BSM searches using (Proto)DUNE

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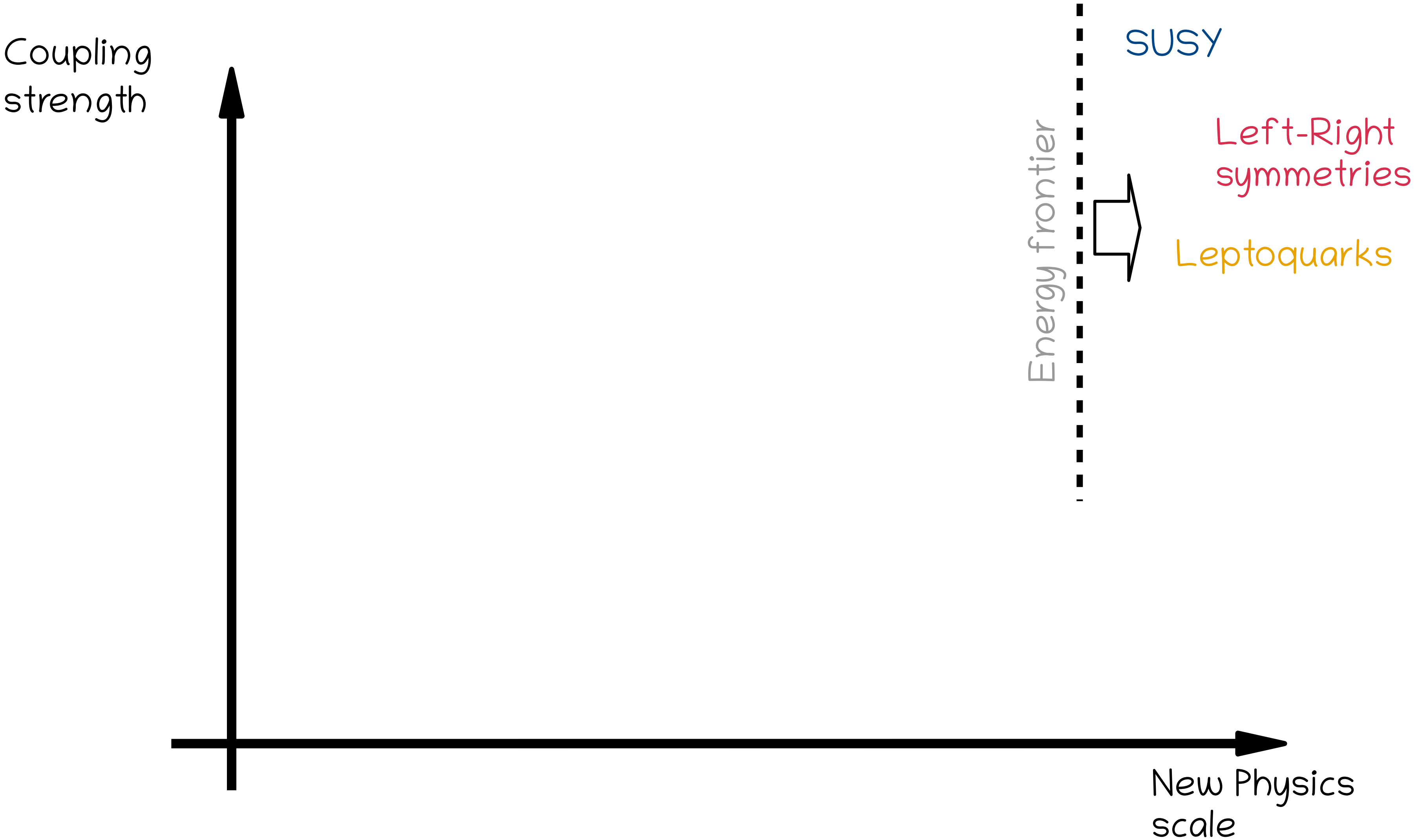
Based on
arXiv:2304.06765 (PC, Jacobo López-Pavón, Laura Molina-Bueno and Salvador Urrea)
arXiv:2309.06492 (PC, Justo Martín-Albo and Salvador Urrea)

Light Dark World, Karlsruhe (Sep 20th, 2023)

Where is the New Physics?



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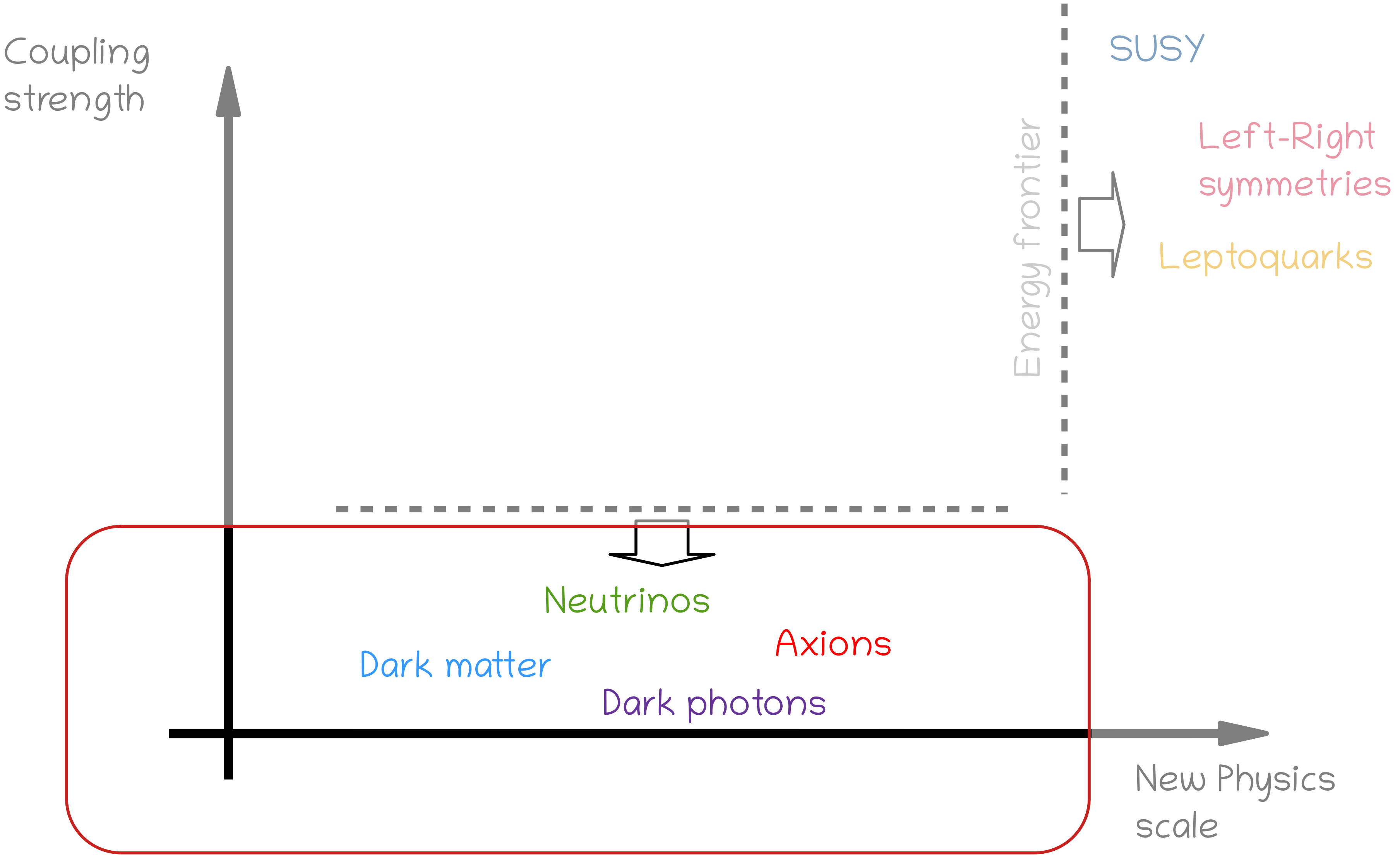
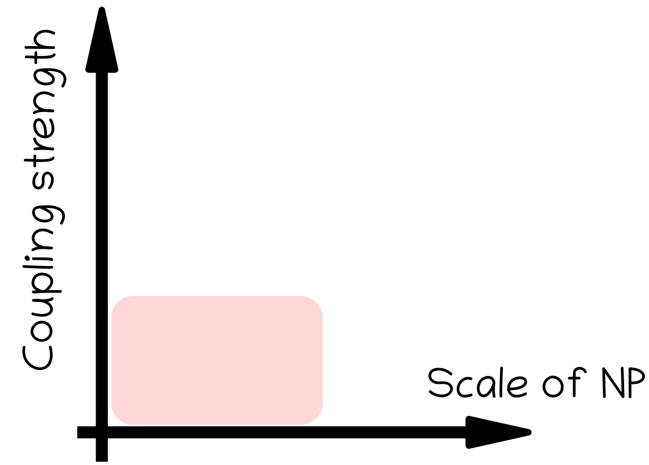
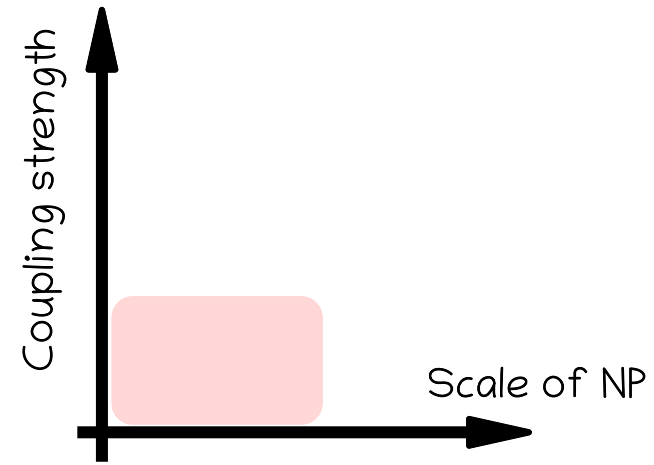


