

Q_{Weak} : A Measurement of the Proton's Weak Charge

A Prospectus

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Abstract

The Q_{Weak} experiment at Jefferson lab will measure the parity-violating elastic electron-proton scattering asymmetry at $Q^2 = 0.026 GeV/c^2$ to obtain the weak charge of the Proton, Q_{Weak}^p to an accuracy of 4%. The result will test the Standard model claim of running of $\sin^2 \theta_W$. As a thesis student I will contribute to the Q_{Weak} experiment mainly in the areas of data acquisition, data-analysis software development and extraction of the physics asymmetry from the accumulated data.

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I. INTRODUCTION

The Q_{Weak} experiment [1] [2] at Jefferson Lab will measure the weak charge of the proton, Q_{Weak}^p , to an accuracy of 4% [3]. The weak charge is related to the weak mixing angle θ_W . Standard Model (SM) predicts a $\sim 3\%$ change of the $\sin^2 \theta_W$ from a high momentum transfer to a low momentum transfer regime, as shown in FIG 1 [4]. This proposed precision measurement of the Q_{Weak}^p will test the SM claim of the running of the weak mixing angle $\sin^2 \theta_W$. As the SM running of $\sin^2 \theta_W$ has been confirmed by many other experiments, the Q_{Weak} experiment will further strengthen the running but any small discrepancy with the predicted value will be a sign of new physics beyond the SM [5]. To measure $\sin^2 \theta_W$, Q_{Weak} will measure the asymmetry in the helicity-dependent cross section of elastic electron-proton scattering. The parity violation of the cross section is estimated to be in the order of $\sim 0.2ppm$ at momentum transfer, $Q^2 = 0.03(GeV/c)^2$ [1].

The precision of the asymmetry measurement and the scale of the experiment caused me to join the Q_{Weak} project at first as a C++ programmer and gradually learn about the experiment. Nowadays, I'm working on the software to determine the average Q^2 of the scattered electrons [6], to select good events based on the beam-line monitors and to calculate averaged over events values for beam line quantities like beam current, position, charge asymmetry and etc. My thesis work will contribute mainly in the areas of data acquisition and data-analysis software

Section II and Sub-section III.1 will provide an overview of the theoretical background and the experiment itself. The rest of the sections will focus more on topics relevant to my contribution to the Q_{Weak} . Finally in Section IV, I will present my contribution to date and emphasize that my thesis time-line will parallel with the Q_{Weak} experiment schedule. It is important to note that the Q_{Weak} collaboration has a set of guidelines for graduate students writing a Q_{Weak} based thesis. These guidelines provide three distinct goals set on the experiment; they are based on a hardware and a software responsibility, and, most importantly, a physics analysis responsibility.

II. PHYSICS MOTIVATION

The Standard Model (SM) is a successful theory of elementary particles. Tests of the SM can be divided into two important branches, high-energy and high precision frontiers. The electromagnetic scattering cross section of lepton scattering, predicted by SM, was verified by experiments [14] * and e^+e^- collisions from several collaborations [11] for energies above the Z-pole are examples of high-energy frontier of SM tests. They have shown agreement with SM observables [15]. The measurement of the anomalous magnetic moment of the electron [16] has verified the SM claim precisely and the Q_{Weak} experiment are examples for the high-precision frontier.

In the meantime, there are specific experimental results that deviate from SM predicted values.

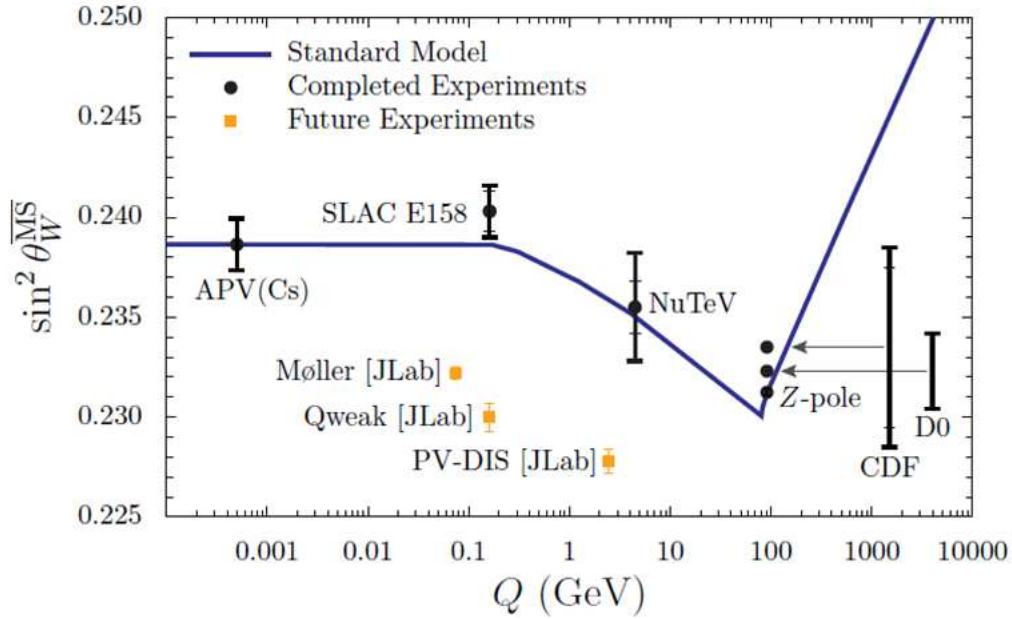


FIG. 1. The running of the $\sin^2 \theta_W$ in the $\bar{M}S$ renormalization scheme [7]. Present measurements include an atomic parity violation measurement (APV(Cs)) [8], SLAC E-158 (Q_{Weak}^e) [9], deep-inelastic neutrino-nucleus scattering, (NuTeV experiment) [10], Z^0 (Z-pole) measurement by combined results of LEP+SLAC [11]. Two more experimental values at Z-pole are shown here from D0 [12] and CDF [13] collaborations. The inner error bars represent the statistical uncertainty while the outer error bars represent the total uncertainty. Finally three proposed experiments are also listed.

* The QED cross section $\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 4\pi\alpha^2/(3s)$ was experimentally verified with the PETRA data shown in the Fig 6.6 of ref[14]

The experimentally observed anomalous magnetic moment of the muon [17] is different from SM prediction by about 3 standard deviations, while observed neutrino mass oscillations [18] are not explained in the SM.

With these experimental verifications, SM is the widely accepted theory of elementary particles and there is a necessity to further do precision experiments to investigate some of the observed subtle deviations. Therefore it is important to measure SM predicted observables experimentally. Such experiments could also open new physics beyond the SM [5].

One such observable in SM is the weak charge of the proton. The weak charge of the proton is chosen due to its suppression by the weak mixing angle. The $\sin^2\theta_W$ and Q_{Weak}^p as $Q^2 \rightarrow 0$ from SM fit to all current data [7];

$$\sin^2\theta_W = 0.23867 \pm 0.00016 \quad (1a)$$

$$Q_{Weak}^p = 0.0713 \pm 0.0008 \quad (1b)$$

A measurement of Q_{Weak}^p at very low Q^2 enables us to obtain the weak mixing angle as $Q \rightarrow 0$. $\sin^2\theta_W$ has already been measured at the Z resonance Q^2 (z-pole) [15] and the SM prediction of the running of the $\sin^2\theta_W$ (FIG 1) is normalized to the Z pole measurement. A measured weak angle at a very low Q^2 could verify the SM running prediction. The APV [8] and the NuTeV results [10] corrected based on recent publication [19] appear to be consistent with SM claim at $Q \rightarrow 0$ but both include extensive model-dependent calculations.

