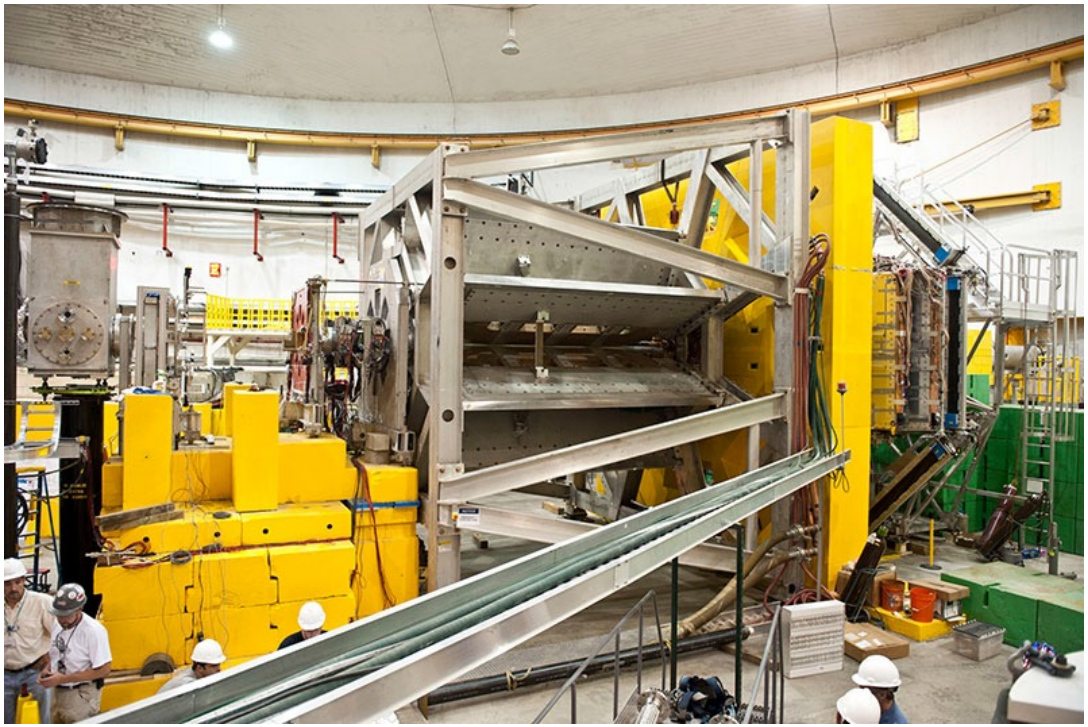
# Beam-Normal Single-Spin Asymmetries from $Q_{weak}$

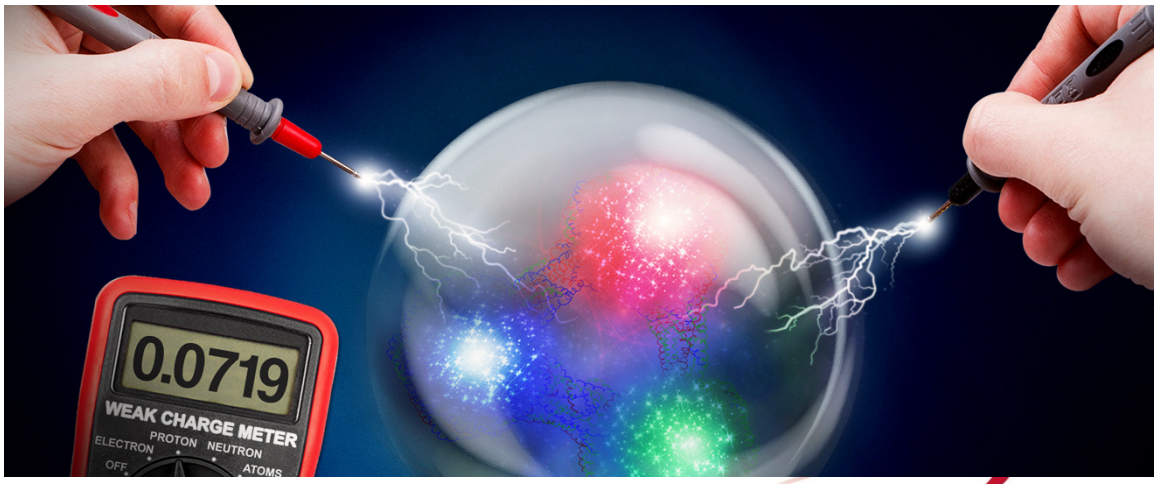



David S. Armstrong

*William & Mary*

*for the $Q_{weak}$ Collaboration*


*"Precision Physics with MOLLER"* workshop
Jefferson Lab Nov. 5-6 2026




NSF

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

# Outline

"Auxillary" results from Qweak:

1) Brief glance at Qweak apparatus

2) $B_n$ from the proton at 1 GeV, low $Q^2$
   most precise such measurement to date.

3) $B_n$ from $^{12}C$ and $^{27}Al$ at forward angle at 1 GeV, low $Q^2$

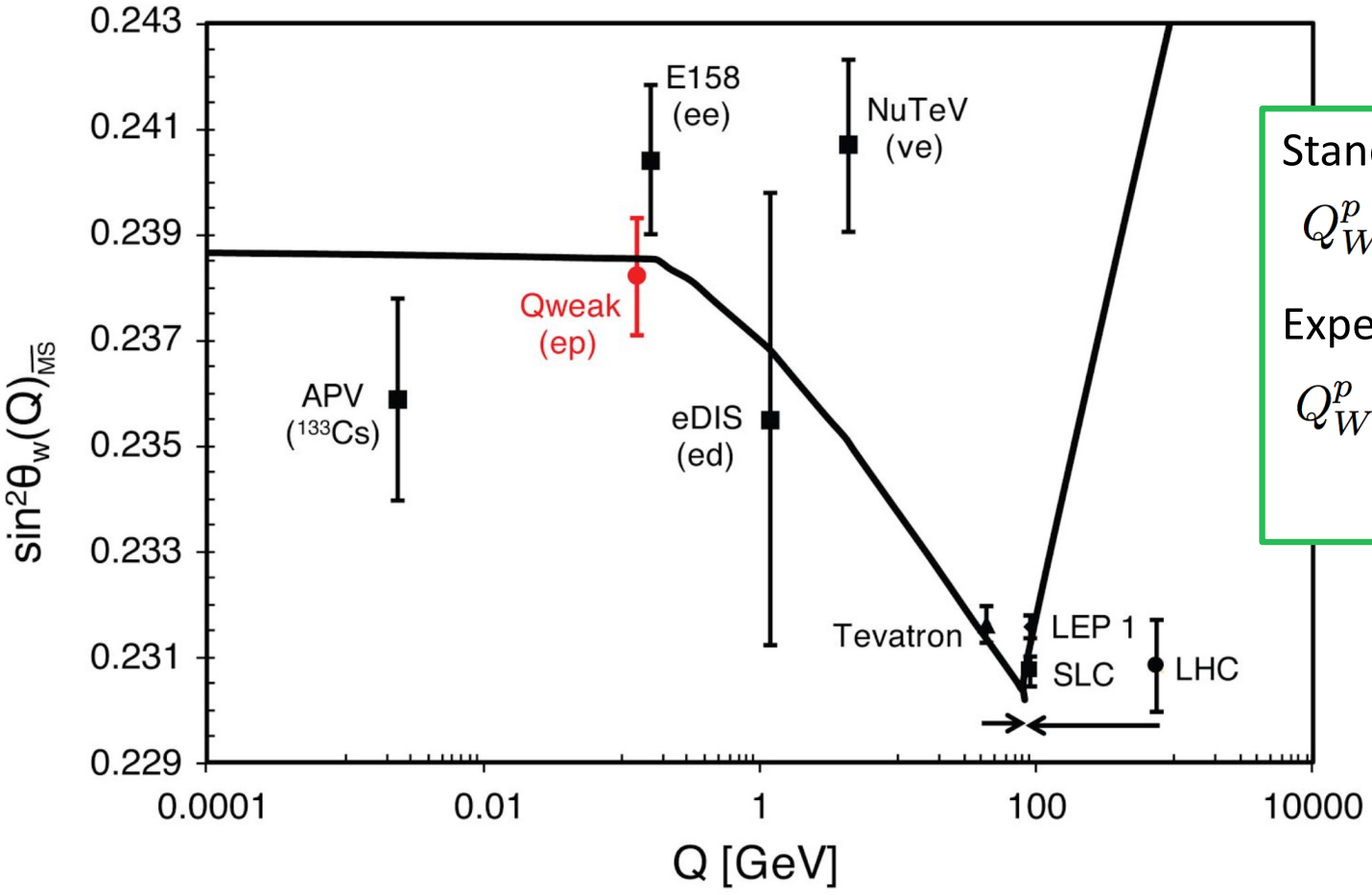
4) $B_n$ for electrons and pions from proton above resonance region at low $Q^2$

)

# $Q_{weak}$: Proton weak charge

Qweak (Hall C, JLab) data-taking 2010-2012

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst}) \text{ ppb at } \langle Q^2 \rangle = 0.0249 \text{ (GeV/}c)^2$$




Standard Model:

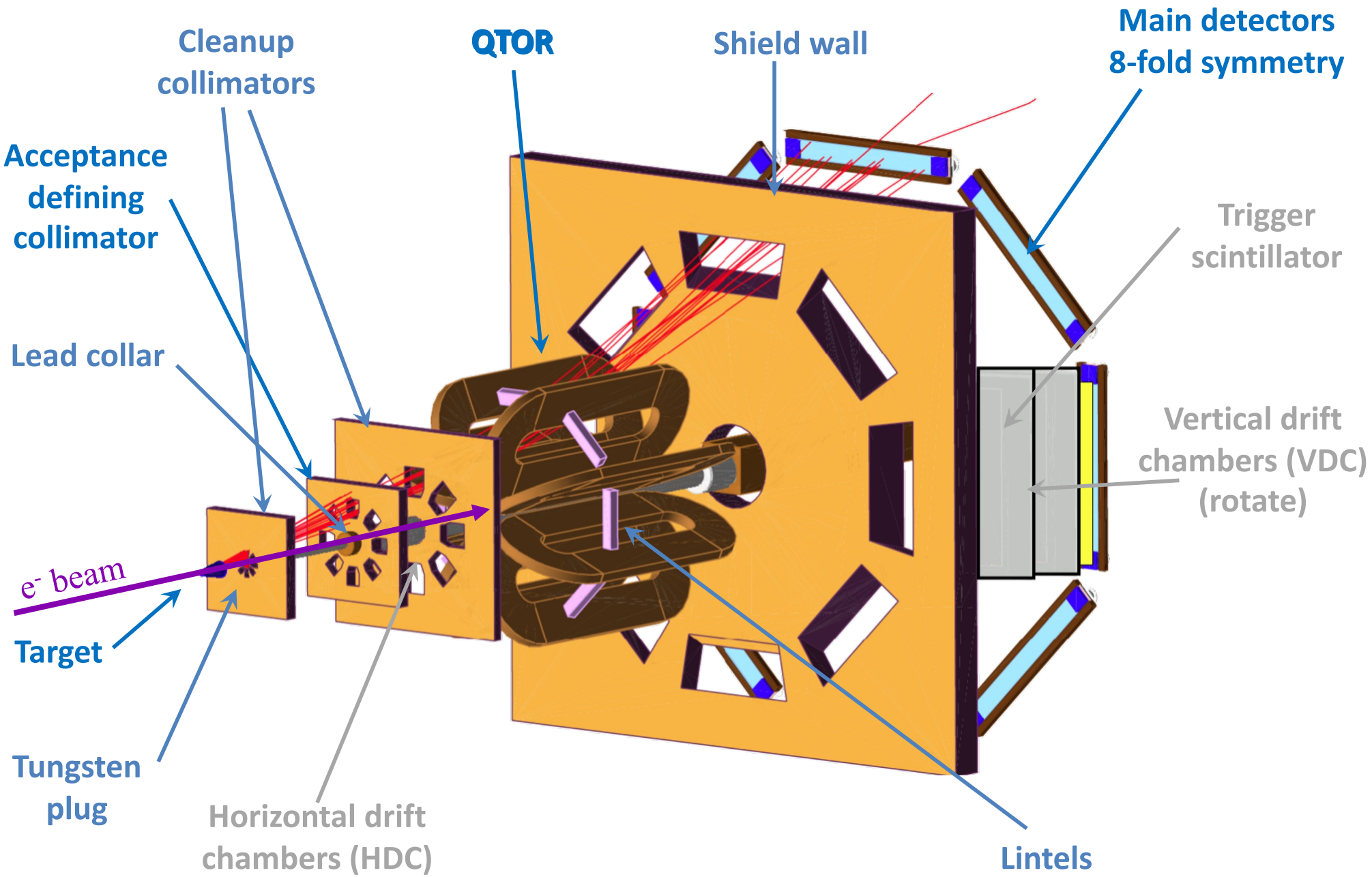
$$Q_W^p = 0.0708 \pm 0.0003$$

Experiment:

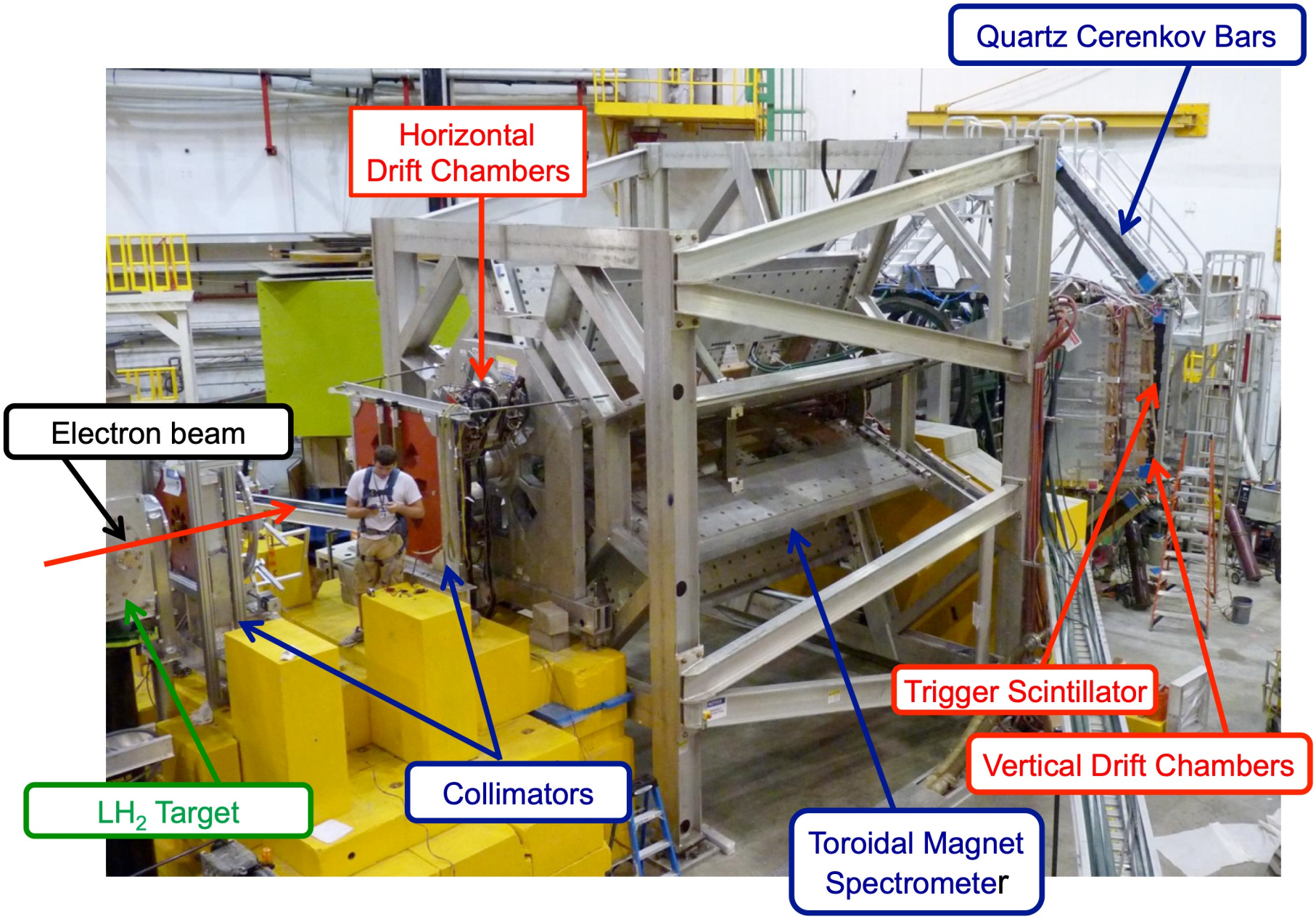
$$Q_W^p = 0.0719 \pm 0.0045$$

Androic *et al.* *Nature* 557 (2018) 207

# The $Q_{weak}$ Apparatus



# The $Q_{weak}$ Apparatus – during installation



# Landscape of BNSSA results

1) Nucleon measurements (*p*, *n* via quasielastic in deuteron)
   - Discovered by SAMPLE (2001)
   - Measurements at forward & backward angles, various $Q^2$: G0, HAPPEX, PVA4

2) Complex Nuclei
   - $^{4}$He at forward angle: HAPPEx
   - $^{12}$C and $^{208}$Pb at forward angle: PREx-1
   - $^{12}$C at forward angle, $Q^2$ dependence: A1
   - $^{28}$Si and $^{90}$Zr at forward angle: A1
   - $^{12}$C, $^{40}$Ca, $^{48}$Ca and $^{208}$Pb at forward angle: PREx-2/CREx
   - $^{208}$Pb at forward angle: A1

