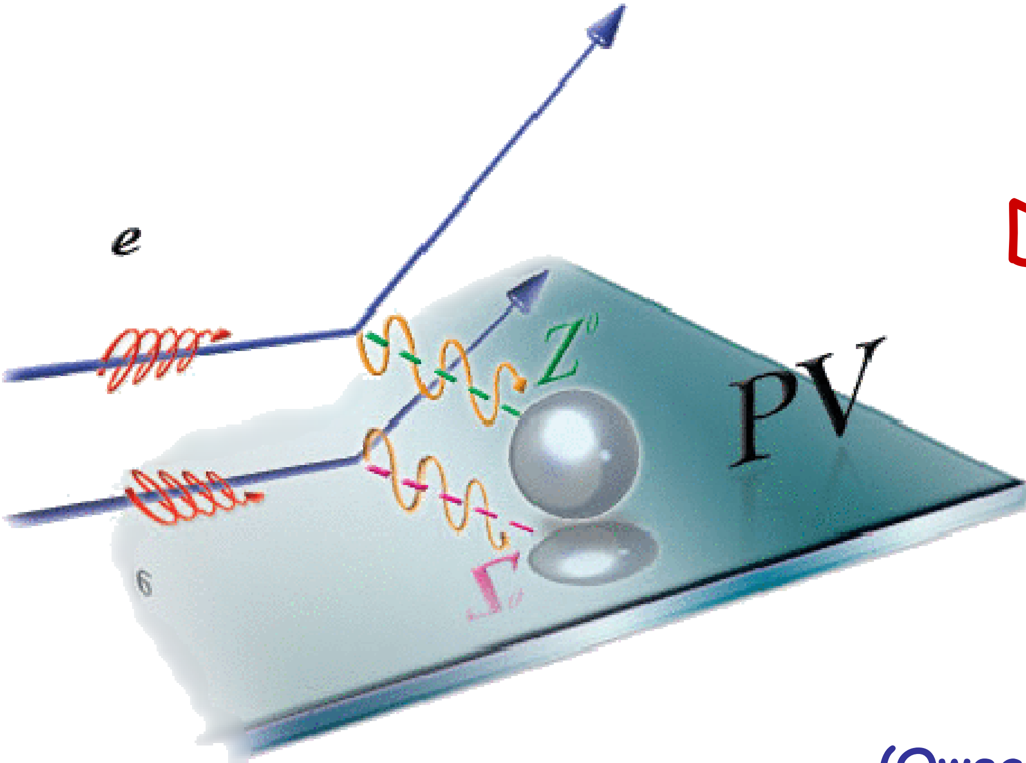
Testing Fundamental Symmetries with Parity-Violating Electron Scattering



David S. Armstrong

College of William & Mary

(Qweak, HAPPEX, G0 Collaborations)

APS April Meeting Denver May 3 2009

The College of WILLIAM & MARY

Jefferson Lab

Outline

- Precision tests of Standard Model
- Parity-violation in electron scattering
  - Early work: SLAC E122 *etc.*
  - Recent work: Strange form factors
- Weak Charges
- Physics Reach of Weak charge of proton
- Qweak experiment at JLab
- After Qweak
- Conclusions

Precision Tests of the Standard Model

- Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics*

- Finding new physics: Two complementary approaches:
  - Energy Frontier (direct) : *eg.* Tevatron, LHC
  - Precision Frontier (indirect) : *(aka Intensity Frontier)*

    eg.
    - $\mu(g-2)$, EDM, $\beta\beta$ decay, $\mu \rightarrow e\,\gamma$, $\mu A \rightarrow eA$, $K^+ \rightarrow \pi^+ \nu\nu$, *etc.*
    - *ν - oscillations*
    - *Atomic Parity violation*
    - *Parity-violating electron scattering*

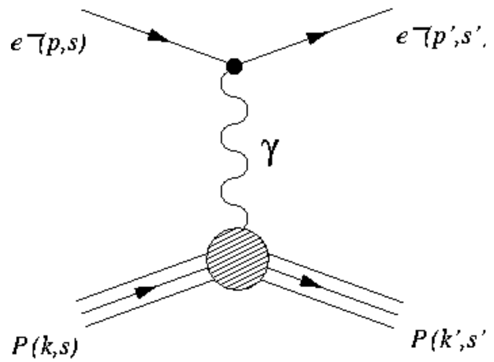
Often at modest or low energy…

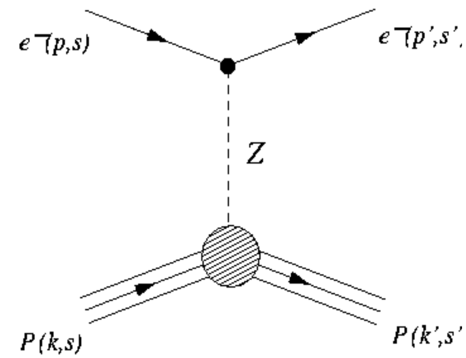
Hallmark of Precision Frontier:

choose observables that are *zero* or *suppressed* in Standard Model

When new physics found in direct measurements, precision measurements useful to determine e.g. couplings…

Parity Violating Electron Scattering:
Weak Neutral Current Amplitudes





$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \, \ell^\mu J_\mu^{EM} \qquad M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A \ell^{\mu 5} J_\mu^{NC} + g_V \ell^\mu J_{\mu 5}^{NC} \right]$$

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2Re(M^{EM*})M^{NC}$

scatter electrons of opposite helicities from unpolarized target

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_{PV}^{NC}|}{|M^{EM}|} \sim \frac{Q^2}{(M_Z)^2}$$

Tiny ($\sim 10^{-6}$) cross section asymmetry isolates weak interaction

First discussed: Ya. B Zel'dovich JETP **36** (1959)

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING ☆

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Received 14 July 1978

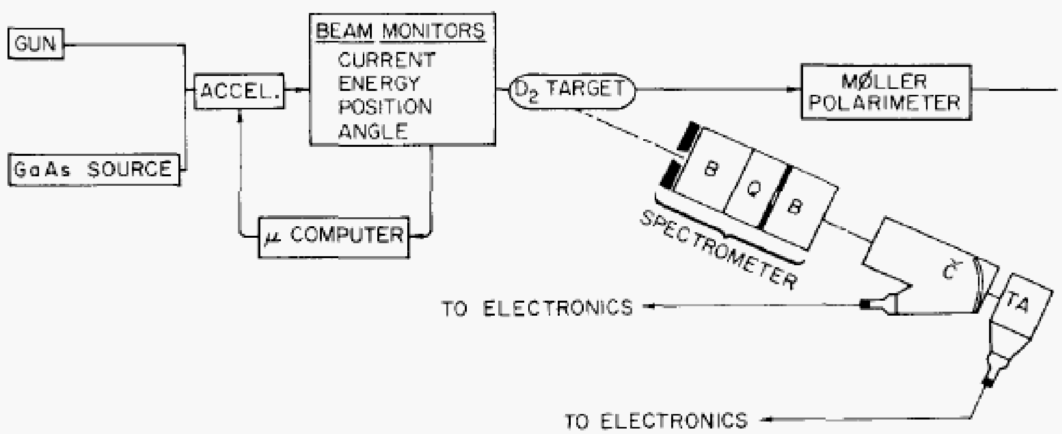
Phys. Lett. 77B (1978)

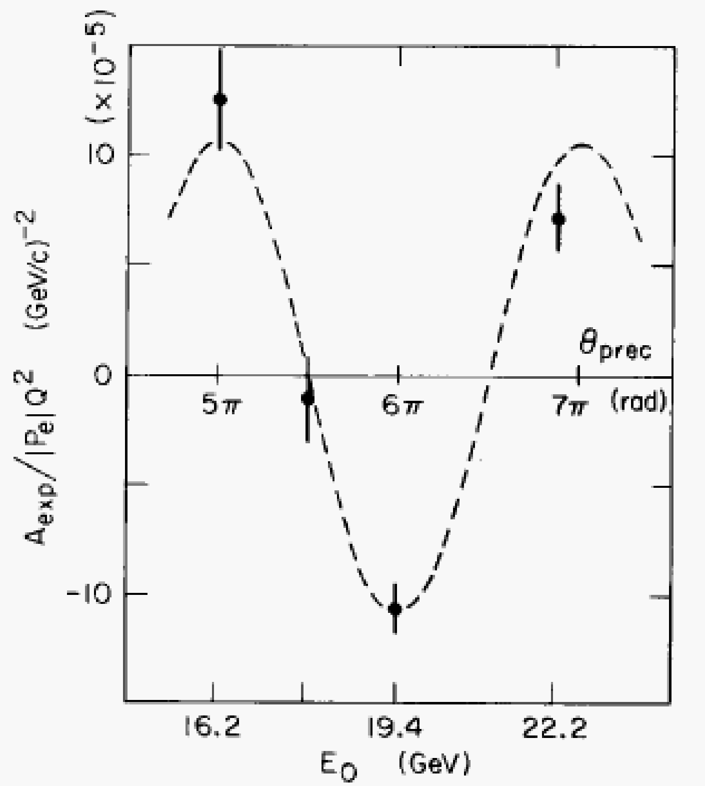
Pioneering Experiment

SLAC E122

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%.

Deep-inelastic scattering from isoscalar target





Textbook Physics: High Energy Physics (D.H. Perkins)

SLAC E122 *cont'd*

Also critical test of parton model

Techniques

Optically pumped electron source: rapid helicity reversal,

integrate scattered flux

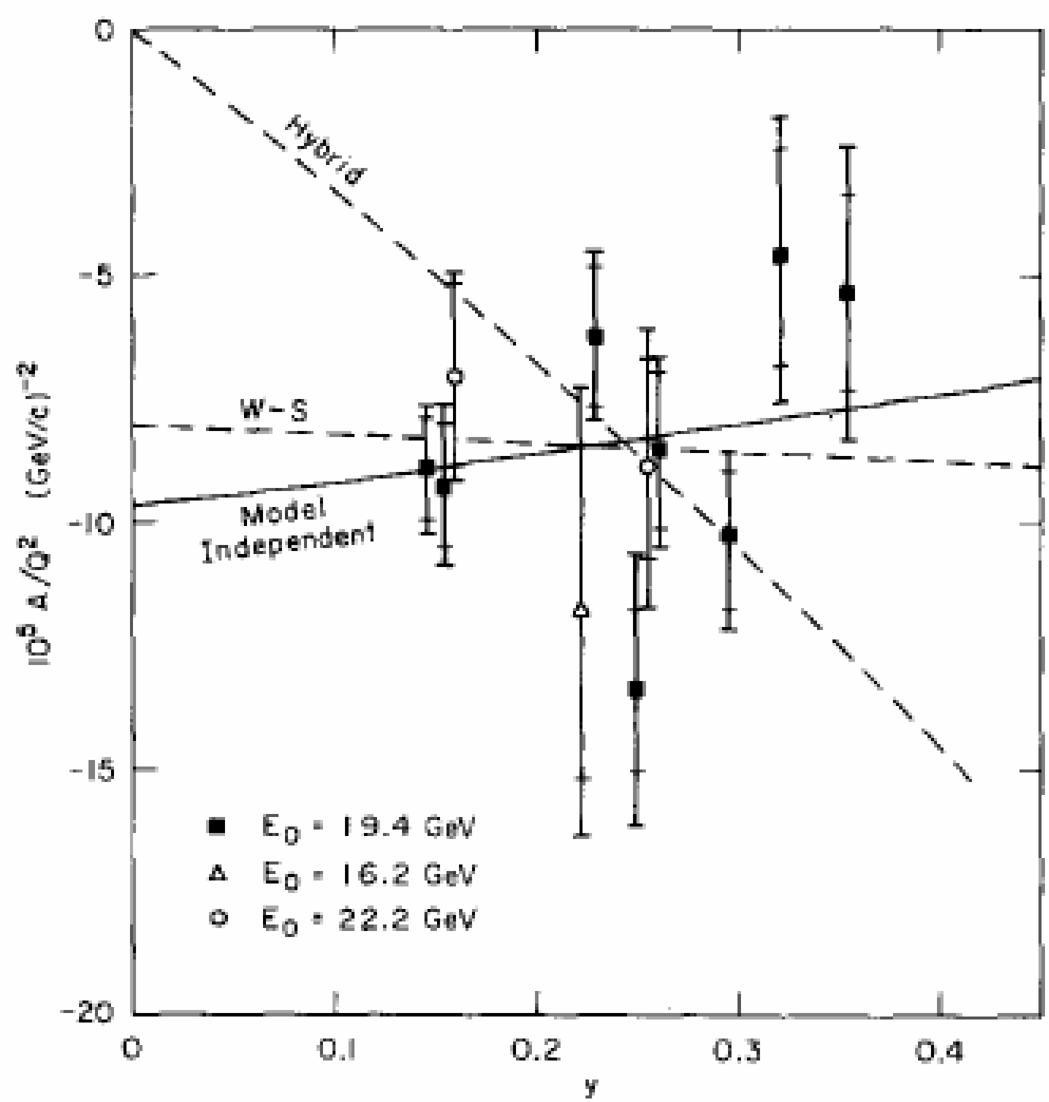
monitor & feedback to control electron beam fluctuations

Followed by:

1989: Mainz ^{9}Be
W. Heil et al.