Therefore, the Q_{Weak} measurement will be an important milestone regarding the current status of the SM because it provides a clean measurement that is free from any complex atomic or nuclear corrections. Results will come in handy to compare with $\sin^2\theta_W$ obtained from purely leptonic regime (completed $E - 158$ [9] and proposed Møller experiment at JLab). Both of these experiments also provide clean results of the $\sin^2\theta_W$ independent of any model dependent calculations in leptonic regime.

Q_{Weak} is a measurement of the weak interaction between quarks and leptons. It probes the weak structure of the proton at very low Q^2 . The Electromagnetic (EM) interaction of the electron with

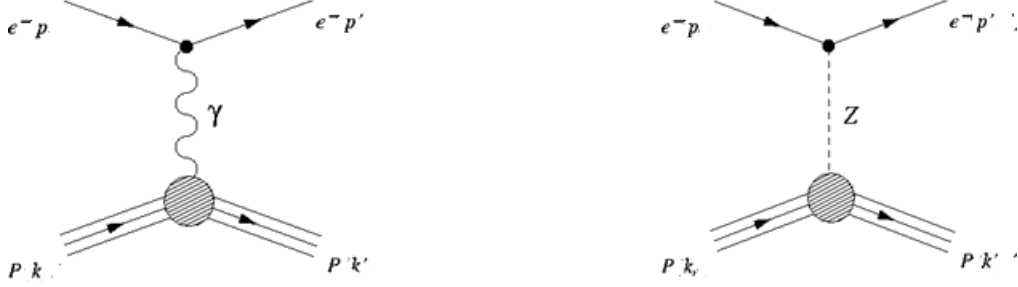


FIG. 2. QED and neutral weak interaction Feynman diagrams for electron scattering off a proton (uud) target

the proton has a stronger coupling, compared to the weak coupling of the electron to the proton at a very low Q^2 value. The Feynman diagrams for such interactions are given in FIG 2.

Since the EM coupling is strong compared to weak coupling at the Q^2 interested in Q_{Weak} obtaining the weak interaction cross-section directly would be impossible*. If we can measure the parity-non-conserving elastic-cross section asymmetry experimentally, it will open an opportunity to probe the weak structure of the proton.

The physics asymmetry of the cross section for two helicity states of the incident electron can be written in terms of the total elastic cross section,

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad (2)$$

where L or R represents the electron helicity, left and right.

By constructing the cross sections using Quantum Electrodynamics (QED) and weak invariant scattering amplitudes, we can estimate the asymmetry [†],

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{M^{NC}}{M^{EM}} \quad (3)$$

At first order the asymmetry is the ratio of invariant scattering amplitudes ($\sim \frac{M^{NC}}{M^{EM}}$). A precision experiment involving a longitudinally polarized electron beam elastically scattering off an unpolarized proton target would reveal the weak properties of the proton by measuring the experimental

* $\sim G_F Q^2 / \alpha \simeq 1 \times 10^{-5} \times 0.03 \times 137 \simeq 10^{-5}$

[†] This is derived for ultra relativistic electrons ($E_{tot} \gg m_e$).

physics asymmetry in Eq 2. This is the fundamental principle of the Parity Violating Electron Scattering (PVES) experiments.

The physics asymmetry for elastically scattered electrons from an unpolarized proton target depends on the EM interaction, weak interaction, as well as the hadronic structure of the proton. Therefore a more detailed expression of the physics asymmetry can be written as[1],

$$A_{PV} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}} \right] \left[\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^Z}{\varepsilon(G_E^\gamma)^2 + \tau(G_M^\gamma)^2} \right] \quad (4)$$

where G_E^γ and G_M^γ are the Sachs electromagnetic form factors of the proton, G_E^Z and G_M^Z are the weak neutral form factors and G_A^Z is the weak neutral axial form factor. The ε and ε' are the kinematic factors defined as,

$$\varepsilon = \frac{1}{1 + 2(1 + \tau)\tan^2\theta/2}, \quad (5a)$$

$$\varepsilon' = \sqrt{\tau(1 + \tau)(1 - \varepsilon^2)} \quad (5b)$$

where the angle θ is the lab frame electron scattering angle while the $\tau = Q^2/4M^2$; M is the proton mass and Q^2 is the four vector momentum transfer.

For extreme forward angles scattering when $\theta \rightarrow 0$, $\varepsilon \rightarrow 1$ and $\tau \ll 1$, equation 4 can be written as[1],

$$A_{PV} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}} \right] [Q^2 Q_{Weak}^P + Q^4 B(Q^2)] \quad (6)$$

where $Q_{Weak}^P = 1 - 4\sin^2\theta_W$ is the weak charge of the proton at tree level while $B(Q^2)$ is the leading term in the hadron-structure contribution. The Q_{Weak} experiment plans to measure the weak charge and hence a very low Q^2 is chosen so that the hadron structure contribution is minimized in the physics asymmetry. The exact contribution from the $B(Q^2)$ can be obtained from preexisting forward angle form factor A_{PV} measurement experiments [20] (Extrapolation from higher Q^2 experiment values) * . The drawback in the low Q^2 measurement is that physics asymmetry, A_{PV} is very small. The optimum value for the Q^2 for the Q_{Weak} experiment has been determined to be near $\sim 0.03(GeV/c)^2$ [1].

* Existing parity violating asymmetries from Experiments and their respective Q^2 values: SAMPLE (MIT/Bates) $\rightarrow 0.1$, HAPPEX-I (Hall A, JLab) $\rightarrow 0.48$, HAPPEX-II/helium (JLab/Hall A) $\rightarrow 0.1$, G0 (JLab/Hall C) $\rightarrow 0.12$ to 1.0, PV-A4 (MAMI) $\rightarrow 0.23, 0.11$ and PV-A4 (backward) $\rightarrow 0.22$

III. Q_{WEAK} EXPERIMENTAL ASPECTS

III.1. Q_{Weak} Experiment in General

The Q_{Weak} experiment involves longitudinally polarized electrons scattering from an unpolarized target, so that electrons have L/R (or \pm) helicity. The experiment then measures the helicity dependent cross section, $\sigma_{L/R}$ by integrating the scattered electron flux. The experimental asymmetry is defined as,

$$A_{LR} = \frac{N_R - N_L}{N_R + N_L} \quad (7)$$

where the N s represent the total electrons flux during Left/Right helicity state. The A_{LR} in the Eq. 7 is the asymmetry of the cross-section provided that the beam luminosity and the solid angle are invariant under the helicity reversal[†]. The A_{LR} is corrected to the beam polarization, P_e , to obtain the required physics asymmetry in the equation 6.

$$A_{PV} = \frac{A_{LR}}{P_e} \quad (8)$$

With this the Q_{Weak} experiment can extract the value for the Q_{Weak}^p with known Q^2 , $B(Q^2)$ and the beam polarization P_e .

The Q_{Weak} is designed to run about 2200 hours of data collection[1]. This is the minimally required time to achieve statistical precision of $\sim 3\%$. The overall precision is limited by the systematic precision of the experiment. Therefore, unless one improves the systematics, running the experiment further will not improve the total precision. With these limits, the proton's weak charge can be measured to $\sim 4\%$ precision [21]. The experimental setup shown in FIG 3 measures the integrated current from scattered electrons. A room-temperature toroidal magnetic spectrometer (Q_{Weak} TORoidal magnet, QTOR) with $B \sim 0.7T$ (QTOR Magnet in the FIG 3) will focus elastic electrons into a set of eight Cerenkov detectors while defocussing inelastic events. While a higher percentage of detected electrons will be elastically scattered electrons, a very small fraction contains inelastic scattering electrons. The basic parameters of the Q_{Weak} experiment are given in Table I [21].

