# The role of strange quarks in nucleon structure

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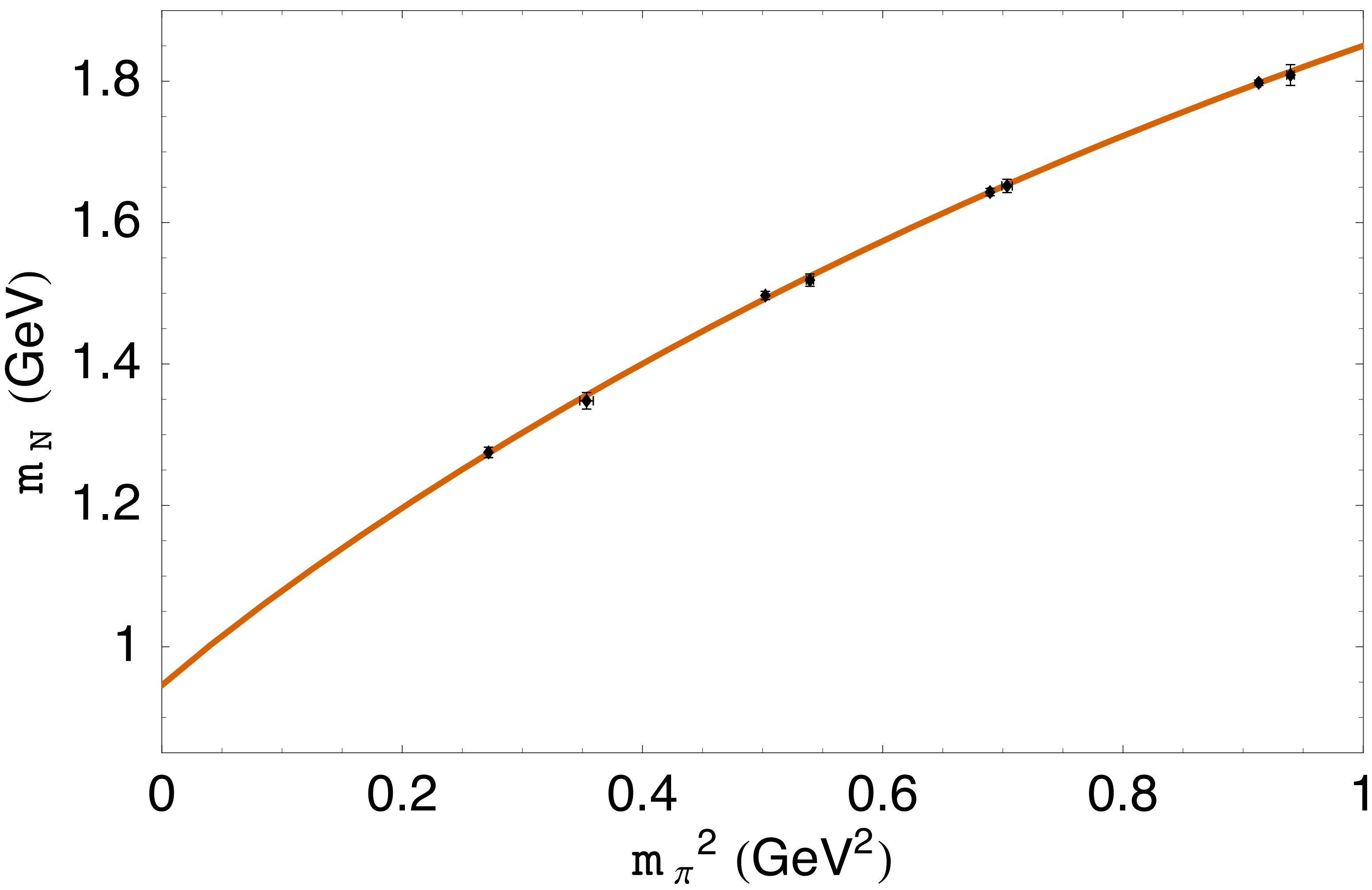
University of Adelaide

Achievements and New Directions in Subatomic Physics:
Workshop in Honour of Tony Thomas's 60th Birthday

University of Adelaide

# Chiral Extrapolation

ChPT: $M_N = c_0 + c_2 m_\pi^2 + \chi_\pi m_\pi^3 + \ldots$




$\chi_\pi \simeq -0.63\text{GeV}^{-2}$

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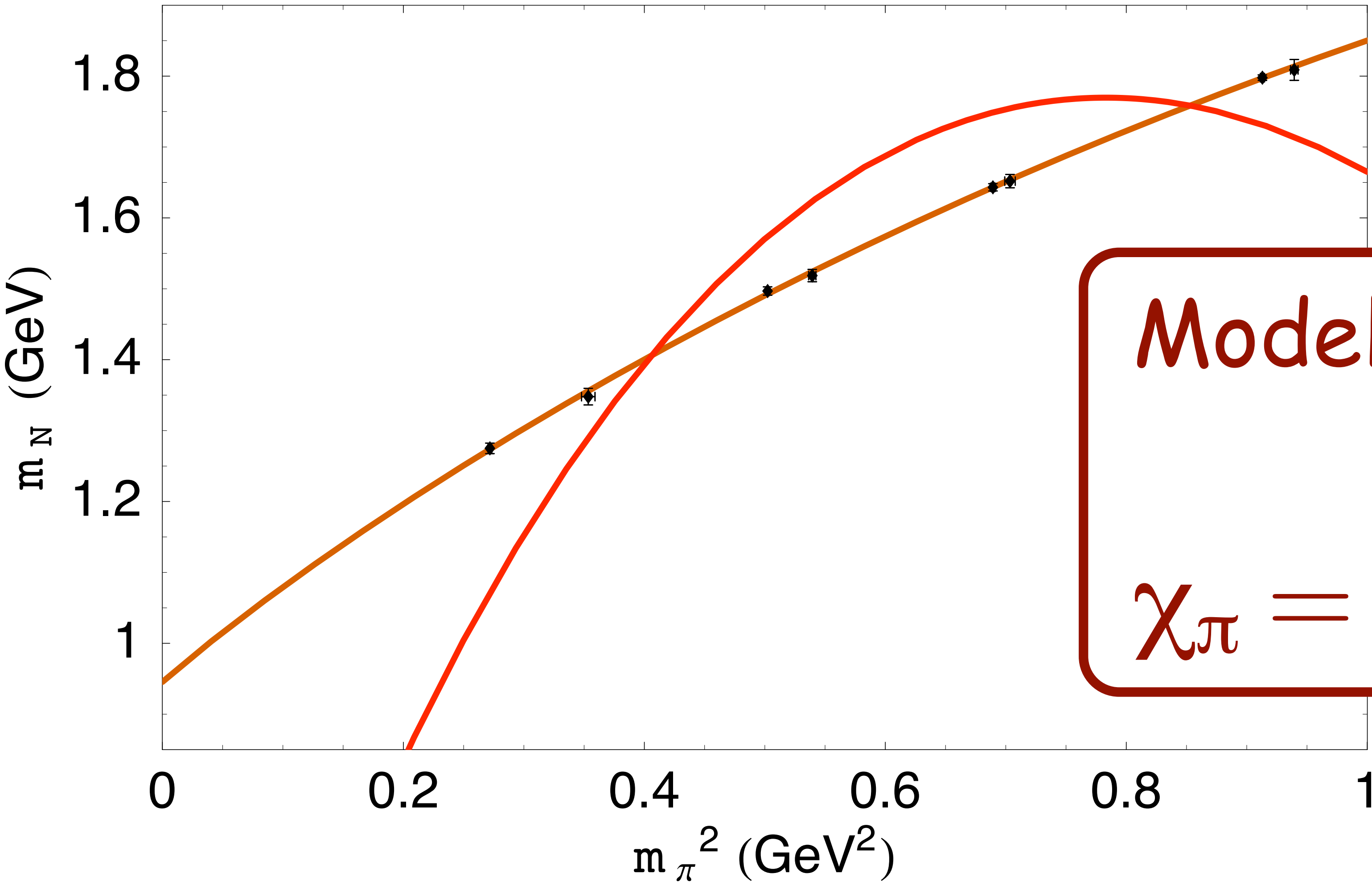
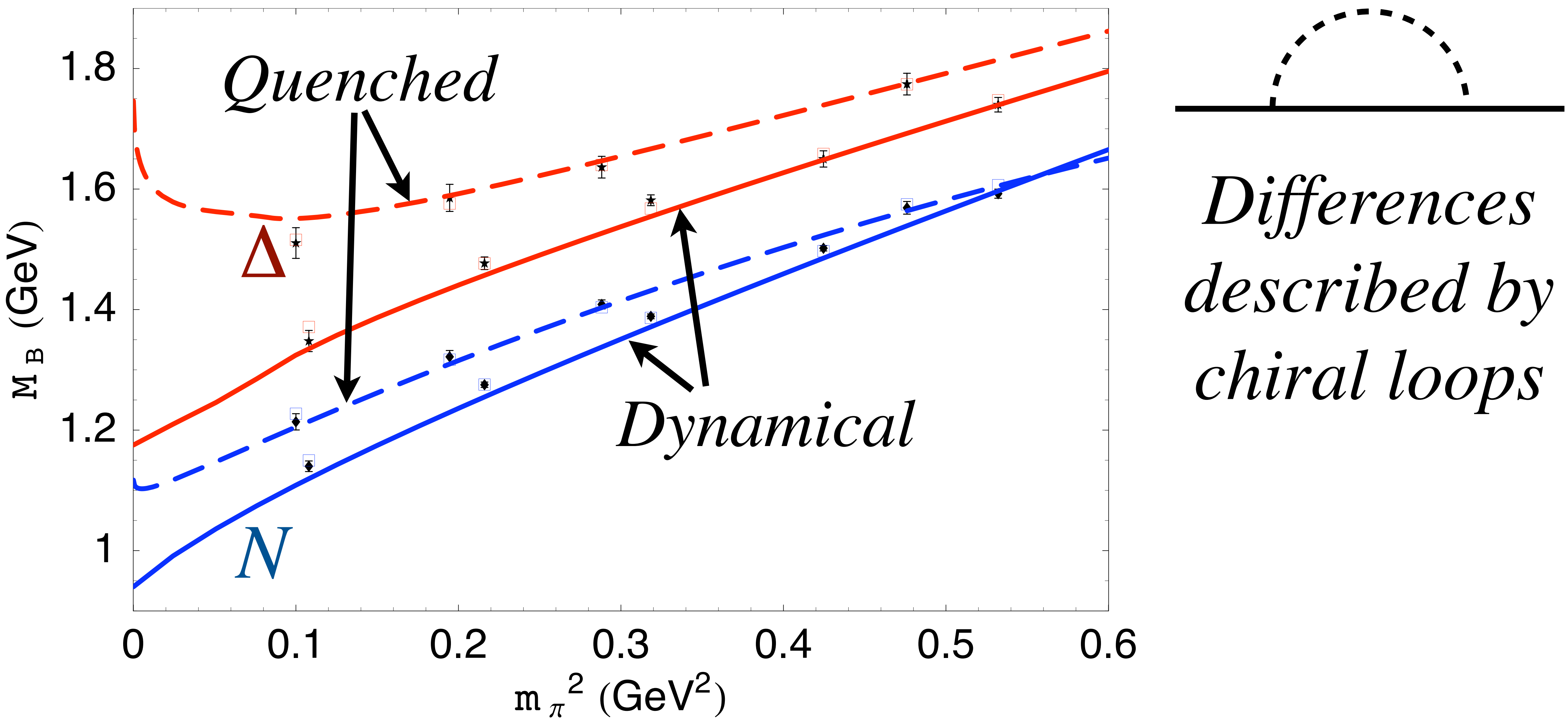



Model-independent value

$\chi_\pi = -5.5 \mathrm{GeV}^{-2}$

$\chi_\pi \simeq -0.63 \mathrm{GeV}^{-2}$

# Quenched QCD vs QCD




*Differences described by chiral loops*

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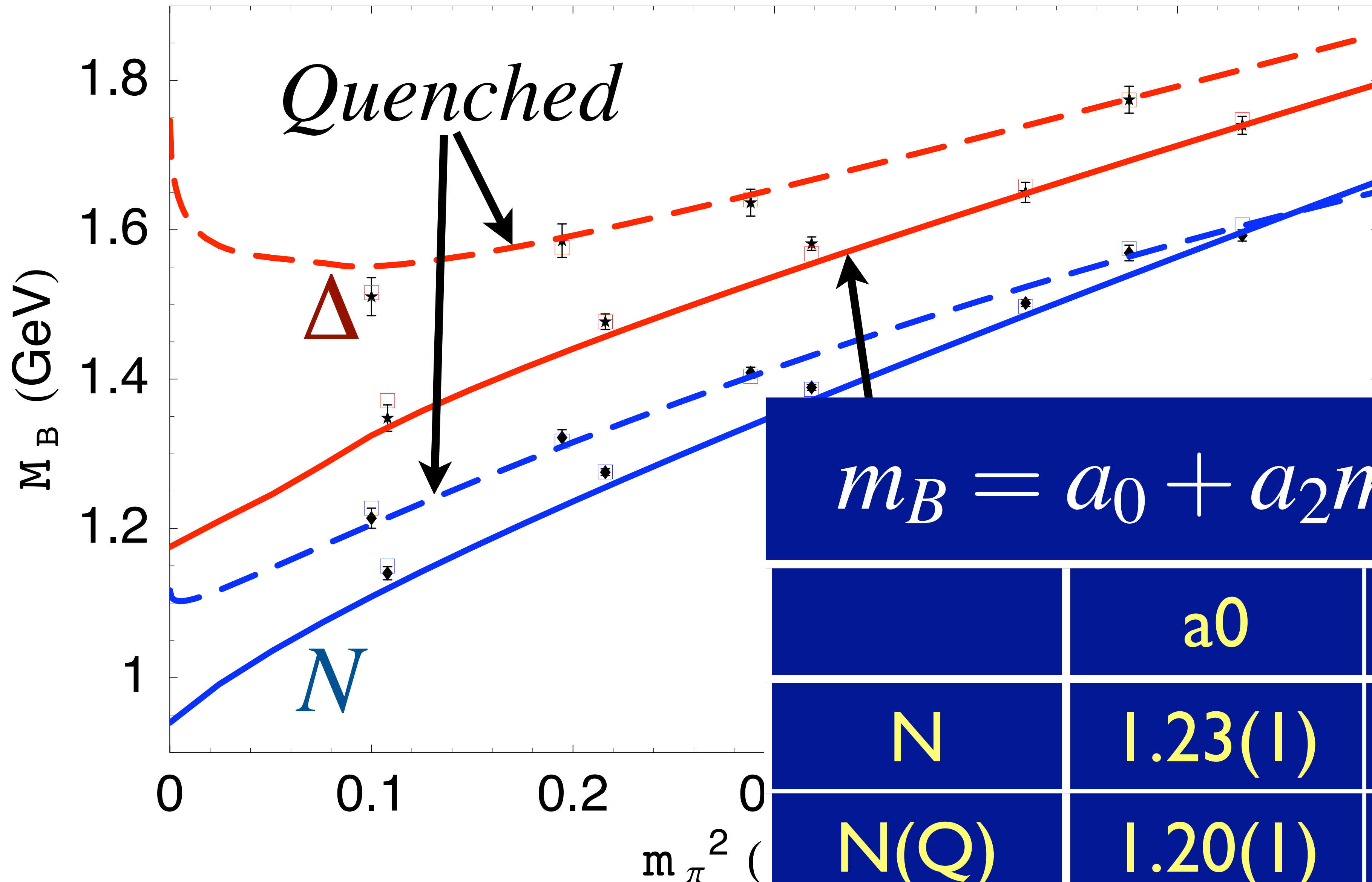


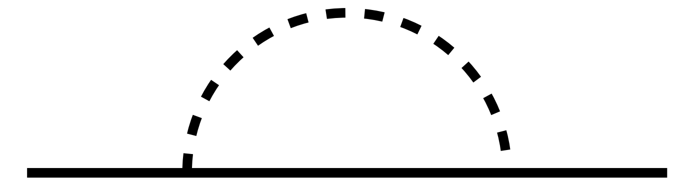

*Differences described by*

$$m_B = a_0 + a_2 m_\pi^2 + a_4 m_\pi^4 + \Sigma$$

| | a0 | a2 | a4 |
|---|---|---|---|
| N | 1.23(1) | 1.13(8) | -0.35(12) |
| N(Q) | 1.20(1) | 1.10(8) | -0.42(13) |
| D | 1.40(3) | 1.11(18) | -0.56(25) |
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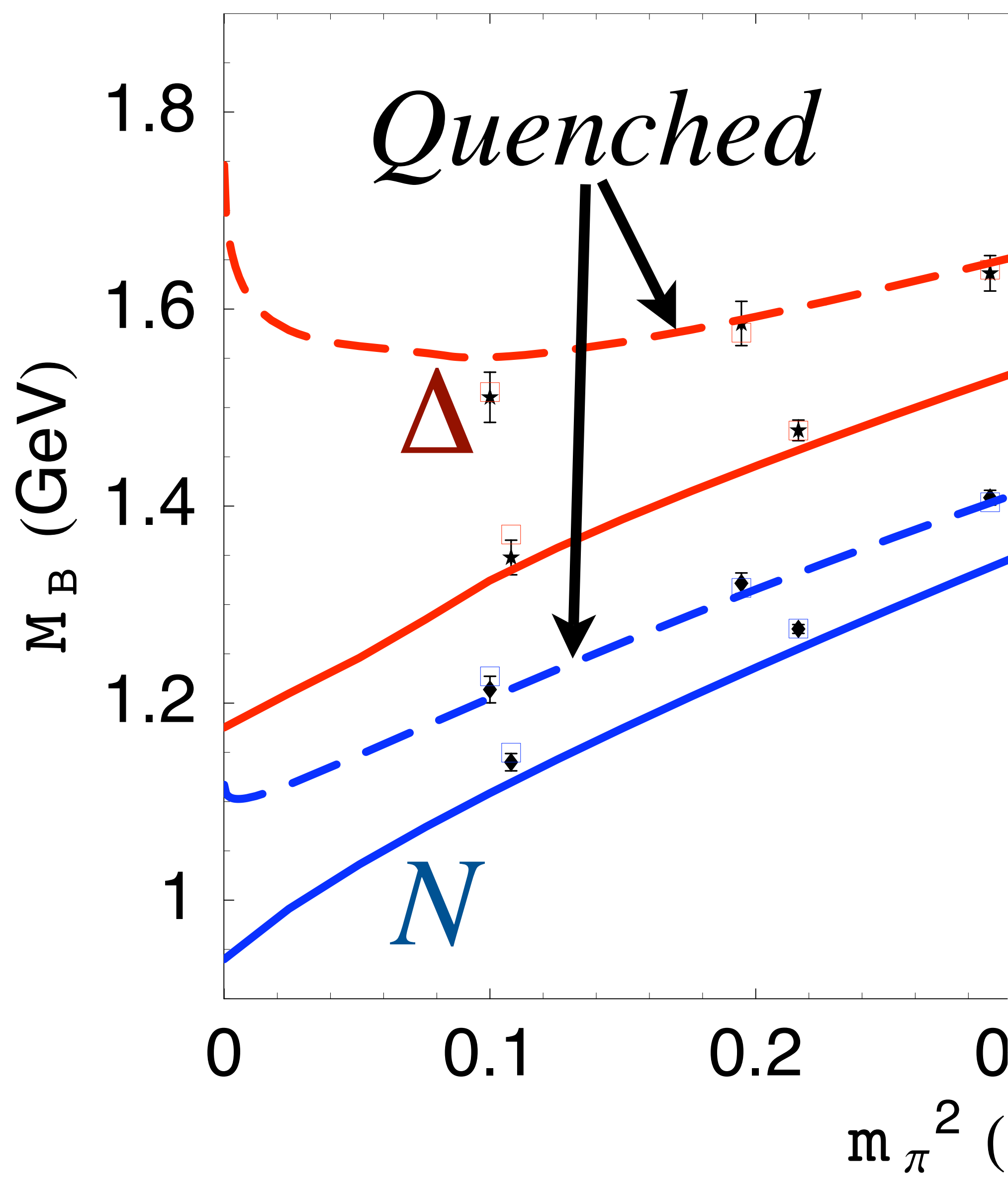


