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Statistical analysis of beta decays and the effective value of g_A

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with J. Suhonen: Phys.Rev. C94 (2016) 5, 055501

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Dirac vs Majorana

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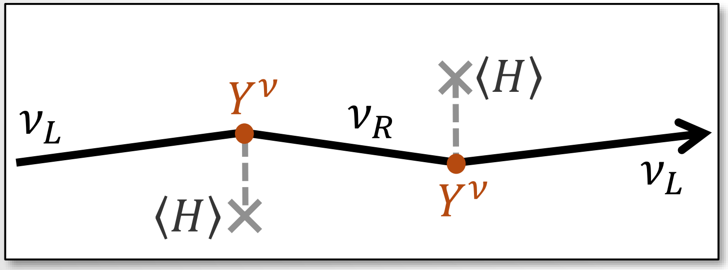
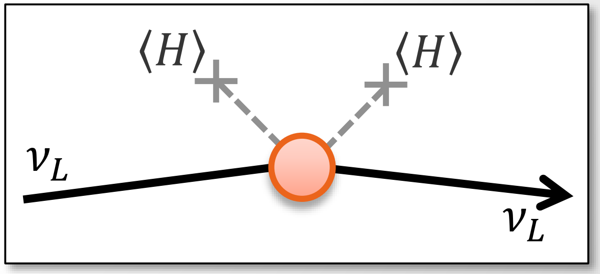
- Two possibilities to define fermion mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation





Beta decays

- Single beta decay

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

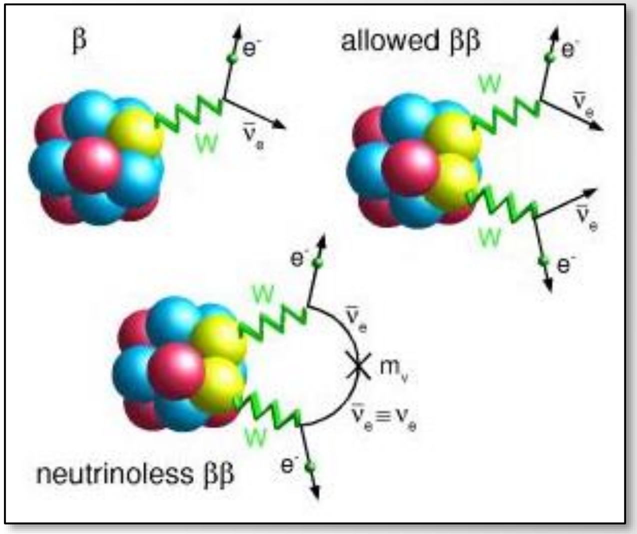
- Allowed double beta ($2\nu\beta\beta$) decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

- Neutrinoless double beta ($0\nu\beta\beta$) decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

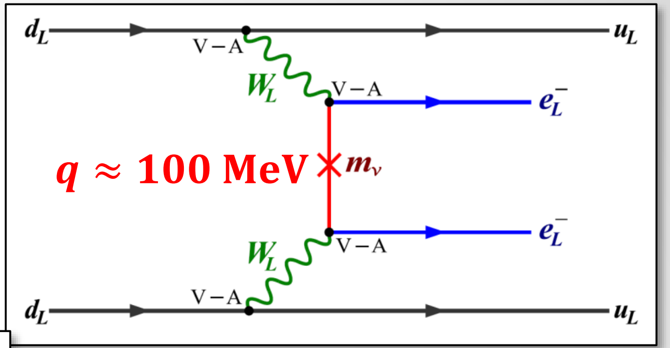
  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Variants
    - $0\nu\beta^+\beta^+$: $(A,Z) \rightarrow (A,Z-2) + 2e^+$
    - $0\nu\beta^+\mathrm{EC}$: $(A,Z) + e^- \rightarrow (A,Z-2) + e^+$
    - $0\nu\mathrm{ECEC}$: $(A,Z) + 2e^- \rightarrow (A,Z-2)$



$0\nu\beta\beta$

- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



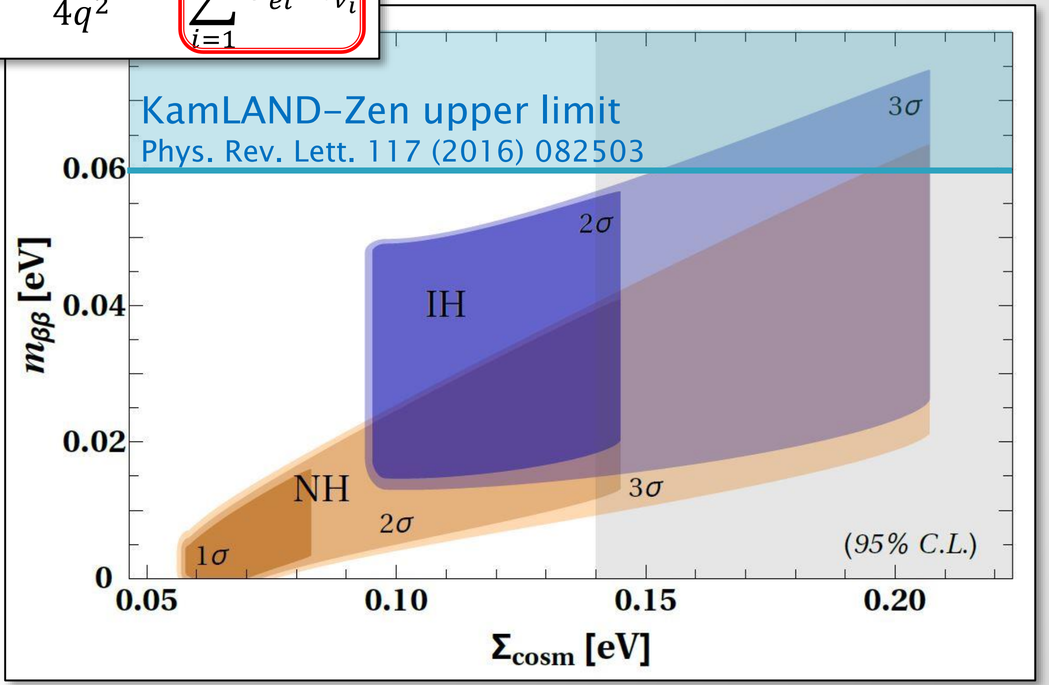
- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{q + \cancel{m}_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}$$

$\rightarrow m_{\beta\beta}$

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$

$$\frac{10^{25}\mathrm{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{eV}\right)^2$$



