Long-lived Particles, ProtoDUNE, and the SPS

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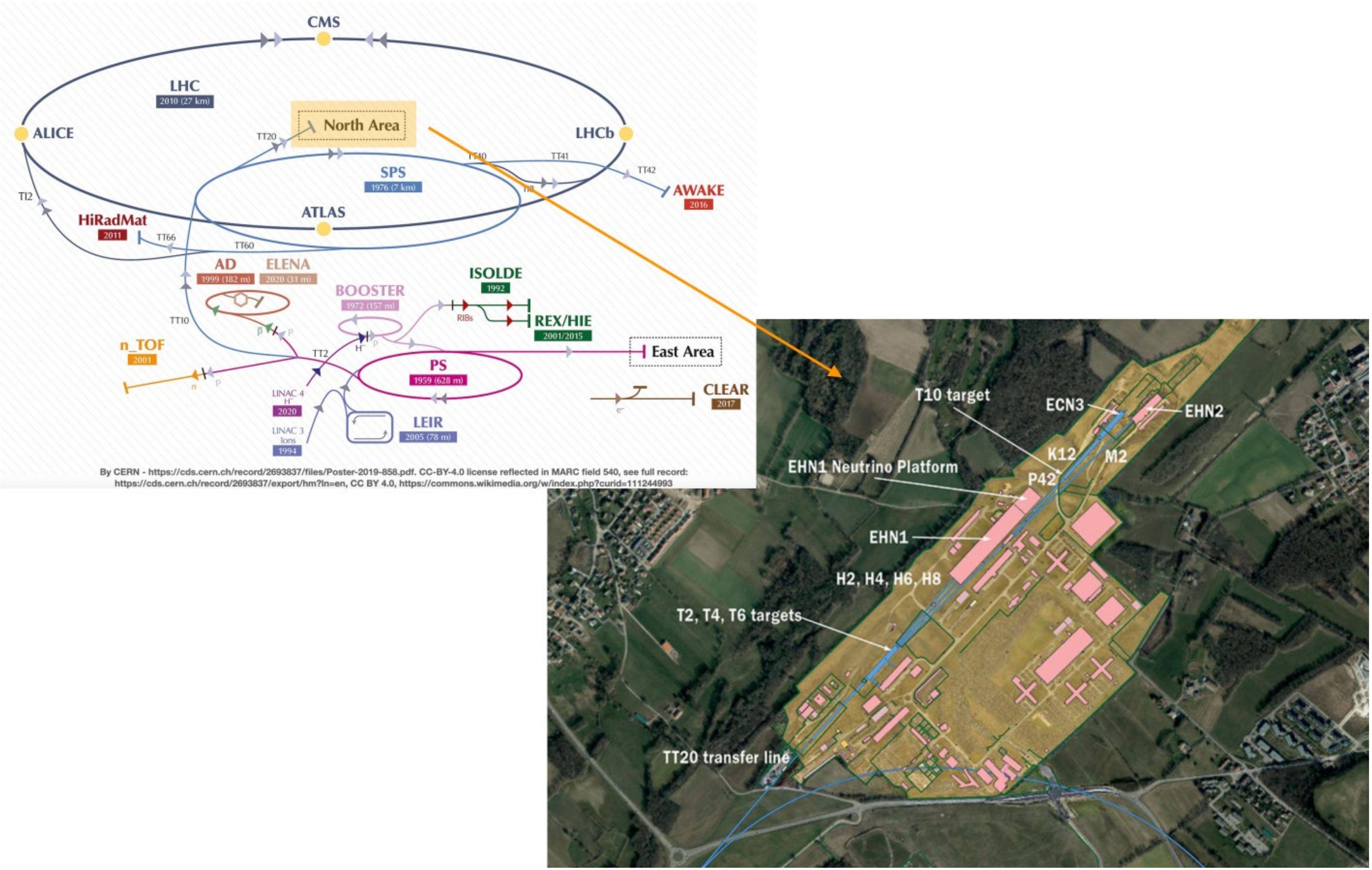
Based on arXiv:2304.06765
In collaboration with Jacobo López-Pavón, Laura Molina-Bueno and Salvador Urrea

RED-LHC Workshop, IFT, Madrid (May 11th, 2023)

