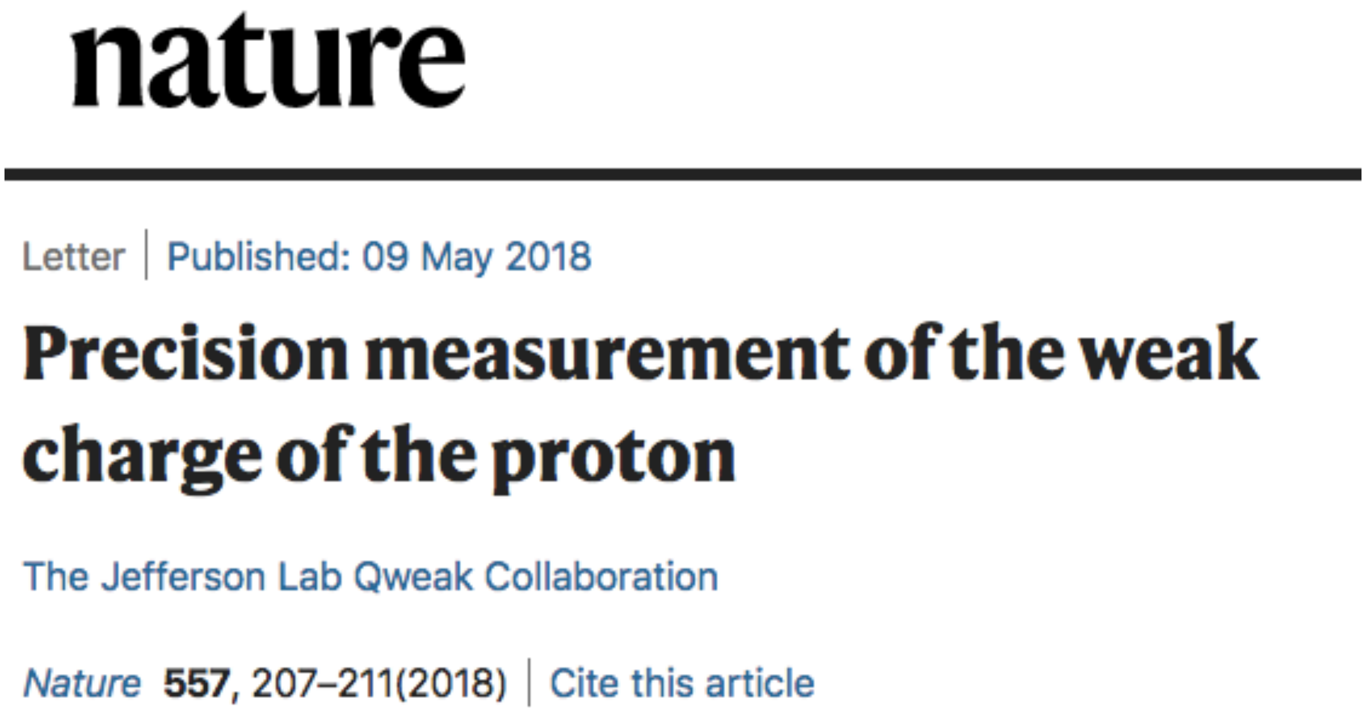
Weak charge of the proton

Ross Young
University of Adelaide

24th Australian Institute of Physics Congress
11–16 December, 2022
Adelaide, Australia



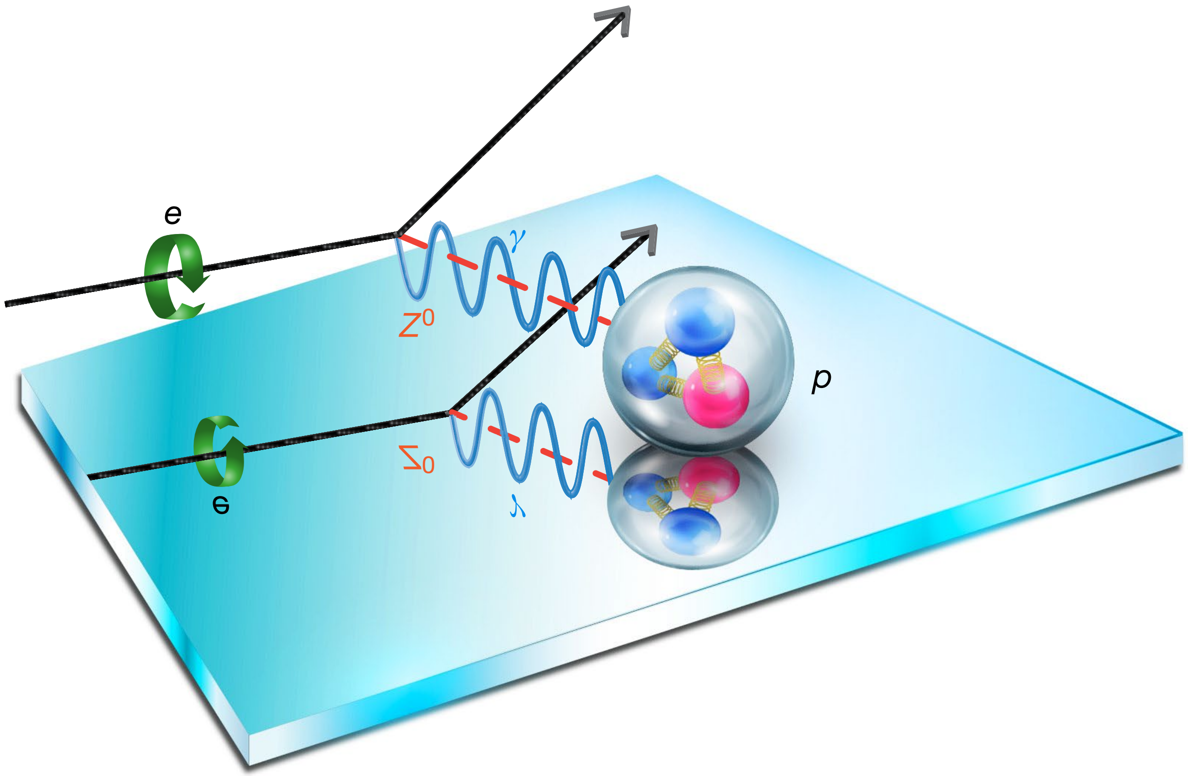
nature

Letter | Published: 09 May 2018

Precision measurement of the weak charge of the proton

The Jefferson Lab Qweak Collaboration

Nature **557**, 207–211(2018) | Cite this article



Outline: This talk will be upside down

Weak charge of the proton

Constraints on new physics

Parity-violating *ep* scattering

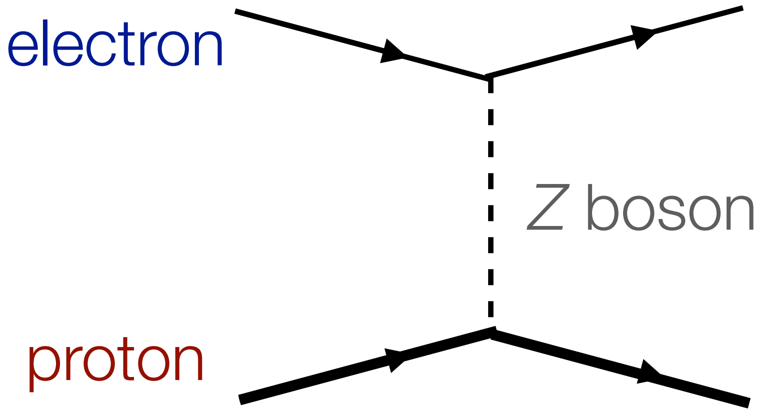
Strange quark distributions in the proton

Revisiting radiative corrections (γZ box)

The final result

Weak charge of the proton

- The “charge” of the proton as seen by the neutral current



Measurement of the proton’s weak charge

$$Q_W^p = 0.0719 \pm 0.0045$$

~6% precision

$$Q_W^p(\text{Standard Model}) = 0.0708 \pm 0.0003$$

Proton weak charge

$$Q_W^p = 0.0719 \pm 0.0045$$

$$Q_W^p(\text{Standard Model}) = 0.0708 \pm 0.0003$$

Theory

$$Q_W^p = 1 - 4\sin^2\theta_W + \text{radiative corrections}$$

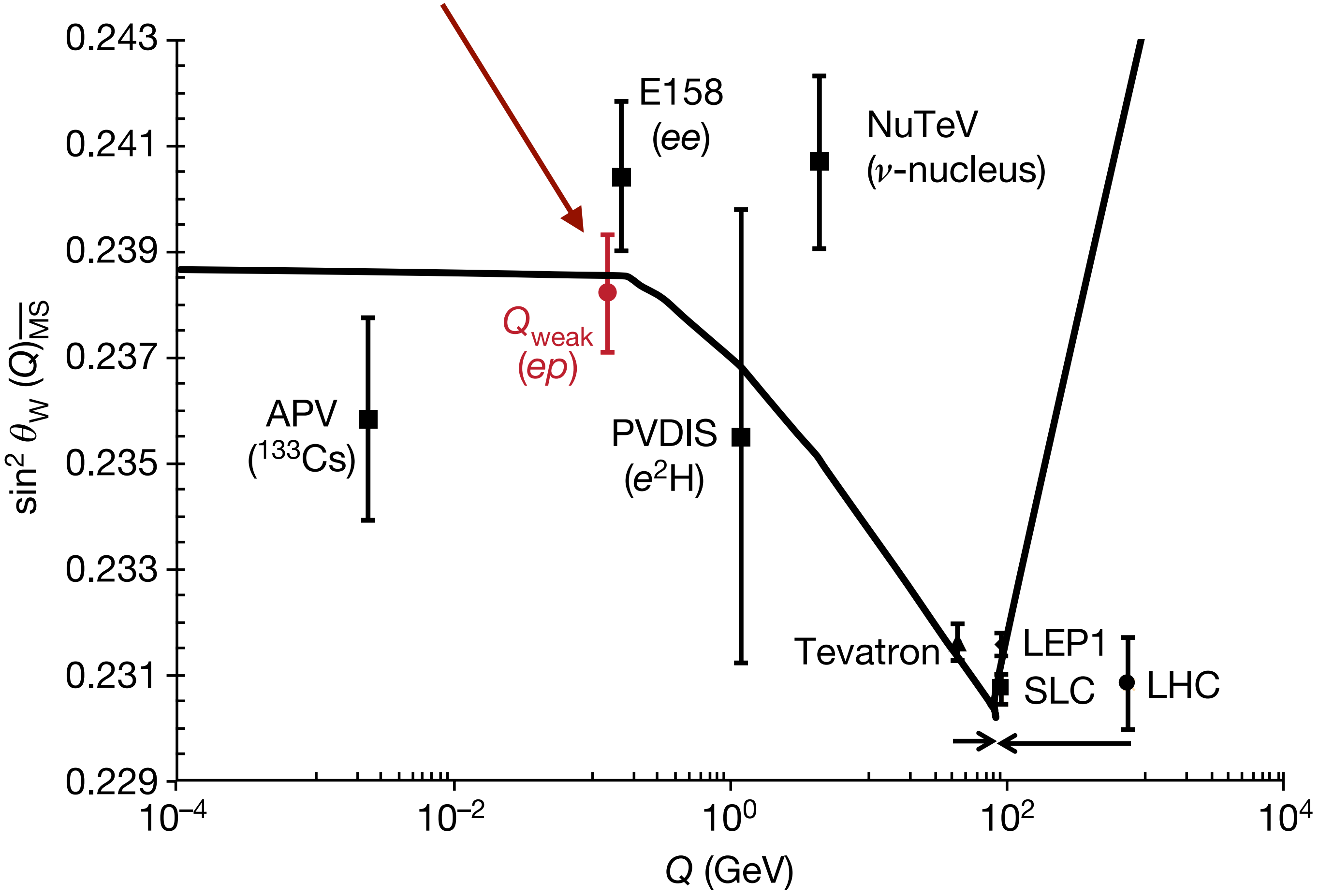
Weak mixing angle

Marciano & Sirlin,
Ramsey-Musolf, Erler *et al*.
…

What does that mean for new physics?

(Running of the) **Weak mixing angle**

- Deviations from Standard Model curve indicate possible new physics



Q-weak result

(Running of the) **Weak mixing angle**

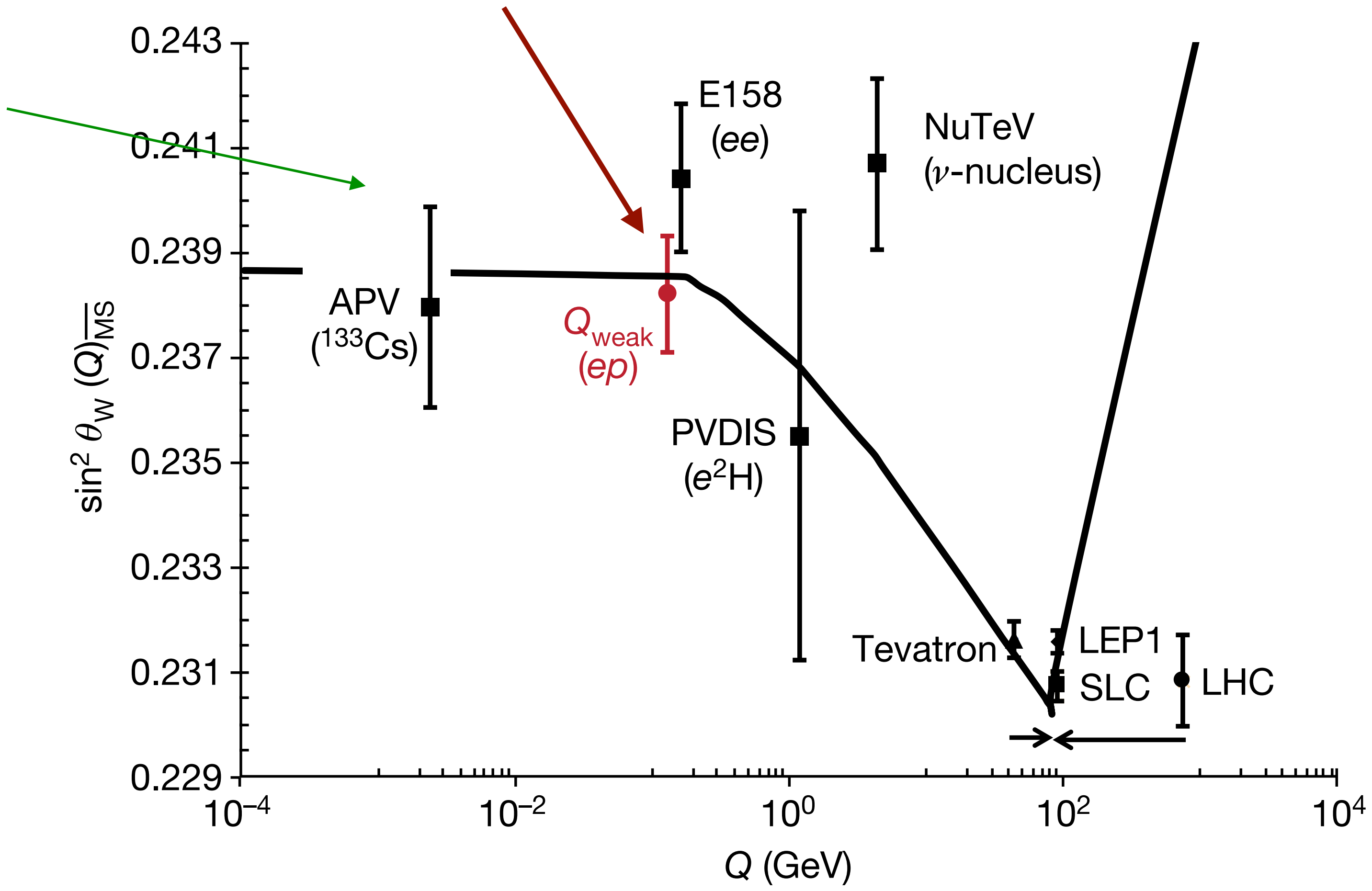
- Deviations from Standard Model curve indicate possible new physics

Cs update

Toh *et al*. PRL(2019)

(Dzuba *et al*., Ginges *et al*.)

