The Electroweak Box

M.J. Ramsey-Musolf

U Mass Amherst

http://www.physics.umass.edu/acfi/

EW Box Workshop, ACFI
September 2017

Goals For This Talk

- *Set the context for the workshop*
- *Introduce topics to be addressed in more detail during following talks & discussions*
- *Pose some challenges for the future*

Goals For This Talk

- *Set the context for the workshop*
- *Introduce topics to be addressed in more detail during following talks & discussions*
- *Pose some challenges for the future*

Caveat: I will not provide a comprehensive review, and some results are undoubtedly out of date. Omissions are not intentional, and I welcome corrections, updates, and other input!

Outline

I. *Context*

II. *PV Electron Scattering*

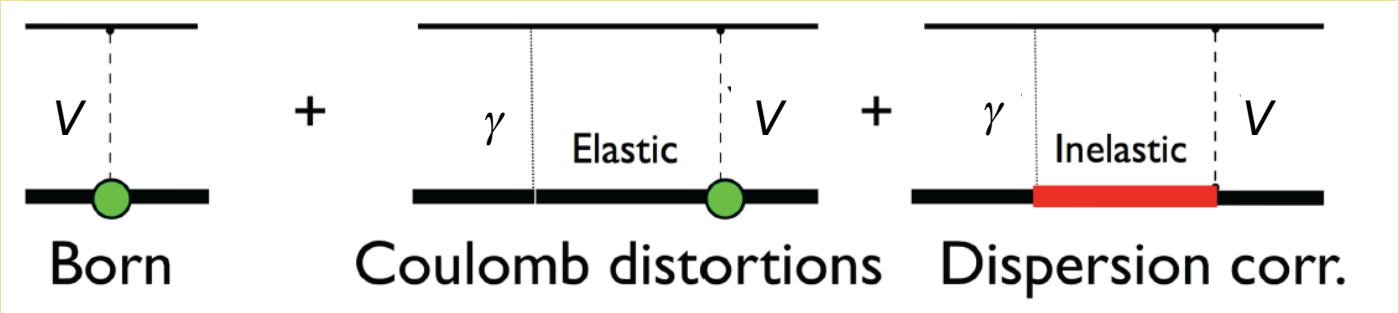
III. *CC Weak Interactions*

IV. *Time Reversal*

V. *Workshop Questions*

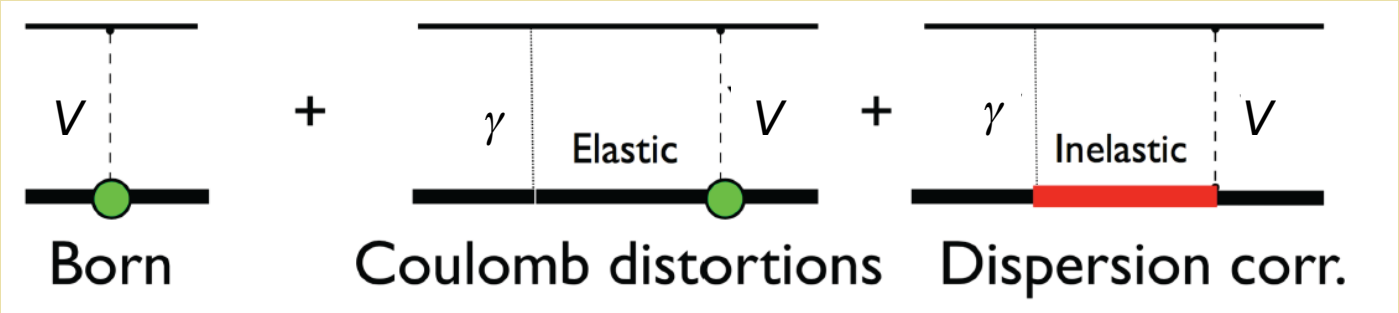
I. Context

Two EW Boson Exchange



$V = Z^0, W, \gamma$

Two EW Boson Exchange

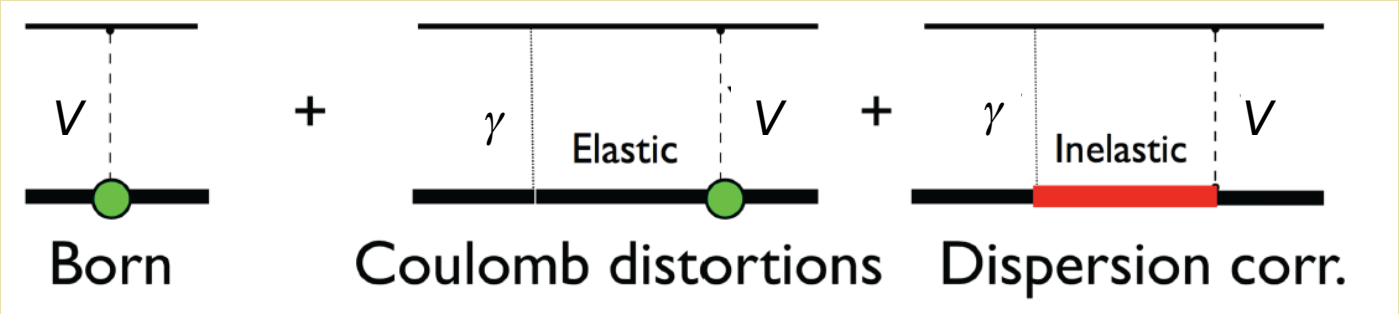


V = Z^0, W, γ

- *QED (γγ) in semileptonic interactions is still a puzzle !*
- *No direct probes of EW boxes (γZ, γW) available, but reliable SM computations needed. Can we trust the quoted theoretical uncertainties ? Can we reduce them further ?*

Dispersion Corrections

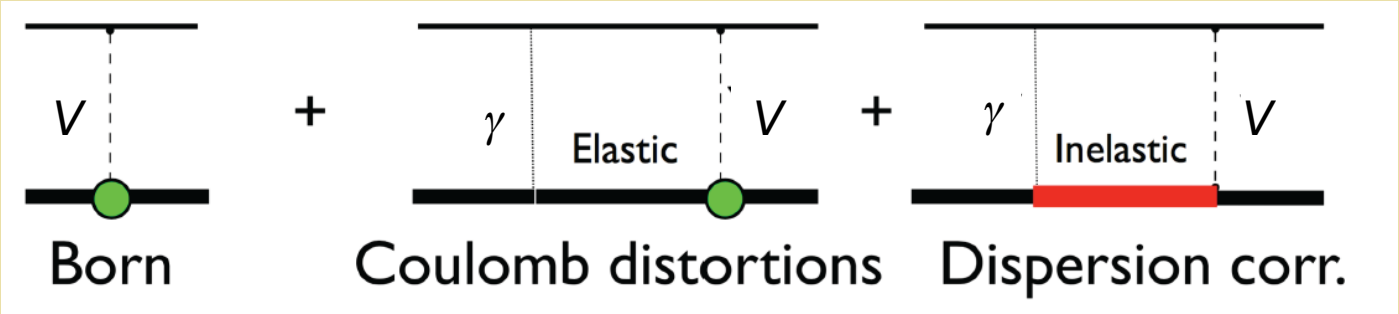
Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests



$V = Z^0, W, \gamma$

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests

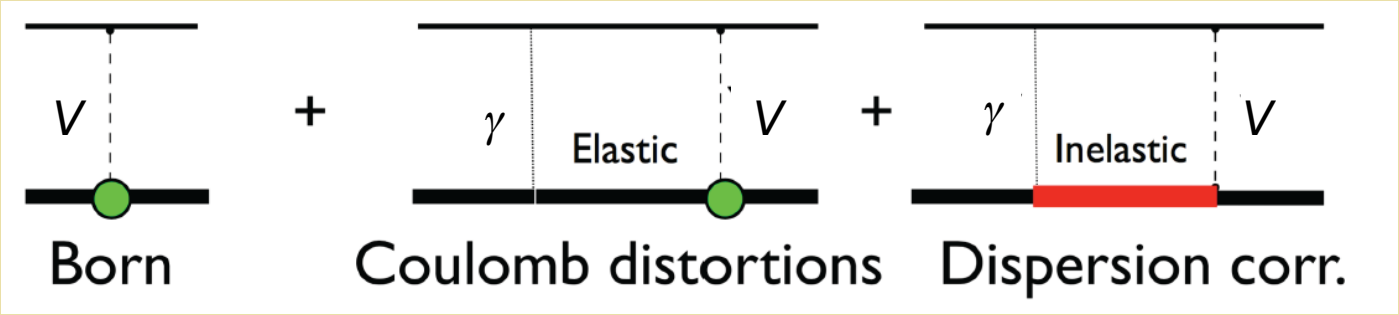


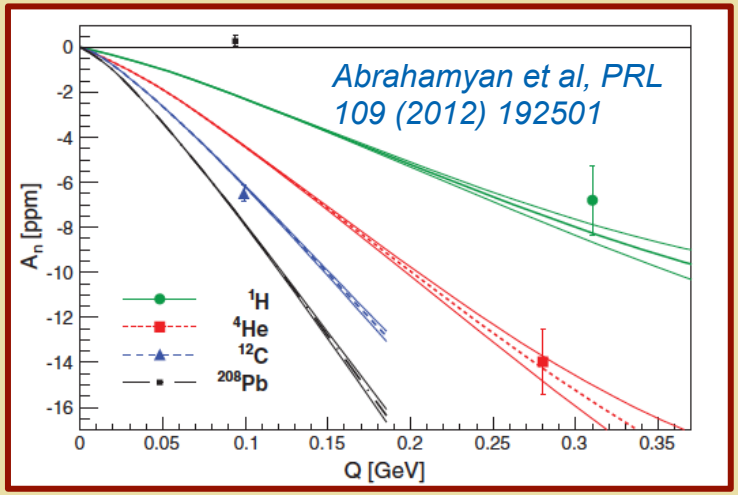
$V = Z^0, W, \gamma$

$V = \gamma$ ***Beam normal asymmetry***

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests

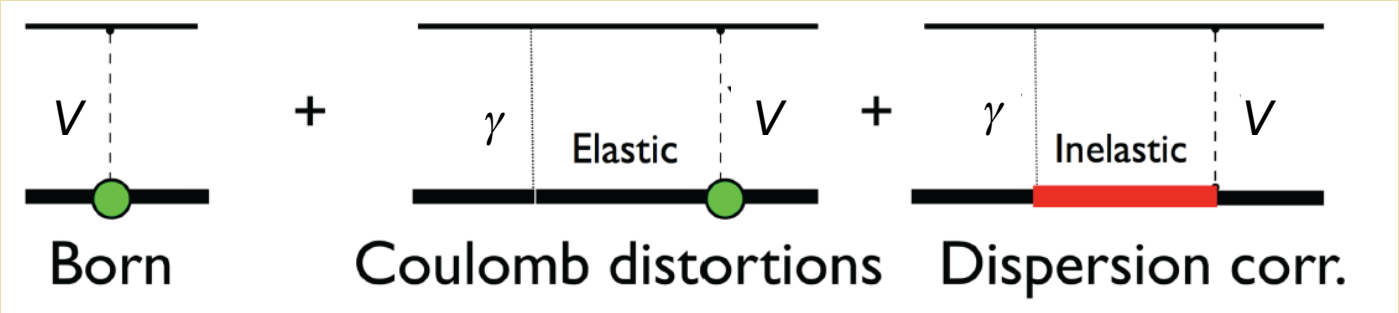




$V = \gamma$ ***Beam normal asymmetry***

- *J Lab Hall A*
- *Future: Mainz, J Lab*

Two EW Boson Exchange

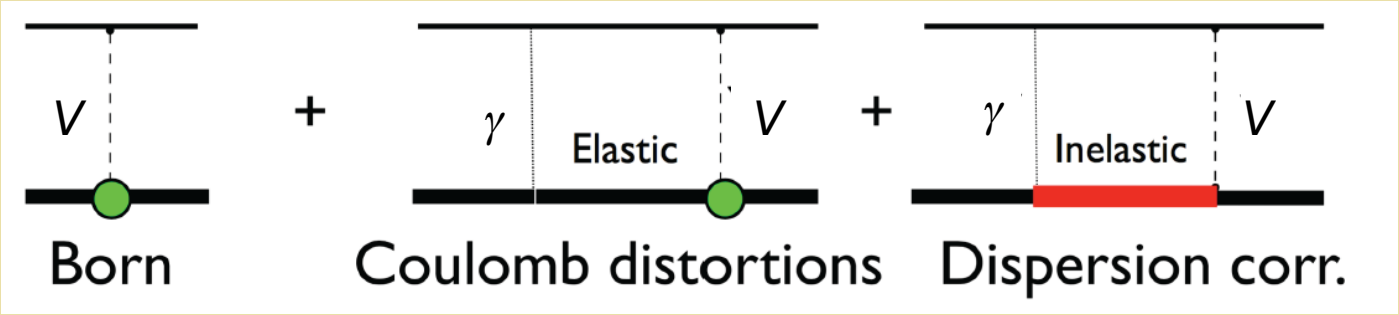


$V = Z^0, W, \gamma$

	$d\sigma$	A_n	A_{PV}	$ft_{1/2}$	$a, A\ldots$	$\delta(E)$	d_A
$\gamma\gamma$	✔	✔	✔	✖	✖	✖	✔
γZ	✖	✖	✔	✖	✖	✖	✖
γW	✖	✖	✖	✔	✔	✔	✖

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry provides, Olympus… provide tests



$V = Z^0, W, \gamma$

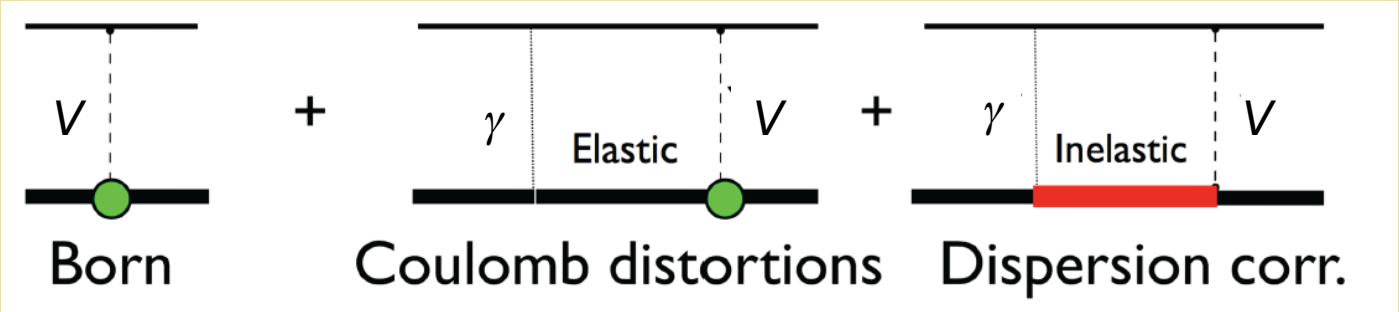
$V = \gamma$ ***Beam normal asymmetry***

Important for $\mathcal{O}$ (0.1%) probes of PV $^{12}C(e,e')$ & superallowed β-decay

$V = Z^0, W$ ***Nucleus-dependent QED & EW corrections***

Dispersion Corrections

Proposal: (1) carry out a consistent set of computations for A_n , PV asymmetry, & δ_{NS} using different methods (2) develop a program of A_n measurements to test computations



$V = Z^0, W, \gamma$

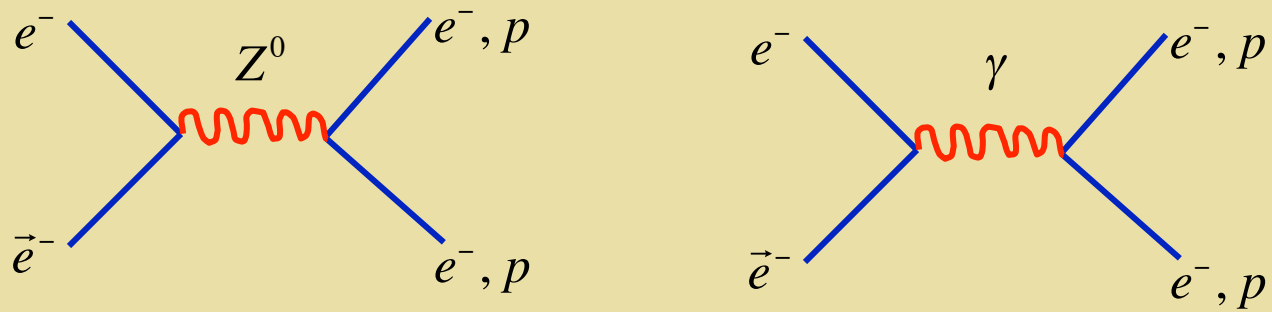
$V = \gamma$ ***Beam normal asymmetry***

$V = Z^0, W$ ***Nucleus-dependent QED & EW corrections***

Important for $\mathcal{O}$ (0.1%) probes of PV $^{12}C(e,e')$ & superallowed β-decay

II. PV Electron Scattering

Parity-Violation & Weak Charges



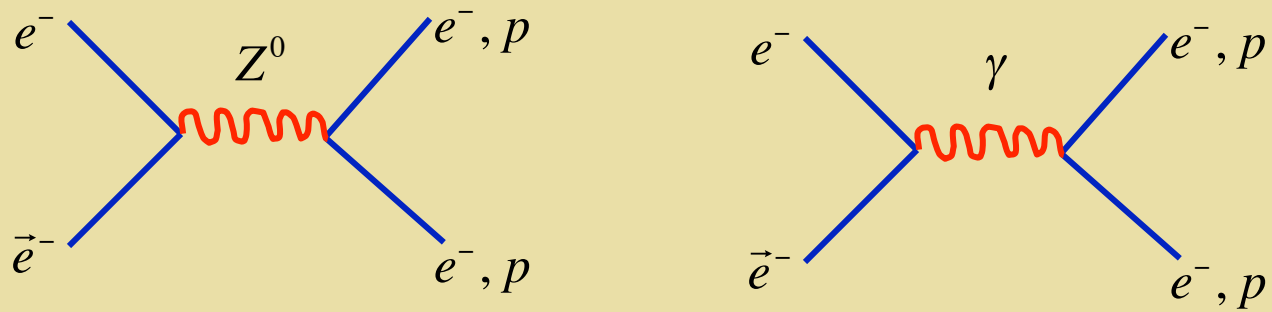
Parity-Violating electron scattering

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

Atomic parity-violation

$$E_1^{PV} / \beta = i\, e\, \mathcal{M} \times 10^{-11}\, a_0\, (Q_W / N) / \beta$$

Parity-Violation & Weak Charges



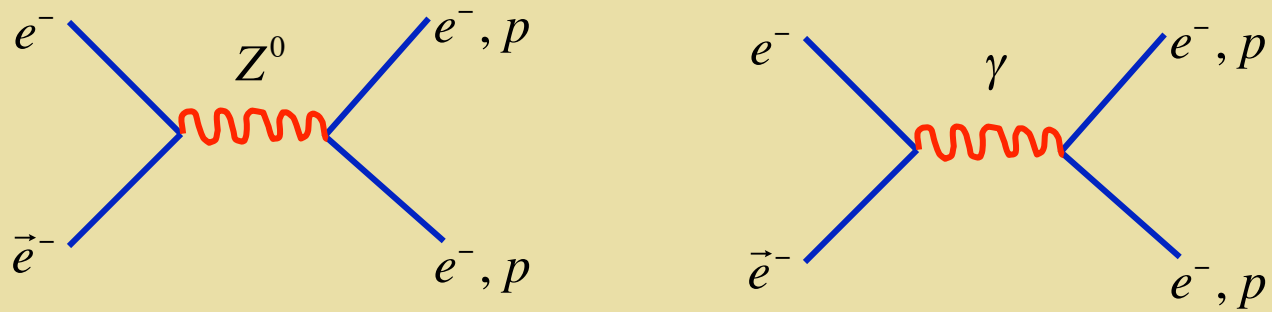
Parity-Violating electron scattering

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

Atomic parity-violation

$$E_1^{PV} / \beta = i\, e\, \mathcal{M} \times 10^{-11}\, a_0\, (Q_W / N) / \beta$$

