AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst
"BETA DECAY AS A PROBE OF NEW PHYSICS"

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NUCLEAR STRUCTURE AND THEORY FOR PRECISION BETA DECAY EXPERIMENTS: NUCLEAR SHAPE CORRECTIONS

COLLABORATORS IN THIS WORK

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מכון ויצמן למדע
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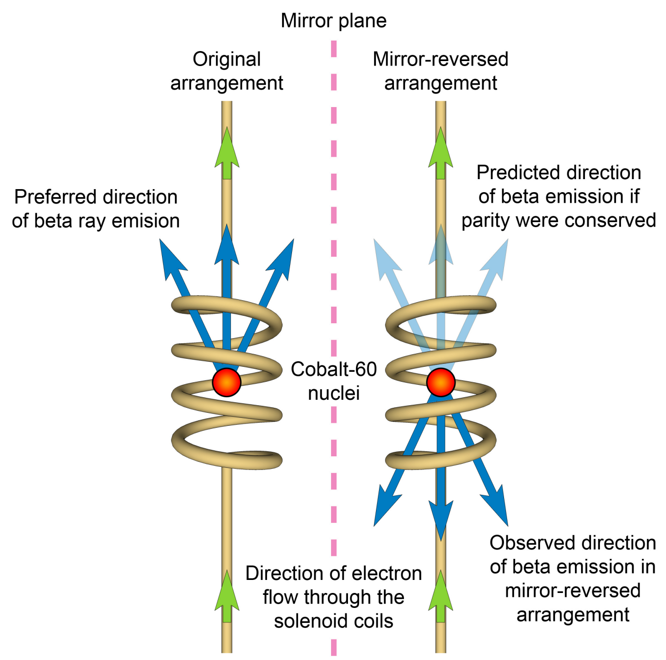
INTRODUCTION

- The standard model is incomplete: dark sector, neutrino masses.
- Finding signatures of beyond the standard model physics in quantum phenomena is one of the heralds of modern physics.
- LHC is the energy frontier.
- Nuclear phenomena are a precision frontier:
  - *New techniques allow unprecedented experimental accuracy.*
  - *Need an accompanying theoretical effort to analyze experimental results and pinpoint new physics*.
  - It's not a very rewarding job…

BSM EFFORTS USING NUCLEAR BETA DECAYS

β decays

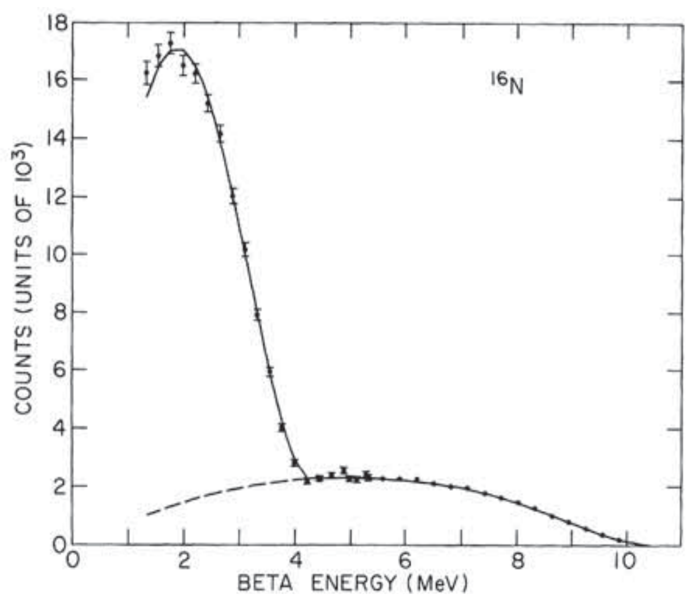
Precision Correlation Studies



Parity breaking

V-A structure

Precision spectrum studies



Neutrino hypothesized

KATRIN

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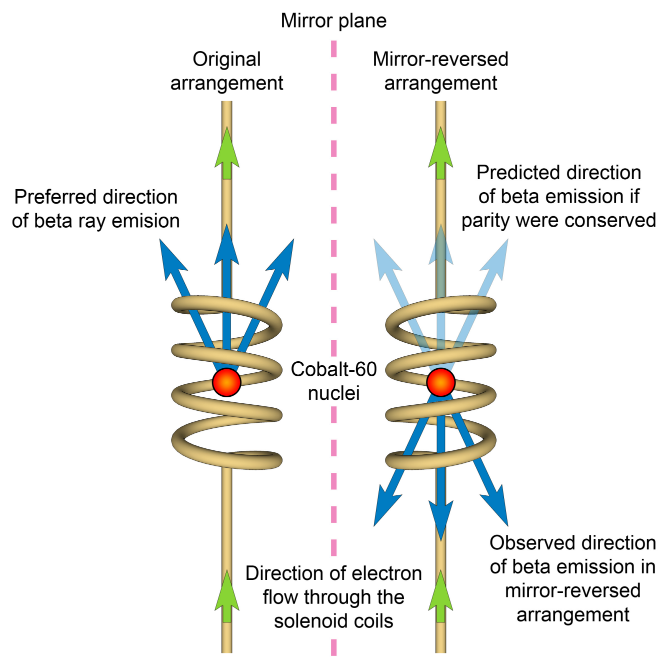

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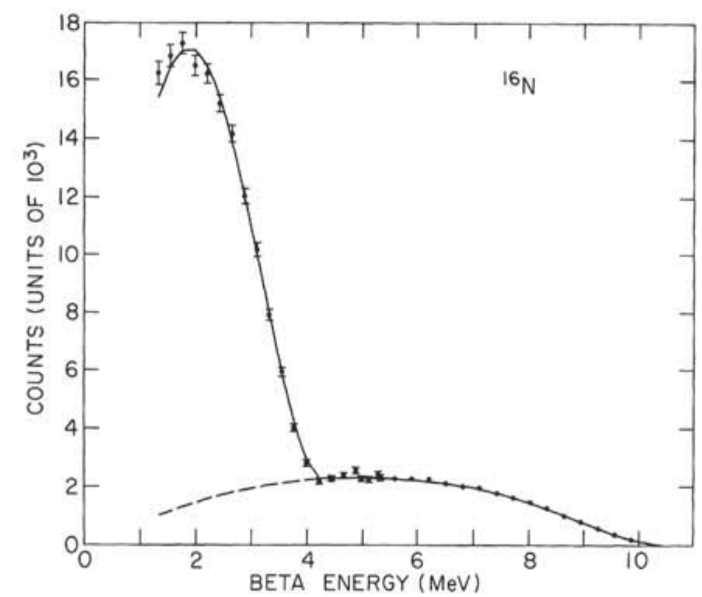

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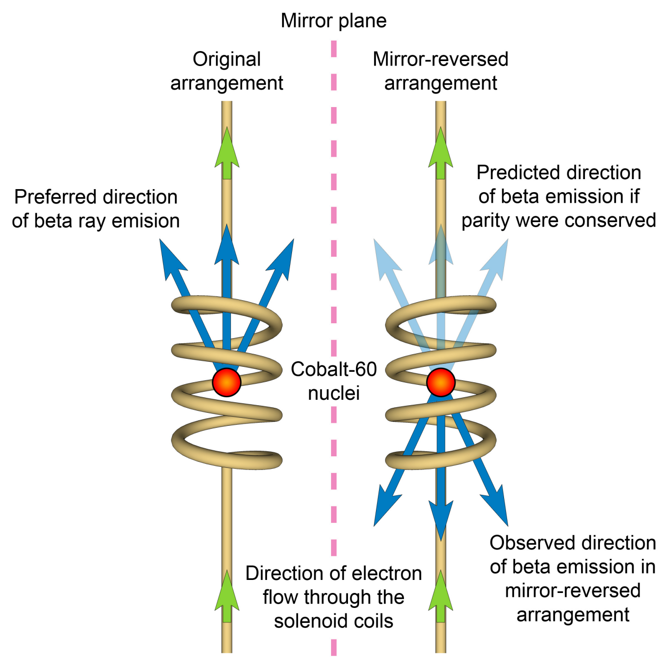
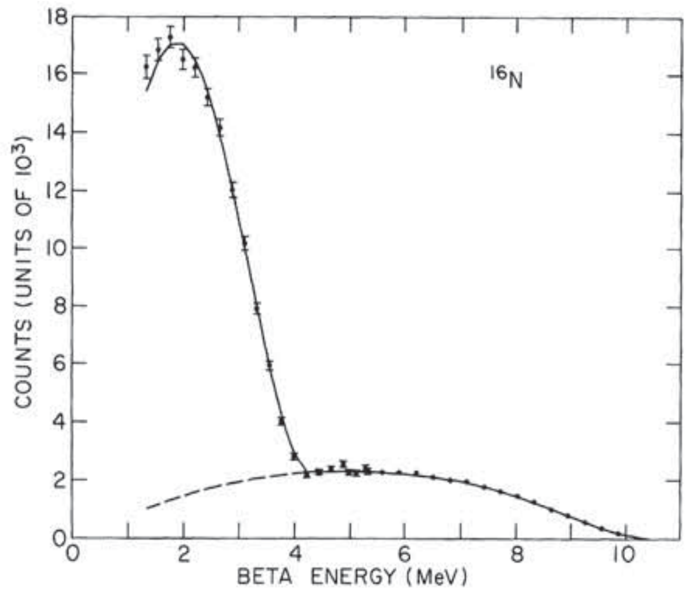


Precision spectrum studies



- "New Physics" searches using beta decays have been moving back and forth, from spectrum to correlation studies.
- Atomic traps acted as the catalyst for precision correlation studies, and many experiments have been constructed since ~2005.
- In the last couple of years, the seesaw seems to tilt towards precision spectrum studies again, based on theoretical expectations for the size of the effect.

Differential β decay rate

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \Sigma(\epsilon)\cdot\Theta(q,\vec{\beta}\cdot\hat{\nu})$$

Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear independent part

$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon) \times (corrections)$$

Classification of β decays

$\Delta J^\pi = 0^+$ (Super)allowed - Fermi transition

$\Delta J^\pi = 0,1^+$ Allowed – Fermi/Gamow-Teller

} $\propto q^0$

$\Delta J^\pi = 0,1,2^-$ Unique First forbidden transition $\propto q^1$

WHERE DOES NUCLEAR STRUCTURE ENTER?

Item	Effect	Formula	Magnitude	
1	Phase space factor [a]	$pW(W_0 - W)^2$	Unity or larger	
2	Traditional Fermi function	F_0		
3	Finite size of the nucleus	L_0		
4	Radiative corrections	R		NUCLEAR STRUCTURE DEPENDENT
5	Shape factor	C	10^{-1}-10^{-2}	
6	Atomic exchange	X		
7	Atomic mismatch	r		
8	Atomic screening	S		
9	Shake-up	See item 7		
10	Shake-off	See item 7		
11	Isovector correction	C_I		NUCLEAR STRUCTURE DEPENDENT
12	Recoil Coulomb correction	Q	10^{-3}-10^{-4}	
13	Diffuse nuclear surface	U		
14	Nuclear deformation	D_{FS} & D_C		
15	Recoiling nucleus	R_N		
16	Molecular screening	ΔS_{Mol}		
17	Molecular exchange	Case by case		
18	Bound state β decay	Γ_b/Γ_c	Smaller than $1 \cdot 10^{-4}$	
19	Neutrino mass	Negligible		

Beta Spectrum Generator: High precision allowed β spectrum shapes

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Differential β decay rate

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Momentum transfer

$\vec{\beta}=\frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

$\vec{\nu}$ neutrino momentum

Nuclear dependent part

Assuming V-A structure

$$\begin{aligned}\Theta(q,\vec{\beta}\cdot\hat{\nu})\\ &= \frac{\Delta J}{2\Delta J+1}\Big\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}\left(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2\right)\\ &\pm\hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*\\ &+\sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2\\ &+\left(1+\hat{\nu}\cdot\vec{\beta}\right)|\langle\|\hat{C}_J\|\rangle|^2\\ &-2\hat{q}\cdot\left(\hat{\nu}+\vec{\beta}\right)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Big]\Big\}, \qquad (4)\end{aligned}$$

$$\hat{C}_{JM}(q)=\int d\vec{x}\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0(\vec{x}) \qquad \propto q^J$$

$$\hat{E}_{JM}(q)=\frac{1}{q}\int d\vec{x}\,\vec{\nabla}\times[j_J(qx)\vec{Y}_{JJM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \qquad \propto q^{J-1}$$

$$\hat{M}_{JM}(q)=\int d\vec{x}\, j_J(qx)\vec{Y}_{JJM}(\hat{x})\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \qquad \propto q^J$$

$$\hat{L}_{JM}(q)=\frac{i}{q}\int d\vec{x}\,\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}), \qquad \propto \hat{E}_{JM}$$

We have similar expressions for Tensor and Scalar structures, and interferences.[Glick-Magid, Gazit, unpublished]

Differential β decay rate

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Momentum transfer

$\vec{\beta} = \frac{\vec{k}}{\epsilon}$, β particle momentum to energy ratio

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Nuclear dependent part

Assuming V-A structure

$$\hat{C}_{JM}(q) = \int d\vec{x}\, j_J(qx) Y_{JM}(\hat{x}) \hat{\mathcal{J}}_0(\vec{x}) \quad \propto q^J$$

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Nuclear-probe coupling operators

$$\begin{aligned}
\Theta(q, \vec{\beta}\cdot\hat{\nu}) &= \frac{\Delta J}{2\Delta J+1}\Bigg\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}\left(|\langle\|\hat{E}_J\|\rangle|^2 + |\langle\|\hat{M}_J\|\rangle|^2\right) \\
&\pm \hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1} 2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^* \\
&+ \sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2 \\
&+ \left(1+\hat{\nu}\cdot\vec{\beta}\right)|\langle\|\hat{C}_J\|\rangle|^2 \\
&- 2\hat{q}\cdot\left(\hat{\nu}+\vec{\beta}\right)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Big]\Bigg\},
\end{aligned} \tag{4}$$

We have similar expressions for Tensor and Scalar structures, and interferences.[Glick-Magid, Gazit, unpublished]

e.g., allowed transitions $\Delta J^{\pi} = 0,1^{+}$

$$d\omega^{V-A} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot \left\{ \frac{\left|C_V\right|^2 + \left|C_V'\right|^2}{2} \left(1 + \hat{\nu} \cdot \vec{\beta}\right) \left| \left\langle J_f \left\| \hat{C}_0^V \right\| J_i \right\rangle \right|^2 + \frac{\left|C_A\right|^2 + \left|C_A'\right|^2}{2} 3 \left(1 - \frac{1}{3} \hat{\nu} \cdot \vec{\beta}\right) \left| \left\langle J_f \left\| \hat{L}_1^A \right\| J_i \right\rangle \right|^2 \right\} + O\left(q\right)$$

Fermi

Gamow-Teller

Correlation coefficient

Assumptions: vanishing momentum transfer (q=0).

