

Recent Advances in Precise Forbidden β -decays for BSM Searches

Ayala Glick-Magid

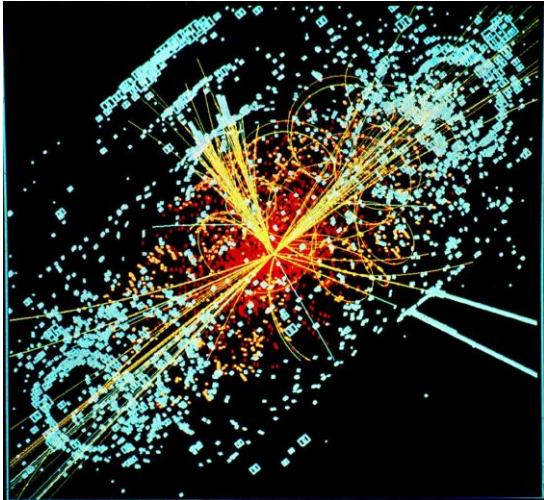


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NUCLEAR THEORY

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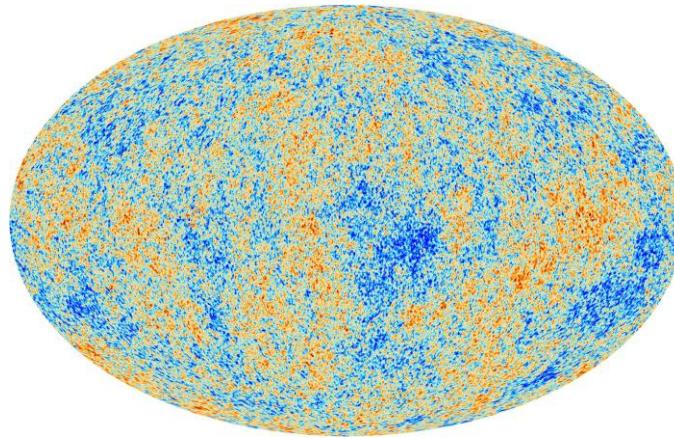
Searches for BSM physics

High energy frontier



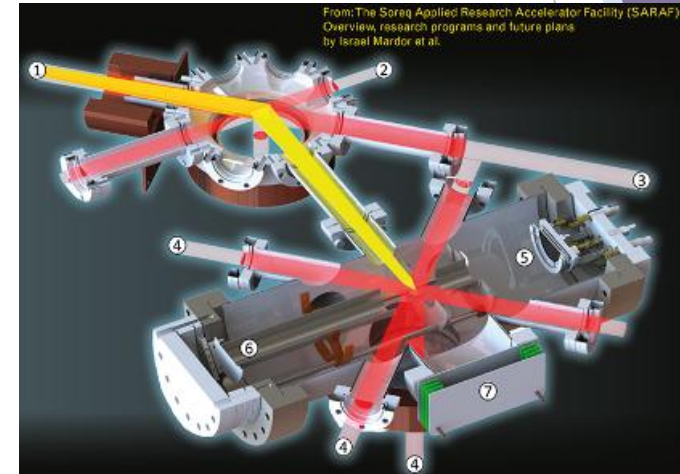
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Astronomical frontier



https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB
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Precision frontier



Mardor et al., [Eur. Phys. J. A 54, 91](#) (2018)

LHC
TeV scale

Nuclear phenomena
 10^{-3} precision level

Cost-effective alternative for discovering New Physics

Requires precision theory – two challenges:

- ***Nuclear-structure many-body problem***
- ***High-order quantum effects***

new experiments

Introduction: BSM Searches & Forbidden β -decays

Nuclear-structure many-body problem

High-order quantum effects

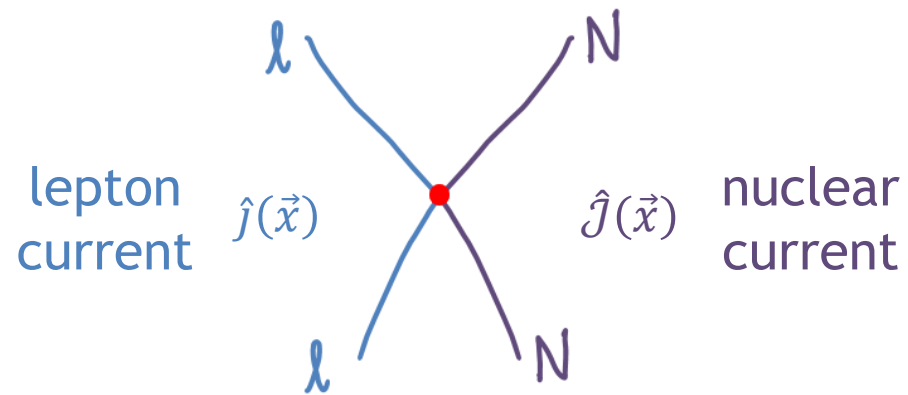
=> ***Forbidden***

Summary

Bonus: allowed

Weak interaction

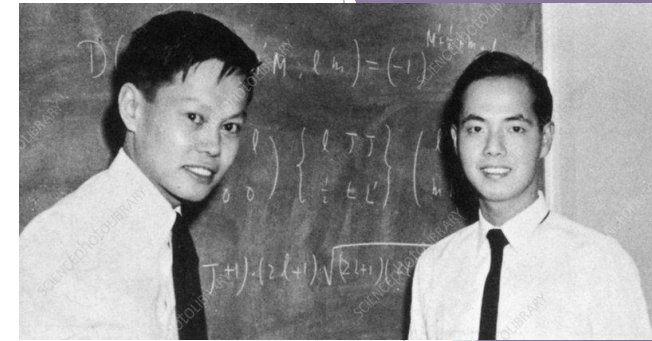
Low energy reaction of
leptons with nucleons



$$\hat{\mathcal{H}}_W \sim C \hat{j}(\vec{x}) \cdot \hat{J}(\vec{x})$$

A-priori: {

- Scalar (C_S)
- PseudoScalar (C_P)
- Vector (C_V)**
- Axial vector (C_A)**
- Tensor (C_T)



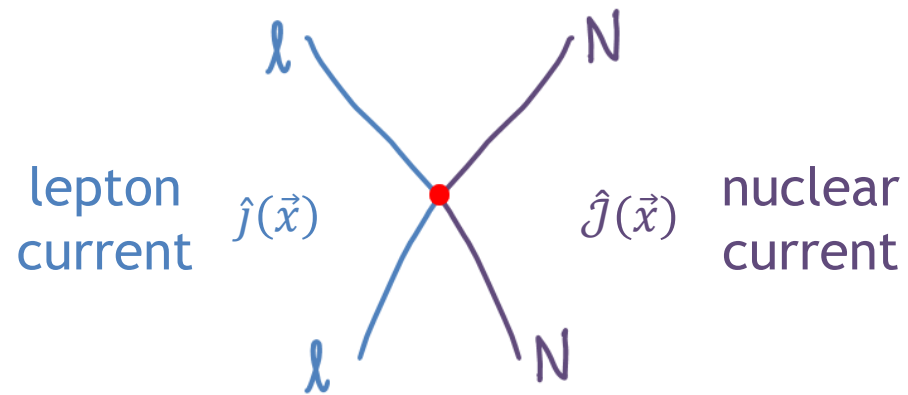
Theory: C.N. Yang and T.D. Lee (Nobel 1957)



Experiment: C.S. Wu:
Parity violation in *nuclear* β -decays
 $\Rightarrow$ Weak SM structure: "**V** - **A**"

Weak interaction

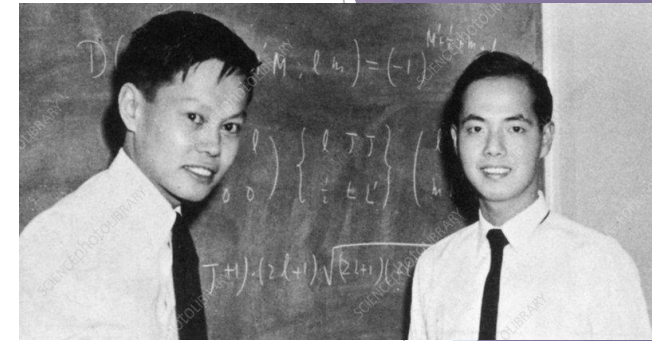
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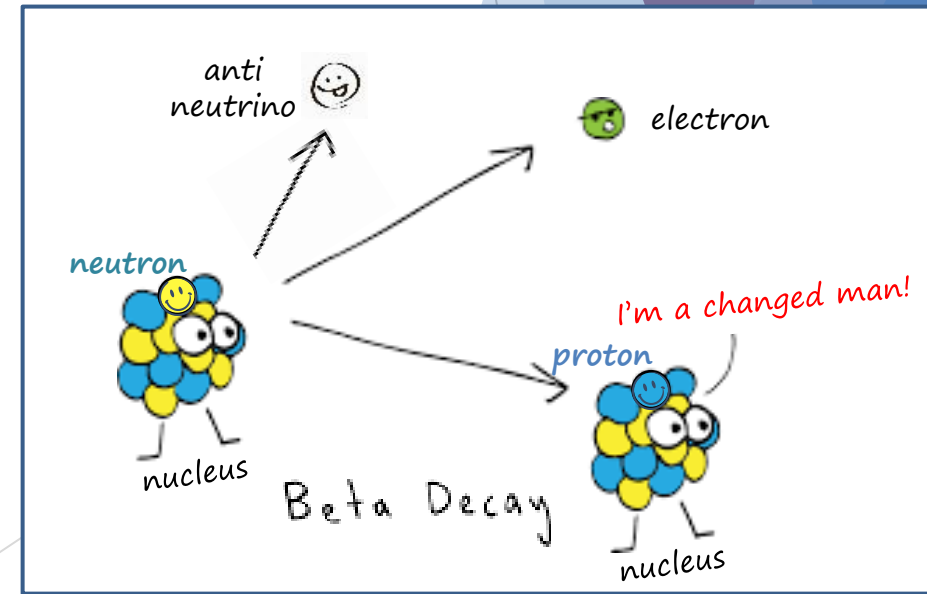
The SM is incomplete

$\gg$ Ongoing searches for C_S, C_P, C_T
in precision *nuclear β -decay* experiments

Nuclear β -decay

Low momentum transfer: $q \sim 0 - 10 \text{ MeV}/c$

Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/8d978444f15f9bbc3bcadb0549816bc7e264b977.svg



Nuclear β -decay

Low momentum transfer: $q \sim 0 - 10 \text{ MeV}/c$

angular
momentum parity

Transitions $J^{\Delta\pi}$:

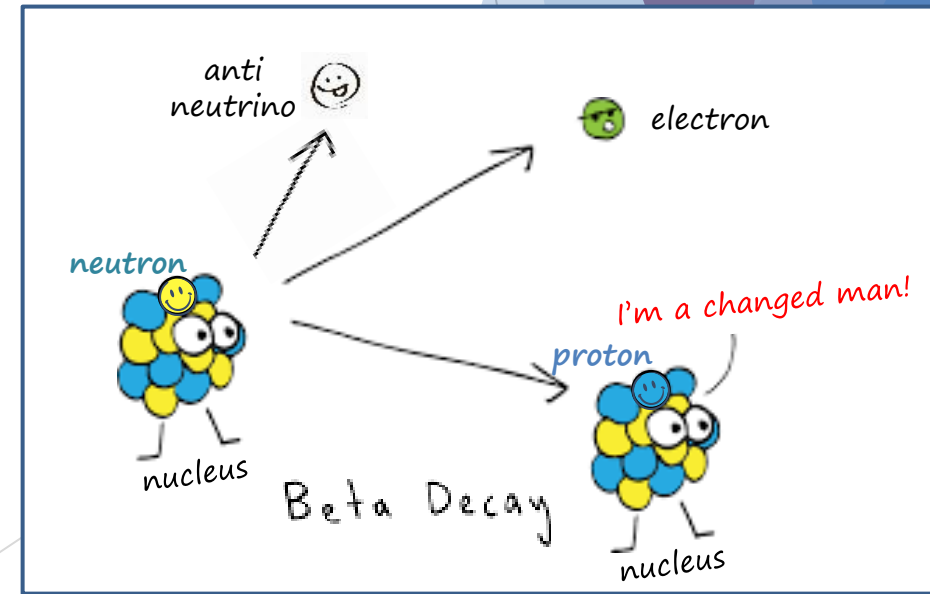
“Allowed”
(when $q \rightarrow 0$)

- 0^+ : Fermi
- 1^+ : Gamow-Teller

“Forbidden”
(vanish for $q \rightarrow 0$)

- All the rest ($J^{\Delta\pi}$)

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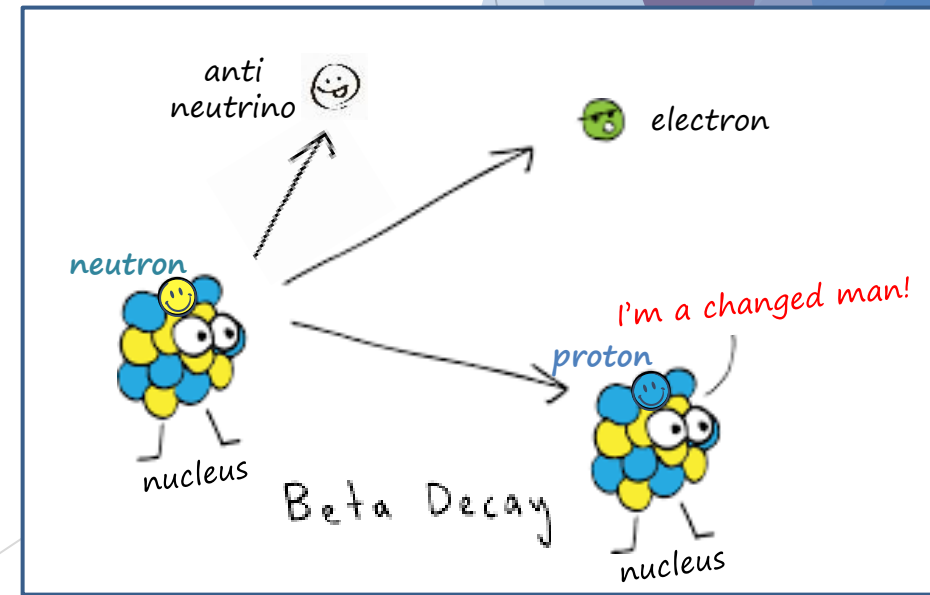


Nuclear β -decay

- Allowed β -decay rate:

$$d\Gamma \propto |\langle \psi_f | \hat{H}_W | \psi_i \rangle|^2 \propto 1 + \overset{\text{Observables}}{a_{\beta\nu}} \vec{\beta} \cdot \hat{\nu} + \overset{\text{Observables}}{b_F} \frac{m_e}{E}$$

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Nuclear β -decay

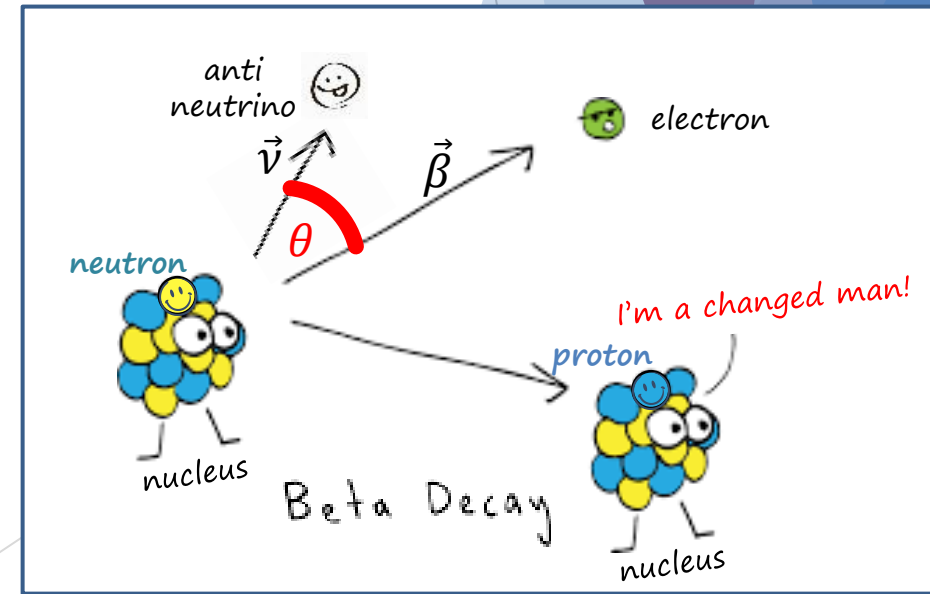
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Measurements (e.g., Gamow-Teller):