1990: MIT/Bates ^{12}C
P.A. Souder et al.

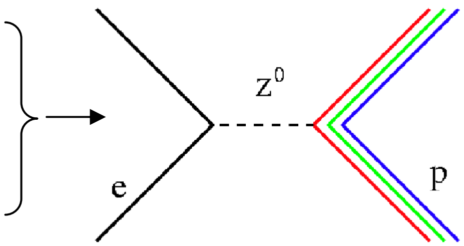
Pivotal to establishing Weinberg-Salam-Glashow SU(2)×U(1) gauge theory



Weak Charges

Govern strength of neutral current interaction with fermion

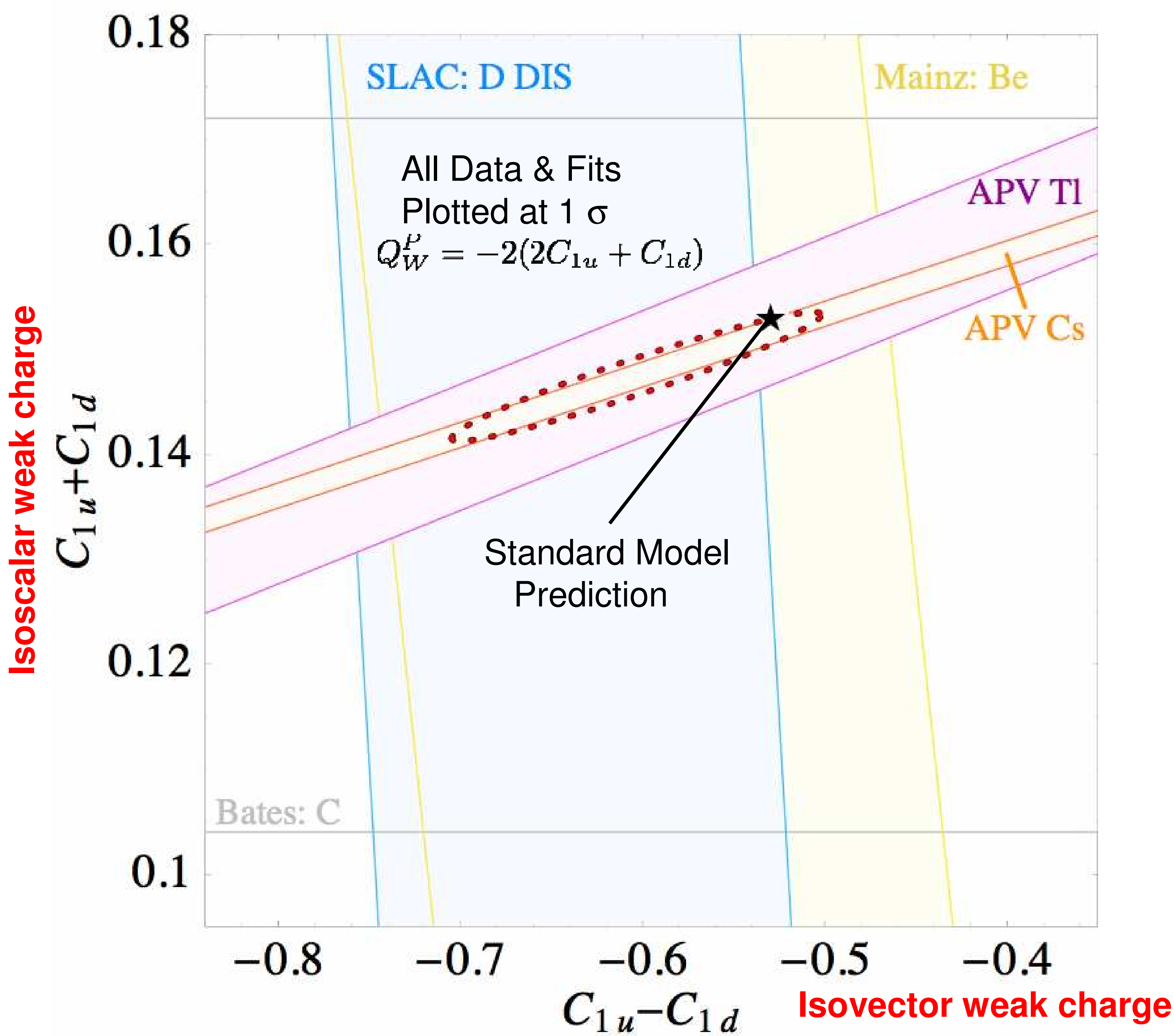
Charge / Particle	Electric	Weak (vector)
u	+2/3	$-2C_{1u} = +1 - 8/3 \sin^2\theta_W$
d	-1/3	$-2C_{1d} = -1 + 4/3 \sin^2\theta_W$
Proton uud	+1	$Q_w^p = 1 - 4 \sin^2\theta_W \approx 0.07$
Neutron udd	0	$Q_w^n = -1$



Note "accidental" suppression of Q_w^p

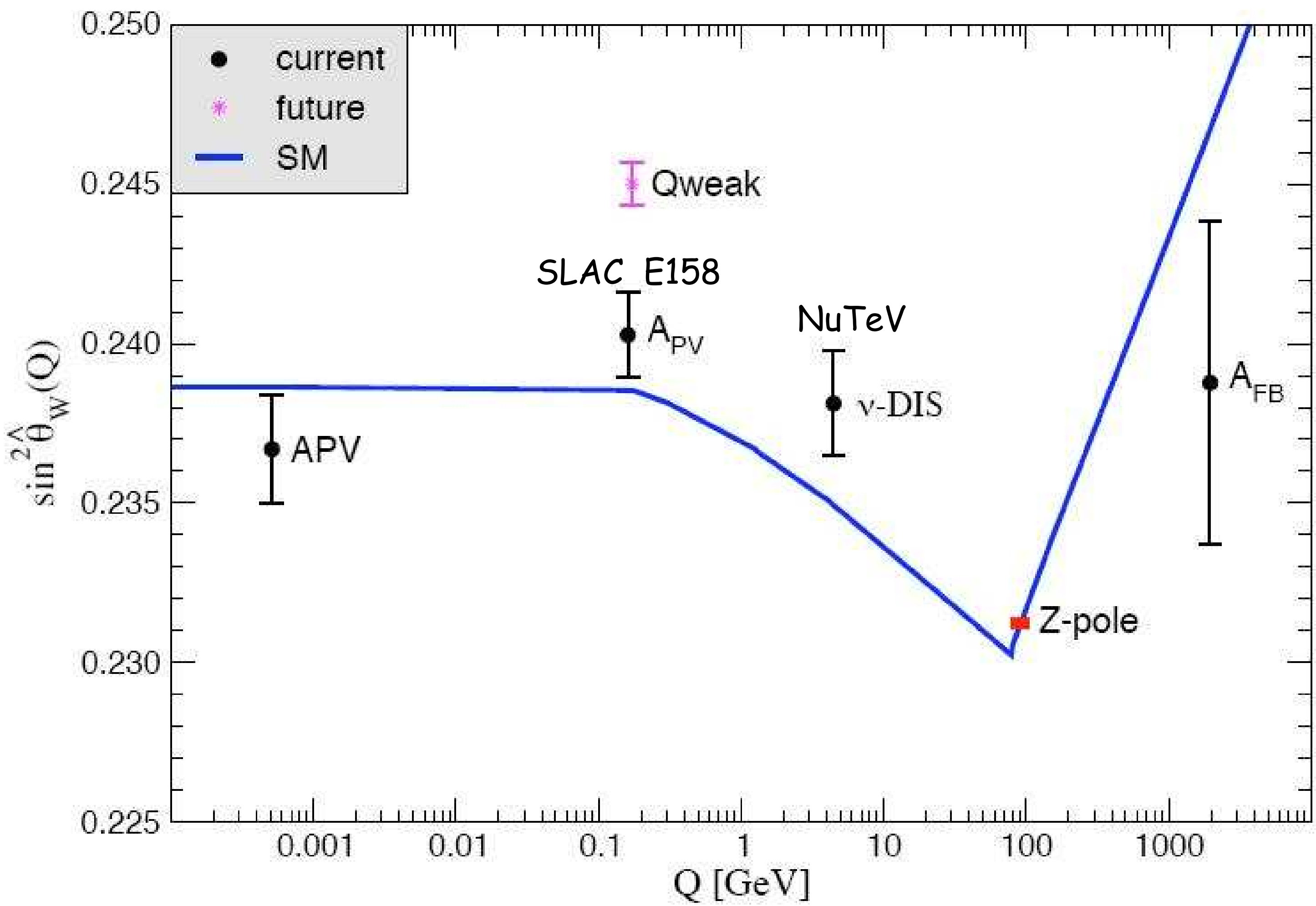
$\rightarrow$ *sensitivity to new physics*

For axial couplings: C_{2u} and C_{2d}



0.18
0.16
0.14
0.12
0.1
−0.8
−0.7
−0.6
−0.5
−0.4
SLAC: D DIS
Mainz: Be
All Data & Fits
Plotted at 1 σ
$Q_W^p = -2(2C_{1u} + C_{1d})$
APV Tl
APV Cs
Standard Model
Prediction
Bates: C
$C_{1u}+C_{1d}$
Isoscalar weak charge
$C_{1u}-C_{1d}$
Isovector weak charge

Running of $\sin^2\theta_W$



PDG 2008 Review: "Electroweak and constraints on New Physics Model"
J. Erler & P. Langacker

Running of $\sin^2\theta_W$: recent developments

1) Atomic Parity Violation (^{133}Cs): W.G. Porsev, K. Beloy, A. Derevianko
arXiv:0902.00335 hep-ph Feb 2009

New calculation of many-body atomic theory (up to triple excitations)
in $6S_{1/2} \rightarrow 7S_{1/2}$ transition (100 Gb basis set)

$Q_W(^{133}Cs)^{exp}$: $-73.25 \pm 0.29 \pm 0.20$

$Q_W(^{133}Cs)^{SM}$: -73.16 ± 0.03

2) NuTeV anomaly: originally quoted 3σ violation of Standard Model

- Erler & Langacker include corrections due to asymmetry in strange quark PDFs (from NuTeV and CTEQ)
- Charge Symmetry violations (*eg* Londergan & Thomas PL B 558(2003)132)
  (u/d quark mass difference) account for 1σ
- I.C. Cloet, W. Bentz, A.W. Thomas arXiv:0901.3359 nucl-th Jan 2009

$\rightarrow$ vector mean fields in nucleus modifies in-medium PDFs

claims entire anomaly accounted for

Weak Charges from Existing PVES experiments

A "strange" digression..