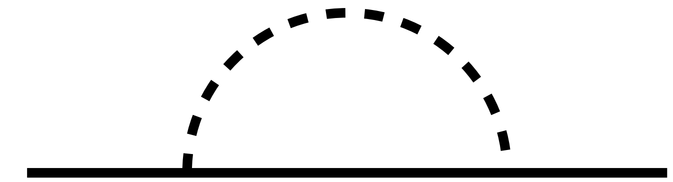

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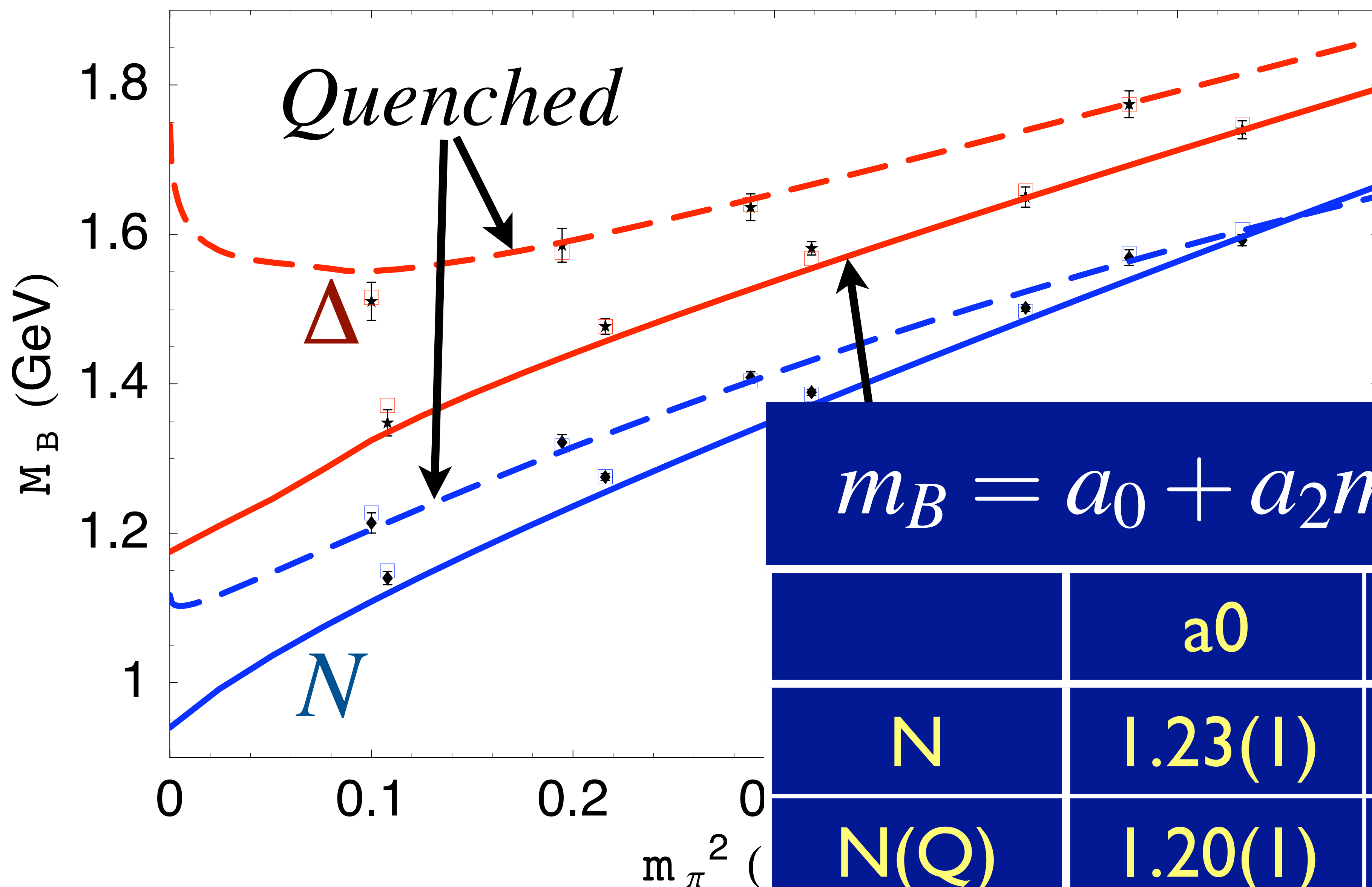


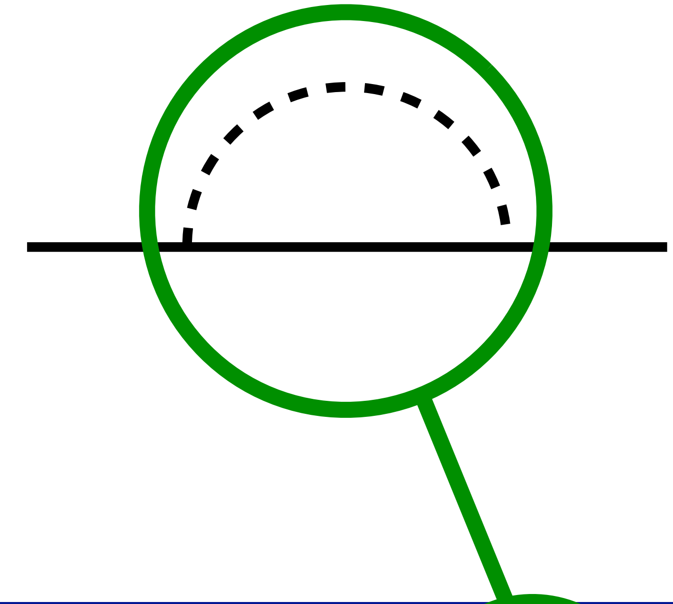

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# Physics!!

- Let’s use these new tools to learn something new
- How about strangeness?

# Elastic Form Factors

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

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

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$$G^p_{E,M} = +\frac{2}{3}G^u_{E,M} - \frac{1}{3}G^d_{E,M} - \frac{1}{3}G^s_{E,M}$$

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2 Equations — 3 Unkowns!

# 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: $\sin^2\theta_W$

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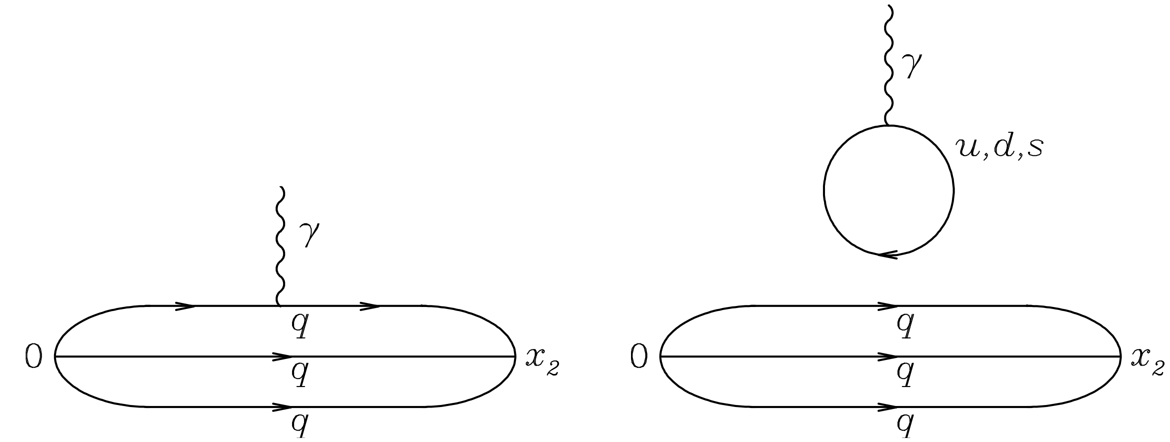
3 Equations — 3 Unkowns

Can isolate strangeness!

# Imposing Charge Symmetry




$$p = \frac{2}{3}u^p - \frac{1}{3}u^n + O_N$$

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$$3O_N = 2p + n - u^p$$

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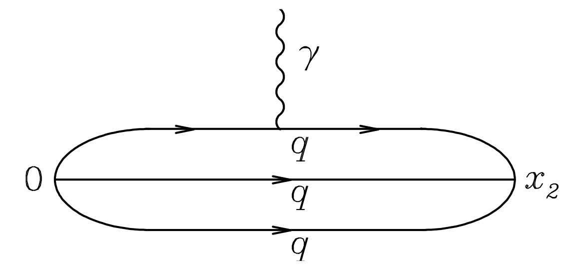


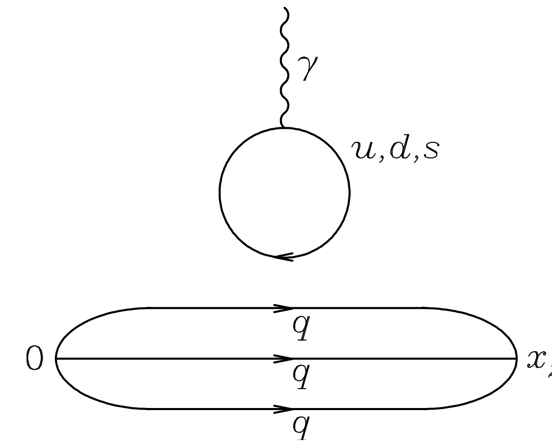


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$$\Sigma^+ - \Sigma^- = u^\Sigma$$

$$3O_N = 2p + n - \frac{u^p}{u^\Sigma}(\Sigma^+ - \Sigma^-)$$

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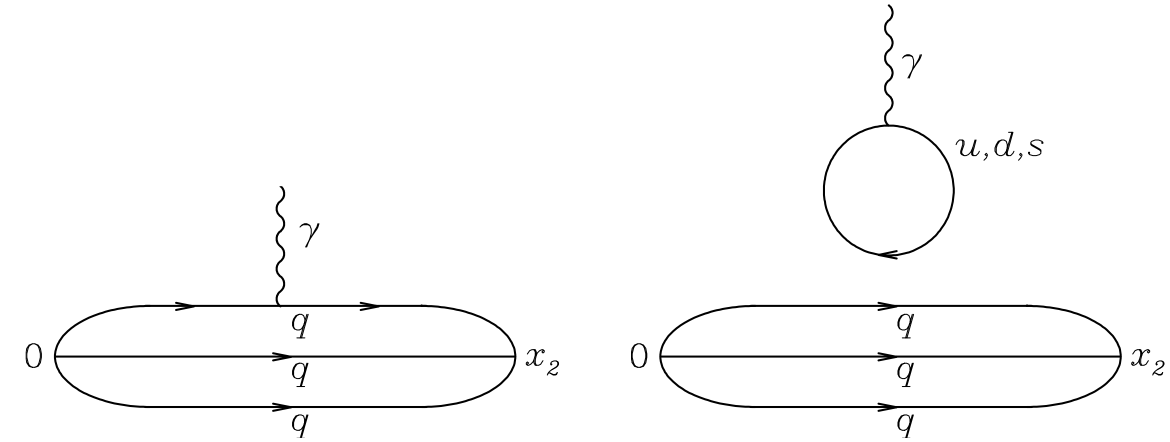


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$$3O_N = p + 2n - u^n$$

$$\Xi^0 - \Xi^- = u^\Xi$$

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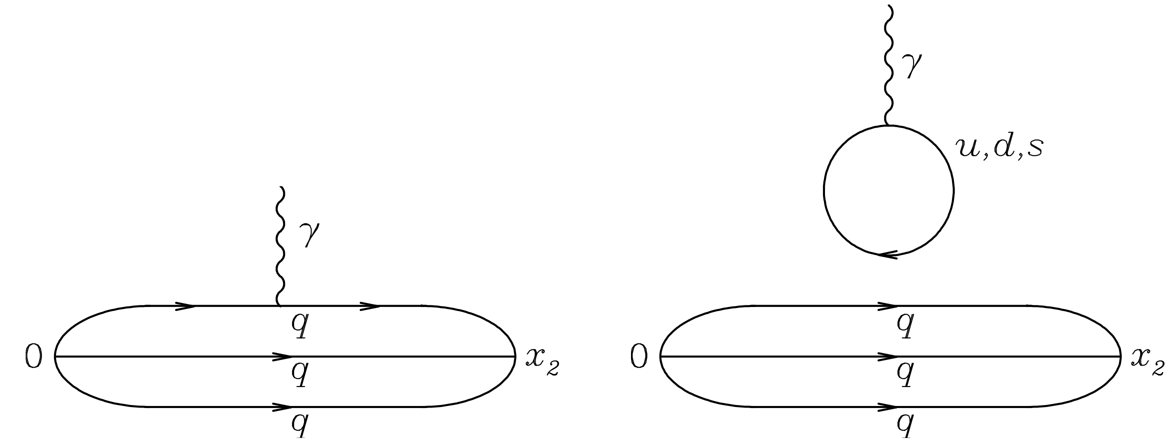


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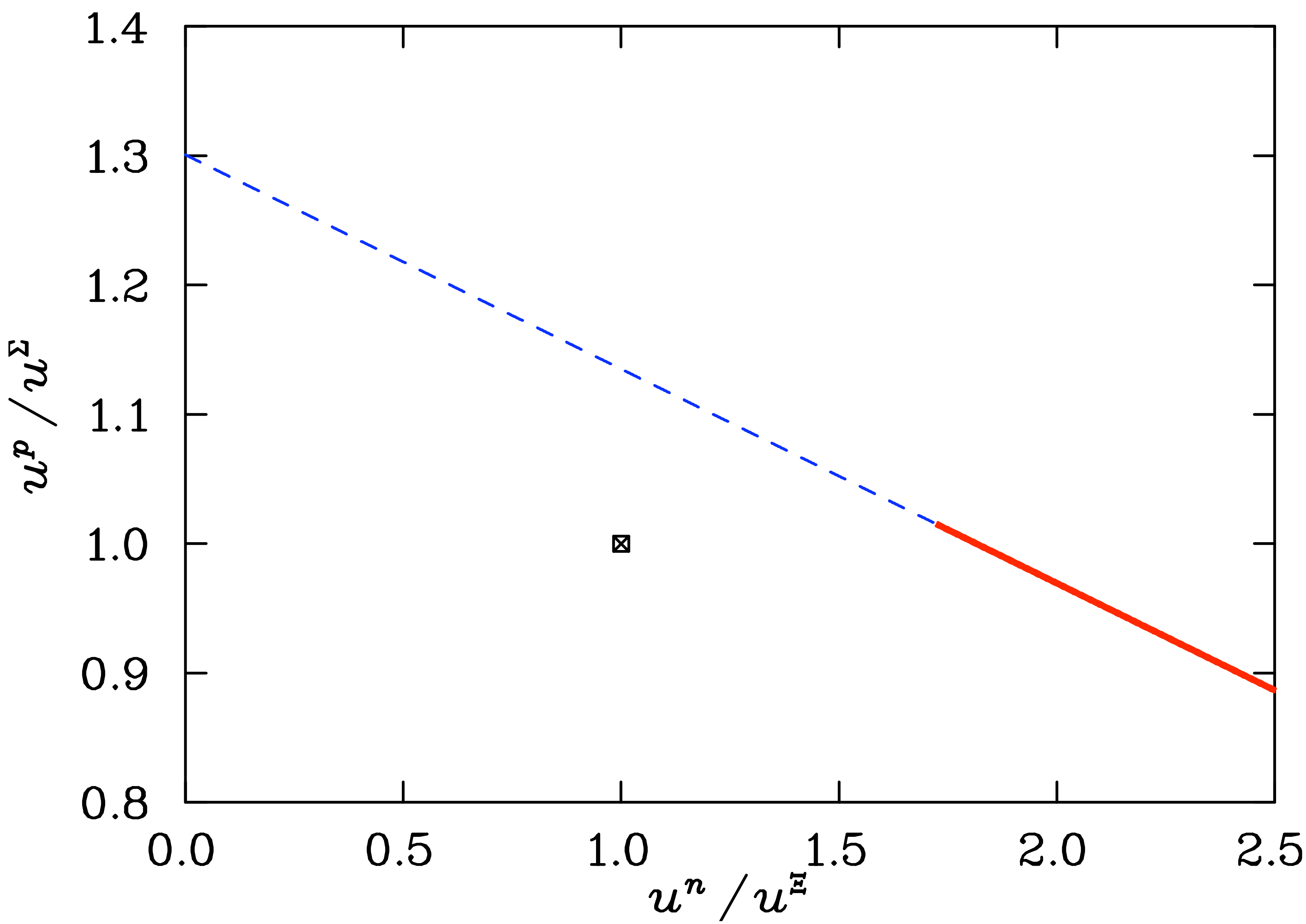
Lattice QCD