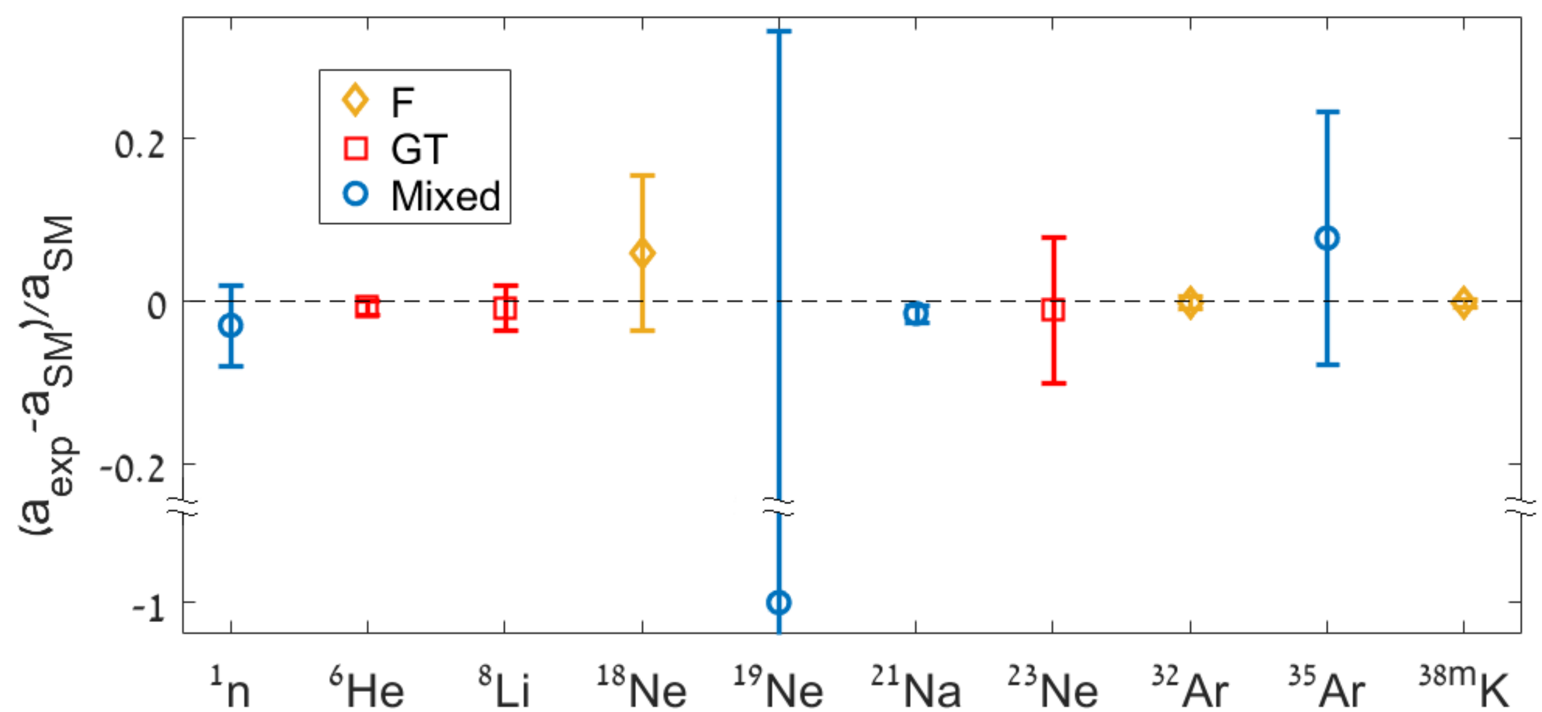
e.g., allowed transitions $\Delta J^{\pi} = 0{,}1^{+}$

$$d\omega^{\text{V+T}} = \frac{4}{\pi^2} k\epsilon \left(W_0 - \epsilon\right)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot$$

Assuming V+T structure

$$\cdot \left\{ \frac{\left|C_V\right|^2 + \left|C_V'\right|^2}{2} \left(1 + \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{C}_0^V \right\| J_i \right\rangle\right|^2 \right.$$

$$\left. + \frac{|C_T|^2 + |C_T'|^2}{2} 3 \left(1 + \frac{1}{3} \hat{\nu} \cdot \vec{\beta}\right) \left|\left\langle J_f \left\| \hat{L}_1^A \right\| J_i \right\rangle\right|^2 \right\} + O(q)$$



e.g., allowed transitions

V-A WITH T CORRECTIONS:

$$\Theta \propto (1 + b\frac{m_e}{\epsilon} + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu})$$

$$a_{\beta\nu} \approx -\frac{1}{3}(1 - \frac{|C_T|^2+|C_T'|^2}{|C_A|^2}), \text{ and } b = 2\frac{C_T+C_T'}{C_A}$$

Caveats:

a) Sensitive to combination of tensor couplings, with spectrum averaging of energy, thus in a specific nucleus – the sensitivity to BSM couplings is QUADRATIC…

b) Spectrum, i.e., integration over angle, sensitive to Fierz term, i.e., insensitive to fully right handed couplings.

M. González-Alonso, O. Naviliat-Cuncic, Kinematic sensitivity to the Fierz term of β-decay differential spectra, Phys. Rev. C 94 (2016) 035503.

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

$$\Theta(q,\vec{\beta}\cdot\hat{\nu}) = \frac{\Delta J}{2\Delta J+1}\Bigg\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}\left(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2\right)$$
$$\pm\hat{q}\cdot\left(\hat{\nu}-\vec{\beta}\right)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*$$
$$+\sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2$$
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$$\Theta(q,\vec{\beta}\cdot\hat{\nu})\propto 1\pm 2\gamma_0\frac{C_T+C_T'}{C_A}\frac{m_e}{\epsilon}$$
$$-\frac{1}{5}\left(2(\hat{\nu}\cdot\vec{\beta})-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right)\left(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\right).$$

$$\propto\ 1-\left(\hat{\beta}\cdot\hat{\nu}\right)^2$$

Glick-Magid, DG, et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

$$\Theta(q, \vec{\beta} \cdot \hat{\nu}) \propto 1 \pm 2\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon} - \frac{1}{5}\left(2(\hat{\nu} \cdot \vec{\beta}) - (\hat{\nu} \cdot \hat{q})(\vec{\beta} \cdot \hat{q})\right)\left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right).$$

$$\propto \quad 1 - \left(\hat{\beta} \cdot \hat{\nu}\right)^2$$

Spectrum, i.e., integration over angle:

$$\frac{dw_{\beta^{\mp}}}{d\epsilon} \propto \Sigma(\epsilon) \left(2 + 4\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon} + \frac{\beta}{5} \frac{(a^2 - 1)\tanh^{-1}(a) + a}{a^2} \times \left(1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right)\right),$$

$$a = 2k\nu/(k^2 + \nu^2)$$

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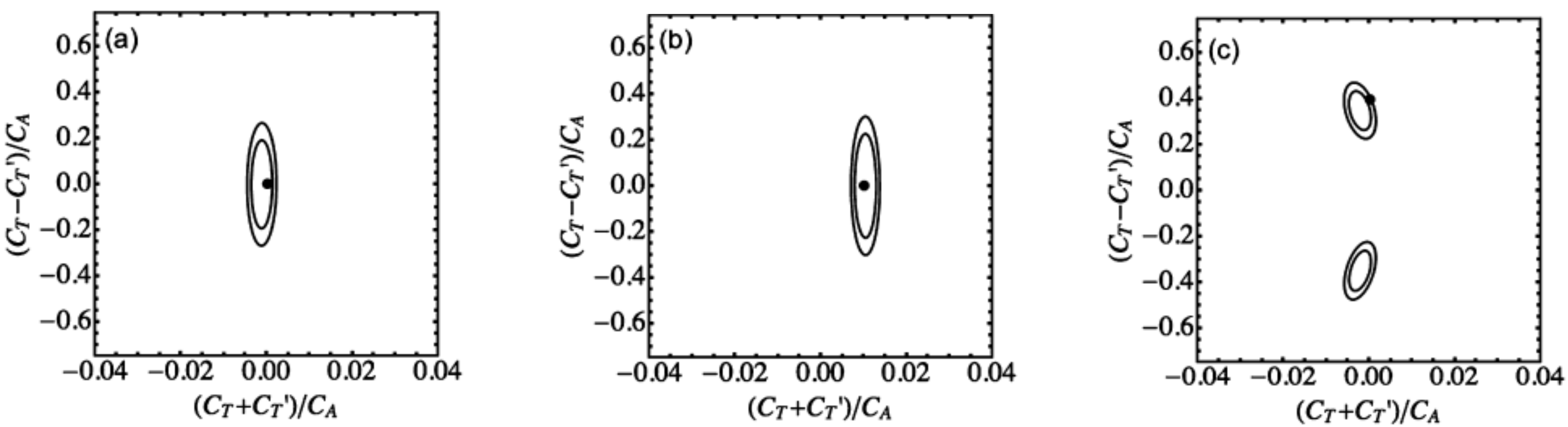
Unique first forbidden $\Delta J^{\pi} = 2^{-}$

Unique possibility to separate between left and right-handed couplings!



$C_T = C_T' = 0$ $\quad$ $C_T/C_A = C_T'/C_A = 0.005$ $\quad$ $C_T/C_A = -C_T'/C_A = 0.2$

Glick-Magid, DG, et al, Beta spectrum of unique first forbidden decays as a novel test for fundamental symmetries, Phys. Lett. B767, 285 (2017)

SHAPE CORRECTIONS

These are nuclear structure dependent corrections.

Needed accuracy of the calculation $\approx 10^{-4} - 10^{-3}$

This dictates the number of corrections needed to be calculated explicitly.

$$\hat{C}_{JM}(q) = \int d\vec{x}\, j_J(qx) Y_{JM}(\hat{x}) \hat{\mathcal{J}}_0(\vec{x}) \quad \propto q^J$$

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$$\frac{qR}{\hbar c} \approx 0.005 - 0.1$$

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$$\frac{1}{(2J+1)!!}$$

$$\frac{qR}{\hbar c} \approx 0.005 - 0.1$$

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$$\mathcal{J}^{\mu\dagger}(\mathbf{r}) = \sum_{i=1}^{A} \tau_i^- [\delta^{\mu 0} J^0_{i,1b} - \delta^{\mu k} J^k_{i,1b}]\delta(\mathbf{r} - \mathbf{r}_i)$$

$$J^0_{i,1b}(p^2) = 1 - g_A \frac{\mathbf{p}\cdot\boldsymbol{\sigma}_i}{2m},$$

$$\mathbf{J}_{i,1b}(p^2) = g_A \boldsymbol{\sigma}_i + i\kappa_V \frac{\boldsymbol{\sigma}_i \times \mathbf{p}}{2m},$$

Exchange currents

Chiral suppression
additional factor 3-5

In beta decays, shape corrections are few per-milles, thus the first correction should be calculated explicitly to reach needed accuracy

SHAPE CORRECTIONS

e.g., allowed transitions

Nuclear effects are important to pinpoint BSM effects:

$$\frac{d\omega^{V-A}_{\beta\mp}}{d\epsilon\frac{d\Omega_k}{4\pi}\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}(Q-\epsilon)^2 k\epsilon F^{\pm}(Z_f,\epsilon)\frac{1}{2J_i+1}\cdot$$
$$\cdot\left\{\frac{|C_V|^2+\left|C_V'\right|^2}{2}\left[1+\delta_1^{0^+}+\left(1+\delta_{\beta\nu}^{0^+}\right)\hat{\nu}\cdot\vec{\beta}\right]\left|\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle\right|^2\right.$$
$$\left.+\frac{|C_A|^2+\left|C_A'\right|^2}{2}3\left[1+\delta_1^{1^+}-\frac{1}{3}\left(1+\delta_{\beta\nu}^{1^+}\right)\hat{\nu}\cdot\vec{\beta}\right]\left|\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle\right|^2\right\}$$

$$\delta_1^{0^+} = -\frac{\nu+\frac{k^2}{\epsilon}}{q}2\Re\mathfrak{e}\frac{\left\langle J_f\left\|\hat{L}_0^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle}$$
$$\delta_{\beta\nu}^{0^+} = -\frac{\epsilon+\nu}{q}2\Re\mathfrak{e}\frac{\left\langle J_f\left\|\hat{L}_0^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{C}_0^V\right\|J_i\right\rangle}$$

$$\delta_1^{1^+} = -\frac{2}{3}\left[\frac{\nu+\frac{k^2}{\epsilon}}{q}\Re\mathfrak{e}\frac{\left\langle J_f\left\|\hat{C}_1^A\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\mp 2\sqrt{2}\frac{\nu-\frac{k^2}{\epsilon}}{q}\Re\mathfrak{e}\left(\frac{C_V^*C_A+C_V'^*C_A'}{|C_A|^2+|C_A'|^2}\frac{\left\langle J_f\left\|\hat{M}_1^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\right)\right]$$
$$\delta_{\beta\nu}^{1^+} = 2\left[\frac{\epsilon+\nu}{q}\Re\mathfrak{e}\frac{\left\langle J_f\left\|\hat{C}_1^A\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\mp 2\sqrt{2}\frac{\epsilon-\nu}{q}\Re\mathfrak{e}\left(\frac{C_V^*C_A+C_V'^*C_A'}{|C_A|^2+|C_A'|^2}\frac{\left\langle J_f\left\|\hat{M}_1^V\right\|J_i\right\rangle}{\left\langle J_f\left\|\hat{L}_1^A\right\|J_i\right\rangle}\right)\right] \quad (39)$$