This talk:
   - proton at forward angle, high precision
   - $^{12}$C, $^{27}$Al at forward angle
   - proton inelastic, beyond resonance region
   - N → Delta (preliminary, unpublished)

} Qweak

# BNSSA on proton

## Experimental Conditions

Transverse beam polarization taken in three data sets:

Two with vertical beam polarization (different run periods)

& One with horizontal

**Beam Conditions:**

$E_e$ = 1.16 GeV

I = 180 $\mu$A

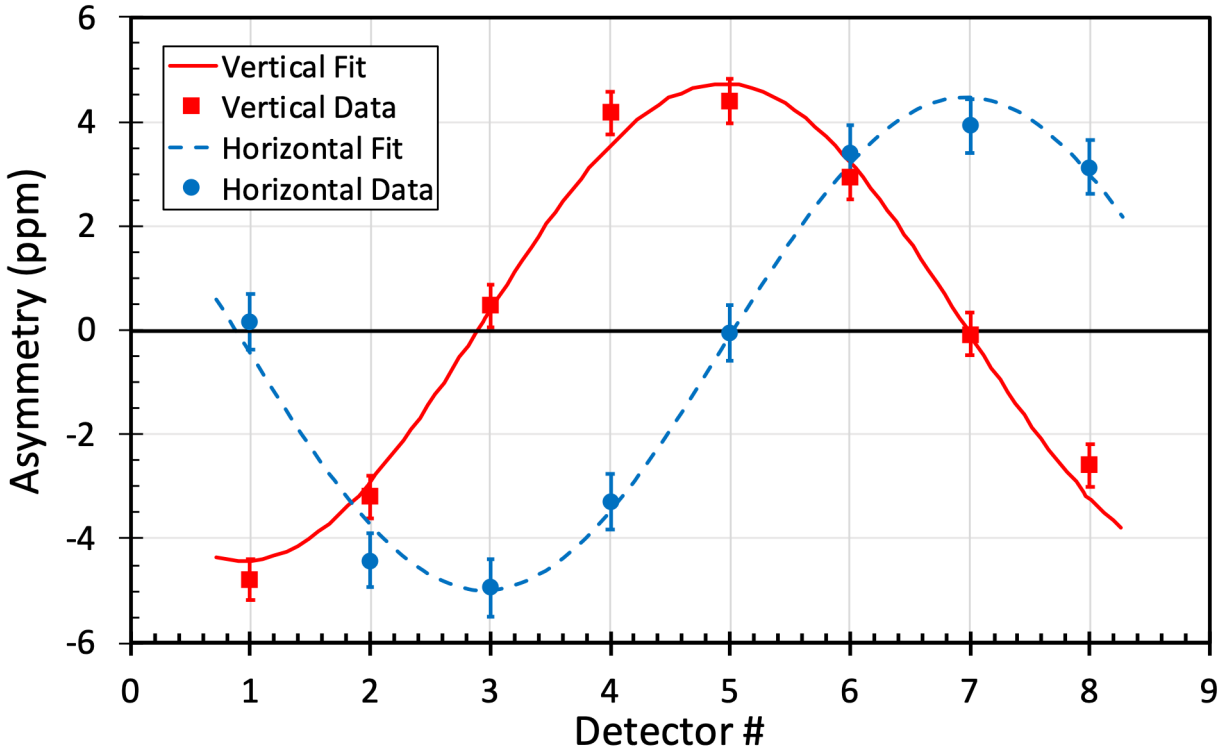
Polarization: P = $88.7 \pm 0.7\%$

**Spectrometer:**

$\langle\theta\rangle = 7.9°$ $5.8° \leq \theta \leq 11.6°$

$\langle Q^2 \rangle$ = 0.0248 GeV$^2$

# BNSSA on proton




| Measurement | $A_{exp}$ (ppm) |
|---|---|
| Period 1, Vertical Transverse Polarization | -4.803 ± 0.089 |
| Period 2, Vertical Transverse Polarization | -4.697 ± 0.142 |
| Period 3, Horizontal Transverse Polarization | -4.837 ± 0.084 |

# BNSSA on proton

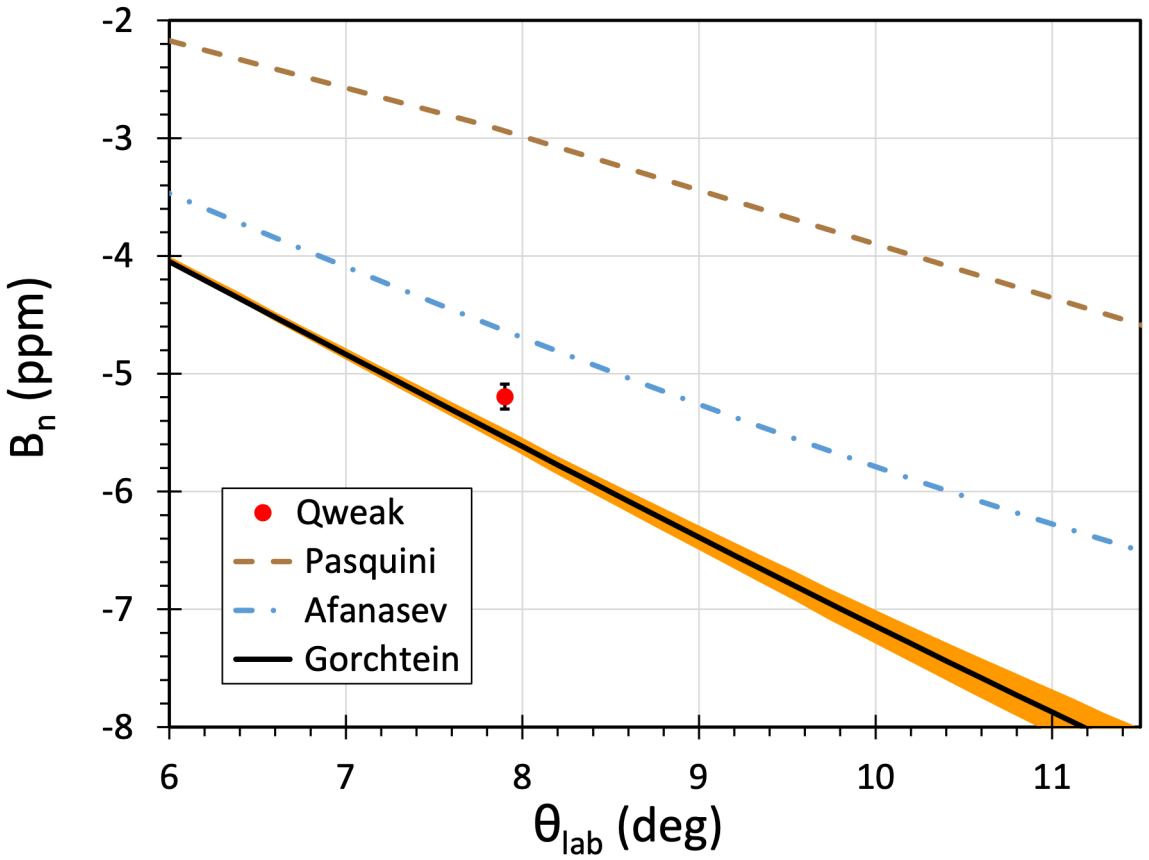
Correct for beam polarization, radiative and acceptance effects, backgrounds and instrumental false asymmetry:

$$B_n = R_{\text{tot}} \left[ \frac{A_{\text{exp}}/P - \sum_{i=1}^{2} f_i A_i}{1 - \sum_{i=1}^{4} f_i} \right] + A_{\text{bias}}$$

| Uncertainty Source | $\frac{\Delta B_n}{B_n}$ (%) |
|---|---|
| Statistics | 1.29 |
| Systematics | |
| $P$: Beam polarization | 0.891 |
| $R_{tot}$: Kinematics and acceptance | 0.423 |
| $R_l$: Electronic Non-linearity | 0.755 |
| Linear regression | 0.656 |
| $R_{av}$: Acceptance averaging | 0.067 |
| $A_1$: Aluminum background asymmetry | 0.409 |
| $f_1$: Aluminum dilution | 0.172 |
| $A_2$: Inelastic background asymmetry | 0.026 |
| $f_2$: Inelastic dilution | 0.076 |
| $A_3$: Beamline neutral asymmetry | 0.004 |
| $f_3$: Beamline neutral dilution | 0.106 |
| $A_4$: Other neutral background asymmetry | 0.198 |
| $f_4$: Other neutral background dilution | 0.212 |
| $A_{\text{bias}}$ | 0.782 |
| Systematics Sub Total | 1.70 |
| Total Uncertainty | 2.13 |

# BNSSA on proton - result

Final result: $B_n = -5.194 \pm 0.067\ (\text{stat}) \pm 0.082\ (\text{syst})\ \text{ppm}$



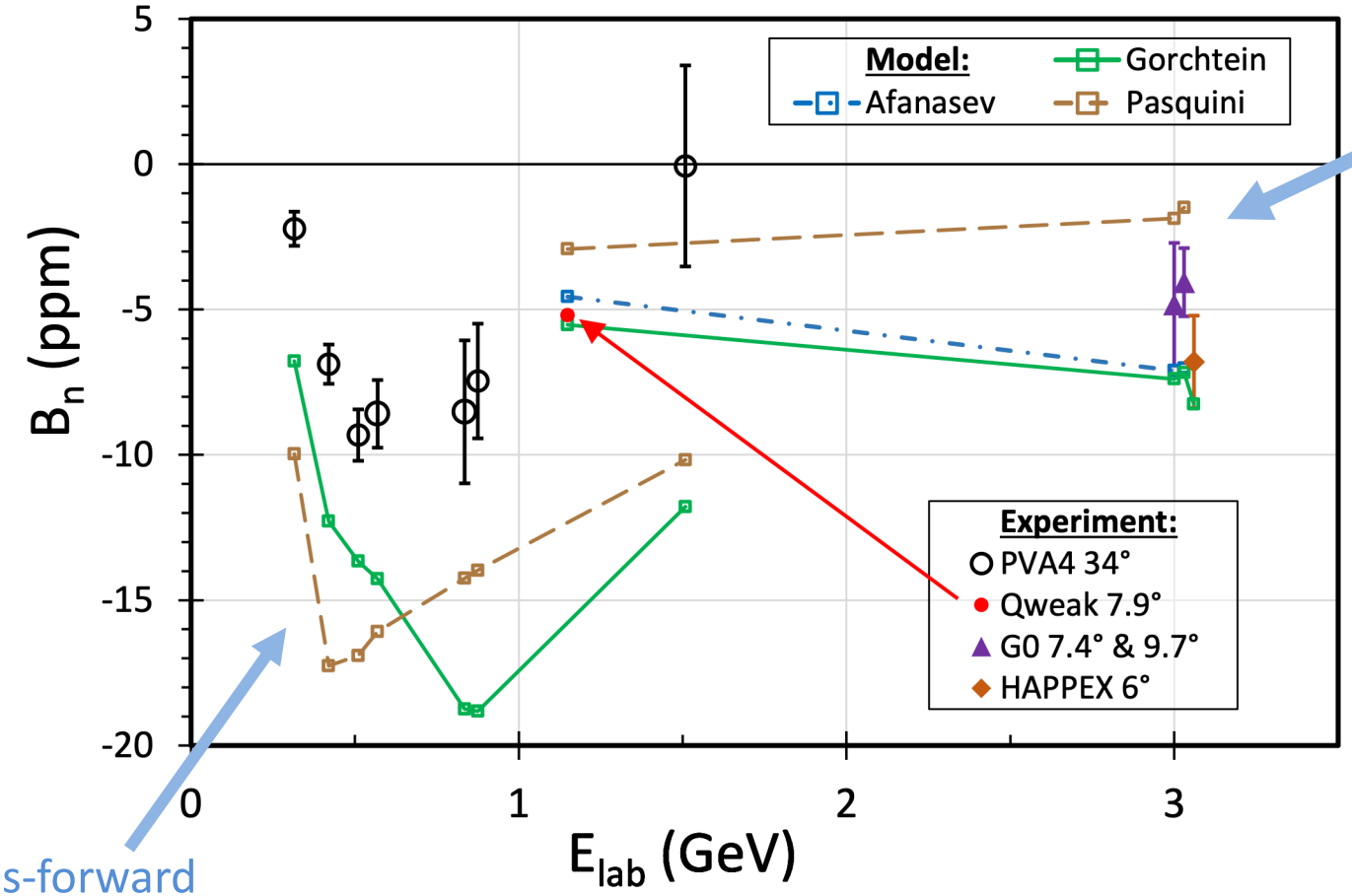

**Models:**

- Pasquini & Vanderhaeghen *Phys Rev C* 70, 045206 (2004) & priv. comm.
- Afanasev & Merenkov *Phys Lett B* 599, 48 (2004) & priv. comm.
- Gorchtein, Guichon & Vanderhaeghen *Nucl. Phys. A* 741, 234 (2004) & priv. comm.

All 3 models agree: inelastic intermediate states dominate at these kinematics. They differ in that G,G&V and A&M include multipion excitations, while P&V only include single-pion excitations.

# BNSSA on proton – world data, forward angles

$\theta_{lab} < 34°$




Far-forward angles ($\theta < 10°$)

Less-forward angles ($\theta > 10°$)

All available models overpredict data for ($\theta > 10°$) angles, but do reasonably well for ($\theta < 10°$), where they are expected to be applicable.

# Part 2: BNSSA on $^{12}C$ and $^{27}Al$

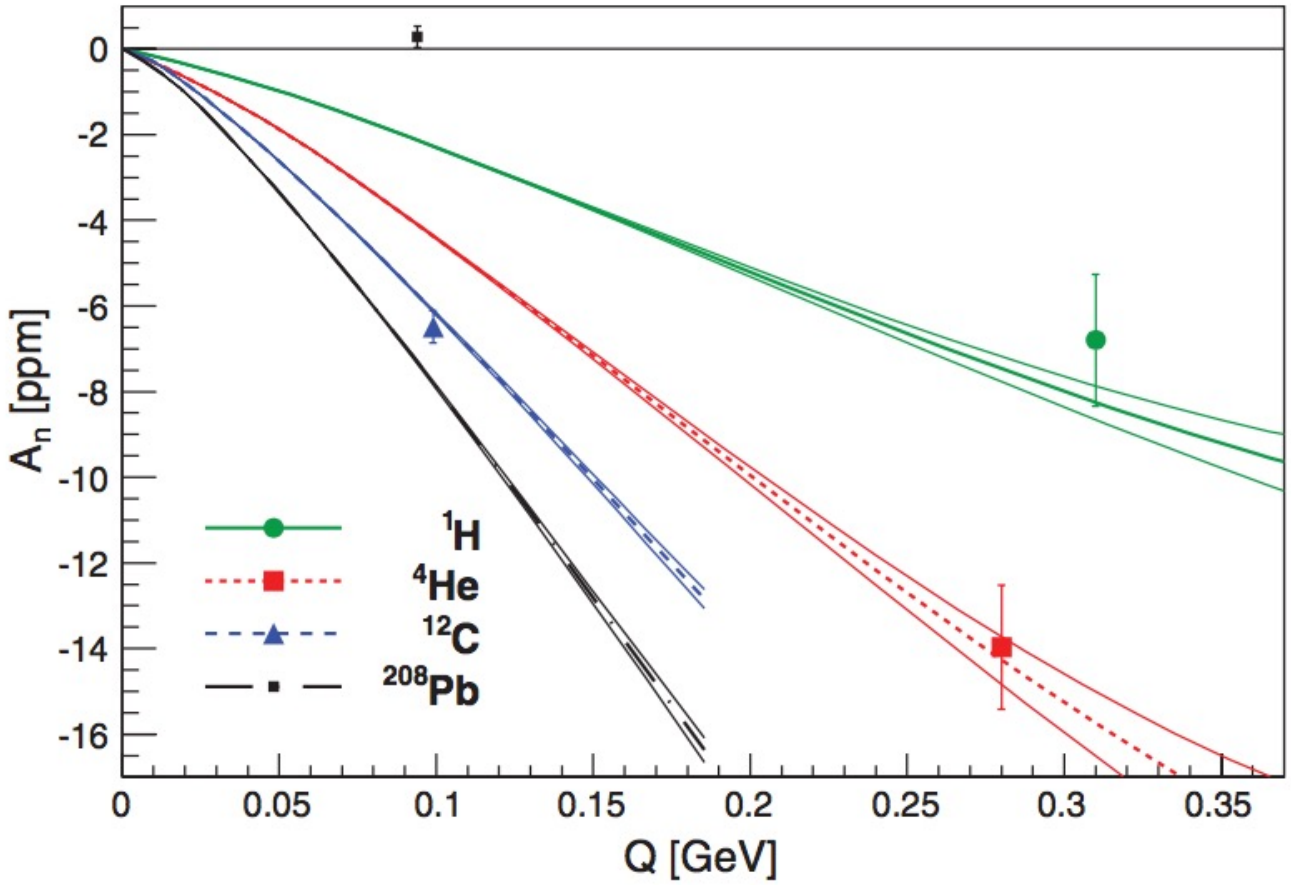
Needed to measure PV asymmetry from $^{27}Al$ as correction to weak charge measurement (and to measure neutron radius in $^{27}Al$)

D. Androic *et al.* *PRL* 128 (2022)132501

Measured BNSSA asymmetry from $^{27}Al$ as correction to the above measurement (correction to the correction!)

