New Physics searches using ProtoDUNE and the CERN SPS accelerator

Salvador Urrea (Salvador.Urrea@ific.uv.es)

Based on arXiv:2304.06765

In collaboration with Pilar Coloma, Jacobo López-Pavón and Laura Molina-Bueno

TAUP 2023 August 31, 2023

VNIVERSITAT DE VALÈNCIA
IFIC INSTITUT DE FÍSICA CORPUSCULAR
Gen—T
CIDEGENT/2018/019
GENERALITAT VALENCIANA

Open problems in Particle Physics

Origin of neutrino masses, Baryon asymmetry of the universe and the origin of dark matter

↓ **Provide solutions**

FIPs

↓

They come in many forms

Vector (***Dark Photon)***, Scalar (***Dark Higgs)***, Fermion (***Heavy neutral lepton***), Pseudo-scalar (***Axion***)

Both the interaction strengths with SM particles and the masses of the FIPs range over many orders of magnitude.

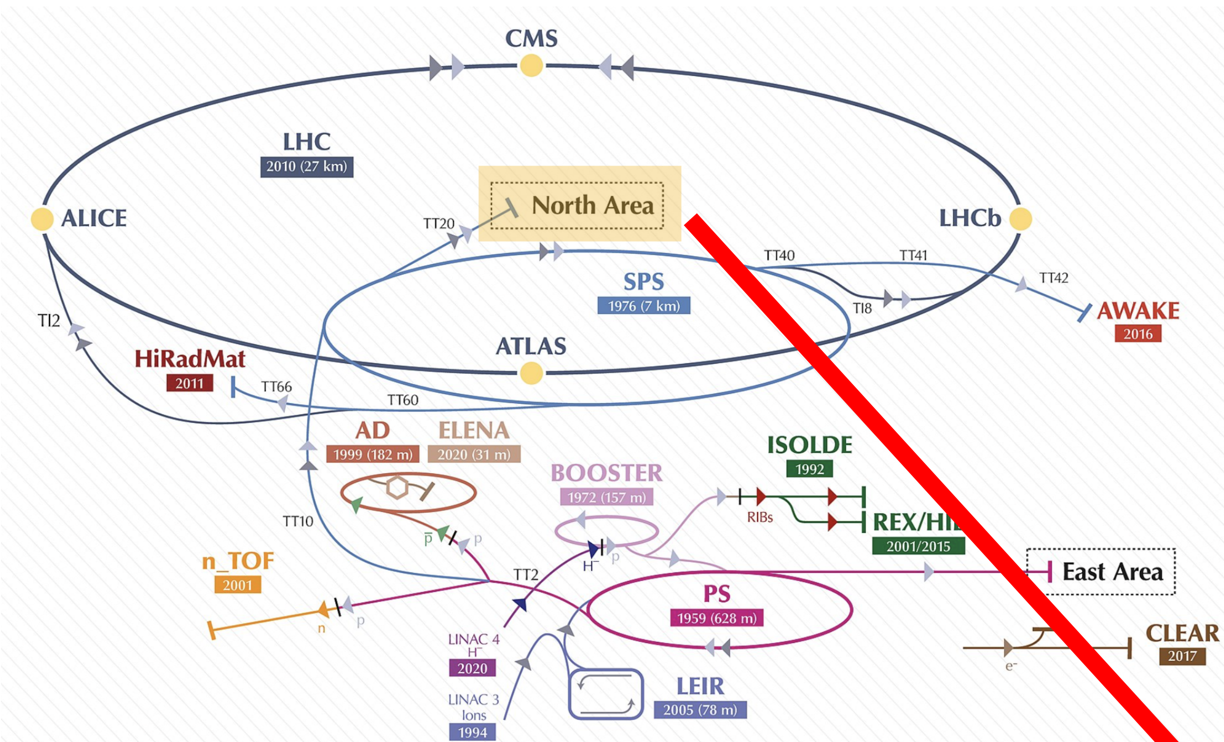
Many different types of experiments are needed

When the interaction stregth is sufficiently large and the mass ranges from 10^{-2} GeV to 10 GeV, it can be accessed by accelerator-based experiments

