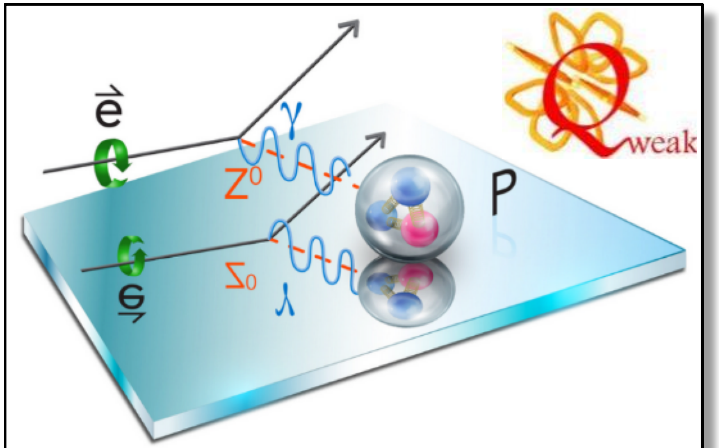
Qweak- Newest Results

Hall C winter meeting
Jan. 28, 2021

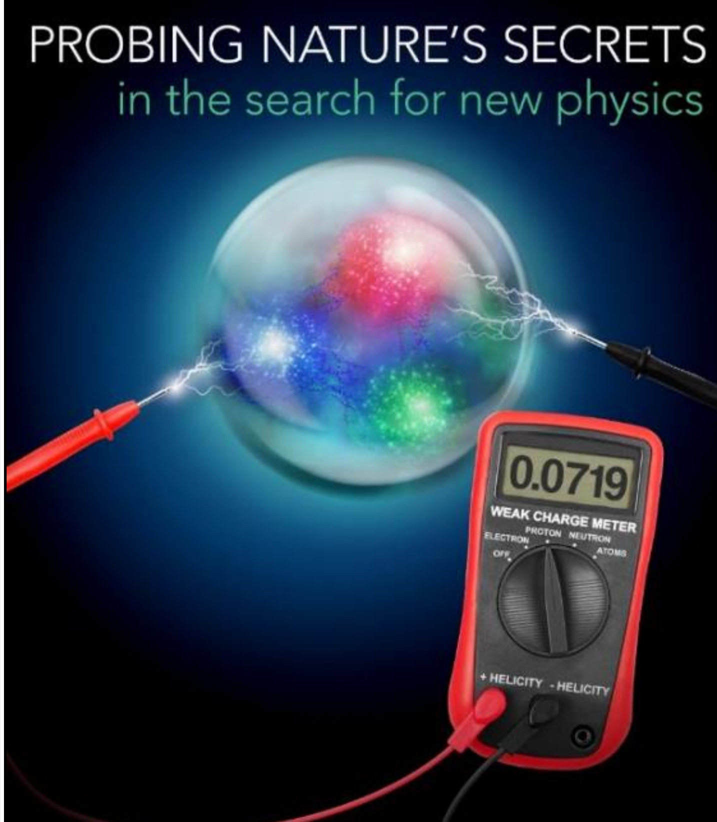
A search for new PV physics at the TeV scale by measuring the proton's weak charge Q_w^p

https://rdcu.be/OIW2



Greg Smith
(Jefferson Lab)
for the Qweak Collaboration

Nature **557**, 207–211 (2018)
doi:10.1038/s41586-018-0096-0



1.16 GeV, 7.9°
$\vec{e}p$ elastic scattering
asymmetry
at the intensity/precision frontier

Exploits PV nature of the weak interaction

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

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):

Past

Future

- ^{12}C & ^{27}Al BNSSA: to pre-readers next week, → PRC
- ^{27}Al Longitudinal (A_{PV}^{27Al}, Q_W^{27Al}, δR_{np}^{27Al}): partial draft
- N → Δ Inelastic PV asymmetry (d_Δ)
- N → Δ BNSSA
- 27 students/theses, several instrumentation papers

$\sin^2\theta_W$ Sensitivity to New Physics

$$4\sin^2\theta_W(0) = 1 - \frac{Q_W^p - \Box_{WW} - \Box_{ZZ} - \Box_{\gamma Z}(0)}{(\rho + \Delta_e)} + \Delta'_e$$

- Precision at Z-pole is better than at low Q, BUT:

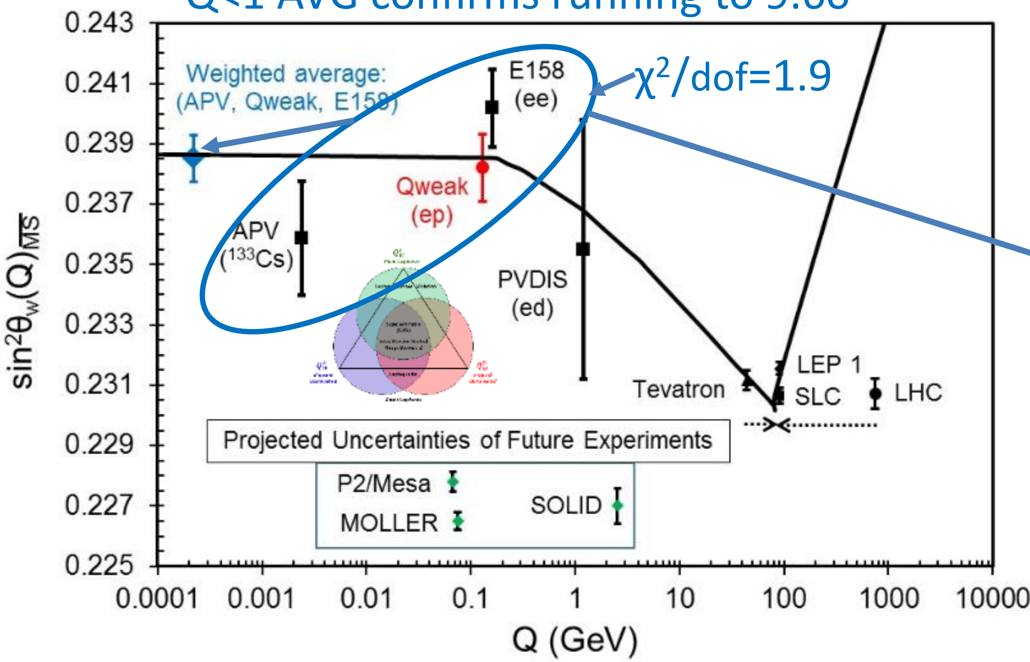
  ** Low-Q expt's are more sensitive to new physics! **