- recent program of elastic (quasi-elastic) parity-violation experiments measuring strange quark contributions to nucleon vector form factors…

Parity-violating asymmetry sensitive to both weak charges *and* to hadron structure

recall Kent Paschke's plenary talk Saturday AM

Hadron Structure effects

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1 - 4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \tilde{G}_A^p}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Axial form factor

assume charge symmetry:

$$4G_{E,M}^{pZ} = \underbrace{(1 - 4\sin^2\theta_W)}_{\text{Proton weak charge (tree level)}} G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - \underbrace{G_{E,M}^{s}}_{\text{Strangeness}}$$

Proton weak charge
charge
(tree level)

Strangeness

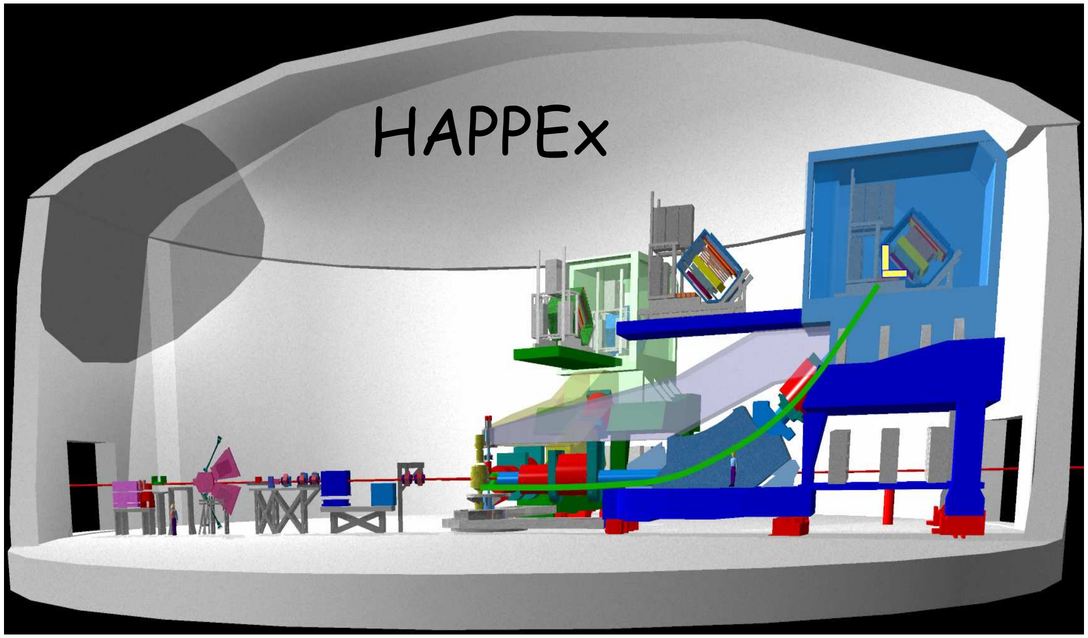
Strange form factor program

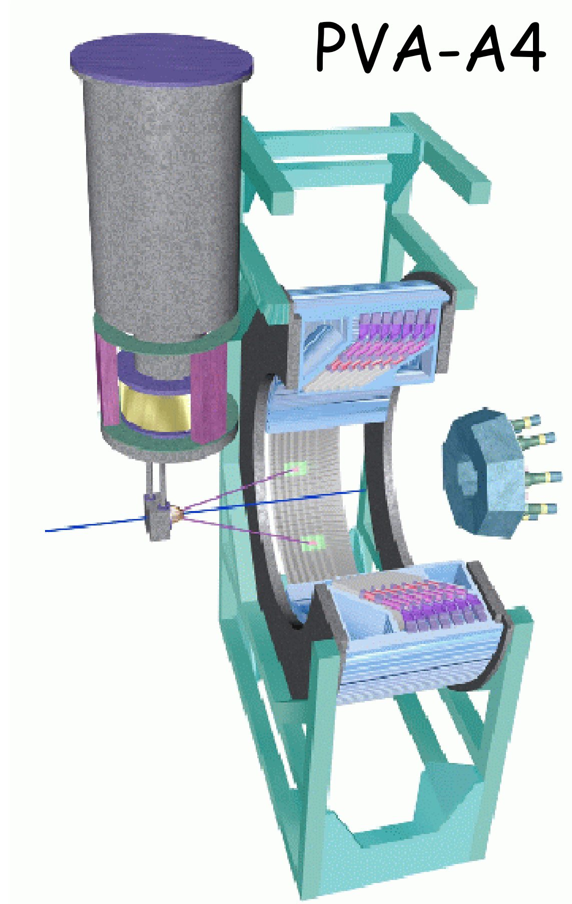
time

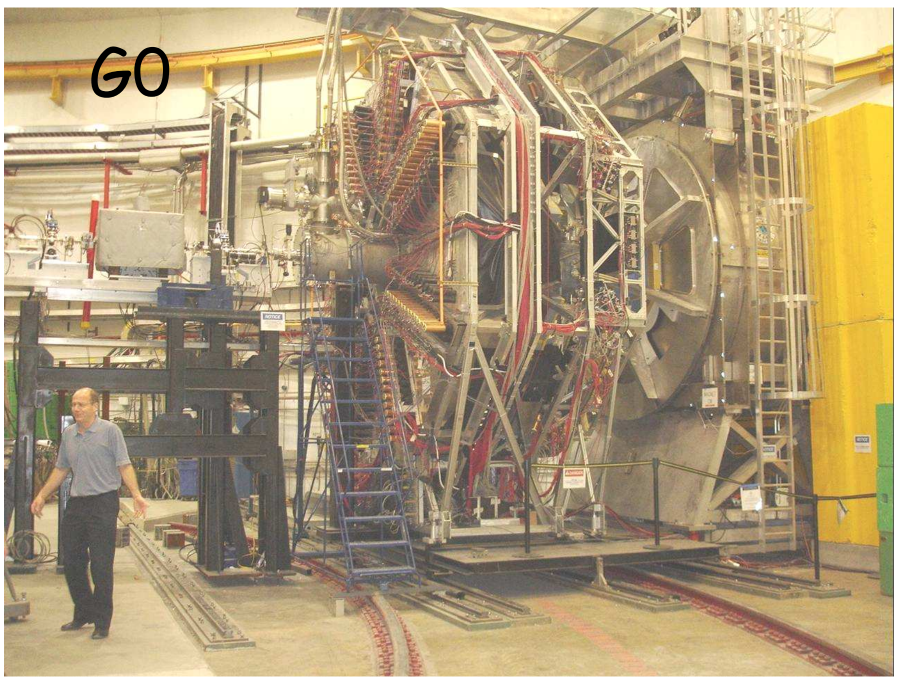
- SAMPLE (MIT/Bates) $Q^2 = 0.1$
- HAPPEx-I (JLab/HallA) $Q^2 = 0.48$
- PV-A4 (MAMI) $Q^2 = 0.23, 0.11$
- G0 (JLab/Hall C) $Q^2 = 0.12 \rightarrow 1.0$
- HAPPEx-II/helium (JLab/Hall A) $Q^2 \approx 0.1$
- PV-A4 (backward) $Q^2 = 0.22$ PRL 102, 151803 (2009)

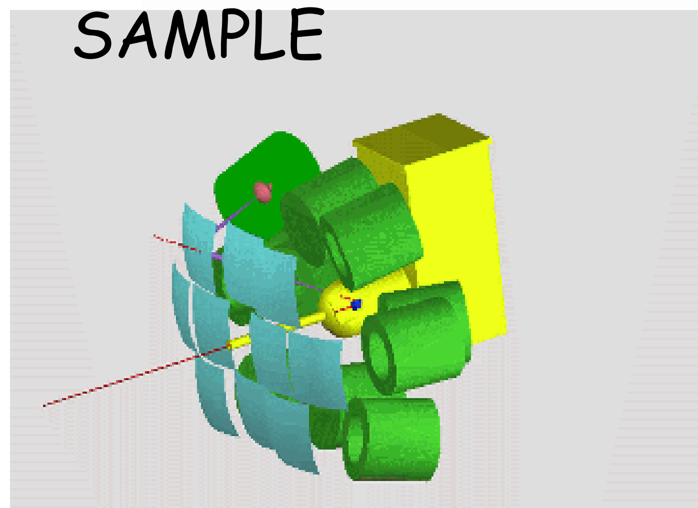
- G0 (backward) $Q^2 = 0.23, 0.63$ (completed)*
- HAPPEx-III (forward) $Q^2 = 0.63$ (Aug-Oct 2009)

