Precision Møller Polarimetry and the MOLLER Experiment at Jefferson Lab

Addison Arcuri, 11 June 2026

Temple University

CNUGS
CHRISTOPHER NEWPORT UNIVERSITY
GRADUATE SUMMER WORKSHOP
AT JEFFERSON LAB
formerly The HUGS Program

MOLLER

Outline

Background:

- What is MOLLER?
- What is Møller polarimetry?

Møller Polarimetry in Hall A:

- What are the systematics?
- What does the data acquisition look like?

Dead Time Model:

- How did previous experiments correct for dead time?
- How will that change for MOLLER?

Accidental Model:

- How did previous experiments correct for accidental coincidences?
- How will that change for MOLLER?

Model Testing:

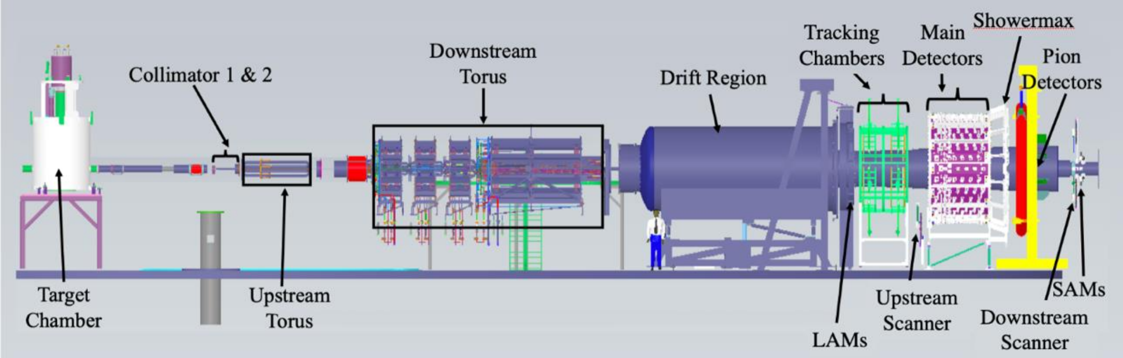
- How well do our updated models correct a known asymmetry?

Background: The MOLLER Experiment

- In polarized beam Møller scattering there is a longitudinal parity-violating rate asymmetry:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = m_e E \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q_W^e \quad \text{where} \quad Q_W^e = 1 - 4\sin^2\theta_w + \text{radiative corrections}$$

- MOLLER extract $\sin^2\theta_w$ from measured A_{PV} (~33±0.8 ppb)
- A_{PV} error goal is 2.4%: 2.1% statistical and 1.1% systematic
  - ±0.00028 on the value of $\sin^2\theta_w$
- Beam: E = ~11 GeV, I = 65µA, ~90% longitudinal polarization



The MOLLER beamline. Møller Polarimeter behind target. Image from [1].

- Measured A_{PV} is proportional to beam polarization
- **Polarimetry is one of the largest systematics with a budget of 0.40%!**
- This is an ambitious precision goal: Previous Hall A experiments (e.g., CREX) had **0.85%** systematic uncertainty for polarimetry

Background: Møller Polarimetery Basics

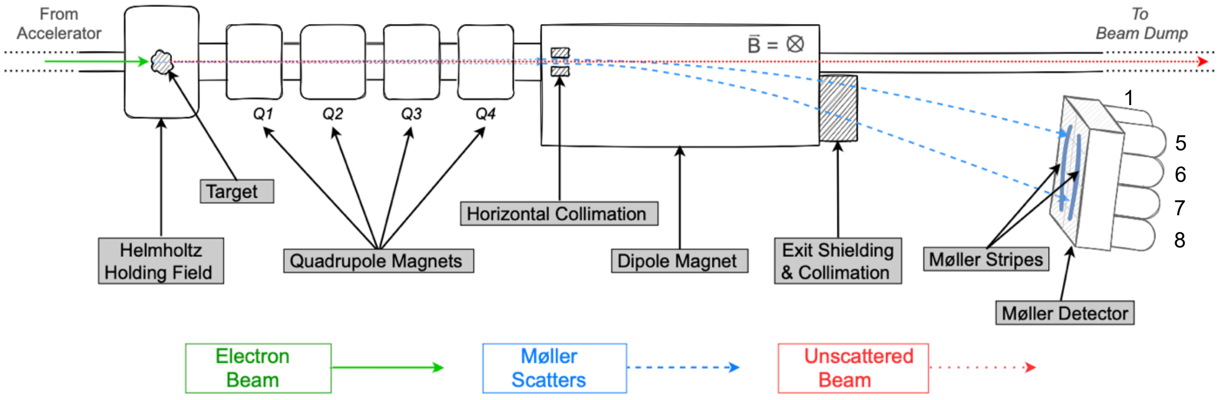
- Møller polarimetry measures the rate asymmetry between beam helicity states when scattering from a polarized target
  - The raw asymmetry (with helicities 1, 0) is: $\mathrm{A_{meas}} = \frac{\mathrm{R_1 - R_0}}{\mathrm{R_1 + R_0}}$
  - The beam polarization is a product of the measured asymmetry, known target polarization, and the angle-averaged analyzing power:

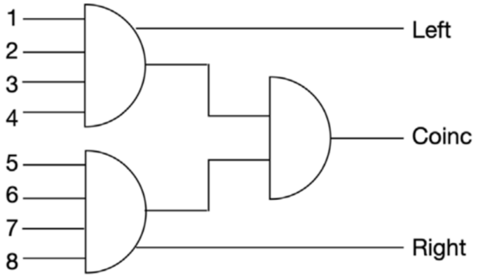
$$P_{beam} = \frac{A_{meas}}{P_{targ}\langle A_{zz}\rangle} \qquad A_{zz} = \frac{(7 + \cos^2\theta)\sin^2\theta}{(3 + \cos^2\theta)^2}$$

  - The analyzing power in the field-normal direction (A_{zz}) peaks at 7/9 for thin target

- Because Møller polarimetry uses a polarized scattering process, this asymmetry is several orders of magnitude larger than the parity-violating $\mathrm{A_{PV}}$ measured by MOLLER!