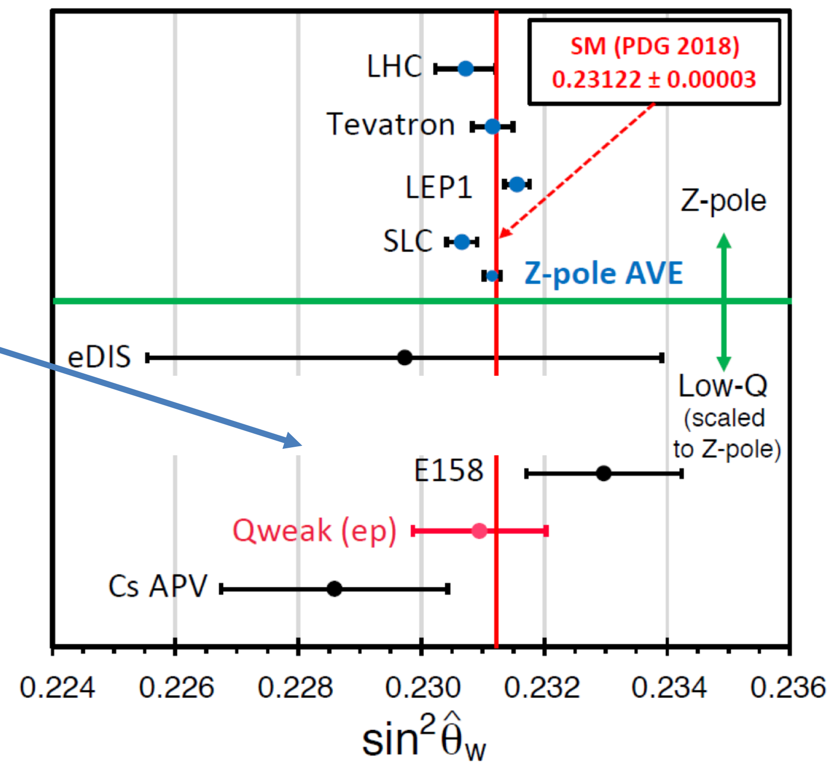
  – Amplitudes A_Z & A_{new}: $A_Z \propto \frac{1}{q^2 - M_Z^2 + iM_Z\Gamma_Z}$ $\quad A_{new} \propto \frac{1}{q^2 - \Lambda^2 + i\Lambda\Gamma_{new}}$

  – ~ Z-pole: A_Z imaginary, A_{new} ~real, so $|A_Z+A_{new}|^2$ has ~no interference term

  – At low Q: A_Z & A_{new} both ~real, so $|A_Z+A_{new}|^2$ is larger by $2A_ZA_{new}$

Q<1 AVG confirms running to 9.6σ

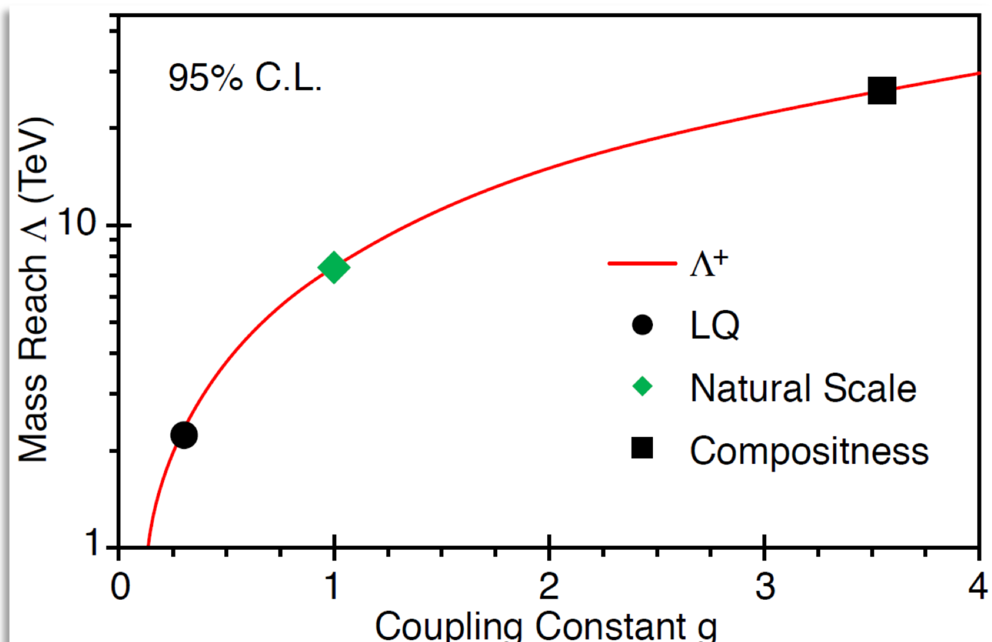




Sensitivity to New Physics Coupling to the Proton

We rule out new PV SL physics below mass scales Λ, using the coupling strength "g" assumed for that new physics

- Proton: $\theta_h = \tan^{-1}(1/2) = 26.6°$
  - Then $\frac{\Lambda_\pm}{g} = v\sqrt{\frac{4\sqrt{5}}{|Q_W^p \pm 1.96\Delta Q_W^p - Q_W^p(SM)|}} = \boxed{7.5\ \mathrm{TeV}}$ @ 95% CL, where $v = \left(G_F\sqrt{2}\right)^{-1/2}$



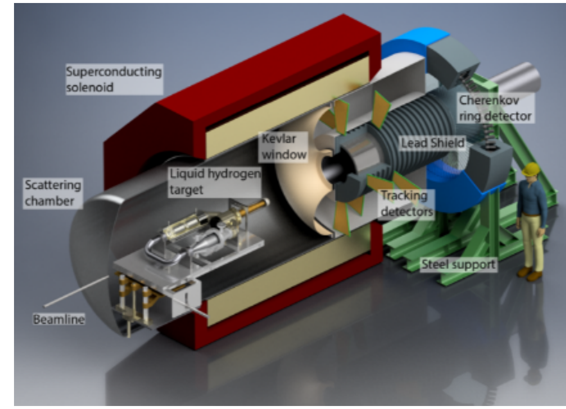
For the "extreme" contact interaction corresponding to e-q compositeness (Eichten et al.,PRL50, 811 (1983)),
$g^2 = 4\pi \rightarrow \Lambda_+ = 26.6$ TeV

