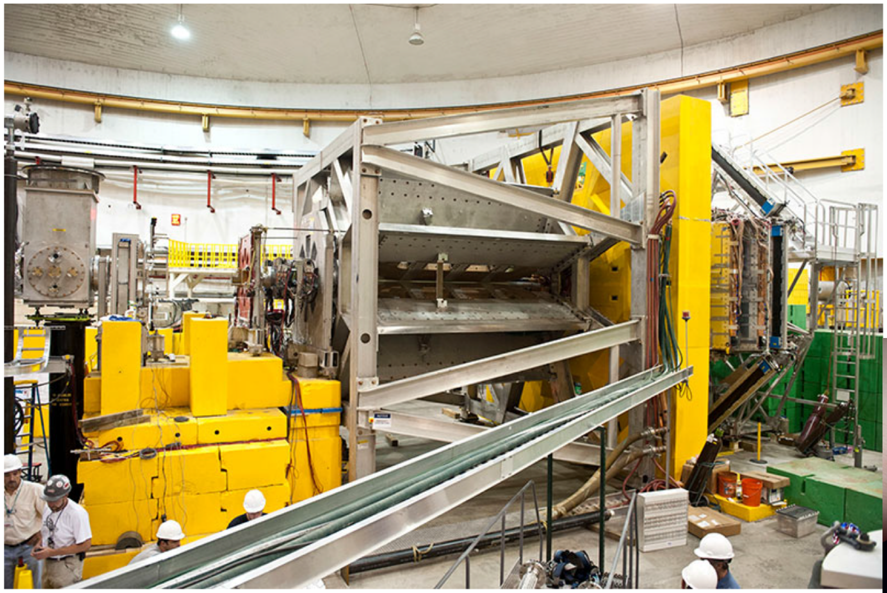
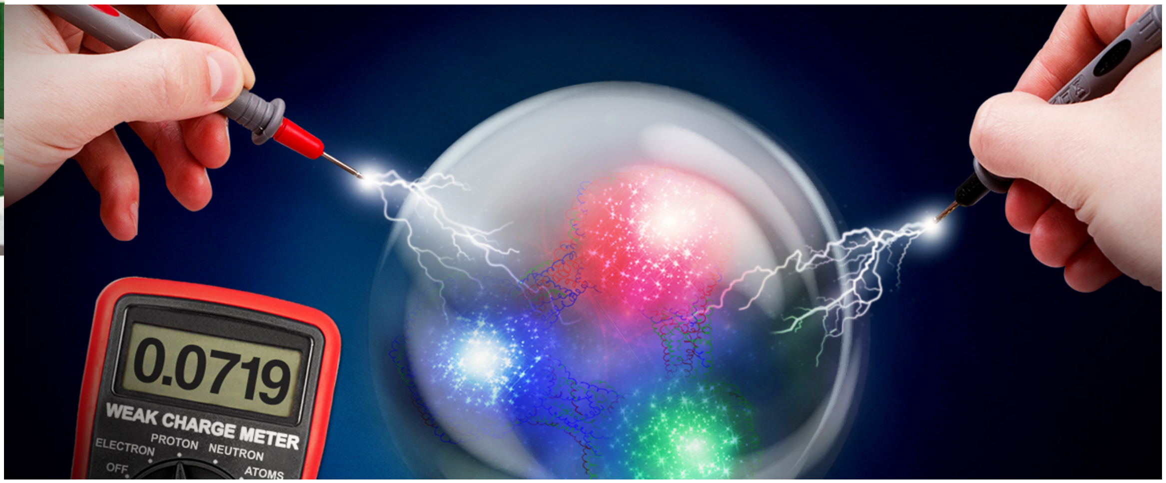
Qweak: The proton's weak charge & the neutron skin in ^{27}Al

David S. Armstrong
William & Mary

for the Qweak Collaboration





Weak Elastic scattering with Nuclei
INT, Seattle WA March 4-8 2019

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

Outline

Two results from Qweak Parity-Violating Electron Scattering (PVES) experiment at Jefferson Lab:

1) **Weak Charge:**
   Precision measurement of proton's weak charge*
   Search for Physics Beyond the Standard Model

   Published: Nature 557, 207 (2018).

2) **PVES on ^{27}Al:**
   Data taken to constrain target-window background for weak charge measurement
   However: provides access to neutron radius in ^{27}Al

   Benchmark of use of PVES to determine neutron radii, eg. PREx, CREx, MREx

   PhD thesis of Kurtis Bartlett (W&M 2018) ; paper under preparation

*(if we consider the proton as a nucleus, then this fits in the title of this workshop)

Part 1:   Weak Charge

Search for physics *Beyond the Standard Model*

- Received Wisdom: Standard Model is incomplete, and is low-energy effective theory of more fundamental physics
- Low energy ($Q^2 << M^2$): Precision Frontier
  complementary to Energy Frontier measurements (LHC)

***If* LHC sees new physics, likely will need additional indirect evidence to pin down its nature**

- ***Neutrons:*** *Lifetime, P- & T-Violating Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2, Mu2e (PSI, TRIUMF, FNAL, J-PARC...)*
- ***Atoms****: atomic parity violation, EDMs etc.*
- ***PVES:*** *Low-energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*

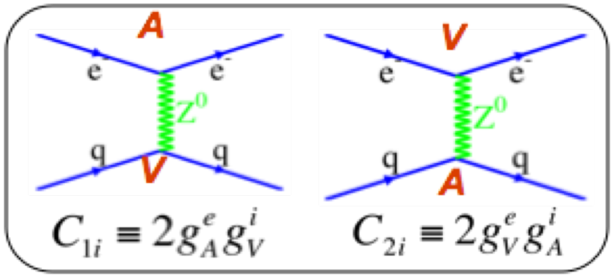
Note: useful to choose observables that are zero or suppressed in the Standard Model, to maximize sensitivity to new physics

Weak Charge

Electroweak Lagrangian → Parity-Violating electron-quark term:

$$\mathcal{L}_{PV}^{EW} = \frac{G_F}{\sqrt{2}}\left[g_A^e(\bar{e}\gamma_\mu\gamma_5 e)\cdot\sum_q g_V^q(\bar{q}\gamma^\mu q) + g_V^e(\bar{e}\gamma_\mu e)\cdot\sum_q g_A^q(\bar{q}\gamma^\mu\gamma_5 q)\right]$$

$$C_{1q} = 2g_A^e g_V^q$$



Small θ Large θ

-Electroweak Charges-

Particle	Electric Charge	Weak Vector Charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

← Proton's Weak Charge

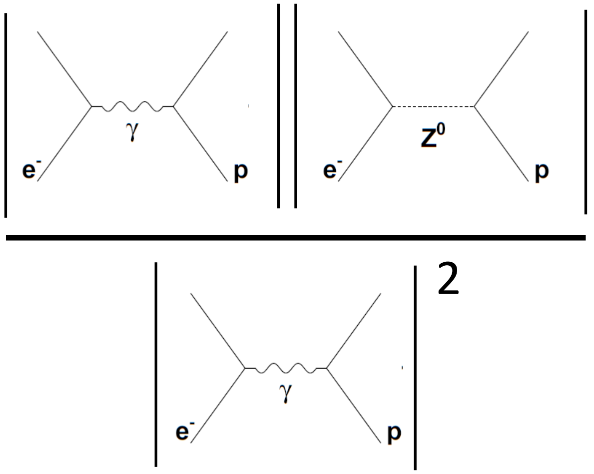
unlike much of the rest of this workshop – flip the approach, and look at the small weak charge (proton).

PVES: Parity-violating electron scattering

Scatter longitudinally-polarized electrons from unpolarized target
Originally proposed by Ya. B. Zeldovich   JETP 36 (1959)

Electroweak interference

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \rightarrow$$



For e-p scattering:

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

For forward angle scattering at low Q^2 :
A_{PV} accesses Q^p_W

"Form factor" term due to finite proton size – hadronic structure (~ 30% for Qweak) – determined well by existing PVES high-Q^2 data

