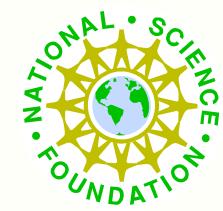


First Determination of the Proton's Weak Charge – Early Results from Q_{weak}



A.K. Opper for the Q_{weak} Collaboration

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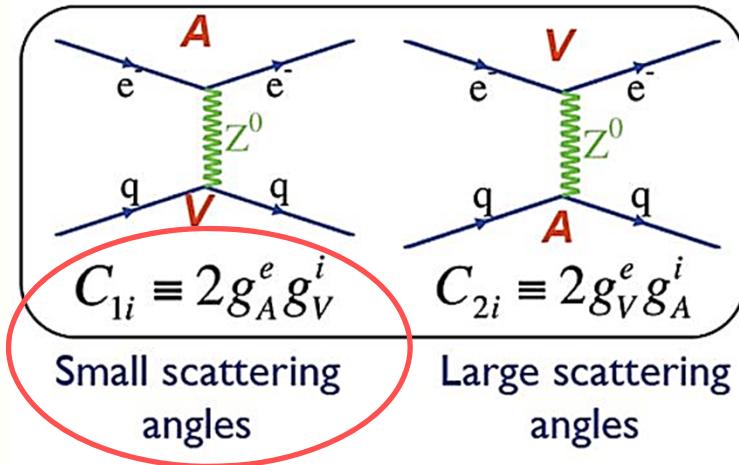


The Weak Charges

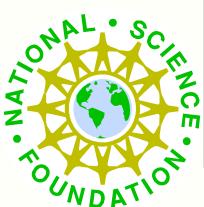
$Q_w(p)$: neutral-weak analog of the proton's electric charge

	Q_{EM}	Weak Vector Charge
u quark	2/3	$-2C_{1u} = 1 - \frac{8}{3}\sin^2\theta_w \approx 1/3$
d quark	-1/3	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_w \approx -2/3$
p (uud)	+1	$1 - 4\sin^2\theta_w \approx 0.07$
n (udd)	0	≈ -1

Q-weak particularly sensitive to quark vector couplings C_{1u} & C_{1d}



- Q_W^p well defined prediction in electroweak SM
- Q_W^p suppressed → sensitive to new physics
- General: $Q_w(Z,N) = -2\{C_{1u}(2Z+N) + C_{1d}(Z+2N)\}$
 - $Q_w(p) = -2(2C_{1u} + C_{1d})$ (this experiment)
 - $Q_w(^{133}\text{Cs}) = -2(188C_{1u} + 211C_{1d})$ (APV)



Status

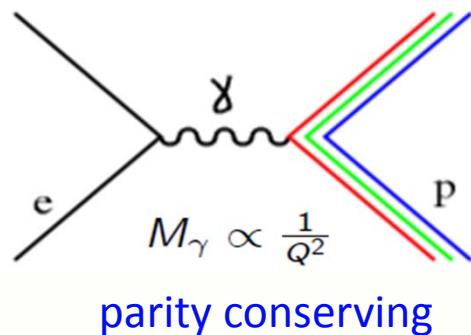
- Qweak Experiment finished successfully
 - Precise measurement of \vec{e} - p analyzing power @ low Q^2
 - 2 years on the floor, ~ 1 year of beam
 - $\sim 4\%$ of total data set analyzed (from commissioning)
 - Results presented here

1st clean determination of $Q_W(p)$, C_{1u} , C_{1d} , $Q_W(n)$

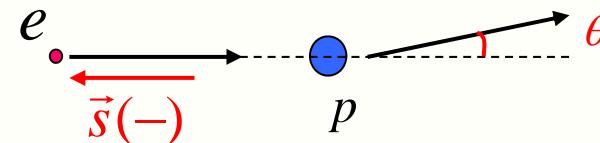
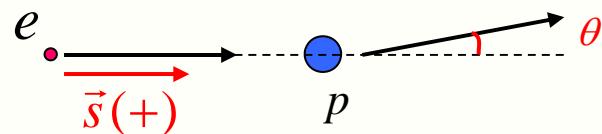
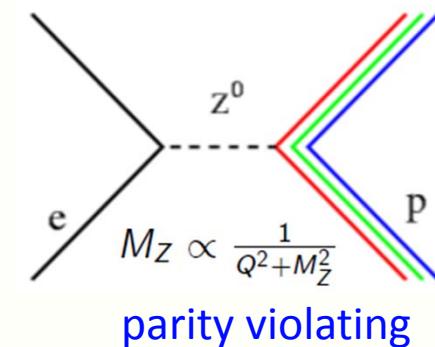
- Remainder of data being analyzed
 - Final result by end of 2014 with $\sim 5x$ better precision
 - Close to proposed goal of 4% on Q_W^p



Extract Q_W^p from Elastic $\vec{e}p$ Scattering



← Interfere →



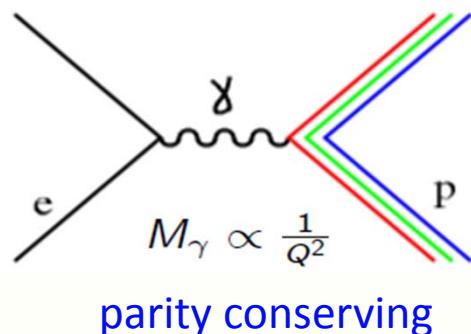
- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right] \sim \frac{|M_{weak}^{PV}|}{|M_{EM}|}$

$$Q^2 \rightarrow 0 \quad A_{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4 \sin^2 \theta_w) \epsilon' G_M^\gamma G_A^Z}{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

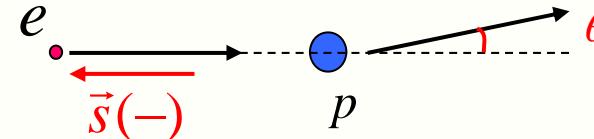
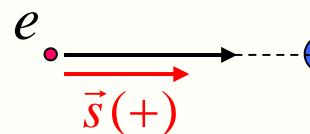
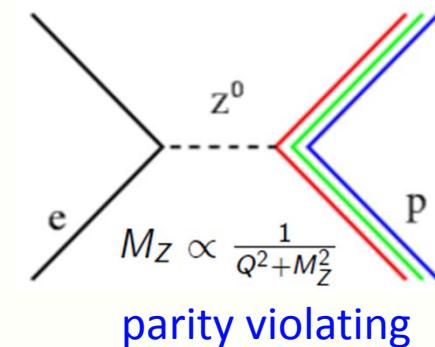
- where $\epsilon = [1 + 2(1 + \tau) \tan^2(\theta/2)]^{-1}$, $\epsilon' = \sqrt{\tau(1 + \tau)(1 - \epsilon^2)}$,
- $\tau = Q^2/4M^2$, $G_{E,M}^\gamma$ are EM FFs, $G_{E,M}^Z$ & G_A^Z are strange & axial FFs,
- and $\sin^2 \theta_w = 1 - (M_W / M_Z)^2$ = weak mixing angle



Extract Q_W^p from Elastic $\vec{e}p$ Scattering



← Interfere →



- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right] \sim \frac{|M_{weak}^{PV}|}{|M_{EM}|}$

$Q^2 \rightarrow 0$
 $\theta \rightarrow 0$

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

– So in a plot of $A_{ep}/\left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs Q^2 :

- Q_W^p is the intercept (anchored by precise data near $Q^2=0$)
- $B(Q^2, \theta)$ is the slope (determined from higher Q^2 PVES data)

This Experiment



At tree level: $Q_w^p = (1 - 4\sin^2\theta_w) \sim 0.072$

Precision measurement: $\delta A = \pm 2\% \Rightarrow \delta Q_w^p = \pm 4\%$

$$\Rightarrow \delta(\sin^2\theta_w) = \pm 0.3\%$$

Meas'd Asymmetry: $A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[Q^2 Q_{weak}^p + Q^4 B(Q^2) \right]$