$$3O_N=p+2n-u^n$$

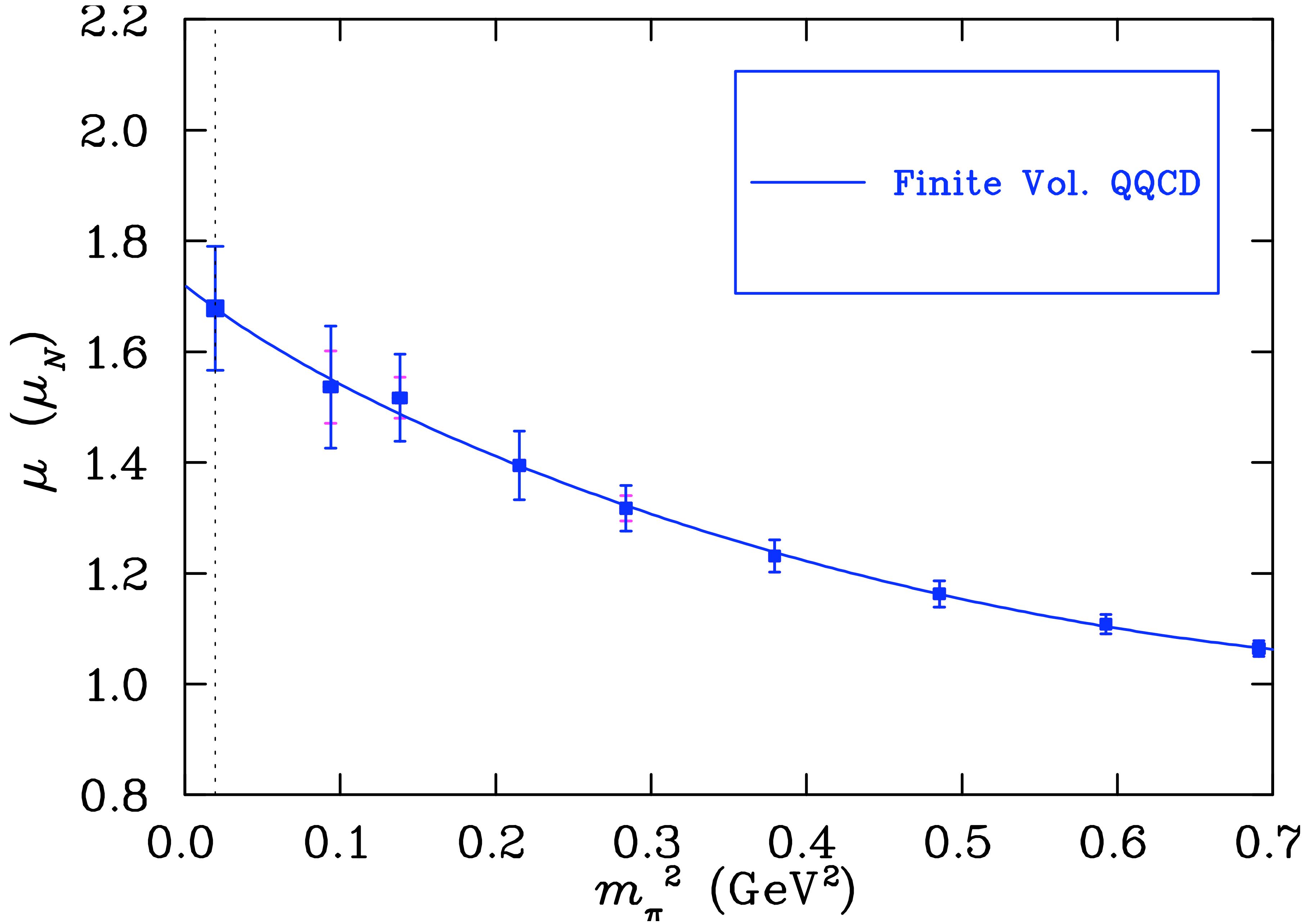
$$\Xi^0-\Xi^-=u^\Xi$$

$$3O_N=p+2n-\frac{u^n}{u^\Xi}(\Xi^0-\Xi^-)$$

# Constraint on GMs



# *u*-quark in the proton



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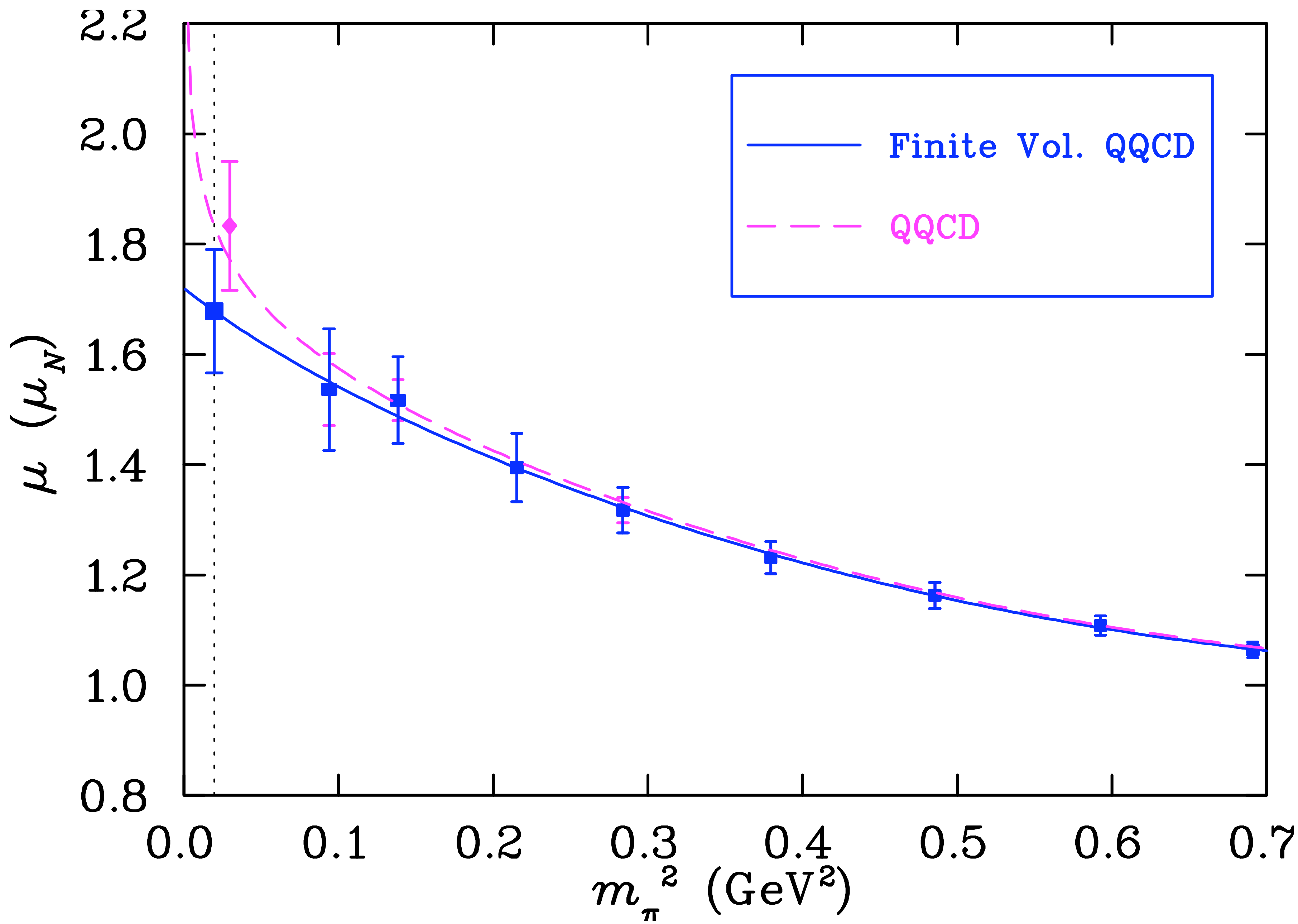

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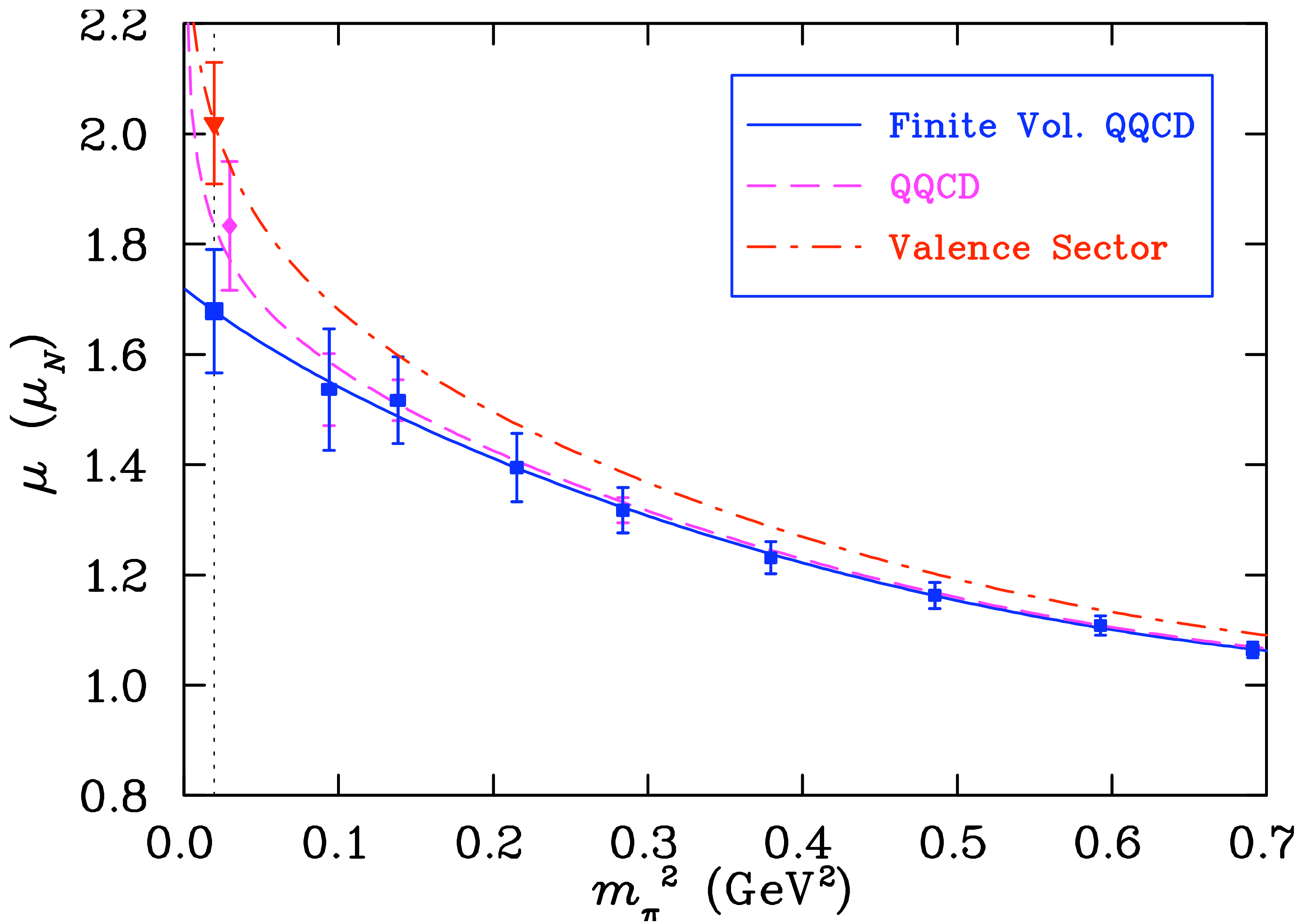

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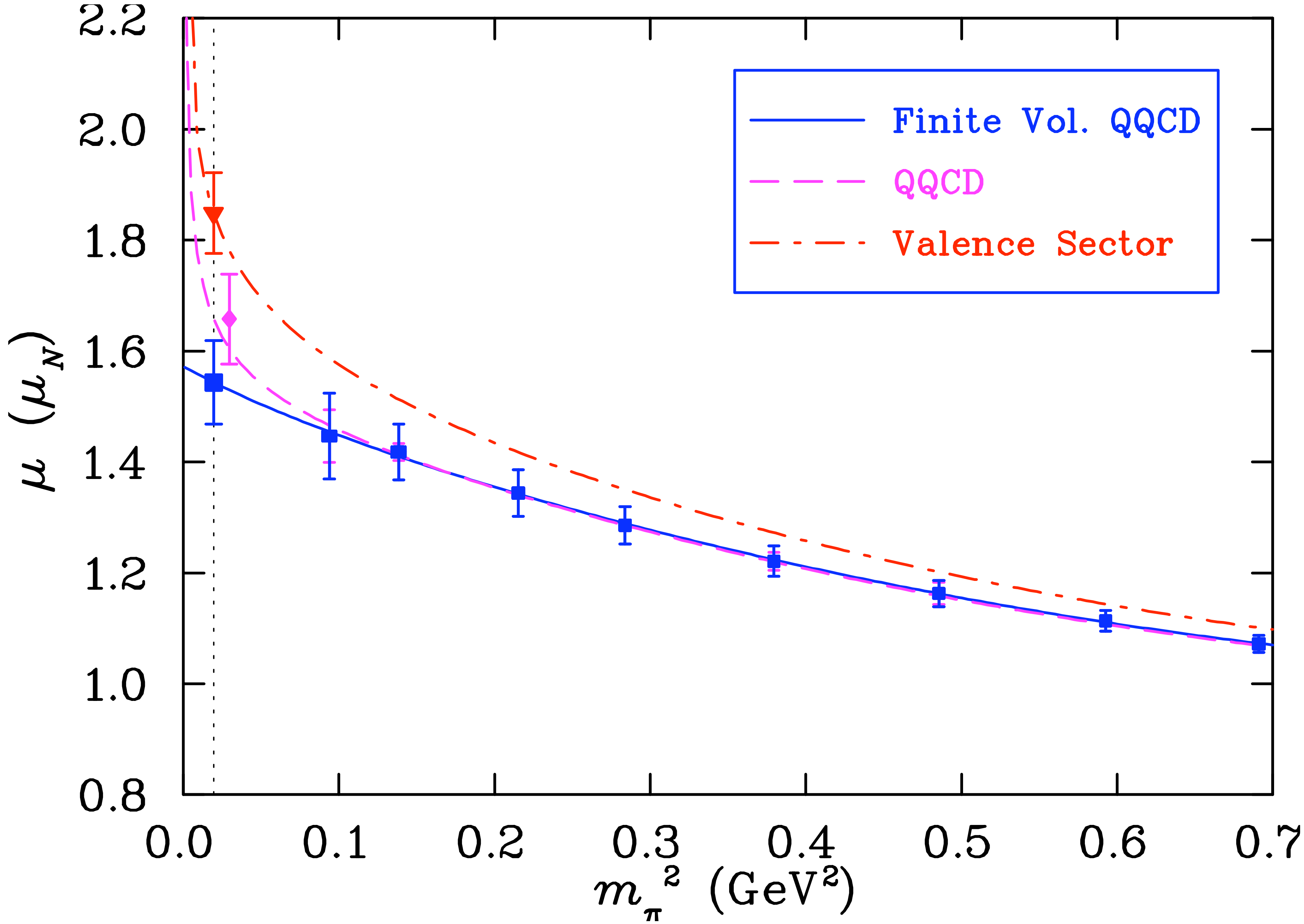
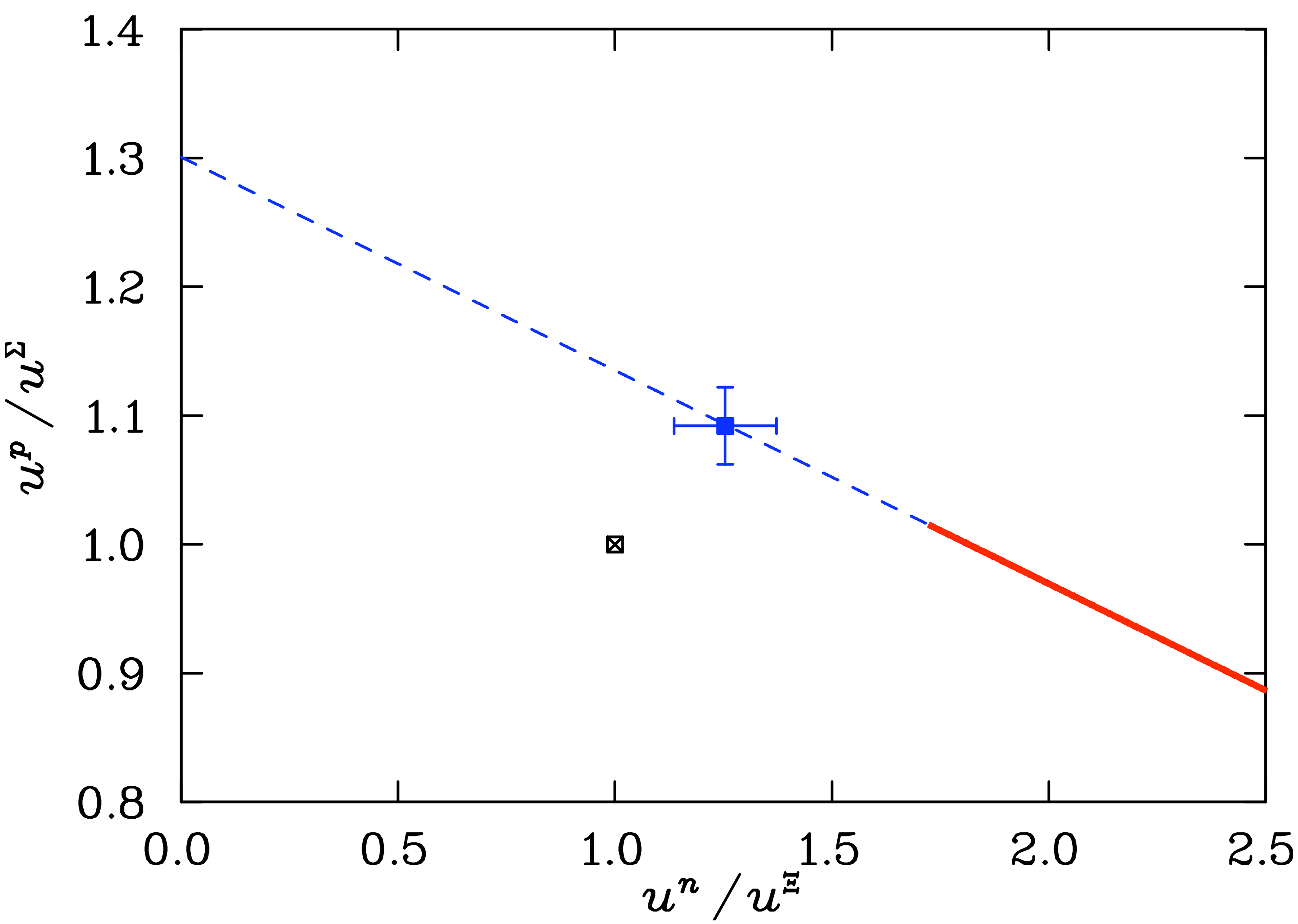


# Magnetic strangeness result



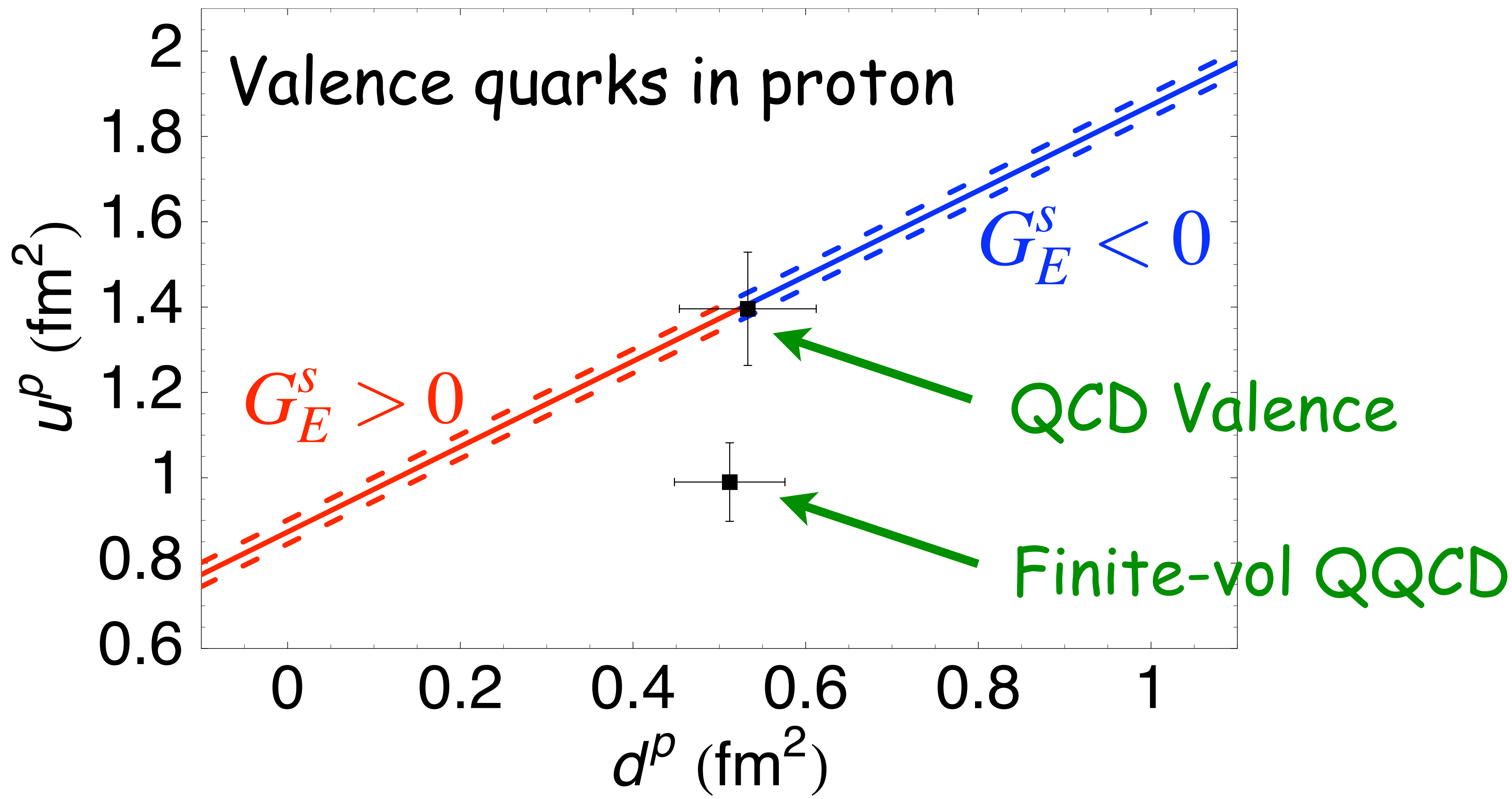

$$\frac{u^p}{u^\Sigma} = 1.092 \pm 0.030$$

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

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

# Repeat analysis for electric radius

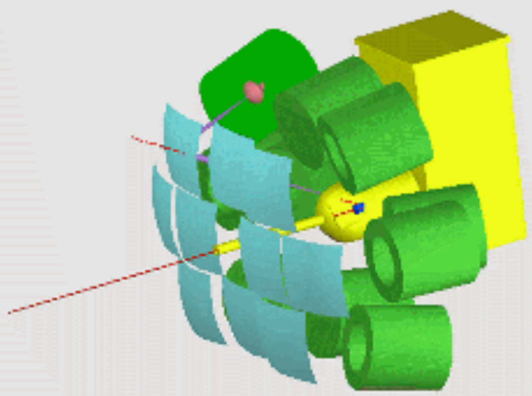
Limited hyperon info, take absolute values from lattice