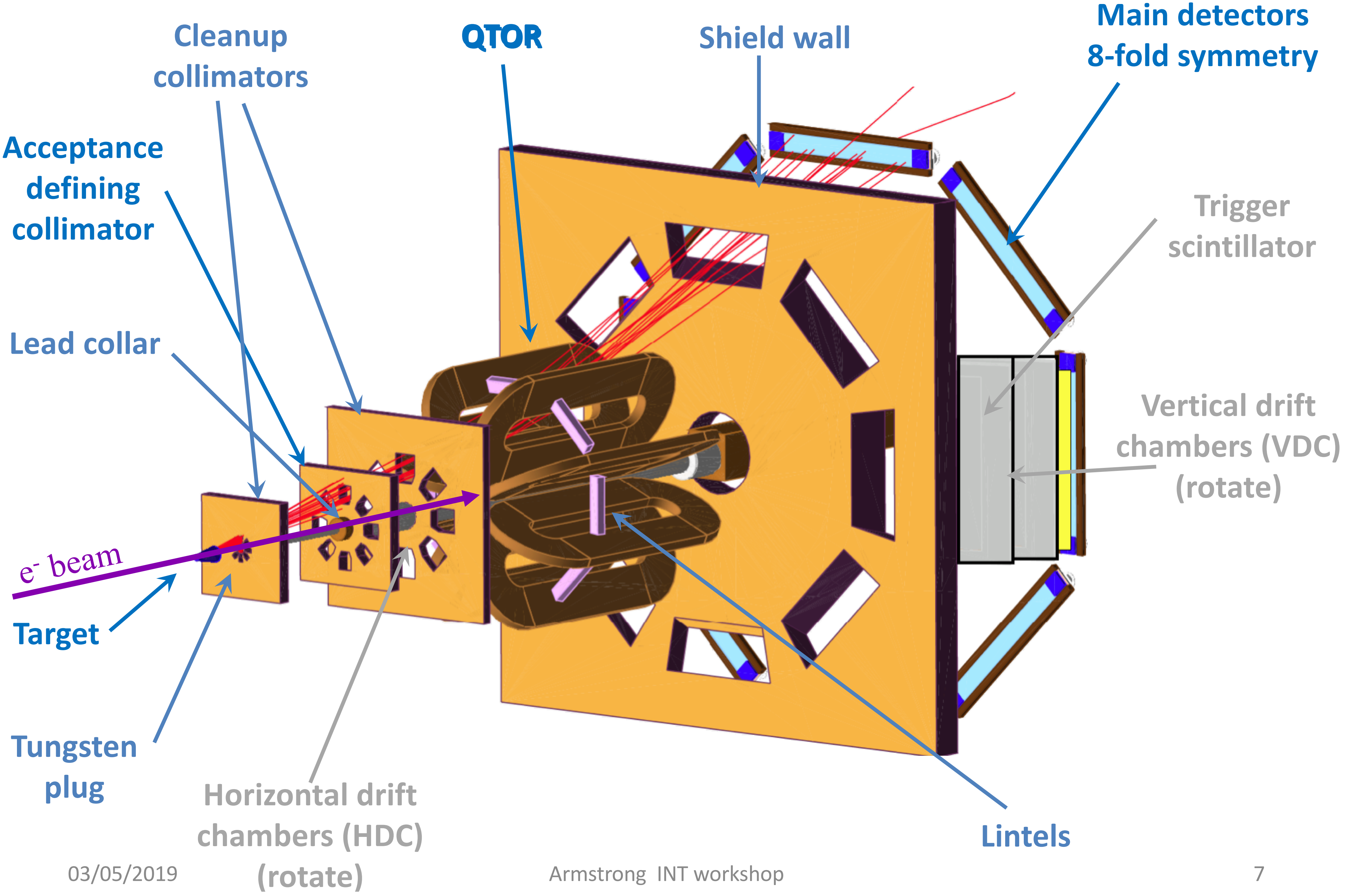
Meeting PVES Challenges

$A_{ep} \approx 200\ ppb$ want $\approx 5\%$ precision

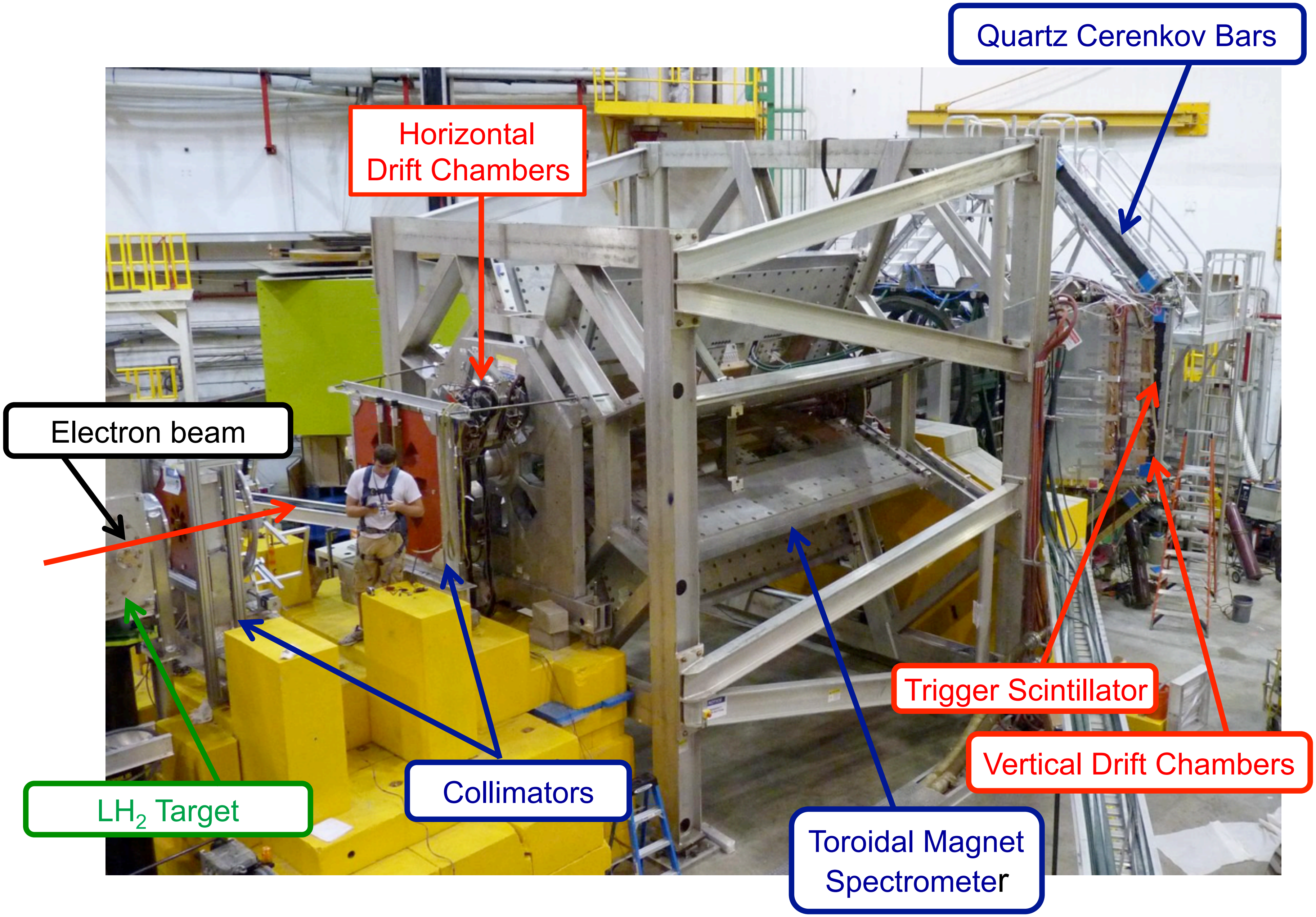
- 180 µA beam current (JLab record)
- High power cryogenic target
- Rapid helicity reversal (960 Hz)
- Small scattering angle: toroidal magnet, large acceptance
- GHz detected rates: data-taking in integrating mode
- Radiation hard detectors
- Low noise 18-bit ADCs
- Exquisite control of helicity-correlated beam parameters
- Four different kinds of helicity reversal:
  - Rapid (Laser beam at source: Pockels cell)
  - Slow (insertable λ/2 plate in laser beam)
  - Ultra slow (Wien-reversal, g-2 spin flip)
- Two independent high-precision beam polarimeters
- Dedicated Tracking system for kinematics determination

Experiment took data in two main running periods:
Run 1: February–May 2011
Run 2: November 2011–May 2012

The Q_{weak} Apparatus



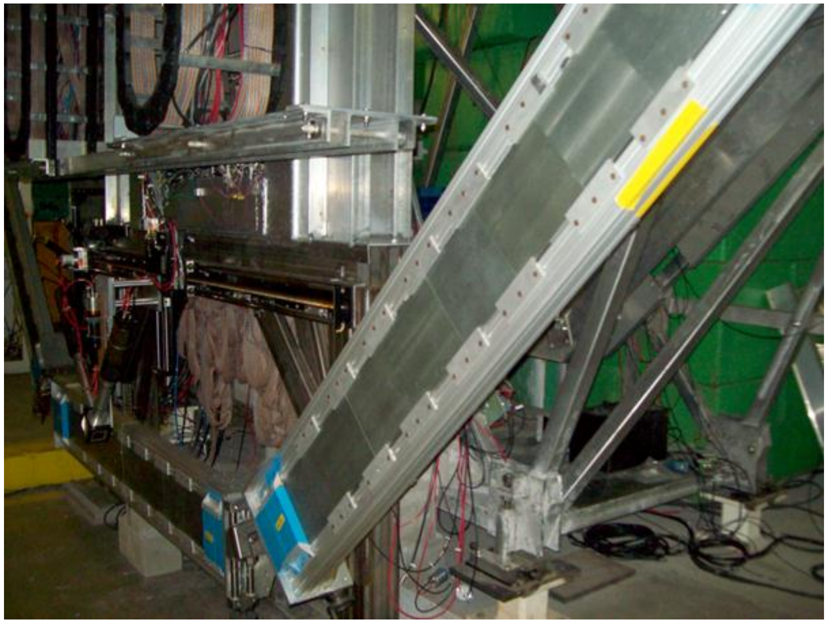
The Q_{weak} Apparatus – during installation



Main Detectors

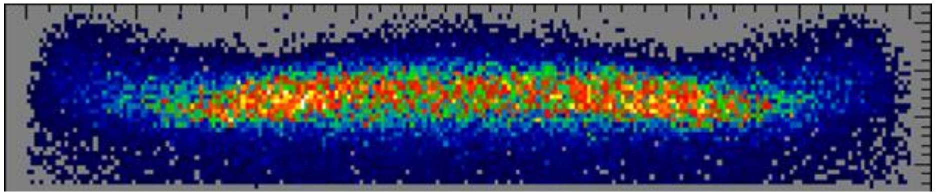
- Main detectors

  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)

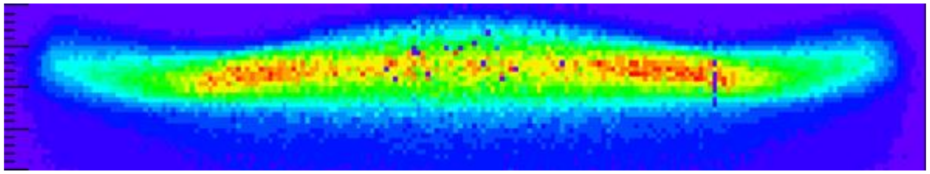


Close up of one detector *in situ*

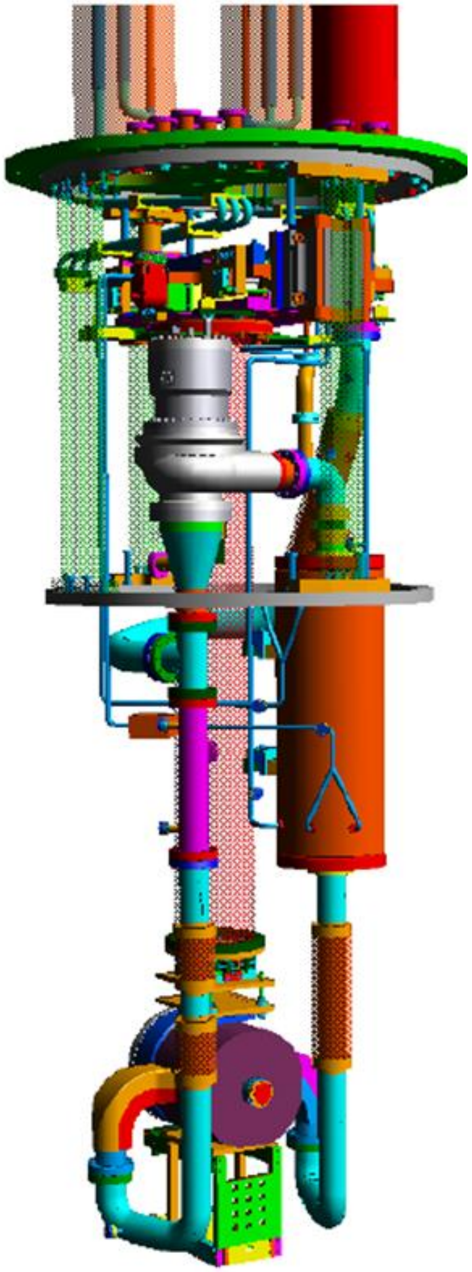
Simulation of scattering rate MD face



Measured



Hydrogen Target



35 cm, 2.5 kW liquid hydrogen target (world's highest power cryotarget)

Designed using Computational Fluid Dynamics

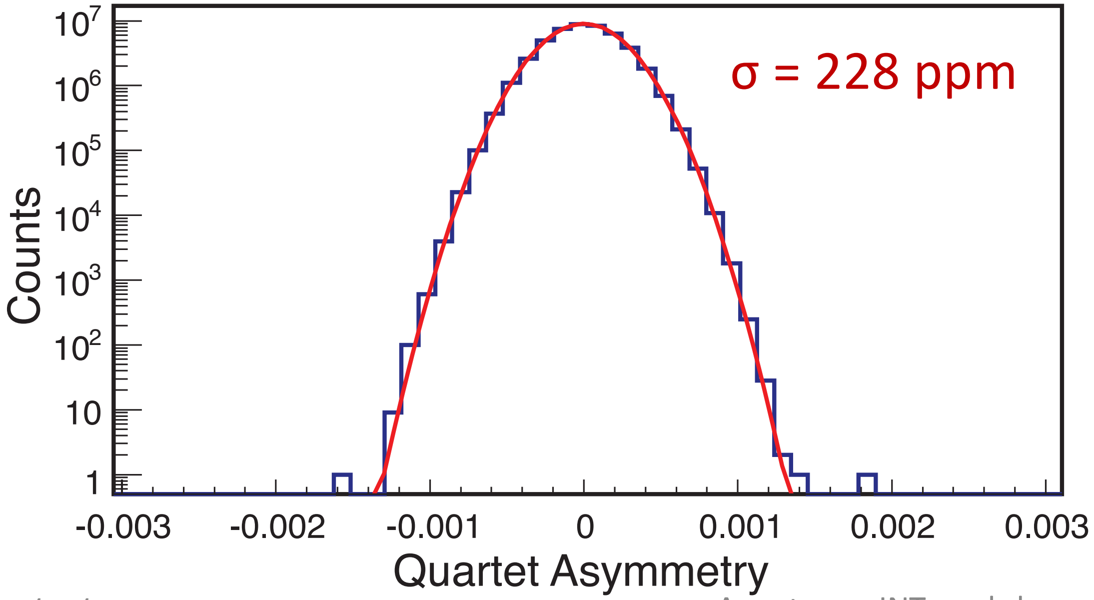
- Temperature ~20 K
- Pressure: 220 kPa
- Beam: 150 – 180 μA
- 4% X_0

Target boiling might have been problematic!