… but also to explore BNSSA in nuclei

# BNSSA on nuclei – PREx 1/HAPPEx




PREx-1/HAPPEx: Abrahamyan *et al.* *PRL* 109,192501 (2012)
Model: Gorchtein & Horowitz *Phys. Rev. C* 77,044606 (2008)

Fine agreement for proton, $^4$He, $^{12}$C – violent disagreement for $^{208}$Pb Puzzle!

# BNSSA on $^{12}C$, $^{27}Al$

## Experimental Conditions

Transverse beam polarization taken in three data sets:

Two with vertical beam polarization (different run periods)

& One with horizontal

**Beam Conditions:**

$E_e$ = 1.16 GeV

I = 75 $\mu$A ($^{12}C$) 24 $\mu$A , 61 $\mu$A ($^{27}Al$)

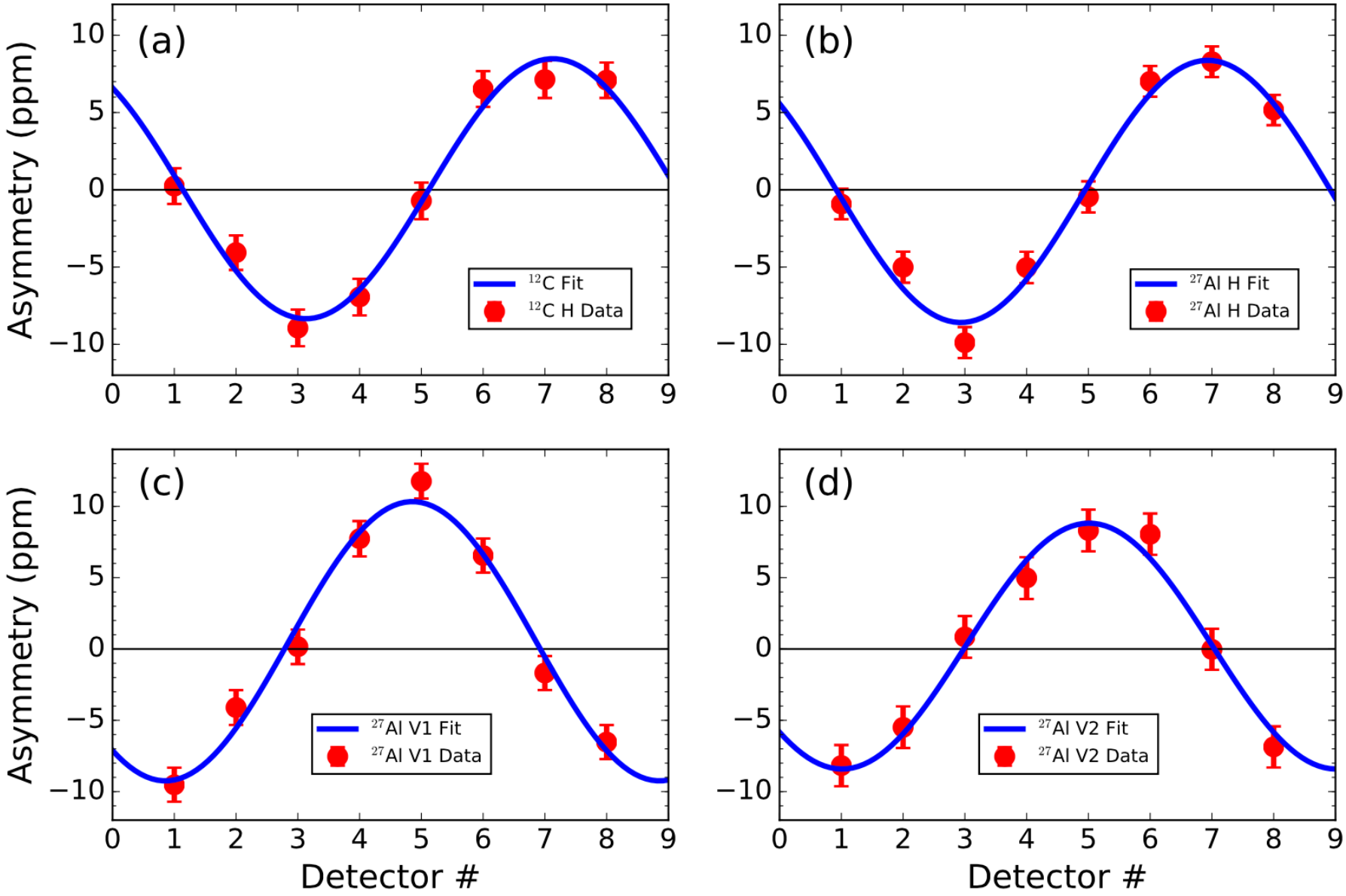
Polarization: P = $88.6 \pm 0.7\%$ ($^{12}C$: Horiz.) ($^{27}Al$ Horiz. & Vert.)

**Spectrometer:**

$\langle\theta\rangle = 8.1°$ ($^{12}C$) , $7.6°$ ($^{27}Al$) $5.8° \leq \theta \leq 11.6°$

$\langle Q^2\rangle$ = 0.0257 GeV$^2$ ($^{12}C$) 0.0236 GeV$^2$ ($^{27}Al$)

# BNSSA on $^{12}C$ & $^{27}Al$

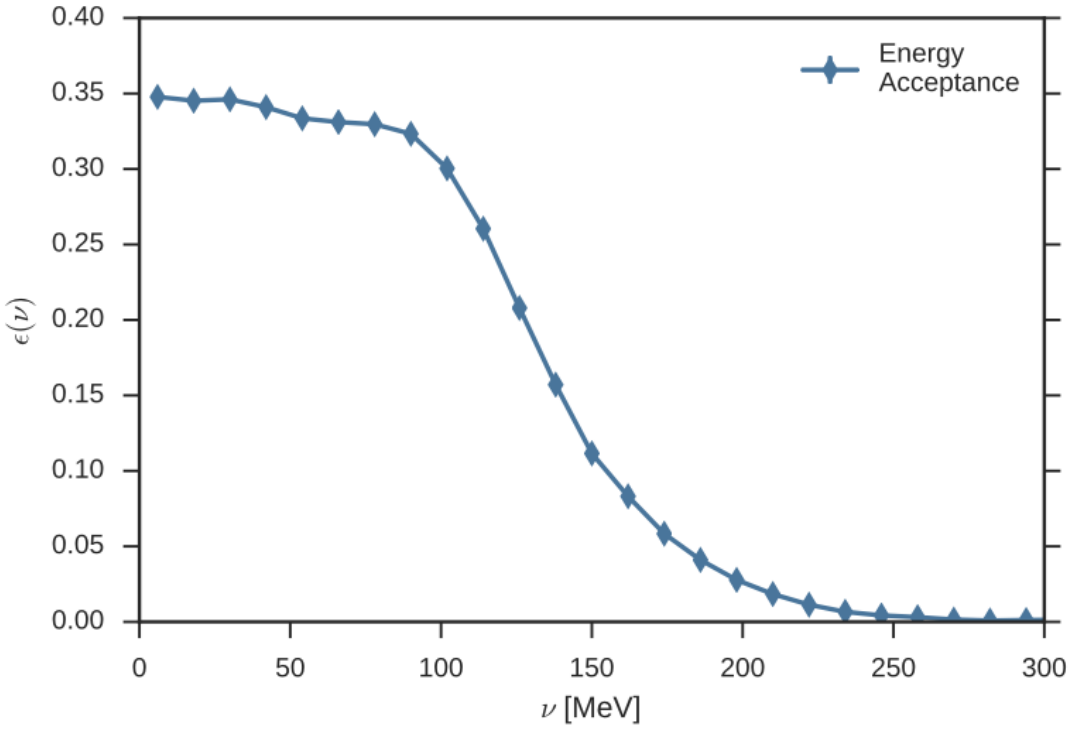


# BNSSA on $^{12}C$, $^{27}Al$ - challenges

## Challenges:

1) Spectrometer not designed with narrow energy acceptance to separate the elastic state from nuclear excited states, quasielastic and inelastic ($N \rightarrow \Delta$) processes.

- 150 MeV wide acceptance
- Non-elastic scattering processes dilute the asymmetry measurement
- Corrections required for nuclear excited states, GDR, quasielastic…

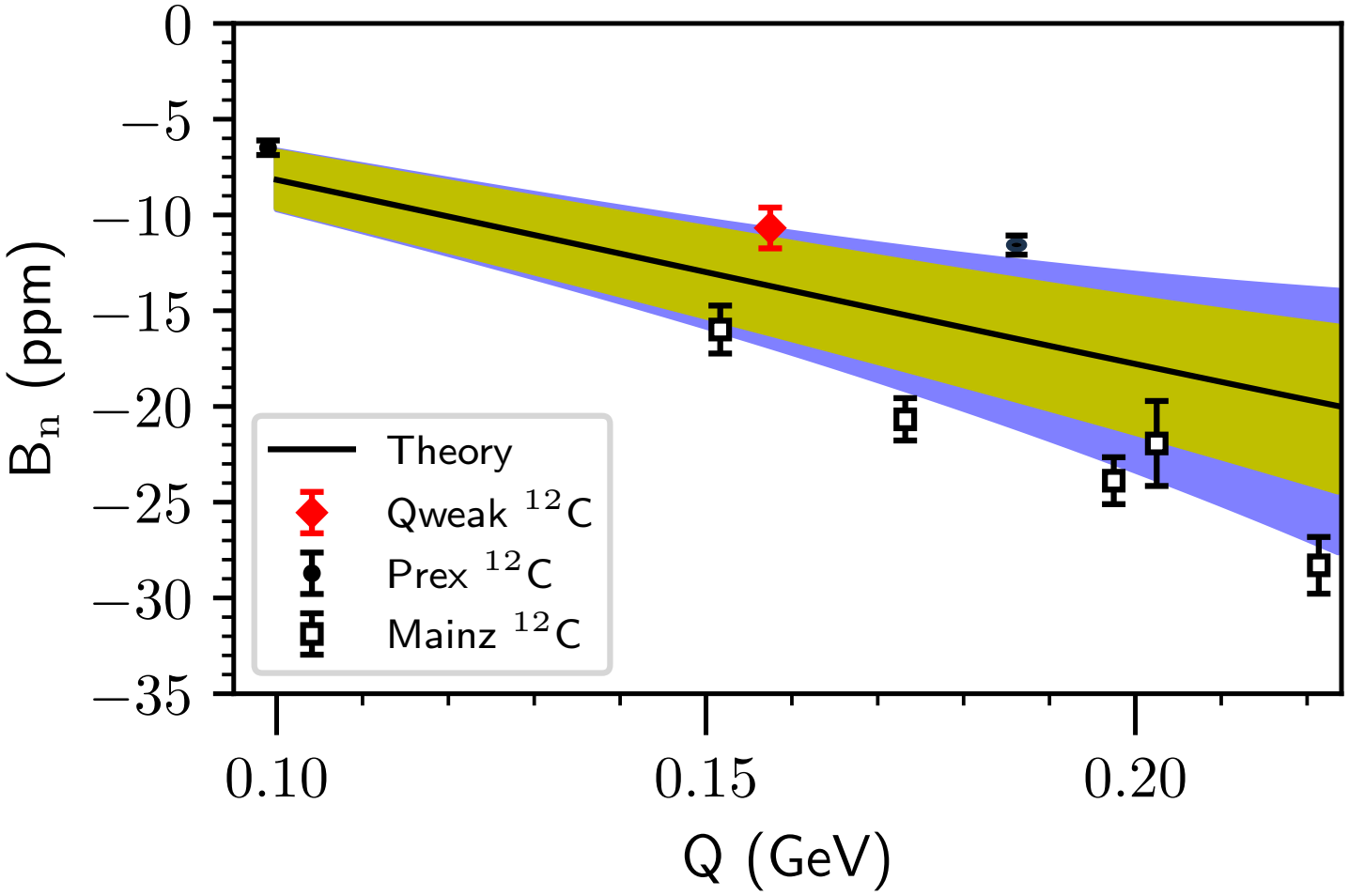



2) For $^{27}Al$: target not pure Aluminum – was an alloy – need to account for background from alloy elements.

# All corrections

| Quantity | Value $^{12}$C | Value $^{27}$Al | $\Delta B_n/B_n$ (%) $^{12}$C | $\Delta B_n/B_n$ (%) $^{27}$Al |
|---|---|---|---|---|
| $P$: Beam Polarization | $0.8852 \pm 0.0068$ | $0.8872 \pm 0.0070$ | 0.9 | 1.0 |
| $R_{\rm tot}$: Kinematics & Radiative effects | $1.0054 \pm 0.0046$ | $1.0054 \pm 0.0046$ | 0.5 | 0.5 |
| $R_{\rm av}$: Acceptance averaging | $0.9862 \pm 0.0036$ | $0.9862 \pm 0.0036$ | 0.4 | 0.4 |
| $R_l$: Electronic non-linearity | $1.0014 \pm 0.0050$ | $1.0014 \pm 0.0050$ | 0.6 | 0.6 |
| $B_{\rm fit}$: Fitting | $0 \pm 0.042$ ppm | $0 \pm 0.050$ ppm | 0.6 | 0.6 |
| $B_{\rm reg}$: Linear Regression | $0 \pm 0.002$ ppm | $0 \pm 0.020$ ppm | < 0.1 | 0.3 |
| $B_{\rm bias}$: Rescattering Bias | $0.125 \pm 0.041$ ppm | $0.125 \pm 0.041$ ppm | 0.6 | 0.6 |
| $f_{\rm neutral}$: | $0.69 \pm 0.45$ % | $0.69 \pm 0.45$ % | 0.8 | 0.7 |
| $B_{\rm neutral}$: | $0 \pm 10$ ppm | $0 \pm 10$ ppm | 0.6 | 0.8 |
| $f_{\rm alloy}$: | — | $5.41 \pm 0.34$ % | — | < 0.1 |
| $B_{\rm alloy}$: | — | $-10.7 \pm 2.0$ ppm | — | 1.3 |
| $f_{\rm QE}$: | $15.9 \pm 2.2$ % | $21.2 \pm 2.9$ % | 1.5 | 2.4 |
| $B_{\rm QE}$: | $-5.2 \pm 1.0$ ppm | $-5.2 \pm 1.0$ ppm | 2.0 | 2.6 |
| $f_{\rm inel}$: | $0.40 \pm 0.06$ % | $0.66 \pm 0.10$ % | 0.4 | 0.7 |
| $B_{\rm inel}$: | $43 \pm 16$ ppm | $43 \pm 16$ ppm | 0.8 | 1.3 |
| $f_{\rm nucl}$ | $4.71 \pm 0.31$ % | $3.88 \pm 0.23$ % | < 0.1 | < 0.1 |
| $B_{\rm nucl}$ | $-10.5 \pm 10.5$ ppm | $-12 \pm 5.5$ ppm | 3.9 | 2.6 |
| Total Systematic | | | 5.3 % | 5.2 % |
| | | Statistical: | 8.4% | 4.8% |

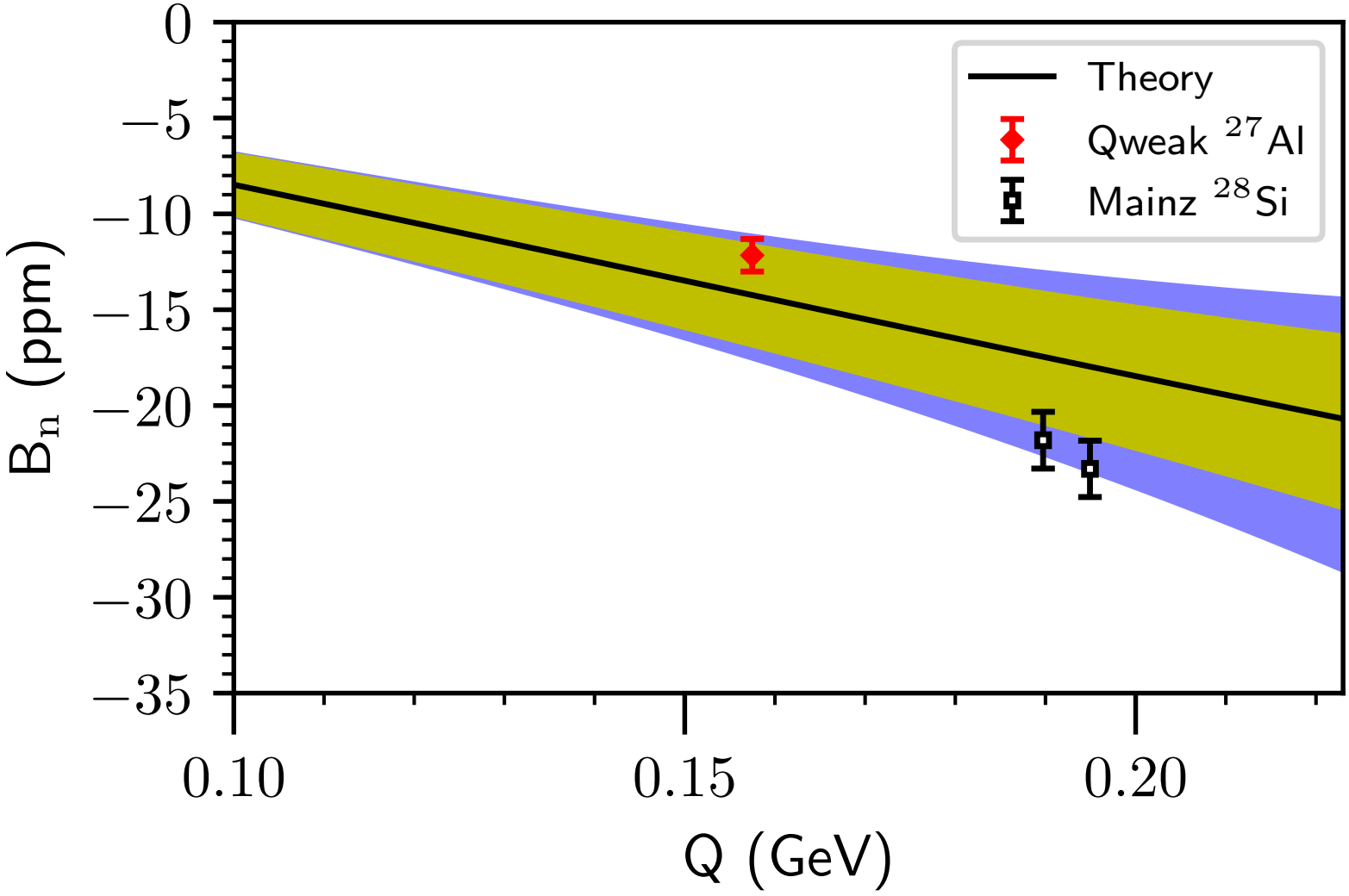
# BNSSA on $^{12}$C: Qweak & world data




Theory: M. Gorchtein priv. comm.
method of Gorchtein & Horowitz
PREx: Abrahamyan *et al.* *PRL* 109,192501 (2012)
Adhikari *et al.* *PRL* 128,142501 (2022)
Mainz/A1: Esser *et al. PRL* 121,022503 (2021)

