Dynamics of strange quarks in the nucleon

Ross Young
Physics Division, ANL

16 April 2009, *Dynamics of Symmetry Breaking*, ANL

Carlini, Thomas, Wang (JLab), Leinweber (Adelaide), Roche (Ohio)

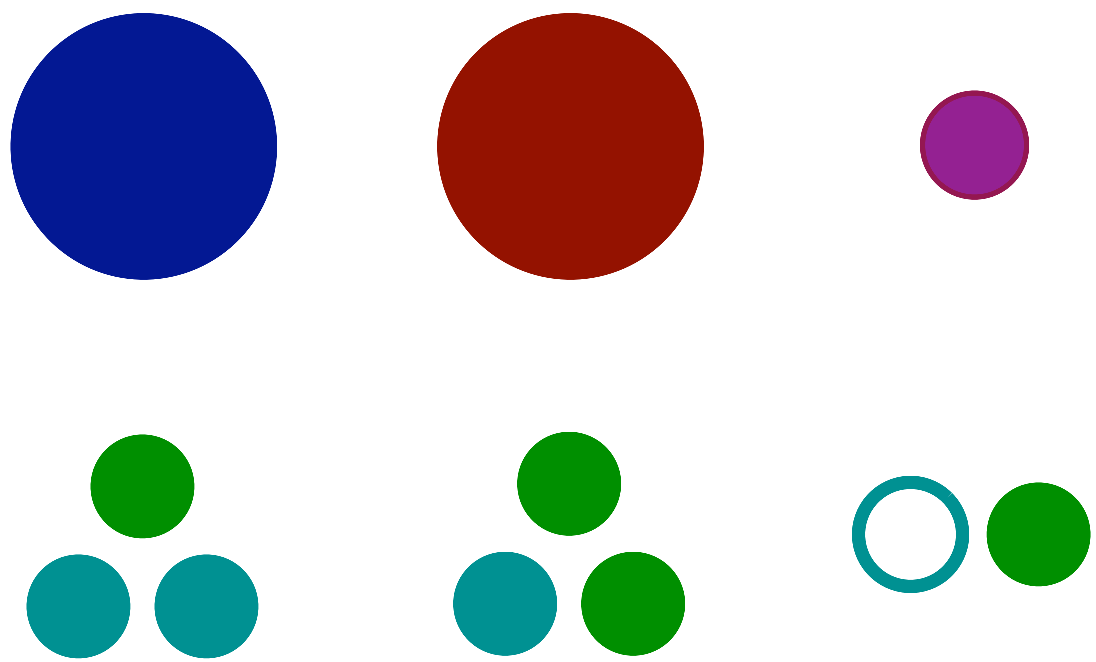
Strong force is from QCD

- Nuclear components are built from quarks

up quark

down quark

Neutron | Proton | Pion



Mass	940 MeV	938 MeV	140 MeV

Quark masses:

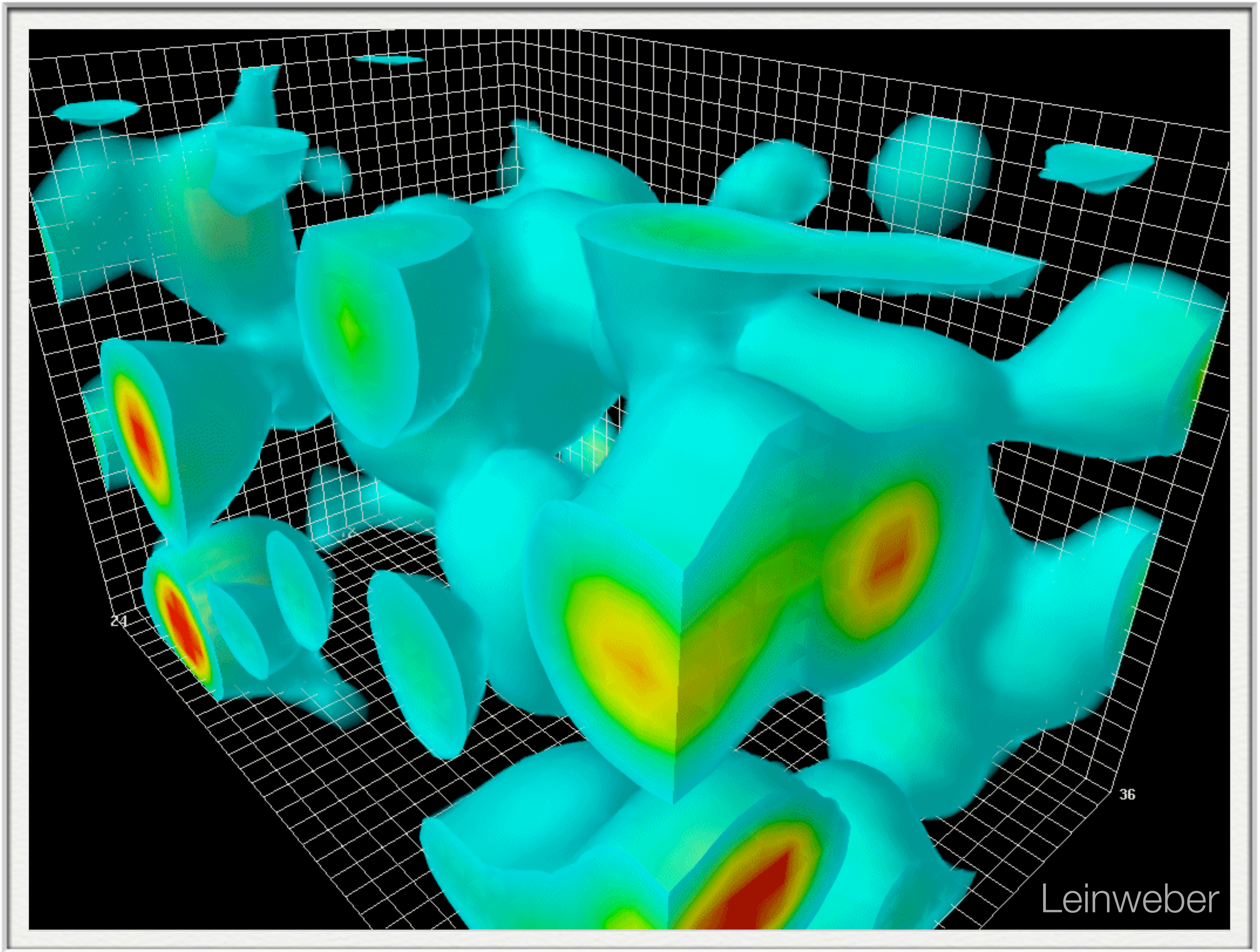
$$m_u \sim 3\,\mathrm{MeV} \quad m_d \sim 7\,\mathrm{MeV}$$

Interaction dynamics constitute ~99% of nucleon mass

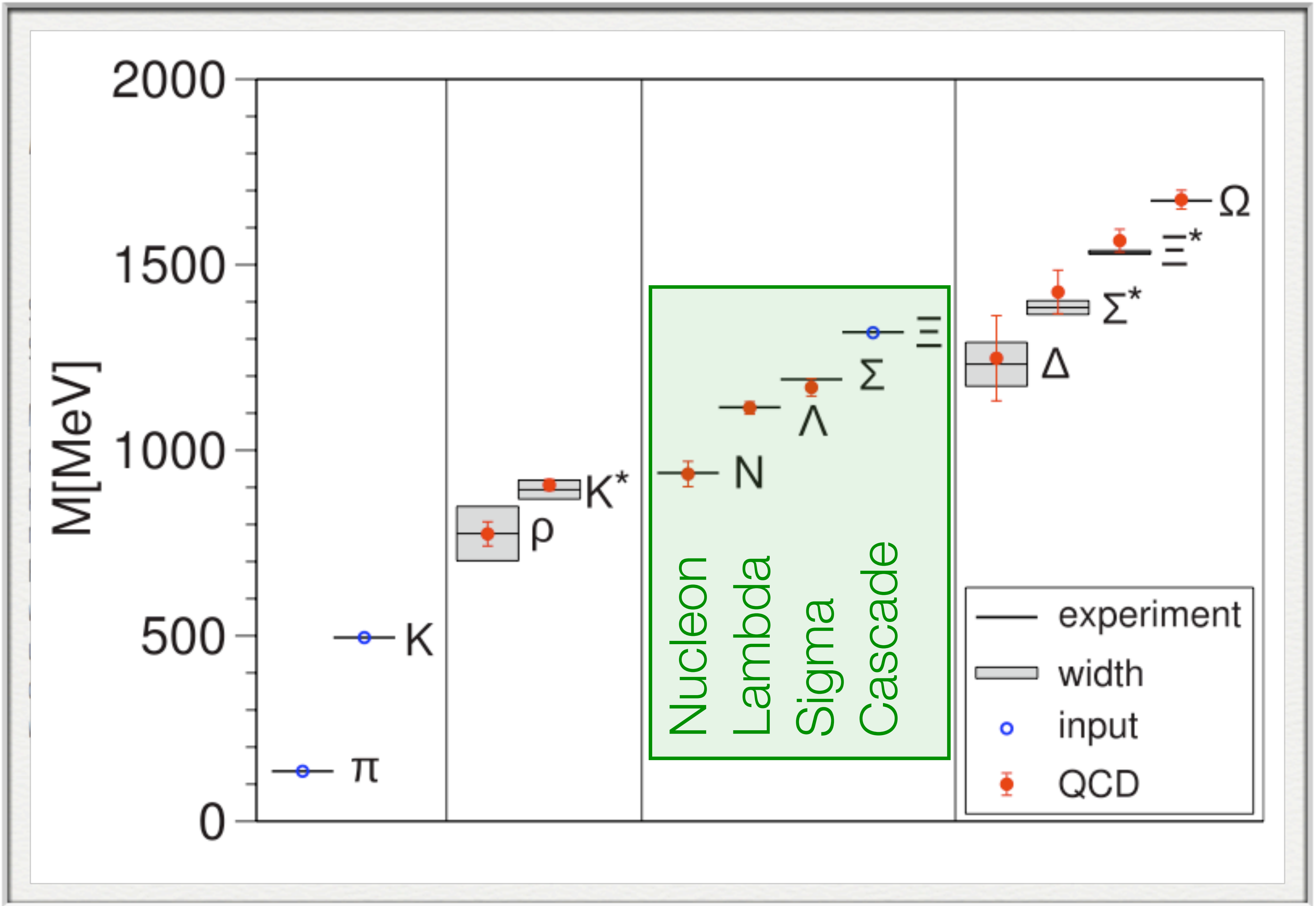
Pion mass ~ *square-root* of quark mass

Understanding QCD?

The vacuum of Quantum Chromodynamics

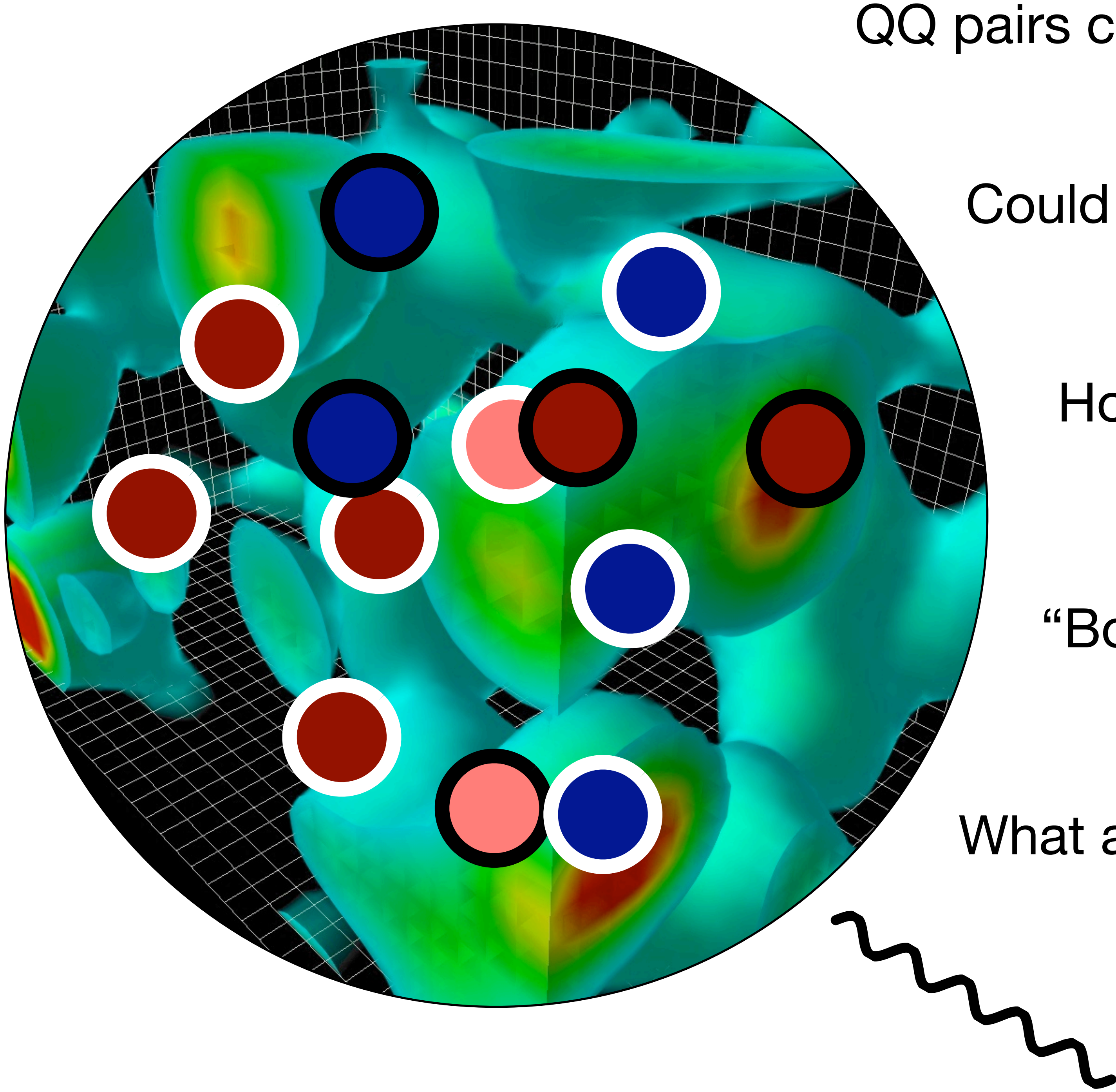


Latest results in Lattice QCD



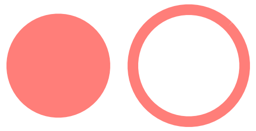
21 NOVEMBER 2008 VOL 322 **SCIENCE** www.sciencemag.org

Binding the nucleon



$Q\bar{Q}$ pairs created by the glue

Could be a strange-quark pair



How can one see quarks in the nucleon?

"Bounce" an electron

What about just the quarks in the glue?

Elastic Form Factors

Electromagnetic form factors characterise the charge and magnetisation distribution in the nucleon

$$G_E(Q^2) \qquad G_M(Q^2)$$

Strangeness is just in glue!

Measure total response from all quarks

Proton

$$G_{E,M}^{p} = +\frac{2}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

Charge symmetry: *up* quark in proton = *down* quark in neutron, ...