Q-weak result



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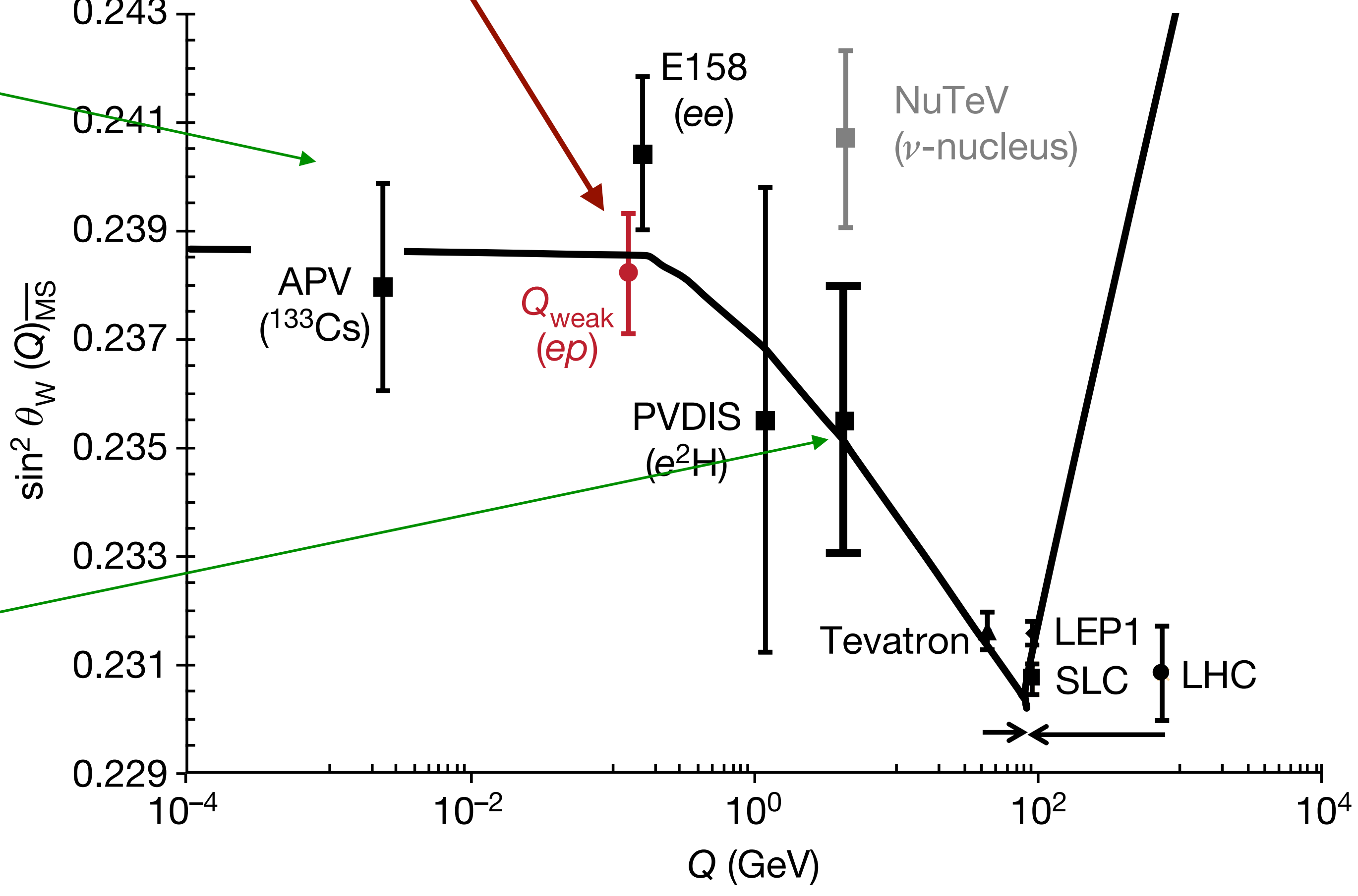


ν-DIS update

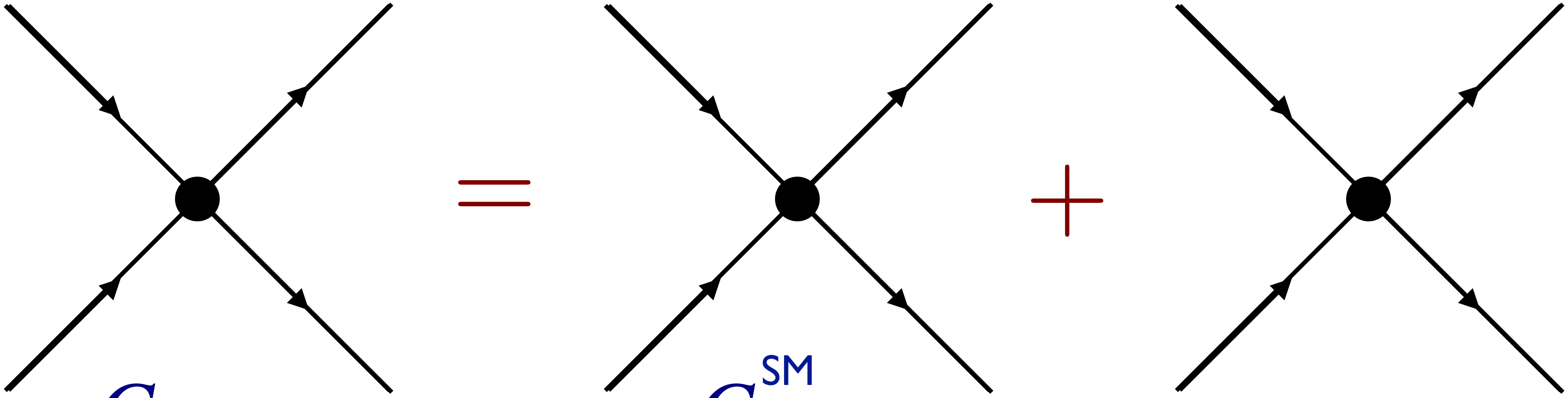
Bentz *et al*. PLB(2010)

Isovector EMC

$m_u \neq m_d$

$\langle s(x)\rangle_{\mathrm{Fe}} \neq \langle \bar{s}(x)\rangle_{\mathrm{Fe}}$

PV electron-quark contact interactions



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

Constrained by low-energy data!

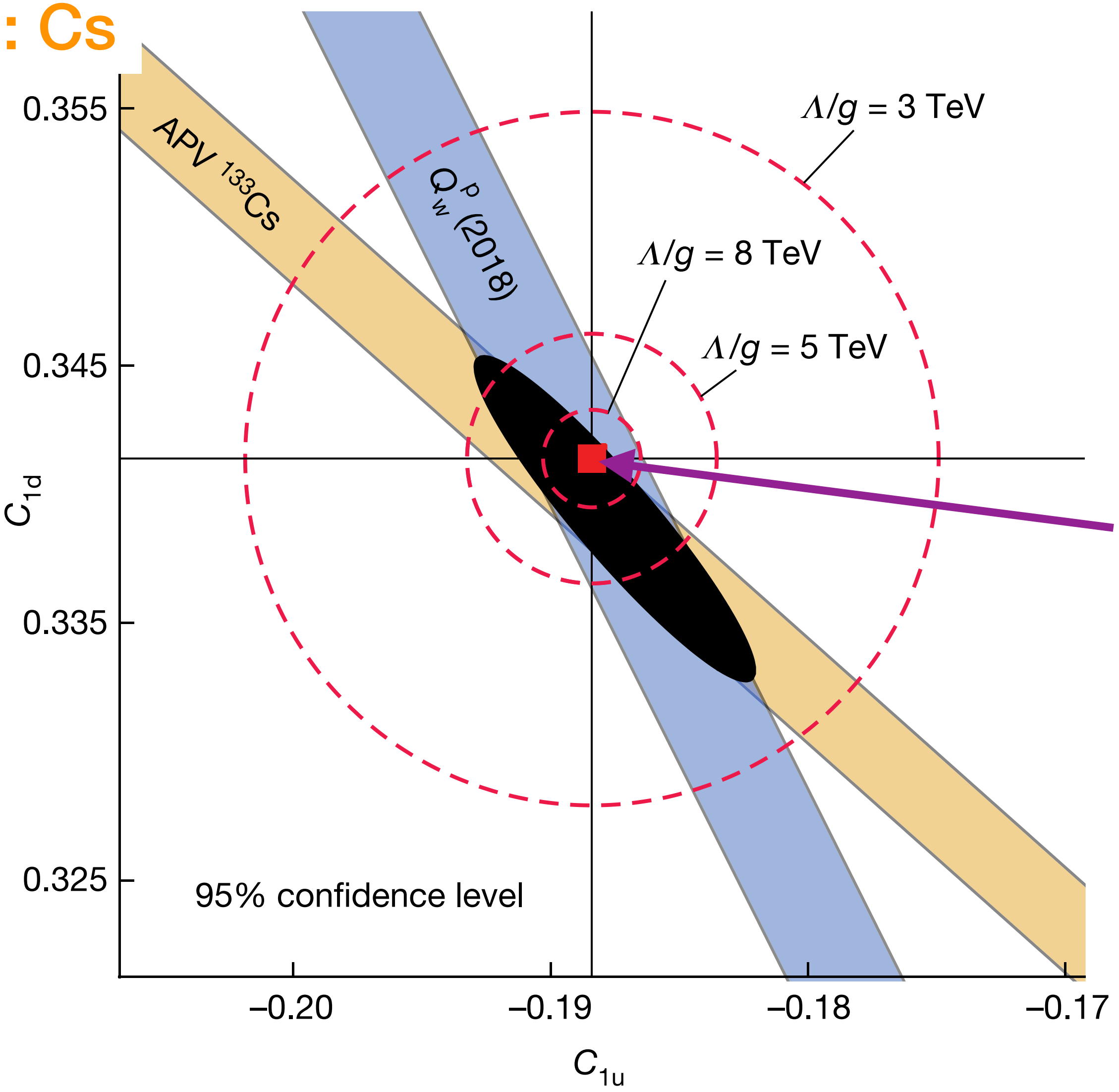
$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{SM}} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C^{\mathrm{SM}}_{1q}\bar{q}\gamma^\mu q$$

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

Erler *et al.*, PRD68(2003)