ProtoDUNE run as a Fixed-target experiment

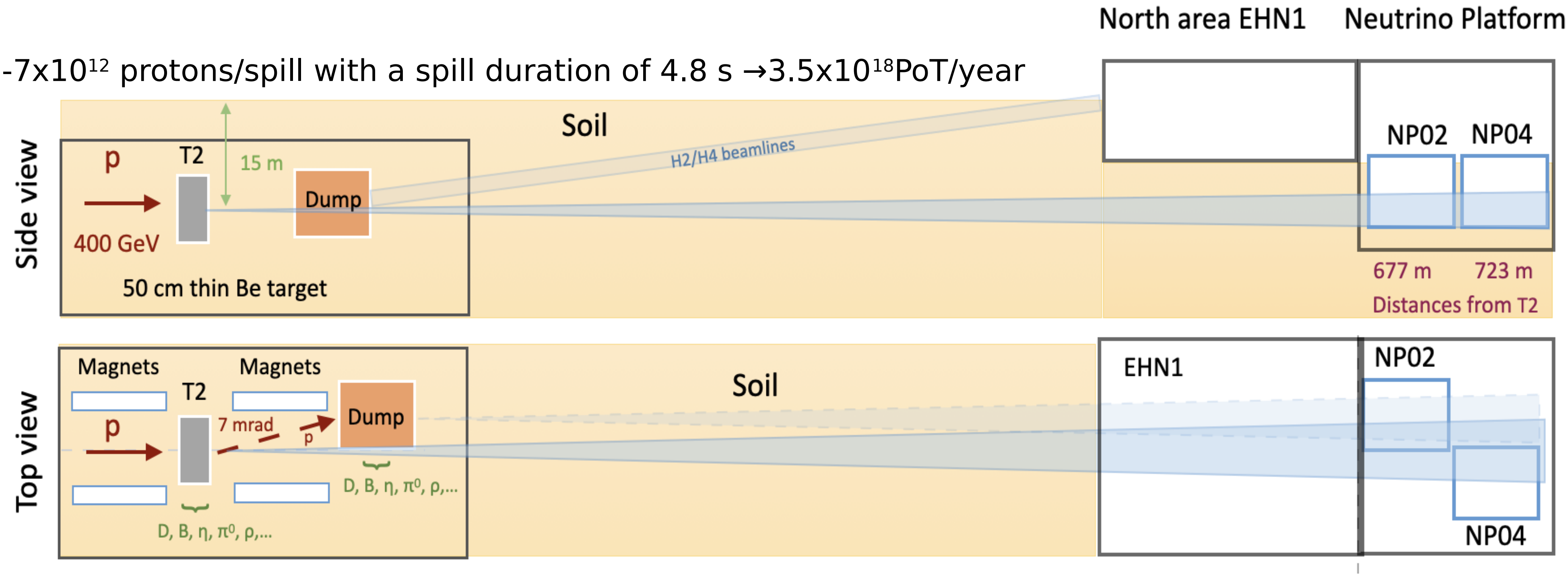
Experimental set-up

Experimental set-up: Extracted beam lines



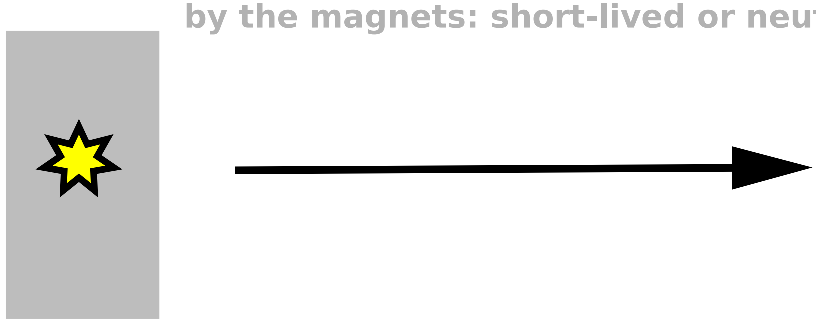
Experimental set-up: T2 target

~5-7x10^{12} protons/spill with a spill duration of 4.8 s →3.5x10^{18}PoT/year



We are only interested in mesons not affected by the magnets: short-lived or neutral

400 GeV protons



Meson production yield Y_M (normalised per PoT)

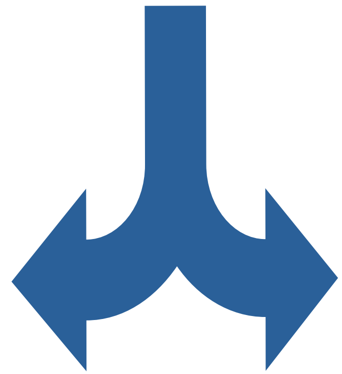
π^0	η	η'	D	D_s	τ
4.03	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
ρ	ω	ϕ	J/ψ	B	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