1) Angular correlation: $a_{\beta\nu} = -\frac{1}{3} \left(1 - \frac{\overset{\text{BSM}}{|C_T^+|^2 + |C_T^-|^2}}{4|C_A|^2} \right)$

Beta decay, Khan Academy, cdn.kastatic.org/ka-perseus-images/8d978444f15f9bbc3bcadb0549816bc7e264b977.svg



$C_A = 1.27$ Axial vector coupling constant (SM)

$C_T^+ (C_T^-) \lesssim 10^{-3}$ Tensor left (right) coupling constants (BSM), unknown

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- electron's
mass,
energy

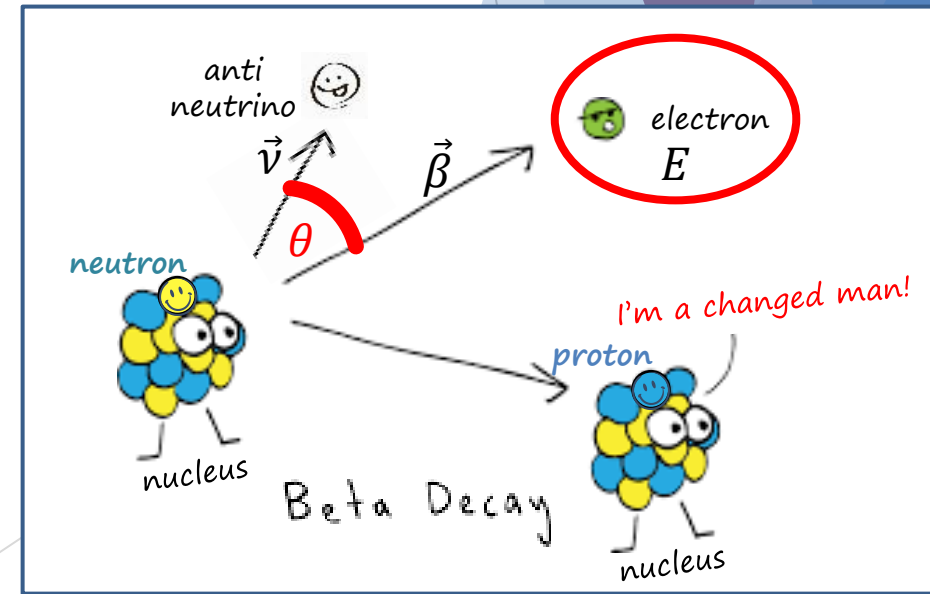
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2) Energy spectrum: Fierz term $b_F^{\beta^\mp} = 0 \overset{\text{BSM}}{\pm} \frac{C_T^+}{C_A}$

- Linear in C_T^+

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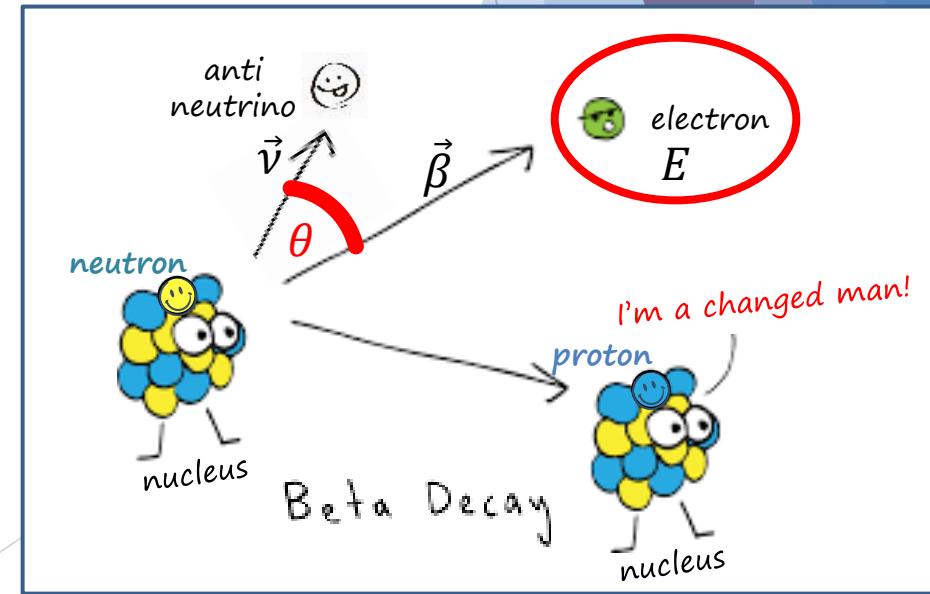
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► Sensitive to right-handed neutrinos C_T^-

2) **Energy spectrum:** Fierz term $b_F^{\beta\mp} = 0 \pm \frac{\overset{\text{BSM}}{C_T^+}}{C_A}$ SM

► Linear in C_T^+

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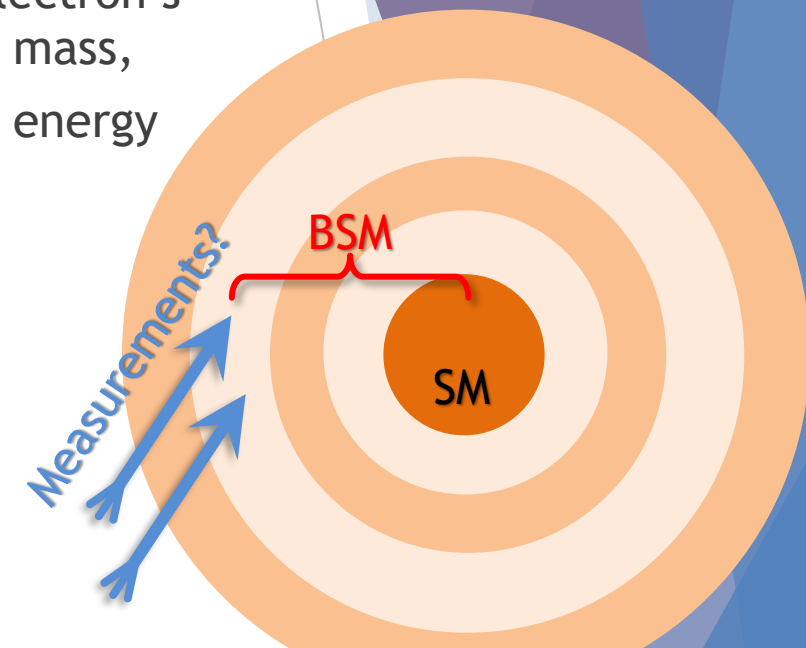
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- Linear in C_T^+



Bonus slides:
Alejandro Garcia (He6-CRES)

Searches for deviations from the SM “V-A” structure

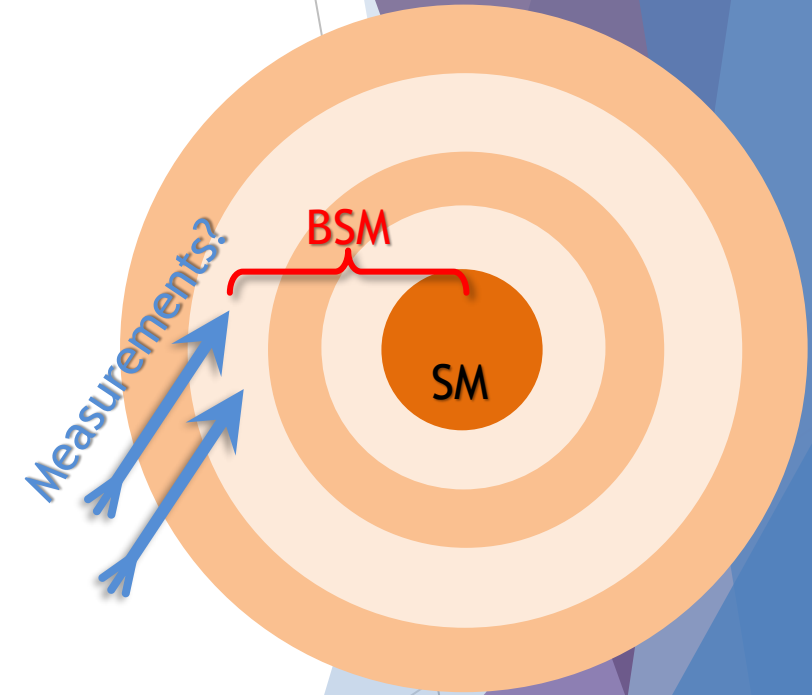
ϵ_T
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Unique 1st-forbidden decays

$$d\Gamma \propto |\langle \psi_f | \hat{H}_W | \psi_i \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$

BSM Predictions & Observables
for **forbidden decays**
for the first time



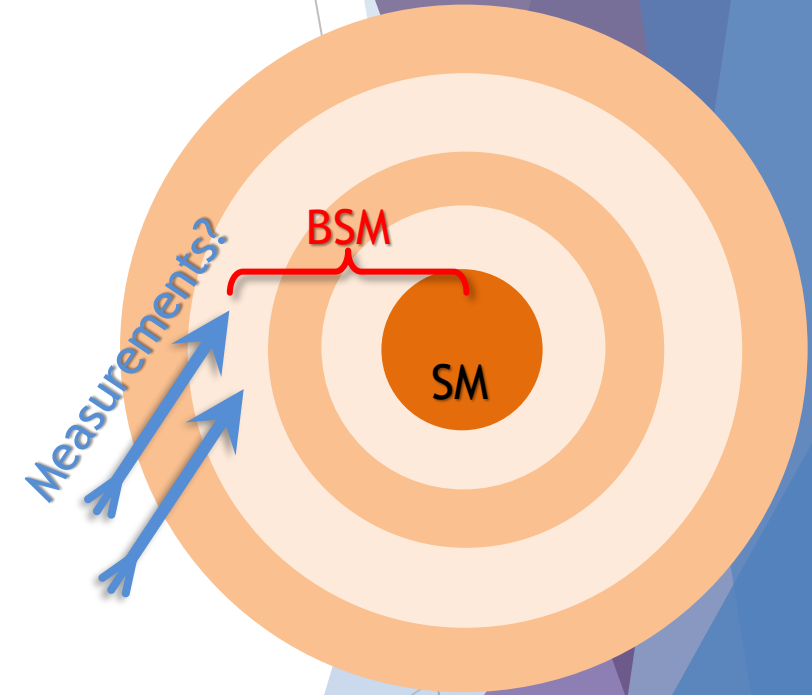
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The β -energy spectrum is sensitive to both $a_{\beta\nu}$ & b_F

- ▶ **Linear** in the BSM signature (b_F)
- ▶ Still sensitive to **right-handed** coupling ($a_{\beta\nu}$)

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BSM Predictions & Observables for **forbidden decays** for the first time

Unique 1st-forbidden decays

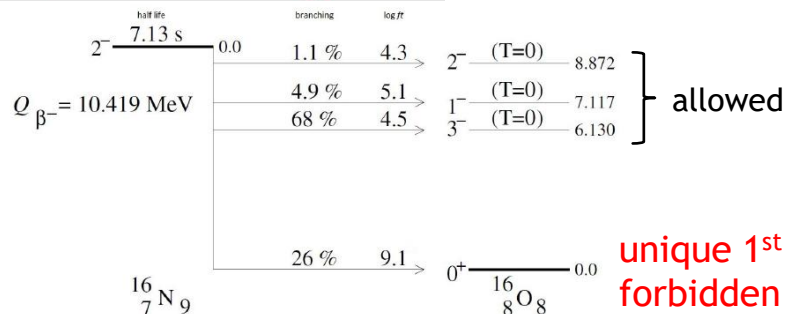
$$d\Gamma \propto |\langle \psi_f || \hat{H}_W || \psi_i \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$

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- **Linear** in the BSM signature (b_F)
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Ongoing Experiments



^{16}N : Large energy separation between forbidden and allowed branches

[Ohayon, Chocron, Hirsh, AGM, et al., Hyp.Int.2018](#)

[AGM et al, PLB 2017](#)

[AGM & Gazit, PRD 2023](#)

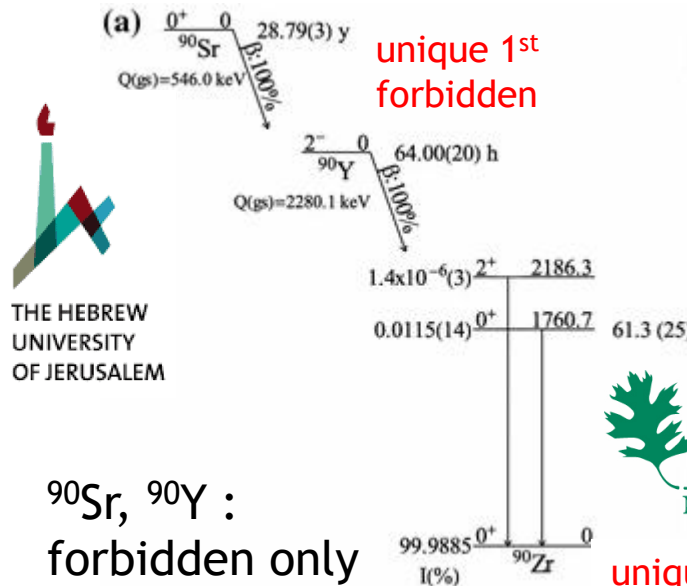
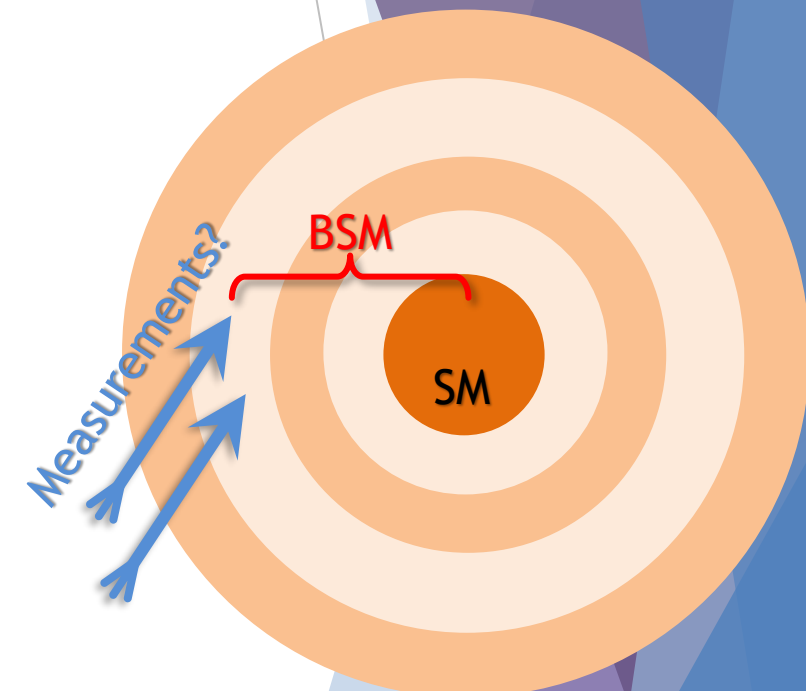


Fig.: Morozov et al. J.Rad.Nuc.Chem.2010



Unique 1st-forbidden decays

$$d\Gamma \propto |\langle \psi_f || \hat{H}_W || \psi_i \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$