Parity-Violation & Neutral Currents

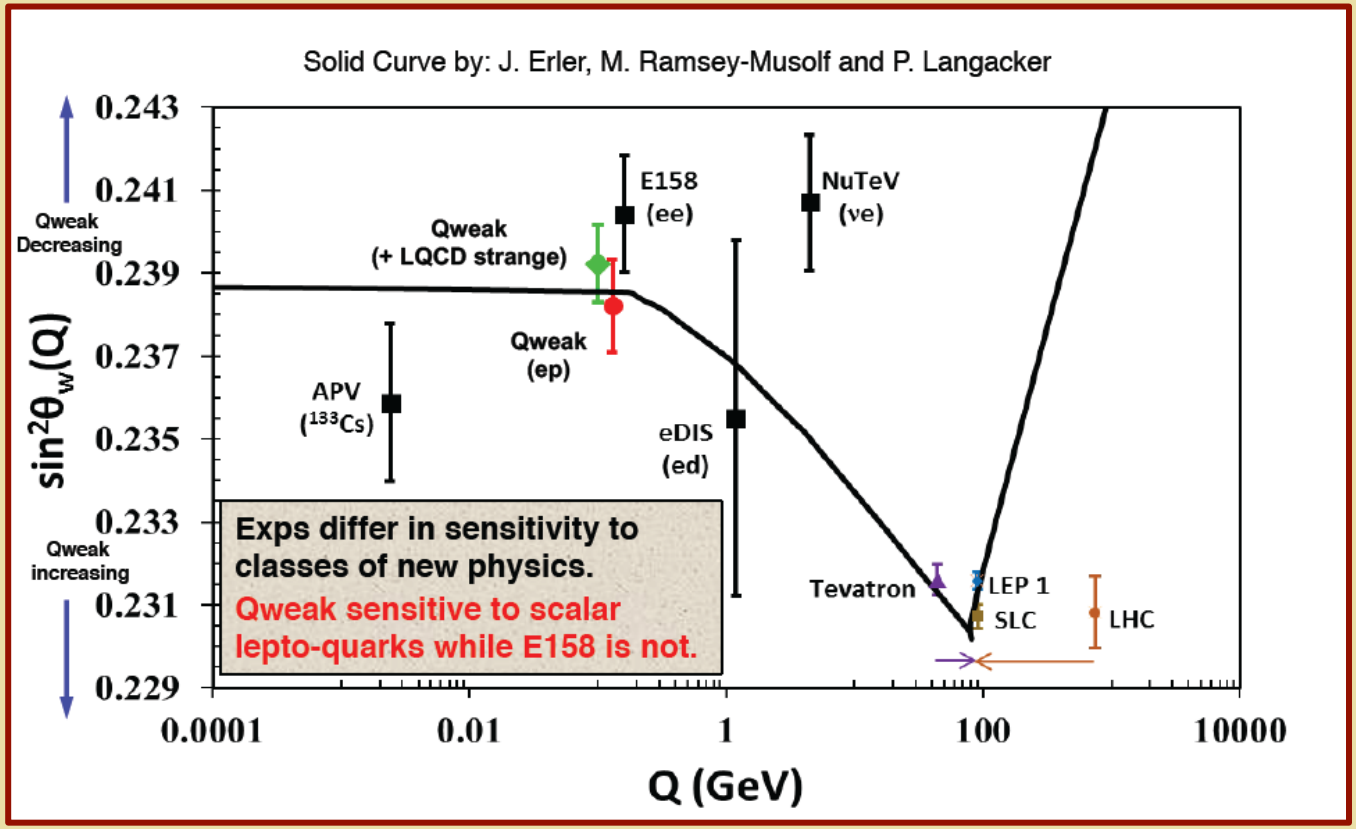


Parity-Violating electron scattering

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

Assume SM NC correct & use to probe hadron & nuclear struture

Parity-Violation & Neutral Currents



R. Carlini, PANIC 2017 Beijing

Weak Mixing in the SM: Uncertainties

Erler & R-M

$$\hat{s}^2 \frac{d\hat{\alpha}}{dt} - \hat{\alpha}\frac{d\hat{s}^2}{dt} = \frac{b_2}{\pi}\hat{\alpha}^2 + \sum_j \frac{b_{2j}}{\pi^2}\hat{\alpha}^2\hat{\alpha}_j + \cdots$$

Full $SU(2)_L \times U(1)_Y$ RGE

$$\sin^2\hat{\theta}_W(\mu) = \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\sin^2\hat{\theta}_W(\mu_0) + \frac{\sum_i N_i^c \gamma_i Q_i T_i}{\sum_i N_i^c \gamma_i Q_i^2}\left[1 - \frac{\hat{\alpha}(\mu)}{\hat{\alpha}(\mu_0)}\right],$$

Relate running of $\sin^2\theta_W$ to running of α

1. *Run α & $\sin^2\theta_W$ to $\mu \sim m_c$*
2. *Bound s-quark contribution to $\alpha(m_c)$ -- relative to u and d contributions -- using heavy quark and $SU(3)_f$ limits*

Uncertainties: $\sin^2\theta_W(0)$

+/- 3×10^{-5} : $\Delta\alpha^{(3)}(m_c)$

+/- 5×10^{-5}: $\Delta\alpha^{(2)}(m_s)$

+/- 3×10^{-5}: OZI

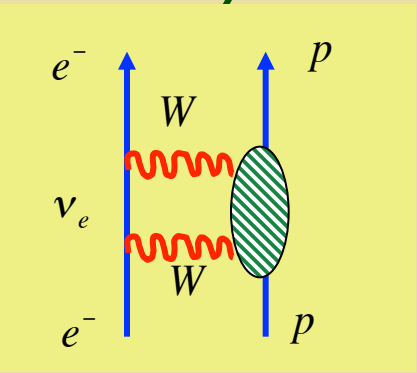
+/- 1.5×10^{-4} : $\sin^2\theta_W(M_Z)$

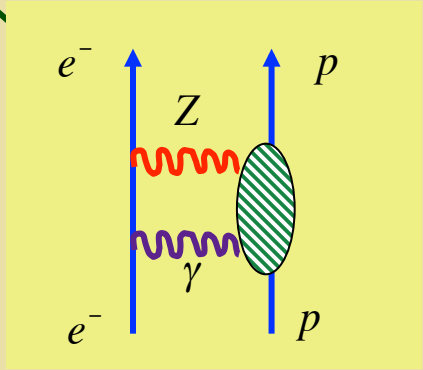
Radiative Correction Uncertainties

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

Erler, Kurylov & R-M

E-Independent





$$\Box_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1 - 4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

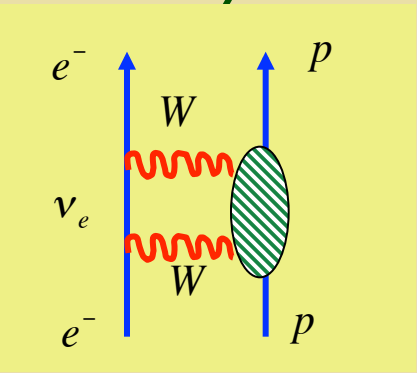
$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2 + 5\left(1 - \frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

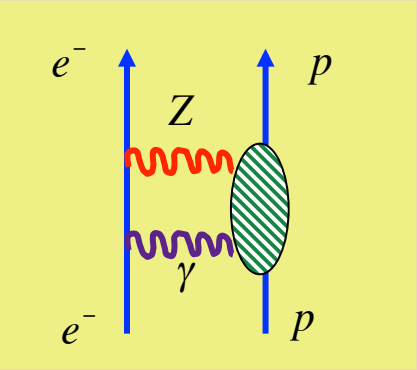
Radiative Correction Uncertainties

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

Erler, Kurylov & R-M

E-Independent





$$\Box_{\gamma Z} = \frac{5\hat{\alpha}}{2\pi}(1 - 4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma Z}(\Lambda)\right]$$

$\delta Q_W \sim 0.7\%$

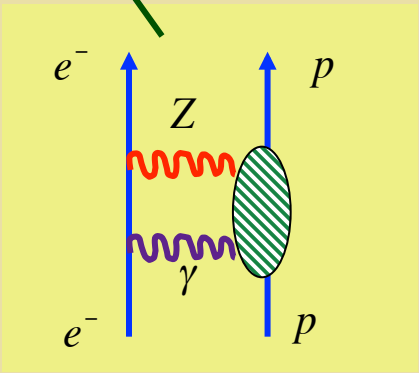
$$\Box_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2 + 5\left(1 - \frac{\alpha_s(M_W^2)}{\pi}\right)\right]$$

$\delta Q_W \sim 0.1\%$

Order α_s^2

Radiative Correction Uncertainties

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



E-dependent: E = 1.165 GeV

Ref. [11]	Ref. [15]	Ref. [17]	This work **
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

[11] Gorchtein & Horowitz

[15] Sibirtsev et al

[17] Rislow & Carlson

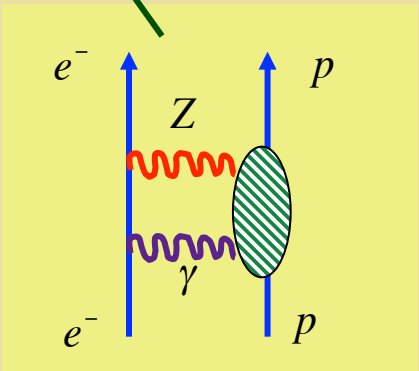
** *Gorchtein, Horowitz, R-M*

1102.3910 [nucl-th]

Radiative Correction Uncertainties

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

E-dependent: E = 1.165 GeV



Ref. [11]	Ref. [15]	Ref. [17]	This work **
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

Equivalent to ~ 2.8% uncertainty in Q_W

[11] Gorchtein & Horowitz

[15] Sibirtsev et al

[17] Rislow & Carlson

** *Gorchtein, Horowitz, R-M*

1102.3910 [nucl-th]

Includes estimate of model uncertainty

Radiative Correction Uncertainties

Electroweak Radiative Corrections

Q_W^p	Standard Model ($Q^2 = 0$) [2016]	0.0708 ± 0.0003
Q_W^p	Experiment Final Uncertainty [2017]	± 0.0045

$$Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Correction to Q^p_{Weak}		Uncertainty
$\Delta \sin\theta_W (M_Z)$		± 0.0006
$Z\gamma$ box (6.4% ± 0.6%)	0.00459	± 0.00044
$\Delta \sin\theta_W (Q)_{hadronic}$		± 0.0003
WW, ZZ box - pQCD		± 0.0001
Charge symmetry		0
Total		± 0.0008

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

Calculations of Two Boson Exchange effects on Q_W^p at our Kinematics:

Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.

Our ΔA_{ep} precise enough that corrections to higher Q^2 points make little difference in extrapolation to zero Q^2.

Energy Dependence γZ correction:
Hall, N.L., Blunden, P.G., Melnitchouk, W., Thomas, A.W., Young, R.D. Quark-hadron duality constraints on γZ box corrections to parity-violating elastic scattering. Phys. Lett. B 753, 221-226 (2016).

Axial Vector γZ correction:
Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of γZ Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).

Q^2 Dependence γZ:
Gorchtein, M., Horowitz, C.J., Ramsey-Musolf, M.J. Model dependence of the γZ dispersion correction to the parity-violating asymmetry in elastic ep scattering. Phys. Rev. C 84, 015502 (2011).

19

Radiative Correction Uncertainties

Electroweak Radiative Corrections

Q_W^p Standard Model ($Q^2 = 0$) [2016]		0.0708 ± 0.0003
Q_W^p Experiment Final Uncertainty [2017]		± 0.0045

$$Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Correction to Q^p_{Weak}		Uncertainty
$\Delta \sin\theta_W (M_Z)$?		± 0.0006
$Z\gamma$ box (6.4% ± 0.6%)	0.00459	± 0.00044
$\Delta \sin\theta_W (Q)_{hadronic}$		± 0.0003
WW, ZZ box - pQCD		± 0.0001
Charge symmetry		0
Total		± 0.0008

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

Calculations of Two Boson Exchange effects on Q_W^p at our Kinematics:

Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.

