Searches for new physics with muons

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based on Haxton, McElvain, Menzo, Rule, JZ, 2406.13818;
Fox, Hostert, Menzo, Pospelov, JZ, 2407.03450; 2306.15631;
...

Discrete 2024, Ljubljana, Dec 4 2024

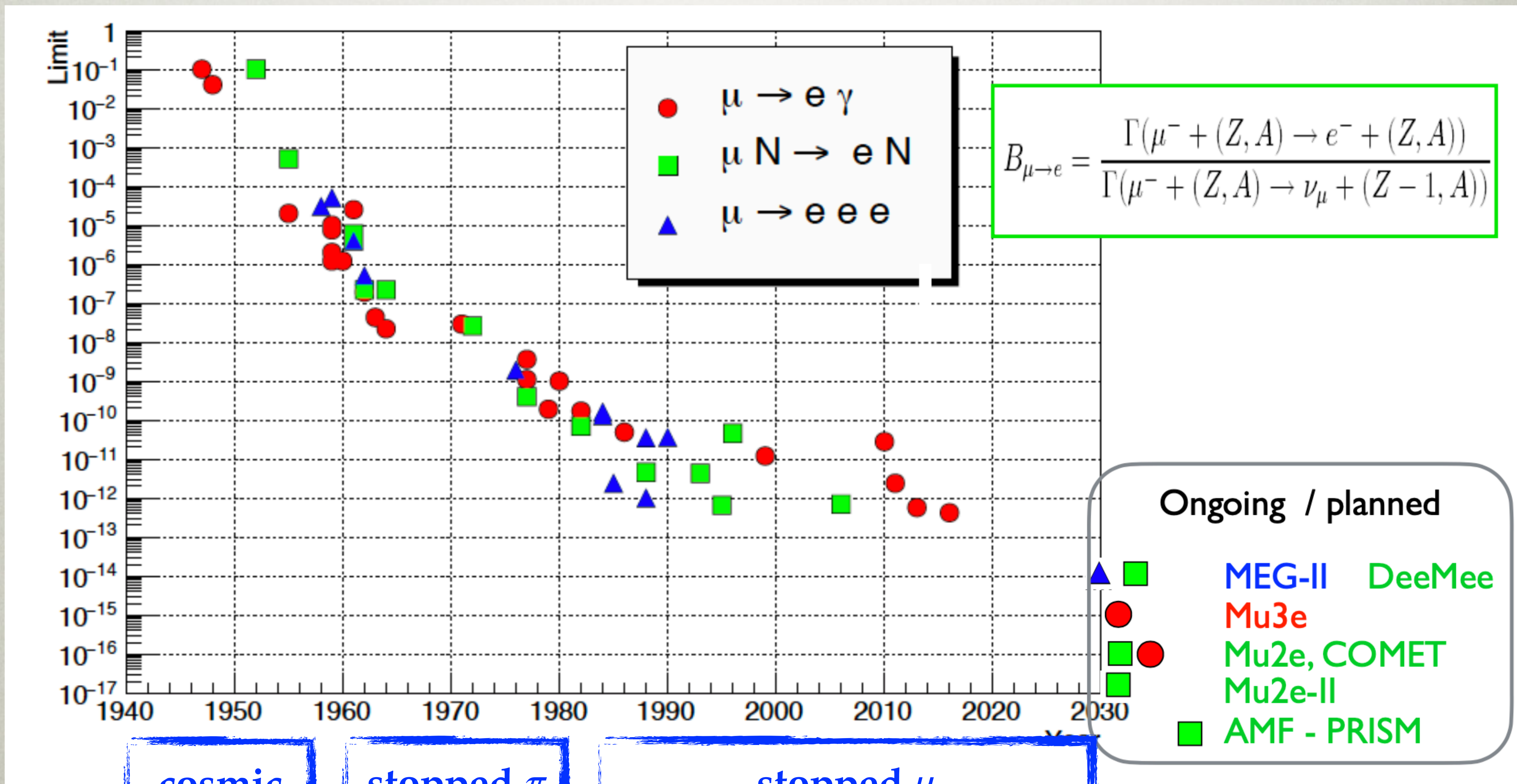
MUONS AND NEW PHYSICS

- muon the lightest unstable particle
  - relatively easy to produce ⇒ large samples available
- can use muons to search for
  - heavy new physics
    - in this talk: EFT based predictions for $\mu \to e$ conversion
  - light new physics
    - in this talk: several examples, including axion

SEARCHING FOR HEAVY NEW PHYSICS

EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s

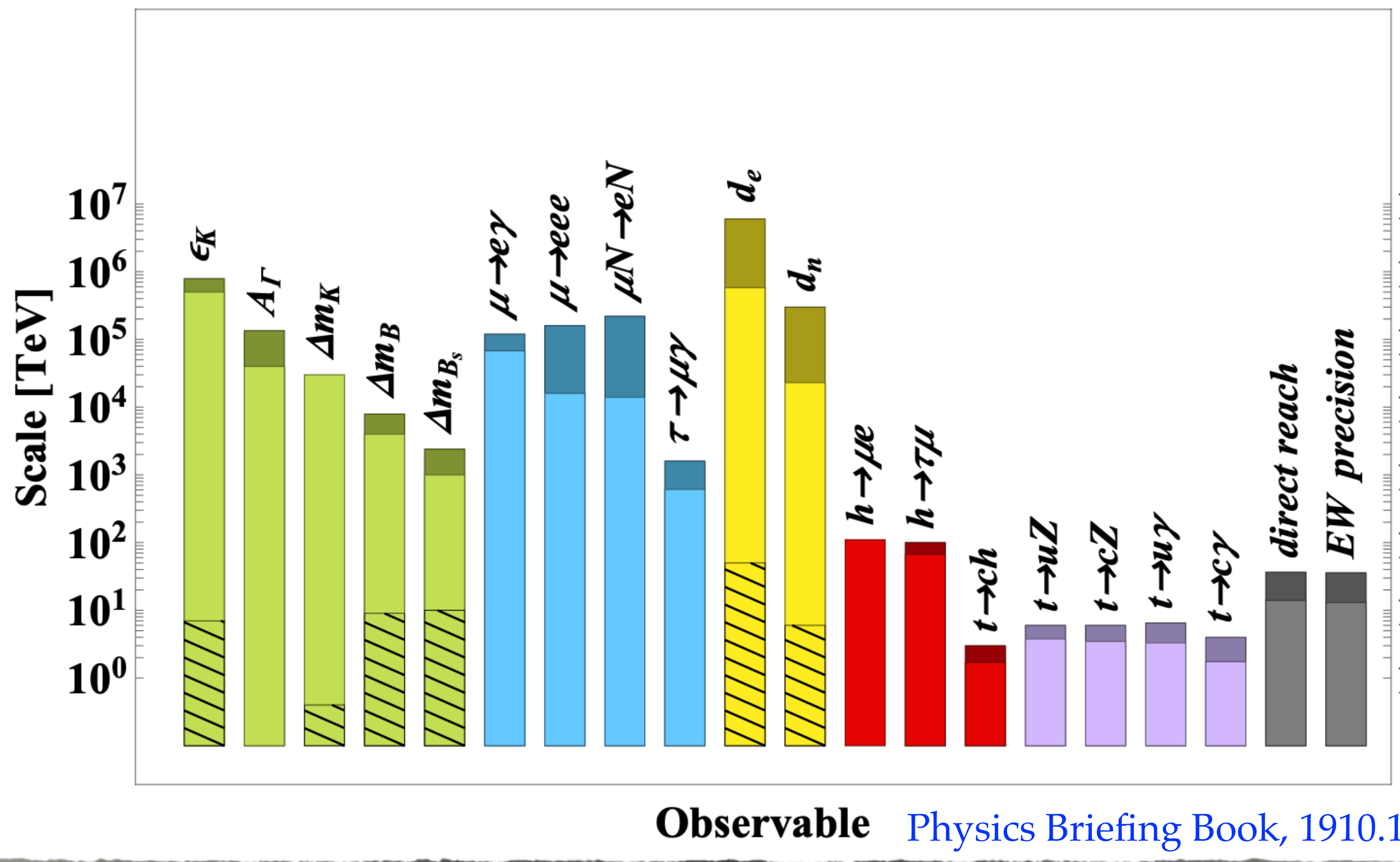


$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

cosmic rays | stopped π beams | stopped μ beams

SEARCHING FOR HEAVY NEW PHYSICS

- high effective scales probed



Physics Briefing Book, 1910.11775

SEARCHING FOR HEAVY NEW PHYSICS

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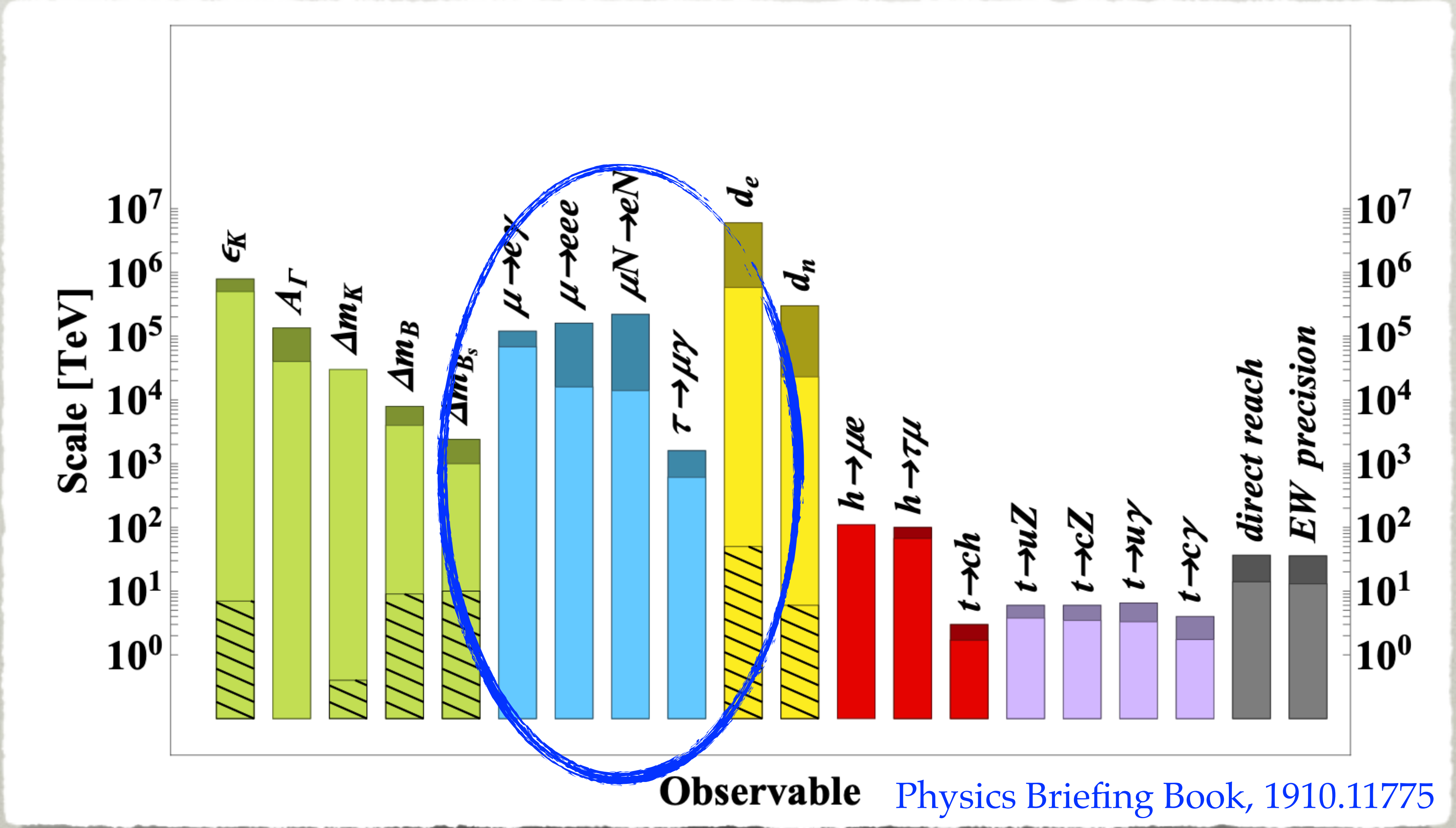


Physics Briefing Book, 1910.11775

EFT BASED PREDICTIONS FOR $\mu \to e$ TRANSITION

Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- in this part of the talk
  - provide an EFT based prediction for $\mu \to e$ conversion
    - assumption: heavy new physics $\Lambda \gg m_\mu$
  - open source code **MuonBridge**

