The Exact and Approximate Symmetries of Electroweak Interactions

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Unique Low Energy Tests exploiting the special properties of Leptons, Nucleons and Nuclei

Outline of Lectures

- Standard Model of Electroweak Interactions
- Searches for Violations of Discrete Symmetries
- Charged Lepton Flavor Violation and Precision Weak Neutral Current Experiments
- Parity-Violating Electron Scattering Experiments, Electroweak Probes of Hadron Structure & Precision Weak Charged Current Experiments

Review and Perspective

- In lecture 1, we introduced the electroweak interaction and its verification using colliders
- In lecture 2, we learned about symmetries and discussed EDM searches to find T-violation
- In lecture 3, we discussed lepton flavor violation and weak neutral current experiments
- Coupled with Vincenzo's lecture yesterday, we are now quite familiar with the language of BSM searches and the role of symmetries at low energies

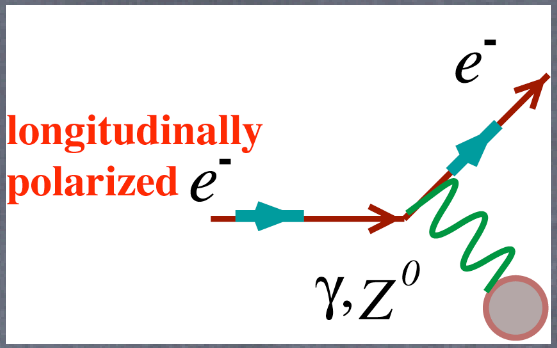
Outline of Lecture #4

- Parity-violating electron scattering as a probe of new flavor diagonal amplitudes at the TeV scale
- Electroweak probes of hadron structure
- Precision charged current experiments
- Muon g-2

Parity-Violating Electron Scattering

Weak Neutral Current (WNC) Interactions at $Q^2 << M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Targets



$$\sigma \propto |A_\gamma + A_{weak}|^2$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

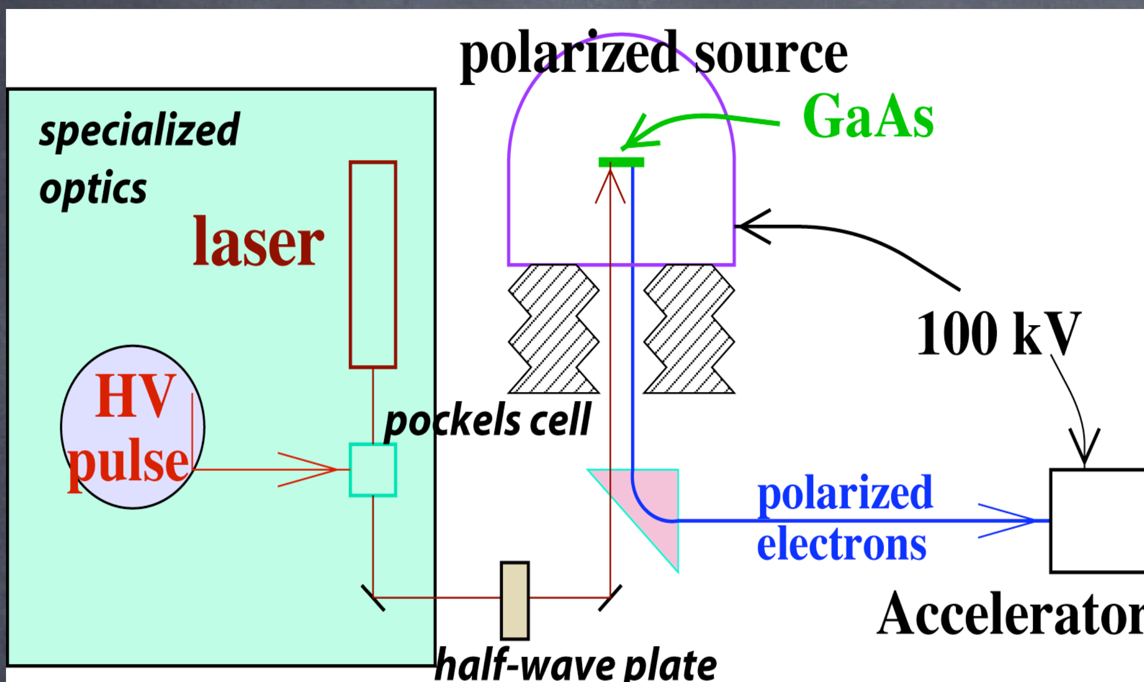
g_V and g_A are function of $\sin^2\theta_W$

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \textit{to} \quad 10^{-4} \cdot Q^2$$

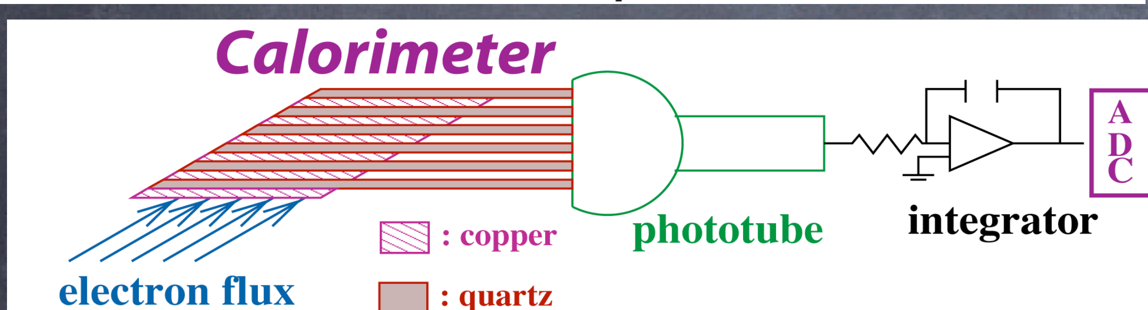
Specific choices of kinematics and target nuclei probes different physics:

- *In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering*
- *Early 90s: target couplings carry novel information about hadronic structure*
- *Now: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale*

Experimental Technique



- Optical pumping of a GaAs wafer
- Rapid helicity reversal: change sign of longitudinal polarization ~ 100 Hz to minimize drifts (like a lockin amplifier)
- Control helicity-correlated beam motion: under sign flip, keep beam stable at the sub-micron level



"Flux Integration": very high rates

direct scattered flux to background-free region

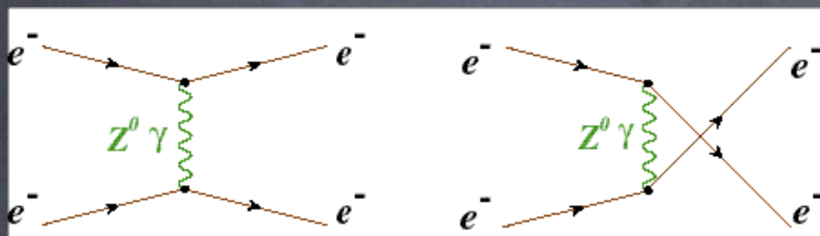
Technical progress over 3 decades has enabled ppb systematic control

Parity-violating electron scattering has become a precision tool:

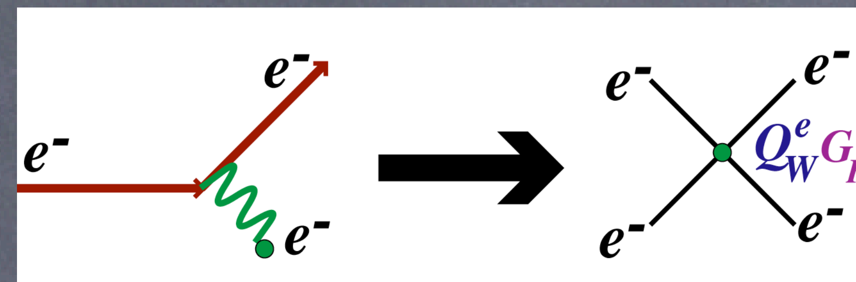
- *Many-body nuclear physics: Neutron skin of ^{208}Pb*
- *Nucleon structure: strangeness contribution to form factors*
- *Valence quark structure: Deep inelastic scattering at high-x*
- *Search for new TeV physics: Precision electroweak parameters*

Parity-Violating Electron-Electron (Møller) Scattering

E158 @ SLAC



50 GeV at SLAC: ~ 150 ppb!

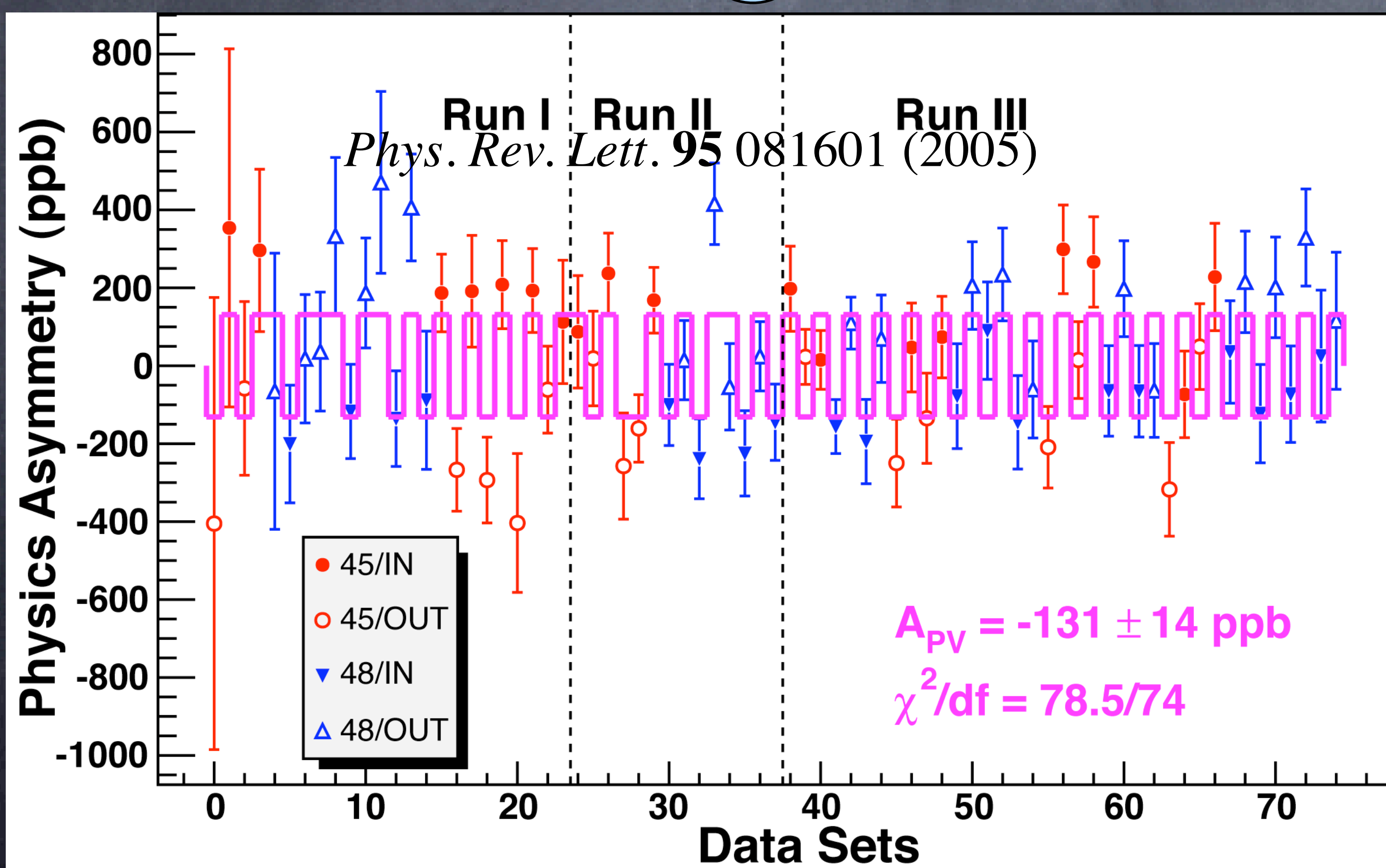


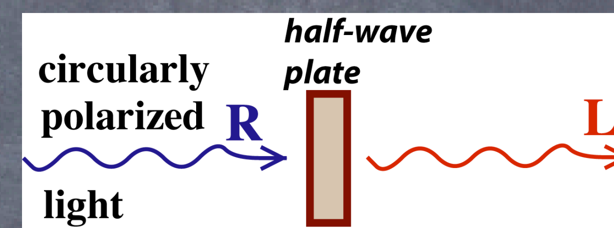
Purely leptonic reaction

$$A_{PV} \propto m_e E_{lab} (1 - 4\sin^2\vartheta_W)$$

$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

End Station A at the Standord Linear Accelerator Center (SLAC)