Setup



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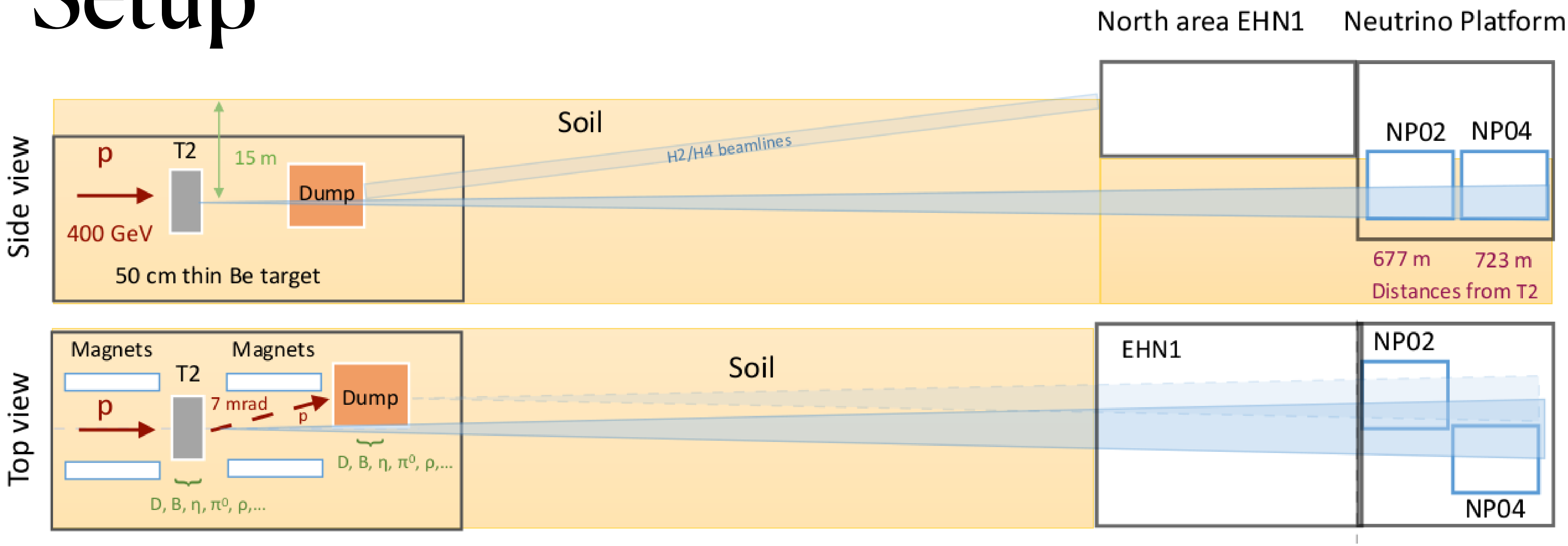
Setup



Main features:

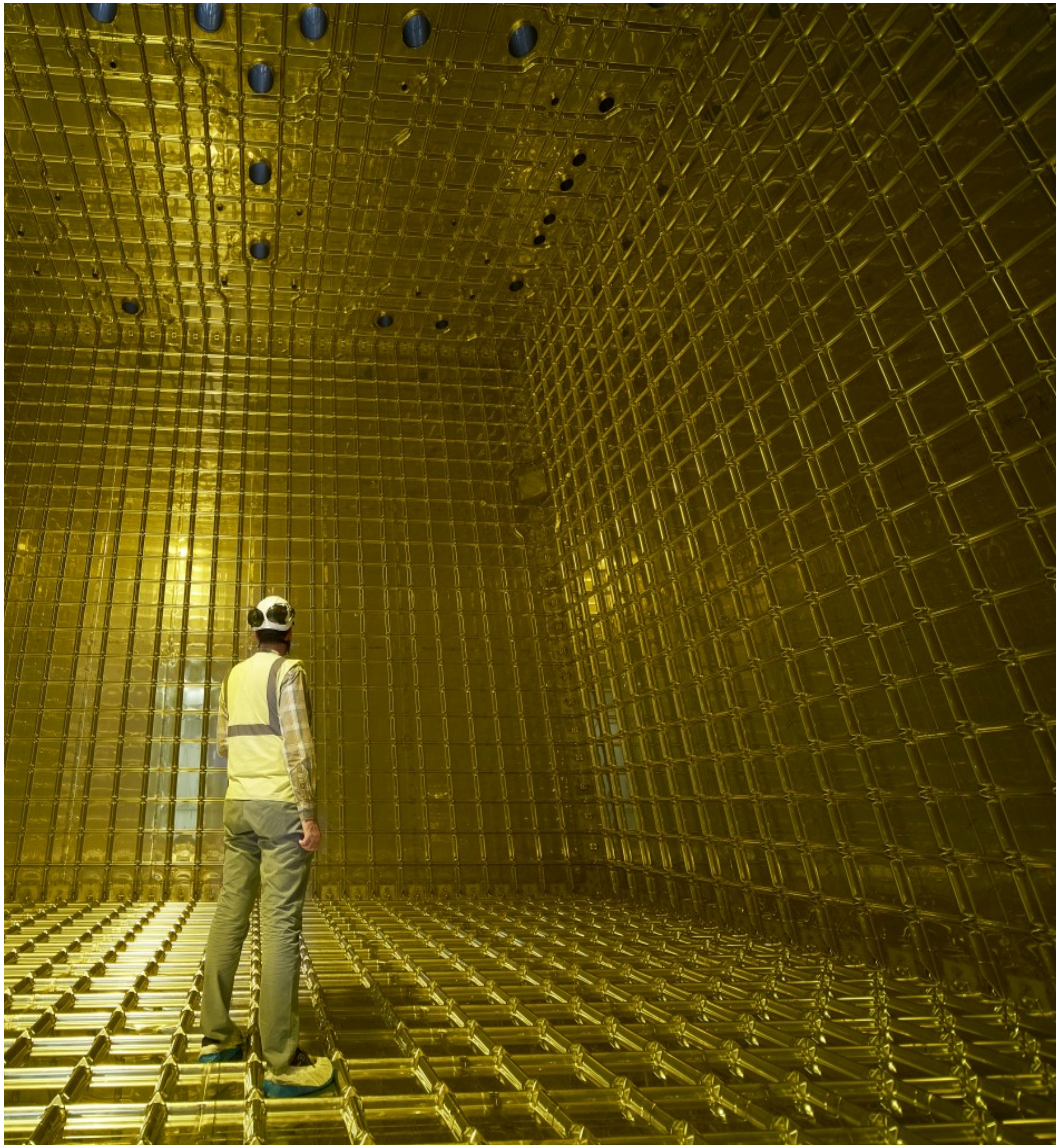
- no decay volume
- very high proton energy!