$\mu \to e$ KINEMATICS

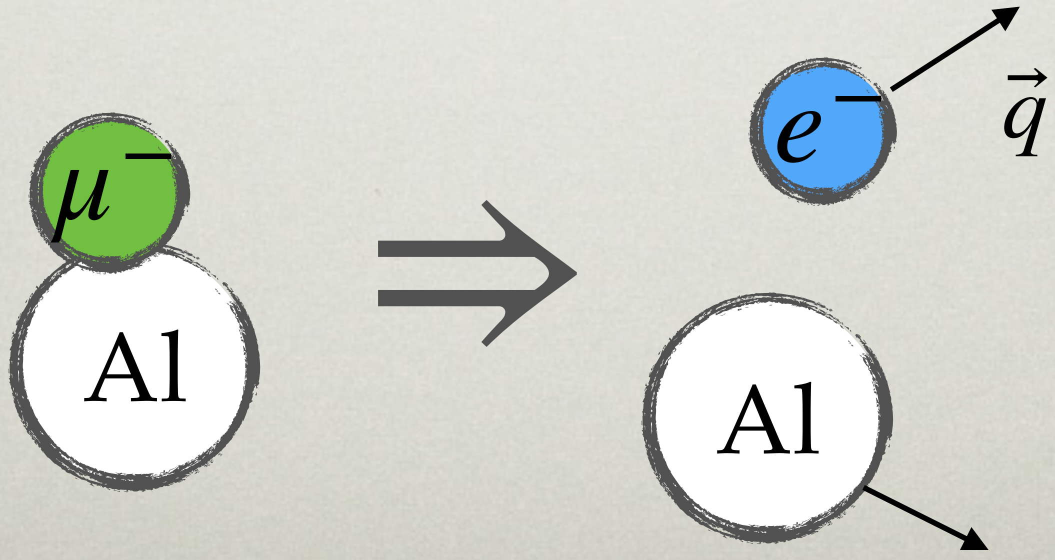
Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- initial state: μ^- in 1s orbital
- final state: relativistic e^- with three momentum

$$\vec{q}^{\,2} = \frac{M_T}{m_\mu + M_T}\left[\left(m_\mu - E_\mu^{\text{bind}}\right)^2 - m_e^2\right],$$

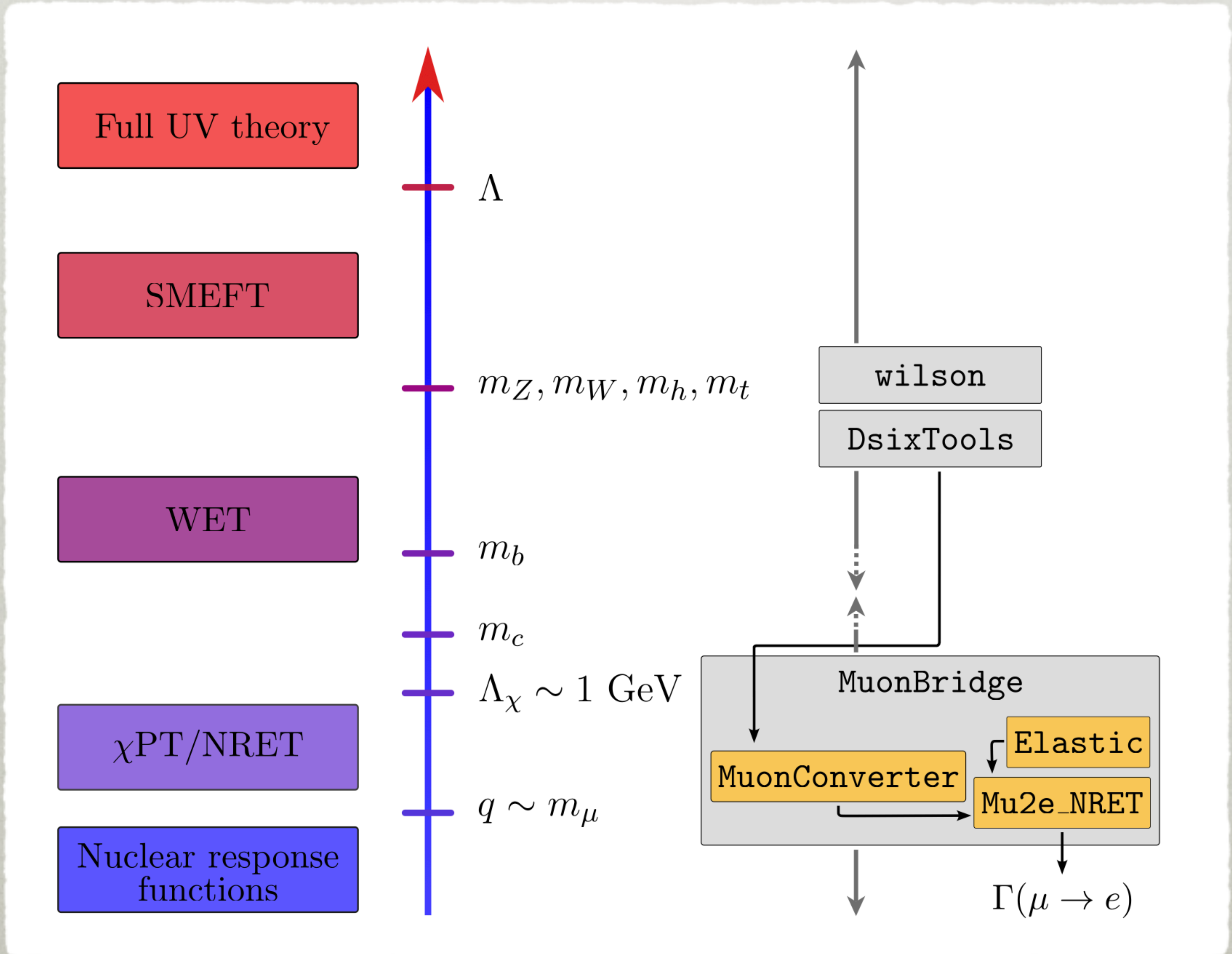
  - $E_\mu^{\text{bind}} \ll m_\mu$ (for ^{27}Al $E_\mu^{\text{bind}} \simeq 0.463\,\text{MeV}$) $\Rightarrow |\vec{q}\,| \sim \mathcal{O}(100\,\text{MeV})$

- we limit the discussion to processes where nucleus is in ground state



Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

TOWER OF EFTs



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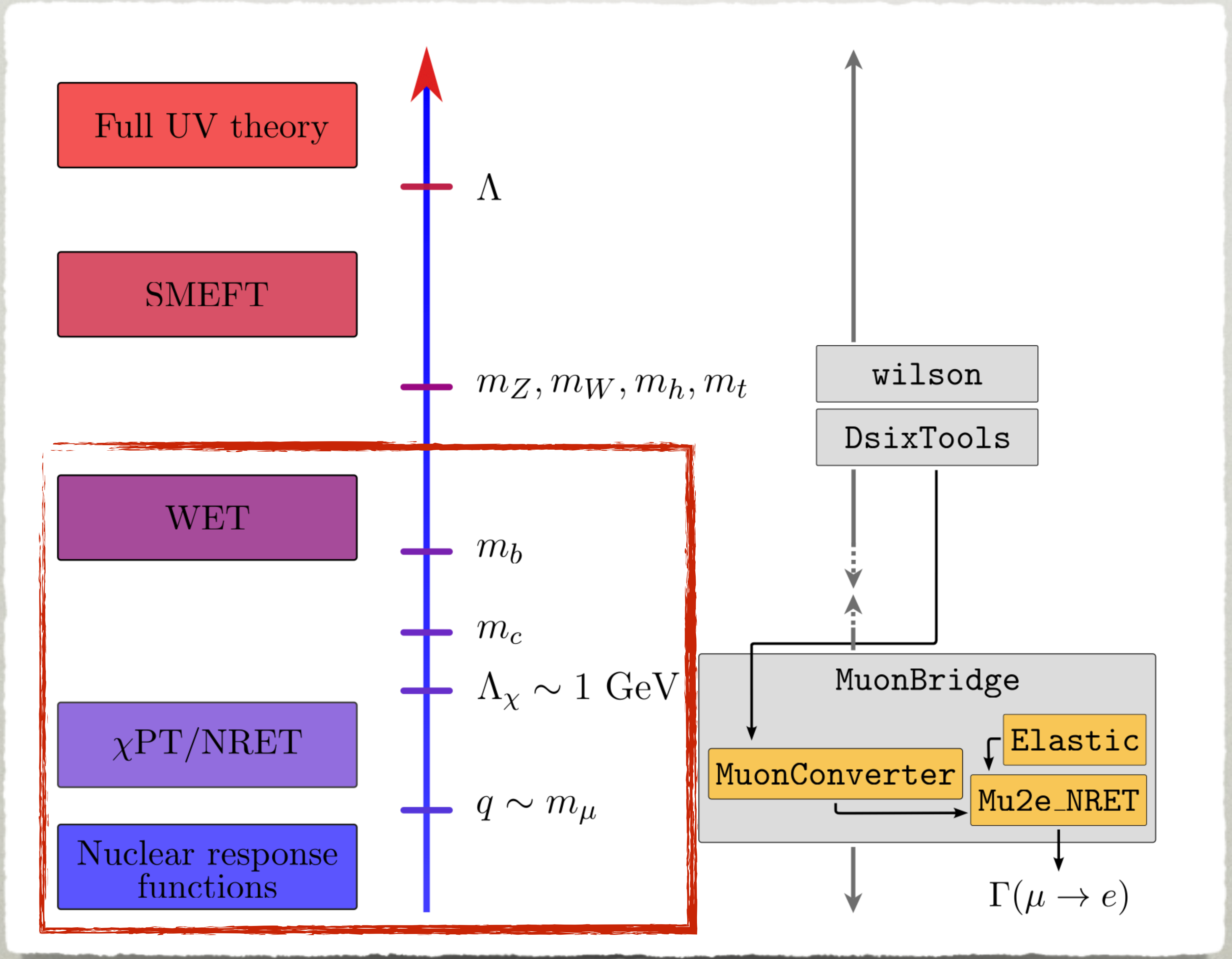

Weak Effective Theory

Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- only need to keep WET operators relevant for $\mu \to e$ conversion
  - work up to and including dimension 7

$$\mathcal{L}_{\rm eff}^{\rm WET} = \sum_{a,d} \hat{\mathcal{C}}_a^{(d)} \mathcal{Q}_a^{(d)},$$

$$\hat{\mathcal{C}}_a^{(d)} = \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}.$$

- 2 dim 5 operators

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{e}\sigma^{\alpha\beta}\mu)F_{\alpha\beta}\,, \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar{e}\sigma^{\alpha\beta}i\gamma_5\mu)F_{\alpha\beta}\,,$$

- 10 dimension 6 ops
- 16 operators at dimension 7

Weak Effective Theory

Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- only need to keep WET operators relevant for $\mu \to e$ conversion

$$\mathcal{Q}_{1,q}^{(6)} = (\bar{e}\gamma_\alpha\mu)(\bar{q}\gamma^\alpha q)\,, \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar{e}\gamma_\alpha\gamma_5\mu)(\bar{q}\gamma^\alpha q)\,,$$

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$$\mathcal{Q}_{5,q}^{(6)} = (\bar{e}\mu)(\bar{q}q)\,, \qquad \mathcal{Q}_{6,q}^{(6)} = (\bar{e}i\gamma_5\mu)(\bar{q}q)\,,$$

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- 10 dimension 6 ops
- 16 operators at dimension 7

Nonrelativistic Effective Theory

Haxton, McElvain, Ramsey-Mussolf, Rule, 2208.07945
Haxton, McElvain, Rule, 2109.13503

- a hierarchy of small parameters

$$y \equiv \left(\frac{qb}{2}\right)^2 > |\vec{v}_N| > |\vec{v}_\mu| > |\vec{v}_T|$$

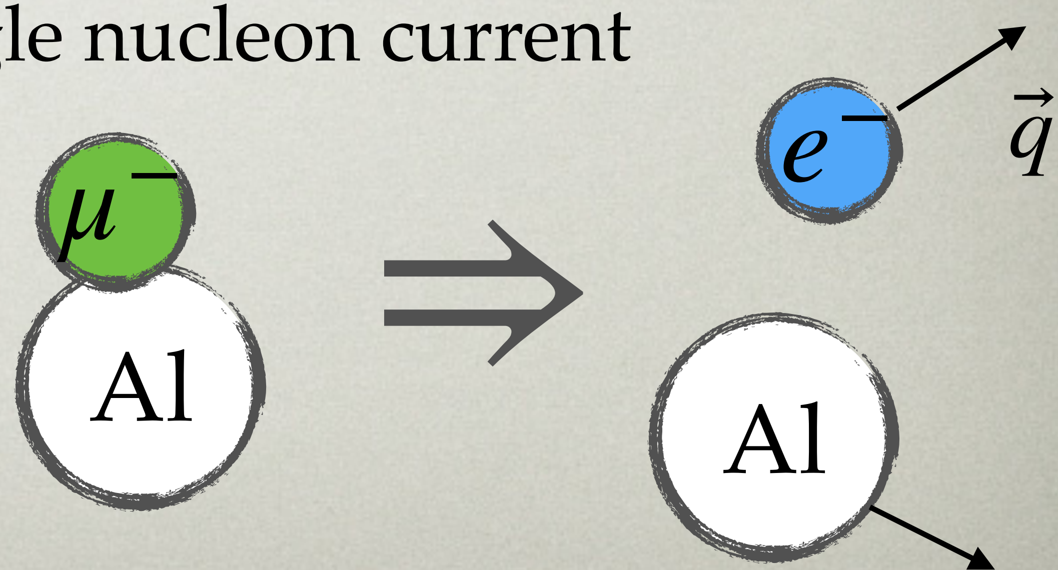
$b \sim$ nuclear size

$\vec{v}_N = (\vec{k}_1 + \vec{k}_2)/2$ average nucleon velocity

bound muon velocity

velocity of outgoing target nucleus

- $y \sim 0.2 - 0.5 \Rightarrow$ nuclear scales are being probed
- Chiral EFT: interactions with single nucleon current dominate
- NRET: can expand in v_N and v_μ,
  - we keep $\mathcal{O}(v_N)$, $\mathcal{O}(v_\mu)$ terms