Our ΔA_{ep} precise enough that corrections to higher Q^2 points make little difference in extrapolation to zero Q^2.

Energy Dependence γZ correction:
Hall, N.L., Blunden, P.G., Melnitchouk, W., Thomas, A.W., Young, R.D. Quark-hadron duality constraints on γZ box corrections to parity-violating elastic scattering. Phys. Lett. B 753, 221-226 (2016).

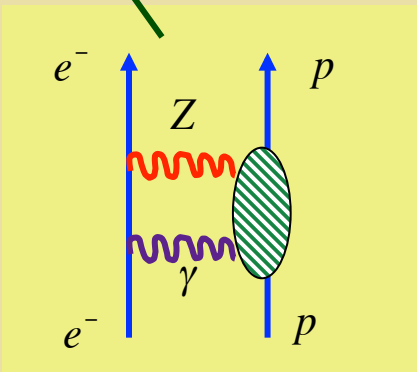
Axial Vector γZ correction:
Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of γZ Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).

Q^2 Dependence γZ:
Gorchtein, M., Horowitz, C.J., Ramsey-Musolf, M.J. Model dependence of the γZ dispersion correction to the parity-violating asymmetry in elastic ep scattering. Phys. Rev. C 84, 015502 (2011).

19

Radiative Correction Uncertainties

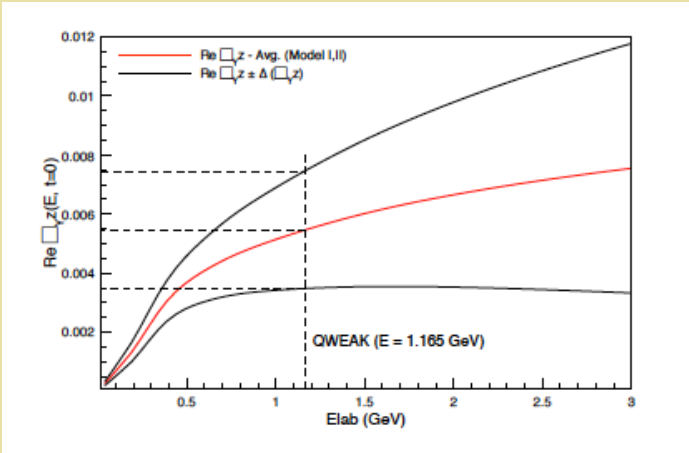
$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2, E)\right]$$



E-dependent: E = 1.165 GeV

Ref. [11]	Ref. [15]	Ref. [17]	This work
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

Lower energy measurement



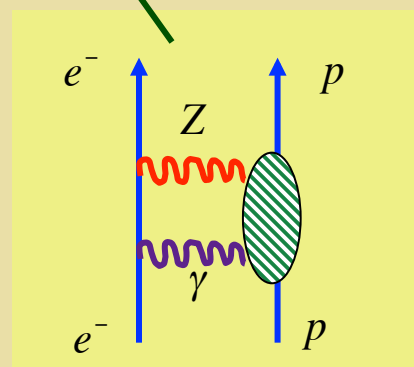
E = 180 MeV, Q^2 =0

[1.32 +/- 0.05 (mod avg) +/- 0.27 (bkg)

$^{+0.11}_{-0.08}$ (res)] x 10^{-3}

Radiative Correction Uncertainties

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



Dominant E-dependence

$$\mathrm{Re}\Box_{\gamma Z_A}(\nu) = \frac{2\nu}{\pi}\int_{\nu_\pi}^{\infty}\frac{d\nu'}{\nu'^2 - \nu^2}\mathrm{Im}\Box_{\gamma Z_A}(\nu')$$

$$\mathrm{Re}\Box_{\gamma Z_V}(\nu) = \frac{2}{\pi}\int_{\nu_\pi}^{\infty}\frac{\nu' d\nu'}{\nu'^2 - \nu^2}\mathrm{Im}\Box_{\gamma Z_V}(\nu')$$

$$\mathrm{Im}\Box_{\gamma Z_A}(\nu) = \alpha_{\mathrm{em}} g_A^e \int_{W_\pi^2}^{s}\frac{dW^2}{(s-M^2)^2}\int_0^{Q^2_{max}}\frac{dQ^2}{1+\frac{Q^2}{M_Z^2}}\left[F_1^{\gamma Z} + \frac{s(Q^2_{max} - Q^2)}{Q^2(W^2 - M^2 + Q^2)}F_2^{\gamma Z}\right]$$

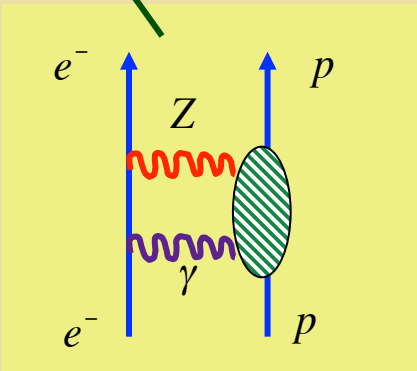
Two Issues:

[1] Existence of sufficient SF data in relevant kinematic region

[2] Isospin rotating $F^{\gamma\gamma} \rightarrow F^{\gamma Z}$

Radiative Correction Uncertainties

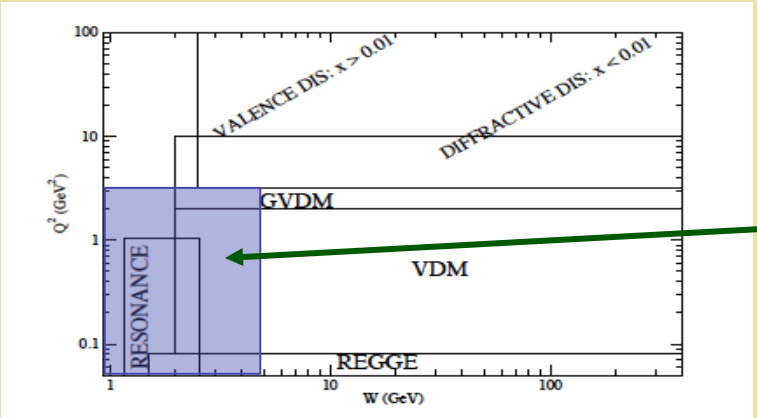
$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2, E)\right]$$



E-dependent: E = 1.165 GeV

Ref. [11]	Ref. [15]	Ref. [17]	This work
$(3 \pm 3)10^{-3}$	$(4.7^{+1.1}_{-0.4})10^{-3}$	$(5.7 \pm 0.9)10^{-3}$	$(5.4 \pm 2.0)10^{-3}$

Additional measurements



Dominant contributions; scarce data

Measure A_{PV} in extrapolation region: direct probe of $F^{\gamma Z}$

EW Radiative Corrections to Moller

A. Czarnecki & W.J. Marciano PRD(1996)

- $A_{RL}(ee) = \alpha\,(1-4\sin^2\theta_W)$ $\sin^2\theta_W(m_Z)_{MS} = \underline{0.23124(6)}$ or
  running + $3.01(25)_{hadronic}$%
  $\sin^2\theta_W(Q=0) = \underline{0.23820(60)}$

  + WWbox (+3.6%) γZbox…(-5.5%) partial cancellation

  + other small 1 loop corrections ➔ -40(3)% reduction!

  E158 $\Delta A_{RL}/A_{RL}$ =±12.5% vs Running unc. ±6%?

Erler & Ramsey-Musolf ➔ factor of 8.6 error reduction!

+3.01(25)%➔+2.99(3)% Theory ±0.6% vs Moller exp ±2.4%

$\Delta\sin^2\theta_W^{RC}$~±0.00007! Pristine

Potentially another factor of 2 reduction via lattice

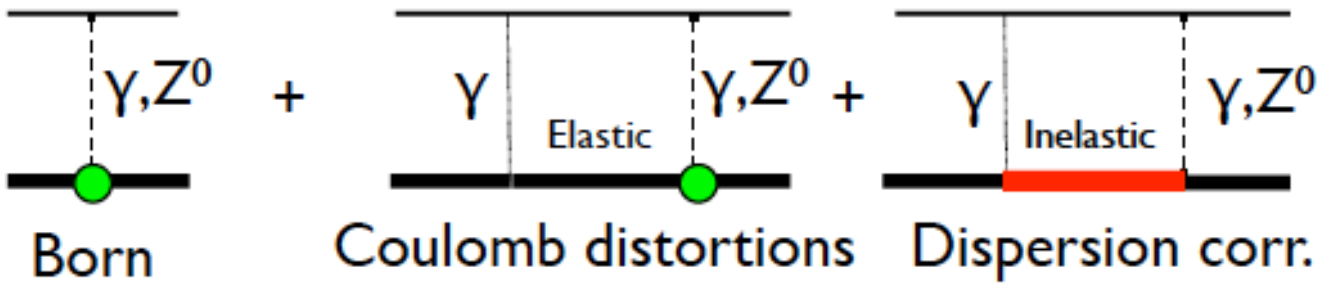
W. Marciano

Beam Normal Asymmetry

- Increasingly important for many precision measurements.
- Can isolate some radiative corrections with only polarized electrons (no need for positrons).
- PREX, CREX provide unique data sets on high Z targets. Comparing these to low Z data allows "Rosenbluth like" separations of different coulomb distortion, dispersion ... contributions vs Z. Instead of long / transverse vs angle, have coulomb distortion / dispersion contributions vs Z.
- Analyzing high Z and low Z data together can provide important additional insight even if only interested in low Z experiments.

C. Horowitz

Beam Normal Asymmetry



- Coulomb distortions are coherent, order $Z\alpha$. Important for PREX (Pb has Z=82).
- Dispersion corrections order α (not $Z\alpha$). Important for QWEAK because correction is order $\alpha/Q_w \sim 10\%$ relative to small Born term (Q_w). --- M. Gorshteyn
- Both Coulomb distortion and dispersion cor. can be important for Transverse Beam Asymmetry A_n for ^{208}Pb. Note Born term gives zero by time reversal symmetry.