SHAPE CORRECTIONS

Unique first forbidden $\Delta J^{\pi} = 2^{-}$

$$\frac{d^5\omega_{\beta^\mp}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon} = \frac{2G^2}{\pi^2}\frac{1}{2J_i+1}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{\pm}(Z_f,\epsilon) \times \left\{\frac{5}{2}\left[1+\delta_1+\frac{2}{5}(1+\delta_{\hat{\nu}\cdot\vec{\beta}})\hat{\nu}\cdot\vec{\beta} + \frac{1}{5}(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\right]\langle\|\hat{L}_2^A\|\rangle^2\right\},$$

with

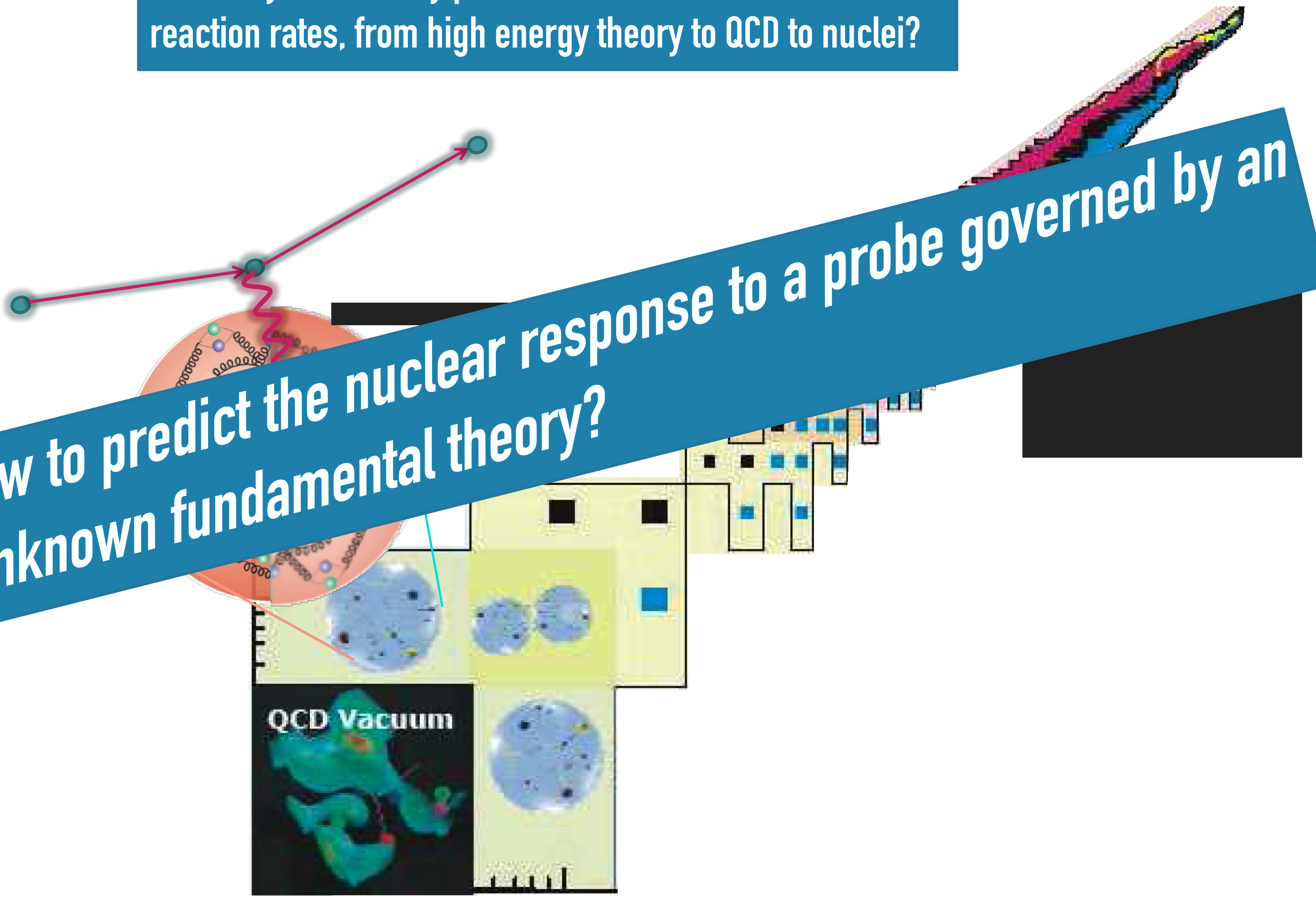
$$\delta_1 = \frac{4}{5}\left\{\pm\sqrt{\frac{3}{2}}\frac{\nu-\frac{k^2}{\epsilon}}{q}\Re\frac{\langle\|\hat{M}_2^V\|\rangle}{\langle\|\hat{L}_2^A\|\rangle} - \frac{\nu+\frac{k^2}{\epsilon}}{q}\Re\frac{\langle\|\hat{C}_2^A\|\rangle}{\langle\|\hat{L}_2^A\|\rangle}\right\},$$

$$\delta_{\hat{\nu}\cdot\vec{\beta}} = 2\left\{\pm\sqrt{\frac{3}{2}}\frac{\epsilon-\nu}{q}\Re\frac{\langle\|\hat{M}_2^V\|\rangle}{\langle\|\hat{L}_2^A\|\rangle} - \frac{\nu+\epsilon}{q}\Re\frac{\langle\|\hat{C}_2^A\|\rangle}{\langle\|\hat{L}_2^A\|\rangle}\right\}$$

Pre-conditions for a precision prediction:

Need to know ratios to 10%.
What about currents?

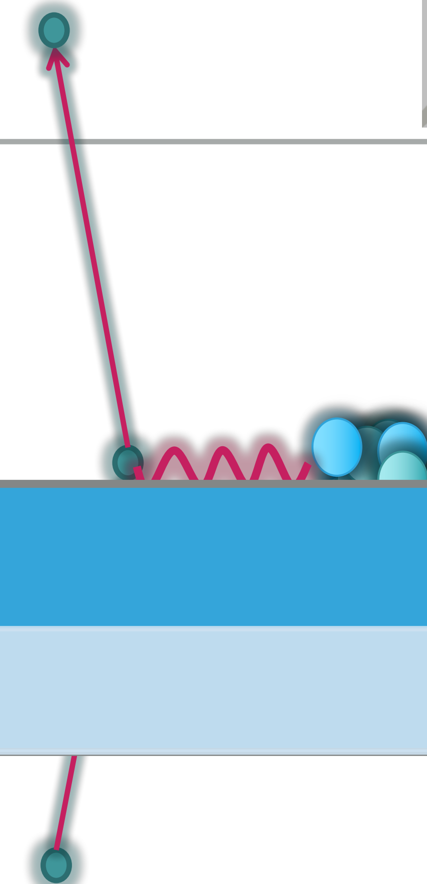
How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?



How to predict the nuclear response to a probe governed by an unknown fundamental theory?

BSM PHYSICS: THE NUCLEAR PHYSICS CHALLENGE

How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?



Ultraviolet physics

unknown high energy physics – a calculation for each candidate high energy theory is tedious

↓

probe-quark interaction

Unknown couplings, multiple possible channels.

↓

Probe-nucleus interaction

Going from quark to nucleon demands solving QCD at low-energies.

↓

Many body calculation of nuclear structure

Nuclear interaction from QCD?	Unified theory of nuclear reactions and structure?	Many body strongly interacting problem.

LOW ENERGY REACTION OF A SPIN $\frac{1}{2}$ PARTICLE WITH A NUCLEUS

Effective Lagrangians

$$e.g., \frac{\mu}{2}\bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$$

$\bar{\chi}\chi\langle\Psi|\bar{q}q|\Psi\rangle$
$;\bar{\chi}\gamma_5\chi\langle\Psi|\bar{q}\gamma_5 q|\Psi\rangle$

$$\bar{\chi}\gamma_\mu\chi\langle\Psi|\bar{q}\gamma^\mu q|\Psi\rangle$$
$$\bar{\chi}\gamma_\mu\gamma_5\chi\langle\Psi|\bar{q}\gamma^\mu\gamma_5 q|\Psi\rangle$$

$$\bar{\chi}\sigma_{\mu\nu}\chi\langle\Psi|\bar{q}\sigma^{\mu\nu}q|\Psi\rangle$$
$$\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\langle\Psi|\bar{q}\sigma^{\mu\nu}q|\Psi\rangle$$

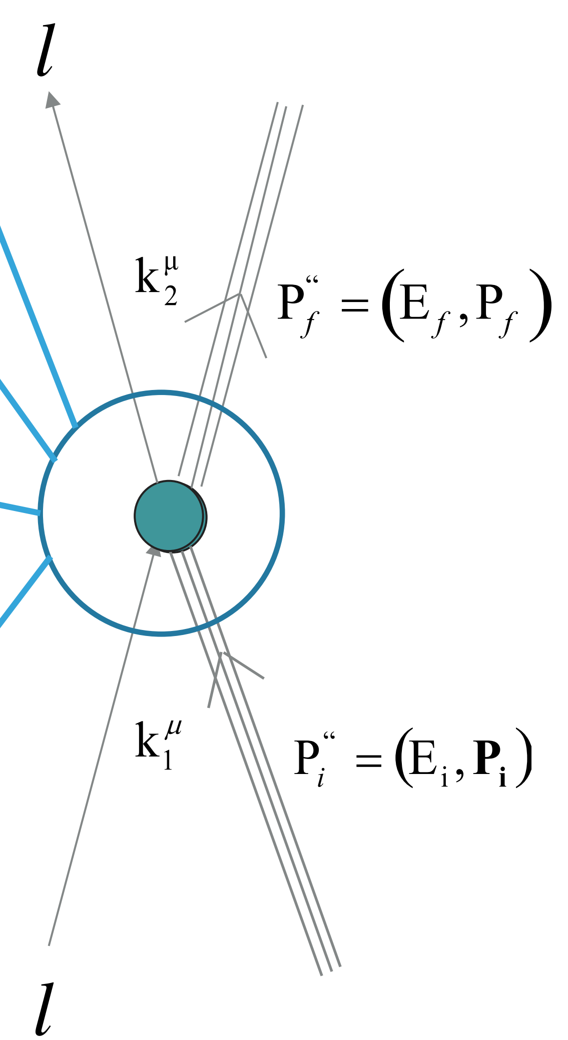
Couplings:

U(1): anapole,
E/M dipole

Scalar, Pseudo-scalar

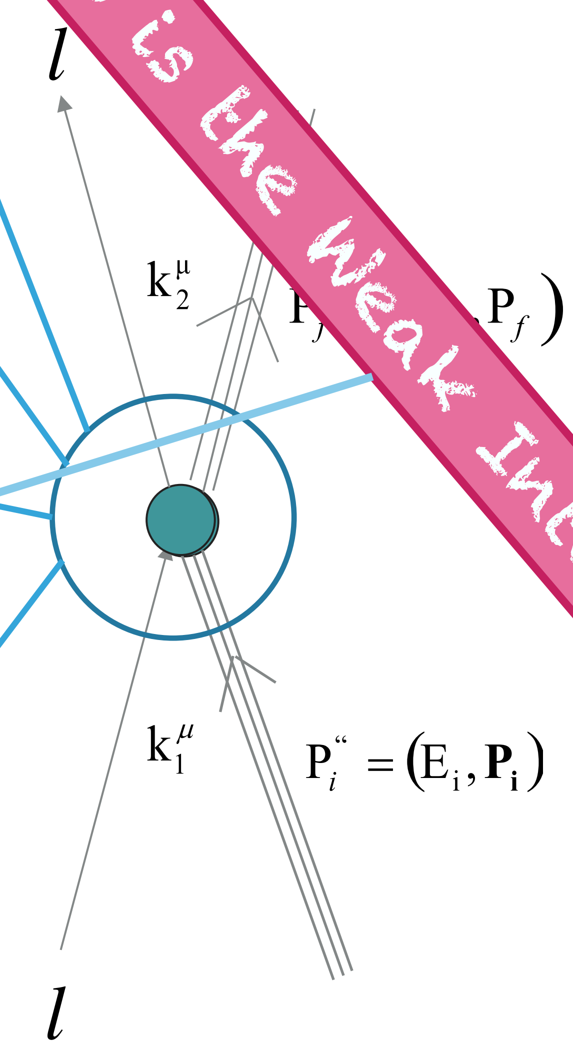
Vector, Axial-vector

Tensor, Pseudo-tensor



LOW ENERGY REACTION OF A SPIN $\frac{1}{2}$ PARTICLE WITH A NUCLEUS

Effective Lagrangians	Couplings:
$e.g., \frac{\mu}{2}\bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$	U(1): anapole, E/M dipole
$\bar{\chi}\chi\langle\Psi\vert\bar{q}q\vert\Psi\rangle$; $\bar{\chi}\gamma_5\chi\langle\Psi\vert\bar{q}\gamma_5 q\vert\Psi\rangle$	Scalar, Pseudo-scalar
$\bar{\chi}\gamma_\mu\chi\langle\Psi\vert\bar{q}\gamma^\mu q\vert\Psi\rangle$ $\bar{\chi}\gamma_\mu\gamma_5\chi\langle\Psi\vert\bar{q}\gamma^\mu\gamma_5 q\vert\Psi\rangle$	Vector, Axial-vector
$\bar{\chi}\sigma_{\mu\nu}\chi\langle\Psi\vert\bar{q}\sigma^{\mu\nu}q\vert\Psi\rangle$ $\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\langle\Psi\vert\bar{q}\sigma^{\mu\nu}q\vert\Psi\rangle$	Tensor, Pseudo-tensor



This is the Weak Interaction

SIZE OF "NEW PHYSICS" BEYOND STANDARD MODEL

$$\begin{aligned}
\mathcal{L}^{\text{eff}}_{ude\nu} = -\frac{G_F^0 V_{ud}}{\sqrt{2}} \Big[& (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \ + \ \tilde{\epsilon}_L\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \epsilon_R\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \ + \ \tilde{\epsilon}_R\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \ + \ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
& + \epsilon_S\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \ + \ \tilde{\epsilon}_S\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\
& - \epsilon_P\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \ - \ \tilde{\epsilon}_P\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \ + \ \ldots \Big] + \text{h.c.}\ ,
\end{aligned}$$

