V_{ud} Outlook : Experiment & Theory

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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My pronouns: he/him/his

Collaborators: All workshop participants

CKM Workshop
ACFI May 2019

Workshop Goals

- ***Review recent theoretical developments in the extraction of V_{ud} and V_{us} from experimental measurements***

- ***Seek a consensus on the current values of theoretical inputs and associated theoretical uncertainties***

- ***Develop a roadmap for future, improved theoretical evaluations and experimental tests***

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:

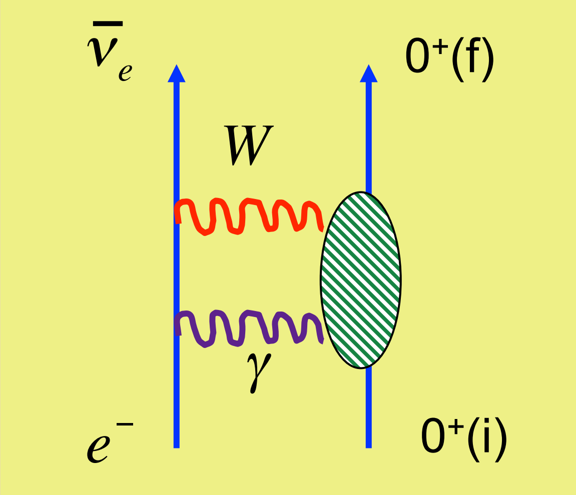
$$\Delta_{CKM} \sim \varepsilon^2 \;\; (\alpha /4\pi)$$

$\varepsilon < 1$ (loop)

Questions for This Discussion

- ***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} ?***
- ***How important are contributions from other region of the low-E nuclear response ? How to compute & how to test computations ?***

Dispersion Relations



Radiative Correction:

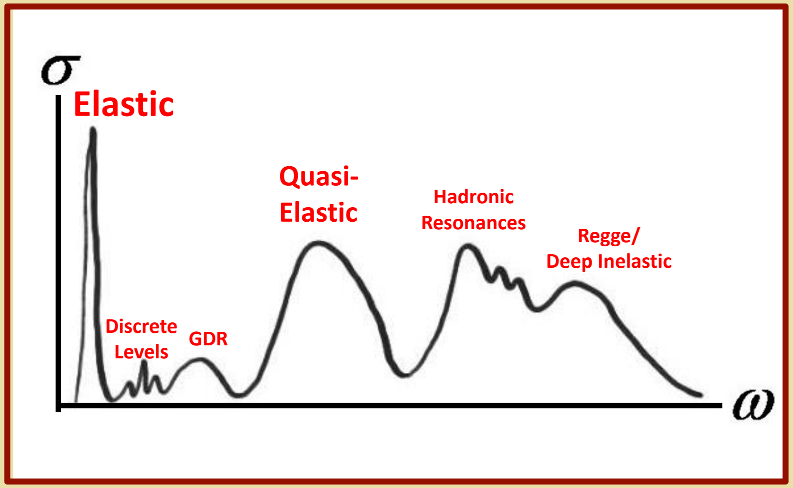
$$\Box^{VA\,(0)}_{\gamma W} = \frac{\alpha}{\pi M}\int\limits_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}\int\limits_0^\infty d\nu\,\frac{(\nu+2q)}{\nu(\nu+q)^2}F_3^{(0)}(\nu,Q^2)$$

$$= \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2 M_W^2}{Q^2[M_W^2+Q^2]}\boxed{M_3^{(0)}(1,Q^2)}$$

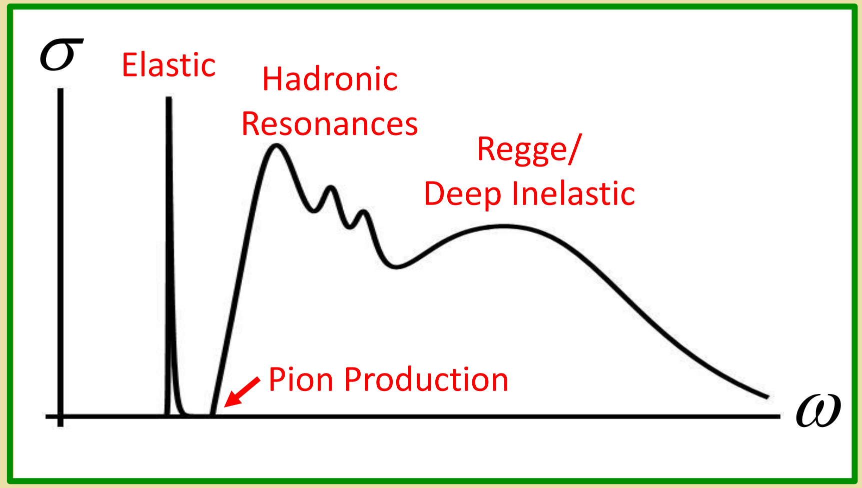
- ***Relate $F_3^{(0)}$ and $M_3^{(0)}$ to data and/or***
- ***Compute $F_3^{(0)}$ and $M_3^{(0)}$ using same methods used to describe semi-leptonic scattering processes with nucleon & nuclear targets***