The following list is a set of key detectors in the experimental setup,

[†] The event rate, $N_{L/R} = eL \int \frac{d\sigma}{d\Omega} d\Omega$.

1. A set of 8 fused silica (Radiation hard) Cerenkov detectors.
2. A set of 16 luminosity detectors to quantify and verify any false asymmetries.
3. A collection of Beam line monitors at the injector and just before the target in the Hall C, will monitor beam current and position.
4. A tracking system will include set of wire chambers and a Gas Electron Multiplier (GEM) triggered by a scintillation trigger. A Quartz scanner will provide a measure of electron rates at Cerenkov detector plane.
5. Two beam polarimeters will accurately measure the beam polarization.

The Q_{Weak} experiment includes a small percentage of beam time to measure the Q^2 to $\sim 0.5\%$ accuracy at low beam counting mode by employing the tracking system [22]. The tracking system will provide a map of light response of Cerenkov detectors, a sanity check on collimators and toroidal fields, and also a limited diagnostic on backgrounds and radiative corrections [23]. The

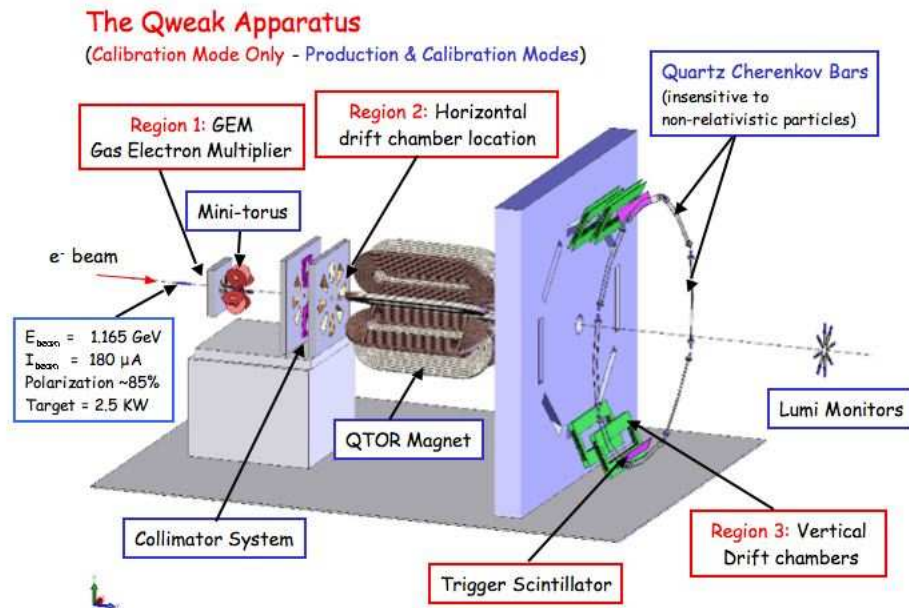


FIG. 3. The Q_{Weak} experimental setup at Hall C, Jefferson lab. The magnetic spectrometer focus elastic events onto eight Cerenkov detectors while collimators block the rest of particles. The region 1,2 and 3 detectors compose the tracking system employed to reconstruct Q^2 precisely.

TABLE I. Basic parameters of the Q_{Weak} experiment

Parameter	Value
Incident beam energy	1.165GeV
Beam Polarization	85%
Beam Current (Current Mode)	180 μA
Corresponding Luminosity	$1.76 \times 10^{39} cm^{-2} s^{-1}$
Beam Current (Tracking Mode)	$< nA$
Target	liquid H (2.5kW)
Target thickness	35cm
Production running time	2544 hours
Nominal scattering angle	7.9 $^\circ$
Angular acceptance	$\pm 3^0$
Total azimuthal ϕ Angular acceptance	49% of 2π
Solid angle, $\Delta\Omega$	37msr
Integrated cross section	4.0 μb
Integrated scattering rate	6.5GHz (0.81MHz per detector)
Acceptance averaged Q^2	0.026(GeV/c) ²
Acceptance averaged experimental asymmetry, $< A >$	-0.200ppm
Acceptance averaged physics asymmetry, $< A >$	-0.234ppm

majority of the beam time is for the asymmetry measurement; it is called the current/parity mode of the experiment. The error budget of the physics asymmetry as well as that for the weak charge of the proton is given in the Table II [21].

III.2. Main Steps of the Q_{Weak} Analysis

The main detector yield per helicity state is measured. Then with the selected good events * one can extract the physics asymmetry by following these steps: [24]

1. Normalize the detector signal yield, N^\pm by the charge measured per helicity state, Q_e^\pm ,

$$Y^\pm = \frac{N^\pm}{Q_e^\pm}$$

* Selected based on a threshold beam current and main detector yield levels. Explained further in the Sub-section IV

TABLE II. The sources of errors in the Q_{Weak} experiment for both the physics asymmetry A_{phys} and the proton's weak charge Q_{Weak}^p .

Sources of error	Contribution to $\Delta A_{phys}/A_{phys}$	Contribution to $\Delta Q_{Weak}^p/Q_{Weak}^p$
Counting Statistics	2.1%	3.2%
Hadronic	-	1.5%
Beam Polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity Correlated beam properties	0.5%	0.7%
Total	2.5%	4.1%

2. Calculate the normalized yield, $Y_{PV}^{\pm} = Y^{\pm} - \Sigma P_k \alpha_K$. Here P_K is the beam position or charge during the event and α_K is the proportionality factor that is to be determined.
3. Calculate the observed asymmetry, $A'_{PV} = \frac{Y_{PV}^+ - Y_{PV}^-}{Y_{PV}^+ + Y_{PV}^-}$, per multiplet.
4. Correct A'_{PV} for the polarization, $A_{PV} = \frac{A'_{PV}}{P_e}$
5. Correct A_{PV} for the background, $A_{PV} = (1 - f)A_{phys} + fA_B$; where $f = \frac{R_B}{R_B + R_E}$ is a dilution factor, R_E and R_B are total elastic rate and background rate respectively and A_B is observed background asymmetry. The background contribution is measured using data collected during dedicated beam time for background calculation.

This will be the universal path to follow, once the experimental data are decoded from their raw formats to detector yields per helicity state.

III.3. DAQ and Data Analysis Software Systems

My thesis work is involved in the Data Acquisition (DAQ) development for the tracking detectors and data analysis software system. Therefore, I will introduce the DAQ and software systems briefly. The DAQ will readout front-end electronic modules connected to the Q_{Weak} detectors. The standard DAQ protocol and the software kit available at JLab is the CEBAF Online Data Acquisition (CODA) [25] [26], and the Q_{Weak} DAQ will be based on CODA. FIG 4 illustrates a simplified CODA read out system. The data analysis software system (**QwAnalysis**) will decode