Dell'Oro, Marcocci, Viel, Vissani, Adv.High Energy Phys. (2016) 2162659

Nuclear Matrix Elements

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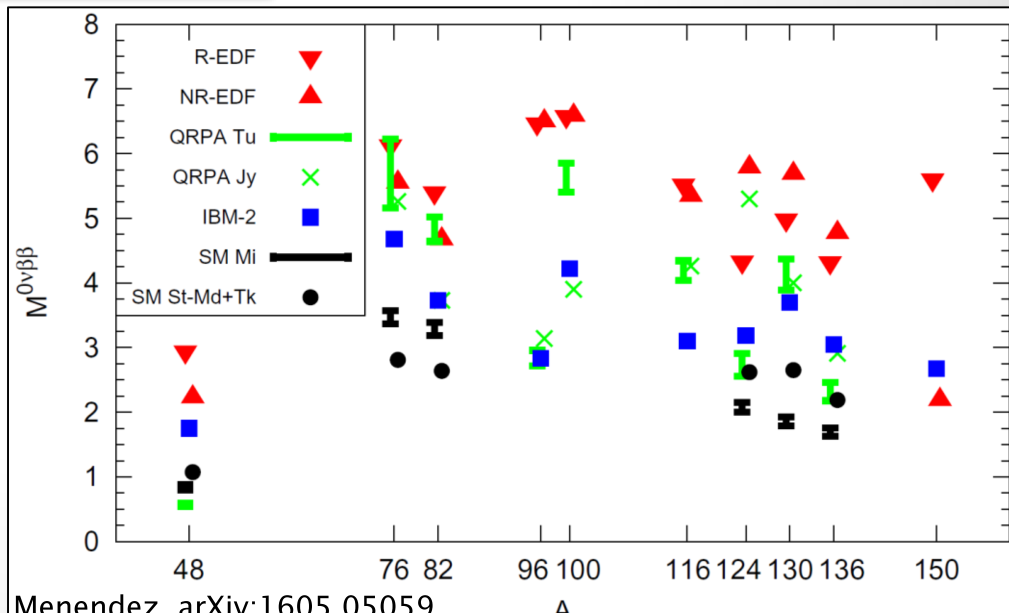
- Hadronic current

$$J^{\mu}(q) = g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5 + \frac{i g_M}{2 m_N}\sigma^{\mu\nu} q_{\nu} - g_P \gamma^5 q^{\mu}$$

- Nuclear Matrix Element $M^{0\nu}$

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)$$

  - Dependence on isotope and operator
  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models



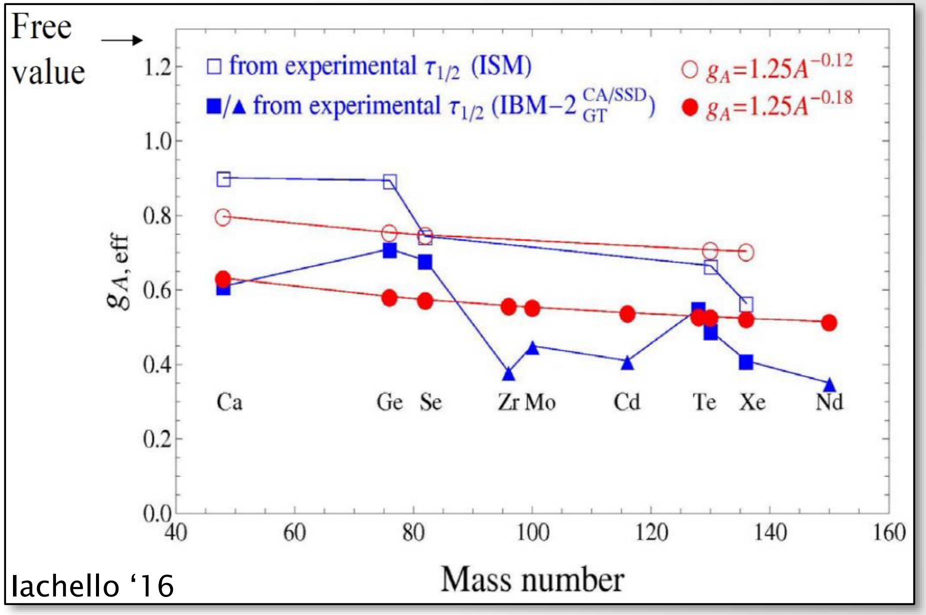
Menendez, arXiv:1605.05059

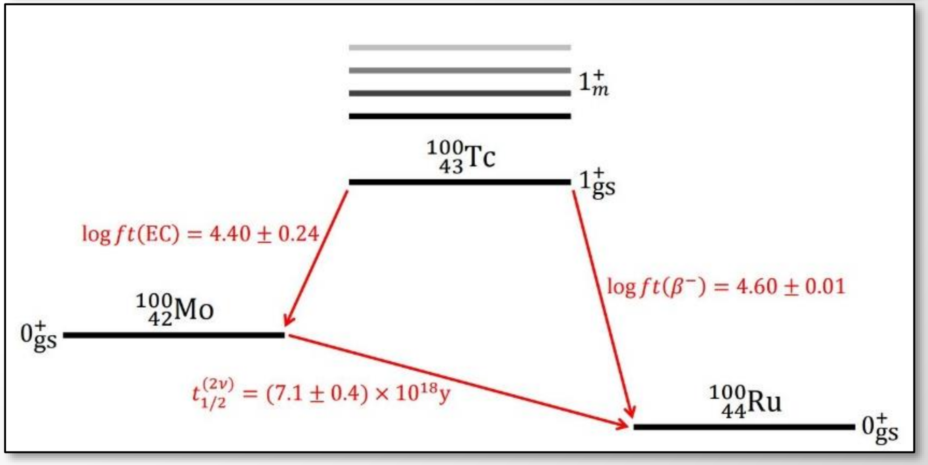
Quenching of g_A?

- Nuclear matrix element

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)$$

- Axial-vector coupling g_A
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of β and $2\nu\beta\beta$ decay with theory: $g_A \approx 0.6\text{–}0.8$
  - If applicable to $0\nu\beta\beta$, strong reduction of sensitivity
  - Genuine effect or short-coming of models?





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- Calculation of single beta / EC and $2\nu\beta\beta$ matrix elements
  J. Suhonen, O. Civitarese, Nucl. Phys. A 924 (2014) 1
  - Woods-Saxon Potential with three different orbital spaces (A=62-80, 98 - 108, 110 - 142)
  - Renormalized Bonn-A G-Matrix
  - g_{pp} and g_{ph} interaction parameters (per even-even system)
  - g_{ph} determined by location of Gamow-Teller Giant Resonance

$$\Delta E_{\mathrm{GT}} = E(1^+_{\mathrm{GTGR}}) - E(0^+_{\mathrm{gs}}) = \left[1.444\,(Z+1/2)\,A^{-1/3} - 30.0\big(N-Z-2\big)A^{-1} + 5.57\right]\mathrm{MeV}.$$

  only on average of theoretical / pheno centroids
  → include uncertainty of 15%
  - g_A as a free parameter per isobaric system

