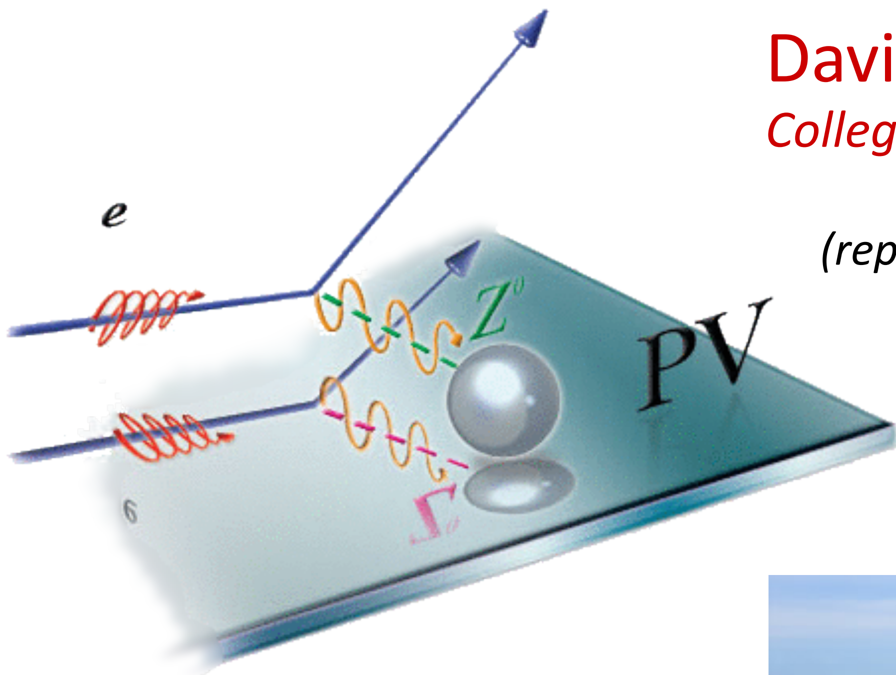
Parity-Violating Electron Scattering at JLab



David S. Armstrong
College of William & Mary

(replacing Juliette Mammei, who kindly provided most of the slides)

MENU 2013
Rome, Italy
Oct 2 2013

The College of WILLIAM & MARY

Jefferson Lab

Parity-Violating Electron Scattering at JLab

Electroweak interaction (neutral current)

- not one of the *canonical* probes for Hadron Physics
  (*i.e.* strong or electromagnetic)

- nevertheless, much of the program should be
  of interest to this community

-Focus today:
- new results since MENU2010
- plans for 12 GeV era at Jefferson Lab

The College of WILLIAM & MARY

Jefferson Lab

Outline

1) Intro to Parity-Violating Electron Scattering (PVES)

2) The Vector Strange Form Factors a ≈ completed program

3) Qweak: first results on the proton's weak charge

4) Neutron radius in Heavy Nuclei

5) Standard Model Tests with PVES: plans at JLab-12 GeV

The College of WILLIAM & MARY

Jefferson Lab

1) Search for physics *Beyond the Standard Model*

– Low energy ($Q^2 << M^2$) precision tests complementary to high energy measurements

- ***Neutrino mass and their role in the early universe*** $0\nu\beta\beta$ *decay*, θ_{13}, β *decay,…*
- ***Matter-antimatter asymmetry in the present universe*** *EDM, DM, LFV,* $0\nu\beta\beta$, θ_{13}
- ***Unseen Forces of the Early Universe*** *Weak decays,* ***PVES****,* g_μ*-2,…*

LHC new physics signals likely will need additional indirect evidence to pin down its nature

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

new since MENU2010: first result from QWeak

2) Study nucleon and nuclear properties

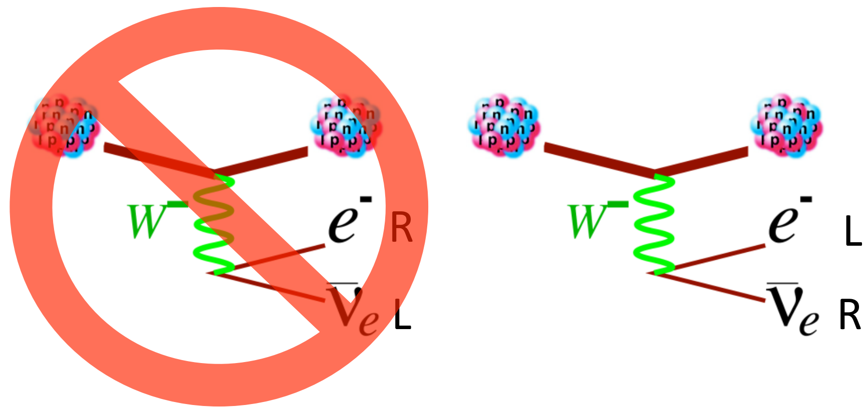
– Strange quark content of nucleon *new since MENU2010: HAPPEX-III*

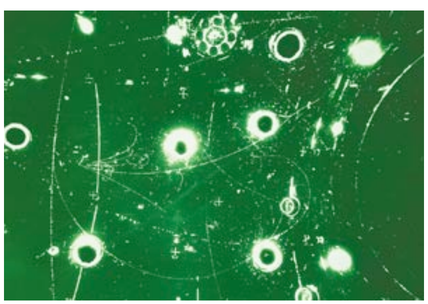
– Neutron radius of heavy nuclei *new since MENU2010 – first PREx results*

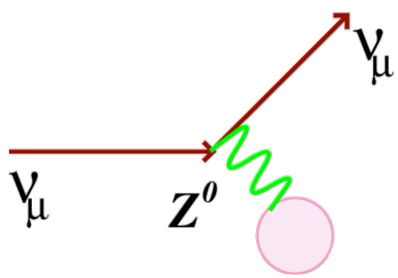
A brief history of parity violation

1930s – weak interaction needed to explain nuclear β decay

1950s – parity violation in weak interaction;
V-A theory to describe ^{60}Co decay



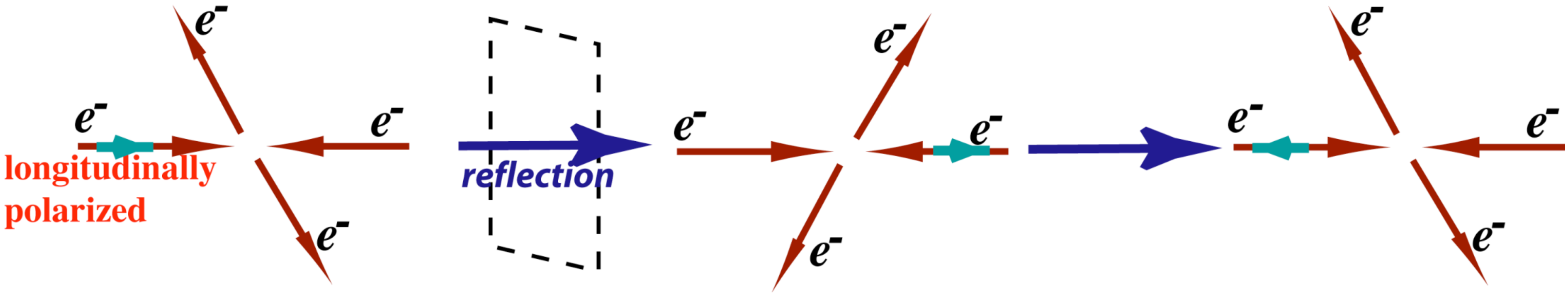




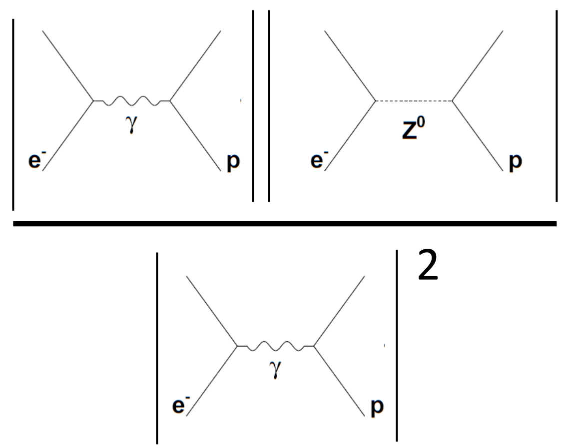
1970s – neutral weak current events at
Gargamelle

late 1970s – parity violation observed in electron scattering - SLAC E122

Parity-violating electron scattering



$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto$$



$$\propto \frac{|M_Z|}{|M_\gamma|}$$

Electroweak interference

$$A_{PV} \propto \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left(g_A^e g_V^T + \beta g_V^e g_A^T \right) \sim 10^{-4} Q^2 \left[GeV^2 \right]$$

SLAC Experiments

SLAC E122 – crucial confirmation of **WSG electroweak model**

- Electron-deuteron deep inelastic scattering
- High luminosity: photoemission from NEA GaAs cathode
- Rapid helicity-flip (sign of e- polarization)
- Polarimetry to determine beam polarization
- Magnetic spectrometer: backgrounds and kinematic separation

A_{PV} ~ 100 ± 10 ppm

$\sin^2\theta_W = 0.20 \pm 0.03$

SLAC E158 – 1999

- electron-electron scattering - purely leptonic interaction
- electron-electron weak attractive force had never been measured!

A_{PV} ~ -131 ± 14 ± 10 ppb

$\sin^2\theta_W = 0.2403 \pm 0.0013$

Genesis of a Strange Idea

$$P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + ...$$

Puzzle: Initial DIS measurements of spin-structure of nucleon (EMC):
valence quarks contribute unexpectedly low fraction to total spin - "Spin Crisis"

Possible reconciliation: large fraction of spin from $s\bar{s}$?
eg. D. B. Kaplan and A. Manohar, Nucl. Phys. B310, 527 (1988).

Theoretical realization: not only did many available nucleon model calculations allow this, but they also allowed (and in some cases *favored*) large strange quark contributions to *other* properties of nucleon.

Consternation and excitement: at the time, data gave no constraint on strange contributions to charge distribution and magnetic moment!

Challenge: how to isolate strange vector form factors?