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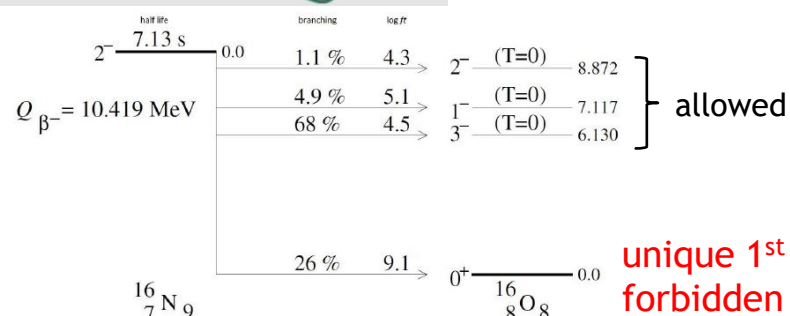
- **Linear** in the BSM signature (b_F)
- Still sensitive to **right-handed** coupling ($a_{\beta\nu}$)

⇒ Development of **MTAS @ ORNL**
Modular Total Absorption Spectrometer
to distinguish between decay transitions

BSM Predictions & Observables
for **forbidden decays**
for the first time



Ongoing Experiments



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⁹⁰Sr, ⁹⁰Y :
forbidden only

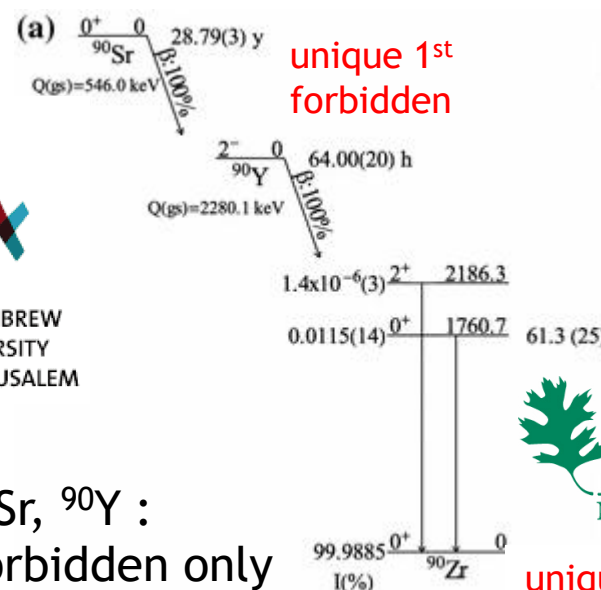


Fig.: [Morozov et al. J.Rad.Nuc.Chem.2010](#)

[Shuai, Rasco, et al., PRD 2022](#)

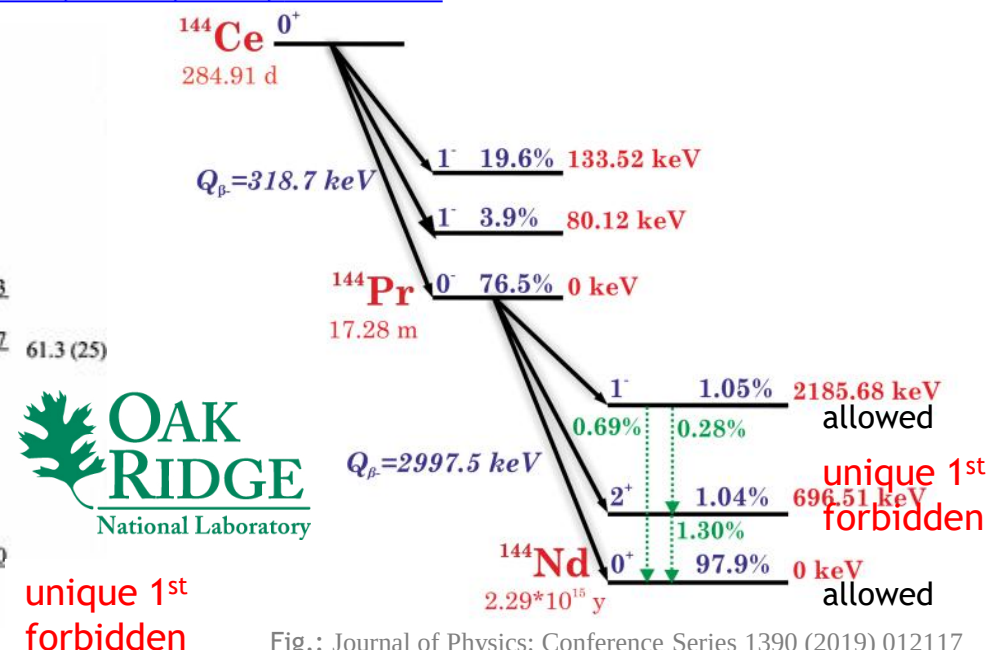


Fig.: [Journal of Physics: Conference Series 1390 \(2019\) 012117](#)

$$\hat{\mathcal{H}}_W \sim C_{\text{sym}} \hat{j}(\vec{x}) \cdot \hat{j}(\vec{x})$$

Lepton current
Nuclear current

Required accuracy

Nuclear charges
Nuclear currents:

$$C_{\text{sym}} \sim g_{\text{sym}} \epsilon_{\text{sym}}$$

$$\langle p | \bar{u} \sigma^{\mu\nu} d | n \rangle \approx g_T \bar{u}_p \sigma^{\mu\nu} u_n$$

Similar terms for the other sym

$$g_V = 1$$

Charge	Value
g_A	1.278(33)
g_T	0.987(55)
g_S	1.02(11)
g_P	349(9)

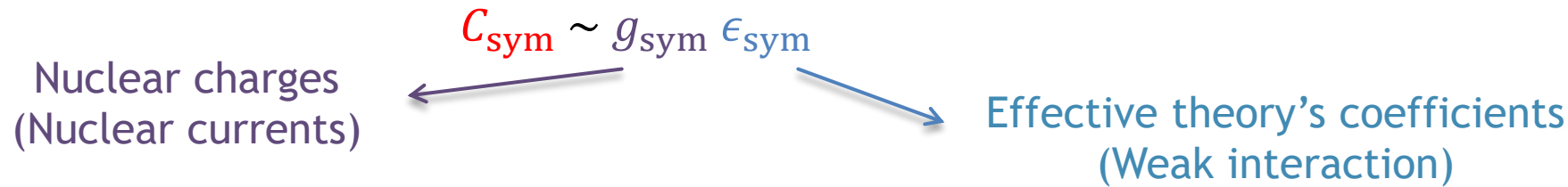
M. Gonzalez-Alonso *et al.*, PPNP 104 165-223 (2019)

> **Same nuclear charges for SM & BSM**

$$\hat{\mathcal{H}}_W \sim \mathcal{C}_{\text{sym}} \hat{j}(\vec{x}) \cdot \hat{j}(\vec{x})$$

$\swarrow$ $\searrow$
 Lepton Nuclear
 current current

Required accuracy



Low energy effective Lagrangian:

$$\mathcal{L}_{udev}^{\text{eff}} = \epsilon_T \bar{e} \sigma_{\mu\nu} \nu_e \cdot \bar{u} \sigma^{\mu\nu} d + \dots$$

$$M_W \approx 80 \text{ GeV}$$

$$\epsilon_{\text{sym}} \propto \left(\frac{M_W}{\Lambda} \right)^n$$

Similar terms for
the other *sym*

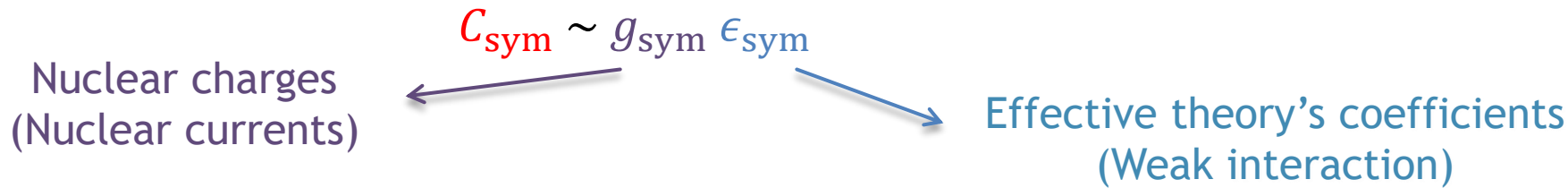
The effective theory's cutoff
↔ New physics scale

$$\begin{aligned}
 n &= 0 \text{ for } \text{sym in SM} \\
 n &\geq 2 \text{ for } \text{sym} \neq \text{SM}
 \end{aligned}$$

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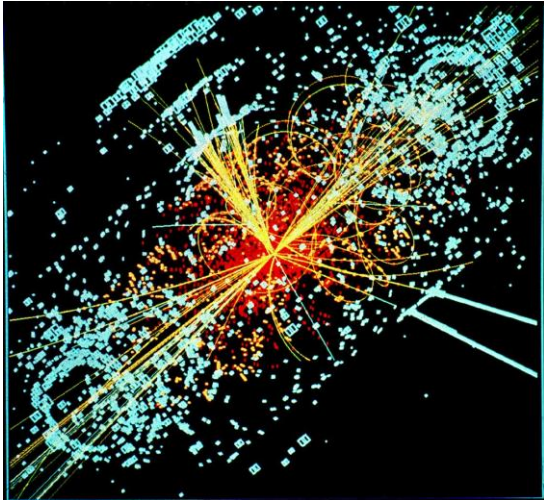
For the simplest BSM operator ($n = 2$): $\text{TeV} \leftrightarrow \mathcal{C}_{\text{sym}} \sim \epsilon_{\text{sym}} \sim 10^{-3}$

New experiments will have a 10^{-3} level of precision

► Sensitive to new physics at the TeV scale

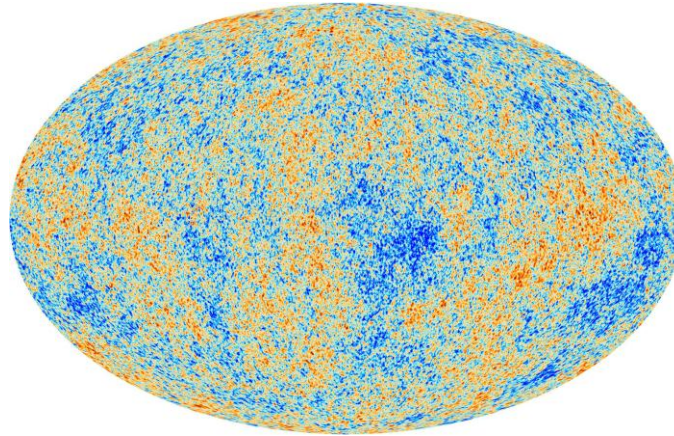
Searches for BSM physics

High energy frontier



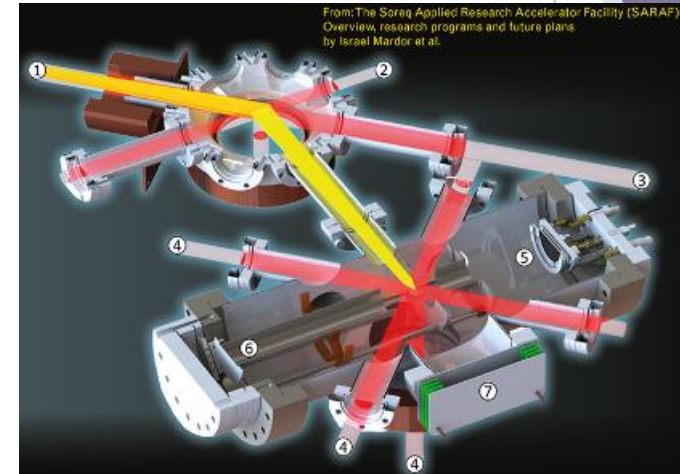
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new experiments

Accuracy: Nuclear structure corrections

$$d\Gamma \propto |\langle \psi_f | \hat{H}_W | \psi_i \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$

Identifying Small Parameters

$$\epsilon_{\text{NR}} \sim \frac{p_{\text{fermi}}}{m_N} \approx 2 \cdot 10^{-1}$$

$$\epsilon_{\text{EFT}} \sim 1 \cdot 10^{-1}$$

$$\epsilon_{qr} \sim qR \approx 5 \cdot 10^{-2}$$

$$\epsilon_c \sim \alpha Z_f \approx 2 \cdot 10^{-2}$$

$$\epsilon_{\text{recoil}} \sim \frac{q}{m_N} \approx 4 \cdot 10^{-3}$$

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Fierz
term

SM
↓
SM correction
 $0 + \delta_b$

$$\triangleright \delta_b = f_b \left(\frac{\langle \psi_f | \hat{C}_J^A | \psi_i \rangle}{\langle \psi_f | \hat{L}_J^A | \psi_i \rangle}, \frac{\langle \psi_f | \hat{M}_J^V | \psi_i \rangle}{\langle \psi_f | \hat{L}_J^A | \psi_i \rangle} \right) + \mathcal{O} \left(\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2 \right)$$

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Multipole Expansion

Accuracy: Nuclear structure corrections

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Angular
correlation

SM SM correction

$$-\frac{1}{5}(1 + \delta_a)$$

Fierz
term

SM SM correction

$$0 + \delta_b$$

► $\delta_a = f_a \left(\frac{\langle \psi_f \| \hat{C}_J^A \| \psi_i \rangle}{\langle \psi_f \| \hat{L}_J^A \| \psi_i \rangle}, \frac{\langle \psi_f \| \hat{M}_J^V \| \psi_i \rangle}{\langle \psi_f \| \hat{L}_J^A \| \psi_i \rangle} \right) + \mathcal{O} \left(\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2 \right)$

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SM $\downarrow$ SM correction

$$-\frac{1}{5}(1 + \delta_a)$$

Fierz
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SM $\downarrow$ SM correction

$$0 + \delta_b$$

$$\delta_b = f_b \left(\underbrace{\frac{\langle \psi_f | \hat{C}_J^A | \psi_i \rangle}{\langle \psi_f | \hat{L}_J^A | \psi_i \rangle}, \frac{\langle \psi_f | \hat{M}_J^V | \psi_i \rangle}{\langle \psi_f | \hat{L}_J^A | \psi_i \rangle}}_{\sim \epsilon_{NR} \epsilon_{qr}, \epsilon_{recoil} \sim 10^{-2}} \right) + \mathcal{O} \left(\underbrace{\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2}_{\sim 5 \cdot 10^{-4}} \right)$$

Identifying Small Parameters

$$\epsilon_{NR} \sim \frac{p_{fermi}}{m_N} \approx 2 \cdot 10^{-1}$$

$$\epsilon_{EFT} \sim 1 \cdot 10^{-1}$$

$$\epsilon_{qr} \sim qR \approx 5 \cdot 10^{-2}$$

$$\epsilon_c \sim \alpha Z_f \approx 2 \cdot 10^{-2}$$

$$\epsilon_{recoil} \sim \frac{q}{m_N} \approx 4 \cdot 10^{-3}$$

Multipole Expansion

Uncertainty Quantification

Accuracy: Nuclear structure corrections

$$d\Gamma \propto |\langle \psi_f || \hat{H}_W || \psi_i \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$

Angular
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SM $\downarrow$ SM correction

$$-\frac{1}{5}(1 + \delta_a)$$

Fierz
term

SM $\downarrow$ SM correction

$$0 + \delta_b$$

Multipole operator's matrix elements
between the nuclear states

$$\delta_b = f_b \left(\underbrace{\frac{\langle \psi_f || \hat{C}_J^A || \psi_i \rangle}{\langle \psi_f || \hat{L}_J^A || \psi_i \rangle}, \frac{\langle \psi_f || \hat{M}_J^V || \psi_i \rangle}{\langle \psi_f || \hat{L}_J^A || \psi_i \rangle}}_{\sim \epsilon_{NR} \epsilon_{qr}, \epsilon_{recoil} \sim 10^{-2}} \right) + \mathcal{O} \left(\underbrace{\frac{\epsilon_{qr}^2}{15}, \epsilon_c^2}_{\sim 5 \cdot 10^{-4}} \right)$$

