Q-weak A Search for New Physics

Helicity Correlated Beam Systematics in the Q_{weak} Experiment

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Q_{weak} will make a 4% measurement of $Q^p{}_w$ using parity violating electron scattering (PVES) which arises from the interference between the electromagnetic(γ) and neutral weak currents(Z^o):

$$A_{\gamma Z^o} = \frac{1}{P_L}\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \simeq -300\text{ppb}$$

The Weak Charge of the Proton ($Q^p{}_w$) is heavily suppressed in the Standard Model (SM). Due to a near cancellation we are uniquely sensitive to $\text{Sin}^2\theta_w$:

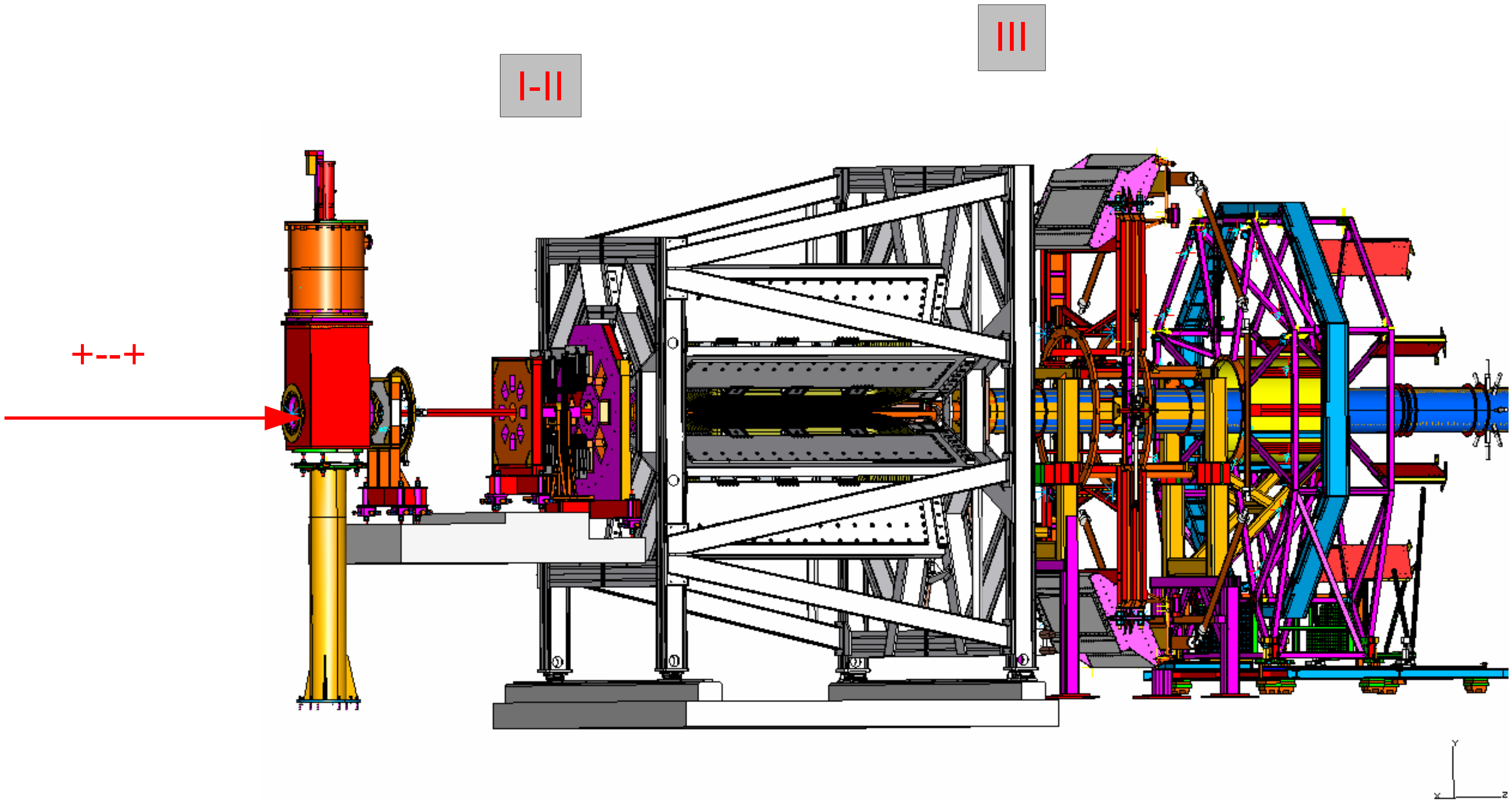
$$Q_w^p = 1 - 4\text{Sin}^2\theta_w \approx -0.048$$