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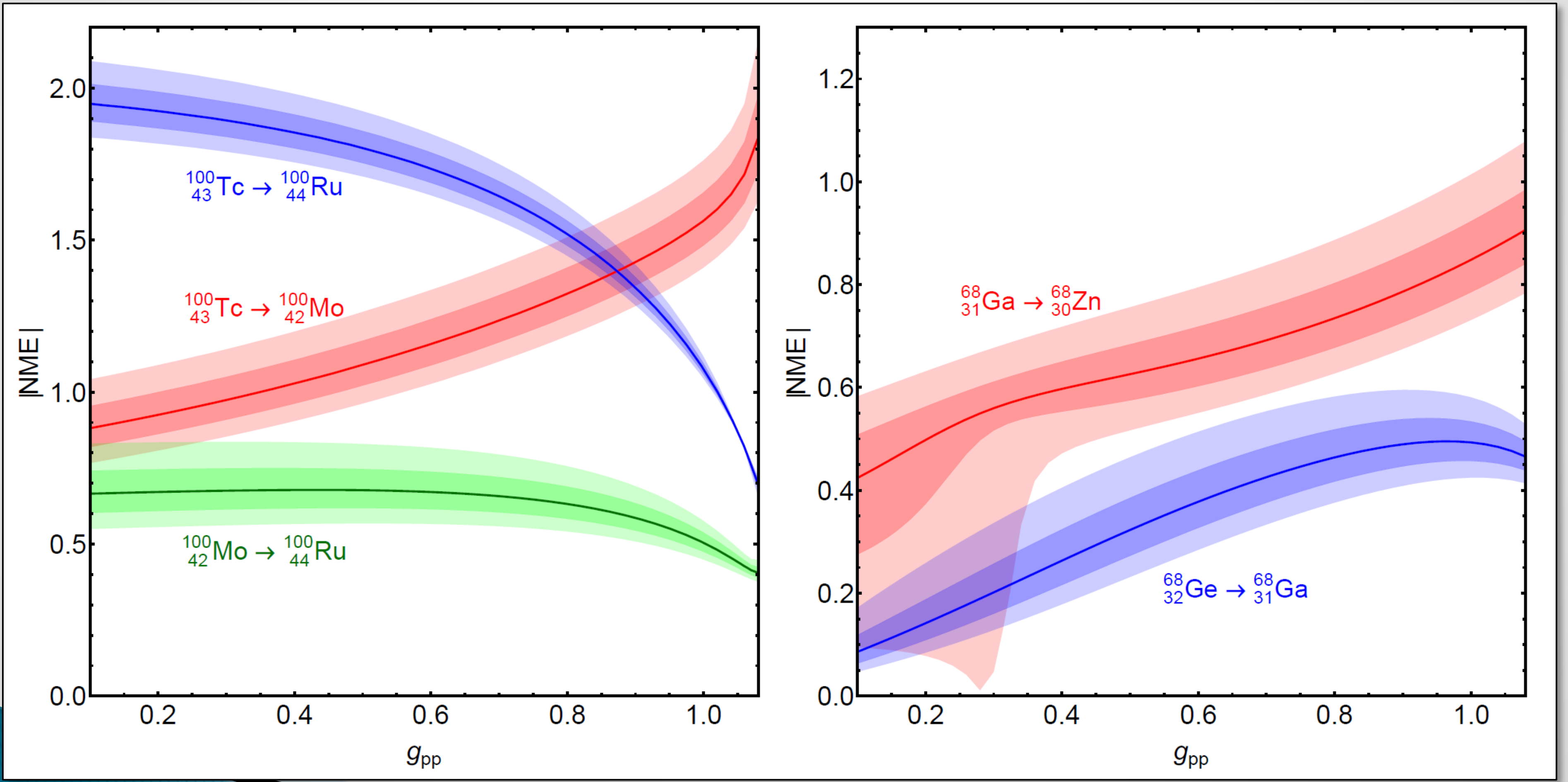

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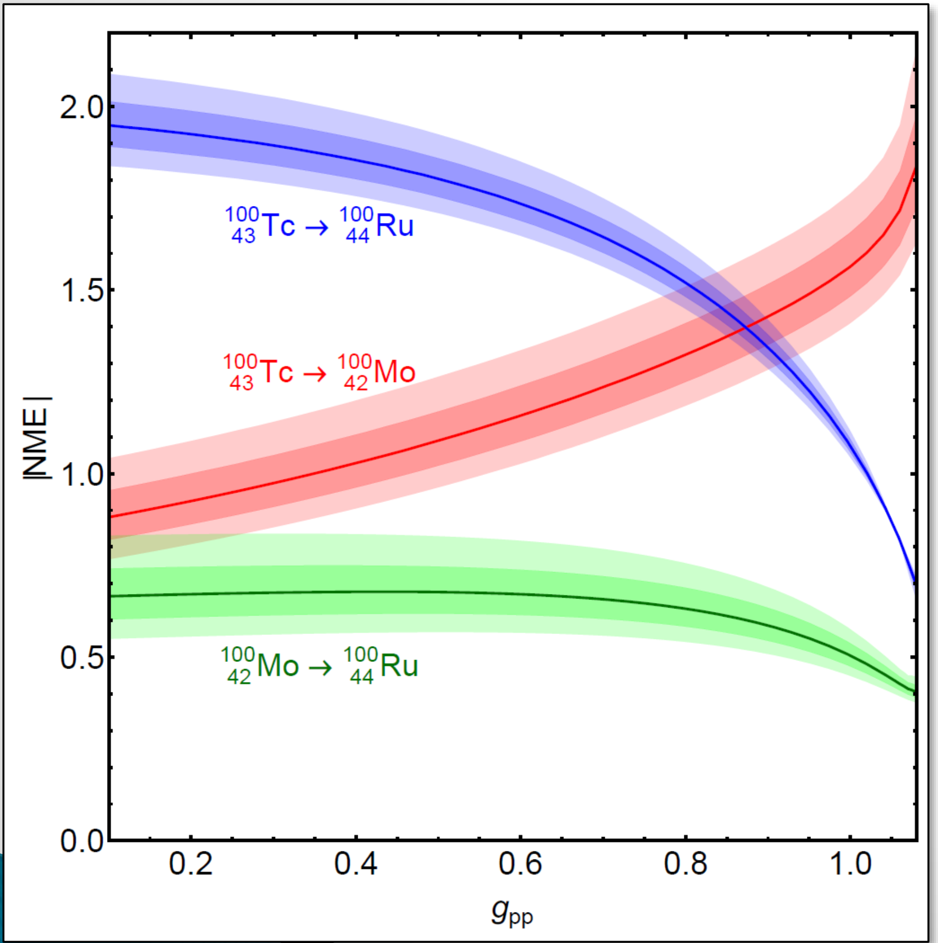