Mainz results: $E_{beam}$ = 0.57 GeV
Qweak: $E_{beam}$ = 1.1 GeV
PREx: $E_{beam}$ = 0.95 GeV, 2.2 GeV

# BNSSA on $^{27}$Al




Theory: M. Gorchtein priv. comm.
method of Gorchtein & Horowitz

Mainz/A1: Esser *et al.* Phys. Lett. B 808, 135664 (2020)

First time BNSSA measured for a non spin-0 complex nucleus

# Part 3: BNSSA on proton at low $Q^2$ above the resonance region

Wanted to extract the PVES asymmetry at similar $Q^2$ but at large $W$:

Test models of γZ box diagrams

- Raised energy to access W above resonance
- Significant $\pi^-$ backgrounds
  - ∴ added crude ”pion detector”
- Beam was not fully longitudinal→ large transverse asymmetries
  - ∴ Took data with ”mixed” (partly longitudinal) as well as pure transverse

**Provided access to:**

PVES for electrons (for γZ box diagram)
PVES for inclusive pion production
BNSSA for electrons
BNSSA for pions

# BNSSA on proton at high W

## Experimental Conditions

Two data sets:

- "Mixed" Longitudinal/Transverse beam $\theta_{beam} \approx 20°$
- Fully Transverse beam

**Beam Conditions:**

$E_e$ = 3.35 GeV

I = 160 – 180 $\mu$A

Polarization: P = $87.0 \pm 0.7\%$

**Spectrometer:**

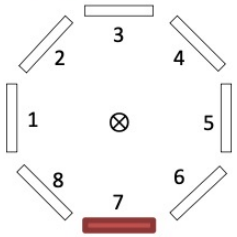
$\langle\theta\rangle = 7.9°$ $\quad 5.8° \leq \theta \leq 11.6°$

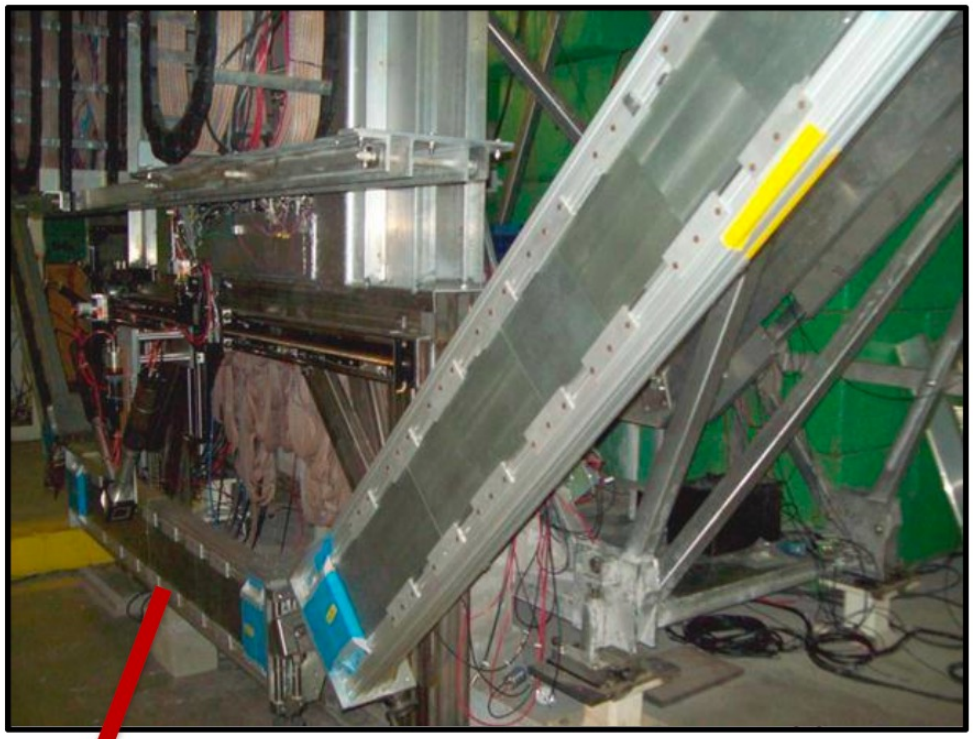
$\langle Q^2 \rangle$ = 0.082 GeV$^2$

$\langle W \rangle$ = 2.23 GeV

# Pion detection

- Large difference between $E$ & $E'$
  - Leads to large pion background
- 4” lead wall placed in front of lowest Čerenkov Detector
  - Ranges out most electrons
  - Leaves mostly pions
- Sacrifice statistics to make a ‘Pion detector’

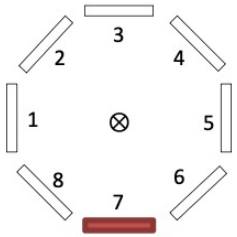


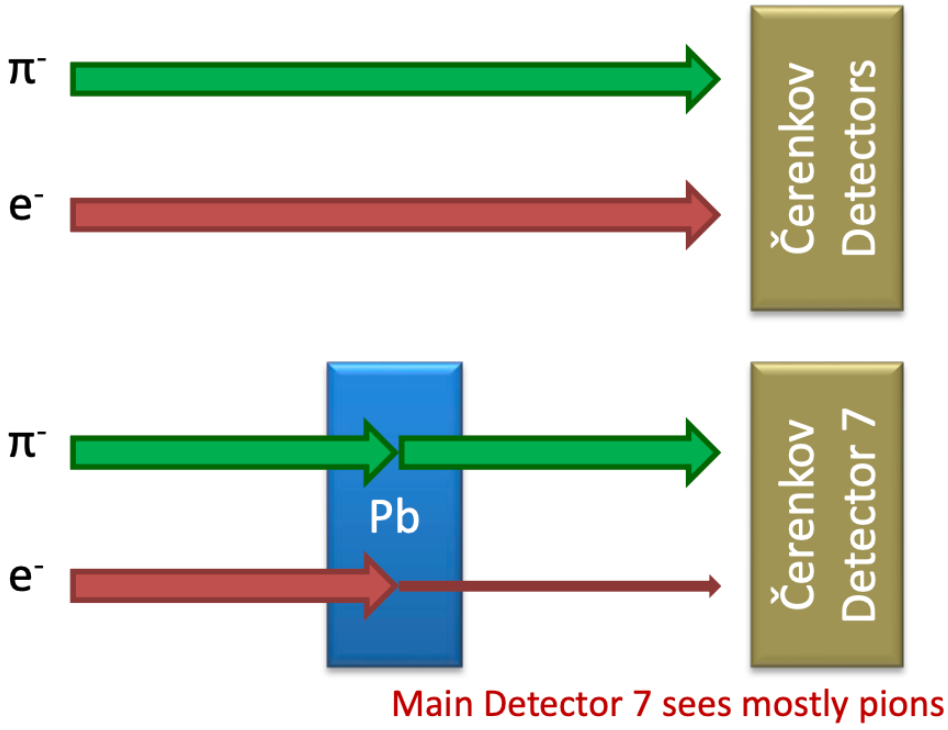





# Pion detection

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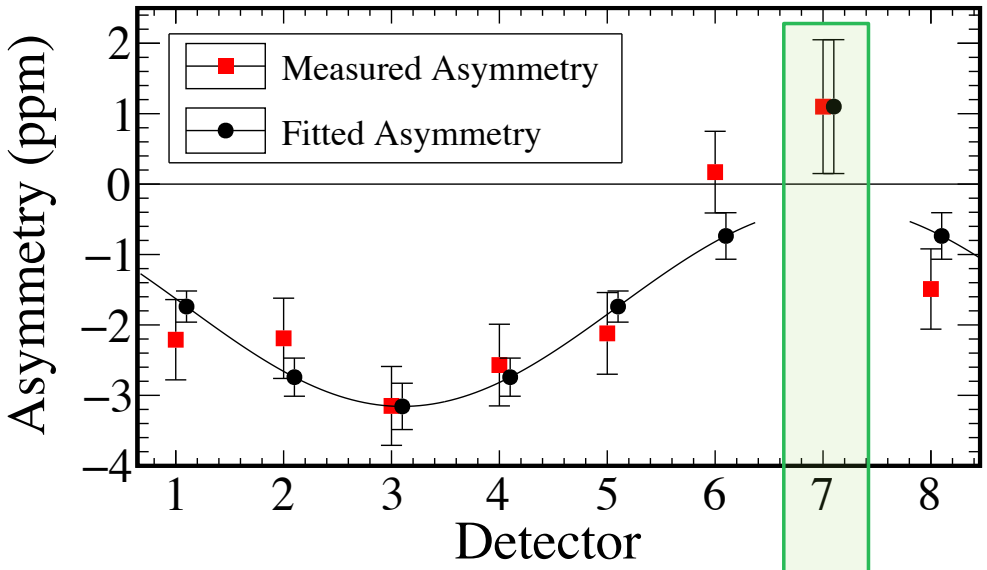




Main Detector 7 sees mostly pions

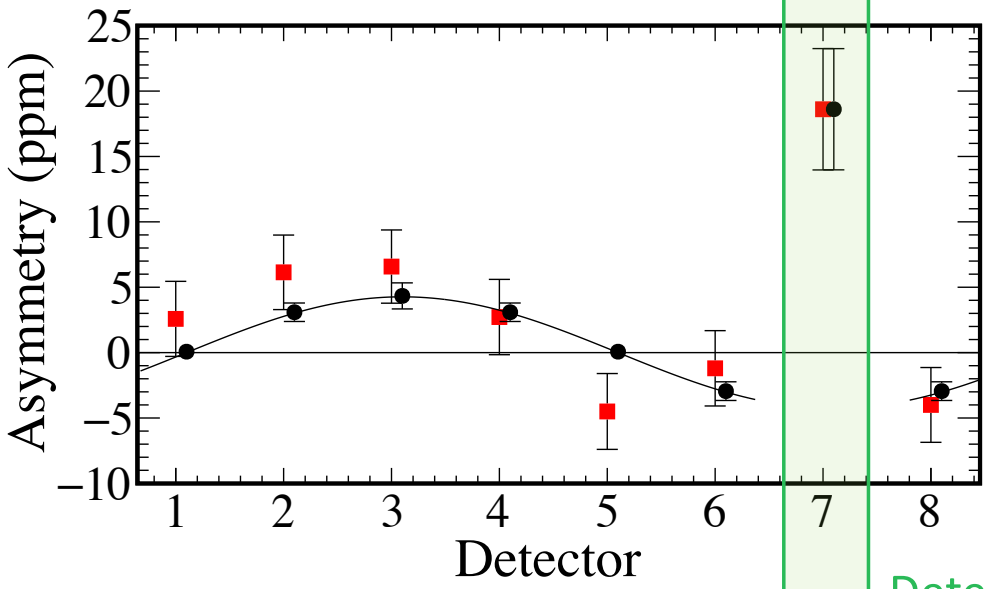


# Azimuthal Deconvolution

a) Mixed




b) Transverse




$$A^{ij}_{\text{meas}} = P(1 - f^i_{\text{NB}})\left[(1 - f^i_\pi)\left(A^L_e \cos\theta^j_P + A^T_e \sin\theta^j_P \sin\phi^i\right) + f^i_\pi\left(A^L_\pi \cos\theta^j_P + A^T_\pi \sin\theta^j_P \sin\phi^i\right)\right]. \quad (8)$$

Detector 7: pion detector

# Extracted asymmetries from

| Asymmetry | Value (ppm) |
|---|---|
| $A_e^L$ | $-5.25 \pm 1.49$ |
| $A_e^T$ | $12.3 \pm 3.6$ |
| $A_\pi^L$ | $25.4 \pm 9.0$ |
| $A_\pi^T$ | $-60.1 \pm 19.3$ |

To get $A_{\text{inel}}$ from $A_e^L$ need to correct for:

| | Yield fraction |
|---|---|
| Elastic radiative-tail | 61.6% |
| Al target windows | 0.8% |
| Punch-through of elastics | 2.2% |

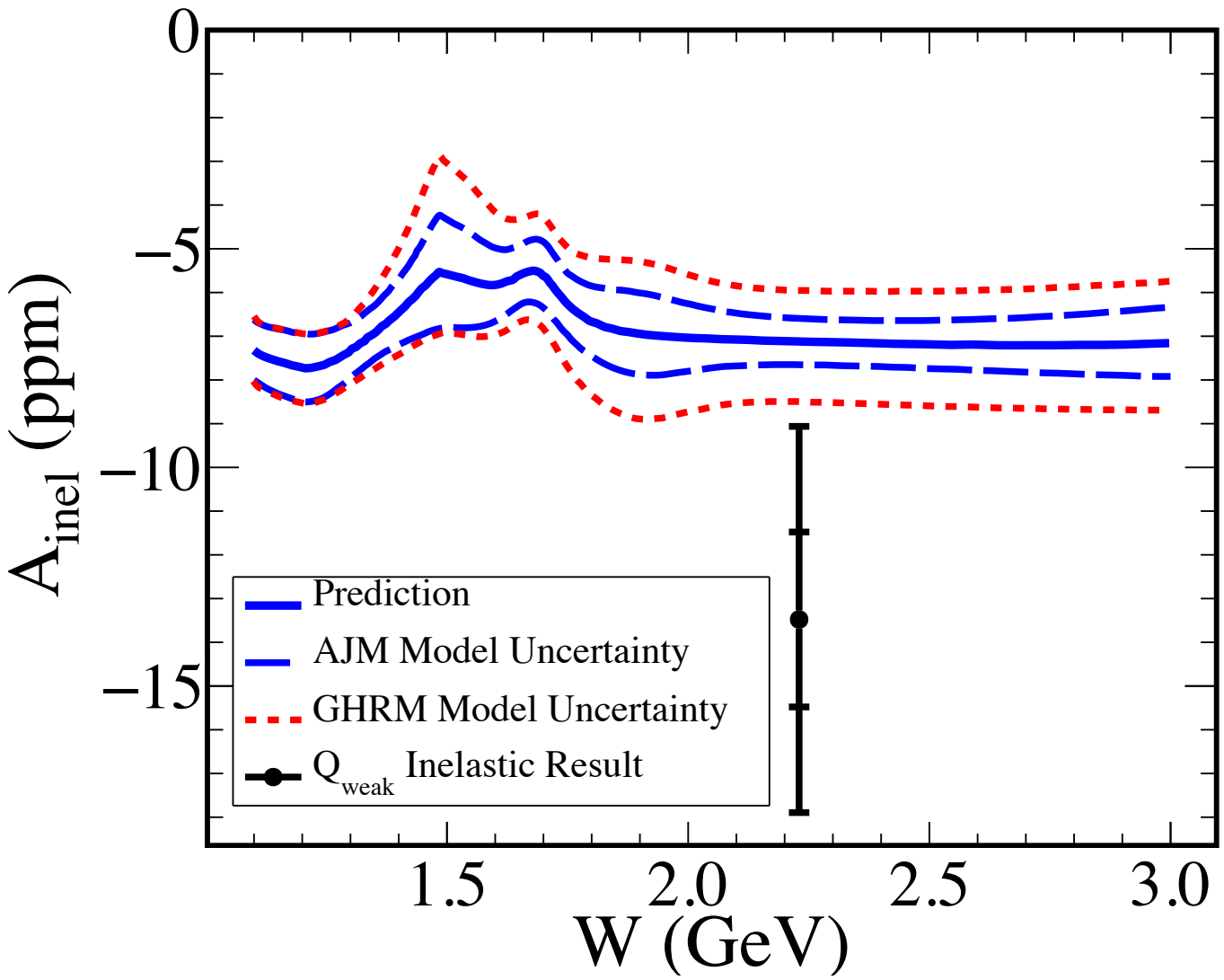
**Result:**

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

# Uncertainties on $A_{inel}$

| Quantity | Quantity | Value | Contribution to $\left(\frac{dA_{Inel}}{A_{Inel}}\right)$ |
|---|---|---|---|
| Pion yield fraction | $f_\pi^{avg}$ | $0.096 \pm 0.029$ | 21.9% |
| | $f_\pi^7$ | $0.81 \pm 0.05$ | |
| Neutral background in MD7 | $f_{NB}^7$ | $0.51 \pm 0.09$ | 12.4% |
| Elastic radiative-tail yield fraction | $f_{El}$ | $0.62 \pm 0.04$ | 9.8% |
| Polarization angle | $\theta_P^{mix}$ | $-19.7^\circ \pm 1.9^\circ$ | 9.3% |
| | $\theta_P^{trans}$ | $92.2^\circ \pm 1.9^\circ$ | |
| Neutral background in unblocked MDs | $f_{NB}^{Un}$ | $0.063 \pm 0.006$ | 1.4% |
| Aluminum window asymmetry | $A_{Al}$ | $-3.8 \pm 5.4$ ppm | 1.0% |
| Beam polarization | $P$ | $0.870 \pm 0.006$ | 0.8% |
| Elastic radiative tail asymmetry | $A_{El}$ | $-0.58 \pm 0.02$ ppm | 0.3% |
| Re-scattering bias effect | $A_{bias}$ | $0.019 \pm 0.028$ ppm | 0.2% |
| Aluminum window yield fraction | $f_{Al}$ | $0.0075 \pm 0.0009$ | 0.2% |
| Punch-through yield fraction | $f_{PT}$ | $0.0220 \pm 0.0007$ | <0.1% |
| Beamline background asymmetry | $A_{BB}$ | $0.012 \pm 0.027$ ppm | <0.1% |
| Punch-through asymmetry | $A_{PT}$ | $-3.96 \pm 0.04$ ppm | <0.1% |
| Regression correction | | $<0.20 \pm 0.00$ ppm | <0.1% |
| Total systematics | | | 28.7% |
| Statistics | | | 15.8% |
| Total | | | **32.8%** |

# PVES above resonance region




AJM, GHRM - ]Hall et al. Phys. Rev. D **88**, 013011 (2013).

$$A/Q^2 = 165 \pm 53 \ \text{ppm/GeV}^2$$

# Inelastic Electron BNSSA

$$A_e^T = +12.3 \pm 3.6 \text{ ppm}$$

Correcting for BNSSA from elastic radiative tail:

$B_n = 22 \pm 4$ ppm (Note the positive sign!)