SIZE OF "NEW PHYSICS" BEYOND STANDARD MODEL

$$\begin{aligned}\mathcal{L}^{\text{eff}}_{ude\nu} = -\frac{G_F^0 V_{ud}}{\sqrt{2}}\Big[& (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \ +\ \tilde{\epsilon}_L\,\bar{e}\gamma_\mu(1+\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \\ & +\epsilon_R\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \ +\ \tilde{\epsilon}_R\,\bar{e}\gamma_\mu(1+\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \\ & +\epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \ +\ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e\cdot\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\ & +\epsilon_S\,\bar{e}(1-\gamma_5)\nu_e\cdot\bar{u}d \ +\ \tilde{\epsilon}_S\,\bar{e}(1+\gamma_5)\nu_e\cdot\bar{u}d \\ & -\epsilon_P\,\bar{e}(1-\gamma_5)\nu_e\cdot\bar{u}\gamma_5 d \ -\ \tilde{\epsilon}_P\,\bar{e}(1+\gamma_5)\nu_e\cdot\bar{u}\gamma_5 d\ +\ \ldots\Big] + \text{h.c.}\,,\end{aligned}$$

$$\epsilon_i, \tilde{\epsilon}_i \propto \left(\frac{m_W}{\Lambda}\right)^n$$

$n = 0$ for $i = V, A$
$n \geq 2$ for $i \neq V, A$

NEW PHYSICS SCALE

For the simplest BSM operator (n=2), a 3 TeV scale means $\epsilon_i, \tilde{\epsilon}_i \approx 10^{-3}$

FROM THE QUARK TO THE NUCLEON

$$
\begin{aligned}
\mathcal{L}^{\text{eff}}_{ude\nu} = -\frac{G_F^0 V_{ud}}{\sqrt{2}} \Big[& (1+\epsilon_L)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \ + \ \tilde{\epsilon}_L\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
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& + \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \ + \ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
& + \epsilon_S\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \ + \ \tilde{\epsilon}_S\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\
& - \epsilon_P\, \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \ - \ \tilde{\epsilon}_P\, \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \ + \ \ldots \Big] + \text{h.c.}\ ,
\end{aligned}
$$

Taking a matrix element between nucleonic states:

$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} \ = \ & \bar{p}\ n\ (C_S\bar{e}\nu_e - C'_S\bar{e}\gamma_5\nu_e) \\
& + \bar{p}\gamma^\mu n\,(C_V\bar{e}\gamma_\mu\nu_e - C'_V\bar{e}\gamma_\mu\gamma_5\nu_e) \\
& + \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\,(C_T\bar{e}\sigma_{\mu\nu}\nu_e - C'_T\bar{e}\sigma_{\mu\nu}\gamma_5\nu_e) \\
& - \bar{p}\gamma^\mu\gamma_5 n\,(C_A\bar{e}\gamma_\mu\gamma_5\nu_e - C'_A\bar{e}\gamma_\mu\nu_e) \\
& + \bar{p}\gamma_5 n\ (C_P\bar{e}\gamma_5\nu_e - C'_P\bar{e}\nu_e) + \text{h.c.}
\end{aligned}
$$

$$
\begin{aligned}
\overline{C}_V + \overline{C}'_V &= 2\,g_V\,(1+\epsilon_L+\epsilon_R) & \overline{C}_V - \overline{C}'_V &= 2\,g_V\,(\tilde{\epsilon}_L+\tilde{\epsilon}_R) \\
\overline{C}_A + \overline{C}'_A &= -2\,g_A\,(1+\epsilon_L-\epsilon_R) & \overline{C}_A - \overline{C}'_A &= 2\,g_A\,(\tilde{\epsilon}_L-\tilde{\epsilon}_R) \\
\overline{C}_S + \overline{C}'_S &= 2\,g_S\,\epsilon_S & \overline{C}_S - \overline{C}'_S &= 2\,g_S\,\tilde{\epsilon}_S \\
\overline{C}_P + \overline{C}'_P &= 2\,g_P\,\epsilon_P & \overline{C}_P - \overline{C}'_P &= -2\,g_P\,\tilde{\epsilon}_P \\
\overline{C}_T + \overline{C}'_T &= 8\,g_T\,\epsilon_T & \overline{C}_T - \overline{C}'_T &= 8\,g_T\,\tilde{\epsilon}_T\ ,
\end{aligned}
$$

FROM THE QUARK TO THE NUCLEON

$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar\nu_e} \;=\;& \bar p\, n\,\left(C_S \bar e \nu_e - C_S' \bar e \gamma_5 \nu_e\right) \\
&+ \bar p \gamma^\mu n \left(C_V \bar e \gamma_\mu \nu_e - C_V' \bar e \gamma_\mu \gamma_5 \nu_e\right) \\
&+ \frac{1}{2} \bar p \sigma^{\mu\nu} n \left(C_T \bar e \sigma_{\mu\nu} \nu_e - C_T' \bar e \sigma_{\mu\nu} \gamma_5 \nu_e\right) \\
&- \bar p \gamma^\mu \gamma_5 n \left(C_A \bar e \gamma_\mu \gamma_5 \nu_e - C_A' \bar e \gamma_\mu \nu_e\right) \\
&+ \bar p \gamma_5 n\,\left(C_P \bar e \gamma_5 \nu_e - C_P' \bar e \nu_e\right) + \text{h.c.}
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$$

$$
\begin{aligned}
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\overline{C}_A + \overline{C}_A' &= -2\, g_A\, (1 + \epsilon_L - \epsilon_R) & \overline{C}_A - \overline{C}_A' &= 2\, g_A\, (\tilde\epsilon_L - \tilde\epsilon_R) \\
\overline{C}_S + \overline{C}_S' &= 2\, g_S\, \epsilon_S & \overline{C}_S - \overline{C}_S' &= 2\, g_S\, \tilde\epsilon_S \\
\overline{C}_P + \overline{C}_P' &= 2\, g_P\, \epsilon_P & \overline{C}_P - \overline{C}_P' &= -2\, g_P\, \tilde\epsilon_P \\
\overline{C}_T + \overline{C}_T' &= 8\, g_T\, \epsilon_T & \overline{C}_T - \overline{C}_T' &= 8\, g_T\, \tilde\epsilon_T\ ,
\end{aligned}
$$

Taking a matrix element between nucleonic states:

$$
\begin{aligned}
\langle p(p_p)|\, \bar u \gamma_\mu d\, |n(p_n)\rangle &= \bar u_p(p_p) \left[g_V(q^2)\, \gamma_\mu + \frac{\tilde g_{T(V)}(q^2)}{2M_N}\, \sigma_{\mu\nu} q^\nu + \frac{\tilde g_S(q^2)}{2M_N}\, q_\mu \right] u_n(p_n)\ , \\
\langle p(p_p)|\, \bar u \gamma_\mu \gamma_5 d\, |n(p_n)\rangle &= \bar u_p(p_p) \left[g_A(q^2) \gamma_\mu + \frac{\tilde g_{T(A)}(q^2)}{2M_N} \sigma_{\mu\nu} q^\nu + \frac{\tilde g_P(q^2)}{2M_N} q_\mu \right] \gamma_5 u_n(p_n)\ , \\
\langle p(p_p)|\, \bar u\, d\, |n(p_n)\rangle &\approx g_S(0)\, \bar u_p(p_p)\, u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ , \\
\langle p(p_p)|\, \bar u\, \gamma_5\, d\, |n(p_n)\rangle &\approx g_P(0)\, \bar u_p(p_p)\, \gamma_5\, u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ , \\
\langle p(p_p)|\, \bar u\, \sigma_{\mu\nu}\, d\, |n(p_n)\rangle &\approx g_T(0)\, \bar u_p(p_p)\, \sigma_{\mu\nu} u_n(p_n) + \mathcal{O}(q/M_N)\ ,
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FROM THE QUARK TO THE NUCLEON

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&+ \frac{1}{2} \bar p \sigma^{\mu\nu} n\, (C_T \bar e \sigma_{\mu\nu} \nu_e - C_T' \bar e \sigma_{\mu\nu} \gamma_5 \nu_e) \\
&- \bar p \gamma^\mu \gamma_5 n\, (C_A \bar e \gamma_\mu \gamma_5 \nu_e - C_A' \bar e \gamma_\mu \nu_e) \\
&+ \bar p \gamma_5 n\, (C_P \bar e \gamma_5 \nu_e - C_P' \bar e \nu_e) + \text{h.c.}
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$$
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\overline{C}_S + \overline{C}_S' &= 2\, g_S\, \epsilon_S & \overline{C}_S - \overline{C}_S' &= 2\, g_S\, \tilde\epsilon_S \\
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Taking a matrix element between nucleonic states:

$$
\begin{aligned}
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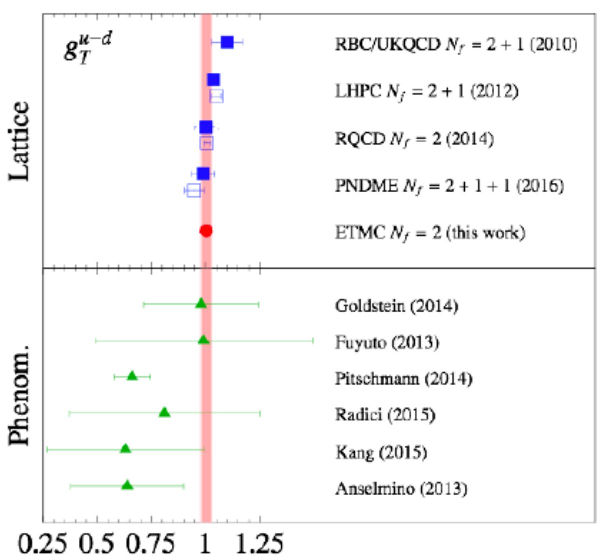
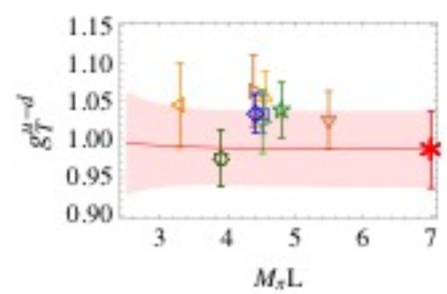
\langle p(p_p)|\, \bar u \gamma_\mu \gamma_5 d\, |n(p_n)\rangle &= \bar u_p(p_p) \left[g_A(q^2) \gamma_\mu + \frac{\tilde g_{T(A)}(q^2)}{2M_N} \sigma_{\mu\nu} q^\nu + \frac{\tilde g_P(q^2)}{2M_N} q_\mu \right] \gamma_5 u_n(p_n)\ , \\
\langle p(p_p)|\, \bar u\, d\, |n(p_n)\rangle &\approx g_S(0)\, \bar u_p(p_p)\, u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ , \\
\langle p(p_p)|\, \bar u\, \gamma_5\, d\, |n(p_n)\rangle &\approx g_P(0)\, \bar u_p(p_p)\, \gamma_5\, u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ , \\
\langle p(p_p)|\, \bar u\, \sigma_{\mu\nu}\, d\, |n(p_n)\rangle &\approx g_T(0)\, \bar u_p(p_p)\, \sigma_{\mu\nu} u_n(p_n) + \mathcal{O}(q/M_N)\ ,
\end{aligned}
$$

FROM THE QUARK TO THE NUCLEON – NON STANDARD COUPLINGS

The $\epsilon's$ are small, not the nuclear charges!





$$g_P = g_A (M_n + M_p)/(m_d + m_u) = 349(9)$$

$$g_S = g_V \frac{(M_n - M_p)^{QCD}}{m_d - m_u} \approx 0.8 - 1.2$$

Axial, Scalar and Tensor Charges of the Nucleon from 2+1+1-flavor Lattice QCD

Tanmoy Bhattacharya,[1,*] Vincenzo Cirigliano,[1,†] Saul D. Cohen,[2,‡] Rajan Gupta,[1,§] Huey-Wen Lin,[3,¶] and Boram Yoon[1,**]
(Precision Neutron Decay Matrix Elements (PNDME) Collaboration)

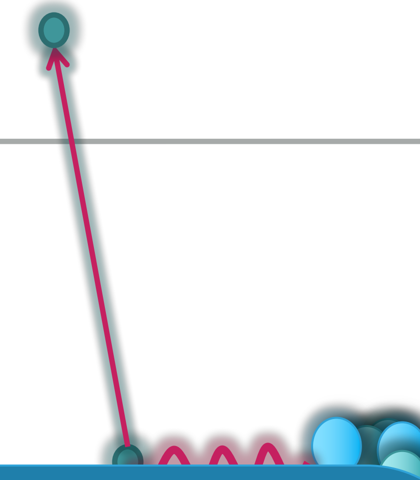
$$\langle p(p_p)|\,\bar{u}\gamma_\mu d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu + \frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\,\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}\,q_\mu\right]u_n(p_n)\ ,$$

$$\langle p(p_p)|\,\bar{u}\gamma_\mu\gamma_5 d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_A(q^2)\gamma_\mu + \frac{\tilde{g}_{T(A)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N}q_\mu\right]\gamma_5 u_n(p_n)\ ,$$

$$\langle p(p_p)|\,\bar{u}\,d\,|n(p_n)\rangle \approx g_S(0)\,\bar{u}_p(p_p)\,u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ ,$$

$$\langle p(p_p)|\,\bar{u}\,\gamma_5\,d\,|n(p_n)\rangle \approx g_P(0)\,\bar{u}_p(p_p)\,\gamma_5\,u_n(p_n) + \mathcal{O}(q^2/M_N^2)\ ,$$

$$\langle p(p_p)|\,\bar{u}\,\sigma_{\mu\nu}\,d\,|n(p_n)\rangle \approx g_T(0)\,\bar{u}_p(p_p)\,\sigma_{\mu\nu}u_n(p_n) + \mathcal{O}(q/M_N)\ ,$$



How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

Symmetries are dictated by fundamental QCD-probe interactions

Physics of the nucleus dictates structure of the operators.

Fundamental physics dictates size of coupling constants.

↓

Probe-nucleus interaction

Going from quark to nucleon demands solving QCD at low-energies.

↓

Many body calculation of nuclear structure

Nuclear interaction from QCD?	Unified theory of nuclear reactions and structure?	Many body strongly interacting problem.