Leptoproduction: Had & Nuc Response

Nuclei



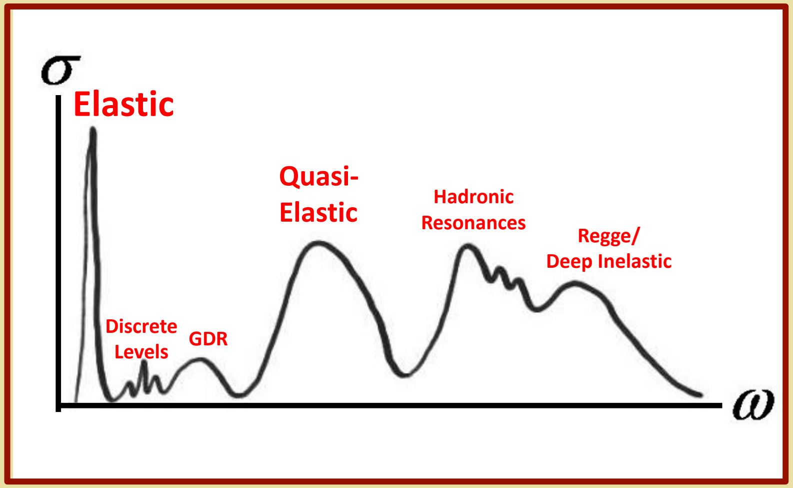
Free nucleons



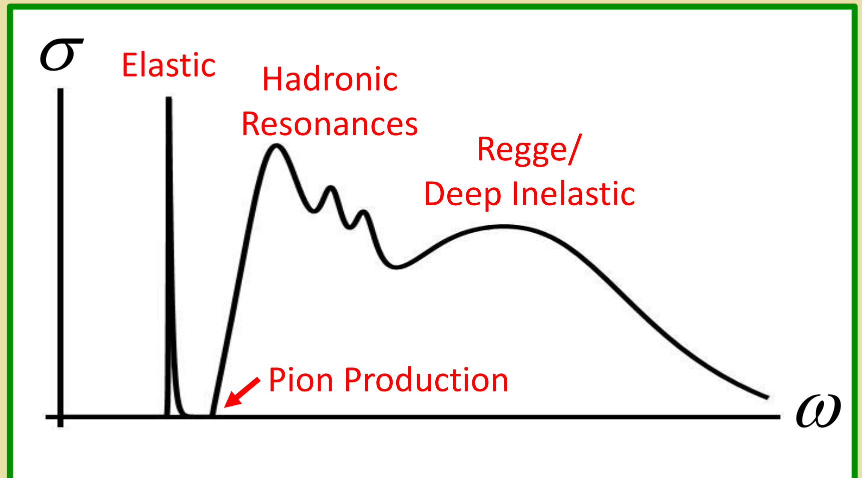
Recent Results: Single Nucleon

Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons



Single nucleon: PRL 121 (2008) 241804

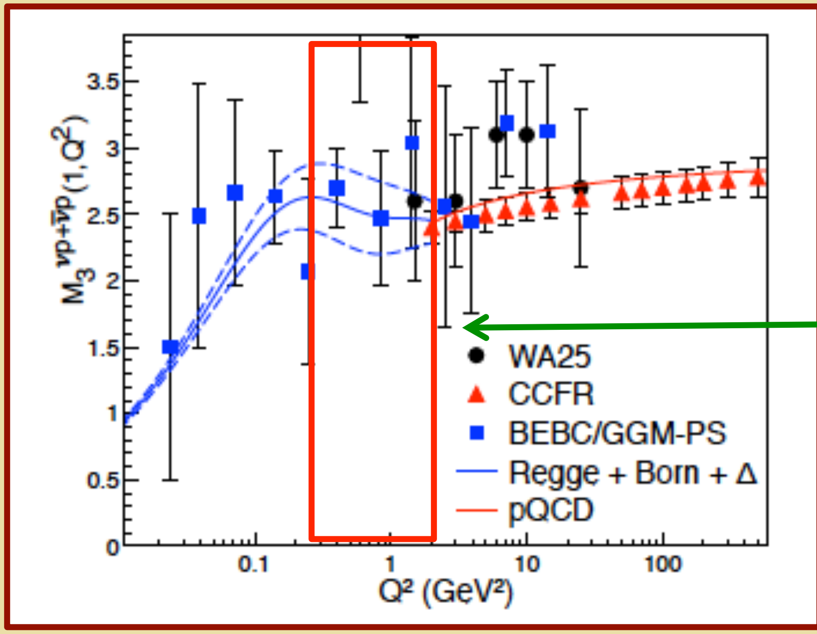
$\Delta_R^V = 0.02361(38) \rightarrow 0.02467\ (22)$

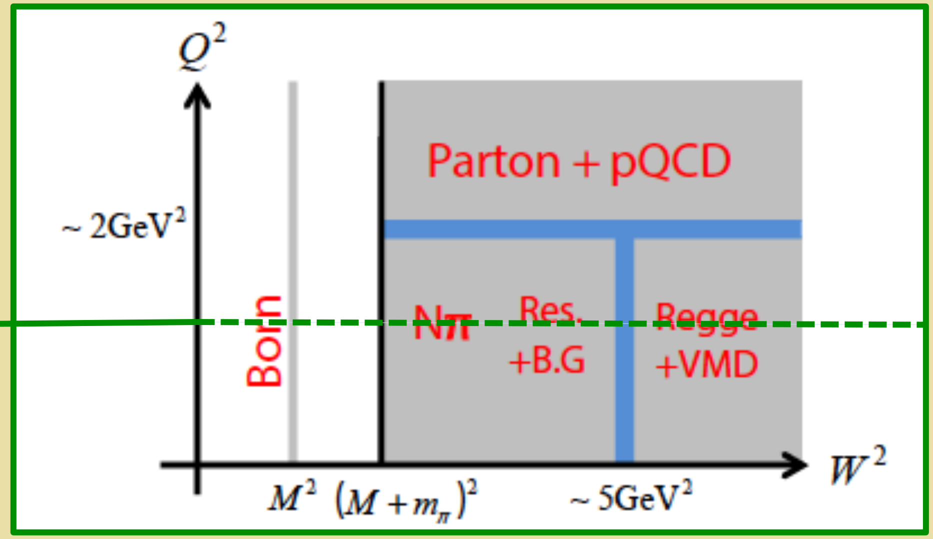
"CMS" Preliminary

$\Delta_R^V = 0.02361(38) \rightarrow 0.02433(32)$

W. Marciano: this workshop

Dispersion Relations





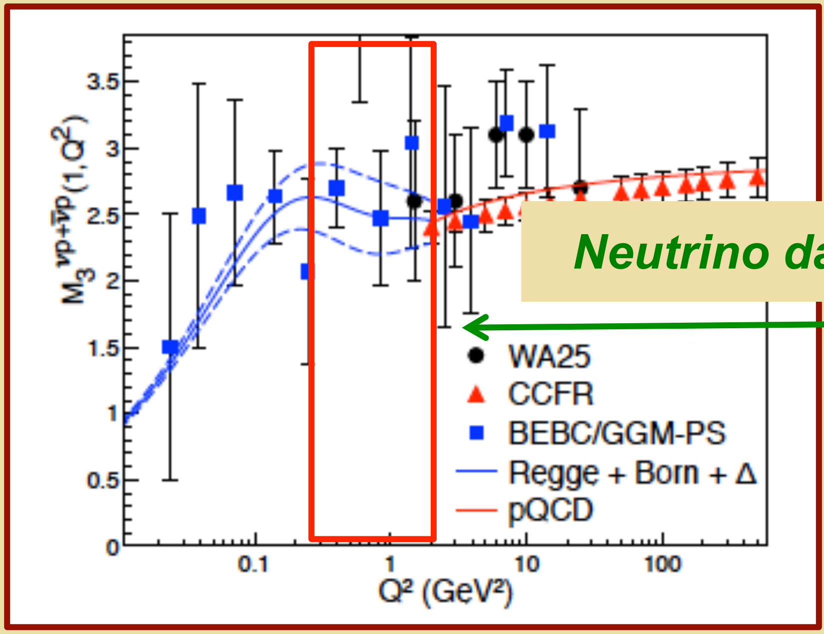
- ***Compute contributions to $M_3^{\nu p+\bar{\nu}p}$ at each Q^2 from different ω regions***
- ***Isospin rotate to $M_3^{(0)}$***

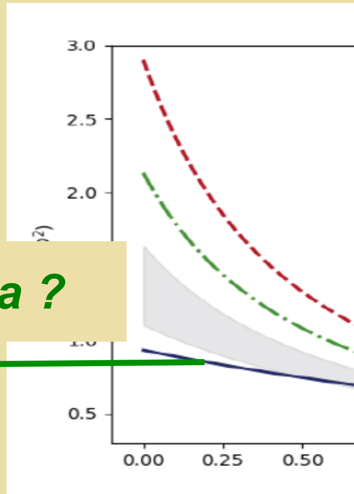
Refinements (WJM):

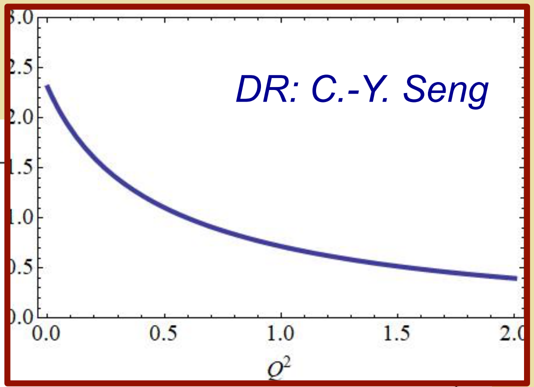
- *Implement 4 loop BjSR for pQCD region*

Large N_C Interpolator

Marciano







Neutrino data ?

