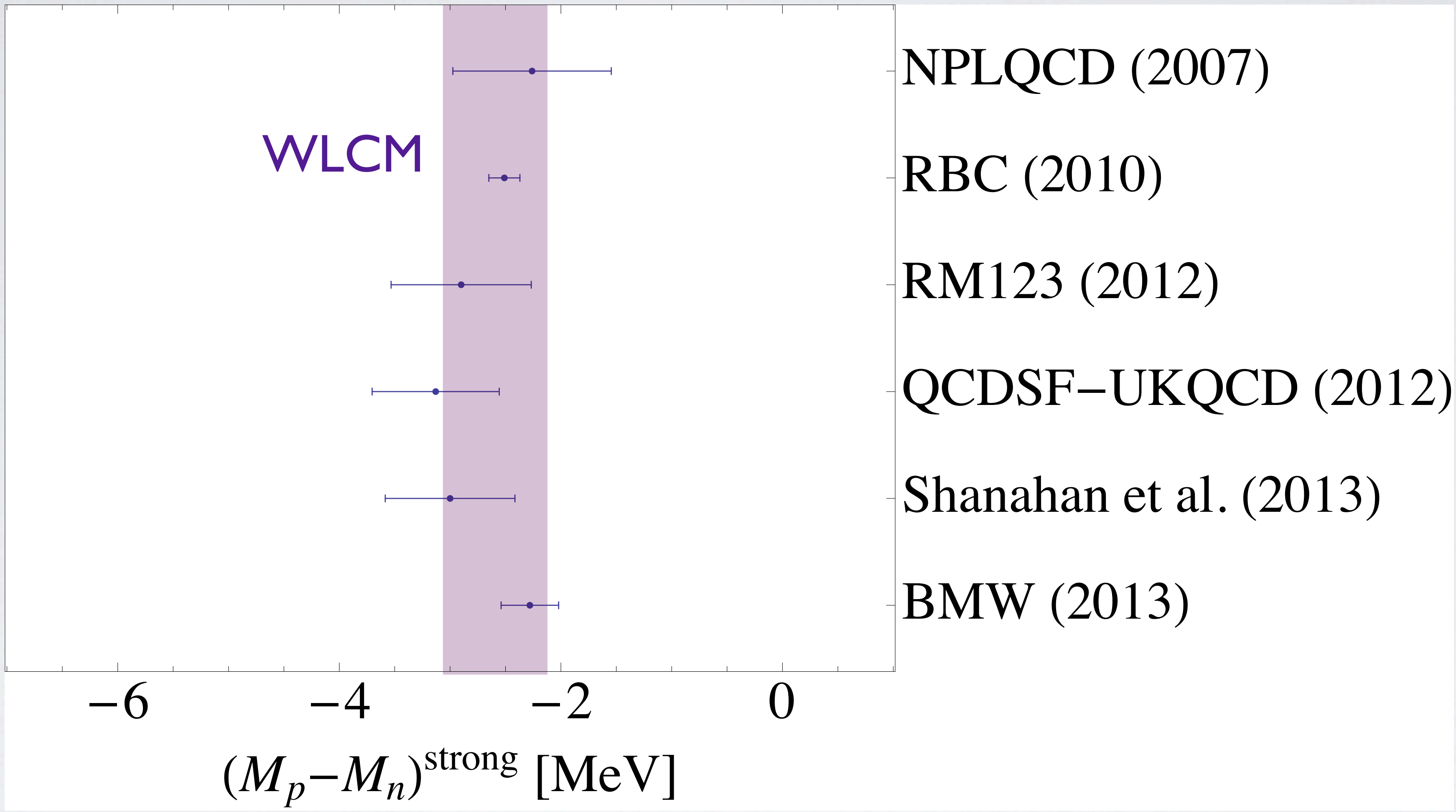
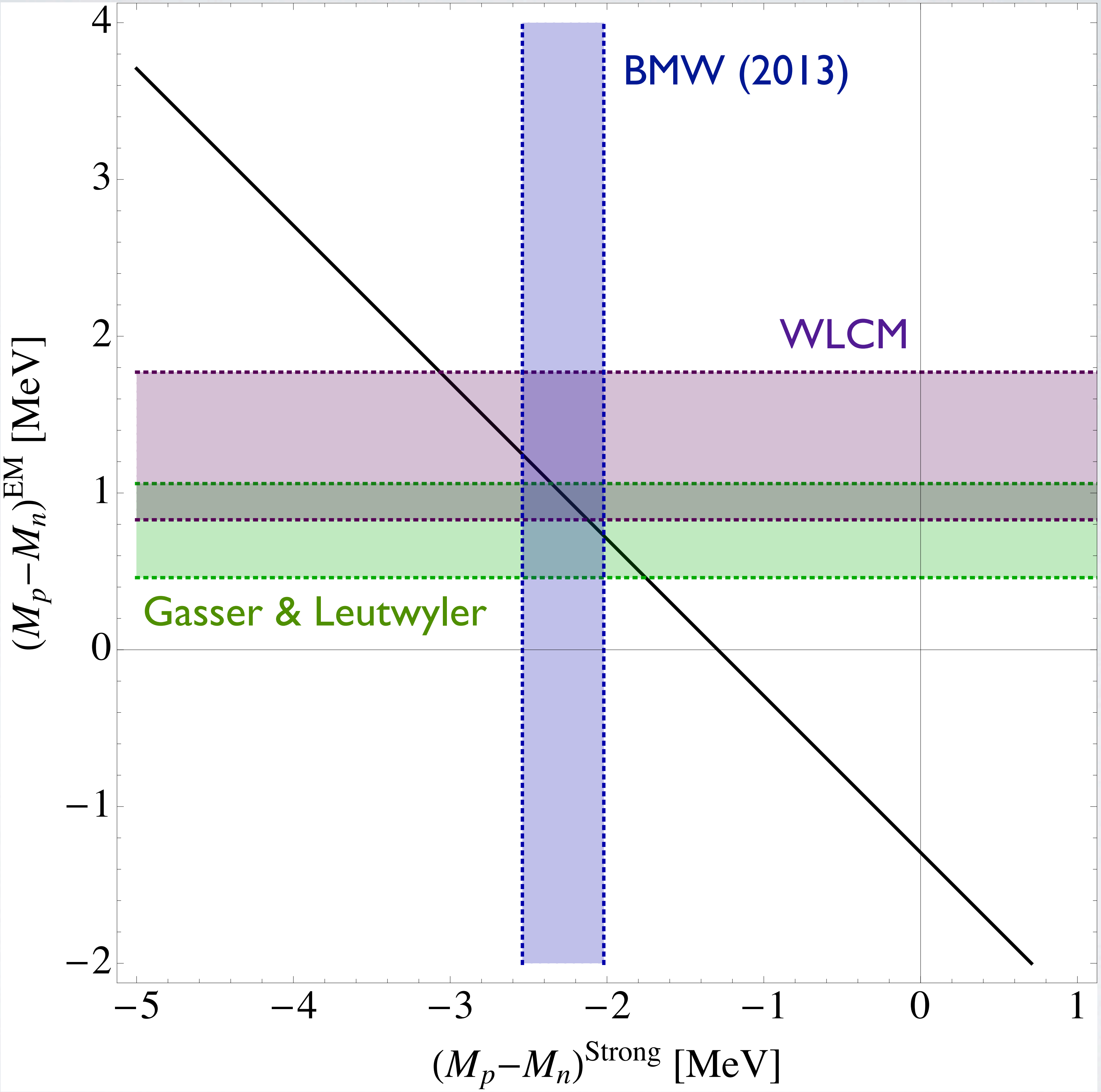