FROM THE QUARK TO THE NUCLEUS

Effective Lagrangians

Couplings:

$e.g., \frac{\mu}{2}\bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$

U(1): anapole, E/M dipole

$\bar{\chi}\chi\langle\Psi|\bar{q}q|\Psi\rangle$

$;\bar{\chi}\gamma_5\chi\langle\Psi|\bar{q}\gamma_5 q|\Psi\rangle$

Scalar, Pseudo-scalar

$\bar{\chi}\gamma_\mu\chi\langle\Psi|\bar{q}\gamma^\mu q|\Psi\rangle$

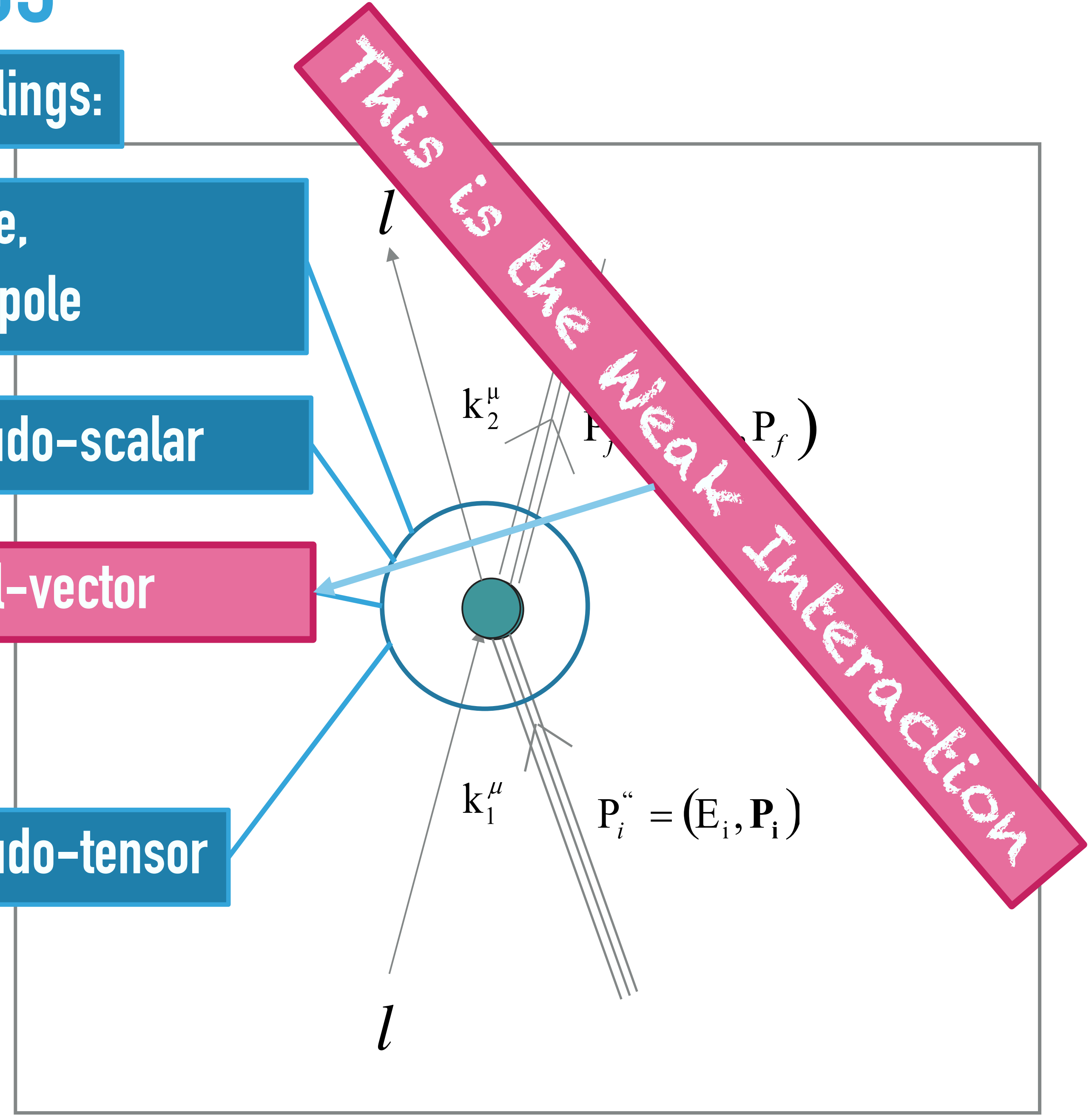
$\bar{\chi}\gamma_\mu\gamma_5\chi\langle\Psi|\bar{q}\gamma^\mu\gamma_5 q|\Psi\rangle$

Vector, Axial-vector

$\bar{\chi}\sigma_{\mu\nu}\chi\langle\Psi|\bar{q}\sigma^{\mu\nu}q|\Psi\rangle$

$\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\langle\Psi|\bar{q}\sigma^{\mu\nu}q|\Psi\rangle$

Tensor, Pseudo-tensor

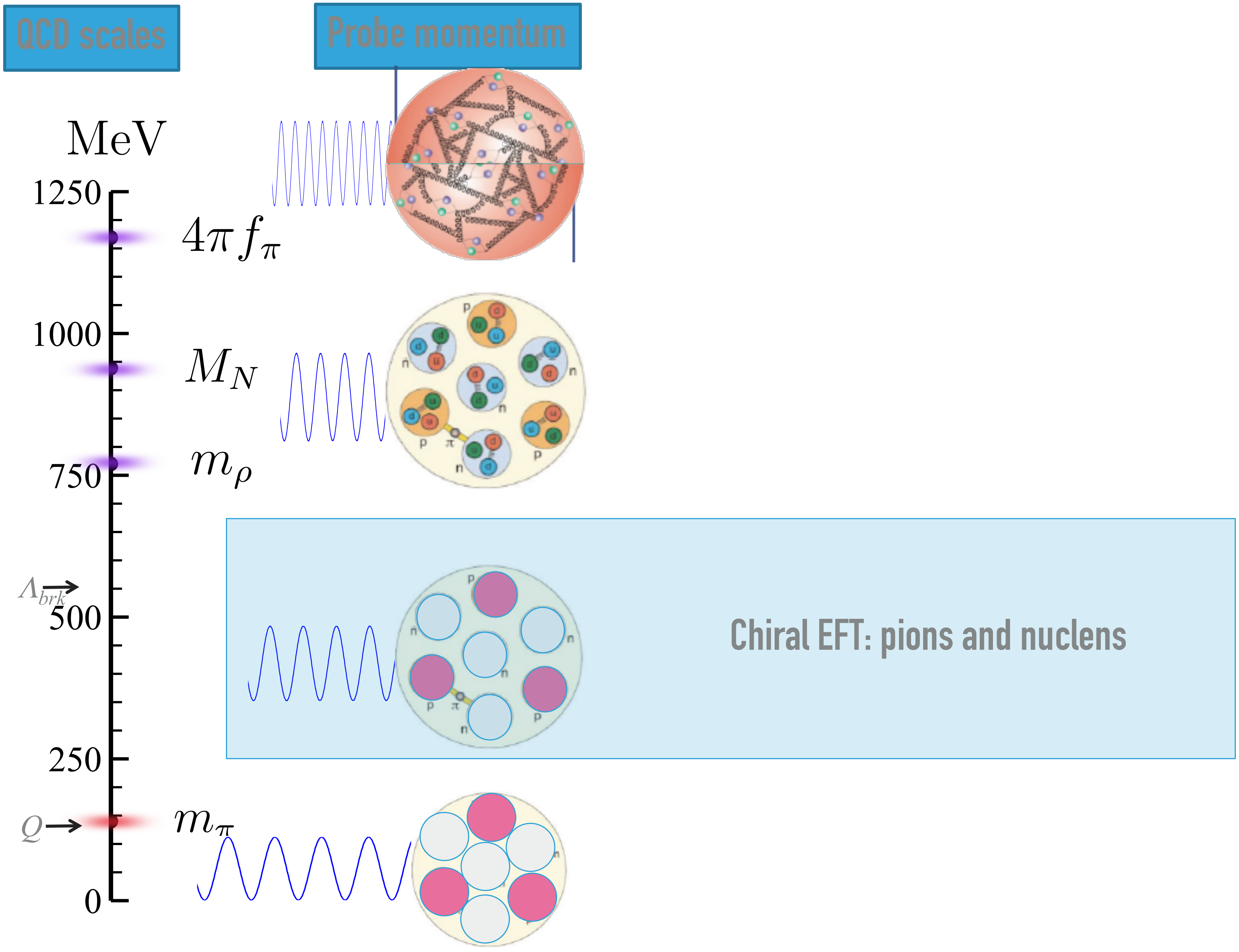


Probe "current" of known Lorentz symmetry

Nuclear "current" of the same symmetry

Decoupled from probe physics!

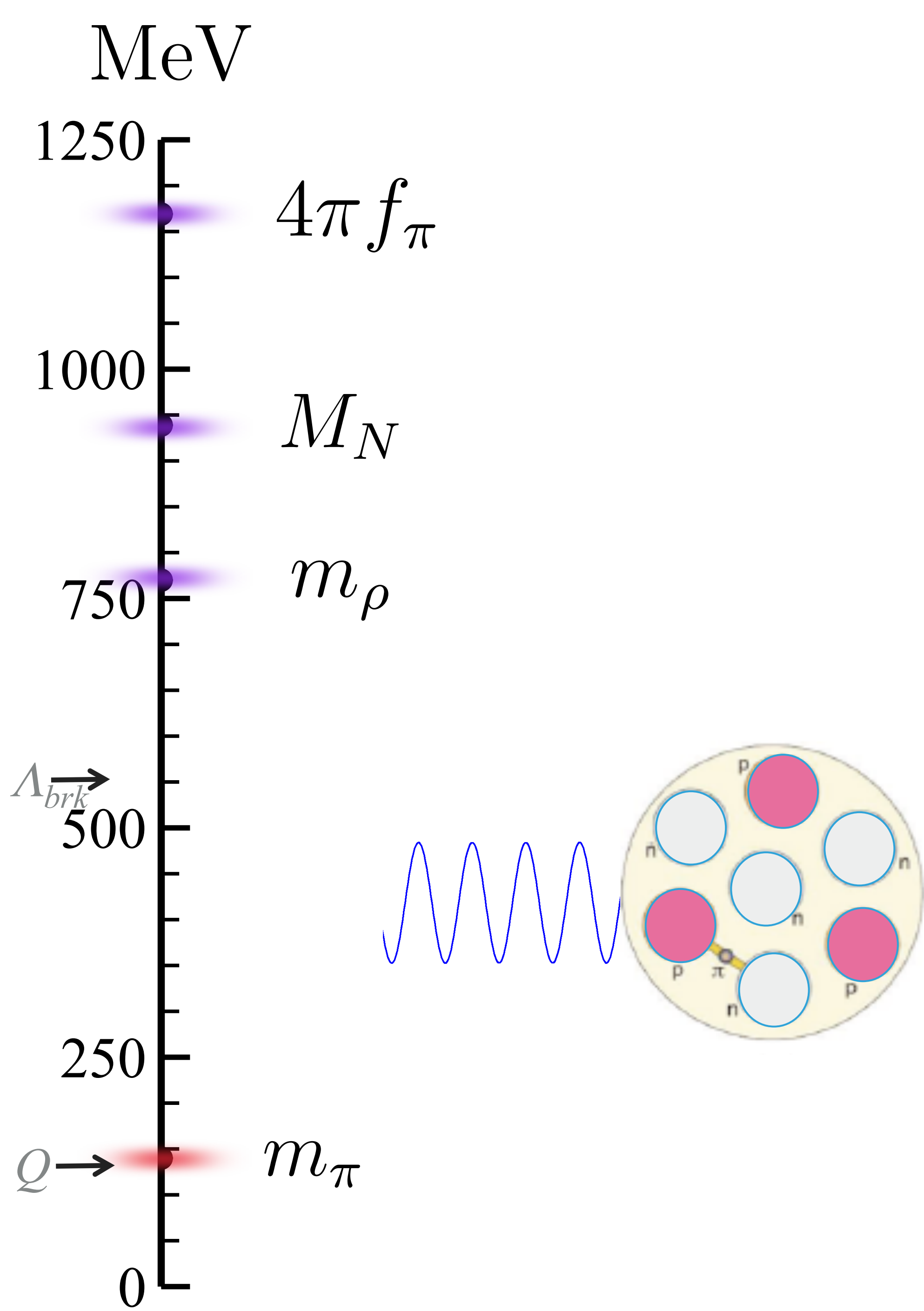
EFFECTIVE FIELD THEORIES OF QCD AT LOW ENERGIES



EFFECTIVE FIELD THEORIES OF QCD AT LOW ENERGIES

QCD scales

Probe momentum



EFT procedure for a specific phenomenon

characteristic momentum Q →
momentum scale in the nucleus
momentum scale of the probe

Λ_{bre}>>*Q* – a high momentum cutoff:
Identify viable d.o.f
Write most general Lagrangian consistent with fund. symmetries.

