New physics searches using ProtoDUNE and the CERN SPS accelerator

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Based on arXiv:2304.06765

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Open problems in particle physics

Origin of neutrino masses

Baryon asymmetry of the Universe

Nature of dark matter

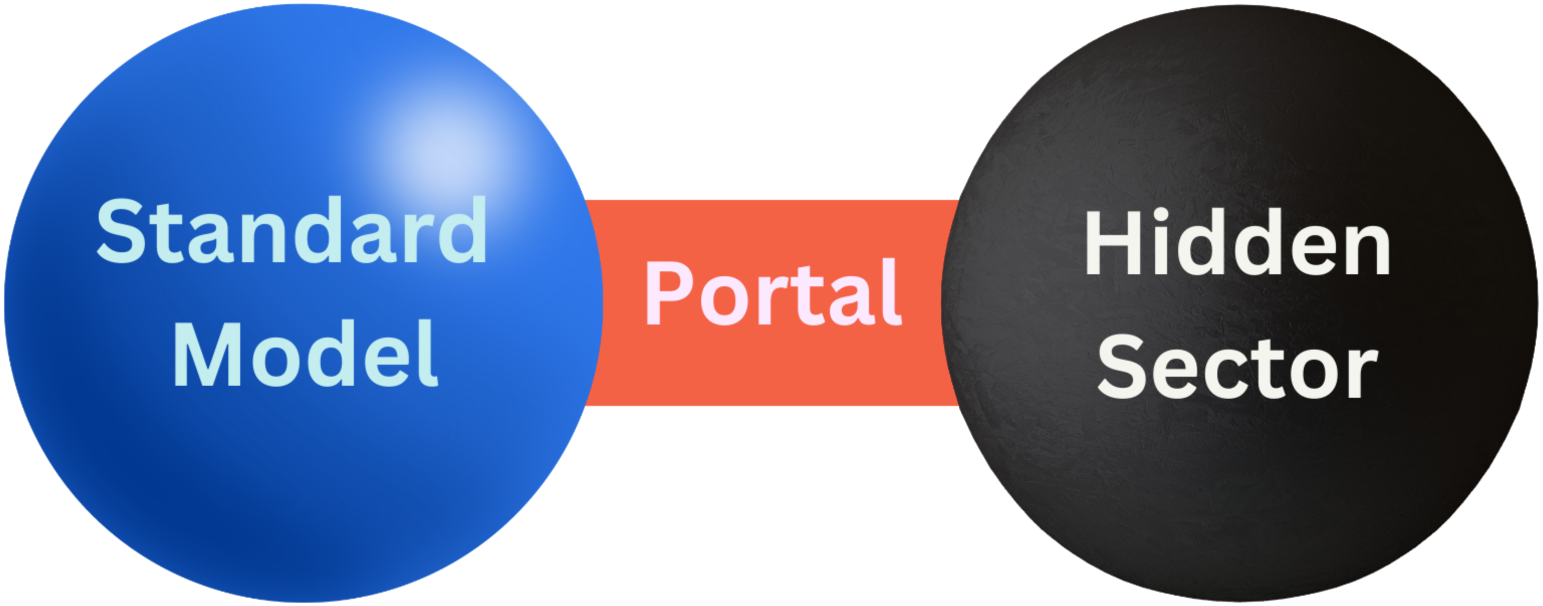
Hierarchy problem

Strong CP problem

Flavor puzzle

Call for new physics

Portals



Scalar (Dark Higgs)

$$\left(\mu S + \lambda S^2\right) H^\dagger H$$

Pseudoscalar (Axions, ALPs)

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \; \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \; \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

Vector (Dark Photon)

$$\frac{\epsilon'}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$$

Neutrino (HNLs)

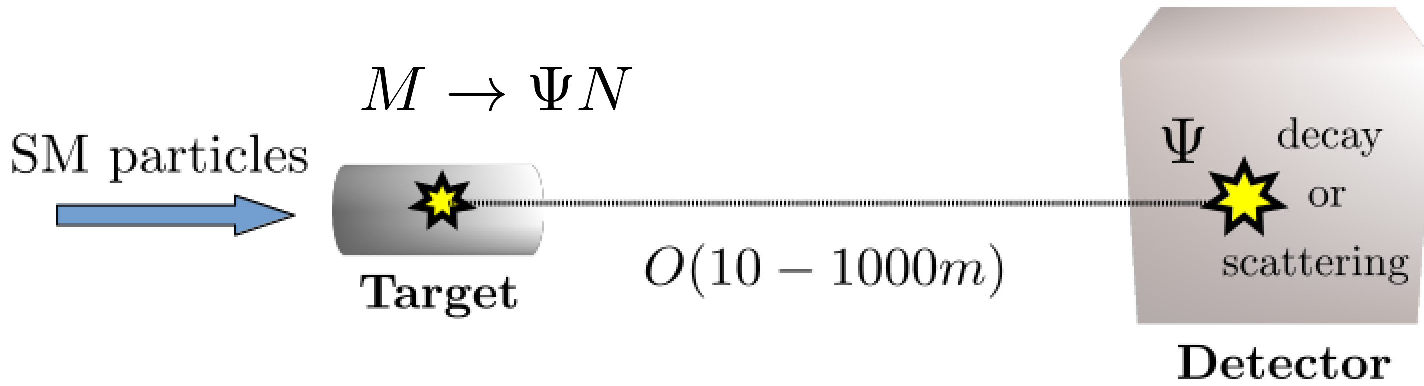
$$Y_{i\alpha} \overline{N_i} \tilde{H}^\dagger L_\alpha$$

Holdom 1986; Batell, Pospelov, Ritz 2009;
Patt, Wilczek 2006; FIPs 2022 report.

FIPs

How do we search for FIPs?

New particles produced in meson decays



Long-lived	Very long-lived (Stable)
(HNL, ALPs, dark photon,...)	(Millicharged particles,...)
Decay in flight inside the detector	Scattering signals

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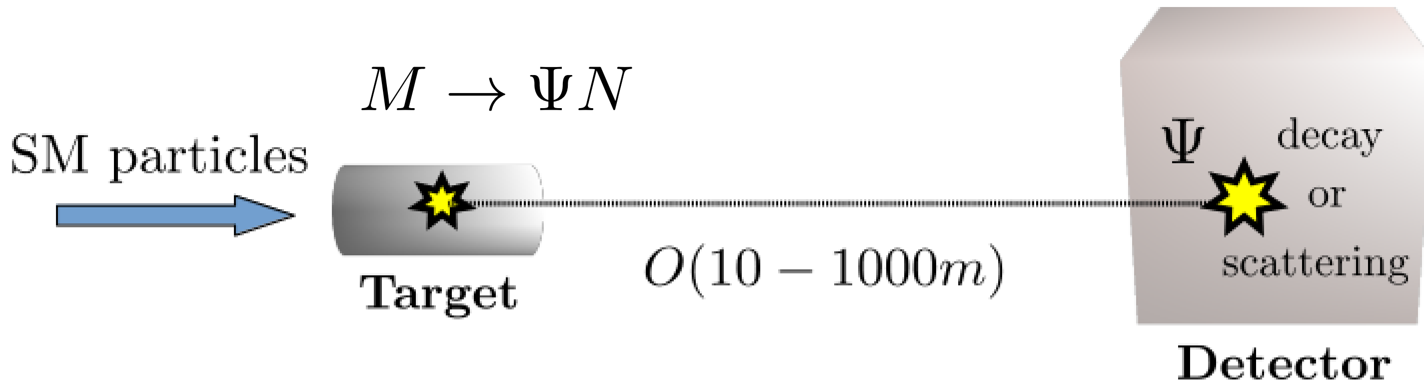
New particles produced in meson decays



Long-lived

(HNL, ALPs, dark photon,...)

Decay in flight inside the detector

Very long-lived (Stable)

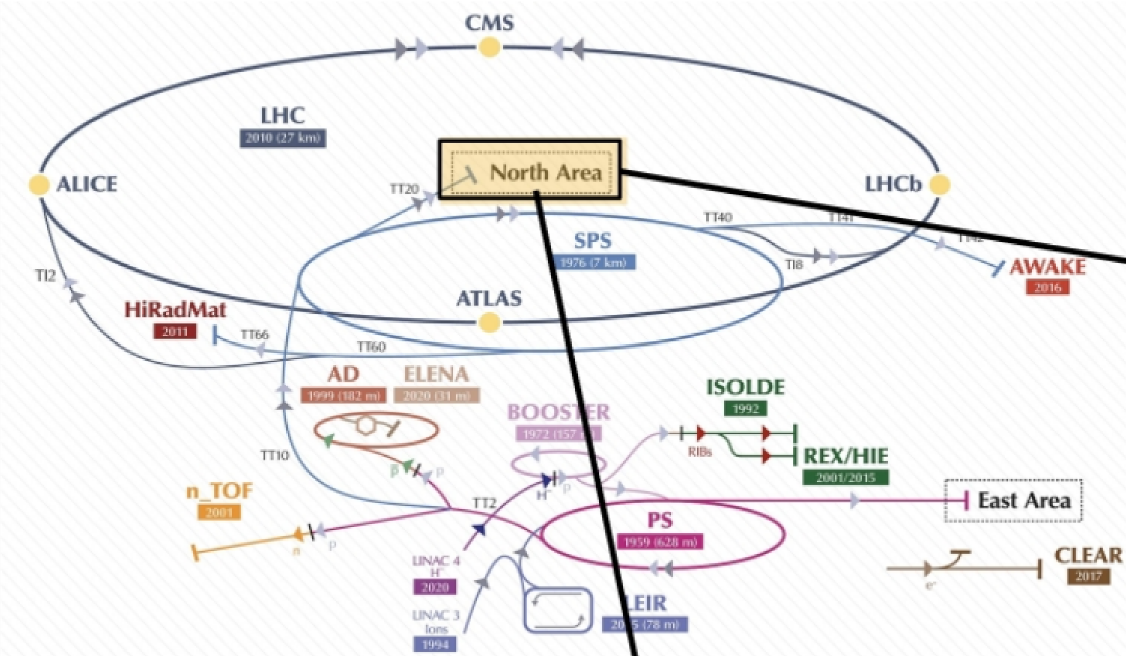
(Millicharged particles,...)

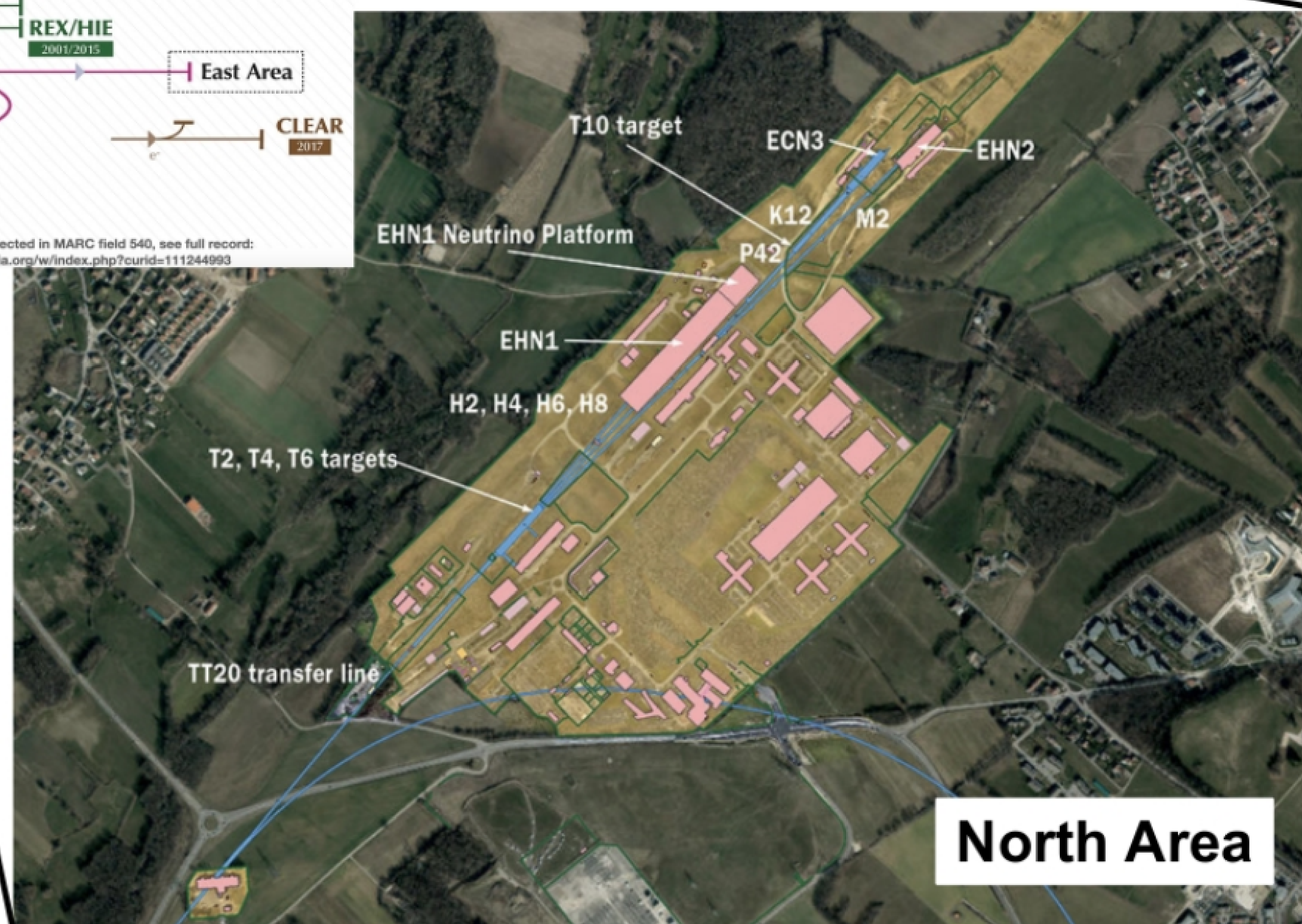
Scattering signals

See our paper **New physics searches using ProtoDUNE and the CERN SPS accelerator** where we study these searches in ProtoDUNE

Experimental set-up ProtoDUNE

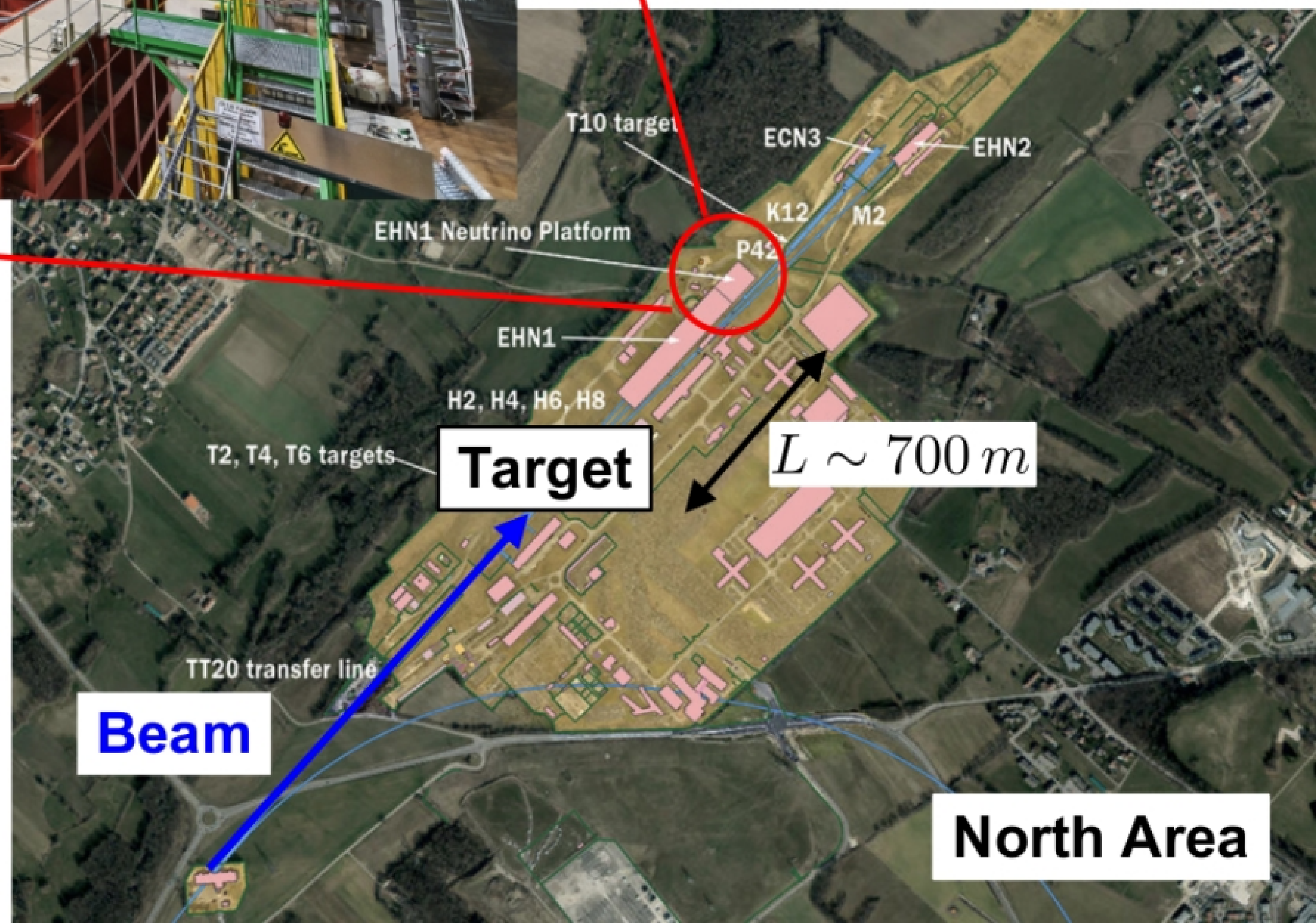
ProtoDUNE: Extracted beam lines





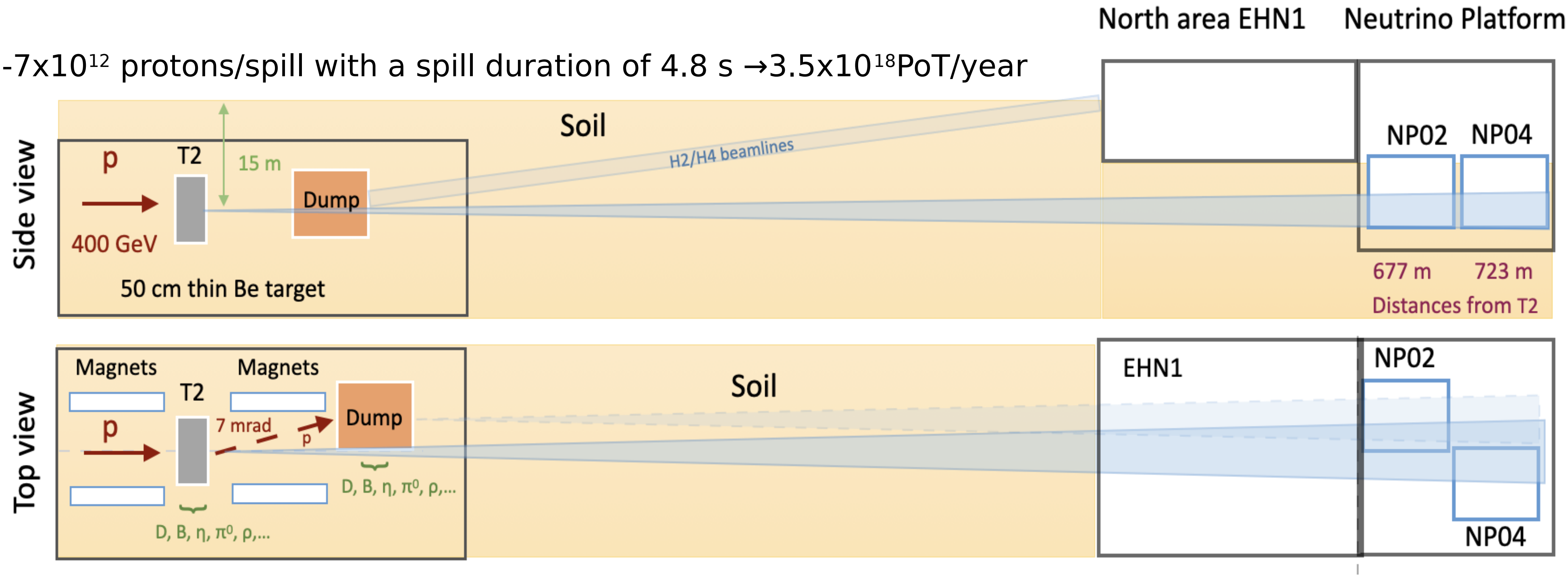
ProtoDUNE: Extracted beam lines

CERN Neutrino Platform
(**ProtoDUNE** detectors)

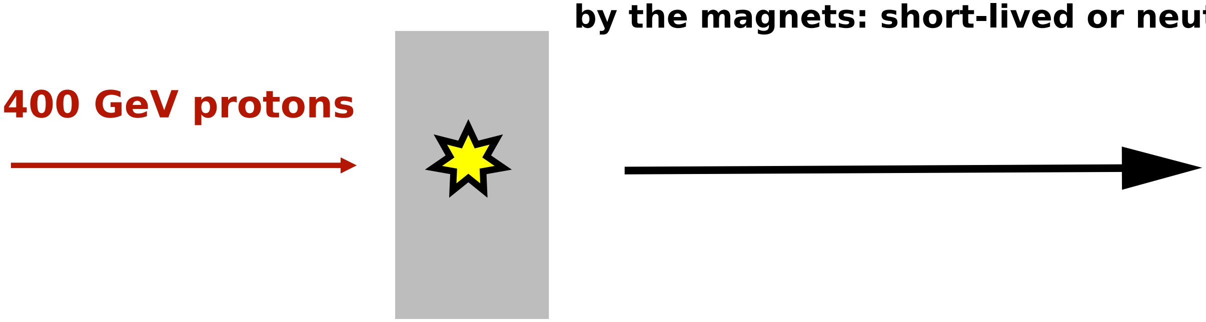


ProtoDUNE: T2 target

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



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



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*

Less background from neutrinos due to the magnets

HNLs

HNL: Production

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{l}_{L\alpha}\gamma_\mu U_{\alpha 4} N + \text{h.c.}\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{N}\gamma^\mu U^*_{\alpha 4}\nu_{L\alpha} + \text{h.c.}\right)$$

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

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

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

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

HNL: Detection

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

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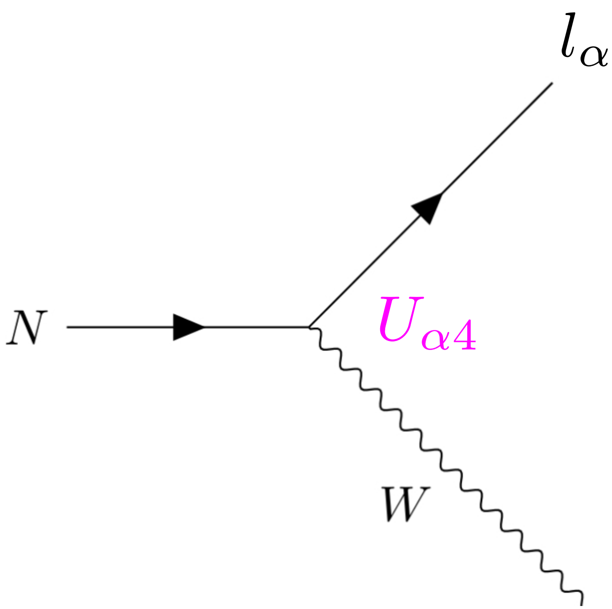
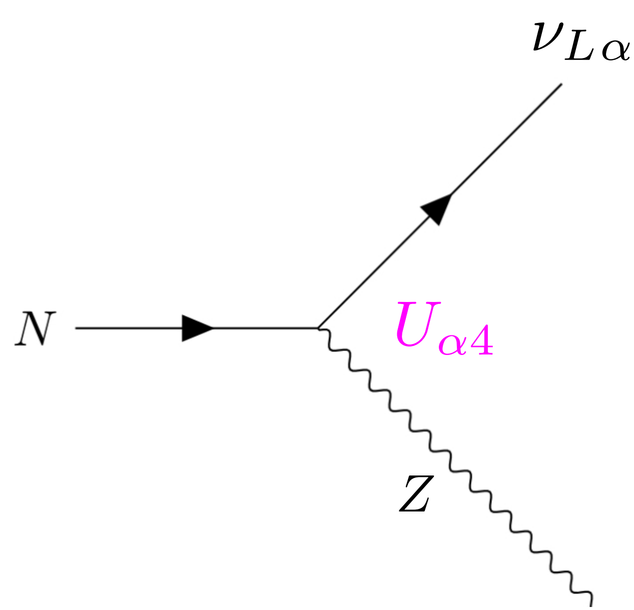
U_{e4} $\qquad$ $U_{\mu 4}$ $\qquad$ $U_{\tau 4}$





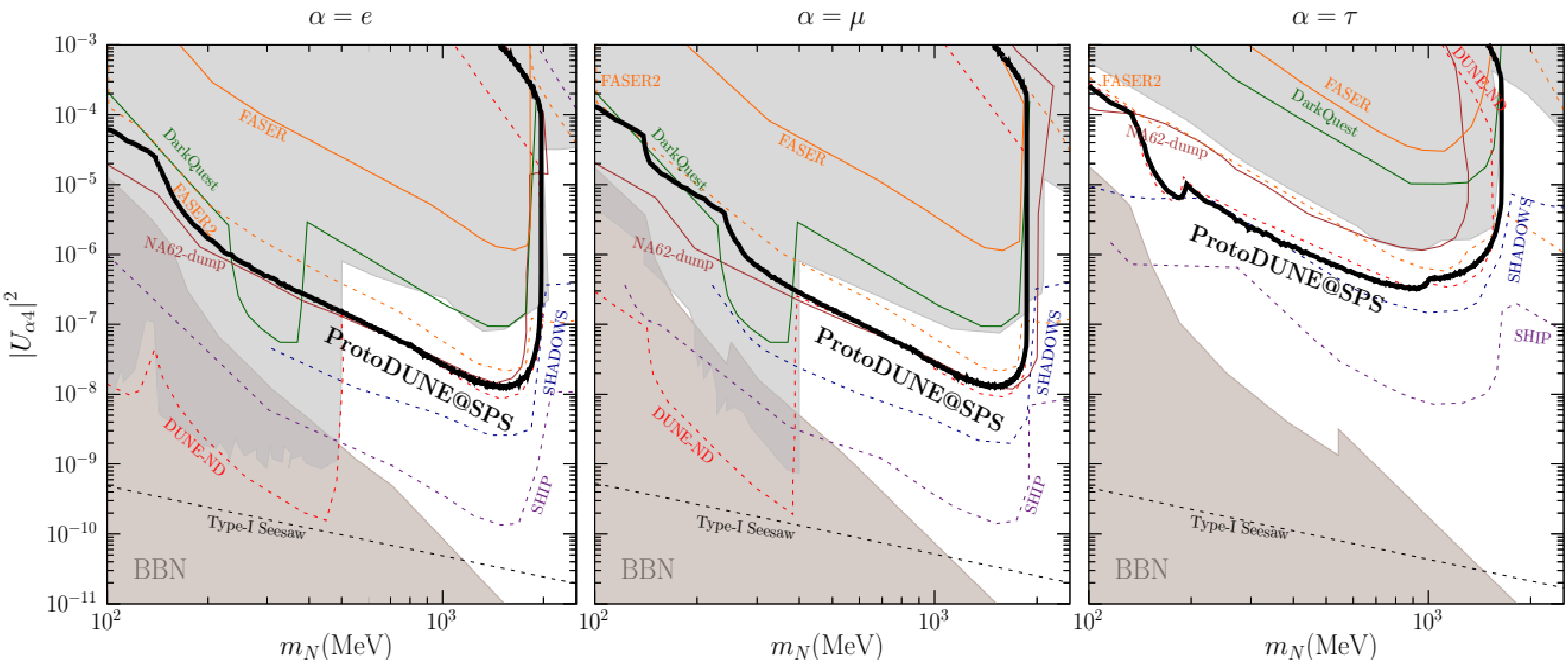
$N \to \nu e \mu, l\pi, \ldots$ $\qquad$ $N \to \nu l^+ l^-, \nu\pi^0, \ldots$

Results HNLs ProtoDUNE

Coloma, P., López-Pavón, J., Molina-Bueno, L., & Urrea, S. (2024). **New physics searches using ProtoDUNE and the CERN SPS accelerator.** JHEP, 01, 134.

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 $\nu\pi^0$



Sensitivity for 5 years

$1.75 \cdot 10^{19}$ PoT

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

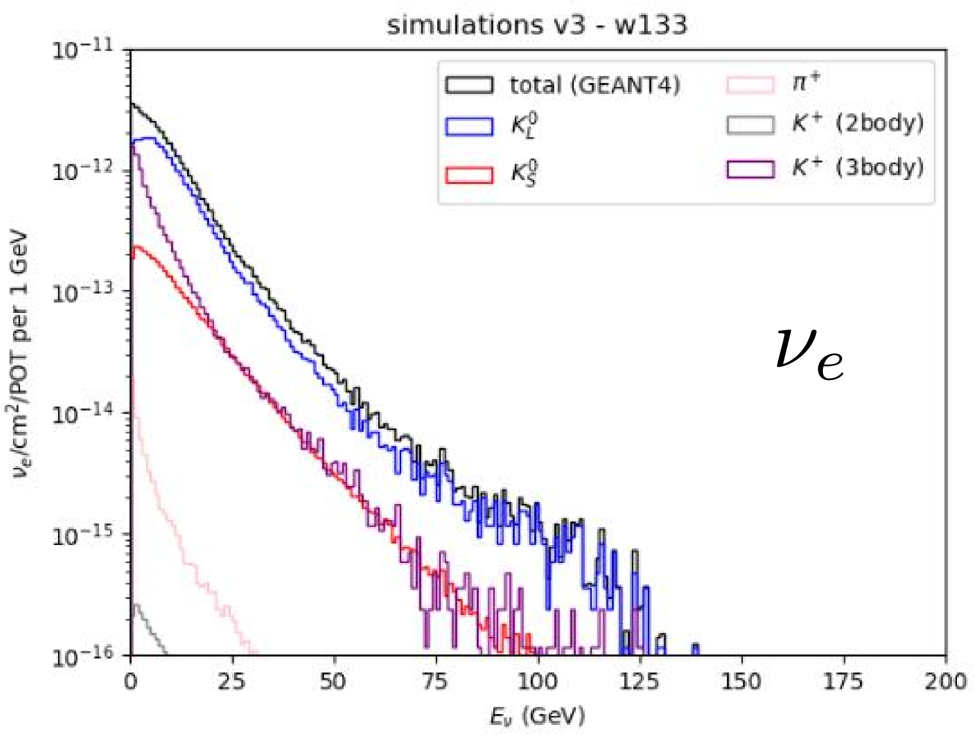
$Br(D_s^- \to \tau^- \overline{\nu}_\tau) = 5.43\%$

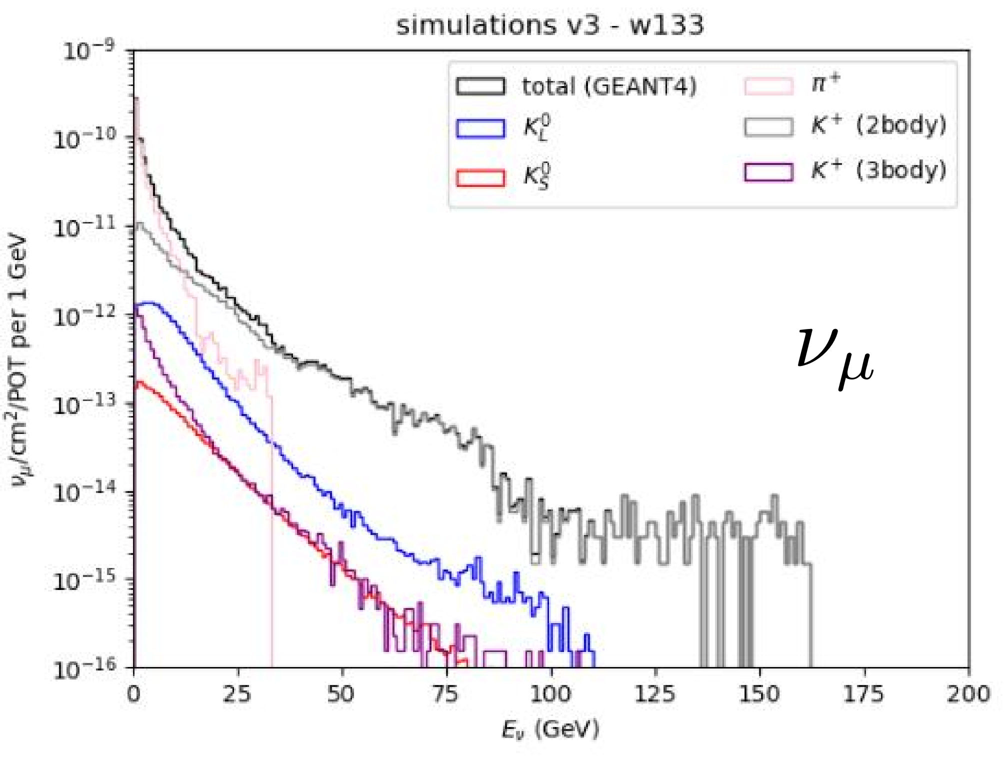
(normalised per PoT)

Work in progress within DUNE

Work in progress

- A Geant4 implementation of the target, dump, and magnets has been used to validate our results and compute the possible neutrino flux and HNL signal.

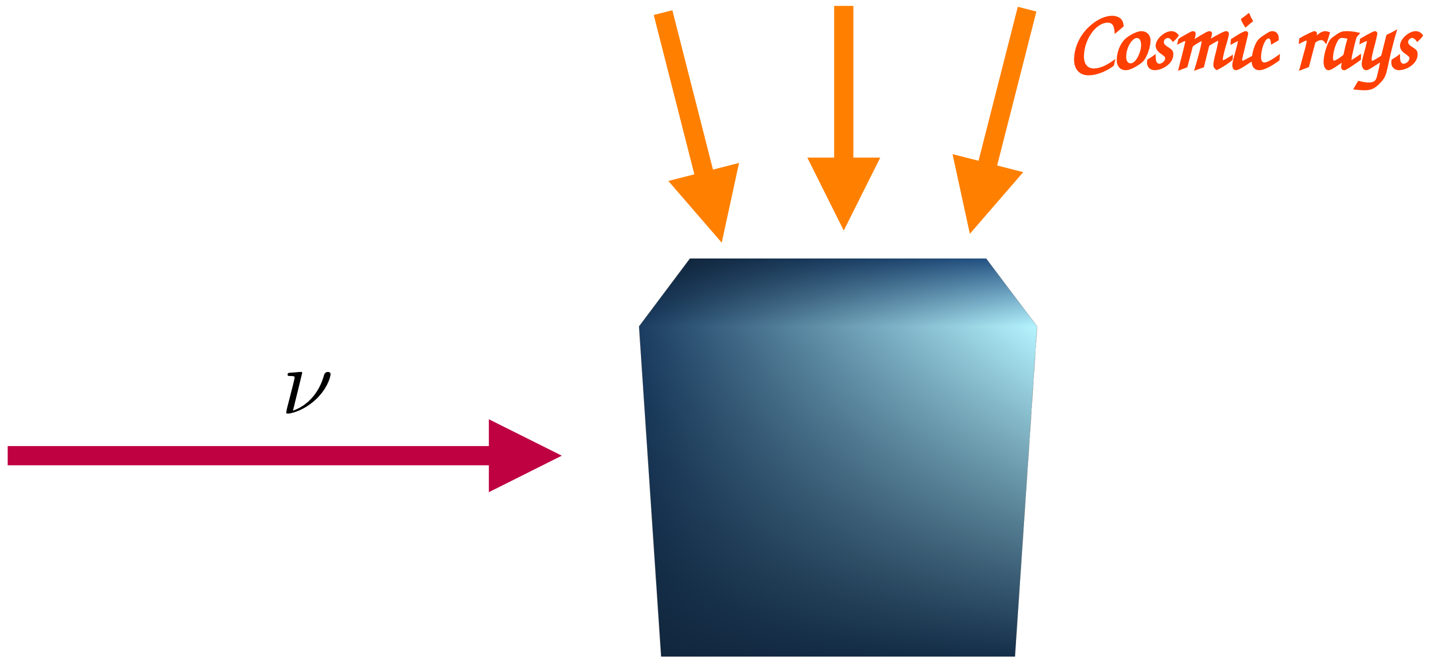




More details in:
https://indico.cern.ch/event/1460367/contributions/6240613/attachments/3001559/5289608/BSM@protoDUNE_NeutrinoWkshp_Animesh.pdf
https://indico.cern.ch/event/1381368/contributions/5963281/attachments/2888251/5062517/molina_LLP2024_2072024_v2.pdf

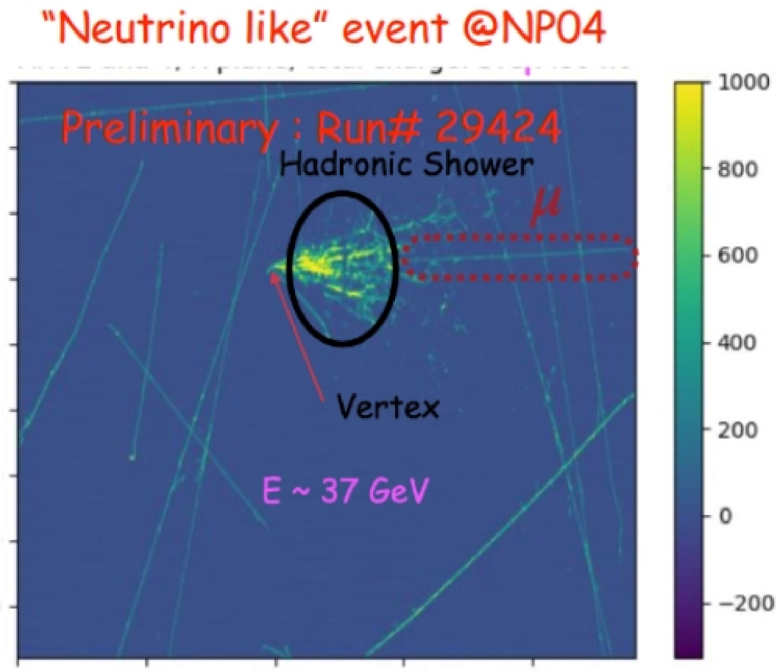
Work in progress

- Can we distinguish events coming from the beam from the cosmics?
- What is the background from neutrinos for BSM searches?



Work in progress

- Developments on the trigger side and in detection simulation.
- A small run (1 week) has been conducted to demonstrate the proof of principle, where we have found potential neutrino-like candidates.



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Conclusions

- ProtoDUNE presents a great opportunity to search for new physics without interfering with CERN's current program.

- We are actively working on it to make it a reality.

Thank you

Back-up

Neutrino Portal

- Simplest extension of SM able to account for **neutrino masses**. Consists in the addition of fermion singlets (N_i) to the SM field content:

Neutrino Portal

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{H}^{\dagger} L_\alpha + \text{ h.c.}$$

How do we give mass to neutrinos?

ΔL conserved

Higgs mechanism

$$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$$

$y_\nu < 6.5 \cdot 10^{-13}$

Why so small?

ΔL largely violated

High scale See-saw

$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$

If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\mathrm{GeV},$

If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\mathrm{GeV},$

Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980

ΔL approximately conserved

Low scale see-saw

$$m_\nu \sim \frac{v^2}{M^2}\mu$$

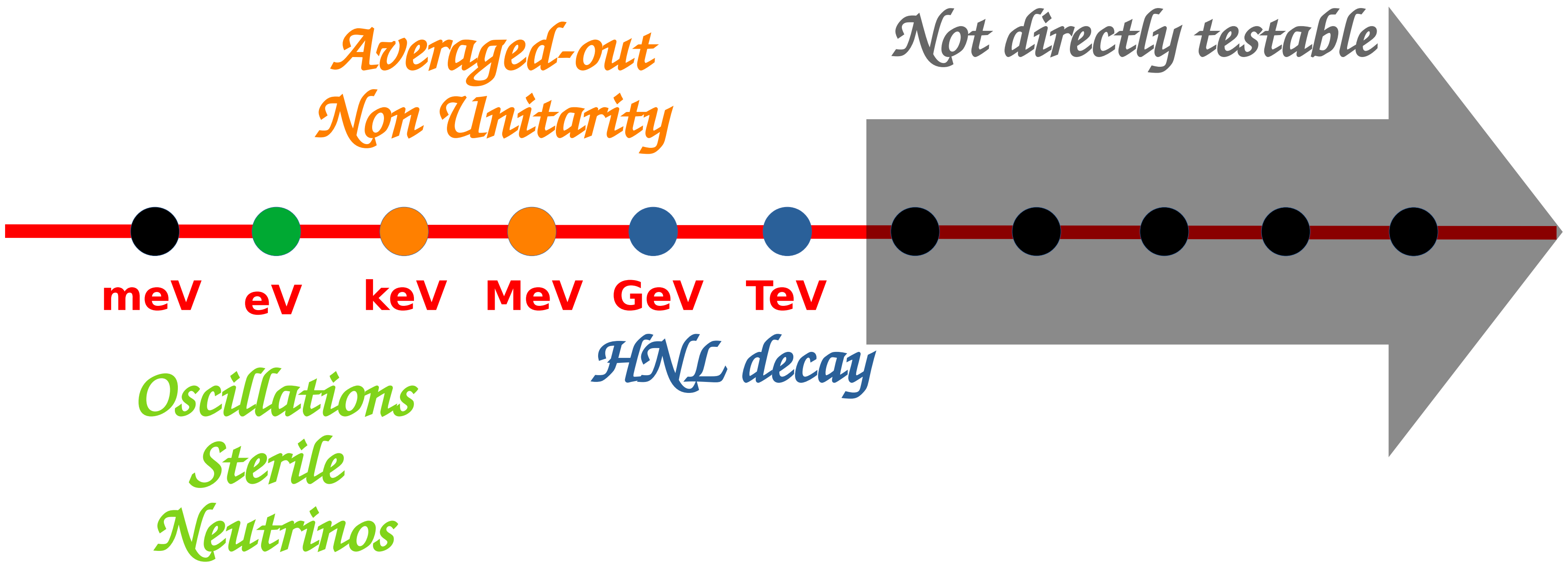
$\mu \ll 1$

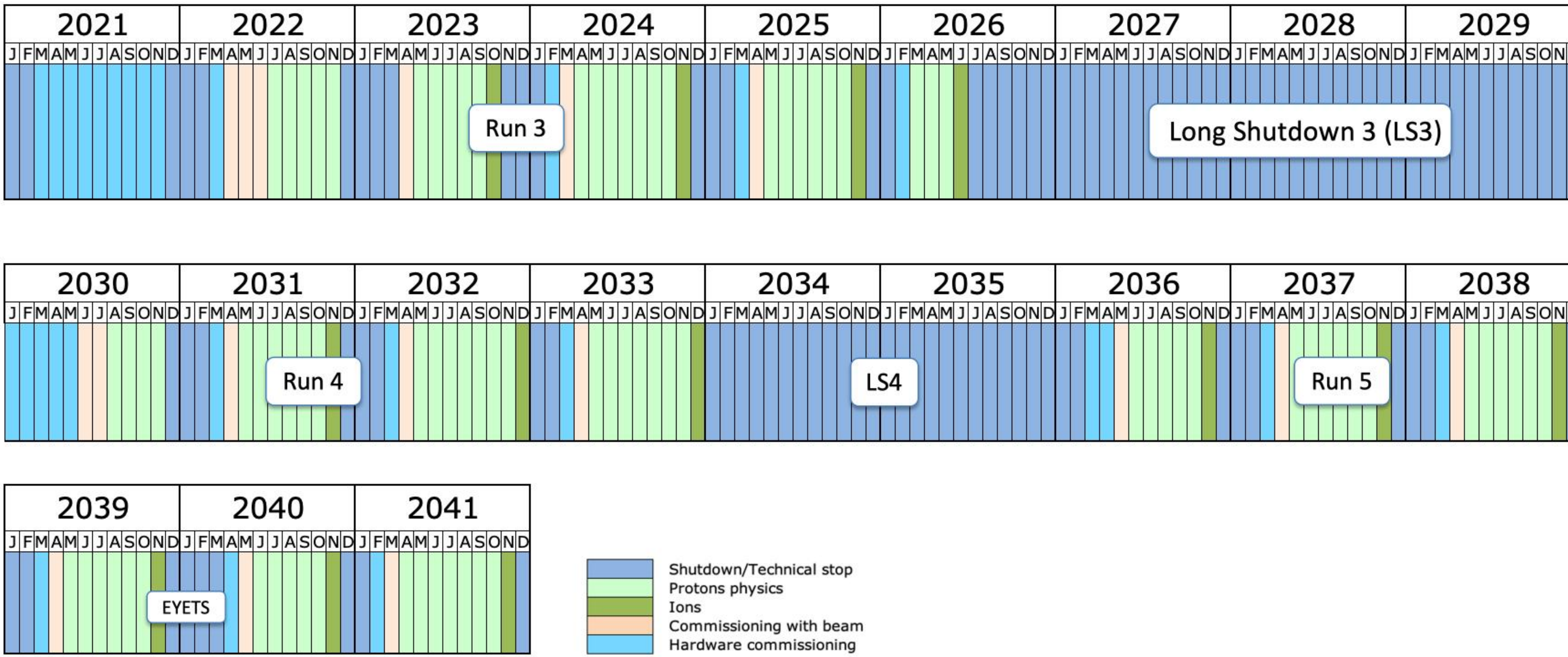
Symmetry protected scenarios

Mohapatra, & Valle 1986 ; Akhmedov, Lindner, Schnapka, and Valle 1996; Gonzalez-Garcia and Valle 1989; Gavela, Hambye, Hernandez 2009; Bernabéu, Santamaria, Vidal, Mendez, and Valle 1987; Mohapatra 1986

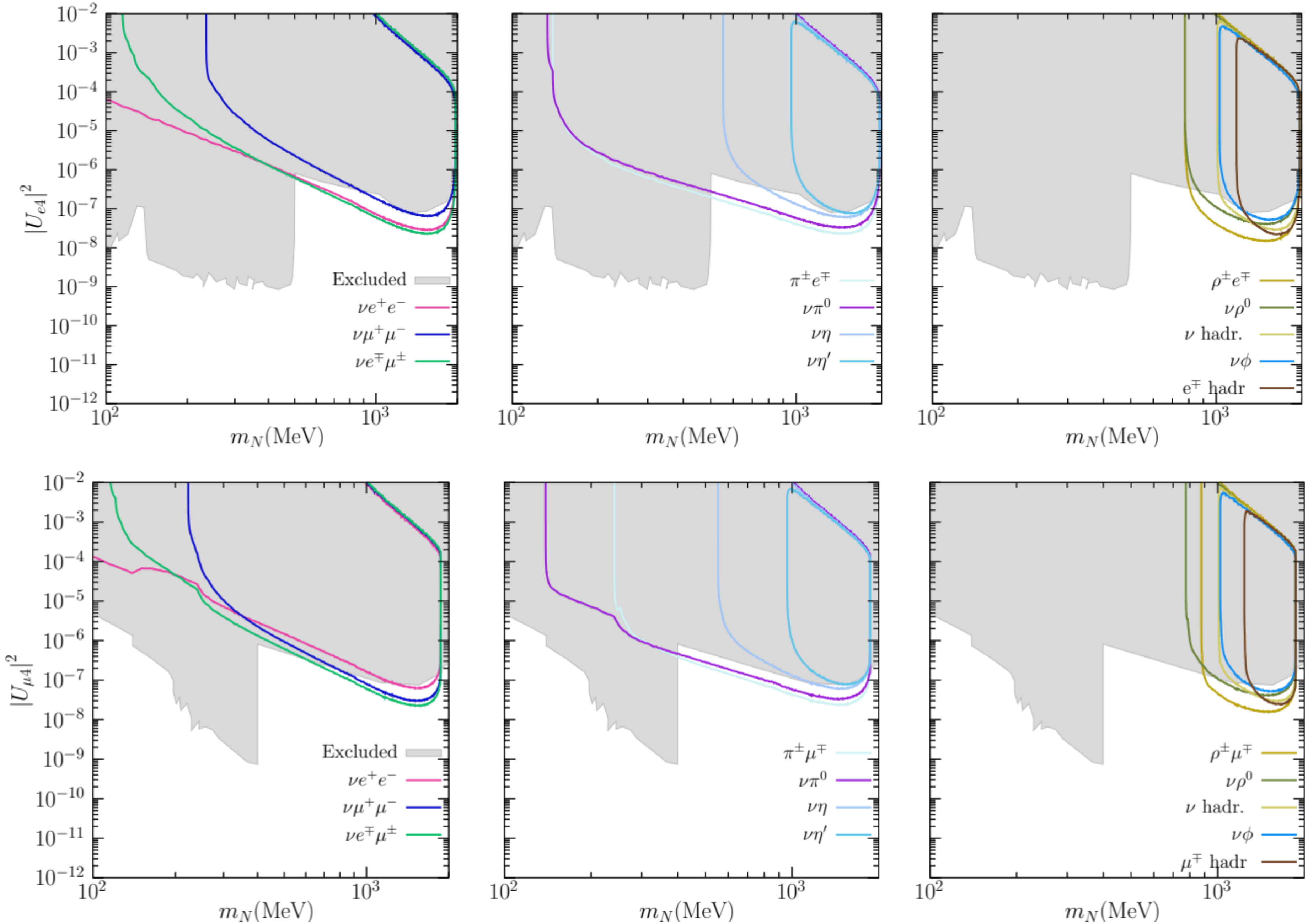
How do we give mass to neutrinos?

New Physics scale M

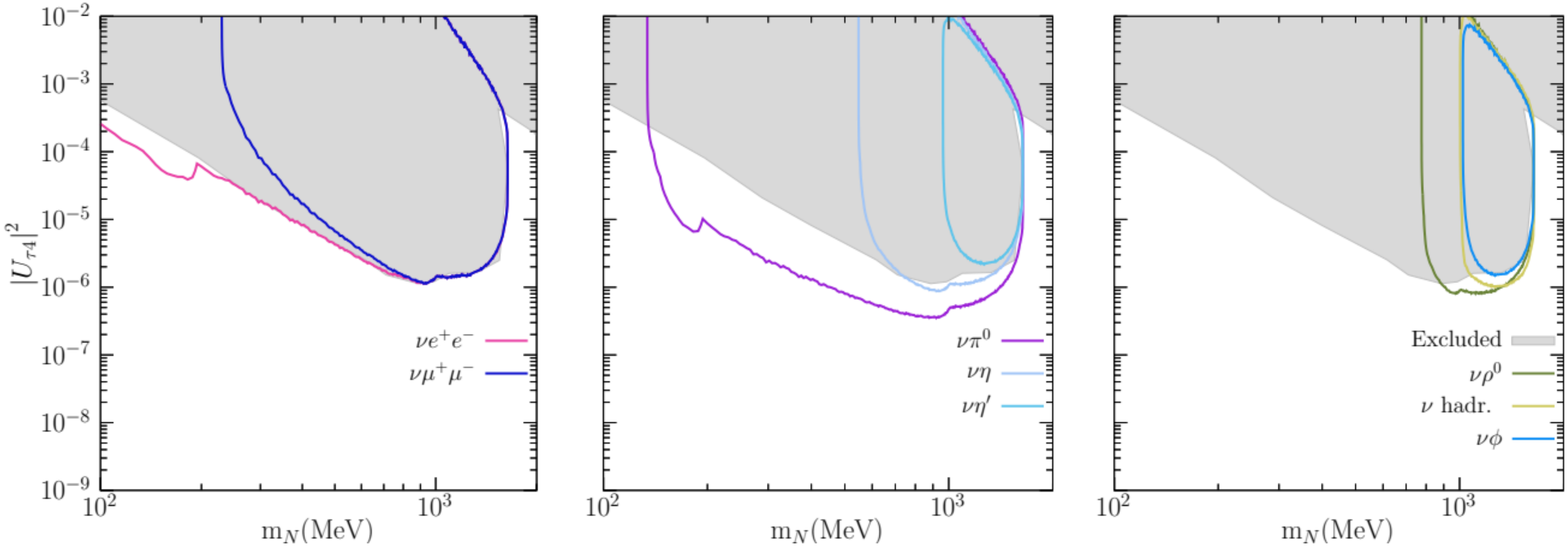


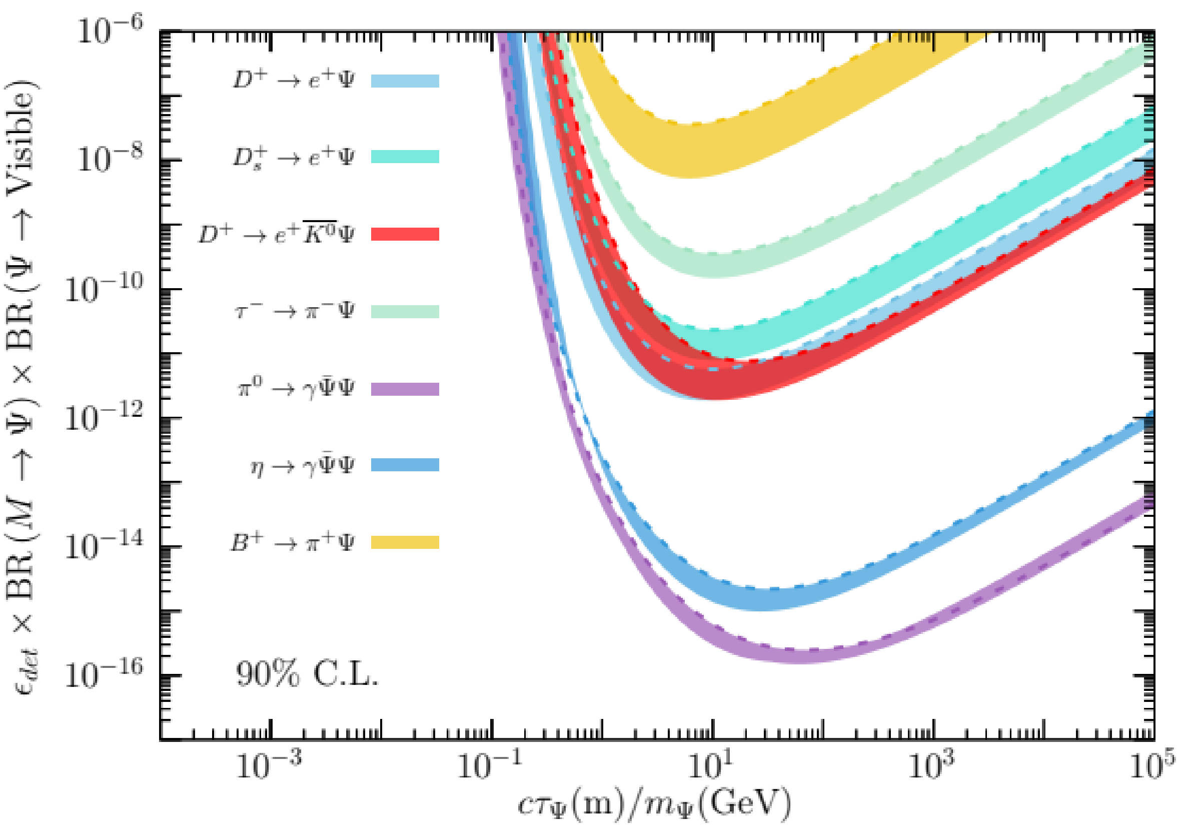


Last update: November 24



$|U_{e4}|^2$
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
$|U_{\mu 4}|^2$
$\pi^\pm\mu^\mp$
$\rho^\pm\mu^\mp$
$\mu^\mp$ hadr

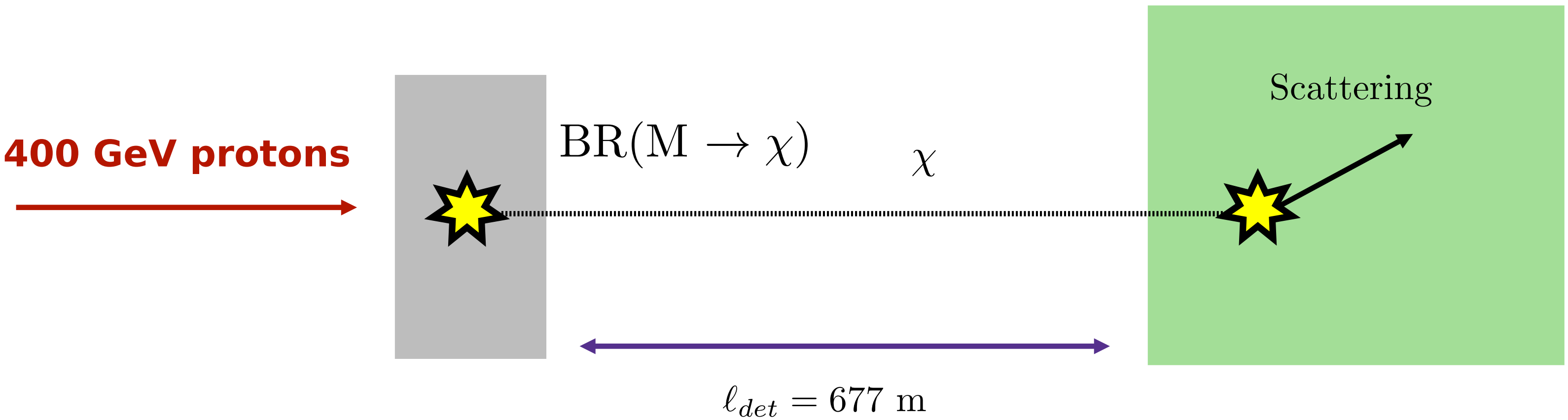




$$\mathcal{P} = e^{\frac{-\ell_{\mathrm{det}}}{L_\Psi}}\left(1 - e^{\frac{-\Delta\ell_{\mathrm{det}}}{L_\Psi}}\right)$$

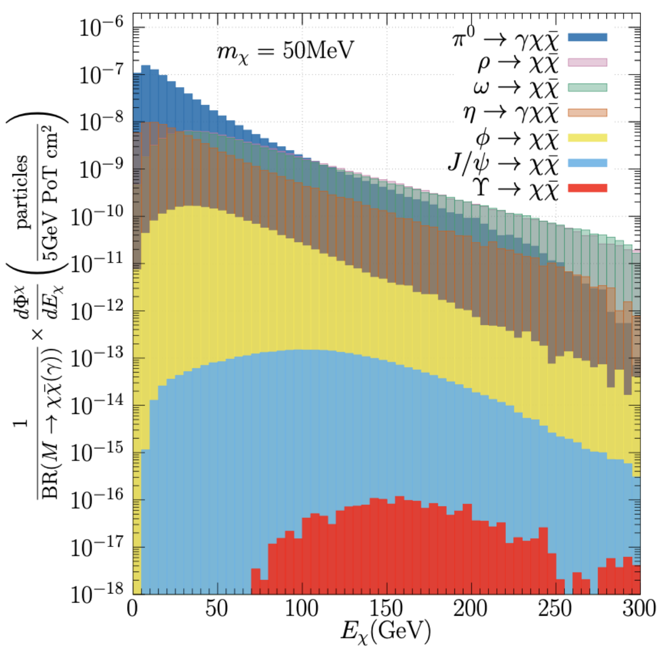
New Physics: stable particles

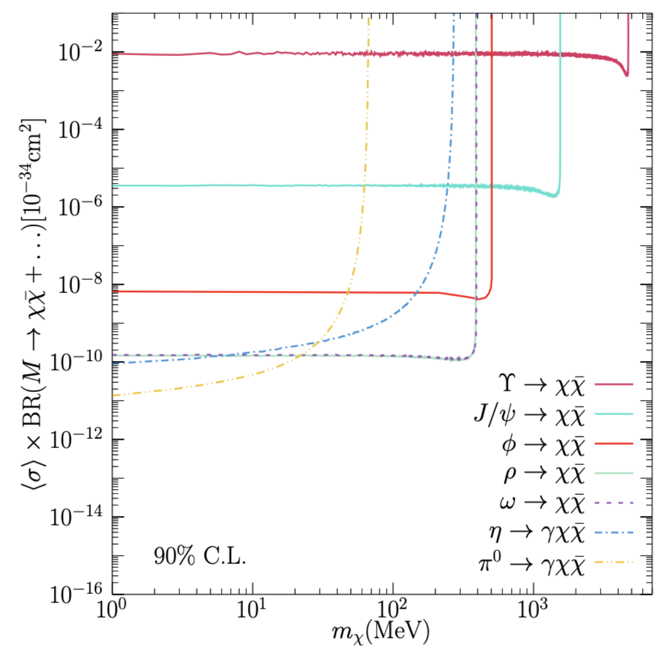
Detector(NP02)
Liquid Argon TPC



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

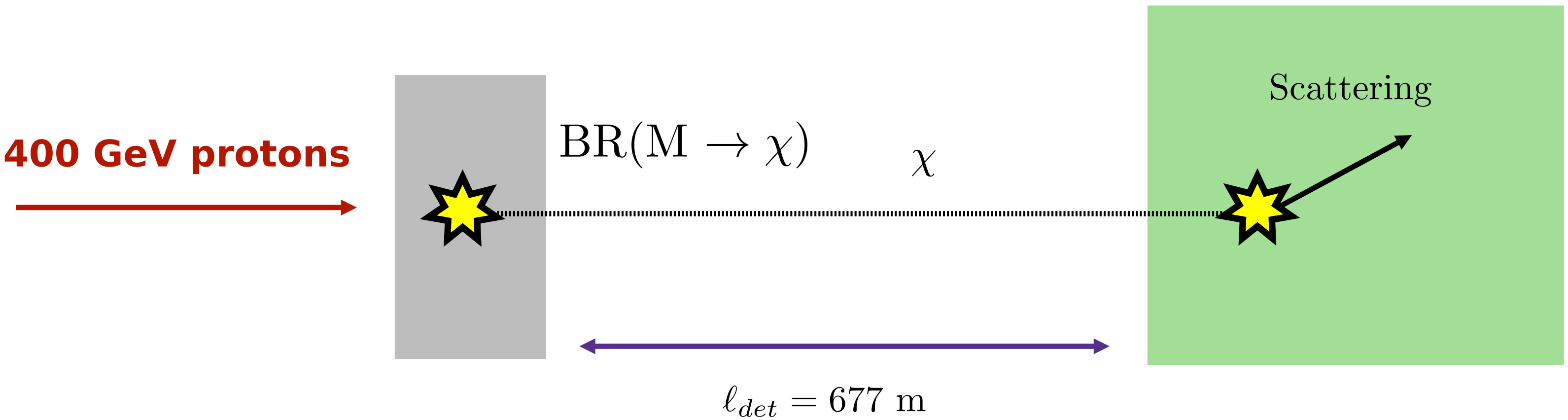
$$\mathrm{N}_{ev} = \epsilon_{\mathrm{det}}\, N_{trg} \langle\sigma\rangle \Phi^\chi N_{\mathrm{PoT}},$$

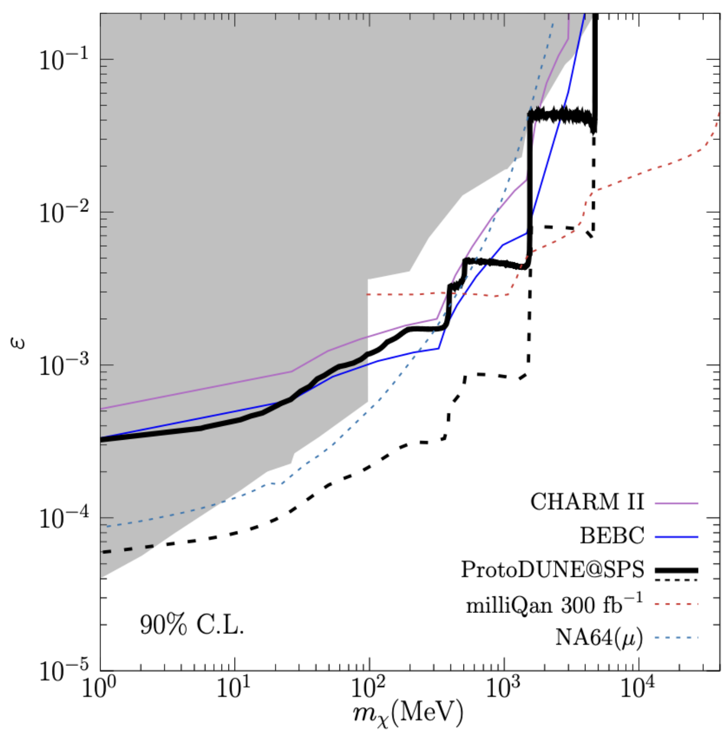




Millicharged particles

Detector(NP02)
Liquid Argon TPC





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

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