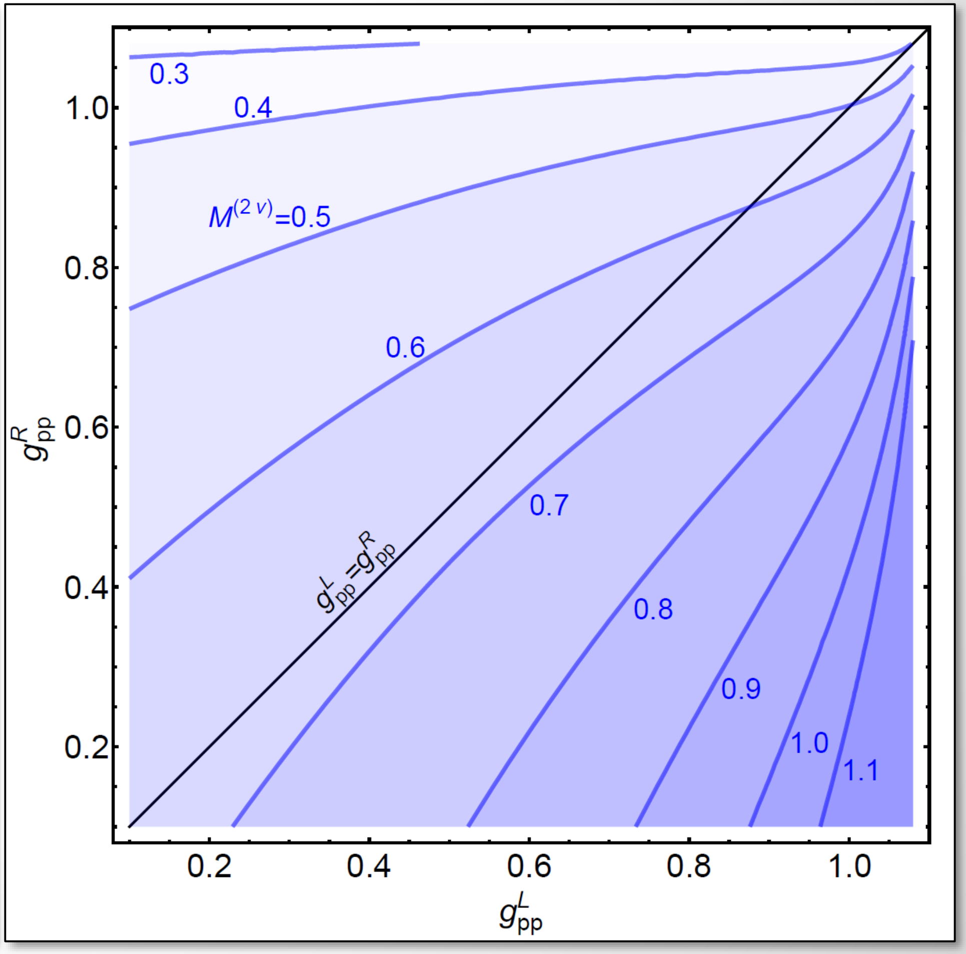

Comparison with Beta Decay / EC Measurements

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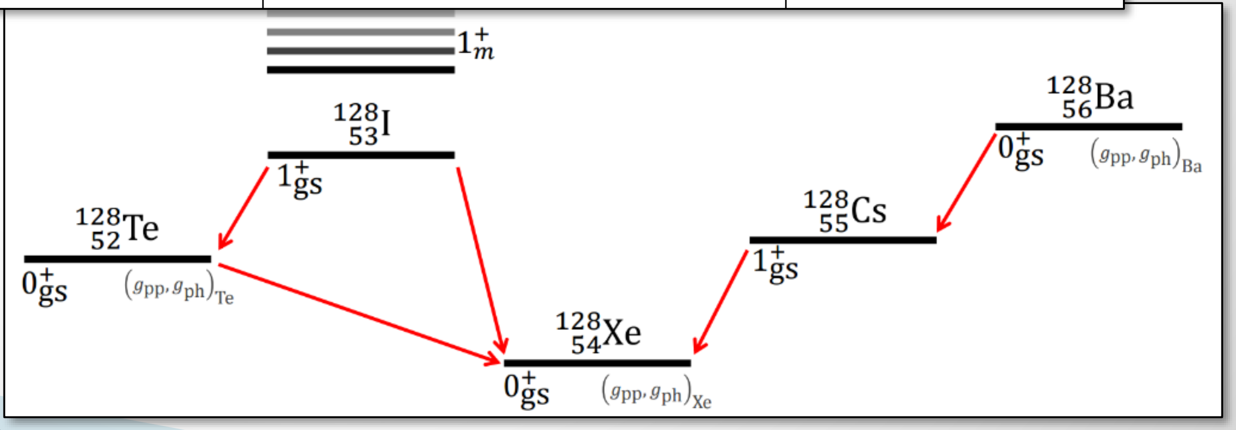
- Fit of model parameters over isobaric system
  - g_A
  - g_{pp}^i (per even-even system)
  - g_{ph}^i (per even-even system) as "nuisance" parameters
- Incorporate allowed $gs \to gs$ GT beta decay / EC rates

A	Z_0	Triplet					$\log ft_L^{\mathrm{exp}}$	$\log ft_R^{\mathrm{exp}}$	g_A^{fit}	g_{pp}^{fit}
116	48	Cd(0^+)	$\leftarrow$	In(1^+)	$\rightarrow$	Sn(0^+)	4.4508 ± 0.1160	4.6839 ± 0.0025	$0.84^{+0.08}_{-0.08}$	$0.65^{+0.07}_{-0.11}$
118	48	Cd(0^+)	$\rightarrow$	In(1^+)	$\rightarrow$	Sn(0^+)	3.9218 ± 0.0629	4.8147 ± 0.0263	$0.88^{+0.09}_{-0.07}$	$0.75^{+0.04}_{-0.09}$
118	49	In(1^+)	$\rightarrow$	Sn(0^+)	$\leftarrow$	Sb(1^+)	4.8147 ± 0.0263	4.5152 ± 0.0122	$0.77^{+0.05}_{-0.06}$	$0.65^{+0.03}_{-0.04}$
118	50	Sn(0^+)	$\leftarrow$	Sb(1^+)	$\leftarrow$	Te(0^+)	4.5152 ± 0.0122	4.9749 ± 0.0579	$0.77^{+0.06}_{-0.05}$	$0.65^{+0.04}_{-0.14}$

