EW Radiative Corrections: View Ahead

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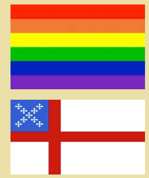

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

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

My pronouns: he/him/his

Collaborators: M. Gorchtein, H. Patel, C. Seng

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Beta Decay Workshop
ECT* April 2019

Goals For This Talk

- *Give a brief recap of the context*
- *Give a look ahead*
- *Discuss possible tests*
- *Put the Wγ box in more general context of EW boxes*
- *Motivate future work*

Outline

I. *Recap*

II. *Future Work: Free Nucleon*

III. *Future Work: Nuclei*

IV. *Electroweak Boxes More Generally*

V. *Outlook*

I. Recap

Precision ~ BSM Mass Scale

Precision Goal:

$$\delta\, \Delta_{CKM} \sim O(10^{-4})$$

Heavy BSM Physics:

$$\Delta_{CKM} \sim C \;\; (v/\Lambda)^2$$

$\Lambda \sim 10$ TeV (tree)

$\Lambda < 1$ TeV (loop)

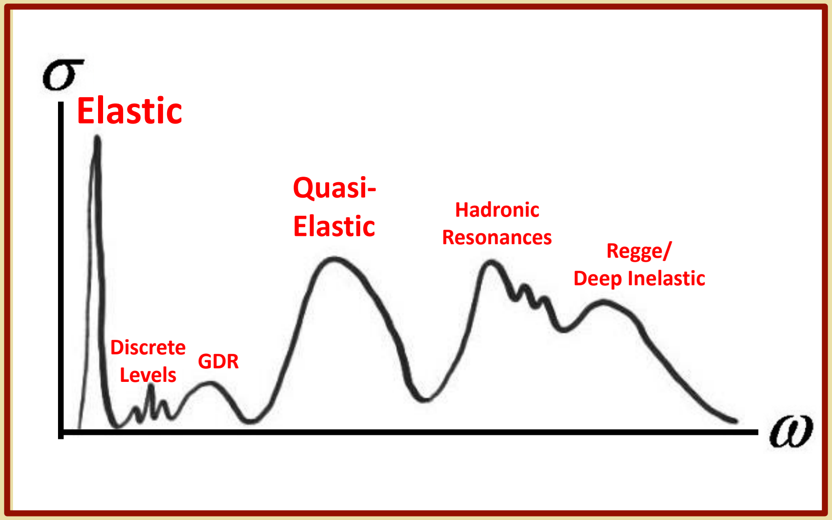
Ultralight BSM Physics:

$$\Delta_{CKM} \sim \varepsilon^2 \;\; (\alpha /4\pi)$$

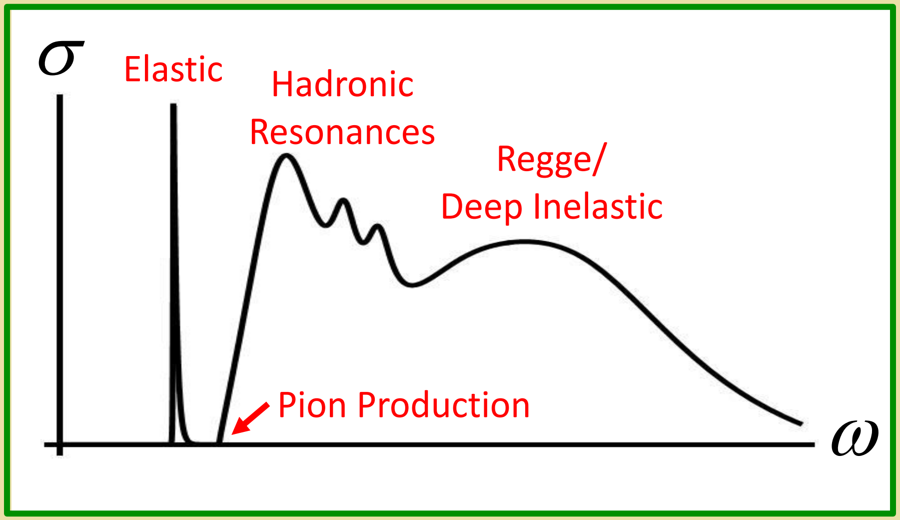
$\varepsilon < 1$ (loop)