Consistent with dispersive estimate by WLCM

New BMW result

Shanahan et al.: better agreement with FLAG quark mass ratio

Current Status



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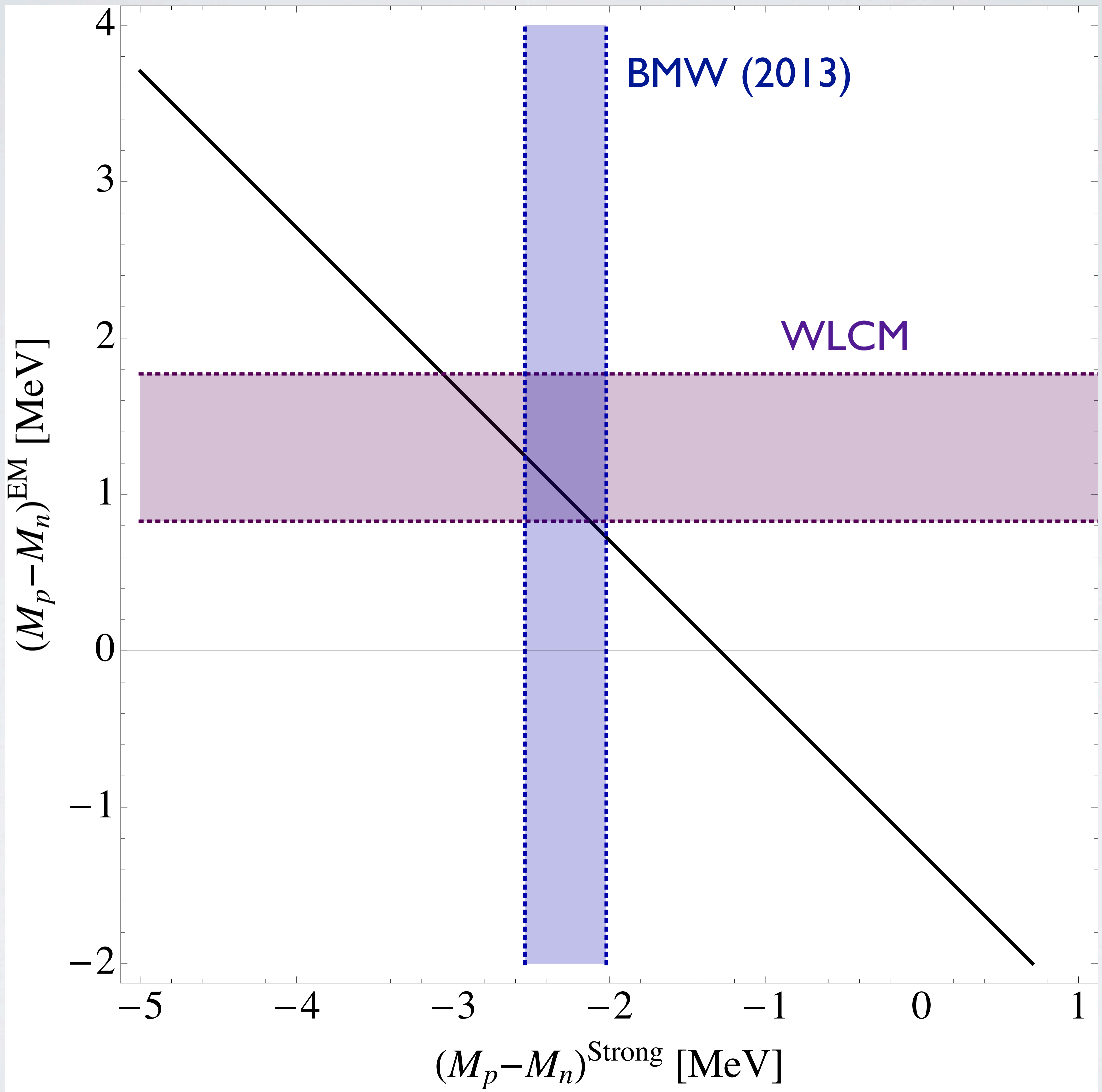


Are charge symmetry violations relevant to nucleon structure?

NuTeV Experiment

NuTeV Experiment

Paschos-Wolfenstein ratio

$$R_{\mathrm{PW}} = \frac{\sigma_{NC}^{\nu\,A} - \sigma_{NC}^{\bar{\nu}\,A}}{\sigma_{CC}^{\nu\,A} - \sigma_{CC}^{\bar{\nu}\,A}}$$

