New Opportunities for Nuclear Structure Calculations for BSM Physics

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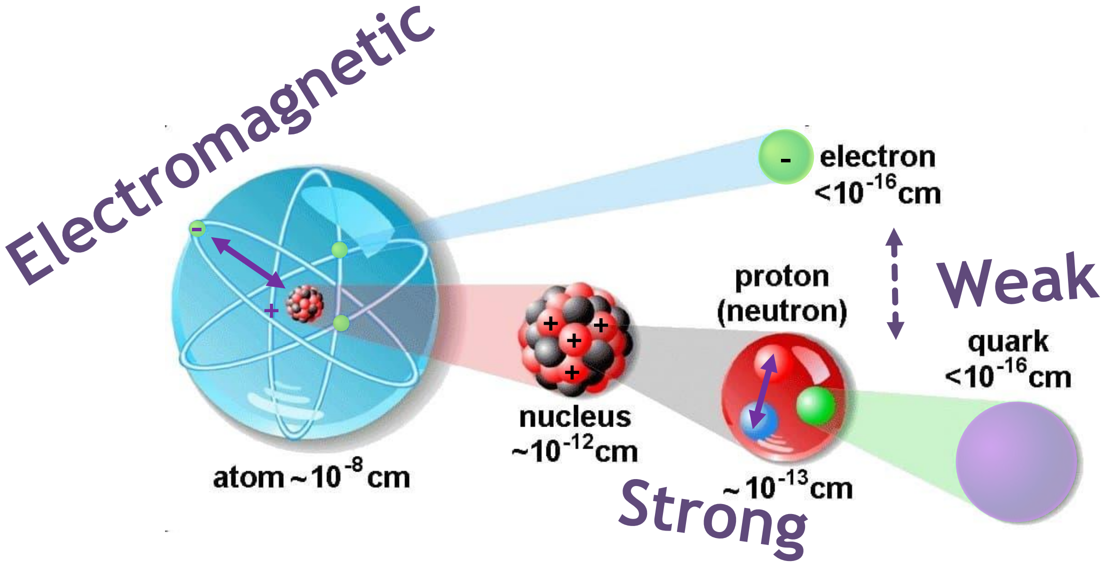
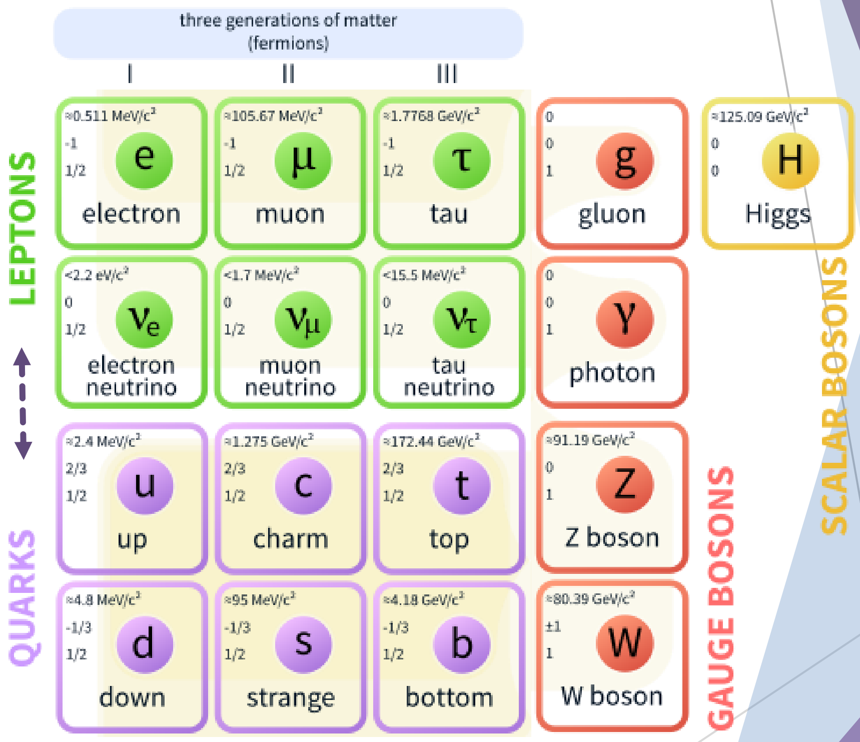
Standard Model (SM)

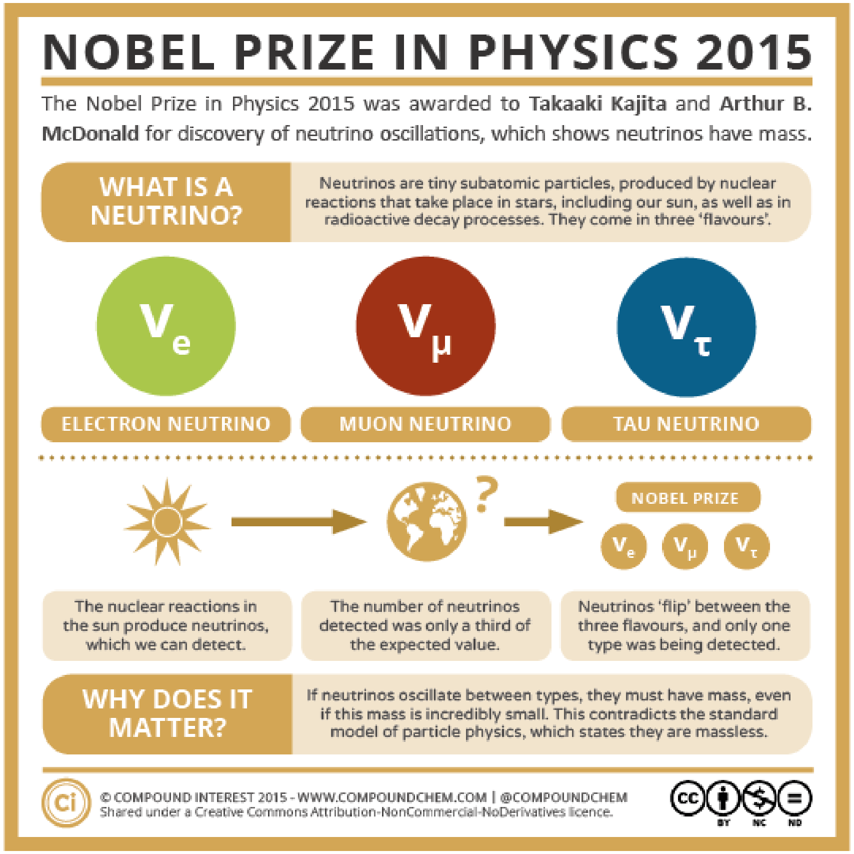
Fundamental Forces



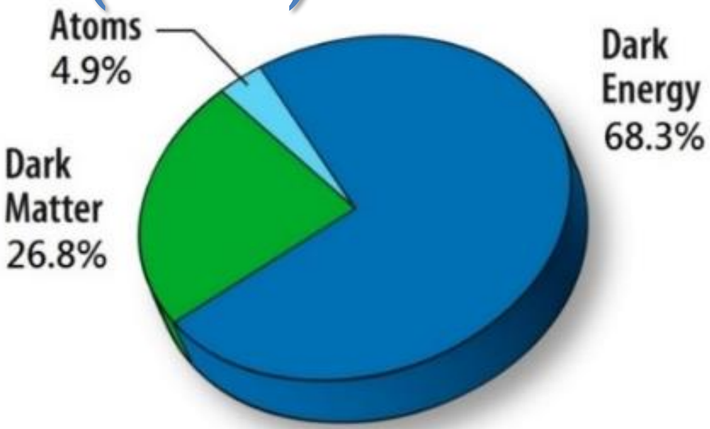
Elementary Particles



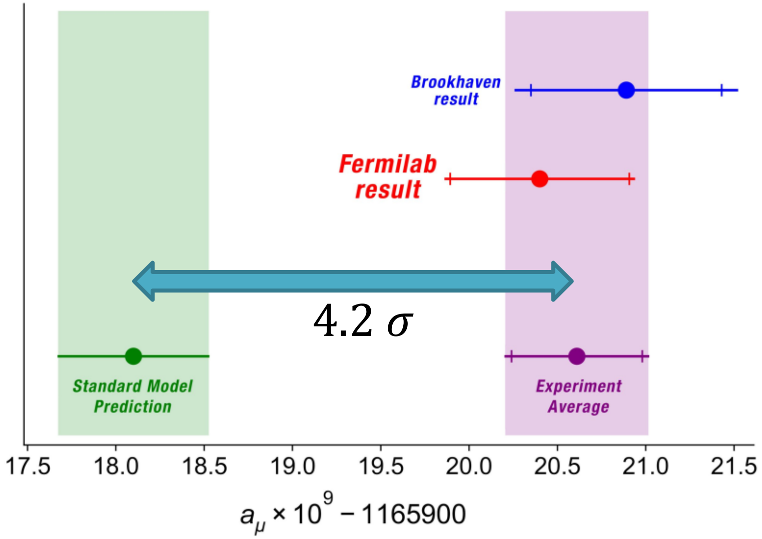
Beyond Standard Model (BSM)



The Neutrino has mass, even though according to the SM it should not



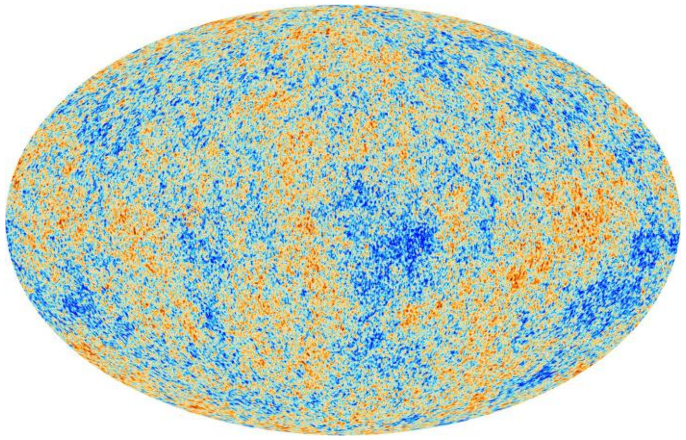
Dark Matter & Energy



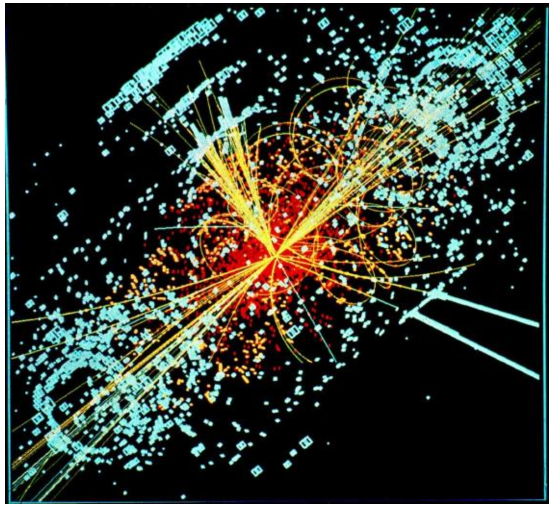
Deviations from the SM at high precision: muon g-2, W mass

Searches for BSM physics

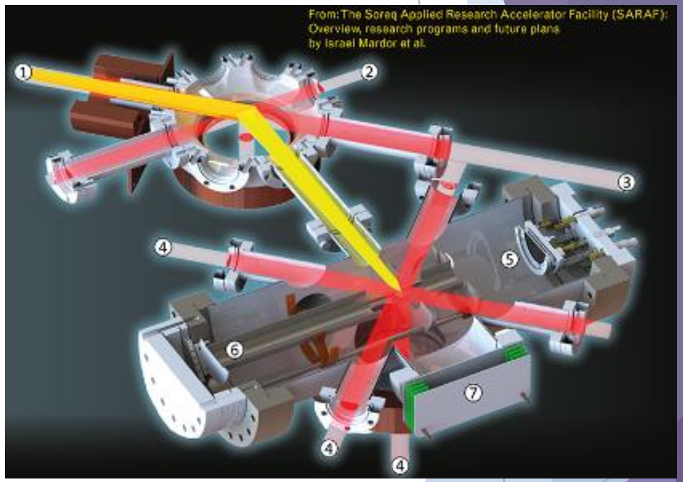
Astronomical Frontier	High Energy Frontier	Precision Frontier
Astronomy	**Particles Physics**	**Nuclear Physics**



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



Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469



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

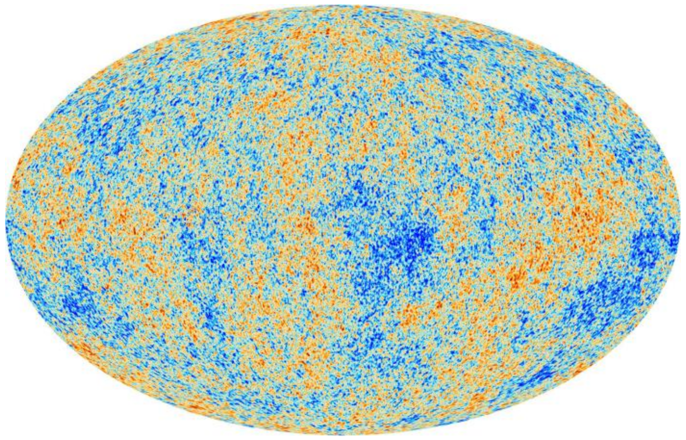
E.g.

- ➢ Dark Matter
- ➢ Lepton Flavor Violation
- ➢ New Weak Interactions

Searches for BSM physics

Precision Frontier

Astronomy	Particles Physics	Nuclear Physics



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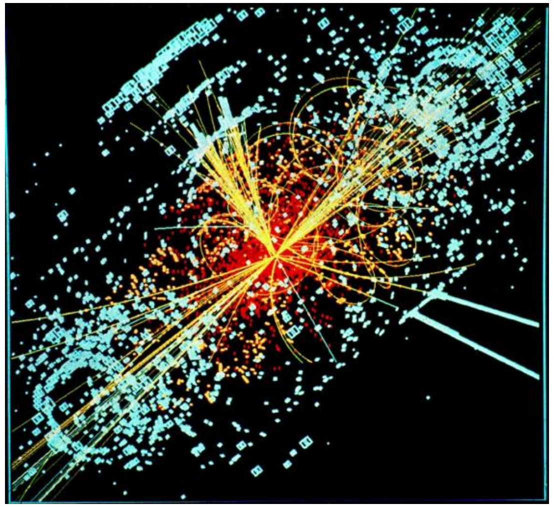

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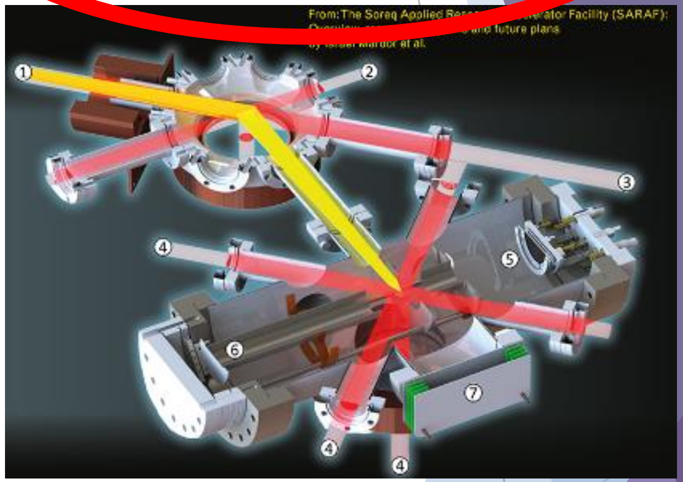


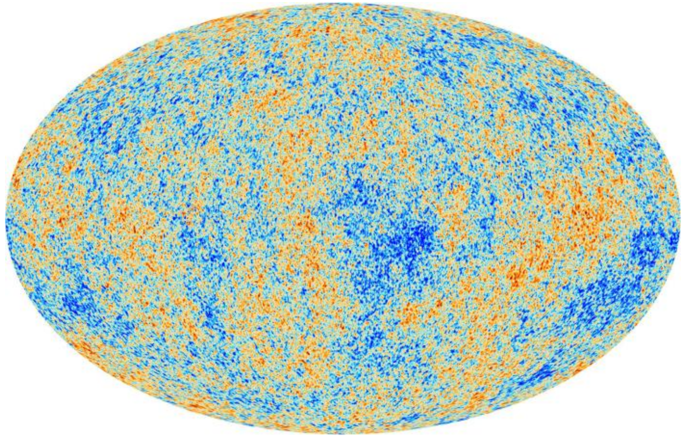
Mardor *et al.*, Eur. Phys. J. A 54, 91 (2018)