Identifying Small Parameters

$$\epsilon_{NR} \sim \frac{p_{fermi}}{m_N} \approx 2 \cdot 10^{-1}$$

$$\epsilon_{EFT} \sim 1 \cdot 10^{-1}$$

$$\epsilon_{qr} \sim qR \approx 5 \cdot 10^{-2}$$

$$\epsilon_c \sim \alpha Z_f \approx 2 \cdot 10^{-2}$$

$$\epsilon_{recoil} \sim \frac{q}{m_N} \approx 4 \cdot 10^{-3}$$

Multipole Expansion

General Theory -
for any transition
& nucleus

Uncertainty
Quantification

$^{16}\text{N} \xrightarrow{\beta^-} ^{16}\text{O}$ forbidden decay

➤ Nuclear-structure many-body problem

$\hat{H}$

Nuclear Hamiltonian

$\chi^{\text{EFT}} @ \text{NN} + 3\text{N}$
(& $\text{N}^2\text{LO}_{\text{opt}}$)

$\langle \psi_f || \quad || \psi_i \rangle$

Nuclear wave functions

$\hat{J}(\vec{x})$

Nuclear currents

1b currents
eff. 2b currents

$\hat{O}_J$

Multipole operators

$\langle \psi_f || \hat{O}_J || \psi_i \rangle$

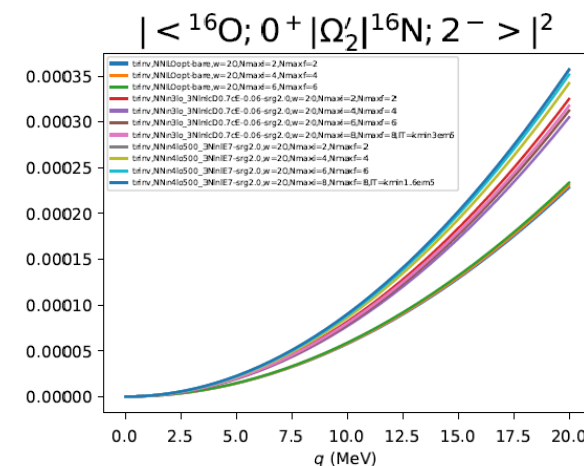
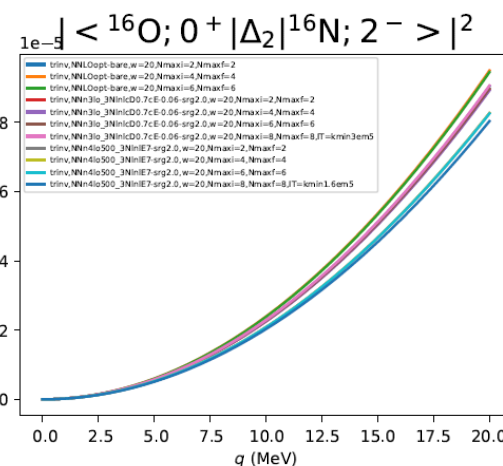
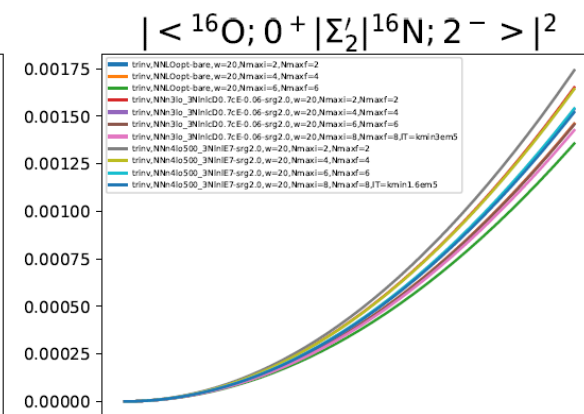
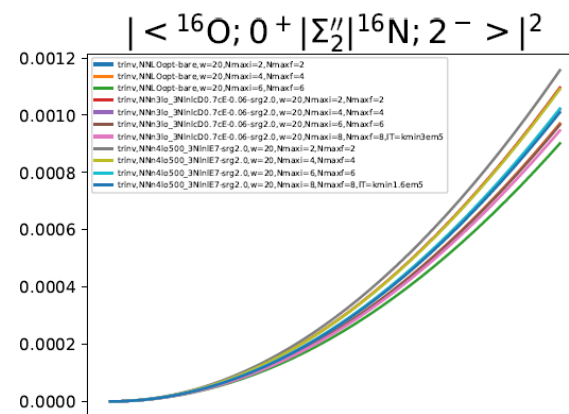
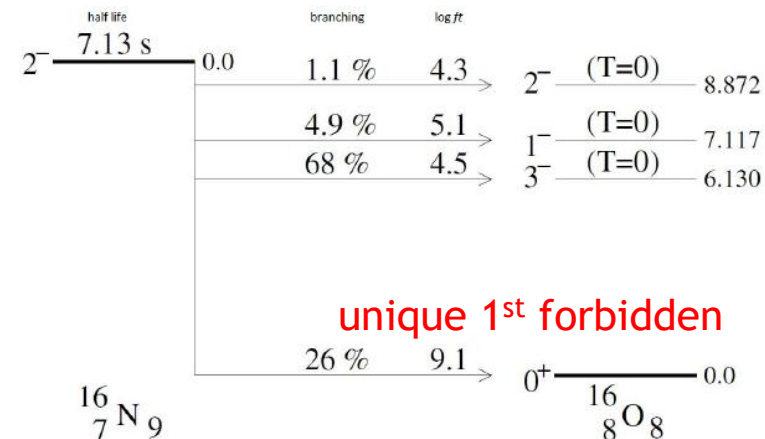
Nuclear matrix elements

Ab initio NCSM

δ_a, δ_b

Observables' corrections

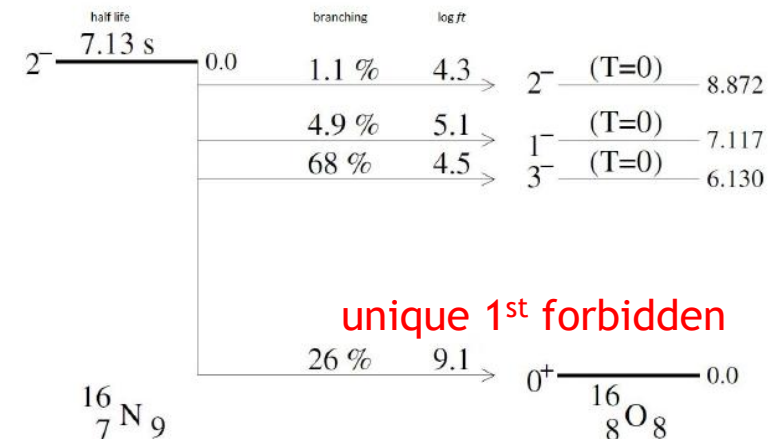
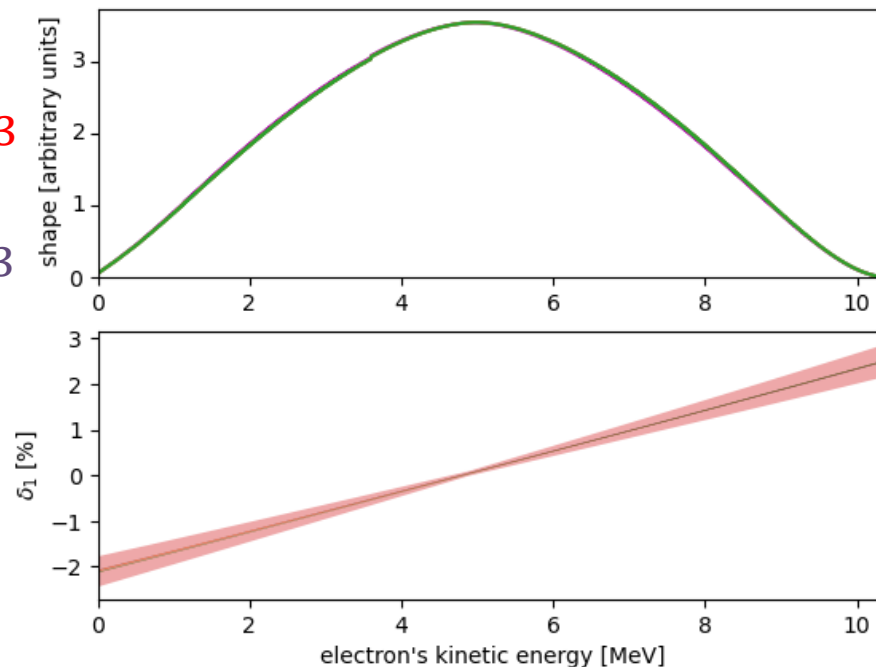
Christian Forssén
Daniel Gazda
Doron Gazit
Lotta Jokiniemi
Kostas Kravvaris
Petr Navrátil



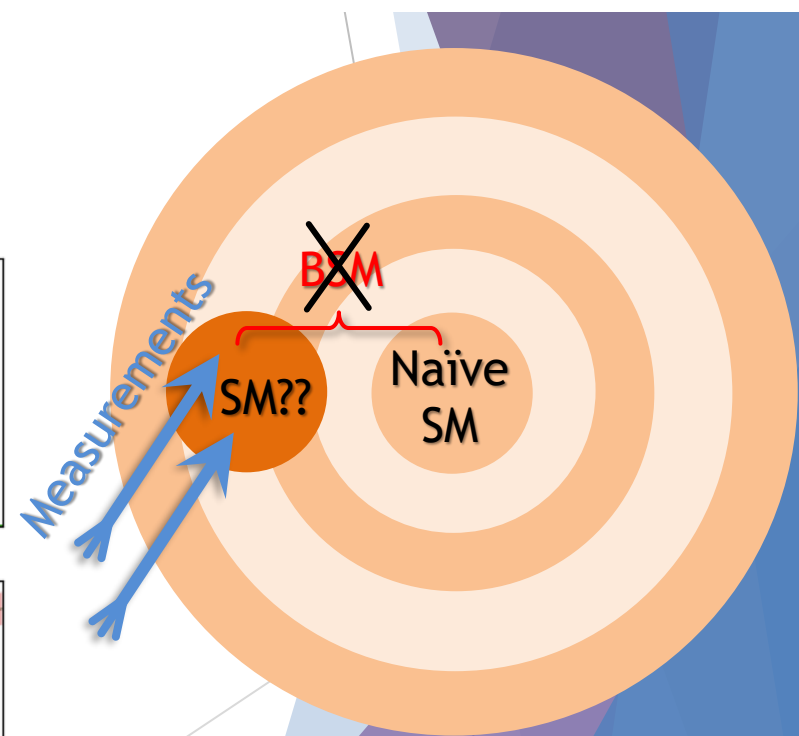
$^{16}\text{N} \rightarrow ^{16}\text{O}$ forbidden spectrum

- ▶ Experiments are aiming a 10^{-3} accuracy
- ▶ The spectrum can be used to extract b_F & $a_{\beta\nu}$

- ▶ $b_F = 0 + \overset{\text{SM}}{\delta_b} + \overset{\text{BSM}}{\frac{C_T^+}{C_A}}$
- ▶ Looking for $\frac{C_T^+}{C_A} \sim 10^{-3}$
- ▶ $\delta_b = -1.23(18) \cdot 10^{-3}$



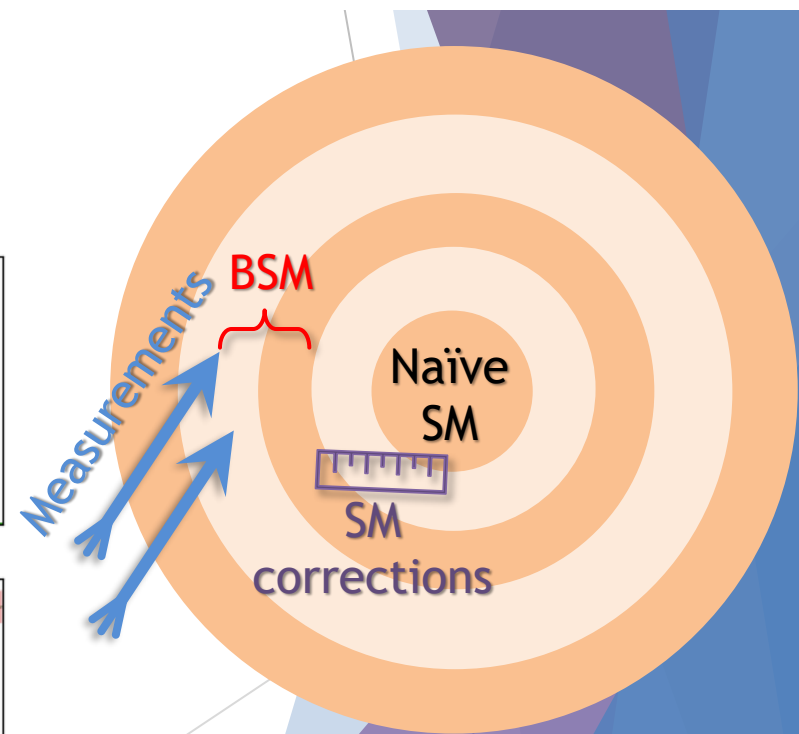
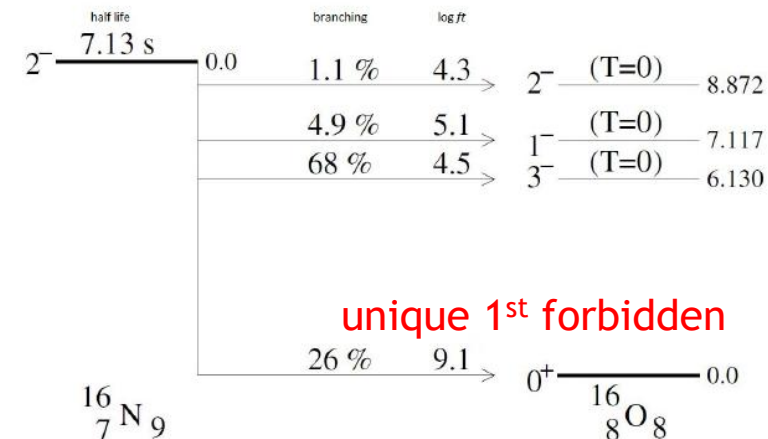
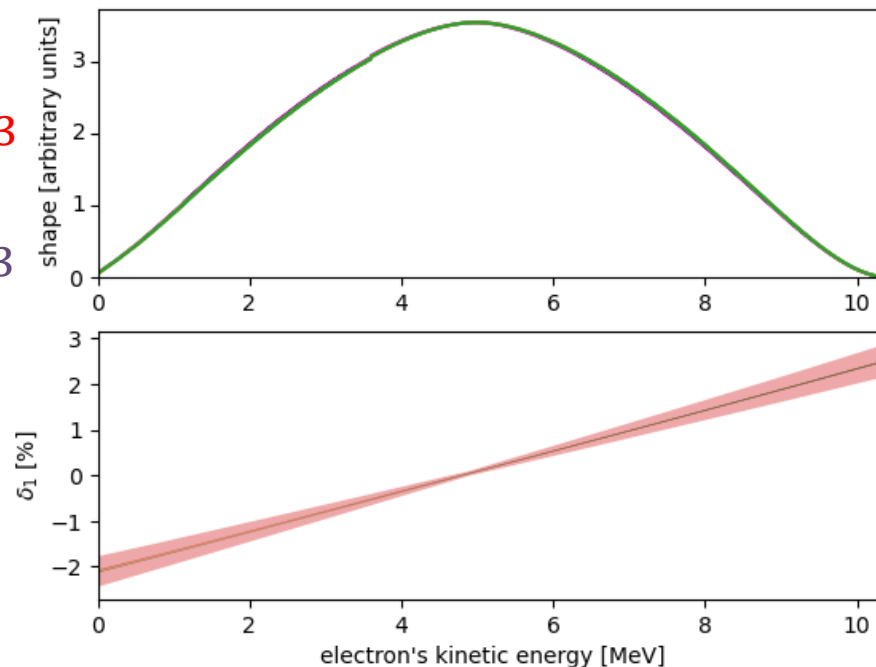
unique 1st forbidden