Distributions obtained from *Pythia*

New Physics

New Physics: Type of searches

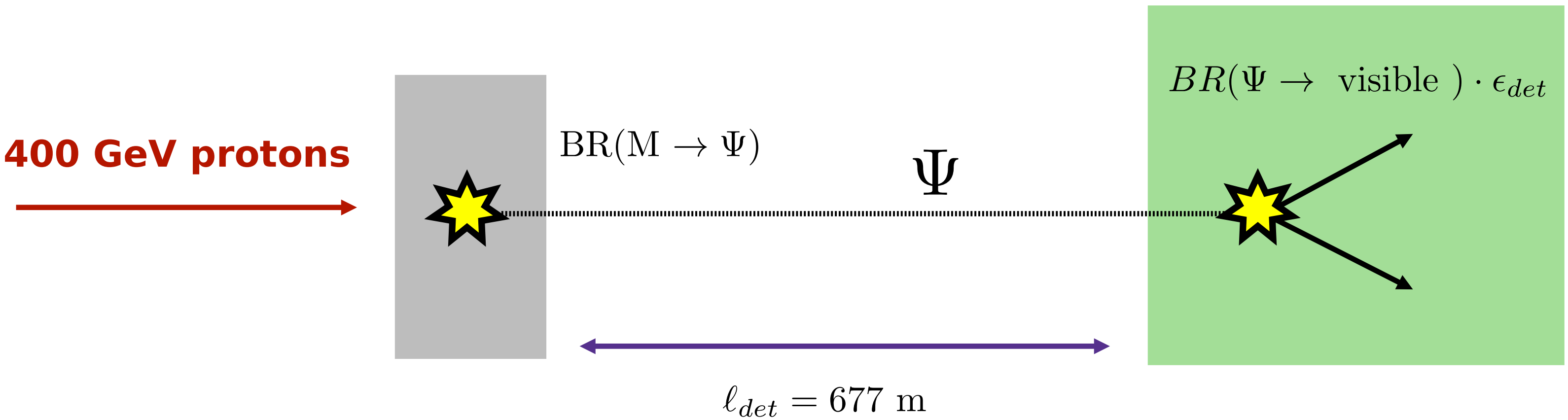
New particles produced in meson decays



Long-lived	Very long-lived (Stable)
(HNL, ALPs, dark photon,...)	(Milicharged particles,...)
Decay in flight inside the detector	Modify cross sections

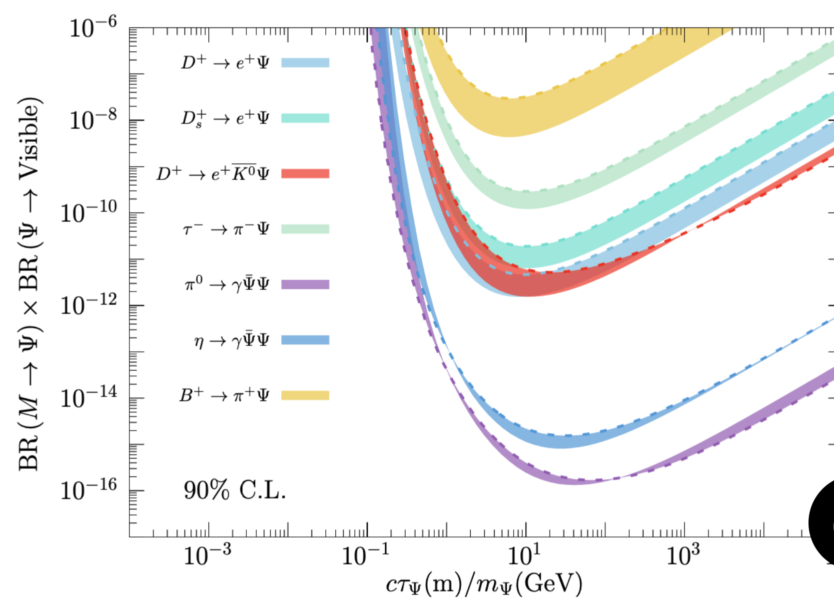
New Physics: Decay in flight inside the detector

Detector(NP02) Liquid Argon TPC



$$\mathrm{N}^M_{dec} = N_{\mathrm{PoT}} Y_M \mathrm{BR}(M \to \Psi) \int dS \int dE_\Psi \mathcal{P}\left(c\tau_\Psi/m_\Psi, E_\Psi, \Omega_\Psi\right) \frac{dn^{M\to\Psi}}{dE_\Psi dS}$$

$$\mathrm{N}_{det} = N^M_{dec} \cdot BR(\Psi \to \text{ visible }) \cdot \epsilon_{det}$$



Large couplings

$$e^{-\frac{\ell_{\mathrm{det}}}{L_\Psi}}$$

$$\mathrm{P} = \mathrm{e}^{\frac{-\ell_{\mathrm{det}}}{L_\Psi}} \left(1 - e^{\frac{-\Delta\ell_{\mathrm{det}}}{L_\Psi}}\right)$$

$$1 - e^{-\frac{\Delta\ell_{\mathrm{det}}}{L_\Psi}} \propto (coupling)^2$$

Small couplings

HNL

HNL: Production

$$L \supset -\frac{m_W}{v}\bar{N}U^*_{\alpha 4}\gamma^\mu l_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\bar{N}U^*_{\alpha 4}\gamma^\mu \nu_{L\alpha}Z_\mu$$