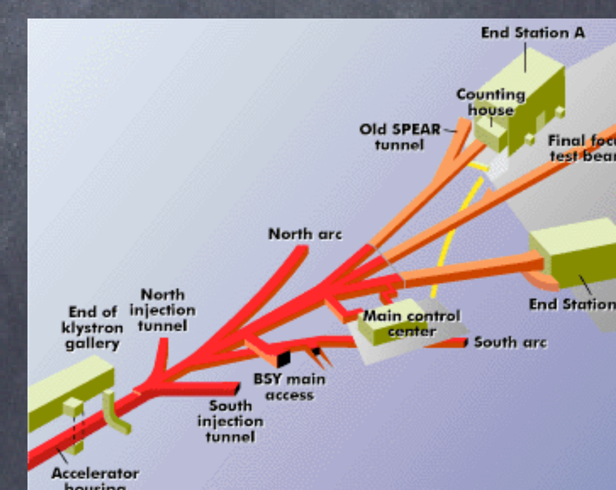




g-2 spin precession

45 GeV: 14.0 revs

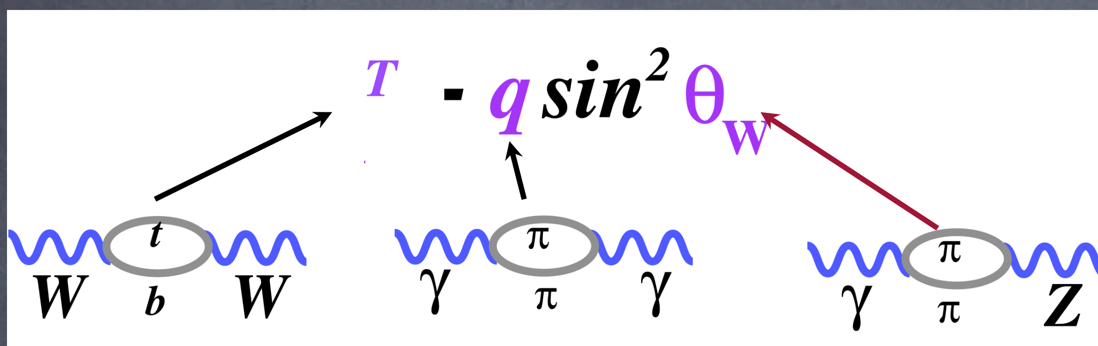
48 GeV: 14.5 revs

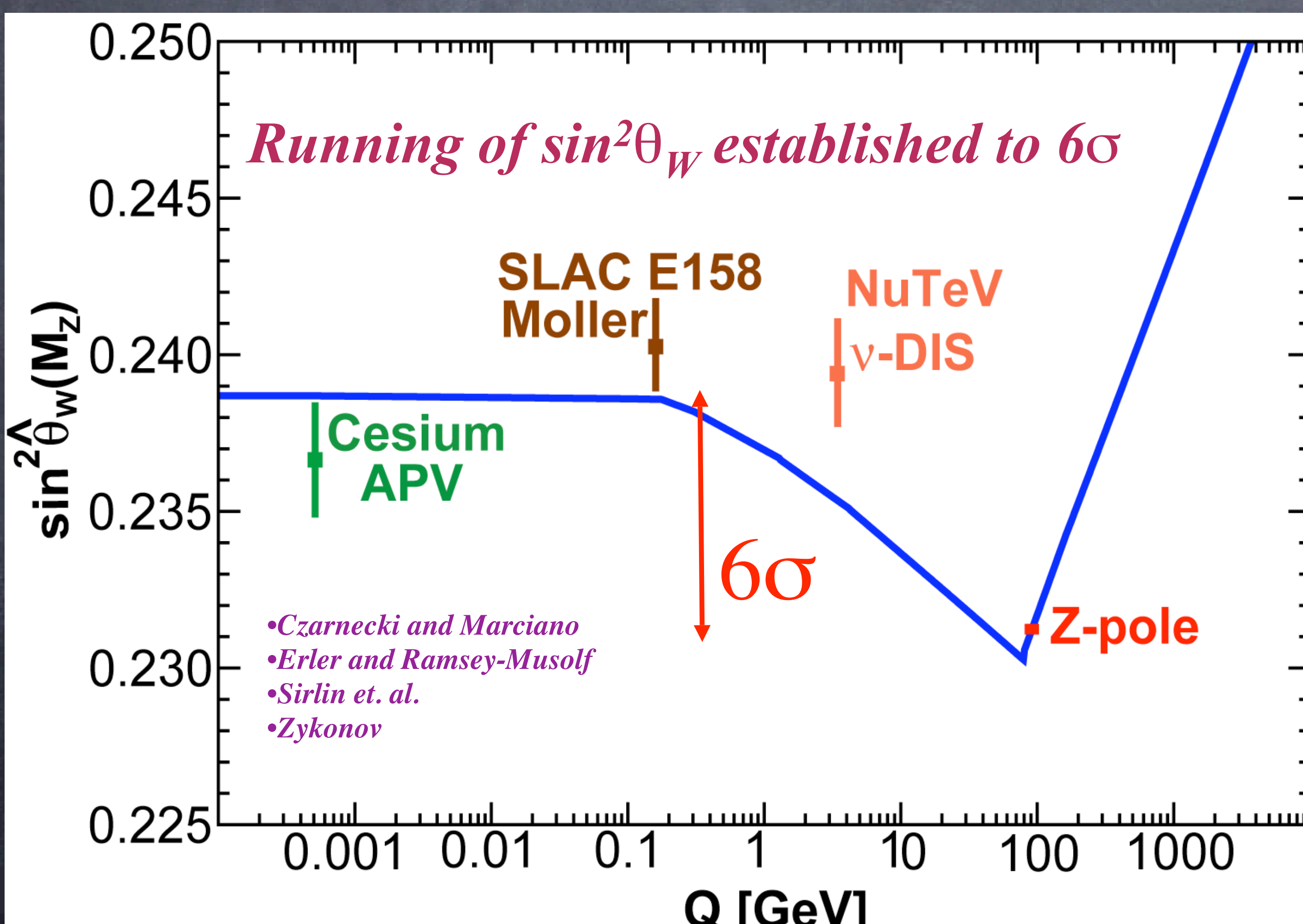


A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

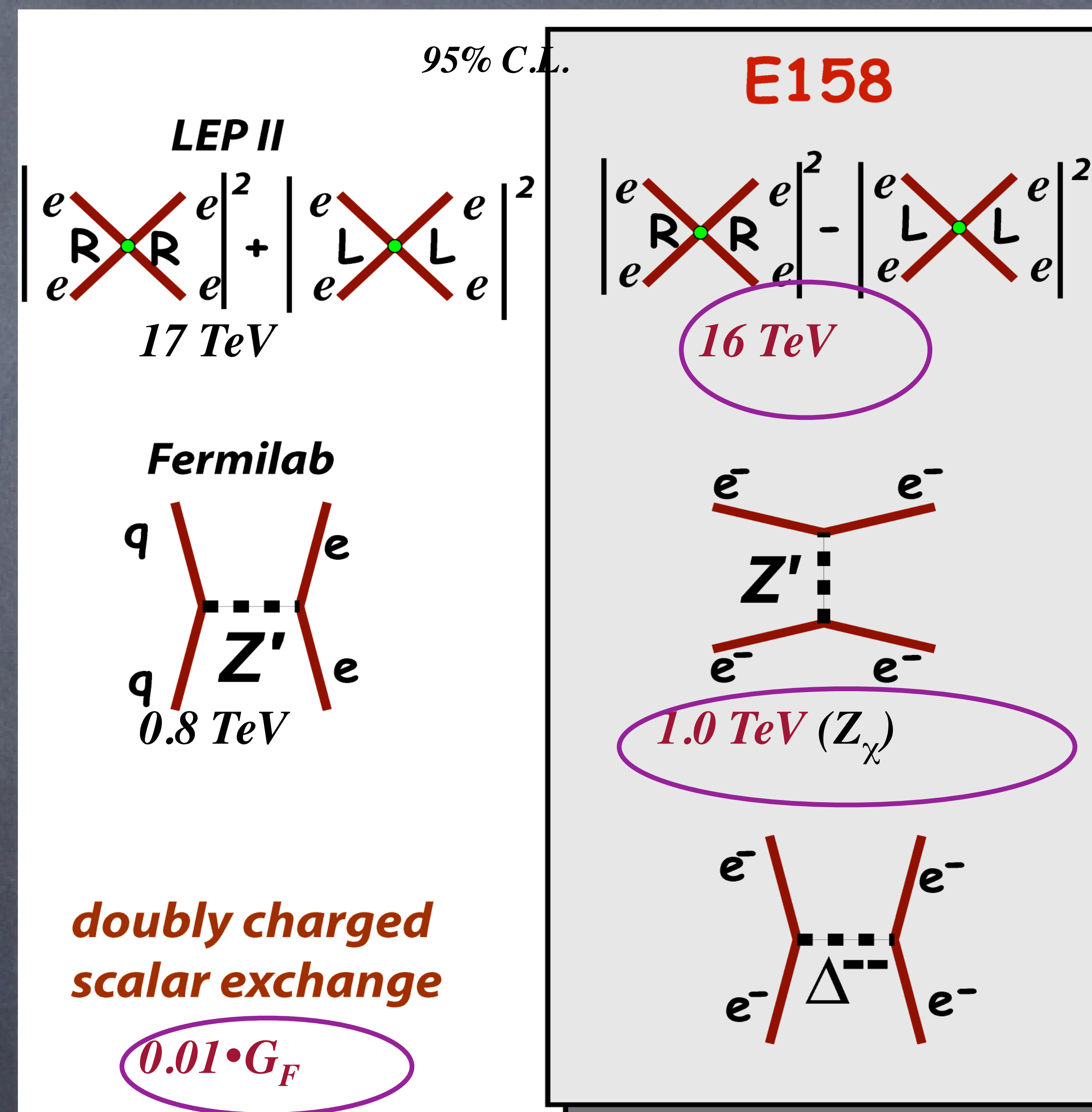
9

E158 Implications



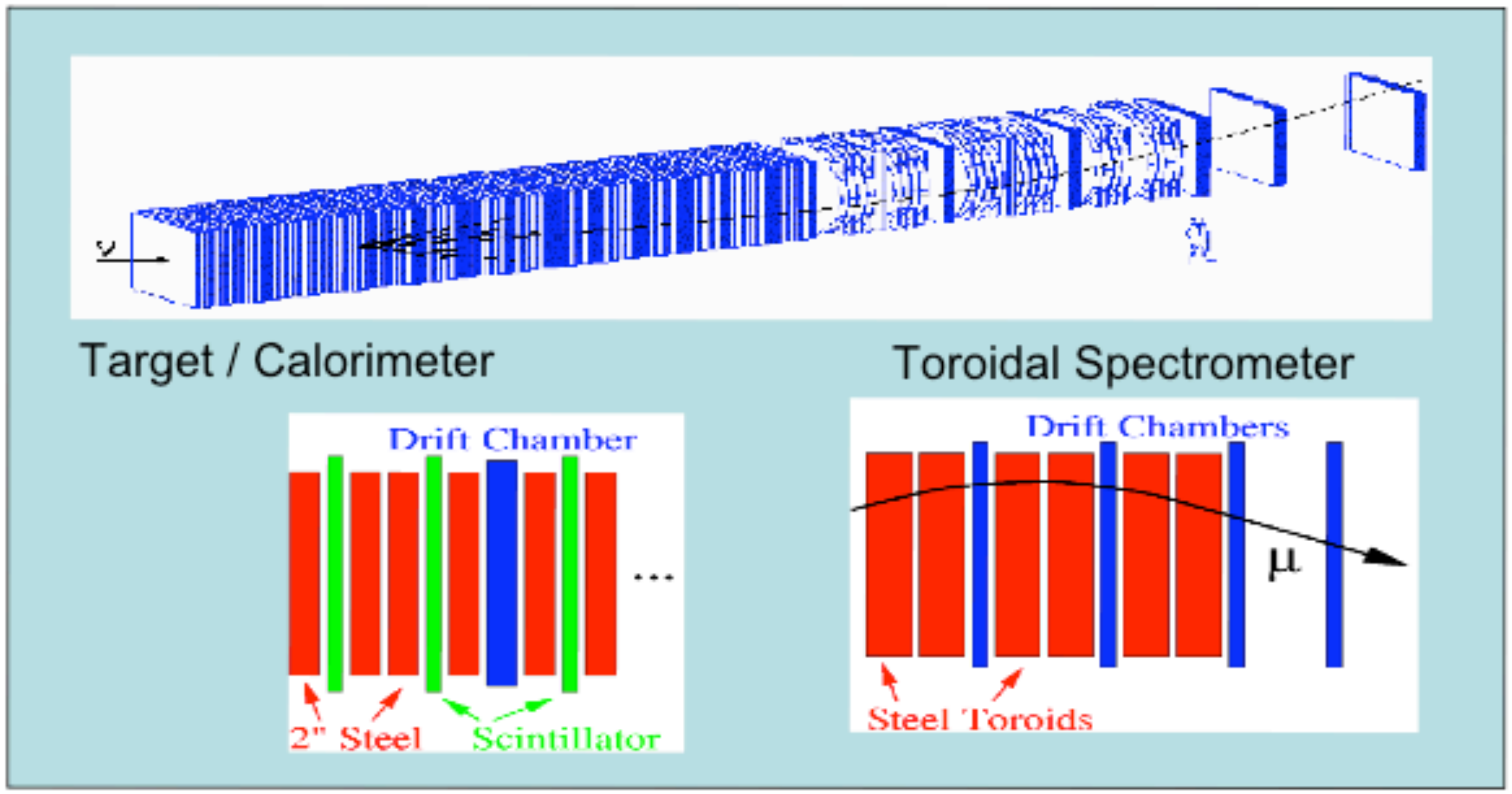


Limits on "New" Physics



Neutrino Deep Inelastic Scattering

NuTeV Neutrino Experiment



$$R^{-} = \frac{\sigma_{\nu N}^{NC} - \sigma_{\bar{\nu} N}^{NC}}{\sigma_{\nu N}^{CC} - \sigma_{\bar{\nu} N}^{CC}} \approx \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W \right)$$

$$\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

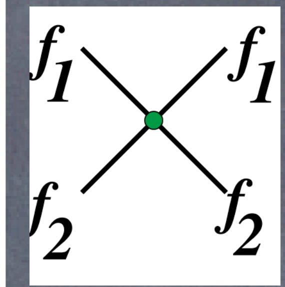
Standard Model prediction is 0.2227 (3σ deviation)

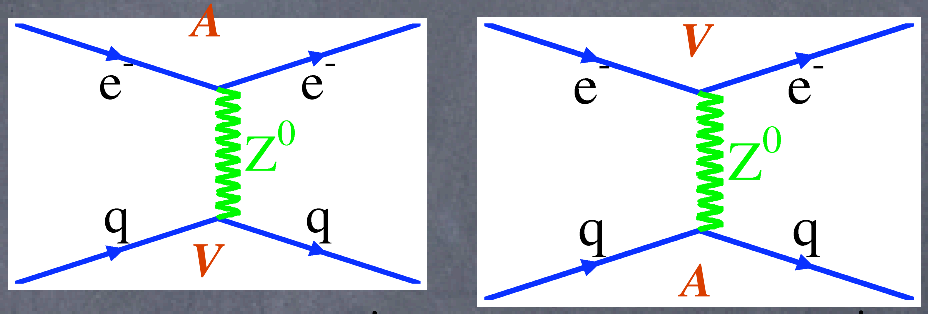
- Most precise measurement of neutrino-quark coupling
- subtle quark physics effects can affect the result
- generated great interest in both nuclear and particle phenomenology

Lepton-Quark Neutral Current Interactions

Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2}\eta_{ij}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma^\mu f_{2j}$$

