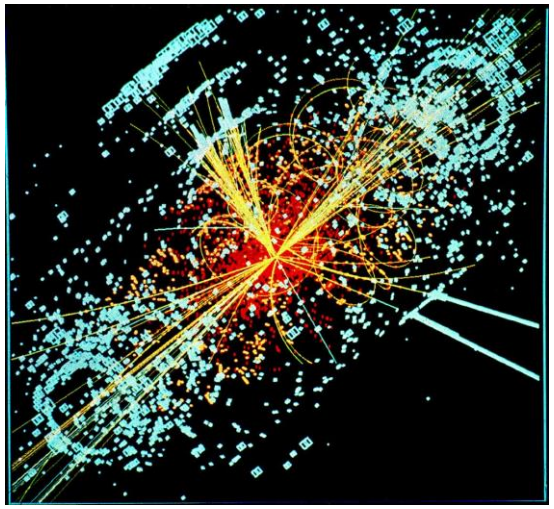
Theory of β-Decay

ECT* workshop 3-7 August 2026: From Nuclear Structure to New Physics

Ayala Glick-Magid

Searches for BSM physics

High energy frontier



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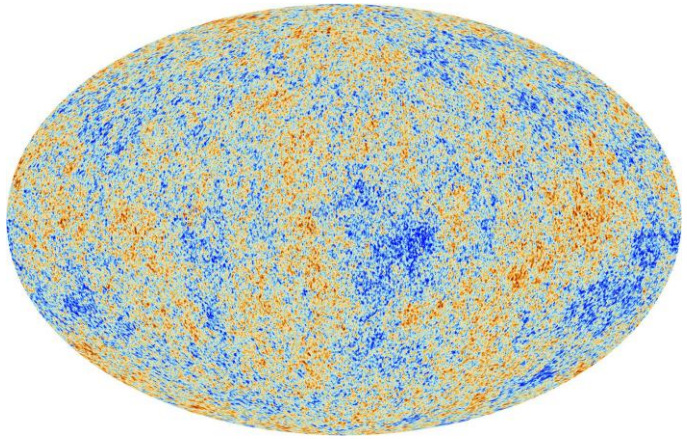
LHC

Astronomical frontier



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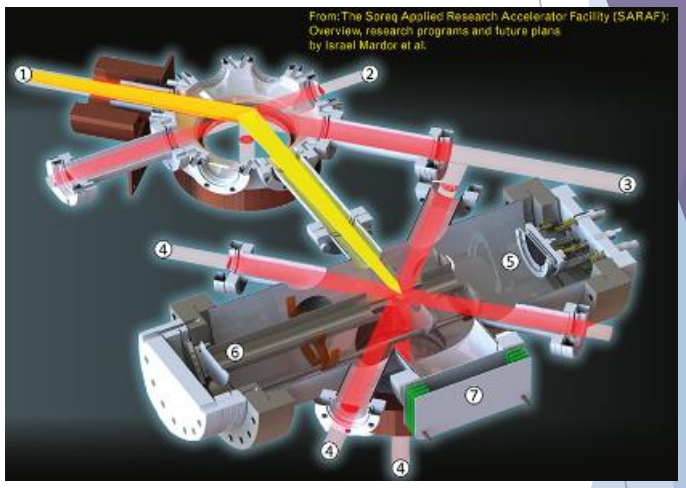
Precision frontier

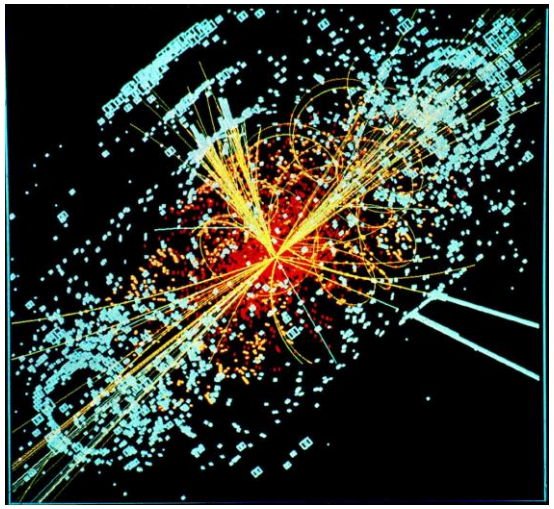


Mardor *et al.*, Eur. Phys. J. A 54, 91 (2018)

Nuclear phenomena

Searches for BSM physics

High energy frontier



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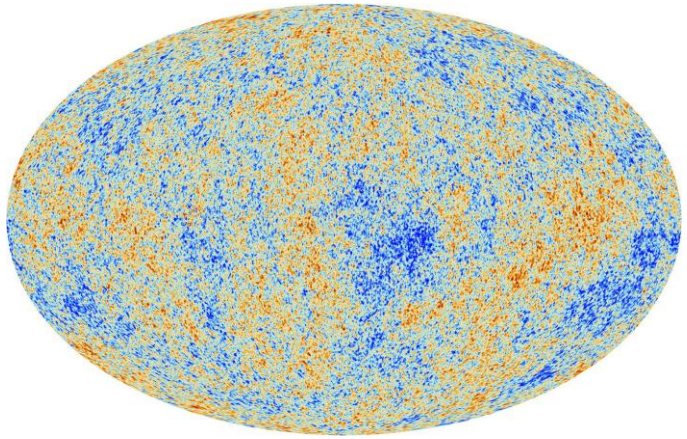

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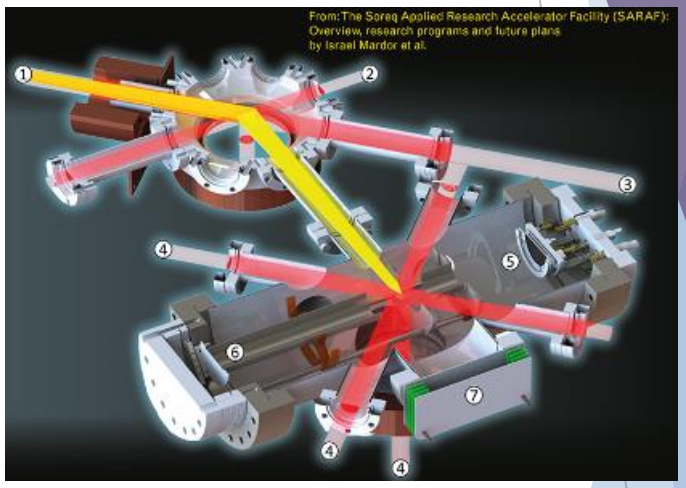

Mardor *et al.*, Eur. Phys. J. A 54, 91 (2018)

LHC
TeV scale

Nuclear phenomena
10^{-3} precision level

new experiments

Searches for BSM physics

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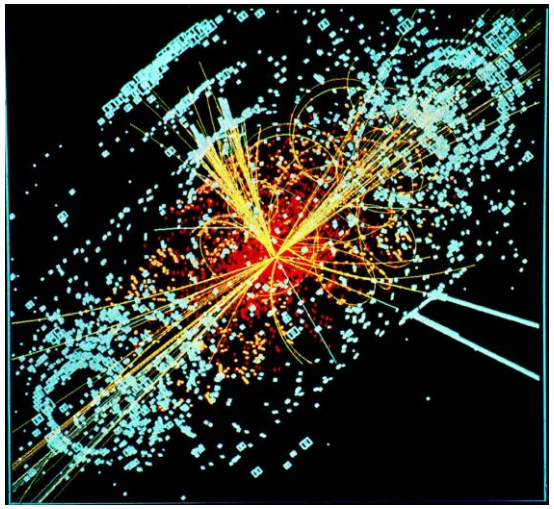

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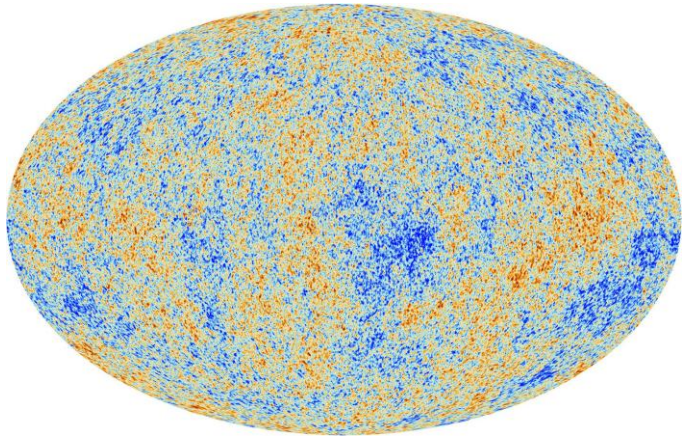

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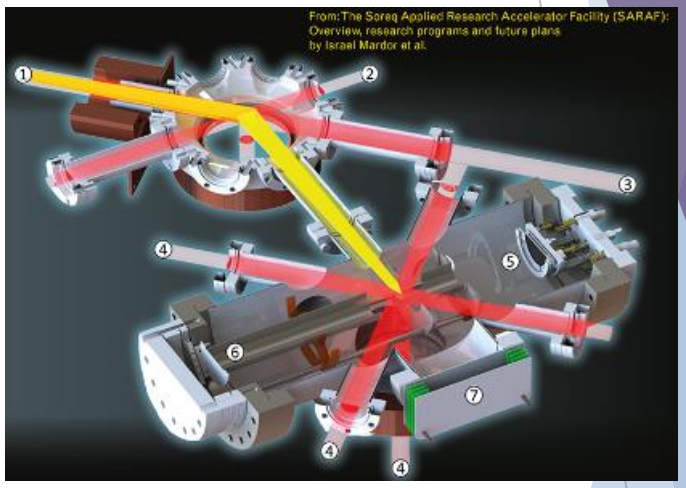

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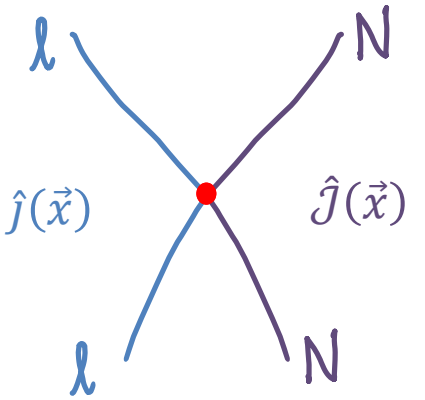
LHC
TeV scale ⟷ Nuclear phenomena
10^{-3} precision level

new experiments

- **Nuclear structure** calculations have an accuracy of $\sim 10^{-2} - 10^{-1}$
  - *Is it possible to give a theoretical framework to these new experiments?*

Weak interaction



lepton current $\hat{j}(\vec{x})$

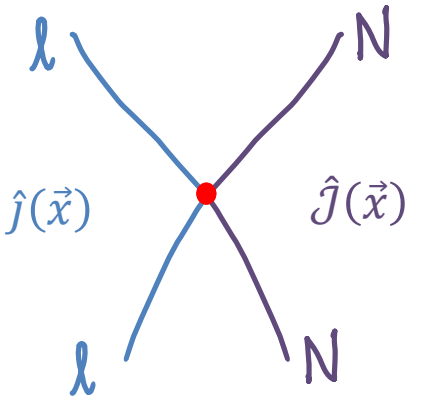
$\hat{\mathcal{J}}(\vec{x})$ nuclear current

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

A-priori:

- **S**calar (C_S)
- **P**seudoScalar (C_P)
- **V**ector (C_V)
- **A**xial-vector (C_A)
- **T**ensor (C_T)

Weak interaction



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

Experiments with *nuclear β-decays*

Weak SM structure:

"$V - A$"

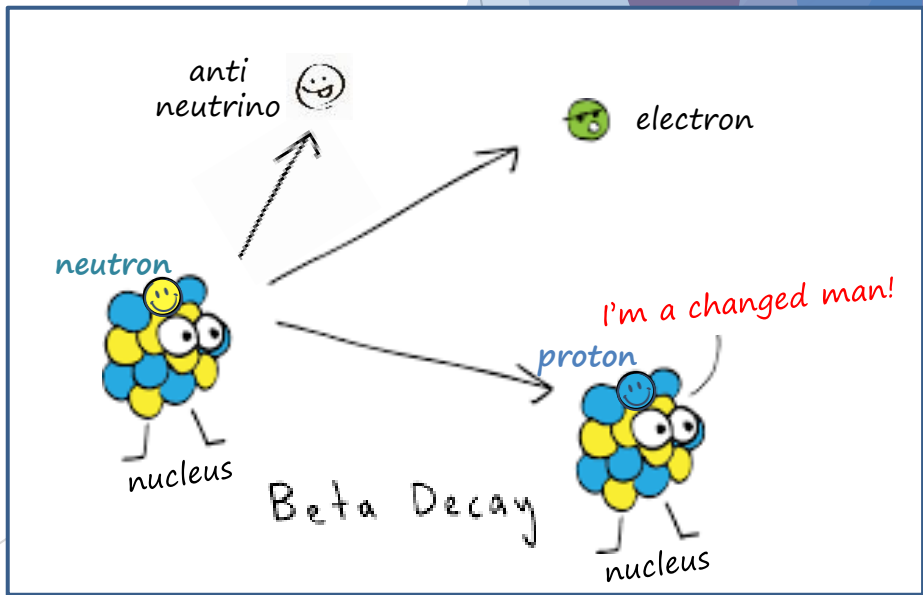
The SM is incomplete

>> Ongoing searches for C_S, C_P, C_T in precision ***nuclear β-decay*** experiments

Nuclear β-decay

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

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



Nuclear β-decay

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

angular momentum

parity

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

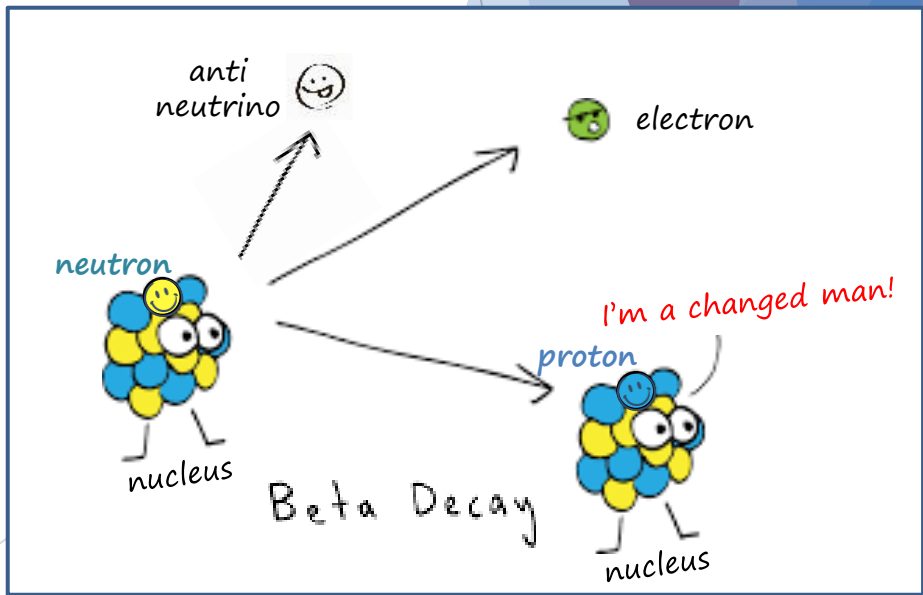
"Allowed" (when $q \to 0$)

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

"Forbidden" (vanish for $q \to 0$)

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

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



✓ Introduction

Allowed

- Theory for BSM
- Structure Calculations

⇒ **Yes, we can**

Forbidden

- Theory for BSM
- Structure Calculations

⇒ **New observable: SPAM**

Summary

Allowed decays

Nuclear β-decay

- β-decay rate:

$$d\omega \propto \left|\langle \psi_f \| \hat{H}_W \| \psi_i \rangle\right|^2 \underset{\textbf{allowed}}{\propto} 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E}$$

Observables

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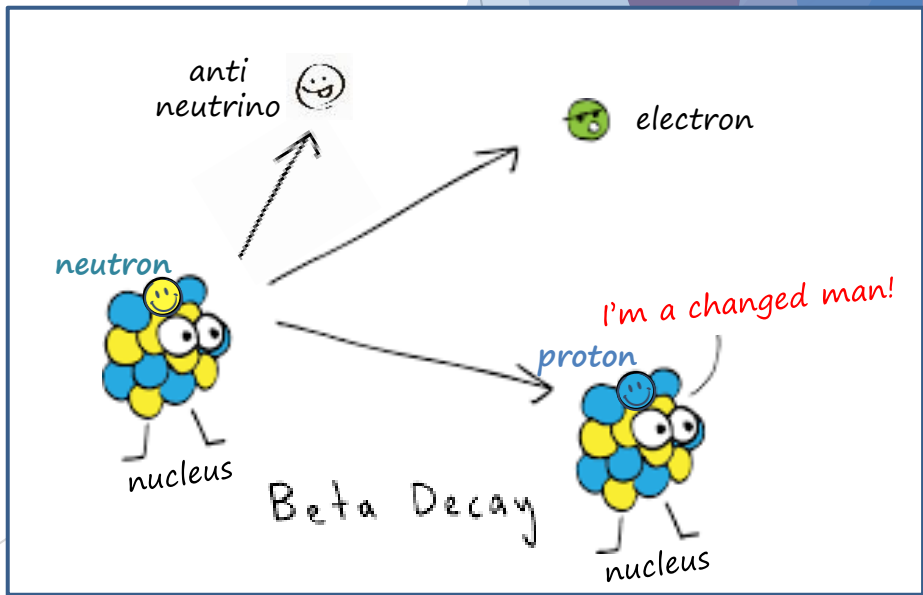

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Observables

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

- **Angular correlation**: $a_{\beta\nu} \overset{\mathrm{SM}}{=} -\frac{1}{3}$

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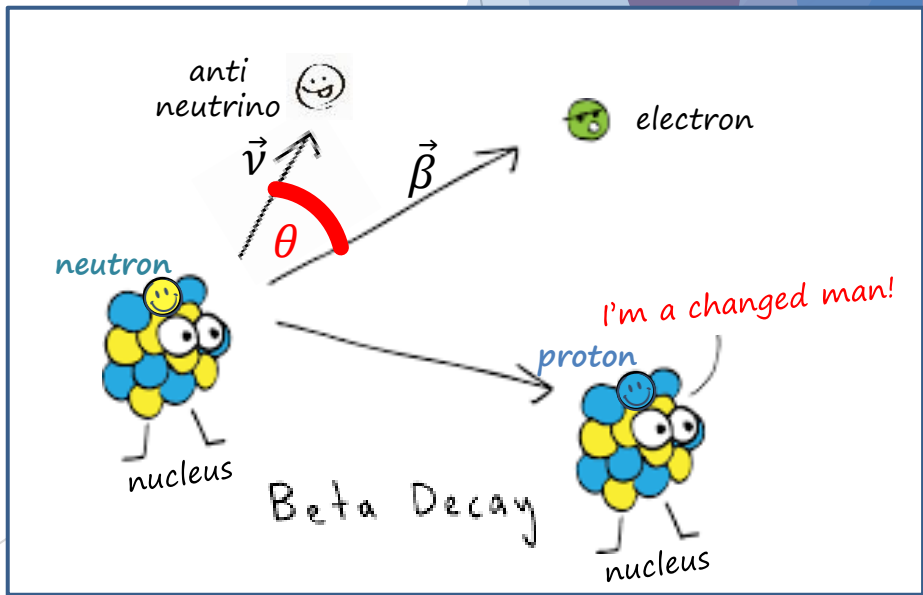

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Measurements *(e.g., Gamow-Teller)*:

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

ϵ_T

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

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

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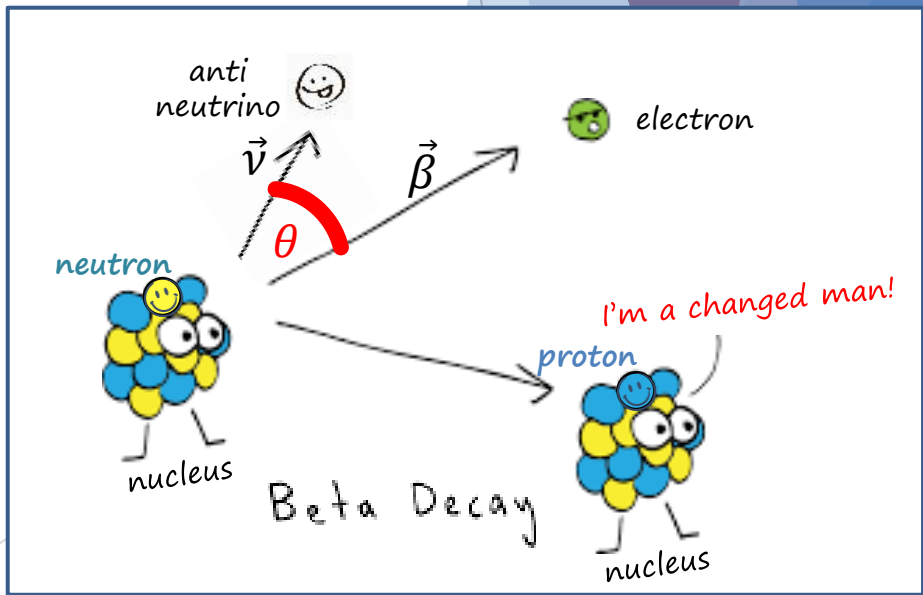