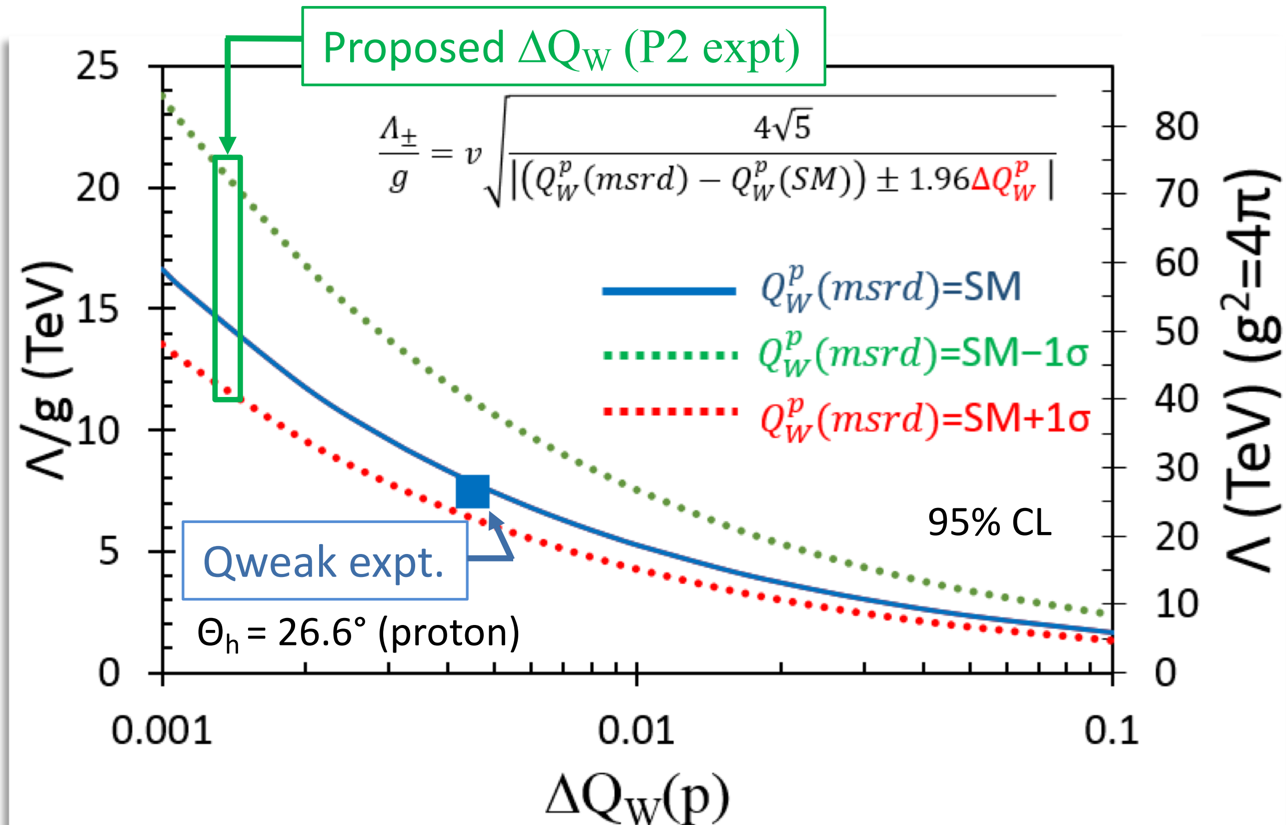
At the other extreme, the coupling usually assumed for leptoquarks (PDG Live)
$g^2 = 4\pi\alpha \rightarrow \Lambda_+ = 2.3$ TeV

These are the highest mass reaches *in the world* for compositeness & LQs to date!

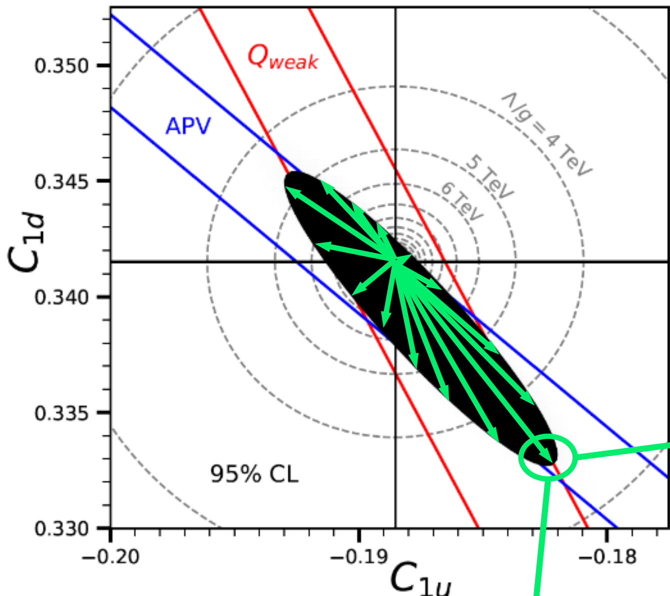
Future Q_W^p Expt's

- P2 @ MESA/Mainz: $\vec{e}p \to ep$ A_{ep} & Q_W^p
  - Weak vector quark charges, $\Delta\sin^2\theta_W$ to ± 0.00033
  - Λ/g to 13.8 TeV. Installs 2021? arXiv: 1802.04759.
  - A_{ep} ~ −40 ± 0.56 ppb (1.4%) (requires 0.25 ppb (syst)!)
    Q^2=0.0045 GeV^2. 155 MeV. 60 cm LH2 (3+ kW). 150 μA.