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	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

ProtoDUNE



Two modules available (we only consider NP02 here):

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

Key advantages:

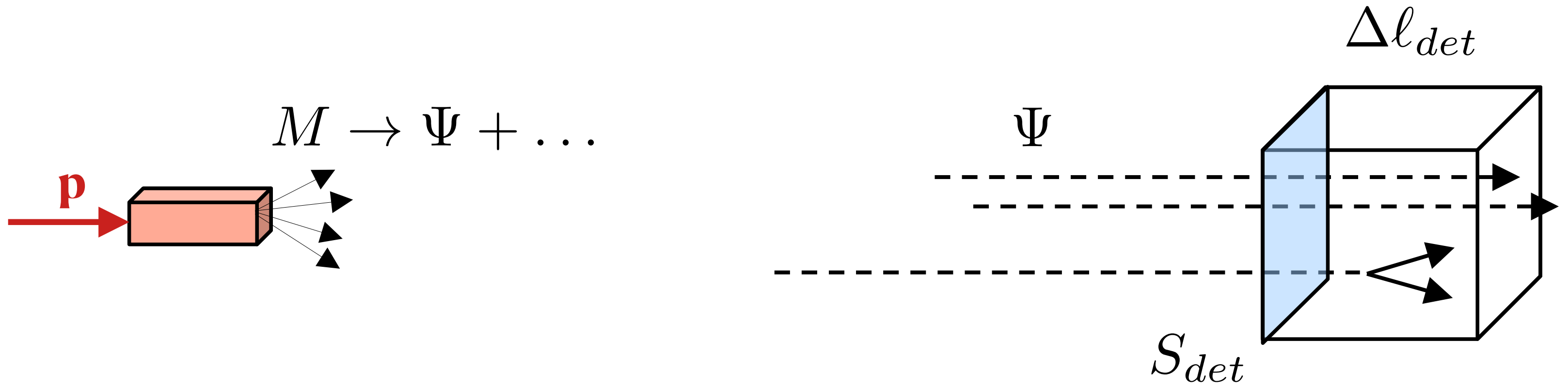
- Excellent reconstruction and particle ID
- Very low detection thresholds

Main disadvantage:

- They are on surface (tons of cosmics!)

Expected number of decays

$$N_{ev} = \underbrace{N_M \mathrm{BR}(M \to \Psi)}_{\text{Number of particles produced}} \underbrace{\mathrm{BR}(\Psi \to \mathrm{Vis})\, \epsilon_{eff}}_{\text{Is the final state observable?}} \int dS \int dE_\Psi\, \underbrace{\mathcal{P}(c\tau_\Psi / m_\Psi, E_\Psi, \Omega_\Psi)}_{\text{Decay probability within detector}} \underbrace{\frac{dn^{M\to\Psi}}{dE_\Psi dS}}_{\text{Dependence with energy and angle}}$$