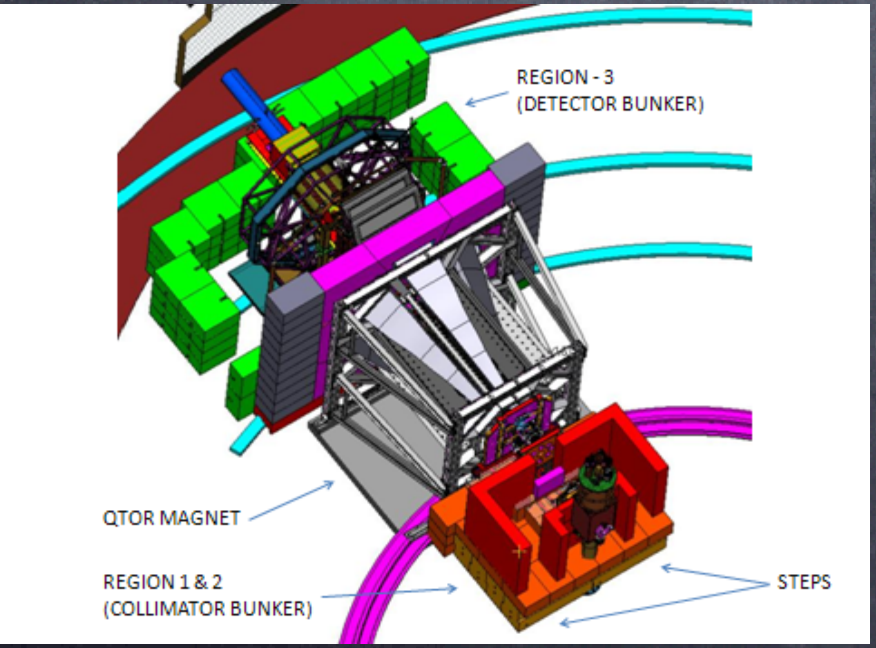




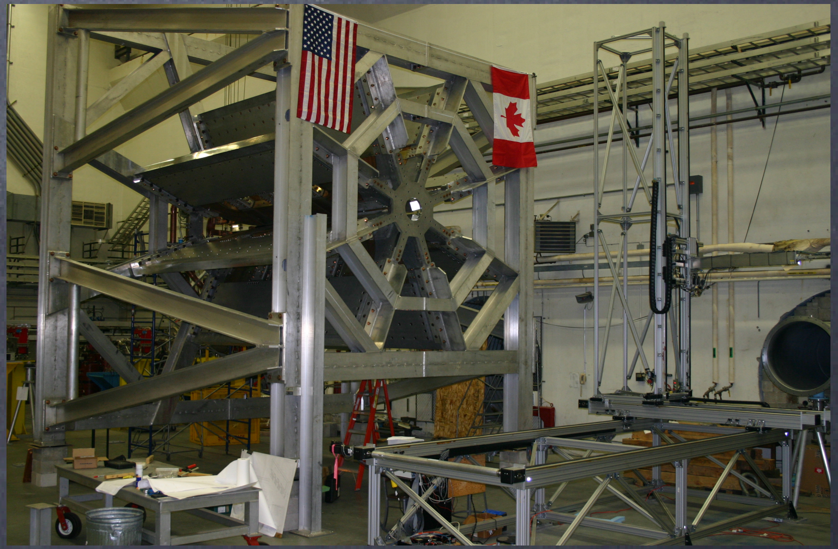
$$C_{1i} \equiv 2g_A^e g_V^i \qquad C_{2i} \equiv 2g_V^e g_A^i$$

$$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$$ → *PV elastic e-p scattering, APV*

$$\delta(C_{2q}) \propto (-\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} + \eta_{LR}^{eq})$$ → *PV deep inelastic scattering*



Qweak
at
Jefferson Lab



Qweak at Jefferson Laboratory

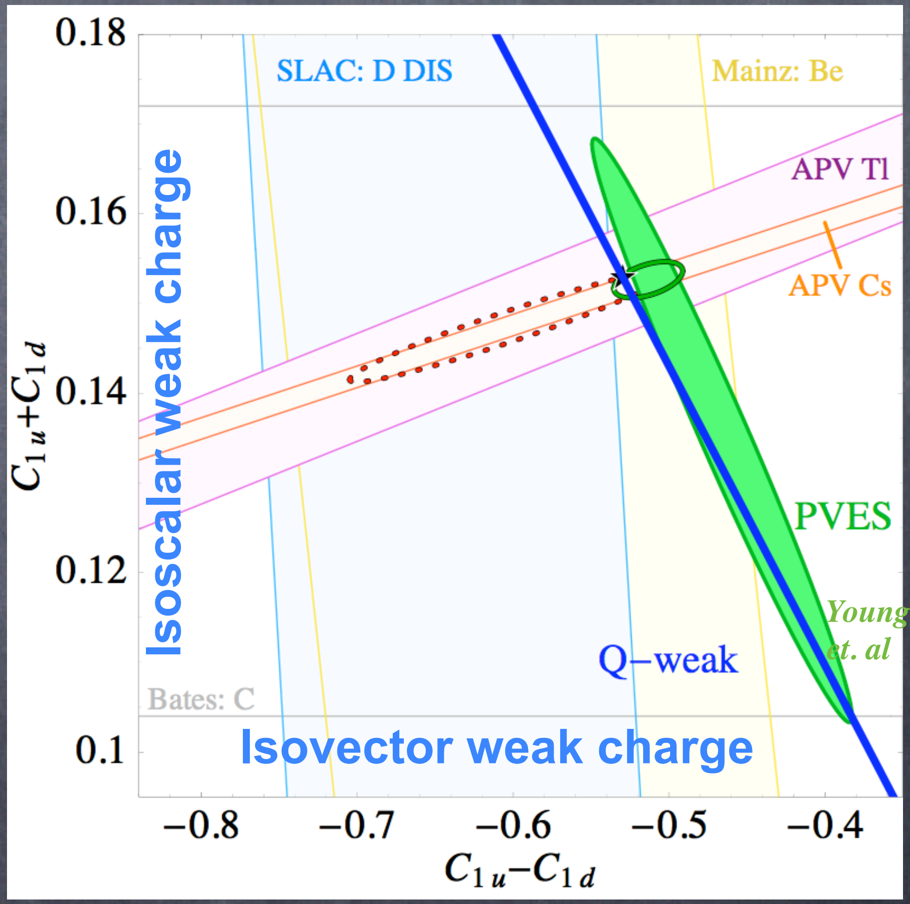
A_{PV} in elastic e-p scattering:

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

$$Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$,
Extracted using global fit

$E = 1.165$ GeV, $\theta_{lab} \sim 9^o$,
$Q^2 = 0.026$ GeV^2



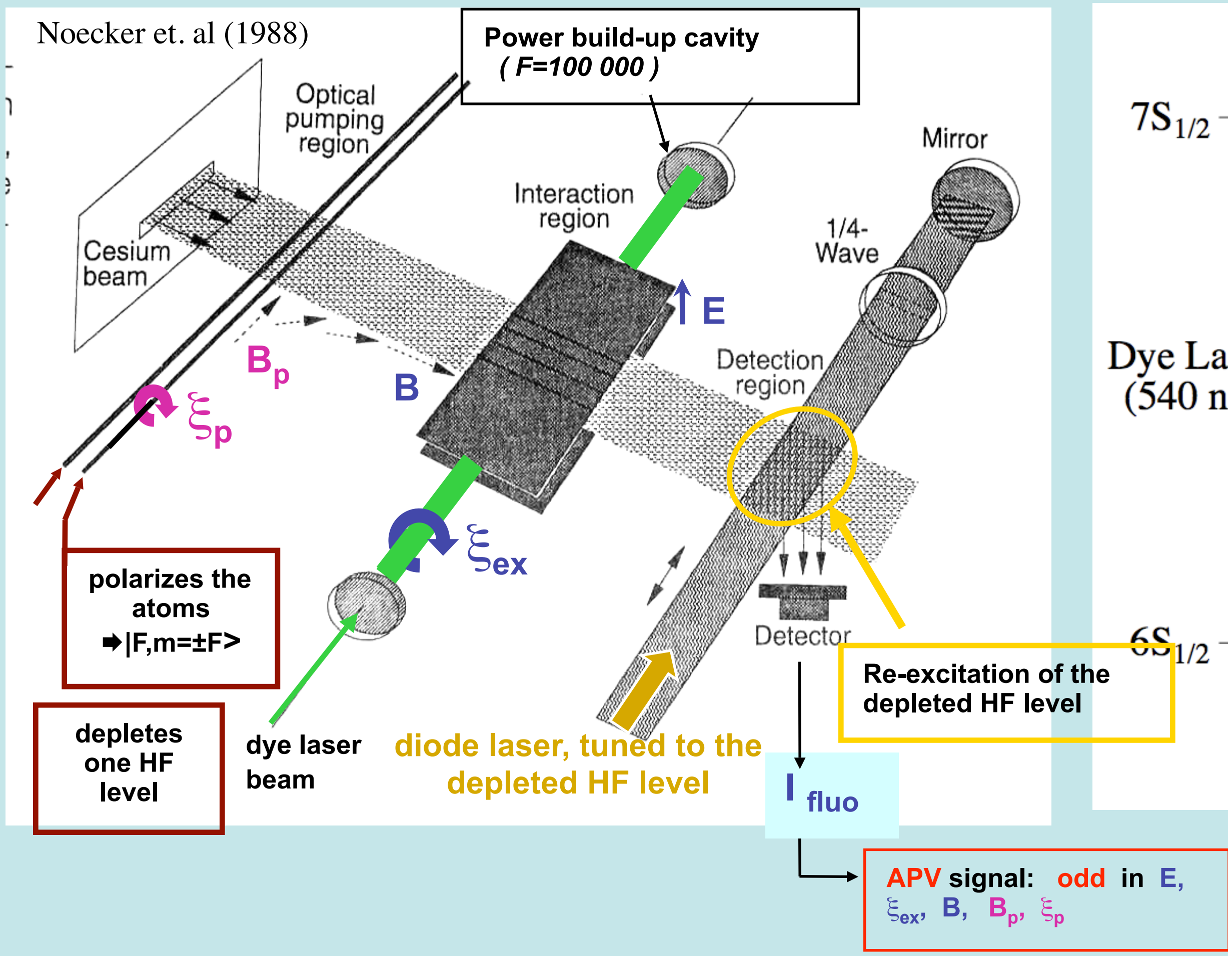
86 scientists from 25 institutions
including U. Manitoba and TRIUMF

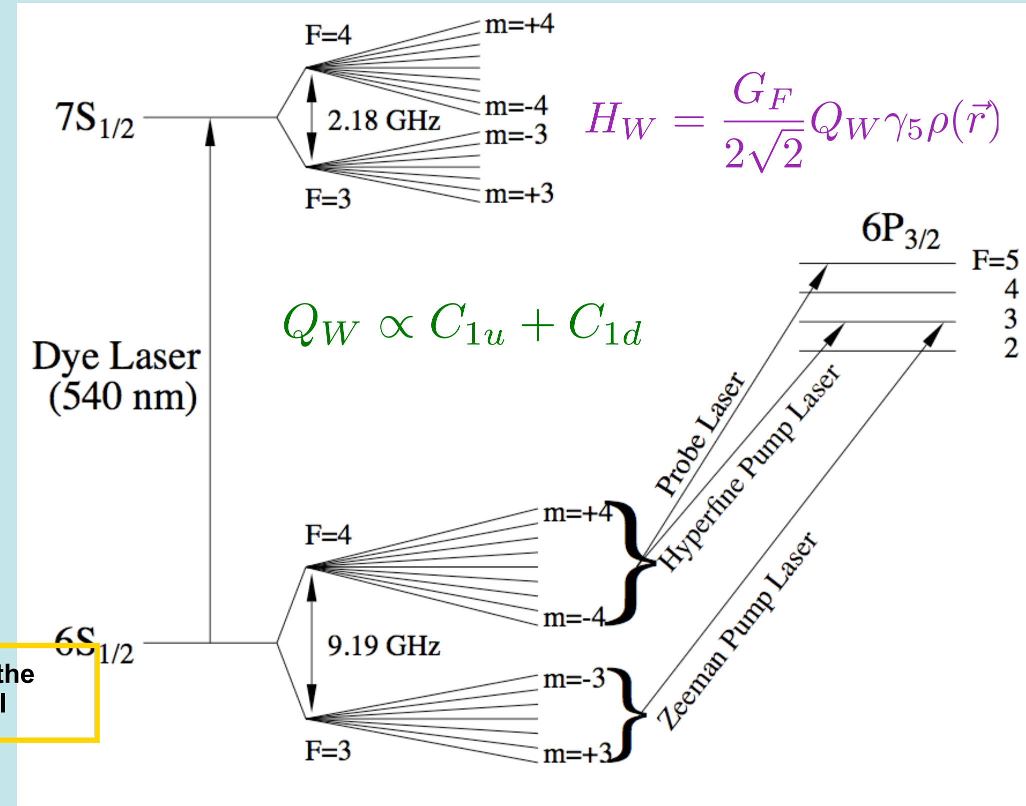
- Design and construction over past several years
- Installation nearly complete
- First beam next week!
- Data ~ 2010 thru mid-2012

New, complementary constraints on lepton-quark interactions at the TeV scale

Atomic Parity Violation

- $6S \rightarrow 7S$ transition in ^{133}Cs is forbidden within QED
- Parity Violation introduces small opposite parity admixtures
- Induce an E1 Stark transition, measure E1-PV interference
- 5 sign reversals to isolate APV signal and suppress systematics
- Signal is ~ 6 ppm, measured to 40 ppb





$$H_W = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

$$Q_W \propto C_{1u} + C_{1d}$$

New alkalis being investigated initiatives include TRIUMF

Electroweak and Hadron Physics Interplay

- nuclei and nucleons are special laboratories to test electroweak interactions
- these are bound states ultimately governed by QCD dynamics
- a detailed knowledge of hadron dynamics is often needed to interpret the measurement and probe the TeV scale
- conversely, the experimental techniques being developed lead to new insights on hadron structure. Some classic examples:
  - elastic electron-nucleon and -nuclear scattering
  - nuclear beta decay and muon capture

