Theory working group

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University of Virginia

Theory working group

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  - Yuichi Uesaka (Kyushu Sangyo University)
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Comments, questions, and members welcome!

Can theory predict $\mu \to e$ rates?

Lepton flavor violation

- LFV accidentally (?) suppressed in SM due to $m_\nu \ll m_e$.
- New physics can easily generate LFV, e.g. via

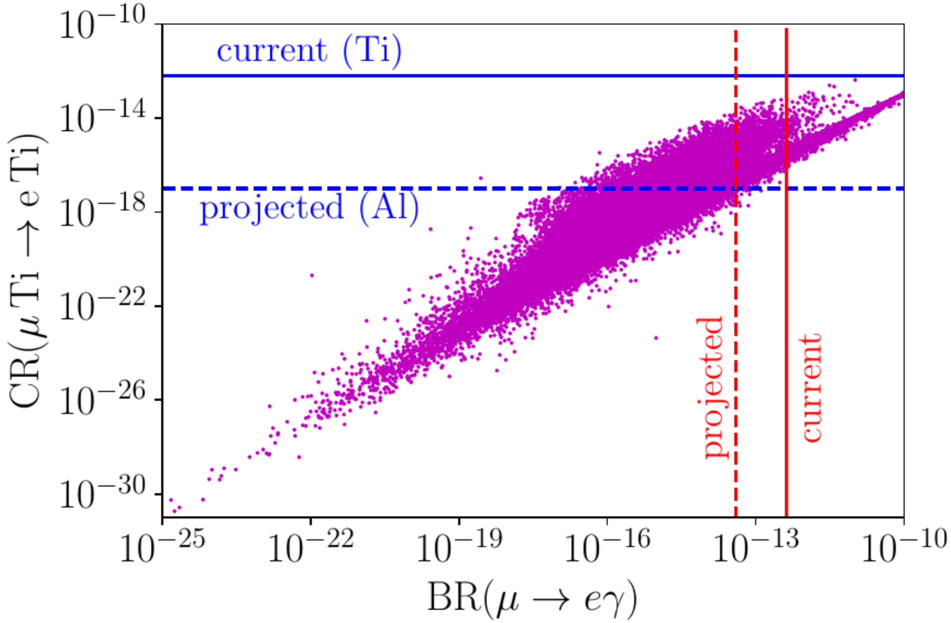
$$\mathsf{L}_{d=6} = \frac{c_{ij}}{\Lambda^2} m_i \bar{\ell}_i \sigma^{\alpha\beta} \ell_j F_{\alpha\beta} + \ldots$$

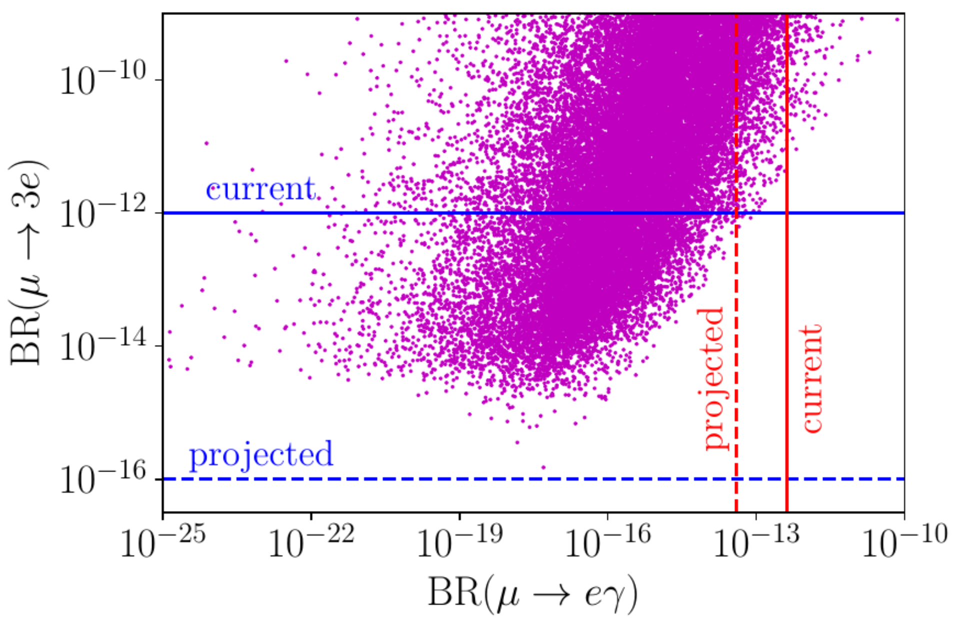
- Most models can suppress LFV arbitrarily via

$$c_{ij} \to \delta_{ij} \quad \text{or} \quad \Lambda \to \infty.$$

- Very few models give (testable) prediction of LFV without any loopholes.