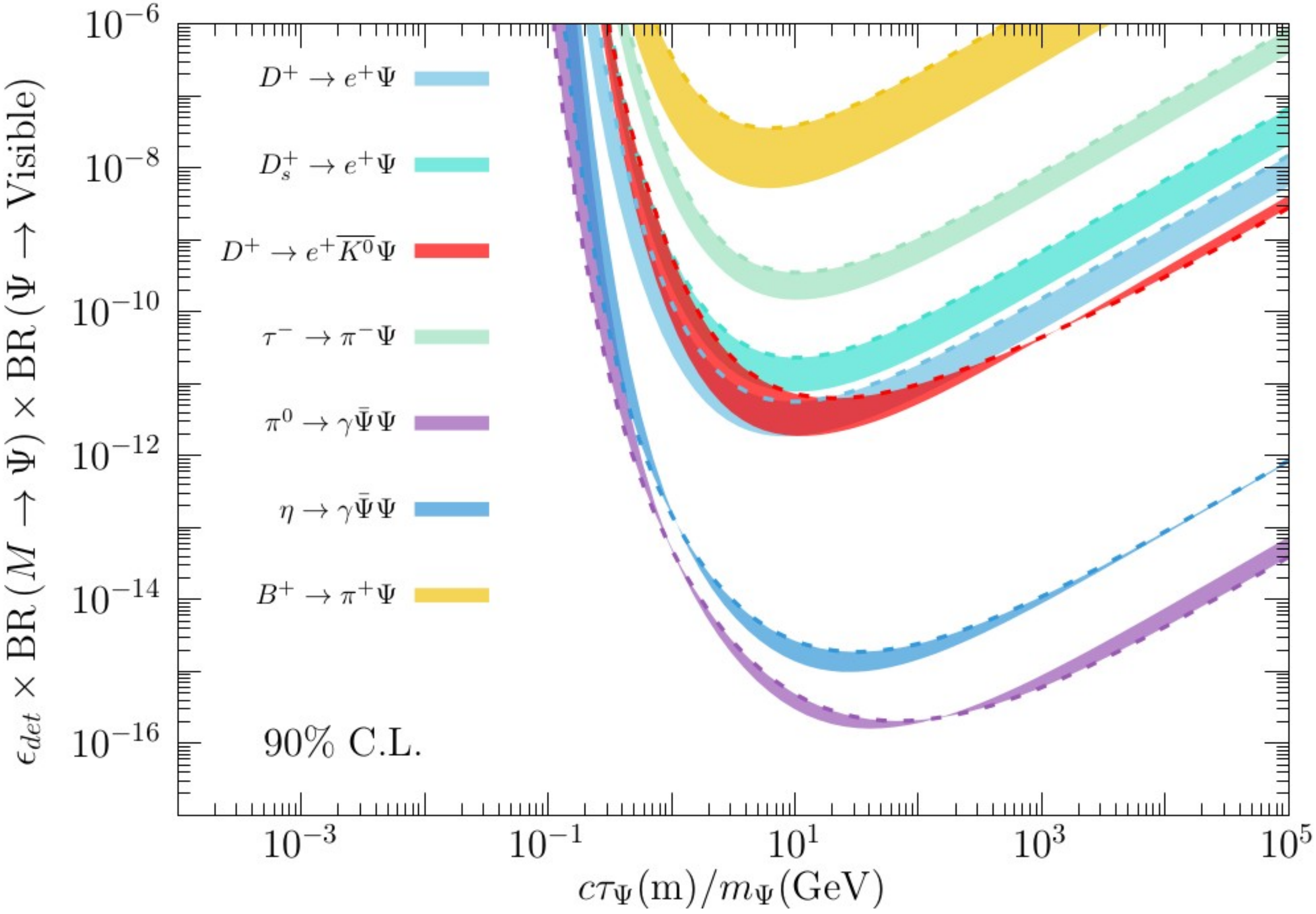


Expected number of decays

$$N_{ev} = N_M \underbrace{\mathrm{BR}(M \to \Psi)\mathrm{BR}(\Psi \to \mathrm{Vis})}_{\text{Model-dependent}}\, \epsilon_{eff} \int dS \int dE_\Psi\, \underset{\substack{\uparrow \\ \text{Model-dependent}}}{\mathcal{P}}(c\tau_\Psi / m_\Psi, E_\Psi, \Omega_\Psi)\, \frac{dn^{M \to \Psi}}{dE_\Psi dS}$$

Model-independent sensitivity

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



→ No correlation assumed between production and decay

→ We assume backgrounds can be efficiently suppressed

Luminosity:

→ 3.5e18 PoT / yr

→ 5 years of data taking

Benchmark scenario: HNL

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

(See yesterday's talks by Martin Hirsch and Xabier Marcano)

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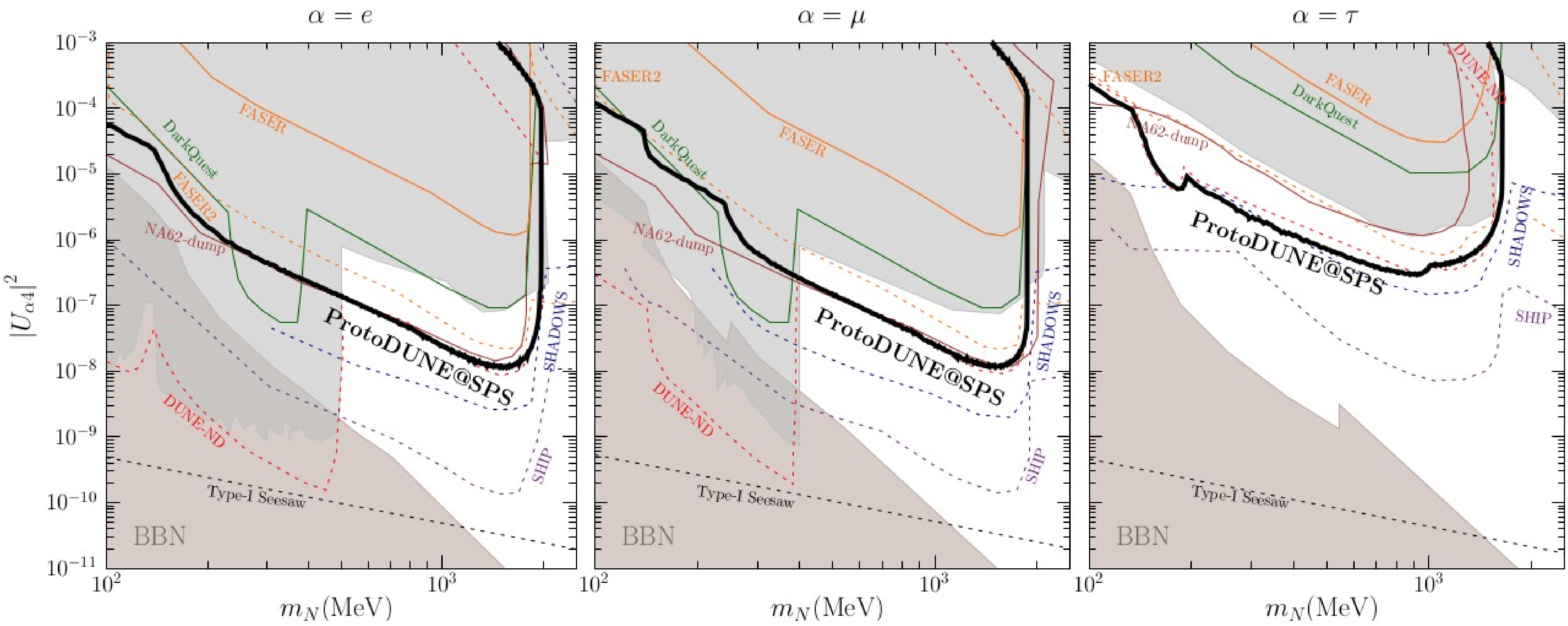
The best bounds for HNL between O(100) MeV - GeV scale come from fixed targets