In the limit of low momentum transfer and small forward angle scattering, leading order term contains $Q^p{}_w$. The next highest order term contains the hadronic structure and is constrained by current world data.

$$A_{\gamma Z} \underset{\substack{Q^2\to 0\\ \theta\to 0}}{\longrightarrow} \frac{-G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 Q_W^p + \underline{Q^4 B(Q^2)}\right]$$

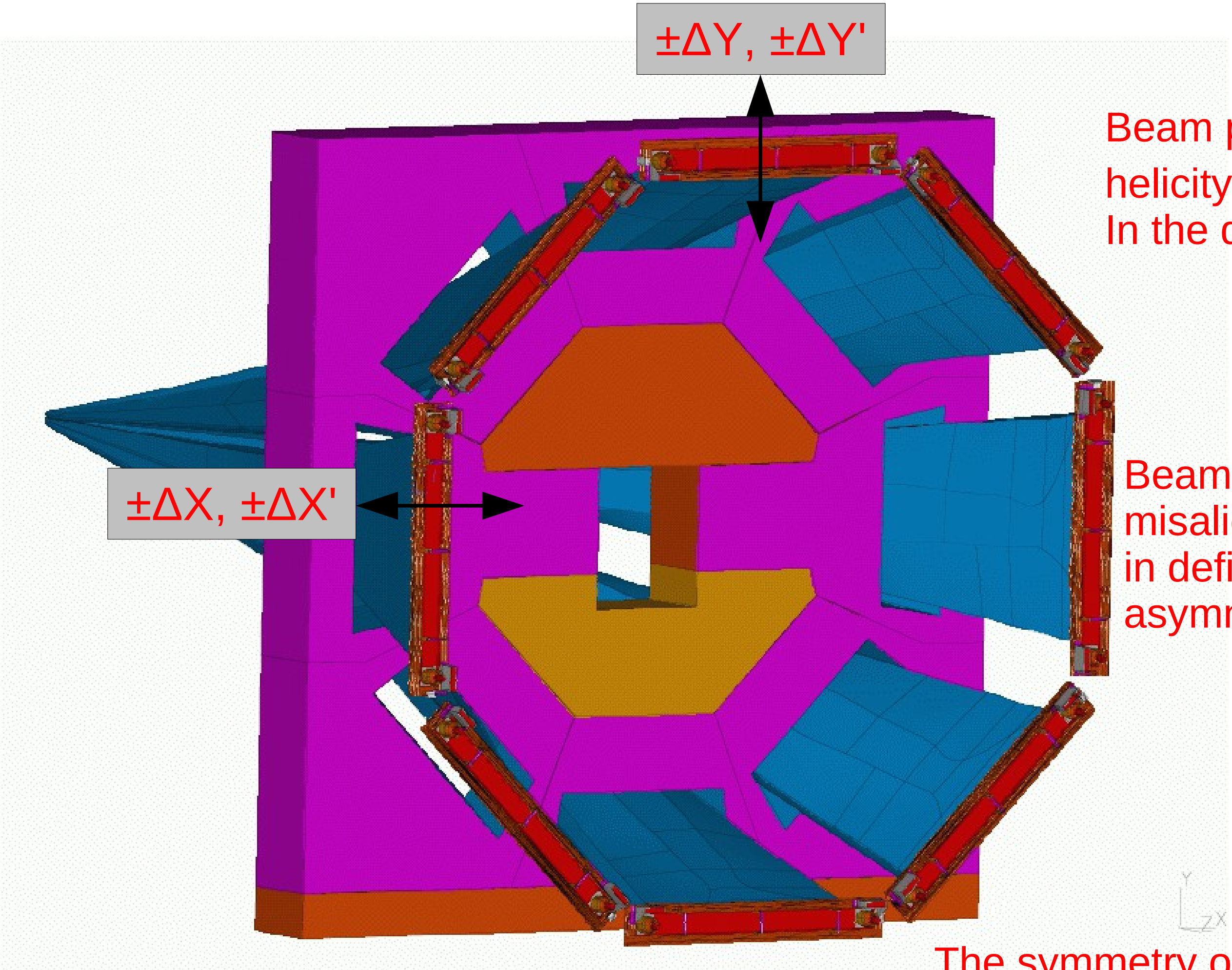
Systematic error ~2%

Experimental Apparatus



- Forward scattering , 85% polarized electrons at Q^2 ~0.03 GeV ^{2} and I = 185 uA from LH_2 target.
- Toroidal spectrometer provides momentum selection of elastically scattered electrons.
- Symmetric array of 8 Cerenkov detectors(800 MHz/bar).

False Asymmetries



Beam property changes by $\pm\Delta x_i$ during helicity flip can generate false asymmetries In the detector array.

Beam parameters such as: beam centroid, misalignments of detector array, and asymmetries in defining collimators can amplify false asymmetries.

The symmetry of the main detector array should help to suppress position and angle changes, however helicity correlated changes in the energy do not see a cancellation.

Q_{weak} would like to measure the sensitivites to these beam parameters in order to correct for false asmmetries.

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Error Budget

Uncertainty	ΔA_{pv} / A_{pv}		ΔQ_w / Q_w
Statistical:	*2.1 %*		*3.2%*
Systematic:			
Hadronic Structure	-------		*1.5%*
Beam Polarimetry	*1.0%*		*1.5%*
Absolute Q^2 Determination	*0.5%*		*1.0%*
Backgrounds	*0.5%*		*0.7%*
Helicity Correlated Beam Properties	*0.5%*	± 1 ppb!	*0.7%*
