Some novel searches for neutrino dipole moments

Michele Frigerio

Laboratoire Charles Coulomb, CNRS & Université de Montpellier

* *Muon collider probes of Majorana neutrino dipole moments and masses*

with **Natascia Vignaroli** , arXiv:2409.02721

* *Testing the dipole moment of GeV-scale sterile neutrinos*

with **Enrico Bertuzzo** , arXiv:241x.xxxxx

Baryon & Lepton Number Violation 2024

KIT Karlsruhe – 8 / 11 October

Searching for new physics ...

Neutrinos: masses vs dipoles

Two Weyl spinors : $\nu = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$ Flavour symmetry $SU(2)_F \;:\; \nu \sim 2_F$

$$\mathcal{L} \supset \nu_\alpha^\dagger \, i\bar{\sigma}^\mu \partial_\mu \, \delta_{\alpha\beta} \, \nu_\beta$$

Kinetic operator: marginal (dim = 4), Δ L = 0, preserves $SU(2)_F$

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$$\mathcal{L} \supset \frac{1}{2} \nu_\alpha \, m_{\alpha\beta} \, \nu_\beta + h.c. \qquad m_{\alpha\beta} = m_{\beta\alpha}$$

$$m \equiv m_A (\epsilon \sigma_A)$$

Mass operator: relevant (dim = 3), Δ L = 2, breaks $SU(2)_F$

m_A real preserves $U(1)_F$: one Dirac fermion

m_A complex breaks $U(1)_F$: two Majorana fermions

$$m_A \sim 3_F$$

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$$\mathcal{L} \supset \frac{1}{2} \nu_\alpha \, \sigma^{\mu\nu} \, \lambda_{\alpha\beta} \, \nu_\beta \, F_{\mu\nu} + h.c. \qquad \lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$$

$$\lambda \sim 1_F$$

Dipole operator: irrelevant (dim = 5), Δ L = 2, preserves $SU(2)_F$

⇒ small mass and large dipole is technically natural !

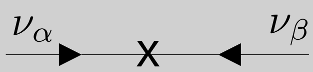
ν dipole from SM EFT operators

Δ L = 2 operators in the SM effective field theory :

dimension-5 $\mathcal{L}_5 = C^5 \mathcal{O}_5$

$$m_{\alpha\beta} = C^5_{\alpha\beta} v^2$$

$$(\mathcal{O}_5)_{\alpha\beta} = (\overline{\ell^c_{L\alpha}} \epsilon H)(H^T \epsilon l_{L\beta})$$



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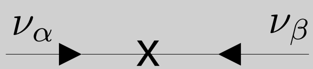
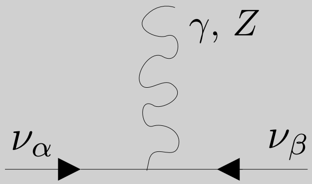


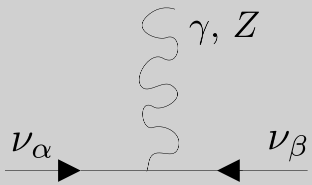
dimension-7 $\mathcal{L}_7 = \sum_i C_i \mathcal{O}_i$ $\lambda_{\alpha\beta} = -2ev^2 \left(C^B_{\alpha\beta} + 2C^W_{\alpha\beta}\right)$

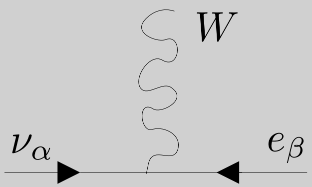
Davidson Gorbahn Santamaria 2005

$$(O_B)_{\alpha\beta} = g' \left(\overline{\ell^c_{L\alpha}} \epsilon H\right) \sigma^{\mu\nu} \left(H^T \epsilon \ell_{L\beta}\right) B_{\mu\nu}$$



$$(O_W)_{\alpha\beta} = ig\varepsilon_{abc} \left(\overline{\ell^c_{L\alpha}} \epsilon \sigma^a \sigma^{\mu\nu} \ell_{L\beta}\right) \left(H^T \epsilon \sigma^b H\right) W^c_{\mu\nu}$$





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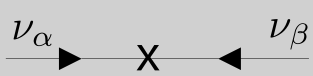

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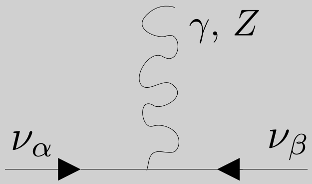

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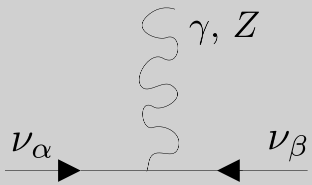
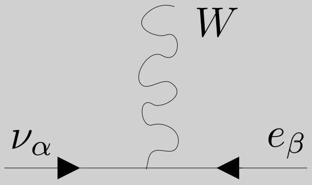
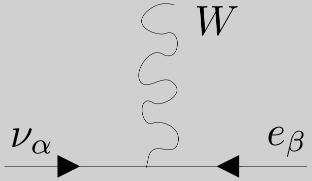




$$(O_M)_{\alpha\beta} = g \left(\overline{\ell^c_{L\alpha}} \epsilon \sigma^{\mu\nu} \ell_{L\beta}\right) \left(H^T \epsilon \sigma^a H\right) W^a_{\mu\nu}$$



+ several other operators

Some current bounds on ν dipole

$$\mu_B \equiv \frac{e}{2m_e}$$

* Solar neutrino elastic scattering on nuclei (photon exchange)

$$\lambda_\nu \simeq \Big(\sum_k |U_{ek}|^2 \sum_j |\lambda_{jk}|^2\Big)^{1/2} < 0.6 \cdot 10^{-11} \mu_B \ (90\% \, C.L.)$$

Giunti Studenikin 1403.6344 **XENON 2207.11330, LZ 2207.03764**

* Stellar energy loss (red giant branch of globular clusters)

$$\lambda_\nu \lesssim 0.1 \cdot 10^{-11} \mu_B \ (95\% \, C.L.)$$

Capozzi Raffelt 2007.03694

- indirect (neutrinos not observed)
- effective combination of flavours
- insensitive to lepton number
- large systematic uncertainties ?

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* Neutrino-to-antineutrino conversion in solar magnetic field

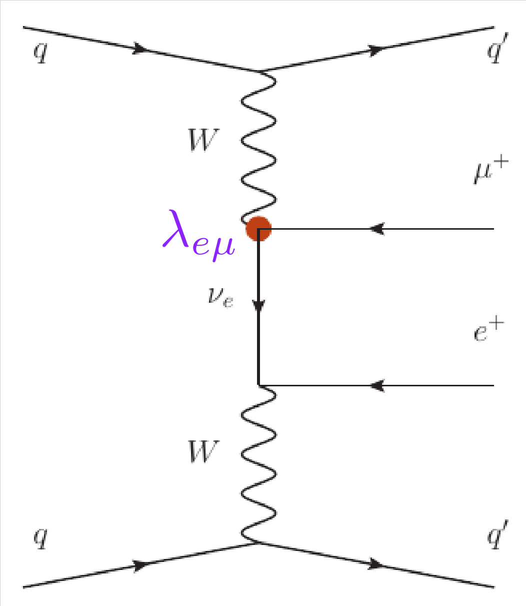
$$\lambda_\nu \lesssim 500 \cdot 10^{-11} \mu_B \left[\frac{kG}{B}\right] \ \ (90\%\, C.L.)$$

KamLAND 2108.08527
Akhmedov Martínez-Miravé 2207.04516

- sensitive to lepton number violation
- large uncertainty on value of solar magnetic field

