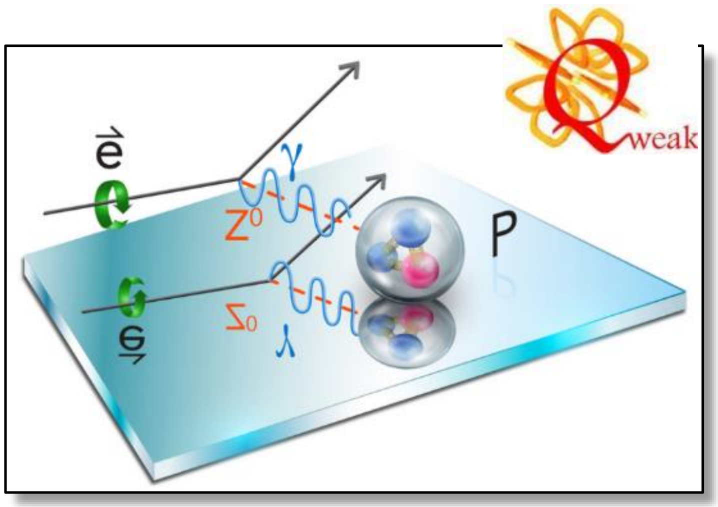
Final Results of the Qweak Experiment

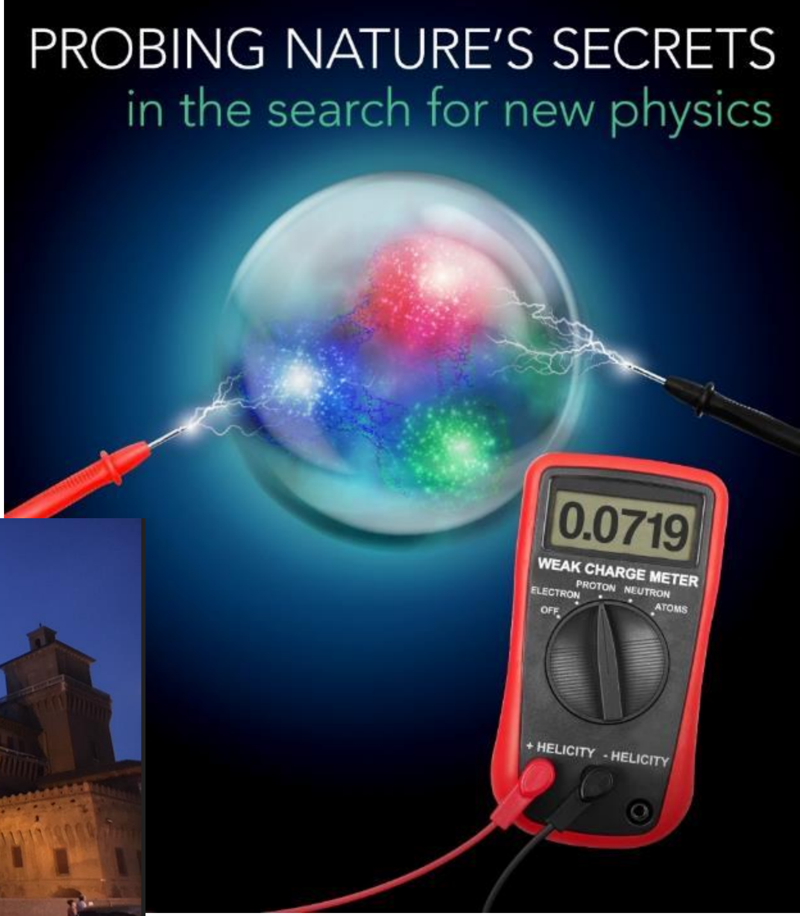
A search for new PV physics at the TeV scale by measuring the proton's weak charge Q_w^p.

https://rdcu.be/OlW2

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

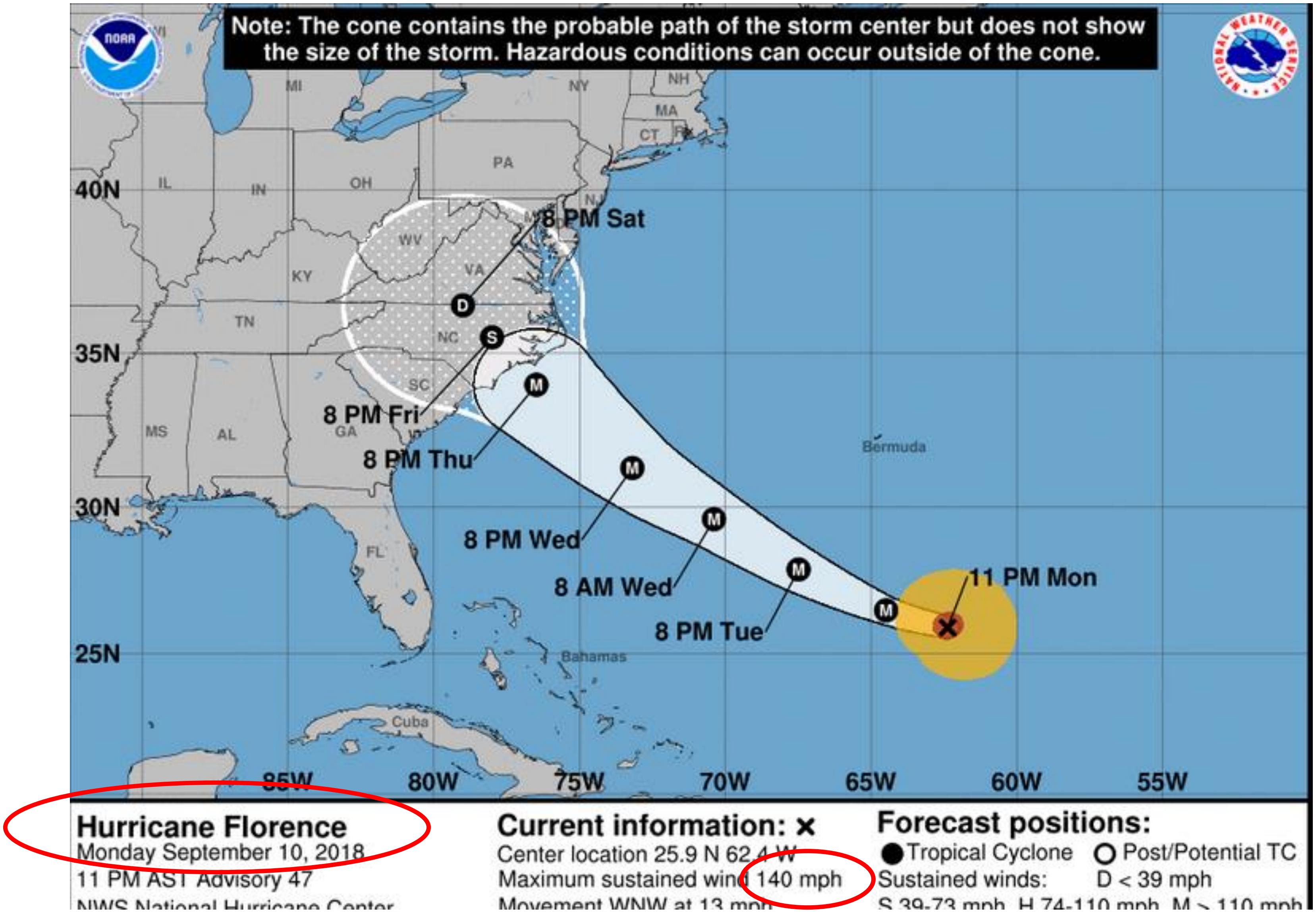


Greg Smith
(Jefferson Lab)
for the Qweak Collaboration

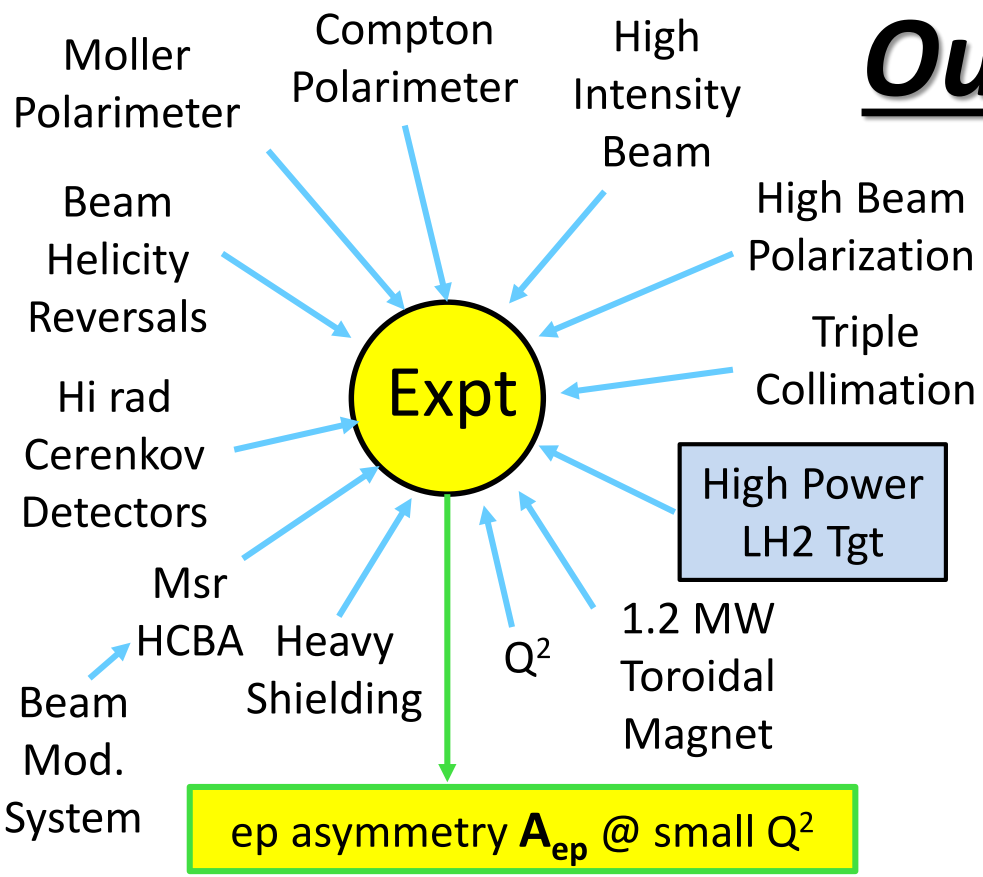


NSERC CRSNG · TRIUMF · Jefferson Lab Thomas Jefferson National Accelerator Facility · Office of Science U.S. DEPARTMENT OF ENERGY · NSF

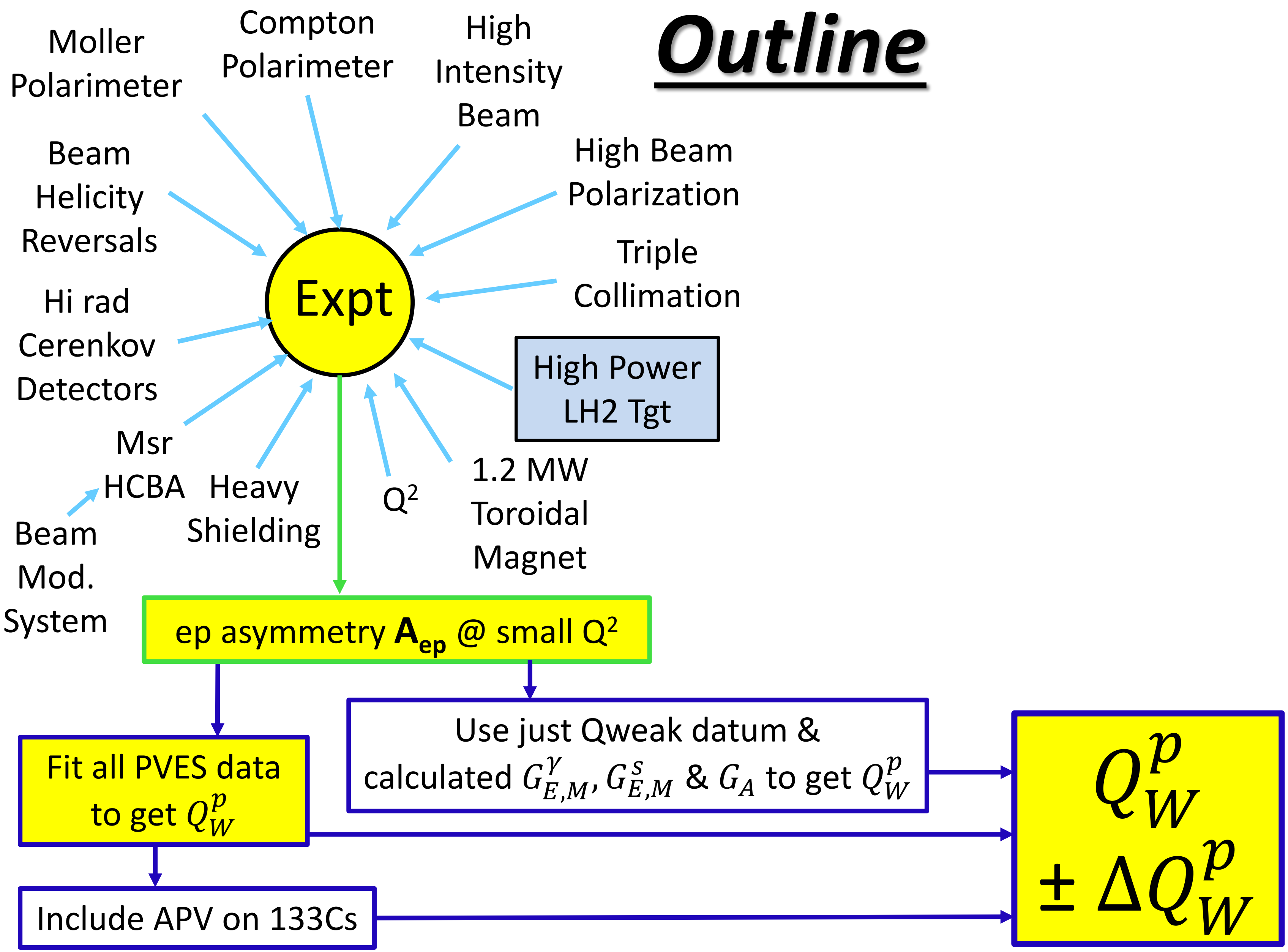
SPIN2018 is in Florence, not Ferrara!



Outline


Moller Polarimeter
Compton Polarimeter
High Intensity Beam
High Beam Polarization
Beam Helicity Reversals
Expt
Triple Collimation
Hi rad Cerenkov Detectors
High Power LH2 Tgt
Msr HCBA
Beam Mod. System
Heavy Shielding
Q2
1.2 MW Toroidal Magnet
ep asymmetry Aep @ small Q2

Outline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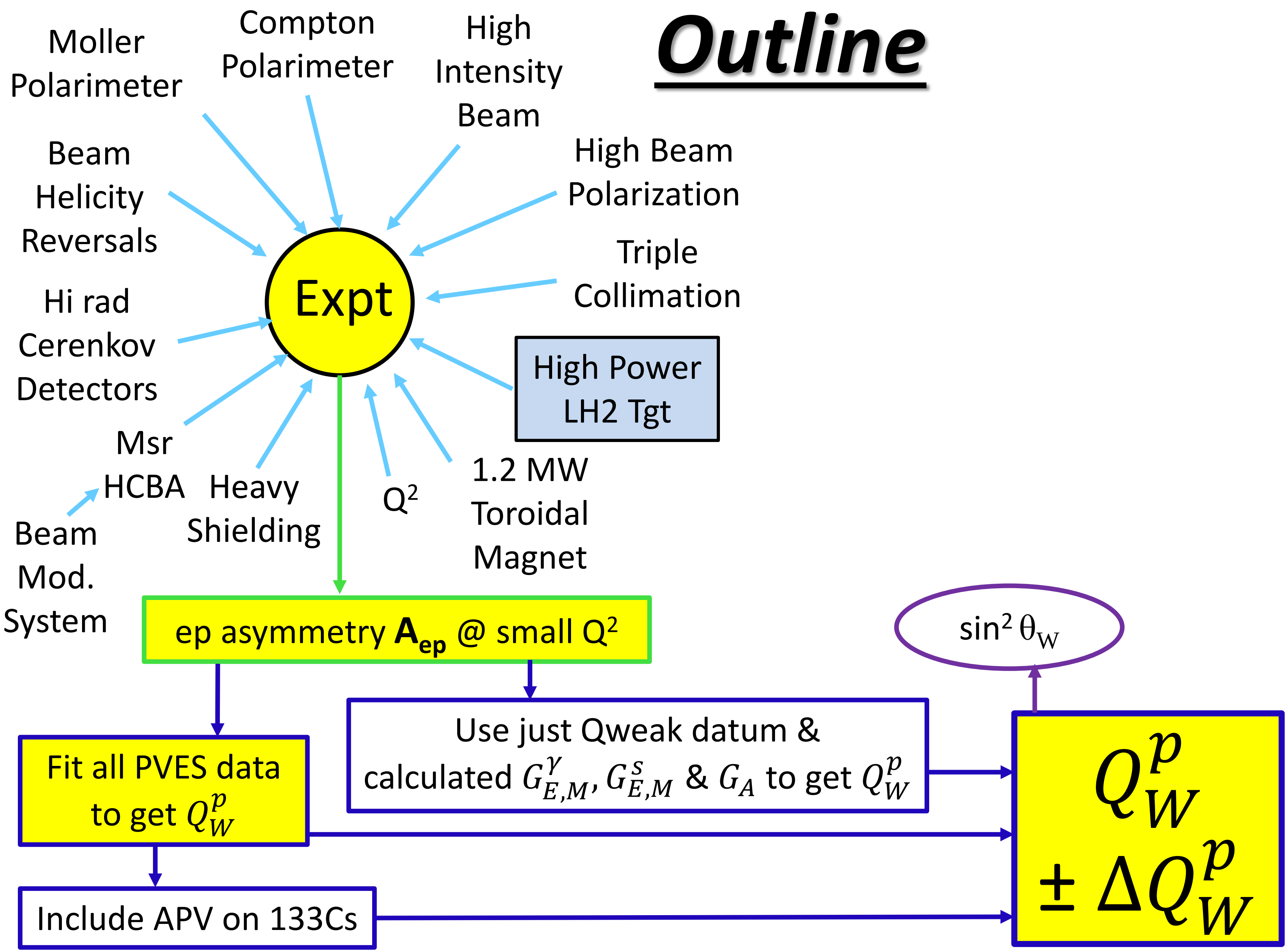
Use just Qweak datum & calculated $G^{\gamma}_{E,M}$, $G^{s}_{E,M}$ & G_A to get Q^p_W
Fit all PVES data to get Q^p_W
Include APV on 133Cs
Q^p_W
$\pm \Delta Q^p_W$

Outline



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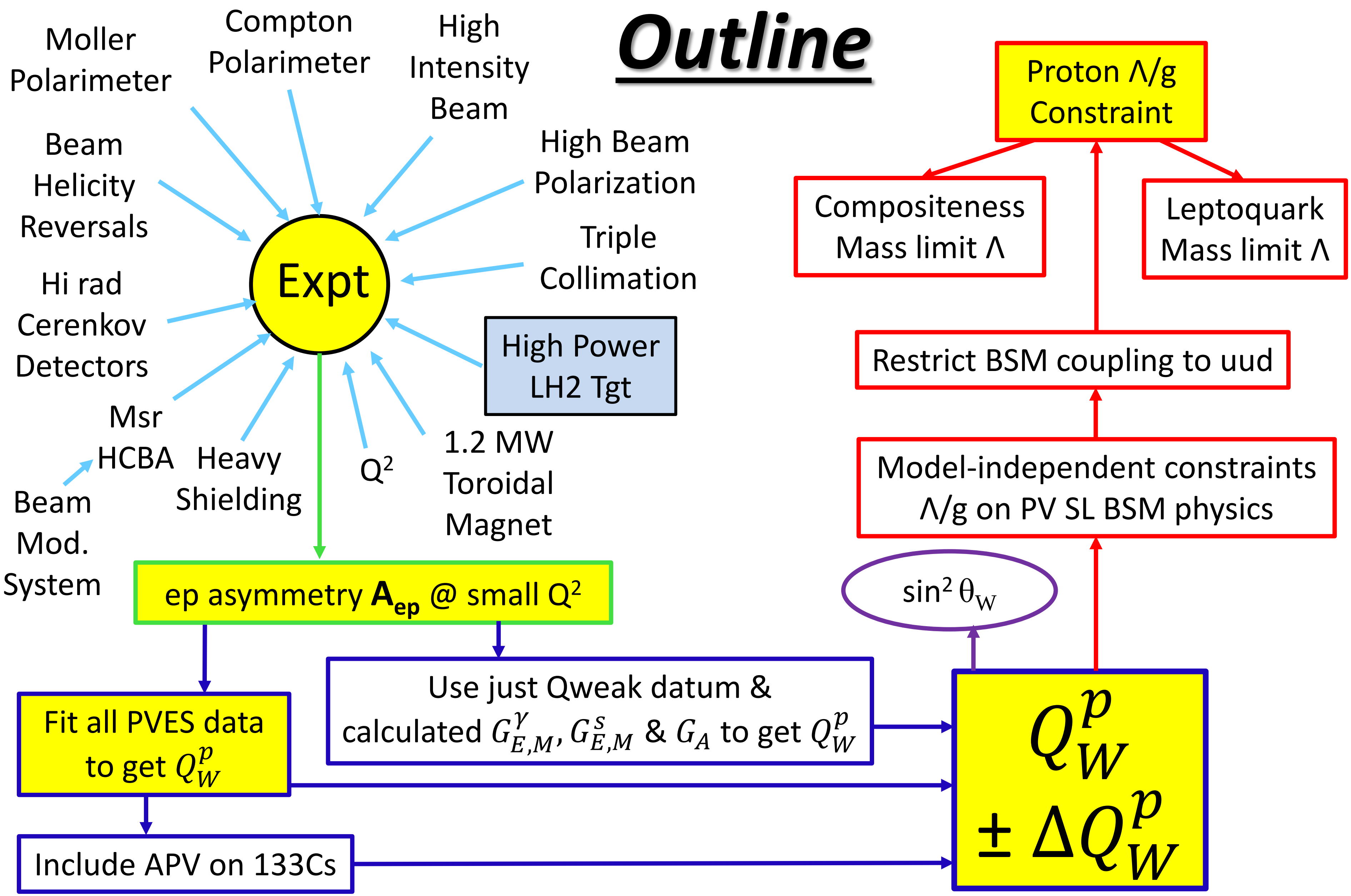

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$Q_W^p \pm \Delta Q_W^p$
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Model-independent constraints Λ/g on PV SL BSM physics
Restrict BSM coupling to uud
Proton Λ/g Constraint
Compositeness Mass limit Λ
Leptoquark Mass limit Λ

In search of the holy grail: cracks in the SM

- Why search? SM has limitations:
  - *Too many parameters* which are not predicted
  - *Does not account for things* like gravity, dark matter/energy, matter/anti-matter asymmetry, etc.
  - *Lack of addt'l particles found* so far thru direct searches in the post-Higgs era

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  - Lack of addt'l particles found so far thru direct searches in the post-Higgs era
- How? Use indirect searches utilizing precise msrmnts of well-predicted SM observables
  - *Compare* precise msrmnts with SM predictions
  - $Q_W(p)$ a good testing ground: *highly suppressed* in SM
    - SM bkg is small → easier to see new physics
  - Has potential to reach *TeV* mass/energy scales beyond those directly accessible with high-energy accelerators

Exploiting Parity-Violation

- The weak interaction is a needle in the EM haystack
  - Strength of EM interaction ~ $(4\pi\alpha/Q^2)^2$
  - Strength of weak interaction ~ $4\pi\alpha G_F/(\sqrt{2}Q^2)$
  - Ratio weak/EM strength is $G_F Q^2/(4\pi\alpha\sqrt{2})$ ~ 2 ppm (at our Q^2)

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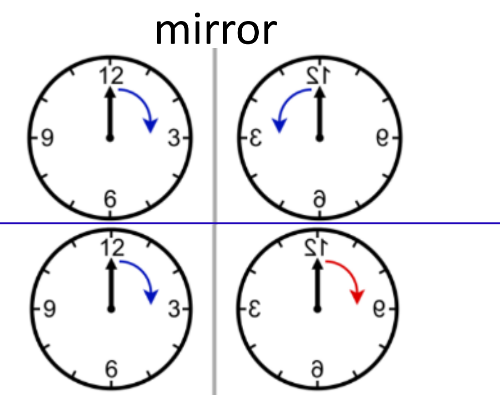
  - EM interaction conserves parity
  - Weak interaction violates parity



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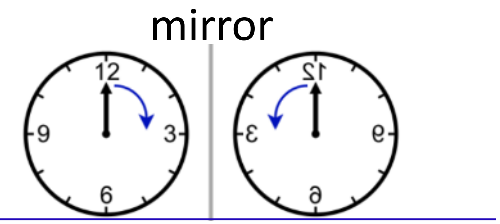


  - Weak interaction violates parity

  - ∴Flip e beam's spin direction 180°
    - Rate of e's scattered by EM int. stays the same
    - Rate of e's scattered by weak int. will differ

Msr the beam spin asymmetry $(\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$ to isolate weak interaction

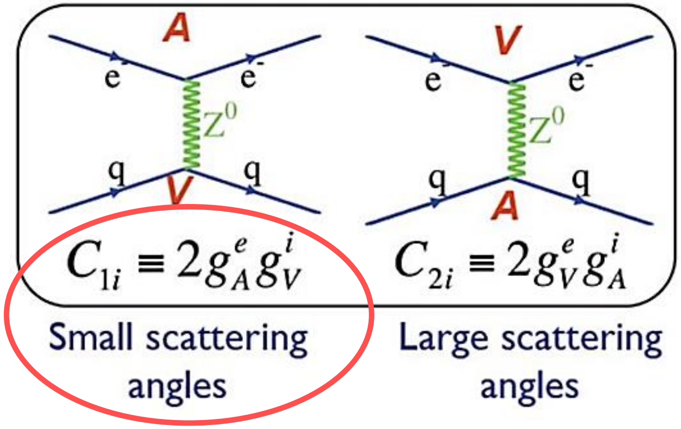
The Weak Charges

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

The SM makes a firm prediction of Q_W^p we can test

	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	$\approx$ -1

Q_{weak} is sensitive to the <u>quark vector couplings</u> C_{1u} & C_{1d}



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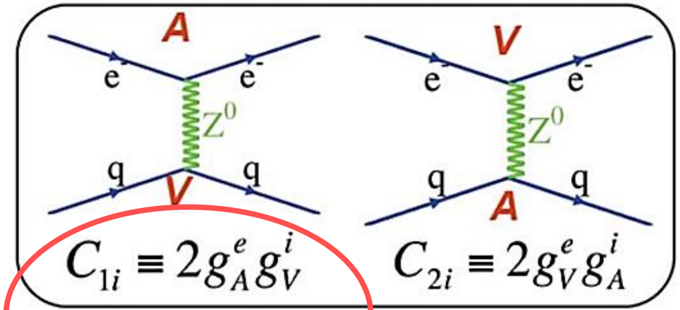


Small scattering angles

Large scattering angles

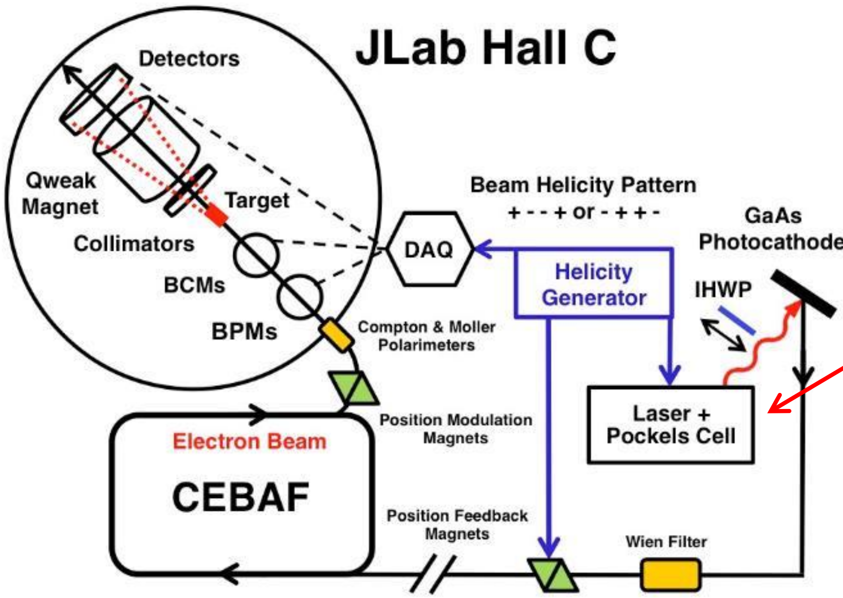
- **General: $Q_w(Z,N) = -2\{C_{1u}(2Z + N) + C_{1d}(Z + 2N)\}$**
  - **Ex: $Q_w(p) = -2(2C_{1u} + C_{1d})$ (this experiment)**
    - **Uses higher Q^2 PVES data to constrain hadronic corrections (about 20%)**
  - **Ex: $Q_w(^{133}Cs) = -2(188C_{1u} + 211C_{1d})$ (APV),** Wood et al, Science 275, 1759 ('97)
    - **Latest atomic corrections** from Dzuba et al, PRL 109, 203003 (2012)
- **Combining $Q_w(p)$ and $Q_w(^{133}Cs)$ → C_{1u} & C_{1d}, $Q_w(n)$**

Design Principals for the Precision Frontier

- Maximize luminosity & acceptance
- Azimuthal Symmetry: To reduce HCBAs, msr xverse, increase dΩ
- Optimize Q^2: higher $Q^2 \rightarrow$ larger A, lower $Q^2 \rightarrow$ larger $d\sigma/d\Omega$, smaller extrap'n to threshold & hadronic structure contributions
- Use cutting edge tech but don't rely too much on unproven tech!
- NULL asymmetry msrmnts: to quantify absence of false asymmetries
- Blind the analysis
- $\Delta A = \Delta A_{qrt}/\sqrt{N_{qrt}}$, where $\Delta A_{qrt} \propto \sigma_{det}, \sigma_{BCM}, \sigma_{tgt}, \tau_{Hel}, \tau_{elec}$ **(qrt : + − − +)**
- Unprecedented precision brings inevitable surprises:
  - For us: HC halo bkg on beam coll., rescattering bias in Pb preradiators
- Redundancy: Ex: 2 polarimeters, many BCMs, BPMs, dummy/bkg tgts, different ways to characterize HCBAs, BB, etc., several ways to flip helicity, …
- Multiple run periods: To improve, & compare rslts under different conditions
- Flexibility: Build in ancillary detectors & capabilities to handle unexpected bkgs

Experimental Technique to Isolate/Measure PV Signal

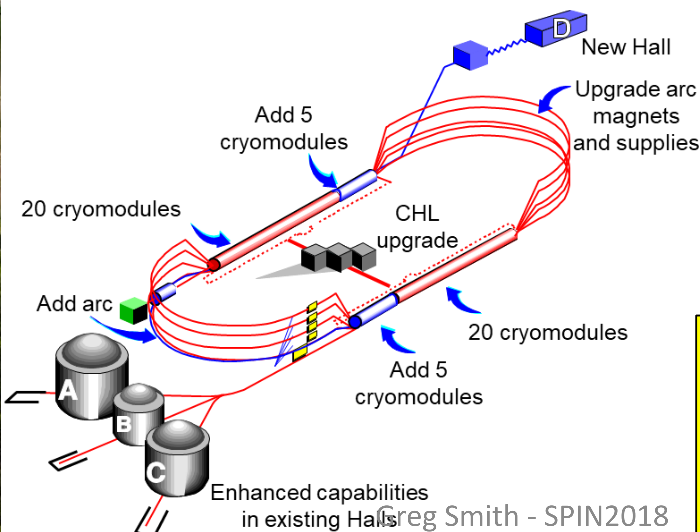
The entire accelerator complex is our apparatus



Multiple ways of reversing electron beam helicity are essential:

"Fast reversal"

1) **Rapid pseudo-random reversal (varying HV on Pockels cell)**
   - **960 Hz** (±∓∓±)



Jefferson Lab in Newport News, VA

- Superconducting RF accelerator
- Continuous e- beam (499 MHz)
- **4** experimental halls
- 12 GeV upgrade complete

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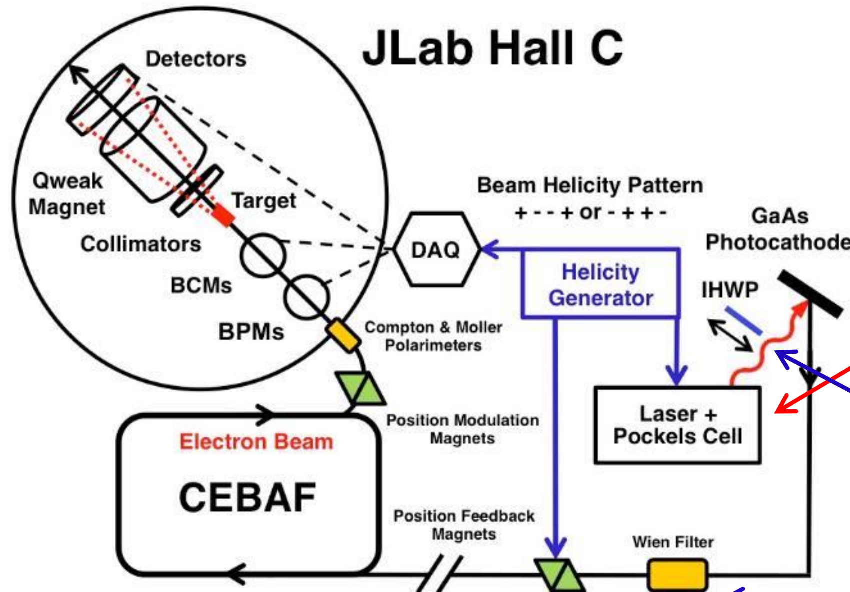

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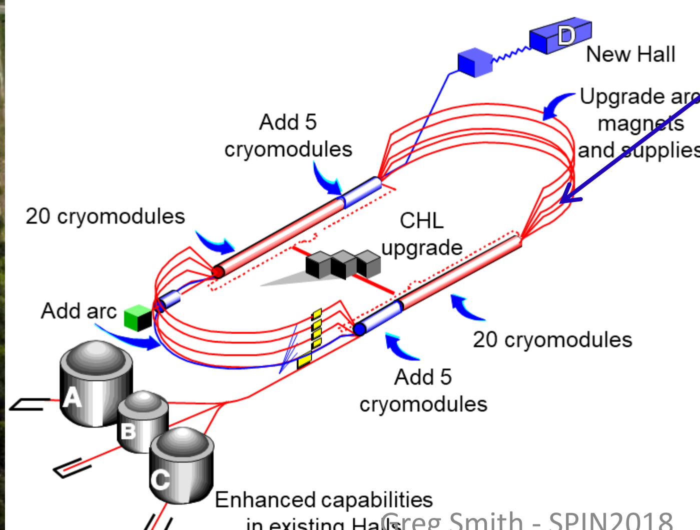
"Slow reversals"

1) **IHWP (insertable half-wave plate)**
   - **~8-hour intervals**
2) **"Double Wien" spin manipulator**
   - **monthly intervals**
3) **g-2 spin flip**
   - **Ran at 2 pass (instead of 1 pass) for ~ 6 weeks**



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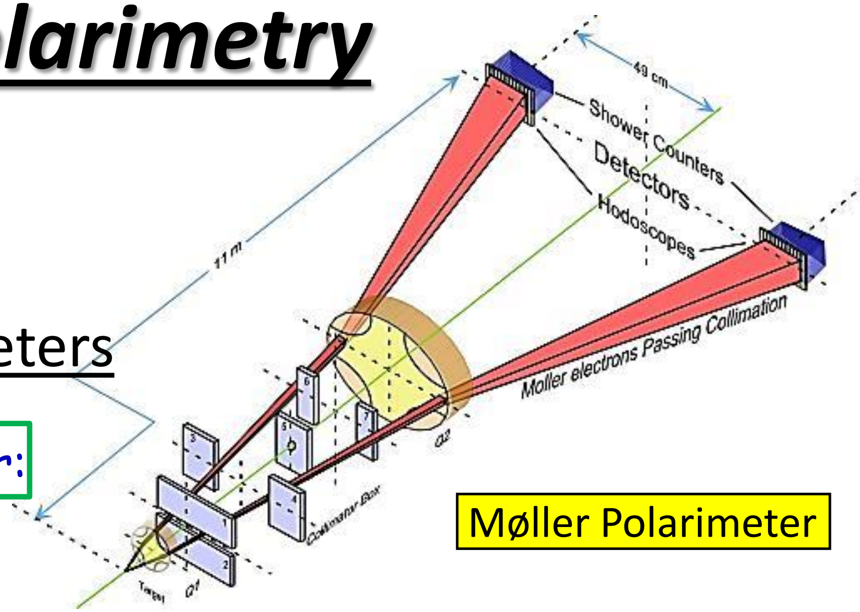
Precision Polarimetry

Qweak required ΔP/P ≤ 1%

Achieved 0.61% !

Strategy: use 2 independent polarimeters



Møller Polarimeter

- 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.

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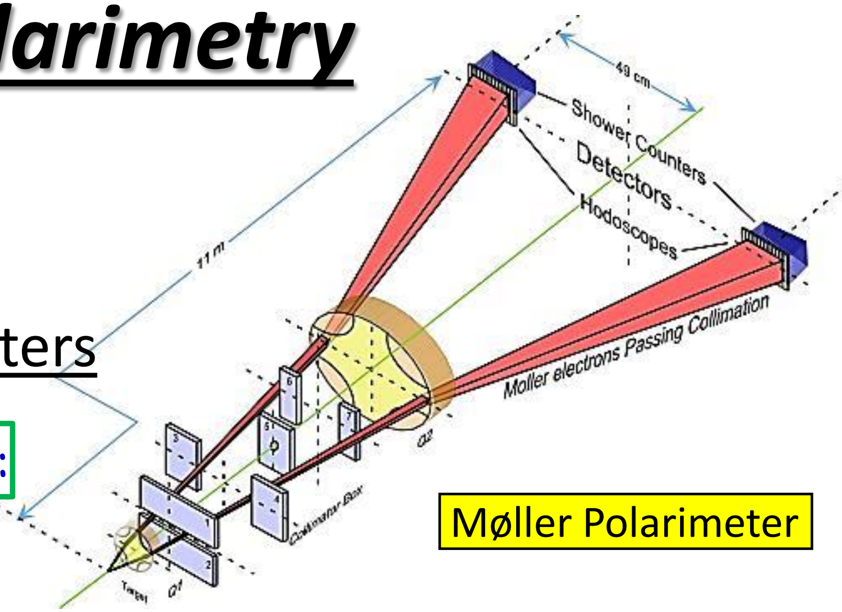

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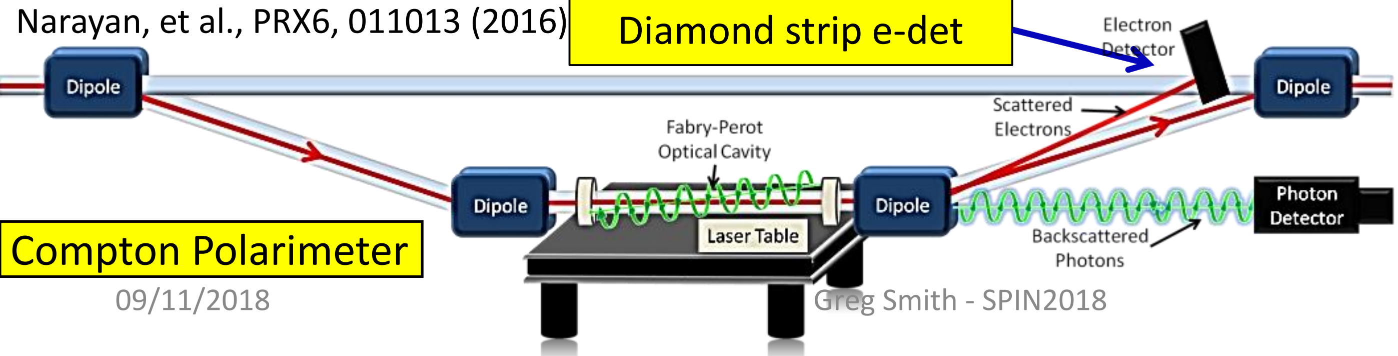
Narayan, et al., PRX6, 011013 (2016)

Diamond strip e-det



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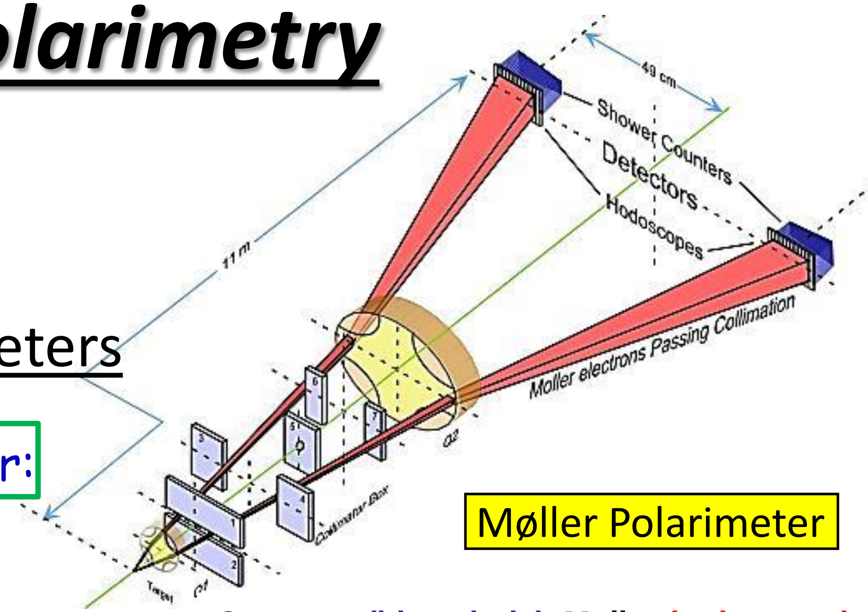
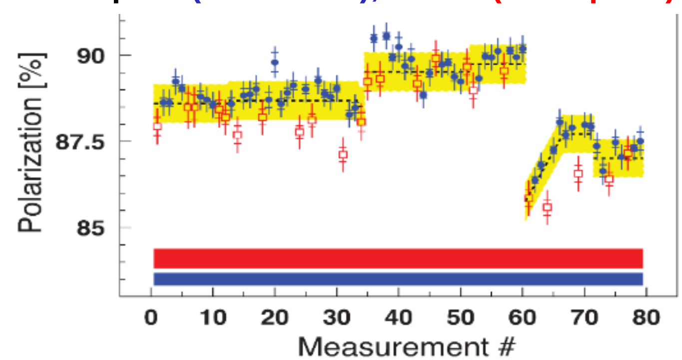


Møller Polarimeter

Compton (blue circle), Moller (red square)



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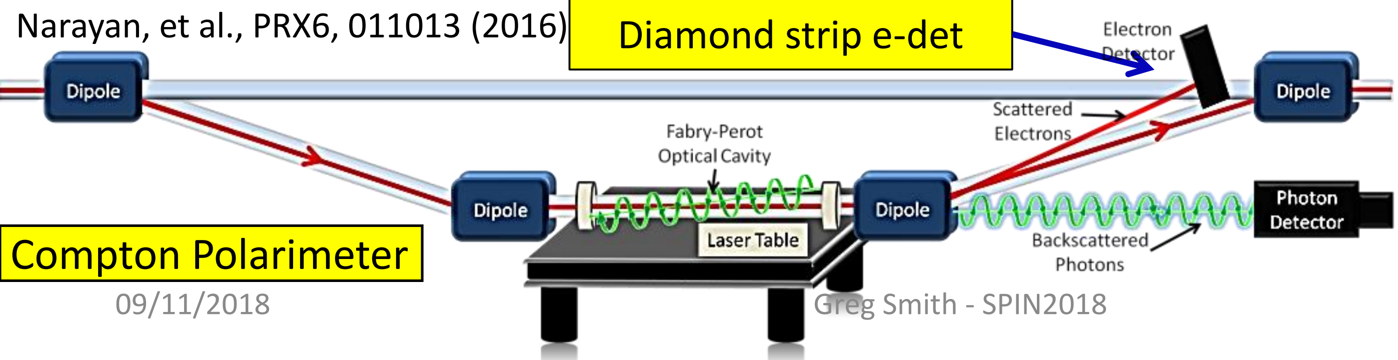
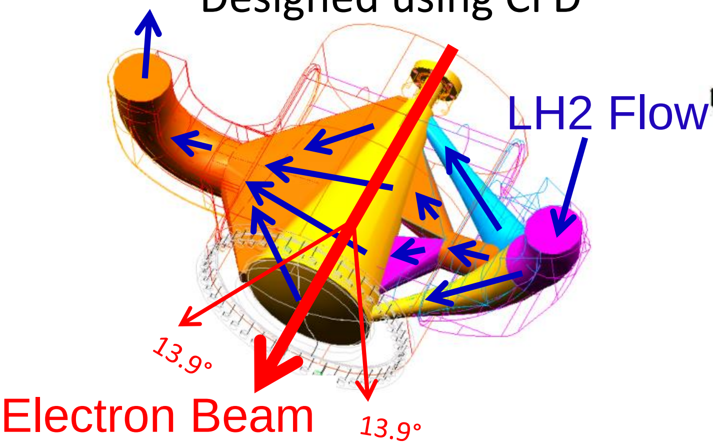


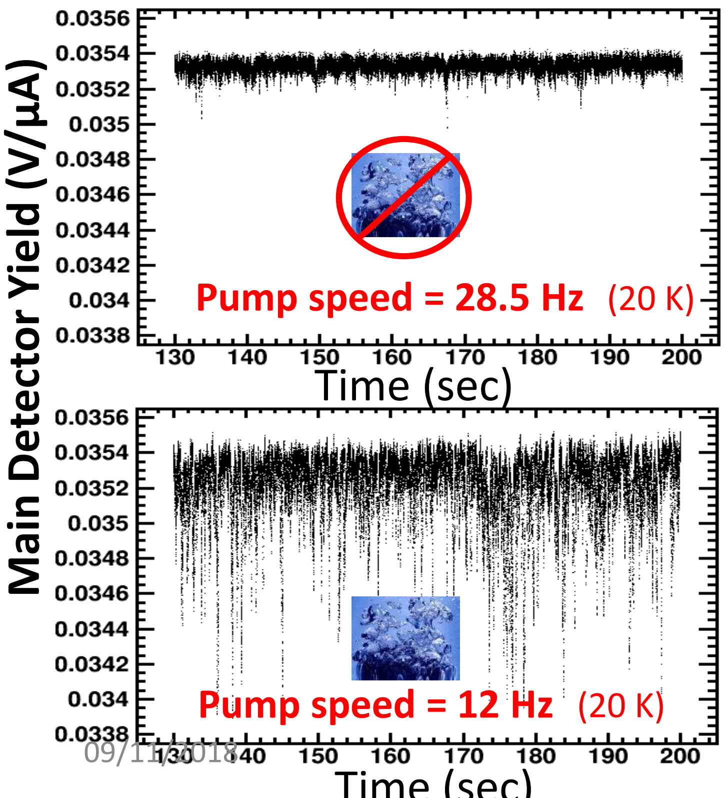
Compton Polarimeter

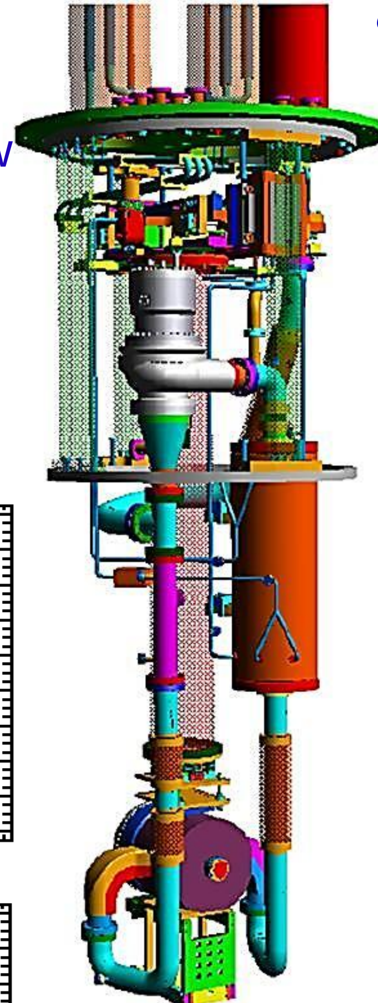
Target Performance

World's highest power (3 kW)
& *lowest msrd noise* (50 ppm)
cryogenic target

Designed using CFD







I_{Beam} = 180 uA
L = 34.4 cm (4% X_0)
P_{beam} = 2.2 kW
A_{spot} = 4 x 4 mm^2
V(LH2) = 58 liters
T = 20.00 K
P ~ 220 kPa
Mass flow 1.2 kg/s
Volume flow ~ 17 l/s

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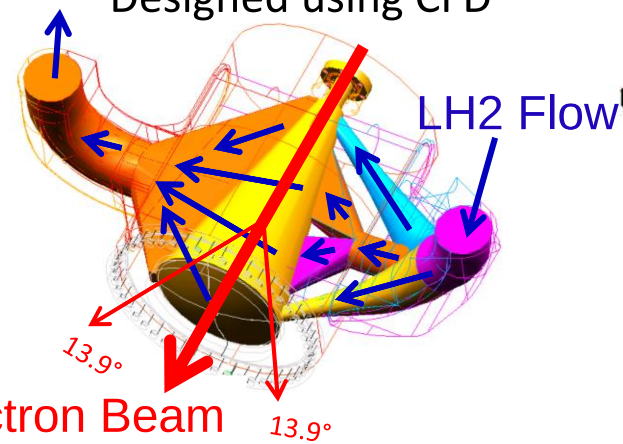

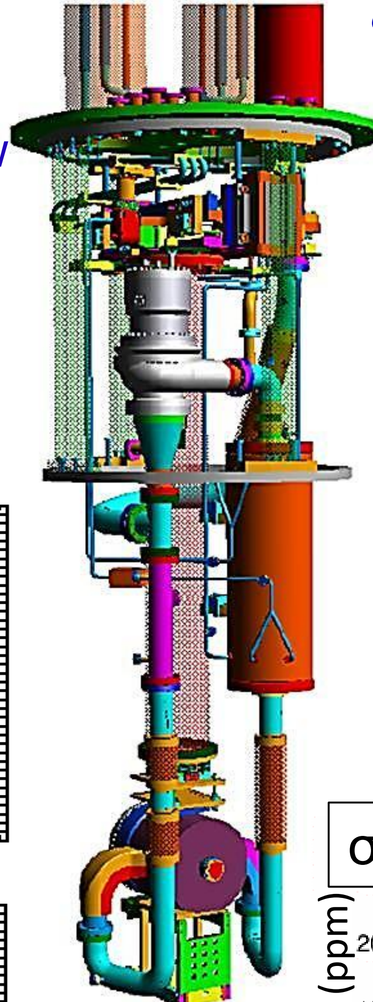

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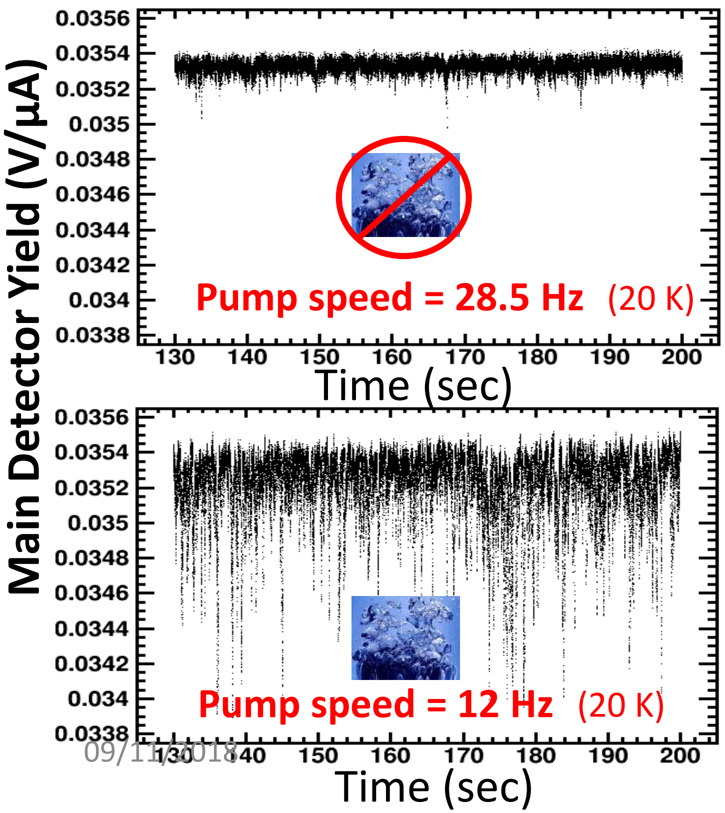
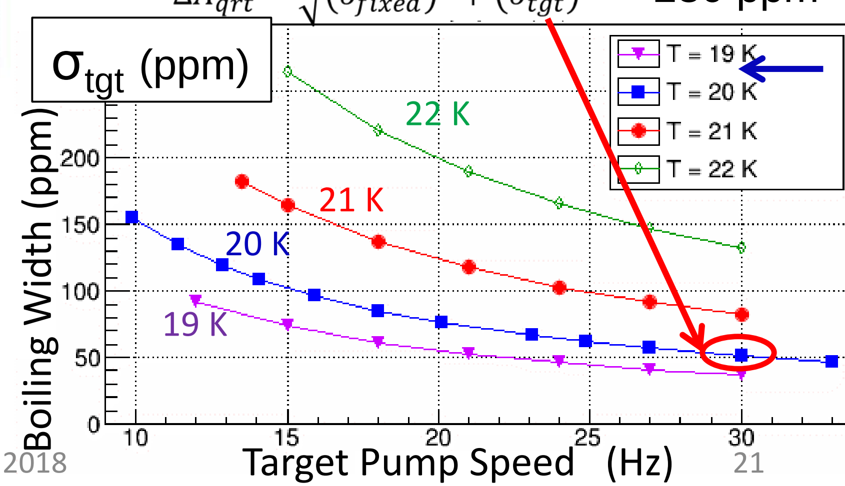


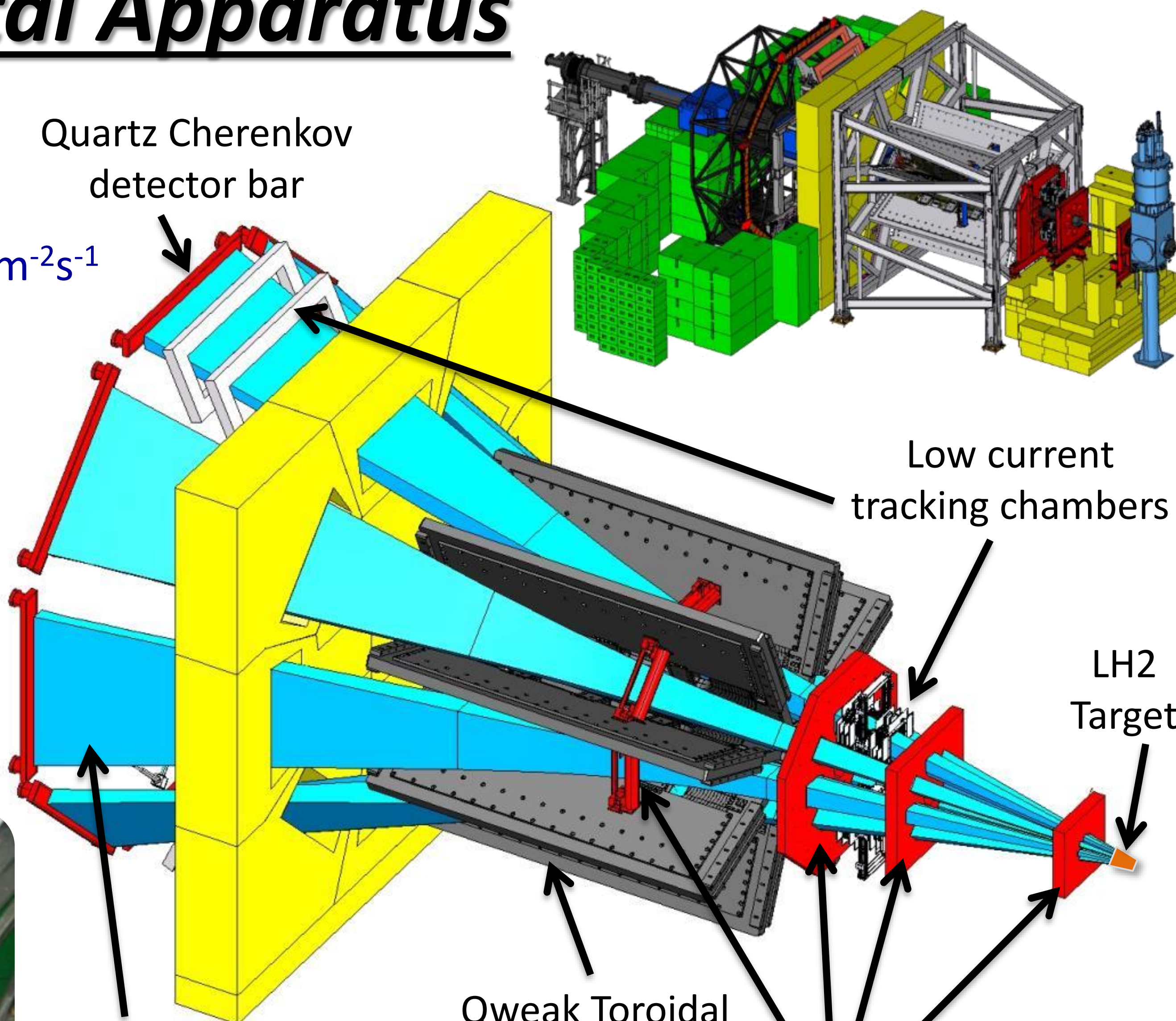
$$\Delta A_{qrt} = \sqrt{(\sigma_{fixed})^2 + (\sigma_{tgt})^2} \sim 230 \text{ ppm}$$



Experimental Apparatus

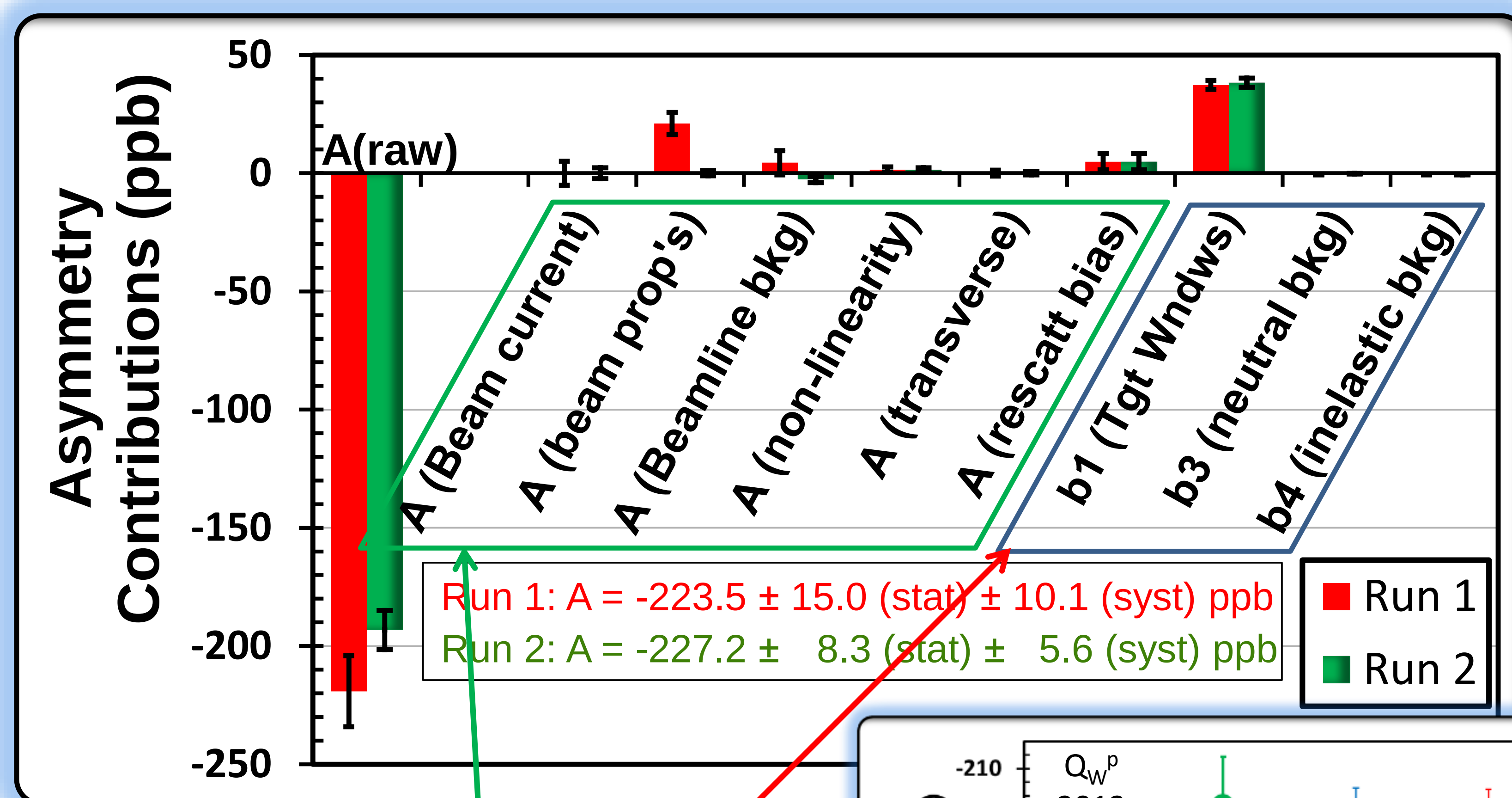
Parameters:

I_{beam} = 180 μA
Luminosity = 1.7 x 10^{39} $cm^{-2}s^{-1}$
E_{beam}= 1.15 GeV
Beam Pol = 89% ± 0.6%
θ = 6° - 12°, <θ> = 7.9°
$<Q^2>$ = 0.025 $(GeV/c)^2$
Integrated Rate ~ 7 GHz
Target = 34.4 cm LH_2,
3 kW, 50 ppm



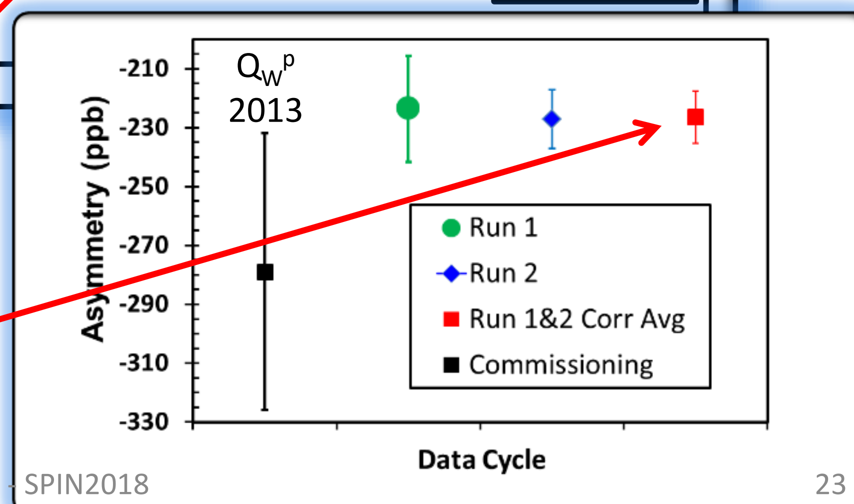
detector bar with Pb pre-radiator

Asymmetry Contributions & Uncertainties



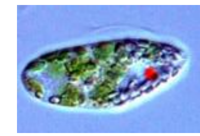
$$A_{ep} = \frac{A_{raw} + A_{false}}{P_{beam}} - f_{back} A_{back}$$

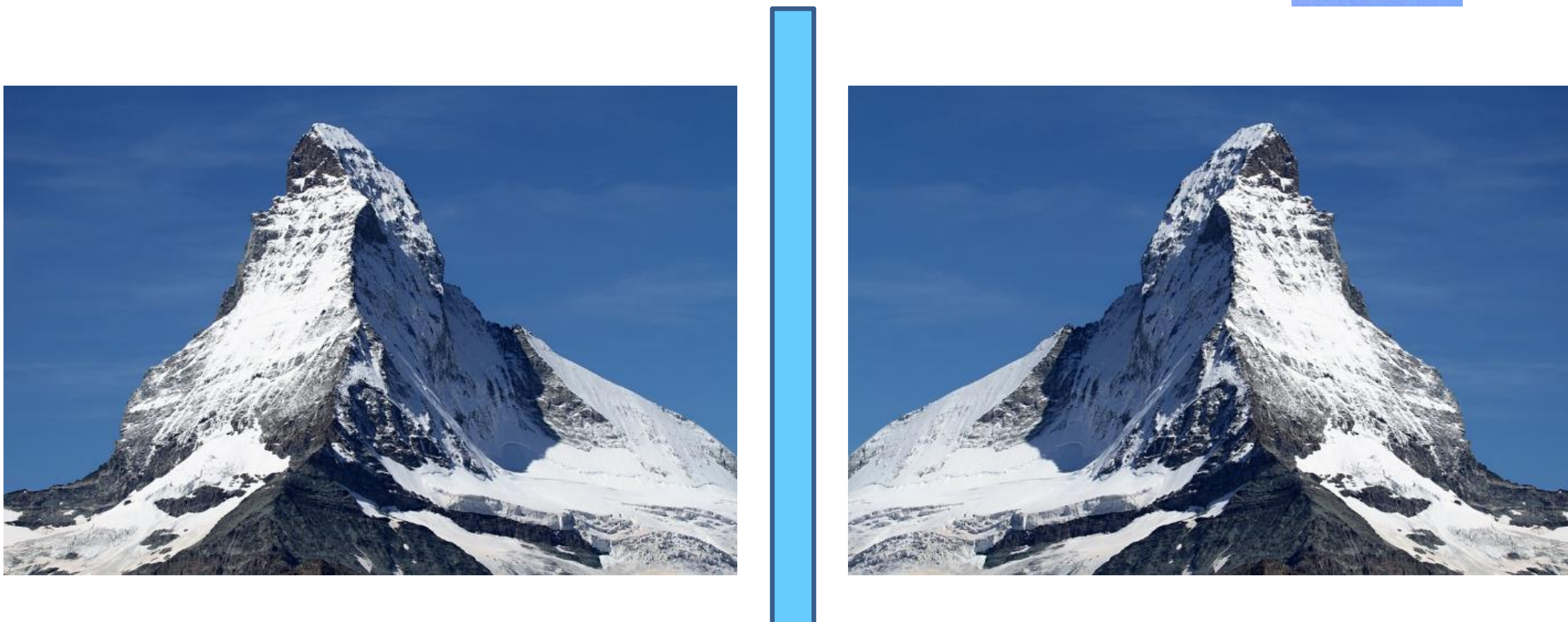
$$= -226.5 \pm 9.3 \text{ ppb}$$



To put this -226.5 ± 9.3 ppb in perspective:

If parity symmetry were violated for mountains,
the Matterhorn (4478 m) & its mirror-image would differ by 1 mm,
& this difference would be msrd to ± 42 μm



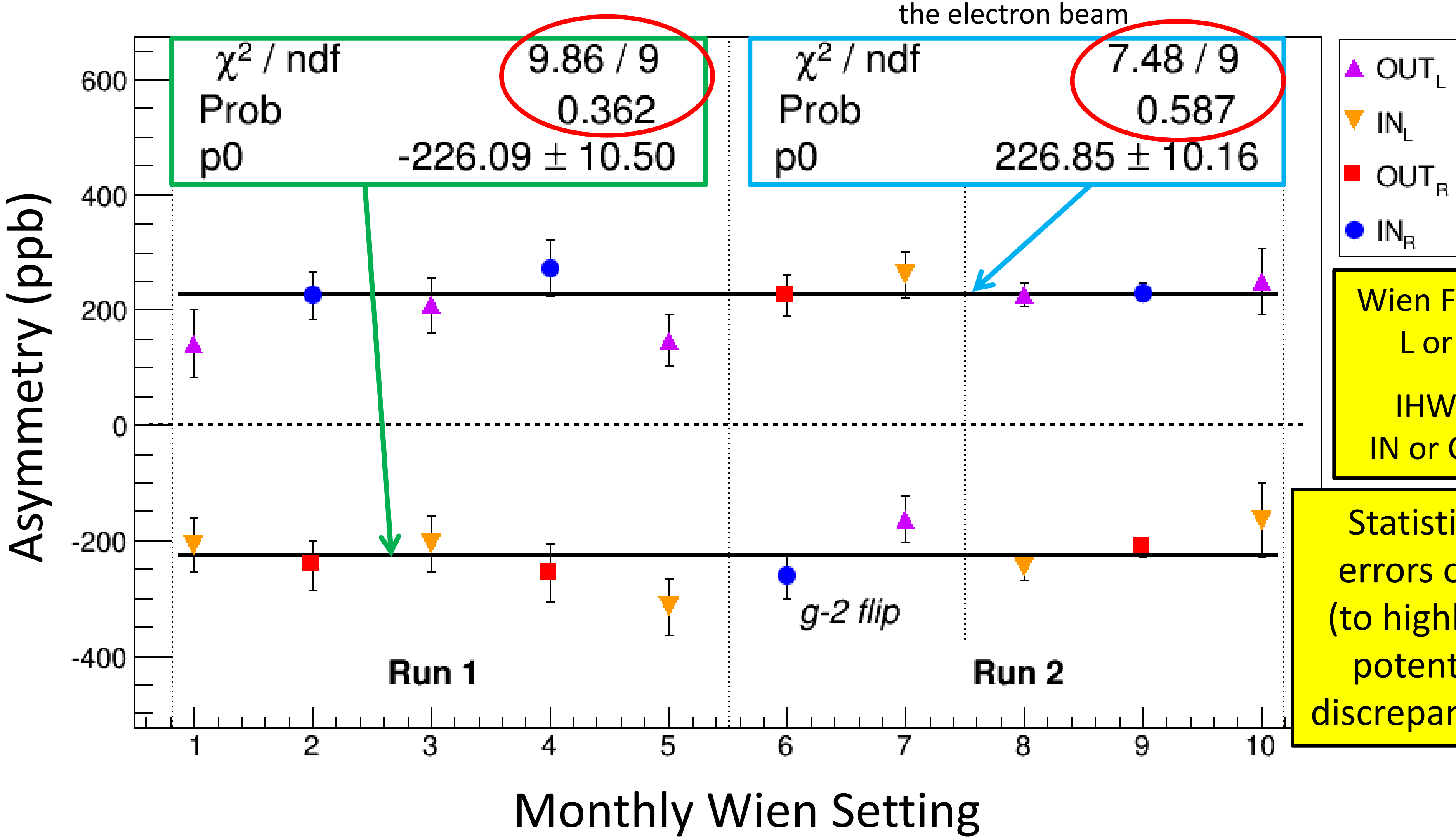


Parity Mirror

Slow-Helicity-Reversal Stability

Wien (L or R) refers to ~monthly reversals of a double-Wien filter in the injector which reverses the spin direction (helicity) of the electron beam

IN or OUT refer to the state of the insertable half-wave plate at the electron source, changed ~8h, which also reversed the spin direction (helicity) of the electron beam



Wien Filter: L or R

IHWP: IN or OUT

Statistical errors only (to highlight potential discrepancies)

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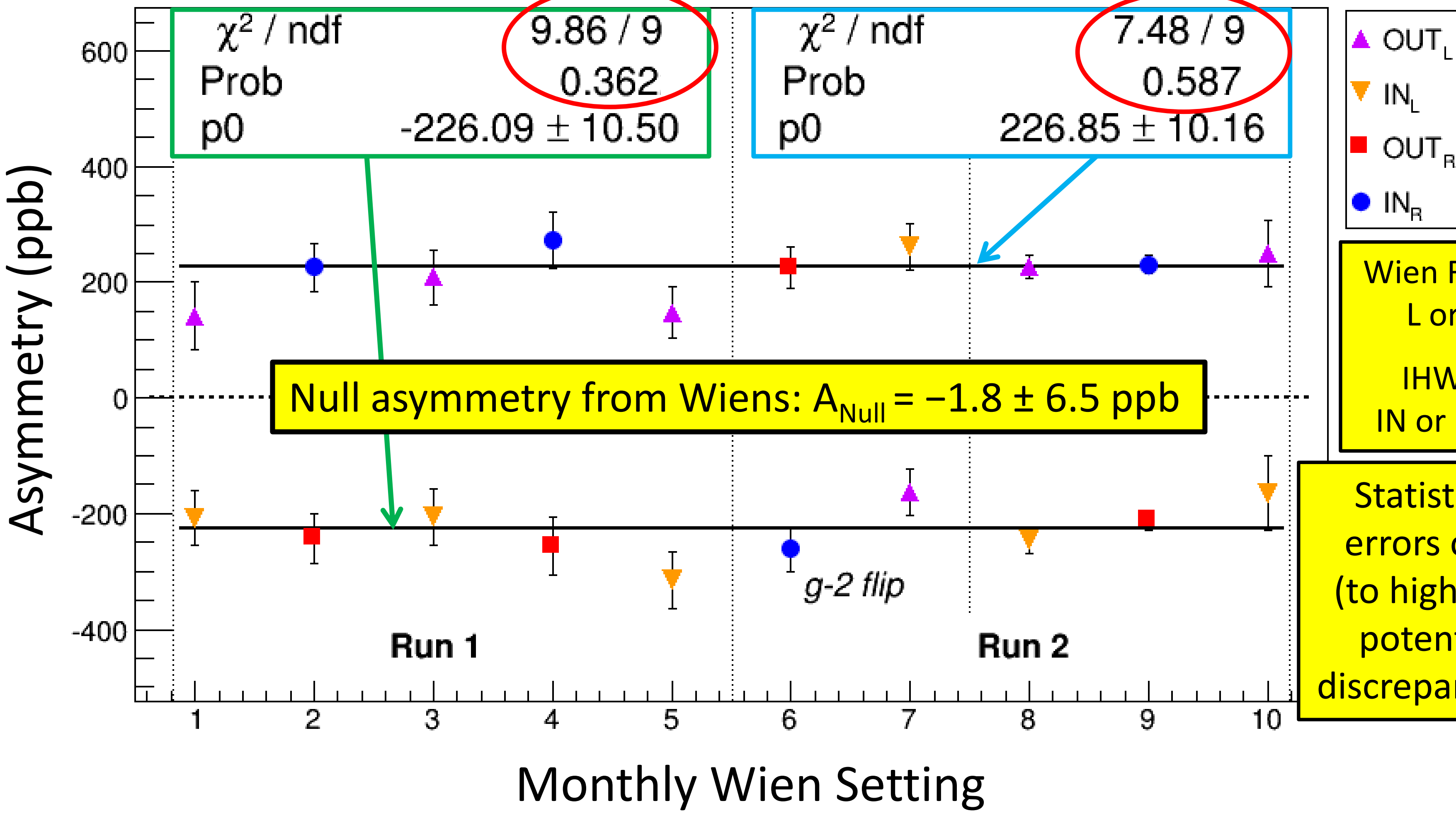

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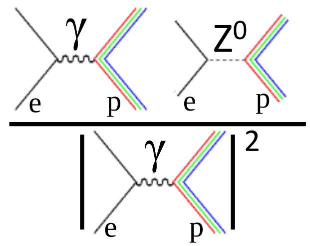
Extracting $Q_W(p)$ from A_{ep}

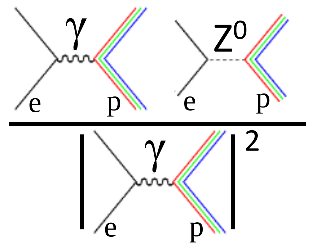
Determining $Q_w(p)$

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \propto$  , where $\sigma^{\pm} = \vec{e}p$ x-sec for e's of helicity ± 1

- $A_{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - (1-4\sin^2\theta_w)\epsilon' G_M^{p\gamma} \overbrace{G_A^Z}^{\text{Axial FF}}}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$ tree level

  - $G_{E,M}^{pZ} = \underbrace{(1 - 4\sin^2\theta_W)}_{Q_W^p} \underbrace{G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma}}_{\text{EM FFs}} - \underbrace{G_{E,M}^{s}}_{\text{Strange FFs}}$ is the proton's neutral weak FF

Determining $Q_w(p)$

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \propto$ 

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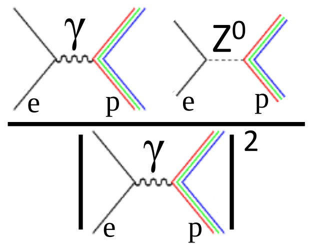
- Recast: $A_{ep}/A_0 \rightarrow \left[Q_w^p + Q^2 \underbrace{B(Q^2, \theta)}_{\text{hadronic structure (FFs)}}\right]$, where $A_0 = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$

Determining $Q_w(p)$

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \propto$ 

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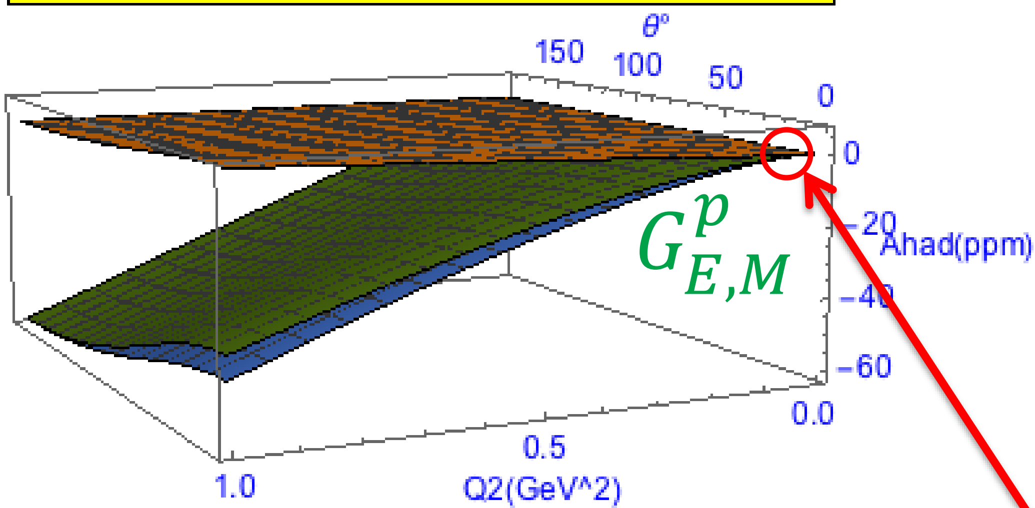
  - So in a plot of A_{ep}/A_0 vs Q^2:
    - **Q_w^p is the *intercept*** (anchored by precise datum near Q^2=0) ← **This Experiment**
    - $B(Q^2,\theta)$ is the ***slope*** (determined from higher Q^2 PVES data)

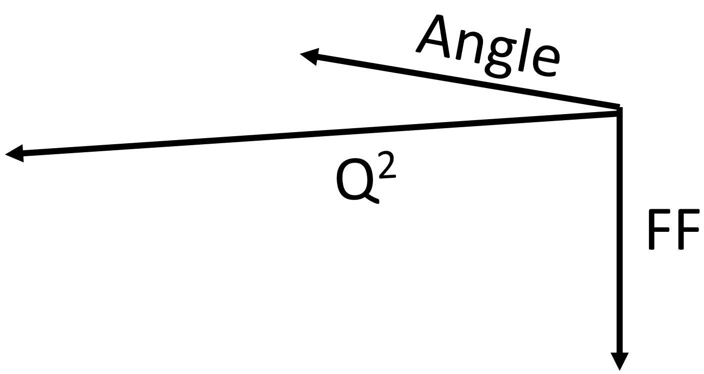
$G_{E,M}^{p}$ is calculated, ~**25%** of A_{ep} at Qweak kinematics

$A_{EM,Strange,Axial}(Q^2,\theta)$

hadronic structure (FFs) minimal at Qweak kinematics

AhadE(red), AhadM(blue), AhadTOT(green)





The Qweak datum is here

$A_{EM,Strange,Axial}(Q^2,\theta)$

hadronic structure (FFs) minimal at Qweak kinematics

$G^p_{E,M}$ is calculated, ~**25%** of A_{ep} at Qweak kinematics

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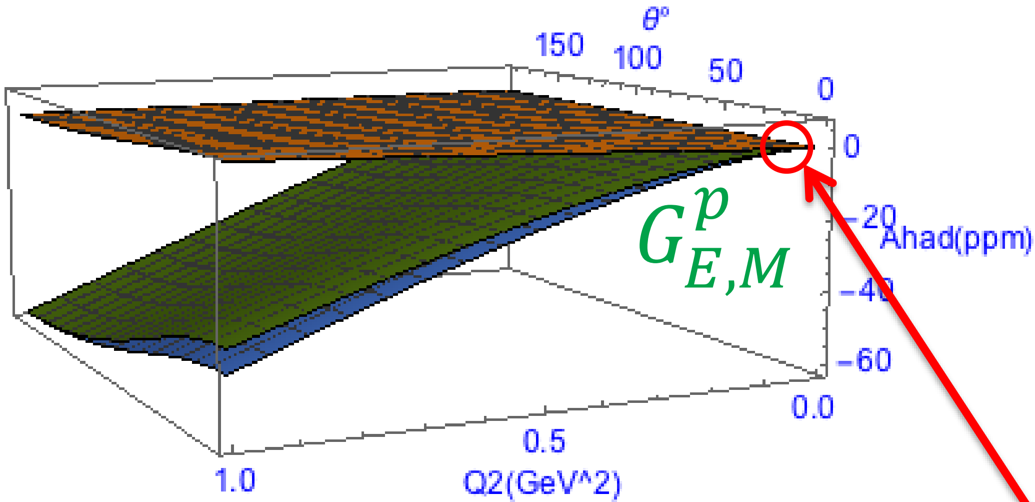
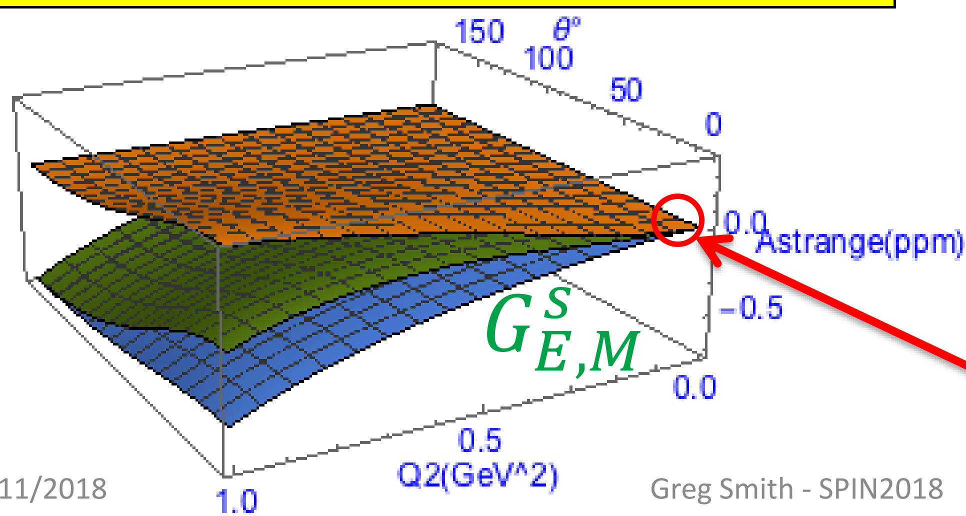


$G^s_{E,M}$ is fit, and **~1%** of A_{ep} at Qweak kinematics

AstrangeE(red), AstrangeM(blue), AstrangeTOT(green)



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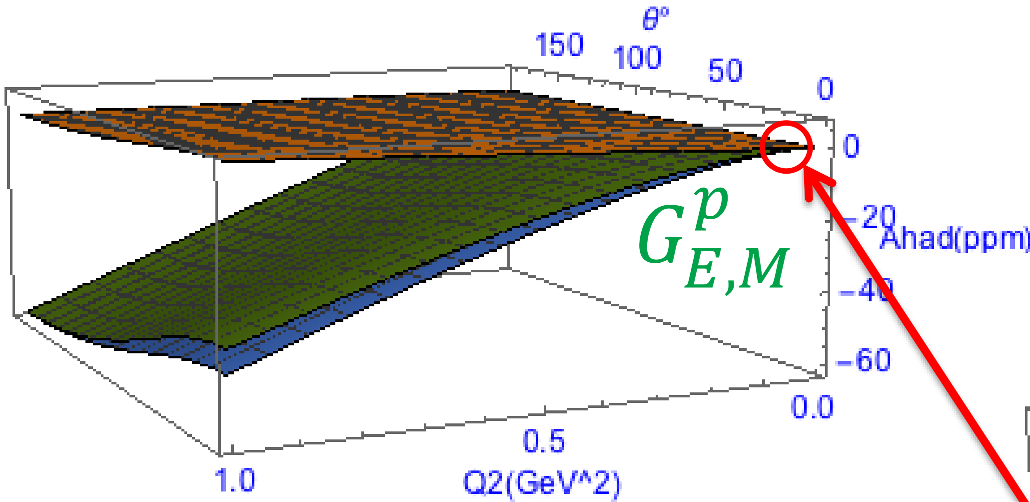
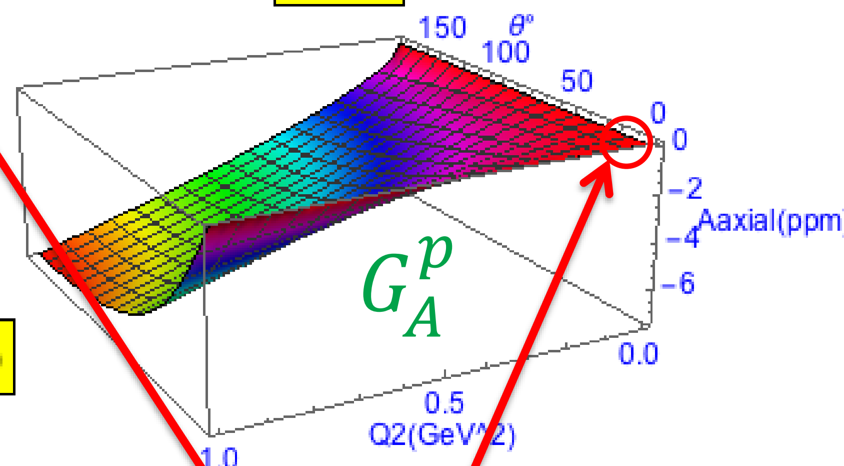


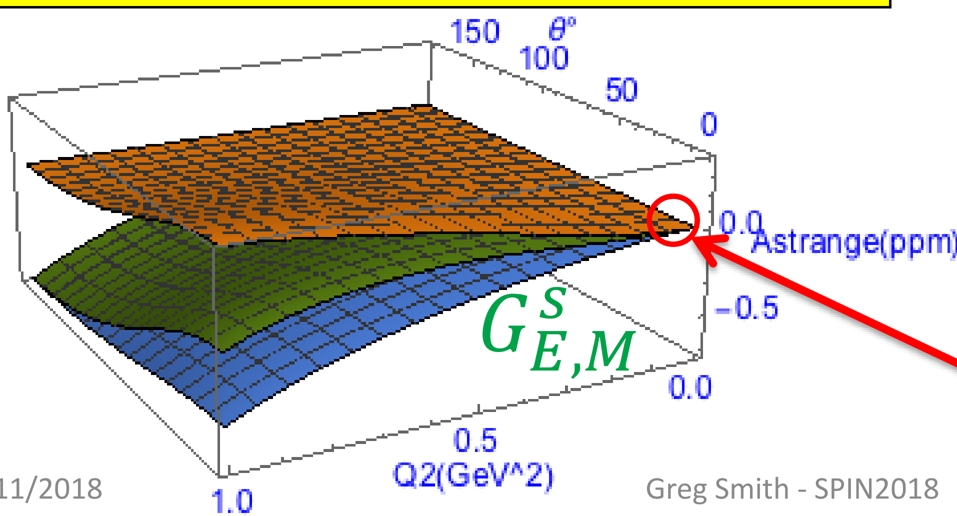
G^p_A is fit, & ~**2%** of A_{ep} at Qweak kinematics

Aaxial



$G^s_{E,M}$ is fit, and ~**1%** of A_{ep} at Qweak kinematics

AstrangeE(red), AstrangeM(blue), AstrangeTOT(green)



The Qweak datum is here

Global PVES Fit Details

- 5 free parameters ala Young, et al. PRL 99, 122003 (2007):
  - C_{1u}, C_{1d}, ρ_s, μ_s, & isovector axial FF G_A^Z

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

  - $G_E^S = \rho_s Q^2 G_D$, $G_M^S = \mu_s G_D$, & G_A^Z use G_D where
    - $G_D = (1 + Q^2/\lambda^2)^{-2}$ with $\lambda = 1$ GeV/c
- Employs all PVES data up to $Q^2 = 0.63$ (GeV/c)^2
  - On p, d, & ^{4}He targets, forward and back-angle data
    - SAMPLE, HAPPEX, G0, PVA4 & this expt. (Qweak):

Tgt	# pts
p	27
d	6
^{4}He	2
χ^2/ν	1.2

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  - On p, d, & ^{4}He targets, forward and back-angle data
    - SAMPLE, HAPPEX, G0, PVA4 & this expt. (Qweak):
- Uses constraints on isoscalar axial FF $G_A^{Z(T=0)}$
  - Zhu, et al., PRD 62, 033008 (2000)
- All ep data corrected for E & Q^2 dependence of $\square_{\gamma Z}$ RC
  - Hall et al., PRD88, 013011 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying Q^2, θ, & λ studied, found to be small

Tgt	# pts
p	27
d	6
^{4}He	2
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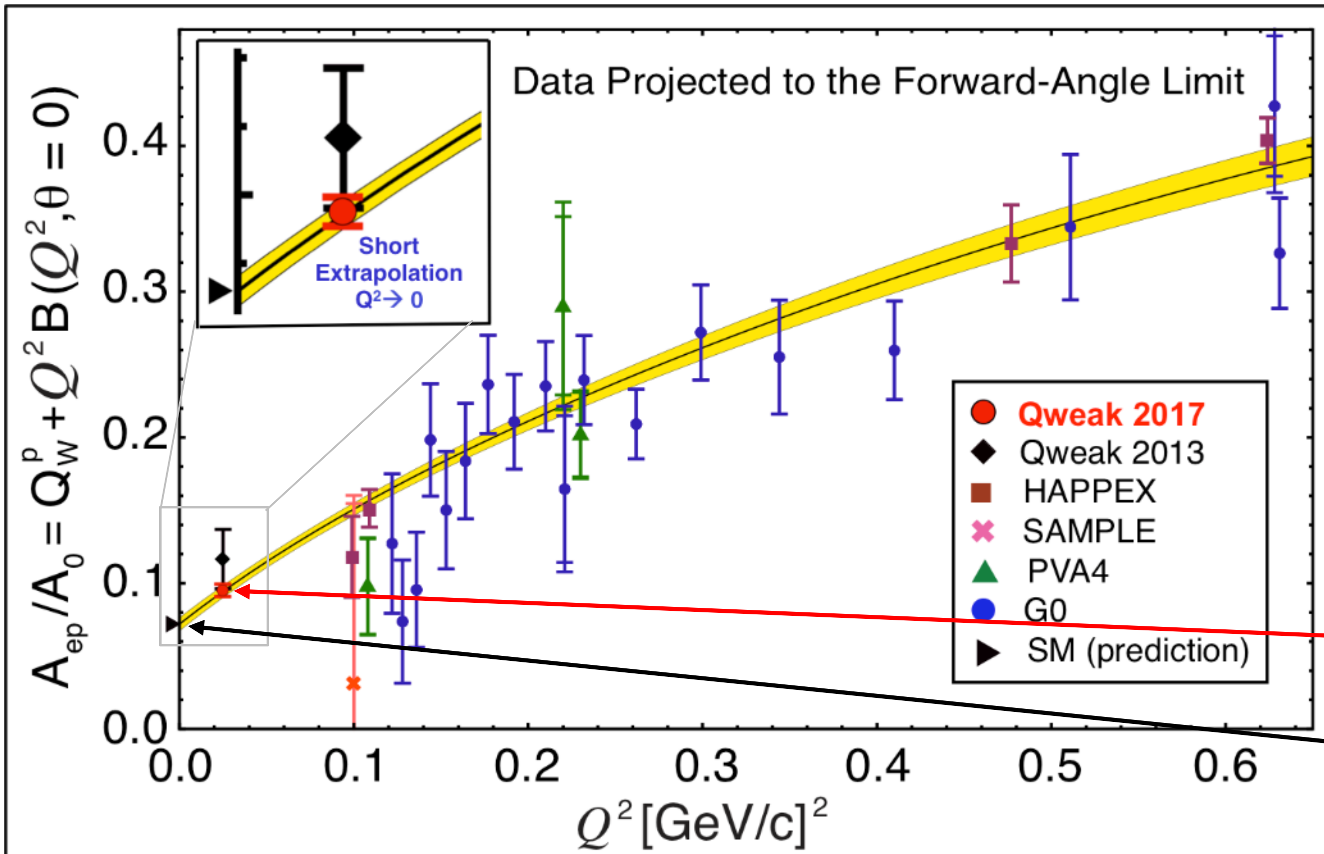
Extracting the Weak Charge from the Asymmetry

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

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

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



34 entries in PVES database

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

Q_W^p **(this result):**
0.0719 ± 0.0045

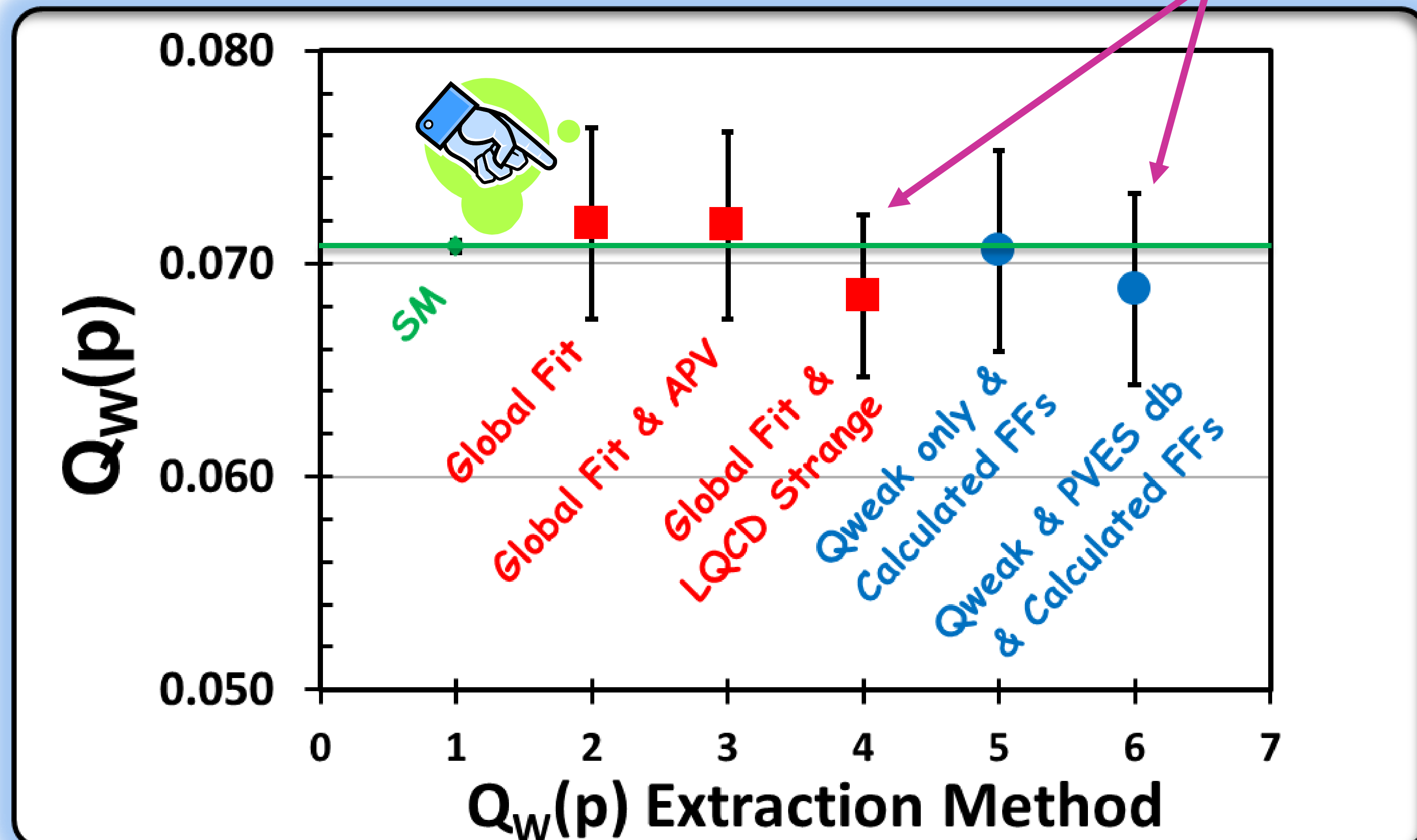
Q_W^p **(SM):**
0.0708 ± 0.0003

This global fit is our primary result for Q_w^p.

Now explore the sensitivity of this result to variations in the experimental and theoretical input used to determine it:

Consistency

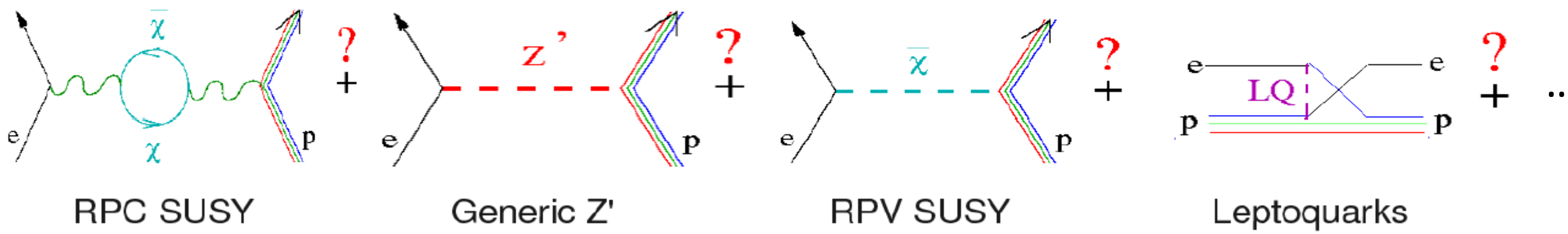
Lattice strange FFs are in slight tension with the fitted strange FFs at higher Q^2



Multi-TeV Mass Reach Λ

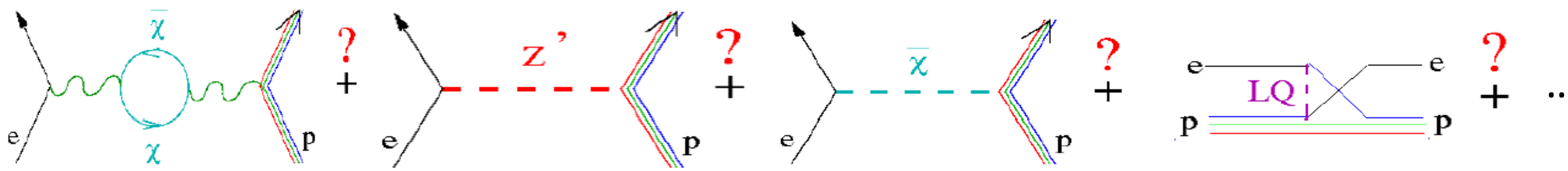
(for coupling strength g)

Sensitivity to New Physics at TeV Scales



- Let the quark flavor dependence of new physics be *completely arbitrary*:
  - Ala (Young, et al. PRL99, 122003 (2007))
  - $h_V^u = \cos\theta_h$, $h_V^d = \sin\theta_h$, $\theta_h = \tan^{-1}(N_d/N_u)$ = flavor mixing angle
- Let q represent the quark flavors u, d and C_{1q} is the vector quark coupling

Sensitivity to New Physics at TeV Scales



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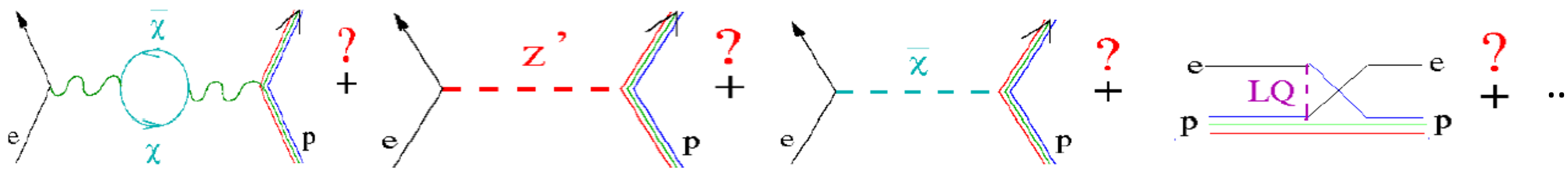
- Let q represent the quark flavors u, d and C_{1q} is the vector quark coupling
- Parameterize new physics scenarios in a general way with a new contact interaction in the Lagrangian characterized by mass scale Λ & coupling g:
  - General Case: $L_{msrd}^{PV} = L_{NC}^{SM} + L_{PV}^{new} = \bar{e}\gamma_\mu\gamma_5 e \sum_q \left(\frac{G_F}{\sqrt{2}} C_{1q} + \frac{g^2}{\Lambda^2} h_V^q\right) \bar{q}\gamma^\mu q$

    i.e. $\left(C_{1u}^{msrd}, C_{1d}^{msrd}\right) = \left(C_{1u}^{SM}, C_{1d}^{SM}\right) + \mathrm{r}(\cos\theta_h + \sin\theta_h)$

Sensitivity to New Physics at TeV Scales



RPC SUSY | Generic Z' | RPV SUSY | Leptoquarks

- Let the quark flavor dependence of new physics be *completely arbitrary*:
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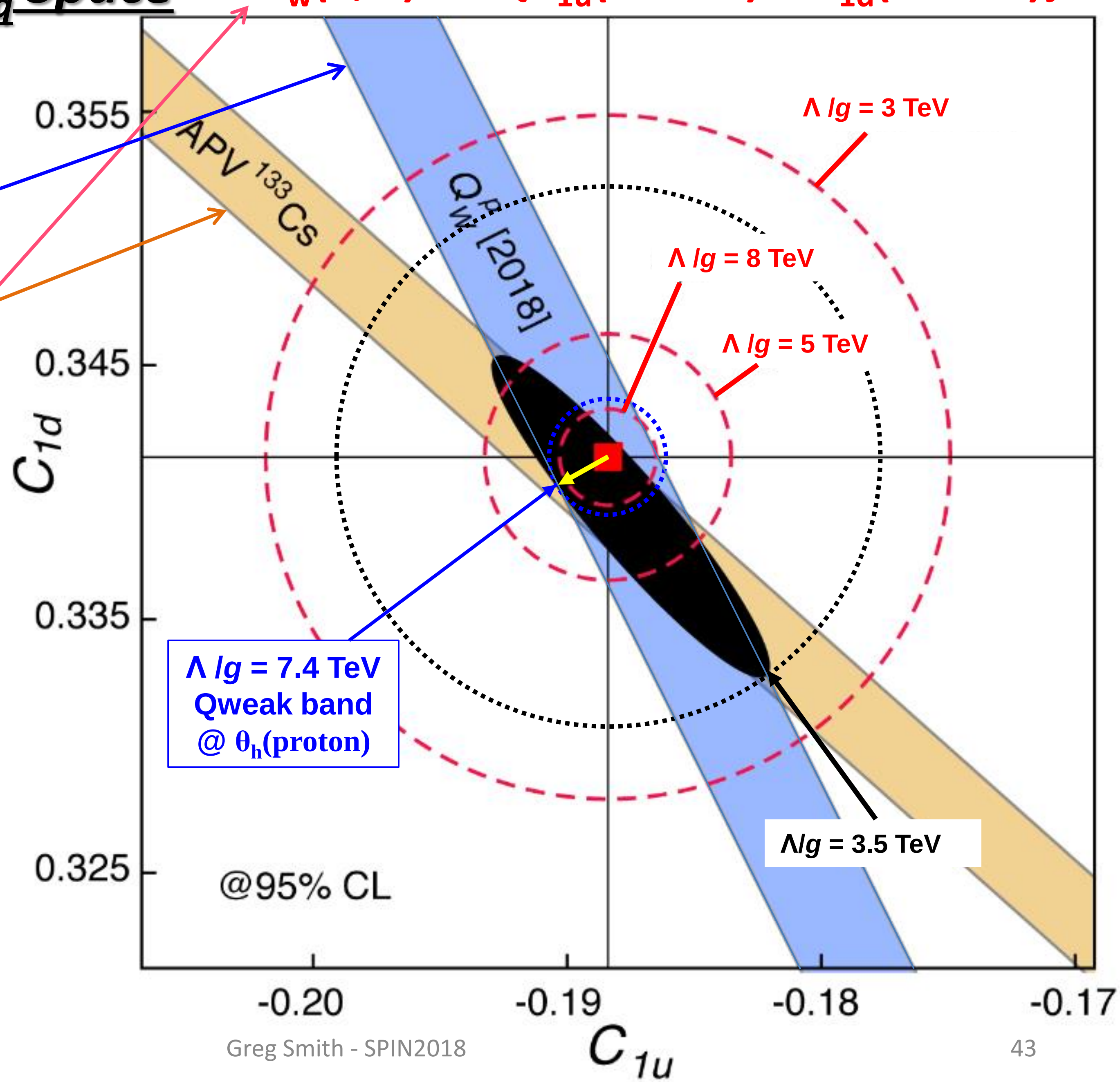
    i.e. $\left(C_{1u}^{msrd}, C_{1d}^{msrd}\right) = \left(C_{1u}^{SM}, C_{1d}^{SM}\right) + \mathrm{r}(\cos\theta_h + \sin\theta_h)$
  - But this is just the polar form of a circle in C_{1q} space!
    - with center at $\left(C_{1u}^{SM}, C_{1d}^{SM}\right)$ and
    - radius $r = \frac{\sqrt{2}}{G_F}\left(\frac{g}{\Lambda}\right)^2$

This is a model-independent result
For SL PV 4 point contact interactions
What do these circles look like?

Λ/g Circles in C_{1q} Space

$Q_w(Z,N) = -2\{C_{1u}(2Z + N) + C_{1d}(Z + 2N)\}$

- The Q_W results on the proton (this expt.) and on cesium (APV) provide independent constraints (bands) on the vector quark couplings C_{1q}.
- Together the H & Cs constraints form an improved (elliptical) constraint.



Sensitivity to New Physics Coupling to the Proton

- Proton: $\theta_h = \tan^{-1}(1/2) = 26.6°$
  - Then $\frac{\Lambda_\pm}{g} = v\sqrt{\frac{4\sqrt{5}}{\left|Q_W^p \pm 1.96\Delta Q_W^p - Q_W^p(SM)\right|}}$

J. Erler et al, ARNS64, 269 (2014)

$$= \frac{7.4\ \text{TeV}\ (\Lambda_+/g)}{8.4\ \text{TeV}\ (\Lambda_-/g)}$$

where:

- $v = \left(G_F\sqrt{2}\right)^{-1/2}$ = 246 GeV = EW (Fermi) scale = vacuum expectation value of the Higgs field, and
- G_F = Fermi coupling constant = 1.166 x 10^{-5} GeV^{-2}

Specific Mass Reach Examples

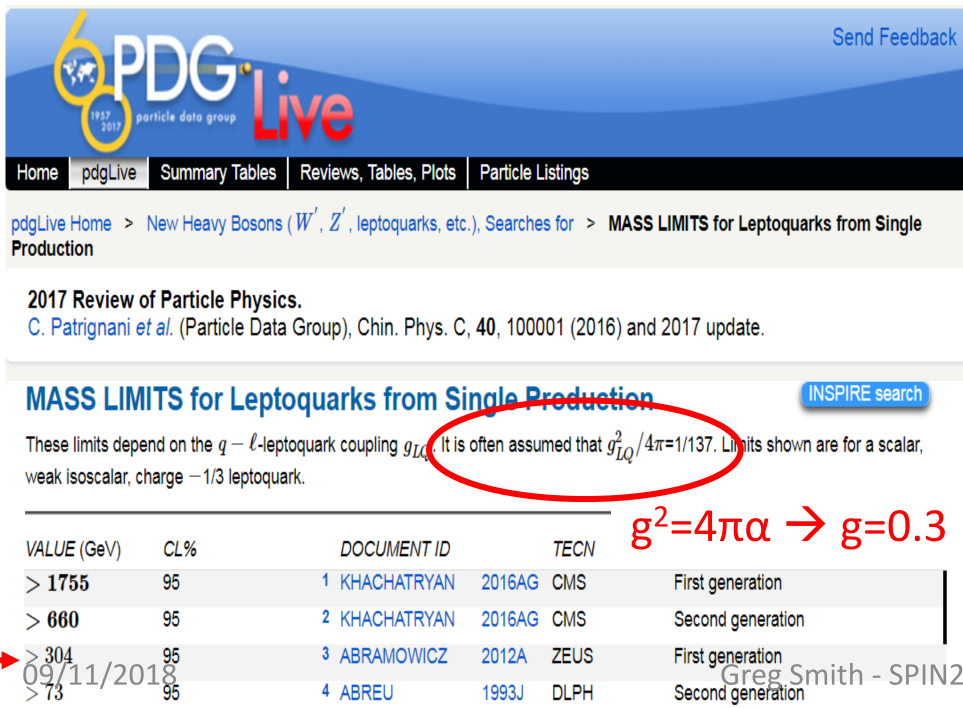
We rule out new PV SL physics below these mass scales Λ,
using the coupling strength "g" assumed for that new physics

- For the "extreme" contact interaction corresponding to e q compositeness, $g^2 = 4\pi \rightarrow \Lambda_+ = 26.3$ TeV (Eichten et al.,PRL50, 811 (1983))

Specific Mass Reach Examples

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

- For the "extreme" contact interaction corresponding to e q compositeness, $g^2 = 4\pi \rightarrow$ $\Lambda_+ = 26.3$ TeV (Eichten et al.,PRL50, 811 (1983))
- At the other extreme, the coupling usually assumed for leptoquarks is $g^2 = 4\pi\alpha \rightarrow$ $\Lambda_+ = 2.3$ TeV.



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pdgLive Home > New Heavy Bosons (W', Z', leptoquarks, etc.), Searches for > **MASS LIMITS for Leptoquarks from Single Production**

2017 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

MASS LIMITS for Leptoquarks from Single Production

INSPIRE search

These limits depend on the $q-\ell$-leptoquark coupling g_{LQ}. It is often assumed that $g^2_{LQ}/4\pi$=1/137. Limits shown are for a scalar, weak isoscalar, charge −1/3 leptoquark.

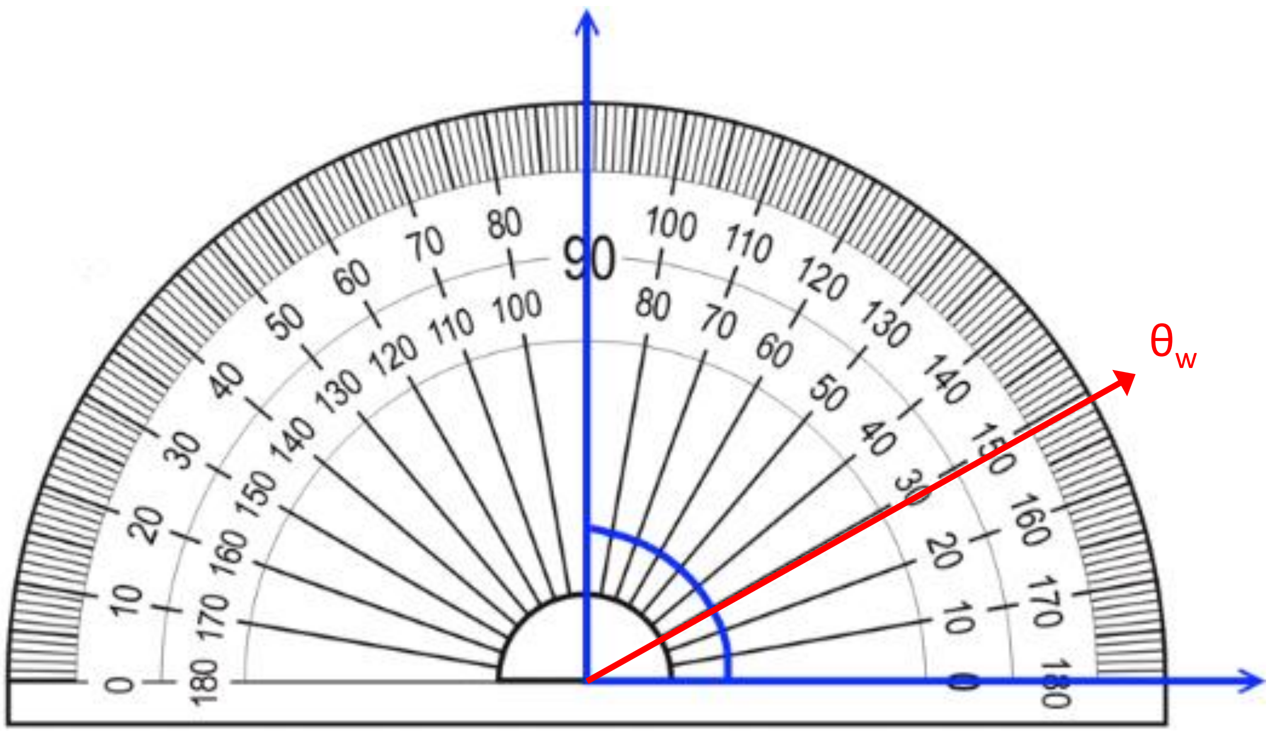
$g^2 = 4\pi\alpha \rightarrow g = 0.3$

VALUE (GeV)	CL%	DOCUMENT ID		TECN	
> 1755	95	1 KHACHATRYAN	2016AG	CMS	First generation
> 660	95	2 KHACHATRYAN	2016AG	CMS	Second generation
> 304	95	3 ABRAMOWICZ	2012A	ZEUS	First generation
> 73	95	4 ABREU	1993J	DLPH	Second generation

ep →

LQ's: heavy (think Pb) color-triplet bosons postulated in SM extensions like technicolor & GUTs. Carry both lepton & baryon #s. Could be part of why there are 3 generations of quarks & leptons.

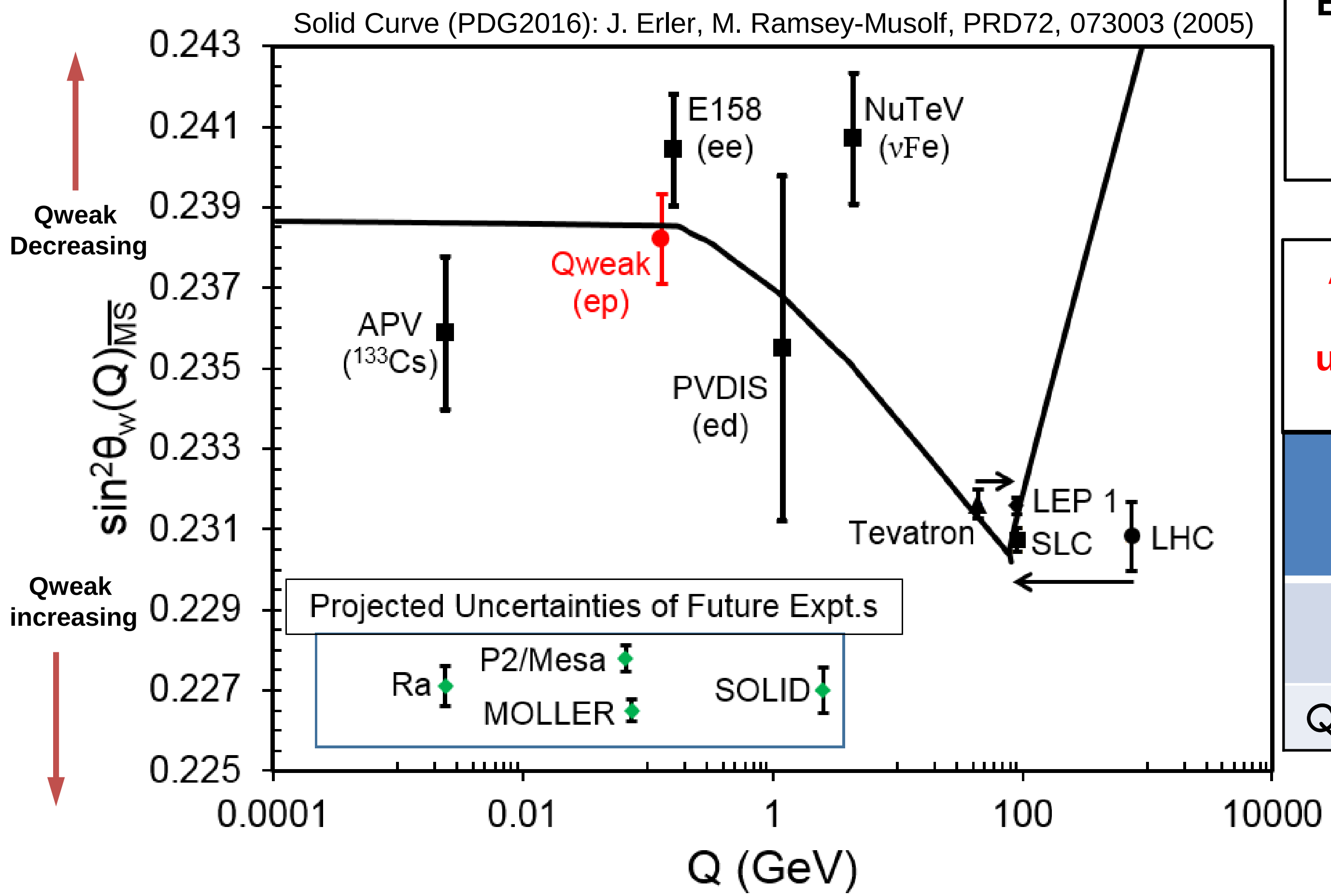
The weak mixing angle



- Not directly predicted by SM, but by other msrmnts of SM quantities. EW theory predicts θ_W is a f(Q).

Running of the Weak Mixing Angle $\sin^2\vartheta_W$

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



Expt's differ in sensitivity to classes of new physics.

Qweak sensitive to scalar lepto-quarks, E158 is not.

Accidental suppression of $Q_W(p)$ in SM makes it unusually sensitive to s2tw. Example:

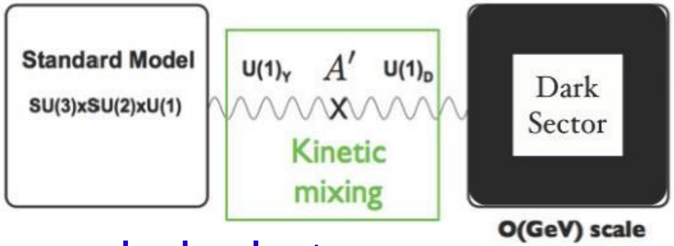
	Weak Charge Precision	$\sin^2\theta_W$ precision
APV: ^{133}Cs	0.59%	0.81%
Qweak p	6.3%	0.46%

Implications for "Dark Parity Violation"

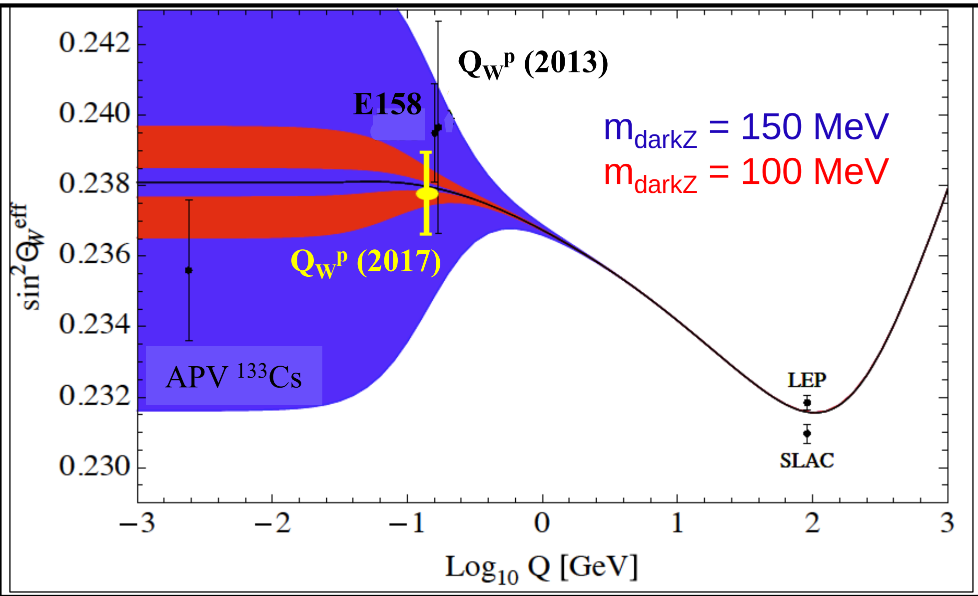
"Dark photon" – possible portal for new force to communicate with SM?

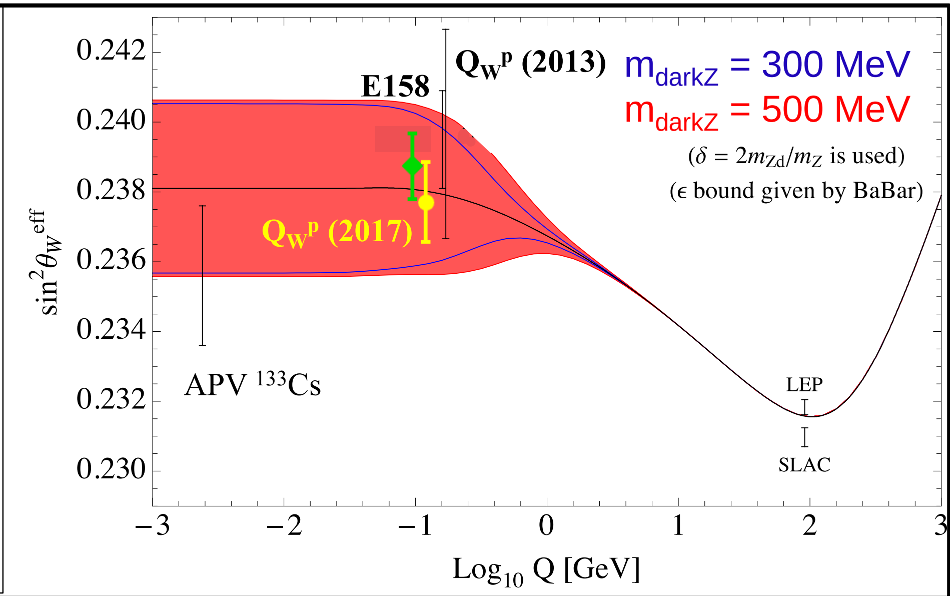
(Davoudiasl, Lee, Marciano, Phys. Rev. D**89**, 095006 (2014), & Marciano (private communication)

- New source of low-energy PV through mass mixing between Z_0 and Z_d
- Sensitivity is at low Q, not Z-pole



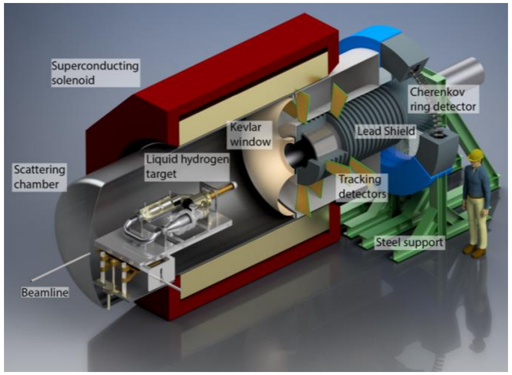
- Complementary to direct searches for heavy dark photons
  - observable even if direct decay modes are "invisible"
- **New Q_{weak} point rules out some of the allowed region**



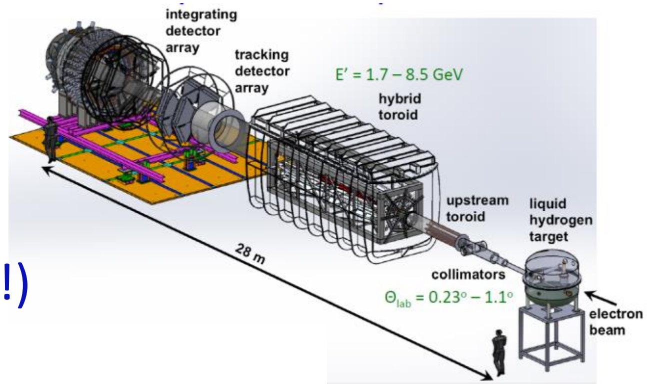


Future PVES Expt's

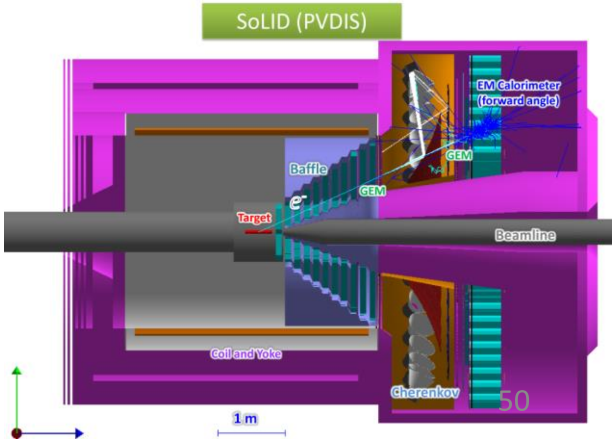
- Qweak → P2 @ MESA/Mainz: $\vec{e}p \rightarrow ep$ A_{ep} & Q_W^p
  - Weak vector quark charges, $\Delta\sin^2\theta_W$ to ± 0.00033
  - Λ/g to 13.8 TeV Installs 2021? arXiv: 1802.04759.
  - A_{ep} ~ −40 ± 0.56 ppb (1.4%) (requires 0.25 ppb (syst)!)
    Q^2=0.0045 GeV^2. 155 MeV. 60 cm LH2 (3+ kW).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



- E158 → MOLLER @ JLab: $\vec{e}e \rightarrow ee$ A_{ee} & Q_W^e
  - Weak charge of electron, $\Delta\sin^2\theta_W$ to ± 0.00028
  - Λ/g to 7.5 TeV. Installs 2023? arXiv:1411.4088.
  - A_{ep} ~ −33 ± 0.84 ppb (2.4%) (requires 0.4 ppb syst!)
  - θ=0.3°-1°. 11 GeV. 1.5 m LH2 (5 kW). 65 μA.



- PVDIS → SOLID @ JLab: $\vec{e}$d DIS
  - Weak axial quark charges, $\Delta\sin^2\theta_W$ to ± 0.00057
  - Λ/g to 6.2 TeV. Installs 2028? arXiv:1409.7741.



- APV(Cs) → APV(Fr, Ra)? Q_W^A

The Qweak Collaboration

101 collaborators 26 grad students
11 post docs 27 institutions

Institutions:

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[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
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[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
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[16] Louisiana Tech University
[17] University of Connecticut
[18] University of Northern British Columbia
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[21] University of New Hampshire
[22] Hendrix College, Conway
[23] University of Adelaide
[24] Syracuse University
[25] Duquesne University

A SEARCH FOR NEW PHYSICS

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Spokespersons Project Manager Grad Students *deceased

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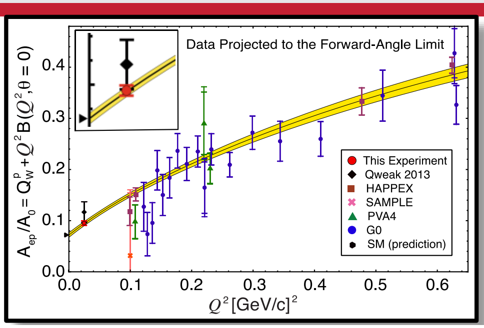
Summary: Q_{weak} expt – precision msrmnt of PV asymmetry in elastic e-p scattering → proton's weak charge

A = −226.5 ± 9.3 ppb
Q_W^p (this result) 0.0719 ± 0.0045
Q_W^p (SM) 0.0708 ± 0.0003



Implications:

- Msrd Q_W^p in good agreement with SM
  - Robust result to changes in method used to obtain it

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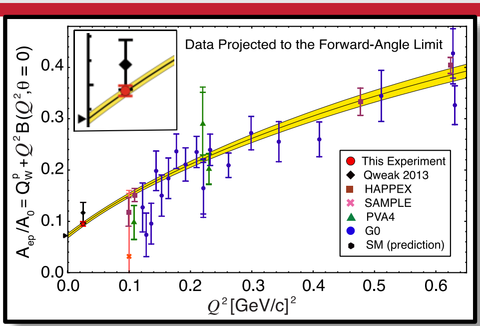

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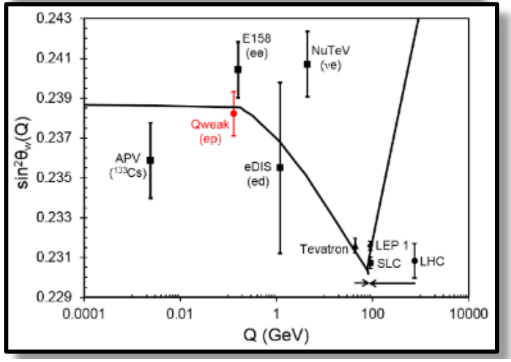

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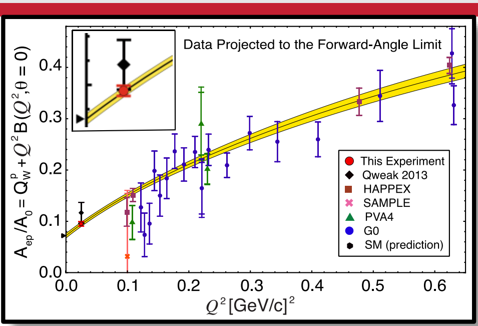
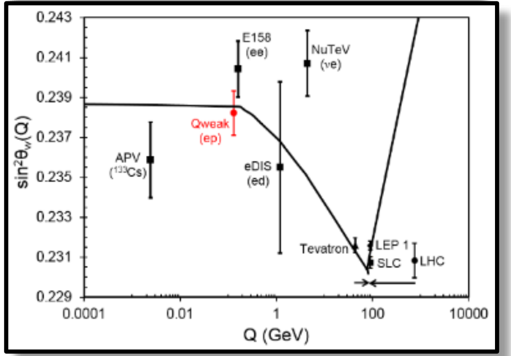
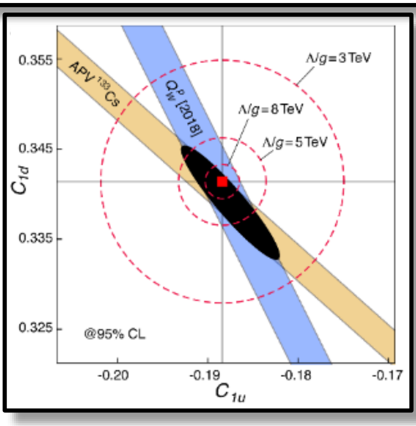
  - —$\Lambda/g < 7.4$ TeV, (< 3.5 TeV for arbitrary flavor ratios)







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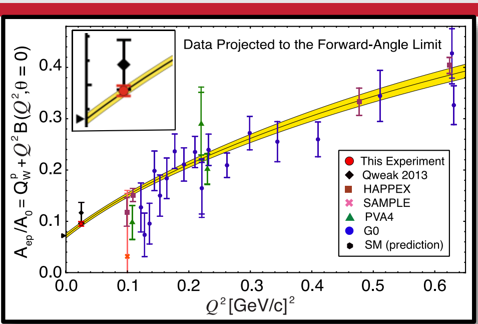
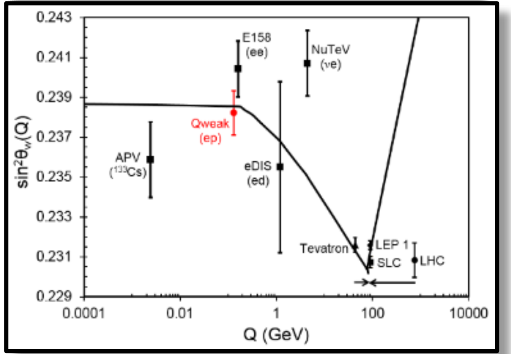
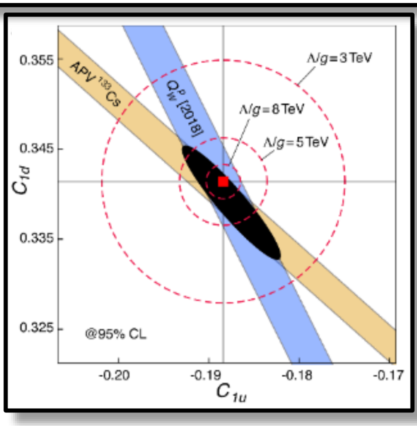
  - $\Lambda/g < 7.4$ TeV, (< 3.5 TeV for arbitrary flavor ratios)
- Will play a role in future analyses of bounds (or discoveries) of a variety of new BSM physics
- Builds scientific & technical foundation for next generation of measurements







Done

SM Tests: Past & Future Precision Low Energy Parity Violation Measurements

$\Lambda/g_{new\ physics}$ @ 95% CL using formalism of

Erler, et.al.- arXiv:1401.6199v1 [hep-ph] 23 Jan 2014

Experiment	% Precision	$\Delta \sin^2 \theta_W$	Λ /g [TeV] (mass reach)		Status
SLAC-E122	8.3	0.011	1.5		published
SLAC-E122	110	0.44	0.25		published
APV (^{205}Tl)	3.2	0.011	3.8		published
APV (^{133}Cs)	0.58	0.0019	9.1		published
SLAC-E158	14	0.0013	4.8		published
Jlab-Hall A	4.1	0.0051	2.2		published
Jlab-Hall A	61	0.051	0.82		published
JLab-Qweak (p)	**6.2**	**0.0011**	**7.4**		**2017**
JLab-SoLID	0.6	0.00057	6.2		conceptual
JLab-MOLLER	2.3	0.00026	11.0		seeking funding
Mainz-P2	2.0	0.00036	13.8		funded (>2020)
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		

Ancillary Measurements

Qweak made several ancillary measurements to determine and constrain background processes and corrections –
many will result in physics publications

- PV asymmetry:
  - elastic ^{27}Al
  - $N \rightarrow D$
    $(E = 1.16\ \mathrm{GeV}, 0.877\ \mathrm{GeV})$
  - Near W = 2.5 GeV
    (related to γZ box)
  - Pion photoproduction
    (E = 3.3 GeV)
- PC Transverse asymmetry:
  - elastic ep
  - elastic ^{27}Al, Carbon
  - $N \rightarrow D$
  - Møller
  - Near W = 2.5 GeV
  - Pion photoproduction
    (E = 3.3 GeV)

Main Uncertainties in the Asymmetry Measurement

All uncertainties in ppb	Run 1	Run 2	Combined
Charge Normalization: A_{BCM}	5.1	2.3	
Beamline Background: A_{BB}	5.1	1.2	
Beam Asymmetries: A_{beam}	4.7	1.2	Note:
Rescattering bias: A_{bias}	3.4	3.4	correlations
Beam Polarization: P	2.2	(1.2)	between
Al target windows: A_{b1}	(1.9)	1.9	factors
Kinematics: R_{Q^2}	(1.2)	1.3	
Total of others $< 5\%$, incl ()	3.4	2.5	
Total systematic uncertainty	10.1	5.6	5.8
Total statistical uncertainty	15.0	8.3	7.3
Total combined uncertainty	18.0	10.0	9.3 (p = 86%)

$$A_{PV}(4\%) = -279 \pm 31(\text{syst}) \pm 35(\text{stat})\text{ ppb} = -279 \pm 47\text{ ppb}$$

$$A_{PV}(\text{full}) = -226.5 \pm 5.8(\text{syst}) \pm 7.3(\text{stat})\text{ ppb} = -226.5 \pm 9.3\text{ ppb}$$

All Corrections to the Asymmetry

$$A_{\rm msr} = A_{\rm raw} + A_T + A_L + A_{\rm BCM} + A_{\rm BB} + A_{\rm beam} + A_{\rm bias}$$

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

f_1: Al f_2: beamline
f_3: neutrals f_4 : inelastics

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

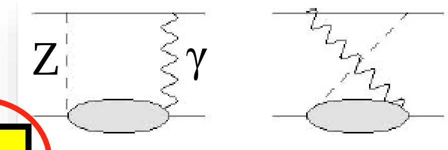
Quantity	Run 1	Run 2	Correlation
$A_{\rm raw}$	-192.7 ± 13.2 ppb	-170.7 ± 7.3 ppb	—
$A_{\rm T}$	0 ± 1.1 ppb	0 ± 0.7 ppb	0
$A_{\rm L}$	1.3 ± 1.0 ppb	1.2 ± 0.9 ppb	1
$A_{\rm BCM}$	0 ± 4.4 ppb	0 ± 2.1 ppb	0.67
$A_{\rm BB}$	3.9 ± 4.5 ppb	-2.4 ± 1.1 ppb	0
$A_{\rm beam}$	18.5 ± 4.1 ppb	0.0 ± 1.1 ppb	0
$A_{\rm bias}$	4.3 ± 3.0 ppb	4.3 ± 3.0 ppb	1
$A_{\rm msr}$	-164.6 ± 15.5 ppb	-167.5 ± 8.4 ppb	—
P	87.66 ± 1.05 %	88.71 ± 0.55 %	0.19
f_1	2.471 ± 0.056 %	2.516 ± 0.059 %	1
A_1	1.514 ± 0.077 ppm	1.515 ± 0.077 ppm	1
f_2	0.193 ± 0.064 %	0.193 ± 0.064 %	1
f_3	0.12 ± 0.20 %	0.06 ± 0.12 %	1
A_3	-0.39 ± 0.16 ppm	-0.39 ± 0.16ppm	1
f_4	0.018 ± 0.004 %	0.018 ± 0.004 %	1
A_4	-3.0 ± 1.0 ppm	-3.0 ± 1.0ppm	1
$R_{\rm RC}$	1.010 ± 0.005	1.010 ± 0.005	1
$R_{\rm Det}$	0.9895 ± 0.0021	0.9895 ± 0.0021	1
$R_{\rm Acc}$	0.977 ± 0.002	0.977 ± 0.002	1
R_{Q^2}	0.9928 ± 0.0055	1.0 ± 0.0055	1
$R_{\rm tot}$	0.9693 ± 0.0080	0.9764 ± 0.0080	1
$\sum f_i$	2.80 ± 0.22 %	2.78 ± 0.15 %	1

Effect of the Proton Radius Puzzle

- The puzzle:
  - ep global analysis: $r_p = 0.875 \pm 0.010$ fm
    - Zhan, et al., Phys. Lett. B **705**, 59 (2011)
  - μp Lamb shift: $r_p = 0.8409 \pm 0.0004$ fm
    - Antognini, et al., Science **339**, 417 (2013)
- But as $Q^2 \rightarrow 0$, $G_E = Z\{1 - Q^2 \langle r^2 \rangle /6 + \ldots\}$
  - So $G_E(ep) = 0.9178$, and $G_E(\mu p) = 0.9241$
    - So $\Delta G_E = 0.7\%$
  - At our Q^2, G_E contributes 26 ppb
    - So $\Delta A \sim (0.7\%)(26 \text{ ppb}) \sim 0.2$ ppb out of 226 ppb msrd
    - → $\Delta Qw(p) = \Delta A_{had}/A_0 = 0.00008$ (~2% of our error bar)

A tiny effect.

Calculations of the $\Box^{V}_{\gamma Z}$ @ E=1.16 GeV



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

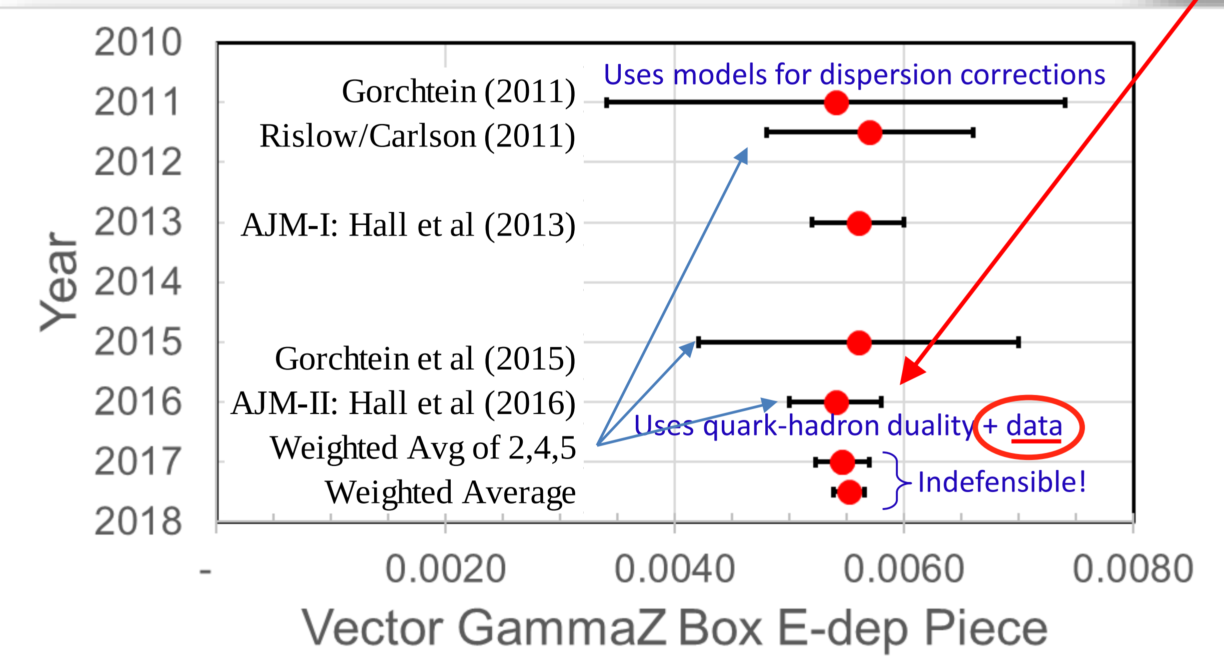
The $\Box_{\gamma Z}$ is the only E & Q^2 dependent EW correction.
→ Correct the PVES data for this E & Q^2 dependence.

- Early calculations primarily dispersion theory type
  - Data can firm up error estimates!
  - Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, Q^2 = 0.09 GeV^2
- Later calculations data-driven

Gamma-Z Box Error:

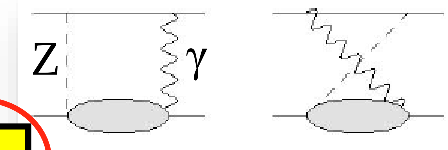
AJM-II: Hall et al. (2016)

	Value	Error
V	0.0054	0.0004
AV	-0.0007	0.0002
Q factor	0.978	0.012
(A+V)Q	0.00460	0.00044
Qw(p) SM	0.07080	0.00030



- Central values similar, but uncertainties vary.
- Theory community can't agree which result we should use.
- But we can see what the impact is on our global fit.

Calculations of the $\Box^V_{\gamma Z}$ @ E=1.16 GeV



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

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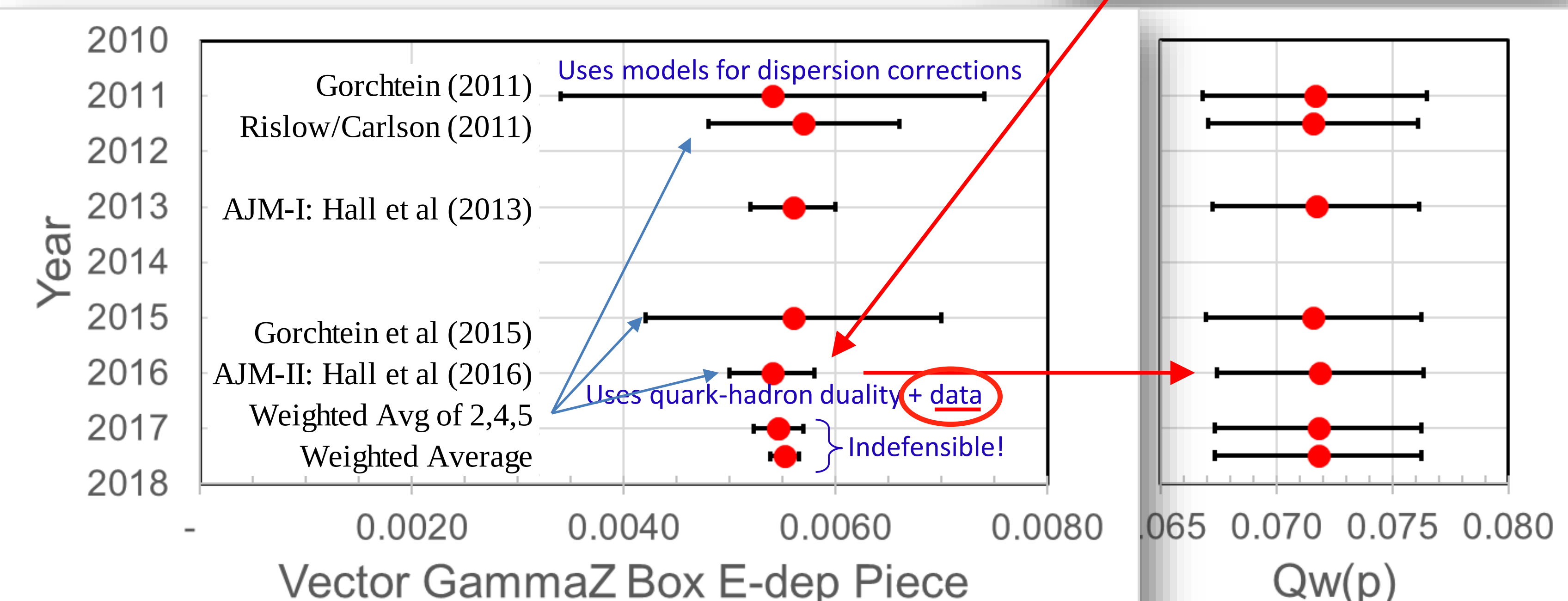
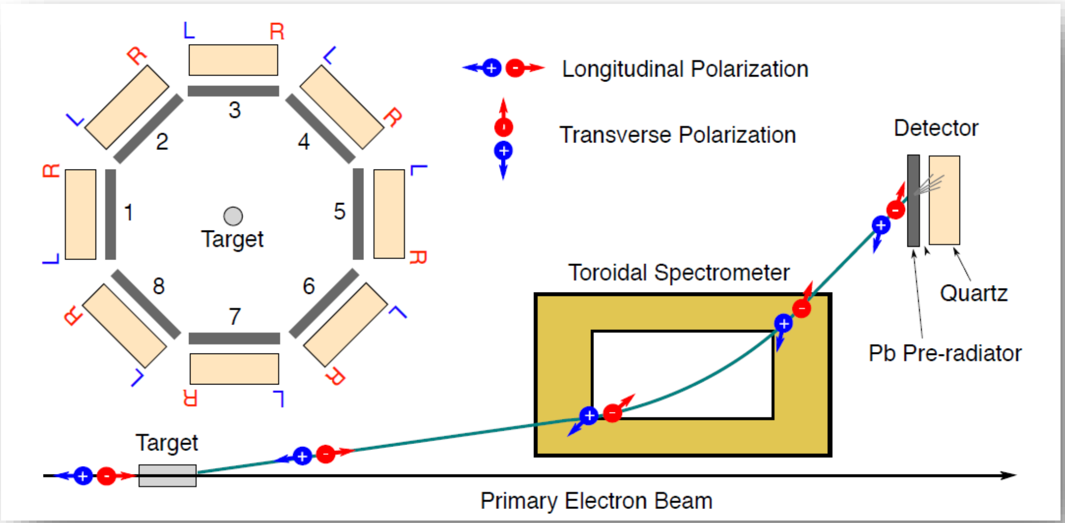
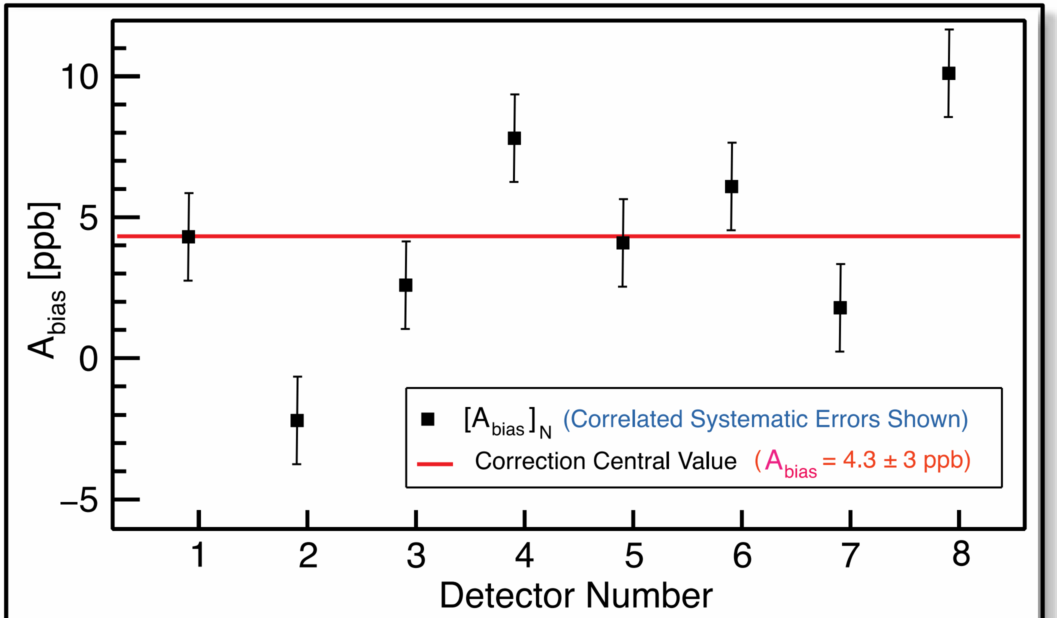


Detector Optical Imperfections: A_{bias} Systematic





Saw a large, consistent asymmetry $A_{diff} = (A_R - A_L) \sim 290$ ppb in the L & R PMTs of each detector bar.

Qweak parity signal = $(A_R + A_L)/2$, so R-L **effect cancels to first order**.

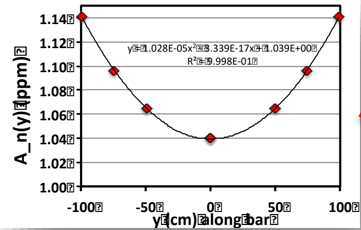
Effect: Transverse P picked up via g-2 precession thru magnet "analyzed" by Pb pre-radiator just in front of bars → L/R asymmetry across each bar.

Minor broken symmetries of as-built apparatus lead to a 4 ± 3 ppb **rescattering bias correction A_{bias}.**

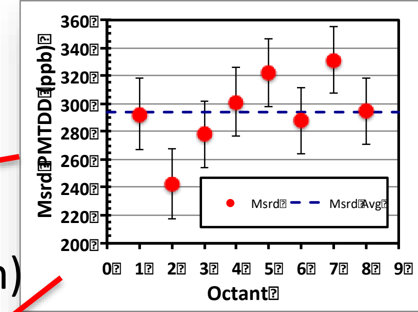
Two approaches taken to model this agreed to within 1 ppb:

1) Phenomenological method: used msrd (or simulated) flux on each bar, & light seen by each PMT, scaled to msrd A_{diff}.

2) GEANT4: modeled Mott MS through the Pb, the flux on & optical properties of each bar.



Macroscopic model



- $\delta y(y) = A_n(y) * scale$ (δy ~ 300 ppb*2m = 600 nm)
  - adjust scale `till PMTDD(calc) = PMTDD(msrd) = A(L) – A(R)

σ±(L/R) from measured PMT^L/R(y) & Flux±(y) in tracking runs

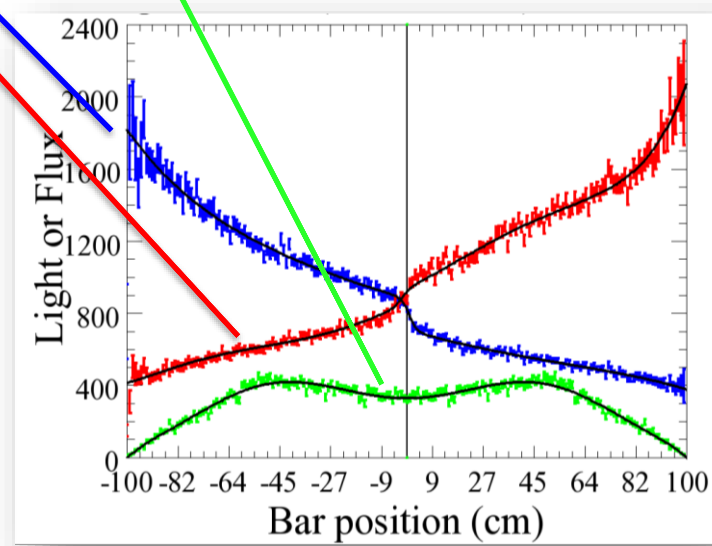
- $\sigma^{\pm}(L) = \sum PMT^{Left}(y)\ Flux^{\pm}(y -/+ \delta y(y))$
- $\sigma^{\pm}(R) = \sum PMT^{Right}(y)\ Flux^{\pm}(y -/+ \delta y(y))$

Form asymmetries at each end of the bars

- $A(L) = (\sigma^{+}(L) - \sigma^{-}(L)) / (\sigma^{+}(L) + \sigma^{-}(L))$
- $A(R) = (\sigma^{+}(R) - \sigma^{-}(R)) / (\sigma^{+}(R) + \sigma^{-}(R))$

Form the quantities of interest

- PMTDD = A(L) – A(R)
- Abias = (A(L) + A(R)) / 2
  - this is what hides in our A_{ep}



The Macroscopic model uses measured input for the light, the flux, & the PMTDD. $A_n(y)$ comes from PMTDD model, or from wags, but is scaled by the msrd PMTDD.

Summary of Results Determined from Q_{weak} A_{ep}

	Quantity	Value	Error	Method
Precision of A_{ep} dominates determination of Q_W^p	Q_W^p	**0.0719**	**0.0045**	Qweak A_{ep} + PVES data base
	$\sin^2\theta_W(Q=0.025)$	**0.2382**	**0.0011**	
	ρ_s	0.20	0.11	
	μ_s	-0.19	0.14	
	$G_A^{Z(T=1)}$	-0.64	0.30	
Including ^{133}Cs APV improves C_{1u}, C_{1d}, & $Q_W(n)$ extraction	Q_W^p	**0.0718**	**0.0044**	Qweak A_{ep} + PVES data base + APV ^{133}Cs
	C_{1u}	-0.1874	0.0022	
	C_{1d}	0.3389	0.0025	
	Q_W^n	**-0.9808**	**0.0063**	
	C_1 correlation = -0.9318			
LQCD constraint on G_E^s & G_M^s improves Q_W^p & $\sin^2\theta_W$ precision	Q_W^p	**0.0685**	**0.0038**	Qweak A_{ep} + PVES data base + LQCD (strange)
	$\sin^2\theta_W(Q=0.025)$	**0.2392**	**0.0009**	
does NOT depend on other PV measurements	Q_W^p	**0.0706**	**0.0047**	Qweak A_{ep} + EMFF's & theory axial FF + LQCD (strange)

EMFFs: Arrington & Sick, PRC **76**, 035201 (2007)
Axial FF: Liu McKeown & Ramsey-Musolf, PRC **76**, 025202 (2007)

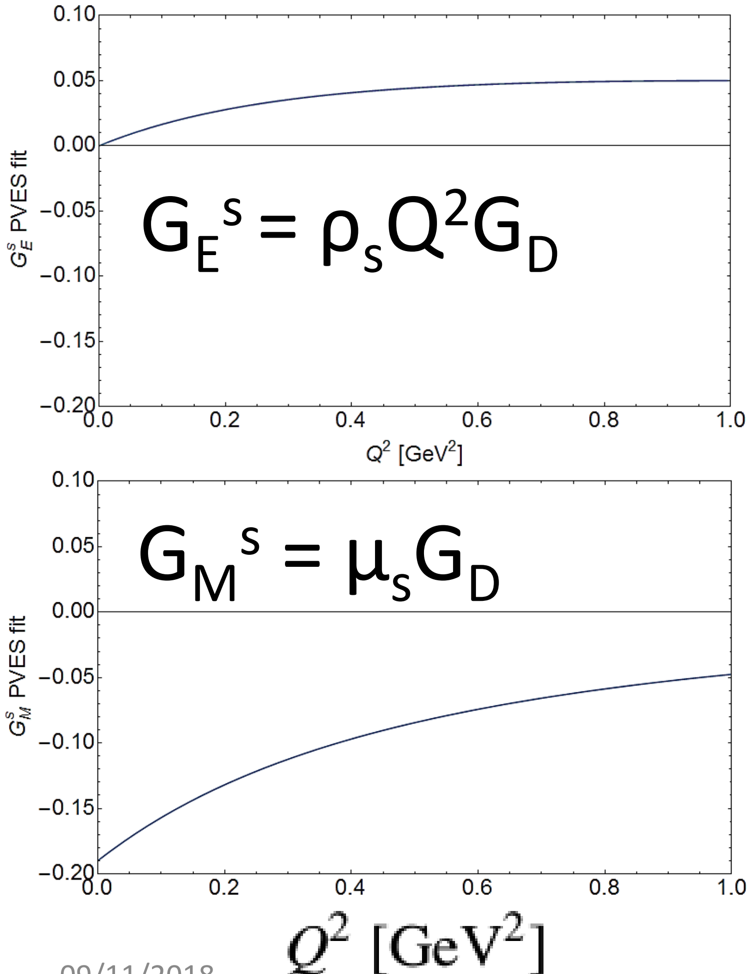
Comparing $G_{E,M}^{s}$ with PVES fit & LQCD

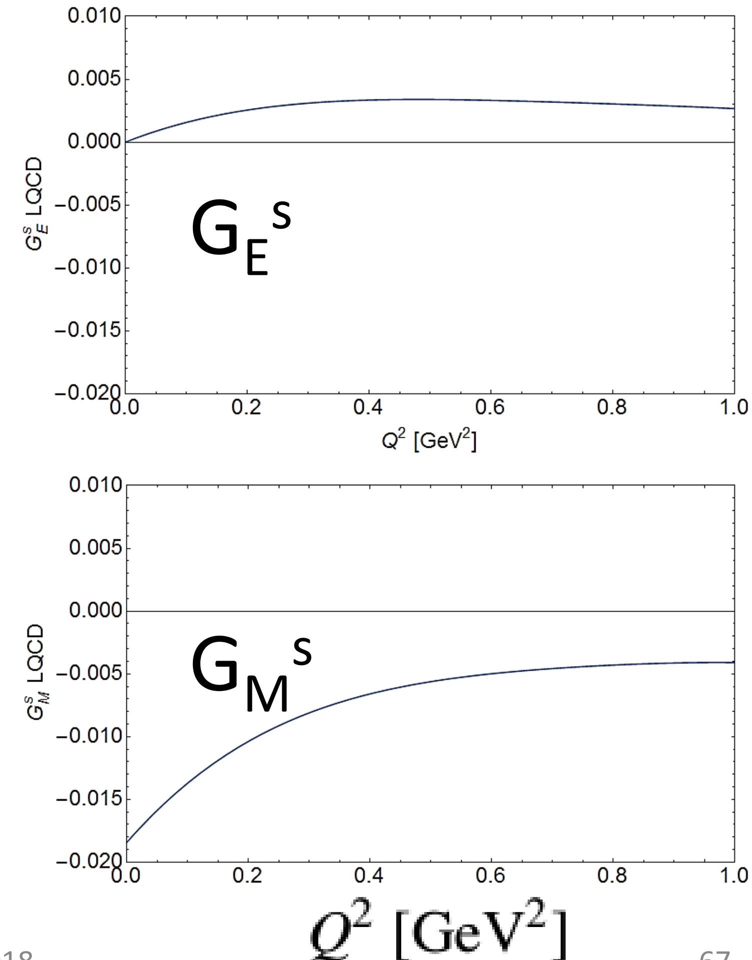
PVES fit has ~ same shape, but different magnitude (x10)

Lattice Results

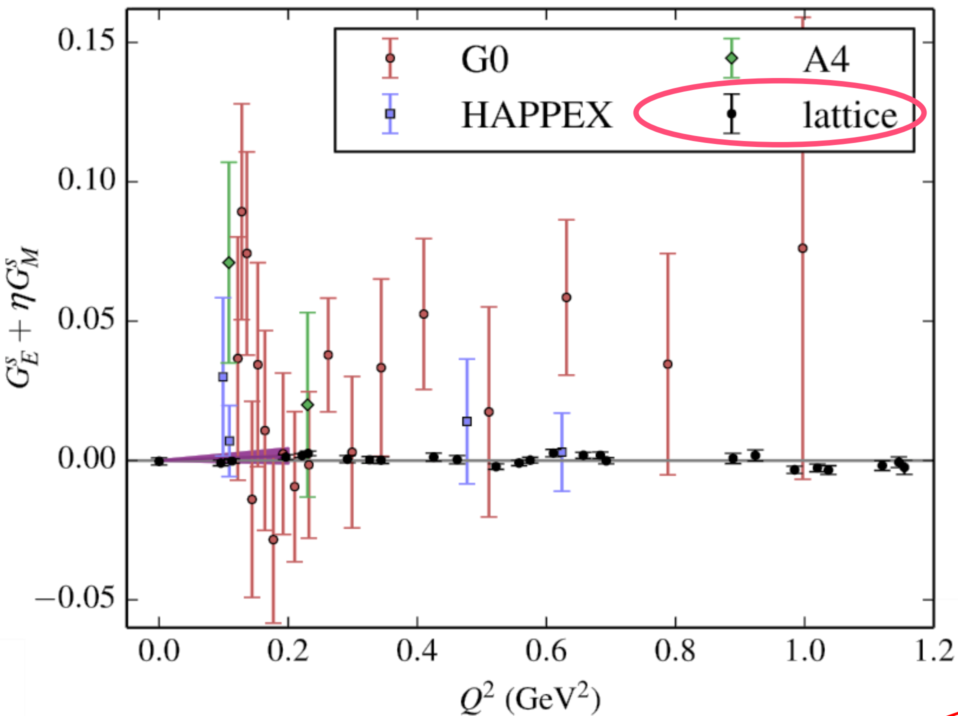
Global PVES Fit

Green et al., PRD92, 031501 (2015)





Tension between PVES data & LQCD



PHYSICAL REVIEW D **92,** 031501(R) (2015)

High-precision calculation of the strange nucleon electromagnetic form factors

Jeremy Green,[1,*] Stefan Meinel,[2,3,†] Michael Engelhardt,[4] Stefan Krieg,[5,6] Jesse Laeuchli,[7] John Negele,[8] Kostas Orginos,[9,10] Andrew Pochinsky,[8] and Sergey Syritsyn[3]

$G^s_{E,M}$

- Important to investigate impact of LQCD on our result
  - LQCD results continue to improve: Green et al. (used here) reached a pion mass of 317 MeV. Since then, the KY group reached the physical pion mass for the 1st time!

KY Grp: Sufian, et al., PRL118, 042001 (2017)

Our Result(s)

Method	Quantity	Value	Error
PVES fit	Q_W^p	**0.0719**	**0.0045**
	ρ_s	0.20	0.11
	μ_s	-0.19	0.14
	$G_A^{Z(T=1)}$	-0.64	0.30
PVES fit + APV	Q_W^p	**0.0718**	**0.0044**
	Q_W^n	-0.9808	0.0063
	C_{1u}	−0.1874	0.0022
	C_{1d}	0.3389	0.0025
	C_1 correlation	-0.9318	
PVES fit + LQCD	Q_W^p	**0.0685**	**0.0038**
Q_{weak} datum only	Q_W^p	**0.0706**	**0.0047**
SM	Q_W^p	**0.0708**	**0.0003**

Shift of 0.0034, or

$$\frac{0.0034}{\sqrt{0.0045^2 + 0.0038^2}}$$
= 0.58 σ
(uncorrelated)

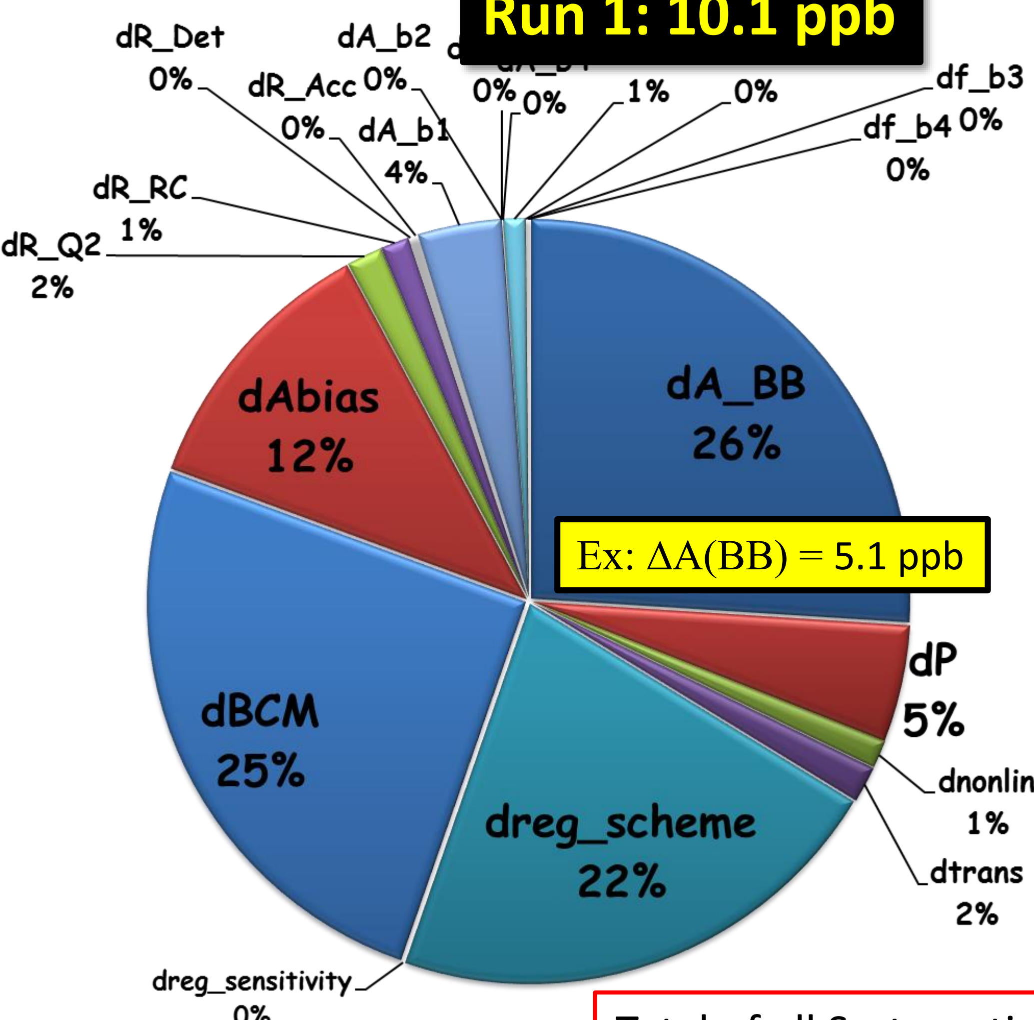
or

0.0034/0.0045 = 0.76 σ
(correlated)

Run 1&2 Systematic Uncertainties

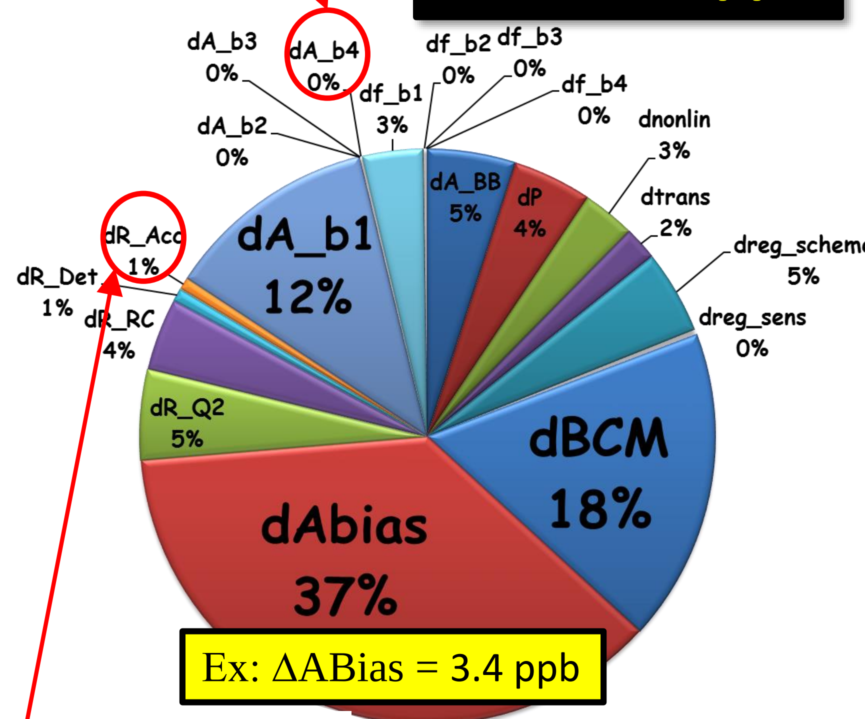
Pies show ΔA_i^2, so total systematic uncertainty is $\mathrm{sqrt}(\sum(\text{slices}))$

Run 1: 10.1 ppb



Total of all Systematic Errors forecast for the P2 Expt: 0.25 ppb

Run 2: 5.6 ppb



Total of all Systematic Errors forecast for the Moller Expt: 0.7 ppb

What is Atomic Parity Violation (APV)?

- Wood, et al., Science 275, 1759 (1997)
  - Q_W(133Cs) = −72.62 ± 0.43 (SM: -73.25 ± 0.02)
- PNC in Cesium is another way to msr electron-quark electroweak coupling constants
  - Parity-forbidden electronic transitions can occur due to (parity-violating) weak neutral currents
  - Expt. relies on creating an interference between a PNC 6S-7S transition amplitude A_{PNC} and a Stark-induced electric dipole 6S-7S E1 transition A_E
  - Input required for SM APV prediction:
    - Electronic structure of the atom, & Z boson mass (the neutral EW force carrier)
  - Cesium electronic structure is the most precisely known (~1%) of atoms used for PNC msrmnts
    - Alkali metal: one valence electron outside a tightly bound core
    - Other atoms used to msr APV: Fr, Tl, Bi, & Pb

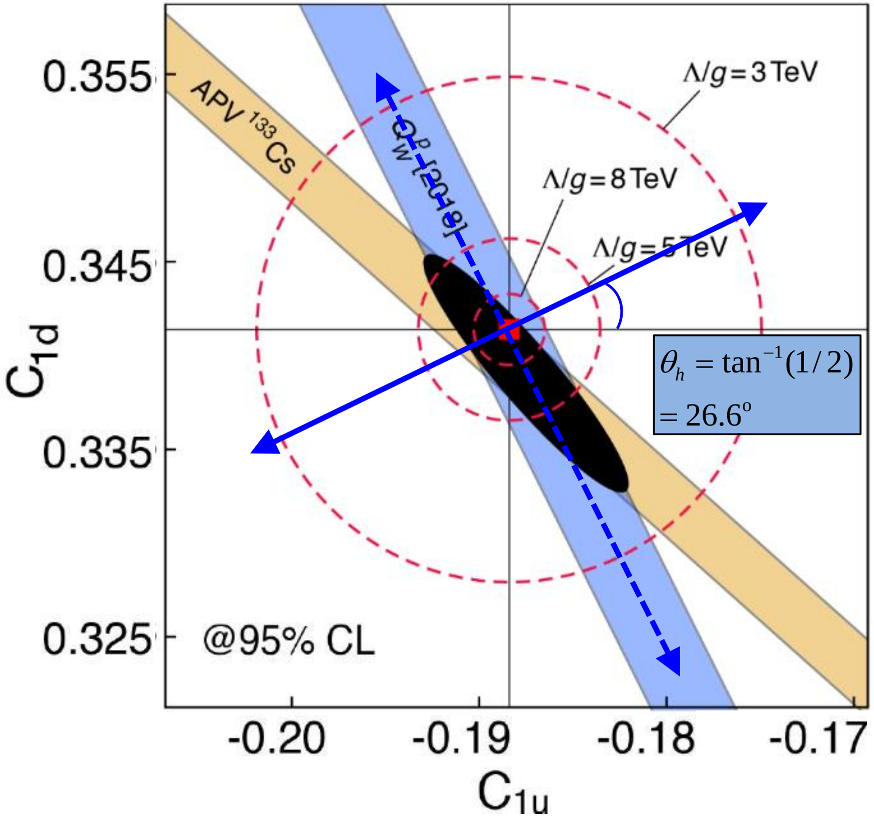
Limits on Semi-Leptonic PV Physics Beyond SM

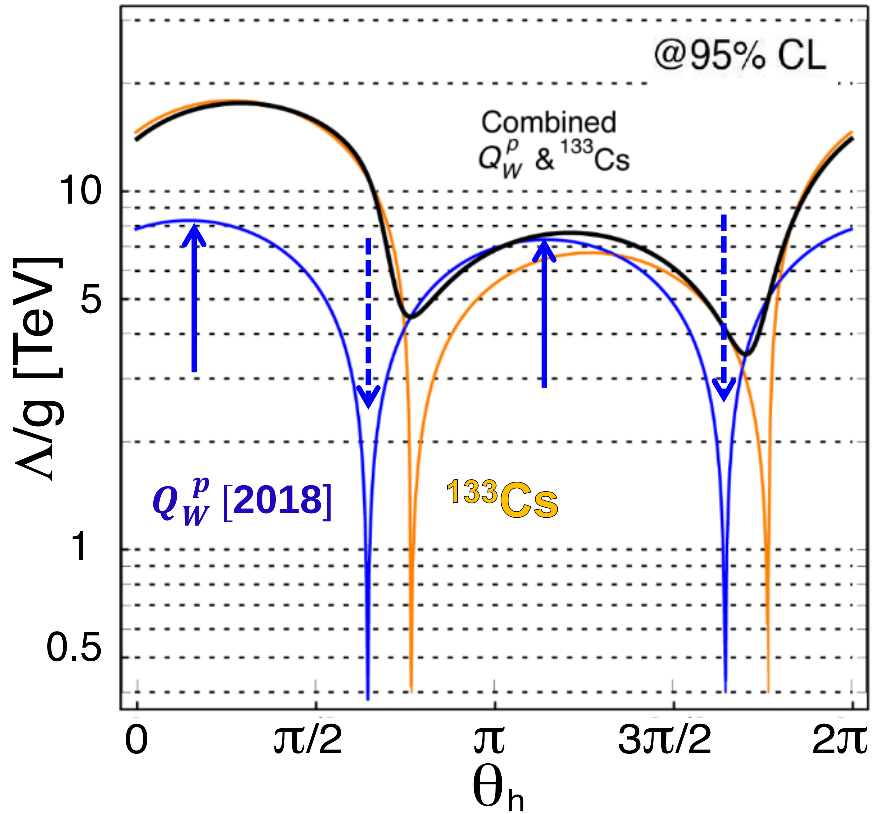
$$Q_W^p = -2(2C_{1u} + C_{1d})$$

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

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

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





SM is red square. Dashed contours indicate value of Λ/g = 3, 5, and 8 TeV.
(133Cs APV from PDG2016 – Wood, Flambaum)

θ_h is "flavor mixing angle" in Lagrangian $\mathcal{L}_{NP}^{PV}$ for new physics at value Λ/g mapped around boundary of experimental limits.

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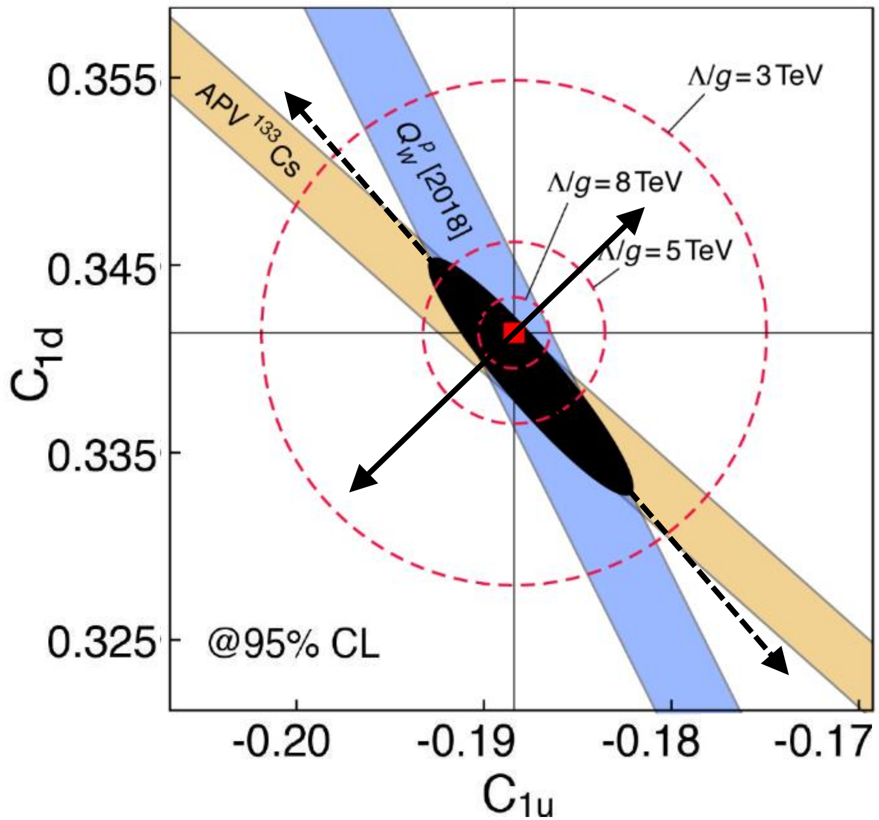

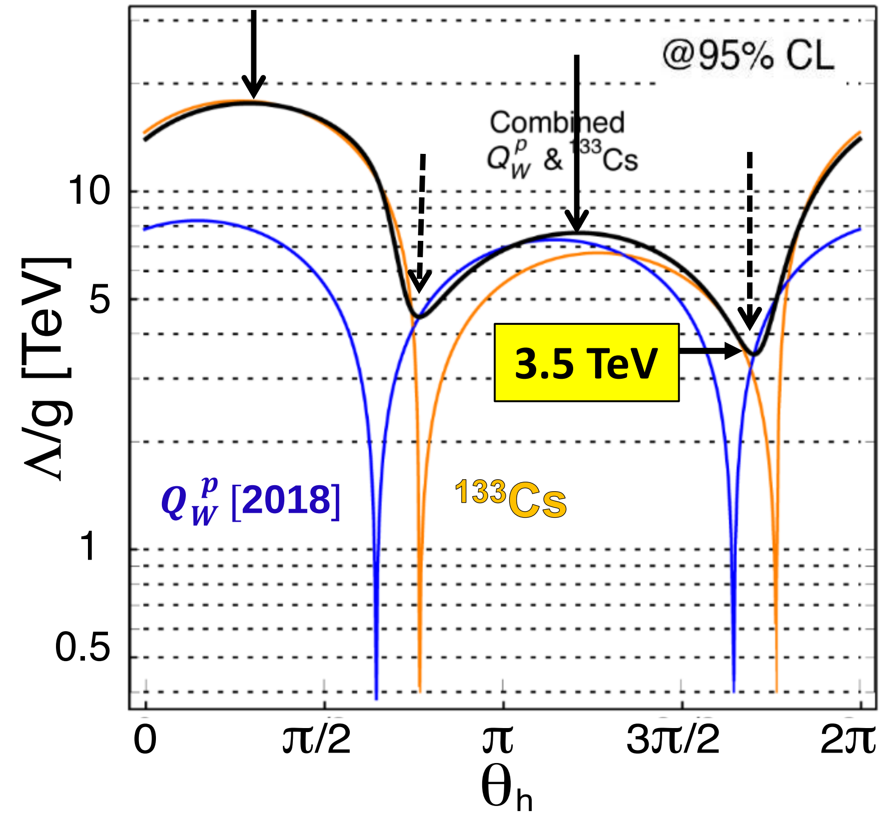

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Isovector Axial Form-Factor

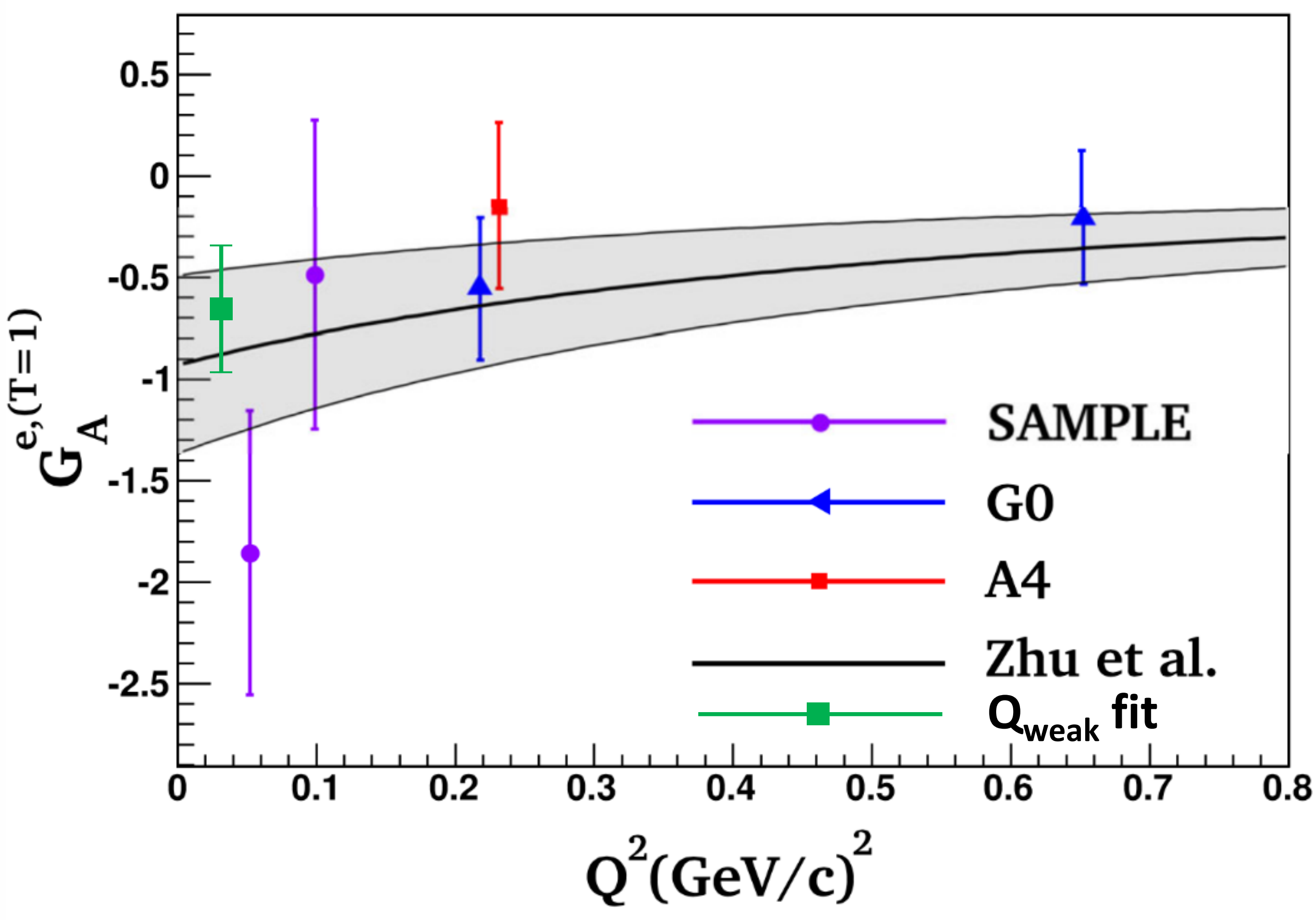


Figure adapted from D. Balaguer Rios *et al.* (PVA4)

Global fit including Q_{weak} is in good agreement with theory

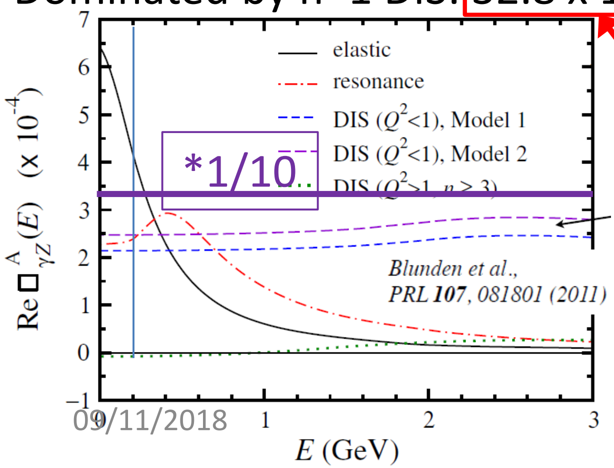
[S.L. Zhu, S.J. Puglia, B.R. Holstein, M.J. Ramsey-Musolf, Phys. Rev. D **62**, 033008 (2000)]

$\Box_{\gamma Z} = \Box^{A}_{\gamma Z} + \Box^{V}_{\gamma Z}$

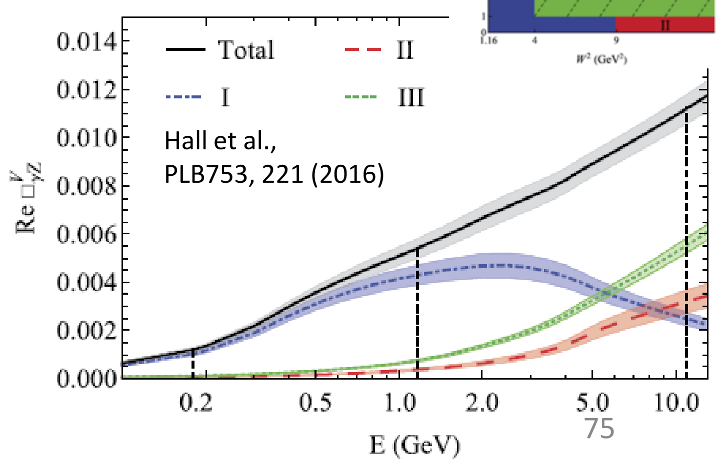
$\Box^{A}_{\gamma Z}$:	$\Box^{V}_{\gamma Z}$:
• V(e) x AV(h)	• AV(e) x V(h)
• Finite at E=0	• Zero at E=0
• E-dependence is small	• E-dependence is large
• @E=0 → 0.0044(2)	• @E=0 →0
• @E=1.165 GeV → 0.0037(2)	• @E=1.165 GeV → 0.0054(4)
• Shift: -0.0007	• Shift: +0.0054

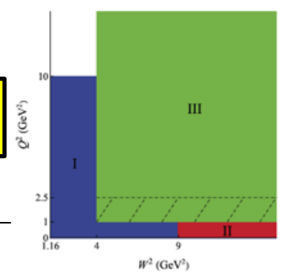
Total shift = 0.0054(4) – 0.0007(2) = 0.0047 at Qweak kinematics

Dominated by n=1 DIS: 32.8×10^{-4}



Off the top of the slide at this scale!



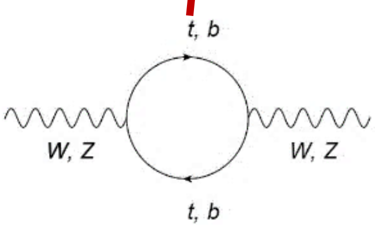


Electroweak Radiative Corrections

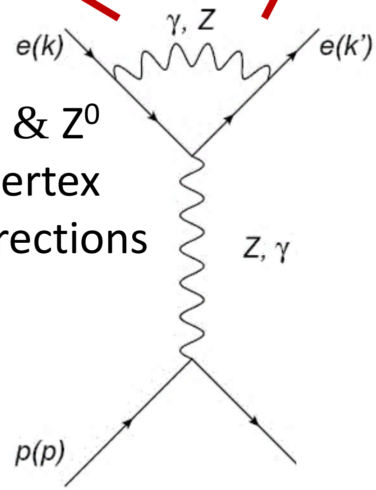
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

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

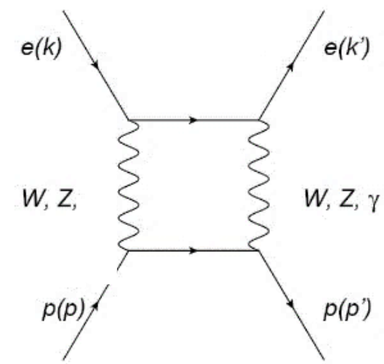
$Z^0/W^{\pm}$ interaction strength renormalization



γ & Z^0 vertex corrections



Box diagrams



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

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

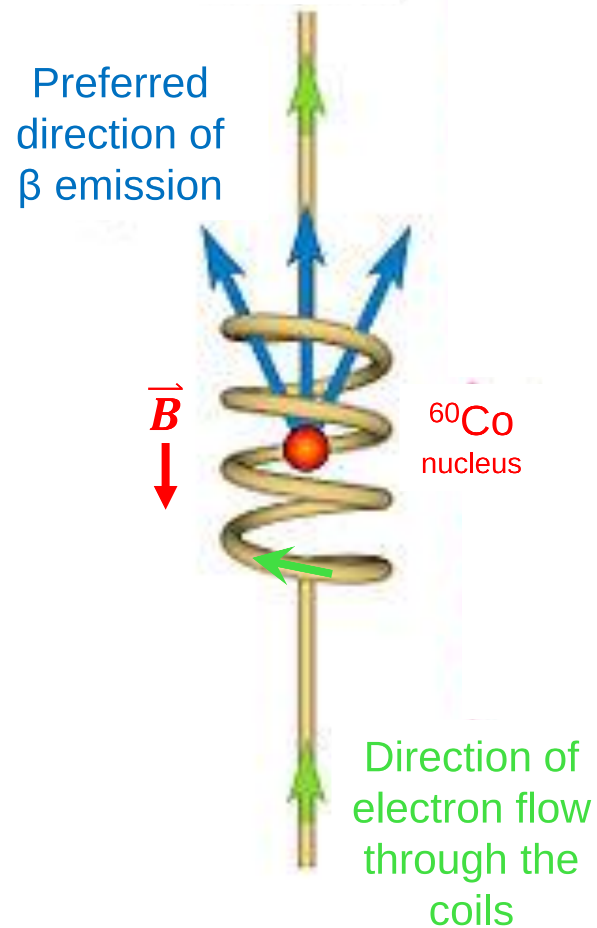
The $\Box_{\gamma Z}$ isn't pQCD friendly due to the photon leg ($\propto \frac{1}{q^2 + i\varepsilon}$)

Input to $\sin^2\theta_W$ Determination

Term	Expression	Value	Reference
ρ_{NC}	$1+\Delta_\rho$	1.00066	1, 2
Δ_e	$-\alpha/2\pi$	−0.001161	1, 2
Δ_e'	$-\frac{\alpha}{3\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{m_e^2}\right)+\frac{1}{6}\right]$	−0.001411	1, 2
$\hat{\alpha}$	$\equiv \alpha(M_Z)$	1/127.95	1, 2
$\hat{s}^2$	$=1-\hat{c}^2 \equiv \sin^2\theta_W(M_Z)$	0.23129	1, 2
$\alpha_s(M_W^2)$	-	0.12072	67
$\Box_{WW}$	$\frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s(M_W^2)}{\pi}\right)\right]$	0.01831	1, 2
$\Box_{ZZ}$	$\frac{\hat{\alpha}}{4\pi\hat{s}^2\hat{c}^2}\left[9/4-5\hat{s}^2\right]\left(1-4\hat{s}^2+8\hat{s}^2\right)\left(1-\frac{\alpha_s(M_Z^2)}{\pi}\right)$	0.00185	1, 2
$\Box_{\gamma Z}$	axial-vector hadron piece of $\Box_{\gamma Z}$: $\Re e\, \Box^{A}_{\gamma Z}$	0.0044	11

The 1957 Wu Experiment

- ^{60}Co β decay (weak interaction)
  - $^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \bar{\nu}_e$
  - The ^{60}Co nucleus was polarized in opposite directions by reversing the magnetic field in a solenoid at ~3 mK.



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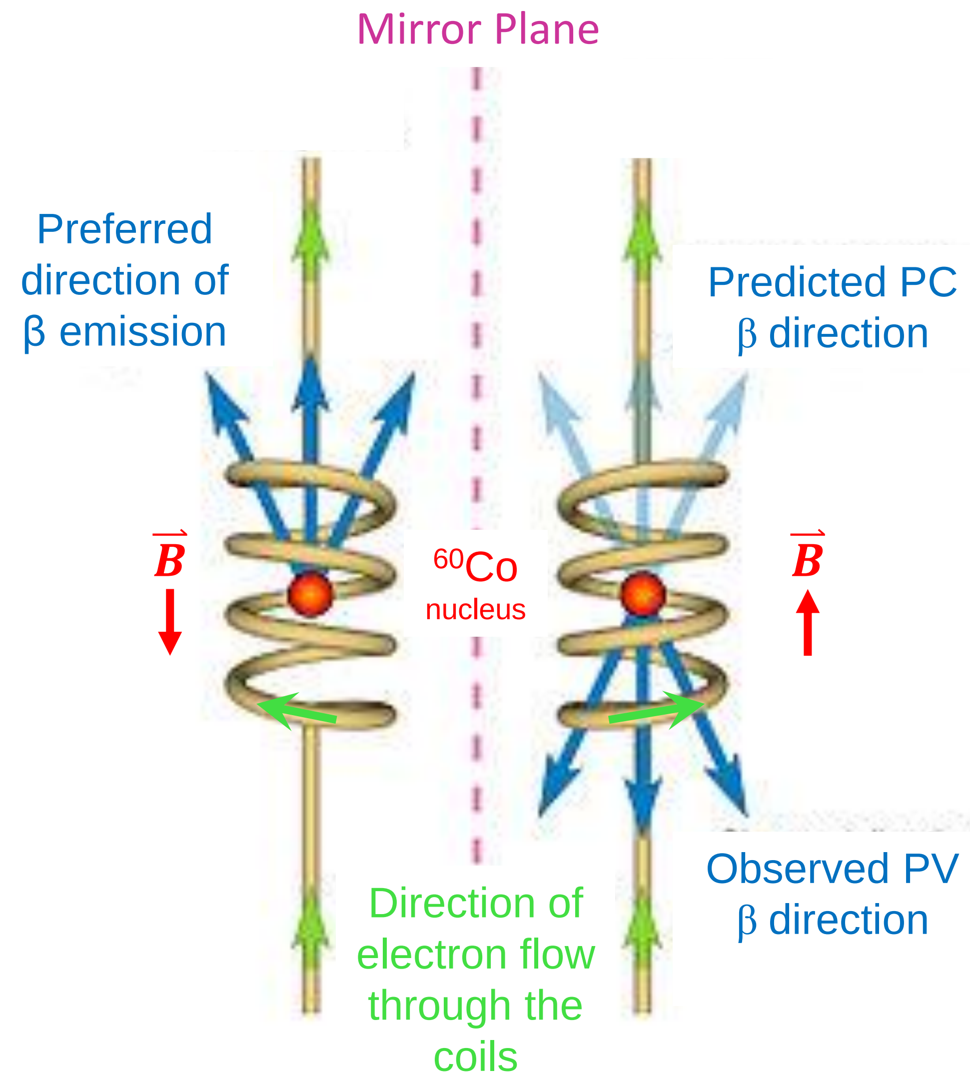
  - $^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \bar{\nu}_e$
  - The ^{60}Co nucleus was polarized in opposite directions by reversing the magnetic field in a solenoid at ~3 mK.
    - The e⁻ were always emitted in the direction opposite to the nuclear spin, even when the spin was flipped (the weak interaction violates parity)



Stand-alone result:

$$A_{PV}^p = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{1}{[\epsilon(G_E^p)^2 + \tau(G_M^p)^2]}$$

Q$_w$(p) Term → $\times\{(\epsilon(G_E^p)^2 + \tau(G_M^p)^2)(1 - 4\sin^2\theta_W)(1 + R_V^p)$

EM Term → $-(\epsilon G_E^p G_E^n + \tau G_M^p G_M^n)(1 + R_V^n)$

Strange Term → $-(\epsilon G_E^p G_E^s + \tau G_M^p G_M^s)(1 + R_V^{(0)})$

Axial Term → $-\epsilon'(1 - 4\sin^2\theta_W)G_M^p G_A^e\}\,, \quad (2)$

ie: $A^p_{PV}(Q^2)/A_0 = Q_W(p) - A_{EM}(Q^2) - A_{strange}(Q^2) - A_{axial}(Q^2)$

- $A^p_{PV}(Q^2)/A_0$: measure
- $Q_W(p)$: extract
- $A_{EM}(Q^2)$: From A&S EM FFs
- $A_{strange}(Q^2)$: From LQCD (or Ross fit)
- $A_{axial}(Q^2)$: Use Liu, McKeown & Musolf, PRC76, 025202 (2007)

A_{EM}, $A_{strange}$, A_{axial}: Calculate

$$Q_w^p = A_{ep}(Q^2)/A_0(Q^2) - Q^2 B(Q^2,\theta)$$

Stand-alone Result: LQCD vs PVES fit

LQCD Strange	Value (ppb)	Error (ppb)	Err/Val (%)	Val/Tot (%)
[1] AE	-26.20	3.63	14%	12%
AM	79.88	1.36	2%	-35%
[2] AEs (LQCD)	-1.11	0.33	29%	0%
AMs (LQCD)	0.77	0.24	30%	0%
[3] Aaxial	5.60	2.36	42%	-2%
Total	58.95	4.55	8%	-26%
AEM	53.68	3.872	7%	-24%
As (LQCD)	-0.34	0.40	119%	0%
Aaxial	5.60	2.36	42%	-2%
Total	58.95	4.55	8%	-26%
[Qweak] Amsrd	-226.50	9.30	4%	100%
Amsrd+AEM,s,ax	-167.55	10.35	6%	74%
A0 (ppm)	-2.229			
Qw(p)	0.0752	-0.0046	6%	107%
gZ	0.0046	0.0005	11%	7%
Qw(p)-gZ	**0.0706**	**0.0047**	7%	100%

PVES Fit Strange	Value (ppb)	Error (ppb)	Err/Val (%)	Val/Tot (%)
AE	-26.20	3.63	14%	12%
AM	79.88	1.36	2%	-35%
AEs (PVES fit)	-10.69	5.88	55%	5%
AMs (PVES fit)	8.18	6.02	74%	-4%
Aaxial	5.60	2.36	42%	-2%
Total	56.77	9.56	17%	-25%
AEM	53.68	3.872	7%	-24%
As (PVES fit)	-2.51	8.42	335%	1%
Aaxial	5.60	2.36	42%	-2%
Total	56.77	9.56	17%	-25%
Amsrd	-226.50	9.30	4%	100%
Amsrd+AEM,s,ax	-169.73	13.34	8%	75%
A0 (ppm)	-2.229			
Qw(p)	0.0761	-0.0060	8%	106%
gZ	0.0046	0.0005	11%	6%
Qw(p)-gZ	**0.0715**	**0.0060**	8%	100%

[1] AE & AM: Arrington & Sick, PRC76 035201 (2007)
[2] AEs & AMs: Green, et al., PRD92, 031501 (2015)
[3] Aaxial & RCs: Liu, McKeown & Ramsey-Musolf, PRC76, 025202 (2007)

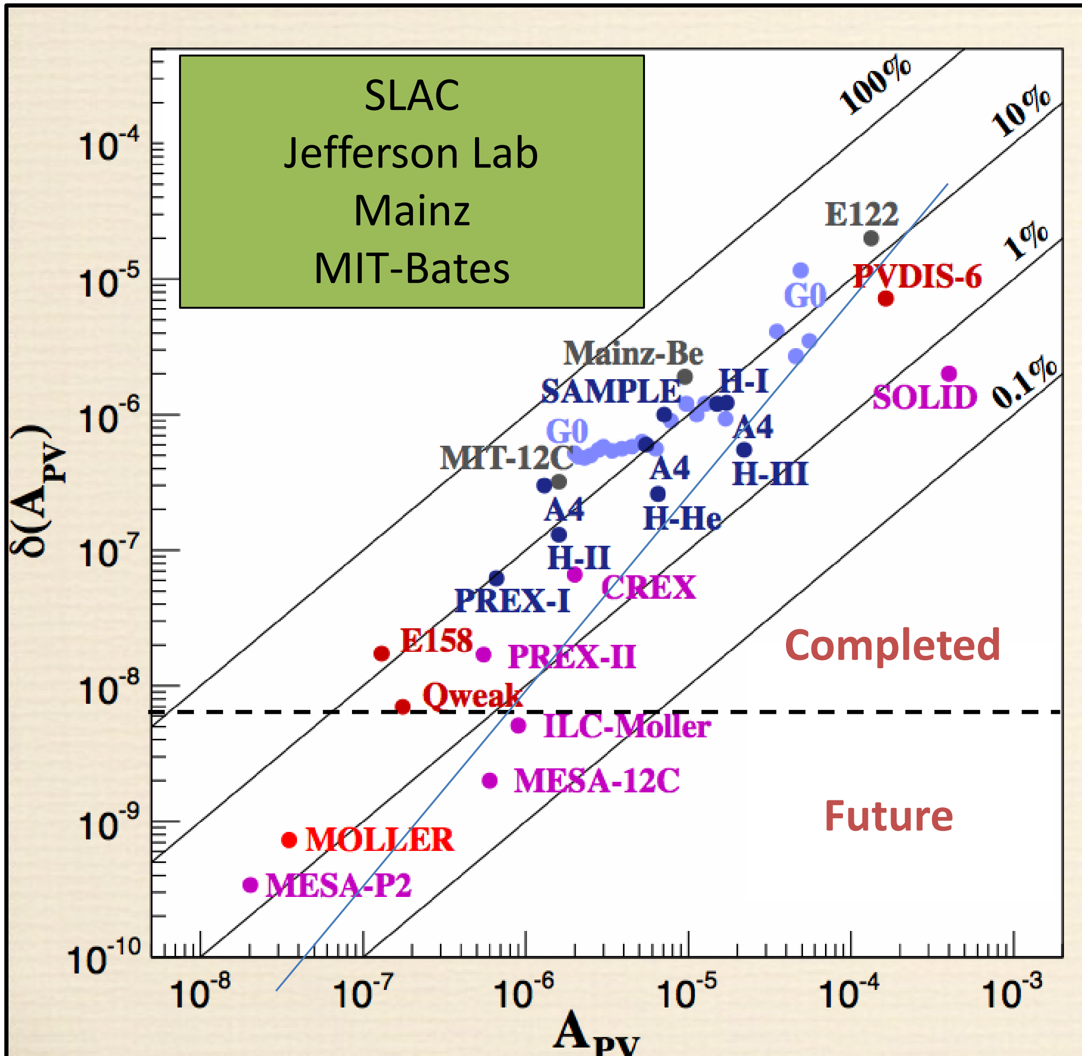
PVES Database

Tgt	# pts
p	28
d	5
^{4}He	2
χ^2/ν	1.2

Target	Q^2	\theta	A_{LR}	\d_stat	\d_syst	\d_cor	Exp	Label	E_est	error(tot)	rel error	A0
Proton	0.1	144	-5.61	0.67	0.88	0	SAMPLE	1	0.195	1.1060	-19.7%	-8.99E-06
Deuteron	0.091	144	-7.77	0.73	0.72	0	SAMPLE	2	0.185	1.0253	-13.2%	-8.18E-06
Deuteron	0.038	144	-3.51	0.57	0.58	0	SAMPLE	3	0.113	0.8132	-23.2%	-3.42E-06
Proton	0.23	35.3	-5.44	0.54	0.26	0	PVA4	4	0.854	0.5993	-11.0%	-2.07E-05
Proton	0.108	35.4	-1.36	0.29	0.13	0	PVA4	5	0.570	0.3178	-23.4%	-9.71E-06
Proton	0.477	12.3	-15.05	0.98	0.56	0	HAPPEX	6	3.353	1.1287	-7.5%	-4.29E-05
Helium4	0.091	5.7	-6.72	0.84	0.21	0	HAPPEX	7	3.058	0.8659	-12.9%	-8.18E-06
Proton	0.099	6.0	-1.14	0.24	0.06	0	HAPPEX	8	3.032	0.2474	-21.7%	-8.90E-06
Proton	0.122	6.7	-1.51	0.44	0.22	0.18	G0	9	3.031	0.5238	-34.7%	-1.10E-05
Proton	0.128	6.8	-0.97	0.41	0.2	0.17	G0	10	3.031	0.4868	-50.2%	-1.15E-05
Proton	0.136	7.1	-1.3	0.42	0.17	0.17	G0	11	3.031	0.4839	-37.2%	-1.22E-05
Proton	0.144	7.3	-2.71	0.43	0.18	0.18	G0	12	3.031	0.4997	-18.4%	-1.30E-05
Proton	0.153	7.5	-2.22	0.43	0.28	0.21	G0	13	3.031	0.5544	-25.0%	-1.38E-05
Proton	0.164	7.8	-2.88	0.43	0.32	0.23	G0	14	3.031	0.5833	-20.3%	-1.47E-05
Proton	0.177	8.1	-3.95	0.43	0.25	0.2	G0	15	3.031	0.5361	-13.6%	-1.59E-05
Proton	0.192	8.4	-3.85	0.48	0.22	0.19	G0	16	3.031	0.5612	-14.6%	-1.73E-05
Proton	0.21	8.8	-4.68	0.47	0.26	0.21	G0	17	3.031	0.5767	-12.3%	-1.89E-05
Proton	0.232	9.3	-5.27	0.51	0.3	0.23	G0	18	3.031	0.6348	-12.0%	-2.09E-05
Proton	0.262	9.9	-5.26	0.52	0.11	0.17	G0	19	3.031	0.5580	-10.6%	-2.36E-05
Proton	0.299	10.6	-7.72	0.6	0.53	0.35	G0	20	3.031	0.8737	-11.3%	-2.69E-05
Proton	0.344	11.5	-8.4	0.68	0.85	0.52	G0	21	3.031	1.2064	-14.4%	-3.09E-05
Proton	0.41	12.6	-10.25	0.67	0.89	0.55	G0	22	3.031	1.2424	-12.1%	-3.69E-05
Proton	0.511	14.2	-16.81	0.89	1.48	1.5	G0	23	3.031	2.2875	-13.6%	-4.60E-05
Proton	0.631	16.0	-19.96	1.11	1.28	1.31	G0	24	3.031	2.1416	-10.7%	-5.68E-05
Proton	0.788	18.2	-30.83	1.86	2.56	2.59	G0	25	3.031	4.0892	-13.3%	-7.09E-05
Proton	0.997	20.9	-37.93	7.24	9	0.52	G0	26	3.031	11.5624	-30.5%	-8.97E-05
Proton	0.109	6.0	-1.58	0.12	0.04	0	HAPPEX	27	3.183	0.1265	-8.0%	-9.80E-06
Helium4	0.077	6.0	-6.4	0.23	0.12	0	HAPPEX	28	2.672	0.2594	-4.1%	-6.93E-06
Proton	0.22	144.5	-17.23	0.82	0.89	0	PVA4	29	0.312	1.2102	-7.0%	-1.98E-05
Proton	0.221	110	-11.25	0.86	0.27	0.43	G0	30	0.352	0.9987	-8.9%	-1.99E-05
Deuteron	0.221	110	-16.93	0.81	0.41	0.21	G0	31	0.352	0.9318	-5.5%	-1.99E-05
Proton	0.628	110	-45.9	2.4	0.8	1	G0	32	0.679	2.7203	-5.9%	-5.65E-05
Deuteron	0.628	110	-55.5	3.3	2	0.7	G0	33	0.679	3.9217	-7.1%	-5.65E-05
Proton	0.624	13.7	-23.8	0.78	0.36	0	HAPPEX	34	3.482	0.8591	-3.6%	-5.61E-05
Deuteron	0.224	145	-20.11	0.87	1.03	0	PVA4	-26	0.315	1.3483	-6.7%	-2.01E-05
Proton	0.025	7.9	-0.2788	0.0351	0.0296		QWEAK	35	1.154	0.0459	-16.5%	-2.25E-06