Signals at neutrino experiments



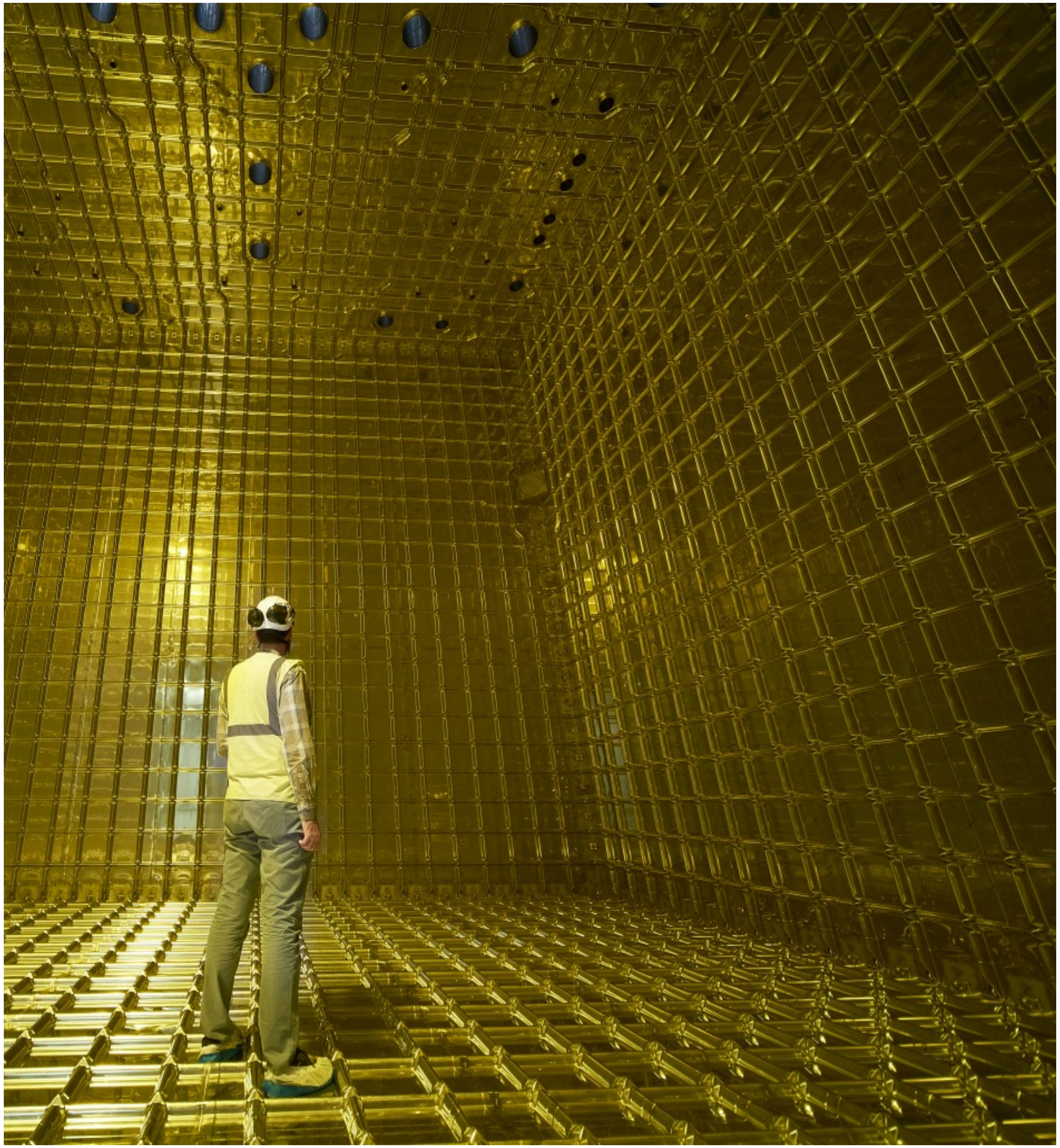
- Feebly-interacting particles:
  - intense sources needed
  - large detectors needed
- Interactions: will induce an excess of recoils → large backgrounds!!
- Long-lived particle decays. Generally lower backgrounds, specially if:
  - Decays can be fully reconstructed
  - The detector has low density

Signals at neutrino experiments



- Feebly-interacting particles:
  - intense sources needed
  - large detectors needed
- Interactions → scale with detector mass
- Long-lived particle decays → scale with detector volume

ProtoDUNE



Two modules available at CERN

- Large fiducial volume, ~250 m³ → ideal for LLP searches
- Filled with LAr! → ideal for the detection of weakly-interacting particles

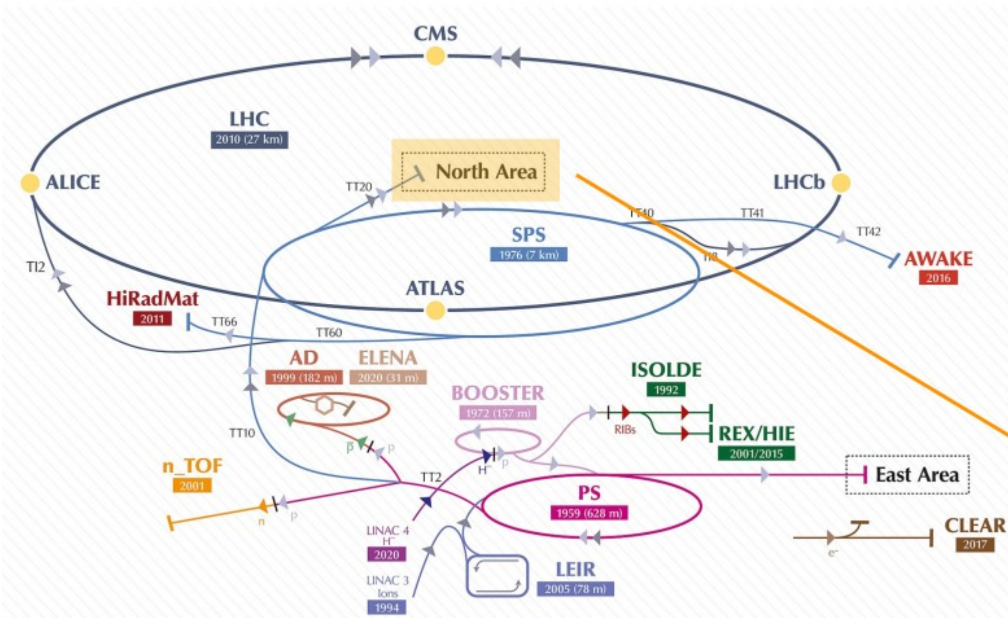
Key advantages:

- Excellent reconstruction and particle ID
- Very low detection thresholds

Main disadvantage:

- They are on surface (tons of cosmics!)

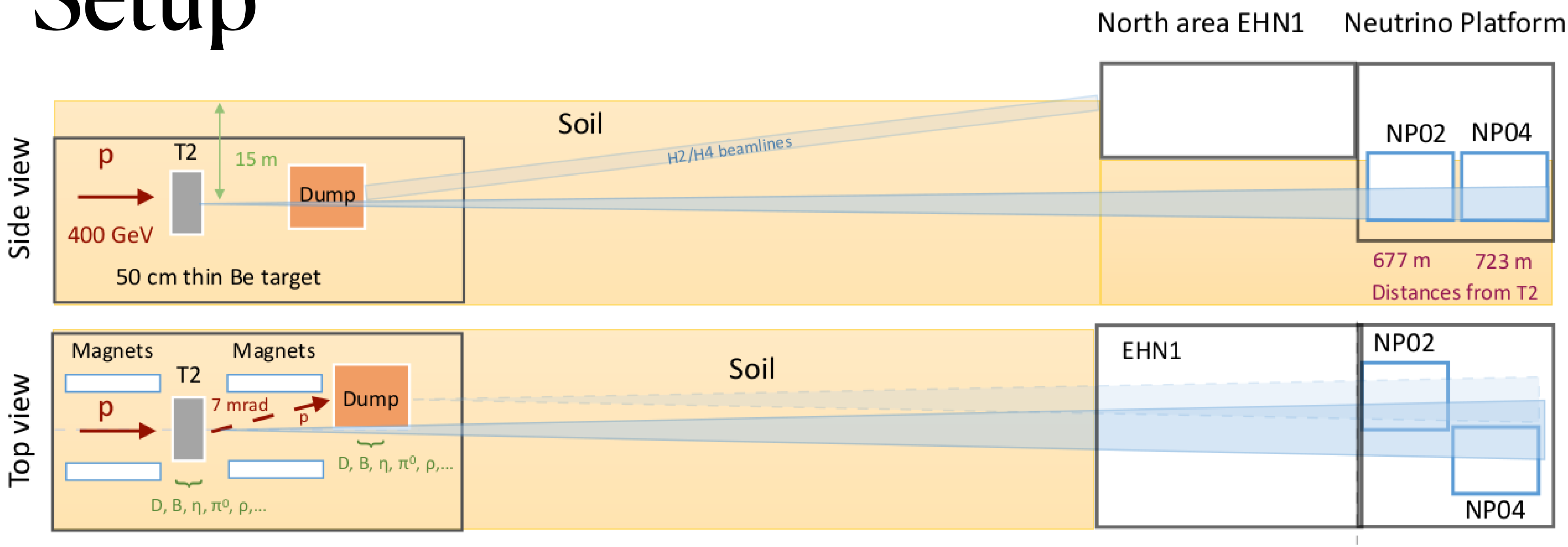
Setup



CMS
LHC
2010 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
TT42
SPS
1976 (7 km)
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
REX/HIE
2001/2015
TT10
n_TOF
2001
TT2
East Area
PS
1959 (628 m)
CLEAR
2017
LINAC 4
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)

T10 target
ECN3
EHN2
K12
M2
EHN1 Neutrino Platform
P42
EHN1
H2, H4, H6, H8
T2, T4, T6 targets
TT20 transfer line

Setup



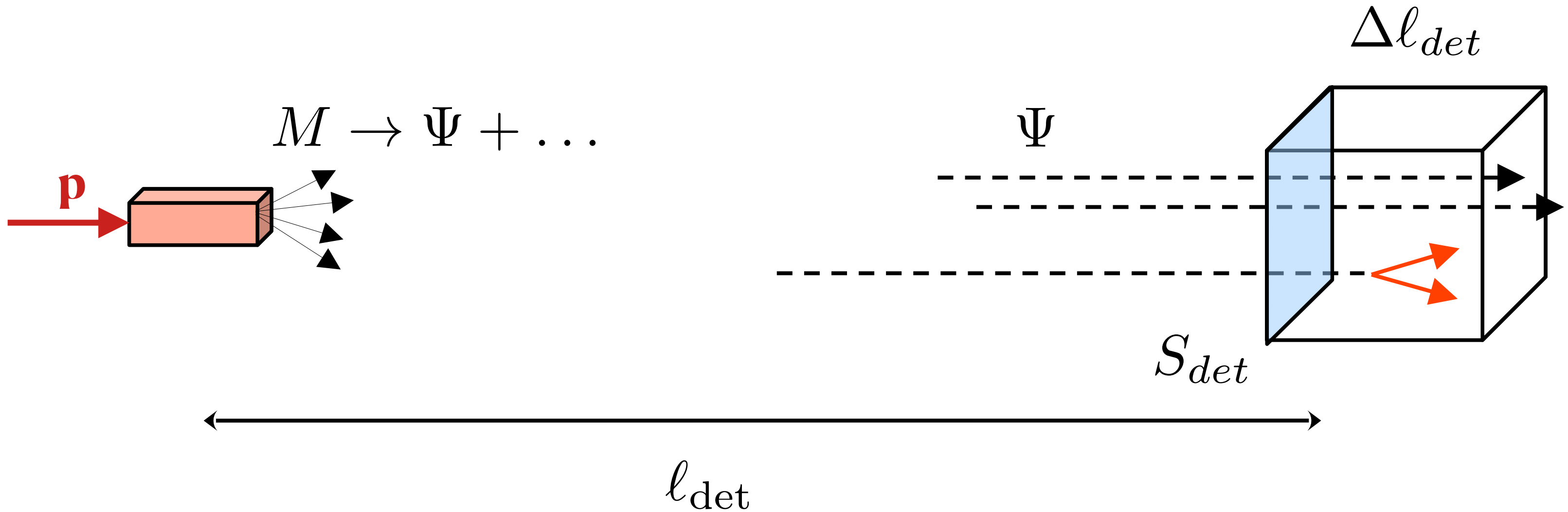
Main features:

- no decay volume
  - → no neutrinos!
- very high proton energy!