$$\log_{10}(f_0 t_{1/2}[s]) = \log_{10}\left(\frac{6147}{B_{GT}}\right)$$

$$B_{GT} = \frac{g_A^2}{2J+1}\left|M_{GT}(g_{pp}, g_{ph})\right|^2$$



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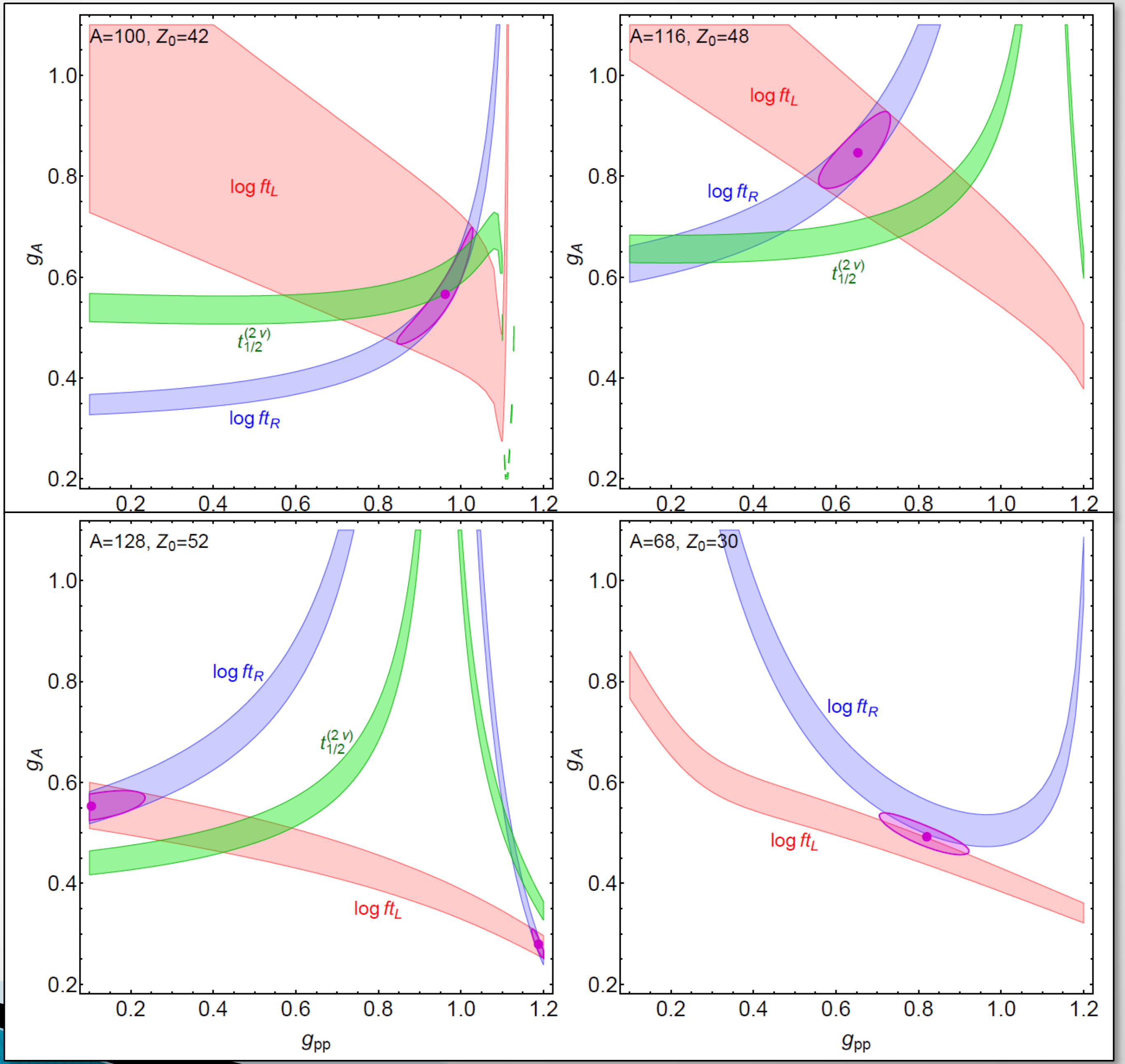
- Markov Chain Monte Carlo to find posterior parameter distribution $p(g_A, g_{pp}^i, g_{ph}^i)$ based on fitness $P = e^{-\chi^2/2}$, e.g. triplet

$$\chi^2 = \left(\frac{\log f t_L^{th}(g_A, g_{pp}^L, \gamma_{ph}^L) - \log f t_L^{exp}}{\delta \log f t_L^{exp}}\right)^2 + \left(\frac{\log f t_R^{th}(g_A, g_{pp}^R, \gamma_{ph}^R) - \log f t_R^{exp}}{\delta \log f t_R^{exp}}\right)^2 + \left(\frac{\gamma_{ph}^R - 1}{0.15}\right)^2 + \left(\frac{\gamma_{ph}^L - 1}{0.15}\right)^2$$

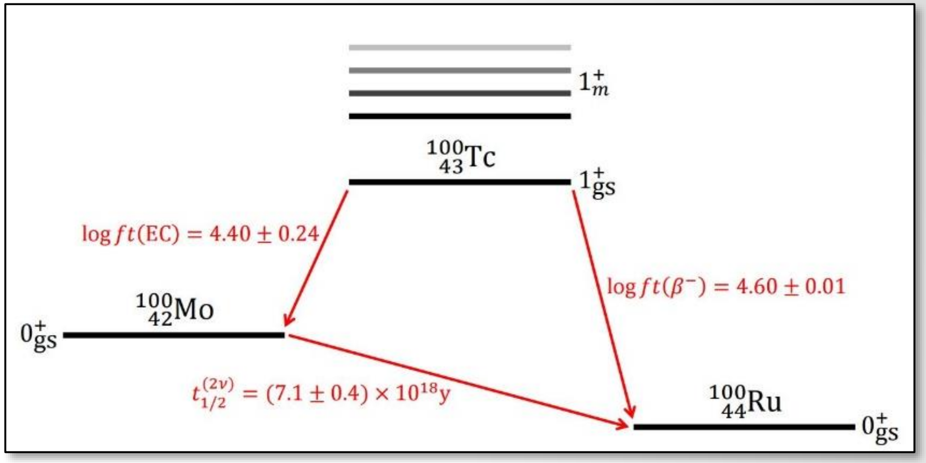
Simplified Triplet Case

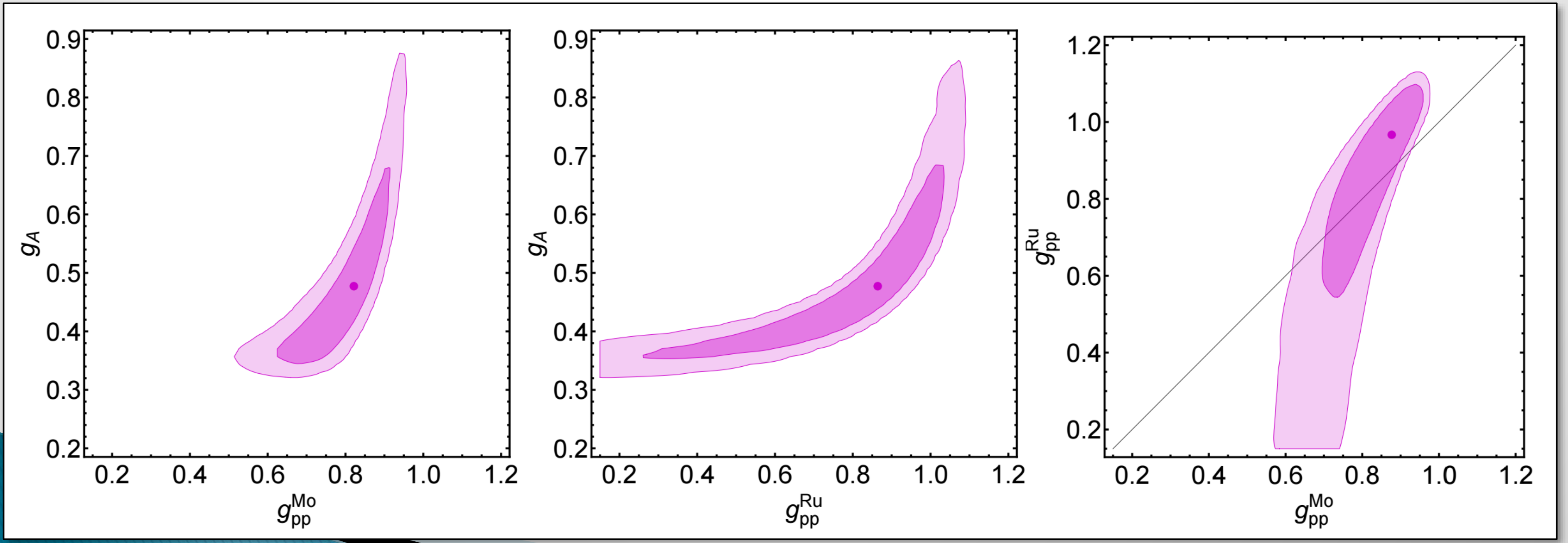
- Two parameters g_A, g_{pp}
- See also A. Faessler at al., J. Phys. G 35 (2008) 075104