$\nu - \bar{\nu}$ & $\frac{\text{neutral current}}{\text{charged current}}$

NuTeV: indirect measure of this ratio

With

Exact charge symmetry

Vanishing partonic strangeness $s(x) - \bar{s}(x)$

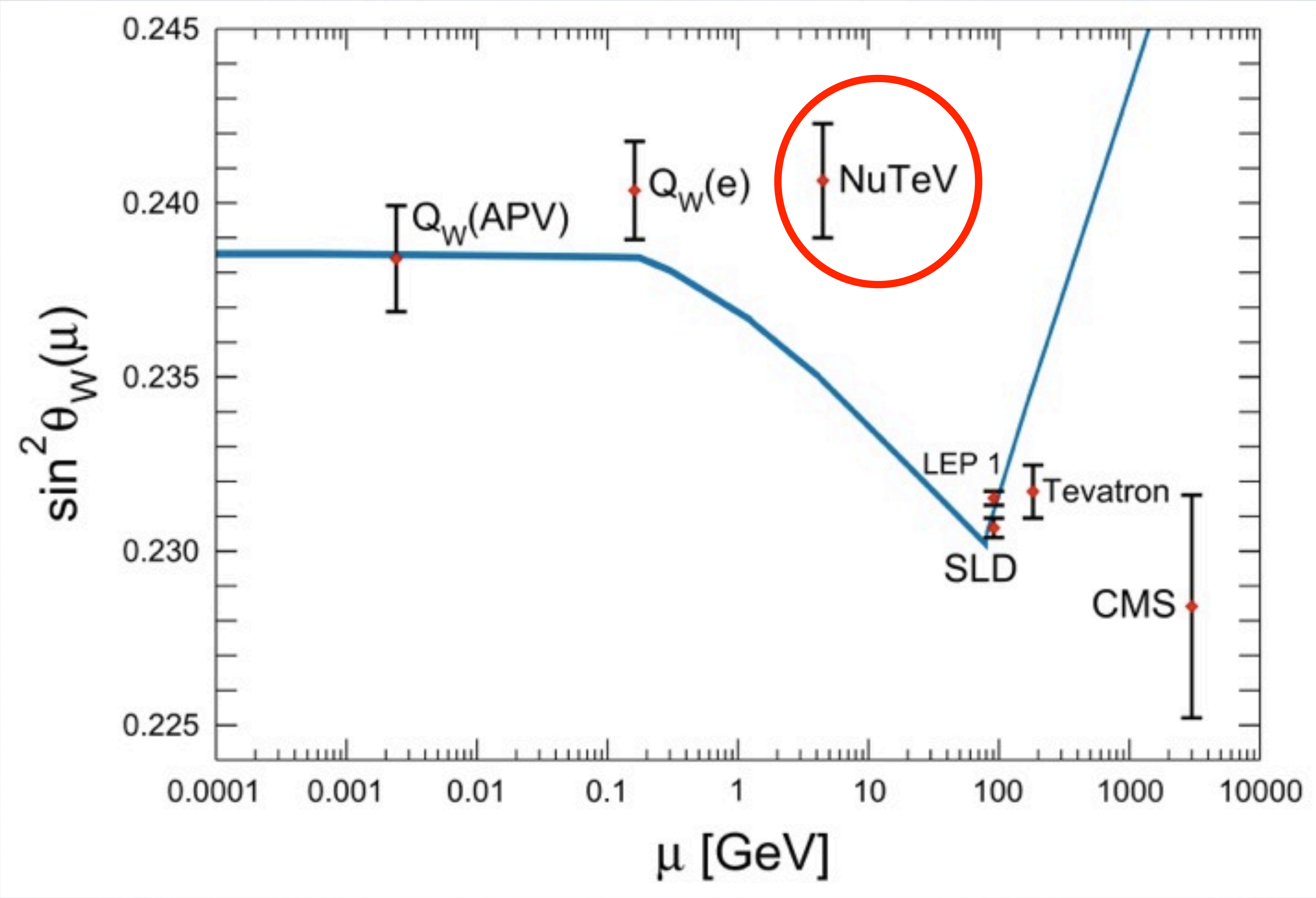
Isoscalar nucleus

⇒ PW ratio direct measure of weak mixing angle

$$R_{\mathrm{PW}} \to \frac{1}{2} - \sin^2\theta_W$$

NuTeV & $\sin^2\theta_W$

NuTeV report a 3-sigma discrepancy from the Standard Model



Relies on assumption that CSV is negligible

Charge symmetry violation in partons

Partonic charge symmetry relations

$$u^p(x) = d^n(x)$$
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Lattice can only make contact with moments

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

Parton CSV

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

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

Parton CSV

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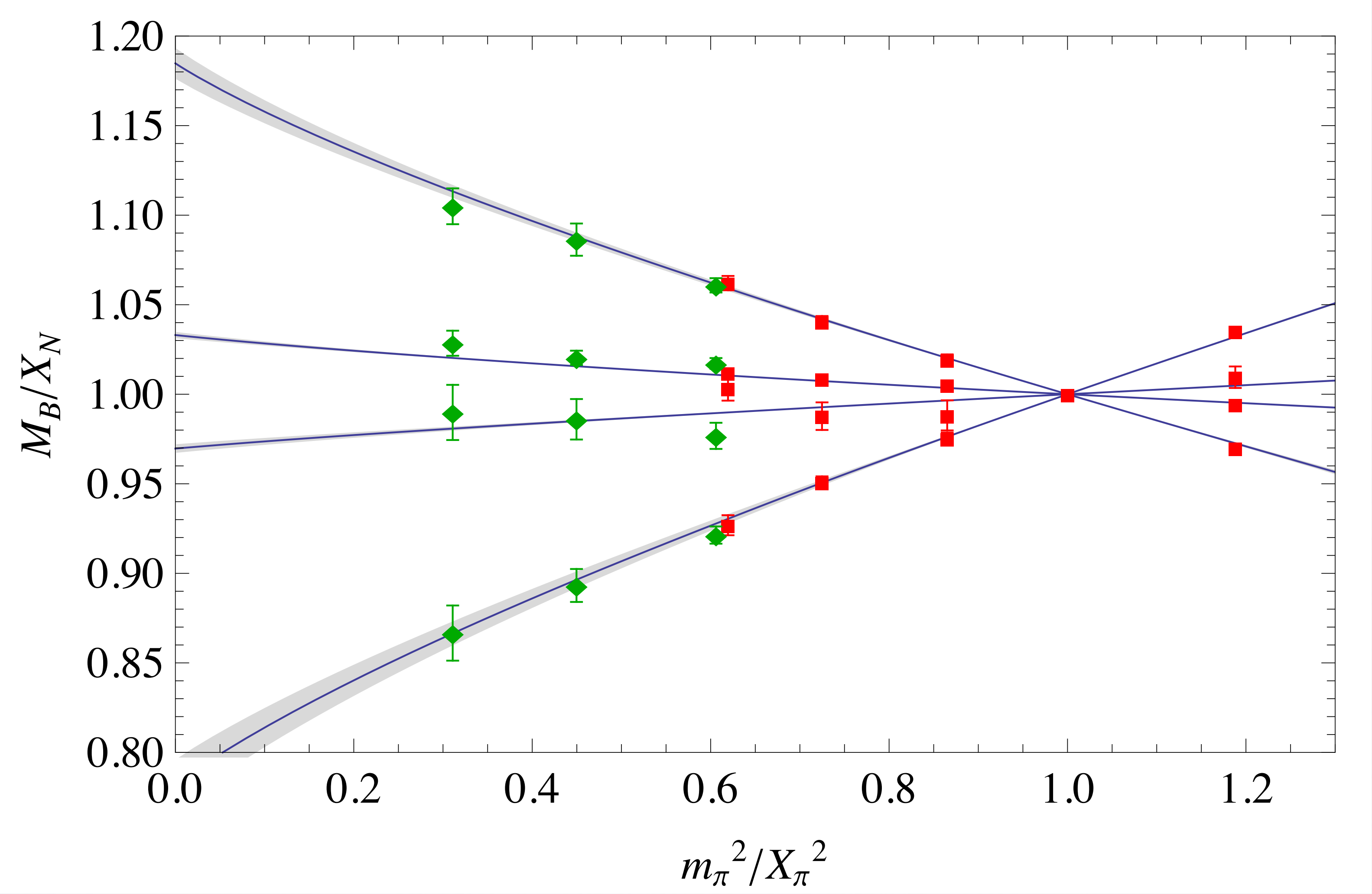
Charge symmetry

