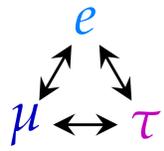


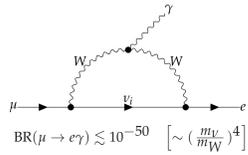
## Lepton Flavour Violation (LFV)

### Search for charged LFV:



Observation  $\Rightarrow$  New Physics

via neutrino oscillations severely suppressed:

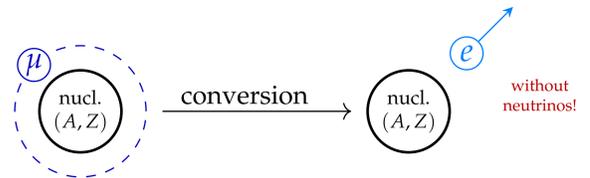


LFV process	current limit	(planned) experiments
$\mu \rightarrow e\gamma$	$< 4.2 \cdot 10^{-13}$ [MEG]	MEG II
$\mu \rightarrow 3e$	$< 1.0 \cdot 10^{-12}$ [SINDRUM]	Mu3e
$\tau \rightarrow \ell\gamma, 3\ell, \ell P, \dots$	$\lesssim 10^{-8}$ [Belle, LHCb, ...]	Belle 2, ...
$\pi^0 \rightarrow \bar{\mu}e$	$< 3.6 \cdot 10^{-10}$ [KTeV]	JEF, REDTOP
$\eta \rightarrow \bar{\mu}e$	$< 6 \cdot 10^{-6}$ [SPEC]	
$\eta' \rightarrow \bar{\mu}e$	$< 4.7 \cdot 10^{-4}$ [CLEO II]	
$Au \mu^- \rightarrow Au e^-$	$< 7 \cdot 10^{-13}$ [SINDRUM II]	Mu2e [3], COMET [7]
$Ti \mu^- \rightarrow Ti e^-$	$< 6.1 \cdot 10^{-13}$ [SINDRUM II]	
$Al \mu^- \rightarrow Al e^-$	$\lesssim 10^{-17}$ (projected)	

current experimental status (incomplete)

## $\mu \rightarrow e$ conversion on nuclei

### Process:



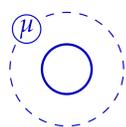
- clean experimental measure:  $|\vec{q}_e| \approx m_\mu$
- only background:  $\mu^- \rightarrow \nu_\mu \bar{\nu}_e e^- \Rightarrow$  Spectrum
- normalisation:  $\mu(A, Z) \rightarrow \nu_\mu(A, Z-1)$

At leading order separation into:



## Effective description of the process

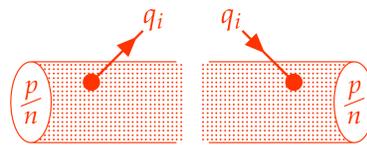
Rate =



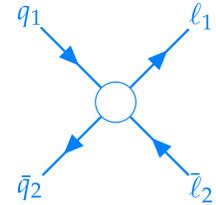
bound state physics



nuclear response



hadronic matrix elements



(short distance) EFT operators

## Master formula: $P \rightarrow \mu e$

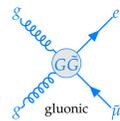
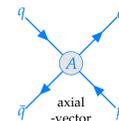
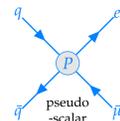
$$\text{Br}_{P \rightarrow \mu^\mp e^\pm} = \frac{(M_P^2 - m_\mu^2)^2}{16\pi\Gamma_P M_P^3} \times \sum_{Y=L,R} |C_Y^P|^2$$

$$C_Y^P = \sum_q \frac{b_q}{\Lambda^2} \left( \pm C_Y^{A,q} f_P^q m_\mu - C_Y^{P,q} \frac{h_P^q}{2m_q} \right) + \frac{4\pi}{\Lambda^3} C_Y^{GG} a_P$$

## Model independent parametrisation of LFV

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2} \sum_{Y=L,R} \sum_{q=u,d,s} \left[ C_Y^{P,q} (\bar{e}\gamma^\mu) (\bar{q}\gamma_5 q) + C_Y^{A,q} (\bar{e}\gamma^\mu \gamma^5) (\bar{q}\gamma_\mu \gamma_5 q) \right] + \frac{i\alpha_s}{\Lambda^3} \sum_{Y=L,R} C_Y^{GG} (\bar{e}\gamma^\mu) G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} + \text{h.c.}$$

Contributing operators to  $P \rightarrow \mu e$ :



## Master formula: SD $\mu \rightarrow e$ conversion

$$\text{Br}_{\mu \rightarrow e}^{\text{SD}} = \frac{4m_\mu^5 \alpha^3 Z^3}{\pi\Gamma_{\text{cap}}(2J+1)} \left( \frac{Z_{\text{eff}}}{Z} \right)^4 \times \sum_{Y=L,R} \sum_{\tau=L,T} \left[ C_Y^{\tau,00} S_{00}^\tau + C_Y^{\tau,11} S_{11}^\tau + C_Y^{\tau,01} S_{01}^\tau \right]$$

$$C_Y^{T,ij} = \left[ \bar{C}_Y^{A,i} (1 + \delta')^i \pm 2\bar{C}_Y^{T,i} \right] \times (i \leftrightarrow j); \quad C_Y^{L,ij} = \left[ \bar{C}_Y^{A,i} (1 + \delta'')^i - \frac{m_\mu}{2m_N} \bar{C}_Y^{P,i} \pm 2\bar{C}_Y^{T,i} \right] \times (i \leftrightarrow j)$$

$$\bar{C}_Y^{P,N} = \frac{1}{\Lambda^2} \sum_q C_Y^{P,q} \frac{m_N}{m_q} g_5^{q,N} - \frac{4\pi}{\Lambda^3} C_Y^{GG} \tilde{a}_N; \quad \bar{C}_Y^{A,N} = \frac{1}{\Lambda^2} \sum_q C_Y^{A,q} g_A^{q,N}; \quad \bar{C}_Y^{T,N} = \frac{1}{\Lambda^2} \sum_q C_Y^{T,q} f_{1,T}^{q,N}$$

