# $Q_{weak}$ Ancillary Measurements

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Hall C Meeting
Newport News, VA
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# Electroweak Interaction

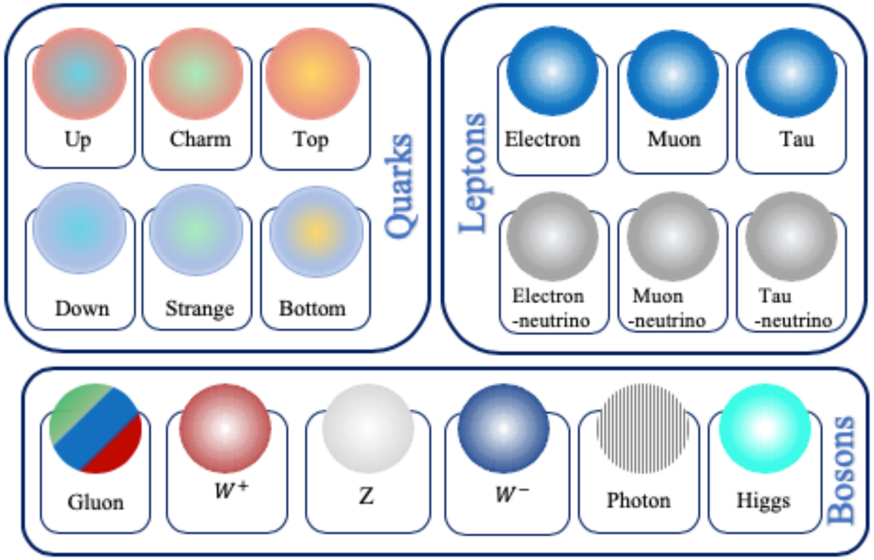
## Standard Model

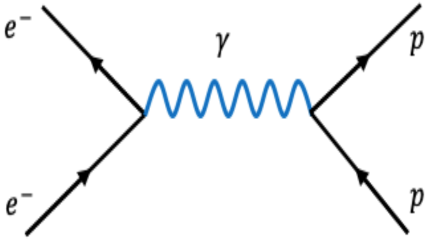
$Q_{weak}$ has used the parity violating asymmetry → to test the Standard Model.

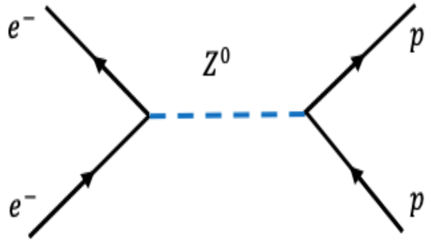
By constantly flipping helicity states of a longitudinally polarized electron beam that scatters in the unpolarized target, $Q_{weak}$ has provided a precision measurement of the SM coupling constant $\sin^2\theta_w$ .

## Electron-proton interaction scattering:

- Electromagnetic force with a photon-mediated → (Conserves parity)
- Weak force driven by $Z^0$ or $W^{\pm}$ boson → (Violates parity)