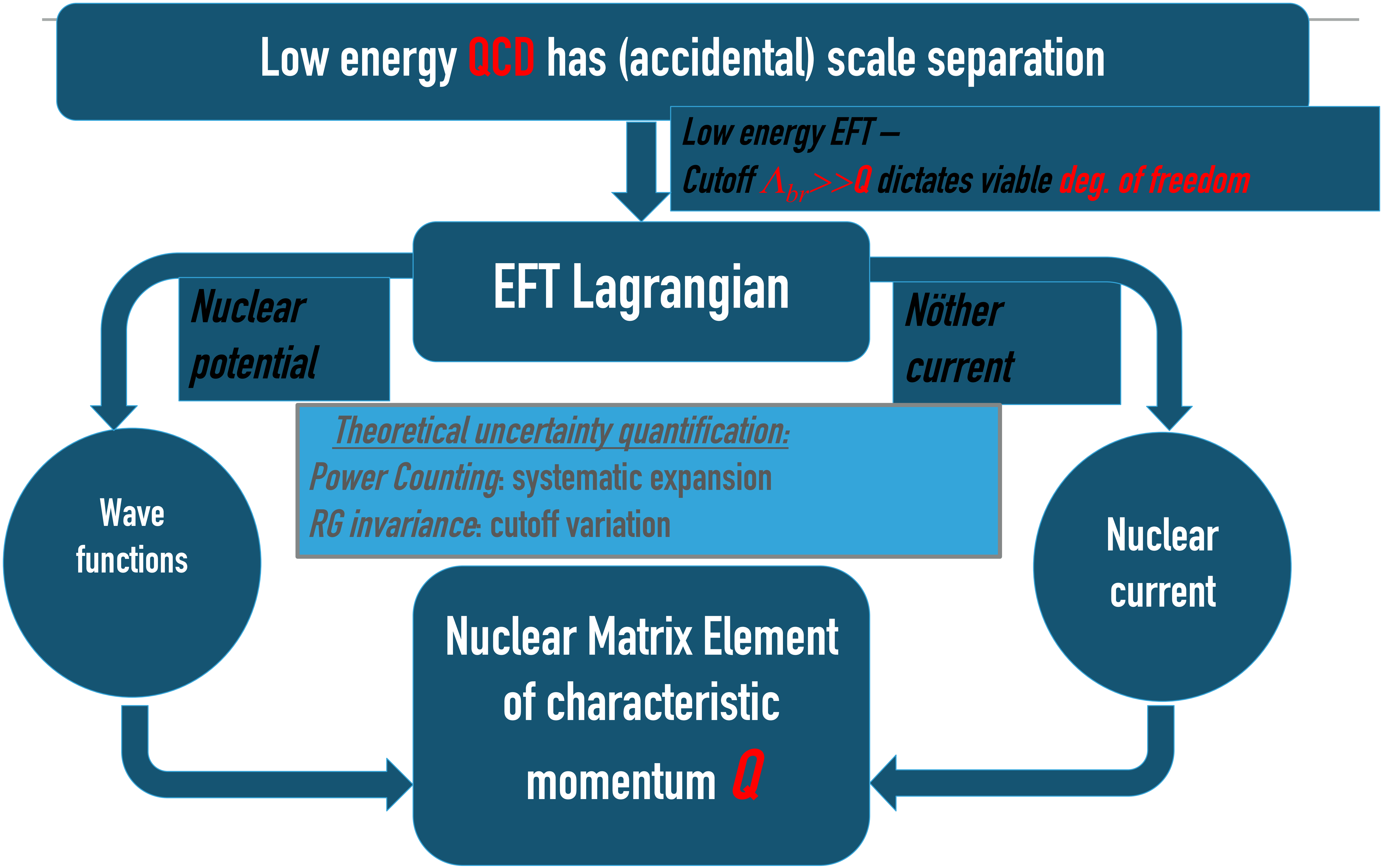
Power counting: Find a systematic way to organize diagrams according to their contribution to the observable.

Weinberg's Power Counting: Each Feynman diagram can be characterized by: $\left(Q/\Lambda\right)^{\nu}$

QCD is strongly interacting – things are not that simple.

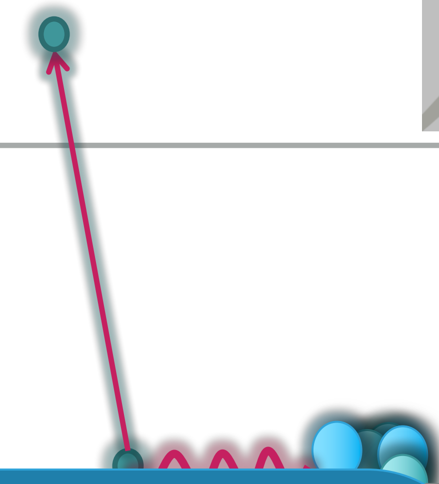
Error assessment: order by order *OR* cutoff variation.

NUCLEUS INTERACTION WITH A PROBE, EFT POINT OF VIEW:



NUCLEAR CURRENTS FROM CHIRAL EFT

Couplings:	Nuclear currents
U(1): anapole, E/M dipole	J_μ^{EM}
Scalar, Pseudo-scalar	$\pi N\ \sigma\ terms$
Vector, Axial-vector	$The\ weak\ gauge!$
Tensor, Pseudo-tensor	$lattice$



How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

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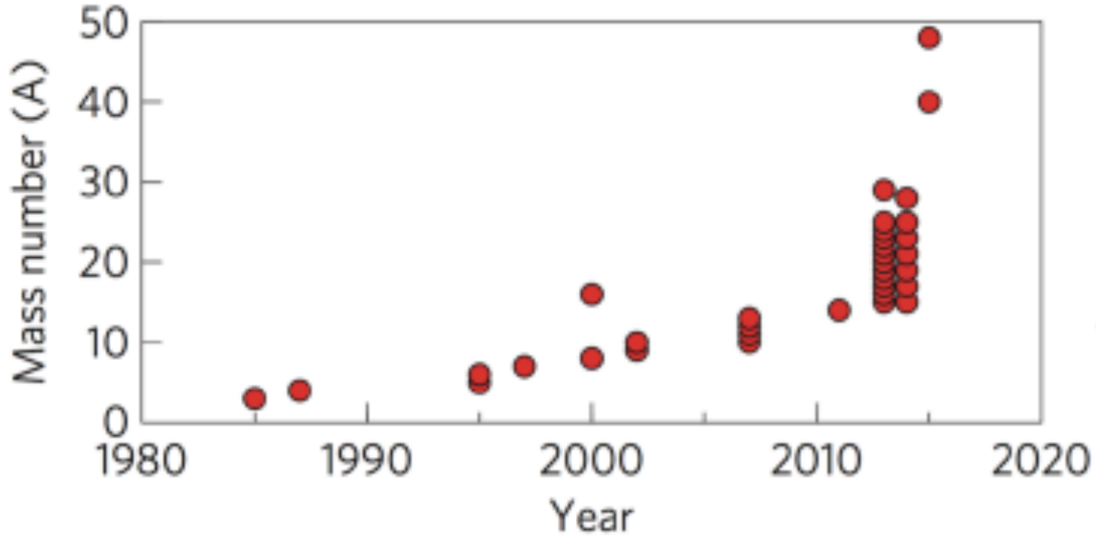
Many body calculation of nuclear structure

Nuclear interaction from QCD?	Unified theory of nuclear reactions and structure?	Many body strongly interacting problem.

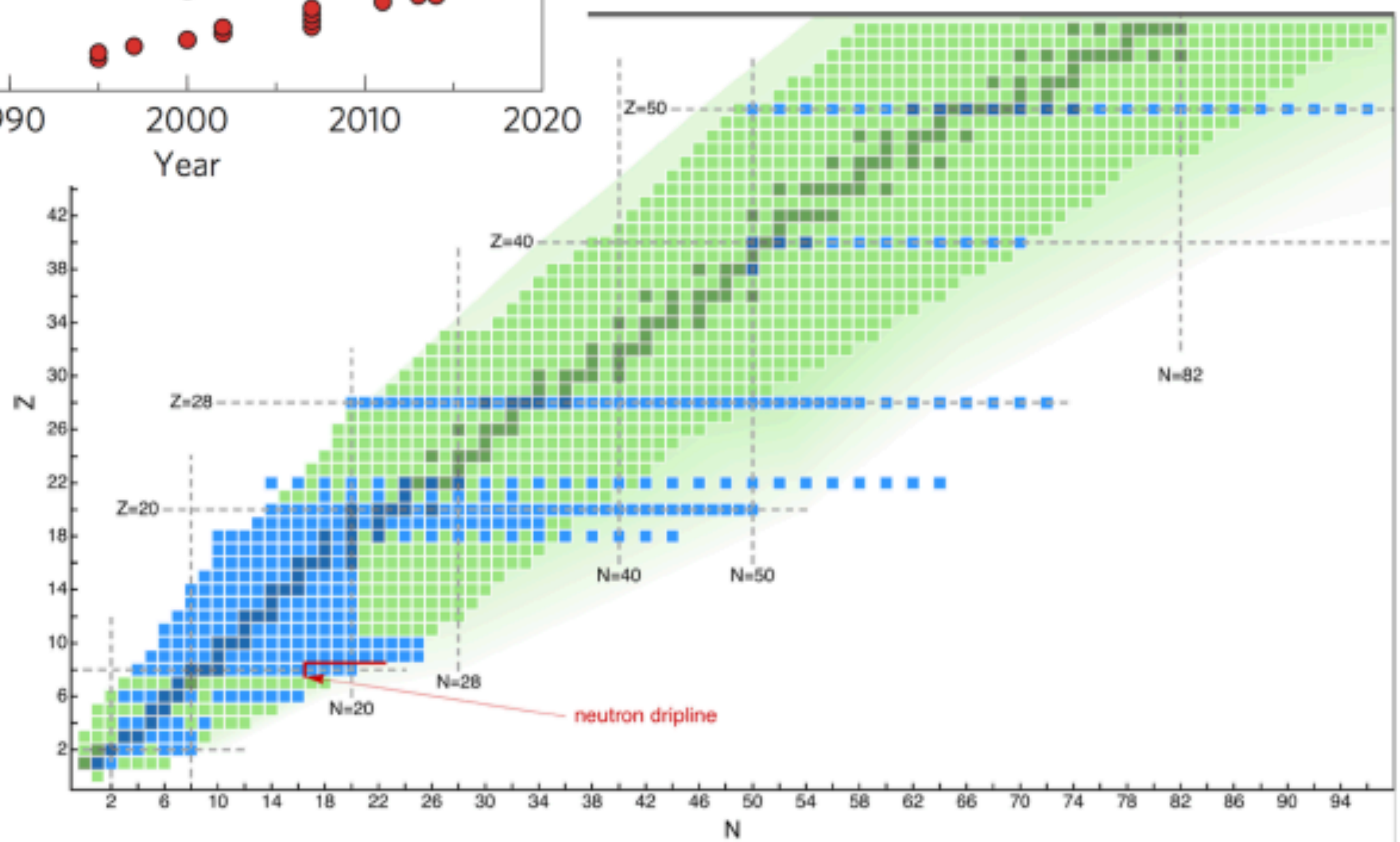
Progress in ab initio calculations of nuclei

dramatic progress in last 5 years to access nuclei up to A ~ 50



from Hagen et al., Nature Phys. (2016)

from Hergert et al., Phys. Rep. (2016)



From Achim Schwenk

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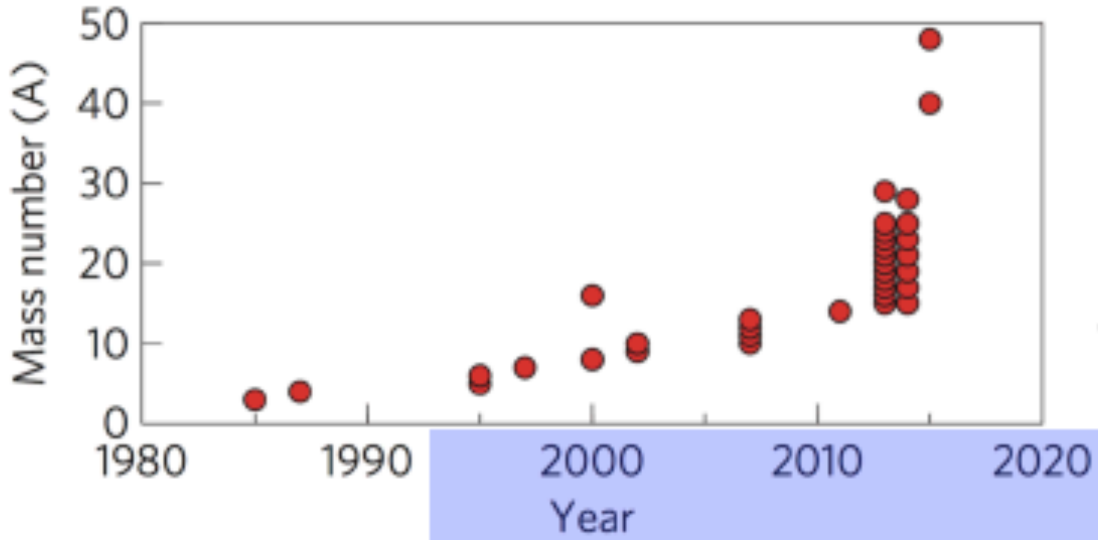

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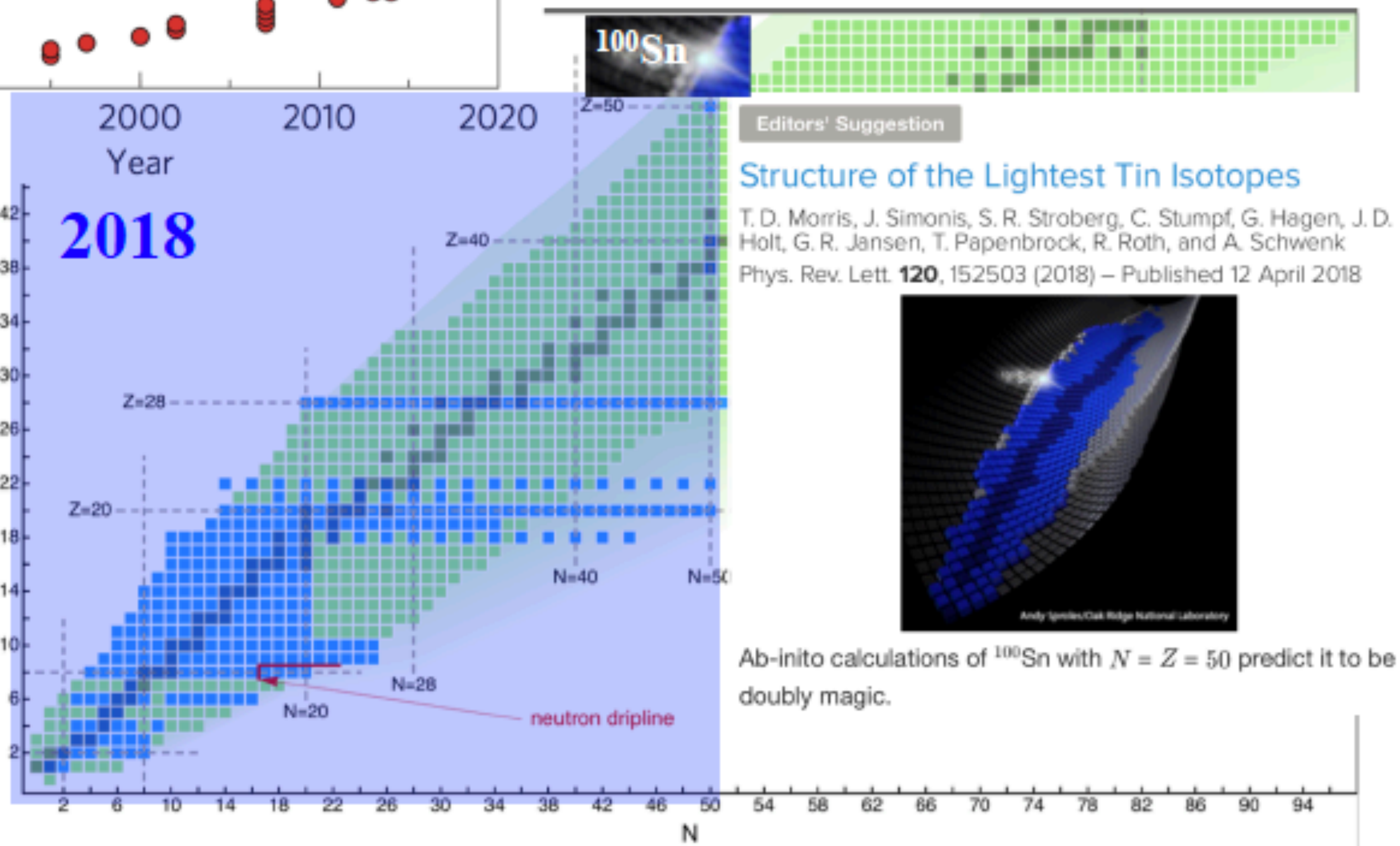