Leptoproduction: Had & Nuc Response

Nuclei

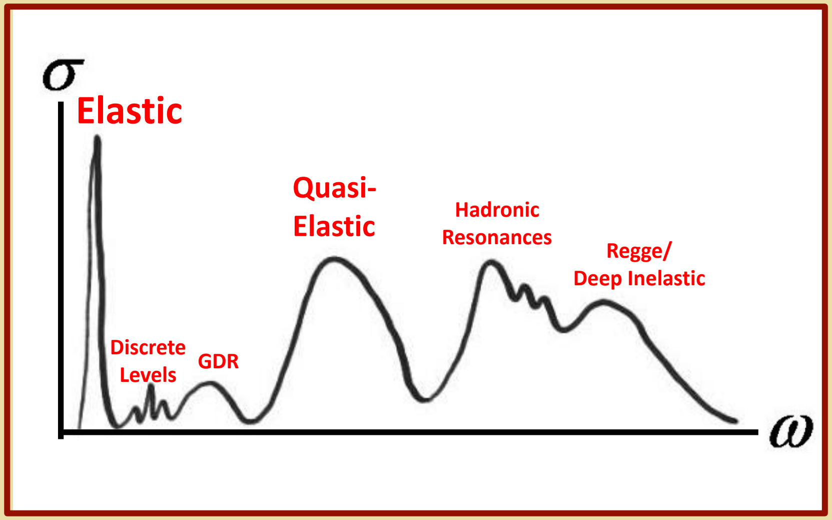


Free nucleons

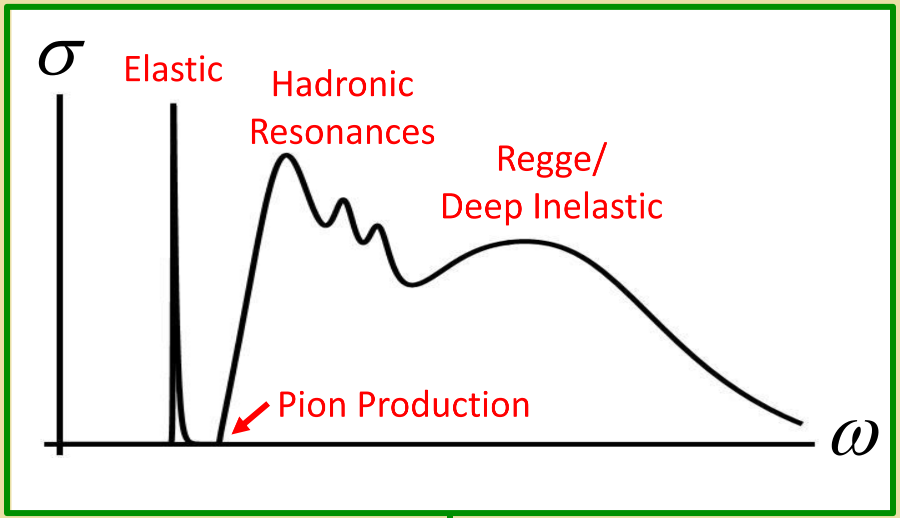


Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons

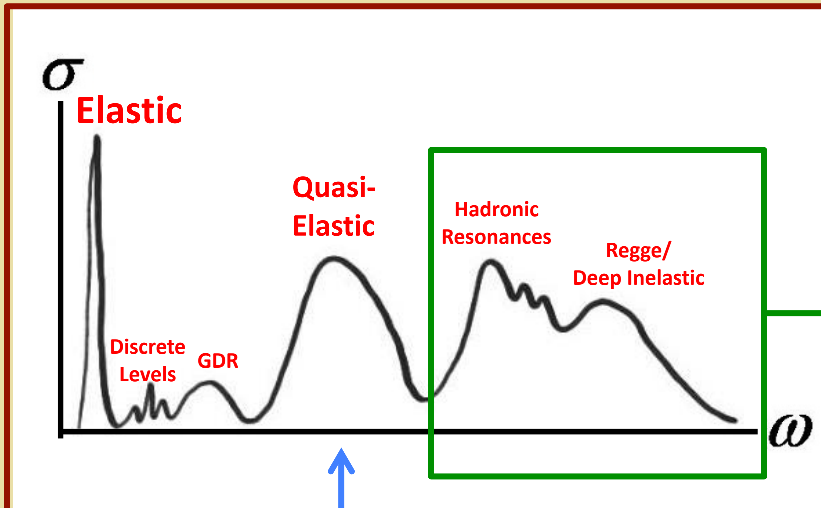


Single nucleon: PRL 121 (2008) 241804

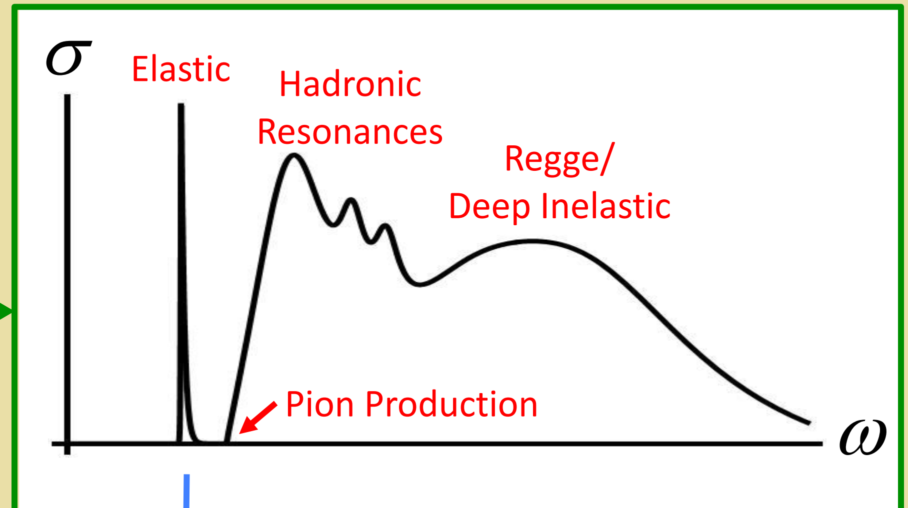
$\Delta_R^V = 0.02361(38) \rightarrow 0.02467\ (22)$

Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons



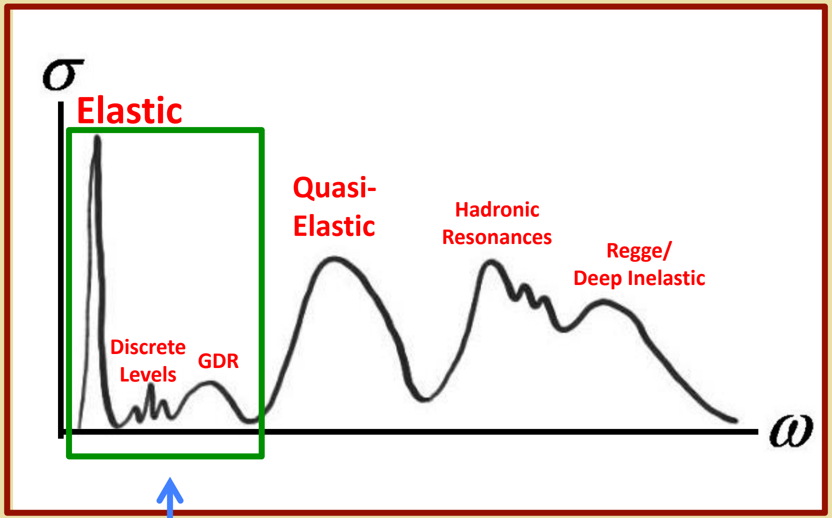
Quasielastic response

Part of δ_{NS} : " C_B^{Nucl} "

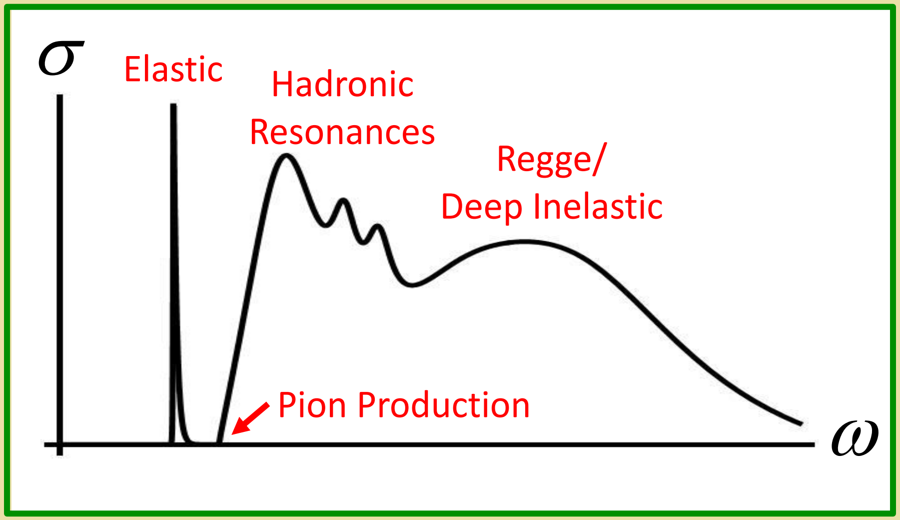
New work

Other Nuclear Corrections

Nuclei



Free nucleons



Low-lying transitions

Part of δ_{NS}

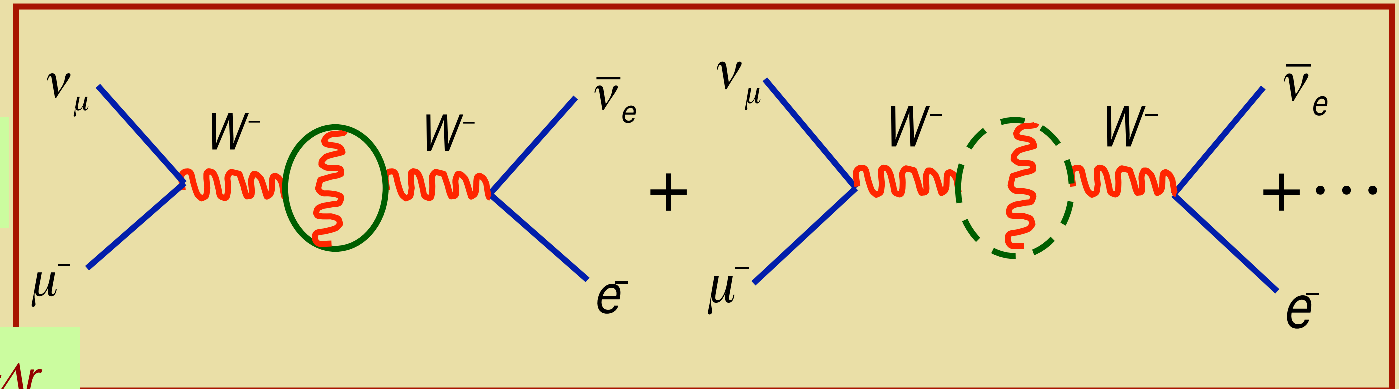
Questions for the Day

- *How robust is the quoted uncertainty on the new value of Δ_R^V ?*
- *What additional tests (theory, experiment) are available ?*
- *What is the roadmap to refined computation of δ_{NS} (QE) ?*
- *How important are contributions from other region of the low-E nuclear response ? How to compute & how to test computations ?*