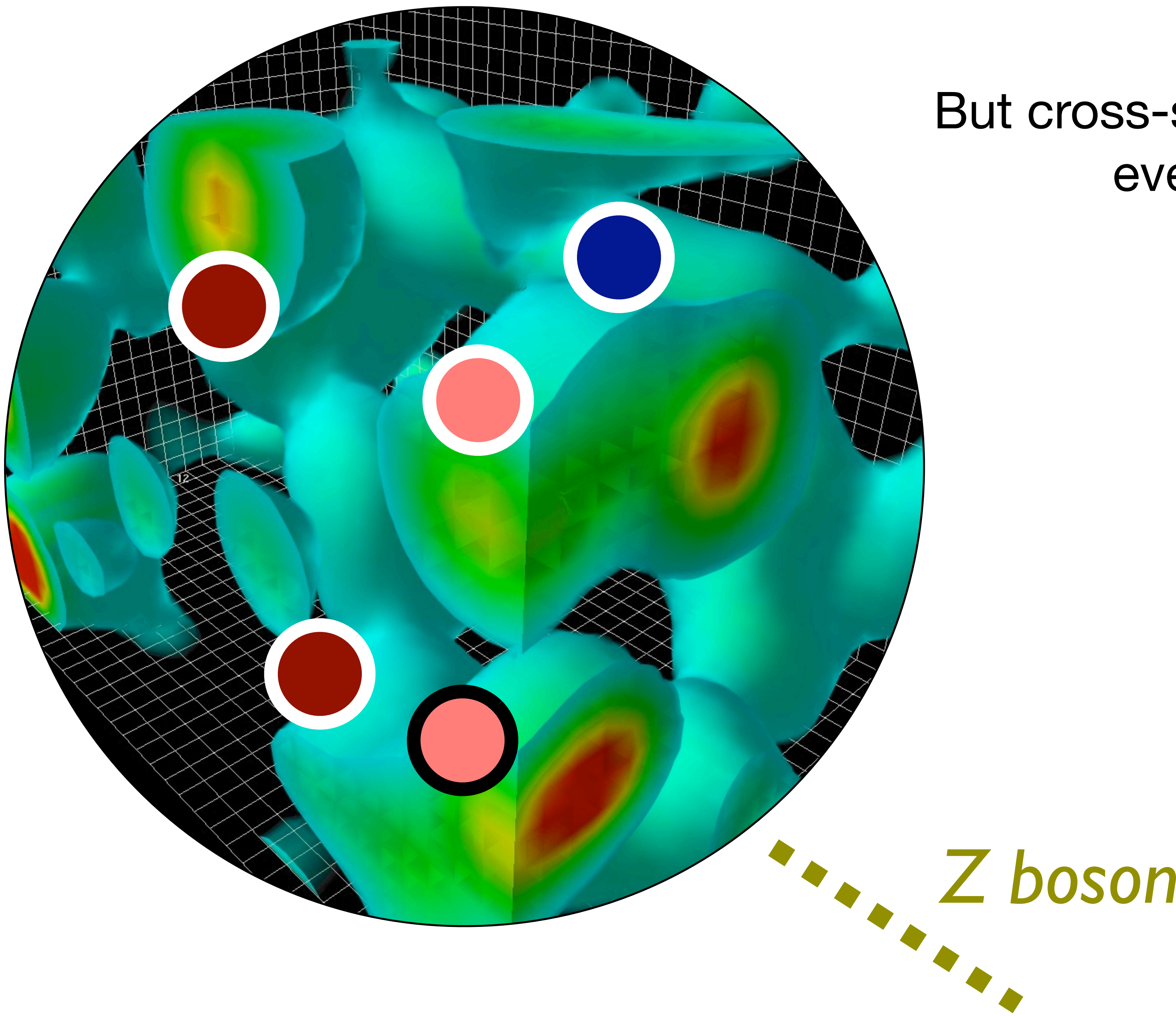
Neutron

$$G_{E,M}^{n} = -\frac{1}{3}G_{E,M}^{u} + \frac{2}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

2 Equations — 3 Unkowns!

Weak Neutral Current

But cross-section for "weak" events is tiny

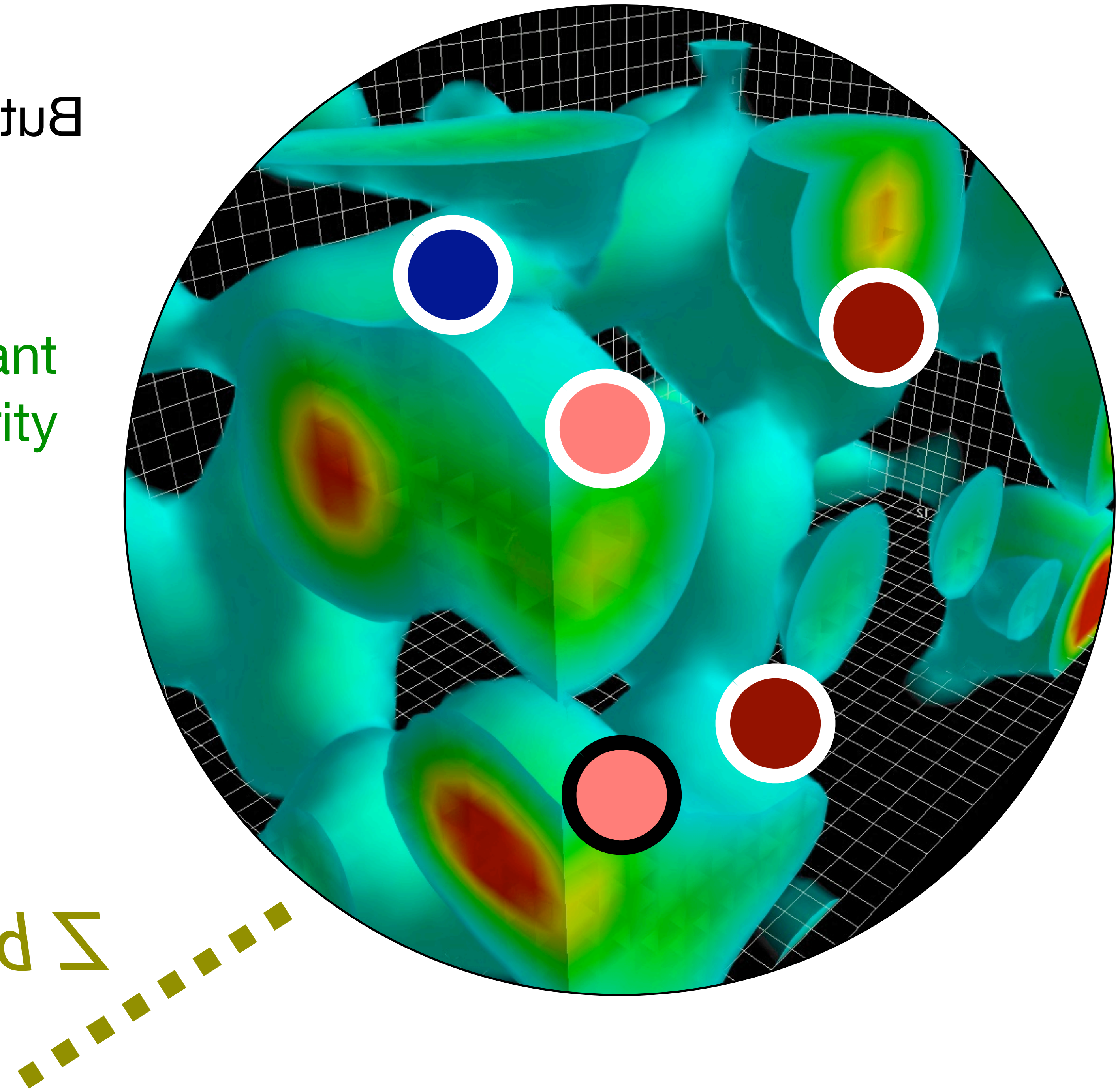


Weak Neutral Current

But cross-section for "weak" events is tiny

Electromagnetism invariant under parity

Dominant electromagnetic contribution cancels, measure interference



Weak Neutral Form Factor

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

Electroweak couplings differ from usual charges

Weak mixing angle: $\sin^2\theta_W$

$$G_{E,M}^{p} = +\frac{2}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

$$G_{E,M}^{n} = -\frac{1}{3}G_{E,M}^{u} + \frac{2}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

3 Equations — 3 Unkowns

Can isolate strangeness!

Strangeness in the Nucleon

- Gell-Mann–Okubo Relation and Pion-Nucleon sigma term $M_N, M_\Lambda, M_\Sigma, M_\Xi$

$$m_s\langle N|\bar{s}s|N\rangle \simeq 335 \pm 132\,\mathrm{MeV}$$

Nelson & Kaplan PLB(1987)

$$\sim M_N^{phys} - M_N^{SU(3)chiral\ \ limit}$$

QCD Lagrangian $\sim \ldots \bar{s}(\not{D} + m_s)s$

$$m_s\langle N|\bar{s}s|N\rangle = m_s\frac{\partial M_N}{\partial m_s}$$

evaluated at *physical* point!

Improved Effective Field Theory estimate

$$m_s\frac{\partial M_N}{\partial m_s} = 113 \pm 108\,\mathrm{MeV}$$

Borasoy & Meissner (1997)

Strangeness Spin Content

- Polarised Deep Inelastic Scattering

$$\int dx\, g_1(x)$$

axial charge g_A

hyperon decay $3F - D$

$$\Delta s = -0.10 \pm 0.04$$

Bass (2004)

Semi-inclusive reactions

$$\Delta s = 0.028 \pm 0.033 \pm 0.009$$

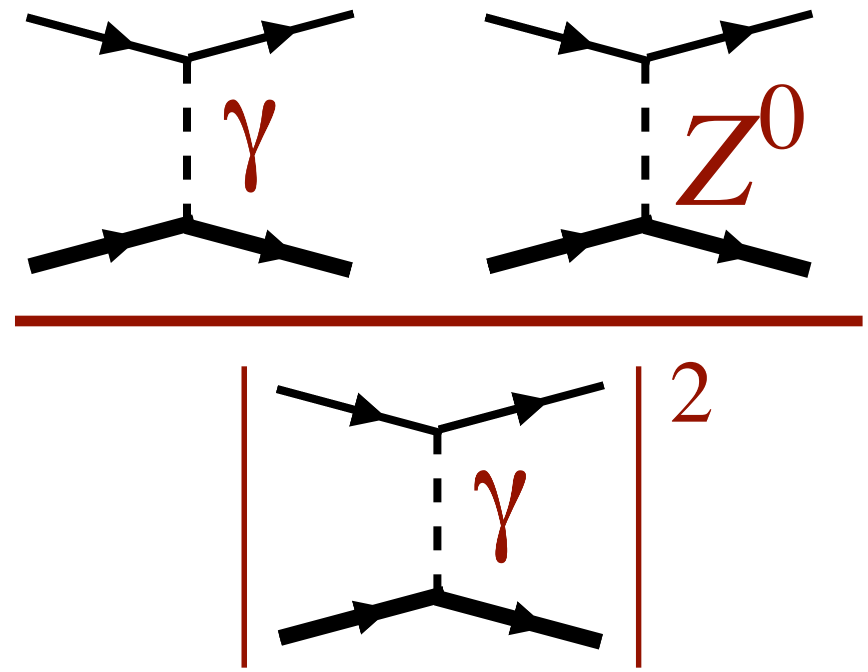
over measured range of *x*

HERMES PRD(2005)

Parity-Violating Electron Scattering

- Asymmetry between right- and left-hand polarised electrons

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\sim \frac{Q^2}{M_Z^2}$$

- Measures the interference between γ and Z_0 exchange

Parity-Violating Asymmetry

- Proton target

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1-4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \tilde{G}_A^p}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Axial form factor

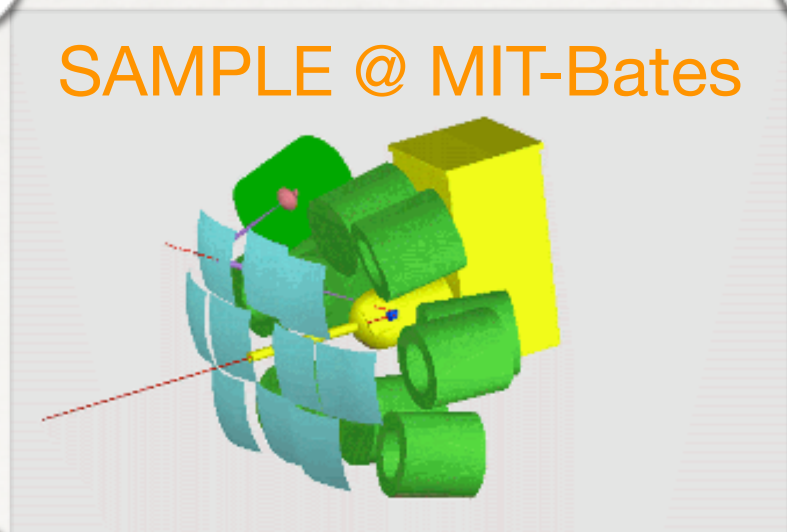
- Assume charge symmetry:

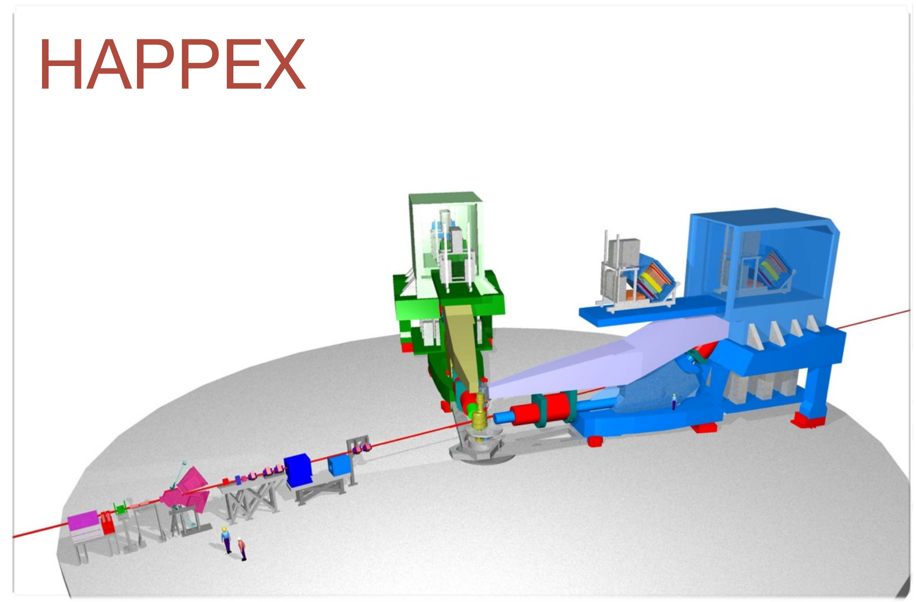
$$G_{E,M}^{pZ} = (1-4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

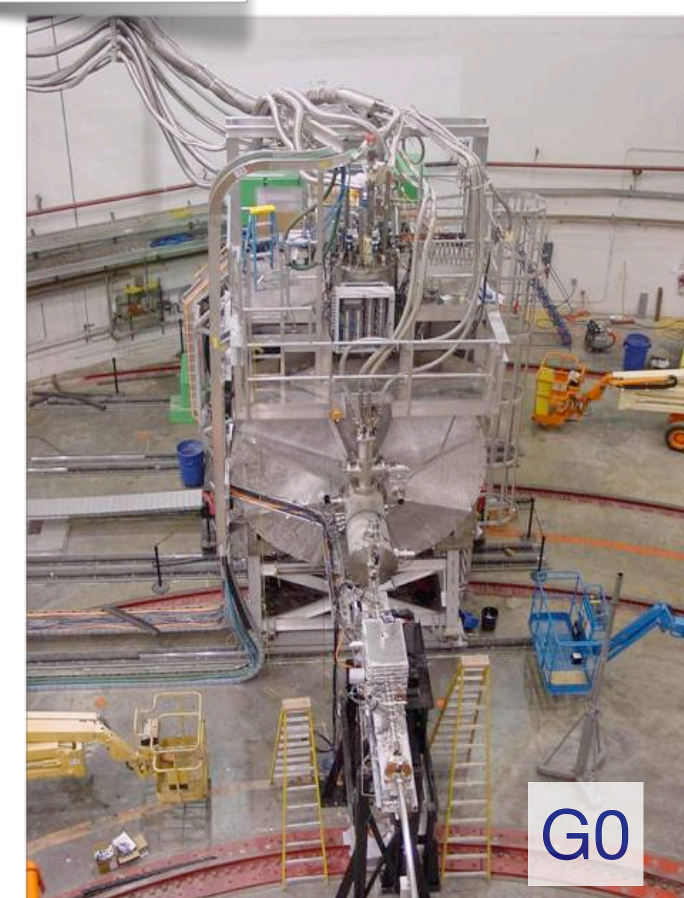
Proton weak charge
(tree level)

Strangeness

Strangeness Measurements





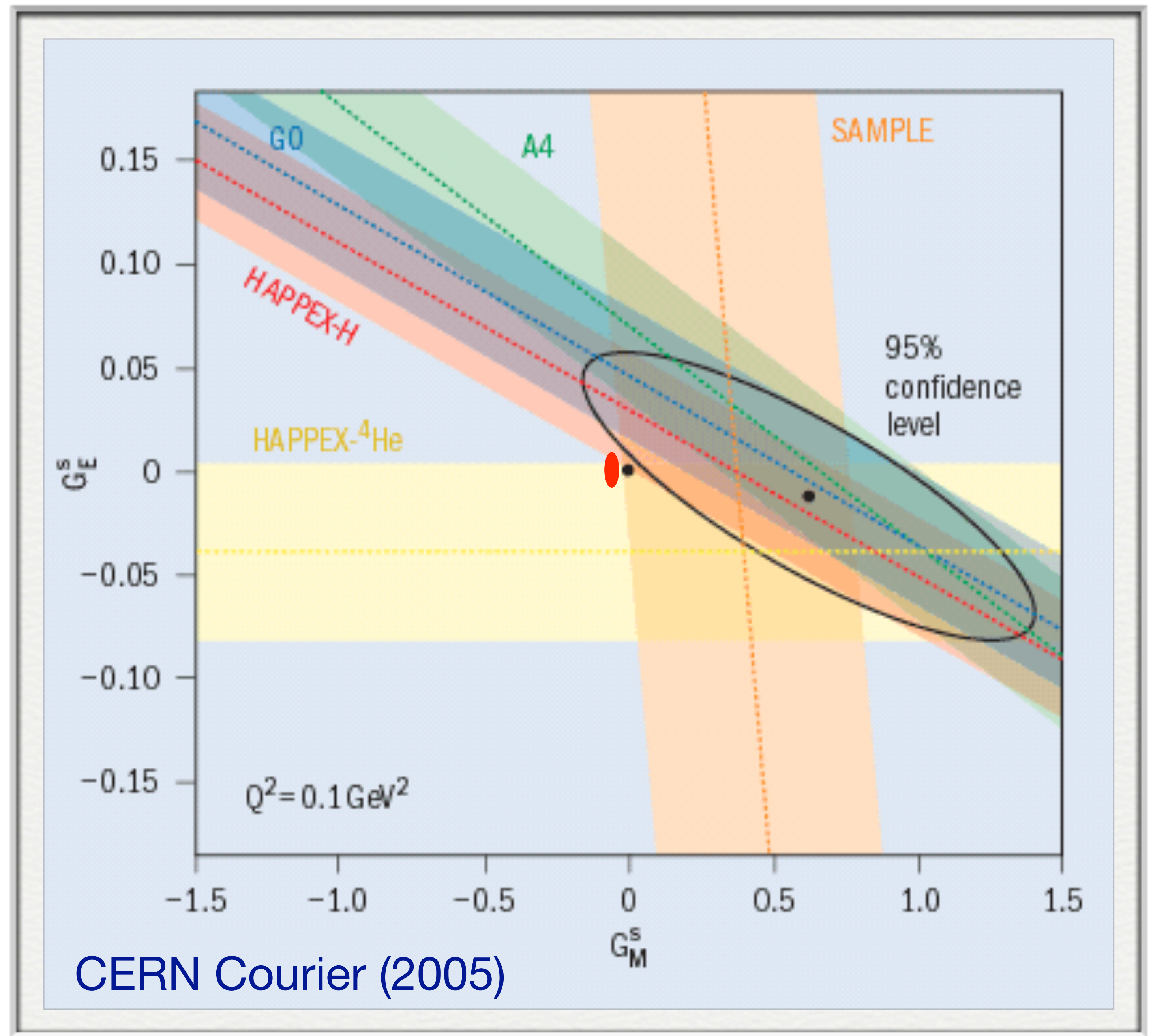


Experimental Status (2005)

- Conglomerate of world's strangeness measurements
- Uses constraint from best theoretical estimate of anapole form factor *Zhu et al*.

