Probing effective muon interactions using the NA64μ experiment

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Muon Four Fermion Effective Operators.

New Phyisics may manifest in processes at energies below the characteristic scale of the underlying theory. An independent way to analyse these effects is the use of the EFTs. In the case of only SM degrees of freedom below the EW scale (SMEFT), we can write the Lagrangian as,

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + ...,$$

Beyond d=5 (Weinberg operator), the least suppressed New Physics would appear in d=6 operators

$$\mathcal{L}_{d=6} = \sum_i \frac{c_i}{v^2}\mathcal{O}_i$$

However, there could be new degrees of freedom appearing at energies below the EW scale, in that case they should be included in the operator expansion. If these new degrees of freedom are Heavy Neutral Leptons, the usual parametrization is given by the SMEFT.

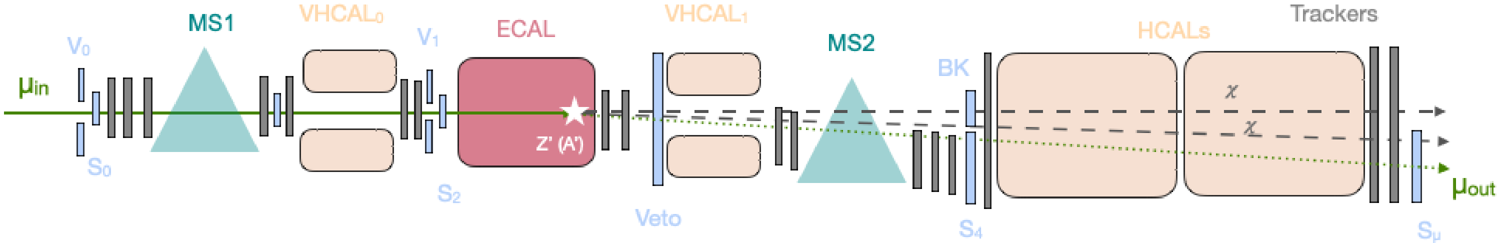
(In our study we will focus in d=6 operators)

NA64μ.

Fixed-target experiment searching for dark photons.

(See Mirald Tuzi's talk)

- Muon beams (160 GeV).
- Lead target.
- Missing energy/momentum signal.
- MOT: 1.98×10^{10} (latest results)
  3.5×10^{11} (current statistics)
  1.0×10^{14} (optimistic future)



SMEFT.

Let us start with the Weak Effective Field Theory,

Jenkins, Manohar, Stoffer: 1709.04486

$$\mathcal{L}_{\rm WEFT} \supset -\sqrt{2}G_F\varepsilon^{\mu,V}_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{\mu}\gamma^\mu\mu) - \sqrt{2}G_F\varepsilon^{\mu,A}_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{\mu}\gamma^\mu\gamma_5\mu)$$

Assuming flavour conservation, the correspondence with the SMEFT parameters is

$$\varepsilon^{\mu,V}_{\alpha\alpha} = \delta_{\mu\alpha}\left(\delta g_L^{W\mu} - \delta g_L^{We} + \frac{1}{2}[c_{\ell\ell}]_{e\mu\mu e}\right) - (1-4s_{\rm w}^2)\delta g_L^{Z\nu_\alpha} + \delta g_L^{Z\mu} + \delta g_R^{Z\mu} - \frac{1}{2}\left(x_{\mu\alpha} + [c_{\ell e}]_{\alpha\alpha\mu\mu}\right),$$

$$\varepsilon^{\mu,A}_{\alpha\beta} = \delta_{\mu\alpha}\left(\delta g_L^{W\mu} - \delta g_L^{We} + \frac{1}{2}[c_{\ell\ell}]_{e\mu\mu e}\right) - \delta g_L^{Z\nu_\alpha} + \delta g_L^{Z\mu} - \delta g_R^{Z\mu} - \frac{1}{2}\left(x_{\mu\alpha} - [c_{\ell e}]_{\alpha\alpha\mu\mu}\right),$$

Falkowski, González-Alonso, Mimouni: 1706.03783

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- — (red) SMEFT vertex corrections to the vertex between the fermions and gauge bosons
- — (green) $x_{\mu\alpha} = [c_{\ell\ell}]_{\alpha\alpha\mu\mu}$ for $\alpha = e, \mu$ and $x_{\mu\tau} = [c_{\ell\ell}]_{\mu\mu\tau\tau}$

SMEFT at NA64.

NA64 is sensitive to the linear combination $\sum_{\alpha} \left(a\,|\varepsilon^{\mu,V}_{\alpha\alpha}|^2 + b\,|\varepsilon^{\mu,A}_{\alpha\alpha}|^2\right)$

However, most of the SMEFT parameters hold strong bounds, with the exception of:

Falkowski, González-Alonso, Mimouni: 1706.03783
Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo: 2301.07036

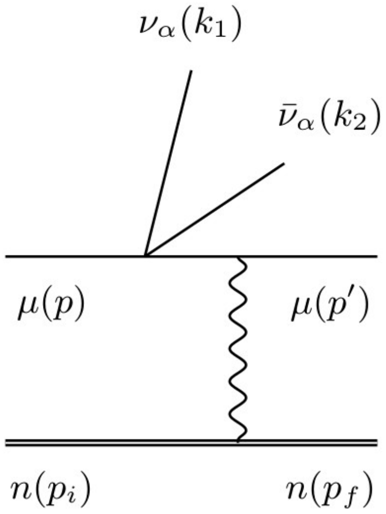
$[c_{\ell\ell}]_{\mu\mu\tau\tau}$ $[c_{\ell e}]_{\tau\tau\mu\mu}$

Unbounded

$[c_{\ell\ell}]_{\mu\mu\mu\mu}$ $[c_{\ell e}]_{\mu\mu\mu\mu}$

Flat direction

$$[\hat{c}_{\ell\ell}]_{\mu\mu\mu\mu} = [c_{\ell\ell}]_{\mu\mu\mu\mu} + \frac{2g_Y^2}{g_L^2 + 3g_Y^2}[c_{\ell e}]_{\mu\mu\mu\mu}$$



$[c_{\ell\ell}]_{\mu\mu\alpha\alpha}$, $[c_{\ell e}]_{\alpha\alpha\mu\mu}$

$$\varepsilon^{\mu,V}_{\alpha\alpha} = -\frac{1}{2}\Big([c_{\ell\ell}]_{\mu\mu\alpha\alpha} + [c_{\ell e}]_{\alpha\alpha\mu\mu}\Big)$$
$$\varepsilon^{\mu,A}_{\alpha\alpha} = -\frac{1}{2}\Big([c_{\ell\ell}]_{\mu\mu\alpha\alpha} - [c_{\ell e}]_{\alpha\alpha\mu\mu}\Big),$$
$$\varepsilon^{\mu,V}_{ee} = \varepsilon^{\mu,A}_{ee} = 0,$$

→

$$\mathcal{O}_{\ell\ell} = \frac{[c_{\ell\ell}]_{\mu\mu\tau\tau}}{v^2}(\overline{L}_\mu\gamma^\mu L_\mu)(\overline{L}_\tau\gamma_\mu L_\tau),$$
$$\mathcal{O}_{\ell e} = \frac{[c_{\ell e}]_{\tau\tau\mu\mu}}{v^2}(\overline{L}_\tau\gamma^\mu L_\tau)(\bar{l}_\mu\gamma_\mu l_\mu),$$

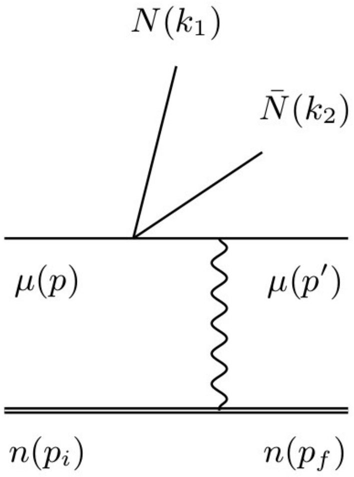
νSMEFT at NA64.