Answer: exploit the weak neutral current as a probe

strange quark contribution

Define the nucleon form factors associated with a given quark current q as:

$$\langle N | \bar{q}\gamma_\mu q | N \rangle = \bar{\psi}_N \left(F_1^q \gamma_\mu + F_2^q \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} \right) \psi_N$$

$$G_M^q = F_1^q + F_2^q$$

$$G_E^q = F_1^q - \tau F_2^q$$

Assume isospin symmetry, and we have

$$\begin{pmatrix} G_{E,M}^{\gamma,p} \\ G_{E,M}^{\gamma,n} \\ G_{E,M}^{Z,p} \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ Q_u^Z & Q_d^Z & Q_s^Z \end{pmatrix} \begin{pmatrix} G_{E,M}^{u} \\ G_{E,M}^{d} \\ G_{E,M}^{s} \end{pmatrix}$$

this → $G_{E,M}^{\gamma,p}$

and this → $G_{E,M}^{\gamma,n}$

are well known

what about this? → $G_{E,M}^{Z,p}$

(Assume neutral weak charges are known) → Q_u^Z, Q_d^Z, Q_s^Z

	Q^γ	Q^Z
u	+2/3	$1 - 8/3 \sin^2\theta_W$
d	−1/3	$-1 + 4/3 \sin^2\theta_W$
s	−1/3	$-1 + 4/3 \sin^2\theta_W$

Nucleon Form Factors

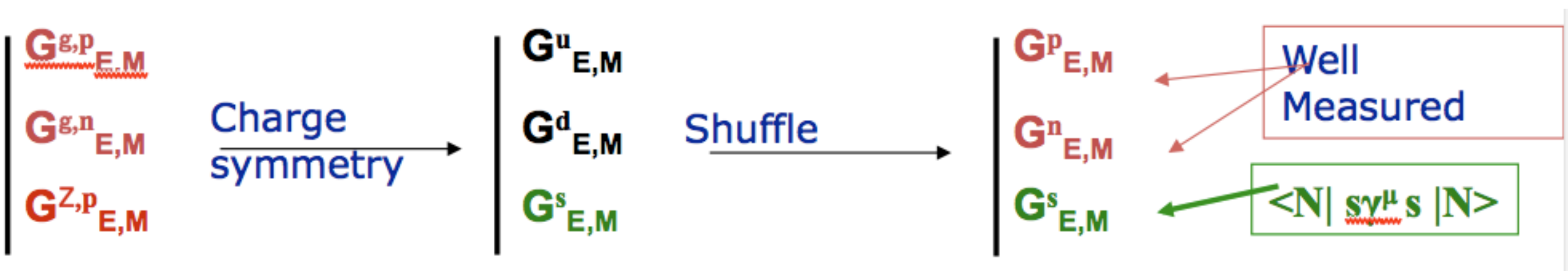
NC and EM probe same hadronic flavor structure, with different couplings:

$$G^{\gamma}_{E/M} = \frac{2}{3} G^{u}_{E/M} - \frac{1}{3} G^{d}_{E/M} - \frac{1}{3} G^{s}_{E/M}$$

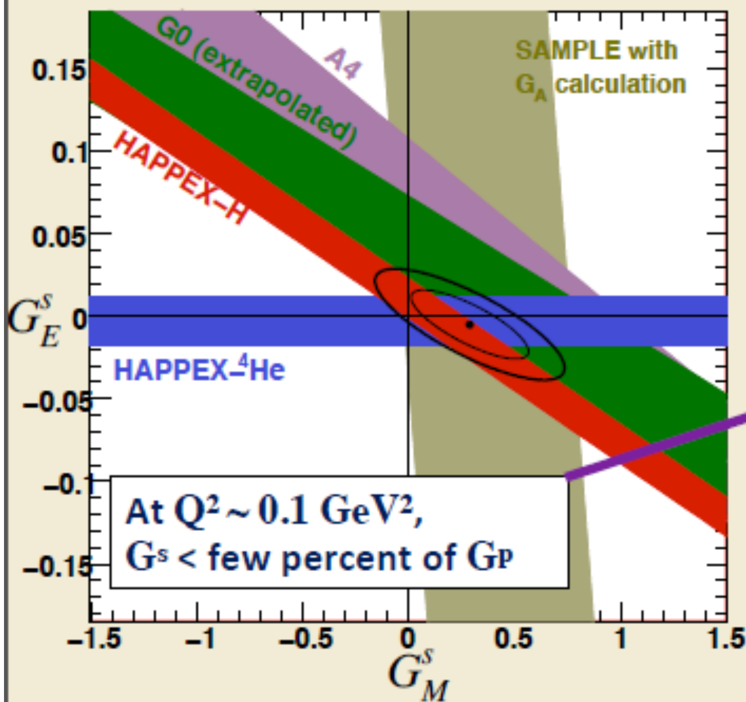
$$G^{Z}_{E/M} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G^{u}_{E/M} - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G^{d}_{E/M} - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G^{s}_{E/M}$$

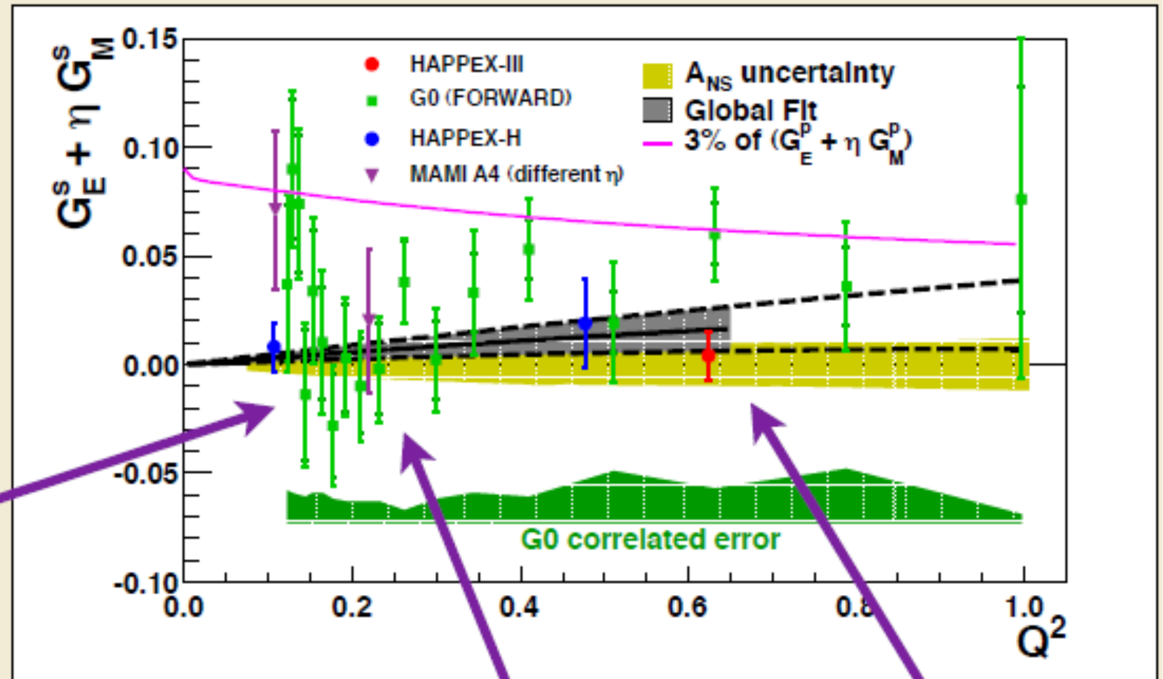
Assume Charge Symmetry:

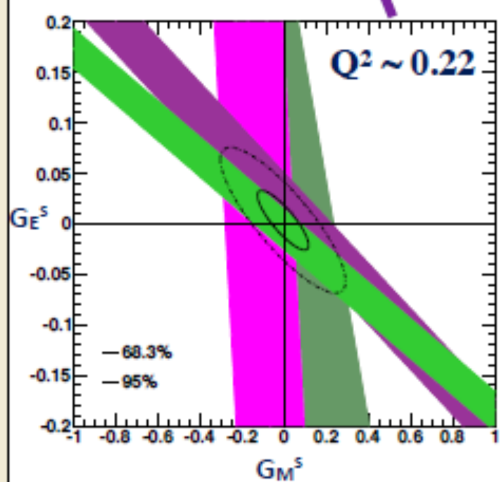
$$G^{p,u}_{E/M} = G^{n,d}_{E/M}, \qquad G^{p,d}_{E/M} = G^{n,u}_{E/M}, \qquad G^{p,s}_{E/M} = G^{n,s}_{E/M}$$

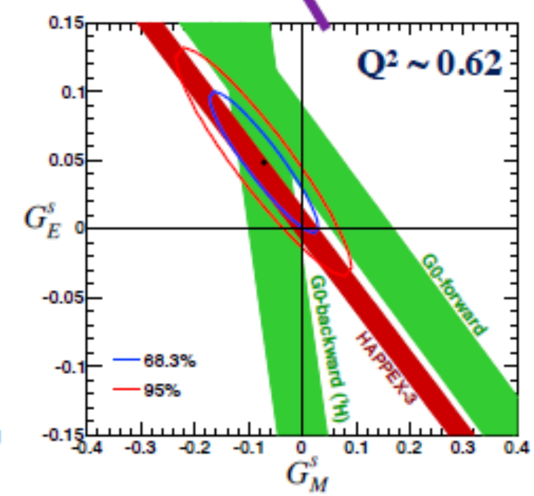


Strange Form Factors









- Probing over a range of low-Q^2, effects are small (<3%) and consistent with zero.
- effects (whether strange quarks, charge symmetry breaking, axial contributions) must go to zero at zero Q^2

Qweak: Proton's weak charge

Q_W^p -Neutral current analog of electric charge:

The Standard Model makes a firm prediction of Q_W^p

	EM Charge	Weak Charge
u	2/3	$1-\frac{8}{3}sin^2(\theta_w) \approx 0.38$
d	-1/3	$-1+\frac{4}{3}sin^2(\theta_w) \approx -0.69$
P (uud)	+1	$1-4\,sin^2(\theta_w) \approx 0.07$
N (udd)	0	-1

"Accidental suppression"
→sensitivity to new physics

Note: $Q_W^n = -1$

Q-weak is particularly sensitive to the quark *vector* couplings (C_{1u} and C_{1d}) .