Meson yields (per PoT):

π^0	η	η'	D	D_s	τ
4.03	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
ρ	ω	ϕ	J/ψ	B	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

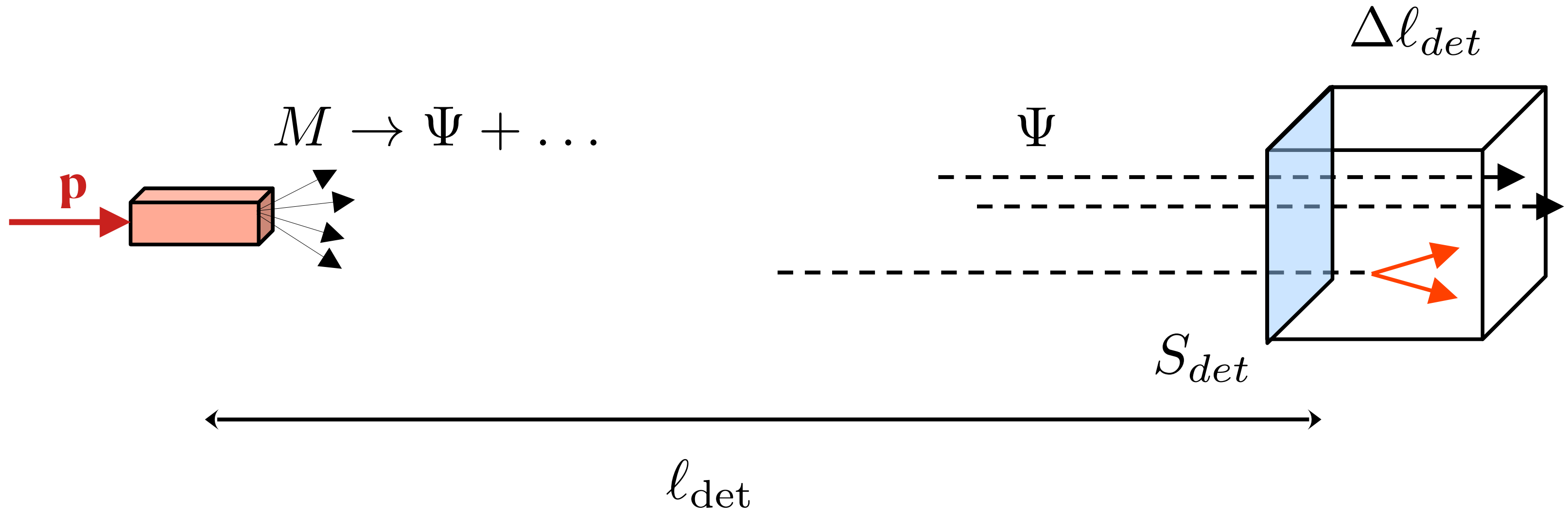
Decays



Expected number of decays

$$N_{ev} = N_M \mathrm{BR}(M \to \Psi)\mathrm{BR}(\Psi \to \mathrm{Vis})\, \epsilon_{det} \int dS \int dE_\Psi\, \mathcal{P}(c\tau_\Psi/m_\Psi, E_\Psi, \Omega_\Psi)\, \frac{dn^{M\to\Psi}}{dE_\Psi dS}$$

- Number of particles produced
- Is the final state observable?
- Decay probability within detector
- Dependence with energy and angle



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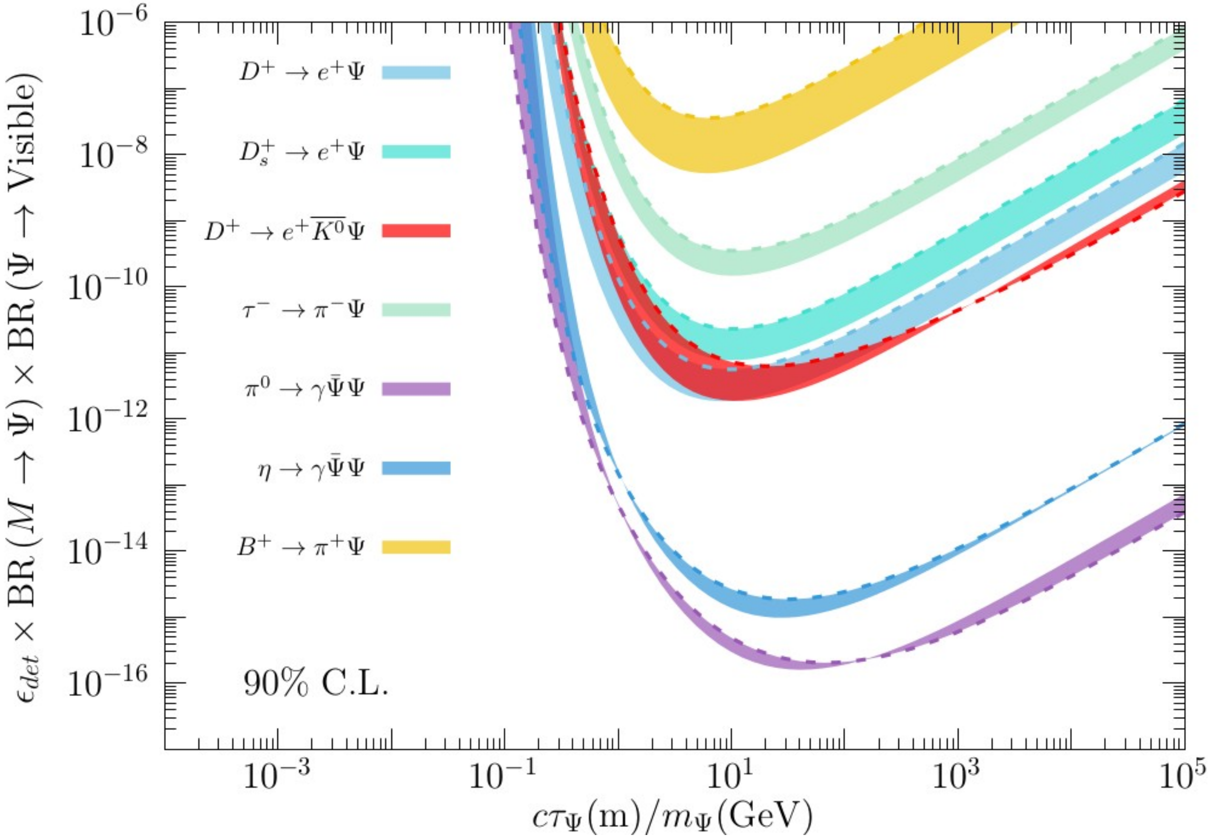
Model-dependent

Model-dependent

Model-independent sensitivity

$$N_{ev} = N_M \mathrm{BR}(M \to \Psi) \mathrm{BR}(\Psi \to \mathrm{Vis}) \epsilon_{det} \int dS \int dE_\Psi \, \mathcal{P}(c\tau_\Psi / m_\Psi, E_\Psi, \Omega_\Psi) \frac{dn^{M\to\Psi}}{dE_\Psi dS}$$



We assume backgrounds can be efficiently suppressed

Luminosity:
→ 3.5e18 PoT / yr
→ 5 years of data taking

Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

Model-independent sensitivity

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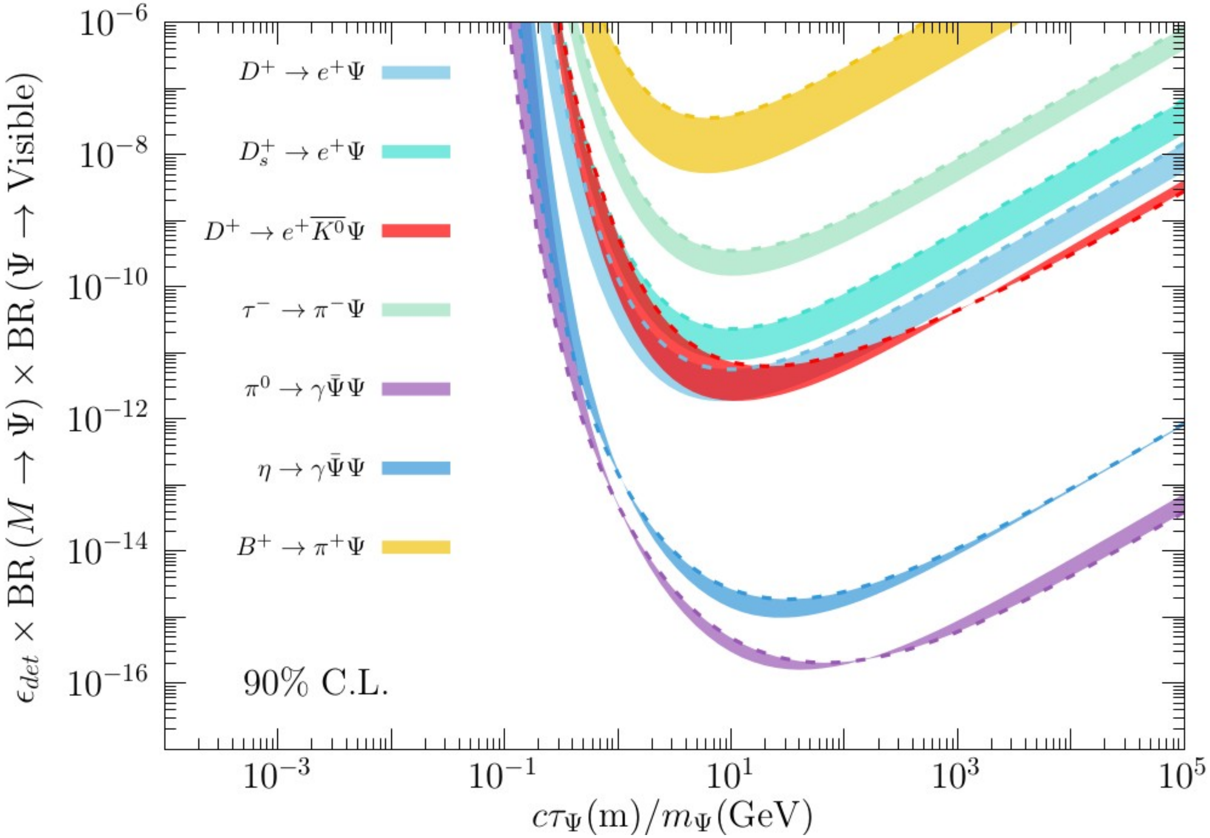

Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

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Luminosity:
→ 3.5e18 PoT / yr
→ 5 years of data taking

→ No correlation assumed between production and decay

Benchmark scenario: HNL

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

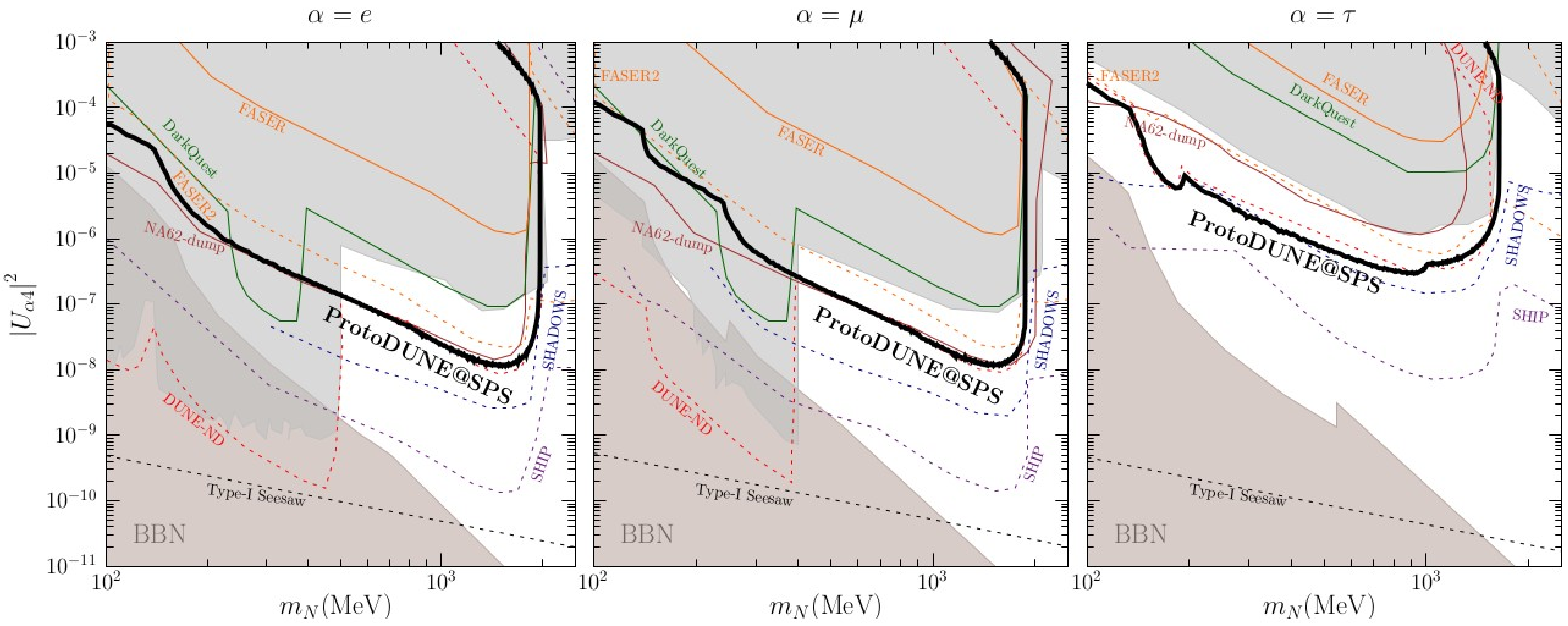
The best bounds for HNL between O(100) MeV - GeV scale come from fixed targets

However:

→ Bounds for HNL at the GeV scale significantly weaker than at lower masses

→ $U_{\tau 4}$ is particularly hard to probe

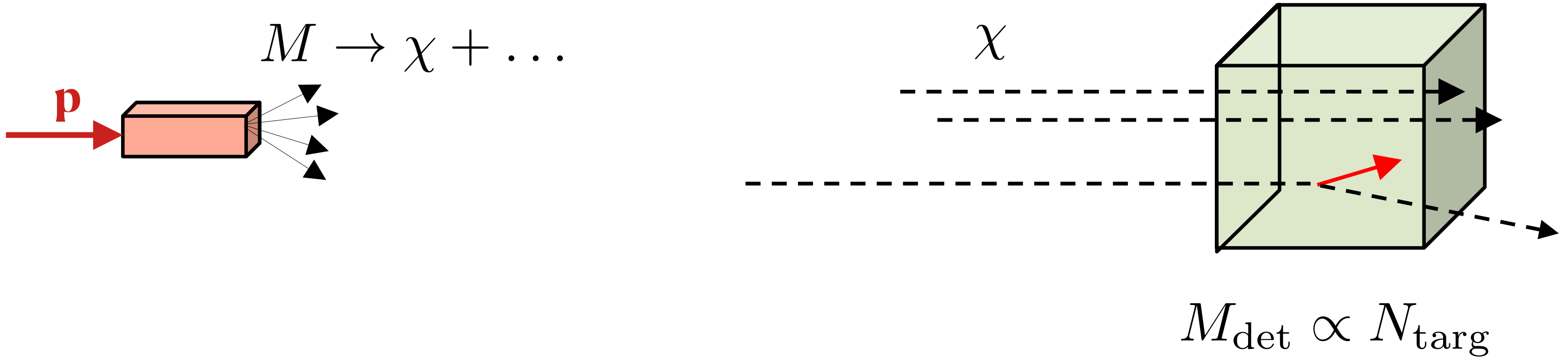
Sensitivities to HNL decays



Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

Decays considered: $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi, \nu\pi^0$

Feeble Interactions



Model-independent case

$$N_{ev} = \mathcal{N}\, \epsilon_{det} \cdot \langle\sigma\rangle \cdot \underbrace{\mathcal{BR}\,\mathrm{PS}\,(m_\chi, m_M)}_{\text{production BR}}\; \tilde{\Phi}^{\chi}$$

Model-independent case

$$N_{ev} = \mathcal{N}\, \epsilon_{det} \cdot \langle \sigma \rangle \cdot \mathcal{BR}\, \mathrm{PS}\left(m_\chi, m_M\right)\, \tilde{\Phi}^\chi$$

Model dependence

Model-independent case

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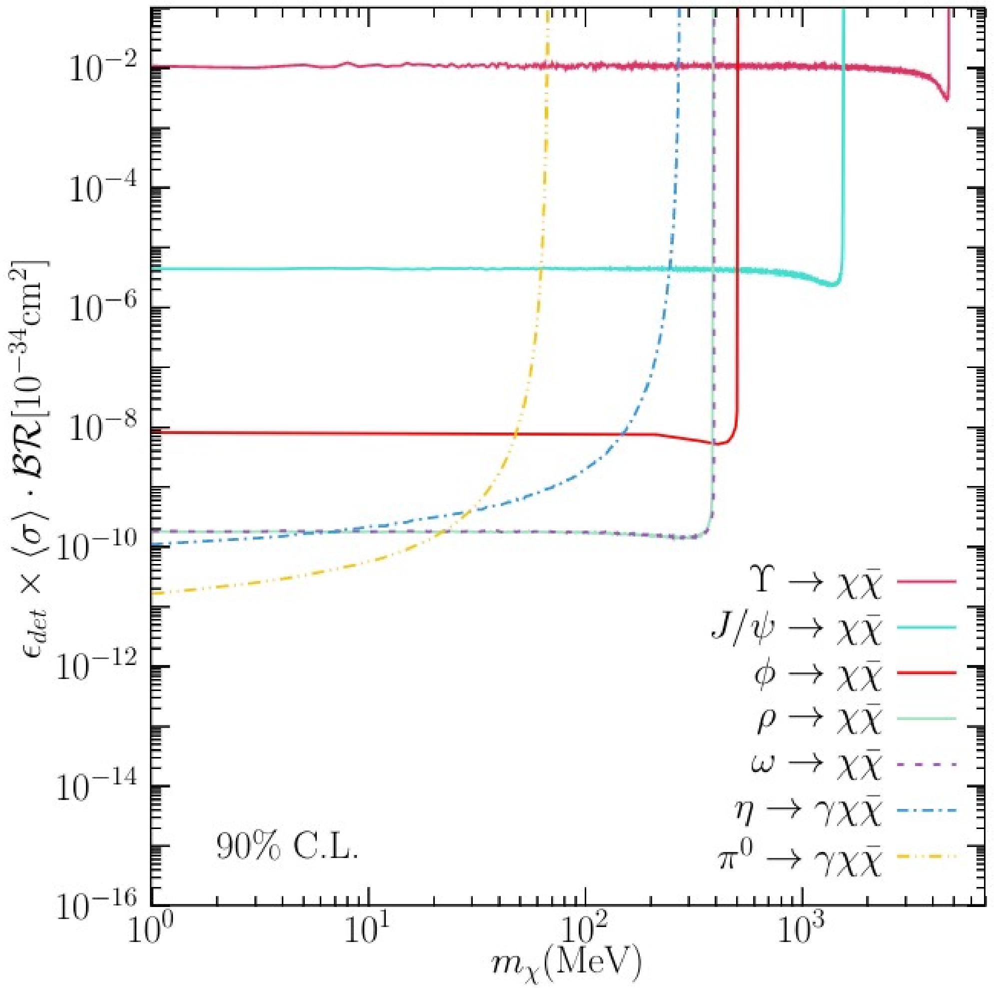

Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

Millicharged particles

MCP would lead to an excess of low-energy electron recoils:

$$\frac{d\sigma}{dT} = \pi\alpha^2\varepsilon^2 \frac{2E_\chi^2 m_e + T^2 m_e - T\left(m_\chi^2 + m_e\left(2E_\chi + m_e\right)\right)}{T^2\left(E_\chi^2 - m_\chi^2\right) m_e^2}$$

Magill, Plestid, Pospelov, Tsai, 1806.03310

In the limit $E_\chi \gg m_\chi, m_e$

$$\sigma \sim \varepsilon^2 \left(\frac{30\ \text{MeV}}{T_{\text{min}}}\right) 10^{-26}\ \text{cm}^{-2}$$

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Potentially large backgrounds: our very rough estimate is ~2e6 / yr
Possible ways to handle it:

- → beam timing
- → angular cuts
- → characterization using beam OFF data

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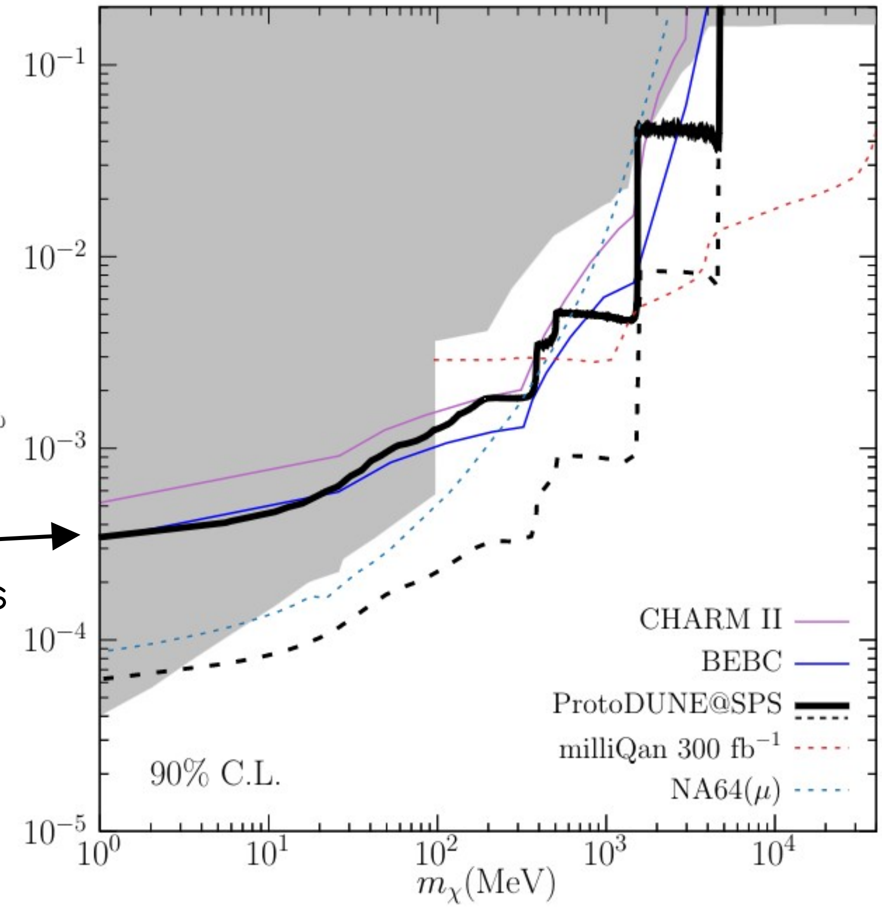
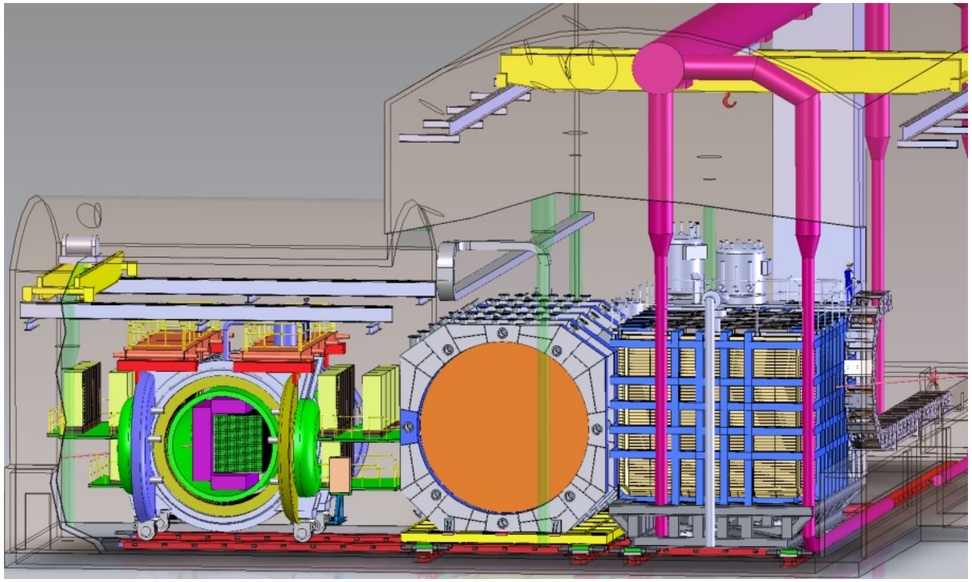
Nominal bg,
unbinned analysis



Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

DUNE - LLP decays

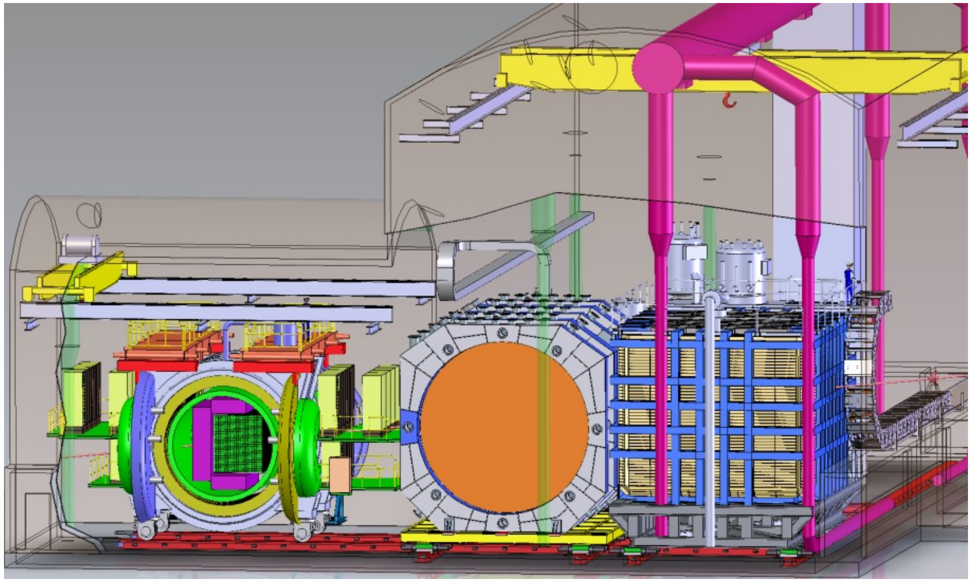
DUNE setup



- Main differences:
  - slightly shorter distance
  - two main near detectors
  - much higher number of PoT (1e21/year)
  - lower proton energy (120 GeV)

Many works in the literature:
Berryman et al, 1912.07622; Jerhot et al, 2201.05170; Kelly, Kumar & Liu, 2011.05995; Batell, Huang & Kelly, 2304.11189; Brdar et al, 2011.07054; Coloma et al, 2007.03701; Co, Kumar & Liu, 2210.02462; Capozzi et al, 2108.03262; Dev et al, 2104.07681;...

DUNE setup



- Main differences:
  - slightly shorter distance
  - two main near detectors
  - much higher number of PoT (1e21/year)
  - lower proton energy (120 GeV)
  - the LBNF beam will have a decay volume, though...

→ more than 10^8 neutrino interactions per year!

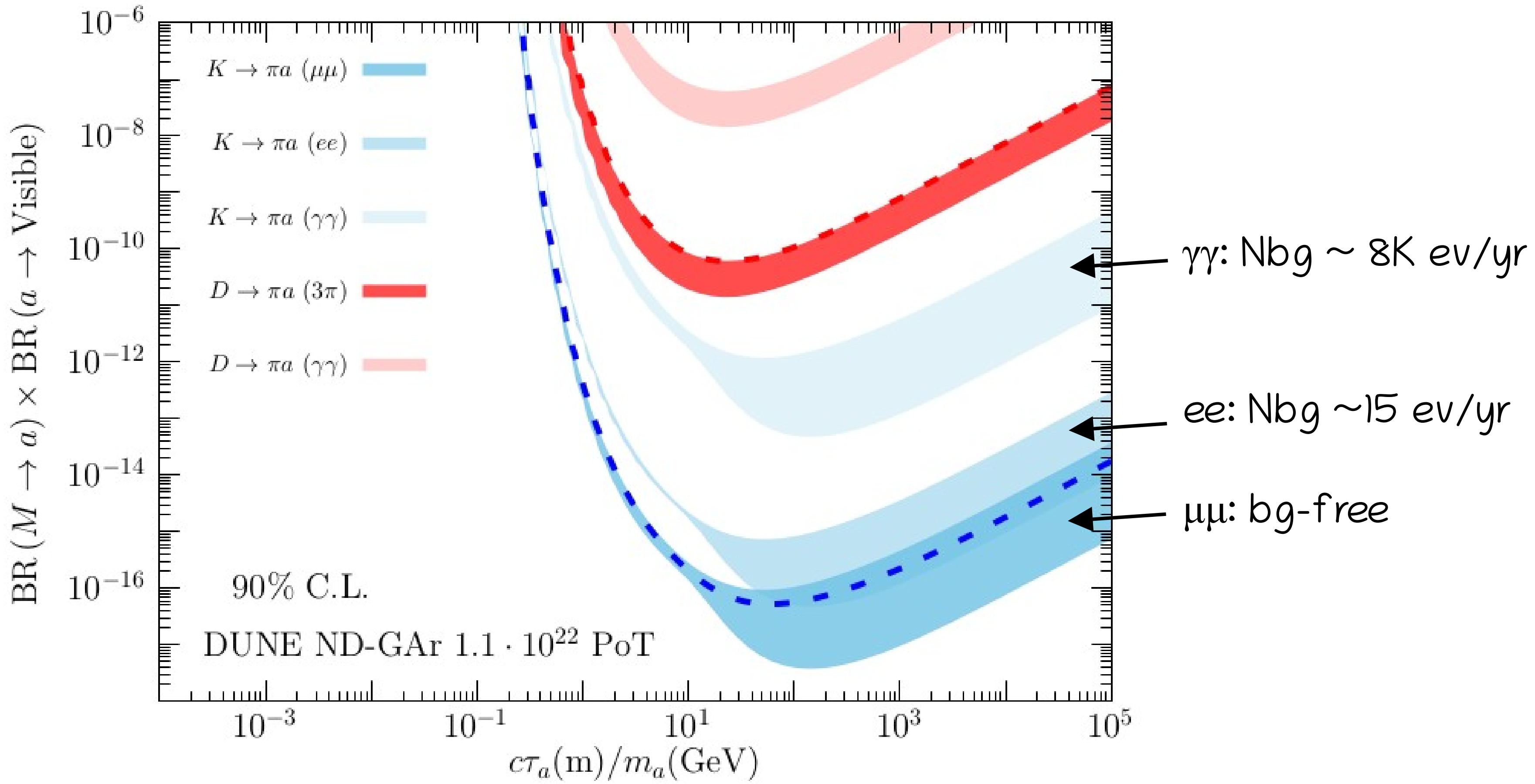
Fewer works with a background calculation: Ballett, Boschi & Pascoli, 1905.00284; Breitbach et al, 2102.03383