Nonrelativistic Effective Theory

e, 2208.07945
e, 2109.13503

$$\mathcal{O}_1 = 1_L\ 1_N\,,\qquad \mathcal{O}'_2 = 1_L\ i\hat{q}\cdot\vec{v}_N\,,$$
$$\mathcal{O}_3 = 1_L\ i\hat{q}\cdot[\vec{v}_N\times\vec{\sigma}_N]\,,\qquad \mathcal{O}_4 = \vec{\sigma}_L\cdot\vec{\sigma}_N\,,$$
$$\mathcal{O}_5 = \vec{\sigma}_L\cdot(i\hat{q}\times\vec{v}_N)\,,\qquad \mathcal{O}_6 = i\hat{q}\cdot\vec{\sigma}_L\ i\hat{q}\cdot\vec{\sigma}_N\,,$$
$$\mathcal{O}_7 = 1_L\ \vec{v}_N\cdot\vec{\sigma}_N\,,\qquad \mathcal{O}_8 = \vec{\sigma}_L\cdot\vec{v}_N\,,$$
$$\mathcal{O}_9 = \vec{\sigma}_L\cdot(i\hat{q}\times\vec{\sigma}_N)\,,\qquad \mathcal{O}_{10} = 1_L\ i\hat{q}\cdot\vec{\sigma}_N\,,$$
$$\mathcal{O}_{11} = i\hat{q}\cdot\vec{\sigma}_L\ 1_N\,,\qquad \mathcal{O}_{12} = \vec{\sigma}_L\cdot[\vec{v}_N\times\vec{\sigma}_N]\,,$$
$$\mathcal{O}'_{13} = \vec{\sigma}_L\cdot(i\hat{q}\times[\vec{v}_N\times\vec{\sigma}_N])\,,\qquad \mathcal{O}_{14} = i\hat{q}\cdot\vec{\sigma}_L\ \vec{v}_N\cdot\vec{\sigma}_N\,,$$
$$\mathcal{O}_{15} = i\hat{q}\cdot\vec{\sigma}_L\ i\hat{q}\cdot[\vec{v}_N\times\vec{\sigma}_N]\,,\qquad \mathcal{O}'_{16} = i\hat{q}\cdot\vec{\sigma}_L\ i\hat{q}\cdot\vec{v}_N\,.$$

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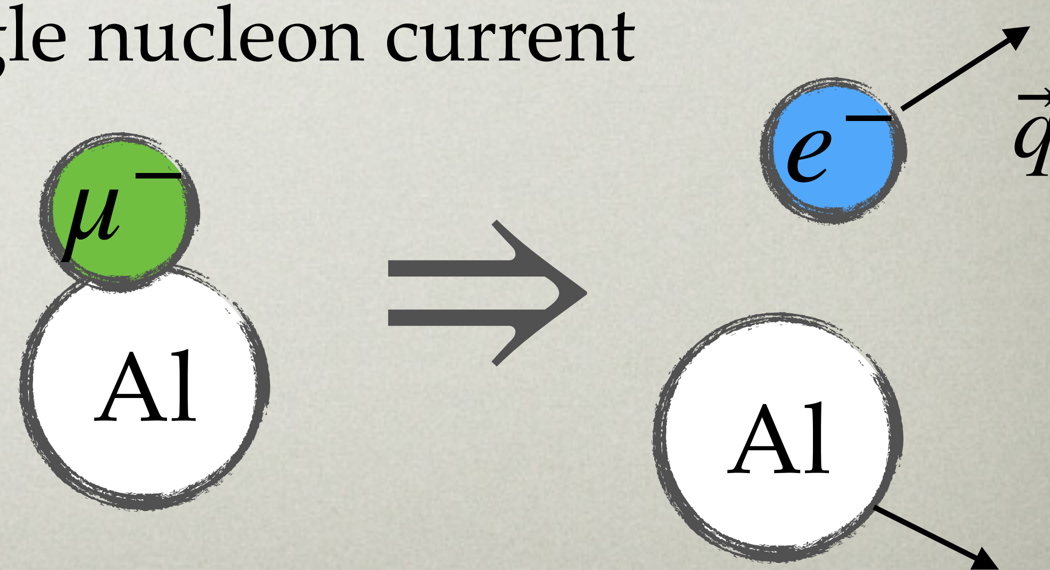


FROM NRET TO RATES

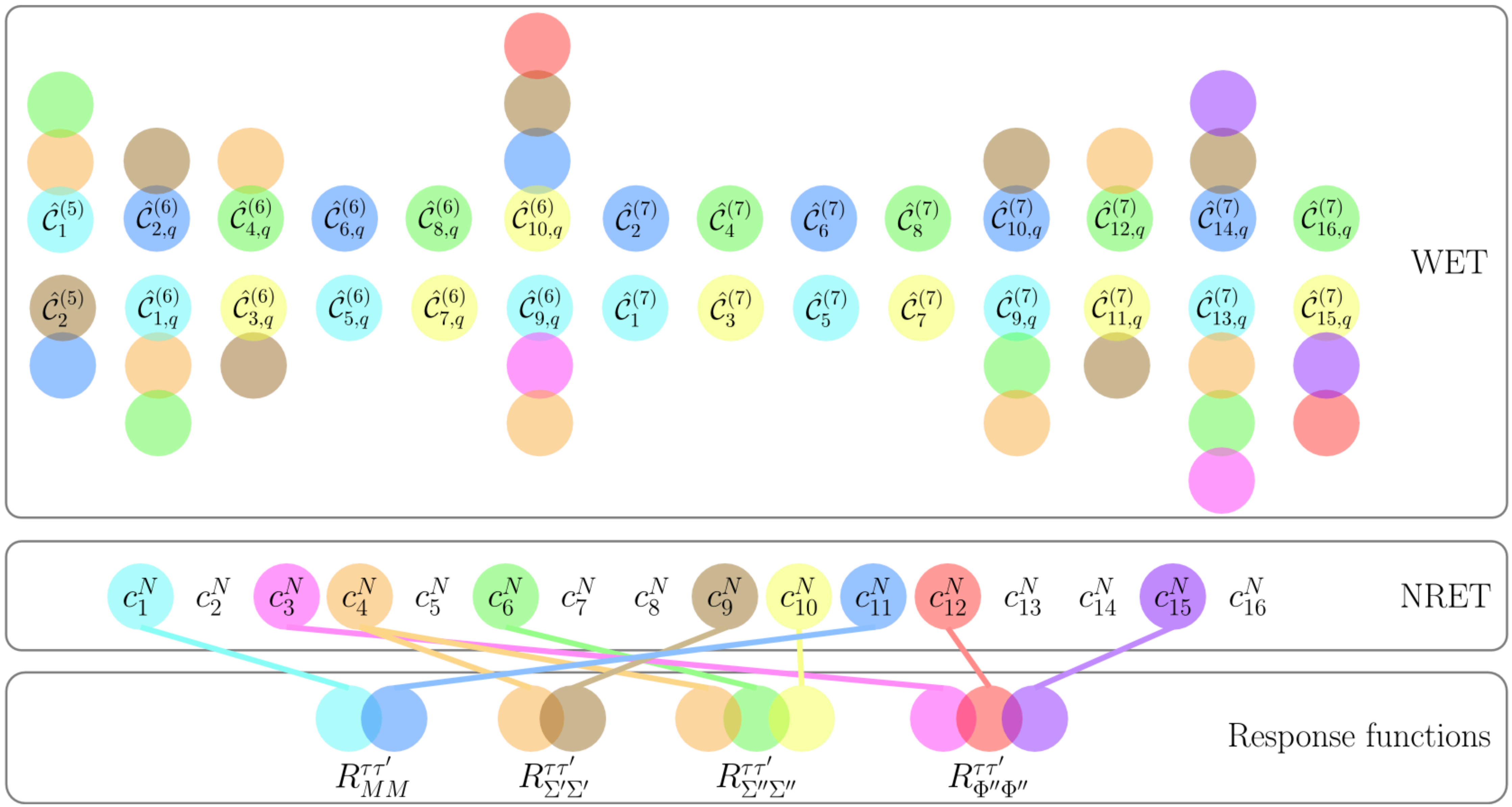
Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- NRET effective Lagrangian

$$\mathcal{L}_{\rm eff}^{\rm NRET} = \sum_{N=n,p} \sum_{i=1}^{16} c_i^N \mathcal{O}_i^N + \cdots ,$$

- low energy coefficients c_i^N functions of $\vec{q}_{\rm eff}^{\,2}$
  - for $\mu \to e$ this is a constant
  - their values from nonperturbative matching of WET to NRET
    - follow from nucleon matrix elements $\langle N | \mathcal{O}_i | N \rangle$
- for $\mu \to e$ transition rate prediction needs nuclear physics:
  - nuclear response functions $W_i \Rightarrow \quad \Gamma(\mu \to e) \propto \sum_i R_i(c_i^2, q_{\rm eff}^2) W_i$
- rough scaling for Al (isocalars):

$$W_M \sim \mathcal{O}(A^2) \gg \left\{ W_{\Sigma'}, W_{\Sigma''}, \frac{q_{\rm eff}}{m_N} W_{M\tilde{\Phi}''} \right\} \gg \left\{ \frac{q_{\rm eff}^2}{m_N^2} W_{\tilde{\Phi}''}, \frac{q_{\rm eff}^2}{m_N^2} W_{\Delta}, \frac{q_{\rm eff}^2}{m_N^2} W_{\tilde{\Phi}'} \right\}$$



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Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

MUONBRIDGE

- the code/repository **MuonBridge** consists of three modules
  - **MuonConverter:** matches WET to NRET
    - can interface with RG running codes
  - **Mu2e_NRET:** calculates the $\mu \to e$ rate

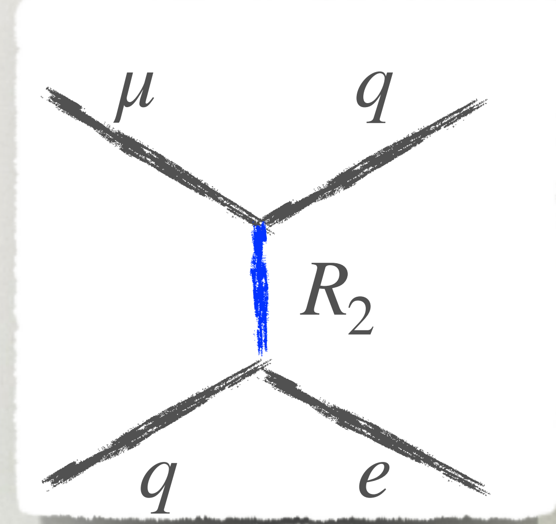
$$B(\mu^- \to e^-) = \frac{\Gamma\left[\mu^- + (A,Z) \to e^- + (A,Z)\right]}{\Gamma\left[\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)\right]},$$

    - particle physics input from **MuonConverter**, i.e., WET Wilson coeffs. C_i
  - **Elastic:** a database of shell model density matrices for calculating nuclear form factors
- comes in both **Python** and **Mathematica** versions

NEW PHYSICS EXAMPLES

- examples
  - R_2 leptoquark
  - light ALP
  - SMEFT

LEPTOQUARK EXAMPLE



- scalar leptoquark R_2 in the (3, 2, 7/6) of the SM gauge group

$$\mathcal{L} \supset y_{2\,ij}^{RL}\, \bar{u}_R^i R_2 L_L^j + y_{2\,ij}^{LR}\, \bar{e}_R^i R_2^* Q_L^j + \text{h.c.},$$

- integrating out R_2 at $\mu = m_{R_2}$ all 10 of the dim 6 operators in WET basis are generated
- in particular operators with quark tensor currents are generated
  - these have coherently enhanced contribs. at subleading powers in v_N, v_μ $\Rightarrow$ kept in **MuonBridge**

$$\mathcal{Q}_{1,q}^{(6)} = (\bar{e}\gamma_\alpha\mu)(\bar{q}\gamma^\alpha q)\,, \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar{e}\gamma_\alpha\gamma_5\mu)(\bar{q}\gamma^\alpha q)\,,$$

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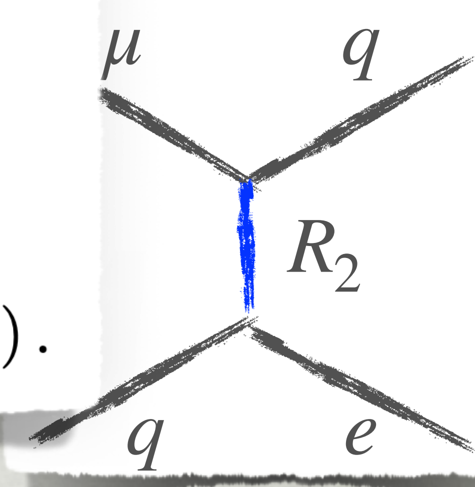

