Q-weak and searches of new physics in parity-violating *e–p* scattering

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Hadronic contributions to new physics searches (HC2NP)
25–30 September, 2016
Puerto de la Cruz, Tenerife, Spain

Acknowledgements

- R. Carlini (JLab), J. Roche (Ohio) & the Q-weak Collaboration
- N. Hall (Adelaide→Manitoba→?), A. Thomas (Adelaide), W. Melnitchouk (JLab), P. Blunden (Manitoba)

Acknowledgements

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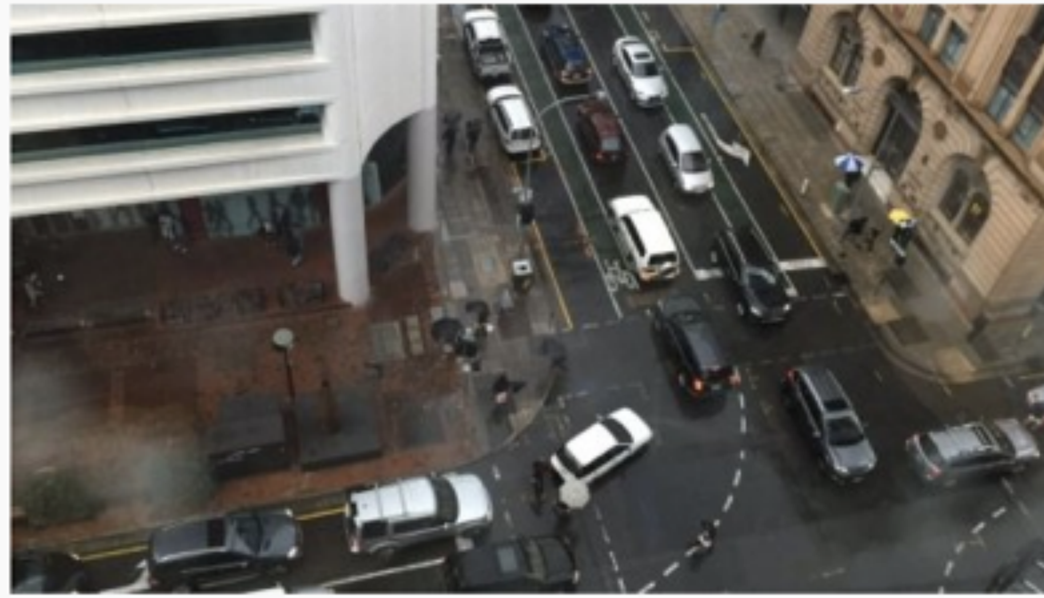
- N. Hall (Adelaide→Manitoba→),
  P. Blunden (Manitoba)

NEWS



LIVE **South Australia loses power as wild weather lashes state**

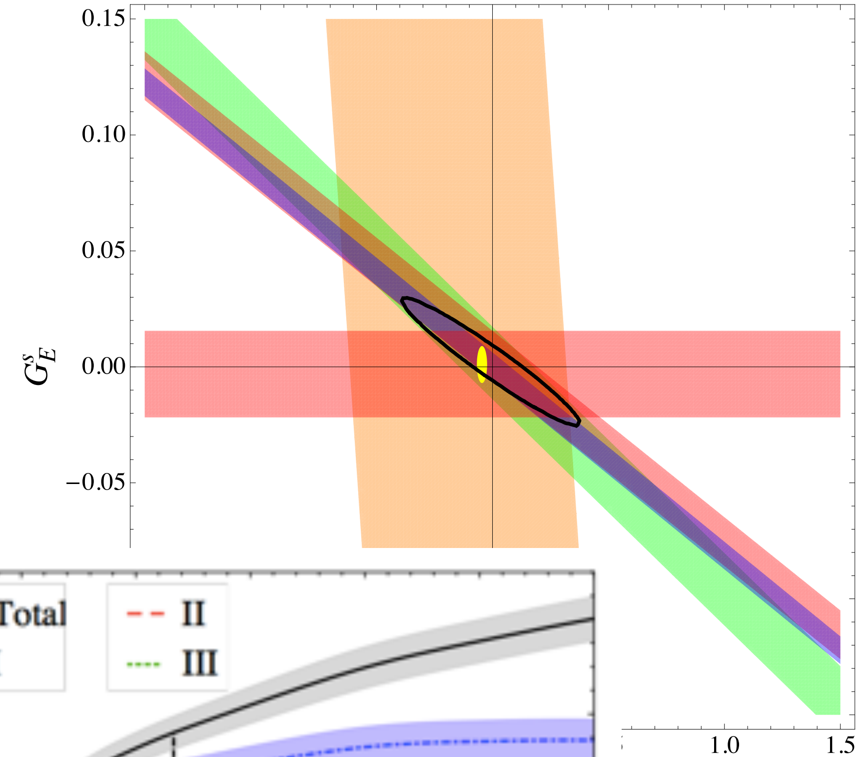
All of South Australia is without power as a massive storm front hits the state, SA Power Networks says. Follow our blog for live updates.

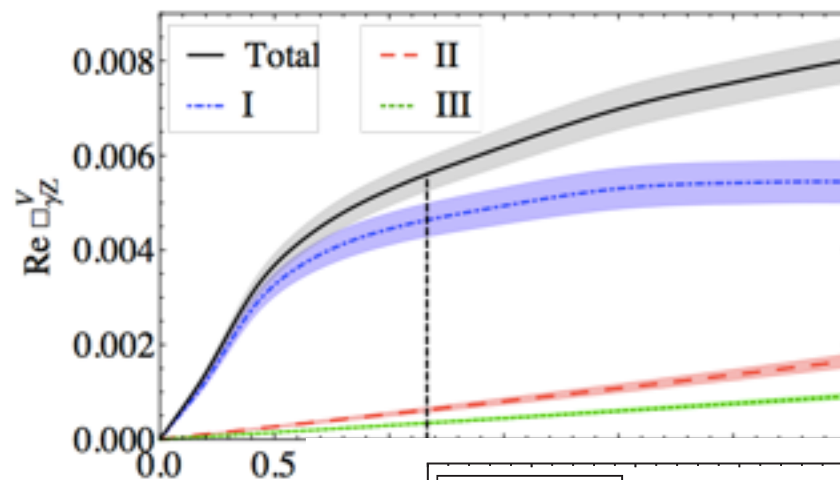
State in darkness as power network fails

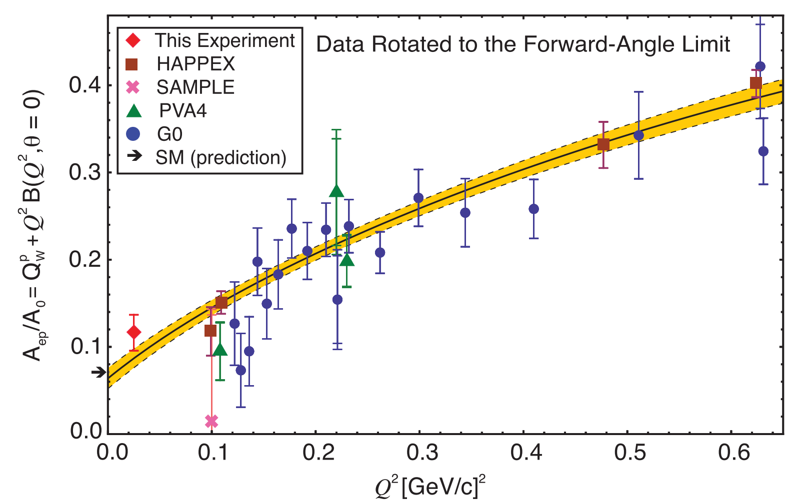
All of South Australia is without power and could be so until the early hours of tomorrow morning after a network failure.

Outline

- Hadron Contributions
  - Strangeness FFs
- 2 New Physics Searches
  - Proton weak charge
  - Radiative corrections
- Current status of the Q-weak experiment







Hadron contributions:
Strange-quark form factors

Electromagnetic currents of the nucleon

- Electromagnetic form factors characterise the charge a magnetisation distribution in the nucleon

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

- Measure total response from all quarks

Strangeness is just in glue!

Proton

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

- Charge symmetry: proton and neutron the “same”: *u*↔d

Neutron

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

2 Equations — 3 Unkowns!

Weak neutral form factor

$$G^{p,Z}_{E,M} = 2\left(1 - \frac{8}{3}\sin^2\theta_W\right) G^u_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^d_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^s_{E,M}$$

- Electroweak couplings differ from usual charges
  - Weak mixing angle: $\sin^2\theta_W$

Weak neutral form factor

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

- 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 Unknowns

Can isolate strangeness!

Weak neutral charge

- Q-weak

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

$Q^2 \to 0$: $G_E^u \to \mathbf{2}$, $G_E^d \to \mathbf{1}$, $G_E^s \to \mathbf{0}$

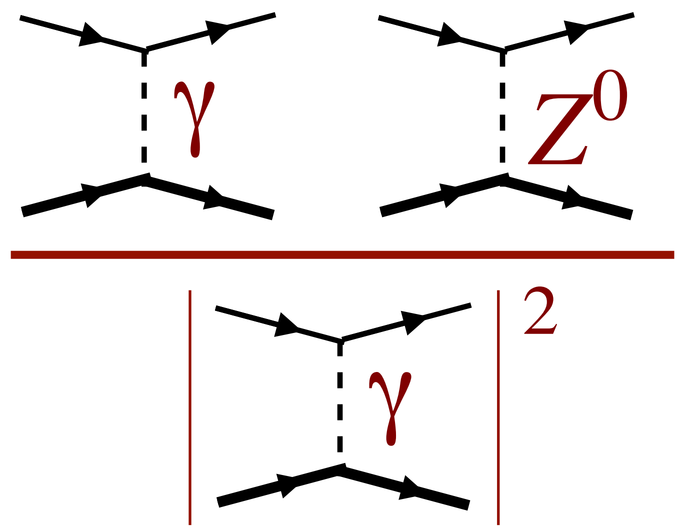
$$G_E^{p,Z}(Q^2 \to 0) = 1 - 4\sin^2\theta_W$$

[tree level]

Parity-violating electron scattering

- Asymmetry between right- and left-hand polarised electrons

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



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

- Measure of interference between γ and Z^0 exchange

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

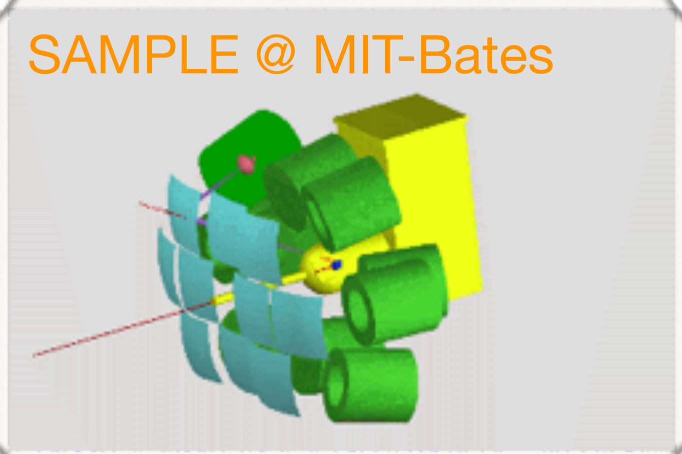
Assume charge symmetry:

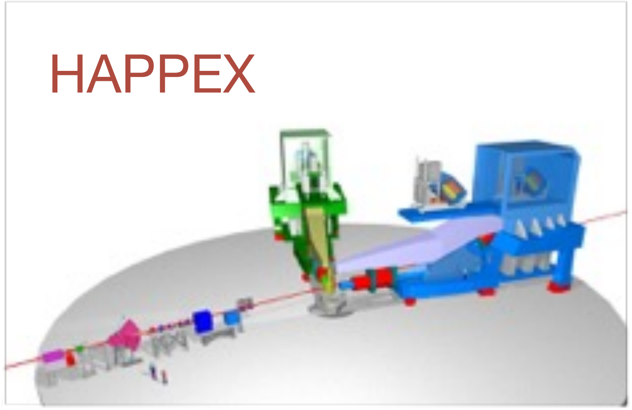
$$G_{E,M}^{pZ} = (1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

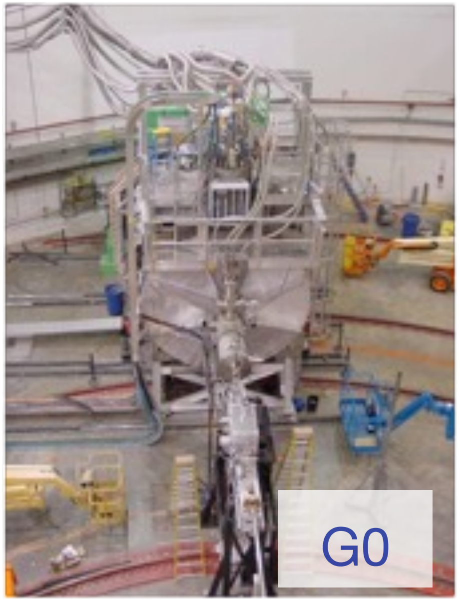
Proton weak charge (tree level)

Strangeness

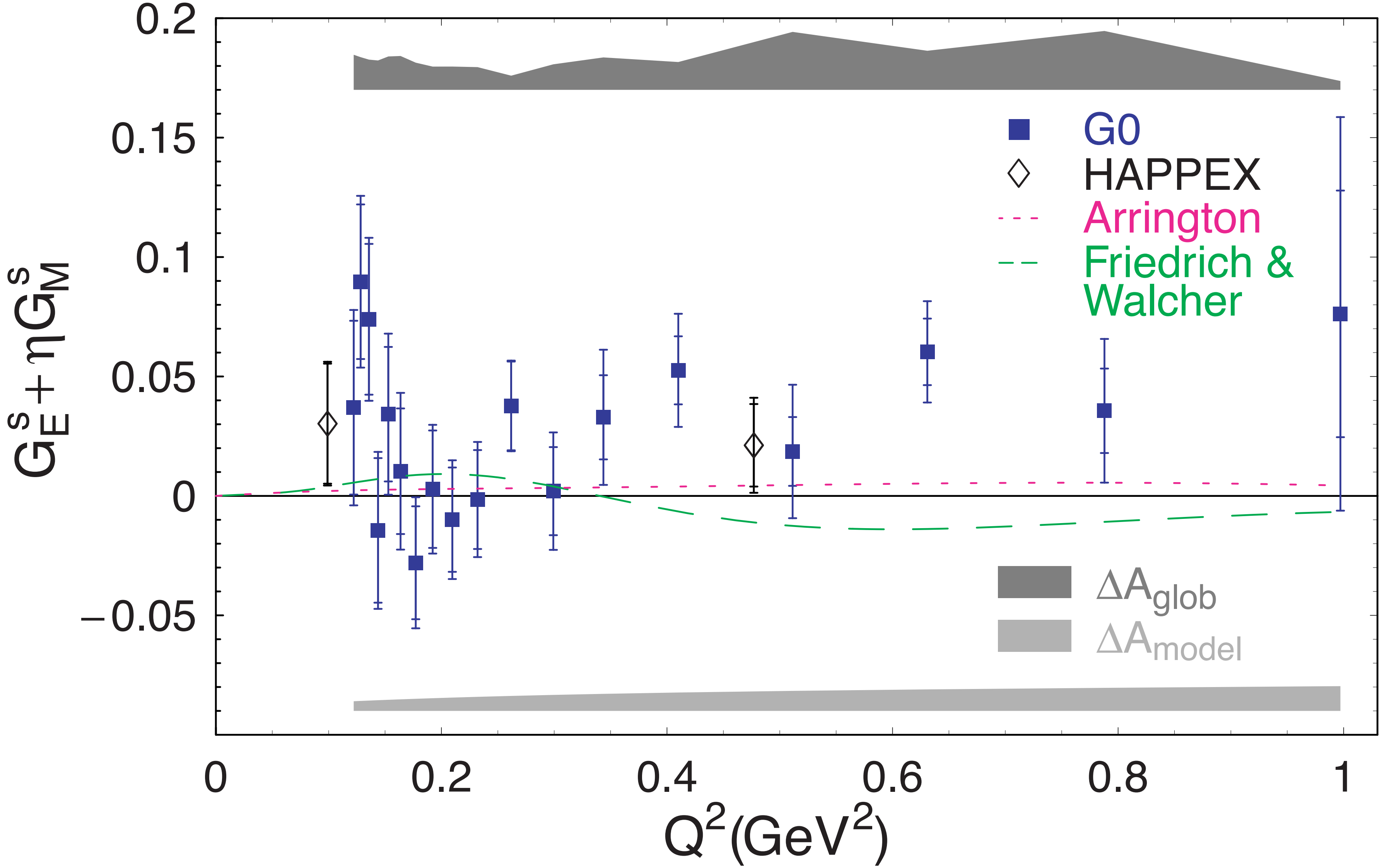
For extraction of strangeness, assume Standard Model!