Møller Polarimetry in Hall A





Asymmetry is found pattern-by-pattern as helicity changes:

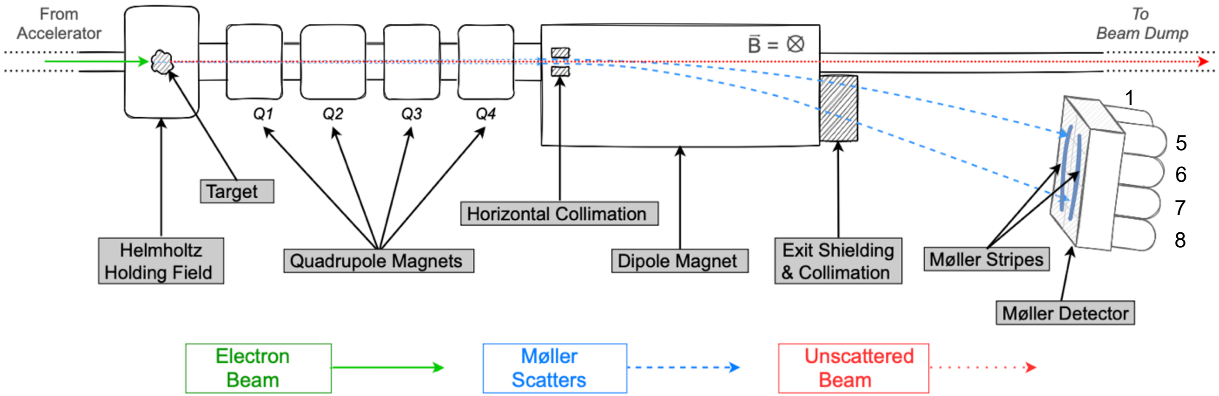
- $A_{meas} = \frac{R_1 - R_0}{R_1 + R_0}$

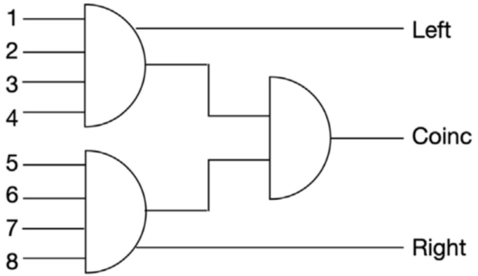
Basic Scaler DAQ coincidence logic. Not shown is Accidental channel, which ANDs a delayed Left signal with Right.

The separate FADC DAQ forms coincidences in software. Not subject of this talk.

Image credits: From [2,3]

Møller Polarimetry in Hall A





Asymmetry is found pattern-by-pattern as helicity changes:

- $A_{meas}^{corr} = \frac{R'_1 - R'_0}{R'_1 + R'_0}$
- 3 Main Corrections to our measured asymmetry
  - Beam Current Normalization: $R \to R'$

Basic Scaler DAQ coincidence logic. Not shown is Accidental channel, which ANDs a delayed Left signal with Right.

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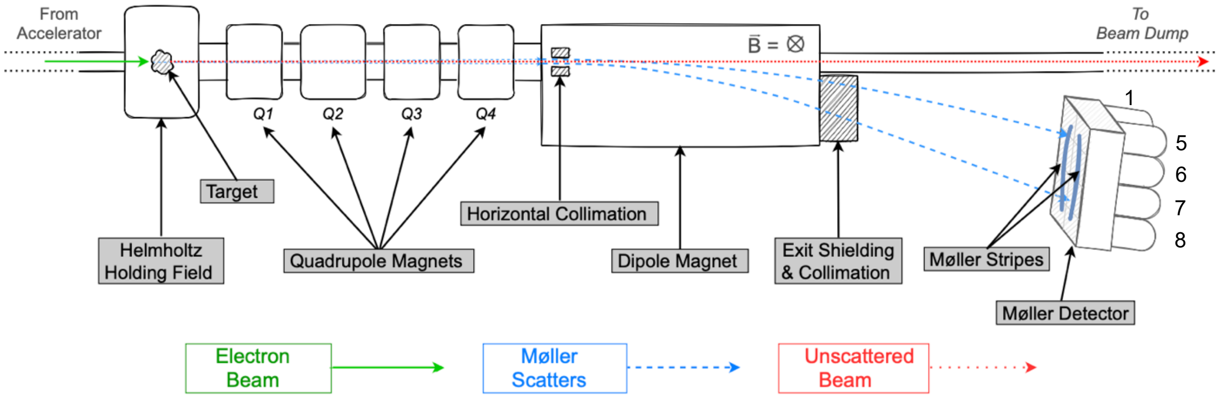
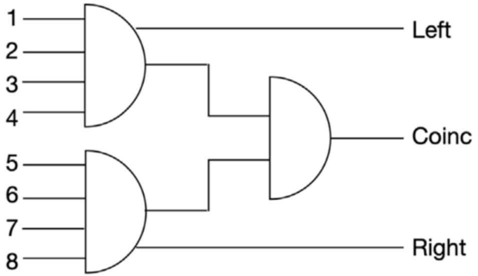
Møller Polarimetry in Hall A





Asymmetry is found pattern-by-pattern as helicity changes:

- $$A^{corr}_{meas} = \frac{(R'_{C,1} - R'_{A,1}) - (R'_{C,0} - R'_{A,0})}{(R'_{C,1} - R'_{A,1}) + (R'_{C,0} - R'_{A,0})}$$
- 3 Main Corrections to our measured asymmetry
  - Beam Current Normalization: R → R'
  - Accidental Correction: R → $R_{C,i} - R_{A,i}$

Basic Scaler DAQ coincidence logic. Not shown is Accidental channel, which ANDs a delayed Left signal with Right.

