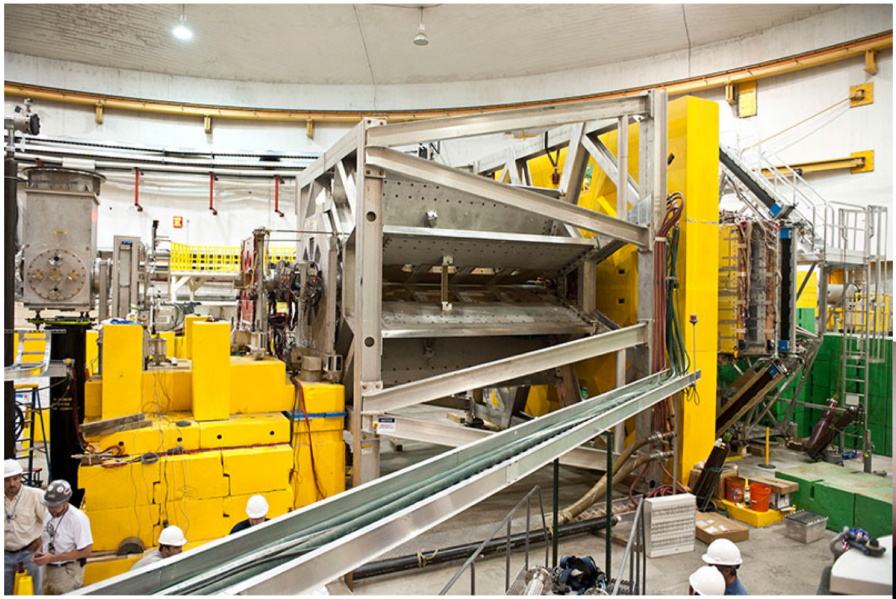
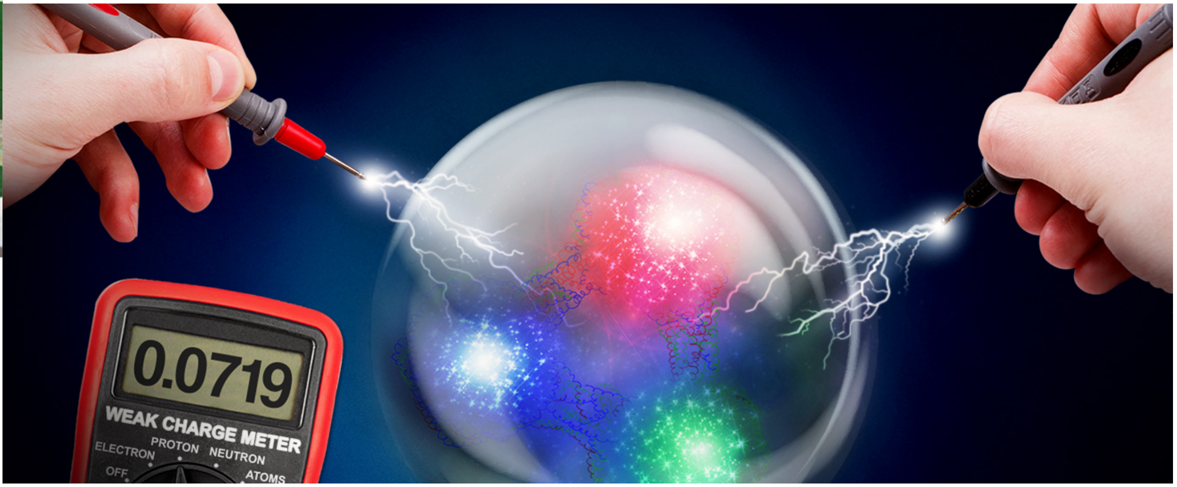
Beam-Normal Single-Spin Asymmetry results from Qweak

David S. Armstrong
William & Mary

for the Qweak Collaboration





Parity Violation and Related Topics
MITP Virtual Workshop July 27-30 2020

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

Outline

Three "Ancillary" results from Qweak

Parity-Violating Electron Scattering experiment at Jefferson Lab.

1) Introduction to Beam-Normal Single-Spin Asymmetry & two-photon physics.

2) Brief glance at Qweak apparatus

3) Final result on B_n from the proton at forward angle:
most precise such measurement to date.

Androic *et al.* arXiv:2006.12435
submitted to PRL, June 2020

4) Near-final results on B_n from ^{12}C and ^{27}Al at forward angle

)

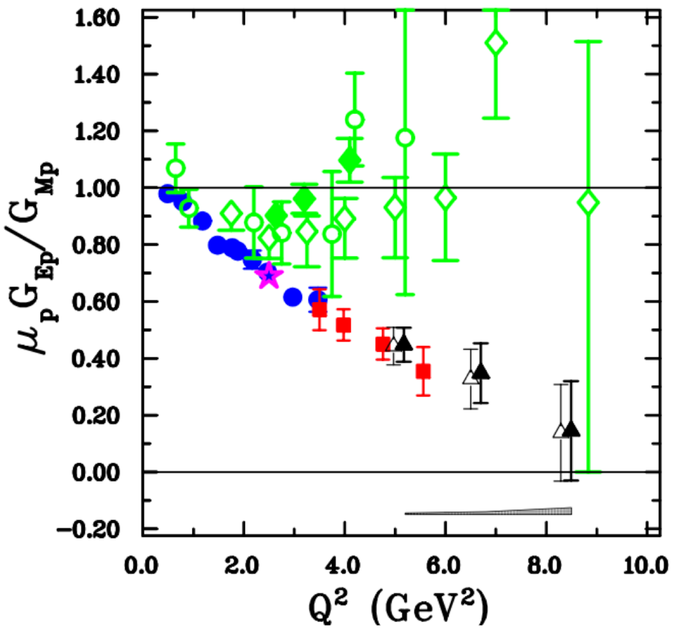
Beyond the Single-Boson exchange

Context: In precision electro-weak experiments, we now need to go beyond Born approximation and consider multi-boson exchange box diagrams *(etc.)*

Examples:

1. γW and WZ box diagrams in superallowed β-decay
   Seng, Gorchtein, Patel, and Ramsey Musolf *PRL* 121, 241804 (2018)
2. γZ box diagrams in weak charge measurements on the proton:
   Gorchtein & Horowitz *PRL* 102, 091806 (2009) *etc.*
   Qweak Androic *et al*. *Nature* 557, 207 (2018)
   Motivation for P2 experiment: Becker *et al. Eur.Phys.J A* 54, 208 (2018)
3. G_E^p/G_M^p : Rosenbluth *vs*. Recoil Polarization: $\gamma\gamma$ box diagrams

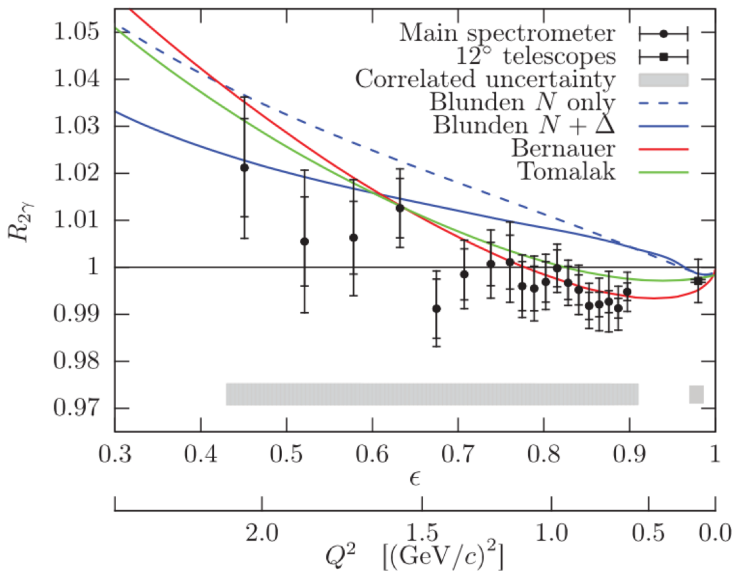
Gorchtein, Guichon & Vanderhaeghen
Nucl. Phys. A741, 234 (2004)
Afanasev, Blunden, Hasell and Raue
Prog. Part. Nucl. Phys. 95, 245 (2017)
A.J.R. Puckett et al.
Phys. Rev. C 96, 055203 (2017)
etc.



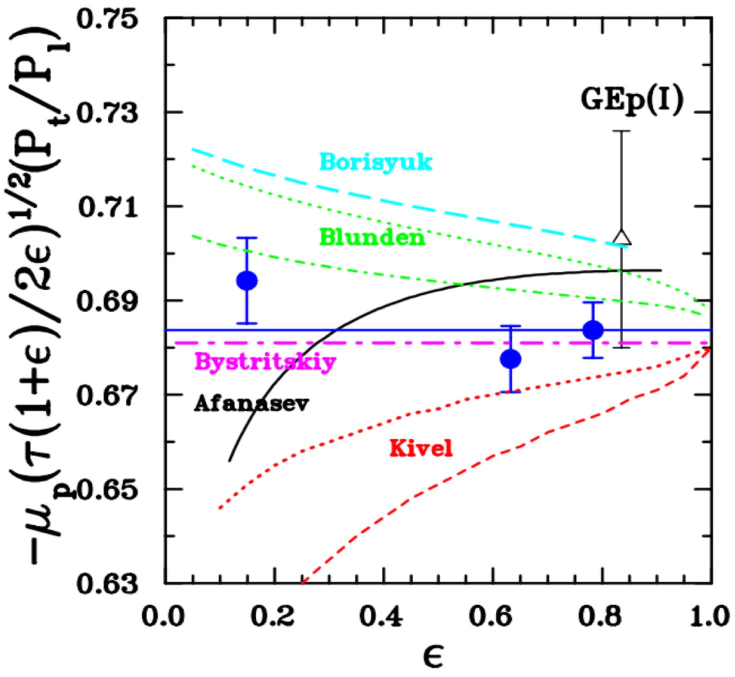
Exploring Two-Photon Physics

A) Difference between e^-p and e^+p (or μ^-p and μ^+p) scattering cross sections:

VEPP-3 Rachek et al. *PRL* 114, 062005(2015)
OLYMPUS Henderson et al. *PRL* 118, 092501 (2018)
CLAS Adhikaram et al. *PRL* 114, 062003 (2015)
MUSE Gilman et al. arXiv:1709.09753 (2017)

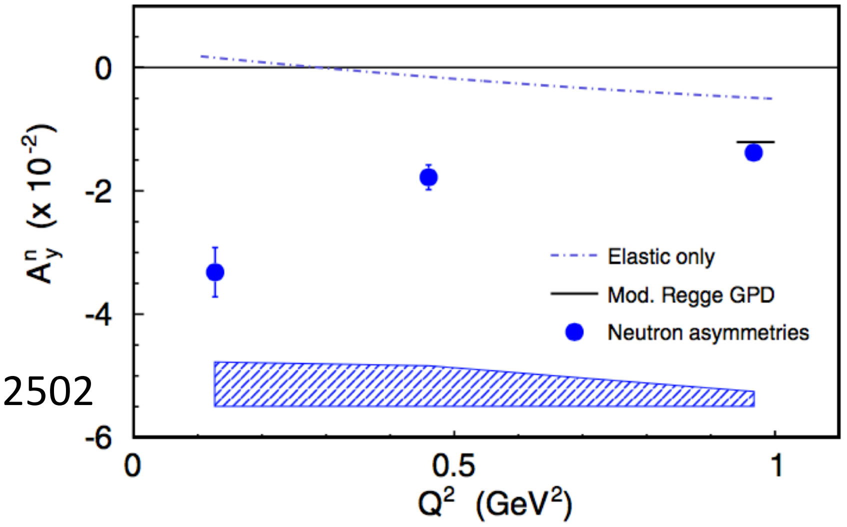


B) ϵ- dependence of recoil polarization measurements:



Puckett et al. Phys. Rev. C 96, 055203 (2017)

C) Target-Normal Single Spin Asymmetries:



Zhang et al. PRL 115,0172502 (2015)

Beam-Normal Single Spin Asymmetry

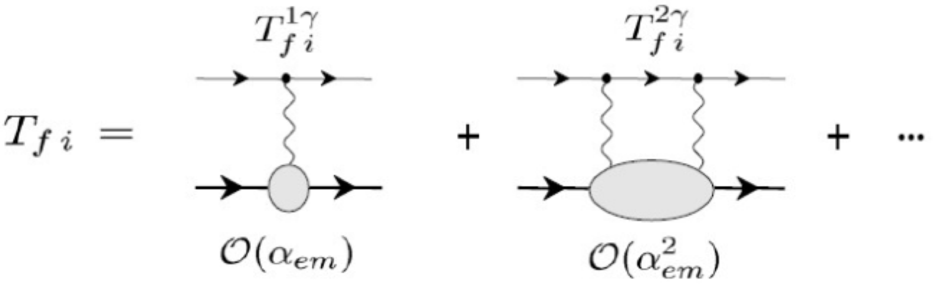
D) Beam-Normal Single-Spin Asymmetry B_n

- 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

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



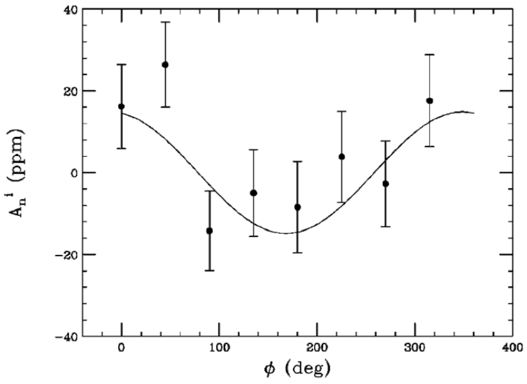
Generates azimuthal asymmetry variation: $A_{\exp}(\phi) \approx B_n \vec{P} \cdot \hat{n}$.

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

$\vec{k}(\vec{k'})$: 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!