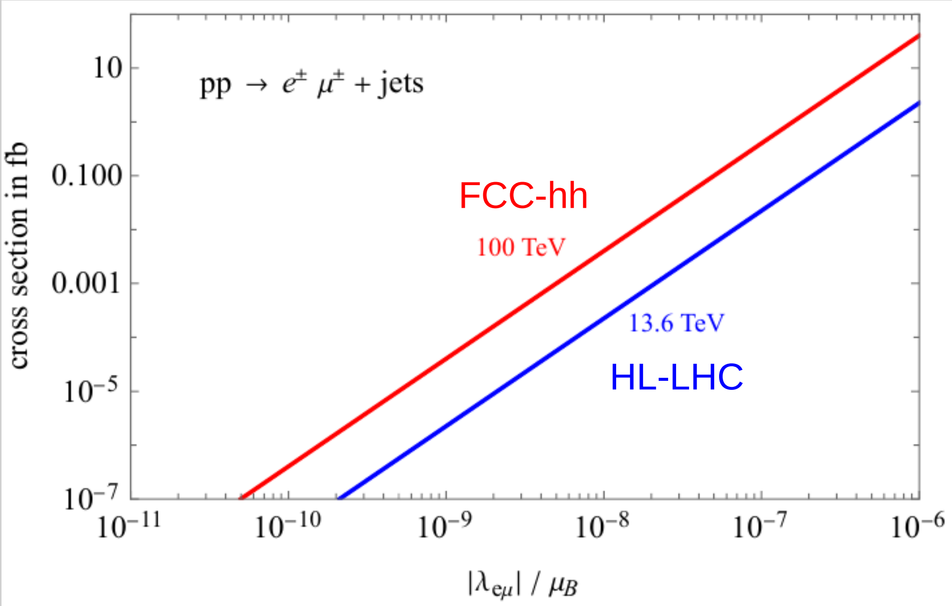
with N.Vignaroli

ν dipole @ future hadron colliders



2 leptons
same-sign
different-flavour
+
2 jets

after
acceptance
cuts



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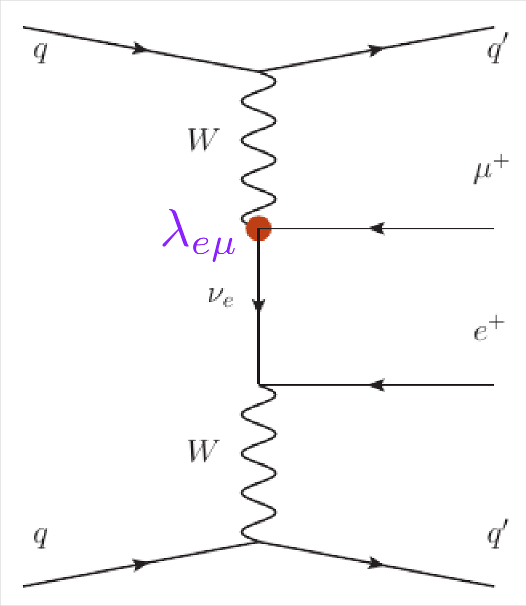

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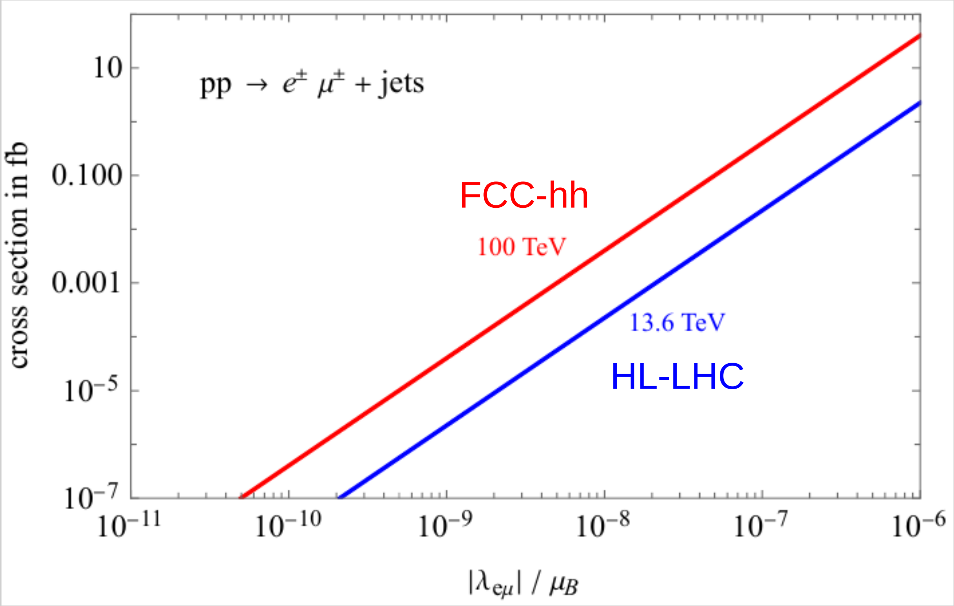


Recasting an LHC analysis for the same final state.

After selection cuts: **signal** efficiency ~ 0.5 and

background (mostly from V V j j) ~ 10 fb [reducible]

ATLAS 2403.15016

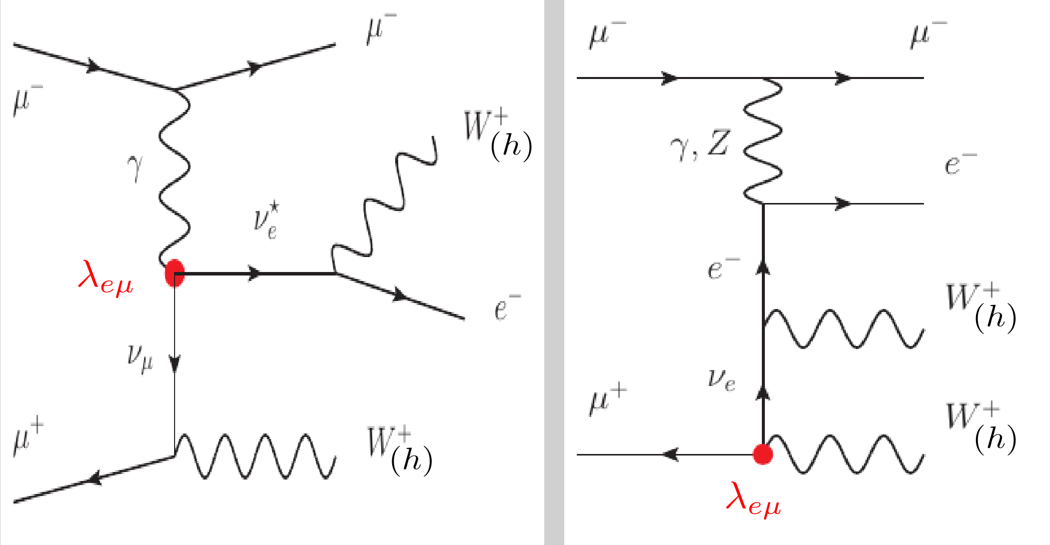
$$\mathrm{HL-LHC}\ \ \{3\ \mathrm{ab}^{-1}\} \qquad |\lambda_{e\mu}|/\mu_B < 2.2\cdot 10^{-7}\ [3.8\cdot 10^{-8}] \quad @\ 2\sigma$$

$$\mathrm{FCC-hh}\ \ \{30\ \mathrm{ab}^{-1}\} \qquad |\lambda_{e\mu}|/\mu_B < 3.8\cdot 10^{-8}\ [2.0\cdot 10^{-9}] \quad @\ 2\sigma$$

Sensitivity about **2-3 orders of magnitude weaker than current bounds**

with N.Vignaroli

ν dipole @ future muon collider (I)



Illustrative for ~ 100 diagrams

2 leptons (**same-sign different-flavour)**
+ 2 fat jets (**W into hadrons**)

Clean, unambiguous signal of
lepton number and flavour violation

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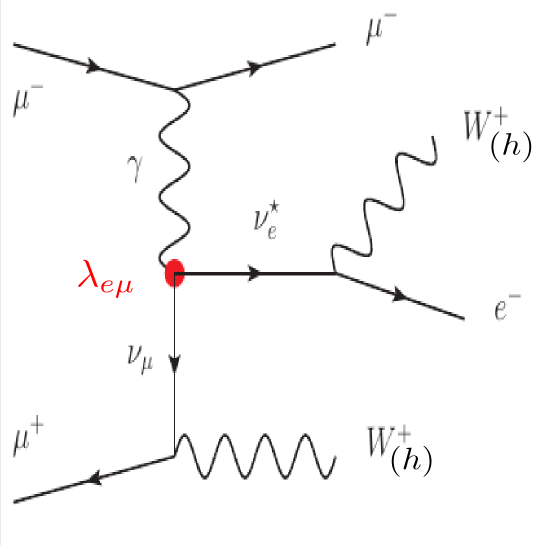