SD  $\mu \rightarrow e$  conversion contains the **same operators** as  $P \rightarrow \mu e$

$\Rightarrow$  we can **relate the limits**

## Bound state physics & Nuclear response

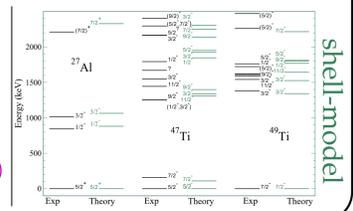
num. solution of Dirac eq.:

$$Z_{\text{eff}}^{\text{Al}} = 11.64, \quad Z_{\text{eff}}^{\text{Ti}} = 17.65$$

(calculated in analogy to [1])

corr. from NLO & 2-body [8]:

$$\delta' = -0.28(5), \quad \delta'' = -0.44(4)$$

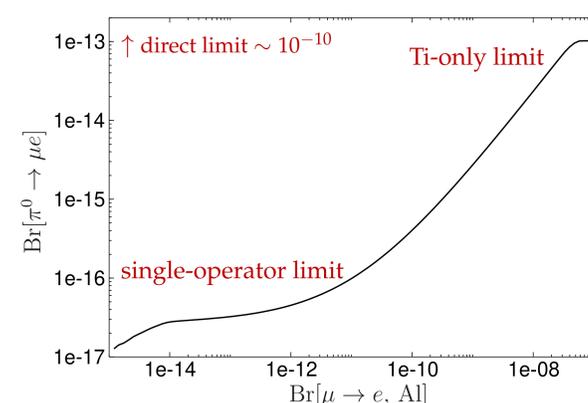


## Hadronic matrix elements

mesons:	[4, 9]				nucleons: [2, 5, 6]					
	$\pi$	$\eta$	$\eta'$		$p$	$n$				
$\frac{h_P^q}{m_q}$	1	0.80	0.77	0.66	0.842	0.777	0.847	-0.427	-0.438	-0.407
$\frac{f_P^q}{m_q}$	-1	0.80	0.77	0.66	-0.427	-0.438	-0.407	0.842	0.777	0.847
$\frac{h_P^q}{2m_q}$	0	-1.26	-1.17	1.45	-0.085	-0.053	-0.035	-0.085	-0.053	-0.035
$a_P$ [GeV <sup>3</sup> ]	0	-	-0.017	-	-	-	-	-	-	-
$\tilde{a}_P^{\text{GS}}$ [GeV <sup>3</sup> ]	0	-0.022	-0.021	-0.056	-0.39(12)	$[N_C \rightarrow \infty]$	-0.39(12)	$[N_C \rightarrow \infty]$	-	-
$h_P^q$										

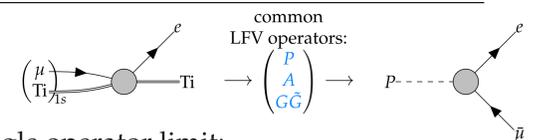
## Projection

Combining Ti limits with future Al limits:



## Results

Calculate  $P \rightarrow \bar{\mu}e$  limits from  $\mu \rightarrow e$  on Ti:



single operator limit:

$P \rightarrow \bar{\mu}e$	derived limit	current limit
$\pi^0$	$\lesssim 4 \times 10^{-17}$	$< 3.6 \times 10^{-10}$
$\eta$	$\lesssim 5 \times 10^{-13}$	$< 6.0 \times 10^{-6}$
$\eta'$	$\lesssim 7 \times 10^{-14}$	$< 4.7 \times 10^{-4}$

all operators:

- flat direction for  $\pi^0$  protected:

$$\text{rigorous limit: } \text{Br}_{\pi^0 \rightarrow \bar{\mu}e} < 1.0 \times 10^{-13}$$

- fine-tuning easily broken by RG corrections

## References

- [1] R. Kitano et al., *Phys. Rev. D* **2002**, 66, 096002.
- [2] A. Airapetian et al., *Phys. Rev. D* **2007**, 75, 012007.
- [3] L. Bartoszek et al., **2014**, DOI 10.2172/1172555.
- [4] R. Escribano et al., *Phys. Rev. D* **2016**, 94, 054033.
- [5] J. Liang et al., *Phys. Rev. D* **2018**, 98, 074505.
- [6] H.-W. Lin et al., *Phys. Rev. D* **2018**, 98, 094512.
- [7] R. Abramishvili et al., *PTEP* **2020**, 2020, 033C01.
- [8] M. Hoferichter et al., *Phys. Rev. D* **2020**, 102, 074018.
- [9] G. S. Bali et al., *JHEP* **2021**, 08, 137.

contact: noel@itp.unibe.ch

## Conclusion: Limits improve by several orders of magnitudes

- $P \rightarrow \mu e$  is mediated by the **same operators** as SD  $\mu \rightarrow e$  conversion allowing for indirect limits
- Use of a **model independent** effective field theory including **all possible operators**
- **Reliable results** going beyond a single-operator limit, stabilised by RG corrections