- Dark Matter
- Lepton Flavor Violation
- New Weak Interactions

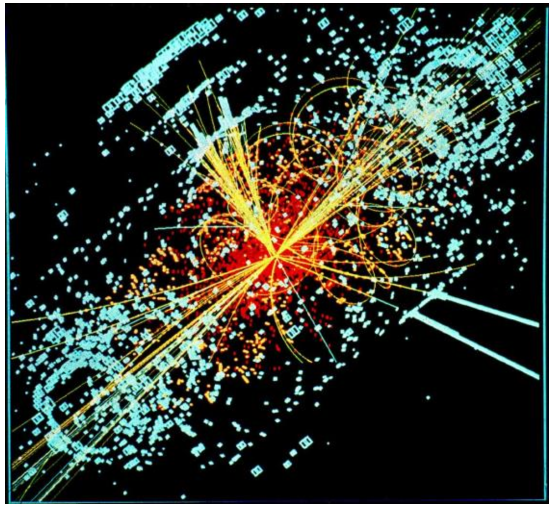
with nuclei…

Searches for BSM physics

✓Introduction



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



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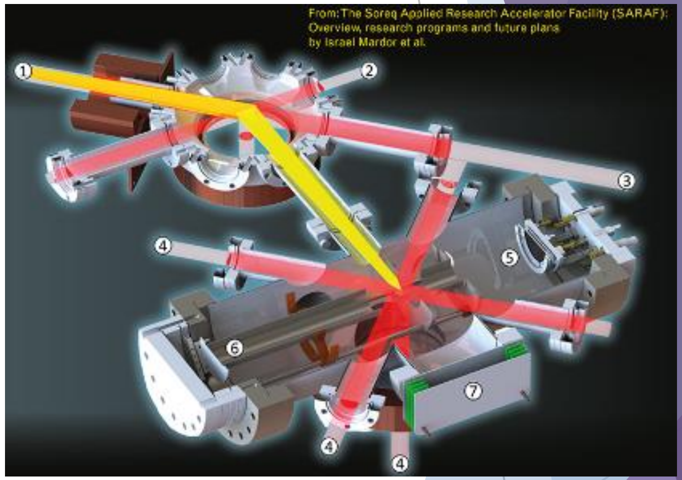


Mardor *et al.*, Eur. Phys. J. A 54, 91 (2018)

- Dark Matter
- Lepton Flavor Violation
- New Weak Interactions

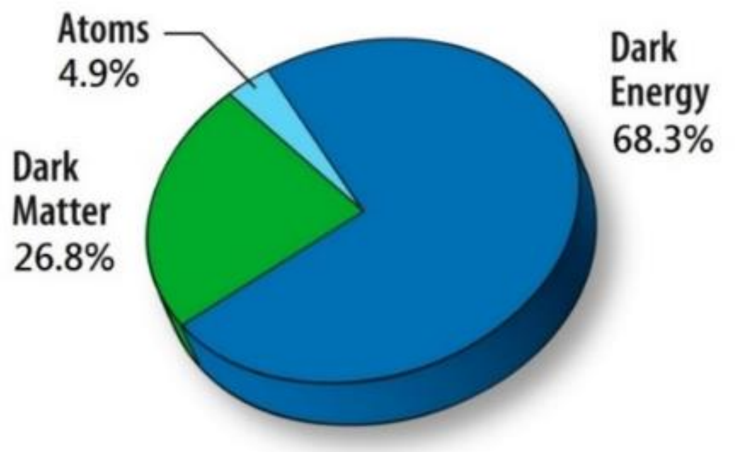
with nuclei…

- **Summary**

Dark Matter

direct detection

Dark Matter Direct Detection



Promising candidates – WIMPs:
Weakly-**I**nteracting **M**assive **P**articles

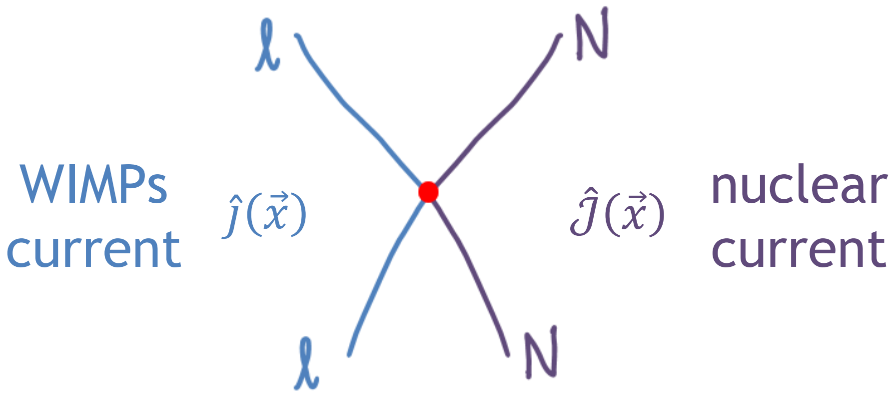
- Challenge – Direct detection:
  - Measuring WIMP scattering off nuclei on detectors
    - Nuclear matrix elements & structure factors
  - Detection capabilities: $q \sim 100\ MeV/c$
  - The structure of the coupling is determined only by symmetry considerations

q - momentum transfer

N. Anand, A. L. Fitzpatrick, W. C. Haxton, Phys.Rev.C89:065501 (2014)
A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, Y. Xu, J.Cosmol.Astropart.Phys2013(02):004 (2013)

WIMPs scattering off nuclei

Low energy reaction of WIMPs with nucleons



$$\mathcal{L}_{int} \sim \bar{\chi} O_{\chi} \chi \, \bar{N} O_N N$$

Non-Relativistic Nuclear Reduction: contact interaction between WIMP's & Nucleon's currents

WIMPs scattering off nuclei

Non-Relativistic Nuclear Reduction

$$\mathcal{L}_{int} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N$$

Scalar $\langle p(p_p)|\bar{u}\, d|n(p_n)\rangle = g_S(q^2)\, \bar{u}_p(p_p)\, u_n(p_n)$

Pseudoscalar $\langle p(p_p)|\bar{u}\, \gamma_5\, d|n(p_n)\rangle = g_P(q^2)\, \bar{u}_p(p_p)\, \gamma_5\, u_n(p_n)$

$$\boxed{\begin{array}{c} 2 \times 2 = 4 \\ \bar{N}N \\ \bar{N}\gamma^5 N \end{array}}$$

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

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

$$\boxed{\begin{array}{c} 4 \times 4 = 16 \\ \bar{N}\dfrac{P^\mu}{m_N}N \\ \bar{N}\sigma^{\mu\nu}\dfrac{q_\nu}{m_N}N \\ \bar{N}\dfrac{P^\mu}{m_N}\gamma^5 N \\ \bar{N}\gamma^\mu\gamma^5 N \end{array}}$$

And similar terms for the WIMPs

WIMPs scattering off nuclei

Non-Relativistic Nuclear Reduction

$$\mathcal{L}_{int} \sim \bar{\chi} O_\chi \chi \, \bar{N} O_N N \approx \sum_{i=1}^{16} c_i O_i \bar{\chi}\chi \bar{N} N$$

$\{O_i\}_{i=1}^{16}$ - 16 non-relativistic operators

built of 4 three-vectors:

- $\frac{i\vec{q}}{m_N}$
- $\vec{v}^\perp \equiv \frac{\vec{P}}{2m_\chi} - \frac{\vec{K}}{2m_N}$
- $\vec{S}_\chi, \vec{S}_N$

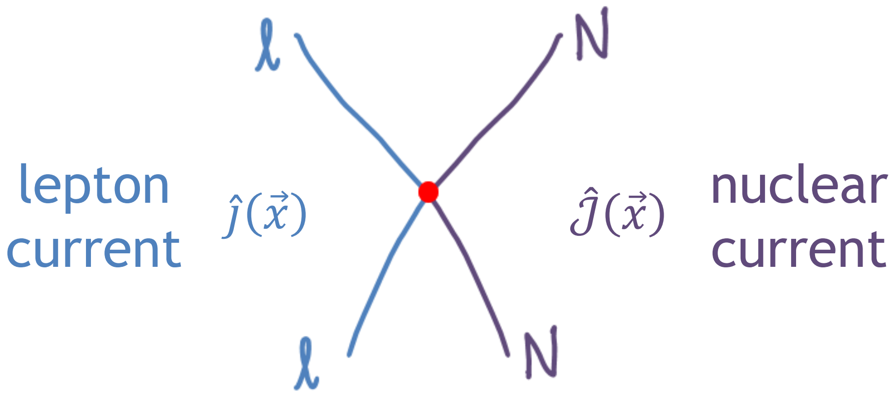
j	$\mathcal{L}^j_{\rm int}$	Nonrelativistic Reduction	$\sum_i c_i \mathcal{O}_i$
1	$\bar{\chi}\chi\bar{N}N$	$1_\chi 1_N$	$\mathcal{O}_1$
2	$i\bar{\chi}\chi\bar{N}\gamma^5 N$	$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$\mathcal{O}_{10}$
3	$i\bar{\chi}\gamma^5\chi\bar{N}N$	$-i\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$
4	$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$	$-\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi\frac{\vec{q}}{m_N}\cdot\vec{S}_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$
5	$\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}N$	$4\frac{m_\chi m_N}{m_M^2}1_\chi 1_N$	$4\frac{m_\chi m_N}{m_M^2}\mathcal{O}_1$
6	$\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$-\frac{m_\chi}{m_N}\frac{\vec{q}^2}{m_M^2}1_\chi 1_N - 4i\frac{m_\chi}{m_M}\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$-\frac{m_\chi}{m_N}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_1 + 4\frac{m_\chi m_N}{m_M^2}\mathcal{O}_3$
7	$\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}\gamma_\mu\gamma^5 N$	$-4\frac{m_\chi}{m_M}\vec{v}^\perp\cdot\vec{S}_N$	$-4\frac{m_\chi}{m_M}\mathcal{O}_7$
8	$i\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5 N$	$4i\frac{m_\chi}{m_M}\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_\chi m_N}{m_M^2}\mathcal{O}_{10}$
9	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}N$	$\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}1_\chi 1_N + 4i\frac{m_N}{m_M}\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)$	$\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_1 - 4\frac{m_N^2}{m_M^2}\mathcal{O}_5$
10	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$4\left(\frac{\vec{q}^2}{m_M^2}\mathcal{O}_4 - \frac{m_N^2}{m_M^2}\mathcal{O}_6\right)$
11	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4i\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\cdot\vec{S}_N$	$-4\frac{m_N}{m_M}\mathcal{O}_9$
12	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5 N$	$\left[i\frac{\vec{q}^2}{m_\chi m_M} - 4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_\chi\right)\right]\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{10} + 4\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{12} + 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$
13	$\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$4\frac{m_N}{m_M}\vec{v}^\perp\cdot\vec{S}_\chi$	$4\frac{m_N}{m_M}\mathcal{O}_8$
14	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$-4i\vec{S}_\chi\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)$	$4\frac{m_N}{m_M}\mathcal{O}_9$
15	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5 N$	$-4\vec{S}_\chi\cdot\vec{S}_N$	$-4\mathcal{O}_4$
16	$i\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K^\mu}{m_M}\bar{N}\gamma^5 N$	$4i\vec{v}^\perp\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_{13}$
17	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$	$-4i\frac{m_N}{m_M}\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi$	$-4\frac{m_N^2}{m_M^2}\mathcal{O}_{11}$
18	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\left[i\frac{\vec{q}^2}{m_N m_M} - 4\vec{v}^\perp\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)\right]$	$\frac{\vec{q}^2}{m_M^2}\mathcal{O}_{11} + 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$
19	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$	$4i\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\vec{v}_\perp\cdot\vec{S}_N$	$4\frac{m_N}{m_M}\mathcal{O}_{14}$
20	$\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5 N$	$-4\frac{\vec{q}}{m_M}\cdot\vec{S}_\chi\frac{\vec{q}}{m_M}\cdot\vec{S}_N$	$-4\frac{m_N^2}{m_M^2}\mathcal{O}_6$

Missing tensor couplings

A. L. Fitzpatrick, W. Haxton et al., J.Cosmol.Astropart.Phys 2013(02):004 (2013)

Why do we need the tensor?
We already have 16 operator basis

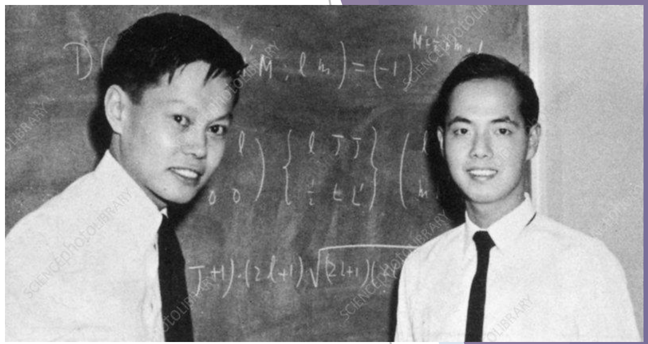
Weak interaction: Low energy reaction of leptons with nucleons



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

A-priori:

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

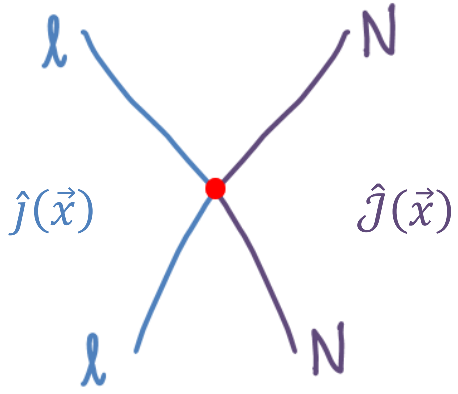


Theory: C.N. Yang and T.D. Lee (Nobel 1957)

Why do we need the tensor?
We already have 16 operator basis

Weak interaction: Low energy reaction of leptons with nucleons

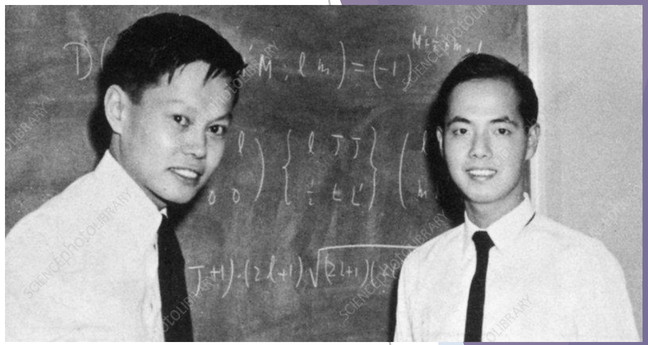
lepton current



nuclear current

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

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

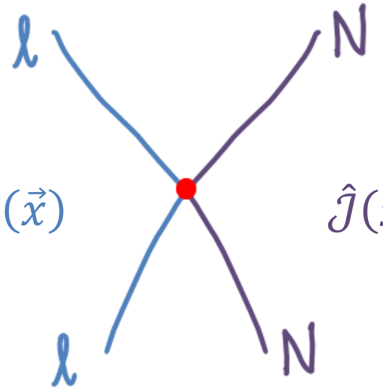
⇒ **Weak SM structure: “$V - A$”**

To identify the interaction’s nature, we need to know the operators & symmetries involved in each of S, P, V, A, T

How do we find the tensor NR EFT?