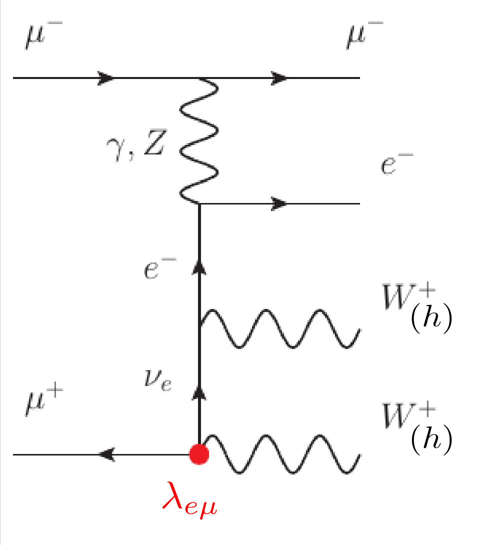

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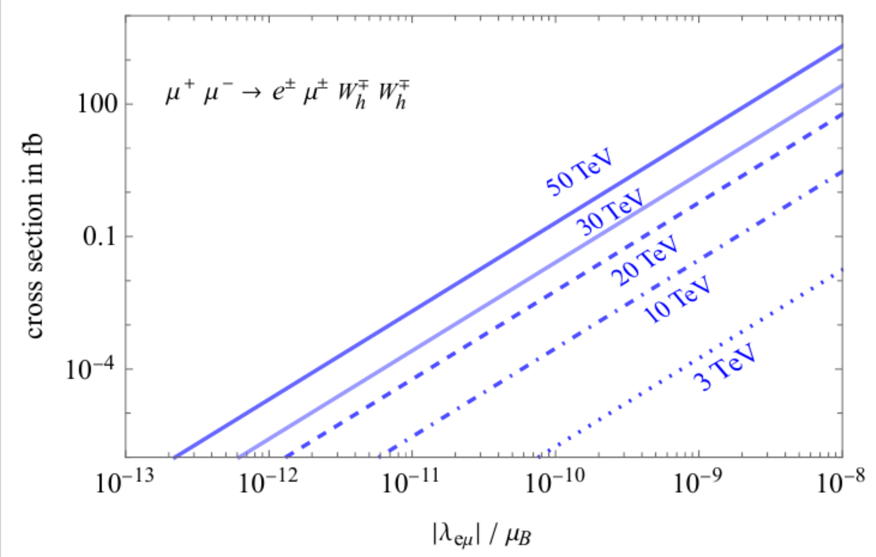

Including acceptance cuts
& reconstruction efficiency

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Achievable integrated luminosity
for 5-years data taking :

$$\mathcal{L} = 10 \left(\frac{\sqrt{s}}{10\,\text{TeV}} \right)^2 \text{ab}^{-1}$$

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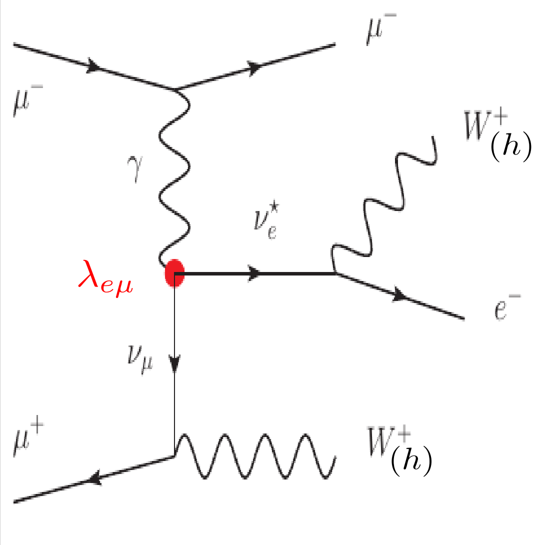

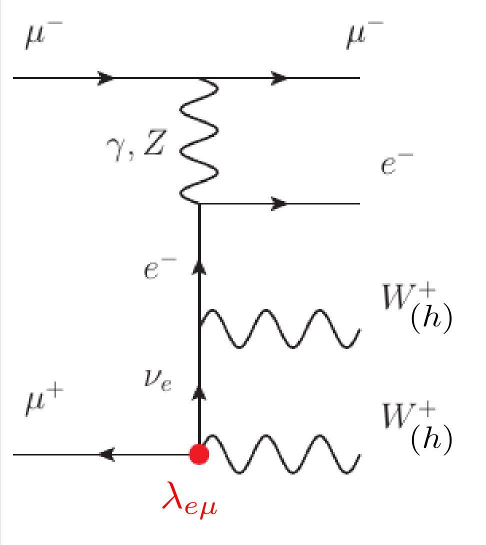

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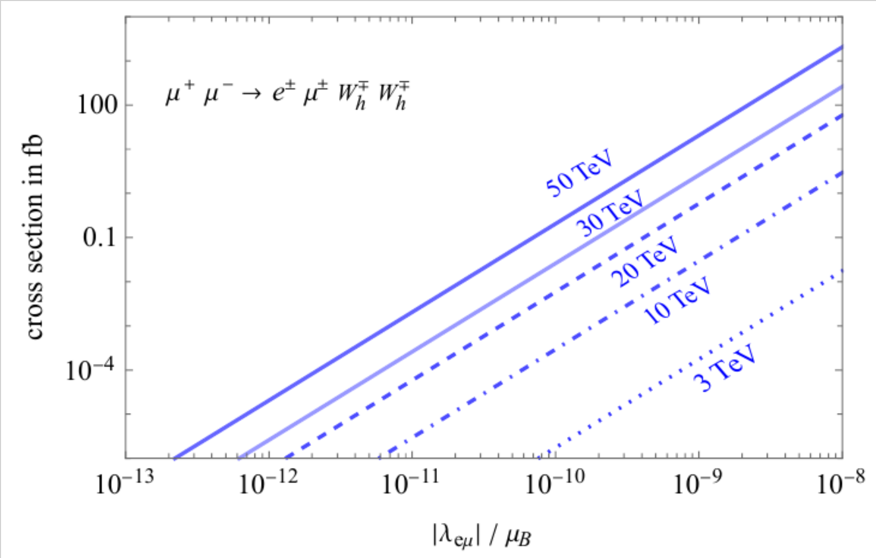

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Signal **simulation & reconstruction** (Madgraph, Pythia8, FastJet, ...)

Same for background (mostly from **W W μ⁺ μ⁻ & W W W W**) ~ 1 ab [reducible]

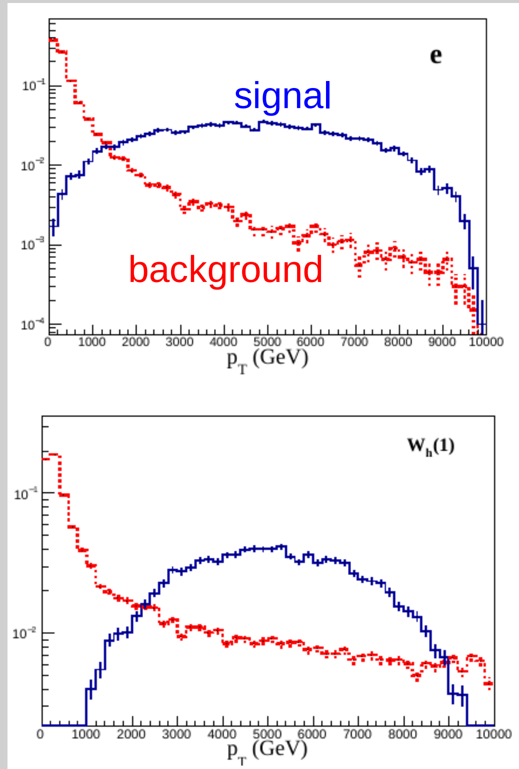
with N.Vignaroli

ν dipole @ future muon collider (II)