$^{16}\text{N} \rightarrow ^{16}\text{O}$ forbidden spectrum

- ▶ Experiments are aiming a 10^{-3} accuracy
- ▶ The spectrum can be used to extract b_F & $a_{\beta\nu}$

- ▶ $b_F = 0 + \delta_b + \frac{C_T^+}{C_A}$
- ▶ Looking for $\frac{C_T^+}{C_A} \sim 10^{-3}$
- ▶ $\delta_b = -1.23(18) \cdot 10^{-3}$
- ▶ Uncertainty $\sim 10^{-4}$



$^{16}\text{N} \rightarrow ^{16}\text{O}$ forbidden angular correlation

half life	branching	log ft	
7.13 s	0.0		2^- (T=0) — 8.872
	1.1 %	4.3	1^- (T=0) — 7.117
	4.9 %	5.1	3^- (T=0) — 6.130
	68 %	4.5	
	26 %	9.1	0^+ — 0.0

unique 1st forbidden

$^{16}_7\text{N}_9 \rightarrow ^{16}_8\text{O}_8$

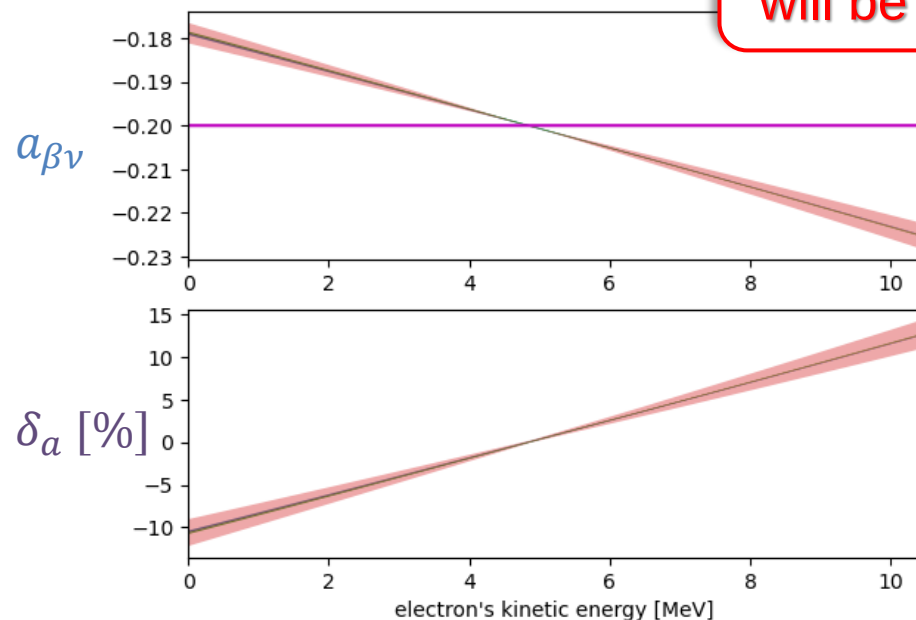
- Experiments are aiming a 10^{-3} accuracy

$$a_{\beta\nu} = -\frac{1}{5} \left(1 + \tilde{\delta}_a + \frac{|C_T^+|^2 + |C_T^-|^2}{4|C_A|^2} \right)$$

SM SM correction BSM

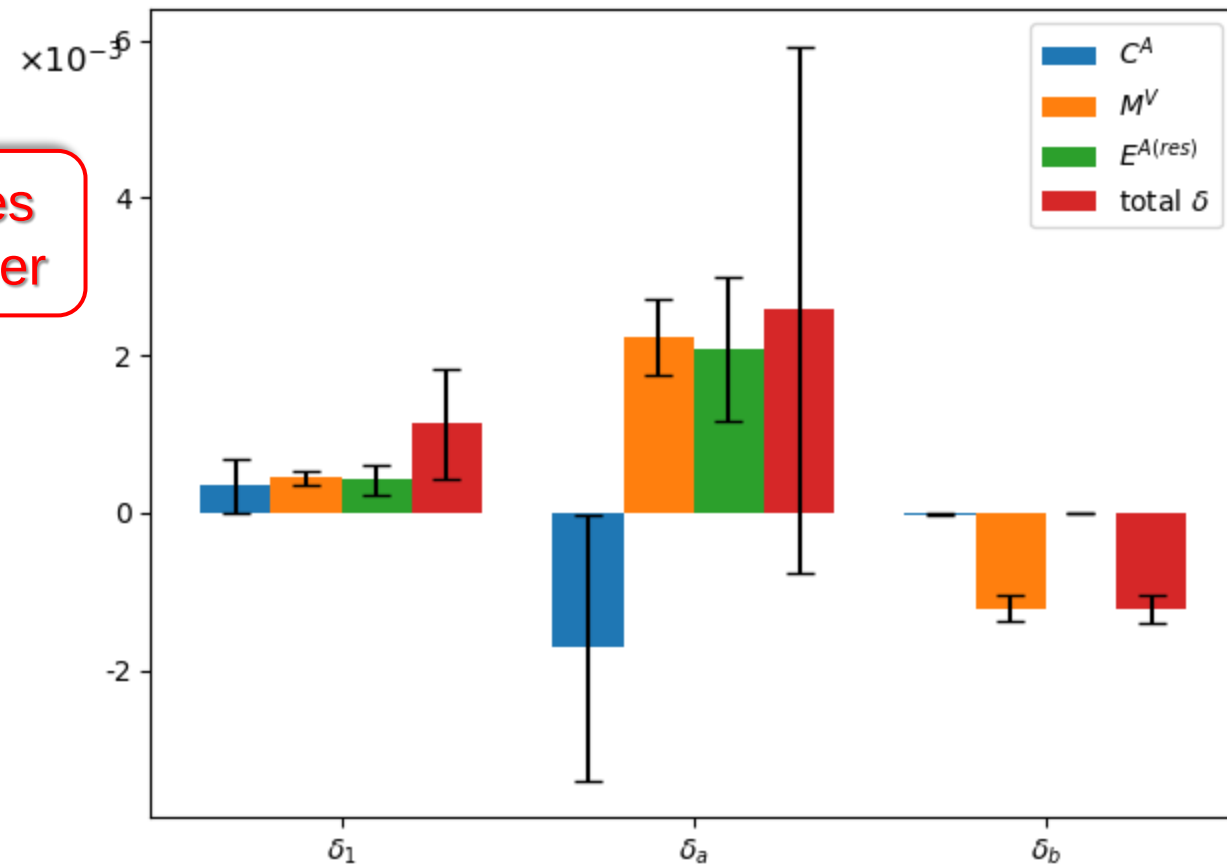
► $\langle \tilde{\delta}_a \rangle = -2.6(3.3) \cdot 10^{-3}$

Uncertainties
will be smaller



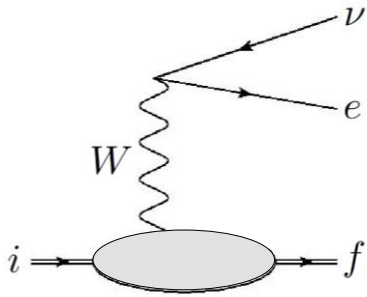
$$C_T^+(C_T^-) \sim 10^{-3}$$

Multipoles contributions to NLO corrections



Accuracy: Radiative corrections

$$d\Gamma \propto |\langle 0^+ || \hat{H}_W || 2^- \rangle|^2 \propto 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon}$$



“Forbidden”
(vanish for $q \rightarrow 0$)

• All the rest ($J^{\Delta\pi}$)

angular
momentum

parity

$$J_i^{\pi_i} \rightarrow J_f^{\pi_f}$$

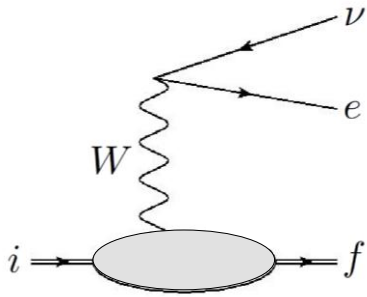
$$|J_i - J_f| \leq J \leq J_i + J_f$$

$$\Delta\pi = \pi_i \cdot \pi_f$$

Accuracy: Radiative corrections

$$d\Gamma \propto |\langle 0^+ || \hat{H}_W || 2^- \rangle|^2 \propto \left\{ 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon} \right\} |\langle 0^+ || \hat{O}_J^W || 2^- \rangle|^2$$

$$\langle 0^+ || \hat{L}_{J=2}^A || 2^- \rangle \propto q^{J-1}, \text{ so } d\Gamma \xrightarrow{q \rightarrow 0} 0$$



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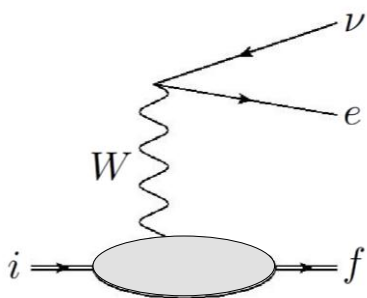
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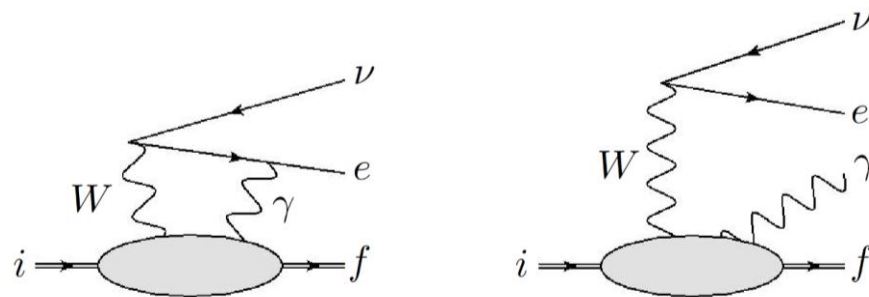
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Radiative Corrections:



$$\langle 0^+ || \hat{O}_J^W \hat{Q}_{J'}^{EM} || 2^- \rangle = \sum_X \langle 0^+ || \hat{O}_J^W || \psi_X \rangle \langle \psi_X || \hat{Q}_{J'}^{EM} || 2^- \rangle$$

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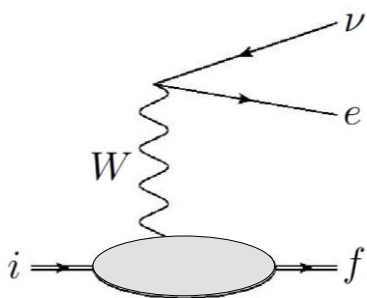
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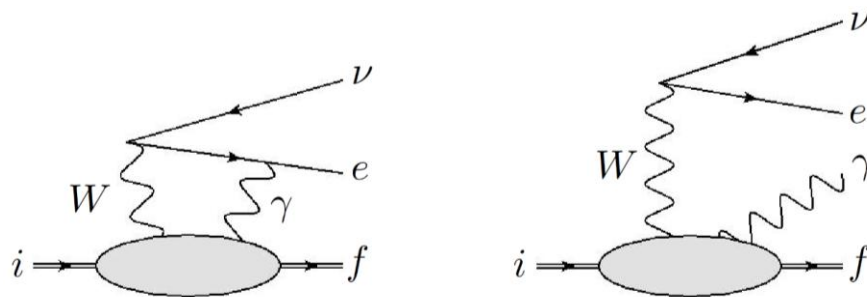
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angular
momentum

parity

No longer limited to $J = 2$ operators
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$$J_i^{\pi_i} \rightarrow J_f^{\pi_f}$$

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Nuclear β -decay

For a general β -decay transition $J_i^{\pi_i} \rightarrow J_f^{\pi_f}$:

$$\Theta(q, \vec{\beta} \cdot \hat{v}) = \sum_{J=|J_i-J_f|}^{J_i+J_f} \Theta^{J\Delta\pi}(q, \vec{\beta} \cdot \hat{v})$$

angular
momentum

parity

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$$|J_i - J_f| \leq J \leq J_i + J_f$$

$$\Delta\pi = \pi_i \cdot \pi_f$$

	$\Delta\pi$	transition	multipoles	BSM
$J = 0$	+	Fermi	$\hat{C}_0^V \sim 1$	$\hat{C}_0^S \approx \frac{g_S}{g_V} \hat{C}_0^V$
	-	1 st forbidden	$\hat{L}_0^A \sim \epsilon_{qr} \sim q$ $\hat{C}_0^A \sim \epsilon_{NR} \sim q$	$\hat{L}_0^T \approx -\frac{i}{\sqrt{2}g_A} g_T \hat{L}_0^A$ $\hat{C}_0^P \approx \frac{q}{2m_N g_A} g_P \hat{L}_0^A$
$J > 0$	$(-)^J$	J^{th} forbidden	$\hat{C}_J^V \sim \epsilon_{qr}^J \sim q^J$ $\hat{M}_J^A \sim \epsilon_{qr}^J \sim q^J$	$\hat{C}_J^S \approx \frac{g_S}{g_V} \hat{C}_J^V$ $\hat{M}_J^T \approx -\frac{i}{\sqrt{2}g_A} g_T \hat{M}_J^A$
	$(-)^{J-1}$	Gamow Teller ($J = 1$) unique $(J - 1)^{\text{th}}$ forbidden	LO: $\hat{L}_J^A \sim \epsilon_{qr}^{J-1} \sim q^{J-1}$ NLO: $\hat{C}_J^A, \hat{M}_J^V \sim \epsilon_{\text{recoil}} \epsilon_{qr}^{J-1}, \epsilon_{NR} \epsilon_{qr}^J \sim q^{J+1}$	$\hat{L}_J^T \approx -\frac{i}{\sqrt{2}g_A} g_T \hat{L}_J^A$ $\hat{C}_J^P \approx \frac{q}{2m_N g_A} g_P \hat{L}_J^A$

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angular
momentum

parity

$$J_i^{\pi_i} \rightarrow J_f^{\pi_f}$$

$$|J_i - J_f| \leq J \leq J_i + J_f$$

$$\Delta\pi = \pi_i \cdot \pi_f$$

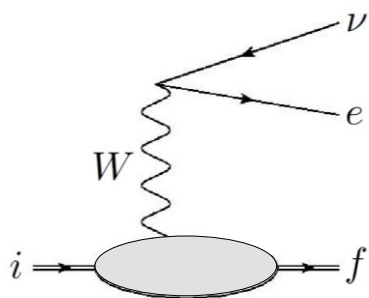
	$\Delta\pi$	transition	multipoles			BSM
$J = 0$	+		Decay process	Intermediate states	Multipole operators	$\hat{C}_0^S \approx \frac{g_S}{g_V} \hat{C}_0^V$
			$i(2^-) \rightarrow f(0^+)$	$i(2_g^-), f(0_g^+)$	$C_0^{\text{em}}, L_2^A, E_2^A$	$\hat{L}_0^T \approx -\frac{i}{\sqrt{2}g_A} \hat{L}_0^A$
	-			$i(1_X^+), f(1_X^-)$	$C_1^{\text{em}}, L_1^{\text{em}}, E_1^{\text{em}}, L_1^A, E_1^A$	$\hat{C}_0^P \approx \frac{q}{2m_N g_A} \hat{L}_0^A$
$J > 0$	$(-)^J$		$i(0^+) \rightarrow f(2^-)$	$i(0_g^+), f(2_g^-)$	$C_0^{\text{em}}, L_2^A, E_2^A$	$\hat{C}_J^S \approx \frac{g_S}{g_V} \hat{C}_J^V$
				$i(1_X^-), f(1_X^+)$	$C_1^{\text{em}}, L_1^{\text{em}}, E_1^{\text{em}}, L_1^A, E_1^A$	$\hat{M}_J^T \approx -\frac{i}{\sqrt{2}g_A} \hat{M}_J^A$
	$(-)^{J-1}$					$\hat{L}_J^T \approx -\frac{i}{\sqrt{2}g_A} \hat{L}_J^A$
						$\hat{C}_J^P \approx \frac{q}{2m_N g_A} \hat{L}_J^A$