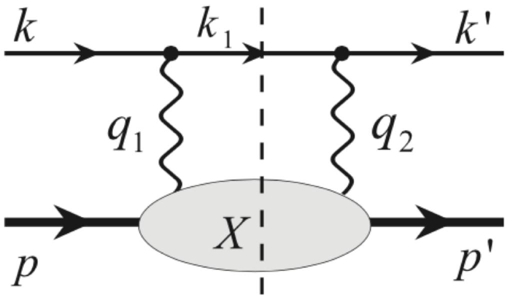
- "Vector Analyzing Power" : SAMPLE , Cooper & Horowitz, E158
- "Transverse Beam Asymmetry" : HAPPEX/PREx
- "Single-Spin Beam Asymmetry" : Afanasev & Merenkov
- "Transverse Beam Spin Asymmetry" : G0 forward, PVA4
- "Beam Transverse Single Spin Asymmetry" : PVA4
- "Beam Normal Spin Asymmetry" : Gorchtein, 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 recentlyused 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.

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

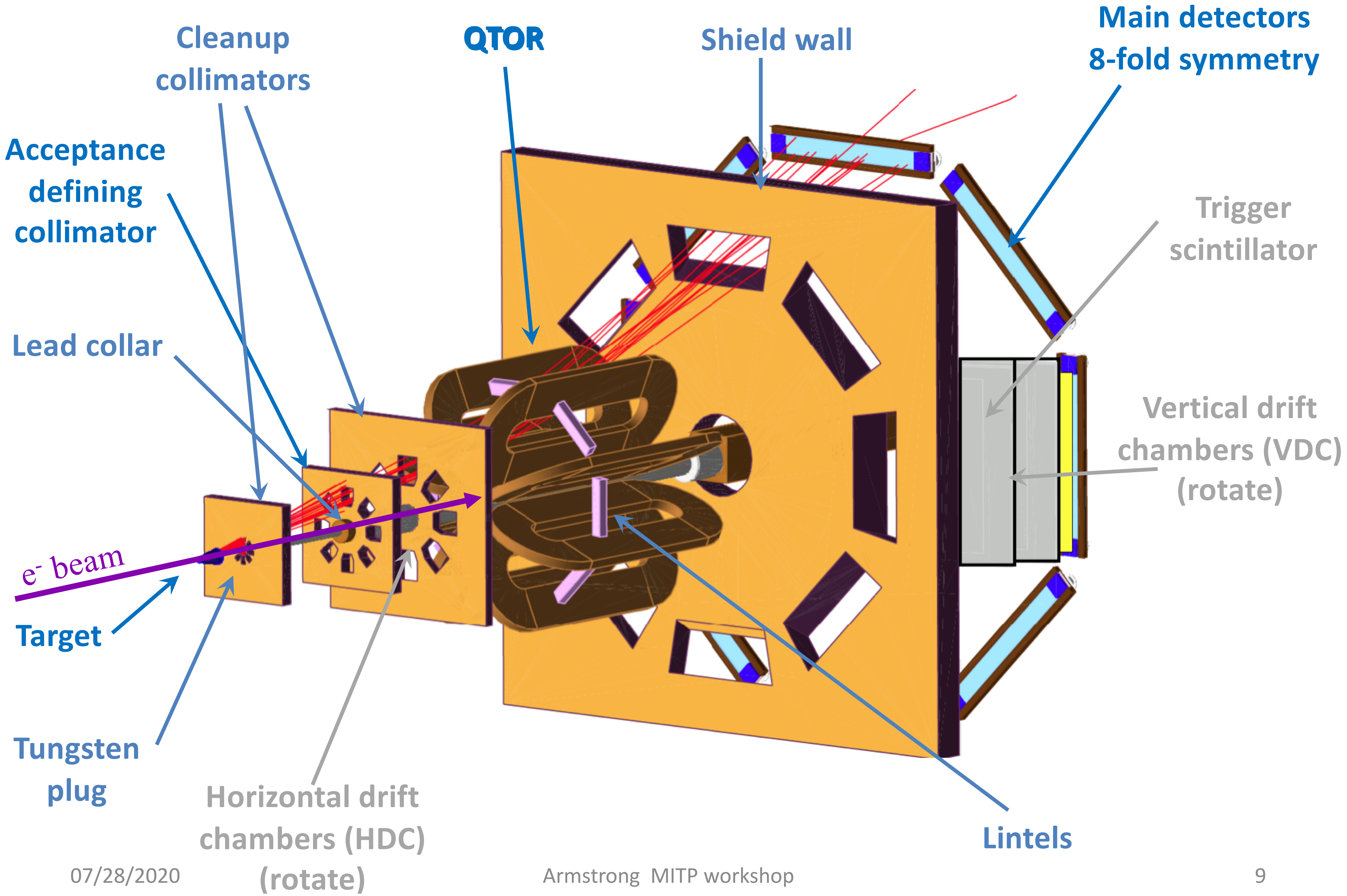
This talk:

- proton at forward angle, high precision
- ^{12}C, ^{27}Al at forward angle

Qweak

- Dustin McNulty will present preliminary results from PREx-2/CREx for ^{12}C, ^{40}Ca, ^{48}Ca and ^{208}Pb in his talk tomorrow – watch for it!

The Q_{weak} Apparatus



Cleanup collimators

QTOR

Shield wall

Main detectors
8-fold symmetry

Acceptance defining collimator

Trigger scintillator

Lead collar

Vertical drift chambers (VDC) (rotate)

e^- beam

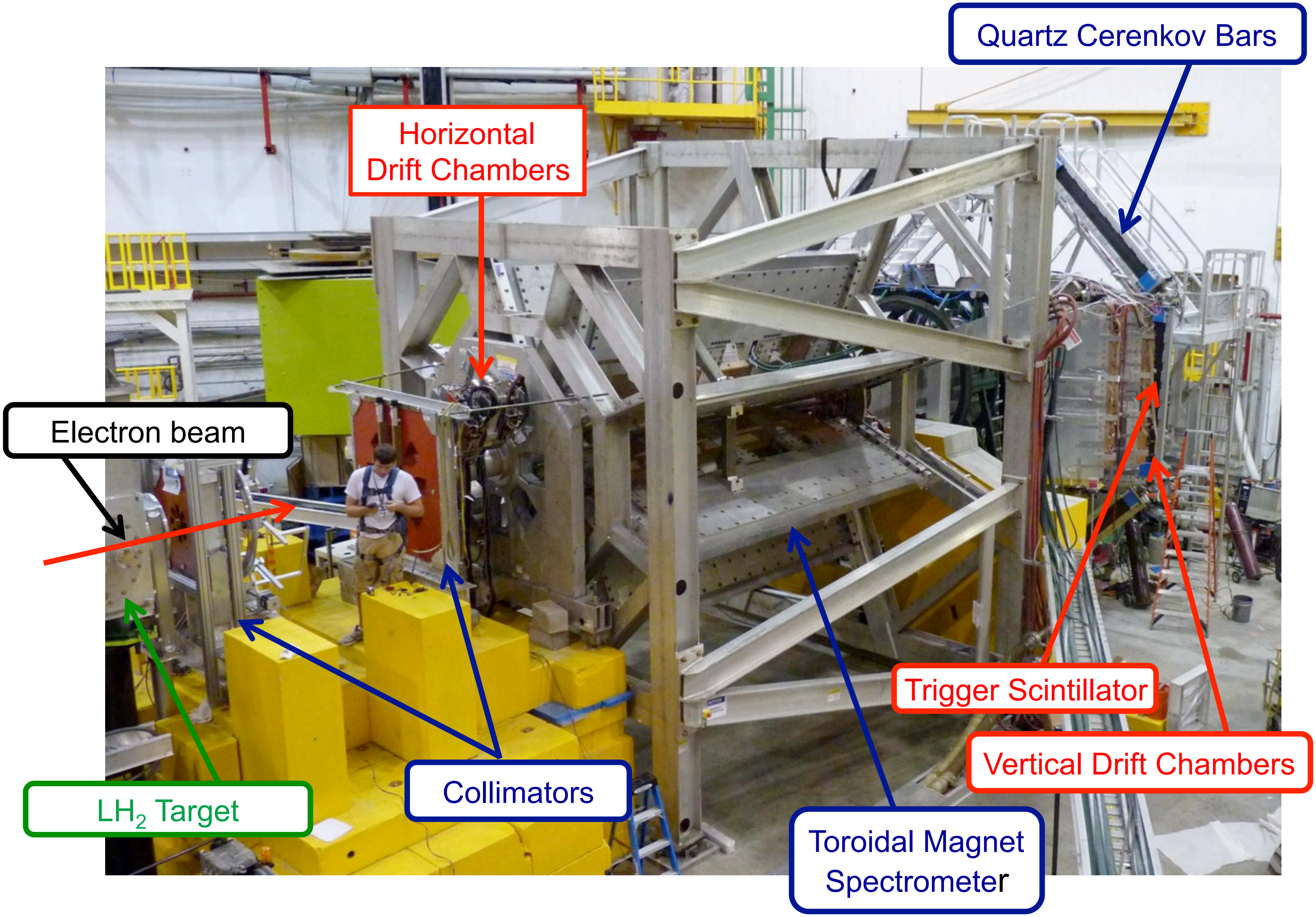
Target

Tungsten plug

Horizontal drift chambers (HDC) (rotate)

Lintels

The Q_{weak} Apparatus – during installation



Quartz Cerenkov Bars

Horizontal Drift Chambers

Electron beam

Trigger Scintillator

Vertical Drift Chambers

LH$_2$ Target

Collimators

Toroidal Magnet Spectrometer

BNSSA on proton

Experimental Conditions

Transverse beam polarization taken in three data sets:
Two with vertical beam polarization (different run periods)
& One with horizontal

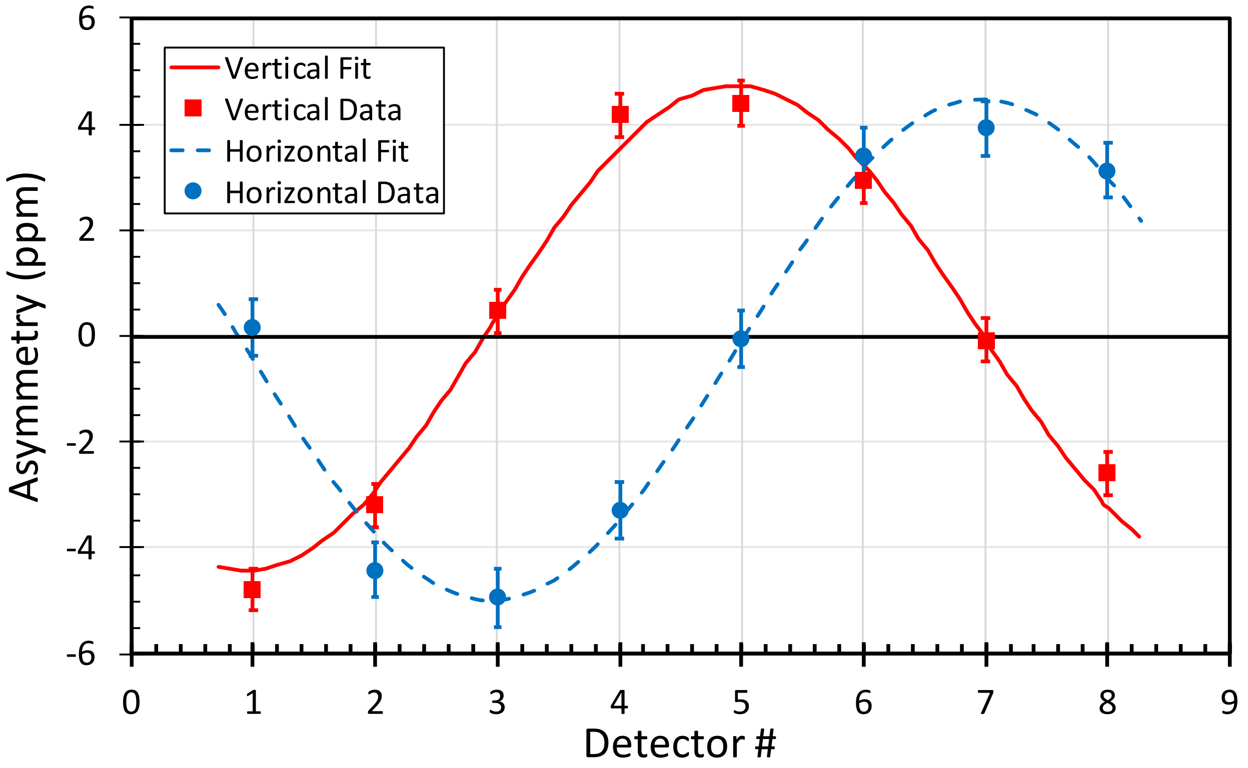
Beam Conditions:

E_e = 1.16 GeV
I = 180 μA
Polarization: P = $88.7 \pm 0.7\%$

Spectrometer:

$\langle\theta\rangle = 7.9° \quad 5.8° \leq \theta \leq 11.6°$
$\langle Q^2\rangle$ = 0.0248 GeV^2

