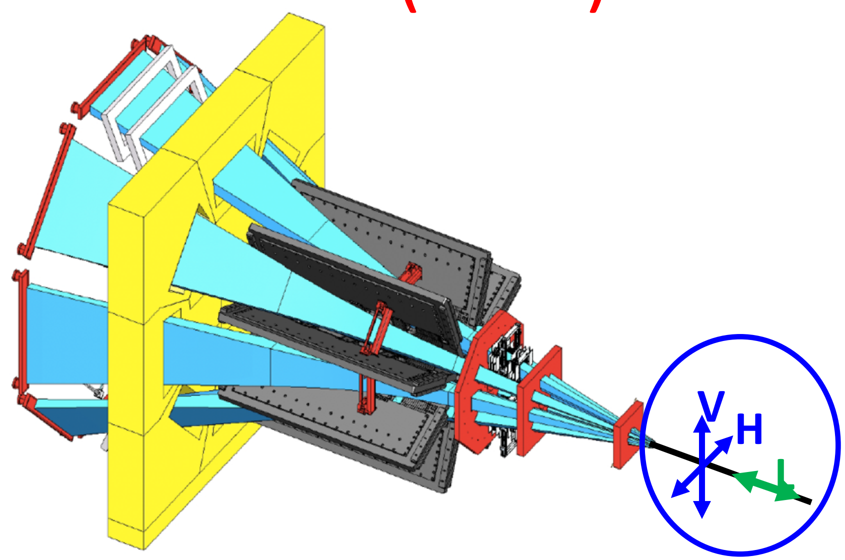
Latest Ancillary Physics Results from Qweak

- Primary result reminder (just 1 slide)
- Final Results for ^{27}Al PV Elastic A_{PV} (Arex)
  - R_n, R_n-R_p, F_{wk}, R_{wk}, R_{wk}-R_{ch}
- Final Results for ^{12}C & ^{27}Al PC BNSSA (brief)



Greg Smith
Jefferson Lab

Hall C Winter Collaboration Meeting
Feb 17, 2022

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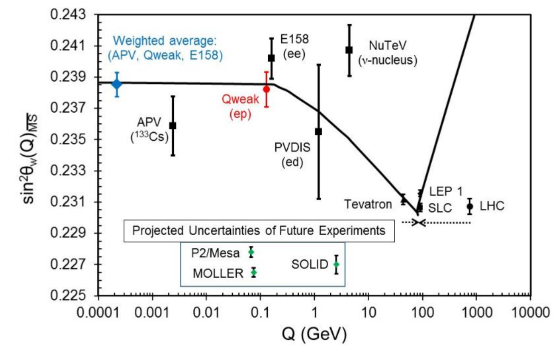
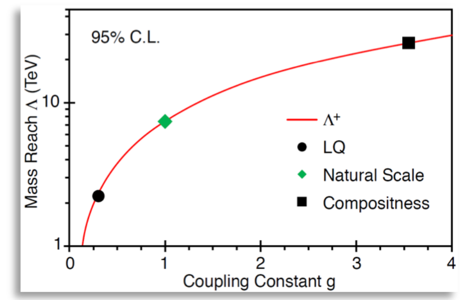
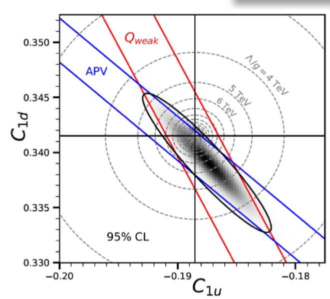
Qweak Primary Results:

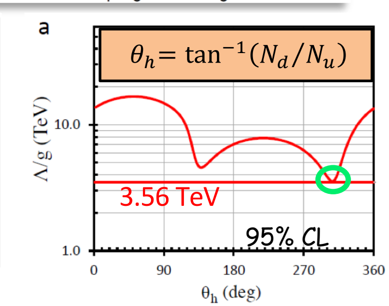
- Q_{weak} Expt. msrd ep $A_{PV} = -226.5 \pm 9.3$ ppb @ $Q^2 = 0.0248$ GeV^2
  - Determined $Q_W(p) = 0.0719 \pm 0.0045$ for the 1st time, < 0.2 σ from SM
  - $\sin^2\theta_W = 0.2383 \pm 0.0011$ (MS-bar) (0.46%)
    - Avg(APV, E158, Q_{weak}) = 0.23861 ± 0.00077 (0.32%)
  - Mass reach Λ = 26.6 TeV ($g^2 = 4\pi$=compositeness, 95% CL)
    - Λ = 2.3 TeV (uud, $g^2 = 4\pi\alpha$=leptoquarks, 95% CL)
    - Λ/g = 7.5 TeV (proton, ie uud, 95% CL)
    - Λ/g = 3.6 TeV (*flavor-independent*, 95% CL)
  - Combined with APV: vector quark couplings C_{1u} & C_{1d}





- Publications:
  - Commissioning result: PRL 111, 141803 (2013)
  - Apparatus: NIM A781, 105 (2015)
  - Final Q_w^p result & SM test: Nature 557, 207 (2018)
  - Q_w^p cookbook & perspectives: ARNS 69, 191 (2019)
  - Layman's description: NPN 29, 15 (2019)





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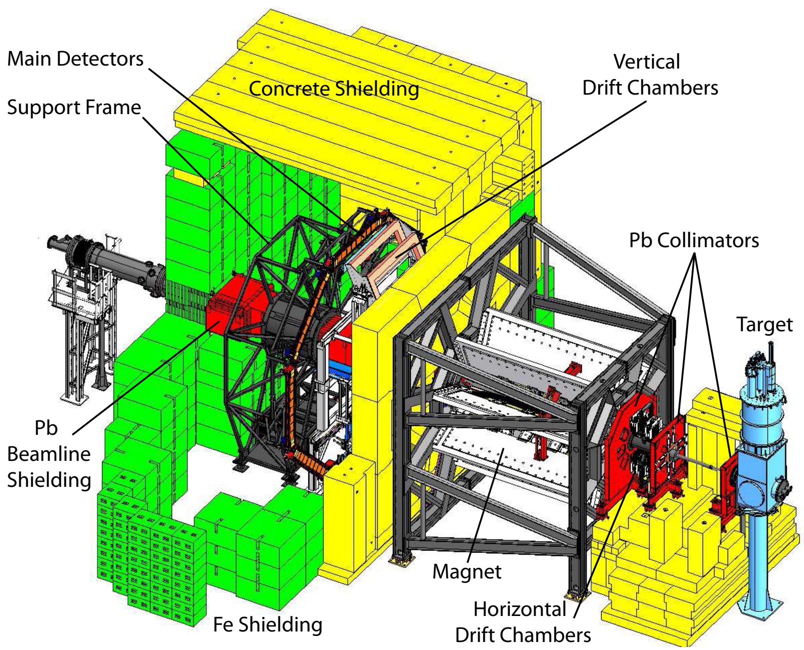
The Elastic PVES ^{27}Al Experiment ("Arex")

arXiv:2112.15412 **[nucl-ex]Submitted to PRL**
Foundation: K. Bartlett PhD thesis, 2018 W&M

- Target:
  - ^{27}Al Alloy (7075), 4.2% X_0 (3.7 mm thick)
  - Located in z at DS end of 35 cm long Qweak LH2 target
- Beam:
  - 1.16 GeV, 65 µA, P=88.8% ± 0.6%
- Spectrometer:
  - $Q^2 = 0.02357 \pm 0.0001$ GeV^2, $\langle\theta_{lab}\rangle = 7.61°$, $5.8° < \theta_{lab} < 11.6°$



Elastic PVES on ^{27}Al: Motivation

- Aluminum A_{PV} msrd to correct for (~20%) tgt-window bkg in Q_w^p
- Al data now further analyzed to isolate the elastic ^{27}Al A_{PV} from non-elastic & other contributions:

$$A_{\rm PV} = \frac{\sigma_+(\theta) - \sigma_-(\theta)}{\sigma_+(\theta) + \sigma_-(\theta)} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha Z\sqrt{2}} \frac{F_{\rm W}(Q^2)}{F_{\rm EM}(Q^2)}$$

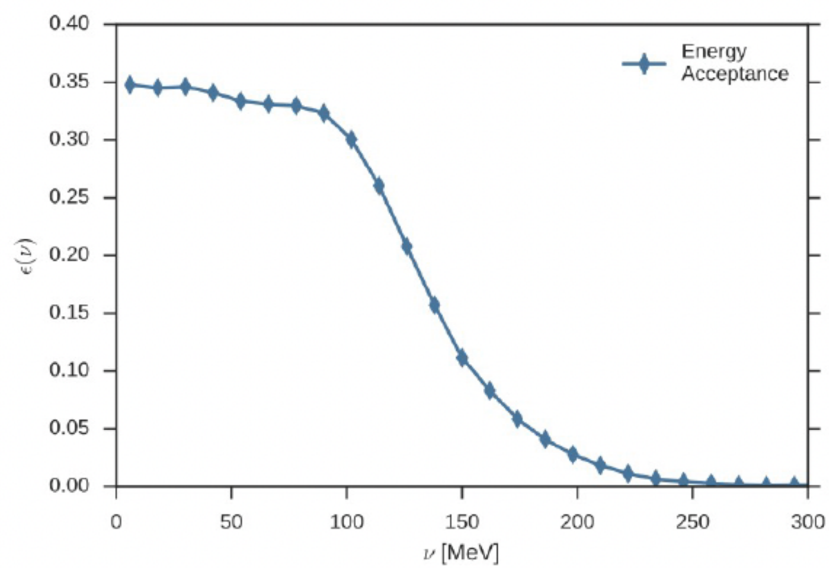
  - A>1 PVES: only ^{12}C (Bates), ^{4}He (Happex), ^{208}Pb (Prex) (soon ^{48}Ca too)
  - Comparing theory to ^{27}Al A_{PV} provides sanity check on Q_w^p bkg corrections
  - Elastic ^{27}Al A_{PV} also provides F_{wk}^{27Al}, $R_{n,wk}^{27Al}$ & skin thicknesses
- We expect n-skin ~0 in a light N~Z nucleus
  - serves as test case for the EW technique used to get R_n in PREX & Crex
  - Important given tension noted in literature between Prex EW and non-EW results as well as recent LIGO/Virgo & NICER results