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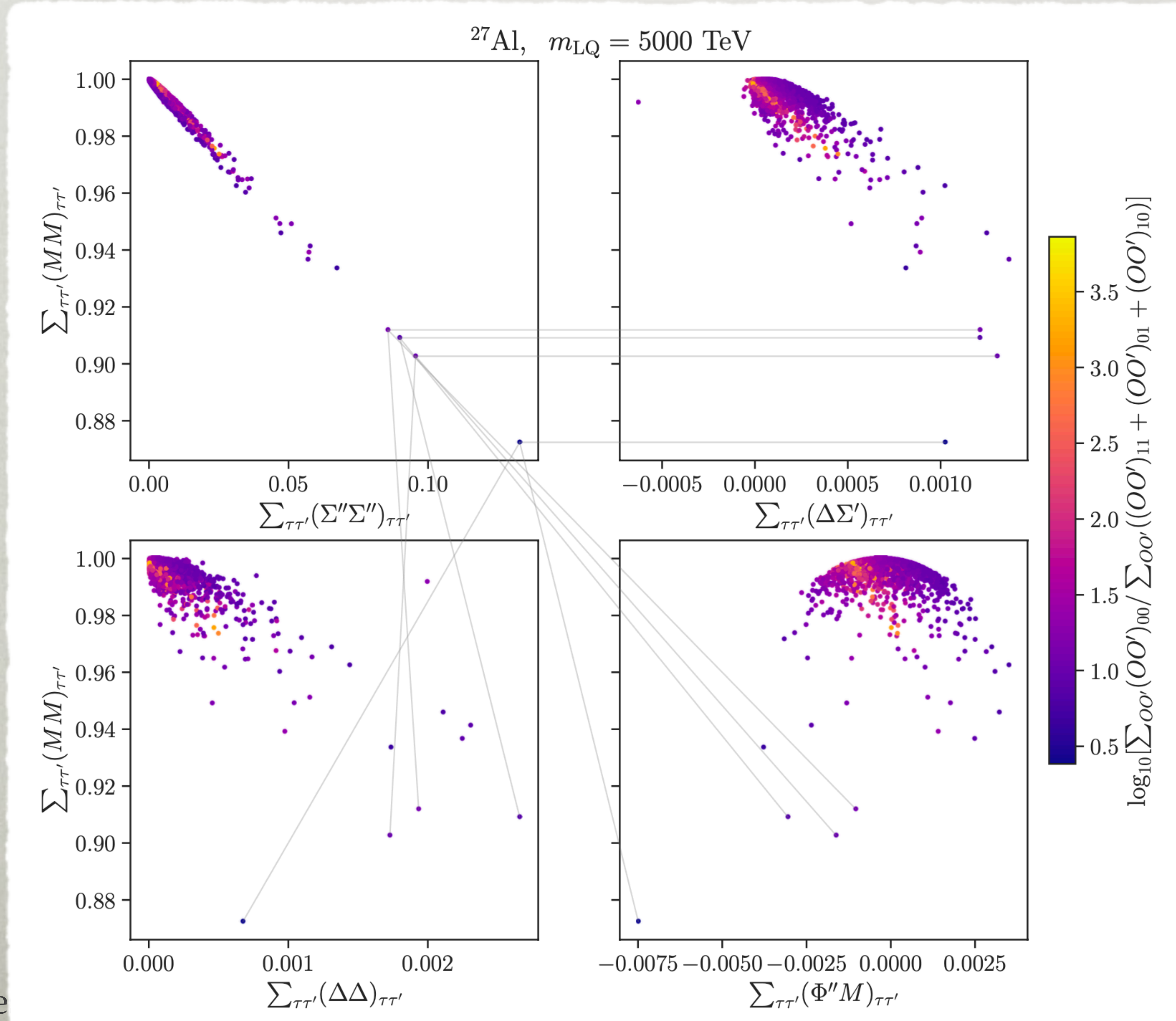
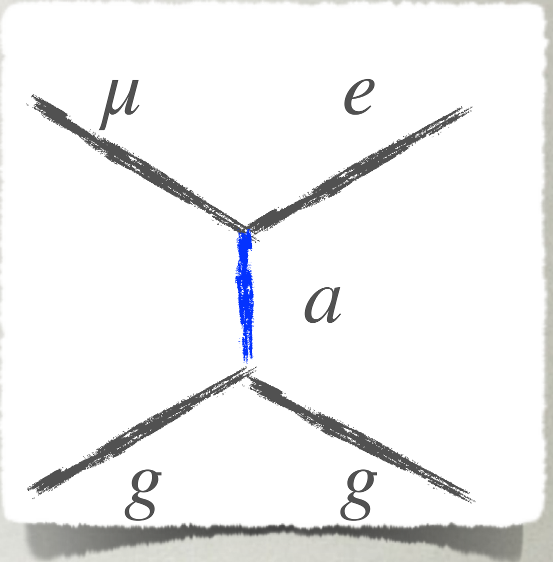
DIFFERENT CONTRIBS.

- a typically point in the parameter space dominated by spin independent contrib.



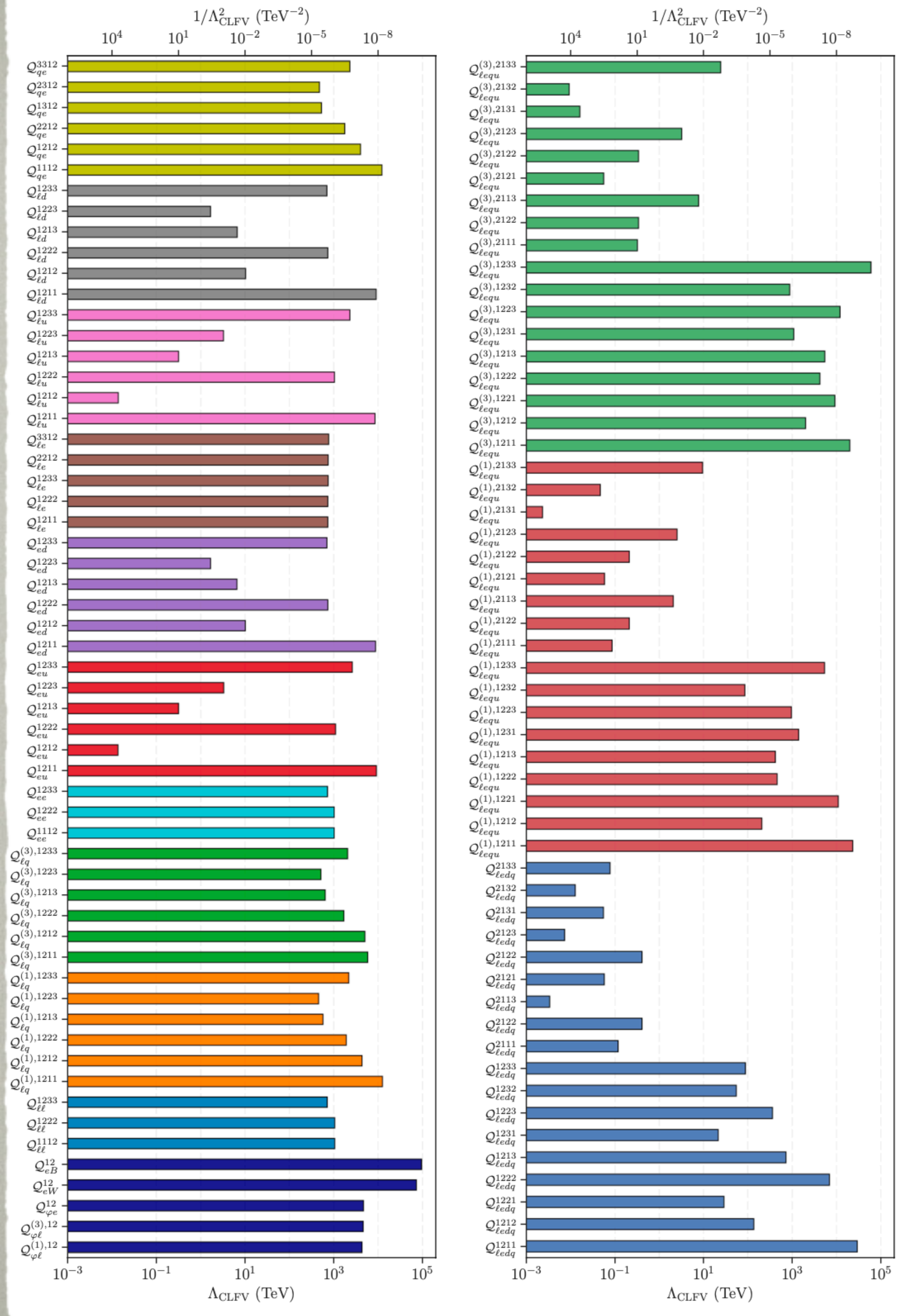
LIGHT ALP



- the same formalism trivially extends to light mediators
- example light ALP coupling to μe and gluons
- strictly speaking WET no longer an appropriate EFT
  - but trivial fix, allow Wilson coeffs to be q^2 dependent, $C_i \propto 1/(m_a^2 - q^2)$
  - since a only weakly couples to gluons: corrections to QCD can be neglected, i.e., just an external probe
  - in $\mu \to e$ the q is fixed, so C_i are even constants

