QWEAK : MEASURING THE PROTON'S WEAK CHARGE

Joshua Hoskins
College of William and Mary

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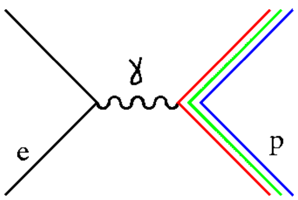
- Low energy $Q^2 \sim 0.03 GeV^2$ precision measurement of $Q_W^P = 1 - 4 Sin^2 \vartheta_W$ to 4%
- Parity violating ep→e'p' scattering
- 180µA of ~85% polarized beam incident on a H_2(l) target
- Possibility of physics beyond the standard model
- Verify and set new limits on the present Standard Model values.
- Precise measurement of weak up/down quark charge through: $Q_W^P = -2(2C_{u1} + C_{d1})$

Parity Violating Electron Scattering

Electromagnetic and Neutral weak currents given by:

$$j^{\mu}_{EM} = -e\gamma^{\mu}e \qquad j^{\mu}_{NC} = -\frac{1}{2\cos\vartheta_w}\left(\bar{e}_L\gamma^{\mu}(1-2\sin^2\vartheta_w)e_L - 2\bar{e}_R\gamma^{\mu}\sin^2\vartheta_w e_R\right)$$

In neutral current processes the left and right helicity fermions couple differently to the Z^o Boson. There is no difference in the photon case. Therefore we can calculate the asymmetry of the total scattering process as so:



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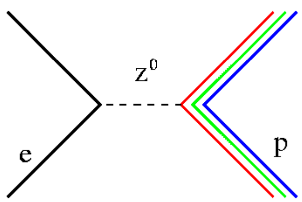


$$\mathcal{M}^2 = \left|\mathcal{M}_{\gamma} + \mathcal{M}_Z\right|^2 \approx \left|\mathcal{M}_{\gamma}\right|^2 + \left|\mathcal{M}_Z\right|^2 + 2\,\mathrm{Re}\,\mathcal{M}_{\gamma}\mathcal{M}_Z$$

$$\mathcal{A}_{\mathcal{LR}} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{\left|\mathcal{M}_Z\right|^2 + 2\,\mathrm{Re}\,\mathcal{M}_Z\mathcal{M}_{\gamma}}{\left|\mathcal{M}\right|^2} \approx \frac{2\,\mathrm{Re}\,\mathcal{M}_Z\mathcal{M}_{\gamma}}{\left|\mathcal{M}_{\gamma}\right|^2}$$

Dominate term in asymmetry

In the limit $Q^2 \sim 0$, $\theta \sim 0$ evaluating and keeping terms of order Q^4 we can calculate the asymmetry to be:

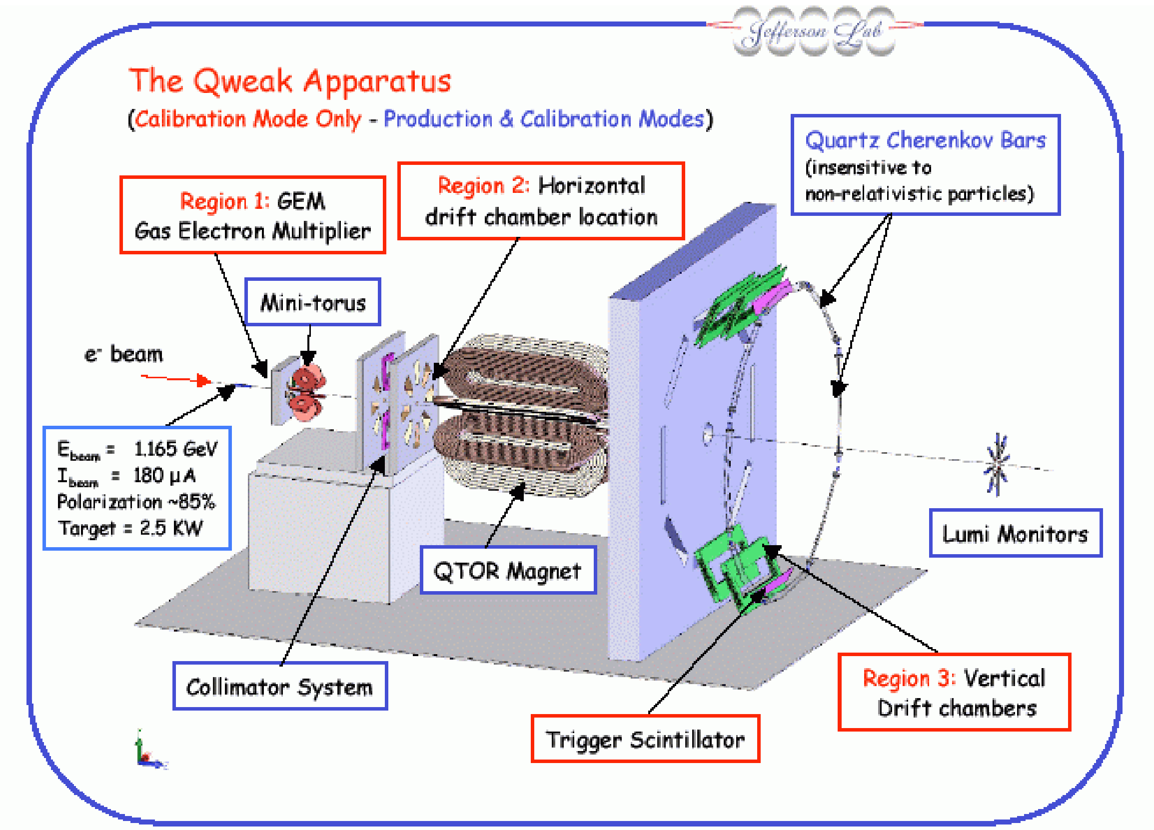
$$\mathcal{A}_{measured} \sim h\frac{G_F}{4\pi\sqrt{2}\alpha}Q^2(Q^P_w + Q^2B + \ldots)$$

This about 300ppb at our low momentum transfer

$$Q^P_W = 1 - 4\sin^2\vartheta_w \sim 0.072 \textit{ at tree level}$$

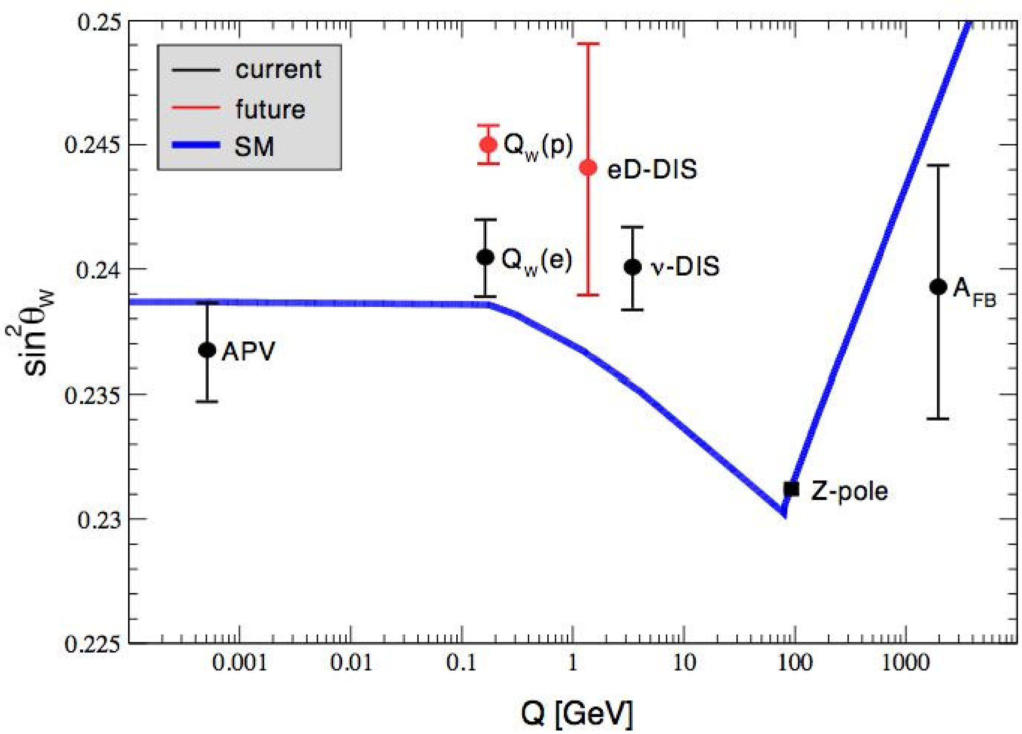
B contains the Hadronic form factor terms