# of resonances ?

$$F(Q^2) = \frac{A}{Q^2+m^2_\rho} + \frac{B}{Q^2+m^2_A} + \frac{C}{Q^2+m^2_{\rho'}}$$

m_ρ =0.776GeV m_A =1.230GeV $m_{\rho'}$ =1.465GeV

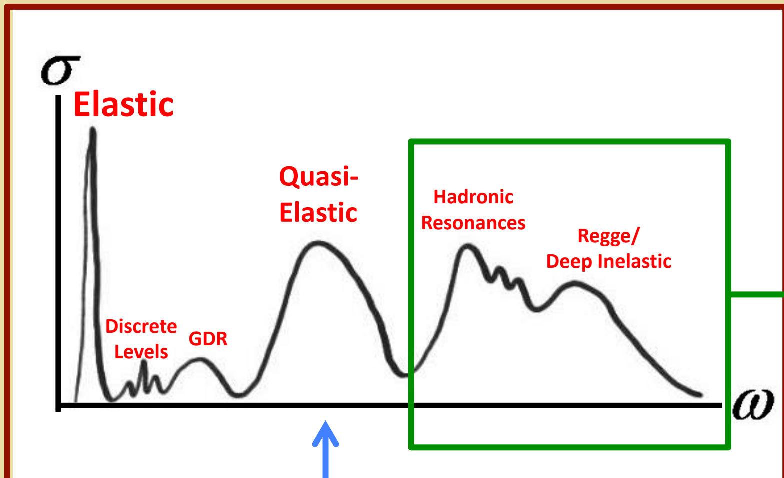
1. Integral Q_0^2- ∞ equals Bj Function Integral=7.885
2. No $1/Q^4$ terms in large Q^2 limit
3. F(0) Arbitrary

Q_0^2 = 1.08 GeV^2

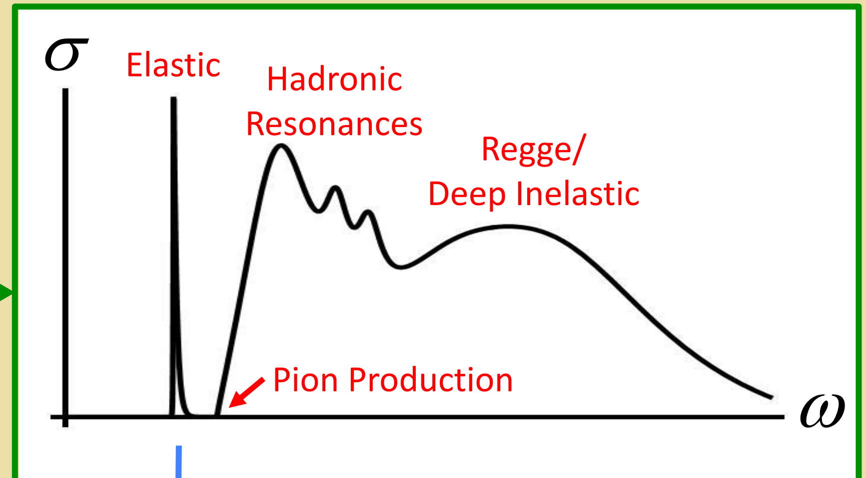
Recent Results: Nuclei

Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons



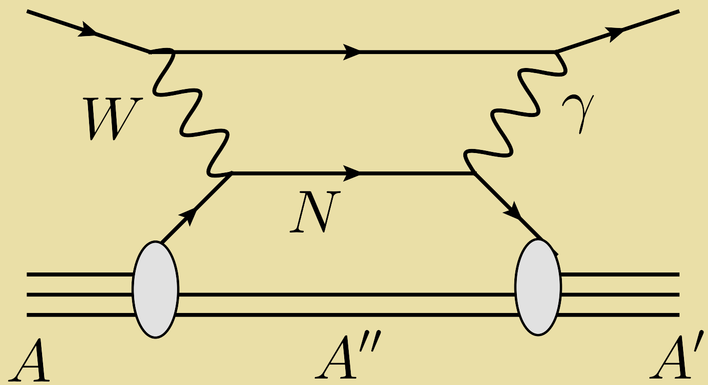
Quasielastic response

Part of δ_{NS} : “ C_B^{Nucl} ”

New work

Impact on δ_{NS}

Gorshteyn



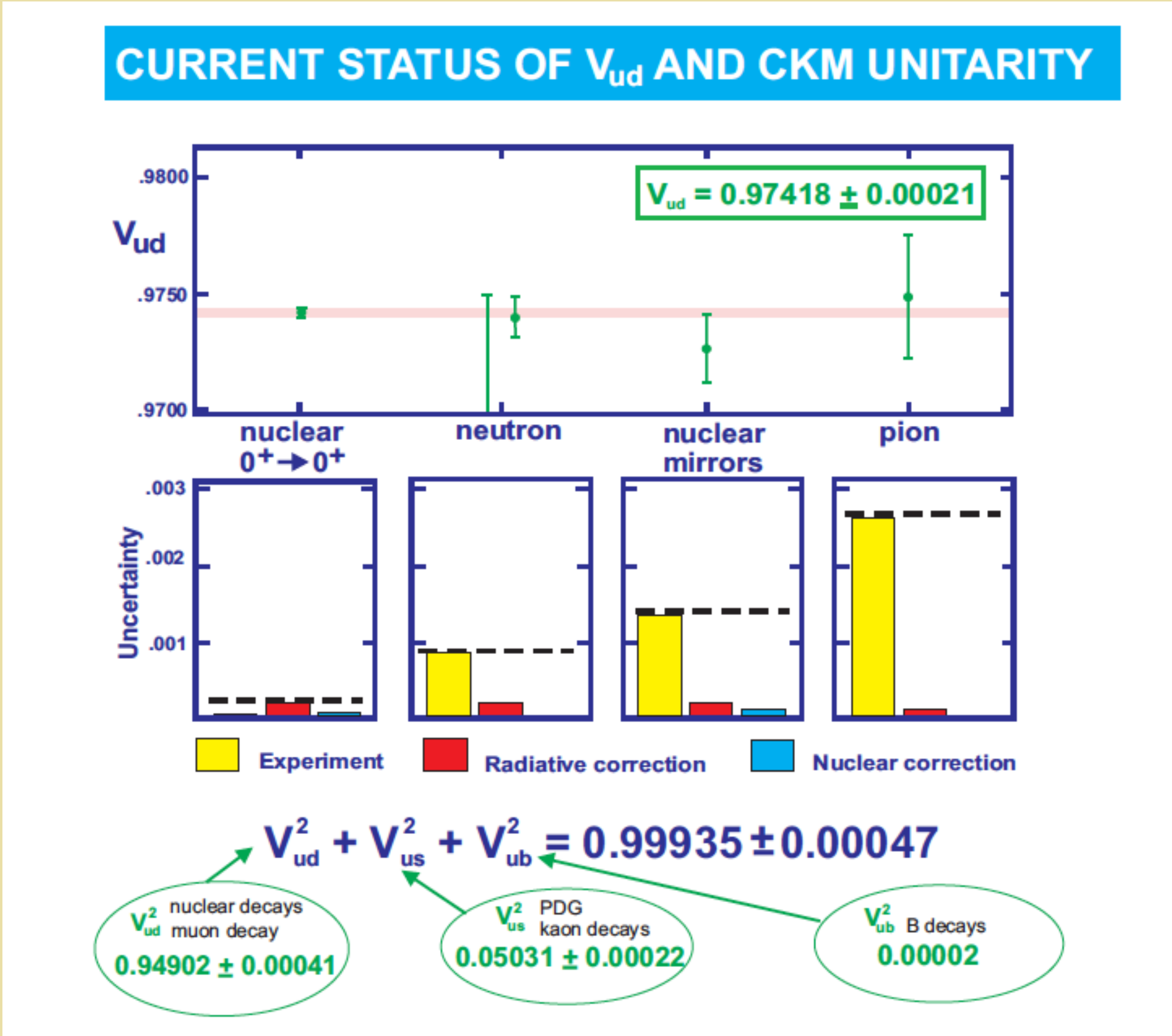
$$\delta_{NS}^{\text{quenched Born}} = -0.058(14)\,\% \longrightarrow \delta_{NS}^{QE} = -0.11(3)\,\%$$

$$\delta_{NS}^{E} = 0 \qquad \delta_{NS}^{QE} = +0.05(5)\,\%$$

No net shift to the Ft central value $\qquad \overline{\mathcal{F}t} = (3072.1 \pm 0.7)s \;\rightarrow\; \overline{\mathcal{F}t} = (3072 \pm 2)s$