Rapid helicity-reversal: 960 Hz

common-mode rejection of boiling noise

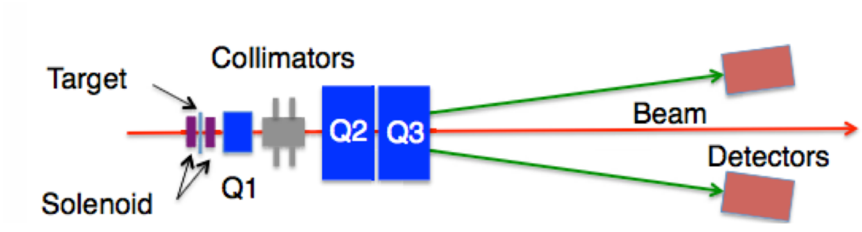
Achieved ~50 ppm noise (< 225 ppm counting statistics)



Beam Polarimetry

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

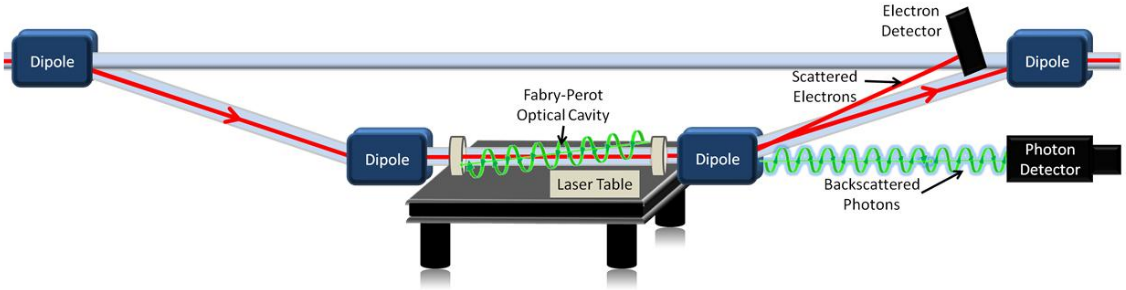
- Precise, but invasive
- Thin, polarized Fe target
- Brute force polarization
- Limited to low current

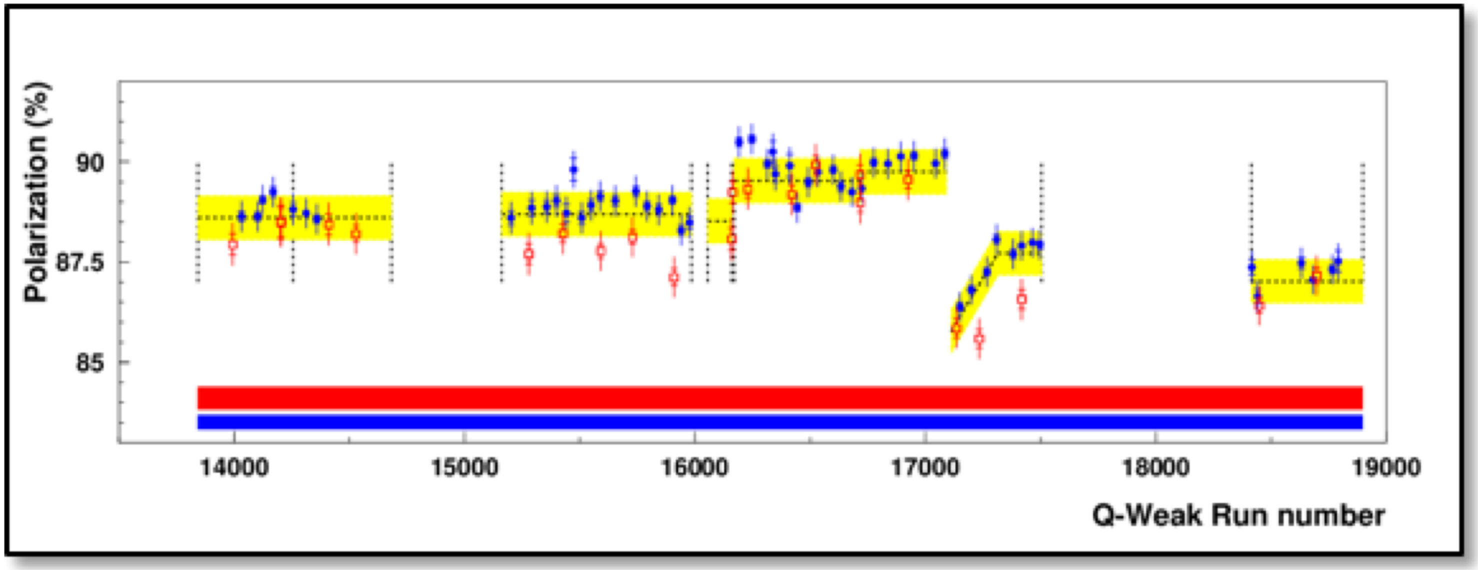


Compton polarimeter $(\vec{e} + \gamma \to e + \gamma)$

- 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)

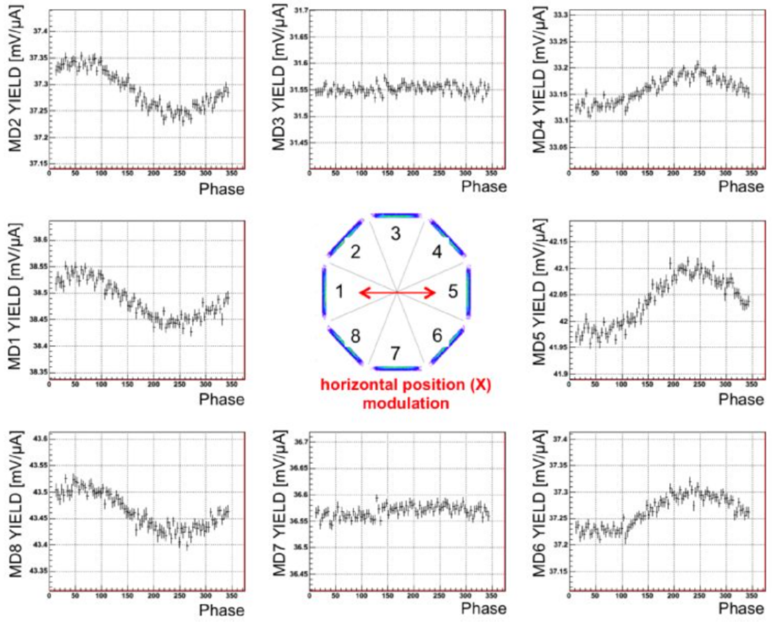
Phys. Lett. B **766**, 339 (2017)

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

Beam Parameter	Run 1 $\Delta\chi_i$	Run 2 $\Delta\chi_i$	Typical $\partial A/\partial\chi_i$
X	-3.5 ± 0.1 nm	-2.3 ± 0.1 nm	-2 ppb/nm
X'	-0.30 ± 0.01 nrad	-0.07 ± 0.01 nrad	50 ppb/nrad
Y	-7.5 ± 0.1 nm	0.8 ± 0.1 nm	< 0.2 ppb/nm
Y'	-0.07 ± 0.01 nrad	-0.04 ± 0.01 nrad	< 3 ppb/nrad
Energy	-1.69 ± 0.01 ppb	-0.12 ± 0.01 ppb	-6 ppb/ppb

Run 1: $A_{\text{beam}} = 18.5 \pm 4.1\,\text{ppb}$ Run 2: $A_{\text{beam}} = 0.0 \pm 1.1\,\text{ppb}$

Target Windows

Background from detected electrons that scattered from thin Aluminum entrance and exit windows:

1. Measure ≈1500 ppb asymmetry from thick dummy target (identical Al alloy).
2. Precisely measure the $(2.52 \pm 0.06)\%$ "dilution" from windows.

Asymmetry: See second half of this talk for details

Dilution:

- Reduce beam current to $< 1\ \mu$A
- "Counting mode" measurement of rates from empty target and full lH_2 target
- Simulation to account for radiative effects on window signal due to hydrogen

Dilution uncertainty 2.8% (relative). Errors shared equally between:

- BCM calibration
- Detector deadtime (unexpectedly large)
- Simulation

Net target window correction: 5% relative error (on 25% correction): 1.2% error, dominated by statistics on Al asymmetry determination

Asymmetry: Dominant Systematic Uncertainties

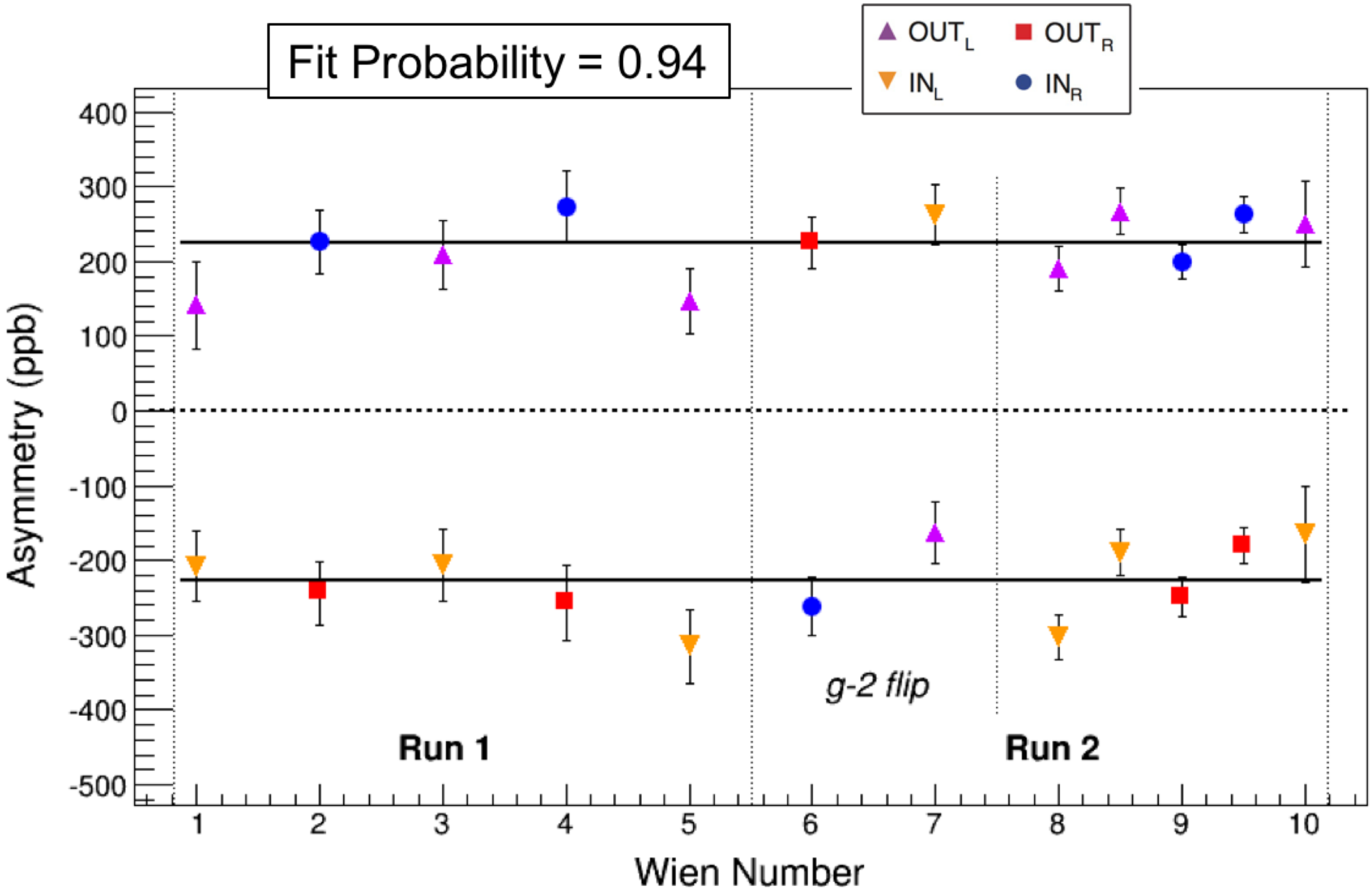
Quantity	Run 1 error (ppb)	Run 1 fractional	Run 2 error (ppb)	Run 2 fractional
BCM Normalization: $A_{\rm BCM}$	5.1	25%	2.3	17%
Beamline Background: $A_{\rm BB}$	5.1	25%	1.2	5%
Beam Asymmetries: $A_{\rm beam}$	4.7	22%	1.2	5%
Rescattering bias: $A_{\rm bias}$	3.4	11%	3.4	37%
Beam Polarization: P	2.2	5%	1.2	4%
Target windows: A_{b1}	1.9	4%	1.9	12%
Kinematics: R_{Q^2}	1.2	2%	1.3	5%
Total of others	2.5	6%	2.2	15%
Combined in quadrature	10.1		5.6	

$$\begin{aligned} A_{\rm msr} = \quad & A_{\rm raw} + A_T + A_L + A_{\rm BCM} \\ & + A_{\rm BB} + A_{\rm beam} + A_{\rm bias} \end{aligned}$$

$$A_{ep} = R_{\rm tot} \frac{A_{\rm msr}/P - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^{4} f_i}$$

$$R_{\rm tot} = R_{\rm RC} R_{\rm Det} R_{\rm Acc} R_{Q^2}$$

Behavior of Asymmetry under Slow Reversals



Three slow reversal types

IN/OUT: reversal of laser helicity (IWHP)

L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

The data behaved as expected under all three types of slow helicity reversal.