Table S II: Intermediate states and multipole operators responsible for the dominant contributions to $T^{\mu\nu}$

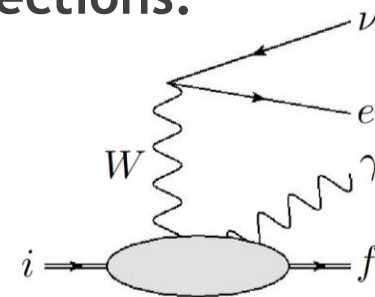
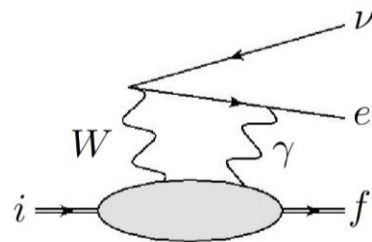
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$$d\Gamma \propto |\langle 0^+ || \hat{H}_W || 2^- \rangle|^2 \propto \left\{ 1 + a_{\beta\nu} \left[1 - (\hat{\beta} \cdot \hat{\nu})^2 \right] + b_F \frac{m_e}{\epsilon} \right\} |\langle 0^+ || \hat{O}_J^W || 2^- \rangle|^2$$

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angular
momentum

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$$d\Gamma \propto f_0 q^0 + f_1 q^1 + f_2 q^2$$

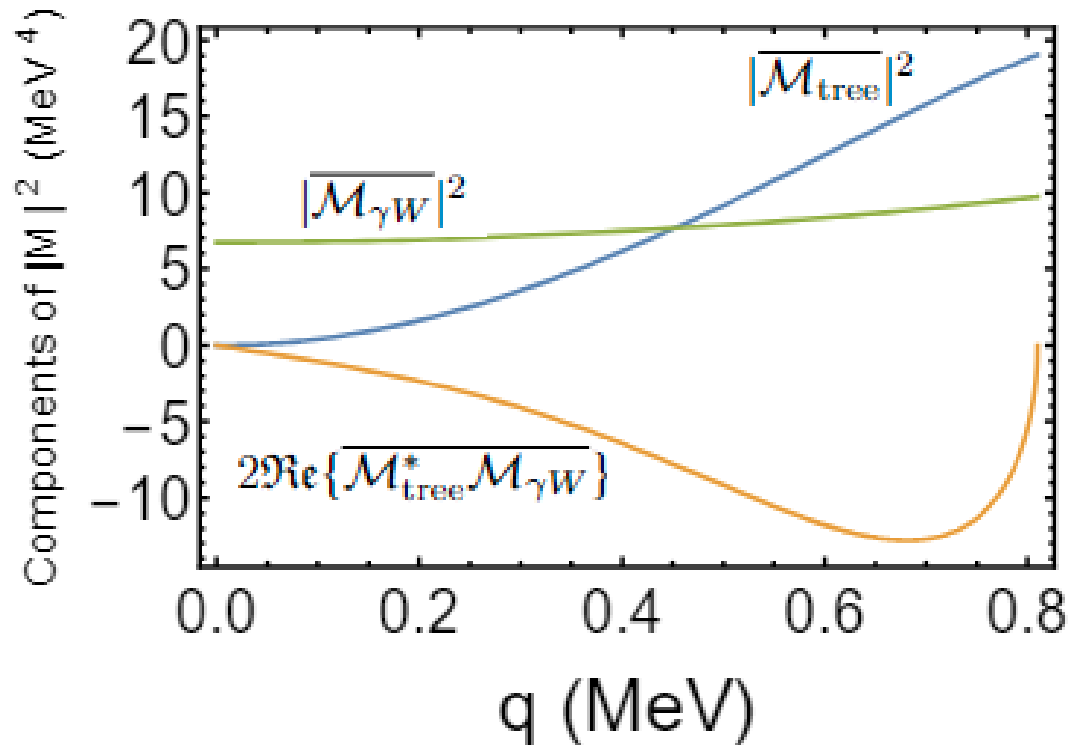
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Unique Forbidden decays

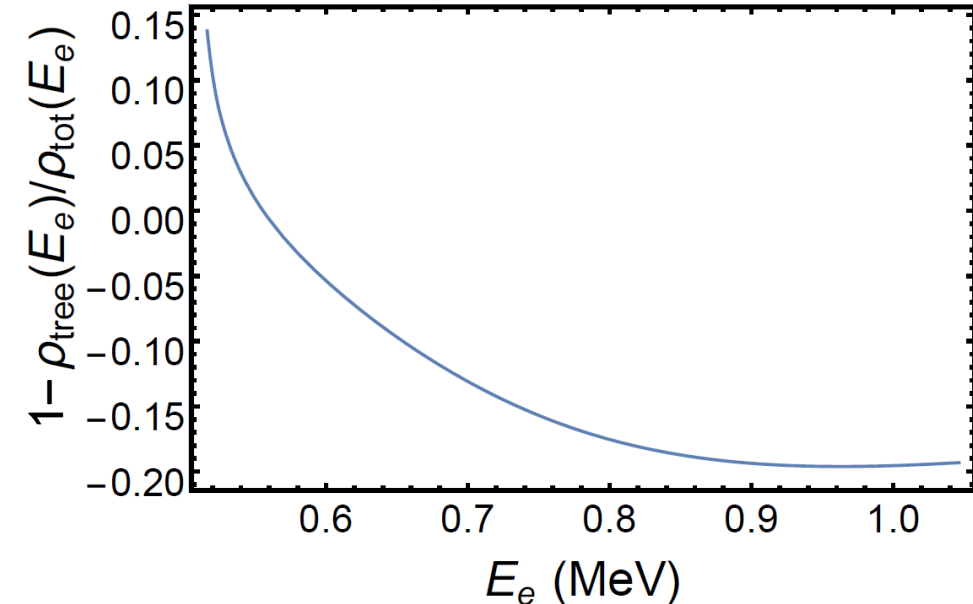
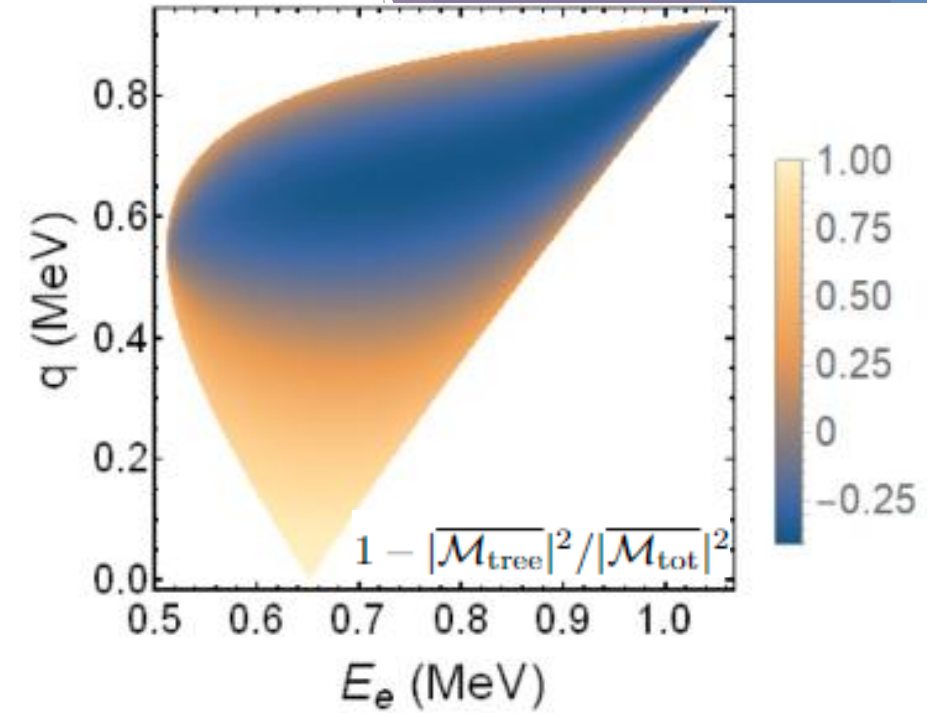
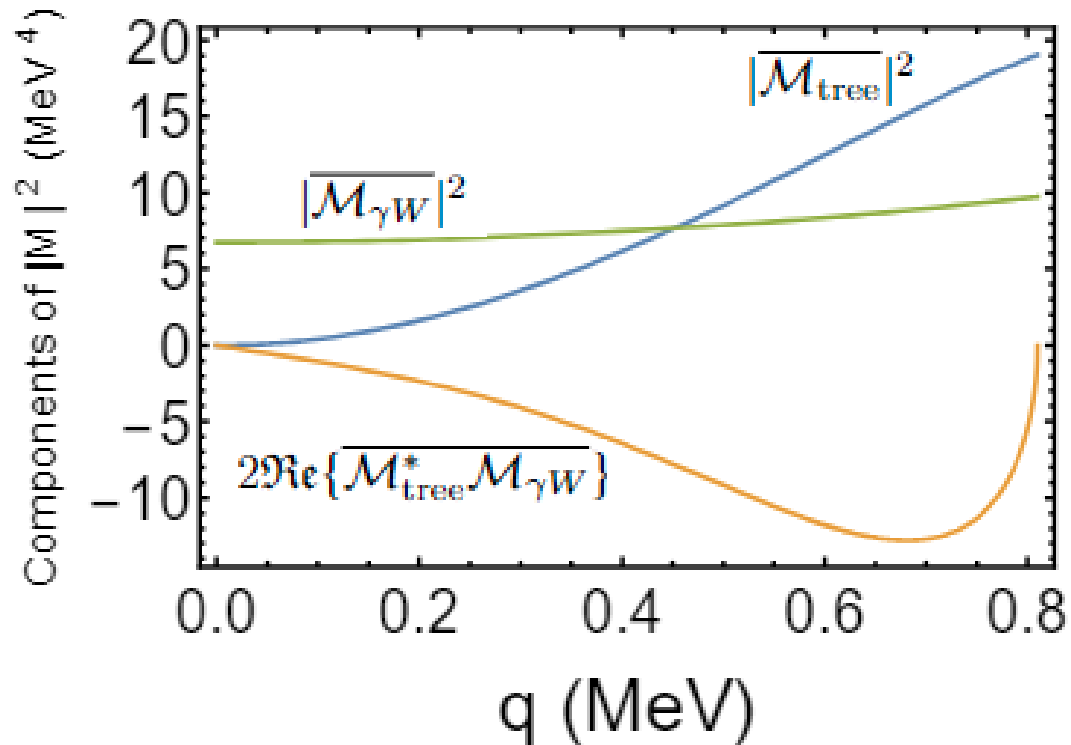
No decay @ $q \rightarrow 0$



$$d\Gamma \propto f_0 q^0 + f_1 q^1 + f_2 q^2$$

Unique Forbidden decays

No decay @ $q \rightarrow 0$

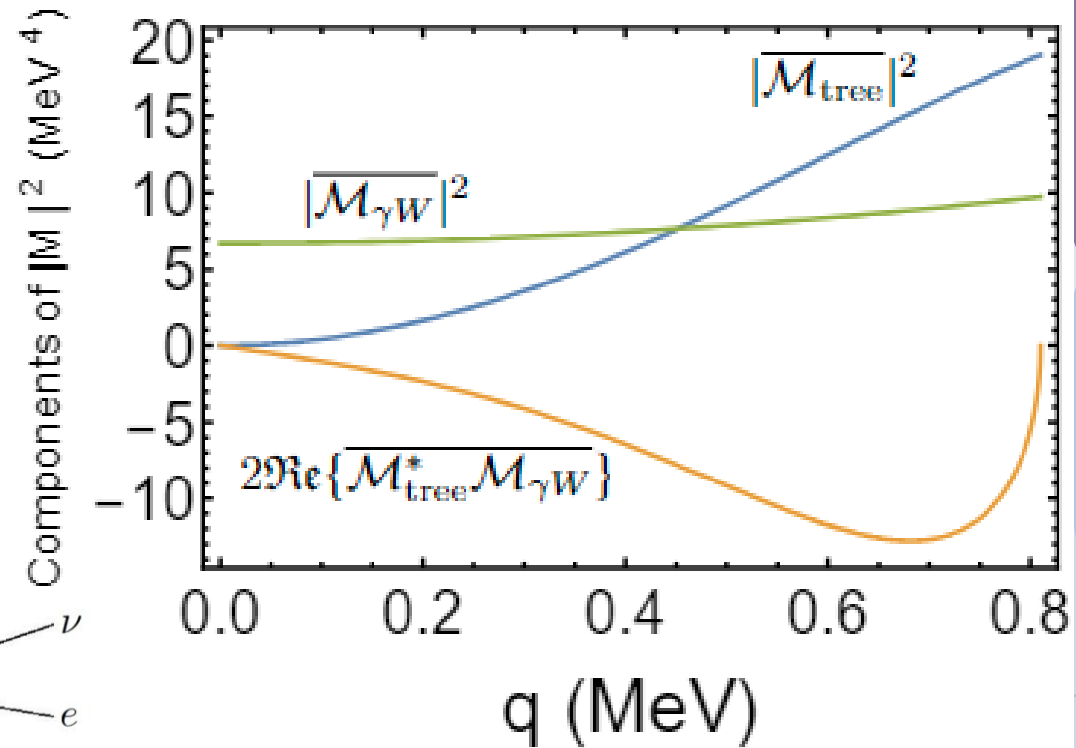
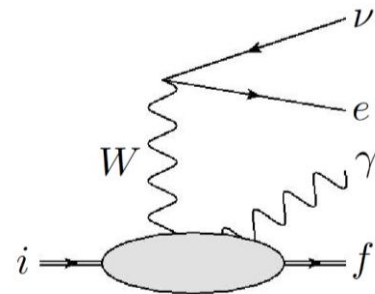
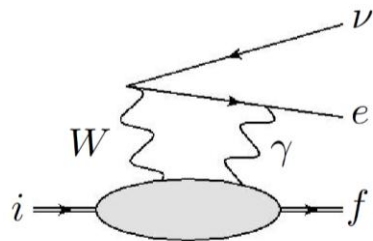


$$d\Gamma \propto f_0 q^0 + f_1 q^1 + f_2 q^2$$

Unique Forbidden decays

No decay @ $q \rightarrow 0$

Light New Physics



$$d\Gamma \propto f_0 q^0 + f_1 q^1 + f_2 q^2$$

Unique Forbidden decays

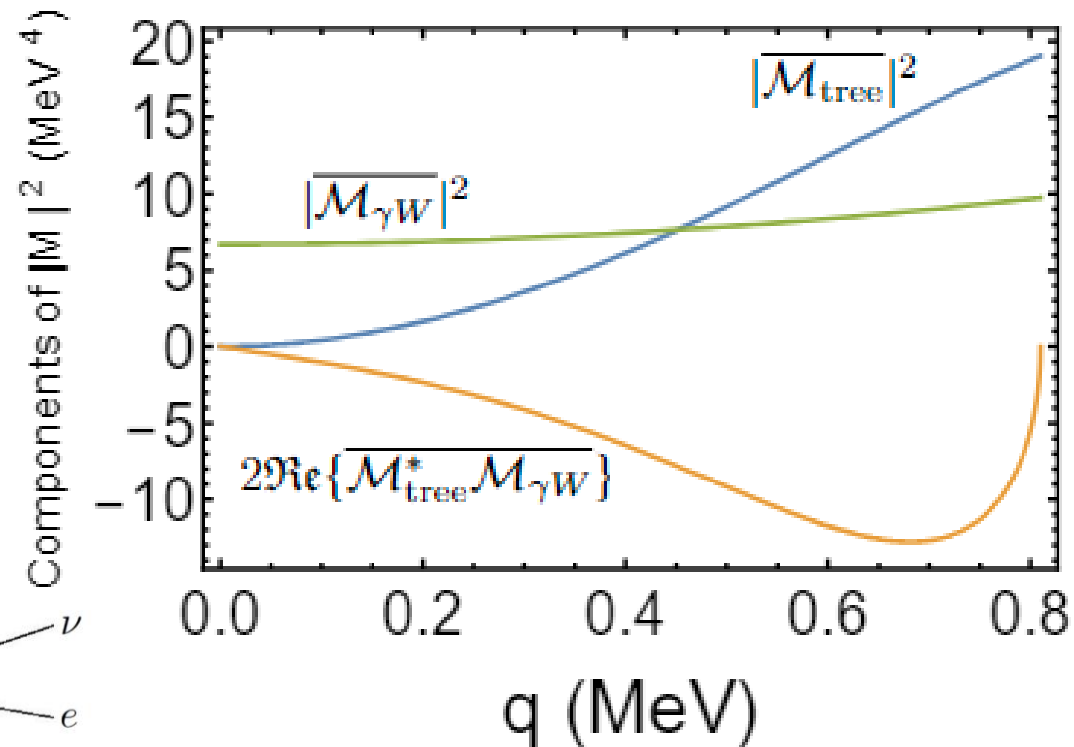
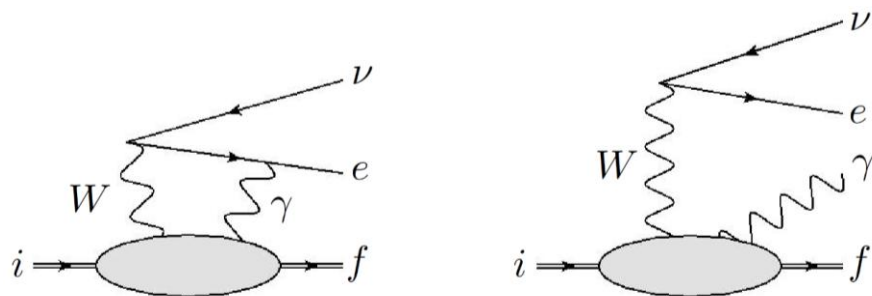
No decay @ $q \rightarrow 0$

Experiments

@ ORNL, HUJI, SOREQ (FRIB?)