Expected value: $A(0.03 \text{ GeV}^2) = A_{Q_w^p} + A_{B(Q^2)}$
 $= -.19 \text{ ppm} \quad -.10 \text{ ppm}$

Experimental considerations:

- need high statistics \rightarrow integrating detector system
- measured asymmetry $\sim P$; $\rightarrow P$ must be large & well measured
- must know **detector-response-weighted $\langle Q^2 \rangle$** and $\langle Q^4 \rangle$
- helicity correlated systematic errors $< 5 \times 10^{-9}$
- need $B(Q^2)$ so we can subtract it
- KISS ie **Keep It Simple, Stupid!**



Qweak Apparatus

Parameters:

$E_{beam} = 1.165 \text{ GeV}$

$\langle Q^2 \rangle = 0.025 \text{ GeV}^2$

$\langle \theta \rangle = 7.9^\circ \pm 3^\circ$

ϕ coverage = 50%
of 2π

$I_{beam} = 180 \mu\text{A}$

Integrated rate =
6.4 GHz

Beam Polarization =
88%

Target = 35 cm LH_2

Cryopower = 3 kW

Electron beam

LH_2 Target

Horizontal
Drift Chambers

Toroidal Magnet
Spectrometer

Trigger Scintillator

Vertical Drift Chambers

Quartz Cerenkov Bars

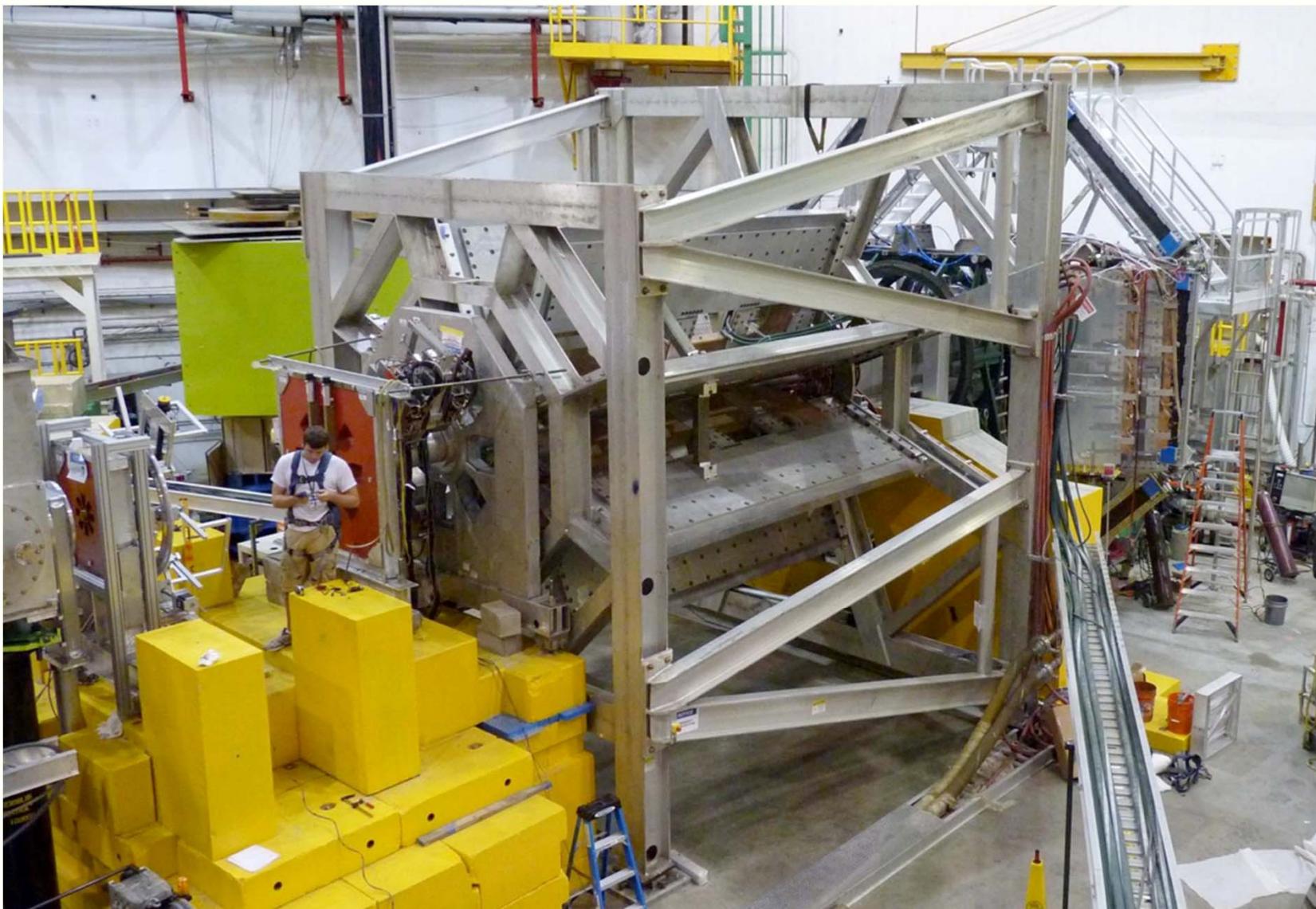


Red = low-current tracking mode only

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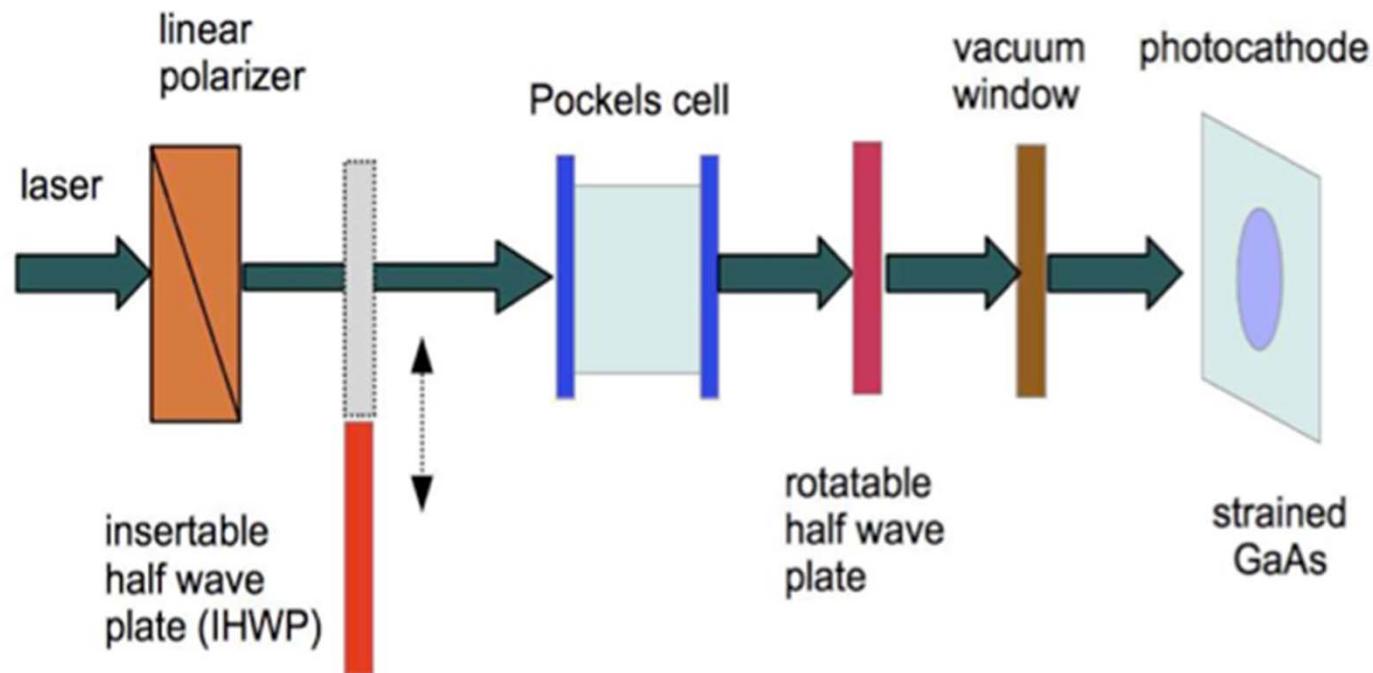
Q_{weak} Apparatus (before shielding)