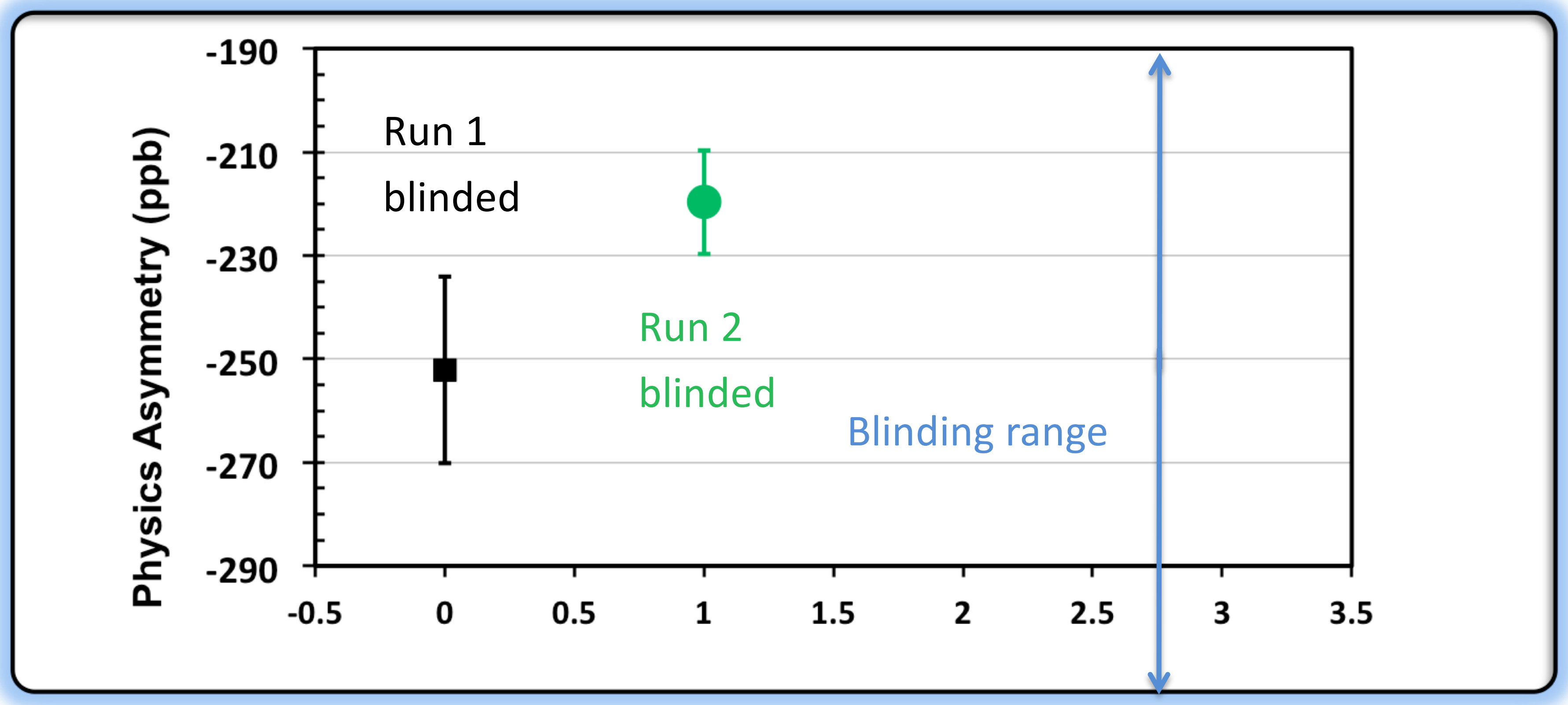
Combining the data without sign corrections gives

NULL average = -1.75 ± 6.51 ppb

- consistent with zero, as expected

Blinded Analysis

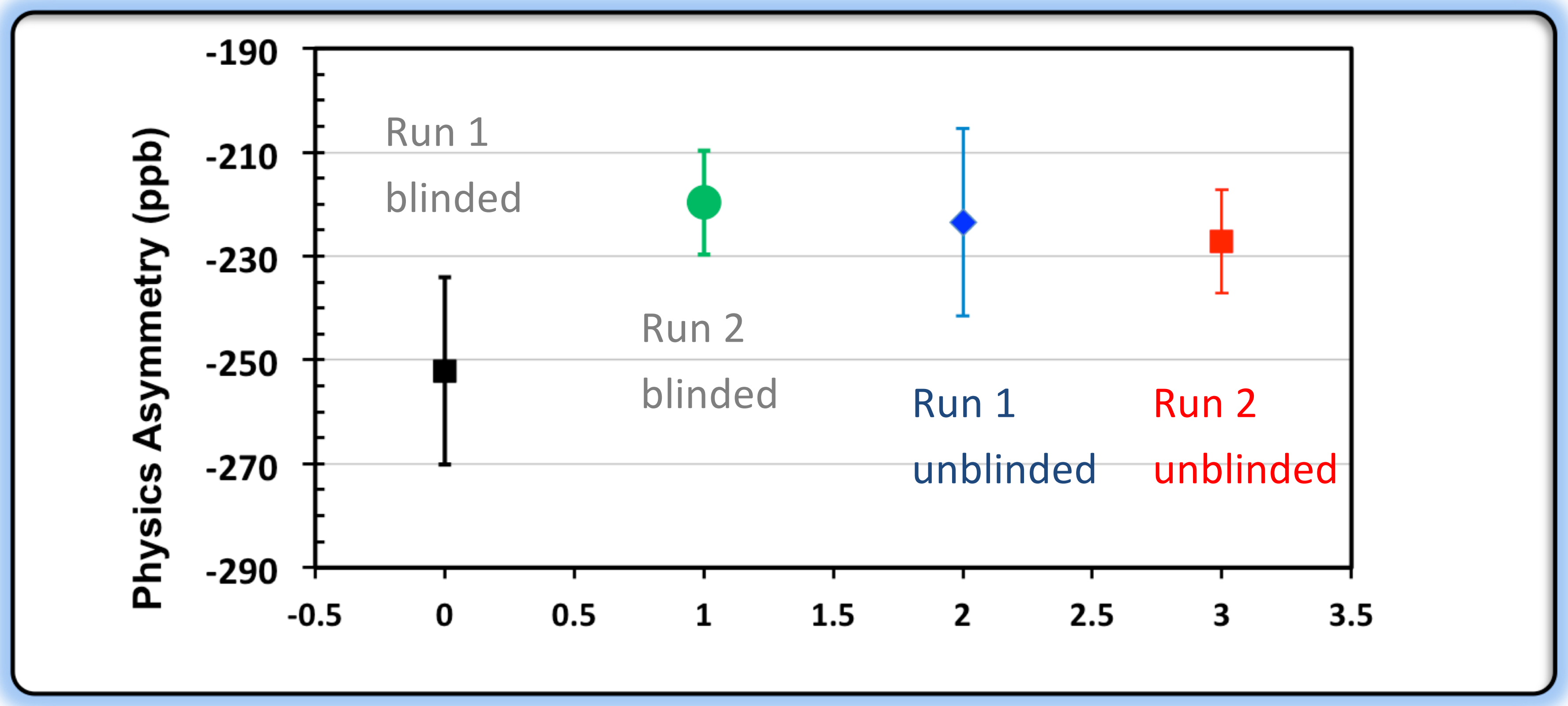
Run 1 and 2 *each* had their own independent "blinding factor" (additive offset in range ± 60 ppb) to avoid analysis bias.



Un-Blinded Results

Marvelous agreement between the two Runs

(several systematic corrections rather different in the two Runs)



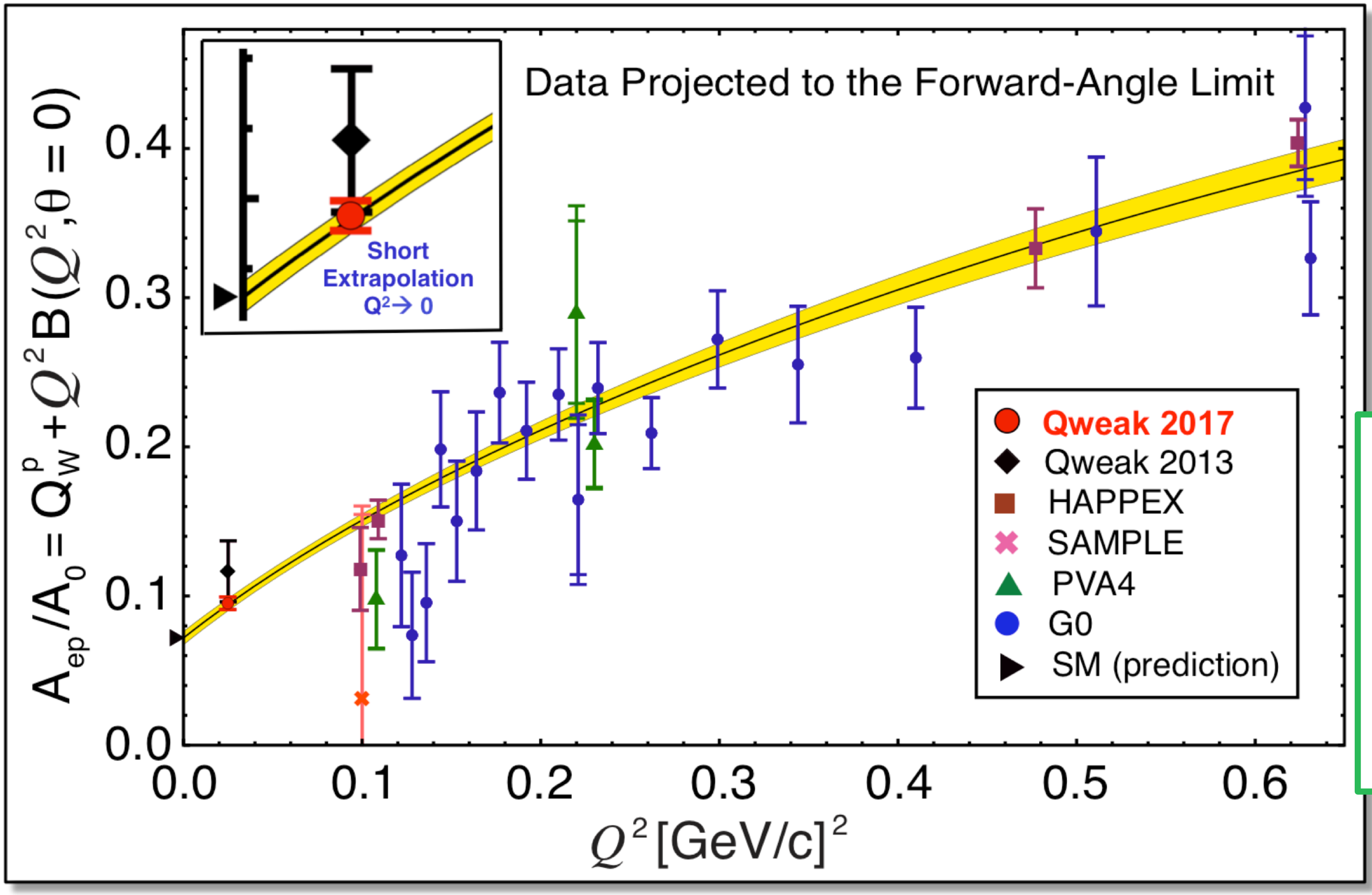
Period	Asymmetry (ppb)	Stat. Unc. (ppb)	Syst. Unc. (ppb)	Tot. Uncertainty (ppb)
Run 1	-223.5	15.0	10.1	18.0
Run 2	-227.2	8.3	5.6	10.0
Run 1 and 2 combined with correlations	-226.5	7.3	5.8	9.3