Scotogenic model

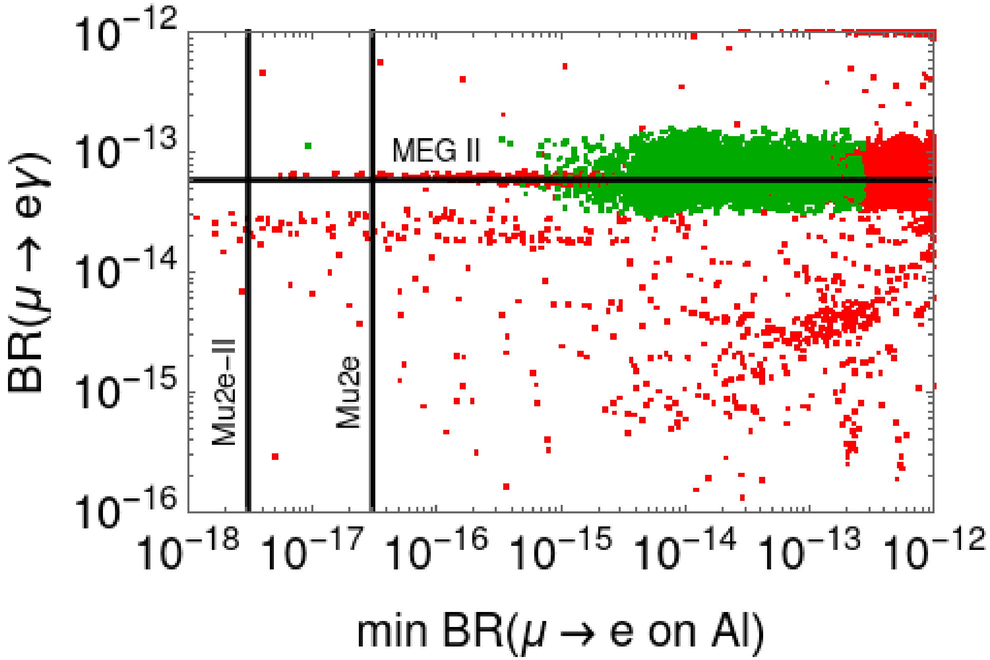


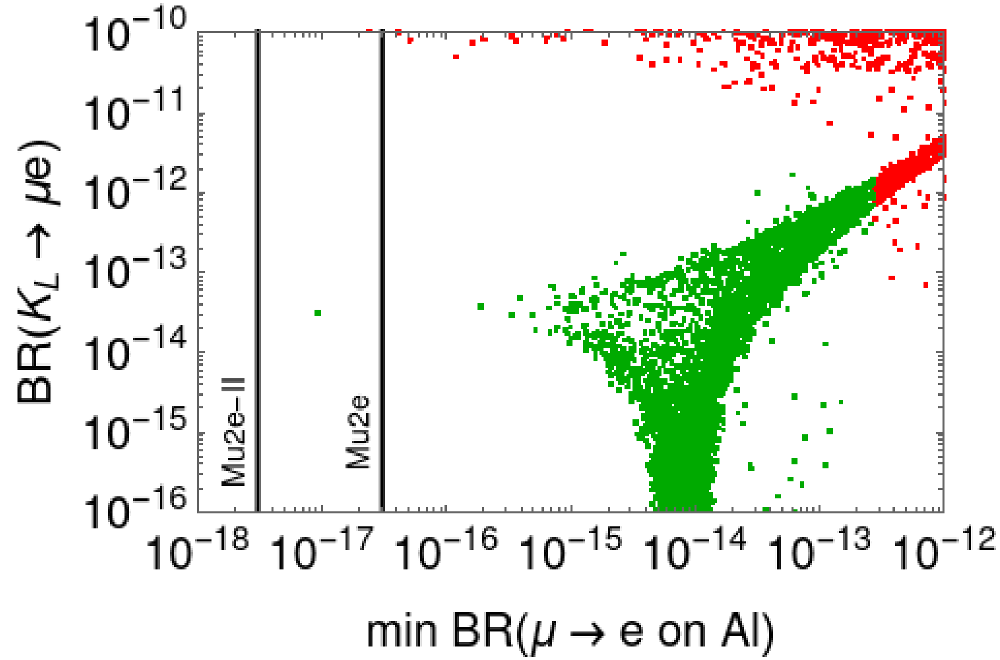


[Vicente & Yaguna, 1412.2545; Lindner, Platscher, Queiroz, 1610.06587]

- Flavor structure fixed by neutrino mass/mixing; scale Λ fixed to get dark matter abundance.
- Predicts testable rates in Mu3e; maybe μ → e conversion.