Triplet Case

- Three parameters g_A, g_{pp}^{Mo}, g_{pp}^{Ru}
- Two nuisance parameters $\gamma_{ph}^{Mo}, \gamma_{ph}^{Ru}$





Isobaric Multiplets

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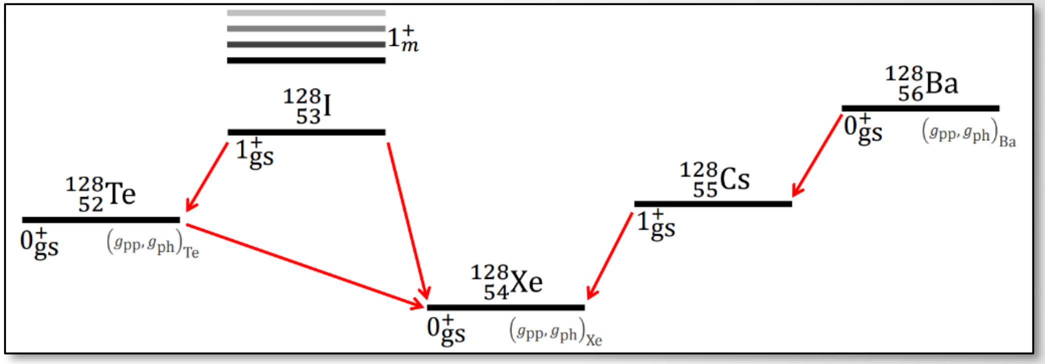
A	Z_0	Multiplet	dof	g_A^{fit}
62	28	$28 \leftarrow 29 \leftarrow 30$	3-2	$0.80^{+0.43}_{-0.01}$
64	28	$28 \leftarrow 29 \rightarrow 30$	3-2	$0.90^{+0.11}_{-0.09}$
66	28	$28 \rightarrow 29 \rightarrow 30$	3-2	$1.00^{+0.19}_{-0.16}$
68	29	$29 \rightarrow 30 \leftarrow 31 \leftarrow 32$	3-3	$0.65^{+0.06}_{-0.07}$
70	29	$29 \rightarrow \underline{30} \leftarrow 31 \rightarrow 32$	3-3	-
78	34	$34 \leftarrow 35 \rightarrow 36$	3-2	$0.35^{+0.59}_{-0.02}$
80	33	$33 \rightarrow \underline{34} \leftarrow 35 \rightarrow 36 \leftarrow 37$	3-4	**1.40**
98	39	$39 \rightarrow 40 \rightarrow 41$	2-2	$0.53^{+0.04}_{-0.03}$
100	41	$41 \rightarrow \underline{42} \leftarrow 43 \rightarrow 44$	3-3	$0.37^{+0.22}_{-0.00}$
102	42	$42 \rightarrow 43 \rightarrow 44$	3-2	$0.34^{+0.16}_{-0.00}$
104	44	$\underline{44} \leftarrow 45 \rightarrow 46$	3-2	$0.59^{+0.28}_{-0.10}$
106	45	$45 \rightarrow 46 \leftarrow 47 \rightarrow 48$	3-3	$0.40^{+0.02}_{-0.02}$
108	44	$44 \rightarrow 45 \rightarrow 46 \leftarrow 47 \rightarrow 48$	4-4	$\mathit{0.41}^{+0.01}_{-0.01}$
110	46	$\underline{46} \leftarrow 47 \rightarrow 48$	3-2	$0.71^{+0.38}_{-0.13}$
112	48	$48 \leftarrow 49 \rightarrow 50$	3-2	$0.67^{+0.19}_{-0.03}$
114	46	$46 \rightarrow 47 \rightarrow \underline{48} \leftarrow 49 \rightarrow 50$	4-4	$\mathit{0.60}^{+0.03}_{-0.03}$
116	48	$\underline{48} \leftarrow 49 \rightarrow 50$	3-2	$0.68^{+0.38}_{-0.01}$
118	48	$48 \rightarrow 49 \rightarrow 50 \leftarrow 51 \leftarrow 52$	4-4	$0.75^{+0.06}_{-0.04}$
120	48	$48 \rightarrow 49 \rightarrow 50 \leftarrow 51$	3-3	$0.71^{+0.06}_{-0.05}$
122	48	$48 \rightarrow 49 \rightarrow \underline{50} \mid 52 \leftarrow 53 \leftarrow 54 \leftarrow 55$	5-5	$\mathit{0.49}^{+0.03}_{-0.03}$
124	54	$54 \leftarrow 55 \leftarrow 56$	3-2	$0.34^{+0.20}_{-0.02}$
126	54	$54 \leftarrow 55 \leftarrow 56$	3-2	$0.35^{+0.20}_{-0.02}$
128	52	$\underline{52} \leftarrow 53 \rightarrow 54 \leftarrow 55 \leftarrow 56$	4-4	$\mathit{0.59}^{+0.05}_{-0.06}$
130	54	$54 \leftarrow 55 \rightarrow 56$	3-2	**0.78**
134	56	$56 \leftarrow 57 \leftarrow 58$	3-2	$0.72^{+0.10}_{-0.08}$
138	58	$58 \leftarrow 59 \leftarrow 60$	3-2	$0.92^{+0.20}_{-0.09}$
140	58	$58 \leftarrow 59 \leftarrow 60 \leftarrow 61 \leftarrow 62 \leftarrow 63 \leftarrow 64$	5-6	$1.10^{+0.07}_{-0.09}$
142	60	$60 \leftarrow 61 \leftarrow 62 \leftarrow 63$	3-3	$1.20^{+0.07}_{-0.12}$