Backgrounds

	Selection cut	Signal efficiency		Background rate/yr	
		ND-LAr	ND-GAr	ND-LAr	ND-GAr
$\mu^+\mu^-$	Two μ-like tracks only	1.00	1.00	3545674	70656
	PID μ and opposite charge sign	0.40	1.00	6226	124
	Transverse momentum < 0.125 GeV/c	0.40	0.99	99	2
	Angle between muons < 0.7 rad	0.40	0.94	0	0
e^+e^-	Two e-like tracks/showers	0.10	1.00	9432	145
	Reconstructed ALP direction	**0.10**	0.99	180	15
$\gamma\gamma$	Two γ showers only	0.05	0.79	36276	14222
	Reconstructed ALP direction	0.05	0.79	6938	**7923**
	Angle between γ showers	**0.05**	—	**1367**	—
$\pi^+\pi^-\pi^0$	Two μ-like tracks, two γ showers	0.04	0.81	2030490	40462
	PID $\pi^\pm$ and charge sign	0.04	0.81	431035	8589
	Transverse momentum < 0.2 GeV/c	0.04	0.79	17182	342
	Angle between pions < 0.15 rad	**0.04**	0.69	**946**	19

Coloma, Martín-Albo and Urrea, 2309.06492

Model-independent results



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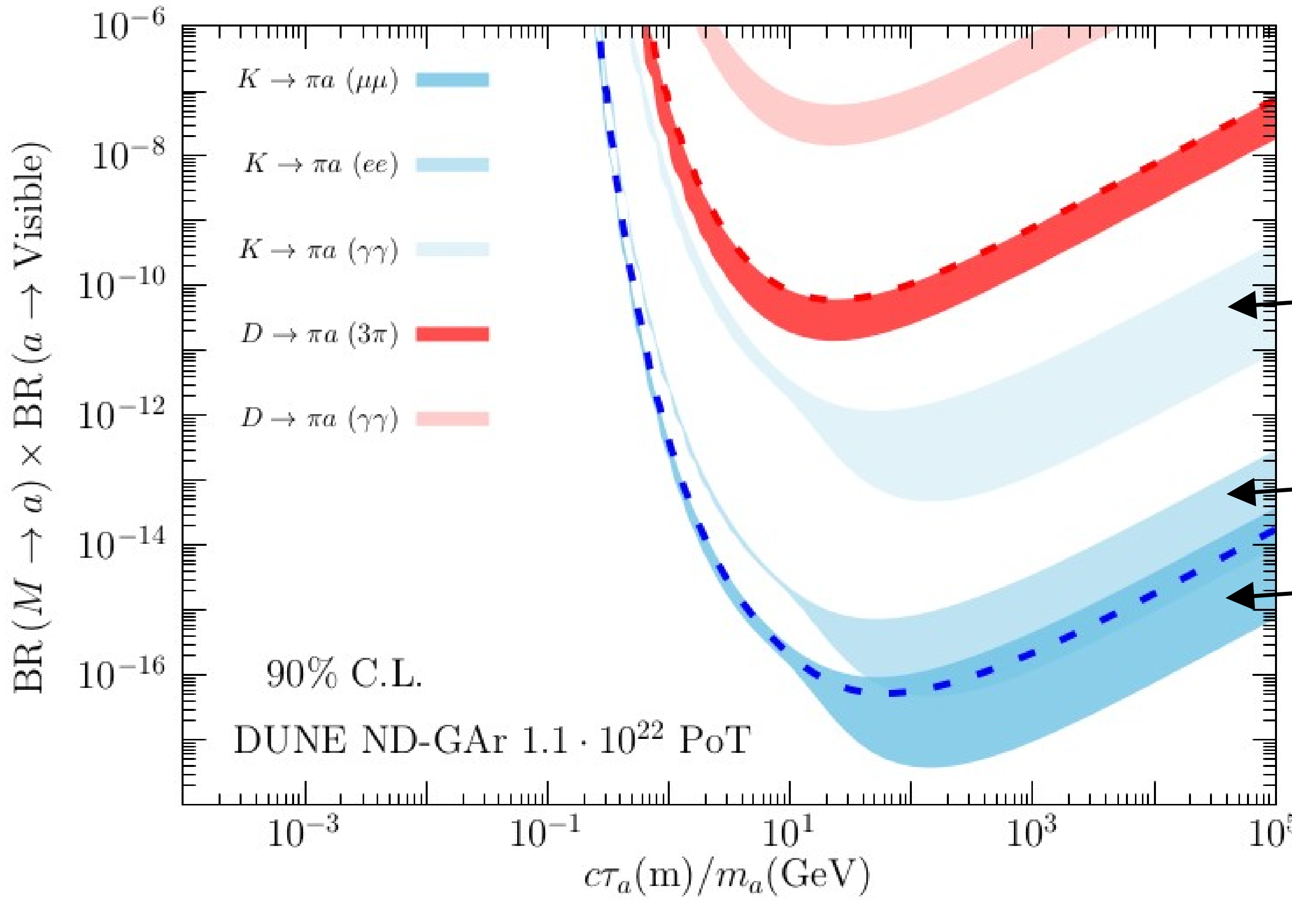


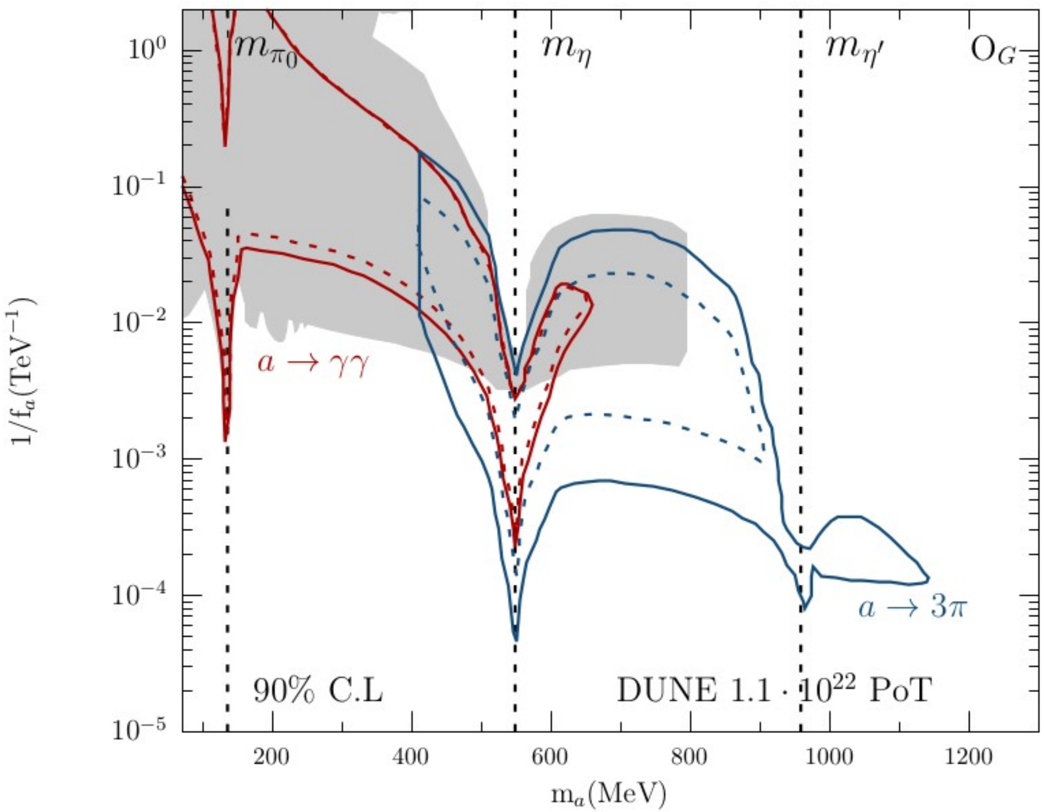
Coloma, Martín-Albo and Urrea, 2309.06492

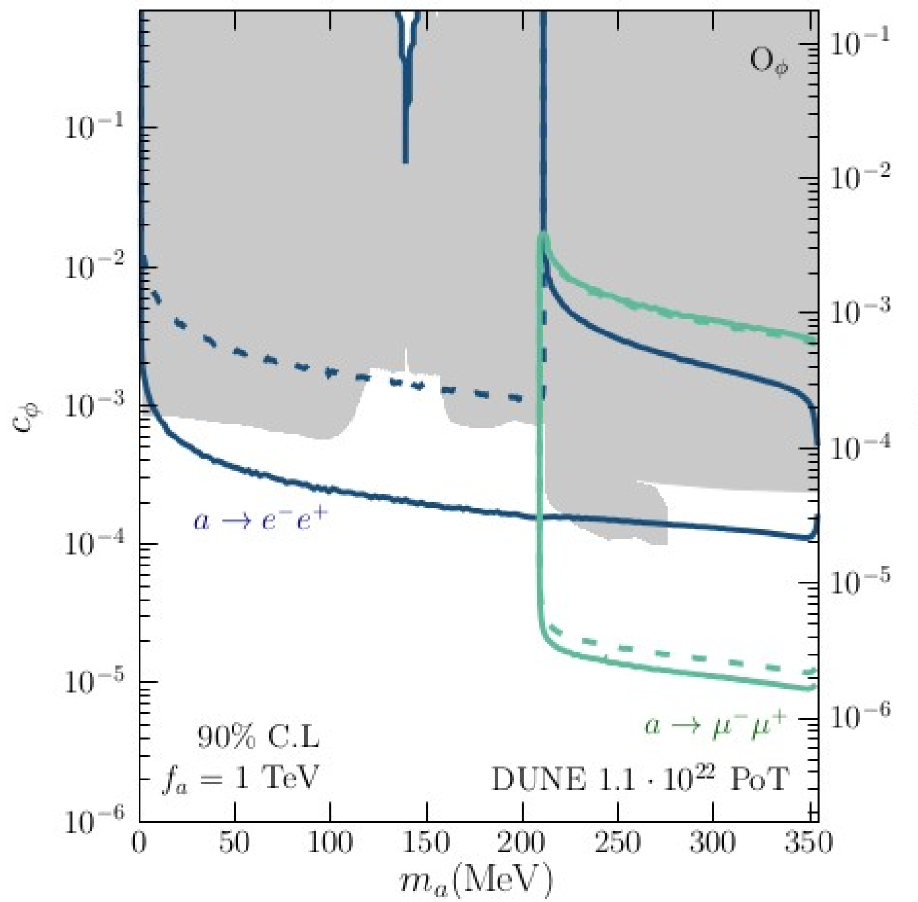
→ Limited by background systematics!! (20%)

Specific ALP scenarios

$$\frac{\alpha_s}{8\pi f_a} a G^b_{\mu\nu} \widetilde{G}^{b\mu\nu}$$

$$c_\phi \frac{\partial^\mu a}{f_a} \phi^\dagger i \overleftrightarrow{D}_\mu \phi$$





Coloma, Martín-Albo and Urrea, 2309.06492

Summary

- Thanks to its location, the protoDUNE modules may be exposed to a beam of new particles produced from the SPS (!!)
- ProtoDUNE@SPS could be sensitive to both decays and scattering, and has the potential to improve over current constraints:
    - With facilities already in place
    - Without interfering with experiments in the CERN North Area
    - Within a very short-timescale

  → A more detailed assessment of backgrounds and efficiencies is required (work in progress)
- On a longer timescale, DUNE has the potential to be a major player in LLP decay searches:
    - a Gaseous TPC will be key to ensure high efficiencies and sufficient background rejection

Thanks!