PSI – September 2013



Polarized Injector



- **Helicity reversal frequency**: 960 Hz (“freeze” bubble motion in the target)
- **Helicity pattern**: pseudo-random “quartets” (+--+ or -+-+, asymmetry calculated for each quartet)
- **Insertable Half-Wave Plate**: “slow reversal” of helicity checks systematic effects cancels certain false asymmetries.

$$A = \frac{N_+ - N_-}{N_+ + N_-} + B$$

Asymmetry is “blinded”
to avoid bias

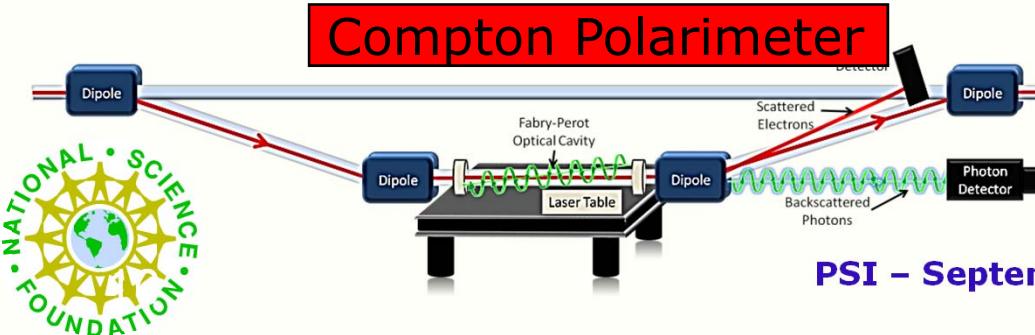


Precision Polarimetry

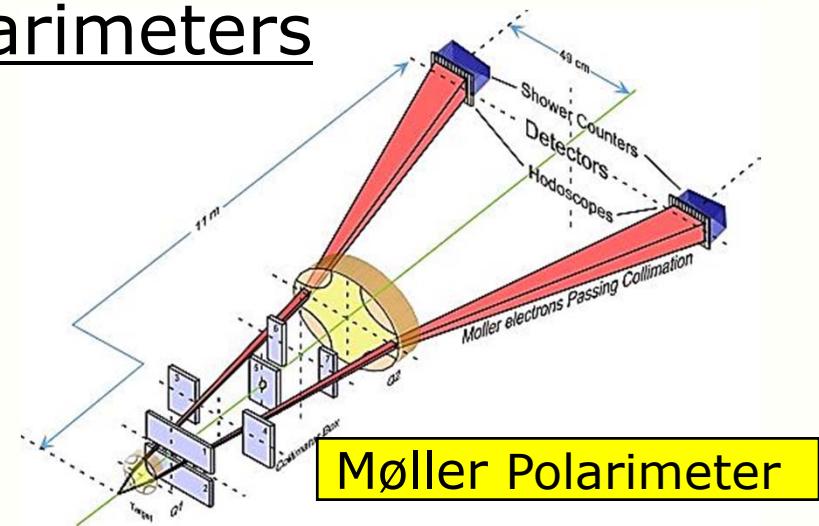
Qweak requires $\Delta P/P \leq 1\%$

Strategy: use 2 independent polarimeters

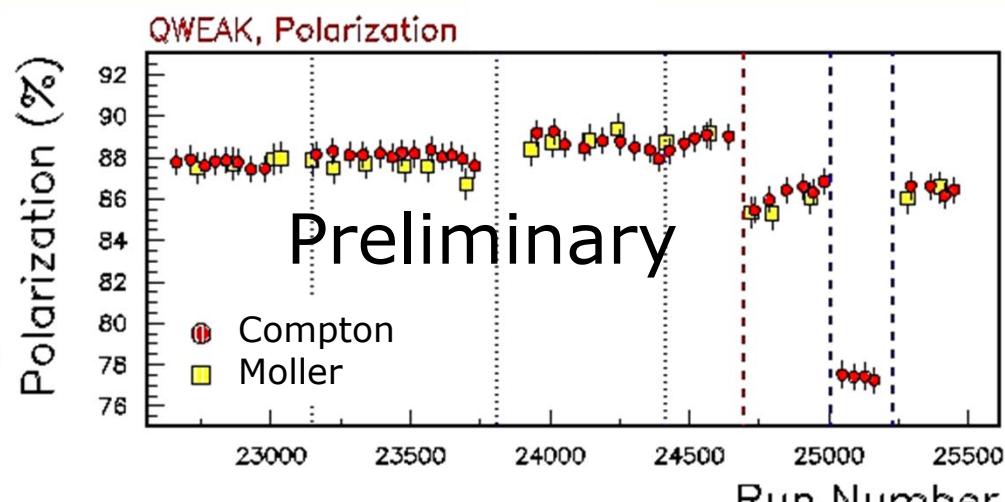
- Use existing <1% Hall C Møller polarimeter:
 - Low beam currents, invasive
 - Known analyzing power provided by polarized Fe foil in a 3.5 T field.
- Use new Compton polarimeter (1%/h)
 - Continuous, non-invasive
 - Known analyzing power provided by circularly-polarized laser



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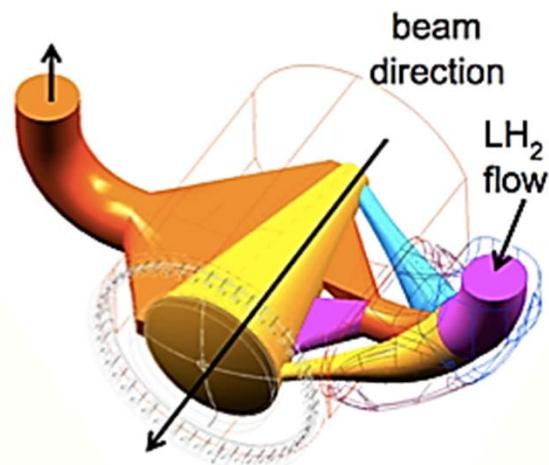


Møller Polarimeter



LH₂ Target Design

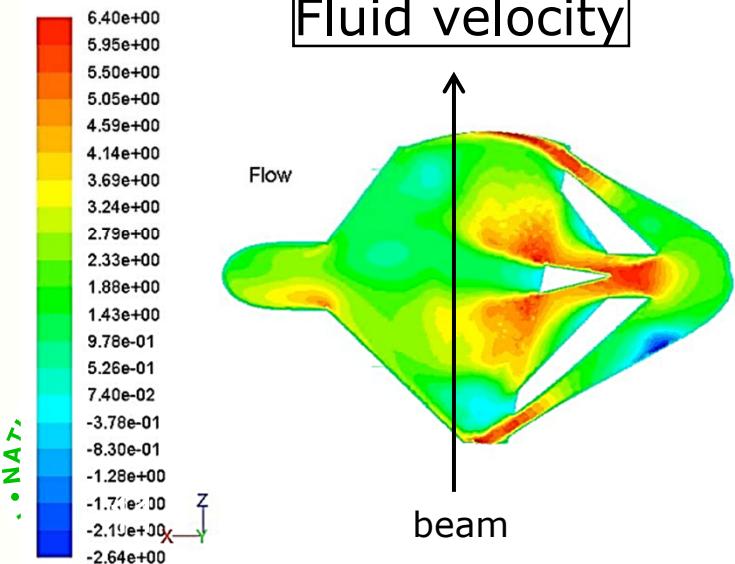
- World's highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations



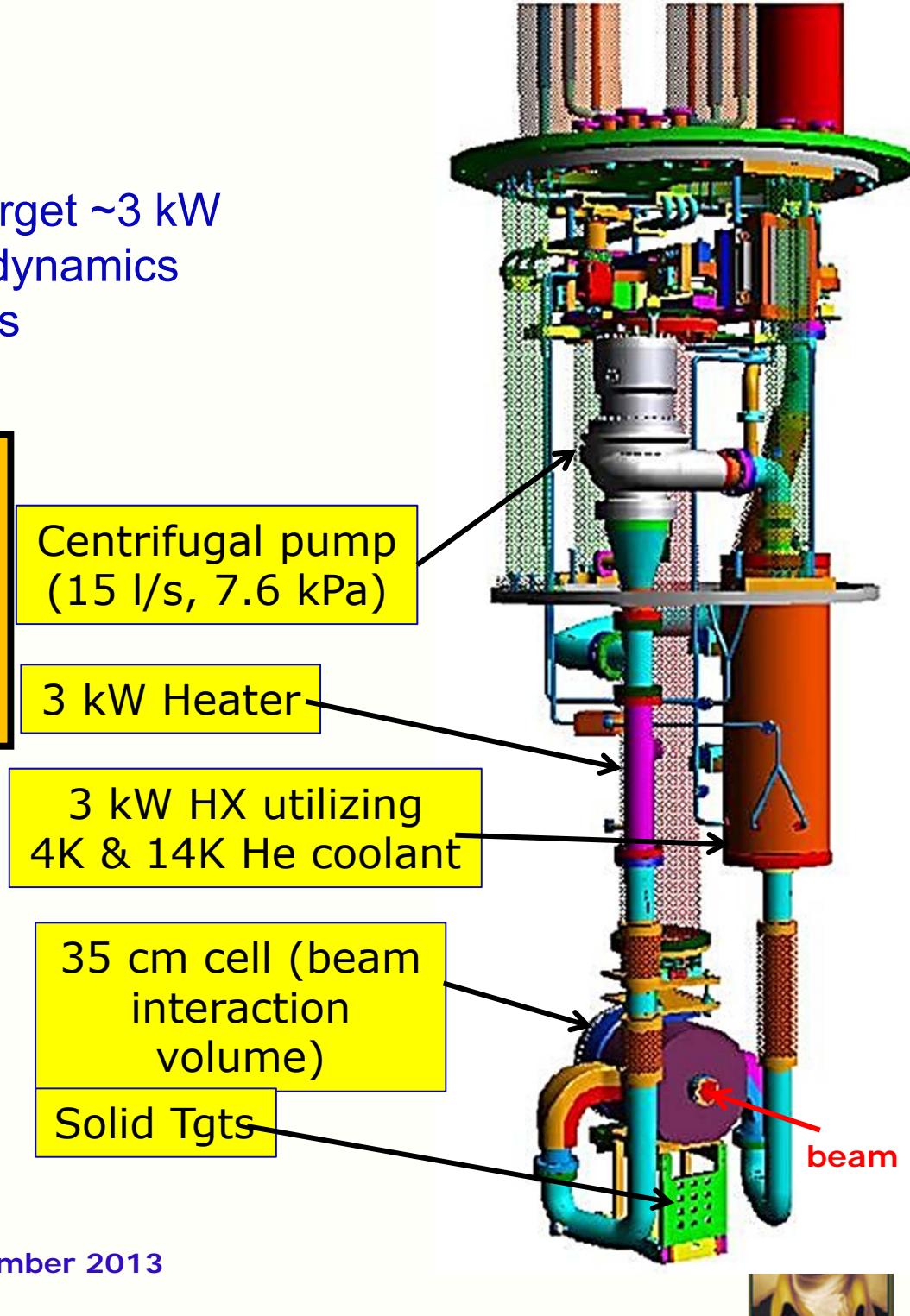
$I_{\text{Beam}} = 180 \mu\text{A}$
 $L = 35 \text{ cm (4\% } X_0)$
 $P_{\text{beam}} = 2.2 \text{ kW}$
 $A_{\text{spot}} = 4 \times 4 \text{ mm}^2$
 $V = 57 \text{ liters}$
 $T = 20.00 \text{ K}$
 $P \sim 220 \text{ kPa}$

Fluid velocity

ANSYS

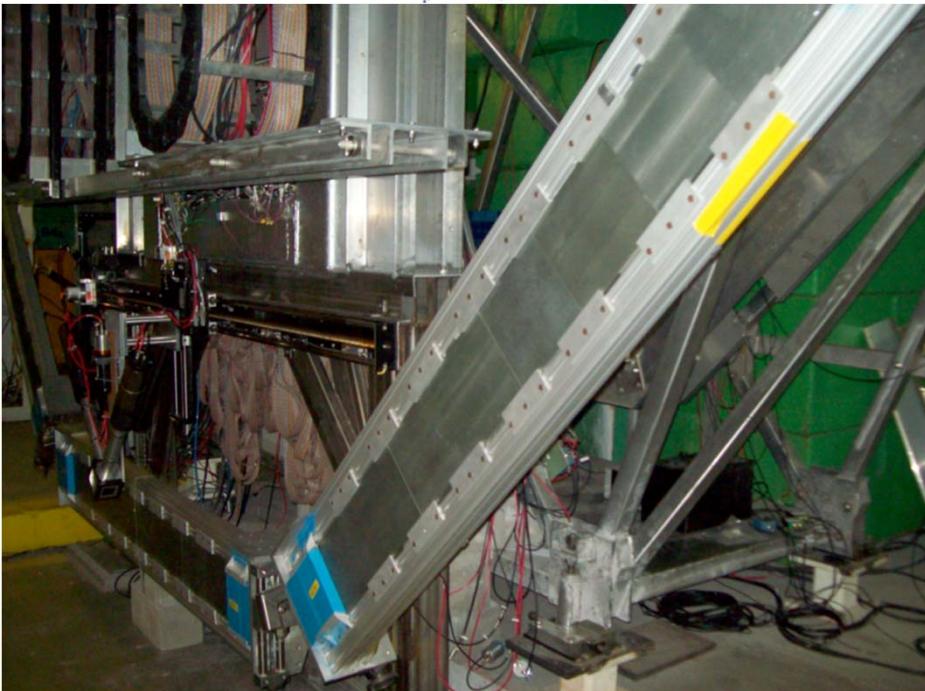
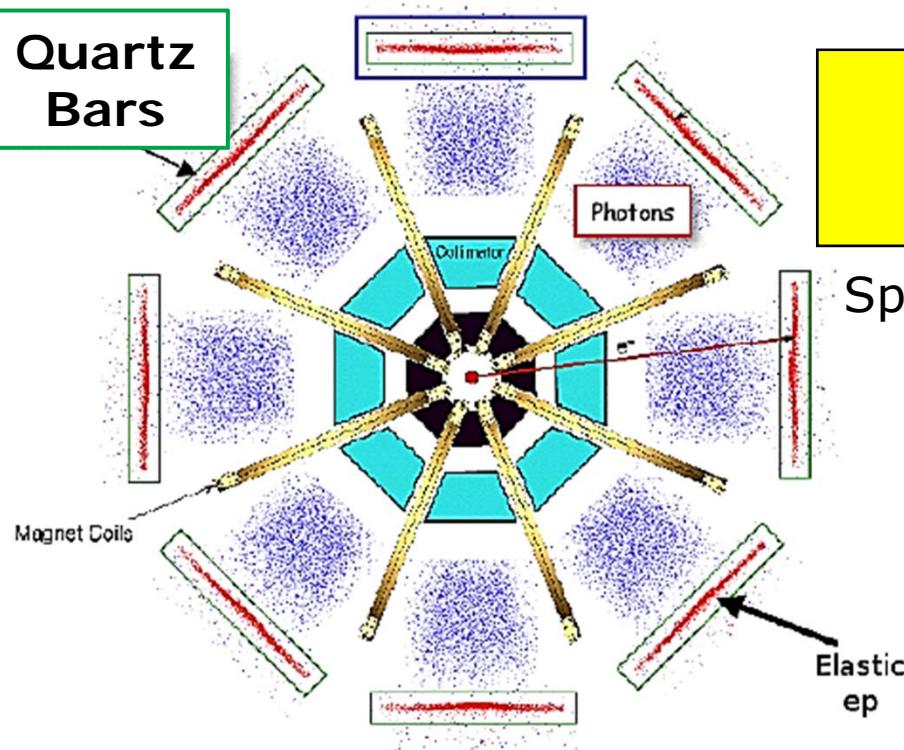