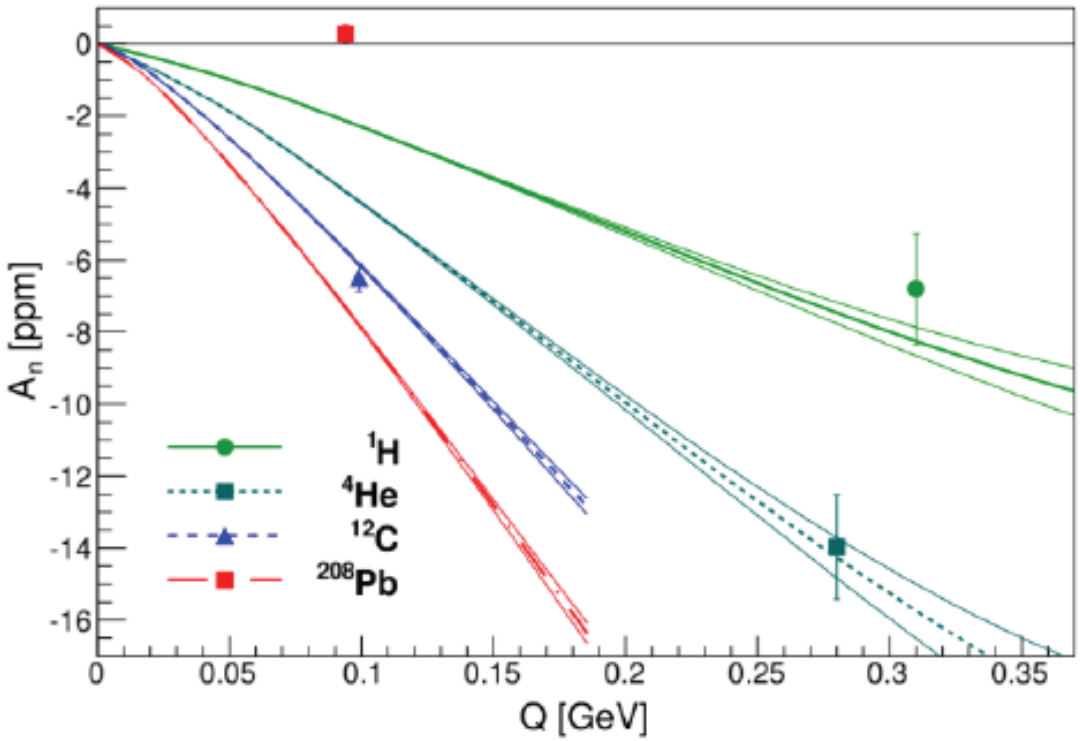
C. Horowitz

Beam Normal Asymmetry

- Left / Right cross section asymmetry for electrons with transverse polarization.
- Potential systematic error for PV from small trans components of beam polarization.
- A_n vanishes in Born approx (time reversal) --> Sensitive probe of 2 or more photon effects. Can measure radiative corrections directly!
- Full dispersion calculations include all excited states but only for 2 photon exchange.

C. Horowitz

A_n for a Range of Nuclei



Theory, experiment agree for H, ^{4}He, ^{12}C, but disagree completely for ^{208}Pb. This is likely do to Coulomb distortions

- Measure A_n for both ^{40}Ca, ^{48}Ca during CREX to study dependence of coulomb distortions on Z and dispersion contributions on N.

C. Horowitz

Coulomb Distortions for PREX

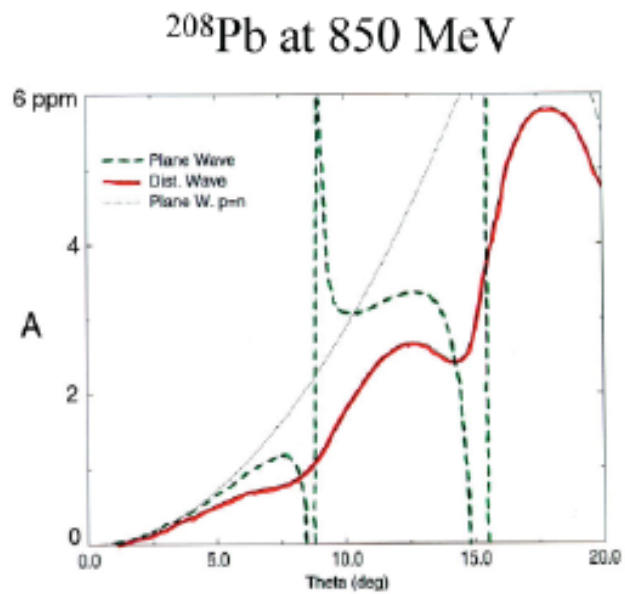
- We sum elastic intermediate states to all orders in Zα by solving Dirac equ. for e moving in coulomb V and weak axial A potentials.

$$A \propto G_F \rho_W(r) \approx 10 \text{ eV} \qquad V(r) \approx 25\text{MeV}$$

- Right handed e sees V+A, left handed V-A

$$A_{pv} = [d\sigma/d\Omega|_{V+A} - d\sigma/d\Omega|_{V-A}]/2d\sigma/d\Omega$$

- Coulomb distortions reduce A_{pv} by ~30%, but they are accurately calculated. Q^2 shared between "hard" weak, and soft interactions so weak amplitude $G_F Q^2$ reduced.



$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

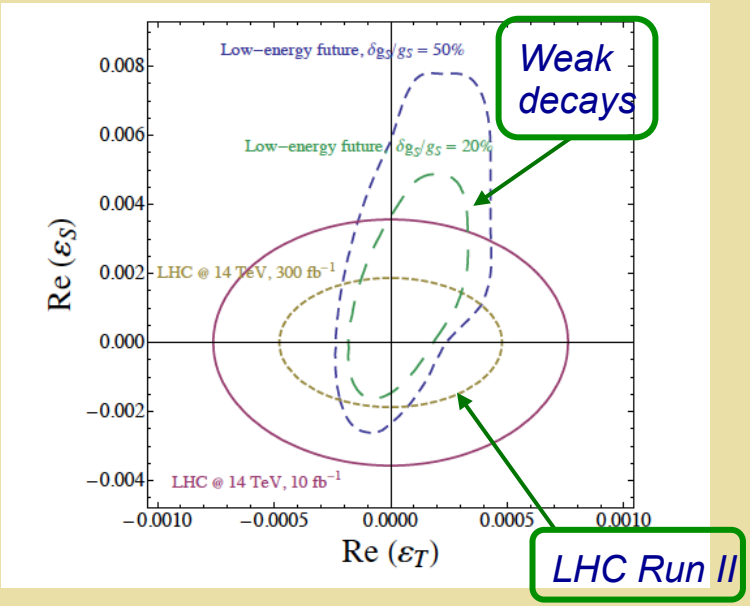
--- With E.D. Cooper

C. Horowitz

III. CC Weak Interactions

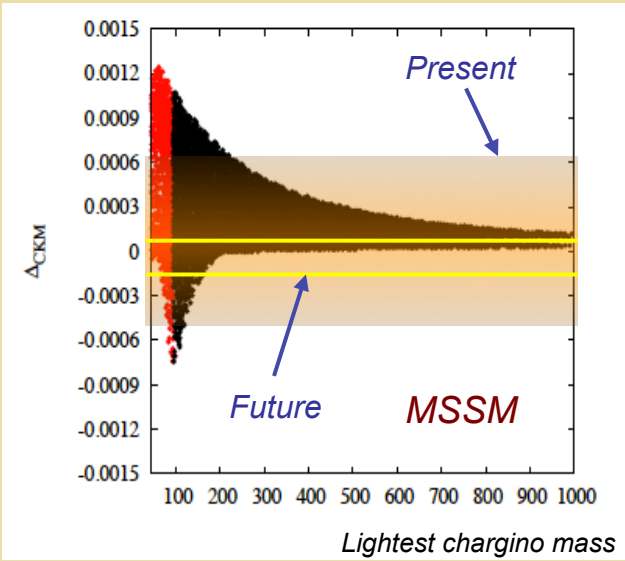
Weak Decays: New Interactions

Decay Correlations: Scalar & Tensor Currents



Bhattacharya et al '12

SUSY Corrections to CKM Unitarity



Bauman et al '12

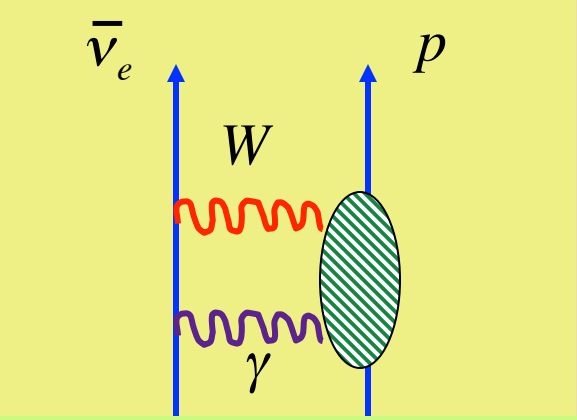
Neutron & Nuclear β−decay: $0^+ \rightarrow 0^+$, Nab, ^{6}He…

Goal: $\varepsilon \sim O(10^{-4})$

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)$$

SM theory input



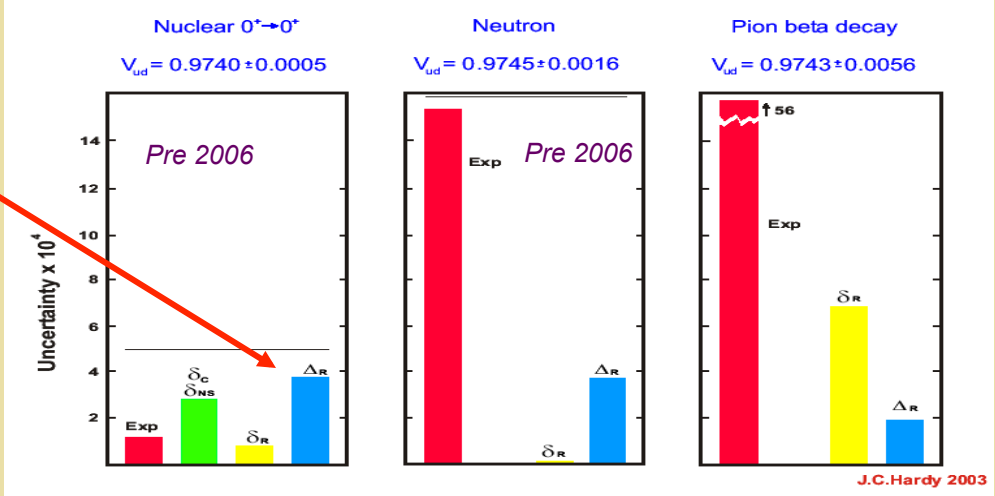
Marciano & Sirlin 2006

β-decay

$$n \rightarrow p\, e^- \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^+ \nu_e$$

$$\pi^+ \rightarrow \pi^0\, e^+ \nu_e$$



$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{8\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)$$