EXPERIMENTAL SETUP



- Beam randomized in helicity to look at asymmetry in cross section.
- Q^2 of electron determined by collimators and QTOR magnet.
- Electron path reconstructed using vertical drift chambers.
- Events measured with Quartz Cherenkov bars

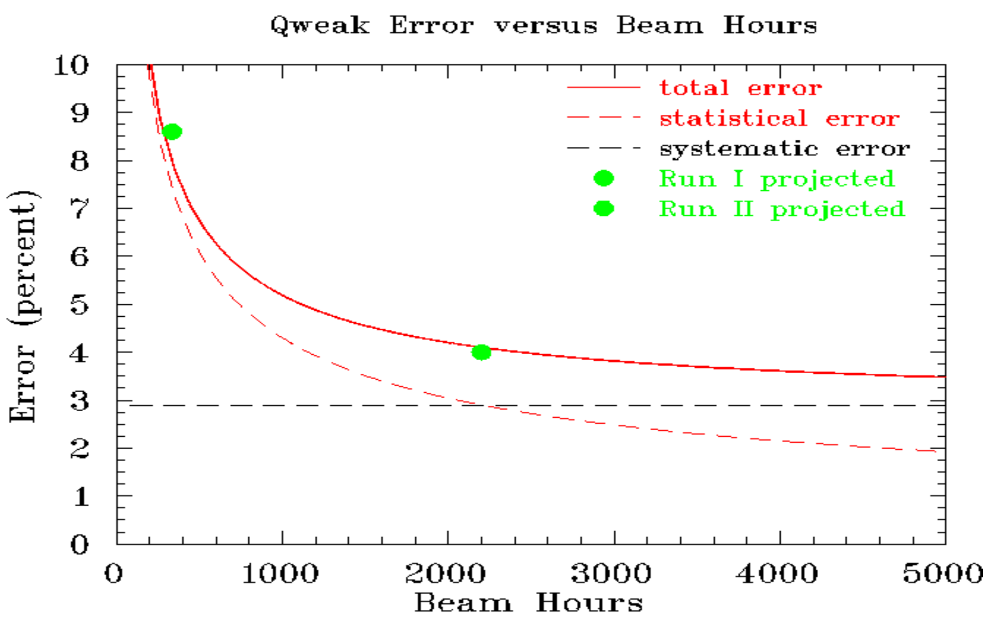
Weak Charge Measurements



- Previous experiments such as NuTeV have shown possible deviations from theoretical expectations.
- Value is very well know at pole.
- Precision measurement away from pole could give new physics, or tightly constrain SM.
- Future experiments such as E185 will measure weak charge of electron.

EXPERIMENTAL ERROR

Input	Contribution to $\Delta A_{phys}/A_{phys}$	Contribution to $\Delta Q_W^p / Q_W^p$
Counting Statistics	1.8%	2.9%
Hadronic structure	—	2.0%
Beam polarimetry	0.9%	1.5%
Absolute Q^2	—	1.1%
Window Backgrounds	0.4%	0.6%
False Asymmetries	0.4%	0.7%
Quadrature Sum	2.2%	4.0%



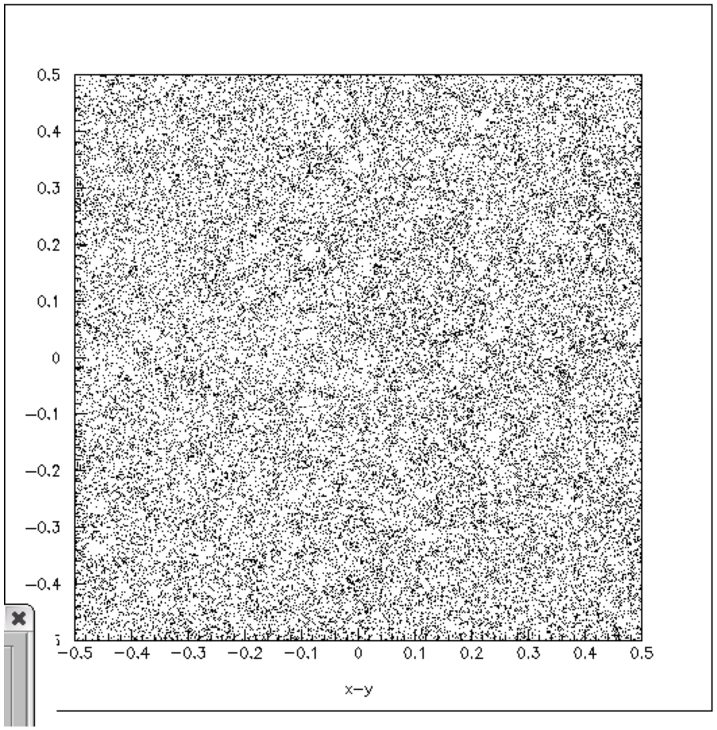
Following the commissioning phase, there will be 2200 hours of runtime to obtain an experimental error of ~4%