We consider the simplified phenomenological benchmarks of one HNL mixing with one SM neutrino of a given flavour

U_{e4} $U_{\mu 4}$ $U_{\tau 4}$

We don't have pions and kaons

Parent	2-body decay	3-body decay
$\pi^+ \to$	e^+N_4	—
	μ^+N_4	
$K^+ \to$	e^+N_4	$\pi^0 e^+ N_4$
	μ^+N_4	$\pi^0 \mu^+ N_4$
$\tau^- \to$	$\pi^- N_4$	$e^- \overline{\nu} N_4$
	$\rho^- N_4$	$\mu^- \overline{\nu} N_4$

Parent	2-body decay	3-body decay
$D^+ \to$	e^+N_4	$e^+\overline{K^0}N_4$
	μ^+N_4	$\mu^+\overline{K^0}N_4$
	τ^+N_4	
$D_s^+ \to$	e^+N_4	—
	μ^+N_4	
	τ^+N_4	

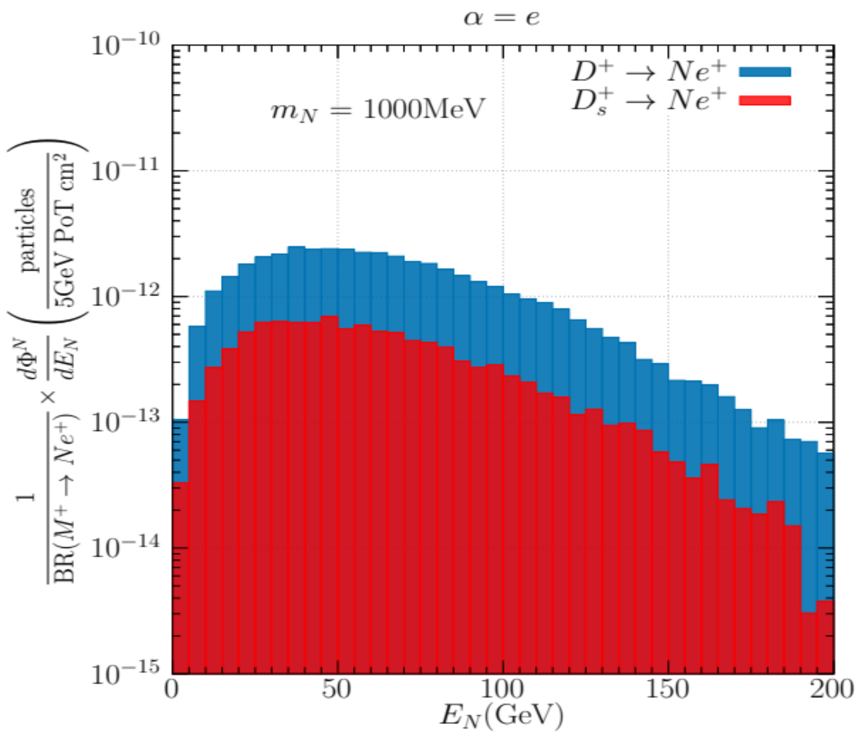
(normalised per PoT)

D	D_s	τ
$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$

$Br(D_s^- \to \tau^- \overline{\nu}_\tau) = 5.43\%$

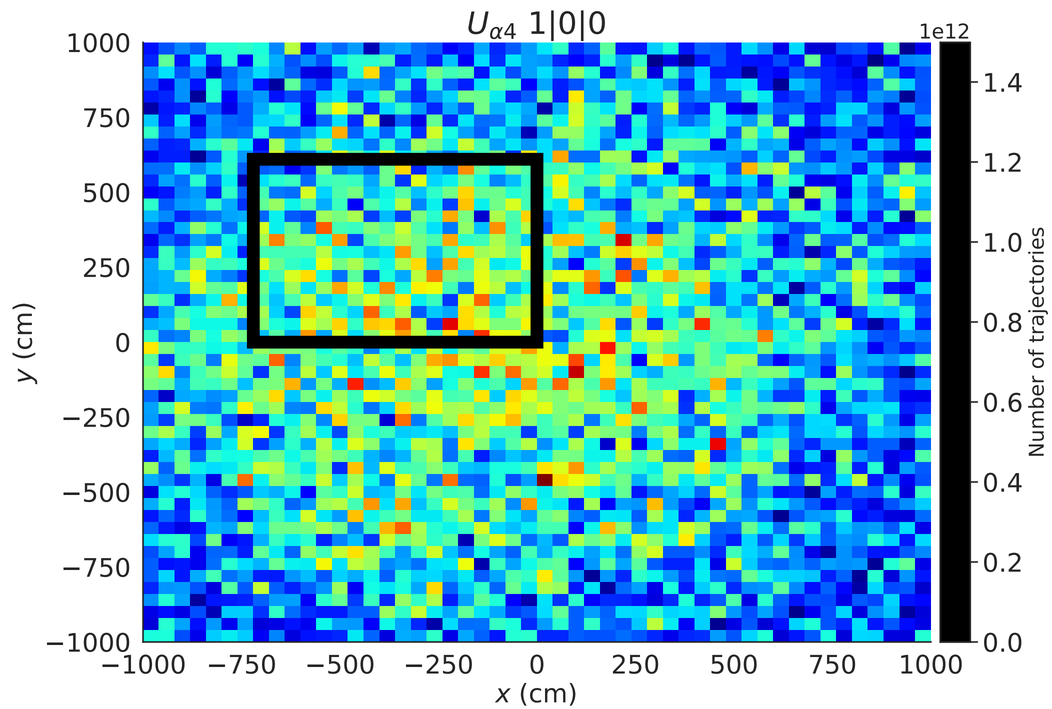
HNL: Fluxes

HNL intersecting the detector



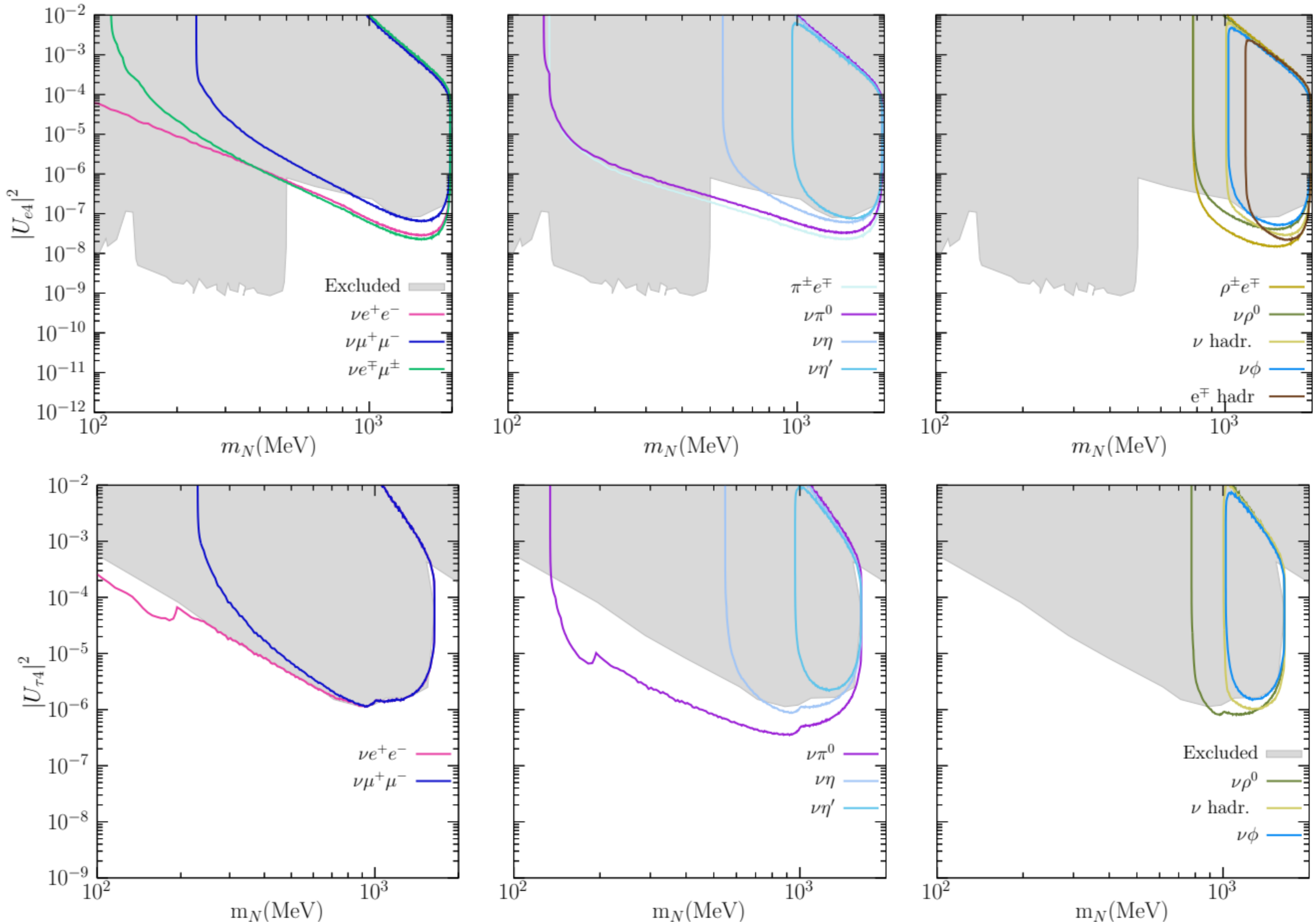
- Quite energetic HNL beam

HNL at z = 677 m



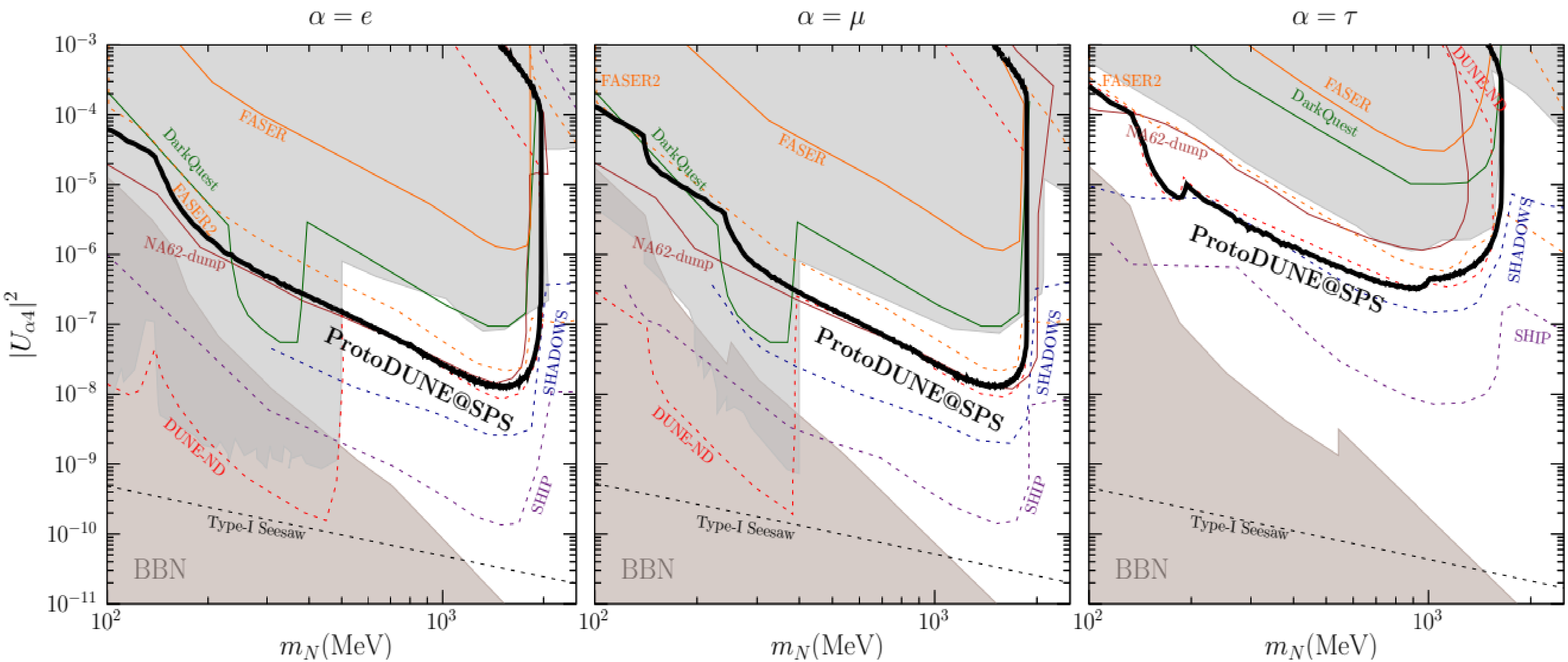
- Wide HNL beam
- Small changes in the geometry will not significantly change the results
- Any of the two ProtoDUNE detectors can be used

HNL: Decays into visible channels



HNL: Decays into visible channels (combination)

We consider the following channels $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi$ and $\nu\pi^0$



Summary

- The excellent imaging capabilities, the large fiducial volume and the convenient location with respect to the T2 target of the ProtoDUNE detectors make them ideal to search for weakly interacting massive particles in Beyond Standard Model scenarios, such as long lived unstable particles and stable particles. In particular HNL and millicharged particles

Outlook

- A dedicated analysis is required to determine the expected backgrounds and efficiencies for the different detection channels consider.

- The development of a dedicated new trigger is needed for this type of searches

- Other models of new physics can be explored: ALPs, light dark matter, etc.

Thank you

VNIVERSITAT DE VALÈNCIA

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Gen—T

GENERALITAT VALENCIANA

HIDDeν

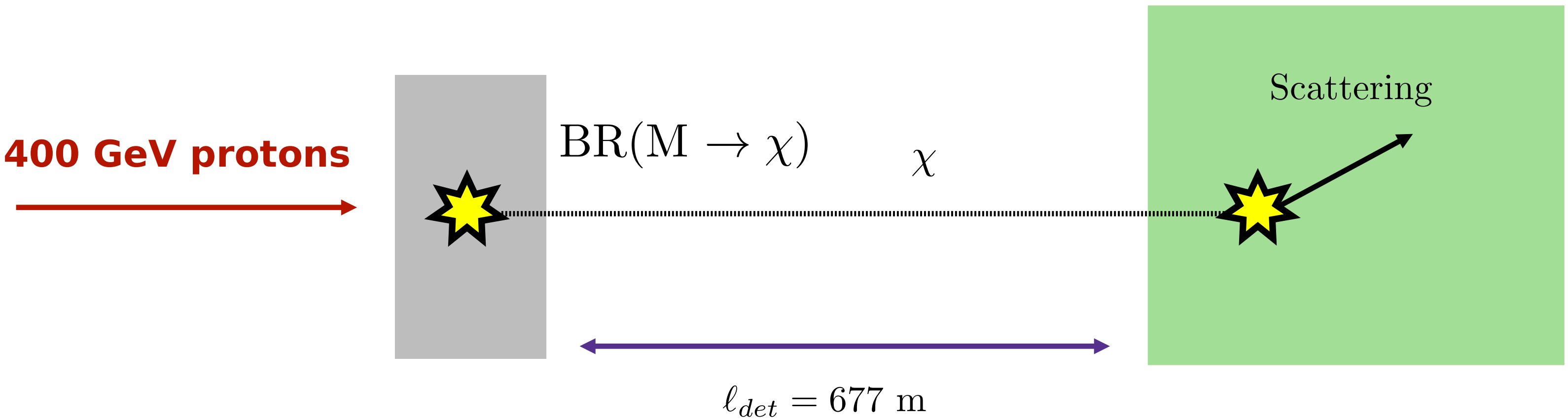
UAM
Universidad Autónoma de Madrid

ift
Instituto de Física Teórica
UAM-CSIC

Back-up

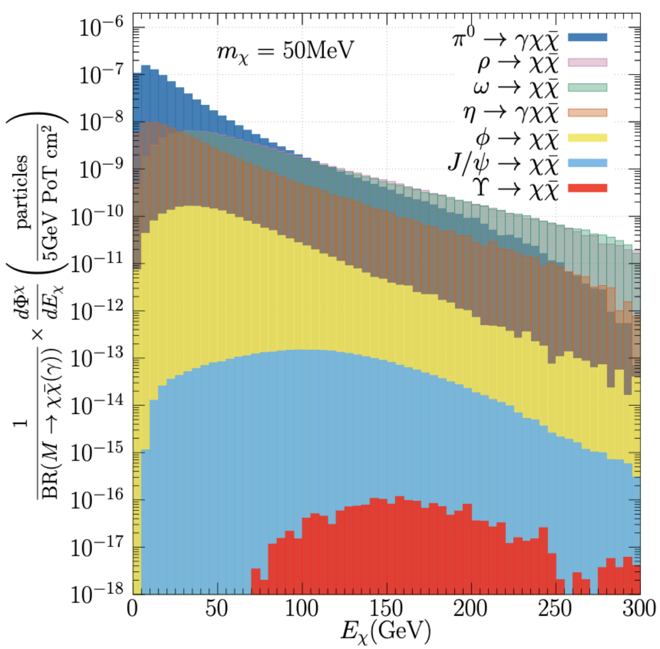
New Physics: stable particles

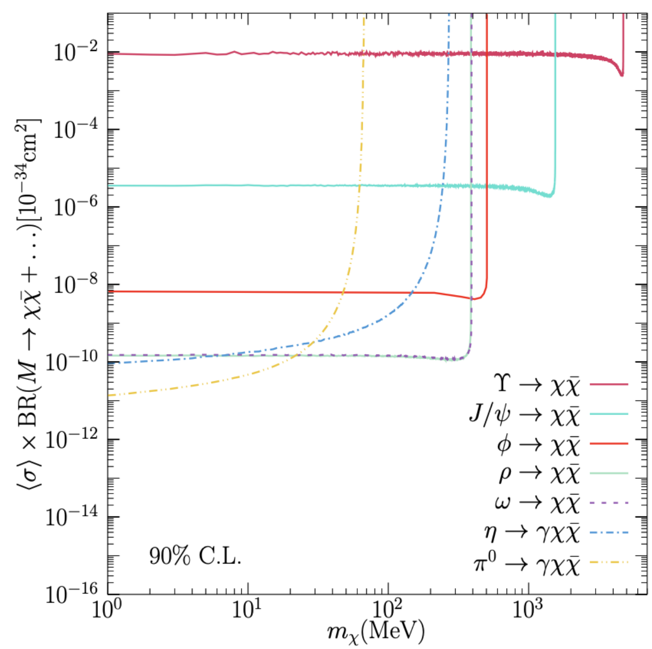
Detector(NP02)
Liquid Argon TPC



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

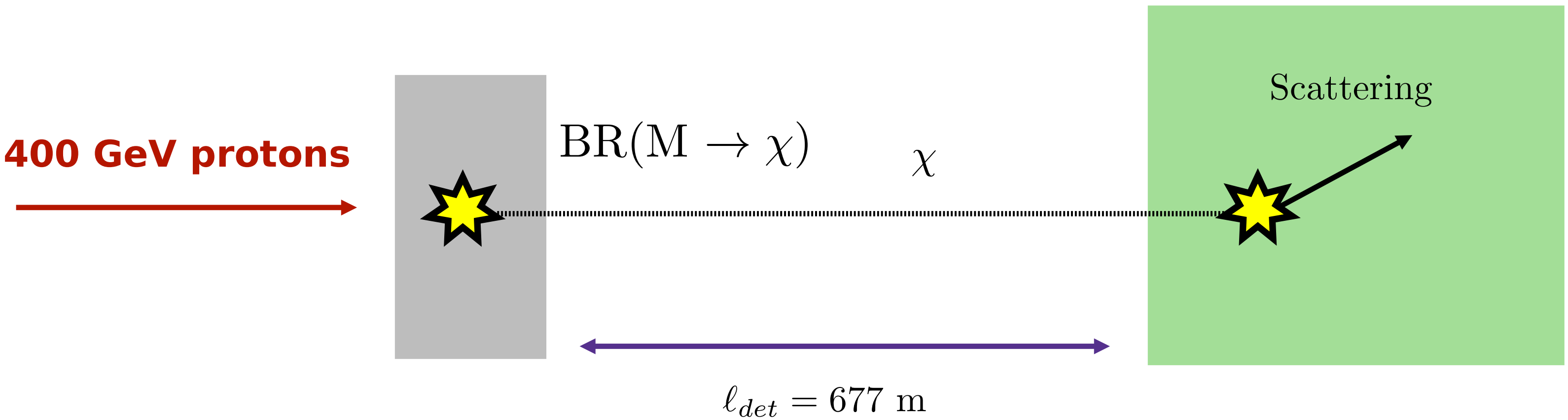
$$\mathrm{N}_{ev} = \epsilon_{\rm det}\, N_{trg}\langle\sigma\rangle\Phi^\chi N_{\rm PoT},$$

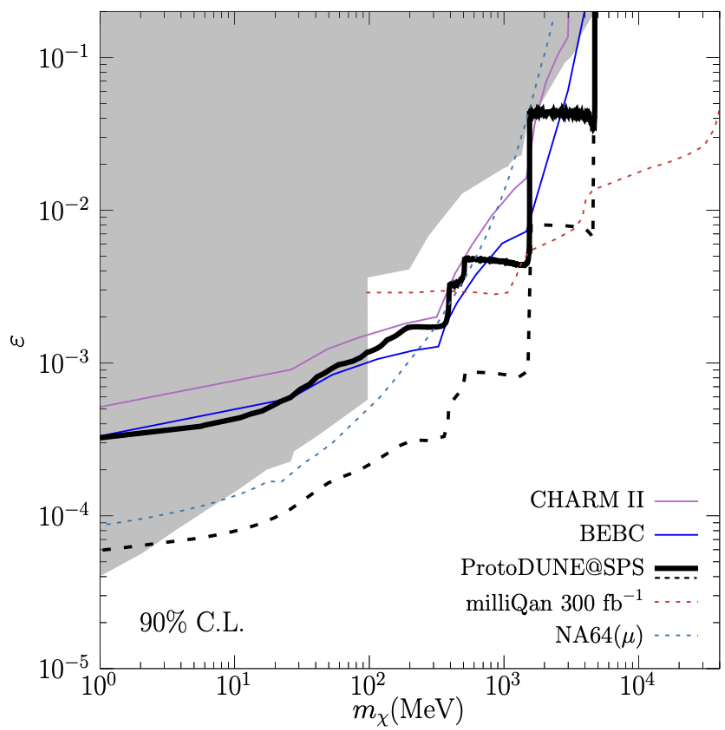




Millicharged particles

Detector(NP02)
Liquid Argon TPC





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

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

HNL: Decays into visible channels