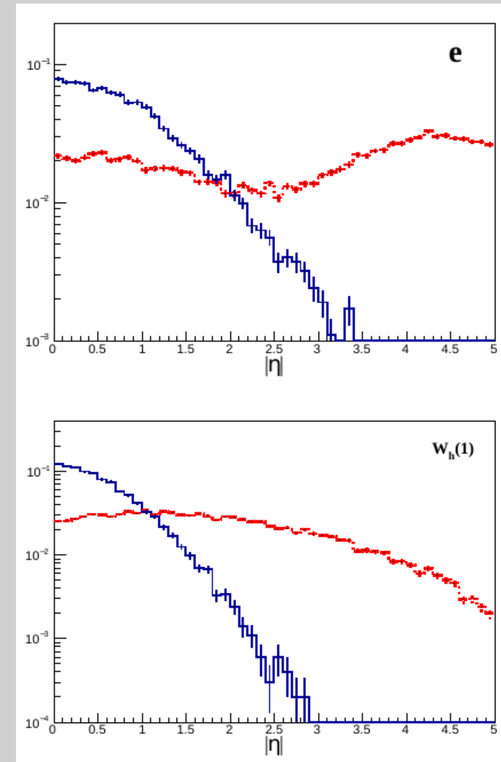
Improving discrimination by **kinematic variables**

Signal events have **higher p_T** & are **more central**

With tailored cuts, **background down to ~ 0.1 ab**



transverse momentum distribution



rapidity distribution

with N.Vignaroli

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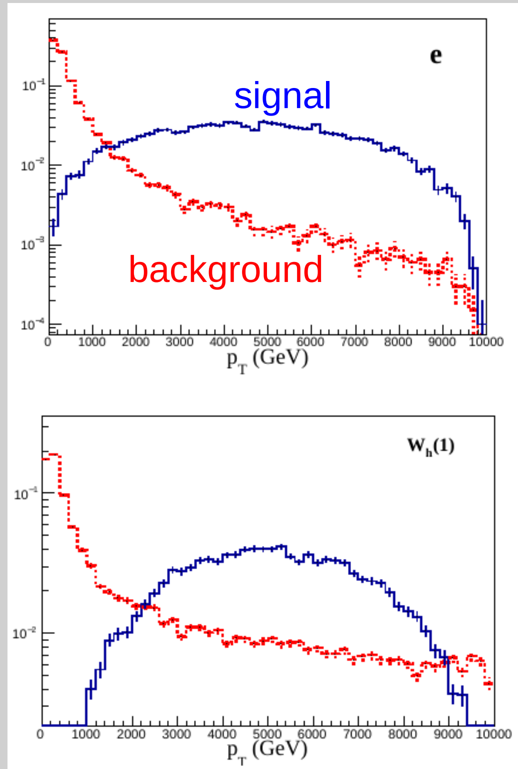
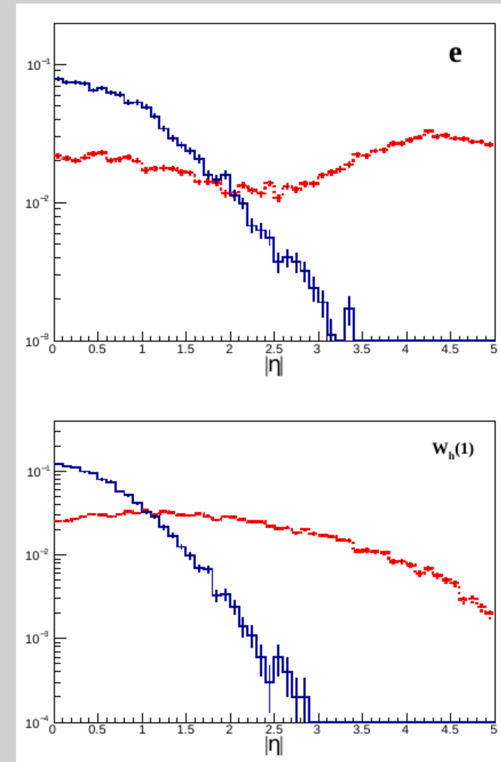


rapidity distribution



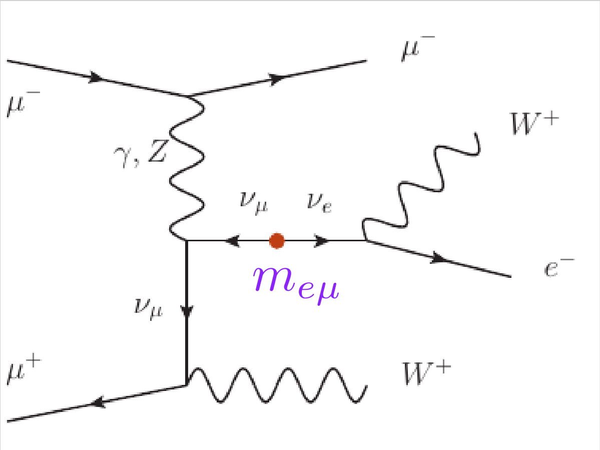
$\sqrt{s}$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\frac{\lvert\lambda_{e\mu}\rvert}{\mu_B}$	$5.4\ [4.8] \cdot 10^{-9}$	$1.5\ [1.1] \cdot 10^{-10}$	$1.9\ [1.2] \cdot 10^{-11}$	$6.6\ [3.9] \cdot 10^{-12}$	$1.5\ [0.8] \cdot 10^{-12}$

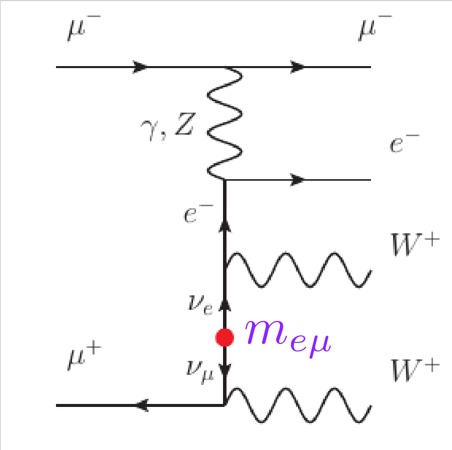
@ 2σ

further background rejection, improved lepton identification

~ current laboratory bound

ν mass @ future muon collider





$$\mathcal{L} \supset \frac{1}{2}\,\nu_\alpha\, m_{\alpha\beta}\, \nu_\beta$$

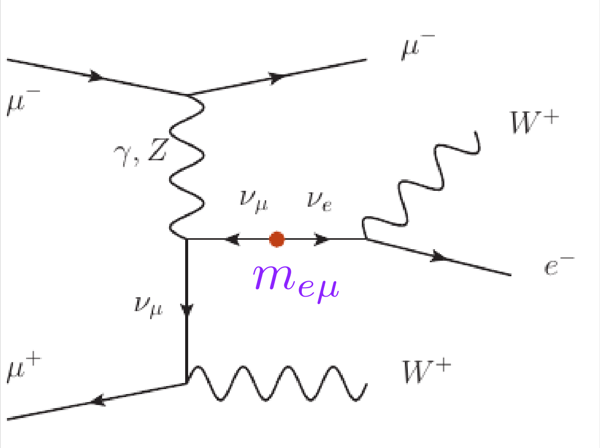
$0\nu 2\beta - \text{decay} \;:\; m_{ee} \lesssim 0.1 \text{ eV}$

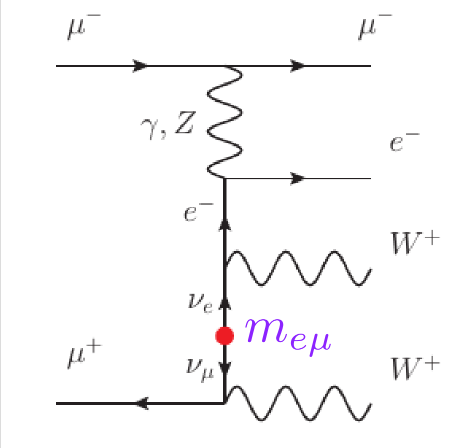
$\text{LHC (FCC} - \text{hh)} \;:\; m_{e\mu,\mu\mu} \lesssim 10 \ (1) \text{ GeV}$