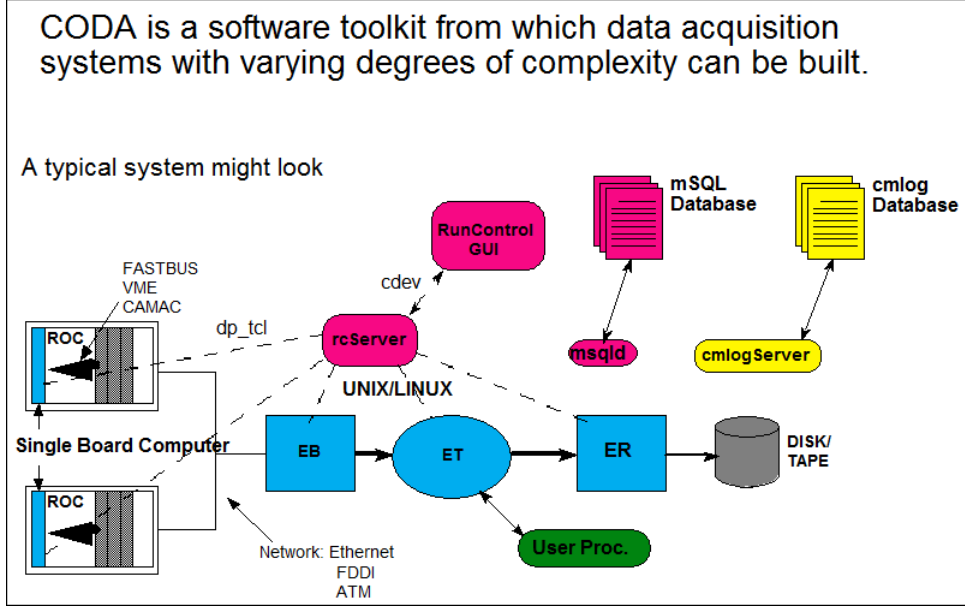


FIG. 4. A sample CODA flow chart for reading a ROC that is connected to detectors.[26] Abbreviations: EB - Event Buffer, ET - Event Transfer, ER - Event Recorder

CODA events to obtain detector yields and other beam parameters, and will also generate the physics asymmetry from CODA events. The outputs of the software system will be saved in a database as well as CERN ROOT [27] data formats. *QwAnalysis* will also provide data for minimizing the Helicity Correlated Beam Asymmetries (HCBA) (by means of feedbacks). The tracking mode of *QwAnalysis* will determine the precise value for Q^2 .

III.3.1. DAQ

DAQ will read-out modules that are electronic interfaces connected to detectors. These modules are connected to Read-Out-Controllers(ROCs) (FIG 4). At the full DAQ readout rate of $1kHz$ approximately 1500Kbytes/s data rate is expected [21]. 2200 hours will generate about 12TBytes of data [21]. The Q_{Weak} DAQ will have two independent modes: Current-mode and tracking mode DAQs. The current mode DAQ will be triggered by the helicity pulse at the injector while the tracking-mode DAQ will be triggered by the trigger scintillator (FIG 3).

The current mode DAQ will read the main detector modules, the luminosity monitor modules and the beam line instrument modules. Since the event rate is $\sim 800MHz$ at $1kHz$ readout rate, we need to integrate the main detector signal. The main detector Photo-Multiplier-Tube (PMT)

TABLE III. Summary of electronic modules read by DAQ for Q_{Weak} detectors

Detector	Type of Module
Main Detectors	TRIUMF VME integrators ^a
Injector Beamline monitors	TRIUMF VME integrators
Hall C Beamline monitors	TRIUMF VME integrators, scalers, I/O Registers
Luminosity monitors	TRIUMF VME integrators
GEM at Region 1 (tracking)	A custom built GEM readout card
Drift Chambers in Region 2 & 3 (tracking)	F1TDCs ^b
Trigger and main detectors	ADCs and etc..
Quartz scanner	TRIUMF VME integrators

^a Consists of low noise current-voltage converter followed by digital integrator. The Digital integrator consists of 18bit ADC, integrating up-to 500ksps (kilo samples per second) which is giving a precision of 2^{27} for a $1ms$ integrated signal. Features includes: 18 bit ADC, a calibration mode, variable sample size, adjustable delay from trigger, programmable features [28]

^b A high resolution , multi hit, VME 64 channels Time-to-Distance Converter (TDC)

signal will be converted to a voltage signal by a current-voltage (I-V) preamplifier. Then the signal will be integrated by VME * digital signal integrator to obtain the total charge within a helicity state [28]. Finally, the DAQ will read out the VME module. The tracking-mode DAQ will read out the tracking detectors in the low current mode. The electronic modules for the Q_{Weak} detectors are listed in Table III [29].

III.3.2. Q_{Weak} Data Analysis Software System

QwAnalysis, the data-analysis software system is the project on which I have started to work in the Q_{Weak} experiment and it will be a significant part of my contribution. So I mostly worked on the tracking software modules, but I have gradually moved to the current mode software system. Since then, I have been working on implementing various event cuts into the current mode system.

In general, the Q_{Weak} data analysis software (**QwAnalysis**) reads CODA generated data either

* Term is originated from VERSAModule Eurocard (VME) bus standard.

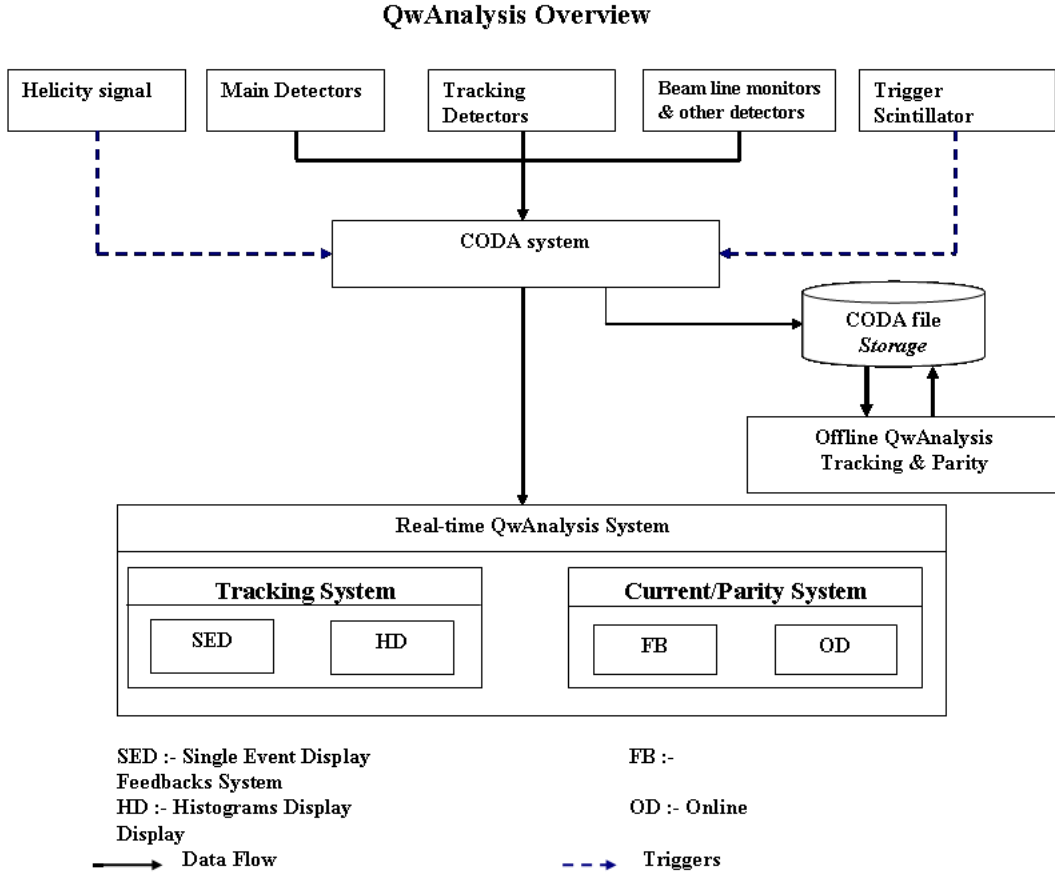


FIG. 5. The QwAnalysis software decodes a CODA event either in offline or online mode to produce various outputs. The primary objective of the offline system is to produce the physics asymmetry, while the online system functions more like a diagnostic tool during the data taking. The flow chart in FIG 6 explains the offline QwAnalysis software.

in real time or offline to produce outputs that determine the quality of the recorded data and accumulates statistics on the asymmetry, respectively. An overview of the QwAnalysis software is given in FIG 5. The CODA module in the diagram performs the DAQ operation to generate the raw data. The dashed-lines connecting the detector systems to the CODA module are the triggering systems that I explained in sub section III.3.1. The two main components of the QwAnalysis are the real-time analyzer and the offline analyzer. Both the systems have separate implementation for tracking and current mode. The offline tracking mode analyzer will reconstruct the electron paths along the three regions of detectors (see FIG 3) to determine the electron kinematics.