Atomic Parity Violation: Cs

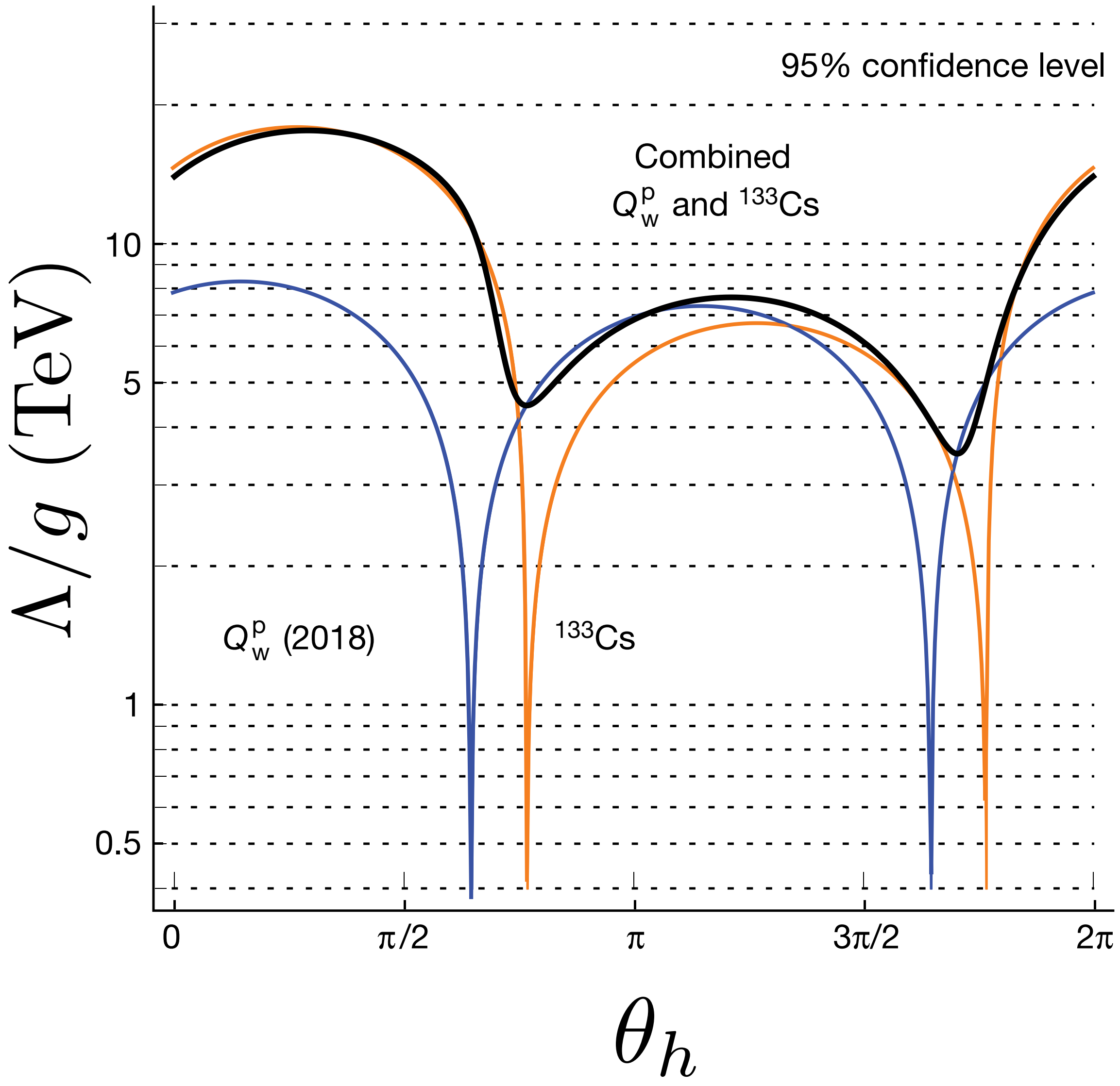
Q-weak



Standard Model

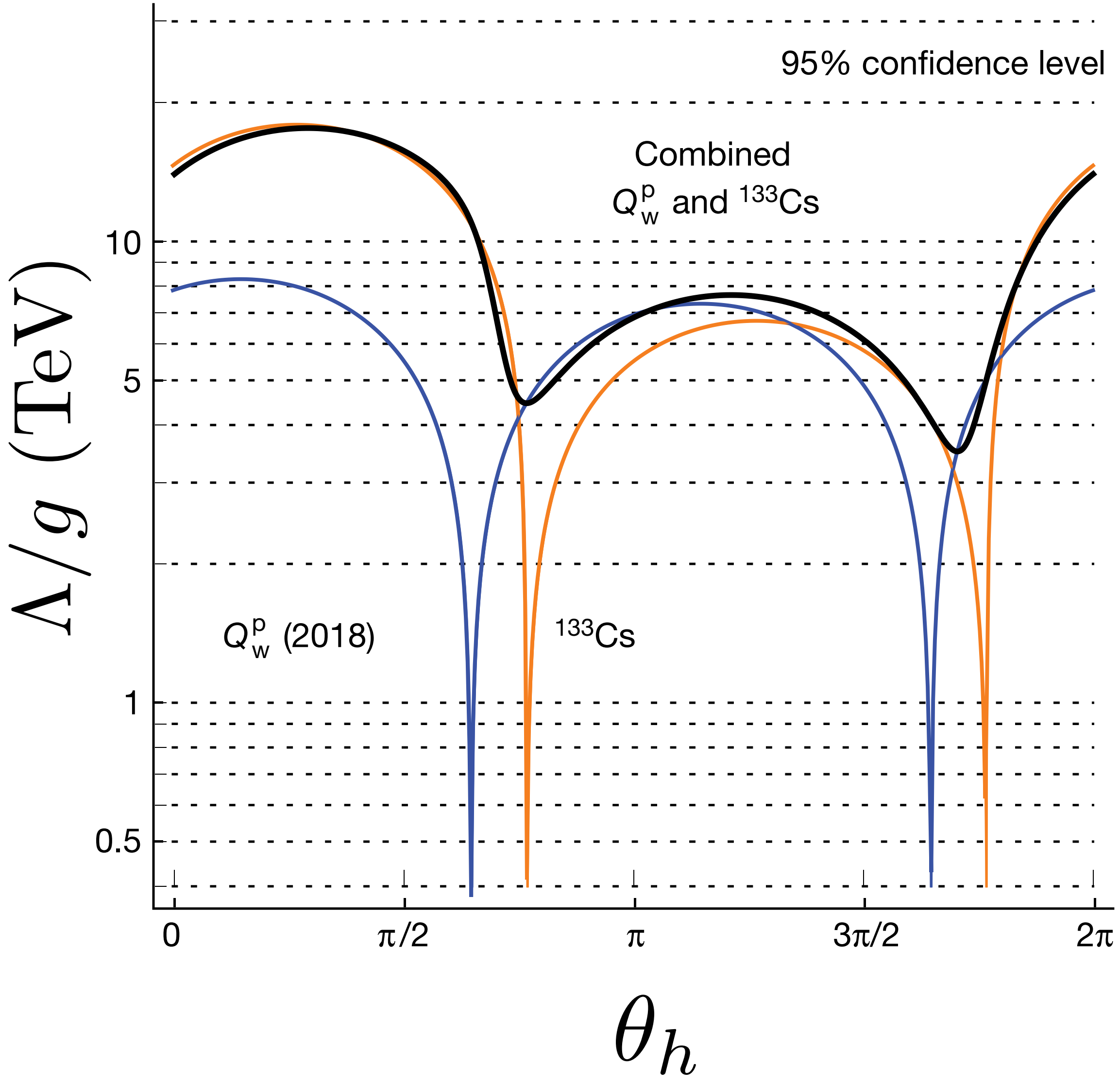
***down* quark**

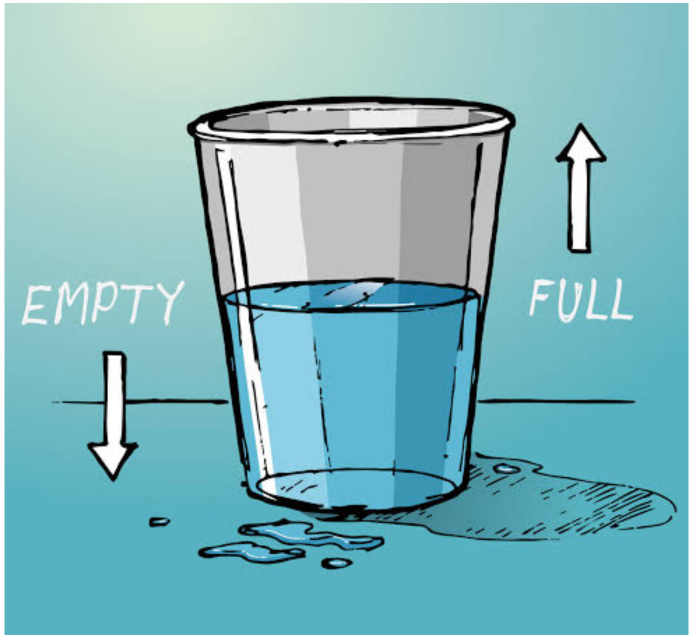
***up* quark**



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

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





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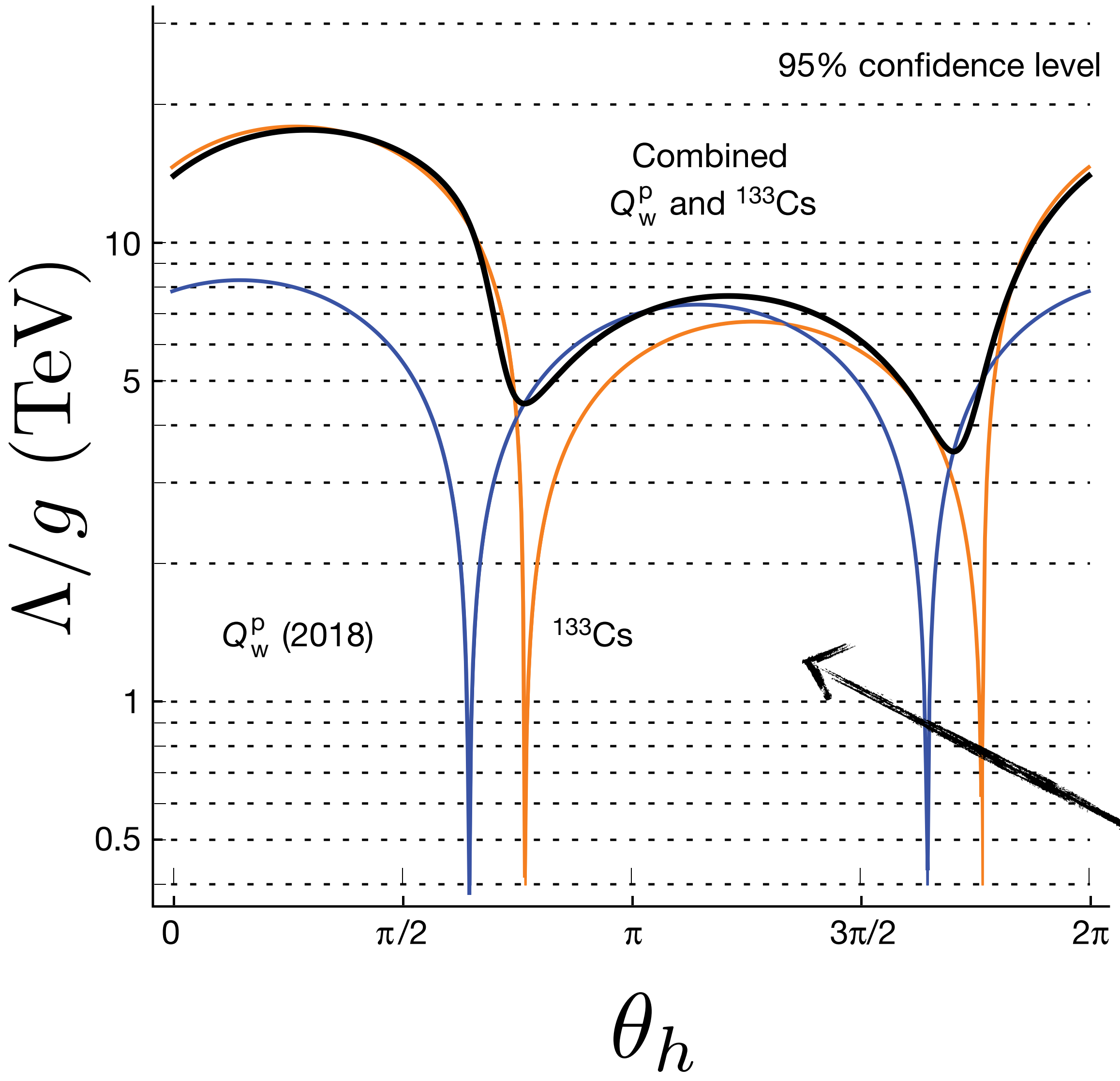

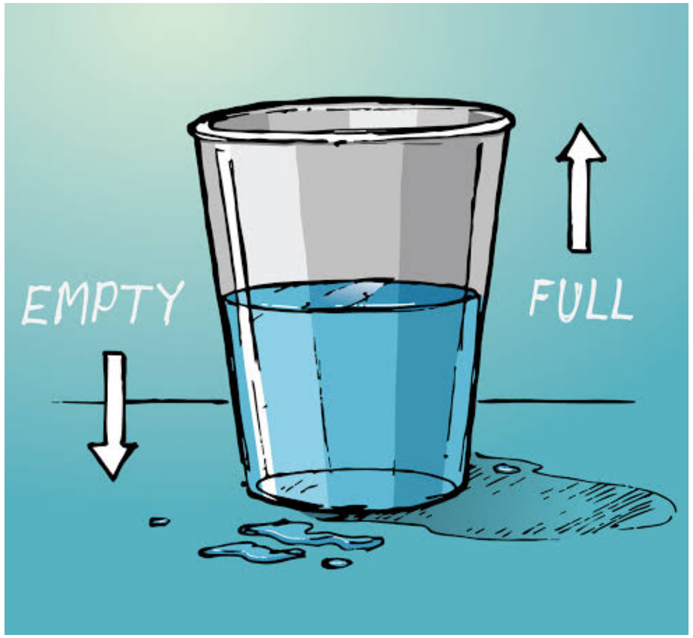

None of these models are possible

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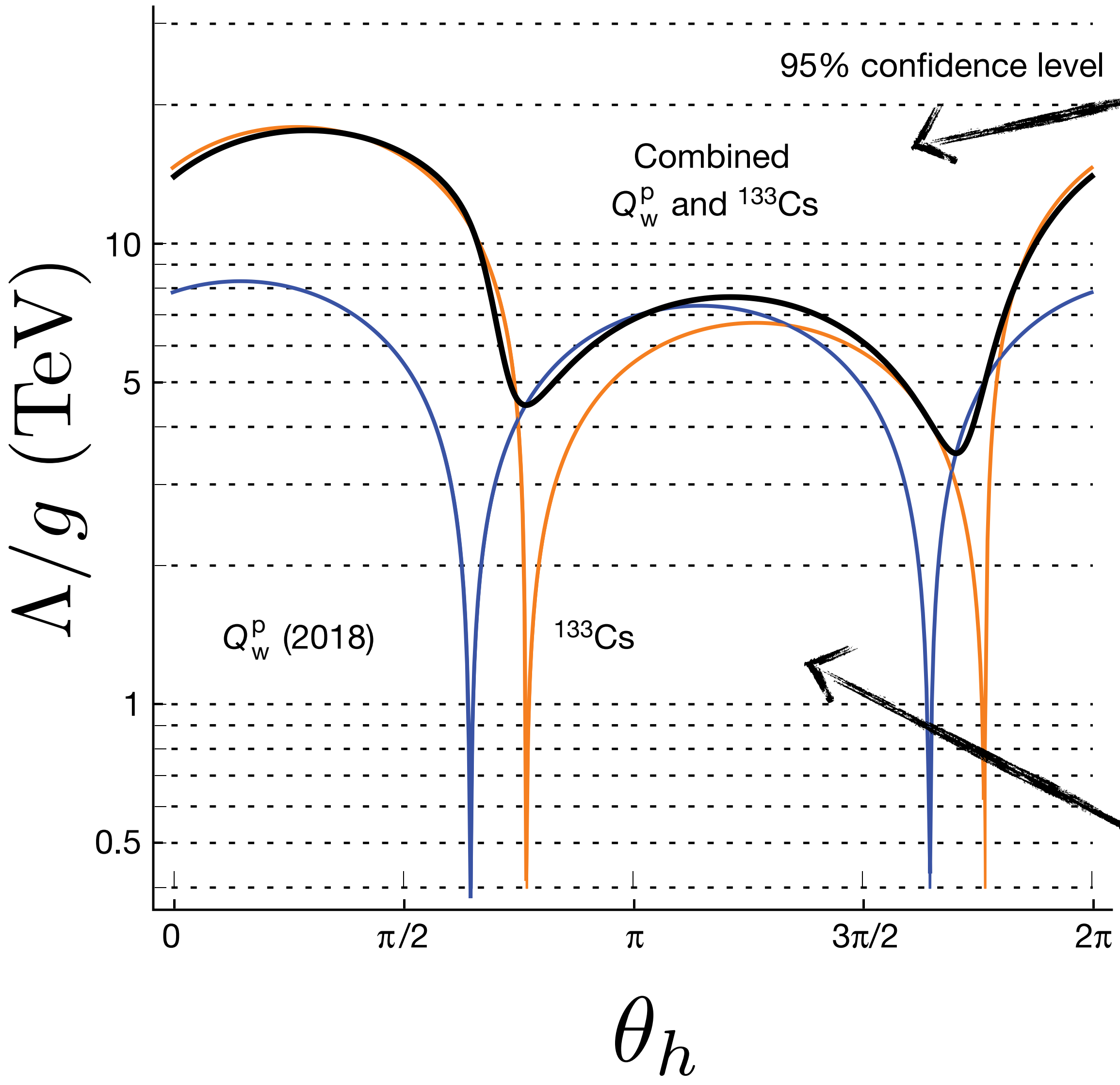
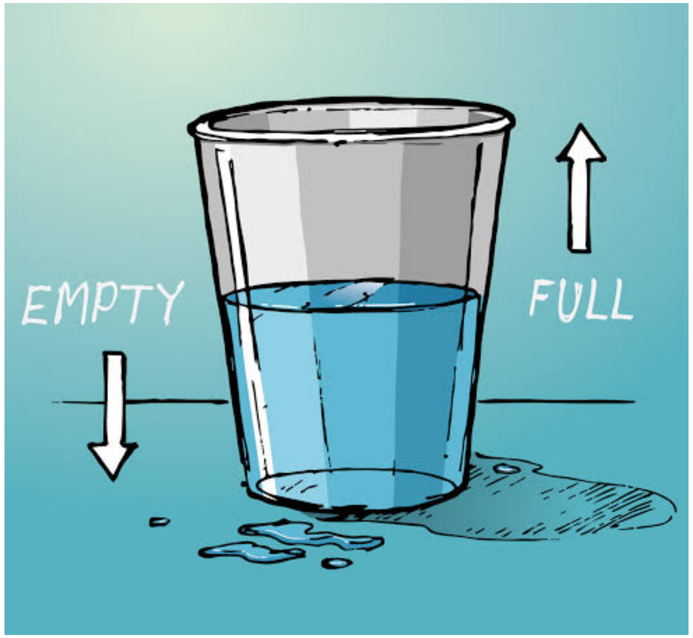


All of these models are possible



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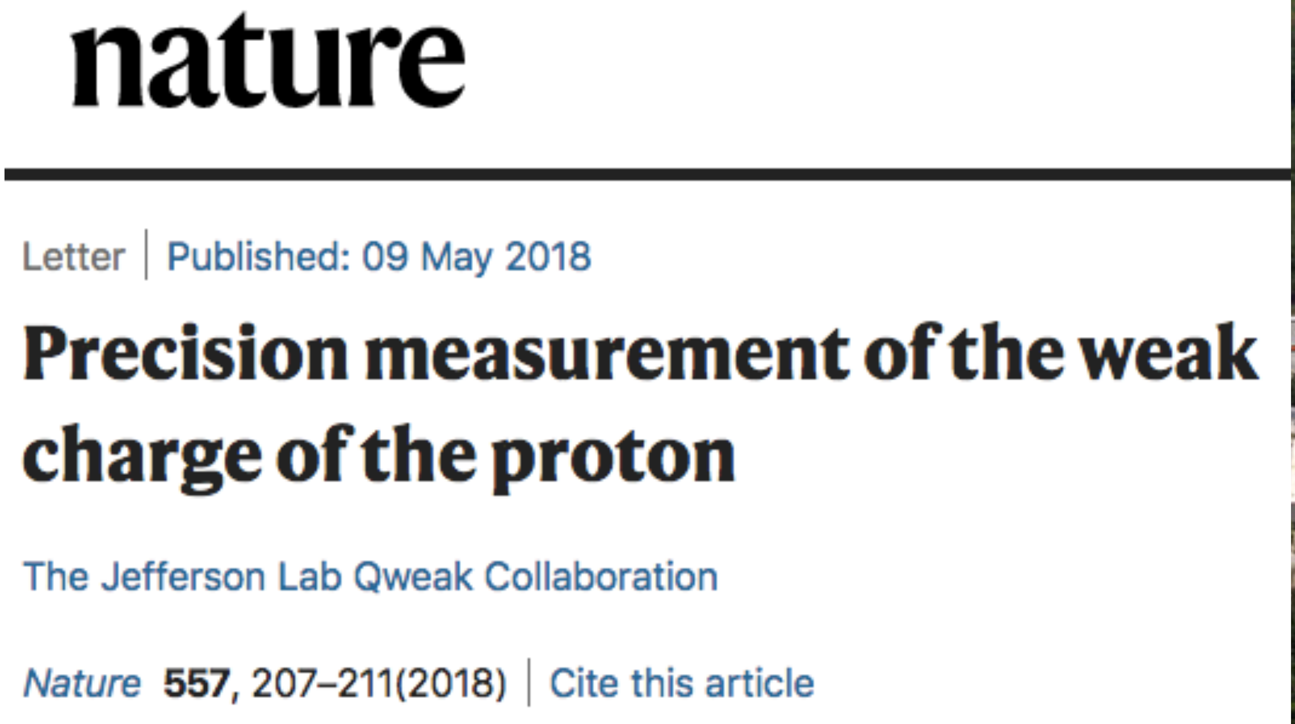
What was measured?