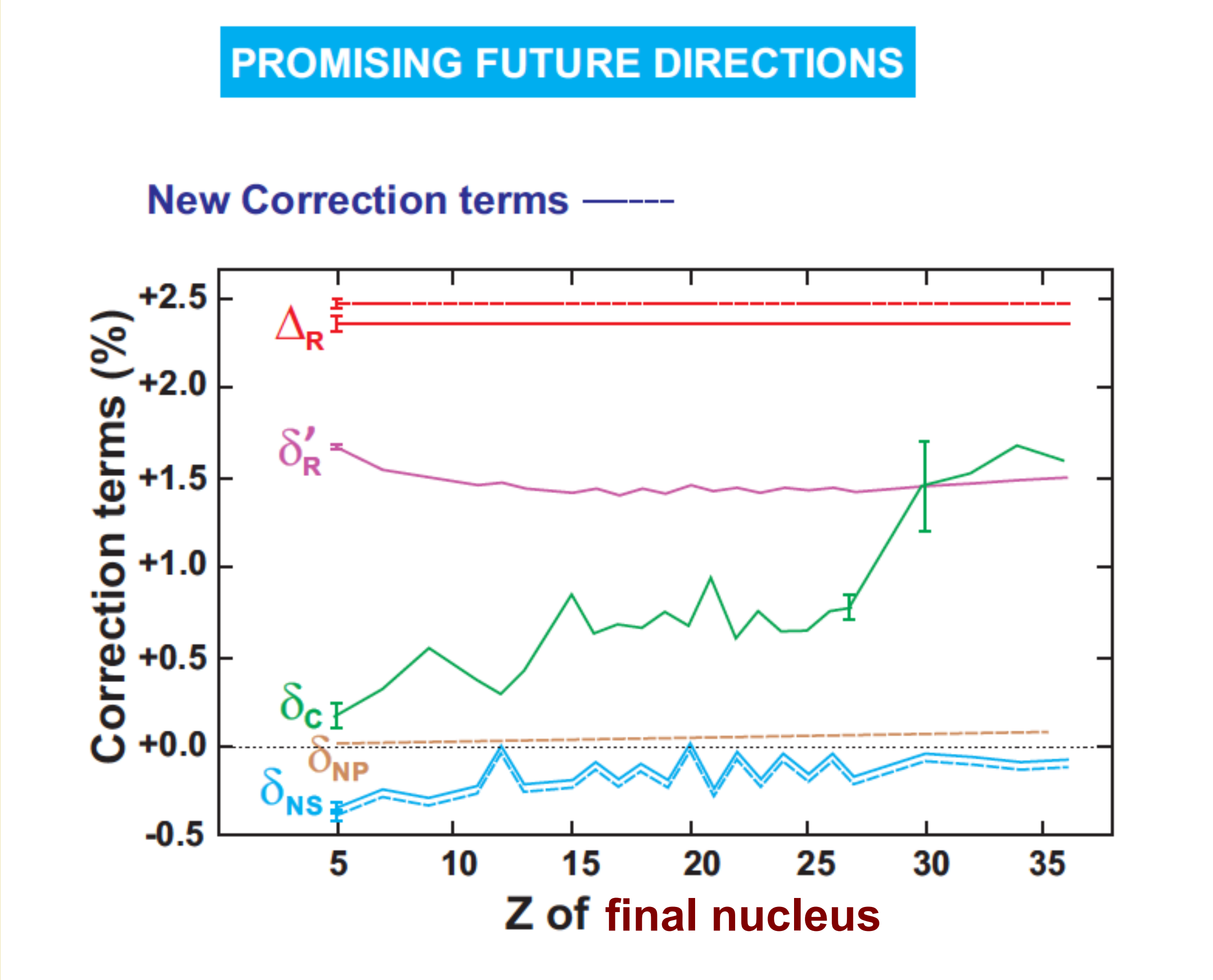
Implications: "Conventional Analysis"