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

# Strangeness Measurements

SAMPLE @ MIT-Bates



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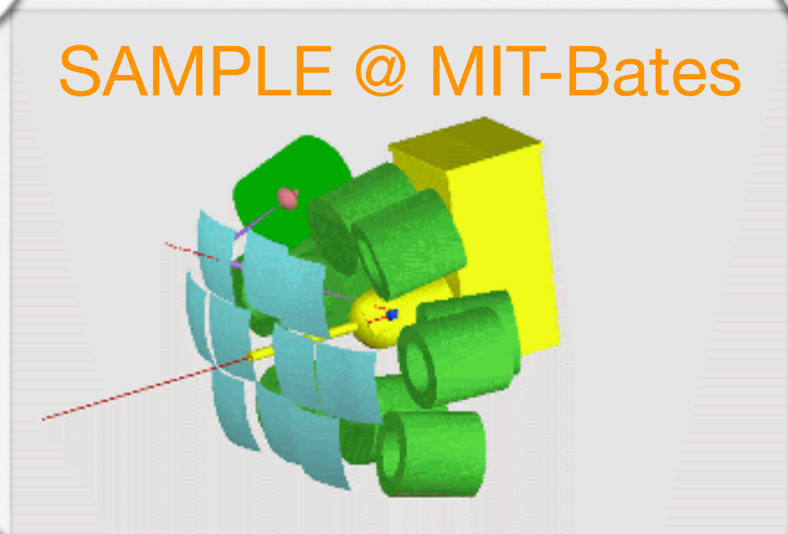


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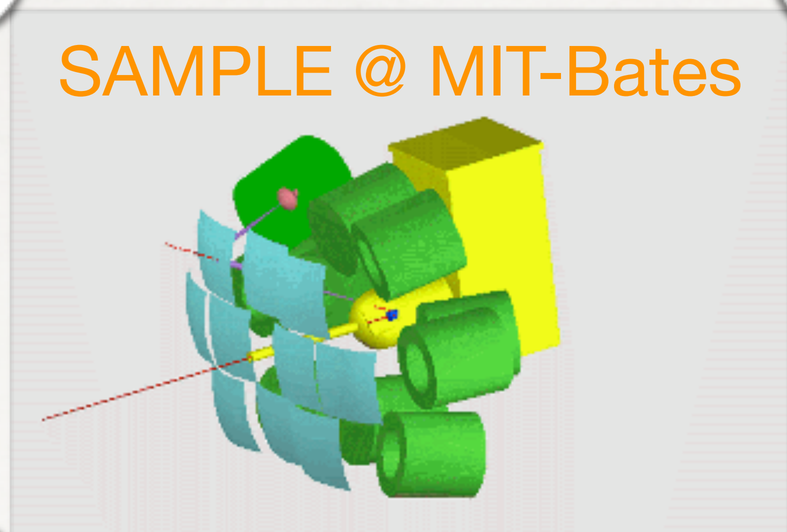


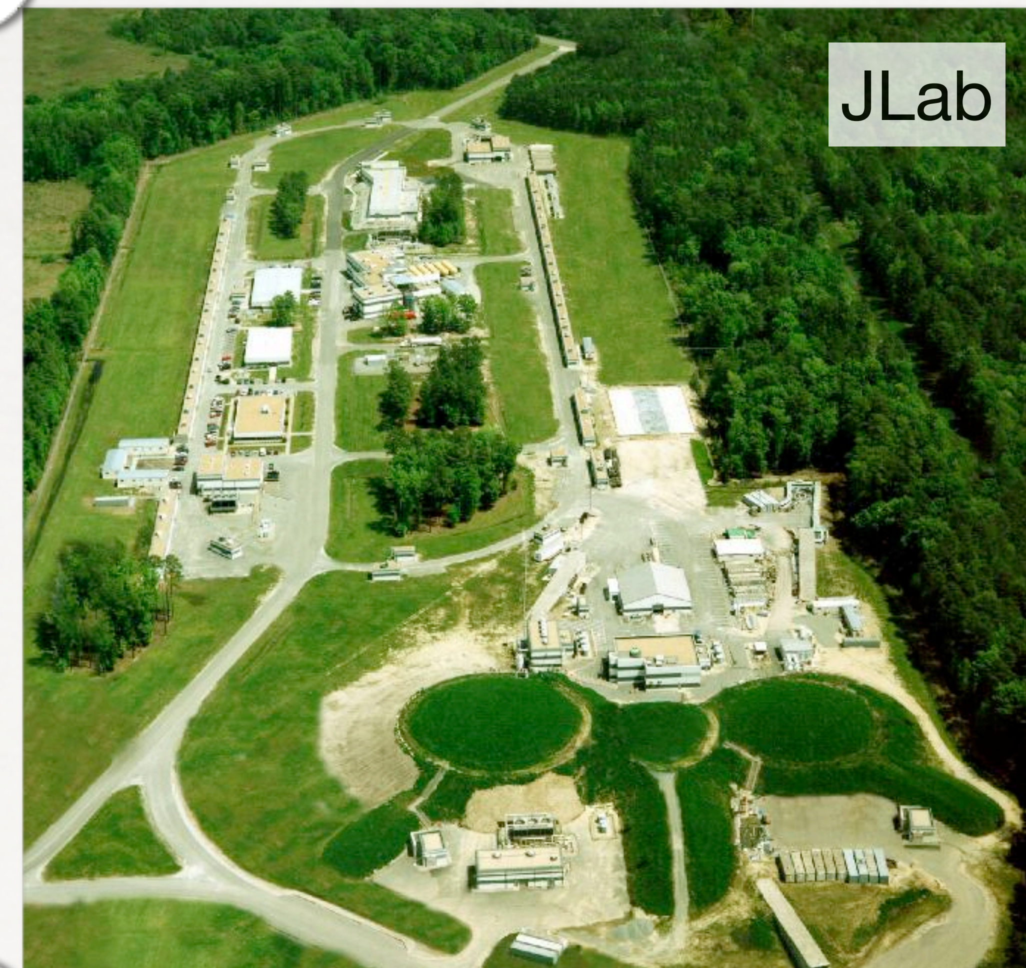


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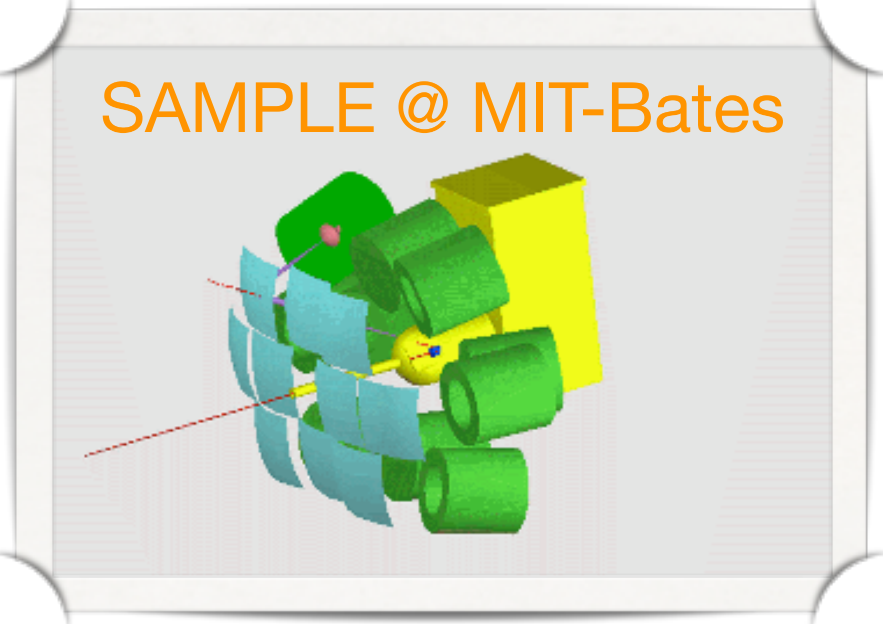


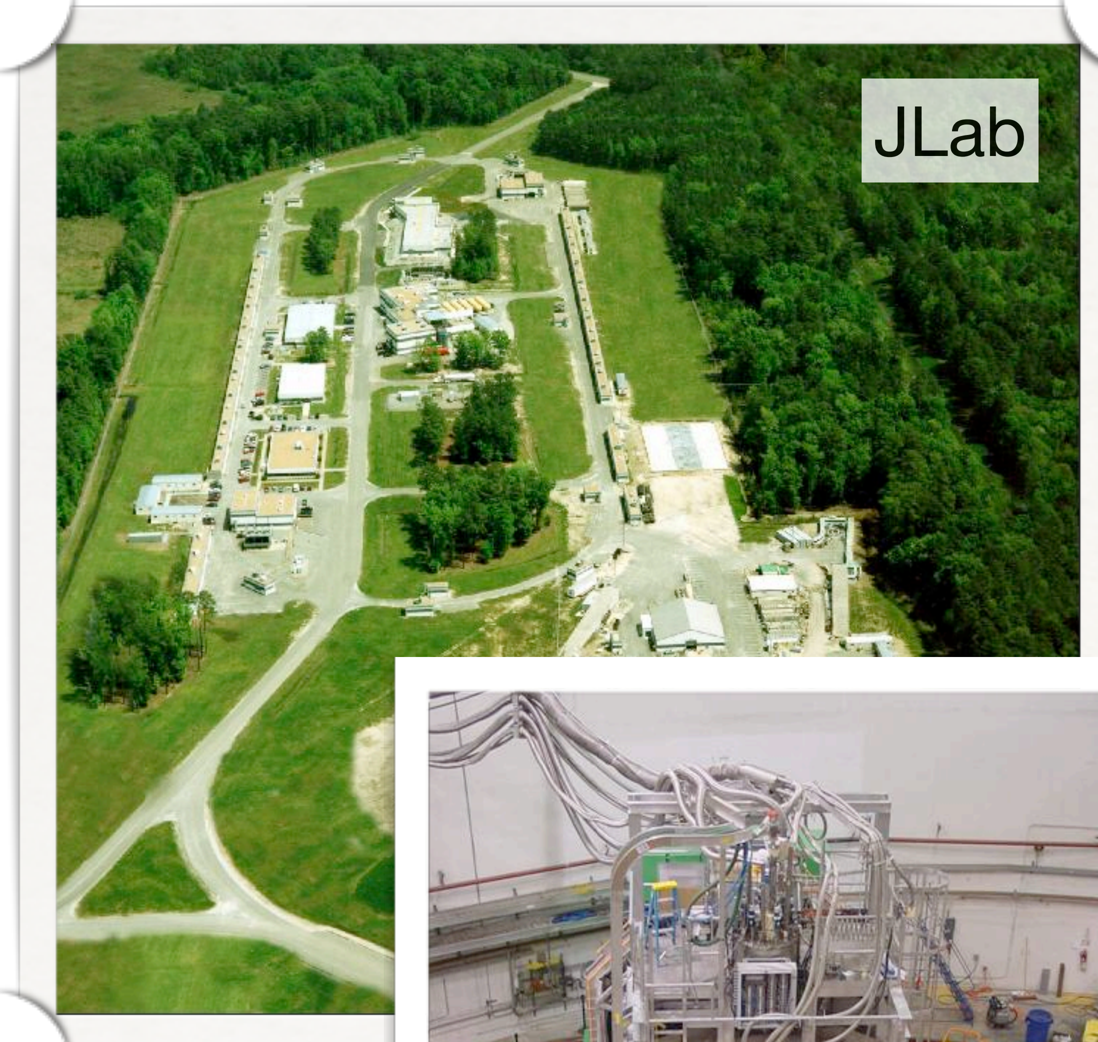



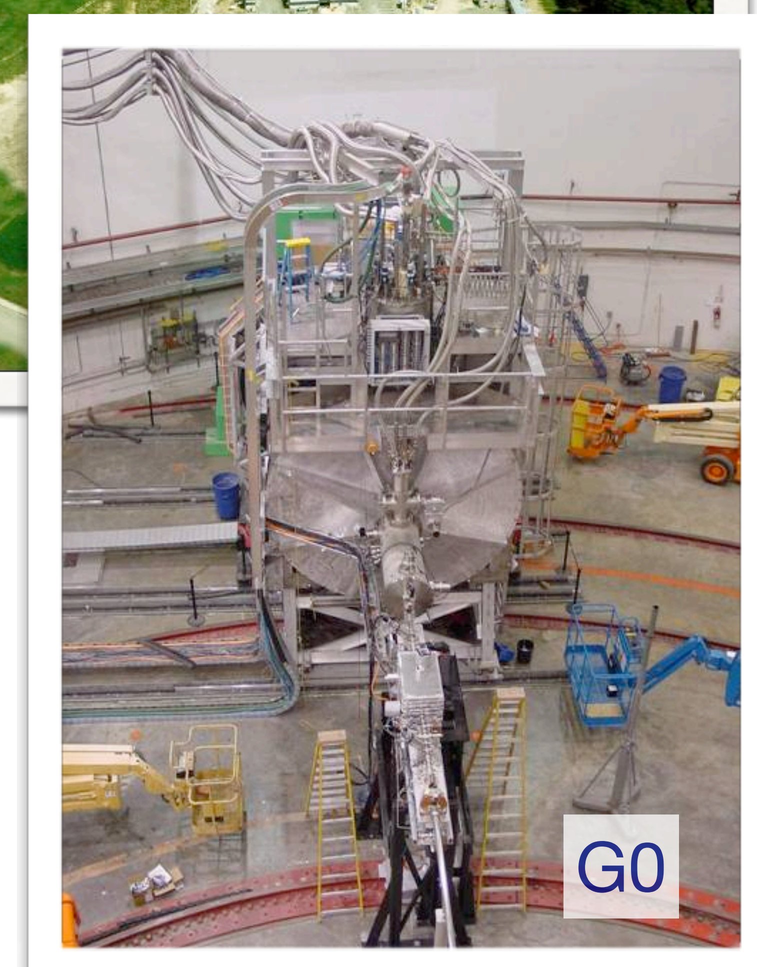

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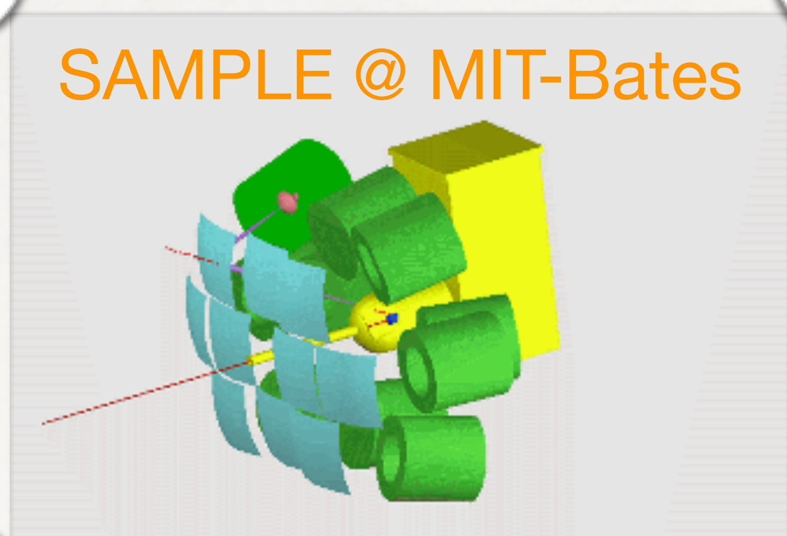
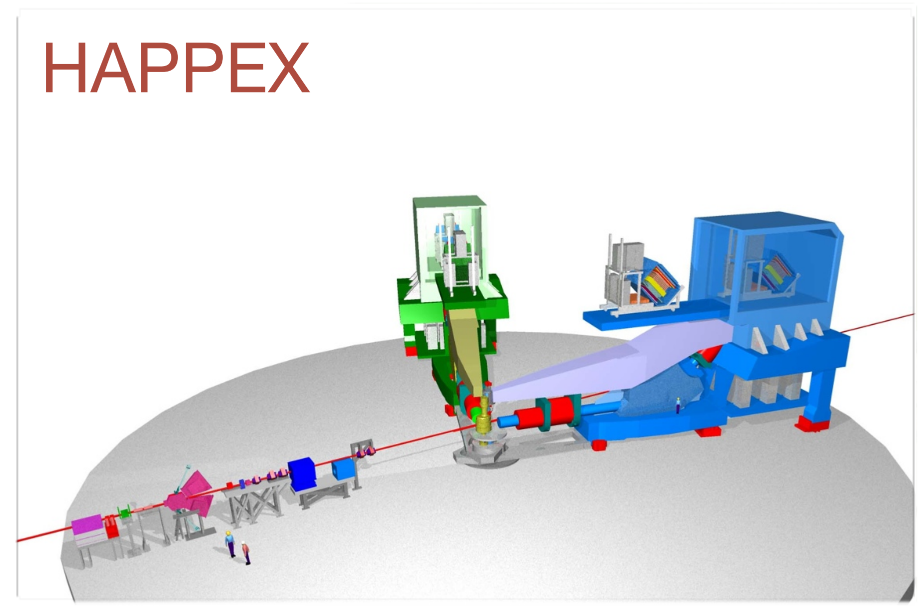
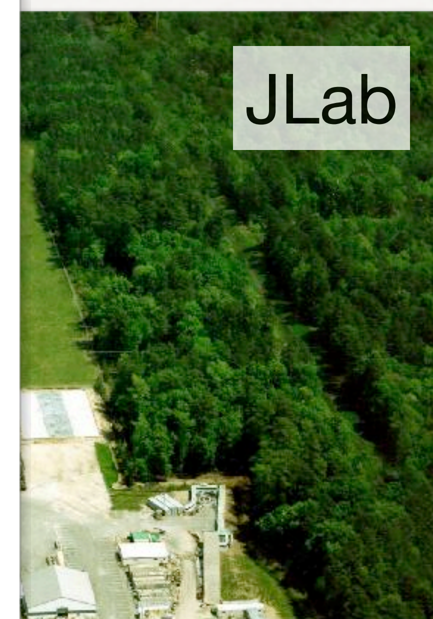
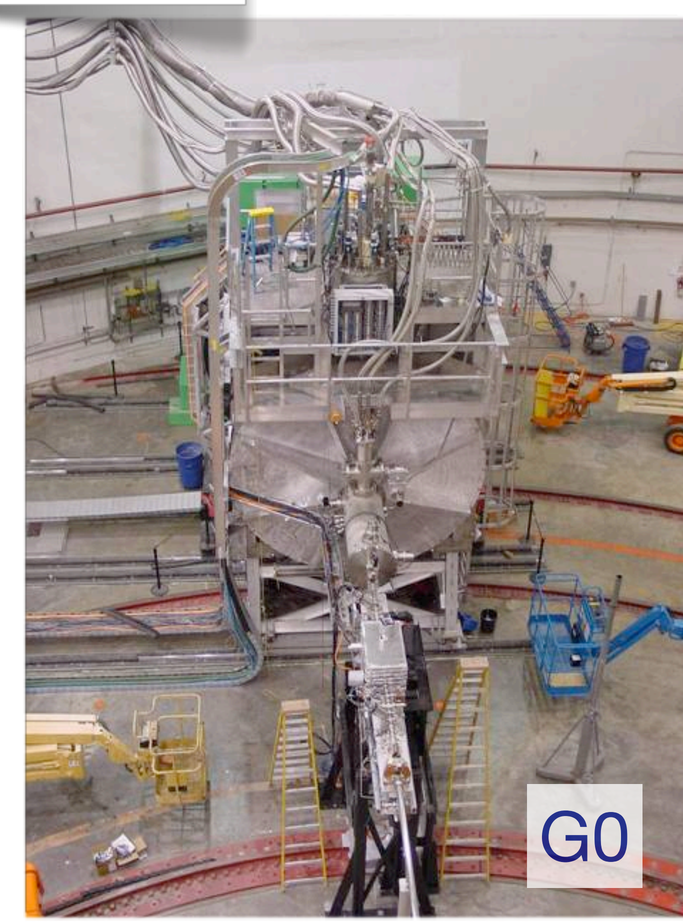