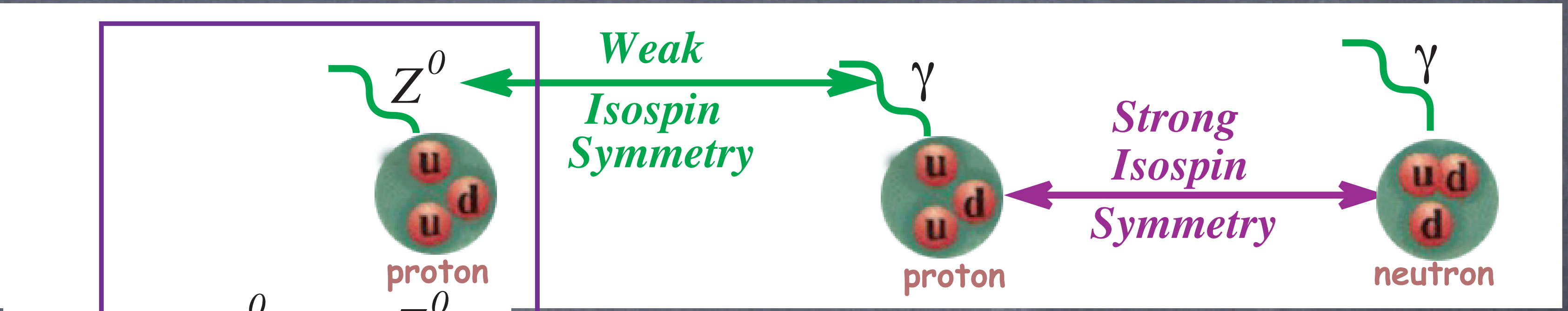
Very recent: Lamb Shift (1s-2s transition) in muonic hydrogen — Proton charge radius

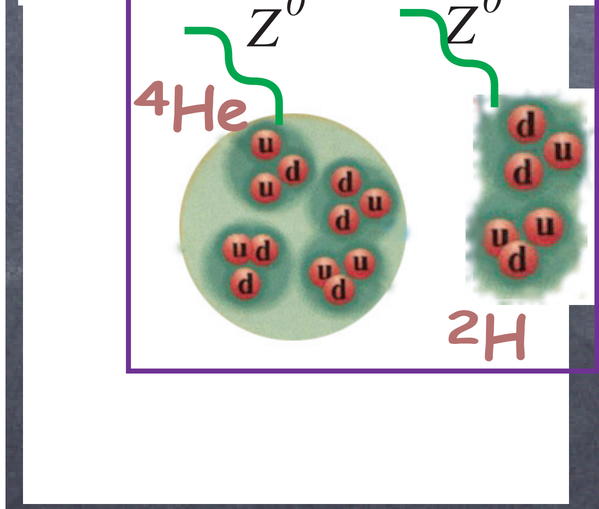
Strange Quarks in the Nucleon

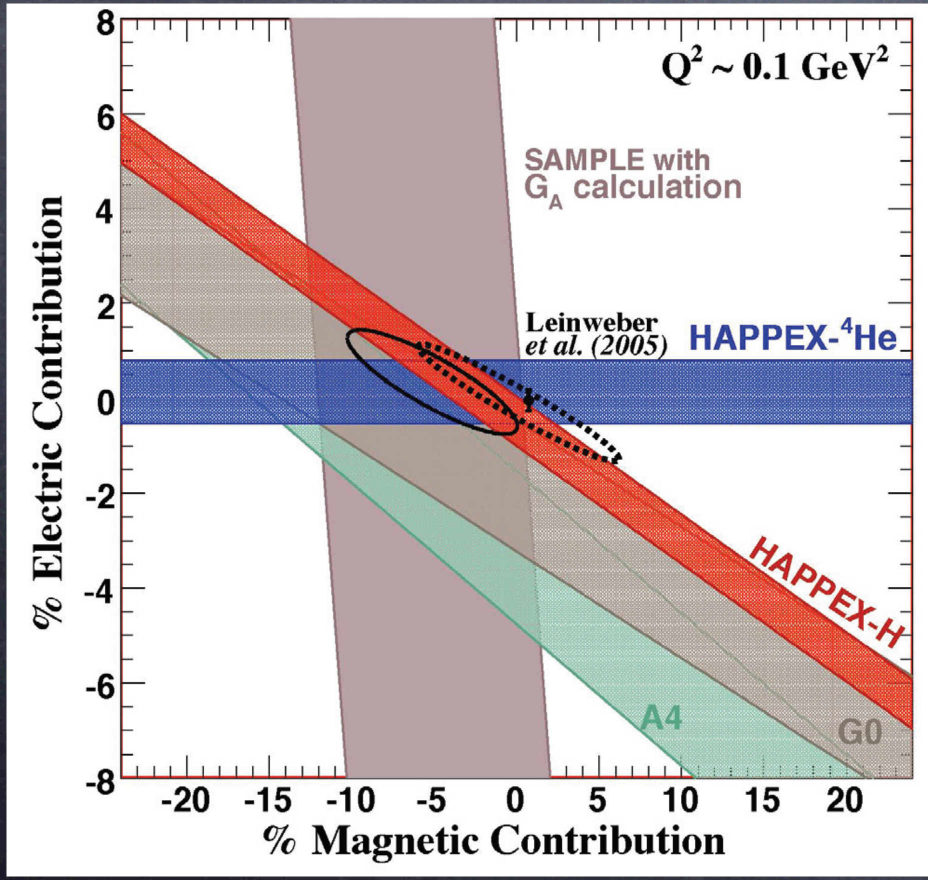
Quark Model ⟷ ? ⟷ *QCD*

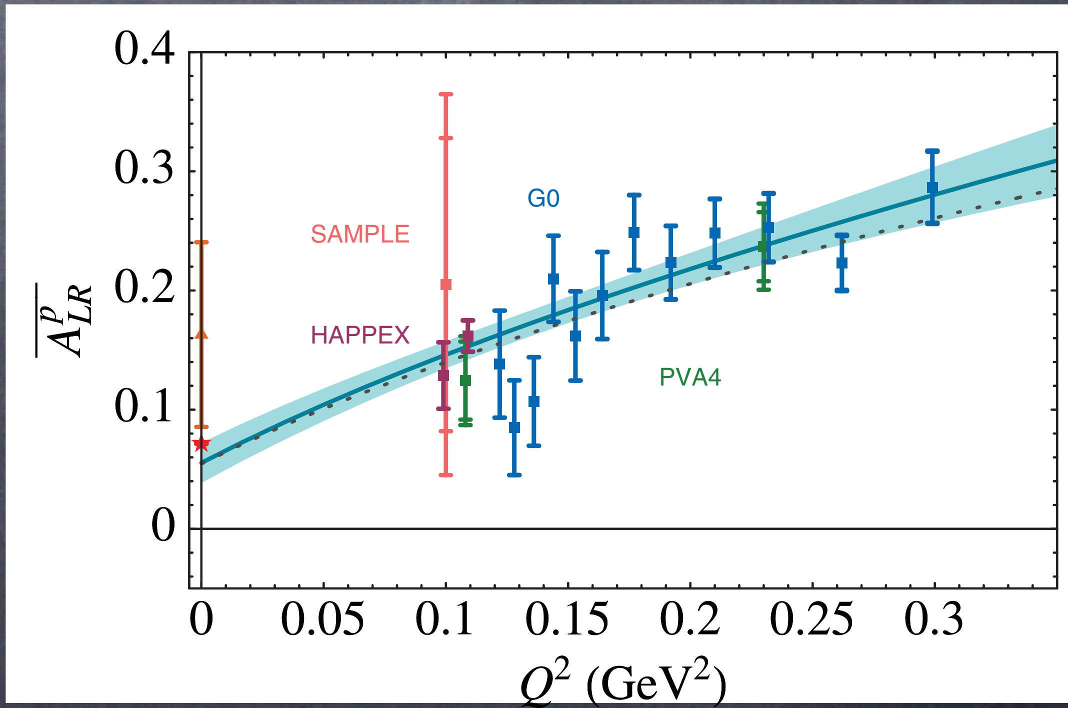
Late 1980's

Strange quarks carry nucleon momentum: Other external properties affected?



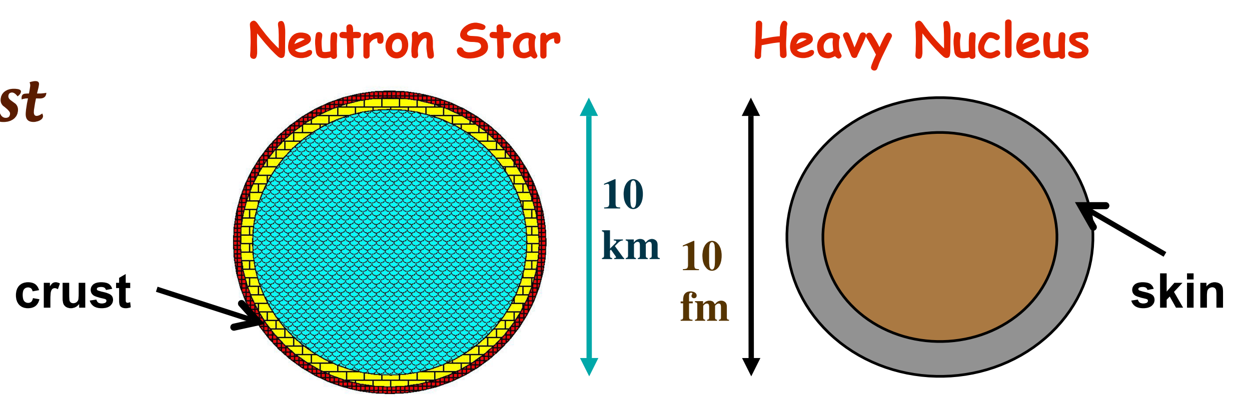






PREX at Jefferson Laboratory

- *Neutron star has solid crust over liquid core.*
- *Heavy nucleus has neutron skin.*



Both neutron skin and neutron star crust are made out of neutron rich matter at similar densities.

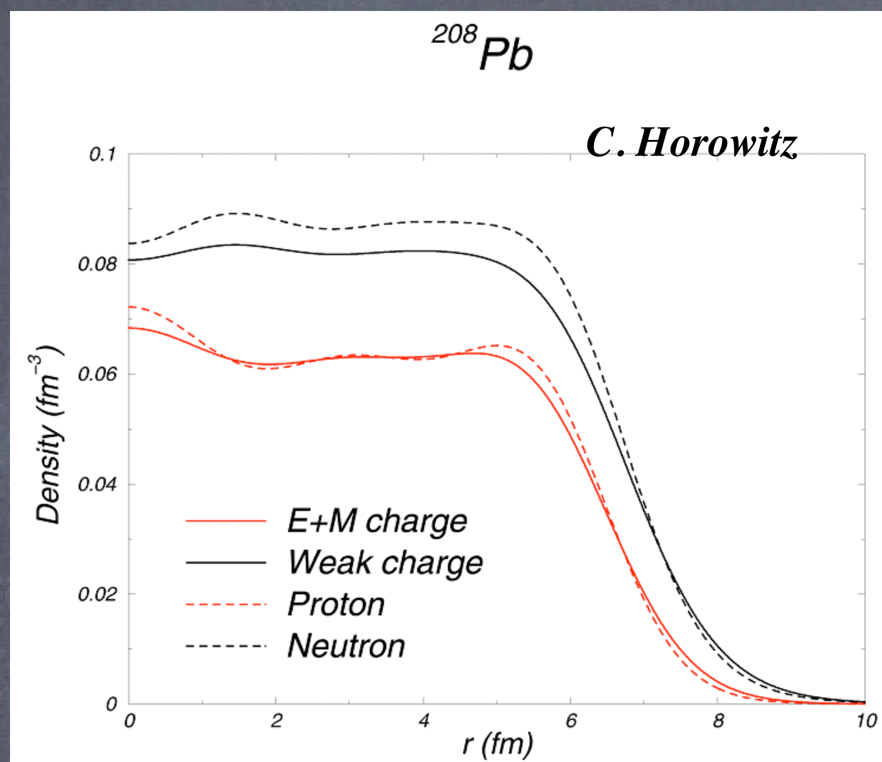
$R_p \sim 5.5$ fm

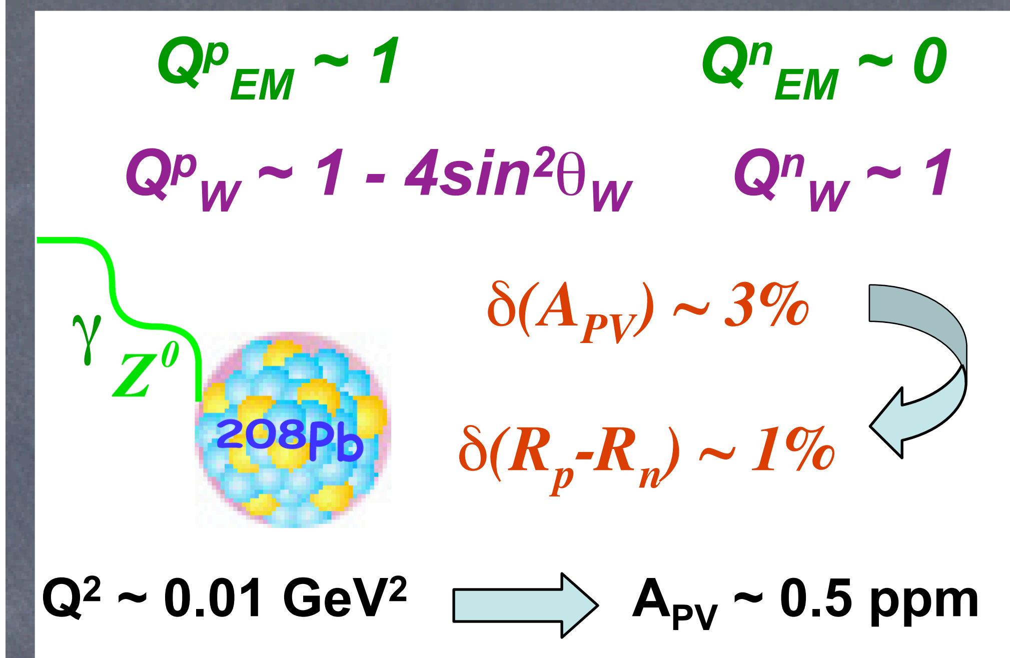
$R_n - R_p \sim 0.1$ to 0.3 fm?