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



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

Bonus: sensitivity to scattering

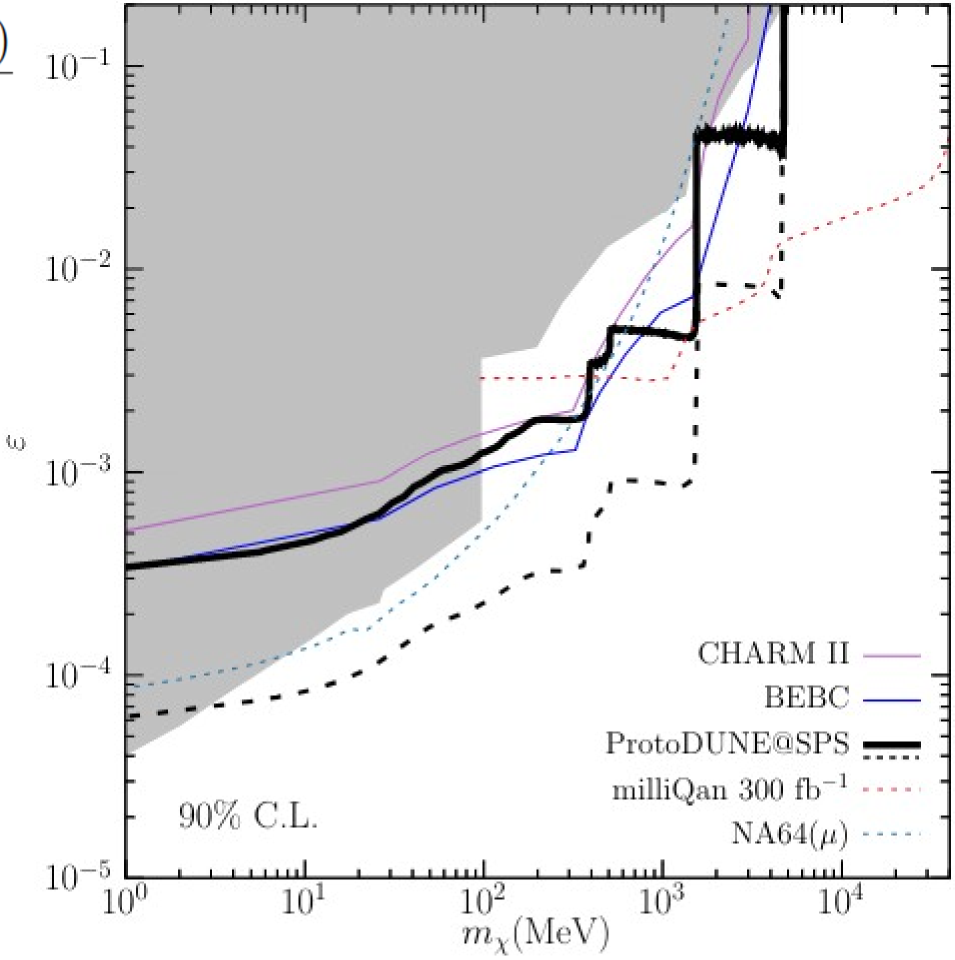
ProtoDUNE can also search for new particles that interact with nuclei or electrons in the detector: either long-lived or stable particles (e.g. millicharged)

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

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

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

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



Summary

- Thanks to its location, the protoDUNE modules may be exposed to a beam of new particles produced from the SPS
- Their large volume, and high mass provide sensitivity to both:
  - Decays (long-lived particles)
  - Scattering (long-lived particles, but also stable particles)
- This setup 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)

Thanks!

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MINISTERIO DE CIENCIA E INNOVACIÓN