No calculations specific to these kinematics (to my knowledge).

Carlson *et al.* [Phys. Rev. D 96, 113010 (2017)]
calculated $B_n$ for $N \rightarrow \Delta(1232)$ at 1.1 GeV, forward angles.
predicted large (40-50 ppm) positive values - similar mechanism above resonance region?
Pasquini [priv. comm] obtained similar result

Qweak has (*preliminary*) data for $B_n$ for $N \rightarrow \Delta(1232)$ [arXiv:1510.00449 CIPANP 2015]
in reasonable agreement with Carlson et al. prediction: see Carl Carlson's talk

MOLLER may see large opposite sign asymmetries from inelastic electrons

# Inclusive $\pi^-$ BNSSA

$$A_\pi^T = -60 \pm 19 \text{ ppm}$$

No correction made for Al window contribution

If signal is dominated by hydrogen: must be multiple meson production

Buncher and Carlson [Phys. Rev. D 93, 074032 (2016)]
calculated $B_n$ in resonance region when single hadrons observed

Found that $B_n$ with single pion observed can arise from single photon exchange via FSI
$B_n$ can be either sign, depending on kinematics

MOLLER may see large transverse asymmetries associated with pions

# Inclusive $\pi^-$ PV asymmetry

$$A_\pi^L = +25 \pm 9 \text{ ppm}$$

No correction made for Al window contribution,

PV from real photoproduction: expect scale of $h_\pi^1 \cong 0.3$ ppm

At 50 GeV, E158 found inclusive pion production asymmetry of order $-1$ ppm

Hyperon production [see Andrew Hurley's talk]
G0 at 3.0 GeV found large positive asymmetries for protons from hyperon decay
[Armstrong et al. PRL 95,092001 (2005)]

Gorchtein [priv. comm.] has suggested may be large contributions from isoscalar exchange:
Virtual $Z^0$ producing multi-pion states, coupling to nucleon via isoscalar Reggeon exchange

MOLLER may see large PV asymmetries associated with pions

# Summary

1) BNSSA on proton
   - Most precise such measurement to date (2%)
   - Need to include $\pi\pi N$ intermediate states to get reasonable agreement between data and models

Androic et al. PRL 125, 112502 (2020)

2) BNSSA on $^{12}$C and $^{27}$Al
   - Reasonable agreement with G&H model using energy-weighted integral over the photoabsorption cross-section.
   - No significant deviation seen from that model's A/Z scaling: no evidence of effect like in *PREx $^{208}$Pb puzzle*

Androic et al. Phys. Rev. C 104, 014606 (2021)

3) BNSSA for electrons & pions on proton at high W, low $Q^2$
   - Large ($\approx 22$ ppm) positive asymmetry for (inelastic) electrons
   - Large ($\approx -60 \pm 20$ ppm) negative asymmetry for inclusive pion production
   - Large ($\approx 25 \pm 9$ ppm) positive PV asymmetry for inclusive pion production

Androic *et al.* Phys. Rev. C 101, 055502 (2020)

# The Qweak Collaboration



**101 collaborators 26 grad students**
**11 post docs 27 institutions**

**Institutions:**

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[2] College of William and Mary
[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
[5] Thomas Jefferson National Accelerator Facility
[6] Ohio University
[7] Christopher Newport University
[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
[17] University of Connecticut
[18] University of Northern British Columbia
[19] University of Winnipeg
[20] George Washington University
[21] University of New Hampshire
[22] Hendrix College, Conway
[23] University of Adelaide
[24] Syracuse University
[25] Duquesne University

A SEARCH FOR NEW PHYSICS
Qweak

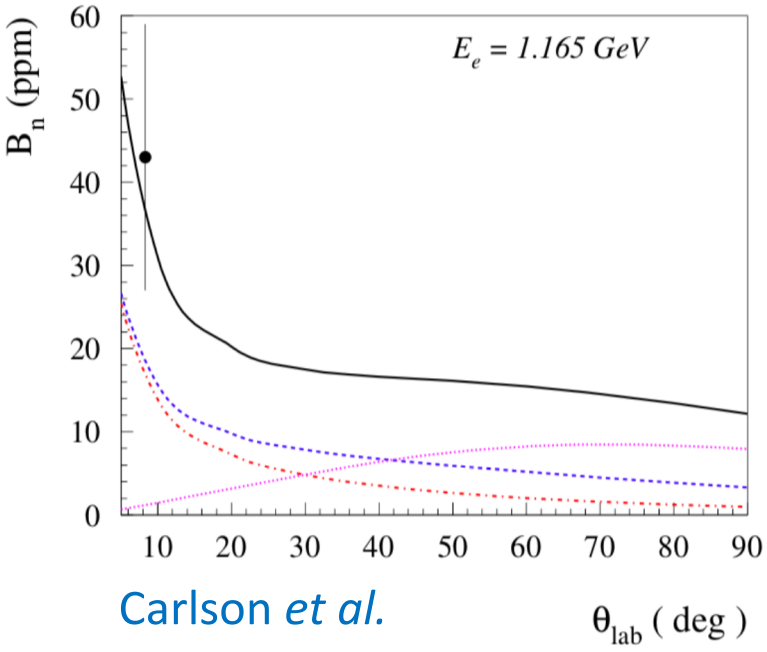

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Spokespersons Project Manager Grad Students *deceased

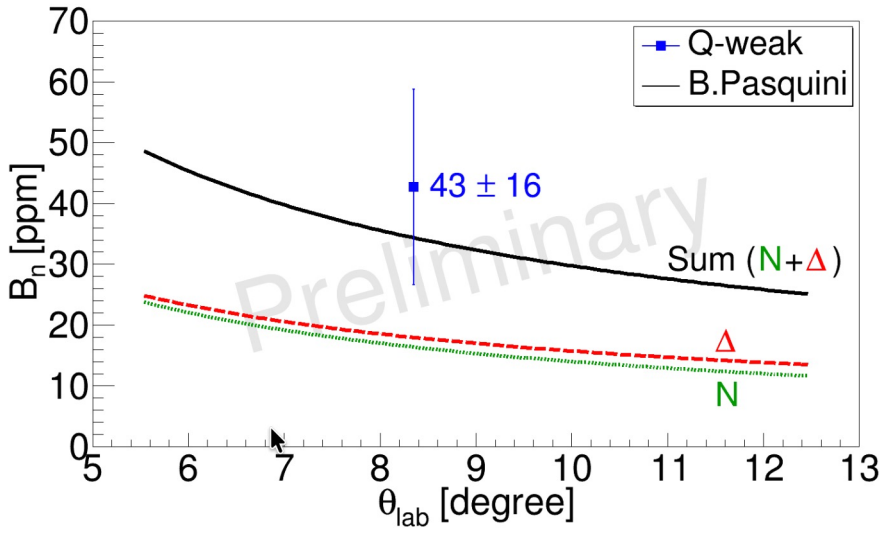
# Extra Slides

# $N \rightarrow \Delta$ BNSSA

Qweak: Preliminary, unpublished




Carlson *et al.*




Pasquini

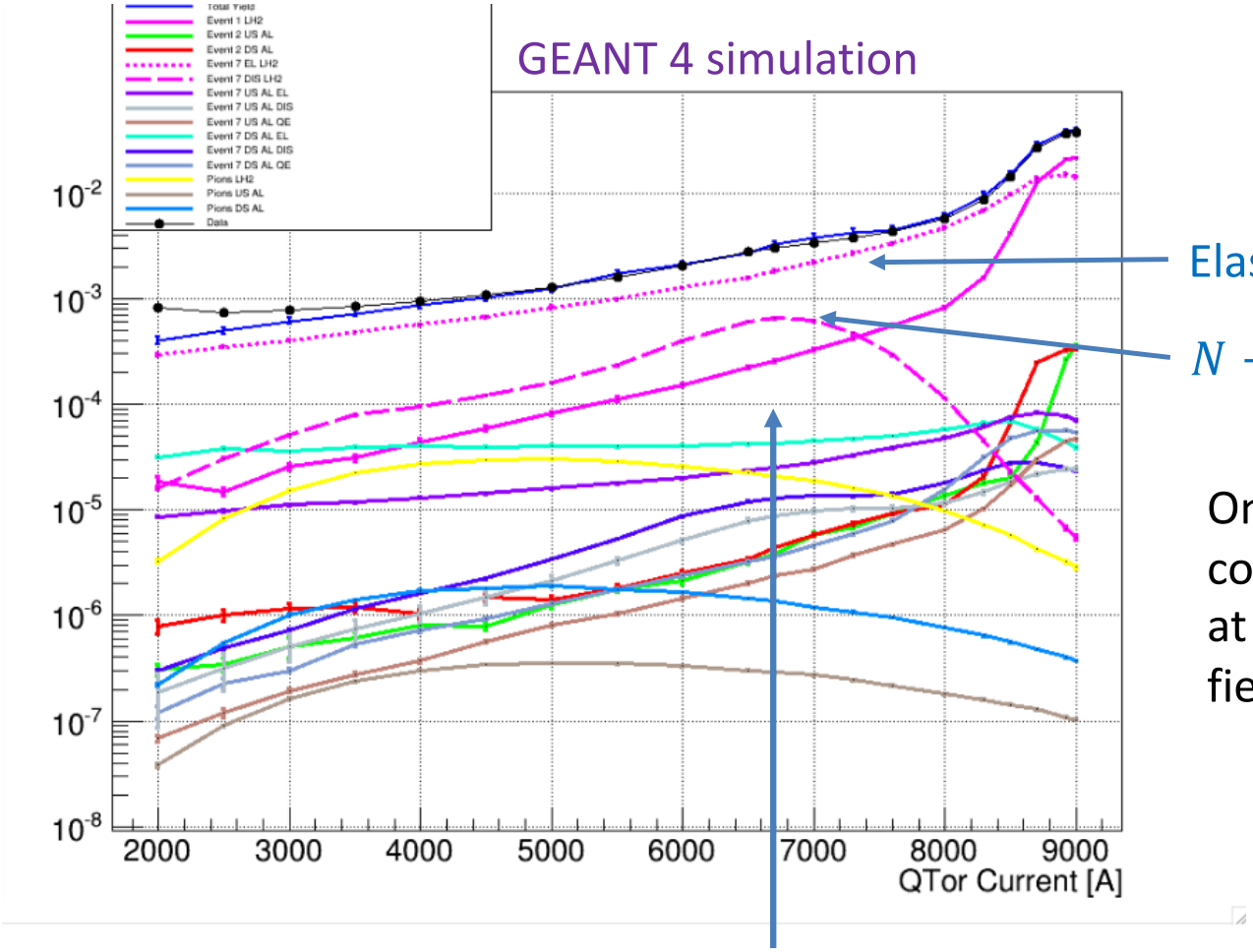
Experimental issue – huge background correction from opposite sign $B_n$ from the elastic radiative tail.

Raw asymmetry of 5 ppm becomes 43 ppm – error bar entirely due to uncertainty on radiative tail contribution – extracted using simulation.

Uncertainty on this simulated radiative tail is the only challenge – hard to benchmark with data….

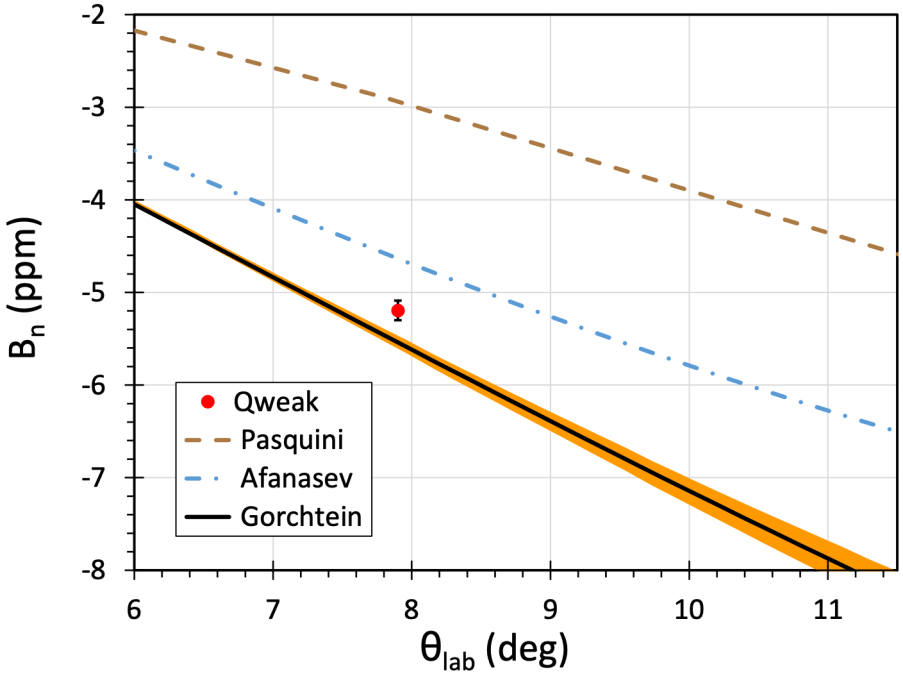
# $N \rightarrow \Delta$ BNSSA

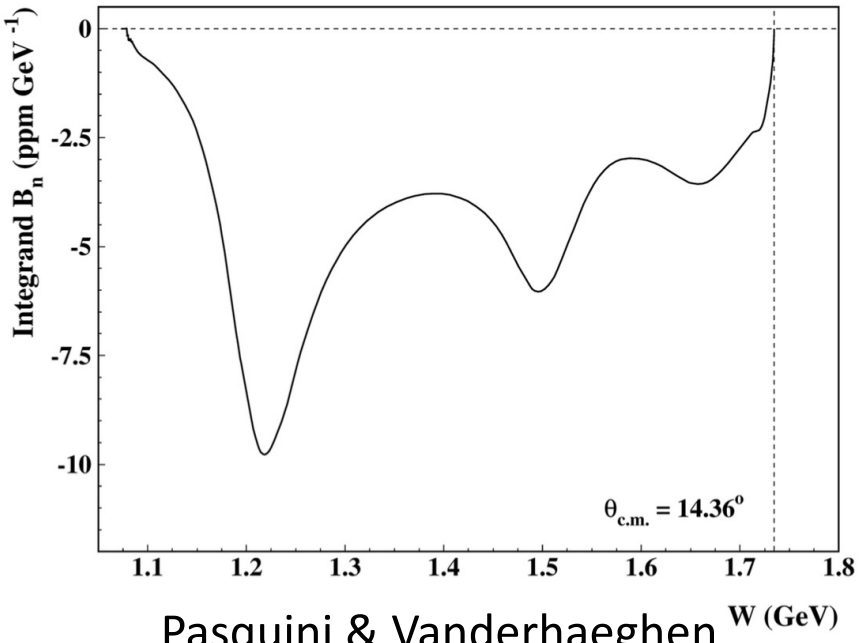
Qweak: Preliminary, unpublished




Only about 20% of yield comes from the $N \rightarrow \Delta$ at the (optimal) magnetic field used.

# BNSSA on proton - result




Pasquini & Vanderhaeghen

Inelastic intermediate states dominate at these kinematics.

Pasquini & Vanderhaeghen: $\pi N$ decays of $\Delta(1232)$, $D_{13}(1520)$ and $F_{15}(1680)$.

Perhaps need to include the $\pi\pi N$ decays of the $D_{13}(1520)$ and $F_{15}(1680)$,
as in the Afanesev & Merenkov and Gorchtein, Guichon & Vanderhaeghen models.