ATLAS 2305.14931
Fuks Neundorf Peters Ruiz Saimpert 2012.09882

with N.Vignaroli

ν mass @ future muon collider





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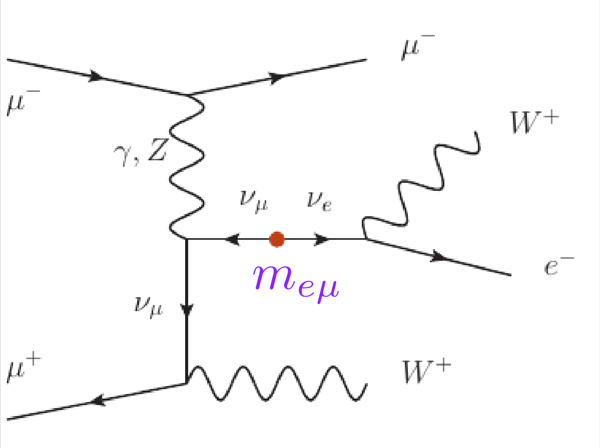
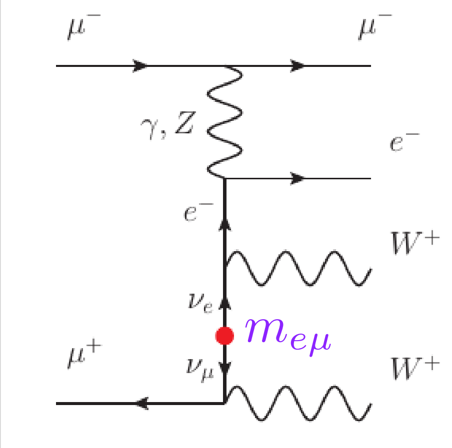
For $\mathbf{m}_{e\mu}$ same analysis as for the dipole $\boldsymbol{\lambda}_{e\mu}$

For $\mathbf{m}_{\mu\mu}$ similar selection, but ~ 5 times larger background (W W μ^+ μ^-)

ν mass @ future muon collider





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$\sqrt{s}$	3 TeV	10 TeV	20 TeV	30 TeV	50 TeV
$\lvert m_{e\mu}\rvert$	110 [100] MeV	3.2 [2.5] MeV	0.50 [0.31] MeV	140 [92] keV	36 [20] keV
$\lvert m_{\mu\mu}\rvert$	300 [140] MeV	10 [3.5] MeV	1.5 [0.44] MeV	420 [130] keV	84 [28] keV

@ 2σ

Improvement up to 5 orders of magnitude !

Still far above the neutrino mass scale ...

A dipole for sterile neutrinos

Effective Field Theory for **SM + 2 sterile neutrinos $\mathbf{N_{1,2}}$**

$$N = \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_N &= i{N_i}^\dagger \bar{\sigma}^\mu \partial_\mu \delta_{ij} N_j \\ &- \left(\frac{1}{2} N_i \mathcal{M}_{ij} N_j - \tilde{H}^\dagger \ell_\alpha Y_{\alpha i} N_i + h.c. \right) \\ &+ \frac{1}{2} \left(d\, N_i \sigma^{\mu\nu} \epsilon_{ij} N_j \, B_{\mu\nu} + h.c. \right) + \ldots \end{aligned}$$

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How large can this dipole be ?

$$d \simeq \frac{g'}{16\pi^2} \frac{g_\star^2}{m_\star} \simeq \frac{1}{3\mathrm{TeV}} \left(\frac{g_\star}{4\pi} \right)^2 \left(\frac{\mathrm{TeV}}{m_\star} \right)$$

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$U(1)_L$ conserving limits

a) $L(N_{1,2}) = 0$: zero Yukawas, no active-sterile mixing, $M_{1,2}$ arbitrary

Barducci Bertuzzo Taoso Toni 2022

b) $L(N_1) = - L(N_2) = 1$:

$$M_\nu = \left(\begin{array}{c|cc} 0 & 0 & m \\ \hline 0 & 0 & M \\ m & M & 0 \end{array} \right)$$

$$m_\alpha \equiv Y_{2\alpha} \frac{v}{\sqrt{2}} \qquad s_\alpha \simeq \frac{m_\alpha}{M} \qquad M_i \simeq M$$

Bounds on active-sterile mixing

In the U(1)$_L$ limit $m_\nu = 0$, still mixing is constrained by a variety of **lepton precision measurements**

* **Indirect bounds** (on sterile neutrinos heavier than charged leptons) :

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Coy Frigerio 2019,2022

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Coy Frigerio 2019,2022

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&\text{for} \quad 2\ \text{GeV} \lesssim M_D \lesssim 80\ \text{GeV}\,, \quad s_{e,\mu}^2 \lesssim 10^{-5}\,, \quad s_\tau^2 \lesssim 10^{-5}\,,\\
&\text{for} \quad 0.5\ \text{GeV} \lesssim M_D \lesssim 2\ \text{GeV}\,, \quad s_{e,\mu}^2 \lesssim 10^{-7}\,, \quad s_\tau^2 \lesssim 10^{-6}\,,\\
&\text{for} \quad 0.2\ \text{GeV} \lesssim M_D \lesssim 0.5\ \text{GeV}\,, \quad s_{e,\mu}^2 \lesssim 10^{-9}\,, \quad s_\tau^2 \lesssim 10^{-5}\,.
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Snowmass Review 2203.08039

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Snowmass Review 2203.08039

Departing from the U(1)$_L$ limit , assuming oscillation data are reproduced by **$N_{1,2}$ seesaw** :

$$\begin{aligned}
&\text{normal ordering } (m_1 < m_2 < m_3): && \hat{s}_e^2 \lesssim 0.1\,, \quad 0.25 \lesssim \hat{s}_\mu^2 \lesssim 0.85\,, \quad \hat{s}_\tau^2 \simeq 1 - \hat{s}_\mu^2\,,\\
&\text{inverted ordering } (m_3 < m_1 < m_2): && 0.05 \lesssim \hat{s}_e^2 \lesssim 0.95\,, \quad \hat{s}_\mu^2 \simeq \hat{s}_\tau^2 \simeq 0.5(1-\hat{s}_e^2)\,,
\end{aligned}$$

Blennow Fernández-Martínez Hernández-García Lopéz-Pavón Marcano Naredo-Tuero et al. 2306.01040

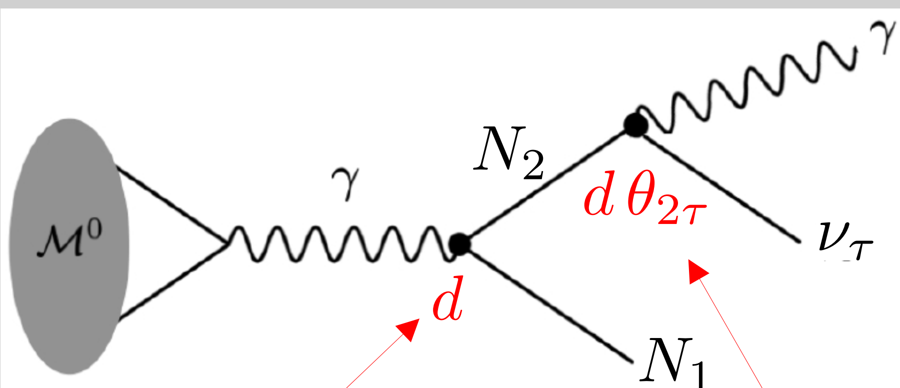
$$\hat{s}_\alpha^2 \equiv \frac{s_\alpha^2}{\sum_\beta s_\beta^2}$$

Sterile production & decay

Beam-dump experiments (SHiP, NA62, CHARM, …):
mesons from protons on target

Photons with E > 1 GeV can be seen in the detector calorimeter

Barducci Bertuzzo Taoso Toni Ternes 2024



sterile production in the target

sterile decay in the detector

with E.Bertuzzo

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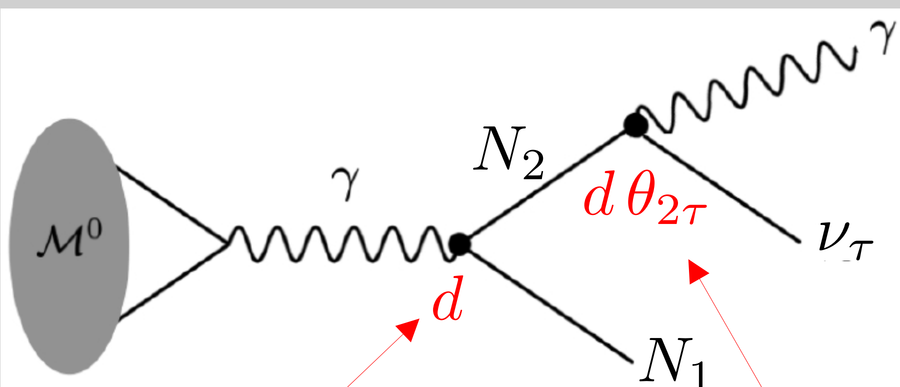