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

QCDSF-UKQCD Lattices

Tune lattice parameters such to have exact SU(3) symmetry at the physical average (light) quark mass

$$\overline{m}_q^{\rm lat} = (m_u + m_d + m_s)^{\rm phys}/3$$



Hold singlet mass fixed on trajectory to physical point

Hyperon PDF moments

Near SU(3) symmetric point

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

Hence we can estimate relevant derivatives

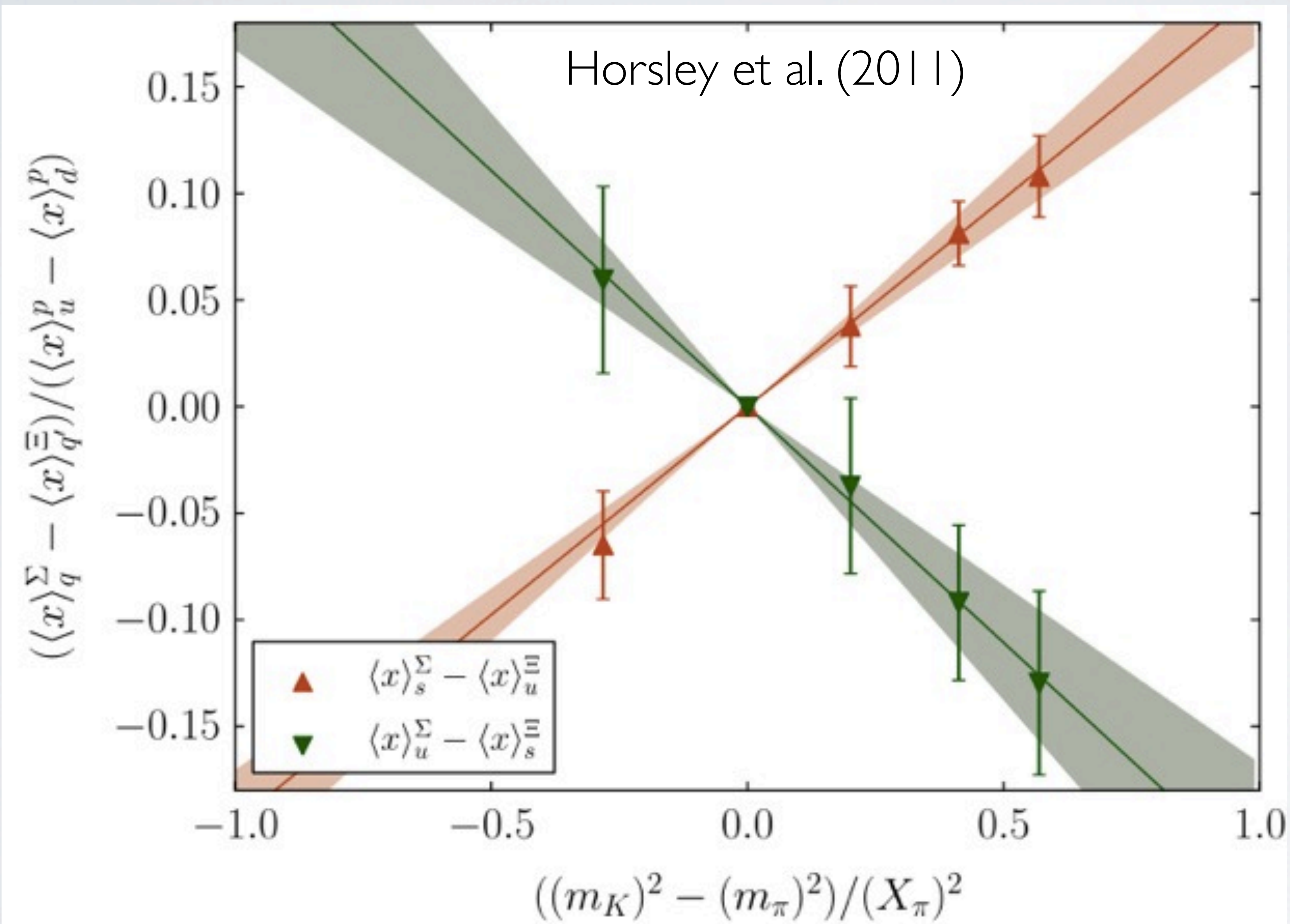
$$\frac{\partial\langle x\rangle_u^p}{\partial m_u} \simeq \frac{\langle x\rangle_s^{\Xi^0} - \langle x\rangle_u^p}{m_s - m_l}, \quad \frac{\partial\langle x\rangle_u^p}{\partial m_d} \simeq \frac{\langle x\rangle_u^{\Sigma^+} - \langle x\rangle_u^p}{m_s - m_l}$$