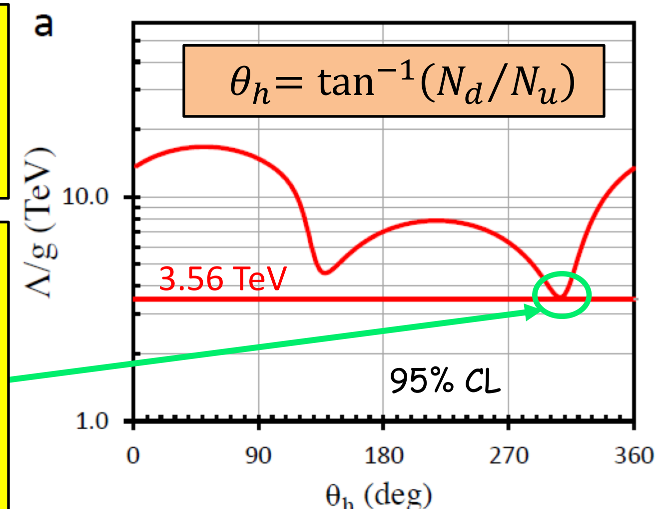


Flavor (θ_h) independent Mass Reach Λ/g (TeV) and Impact of new Experiments



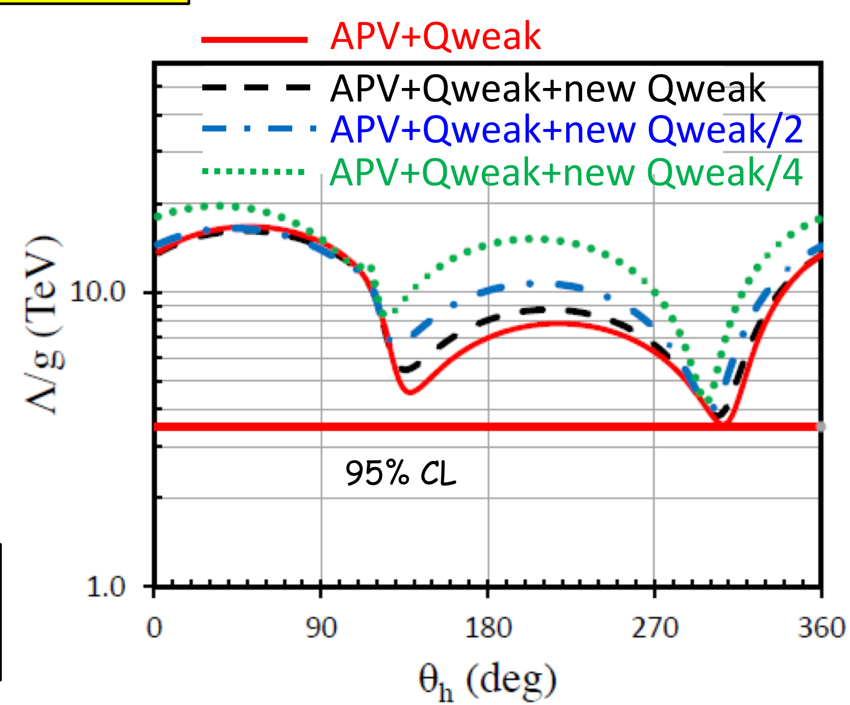
θ_h-ind. Λ/g ~perimeter of combined Qweak & APV ellipse.

Explore impact of new $Q_W(p)$ and/or APV expts with the same, ½, or ¼ the existing uncertainties.



Flavor (θ_h) independent Mass Reach Λ/g (TeV)	Same errors	With errors/2	With errors/4
Existing Qw(p) & APV	3.56	–	–
+ New Qw(p)	3.8	4.0	4.2
+ New APV	4.1	4.6	4.9
+ New Qw(p) + New APV	4.5	6.0	9.5

Because θ_h-ind. Λ/g already requires 2 precision expt's, addition of a 3[rd] doesn't help much



Qweak Ancillary Results

Systematic studies made to support our primary A_{PV} result on ^{1}H are interesting in their own right:

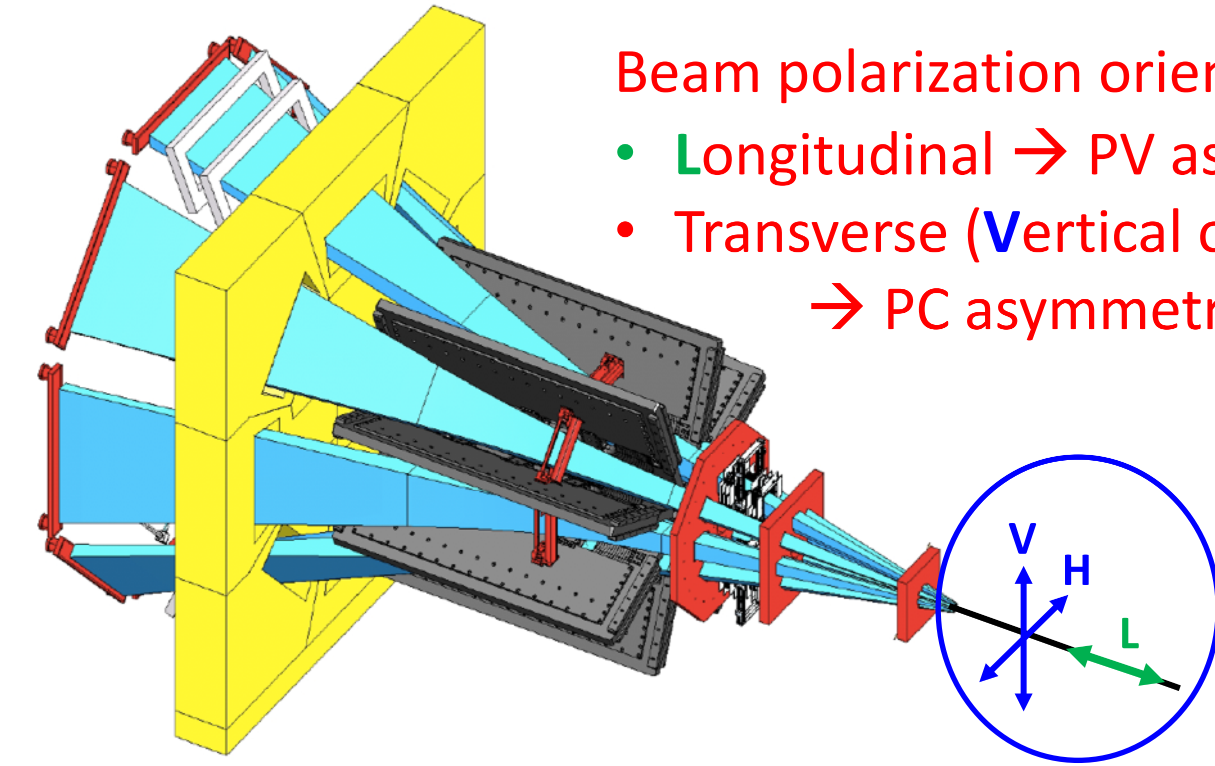
- PV ep A_{inel} above the resonance region
  - 3-pass data, J. Dowd thesis, PRC 101, 055503 (2020)
- Elastic ^{1}H BNSSA
  - B. Waidyawansa thesis, PRL 125, 112502 (2020)
- Elastic ^{12}C & ^{27}Al BNSSA
  - M.J. McHugh & K. Bartlett theses
- Inelastic ep→e'Δ BNSSA
  - Nuruzzaman thesis
- Elastic A_{PV}^{27Al}, Q_{W}^{27Al}, δR_{np}^{27Al}
  - K. Bartlett thesis
- Inelastic ep→e'Δ A_{PV}
  - A. Lee, H. Nuhait, T. AlShayeb theses

QE bkg B_n

Inel bkg B_n

Inel, QE, discrete state, & alloy bkg dilutions

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)
- Re(TPE) from $e^{\pm}p$ xsecs

  OR

  from Im(TPE) via dispersion relations
- 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