Full Results – Triplets

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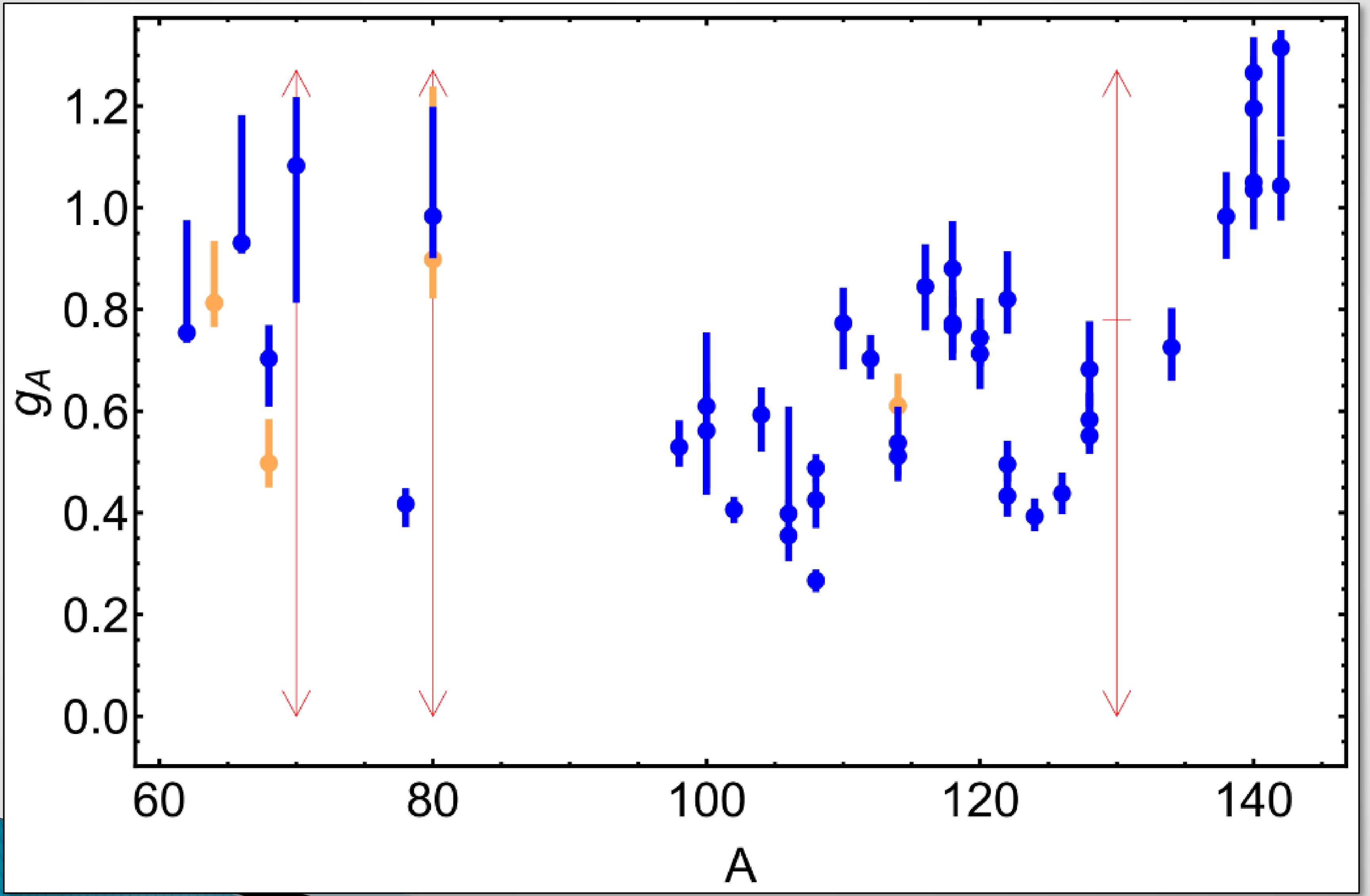

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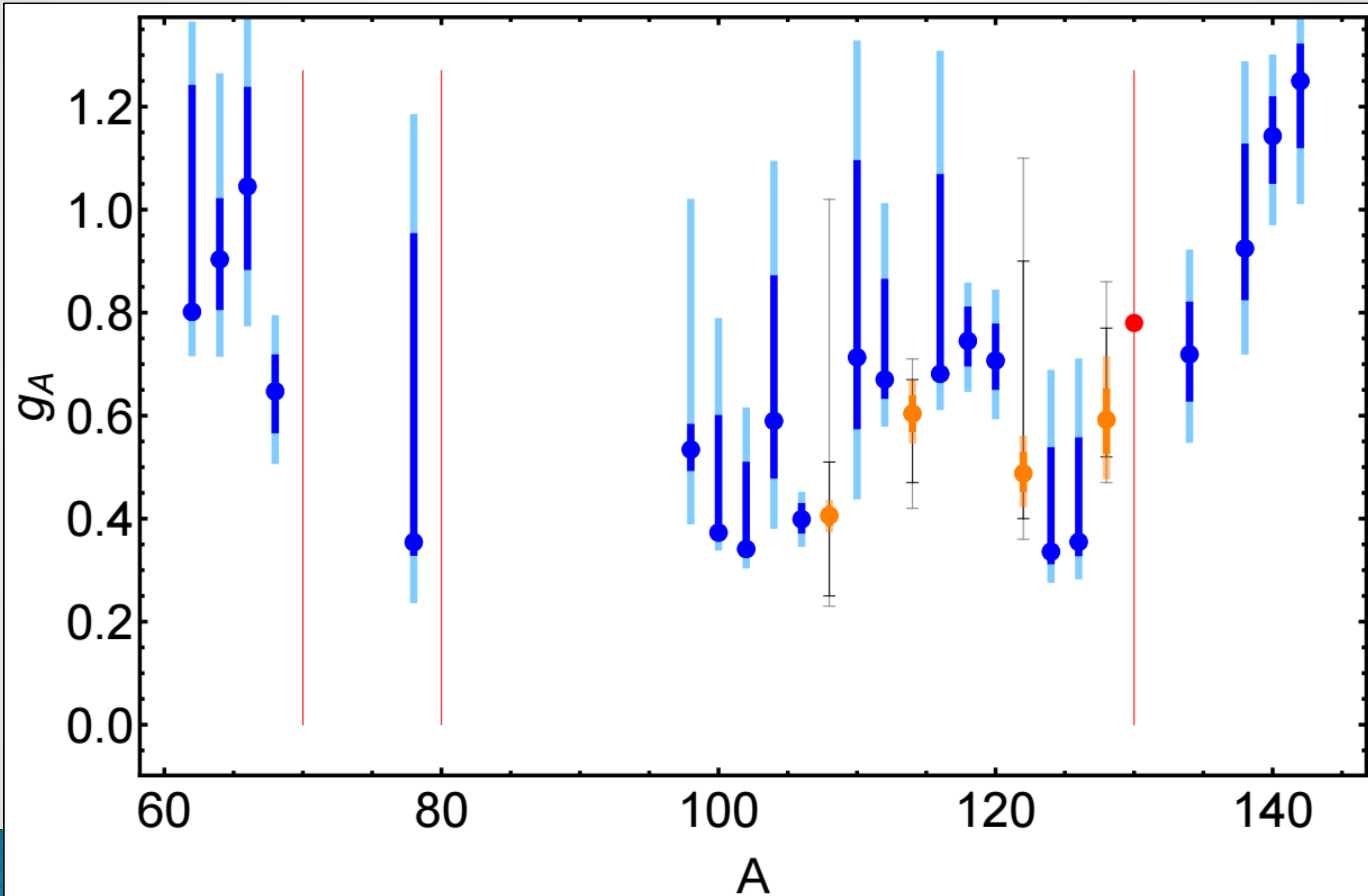