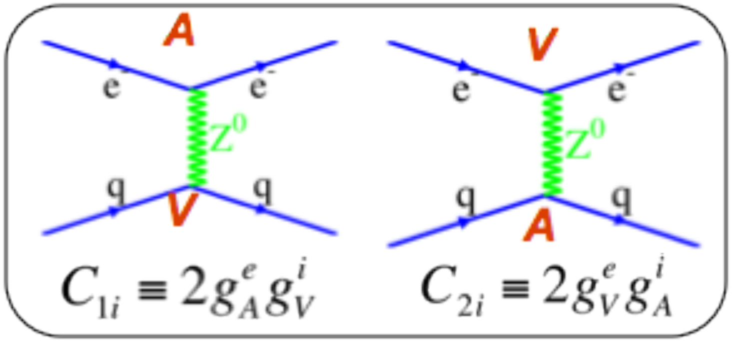
$$Q_W^p = -2(2C_{1u} + C_{1d})$$
$$Q_W^n = -2(C_{1u} + 2C_{1d})$$

Qweak: Proton's weak charge

For electron-quark scattering:

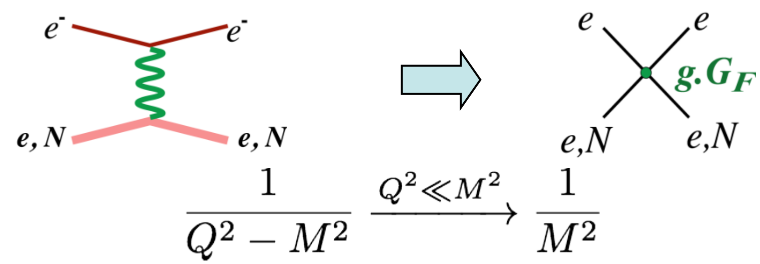
$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha}(g_A^e g_V^i + \beta g_V^e g_A^i)$$

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



Small θ Large θ

Use four-fermion contact interaction to parameterize the effective PV electron-quark couplings (mass scale and coupling)



New physics:

$$\sigma \propto |M_\gamma + M_Z + M_{\rm new}|^2$$
$$\sim |M_\gamma|^2 + 2M_\gamma M_Z^* + 2M_\gamma M_{\rm new}^*$$

new Z', leptoquarks, SUSY ...

Planned 4% measurement of proton's weak charge - probes TeV scale new physics

$$\frac{\Lambda}{g} \sim \left(\sqrt{2} G_F \Delta Q_W^p\right)^{-\frac{1}{2}} \sim O(\mathrm{TeV})$$

Erler, Kurylov, and Ramsey-Musolf, PRD 68, 016006 2003

Extracting the weak charge

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

Hadron structure enters here: electromagnetic and electroweak form factors…

Reduced asymmetry more convenient:

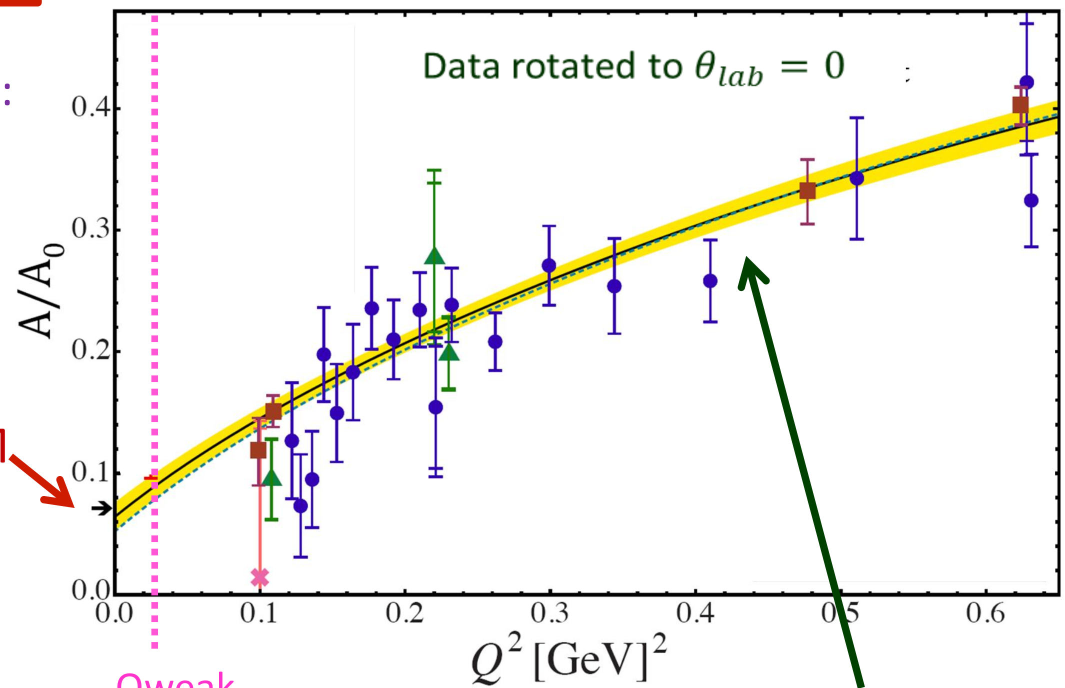
$$A_{red} = \frac{A_{PV}}{A_0} \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

One must extrapolate to $Q^2 = 0$.

We measure A_{phys}^{PV}

at $Q^2 = 0.025\ GeV^2$.

SM

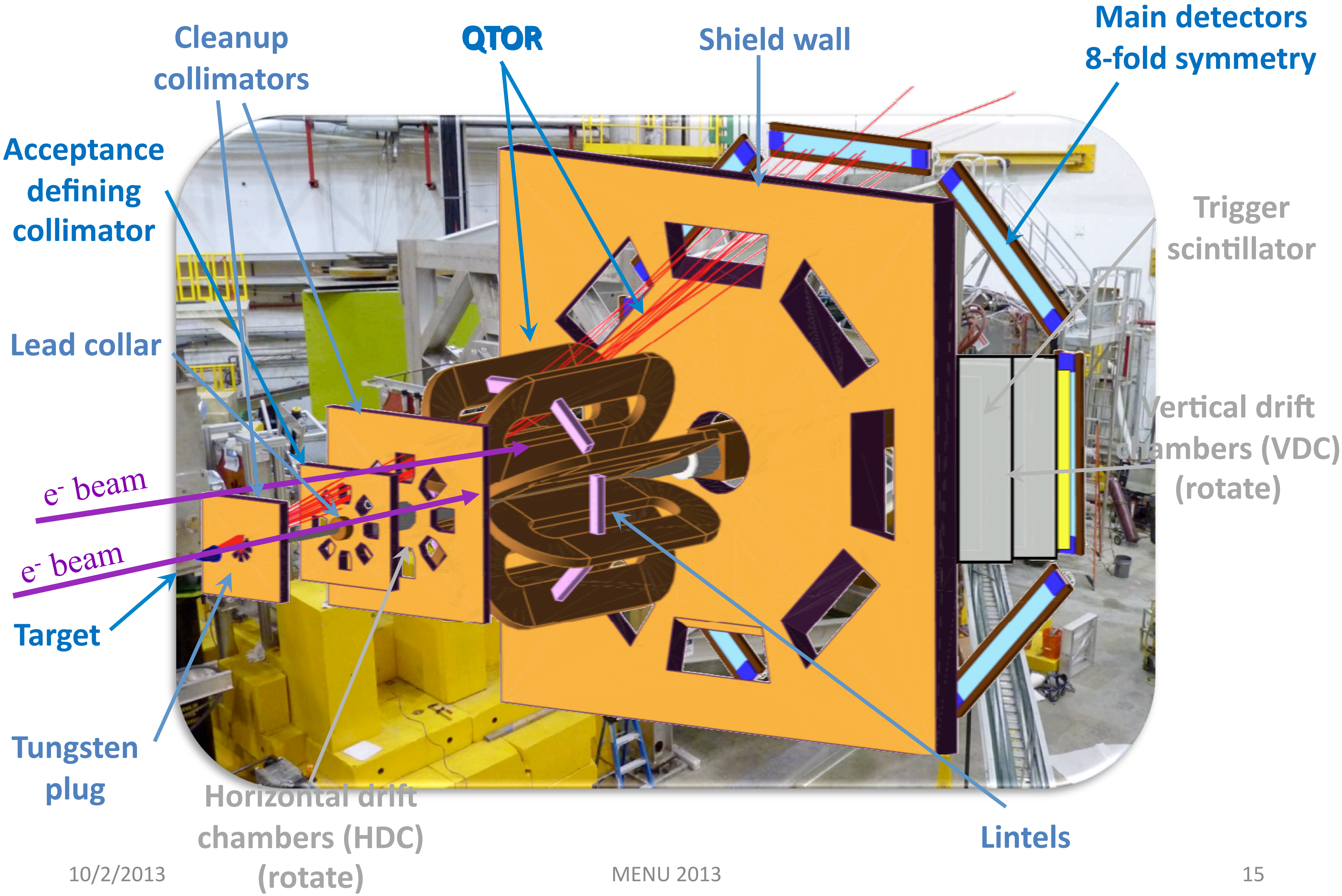


Qweak kinematics

Hadronic term extracted from fit

The previous strange form factor program (experiments at MIT/Bates, JLab and MAMI) allow us to subtract our hadronic contribution