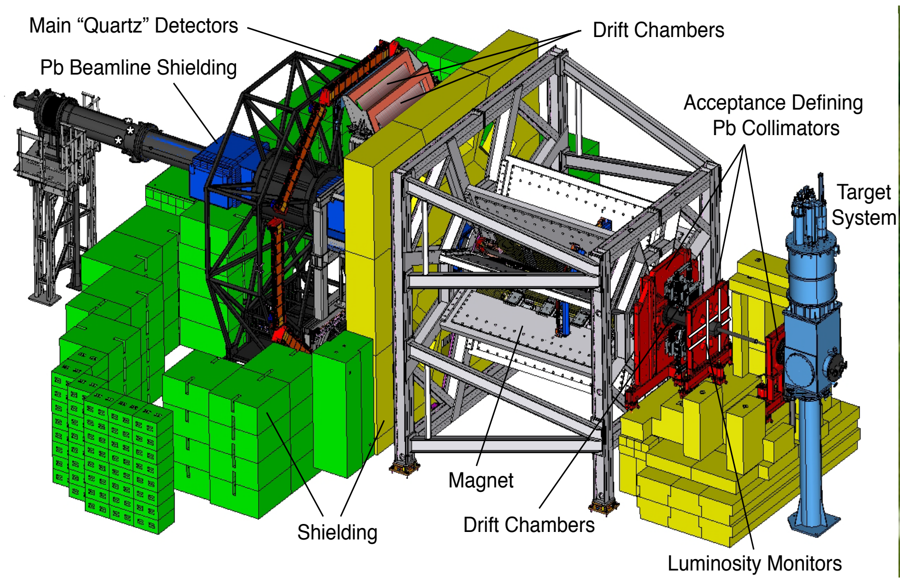



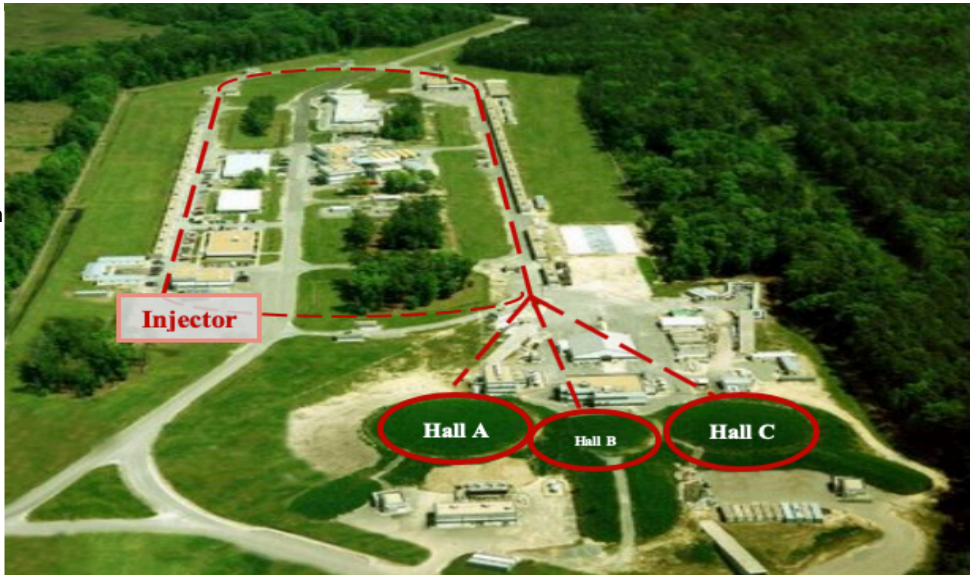



# Parity Violating Asymmetries in $Q_{weak}$

In $Q_{weak}$, we scattered longitudinally polarized electrons off protons in an unpolarized liquid hydrogen target, and off of an Aluminum dummy target.

- $\vec{e} + p \rightarrow e^- + p$ (Main measurement elastic - measures weak charge of the proton)
- $\vec{e} + p \rightarrow e^- + \Delta^+ \rightarrow N + \pi + e^-$ (Ancillary measurement, inelastic - new physics in the $N \rightarrow \Delta$ channel)
- $\vec{e} + p \rightarrow e^- + p$, $\vec{e} + p \rightarrow e^- + X + \pi^-$ (above the resonance region $\rightarrow \square_{\gamma Z}$ )
- $\vec{e} + {}^{27}Al \rightarrow e^- + {}^{27}Al$ (PV Aluminum asymmetry)



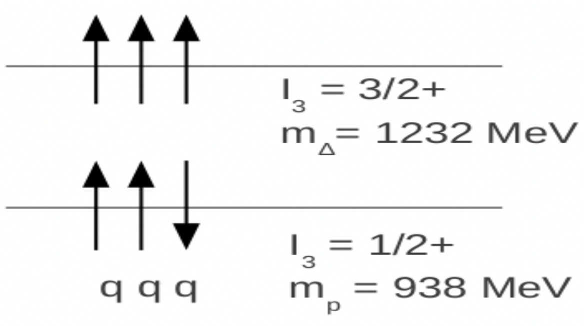



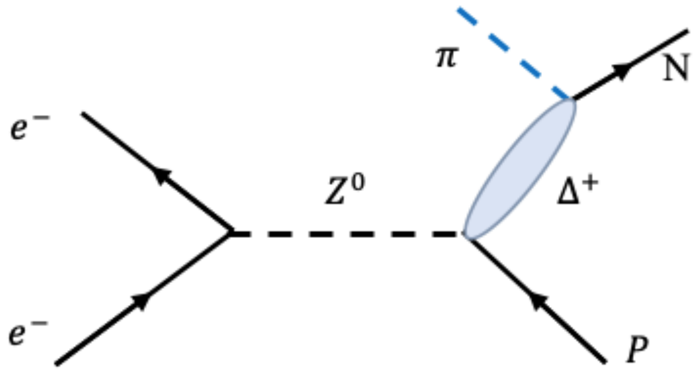
# Parity-Violating Asymmetries in Inelastic Scattering

## Reasons for measuring the inelastic asymmetries:

1. To correct the primary measurement for inelastic background asymmetry
2. Using the $N \rightarrow \Delta$ asymmetry to access **$d_\Delta$**, a low energy constant related to hadronic parity violation

- The $N \rightarrow \Delta$ transition can be pictured as the $Z^0$ boson (neutral current) flipping a single quark spin in the constituent quark model



# PV Inelastic Measurement

The inelastic PV asymmetry has two measured kinematics for $Q_{weak}$

| Beam Energy | $Q^2$ | W | $\theta$ |
|---|---|---|---|
| 0.877 GeV | 0.011 ± 0.00013 $GeV^2$ | 1.189 GeV | 8.4° |
| 1.16 GeV | 0.021 ± 0.0001 $GeV^2$ | 1.212 GeV | 8.3° |

The PV asymmetry for Δ production can be written as :

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-},$$

where $\sigma_+$ ($\sigma_-$) is the cross-section for Δ production for positive (negative) helicity electron beam.