Total:	*2.5%*		*4.1%*

Our goal is to keep total corrections at run's end to less than 10 ppb (assuming a 10% measurement).

$$\Delta A_{position} = \frac{\partial A}{\partial X_{position}} \Delta X_{position} \sim 100\ ppm/mm * 1 nm = 0.1\ ppb$$

Error this small → not a problem

$$\Delta A_{Energy} = \frac{\partial A}{\partial E} \Delta E \sim 3\ ppm/ppm * \Delta E$$

ΔE should be no larger than 3.3 ppb

How we measure Helicity Correlated Beam Sensitivities

So how do we measure helicity correlated beam systematics?

Extraction from Natural Beam Motion: Covariance Analysis
– Jim Birchall(U. Manitoba) and Jan Balewski(MIT)

Detector response to natural beam motion is measured. Using a covariance analysis, orthogonalized sensitivities are determined and corrected using linear regression.

Driven Beam Modulation System – Qweak Beam Modulation Group

Using kicker coils the beam is modulated in position/angle. Measuring the detector response during modulation we are able to calculate the detector sensitivites. False asymmetries can can then be corrected through linear regression.

Covariance Analysis of Natural Beam Motion

Consider a first order model for the false asymmetry ε in the main detector:

$$\epsilon \;=\; a\,\delta x + b\,\delta x' + c\,\delta y + d\,\delta y + e\,\delta E$$

One can calculate by multipling through and taking the average:

$$\bar{\epsilon}\,\overline{\delta x} \;=\; a\,\overline{\delta x^2} + b\,\overline{\delta x'}\,\overline{\delta x} + c\,\overline{\delta y}\,\overline{\delta x} + d\,\overline{\delta y}\,\overline{\delta x} + e\,\overline{\delta E}\,\overline{\delta x}$$