Spectrum is sensitive to:

- ⚡ Exotic Weak Interactions
- ⚡ Right-handed New Physics
- ⚡ Light New Physics



$$d\Gamma \propto f_0 q^0 + f_1 q^1 + f_2 q^2$$

Summary:

Forbidden β -decays

No decay @ $q \rightarrow 0$

Experiments

@ ORNL, HUJI, SOREQ (FRIB?)

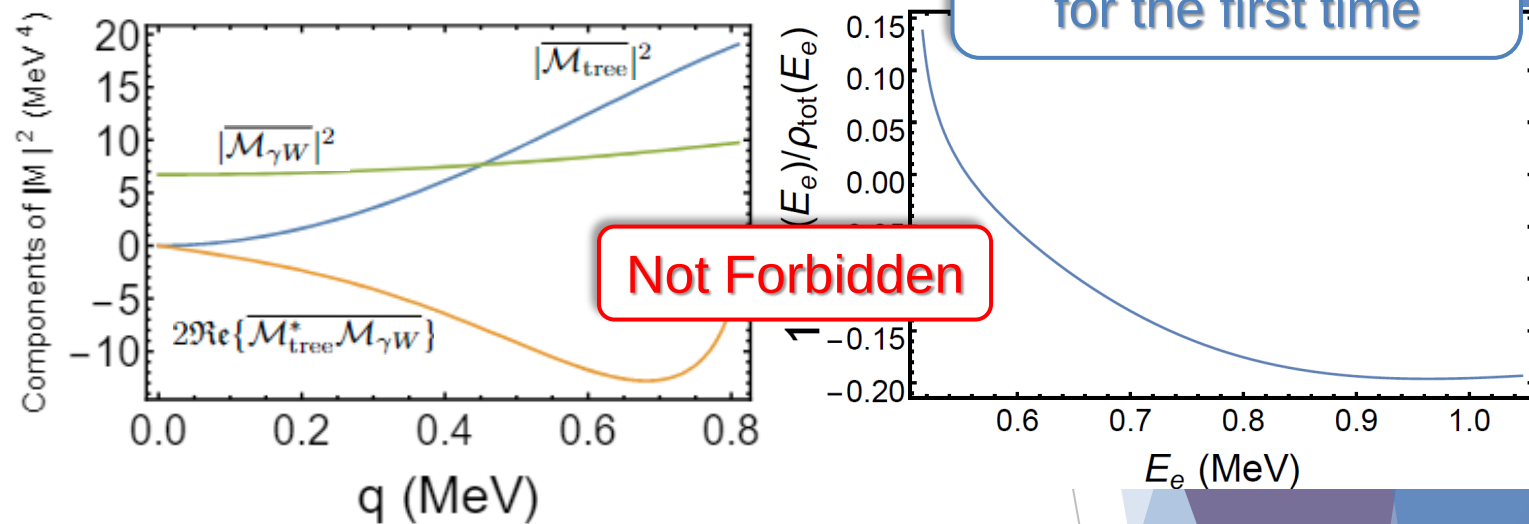
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Requires precision theory – 2 challenges:

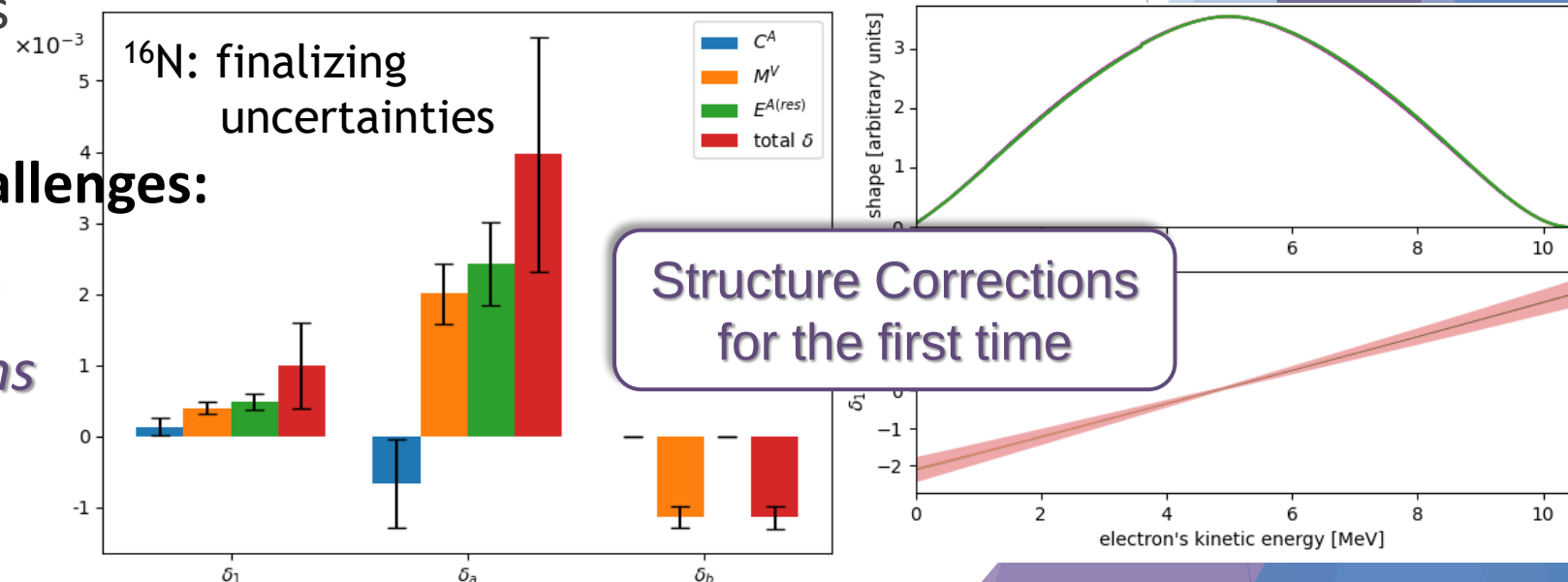
- High-order quantum effects
- Nuclear-structure corrections

High-order quantum effects



Radiative corrections
for the first time

Nuclear-structure corrections



Structure Corrections
for the first time

Summary:

Forbidden β -decays

No decay @ $q \rightarrow 0$

Experiments

@ ORNL, HUJI, SOREQ (FRIB?)

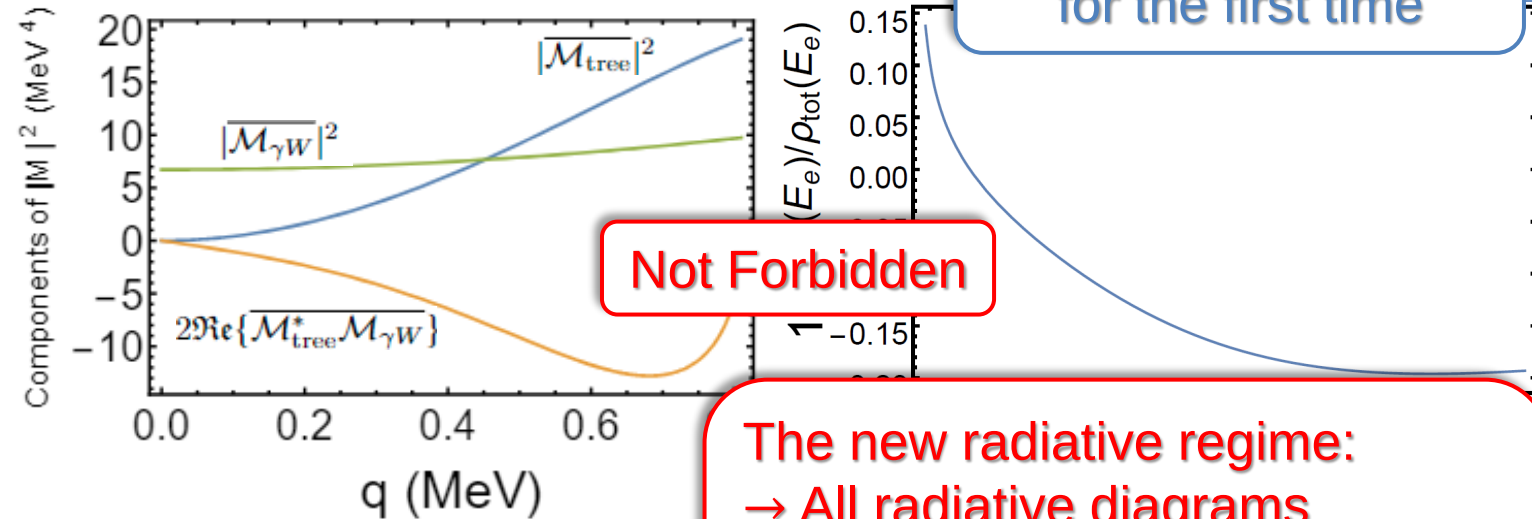
Spectrum is sensitive to:

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Requires precision theory – 2 challenges:

- High-order quantum effects
- Nuclear-structure corrections
- Outlook: Combining!

High-order quantum effects



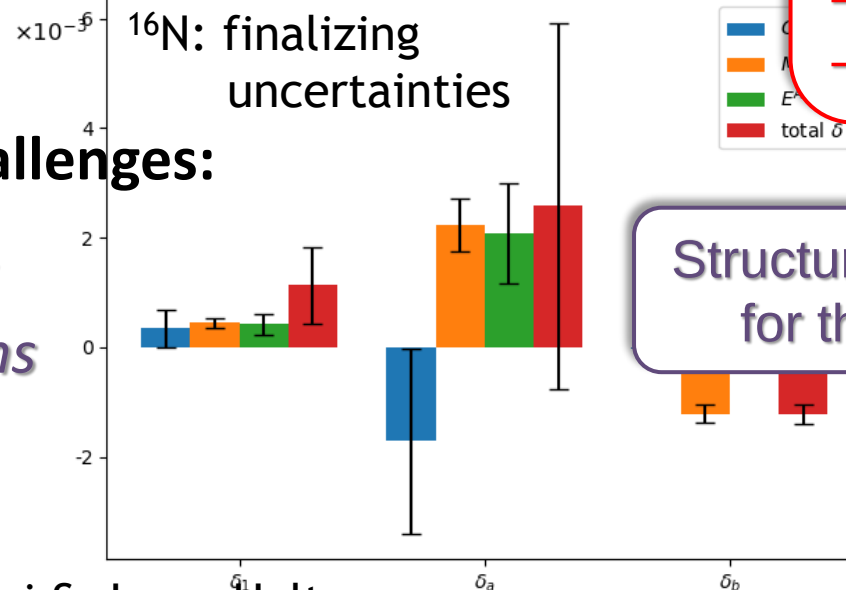
Radiative corrections for the first time

The new radiative regime:

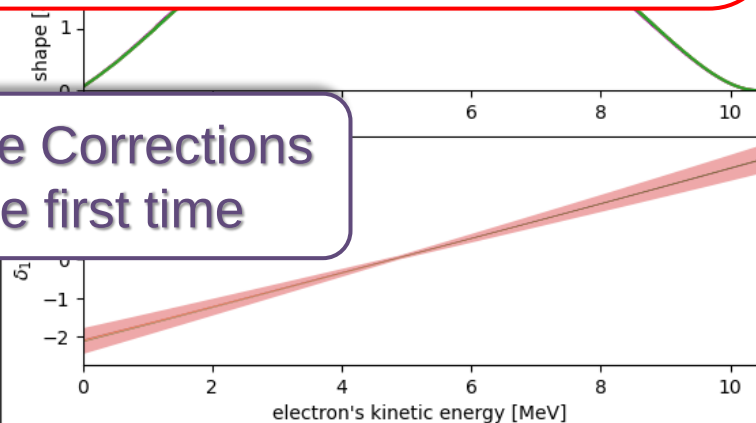
- All radiative diagrams
- With nuclear matrix elements
- Operators hierarchy
- Light new physics possibilities

Nuclear-structure corrections

Multipoles contributions to NLO corrections



Structure Corrections for the first time



^{90}Sr , ^{90}Y : ongoing with Lotta Jokiniemi & Jason Holt

Bonus: He6-CRES (allowed)

Alejandro Garcia

He6-CRES – Scientific Motivation

Phys. Rev. Lett. **131**, 082502 (2023)

New J. Phys. **26**, 083021 (2024)

Chirality-flipping interactions in beta decays

$$\mathcal{L}_{CC} = -\sqrt{2}G_F^0 V_{ud} \left[\bar{e}^L \gamma_\mu \nu_e^L \cdot \bar{u}^L \gamma^\mu d^L \right. \\ \left. + \epsilon_S \bar{e}^R \nu_e^L \cdot \bar{u} d \right. \\ \left. + \epsilon_T \bar{e}^R \sigma_{\mu\nu} \nu_e^L \cdot \bar{u}^R \sigma^{\mu\nu} d^L \right]$$

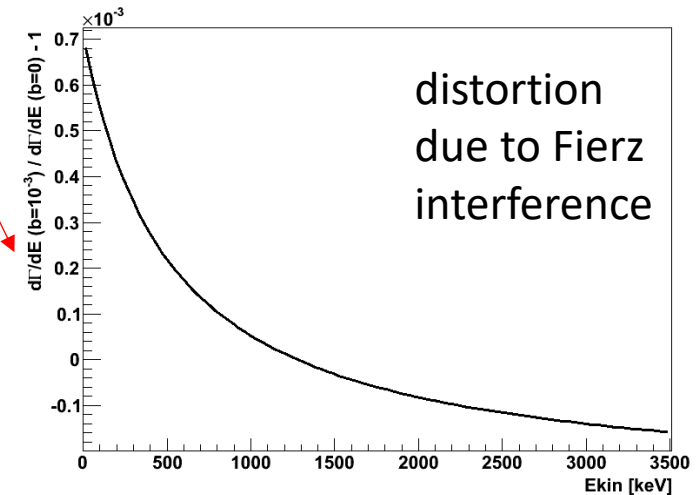
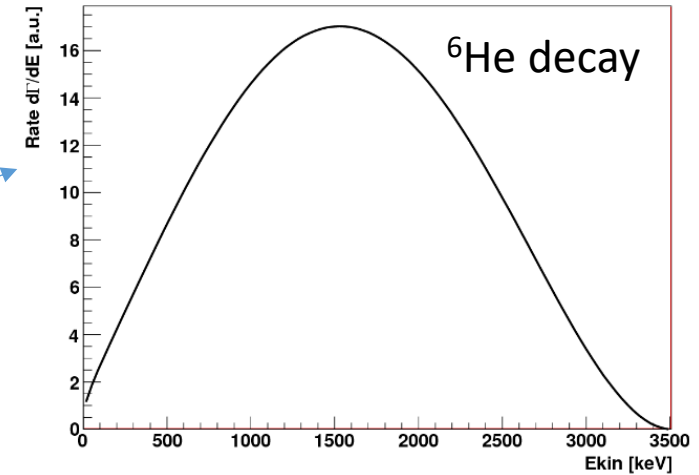
Many models of new physics naturally predict $\epsilon_S, \epsilon_T \neq 0$.