# PV Inelastic Measurement of $d_\Delta$ Extraction

**PV Inelastic measurement:**

- The low energy constant $d_\Delta$ can be determined from N → Δ asymmetry

$$A_{N\Delta}^{PV} = -\frac{G_F}{\sqrt{2}}\frac{Q^2}{2\pi\alpha}\left[\Delta_{(1)}^{\pi} + \Delta_{(2)}^{\pi} + \Delta_{(3)}^{\pi}\right]$$

Contains $d_\Delta$

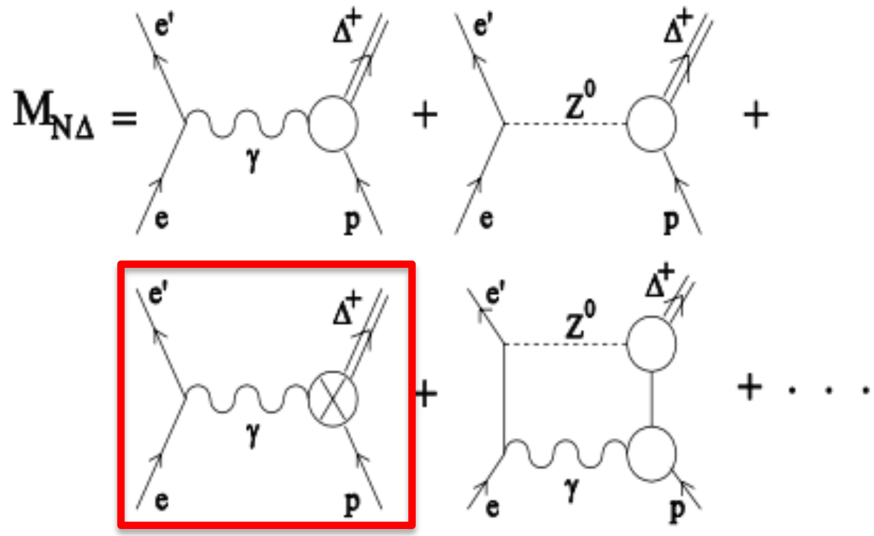
- $\Delta_{(1)}^{\pi}$ is the T=1, standard model coupling (Isovector weak charge)
- $\Delta_{(2)}^{\pi}$ are the non-resonant contributions
- $\Delta_{(3)}^{\pi}$ is the T=1, axial vector nucleon response

# Axial Radiative Corrections and Siegert Contribution

$\Delta^{\pi}_{(3)} \propto (1 + R^{\Delta}_{A})\, G^{A}_{N\Delta}$

$A^{PV}_{N\Delta}$ gives **DIRECT ACCESS** to $G^{A}_{N\Delta}$

$$R^{\Delta}_{A} = R^{ewk}_{A} + R^{Siegert}_{A} + R^{Anapole}_{A} + R^{Box}_{A}$$




up to numerical factors, this matrix element is $d_{\Delta}$

## Siegert Contribution

$$A^{PV}_{N\Delta} = -\frac{G_F}{\alpha} Q^2 \left[ a \frac{\omega}{Q^2} + Anapole \right]$$

$^1/_{Q^2}$ from the photon propagator cancels the leading $Q^2$ dependence, resulting in a possibly non-zero $A^{PV}_{N\Delta}$ at $Q^2=0$.

# Axial Radiative Corrections and Siegert Contribution

PV $\gamma N\Delta$ E1 amplitude (Siegert's Theorem) $\rightarrow$ $\mathbf{d}_\Delta (\sim g_\pi)$

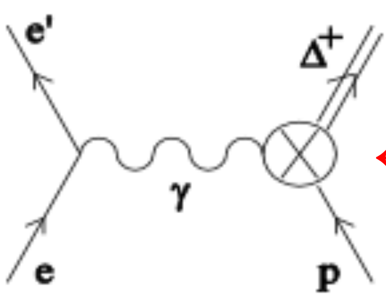
If $d_\Delta$ is significantly different from zero,

$$A_{N\Delta}^{PV}(Q^2 = 0) \neq 0!$$

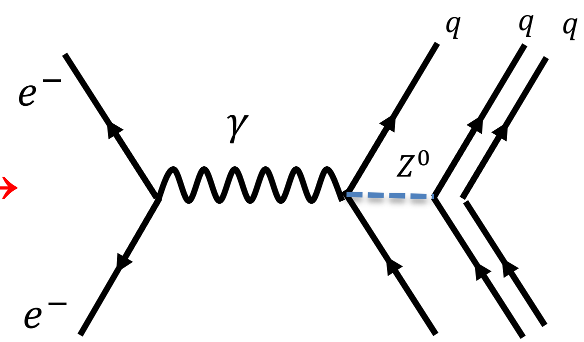
$g_\pi = 3\times10^{-8}$ is the natural scale for $\mathbf{d}_\Delta$

where $g_\pi$ is the hadronic PV coupling constant for charged current interactions

- Same matrix element drives Weak Hyperon Decay (e.g. $\Sigma^+ \rightarrow p + \gamma$) and a model* suggests $d_\Delta$ could be as large as ~ 100 $g_\pi$




← PV Hadronic Vertex →




$\gamma$ couples to → q-q weak interaction inside nucleon

* S.-L Zhu et al., Phys Rev D65:033001, 2002.

# Asymmetry Extraction Formula

To extract the inelastic Asymmetry, the false asymmetries need to be removed from the raw asymmetry.

$$\boldsymbol{A_{msr}} = \boldsymbol{A_{raw}} + A_{BCM} + A_{beam} + A_{BB} + A_L + A_T + A_{bias} - A_{blind}$$

where $A_{raw}$ is the uncorrected measured asymmetry , $A_{BCM}$ is a correction due to beam charge normalization, $A_{beam}$ is the correction for false asymmetries due to helicity-correlated beam variations, $A_{BB}$ is the beam background asymmetry, $A_L$ *is* the linearity correction ,
$A_T$ is the transverse asymmetry, $A_{bias}$ is due to re-scattering bias, and $A_{blind}$ is constant blinding offset.