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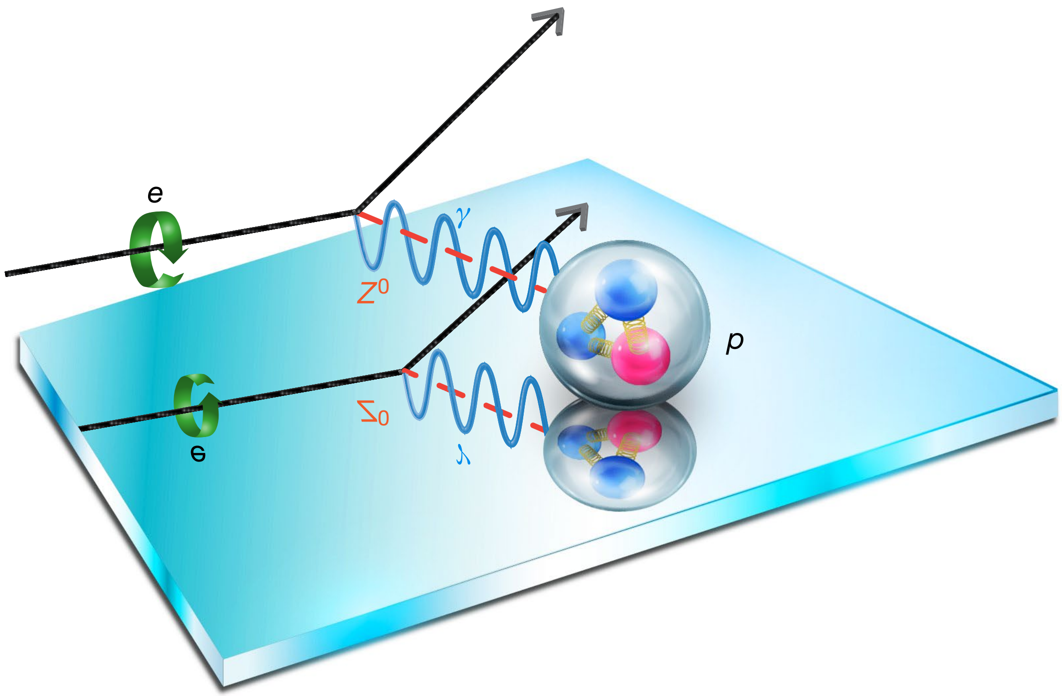
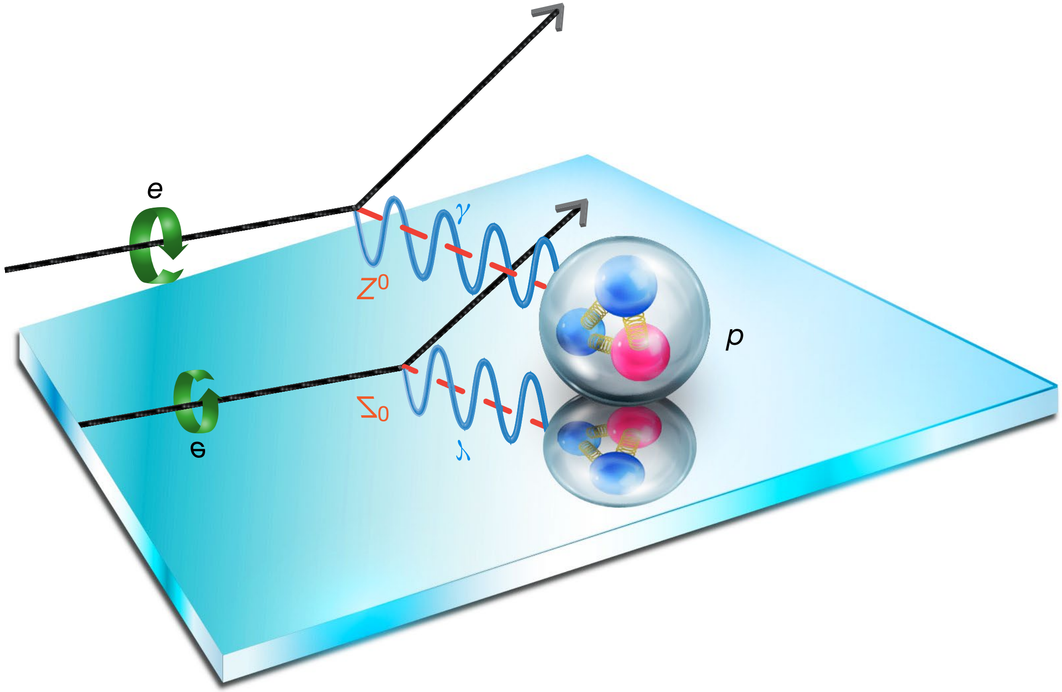
Newport News, VA



Q-weak: *A precision test of the Standard Model and determination of the weak charges of the quarks through parity-violating electron scattering*



$$A_{\mathrm{ep}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_R} = -227.2 \pm 8.3(\mathrm{stat.}) \pm 5.6(\mathrm{syst.})\ \mathrm{ppb}$$

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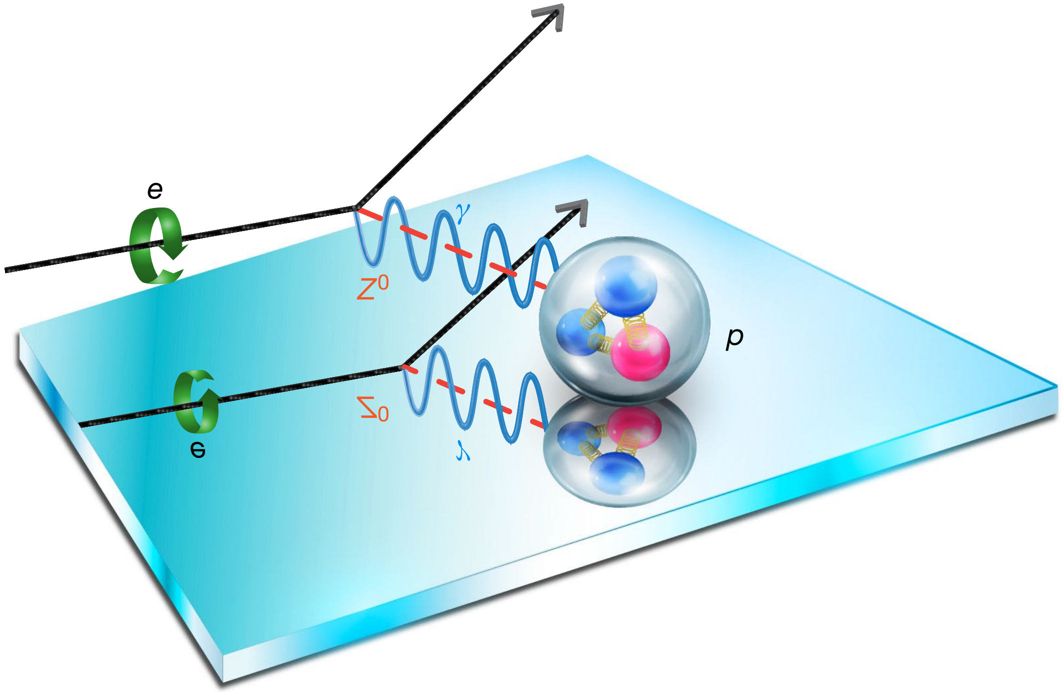

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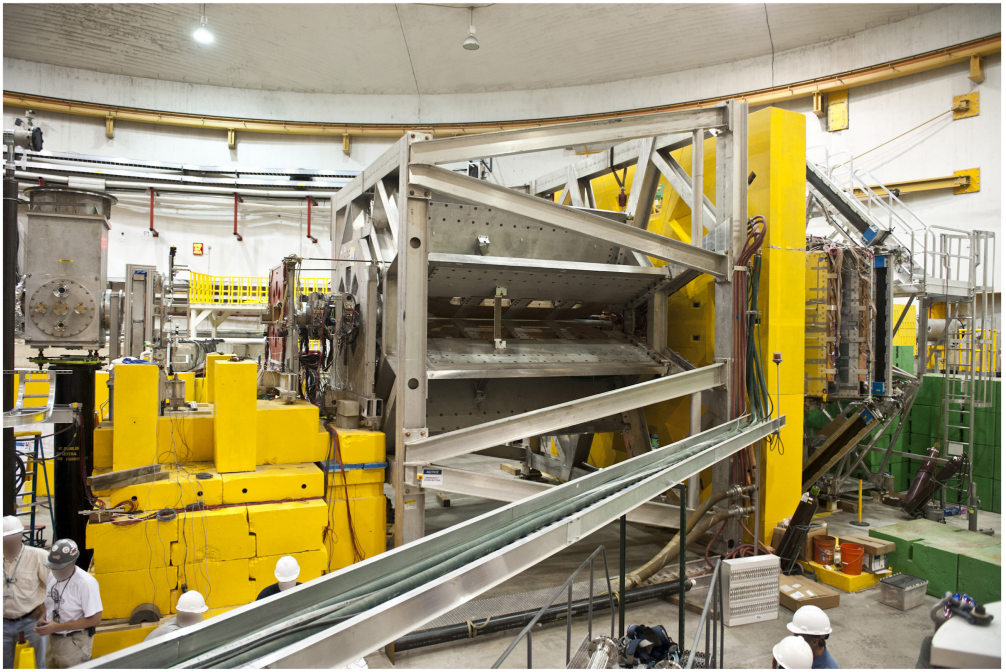
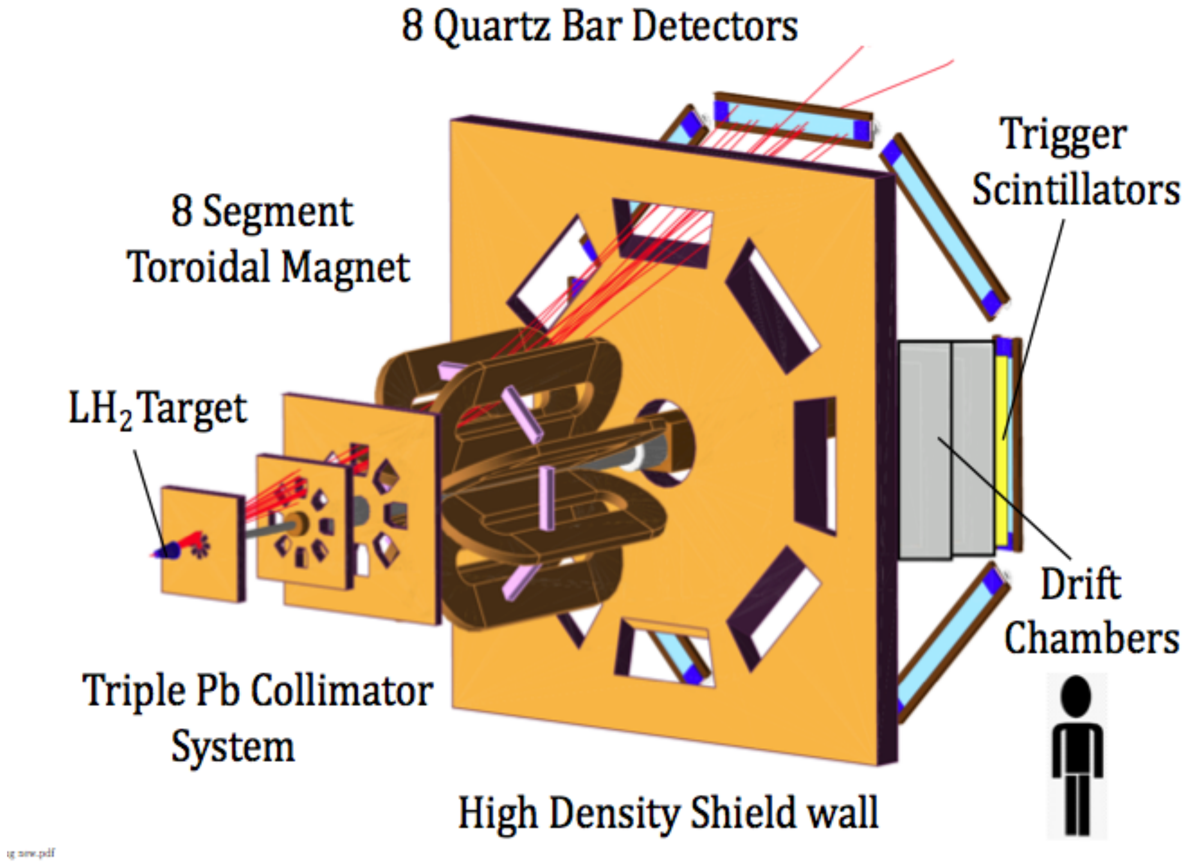
parts per billion!



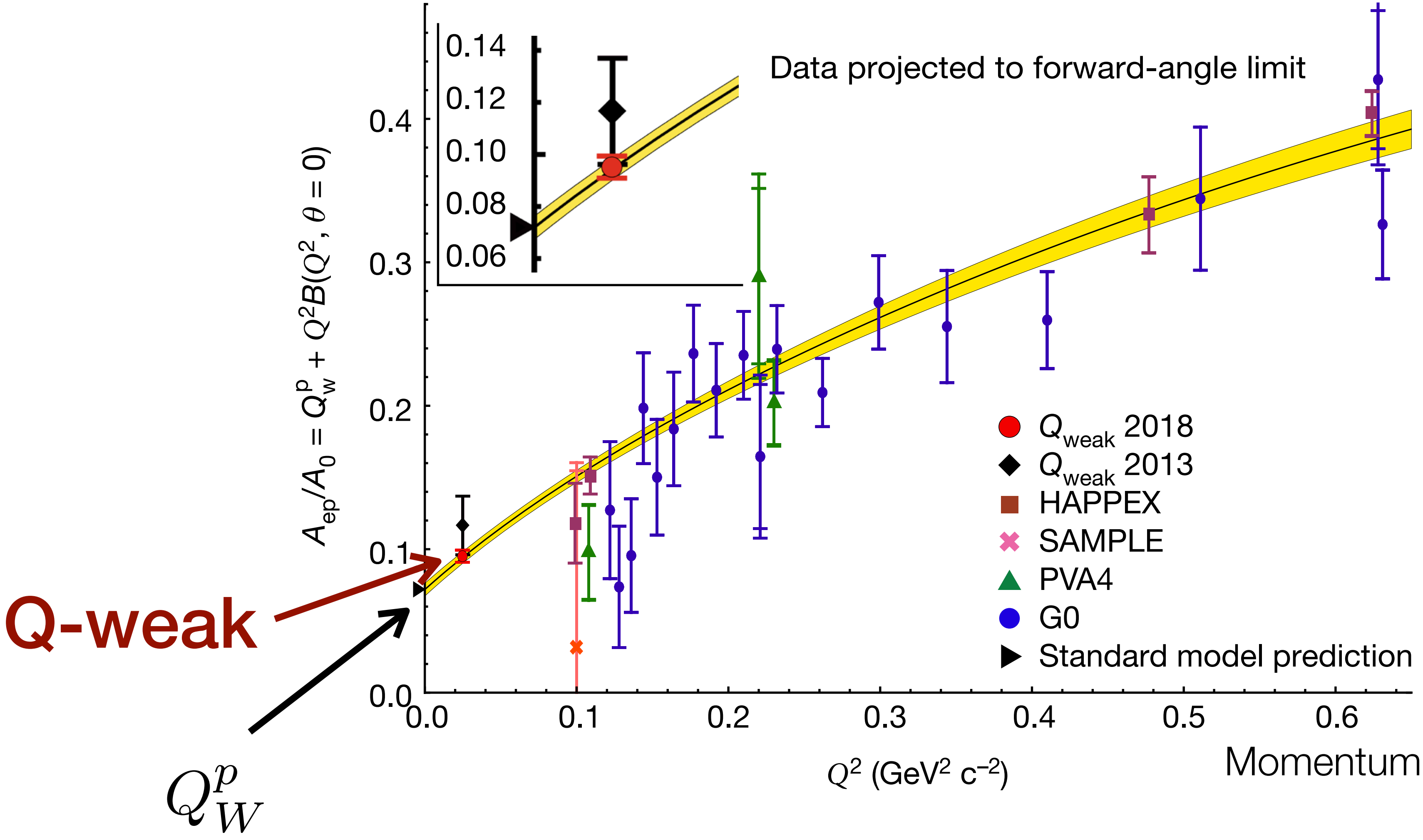
The Q-weak experiment

- Highly-polarised intense beam (180μA)
- Fast beam-helicity flip (960 Hz)
- Precision polarimetry (±0.6%)
- High-power target refrigeration (3kW)