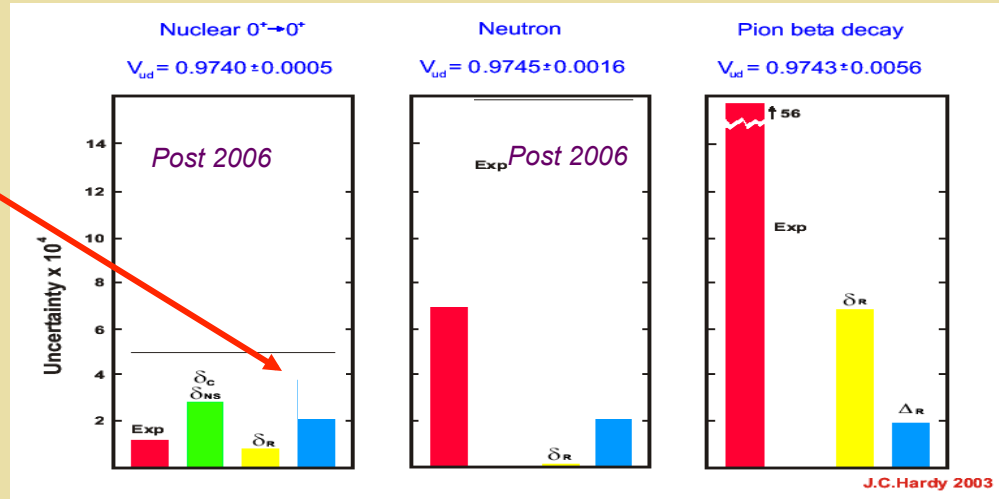
SM theory input

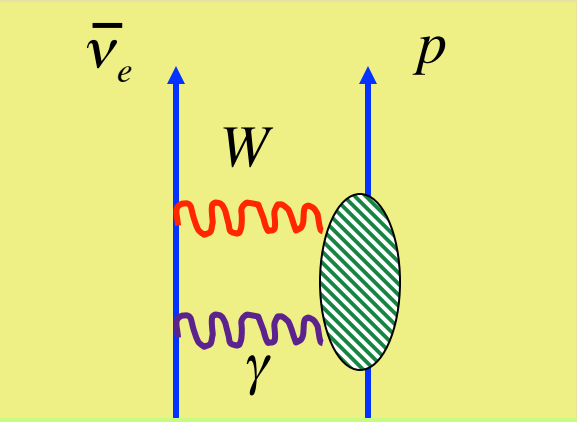
β-decay

$$n \rightarrow p\, e^- \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^+ \nu_e$$

$$\pi^+ \rightarrow \pi^0\, e^+ \nu_e$$

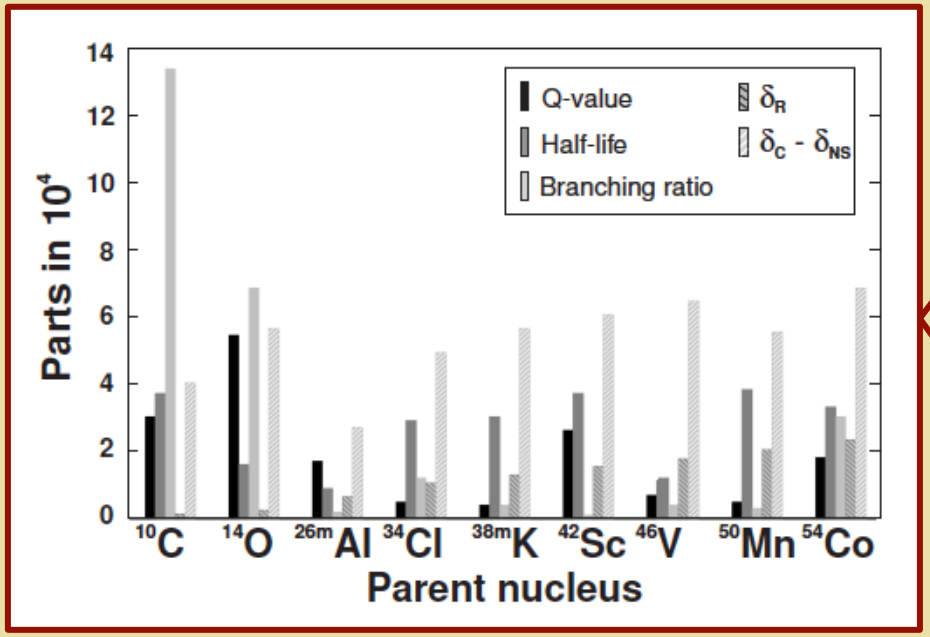




Recent Marciano & Sirlin

$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{8\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}