Similar effect seen earlier by G0 at 3.0 GeV beam energy:

Armstrong *et al.* *PRL* 99, 092301 (2007)

# $^{12}C$ and $^{27}Al$: Non-elastic backgrounds

Quasielastic and inelastic ($N \rightarrow \Delta$) backgrounds:

**Dilution** (background fraction): $f_i$

- Use GEANT 4 simulation with cross-section parameterization from empirical fits to data
  (M. Christy, Priv. Comm)

$f_{QE}$ = $21.2 \pm 2.9$ % ($^{27}Al$) $15.9 \pm 2.2$ % ($^{12}C$)

$f_{inel}$ = $0.66 \pm 0.10$ % ($^{27}Al$) $0.40 \pm 0.06$ % ($^{12}C$)

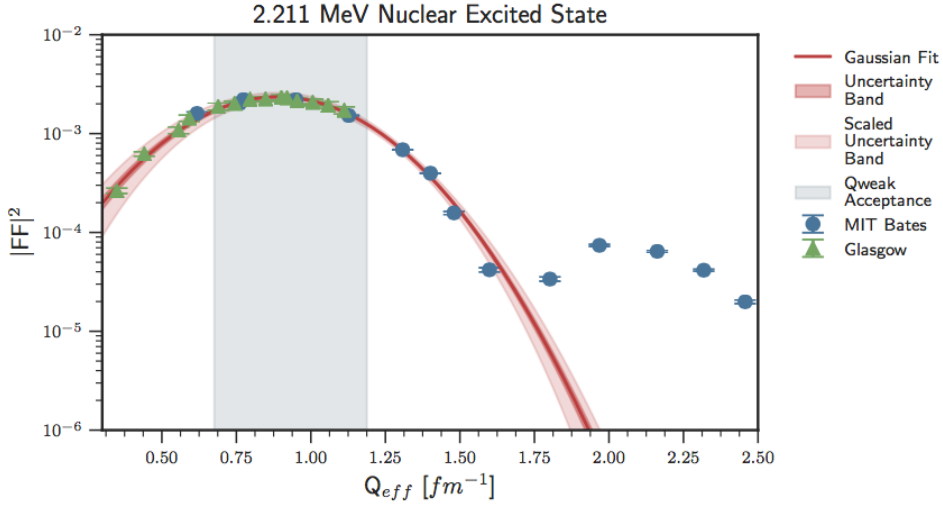
**Asymmetry:** $A_i$

- Quasielastic:
  used our proton $B_n$ measurement, inflated uncertainty: $A_{QE} = -5.2 \pm 1.0$ ppm
- Inelastic:
  made a separate measurement: $A_{inel} = +43 \pm 16$ ppm

# $^{12}$C and $^{27}$Al: BNSSA on nuclear excited states

**Low-lying levels:**

- Use form factor data from Glasgow(1970s) and MIT/Bates (1980s) in our kinematic range.
- Fit FF data to Gaussians, input to GEANT 4




$^{27}$Al

| Energy (MeV) | $J^P$ | Background fraction ($f_i$) (%) |
|---|---|---|
| 0.844 | $1/2^+$ | $0.27 \pm 0.04$ |
| 1.014 | $3/2^+$ | $0.41 \pm 0.10$ |
| 2.211 | $7/2^+$ | $1.35 \pm 0.16$ |
| 2.735 | $5/2^+$ | $0.19 \pm 0.02$ |
| 2.990 | $3/2^+$ | $0.93 \pm 0.07$ |
| 4.540 | | $0.06 \pm 0.01$ |
| 4.812 | $5/2^+$ | $0.09 \pm 0.02$ |
| 5.430 | | $0.17 \pm 0.03$ |
| 5.668 | $9/2^+$ | $0.08 \pm 0.02$ |
| 7.228 | $9/2^+$ | $0.18 \pm 0.06$ |
| 7.477 | | $0.10 \pm 0.07$ |
| 21 | $1^-$ (GDR) | $0.045 \pm 0.022$ |
| Total | | $3.88 \pm 0.23$ % |

$^{12}$C

| Energy (MeV) | $J^P$ | Background fraction ($f_i$) (%) |
|---|---|---|
| 4.44 | $2^+$ | $2.86 \pm 0.29$ |
| 7.65 | $0^+$ | $0.92 \pm 0.09$ |
| 9.64 | $3^-$ | $0.93 \pm 0.09$ |
| 24 | $1^-$ (GDR) | $0.077 \pm 0.038$ |
| Total | | $4.71 \pm 0.31$ % |

No guidance on $B_n$ for these states – assumed same as ground state but with 50% uncertainty

# $^{27}$Al – alloy corrections

Correction method:

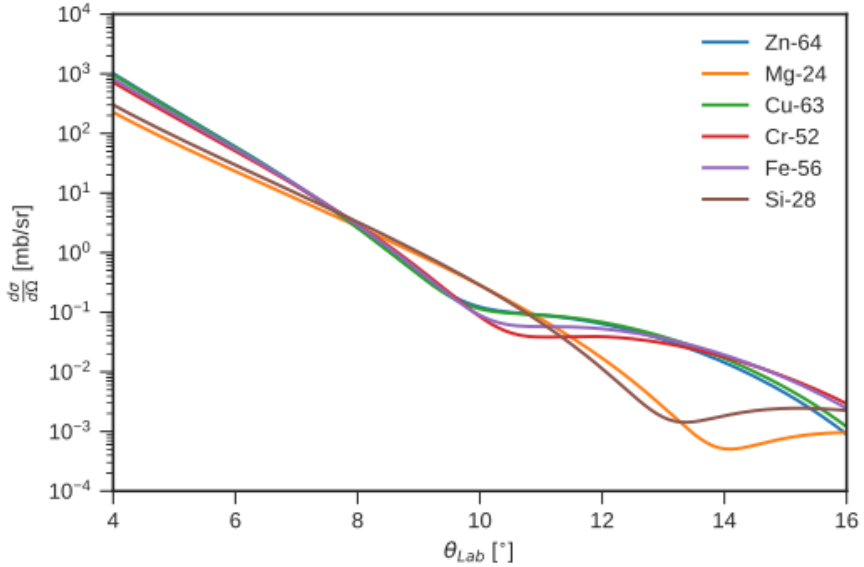
- Considered most abundant isotopes of Zn, Mg, Cu, Cr, Fe, and Si
- Considered only elastic scattering

- Dilutions: use distorted-wave cross sections from Horowitz and Lin for Zn, Mg, Cu, Cr, Fe, Si. For Mn and Ti, used Born approximation cross-section model, with Fourier-Bessel form factor fit.

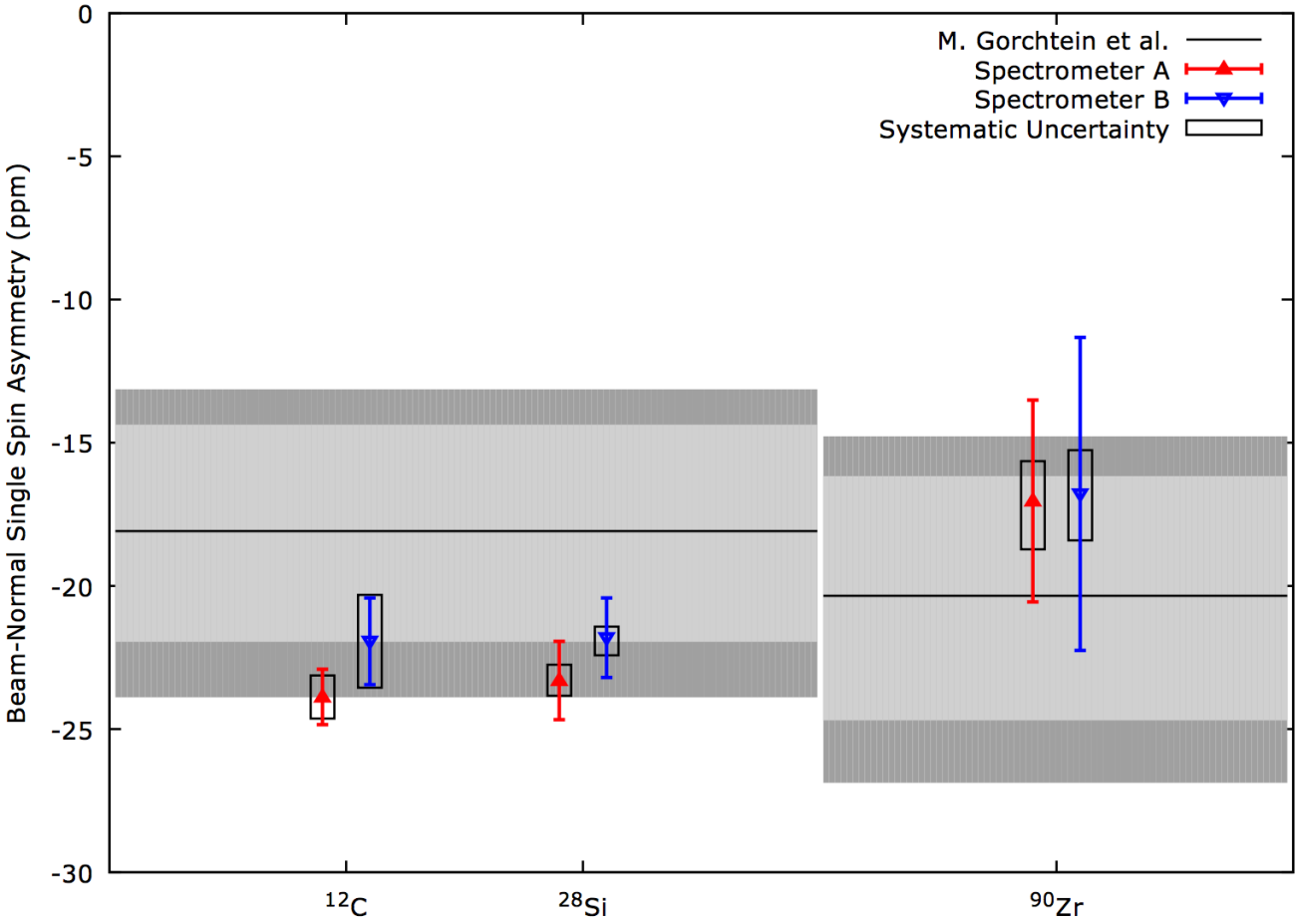
Asymmetries:
Assumed A/Z scaling of proton $B_n$ measured value at these kinematics

# $^{27}$Al – alloy corrections

| Element | Background fraction ($f_i$) (%) | Asymmetry ($B_i$) (ppm) |
|---|---|---|
| Zn | $2.375 \pm 0.249$ | $-11.0 \pm 3.3$ |
| Mg | $2.088 \pm 0.219$ | $-10.3 \pm 3.1$ |
| Cu | $0.683 \pm 0.073$ | $-11.1 \pm 3.3$ |
| Cr | $0.100 \pm 0.011$ | $-11.0 \pm 3.3$ |
| Si | $0.080 \pm 0.009$ | $-10.2 \pm 3.0$ |
| Fe | $0.054 \pm 0.006$ | $-10.9 \pm 3.3$ |
| Mn | $0.018 \pm 0.009$ | $-11.1 \pm 3.3$ |
| Ti | $0.014 \pm 0.007$ | $-11.0 \pm 3.3$ |
| net Alloy | $5.41 \pm 0.34$ | $-10.7 \pm 2.0$ |



# Other Nuclear BNSSA results: Mainz/A1

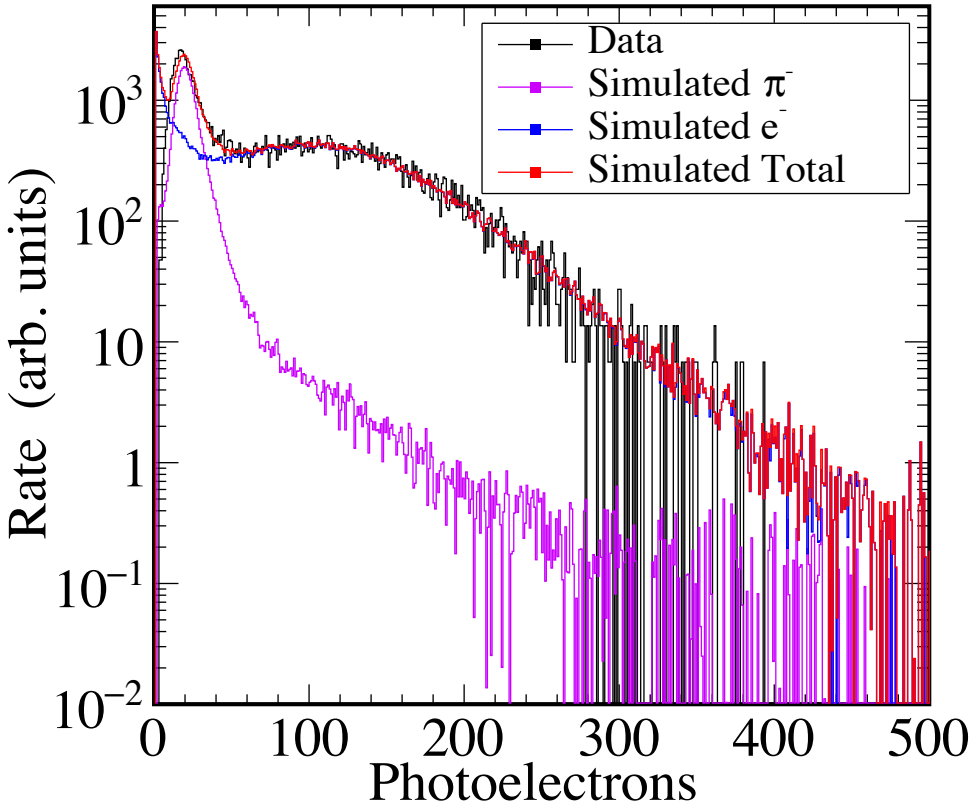



Esser et al.
Phys. Lett. B 808, 135664 (2020).

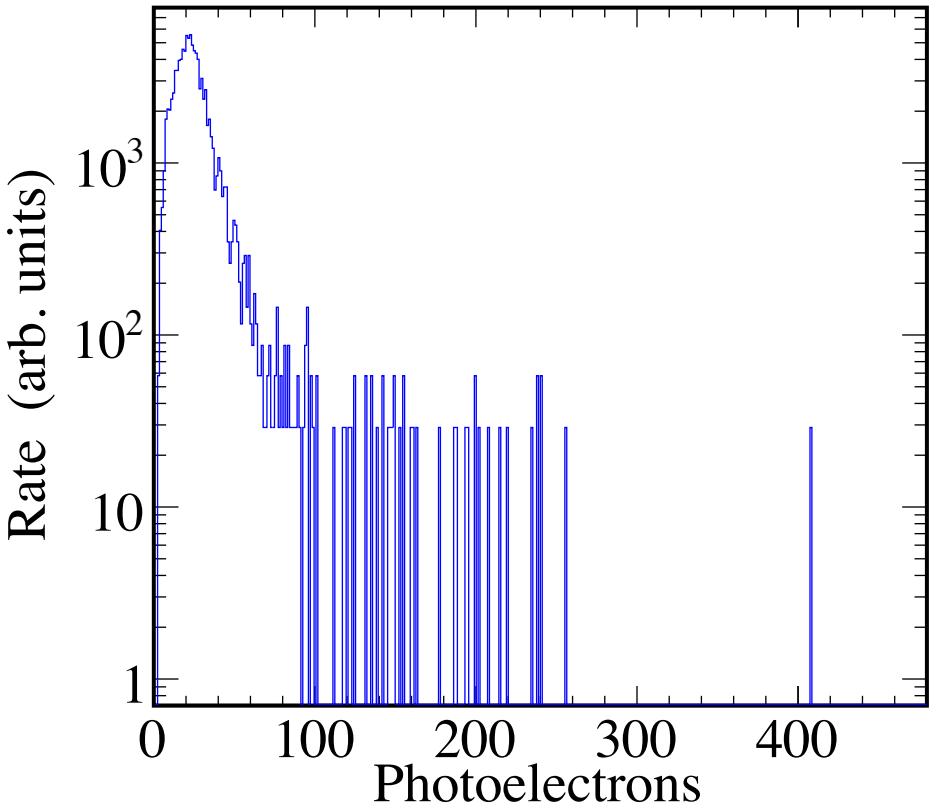
Theory:
Gorchtein & Horowitz

Reasonable agreement with theory – no significant A dependence.
No sign of cause of $^{208}$Pb puzzle.

# Proton at high W: Pion Identification  Inelastic measurement




Typical “unblocked” detector



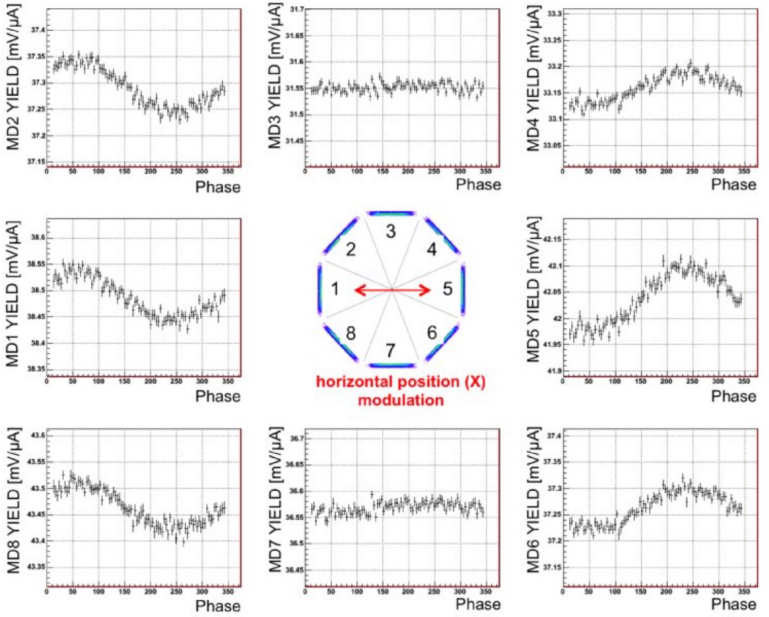

”blocked” (pion) detector

# $^{12}$C and $^{27}$Al: Helicity-Correlated Beam Parameter Sensitivities

$$A_{beam} = \sum_i \frac{\partial A}{\partial \chi_i} \Delta \chi_i$$

where $i$ runs over x,y,x'(angle),y'(angle), and energy.