$Q^2 = 0.1\,\mathrm{GeV}^2$

Strange Electric



CERN Courier (2005)

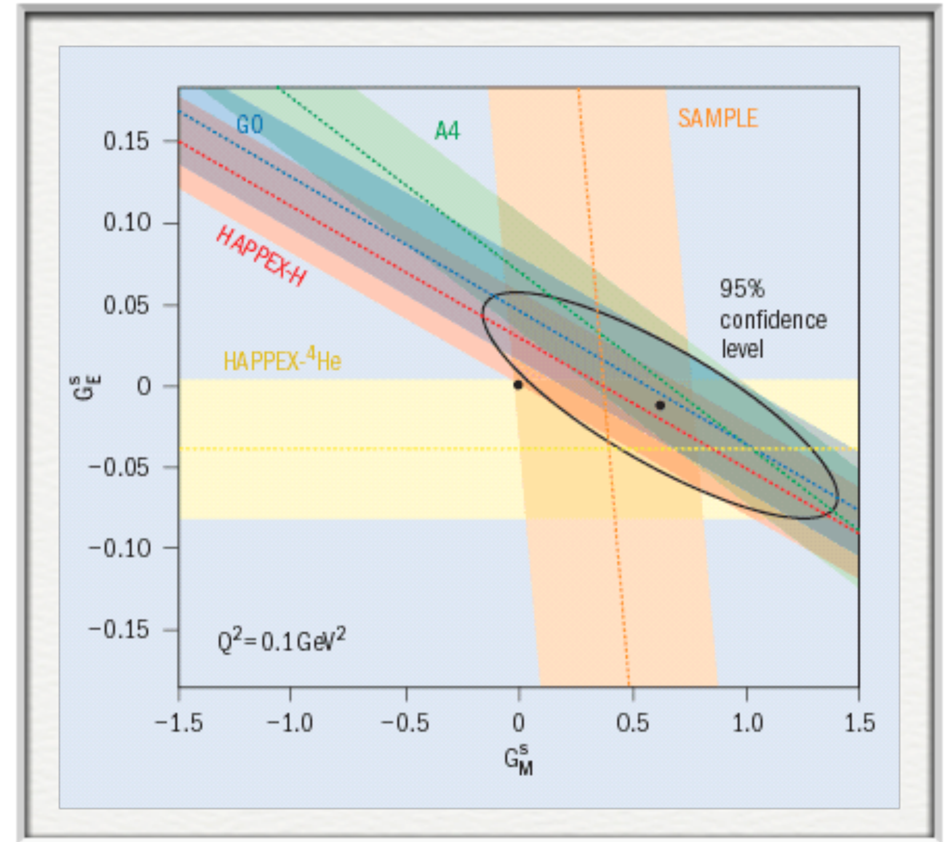
Strange Magnetic

Global Analysis

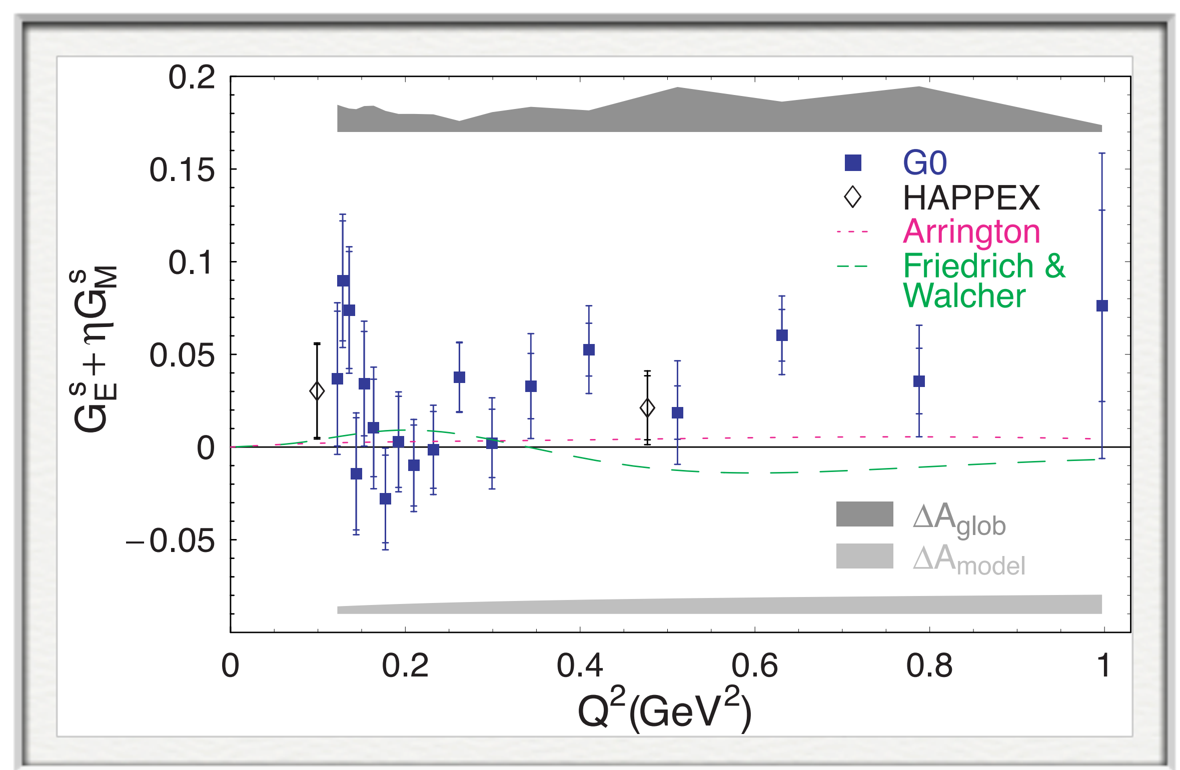
- Extract the anapole contribution from experiment

$$\tilde{G}_A^N = \tilde{g}_A^N (1 + Q^2/\Lambda^2)^{-2}$$

- Fit strangeness to measured asymmetries
  - Consistent treatment of electromagnetic form factors and radiative corrections



- Use all available data for $Q^2 < 0.3\,\mathrm{GeV}^2$

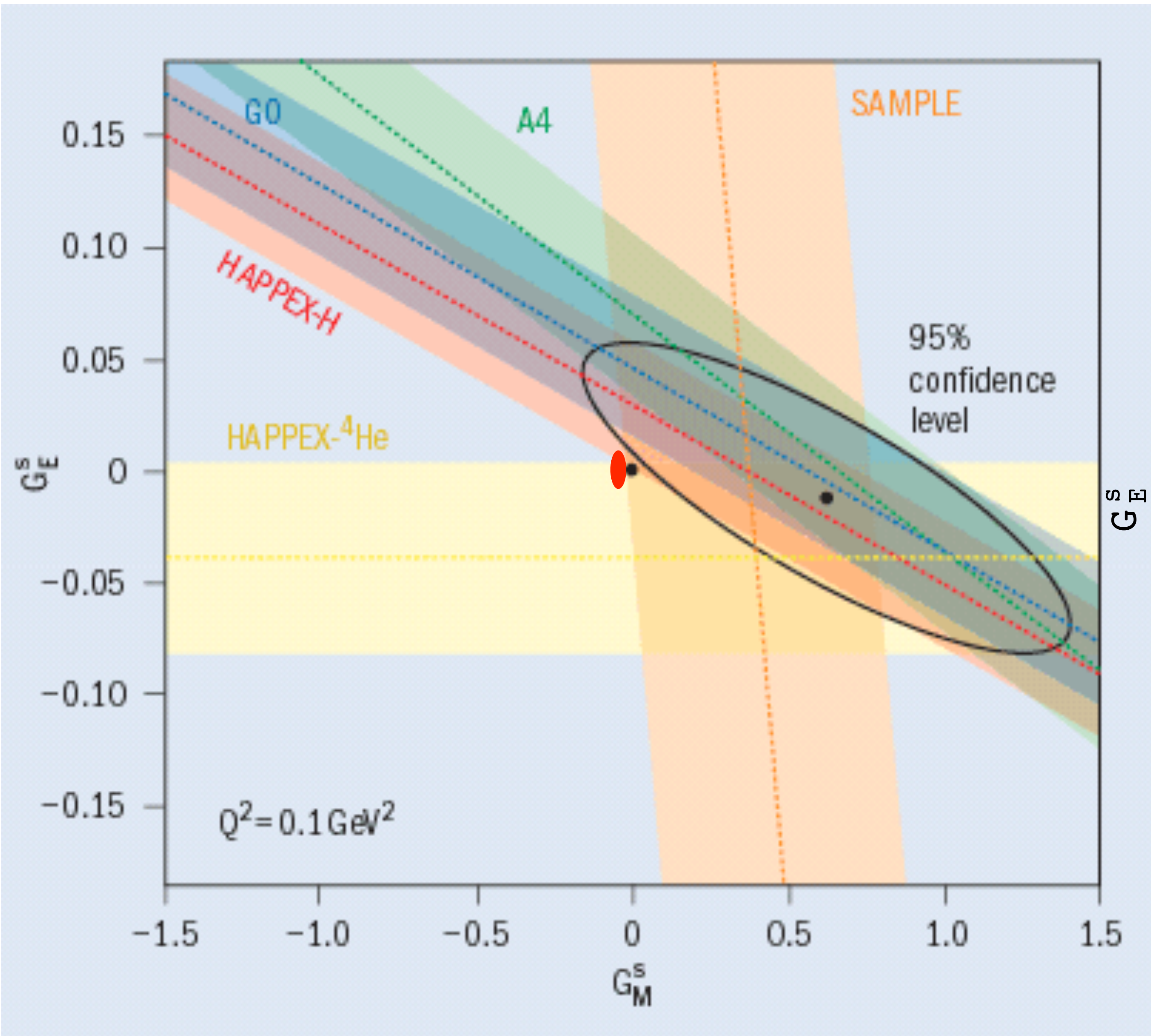


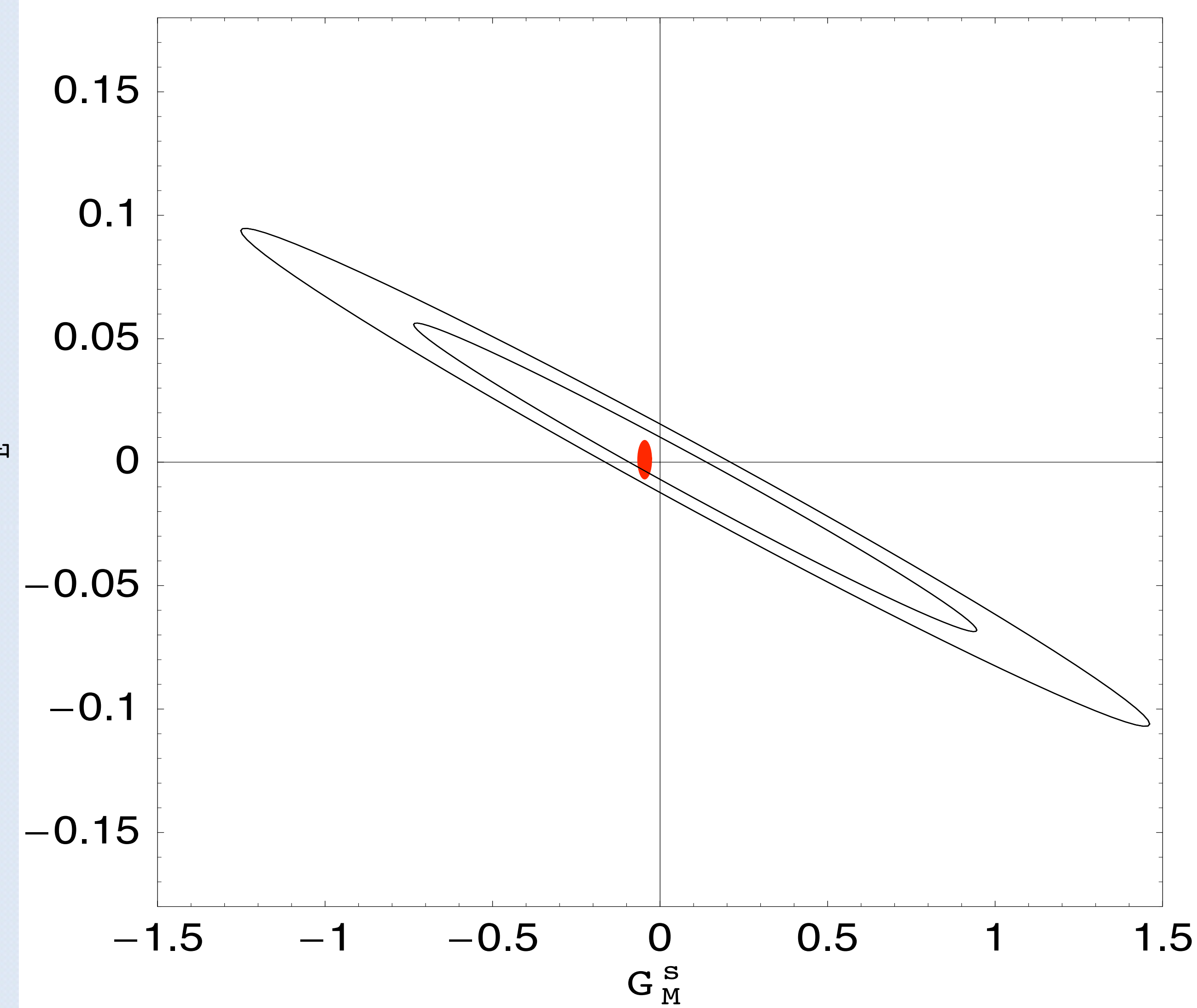
- Taylor expansion of strangeness

$$G_E^s = \rho_s Q^2 + \rho_s' Q^4 + \ldots$$
$$G_M^s = \mu_s + \mu_s' Q^2 + \ldots$$