**Multiplicative Corrections**

$$\boldsymbol{R_{tot}} = R_{det} R_{rc} R_{acc} R_{Q^2}$$

The PV asymmetry can be extracted from the measured asymmetry after correcting for the beam polarization, false asymmetries and backgrounds.

$$\boldsymbol{A_{inel}} = R_{tot} \frac{\frac{A_{msr}}{P} - \sum_{i=1-4} f_i A_i}{1 - f_{tot}}$$

P is beam polarization, $A_i$ *are* the background asymmetries, and the $f_i$ are background dilutions.

# $N \rightarrow \Delta$ Asymmetries Tables @ 1.16 GeV

| Asymmetries | Run1 | Run2 |
|---|---|---|
| $A_{raw}$ | -1.36 $\pm$ 0.22 ppm | -0.685 $\pm$ 0.17 ppm |
| **False Asymm.** | | |
| $A_{bcm}$ | 0 $\pm$ 0.040 ppm | 0 $\pm$ 0.030 ppm |
| $A_{beam}$ | 0.04 $\pm$ 0.04 ppm | - 0.052 $\pm$ 0.052 ppm |
| $A_{BB}$ | 0.518 $\pm$ 0.24 ppm | 0.093 $\pm$ 0.194 ppm |
| $A_{L}$ | 0.002 $\pm$ 0.0011 ppm | 0.0010$\pm$0.0008 ppm |
| $A_{T}$ | 0 $\pm$ 0.032 ppm | 0 $\pm$ 0.012 ppm |
| $A_{bias}$ | 0.0043 $\pm$ 0.01 ppm | 0.0043 $\pm$ 0.01ppm |
| $A_{blind}$ | - 0.02534 $\pm$ 0 ppm | 0.00669 $\pm$ 0 ppm |

| Kinematics | Value |
|---|---|
| $Q^2$ | 0.0208 $\pm$ 0.00009 (GeV/c)$^2$ |
| W | 1.212 $\pm$ 0.0002 GeV |

| Dilution Factors | Value |
|---|---|
| $f_{ep}$ | 0.7242 $\pm$ 0.03621 ppm |

$f_{ep}$ is a large dilution

- Much effort put into simulations vs. QTOR to reduce the uncertainty on $f_{ep}$

# Asymmetry Extraction Formula at 1.16 GeV

$$A_{msr} = A_{raw} + A_{BCM} + A_{beam} + A_{BB} + A_L + A_T + A_{bias} - A_{blind}$$

$A_{msr}$ **(Run1) = - 0.770 ± 0.33 ppm,** $A_{msr}$ **(Run2) = - 0.645 ± 0.26 ppm**

**Multiplicative Factors**

$$R_{tot} = R_{det} R_{rc} R_{acc} R_{Q^2}$$

$R_{tot}$ **= 0.9909**

**Background Dilutions**

$$f_{tot} = f_{ep} + f_{Al} + f_{nt} + f_{pion} + f_{BB}$$

$f_{tot}$ **= 0.8105**

$$A_{inel} = R_{tot} \frac{\frac{A_{msr}}{P} - f_{ep}A_{ep} - f_{Al}A_{Al} - f_{nt}A_{nt} - f_{pion}A_{pion}}{1 - f_{tot}}$$

$f_{ep}A_{ep}$ = - 0.1375, $f_{Al}A_{Al}$ = 0.0576, $f_{nt}A_{nt}$ = - 0.00734 , $f_{pion}A_{pion}$ = 0.0482

**$A_{inel}$ (Run1) = - 4.49 ± 1.34 stat ± 1.79 sys ppm**

**$A_{inel}$ (Run2) = - 3.60 ± 1.003 stat ± 1.43 sys ppm**

**$A_{inel\_total}$ = - 3.91 ± 1.51 ppm**

**Dissertation for T. ALshayeb**

# Outstanding Issues for N$\rightarrow\Delta$ Final Results

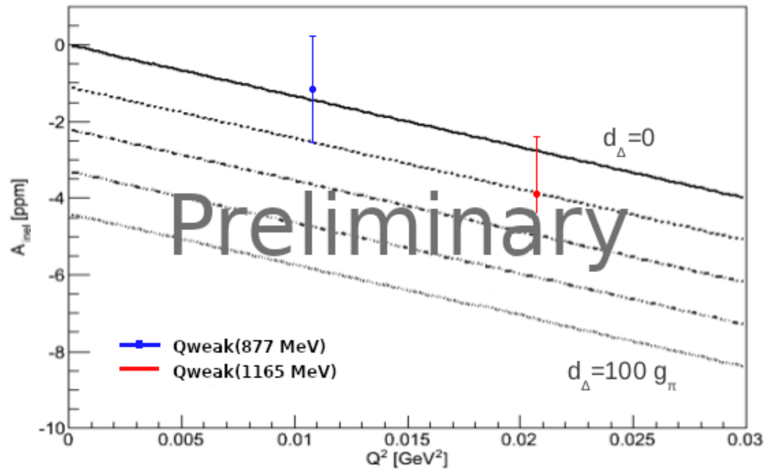
- **Pion simulation** (getting best pion dilution fractions possible)
- **Pion asymmetry** (reaching out for theoretical guidance)