Need to determine the sensitivities: $\frac{\partial A}{\partial \chi_i}$



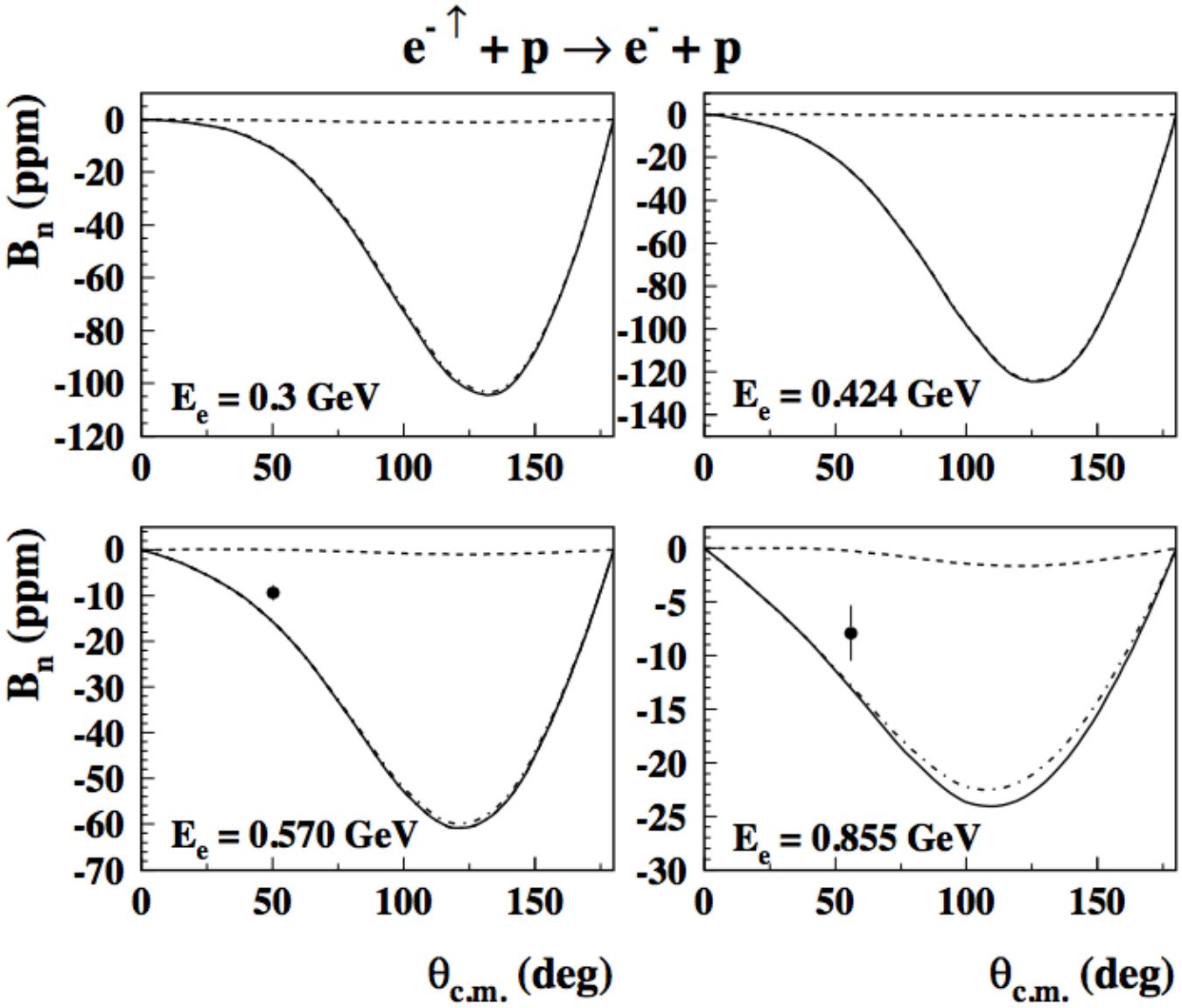

Natural: Linear regression of natural beam motion

Driven: Drive sinusoidal beam oscillations with large amplitude

| Data Set | $A_{exp}$ (raw) (ppm) | $\chi^2$/dof | $A_{exp}$ (regressed) (ppm) | $\chi^2$/dof | regressed-raw (ppm) |
|---|---|---|---|---|---|
| $^{12}$C Horizontal | $-8.57 \pm 0.61$ | 0.80 | $-8.50 \pm 0.61$ | 0.81 | 0.07 |
| $^{27}$Al Vertical #1 | $-9.32 \pm 0.61$ | 1.16 | $-9.91 \pm 0.61$ | 1.16 | -0.59 |
| $^{27}$Al Horizontal | $-8.54 \pm 0.51$ | 1.14 | $-8.60 \pm 0.50$ | 1.17 | -0.06 |
| $^{27}$Al Vertical #2 | $-8.02 \pm 0.74$ | 0.62 | $-8.73 \pm 0.73$ | 0.64 | -0.71 |
| $^{27}$Al average | $-8.69 \pm 0.34$ | | $-9.04 \pm 0.34$ | | -0.35 |

# Previous BNSSA results on proton – Forward angles

Calculation of Pasquini & Vanderhaeghen: *Phys Rev C* 70, 045206 (2004)

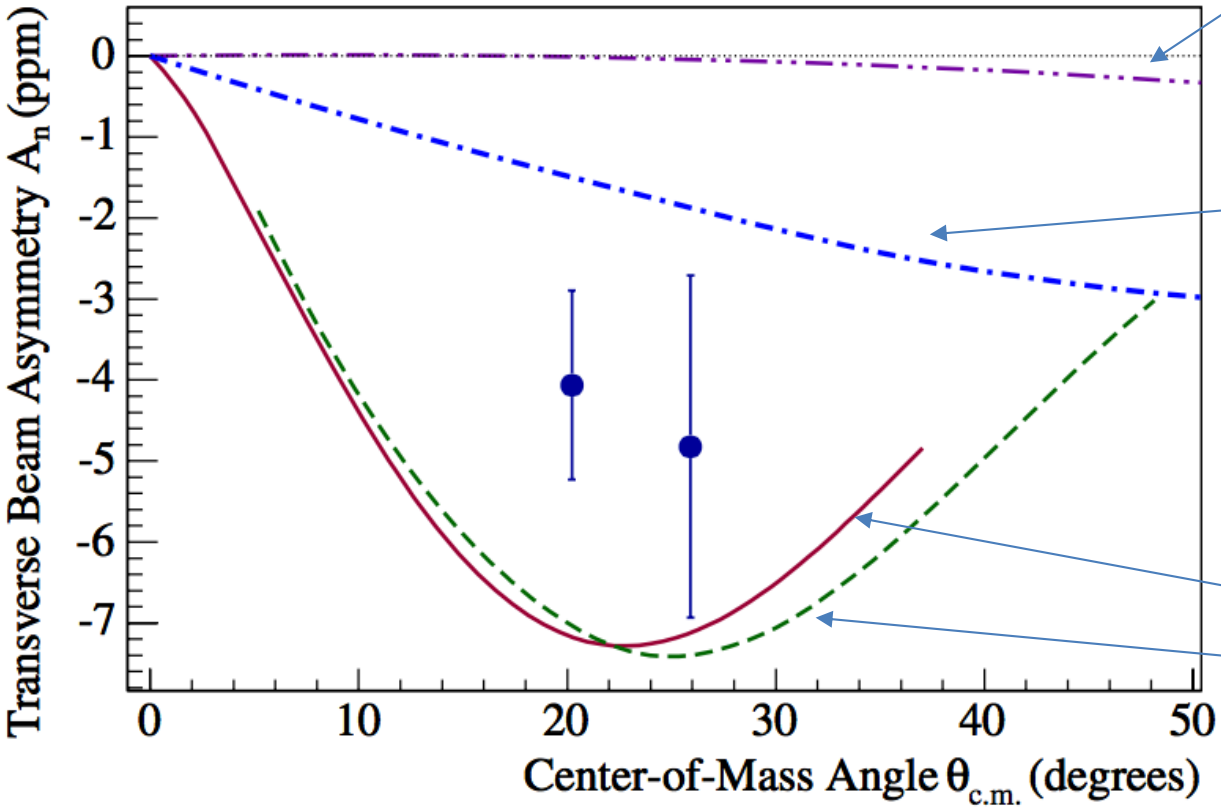



Dashed lines:
elastic
intermediate state
contribution

Solid lines:
Total

PVA4: Maas *et al.*
*PRL* **94,** 082001 (2005)

# Previous BNSSA results on proton – Forward angle




Elastic intermediate state only

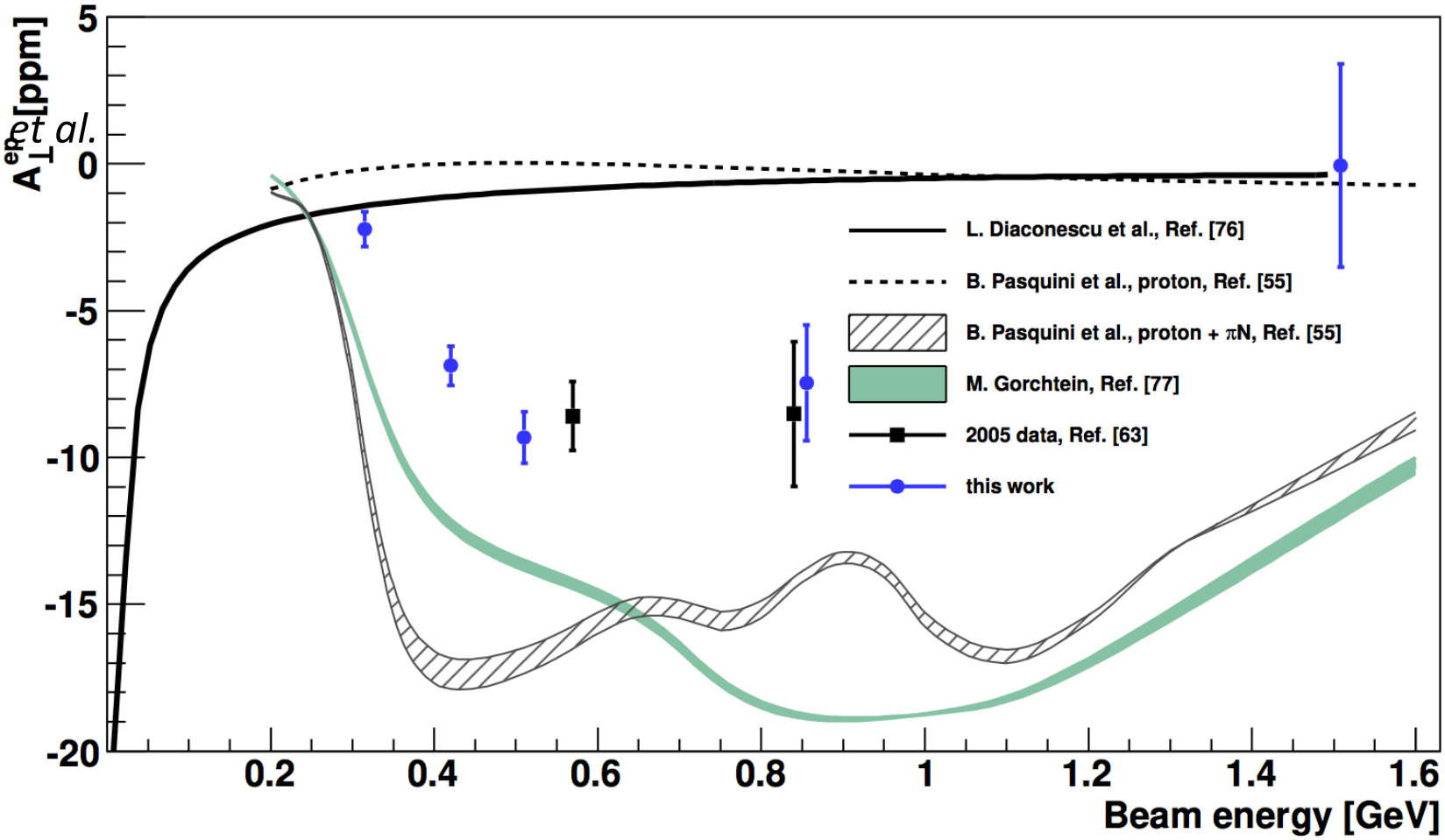
Include $\pi N$ intermediate states (Pasquini & Vanderhaeghen)

Optical theorem and full photoabsorption $\sigma$ (Gorchtein; Afanasev and Merenkov)

G0: Armstrong *et al.* *PRL* 99, 092301 (2007)

# Previous BNSSA results on proton – Forward angles

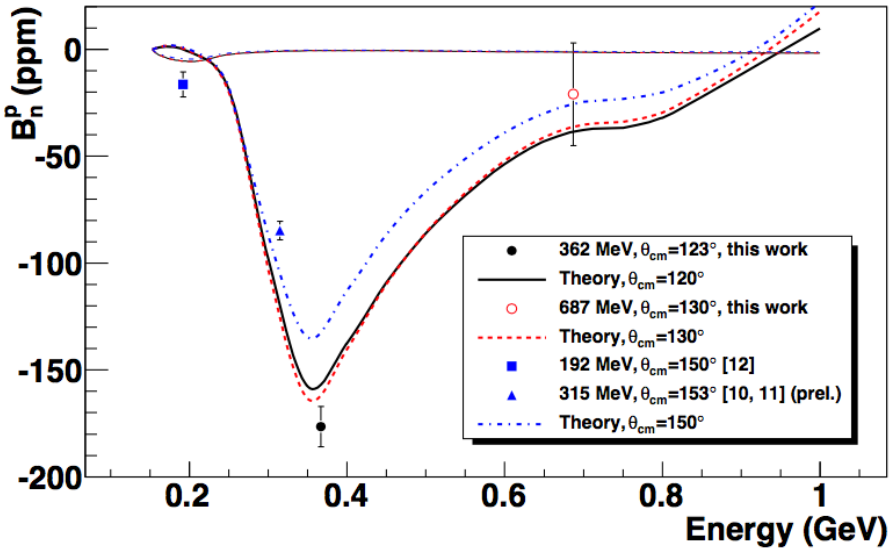
Calculations: Pasquini & Vanderhaeghen: *Phys Rev C* 70, 045206 (2004)
Gorchtein *Phys Rev C* 73, 055201 (2006)
Disconescu & Ramsey-Musolf *Phys. Rev. C* 70, 054003 (2004)




*et al.*

PVA4: Maas *et al.* *PRL* 94, 082001 (2005)
: Guo *et al.* *PRL* 124, 122003 (2020)

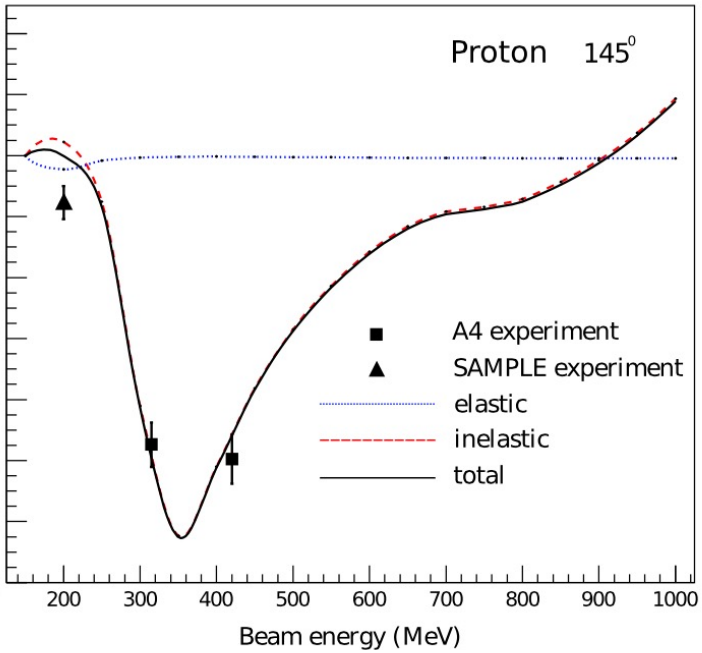
# BNSSA results on proton – Backward angles