BNSSA on proton

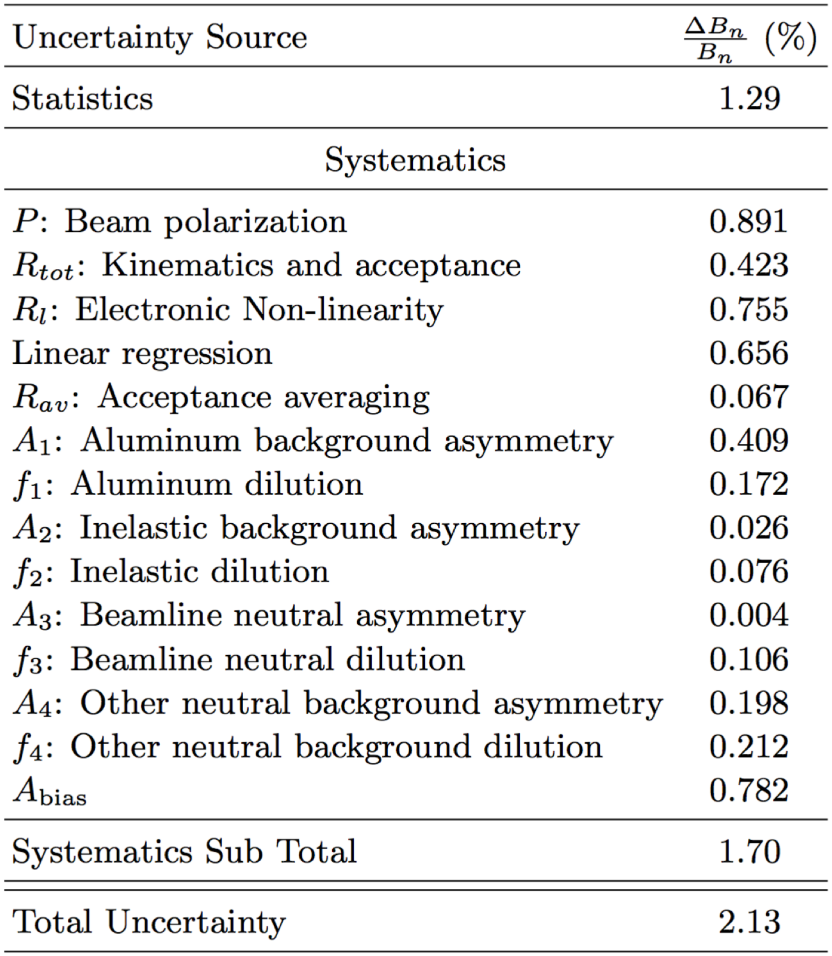


Measurement	A_{exp} (ppm)
Period 1, Vertical Transverse Polarization	-4.803 ± 0.089
Period 2, Vertical Transverse Polarization	-4.697 ± 0.142
Period 3, Horizontal Transverse Polarization	-4.837 ± 0.084

BNSSA on proton

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

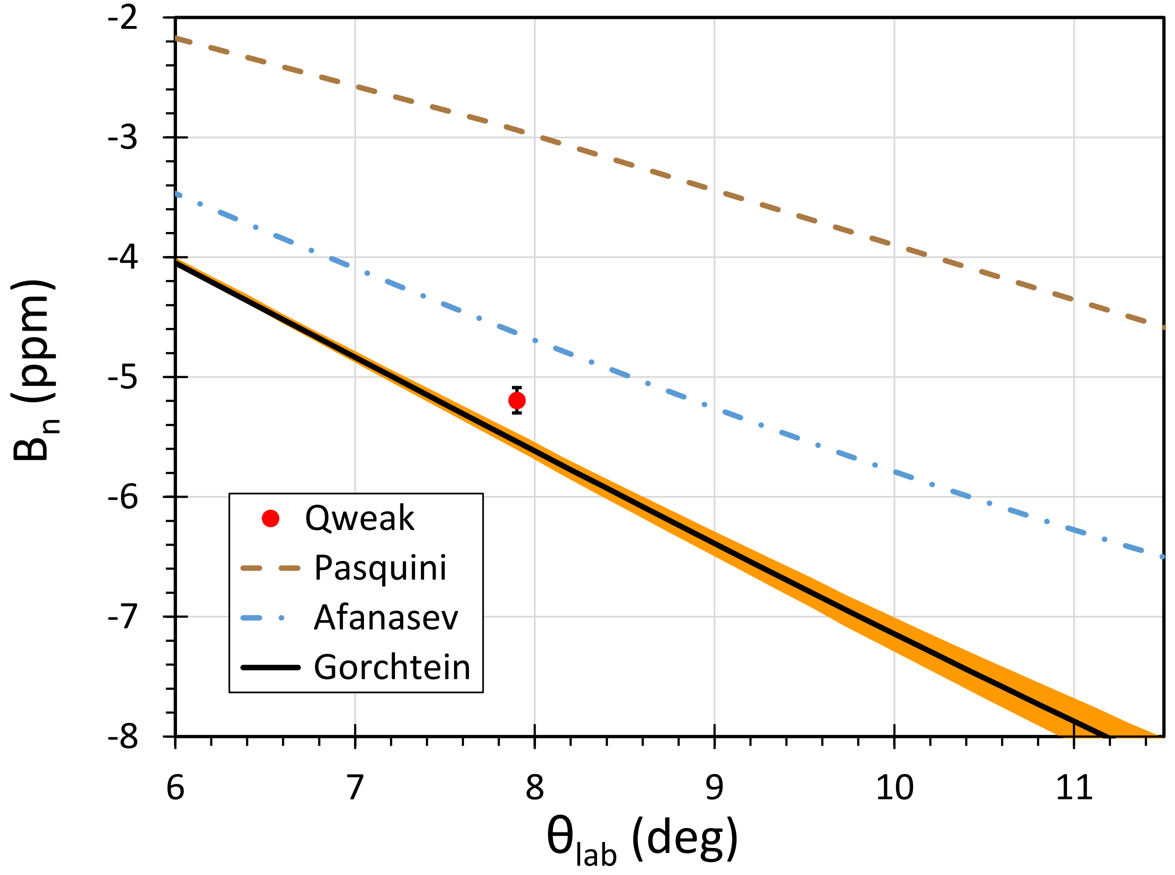
$$B_n = R_{\text{tot}} \left[\frac{A_{\text{exp}}/P - \sum_{i=1}^{2} f_i A_i}{1 - \sum_{i=1}^{4} f_i} \right] + A_{\text{bias}}$$



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_{bias}	0.782
Systematics Sub Total	1.70
Total Uncertainty	2.13

BNSSA on proton - result

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

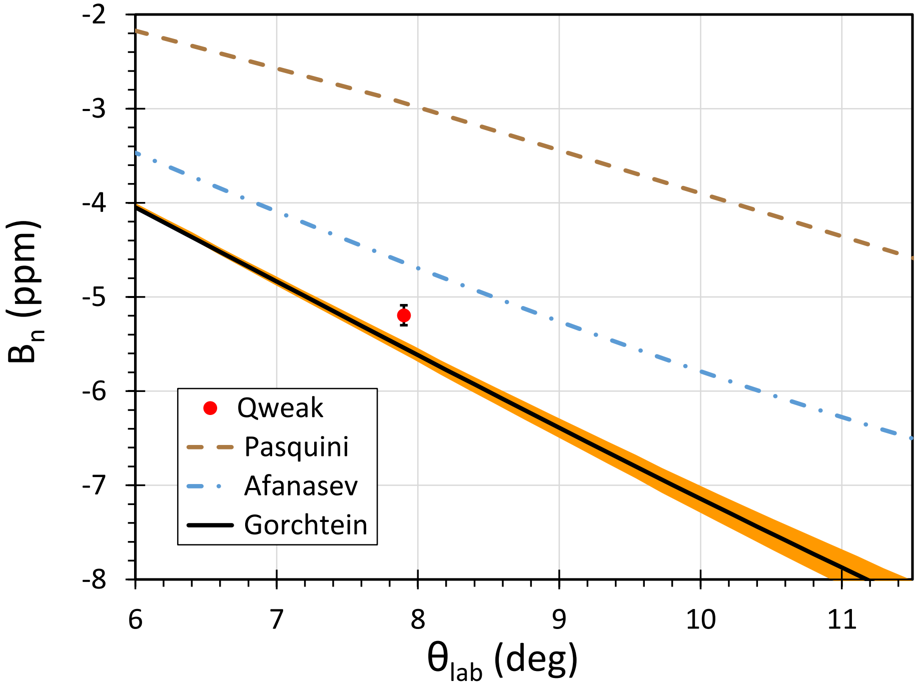


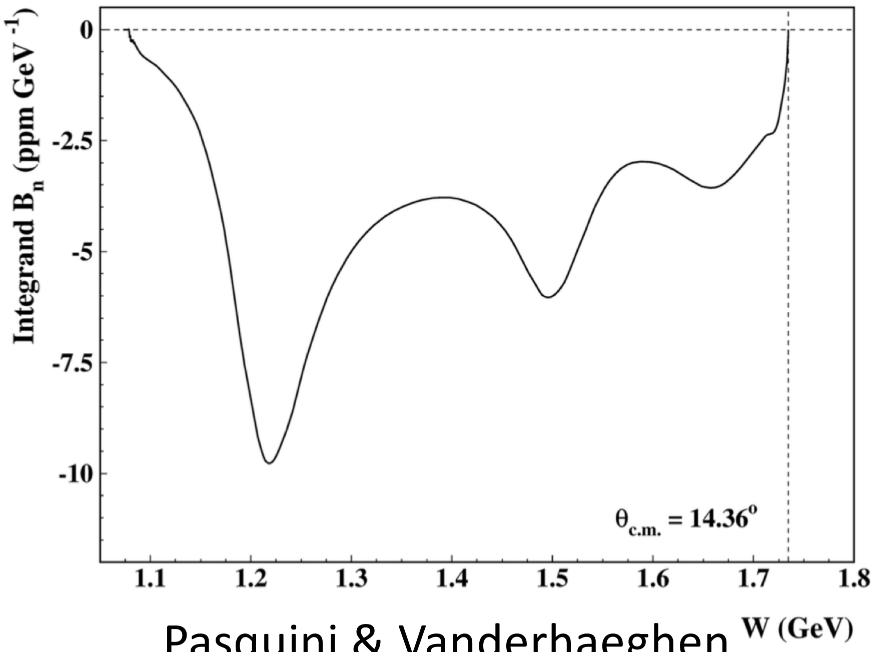
Models:

- 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 - result





Pasquini & Vanderhaeghen

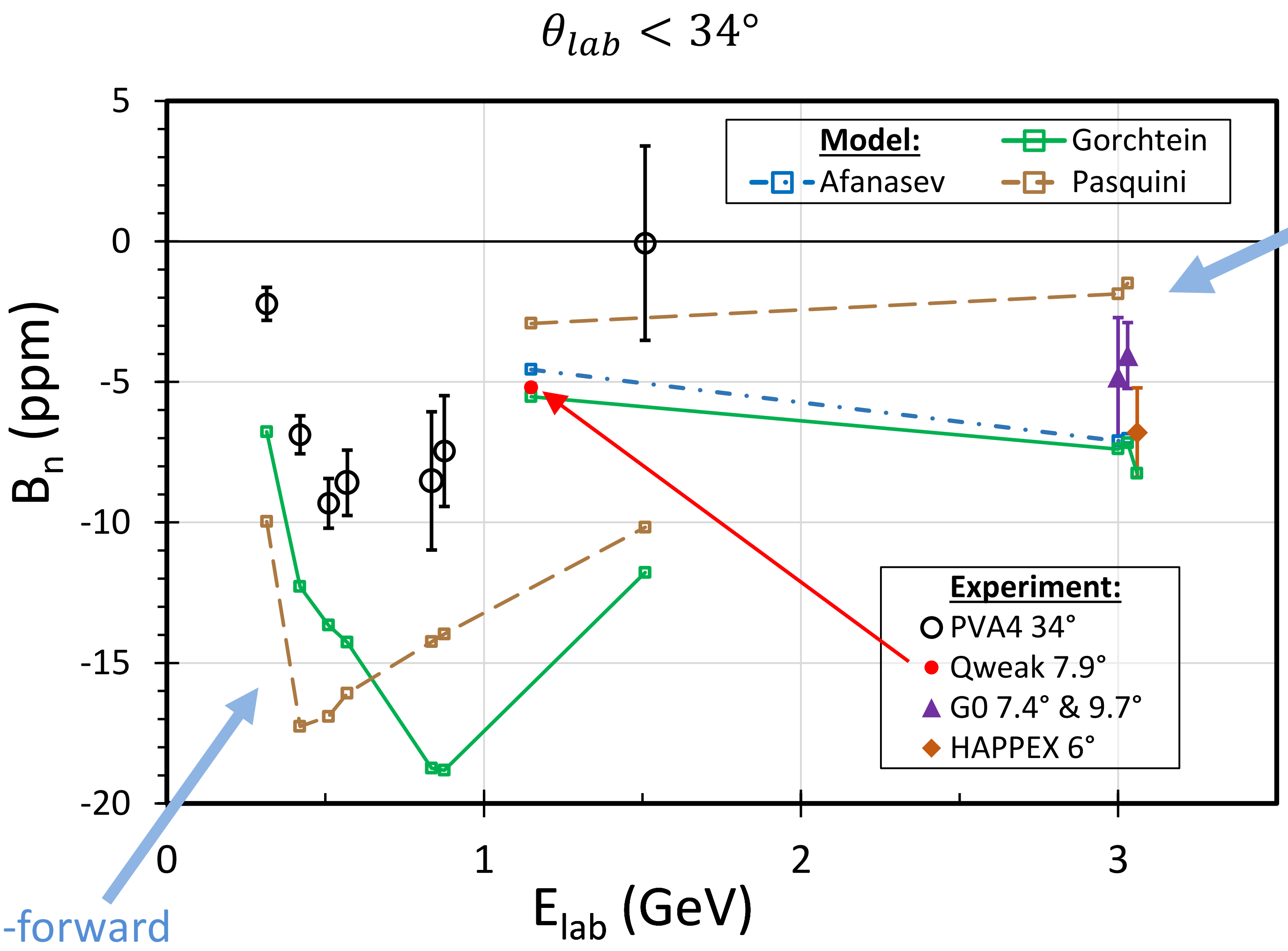
Inelastic intermediate states dominate at these kinematics.