Strangeness form factors

$$Q^2 = 0.1\,\mathrm{GeV}^2$$



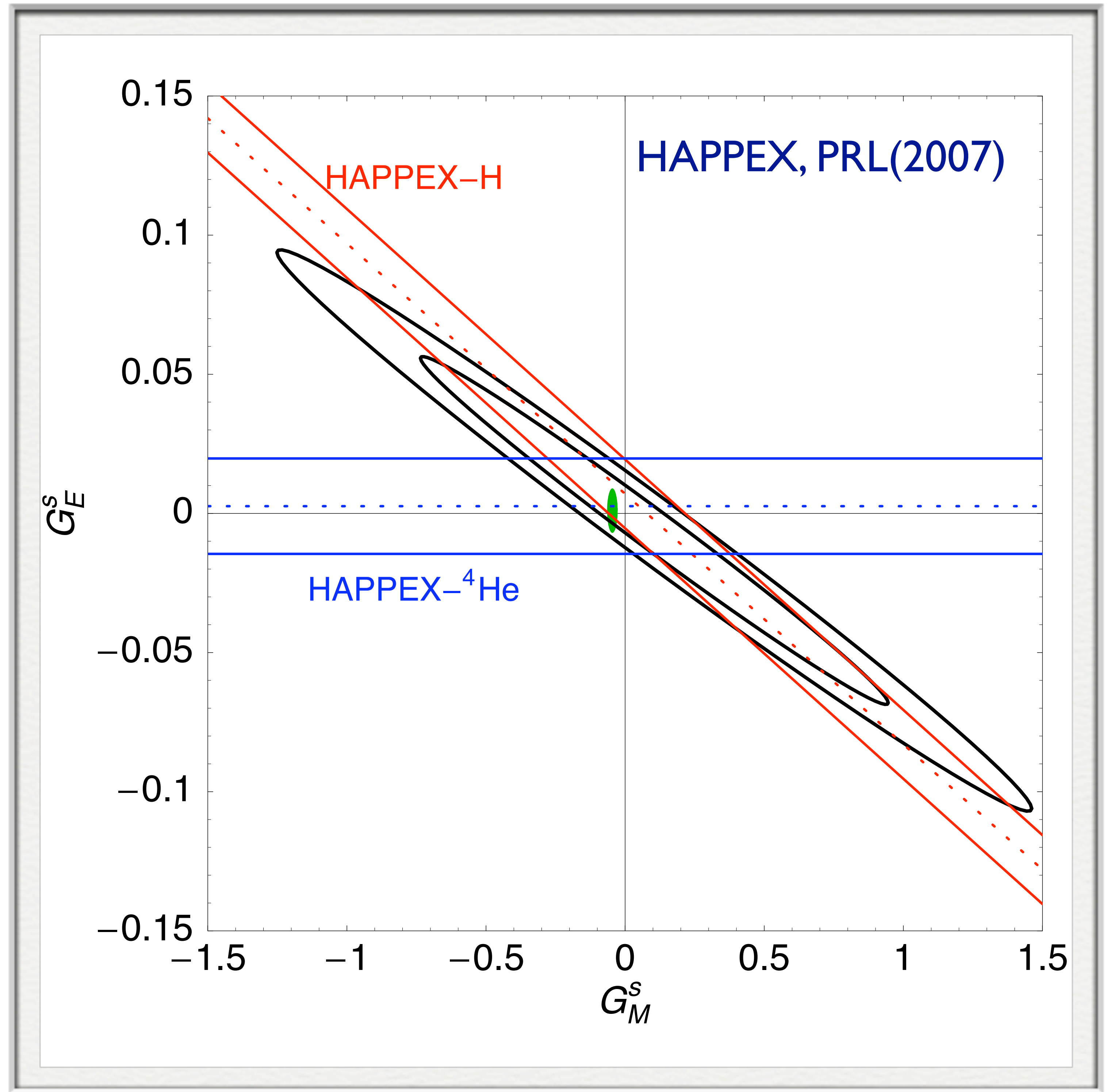


RDY *et al.* PRL(2006)

New HAPPEX Measurement

- Excellent agreement with global analysis

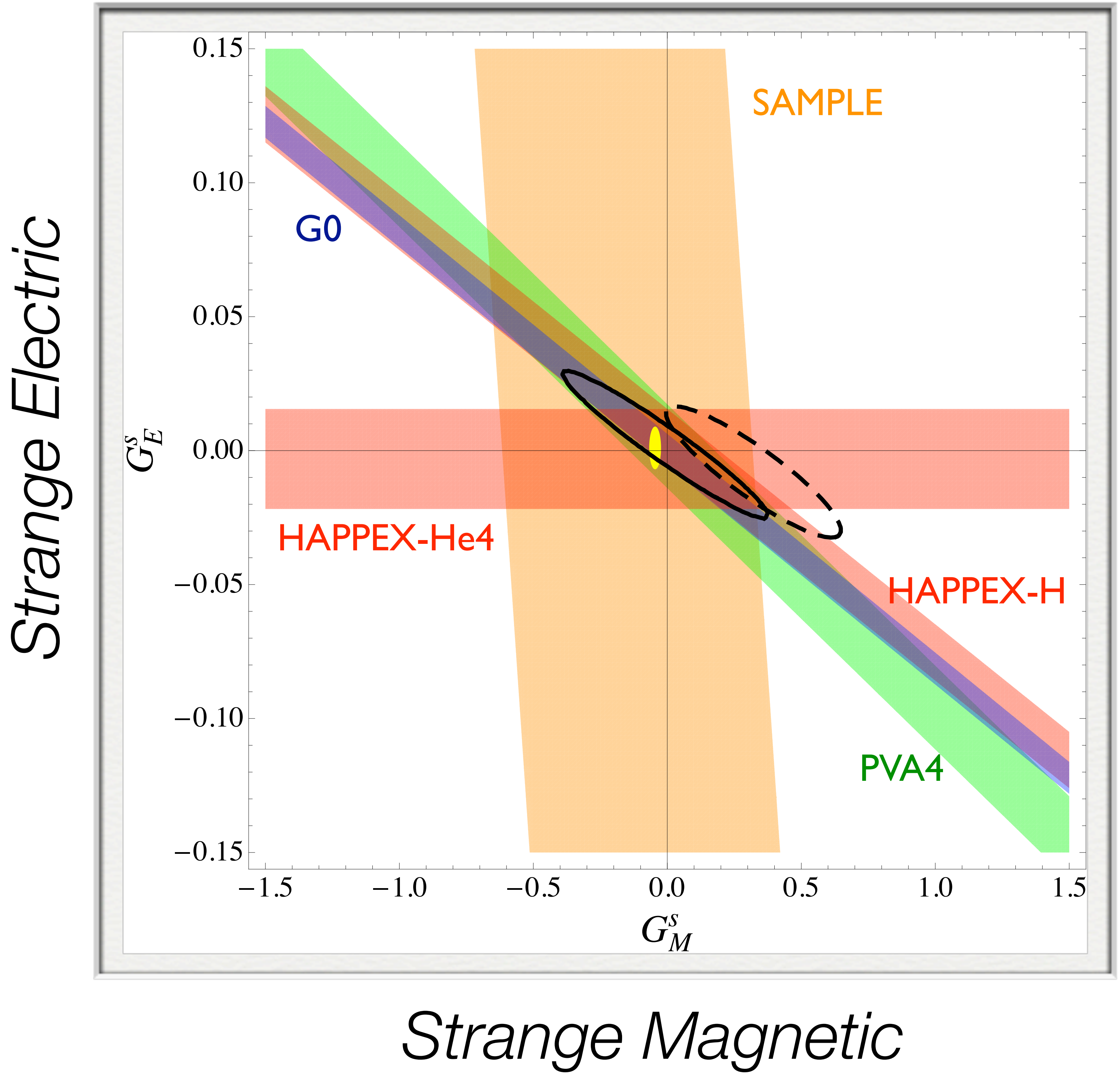
Strange Electric



Strange Magnetic

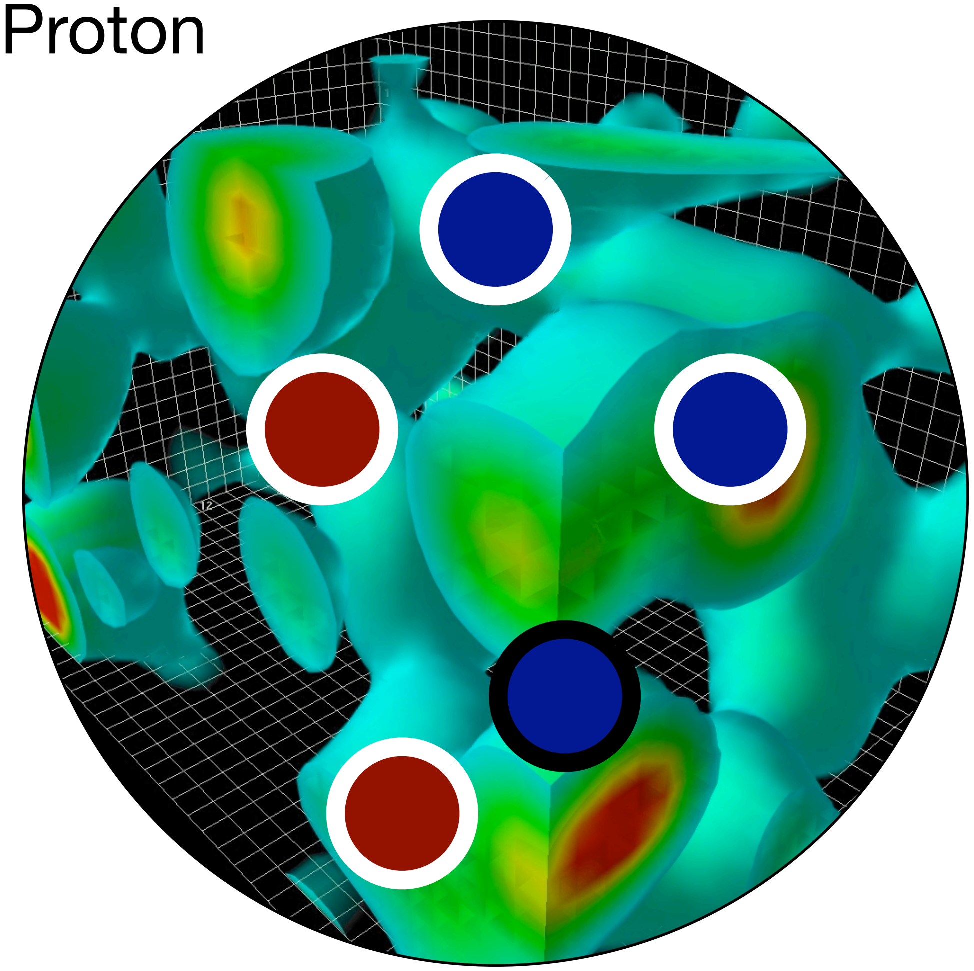
Combined Analysis

- Combined constraints on current knowledge of strangeness content.
- Strangeness is small!
- 95% confidence:
  < 5% charge radius
  < 6% magnetic moment
- In support of theory estimate

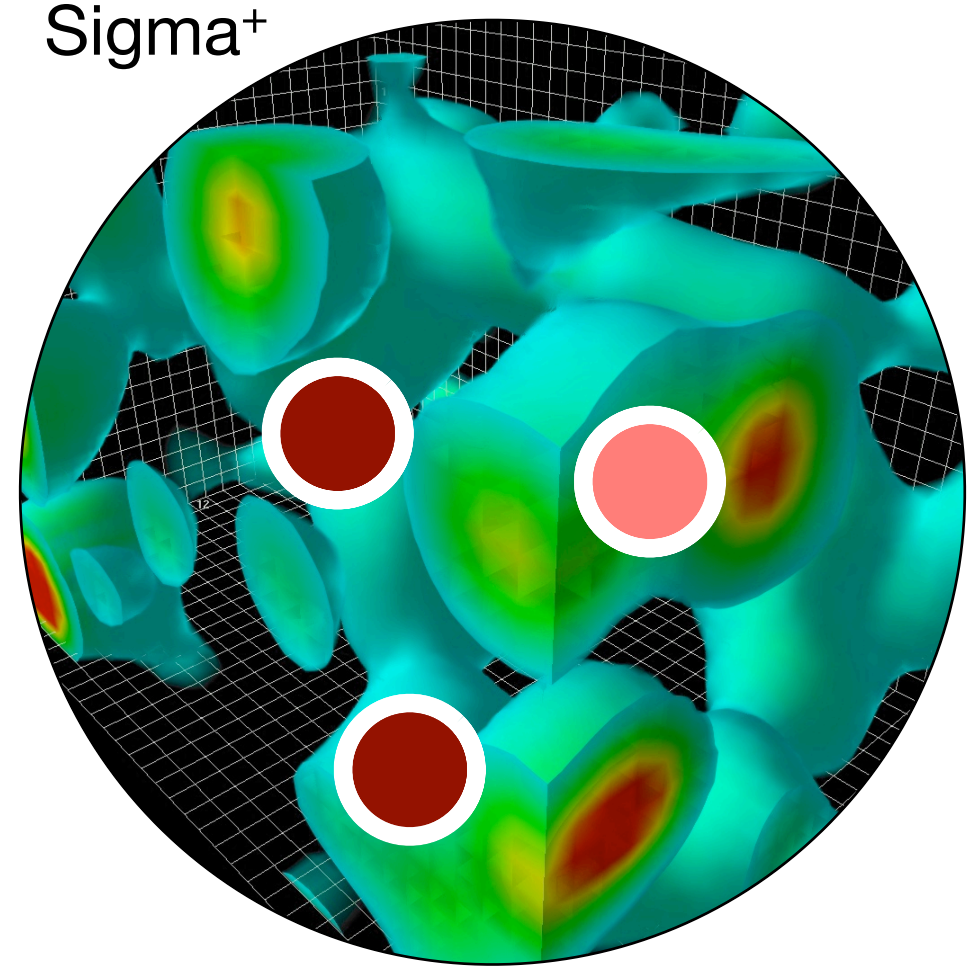


Theory Method

Proton



Sigma$^+$



Valence *up*

Valence *down*

Sea *up*/*down*/*strange*

Valence *up*

Valence *strange*

Sea *up*/*down*/*strange*

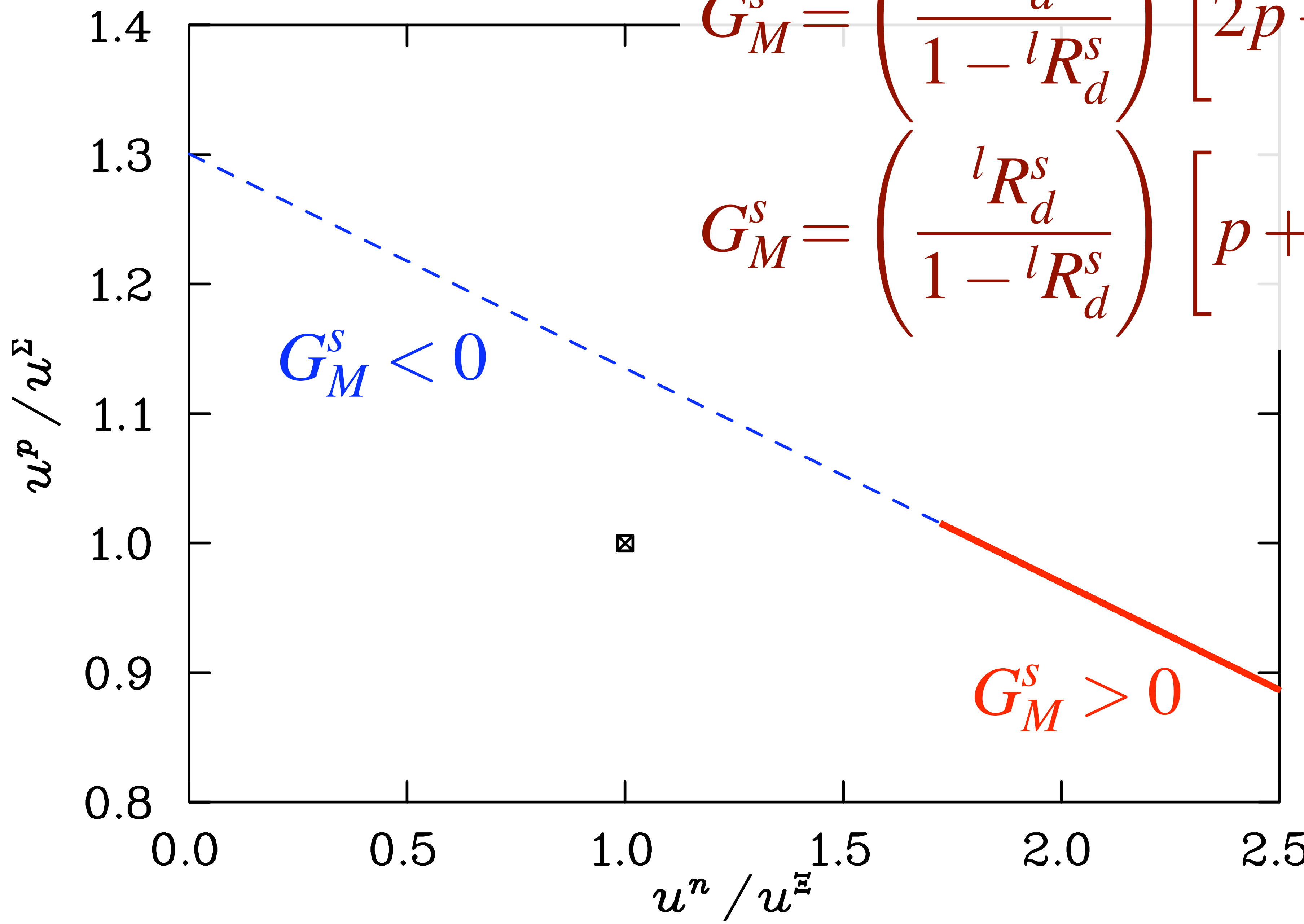
Extract best-estimate of valence from lattice QCD