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m_e → electron's mass, E → energy

$a_{\beta\nu}$, b_{F}: Observables

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- **Energy spectrum**: Fierz term $b_{\mathrm{F}}^{\beta^{\mp}} \overset{\text{SM}}{=} 0$

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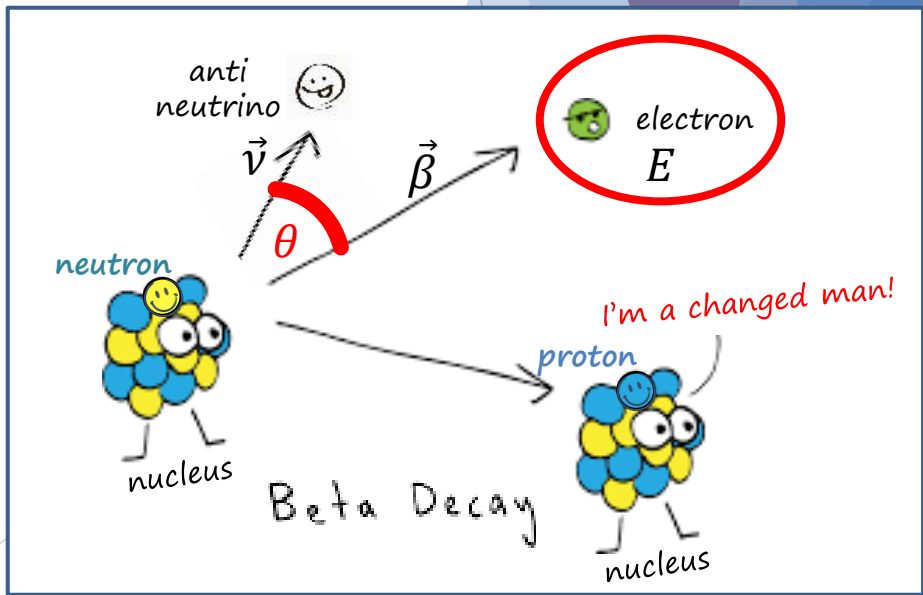

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m_e → electron's mass, E → energy

$a_{\beta\nu}$, b_{F} → Observables

Similar terms for Fermi ($C_T \to C_S$)

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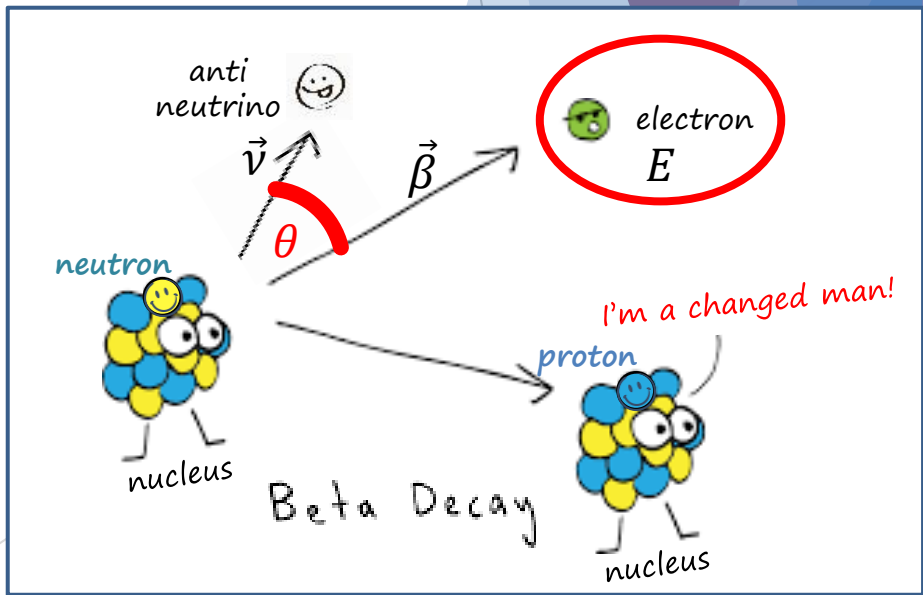

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Measurements *(e.g., Gamow-Teller)*:

Assuming a TeV scale

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  - Quadratic in C_T^+, C_T^-
- **Energy spectrum**: Fierz term $b_{\mathrm{F}}^{\beta^\mp} \overset{\text{SM}}{=} 0 \pm \frac{\overset{\text{BSM}}{C_T^+}}{C_A} \sim 10^{-3}$
  - Vanishes for right-handed neutrinos ($C_T^+ = 0$)

new experiments aim $\lesssim 10^{-3}$ precision level

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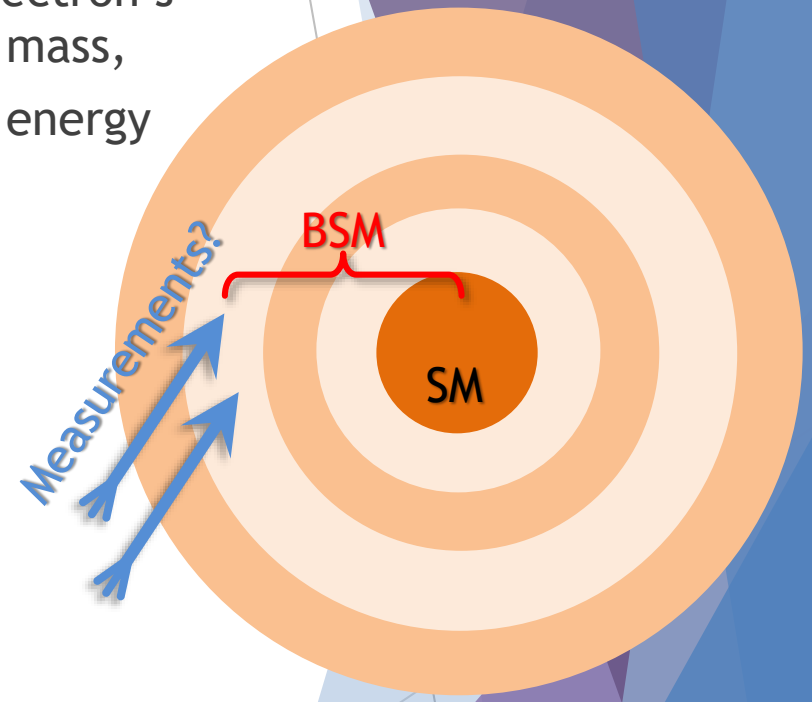

Searches for deviations from the SM "V-A" structure

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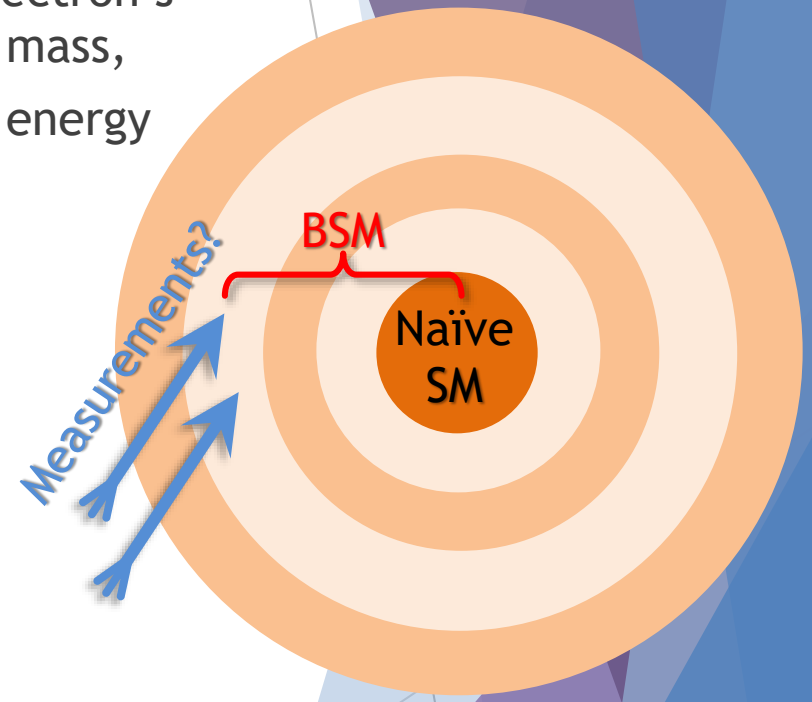

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$\boldsymbol{q \to 0}$

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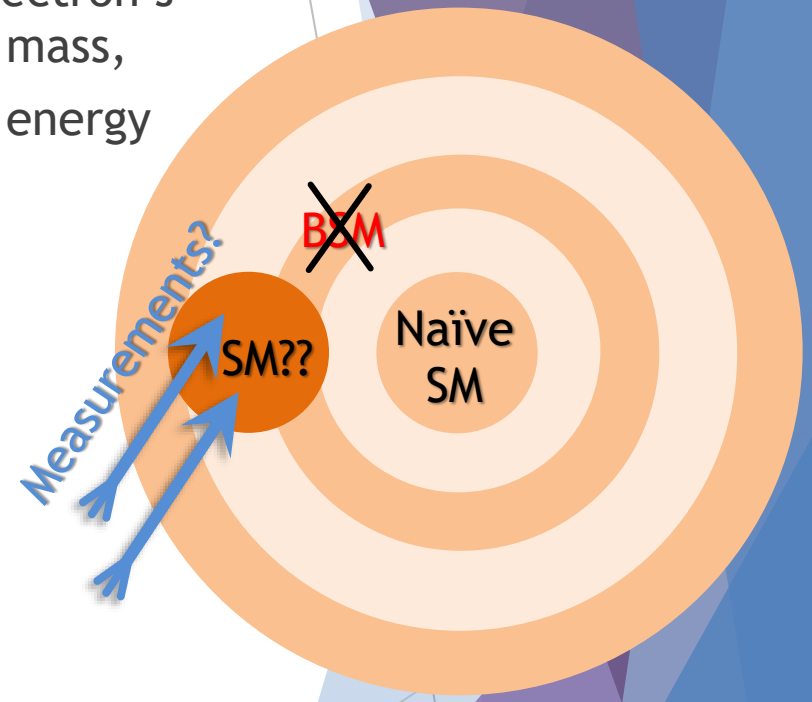

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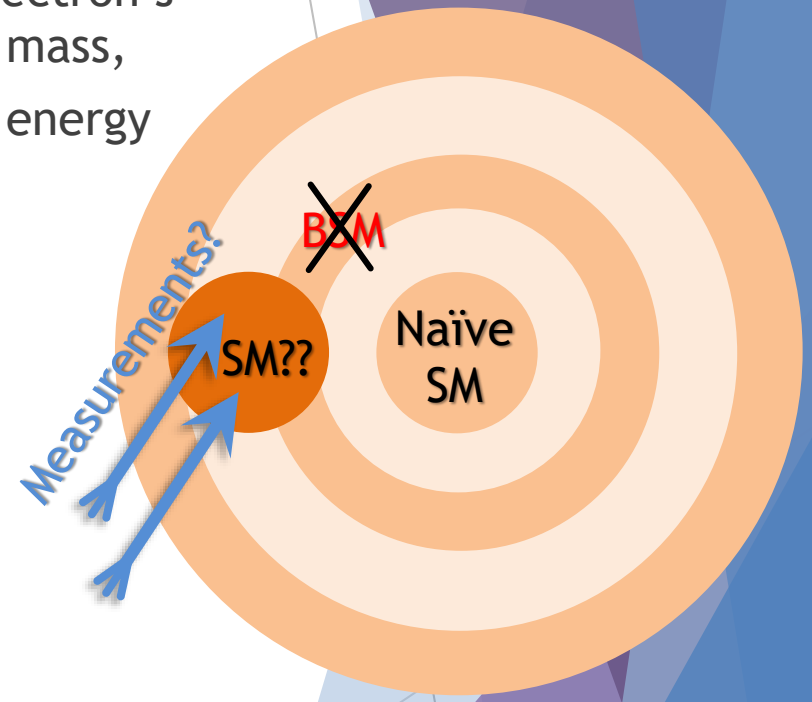

Searches for deviations from the SM "V-A" structure

>> An accurate theory is needed

Their structure corrections

Identifying small parameters

q – momentum transfer
R – nucleus's radius
m_N – nucleon's mass
P_{fermi} - Fermi momentum
α – fine structure constant
Z - final nucleus's charge

- Kinematic parameters – β-decays have low momentum transfer:
  - $\epsilon_{qr} \sim qR \approx 0.01A^{1/3}$ *
  - $\epsilon_{\text{recoil}} \sim \frac{q}{m_N} \approx 0.002$ *
- The nuclear model:
  - $\epsilon_{\text{NR}} \sim \frac{P_{\text{fermi}}}{m_N} \approx 0.2$
  - $\epsilon_{\text{EFT}} \sim 0.1$
- The Coulomb force:
  - $\epsilon_c \sim \alpha Z \approx 0.007Z$
- Numeric calculation:
  - ϵ_{solver}

* For an endpoint of $\sim 2\ MeV$

AGM & Gazit, J.Phys.G 2022

SM corrections

- β-decay rate:

$$d\omega \propto \left|\langle \psi_f \| \hat{H}_W \| \psi_i \rangle\right|^2 \quad \overset{\textit{e.g., Gamow-Teller}}{\propto} \quad 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E}$$

Observables

Identifying small parameters

$$\epsilon_{\mathrm{NR}} \sim \frac{P_{\mathrm{fermi}}}{m_N} \approx 2\cdot 10^{-1}$$
$$\epsilon_{\mathrm{EFT}} \sim 1\cdot 10^{-1}$$
$$\epsilon_{qr} \sim qR \approx 5\cdot 10^{-2}$$
$$\epsilon_{c} \sim \alpha Z_f \approx 2\cdot 10^{-2}$$
$$\epsilon_{\mathrm{recoil}} \sim \frac{q}{m_N} \approx 4\cdot 10^{-3}$$

AGM & Gazit, J.Phys.G 2022

SM corrections

- β-decay rate:

$$d\omega \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \propto 1 + a_{\beta\nu}\vec{\beta}\cdot\hat{\nu} + b_{\mathrm{F}}\frac{m_e}{E}$$

e.g., Gamow-Teller

Angular correlation

SM: $-\frac{1}{3}(1+\delta_a)$ — SM correction

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

Identifying small parameters

$$\epsilon_{\mathrm{NR}} \sim \frac{P_{\mathrm{fermi}}}{m_N} \approx 2\cdot 10^{-1}$$
$$\epsilon_{\mathrm{EFT}} \sim 1\cdot 10^{-1}$$
$$\epsilon_{qr} \sim qR \approx 5\cdot 10^{-2}$$
$$\epsilon_c \sim \alpha Z_f \approx 2\cdot 10^{-2}$$
$$\epsilon_{\mathrm{recoil}} \sim \frac{q}{m_N} \approx 4\cdot 10^{-3}$$

Multipole Expansion

AGM & Gazit, J.Phys.G 2022

SM corrections

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e.g., Gamow-Teller

Angular correlation → SM correction: $-\frac{1}{3}(1+\delta_a)$

Fierz term → SM correction: $0+\delta_b$

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

$\sim \epsilon_{\mathrm{NR}}\epsilon_{qr}, \epsilon_{\mathrm{recoil}} \sim 10^{-2}$; $\sim 5\cdot 10^{-4}$

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Multipole Expansion

AGM & Gazit, J.Phys.G 2022

SM corrections

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Multipole operator's matrix elements between the nuclear states

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

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Multipole Expansion

General Theory
for any nucleus & transition
(allowed & forbidden)

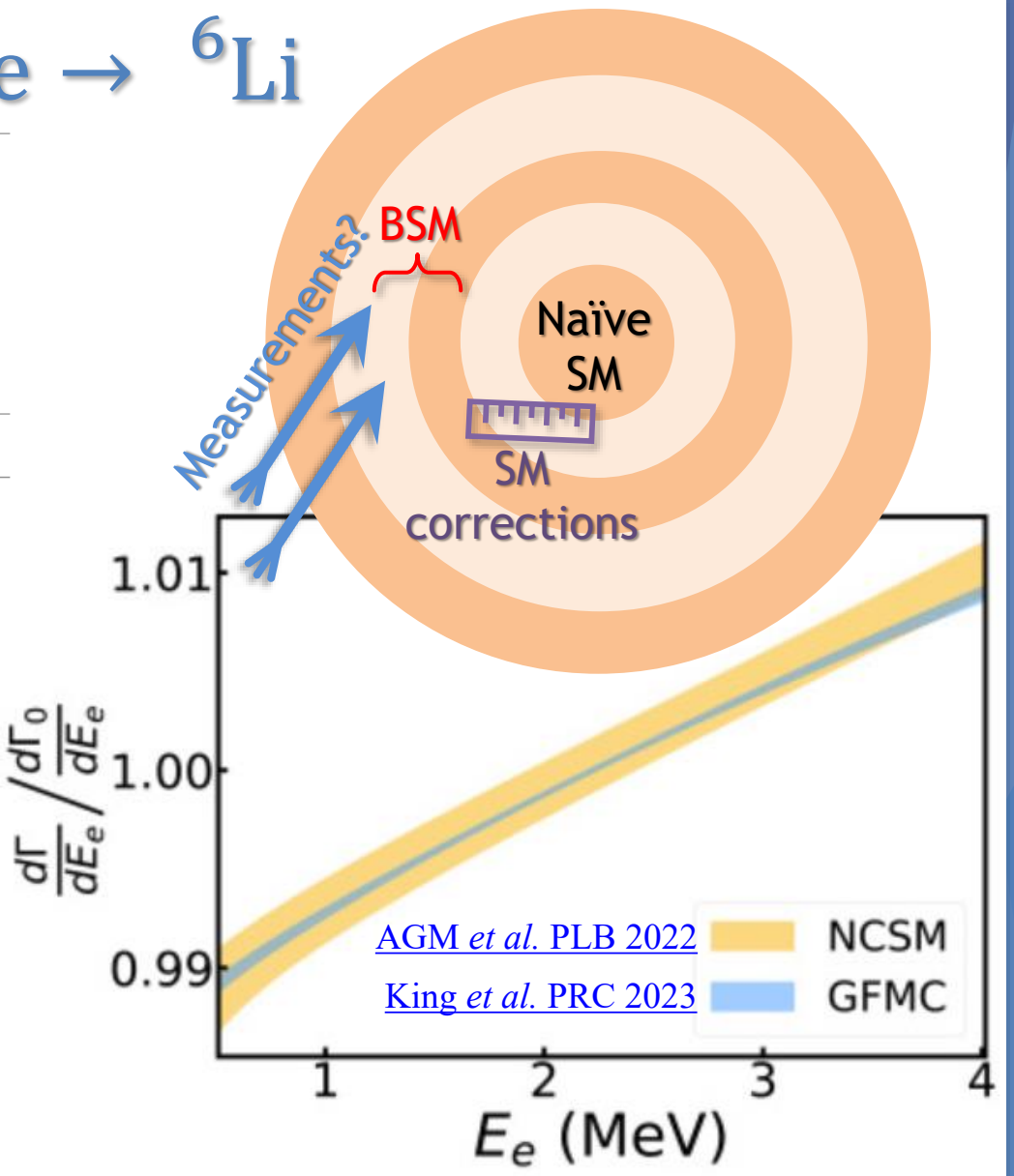
AGM & Gazit, J.Phys.G 2022

Observable	Symbol	AGM *et al.* PLB 2022 NCSM [13]	King *et al.* PRC 2023 GFMC [15]
Fierz-like term	δ_b	$-1.52\,(18)\times10^{-3}$	$-1.47\,(3)\times10^{-3}$
Angular-correlation correction	$\langle\,\tilde{\delta}_a\,\rangle$	$-2.54\,(68)\times10^{-3}$	$-1.43\,(20)\times10^{-3}$
Total extracted angular-correlation	a	$-0.3331\,(32)$	$-0.3327\,(30)$
Multipole operator	Symbol	NCSM [13]	GFMC [15]
Longitudinal	$\langle\,\hat{L}_1^A / i\,\rangle$	0.464(16)	$-0.447\,(7)$
Electric	$\langle\,\hat{E}_1^A / i\,\rangle$	0.657(23)	$-0.633\,(10)$
Magnetic 1 / MeV	$\langle\,\hat{M}_1^V / iq\,\rangle$	$-1.36\,(15)\times10^{-3}$	$1.36\,(2)\times10^{-3}$
Coulomb 1 / MeV	$\langle\,\hat{C}_1^A / iq\,\rangle$	$-1.39\,(18)\times10^{-4}$	$1.10\,(5)\times10^{-4}$

Calaprice, PRC 1975

Holstein's form factor	Symbol	NCSM [13]	GFMC [15]	Shell model [231]	Exp. [231]
Gamow–Teller	$\lvert c\rvert$	2.85(14)	2.74(4)		2.75(3)
Weak magnetism	$\lvert b_{\mathrm{WM}}\rvert$	66.7 (8.3)	66.4(1.1)		69.0 (1.0)
Induced tensor	$\lvert d^I\rvert$	7.73(59)	5.37(23)	2.4	
Induced tensor to GT ratio	$\lvert d^I / (Ac)\rvert$	0.45(4)	0.33(1)	0.12	2.0 (1.5)

Sargsyan, King, AGM & Seng, PPNP 2026



Forbidden decays

Nuclear β-decay

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

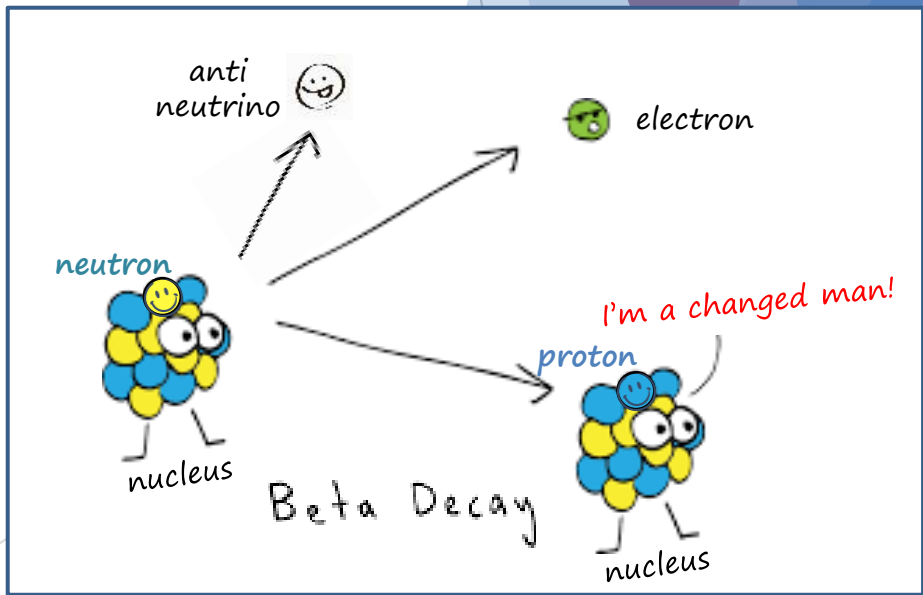
angular momentum

parity

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

"Allowed" (when $q \to 0$)	• Fermi (0^+) • Gamow-Teller (1^+)
"Forbidden" (vanish for $q \to 0$)	• All the rest $(J^{\Delta\pi})$

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

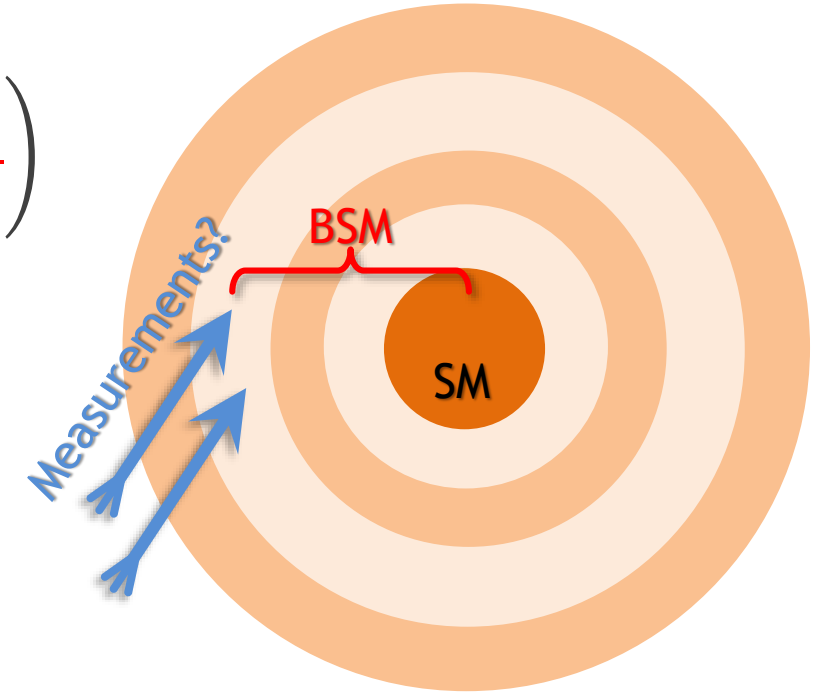


Allowed decays

$$d\Gamma \propto \left|\langle \psi_f \| \hat{H}_W \| \psi_i \rangle\right|^2 \propto 1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu}$$

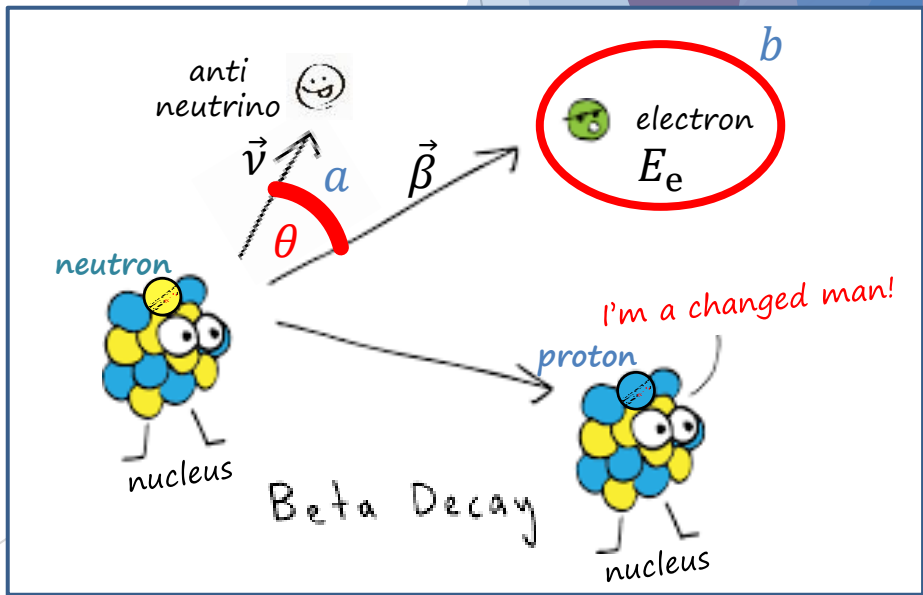
		SM		BSM
1)	$\boldsymbol{b}$ =	0	$\pm$	$\frac{C_T^+}{C_A}$

2) $$\boldsymbol{a} = -\frac{1}{3}\left(1 - \frac{\left|C_T^+\right|^2 + \left|C_T^-\right|^2}{4\left|C_A\right|^2}\right)$$



(E.g., Gamow-Teller)

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

Unique forbidden decays

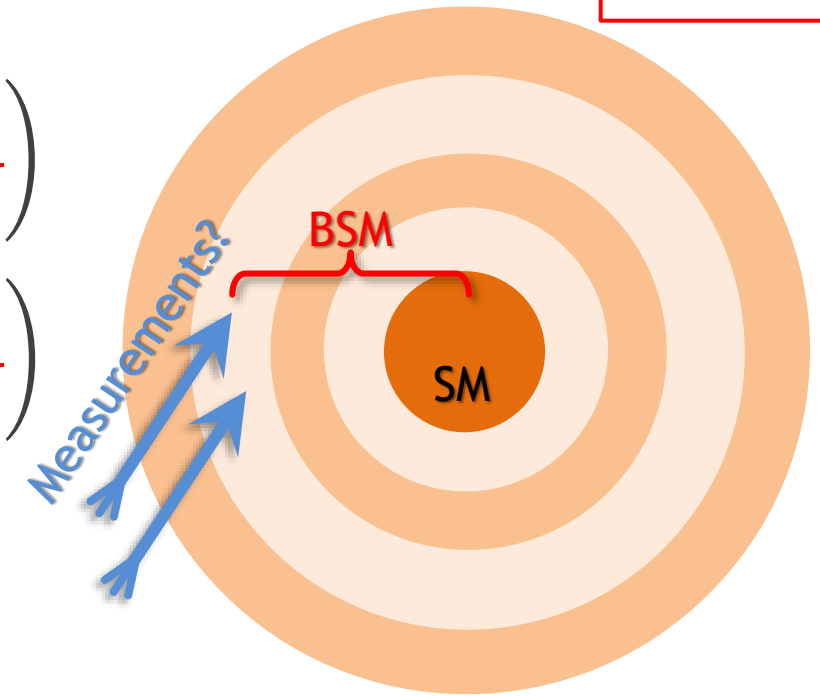
$$d\Gamma \propto \left|\langle \psi_f \| \hat{H}_W \| \psi_i \rangle\right|^2 \propto 1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]$$

AGM & Gazit, PRD 2023

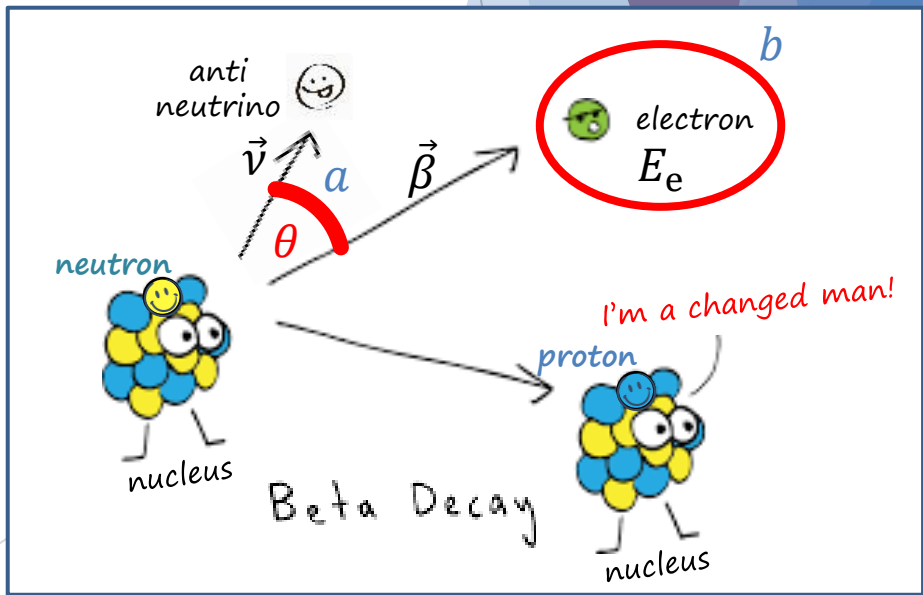
		SM		BSM
1)	$\boldsymbol{b}$	$= 0$	$\pm$	$\frac{C_T^+}{C_A}$
2)	$\boldsymbol{a}$	$= -\frac{1}{5}\left(1 - \frac{\lvert C_T^+\rvert^2 + \lvert C_T^-\rvert^2}{4\lvert C_A\rvert^2}\right)$		
3)	$\boldsymbol{a_2}$	$= \frac{1}{5}\left(1 - \frac{\lvert C_T^+\rvert^2 + \lvert C_T^-\rvert^2}{4\lvert C_A\rvert^2}\right)$		

(E.g., Unique 1st-forbidden)

BSM Predictions & Observables for all forbidden decays



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



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

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Unique Forbidden decays – radiative LO

~~No~~ decay @ $q \to 0$

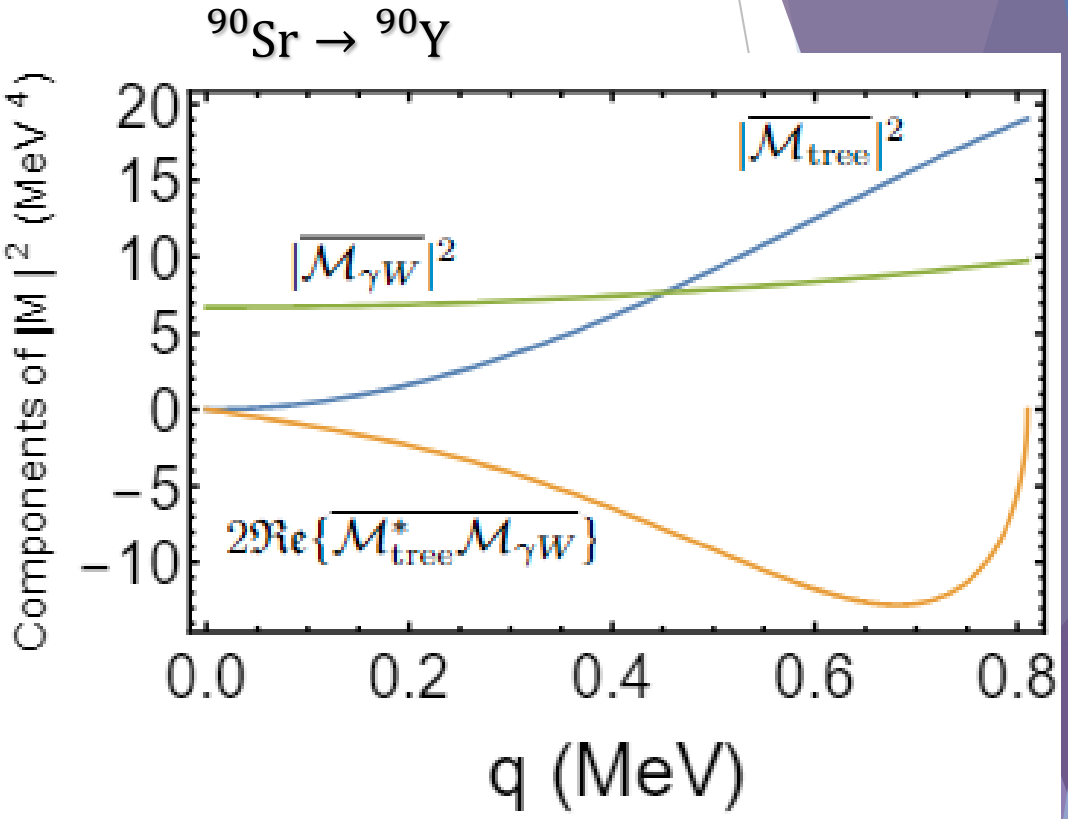
Experiments

@ ORNL, CEA Saclay, HUJI, SOREQ

- New possibilities with MTAS @ORNL

Spectrum is sensitive to:

- Exotic Weak Interactions
- *Light New Physics*



$$d\Gamma \propto \underbrace{f_0 q^0}_{|\overline{\mathcal{M}_{\gamma W}}|^2} + \underbrace{f_1 q^1}_{2\Re e\{\overline{\mathcal{M}^*_{tree}\mathcal{M}_{\gamma W}}\}} + \underbrace{f_2 q^2}_{|\overline{\mathcal{M}_{tree}}|^2}$$

See backup slides for details

Seng, AGM, Cirigliano, PRL 2025

Their structure corrections

Accuracy: Nuclear structure corrections

$$d\Gamma \propto \left|\langle\psi_f\|\hat{H}_W\|\psi_i\rangle\right|^2 \propto 1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]$$

SM correction: $1 + \delta_1$

SM correction: $0 + \delta_b$

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

SM correction: $\frac{1}{5}(1 + \delta_{a_2})$

Multipole operator's matrix elements between the nuclear states

$$\delta = f\left(\frac{\langle\psi_f\|\hat{M}^V_J\|\psi_i\rangle}{\langle\psi_f\|\hat{L}^A_J\|\psi_i\rangle}, \frac{\langle\psi_f\|\hat{C}^A_J\|\psi_i\rangle}{\langle\psi_f\|\hat{L}^A_J\|\psi_i\rangle}\right) + \mathcal{O}\left(\epsilon_{qr}^2, \epsilon_c^2\right)$$

$\sim \epsilon_{\mathrm{NR}}\epsilon_{qr} \sim 10^{-2}$ $\qquad$ $\sim 10^{-4}$

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Multipole Expansion

General Theory – for any transition & nucleus

Uncertainty Quantification

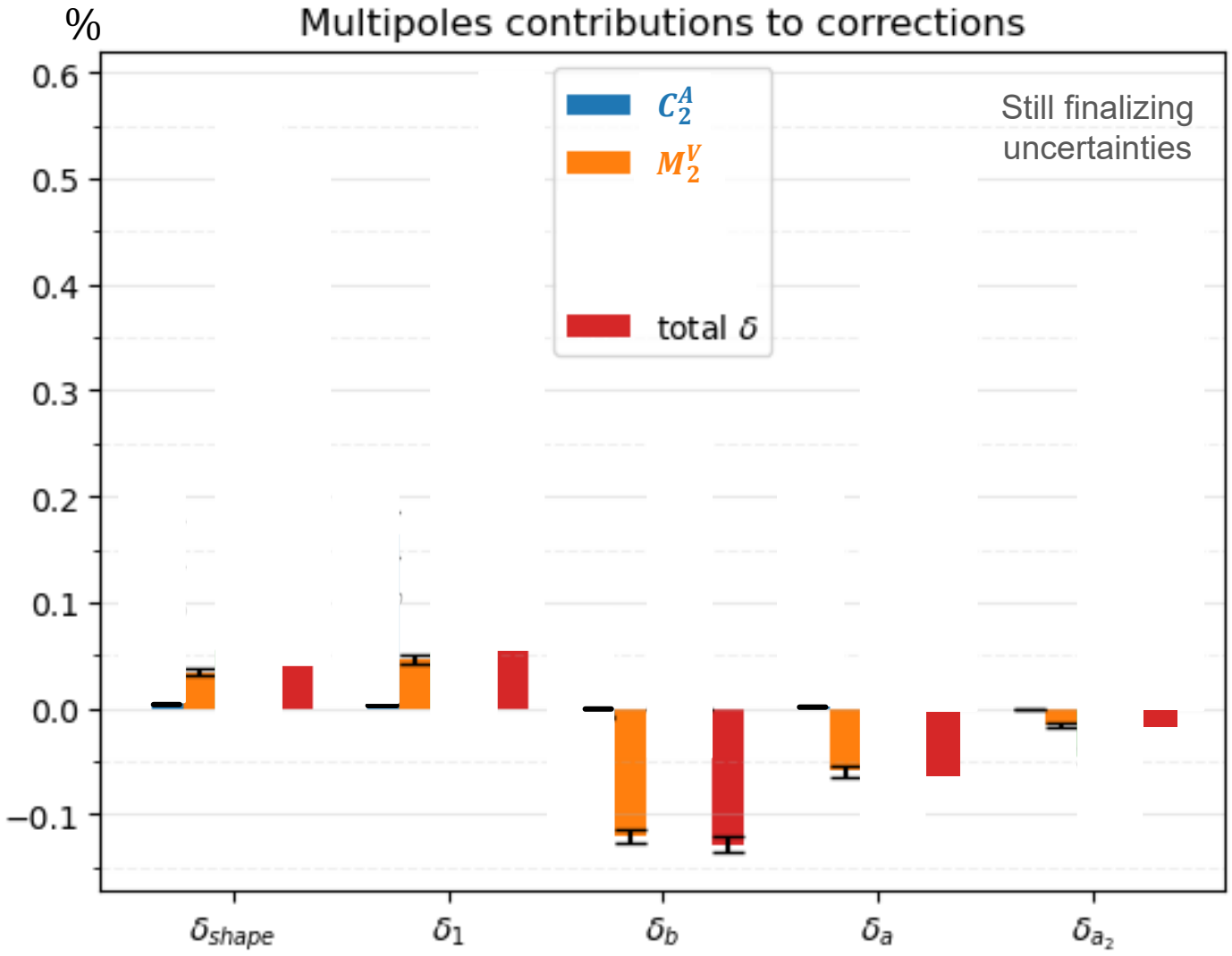
AGM & Gazit, J.Phys.G 2022

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

Leading Order: $L_2^{A(0)}$ (~ Holstein's *c*)

The known corrections:

- Weak Magnetism M_2^V (~ Holstein's *b*)
- Induced Tensor C_2^A (~ Holstein's *d*)



AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

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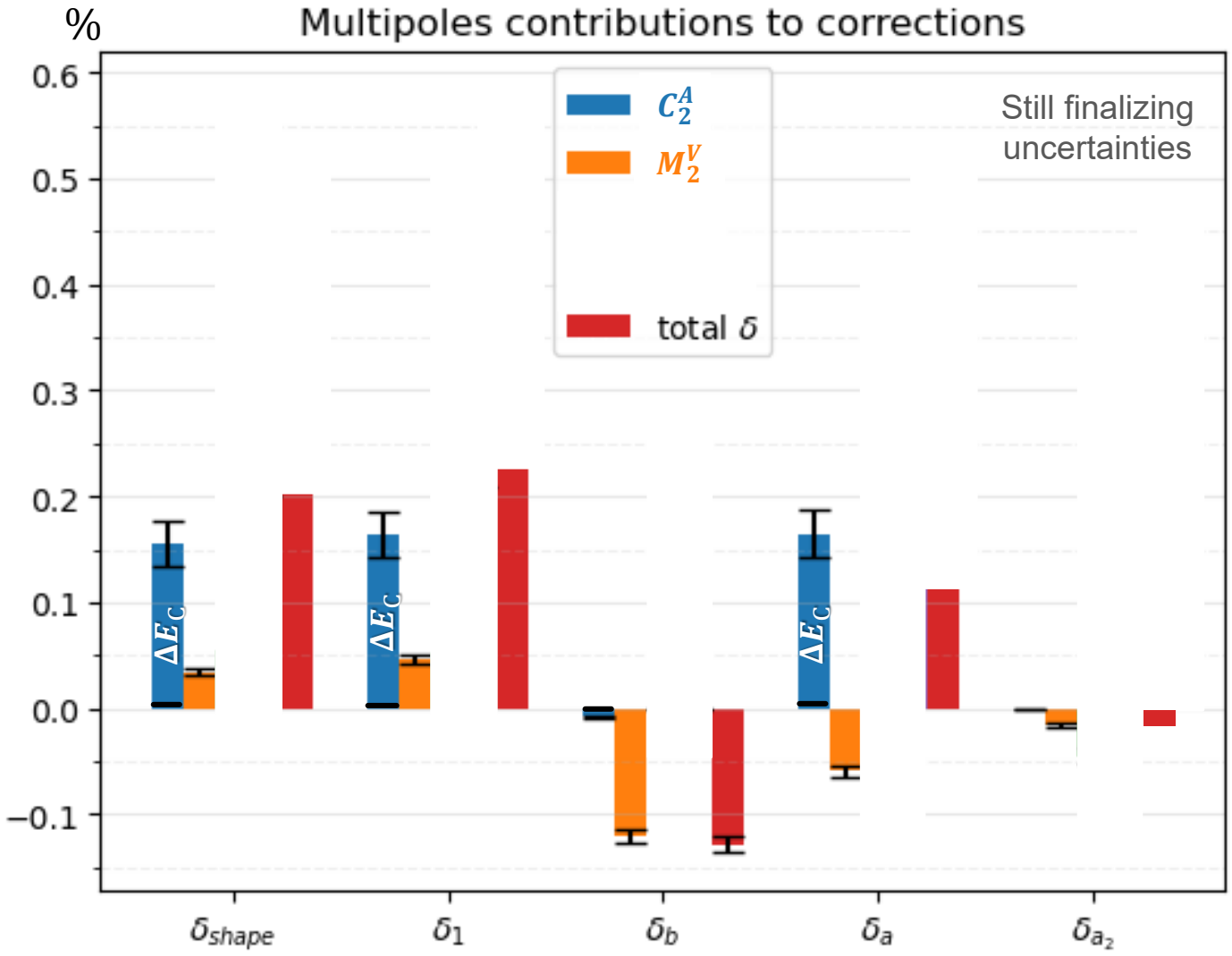
- $C_2^A \propto E_0 + \Delta E_c$

Coulomb Displacement Energy!



AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

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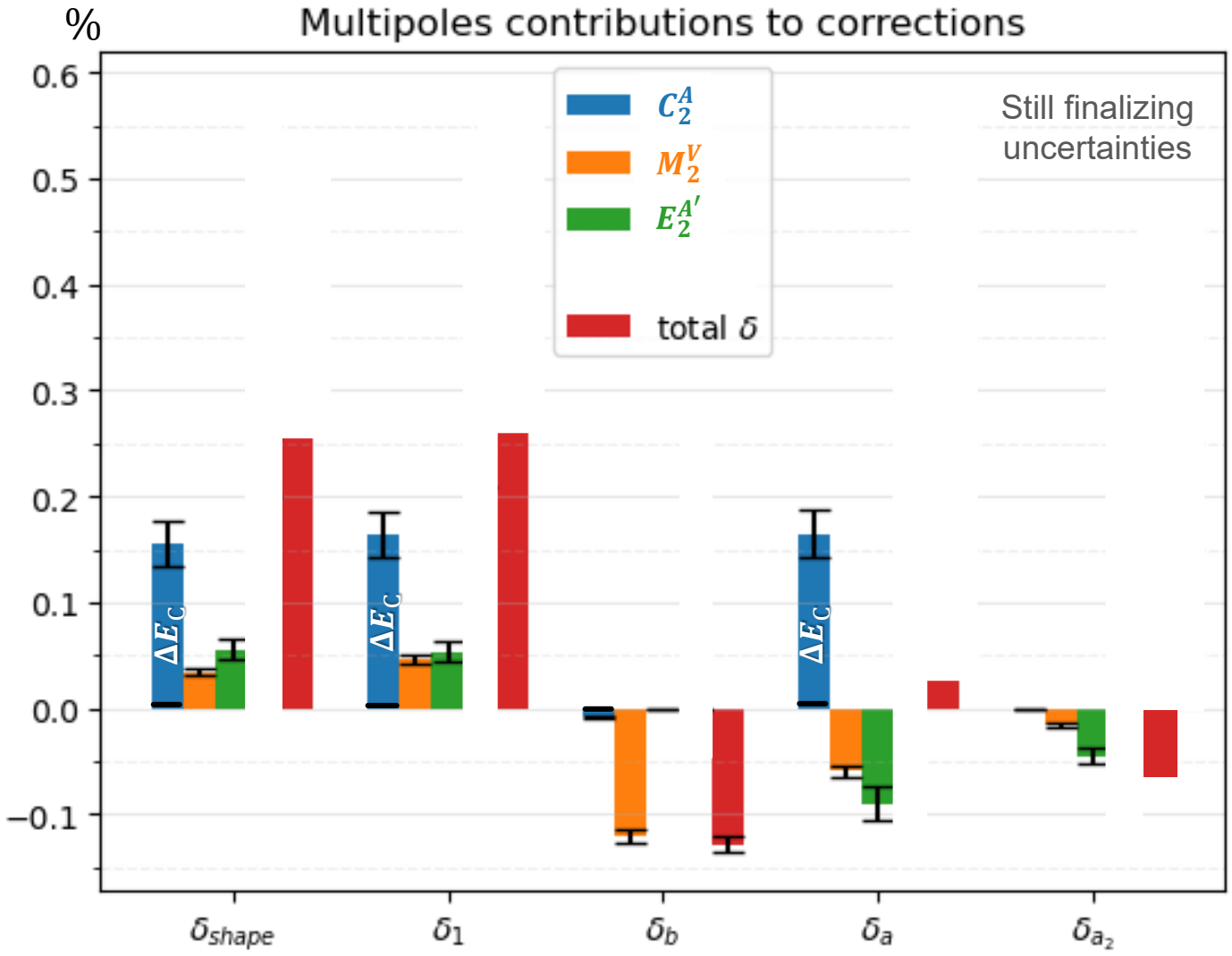
- $E_2^A \propto L_2^A + \underbrace{\mathcal{O}(\epsilon_{qr}^2)}_{E_2^{A'} \sim 10^{-3}}$



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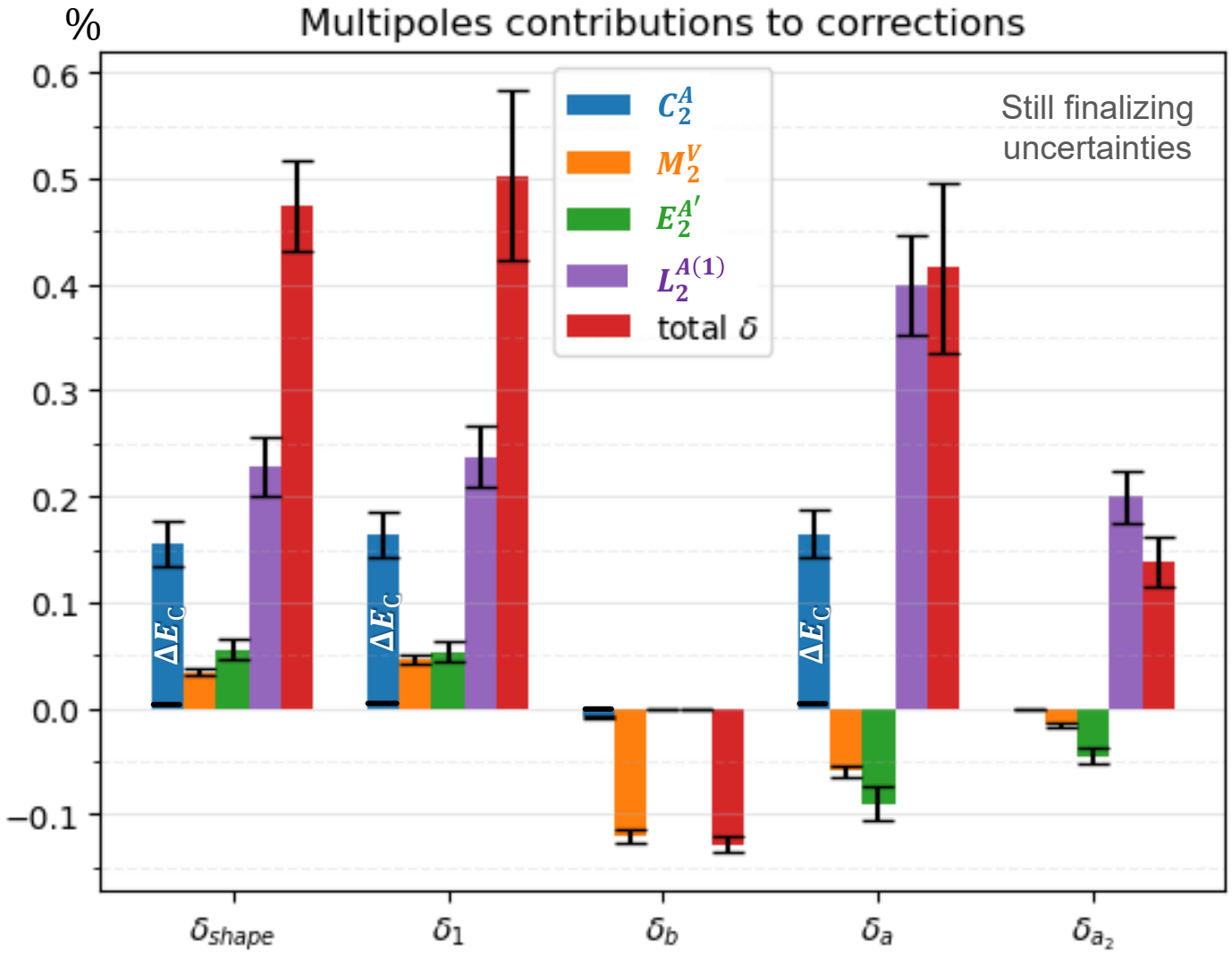

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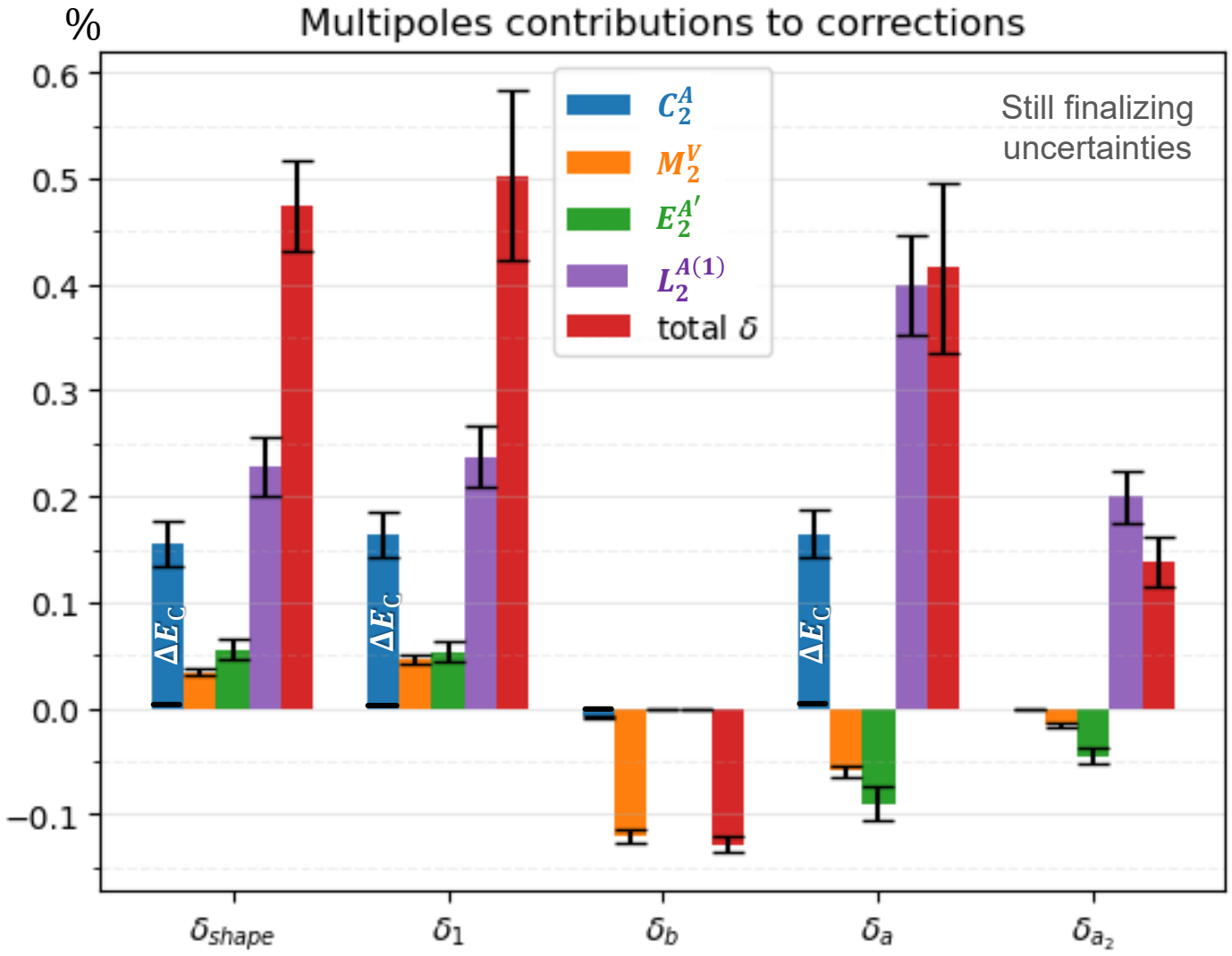
- Well-known WM $\boldsymbol{M_2^V}$ & $\boldsymbol{C_2^A}$ are relatively small
- Dominant Coulomb correction $\boldsymbol{\Delta E_c}$
- Higher-order axial corrections $\boldsymbol{E_2^{A'}}$ & $\boldsymbol{L_2^{A(1)}}$ are the dominant



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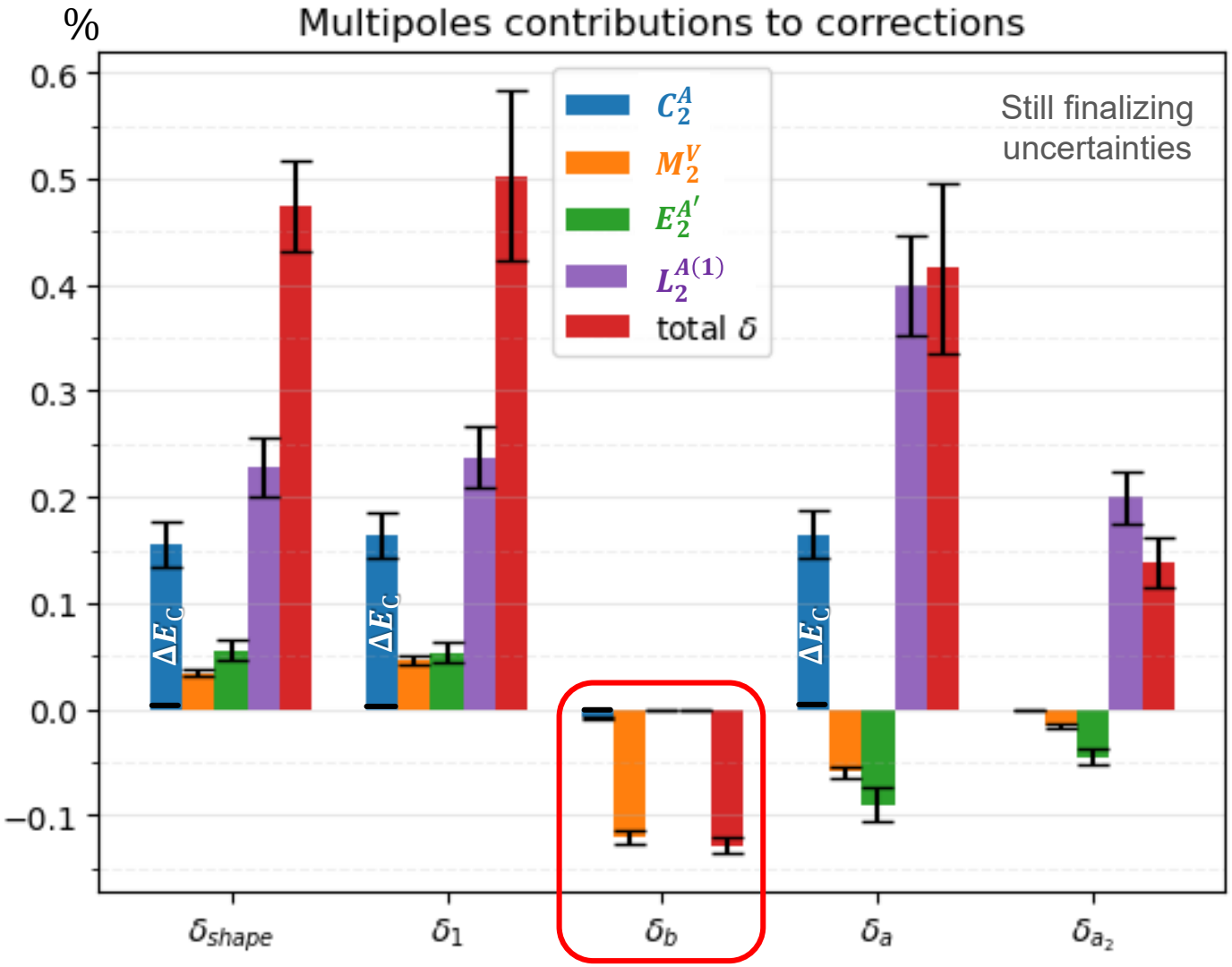
- b's structure corrections are different:
  - Not affected by the dominant higher-order axial contributions $E_2^{A'}$ & $L_2^{A(1)}$
  - Suppressed Coulomb correction ΔE_c
  - leaving only the weak magnetism M_2^V



AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

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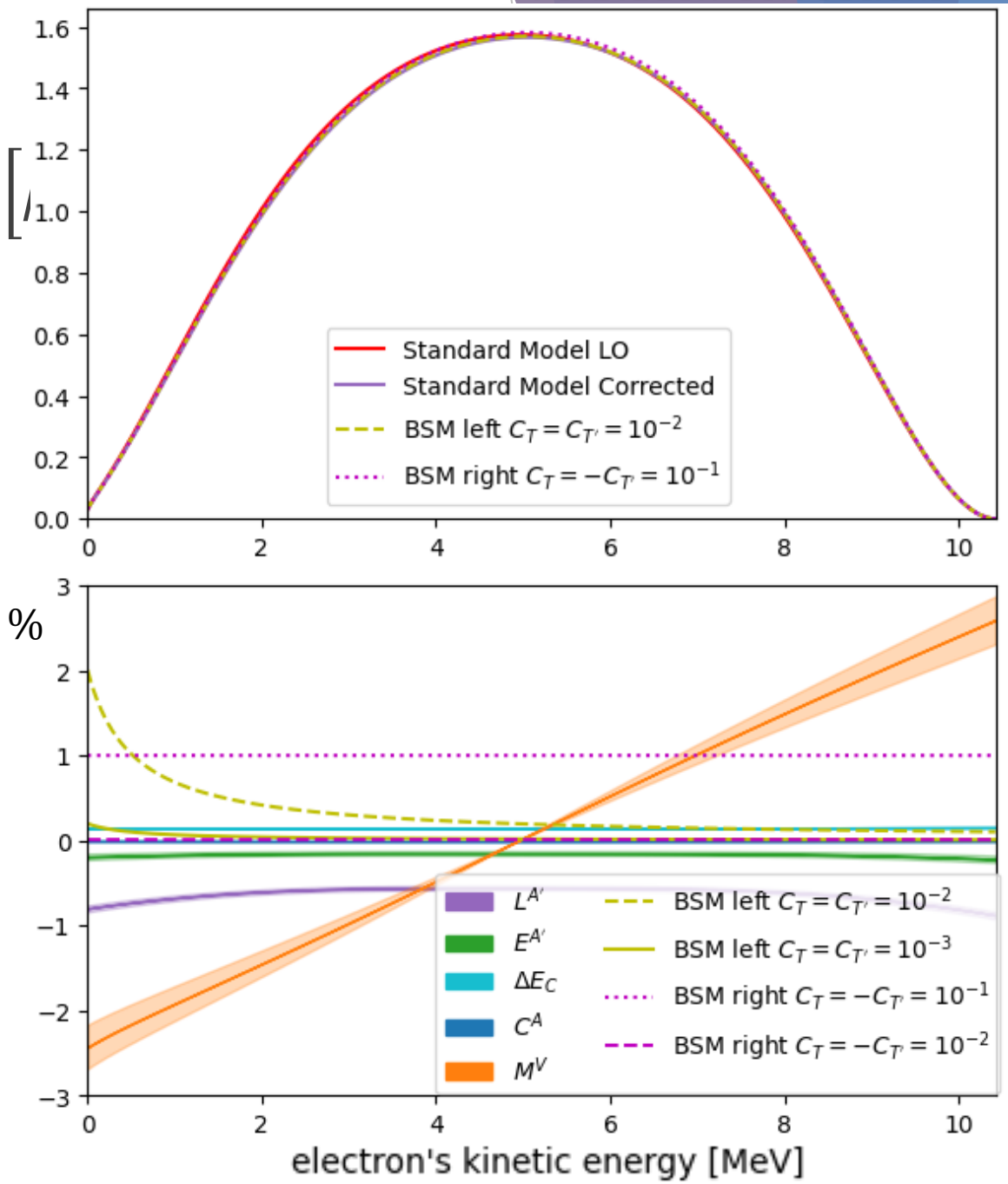

AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

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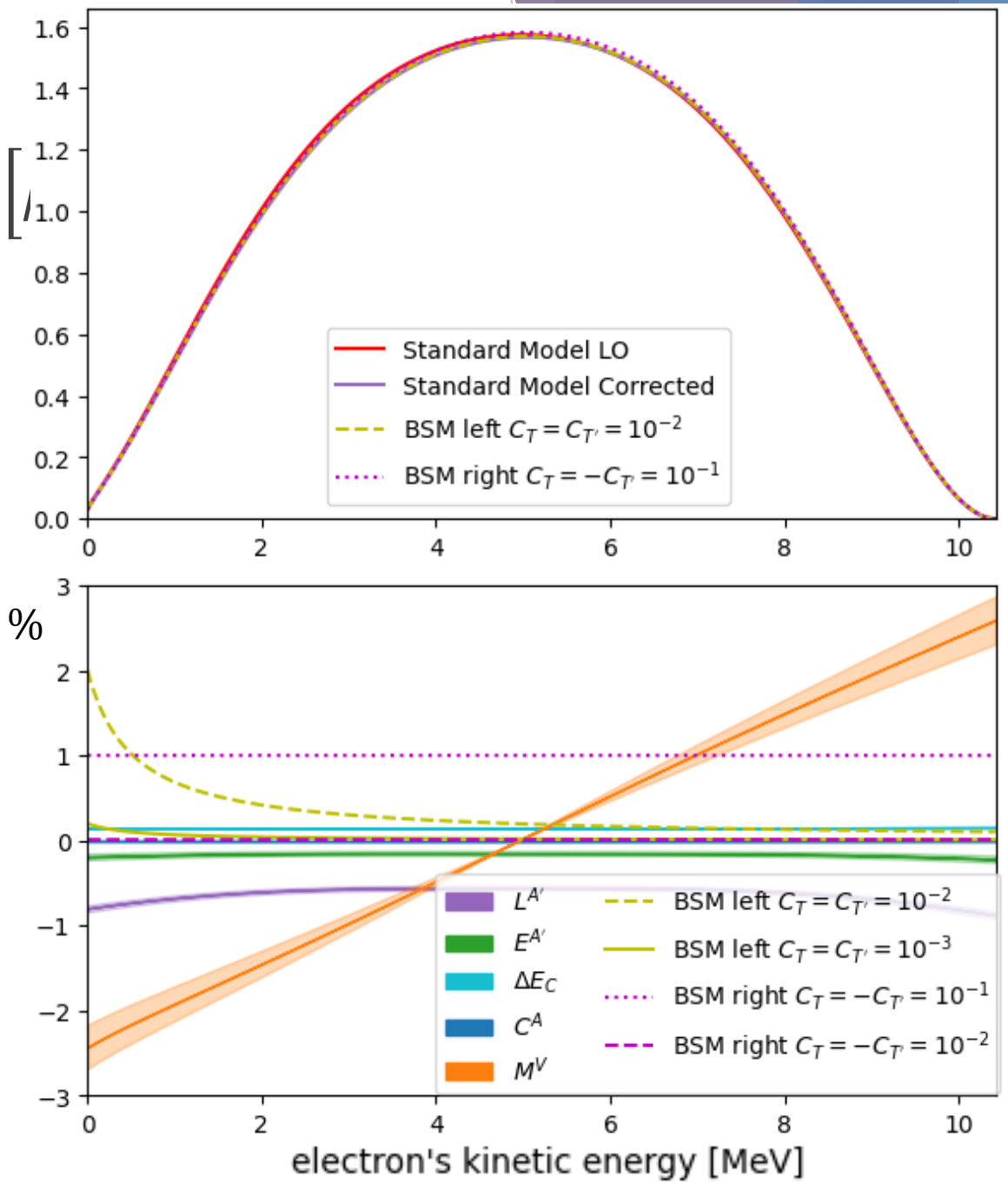
- Corrections are smaller near the spectral maximum ("peak")
- LO spectrum is symmetric around the peak
- **BSM b** produces an energy distortion $\propto \frac{m_e}{E_e}$
- Corrections (but M_2^V) are **independent of E_e**



AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

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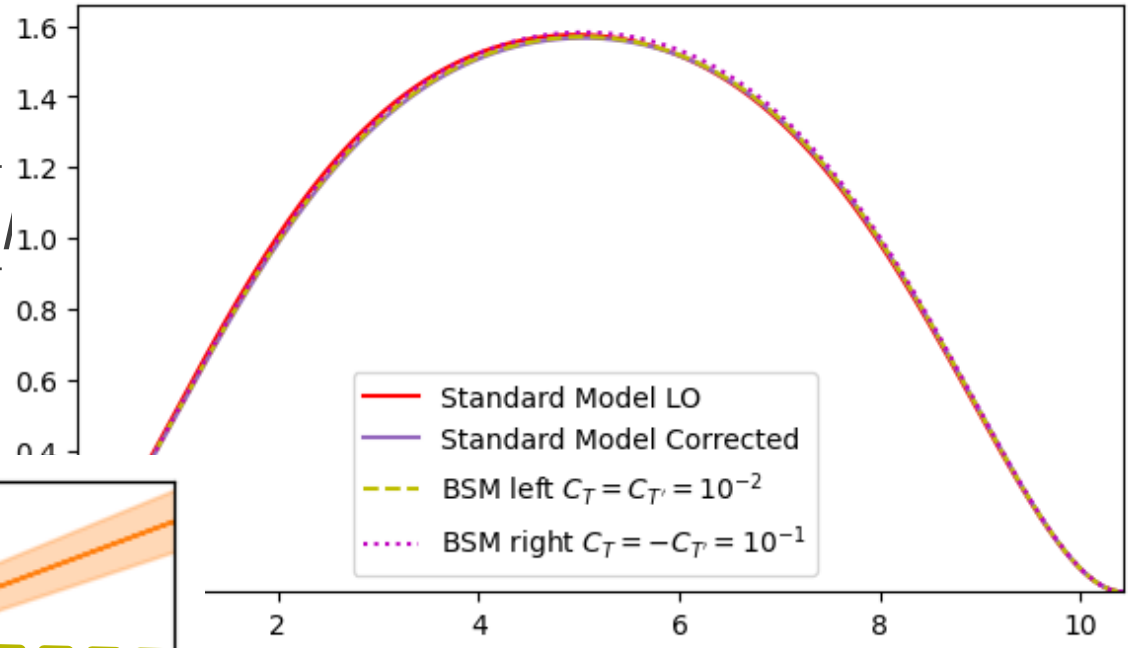
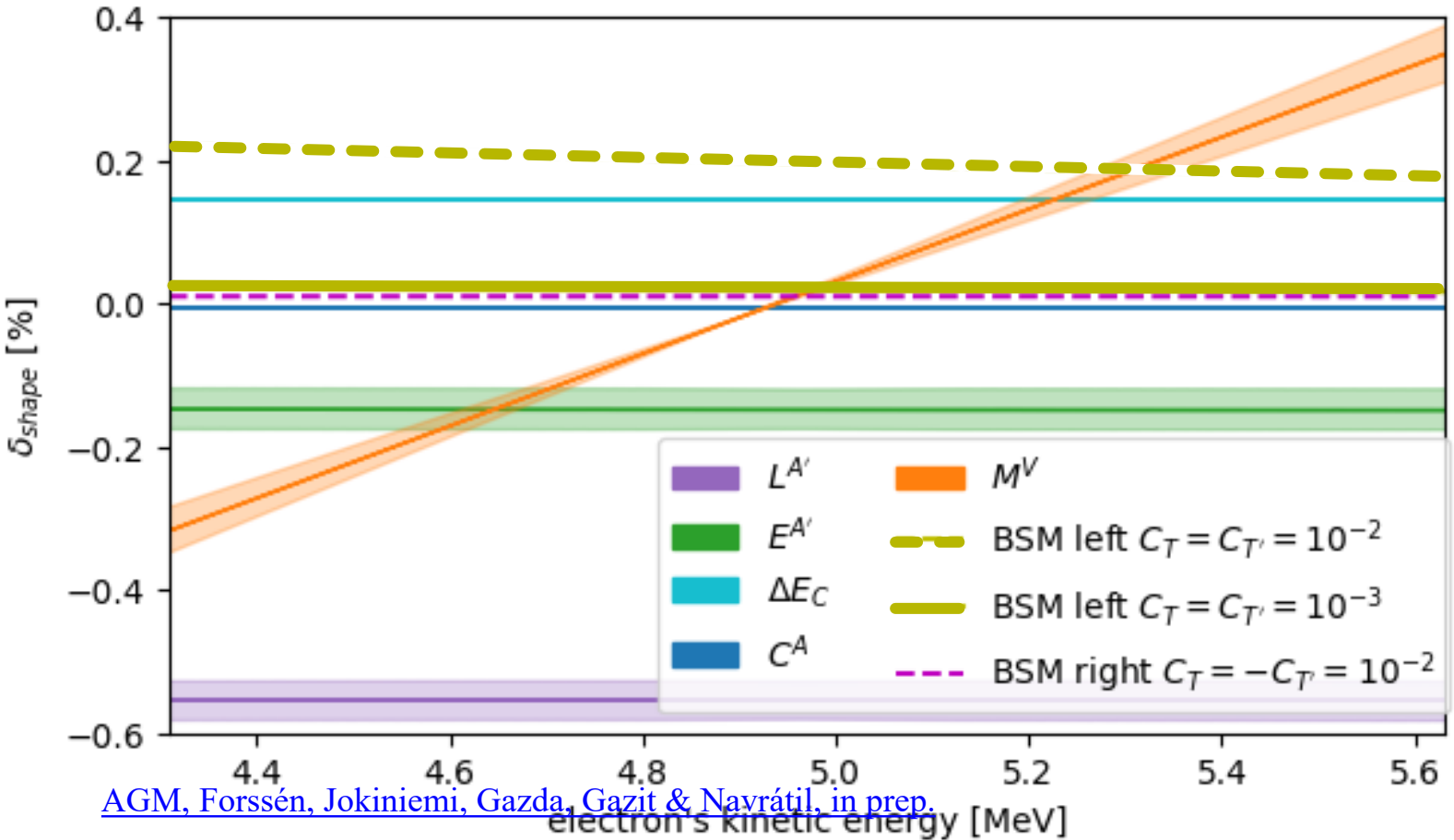
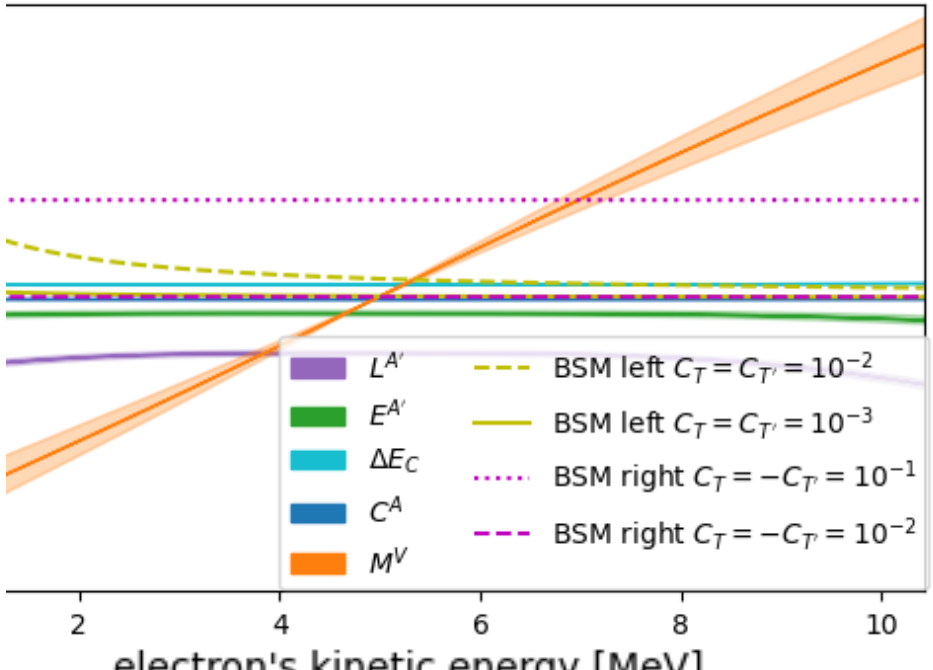
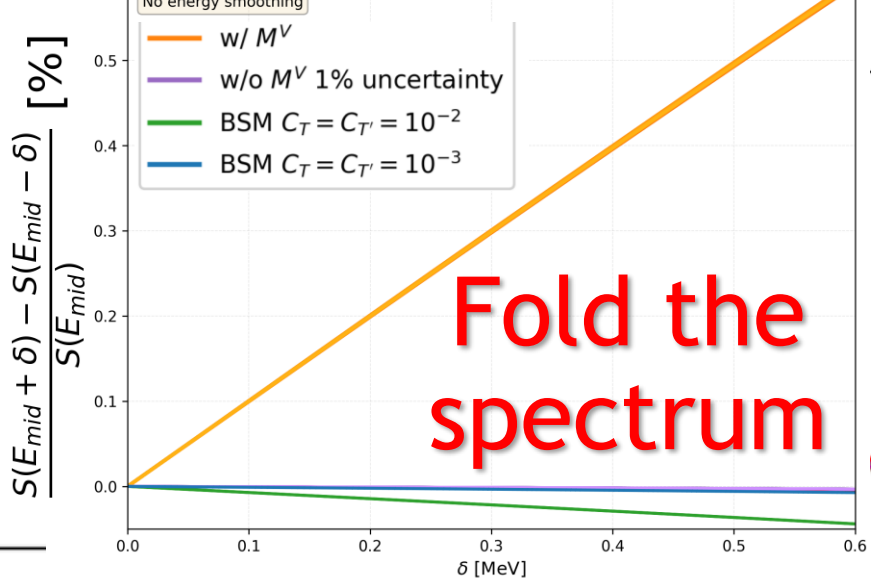


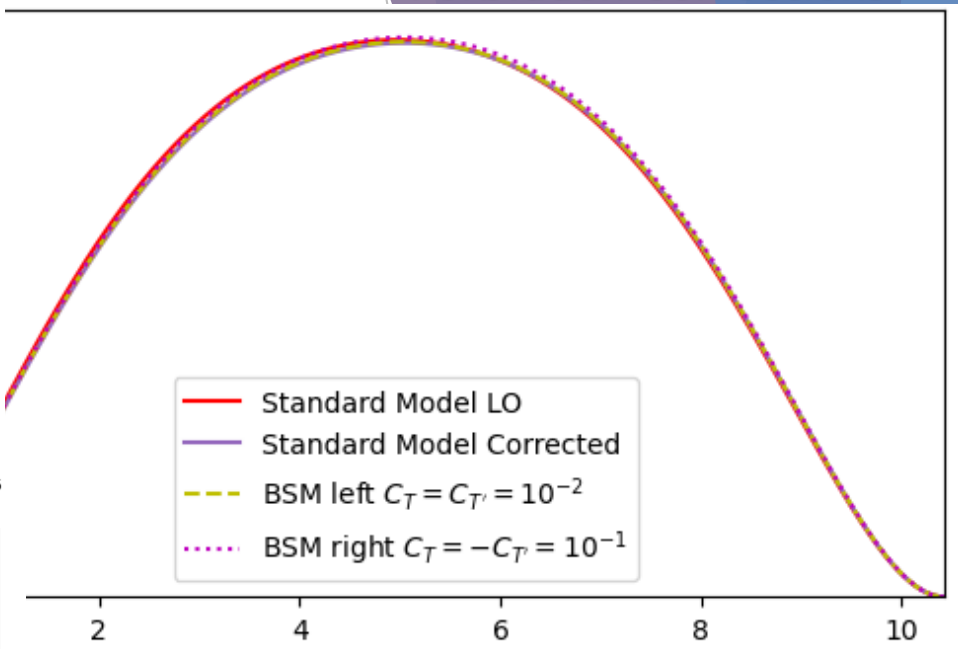


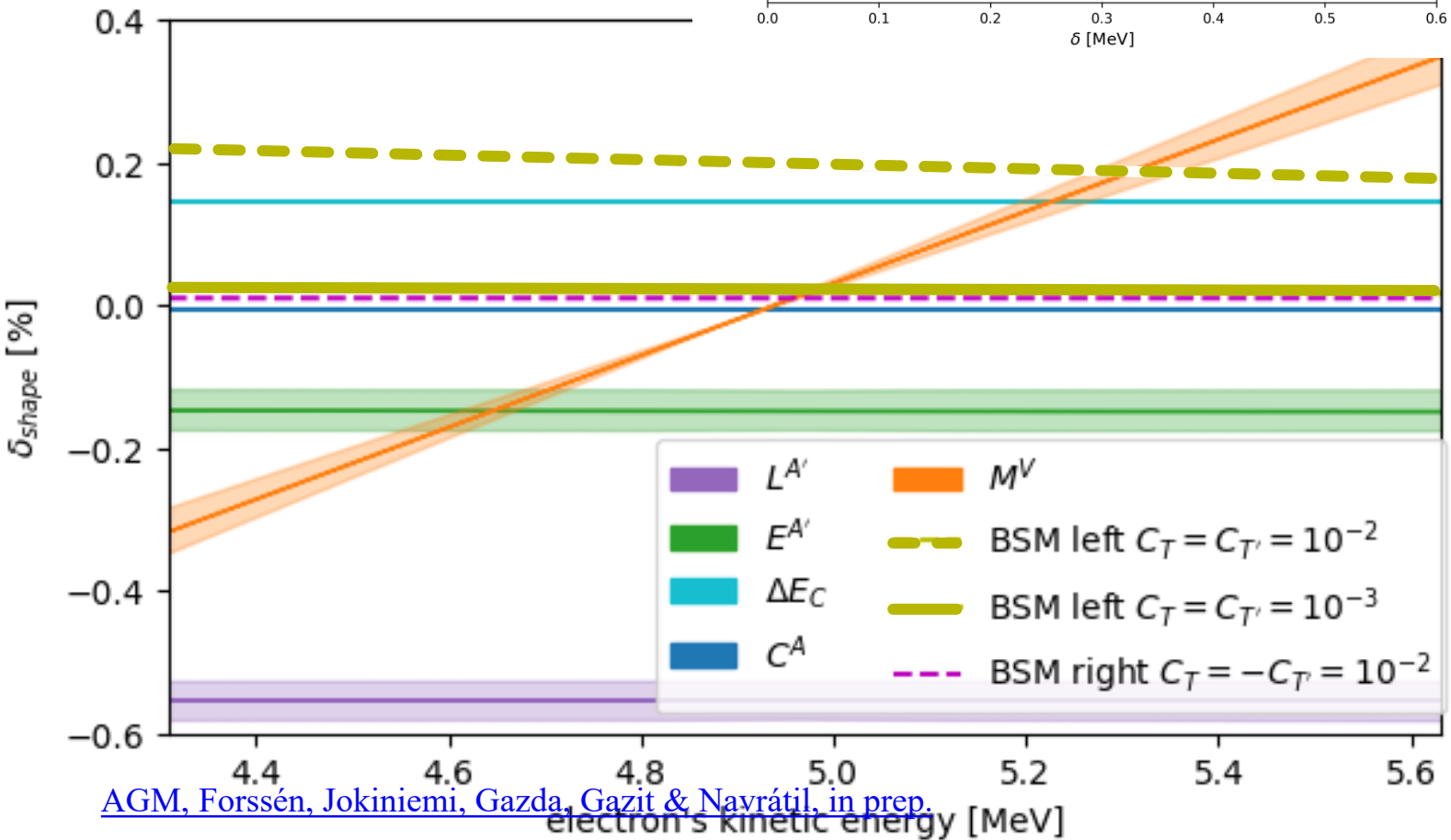


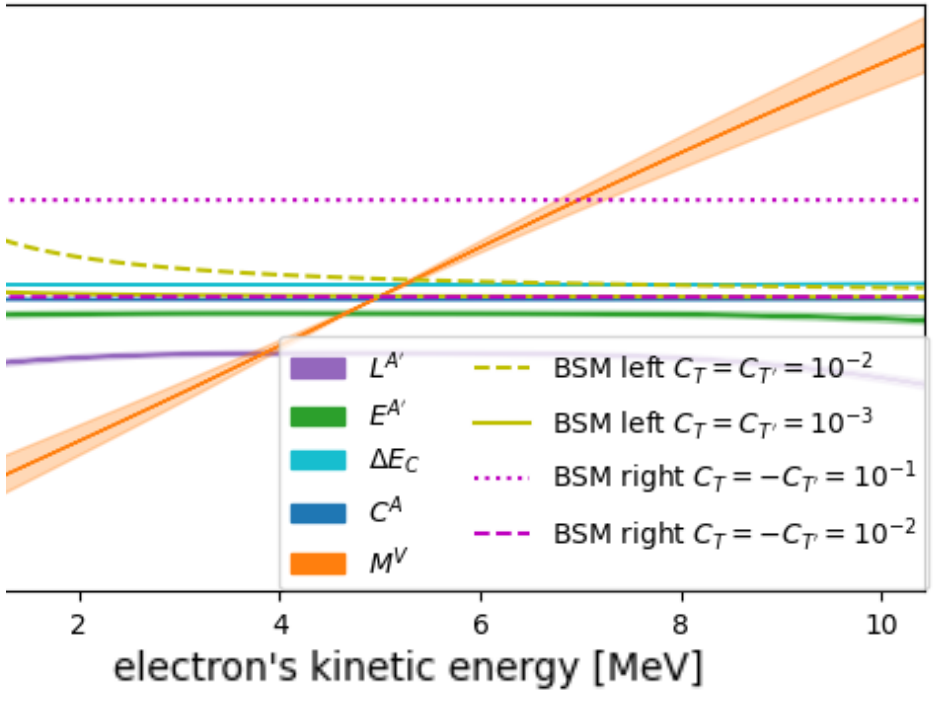
AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

Fold the spectrum

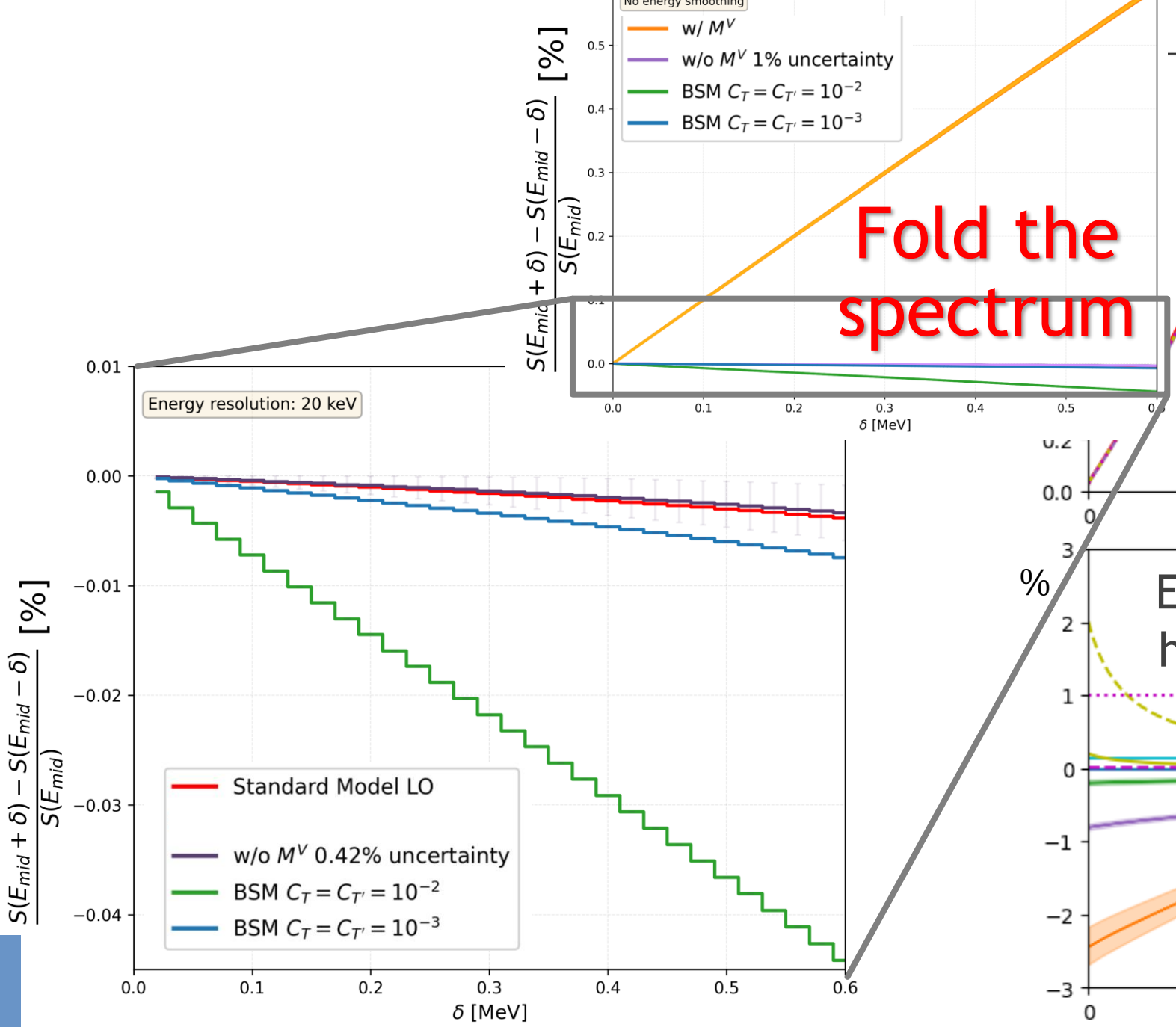




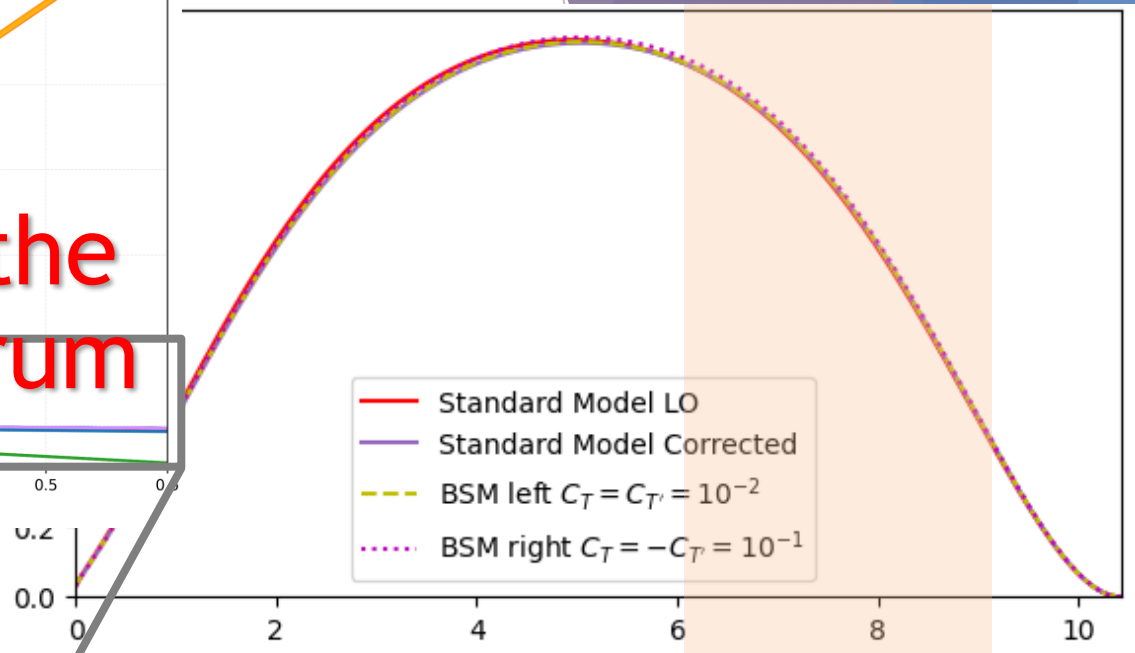


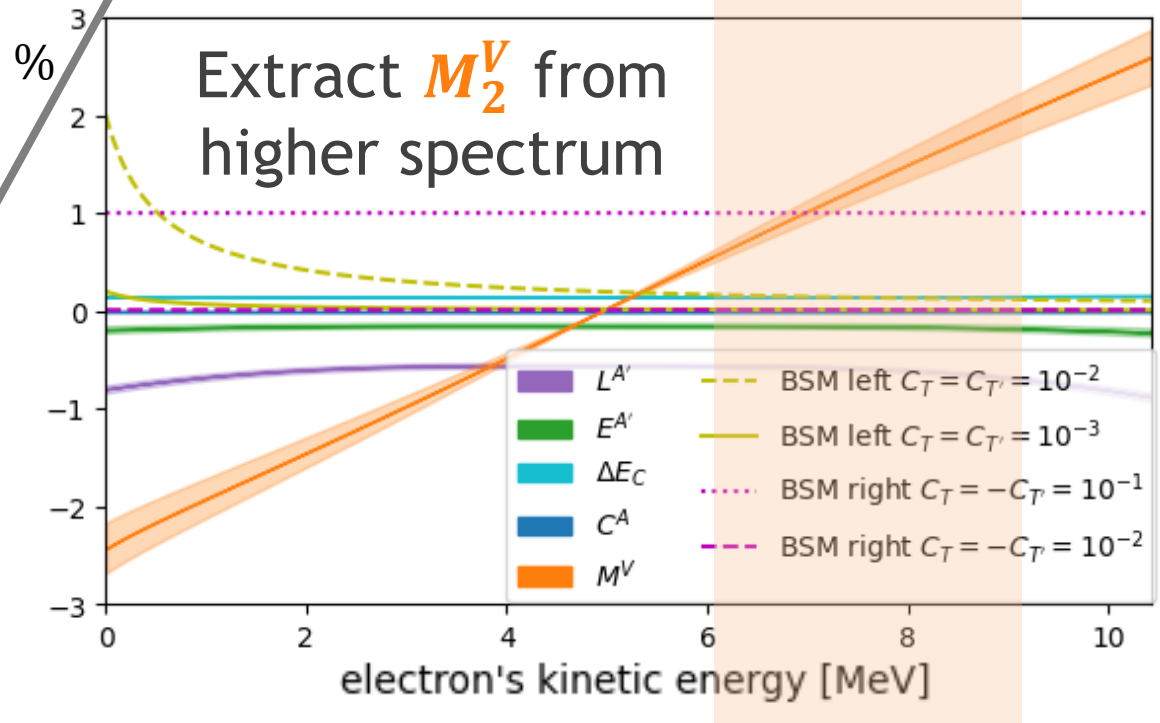


AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.



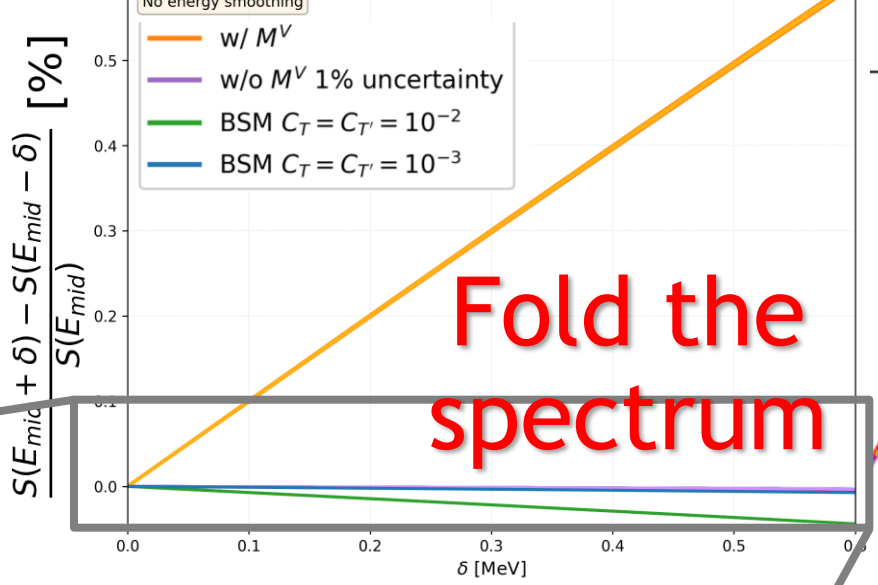
Fold the spectrum



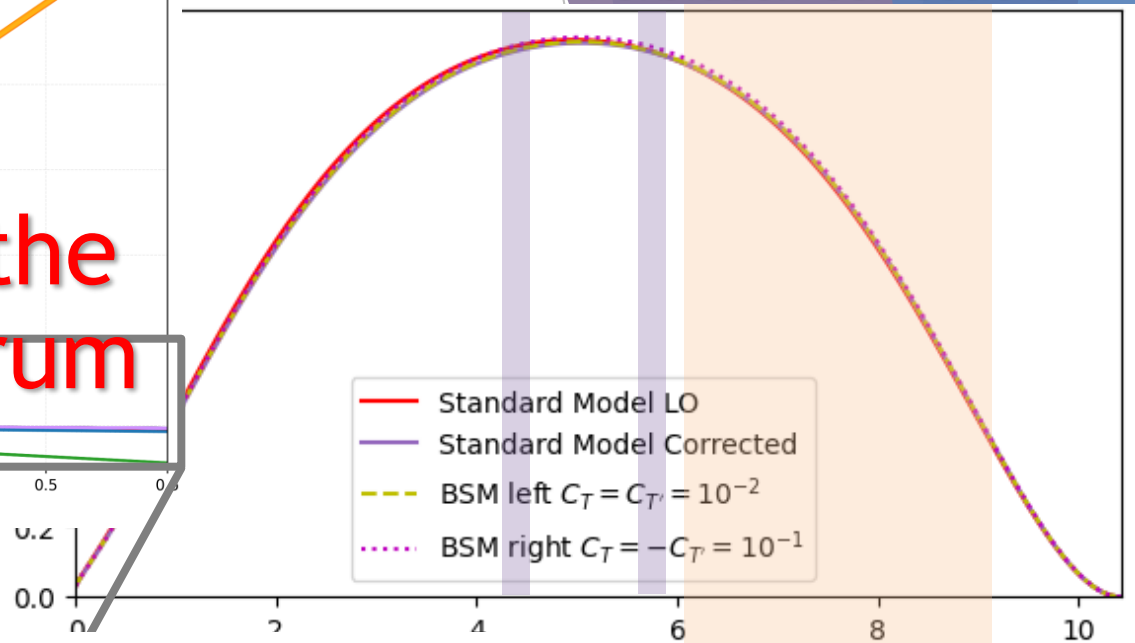


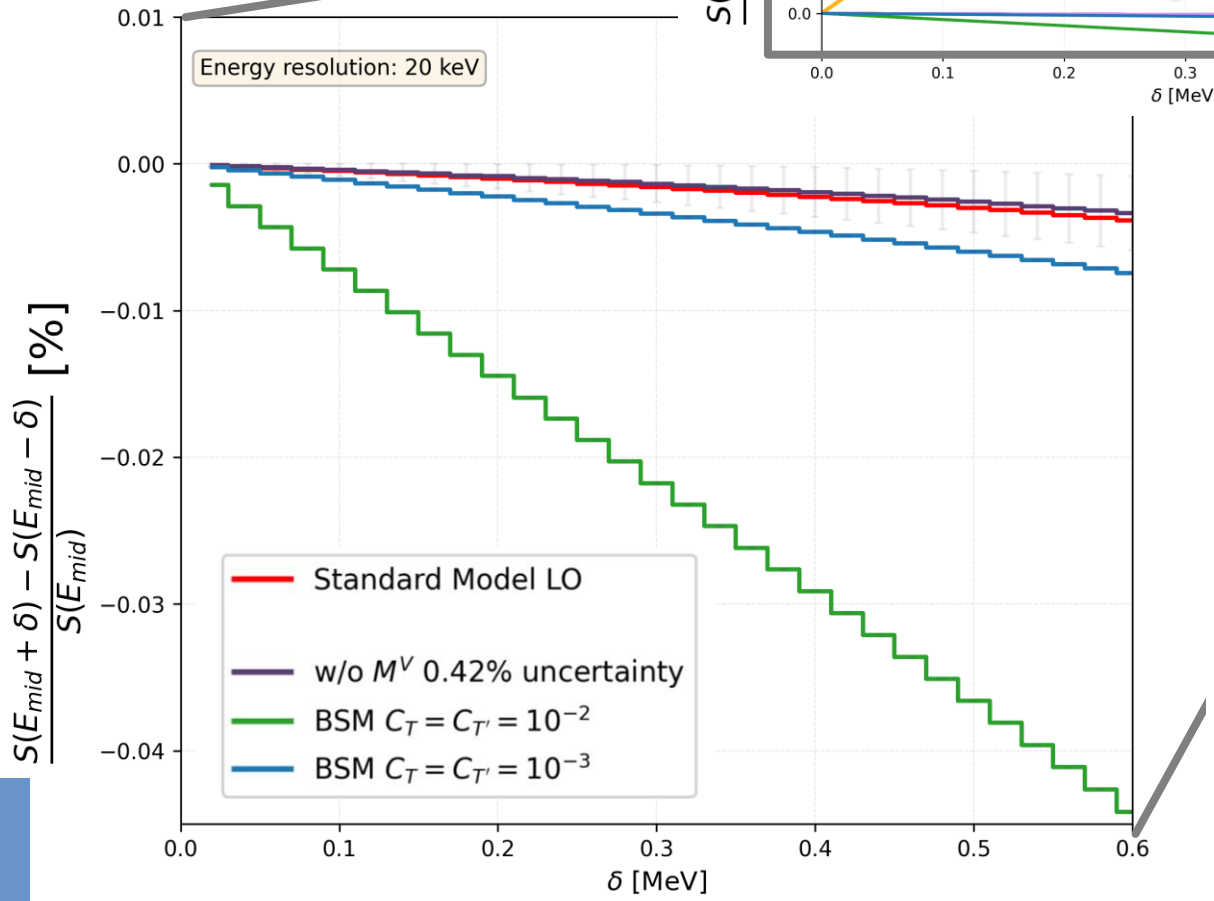
AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

Spectrum Peak Asymmetry Method (SPAM)

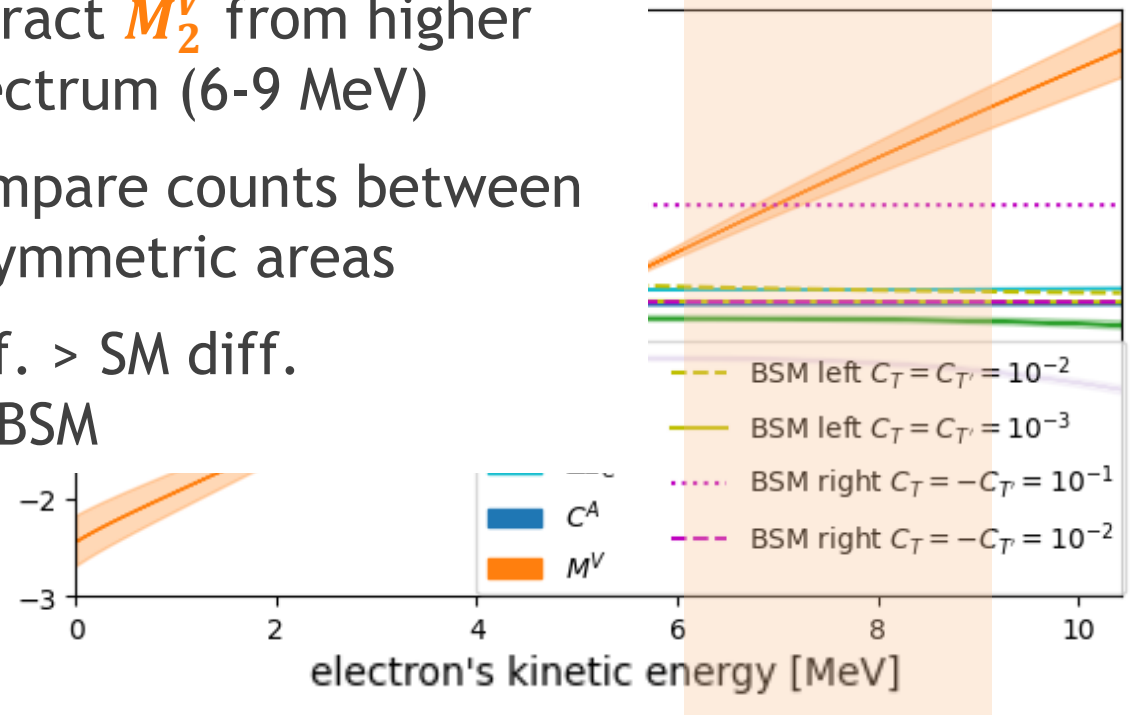


Fold the spectrum



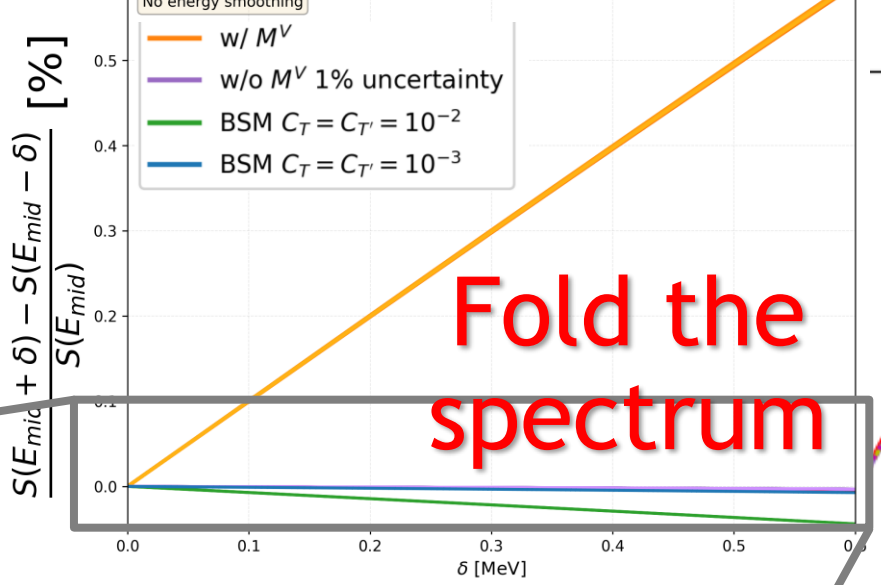


- Extract M_2^V from higher spectrum (6-9 MeV)
- Compare counts between 2 symmetric areas
- Diff. > SM diff. => BSM

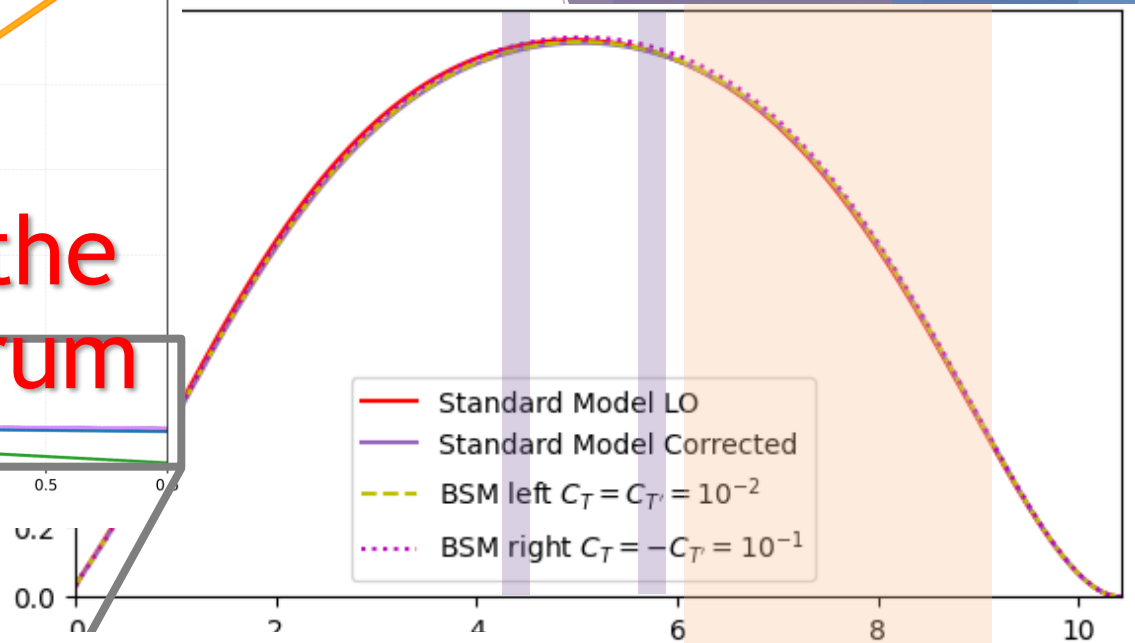


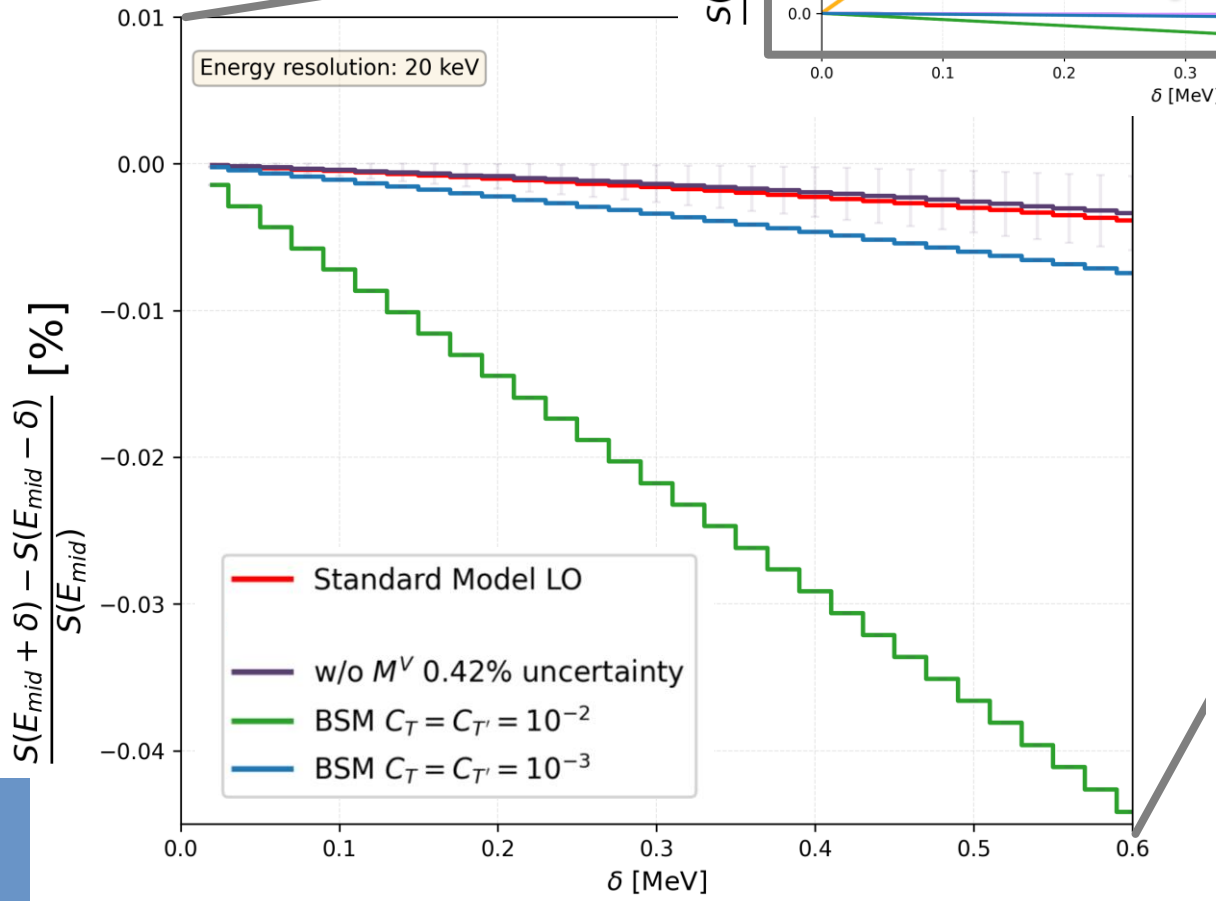
AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

Spectrum Peak Asymmetry Method (SPAM)

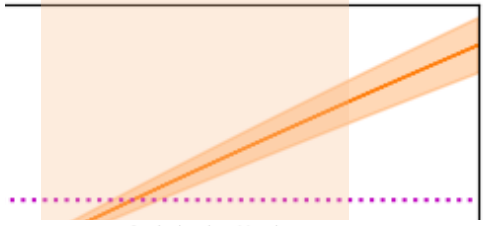


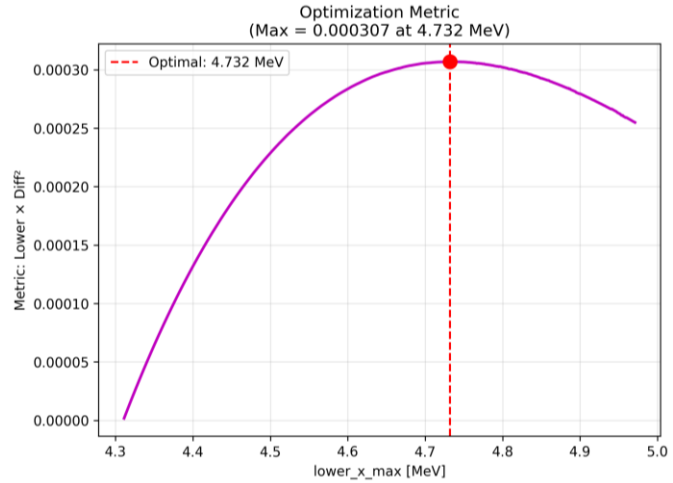
Fold the spectrum





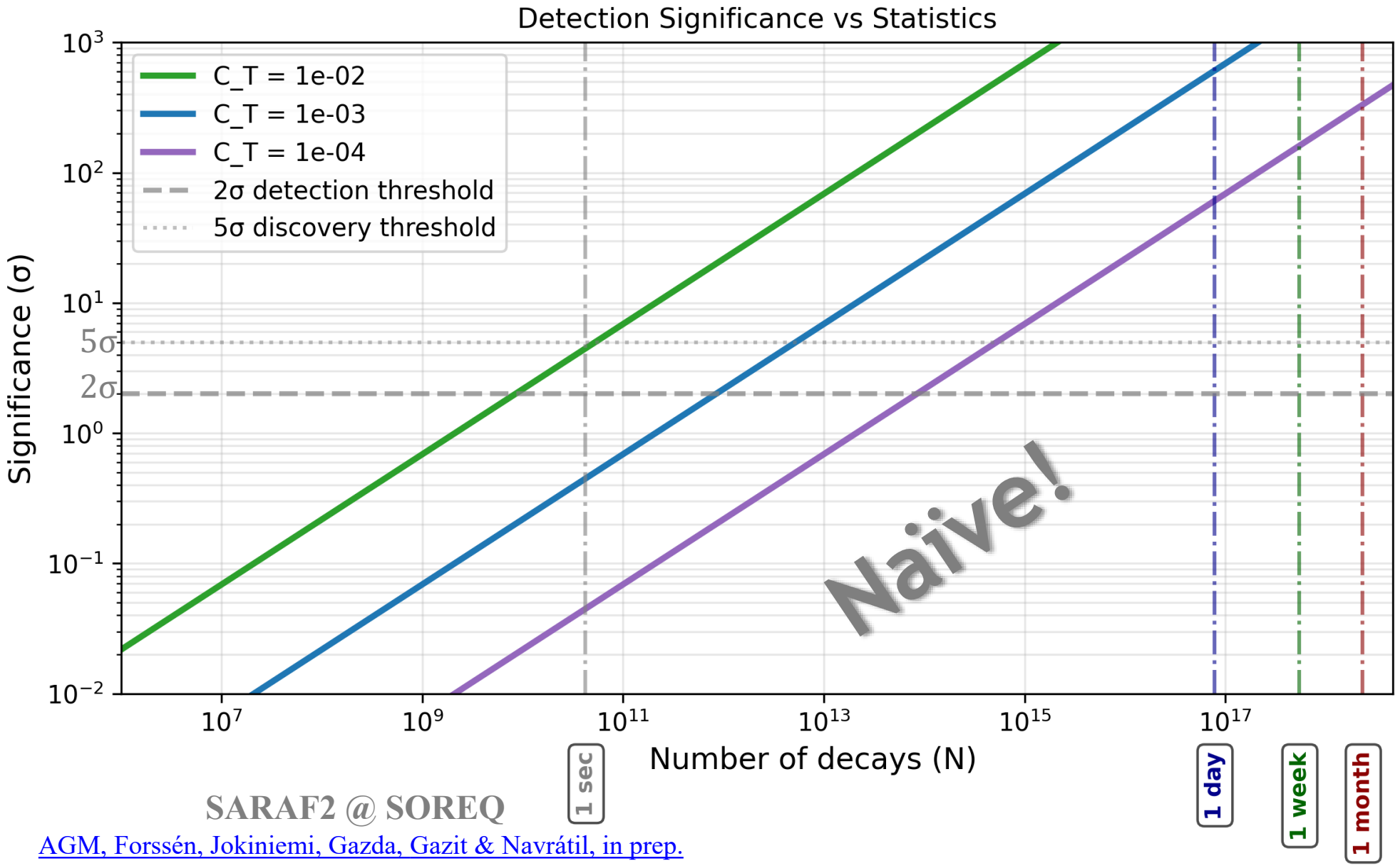
- Extract M_2^V from higher spectrum (6-9 MeV)
- Compare counts between 2 symmetric areas
- Diff. > SM diff. => BSM
- Optimize the areas for effect vs. noise





AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

Spectrum Peak Asymmetry Method (SPAM)



SARAF2 @ SOREQ

AGM, Forssén, Jokiniemi, Gazda, Gazit & Navrátil, in prep.

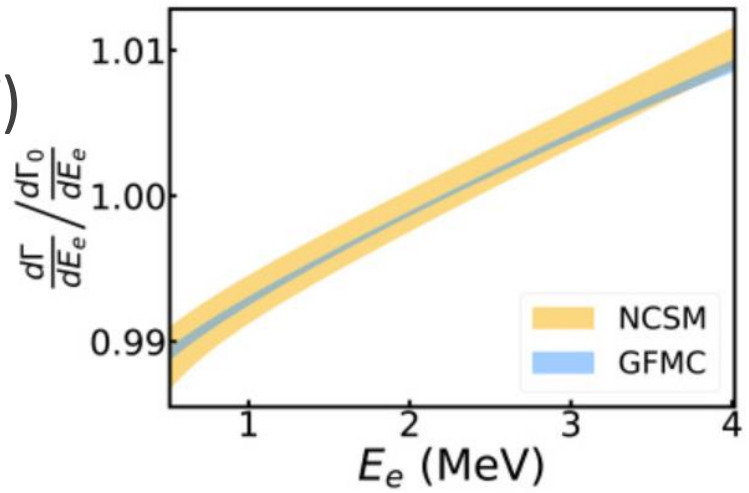
Allowed:

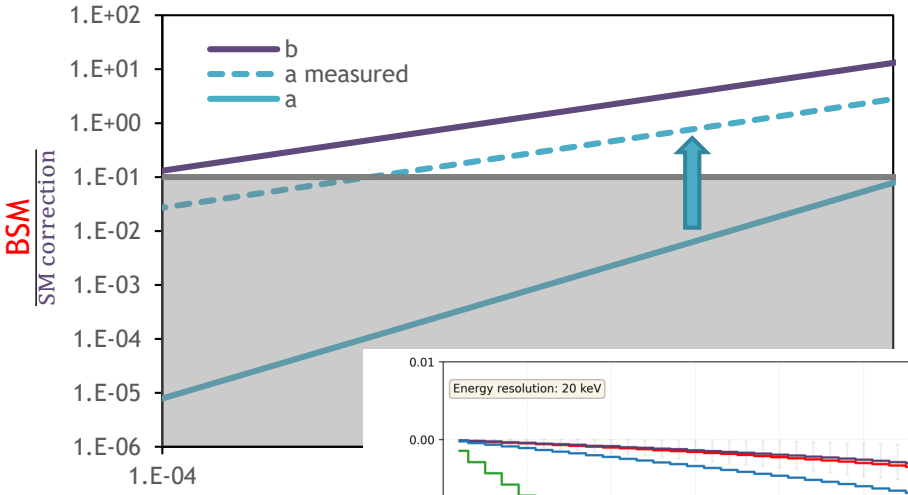
Measure a or b for ***scalar*** (Fermi) or ***Tensor*** (GT)

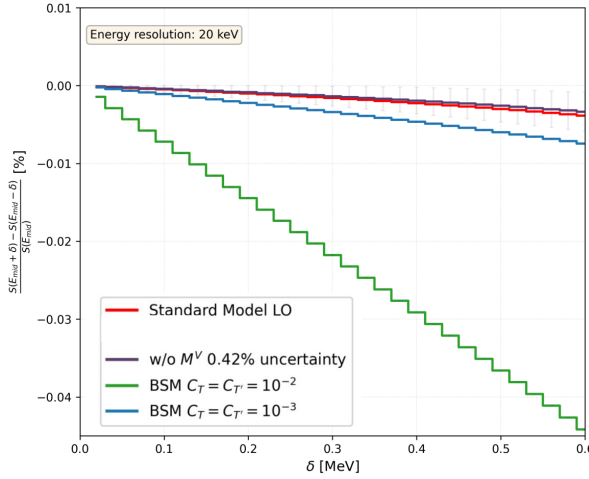
We are getting better and better

Experiments

@ FRIB, TRIUMF, CENPA, …







Unique Forbidden:

~~**No**~~ **decay @ $q \to 0$**

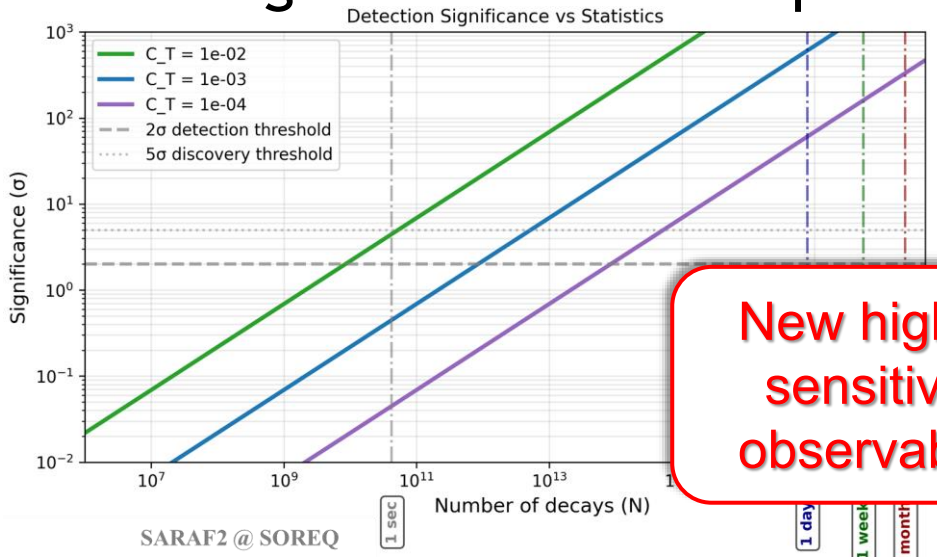
Spectrum is sensitive to:

- *Light New Physics*
- *SPAM* for ***Tensor***

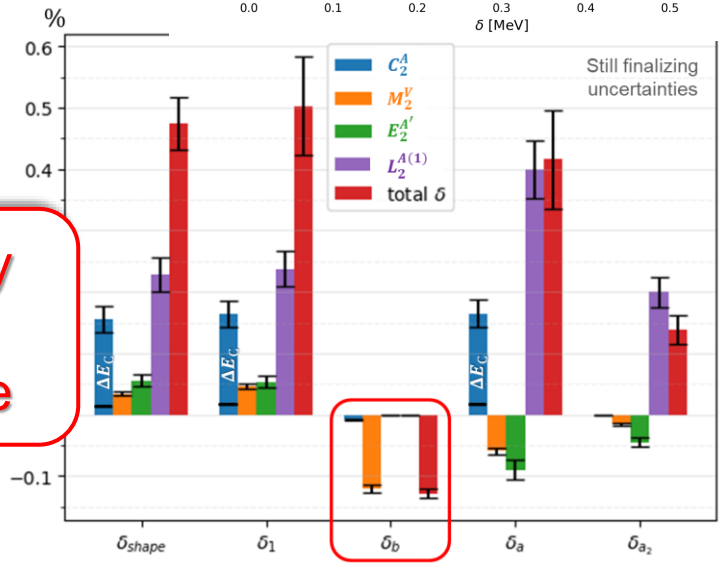
Experiments

@ ORNL, CEA Saclay, SOREQ

Needed from exp.:
Magnetic and other operators



New highly sensitive observable



- New possibilities with MTAS @ORNL

Thanks!

TRIUMF
Petr Navrátil

Chalmers U.
Christian Forssén

TU Darmstadt
Lotta Jokiniemi

ÚJF Rez
Daniel Gazda

Hebrew U.
Daniel Ben Atar
Doron Gazit
Guy Ron

SOREQ
Sergey Vaintraub

UTK
Chien-Yeah Seng

INT
Vincenzo Cirigliano

ORNL
Charlie Rasco

Caen U. & FRIB
Oscar Naviliat-Cuncic

LPC Caen
Leendert Hayen

LANL
Garrett King

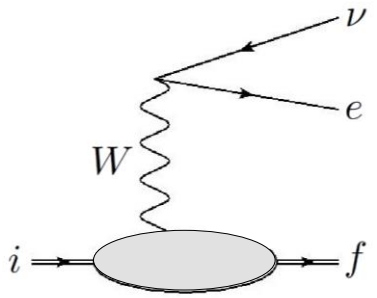
FRIB & MSU
Grigor Sargsyan

Some Details

Forbidden - Radiative

Unique 1st-forbidden

$$d\Gamma \propto \left|\langle 0^+ \| \hat{H}_W \| 2^- \rangle\right|^2 \propto \; 1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]$$



"Forbidden" (vanish for $q \to 0$)

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

angular momentum

parity

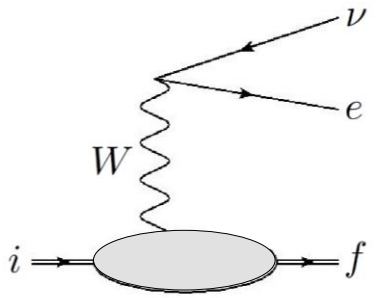
$$J_i^{\pi_i} \to J_f^{\pi_f}$$

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

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

Unique 1st-forbidden

$$d\Gamma \propto \left|\langle 0^+ \| \hat{H}_W \| 2^- \rangle\right|^2 \propto \left\{1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]\right\}\left|\langle 0^+ \| \hat{O}_J \| 2^- \rangle\right|^2$$



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$$2^- \to 0^+$$
$$|2-0| \le J \le 2+0$$
$$\Delta\pi = -$$

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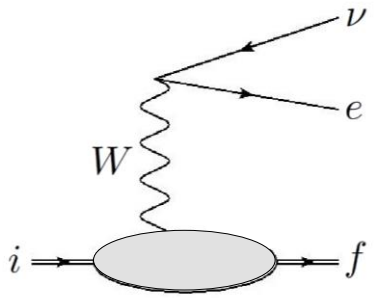
$$\propto q^{J-1} \underset{q\to 0}{\longrightarrow} 0$$



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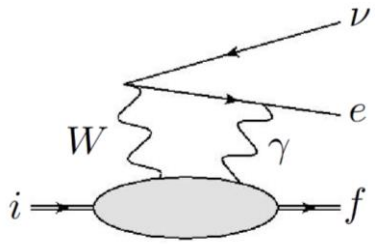
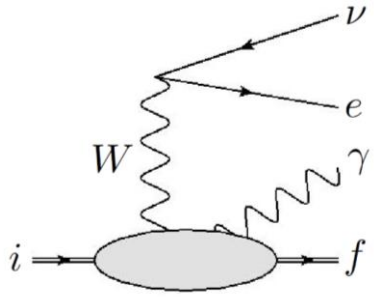
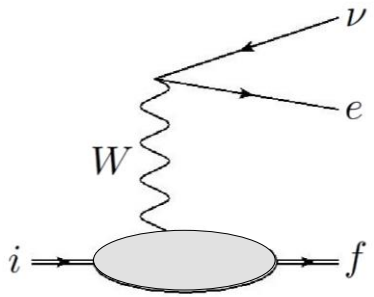
$$\propto q^{J-1} \underset{q\to 0}{\longrightarrow} 0$$

Forbidden!

Radiative Corrections:







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

"Forbidden" (vanish for $q \to 0$)

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

angular momentum — parity

$$2^- \to 0^+$$
$$|2-0| \le J \le 2+0$$
$$\Delta\pi = -$$

Seng, AGM, Cirigliano, PRL 2025

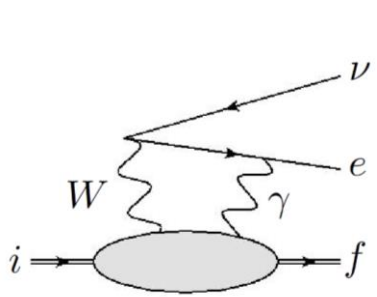
Unique 1st-forbidden

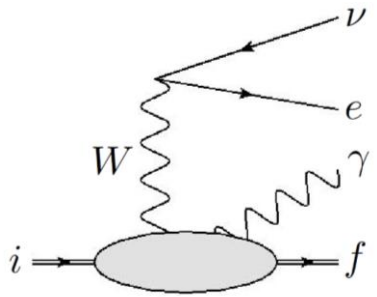
$$d\Gamma \propto \left|\langle 0^+ \| \hat{H}_W \| 2^- \rangle\right|^2 \propto \left\{1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]\right\}\left|\langle 0^+ \| \hat{O}_J \| 2^- \rangle\right|^2$$

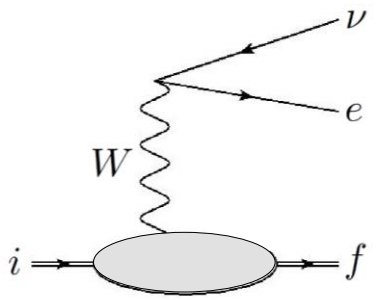
$$\propto q^{J-1} \underset{q\to 0}{\longrightarrow} 0$$

Forbidden!

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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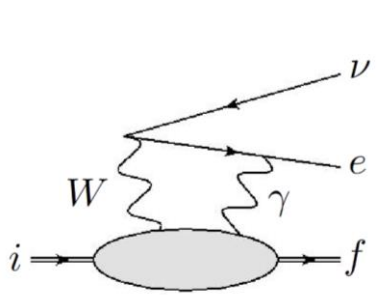
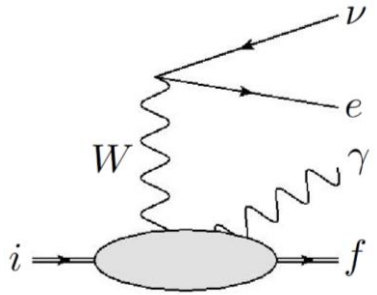
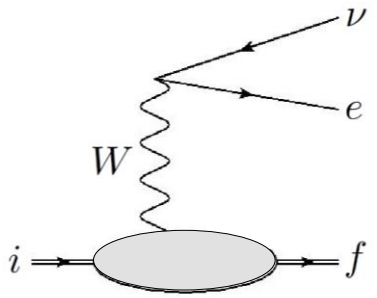
$$\propto q^{J-1} \underset{q\to 0}{\longrightarrow} 0$$

Forbidden!

Radiative Corrections:







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

No longer limited to $J = 2$ operators to satisfy the selection rule!

$$|J_X - 0| \le J \le J_X + 0$$
$$|2 - J_X| \le J' \le 2 + J_X$$

angular momentum

parity

$$2^- \to 0^+$$
$$|2 - 0| \le J \le 2 + 0$$
$$\Delta\pi = -$$

Seng, AGM, Cirigliano, PRL 2025

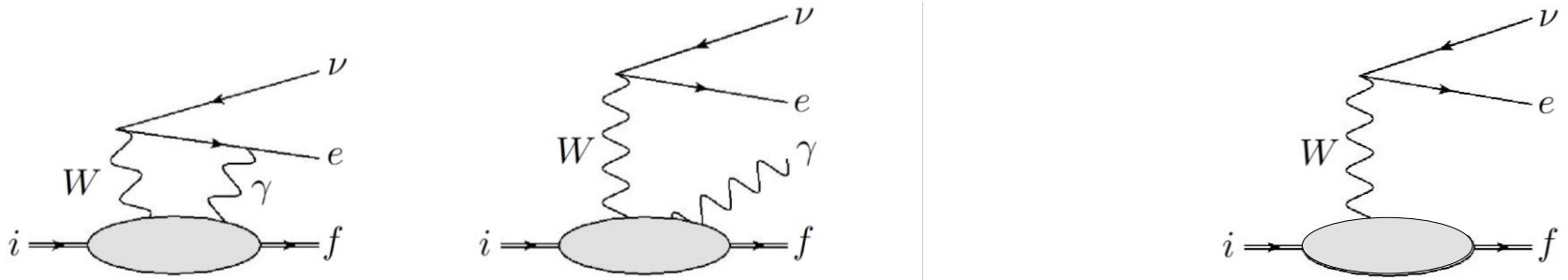
Unique 1st-forbidden

$$d\Gamma \propto \left|\langle 0^+ \| \hat{H}_W \| 2^- \rangle\right|^2 \propto \left\{1 + \boldsymbol{b}\frac{m_e}{E_e} + \boldsymbol{a}\,\vec{\beta}\cdot\hat{\nu} + \boldsymbol{a_2}\left[\beta^2 - \left(\hat{\beta}\cdot\hat{\nu}\right)^2\right]\right\}\left|\langle 0^+ \| \hat{O}_J \| 2^- \rangle\right|^2$$

$$\propto q^{J-1} \xrightarrow[q\to 0]{} 0$$

Forbidden!

Radiative Corrections:



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

No longer limited to $J = 2$ operators to satisfy the selection rule!

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

interference

angular momentum

parity

$$2^- \to 0^+$$

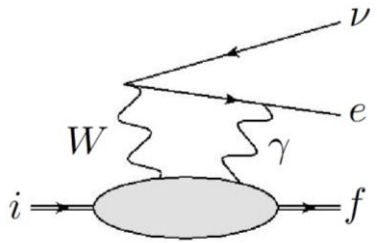
$$|2 - 0| \le J \le 2 + 0$$

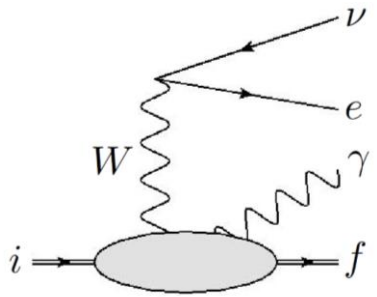
$$\Delta\pi = -$$

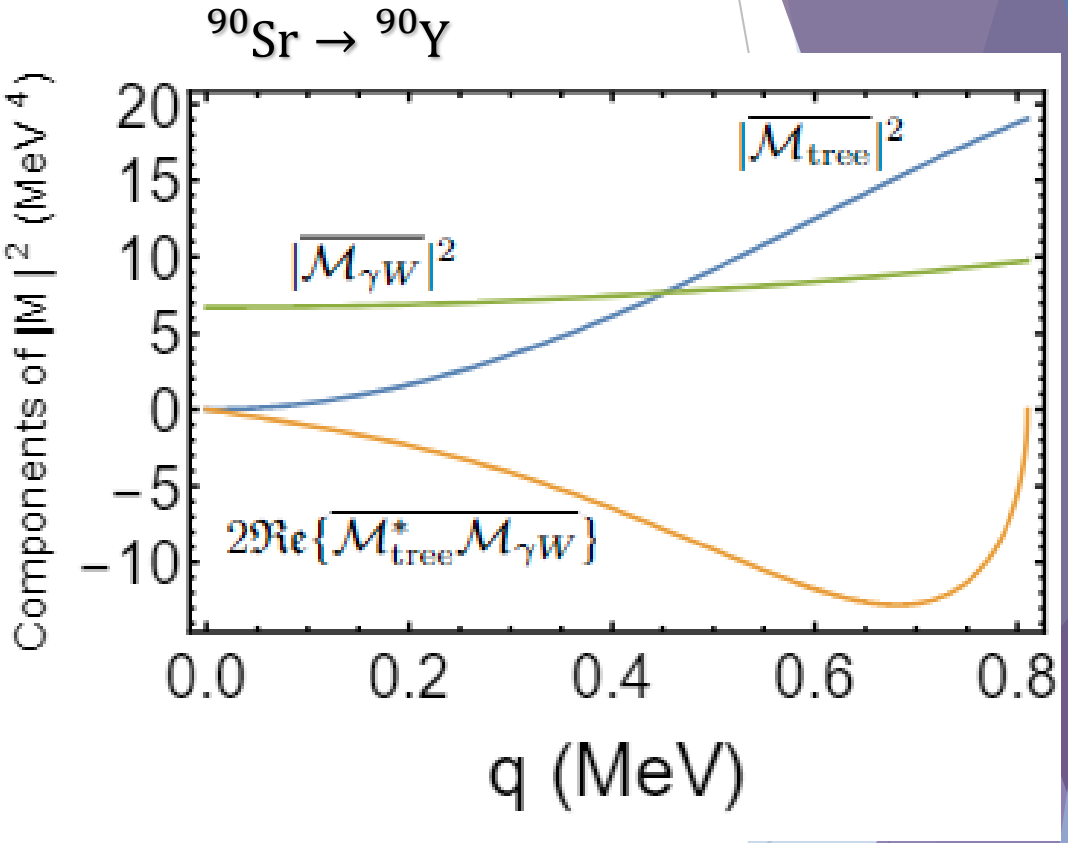
Seng, AGM, Cirigliano, PRL 2025

Unique Forbidden decays

~~No~~ decay @ $q \to 0$





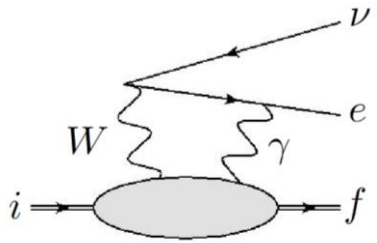


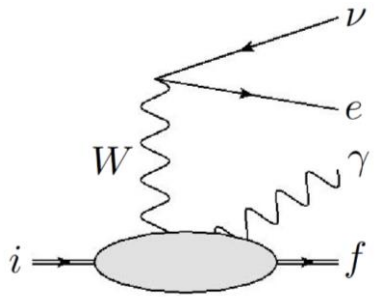
$$d\Gamma \propto \underbrace{f_0 q^0}_{|\overline{\mathcal{M}_{\gamma W}}|^2} + \underbrace{f_1 q^1}_{2\Re\mathrm{e}\{\overline{\mathcal{M}^*_{\mathrm{tree}}\mathcal{M}_{\gamma W}}\}} + \underbrace{f_2 q^2}_{|\overline{\mathcal{M}_{\mathrm{tree}}}|^2}$$

Seng, AGM, Cirigliano, PRL 2025

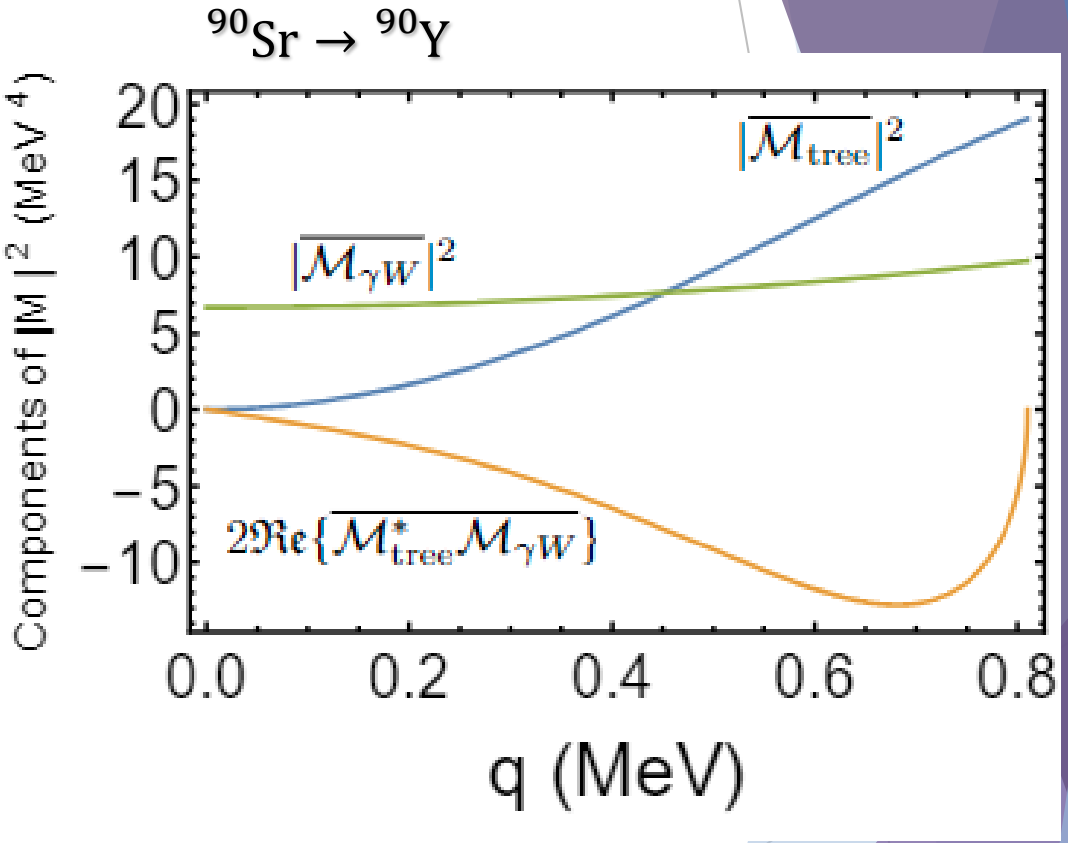
Unique Forbidden decays

~~No~~ decay @ $q \to 0$





Light New Physics



$$d\Gamma \propto \underbrace{f_0 q^0}_{|\overline{\mathcal{M}_{\gamma W}}|^2} + \underbrace{f_1 q^1}_{2\Re e\{\overline{\mathcal{M}^*_{tree}\mathcal{M}_{\gamma W}}\}} + \underbrace{f_2 q^2}_{|\overline{\mathcal{M}_{tree}}|^2}$$

Seng, AGM, Cirigliano, PRL 2025

Unique Forbidden decays

~~No~~ decay @ $q \to 0$

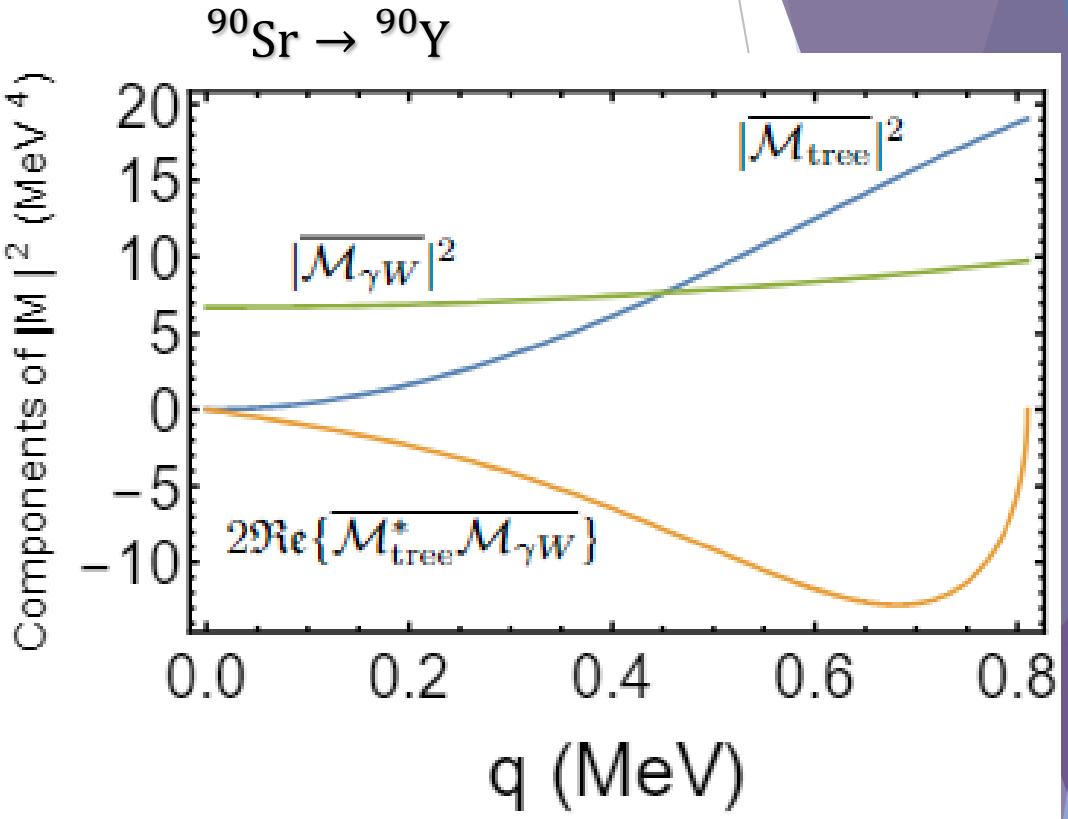
Experiments

@ ORNL, CEA Saclay, HUJI, SOREQ

- New possibilities with MTAS @ORNL

Spectrum is sensitive to:

- Exotic Weak Interactions
- *Light New Physics*



$$d\Gamma \propto \underbrace{f_0 q^0}_{|\overline{\mathcal{M}_{\gamma W}}|^2} + \underbrace{f_1 q^1}_{2\Re\mathrm{e}\{\overline{\mathcal{M}^*_{\mathrm{tree}}\mathcal{M}_{\gamma W}}\}} + \underbrace{f_2 q^2}_{|\overline{\mathcal{M}_{\mathrm{tree}}}|^2}$$

Seng, AGM, Cirigliano, PRL 2025