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

Just need to determine hyperon moments about SU(3) symmetric point

Charge Symmetry Violation

Lattice results for quark-mass dependence of hyperon momentum fractions



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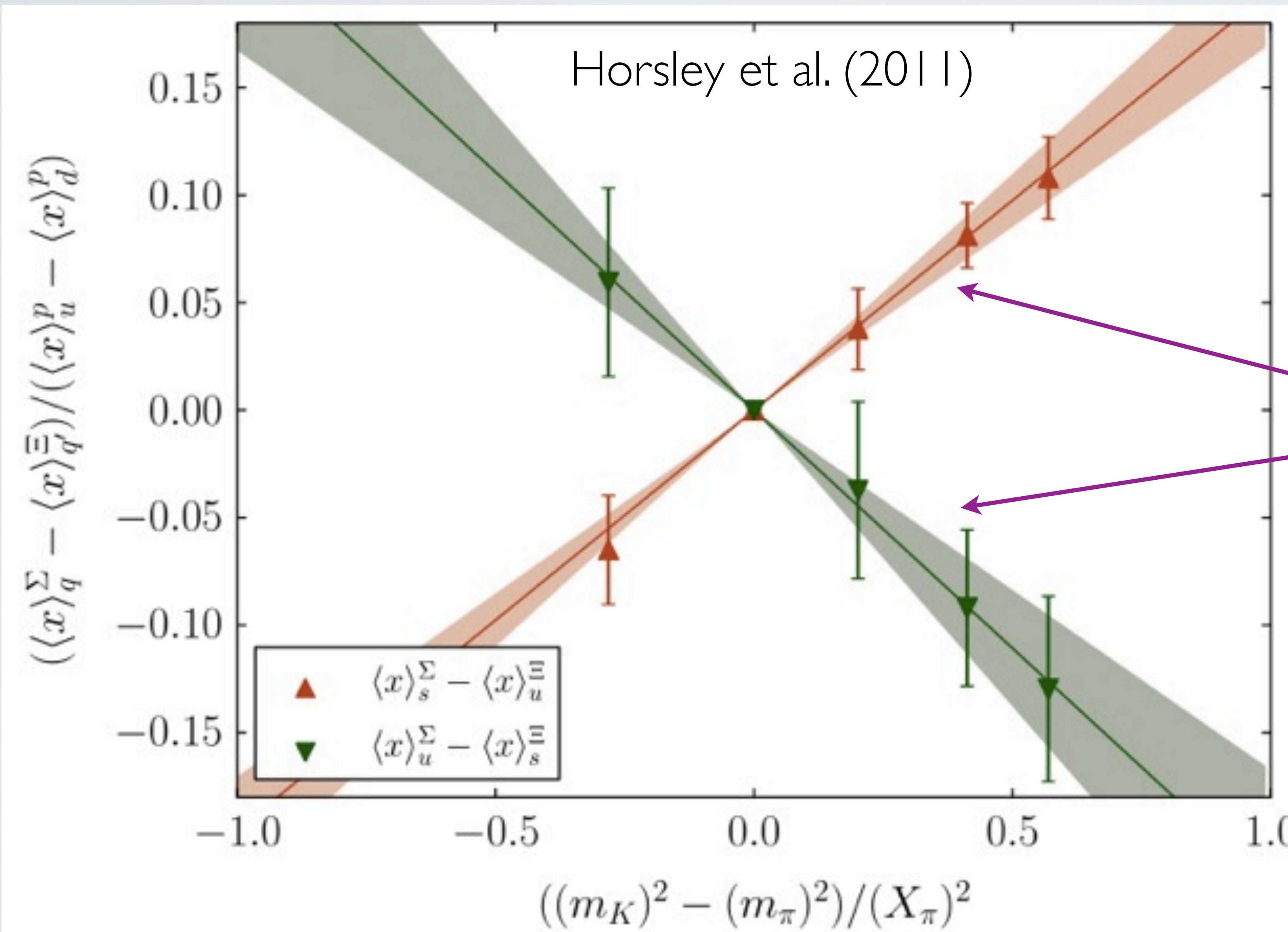

Slopes determine CSV at SU(3) symmetric point

Chiral extrapolation of hyperon moments

Tree-level operators

$$\left[\alpha^{(n)}(\overline{B}B\lambda_q) + \beta^{(n)}(\overline{B}\lambda_q B) \ + \sigma^{(n)}(\overline{B}B)\mathrm{Tr}(\lambda_q)\right] p^{\{\mu_1} \dots p^{\mu_n\}} - \mathrm{Tr}$$

$\mathcal{O}(m_q)$ counterterms

$$\begin{aligned}
\Big\{ & b_1^{(n)}\mathrm{Tr}\left[\overline{B}\left[[\lambda_q, B], M\right]\right] + b_2^{(n)}\mathrm{Tr}\left[\overline{B}\{[\lambda_q, B], M\}\right] \\
& + b_3^{(n)}\mathrm{Tr}\left[\overline{B}\left[\{\lambda_q, B\}, M\right]\right] + b_4^{(n)}\mathrm{Tr}\left[\overline{B}\{\{\lambda_q, B\}, M\}\right] \\
& + b_5^{(n)}\mathrm{Tr}\left[\overline{B}B\right]\mathrm{Tr}\left[\lambda_q M\right] + b_6^{(n)}\mathrm{Tr}\left[\overline{B}B\lambda_q\right]\mathrm{Tr}\left[M\right] \\
& + b_7^{(n)}\mathrm{Tr}\left[\overline{B}\lambda_q B\right]\mathrm{Tr}\left[M\right] + b_8^{(n)}\mathrm{Tr}\left[\overline{B}MB\right]\mathrm{Tr}\left[\lambda_q\right] \\
& + b_9^{(n)}\mathrm{Tr}\left[\overline{B}BM\right]\mathrm{Tr}\left[\lambda_q\right] \\
& + b_{10}^{(n)}\mathrm{Tr}\left[\overline{B}\lambda_q\right]\mathrm{Tr}\left[MB\right] \Big\} p^{\{\mu_1} \dots p^{\mu_n\}} - \mathrm{Tr}
\end{aligned}$$