The offline QwAnalysis system for current mode is shown in FIG 6. In the flow chart; first,

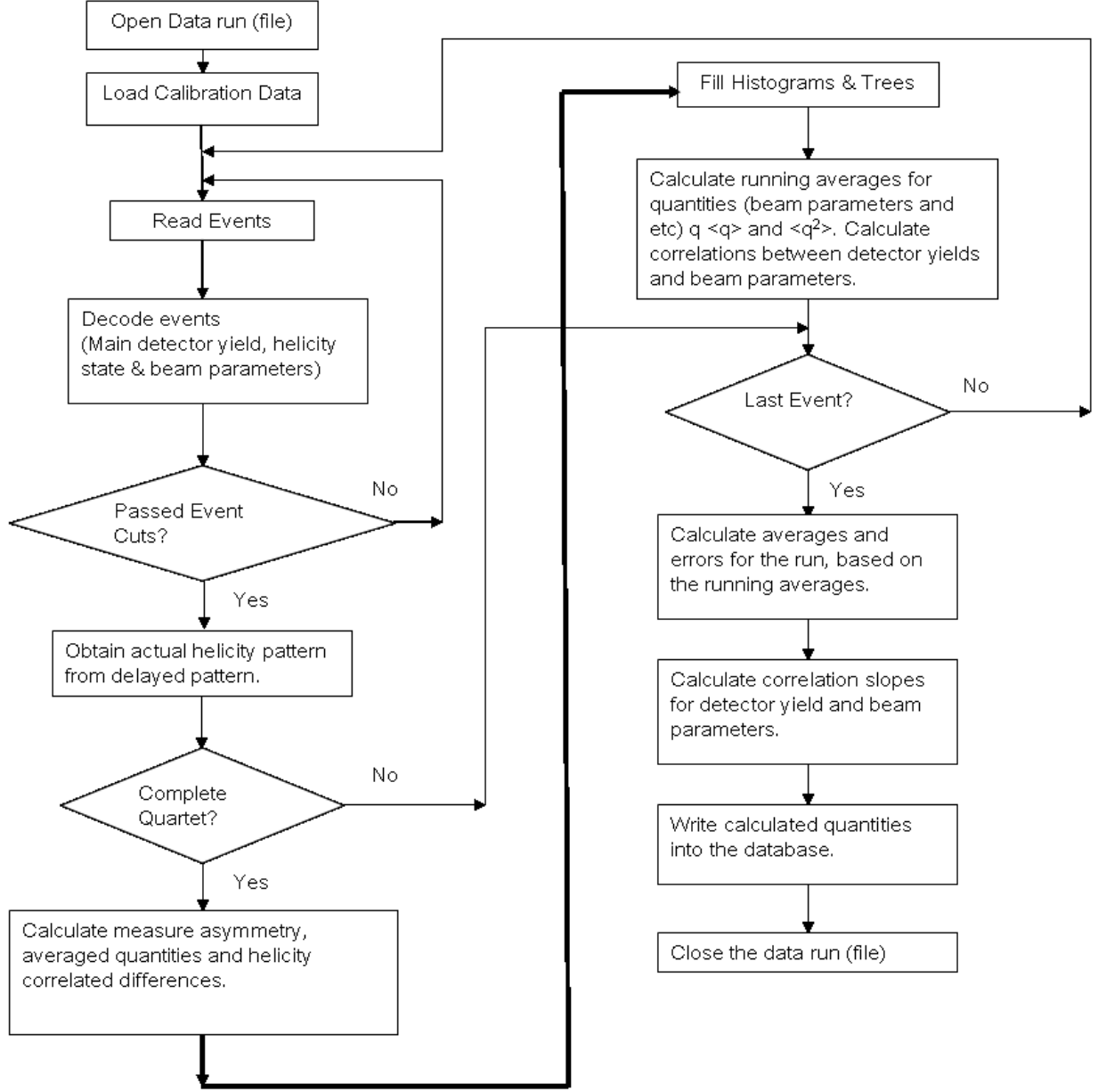


FIG. 6. Main flow for the offline Q_{Weak} data analyzer.

only good events are selected (see Section IV.1.2). Then a set of events (the no.of events depends on the helicity multiplet) is chosen that has a complete helicity multiplet. Finally, for this event, multiplet detector yields are calculated. Once the yields are corrected universal asymmetry extracting method described in Section III.2 can be applied. The calculated entries are saved to a database/data files, and generate histograms and trees for viewing. There will be several passes through the **QwAnalysis** engine before the final results are produced.

Running a `QwAnalysis` engine in real time will provide two advantages. One is that it provides real time display of the beam parameters and main detector yields to the physicists. In the tracking mode, the online analyzer will provide a single event display that will show electron tracks generated on the tracking detectors. The second important other advantage is the feedback system. Feedback systems will minimize the energy, charge and position asymmetries of the experiment that creates false asymmetries.

IV. MY CONTRIBUTION TO THE Q_{WEAK} EXPERIMENT

So far my work involved building the Q_{Weak} data analyzer and up to now I have been working on the parity and tracking software development of the offline Q_{Weak} data analyzer. I will explain them in a brief summary in the next section and then in the section IV.2 I will present my thesis goals and a time line.

IV.1. What I have been Doing so far in Q_{Weak}

IV.1.1. *My Offline Tracking Data Analyzer Work*

I have been working on the tracking data analyzer from the beginning. Mainly I was developing a framework to store observed tracking detector hits from all three different regions in a universal container, so that they are handled uniformly during electron track reconstruction algorithms during the offline tracking mode. The outcome of my work has been implemented into the Q_{Weak} data analyzer [6] successfully. There has been progress made in tracking detector implementation using this framework. The following list summarizes what I have been doing in the tracking data analyzer.

- Implemented a global framework for CODA event decoding routines for tracking detectors in all regions.
- Developed CODA event decoding based on the above framework for the region 2 and generated a set of observed detector hits.
- Optimized the already available track decoding routines.

- Mapped tracking detector electronic channel and geometric information to the analyzer
- Generated CERN ROOT [27] histograms and a Tree for region 2 events.
- Connected the track decoding system with track reconstructing system for region 2 detectors.
- Integrated two different electronic modules into the tracking analyzer.

IV.1.2. My Offline Parity Data Analyzer Work

I have been developing a procedure to extract good events for analysis based on the beam-line current and position monitoring devices. Good events are selected by two steps. First, the beam line hardware devices are checked for hardware errors like encoding and transmission errors. Then, the beam current and position are checked for an acceptable range (applying event cuts). Once a good event is selected it is included in further calculations that include asymmetries, yields and their statistical averages and errors.

The event cut procedure currently removes any event due to a drop (and beam trips) in the beam currents, beam positioning error, beam-line monitoring devices saturation, or any hardware failures resulting in loss of information. The hardware test is applied first, and then event cuts are applied on each device. Event cuts can be independently set on individual hardware devices while hardware checks are performed on all the devices.

The basis for the asymmetry calculation in Q_{Weak} is a quartet (the helicity pattern or the event multiplet). The quartet consists of four “consecutive good events”. Once the quartet is complete, the running sum of quantities, q ($\langle q \rangle$ $\langle q^2 \rangle$), are calculated along with the experimental asymmetry. The quantity q can be beam charge, relative positions of the beam and their experimental asymmetry, $A_q = \frac{q_+ - q_-}{q_+ + q_-}$, where \pm represent positive and negative helicity yields per quartet, respectively. In the end of a CODA run averages and errors are calculated using running sums.