- *A neutron skin is expected: how thick is it?*
- *The extent of the skin constrains the transition density from solid crust to liquid core in a neutron star*
- *The density dependence of the symmetry energy constrains the composition of the neutron star core: important implications for rate of neutron star cooling*

An experimental clean measurement of skin is now viable:

PREX and Neutron Stars





Construction and Installation took place over the last 6 months

A technically demanding measurement:

- Rate ~ 2 GHz
- Separate excited state at 2.4 MeV
- Stat. Error ~ 15 ppb
- Syst. Error ~ 1 to 2 %

Physics run April - mid June

expect to have < 3% measurement of neutron radius

Result highly prized by nuclear structure and nuclear astrophysics communities

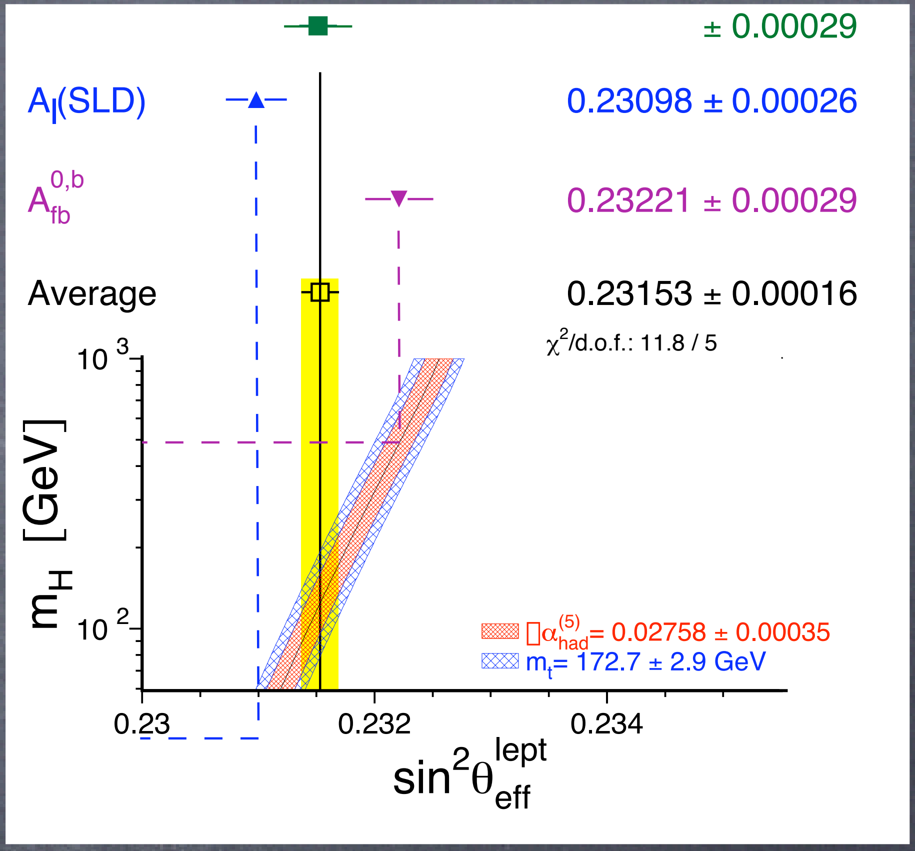
MOLLER at Jefferson Laboratory

Measurement of Lepton-Lepton Electroweak Reaction

E_{beam} = 11 GeV   75 μA   80% polarized —~ 38 weeks (~ 2 yrs)→ *$\delta(A_{PV})$ = 0.73 ppb*

A_{PV} = 35.6 ppb → **$\delta(Q^e_W)$ = ± 2.1 (stat.) ± 1.0 (syst.) %**

$\delta(\sin^2\theta_W)$ = ± 0.00026 (stat.) ± 0.00012 (syst.) → *~ 0.1%*



Project design, construction and installation will take 4-5 years

Jefferson Lab 12 GeV Upgrade

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j \xrightarrow{A_{PV}} \frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5 \text{ TeV}$$

Best current limits on 4-electron contact interactions: LEPII at 200 GeV

(Average of all 4 LEP experiments)

$$\frac{\Lambda}{\sqrt{|g^2_{RR} + g^2_{LL}|}} = 4.4 \text{ TeV} \quad \text{OR} \quad \frac{\Lambda}{g_{RL}} = 5.2 \text{ TeV}$$

insensitive to $|g^2_{RR} - g^2_{LL}|$

Precision Tests of the Weak Charged Current

$$L_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \left[\overline{U_i} \gamma^\mu (1-\gamma^5) \mathbf{V}_{ij} D_j + \overline{\nu_k} \gamma^\mu (1-\gamma^5) l_k \right] + \text{h.c.}$$

$$M^{CC} \approx \frac{g^2}{8M_W^2} (V-A) \otimes (V-A)$$

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \quad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \nu = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \quad l = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

Fermi Constants

μ **decay** $\quad \frac{G_F^\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2} \left(1 + \Delta r_\mu\right)$

β **decay** $\quad \frac{G_F^\beta}{\sqrt{2}} = \frac{g^2}{8M_W^2} V_{ud} \left(1 + \Delta r_\beta\right)$

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathbf{V}\mathbf{V}^\dagger = \mathbf{V}^\dagger \mathbf{V} = I$$
$$\Downarrow$$
$$\sum_\beta V_{\alpha\beta} V^*_{\gamma\beta} = \delta_{\alpha\gamma}$$

$g^2 / 8M_W^2$ **is universal**

New physics

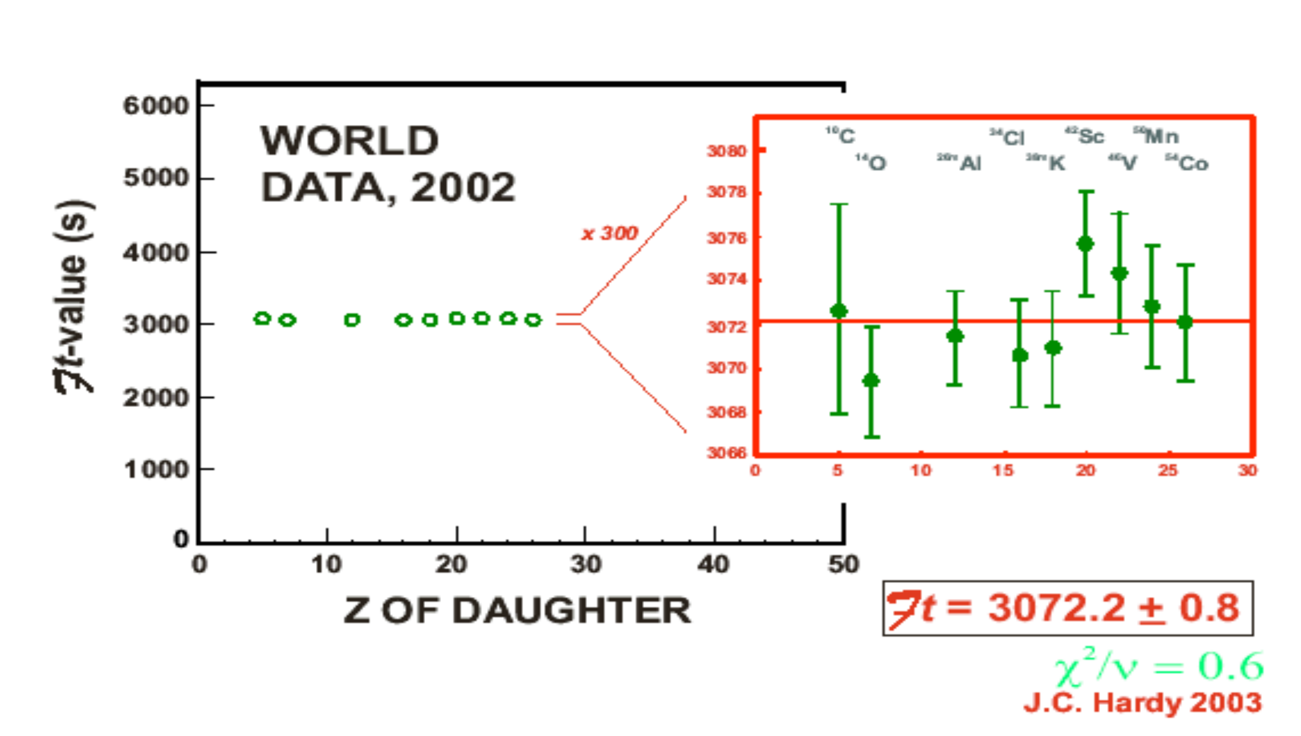
Universality obscured by $\quad G_F^\beta / G_F^\mu = V_{ud} \left(1 + \Delta r_\beta - \Delta r_\mu\right)$

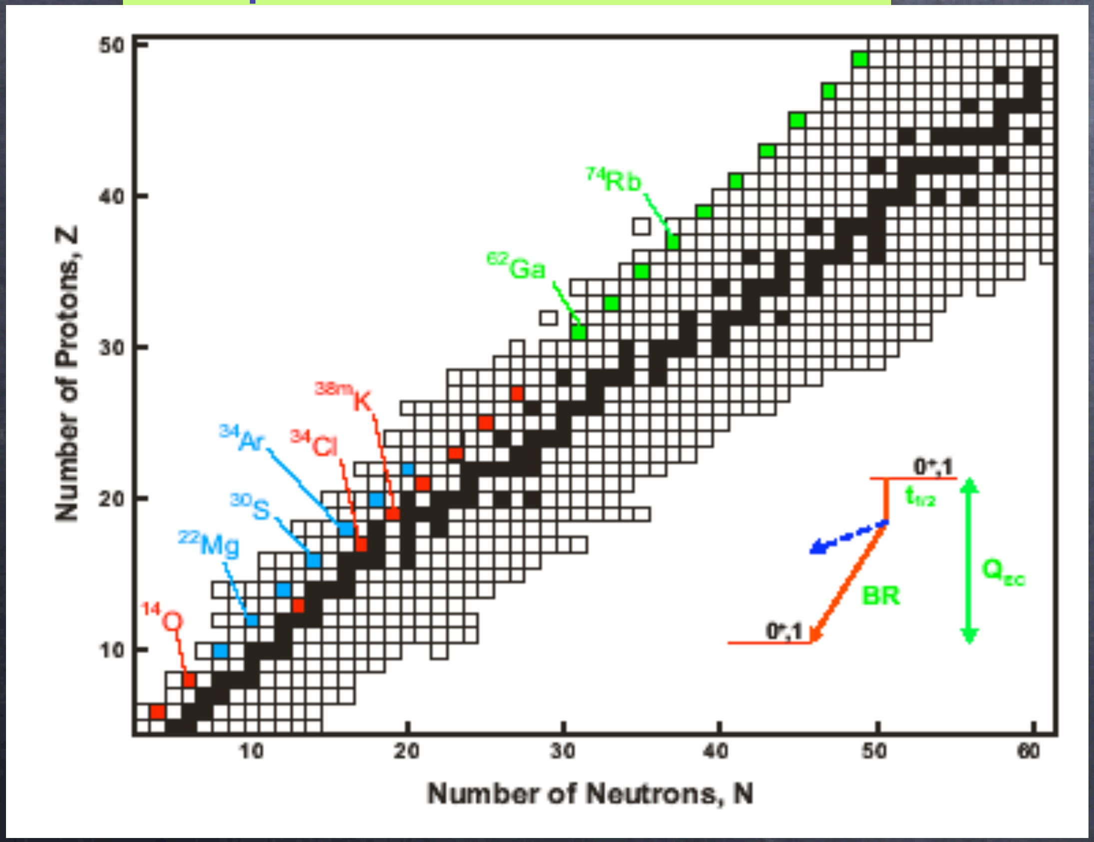
Super-Allowed Beta Decays

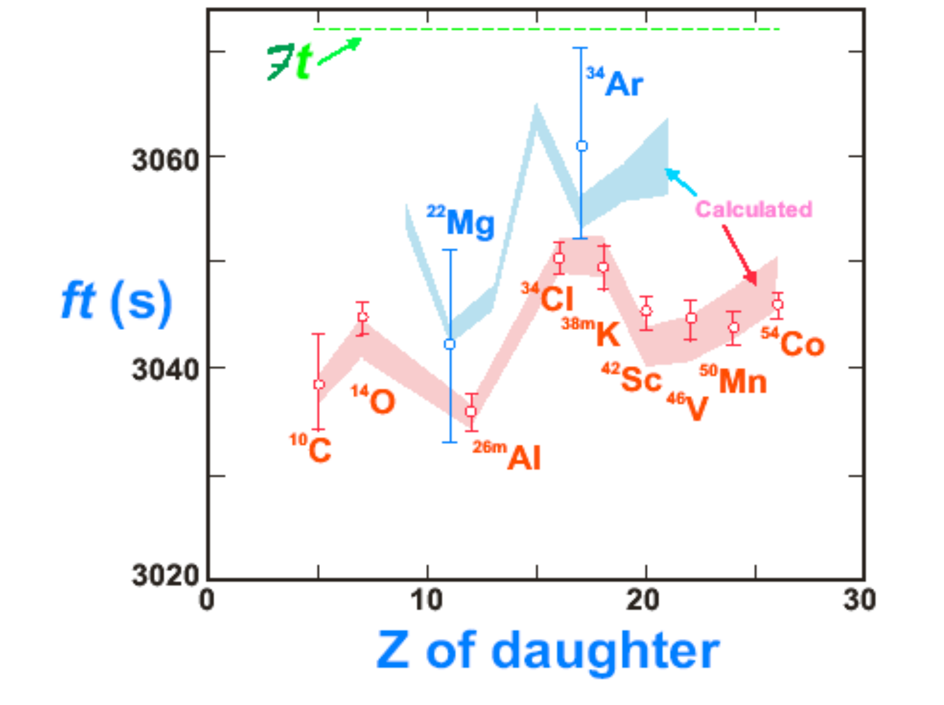
0^+ to 0^+ "Superallowed"

$$Ft = ft(1+\delta_R' + \delta_{NS})(1-\delta_C)$$
$$= K/2(G_F^\beta)^2$$

Nuclear structure-dependent corrections







Beta Decay Correlation Coefficients

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \mathcal{N}(E_e)\left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e} + \langle \vec{J} \rangle \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right]\right.$$