Discrepancy with experiment must be the sea

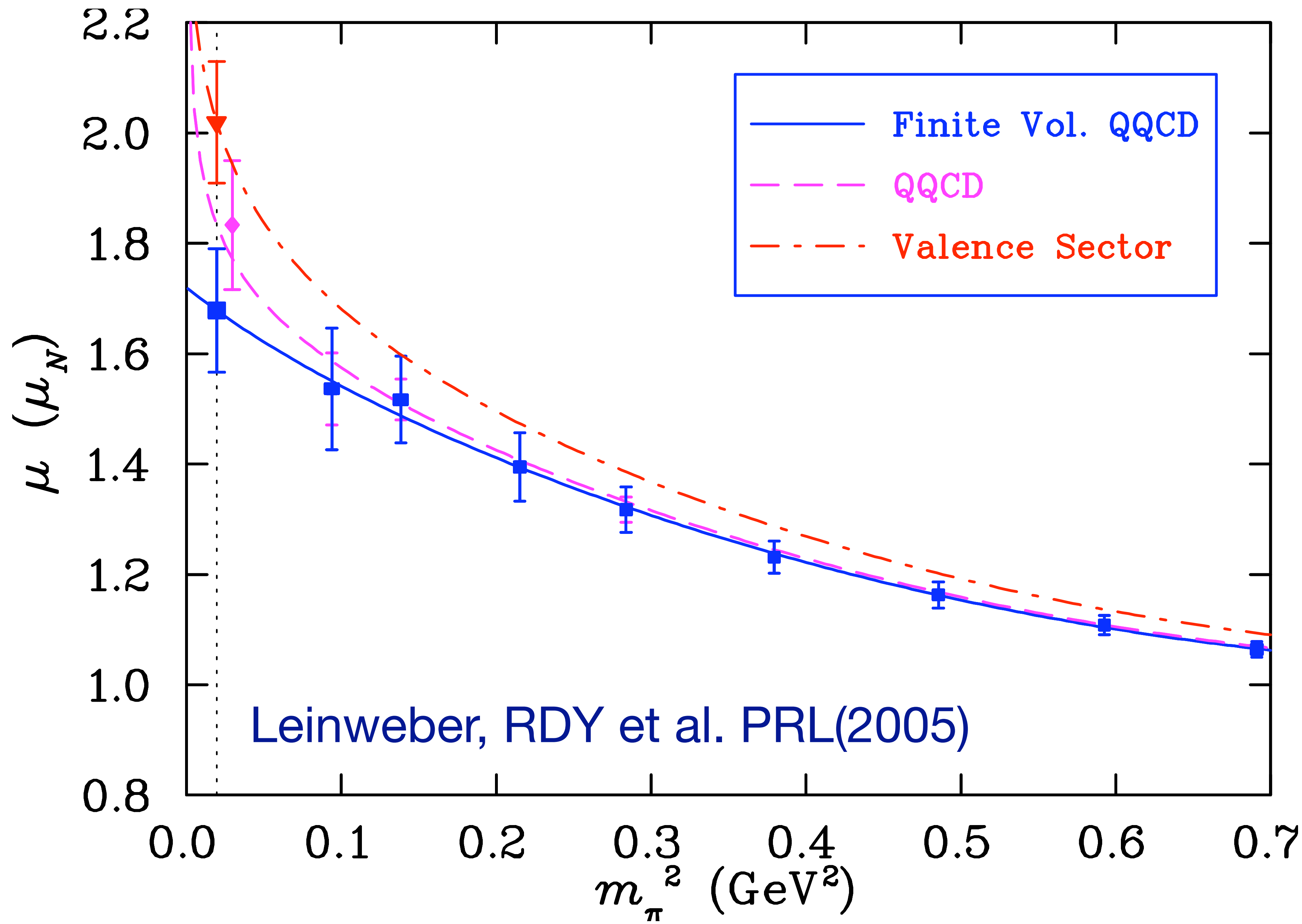
Constraint on GMs

$$G_M^s = \left(\frac{{}^{l}R_d^s}{1 - {}^{l}R_d^s}\right)\left[2p + n - \frac{u^p}{u^\Sigma}(\Sigma^+ - \Sigma^-)\right]$$

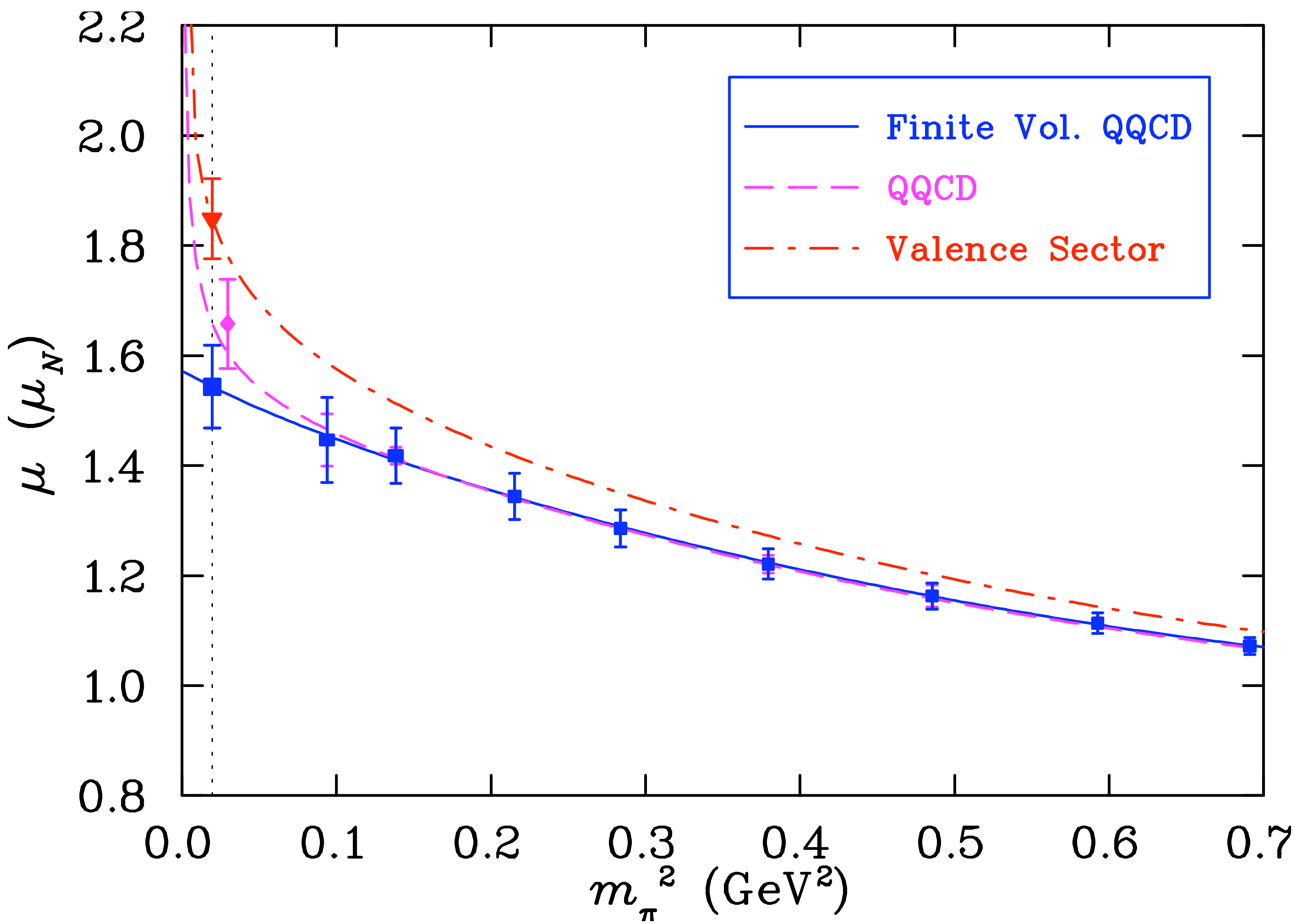
$$G_M^s = \left(\frac{{}^{l}R_d^s}{1 - {}^{l}R_d^s}\right)\left[p + 2n - \frac{u^n}{u^\Xi}(\Xi^0 - \Xi^-)\right]$$



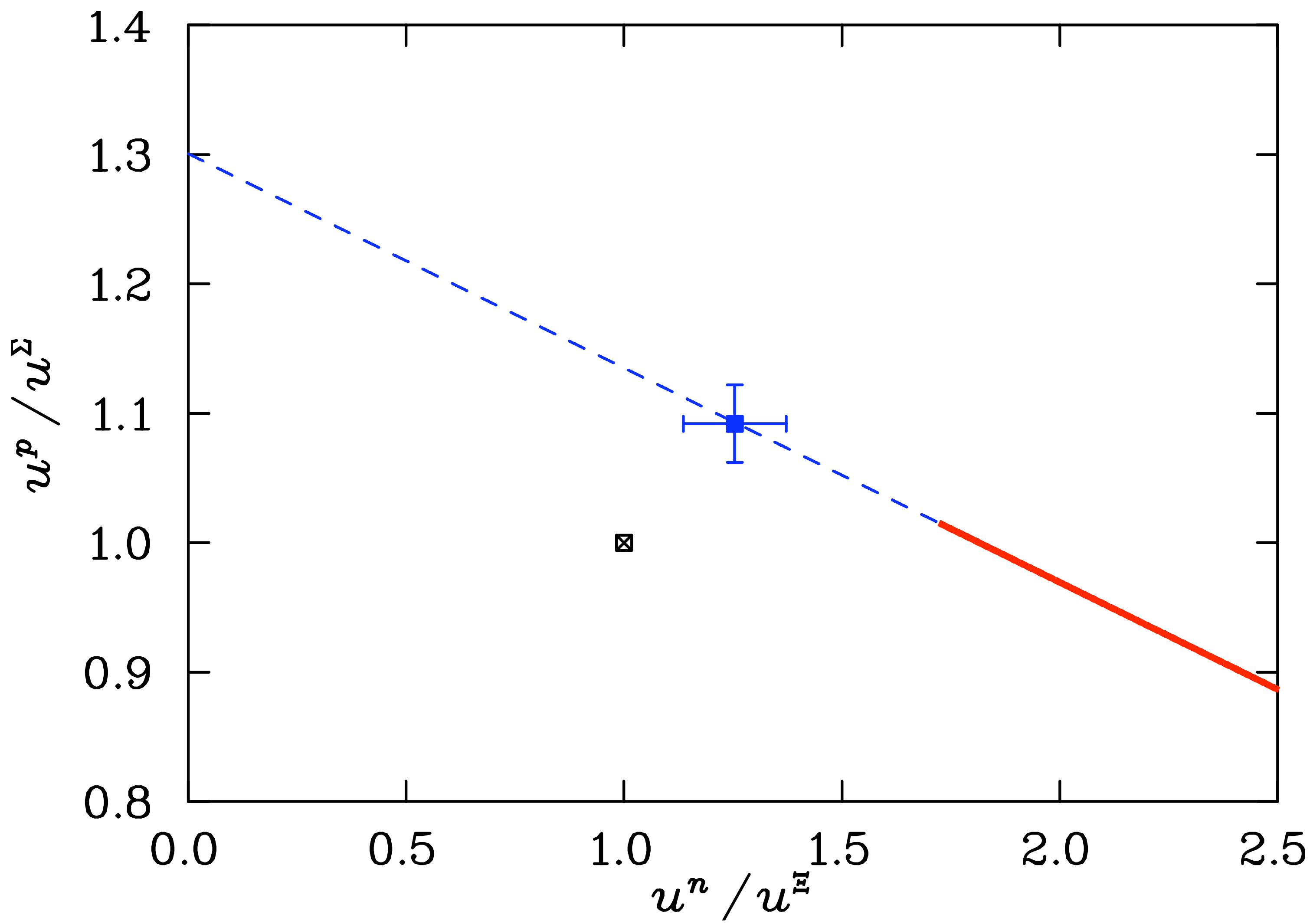
Valence *u*-quark in Proton



Valence *u*-quark in Sigma



Final Result

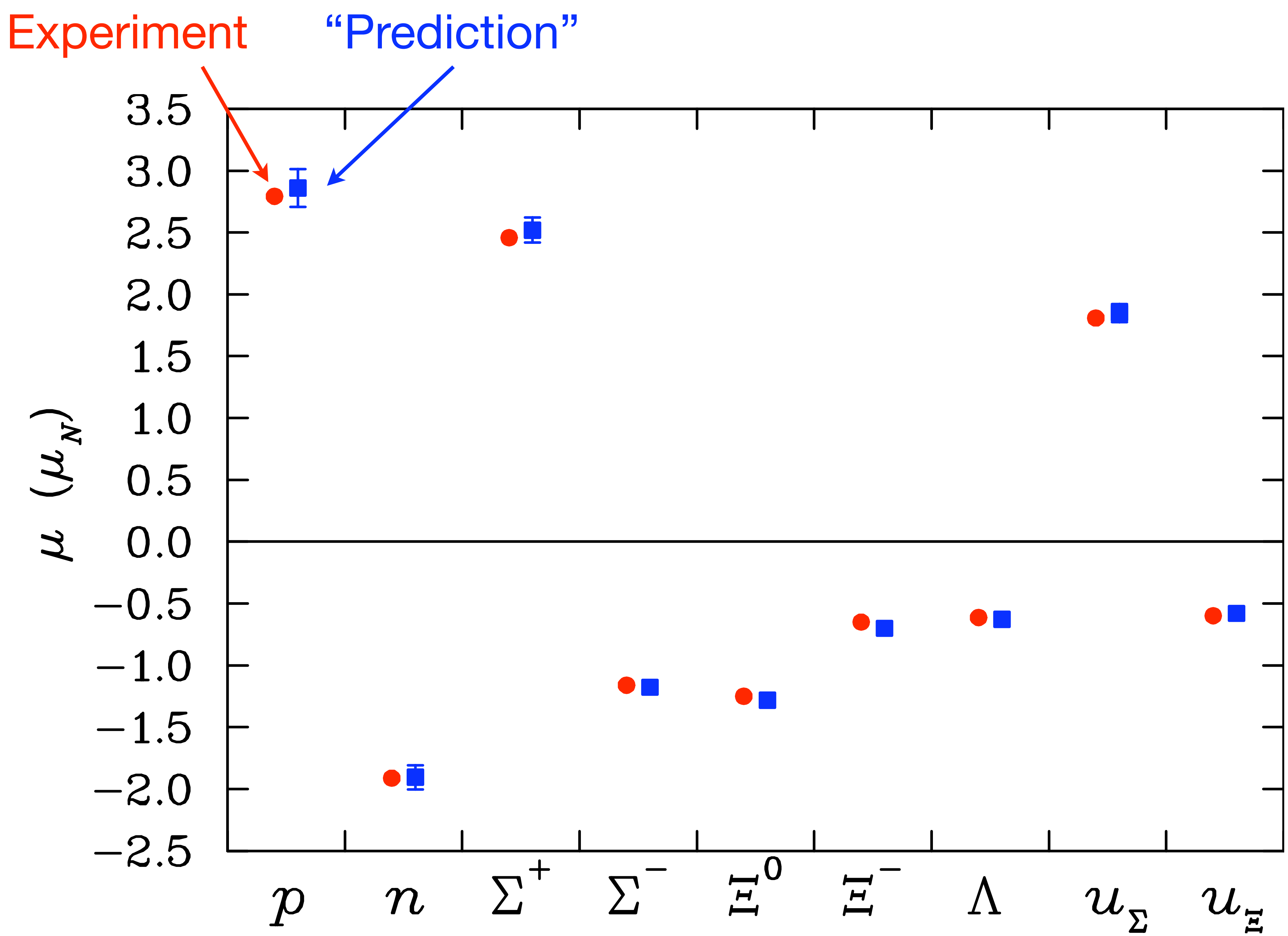


$$\frac{u^p}{u^\Sigma} = 1.092 \pm 0.030$$

$$\frac{u^n}{u^\Xi} = 1.254 \pm 0.124$$

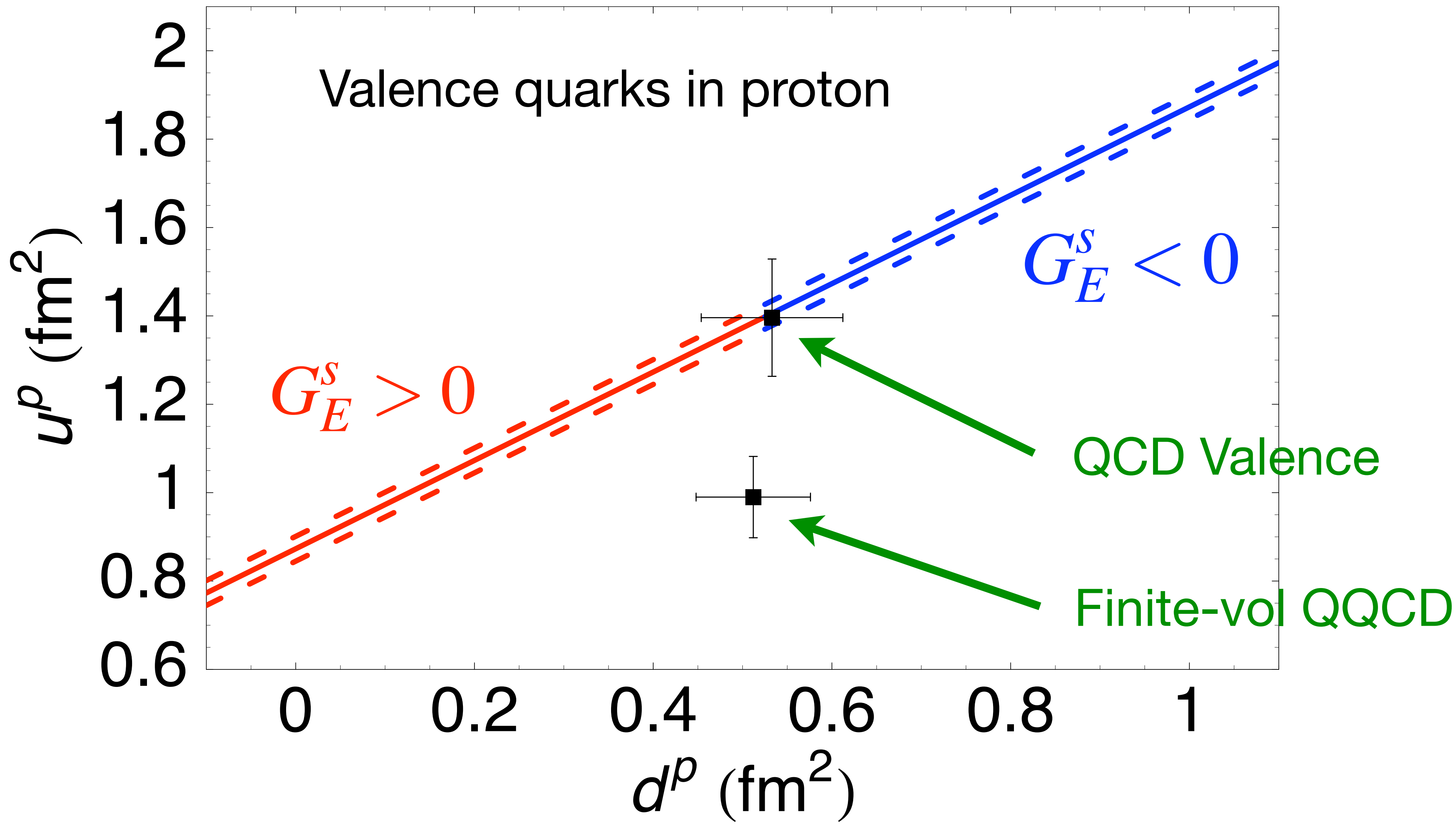
$$G_M^s = -0.046 \pm 0.022\,\mu_N$$

Octet Magnetic Moments



Leinweber, RDY et al. PRL(2005)