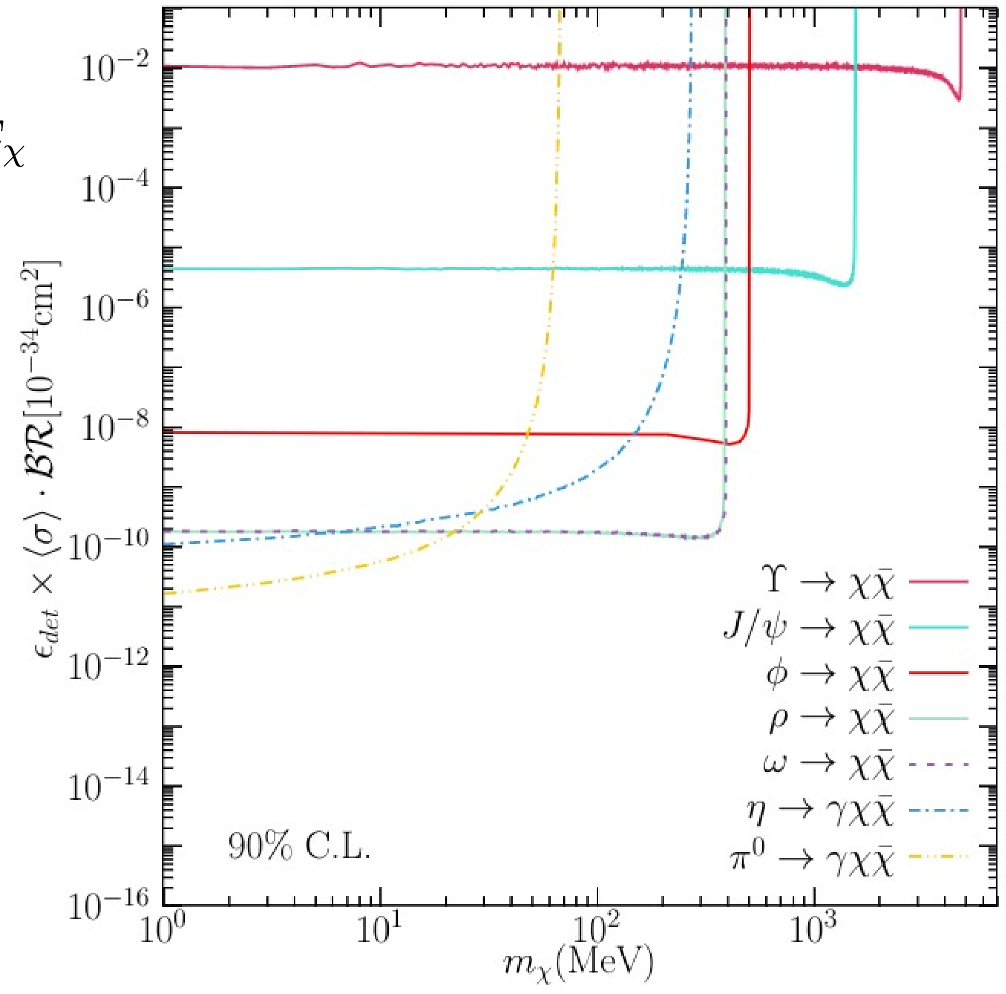
Work supported by Grants RYC2018-024240-I, PID2019-108892RB-I00, CEX2020-001007-S, PID2022-142545NB-C21

Backup

Model-independent case

$$N_{ev} = \mathcal{N}\,\epsilon_{det}\cdot\langle\sigma\rangle\cdot\mathcal{BR}\ \mathrm{PS}\,(m_\chi, m_M)\ \tilde{\Phi}^\chi$$

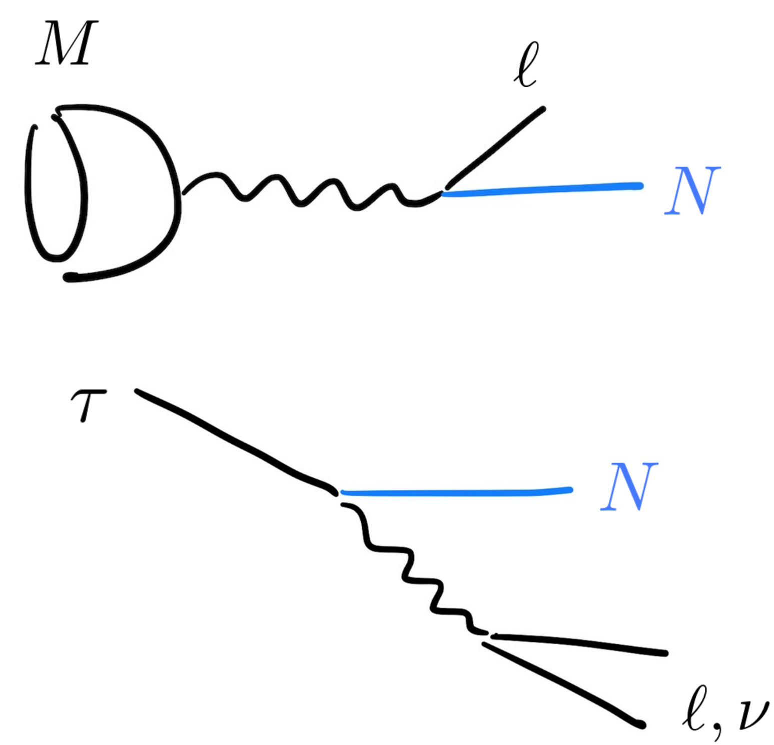
$$\langle\sigma\rangle = \frac{1}{\tilde{\Phi}^\chi}\int_0^\infty\int_{T^{\min}}^{T^{\max}} \frac{d\sigma}{dT}(E_\chi,\{X\})\,\frac{d\tilde{\Phi}^\chi}{dE_\chi}\,dT\,dE_\chi$$