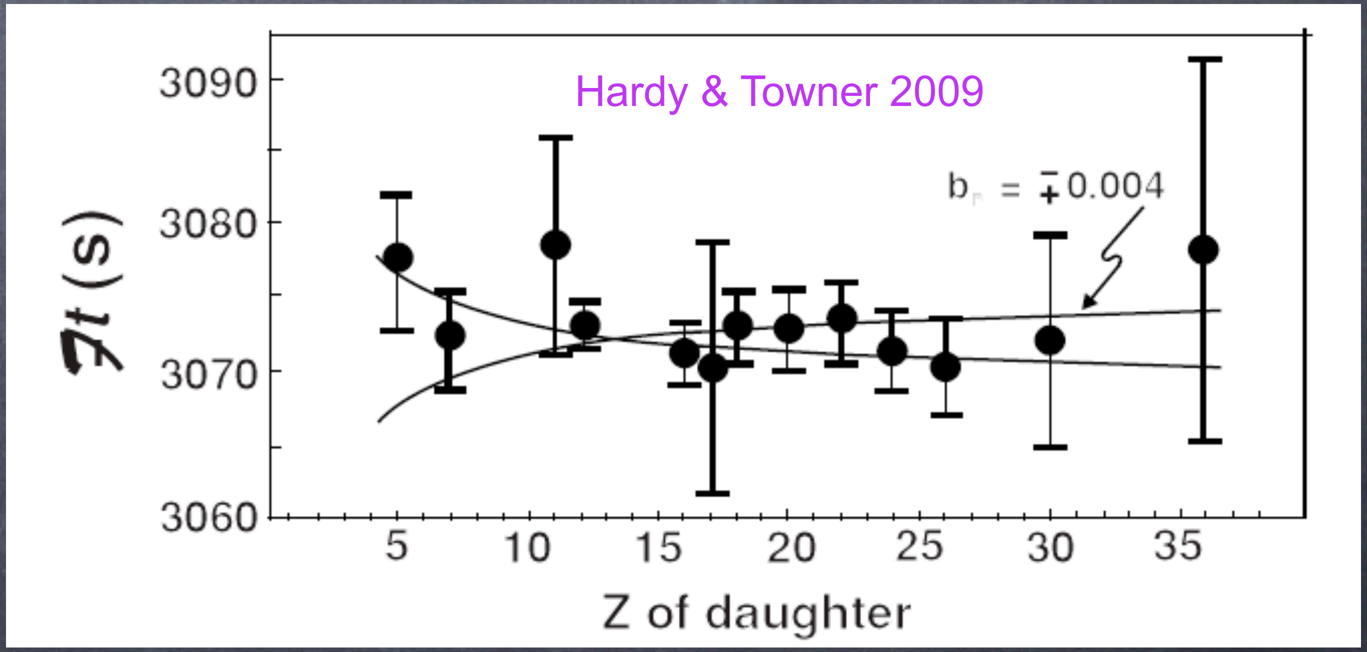
Jackson, Treiman, Wyld

$$\Gamma = \sqrt{1 - (Z\alpha)^2}$$

- Unique sensitivity to S,T operators (via interference terms $\propto m_e/E_e$)

- Example: limit on b from $0^+ \to 0^+$ transitions corresponds to

$$\frac{\Lambda}{\sqrt{C_S}} \geq 7\,\mathrm{TeV}$$



$$b_F = -0.0022 \pm 0.0026$$

The Neutron

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq k_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a\frac{\vec{k}_e \cdot \vec{k}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{k}_e}{E_e} + B\frac{\vec{k}_\nu}{E_\nu} + D\frac{\vec{k}_e \times \vec{k}_\nu}{E_e E_\nu}\right)\right]$$

with:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2}$$

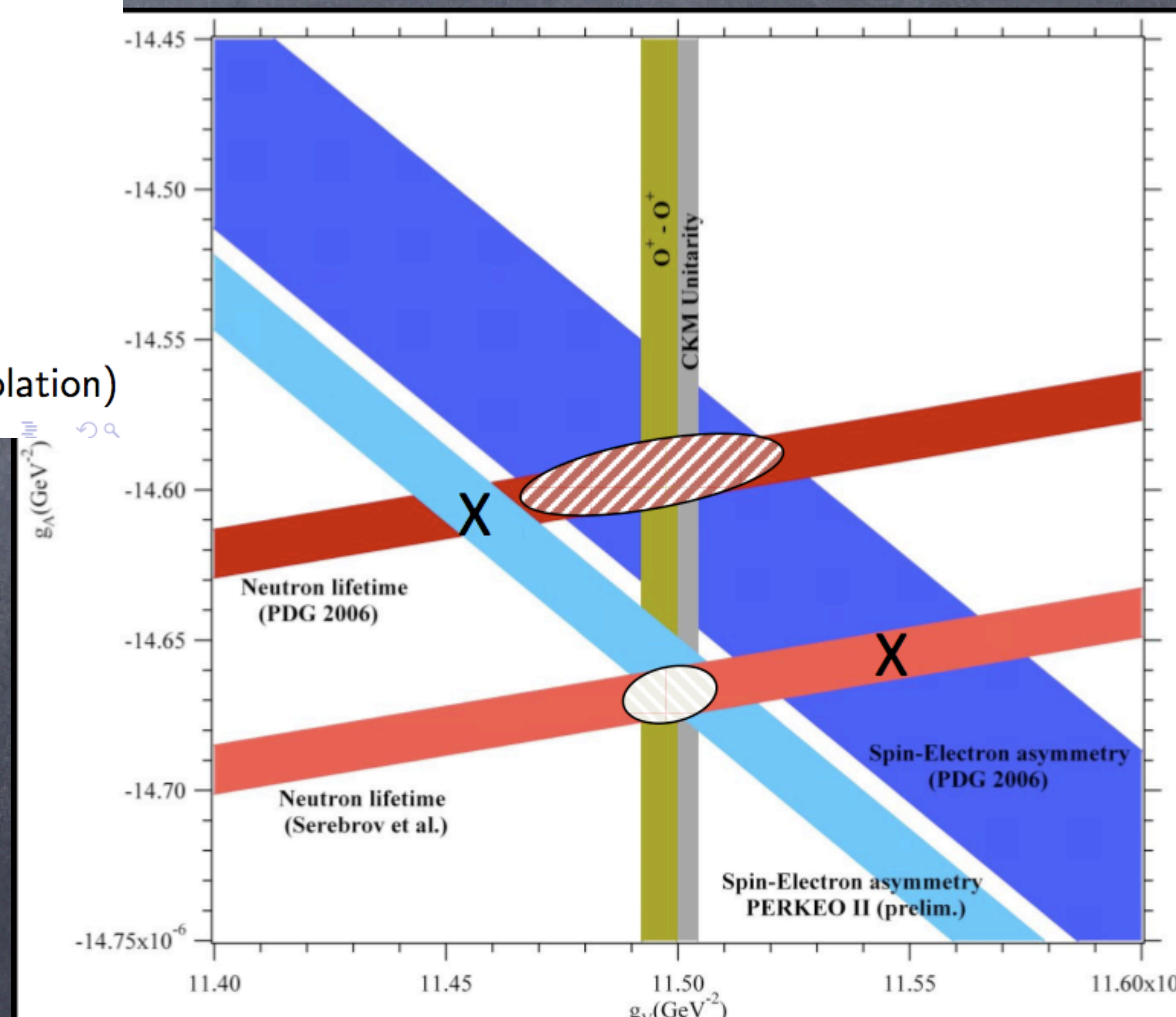
$$B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2} \qquad D = 2\frac{\mathrm{Im}(\lambda)}{1 + 3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ CKM V_{ud}) ($D \neq 0 \Leftrightarrow T$ inv. violation)

Major initiatives in Canada, USA, Europe and Japan

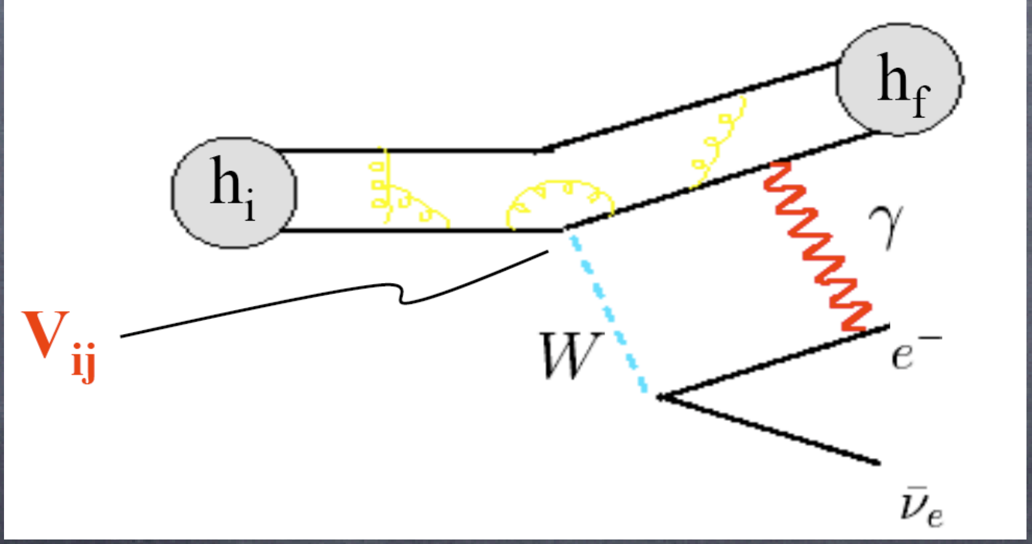
Independent measure of V_{ud}

Other terms sensitive TeV scale BSM physics



Semi-Leptonic Decays

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$	$\pi \to \mu\nu$	$\tau \to h_{NS}\,\nu_\tau$
V_{us}	$K \to \pi\ \ell\nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S \nu_\tau$ $(inclusive)$



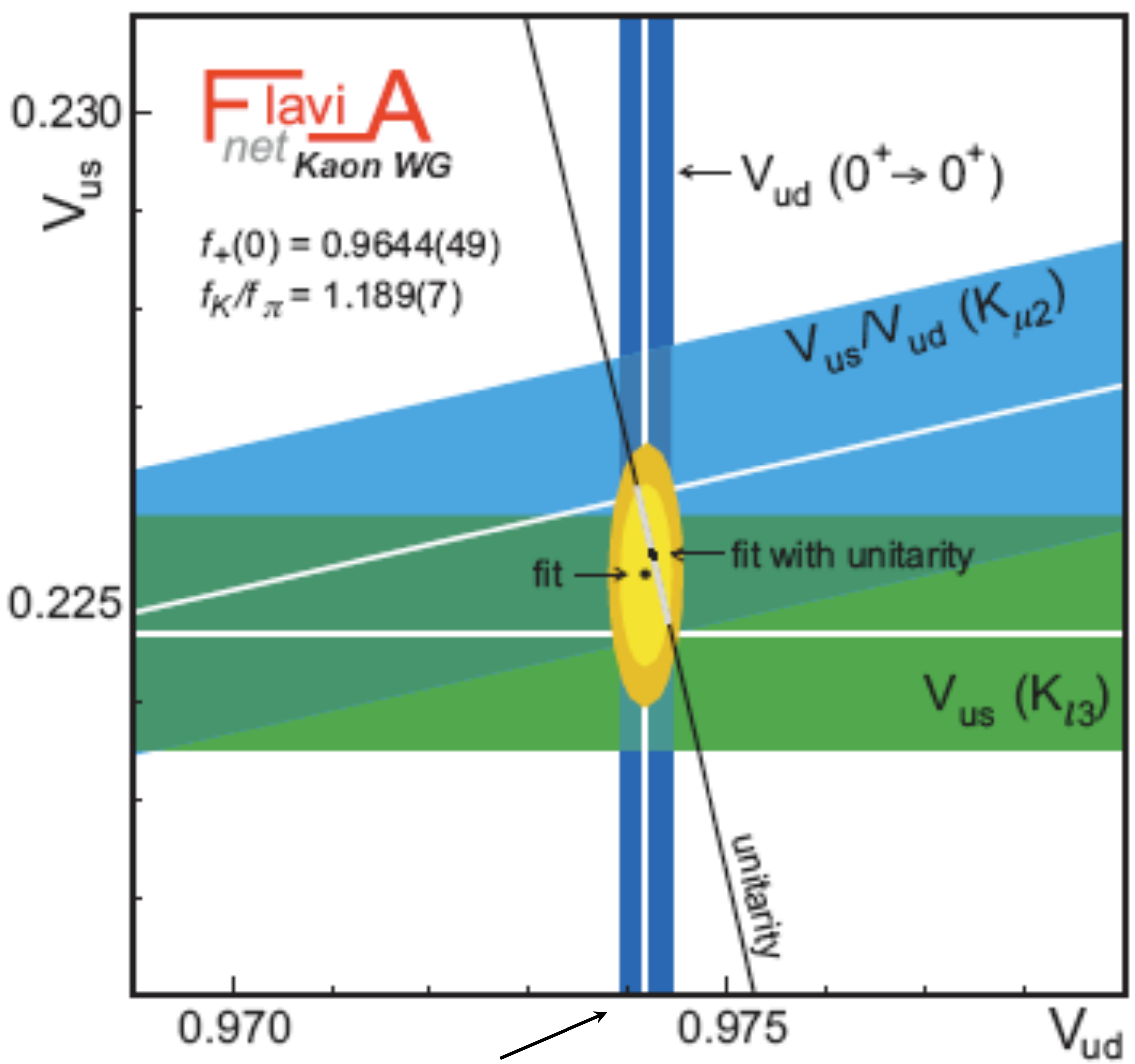
$$\Gamma_{ij} = \left[G_F^{(\mu)} V_{ij}\right]^2 \times |M_{\rm had}|^2 \times (1+\delta_{\rm em}) \times F_{\rm kin}$$

Hadronic matrix elements

Radiative corrections

Global Fit to V_{ud} and V_{us}

arXiv:0907.5386



V_{ud} from $0^+ \to 0^+$

Fit result

$$V_{ud} = 0.97425\ (22)$$
$$V_{us} = 0.2252\ (9)$$

$\chi^2/\text{dof} = 0.65/1$

$$|V_{ud}|^2 + |V_{us}|^2 = 0.9999(6)$$

Error equally shared between V_{ud} and V_{us}

- Remarkable agreement with Cabibbo universality: $\Delta_{CKM} = -(1 \pm 6) * 10^{-4}$

Marciano-Sirlin

- Confirms large EW rad. corr. $(2\ \alpha/\pi\ \log(M_Z/M_p) = +3.6\%)$
- It would naively fit $M_Z = (90 \pm 7)$ GeV

Precision Muon Decay Measurements

TWIST
at
TRIUMF

◎ Muon decay ("Michel") parameters ρ, η, $\mathbf{P}_\mu\xi$, δ

- muon differential decay rate *vs.* energy and angle:

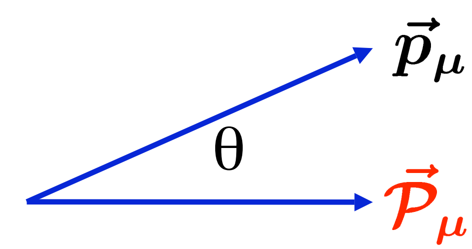
$$\frac{d^2\Gamma}{dx\; d\cos\theta} = \frac{1}{4} m_\mu W_{\mu e}^4 G_F^2 \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x,\rho,\eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x,\xi,\delta)\} + R.C.$$