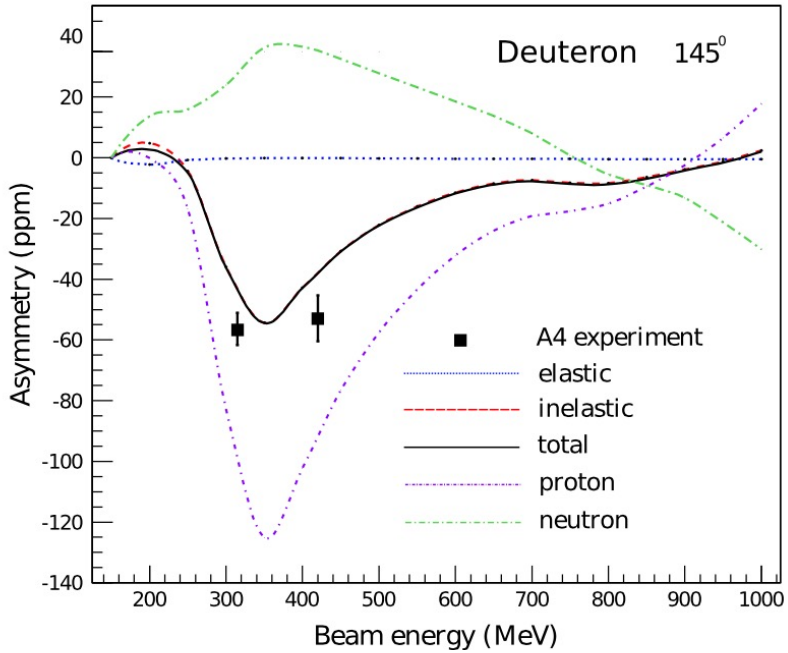



G0: Androic *et al. PRL* 107 (2011)022501

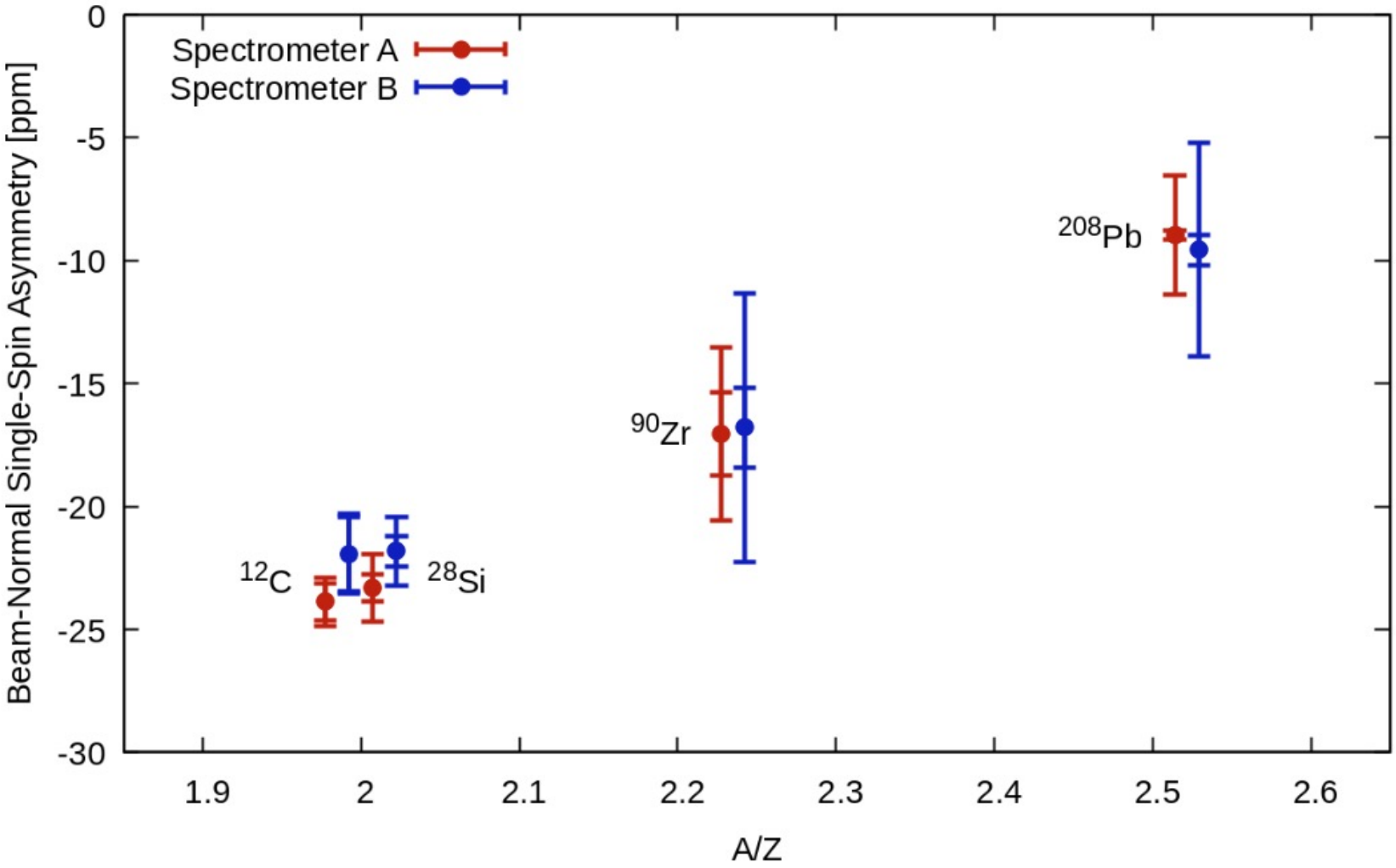
Model: Pasquini & Vanderhaeghen

PVA4: Balaguer Rios *et al.* *PRL* 119, 012501 (2017)



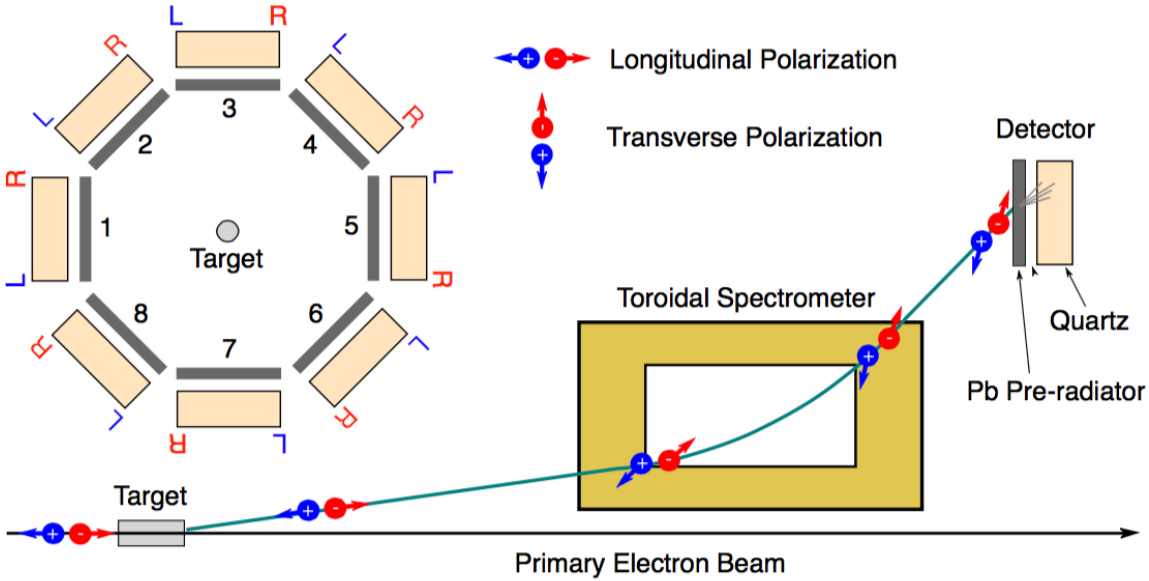



# Mainz/A1 results on $^{208}$Pb




Esser *et al.* PRL 135,232502 (2025)

# Secondary Scattering




- Spin precession of scattered $e^-$ in magnet: some transverse polarization $P_T$
- $P_T$ analyzed by scattering in Pb pre-radiators → transverse asymmetry in detectors: opposite sign in the two PMTs ( $R$ & $L$ ) in each detector

  $A_{diff} = A_R - A_L$ Parity Signal = $\frac{A_R + A_L}{2}$ ∴ Effect cancels to first order

- Analyzing power in Pb:
  1. Beam-normal single spin asymmetry (high energy): $2\gamma$ exchange
  2. Mott scattering (low energy in shower) → dominant effect

  $A_{diff}$ is of same scale (hundreds of ppb) as $A_{PV}$

# Beam-Normal Single Spin Asymmetry

Beam-Normal Single-Spin Asymmetry $B_n$

- transversely-polarized electron beam, unpolarized target
- parity-conserving asymmetry, time-reversal odd

$= 0$ in the single-photon exchange (Born) approximation

- At very low beam energies, this is known as the Mott asymmetry

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\Im(T^{1\gamma *} \cdot AbsT^{2\gamma})}{|T^{1\gamma}|^2} \approx \mathcal{O}(\alpha \frac{m}{E}) \approx \text{ppm}$$

$$T_{fi} = \quad T^{1\gamma}_{fi} \quad + \quad T^{2\gamma}_{fi} \quad + \cdots$$

$\mathcal{O}(\alpha_{em})$ $\mathcal{O}(\alpha^2_{em})$

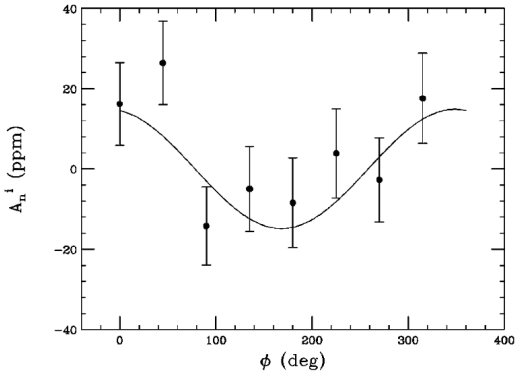
Generates azimuthal asymmetry variation: $A_{\text{exp}}(\phi) \approx B_n \vec{P} \cdot \hat{n}$

$$\hat{n} = (\vec{k} \times \vec{k'})/(|\vec{k} \times \vec{k'}|)$$

$\vec{k}(\vec{k'})$: Incoming(outgoing) electron

First observation of $B_n$

SAMPLE: Wells et al.
PRL 63, 064001 (2001)



# Aside: Nomenclature

Unfortunately, little consistency on what to **name** this observable!

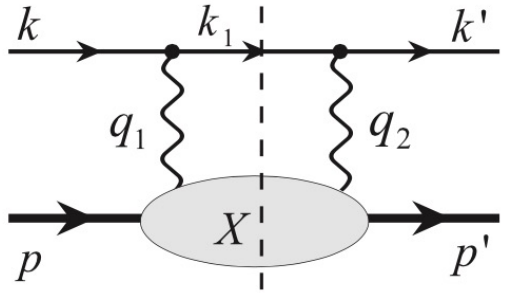
- "Vector Analyzing Power" : SAMPLE , Cooper & Horowitz, E158
- "Transverse Beam Asymmetry" : HAPPEX/PREx
- "Single-Spin Beam Asymmetry" : Afanasev & Merenkov
- "Transverse Beam Spin Asymmetry" : G0 forward, PVA4
- "Beam Transverse Single Spin Asymmetry" : PVA4
- "Beam Normal Spin Asymmetry" : Gorchtein, Vanderhaeghen, PVA4
- "Beam-Normal Single-Spin Asymmetry" : G0 backward, Qweak, Carlson, PVA4, A1

- **Symbols:** $A_n$ , $A_t$ , $A_\perp$ , $A_y$ , $B_n$

According to the Madison convention (1971) the symbol should be $A_y$ …. but this has been recently used for the target-normal single-spin asymmetry *(aargh!)*

# Why BNSSA is of interest

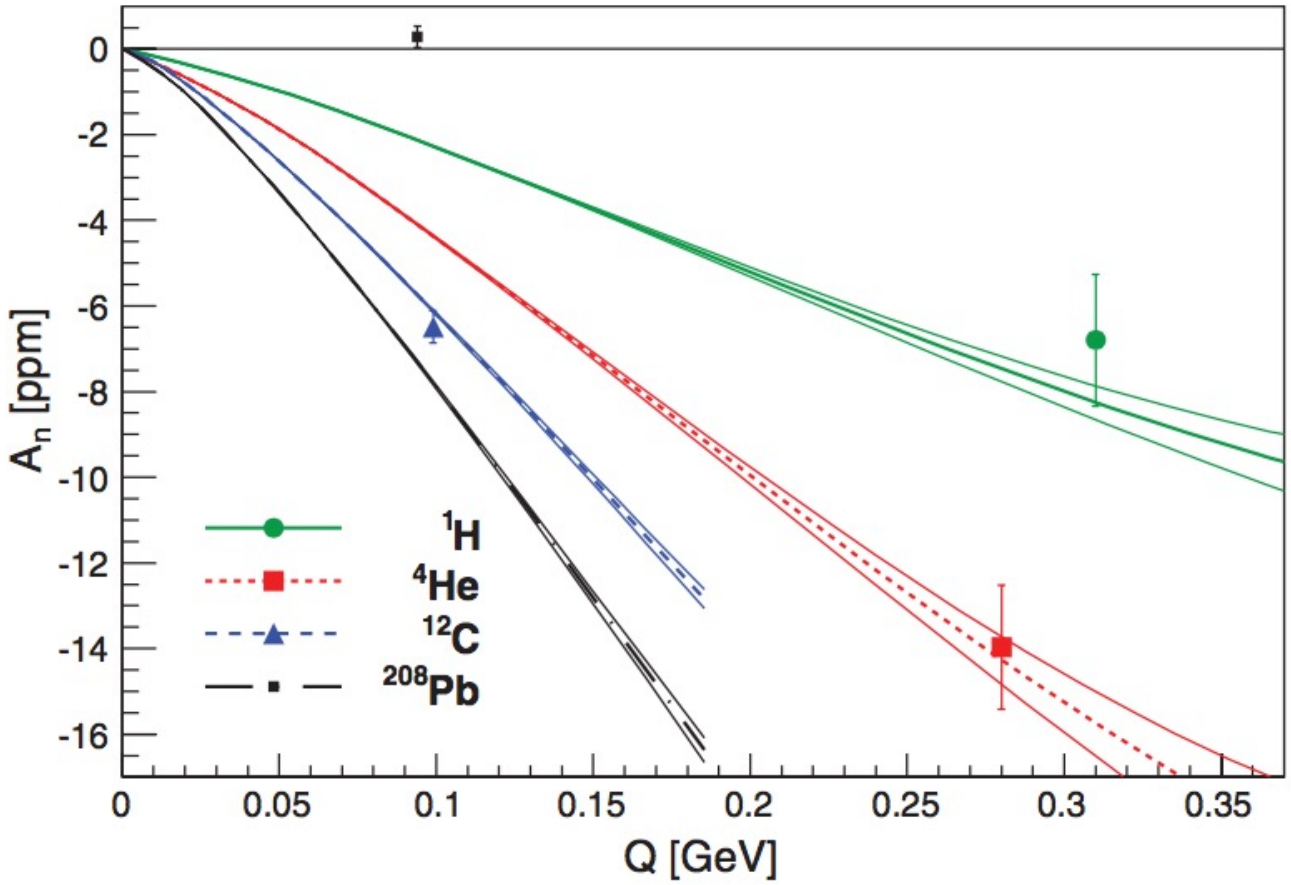
1. Understanding two-photon exchange on dispersion-theoretical framework:
   i) effects on $G_E^p/G_M^p$ are from real part of $T^{2\gamma}$
   ii) $B_n$ depends on imaginary part of $T^{2\gamma}$
   - both require wide range of hadronic intermediate states:




   - Models can be tested by both kinds of observables.

*1.* $B_n$ can cause a false asymmetry in precision parity-violating electron scattering measurements if apparatus doesn't have perfect symmetry and if beam polarization is not perfectly longitudinal.

# BNSSA on nuclei – PREx 1/HAPPEx



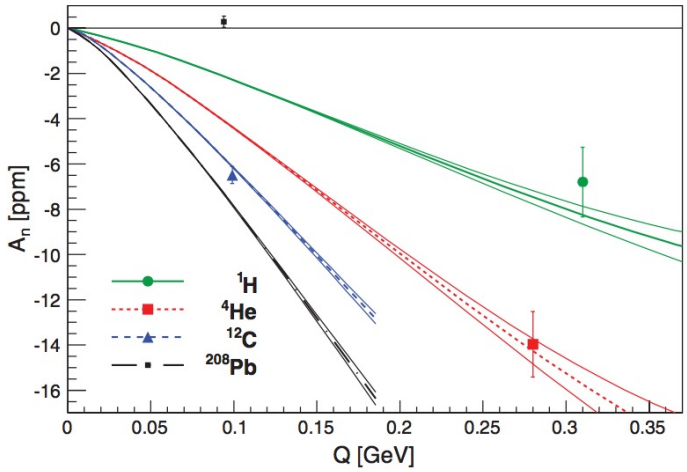

PREx-1/HAPPEx: Abrahamyan *et al.* *PRL* 109,192501 (2012)
Model: Gorchtein & Horowitz *Phys. Rev. C* 77, 044606 (2008)

Fine agreement for proton, $^4$He, $^{12}$C – violent disagreement for $^{208}$Pb Puzzle!

# BNSSA on nuclei – Gorchtein & Horowitz model

- Dispersion relations, generalized to nuclear targets

- Elastic intermediate state: nuclear elastic form factor
- Inelastic intermediate states:
  applicable for low $Q^2$
  use optical model $C_0$: energy-weighted integral of photoabsorption $\sigma$ – contribution scales as A/Z.




$$B_n \sim C_0 \log\left(\frac{Q^2}{m_e^2 c^2}\right) \frac{F_{\text{Compton}}(Q^2)}{F_{\text{ch}}(Q^2)}$$

Additional nuclear target dependence could arise in model:

- Terms not enhanced by large log

- Compton slope parameter: $\frac{F_{\text{Compton}}(Q^2)}{F_{\text{ch}}(Q^2)}$

Would like to study $B_n$ for range of nuclei, ideally between $^{12}$C and $^{208}$Pb, especially to gain insight into $^{208}$Pb puzzle