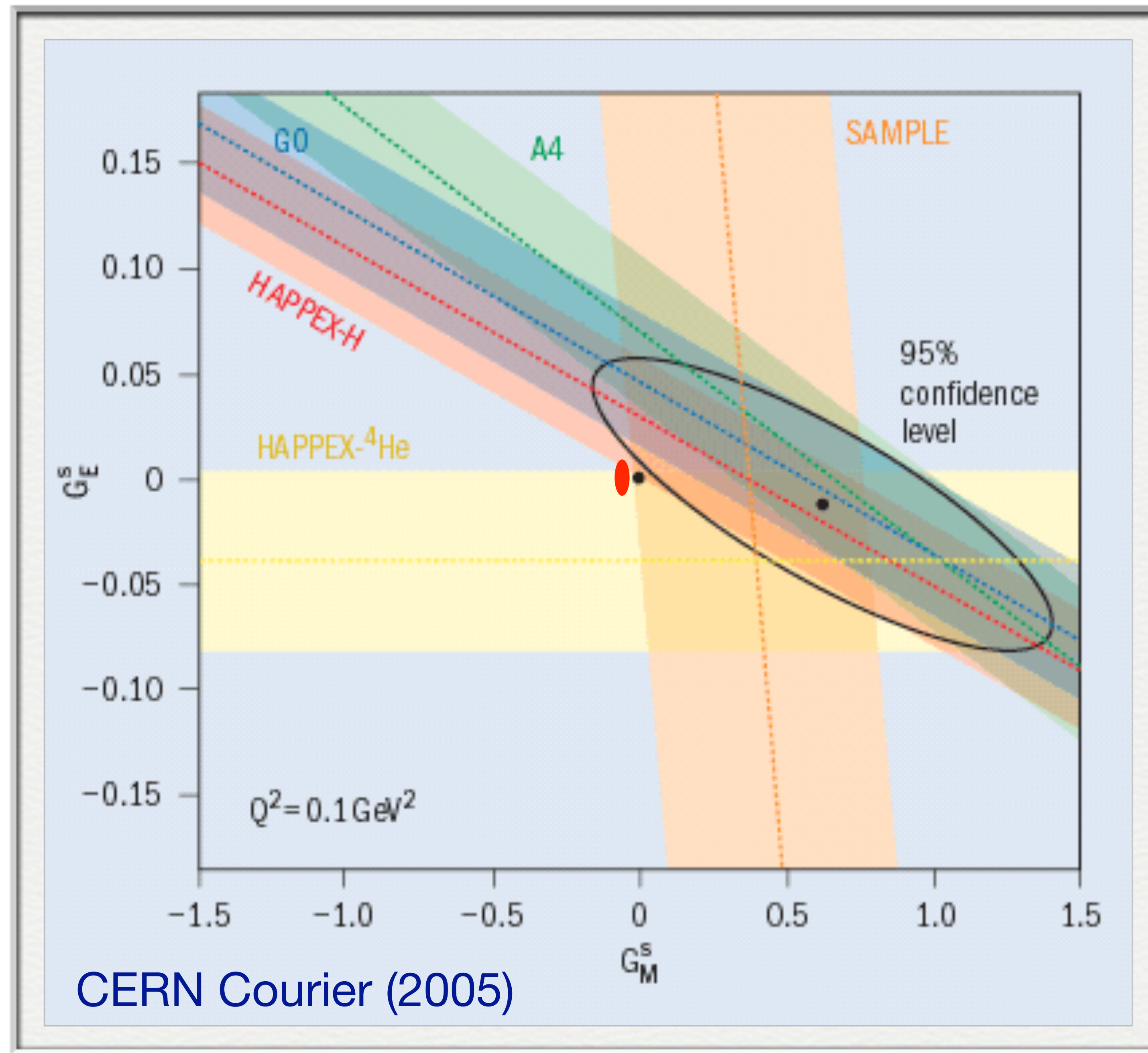




# Experimental Status (2005)

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

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



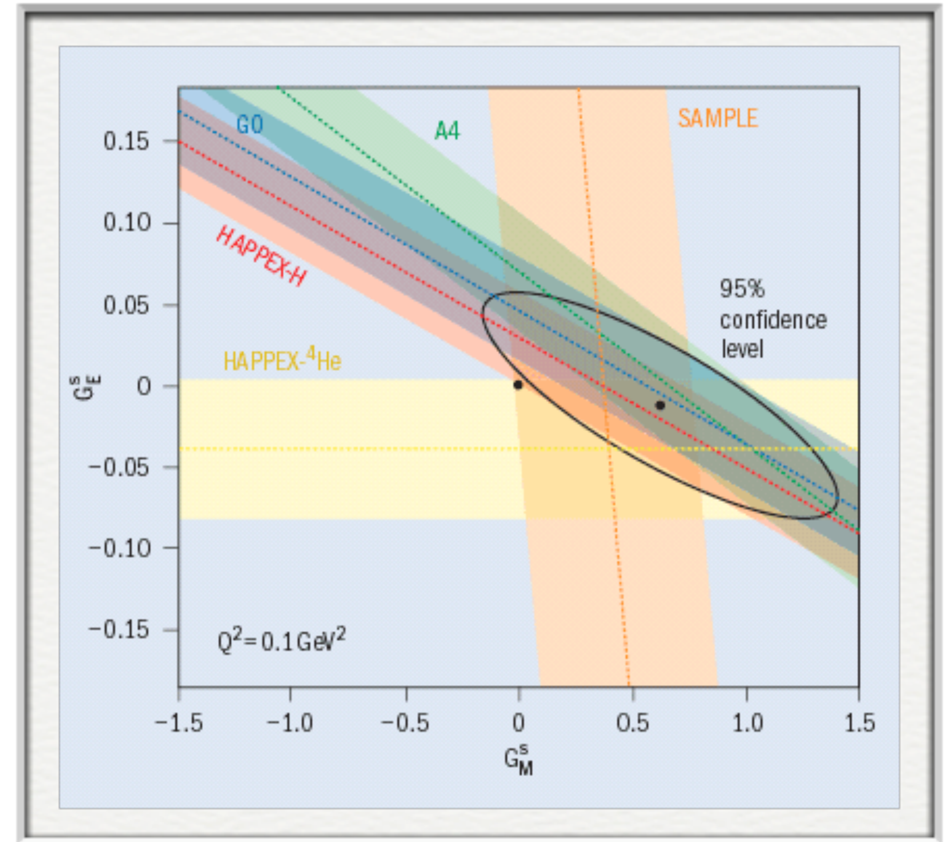

Strange Electric

Strange Magnetic

# Global Analysis

- Extract the anapole contribution from experiment

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

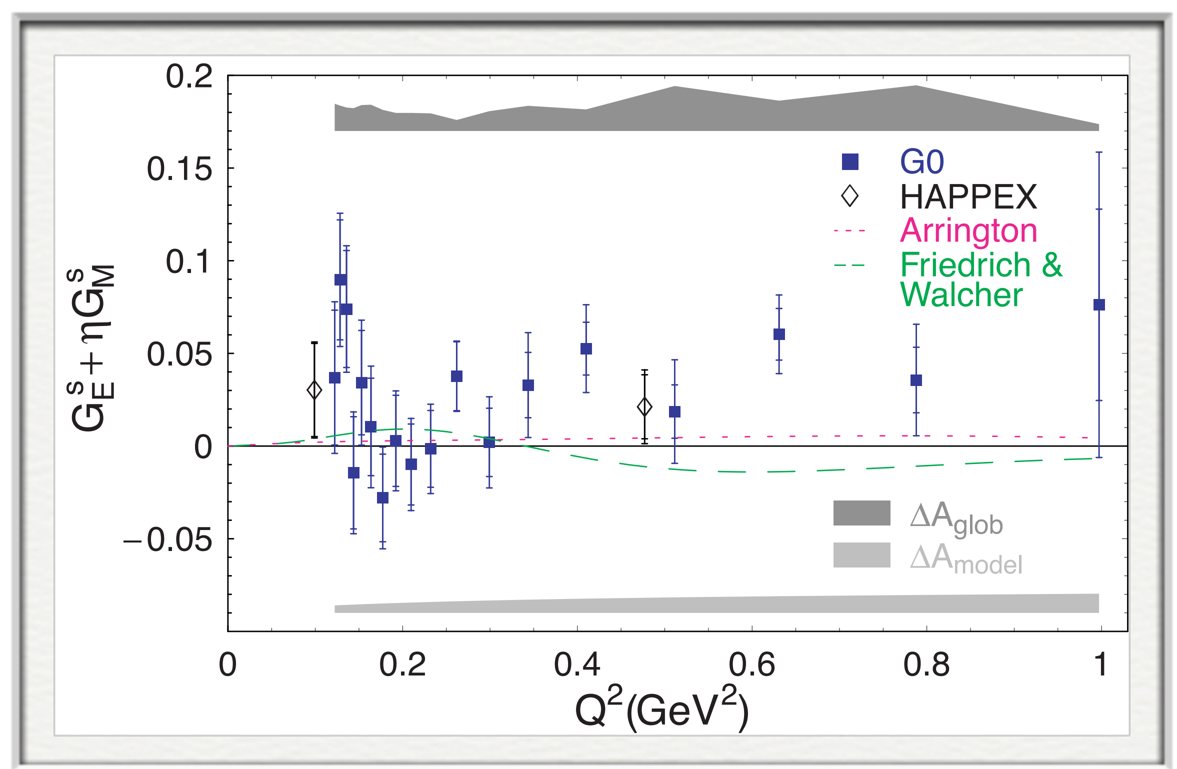



- Fit strangeness to measured asymmetries
  - Consistent treatment of electromagnetic form factors and radiative corrections

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

- Taylor expansion of strangeness

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



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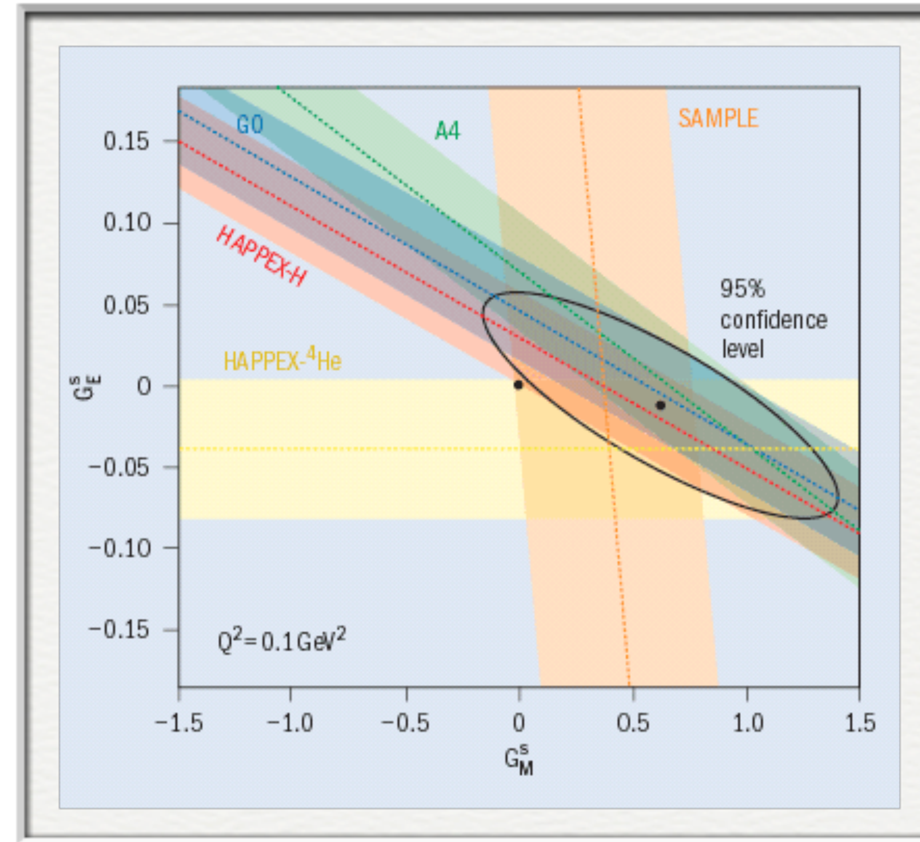