European Union
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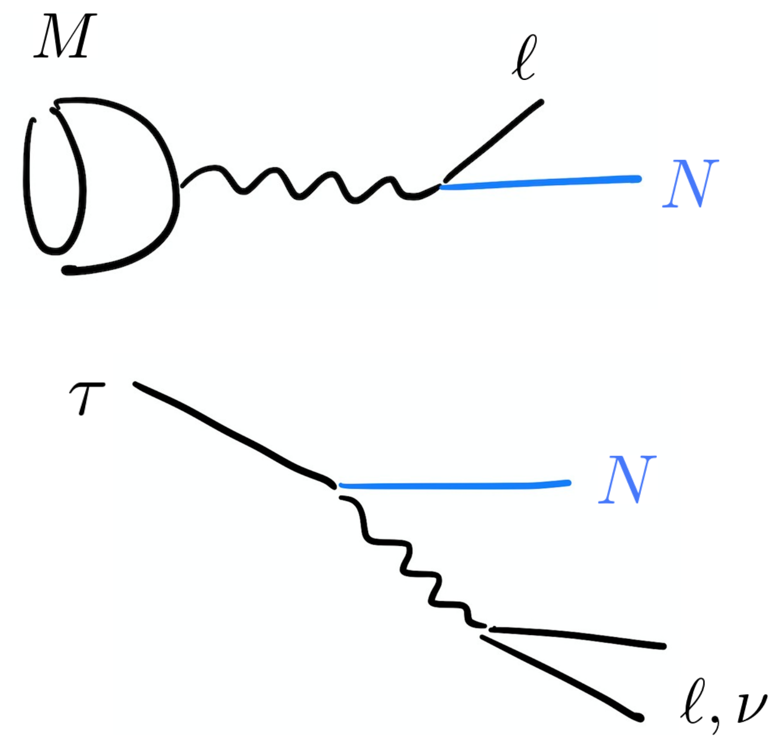
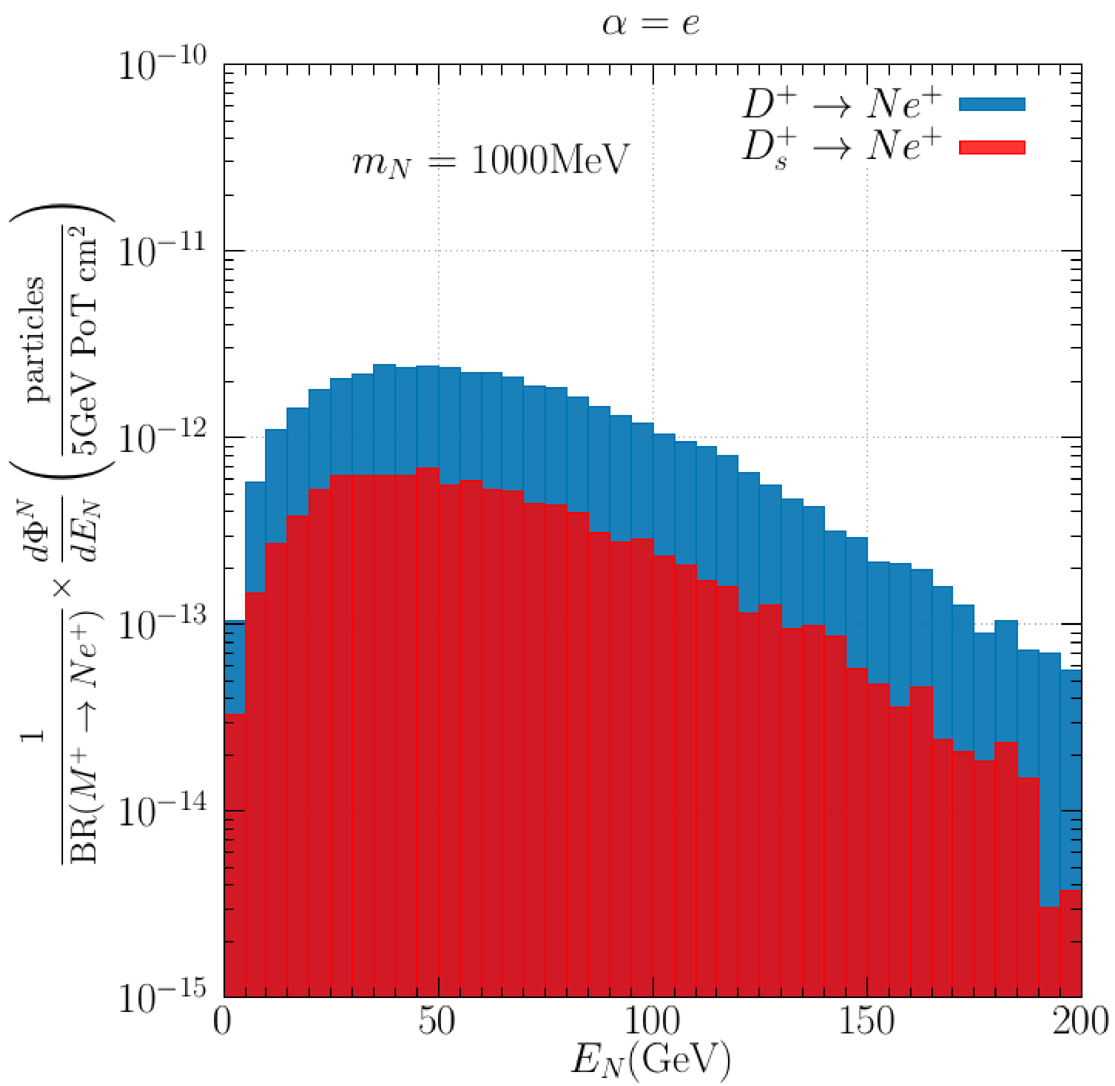
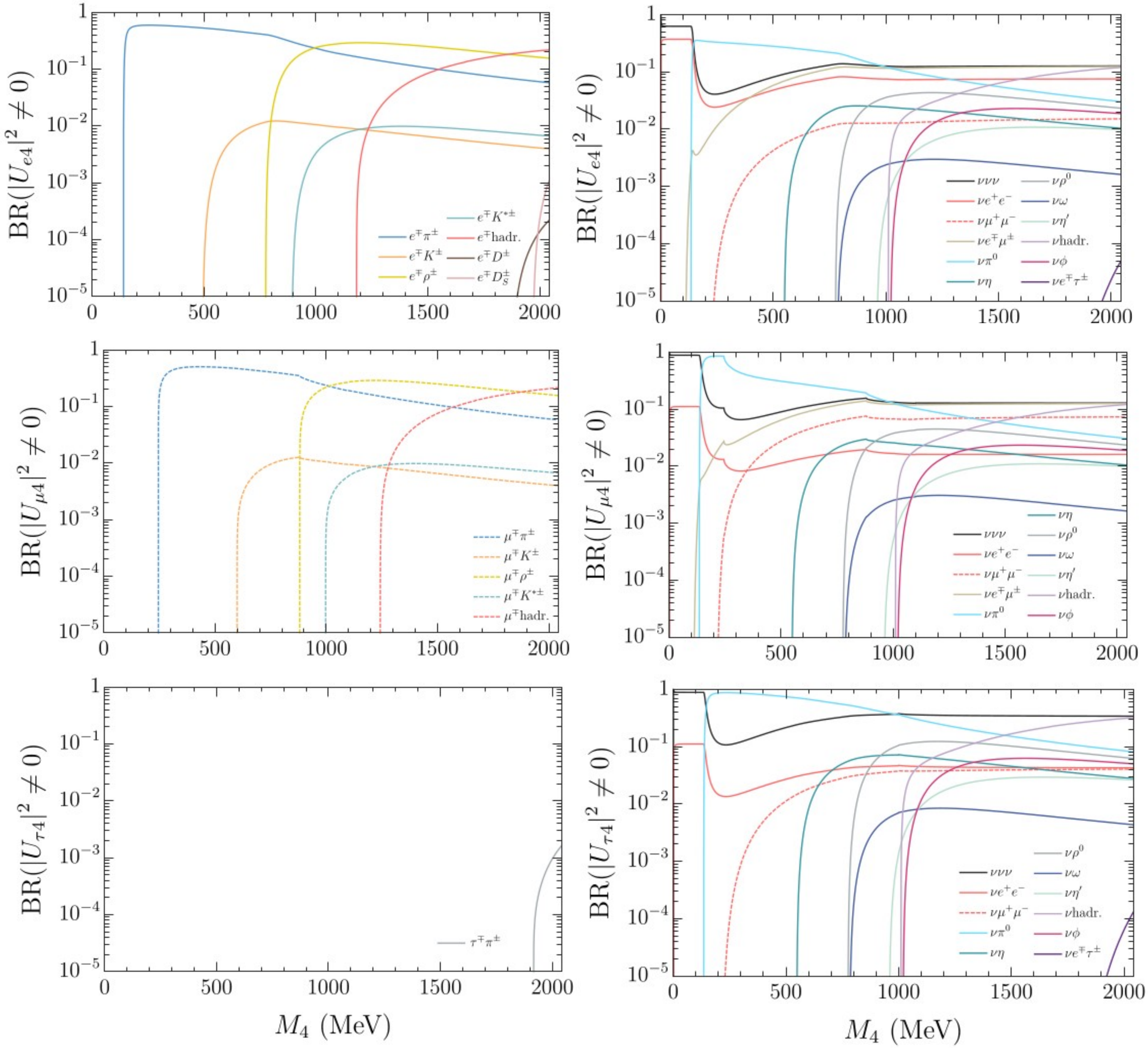
Backup