Low energy reaction of
WIMPs with nucleons

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



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

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

$$\langle k_f \left| \mathcal{J}^a_{\mu\nu} \right| k_i \rangle = \bar{u}(k_f) \frac{1}{2} \left[g_T(q^2)\, \sigma_{\mu\nu} + \tilde{g}_T^{(1)}(q^2) \left(\frac{q_\mu}{m_M}\gamma_\nu - \frac{q_\nu}{m_M}\gamma_\mu \right) + \right.$$

$$\left. + \tilde{g}_T^{(2)}(q^2) \left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{K^\mu}{m_M} \right) + \tilde{g}_T^{(3)}(q^2) \left(\gamma_\mu \frac{\not{q}}{m_M}\gamma_\nu - \gamma_\nu \frac{\not{q}}{m_M}\gamma_\mu \right) \right] \tau^a u(k_i)$$

$4 \times 4 = 16$

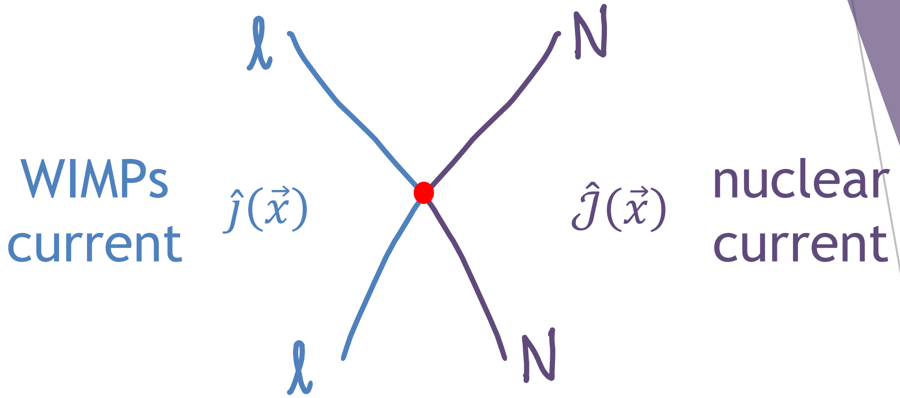
$\bar{N}\sigma_{\mu\nu}N$

$\bar{N}\dfrac{q_\mu}{m_N}\gamma_\mu N$

$\bar{N}\dfrac{q_\mu}{m_N}\dfrac{K_\nu}{m_N}N$

$\bar{N}\gamma_\mu \dfrac{\not{q}}{m_N}\gamma_\nu N$

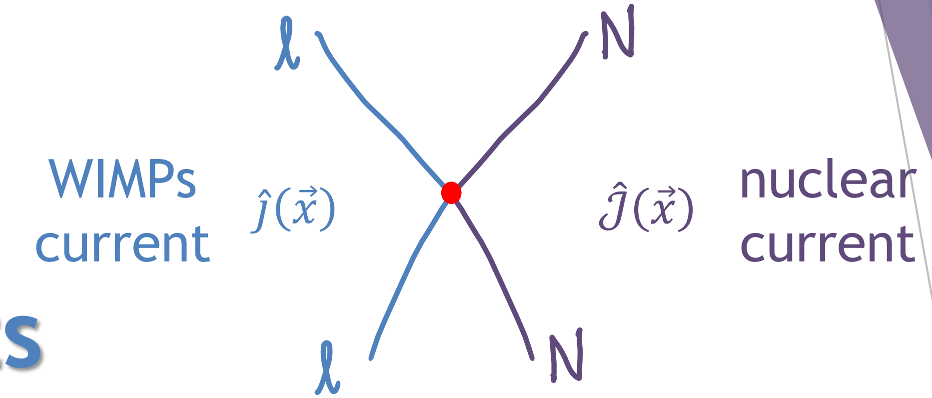
Tensor



$$\mathcal{L}_{int} \sim \hat{j}^{\mu\nu}(\vec{x})\,\hat{J}_{\mu\nu}(\vec{x})$$

AGM & Gazit, PRD 2023

Tensor
$\longrightarrow$ vector-like objects



$$\mathcal{L}_{int} \sim \hat{j}^{\mu\nu}(\vec{x})\, \hat{J}_{\mu\nu}(\vec{x})$$

Tensor interactions

- ~~Symmetric:~~
  - ~~A space-time-metric and the~~ stress-energy tensor
- Antisymmetric
  - Fermionic probes

$$\Longrightarrow l_{00} = 0$$

$$\Longrightarrow l_{\cdot 0} = -l_{0\cdot}$$

$$\Longrightarrow l_{ij} \longrightarrow \left[l_{ij}\right]^{(1)}$$

$$l_{\mu\nu} = \begin{pmatrix} \cancel{l_{00}} & \left(\leftarrow \quad \vec{l}_{0\cdot} \quad \rightarrow \right) \\ \begin{pmatrix} \uparrow \\ -\vec{l}_{0\cdot} \\ \downarrow \end{pmatrix} & \begin{pmatrix} \\ \quad \vec{l}^{(1)} \quad \\ \\ \end{pmatrix} \end{pmatrix}$$

AGM & Gazit, PRD 2023

DM Tensor Interactions

j	$\mathcal{L}^j_{\text{int}}$	Nonrelativistic Reduction	$\Sigma_i c_i \mathcal{O}_i$
21	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{N}\sigma_{\mu\nu}N$	$8\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{\sigma}_N}{2} + \mathcal{O}\left(\frac{1}{m^2}\right)$	$8\mathcal{O}_4$
22	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{N}\left(\frac{q_\mu}{m_M}\gamma_\nu - \frac{q_\nu}{m_M}\gamma_\mu\right)N$	$-\frac{iq^2}{m_\chi m_M}1_\chi 1_N - \frac{4iq^2}{m_N m_M}\left(\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{\sigma}_N}{2}\right)$ $-\frac{4}{m_M}\frac{\vec{\sigma}_\chi}{2}\cdot\left(\vec{q}\times\vec{v}^\perp\right) + \frac{4i}{m_N m_M}\left(\frac{\vec{\sigma}_N}{2}\cdot\vec{q}\right)\left(\frac{\vec{\sigma}_\chi}{2}\cdot\vec{q}\right) + \mathcal{O}\left(\frac{1}{m^3}\right)$	$-i\frac{\vec{q}^2}{m_M m_\chi}\mathcal{O}_1 - 4i\frac{\vec{q}^2}{m_M m_N}\mathcal{O}_4$ $+4i\frac{m_N}{m_M}\mathcal{O}_5 + 4i\frac{m_N}{m_M}\mathcal{O}_6$
23	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{N}\left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{K^\mu}{m_M}\right)N$	$-2i\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}1_\chi 1_N - 8\frac{m_N}{m_M^2}\frac{\vec{\sigma}_\chi}{2}\cdot\left(\vec{q}\times\vec{v}^\perp\right) + \mathcal{O}\left(\frac{1}{m^4}\right)$	$-2i\frac{m_N}{m_\chi}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_1 + 8i\frac{m_N^2}{m_M^2}\mathcal{O}_5$
24	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{N}\left(\gamma_\mu\frac{\slashed{q}}{m_M}\gamma_\nu - \gamma_\nu\frac{\slashed{q}}{m_M}\gamma_\mu\right)N$	$8i\left(\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{q}}{m_M}\right)\left(\frac{\vec{\sigma}_N}{2}\cdot\vec{v}^\perp\right) + \mathcal{O}\left(\frac{1}{m^3}\right)$	$8\frac{m_N}{m_M}\mathcal{O}_{14}$
25	$\bar{\chi}\left(\frac{q^\mu}{m_M}\gamma^\nu - \frac{q^\nu}{m_M}\gamma^\mu\right)\chi\bar{N}\sigma_{\mu\nu}N$	$\frac{iq^2}{m_N m_M}1_\chi 1_N + \frac{4}{m_M}\frac{\vec{\sigma}_N}{2}\cdot\left(\vec{q}\times\vec{v}^\perp\right)$ $+\frac{4i}{m_\chi m_M}\vec{q}^2\left(\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{\sigma}_N}{2}\right) - \frac{4i}{m_\chi m_M}\left(\vec{q}\cdot\frac{\vec{\sigma}_\chi}{2}\right)\left(\vec{q}\cdot\frac{\vec{\sigma}_N}{2}\right) + \mathcal{O}\left(\frac{1}{m^4}\right)$	$i\frac{q^2}{m_N m_M}\mathcal{O}_1 - 4i\frac{m_N}{m_M}\mathcal{O}_3$ $+4i\frac{\vec{q}^2}{m_\chi m_M}\mathcal{O}_4 - 4i\frac{m_N^2}{m_\chi m_M}\mathcal{O}_6$
26	$\bar{\chi}\left(\frac{q^\mu}{m_M}\gamma^\nu - \frac{q^\nu}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\frac{q_\mu}{m_M}\gamma_\nu - \frac{q_\nu}{m_M}\gamma_\mu\right)N$	$-\frac{iq^2}{m_\chi m_M}1_\chi 1_N - \frac{4iq^2}{m_N m_M}\left(\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{\sigma}_N}{2}\right)$ $-\frac{4}{m_M}\frac{\vec{\sigma}_\chi}{2}\cdot\left(\vec{q}\times\vec{v}^\perp\right) + \frac{4i}{m_N m_M}\left(\frac{\vec{\sigma}_N}{2}\cdot\vec{q}\right)\left(\frac{\vec{\sigma}_\chi}{2}\cdot\vec{q}\right) + \mathcal{O}\left(\frac{1}{m^4}\right)$	$-i\frac{q^2}{m_\chi m_M}\mathcal{O}_1 - 4i\frac{q^2}{m_N m_M}\mathcal{O}_4$ $+4i\frac{m_N}{m_M}\mathcal{O}_5 + 4i\frac{m_N}{m_M}\mathcal{O}_6$
27	$\bar{\chi}\left(\frac{q^\mu}{m_M}\gamma^\nu - \frac{q^\nu}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{K^\mu}{m_M}\right)N$	$-4\frac{m_N}{m_M}\frac{q^2}{m_M^2}1_\chi 1_N + \mathcal{O}\left(\frac{1}{m^4}\right)$	$-4\frac{m_N}{m_M}\frac{q^2}{m_M^2}\mathcal{O}_1$
28	$\bar{\chi}\left(\frac{q^\mu}{m_M}\gamma^\nu - \frac{q^\nu}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\gamma_\mu\frac{\slashed{q}}{m_M}\gamma_\nu - \gamma_\nu\frac{\slashed{q}}{m_M}\gamma_\mu\right)N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
29	$\bar{\chi}\left(\frac{q^\mu}{m_M}\frac{P^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{P^\mu}{m_M}\right)\chi\bar{N}\sigma_{\mu\nu}N$	$2i\frac{m_\chi}{m_N}\frac{\vec{q}^2}{m_M^2}1_\chi 1_N + 8\frac{m_\chi}{m_M^2}\frac{\vec{\sigma}_N}{2}\cdot\left(\vec{q}\times\vec{v}^\perp\right) + \mathcal{O}\left(\frac{1}{m^4}\right)$	$2i\frac{m_\chi}{m_N}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_1 - 8i\frac{m_\chi m_N}{m_M^2}\mathcal{O}_3$
30	$\bar{\chi}\left(\frac{q^\mu}{m_M}\frac{P^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{P^\mu}{m_M}\right)\chi\bar{N}\left(\frac{q_\mu}{m_M}\gamma_\nu - \frac{q_\nu}{m_M}\gamma_\mu\right)N$	$-4\frac{m_\chi}{m_M}\frac{q^2}{m_M^2}1_\chi 1_N + \mathcal{O}\left(\frac{1}{m^4}\right)$	$-4\frac{m_\chi}{m_M}\frac{q^2}{m_M^2}\mathcal{O}_1$
31	$\bar{\chi}\left(\frac{q^\mu}{m_M}\frac{P^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{P^\mu}{m_M}\right)\chi\bar{N}\left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{K^\mu}{m_M}\right)N$	$-8\frac{m_\chi m_N}{m_M^2}\frac{\vec{q}^2}{m_M^2}1_\chi 1_N + \mathcal{O}\left(\frac{1}{m^4}\right)$	$-8\frac{m_\chi m_N}{m_M^2}\frac{\vec{q}^2}{m_M^2}\mathcal{O}_1$
32	$\bar{\chi}\left(\frac{q^\mu}{m_M}\frac{P^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{P^\mu}{m_M}\right)\chi\bar{N}\left(\gamma_\mu\frac{\slashed{q}}{m_M}\gamma_\nu - \gamma_\nu\frac{\slashed{q}}{m_M}\gamma_\mu\right)N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
33	$\bar{\chi}\left(\gamma^\mu\frac{\slashed{q}}{m_M}\gamma^\nu - \gamma^\nu\frac{\slashed{q}}{m_M}\gamma^\mu\right)\chi\bar{N}\sigma_{\mu\nu}N$	$-8i\left(\frac{\vec{\sigma}_N}{2}\cdot\frac{\vec{q}}{m_M}\right)\left(\frac{\vec{\sigma}_\chi}{2}\cdot\vec{v}^\perp\right) + \mathcal{O}\left(\frac{1}{m^3}\right)$	$-8\frac{m_N}{m_M}\mathcal{O}_{13}$
34	$\bar{\chi}\left(\gamma^\mu\frac{\slashed{q}}{m_M}\gamma^\nu - \gamma^\nu\frac{\slashed{q}}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\frac{q_\mu}{m_M}\gamma_\nu - \frac{q_\nu}{m_M}\gamma_\mu\right)N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
35	$\bar{\chi}\left(\gamma^\mu\frac{\slashed{q}}{m_M}\gamma^\nu - \gamma^\nu\frac{\slashed{q}}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\frac{q^\mu}{m_M}\frac{K^\nu}{m_M} - \frac{q^\nu}{m_M}\frac{K^\mu}{m_M}\right)N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
36	$\bar{\chi}\left(\gamma^\mu\frac{\slashed{q}}{m_M}\gamma^\nu - \gamma^\nu\frac{\slashed{q}}{m_M}\gamma^\mu\right)\chi\bar{N}\left(\gamma_\mu\frac{\slashed{q}}{m_M}\gamma_\nu - \gamma_\nu\frac{\slashed{q}}{m_M}\gamma_\mu\right)N$	$\frac{32}{m_M^2}\left[q^2\left(\frac{\vec{\sigma}_\chi}{2}\cdot\frac{\vec{\sigma}_N}{2}\right) - \left(\frac{\vec{\sigma}_N}{2}\cdot\vec{q}\right)\left(\frac{\vec{\sigma}_\chi}{2}\cdot\vec{q}\right)\right] + \mathcal{O}\left(\frac{1}{m^4}\right)$	$32\frac{q^2}{m_M^2}\mathcal{O}_4 - 32\frac{m_N^2}{m_M^2}\mathcal{O}_6$

$$\mathcal{O}_1 \equiv 1_\chi 1_N,$$
$$\mathcal{O}_3 \equiv i\vec{S}_N\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right),$$
$$\mathcal{O}_4 \equiv \vec{S}_\chi\cdot\vec{S}_N,$$
$$\mathcal{O}_5 \equiv i\vec{S}_\chi\cdot\left(\frac{\vec{q}}{m_N}\times\vec{v}^\perp\right),$$
$$\mathcal{O}_6 \equiv \left(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}\right)\left(\vec{S}_N\cdot\frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{13} \equiv i\left(\vec{S}_\chi\cdot\vec{v}^\perp\right)\left(\vec{S}_N\cdot\frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{14} \equiv i\left(\vec{S}_\chi\cdot\frac{\vec{q}}{m_N}\right)\left(\vec{S}_N\cdot\vec{v}^\perp\right).$$

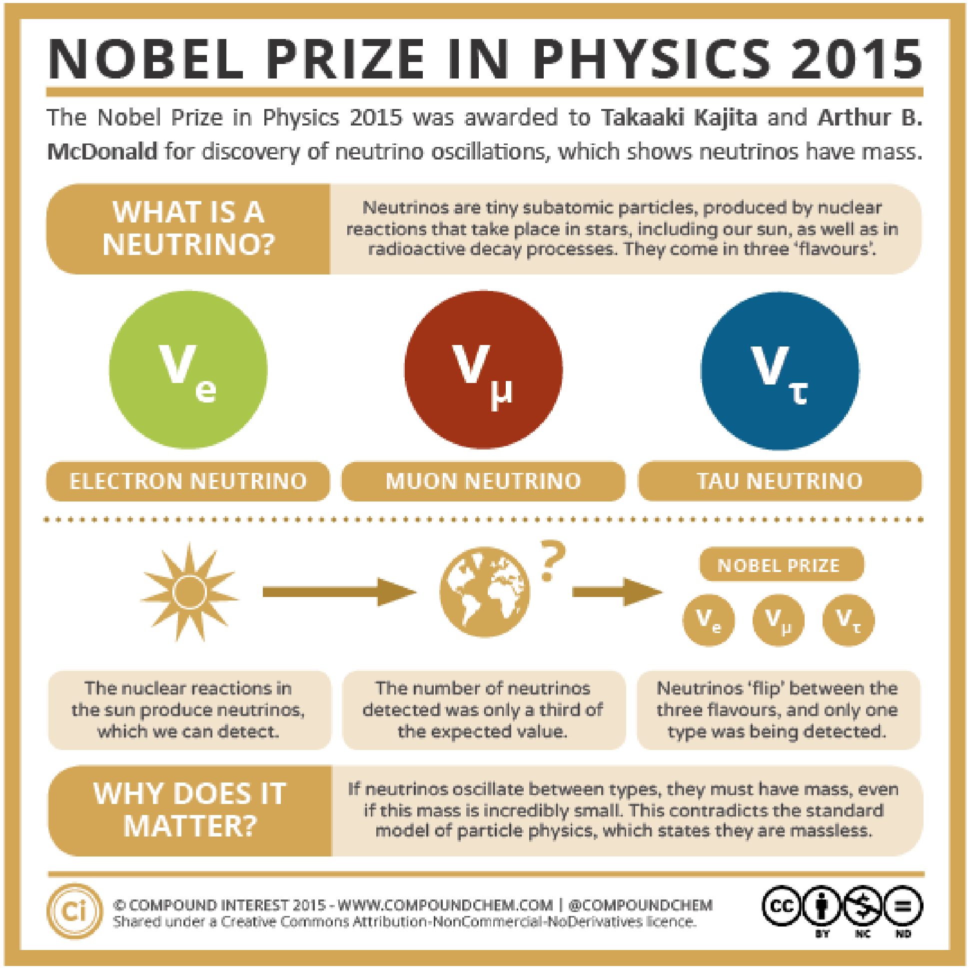
To identify the interaction's nature
we need to know the operators & symmetries
involved in each of S, P, V, A, T