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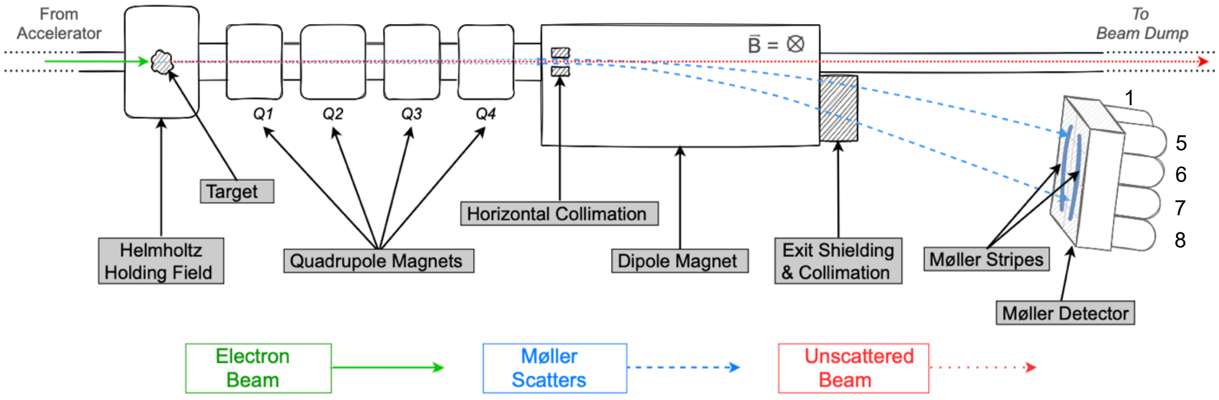
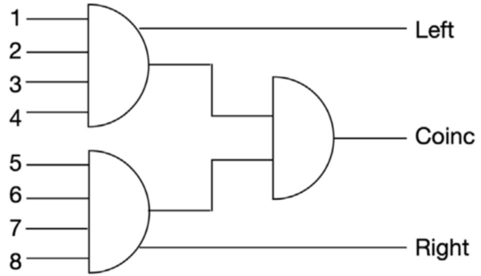
Image credits: From [2,3]

Møller Polarimetry in Hall A





Asymmetry is found pattern-by-pattern as helicity changes:

- $$A^{corr}_{meas} = \frac{(R'_{C,1}-R'_{A,1})e^{R_1\tau} - (R'_{C,0}-R'_{A,0})e^{R_0\tau}}{(R'_{C,1}-R'_{A,1})e^{R_1\tau} + (R'_{C,0}-R'_{A,0})e^{R_0\tau}} \approx 5.4\%$$
- 3 Main Corrections to our measured asymmetry
  - Beam Current Normalization: $R \rightarrow R'$
  - Accidental Correction: $R \rightarrow R_{C,i} - R_{A,i}$
  - Dead Time Correction: $R \rightarrow Re^{R_i\tau}$
    - **Rate-dependent. Creates false Asymmetry!**

Basic Scaler DAQ coincidence logic. Not shown is Accidental channel, which ANDs a delayed Left signal with Right.

The separate FADC DAQ forms coincidences in software. Not subject of this talk.

Image credits: From [2,3]

Møller Polarimetry Systematics

	Problem	CREX (%)	MOLLER Goal (%)
	Foil Saturation Polarization	0.28	0.24
*	Foil Degree of Saturation	0.50	0.10
	Azz + Levchuk	0.16	0.15
	Radiative Corrections	—	0.10?
*	Dead Time	0.15	0.10
*	Accidentals	0.04	0.10
	Current Dependence	0.50	0.15
	Aperture Transmission	0.10	0.10
	Null Asymmetry	0.22	0.10
	Electron Source Variation	0.06	0.02
	Leakage Currents	0.18	0.10
	Overall	0.85	0.42

Møller Polarimetry systematics for CREX (2019) and MOLLER goals

- Foil Saturation Polarization is global knowledge of iron saturation
- A_{zz}+Levchuk improvements from better simulation/iron wavefunctions
- Current Dependence and Aperture Transmission will require dedicated studies during MOLLER
- Null Asymmetry, Electron Source Variation, and Leakage Currents will be measured during MOLLER runs
- **Foil Degree of Saturation, Radiative Corrections, Dead Time, and Accidentals have ongoing or planned pre-MOLLER studies.**
  - **Dead Time and Accidental improvements are focus of this talk**

DAQ Tuning With Emulator

Our CAEN 5810b detector emulator simulates detector events

- Two physical output channels + coincident pulse injection into both channels
- Feeds into DAQ in place of inactive PMTs
- Very useful in tuning the DAQ

Ex: Emulator revealed problem with accidentals

- With uncorrelated singles only, DAQ measured ~1.20x more coincidences than accidentals
- Solved by adding discriminator immediately before the delayed left signal is ANDed, tuning until rates are equal

Detector emulator in use. The two physical outputs are plugged into the polarimeter DAQ FIFO where the detector PMT signals enter the system.

Scaler DAQ Dead Time: Old Model & Shortfalls

For Poisson distributed events with average rate R, the probability that k events will fall in a window of length t is given by:

$$P(k,t) = \frac{(Rt)^k}{k!}e^{-Rt}$$

An event followed by 1 or more additional events within a dead time window τ_d results in dead time. The probability of dead time is therefore: 1 – P(0, τ_d)

$$P_{\text{dead}} = 1 - P(0,\tau_d) = 1 - \frac{1}{1}e^{-R\tau_d} = 1 - e^{-R\tau_d}$$

Converting to rates and leaving the event rate as “R” for the time being:

$$R_{\text{dead}} = R_{\text{true}}(1 - e^{-R\tau_d})$$

$$R_{\text{true}} = R_{\text{meas}} + R_{\text{dead}} = R_{\text{meas}} + R_{\text{true}}(1 - e^{-R\tau_d})$$

For Møller coincidences we have:

$$R_C^{\text{true}} = R_C^{\text{meas}} + R_C^{\text{true}}(1 - e^{-R\tau_d})$$

Scaler DAQ Dead Time: Old Model & Shortfalls

- The true rate is given by: $$R_C^{\text{true}}(1-(1-e^{-R\tau_d})) = R_C^{\text{meas}}$$

$$R_C^{\text{true}} = \frac{R_C^{\text{meas}}}{(1-(1-e^{-R\tau_d}))} = \frac{R_C^{\text{meas}}}{e^{-R\tau_d}} = R_C^{\text{meas}} e^{R\tau_d} \Rightarrow \boxed{R_C^{\text{true}} = R_C^{\text{meas}} e^{R\tau_d}}$$

- This is the "old model". In previous PREX-2 and CREX experiments single τ_d = 15.7 ns was used
  - Found using a fixed 4.4 kHz LED flasher system during runs to determine number of pulses missed

- Now consider the detector can be deadened by single left, single right, or coincident events ($R = R_L^s + R_R^s + R_C$), which may in principle have <u>differing time constants</u>:

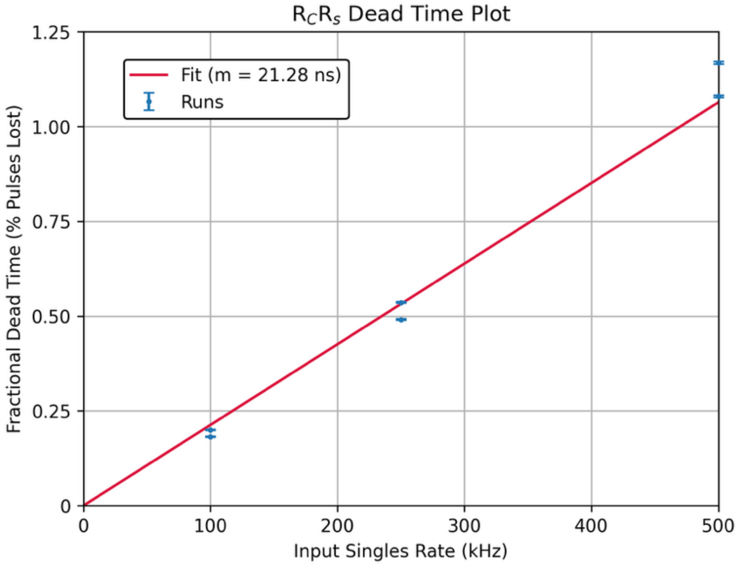
$$R_C^{\text{true}} = R_C e^{(R_C + R_L^s + R_R^s)\tau_d}$$

$$\boxed{R_C^{\text{true}} = R_C e^{(R_C)\tau_{dC} + (R_L^s + R_R^s)\tau_{ds}}}$$

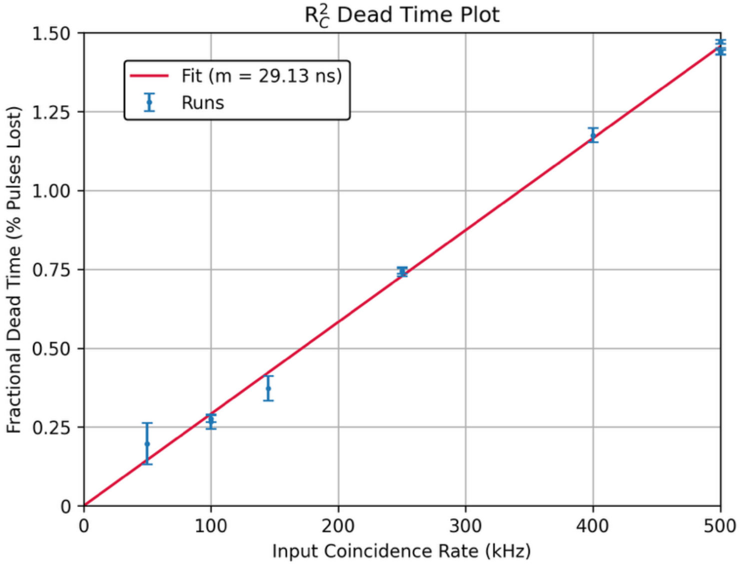
The New Model

Scaler DAQ Dead Time Constants

Using the detector emulator, we were able to isolate the individual dead time constants τ_{ds} and τ_{dC} and show that they do differ. Both are greater than the previous $\tau_d = 15.7$ ns.



These runs had fixed coincidences at 100 kHz. Singles were varied at Poisson rates 100–500 kHz. Dead time loss was linear, with slope: $\tau_{ds} = 21.3$ ns



In these, a variety of Poisson coincidence rates between 50–500 kHz were tested. No singles. Dead time loss was linear, with slope: $\tau_{dC} = 29.1$ ns

Scaler DAQ Accidental Corrections

We previously determined accidental coincidence count by ANDing delayed Left with Right, giving a real-time measure of false coincidences from background events.

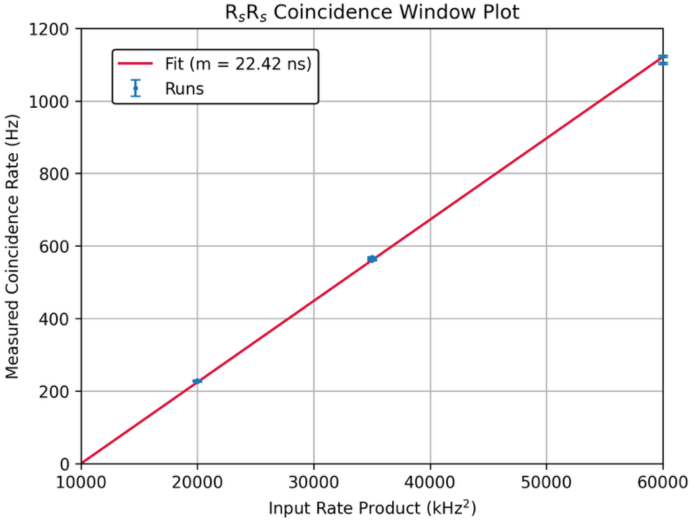
We found this method to be flawed. Decompose rates into singles and Coincidences:

$$R_A = R_L R_R \tau_A = (R_L^s + R_C)(R_R^s + R_C)\tau_A \quad \Rightarrow \quad R_A = \left(R_L^s R_R^s + (R_L^s + R_R^s)R_C + {R_C}^2\right)\tau_A$$

Only the first $R_L^s R_R^s$ term contributes. Our physical accidental channel has been oversubtracting!

We can determine τ_A and create our accidental correction from it.

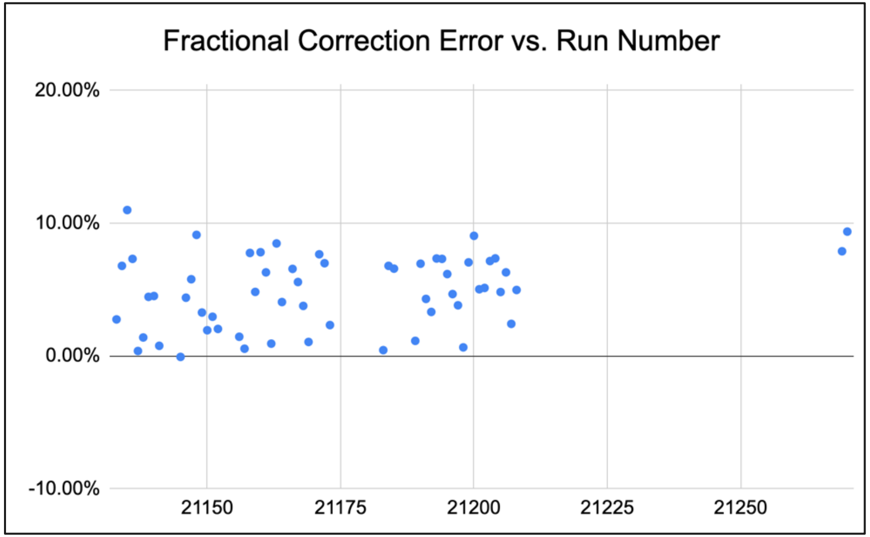
- One channel was held at a fixed rate, while the other took varied Poisson rates
- The measured coincidence rate follows a linear relation with rate product
- The slope yields constant: $\tau_A = 22.4$ ns



Scaler DAQ Dead Time + Accidentals Model Test

Using constants determined via the methods shown, we can construct a model to correct for dead time and accidentals.