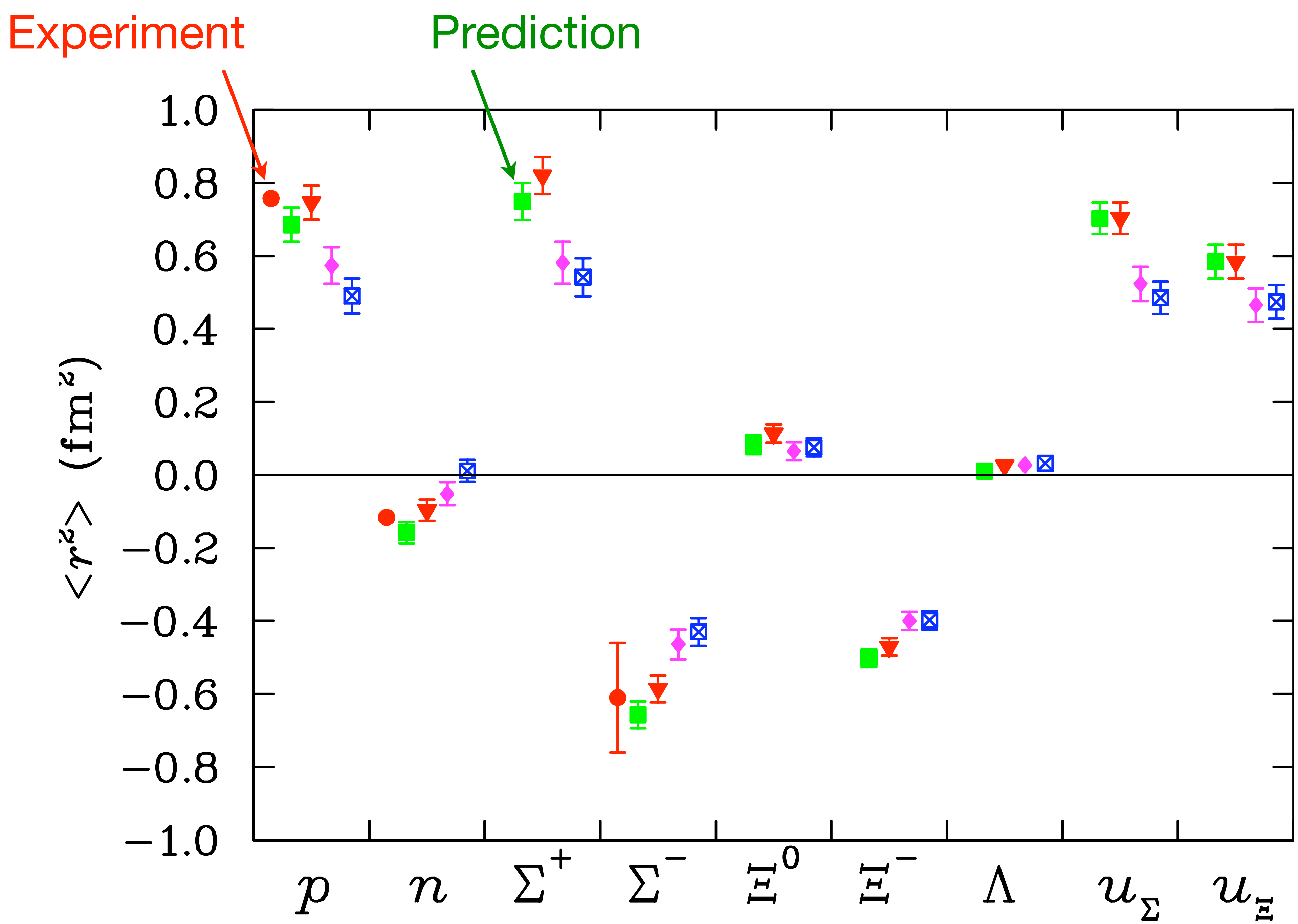
Electric Strangeness



$$G_E^s(Q^2 = 0.1) = +0.001 \pm 0.004 \pm 0.004$$

Leinweber, RDY et al. PRL(2006)

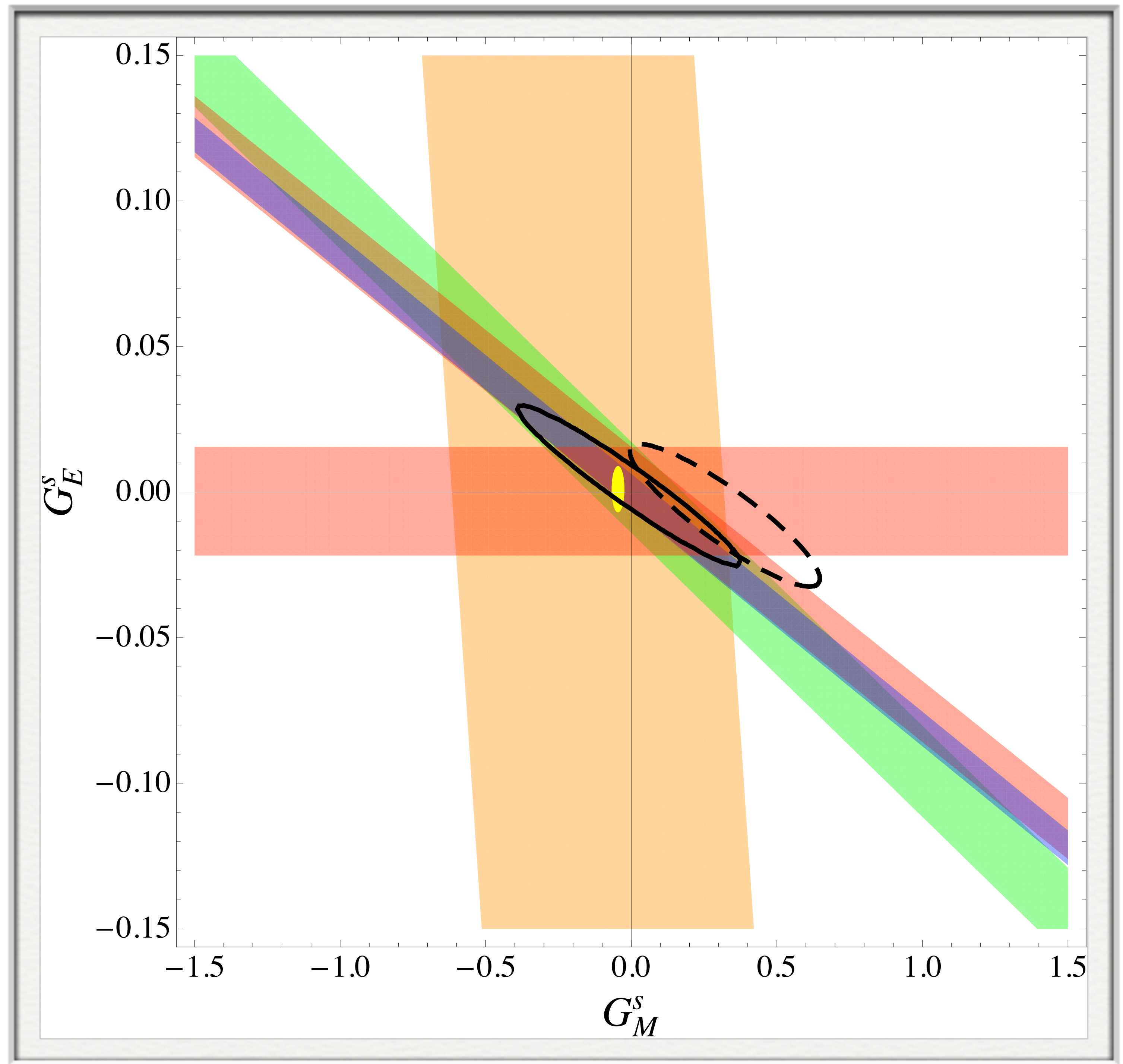
Octet Baryon Charge Radii



Wang, Leinweber, Thomas, RDY, arXiv:0810:1021

Comparison with Experiment

- Theory estimate suggests a very small strangeness content!



Strange Electric

Strange Magnetic

Why are other strange quantities so big?

- Spin content

$$\Delta s = -0.10 \pm 0.04$$

Bass (2004)

$$\Delta s = 0.028 \pm 0.033 \pm 0.009$$

HERMES PRD(2005)

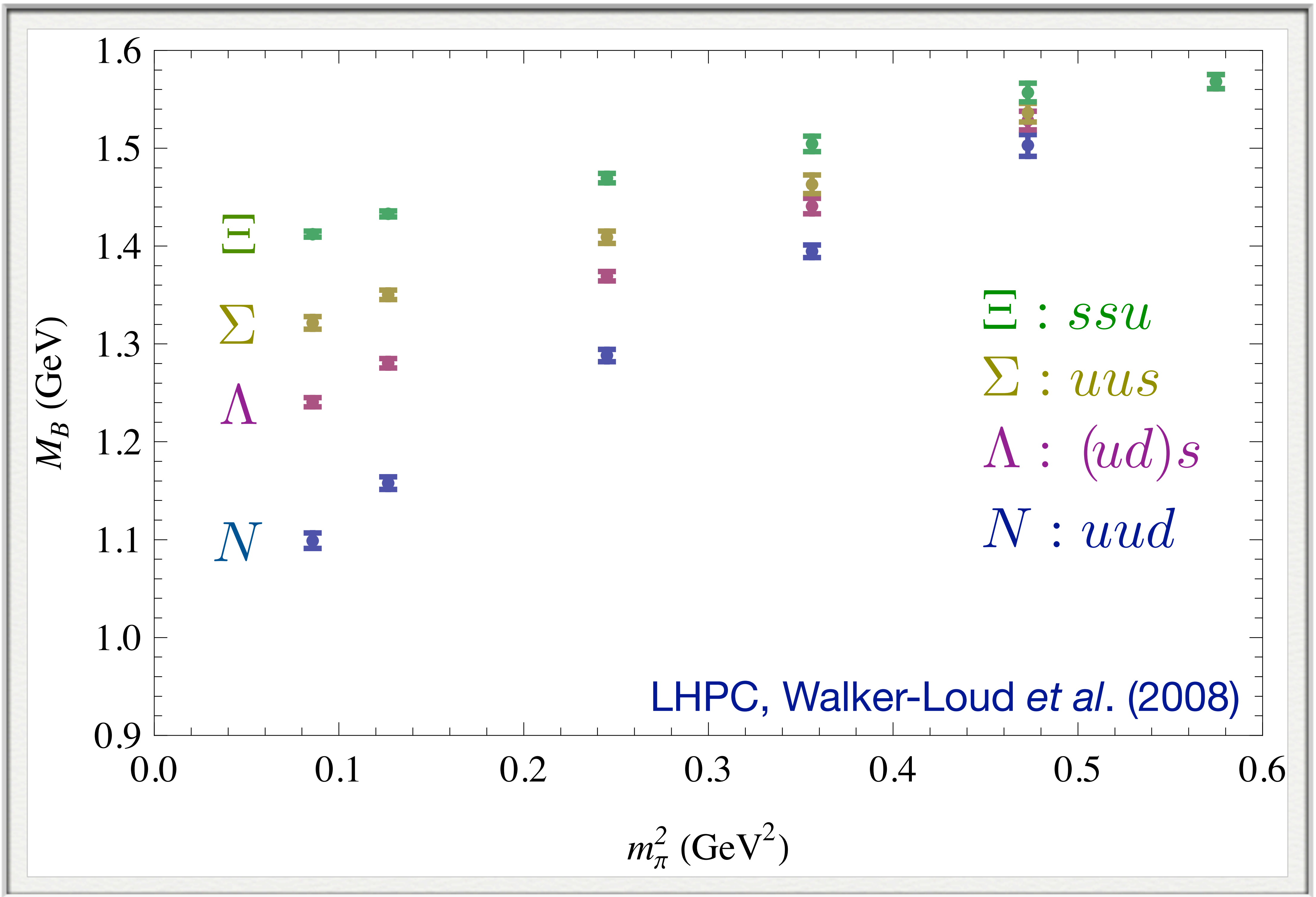
- Sigma term

$$m_s \frac{\partial M_N}{\partial m_s} = 113 \pm 108\,\mathrm{MeV}$$

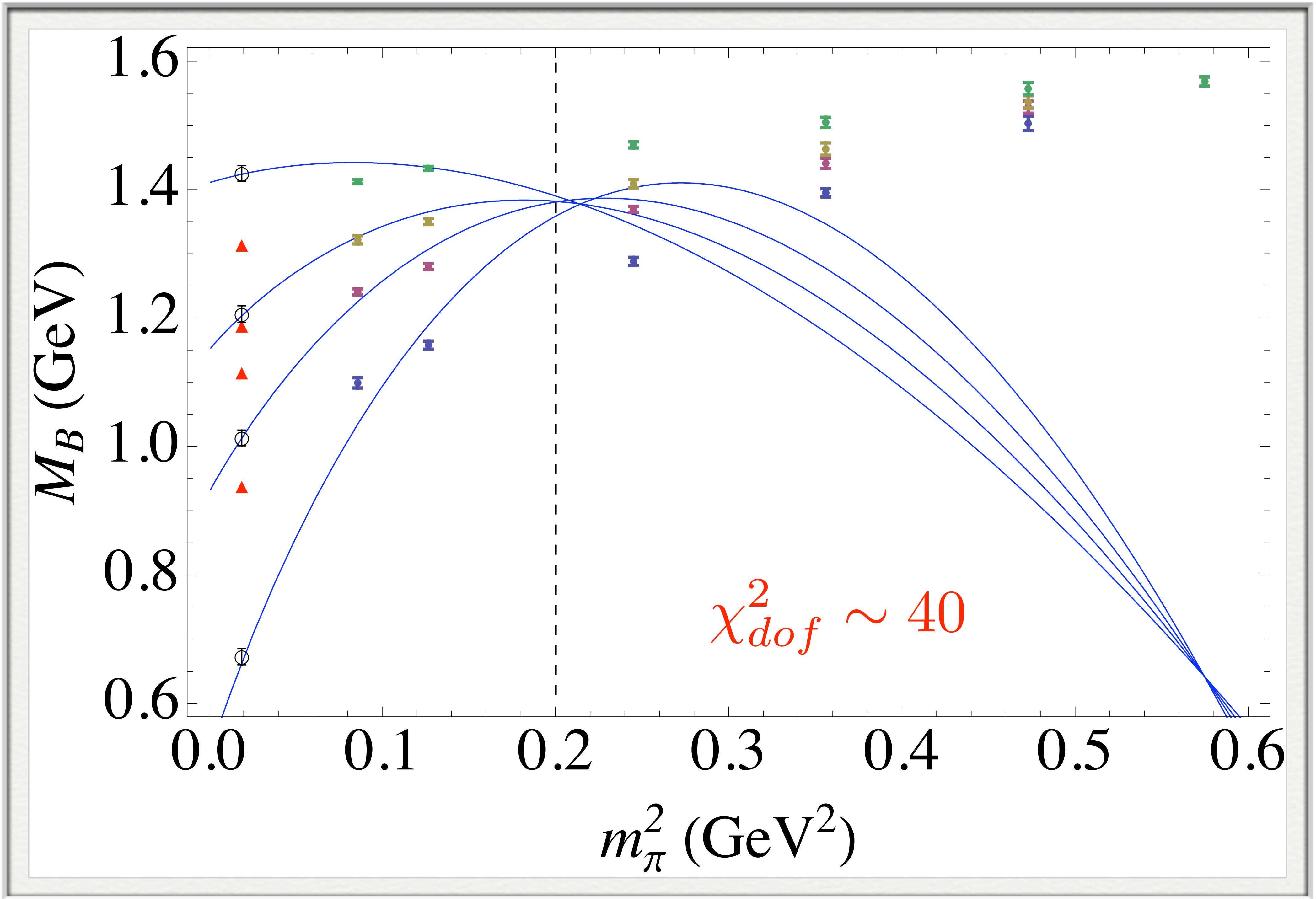
Borasoy & Meissner (1997)