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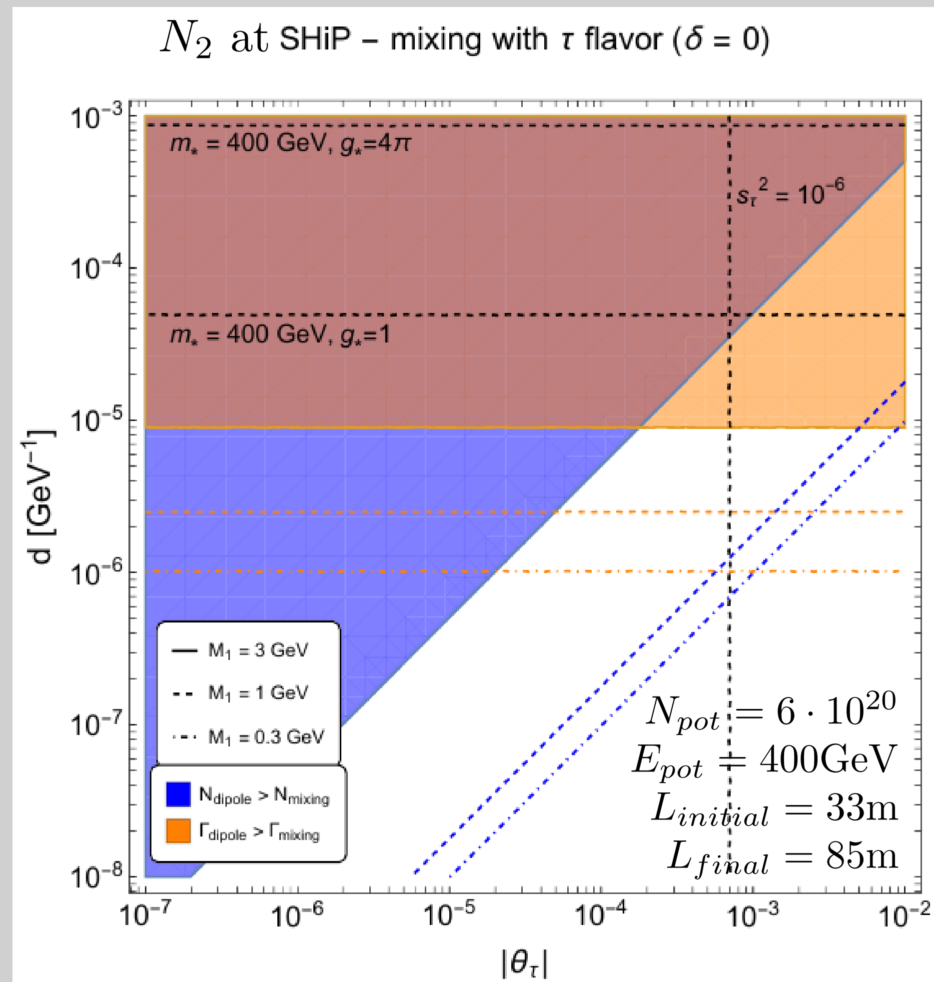
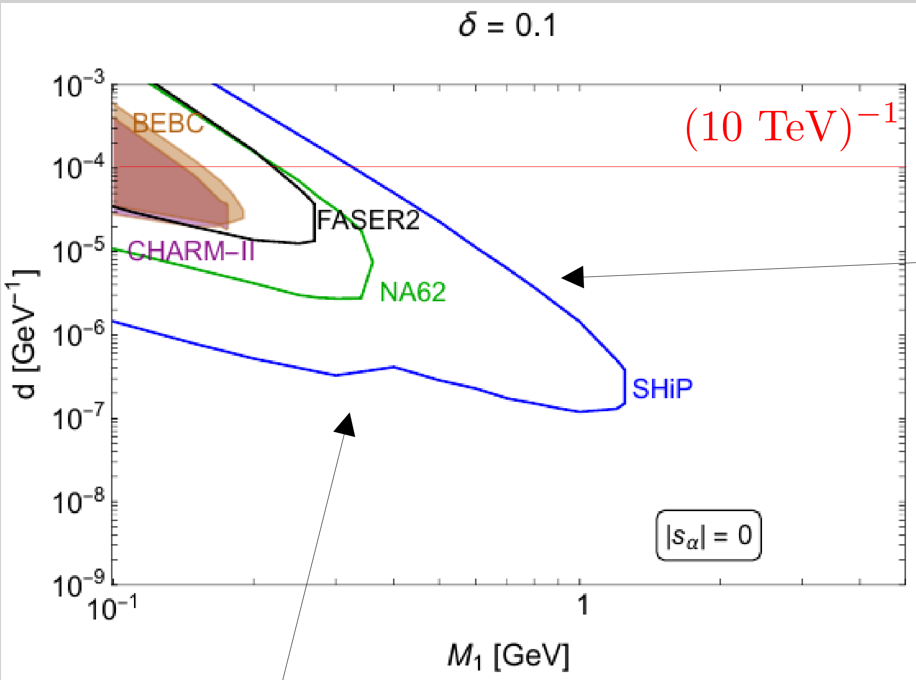


Production both from dipole & active-sterile mixing

Photon signal from **decays** via dipole only

Future experimental sensitivity (I)



Dipole only : no active-sterile mixing

$$N_2 \to N_1 \gamma$$

2 σ contours
assuming
no background

N_2 decays before the detector

N_2 decays after the detector

preliminary

with E.Bertuzzo

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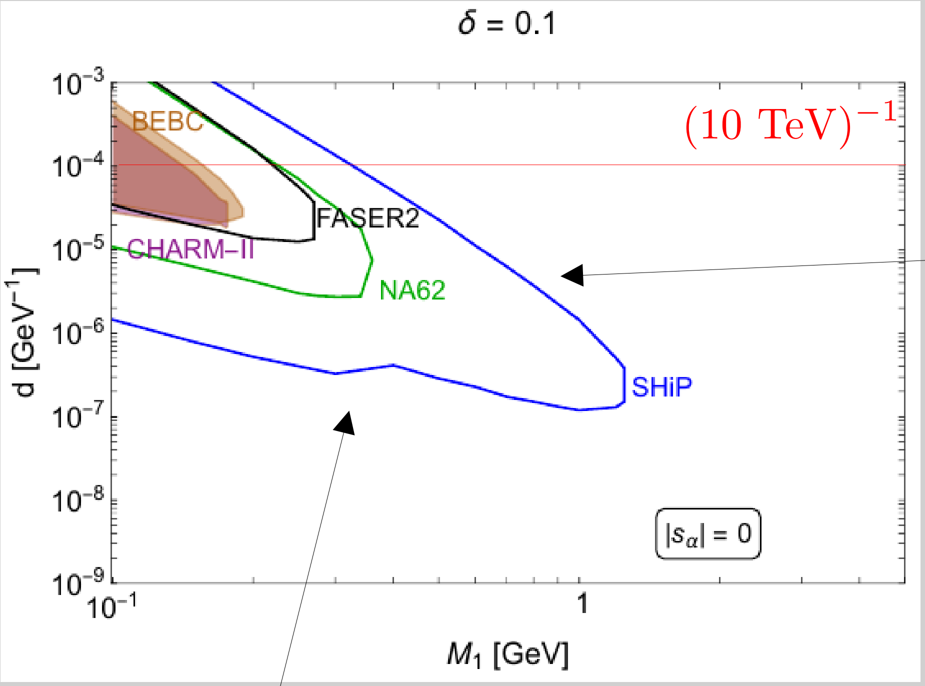