Hardy

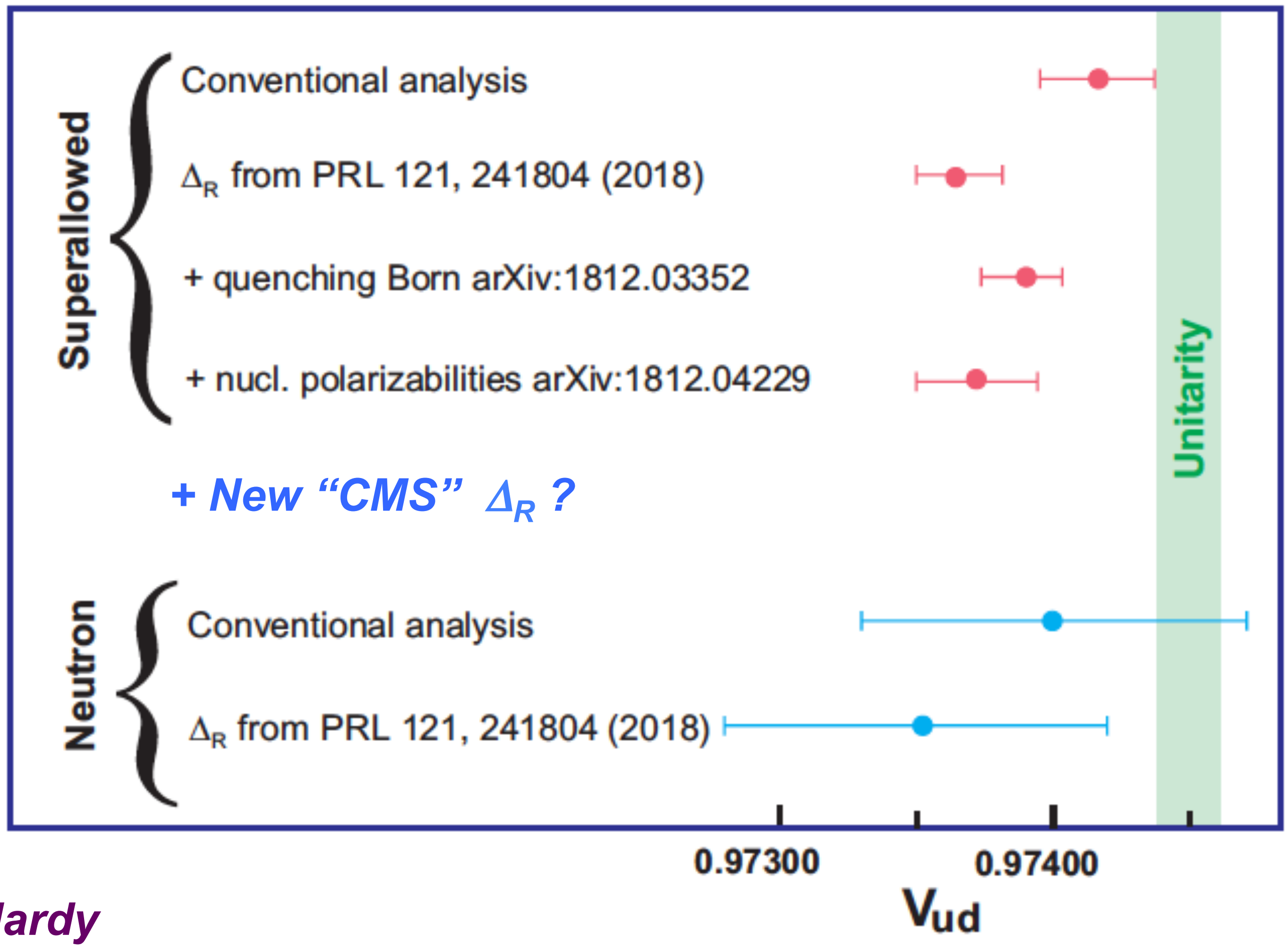


Implications

Hardy



Implications



Hardy

Tests & Improvements: Single Nucleon

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)*

Lattice QCD & $M_3^{(0)}\,(Q^2)$

Feynman-Hellmann Theorem *Seng*

$$\frac{dE_{n,\lambda}}{d\lambda} = \left\langle n_\lambda \left| \frac{\partial H_\lambda}{\partial\lambda} \right| n_\lambda \right\rangle$$

$$H_\lambda = H_0 + 2\lambda_1 \int d^3x \cos(\vec{q}\cdot\vec{x}) J^2_{em}(\vec{x}) - 2\lambda_2 \int d^3x \sin(\vec{q}\cdot\vec{x}) J^3_A(\vec{x})$$

$$\boxed{\left(\frac{\partial^2 E_{N,\lambda}(\vec{p})}{\partial\lambda_1\partial\lambda_2}\right)_{\lambda=0} =: \frac{iq_x}{Q^2\omega} T_3^N(\omega, Q^2).}$$

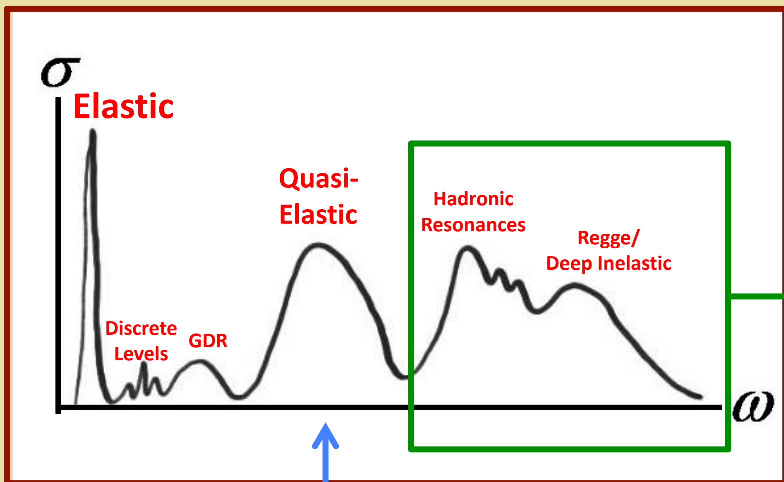
CYS and U.G-Meissner, hep-ph/1903.07969

$$\boxed{\left(\frac{\partial^2 E_{N,\lambda}(\vec{p})}{\partial\lambda_1\partial\lambda_2}\right)_{\lambda=0} = \frac{4q_x}{Q^2}\int_0^1 dx \frac{F_3^N(x,Q^2)}{1-\omega^2x^2}} \,,$$

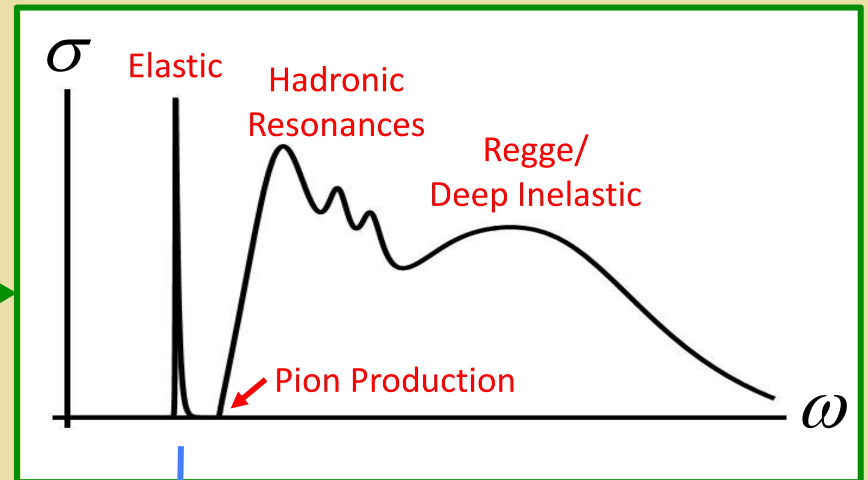
Tests & Improvements: Nuclei

Leptoproduction: Had & Nuc Response

Nuclei



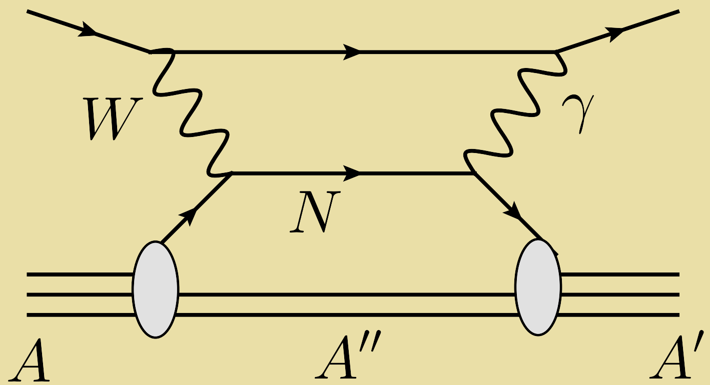
Free nucleons



Quasielastic response

Part of δ_{NS} : " C_B^{Nucl} "

Impact on δ_{NS}



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

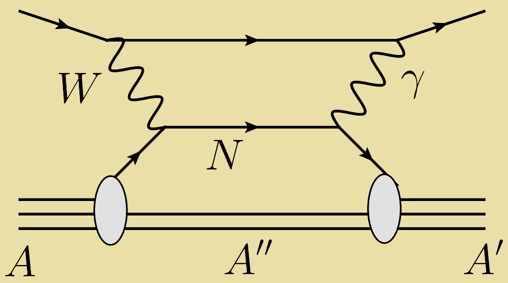
Neglects A-dep variations

Ave over 20 transitions

Optimistic:

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

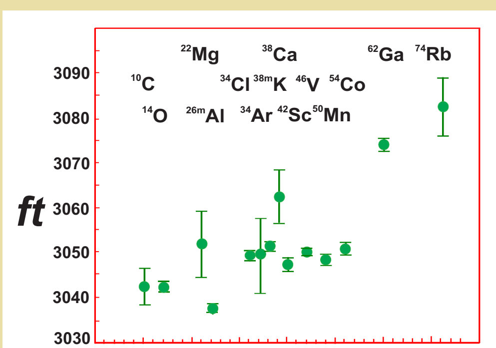
QE Contribution: Refinements

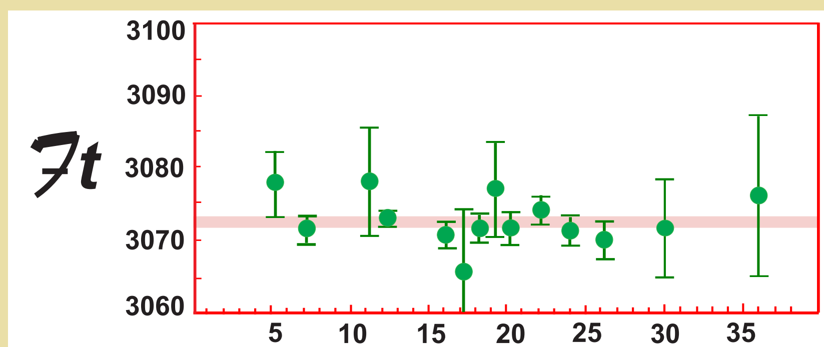


Apply state-of-art methods

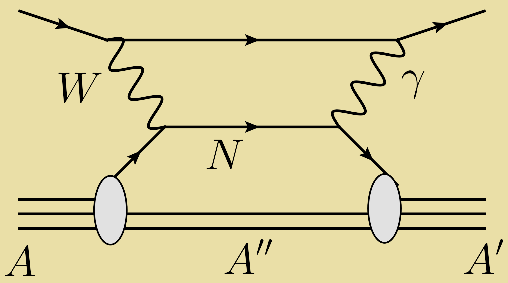
- *Correlations*
- *2-body currents*
- *Rel corrections*
- *Recent MIT group: 2N knockout*

Consistency w/ CVC ?





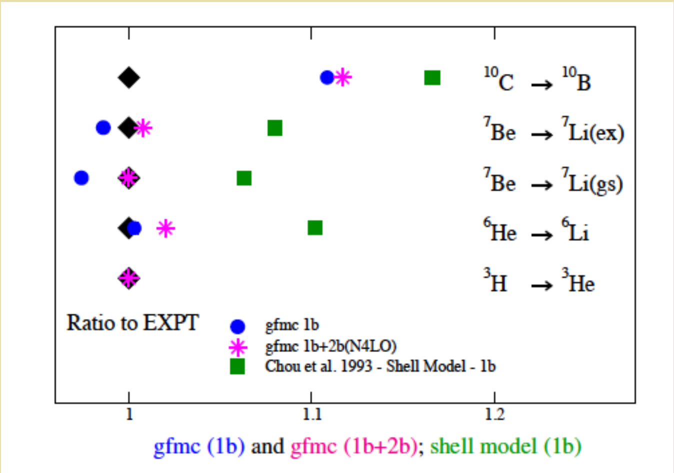
QE Contribution: Refinements



Quantum Monte Carlo

- *GFMC: ^{10}B*
- *Auxiliary Field MC: higher A*

LO β-Decay



GFMC & AFMC

Pastore

$$R(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right)\langle 0|O^\dagger(\mathbf{q})|f\rangle\langle f|O(\mathbf{q})|0\rangle$$

$$R(q,\omega) = \int dt \langle 0|O^\dagger(\mathbf{q})\, e^{i(H-\omega)t}\, O(\mathbf{q})|0\rangle$$

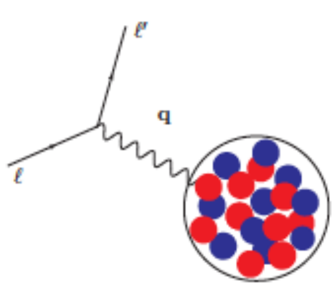
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_i t_i + \sum_{i<j} \upsilon_{ij}$$

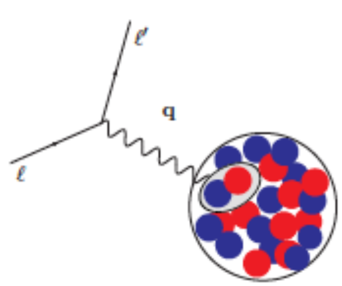
and

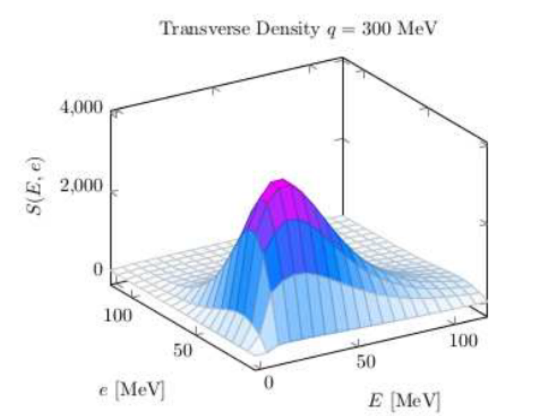
$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O$$

1b



2b





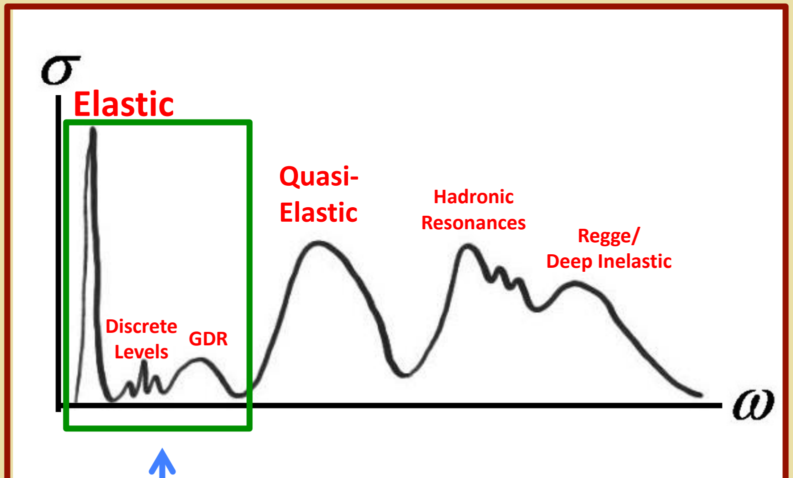
Transverse "response-density" 1b + 2b for ^4He