Helicity Correlated Beam Systematics

- Due to transverse dithering of the beam on the target and deformation during the helicity change.
- Some transverse offset could come from the QTOR field being larger/smaller on opposite sides.
- Modeling systematic errors in GEANT gives an idea of the sensitivity of our measurements to these effects.
- Becomes a source of significant false asymmetries in PV scattering at our level of sensitivity.

- Determining the effects precisely as a function of beam position and shape allows us to subtract out false asymmetries.

Geant Simulation fits



- Raster of beam covers $x_o \pm \Delta x$ in x and $y_o \pm \Delta y$ in y
- Δx and Δy may change by $\pm\ \delta_{\Delta x}/\delta_{\Delta y}$ on helicity flip of beam giving a total deviation of up to 4 $\delta_{\Delta x}$ / $\delta_{\Delta y}$ in the beam diameter.
- Beam direction covers range of $\theta+\Delta\theta$ to $\theta-\Delta\theta$.
- Fits are made to single Cherenkov bars, diametrically opposed bars, and the whole array as a function of position and angle on target.
- These fits give a straight forward way to calculate false asymmetries due to the helicity flipping and beam dithering.

Fitting the scattering position on target in x and y on a single bar, gives a scattering distribution as a function of position, from which the asymmetry can be calculated.

$$\mathcal{R}(x,y,\theta) = a(1 + bx_o^2 + b' y_o^2 + c\vartheta_o^2 + dx_o\vartheta_o + ex_o + f\vartheta_o + \frac{1}{3}(b\Delta x^2 + b'\Delta y^2)$$

$$\mathcal{A} = (2bx_o + d\vartheta_o + e)\delta x + (2c\vartheta_o + dx_o + f)\delta\vartheta_o + \frac{2}{3}(b\Delta x\delta_{\Delta x} + b'\Delta y\delta_{\Delta y})$$

Worst Case QTOR magnet asymmetries

$$\mathcal{R}(x,y,\theta) = a(1 + bx_o^2 + b' y_o^2 + c\vartheta_o^2 + dx_o\vartheta_o + ex_o + f\vartheta_o + \frac{1}{3}(b\Delta x^2 + b'\Delta y^2)$$

Optimally the linear terms are zero for a perfect array, however for worst case scenarios there is a distortion that seems to squeeze the scattered array by some value x_{bar}.

Table 1: Fits to rate as function of beam position and angle on target

Term	Single bar	Pair of bars	Whole array
b (cm^{-2})	0.011 ± 0.004	0.008 ± 0.003	0.0014 ± 0.0021
b' (cm^{-2})	-0.011 ± 0.004	-0.008 ± 0.003	0.0014 ± 0.0021
c (deg^{-2})	0.157 ± 0.033	0.144 ± 0.023	0.046 ± 0.011
d (cm^{-1}deg^{-1})	0.048 ± 0.019	0.087 ± 0.014	0.029 ± 0.007
e (cm^{-1})	0.123 ± 0.001	$(0.0027 \pm 0.0004)x_{bar}$	$(0.0017 \pm 0.0001)x_{bar}$
f (deg^{-1})	0.549 ± 0.003	$(-0.0066 \pm 0.0001)x_{bar}$	$(-0.0040 \pm 0.0001)x_{bar}$

x_{bar} of 1cm would result from ~0.7% deviation in the QTOR field

Total Helicity Correlated Asymmetries

$$\mathcal{R}(r_o, x_{bar}) \sim 1 + b_r r_o^2 + e_r r_o x_o + \frac{b}{3}(\Delta x^2 + \Delta y^2)$$

$$b_r = b + c\alpha^2 + d\alpha \quad e_r = e + f\alpha$$

$$\mathcal{A} = 0.0064 r_o + 0.0015 x_{bar} + \frac{0.0064}{3}(\Delta x \delta_{\Delta x} + \Delta y \delta_{\Delta y})$$

Choosing our coordinate system so that x=r, and assuming the beam deforms when the helicity is flipped gives:

Table 2 shows estimated false asymmetries for beam position, size and direction modulations based on the coefficients presented in table 1.