Extracting Weak Charge from Asymmetry Result

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

Global fit of world PVES data up to Q^2 = 0.63 GeV^2 to extract proton's weak charge:

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$



33 entries in PVES

(e-p, e-d, e-^{4}He)

database

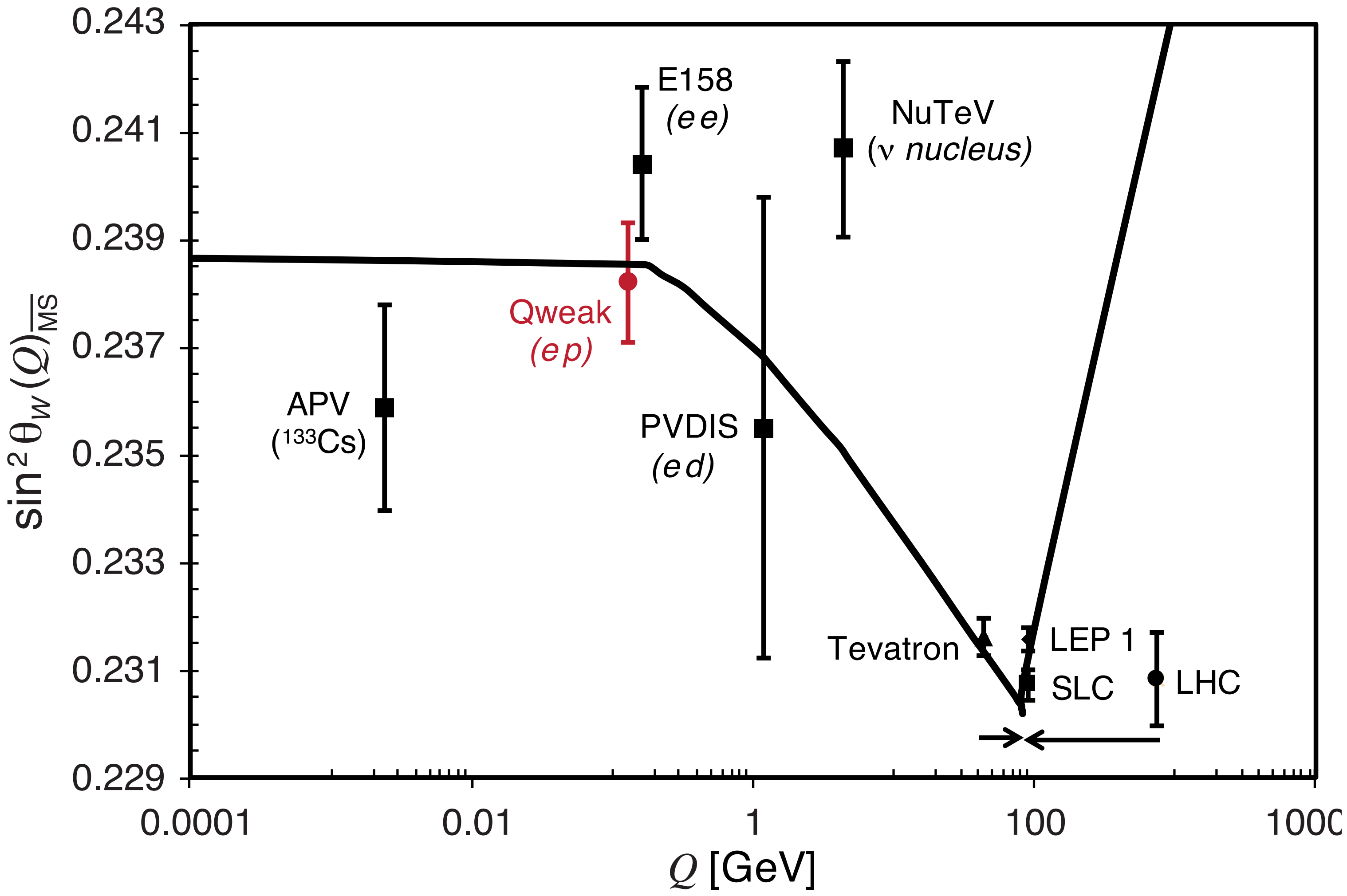
Standard Model:

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

Experiment:

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

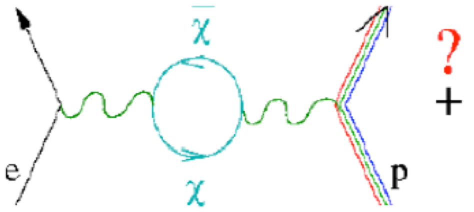
Running of the Weak Mixing angle $\sin^2\theta_W$



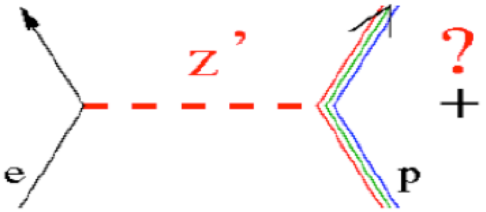
Solid Curve:
J. Erler, M. Ramsey-Musolf, P. Langacker

Note: interference effects of heavy new physics (*i.e.* Z', leptoquarks) suppressed at Z resonance → LEP/SLC mass limits ≤ TeV, while low-energy observables probe few TeV scale, as well as light new physics.

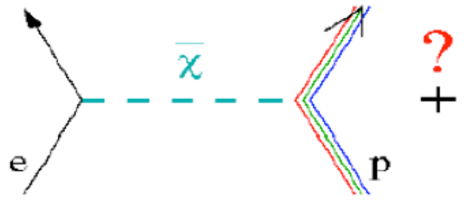
Sensitivity to New Physics at TeV scale



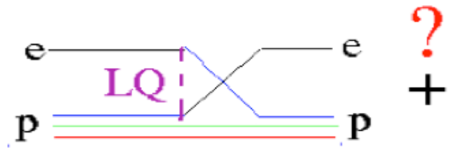
RPC SUSY



Generic Z'



RPV SUSY



Leptoquarks

Parameterize generically by adding contact term to Lagrangian:

$$\mathcal{L}^{\rm eq}_{\rm NC} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q.$$

Standard Model term

$$\mathcal{L}^{\rm PV}_{\rm NP} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h^q_V\bar{q}\gamma^\mu q$$

New Physics term

g=coupling
Λ=mass scale

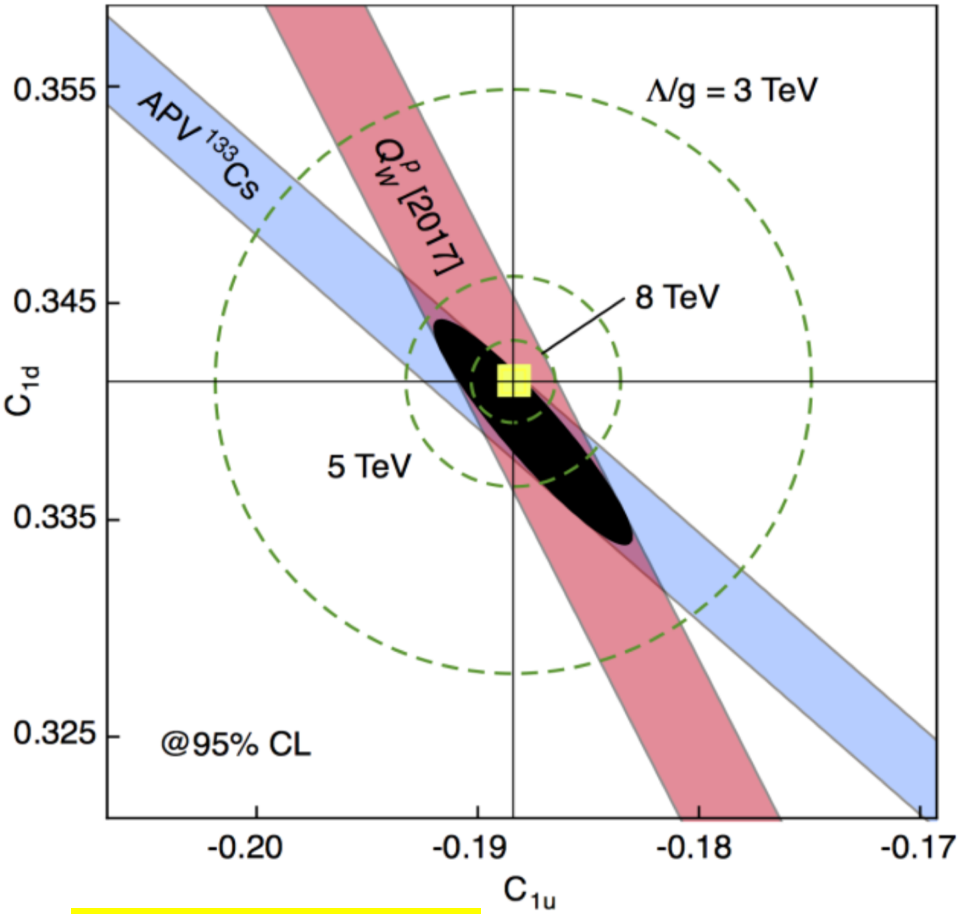
Limits on Semi-Leptonic PV Physics beyond the SM

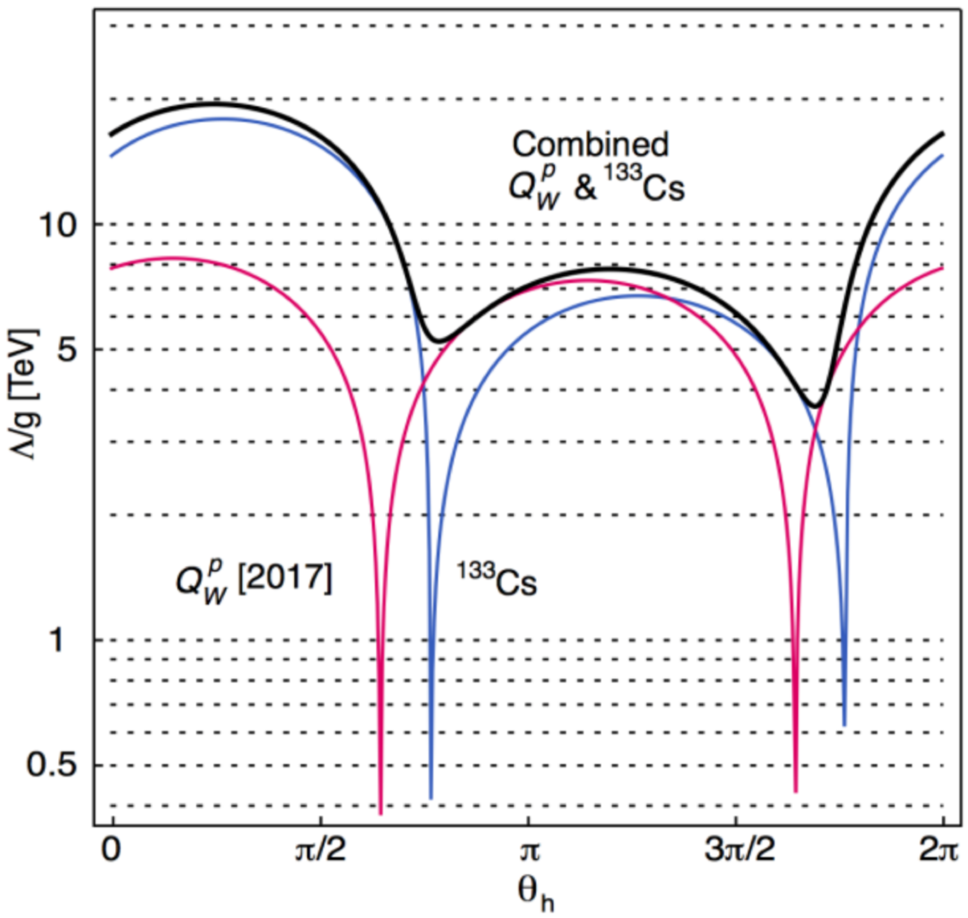
$$Q_W^p = -2(2C_{1u} + C_{1d})$$

New Physics Ruled Out
@95% CL Below Mass Scale of Λ/g

$$\mathcal{L}_{\rm NP}^{\rm PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$