Return to Baryon Masses

- New Lattice QCD results

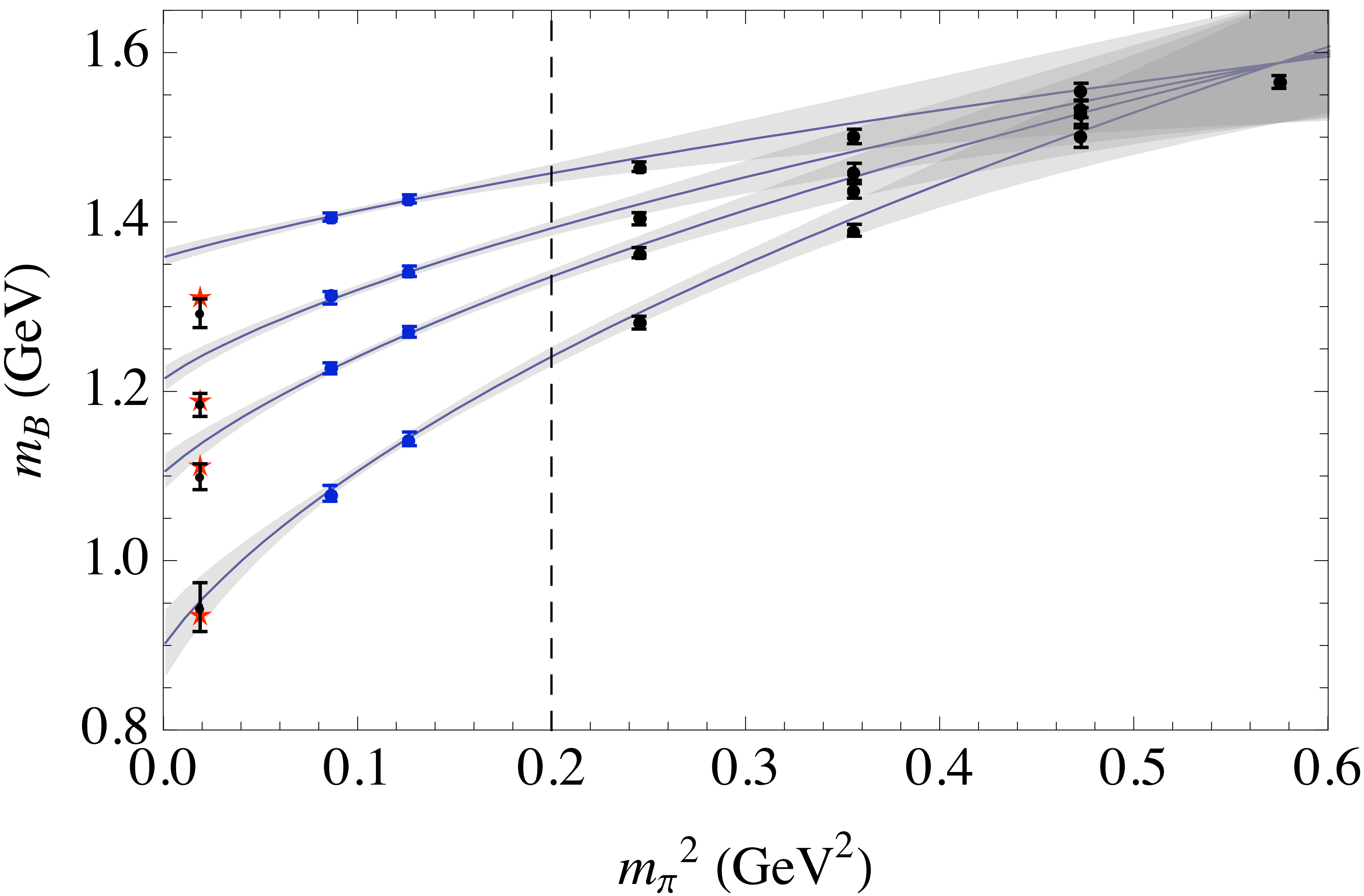


Next-leading order result of Effective Field Theory



Finite-Range Regularisation

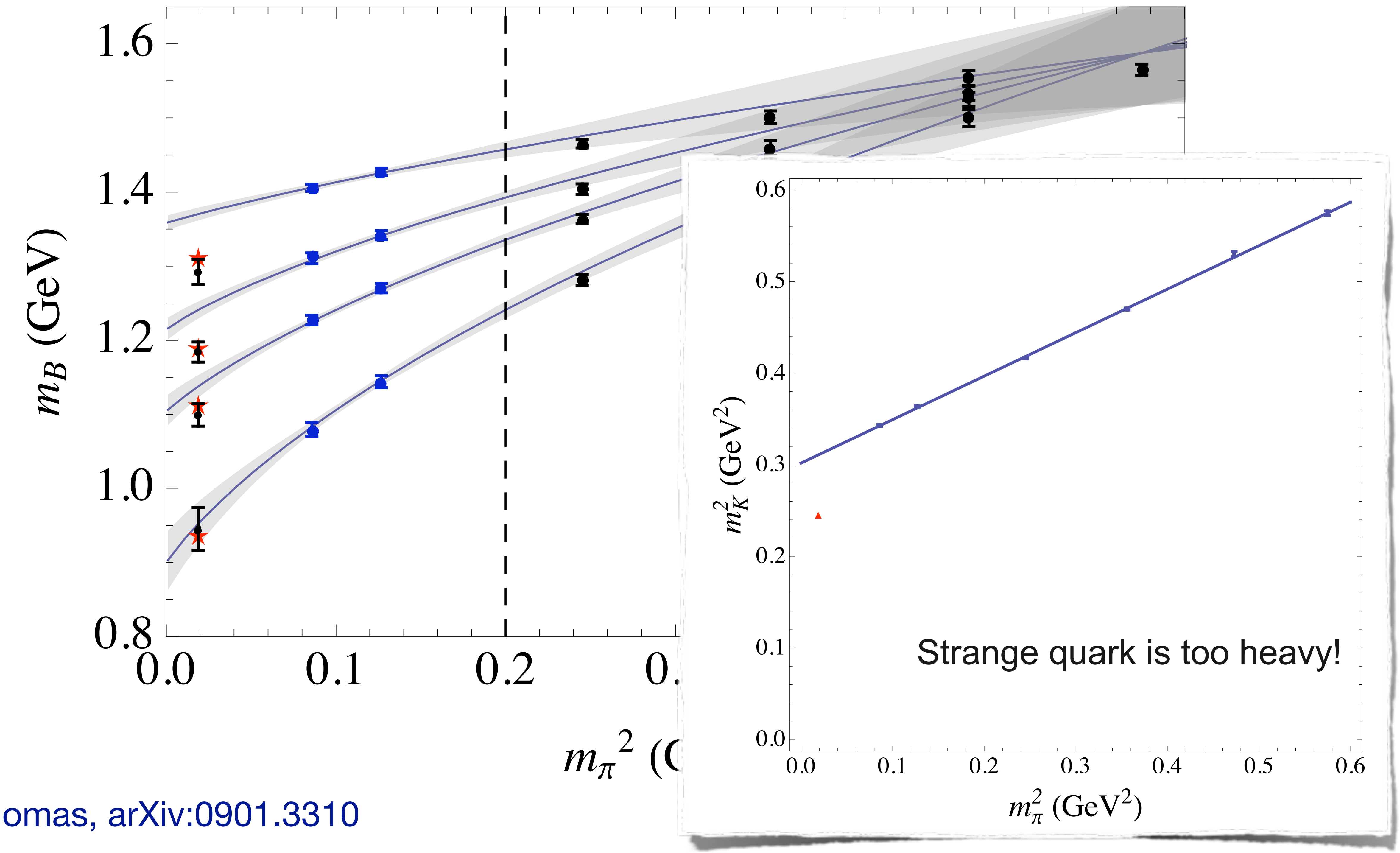
- One additional fit parameter, the regularisation scale



RDY & Thomas, arXiv:0901.3310

Finite-Range Regularisation

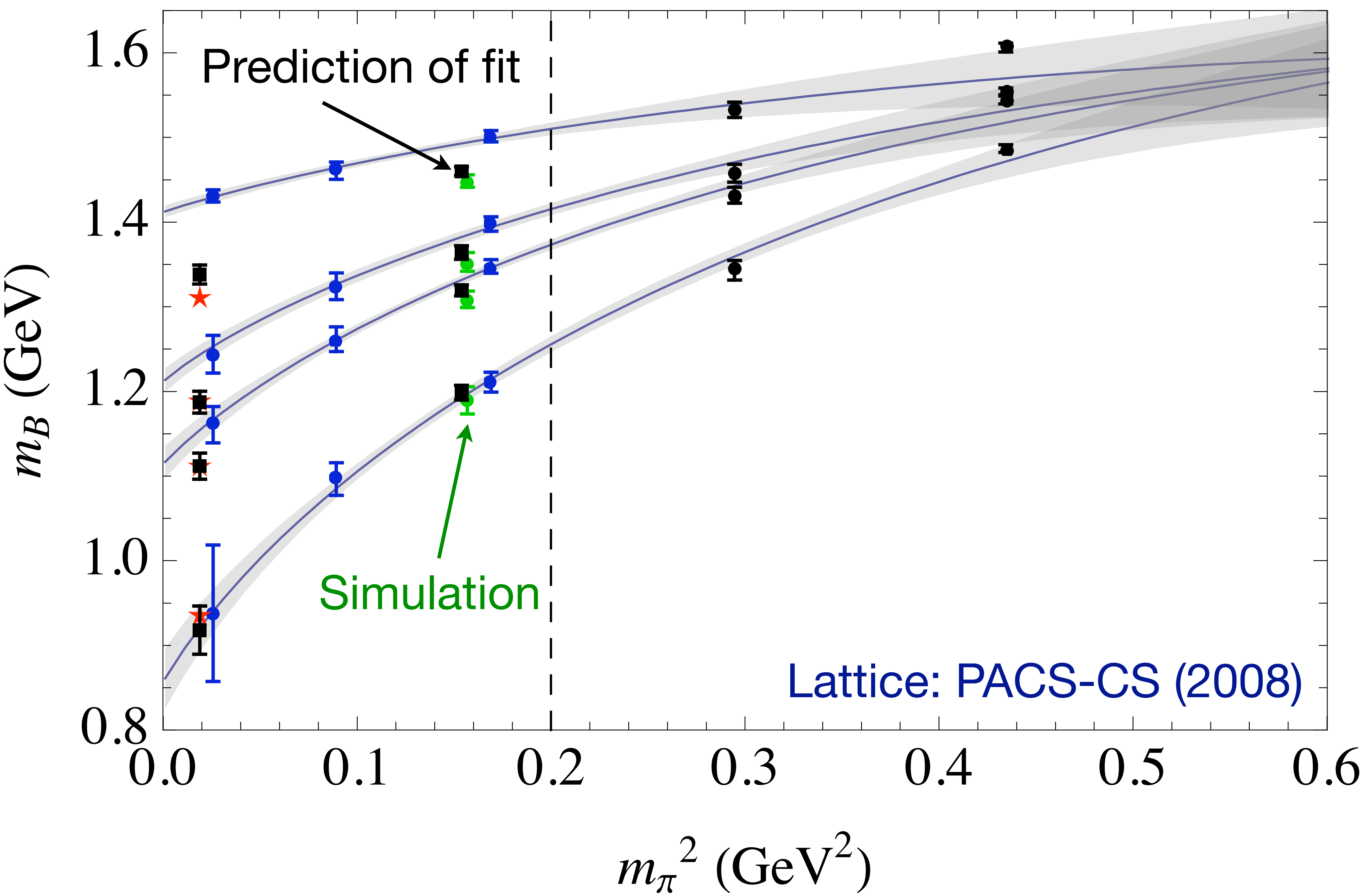
- One additional fit parameter, the regularisation scale



RDY & Thomas, arXiv:0901.3310

Check strange-mass correction

- FRR EFT fit to PACS-CS results



RDY & Thomas, arXiv:0901.3310

Baryon Mass Results

- Absolute masses competitive precision with recent Science article
- Can determine the sensitivity of observables to strange-quark mass
    - Important for lattice QCD: fine-tuning the strange-quark mass is computationally expensive
- Can extract strangeness nucleon sigma term

$$m_s \frac{\partial M_N}{\partial m_s} = 19 \pm 10 \pm 7 \pm 3\,\text{MeV}$$

Statistics — Lattice discretisation — Model-dependence

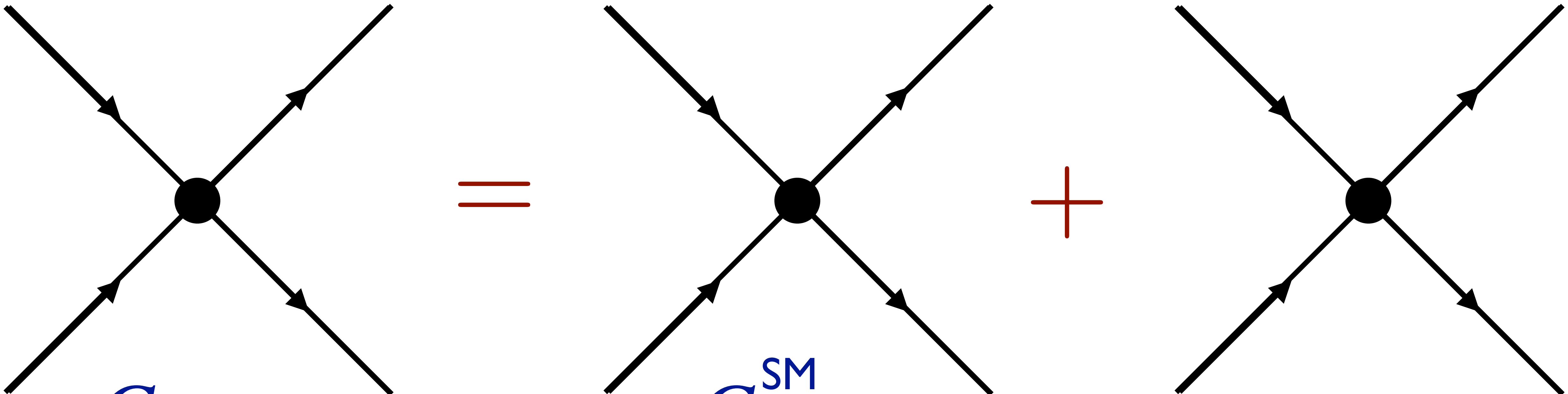
$$m_s \frac{\partial M_N}{\partial m_s} = 113 \pm 108\,\text{MeV}$$

Borasoy & Meissner (1997)

Strangeness scalar term is small

RDY & Thomas, arXiv:0901.3310

Searching for new physics



$$C_{1(2)q} = C^{\mathrm{SM}}_{1(2)q} + \text{new physics}$$

Constrained by low-energy data!