Pasquini & Vanderhaeghen: πN 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)

BNSSA on proton – world data, forward angles



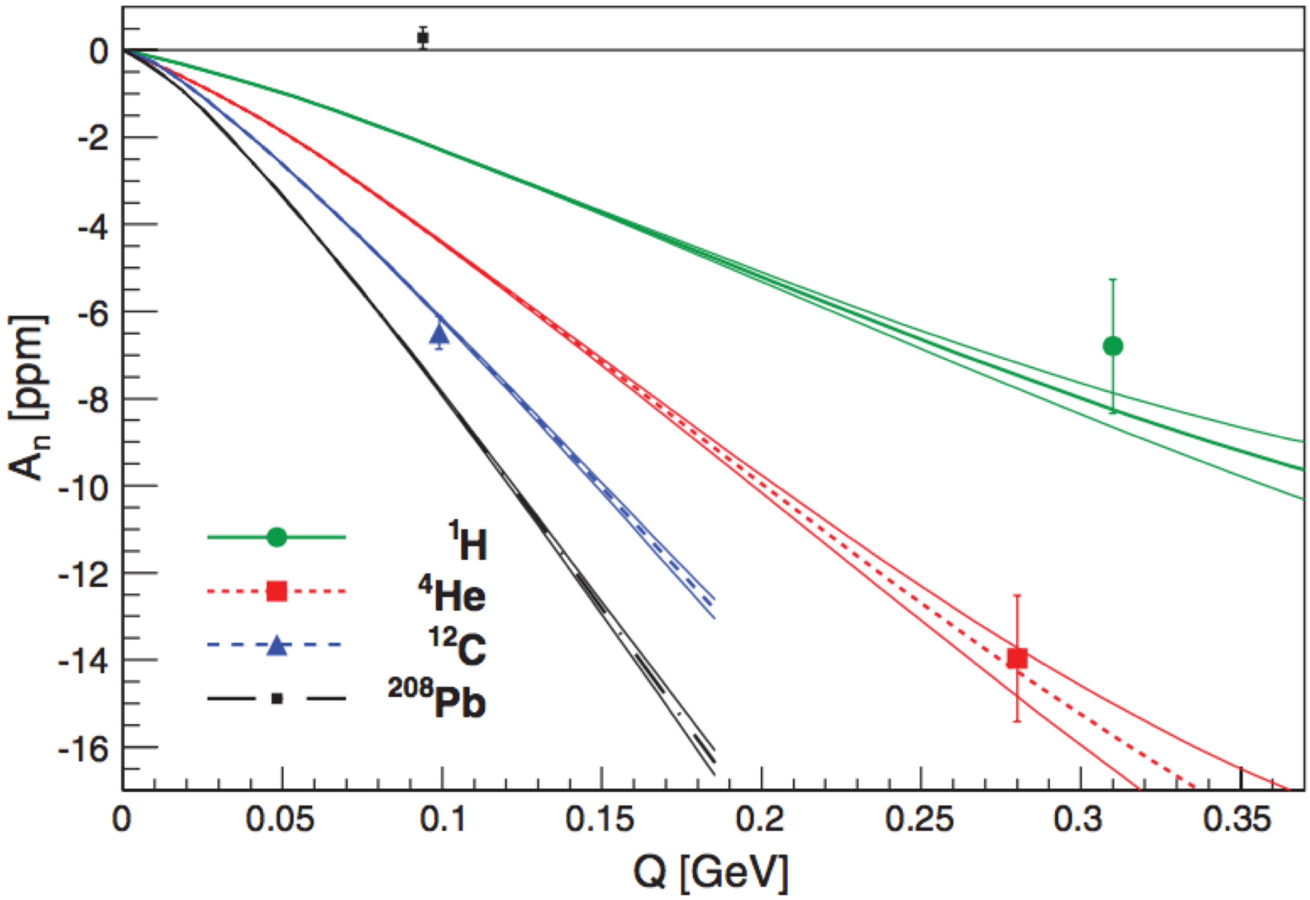
Far-forward angles ($\theta < 10°$)

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

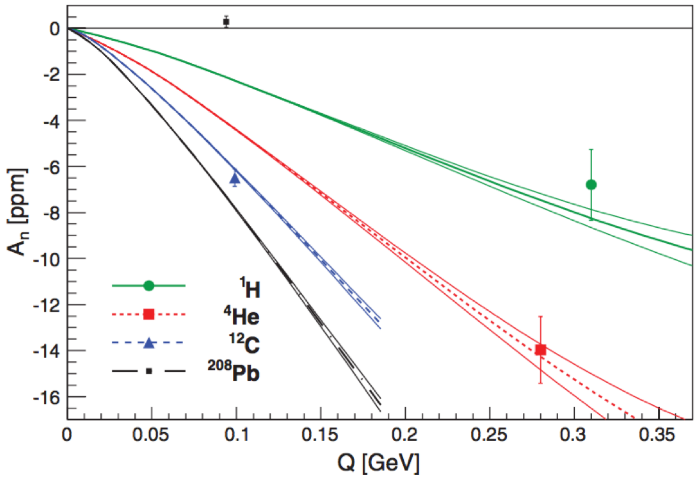
BNSSA on nuclei – PREx 1/HAPPEx



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 σ – contribution scales as A/Z.

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

Additional nuclear target dependence could arise in model:

- Terms not enhanced by large log

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

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

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

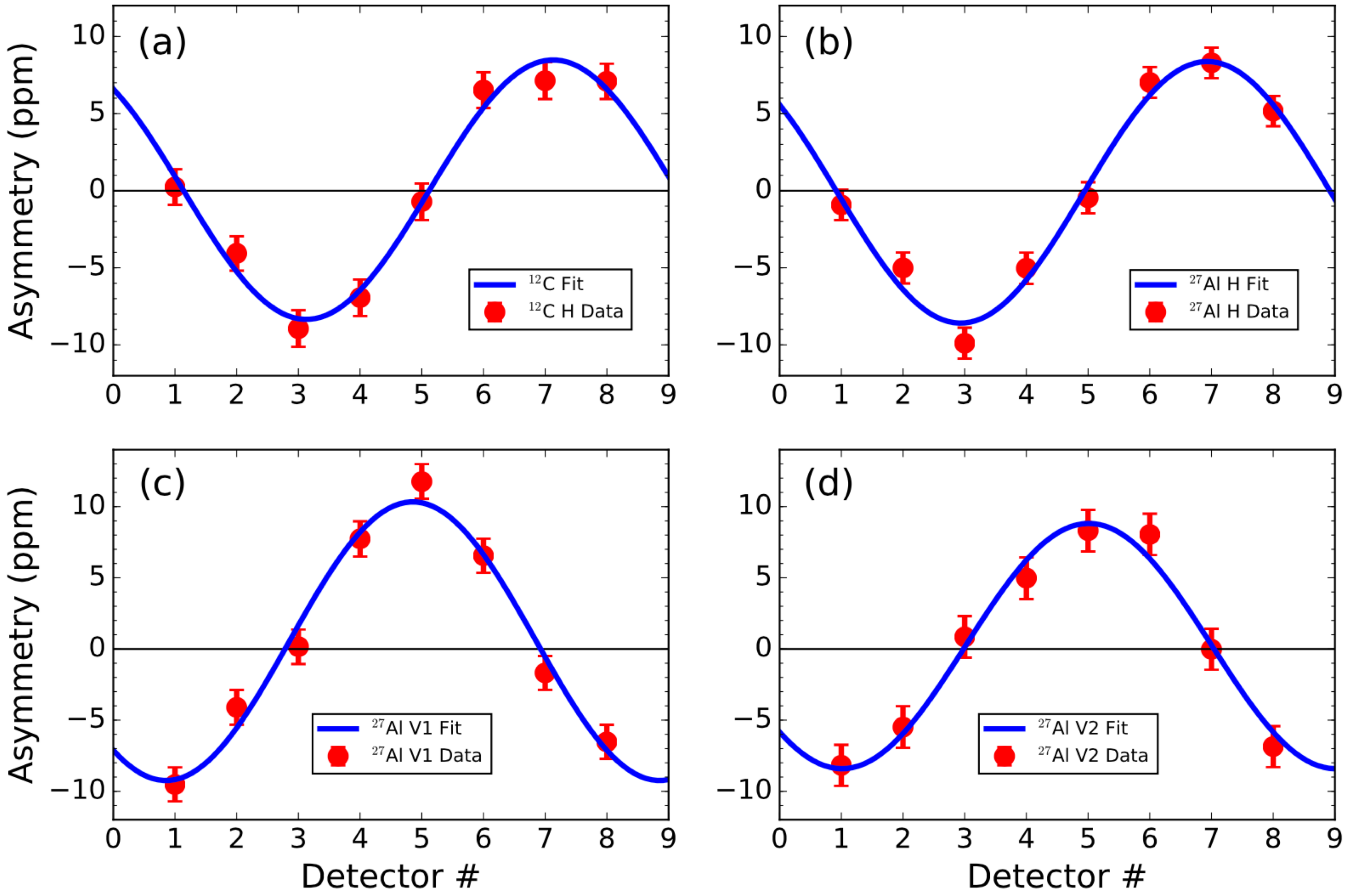
Beam Conditions:

E_e = 1.16 GeV
I = 75 μA (^{12}C) 24 μA , 61 μA (^{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

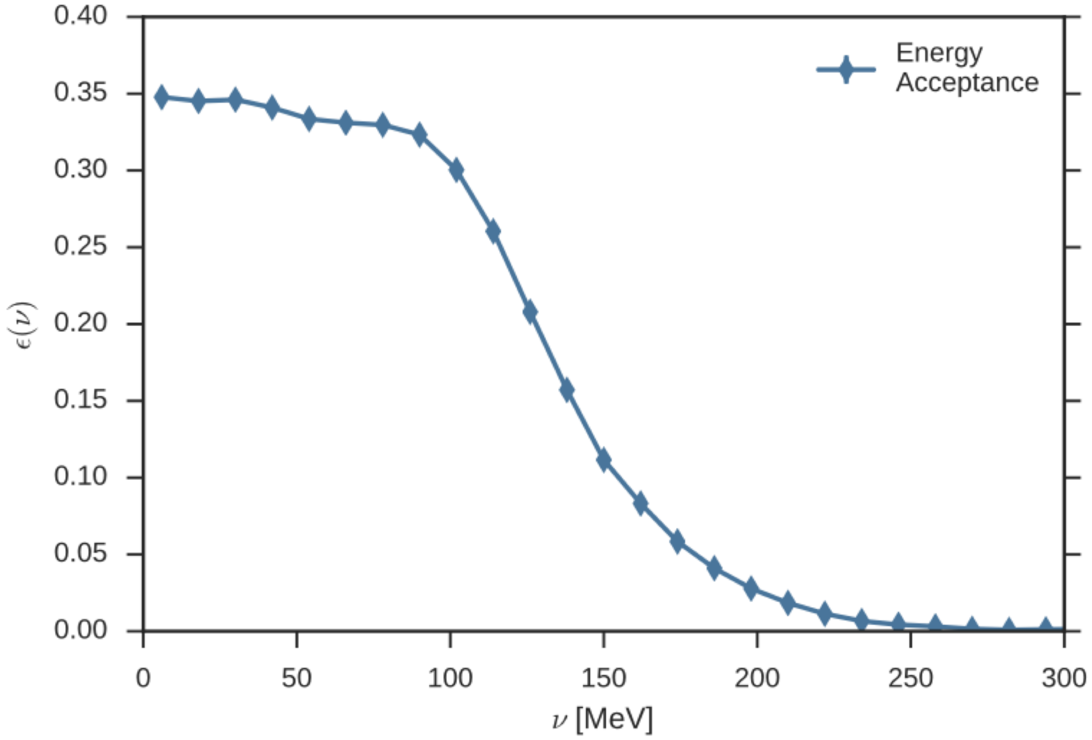


BNSSA on ^{12}C, ^{27}Al - challenges

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.

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

  (P. Bosted and V. Mamyan arXiv:1203.2262v2)

f_{QE} = 12.8 ± 1.3 % (^{27}Al) 9.6 ± 4.0 % (^{12}C)

f_{inel} = ≈7.4 % (^{27}Al) ≈4.5 % (^{12}C)

These are being refined – put more recent Hall C data at low Q^2 in fit to world data – remaining task before publication

Asymmetry: A_i

- Quasielastic:

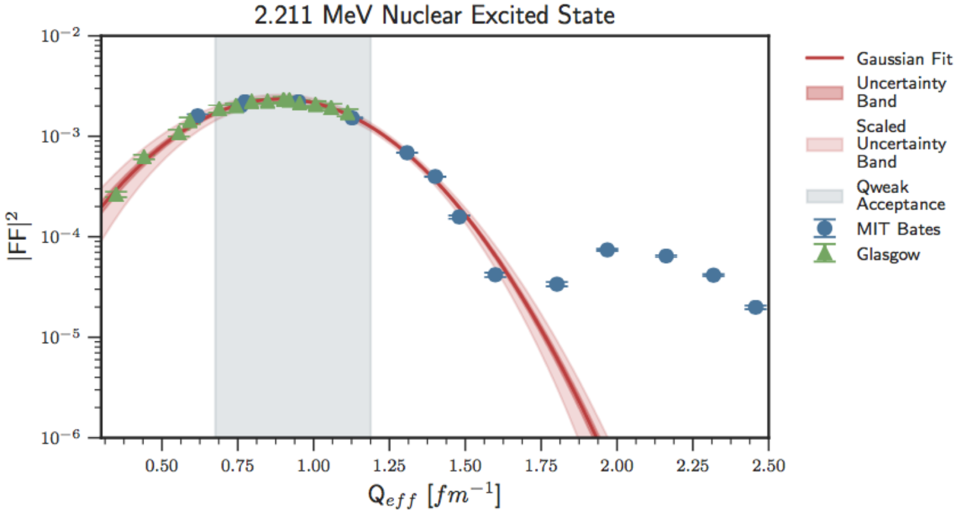
  used our proton B_n measurement, inflated uncertainty: $A_{QE} = -5.2 \pm 1.0$ ppm
- Inelastic:

  made a separate measurement: $A_{inel} = +43 \pm 16$ ppm

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	relative yield (%)
0 (ground)	$5/2^+$	95.6 ± 0.4
0.844	$1/2^+$	0.27 ± 0.04
1.014	$3/2^+$	0.41 ± 0.10
2.211	$7/2^+$	1.35 ± 0.16
2.735	$5/2^+$	0.19 ± 0.02
2.990	$3/2^+$	0.93 ± 0.07
4.540		0.06 ± 0.01
4.812	$5/2^+$	0.09 ± 0.02
5.430		0.17 ± 0.03
5.668	$9/2^+$	0.08 ± 0.02
7.228	$9/2^+$	0.18 ± 0.06
7.477		0.10 ± 0.07
21	(GDR)	0.58 ± 0.29