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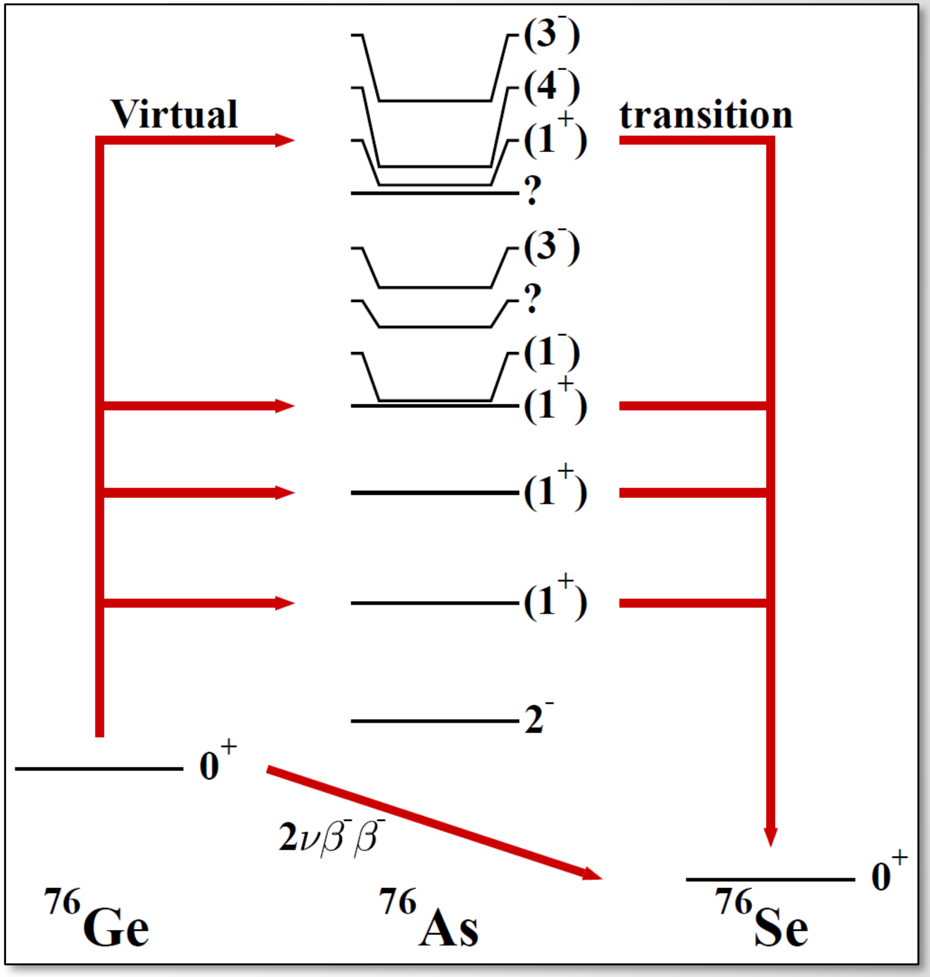
Unclear!

- Processes different at nucleon level
- Probing different transitions
- Incorporate more experimental information
  - Higher, forbidden beta decays
  - Charge exchange reactions
  - Muon capture



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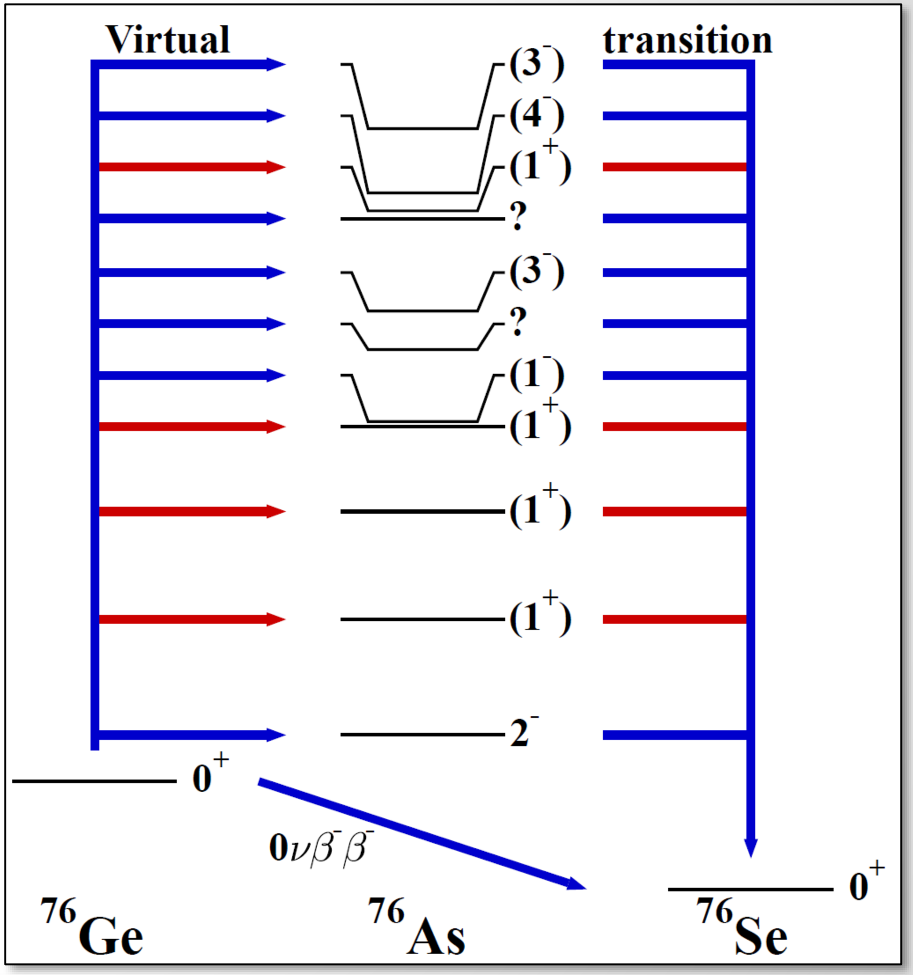

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Conclusion

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- **Interpretation of $0\nu\beta\beta$ requires precise NMEs**
  - Estimate of experimental sensitivity
  - Determination of $0\nu\beta\beta$ mass or falsification of Majorana scenario
- **Need to determine magnitude of g_A quenching in $0\nu\beta\beta$**
  - At least: additional source of uncertainty
  - Potentially: reduced sensitivity
- **Solution likely requires concerted effort**
  - Theoretical improvements, e.g. 2-body currents at higher momentum transfer [Menendez, Gazit, Schwenk, Phys. Rev. Lett. 107 (2011) 062501]
  - Experimental probes, e.g. NUMEN
  - Unbiased confrontation of theory with experiment
- **Given analysis example of consistent fit**
  - Full theory parameter variation against combined experimental data