$\mathscr{D}(p', P'; q)$

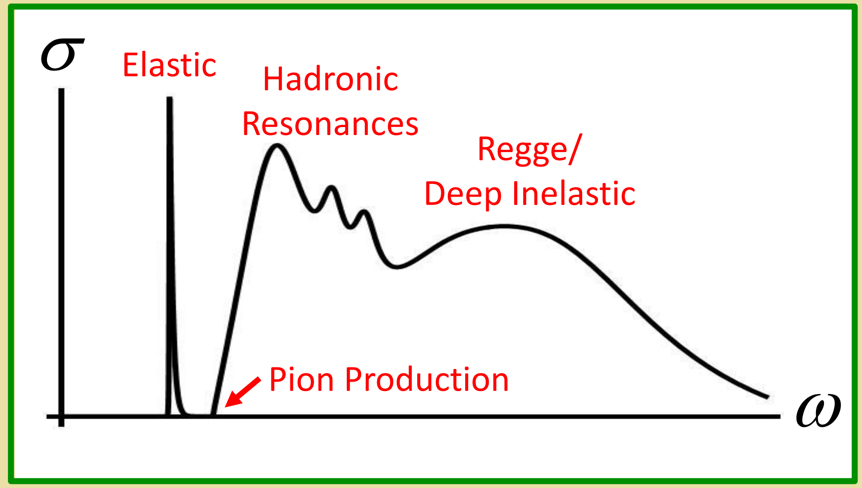
* Preliminary results *

Other Nuclear Corrections

Nuclei



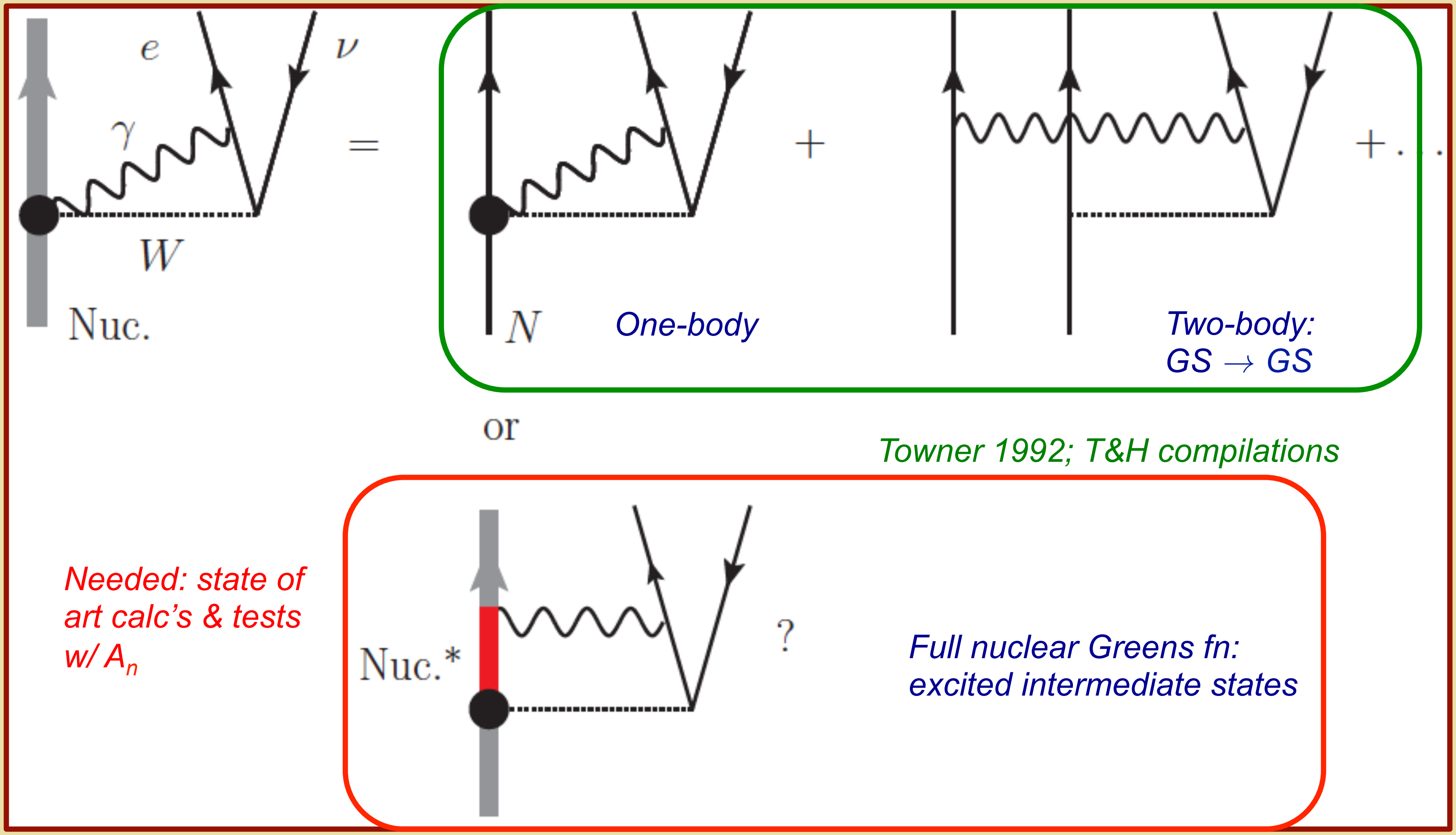
Free nucleons



Low-lying transitions

Part of δ_{NS}

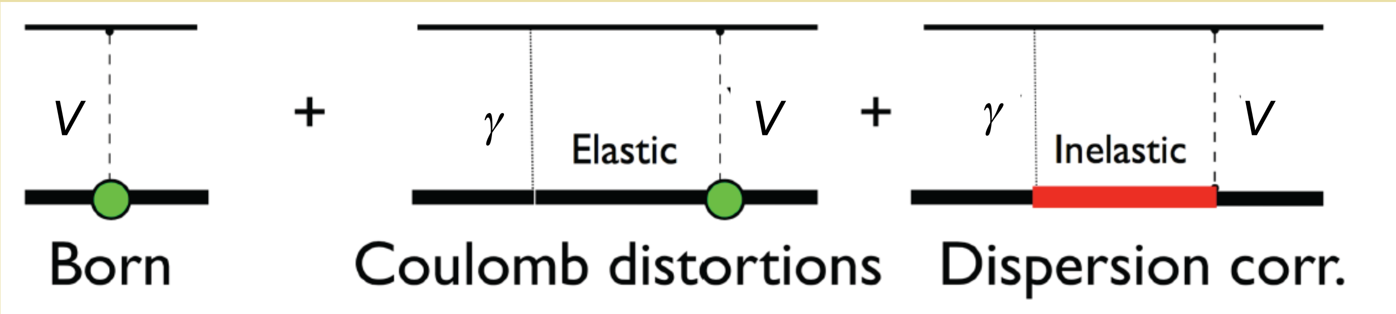
$0^+ \to 0^+$ Decay: δ_{NS}

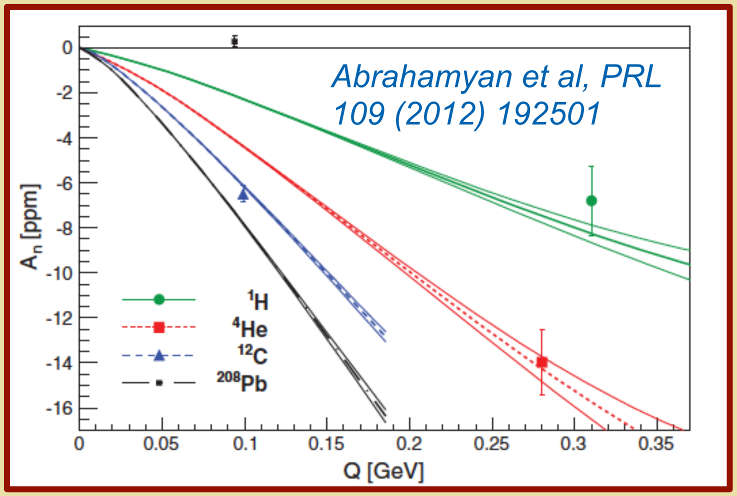


J. Engel

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

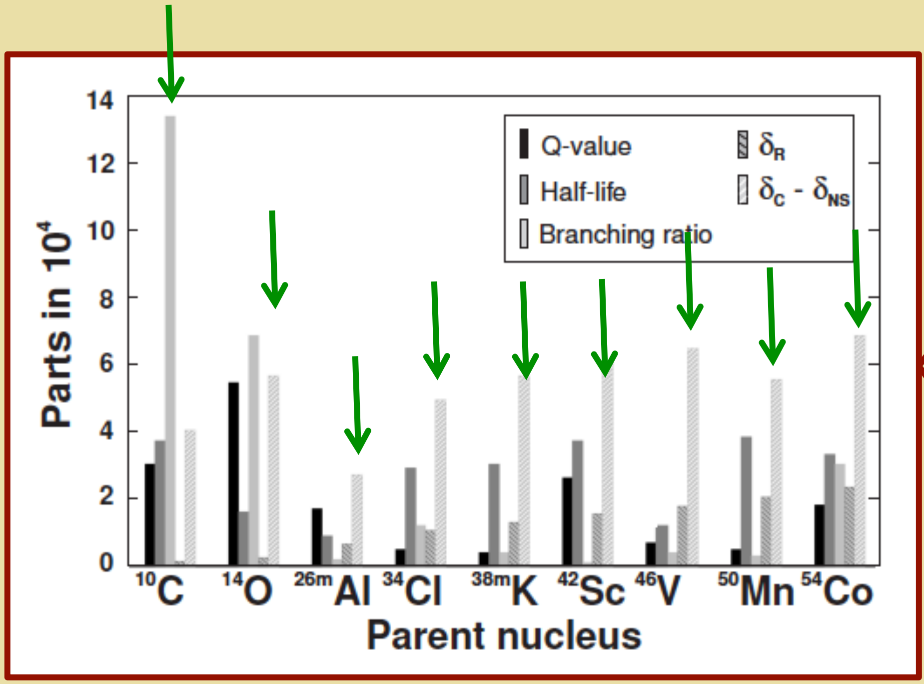




$V = \gamma$ ***Beam normal asymmetry***

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

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



b_F : scalar currents

Input for V_{ud} & CKM unitarity test

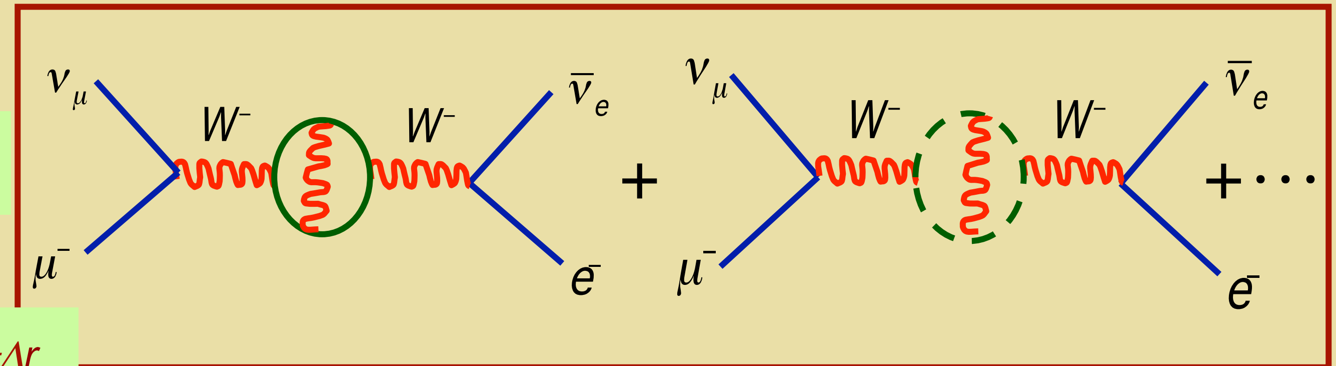
- ***e^+ vs e^- ?***
- ***Muons ?***

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*

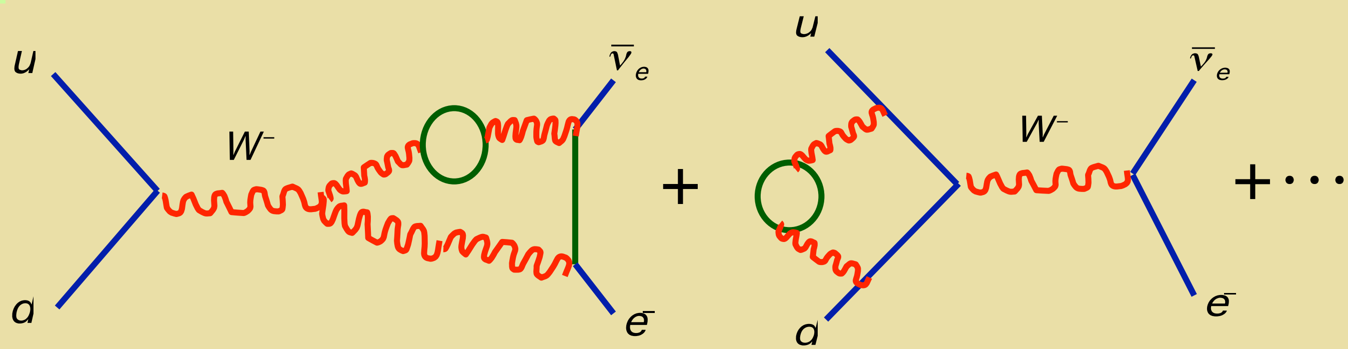
"Next Frontier" : Higher Order EW RC

Propagator

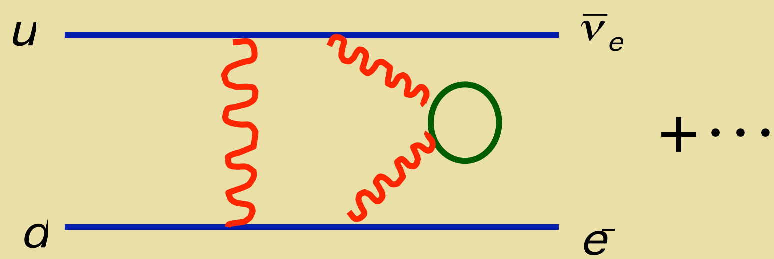


Cancel from $\Delta r_\beta - \Delta r_\mu$

Vertex &
External leg



Box



Other Issues

Ivanov: C_{PS} + Wilkinson term

V_{ud} from the neutron beta decay

$$|V_{ud}| = \sqrt{\frac{5099.81}{\tau_n(1+\Delta_R)(1+2.7\times10^{-4})_W(1-0.33C_{ps})}}$$

$$\Delta_R = \frac{\alpha}{2\pi}\,\bar{g}(E_0) + \Delta_R^V$$