Strangeness measurements



G0 Experiment

Broad Q2 coverage

Global analysis

RDY *et al.* PRL(2006)

- Explore sensitivity to Q2 cut
- Fit "Effective axial charge" (includes anapole)
  - Assume dipole form $$\tilde{G}_A^N = \tilde{g}_A^N (1 + Q^2/\Lambda^2)^{-2}$$
- Parameterise strangeness
  - Taylor expansion:

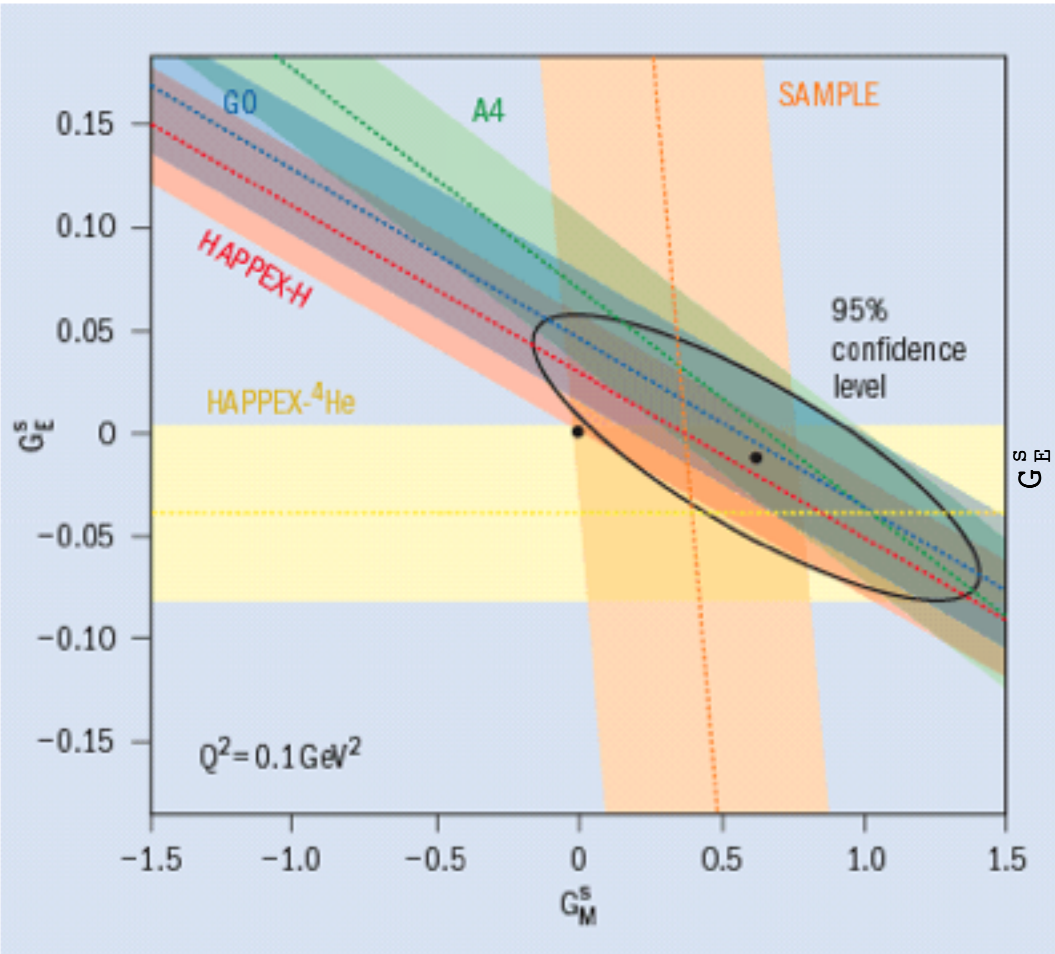
$$G_E^s = \rho^s Q^2 + \rho_2^s Q^4 + \ldots$$
$$G_M^s = \mu^s + \mu_2^s Q^2 + \ldots$$

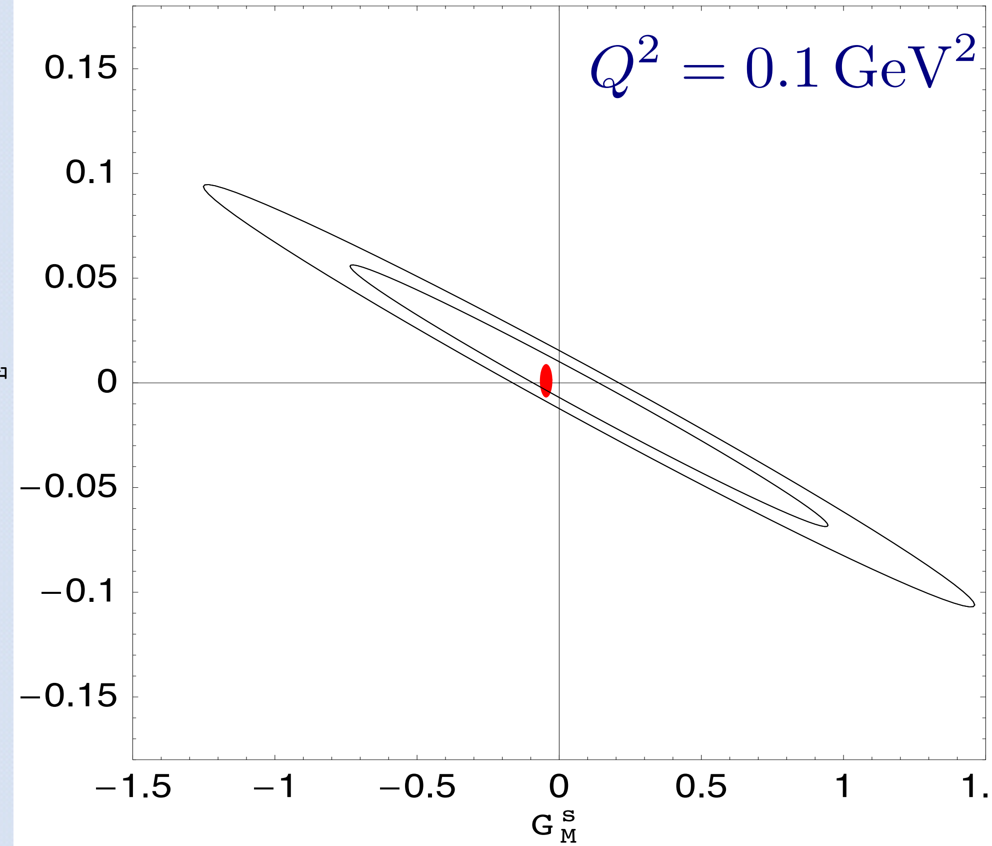
"leading-order polynomial" ($\rho^s Q^2$, μ^s)

"second-order polynomial" ($\rho^s Q^2 + \rho_2^s Q^4$, $\mu^s + \mu_2^s Q^2$)

  - Dipole:

$$G_E^s = \rho^s Q^2 \left(\frac{1}{1 + Q^2/\Lambda^2} \right)^2$$
$$G_M^s = \mu^s \left(\frac{1}{1 + Q^2/\Lambda^2} \right)^2$$



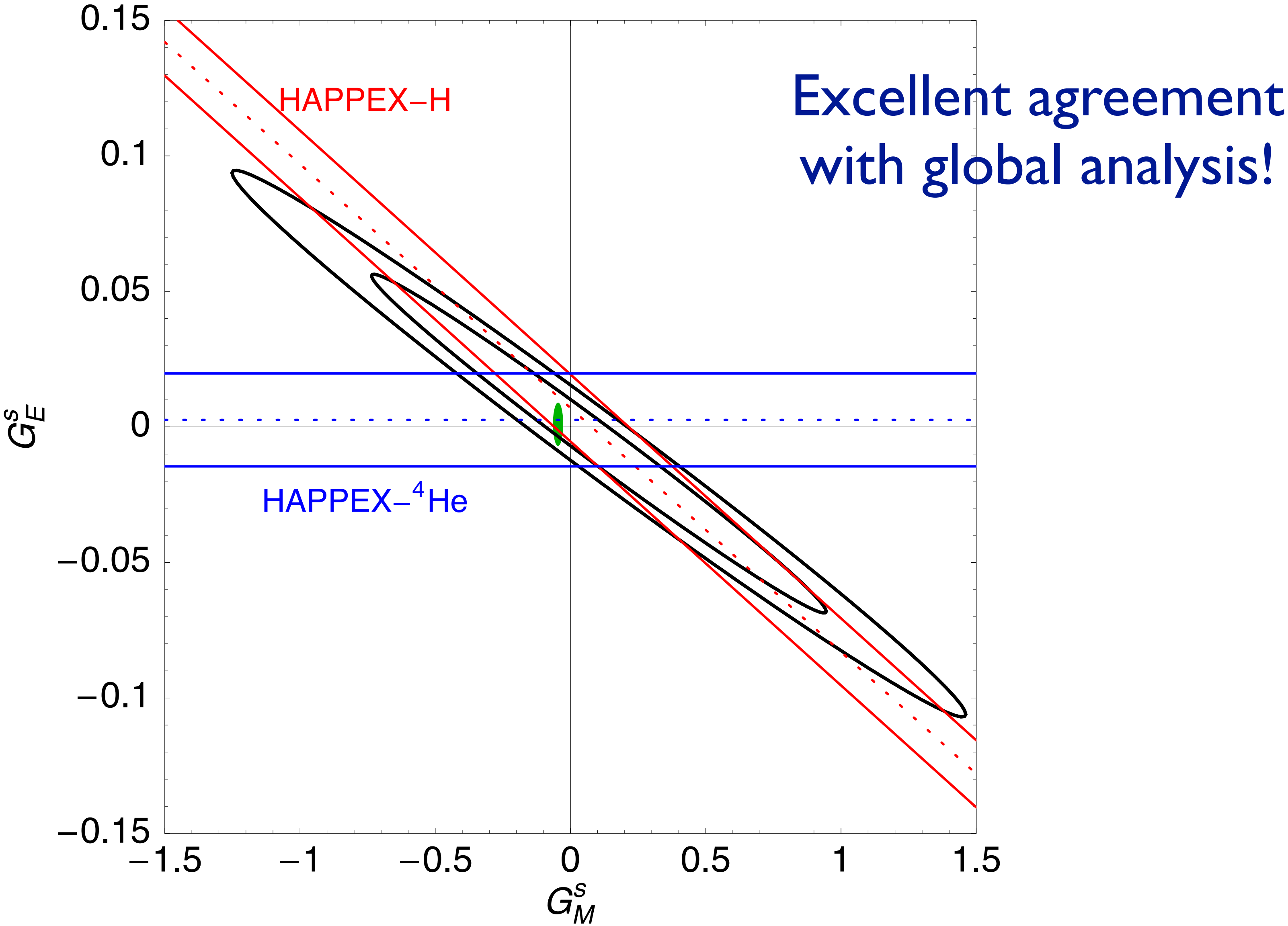


RDY et al. PRL(2006)

GMs-GEs

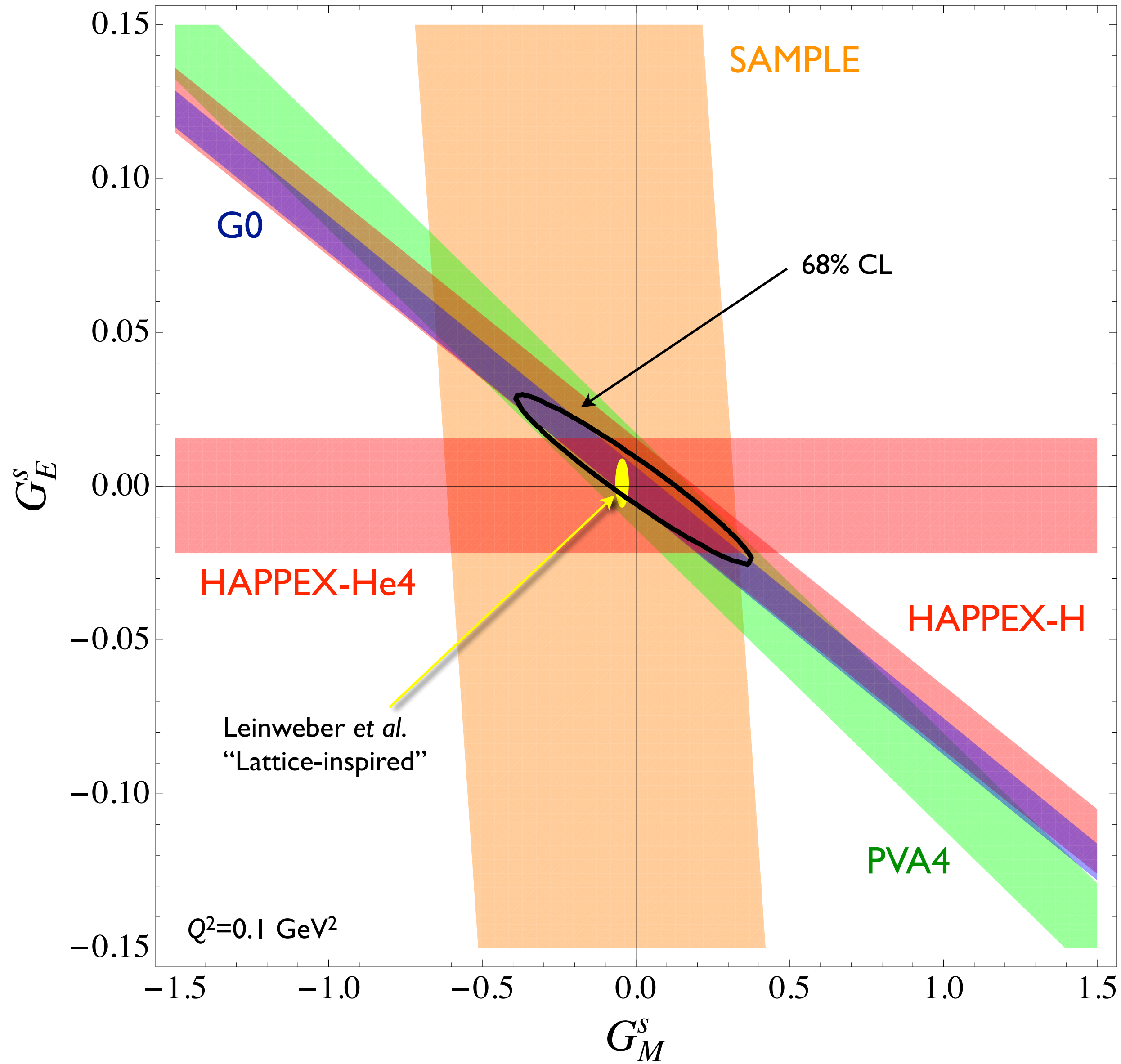
Leading-order Taylor

$$Q^2_{\mathrm{max}} = 0.3\,\mathrm{GeV}^2$$



HAPPEX (2006)

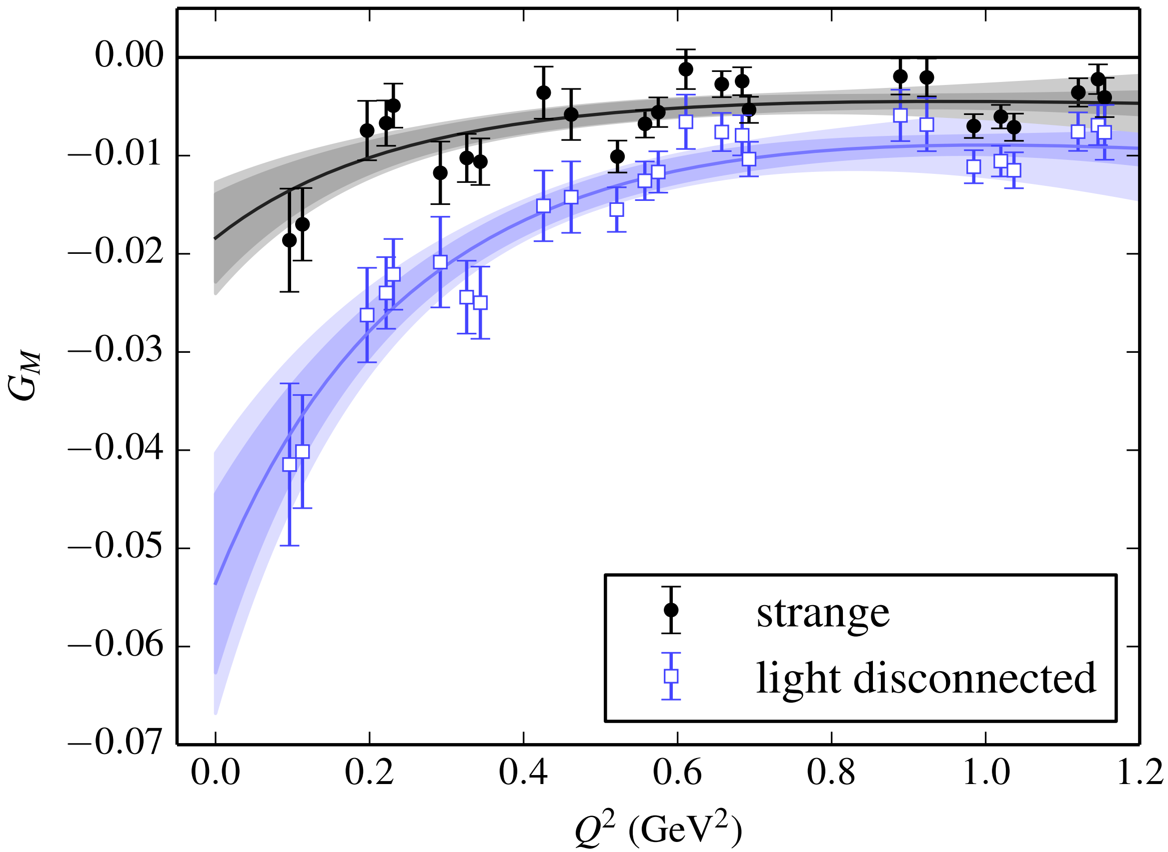
New measurement **after** global analysis