Pati-Salam leptoquark





[Heeck & Teresi, 1808.07492]

- Flavor structure fixed by neutrino mass/mixing; scale Λ fixed to explain B-meson anomaly R(K).
- Predicts testable rates in Mu2e!
- Radiative m_ν plus B-meson: $\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Au}) > 3 \times 10^{-13}$!

[Bigaran, Gargalionis, Volkas, 1906.01870]

Can theory predict $\mu \to e$ rates?

- Yes, but requires link to BSM anomaly to fix Λ:
  - Dark matter, B-meson, g-2, …
  - … and some known flavor structure.
- Very rare!

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Can theory predict $\mu \to e$ *ratios*?

μ → e conversion

$$\mathrm{BR}(\mu \to e) \propto \left| D C_{DL} + S^p C^p_{S,L} + V^p C^p_{V,R} + S^n C^n_{S,L} + V^n C^n_{V,R} \right|^2 + (L \leftrightarrow R)$$

- Overlap integrals from nuclear structure:

Nucleus	D	$S^{(p)}$	$V^{(p)}$	$S^{(n)}$	$V^{(n)}$
$^{4}_{2}\mathrm{He}$	0.000625	0.000262	0.000263	0.000262	0.000263
$^{7}_{3}\mathrm{Li}$	0.00138	0.000581	0.000585	0.000775	0.000780
$^{9}_{4}\mathrm{Be}$	0.00268	0.00113	0.00114	0.00141	0.00142
$^{11}_{5}\mathrm{B}$	0.00472	0.00200	0.00202	0.00240	0.00242
$^{12}_{6}\mathrm{C}$	0.00724	0.00308	0.00312	0.00308	0.00312
$^{14}_{7}\mathrm{N}$	0.0103	0.0044	0.0044	0.0044	0.0044

[Kitano, Koike, Okada, hep-ph/0203110]

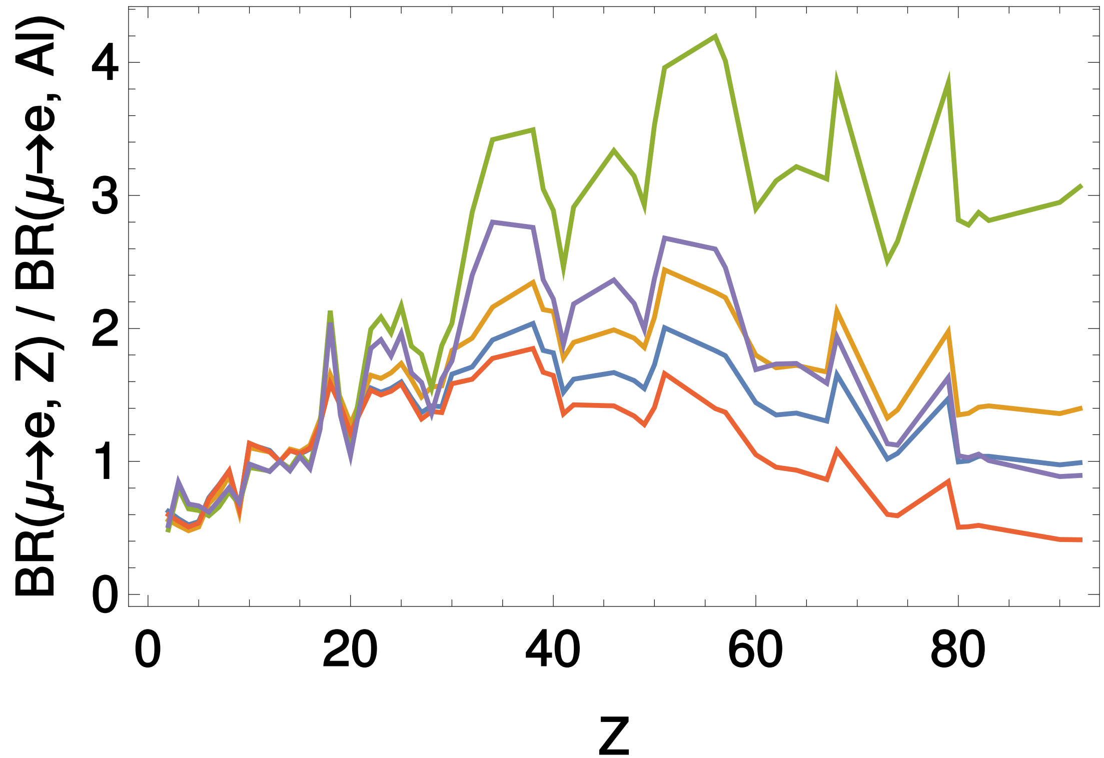
- C = coefficients of BSM operators at low energies, e.g.