$$C_{1u} \sim Q_e^W Q_u^W$$

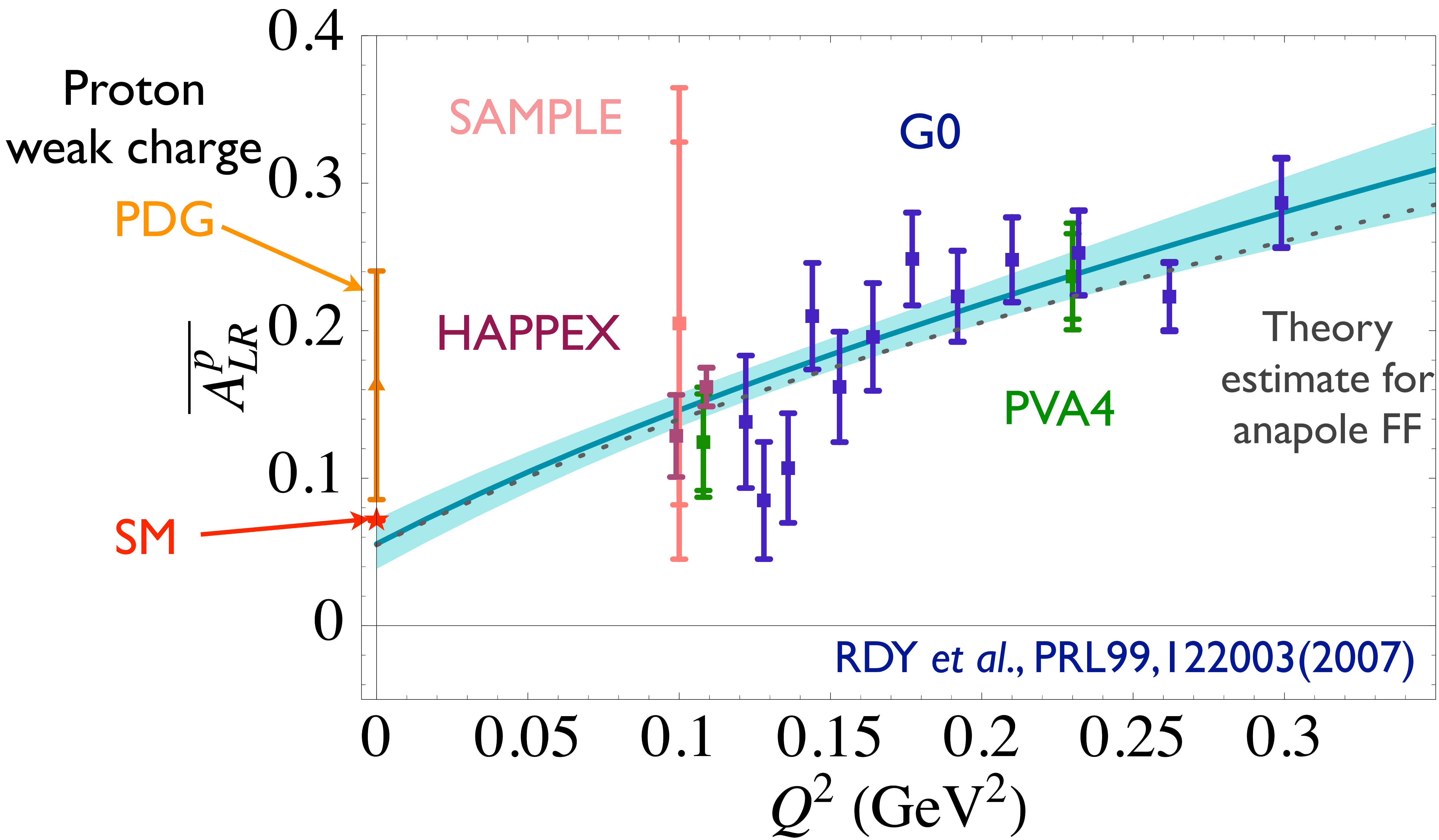
$$C_{1d} \sim Q_e^W Q_d^W$$

Yukawa potential

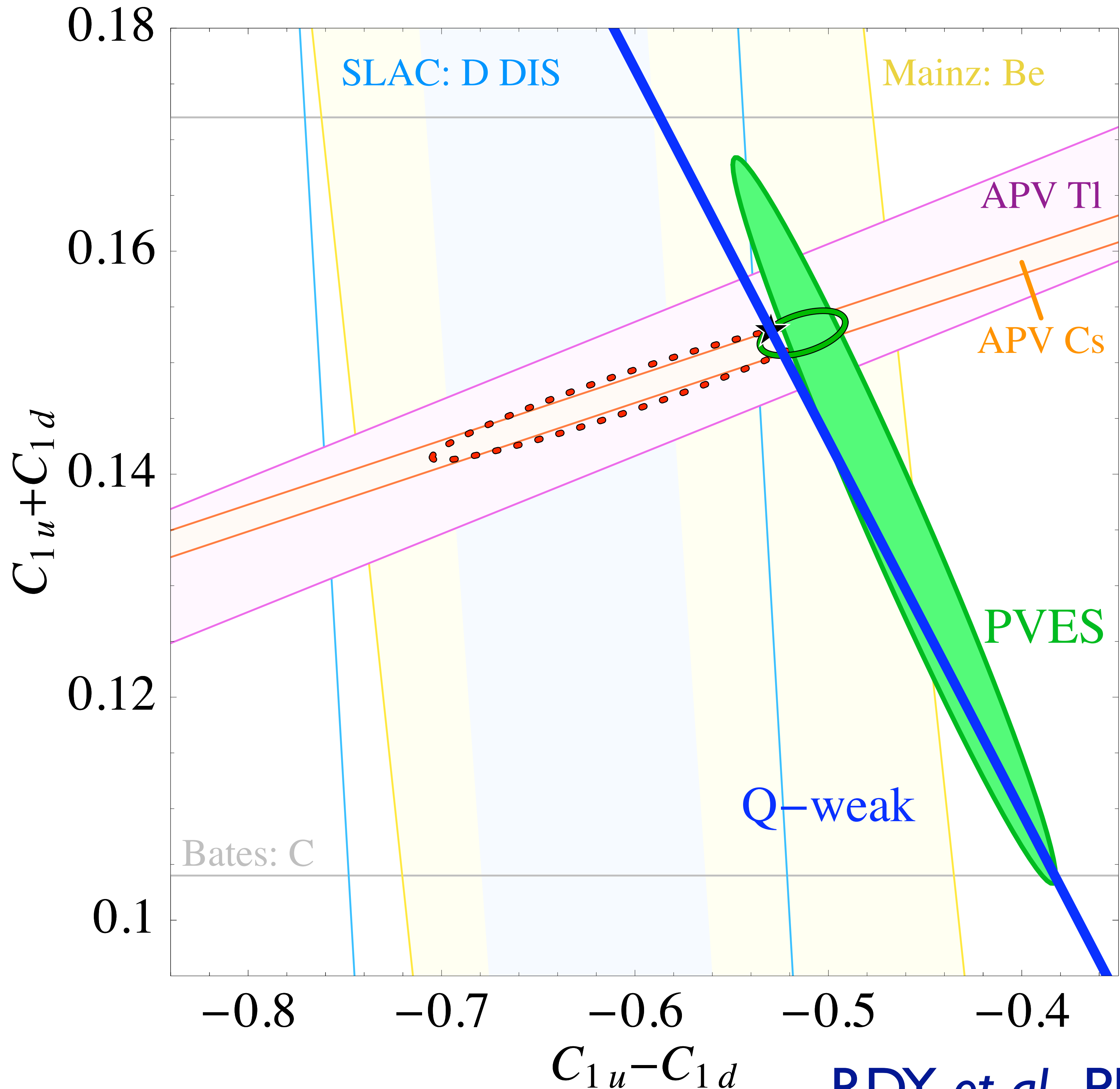
$$\sim \frac{Q_e^W Q_q^W}{r} e^{-M_Z r}$$

$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{SM}} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C^{\mathrm{SM}}_{1q} \bar{q}\gamma^\mu q$$

Proton weak charge extrapolation

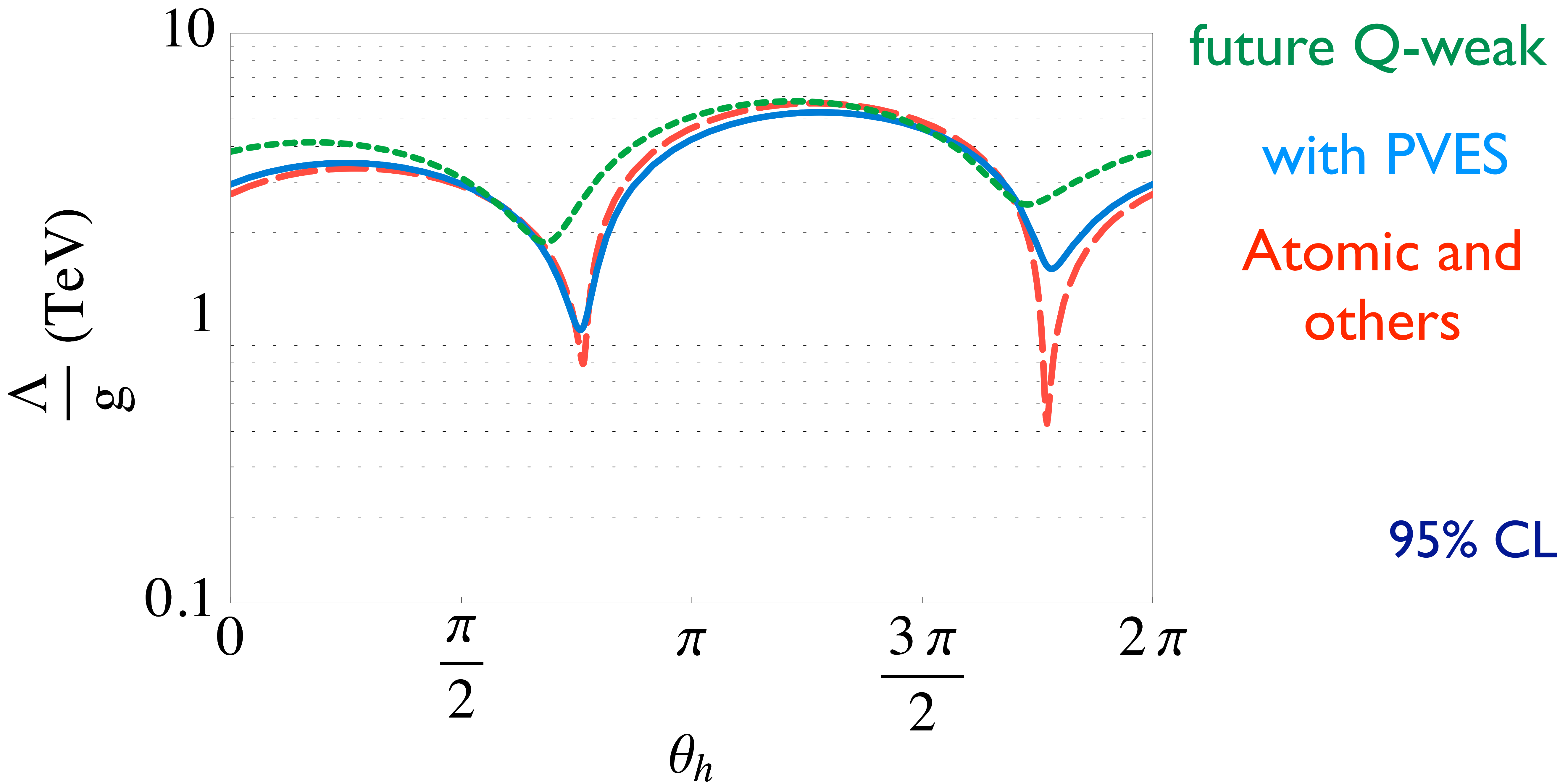


Current knowledge and future: Qweak



RDY *et al.*, PRL(2007)

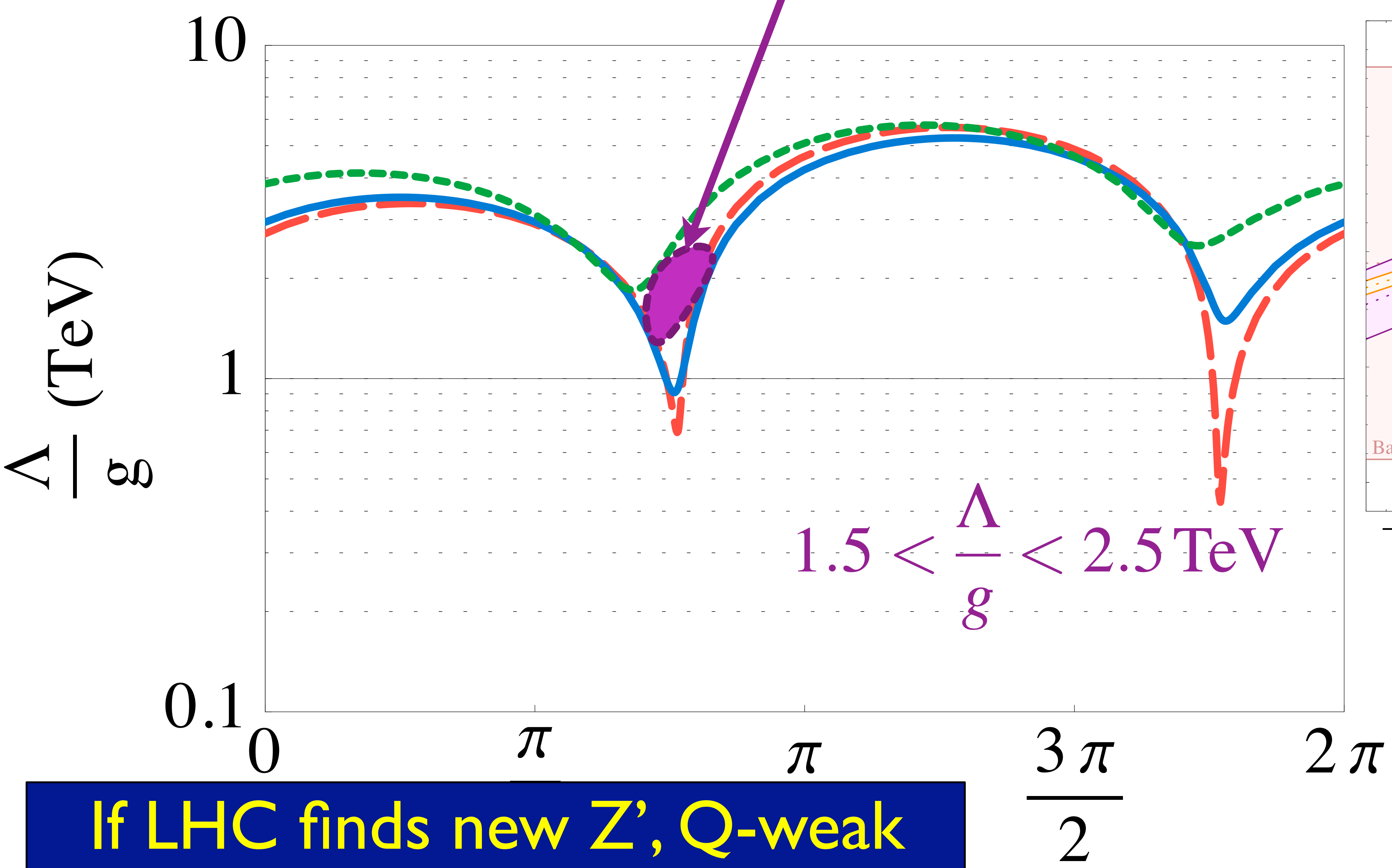
Q-weak: Assuming SM

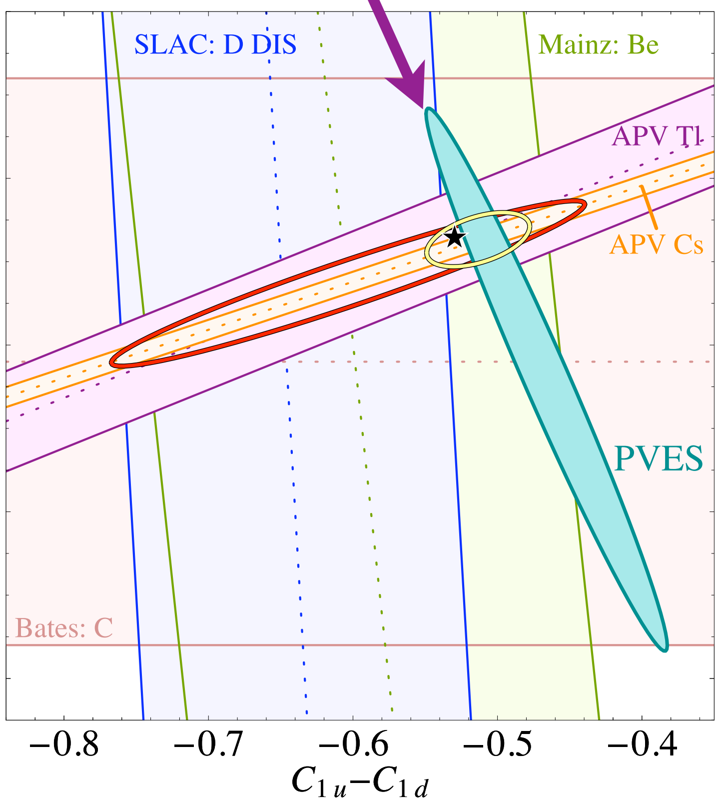


Q-weak constrains new physics to beyond 2 TeV

Q-weak Discovery Potential

Assume Q-weak takes central value of current measurements





If LHC finds new Z', Q-weak will help determine nature of interaction

Summary

- Strange quarks provide an ideal testing ground for probing the quark-antiquark dynamics of quark binding
- Latest experimental & theoretical results suggest strangeness electromagnetic currents in the nucleon are small
- Strangeness quantities appear to be reducing from earlier estimates
- We are entering an era of precision physics in nonperturbative QCD
- Precision studies can play a significant role in the search for new physics