Yellow box: SM values

APV: atomic parity violation ^{133}Cs C.S. Wood et al. Science **275**, 1759 (1997); Dzuba et al. PRL **109**, 203003 (2012)

SM tests with Precision Low-Energy Parity Violation

Experiment	**% Precision**	**$\Delta\sin^2\theta_W$**	**Λ /g [TeV]** (mass reach)
SLAC-E122	8.3	0.011	1.5
SLAC-E122	110	0.44	0.25
APV (^{205}Tl)	3.2	0.011	3.8
APV (^{133}Cs)	0.58	0.0019	9.1
SLAC-E158	14	0.0013	4.8
Jlab-Hall A	4.1	0.0051	2.2
Jlab-Hall A	61	0.051	0.82
JLab-Qweak (p)	**6.2**	**0.0011**	**7.5**
JLab-SoLID	0.6	0.00057	6.2
JLab-MOLLER	2.3	0.00026	11.0
Mainz-P2	2.0	0.00036	13.8
APV (^{225}Ra$^+$)	0.5	0.0018	9.6
APV (^{213}Ra$^+$ / ^{225}Ra$^+$)	0.1	0.0037	4.5
PVES (^{12}C)	0.3	0.0007	14

Published

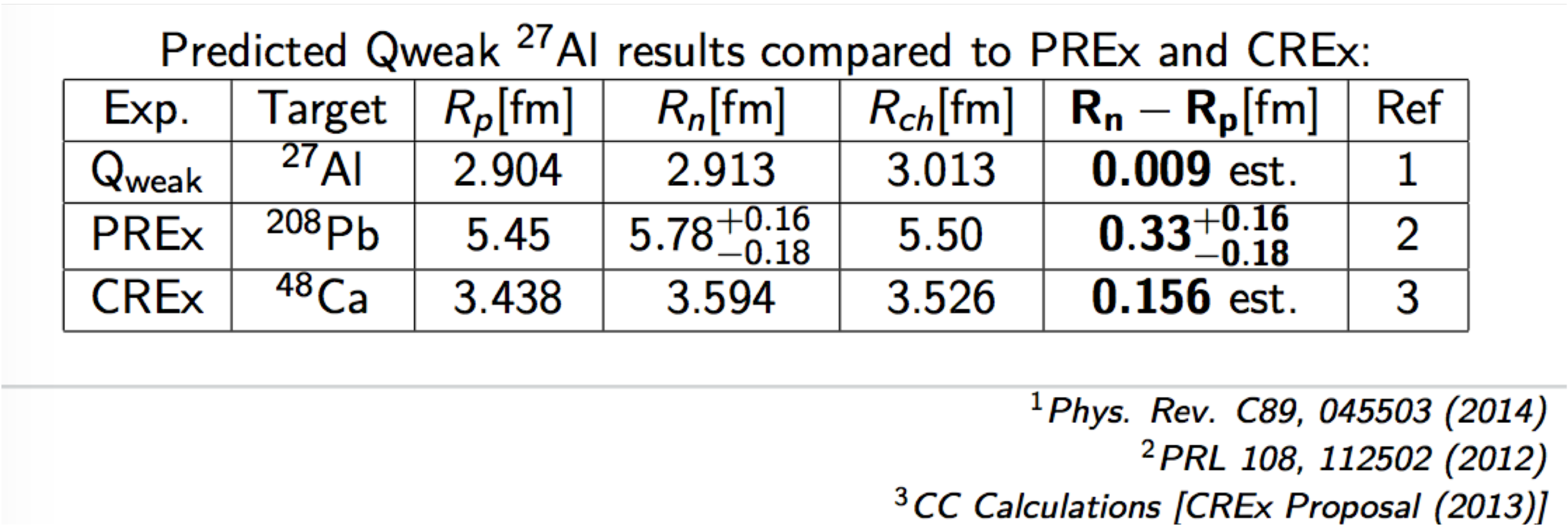
Planned

Part 2) Elastic PVES on ^{27}Al

Context: only three previous elastic PVES measurements on complex nuclei:

1. ^{4}He (HAPPEX) *PRL 96, 022003 (2006)*
2. ^{12}C (MIT/Bates) *PRL 65, 694 (1990)*
3. ^{208}Pb (PREX-I) *PRL 108, 112502 (2012)*

- According to Horowitz, a 4% precision measurement of the $A_{elastic}$ of pure ^{27}Al is sensitive to 2% changes in R_n (neutron distribution radius).
- ^{27}Al's R_n help benchmark theory for PREx, CREx
  maybe another "bridge" between *ab-initio* and DFT models?



Predicted Qweak ^{27}Al results compared to PREx and CREx:

Exp.	Target	R_p[fm]	R_n[fm]	R_{ch}[fm]	$\mathbf{R_n - R_p}$[fm]	Ref
Q_{weak}	^{27}Al	2.904	2.913	3.013	**0.009** est.	1
PREx	^{208}Pb	5.45	$5.78^{+0.16}_{-0.18}$	5.50	$\mathbf{0.33^{+0.16}_{-0.18}}$	2
CREx	^{48}Ca	3.438	3.594	3.526	**0.156** est.	3

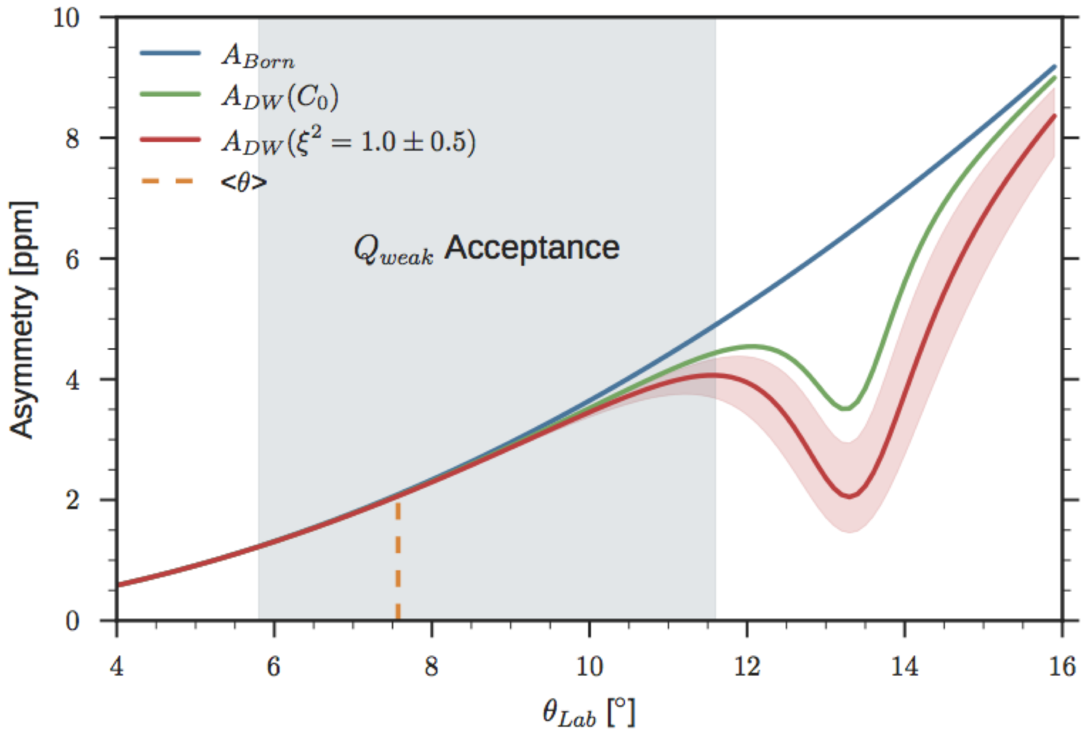
[1] *Phys. Rev. C89, 045503 (2014)*

[2] *PRL 108, 112502 (2012)*

[3] *CC Calculations [CREx Proposal (2013)]*

PVES on ^{27}Al - prediction

Prediction of $A_{elastic}$ using DWBA *C. J. Horowitz Phys. Rev. C 89, 045503 (2014)*



At Qweak's average acceptance, predicts $A_{elastic}$ (Al) ≈ 2.1 ppm

(E_{beam} = 1.16 GeV)

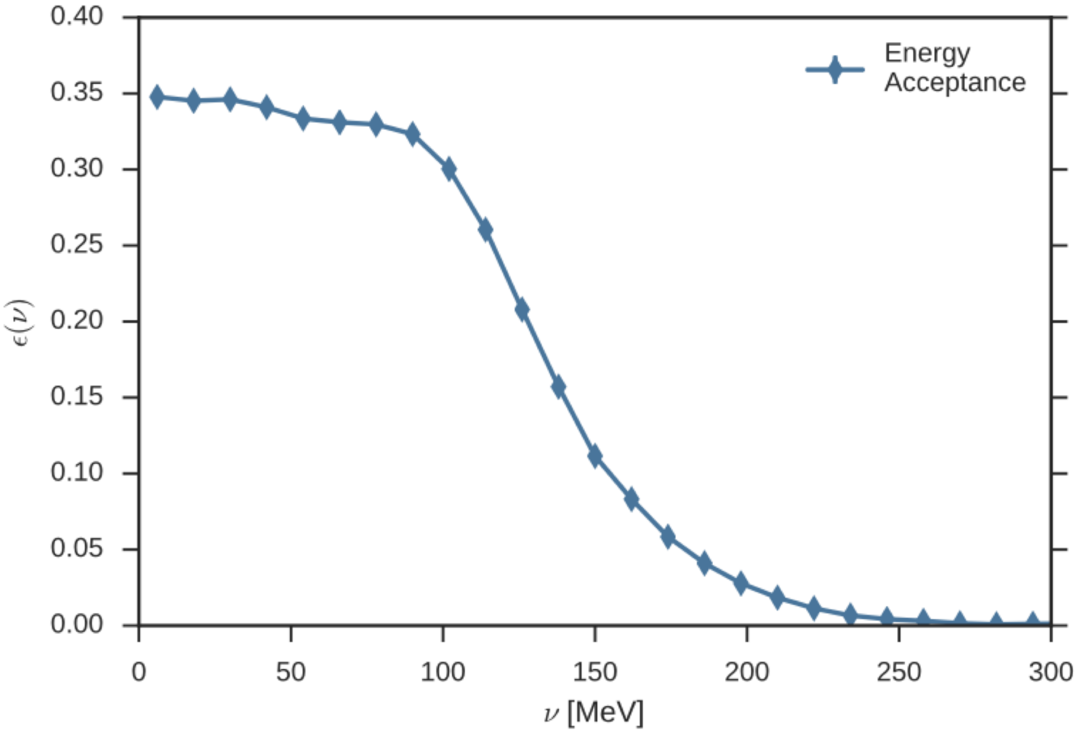
Aside: of we course, we made no attempt to optimize the Q = 153 MeV = 0.78 fm^{-1} to maximize sensitivity to neutron radius – kinematics dictated by optimization of weak charge measurement.

Elastic PVES on ^{27}Al - challenges

Two Primary Challenges in ^{27}Al elastic analysis:

1. Target not made of pure aluminum: alloy instead.
2. Spectrometer not designed with narrow energy acceptance to separate elastic state from excited states in nuclei.