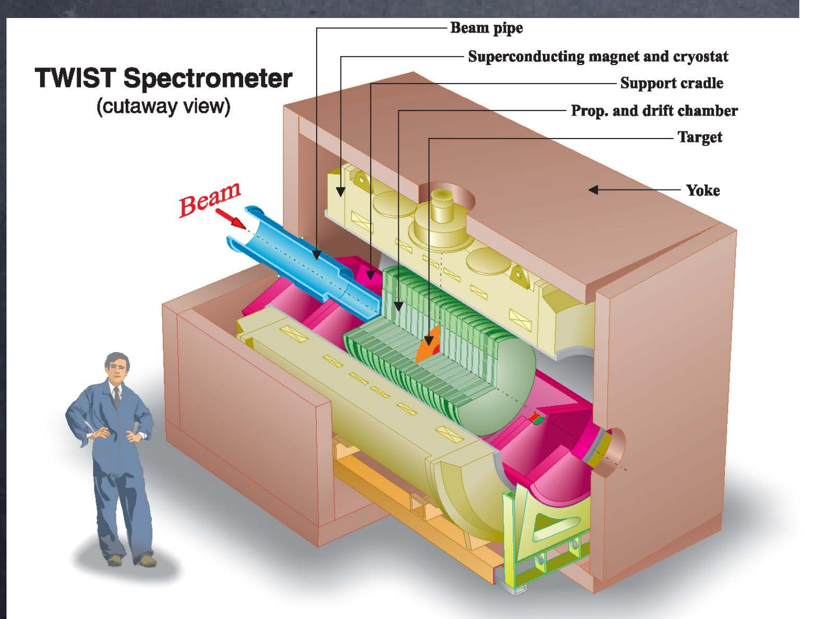
- where

$$\mathcal{F}_{IS}(x,\rho,\eta) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

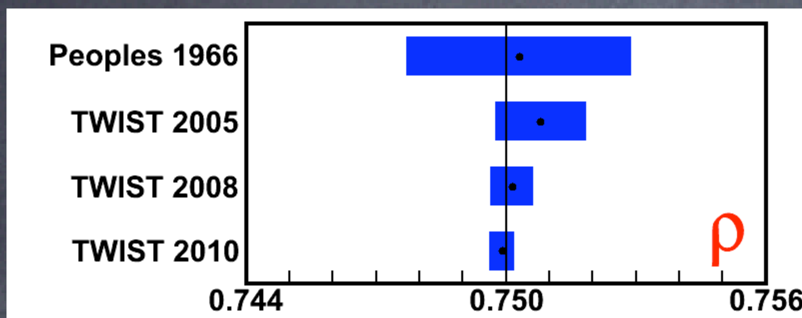
$$\mathcal{F}_{AS}(x,\xi,\delta) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left\{4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right\}\right]$$

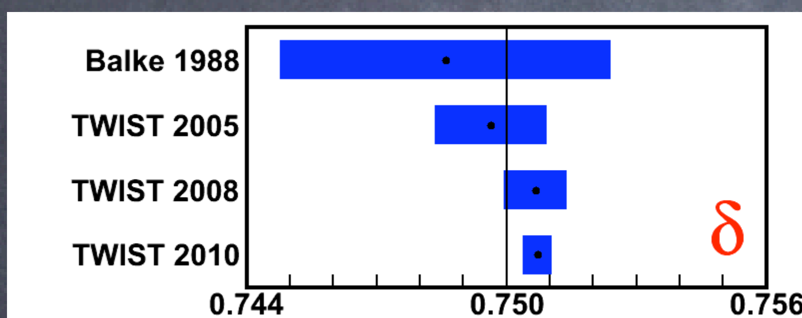
and $W_{\mu e} = \frac{m_\mu^2 + m_e^2}{2m_\mu}$, $x = \frac{E_e}{W_{\mu e}}$, $x_0 = \frac{m_e}{W_{\mu e}}$.

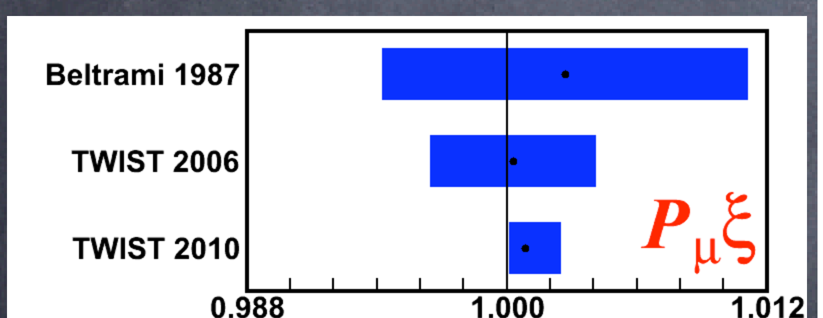




TWIST Results

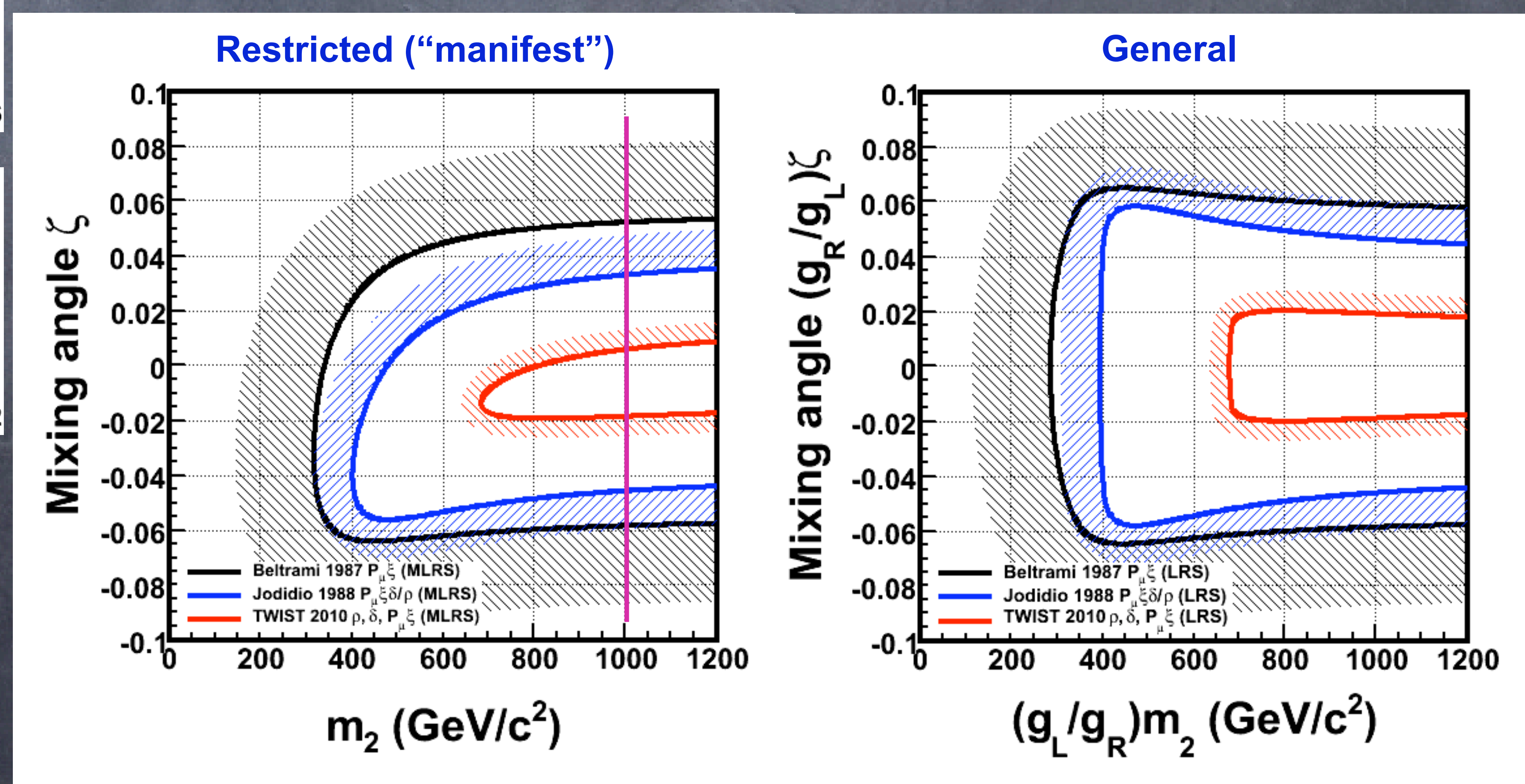






Important new limits on right-handed currents

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta, \quad W_R = e^{i\omega}(-W_1 \sin\zeta + W_2 \cos\zeta)$$

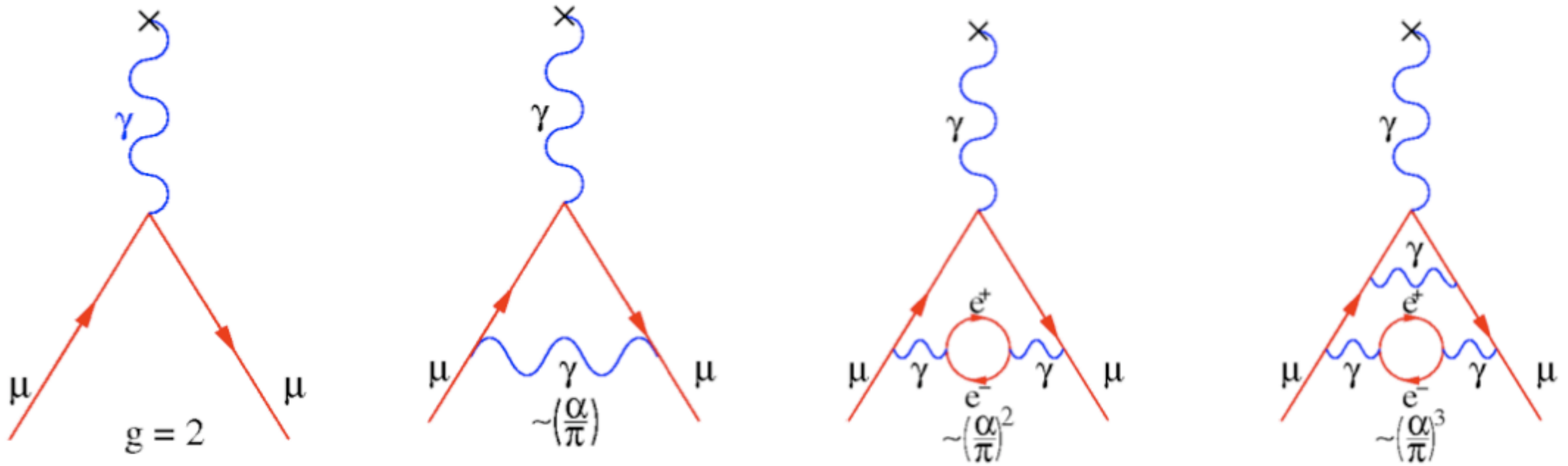


Muon g-2

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}, \qquad \vec{s} = \frac{\hbar}{2}\vec{\sigma}$$

- Dirac predicts in g=2 in 1928
- 1947 : Measurements of Kusch and Foley found g_e deviates from 2
- Schwinger calculated :

$$g_e = 2(1 + a_e), \qquad \text{where} \qquad a_e = \frac{(g_e - 2)}{2} = \frac{\alpha}{2\pi} \approx 0.00116$$

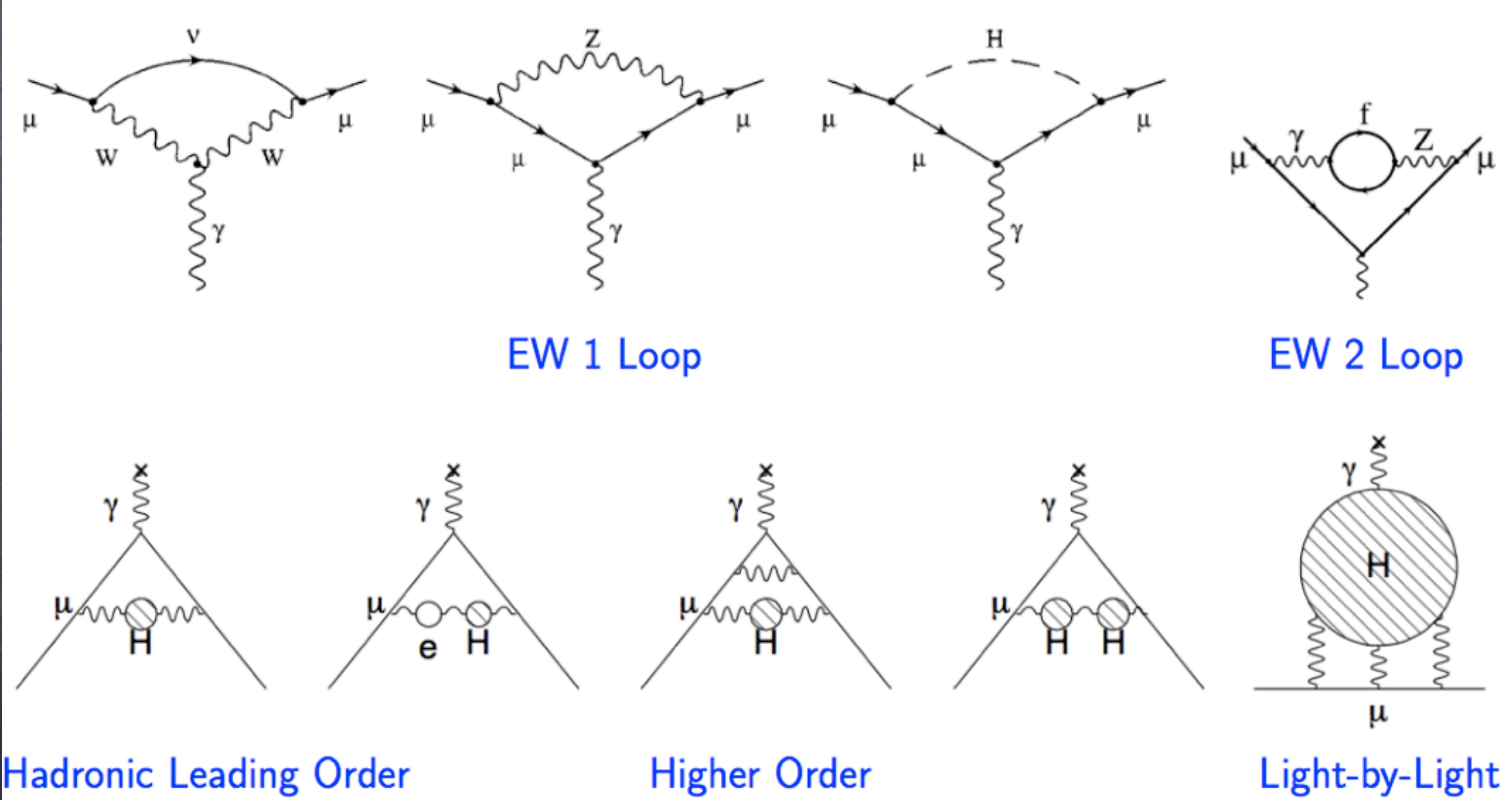


Dirac Schwinger Kinoshita and others

- a_e due to corrections from virtual particles appearing in loops (radiative corrections)
- 1 part in 850 effect, huge success for QED !