# $A_{inel}$ Plotted vs $Q^2$

- Plot from S.-L Zhu et al., Phys Rev D65:033001, 2002.
- Curves were determined for

  $E_{beam}$ = 424 MeV,

so there is a theory error applied($3g_\pi$)




- **$Q_{weak}$ 1.16 GeV values:**

$A_{inel}$ = -3.91 ± 0.80 (stat) ± 1.27 (syst) ppm (preliminary)
$d_\Delta$ = ( 26 ± 18 (stat) ± 29 (syst) ± 3 (theory)) $g_\pi$ (preliminary)

- **$Q_{weak}$ 877 MeV values:**

$A_{inel}$ = −1.2 ± 0.98 (stat) ± 0.99 (syst) ppm (preliminary)
$d_\Delta$ = (−8 ± 22 (stat) ± 22 (syst) ± 3 (theory)) $g_\pi$ (preliminary)

- $G_0$ has published a value: $d_\Delta$ = (8.1 ± 23.7 ± 8.3 ± 0.7) $g_\pi$

(Androic et al ($G_0$ collaboration), PRL 108, 122002 (2012))

All three measurements have $d_\Delta$ consistent with zero within errors

## PV Asymmetry in e + p Scattering above the Resonance Region (constrains $\Box_{\gamma Z}$)

The weak charge of proton (uud) and neutron (udd), at tree level are :

$$Q_W^p = 1 - 4\sin^2\theta_W \quad \text{and} \quad Q_W^n = -1$$

Proton's weak charge with electroweak radiative corrections, which can be written as:

determined in Ref [3]

$$Q_W^p = (1 + \Delta_\rho + \Delta_e)(1 - 4\sin^2\theta(0) + \Delta_e') + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0),$$

can be calculated by perturbative QCD

where $\Delta_\rho$ is a vacuum polarization correction, $\Delta_e$ is a vertex correction to the $\gamma e$ vertex, $\Delta_e'$ is a vertex correction to the Ze vertex, and $\Box_{WW}$, $\Box_{ZZ}$, and $\Box_{\gamma Z}$ are corrections for two-boson exchange interactions.

### Beam Properties

$E = 3.35$ GeV, $\theta_{pol} = 92.2°$ → **Transverse Mode**

$E' \approx 1.1$ GeV, $W = 2.23$ GeV

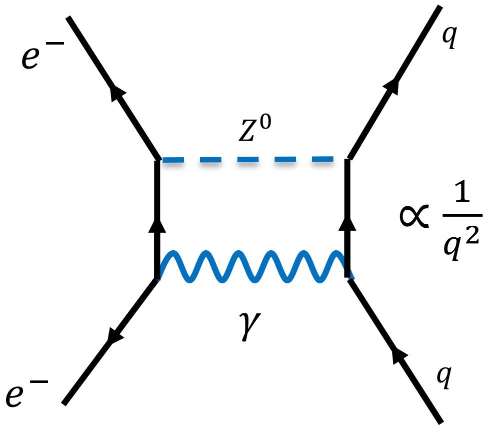
$P = 89\%$, $Q^2 = 0.082\ \text{GeV}^2$

[3] J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, Phys. Rev. D68, 016006 (2003).

# γZ box ($\square_{\gamma Z}$) Motivation

**In 2009, Gorchtein and Horowitz determined $\square^V_{\gamma Z}$ [4]:**

- Larger than previously expected
- Significant hadronic physics uncertainties
- Strong energy dependence




**$Q_{weak}$ measured $Q^p_W$**

- Must include electroweak radiative corrections
- Sensitive to large $W$ and low $Q^2$

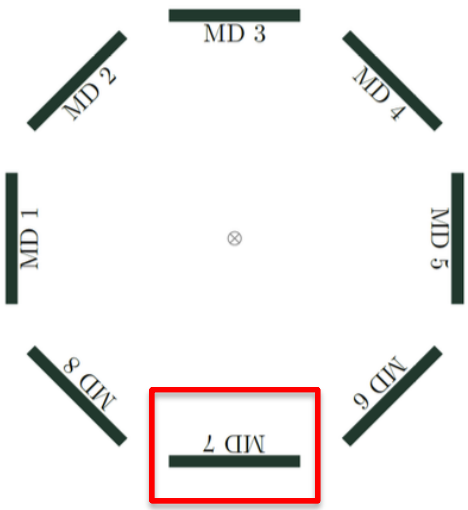
[4] Gorchtein and Horowitz. *Phys. Rev. Lett.* **102**, 091806 (2009)

# Pion Background

- A large difference between $E$ & $E'$ ($E - E' > 2$ GeV)

  leads to a large pion background

- A 4-inch lead wall (absorber ~18 radiation lengths) placed in front of lowest Čerenkov Detector (MD7) to create a pion detector and determine the $\pi^-$ contribution while positively charged pions ($\pi^+$) were swept away by the magnet.




- The rate of charged particles in the detectors without a Pb absorber :
  - 27% pions
  - 73% electrons.