Measured asymmetry → weak charge

Q-weak (normalised) asymmetry

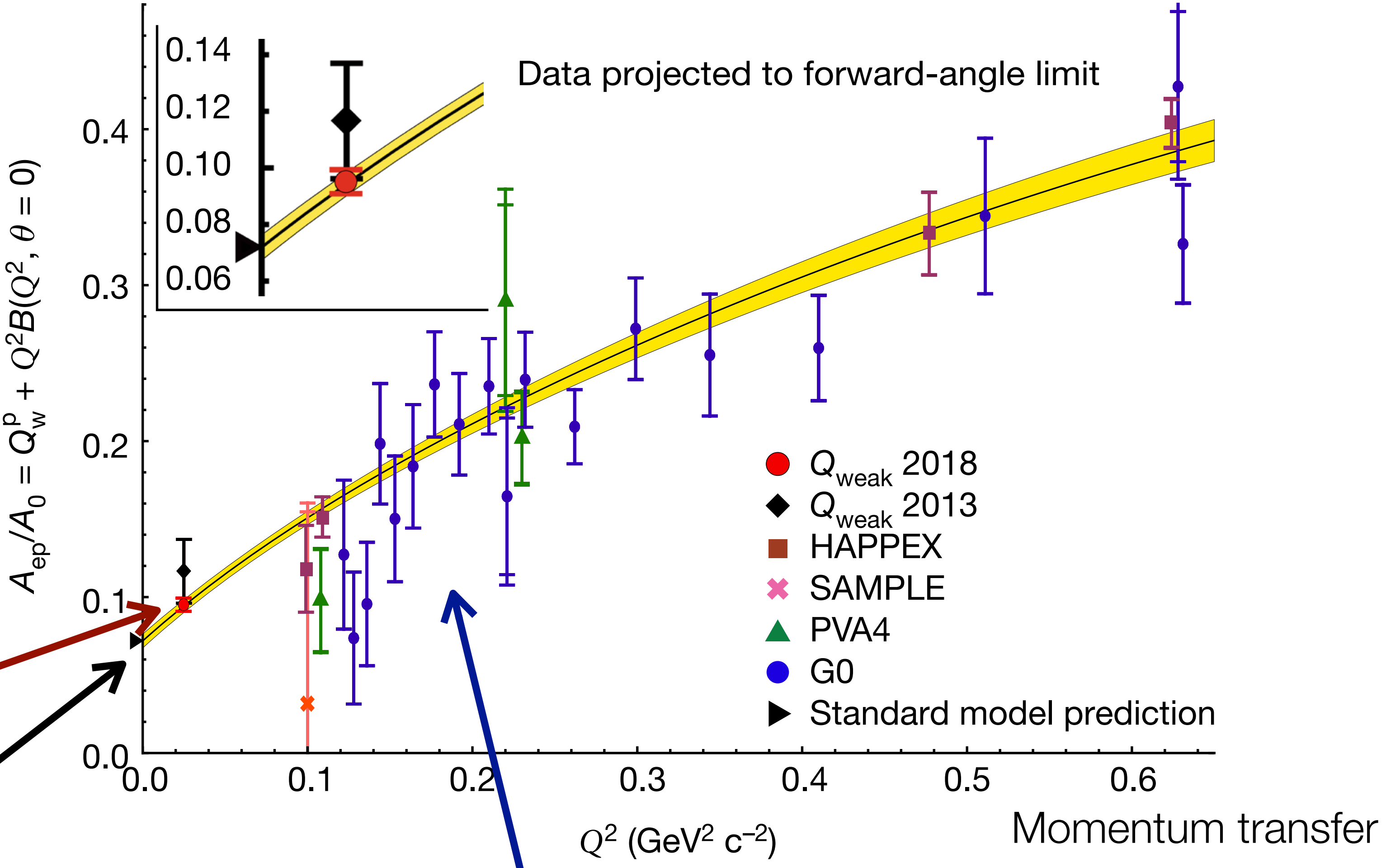


Q-weak

Q_W^p

Momentum transfer

Q-weak (normalised) asymmetry

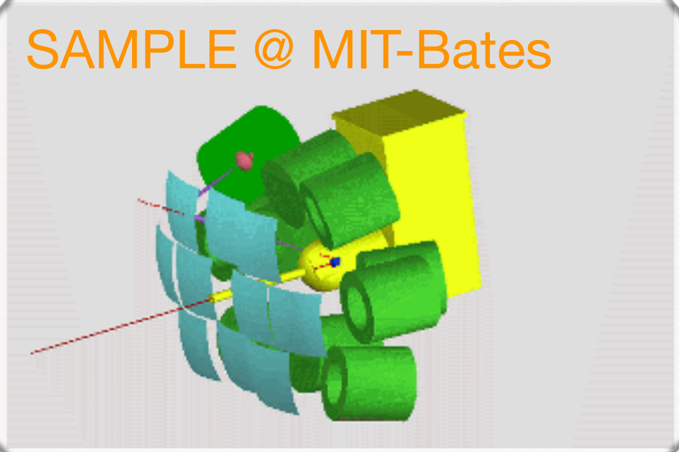


Q-weak

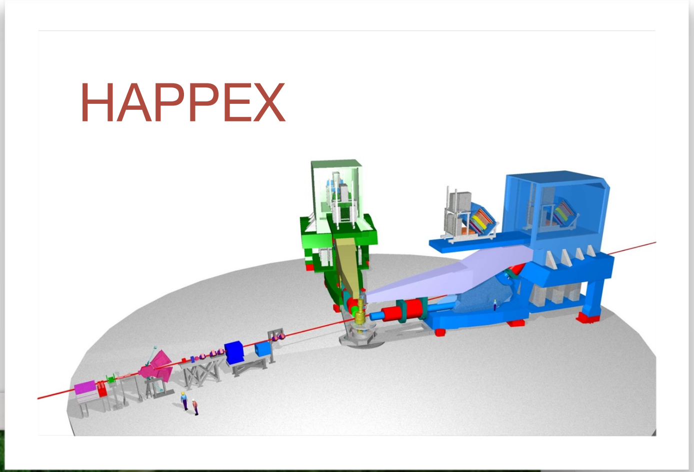
Q_W^p

Shape of curve corresponds to shape of proton seen through a neutral-current lens:

Uncertainty limited by knowledge of strange quark EM form factors



SAMPLE @ MIT-Bates



HAPPEX

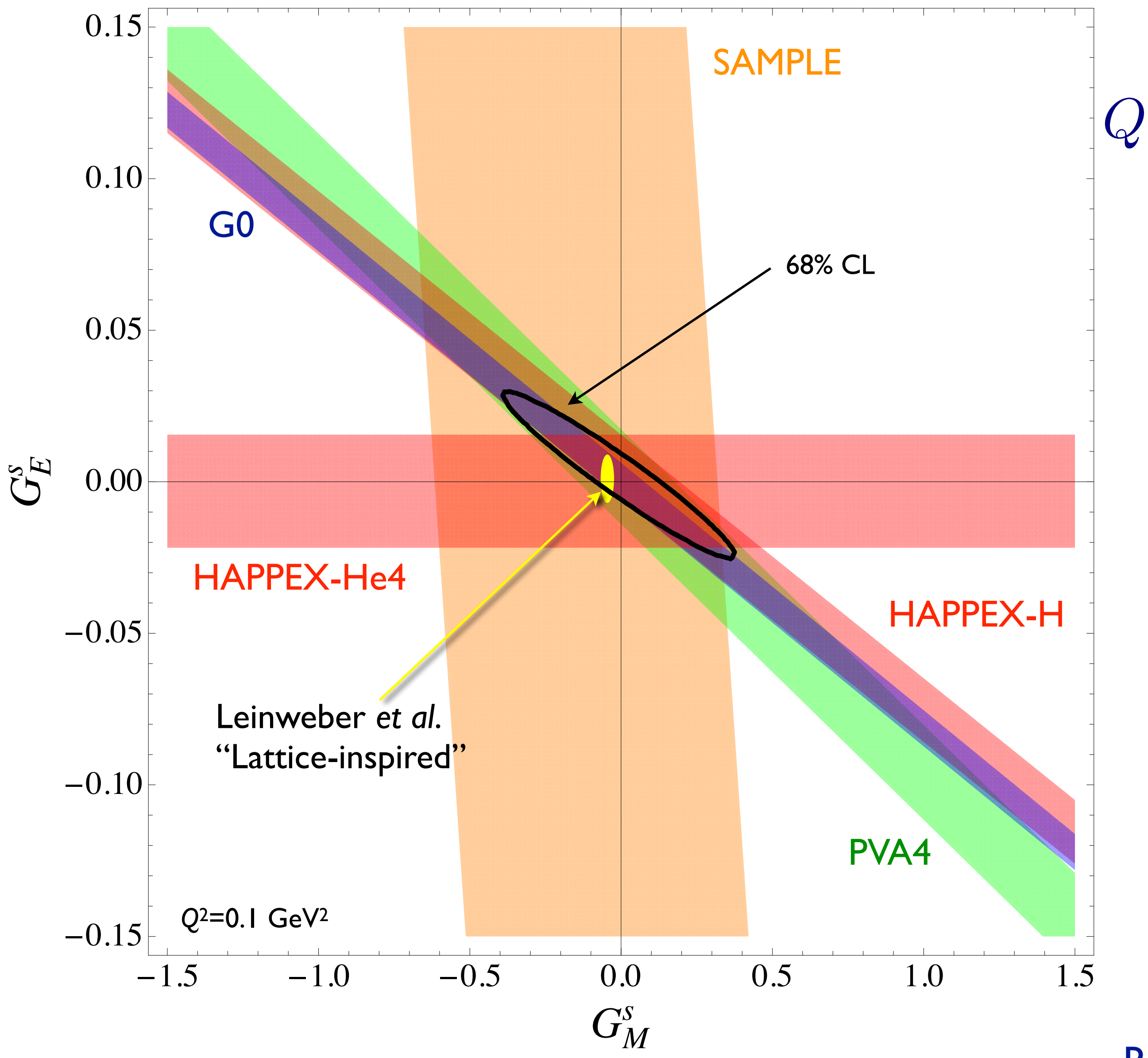
PVA4 @ MAMI

JLab

G0

Strangeness measurements

“Hadronic background”



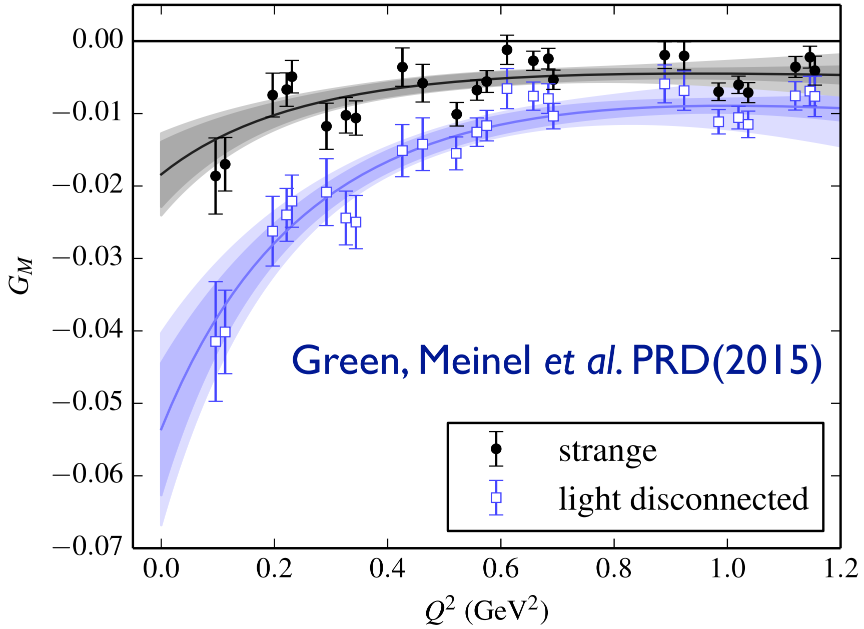
$Q^2 = 0.1\,\mathrm{GeV}^2$

RDY et al. PRL(2007)

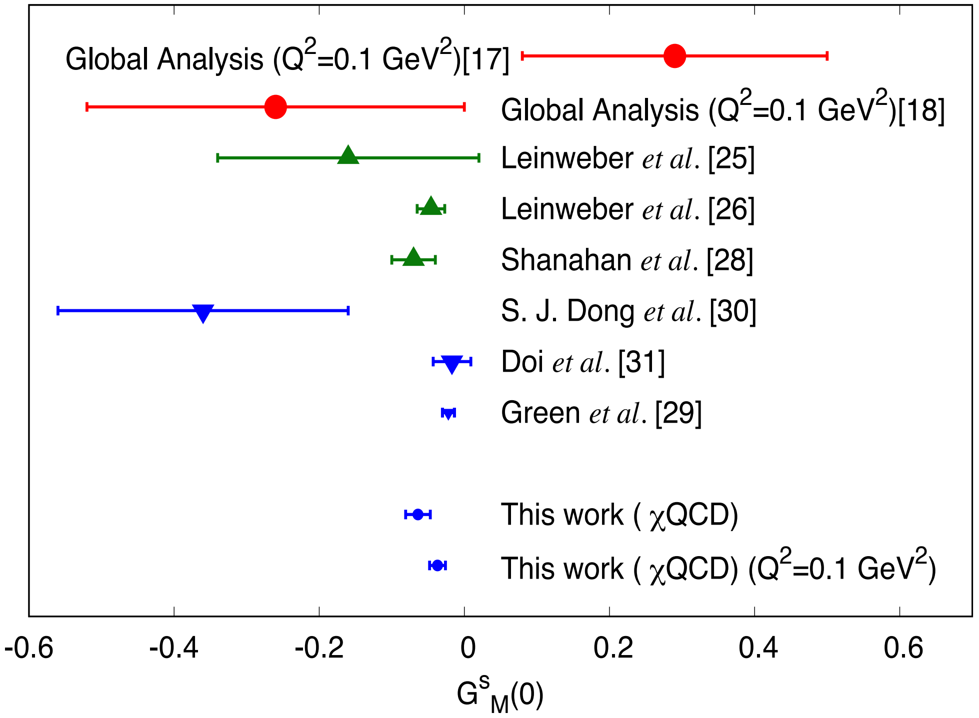
Combined global analysis

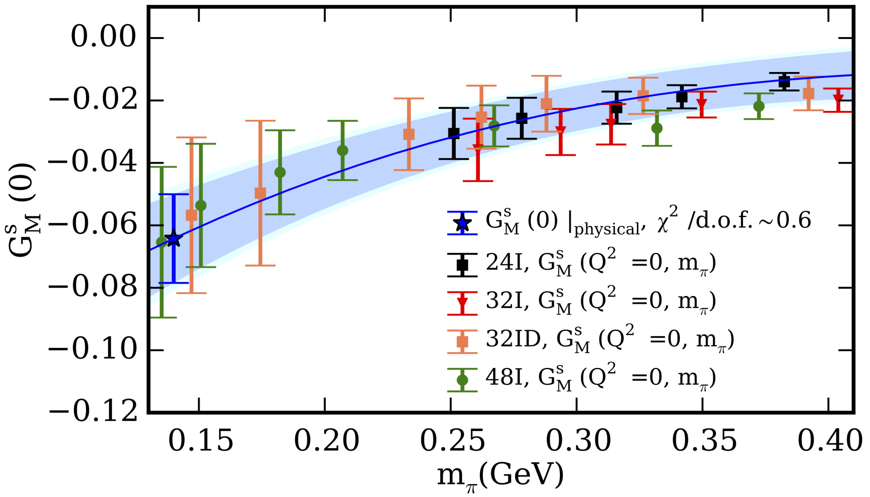
Theory expectations much smaller than experimental limits