September 2013



Quartz Cerenkov Detectors

Quartz Bars

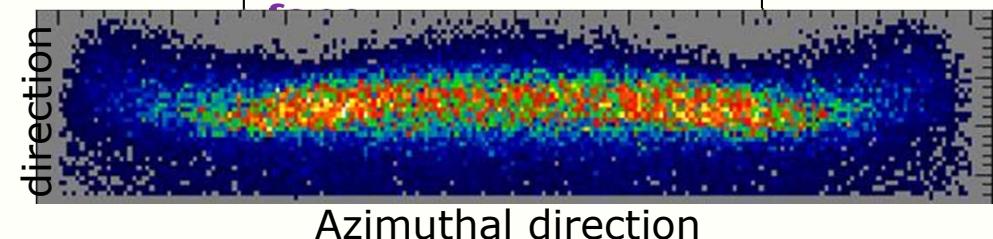


Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

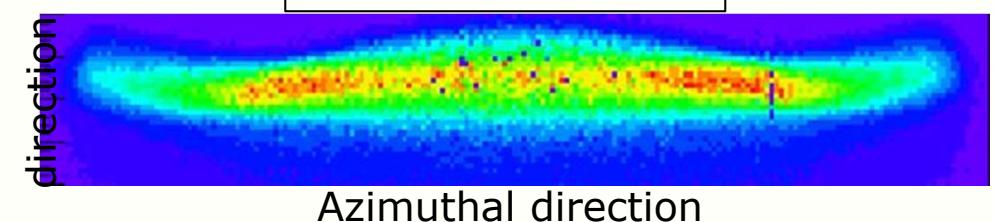
Spectrosil 2000:

- Eight bars, each 2 m long, 1.25 cm thick
- Rad-hard
- Non-scintillating, low-luminescence

Simulation of MD



Measured



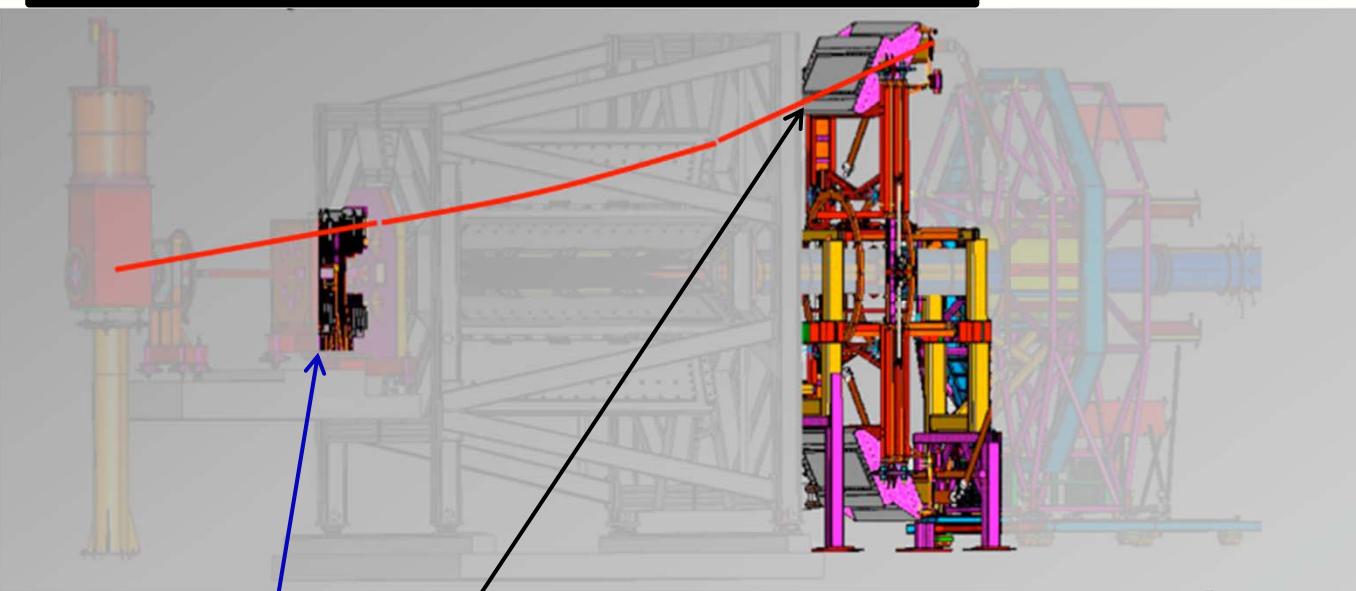
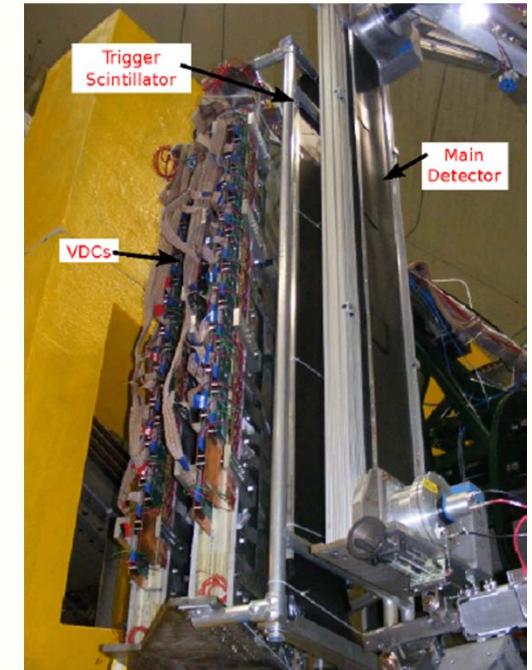
Yield 100 pe's/track with 2cm Pb pre-radiators
Resolution limited by shower fluctuations.



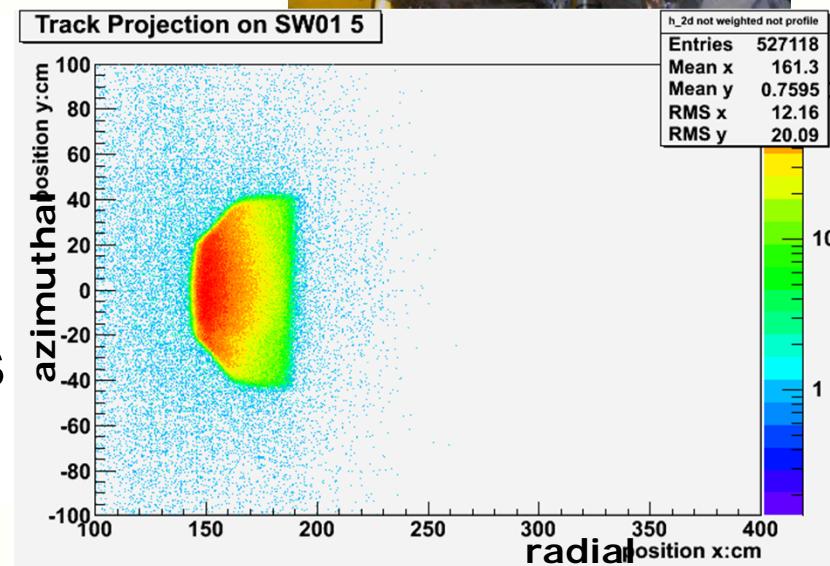
Determining the Kinematics

Required uncertainty on Q^2 is 0.5%
Combination of tracking & simulation

$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha} [Q_W^p + F(\theta, Q^2)]$$