# $A_{inel}$ Plotted for □$_{\gamma Z}$

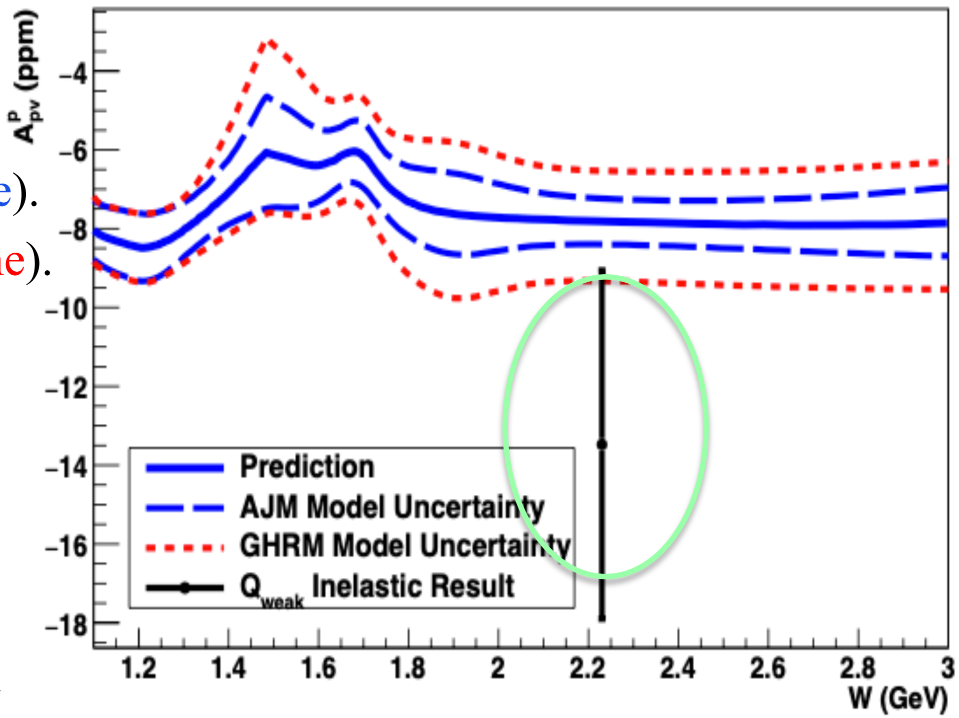
- **Predicted value** (solid blue line):
  $Q^2 = 0.09$ GeV$^2$

- AJM model uncertainties (blue dashed line).
- GHRM model uncertainties (red dotted line).

- **The $Q_{weak}$ inelastic result:**
  $Q^2 = 0.082 \pm 0.004$ GeV$^2$
  $W = 2.23$ GeV

$A_{inel} = -13.5 \pm 2.0$ (stat) $\pm 3.9$ (syst) ppm
$A_{inel} = -13.5 \pm 4.4$ (total) ppm

dominated by systematic uncertainties ~ 28.7%

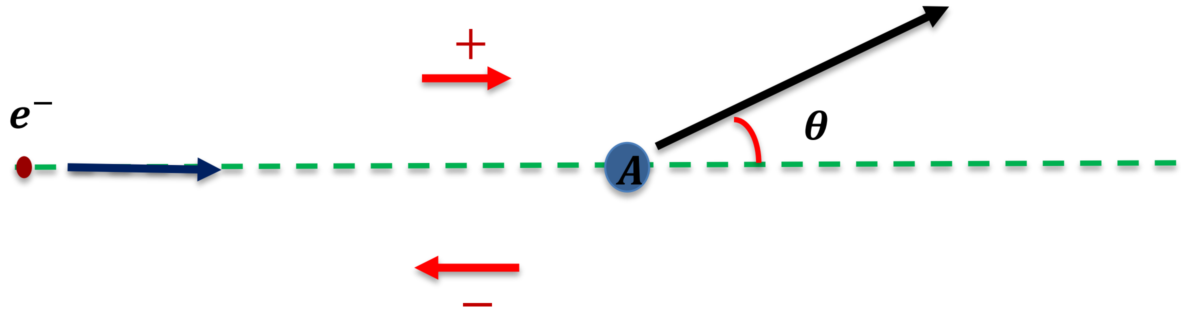



Theoretical estimation of the asymmetry of inelastic PV versus W [2].

Submitted to the PHYS Rev C. (arXiv:1910.14591v1)