The Qweak Apparatus



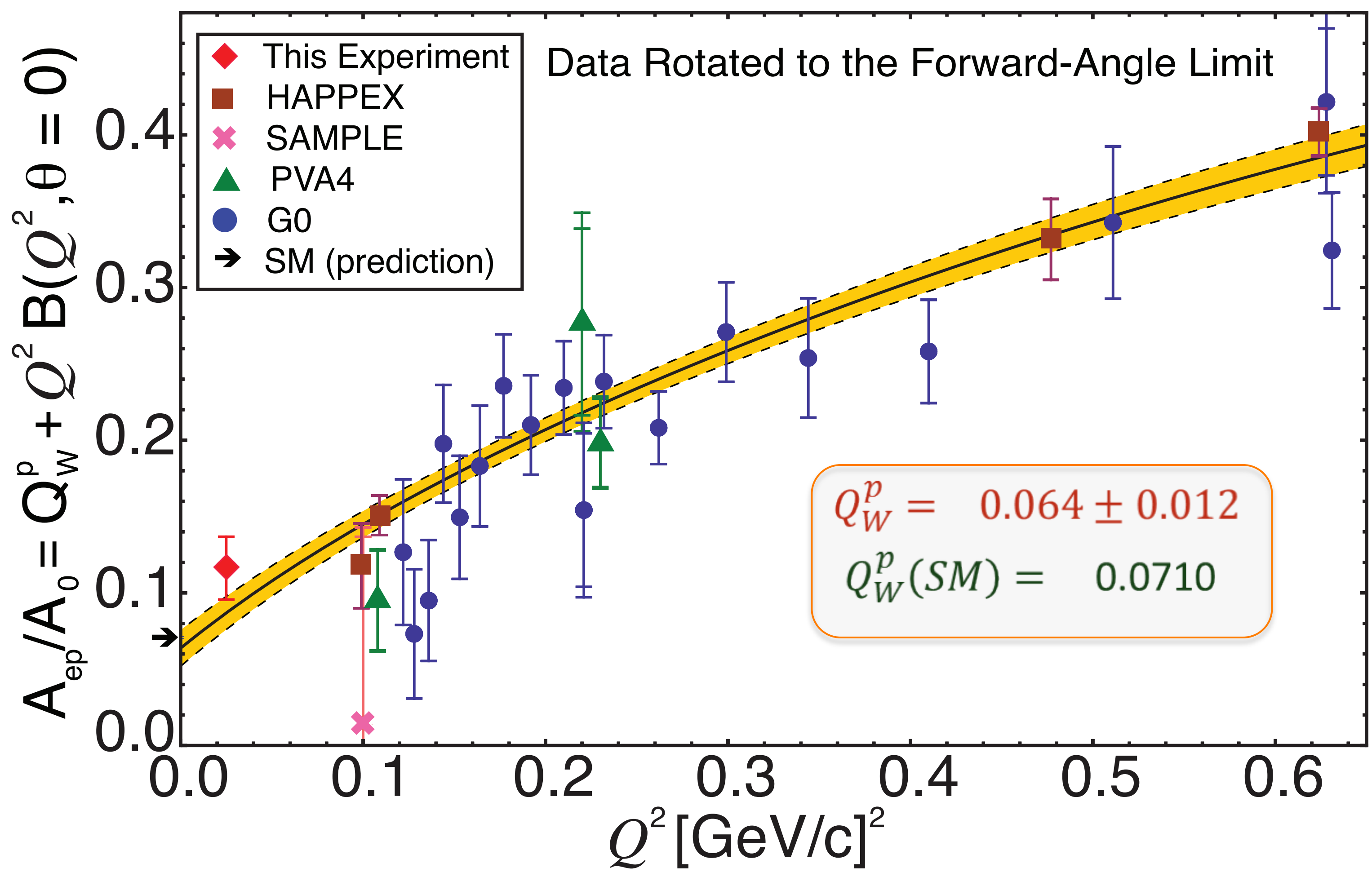
Reduced Asymmetry

4% of total data

in the forward-angle limit (θ=0)

$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}$$

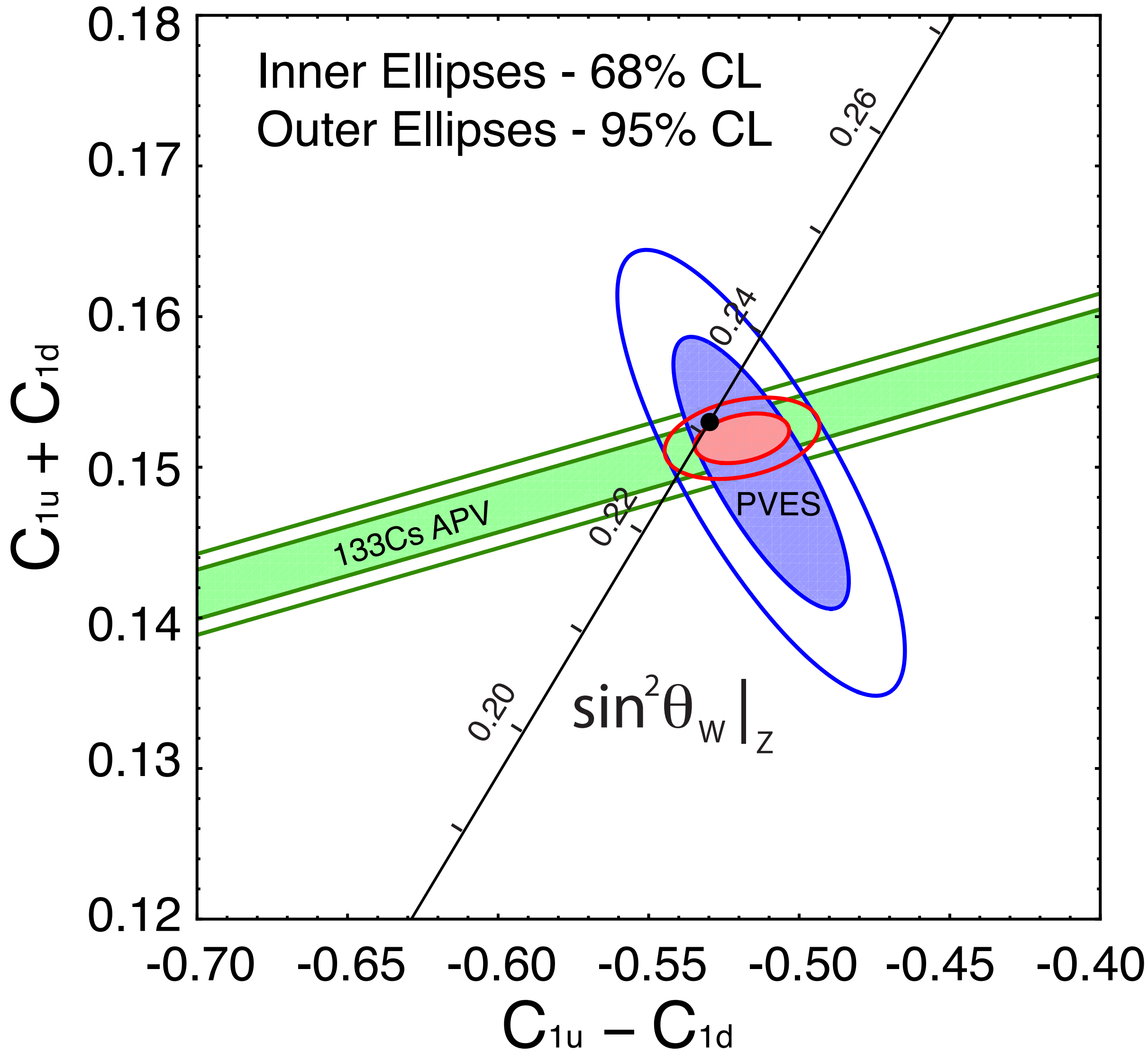
$$\overline{A^p_{\rm LR}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + Q^2 B(Q^2)]$$



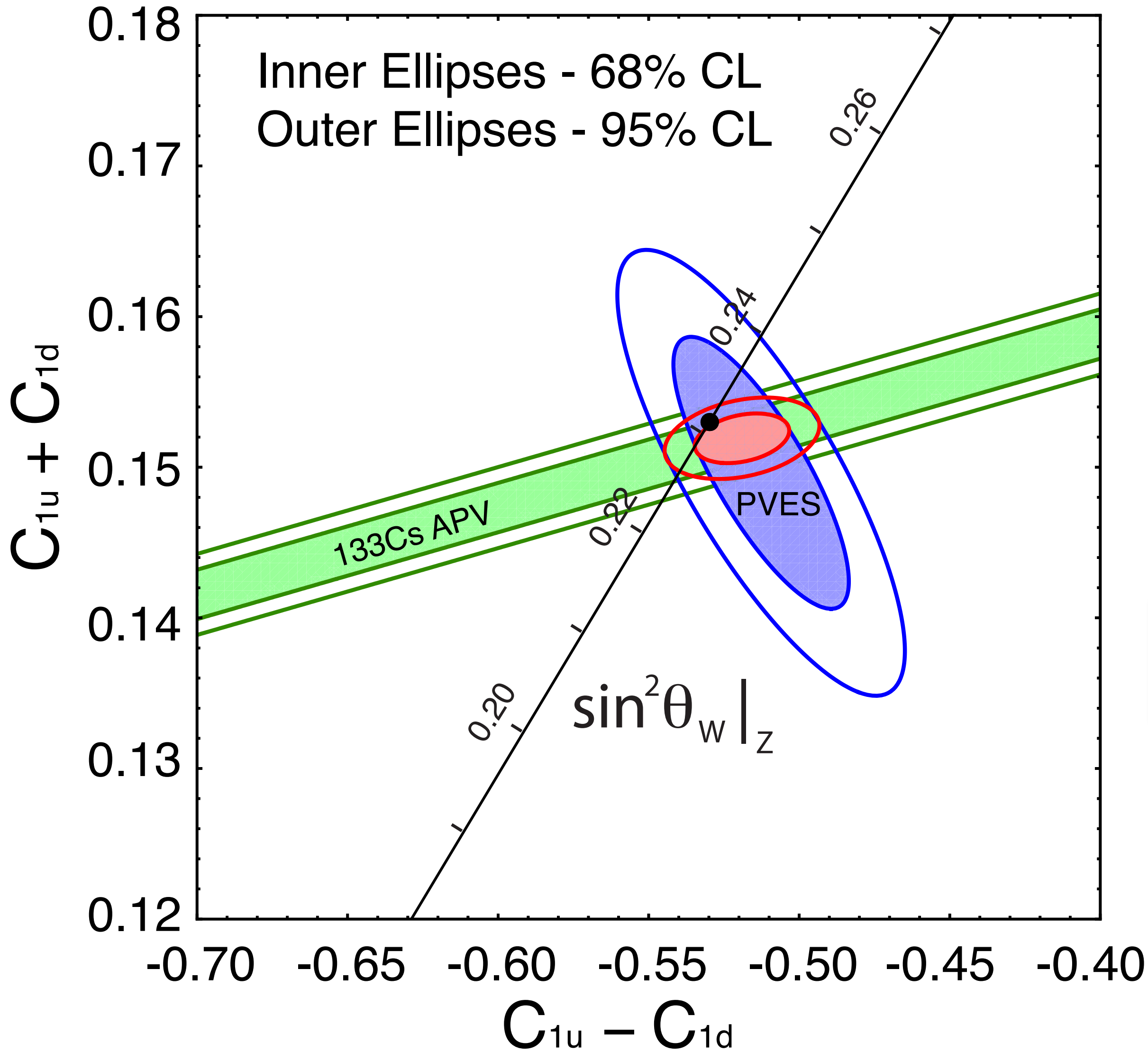
Hadronic part extracted through global fit of PVES data.