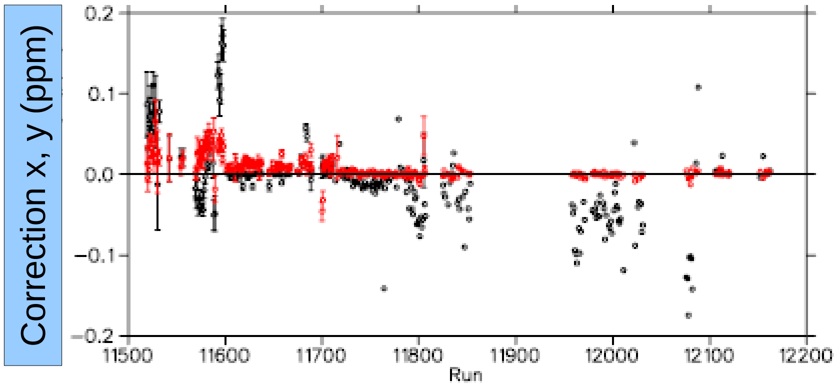
$$\overline{\epsilon\,\delta x} \;=\; a\,\overline{\delta x\,\delta x} + b\,\overline{\delta x'\,\delta x} + c\,\overline{\delta y\,\delta x} + d\,\overline{\delta y\,\delta x} + e\,\overline{\delta E\,\delta x}$$

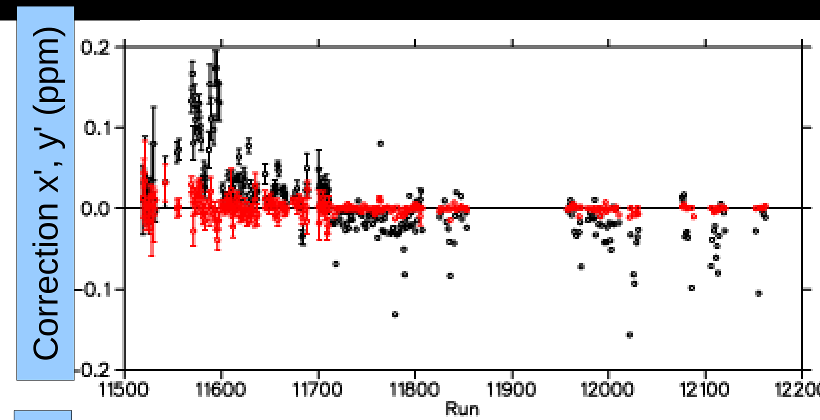
Taking the difference:

$$cov(\epsilon,\delta x) \;=\; a\,var(\delta x) + b\,cov(\delta x',\delta x) + c\,cov(\delta y,\delta x) + d\,cov(\delta y,\delta x) + e\,cov(\delta E,\delta x)$$

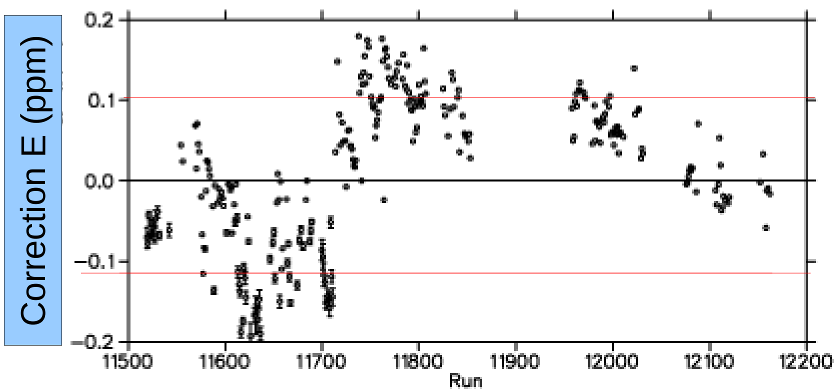
Doing the above for each variable, δx, δx', δy, δy', δE we can generate a set of five linear equations that can be solved in the usual way for sensitivities a, b, ...ect.