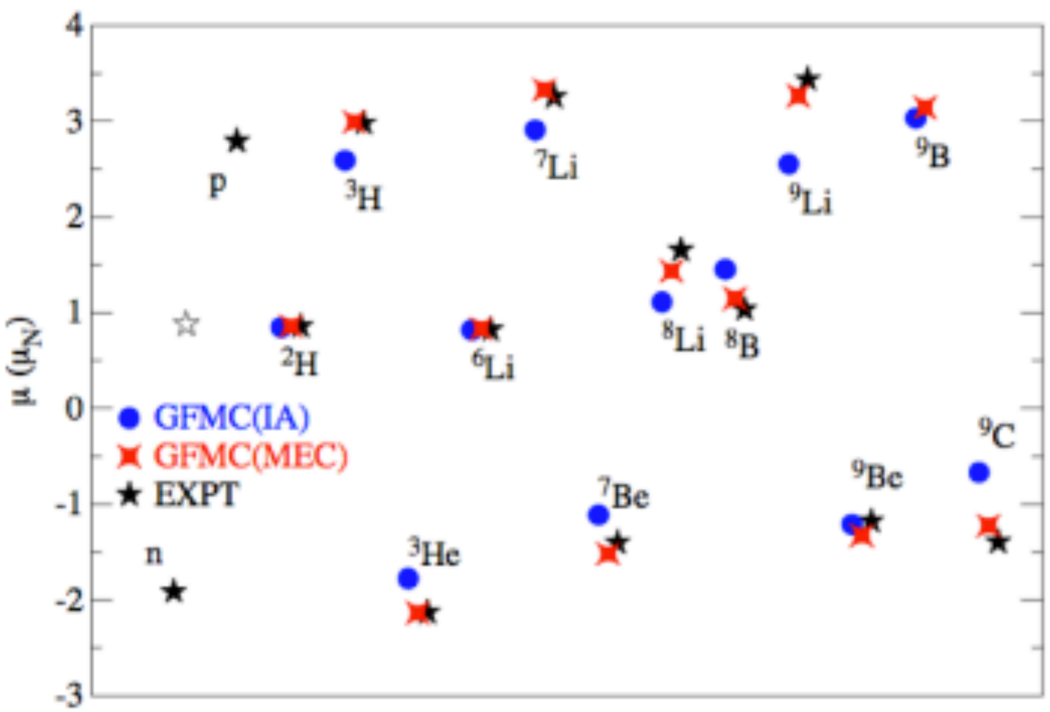
From Achim Schwenk

Frontier: Chiral EFT for electroweak currents

consistent electroweak one- and two-body (meson-exchange) currents

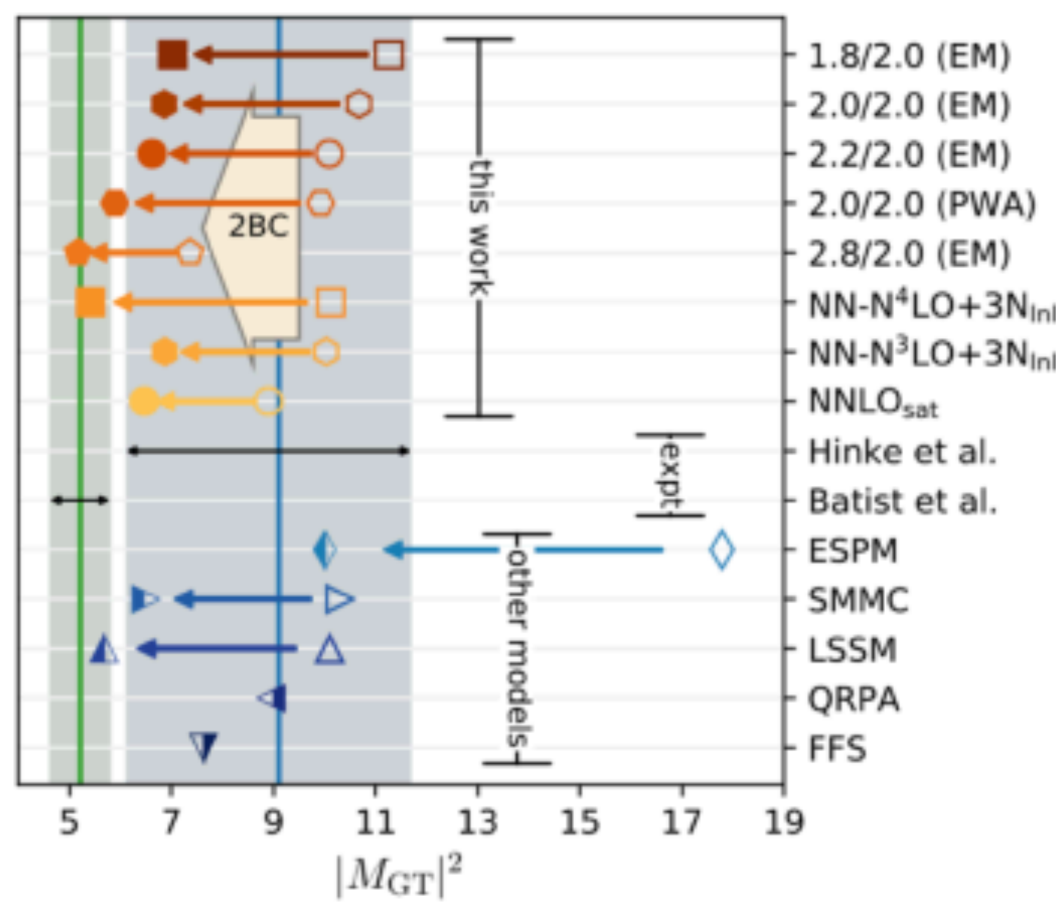
magnetic moments in light nuclei

Pastore et al. (2012-)



Gamow-Teller beta decay of ^{100}Sn

Gysbers, Hagen et al.

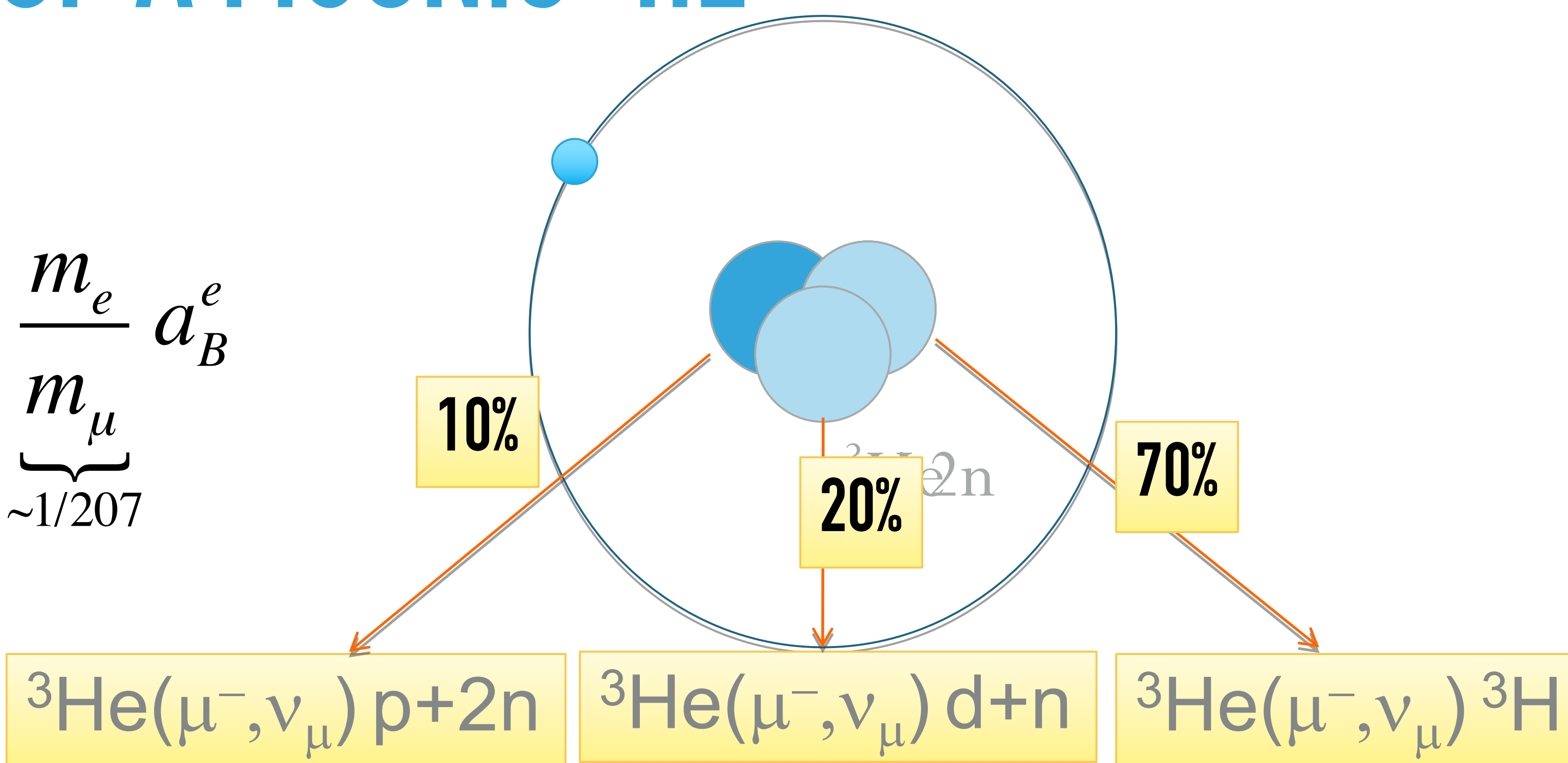


two-body currents are key for quenching puzzle of beta decays

From Achim Schwenk

THE DECAY OF A MUONIC ^{3}HE

$$a_B^{\mu} = \frac{\hbar}{Z m_{\mu} c \alpha} = \underbrace{\frac{m_e}{m_{\mu}}}_{\sim 1/207} a_B^{e}$$



$$Capture\ \ prob. \sim Z \cdot \left|\psi_{1S}(0)\right|^2 \sim \left(\frac{m_{\mu}}{m_e}\right)^3 Z^4$$

- In order to probe the weak structure of the nucleon, one has to keep the nuclear effects under control.

RESULTS

$$\Gamma = \left\{ \frac{2G^2 |V_{ud}|^2 E_\nu^2}{2J_{^3\mathrm{He}}+1} \left(1 - \frac{E_\nu}{M_{^3\mathrm{H}}}\right) |\psi_{1s}^{av}|^2 \Gamma_N \right\} (1+RC)$$

$$\Gamma = 1499(2)_\Lambda (3)_{NM} (5)_t (6)_{RC} = 1499 \pm 16 \ \text{Hz}$$

$$\Gamma_{EXP} = 1496 \pm 4 \, \text{Hz}$$

DG, Phys. Lett. **B666**, 472 (2008),

INDUCED TENSOR:

- From QCD sum rules: $$\frac{g_t}{g_A} = -0.0152(53)$$
- Experimentally [Wilkinson, Nucl. Instr. Phys. Res. A 455, 656 (2000)]:

$$\left|\frac{g_t}{g_A}\right| < 0.36 \ \text{ at } \ 90\%$$

- This work: $$\frac{g_t}{g_A} = -0.1(0.68)$$

$$\delta J^{\mu A} = \frac{i g_t}{2M_N} \sigma^{\mu\nu} \gamma_5 q_\nu$$

INDUCED SCALAR (LIMITS CVC):

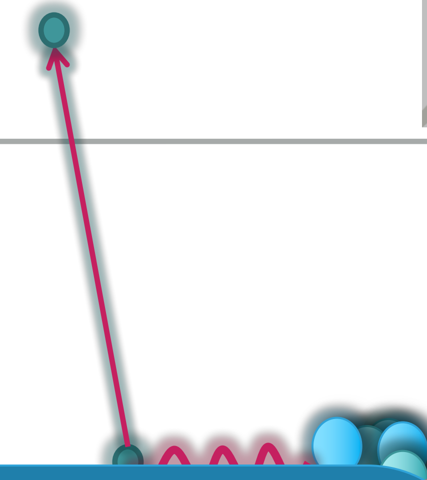
- Experimentally [Severijns et. al., RMP 78, 991 (2006)]:

$$g_S = 0.01 \pm 0.27$$

- This work:

$$g_S = -0.005 \pm 0.04$$

$$\delta J^{\mu V} = \frac{g_S}{m_\mu} q^\mu$$



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Many body methods can reach 2% absolute accuracy for light nuclei, 10% accuracy for heavy nuclei ratios are known much better because of the small expansion parameter.