*analysis recently unblinded; results to be released May 20


HAPPEx


PVA-A4


G0


SAMPLE

Proton Strange form factors: a snapshot

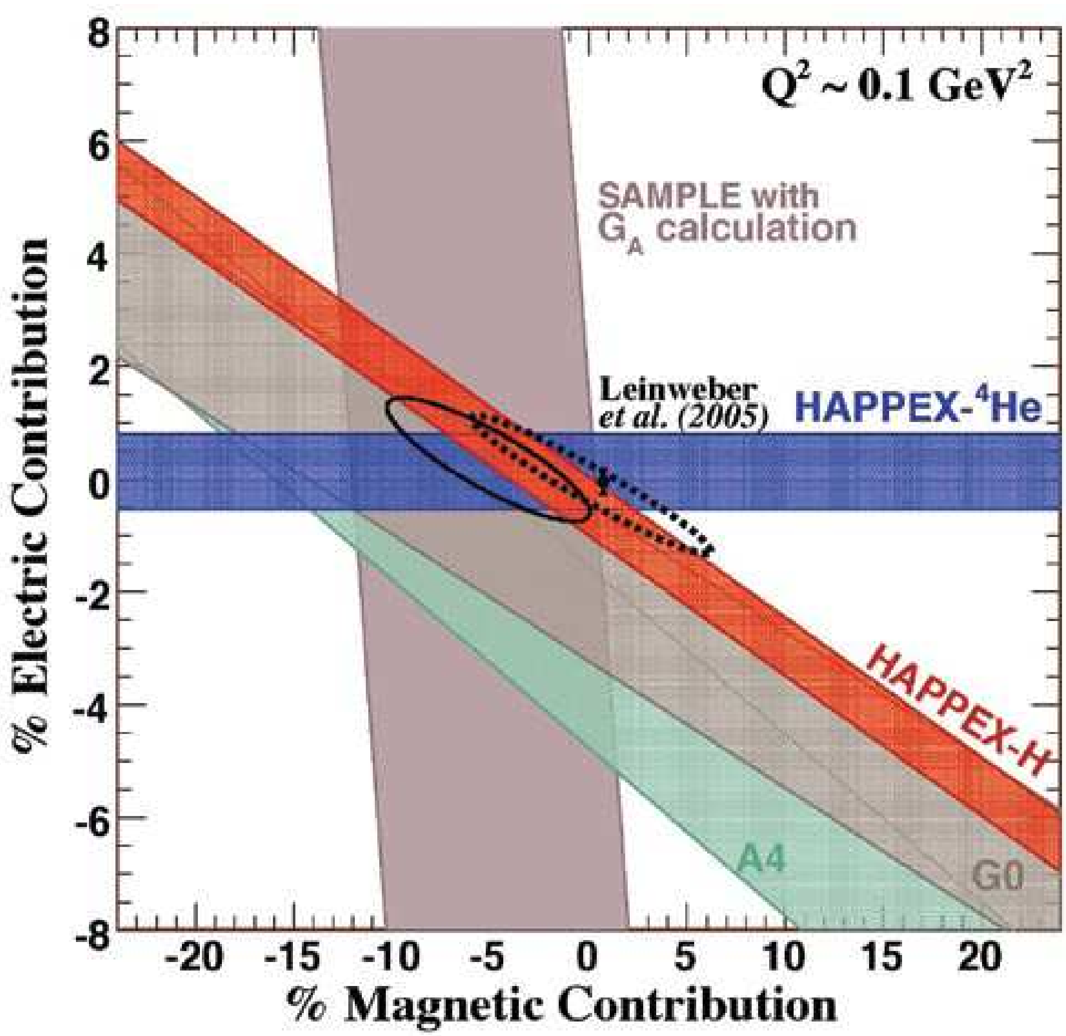


Figure appeared in NSAC 2007 Long Range plan

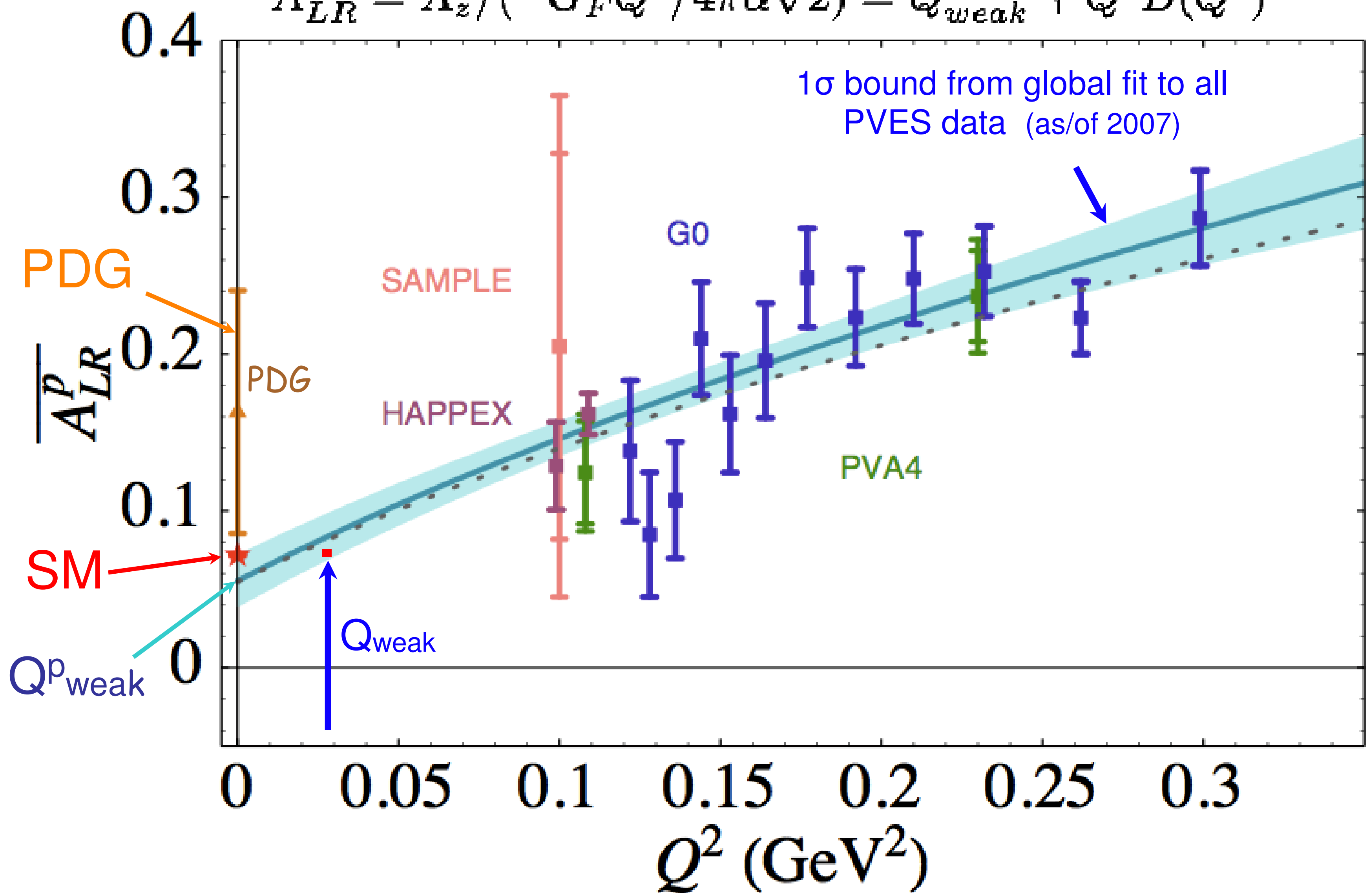
Marvelous consistency of difficult experiments!

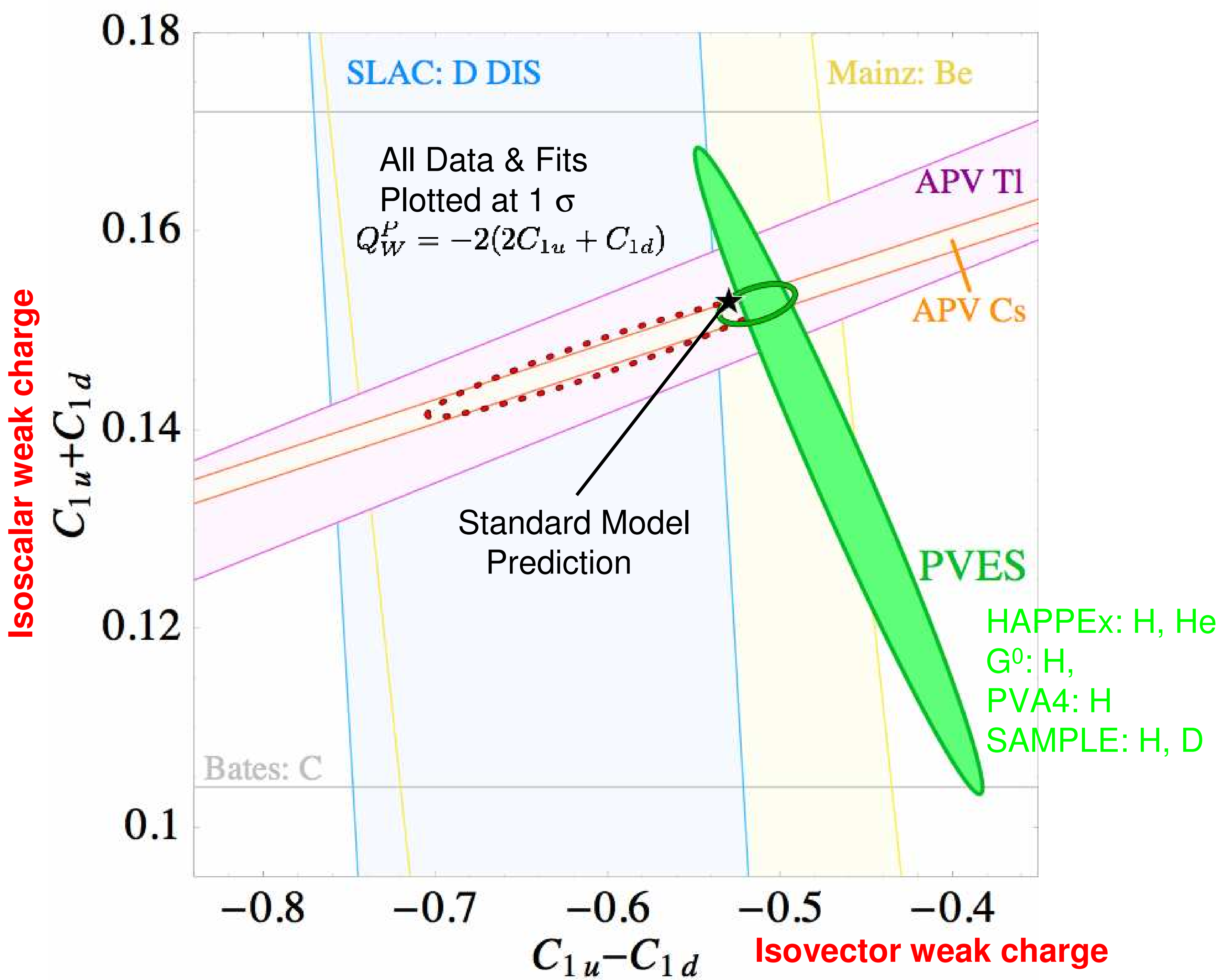
What about weak charge?

Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(R.D. Young et al. PRL 99, 122003 (2007))

$$A^p_{LR} = A_z/(-G_F Q^2/4\pi\alpha\sqrt{2}) = Q^p_{weak} + Q^2 B(Q^2)$$





SLAC: D DIS
Mainz: Be
All Data & Fits
Plotted at 1 σ
$Q_W^p = -2(2C_{1u} + C_{1d})$
APV Tl
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Standard Model
Prediction
PVES
HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D
Bates: C
0.18
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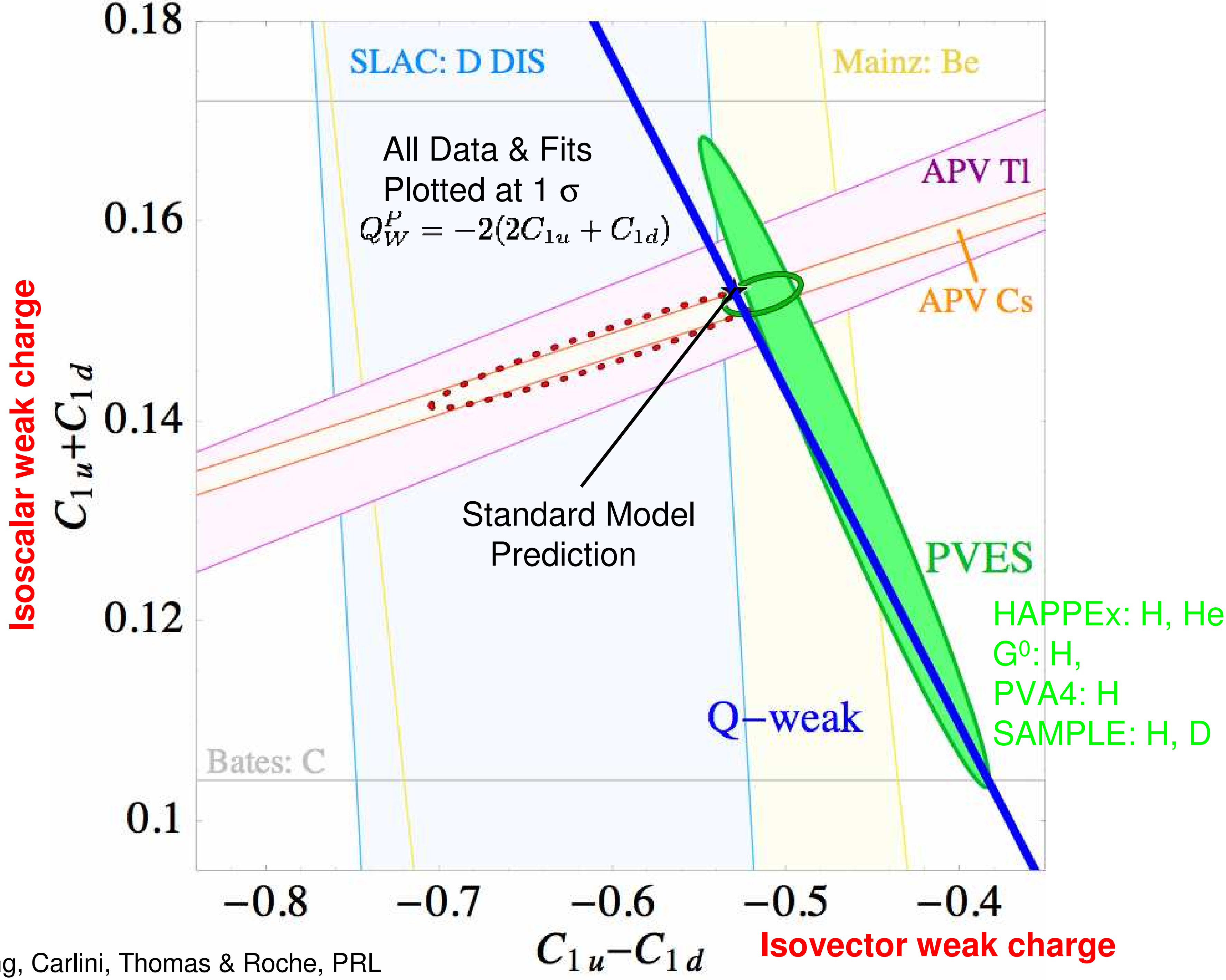
$C_{1u}+C_{1d}$
Isoscalar weak charge
$C_{1u}-C_{1d}$
Isovector weak charge