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

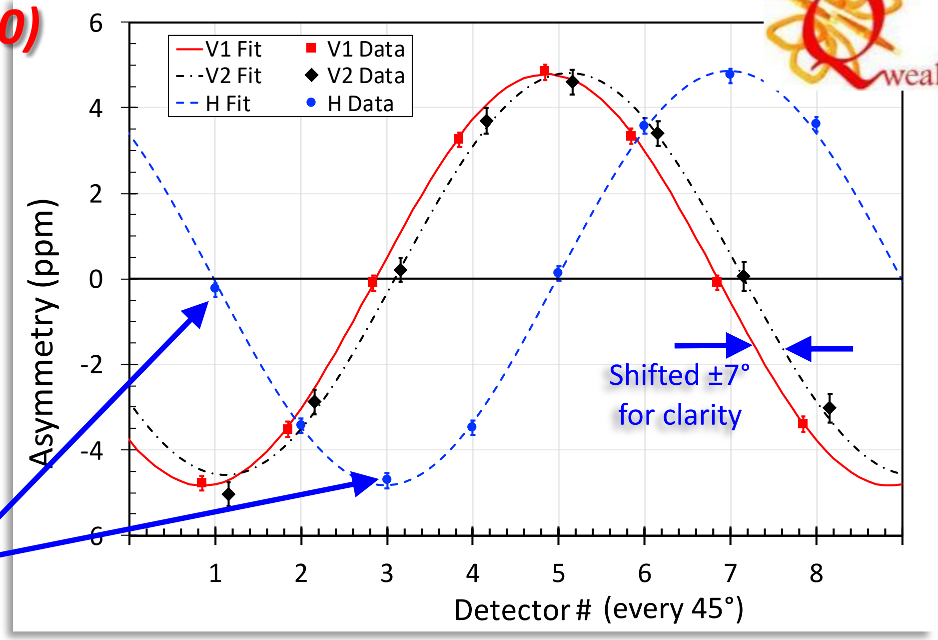
$$B_n = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} = \frac{2\,\mathcal{I}m(\mathcal{M}_{\gamma\gamma}\mathcal{M}_\gamma^*)}{|\mathcal{M}_\gamma|^2}$$

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

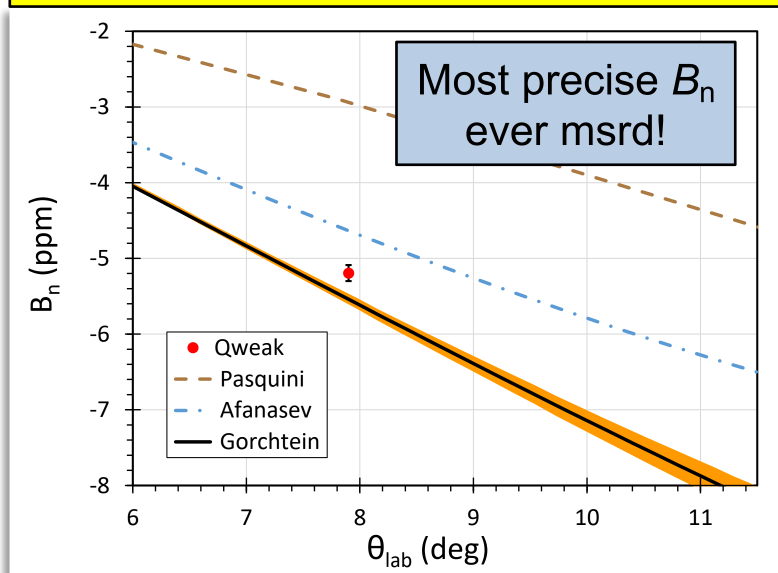
$$\hat{n} = (\vec{k}\times\vec{k}')/(|\vec{k}\times\vec{k}'|)$$

$$R_l R_{\text{av}} B_{\text{exp}} \sin(\phi_s - \phi_i + \phi_{\text{off}}) + C = \boxed{A_{\text{raw}} - \sum^{5} \left(\frac{\partial A}{\partial \chi_j}\right)\Delta\chi_j}$$

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



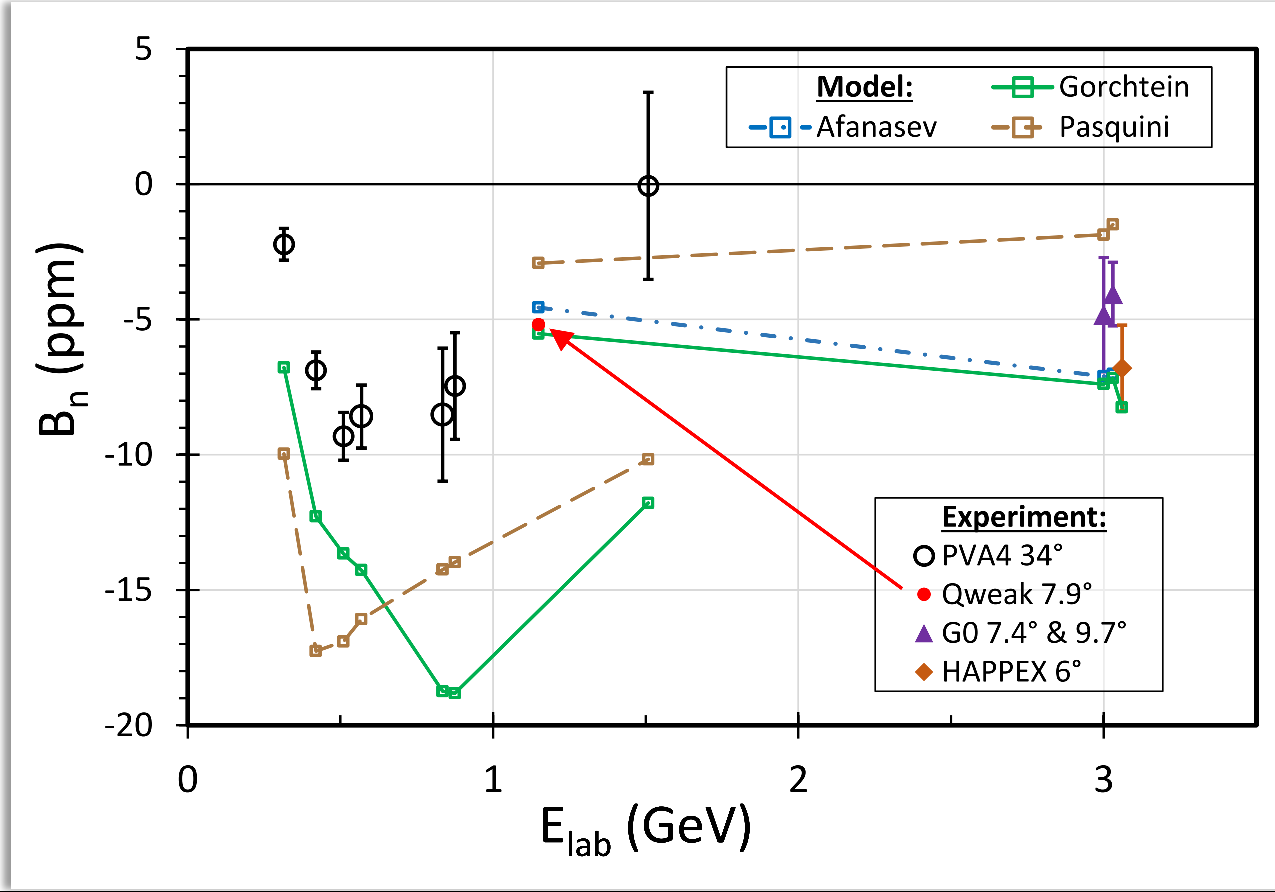
B_n = -5.19 ± 0.07 (stat) ± 0.08 (syst) ppm



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.