Strangeness updates



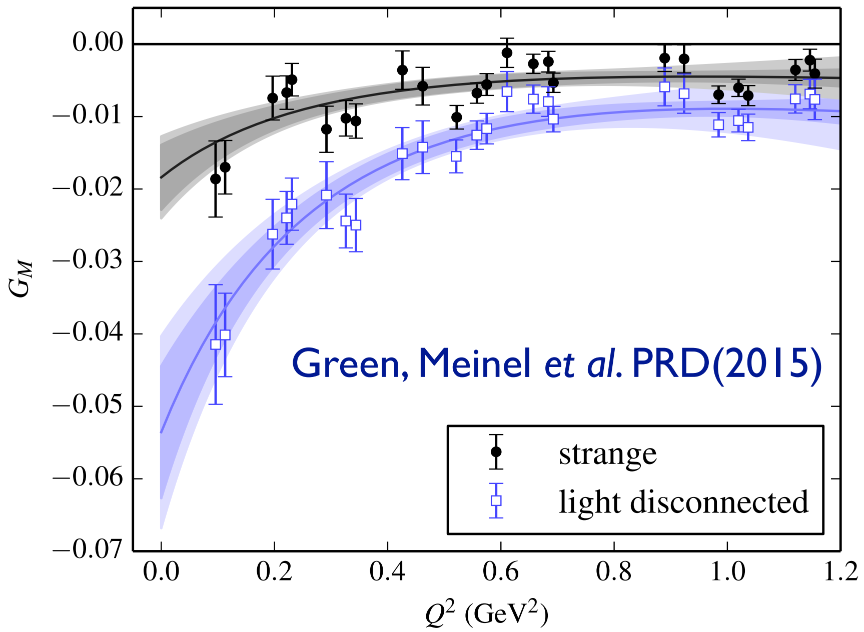
Green, Meinel *et al.* PRD(2015)





Sufian *et al.* PRL(2017)

Strangeness updates



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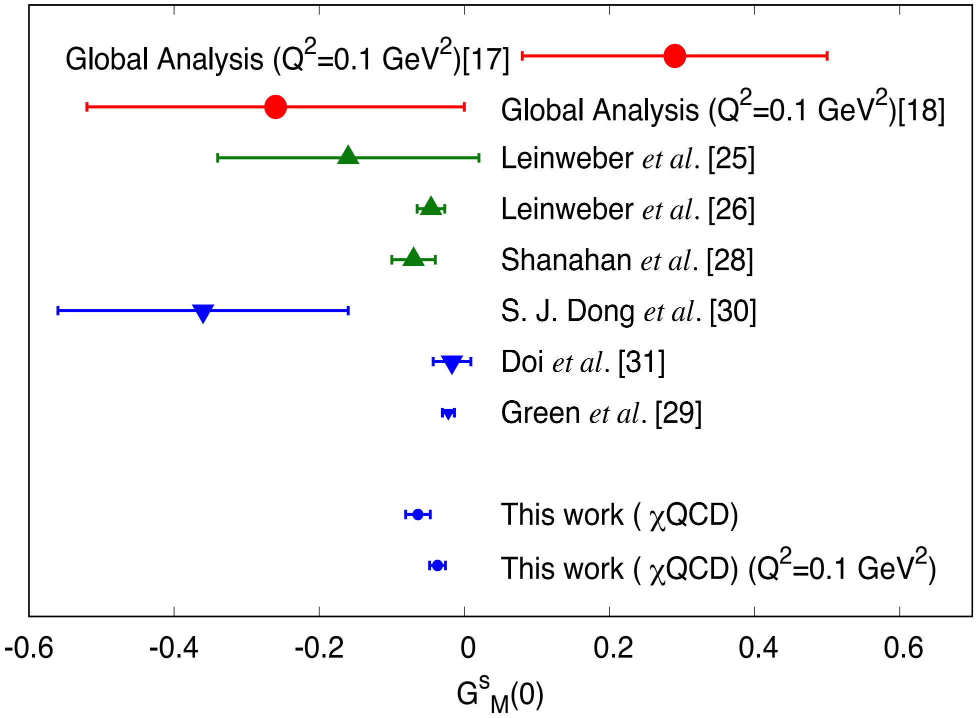
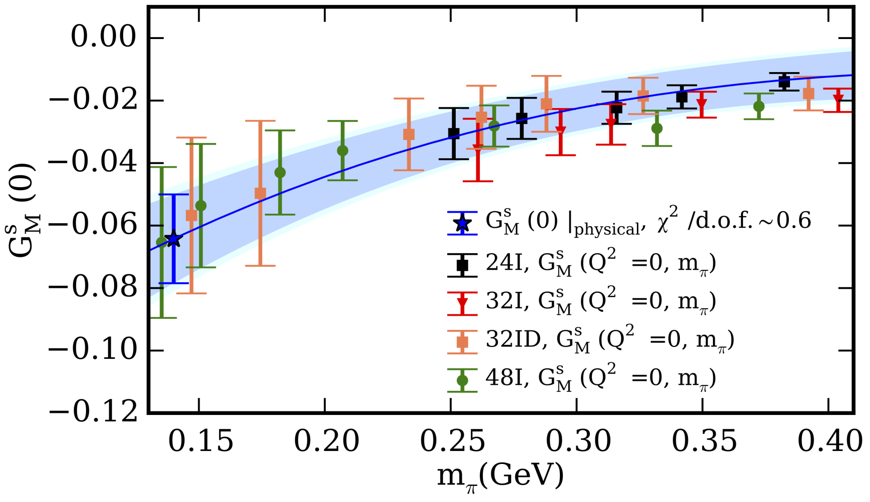




Sufian *et al.* PRL(2017)

Particle physics

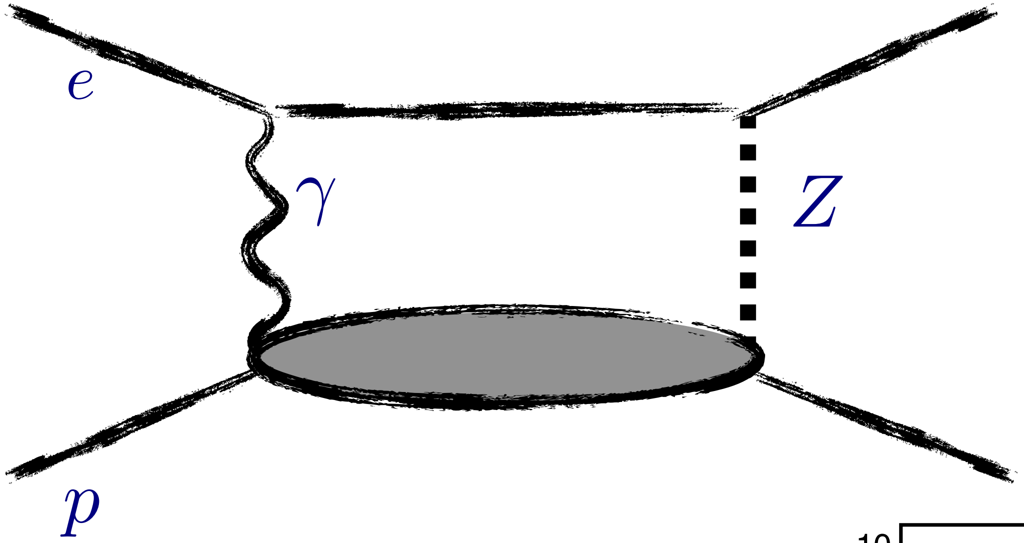
Strangeness in the proton

Ross D. Young

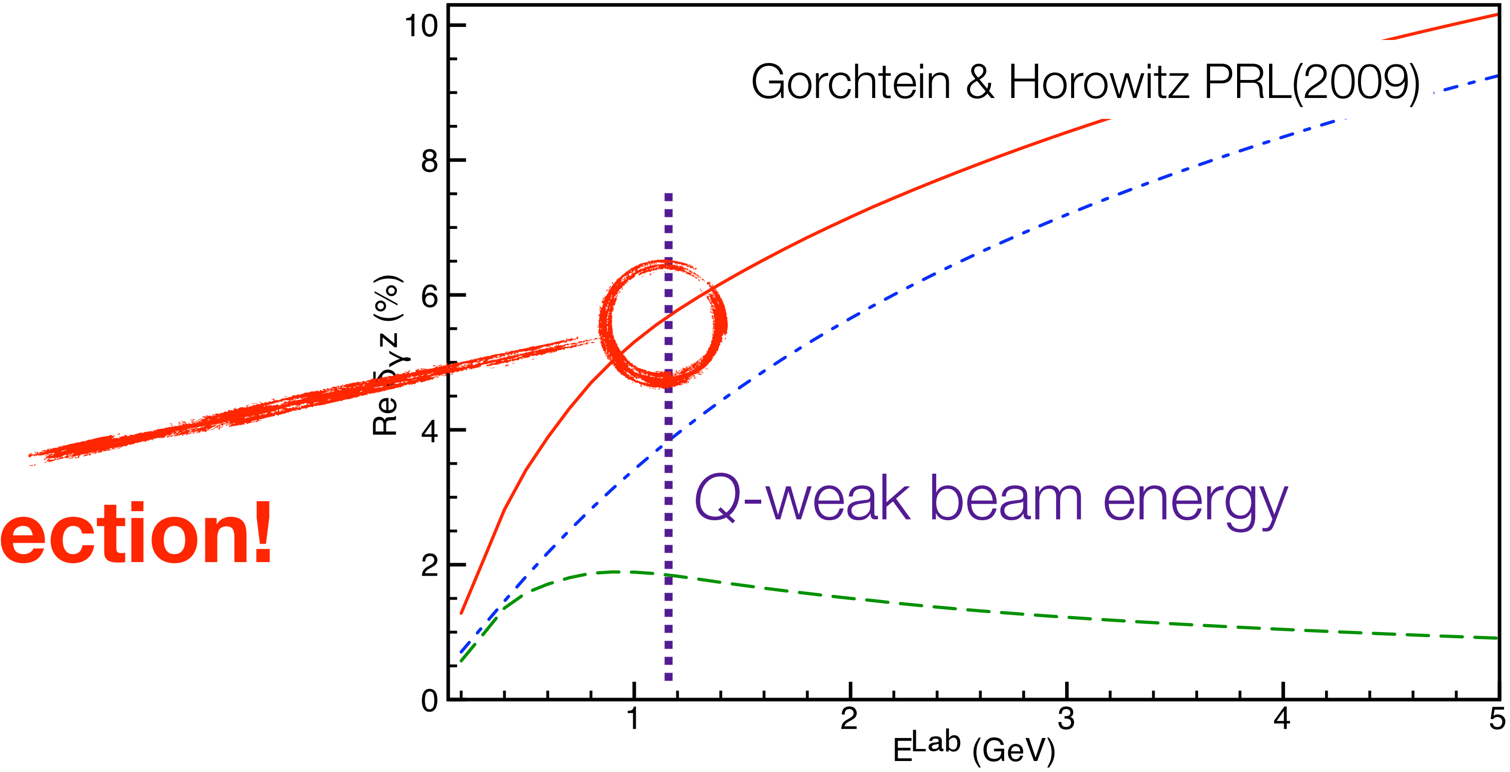
Nature **544**, 419–420 (2017) | Cite this article

A revision to radiative corrections

Radiative corrections: γZ box



Target specific radiative correction



6% correction!

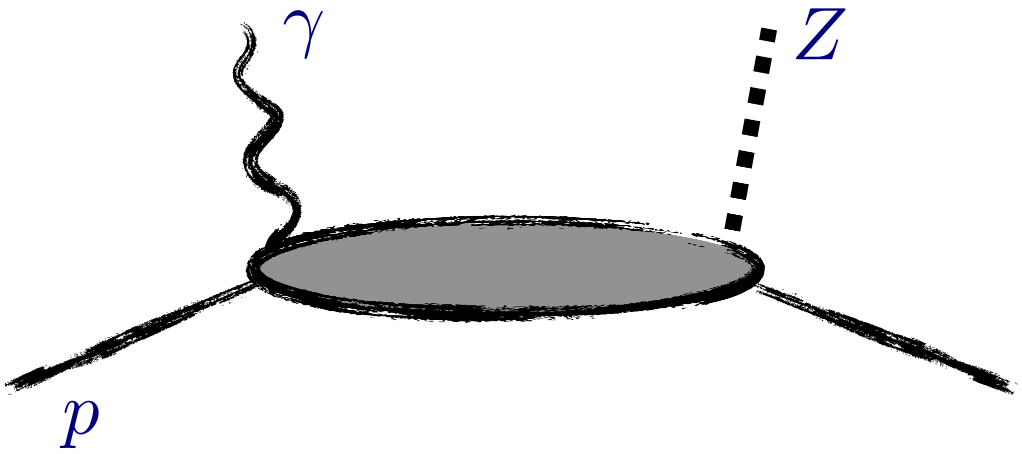
Why is the gamma-Z box so big?

- It isn't, but the weak charge is small

$$Q_W^p = 1 - 4\sin^2\theta_W \simeq 0.07$$

How to evaluate?

- Require knowledge of the interference structure function



gamma-Z box

- Forward dispersion relation:

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

- Imaginary part given by:

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

gamma-Z box

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

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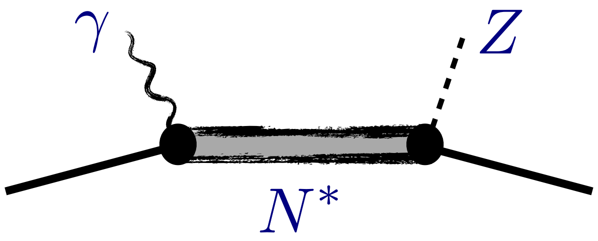
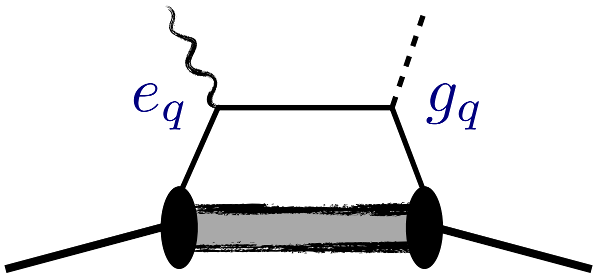
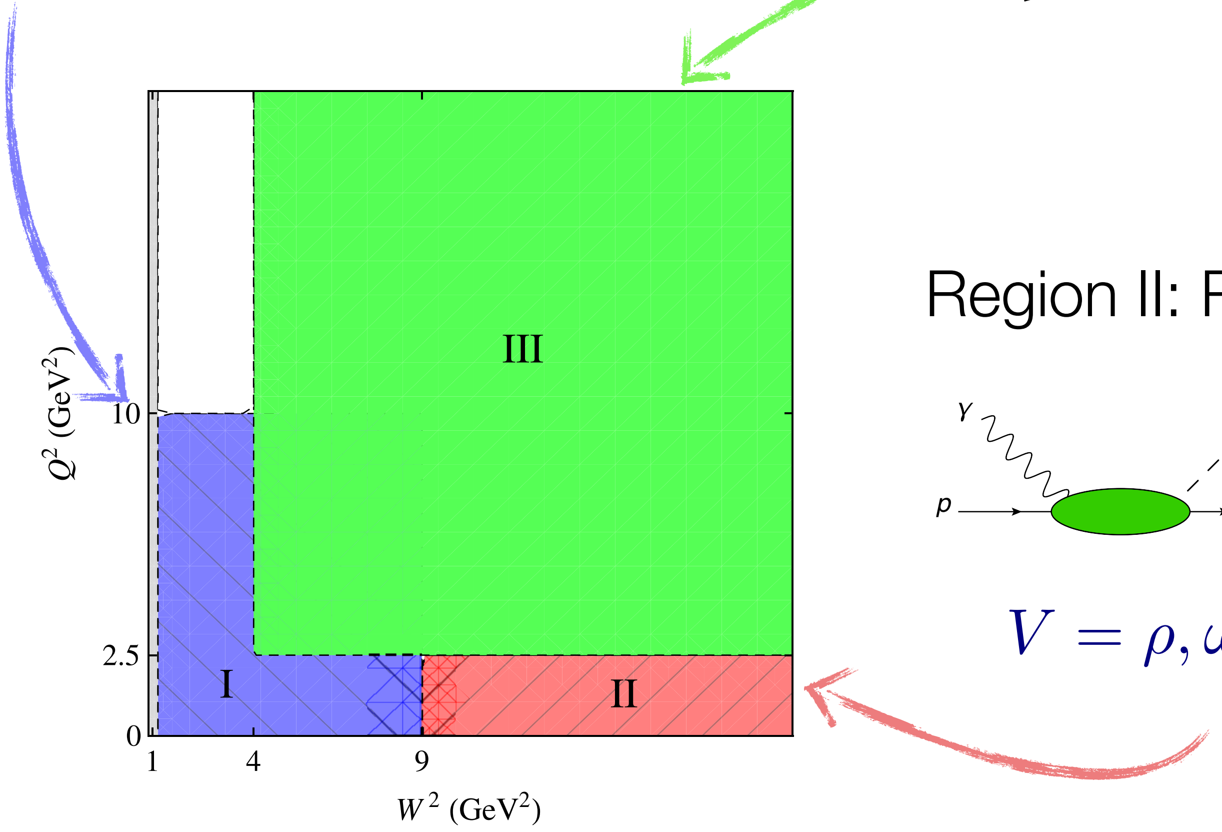
γZ interference structure functions