Young, Carlini, Thomas & Roche, PRL

Energy Scale of an Indirect Search

- Estimate sensitivity to new physics Mass/Coupling ratio
  $\rightarrow$ add new contact term to the electron-quark Lagrangian:

Erler et al. PRD 68, 016006 (2003)

$$
\begin{aligned}
\mathcal{L}_{e-q}^{PV} &= \mathcal{L}_{SM}^{PV} + \mathcal{L}_{New}^{PV} \\
&= -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q
\end{aligned}
$$

Λ = mass g = coupling

$$\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}}$$

TeV scale can be reached with a 4% Qweak experiment.
If Qweak didn't happen to be suppressed, would have to do a 0.4% measurement to reach the TeV-scale.

New Physics Reach

Erler et al., PRD68(2003)

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

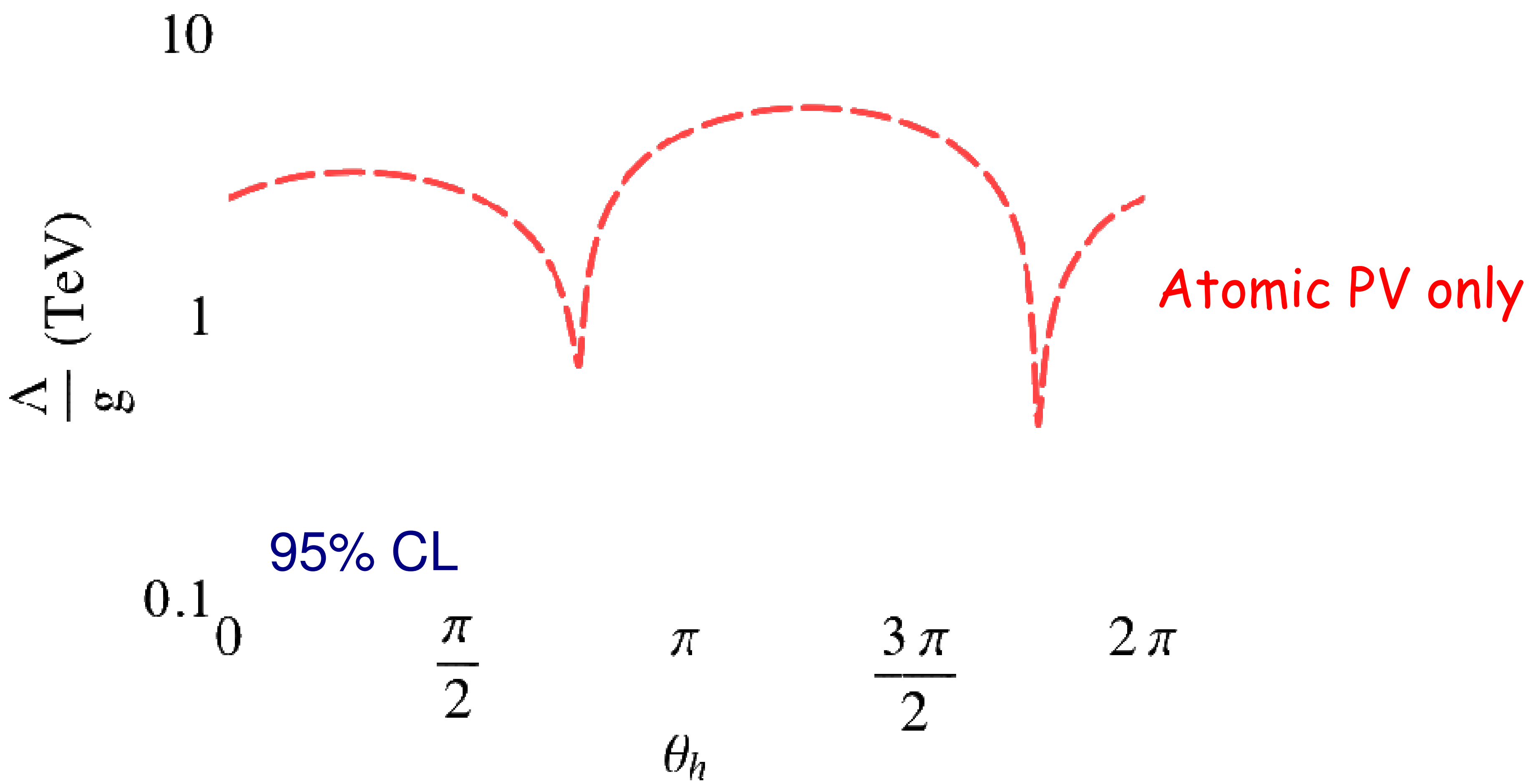
$$\mathcal{L}_{\rm NP}^{\rm PV} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\bar{q}\gamma^\mu q$$

Arbitrary quark flavour dependence of new physics:

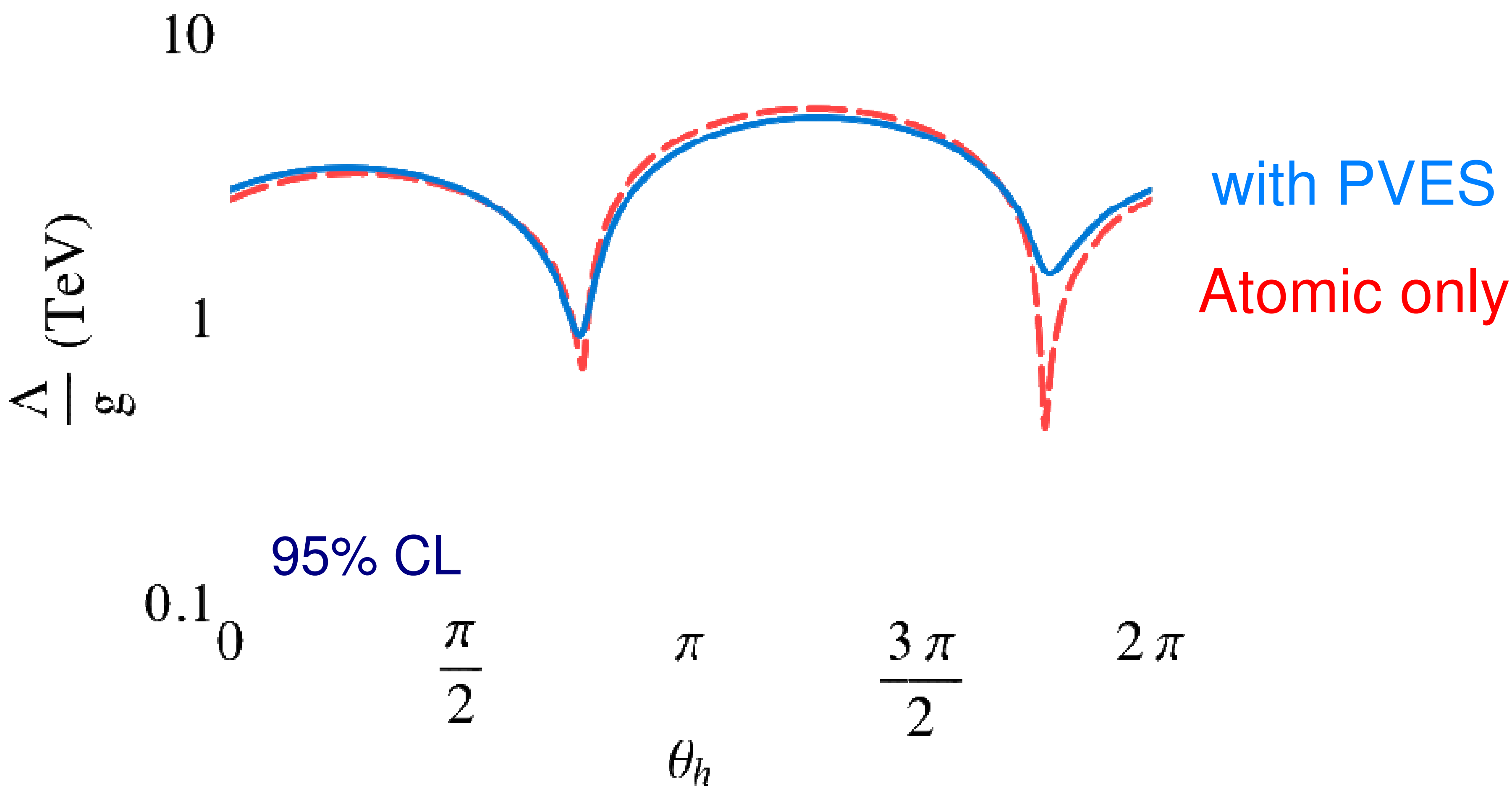
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