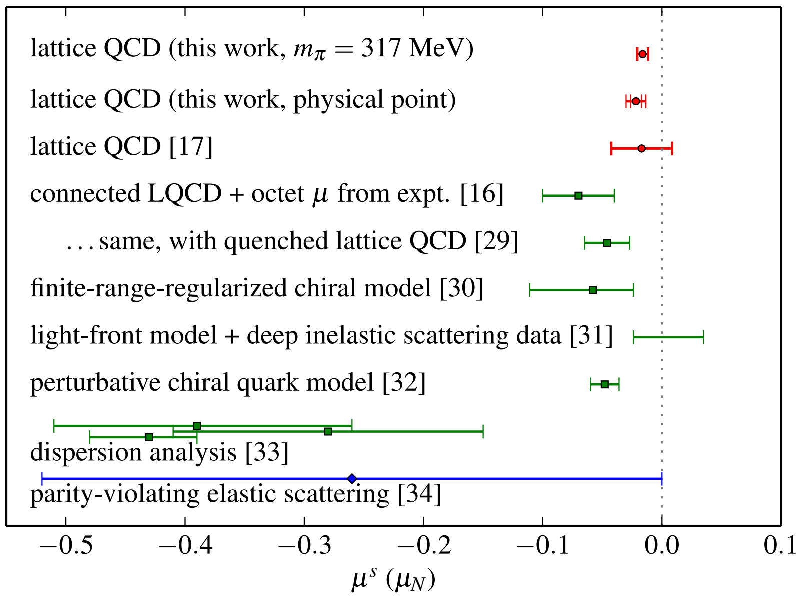
RDY et al. PRL(2007)

Combined global analysis

For latest global analysis, see e.g. González-Jiménez *et al*. PRD(2014)



Green, Meinel *et al.* PRD(2015)



Lattice QCD advances

Fantastic increase in precision in direct calculation!

2 New Physics Searches:
Weak charge of the proton

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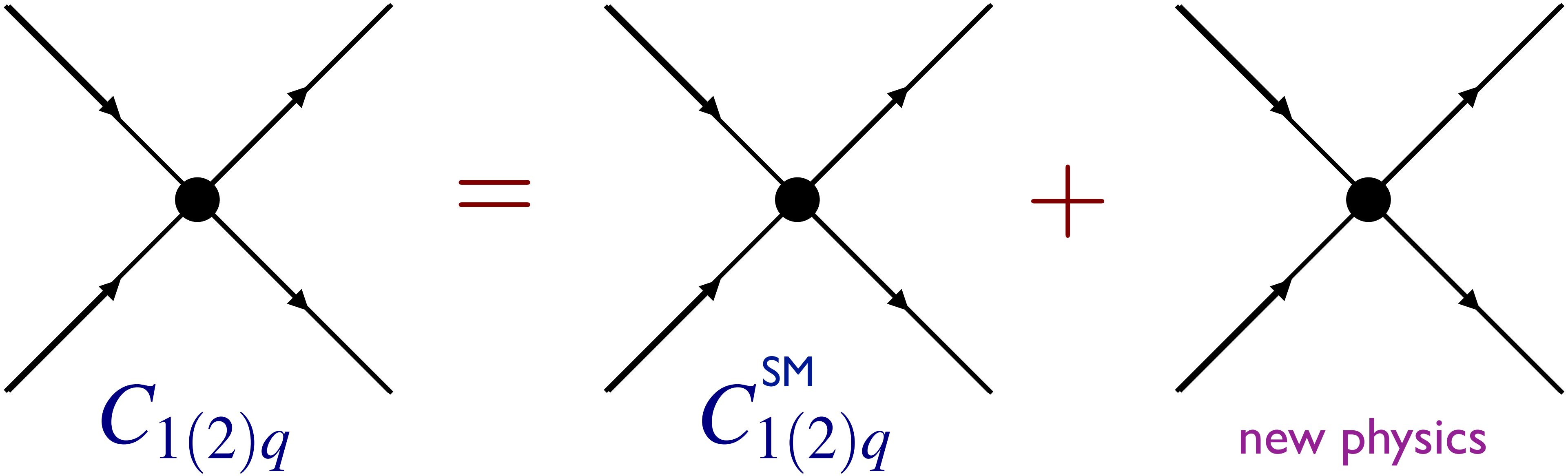
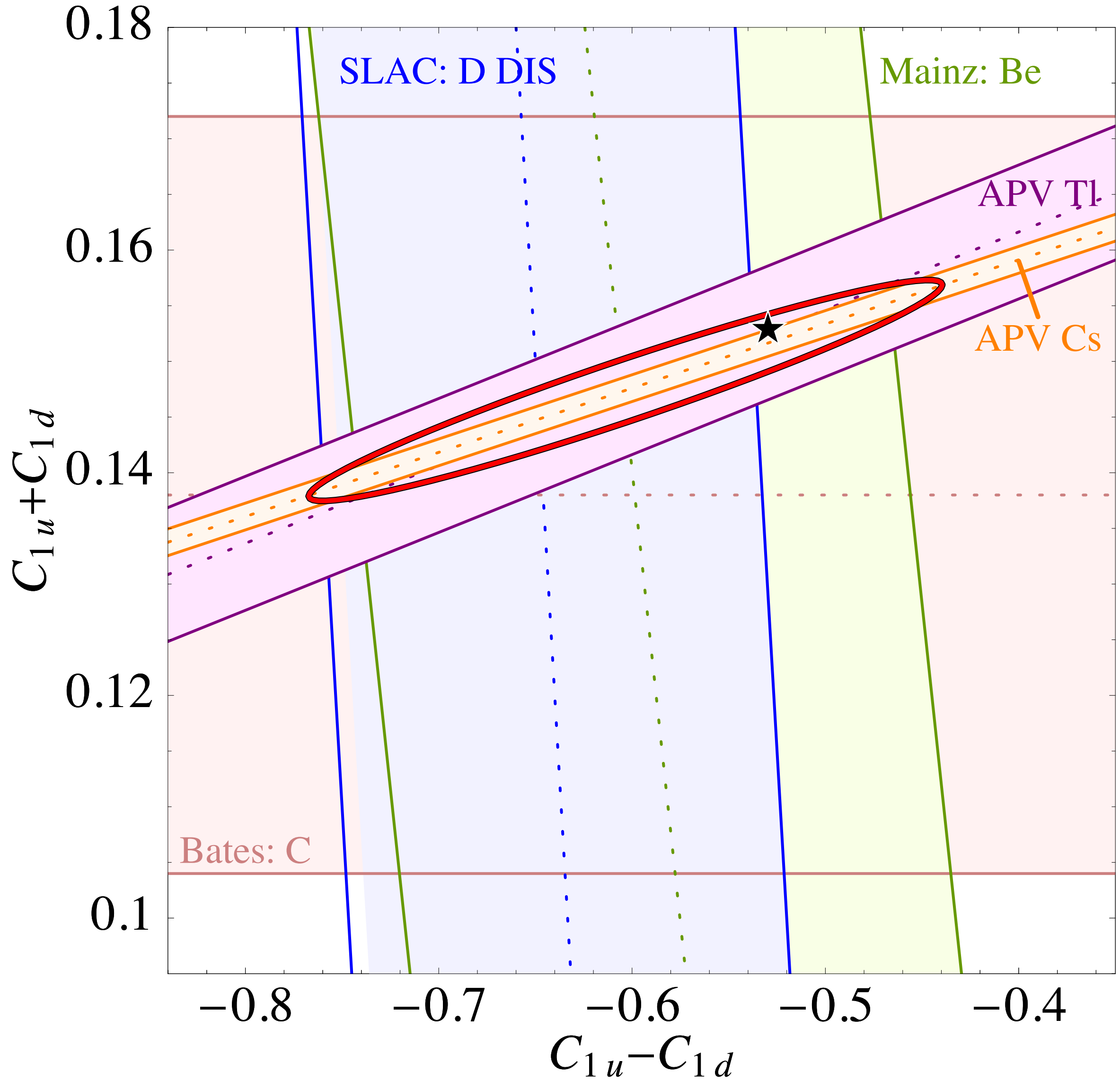
Weak charge of the proton

PV electron-quark couplings



Constrained by low-energy data!

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



95% CL

C1q quark-vector
(electron axial) couplings
c. 2006

High precision atomic parity violation measurement

Proton PV asymmetry

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

Neutral-weak form factors

Assume charge symmetry:

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

Proton weak charge — Strangeness

$$Q_{\text{weak}}^p = -2(2C_{1u} + C_{1d})$$

Proton PV asymmetry

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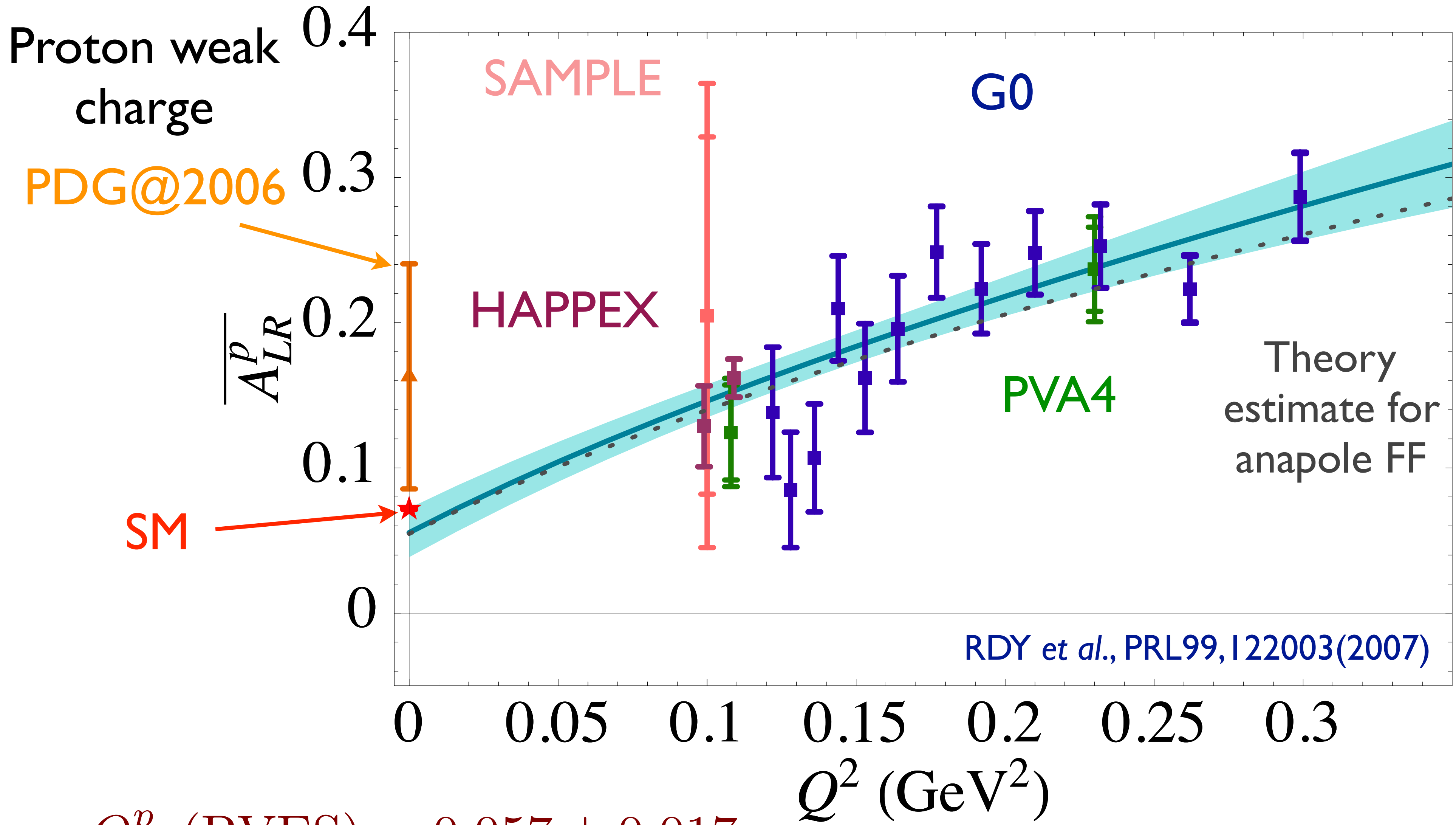
Proton weak charge

Strangeness

$$Q_{\text{weak}}^{p} = -2(2C_{1u} + C_{1d})$$

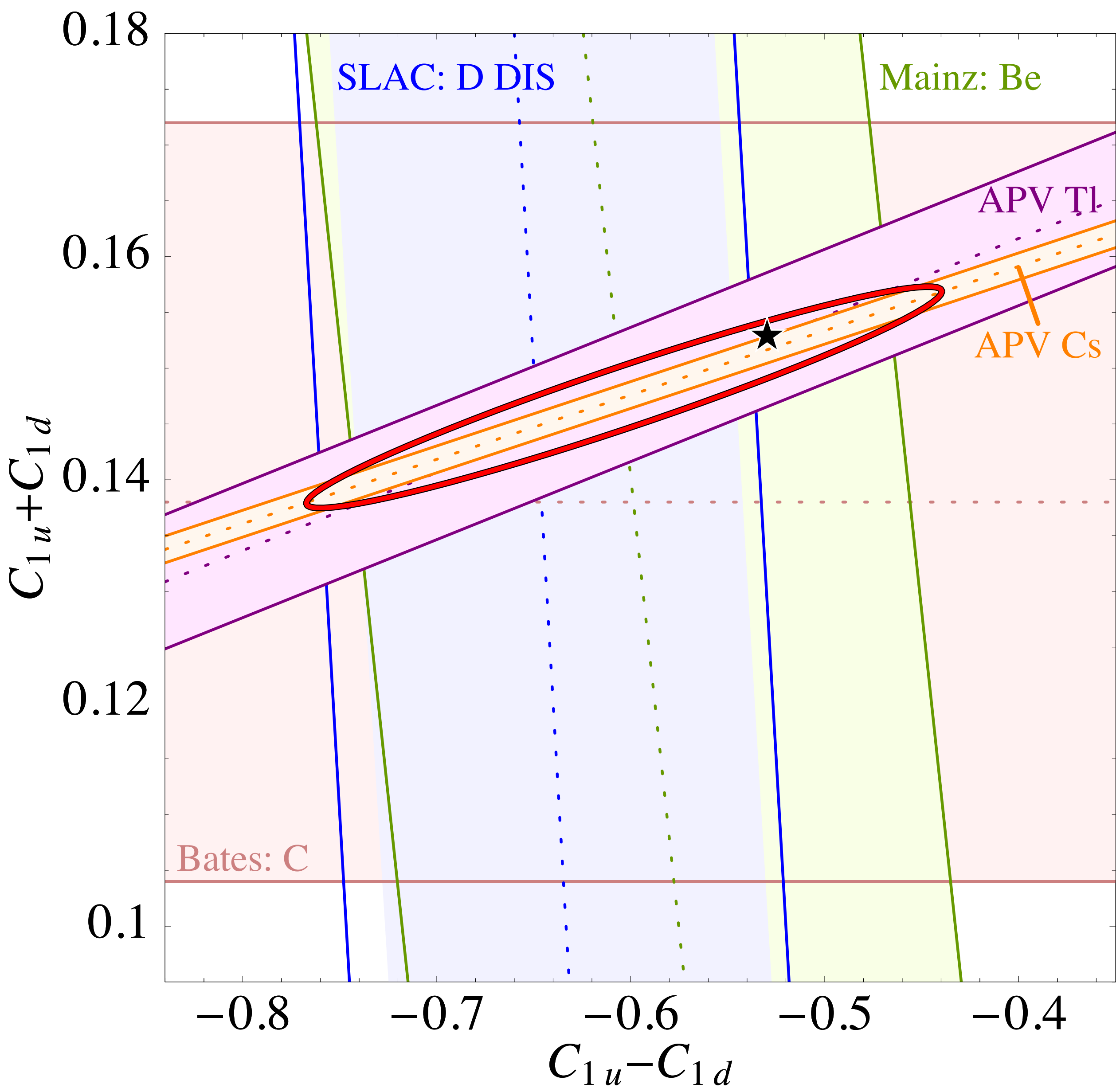
Use data to constrain the parameters of the electroweak theory