II. Future: Single Nucleon

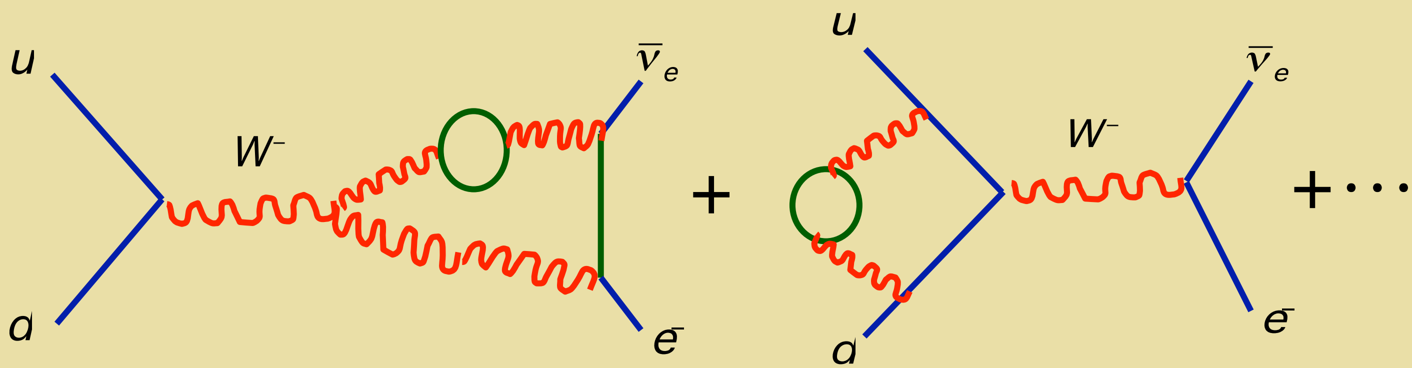
“Next Frontier” : Higher Order EW RC

Propagator

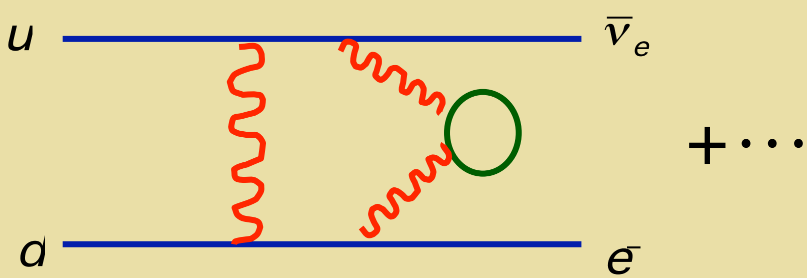


Cancel from $\Delta r_\beta - \Delta r_\mu$

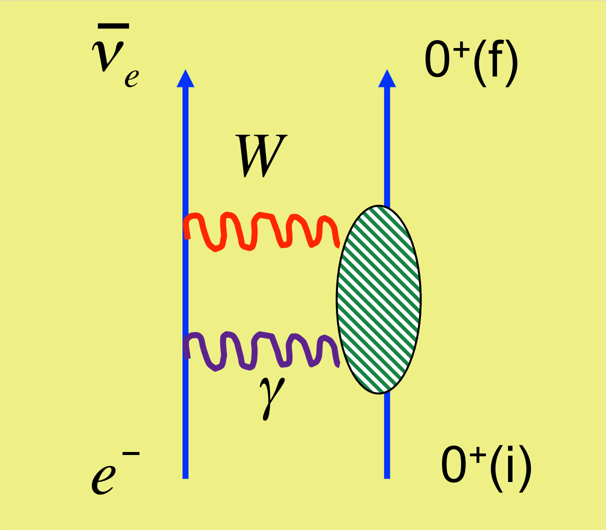
Vertex &
External leg



Box

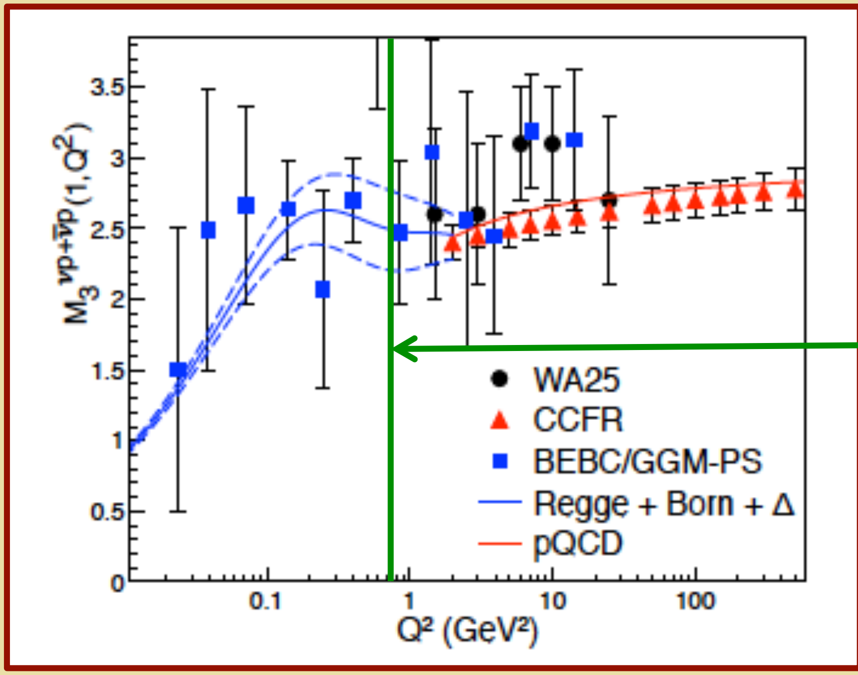


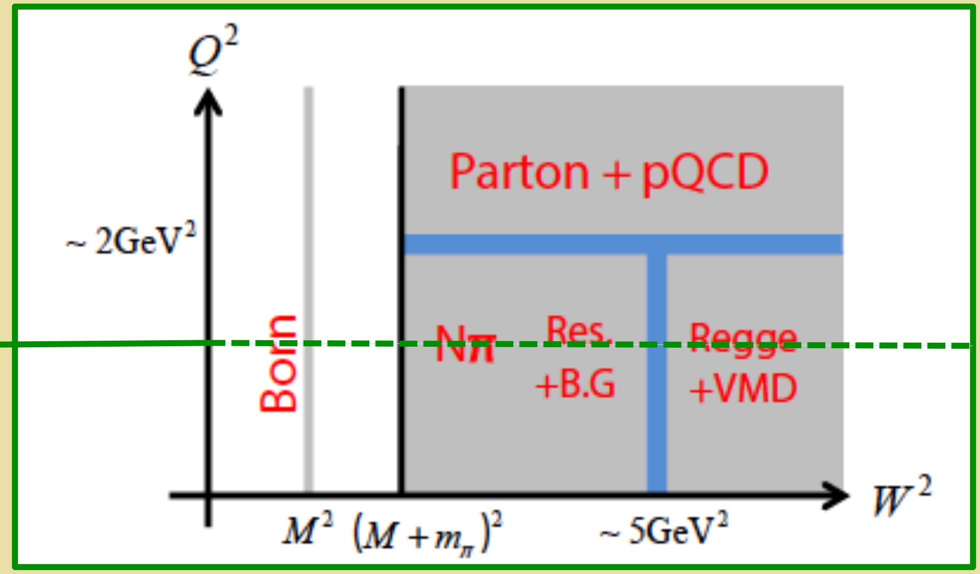
Long Distance: Hadronic & Nuclear



Neutrino Scattering

Free nucleons

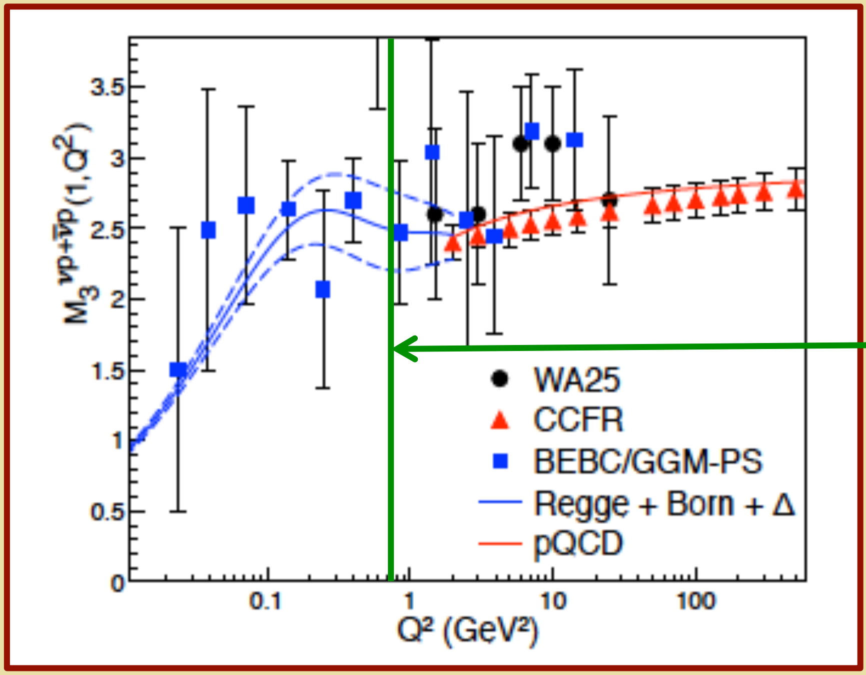


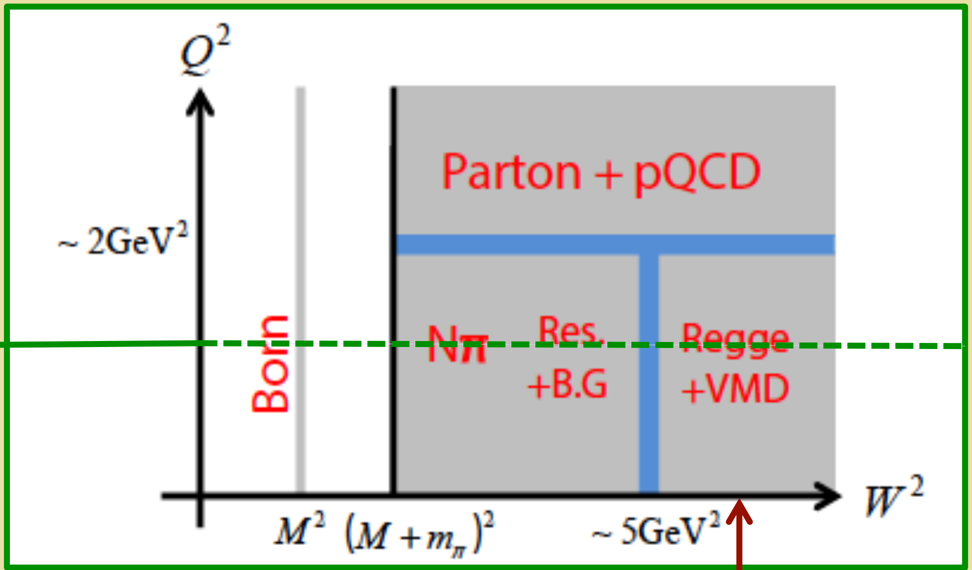


- ***Compute contributions to $M_3^{\nu p+\bar{\nu}p}$ at each Q^2 from different ω regions***
- ***Isospin rotate to $M_3^{(0)}$***