IV.1.3. My Hardware/DAQ Work on the Q_{Weak}

Currently, I am working on region 1 electronic modules. The task is to set up the CODA configuration, so that the region 1 detector modules can properly communicate with the CODA system.

IV.2. My Thesis Goals and Time Line

Here are my primary goals on the Q_{Weak} experiment:

1. Set up the tracking DAQ environment and maintain it during the experimental run.
2. Continue to work on the tracking analyzer.
3. Extract the physics asymmetry by analyzing the data produced by the `QwAnalysis` system.

I will be one of four graduate students who are working on this.

As these are set at more general level now I will dissect and organize them along with the Q_{Weak} experiment schedule in FIG 7

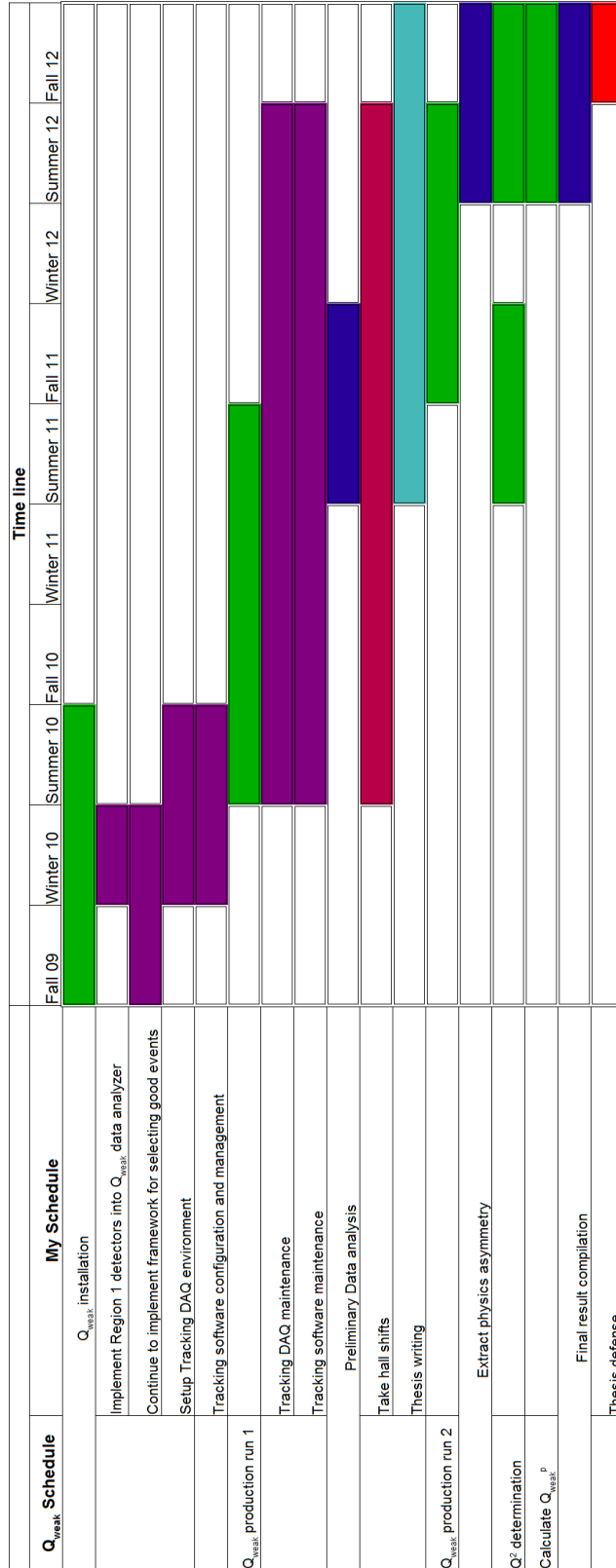


FIG. 7. Q_{Weak} experiment and my thesis time line. The green strips represent the Q_{Weak} schedule while violet strips are my schedule. The common data analysis work schedule is in blue strips.

Appendix A: Q_{Weak} Track Decoder Framework

I have attached my technical document [7] for further reading on my work with the Q_{Weak} collaboration.

1. Introduction

It is essential to calculate Q^2 to 0.5 % precision to determine the weak charge of the proton, Q_{Weak}^p , to a precision of ~ 4 % [21]. The Q_{Weak} experimental setup has a dedicated electron tracking apparatus [22] to achieve this goal. The three main tracking detectors are the GEMs in region 1 (R1), Horizontal Drift Chambers (HDC) in region 2 (R2) and Vertical Drift Chambers (VDC) in region 3 (R3). The DAQ system is triggered by a scintillator detector in front of the main detector setup. Electrons passing through the tracking detectors interact with a limited set of wires/elements in each region. For each event in the CODA file, QTD decodes and presents the hit¹ channels² to the QTR in a predefined format. Hit wires/elements generate `QwHit` objects. These `QwHit` instances are contained in `QwHitContainer` (basically an array).

In section 2, I will be explaining the main flow of the QTD framework. The entire framework is modular (Based on object oriented principles) so that the framework is highly expandable with respect to adding new detector classes. I have included C++ coding examples to clarify the methodology used. In the same section I will explain the CODA event handling. The CODA events are decoded in a generic way such that each detector class can handle their own wire/element hits by reading the generically decoded CODA event. I will also introduce the Histograms and Trees generated by the QTD in the Section 3. There are several appendices at the end of the article with more C++ technical details, wire/element hit information , detector electronics mapping and the CODA event handling information.

¹ A hit means that a wire/element has been interacted with passing electron.

² Wires/Elements are connected to electronic channels directly or indirectly

2. QTD Flow

The QTD framework was built to be modular so adding new Q_{Weak} detectors will be convenient. To achieve this feature, all subsystems (tracking detectors) must inherit the common abstract detector class `VQwSubsystem`. The result is that QTD framework handles all Q_{weak} detectors through common routine calls. The main flow of the QTD is illustrated by the flowchart diagram ,FIGs 8 and, FIG 9 which lists individual subsystem processes that are invoked for each event. These diagrams include important processes within the QTD class framework.

Processes in the box labeled “1” in FIG 8 are involved in the initialization of the main classes including the tracking detector classes. The virtual class `VQwSubsystemTracking` dictates the existence of the main routines of the detector class and any tracking detector class must be derived from it. The main routines of the detector class include loading electronic channel maps and detector geometry, setting up ROOT histograms and a tree, decoding CODA events, filling histograms and a tree and finally updating the global wire hit structure (`QwHitContainer`). The tracking detectors are added into an array of the handling class `QwSubsystemArrayTracking`. This class employs polymorphic functionality that allows the handling of different detector classes or subsystems. This enables invoking common tracking detector routines through a single routine call to this array. See the example code below.

```
QwSubsystemArrayTracking QwDetectors;  
QwDetectors.push_back(new QwDriftChamberHDC("R2"));  
QwDetectors.push_back(new QwTriggerScintillator("TS"));  
QwDetectors.push_back(new QwMainDetector("MD"));
```

The above code defines the array and adds detectors to it. The code given below illustrates how electronic channel maps can be loaded into each subsystem through the handling class `QwSubsystemArrayTracking`.

```
QwDetectors.GetSubsystem("R2")->LoadChannelMap("qweak_cosmics_hits.map");
```

Where the map file “ `qweak_cosmics_hits.map` ” is loaded to the subsystem “R2”.