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



PVES on ^{27}Al

Experimental Conditions

Data taken during second Qweak running period:
Nov 2011 – May 2012 (interspersed with lH_2 running)

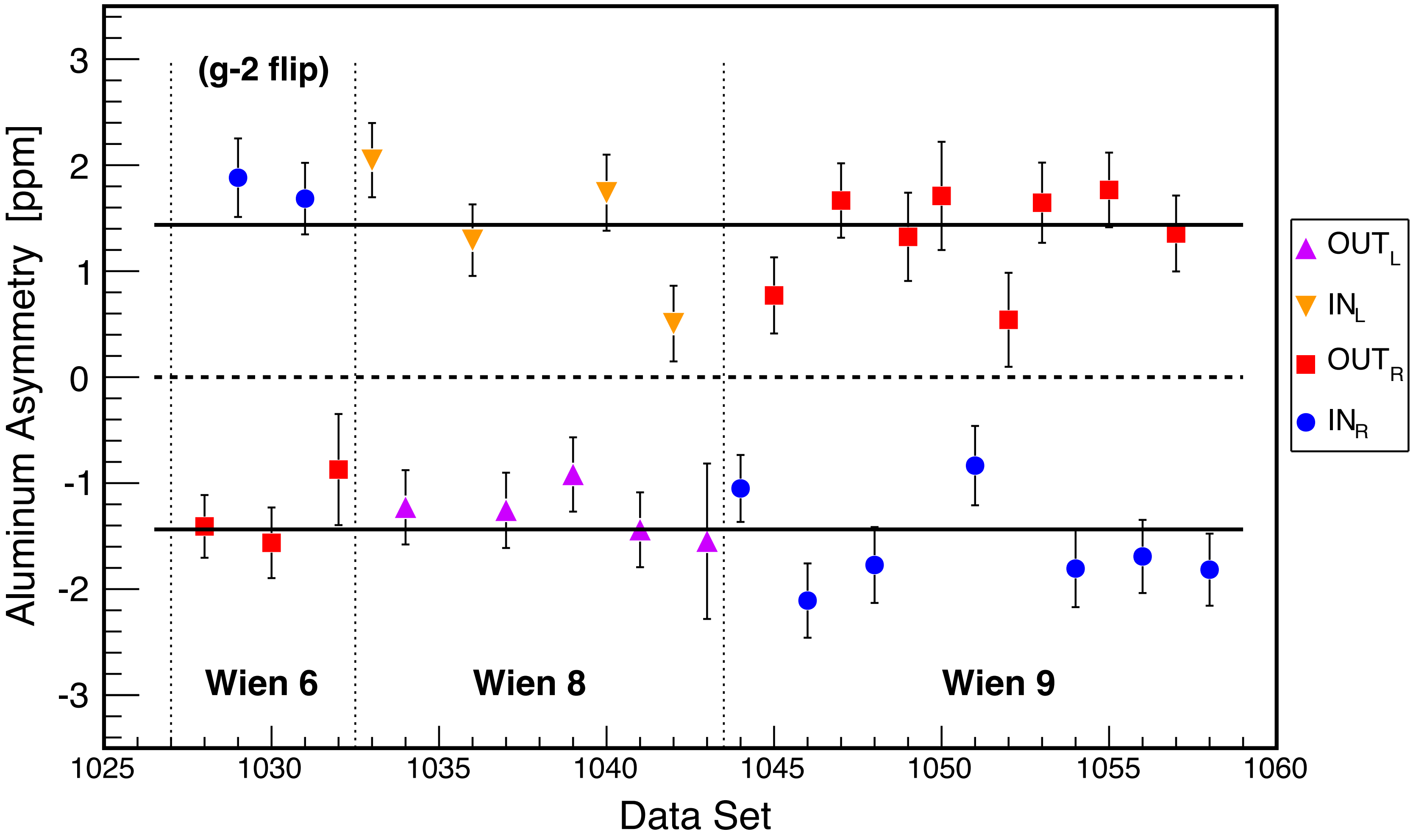
Target: ^{27}Al alloy 4.2% X_0 (3.7 mm thick)

Beam Conditions:
E_e = 1.16 GeV
I = 65 μA
Polarization = 88%

Spectrometer:
$\langle\theta\rangle = 7.6°$ $5.8° \leq \theta \leq 11.6°$
$\langle Q^2 \rangle$ = 0.0236 GeV^2
150 MeV energy acceptance

- Sufficient statistics taken for target-window correction for weak charge measurement.

PVES on ^{27}Al - asymmetries



- Asymmetry is well-behaved under three kinds of slow helicity reversal.
- Corrections for helicity-correlated beam properties at the few ppb scale.

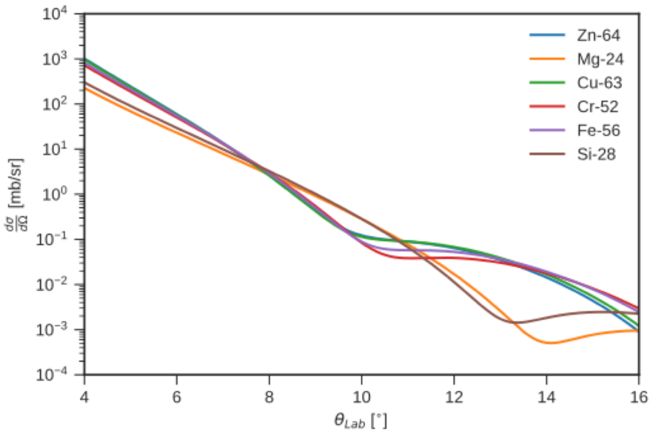
PVES on ^{27}Al – alloy corrections

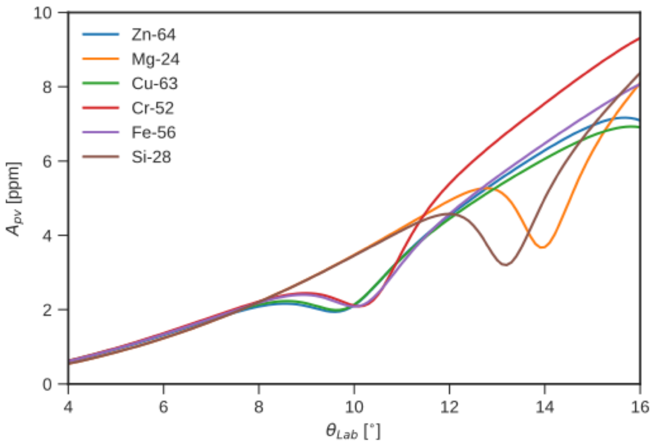
Aluminum alloy elements [w%]

Element	Run 1	Run 2
Al	89.53	89.23
Zn	5.90	5.87
Mg	2.60	2.63
Cu	1.50	1.81
Cr	0.19	0.19
Fe	0.14	0.11
Si	0.08	0.09
Mn	0.04	0.04
Ti	0.02	0.03

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.



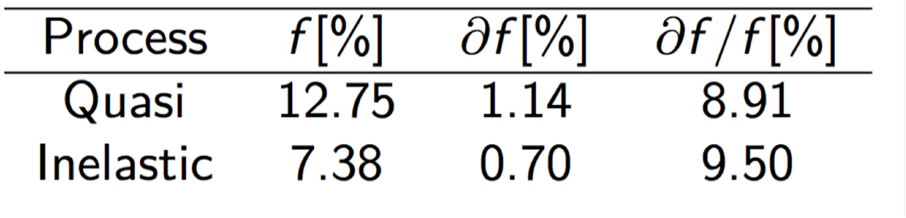


PVES on ^{27}Al – non-elastic backgrounds

Quasielastic and inelastic ($N \rightarrow \Delta$) backgrounds (low-lying nuclear levels & GDR negligible)

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)



Process	$f[\%]$	$\partial f[\%]$	$\partial f/f[\%]$
Quasi	12.75	1.14	8.91
Inelastic	7.38	0.70	9.50

Asymmetry: A_i

- Quasielastic: theoretical support from Horowitz and Lin
  - $A_{QE} = -0.34 \pm 0.34$ ppm

- Inelastic: made a low-statistics measurement: $A_{inel} = 1.61 \pm 1.15$ ppm $(\frac{\partial A}{A} = 71\%)$

  This turns out to be largest systematic uncertainty

  → theoretical input to reduce uncertainty?

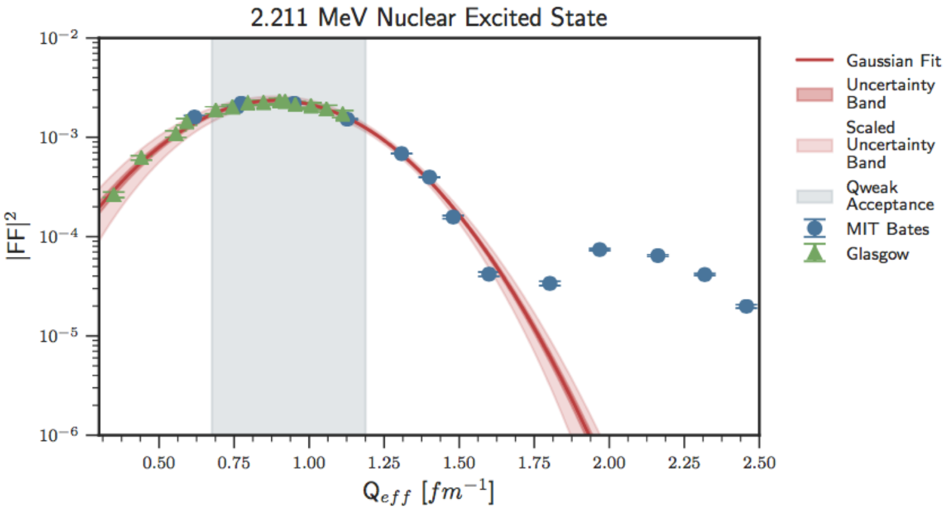
PVES on ^{27}Al – nuclear excited states

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
- All are dominantly isoscalar transitions, so

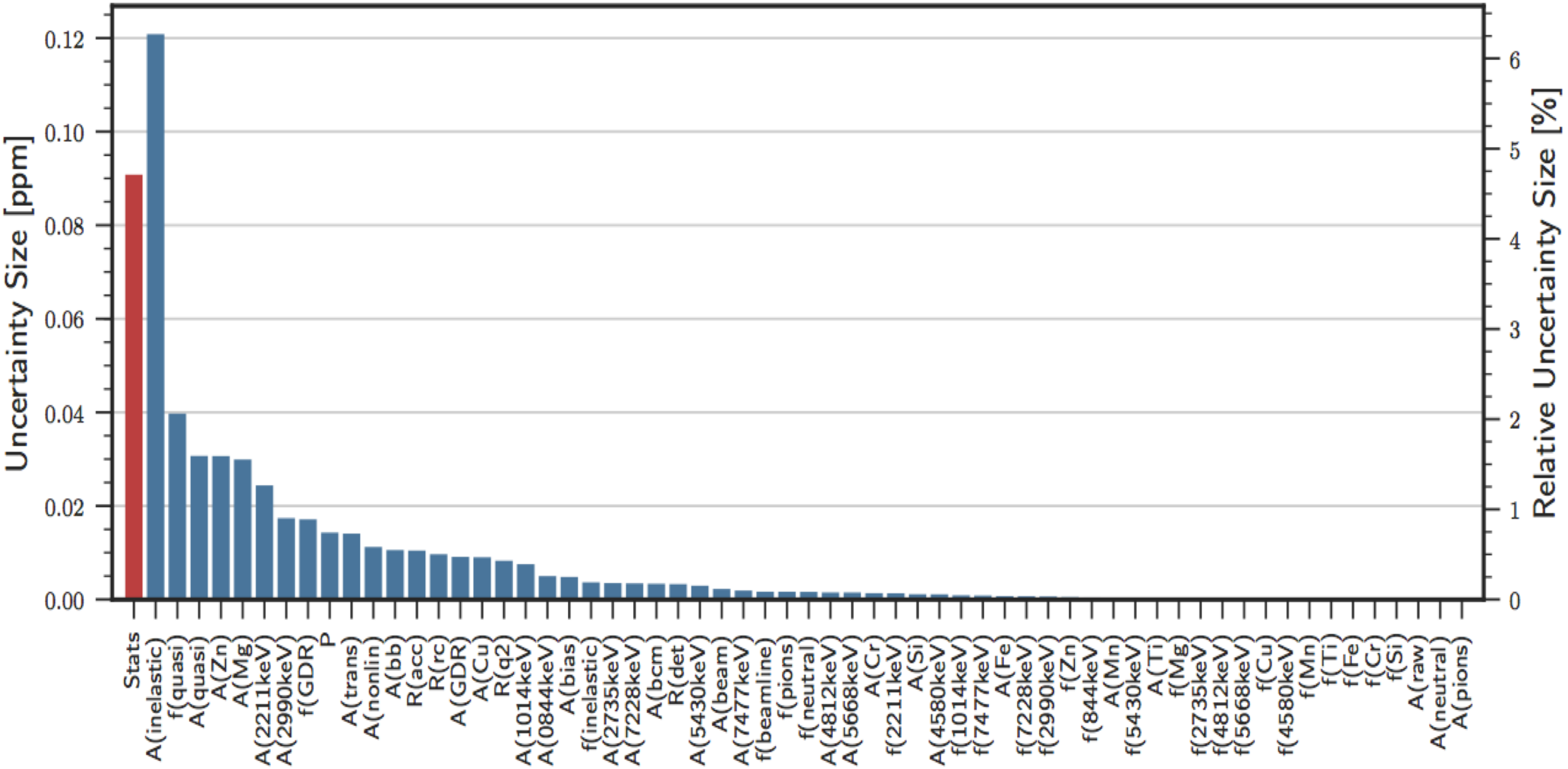
$$A_{Born} = A_{PV}^{eA} = A_0 Q_W = A_0[ZQ_W^p + NQ_W^n],$$

- Assume conservative 50% uncertainty on Asymmetries due to isospin mixing.

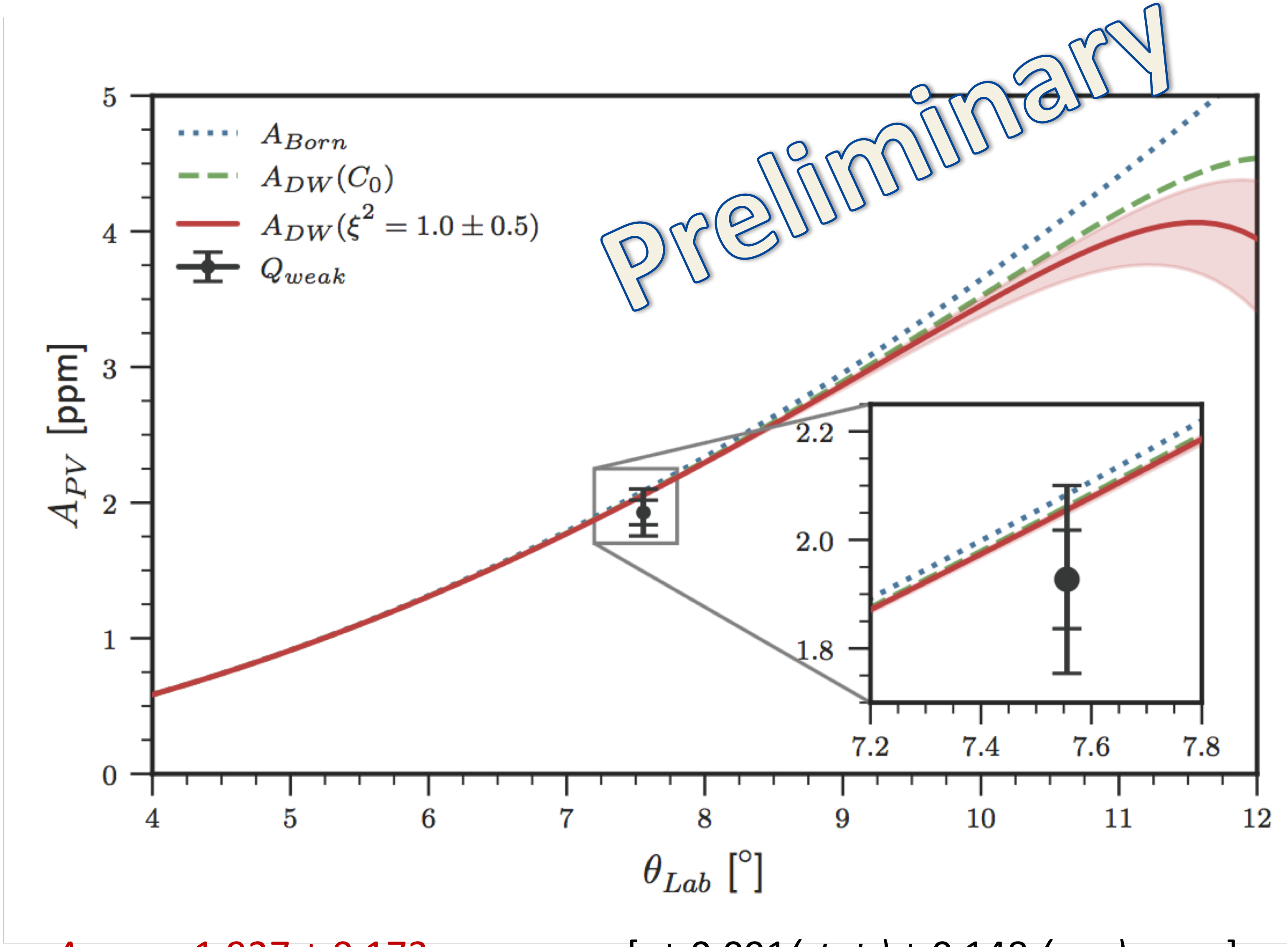


Energy Level [MeV]	Background Fraction (f_i) [%]	Asymmetry (A_i) [ppm]
0.844	0.27 ± 0.04	2.619 ± 1.310
1.014	0.41 ± 0.10	2.563 ± 1.282
2.211	1.35 ± 0.16	2.543 ± 1.271
2.735	0.19 ± 0.02	2.590 ± 1.295
2.990	0.93 ± 0.07	2.617 ± 1.308
4.580	0.06 ± 0.01	2.783 ± 1.392
4.812	0.09 ± 0.02	2.379 ± 1.189
5.430	0.17 ± 0.03	2.490 ± 1.249
5.668	0.08 ± 0.02	2.542 ± 1.271
7.228	0.18 ± 0.06	2.706 ± 1.353
7.477	0.10 ± 0.07	2.753 ± 1.377

PVES on ^{27}Al – systematics



PVES on ^{27}Al - result

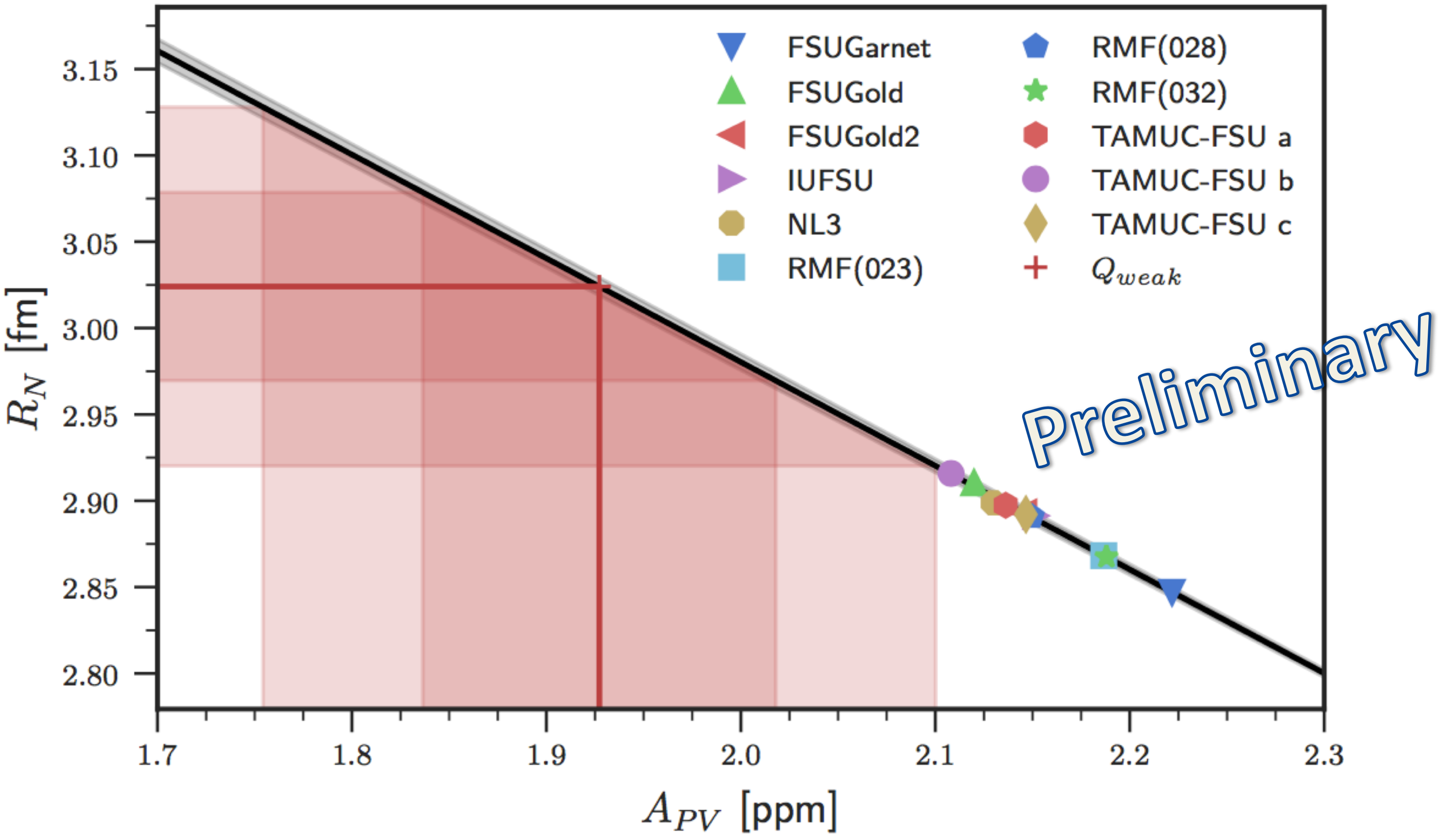


$A_{elastic}$ = 1.927 ± 0.173 ppm [± 0.091*(stat.)* ± 0.148 *(sys.)* ppm]

$\partial A/A$ = 9 %

PhD Thesis - Kurtis Bartlett W&M 2018

^{27}Al – extracting R_n



Calculations by C. Horowitz, F. Fattoyev & Z. Lin *(priv. comm.)*

- RMF models tuned to reproduce nucleon binding energies, charge radii, and strengths of the isoscalar and isovector giant resonances in various nuclei
- these models predict masses for neutron stars that agree with observations.

Our $A_{elastic}$ yields:

$$R_n = (3.024 \pm 0.104)\ \text{fm}$$

^{27}Al - skin thickness

Skin Thickness: $R_n - R_p$

Using the value $R_p = 2.932 \text{ fm}$ from a set of relativistic mean field models:

$$\begin{aligned} R_n - R_p &= (3.027 \pm 0.104) - (2.932 \pm 0.007) \text{ fm} \\ &= 0.092 \pm 0.104 \text{ fm} \end{aligned}$$

- Consistent with zero, as makes intuitive sense, of course (Z=13, N=14).
- $A_{inelastic}$ contribution to asymmetry largest systematic in R_n and thus in skin thickness – improvable with help from theory?

Result being prepared for publication.

Summary

1) Weak Charge: Precision measurement of proton's weak charge:

$$\boxed{Q_W^p = 0.0719 \pm 0.0045}$$

Excellent agreement with Standard Model prediction = 0.0708

Constrains generic new parity-violating "Beyond the Standard Model" physics at TeV scale: $\Lambda/g > 3.6$ TeV (arbitrary u/d ratio of couplings)

Published: Nature 557, 207 (2018).

Important addition to global electroweak fits to constrain many new physics scenarios.

2) PVES on ^{27}Al: Only the 4th ever elastic parity-violation result on complex nucleus

Neutron radius in ^{27}Al: $R_n = (3.024 \pm 0.104)$ fm

Neutron skin thickness: $R_n - R_p = 0.092 \pm 0.104$ fm

Benchmark of use of PVES to determine neutron radii.

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