Shanahan, Thomas & RDY, PRD(2013)114515

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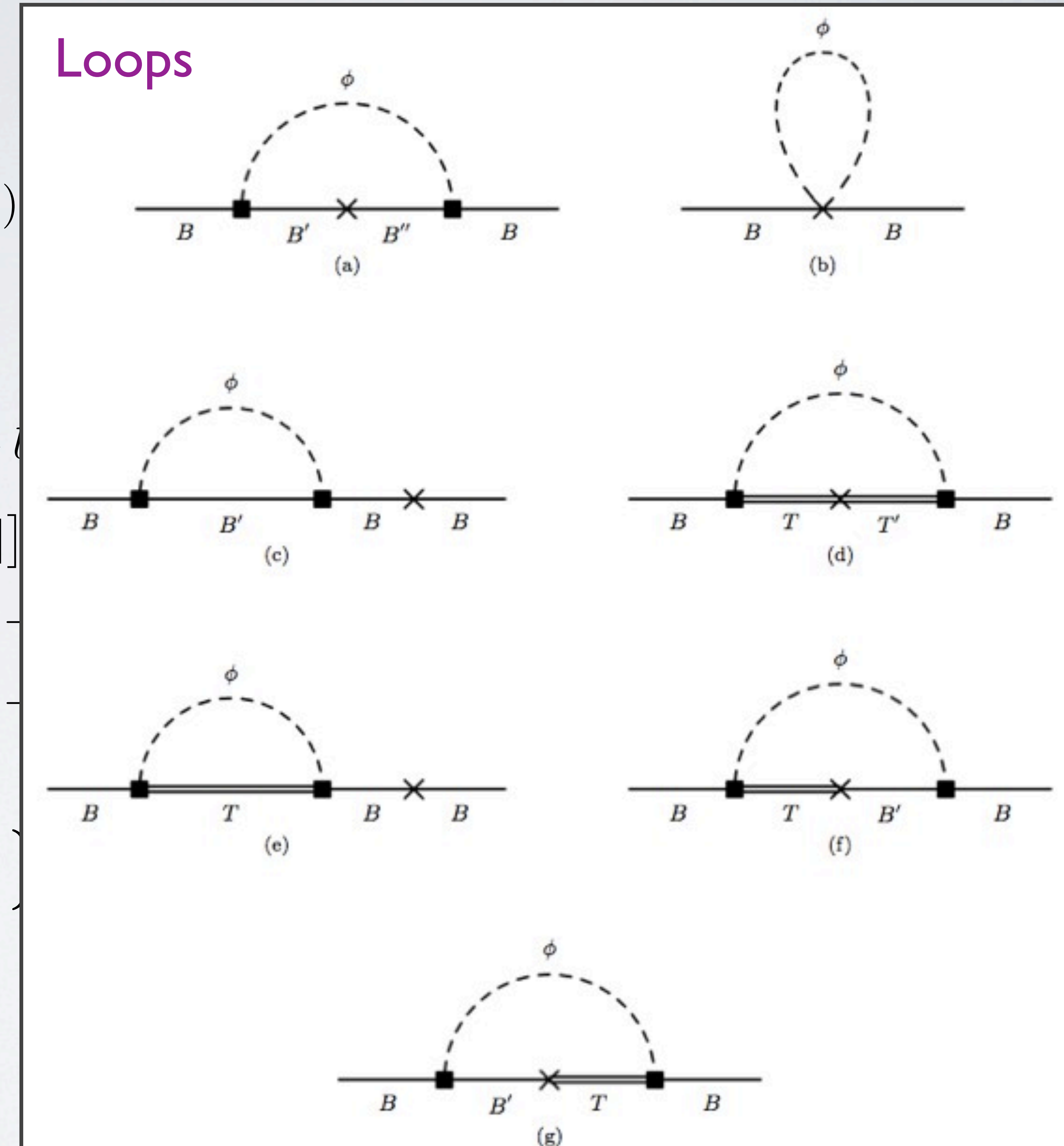

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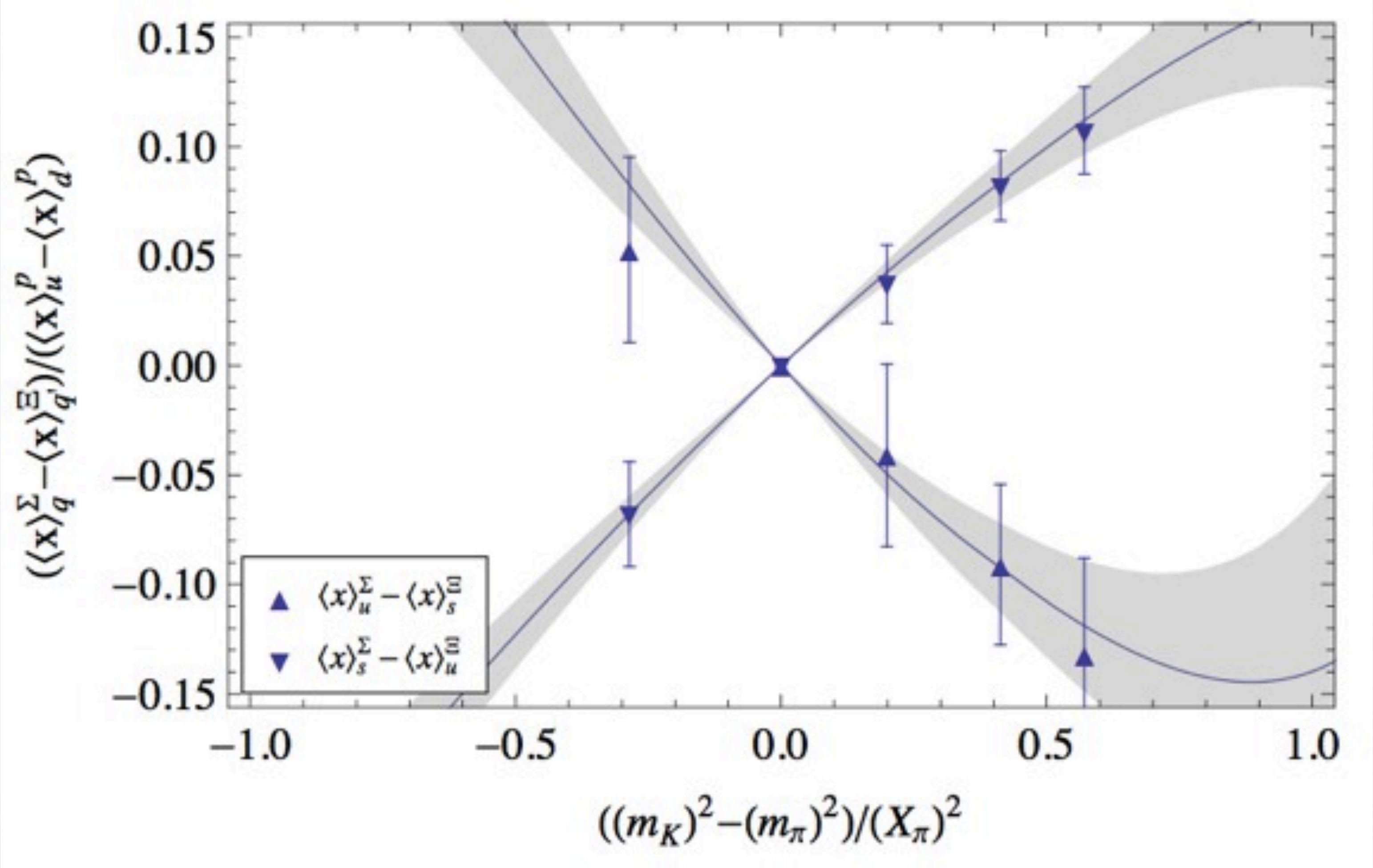
Chiral extrapolation of CSV