$$L = 2\sqrt{2} G_F \left[C_{DL} \times m_\mu \bar{e}_R \sigma^{\alpha\beta} \mu_L F_{\alpha\beta} + C^p_{V,R} \times \bar{e}_R \gamma^\alpha \mu_R \bar{p} \gamma_\alpha p + \dots \right]$$

Z dependence

$$\mathrm{BR}(\mu \to \mathrm{e}) \propto |\mathrm{D}C_{\mathrm{DL}} + \mathrm{S}^{\mathrm{p}} C^{\mathrm{p}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{p}} C^{\mathrm{p}}_{\mathrm{V,R}} + \mathrm{S}^{\mathrm{n}} C^{\mathrm{n}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{n}} C^{\mathrm{n}}_{\mathrm{V,R}}|^2 + (\mathrm{L} \leftrightarrow \mathrm{R})$$

- If one C dominates we can predict ratios!



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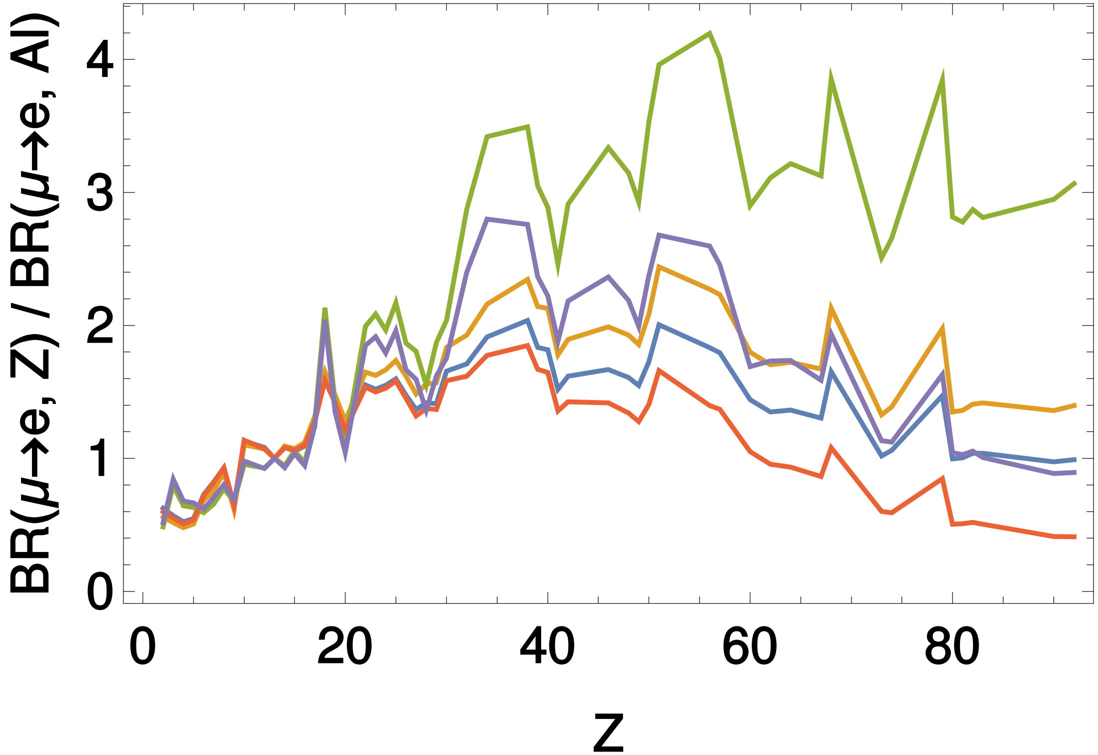
- If one C dominates we can predict ratios!
- Not really though, this assumes we have the "right" C basis.
- General model:
  - all C present, interference possible!
  - BR(μ → e) could be ~0 for up to 4 nuclei, ≠ 0 for rest.



Aluminium

$$\mathrm{BR}(\mu \to \mathrm{e}) \propto |\mathrm{D}C_{\mathrm{DL}} + \mathrm{S}^{\mathrm{p}}C^{\mathrm{p}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{p}}C^{\mathrm{p}}_{\mathrm{V,R}} + \mathrm{S}^{\mathrm{n}}C^{\mathrm{n}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{n}}C^{\mathrm{n}}_{\mathrm{V,R}}|^2 + (\mathrm{L} \leftrightarrow \mathrm{R})$$

- Consequence 1: conservative translation of current μ→e limits gives bound

$$\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Al}) < 5 \times 10^{-11}.$$