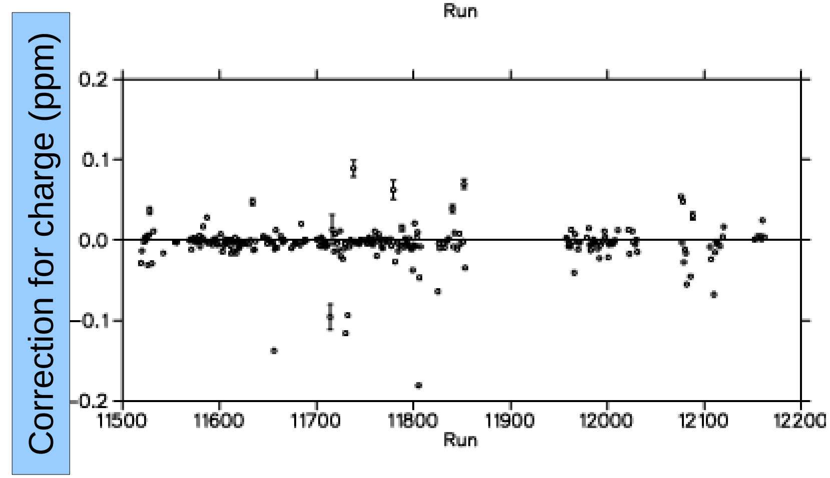
Natural Beam Motion Results

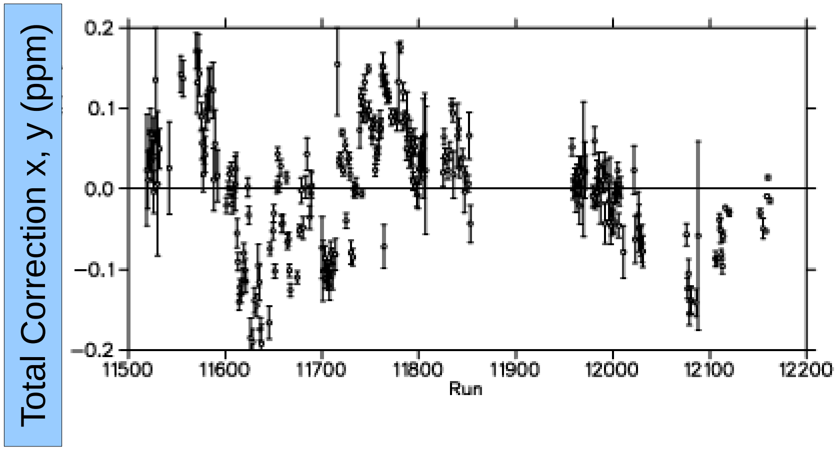




Red Y
Black X



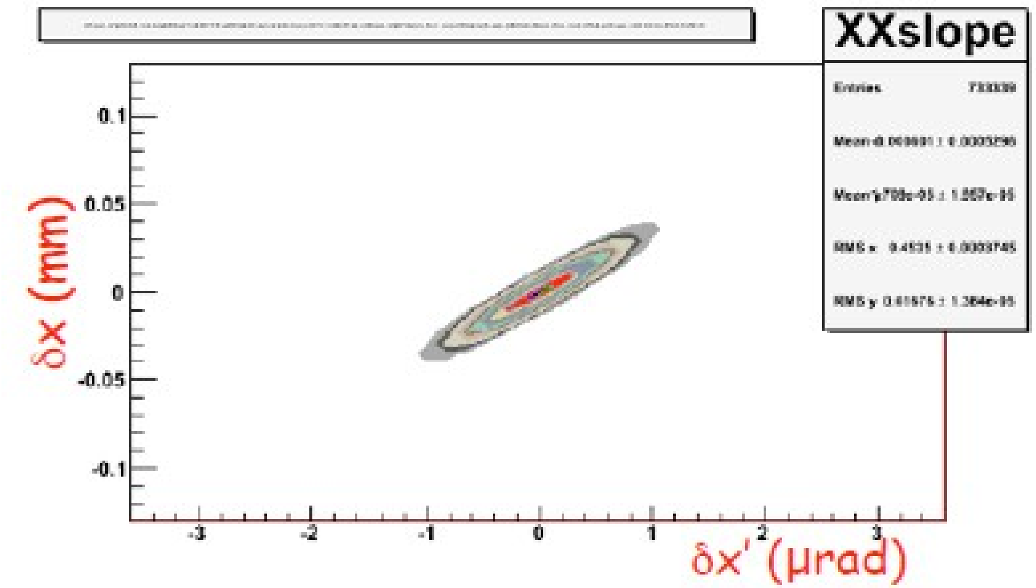




Sum of corrections dominated by Energy correction, ± ½ our physics asymmetry!