Just as for baryon masses, we can fit isospin symmetric lattice results for hyperons

No new parameters in EFT to determine CSV



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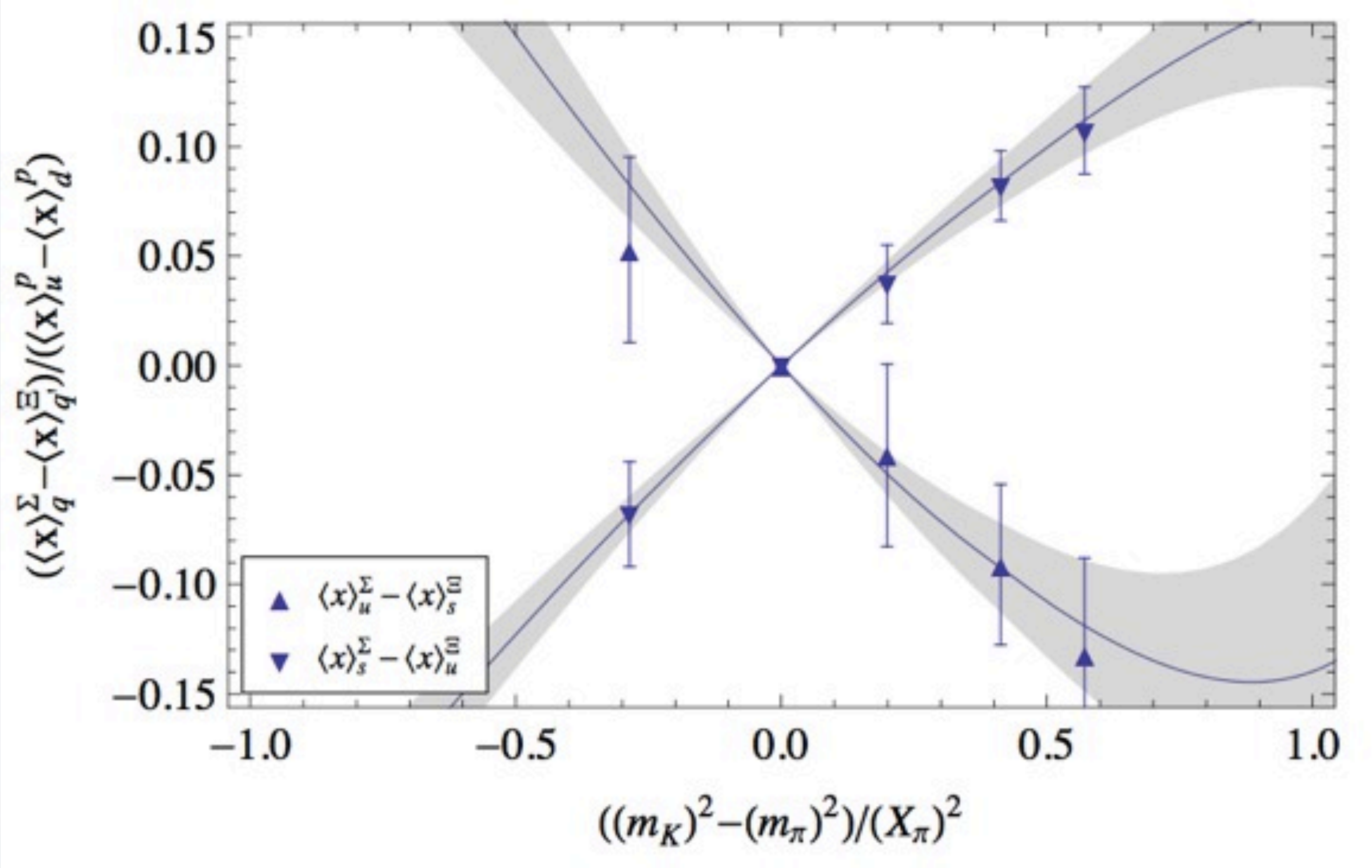

Our result

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

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

Shanahan, Thomas & RDY, PRD(2013)094515

Back to NuTeV

Correction to the Paschos-Wolfenstein ratio from CSV

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

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Our result + CSV from QED parton evolution