AGM, arXiv:2312.08339

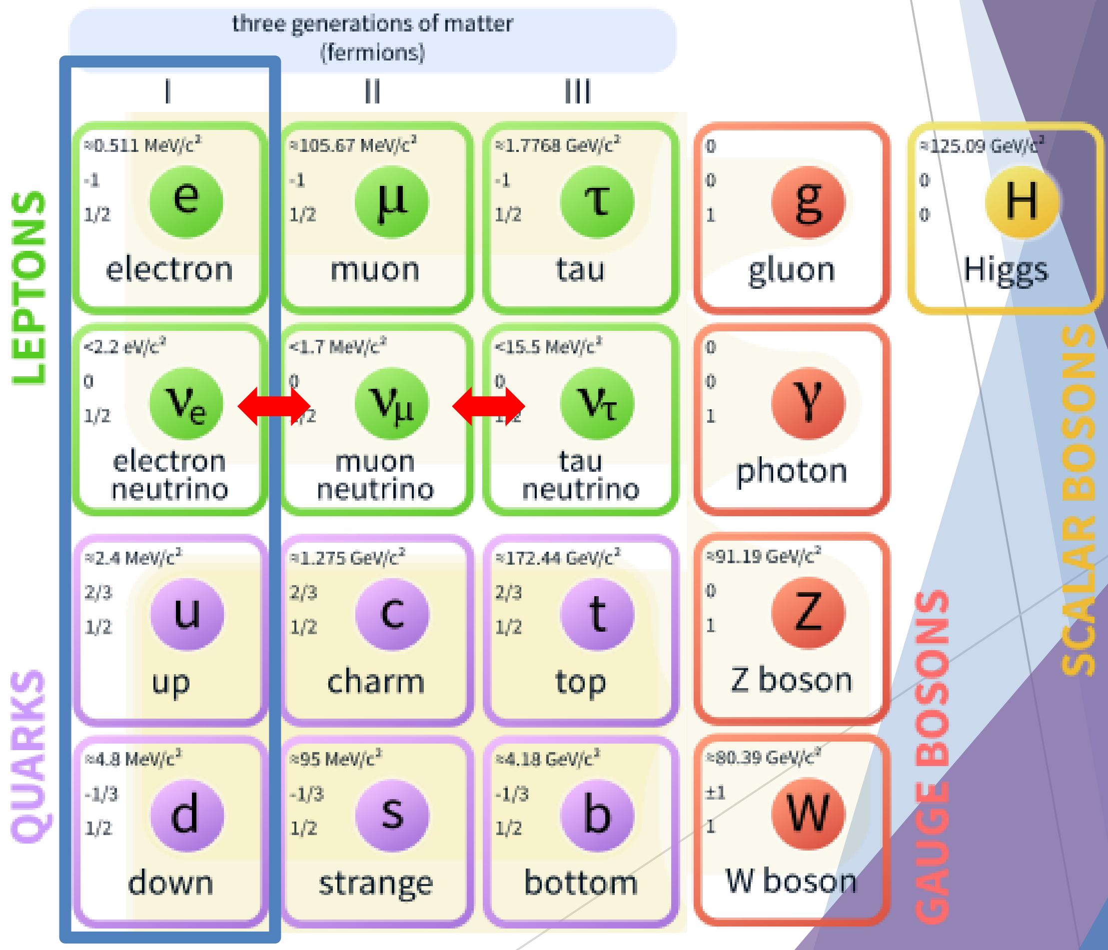
Lepton Flavor Violation

$\mu \rightarrow e$ conversion

Beyond Standard Model (BSM)

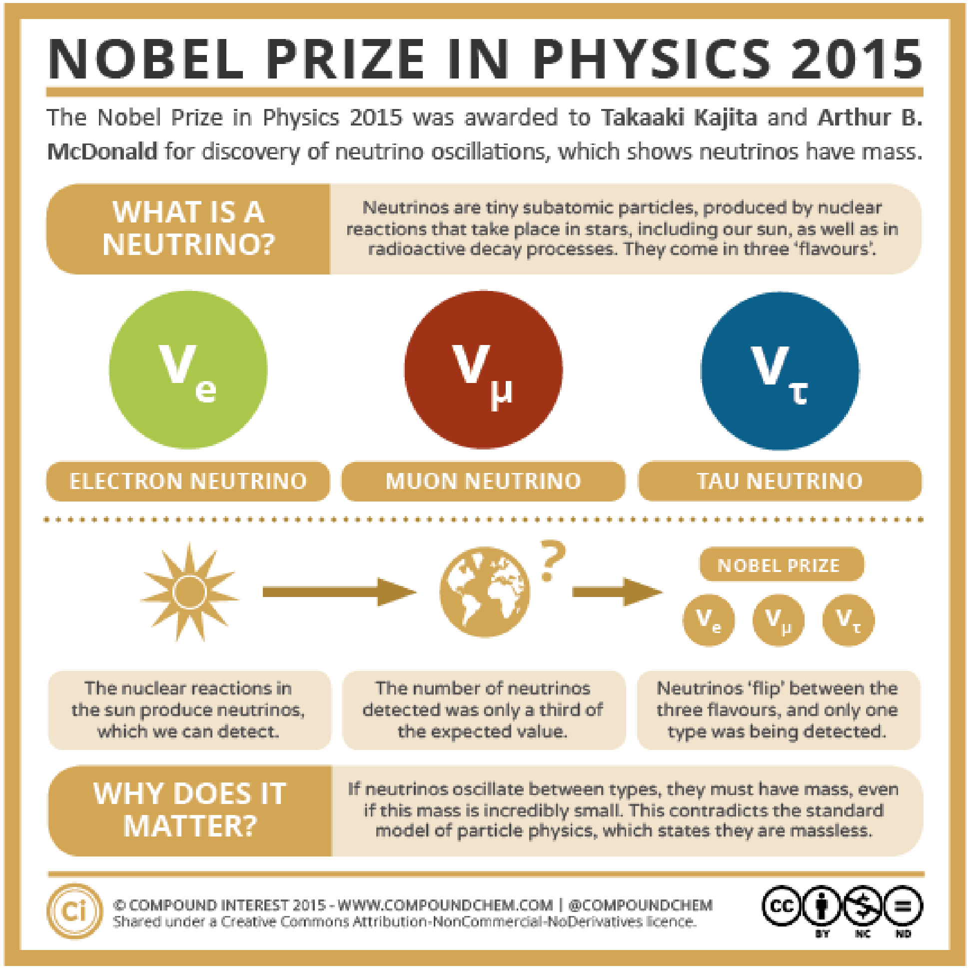


Elementary Particles

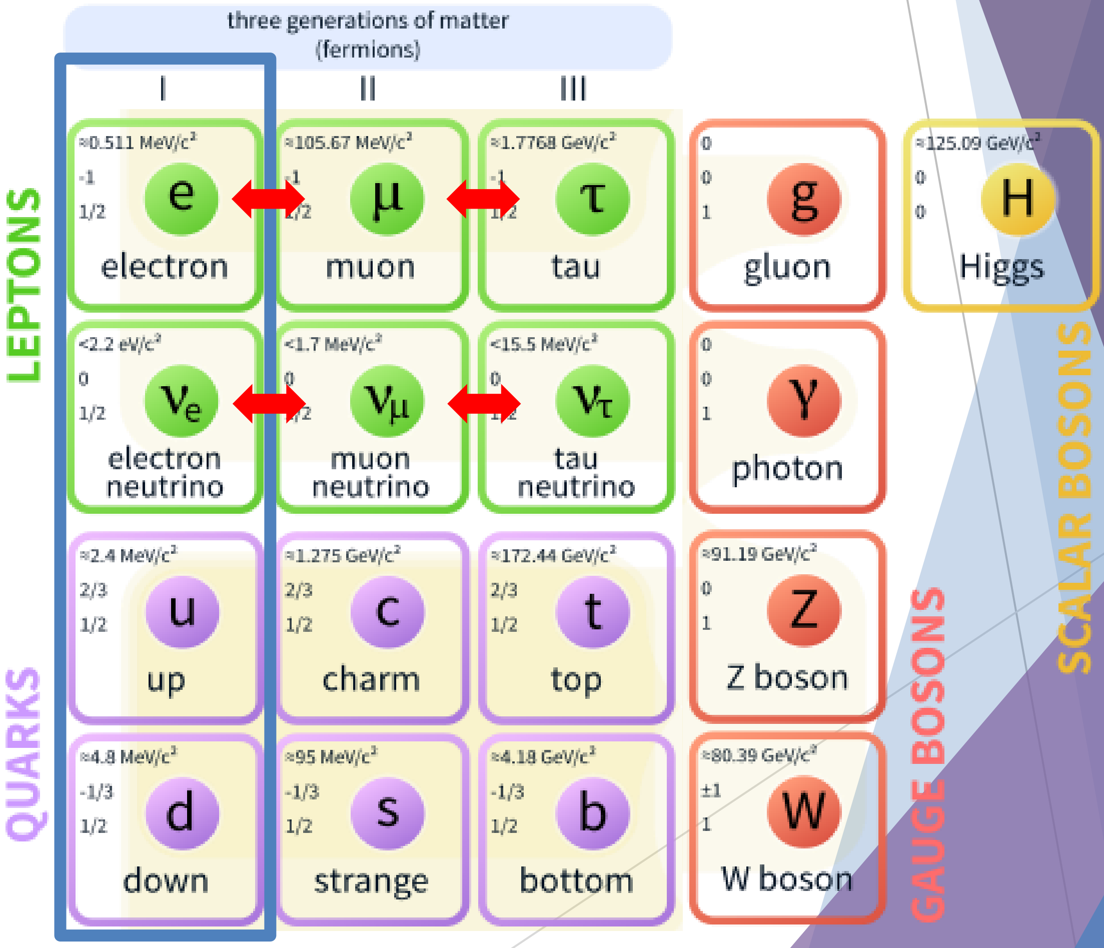


Lepton Flavor Violation

Beyond Standard Model (BSM)



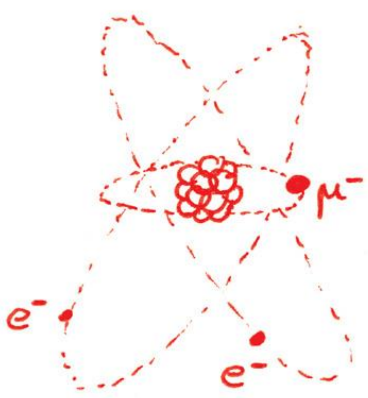
Elementary Particles



Charged Lepton Flavor Violation

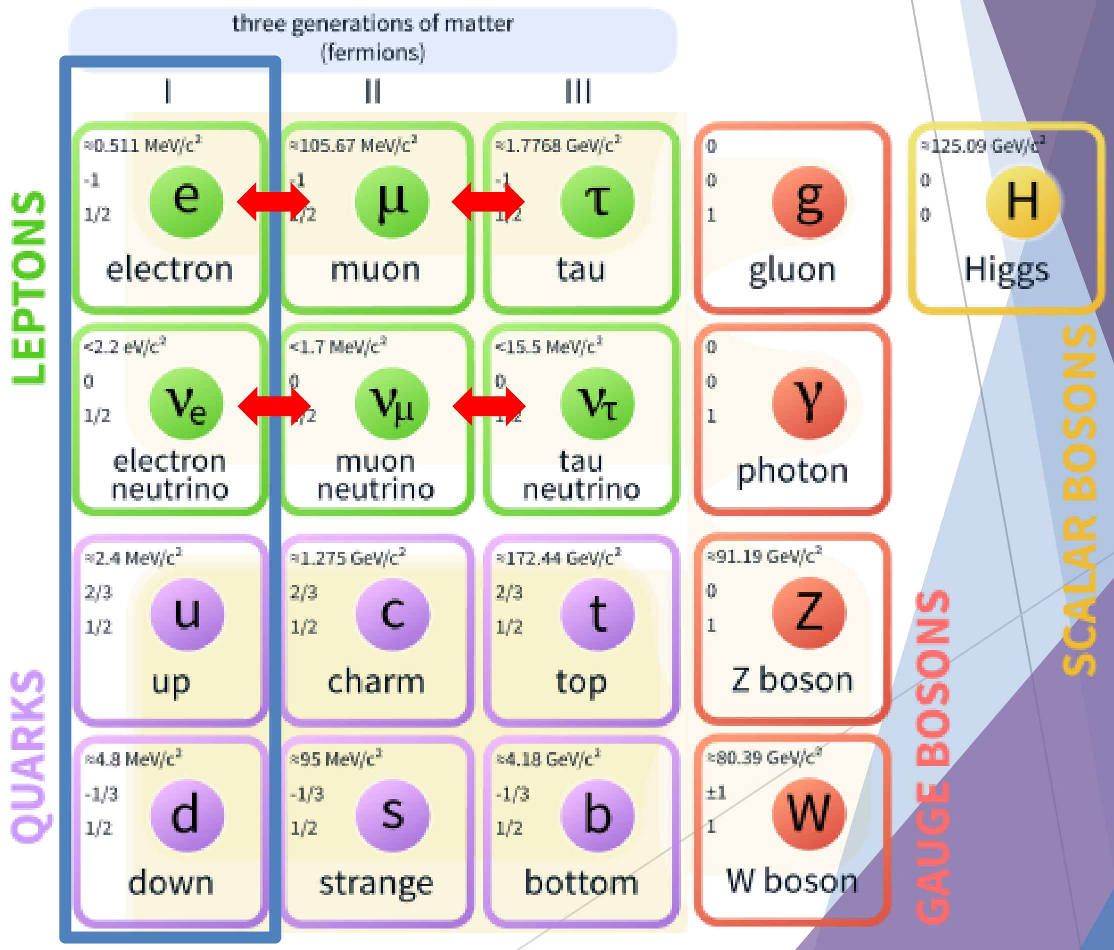
Beyond Standard Model (BSM)
with nuclei…

This is what we start with.



(Credit: symmetry magazine)

Elementary Particles

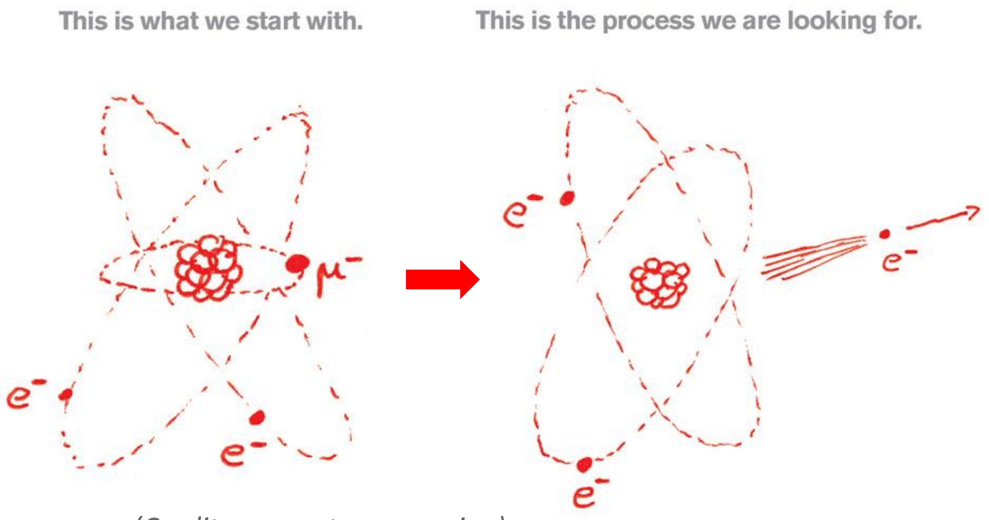


Charged Lepton Flavor Violation

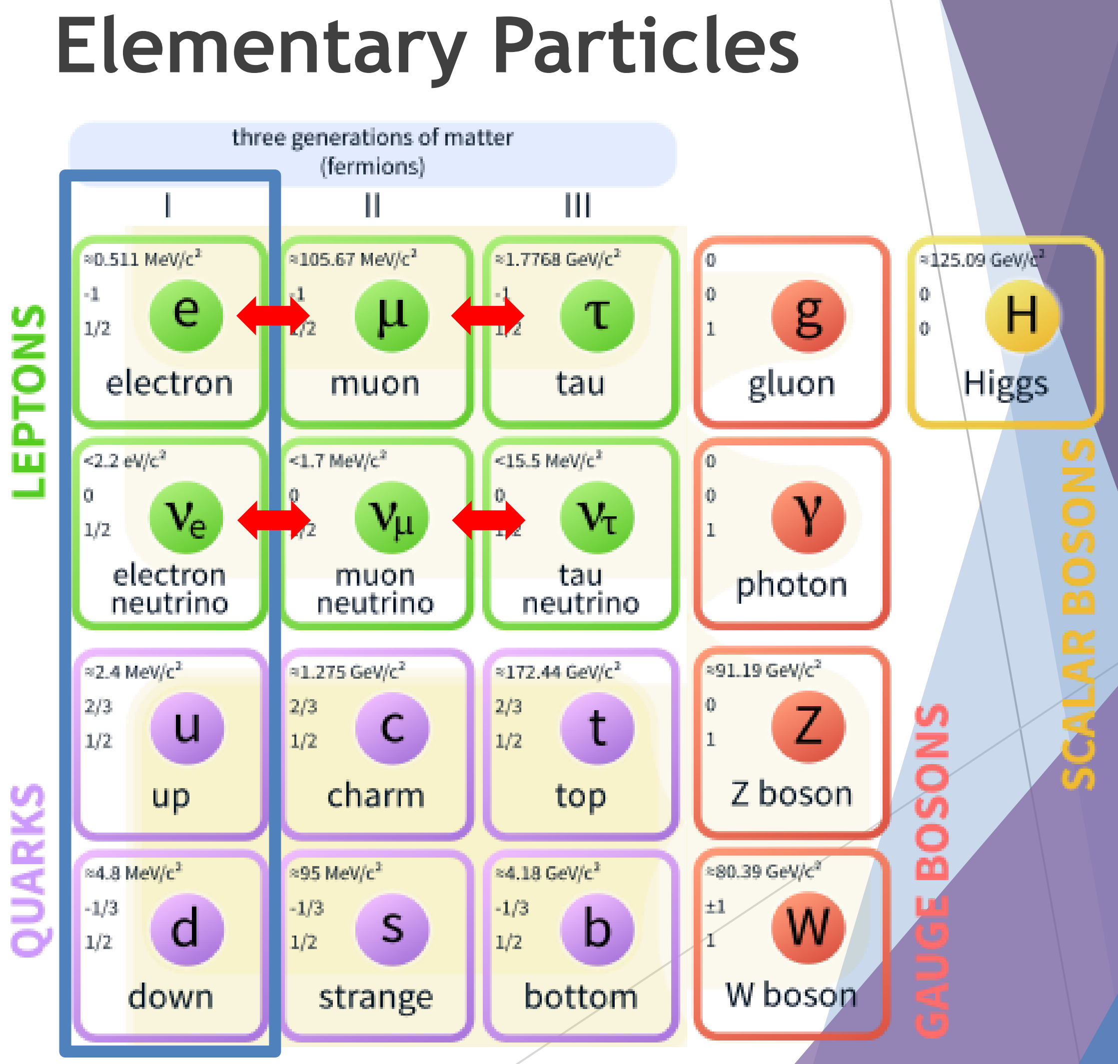
Beyond Standard Model (BSM)

with nuclei…

$\mu \rightarrow e$ conversion

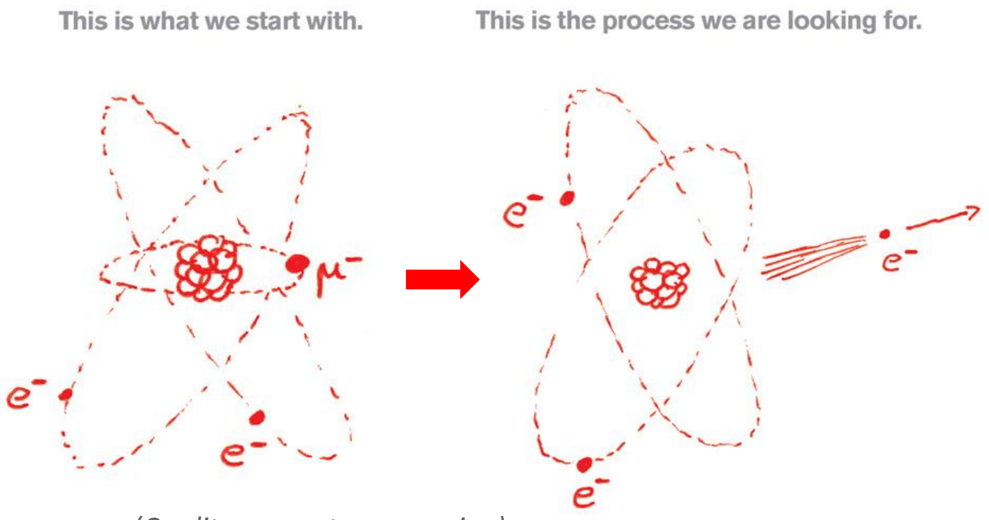


(Credit: symmetry magazine)



Charged Lepton Flavor Violation

$\mu \to e$ conversion



(Credit: symmetry magazine)

TABLE IX. Existing limits on branching ratios for $\mu \to e$ conversion, taken from the tabulation of [75].

Process	Limit	Lab/Reference
$\mu^- + {}^{32}\mathrm{S} \to e^- + {}^{32}\mathrm{S}$	7×10^{-11}	SIN [76]
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	1.6×10^{-11}	TRIUMF [77]
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	4.6×10^{-12}	TRIUMF [78]
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	4.3×10^{-12}	PSI [79]
$\mu^- + \mathrm{Ti} \to e^- + \mathrm{Ti}$	6.1×10^{-13}	PSI [80]
$\mu^- + \mathrm{Cu} \to e^- + \mathrm{Cu}$	1.6×10^{-8}	SREL [81]
$\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}$	7×10^{-13}	PSI [82]
$\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}$	4.9×10^{-10}	TRIUMF [78]
$\mu^- + \mathrm{Pb} \to e^- + \mathrm{Pb}$	4.6×10^{-11}	PSI [83]

branching ratio with respect to muon capture in the same nucleus

- Future experiments: mu2e @ Fermilab, COMET @ J-PARC

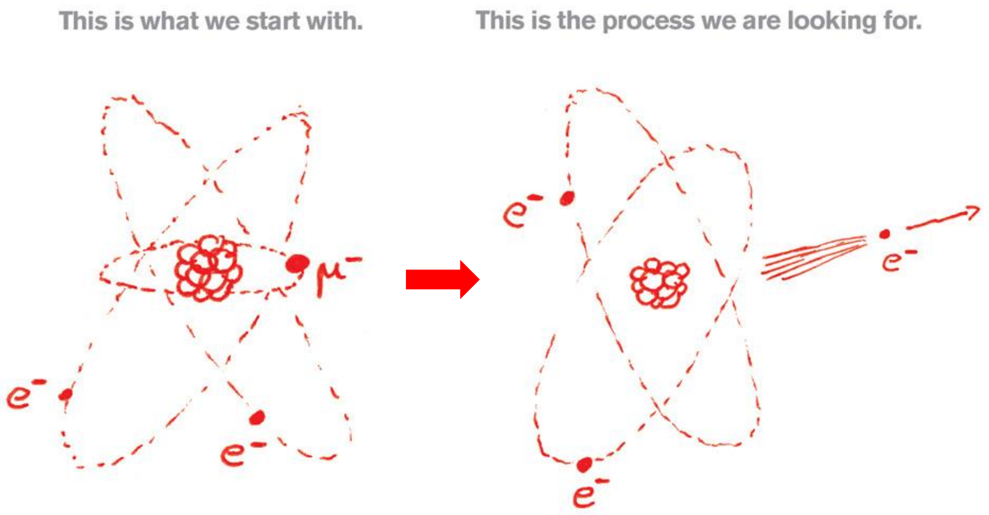
$$(^{27}\mathrm{Al}) \sim 10^{-17}$$

4 orders of magnitude enhancement!

W. C. Haxton, E. Rule, K. McElvain, M. J. Ramsey-Musolf. Phys.Rev.C, 107:035504 (2023)

- $q \sim m_\mu$
- The electron is "fully relativistic"

$\mu \to e$ conversion



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$\mu^- + {}^{32}S \to e^- + {}^{32}S$	7×10^{-11}	SIN [76]
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$\mu^- + Ti \to e^- + Ti$	6.1×10^{-13}	PSI [80]
$\mu^- + Cu \to e^- + Cu$	1.6×10^{-8}	SREL [81]
$\mu^- + Au \to e^- + Au$	7×10^{-13}	PSI [82]
$\mu^- + Pb \to e^- + Pb$	4.9×10^{-10}	TRIUMF [78]
$\mu^- + Pb \to e^- + Pb$	4.6×10^{-11}	PSI [83]

branching ratio with respect to muon capture in the same nucleus

- Future experiments: mu2e @ Fermilab, COMET @ J-PARC

$$({}^{27}\mathrm{Al}) \sim \mathbf{10^{-17}}$$

NREFT Missing tensor couplings

4 orders of magnitude enhancement!

$\mu \to e$ Tensor Interactions

j	$\mathcal{L}^j_{\text{int}}$	Pauli Operator Reduction	$\Sigma_i c_i \mathcal{O}_i$
21	$\bar{\chi}_e \sigma^{\mu\nu} \chi_\mu \bar{N} \sigma_{\mu\nu} N$	$-\frac{q}{m_N} 1_L 1_N - 2i 1_L \hat{q} \cdot (\vec{v}_N \times \vec{\sigma}_N) + 2\vec{\sigma}_L \cdot \vec{\sigma}_N + 2\vec{\sigma}_L \cdot [\hat{q} \times (\vec{v}_N \times \vec{\sigma}_N)]$ $+i(\hat{q} \times \vec{v}_\mu) \cdot \vec{\sigma}_N - (\vec{v}_\mu \cdot \vec{\sigma}_L)(\hat{q} \cdot \vec{\sigma}_N) - [\hat{q} \times (\vec{v}_\mu \times \vec{\sigma}_L)] \cdot \vec{\sigma}_N + \mathcal{O}\left(\frac{q^2}{m_N^2}\right)$	$-\frac{q}{m_N} \mathcal{O}_1 - 2\mathcal{O}_3 + 2\mathcal{O}_4 - 2i\mathcal{O}_{13}$ $+\mathcal{O}_5^f + 2i\mathcal{O}_{14}^f + 2i\mathcal{O}_{13}^{f'}$
22	$\bar{\chi}_e \sigma^{\mu\nu} \chi_\mu \bar{N} \left(\frac{q_\mu}{m_N}\gamma_\nu - \frac{q_\nu}{m_N}\gamma_\mu\right) N$	$-2i\frac{q}{m_N} 1_L 1_N + i\frac{q^2}{m_N^2}(\vec{\sigma}_L \cdot \vec{\sigma}_N) - 2\frac{q}{m_N}\vec{\sigma}_L \cdot (\hat{q} \times \vec{v}_N)$ $+i\frac{q^2}{m_N^2}(\hat{q} \cdot \vec{\sigma}_N)(\vec{\sigma}_L \cdot \hat{q}) + i\frac{q}{m_N}(\vec{v}_\mu \cdot \hat{q}) 1_N - \frac{q}{m_N}\hat{q} \cdot (\vec{v}_\mu \times \vec{\sigma}_L) 1_N + \mathcal{O}\left(\frac{q^3}{m_N^3}\right)$	$-2i\frac{q}{m_N}\mathcal{O}_1 + i\frac{q^2}{m_N^2}\mathcal{O}_4 + 2i\frac{q}{m_N}\mathcal{O}_5$ $-i\frac{q^2}{m_N^2}\mathcal{O}_6 + 2i\frac{q}{m_N}\mathcal{O}_2^{f'} + 2i\frac{q}{m_N}\mathcal{O}_3^f$
23	$\bar{\chi}_e \sigma^{\mu\nu} \chi_\mu \bar{N}' \left(\frac{q_\mu}{m_N} v_{N\nu} - \frac{q_\nu}{m_N} v_{N\mu}\right) N$	$\frac{q}{m_N}\left[-2i 1_L \cdot 1_N + 2\vec{\sigma}_L \cdot (\hat{q} \times \vec{v}_N) + i(\hat{q} \cdot \vec{v}_\mu) 1_N - \hat{q} \cdot (\vec{v}_\mu \times \vec{\sigma}_L) 1_N\right] + \mathcal{O}\left(\frac{q^3}{m_N^3}\right)$	$2\frac{q}{m_N}\left(-i\mathcal{O}_1 - i\mathcal{O}_5 + \mathcal{O}_2^{f'} + i\mathcal{O}_3^f\right)$
24	$\bar{\chi}_e \sigma^{\mu\nu} \chi_\mu \bar{N} \left(\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu - \gamma_\nu \frac{\not{q}}{m_N}\gamma_\mu\right) N$	$-4i\frac{q}{m_N}\left[(\vec{\sigma}_L \cdot \vec{\sigma}_N) + 4i\frac{q}{m_N}(\vec{\sigma}_L \cdot \hat{q})(\vec{\sigma}_N \cdot \hat{q}) + i(\hat{q} \cdot \vec{\sigma}_L)(\vec{v}_N \cdot \vec{\sigma}_N)\right]$ $-4i\frac{q}{m_N}\left\{i\left(\hat{q} \times \frac{\vec{v}_\mu}{2}\right) \cdot \vec{\sigma}_N - \left[\hat{q} \times \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right)\right] \cdot \vec{\sigma}_N\right\} + \mathcal{O}\left(\frac{q^3}{m_N^3}\right)$	$-4i\frac{q}{m_N}(\mathcal{O}_4 + \mathcal{O}_6 - i\mathcal{O}_{14})$ $-4i\frac{q}{m_N}\left(\mathcal{O}_5^f + i\mathcal{O}_{13}^{f'}\right)$
25	$\bar{\chi}_e \left(\frac{q^\mu}{m_L}\gamma^\nu - \frac{q^\nu}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \sigma_{\mu\nu} N$	$\frac{q}{m_L}\left\{2i(\vec{\sigma}_L \cdot \vec{\sigma}_N) - 2i(\hat{q} \cdot \vec{\sigma}_L)(\hat{q} \cdot \vec{\sigma}_N) + \frac{i}{2}\frac{q}{m_N} 1_L 1_N - 1_L \hat{q} \cdot (\vec{v}_N \times \vec{\sigma}_N)\right\}$ $+\frac{q}{m_L}\{(\hat{q} \times \vec{v}_\mu) \cdot \vec{\sigma}_N + i[\hat{q} \times (\vec{v}_\mu \times \vec{\sigma}_L)] \cdot \vec{\sigma}_N\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^2}{m_N^2}\right)$	$i\frac{q}{m_L}\left(2\mathcal{O}_4 + 2\mathcal{O}_6 + \frac{1}{2}\frac{q}{m_N}\mathcal{O}_1 + \mathcal{O}_3\right)$ $+2\frac{q}{m_L}\left(-i\mathcal{O}_5^f + \mathcal{O}_{13}^{f'}\right)$
26	$\bar{\chi}_e \left(\frac{q^\mu}{m_L}\gamma^\nu - \frac{q^\nu}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \left(\frac{q_\mu}{m_N}\gamma_\nu - \frac{q_\nu}{m_N}\gamma_\mu\right) N$	$\frac{q^2}{m_L m_N}\left[-1_L 1_N + \frac{q}{m_N}(\vec{\sigma}_L \cdot \vec{\sigma}_N) - \frac{q}{m_N}(\hat{q} \cdot \vec{\sigma}_N)(\hat{q} \cdot \vec{\sigma}_L) + 2i\vec{\sigma}_L \cdot (\hat{q} \times \vec{v}_N)\right]$ $+\frac{q^2}{m_L m_N}[-(\hat{q} \cdot \vec{v}_\mu) 1_N - i\hat{q} \cdot (\vec{v}_\mu \times \vec{\sigma}_L) 1_N] + \mathcal{O}\left(\frac{q}{m_L}\frac{q^3}{m_N^3}\right)$	$\frac{q^2}{m_L m_N}\left(-\mathcal{O}_1 + \frac{q}{m_N}\mathcal{O}_4 + \frac{q}{m_N}\mathcal{O}_6 + 2\mathcal{O}_5\right)$ $+\frac{q^2}{m_L m_N}\left(2i\mathcal{O}_2^{f'} - 2\mathcal{O}_3^f\right)$
27	$\bar{\chi}_e \left(\frac{q^\mu}{m_L}\gamma^\nu - \frac{q^\nu}{m_L}\gamma^\mu\right) \chi_\mu \bar{N}' \left(\frac{q_\mu}{m_N} v_{N\nu} - \frac{q_\nu}{m_N} v_{N\mu}\right) N$	$\frac{q}{m_L}\frac{q}{m_N}\{-1_L 1_N + 2i\vec{\sigma}_L \cdot (\hat{q} \times \vec{v}_N)\}$ $-\frac{q}{m_L}\frac{q}{m_N}\{(\hat{q} \cdot \vec{v}_\mu) 1_N + i\hat{q} \cdot (\vec{v}_\mu \times \vec{\sigma}_L) 1_N\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^3}{m_N^3}\right)$	$\frac{q^2}{m_L m_N}(-\mathcal{O}_1 + 2\mathcal{O}_5)$ $+\frac{q^2}{m_L m_N}\left(2i\mathcal{O}_2^{f'} - 2\mathcal{O}_3^f\right)$
28	$\bar{\chi}_e \left(\frac{q^\mu}{m_L}\gamma^\nu - \frac{q^\nu}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \left(\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu - \gamma_\nu \frac{\not{q}}{m_N}\gamma_\mu\right) N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
29	$\bar{\chi}_e \left(\frac{q^\alpha}{m_L} v_\mu^\nu - \frac{q^\nu}{m_L} v_\mu^\alpha\right) \chi_\mu \bar{N} \sigma_{\alpha\nu} N$	$2\frac{q}{m_L}\left\{\frac{i}{2}\frac{q}{m_N} 1_L 1_N - 1_L \hat{q} \cdot (\vec{v}_N \times \vec{\sigma}_N) + (\hat{q} \times \vec{v}_\mu) \cdot \vec{\sigma}_N\right\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^2}{m_N^2}\right)$	$i\frac{q}{m_L}\left(\frac{q}{m_N}\mathcal{O}_1 + 2\mathcal{O}_3 - 4\mathcal{O}_5^f\right)$
30	$\bar{\chi}_e \left(\frac{q^\alpha}{m_L} v_\mu^\nu - \frac{q^\nu}{m_L} v_\mu^\alpha\right) \chi_\mu \bar{N} \left(\frac{q_\alpha}{m_N}\gamma_\nu - \frac{q_\nu}{m_N}\gamma_\alpha\right) N$	$2\frac{q^2}{m_L m_N}\left\{-1_L 1_N + \left(\hat{q} \cdot \frac{\vec{v}_\mu}{2}\right) 1_N + i\hat{q} \cdot \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right) 1_N\right\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^3}{m_N^3}\right)$	$2\frac{q^2}{m_L m_N}\left(-\mathcal{O}_1 - i\mathcal{O}_2^{f'} + \mathcal{O}_3^f\right)$
31	$\bar{\chi}_e \left(\frac{q^\alpha}{m_L} v_\mu^\nu - \frac{q^\nu}{m_L} v_\mu^\alpha\right) \chi_\mu \bar{N}' \left(\frac{q_\alpha}{m_N} v_{N\nu} - \frac{q_\nu}{m_N} v_{N\alpha}\right) N$	$2\frac{q^2}{m_L m_N}\left\{-1_L 1_N + \left(\hat{q} \cdot \frac{\vec{v}_\mu}{2}\right) 1_N + i\hat{q} \cdot \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right) 1_N\right\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^3}{m_N^3}\right)$	$2\frac{q^2}{m_L m_N}\left(-\mathcal{O}_1 - i\mathcal{O}_2^{f'} + \mathcal{O}_3^f\right)$
32	$\bar{\chi}_e \left(\frac{q^\alpha}{m_L} v_\mu^\nu - \frac{q^\nu}{m_L} v_\mu^\alpha\right) \chi_\mu \bar{N} \left(\gamma_\alpha \frac{\not{q}}{m_N}\gamma_\nu - \gamma_\nu \frac{\not{q}}{m_N}\gamma_\alpha\right) N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
33	$\bar{\chi}_e \left(\gamma^\mu \frac{\not{q}}{m_L}\gamma^\nu - \gamma^\nu \frac{\not{q}}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \sigma_{\mu\nu} N$	$-4i\frac{q}{m_L}\{(\hat{q} \cdot \vec{\sigma}_L)(\hat{q} \cdot \vec{\sigma}_N) - \vec{\sigma}_L \cdot [\hat{q} \times (\vec{v}_N \times \vec{\sigma}_N)]\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^2}{m_N^2}\right)$ $-4i\frac{q}{m_L}\left(\frac{\vec{v}_\mu}{2} \cdot \vec{\sigma}_L\right)(\hat{q} \cdot \vec{\sigma}_N) + \mathcal{O}\left(\frac{q}{m_L}\frac{q^2}{m_N^2}\right)$	$4\frac{q}{m_L}\left(i\mathcal{O}_6 + \mathcal{O}'_{13}\right)$ $-4\frac{q}{m_L}\mathcal{O}_{14}^f$
34	$\bar{\chi}_e \left(\gamma^\mu \frac{\not{q}}{m_L}\gamma^\nu - \gamma^\nu \frac{\not{q}}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \left(\frac{q_\mu}{m_N}\gamma_\nu - \frac{q_\nu}{m_N}\gamma_\mu\right) N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
35	$\bar{\chi}_e \left(\gamma^\mu \frac{\not{q}}{m_L}\gamma^\nu - \gamma^\nu \frac{\not{q}}{m_L}\gamma^\mu\right) \chi_\mu \bar{N}' \left(\frac{q_\mu}{m_N} v_{N\nu} - \frac{q_\nu}{m_N} v_{N\mu}\right) N$	$\mathcal{O}\left(\frac{1}{m^6}\right)$	
36	$\bar{\chi}_e \left(\gamma^\mu \frac{\not{q}}{m_L}\gamma^\nu - \gamma^\nu \frac{\not{q}}{m_L}\gamma^\mu\right) \chi_\mu \bar{N} \left(\gamma_\mu \frac{\not{q}}{m_N}\gamma_\nu - \gamma_\nu \frac{\not{q}}{m_N}\gamma_\mu\right) N$	$8\frac{q^2}{m_L m_N}\{(\vec{\sigma}_L \cdot \vec{\sigma}_N) - (\hat{q} \cdot \vec{\sigma}_L)(\hat{q} \cdot \vec{\sigma}_N) - (\hat{q} \cdot \vec{\sigma}_L)(\vec{v}_N \cdot \vec{\sigma}_N)\}$ $+8\frac{q^2}{m_L m_N}\left\{-i\left(\hat{q} \times \frac{\vec{v}_\mu}{2}\right) \cdot \vec{\sigma}_N + \left[\hat{q} \times \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right)\right] \cdot \vec{\sigma}_N\right\} + \mathcal{O}\left(\frac{q}{m_L}\frac{q^3}{m_N^3}\right)$	$8\frac{q^2}{m_L m_N}(\mathcal{O}_4 + \mathcal{O}_6 + i\mathcal{O}_{14})$ $-8\frac{q^2}{m_L m_N}\left(\mathcal{O}_5^f + i\mathcal{O}_{13}^{f'}\right)$

New operators!
Easier for identifying the nature of the CLFV

$$\mathcal{O}_1 \equiv 1_L 1_N,$$
$$\boxed{\mathcal{O}_3 \equiv 1_L i\hat{q} \cdot (\vec{v}_N \times \vec{\sigma}_N)},$$
$$\mathcal{O}_4 \equiv \vec{\sigma}_L \cdot \vec{\sigma}_N,$$
$$\mathcal{O}_5 \equiv \vec{\sigma}_L \cdot (i\hat{q} \times \vec{v}_N),$$
$$\mathcal{O}_6 \equiv (i\hat{q} \cdot \vec{\sigma}_L)(i\hat{q} \cdot \vec{\sigma}_N),$$
$$\boxed{\mathcal{O}'_{13} \equiv \vec{\sigma}_L \cdot [i\hat{q} \times (\vec{v}_N \times \vec{\sigma}_N)]}$$
$$\mathcal{O}_{14} \equiv (i\hat{q} \cdot \vec{\sigma}_L)(\vec{v}_N \cdot \vec{\sigma}_N).$$
$$\mathcal{O}_2^{f'} \equiv i\hat{q} \cdot \frac{\vec{v}_\mu}{2} 1_N,$$
$$\mathcal{O}_3^f \equiv i\hat{q} \cdot \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right) 1_N,$$
$$\mathcal{O}_5^f \equiv \left(i\hat{q} \times \frac{\vec{v}_\mu}{2}\right) \cdot \vec{\sigma}_N,$$
$$\mathcal{O}_{13}^{f'} \equiv \left[i\hat{q} \times \left(\frac{\vec{v}_\mu}{2} \times \vec{\sigma}_L\right)\right] \cdot \vec{\sigma}_N,$$
$$\mathcal{O}_{14}^f \equiv \left(\frac{\vec{v}_\mu}{2} \cdot \vec{\sigma}_L\right)(i\hat{q} \cdot \vec{\sigma}_N).$$

Matching data
$\Longrightarrow$ Must be Tensor

AGM, arXiv:2312.08339

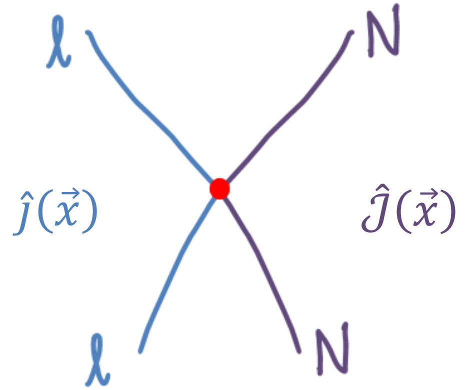
New weak interactions

Nuclear β-decay

Weak interaction

Low energy reaction of
leptons with nucleons

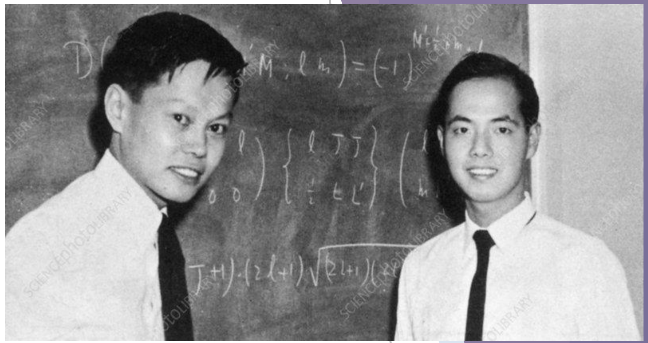
lepton current



nuclear current

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

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)

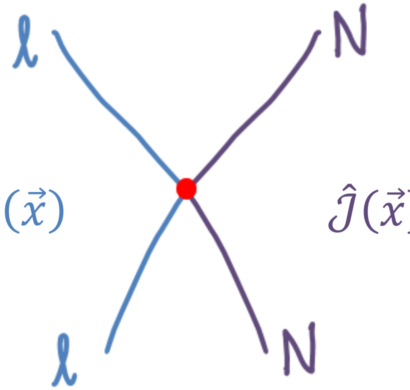
Experiment: C.S. Wu:
Parity violation in ***nuclear β-decays***

⇒ **Weak SM structure: "$V - A$"**

Weak interaction

Low energy reaction of
leptons with nucleons

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



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

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

A-priori:
- Scalar (C_S)
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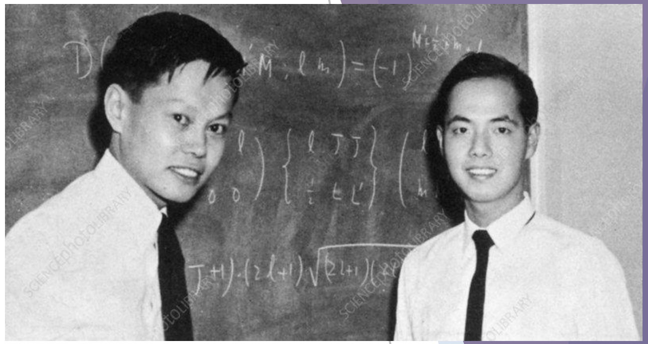


Theory: C.N. Yang and T.D. Lee (Nobel 1957)

Experiment: C.S. Wu:
Parity violation in ***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

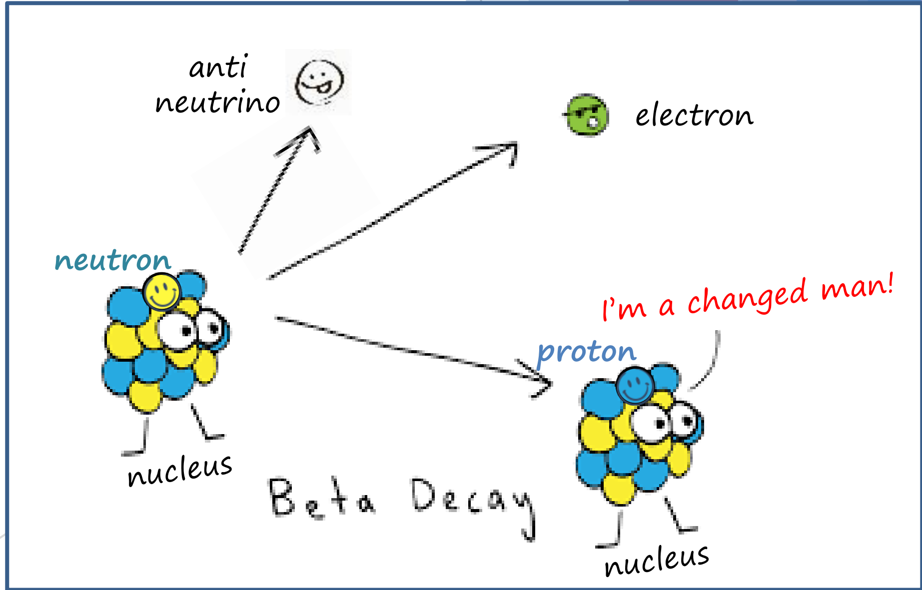
Low momentum transfer: $q \sim 0 - 10\ \mathrm{MeV/c}$

angular momentum

parity

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

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



Nuclear β-decay

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

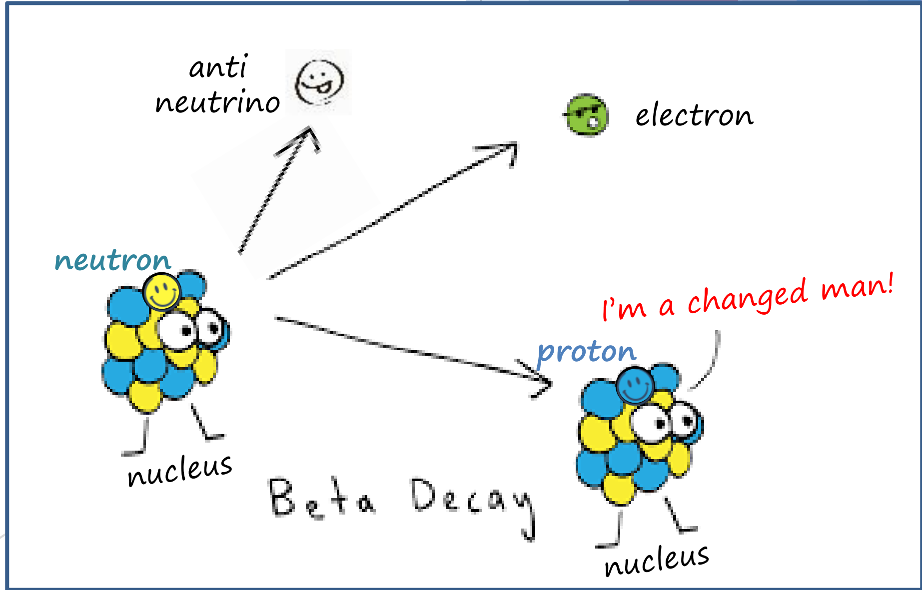
angular momentum

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



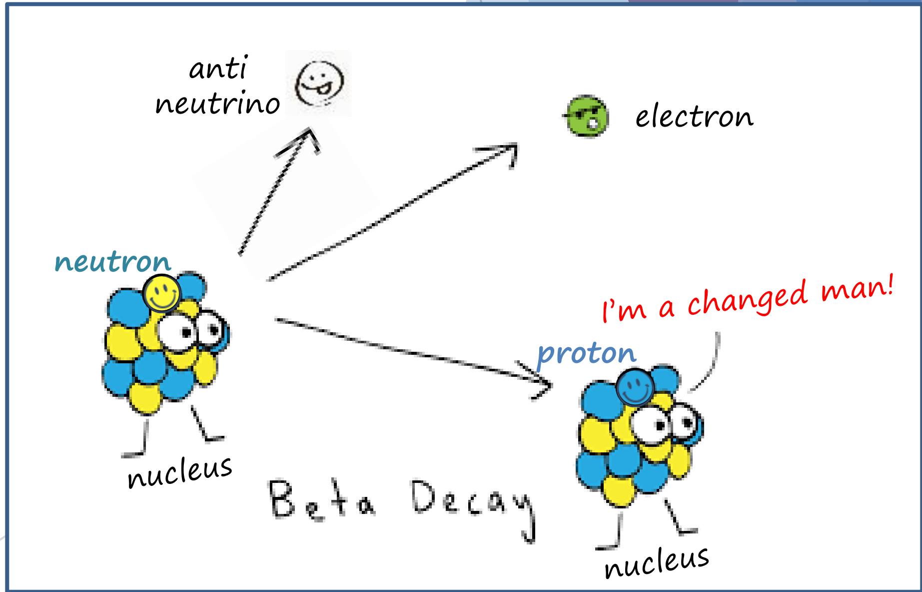
Nuclear β-decay

- β-decay rate:

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

Observables

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



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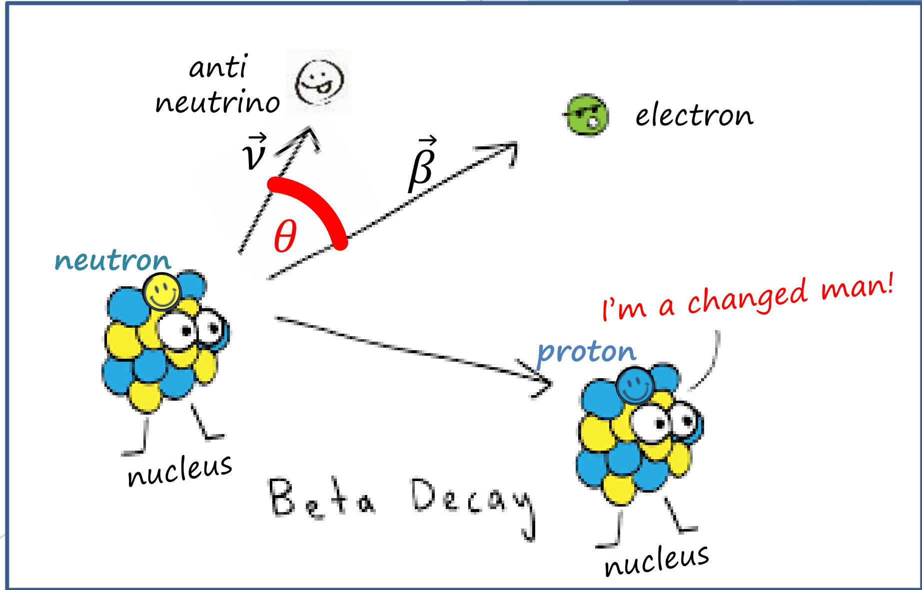
Measurements *(e.g., Gamow-Teller)*:

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

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



$\epsilon_T \sim$

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

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

Nuclear β-decay

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Observables

electron's mass, energy

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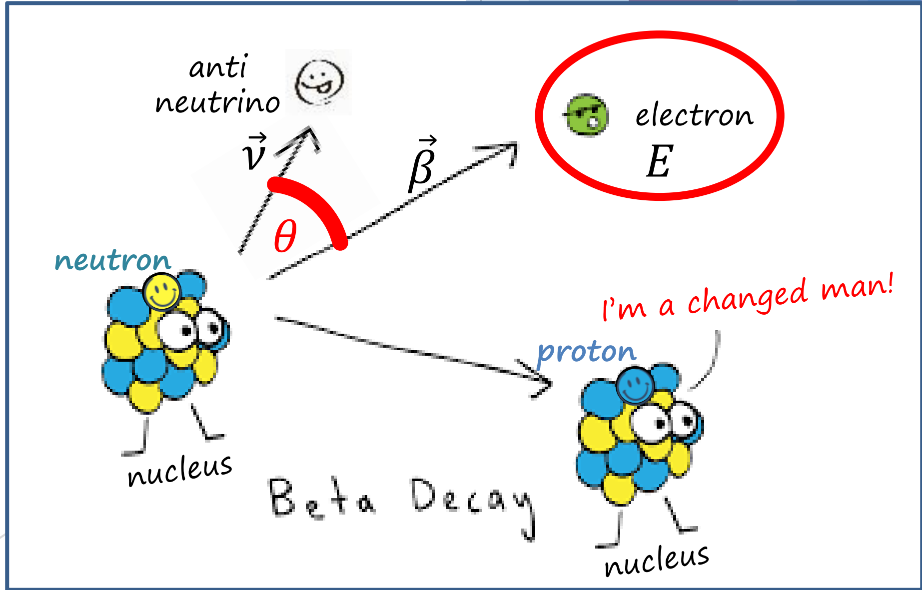

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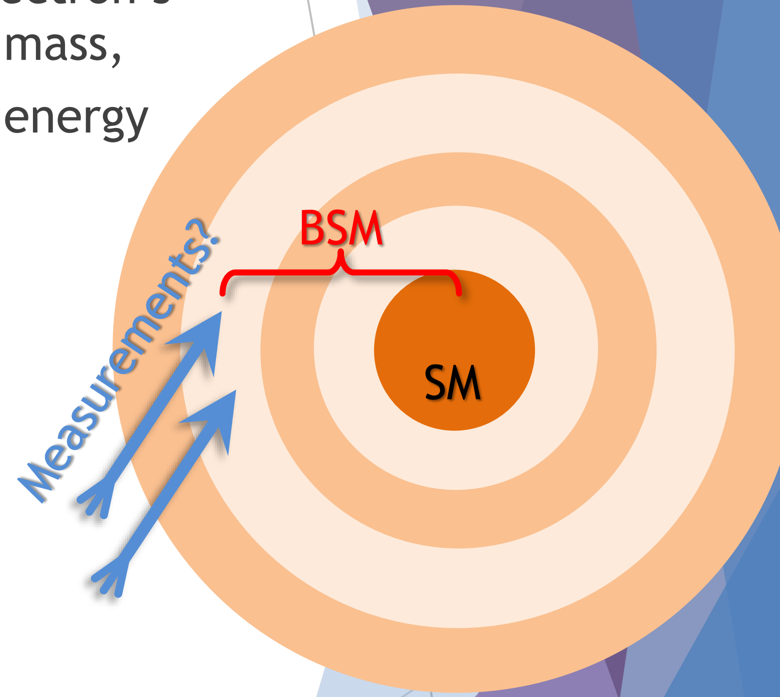
Observables

electron's mass, energy



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

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electron's mass, energy

Observables

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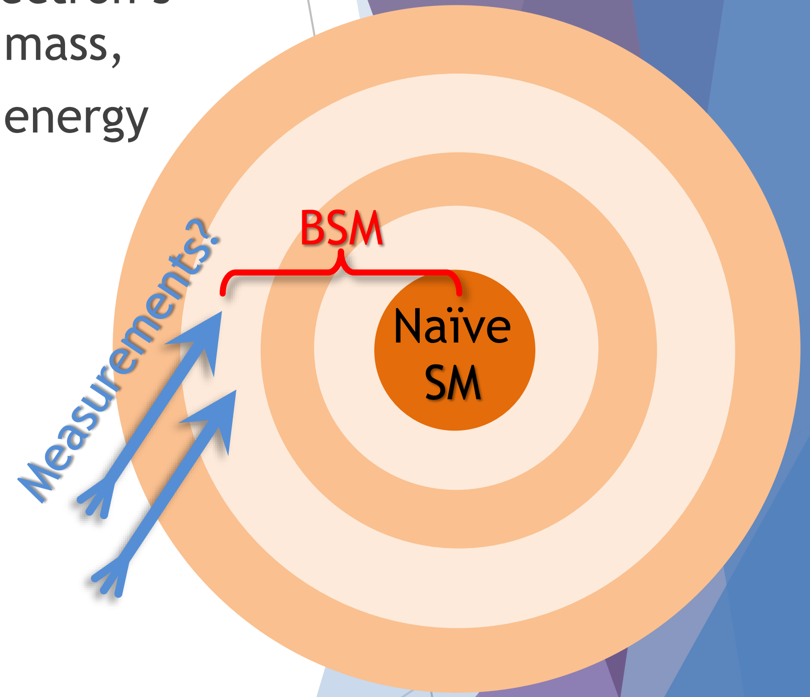

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$m_e \to$ electron's mass, $E \to$ energy

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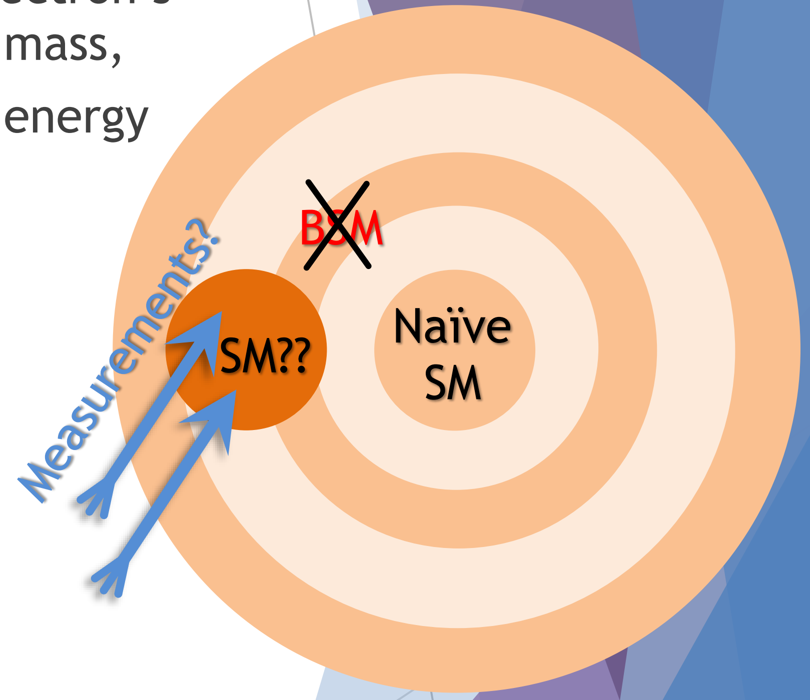

$\boxed{\textbf{Searches for deviations from the SM “V-A” structure}}$

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electron's mass, energy

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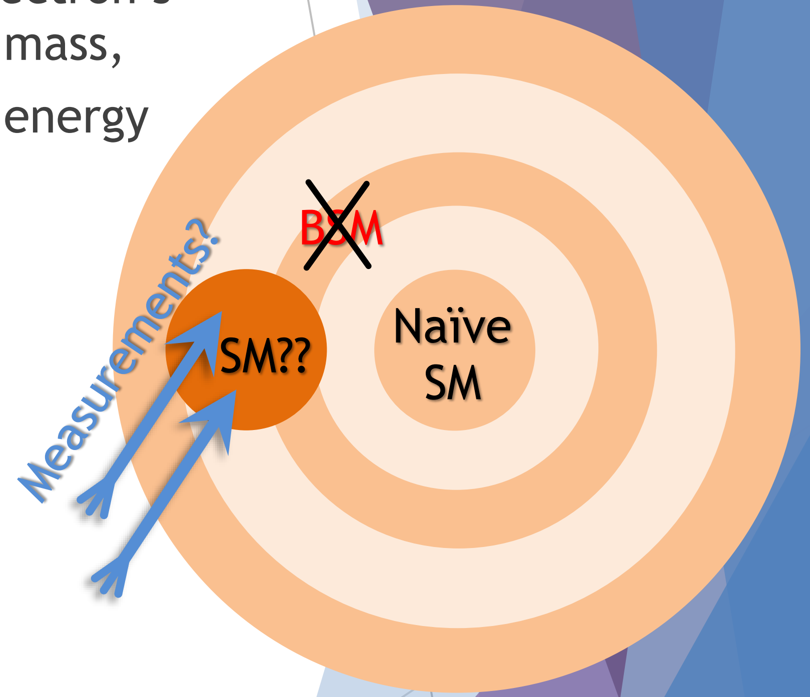


Searches for deviations from the SM "V-A" structure

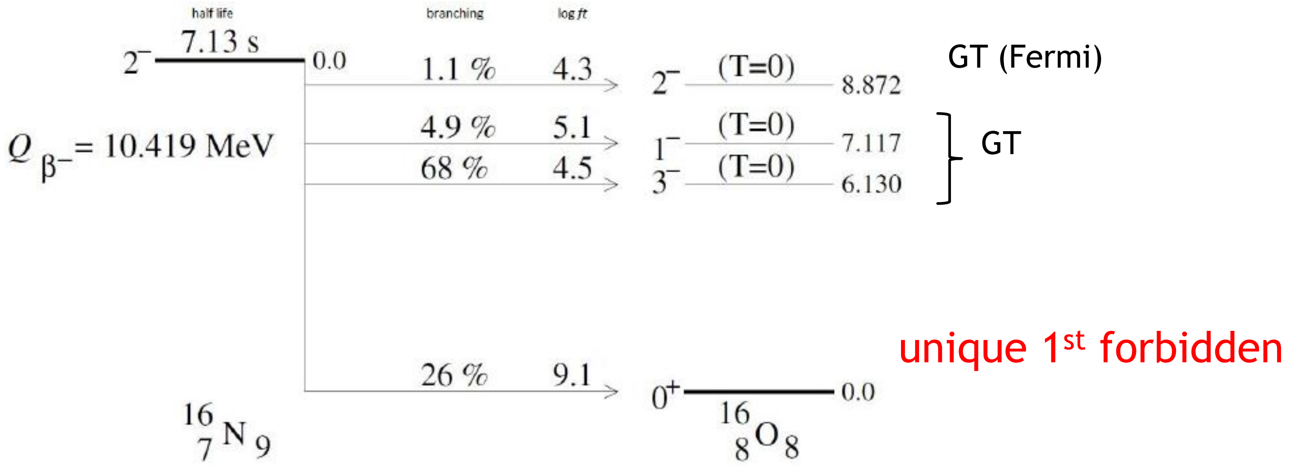
>> More accurate theory is needed

Unique 1st-forbidden decays

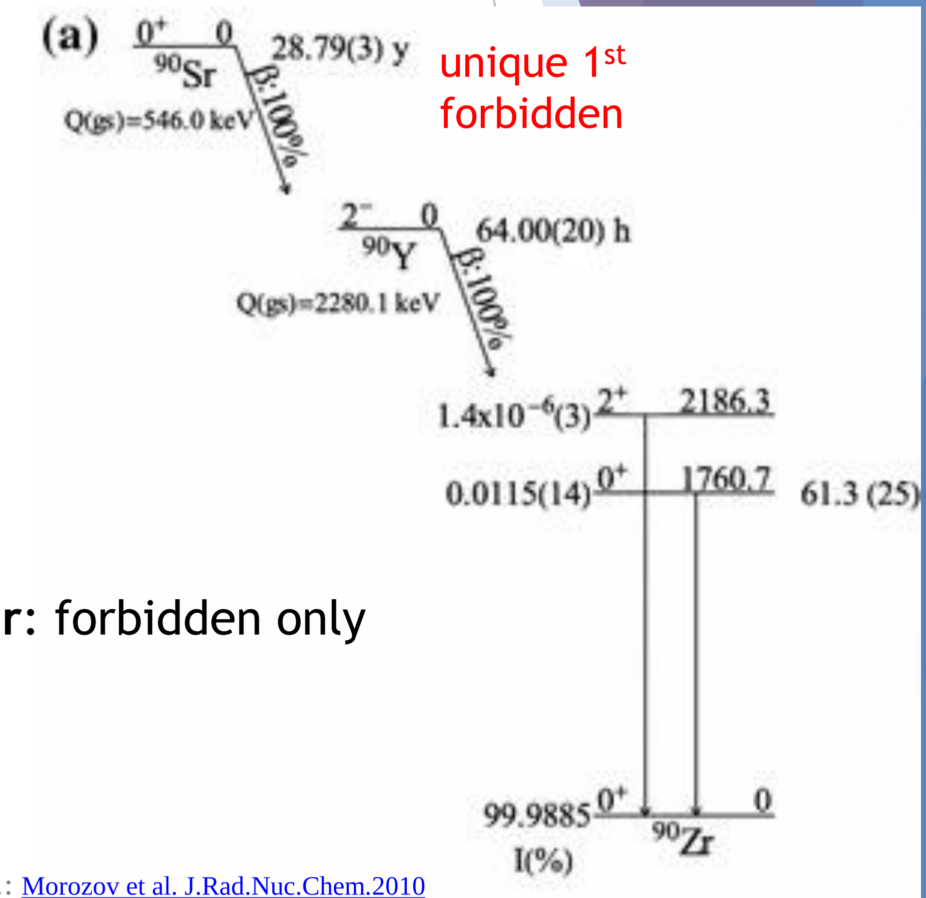
$$d\omega \propto 1 + a_{\beta\nu}\left[1-\left(\hat{\beta}\cdot\hat{\nu}\right)^2\right] + b_F\frac{m_e}{\epsilon}$$

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

- Allows simultaneous extraction of C_T^+ and C_T^-
- Increases the accuracy level



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



^{90}Sr: forbidden only

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

AGM *et al*, PLB 2017

Ohayon, Chocron, Hirsh, AGM, *et al.*, Hyp.Int.2018

Ab initio calculations of ${}^{16}\mathrm{N} \xrightarrow{\beta^-} {}^{16}\mathrm{O}$ forbidden decay

$\hat{H}$

Nuclear Hamiltonian

χEFT @ $\mathrm{N^2LO_{opt}}$

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

Nuclear wave functions

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

Nuclear currents

LO (1-body currents)

$\hat{O}_J$

Multipole operators

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

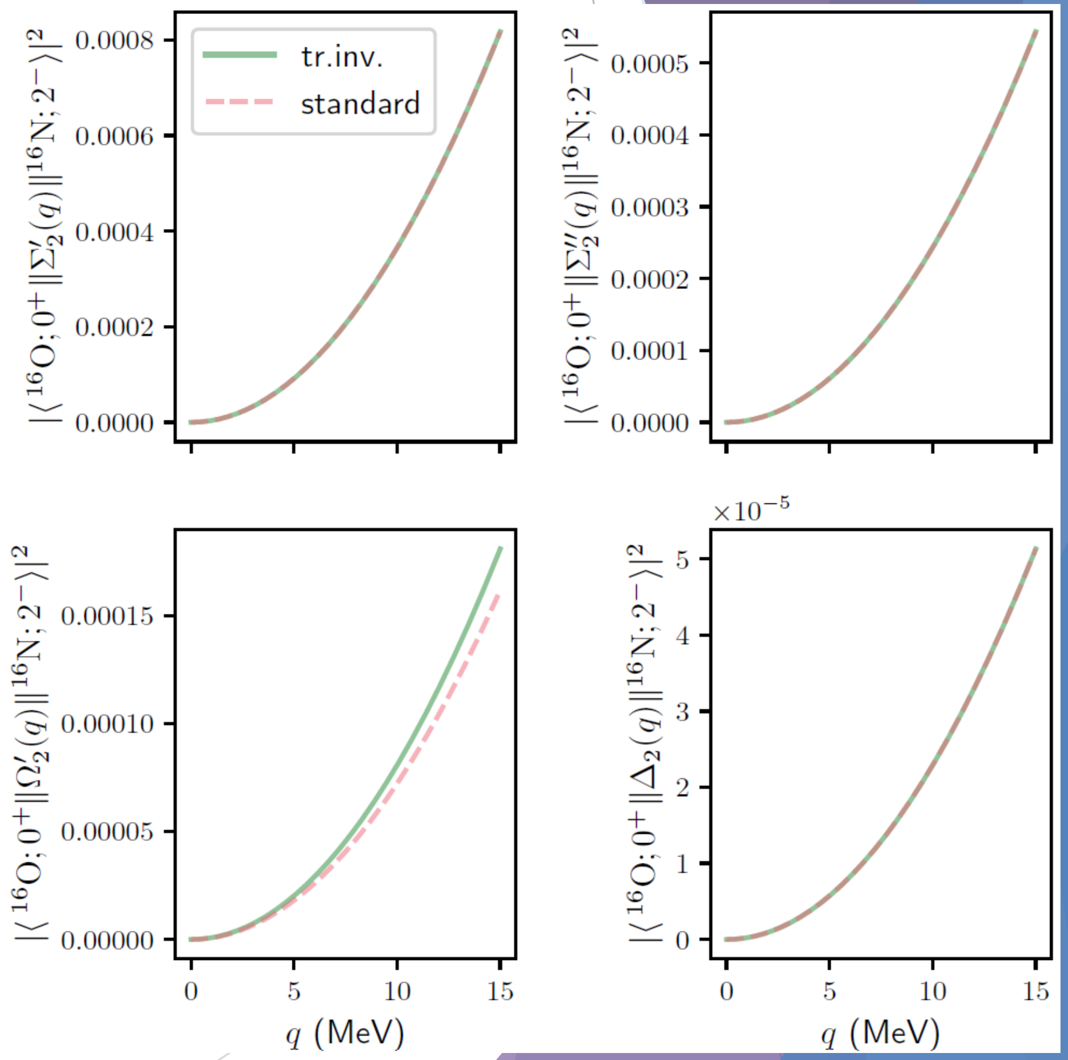
Nuclear matrix elements

Ab initio No-Core Shell Model (NCSM)

δ_a, δ_b

Observables' corrections

Lotta Jokiniemi
Petr Navrátil
Daniel Gazda
Christian Forssén



$^{16}N \to {}^{16}O$ forbidden spectrum

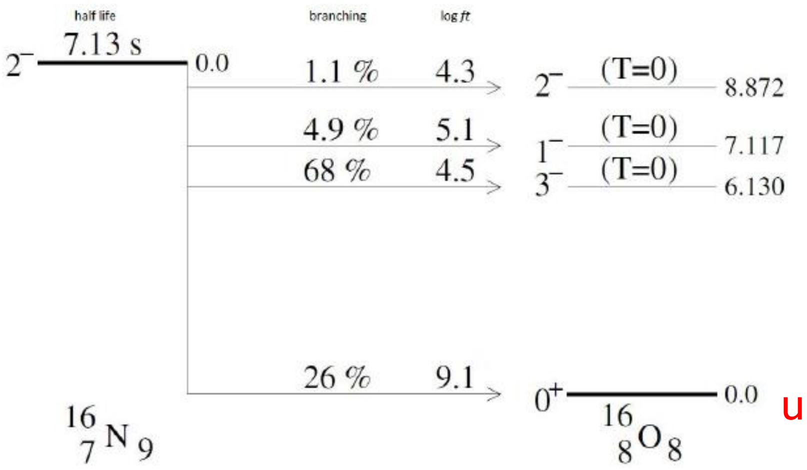
- Experiments are aiming a 10^{-3} accuracy
- The spectrum can be used to extract b_F & $a_{\beta\nu}$

SM correction

SM BSM

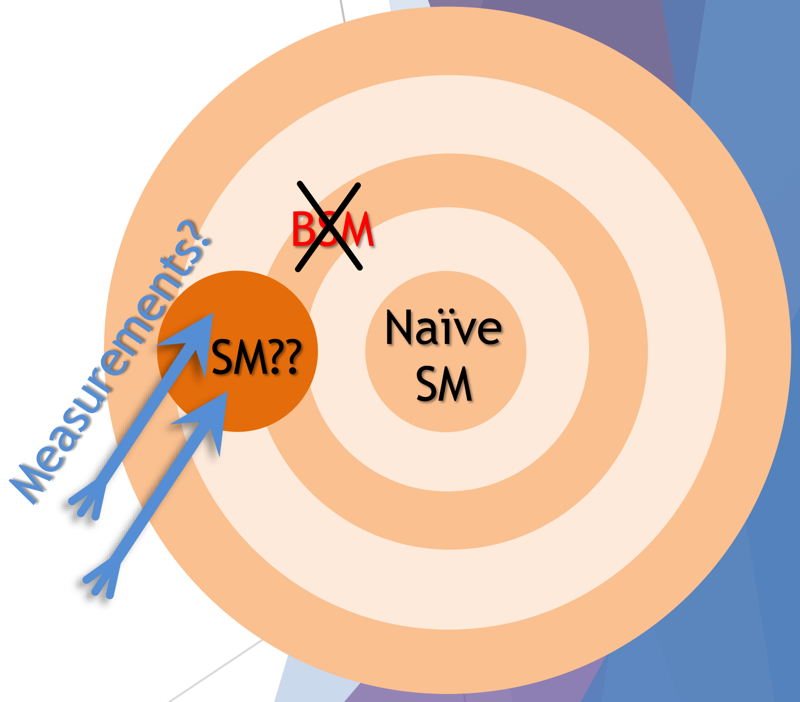
- $b_F = 0 + \delta_b + \frac{C_T^+}{C_A}$
- Looking for $\frac{C_T^+}{C_A} \sim 10^{-3}$
- $\delta_b = -1.04(13) \cdot 10^{-3}$

Preliminary



unique 1st forbidden

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



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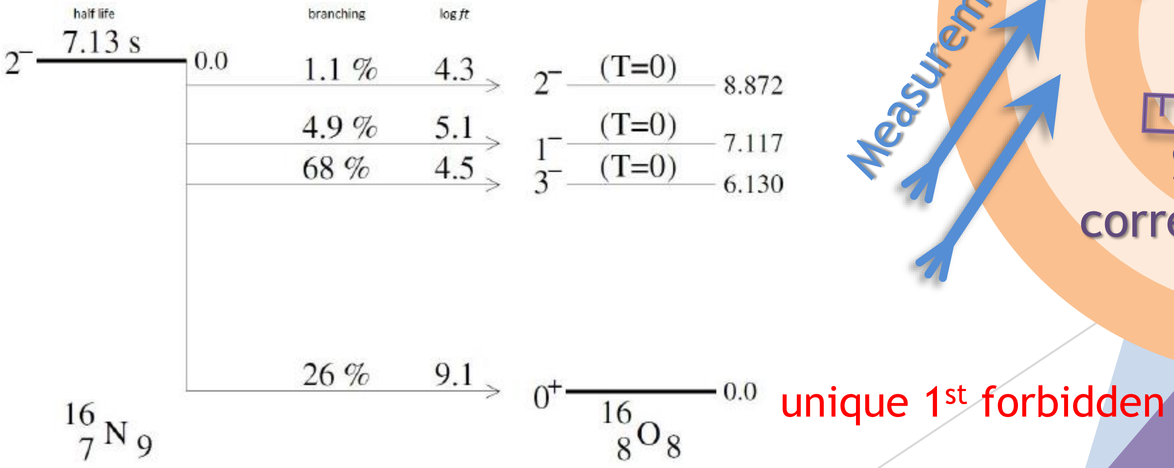
SM SM correction BSM

- $b_F = 0 + \delta_b + \frac{C_T^+}{C_A}$
- Looking for $\frac{C_T^+}{C_A} \sim 10^{-3}$
- $\delta_b = -1.07(13) \cdot 10^{-3}$
- Uncertainty $\sim 10^{-4}$

Preliminary



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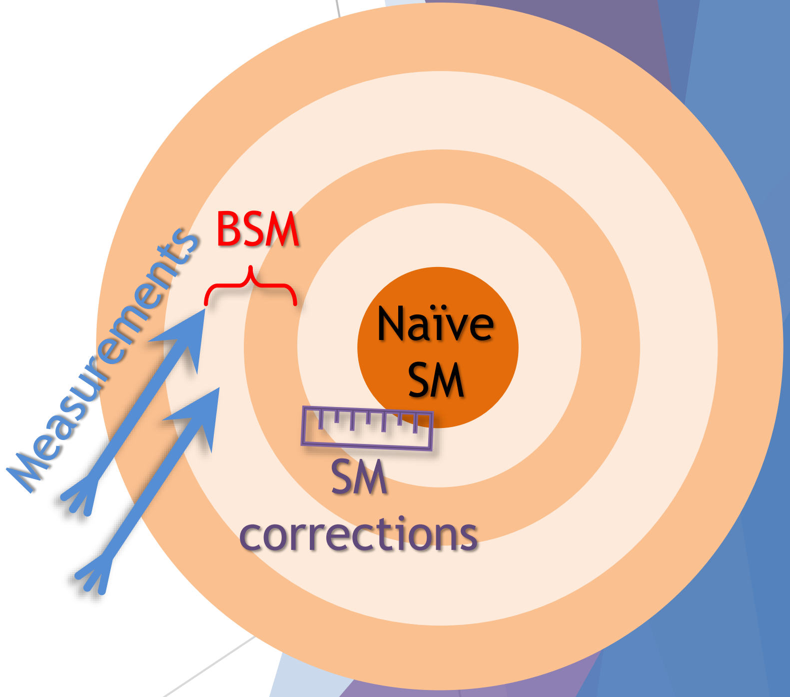


$^{16}\mathrm{N} \rightarrow {}^{16}\mathrm{O}$ forbidden angular correlation

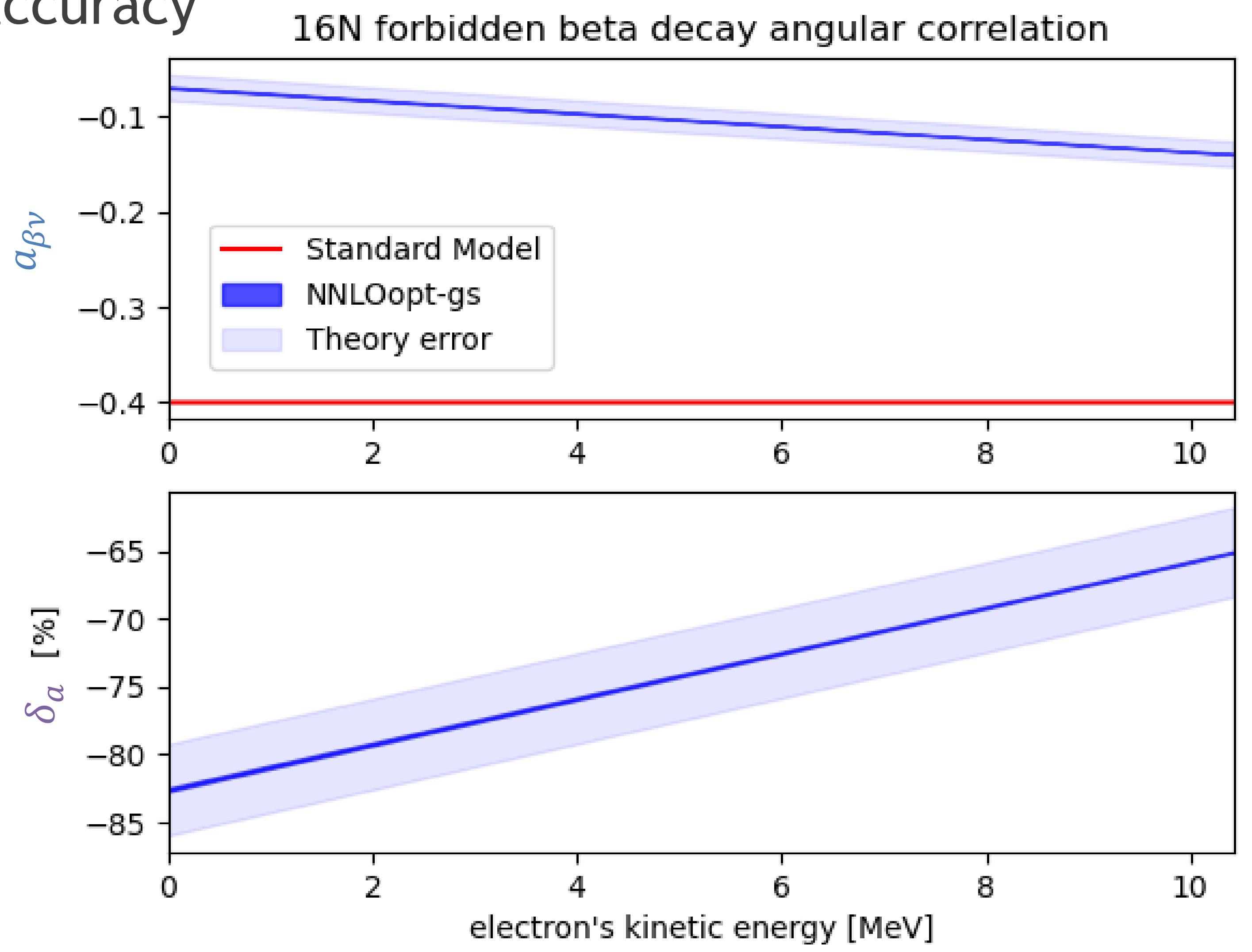
- Experiments are aiming a 10^{-3} accuracy

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

- $$a_{\beta\nu} = -\frac{2}{5}\Big(\underbrace{1}_{\text{SM}} + \underbrace{\tilde{\delta}_a}_{\text{SM correction}} + \underbrace{\frac{|C_T^{+}|^2 + |C_T^{-}|^2}{4|C_A|^2}}_{\text{BSM}}\Big)$$

- $\langle \tilde{\delta}_a \rangle = -0.609(15)$

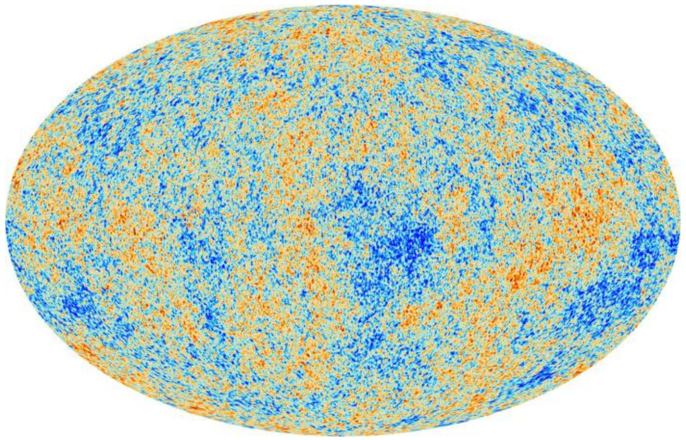
Very Preliminary



Summary: BSM Searches with nuclei…

Precision Frontier

Astronomy

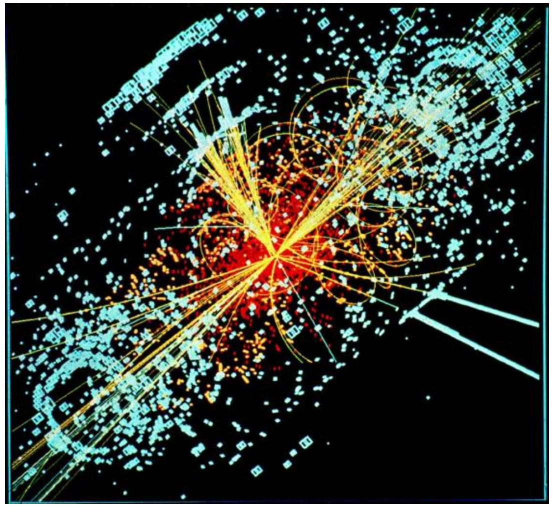


https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

- Dark Matter direct detection

^{19}F ^{23}Na

Particles Physics

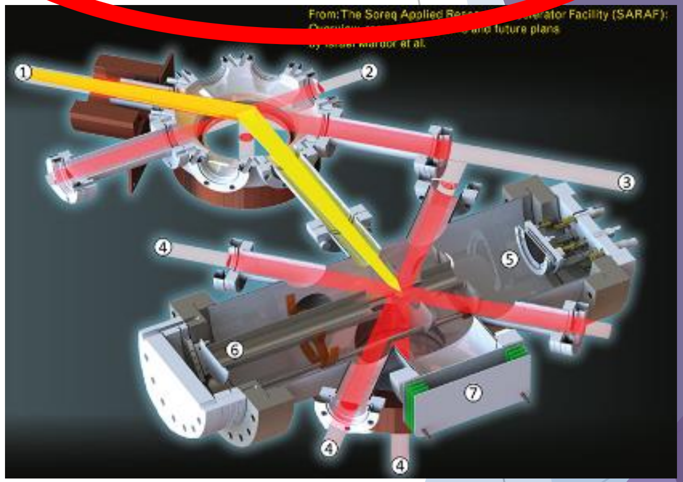


Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

- Lepton Flavor Violation with $\mu \to e$ conversion

^{27}Al Ti ^{23}Ne ^{63}Cu

Nuclear Physics



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

- New Weak Interactions with β-decays

^{90}Sr ^{16}N ^{6}He ^{23}Ne

and many more…

Thanks!

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