# Elastic PV Aluminum Asymmetry

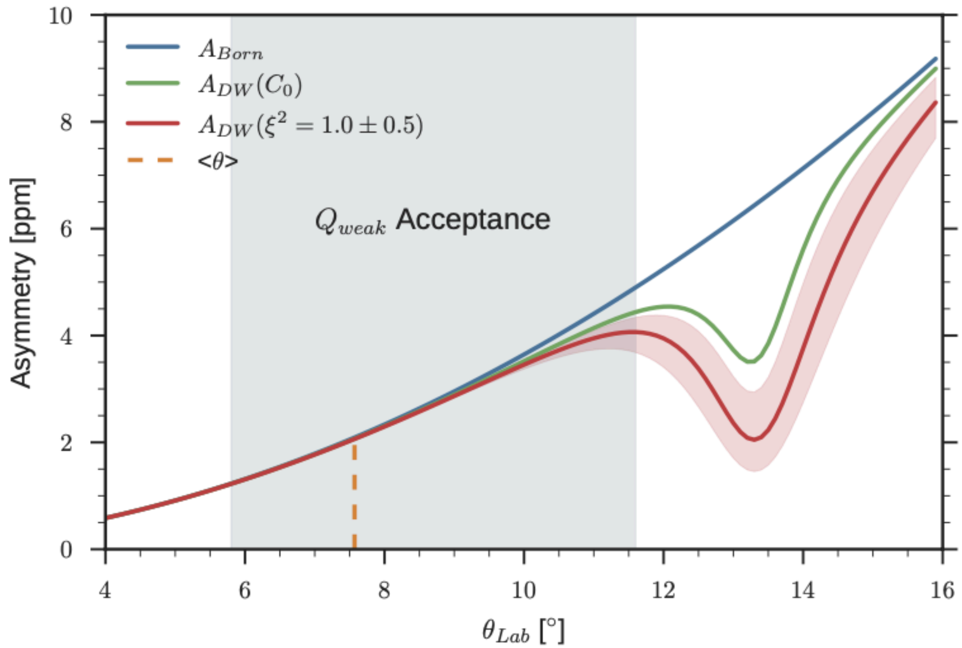
- $Q_{weak}$ has made the first parity violating elastic and beam-normal single-spin asymmetries from the $^{27}$Al nucleus to determine the aluminum target background.
- A single asymmetry measurement allows the weak charge density to be extracted.
- Neutron skin thickness will be extracted.



# Horowitz's Theory of $^{27}$Al Asymmetry

- Beam Energy = 1.16 GeV
- $Q^2 = 0.024\ GeV^2$
- P = 88%

At the average acceptance of $Q_{weak}$, Born approximation asymmetry $A_{PV}$ predicts ≈ 2.1 ppm.




Preliminary analysis graph of the PV $Q_{Weak}$ $^{27}$Al asymmetry with C.J Horowitz's theory curves.

C. J. Horowitz Phys. Rev. C 89, 045503 (2014)

# Outstanding Issues for $^{27}$Al Final Results

- Meson exchange current contribution predicted to be large by using the Bosted-Mamyan fit.
- New model for simulations including MEC's to more accurately predict MEC contribution to yield (E. Christy).
- Reaching out for theoretical guidance for PV MEC asymmetry (C. Horowitz).

# Additional Topics: BNSSA Measurements

- **Beam-Normal Single-Spin Asymmetry:** parity-conserving asymmetry from transversely polarized electron beams on unpolarized targets.

| Elastic BNSSA ($e^-$ - p) | N→ Δ BNSSA | Elastic $e^-$ - $^{27}$Al BNSSA | Elastic $e^-$ - $^{12}$C BNSSA | Moller $e^-$ - $e^-$ BNSSA |
|---|---|---|---|---|
| *Preliminary results finished (thesis)<br><br>* Paper under revision<br><br>* Horizontal and vertical transverse data | * Preliminary results finished (two theses)<br><br>* Data is only horizontal<br><br>* $\pi^-$ dilutions and asymmetries need to be finalized | *Preliminary results finished (thesis)<br><br>* Horizontal and vertical data<br><br>* MEC issues to be resolved | *Preliminary results finished (thesis)<br><br>* Data is horizontal only<br><br>* Some analysis issues to be resolved | * Initial analysis results finished<br><br>* Final analysis needs to be performed |

# Conclusion

- For Parity Violating Asymmetries on the $N \rightarrow \Delta$ resonance,

$\rightarrow$ Preliminary $d_\Delta$ value is consistent with zero for both beam 877 MeV and 1.16 GeV energies; however, is inconsistent with models that predict $d_\Delta$ as high as 100 $g_\pi$.

$\rightarrow$ $f_\pi$ and $A_\pi$ need final values to obtain final $N \rightarrow \Delta$ PV asymmetries.

- For Parity Violating Asymmetry in e + p above the resonance region $\rightarrow \Box_{\gamma Z}$,

$\rightarrow$ is consistent with the prediction of the model.

$\rightarrow$ transverse and PV $\pi^-$ asymmetries measured also.

- For Parity Violating Asymmetry for $^{27}$Al,

$\rightarrow$ MEC issues to be resolved!

- Several BNSSA measurements performed as well!

# The $Q_{weak}$ Collaboration

99 collaborators 25 grad students
10 post docs 23 institutions

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[5] Thomas Jefferson National Accelerator Facility
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[8] University of Manitoba,
[9] University of Virginia
[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
[15] Idaho State University
[16] Louisiana Tech University
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Spokespersons Project Manager Grad Students

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[3] J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, Phys. Rev. D68, 016006 (2003).

[4] Gorchtein and Horowitz. Phys. Rev. Lett. 102, 091806 (2009)