- Tested model by running the emulator at various rates with an artificial asymmetry of 33.33% and applying corrections
- The result of one set of tests is shown. These use the slightly different constants from Don Jones' analysis: τ_{dC} = 29.4 ns, τ_{dS} = 19.8 ns, τ_{A} = 21.0 ns
- Corrects asymmetry to within 10%

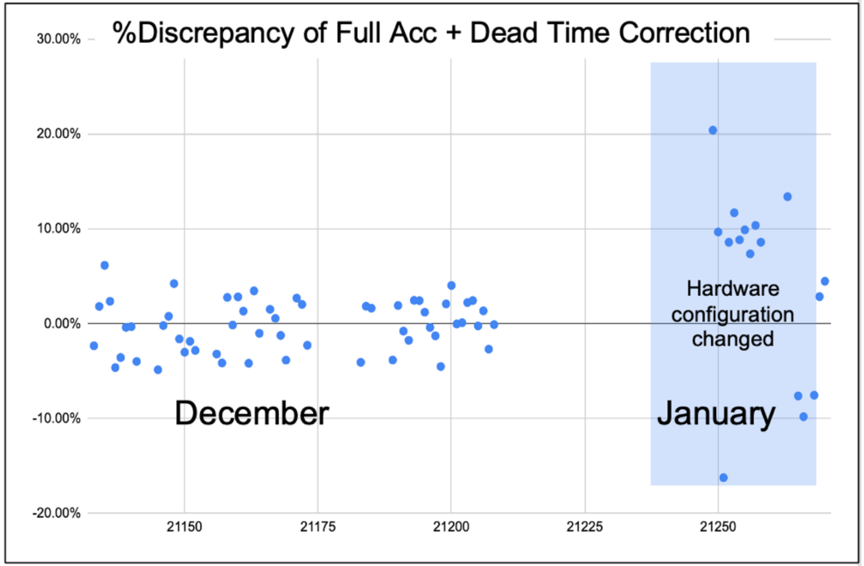


Fractional error of correction for several test runs. The input left, right, and coincidence rates took a variety of values in the range from 25–500 kHz.
Credit: Don Jones, internal presentation.

Scaler DAQ Dead Time + Accidentals Model Test

An empirical correction of the same type can be made by choosing the constants that minimize RMS errors

- Values used differ slightly from those determined from fitting emulator data
  - τ_{dC} = 30.5 ns, τ_{ds} = 18.1 ns, τ_{A} = 22.6 ns
- At right, the result of using such constants to correct the same data is shown:
  - Discrepancy is now within ±5% for most runs taken with our typical DAQ setup
  - January runs used a different emulator/ DAQ setup which was not well-behaved



The empirical correction on the same test runs.
Plot credit: Donald Jones, internal presentation.

Conclusions

- Scaler DAQ used a single $e^{R_i \tau}$ dead time correction with τ_d = 15.7 ns
  - Constructed new correction with two dead time constants
  - Correction term is: $e^{(R^s_{i,L}+R^s_{i,R})\tau_{dS} + R_{i,C}\,\tau_{dS}}$, with τ_{dC} = 29.1 ns, and τ_{dS} = 21.3 ns
- It estimated accidentals with coincidence channel formed from a delayed left signal
  - New correction in which accidentals are estimated by the term $R_A = R^s_L R^s_R \tau_A$, with constant $\tau_A = 22.4$ ns
- These corrections were tested by creating an artificial rate asymmetry of 33.33% and correcting the measured rates at a variety of input rates.
  - Model correction is accurate to within ~10%
- Current and future research will conduct similar analysis on the FADC DAQ, which includes waveform readout
  - Beyond the scope of this talk (time!)