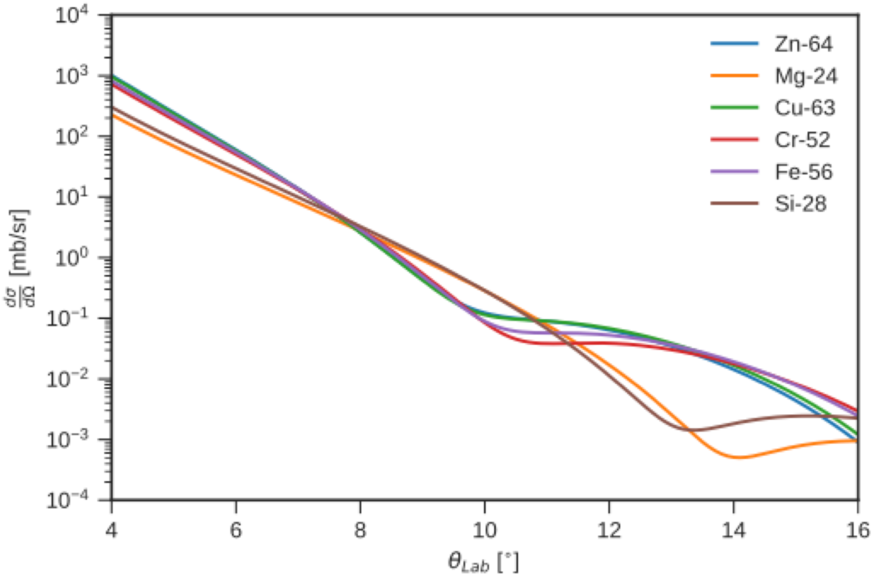
^{12}C

Energy (MeV)	J^P	relative yield (%)
0 (ground)	0^+	71.6 ± 7.9
4.44	2^+	3.5 ± 0.3
7.65	0^+	10.3 ± 2.1
9.64	3^-	11.6 ± 1.4
24	1^- (GDR)	1.9 ± 0.4

No guidance on B_n for these states – make no correction for them

^{27}Al – alloy corrections

Element	Background fraction (f_i) (%)
Zn	2.375 ± 0.249
Mg	2.088 ± 0.219
Cu	0.683 ± 0.073
Cr	0.100 ± 0.011
Si	0.080 ± 0.009
Fe	0.054 ± 0.006
Mn	0.018 ± 0.009
Ti	0.014 ± 0.007
net Alloy	5.41 ± 0.34



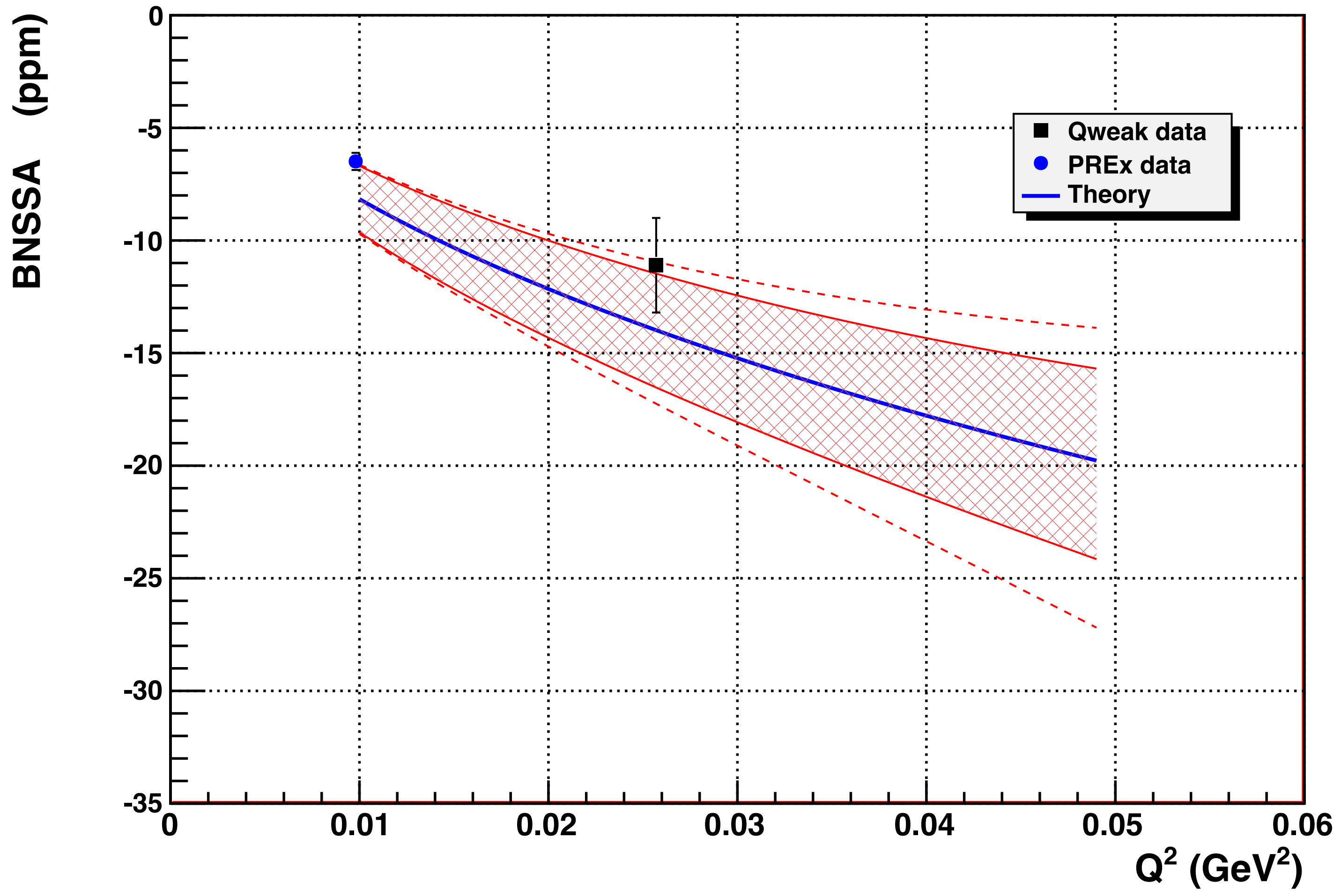
Correction method:

- Considered most abundant isotopes of Zn, Mg, Cu, Cr, Fe, and Si
- Considered only elastic scattering
- Dilution calculation using distorted-wave cross sections from Horowitz and Lin for Zn, Mg, Cu, Cr, Fe, Si. Asymmetries from same calculation.
- For Mn and Ti, used Born approximation cross-section model, with Fourier-Bessel form factor fit.

Asymmetries:

Assumed Gorchtein & Horowitz model A/Z scaling

BNSSA on ^{12}C: Qweak and PRex-1

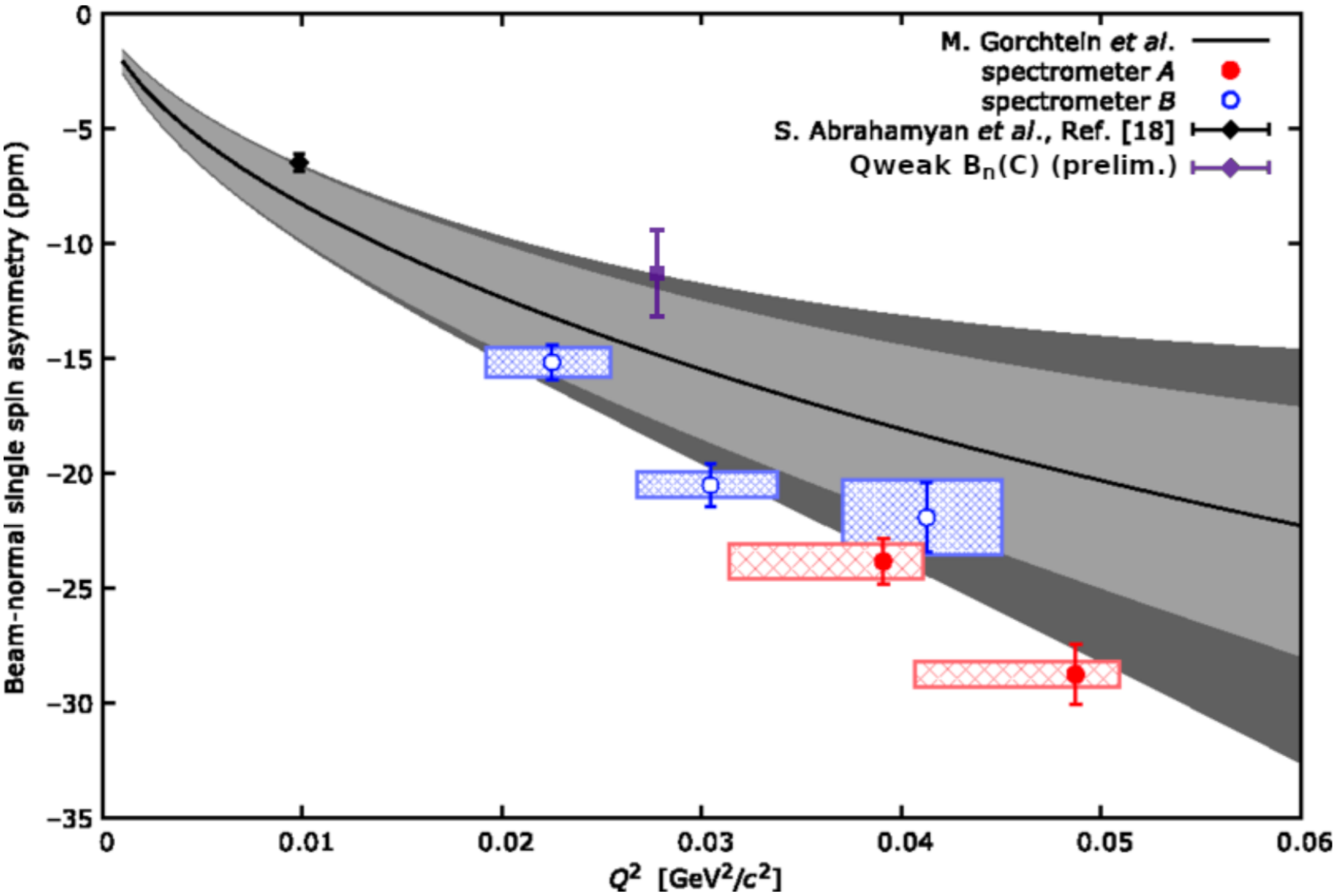


Theory: M. Gorchtein priv. comm.

method of Gorchtein & Horowitz

PREx-1: Abrahamyan *et al.* *PRL* 109,192501 (2012)

BNSSA on ^{12}C : World data



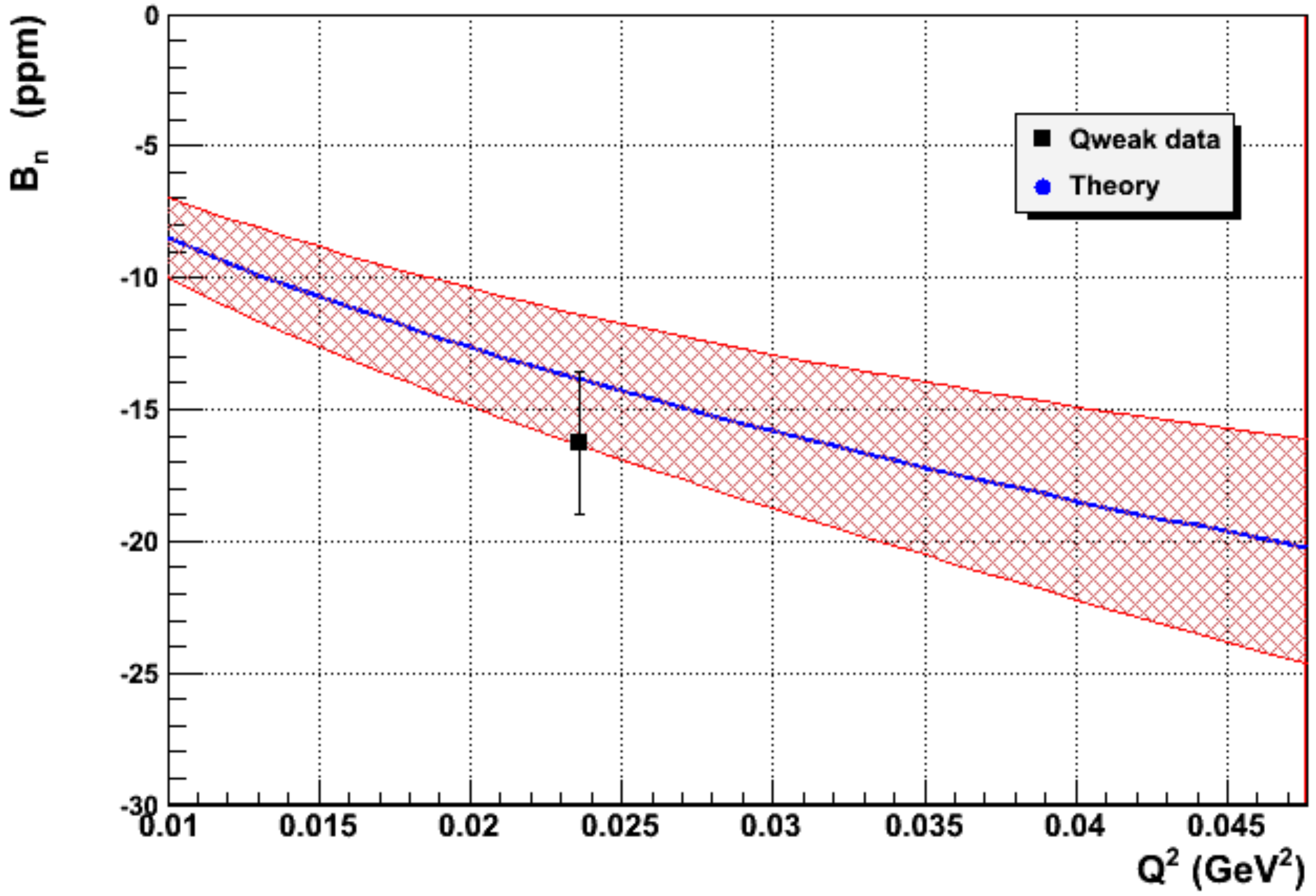
PREx-1: Abrahamyan *et al.* *PRL* 109,192501 (2012)