[5] arXiv:1910.14591v1

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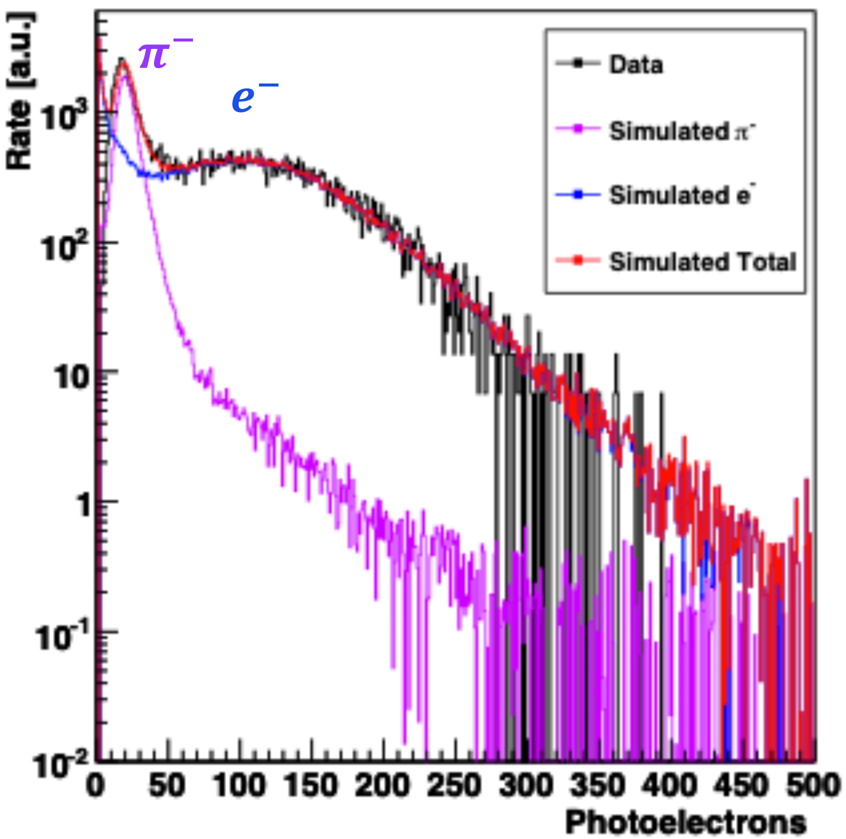
# Pion Asymmetry Extraction

- **Extracting pion yield-fraction in unblocked detectors**




A typical fitted spectrum

- Using Event-Mode data (ADC) pulse height spectrum to distinguish particle types.

- Monte-Carlo simulation of $e-$ and $\pi-$

•Average Pion Yield Fraction for unblocked detectors with conservative bound:

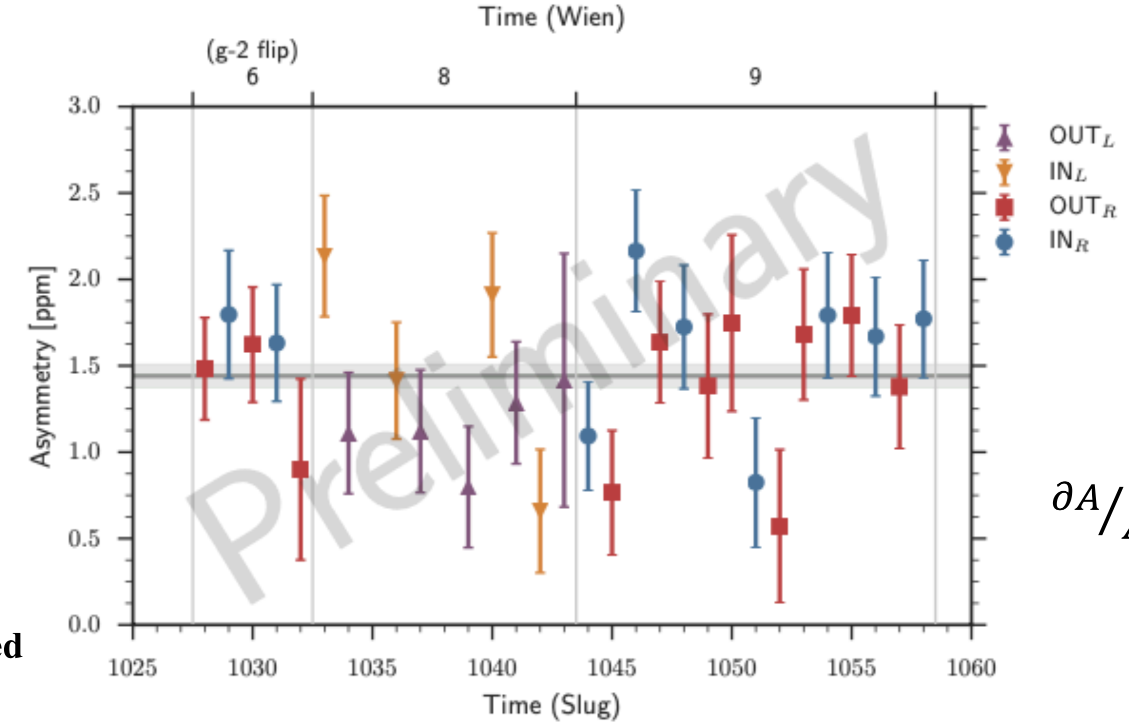
$$f_{\pi-}^{avg} = 0.096 \pm 0.029$$

Different method used for detector with lead wall:

$$f_{\pi-}^{MD7} = 0.811 \pm 0.056$$

# $^{27}$Al Asymmetry Data and Uncorrected Data

- A 4 % calculation of the pure $^{27}$Al APV, according to Horowitz, is sensitive to 2% changes in $R_n$
- $Q_{weak}$ has 4.9 % asymmetry measurement on the $^{27}$Al alloy without background corrections




$\partial A/_A = 4.7$ % (stat)

**Helicity Sign Corrected**

# Improved $^{27}$Al MEC Model