LIMIT ON $\mu^- \to e^-$ CONVERSION

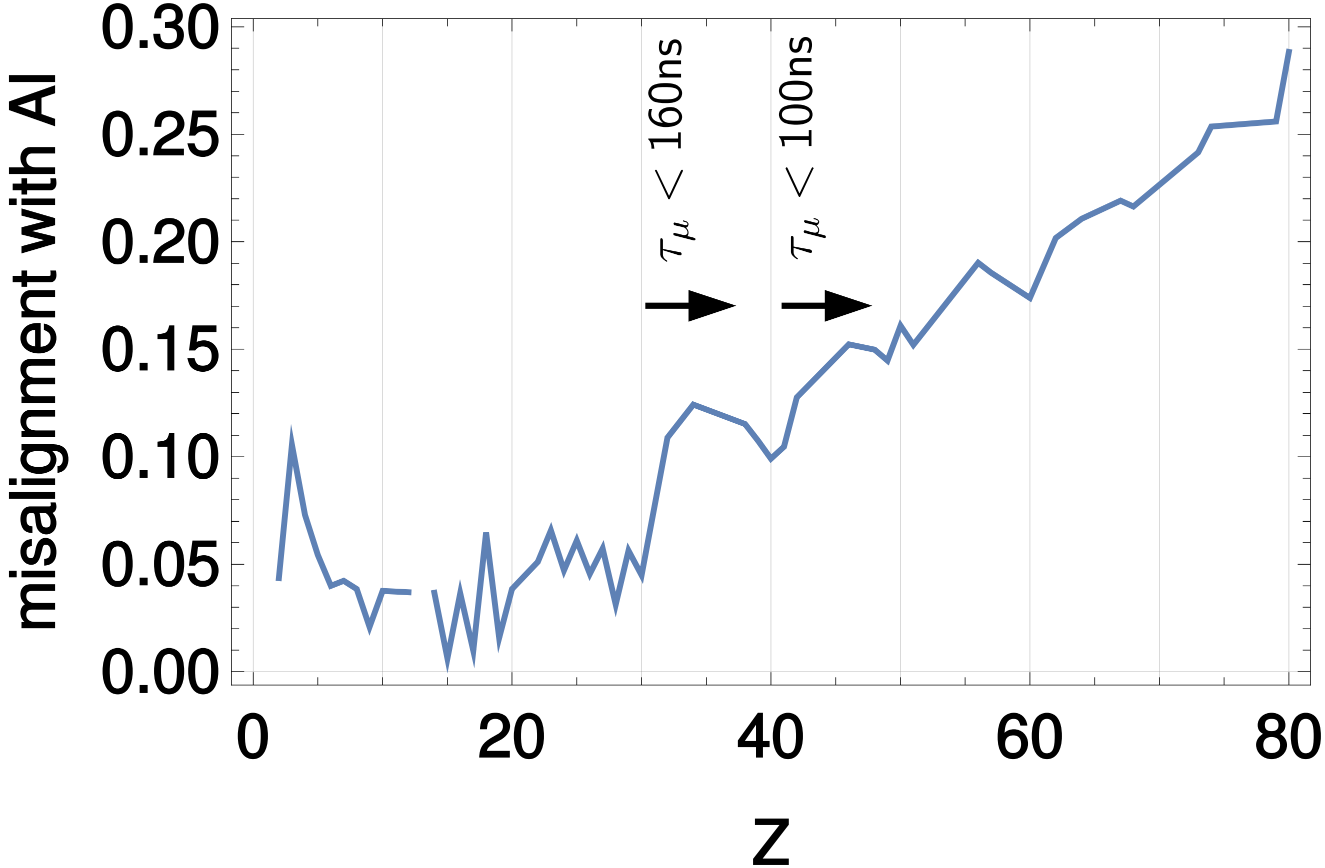
$\sigma(\mu^-\ ^{32}\mathrm{S} \to e^-\ ^{32}\mathrm{S})\ /\ \sigma(\mu^-\ ^{32}\mathrm{S} \to \nu_\mu\ ^{32}\mathrm{P}^*)$	$< 7 \times 10^{-11}$
$\sigma(\mu^-\ \mathrm{Cu} \to e^-\mathrm{Cu})\ /\ \sigma(\mu^-\ \mathrm{Cu} \to$ capture$)$	
$\sigma(\mu^-\ \mathrm{Ti} \to e^-\mathrm{Ti})\ /\ \sigma(\mu^-\ \mathrm{Ti} \to$ capture$)$	$< 4.3 \times 10^{-12}$
$\sigma(\mu^-\ \mathrm{Pb} \to e^-\mathrm{Pb})\ /\ \sigma(\mu^-\ \mathrm{Pb} \to$ capture$)$	$< 4.6 \times 10^{-11}$
$\sigma(\mu^-\ \mathrm{Au} \to e^-\mathrm{Au})\ /\ \sigma(\mu^-\ \mathrm{Au} \to$ capture$)$	$< 7 \times 10^{-13}$

- Consequence 2: Al has *four blind directions* in C space!
  - $\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Al})$ could be heavily suppressed.
  - $\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Z})/\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Al})$ could be «1 or »1.