EW vs non-EW Tension

- PVES (EW) ^{208}Pb Prex: R_{n-p}= 0.283 ± 0.071 fm (PRL 126, 172502 (2021))
- Non-EW ^{208}Pb results: R_{n-p}= 0.18 ± 0.027 fm (Tsang et al, PRC86, 015803 (2012))
  – 2012 ^{208}Pb world avg: Elastic $\vec{p}$A on Ni&Pb isotopes, 26 $\bar{p}$A decays, EDP (electric dipole polarizability) & PDR
    - EDP: electric dipole field excites the GDR, the collective motion of p's against n's, and vibrations of the N=Z symmetric core against the n-skin
    - Uncertainty floor of ± 0.05 fm (2* EDP error) was imposed!!!
    - Error reduces considerably if post-2012 data included
- J. Piekarewicz, Phys. Rev. C **104**, 024329 (2021) Abstract (paraphrased):
  – **"Conclusions:** *The R^{208}_{skin} extracted from PVES and the EDP are two of the cleanest experimental tools used to constrain the symmetry energy. However, the recent PVES value of R^{208}_{skin} that suggests a fairly stiff symmetry energy stands in stark contrast to the conclusions derived from the EDP. At present, I offer no solution to this dilemma."*

Analysis Challenges

- Target is not pure ^{27}Al
  - Must correct for 8 other elements, total dilution 5.4%
- Spectrometer was designed for H_2
  - has a large momentum acceptance 150 MeV wide
  - Accepts non-elastic processes which dilute msrd A_{PV}
  - Have to also correct for
    - Nuclear excited states
    - GDR
    - Inelastic (N → Δ)
    - Quasielastic events



Excited State Asymmetries (W.u.-hoo!)

- Nominally, Born approx.: $A_{PV} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha\sqrt{2}} \left(Q_W^p + \frac{N}{Z} Q_W^n \right) \approx 2.5 \text{ ppm}$
  - ***Sign*** of A_{PV} depends on whether state is isoscaler/collective (+) or isovector (+ or -)
  - Shell model: ^{27}Al (J^π=5/2$^+$ g.s.) = 1d5/2 p-hole coupled to the 0$^+$, 2$^+$, and 4$^+$ states in ^{28}Si
  - Weisskopf units (**W.u.'s**) (~ E2 transition strength):
    - ~ # of nucleons participating in transition
    - W.u. $\lesssim$ 1 → single-particle (isovector) state
    - W.u. > 1 → isoscalar/collective state
  - Wu > 1 (or excited in ΔT=0 (α,α) transitions ➔ A_{PV} = +2.5 ppm ± 50% error
  - Wu $\lesssim$ 1 (which could be p or n s.p. states) ➔ A_{PV} = +2.5 ppm ± 200% error
    - to cover potential contributions to A_{PV} of the opposite sign
  - Results:

$$f_{\text{nucl}}: \quad 3.83 \pm 0.23\ \%$$
$$A_{\text{nucl}}: \quad 2.58 \pm 1.40\ \text{ppm}$$

E_ex (MeV)	f_i	Jpi	E2 W.u.	
0.844	0.27	1/2+	7.86	isoscalar
1.014	0.41	3/2+	7.8	isoscalar
2.211	1.35	7/2+	15	isoscalar
2.735	0.19	5/2+	8.7	isoscalar
2.990	0.93	3/2+	0.6	s.p.
4.580	0.06	7/2+	0.31	s.p.
4.812	0.09	5/2+	1.7	s.p.
5.430	0.17	9/2+	0.64	s.p.
5.668	0.08	9/2+	0.56	s.p.
7.228	0.18	9/2-	(alpha,alpha)	isoscalar
7.477	0.1	7/2-	(alpha,alpha)	isoscalar

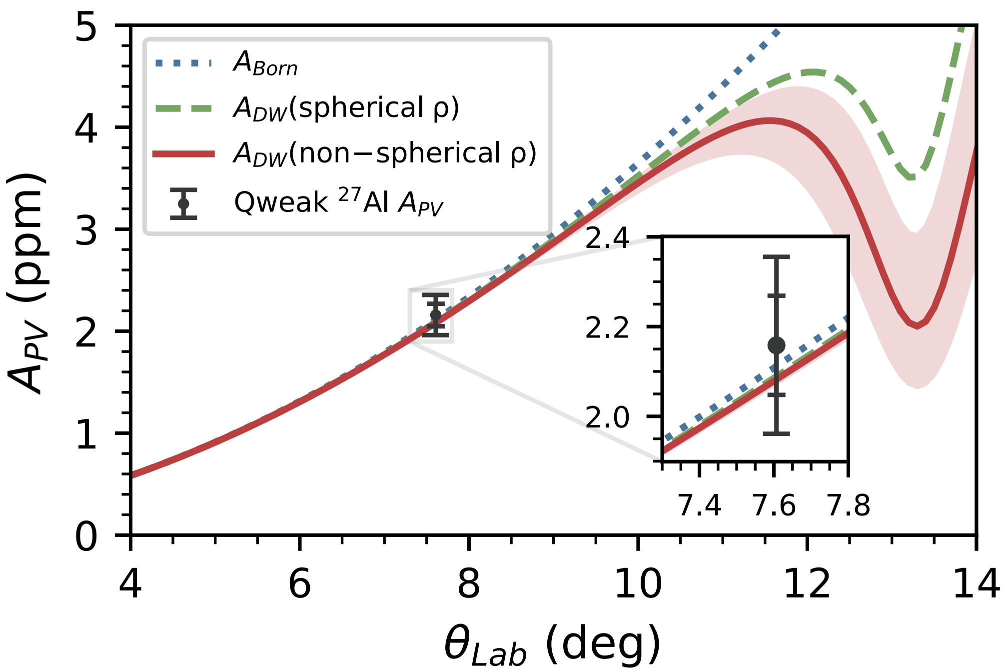
References:

- M. Lickert, et al, "*The Structure of 27Al*", Z.Phys. A331, 409 (1988)
- M. Basunia, Nuclear Data Sheets 112, 1875 (2011)

PVES Elastic 27Al Asymmetry Result

DWBA Curves: C.J. Horowitz, PRC 89, 045503 (2014)

PhD thesis: Kurtis Bartlett W&M 2018



$$A_{\mathrm{msr}} = A_{\mathrm{raw}} + A_{\mathrm{BCM}} + A_{\mathrm{reg}} + A_{\mathrm{BB}} + A_{\mathrm{L}} + A_{\mathrm{T}} + A_{\mathrm{bias}}$$

$$A_{\mathrm{PV}} = R_{\mathrm{tot}} \frac{A_{\mathrm{msr}}/P - \sum_i f_i A_i}{1 - \sum_i f_i};$$

A_{PV} = 2.16 ± 0.19 ppm
[± 0.11 (stat) ± 0.16 (syst)]

Q^2 = 0.02357 ± 0.00010 GeV^2
<θ_{lab}> = 7.61° ± 0.02°
<E_{lab}> = 1.157 GeV

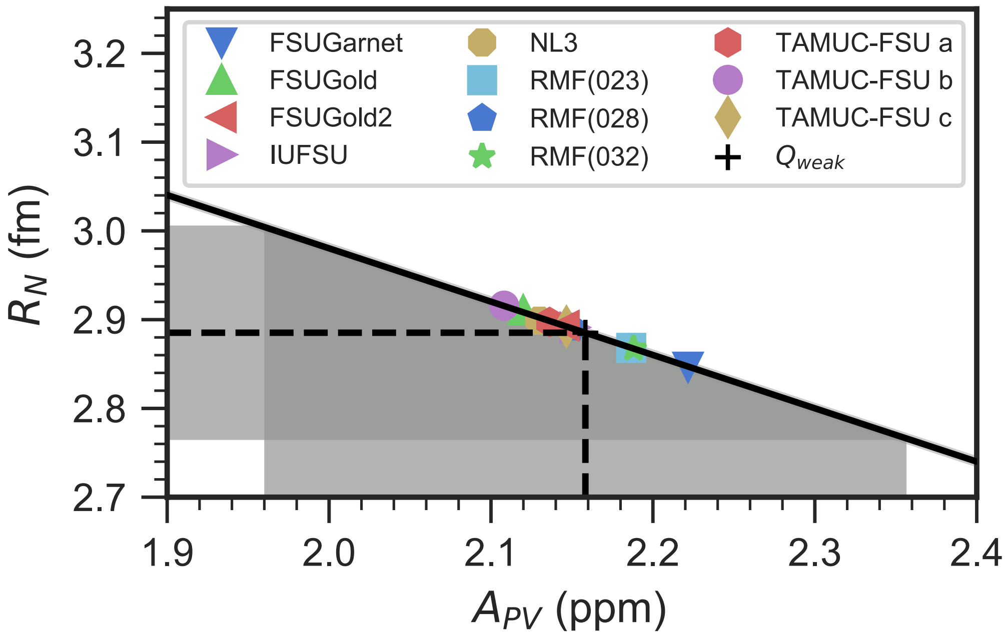
Dominant Systematics (ΔA/A (%)):

- f_{QE} 5.0%
- A_{QE} 2.4%
- A_{nucl} 3.6%
- A_{inel} 2.6%
- A_{alloy} 2.1%

Total systematics: 7.6%
Statistics: 5.1%

<u>Agreement</u> of predictions with our A_{PV} result is <u>good</u>!

PVES Elastic 27Al Observables



$$R_n = (-0.6007 \pm 0.0002)\frac{A_{\mathrm{PV}}}{\mathrm{ppm}} + (4.1817 \pm 0.0011)\ \mathrm{fm}$$

Correlation coef 0.997

Many-models correlation plot from
C. Horowitz, F. Fattoyev & Z. Lin

RMF models tuned to reproduce binding energies, charge radii, GDR strengths, etc. in different nuclei

A_{PV} = 2.16 ± 0.19 ppm

R_n = 2.89 ± 0.12 fm

R_n - R_p = -0.04 ± 0.12 fm

Using

$$R_p = \left(R_{\mathrm{ch}}^2 - \langle r_p^2 \rangle - \frac{N}{Z}\langle r_n^2 \rangle - \frac{3}{4m_N^2} - \langle r_{\mathrm{so}}^2 \rangle \right)^{1/2}$$
$$= 2.925 \pm 0.007\ \mathrm{fm},$$

with
R_{ch} = 3.035 ± 0.002 fm,
r_p = 0.8751 ± 0.0061 fm,
$\langle r_n^2 \rangle$ = −0.1161 ± 0.0022 fm^2,
& $\langle r_{so}^2 \rangle$ = −0.017 fm^2

Test case using EW method to get R_n on ^{27}Al passes!

PVES Elastic 27Al Weak Form Factor

$$A_{\rm PV} = \frac{\sigma_+(\theta) - \sigma_-(\theta)}{\sigma_+(\theta) + \sigma_-(\theta)} \approx \frac{G_F Q^2 Q_W}{4\pi\alpha Z\sqrt{2}} \frac{F_{\rm W}(Q^2)}{F_{\rm EM}(Q^2)}$$

- Measure elastic ^{27}Al A_{PV} = 2.16 ± 0.19 ppm
- Calculate $Q_W(^{27}\text{Al})$ = -12.92 ± 0.014
  - using fully radiated formula in PDG EW Review
- Calculate $F_{EM}(Q^2\text{=0.02357 GeV}^2)$ = 0.384 ± 0.012
  - Following K. Mesick (nee Meyers) thesis:
    - used method described by Stovall, Vinciguerra, & Bernheim, NPA 91, 513 (1967)
    - checked to 3% using xsec/FF data from Li, Yearian & Sick, PRC 9, 1861 (1974)
- Plug in to Born (tree-level) expression to get

$F_W(^{27}\text{Al}, Q^2\text{=0.02357 GeV}^2)$ = 0.393 ± 0.038

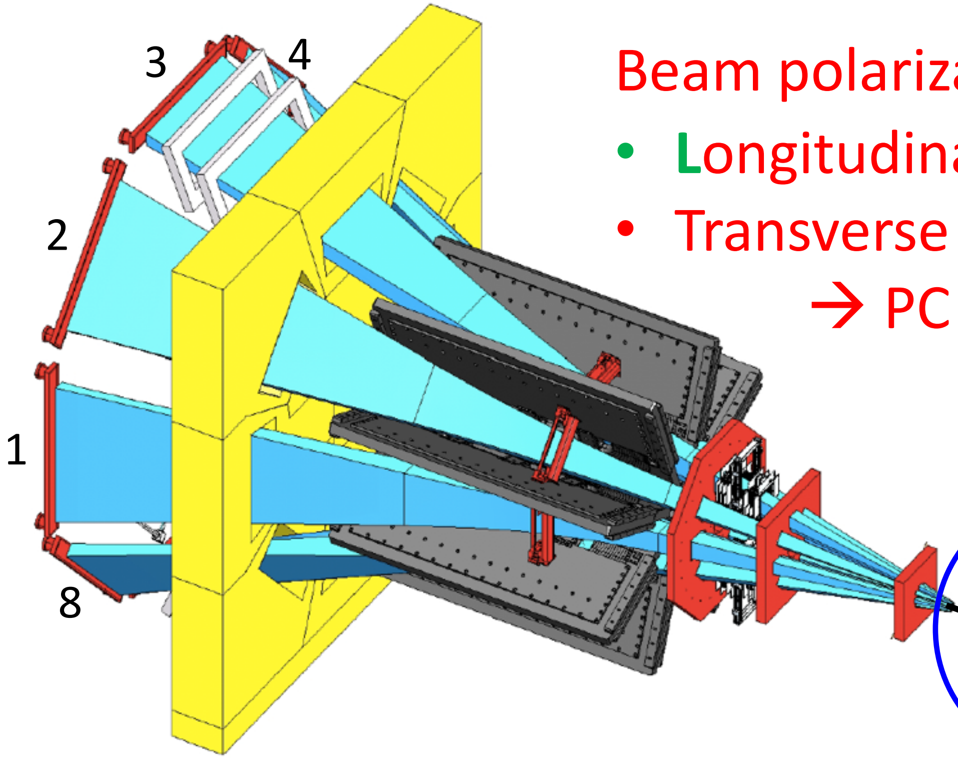
Born (tree-level) for weak Obsrvbles

- DWBA accurately predicts our msrd A_{PV}
- We have a 9.1% result for our ^{27}Al A_{PV}
  - radiative effects typically ~1%
  - Note: our determination of $Q_w(^{27}Al) = -12.92 \pm 0.01$ fully radiated
- Z=13 means less Coulomb distortion ($\propto$ Z)
  - relative to ^{208}Pb (Z=82)
- Followed Koshchii et al, PRC 102, 022501 (2020), "Weak charge & weak radius of ^{12}C":

TABLE III. Derived ^{27}Al Observables

Observable	Value	Uncertainty	Units
R_n	2.89	0.12	fm
$R_n - R_p$	-0.04	0.12	fm
→ $F_{wk}(Q^2 = 0.0236\ \mathrm{GeV}^2)$	0.393	0.038	
$\Delta = ZA_{PV}/(A_0 Q_W) - 1$	0.025	0.094	
→ $R_{wskin} = -3\Delta/(Q^2 R_{ch})$	-0.04	0.15	fm
→ $R_{wk} = R_{wskin} + R_{ch}$	3.00	0.15	fm
$\lambda \equiv (R_{wk} - R_{ch})/R_{ch}$	-1.3	5.0	%

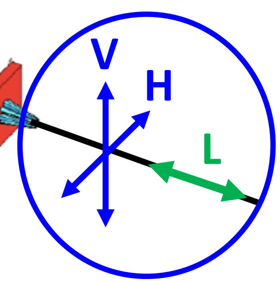
Beam Normal Single Spin Asymmetries

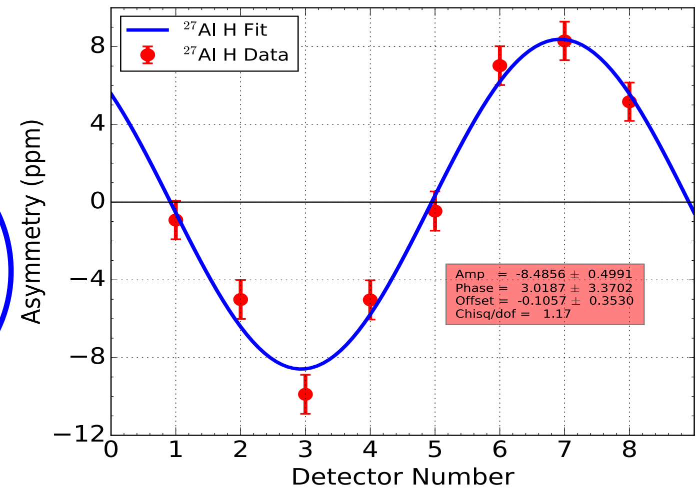


Beam polarization orientation:

- Longitudinal → PV asymmetries A_{PV} → Q_w^p
- Transverse (Vertical or Horizontal)

  → PC asymmetries B_n or BNSSA

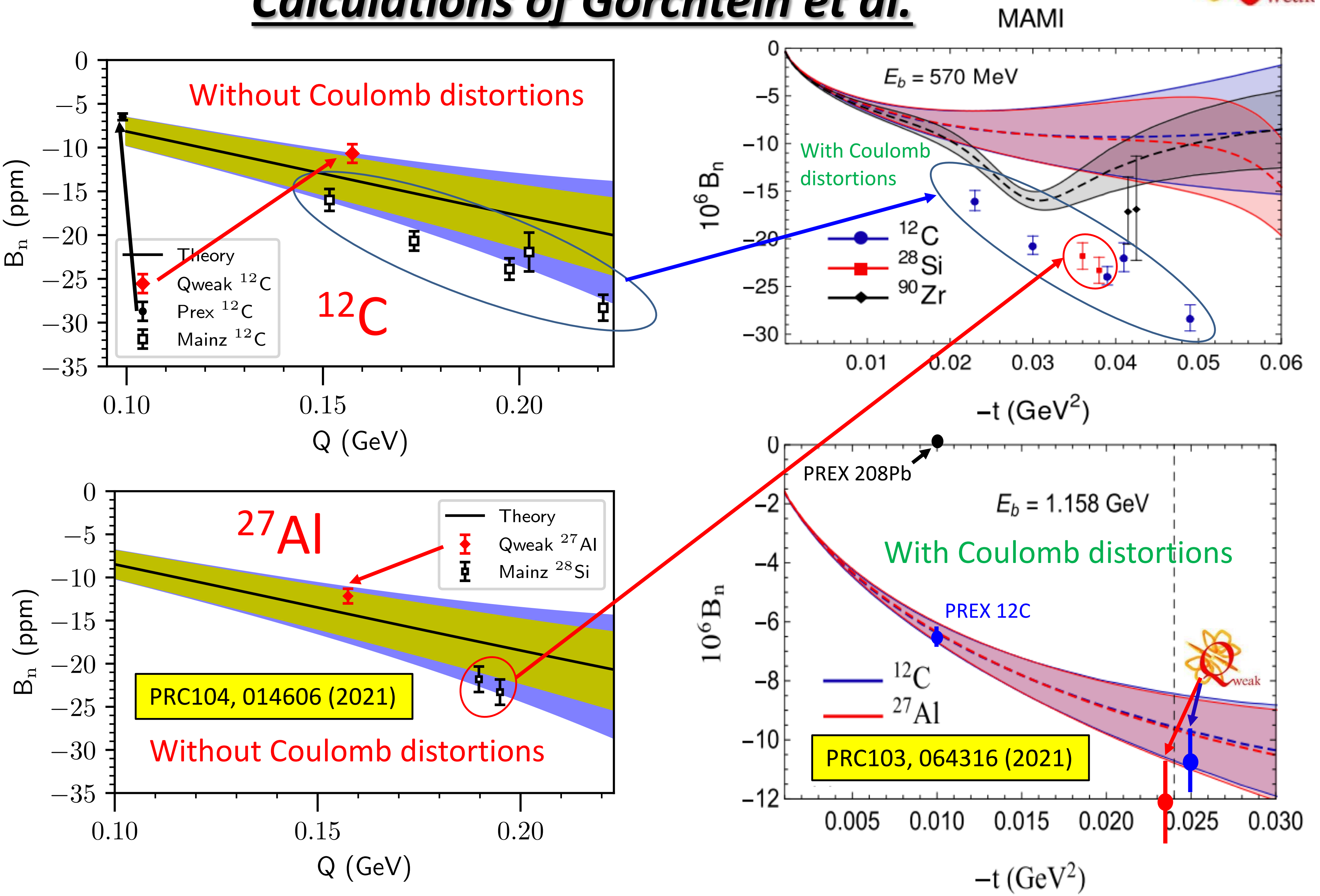




- B_n=0 in OPE
- $B_n \neq 0$ → TPE (Im(TPE))
- TPE is leading explanation for proton FF puzzle (LT vs PT G_E^p / G_M^p)
- Test predictions of Im(TPE) by comparing to B_n

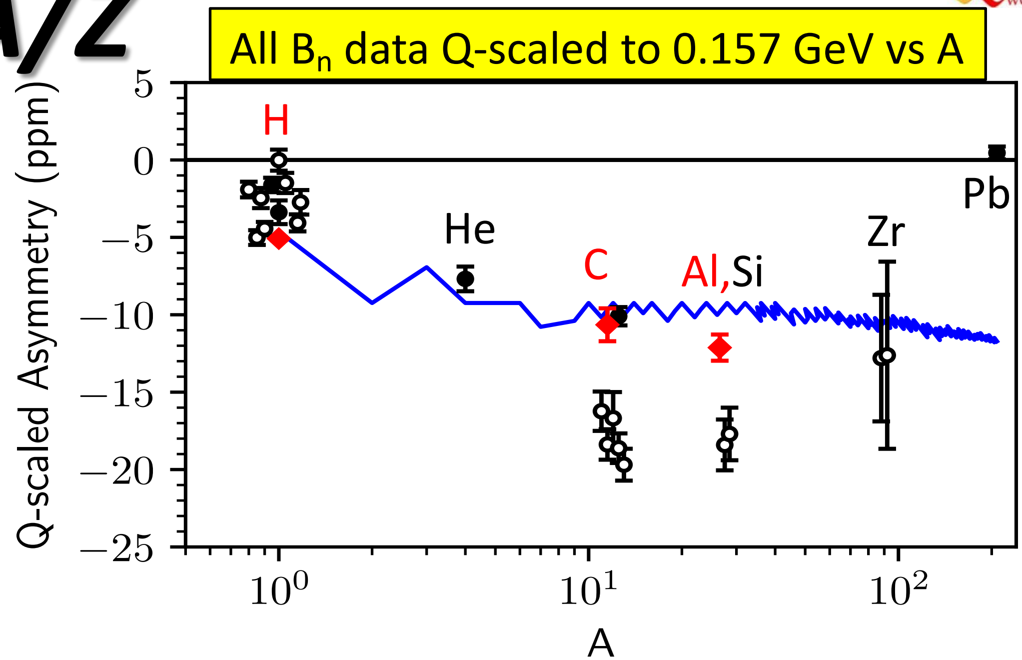
B_n manifests itself as the amplitude of an azimuthal variation of the asymmetry when beam is polarized transverse to its incident p

Effect of Coulomb Distortions on the Optical Model Calculations of Gorchtein et al.

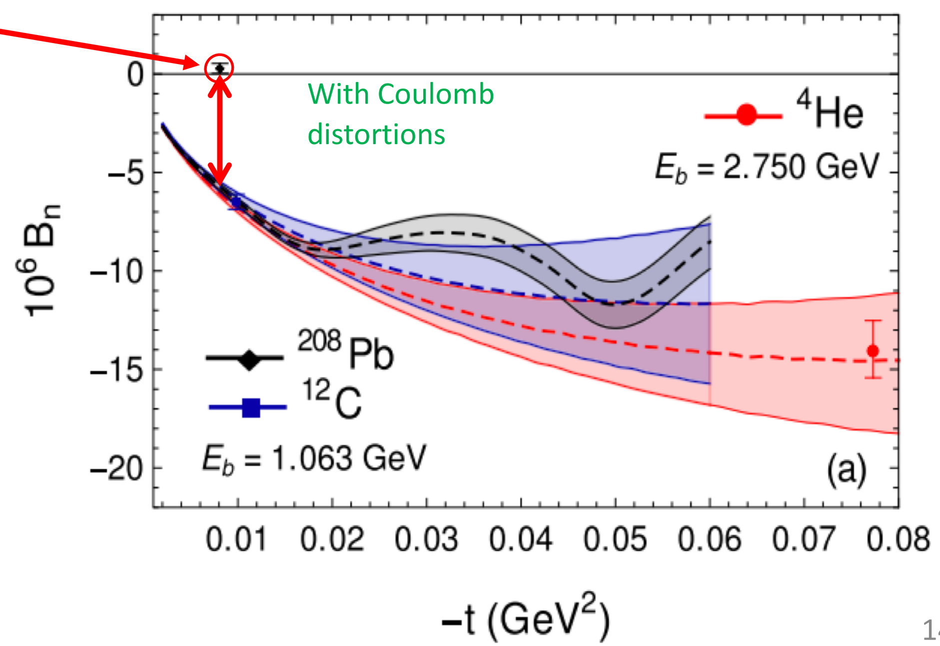


Scaling: $B_n = kQ\ A/Z$

Scaling: PRL 109, 192501 (2012)



- Red: Qweak data on ^{1}H, ^{12}C, ^{27}Al (Q=0.157 GeV)
- Symbols:
  - Solid: θ ≲ 10°
  - Open: θ ≳ 10°
- Blue curve is kA/Z, with k = -30 ppm/GeV (and Q=0.157 GeV)
- PREX ^{208}Pb datum an outlier with other data, scaling, & theory- not understood why:
  - Coulomb distortions? No. See Koshchii et al., PRC103, 064316 (2021)
  - "nuclear" region of the photoabsorption x-sec?

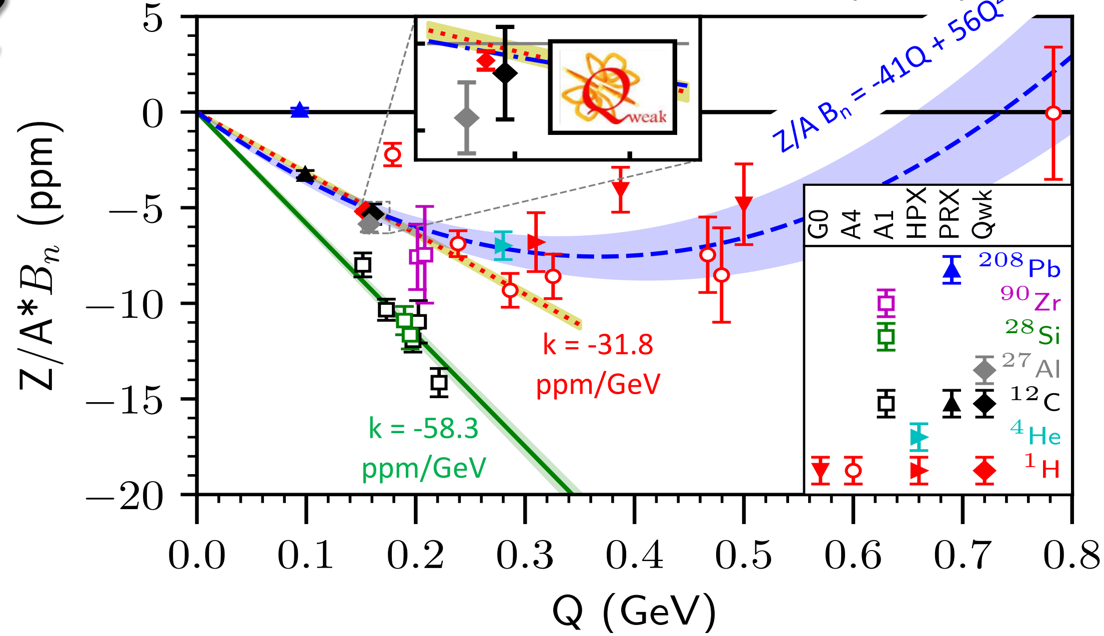


Scaling: $B_n = kQ\ A/Z$

$kQ = Z/A\ B_n$

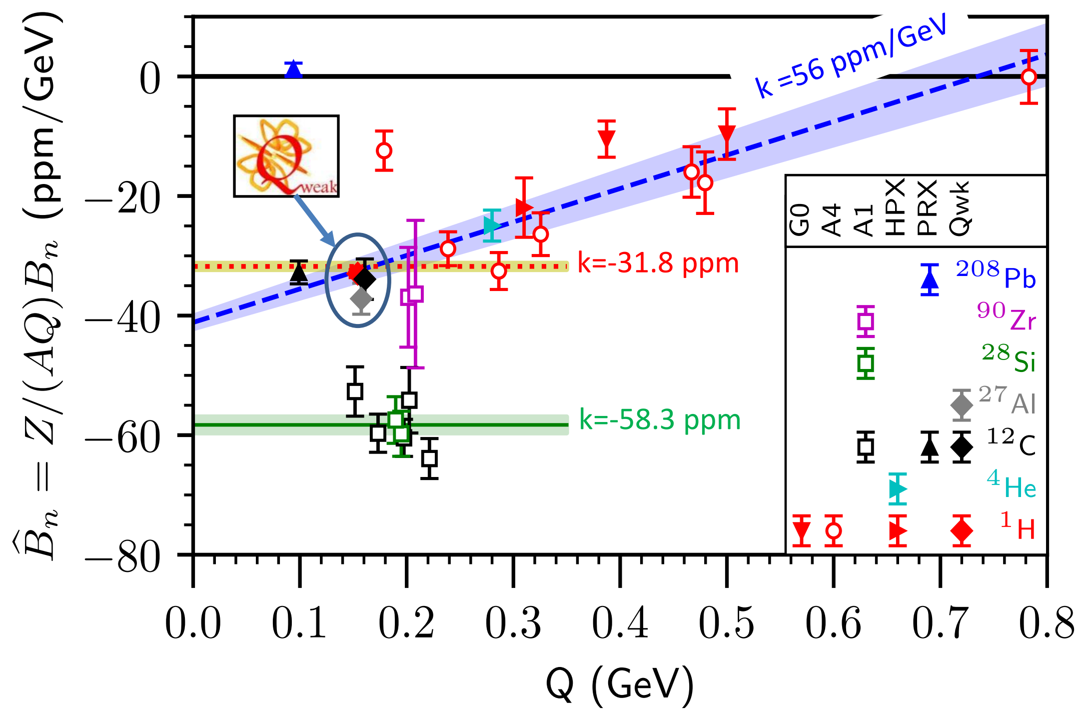
- $Q > 0.35$ GeV ^1H data require a quadratic term
- Mainz $\theta \gtrsim 10°$ data have twice the slope of other data with $\theta \lesssim 10°$

Androic, et al., PRC 104, 014606 (2021)



$k = Z/(AQ)\ B_n$

- All the far-forward angle (θ <10°) data from ^1H to ^{27}Al can be described by the same slope out to Q ~ 0.35 GeV.
- PREX ^{208}Pb datum still an outlier



Summary

- Elastic PVES A_{PV} on ^{27}Al: arXiv:2112.15412 **[nucl-ex], submitted to PRL**
  - First msr of ^{27}Al A_{PV}
  - DWBA predictions accurately predict msrd A_{PV}
  - n-skin ~ 0 as expected for N~Z ^{27}Al
  - Successful benchmark of EW method used to get R_n
    - Despite tension noted in EW R_n of ^{208}Pb
- Elastic BNSSA on ^{12}C & ^{27}Al: Phys. Rev. C 104, 014606 (2021)
  - First B_n on ^{27}Al
  - Qweak (^{1}H, ^{12}C, & ^{27}Al) & all other $\theta \lesssim 10°$ data consistent with Gorchtein TPE calculations:
    - Except ^{208}Pb
    - *Agreement with Mainz $\theta > 10°$ ^{12}C & ^{28}Si results fails with Coulomb corrections*
  - Empirically: Q-dependence of all ^{1}H $B_n Z/A$ data, & all the $\theta < 10°$, A > 1 data can be described by the same slope out to Q = 0.35 GeV
    - Q > 0.35 GeV data have a higher-order Q-dependence
    - Larger-angle ($\theta > 10°$) data from Mainz ^{12}C & ^{28}Si consistent with a slope ~2* steeper
    - ^{208}Pb an outlier

Thank you!

101 collaborators 27 grad students
10 post docs 23 institutions

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Spokespersons Project Manager Grad Students

NSERC CRSNG TRIUMF Jefferson Lab Thomas Jefferson National Accelerator Facility Office of Science U.S. DEPARTMENT OF ENERGY NSF

BACKUP SLIDES

Q_{weak} Papers

- Commissioning result: PRL 111, 141803 (2013)
- Apparatus: NIM A781, 105 (2015)
- Final Q_w^p result & SM test: Nature 557, 207 (2018)
- Q_w^p cookbook & perspectives: ARNS 69, 191 (2019)
- Layman's description: NPN 29, 15 (2019)
- 3-pass A_{inel} in resonance region: PRC 101, 055503 (2020)
- ^{1}H BNSSA: PRL 125, 112502 (2020):
- ^{12}C & ^{27}Al BNSSA: PRC 104, 014606 (2021)

Past

Future

- ^{27}Al Longitudinal (A_{PV}^{27Al}, Q_{W}^{27Al}, δR_{np}^{27Al}): submitted to PRL
- N → Δ BNSSA @ 1160 MeV (Nurruzaman) & 877 MeV (Anna Lee)
  - This & next 2 need elastic radiative tail simulations (new: Devi Adhikari)
- N → Δ Inel A_{PV} (d_{Δ}) @ 877 MeV (Anna Lee) & 1160 (Leacock, Thamraa, Hend)
- Moller scattering BNSSA
- 27 students/theses, several instrumentation papers

PVES Elastic 27Al Corrections & Systematic Error Contributions

Quantity	Value	$\Delta A_{\rm PV}/A_{\rm PV}$ (%)
$A_{\rm msr}$:	1.436 ± 0.014 ppm	1.0
P:	0.8880 ± 0.0055	0.7
$R_{\rm tot}$:	0.9855 ± 0.0087	0.9
$f_{\rm QE}$:	21.2 ± 2.9 %	5.0
$A_{\rm QE}$:	-0.34 ± 0.17 ppm	2.4
$f_{\rm nucl}$:	3.83 ± 0.23 %	0.1
$A_{\rm nucl}$:	2.58 ± 1.40 ppm	3.6
$f_{\rm inel}$:	0.665 ± 0.099 %	0.2
$A_{\rm inel}$:	-0.58 ± 5.83 ppm	2.6
$f_{\rm alloy}$:	5.41 ± 0.34 %	0.1
$A_{\rm alloy}$:	1.90 ± 0.58 ppm	2.1
$f_{\rm pions}$:	0.06 ± 0.06 %	0.1
$A_{\rm pions}$:	0 ± 20 ppm	0.8
$f_{\rm neutral}$:	0 ± 0.45 %	0.1
$A_{\rm neutral}$:	1.7 ± 0.2 ppm	0.0
$f_{\rm beamline}$:	0.69 ± 0.06 %	0.1
$f_{\rm GDR}$:	0.045 ± 0.023 %	0.1
$A_{\rm GDR}$:	-2.22 ± 1.11 ppm	0.0
Total Systematic		7.6

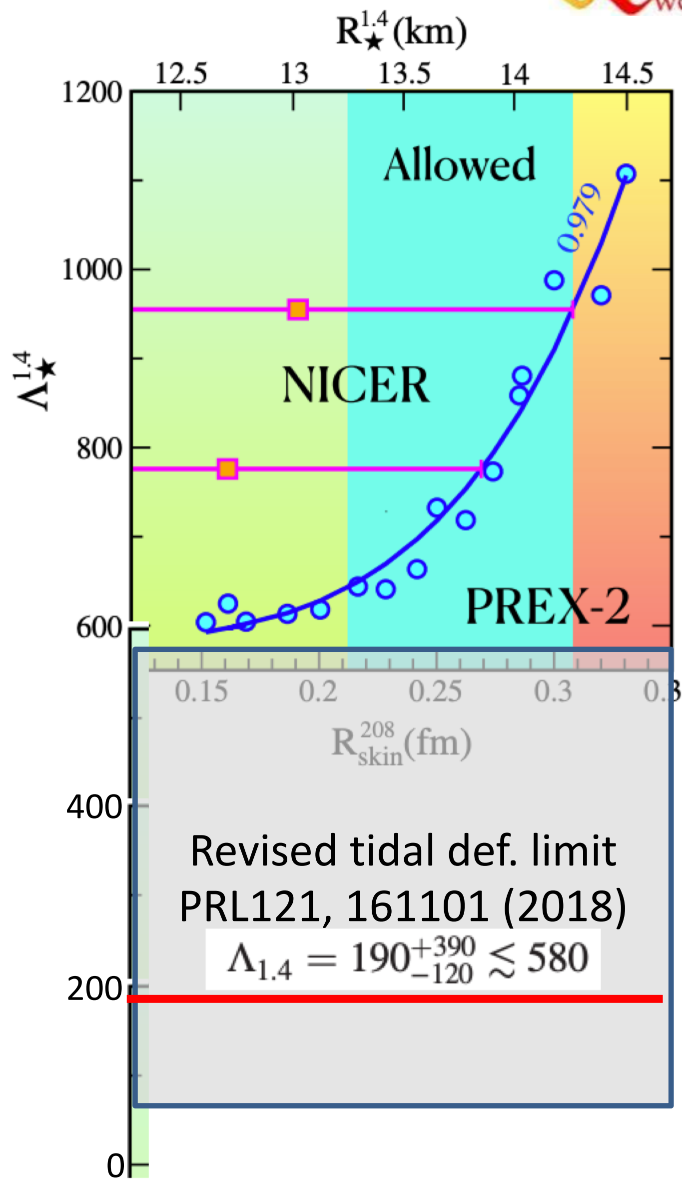
Astrophysical Tension

Reed, Fattoyev, Horowitz, Piekarewicz, PRL 126, 172503:

- Blue box is overlap of 1st NICER & Prex.
  - 2nd NICER result has less overlap, as indicated by lower purple horizontal datum
- Original LIGO tidal deformability $\Lambda_{1.4}$ < 800 is consistent (PRL 119, 161101 (2017))
- New GW170817 tidal deformability result is "more challenging":

  $$\Lambda_{1.4} = 190^{+390}_{-120} \lesssim 580$$ (red line, grey box)

  Abbott, et al, (Virgo & LIGO) PRL 121, 161101 (2018)
  - Favors models with smaller ^{208}Pb skin, more compatible with non-EW results than Prex
- However, given the existing uncertainties, there are no gross discrepancies between any of these results

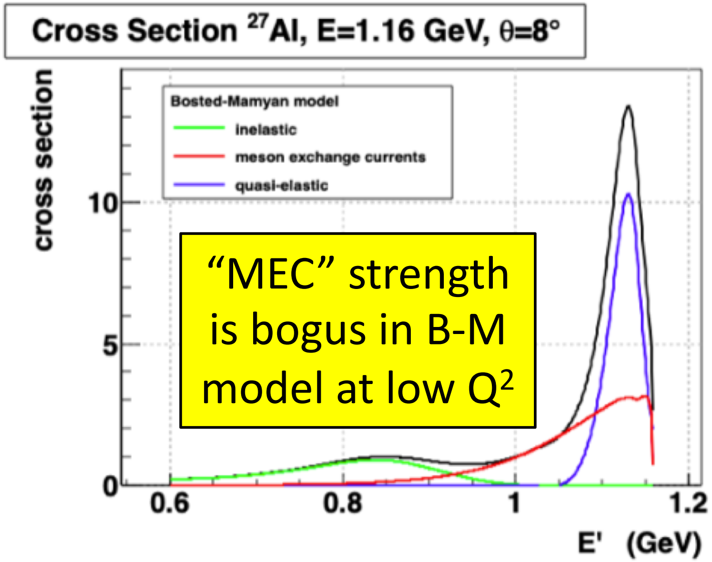


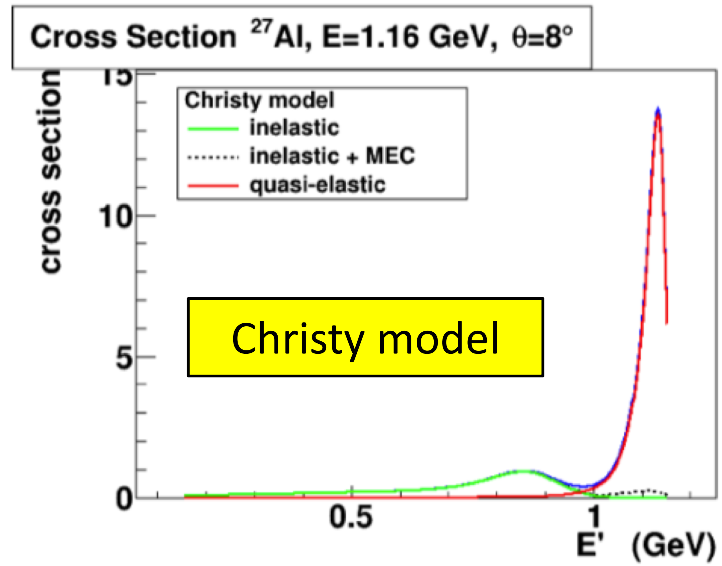
^{27}Al QE & Inel dilution Corrections

– QE & Inel f_i : dilutions from simulations using a generator based on phenomonological fits from Bosted/Mamyan, later scaled to Christy's fits

PRC 104, 014606 (2021)

- HUGE improvement over Bosted/Mamyan at (our) low Q^2!





– QE A_i from RFG model: Horowitz & Piekarewicz, PRC 47, 2924 (1993)

– Inel A_i scaled from brief msrmnt at low spect. B: $A^{75} = f^{75}_{\rm el} A^{75}_{\rm el} + f^{75}_{\rm inel} A^{75}_{\rm inel}$

msrd; simulation; Q^2-scaled from full field; Q^2-scaled to full field

– Results:

	f_i (%)	A_i (ppm)
QE	21.2 ± 2.9	-0.34 ± 0.17
Inel (N→ Δ)	0.665 ± 0.99	-0.58 ± 5.83

Qweak Ancillary Results

From systematic studies made to support our primary ep A_{PV} result

- PV ep A_{inel} above the resonance region
  - 3-pass data, J. Dowd thesis, PRC 101, 055503 (2020)
- Elastic ^{1}H BNSSA
  - B. Waidyawansa thesis, PRL 125, 112502 (2020)

QE bkg B_n

- Elastic ^{12}C & ^{27}Al BNSSA

PRC 104, 014606 (2021)

  - M.J. McHugh & K. Bartlett theses

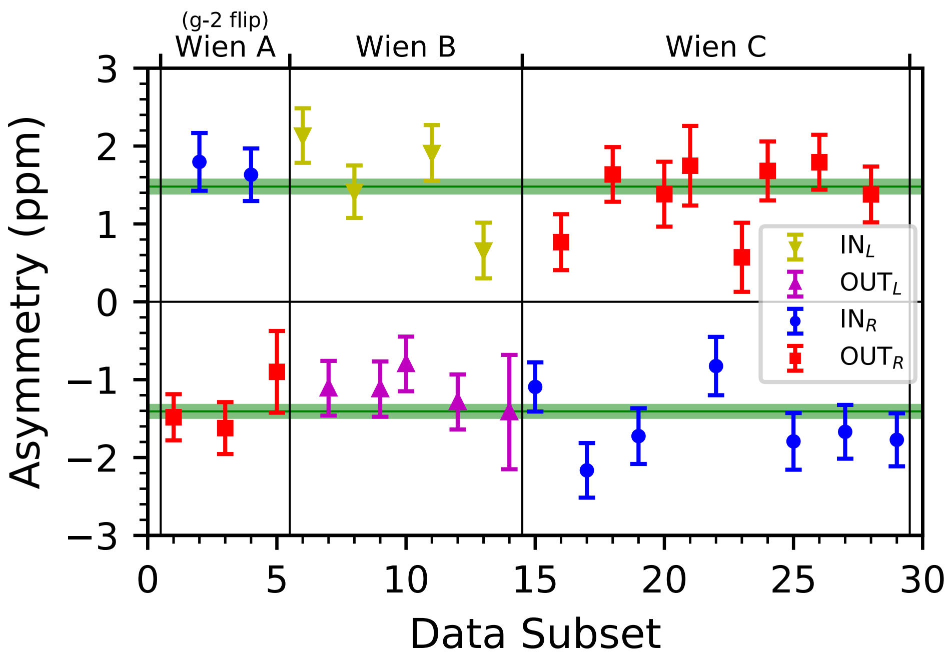
Inel bkg B_n

- Inelastic ep→e'Δ BNSSA
  - Nuruzzaman thesis

Inel, QE, discrete state, & alloy bkg dilutions

- Elastic A_{PV}^{27Al}, Q_{W}^{27Al}, δR_{np}^{27Al} submitted to PRL
  - K. Bartlett thesis
- Inelastic ep→e'Δ A_{PV}
  - A. Lee, H. Nuhait, T. AlShayeb theses

PV ^{27}Al Raw Data Quality



Beam Helicity slow reversals:

- Insertable half-wave plate in the polarized source every ~8h
- Reversals of the double Wien spin filter in injector every ~month
- 1 pass → 2 pass → 1 pass: g-2 flip

Average	Asymmetry(ppm)	$\chi^2/d.o.f.$	χ^2 Prob.
NEG	-1.407 ± 0.093	1.26	0.225
POS	1.480 ± 0.099	1.62	0.073
NULL	0.036 ± 0.068	–	–
$A_{\rm raw}$	1.441 ± 0.068	1.39	0.082

- Asymmetry well-behaved under 3 kinds of slow helicity reversal
- Corrections for HC beam properties small: 0.4 ± 1.4 ppb

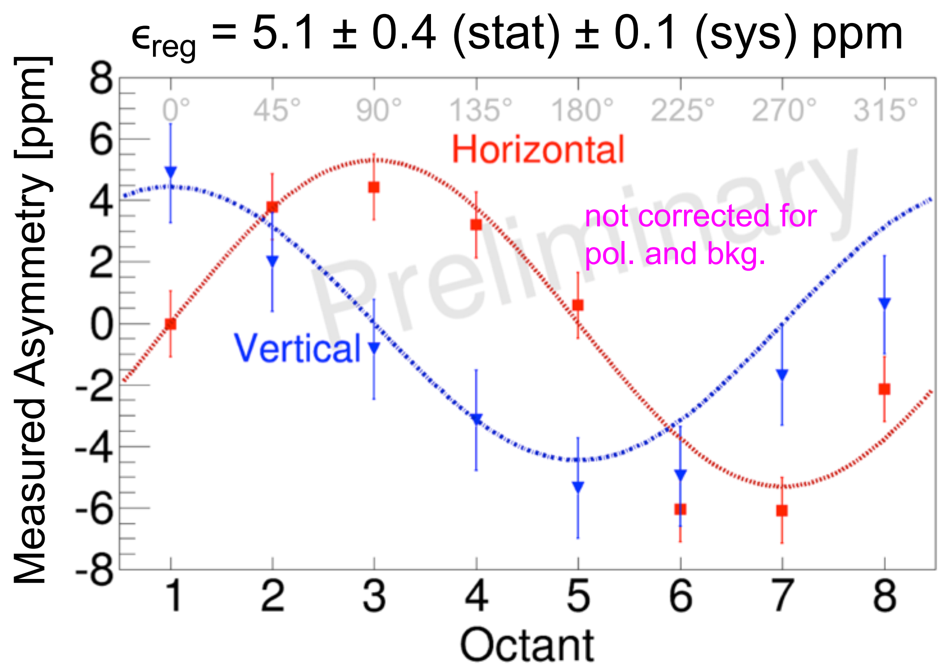
Beam Normal Single Spin Asymmetry in Δ Resonance

Q-weak has measured Beam Normal Single Spin Asymmetry (B_n) in the N-to-Δ transition on H_2

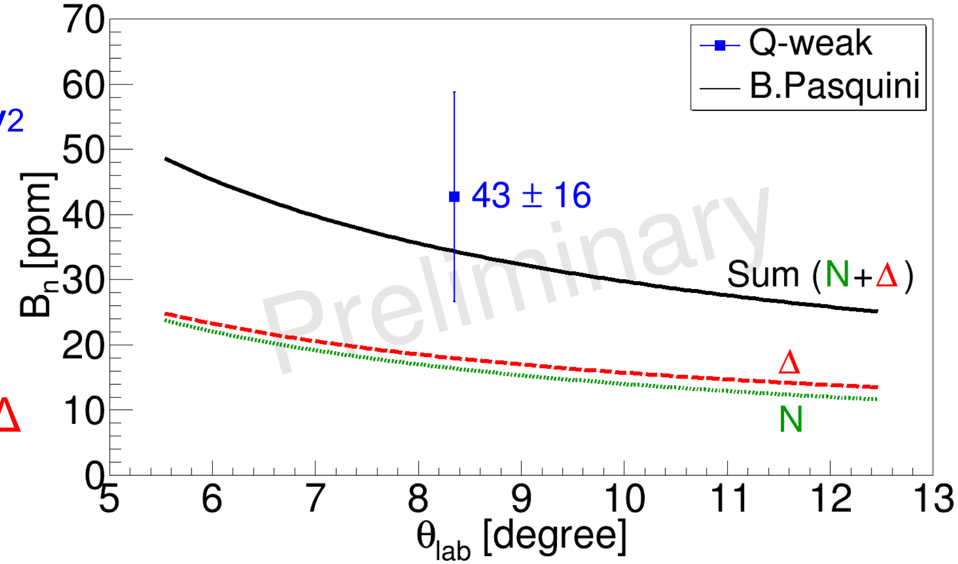
$$B_n = \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} = \frac{2\mathrm{Im}(T_{1\gamma} \times T_{2\gamma})}{|T_{1\gamma}|^2}$$

After correcting for polarization and backgrounds

$B_n = 43 \pm 16$ ppm



- $\langle E \rangle$ = 1.16 GeV
- $\langle W \rangle$ = 1.2 GeV
- $\langle \theta \rangle$ = 8.3°
- $\langle Q^2 \rangle$ = 0.021 GeV^2



- Unique tool to study $\gamma^*\Delta\Delta$ form factors
- Q-weak along with world data has potential to constrain models and study charge radius and magnetic moment of Δ

PV ep A_{inel} above the resonance region

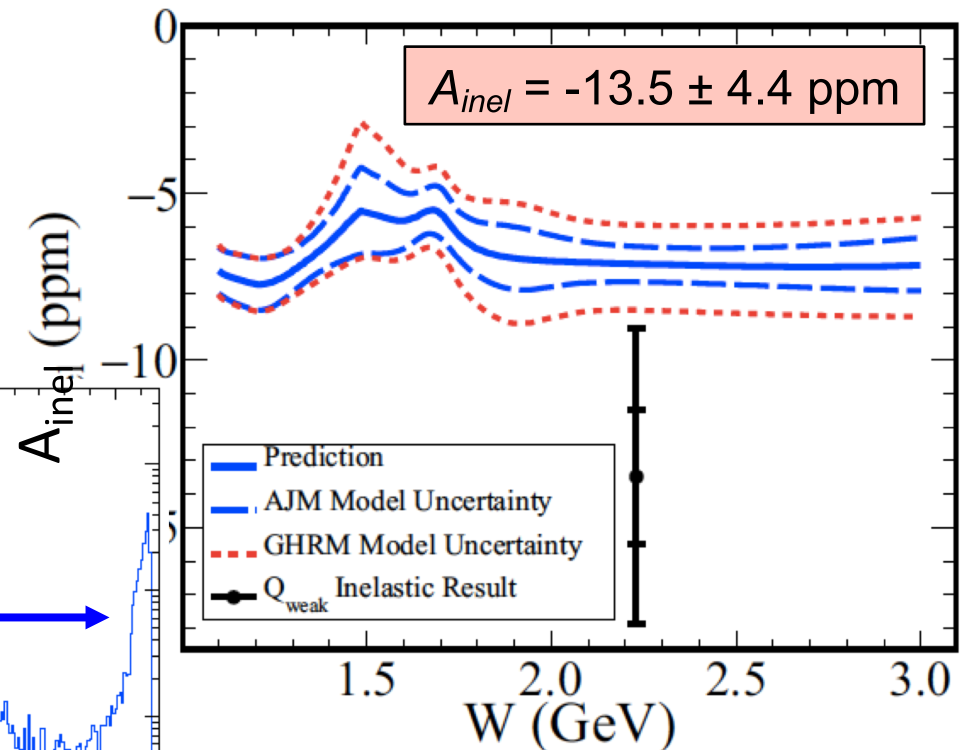
- Helps validate modeling of the γZ interference structure functions $F_1^{\gamma Z}$ & $F_2^{\gamma Z}$, used for determination of the two-boson exchange γZ box diagram contribution to PV elastic scattering measurements
- A positive PV asymmetry for inclusive π− production was observed, as well as a positive BNSSA for scattered electrons, and a negative BNSSA for inclusive π− production

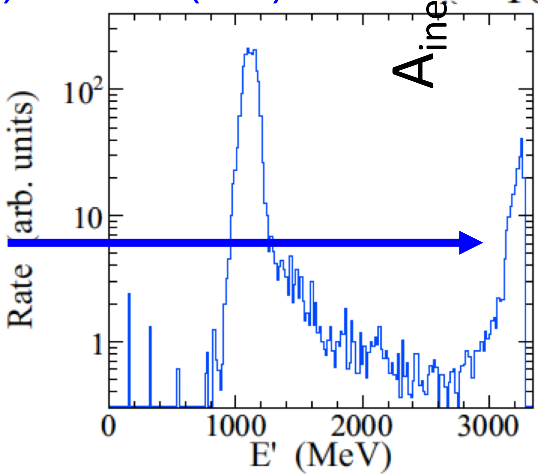
Kinematics:

- $\langle E \rangle$ = 3.35 GeV $\langle W \rangle$ = 2.23 GeV
- $\langle Q^2 \rangle$ = 0.082 GeV^2
- $\langle P_{mixed} \rangle$ = 0.870 ± 0.006, but mixed 94% (long) & 34% (hor)

Special Corrections:

- e/π/μ/γ/n fraction (higher E → more π's)
- 3 GeV elastics punch-thru shieldwall designed for 1 GeV elastics





BNSSA Backup Slides

BNSSA Database

Expt	A	θ(lab) (deg)	E(lab) (GeV)	Q (GeV)	B_n (ppm)	ΔB_n (ppm)	Fitting Group	Ref
A4	^{1}H	33.9	0.3151	0.179	-2.220	0.587	1,1a	[25]
A4	^{1}H	34.1	0.5102	0.286	-9.320	0.884	1,1a	[25]
A4	^{1}H	34.1	0.8552	0.467	-7.460	1.973	1	[25]
A4	^{1}H	34.3	0.4202	0.239	-6.880	0.676	1,1a	[25]
A4	^{1}H	34.1	1.5084	0.783	-0.060	3.459	1	[25]
A4	^{1}H	35.0	0.5693	0.326	-8.590	1.164	1,1a	[24]
A4	^{1}H	35.3	0.8552	0.480	-8.520	2.468	1	[24]
G0	^{1}H	7.5	3.0310	0.387	-4.060	1.173	1	[22]
G0	^{1}H	9.6	3.0310	0.500	-4.820	2.111	1	[22]
Qweak	^{1}H	7.9	1.1490	0.157	-5.194	0.106	1,1a	[27]
HAPPEX	^{1}H	6.0	3.0260	0.310	-6.800	1.540	1,1a	[33]
HAPPEX	^{4}He	6.0	2.7500	0.280	-13.970	1.450	1,1a	[33]
A1	^{12}C	15.1	0.5700	0.152	-15.984	1.252	2	[34]
A1	^{12}C	17.7	0.5700	0.173	-20.672	1.106	2	[34]
A1	^{12}C	20.6	0.5700	0.202	-21.933	2.219	2	[34]
A1	^{12}C	23.5	0.5700	0.197	-23.877	1.225	2	[34]
A1	^{12}C	25.9	0.5700	0.221	-28.296	1.480	2	[34]
PREX	^{12}C	5.0	1.0630	0.099	-6.490	0.380	1,1a	[33]
Qweak	^{12}C	7.9	1.1580	0.159	-10.680	1.065	1,1a	-
Qweak	^{27}Al	7.9	1.1580	0.154	-12.160	0.849	1,1a	-
A1	^{28}Si	19.4	0.5700	0.190	-21.807	1.480	2	[35]
A1	^{28}Si	23.5	0.5700	0.195	-23.302	1.470	2	[35]
A1	^{90}Zr	20.7	0.5700	0.205	-16.787	5.688	2	[35]
A1	^{90}Zr	23.5	0.5700	0.205	-17.033	3.848	2	[35]
PREX	^{208}Pb	5.0	1.0630	0.094	0.280	0.250	–	[33]

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

BNSSA Empirical Fits

TABLE VII. Fit results.

Group	Linear ($\widehat{B}_n$) (ppm/GeV)	Quadratic (β) (ppm/GeV^2)	# data	χ^2/dof
1	-41.1 ± 1.1	56.0 ± 4.8	15	4.4
1a	-31.8 ± 0.5	–	10	6.4
2	-58.3 ± 1.4	–	9	2.0

^{1}H BNSSA PRL 125, 112502 (2020)

$$B_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{2\,\mathcal{I}m(\mathcal{M}_{\gamma\gamma}\mathcal{M}_{\gamma}^{*})}{|\mathcal{M}_{\gamma}|^2}$$

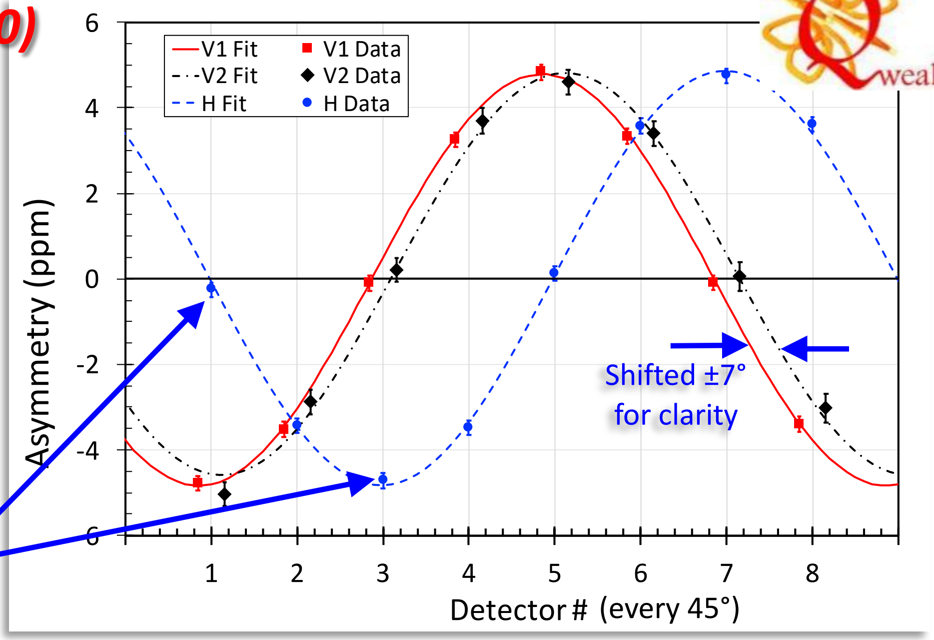
$$A_{\rm exp}(\phi) \approx B_n \vec{P}\cdot\hat{n}$$

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

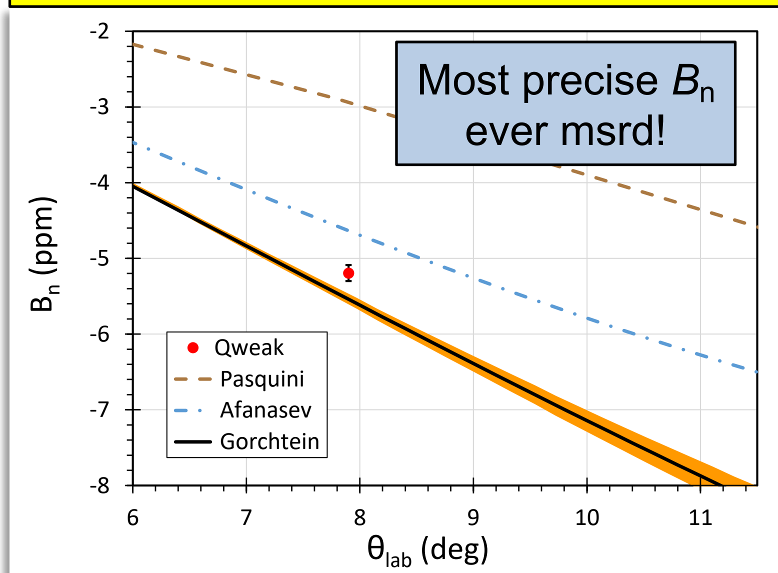
$$R_l R_{\rm av} B_{\rm exp} \sin(\phi_s - \phi_i + \phi_{\rm off}) + C$$

$$= A_{\rm raw} - \sum^{5} \left(\frac{\partial A}{\partial \chi_j}\right)\Delta\chi_j$$

$$B_n = R_{\rm tot}\left[\frac{\frac{B_{\rm exp}}{P} - \sum_i f_i B_i}{1-\sum_i f_i}\right] + B_{\rm bias}$$



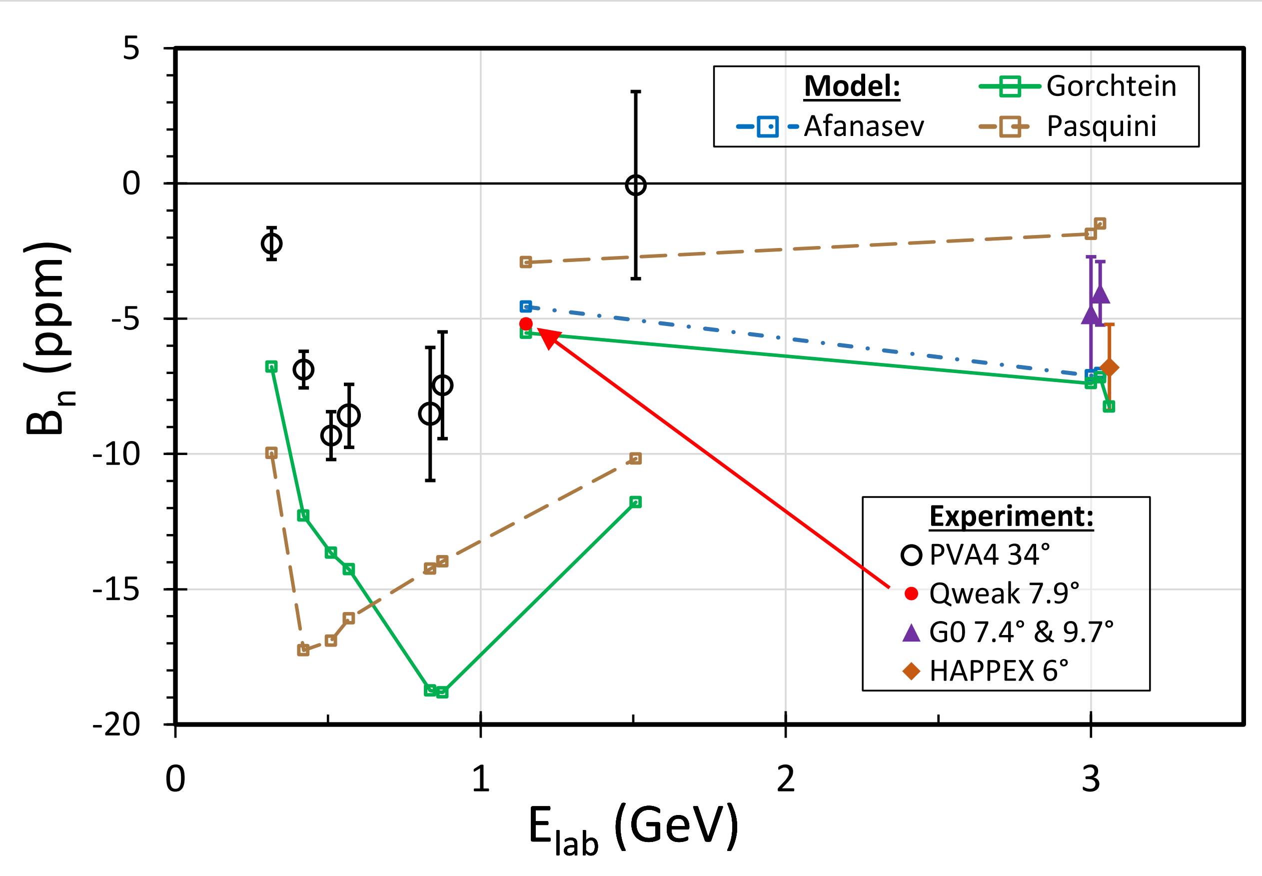
B_n = -5.19 ± 0.07 (stat) ± 0.08 (syst) ppm



Pasquini & Vanderhagen: model intermediate hadronic state (VVCS) with electro-absorption amplitudes. Limited to πN states only (bad), but should apply at all angles (good).

Afanasev & Merenkov, and **Gorchtein**: use the optical theorem to relate the VVCS amplitude to the total photo-absorption σ. Includes all intermediate states (good), but only strictly valid in the forward-angle limit (bad).

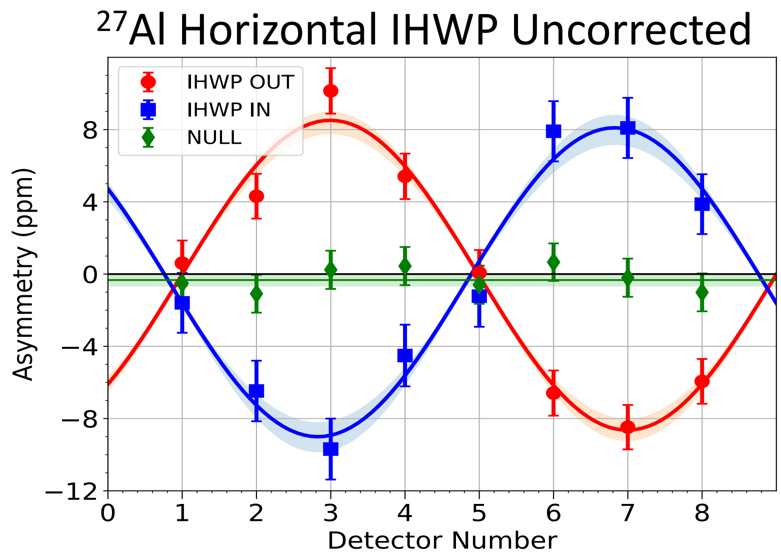
Global ^{1}H BNSSA Data PRL 125, 112502 (2020)

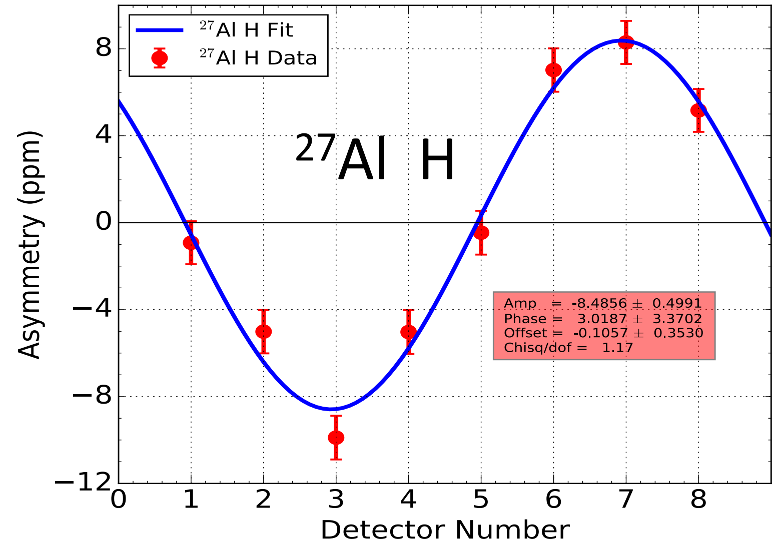


Predictions (open squares) at different kinematics from each group are connected by solid (Gorchtein), dashed (Pasquini & Vanderhagen) & dash-dot (Afanasev & Merenkov) lines to guide the eye.

Agreement of predictions with the far-forward angle (θ<10°) data (solid symbols) is better than for the θ>10° data (open symbols).

^{12}C & ^{27}Al BNSSA Data





Final B_n Results after all corrections are ~ 10%