SMEFT

- bounds on relevant SMEFT ops., assuming $B(\mu \to e) < 10^{-17}$



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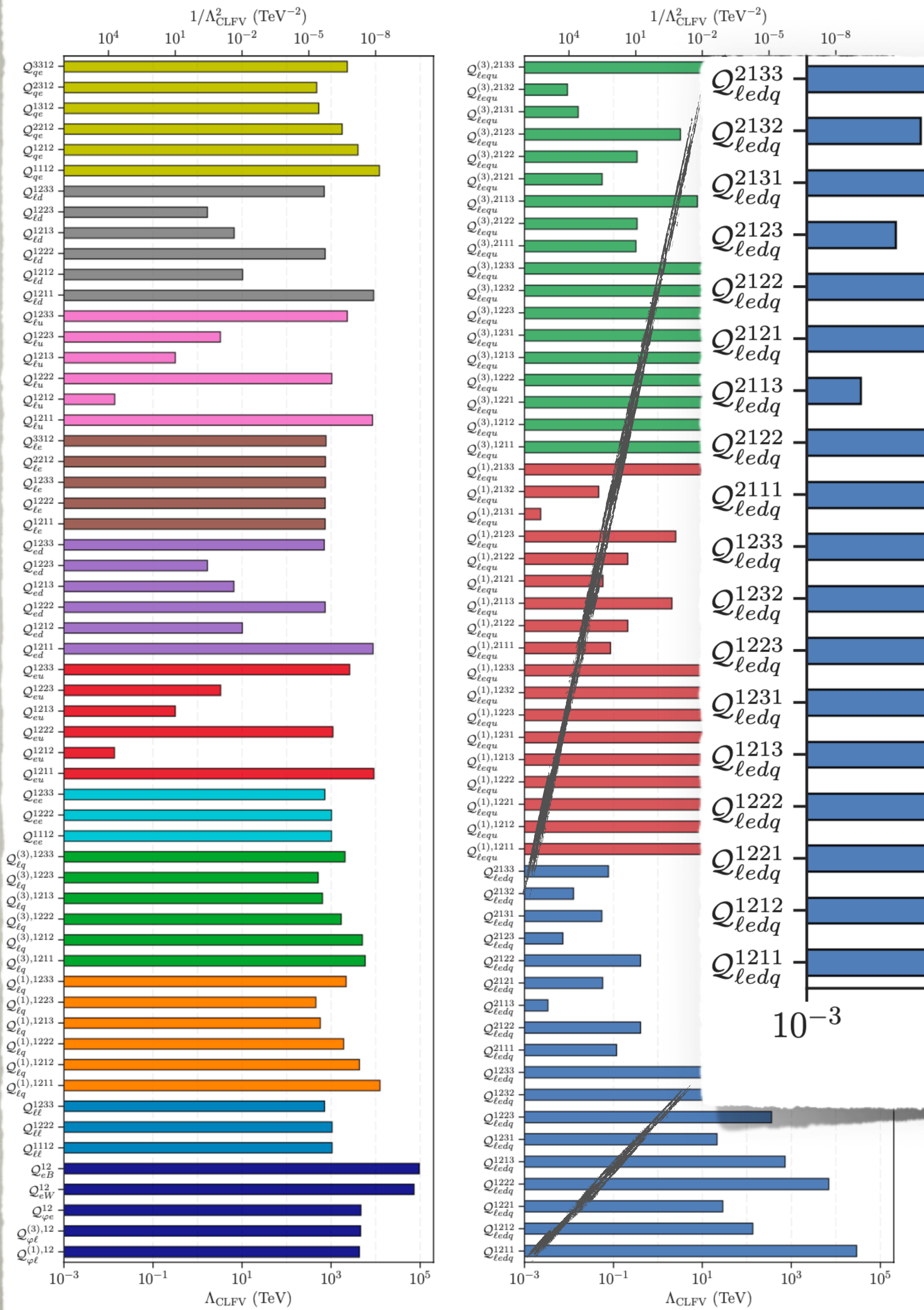
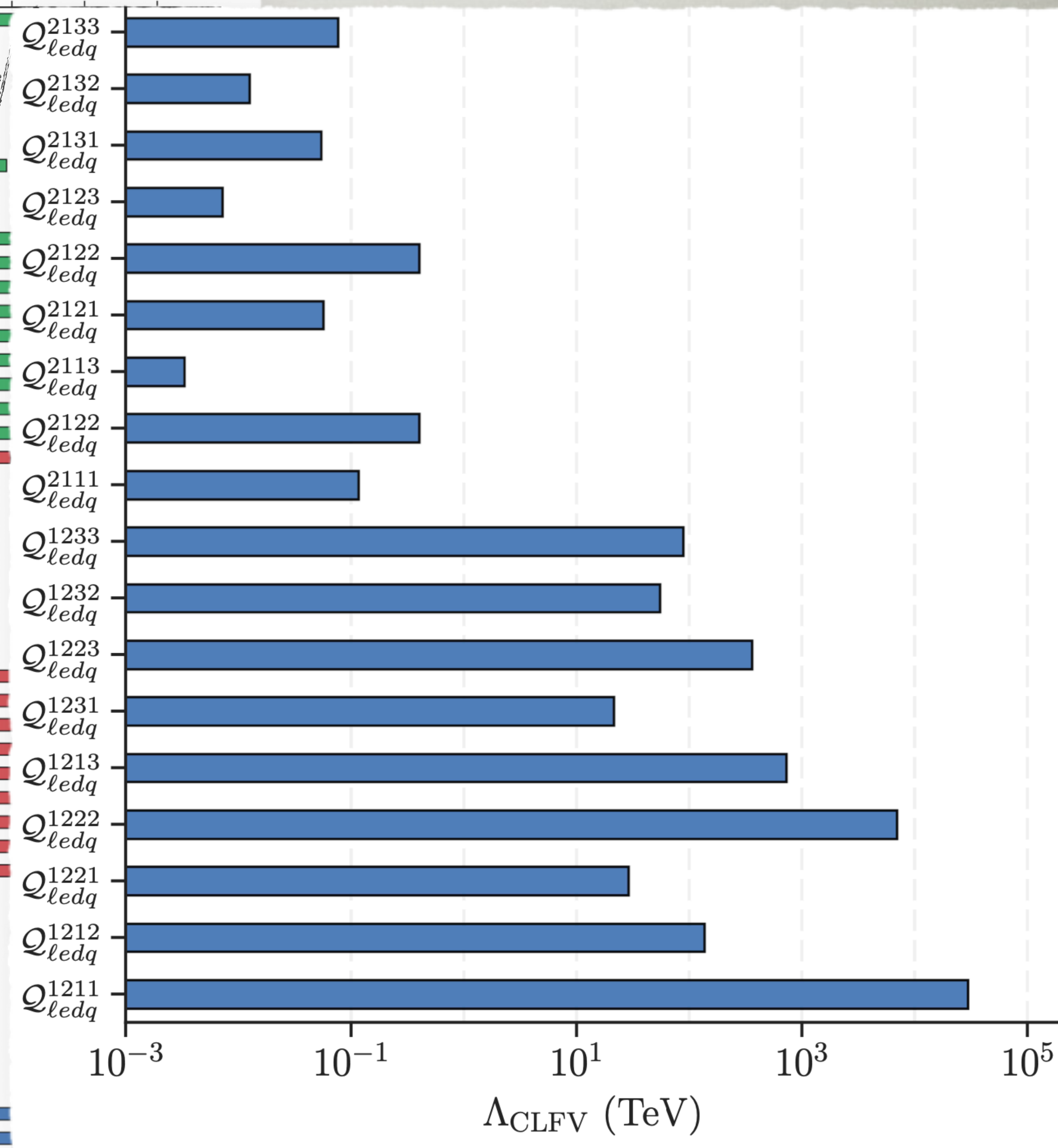
MEFT ops.,

10^{-17}



$1/\Lambda^2_{\rm CLFV}$ (TeV^{-2})
$\Lambda_{\rm CLFV}$ (TeV)
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}



$Q^{2133}_{\ell edq}$
$Q^{2132}_{\ell edq}$
$Q^{2131}_{\ell edq}$
$Q^{2123}_{\ell edq}$
$Q^{2122}_{\ell edq}$
$Q^{2121}_{\ell edq}$
$Q^{2113}_{\ell edq}$
$Q^{2122}_{\ell edq}$
$Q^{2111}_{\ell edq}$
$Q^{1233}_{\ell edq}$
$Q^{1232}_{\ell edq}$
$Q^{1223}_{\ell edq}$
$Q^{1231}_{\ell edq}$
$Q^{1213}_{\ell edq}$
$Q^{1222}_{\ell edq}$
$Q^{1221}_{\ell edq}$
$Q^{1212}_{\ell edq}$
$Q^{1211}_{\ell edq}$
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}
$\Lambda_{\rm CLFV}$ (TeV)

SEARCHING FOR LIGHT NEW PHYSICS

LIGHT NEW PARTICLES

- search for $\mu \to eX \Rightarrow$ enhanced sensitivity to UV scales
- how generic are light new particles?
  - any spontaneously broken global symmetry
  - $\Rightarrow$ massless Nambu-Goldstone boson
- very large datasets in principle available
  - what does $\mathcal{O}(10^{15} - 10^{17})$ muons at MEG-II, Mu3e, Mu2e buy us in terms for $\mu \to eX$ searches?
  - compare with current limits on $\mu \to eX$
    - done using $2 \times 10^7 \mu$ @ Jodidio et al. (1986), and $6 \times 10^8\ \mu$ @ TWIST (2015)

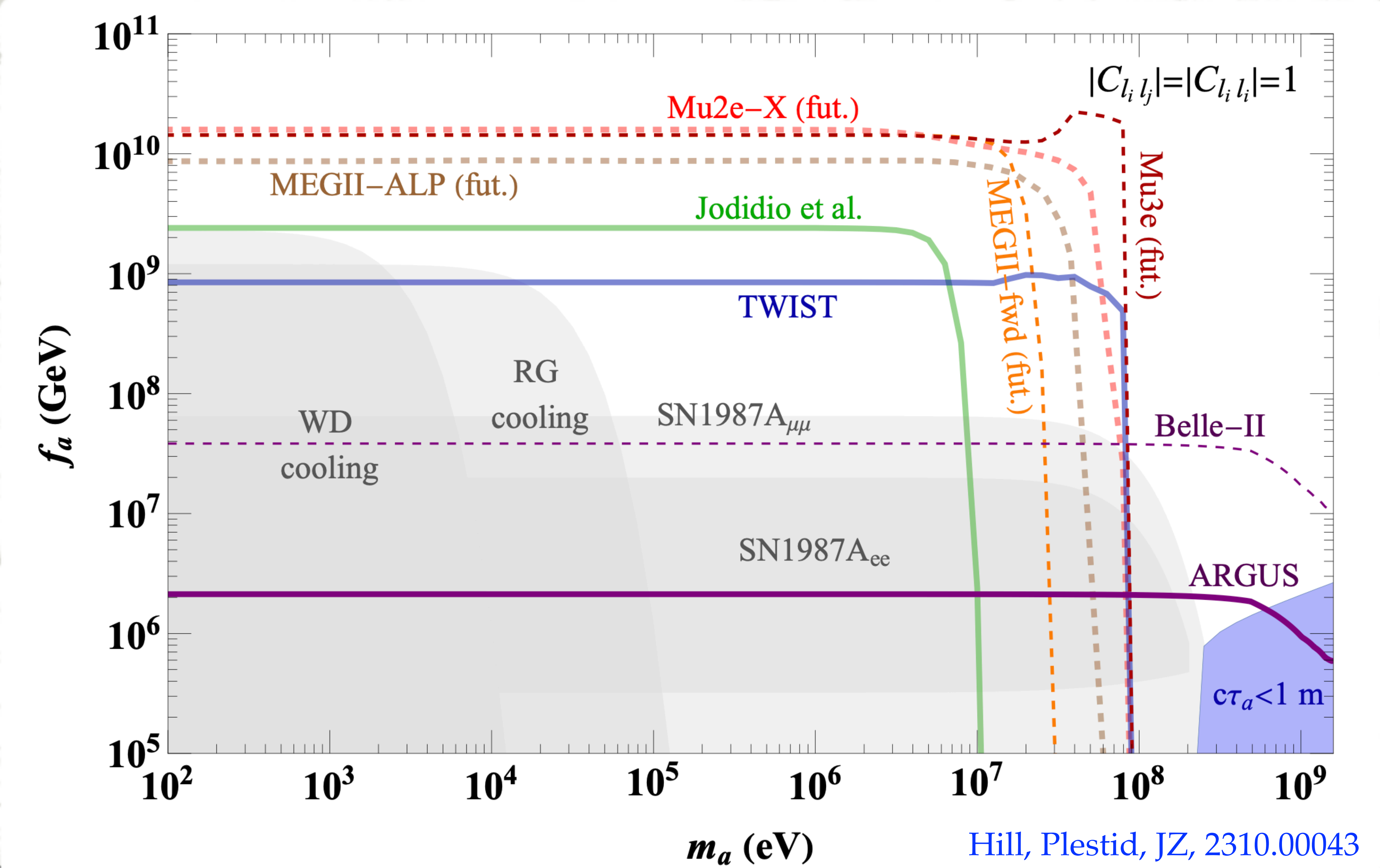
SEARCHING FOR LIGHT NEW PHYSICS

- can we use large datasets of stopped muons for light NP searches?
  - answer experiment dependent
- three examples
  - search for $\mu \to ea$ with calibration run at Mu2e
  - search for $\mu \to 5e$ at Mu3e
  - search for $\mu p \to$ dark sector at Mu2e

many more examples, see, e.g., Tammaro et al, 2410.13941; Redigolo et al, 2311.17915; Redigolo et al, 2311.17913

ALP WITH ANARCHIC COUPLINGS TO LEPTONS

- calibration run at Mu2e with μ^+ not μ^- — Hill, Plestid, JZ, 2310.00043
  - $\Rightarrow$ can search for $\mu \to ea$ decays



MULTI-ELECTRON NEW PHYSICS

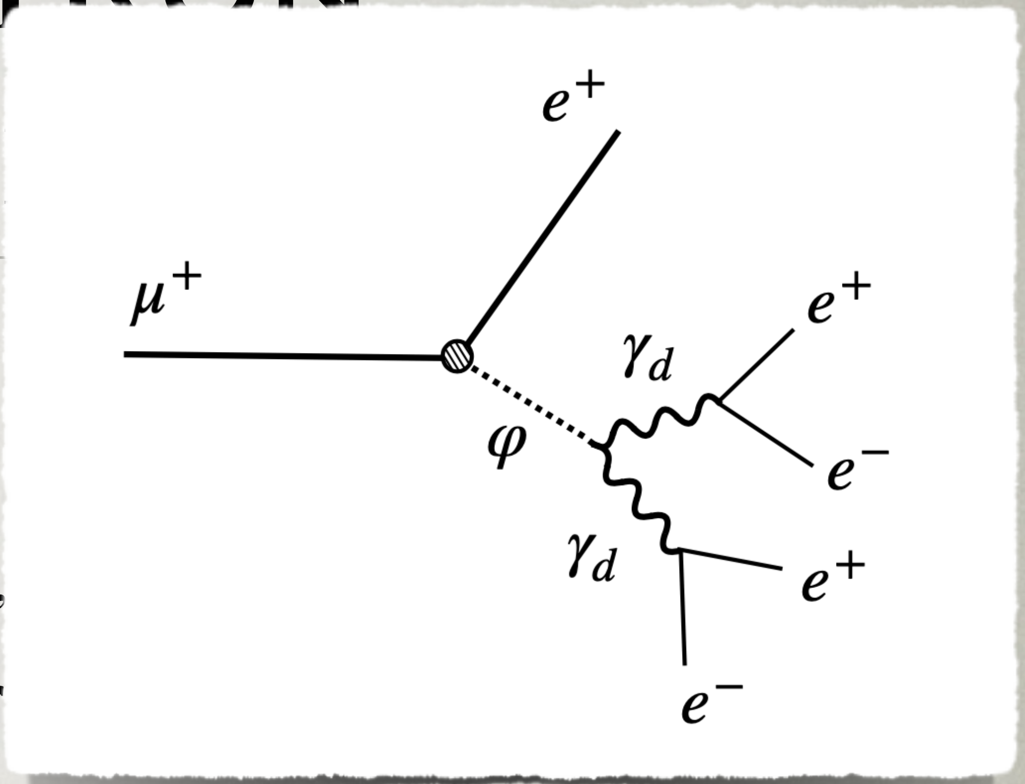
Hostert, Menzo, Pospelov, JZ, 2306.15631

- Mu3e searches for $\mu \to 3e$
  - sensitive also to soft electrons: $p_{T,\mathrm{th}} \sim 10$ MeV
- $\Rightarrow$ one can efficiently search also for $\mu \to 5e$
  - dark photon + light dark Higgs + LFV op.