$$Q_W^p(\text{PVES}) = 0.057 \pm 0.017$$

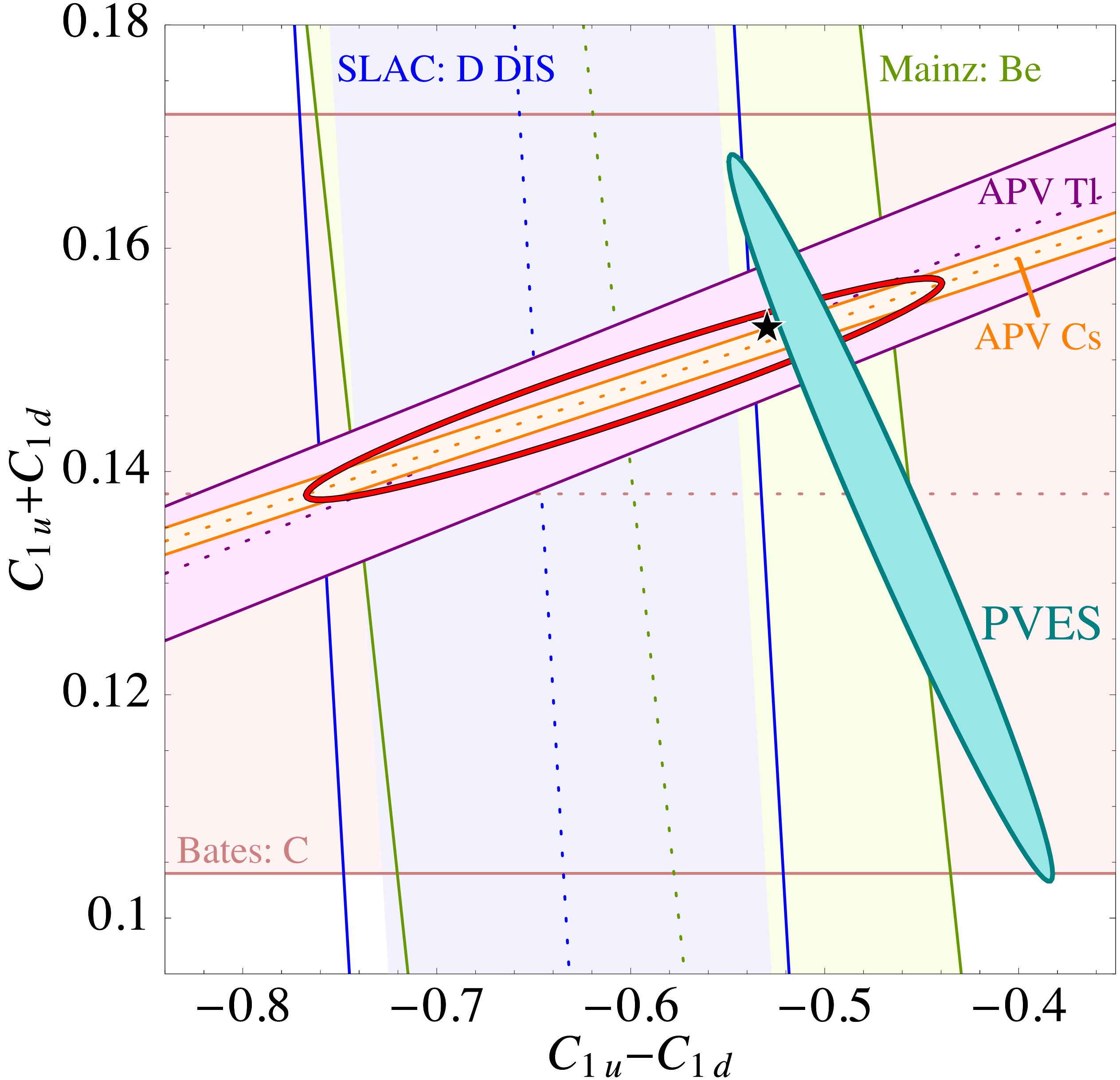
$$Q_W^p(\text{SM}) = 0.0710 \pm 0.0007$$

Proton extrapolation | Weak charge: $\sim 24\%$



Update on C1q couplings

"Strangeness" measurements constraint electroweak interaction



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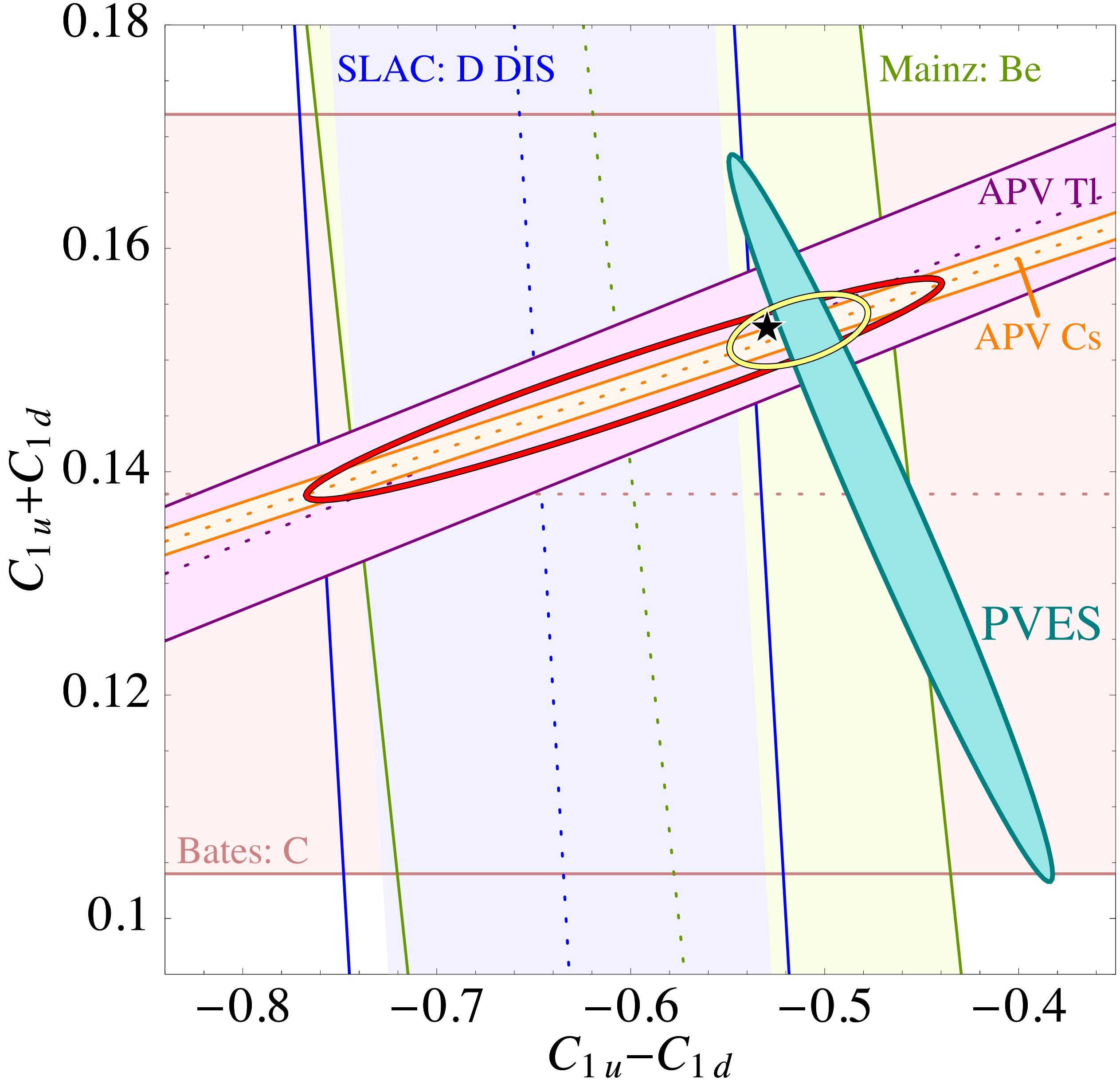

Update on C1q couplings

"Strangeness" measurements constraint electroweak interaction

Bounds on NP contact interaction

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

Erler *et al.*, PRD68(2003)

$$\mathcal{L}_{\rm NP}^{\rm PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\bar{q}\gamma^\mu q$$

Bounds on NP contact interaction

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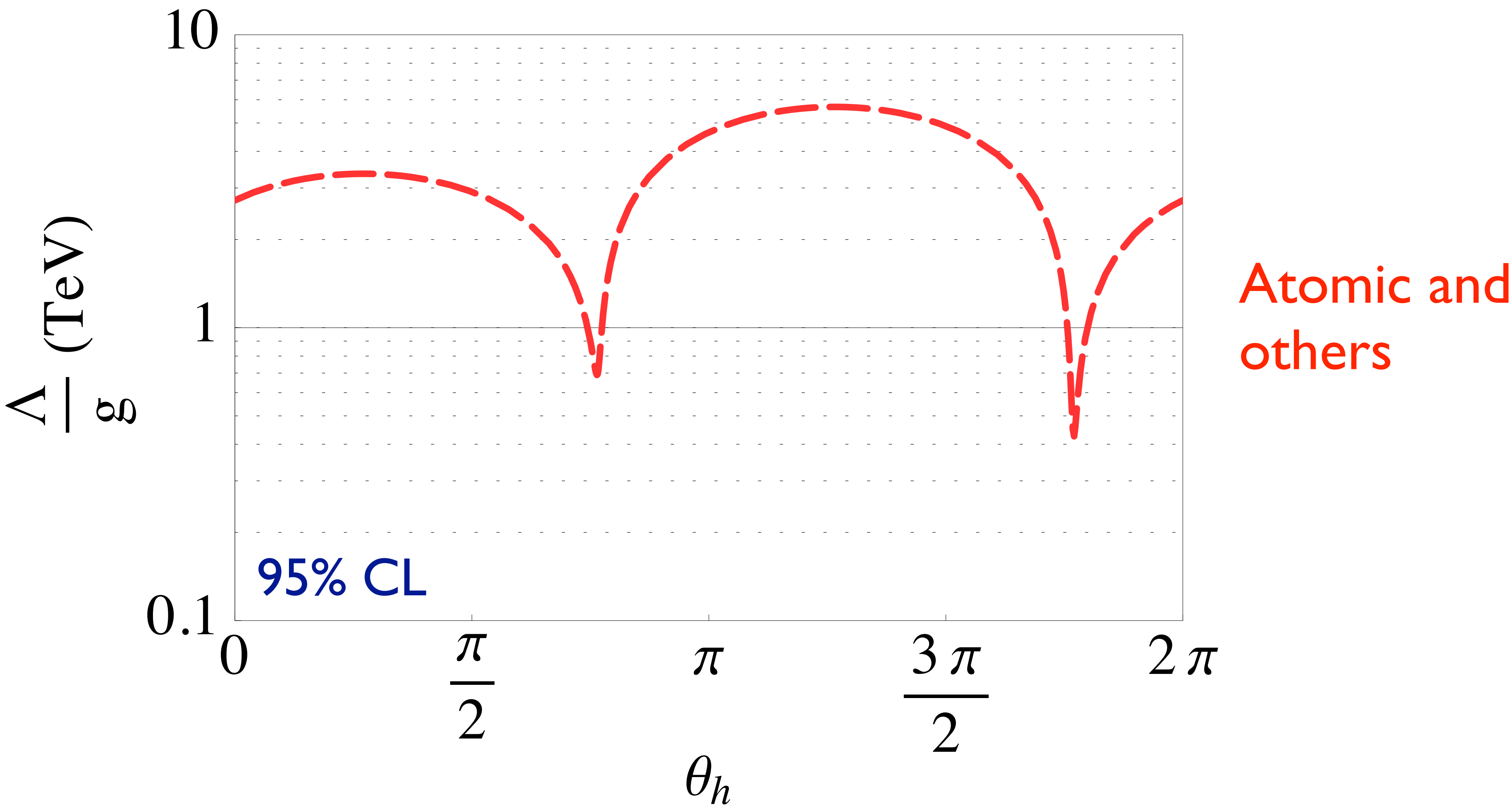
$$\mathcal{L}_{\mathrm{NP}}^{\mathrm{PV}} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

Full isospin coverage for limits on new physics!

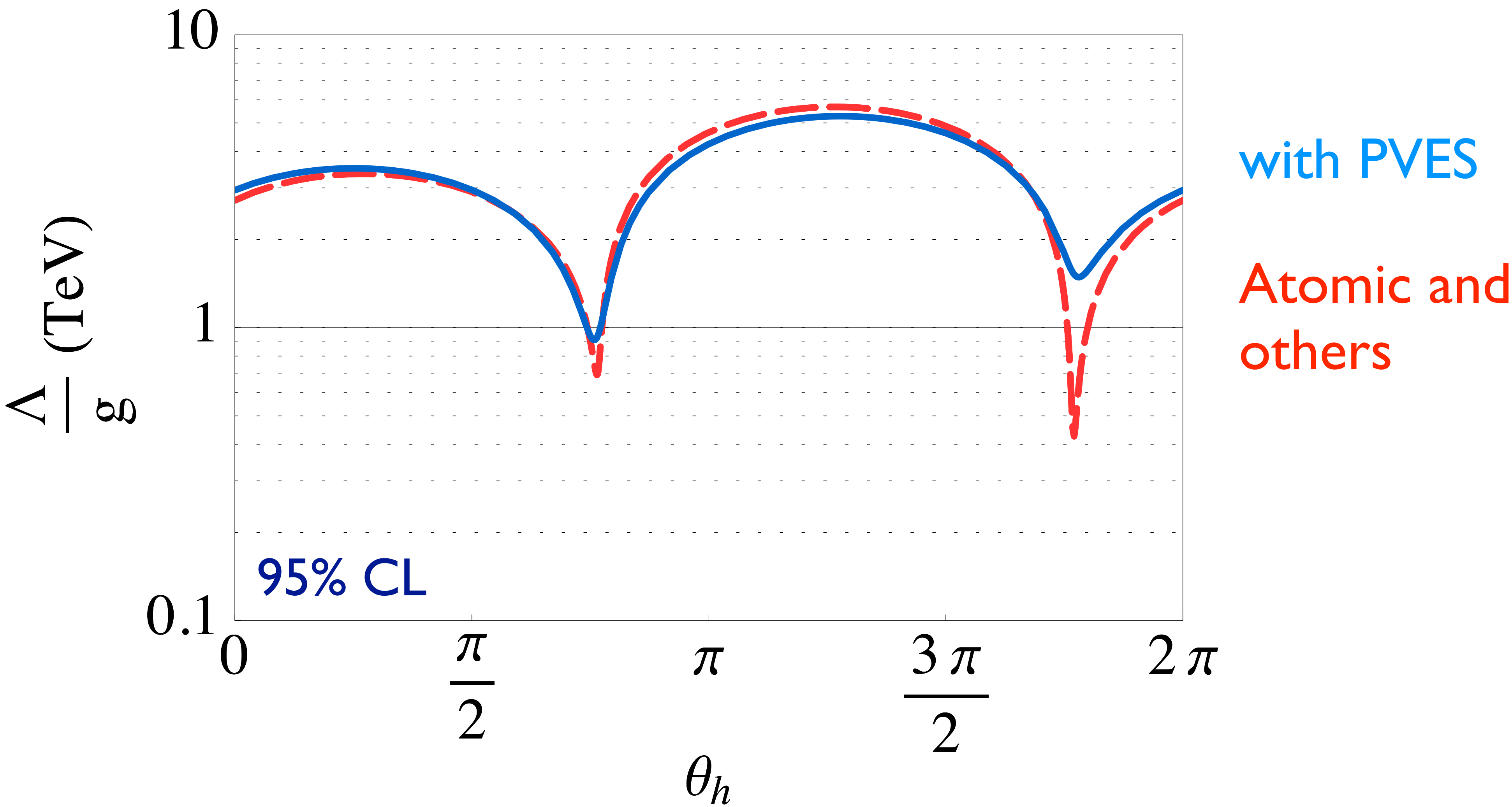
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