Complementarity of second target

$$\mathrm{BR}(\mu \to \mathrm{e}) \propto |\mathrm{D}C_{\mathrm{DL}} + \mathrm{S}^{\mathrm{p}}C^{\mathrm{p}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{p}}C^{\mathrm{p}}_{\mathrm{V,R}} + \mathrm{S}^{\mathrm{n}}C^{\mathrm{n}}_{\mathrm{S,L}} + \mathrm{V}^{\mathrm{n}}C^{\mathrm{n}}_{\mathrm{V,R}}|^2 + (\mathrm{L} \leftrightarrow \mathrm{R})$$

- If you measure μ→e on Al you want a second target that is *sensitive* to Al's blind directions. [Davidson, Kuno, Yamanaka, 1810.01884]



Large Z is preferred but bad for Mu2e bc of short τ_μ.

Complementarity of second target

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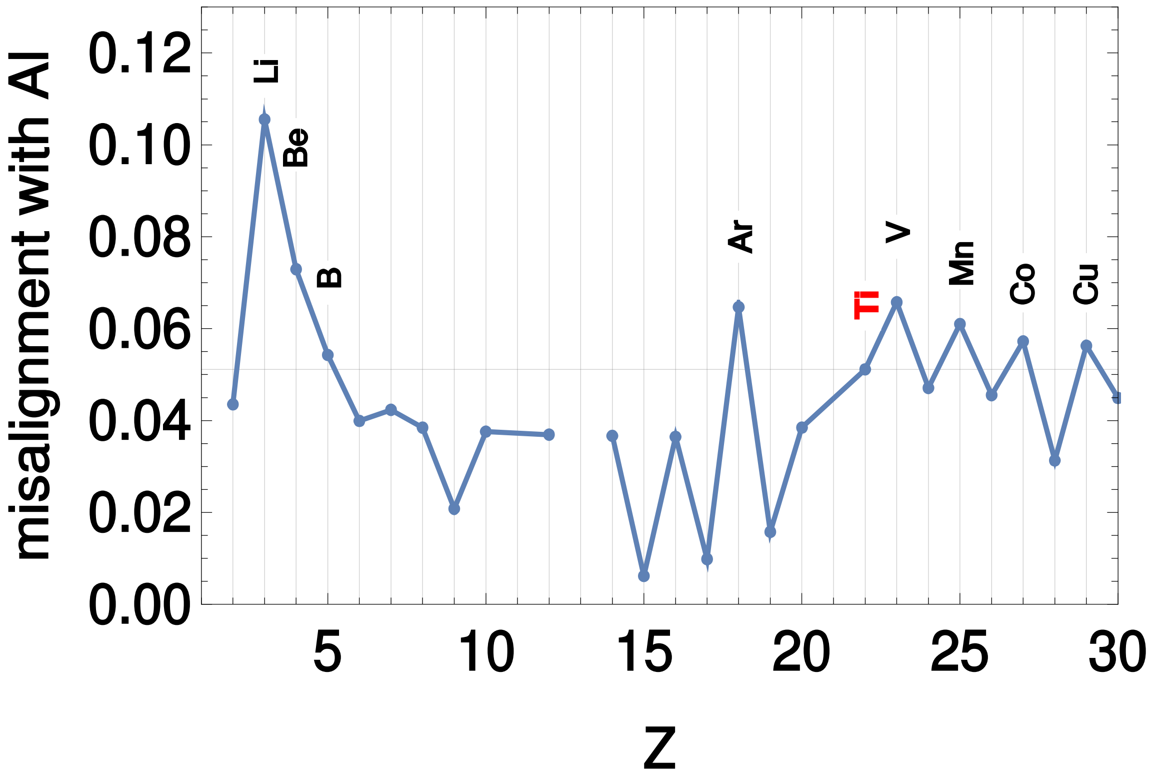