$$\overline{A^p}^{data}(\theta=0,Q^2) = \overline{A^p}^{data}(\theta^{data},Q^2)$$

The C_{1q} & the neutron's weak charge



The C_{1q} & the neutron's weak charge



Combining this result with the most precise atomic parity violation experiment we can also extract, for the first time, the neutron's weak charge:

$$Q_W^n = -0.975 \pm 0.010$$

$$Q_W^n(SM) = -0.9890$$

Qweak – first result

First result (4% of data set):

$A^{p}_{PV} = -279 \pm 35(stat) \pm 29\ (sys)$ ppb

$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ GeV^2$

The weak charges

$Q^{p}_{W} = \quad 0.064 \pm 0.012$

$Q^{p}_{W}(SM) = \quad 0.0710$

$Q^{n}_{W} = -0.975 \pm 0.010$

$Q^{n}_{W}(SM) = -0.9890$

Lots of work to push down systematic errors, but no show-stoppers found….

Expect final result in 12-18 months time.

More details: Fundamental Symmetries 3, this afternoon

A MENU of Auxiliary Measurements

Qweak has data (under analysis) on a variety of observables
of potential interest for Hadron physics:

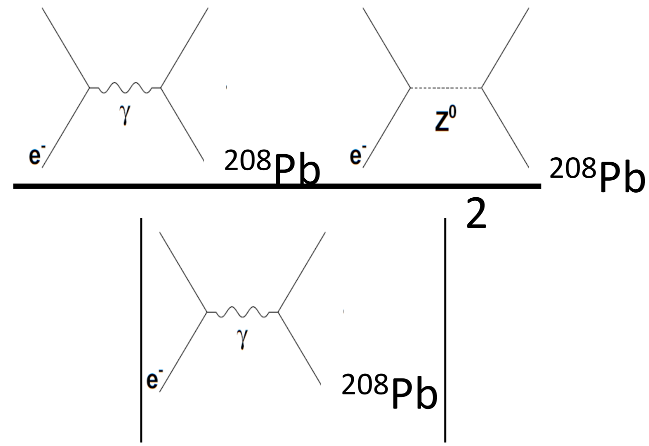
- Beam normal single-spin asymmetry* for elastic scattering on proton
- Beam normal single-spin asymmetry for elastic scattering on ^{27}Al
- PV asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry near W= 2.5 GeV
- Beam normal single-spin asymmetry in pion photoproduction
- PV asymmetry in inelastic region near W=2.5 GeV (related to γZ box diagrams)
- PV asymmetry for elastic/quasielastic from ^{27}Al
- PV asymmetry in pion photoproduction

*: *aka* vector analyzing power *aka* transverse asymmetry;
generated by imaginary part of two-photon exchange amplitude
(*pace* Wim van Oers)

Neutron skin – PREx

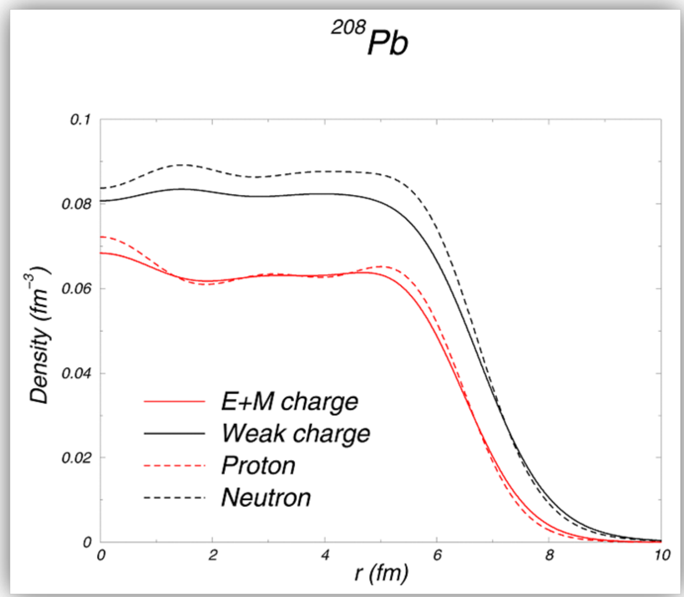
Exploit the large weak charge of neutron to extract radius of neutron distribution in heavy nucleus; theoretically clean probe.

$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx$$



$$= \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

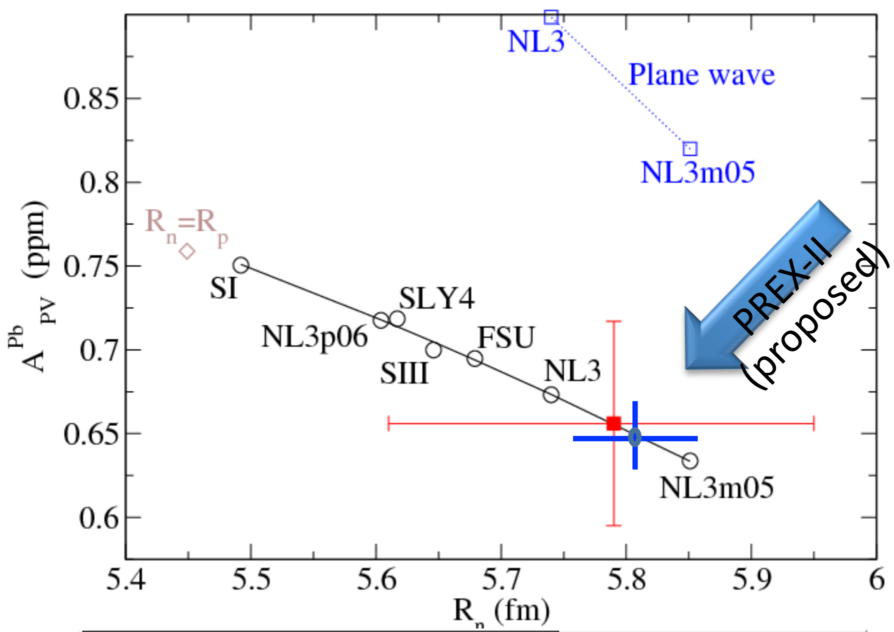
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_{n,p}(r)$$

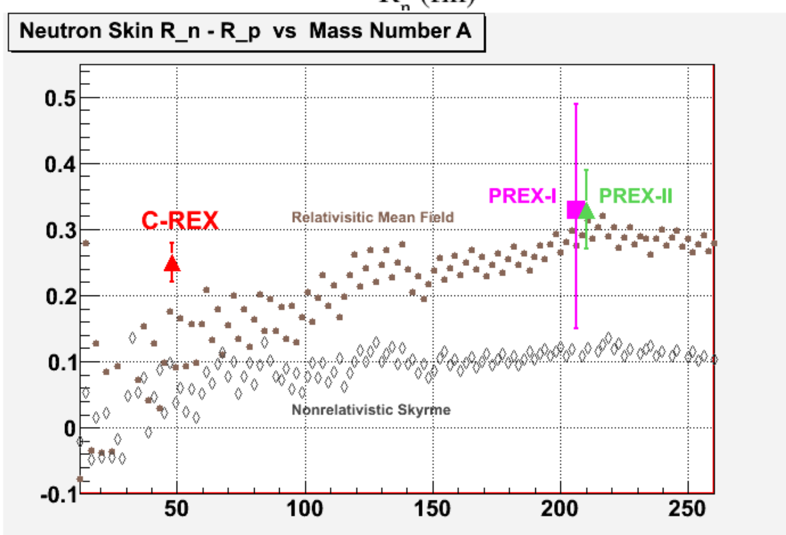


First result of PREx experiment at JLab:
PRL 108(2012)112502

A_{PV} = 0.656 ± 0.060 (stat) ± 0.014 (syst) ppm

PREX, PREX II and CREX





Theory from P. Ring et al. Nucl. Phys. A 624 (1997) 349

$$R_n - R_p = 0.33 \begin{array}{l} +0.16 \\ -0.18 \end{array}$$

^{208}Pb more closely approximates infinite nuclear matter

The ^{48}Ca nucleus is smaller, so A_{PV} can be measured at a Q^2 where the figure of merit is higher

R_n^{208} and R_n^{48} are expected to be correlated, but the correlation depends on the correctness of the models

The structure of ^{48}Ca can be addressed in detailed microscopic models

Measure both R_n^{208} and R_n^{48} - test nuclear structure models over a large range of A

More info: yesterday's talks by G. Urcioli and M. Thiel in Fundamental Symmetries 2

Future: PVES at JLab in 12 GeV era

MOLLER - precision Standard Model test by measuring weak charge of electron in PV electron-electron scattering (revisit SLAC E158)

SOLID - precision Standard Model test by measuring PV DIS on deuteron: access the quark weak axial couplings C_{2q}

(also – a similar measurement was made at 6 GeV in Hall A at Jefferson Lab, X. Zheng et al., being readied for publication, but I'm not authorized to show the results; stay tuned…)

Large kinematic coverage: disentangle CSV and higher-twist effects

MOLLER at 12 GeV

Coupling constants

$$\mathcal{L}_{NEW}^{PV} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda_{ij}^2} \bar{e}_i \gamma_i e_i \bar{e}_j \gamma^\mu e_j$$

Mass scale

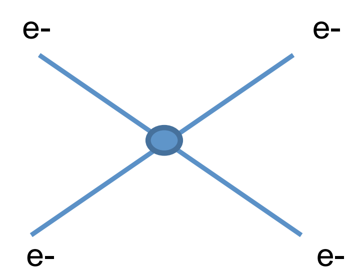
$$g_{ij} = g_{ij}^*$$

$$e_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\psi_e$$

$$g_{LR} = g_{RL}$$

2.3% MOLLER uncertainty

$$\frac{\Lambda}{\sqrt{|g_{LL}^2 - g_{RR}^2|}} = \frac{\Lambda}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} \rightarrow \mathbf{7.5\ TeV}$$

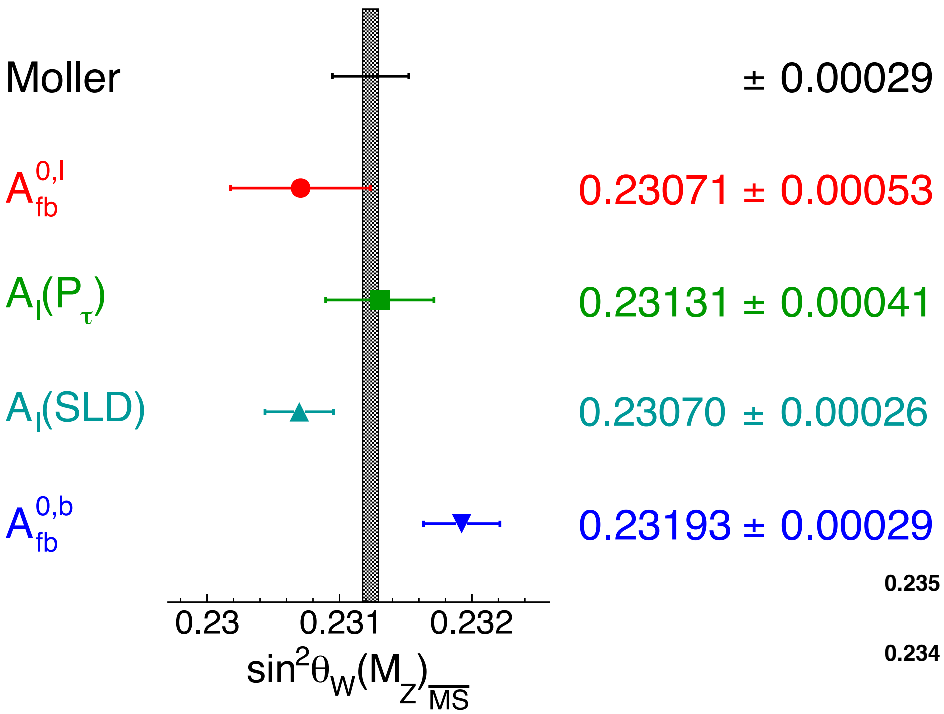


LEP2 (g_{LR} and sum) mass scale sensitivity ~5.2 and 4.4 TeV

Doubly-charged scalar, heavy Z', SUSY, dark Z…

Lepton compositeness – strong coupling – 47 TeV

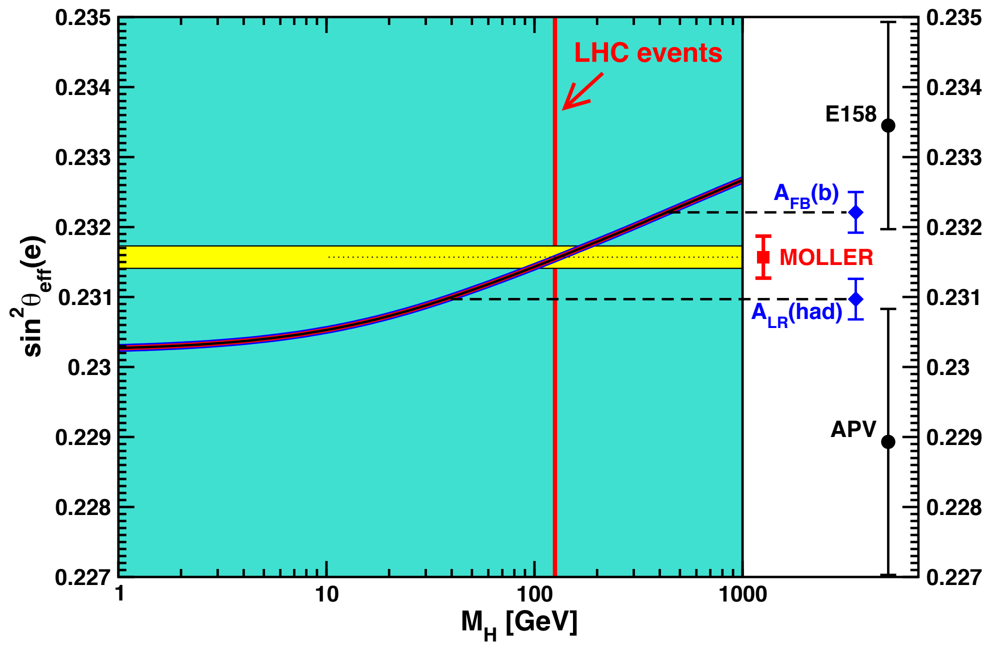
MOLLER and weak mixing angle



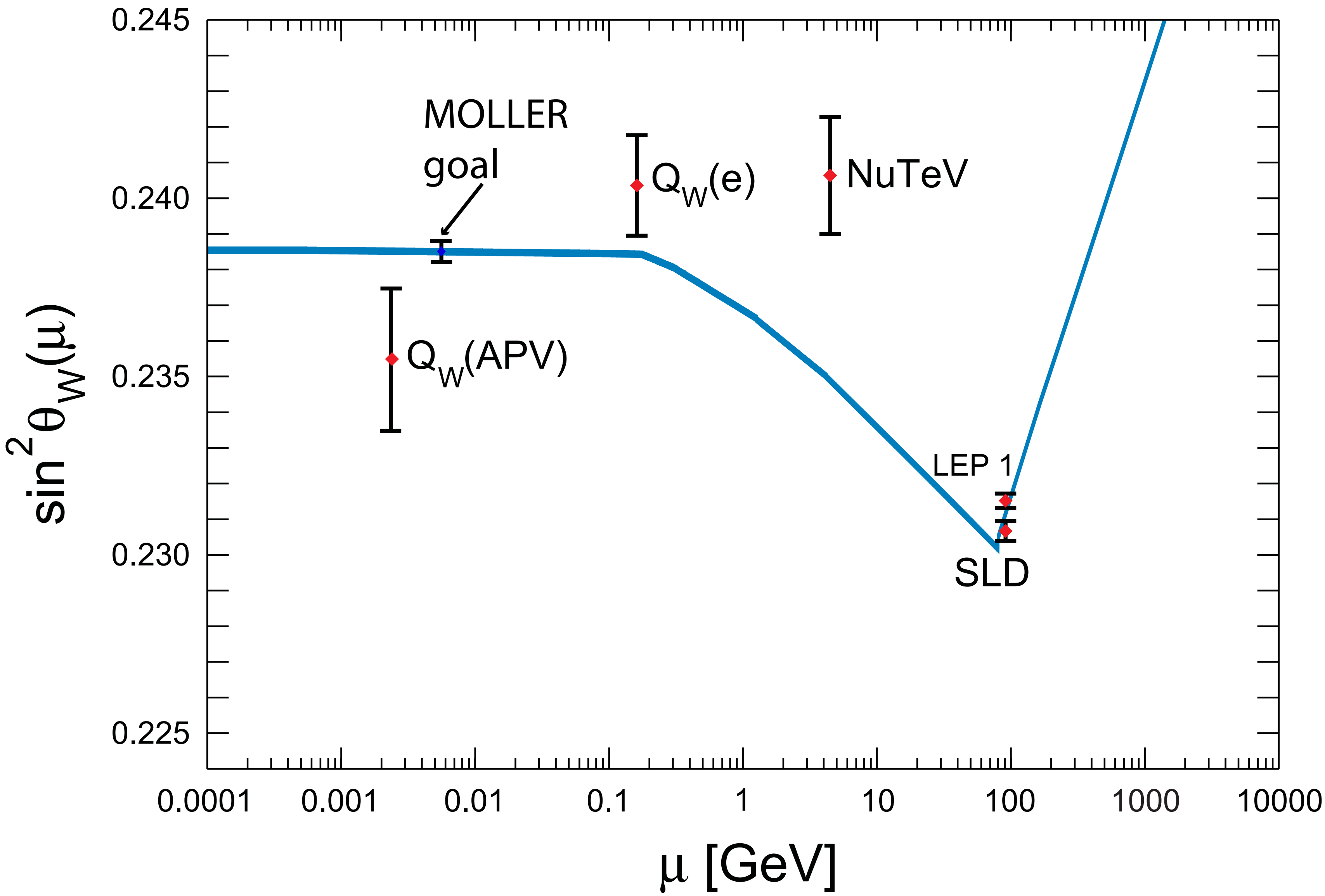
Reminder: at tree-level

$Q_W^e = \quad (1 - 4\sin^2\theta_W)$

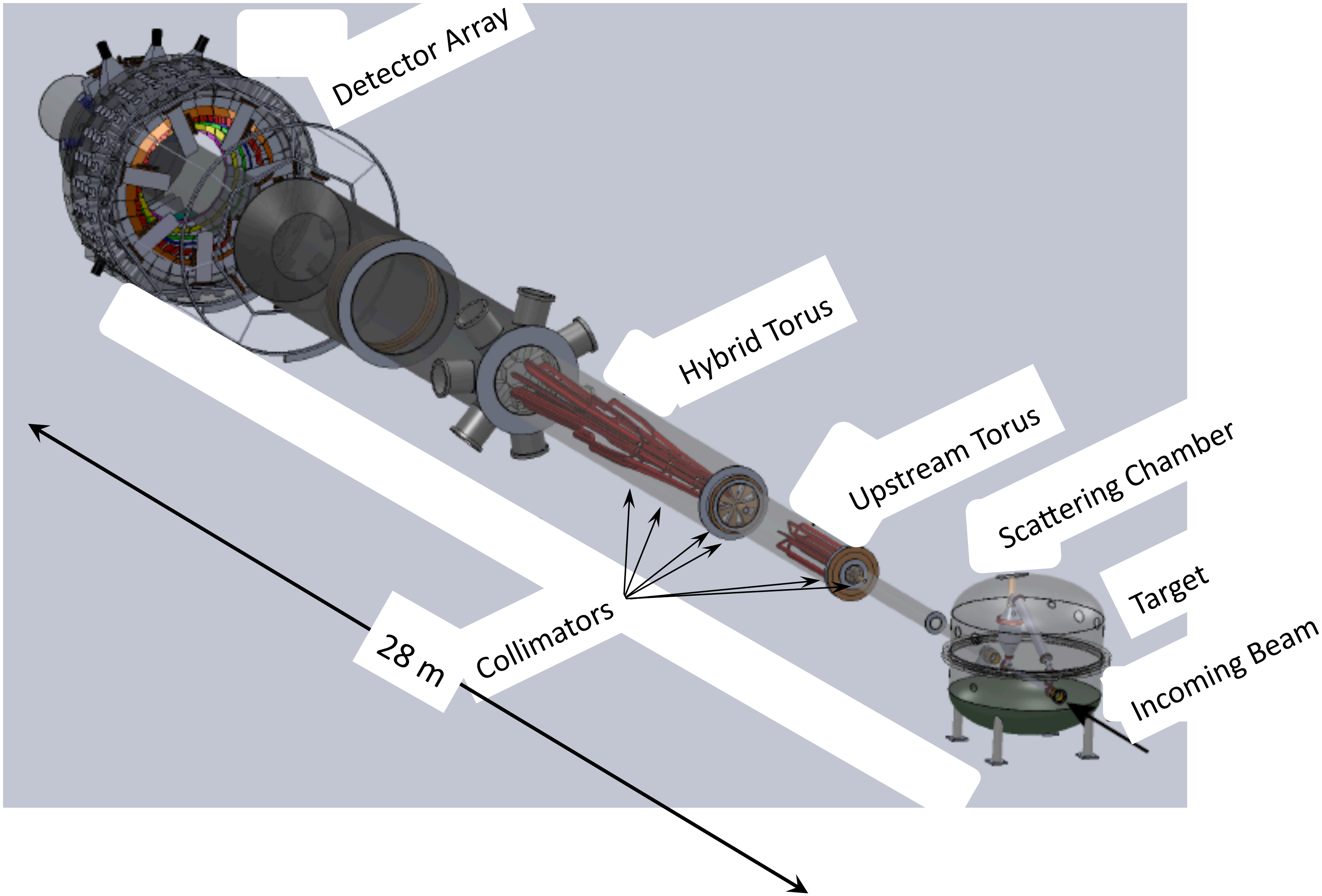
Higgs discovery at LHC allows firm prediction of MOLLER asymmetry in Standard Model

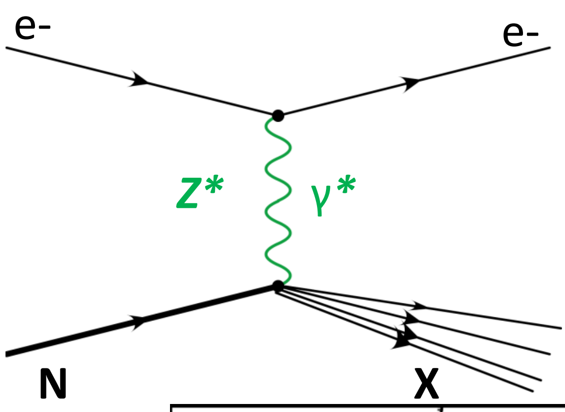


MOLLER and weak mixing angle



The MOLLER Experiment





SOLID – accessing the C_{2q}'s

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

Cahn and Gilman, PRD **17** 1313 (1978) polarized electrons on deuterium

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$x \equiv x_{Bjorken}$$

$$y \equiv 1 - E'/E$$

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W \approx -0.19$$

$$C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W \approx 0.35$$

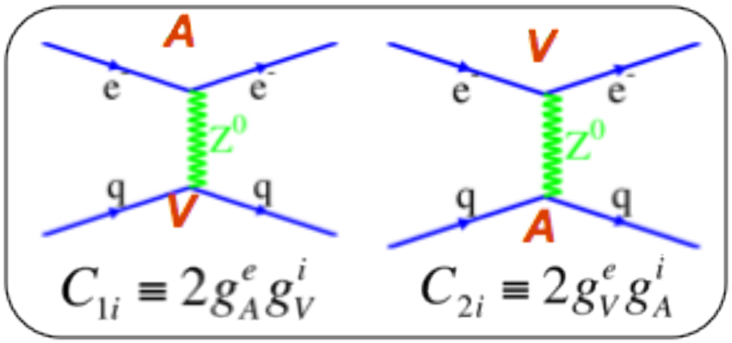
$$C_{2u} = -\tfrac{1}{2} + 2\sin^2\theta_W \approx -0.04$$

$$C_{2d} = \tfrac{1}{2} - 2\sin^2\theta_W \approx 0.04$$

$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} = (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^i + \beta g_V^e g_A^i\right)$$

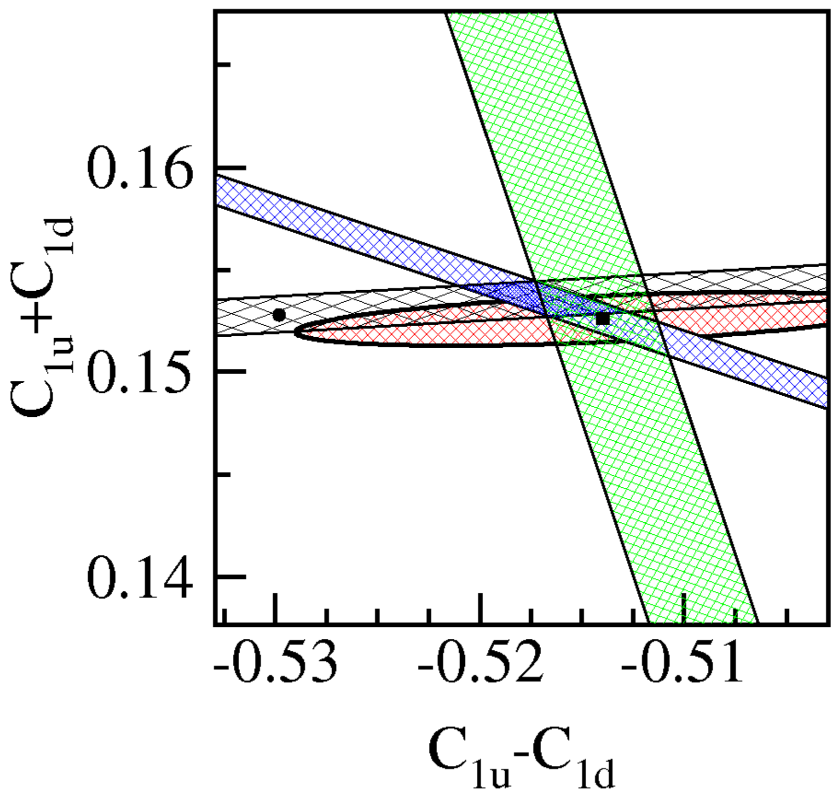


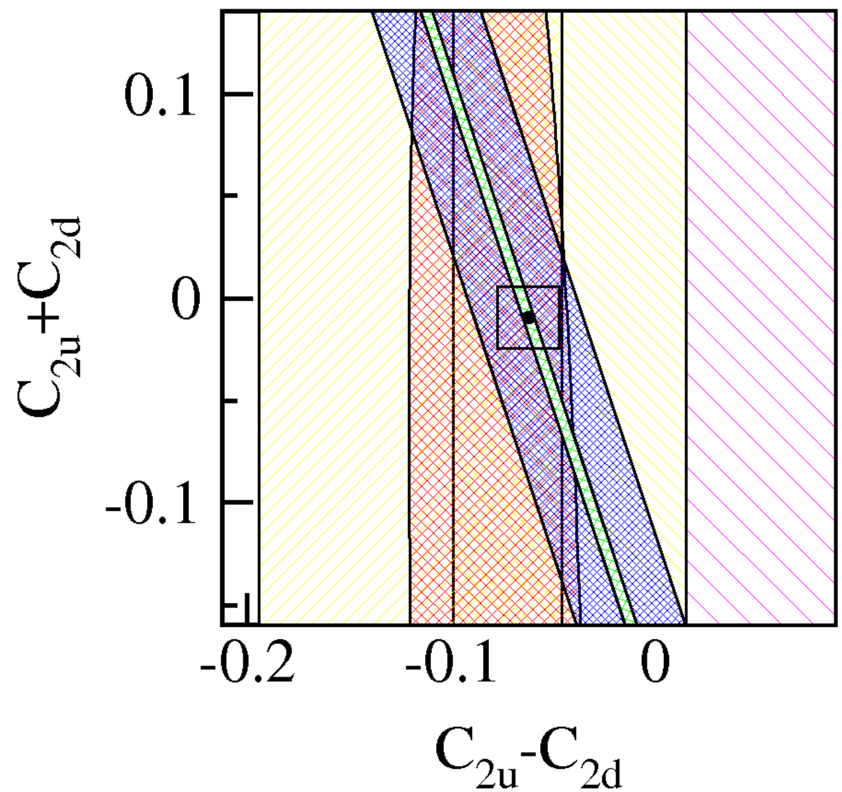
Small θ Large θ

Red ellipses are PDG fits

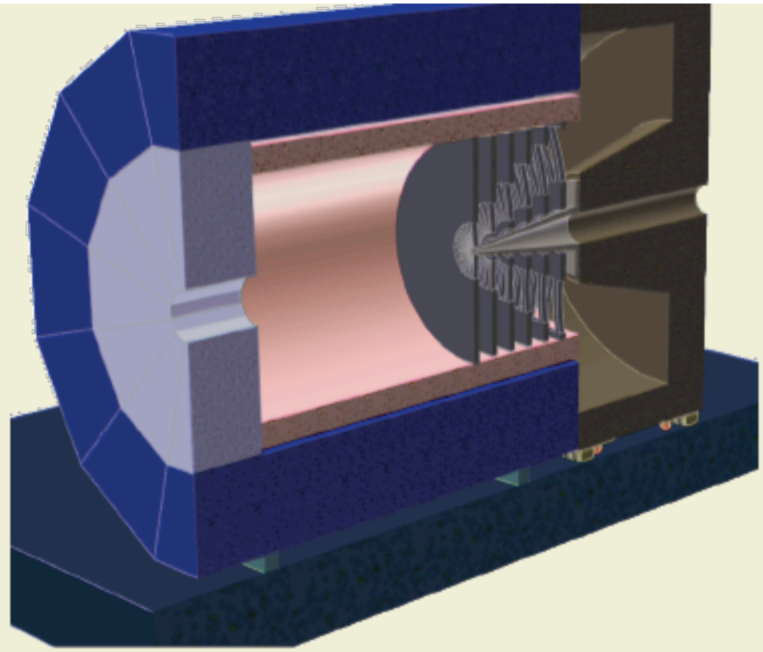
Blue bands represent expected data: Qweak (left) and PVDIS--6GeV (right)