Energy *very* important.

Natural Beam Motion Weaknesses



Natural beam motion highly correlated – hard to decouple.

Correlation of δx,δx' was found to be very high.

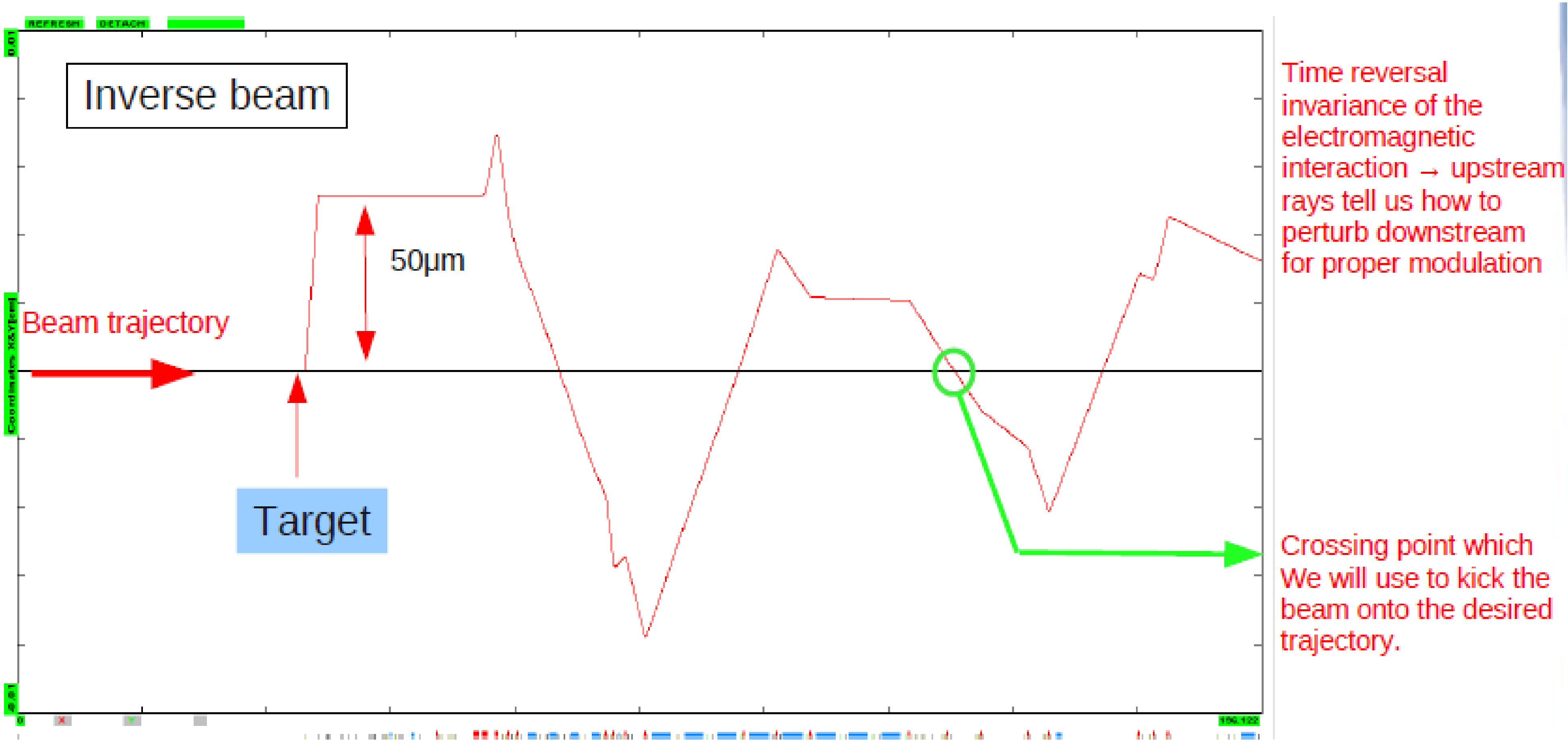
Correlation coefficient ~0.999!