Charge Conj. $+$: electron
Symmetry $-$: positron

$$\frac{dN}{dE} = \left(\frac{dN}{dE} \right)_{\text{standard}} \left(1 + b \frac{m}{E} \right)$$

'Fierz interference'

$$b \approx \begin{cases} \pm 8\epsilon_T/g_A & \text{for GT} \\ \pm \epsilon_S & \text{for Fermi} \end{cases}$$

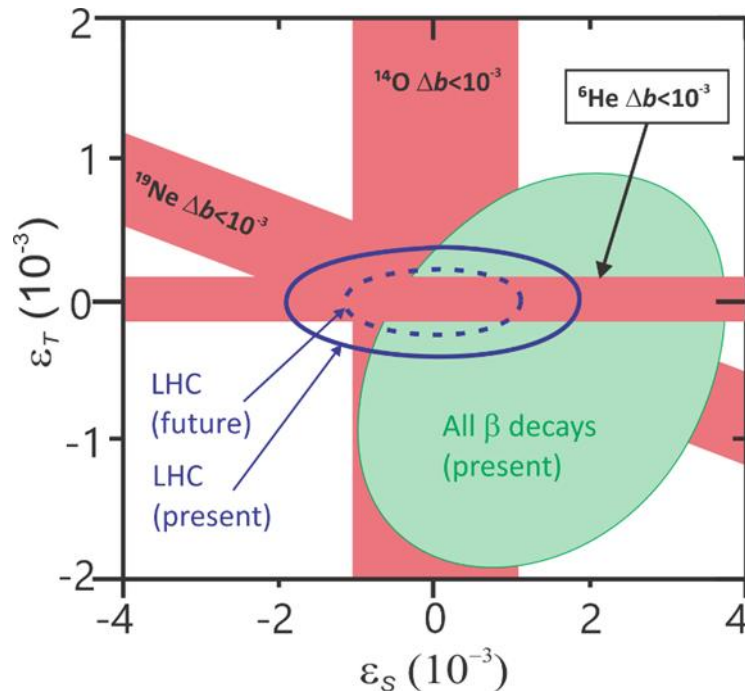


He6-CRES – Measurement basics

Beta decay in magnetic field
measure cyclotron freq,
extract energy E

$$E = \frac{qBc^2}{\omega_c}$$

${}^6\text{He}$ (β^-), ${}^{14}\text{O}$ (β^+), ${}^{19}\text{Ne}$ (β^+)
endpoints > 1 MeV

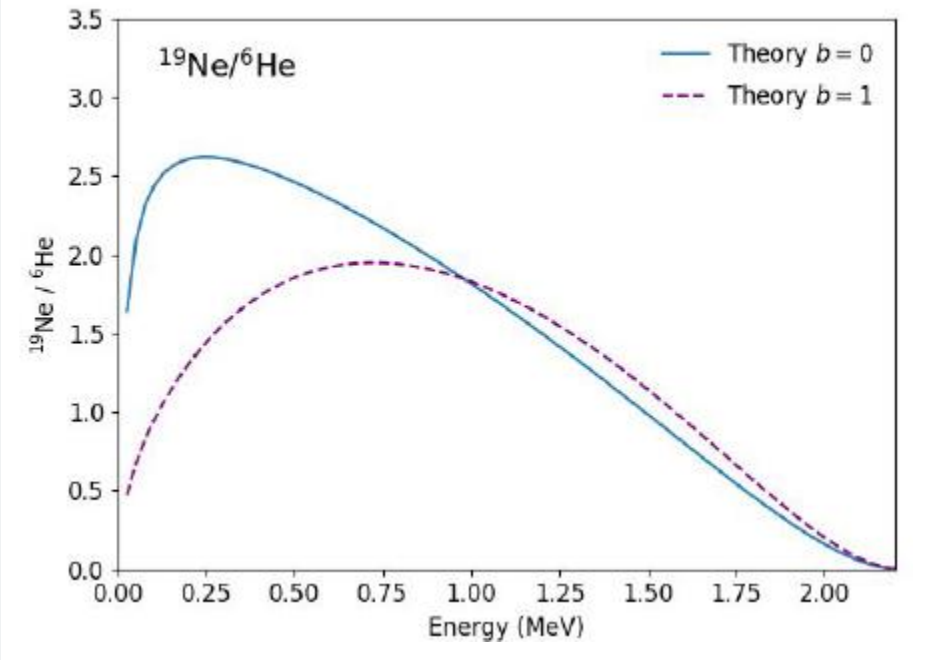


Ratios of counts enhance **signal**,
cancel systematic uncertainties

Example (assume $\epsilon_S = 0$ for simplicity):

$$N({}^{19}\text{Ne}) \propto 1 - \epsilon_T k_1 m/E$$

$$N({}^6\text{He}) \propto 1 + \epsilon_T k_2 m/E$$



He6-CRES – Photos

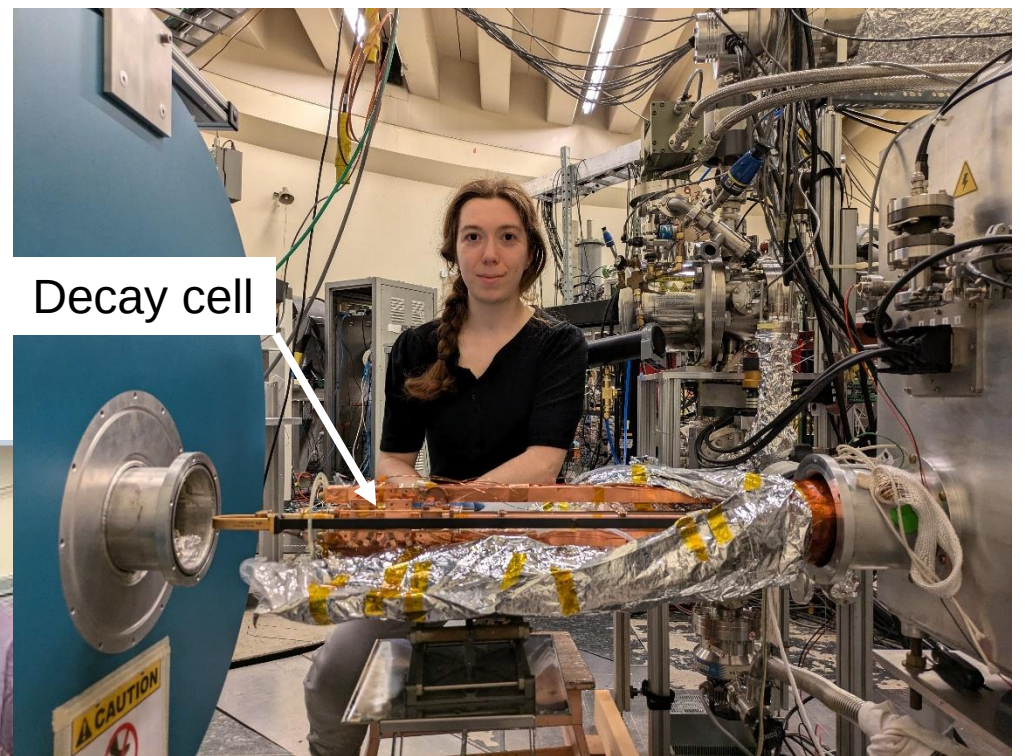
Cryo-box insides



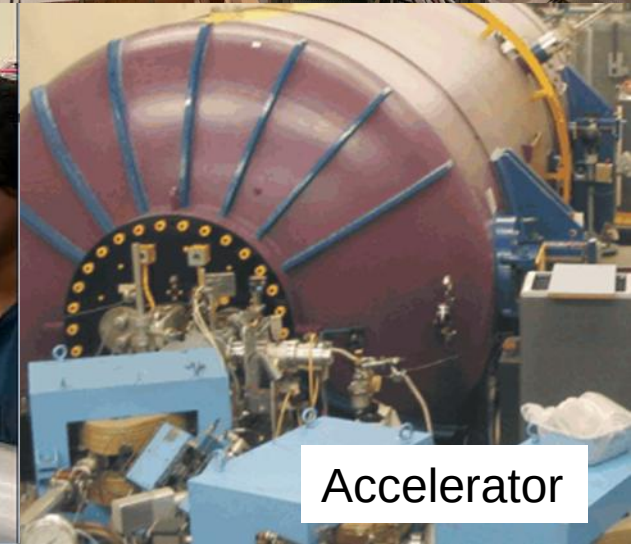
Assembly



Decay cell

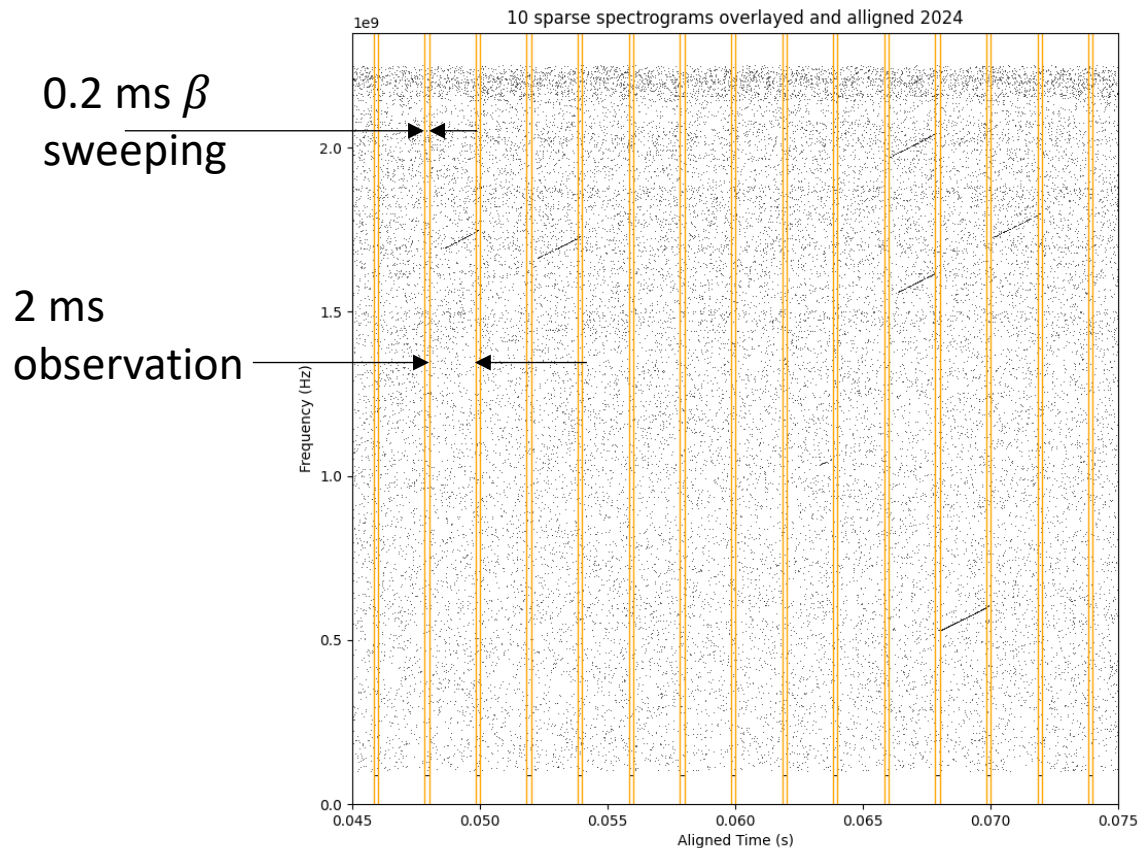


Accelerator



He6-CRES – Example uncertainties

Use electric field to sweep out β 's
for cleaner events



Upcoming Run

Net data acquisition time: 64 hours

Statistical uncertainty: $\Delta b \approx 6 \times 10^{-3}$

Systematic uncertainties

Source	$\Delta b \times 10^2$
Beta monitor instability	0.3
Scattering	0.05
Magnetic instabilities and differences	0.1
RF Temperature differences/drift	0.3
Rate-dependent detection efficiency	< 0.1
Contaminants	?
Theory	0.1

He6-CRES – Collaboration & goals

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He6-CRES phases

Phase I: proof of principle

Observe ^{83}Kr lines
Understand RF issues and spectra
Study power distribution
Show detection of cycl. radiation from ^6He

Done

Phase II: first measurement

^6He and ^{19}Ne measurements: ($b < 10^{-2}$)
Develop ^{79}Kr and ^{14}O sources.
Develop next beta monitor.
Analysis of uncertainties and improvements.
 ^6He and ^{19}Ne measurements: ($b < 10^{-3}$)

Next 3 years:

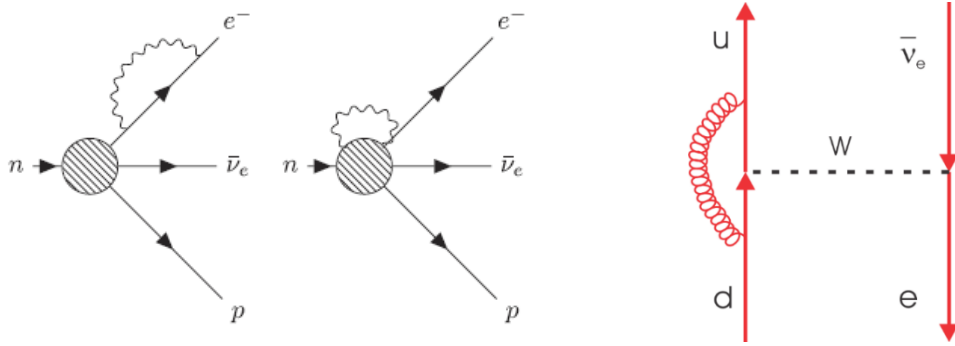
- Phase II
- Prepare proposal Phase III

Phase III: ultimate measurement ($b < 10^{-4}$)

^{14}O measurements.
Ion-trap system.

He6-CRES – Theory Needs

The dominant uncertainties on the SM spectra are radiative and recoil-order corrections [1,2]



Summary

- ${}^6\text{He}$ seems under control [3,4]
- For ${}^{14}\text{O}$ and ${}^{19}\text{Ne}$:

Uncertainties in our calculations of beta spectra are at the 10^{-3} level, below present experimental sensitivity but needs improvement for reaching ultimate goals.

This is a call to our theory colleagues to help us in moving beyond this limiting uncertainty.

Help from Nature:

- Dominant part of the recoil-order correction (Weak Magnetism)
 ${}^{19}\text{Ne}$: related to well-known magnetic moments of initial/final states
 ${}^{14}\text{O}$: no such contribution.
- For both decays a symmetry implies that pseudo-induced tensor matrix element, typical source of uncertainties, is highly suppressed.

Peter Gysbers
Petr Navrátil

- [1] Hayen et al. *Rev. Mod. Phys.* **90**, 015008 (2018)
- [2] Glick-Magid et al. *J. Phys. G* **49** 105105 (2022)
- [3] Glick-Magid et al. *Phys. Lett.* **B832** 137259 (2022)
- [4] King et al. *Phys. Rev. C* **107**, 015503 (2023)



Thanks!

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