Data sets limits on $\dfrac{g^2}{\Lambda^2}$

“Isospin” dependence of NP bounds

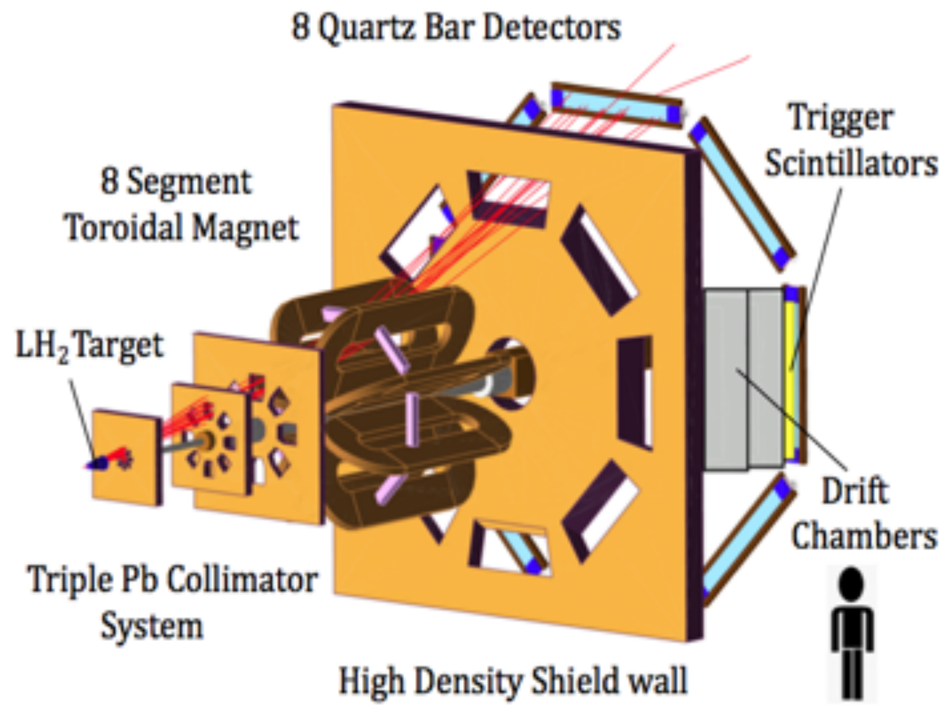


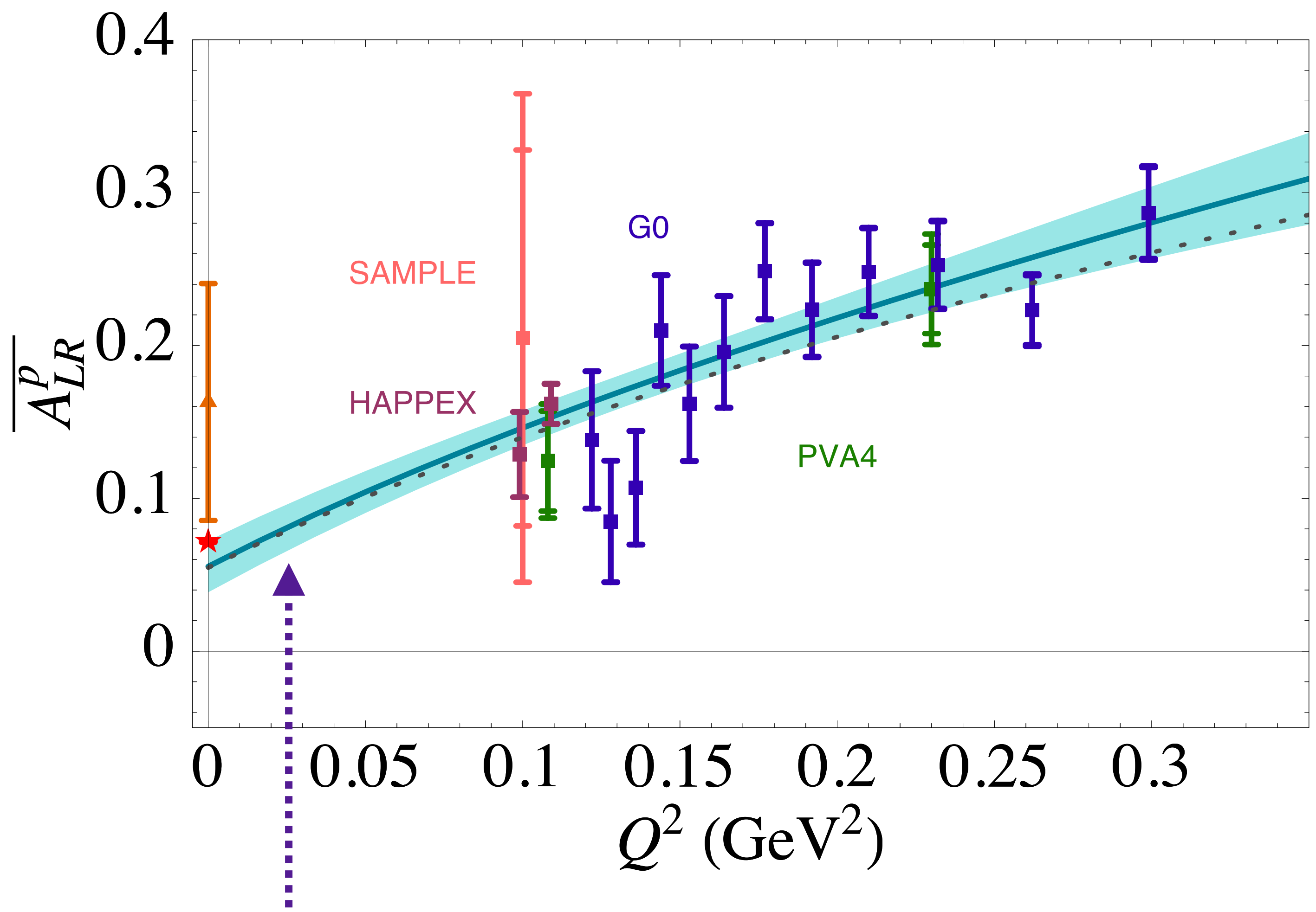
“Isospin” dependence of NP bounds



New physics scale >0.9 TeV! (from 0.4 TeV)

Q-weak Experiment

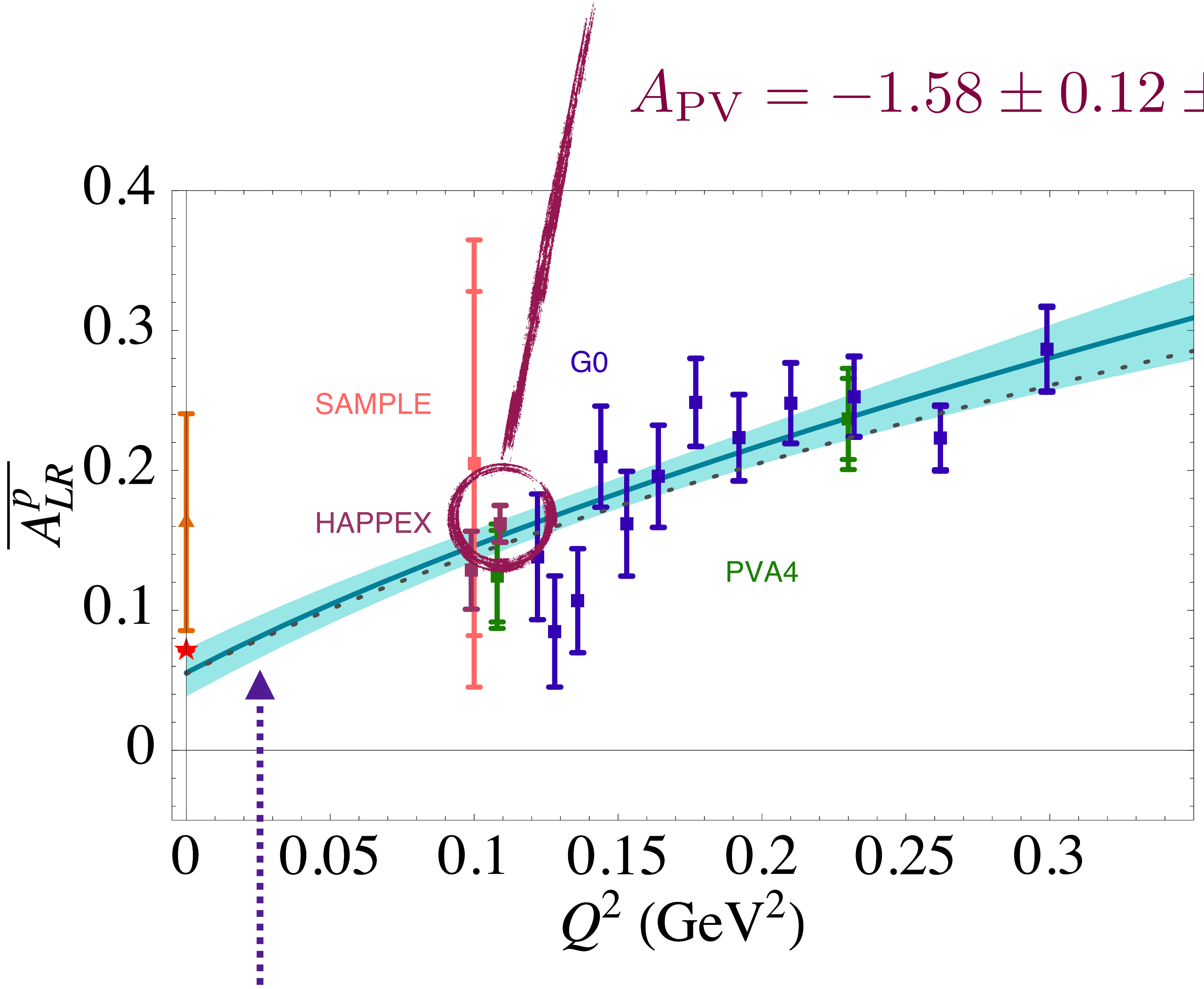




Q-weak: precision measurement @ low Q^2

HAPPEX: previous most precise measurement

$$A_{\rm PV} = -1.58 \pm 0.12 \pm 0.04\,\text{ppm}$$



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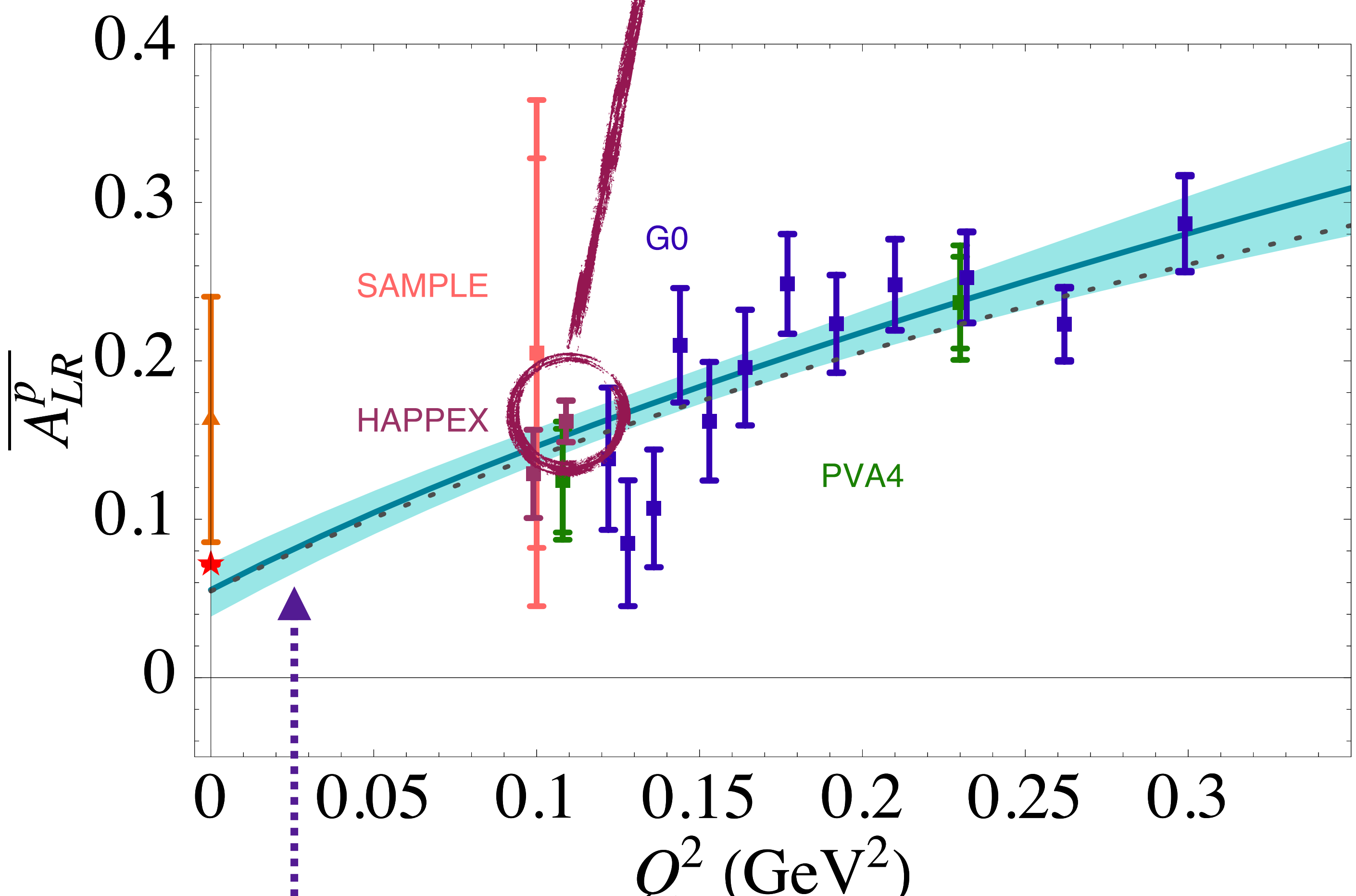


Q-weak: precision measurement @ low Q^2

$$A_{\mathrm{PV}} \sim -270\,\mathrm{ppb} \pm 2.5\% \quad \Rightarrow \Delta Q^p_W \sim 4\%$$

Turn on *Q*-weak and wait!

Turn on Q-weak and wait!

PRL **102,** 091806 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

Dispersion γZ-Box Correction to the Weak Charge of the Proton

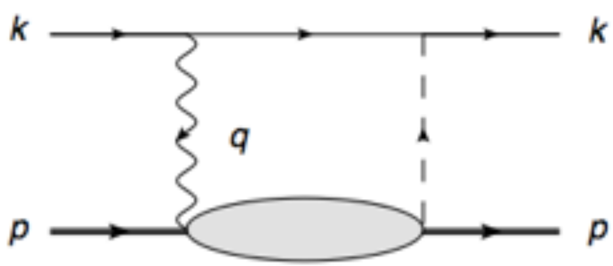
M. Gorchtein and C. J. Horowitz

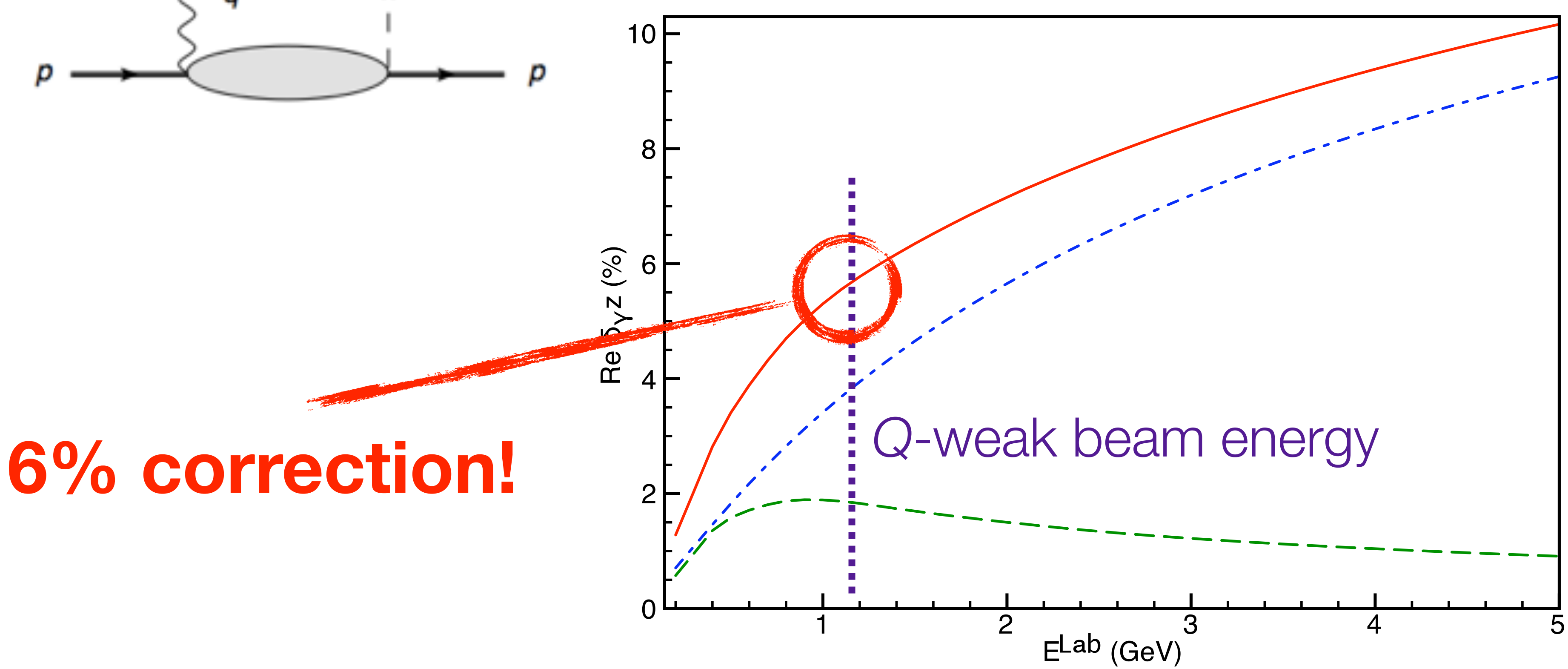
Nuclear Theory Center and Department of Physics, Indiana University, Bloomington, Indiana 47408, USA