Neutrino Scattering

Free nucleons



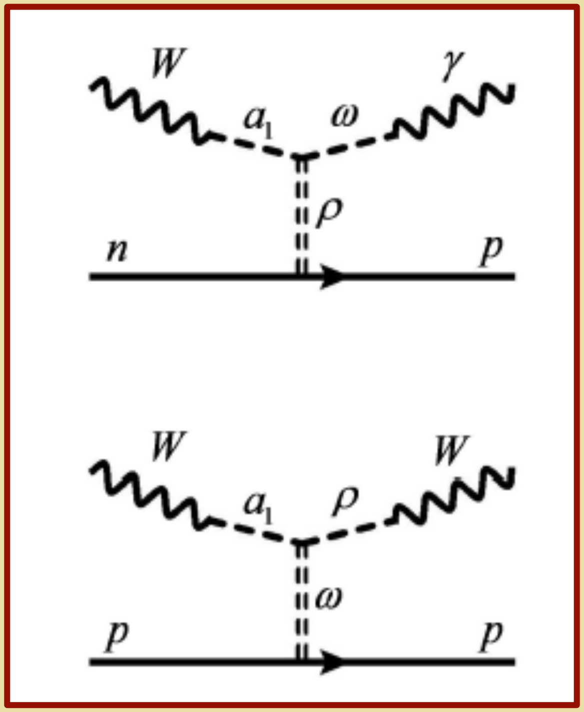


Regge

- ***Compute contributions to $M_3^{\nu p+\bar{\nu}p}$ at each Q^2 from different ω regions***

- ***Isospin rotate to $M_3^{(0)}$***

Regge Contribution



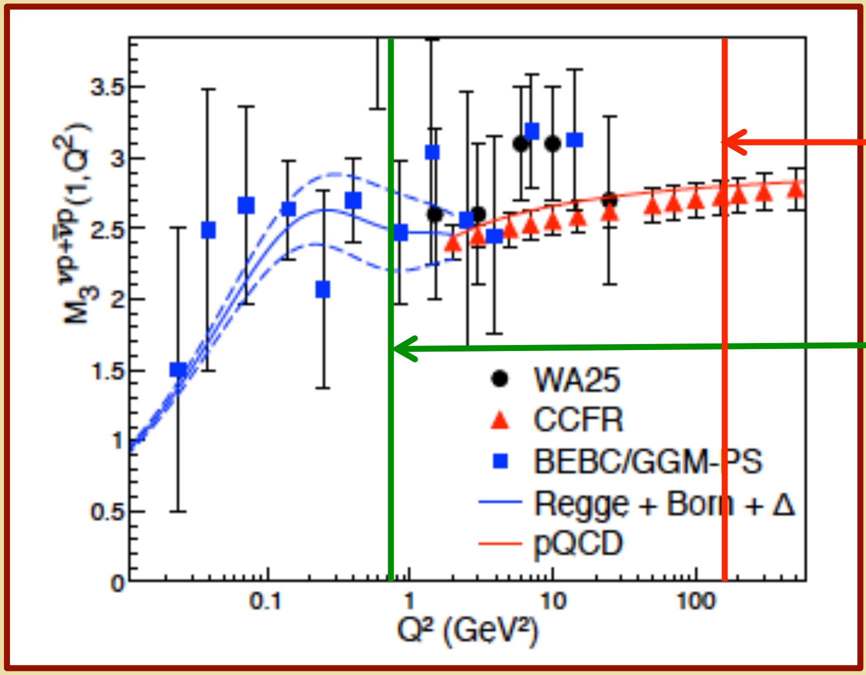
$$F_{3,\mathbb{R}}^{\nu p+\bar{\nu}p} = \frac{C(Q^2)f_{th}(W)}{\left[1+Q^2/m_\rho^2\right]\left[1+Q^2/m_{a_1}^2\right]}\left(\frac{\nu}{\nu_0}\right)^{\alpha_0}$$
$$\downarrow$$
$$F_{3,\mathbb{R}}^{(0)} = \frac{1}{36}\frac{C_{\gamma W}(Q^2)f_{th}(W)}{\left[1+Q^2/m_\rho^2\right]\left[1+Q^2/m_{a_1}^2\right]}\left(\frac{\nu}{\nu_0}\right)^{\alpha_0}$$