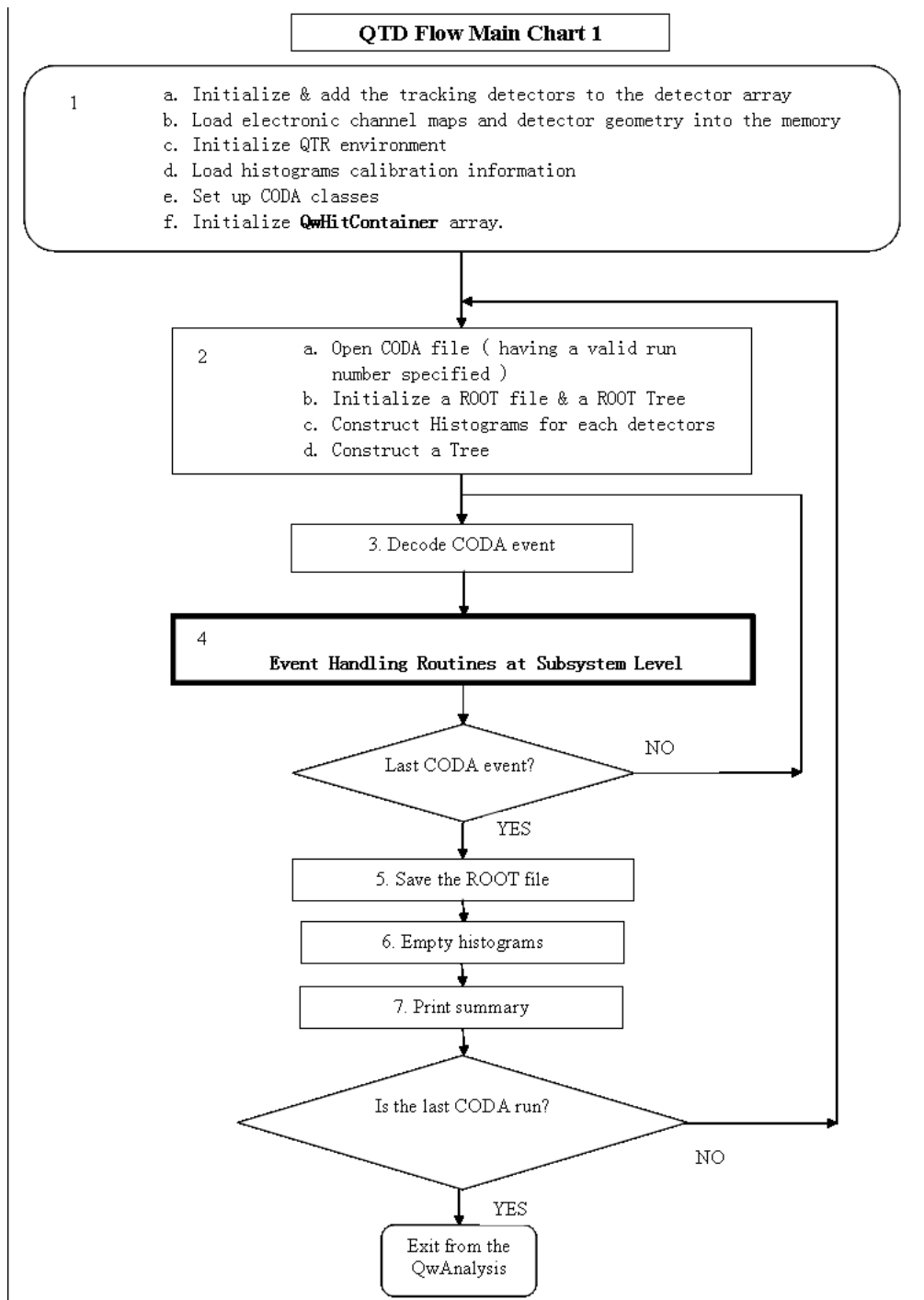


FIG. 8. This is the flowchart of the QTD system. The number on each process box is used as a reference in the text. “Event Handling Routines at Subsystem Level” is expanded in FIG 9, to give a list of processes each subsystem must have.

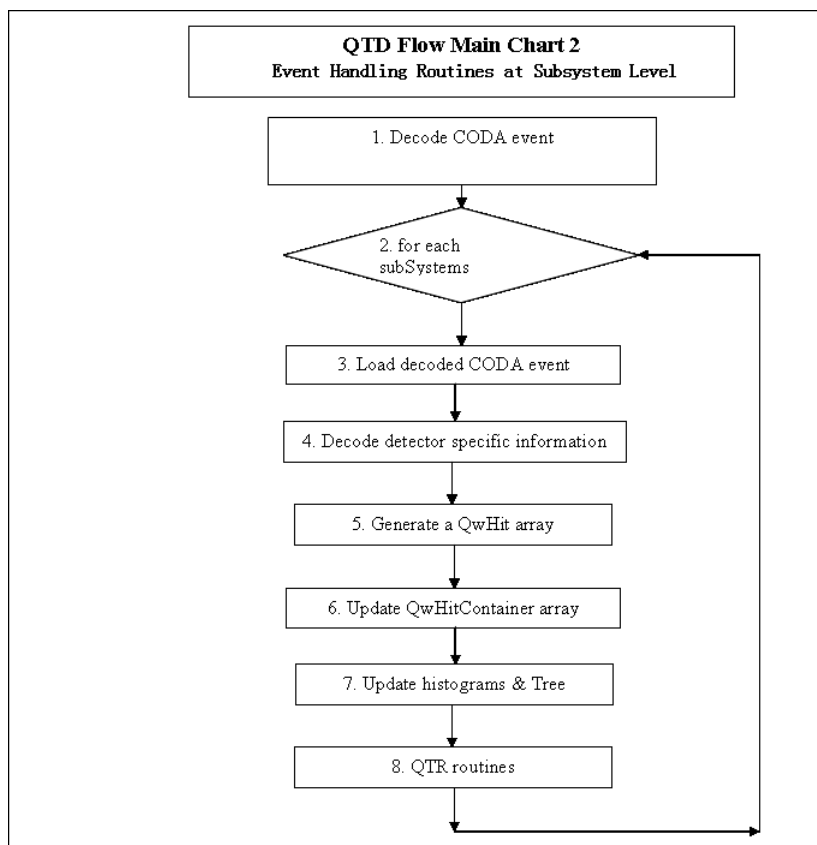


FIG. 9. This diagram only provides a set of routines a QTD subsystem goes through for each event. The number on each process box is used as a reference in the text.

Once the initialization has completed, QTD opens a CODA file³ and outputs a ROOT data file. For each event, the code executes the loop containing box “3” and “4”. The CODA file (run) is opened using routines in the class `QwEventBuffer`. A chunk of data is read from the CODA file through the `QwEventBuffer::GetEvent()` routine. The data are then passed to each subsystem (e.g. “R2 or “R3”). Then each subsystem decodes event data related to their own subsystem and reduces them to pass to the `QwHitContainer` as units of `QwHit` objects. These steps are detailed in the FIG 9. The code below summarizes the important steps of boxes “3” and “4” in FIG 8.

```

QwEventBuffer QwEvt;
eventbuffer.OpenDataFile(run);
  
```

³ The entire ODA event data is arranged into a set of data files. Each file has a set of events (approximately one hour worth of data). Each of these CODA files have a specific run number.


```

while (QwEvt.GetEvent()){
QwEvt.FillSubsystemData(QwDetectors);
QwDetectors.ProcessEvent();
QwDetectors.FillHistograms();
QwDetectors.GetHitList(grandHitList);
}

```

Finally in the “8” a generated `QwHitContainer` array containing wire/element data from all the subsystems is passed to the QTR.