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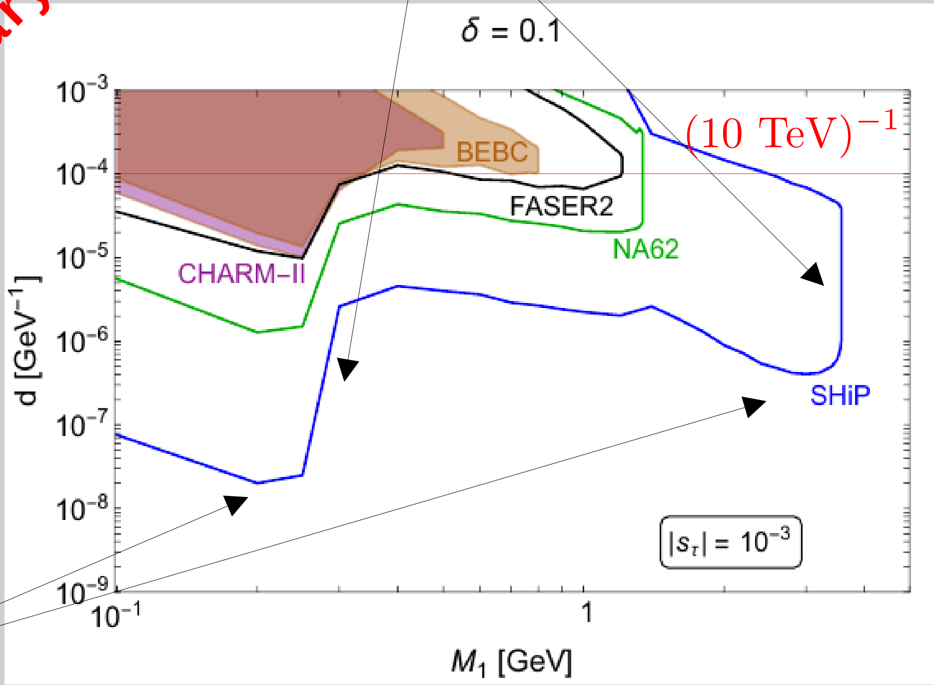
N_2 decays before the detector

N_2 decays after the detector

Thresholds due to meson masses

preliminary



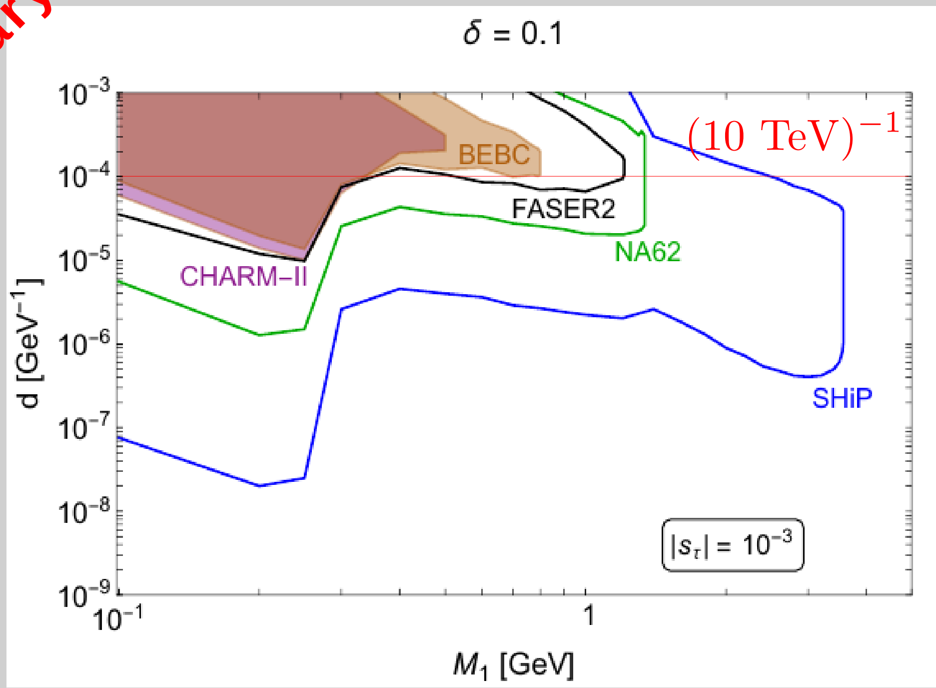
Dipole + mixing with τ flavour

$$N_2 \rightarrow \nu_\tau \gamma$$
$$N_2 \rightarrow N_1 \gamma$$
$$N_1 \rightarrow \nu_\tau \gamma$$

Production dominated by mixing

Future experimental sensitivity (II)

$$\delta \equiv \frac{M_2 - M_1}{M_2 + M_1}$$

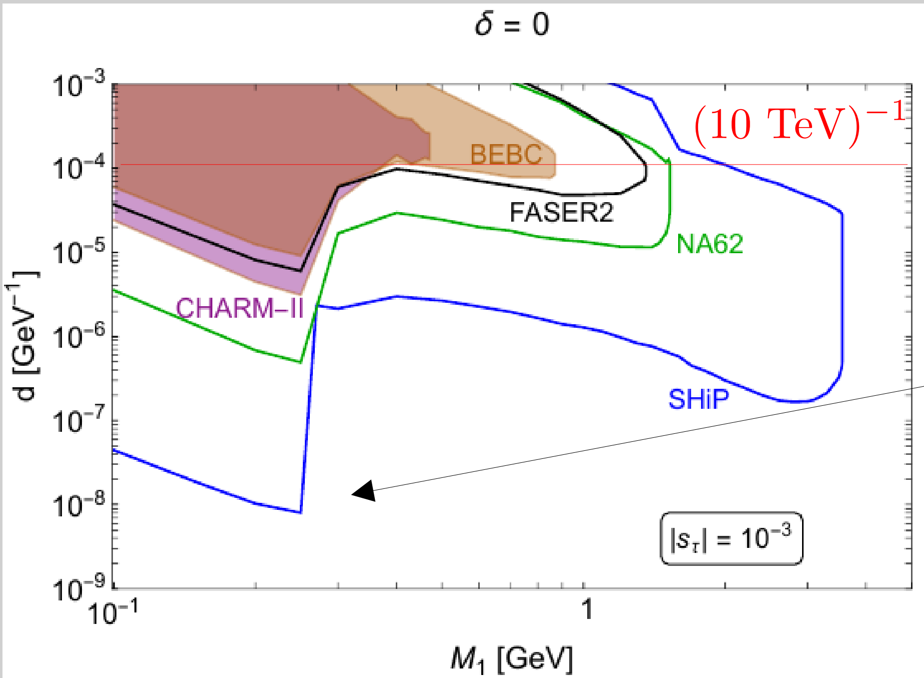


N_2-N_1 mass splitting : $U(1)_L$ breaking

$$N_2 \to \nu_\tau \gamma$$
$$N_2 \to N_1 \gamma$$
$$N_1 \to \nu_\tau \gamma$$

with E.Bertuzzo

Future experimental sensitivity (II)