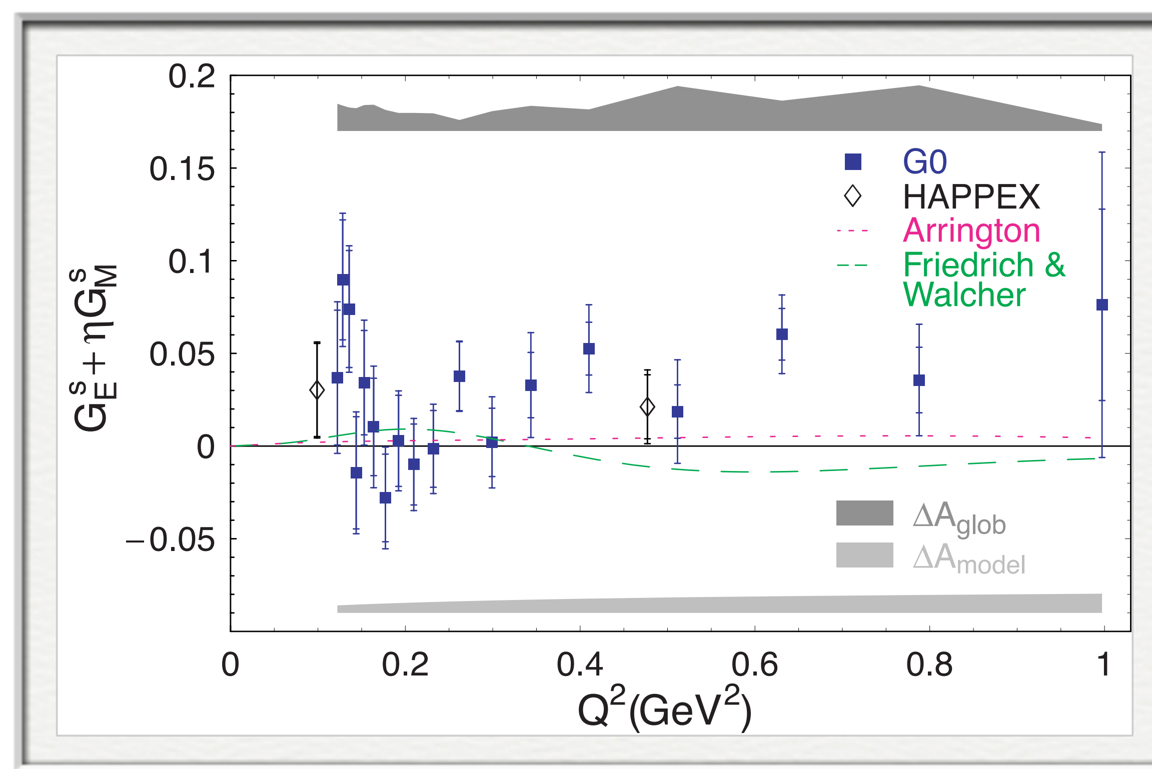

# Strangeness form factors

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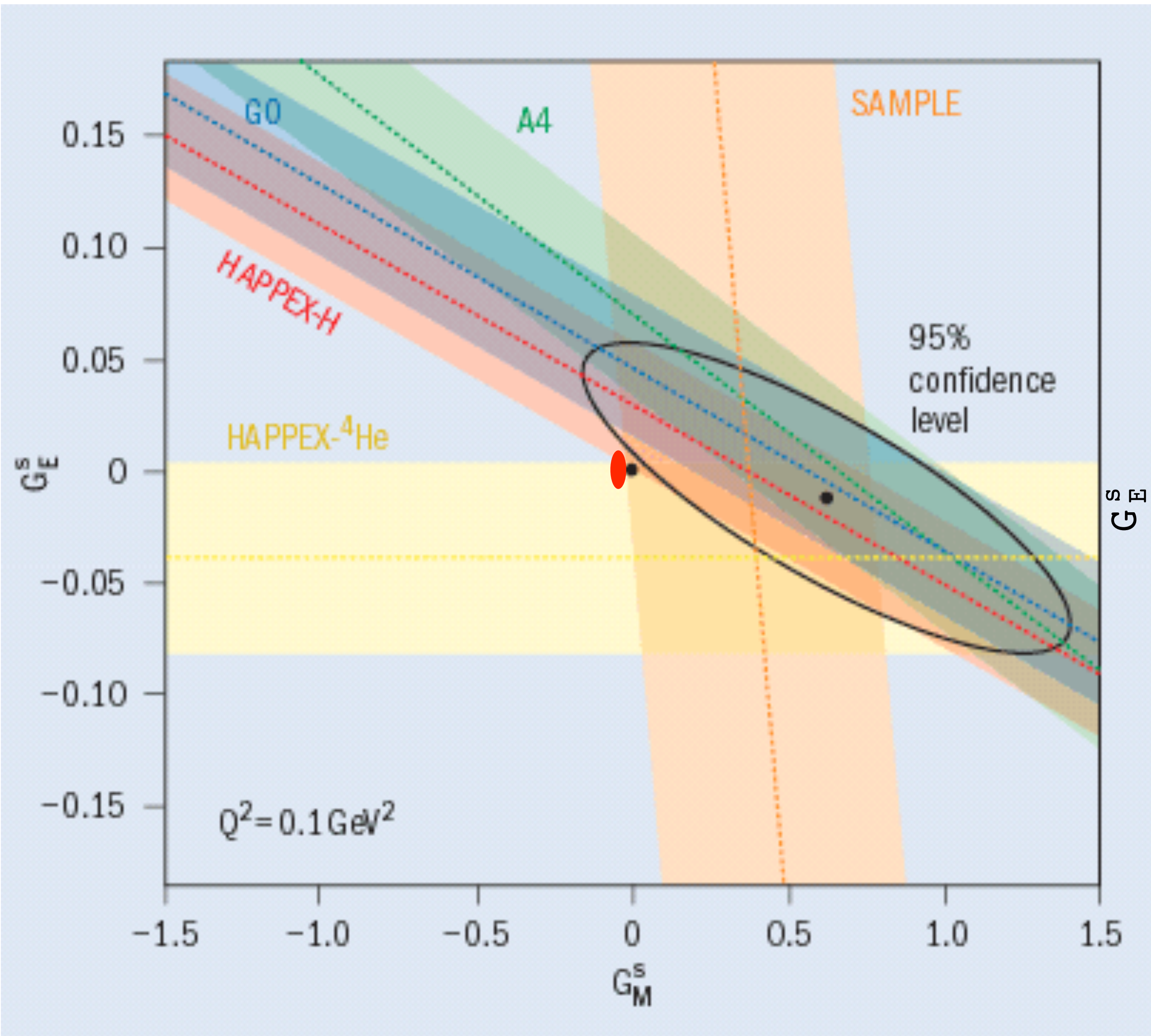
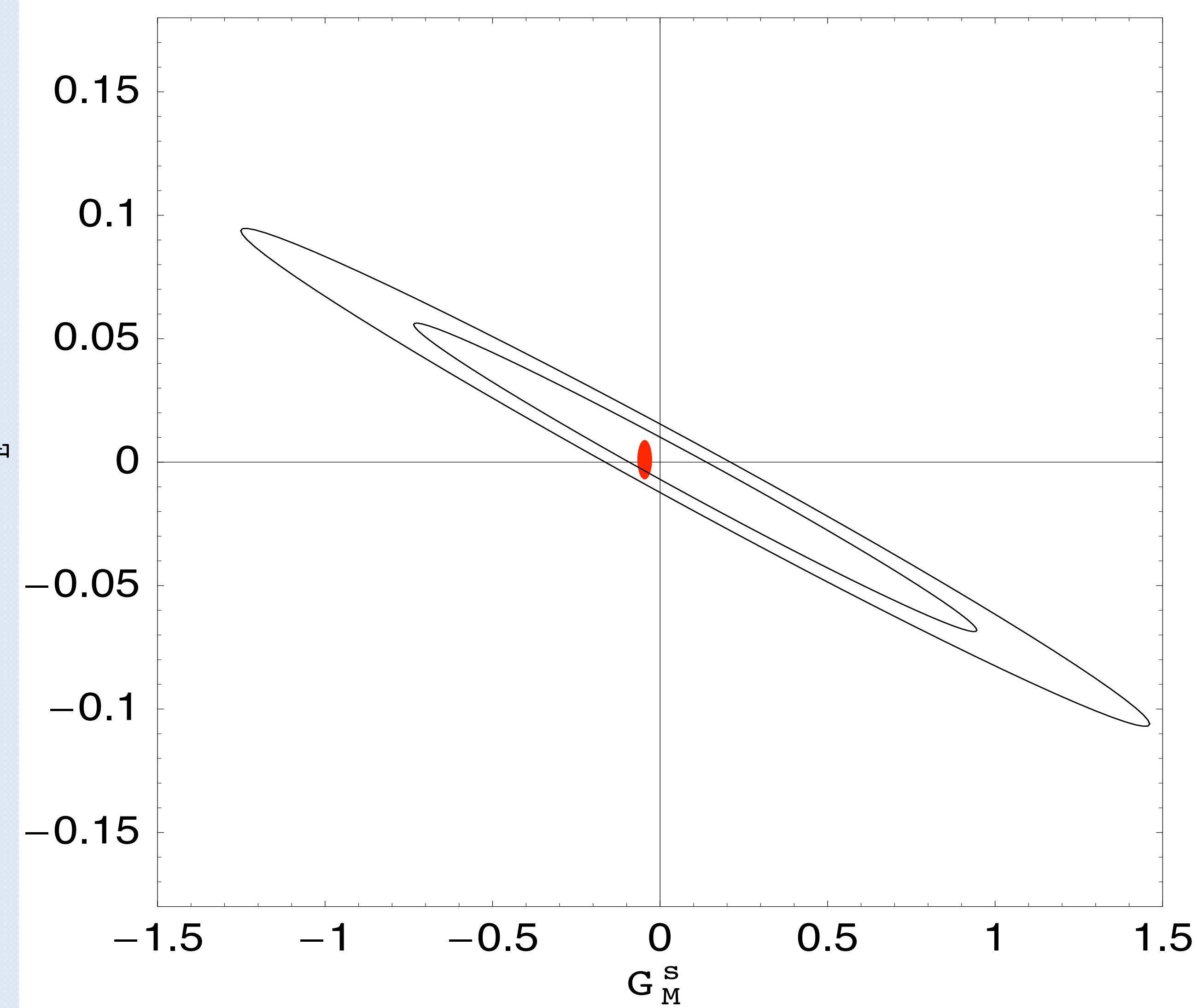
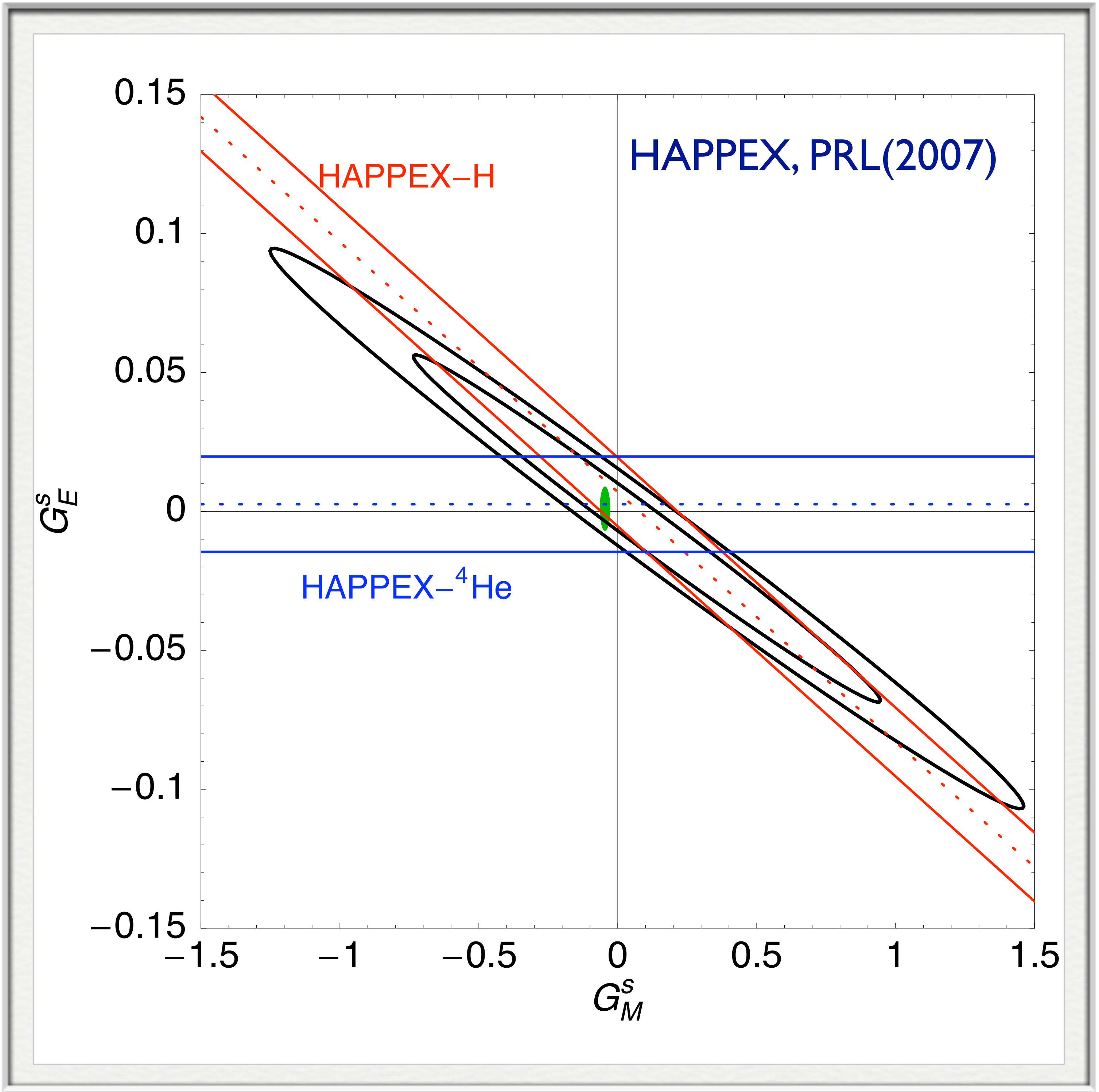


# New HAPPEX Measurement

- Excellent agreement with global analysis

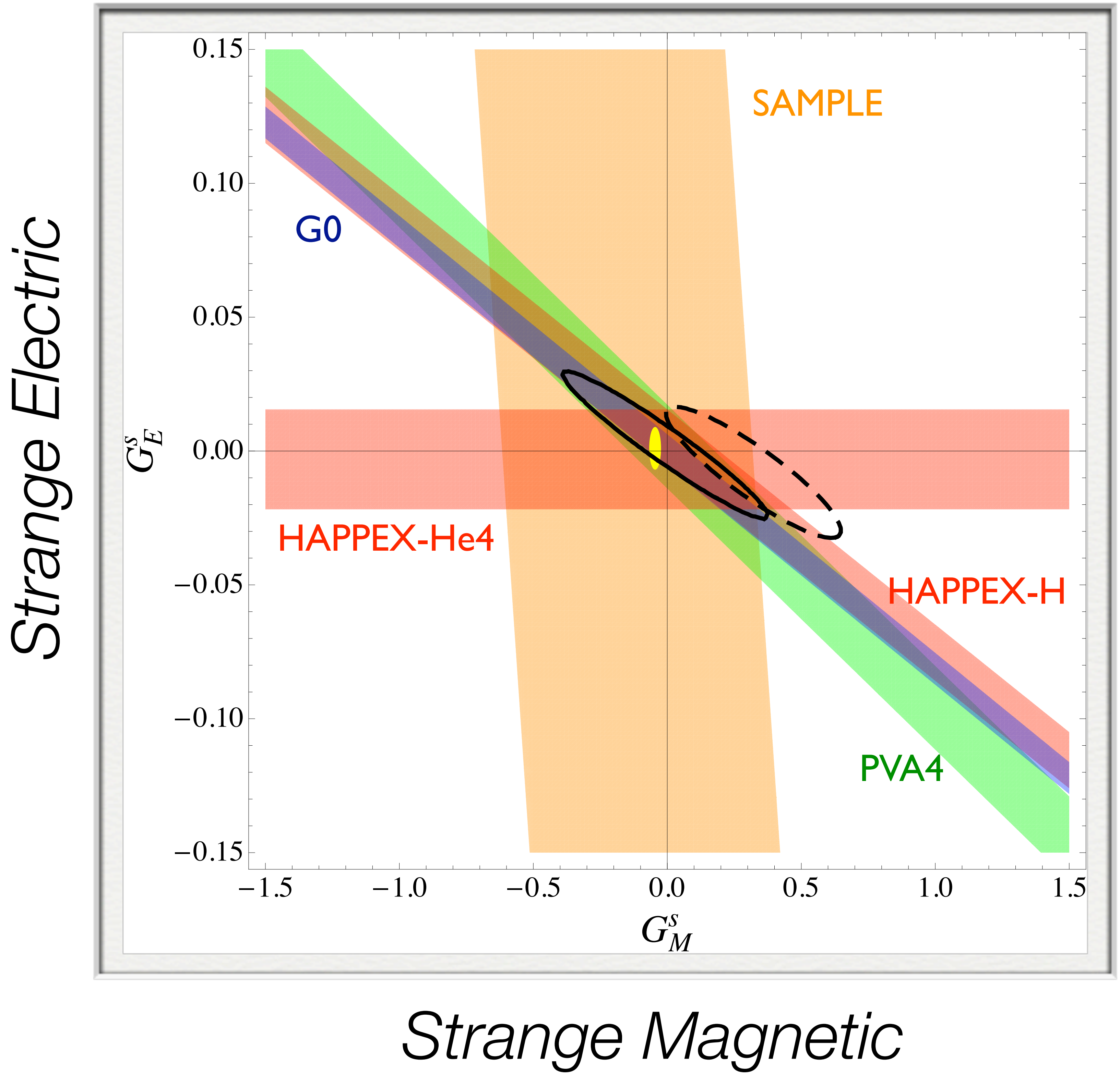
Strange Electric



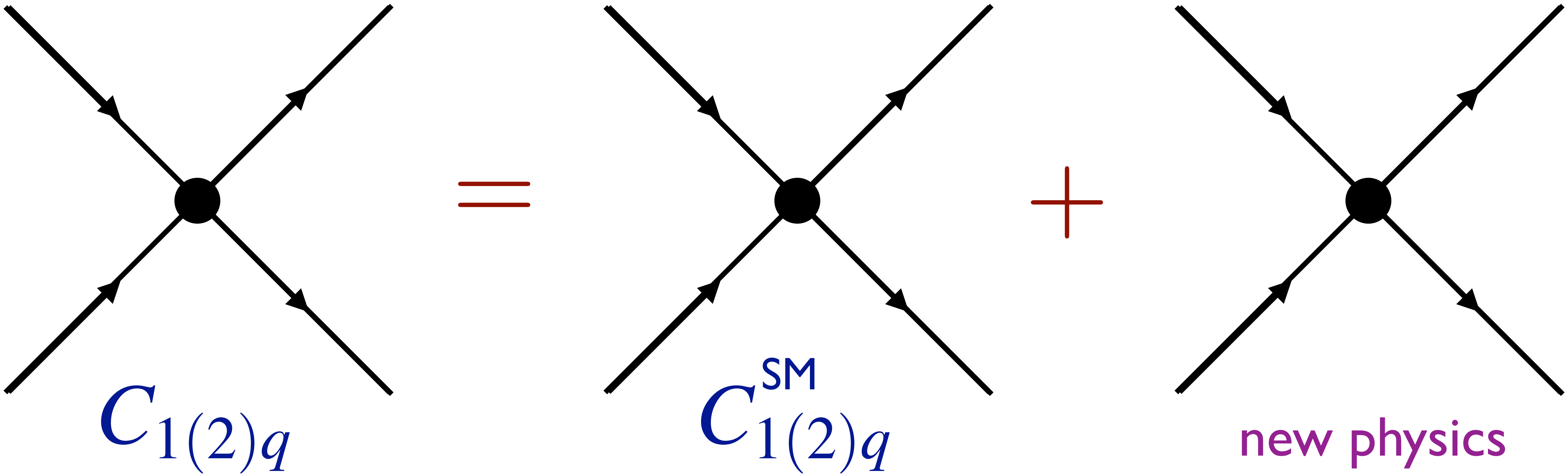

Strange Magnetic

# 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



# Searching for new physics



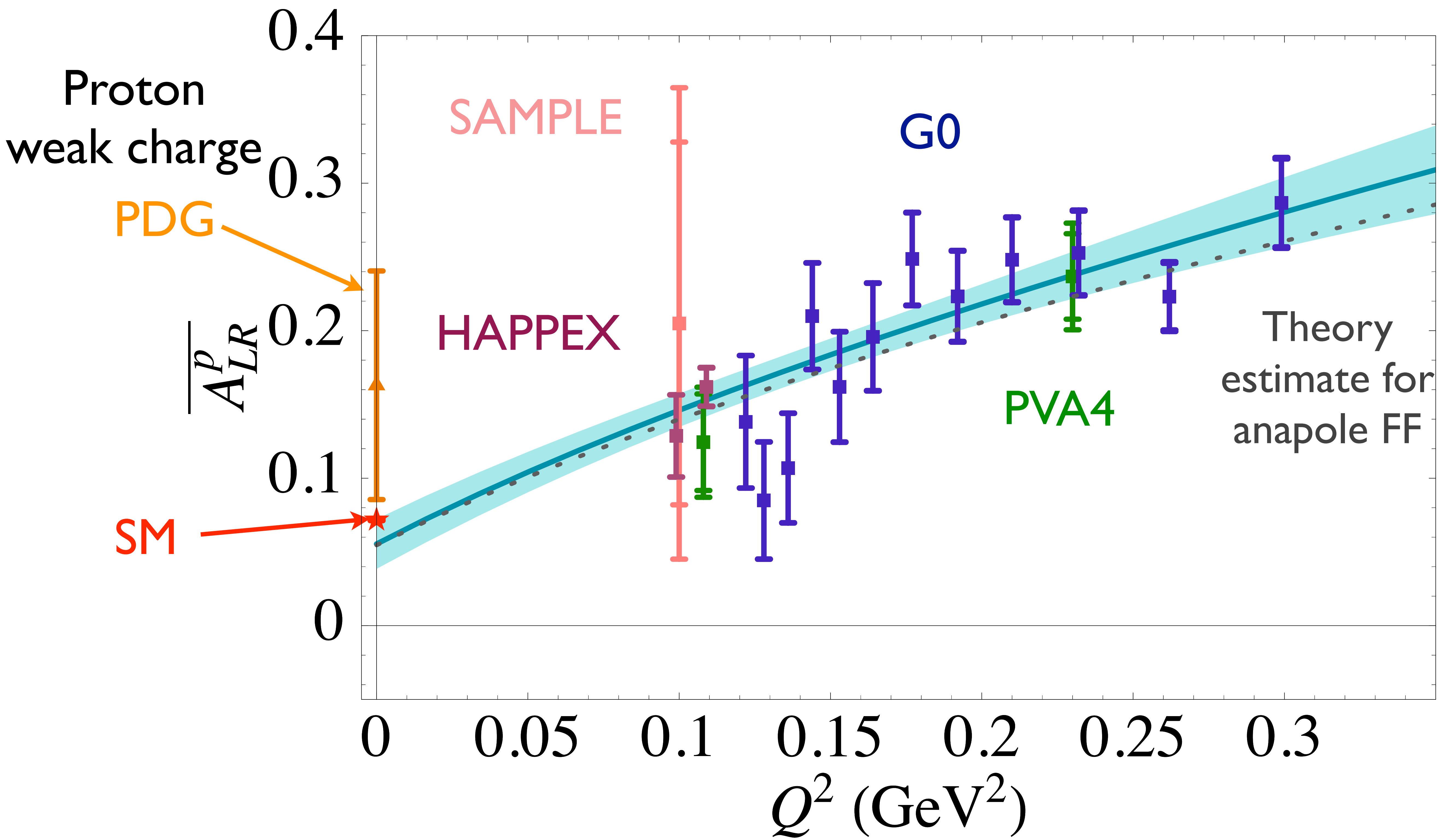

Constrained by low-energy data!