$$\mathscr{L}_{\mathrm{LFV}} = -\frac{C_{ij}}{\Lambda}\phi\left(\bar{L}_i H\right)\ell_j + \mathrm{h.c.},$$

- Mu3e sensivity for 10^3 signal evnts. $\Rightarrow \mathscr{B}(\mu^+ \to e^+ h_d) \sim 10^{-12}$
  - depending on effectiveness of kinematical rejections of bckg., $\mathscr{B}(\mu^+ \to e^+ h_d) \sim 10^{-15}$ may be possible
  - $\Rightarrow$ sensitivity to LFV effective scale of $\Lambda \sim 10^{15} - 10^{16}$ GeV

MULTI-ELECTRON NEW PHYS



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  - sensitive also to soft electrons: $p_{T,}$
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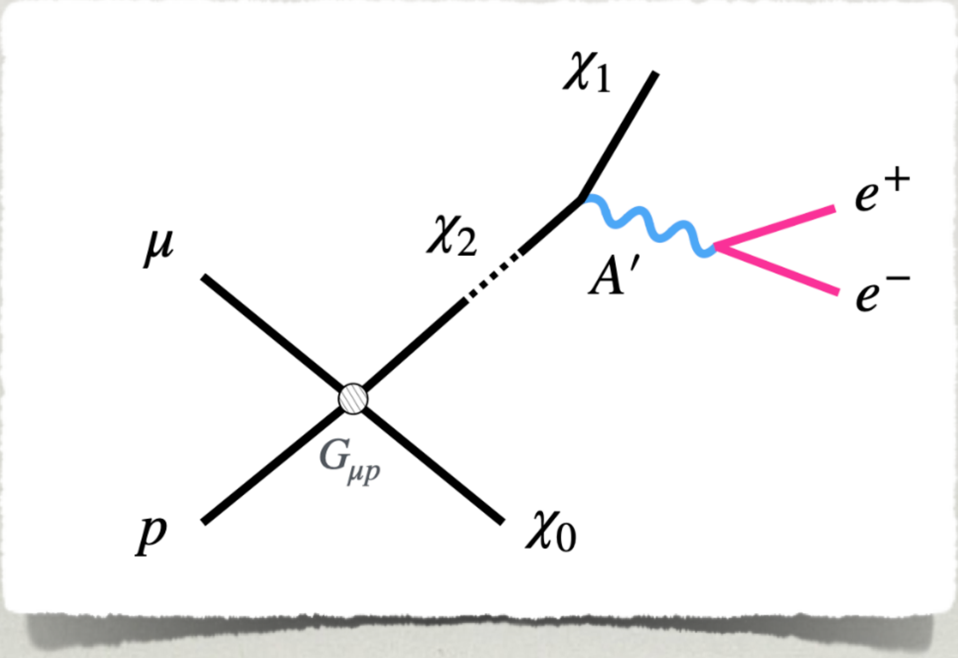
MUON-INDUCED BARYON NUMBER VIOLATION

Fox, Hostert, Menzo, Pospelov, JZ, 2407.03450

- if μ^- and proton annihilate $\Rightarrow$ energy release can give signal above $\mu \to e$ endpoint



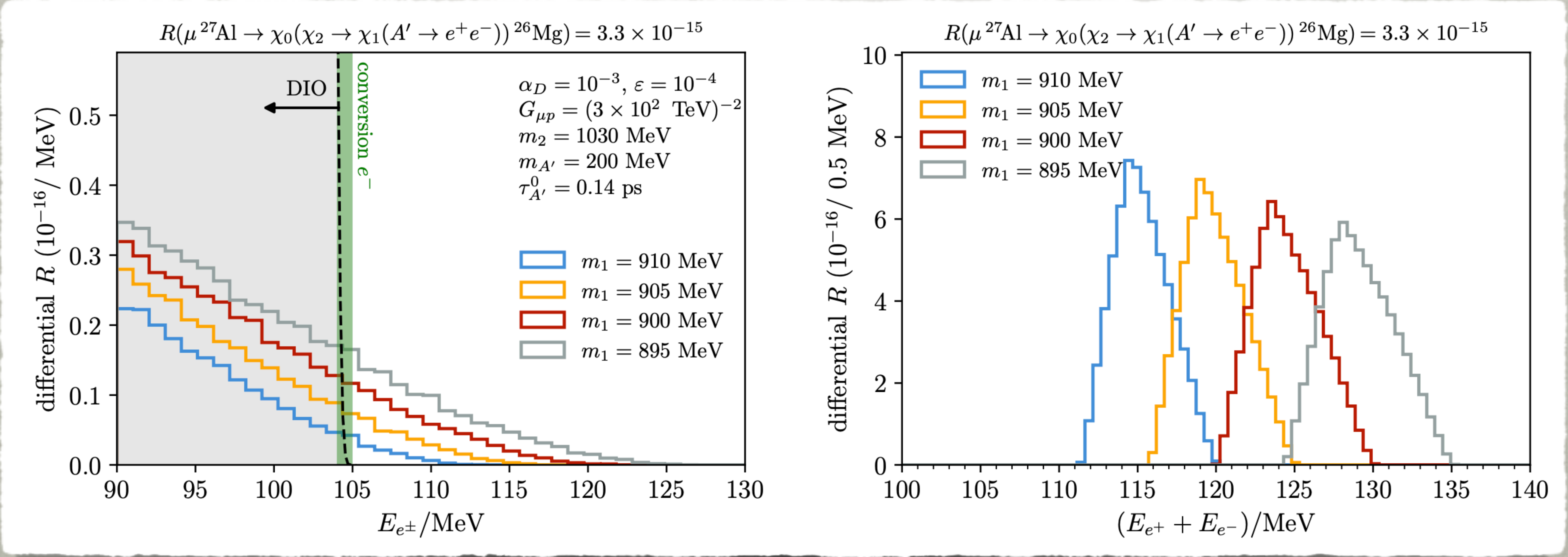
- proton decay limits require $m_\mu + m_p \simeq m_{\chi_0} + m_{\chi_1}$
  - still, possible to get e^- above DIO

NUMERICAL EXAMPLE

- sample benchmark point

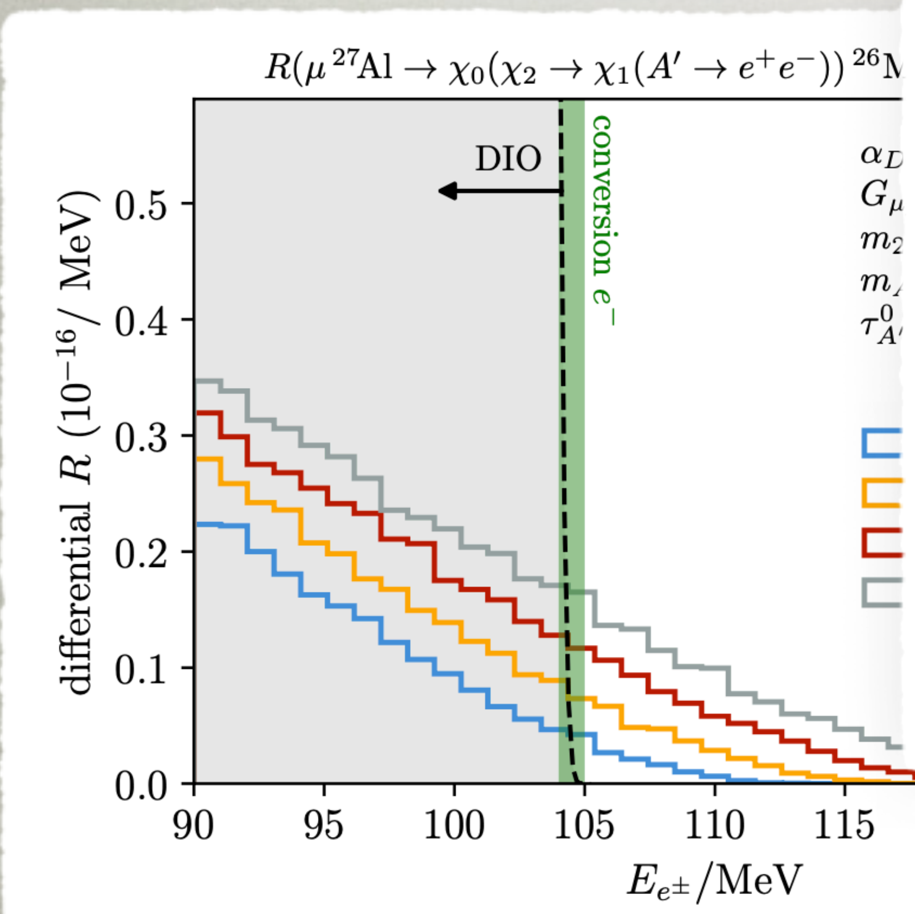
Fox, Hostert, Menzo, Pospelov, JZ, 2407.03450

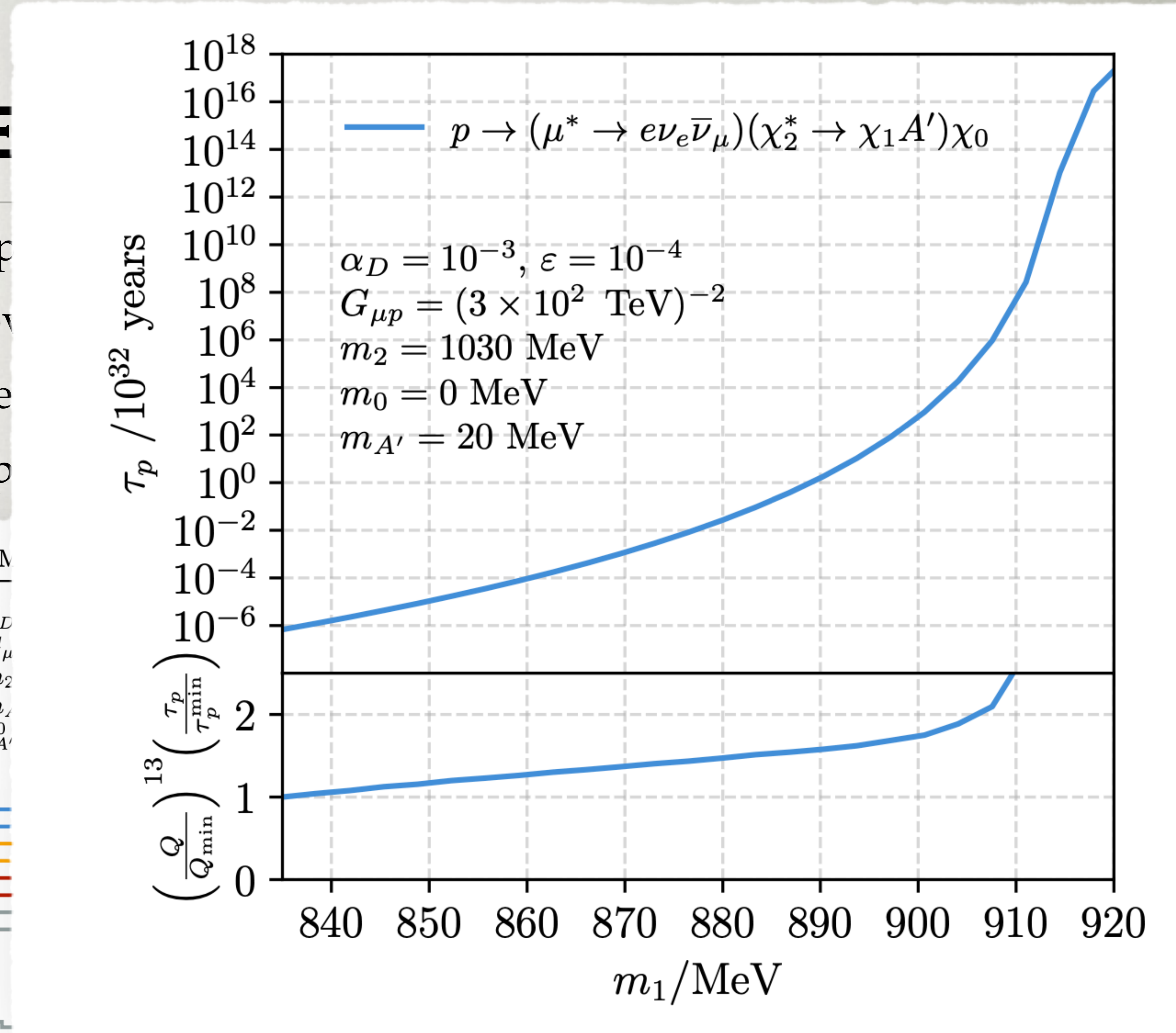
  - energy of e^- above DIO endpoint
  - $e^-$and e^+ energies peak, since all other particles are nonrelativistic
  - proton decay is phase space suppressed



NUME

- sample benchmark p
  - energy of e^- abov
  - $e^-$and e^+ energie
  - proton decay is p





TOPICS NOT COVERED

- note: many interesting topics that I did not have time to touch upon

The Muon Smasher's Guide, 2103.14043

- new physics reach of $\mu^+\mu^-$ (Muon Collider) or μ^+e^- (μTristan) colliders

Hamada et al, 2201.06664
Kriewald et al, 2412.04331

- the physics of $(g-2)_\mu$

see talk by D. Giusti

- new muon-phylic forces such as $L_\mu - L_\tau$, or $B_3 - L_\mu$

see talk by B. Allanach

- muon decays with displaced vertices

see talk by M. Tammaro

- ....