HNL fluxes

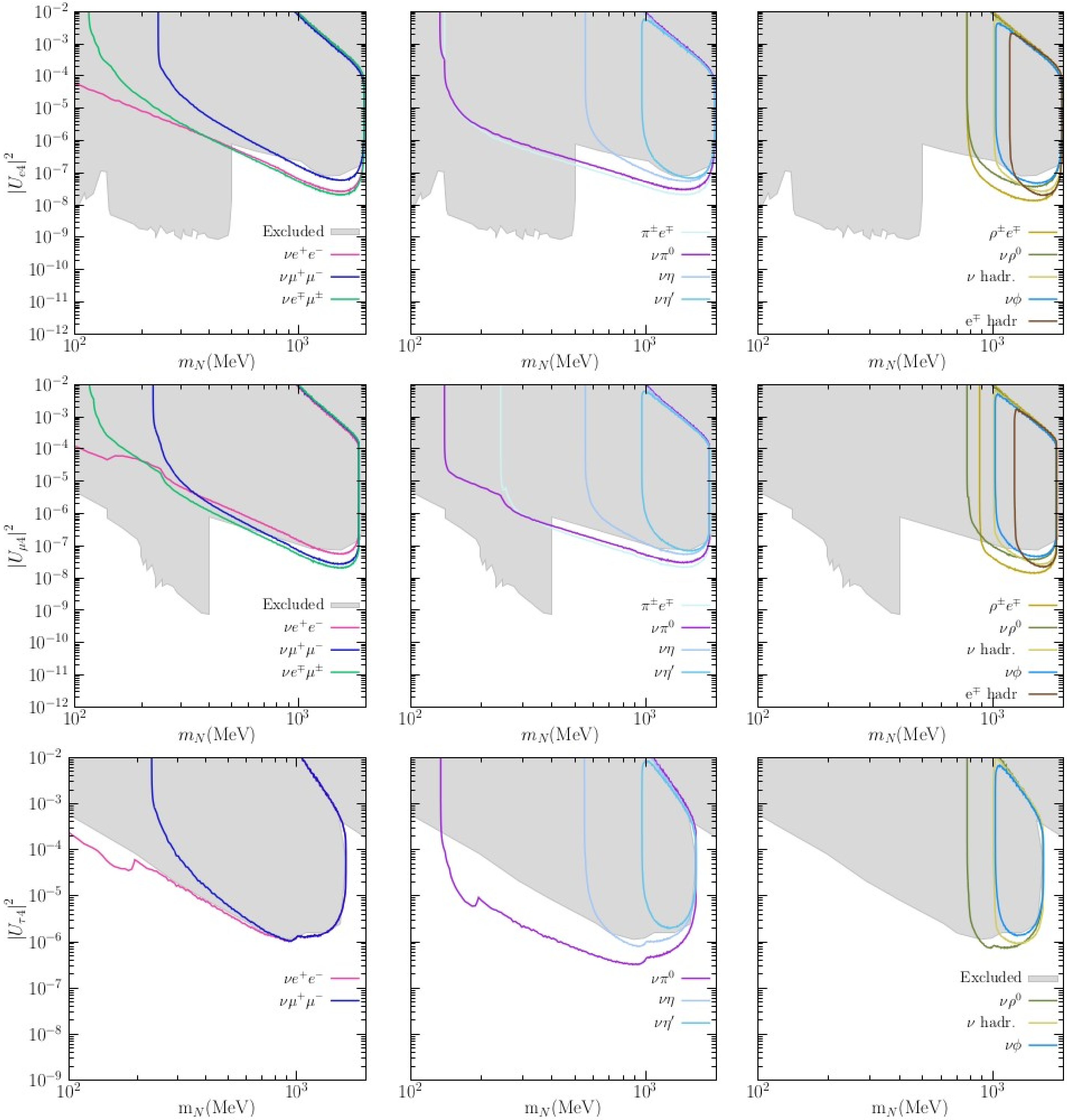
$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4}N$$







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


$|U_{e4}|^2$
$|U_{\mu 4}|^2$
$|U_{\tau 4}|^2$
m_N(MeV)
10^2
10^3
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
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

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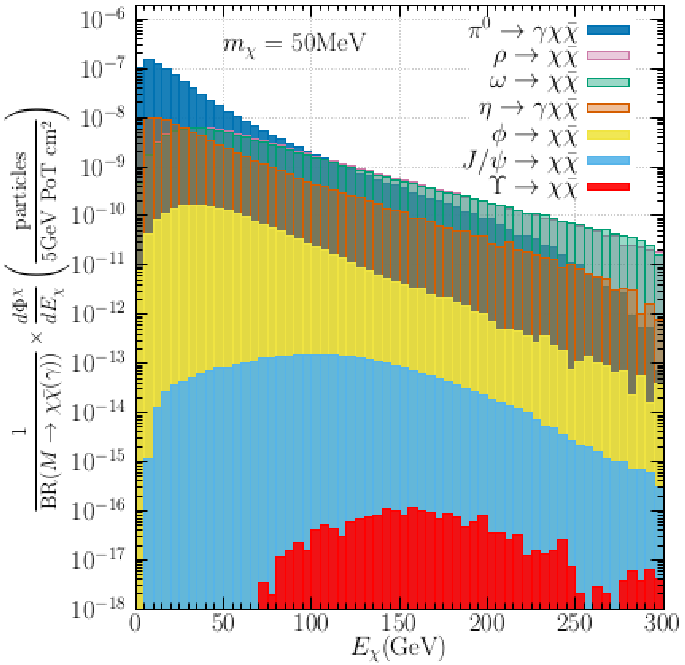

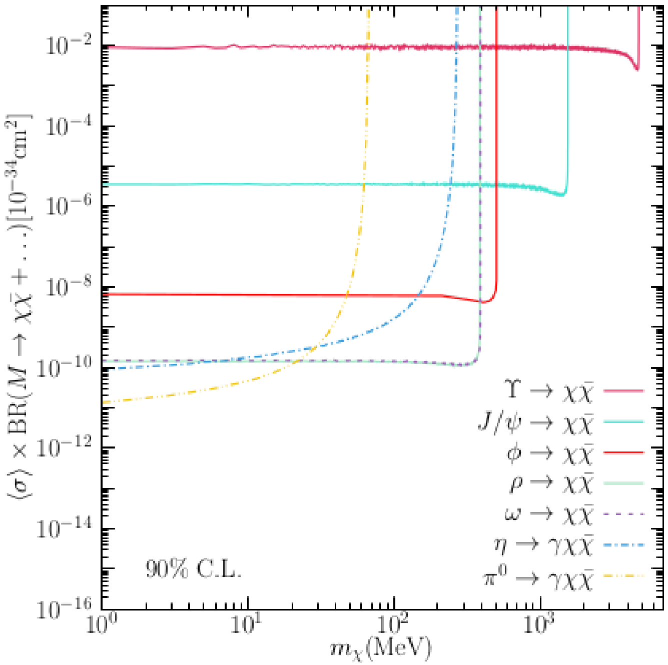

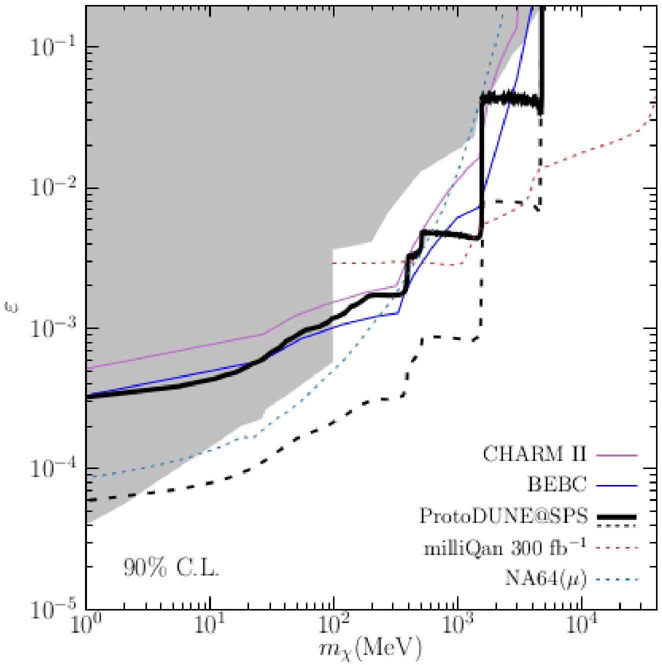

$$\langle\sigma\rangle = \frac{1}{\Phi^\chi}\int_0^\infty \int_{T^{\min}}^{T^{\max}} \frac{d\sigma}{dT}\left(E_\chi, \{X\}\right)\frac{d\Phi^\chi}{dE_\chi} dT dE_\chi$$