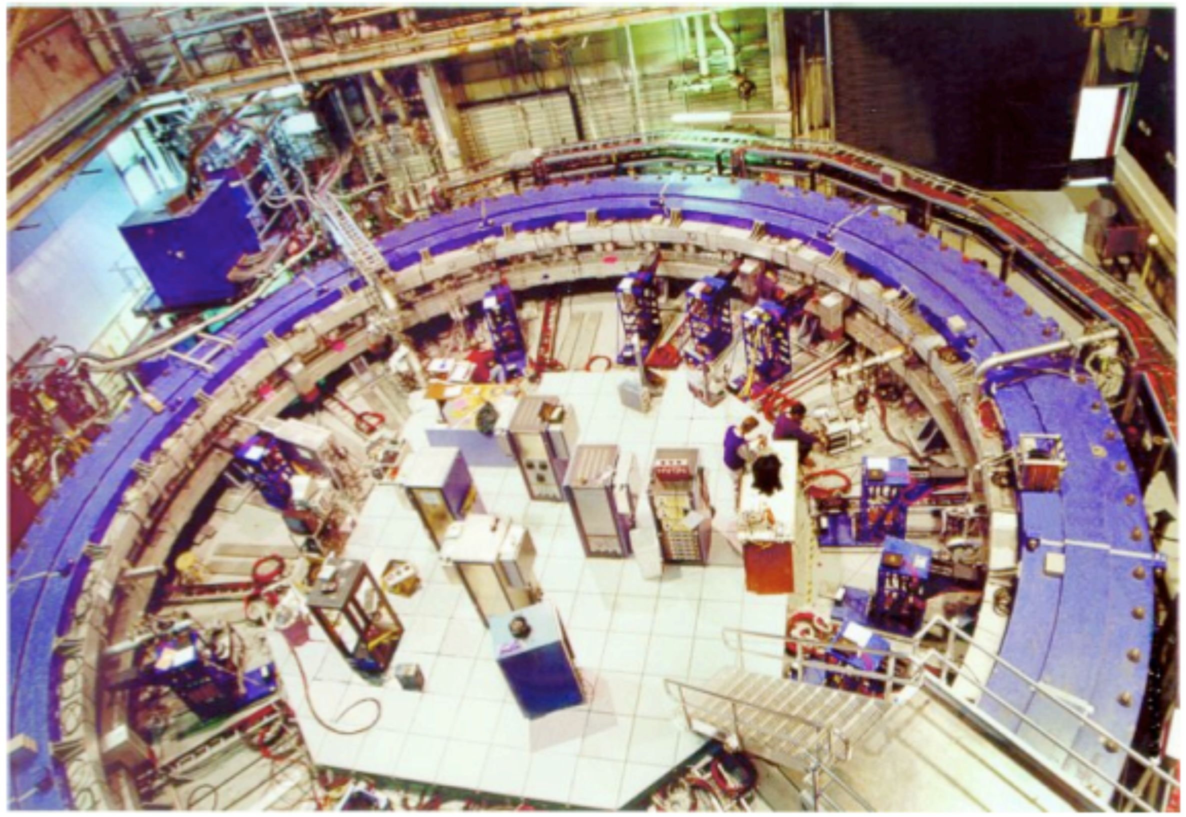
Radiative Corrections

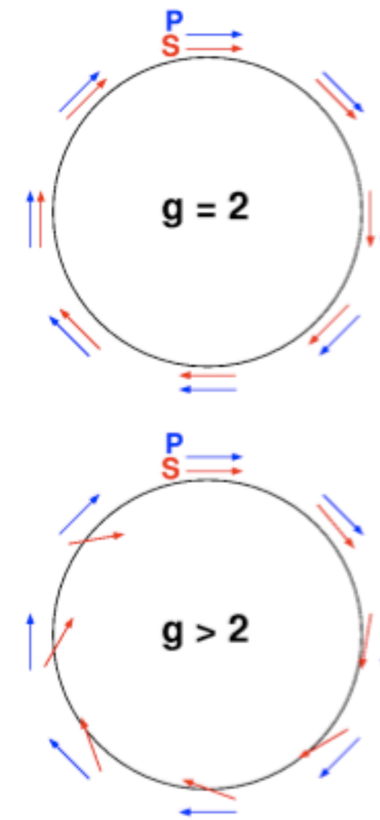
$$a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$



$\Rightarrow$ a_μ gets contributions from *all* physics - including the unknown

g-2 Experiment at BNL





- Inject polarized muons at 3.094 GeV/c into superferric storage ring, radius = 711.2 cm
- Muon spin precesses in homogeneous 1.45 T field, time dilated lifetime of 64.4 μs, measure for 700 μs

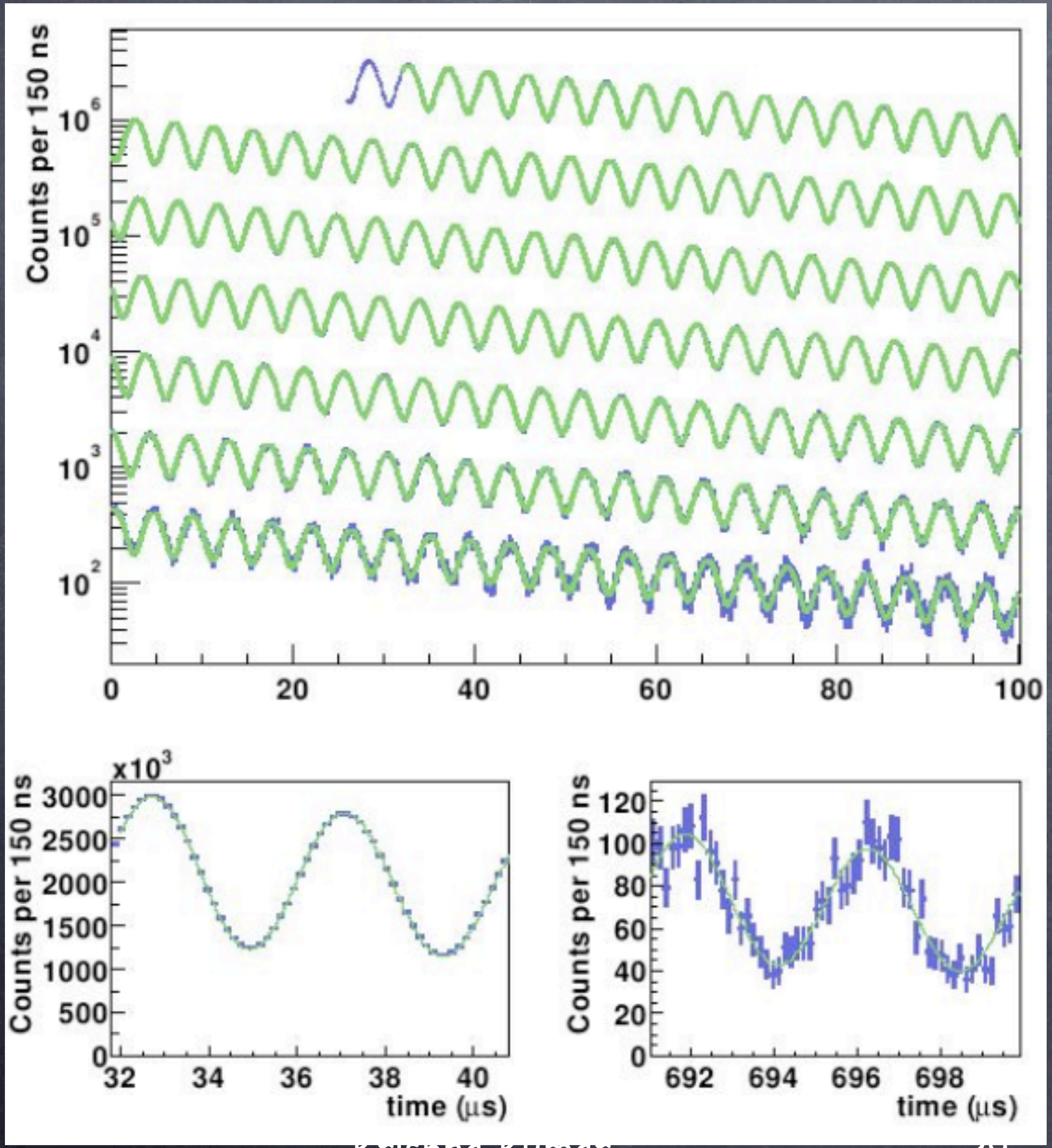
$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c \quad : \quad \text{difference between spin and cyclotron frequencies}$$

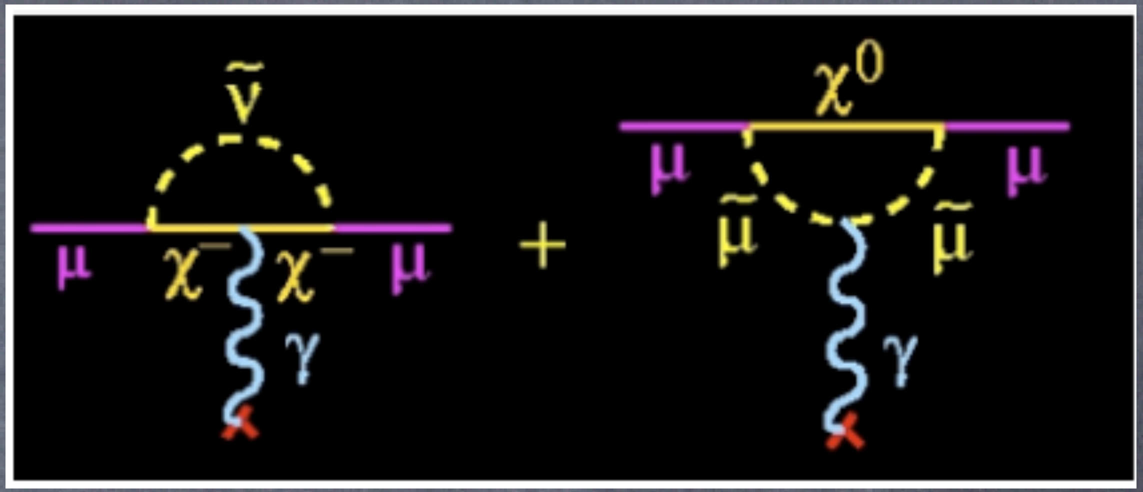
$$\vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] \quad \Rightarrow \text{ at } \gamma = 29.3 \quad \Rightarrow \quad \vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B}\right]$$

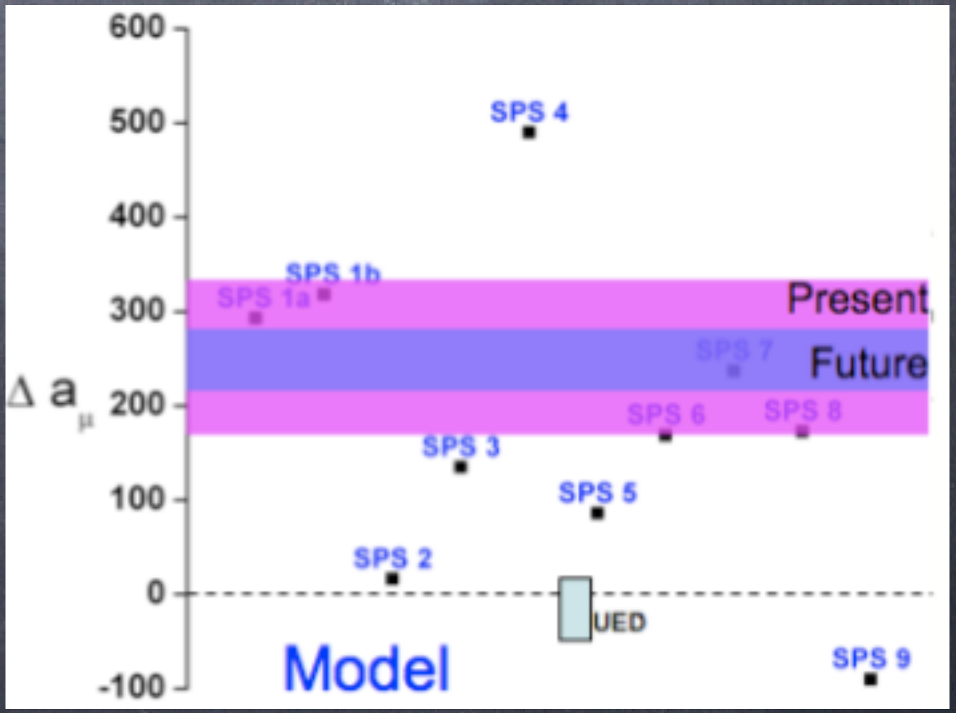
$\Rightarrow$ To determine a_μ, need to measure ω_a and B

- Muon spin direction correlated with decay electron direction, and $E_{\text{lab}} \approx \gamma\, E^* \,(1 + \cos\theta^*)$

g-2 Data and Plans







Summary

- Weak Neutral Current Measurements are an important complement to search for TeV-scale flavor diagonal interactions
- Electroweak experiments probe novel aspects of hadron structure
- Charged Current Interactions search for new physics in sectors often not accessible at colliders
- muon g-2 is a very sensitive indirect search for SUSY

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- www.particleadventure.org

Conclusions and Perspectives

- I hope you had at least some fraction of the fun I had in preparing these lectures
- Nuclear theory & experiments will continue to explore fundamental symmetries and interpret/complement collider experiments uncover the underlying theories of nature
- We need you all to develop the next generation of clever ideas that will move this subfield forward into the future