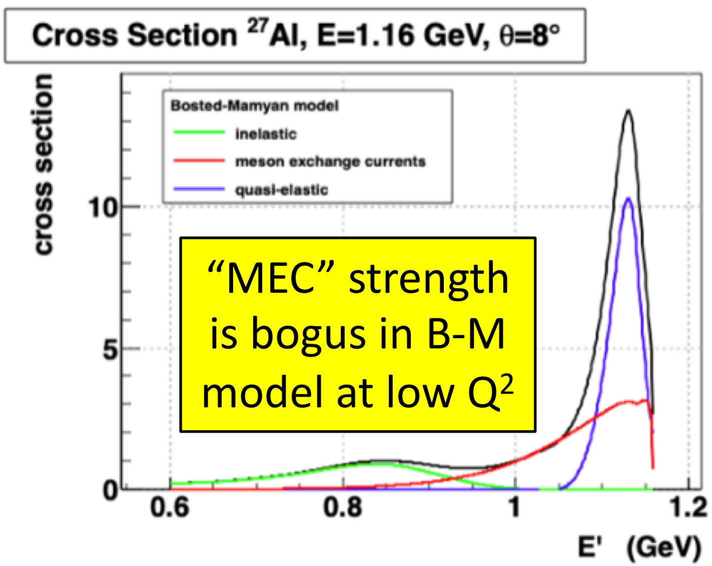
Agreement of predictions with the far-forward angle (θ<10°) data (solid symbols) is better than for the θ>10° data (open symbols).

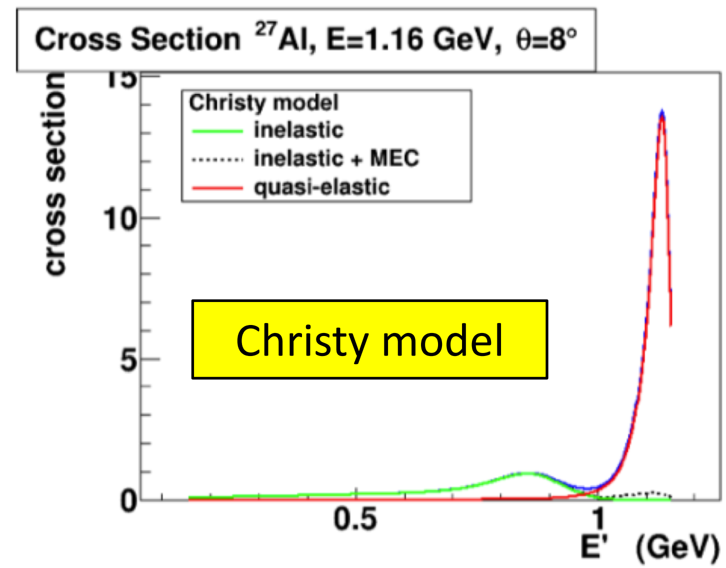
^{12}C & ^{27}Al BNSSA Corrections

- **Pro**: Qweak's 8 detectors arrayed azimuthally about the beam axis *ideal* for B_n msrmnts!
  - B_n is the amplitude of the azimuthal asymmetry variation
  - Statistics come in quickly compared to other expt.'s
- **Con**: Q_{weak} apparatus was designed for ^1H: 10% $\Delta p/p$!
  - If A>1, detectors don't separate elastics from QE, Inelastic eN→e'Δ, discrete excited states, GDR, or other elements in (Al) tgt alloy
  - If A>1, to report an elastic B_n, we have to make corrections for all of these non-elastic processes, which other expt.'s don't have to make
    - Where possible, employ our own data. Where not, use literature & sims!
    - Use conservative uncertainties for these corrections

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

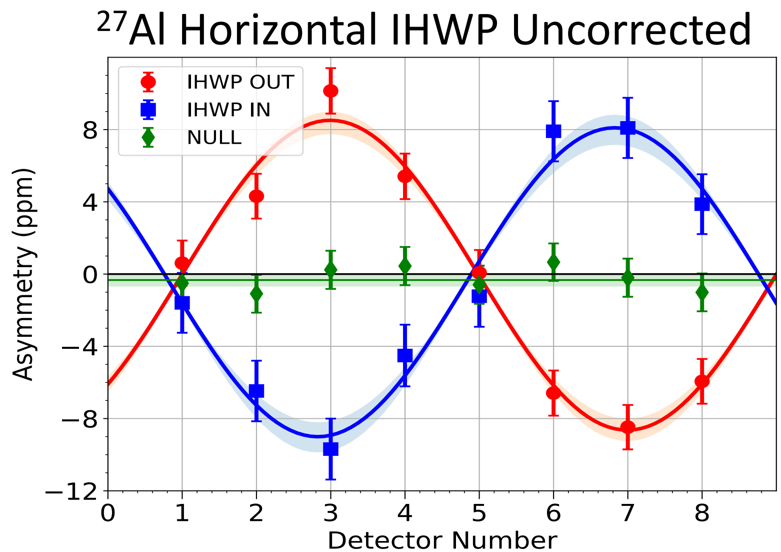
- QE & Inel: dilutions from simulations using a generator based on phenomonological fits from Bosted/Mamyan, later scaled to Christy's fits
  - HUGE improvement over Bosted/Mamyan at (our) low Q^2!