A1: Esser *et al.* *PRL* 121, 022503 (2018)

A1 results: E_{beam} = 0.57 GeV

PREx, Qweak: Ebeam ≈1.1 GeV

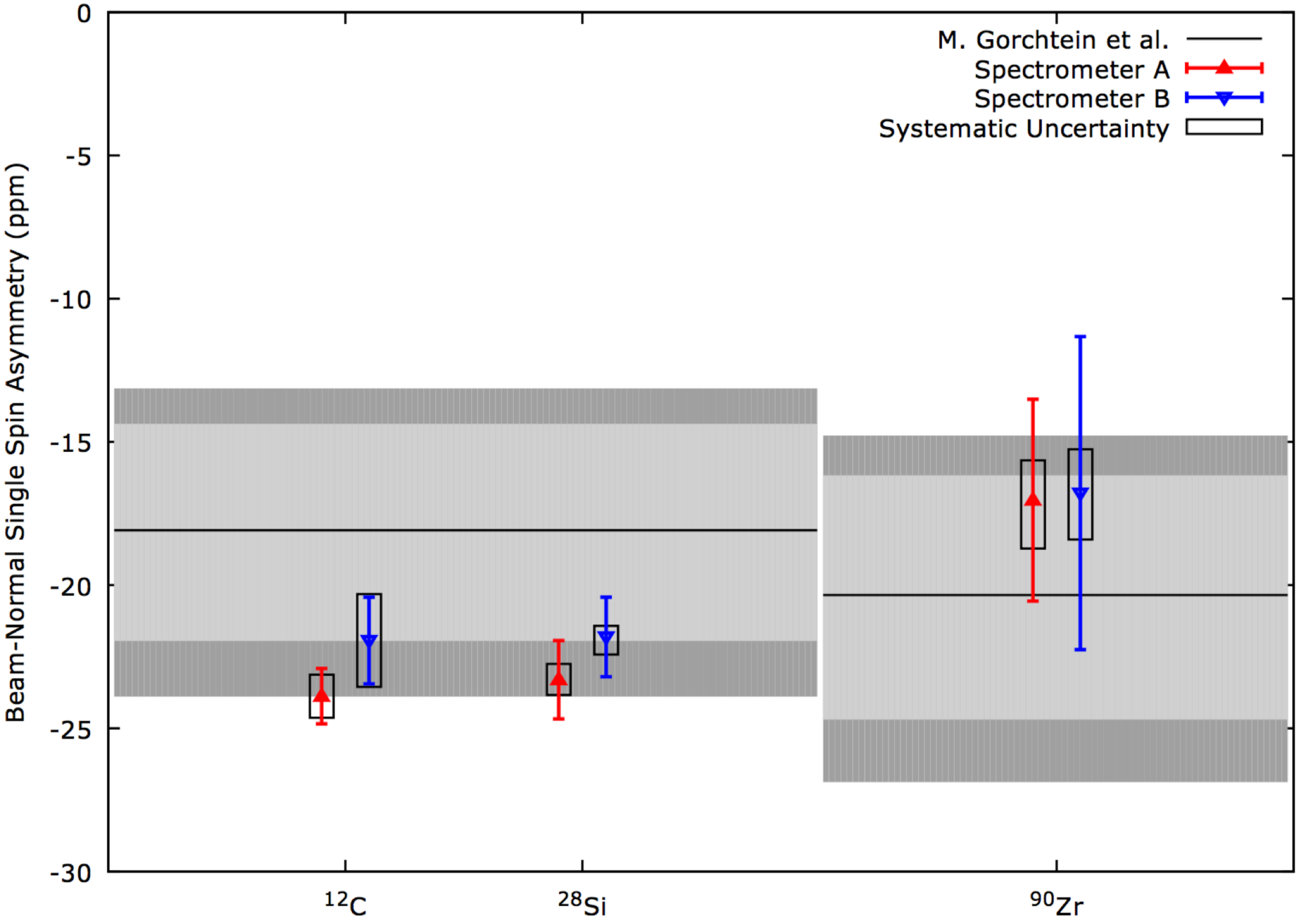
BNSSA on ^{27}Al



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

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

Other Nuclear BNSSA results: Mainz/A1



Esser et al.
arXiv:2004.14682
(submitted to Phys Lett B)

Theory:
Gorchtein & Horowitz

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

Q_{weak} Auxiliary Measurements

Many ancillary measurements done to quantify various systematic effects.
Q_{weak} has data on a variety of other observables of interest:

- Beam normal single-spin asymmetry for elastic scattering on proton
- Beam normal single-spin asymmetry for elastic scattering on ^{27}Al, ^{12}C

} this talk

- PV asymmetry in inelastic region near W=2.5 GeV (related to γZ box diagrams)
- Beam normal single-spin asymmetry for electrons and pions near W= 2.5 GeV

"Parity-violating electron-proton scattering at low Q^2 above the resonance region"
Androic *et al.* Phys. Rev. C 101, 055502 (2020)

- PV asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ region.
- PV asymmetry for elastic scattering from ^{27}Al - neutron radius for ^{27}Al
- PV asymmetry in Moller scattering at forward angles

} Finishing up analysis

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

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:

  PREx ^{208}Pb result remains a puzzle
- Nuclear excited state contributions to ^{12}C : similar B_n to ground state

Thanks to the organizers for inviting me to give this talk.
Thanks for listening!
I hope to see many of you next year in Mainz at PAVI 2021.

The Qweak Collaboration

101 collaborators 26 grad students
11 post docs 27 institutions

Institutions:

[1] University of Zagreb
[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

D. Androic,[1] D.S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] K. Bartlett,[2] J. Beaufait,[5] R.S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7,25] J. Birchall,[8] R.D. Carlini,[5, 2] G.D. Cates,[9] J.C. Cornejo,[2] S. Covrig,[5] M.M. Dalton,[9] C.A. Davis,[10] W. Deconinck,[2] J. Diefenbach,[11] J.F. Dowd,[2] J.A. Dunne,[12] D. Dutta,[12] W.S. Duvall,[13] M. Elaasar,[14] W.R. Falk*,[8] J.M. Finn*,[2,] T. Forest,[15, 16], C. Gal,[9] D. Gaskell,[5] M.T.W. Gericke,[8] J. Grames,[5] V.M. Gray,[2] K. Grimm,[16, 2] F. Guo,[4] J.R. Hoskins,[2] K. Johnston,[16] D. Jones,[9] M. Jones,[5] R. Jones,[17] M. Kargiantoulakis,[9] P.M. King,[6] E. Korkmaz,[18] S. Kowalski,[4] J. Leacock,[13] J. Leckey,[2,] A.R. Lee,[13] J.H. Lee,[6, 2,] L. Lee,[10] S. MacEwan,[8] D. Mack,[5] J.A. Magee,[2] R. Mahurin,[8] J. Mammei,[13,] J.W. Martin,[19] M.J. McHugh,[20] D. Meekins,[5] J. Mei,[5] R. Michaels,[5] A. Micherdzinska,[20] A. Mkrtchyan,[3] H. Mkrtchyan,[3] N. Morgan,[13] K.E. Myers,[20] A. Narayan,[12] L.Z. Ndukum,[12] V. Nelyubin,[9] H. Nuhait,[16] Nuruzzaman,[11, 12] W.T.H van Oers,[10, 8] A.K. Opper,[20] S.A. Page,[8] J. Pan,[8] K.D. Paschke,[9] S.K. Phillips,[21] M.L. Pitt,[13] M. Poelker,[5] J.F. Rajotte,[4] W.D. Ramsay,[10, 8] J. Roche,[6] B. Sawatzky,[5] T. Seva,[1] M.H. Shabestari,[12] R. Silwal,[9] N. Simicevic,[16] G.R. Smith,[5] P. Solvignon*,[5] D.T. Spayde,[22] A. Subedi,[12] R. Subedi,[20] R. Suleiman,[5] V. Tadevosyan,[3] W.A. Tobias,[9] V. Tvaskis,[19, 8] B. Waidyawansa,[6] P. Wang,[8] S.P. Wells,[16] S.A. Wood,[5] S. Yang,[2] R.D. Young,[23] P. Zang,[24] and S. Zhamkochyan [3]

Spokespersons Project Manager Grad Students *deceased

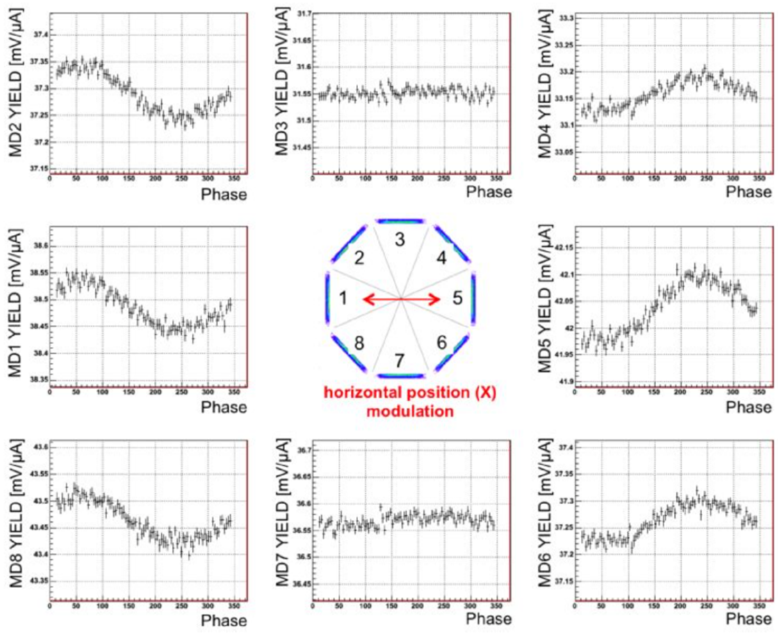
Extra Slides

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: $\frac{\partial A}{\partial \chi_i}$



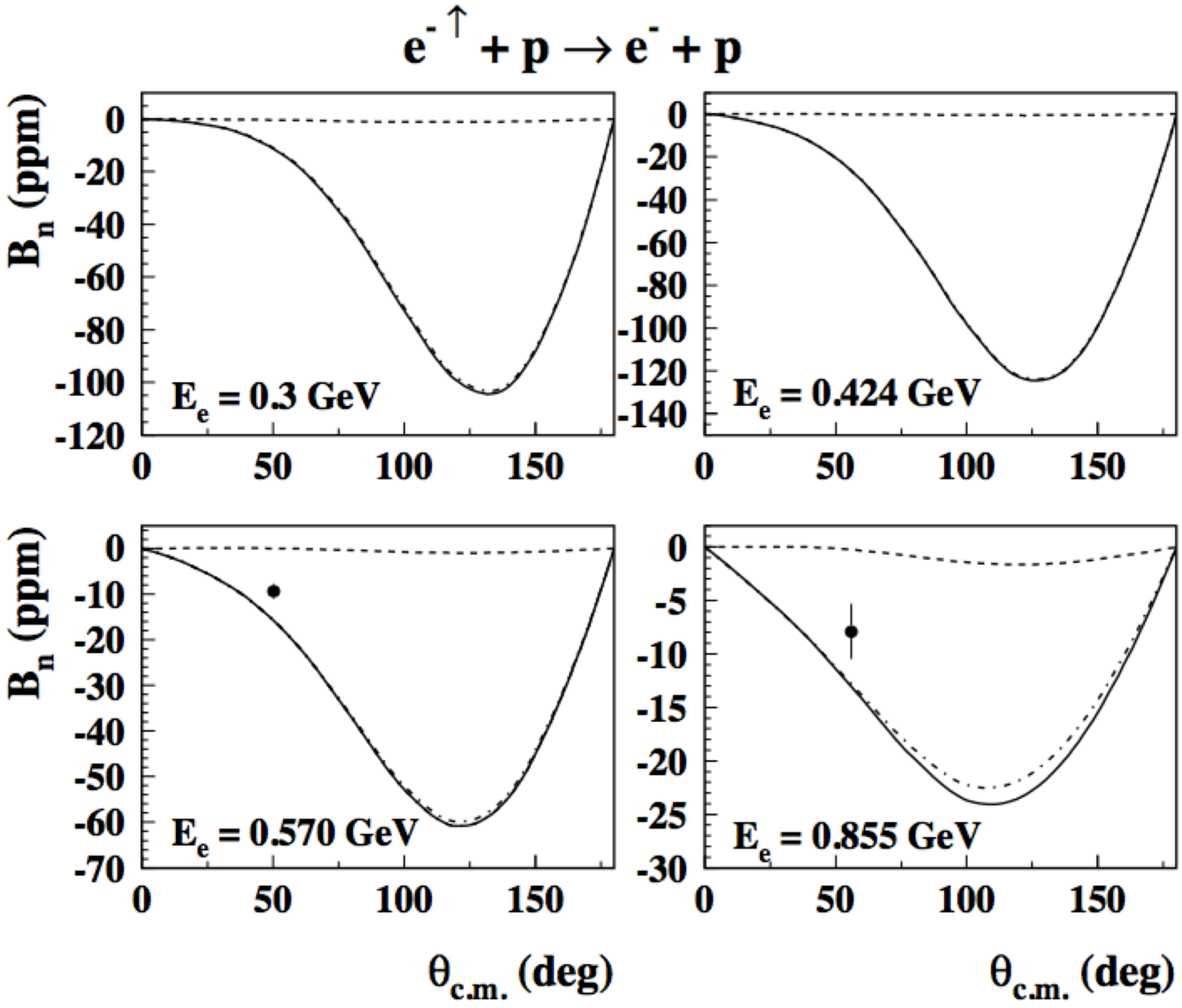
Natural: Linear regression of natural beam motion