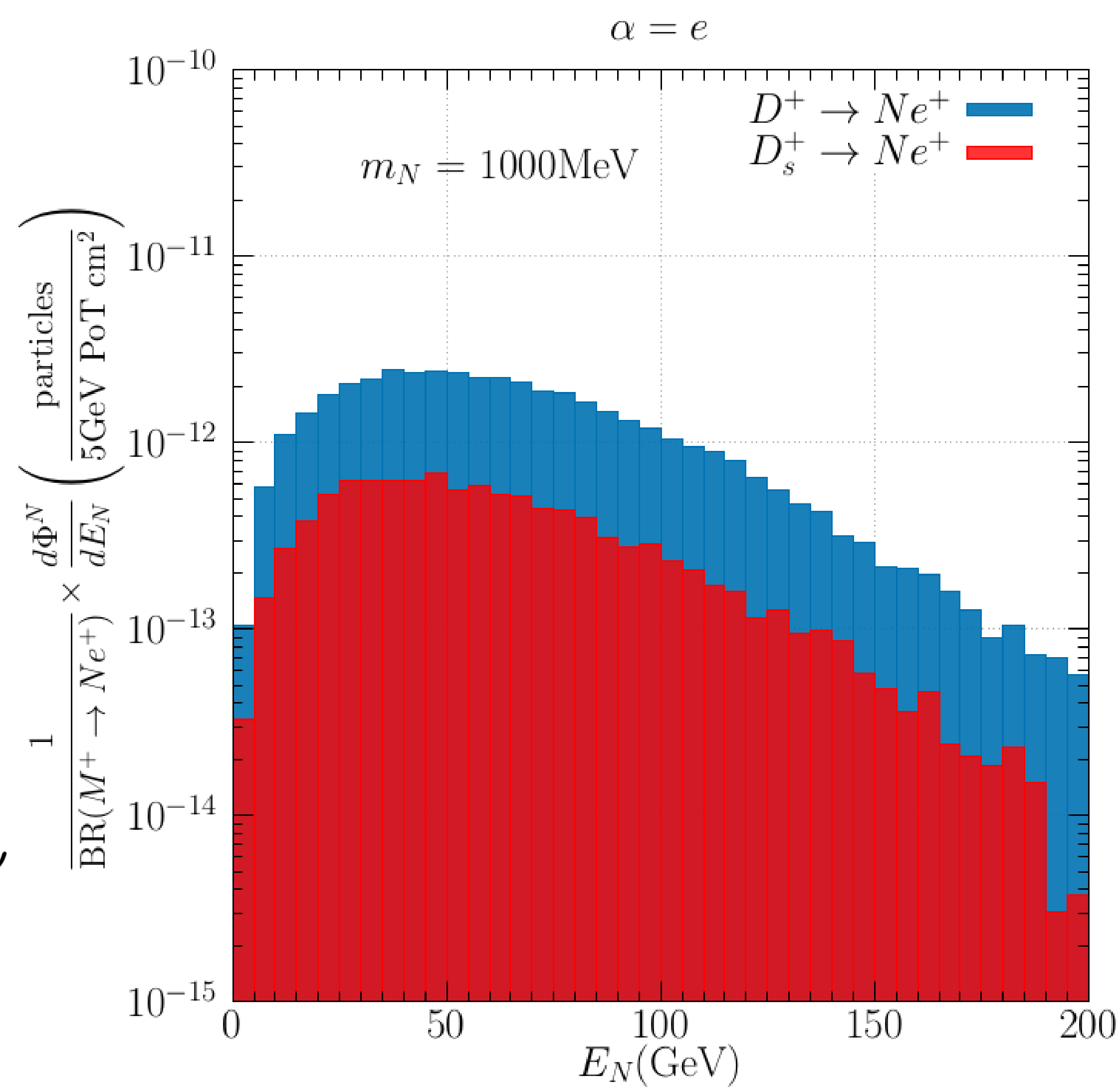


Coloma, López-Pavón, Molina-Bueno & Urrea, 2304.06765

HNL fluxes

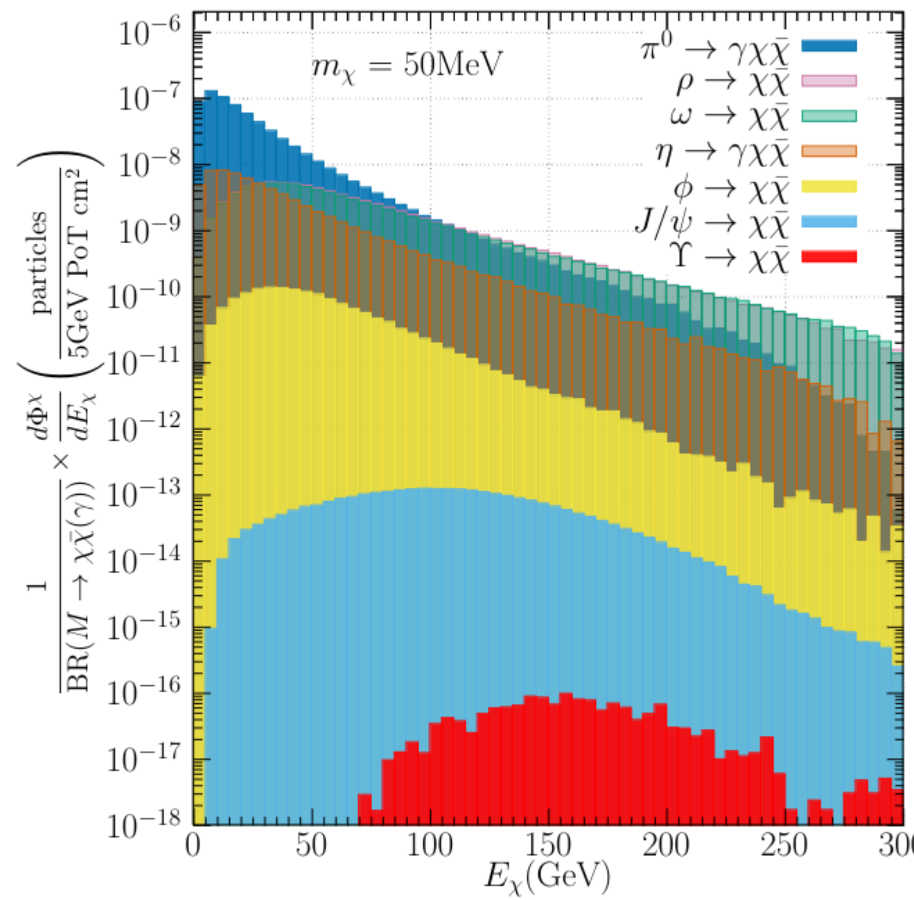
$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4}N$$





Model-independent case

$$N_{ev} = N_{\mathrm{PoT}}\, N_{trg}\, \epsilon_{det} \cdot \langle \sigma \rangle \cdot \Phi^{\chi}$$



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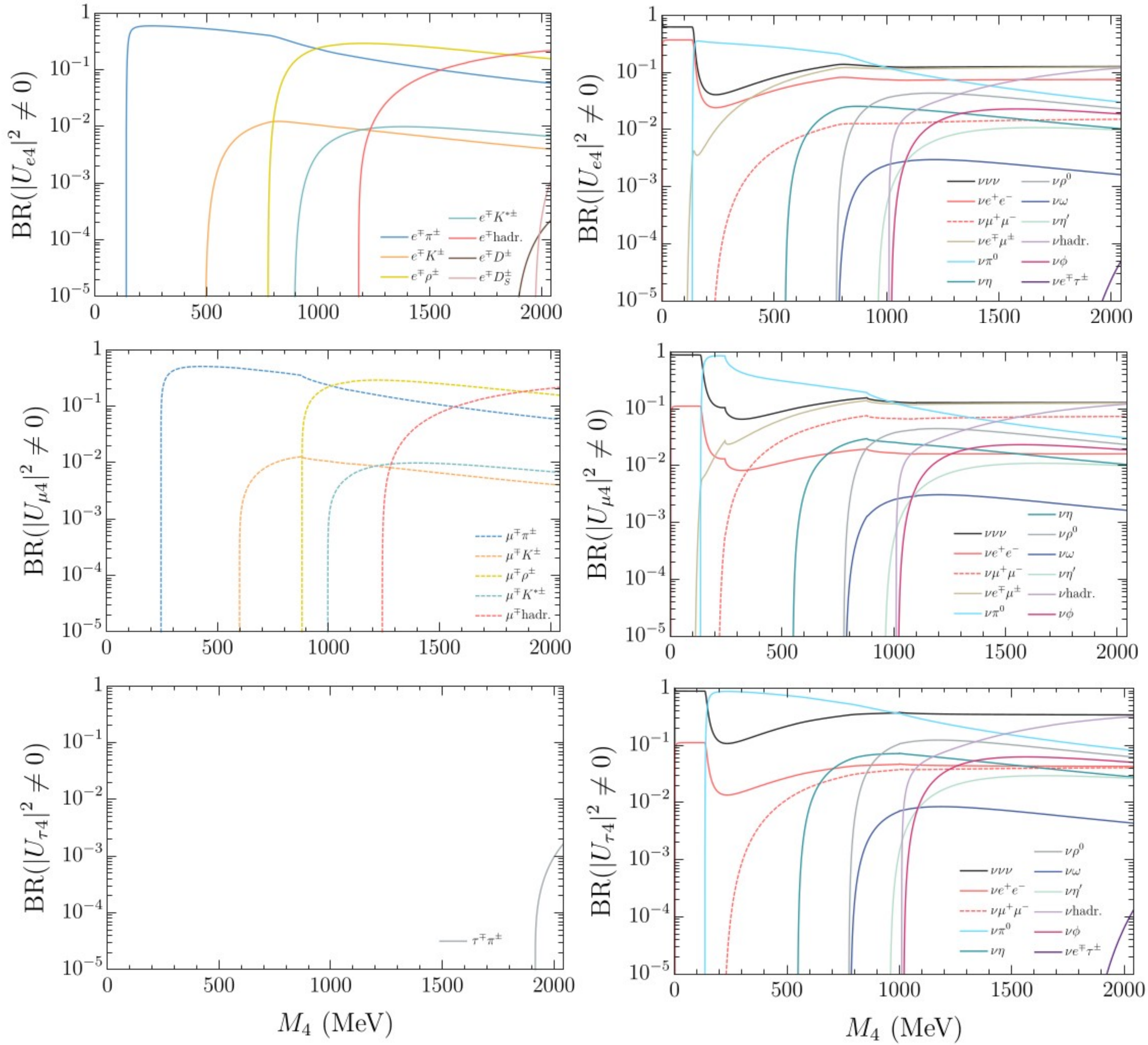
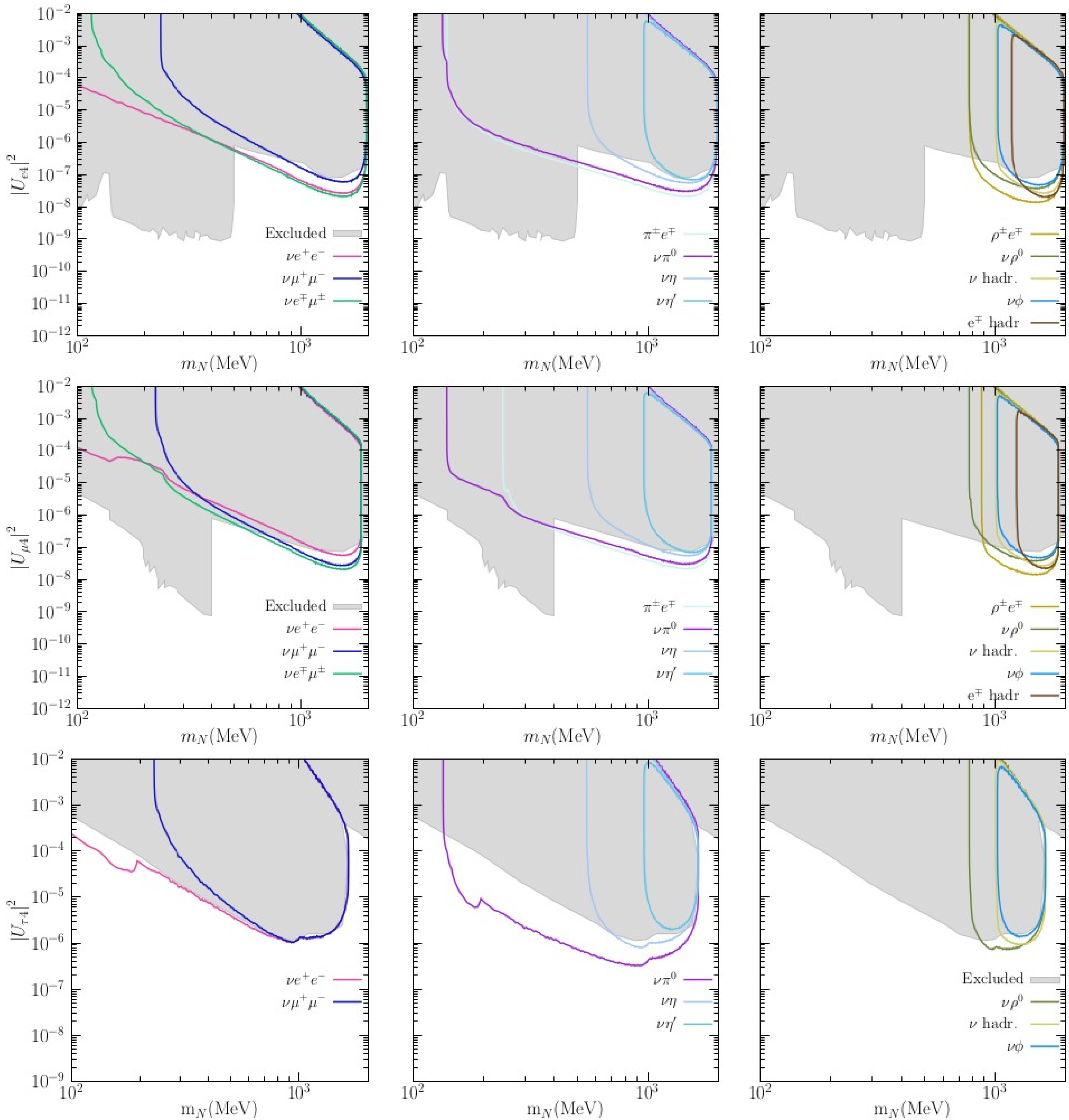


Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Pavlovic, 2007.03701



$|U_{e4}|^2$
$|U_{\mu4}|^2$
$|U_{\tau4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm e^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm e^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
$e^\mp$ hadr