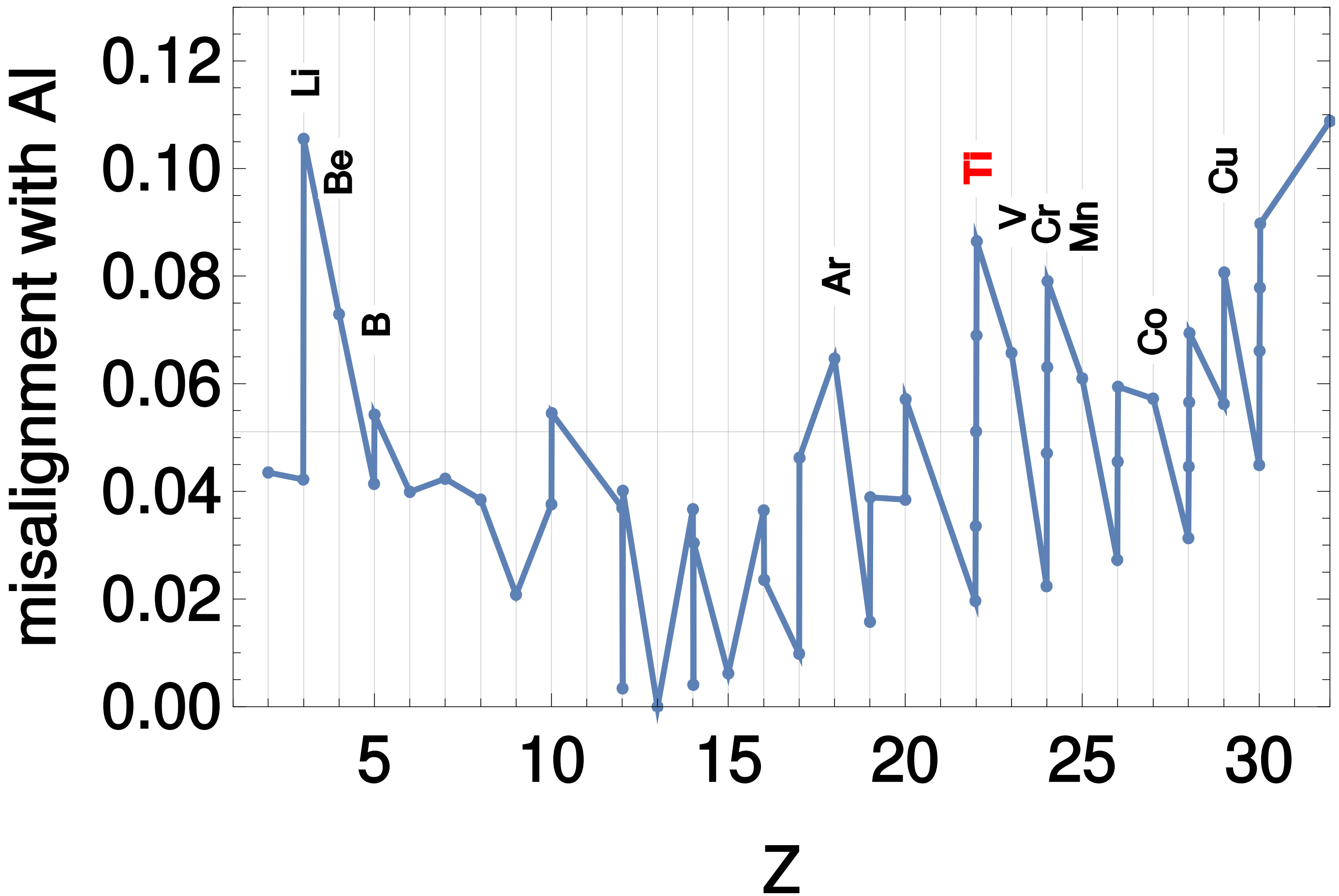
Lithium-7 best among Z < 30 targets!

	τ_μ/ns	spin	NA	DIO
$^{7}_{3}$Li	2187	3/2	92%	–
$^{9}_{4}$Be	2168	3/2	100%	–
$^{51}_{23}$V	280	7/2	99.8%	–
$^{55}_{25}$Mn	230	5/2	100%	–
$^{48}_{22}$Ti	329	0	74%	yes
$^{27}_{13}$Al	865	5/2	100%	yes

Isotopes

$$\mathrm{BR}(\mu \to \mathrm{e}; \mathrm{Z}) = \sum_{\mathrm{N}} \mathrm{BR}(\mu \to \mathrm{e}; (\mathrm{Z}, \mathrm{N})) \times \mathrm{abundance}(\mathrm{N})$$

- Isotopes have fewer flat directions.



- Ti-50 is second best choice after Li-7!

isotope	spin	NA
$^{46}_{22}\mathrm{Ti}$	0	8%
$^{47}_{22}\mathrm{Ti}$	5/2	7%
$^{48}_{22}\mathrm{Ti}$	0	74%
$^{49}_{22}\mathrm{Ti}$	7/2	5%
$^{50}_{22}\mathrm{Ti}$	0	5%

Mu2e(-II) targets

$$\mathsf{BR}(\mu \to \mathsf{e}; \mathsf{Z}) = \sum_{\mathsf{N}} \mathsf{BR}(\mu \to \mathsf{e}; (\mathsf{Z}, \mathsf{N})) \times \mathsf{abun}(\mathsf{N}) + \text{spin-dep. } \mathsf{BR}$$

- Titanium would make great *first* target!
  - Many isotopes & spins reduce flat directions.
  - Non-observation gives many limits at once.
  - Observation: change to enriched Ti targets to reduce systematic uncertainties, eventually use other elements to probe specific directions in C space (Al, Li, V, Au…).
- As second target after Al consider enriched Ti-50, then switch to other Ti isotopes.
- Ultimately, measure μ→e on as many targets as possible to distinguish operators & spin-dependence.!