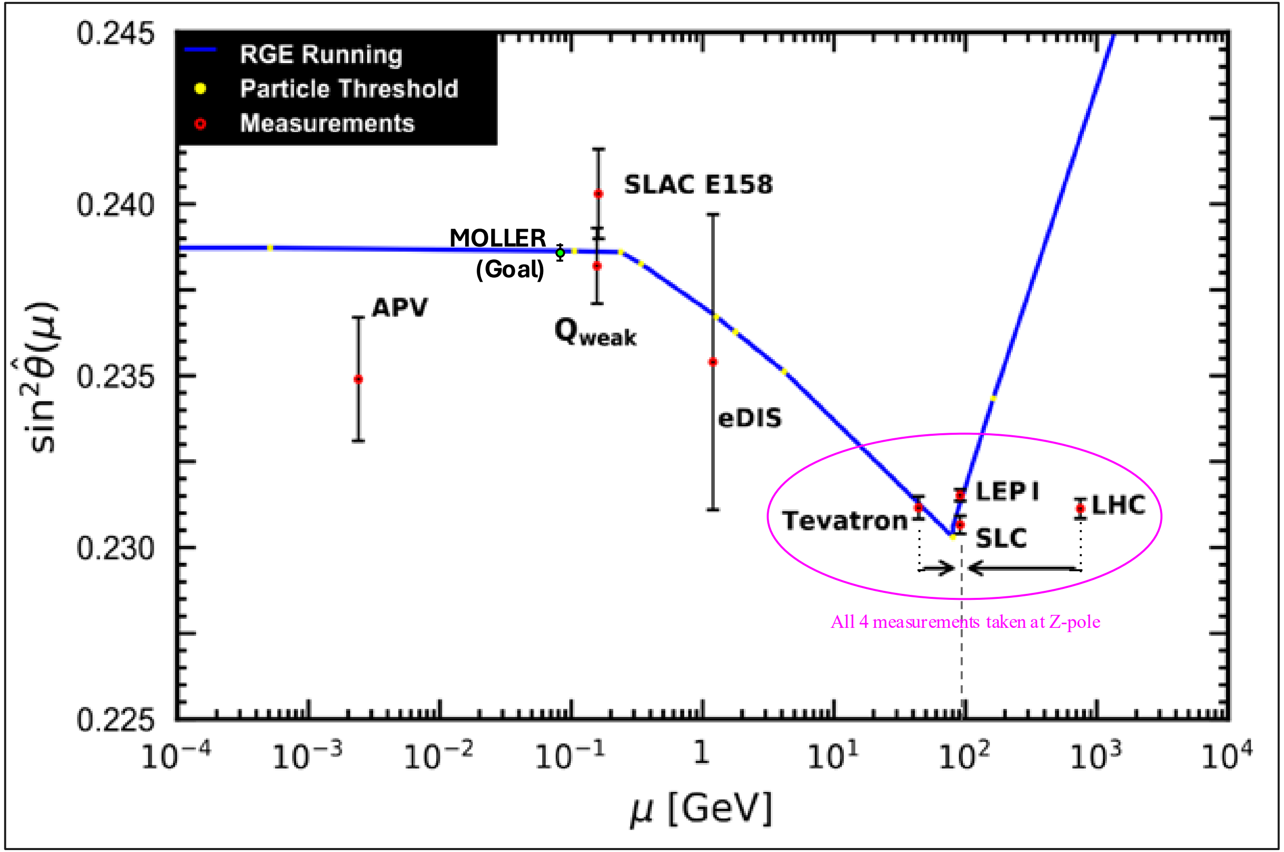
Numbered Figure Credits

- [1]: MOLLER Collaboration, MOLLER Technical Design Report
- [2]: D. E. King, Utilizing Parity Violating Electron Scattering As a Probe to Measure the Neutron Radius of 208-Pb
- [3]: D. E. King et al, Precision Møller polarimetry for PREX-2 and CREX

Backup/Extra Slides

Prior Weak Mixing Angle Measurements

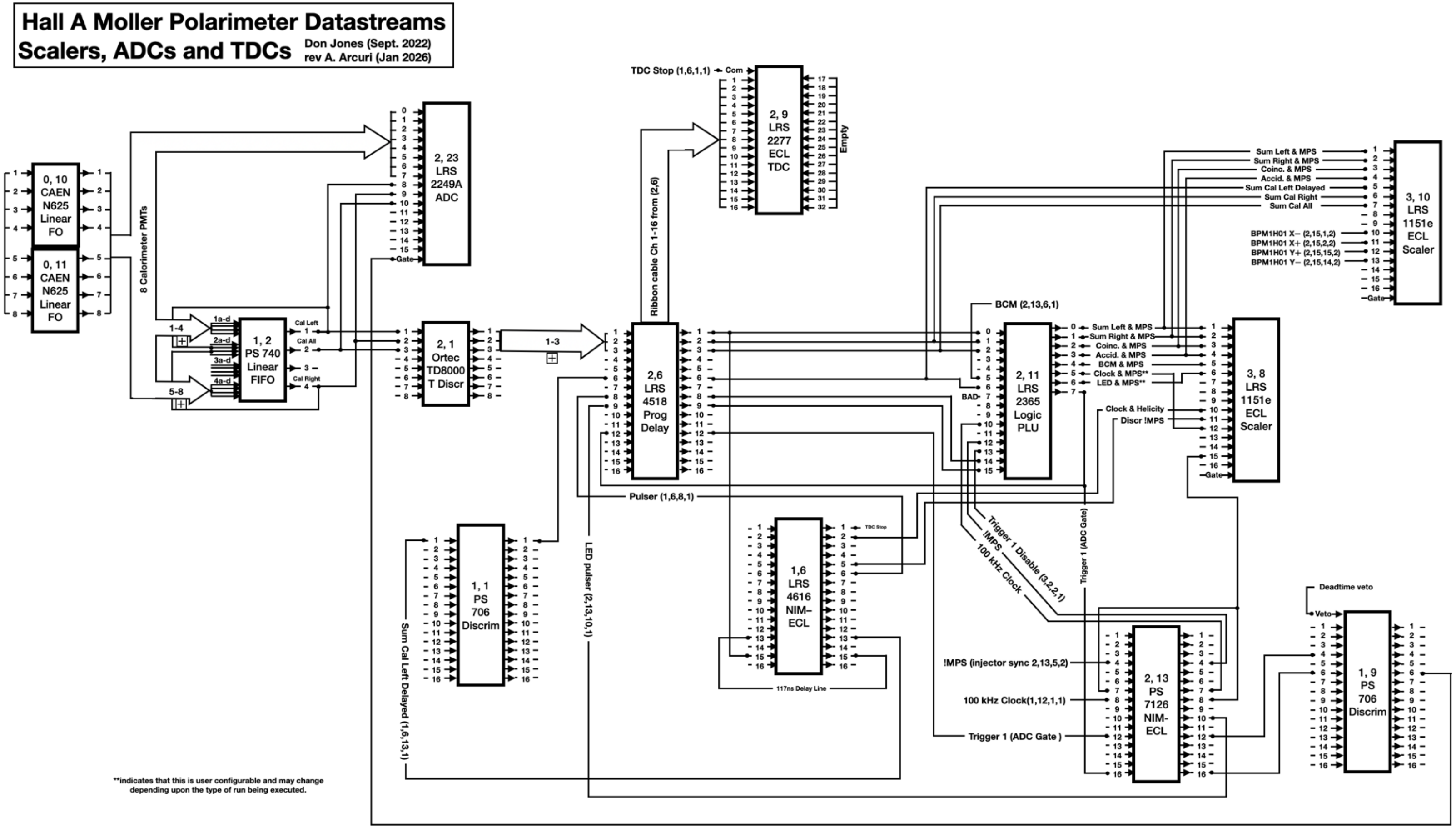
Image adopted from: Particle Data Group, PDG Book 2024



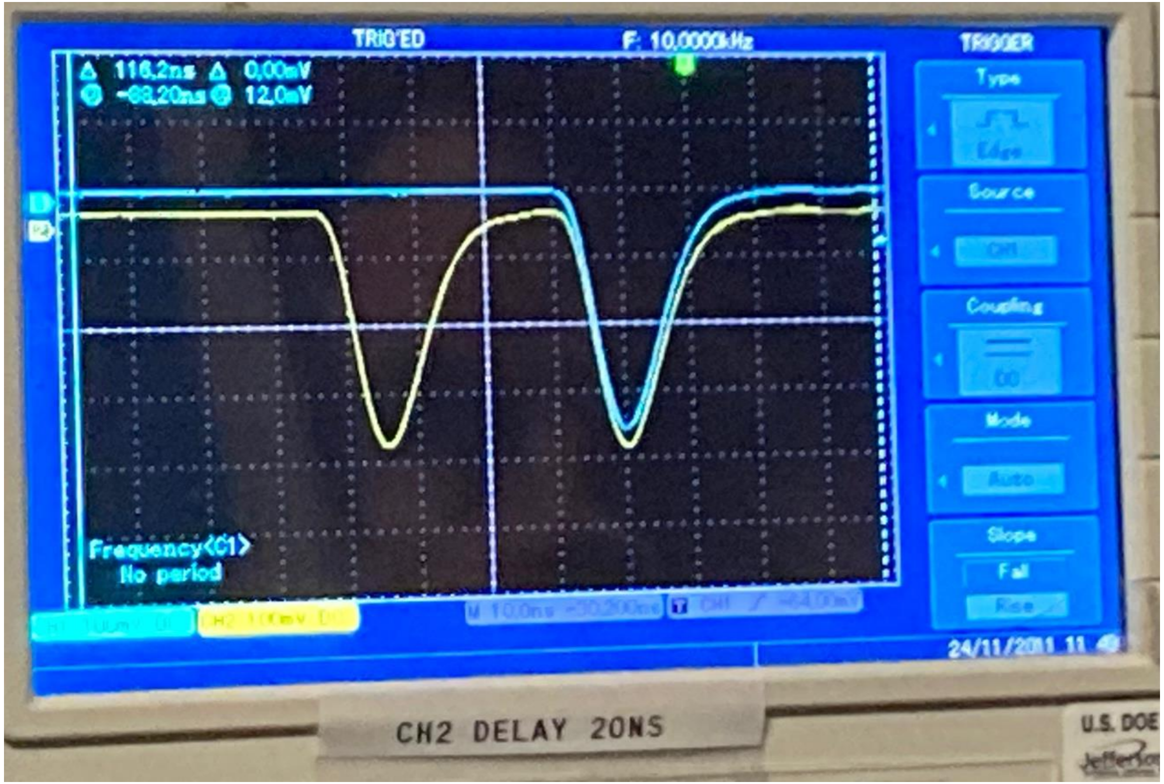
Previous measurements of the weak mixing angle, including the projected measurement for MOLLER.

Plot Credit: PDG Book 2024, modified by Eric King.

Hall A Møller Pol Scaler DAQ Diagram (Simplified)



Dead Time Constant τ_{ds}: Physical Interpretation

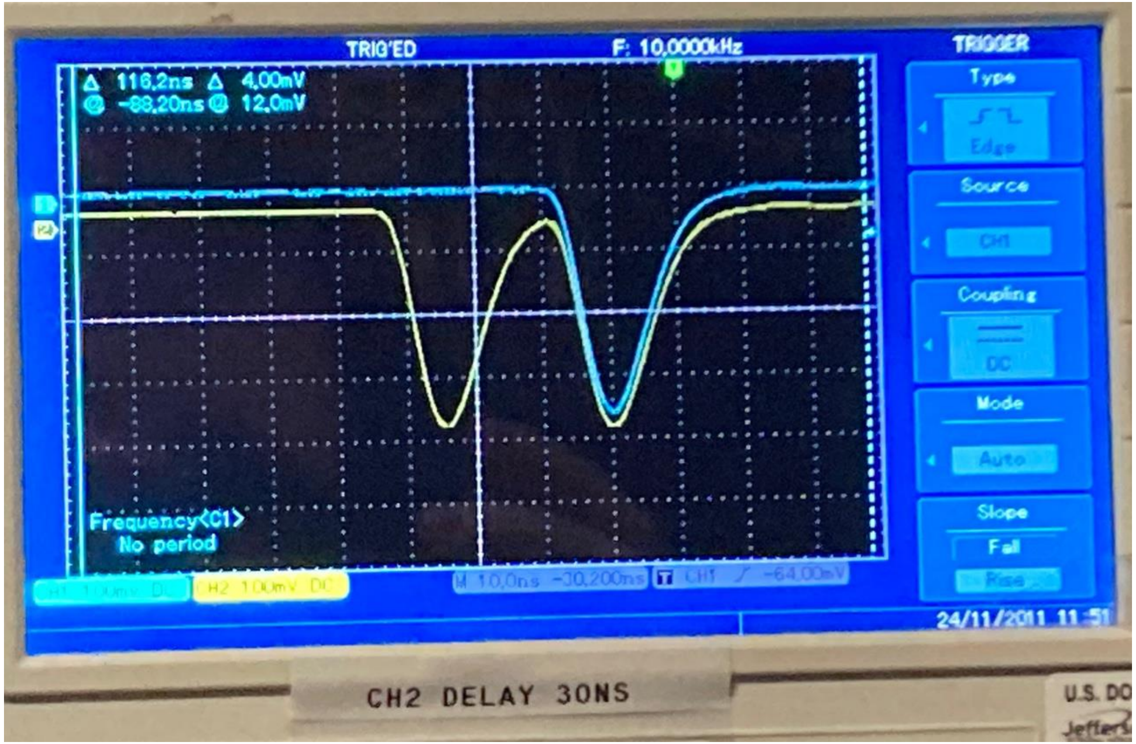


Consider the case of a single Right pulse (yellow) preceding a Coincidence pair (yellow & blue) by some time.

2 Right pulses, 1 Left pulse, and 1 Coincidence are counted.

Good!

Dead Time Constant τ_{ds}: Physical Interpretation



Decrease the separation between the Right single pulse and Coincidence pair.

1 Right pulse, 1 Left pulse, and **0 Coincidences** are counted.

Not good! Second Right pulse is missed entirely, meaning we now lose our Coincidence count!

Dead Time Constant τ_{ds}: Physical Interpretation

1 Left pulse, 1 right pulse, and 1 coincidences are counted.

Coincidence detection is restored as resolution between the two Right pulses is lost entirely.

The range of delay timings which result in lost Coincidences is the physical interpretation of τ_{ds}

FADC DAQ Dead Time (Event Spacing)

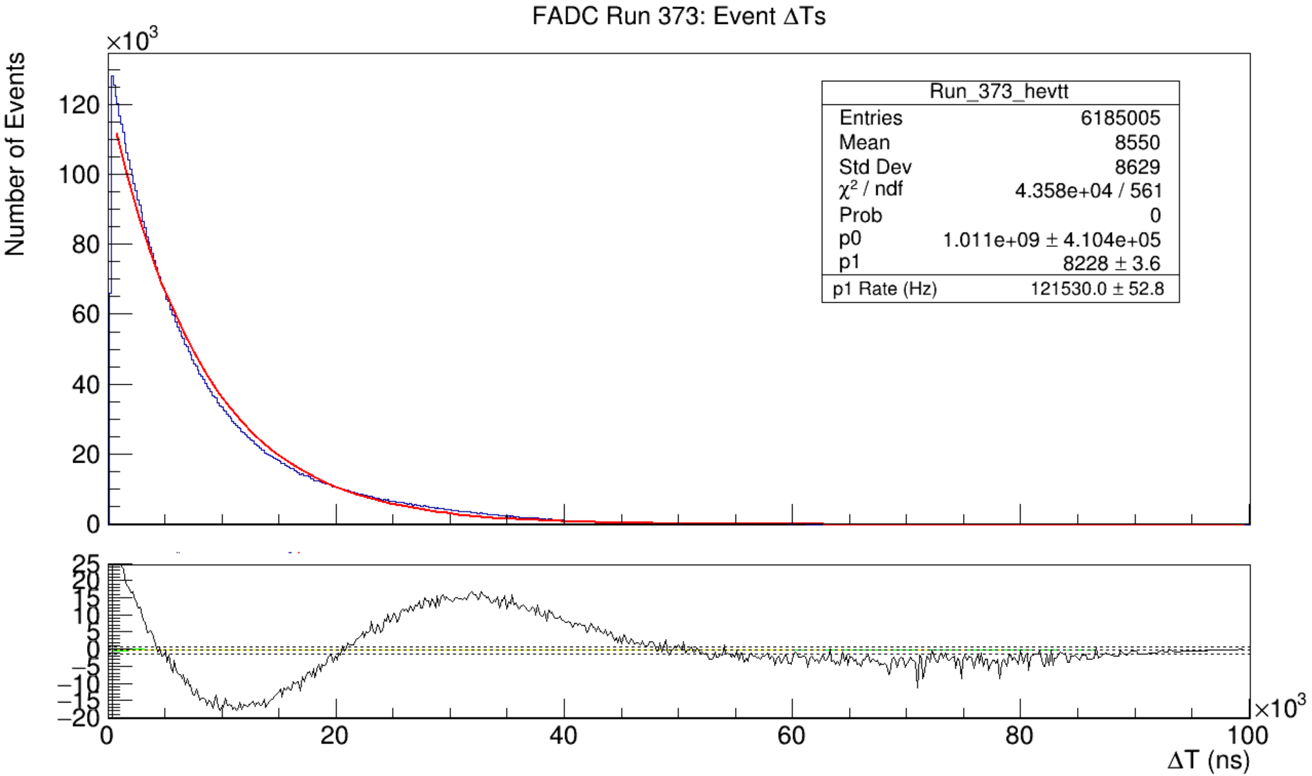
Run 373 DT Plot

Block and buffer level 5, Left/Right/MPS trigger, no prescaling, waveform readout

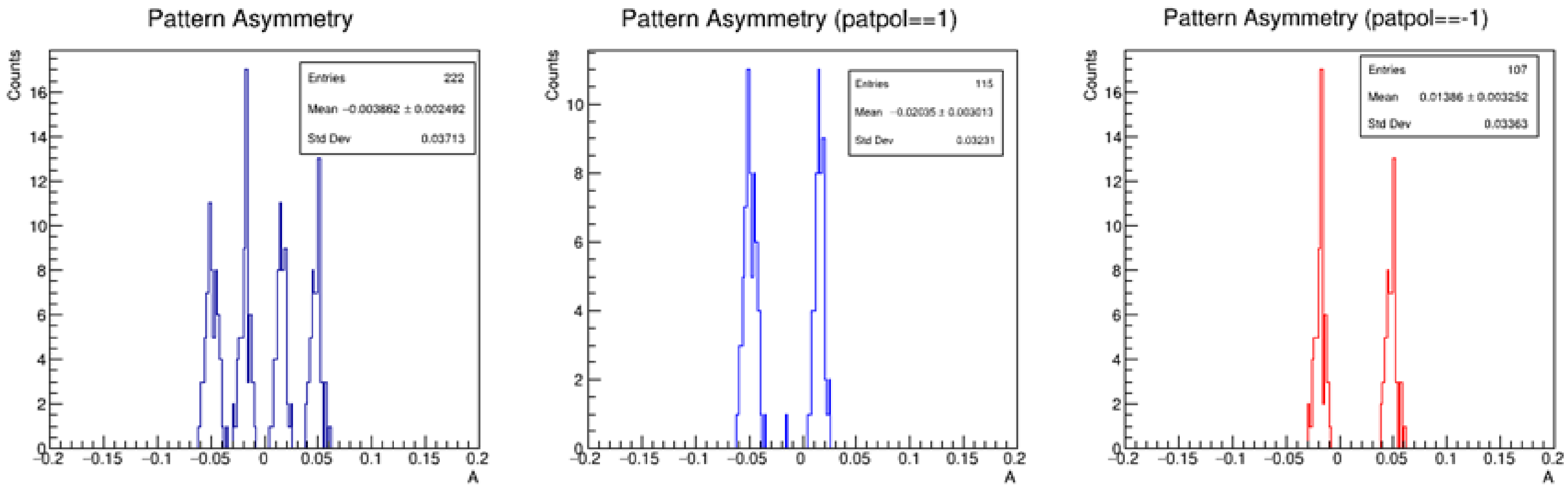
CODA readout live time of ~80%

Overall coincidence dead time was 20.68% ± 0.02%.

Due to the readout dead time a simple exponential distribution is not seen. 10–30 μs deviation.



FADC DAQ False Asymmetry on Emulator Data



Ran at settings where issue is known to occur: Block/Buffer level of 5, MPS or Left or Right trigger, waveform readout, Left, Right, Coincidence rates of 50 kHz.

CODA readout live time was ~80% overall. Not surprising at these block and buffer levels.

The unexpected issue is clear in the asymmetry plots. The difference between the pol=1 asymmetry and pol=-1 asymmetry is **7.72σ**.