- **HDCs** upstream of magnet $\rightarrow \theta$
 - $Q^2 = 2E^2 (1-\cos\theta) / [1 + E/M(1-\cos\theta)]$
- **VDCs** & trigger scintillators after magnet \rightarrow light weighted Q^2 across quartz bars



LH₂ Data Quality (blinded asymm)

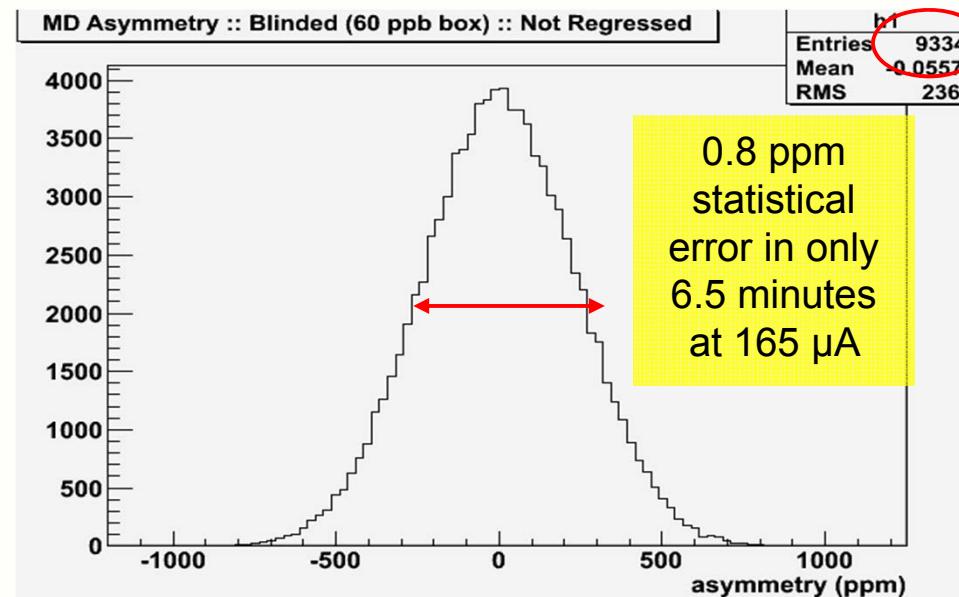
Convergence to mean $\sim \text{rms}/\sqrt{N}$

Width is relevant FOM

At 165 μA , total detected rate is 5.83 GHz.

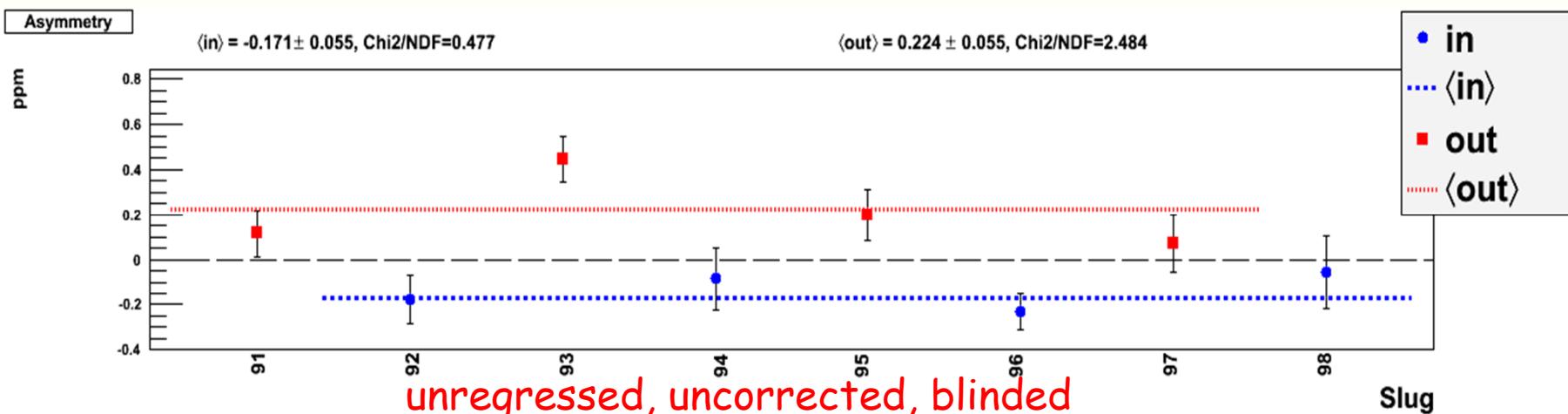
→ Pure counting statistics: 215 ppm
+ detector shower fluctuations 232 ppm
+ current normalization and target 235 ppm

Width is understood and about 10% above c.s.



Electron helicity reversed every 1 msec by *electronic* means

Insertable Half Wave Plate (IHWP) → *optically* flips the helicity before every 8 hour “slug”
→ signal changes sign



Beam Property Requirements

Beam value	Requirement	Achieved	
		Run I	Run II
X-position at target [nm]	<2	3.6 +/- 0.39	-0.95 +/- 0.06
Y-position at target [nm]	<2	-6.9 +/- 0.39	-0.24 +/- 0.28
X-angle at target [nrad]	<30	-0.22 +/- 0.012	-0.07 +/- 0.017
Y-angle at target [nrad]	<30	-0.18 +/- 0.015	-0.06 +/- 0.011
Position at dispersion (3c12X)[nm]	-	-13.6 +/- 0.23	-0.83 +/- 0.30
Energy dE/E [ppb]	<1	<3.8 +/- 0.06	<0.23 +/- 0.08



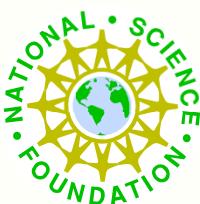
Constructing the Asymmetry

False Asymmetries

- $A_{\text{msr}} = A_{\text{raw}} + A_T - A_{\text{reg}}$
 - $A_{\text{raw}} = (Y^+ - Y^-) / (Y^+ + Y^-)$
 - Charge normalized ep yields for $\pm e$ -helicity
 - A_T = remnant transverse asymmetry measured with explicitly P_T beam
 - $A_{\text{reg}} = \sum \left(\frac{\partial A}{\partial \chi_i} \right) \Delta \chi_i$, measured with natural & driven beam motion for (x, y, x', y', E) using BPMs
 - A_Q driven to 0 with feedback

Backgrounds

- $A_{\text{ep}} = R_{\text{tot}} \frac{A_{\text{msr}}/P - \sum_{i=1}^4 f_i A_i}{1-f_{\text{tot}}}$
 - $R_{\text{tot}} = R_{Q^2} R_{\text{RC}} R_{\text{Det}} R_{\text{Bin}} = 0.98$
 - $f_{\text{tot}} = \sum f_i = 3.6\%$
 - f_i = fraction of yield from bkg i
 - A_i = asymmetry of bkg i
 - b_1 from Al windows of tgt cell (dominant bkg)
 - b_2 from beamline bkg
 - b_3 from other soft neutral bkg
 - b_4 from $N \rightarrow \Delta$ inelastic bkg



For “25% Commissioning Data set”