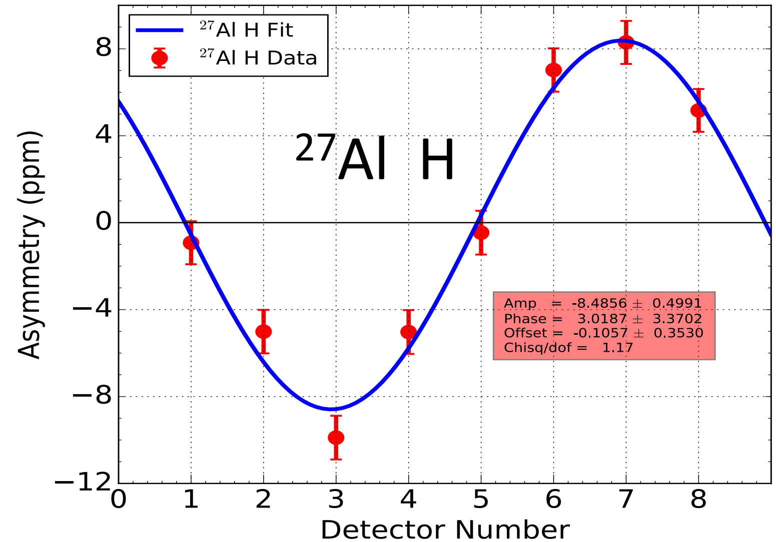




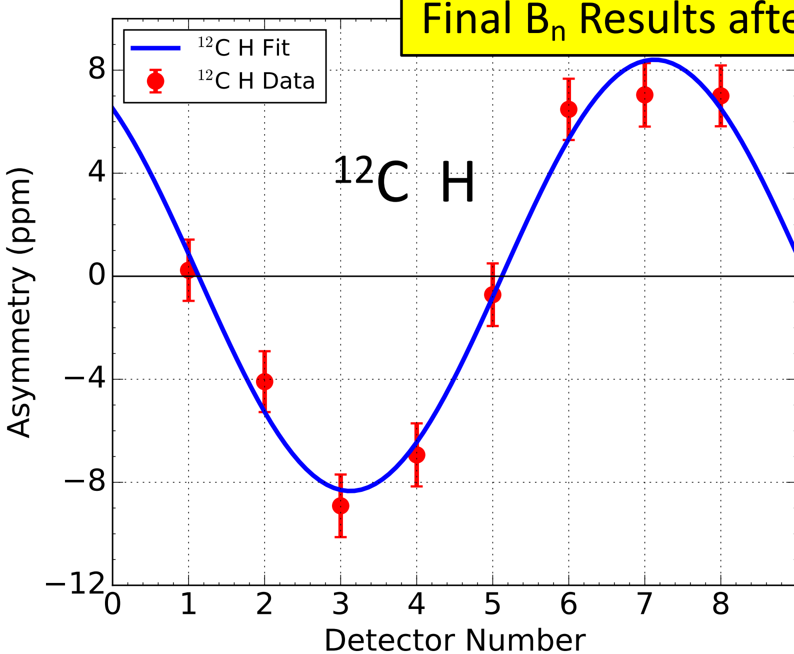
- QE B_n from our ^{1}H result ± 10* msrd error (to account for medium effects & n's)
- Inel B_n from our eN→e'Δ preliminary result (Nuruzzaman's thesis)
- Discrete state dilutions from literature → sims, B_n ≈ elastic ± 100%
- GDR: dilution from Goldhaber-Teller (NP43, 242 (1963)), B_n ≈ elastic ± 100%
- 8 ^{27}Al alloy dilutions from assay, 10% RMF calc's, & simulation, $B_n \approx \alpha A/Z Q$ ± 30%, scaled from our ^{1}H elastic α =-33 ppm/GeV with Q=0.157 GeV

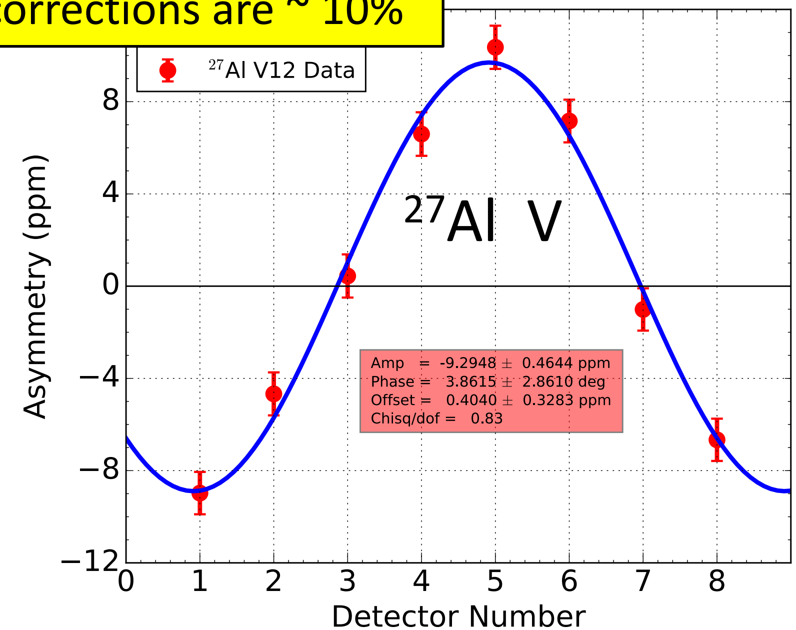
^{12}C & ^{27}Al BNSSA Data





Final B_n Results after all corrections are ~ 10%





Beam Normal Single Spin Asymmetry in Δ Resonance

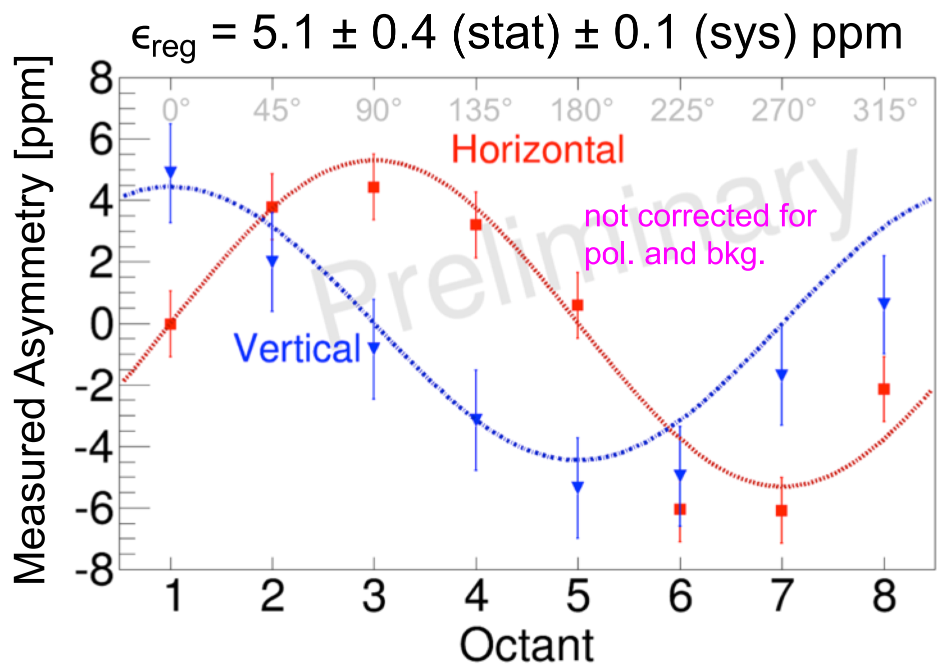
Q-weak has measured Beam Normal Single Spin Asymmetry (B_n) in the N-to-Δ transition on H_2