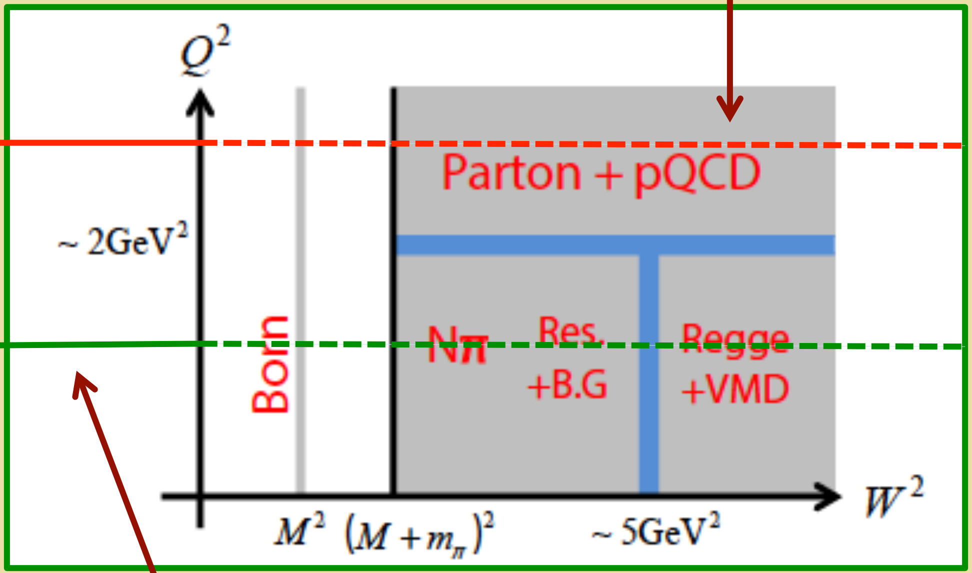
- ***Matching at Q^2 = 0 and Q^2 = 2 (GeV)^2 [pQCD regime] → $C_{\gamma W}$ (Q^2) = C(Q^2)***
- ***Factor of 1/36: matching at pQCD scale***

Neutrino Scattering

DIS

Free nucleons





Born + (π N + Res) + Regge

- Compute contributions to $M_3^{\nu p+\bar{\nu}p}$ at each Q^2 from different ω regions
- Isospin rotate to $M_3^{(0)}$

Future Tests

- *Lattice computation of $M_3^{(0)}(Q^2)$*
- *PV electron scattering*

Isospin relation

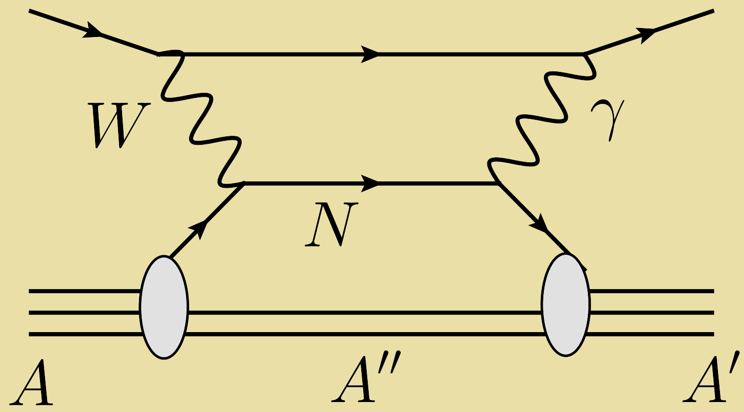
$$\boxed{4F_3^{(0)} = F_{3,\gamma Z}^{p} - F_{3,\gamma Z}^{n}}$$

  - *SoLID ?*
  - *EIC ?*

- *More neutrino data for $M_3^{(0)}(Q^2)$*

III. Future: Nuclei

Impact on δ_{NS}



$$\Delta\,\delta_{NS} = \frac{\alpha}{\pi}\left(C_{QE} - q_S^{(0)} q_A C_B\right) = -(4.6 \pm 0.9) \times 10^{-4}$$

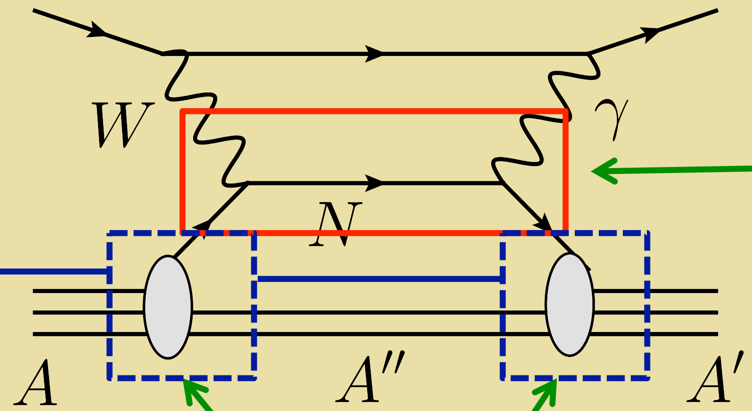
Neglects A-dep variations

Ave over 20 transitions

Optimistic:
- *Correlations*
- *2-body currents*
- *Rel corrections*

Quasielastic Contribution to δ_{NS}

Conceptual issue: response function for $A \neq A'$



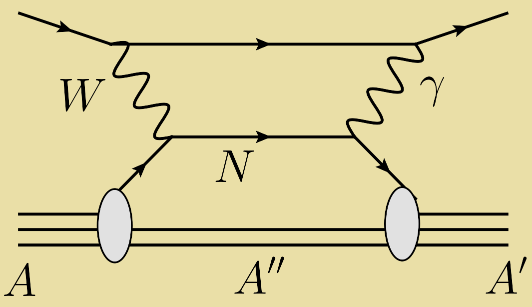
Free nucleon $W^{\mu\nu}$

Nucleon distribution functions

$$W^{\mu\nu} = \frac{3\mathcal{N} m_{\mathrm{N}}^2}{4\pi p_{\mathrm{F}}^3} \int \frac{\mathrm{d}^3 \boldsymbol{p}}{E(\boldsymbol{p})E(\boldsymbol{p}+\boldsymbol{q})} \delta\{\omega - [E(\boldsymbol{p}+\boldsymbol{q}) - E(\boldsymbol{p})]\}$$
$$\times \theta(p_{\mathrm{F}} - |\boldsymbol{p}|)\theta(|\boldsymbol{p}+\boldsymbol{q}| - p_{\mathrm{F}}) f^{\mu\nu}(P+Q, P),$$