Source of Error (A)	Contribution (ppm)
A_meas Statistics	0.0358
A_meas Systematic*	0.0151
Polarization	0.0049
AI Window Asym	0.0087
AI Window Dilution	0.0046
QTOR Transport Asym	0.0021
QTOR Transport Dilution	0.0017
Beamline Asym	0.0232
Beamline Dilution	0.0035
N \rightarrow Δ Asym	0.0002
N \rightarrow Δ Dilution	0.0006
Det. Bias correction**	0.0019
EM Rad. Corrections	0.0014
Total Systematic	0.0302
Total	0.0469 (16%)

$$A_{PV} = \frac{\frac{A_{meas}}{P} - \sum f_i A_i}{1 - \sum f_i}$$

$$A_{meas} = -204.6 \pm 30.5 \text{ ppb}$$

$$A_{PV} = -279 \pm 35 \text{ (stat)} \\ \pm 31 \text{ (sys) ppb}$$

Correction	Correction (ppm)
Polarization	-0.0265
Aluminum Windows	-0.0642
QTOR transport channel (neutrals)	0.0000
Beamline Backgrounds (neutrals)	+0.0102
N \rightarrow Δ electrons	+0.0006
EM radiative effects + Detector bias	-0.0088
Total	-0.0829

*Includes cut dependence, regression systematics, detector non-linearities, and transverse asymmetry

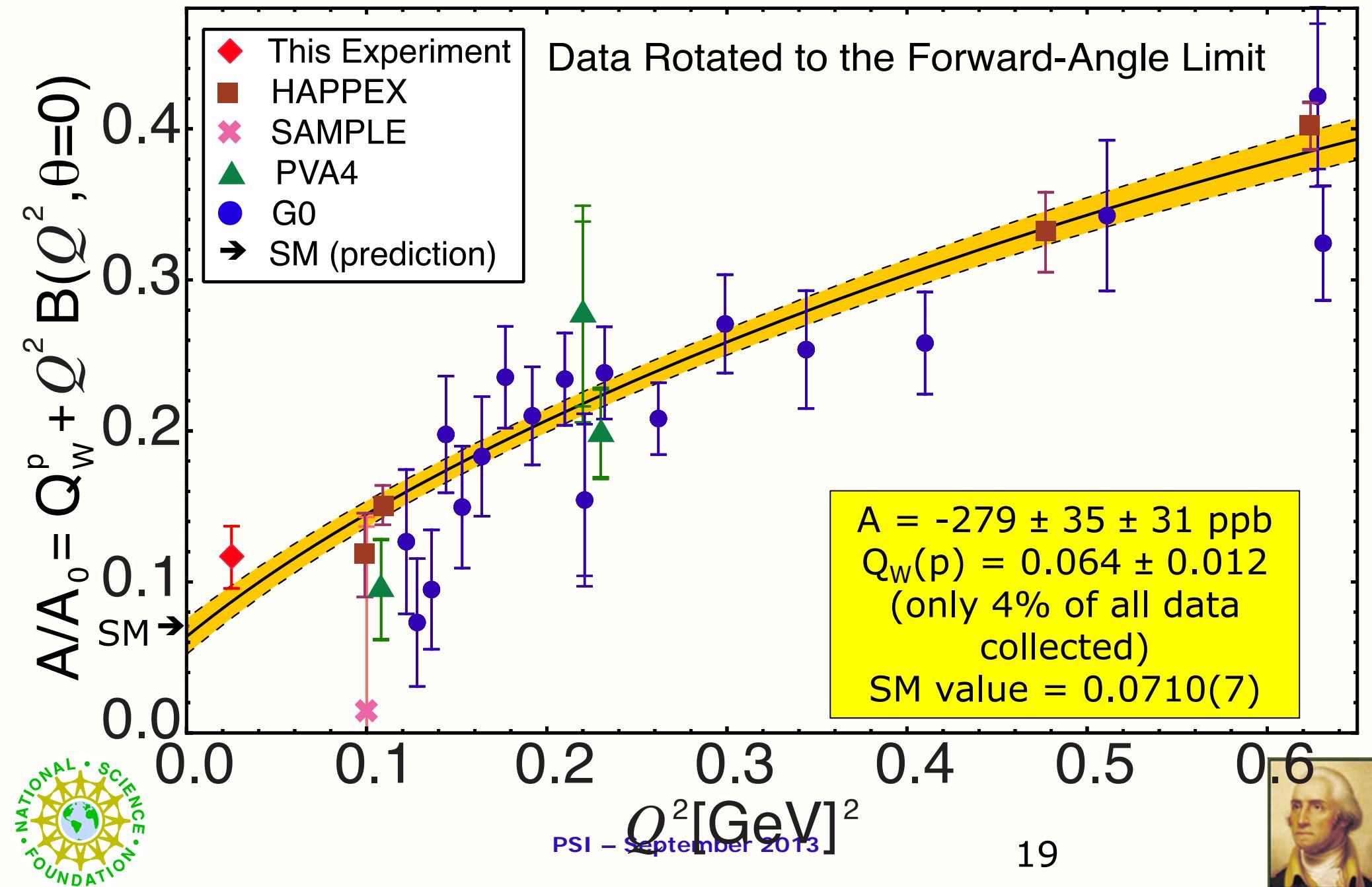
**Simulation-based correction for variation in light produced across the detectors & non-uniform Q² distributions.

Global PVES Fit Details

- Effectively 5 free parameters:
 - C_{1u} , C_{1d} , ρ_s , μ_s , & isovector axial FF G_A^Z
 - $G_E^S = \rho_s Q^2 G_D$, $G_M^S = \mu_s G_D$, & G_A^Z use G_D where
 - $G_D = (1 + Q^2/\lambda^2)^{-2}$ with $\lambda = 1 \text{ GeV}/c$
- Employs all PVES data up to $Q^2 = 0.63 \text{ (GeV}/c)^2$
 - On p, d, & ${}^4\text{He}$ targets, forward and back-angle data
 - SAMPLE, HAPPEX, G0, PVA4
- Uses constraints on isoscalar axial FF G_A^Z
 - Zhu, et al., PRD 62, 033008 (2000)
- All data corrected for E & Q^2 dependence of \square_{YZ} RC
 - Hall et al., arXiv:1304.7877 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying Q^2 , θ , & λ studied, found to be small