Table 2: Estimated false asymmetries in units of 10^{-10}

Modulation	Conditions	Single Bar	Pair of Bars	Whole Array
Position	$x_0 = 1$ mm, $\delta x = \pm 2$ nm $\theta_0 = 60$ μrad	250	3.8	0.8
Position + distorted array	$x_0 = 1$ mm, $\delta x = \pm 2$ nm $\theta_0 = 60$ μrad, $x_{bar} = 1$ cm	250	9.2	4.2
Correlated position & angle	$x_0 = 1$ mm, $\delta x = \pm 2$ nm on axis at raster	-	-	1.3
Correlated position & angle + distorted array	$x_0 = 1$ mm, $\delta x = \pm 2$ nm on axis at raster $x_{bar} = 1$ cm	-	-	4.3
Beam size	$\Delta x = \Delta y = 2$ mm, $\delta_{\Delta x} = \pm\delta_{\Delta y} = \pm 2$ nm	5.9	4.3 $\delta_{\Delta y} = -\delta_{\Delta x}$	0.7 $\delta_{\Delta y} = \delta_{\Delta x}$
Correlated position & angle	$\Delta x = \Delta y = 2$ mm, $\delta_{\Delta x} = \delta_{\Delta y} = \pm 2$ nm on axis at raster	-	-	1.7 $\delta_{\Delta y} = \delta_{\Delta x}$
Direction	$\theta_0 = 60$ μrad, $\delta\theta = \pm 30$ nrad	9500	17(165) $x_0 = 0(1$ mm$)$	5.4(55)
Direction + distorted array	$\theta_0 = 60$ μrad, $\delta\theta = \pm 30$ nrad $x_{bar} = 1$ cm	9500	130(280) $x_0 = 0(1$ mm$)$	74(125)

SUMMARY

- Qweak will give an interpretable measurement of the proton's weak charge.
- PV electron scattering gives us a precise method to measure fundamental properties of the proton.
- The near cancellation of the Q_w^P causes it to be extremely sensitive to $\sin^2\theta_w$ making it possible to test the running of the coupling very precisely.
- Could lead to and constraint new physics that might be found at the LHC.
- On the precision level of Qweak false asymmetries can come about due to systematic beam effects.
- In order to make the precision measurement we want, helicity correlated beam systematics must be understood and accounted for.

Extra Reference slides

Asymmetry Calculation

But how do we get to Q_w from the asymmetry?

$$\mathcal{M}_Z\mathcal{M}_\gamma = \frac{e^2 G_F}{\sqrt{2}Q^2} Tr[\overline{u}(p')\Gamma^\mu_{P\gamma}u(p)u(p')\Gamma^\mu_{Z\gamma}u(p')]$$

$$\times Tr[\overline{u}(l')\gamma_\mu u(l)\overline{u}(l)((1-2x)\gamma_\nu(1-\gamma_5)-2x\gamma_\nu(1+\gamma_5))u(l')]$$

In the limit $Q^2 \sim 0$, $\theta \sim 0$ evaluating and keeping terms of order Q^4 we can calculate the asymmetry to be:

$$\mathcal{A}_{measured} \sim h\frac{G_F}{4\pi\sqrt{2}\alpha}Q^2(Q_w^P + Q^2 B + \ldots)$$

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$$Q_W^P = 1 - 4\sin^2\vartheta_w \sim 0.072 \; \textit{at tree level}$$

B contains the Hadronic form factor terms

Sensitivity to New Physics

Sensitivity of mass/couplings can be estimated from the effective electron-quark Lagrangian by adding a new contact term.