e.g. Relativistic Fermi Gas *Donnelly et al '91*

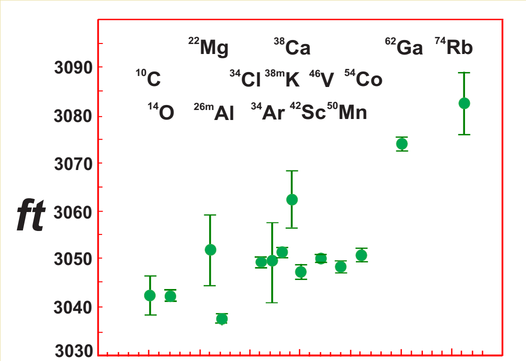
QE Contribution: Refinements

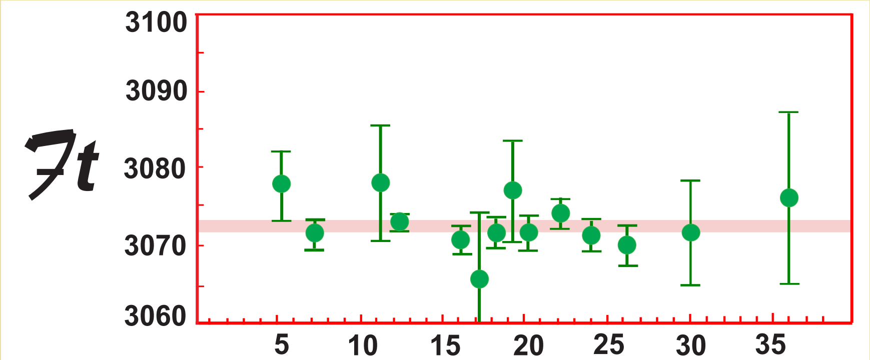


Apply state-of-art methods

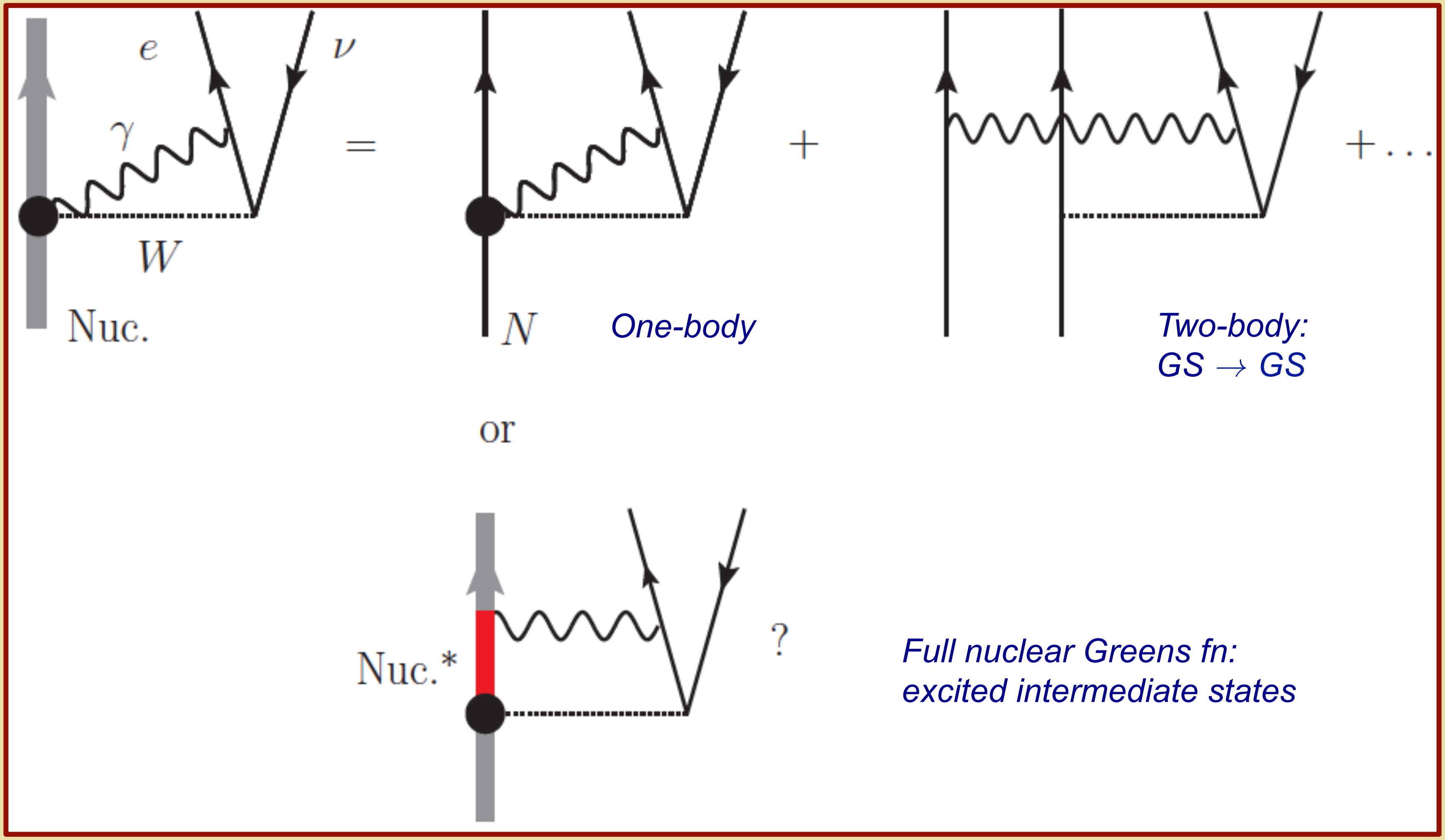
- *Correlations*
- *2-body currents*
- *Rel corrections*

Consistency w/ CVC ?