Once CODA data is decoded, further processing of event data is done by `QwSubsystemArrayTracking::Process`. At the end of event processing an array of wire/element hits is obtained, they are updated with appropriate Histograms (and a Tree). Then the `QwHitContainer` array (the object `grandHitList`) is updated with decoded wire/element hits array generated for each detector from all the regions (1,2 &3) ⁴. Finally the processes in boxes “5,6 & 7” in the FIG 8 will perform the book keeping and clean up at the end of each run.

a. Modular Class Framework and Common Functionality of the tracking Detector Classes

Each tracking detector class is derived from `VQwSubsystemTracking` to have common routines for primary functionality. The class `VQwSubsystemTracking` is derived from general `VQwSubsystem` parent which is the generic class for the Qweak detectors. FIG 10 illustrates this modular class framework. The detector array `QwSubsystemArrayTracking` is derived from the `QwSubsystemArray` which is derived from `std::vector<VQwSubsystem>`. So the `QwSubsystemArrayTracking` array can hold tracking detectors that have inherited the common class `VQwSubsystemTracking`. FIG 11 provides more clear view of this class hierarchy.

b. An Example of a Subsystem Implementation: Region 2 Drift Chambers

Each subsystem in the QTD is supplied with data array for each event and the QTD requires each subsystem output to have the valid wire signals that can be added into `QwHitContainer`

⁴ currently only region 2 has real data and in the region 3 we use fake data.

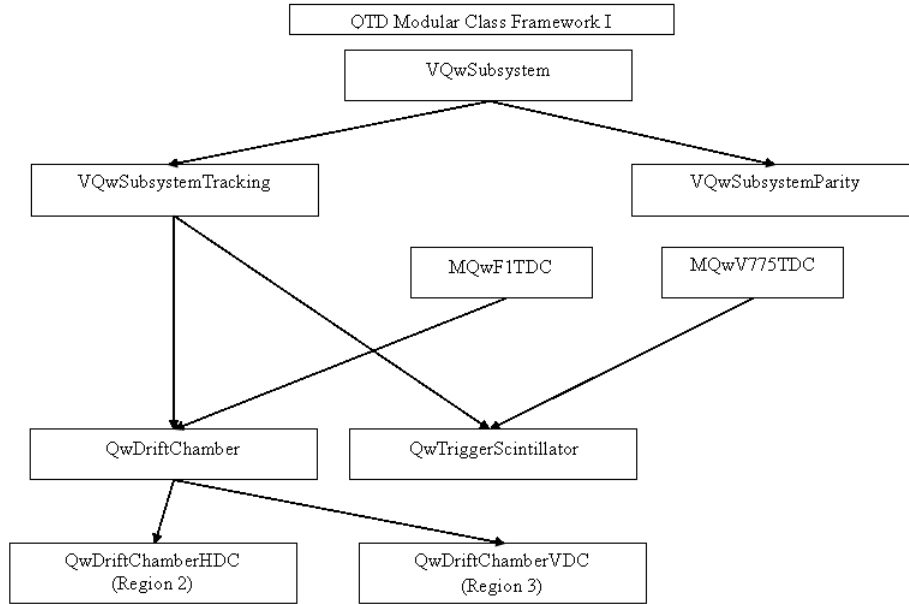


FIG. 10. The current level of hierarchy in the QTD for subsystems (detectors). The Region 2 & 3 detectors are inherited from the `QwDriftChamber` class due to their similarities in QTD implementation

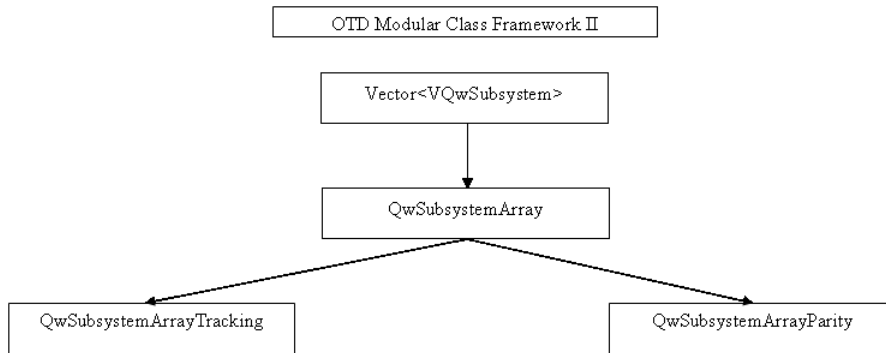


FIG. 11. QTD manages all subsystem routines through common routine calls to `QwSubsystemArrayTracking` array. The modular class framework of the common routine handling is explained in the diagram. The `QwSubsystemArrayParity` handles the common routine calls in the current/parity mode Qweak Analyzer.

object. Each subsystem must provide the functionality to decode the receiving event data array input to produce the `QwHit` array as well as it has to define its set of histograms. As depicted in FIG 10, the region 2 subsystem is implemented through `QwDriftChamberHDC`. A summary of

primary routines and their functionality, that region 2 subsystem has to implement in order to properly integrate in to the QTD is given below.

The `QwDriftChamberHDC` version of the routine;

```
VQwSubsystem::ProcessEvBuffer(const UInt_t roc_id, const UInt_t bank_id,  
    UInt_t* buffer, UInt_t num_words)
```

provides CODA event data array decoding functionality to obtain the F1TDC data words and store them in an array of `QwHit`. Further data handling can be done on F1TDC raw timing data by implementing the necessary code at;

```
QwSubsystemArrayTracking::ProcessEvent()
```

This routine is used to calculate actual drift distance from the raw TDC data. The generated hit array must be passed to the QTD main routine. This is achieved by implementing the routine

```
void GetHitList(QwHitContainer & grandHitContainer)
```

which appends the array into the grand hit list (`QwHitContainer`). Initializing routines;

```
Int_t LoadChannelMap(TString mapfile )  
Int_t LoadInputParameters(TString mapfile)
```

provide electronic channel information on F1TDC and other electronic modules and Histogram parameters, respectively. Required histograms are created and filled on event by event basis by using;

```
void ConstructHistograms(TDirectory *folder, TString &prefix)  
void FillHistograms()
```

The above routines must be implemented in order for any subsystem to work within the QTD framework.

The drift chambers in the region 2 and region 3 use Time-to-Digital Converters (TDC) ⁵ to obtain drift times for chamber wires. The class that supports CODA event decoding when the electronic modules are F1TDC is called MQwF1TDC class. This class provides necessary routines, parameters, and constants to decode CODA event read out through F1TDC modules. During a testing session, region 3 drift chambers were connected to V775 TDC modules. So to decode events read by V775 modules all that was required to do was to change the inheriting class from MQwF1TDC to the MQwV775TDC class. Where the class MQwV775TDC is the class that helps to decode V775 TDC modules.

3. Histograms and Tree

The QTD and QTR both support CERN ROOT histograms and Trees as the way to represent vast data produced in Q_{Weak} . Each detector class (a subsystem) added to the system has its own capability to generate histograms and contribute to the tree. All the histograms that are to be generated must also have calibration details included in the calibration file for the QTD. The file contains calibration details for all the subsystems. The file includes QTD standard histograms names, bin sizes and ranges. The QwHistogramHelper class which has a global definition within the QTD, manages the libraries of CERN ROOT histograms. This global object reads the histogram calibration file and provides the calibration details for the VQwSubsystem::ConstructHistograms() routine.

The QTD framework currently generates a single ROOT Tree (TTree) containing QwHitContainer information. So each wire in the region 2 has a branch in the tree containing leaves of drift time and distance. Currently region 3 has faked hits from region 2 detector set up. So both region 2 and region 3 have entries in the Tree. QwHitContainer array provides the wire hit times and drift to the fill the Tree.

⁵ either F1TDC or V775TDC are used as electronic modules in region 2 and 3 drift chambers

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