Region I: Resonances

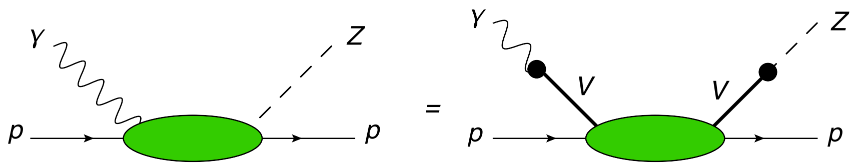


Region III: Partonic



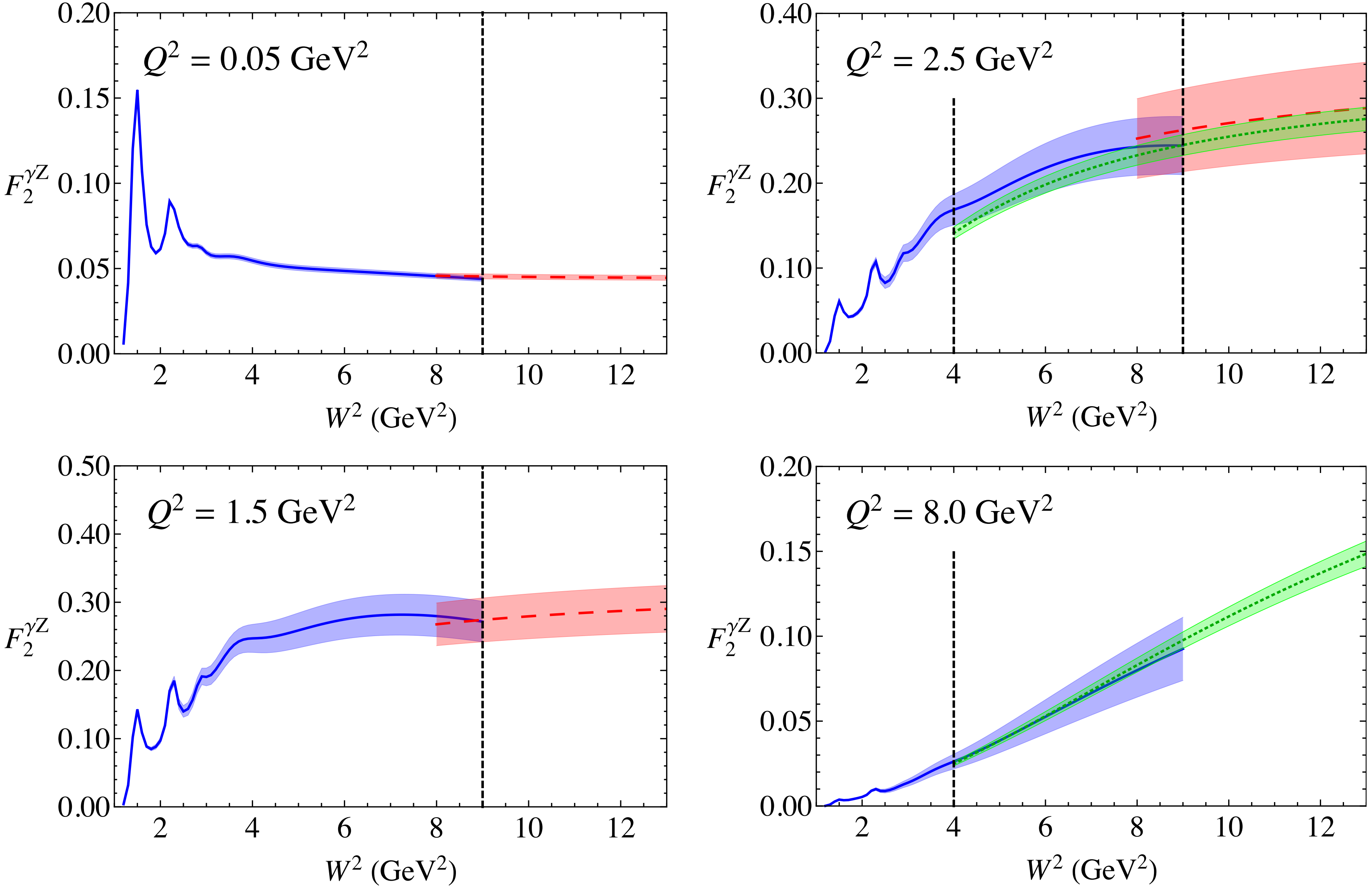


Region II: Regge

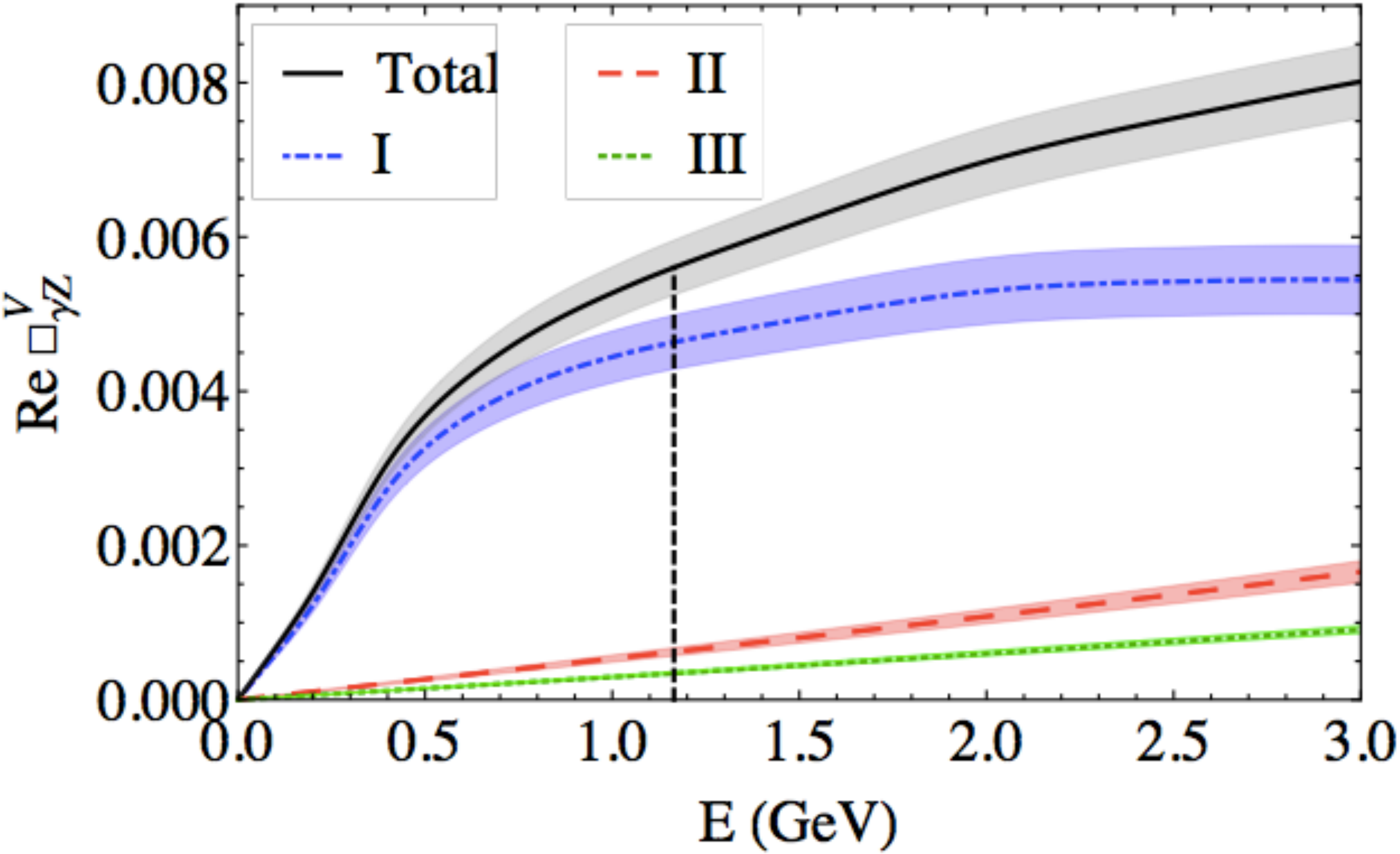


$$V = \rho, \omega, \phi + \text{ continuum}$$

Integration region



Boundary matching: γZ structure functions



Hall *et al.*, PRD(2013)

Our result

AJM: Adelaide-JLab-Manitoba

“Independent” theoretical determinations

$\mathrm{GH}\ (2009)$

Gorchtein *et al*.

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

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

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

Rislow & Carlson

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

“Independent” theoretical determinations

$$\begin{aligned}
\text{GH}\ (2009)&\\
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\end{aligned}$$

Gorchtein *et al*.

Rislow & Carlson

Good agreement
on central value

“Independent” theoretical determinations

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\end{aligned}$$

Gorchtein *et al*.

Rislow & Carlson

Good agreement
on central value

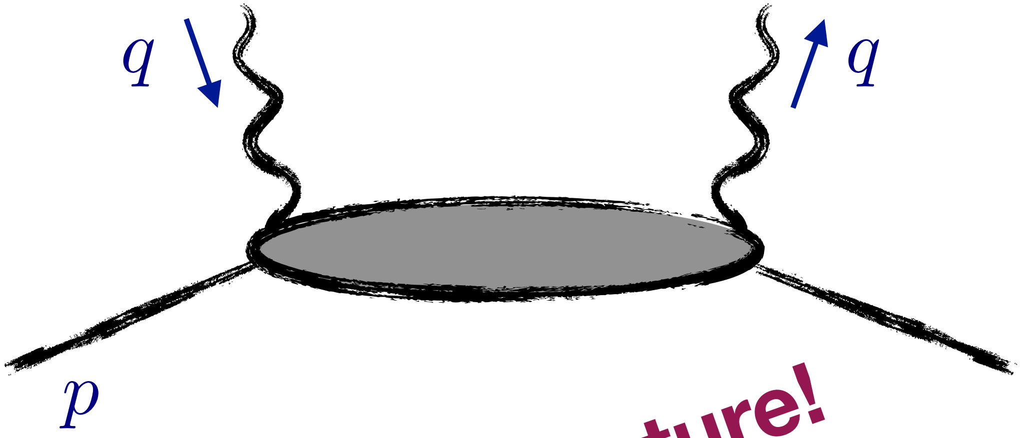
A little debate over
uncertainty

Improved constraint from lattice QCD?

$$E = E_0 + \lambda \langle N|V|N\rangle + \lambda^2 \sum_{X \neq N} \frac{\langle N|V|X\rangle\langle X|V|N\rangle}{E_0 - E_X} + \dots$$

Chambers, RDY *et al*., PRL(2017)
Can, RDY *et al*., PRD(2020)

Immerse nucleon in weak external (magnetic) field



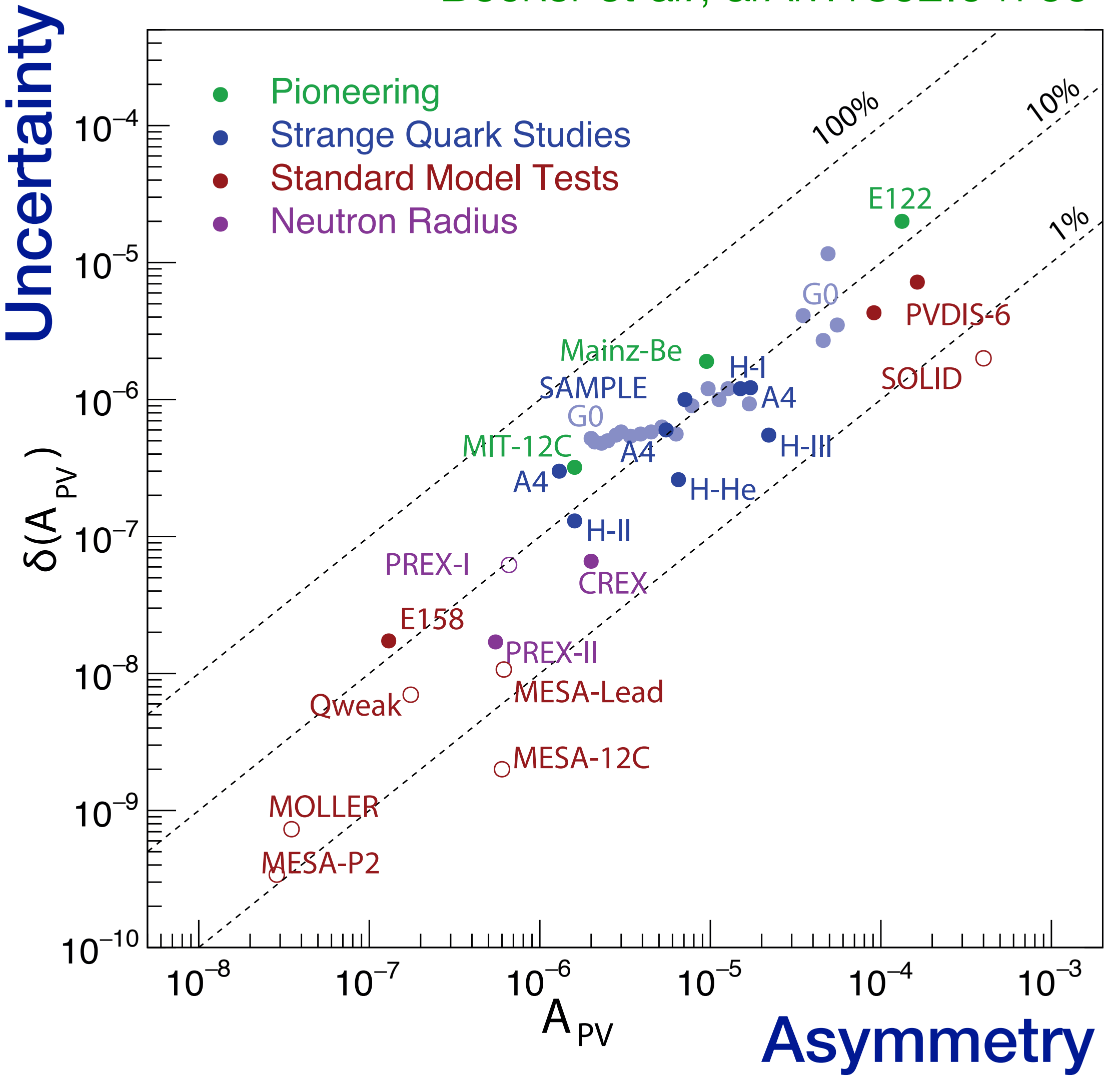
... for the future!