$$0.33C_{ps} = -3.86\times10^{-5}\,\left(0.127 + \mathrm{Re}(C_P - \bar{C}_P)\right)$$

Neutron beta decay: $V_{ud} = 0.973\underline{70}(14)$

Hayen: RC for GT decays

There is now an additional RC which is *not* included in Δ_V^R for GT decays

More generally, based on "old" approach

$$\Delta\frac{dN}{dW} \propto \pm\frac{2}{5}\frac{\alpha Z}{MRc_1}(\pm 2b + d)$$

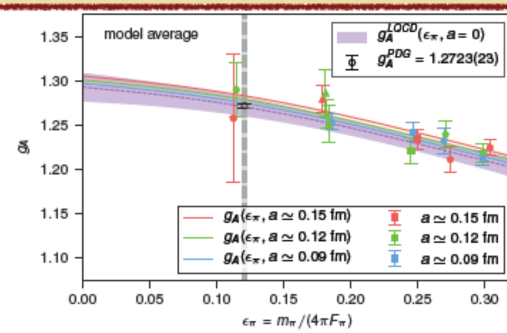
where b/Ac_1 is weak magnetism, $d_A c_1$ is induced tensor (0 for isospin multiplet decays)

Other Issues

Walker-Loud: g_A from LQCD

Final result

statistical	0.81%
chiral extrapolation	0.31%
$a \to 0$	0.12%
$L \to \infty$	0.15%
isospin	0.03%
model selection	0.43%
total	0.99%



$$g_A^{\mathrm{QCD}} = 1.2711(103)^s(39)^\chi(15)^a(19)^V(04)^I(55)^M$$

How precise can we get g_A?

- Without changing strategy, **we should be able to get 0.5% this year** by improving the three physical pion mass points - with our INCITE allocation on Summit at OLCF
- To achieve 0.2% precision, at least a 4th lattice spacing will be required, ideally at two or more pion masses. This can still be achieved with Summit
- We heard yesterday of a 0.4% radiative correction from QED - we should also compute this and compare
- **How precisely should we push this calculation?**