CONCLUSIONS

- EFT approach well suited for predicting the $\mu \to e$ conversion rates
  - results available in the form of a public code **MuonBridge**
- rare muon decays can be used to search for light NP
  - QCD axion, $\mu \to 5e$, $\mu p \to$ dark s.,

BACKUP SLIDES

TOWER OF EFTs

- below $\mu = 2\,\text{GeV}$ a series of EFTs
  - Weak Effective Theory (WET): d.o.f.s quarks and gluons
    Haxton, McElvain, Menzo, Rule, JZ, 2406.13818
  - (Covariant EFT with relativistic nucleons)
    Haxton, McElvain, Ramsey-Mussolf, Rule, 2208.07945
  - NRET: d.o.f.s non-rel nucleons
    Haxton, McElvain, Rule, 2109.13503
    - (Chiral EFT for nucleus)
    - chiral counting shows that leading effect from $\mu \to e$ on single nucleon currents

WET

Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

- 10 dimension 6 ops

$$\mathcal{Q}_{1,q}^{(6)} = (\bar{e}\gamma_\alpha\mu)(\bar{q}\gamma^\alpha q)\,, \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar{e}\gamma_\alpha\gamma_5\mu)(\bar{q}\gamma^\alpha q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\bar{e}\gamma_\alpha\mu)(\bar{q}\gamma^\alpha\gamma_5 q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar{e}\gamma_\alpha\gamma_5\mu)(\bar{q}\gamma^\alpha\gamma_5 q)\,.$$
$$\mathcal{Q}_{5,q}^{(6)} = (\bar{e}\mu)(\bar{q}q)\,, \qquad \mathcal{Q}_{6,q}^{(6)} = (\bar{e}i\gamma_5\mu)(\bar{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(6)} = (\bar{e}\mu)(\bar{q}i\gamma_5 q)\,, \qquad \mathcal{Q}_{8,q}^{(6)} = (\bar{e}i\gamma_5\mu)(\bar{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(6)} = (\bar{e}\sigma^{\alpha\beta}\mu)(\bar{q}\sigma_{\alpha\beta}q)\,, \qquad \mathcal{Q}_{10,q}^{(6)} = (\bar{e}i\sigma^{\alpha\beta}\gamma_5\mu)(\bar{q}\sigma_{\alpha\beta}q)\,.$$

- additional 16 operators at dimension 7
- related to other WET bases used in the literature by linear transf.
- note: tensor currents appear already at dimension 6

NUCLEAR RESPONSE FUNCTIONS

- $W_M(q)$: from vector operator
  - in $q \to 0$ limit counts nucleons ⇒ spin-indep. (coherent) scatter.
- $W_{\Sigma''}$ and $W_{\Sigma'}$: longit. and transverse axial ops.
  - measure the nucleon spin content of the nucleus
- W_Δ , $W_{\tilde{\Phi}'}$, $W_{\tilde{\Phi}''}$: sensitive to velocities of nucleons
  - reflect the composite structure of the nucleus
  - coherence over half-filled shells for $W_{\tilde{\Phi}''}$
- rough scaling for Al (isocalars):

$$W_M \sim \mathcal{O}(A^2) \gg \left\{ W_{\Sigma'}, W_{\Sigma''}, \frac{q_{\rm eff}}{m_N} W_{M\tilde{\Phi}''} \right\} \gg \left\{ \frac{q_{\rm eff}^2}{m_N^2} W_{\tilde{\Phi}''}, \frac{q_{\rm eff}^2}{m_N^2} W_\Delta, \frac{q_{\rm eff}^2}{m_N^2} W_{\tilde{\Phi}'} \right\}$$

- six more response functions + 2 interf. terms at $\mathcal{O}(v_\mu)$

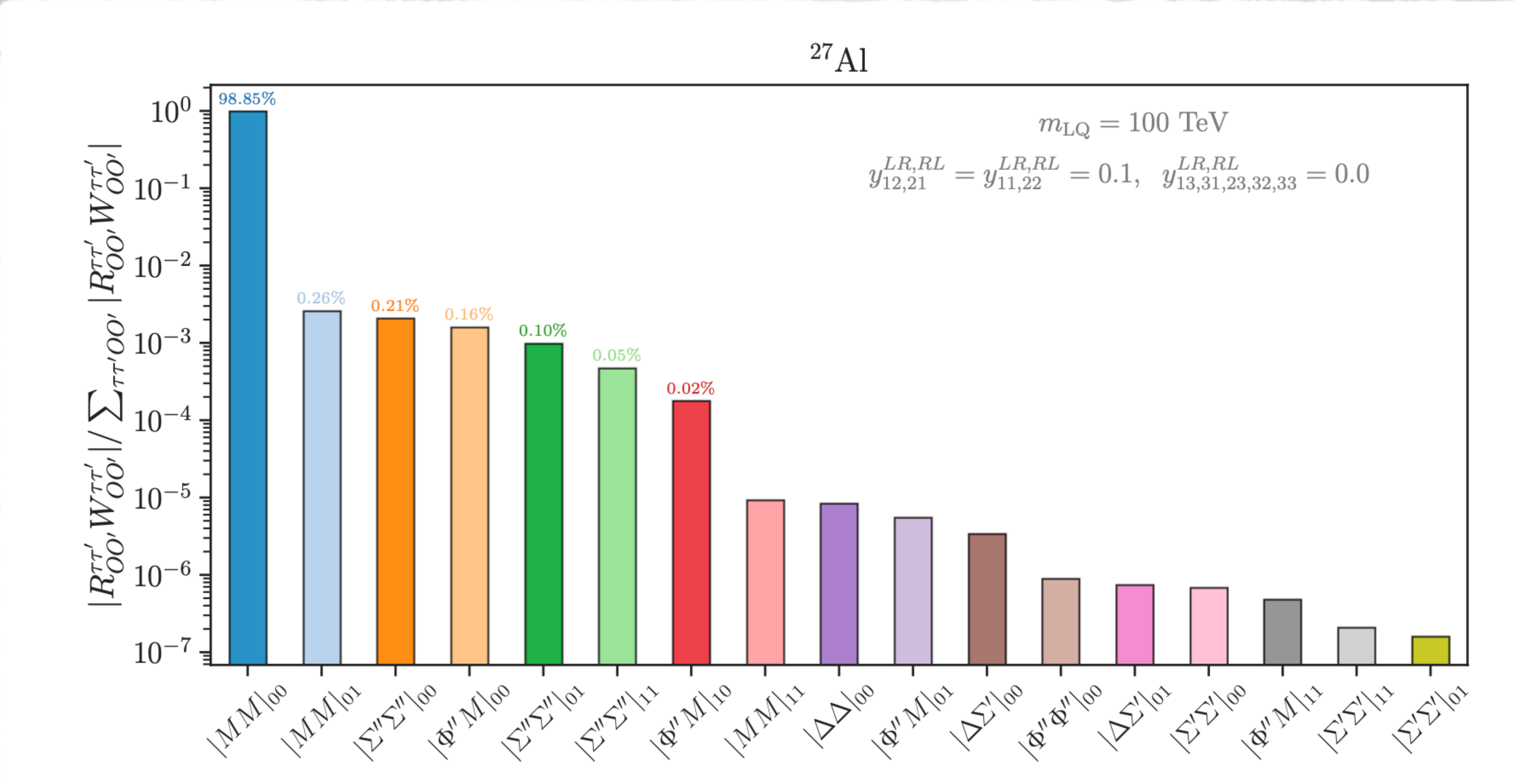
COMMENTS

- since q_{eff} changes by only ~5% from C to W
  - $c_i^N(q_{\text{eff}})$ are basically constants
- $\Rightarrow$ from $\mu \to e$ can measure only a few linear combinations of Wilson coeffs
  - 3 combinations at $\mathcal{O}(v_N^0, v_\mu^0)$
    - vector/scalar, axial, pseudoscalar currents
  - + 5 combinations at $\mathcal{O}(v_N, v_\mu^0)$
    - but only one ($W_{M\Phi''}$)comparable to SD $\mathcal{O}(v_N^0, v_\mu^0)$ ($W_{\Sigma\Sigma'}$,$W_{\Sigma'\Sigma'}$)
  - this is for isoscalar-isocalar W's, since also isovector-isoscalar, isovector-isovector, 3x those nos. in total
- to understand UV physics important to measure both $\mu \to e$ on different targets and $\mu \to e\gamma$ ($\mu \to 3e$)
  - more information possible from inelastic $\mu + \text{Al} \to e + \text{Al}^*$

Haxton, Rule, 2404.17166

DIFFERENT CONTRIBS.

- a typically point in the parameter space dominated by spin independent contrib.



MINIMAL DARK SECTOR MODEL

- higgsed dark abelian gauge group $U(1)_d$
  - dark photon γ_d, light dark Higgs h_d
- coupling to SM
  - kinetic mixing
  - flavor violating dim 5 Yukawa
  - scalar quartic $\lambda'(\phi^\dagger\phi)(H^\dagger H)$ assumed to be suppressed

$$\mathscr{L}_{\mathrm{DS}} = (D_\mu\phi)^\dagger D^\mu\phi - \frac{1}{4}F_d^{\mu\nu}F_{d\,\mu\nu} - \frac{\varepsilon}{2}F_d^{\mu\nu}F_{\mu\nu} - \mu^2\left(\phi^\dagger\phi\right) - \lambda\left(\phi^\dagger\phi\right)^2,$$

$$\mathscr{L}_{\mathrm{LFV}} = -\frac{C_{ij}}{\Lambda}\phi\left(\bar{L}_i H\right)\ell_j + \mathrm{h.c.},$$

- couplings to leptons

$$\mathscr{L} \supset -m_{\ell_i}\bar{\ell}_{Li}\ell_{Ri}\left(1+\frac{h}{v}\right) - y_{ij}\bar{\ell}_{Li}\ell_{Rj}h_d\left(1+\frac{h}{v}\right) + \mathrm{h.c.},$$

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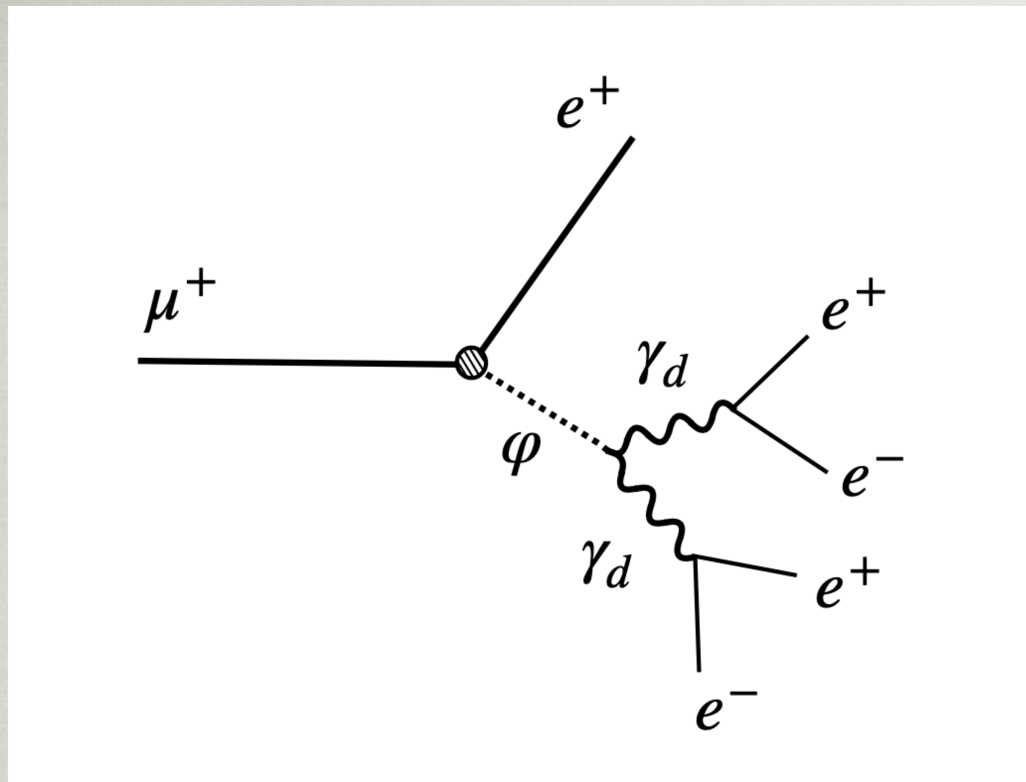