Easy to study full flavour dependence of Compton amplitude

see also:
Somfleth (UA Honours thesis, 2015)
Alkithiri (UA PhD thesis, 2019)
Seng & Meißner PRL(2019)

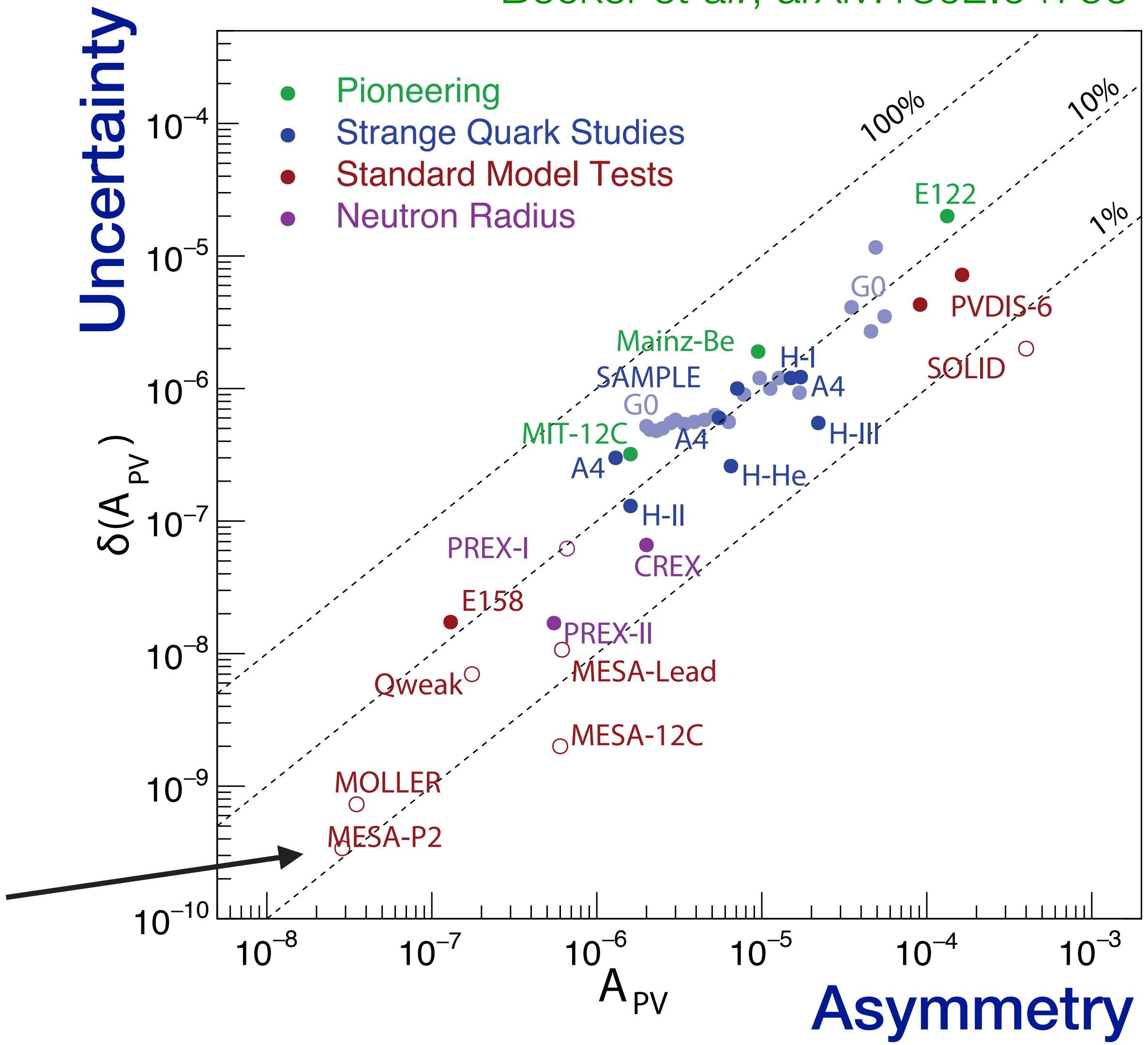
What’s next?

Next-generation experiments



Becker *et al.*, arXiv:1802.04759

Next-generation experiments



Becker *et al.*, arXiv:1802.04759

P2@MESA in Mainz

Proton weak charge

Low-energy beam to lessen sensitivity to γZ box

Next-generation experiments

MOLLER@JLab

PV *ee*

Hydrogen target: inelastic scattering from p

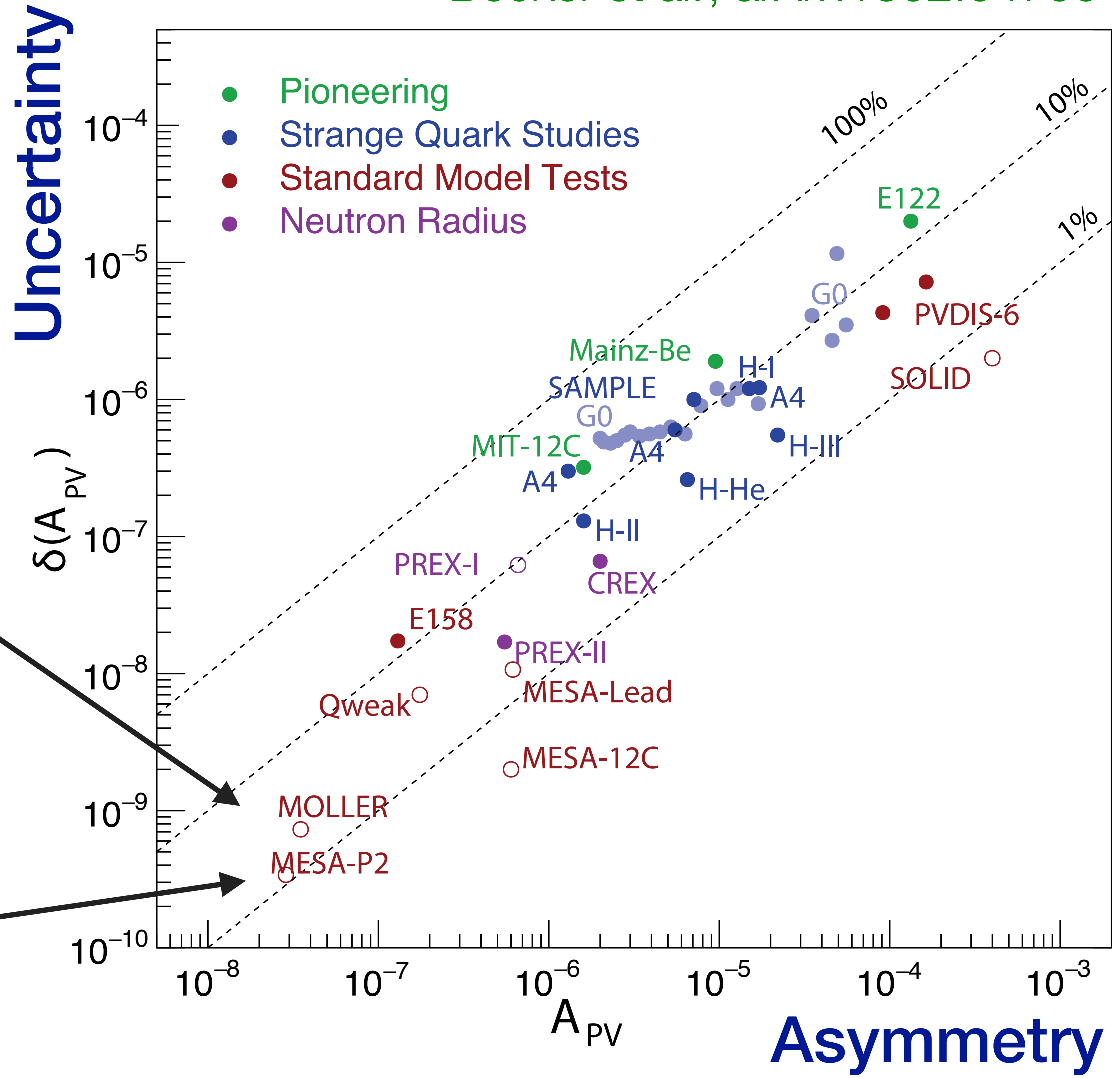
(hence γZ SFs important)

P2@MESA in Mainz

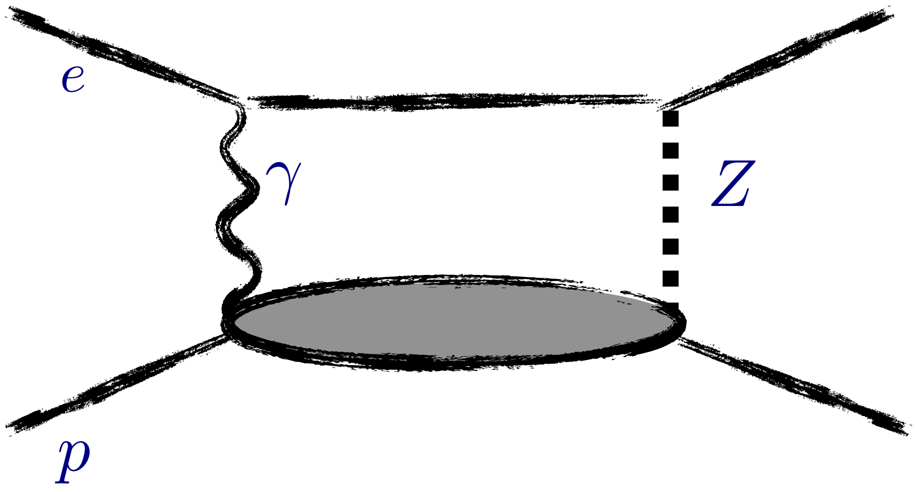
Proton weak charge

Low-energy beam to lessen sensitivity to γZ box

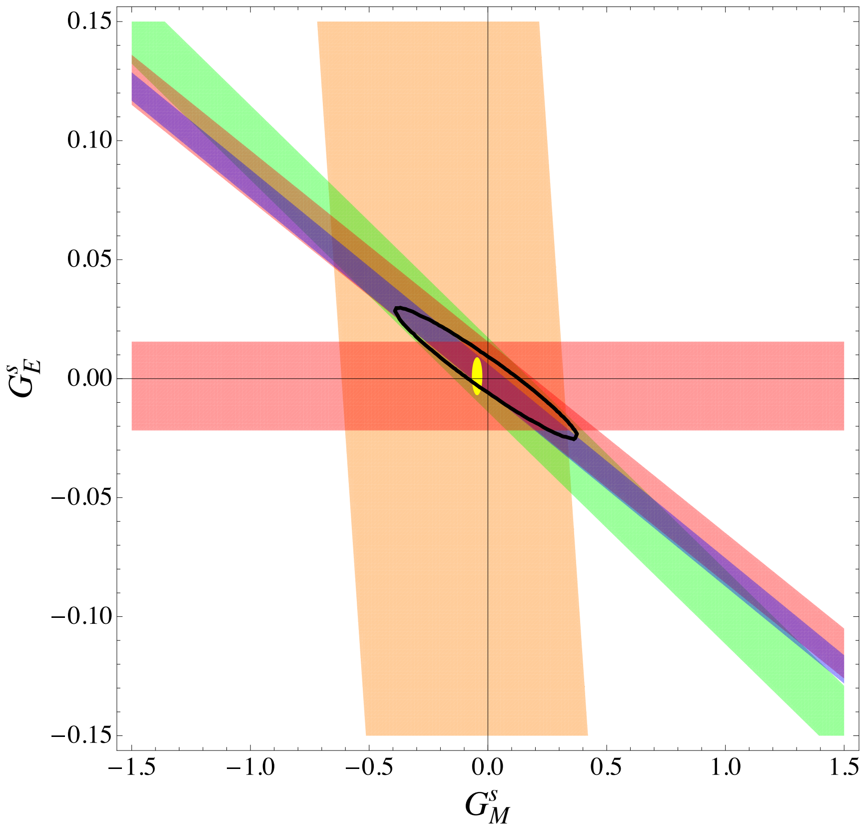
Becker *et al.*, arXiv:1802.04759



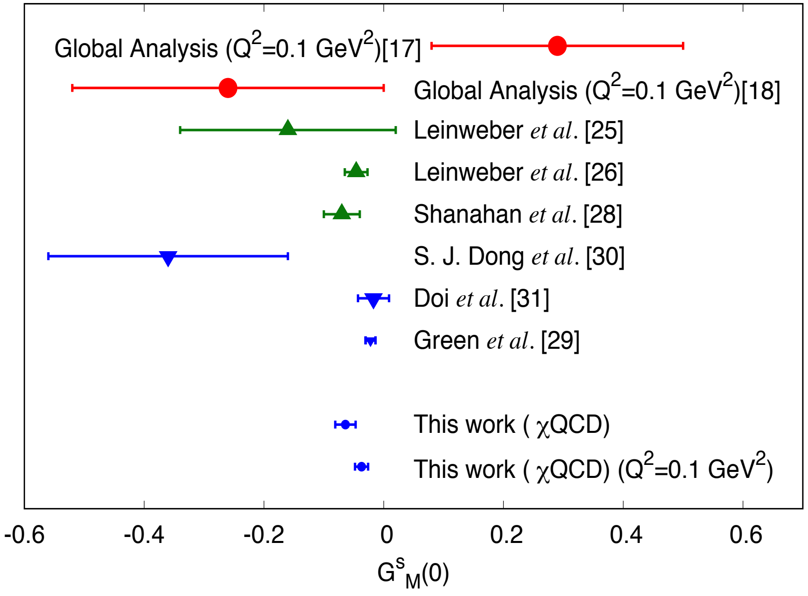
To summarise…

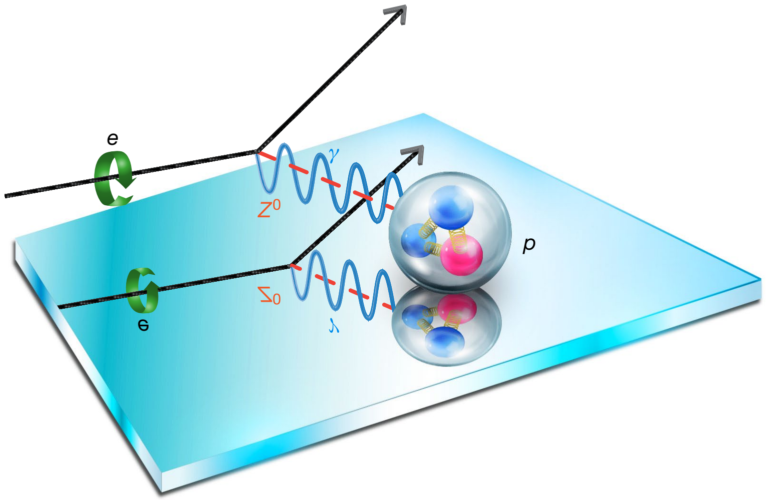


Data-driven analysis of (energy dependent) γZ box



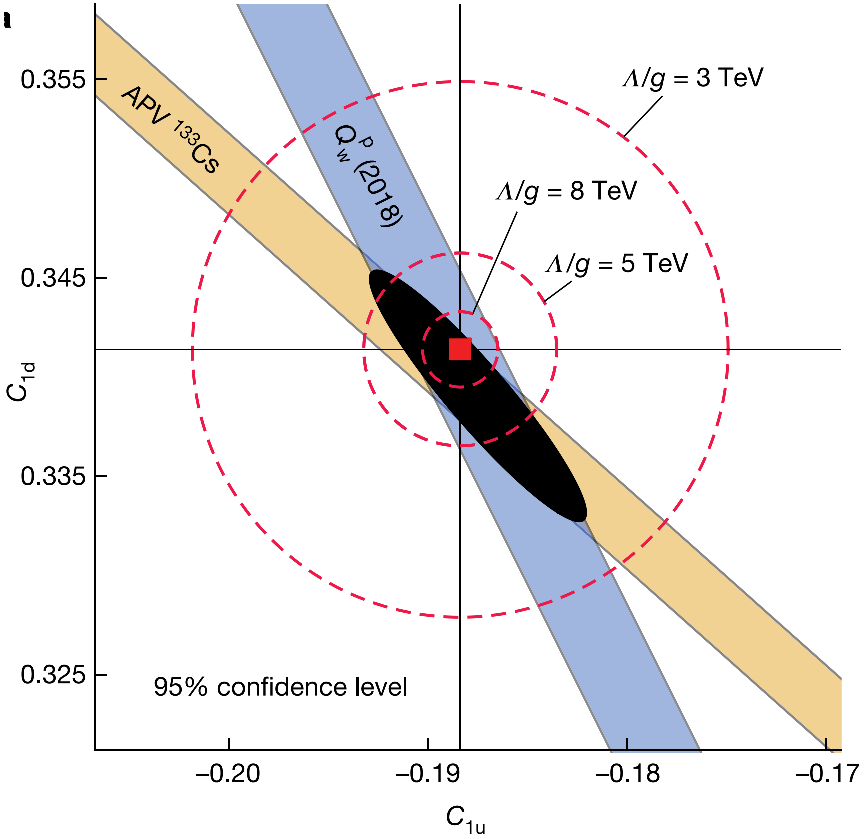
Strangeness theory precision exceeds experiment [Data-driven analysis for final Q-weak]





$$Q_W^p = 0.0719 \pm 0.0045$$

$$Q_W^p(\mathrm{SM}) = 0.0708 \pm 0.0003$$



Bounds on new physics (Z's)