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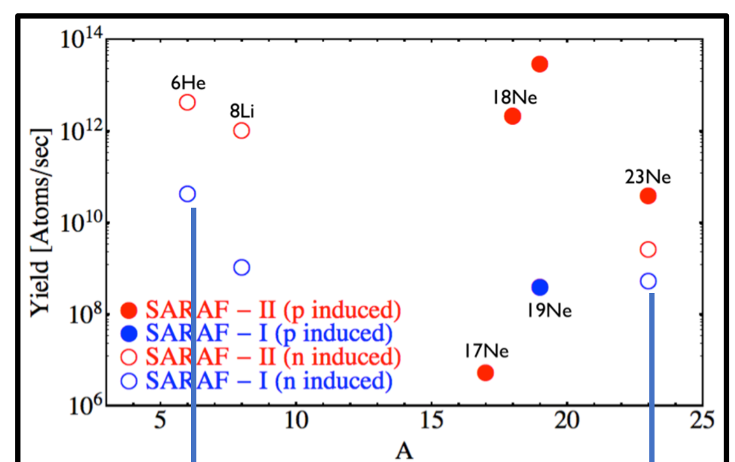
DOI 10.1140/epja/i2018-12526-2

THE EUROPEAN
PHYSICAL JOURNAL A

Review

The Soreq Applied Research Accelerator Facility (SARAF): Overview, research programs and future plans

ON-GOING EXPERIMENTS IN SARAF



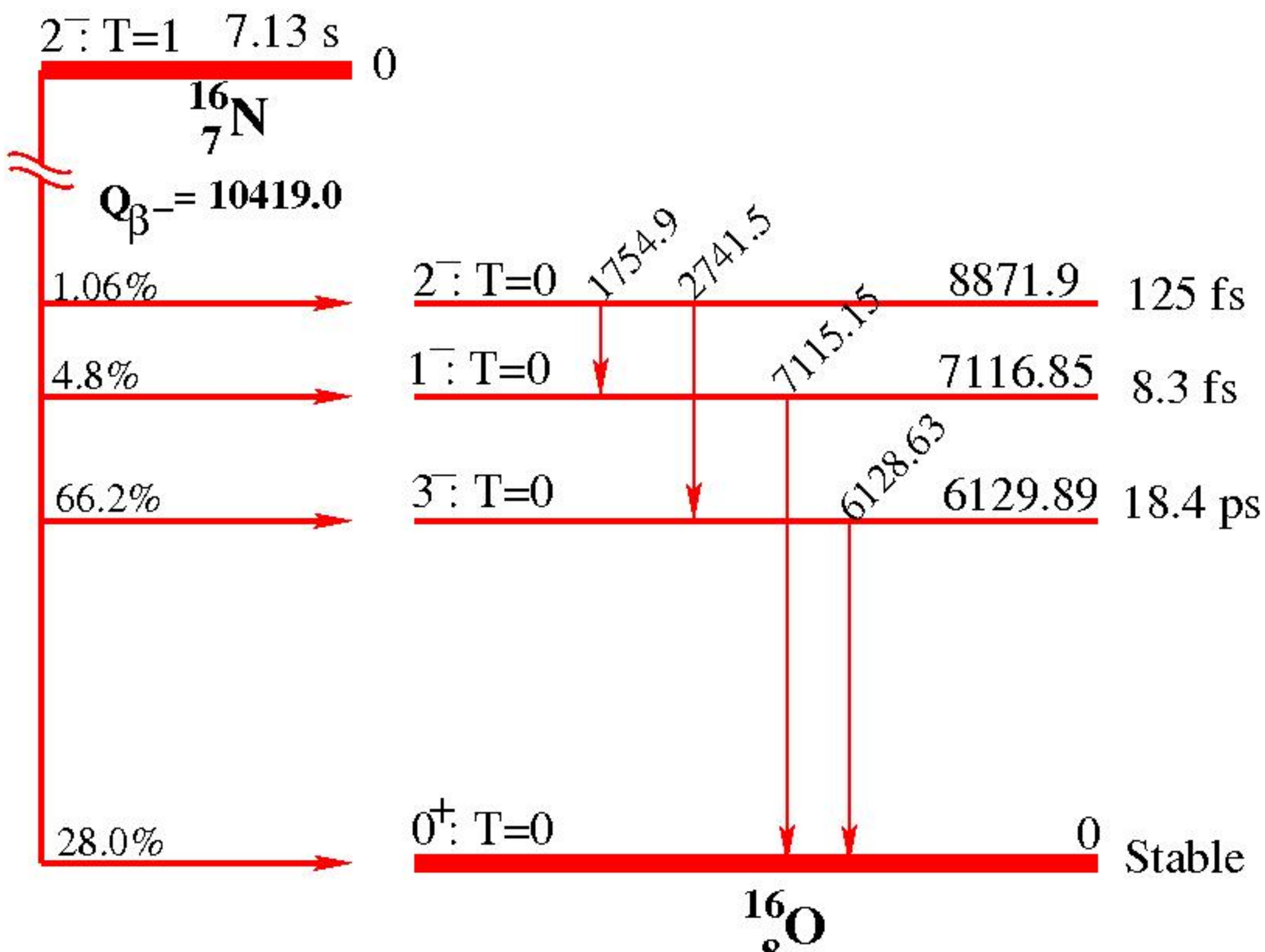
^{6}**He**:

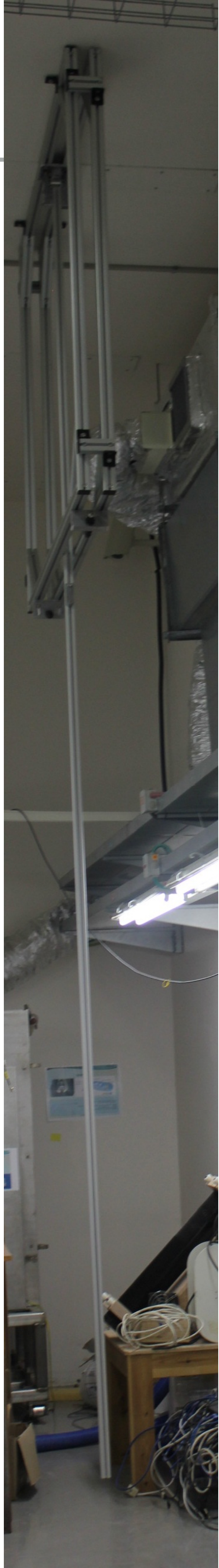
Production
Trap in **EIBT**
and measure
kinematics.

^{23}**Ne**:

Production
Branching-Ratio
Trap in **MOT** and
measure
kinematics

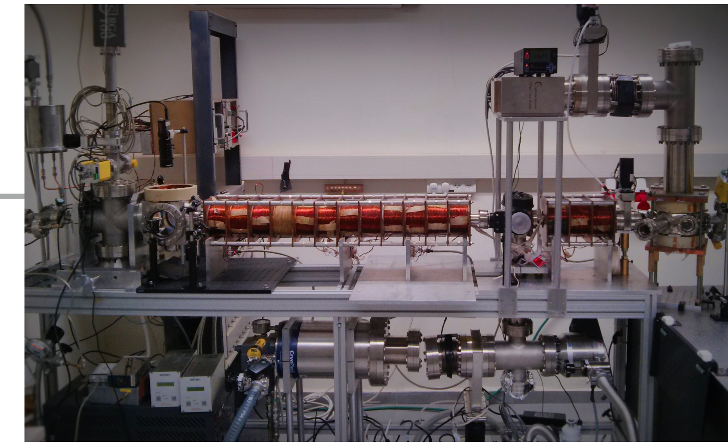
$^{16}N \rightarrow {}^{16}O$ – NUCLEAR PHYSICS TEST CASE





1. Different $\beta-\nu$ correlation properties for GT and unique 1st forbidden – ***BSM test***

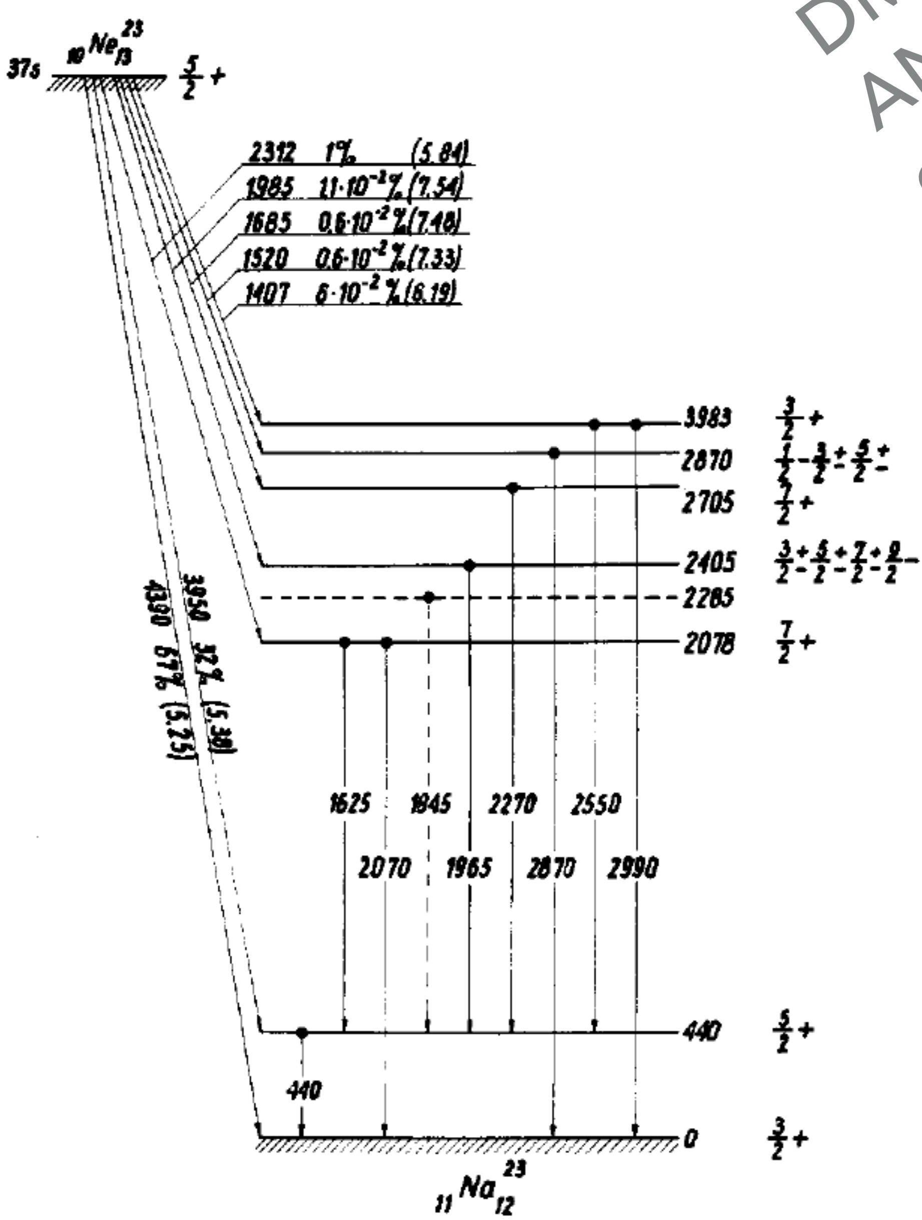
2. Unique 1st forbidden spectrum – ***BSM test***



NEON ISOTOPES

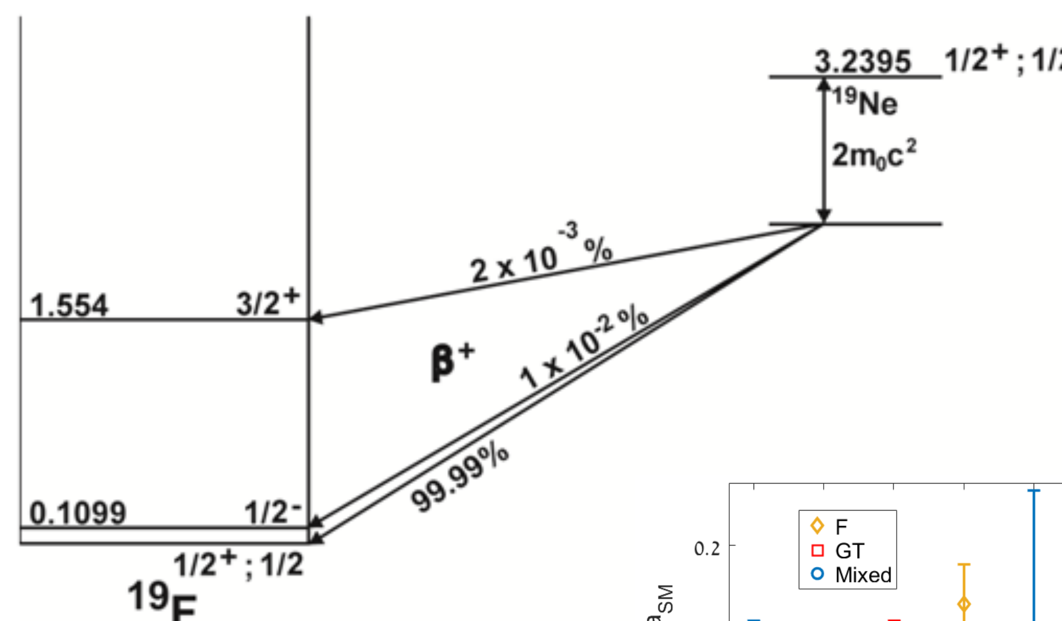
^{23}Ne Decay to ^{23}Na

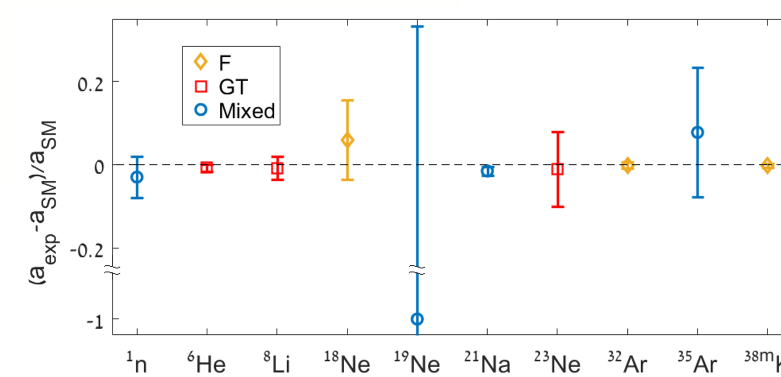
DAMA, DM-ice, ANAIS experiments



^{19}Ne Decay to ^{19}F

PICASSO, SIMPLE, COUPP experiments





SUMMARY

- Nuclear beta decays are an important front for “new physics” discoveries.
- New experiments will have 0.01-0.1% level precision.
- Important shape (and radiative) corrections that should be calculated, these are challenging calculations, but seem feasible:
  - Worse case: we have great tests for the nuclear interactions.
  - Best case: experimentalists are satisfied with theory
- An ongoing effort of the nuclear theory community:
  ECT* workshop:
  “Precise beta decay calculations for searches for new physics”, April 8-12, 2019.

Spectrum $\beta - \nu$ correlations