⇒ Reduce NuTeV Standard Model discrepancy by ~1-sigma

Back to NuTeV

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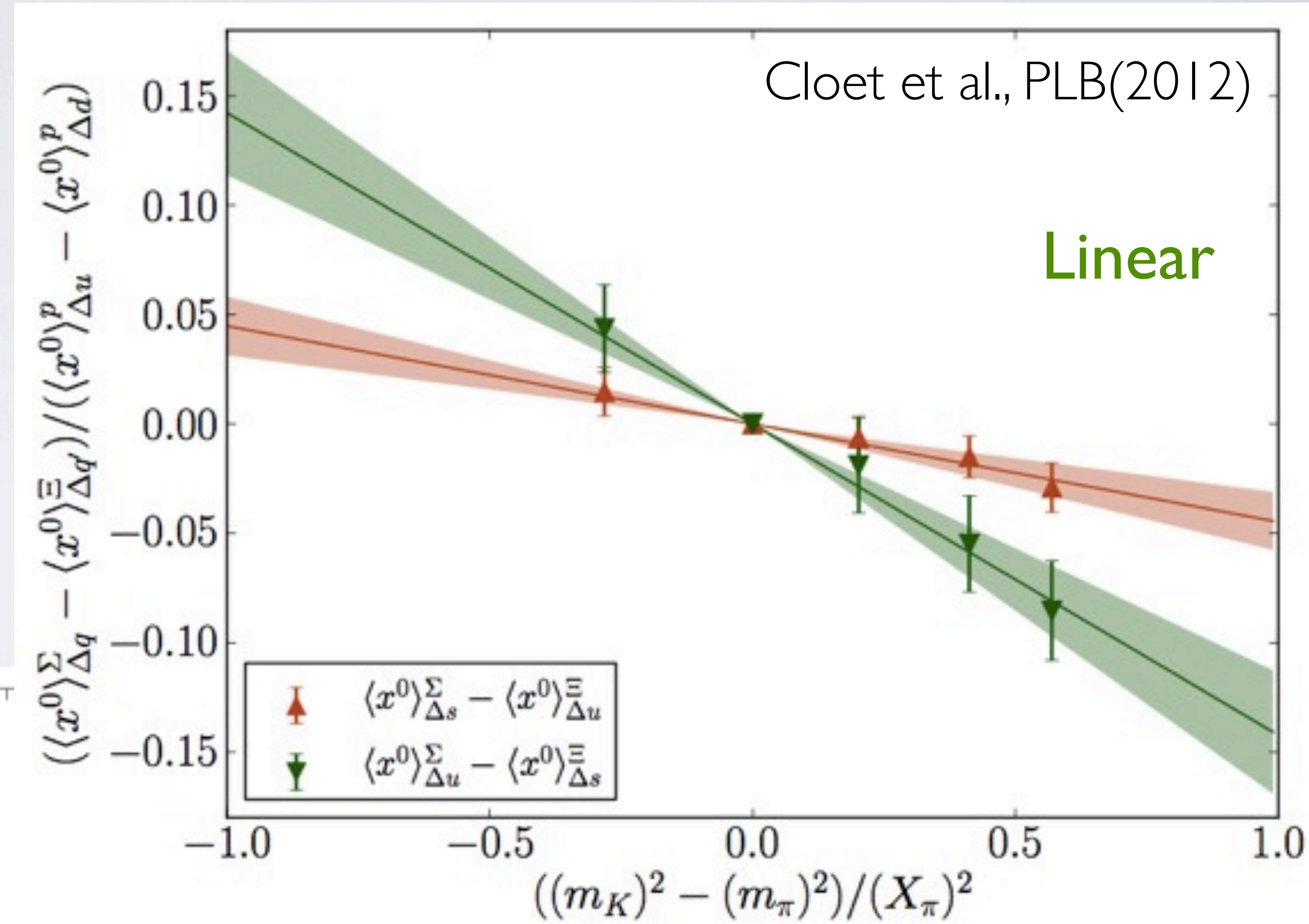
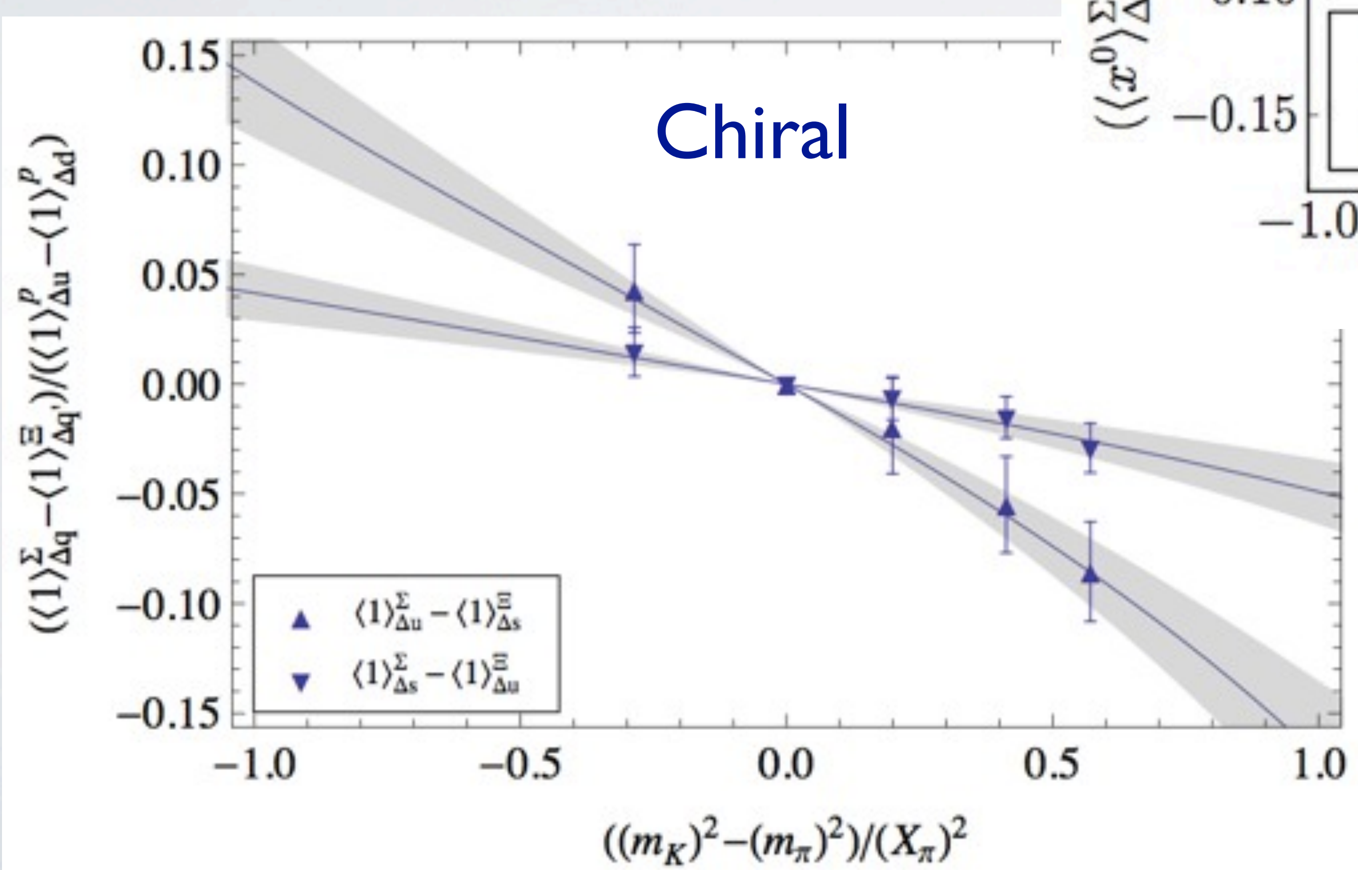
Futher corrections: Non-isoscalar nucleus, strangeness

see Bentz, Cloet, Londergan & Thomas PLB(2010)

Spin-dependent CSV

~1% correction to the Bjorken sum rule





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Summary

Effects of charge symmetry violation are becoming increasingly significant in precision studies

Improved understanding of the proton-neutron mass splitting

Subtracted Cottingham formula & new lattice results

Unambiguously resolved CSV parton moments in lattice QCD

Reduces the NuTeV anomaly

Could improve sensitivity of future SM tests: eg. PVDIS@JLab

Spin-dependent CSV could be seen at future electron collider

Thanks [see *parallel talk*: P. Shanahan, 9:20am Tuesday]

Phiala Shanahan, Tony Thomas, James Zanotti, QCDSF-UKQCD