Driven: Drive sinusoidal beam oscillations with large amplitude

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

BNSSA results on proton – Forward angles

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

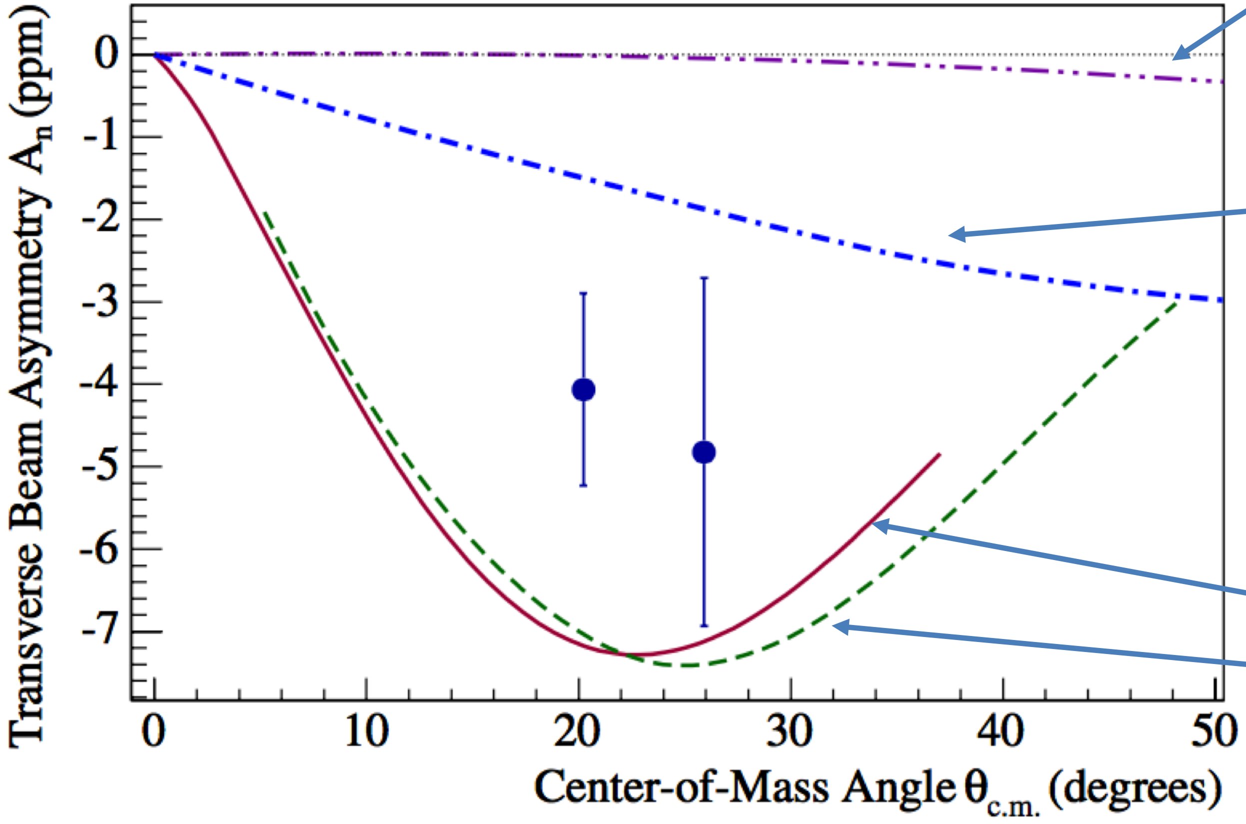


Dashed lines:
elastic
intermediate state
contribution

Solid lines:
Total

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

BNSSA results on proton – Forward angle



Elastic intermediate state only

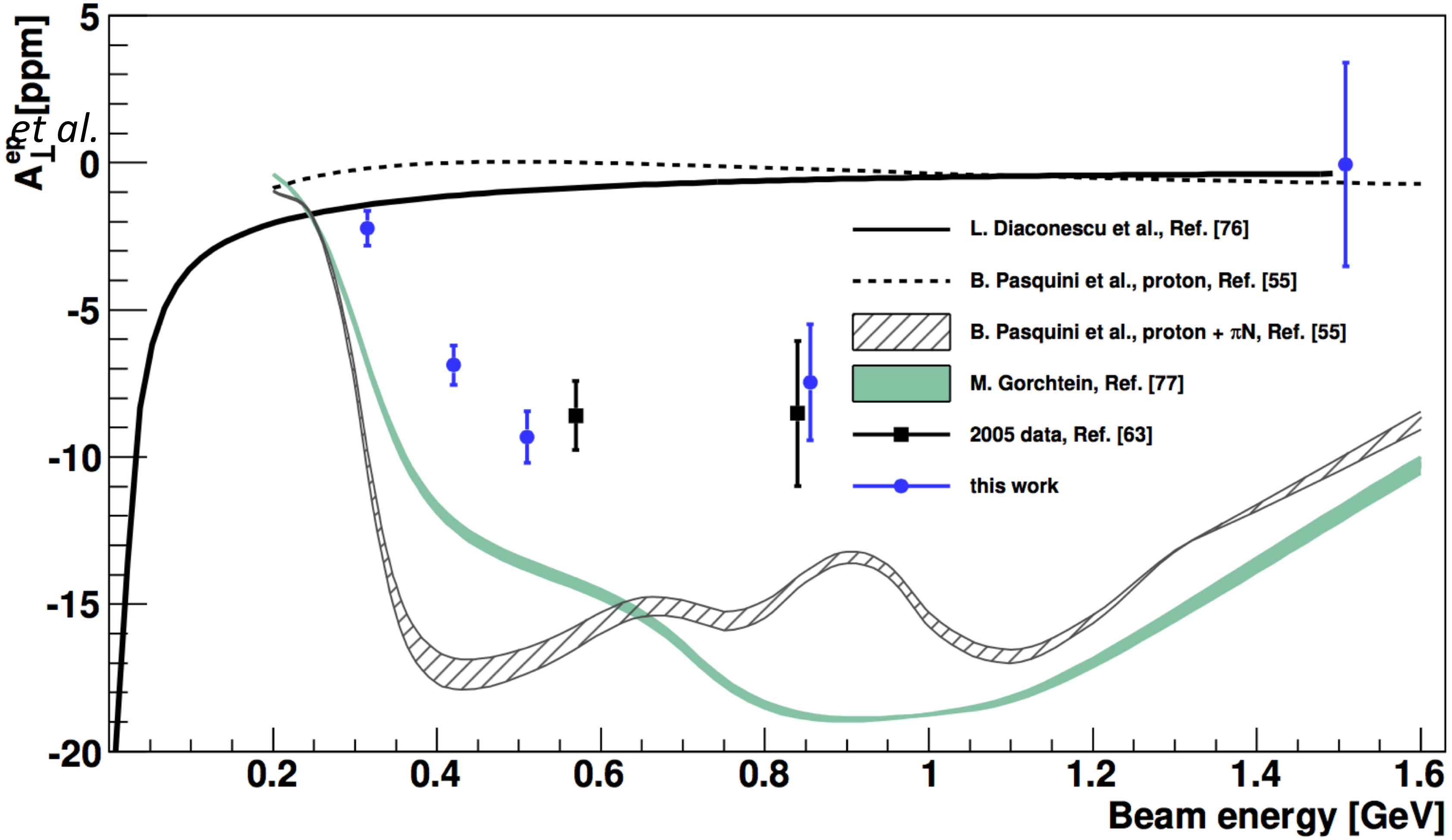
Include πN intermediate states (Pasquini & Vanderhaeghen)

Optical theorem and full photoabsorption σ (Gorchtein; Afanasev and Merenkov)

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

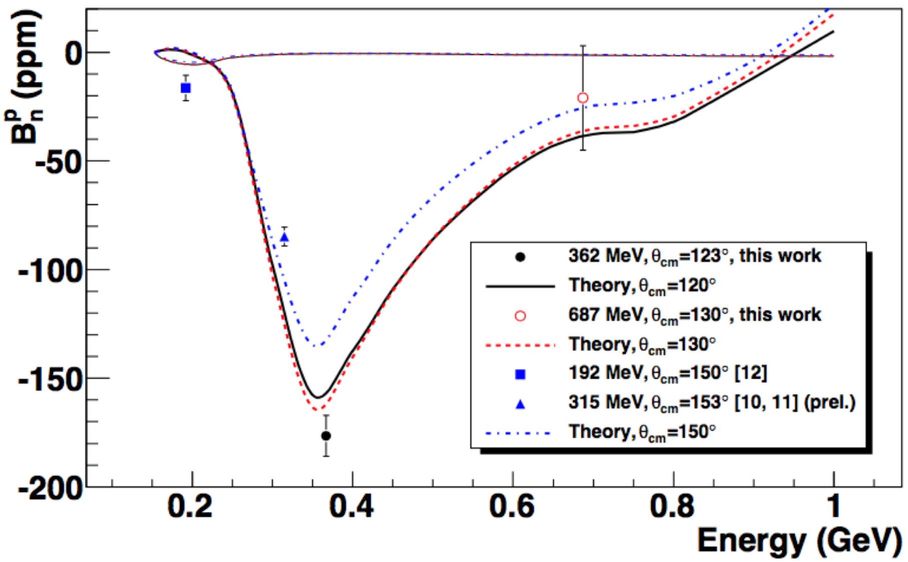
BNSSA results on proton – Forward angles

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)



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

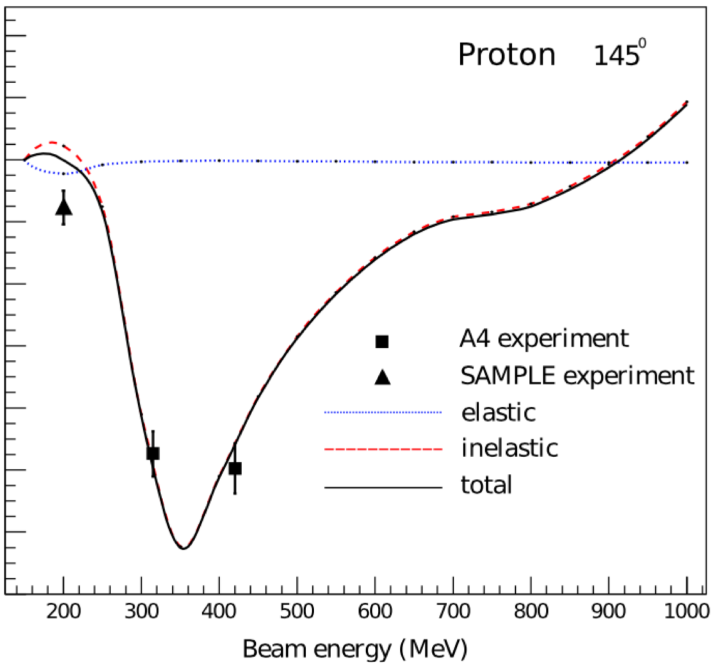
BNSSA results on proton – Backward angles

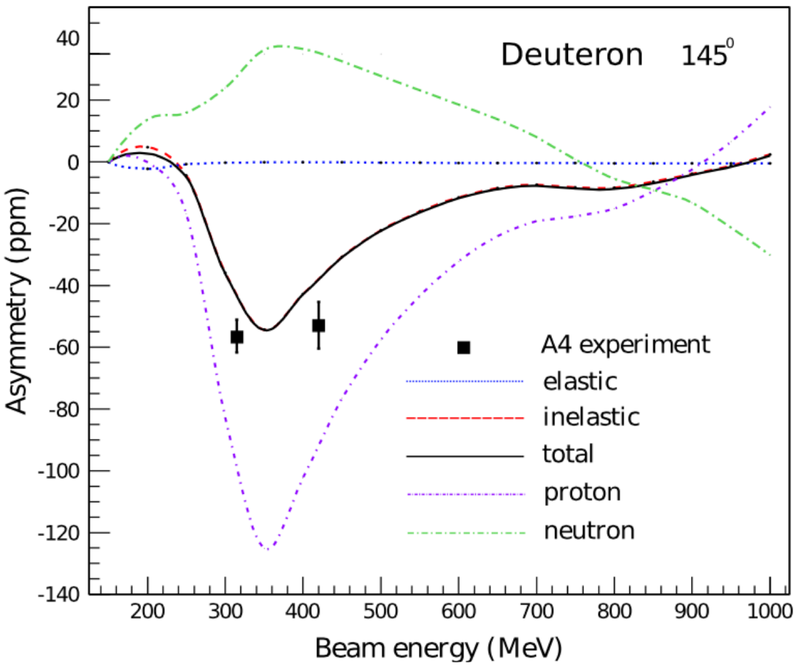


G0: Androic *et al. PRL* 107 (2011)022501

Model: Pasquini & Vanderhaeghen

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

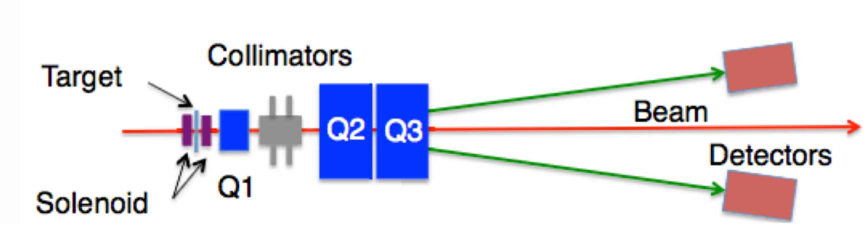




Beam Polarimetry

Møller polarimeter $(\vec{e}+\vec{e} \to e+e)$

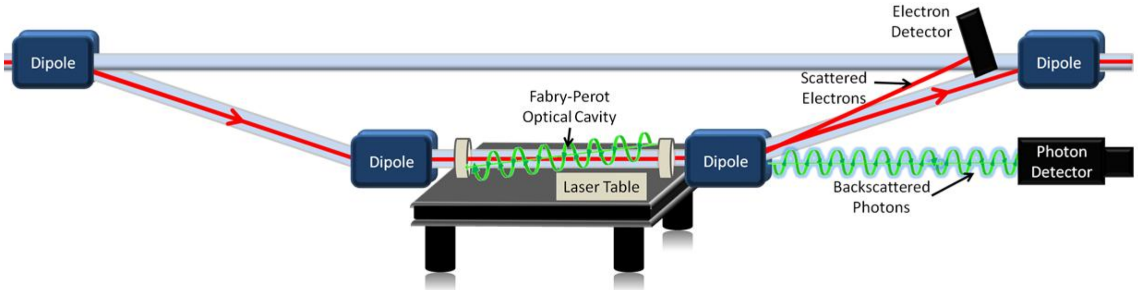
- Precise, but invasive
- Thin, polarized Fe target
- Brute force polarization
- Limited to low current

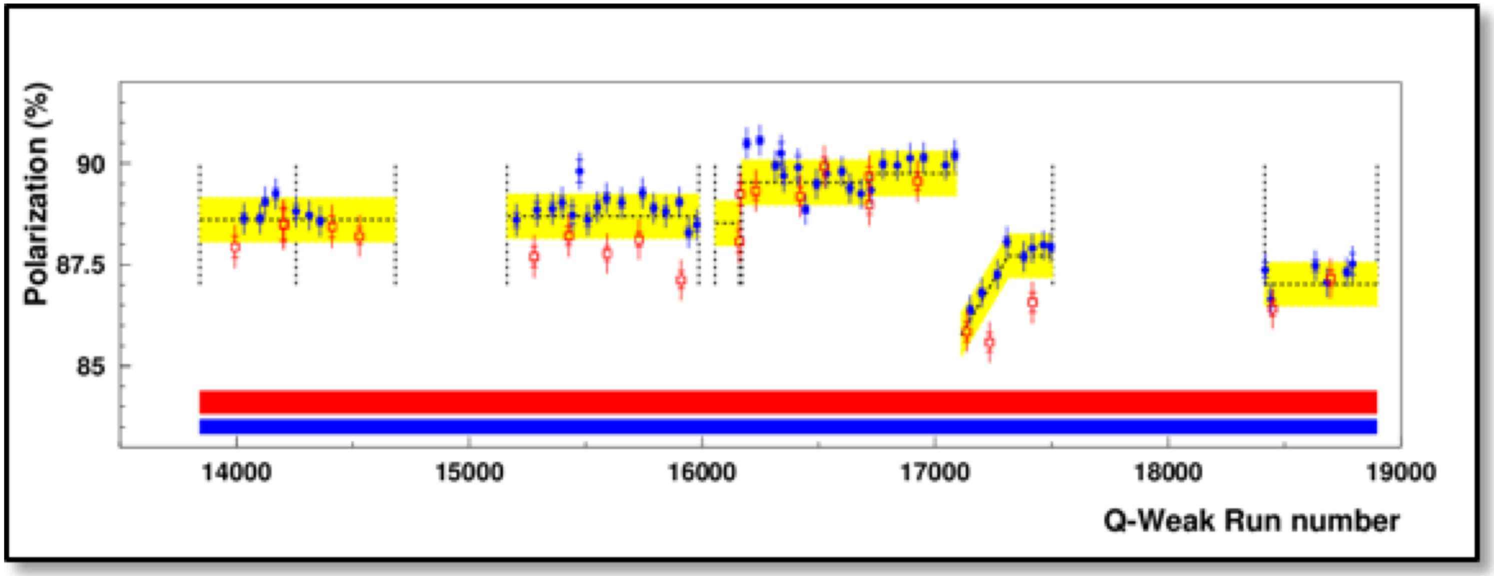


Compton polarimeter $(\vec{e}+\gamma \to e+\gamma)$

- Installed for Q-weak
- Runs continuously at high currents
- Statistical precision: 1% per hour
- Electron Detector: Diamond strips

Detect *both* recoil electron and photon.





0.6% precision achieved in Run 2

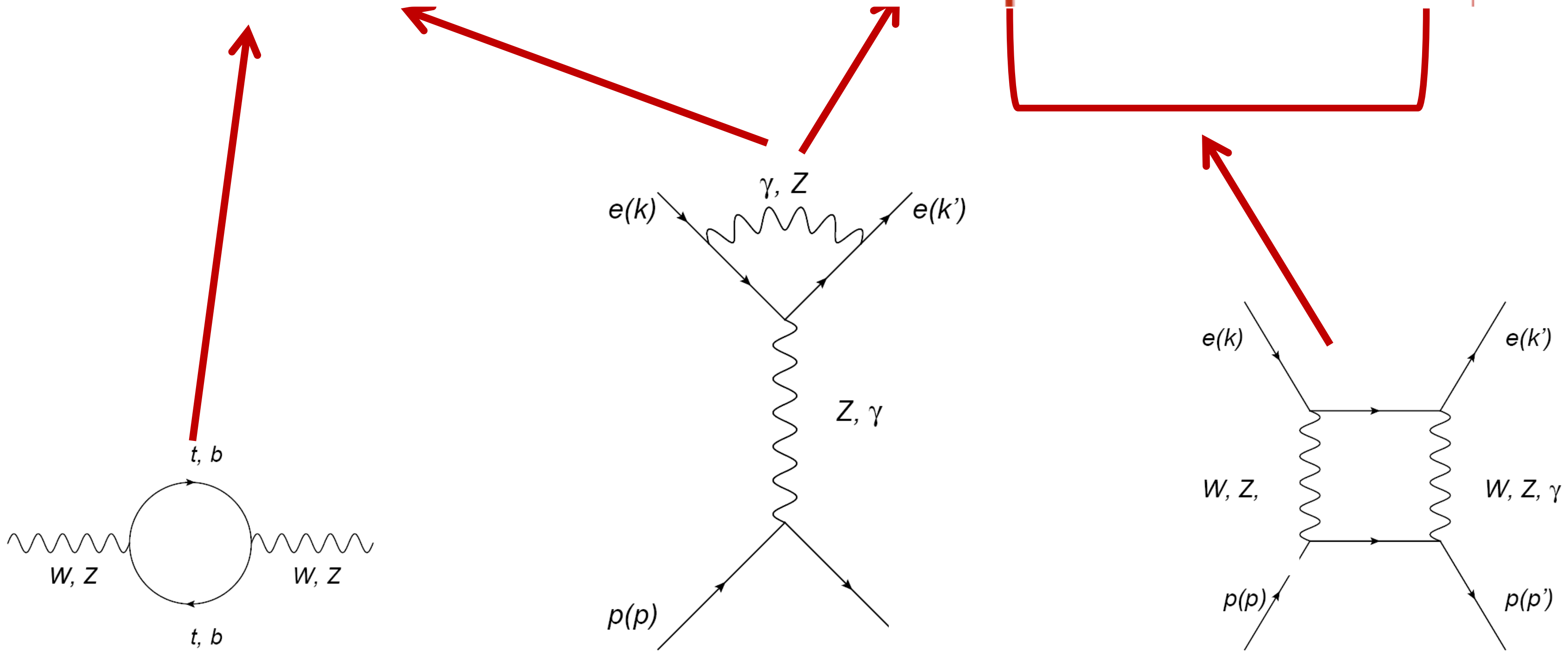
Phys. Rev. X **6**, 011013 (2016)

Phys. Lett. B **766**, 339 (2017)

Electroweak Radiative Corrections

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



Full expression for Q_W^p has energy dependent corrections – need precise calculations

The $\Box_{WW}$ and $\Box_{ZZ}$ are well determined from pQCD ($\propto \frac{1}{q^2 - M^2_{W(Z)} + i\epsilon}$)

The $\Box_{\gamma Z}$ isn't pQCD friendly due to the photon leg ($\propto \frac{1}{q^2 + i\varepsilon}$)

Electroweak Radiative Corrections

$$\boxed{Q_W^p \quad \text{expt. precision :} \qquad \pm\, 0.0045}$$

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

Correction to Q_W^p	Uncertainty
$\Delta\sin^2\theta_W(M_Z)$	± 0.0006
$\Box_{WW}, \Box_{ZZ}$ - pQCD	± 0.0003
$\Delta\rho$ (hadronic loops)	± 0.0003
$\Box_{\gamma Z}$	0.00459 ± 0.00044

Erler, Kurylov
& Ramsey-Musolf
PRD **68**, 016006 (2008)

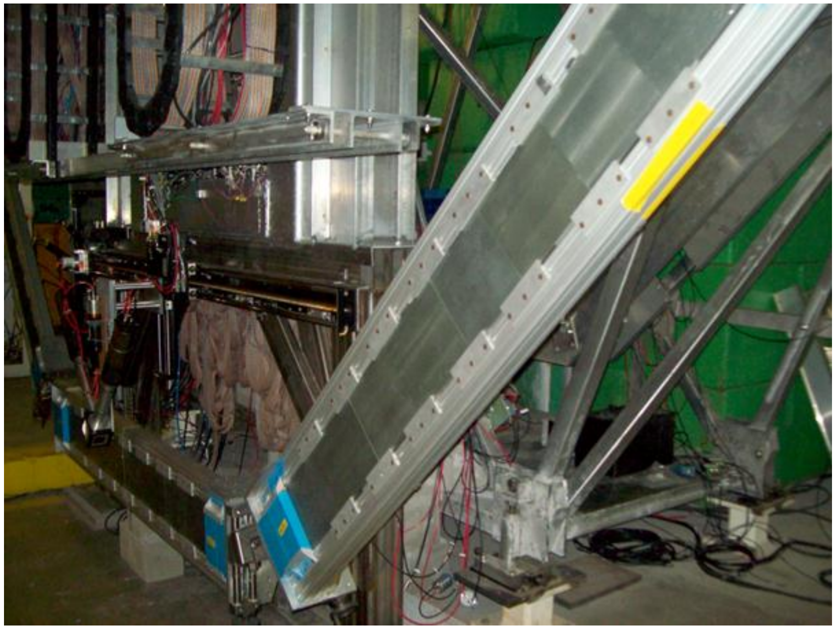
Calculation	$\Box_{\gamma Z}$ (vector) contribution to Q_W^p
Sibirtsev, Blunden, Melnitchouk & Thomas PRC **82**, 013011 (2010)	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson PRD **83**, 113007 (2011)	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Musolf PRC **84**, 015502 (2011)	0.0054 ± 0.0020
Hall, Blunden, Melnitcouk, Thomas & Young Phys.Lett.B **753**, 221 (2016)	0.0052 ± 0.00043

Main Detectors

- Main detectors

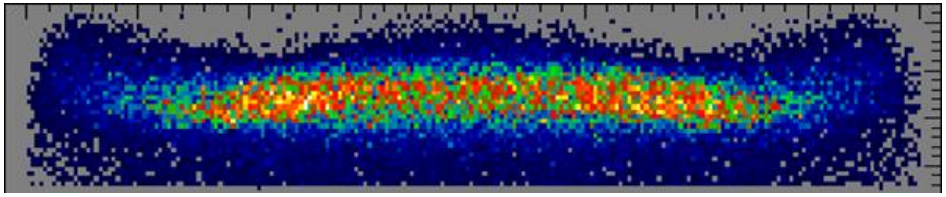
  Toroidal magnet focuses elastic electrons onto each bar

  - 8 fused-silica Cerenkov bars: 200 cm x 18 cm x 1.25 cm
  - Rad-hard, low luminescence
  - 900 MHz e^- per detector
  - Azimuthal symmetry maximizes rates & reduces systematic uncertainties
  - 2 cm lead pre-radiators: a) reduce soft backgrounds discovered in commissioning
    b) boost signal size (but cost to energy resolution)

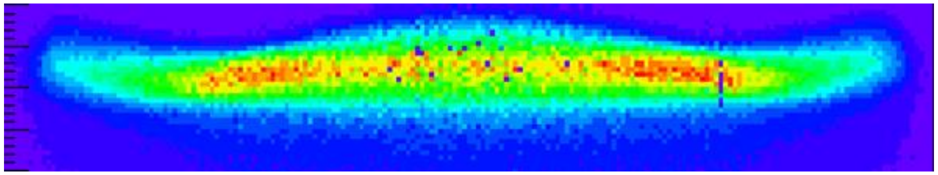


Close up of one detector *in situ*

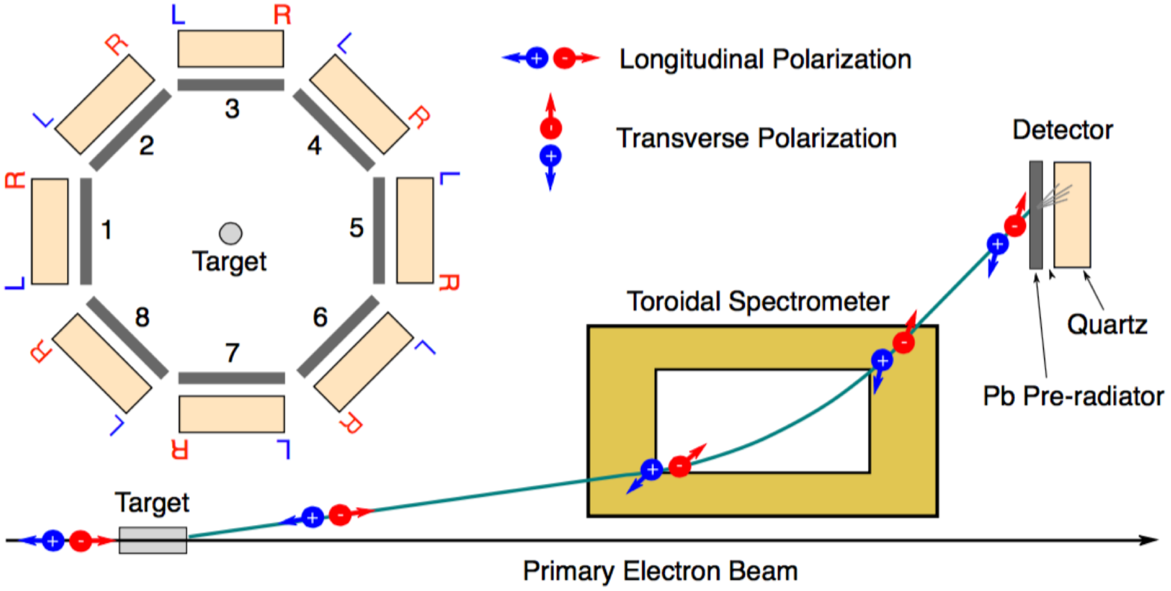
Simulation of scattering rate MD face



Measured



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): 2γ exchange
  2. Mott scattering (low energy in shower) → dominant effect

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