Green bands are proposed SOLID PVDIS





SOLID – Large Acceptance Device

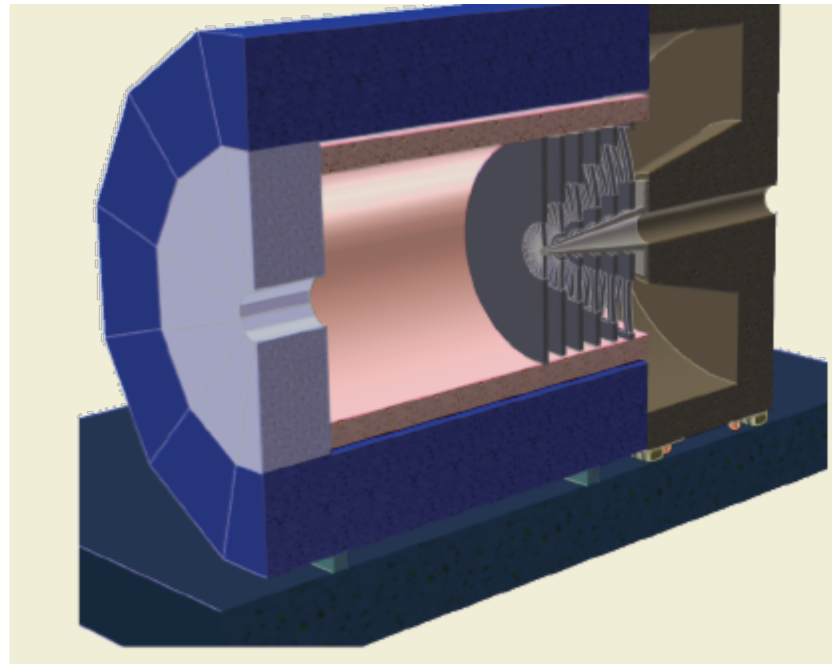


- **Moderate running times**
  - Large Acceptance
  - High Luminosity on LH2 & LD2
- **Better than 1% errors for small bins**
- **Kinematics:**
  - Large Q^2 coverage
  - x-range 0.25-0.75
  - $W^2 > 4$ GeV^2

- **Requirements:**
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Baffling to cut backgrounds
  - Trajectories measured after baffles
  - Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics
  - Precision polarimetry (0.4%) Compton and atomic hydrogen Moller

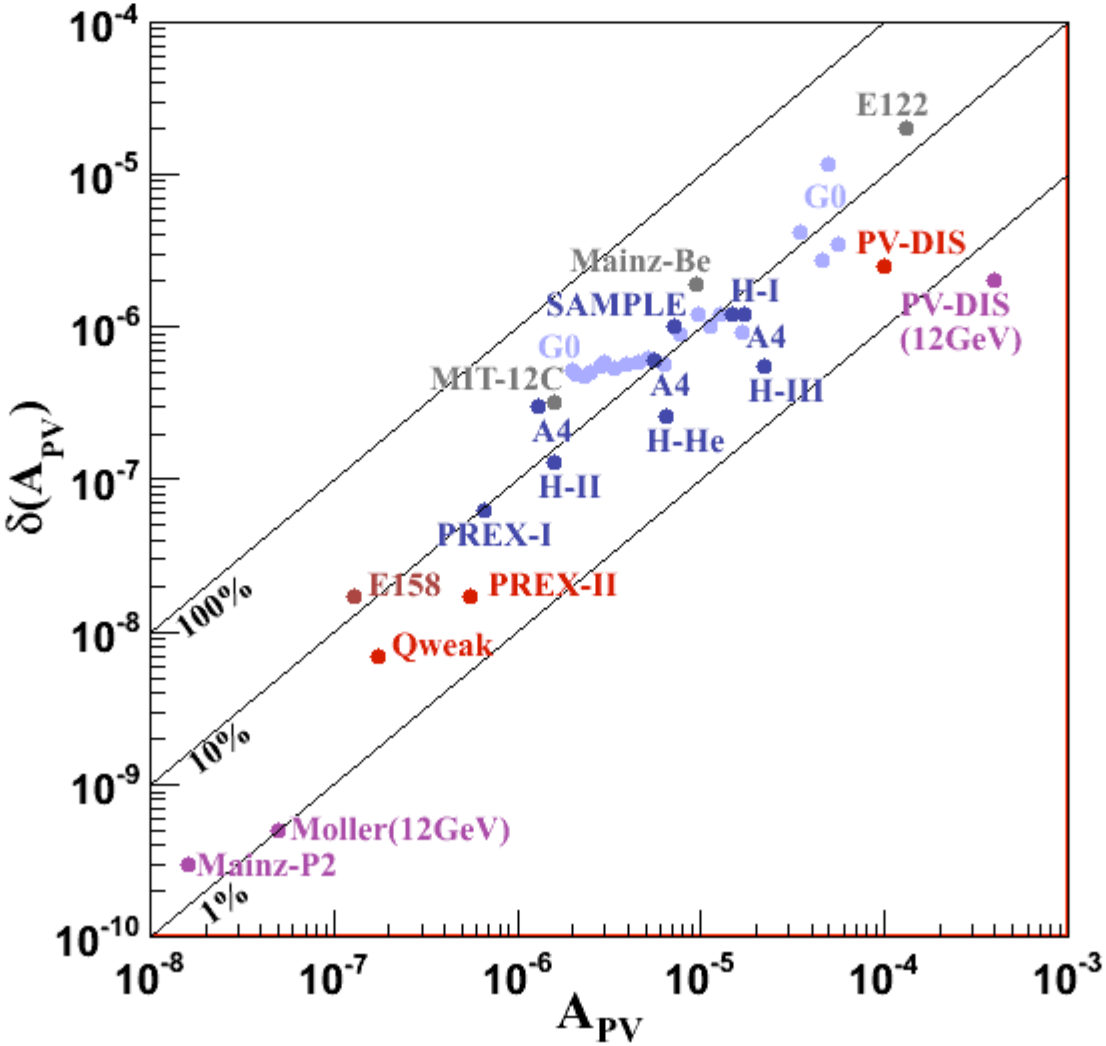
SOLID – Parity-Conserving Physics

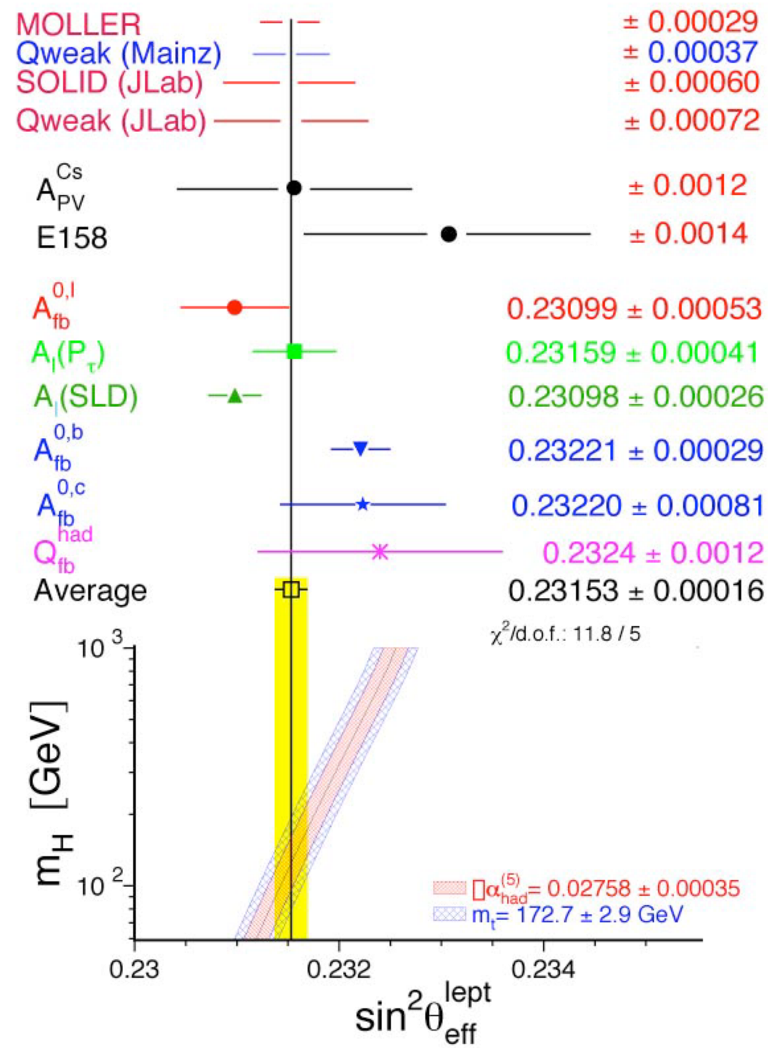
- SIDIS with Transversely Polarized 3He
  approved 90 days
- SIDIS with Longitudinally Polarized 3He
  approved 35 days
- SIDIS with Transversely Polarized Proton
  approved 120 days
- Near Threshold Electroproduction of J/Psi
  approved 60 days



PVDIS approved for 169 days (half of full request)

PVES Experiment Summary





Summary

- Strange vector form factors of proton – small, consistent with zero.
- Qweak: First measurement of proton's weak charge, consistent with Standard Model, 25x more data on tape
- PREx: two-sigma evidence for neutron "skin" of ^{208}Pb; will improve after JLab comes online after 12 GeV upgrade, and will extend to ^{48}Ca
- MOLLER and SOLID: major programs after JLab upgrade two complementary Standard Model tests.

Grazie to the MENU 2013 organizers for inviting Juliette Mammei to give this talk, and for accepting me as a poor substitute….