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

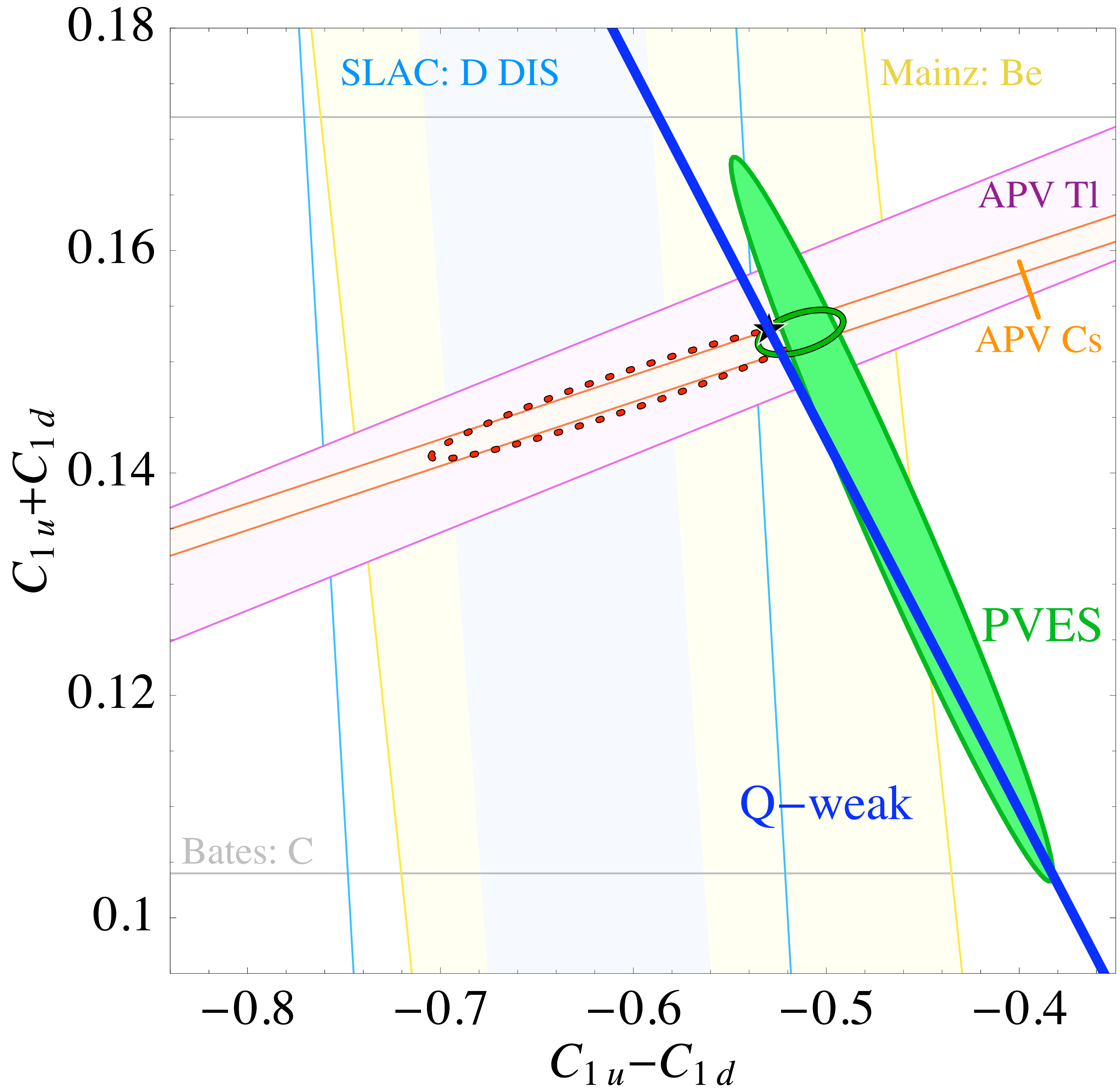
$$C_{1d} \sim Q_e^W Q_d^W$$

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

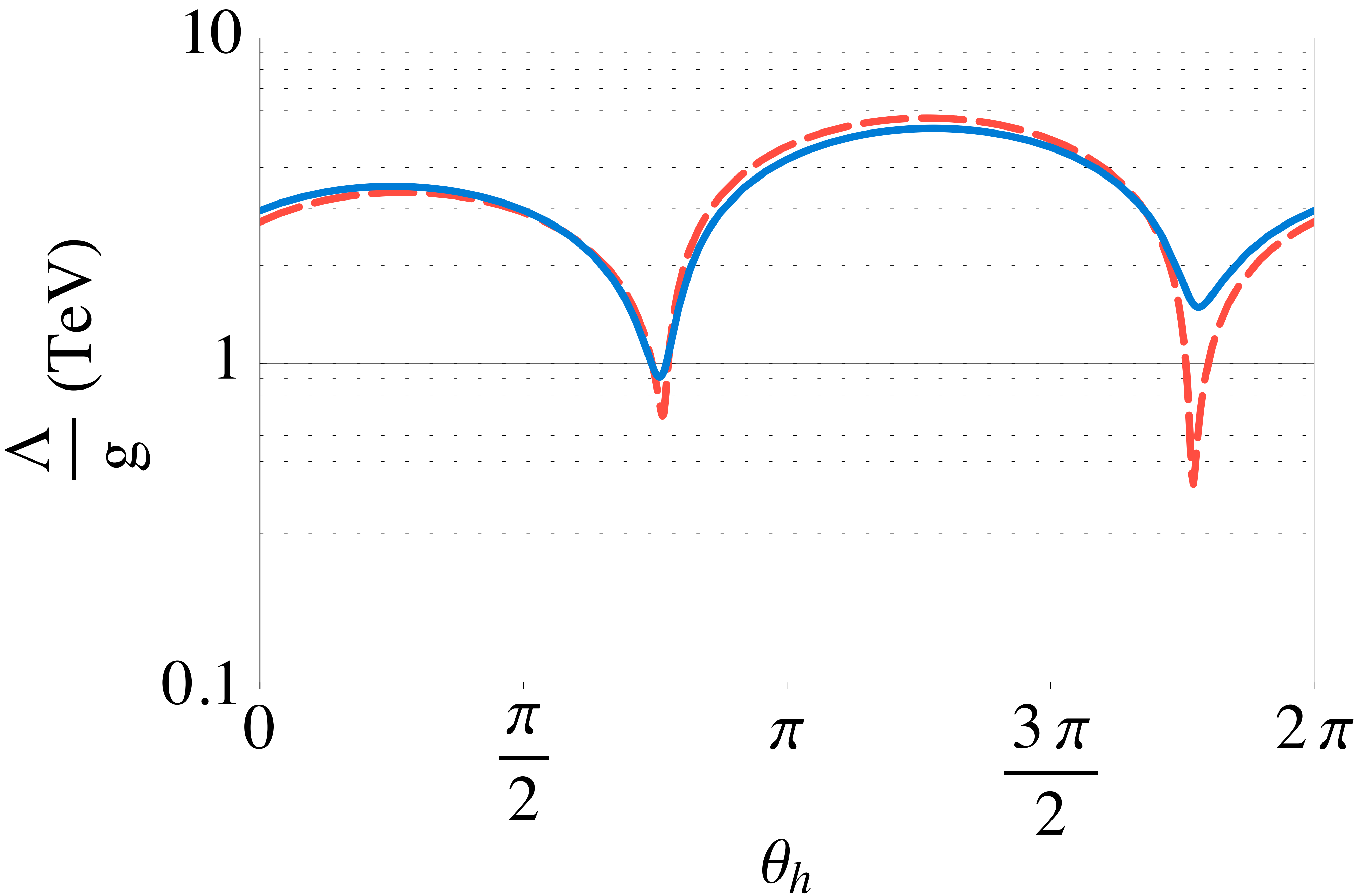
# Proton weak charge extrapolation



# Current knowledge and future: Q-weak



# Q-weak: Assuming SM

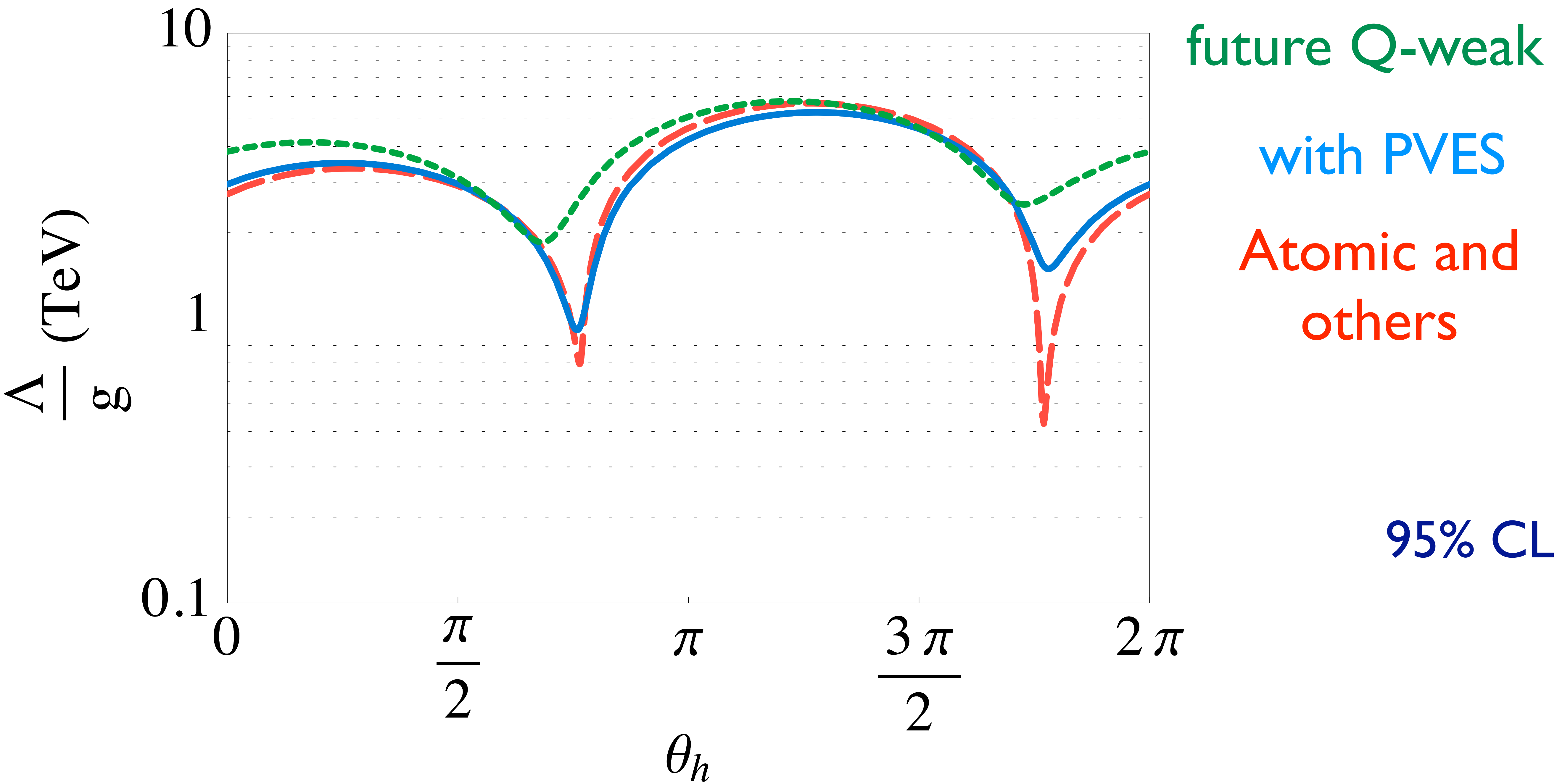



with PVES

Atomic and others

95% CL

# Q-weak: Assuming SM




Q-weak constrains new physics to beyond 2 TeV

# Strange condensate 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)

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

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Improved Effective Field Theory estimate

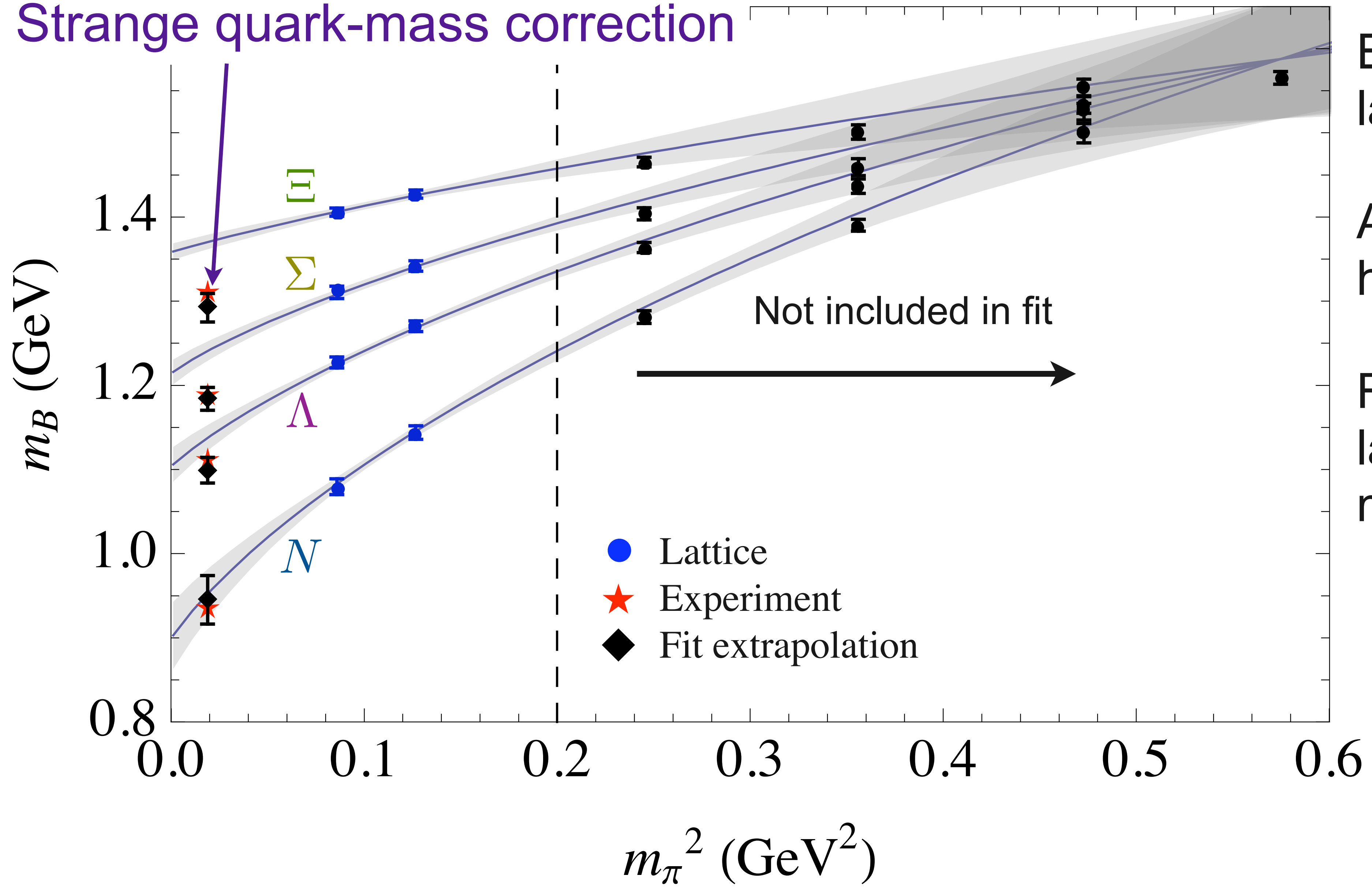
$$m_s \frac{\partial M_N}{\partial m_s} = 113 \pm 108\,\text{MeV}$$

Borasoy & Meissner (1997)

# Fit to 8 LHPC points

$m_s^{latt} \sim 1.3 m_s^{phys}$

Strange quark-mass correction



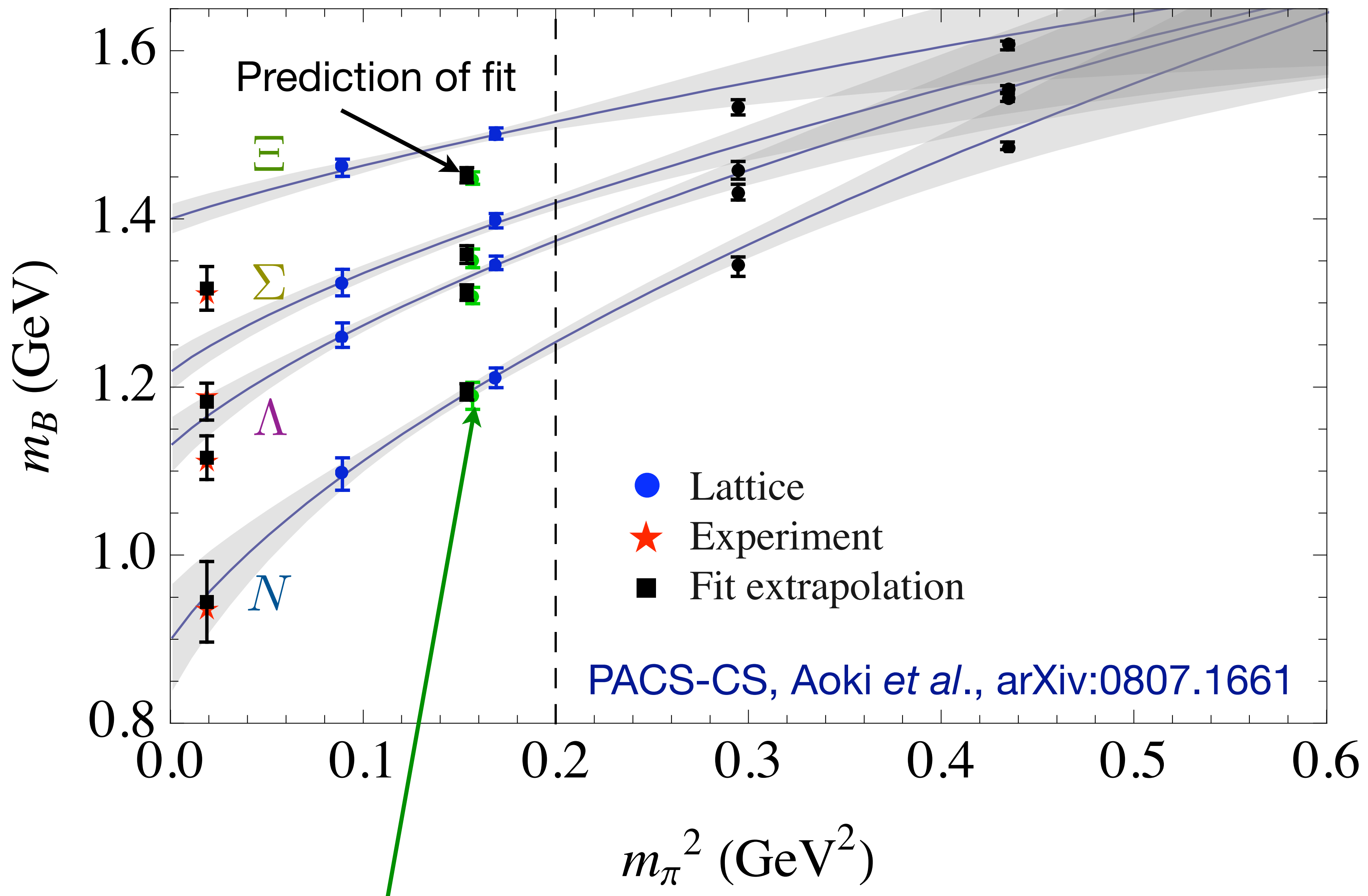

Excellent description of lattice results

Accurate prediction of heavier simulation data

Reliable correction for lattice simulation quark mass

# Fit to 8 PACS-CS points

PACS-CS: 2+1-flavour simulation; different action discretization to LHPC




Correction in strange quark mass demonstrated to be reliable against numerical simulation

As for LHPC, excellent agreement with observed spectrum

PACS-CS have an additional run with a different strange quark mass

# Quantifying Sources of Uncertainty

## Nucleon Mass (GeV)

**Discretisation**

| | |
|---|---|
| LHPC | $0.945 \pm 0.029$ |
| PACS-CS | $0.954 \pm 0.042$ |

Extrapolated baryon masses and fit parameters (LECs) in agreement
**— good news for us and lattice practitioners**

**Regulator**

| | |
|---|---|
| Dipole | $0.9410$ |
| Sharp | $0.9452$ |

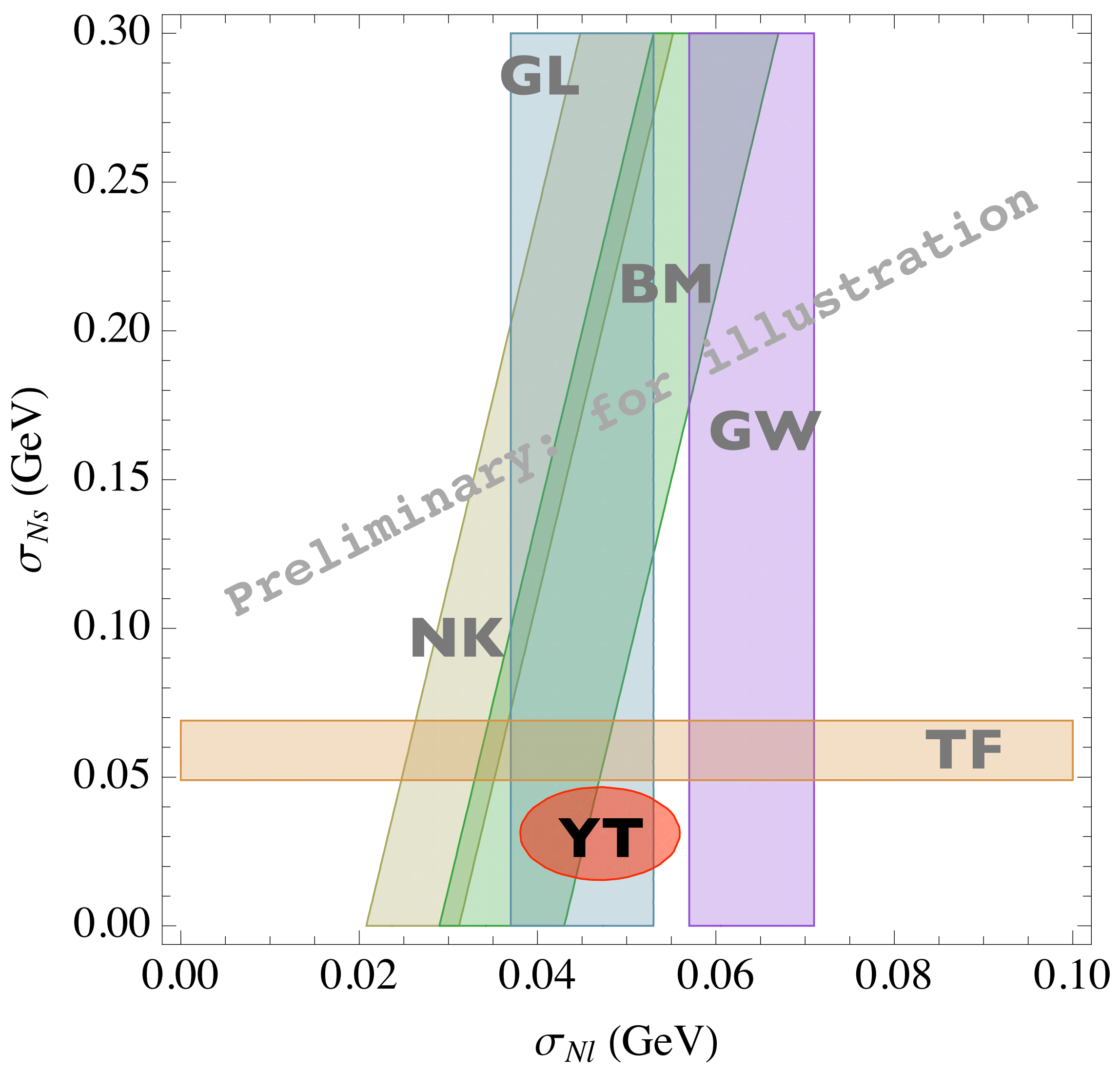
Small dependence on choice of regulator
— similarly for other functional forms

| Source | MeV |
|---|---|
| **Statistical** | **23.6** |
| **Discretisation** | **4.2** |
| **Model** | **3.1** |
| Regulator | 2.1 |
| $f_\pi$ (5%) | 0.7 |
| $F$ (15%) | 1.3 |
| $D$ (15%) | 1.3 |
| $\mathcal{C}$ (15%) | 0.9 |
| $\Delta_{10-8}$ (15%) | 0.4 |