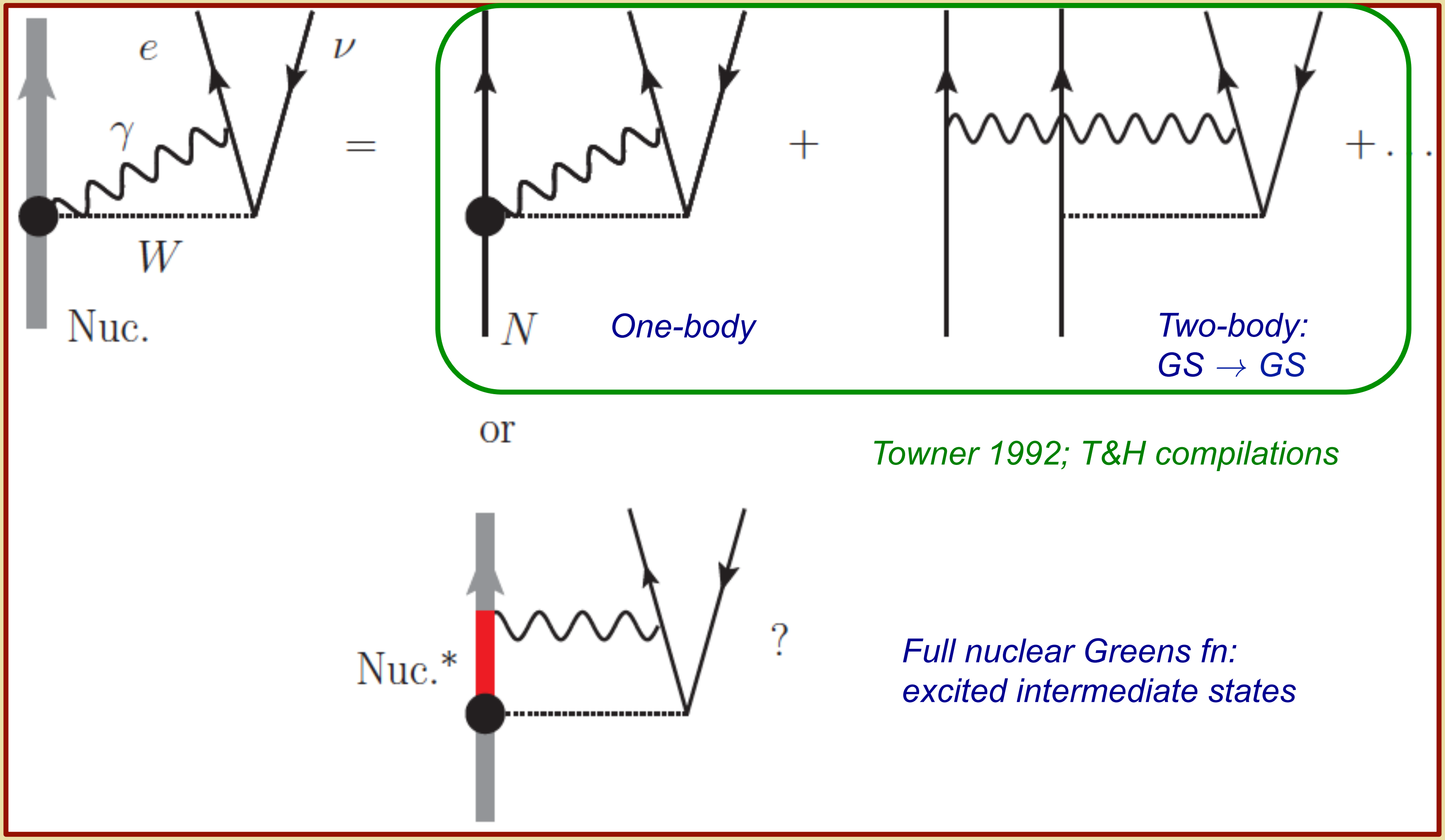


$0^+ \rightarrow 0^+$ Decay: δ_{NS}



J. Engel

$0^+ \to 0^+$ Decay: δ_{NS}



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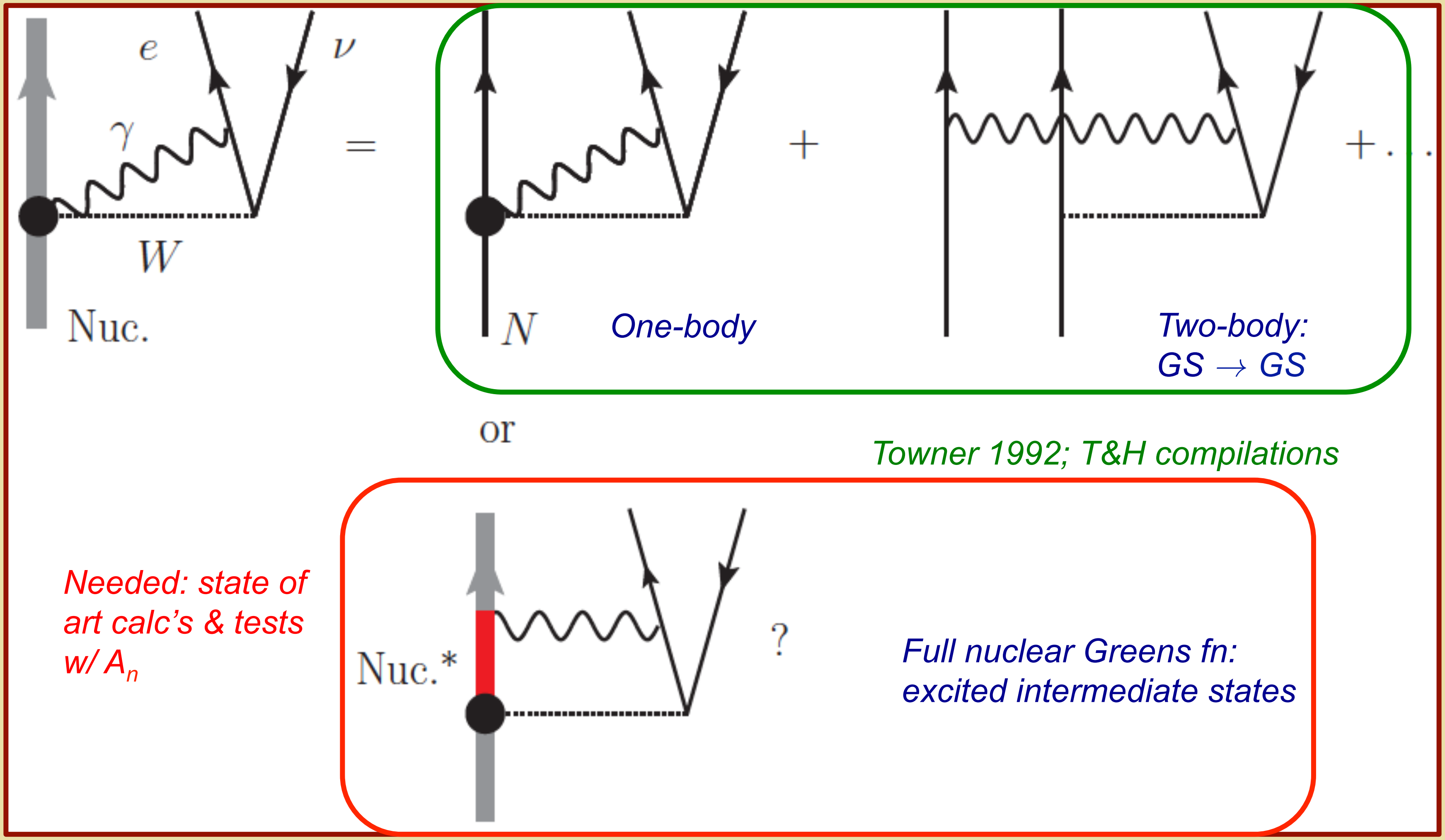
$0^+ \rightarrow 0^+$ Decay: δ_{NS}

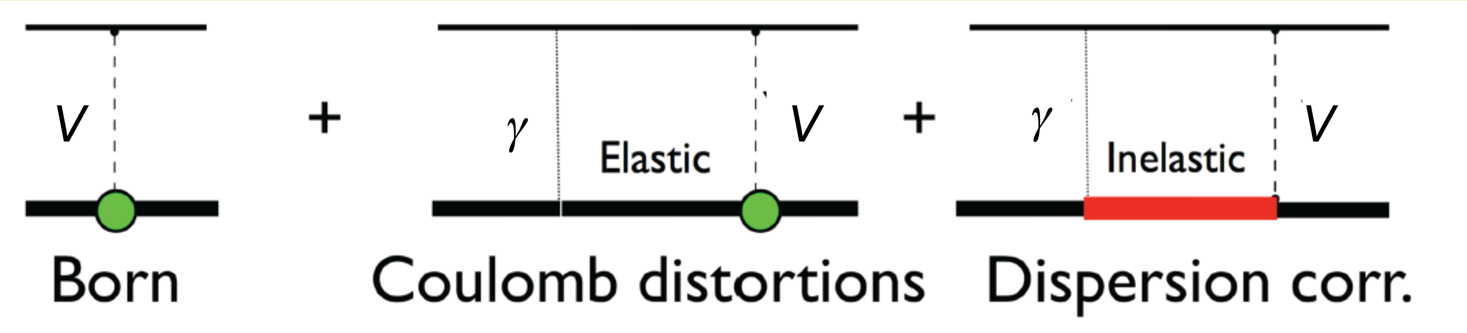


J. Engel

IV. EW Boxes More Generally

Dispersion Corrections

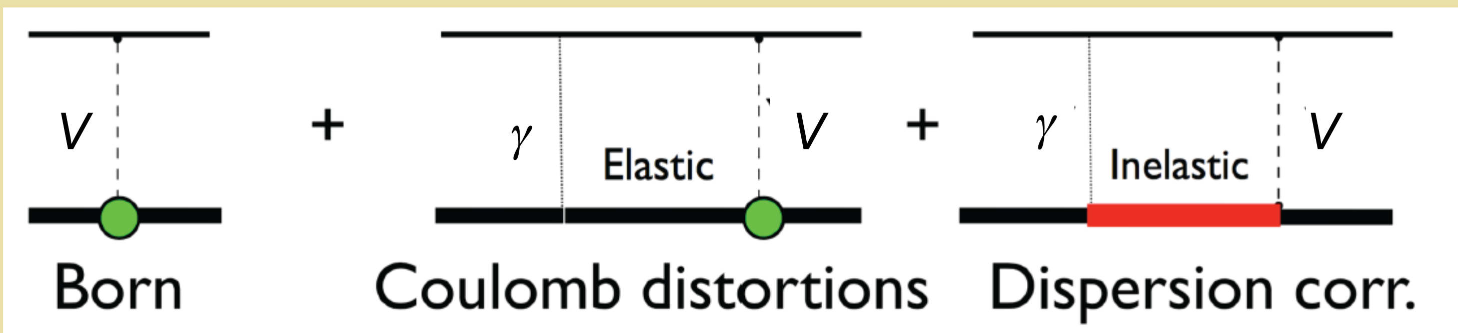
Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests



V = Z^0, *W*, γ

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

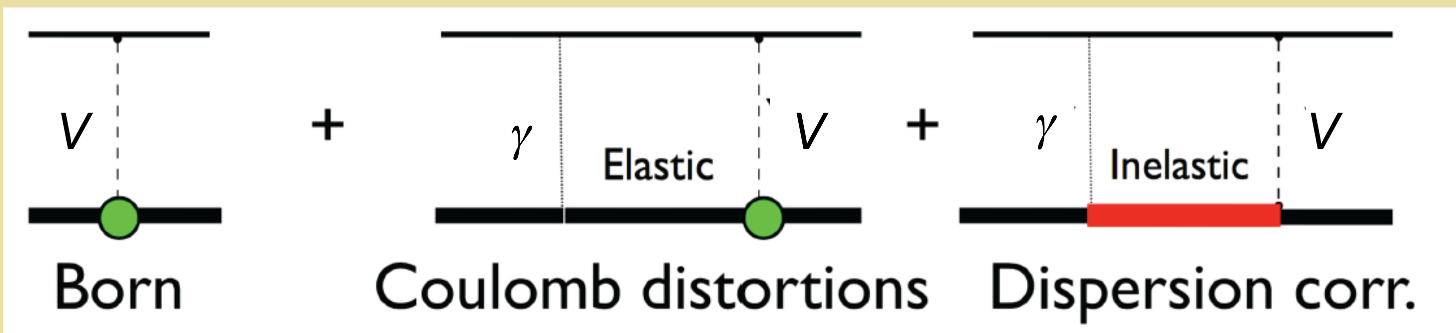


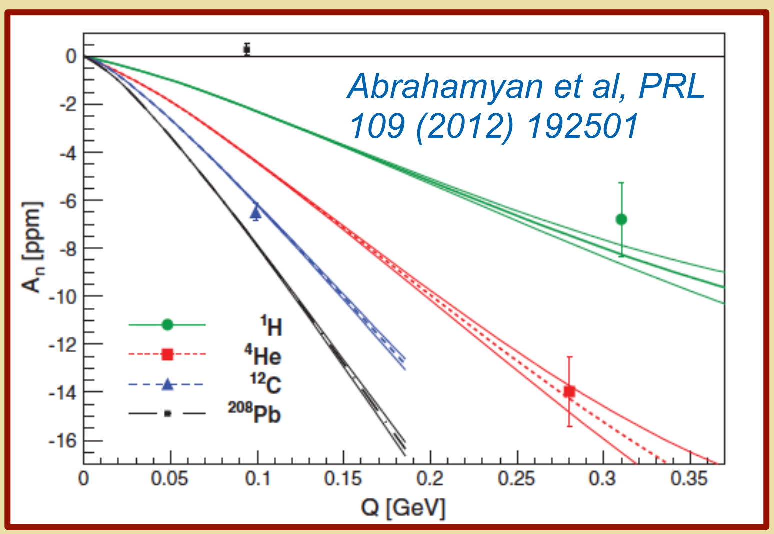
$V = Z^0, W, \gamma$

$V = \gamma$ ***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



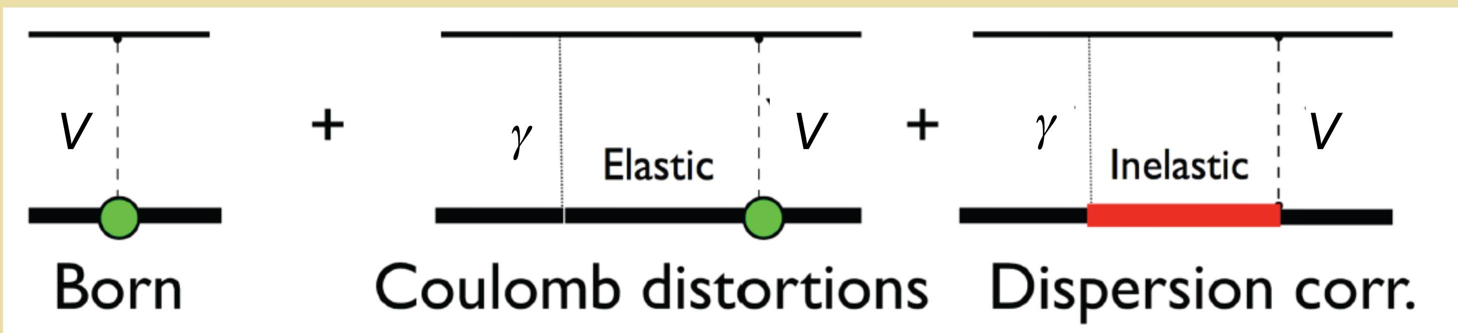


$V = \gamma$ ***Beam normal asymmetry***

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

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



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

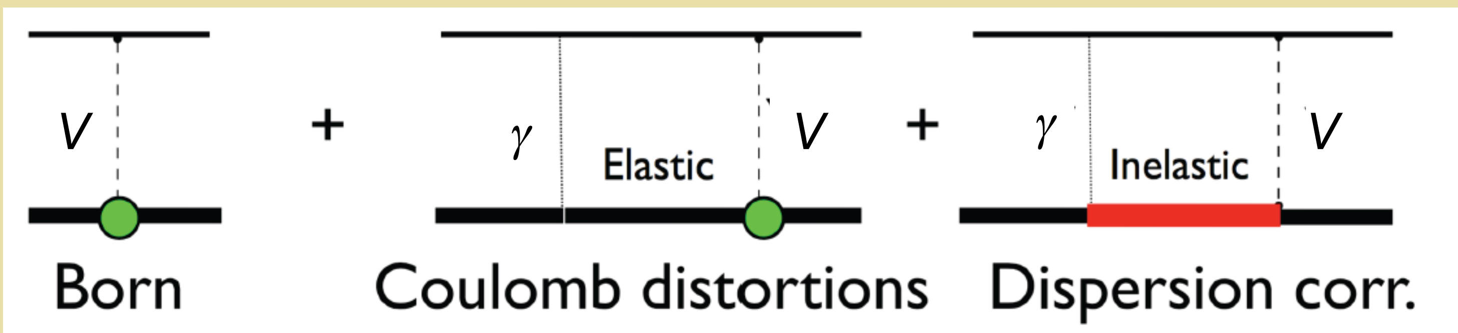
$V = \gamma$ ***Beam normal asymmetry***

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

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

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



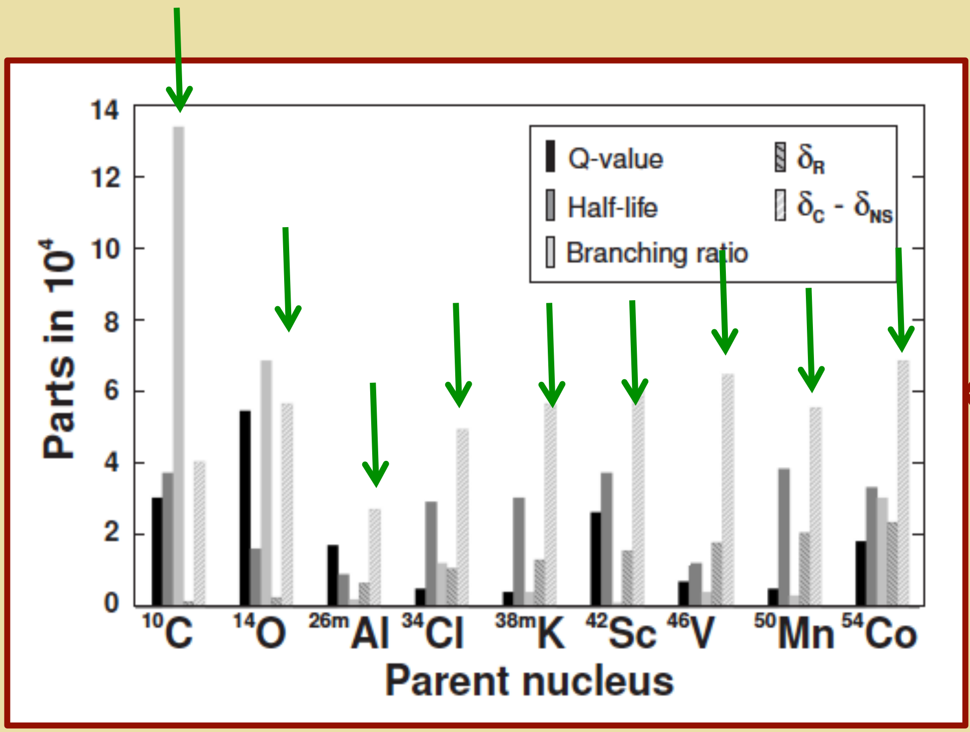
$V = Z^0, W, \gamma$

$V = \gamma$ ***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

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



b_F : scalar currents

Input for V_{ud} & CKM unitarity test

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

- *Re-compute with state-of-the-art many-body methods*
- *Test w/ A_n predictions & expt for ^{10}B, ^{14}N, ^{26}Mg, ^{34}S, ^{38}Ar, ^{42}Ca, ^{46}Ti, ^{50}Cr, ^{54}Fe*
- *Investigate strategy for obtaining reduced error bars*

IV. Outlook

- *Studies of neutron and nuclear β-decay are heading to a new era of precision, with a goal $\delta\Delta_{CKM}$ ~ $O(10^{-4})$*
- *Hadronic and nuclear uncertainties in computing the $W\gamma$ box radiative correction remain one of the key challenges to reaching this goal*
- *Recent developments using dispersion relations open a new path toward reducing this uncertainty with an opportunity for new experimental tests using leptoproduction & theoretical tests with lattice QCD*
- *There exists an exciting opportunity to implement a unified, comprehensive program EW box computations (β-decay, PV electron scattering) and experimental tests with polarized electron-nucleus scattering (A_n).*