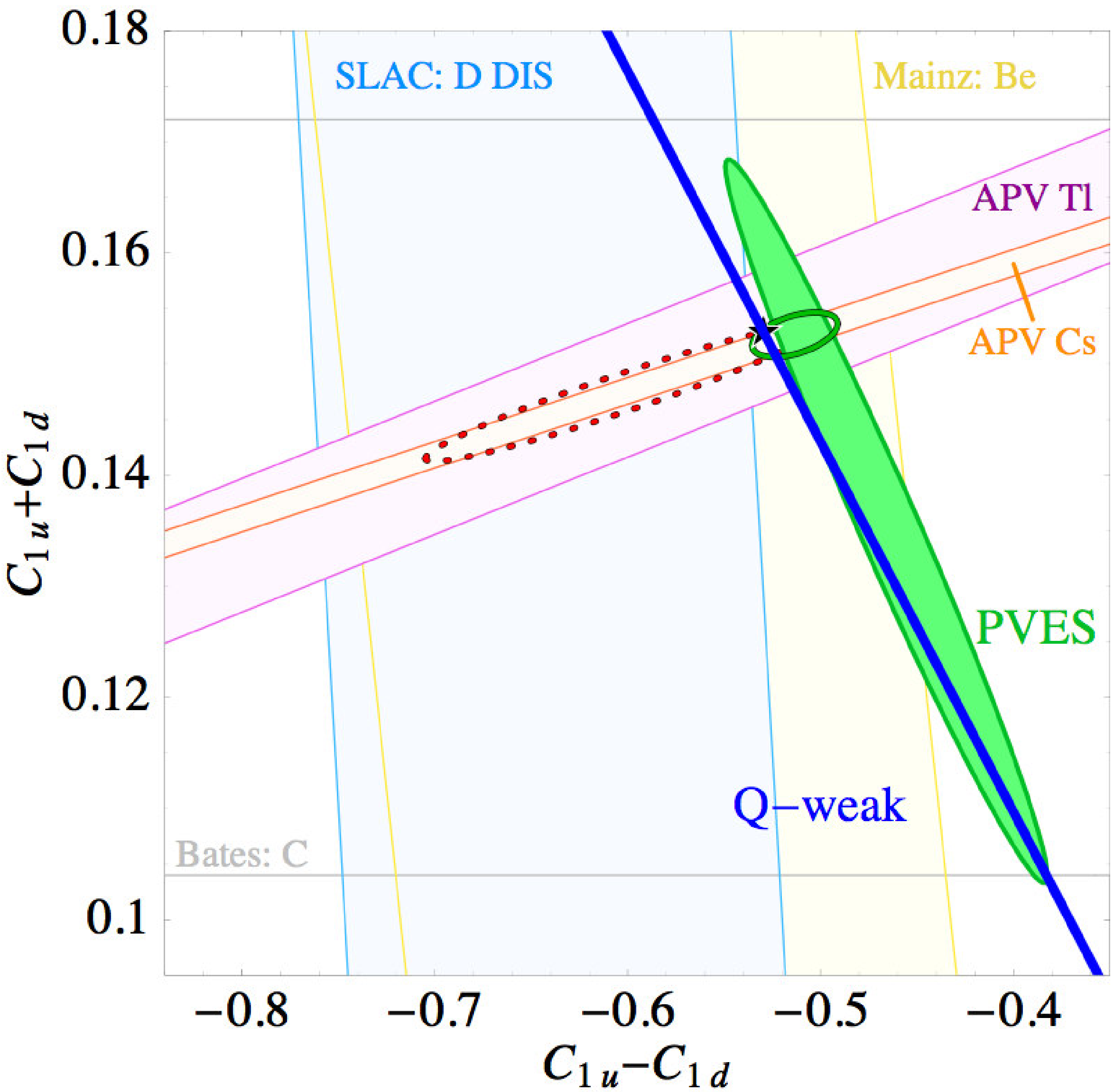
$$\mathcal{L} = \mathcal{L}_{SM}^{PV} + \mathcal{L}_{New}^{PV} = \frac{-G_f}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q} \bar{q}\gamma_\mu\gamma_5 q + \frac{-g^2}{4\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_f h_{qv} \bar{q}\gamma_\mu\gamma_5 q$$

Where g is the coupling constant, Λ is the mass scale, and h_{qv} is the Quark-specific coefficients. It is easily seen the:

$$\frac{g}{\Lambda} \propto \frac{1}{\sqrt{\sqrt{2} G_f Q_w^p}} \approx 4.5 TeV$$

For the proton this gives sensitivity on the order of the multi-TeV scale.

Constraint of Weak Quark-Charge



Qweak completes the set of PV measurements needed to determine the C_{1u} and C_{1d} quark coupling constants.