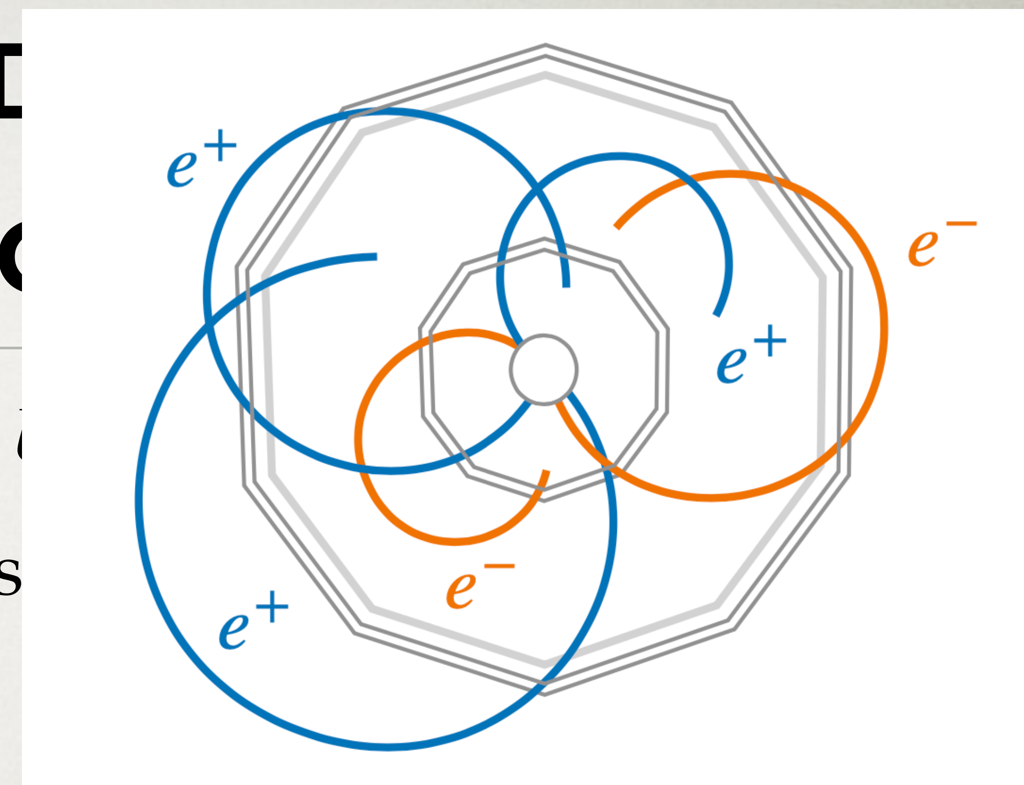

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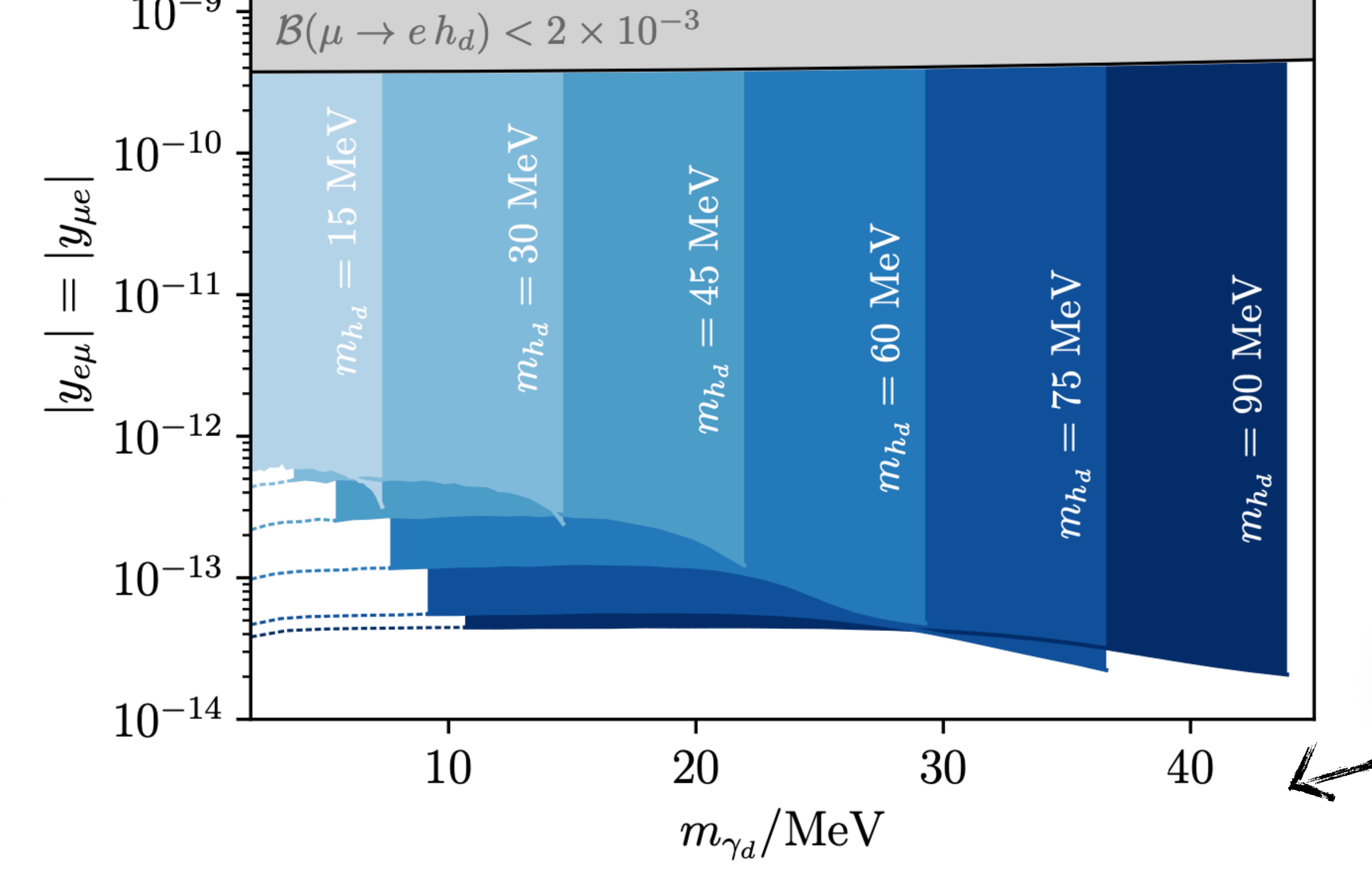
ESTIMATED SENSITIVITY

- assume $N_\mu = 10^{15}$
- backgrounds
  - intrinsic: $\mu^+ \to 3e^+ 2e^- 2\nu$ suppress to $\mathcal{O}(1)$ evnt level by E_{miss} cuts
  - accidental: simultaneous $\mu \to 3e2\nu$ and $\mu \to e2\nu$ decays with extra e^- from e^+ Bhabha scattering in target
    - $\mathcal{O}(10^3)$ evnts without kinem. cuts
- Mu3e sensivity conservatively set by requiring 10^3 signal evnts. $\Rightarrow \mathcal{B}(\mu^+ \to e^+ h_d) < 10^{-12}$
  - if kinematical rejection as powerful for $\mu \to 5e$ as for $\mu \to 3e$, can well be a bckg. free search up to $\mathcal{B}(\mu^+ \to e^+ h_d) \sim 10^{-15}$

VITY



$\Lambda \sim 10^{15} - 10^{16}$GeV

$e2\nu$ decays

with extra e^- from e^- Bhabha scattering in target

- $\mathcal{O}(10^3)$ evnts without kinem. cuts

- Mu3e sensivity conservatively set by requiring 10^3 signal evnts. $\Rightarrow \mathcal{B}(\mu^+ \to e^+ h_d) < 10^{-12}$
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COMPLEMENTARY PROBES

- complete list of dim 6 CLFV operators

	4-leptons operators		Dipole operators
$Q_{\ell\ell}$	$(\bar L_L\gamma_\mu L_L)(\bar L_L\gamma^\mu L_L)$	Q_{eW}	$(\bar L_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar e_R\gamma_\mu e_R)(\bar e_R\gamma^\mu e_R)$	Q_{eB}	$(\bar L_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar L_L\gamma_\mu L_L)(\bar e_R\gamma^\mu e_R)$		
	2-lepton 2-quark operators		
$Q^{(1)}_{\ell q}$	$(\bar L_L\gamma_\mu L_L)(\bar Q_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar L_L\gamma_\mu L_L)(\bar u_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar L_L\gamma_\mu\tau_I L_L)(\bar Q_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar e_R\gamma_\mu e_R)(\bar u_R\gamma^\mu u_R)$
Q_{eq}	$(\bar e_R\gamma^\mu e_R)(\bar Q_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar L^a_L e_R)(\bar d_R Q^a_L)$
$Q_{\ell d}$	$(\bar L_L\gamma_\mu L_L)(\bar d_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar L^a_L e_R)\epsilon_{ab}(\bar Q^b_L u_R)$
Q_{ed}	$(\bar e_R\gamma_\mu e_R)(\bar d_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar L^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar Q^b_L\sigma^{\mu\nu}u_R)$
	Lepton-Higgs operators		
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar L_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar L_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar L_L e_R\Phi)(\Phi^\dagger\Phi)$

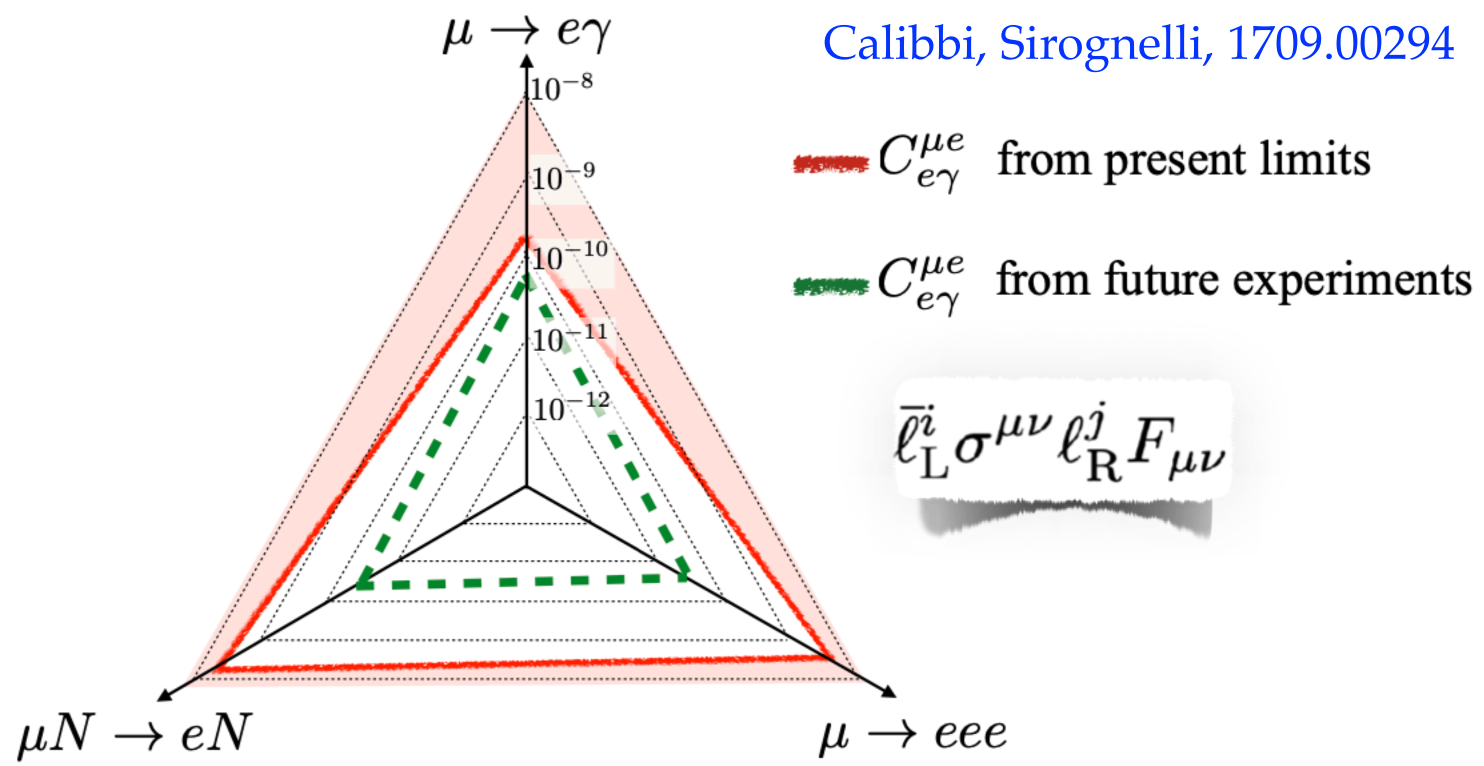
probed by
$\mu\to e\gamma$
$\mu\to 3e$
$\mu\to e$

DIPOLE OPERATOR DOMINANCE

- simplified scenario - assume the dipole operator dominates
- interesting to compare the reach of different experiments

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)\,,$$

$$\mathrm{CR}(\mu\ \mathrm{N} \to e\ \mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)\,.$$



$$\bar{\ell}_{\mathrm{L}}^{i}\sigma^{\mu\nu}\ell_{\mathrm{R}}^{j}F_{\mu\nu}$$