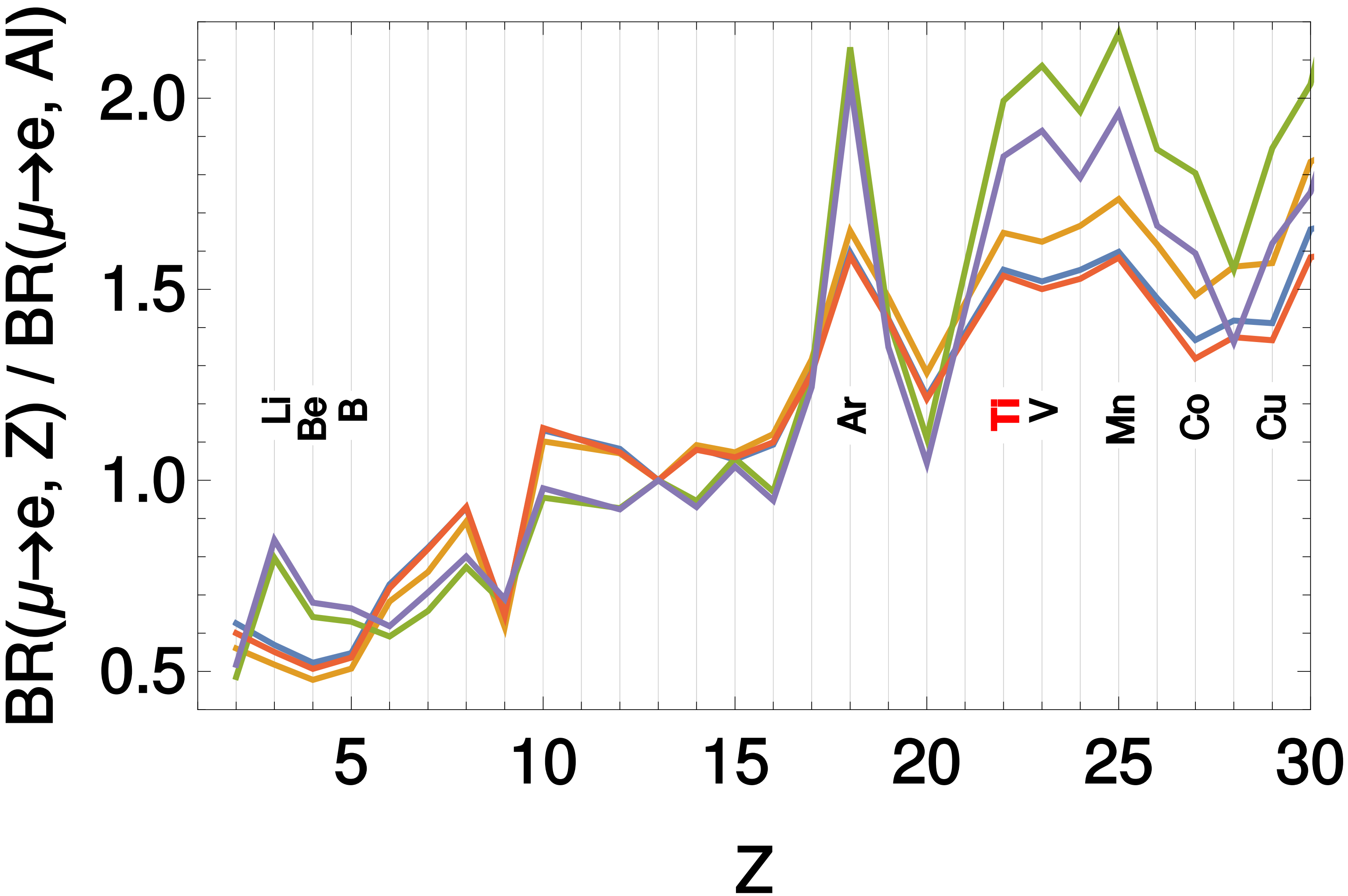
Summary

- Difficult to predict testable LFV rates but not impossible. Leptoquarks (e.g. for B anomalies) great for Mu2e.
- Prediction difficult even if we observe e.g. $\mu \to e$ on Al.
- Have to measure LFV in as many channels as possible to pin down underlying model.
- Lithium good complementary second target after Al.
- Titanium good *first* target, enriched Ti good *2nd, 3rd, ...*
- We are in the process of calculating DIO for relevant elements and study isotope dependence, stay tuned!

Backup

Single-operator Z dependence

- Zoom into Z < 30 region:



Single-operator Z dependence

- With isotopes: