Light Dark World 2025

Exploring the Light Dark World with NA64

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ASTROPARTICLES Astroparticles and High Energy Physics Group

Introduction.

Who are the inhabitants of the Light Dark World?

There is a plethora of candidates that can lie in what we call the Light Dark World:

- Neutrinos, heavy neutral leptons
- Axions, axion like particles (ALPs), ultralight scalars
- Light dark matter, inelastic dark matter
- Millicharged particles

There could be also new interactions making the Light Dark World more complex:

- U(1) gauge interactions, Z', dark photon
- New scalar interactions
- Violation of leptonic number
- EFT approach

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How can we detect the inhabitants of the Light Dark World?

There is a plethora of different experiments that can dig the surface of the Light Dark World:

- Colliders: LHC, forward experiments, Belle II
- Direct detection: LUX, CDMS, Xenon, PandaX
- Neutrino experiments: COHERENT, DUNE
- Fixed-target experiments: NA62, NA64

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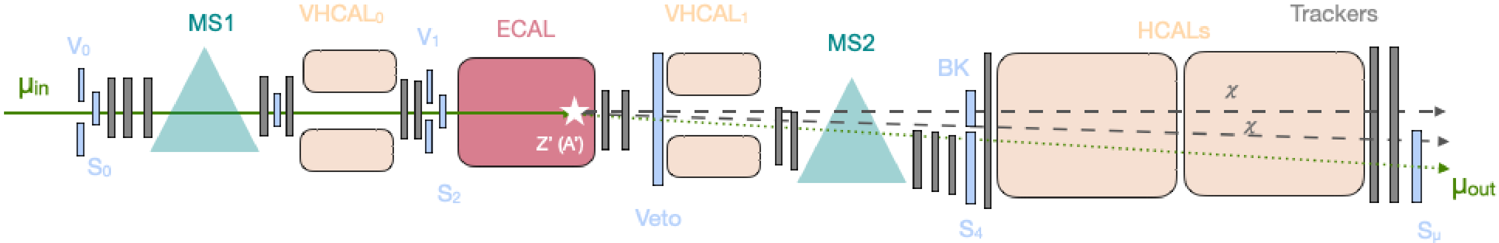
NA64μ.

Fixed-target experiment searching for the Light Dark World.

(See Paolo's talk)

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



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)

SMEFT.

Let us start with the Weak Effective Field Theory,

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

Assuming flavour conservation, the correspondence with the SMEFT parameters is

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

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

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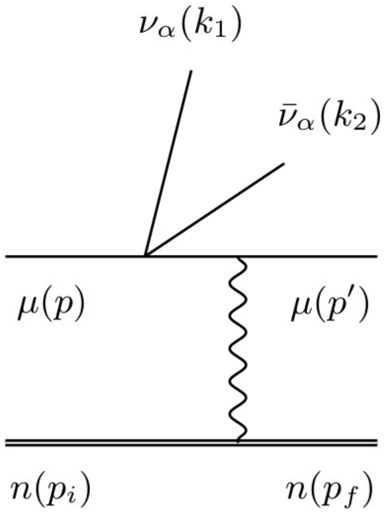
— SMEFT vertex corrections to the vertex between the fermions and gauge bosons

— $x_{\mu\alpha} = [c_{\ell\ell}]_{\alpha\alpha\mu\mu}$ 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 $\sum_{\alpha} \left(a\,|\varepsilon^{\mu,V}_{\alpha\alpha}|^2 + b\,|\varepsilon^{\mu,A}_{\alpha\alpha}|^2\right)$



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

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

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

Unbounded

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

Flat direction

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

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

→

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

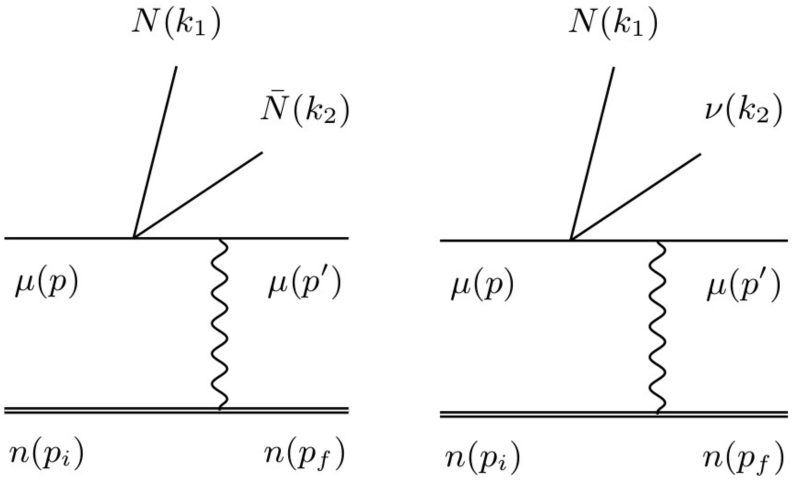
νSMEFT at NA64.

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

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



$\mathcal{O}_{\mu\mu}$, $\mathcal{O}^{\mu}_{LN}$ $\quad$ $\mathcal{O}^{\mu\mu}_{LNL\ell}$

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,

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

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,

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

Photon flux

Squared amplitude

and the total number of events,

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

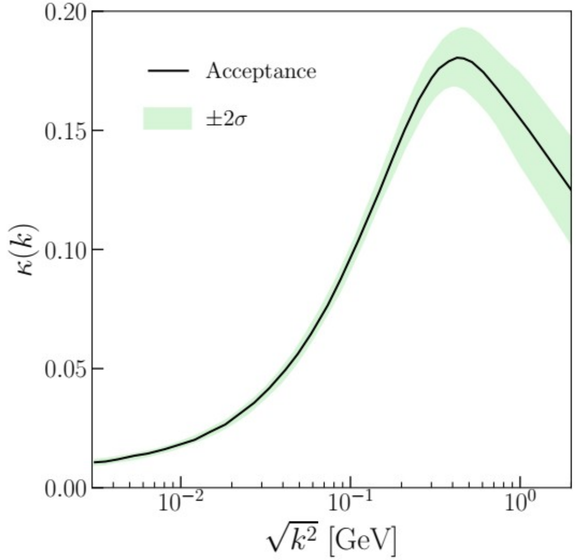
SMEFT & νSMEFT at NA64.

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

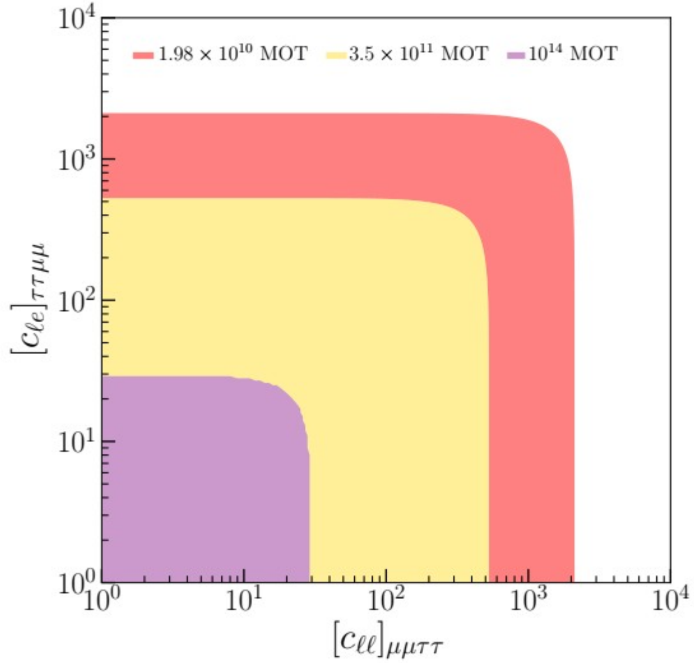
In order to set constraints we compute the 90% CL requiring that

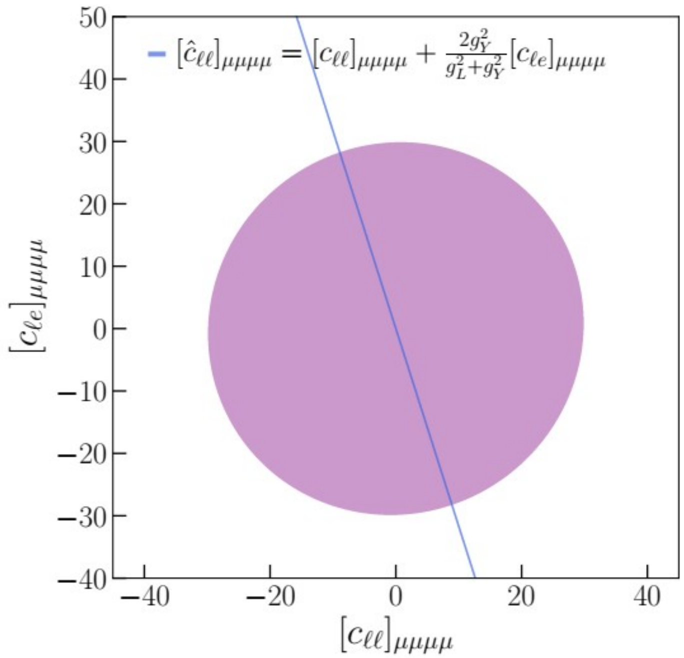
$$N_S \leq 2.303$$

since we have a Poisson distribution with zero background.

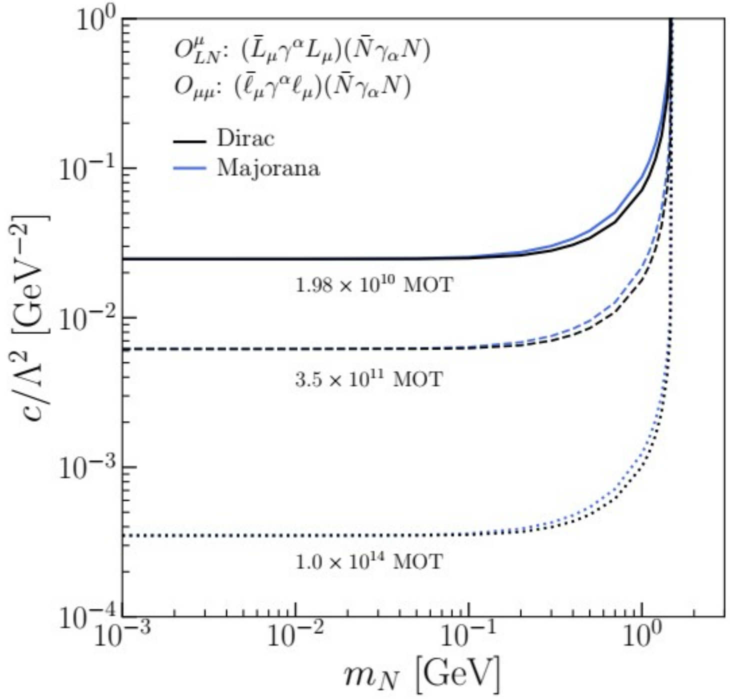


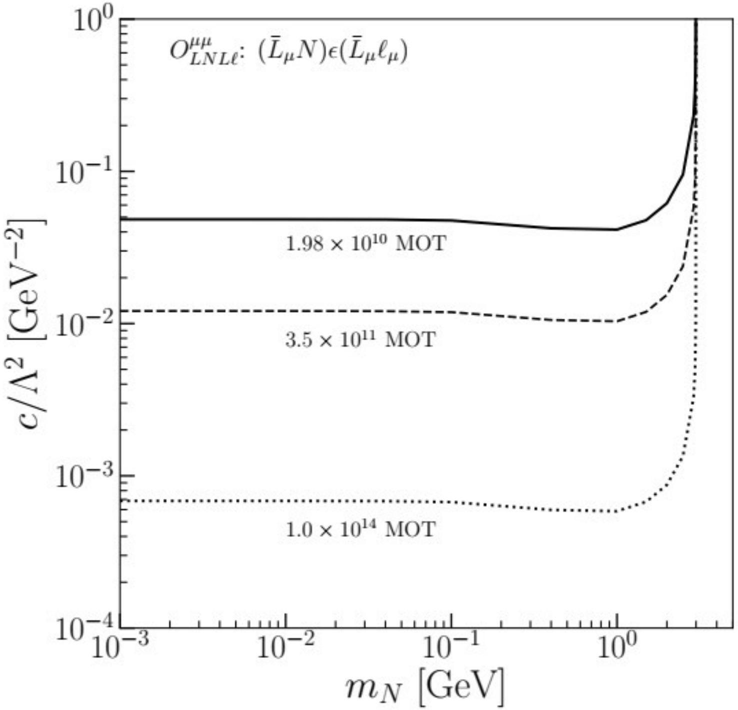
SMEFT bounds at NA64.





νSMEFT bounds at NA64.





SMEFT & νSMEFT bounds at NA64.

Units in [GeV^{-2}]

Type	Operator		Current NA64μ bound	Ultimate NA64μ Sensitivity
NC-SMEFT	$[c_{\ell\ell}]_{\mu\mu\tau\tau}$	$(\overline{L}_\mu\gamma^\mu L_\mu)(\overline{L}_\tau\gamma_\mu L_\tau)$	$[-3.49, 3.49] \times 10^{-2}$	$[-4.94, 4.94] \times 10^{-4}$
	$[c_{\ell e}]_{\tau\tau\mu\mu}$	$(\overline{L}_\tau\gamma^\mu L_\tau)(\bar{l}_\mu\gamma_\mu l_\mu)$	$[-3.49, 3.49] \times 10^{-2}$	$[-4.94, 4.94] \times 10^{-4}$
NC-νSMEFT	$\mathcal{O}_{\mu\mu}$	$(\bar{l}_\mu\gamma^\mu l_\mu)(\overline{N}\gamma_\mu N)$	2.47×10^{-2}	3.49×10^{-4}
	$\mathcal{O}^\mu_{LN}$	$(\overline{L}_\mu\gamma^\mu L_\mu)(\overline{N}\gamma_\mu N)$	2.47×10^{-2}	3.49×10^{-4}
CC-νSMEFT	$\mathcal{O}^{\mu\mu}_{LNL\ell}$	$(\overline{L}_\mu N)\epsilon(\overline{L}_\mu \ell_\mu)$	4.84×10^{-2}	6.84×10^{-4}

We have shown that NA64μ can probe several four lepton effective operators in the SMEFT and νSMEFT completely unbounded so far and break one of the current flat directions.

Inelastic Dark Matter.

Inelastic Dark Matter (IDM) mediated by a kinematically-mixed dark photon:

$$\mathcal{L} \supset \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu (g_D J^\mu_{\rm DS} - e\epsilon J^\mu_{\rm EM}) \quad (\text{DS} \equiv \text{Dark Sector})$$

while the inelastic Dark Matter sector is given by,

$$\begin{aligned} \mathcal{L} \supset\ & \bar{\psi}_L i(\not\partial - i g_D \not A')\psi_L + \bar{\psi}_R i(\not\partial - i g_D \not A')\psi_R \\ & - m_D \bar{\psi}\psi - \left(\frac{\mu_L}{2}\bar{\psi}^c_L \psi_L + \frac{\mu_R}{2}\bar{\psi}^c_R \psi_R + h.c.\right) \end{aligned}$$

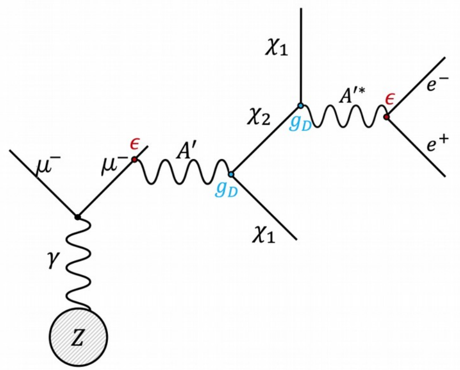
The IDM regime is achieved in the limit where the rotation angle between the gauge and mass basis is maximal,

$$\tan 2\theta = \frac{m_D}{\Delta\mu} \to \infty, \qquad (\Delta\mu = \mu_L - \mu_R \simeq 0) \qquad J^\mu_{\rm DS} = i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathcal{O}(\Delta\mu/m_D)$$

$$m_{A'}, \quad \epsilon, \quad m_{\chi_1}, \quad \alpha_D = g_D^2/4\pi, \quad \Delta = m_{\chi_2} - m_{\chi_1}$$

$$(\Delta = 0.4 m_{\chi_1} \quad \text{to} \quad 0.01 m_{\chi_1})$$

IDM production at NA64.



The IDM production cross section is given by,

$$d\sigma(\mu N \to \mu N \chi\bar{\chi}) = d\sigma(\mu N \to \mu N A') \times \mathrm{BR}(A' \to \chi\bar{\chi})$$

$$\mathrm{BR}(A' \to \chi\bar{\chi}) \simeq 1$$

The 2→3 process can be computed using the Weiszäcker-Williams (WW) approximation,

$$\left(\frac{d\sigma}{dx}\right)_{WW} = \epsilon^2\alpha^3\sqrt{x^2 - \frac{m_{A'}^2}{E_\mu^2}}\,\frac{1-x}{x}\sum_{i=1}^{6}\Delta I_i^V(x,\tilde{u})$$

And the total number of A' produced in NA64 is,

$$N_{A'} = \mathcal{N}_{\mathrm{MOT}} n_{\mathrm{Pb}} L_{\mathrm{T}} \int d\sigma(\mu N \to \mu N A')$$

IDM detection at NA64.

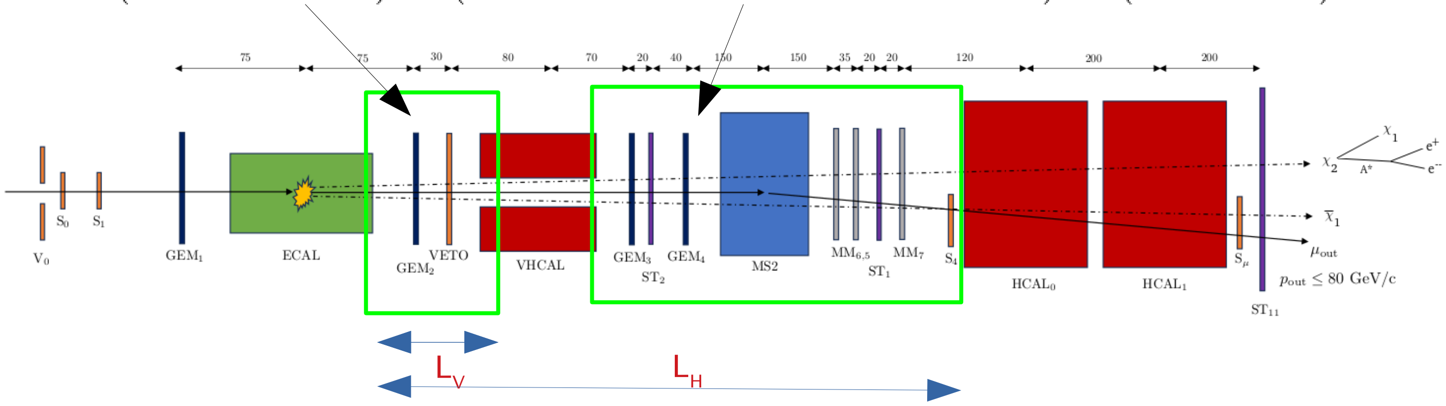
The decay width of χ_2 is given by, $\Gamma(\chi_2 \to \chi_1 e^+ e^-) = \mathcal{K}\frac{4\epsilon^2 \alpha \alpha_D}{15\pi m_{A'}^2}\Delta^5$

with $\mathcal{K} = 0.640$ a correction factor for the masses.

The probability of an invisible signal reads,

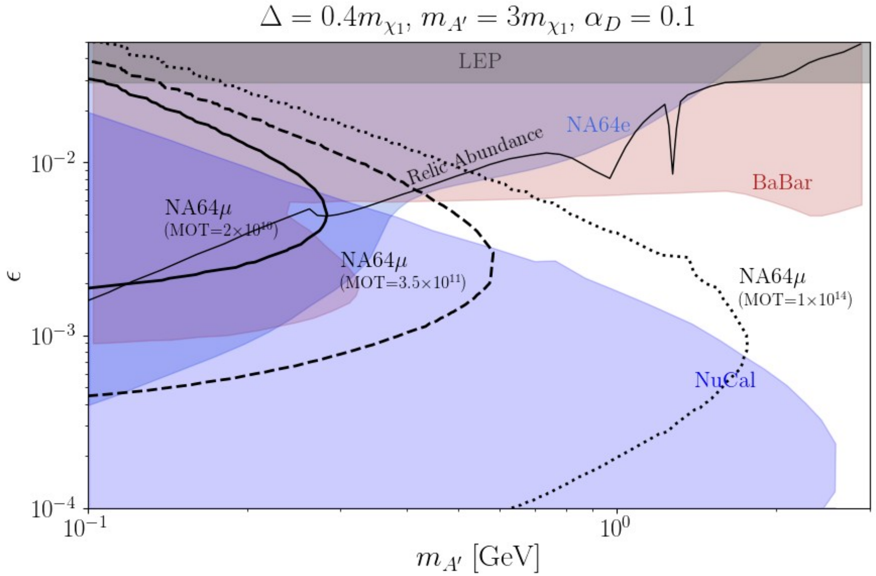
$$P_{\text{inv}} = e^{(-L_{\text{exp}}/\ell_{\text{lab}})}$$

$$P_{\text{inv}} = (1 - e^{-L_V/\ell_{\chi 2}}) + (e^{-(L_V + L_{VHCAL})/\ell_{\chi 2}} - e^{-L_H/\ell_{\chi 2}}) + (e^{-L_{\text{exp}}/\ell_{\chi 2}})$$

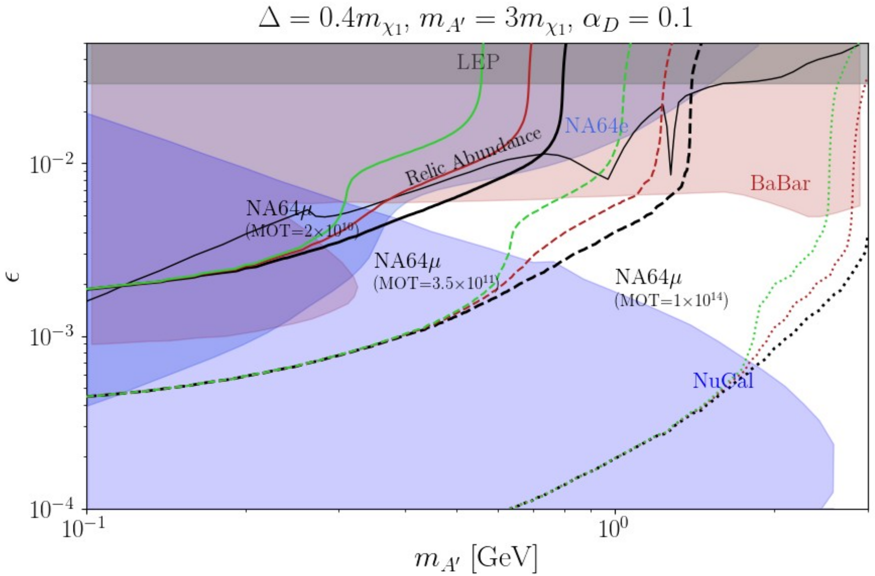


Results.

Outside



Inner decays allowed



Number of events tagged as invisible inside the detector: 100% 50% 20%

Conclusions.

SMEFT and νSMEFT

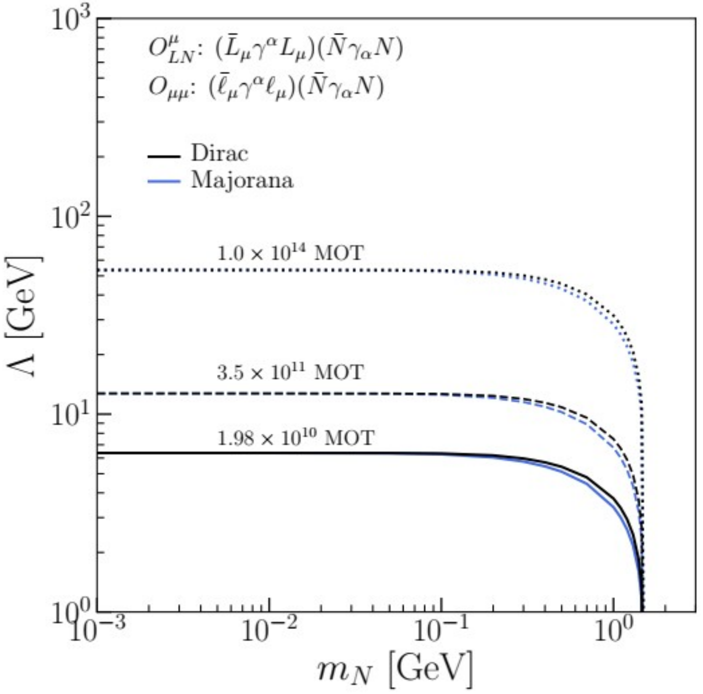
- We have shown that NA64μ can probe several four lepton effective operators in the SMEFT and νSMEFT completely unbounded so far and break one of the current flat directions
- There is room for improvement with a better understanding of the efficiency of the experiment.

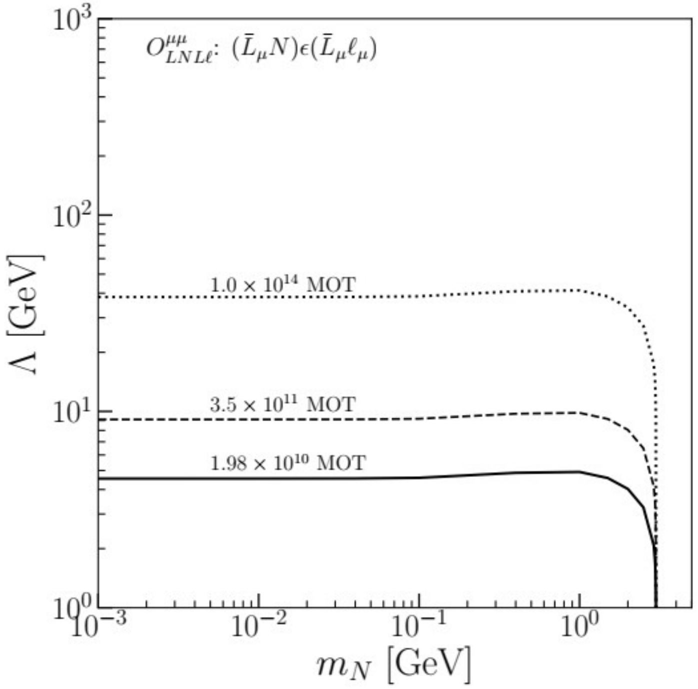
$\Lambda\sim$ 50-60 GeV for operators of the type: $(\bar{\ell}_\mu \gamma^\mu \ell_\mu)(\bar{N}\gamma_\mu N)$ $(\bar{L}_\mu \gamma^\mu L_\mu)(\bar{N}\gamma_\mu N)$ $(\bar{L}_\mu N)\epsilon(\bar{L}_\mu \ell_\mu)$

Inelastic Dark Matter

- We have derived bounds for the inelastic dark matter mediated via dark photon.
- These bounds can cover an area that lies between other experiments (BaBar,NuCal).
- A better understanding of the efficiency and the decays inside the detector could improve the bounds.

Back-up slides.


O^{μ}_{LN}: $(\bar{L}_\mu \gamma^\alpha L_\mu)(\bar{N}\gamma_\alpha N)$
$O_{\mu\mu}$: $(\bar{\ell}_\mu \gamma^\alpha \ell_\mu)(\bar{N}\gamma_\alpha N)$
Dirac
Majorana
1.0×10^{14} MOT
3.5×10^{11} MOT
1.98×10^{10} MOT
Λ [GeV]
m_N [GeV]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