(Received 4 November 2008; published 6 March 2009)

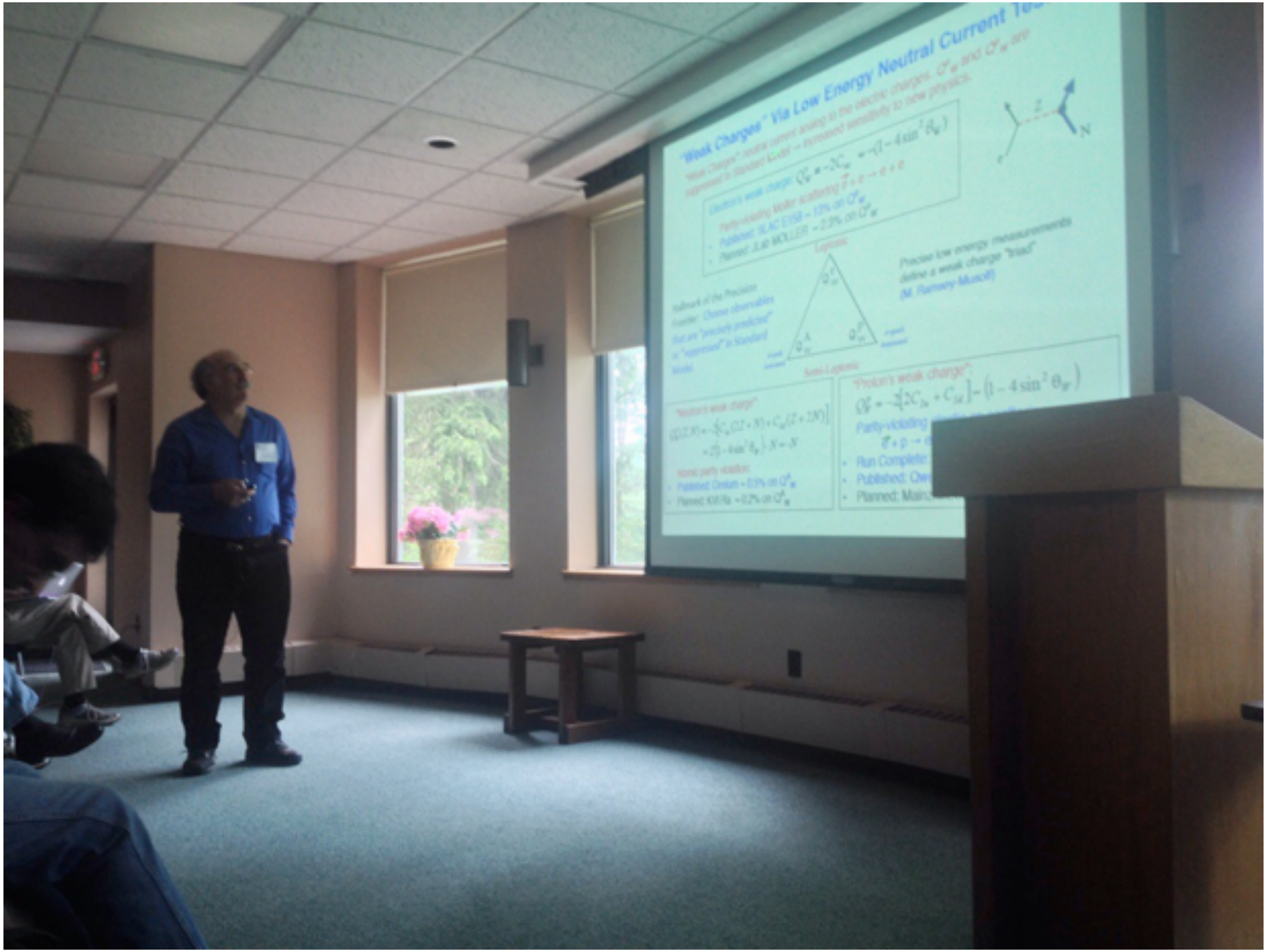
Radiative corrections: γZ box

- Significant **energy-dependent** correction from inelastic hadronic states identified by Gorchtein & Horowitz PRL(2009)
  - Forward scattering limit evaluated through dispersion relation





Q-weak experimentalist reaction!



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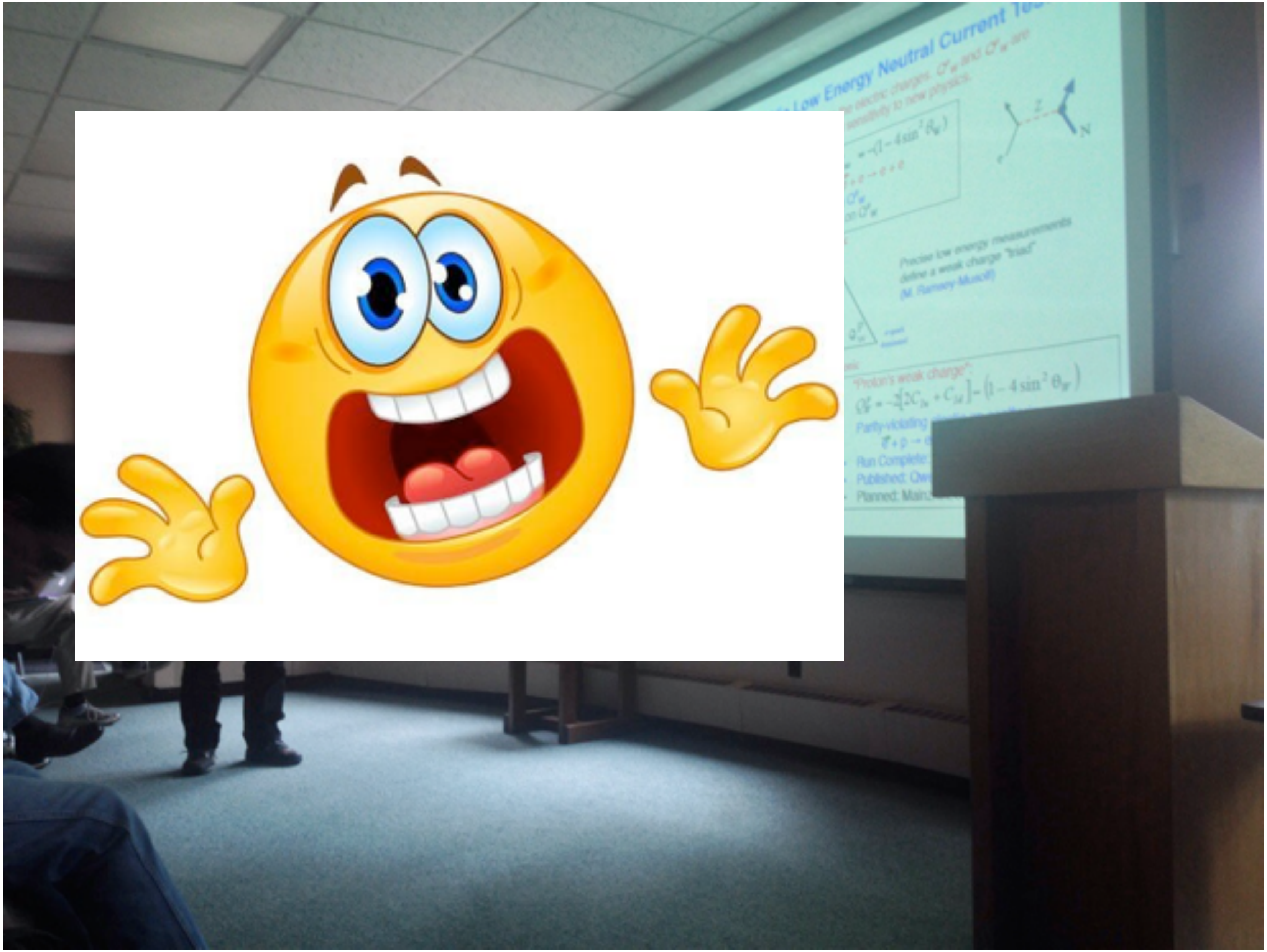

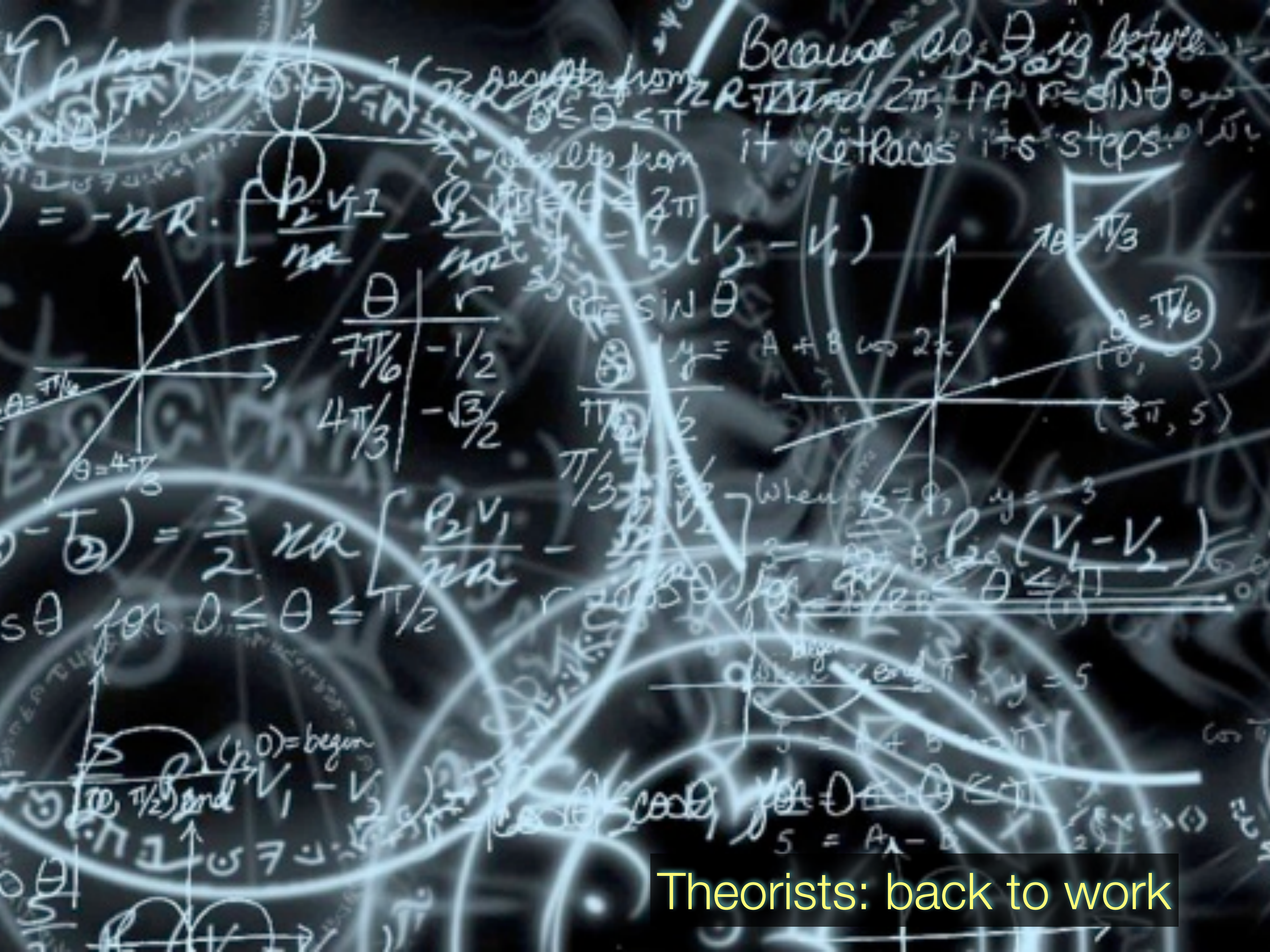

Theorists: back to work

gamma-Z box

- Forward dispersion relation:

$$\Re e\, \Box^{V}_{\gamma Z}(E) = \frac{2E}{\pi} \int_0^\infty dE' \, \frac{1}{E'^2 - E^2} \; \Im m\, \Box^{V}_{\gamma Z}(E')$$

- Imaginary part given by:

$$\Im m\, \Box^{V}_{\gamma Z}(E) = \frac{\alpha}{(s - M^2)^2} \int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{\max}} \frac{dQ^2}{1 + Q^2/M_Z^2} \times \left(F_1^{\gamma Z} + F_2^{\gamma Z} \frac{s\,(Q^2_{\max} - Q^2)}{Q^2(W^2 - M^2 + Q^2)} \right)$$