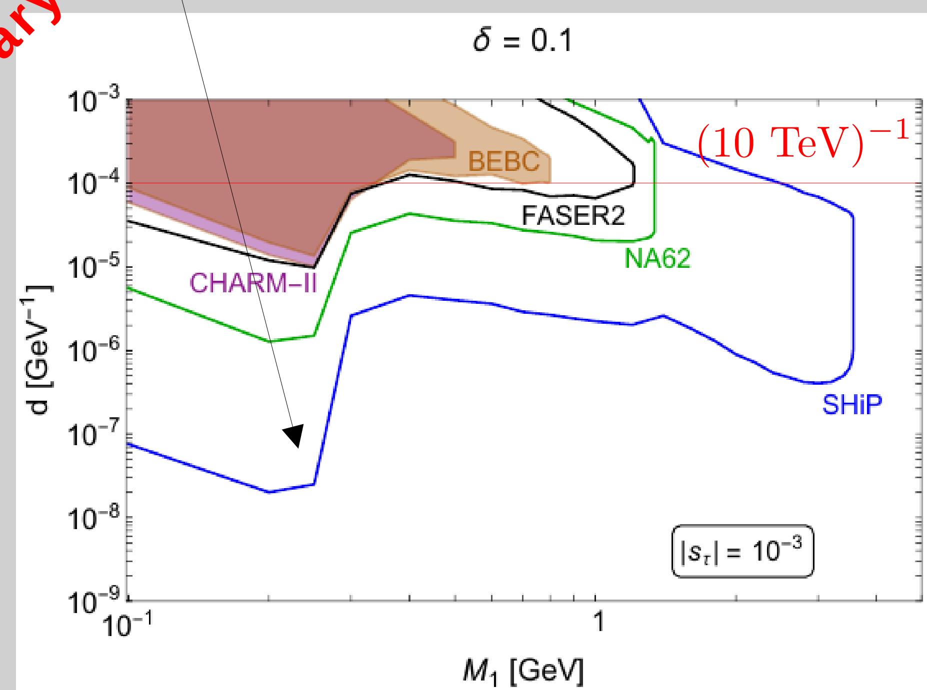
N$_2$-N$_1$ mass degeneracy : U(1)$_L$ limit

$$N_D \to \nu_\tau \gamma$$

$$\delta \equiv \frac{M_2 - M_1}{M_2 + M_1}$$

Minor differences in sensitivity regions

preliminary



N$_2$-N$_1$ mass splitting : U(1)$_L$ breaking

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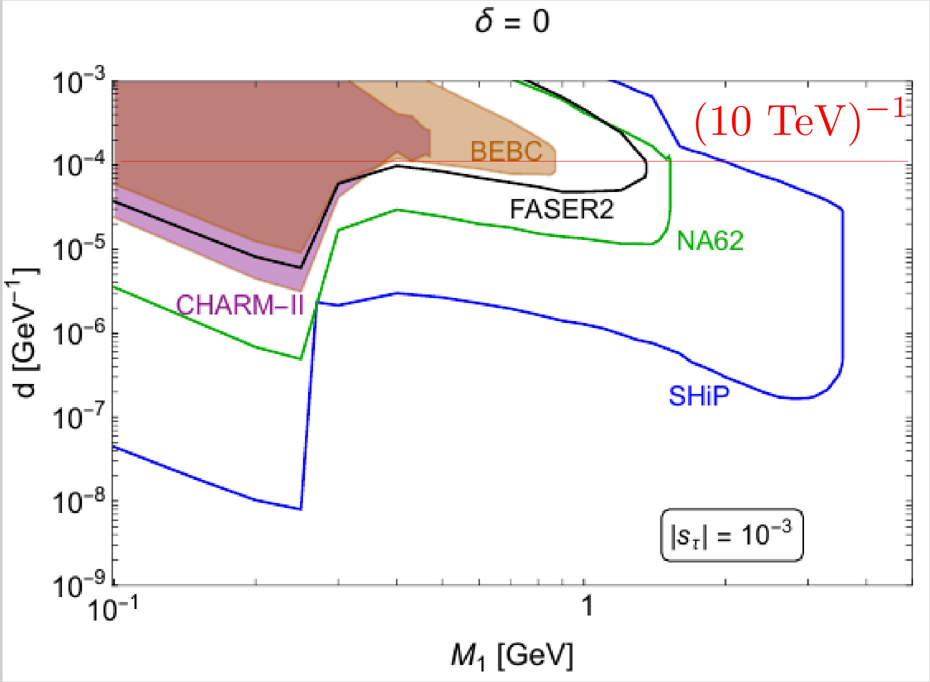
Future experimental sensitivity (III)



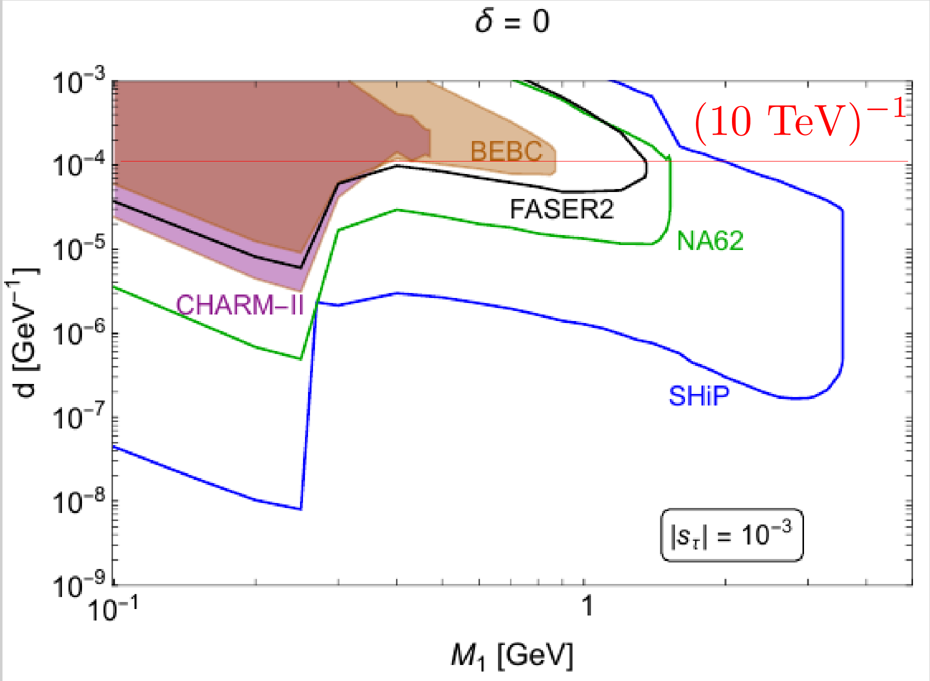
Mixing with τ flavour

$$N_D \to \nu_\tau \gamma$$

preliminary

with E.Bertuzzo

Future experimental sensitivity (III)

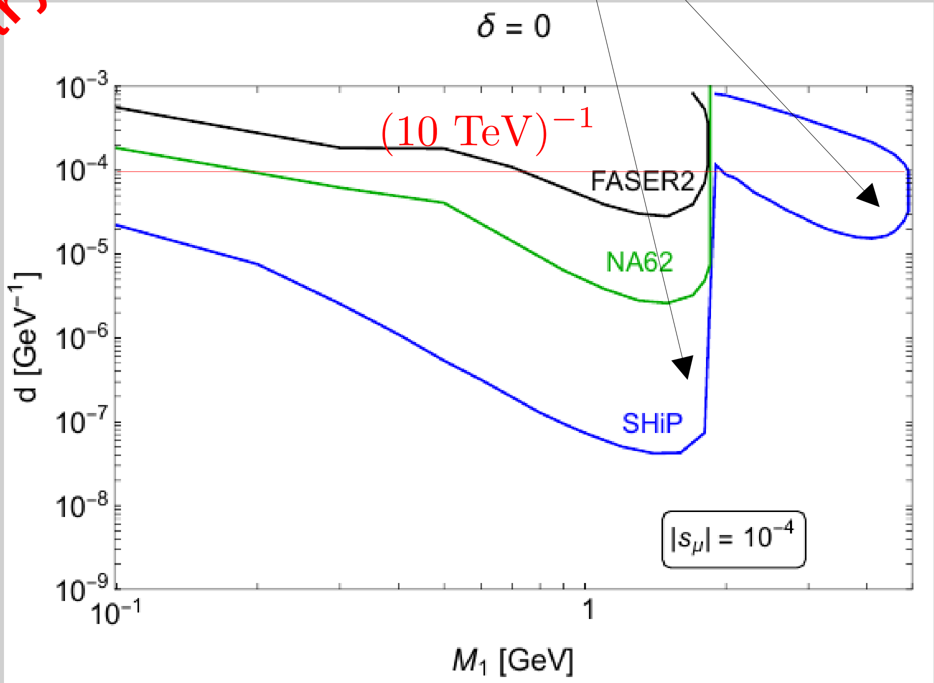


Mixing with τ flavour

$$N_D \to \nu_\tau \gamma$$

Meson thresholds move to larger M_1
(with reduced sensitivity to dipole)

preliminary



N production suppressed,
as allowed **mixing is smaller for μ flavour**

N production channels involving μ
remain **open at higher masses**

Mixing with μ flavour

$$N_D \to \nu_\mu \gamma$$

… waiting for some ν light