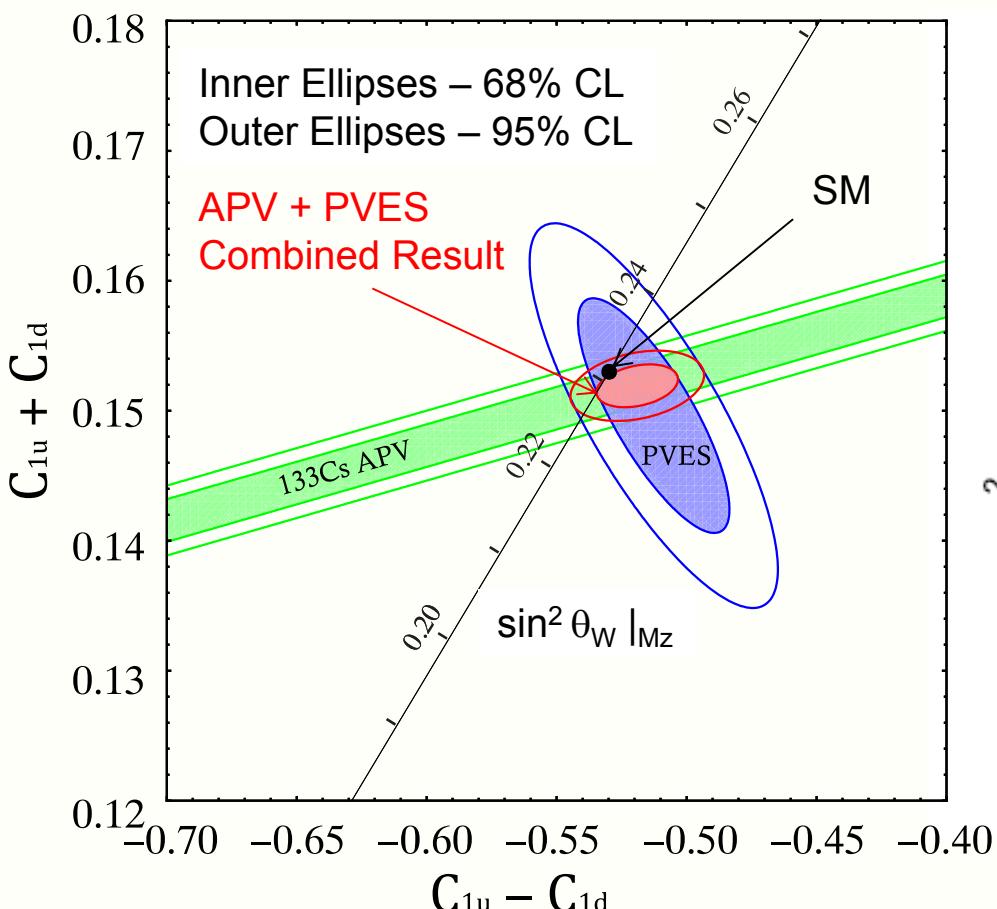


Global Fit of $Q^2 < 0.63$ $(\text{GeV}/c)^2$ PVES Data



Combined Analysis

Extract: C_{1u} , C_{1d} , Q^n_W

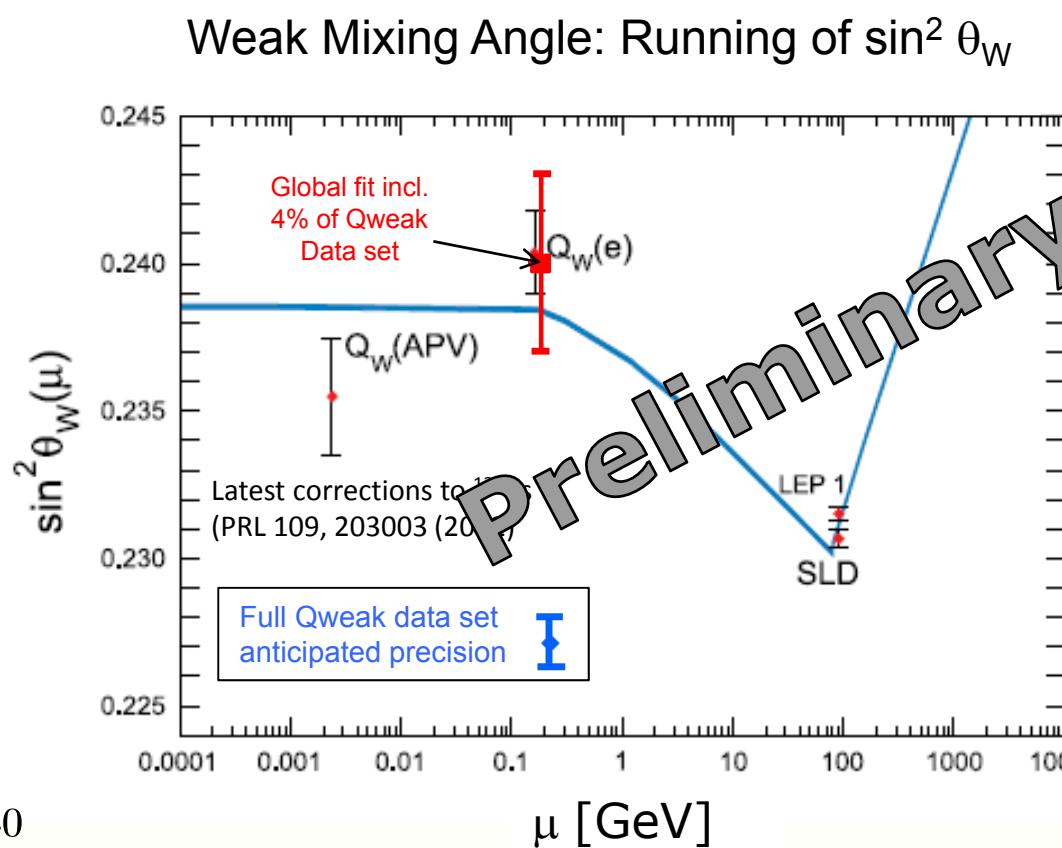


$$Q^n_W = -2(C_{1u} + 2C_{1d}) \\ = -0.975 \pm 0.010$$

$$C_{1u} = -0.184 \pm 0.005 \\ C_{1d} = 0.336 \pm 0.005$$

Qweak + Higher Q^2 PVES

Extract: Q^p_W , $\sin^2 \theta_W$



$$Q^p_W = -2(2C_{1u} + C_{1d}) \\ = 0.064 \pm 0.012 \\ \text{SM prediction} = 0.0710(7)$$

Remainder of experiment still being analyzed, final result before end of 2014. Expect final ΔA_{e-p} result will have $\sim 5 \times$ better precision.

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Summary arXiv:1307.5275 & Status

- Measured $A_{ep} = -279 \pm 35$ (statistics) ± 31 (systematics) ppb
 - Smallest & most precise ep asymmetry ever measured
- First determination of $Q_W(p)$:
 - $Q_w(p) = 0.063 \pm 0.012$ (from only 4% of all data collected)
 - (SM value = 0.0710(7))
 - New physics reach $\Lambda/g = \frac{1}{2}(\sqrt{2} G_F \Delta Q_W)^{-1/2} \sim 1.1$ TeV
- First determination of $Q_W(n) = -2(C_{1u} + 2C_{1d})$:
 - By combining our result with APV
 - $Q_w(n) = -0.975 \pm 0.010$ (SM value = -0.9890(7))
- Final results with ~ 5 times smaller uncertainties in about a year
 - Expected physics reach of $\Lambda/g \sim 2.3$ TeV.
 - SM test, sensitive to Z's and LQs



The Qweak Collaboration



- 95 collaborators
- 23 grad students
- 10 post docs
- 23 institutions:

JLab, W&M, UConn, TRIUMF, MIT, UMan., Winnipeg, VPI, LaTech, Yerevan, MSU, OU, UVa, GWU, Zagreb, CNU, HU, UNBC, Hendrix, SUNO, ISU, UNH, Adelaide

D.S. Armstrong, A. Asaturyan, T. Averett, J. Balewski, J. Beaufait, R.S. Beminiwattha, J. Benesch, F. Benmokhtar, J. Birchall, R.D. Carlini¹, J.C. Cornejo, S. Covrig, M.M. Dalton, C.A. Davis, W. Deconinck, J. Diefenbach, K. Dow, J.F. Dowd, J.A. Dunne, D. Dutta, W.S. Duvall, M. Elaasar, W.R. Falk, J.M. Finn¹, T. Forest, D. Gaskell, M.T.W. Gericke, J. Grames, V.M. Gray, K. Grimm, F. Guo, J.R. Hoskins, K. Johnston, D. Jones, M. Jones, R. Jones, M. Kargiantoulakis, P.M. King, E. Korkmaz, S. Kowalski¹, J. Leacock, J. Leckey, A.R. Lee, J.H. Lee, L. Lee, S. MacEwan, D. Mack, J.A. Magee, R. Mahurin, J. Mammei, J. Martin, M.J. McHugh, J. Mei, R. Michaels, A. Micherdzinska, K.E. Myers, A. Mkrtchyan, H. Mkrtchyan, A. Narayan, L.Z. Ndukum, V. Nelyubin, Nuruzzaman, W.T.H van Oers, A.K. Opper, S.A. Page¹, J. Pan, K. Paschke, S.K. Phillips, M.L. Pitt, M. Poelker, J.F. Rajotte, W.D. Ramsay, J. Roche, B. Sawatzky, T. Seva, M.H. Shabestari, R. Silwal, N. Simicevic, G.R. Smith², P. Solvignon, D.T. Spayde, A. Subedi, R. Subedi, R. Suleiman, V. Tadevosyan, W.A. Tobias, V. Tvaskis, B. Waidyawansa, P. Wang, S.P. Wells, S.A. Wood, S. Yang, R.D. Young, S. Zhamkochyan

¹Spokespersons ²Project Manager Grad Students

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