gamma-Z box

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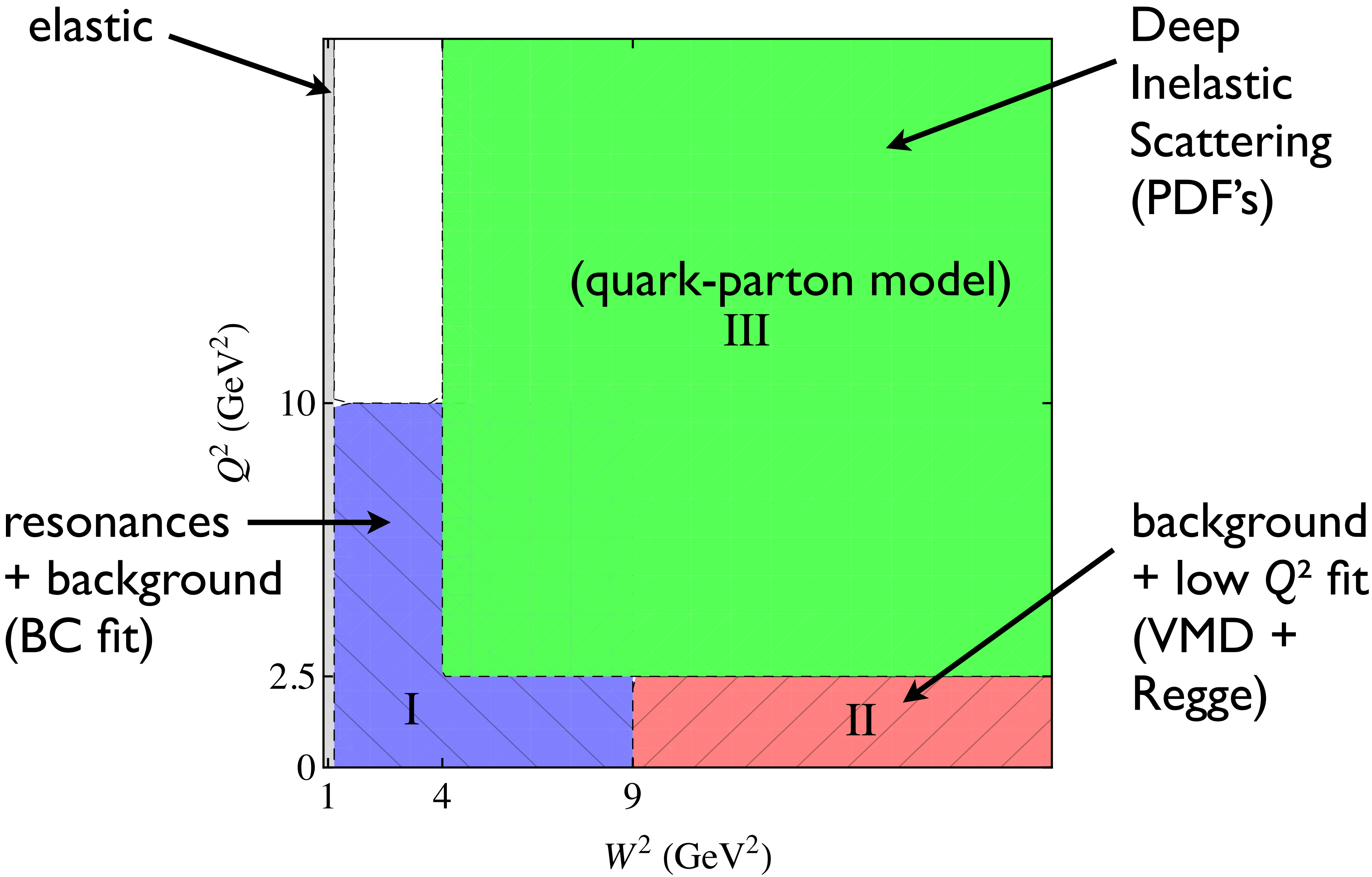
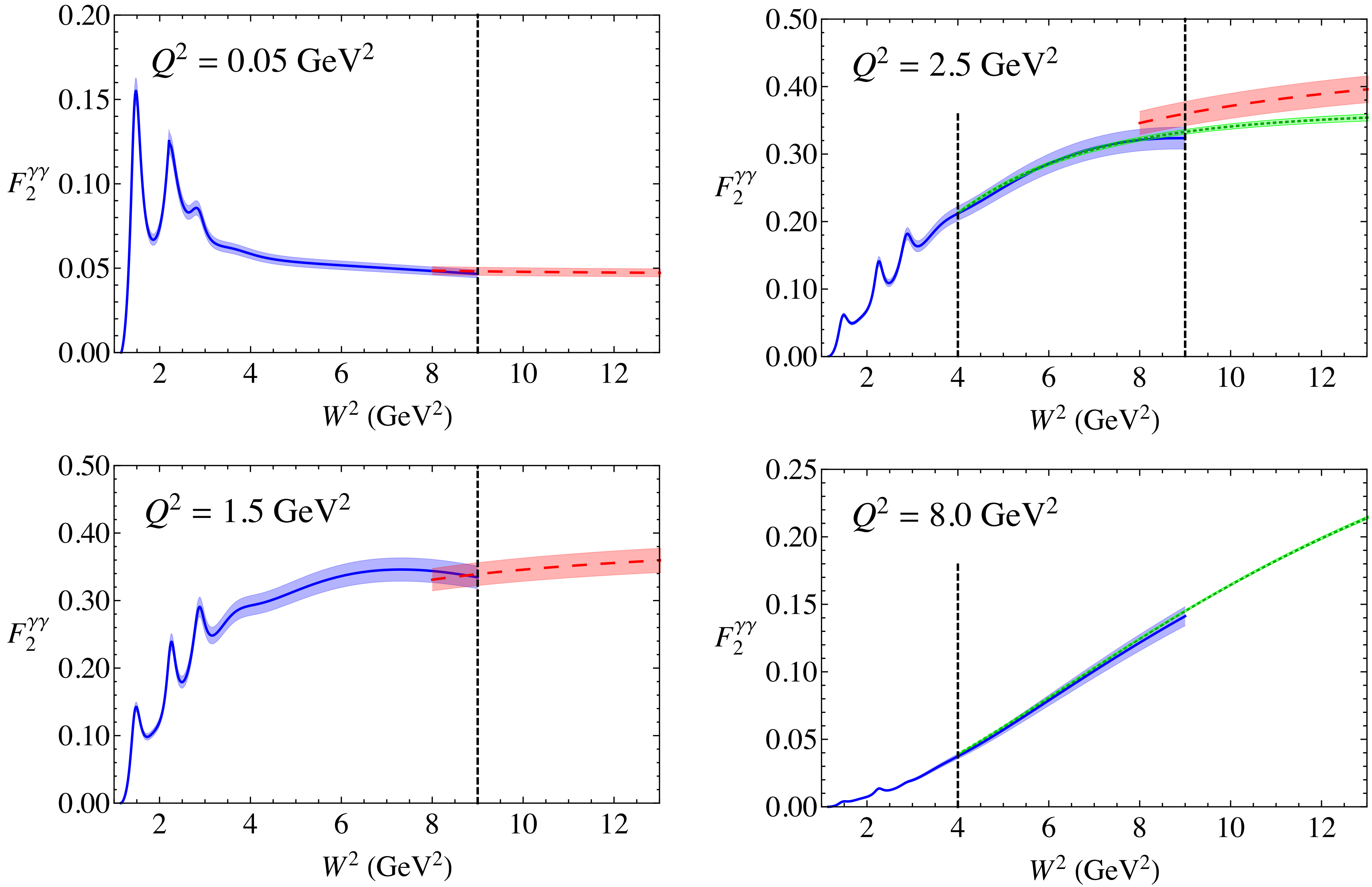
γZ interference structure functions



Integration region | Divide space



Boundary matching: $\gamma\gamma$ structure functions

$F^{\gamma Z}$ from $F^{\gamma\gamma}$?

- Region III (Scaling):

$$F_2^{\gamma} = \sum_q e_q^2 x(q + \bar{q})$$

$$F_2^{\gamma Z} = \sum_q 2 e_q g_V^q x(q + \bar{q})$$

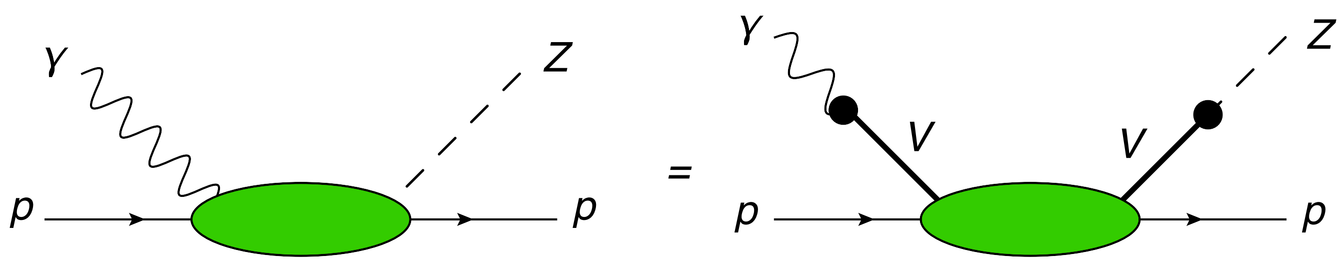
- Region I (Resonances):
    - Bosted-Christy empirical parameterisation

$$\sigma_{T,L} = \sigma_{T,L}(res) + \sigma_{T,L}(bg)$$

    - Resonances: Use PDG *p* and *n* helicity amplitudes to determine electroweak couplings

Background rotation

- VMD model of background contribution



V = ρ, ω, φ + continuum

- Use weak isospin rotation on VMD model

$$\sigma_V^{\gamma Z} = \kappa_V \, \sigma_V^{\gamma\gamma}$$

$$\kappa_\rho = 2 - 4\sin^2\theta_W, \quad \kappa_\omega = -4\sin^2\theta_W, \quad \kappa_\phi = 3 - 4\sin^2\theta_W$$

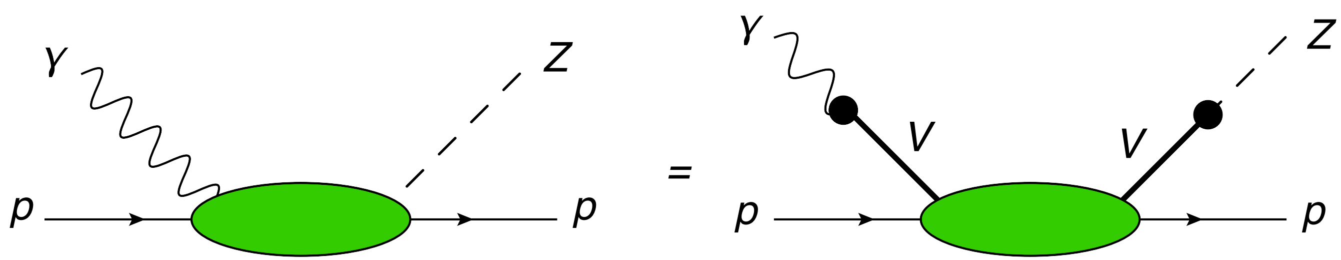
$$\frac{\sigma^{\gamma Z}}{\sigma^{\gamma\gamma}} = \frac{\kappa_\rho + \kappa_\omega R_\omega + \kappa_\phi R_\phi + \kappa_C R_C}{1 + R_\omega + R_\phi + R_C}$$

$$R_V = \frac{\sigma^{\gamma^* p \to V p}}{\sigma^{\gamma^* p \to \rho p}}$$

production cross section ratio for vector meson V to ρ meson

Background rotation

- VMD model of background contribution



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- Use weak isospin rotation on VMD model

$$\sigma_V^{\gamma Z} = \kappa_V \, \sigma_V^{\gamma\gamma}$$

$$\kappa_\rho = 2 - 4\sin^2\theta_W, \quad \kappa_\omega = -4\sin^2\theta_W, \quad \kappa_\phi = 3 - 4\sin^2\theta_W$$

$$\frac{\sigma^{\gamma Z}}{\sigma^{\gamma\gamma}} = \frac{\kappa_\rho + \kappa_\omega R_\omega + \kappa_\phi R_\phi + \kappa_C R_C}{1 + R_\omega + R_\phi + R_C}$$

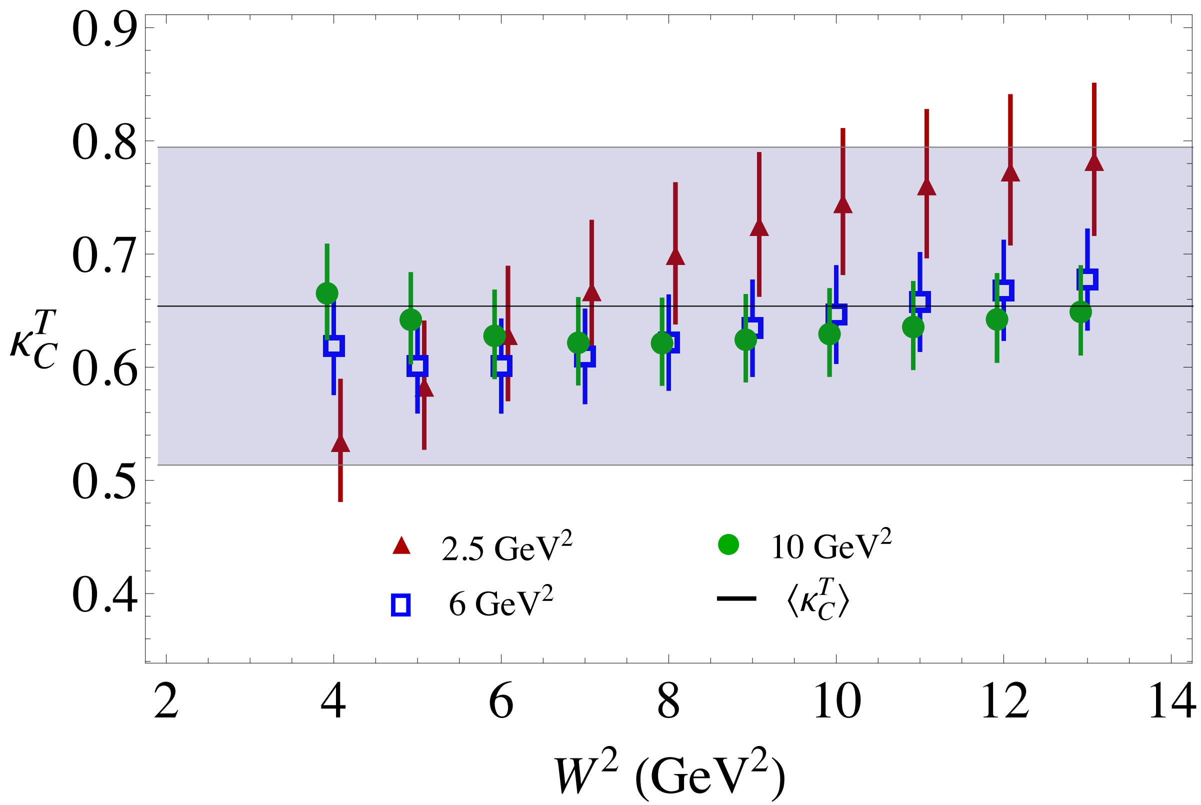
continuum parameter

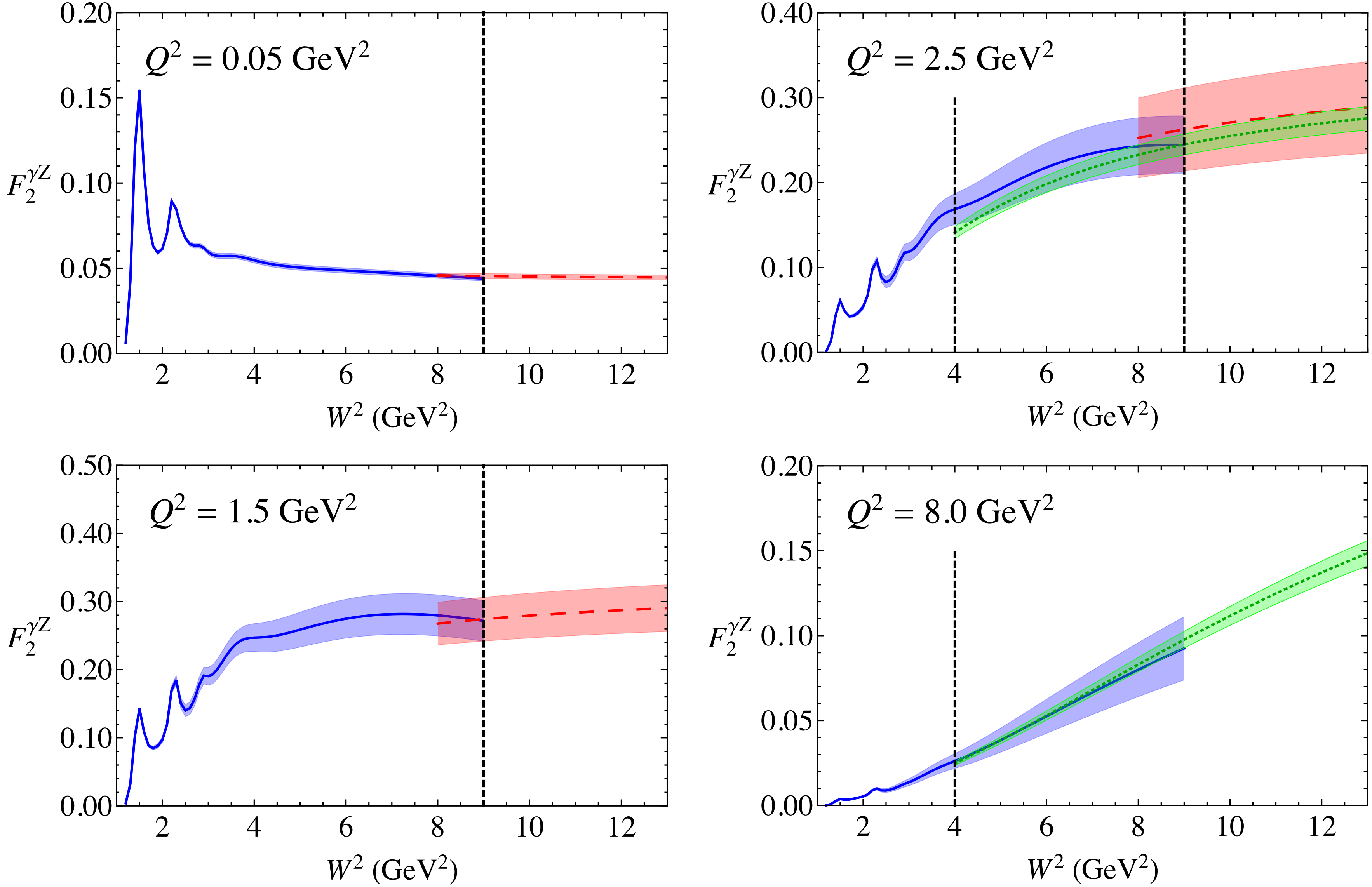
$$R_V = \frac{\sigma^{\gamma^* p \to V p}}{\sigma^{\gamma^* p \to \rho p}}$$

production cross section ratio for vector meson V to ρ meson

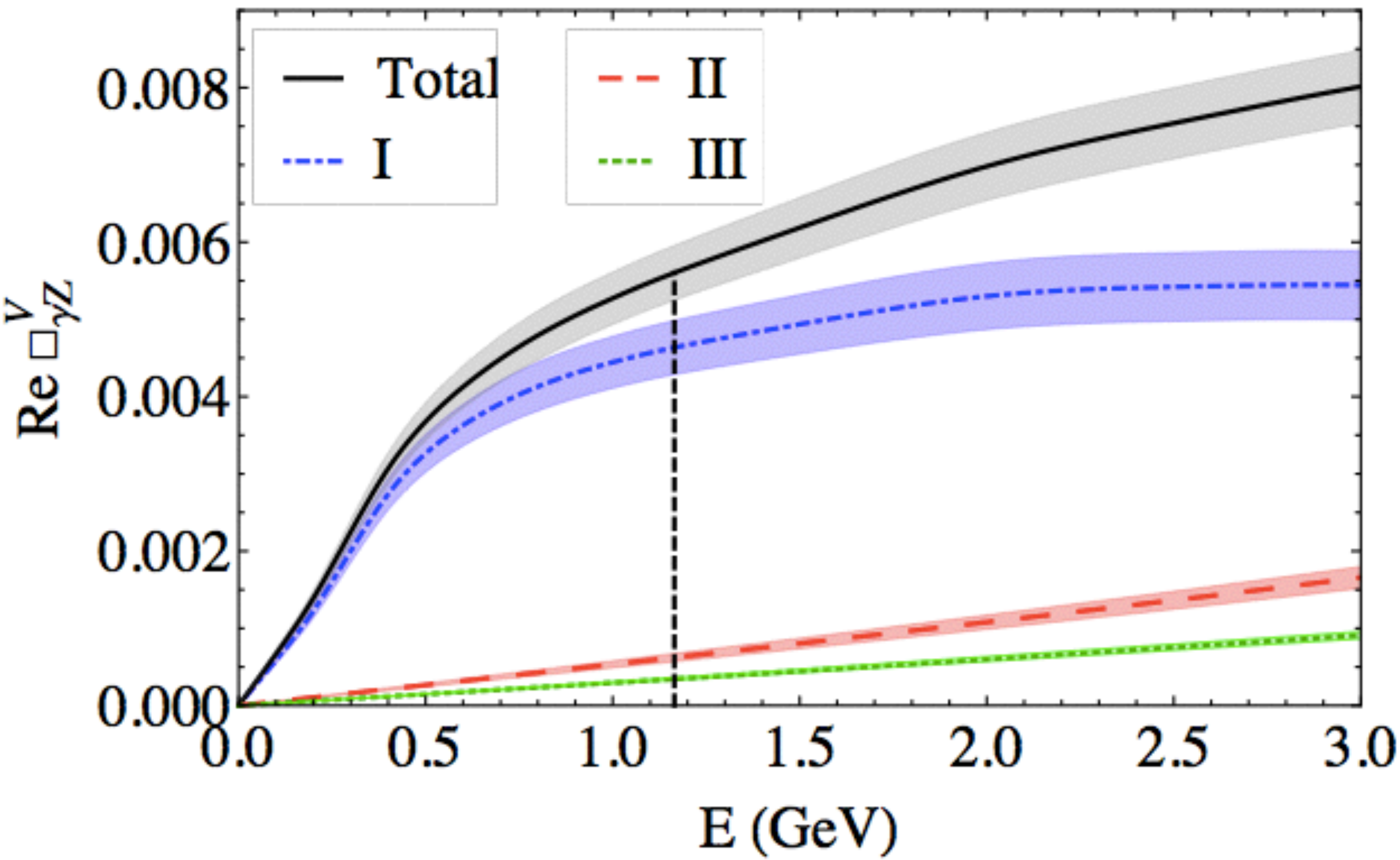
Matching at boundary

- Unknown continuum “rotation” parameter constrained by matching to boundary with scaling region





Consistent matching at boundaries



Hall *et al.*, PRD(2013)

Final result

AJM: Adelaide-JLab-Manitoba

Comparison

$$\text{GH (2009)}$$

$$\text{SBMT (2010)}\ (4.7^{+1.1}_{-0.4}) \times 10^{-3}$$

$$\text{GHRM (2011)}\ (5.4 \pm 2.0) \times 10^{-3}$$

$$\text{RC (2011)}\ (5.7 \pm 0.9) \times 10^{-3}$$

$$\text{AJM (2013)}\ (5.6 \pm 0.4) \times 10^{-3}$$

Gorchtein *et al*.

Rislow & Carlson

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Gorchtein *et al*.

Rislow & Carlson

Good agreement
on central value

Comparison

$$\begin{aligned}
\text{GH (2009)} & \\
\text{SBMT (2010)} & \quad (4.7^{+1.1}_{-0.4}) \times 10^{-3} \\
\text{GHRM (2011)} & \quad (5.4 \pm 2.0) \times 10^{-3} \\
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\text{AJM (2013)} & \quad (5.6 \pm 0.4) \times 10^{-3}
\end{aligned}$$

Gorchtein *et al*.

Rislow & Carlson

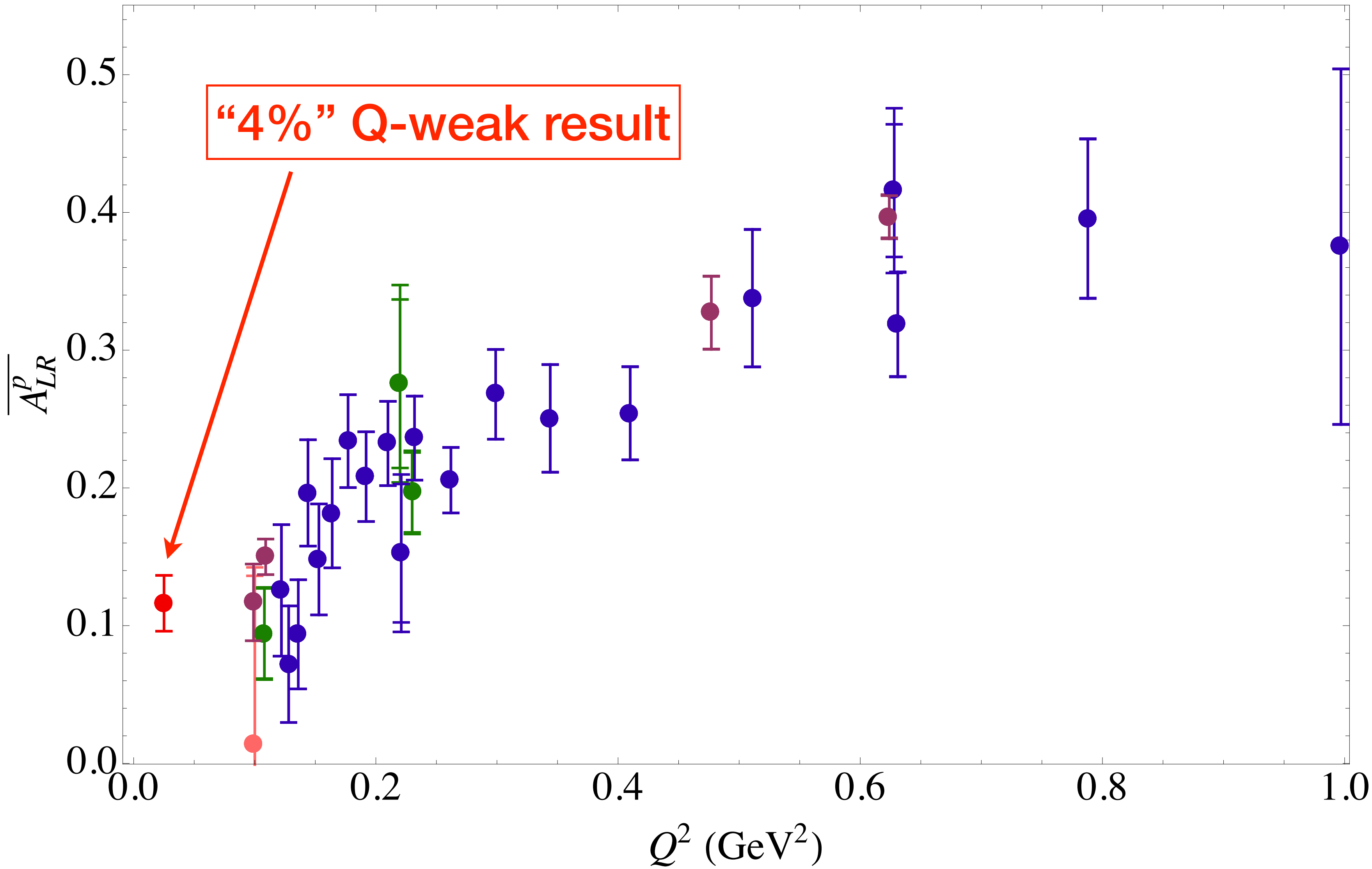
Good agreement on central value

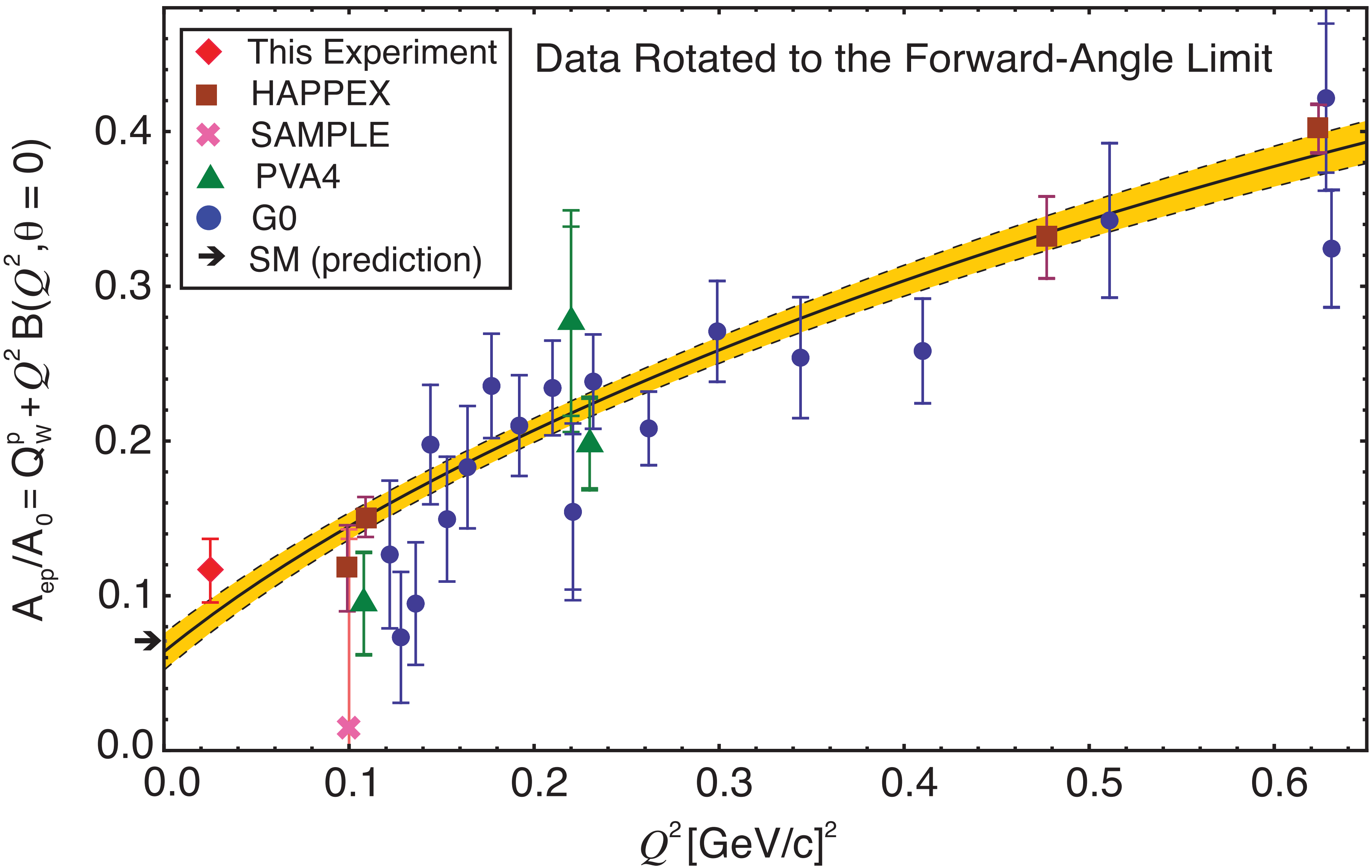
A little debate over uncertainty

Q-weak Experiment:
First 4% of data collection

Proton asymmetry measurements

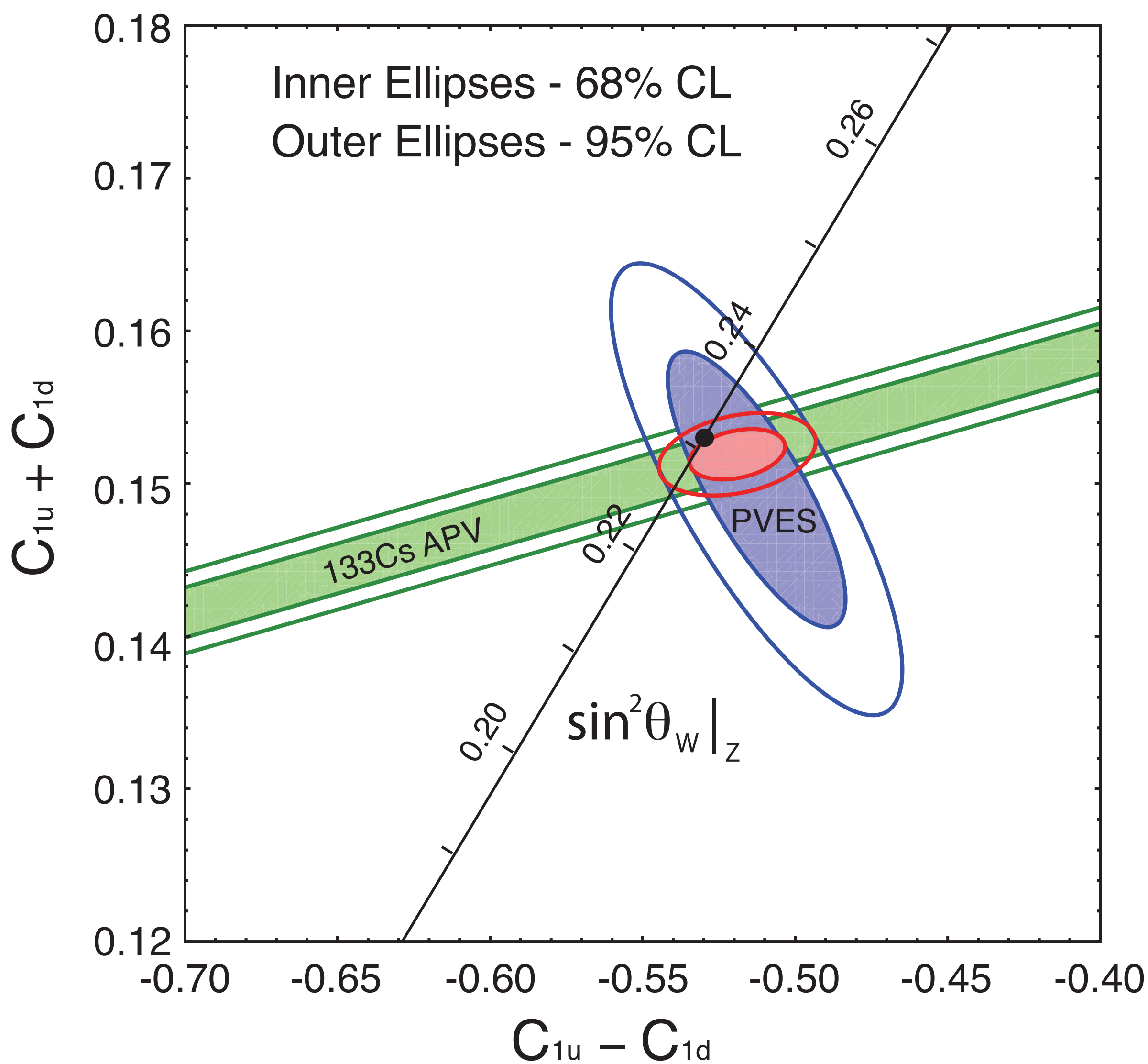
- Forward scattering projection





Weak charge extrapolation

Q-weak, PRL(2013)



Weak charges

Excellent agreement with SM

Conclusions

- New knowledge of the flavour separation of nucleon form factors from precision electroweak measurements
  - Tremendous advance in lattice QCD computations
- Can achieve high-precision search for new physics in the environment of the proton!!
- Requires significant control of theoretical constraints
  - gamma-Z box was a surprise: important it was caught early
  - AJM model, constrained estimate of box contribution: ~0.5% on *Q*-weak
- We await full statistics of *Q*-weak to probe new physics into the multi-TeV region