In this case NA64 is sensitive to the NC operators

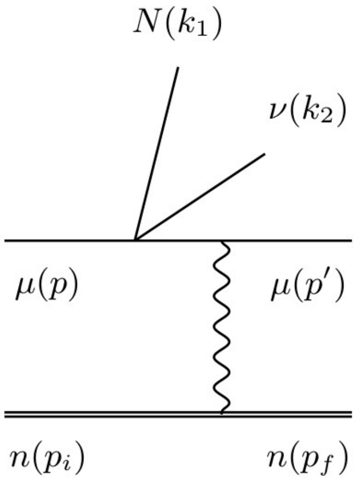
$$\mathcal{O}_{\mu\mu} = \frac{C_{\mu\mu}}{\Lambda^2}(\bar{\ell}_\mu \gamma^\mu \ell_\mu)(\bar{N}\gamma_\mu N),$$
$$\mathcal{O}^{\mu}_{LN} = \frac{C^{\mu}_{LN}}{\Lambda^2}(\bar{L}_\mu \gamma^\mu L_\mu)(\bar{N}\gamma_\mu N),$$

and the CC operator

$$\mathcal{O}^{\mu\mu}_{LNL\mu} = \frac{C^{\mu\mu}_{LNL\mu}}{\Lambda^2}(\bar{L}_\mu N)\epsilon(\bar{L}_\mu \ell_\mu),$$



$\mathcal{O}_{\mu\mu}$, $\mathcal{O}^{\mu}_{LN}$



$\mathcal{O}^{\mu\mu}_{LNL\ell}$

These operators are currently unbounded!!!

SMEFT & νSMEFT at NA64.

$$\mu(p) + \mathcal{N}(p_i) \to \mu(p') + \mathcal{N}(p_f) + \chi_1(k_1) + \chi_2(k_2)$$

The cross section of the process is written as

$$\frac{d\sigma(\mu\mathcal{N} \to \mu\mathcal{N}\chi_1\chi_2)}{dk^2} = \sum_{i,j}\left\{\frac{1}{2\pi}\int d\Phi_2(k_1,k_2)\sum_{s_1,s_2}\mathcal{J}_i^{\alpha}(\mathcal{J}_j^{\beta})^{\dagger}\right\} \times \left\{\int d\Phi_3(p_f,p',k)\frac{\overline{\mathcal{M}_{i\alpha}\mathcal{M}_{j\beta}^{\dagger}}}{4|\vec{p}|M}\right\}$$

after some manipulation,

$$d\sigma(\mu\mathcal{N} \to \mu\mathcal{N}\chi_1\chi_2) = \underline{d\sigma_{\alpha\beta}^{2\to3}}\,\frac{c^2}{\Lambda^4}\,\frac{dk^2}{(2\pi)}\,\underline{\xi^{\alpha\beta}}$$

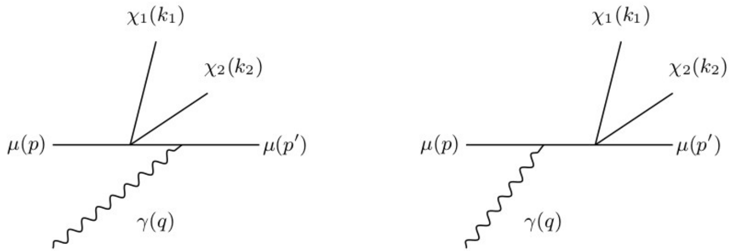
2→3 process

1→2 process

$$\xi^{\alpha\beta} = \int d\Phi_2(k_1,k_2)\sum_{\text{spins}}\mathcal{J}^{\alpha}(\mathcal{J}^{\beta})^{\dagger}$$

SMEFT & νSMEFT at NA64.

$$\mu(p) + \mathcal{N}(p_i) \to \mu(p') + \mathcal{N}(p_f) + \chi_1(k_1) + \chi_2(k_2)$$



Using the Weiszäcker-William approximation,

$$\left.\frac{d\sigma^{2\to3}_{\alpha\beta}}{dx}\right|_{\rm WW} = \frac{\alpha}{16\pi^2}\frac{1-x}{x}\sqrt{x^2 - \frac{k^2}{E_\mu^2}}\int_{\tilde{u}_{\rm min}}^{\tilde{u}_{\rm max}} \frac{d\tilde{u}}{\tilde{u}^2}\overline{|\mathcal{M}_\alpha\mathcal{M}_\beta^\dagger|}_{2\to3}\chi^{\rm WW}$$

Photon flux

Squared amplitude

and the total number of events,

$$N_S = N_{\rm MOT}\frac{\rho_\mathcal{N}}{m_\mathcal{N}}L_{\rm T}^{\rm eff}\int_{(m_{\chi_1}+m_{\chi_2})/E_\mu}^{1-\frac{m_\mu}{E_\mu}} dx \int_{(m_{\chi_1}+m_{\chi_2})^2}^{x^2E_\mu^2} dk^2\kappa(k)\frac{d\sigma}{dxdk^2}$$

SMEFT & νSMEFT at NA64.

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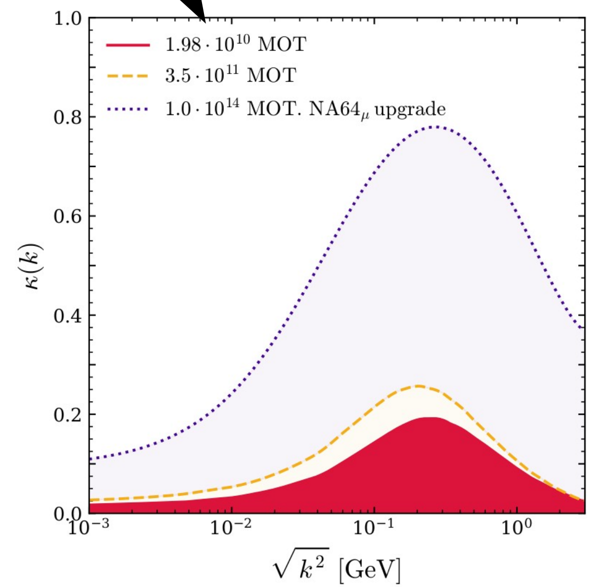


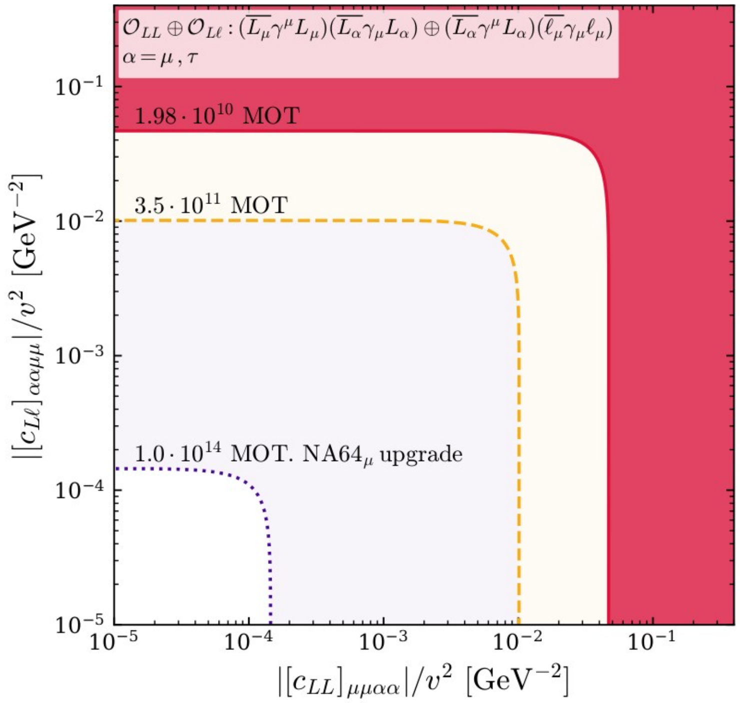
In order to set constraints we compute the 90% CL requiring that

$$N_S \leq 2.44$$

Feldman, Cousins: physics/9711021

since we have a Poisson distribution with zero background.

SMEFT bounds at NA64.



$$\left|\frac{[c_{LL}]_{\mu\mu\alpha\alpha}}{v^2}\right|^2 + \left|\frac{[c_{L\ell}]_{\alpha\alpha\mu\mu}}{v^2}\right|^2 - 0.1\left|\frac{[c_{LL}]_{\mu\mu\alpha\alpha}[c_{L\ell}]_{\alpha\alpha\mu\mu}}{v^4}\right| \lesssim 2.1 \cdot 10^{-8} \text{ GeV}^{-4}$$

$$\alpha = \mu \qquad [\hat{c}_{LL}]_{\mu\mu\mu\mu} \leq 0.21 \; (68\% \text{ CL})$$

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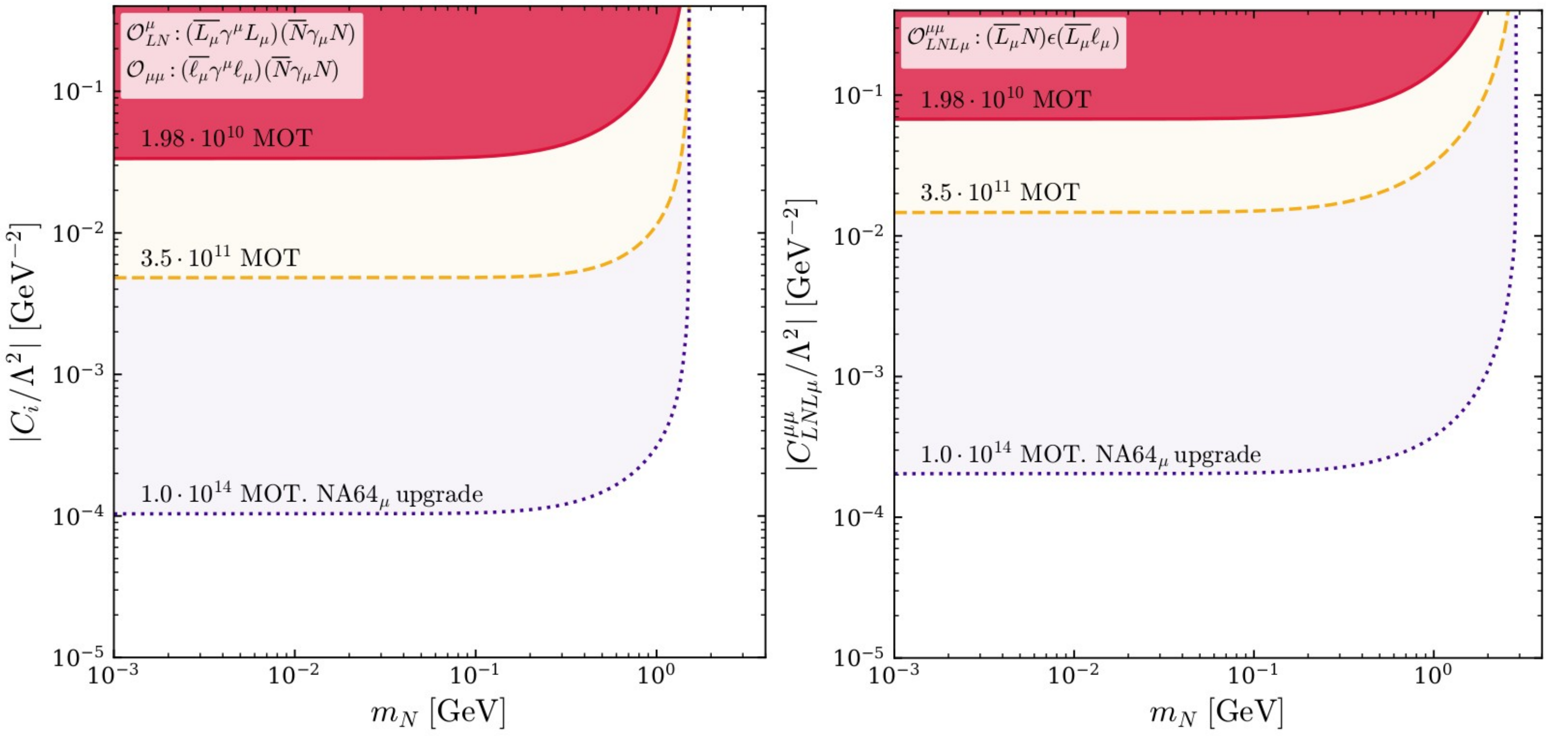
$$\left|\frac{[c_{LL}]_{\mu\mu\mu\mu}}{v^2}\right| \lesssim 5.0 \cdot 10^{-5} \text{ GeV}^{-2} \quad \text{and} \quad \left|\frac{[c_{L\ell}]_{\mu\mu\mu\mu}}{v^2}\right| \lesssim 1.4 \cdot 10^{-4} \text{ GeV}^{-2}$$

νSMEFT bounds at NA64.



SMEFT & νSMEFT bounds at NA64.

Units in [GeV^{-2}]

Type	Operator		Current NA64μ sensitivity	Future NA64μ sensitivity
NC-SMEFT	$[\mathcal{O}_{LL}]_{\mu\mu\alpha\alpha}$	$(\overline{L}_\mu \gamma^\mu L_\mu)(\overline{L}_\alpha \gamma_\mu L_\alpha)$	$1.0 \cdot 10^{-2}$	$1.4 \cdot 10^{-4}$
	$[\mathcal{O}_{L\ell}]_{\alpha\alpha\mu\mu}$	$(\overline{L}_\alpha \gamma^\mu L_\alpha)(\overline{\ell}_\mu \gamma_\mu \ell_\mu)$	$1.0 \cdot 10^{-2}$	$1.4 \cdot 10^{-4}$
NC-νSMEFT	$\mathcal{O}_{\mu\mu}$	$(\overline{\ell}_\mu \gamma^\mu \ell_\mu)(\overline{N} \gamma_\mu N)$	$4.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-4}$
	$\mathcal{O}_{LN}^{\mu}$	$(\overline{L}_\mu \gamma^\mu L_\mu)(\overline{N} \gamma_\mu N)$	$4.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-4}$
CC-νSMEFT	$\mathcal{O}_{LNL\ell}^{\mu\mu}$	$(\overline{L}_\mu N)\epsilon(\overline{L}_\mu \ell_\mu)$	$1.5 \cdot 10^{-2}$	$2.0 \cdot 10^{-4}$

Conclusions.

SMEFT and νSMEFT

- We have shown that NA64μ is a powerful experiment to explore New Physics
- Current and future data can probe several four lepton effective operators in the SMEFT and νSMEFT completely unbounded so far and break one of the current flat directions

Current data	Future	New Physics Scale
$\left\|[c_{LL}]_{\mu\mu\alpha\alpha}\right\| / v^2 \leq 1.0 \cdot 10^{-2}\ \mathrm{GeV}^{-2}$	$\left\|[c_{LL}]_{\mu\mu\alpha\alpha}\right\| / v^2 \leq 1.4 \cdot 10^{-4}\ \mathrm{GeV}^{-2}$	$\Lambda \gtrsim 83\ \mathrm{GeV}$
$\left\|C^{\mu}_{LN}\right\| / \Lambda^2 \leq 4.8 \cdot 10^{-3}\ \mathrm{GeV}^{-2}$	$\left\|C^{\mu}_{LN}\right\| / \Lambda^2 \leq 1.0 \cdot 10^{-4}\ \mathrm{GeV}^{-2}$	$\Lambda \gtrsim 100\ \mathrm{GeV}$

- There is room for improvement with a better understanding of the efficiency of the experiment.