Data sets limits on: $\dfrac{g^2}{\Lambda^2}$

Lower Bound for "Parity Violating" New Physics

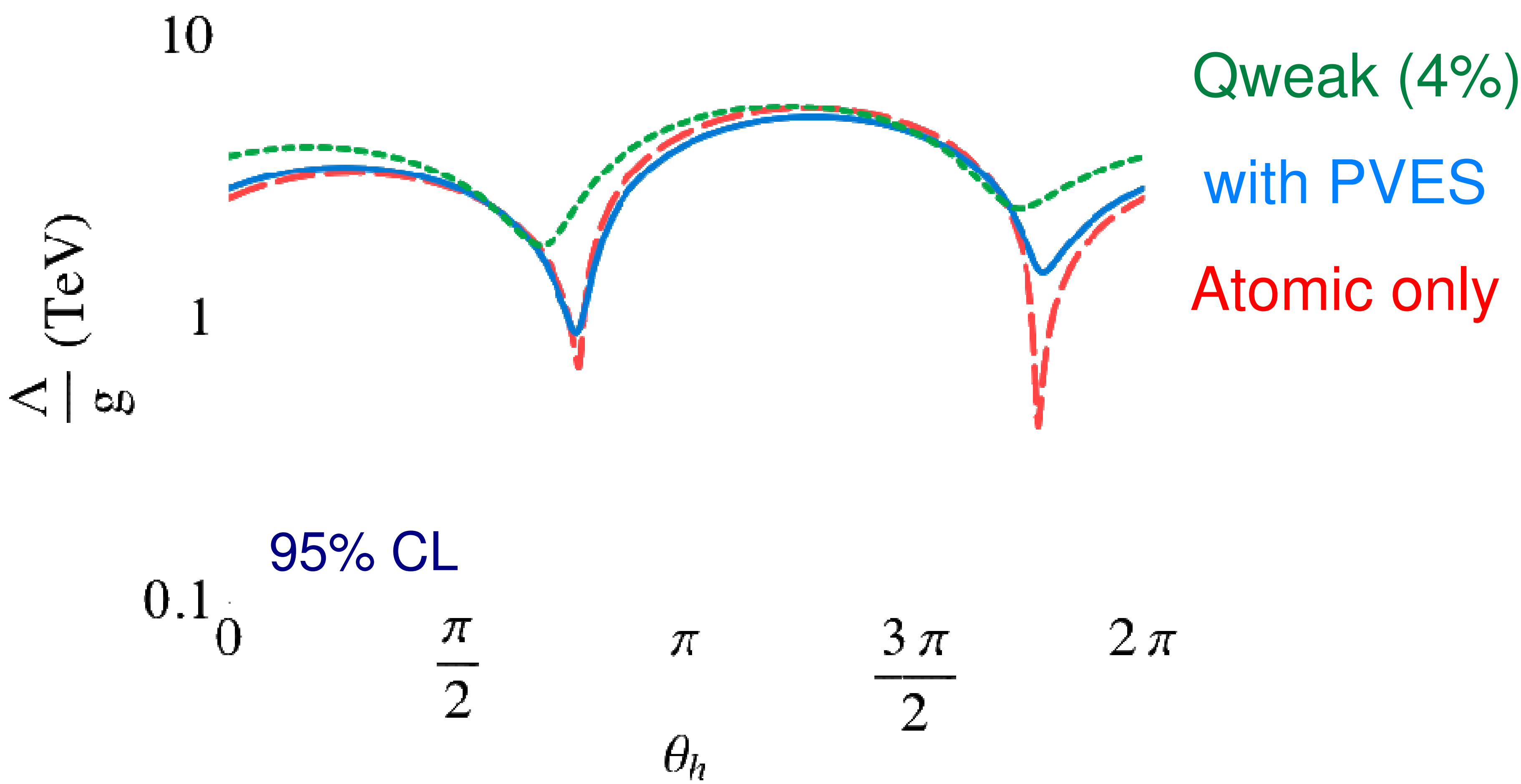


Lower Bound for "Parity Violating" New Physics



New PV physics scale > 0.9 TeV! (from 0.4 TeV)

Lower Bound for "Parity Violating" New Physics



Qweak constrains new PV physics to beyond 2 TeV

Analysis by R.D.Young et al.

New Physics: Examples

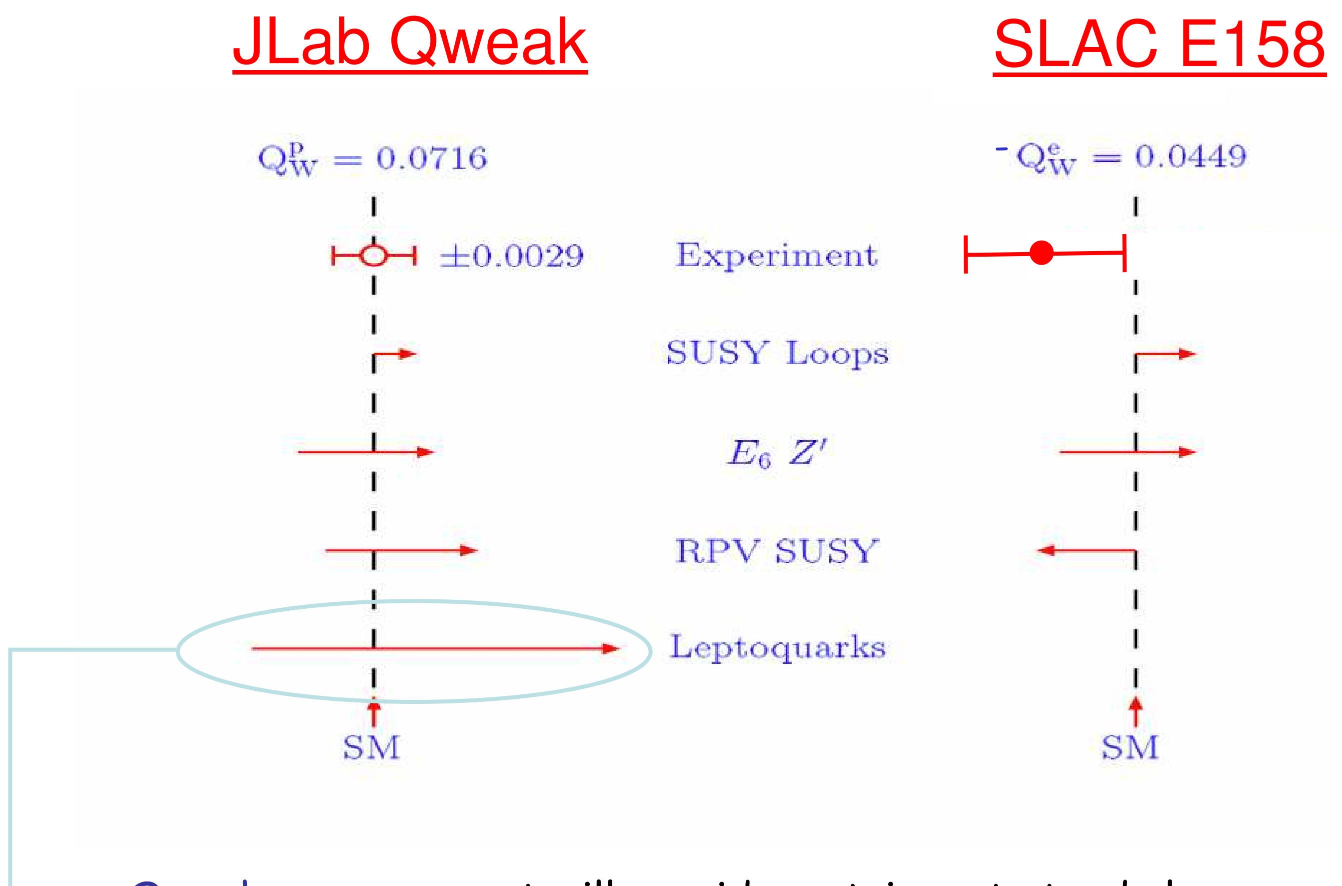
- Extra neutral gauge bosons: Z' *eg.* *E6* $\rightarrow SO(10)\times U(1)\psi$ GUT,
  SUSY, left/right symmetric models, technicolor,
  string theories…
- Composite fermions
- Leptoquarks (scalar LQs can arise in R-parity violating SUSY)

M.J. Ramsey-Musolf PRC 60(1999)015501; PRD62(2000)056009

J. Erler, A. Kurylov, M.J. Ramsey-Musolf PRD 68(2003)016006

Direct search at Tevatron : $M_{Z'\psi} > 0.82$ TeV
CDF PRL 99 (2007)171802

Complementarity of proton & electron weak charge



- Qweak measurement will provide a stringent stand alone constraint on Leptoquark based extensions to the SM.
- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

Electroweak Global Fit

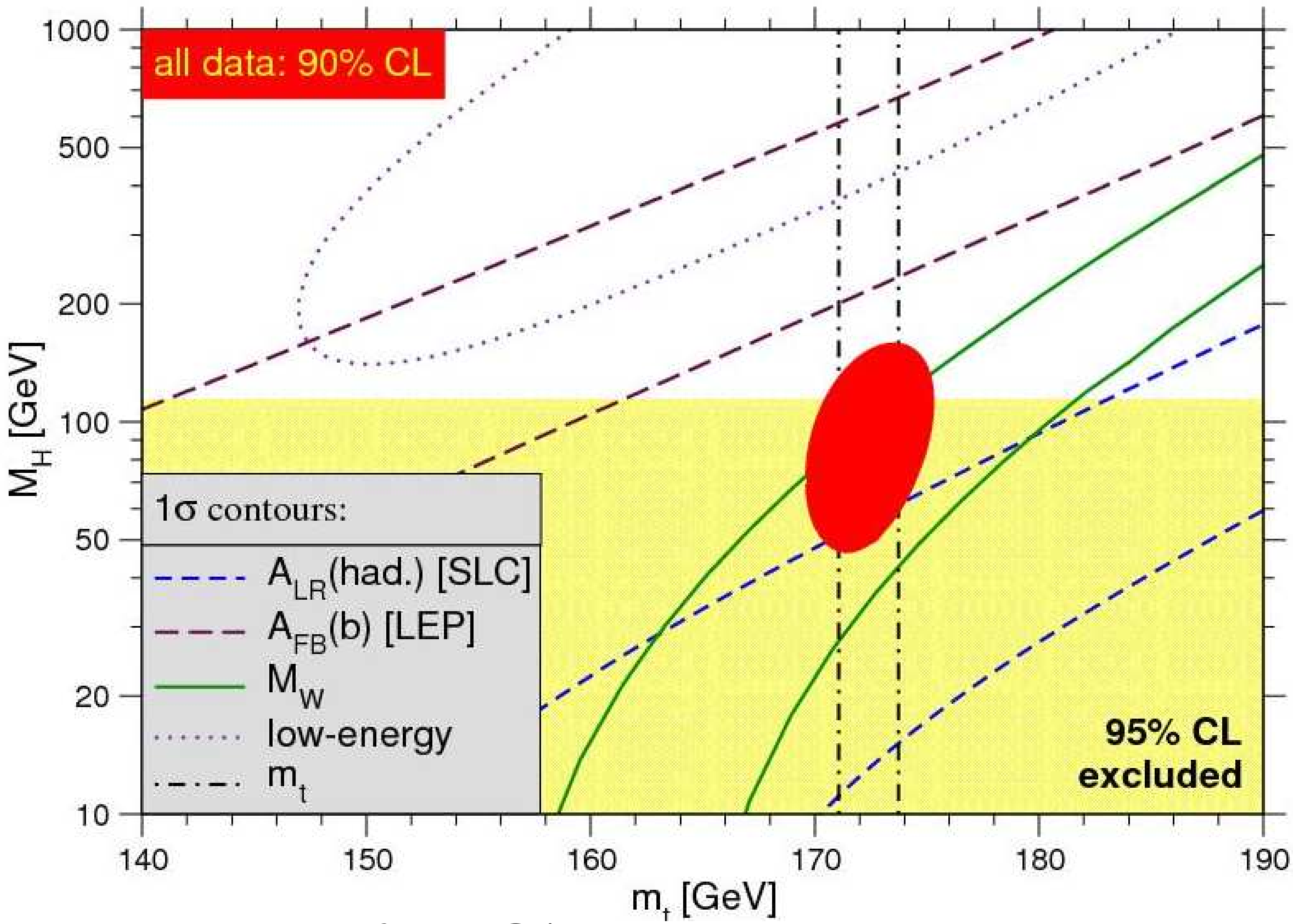


Figure courtesy of Jens Erler

The QWeak Collaboration

D.S. Armstrong, A. Asaturyan, T. Averett, J. Benesch, J. Birchall, P. Bosted, A. Bruell, C. Capuano, **R. D. Carlini[1]** ,G. Cates, C. Carrigee, S. Chattopadhyay, S. Covrig, C. A. Davis, K. Dow, J. Dunne, D. Dutta, R. Ent, J. Erler, W. Falk, H. Fenker, J.M. Finn, T. A. Forest, W. Franklin, D. Gaskell, M. Gericke, J. Grames, K. Grimm, F.W. Hersman, D. Higinbotham, M. Holtrop, J.R. Hoskins, K. Johnston, E. Ihloff, M. Jones, R. Jones, K. Joo, J. Kelsey, C. Keppel, M. Khol, P. King, E. Korkmaz, **S. Kowalski[1]**, J. Leacock, J.P. Leckey, L. Lee, A. Lung, D. Mack, S. Majewski, J. Mammei, J. Martin, D. Meekins, A. Micherdzinska, A. Mkrtchyan, H. Mkrtchyan, N. Morgan, K. E. Myers, A. Narayan, A. K. Opper, **S.A. Page[1]**, J. Pan, K. Paschke, M. Pitt, M. Poelker, T. Porcelli, Y. Prok, W. D. Ramsay, M. Ramsey-Musolf, J. Roche, N. Simicevic, **G. Smith[2]**, T. Smith, P. Souder, D. Spayde, B. E. Stokes, R. Suleiman, V. Tadevosyan, E. Tsentalovich, W.T.H. van Oers, W. Vulcan, P. Wang, S. Wells, S. A. Wood, S. Yang, R. Young, H. Zhu, C. Zorn

[1]Spokespersons
[2]Project Manager

College of William and Mary, University of Connecticut, Instituto de Fisica, Universidad Nacional Autonoma de Mexico, University of Wisconsin, Hendrix College, Louisiana Tech University, University of Manitoba, Massachusetts Institute of Technology, Thomas Jefferson National Accelerator Facility, Virginia Polytechnic Institute & State University, TRIUMF, University of New Hampshire, Yerevan Physics Institute, Mississippi State University, University of Northern British Columbia, Ohio University, Hampton University, University of Winnipeg, University of Virginia, George Washington University, Syracuse University, Idaho State University, University of Connecticut, Christopher Newport University

QWeak Experiment Overview

- Forward-angle elastic scattering 1.16 GeV e's from proton at 8°

  $Q^2 = 0.026\ (GeV/c)^2$

  Hall C at Jefferson Lab
- Expected Asymmetry: 234 parts per billion
- Capitalize on success/techniques of PV program
- Installation begins November 2009
- Runs June 2010 to May 2012
  - Final expt. in Hall C before 12 GeV upgrade

Some Challenges:

- 6.5 GHz rate – rad-hard detectors *(see D. Mack's talk - J10 5)*
- 2.5 kW cryogenic lH_2 target *(see S. Covrig's talk - J10 6)*
- Helicity-correlated beam properties:

  intensity <0.1 ppm position <2 nm angle < 30 nrad

  diameter <0.7 μm energy $\Delta E/E < 10^{-9}$
- 1% precision on electron beam polarization

Error Budget

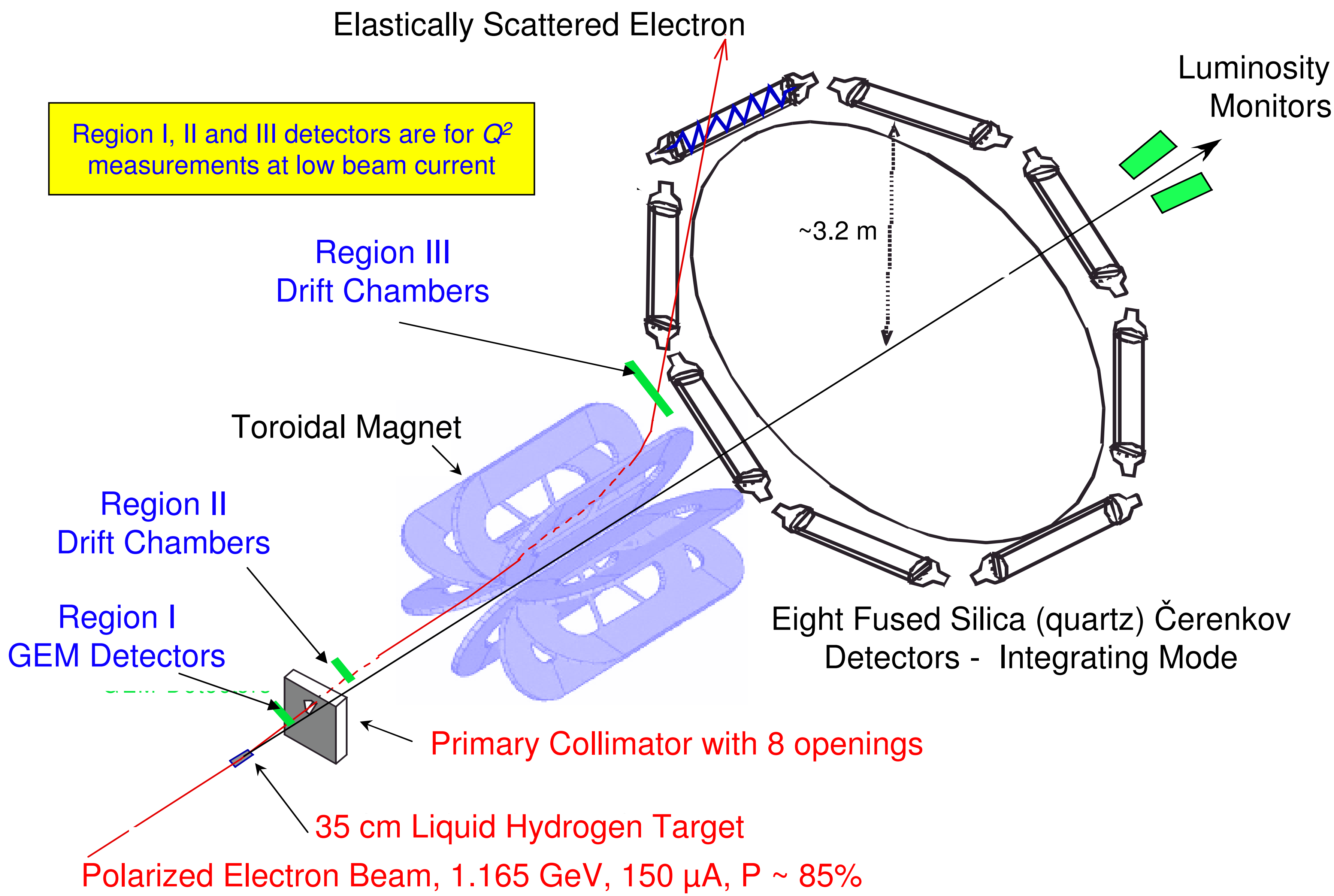
2% on A_{PV} $\approx$ 4% on Q_w $\approx$ 0.3% on $sin^2\theta_W$

Uncertainty	$\Delta A_{PV}/A_{PV}$	$\Delta Q_w/Q_w$
Statistical (2,544 hours at 180 μA)	2.1%	3.2%
Systematic:		2.6%
Hadronic structure uncertainties	---	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity correlated beam properties	0.5%	0.7%
Total:	2.5%	4.1%

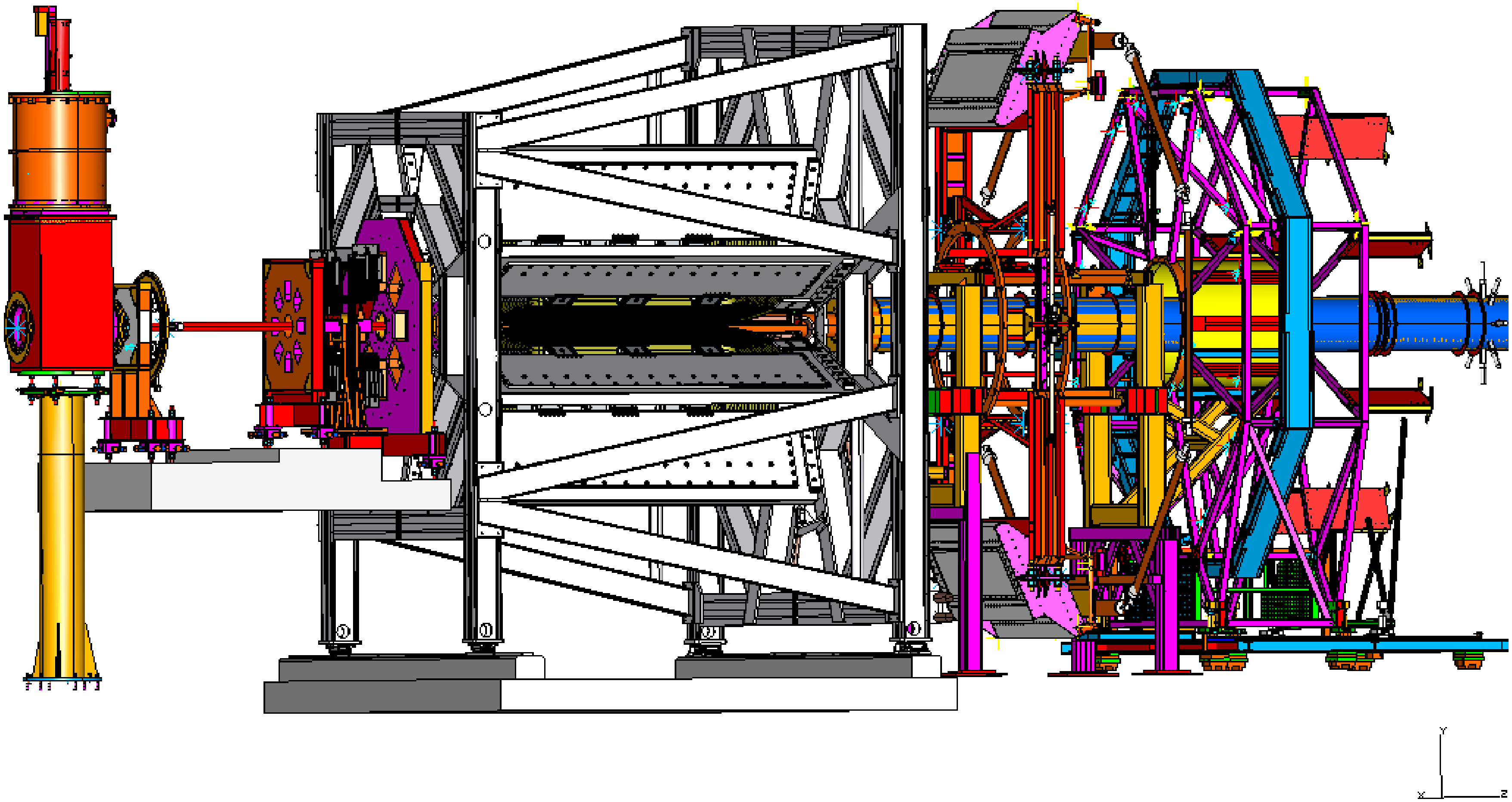
$$\overline{A_{LR}^p} = A_z/(-G_F Q^2/4\pi\alpha\sqrt{2}) = Q^p_{weak} + Q^2 B(Q^2)$$

Final error on $\Delta\sin^2\theta_W$ / $\sin^2\theta_W$ includes QCD uncertainties (1-loop) in calculation of the running 0.2% $\rightarrow$ 0.3%.

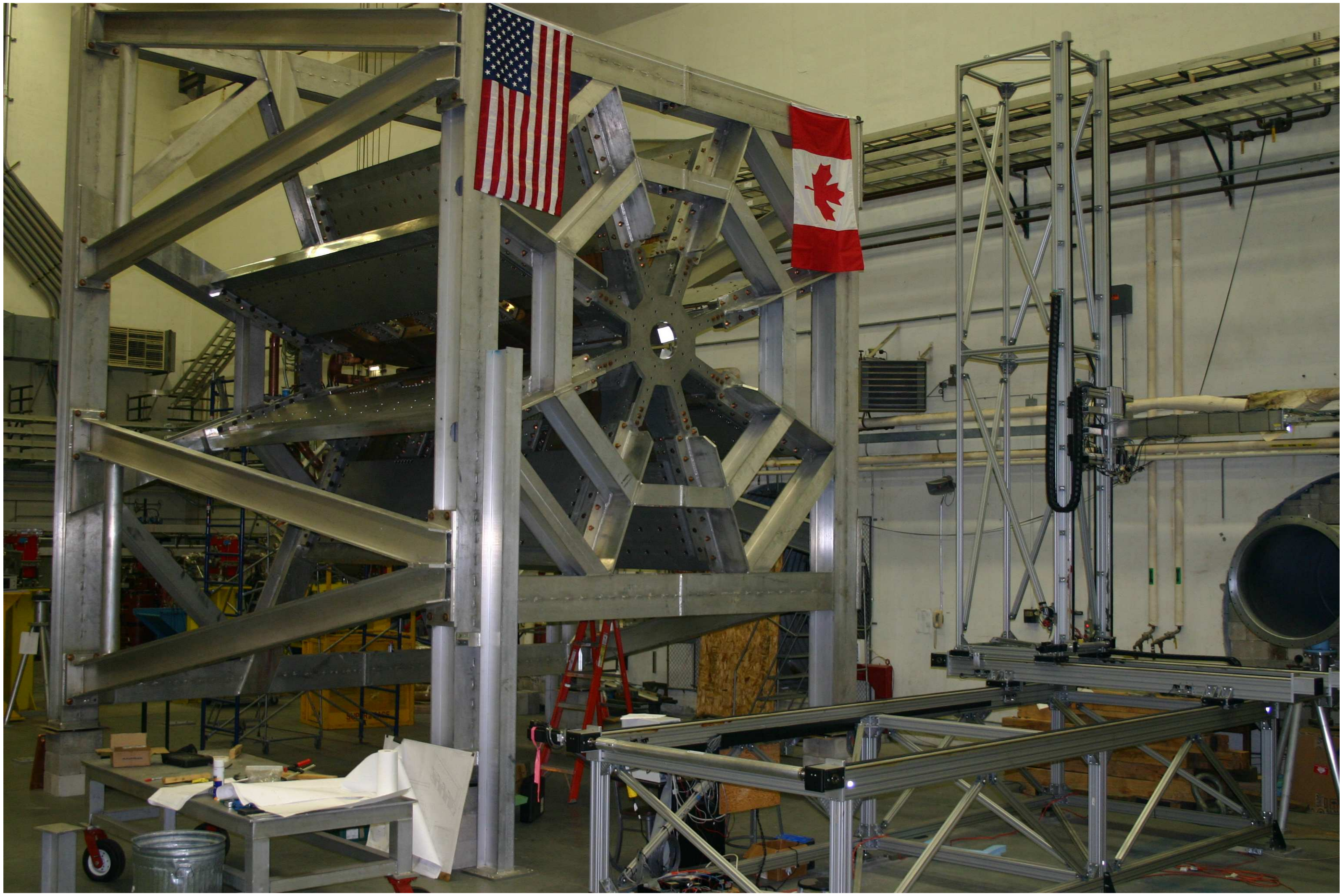
Schematic of the QWeak Experiment



QWeak experiment



Qweak Magnet



Experiment on track for first beam May 2010

What's after Qweak?

- PVDIS: Parity-violating Deep Inelastic Scattering at 11 GeV JLab

  → go after C_{2u} and C_{2d} and higher-twist in nucleon

  Exploratory 6 GeV version to run this Fall in Hall A

- Parity-violating Moller (e-e) scattering at 11 GeV/JLab

  → improve on E158 precision

  experiment approved this January

Parity-violating Moller at 11 GeV

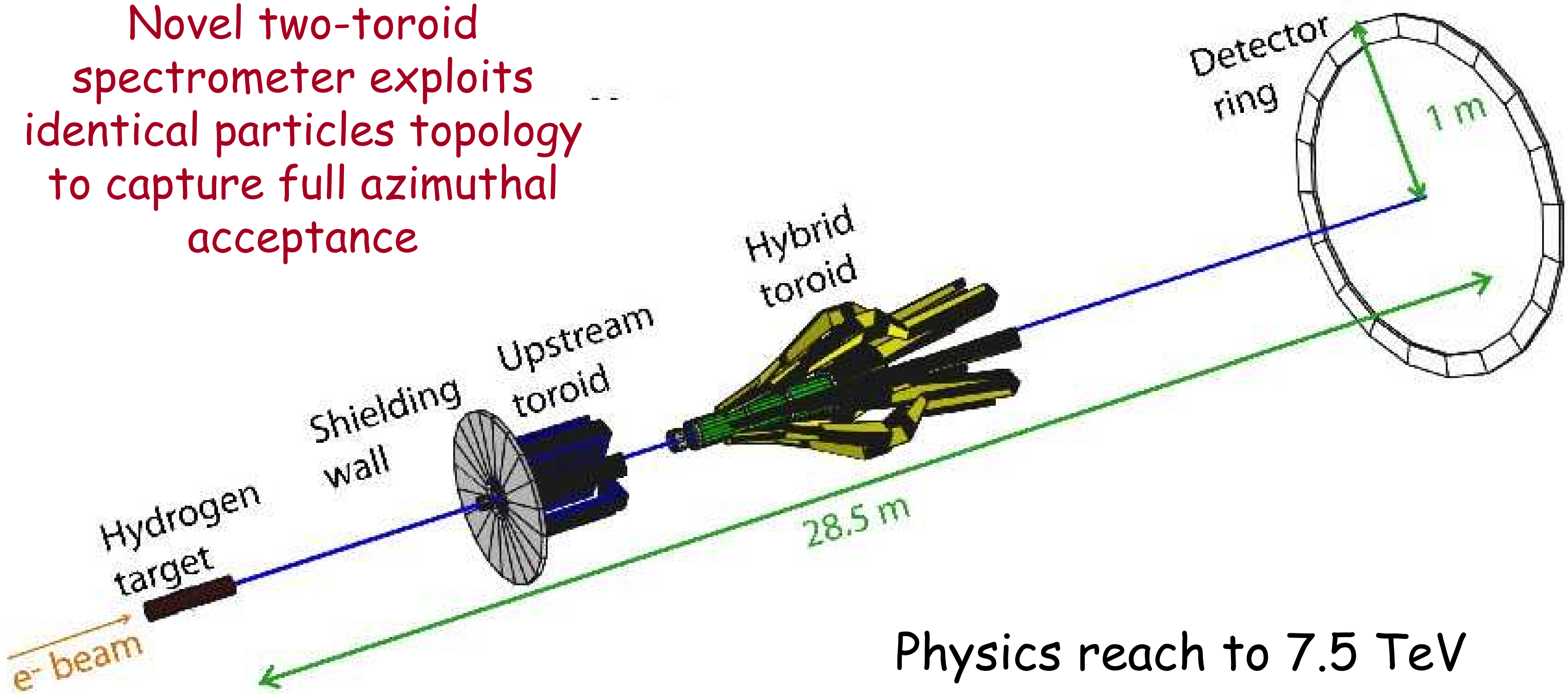
Goal: measure 36 ppb asymmetry with 0.7 ppb error

Would determine Q^e_{weak} to 2.3%

$\sin^2\theta_W$ to ± 0.00026(stat) ± 0.00013(syst)

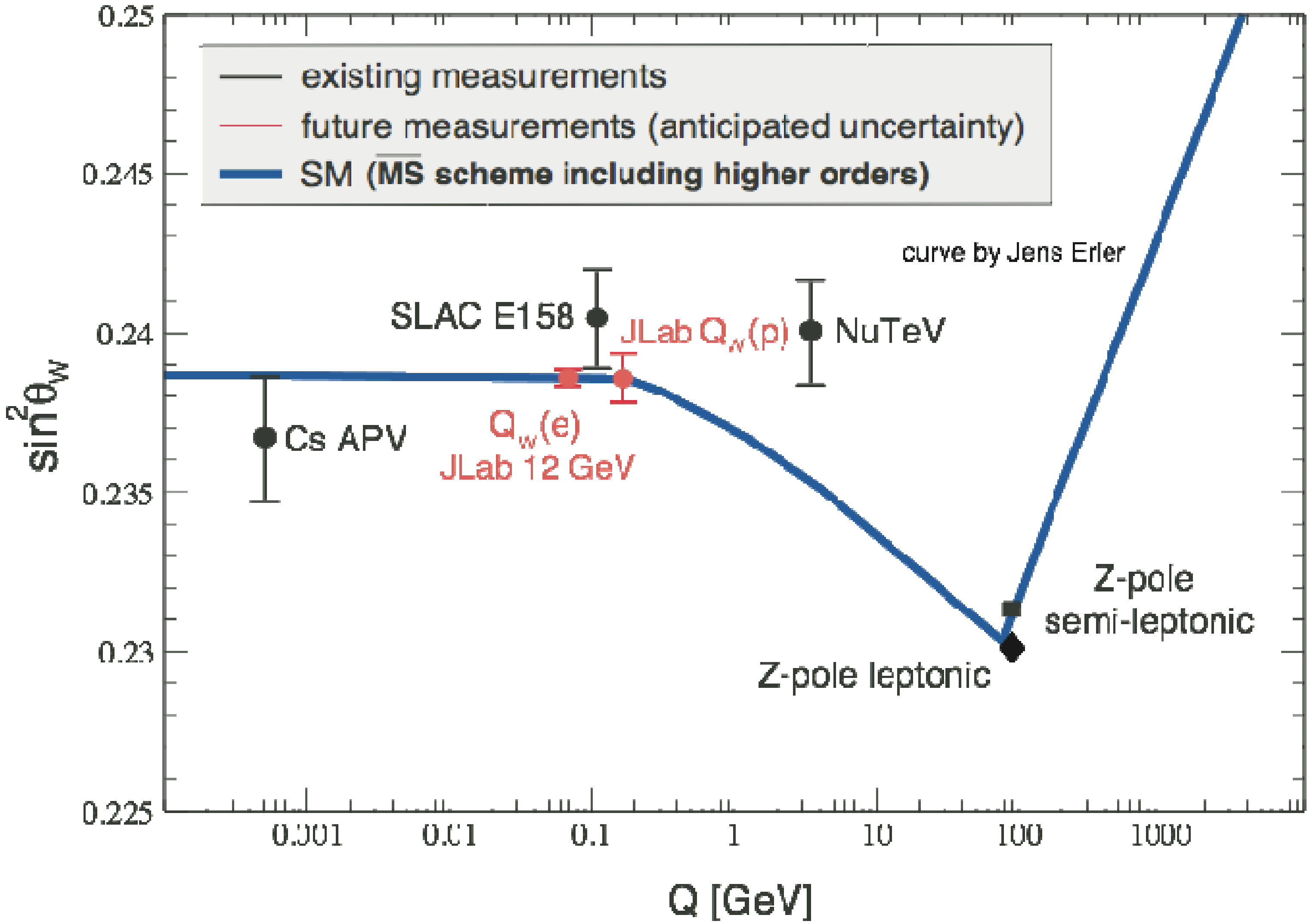
competitive with most precise collider data at Z-pole

Novel two-toroid spectrometer exploits identical particles topology to capture full azimuthal acceptance



Physics reach to 7.5 TeV

Moller experiment with JLab upgrade



Conclusion

- Parity-violating electron scattering useful tool in arsenal of precision tests of Standard Model
- Already providing constraints on new physics
- Qweak experiment at JLab will extend reach in TeV scale for certain classes of new physics
- Program developing for major PV experiments for 12 GeV upgraded JLab

- *finis* -

Electroweak Radiative Corrections

Q^p_{Weak}	Standard Model ($Q^2 = 0$)	0.0713 ± 0.0008
Q^p_{Weak}	experiment precision goal	± 0.003

Source	Q^p_{Weak} Uncertainty
$\Delta \sin \theta_W (M_Z)$	±0.0006
$Z\gamma$ box	±0.0005
$\Delta \sin \theta_W (Q)_{hadronic}$	±0.0003
WW, ZZ box - pQCD	±0.0001
Charge symmetry	0
Total	±0.0008

Erler et al., PRD 68(2003)016006.

Estimates of 2 Boson Exchange effects on A_{PV} at Qweak Kinematics

TPE	(Blunden et.al.)	-0.05%	
TBE	(Tjon, Blunden, Melnitchouk) arXiv:0903.2759	0.13%	(N and Δ)
TBE	(Gorchtein & Horowitz) Phys. Rev. Lett. 102, 091806 (2009)	~ 6%	(dispersion relations)