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

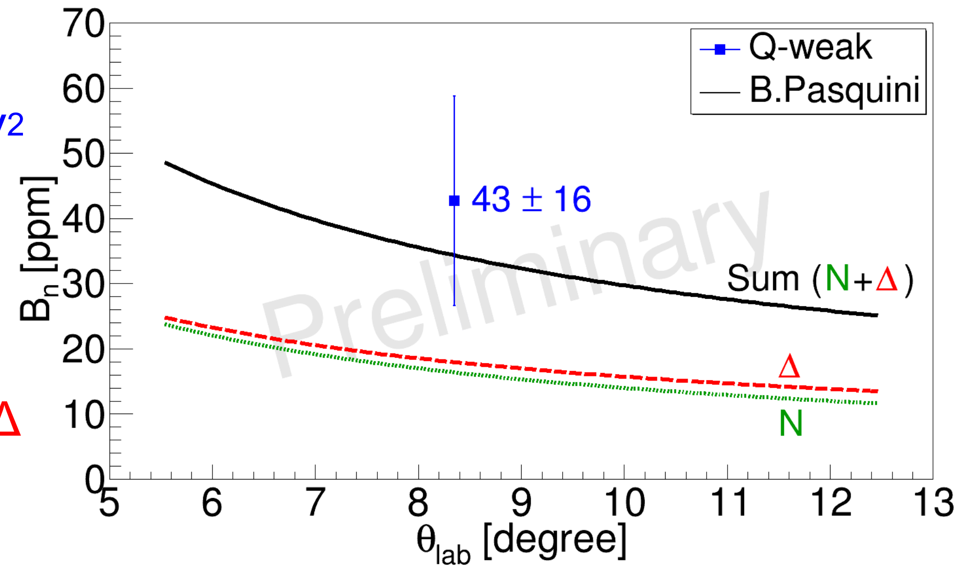
After correcting for polarization and backgrounds

B_n = 43 ± 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

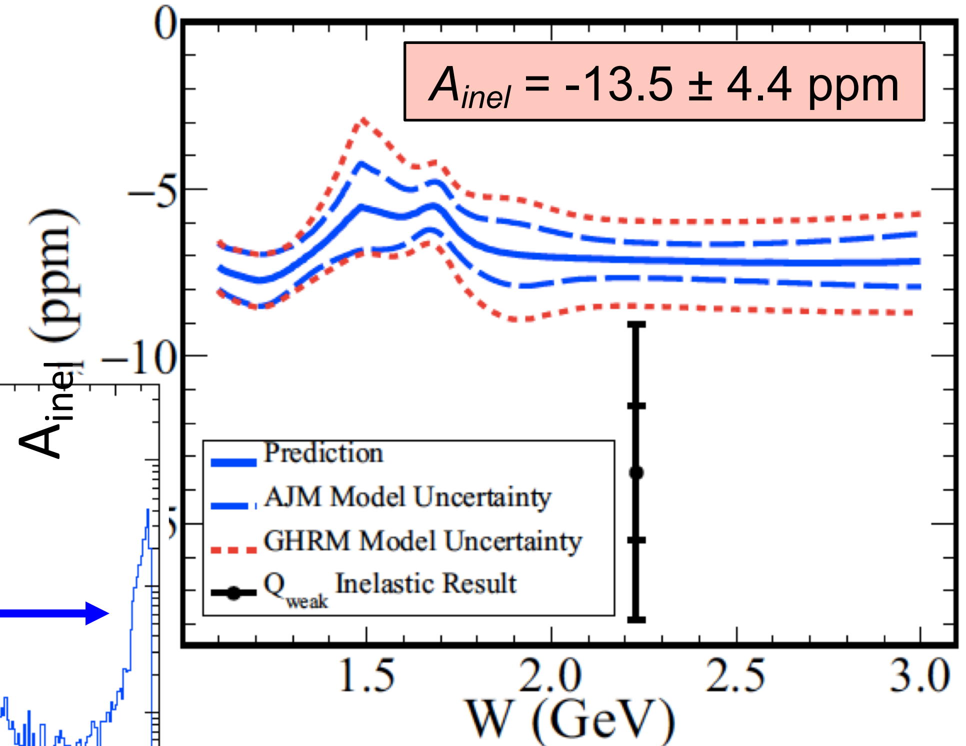


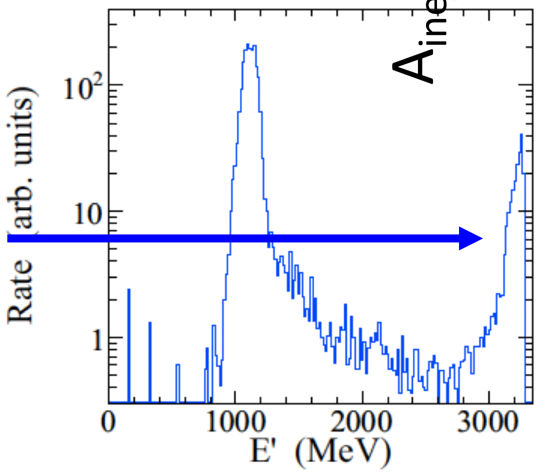
PV ep A_{inel} above the resonance region

- 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





Summary

- Q_{weak} Expt. msrd ep A = −226.5 ± 9.3 ppb @ $Q^2 = 0.0248\ GeV^2$
  - Determined $Q_W(p) = 0.0719 \pm 0.0045$, < 0.2 σ from SM
  - $\sin^2\theta_W = 0.2383 \pm 0.0011$(MS-bar), Avg(APV, E158, Q_{weak}) = 0.23861 ± 0.00077
  - Mass reach Λ = 26.6 TeV (uud, g^2=4π=compositeness, 95% CL)
    - Λ = 2.3 TeV (uud, g^2=4πα=leptoquarks, 95% CL)
    - Λ/g = 7.5 TeV (proton, ie uud, 95% CL), Λ/g = 3.6 TeV (flavor-independent, 95% CL)
- BNSSA:
  - ^1H B_n = -5.19 ± 0.07 (stat) ± 0.08 (syst) ppm (published)
    - Consistent with calculations & other far-forward angle data
  - ^{12}C & ^{27}Al elastic results ready for pre-readers
  - Inelastic ep→e'Δ preliminary (thesis) result B_n = 43 ± 16 ppm, paper "soon"
- Elastic A_{PV}^{27Al}, Q_W^{27Al}, δR_{np}^{27Al} paper this summer?
- Inelastic ep→e'Δ APV at 3.3 GeV (published) and at 1.1 GeV ("soon")

Thank you!