Because the natural jitter of the beam is so small it takes a long time to get a precise measurement of the sensitivity slopes.

Driven Modulation System

- The beam modulation system used pairs of coils positioned along the beamline to “kick” the electron beam onto a trajectory resulting in a “pure” X,X',Y,Y' offset at the target.
- An SRF cavity is used to modulate the beam energy.
- Has the advantage of producing a more linearly independent set of slopes.

Driving the Electron Beam



Using a ray tracing program (OPTIM), we can determine the trajectory of the beam by sending rays upstream from the target. By kicking the beam on to the "magic orbit" we can produce desired position/angle on the target.

Asymmetry Correction

$$\Delta A = \sum_{i=1..5} \frac{1}{\bar{Y}} \frac{\partial Y}{\partial x_i} \Delta x_i + \frac{\partial A_{md}}{\partial A_q} \Delta A_q$$

The goal is to determine the normalized detector sensitivities, which are not directly measurable. However using the relation:

$$\frac{\partial Y}{\partial C_j} = \sum_i \frac{\partial Y}{\partial M_i} \frac{\partial M_i}{\partial C_j}$$

M ≡ Monitor {targetX, targetY, Energy, targetXSlope, targetYSlope
C ≡ Coil {Parameterization of ramp function, ie. Phase of modulation}
Y ≡ Main Detector Yield.

$$\frac{\partial Y}{\partial M_i} = \frac{\partial Y}{\partial C_j} \left(\frac{\partial M_i}{\partial C_j} \right)^{-1}$$

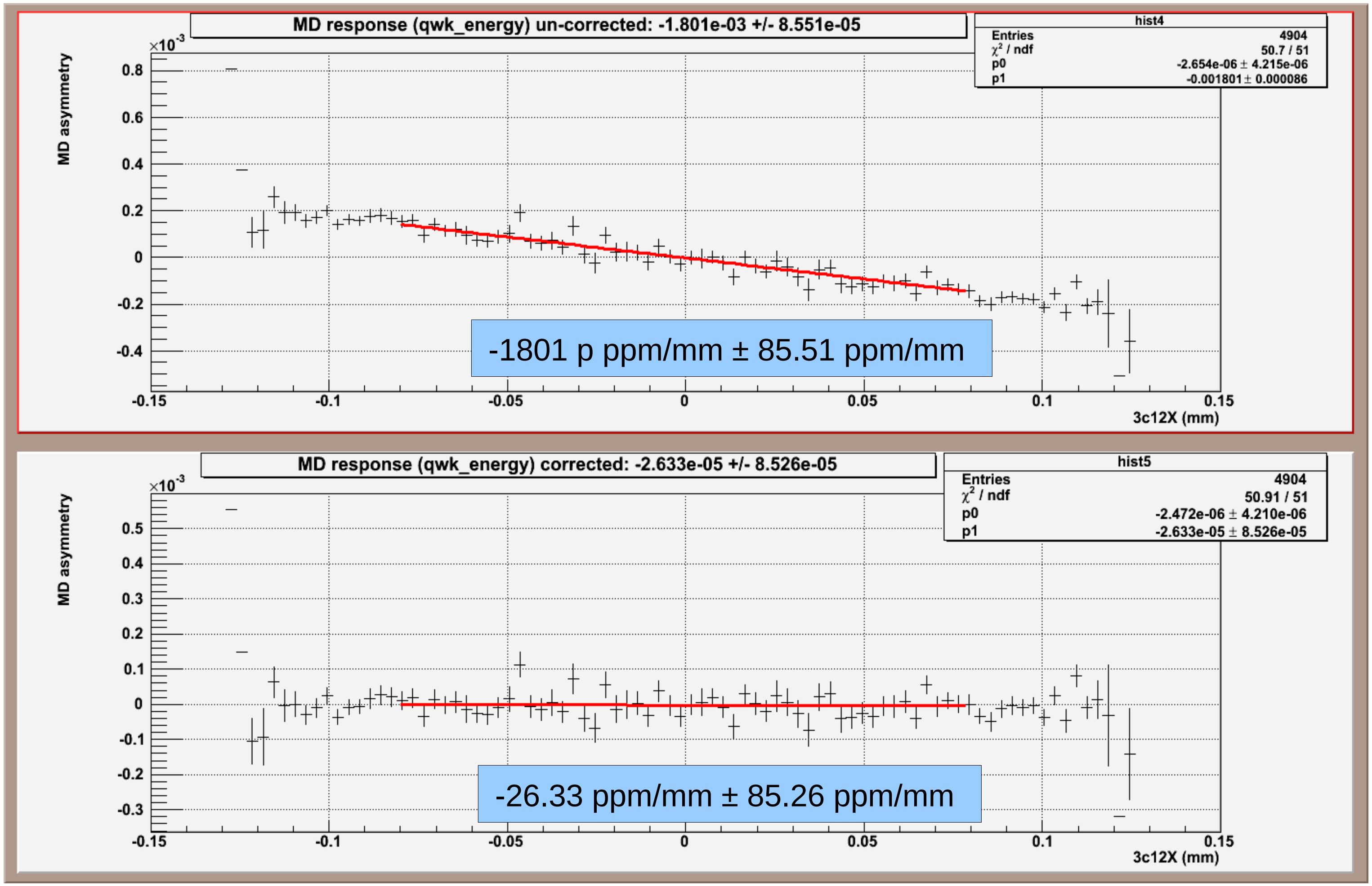
Matrix inversion gives us detector sensitivities in the target basis + 3C12X. Slopes in terms of Monitor and Coil are calculated algebraically using a simple fit to a regression line:

$$Y = \hat{\beta}_j C_j \qquad M_i = \hat{\beta}_k C_k$$

$$\hat{\beta} = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sum_i (x_i - \bar{x})^2} = \frac{Cov[x, y]}{Var[x]}$$

Beam Modulation Regression Check

As a first check we see if we can zero out the modulated data.



Extracted sensitivies completely zero out energy dependence detector asymmetry.

Beam Modulation Regression Check

Monitor	Unregressed	Regressed	Regressed + ΔA_q	
Target X	483.9 ± 46.42	-112.4 ± 46.36	176.3 ± 46.28	$20\sigma \rightarrow 2\sigma \rightarrow 3\sigma$
Target Y	847.7 ± 62.81	-223.5 ± 62.73	-53.71 ± 62.62	$13\sigma \rightarrow 3.5\sigma \rightarrow 0.8\sigma$
3C12X	-1400 ± 40.18	-454.2 ± 40.20	-14.69 ± 40.14	$35\sigma \rightarrow 11\sigma \rightarrow 0.4\sigma$
Target X’	12.70 ± 1.26	-8.34 ± 1.26	-0.60 ± 1.26	$10\sigma \rightarrow 7\sigma \rightarrow 0.5\sigma$
Target Y’	25.85 ± 1.99	-17.44 ± 1.99	-10.51 ± 1.99	$13\sigma \rightarrow 9\sigma \rightarrow 5\sigma$

Beam Modulation corrections greatly reduce slopes in first pass but still leave significant corrections to be made.

Beam Modulation correction + correction for charge asymmetry shows significant improvement. Target X and target Y’ still not fully corrected.

The fact that the slopes are reduced after correcting for charge differences proves two things we already knew:

- There are small but significant non-linearities in the system (signal chain and/or beam position monitors).
- These charge differences are strongly correlated with position differences.

These new results highlight, however, the importance of including charge differences in Qweak's natural beam motion linear regression to properly account for correlations between position and charge.

Summary and Future Work

Summary

- Understanding and correcting for Helcity Correlated Beam Systematics is an important part of making a precise measuremeant of Q^p_w.
- Both Natural Beam Motion analysis and Driven Beam Modulation provide
- powerful tools to measure these effects.

Future Work

- Driven Modulation Analysis has been shown to correct modulated data → Self consistent. Need to look more closely at correction of non-modulated data.
- Investigate the effects of charge asymmetry on sensitivity slopes.
- Look at analysis using different detectors.
- Make Driven Modulation Analysis a permanent staple of Q_{weak} physics analysis.