# Baryon Sigma Terms

$$\bar{\sigma}_{Bq} = \frac{m_q}{M_B}\frac{\partial M_B}{\partial m_q}$$

| | $N$ | $\Lambda$ | $\Sigma$ | $\Xi$ |
|---|---|---|---|---|
| $\bar{\sigma}_{Bl}$ | **0.050(9)(1)(3)** | **0.028(4)(1)(2)** | **0.0212(27)(1)(17)** | **0.0100(10)(0)(4)** |
| $\bar{\sigma}_{Bs}$ | **0.033(16)(4)(2)** | **0.144(15)(10)(2)** | **0.187(15)(3)(4)** | **0.244(15)(12)(2)** |




πN Sigma Term (Expt):
GL: Gasser & Leutwyler (1991)
GW: Pavan et al. (2001)

Octet Masses & Breaking:
Gasser (1981)
NK: Nelson & Kaplan (1987)
BM: Borasoy & Meissner (1997)

3-flavour Lattice QCD:
YT: Young & Thomas (2009)
TF: Toussaint & Freeman (2009)

We determine precisely *both* the light and strange quark sigma terms

# *Spin-independent neutralino cross sections*

- Ellis, Olive & Savage, PRD(2008)
  - Constrained Minimal Supersymmetric Standard Model (CMSSM)
  - Neutralino as dark matter candidate
  - Scalar contact interaction

$$\mathcal{L}_{SI} = \sum_i \alpha_{3i} \bar{\chi}\chi \bar{q}_i q_i$$

$$\sigma^p_{SI} \propto |f_p|^2$$

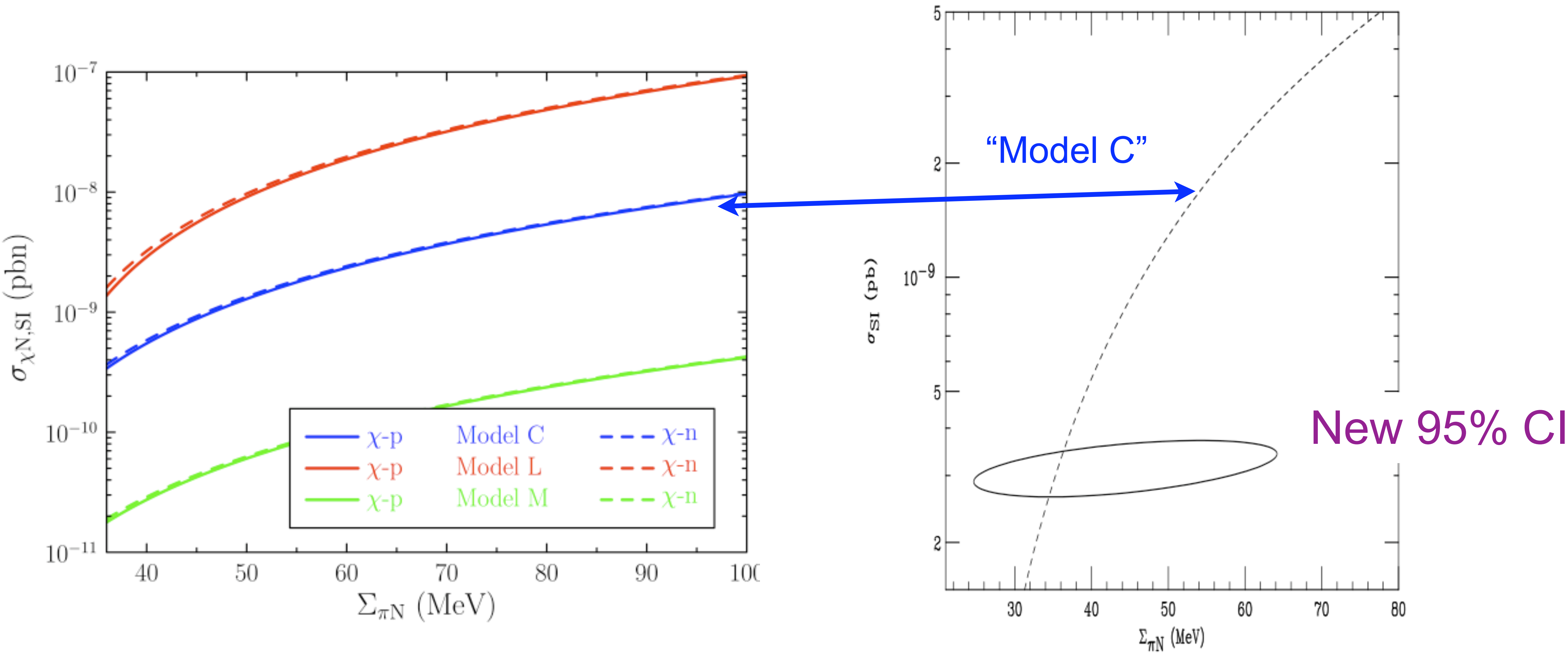
$$\frac{f_p}{M_p} = \sum_{q=u,d,s} \bar{\sigma}_{pq} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f^p_{TG} \sum_{q=c,b,t} \frac{\alpha_{3q}}{m_q}$$

$$f^p_{TG} = 1 - \sum_{q=u,d,s} \bar{\sigma}_{pq}$$

Trace anomaly:
Shifman, Vainstein & Zakharov, PLB(1978)

*Uncertainty dominated by knowledge of light-quark sigma terms*

# Updated cross sections for benchmark models




Ellis, Olive & Savage

Strong dependence on sigma term from poorly known strangeness

Giedt, Thomas & Young, PRL (2009)

**Tremendous advance in precision from new lattice QCD results**

**Nuclear physics & lattice QCD can help discriminate supersymmetry scenarios**

# Summary

- Strange quarks play a relatively small role in the nucleon structure
- “Spin-offs”: precision electroweak physics, dark matter scattering

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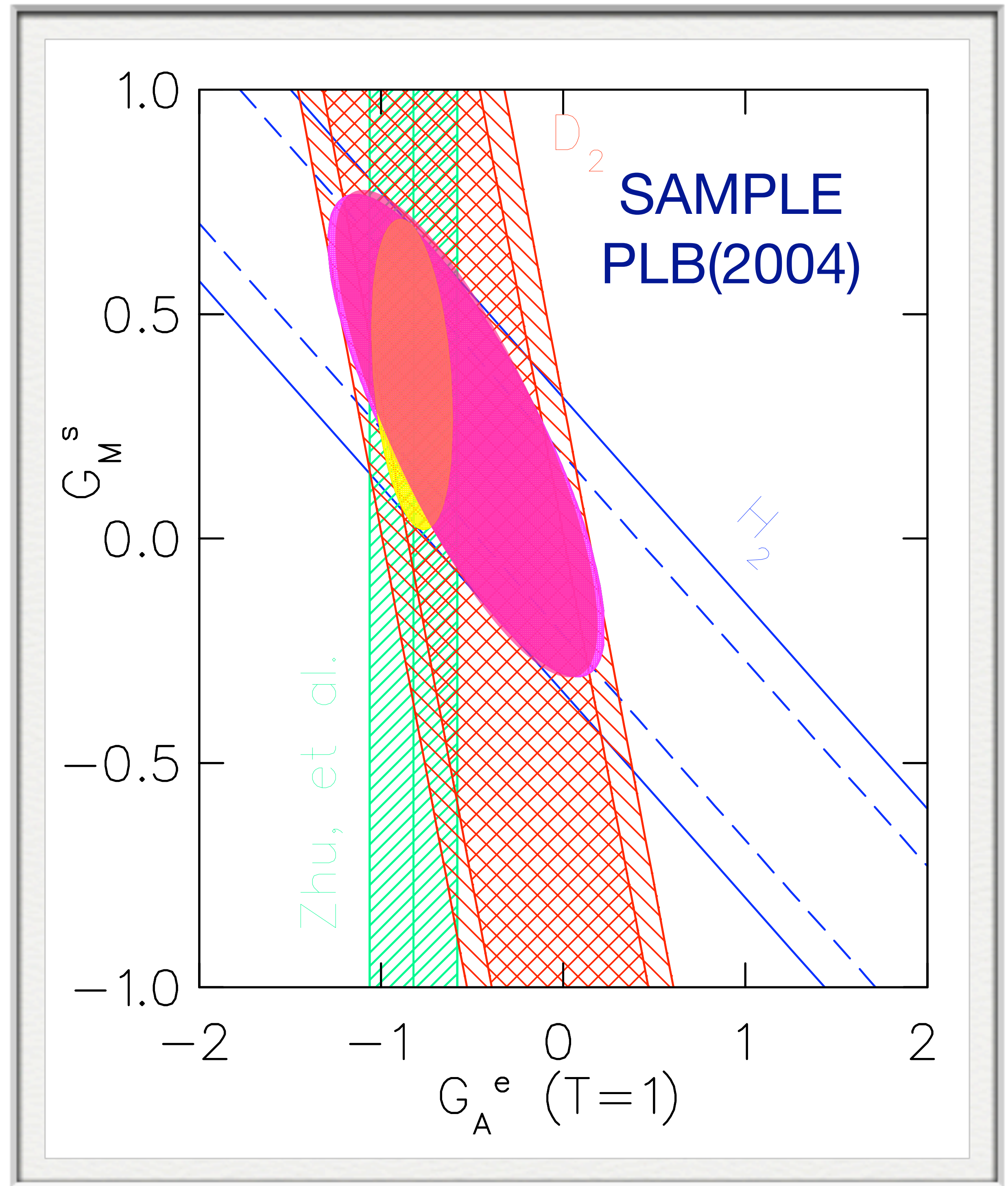
HAPPY BIRTHDAY TONY!

# Anapole Form Factor

- Backward angle measurements have increased sensitivity to axial form factor.
- Anapole corresponds to an electroweak correction to the proton structure
- Anapole form factor is not **measured** in any other process

*Strange Magnetic*




*Axial+Anapole*

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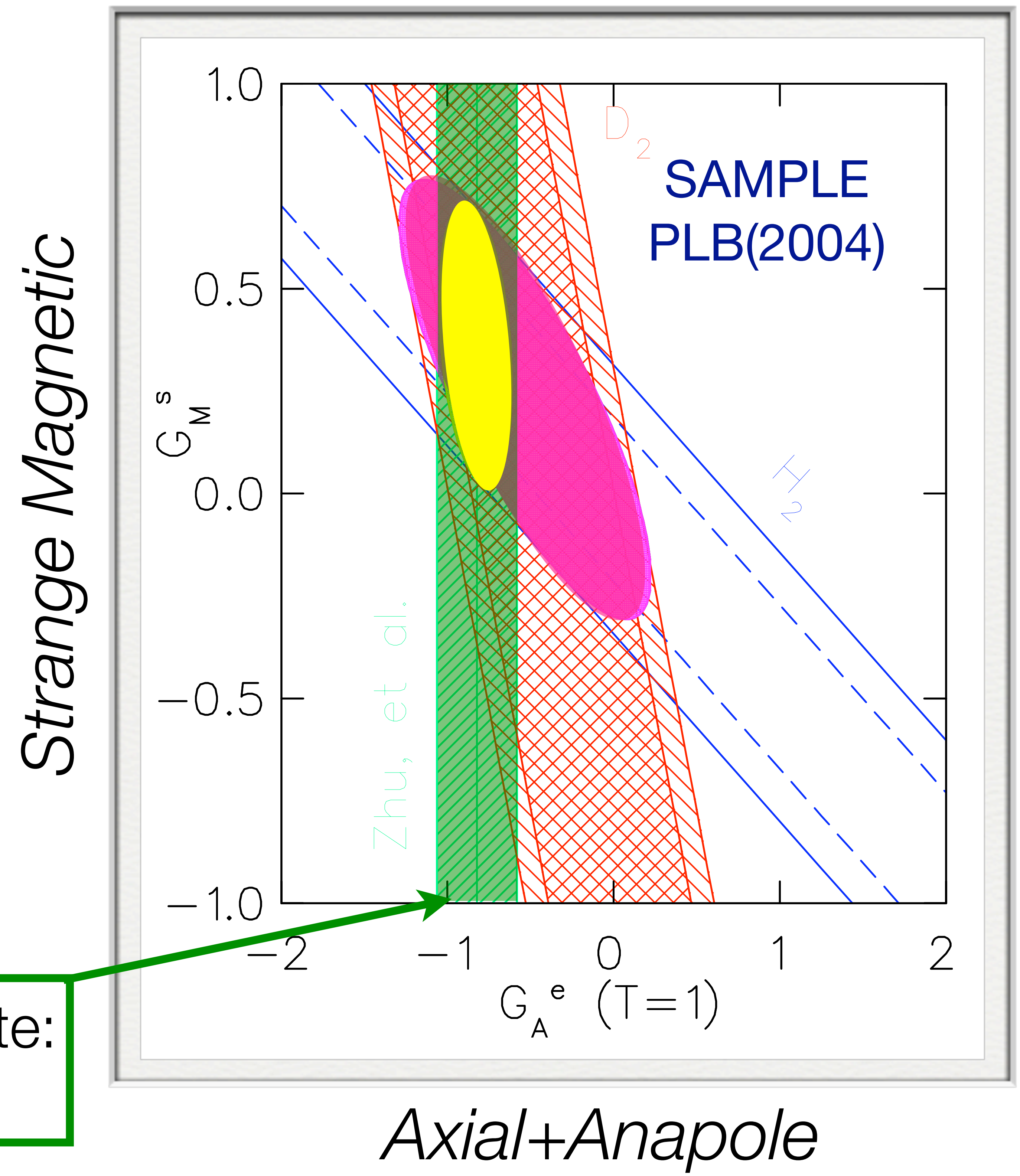
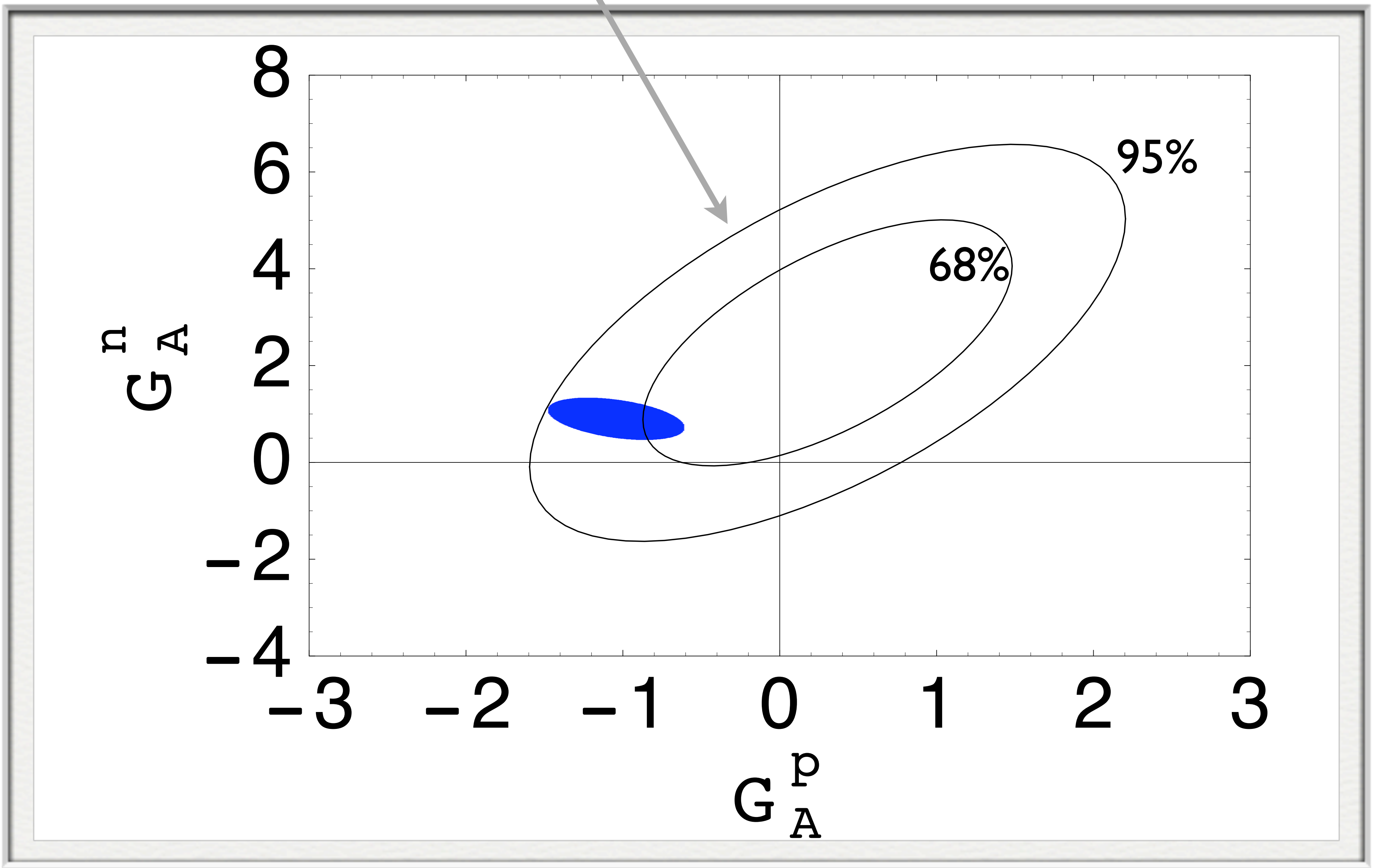
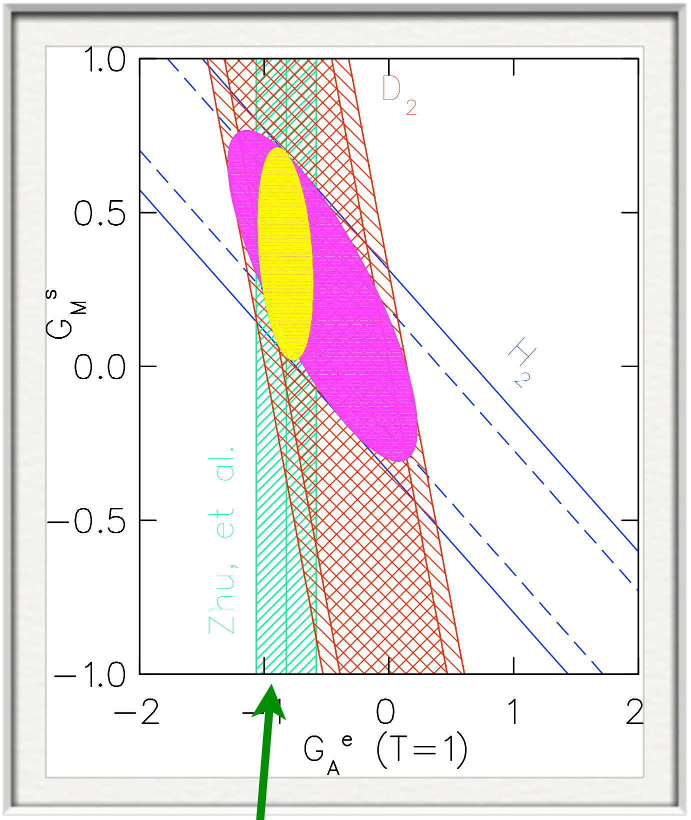


# The axial/anapole term

- Global constraint from data




Theory, Zhu *et al.*