Parity-Violating Electron Scattering
History & Relative Experimental Difficulty

Higher Measurement Precision Required



Smaller Asymmetry

Pioneering PVDIS (1978)
early SM test – Prescott *et al.*

SLAC E122: $\Delta A_{PV} = \pm 10$ ppm

Strange FF Searches (98 – 09)
SAMPLE, G^0, A4, HAPPEX

$\Delta A_{PV} \sim 0.25$ ppm – 2 ppm

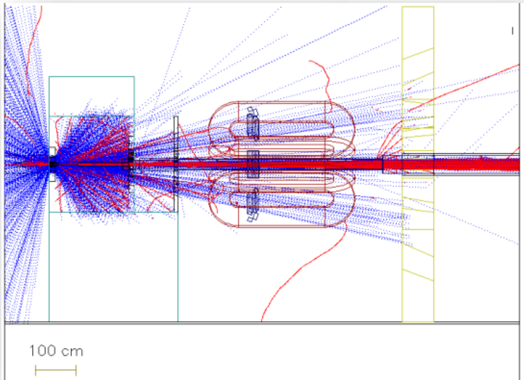
High Precision SM Tests
(2003 – 2017)

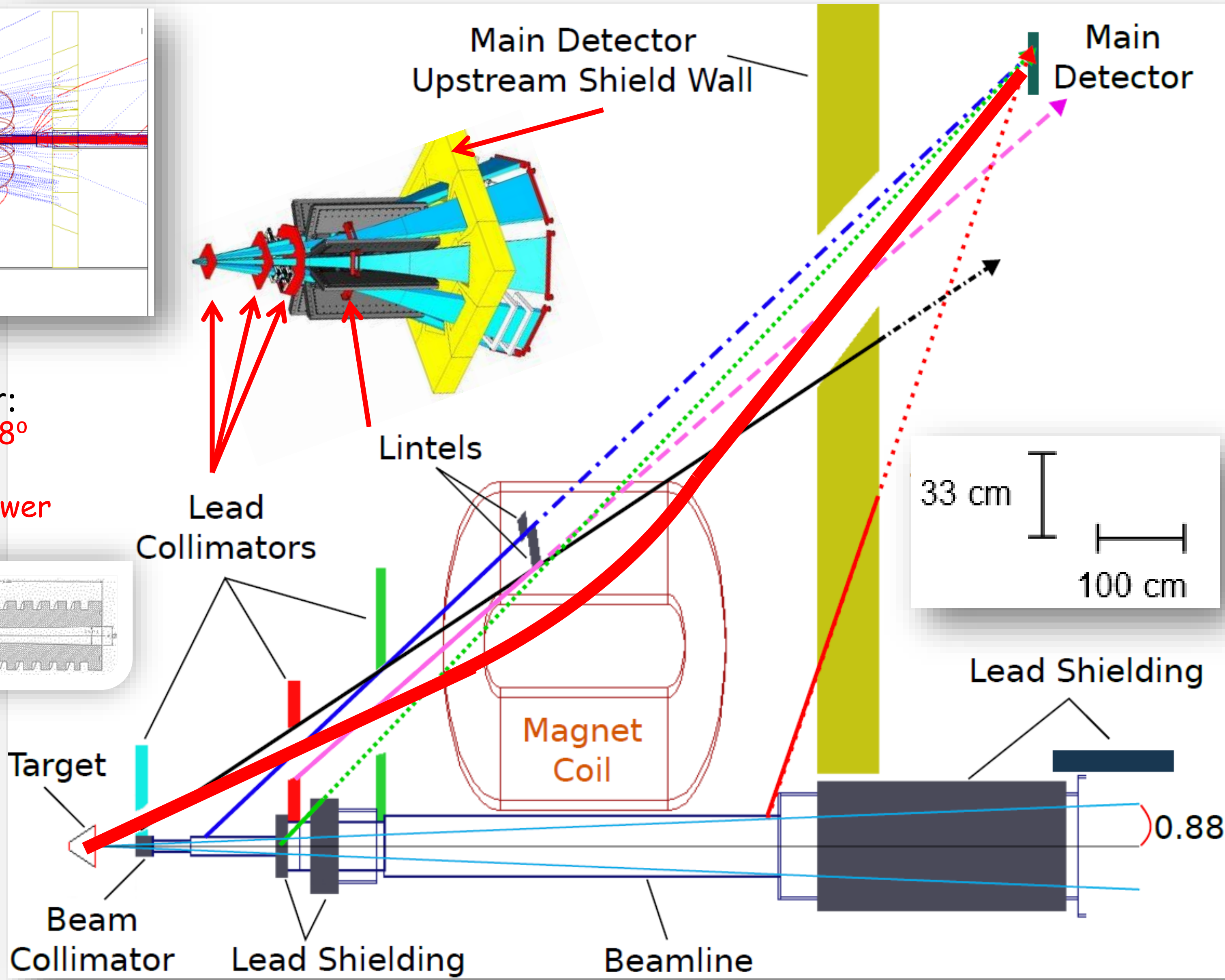
SLAC E158: $\Delta A_{PV} \sim 17$ ppb
JLab Q_{weak}: $\Delta A_{PV} \sim 9$ ppb

Future sub-ppb SM Tests

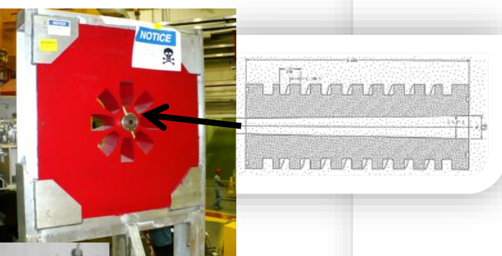
Jlab MOLLER: $\Delta A_{PV} \sim 0.8$ ppb
Mainz P2: $\Delta A_{PV} \sim 0.34$ ppb

Neutral line-of-sight Collimation





Beam Collimator:
- 14.9 mm φ, ±0.88°
- 47 cm ds of tgt
- 1.6 kW beam power



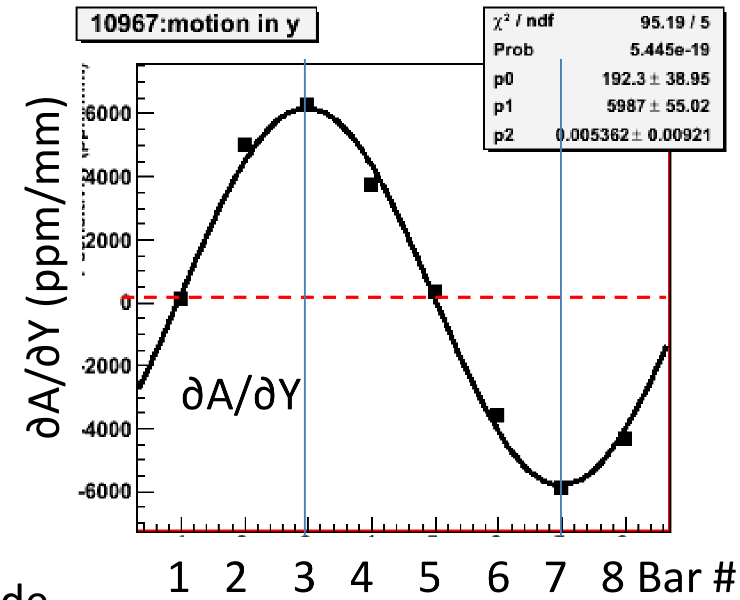
Helicity-Correlated Beam Parameter Sensitivities

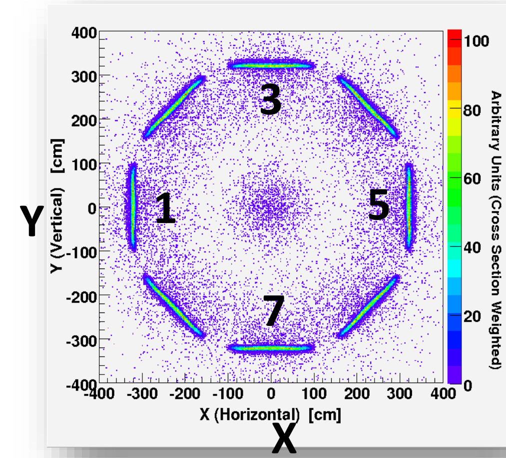
$A_{beam} = \sum_i \frac{\partial A}{\partial \chi_i} \Delta\chi_i$

where i runs over x,y,x'(angle),y'(angle), and energy.

Natural: Linear regression of natural beam motion

Driven: Drive sinusoidal beam oscillations with large amplitude





Avg gives net correction, suppressed by symmetry

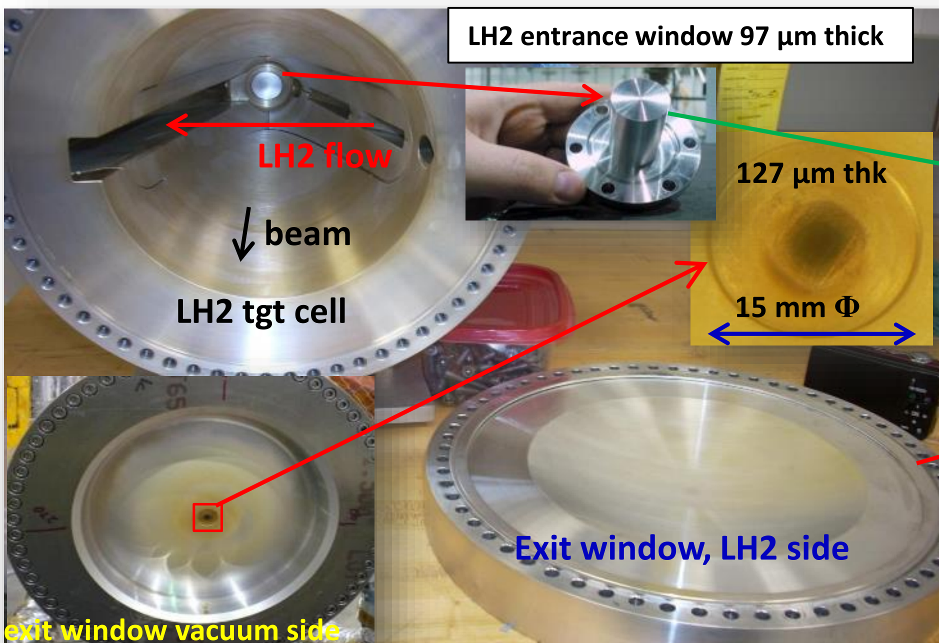
Beam Parameter	Run 1 $\Delta\chi_i$	Run 2 $\Delta\chi_i$	Typical $\partial A/\partial\chi_i$
X	-3.5 ± 0.1 nm	-2.3 ± 0.1 nm	-2 ppb/nm
X'	-0.30 ± 0.01 nrad	-0.07 ± 0.01 nrad	50 ppb/nrad
Y	-7.5 ± 0.1 nm	0.8 ± 0.1 nm	< 0.2 ppb/nm
Y'	-0.07 ± 0.01 nrad	-0.04 ± 0.01 nrad	< 3 ppb/nrad
Energy	-1.69 ± 0.01 ppb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

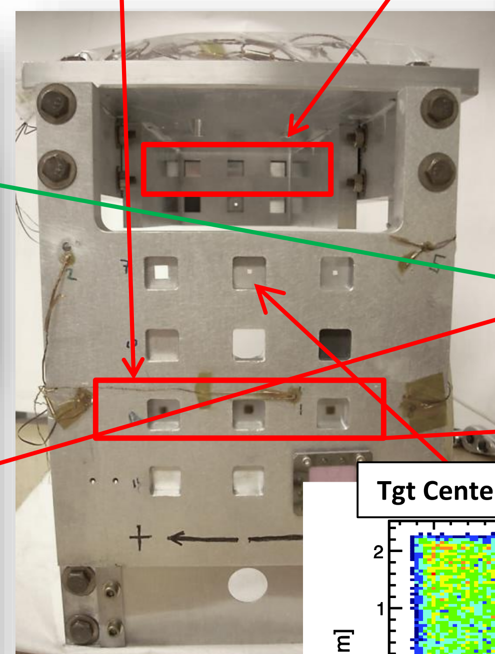
Run 1: $A_{\text{beam}} = 18.5 \pm 4.1$ppb Run 2: $A_{\text{beam}} = 0.0 \pm 1.1$ppb

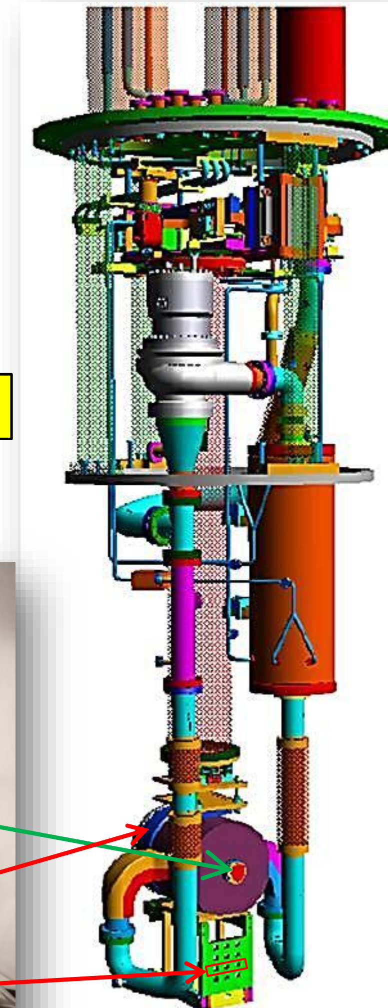
Aluminum (Target Window) Background

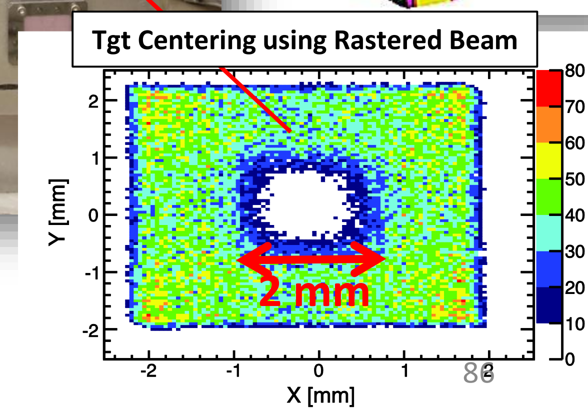
Dominant correction to the asymmetry: Bkg from e's that scatter from aluminum entrance and exit windows on hydrogen target

- **Dilution fraction (f_1):** Directly measured with empty target
- **Asymmetry (A_1):** Directly measured on thick "dummy" targets of identical alloy as LH2 target windows
- Corrections for effects of LH_2 made using simulation and data-driven models of elastic and quasi-elastic scattering







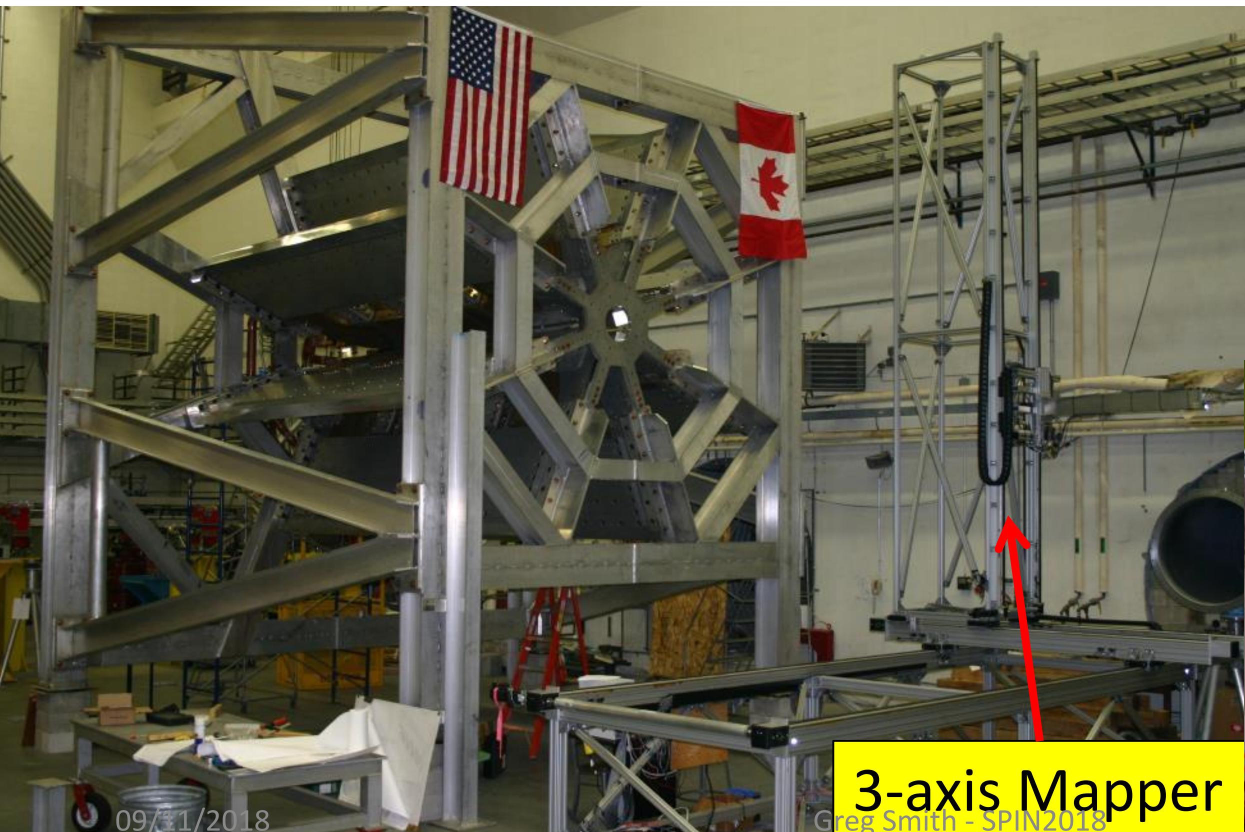


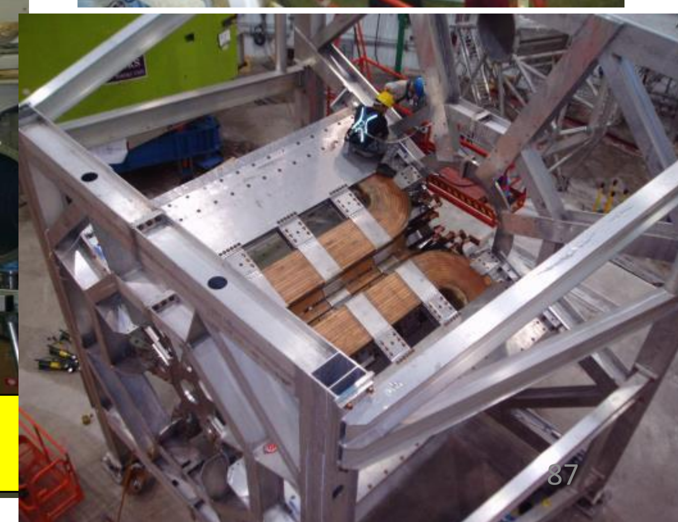
$f_1 = 2.52 \pm 0.06$ % $A_1 = 1517 \pm 77$ ppb
-38 ppb correction to msrd A_{ep} (~20%)

QTOR Magnet

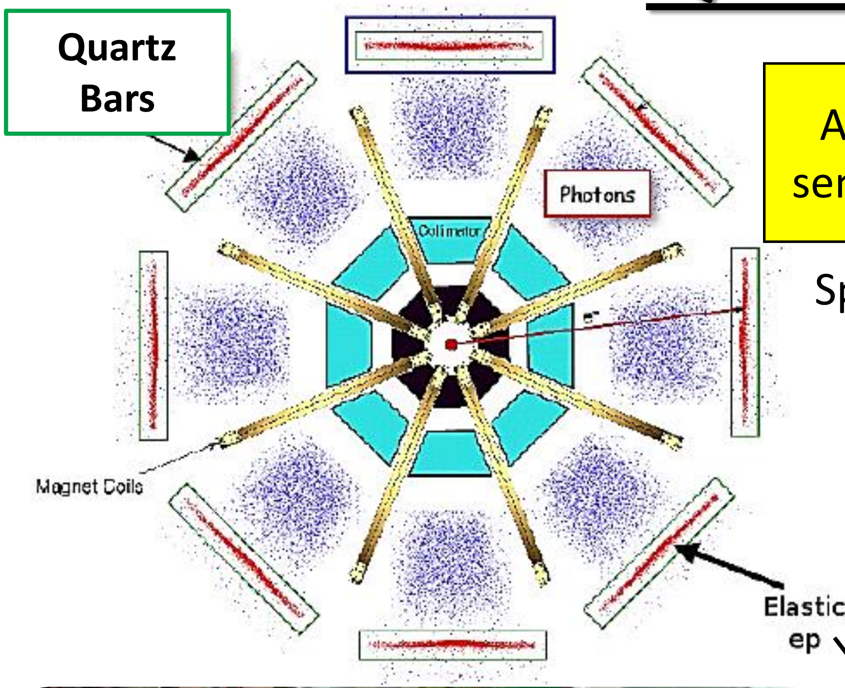
- Manitoba / TRIUMF / MIT-Bates / JLab
- Open geometry resistive toroid, for maximum solid angle acceptance
- Eight water cooled, dble pancake coils
- Separates elastics from inelastics at focus

Power Supply:
150 V, 9100 A
(1.4 MW)





Quartz Cerenkov Detectors

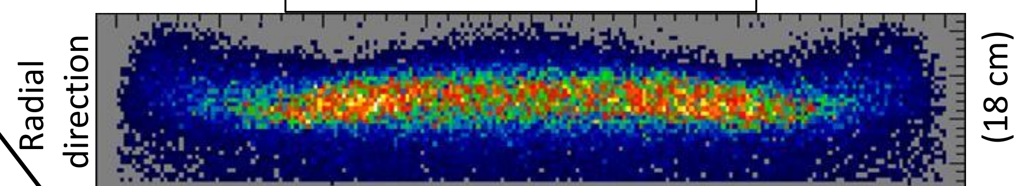


Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

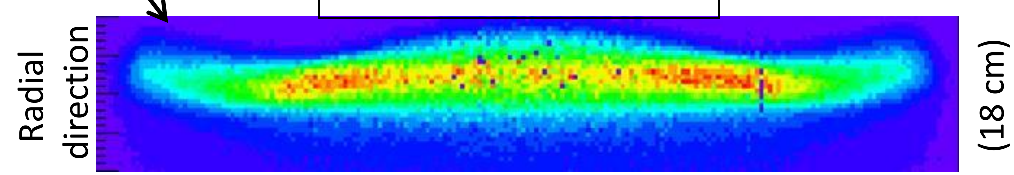
Spectrosil 2000 (fused silica) Cerenkov radiators:

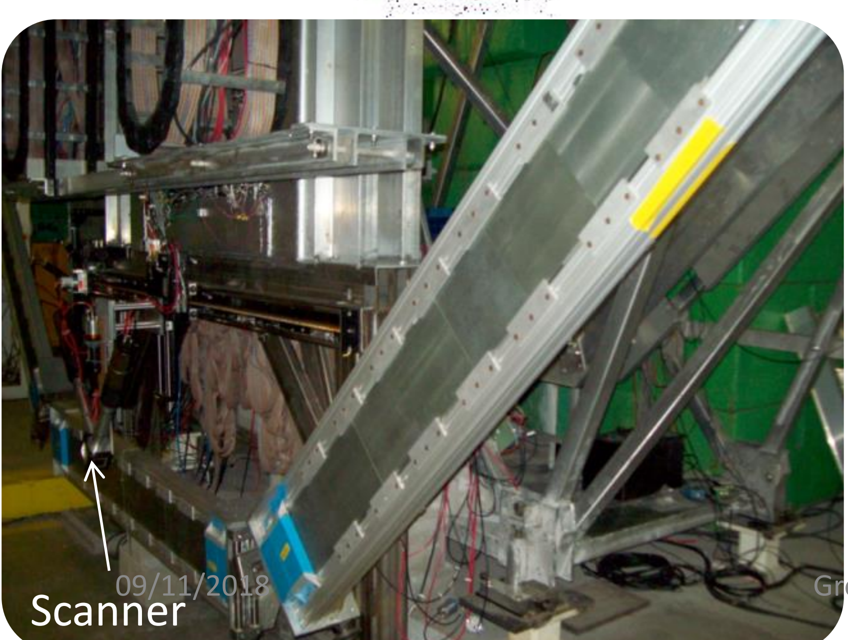
- Eight bars, each 2 m long, 18 cm hi, 1.25 cm thick
- Rad-hard. non-scintillating, low-luminescence

Simulation of MD face:



Measured



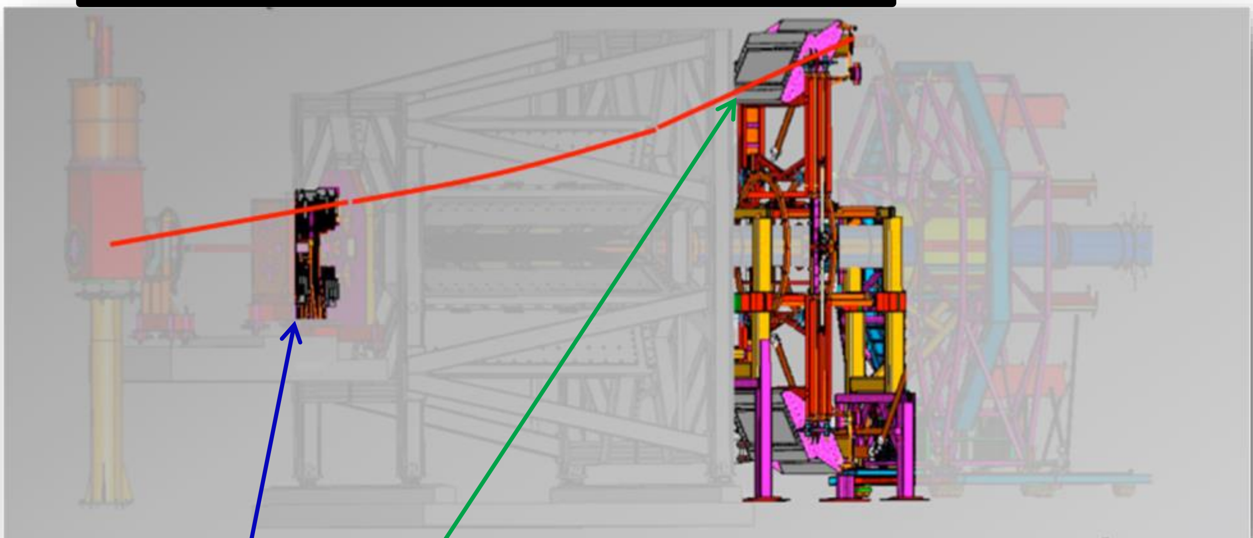


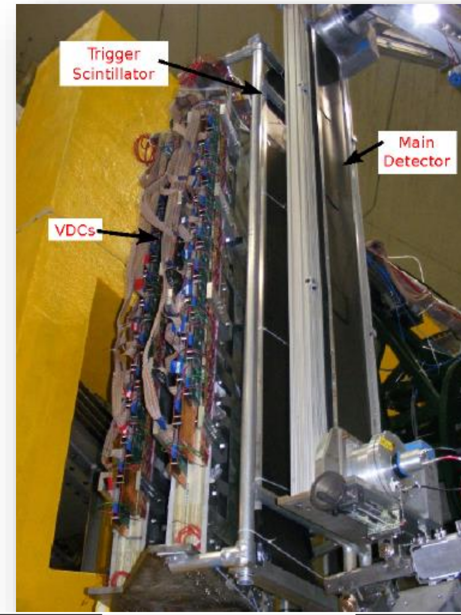
Yield 100 pe's/track with 2 cm Pb pre-radiators
Resolution (~10%) limited by shower fluctuations.

Determining the Kinematics

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

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





- HDCs before magnet to msr θ
  - $Q^2 = 2E^2(1-\cos\theta) / [1 + E/M(1-\cos\theta)]$
- VDCs & trigger scintillators after magnet to msr light weighted Q^2 across quartz bars

$Q^2 = 0.0249\ (\text{GeV}/c)^2$
$q = 0.80\ \text{fm}^{-1}$