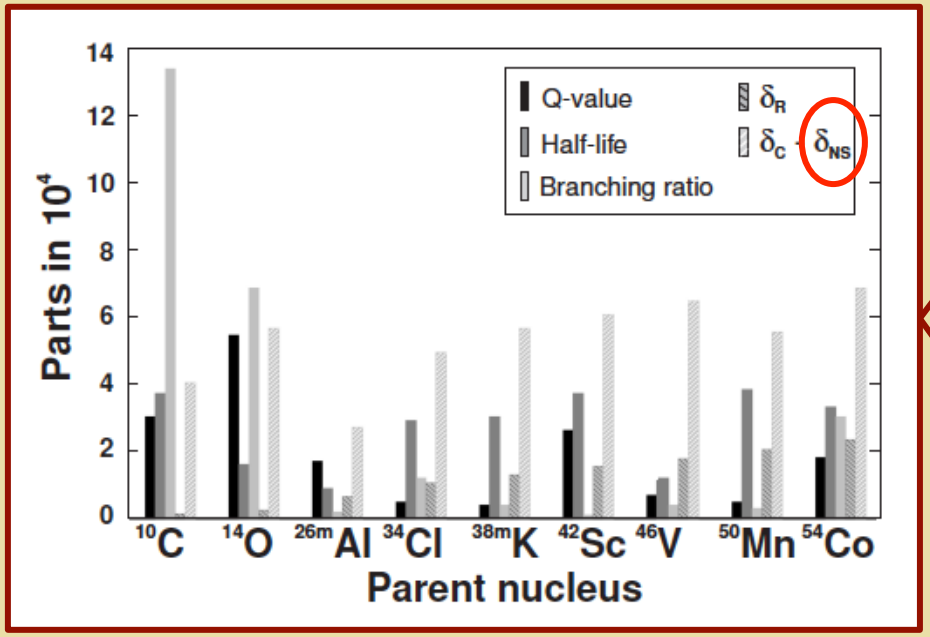


b_F : scalar currents

Input for V_{ud} & CKM unitarity test

Towner & Hardy, PRC 91 (2015) 2, 025501

$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}

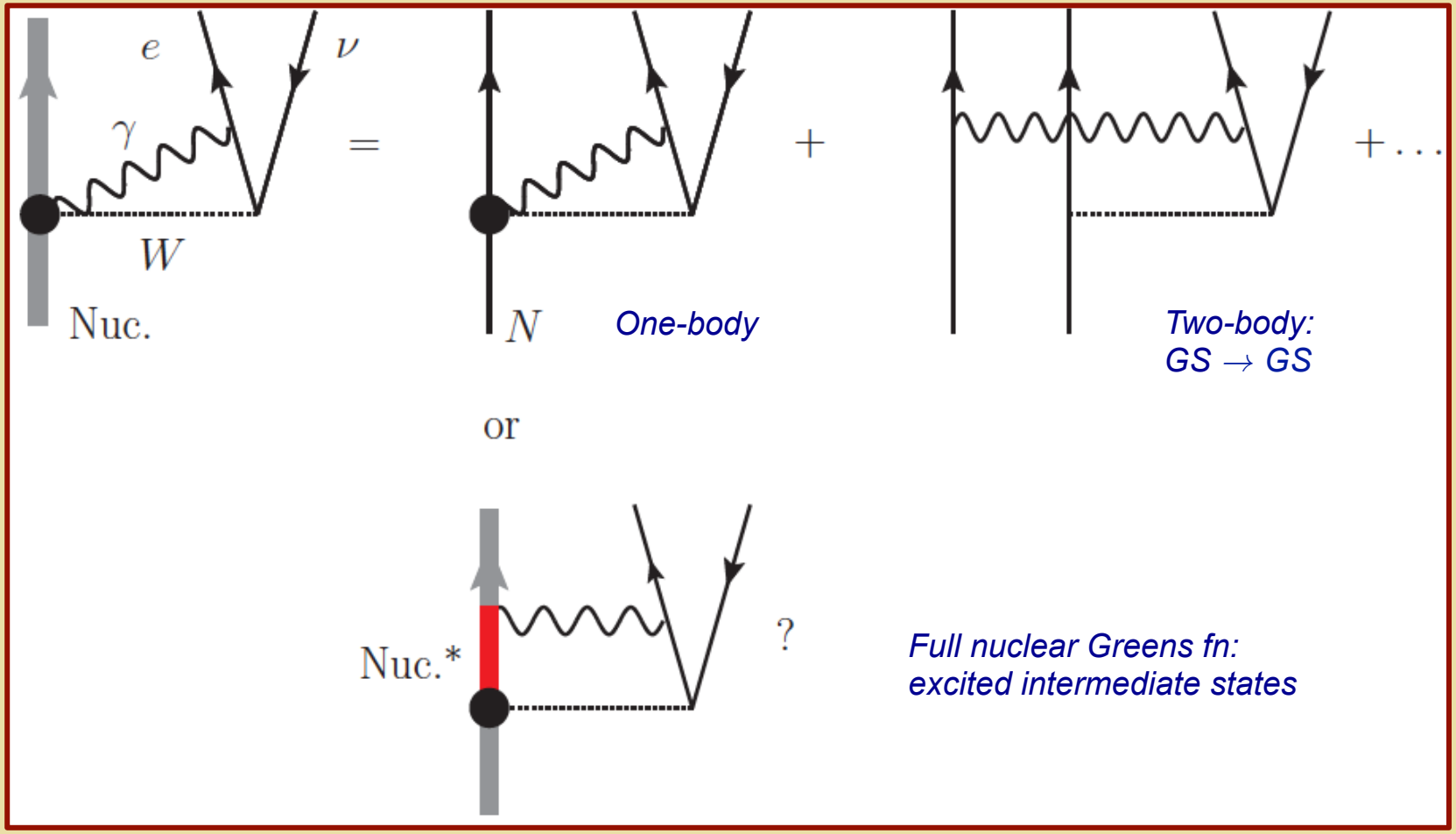


Towner & Hardy, PRC 91 (2015) 2, 025501

b_F : scalar currents

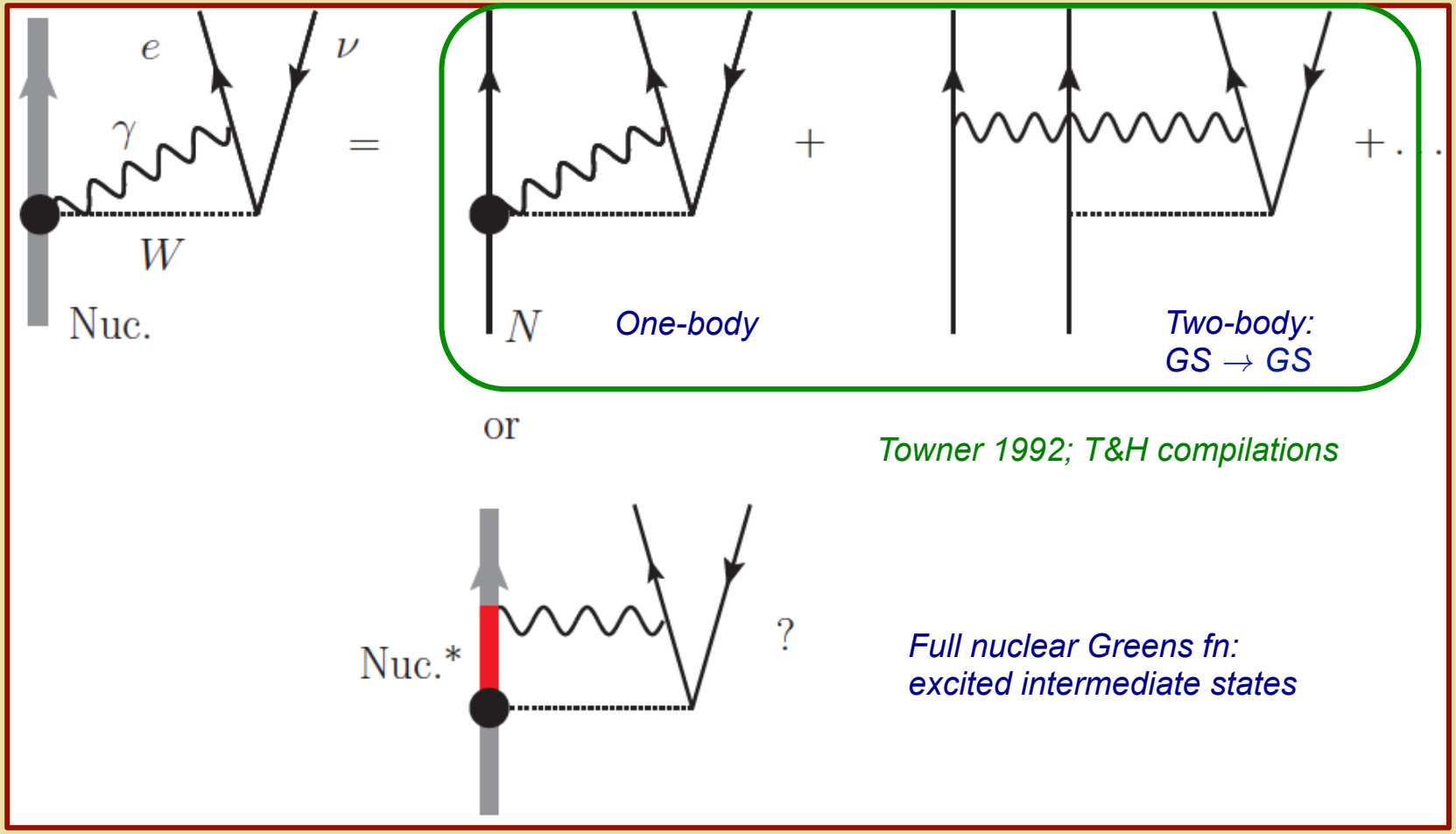
Input for V_{ud} & CKM unitarity test

$0^+ \rightarrow 0^+$ Decay: δ_{NS}



J. Engel

$0^+ \rightarrow 0^+$ Decay: δ_{NS}

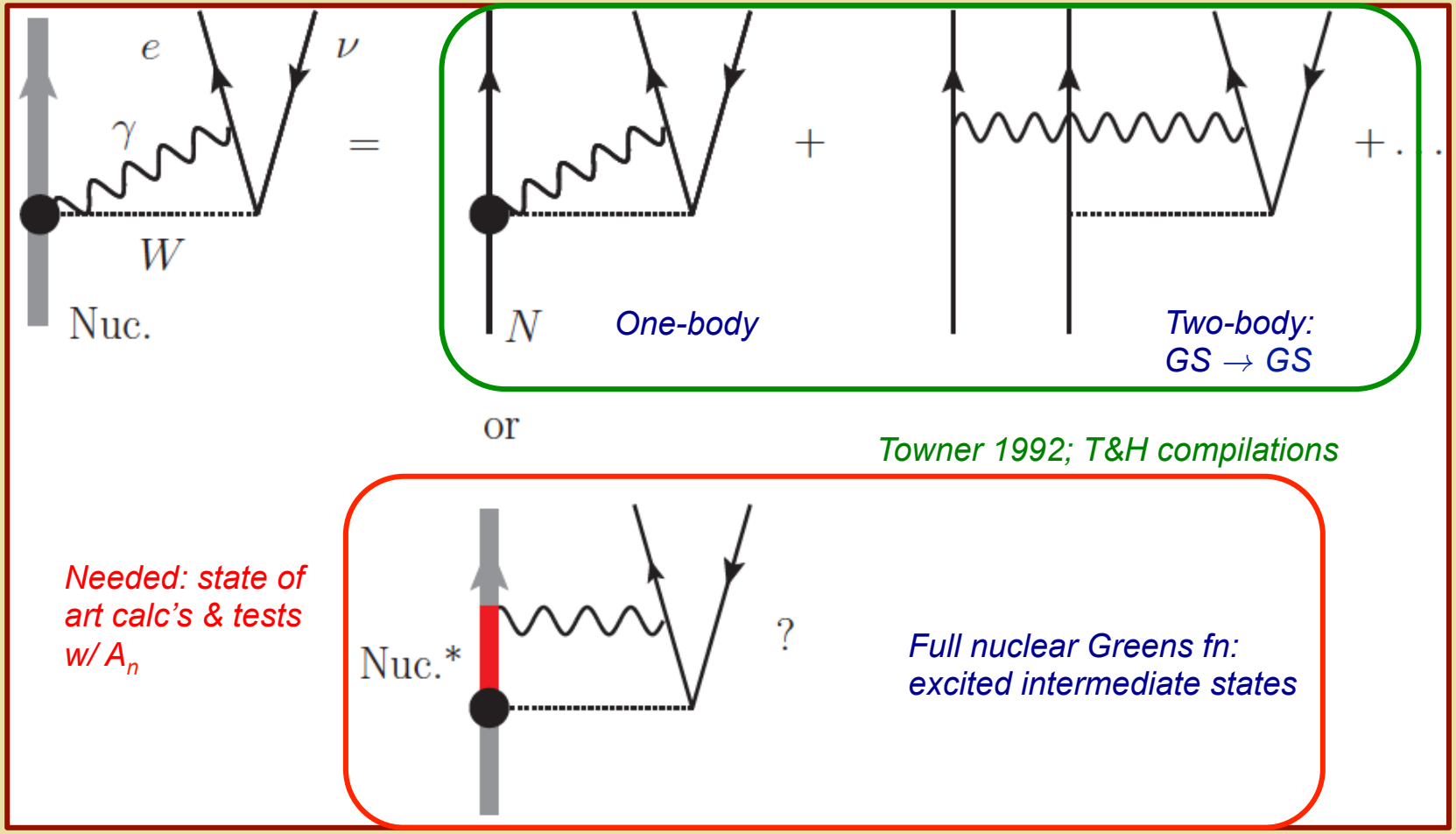


Towner 1992; T&H compilations

Full nuclear Greens fn:
excited intermediate states

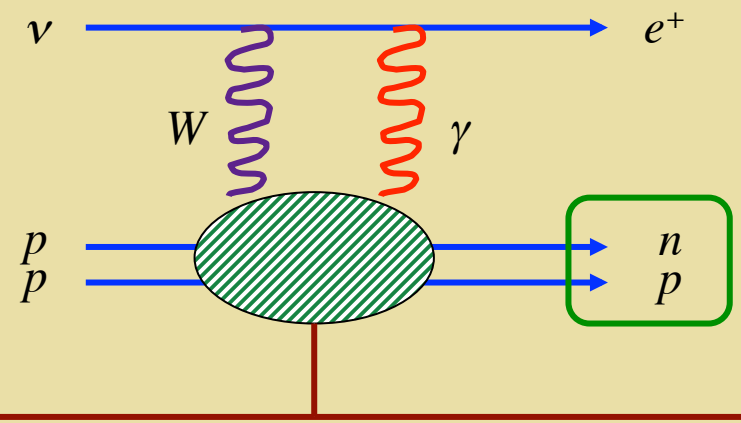
J. Engel

$0^+ \rightarrow 0^+$ Decay: δ_{NS}



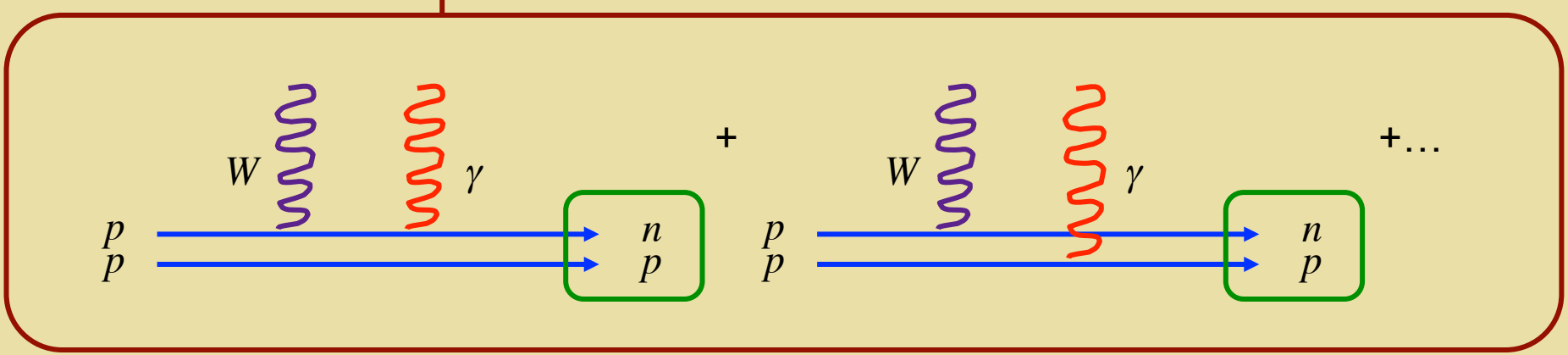
J. Engel

Dispersion Corrections: pp Reaction



$$\phi(^8\mathrm{B}) \propto (1+\delta S_{11})^{-2.73}(1+\delta S_{33})^{-0.43}(1+\delta S_{34})^{0.85} \times(1+\delta S_{17})^{1.0}(1+\delta S_{e7})^{-1.0}(1+\delta S_{1\ 14})^{-0.02},$$

$$\sigma(E) = \frac{S(E)}{E}\ \exp\left[-2\pi\eta(E)\right]$$

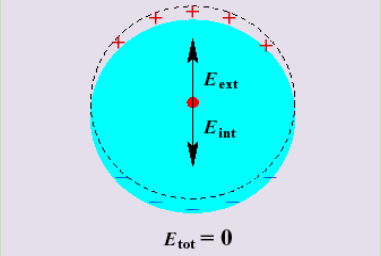


Project: pionless EFT computation

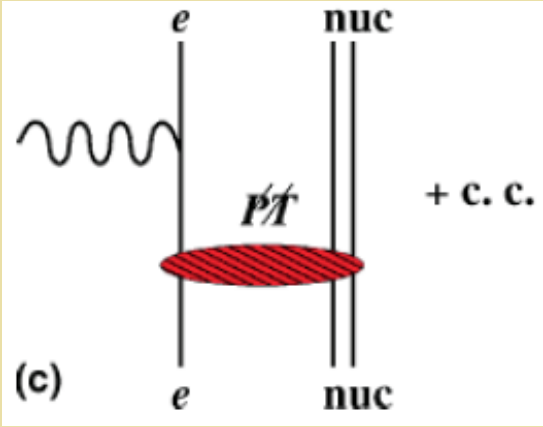
IV. Time Reversal

Diamagnetic Systems: P- & T-Odd Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Diamagnetic Systems

Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$
C_J	E	✖	✖	O
$T^M{}_J$	O	✖	✖	E
$T^E{}_J$	✖	O	E	✖

Diamagnetic Systems

Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	$\boxed{\text{O}}$	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	$\boxed{\text{E}}$	*MQM….*
$T^E{}_J$	✖	$\boxed{\text{O}}$	E	✖	*Anapole…*

Diamagnetic Systems

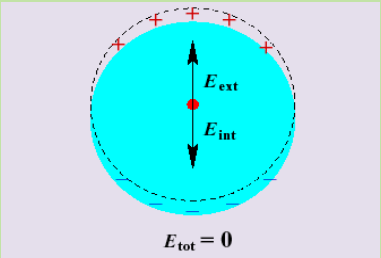
Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
$T^M{}_J$	O	✖	✖	E	*MQM….*
$T^E{}_J$	✖	O	E	✖	*Anapole…*

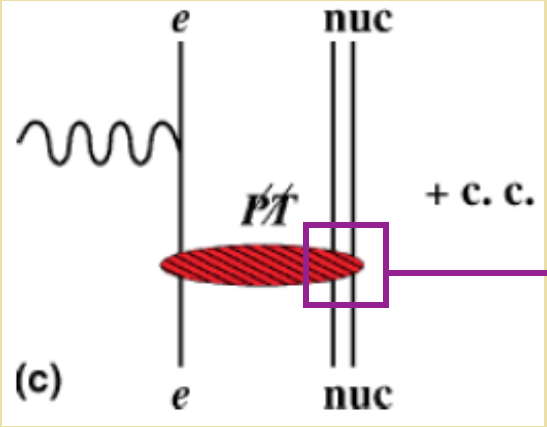
Nuclear Enhancements

Diamagnetic Systems: Schiff Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Schiff moment, MQM,…

Nuclear Schiff Moment

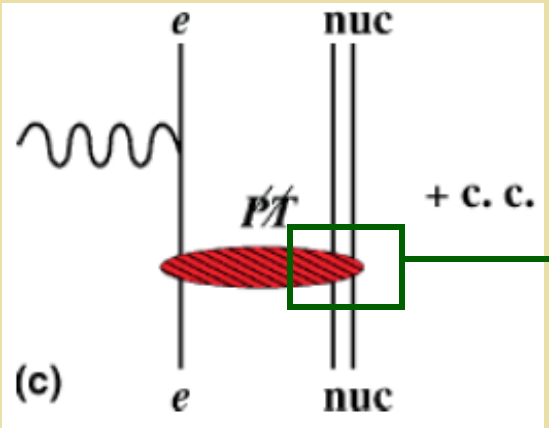
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

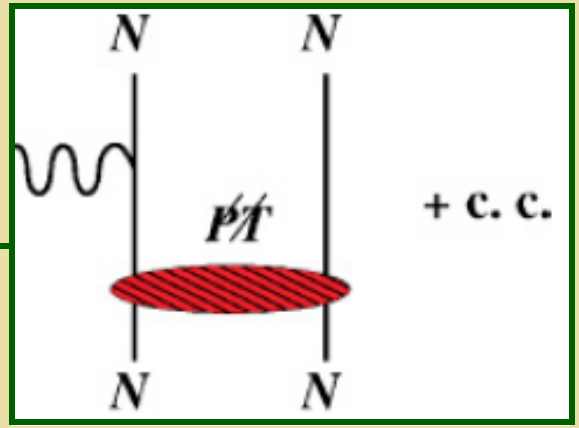
$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements





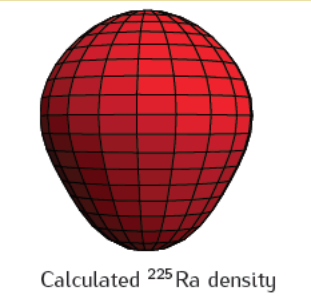
Schiff moment, MQM,…

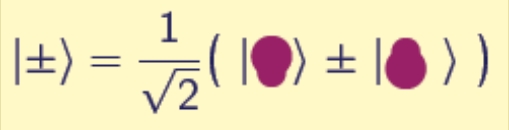
Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

EDMs of diamagnetic atoms (^{199}Hg)

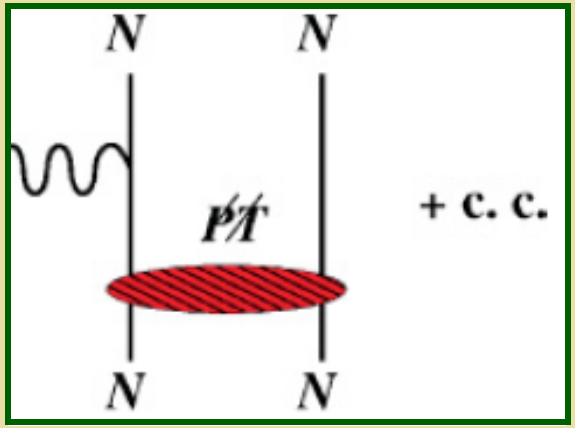
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation





Opposite parity states mixed by H^{TVPV}



Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

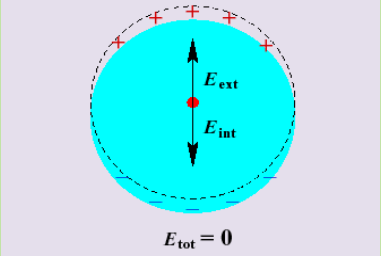
"Nuclear amplifier"

EDMs of diamagnetic atoms (^{225}Ra)

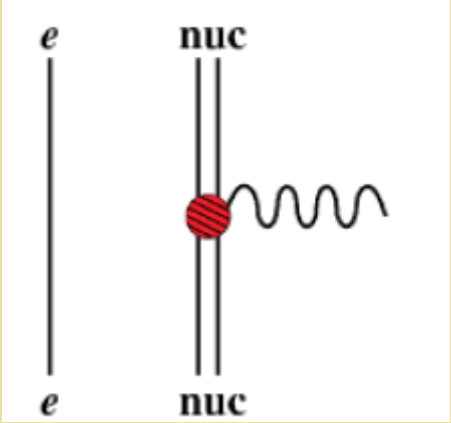
Thanks: J. Engel

Schiff Screening & Corrections

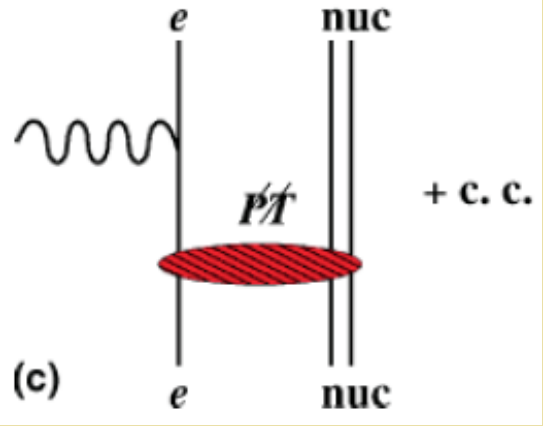
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



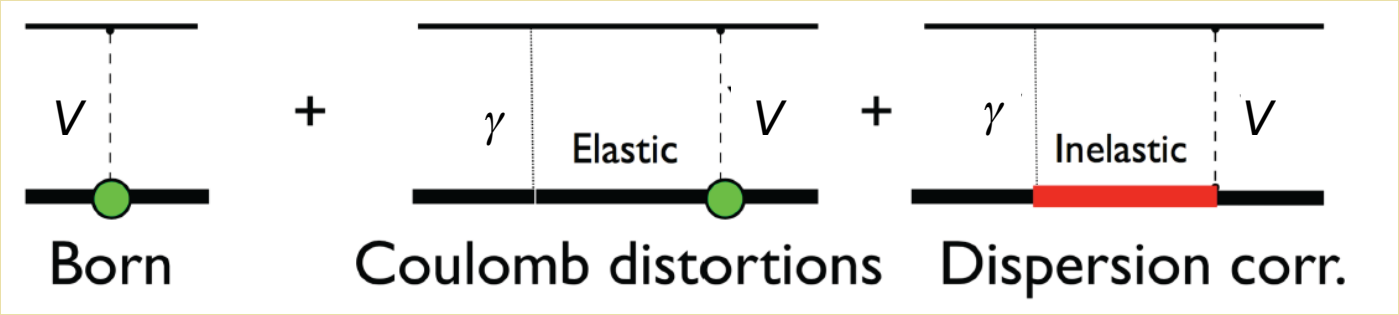
Schiff moment, MQM,…

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
T^M_J	O	✖	✖	E	*MQM….*
T^E_J	✖	O	E	✖	$T^E_{J=1} \otimes T^E_{J=2}$?

EDMs of diamagnetic atoms (^{199}Hg)

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests



$V = Z^0, W, \gamma$

$V = \gamma$ ***Diamagnetic EDM***

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$	
C_J	E	✖	✖	O	*EDM, Schiff…*
T^M_J	O	✖	✖	E	*MQM….*
T^E_J	✖	O	E	✖	$T^E_{J=1} \otimes T^E_{J=2}$?

V. Workshop Questions

- *What is the path forward for improving our understanding of $\gamma\gamma$ exchange in semileptonic processes?*

- *How reliable are the present contributions of $Z\gamma$ and $W\gamma$ boxes for nucleons and nuclei ?*

- *What additional theoretical developments/ computations are needed?*

- *Is there a program of experimental measurements that could be used to refine theoretical predictions ?*

Back Up Slides