New Physics searches using *ProtoDUNE* and *the SPS accelerator*

Based on https://arxiv.org/pdf/2304.06765.pdf

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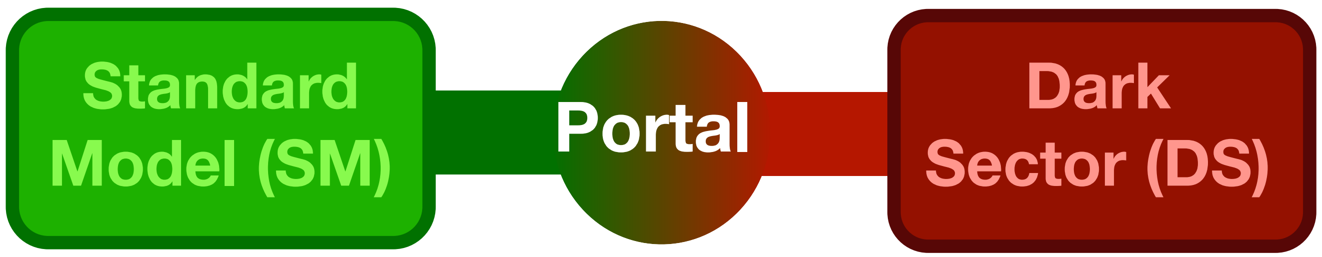
Motivation: *Feebly interacting particles*

An interesting framework to explain SM open questions with New Physics at low energy scales

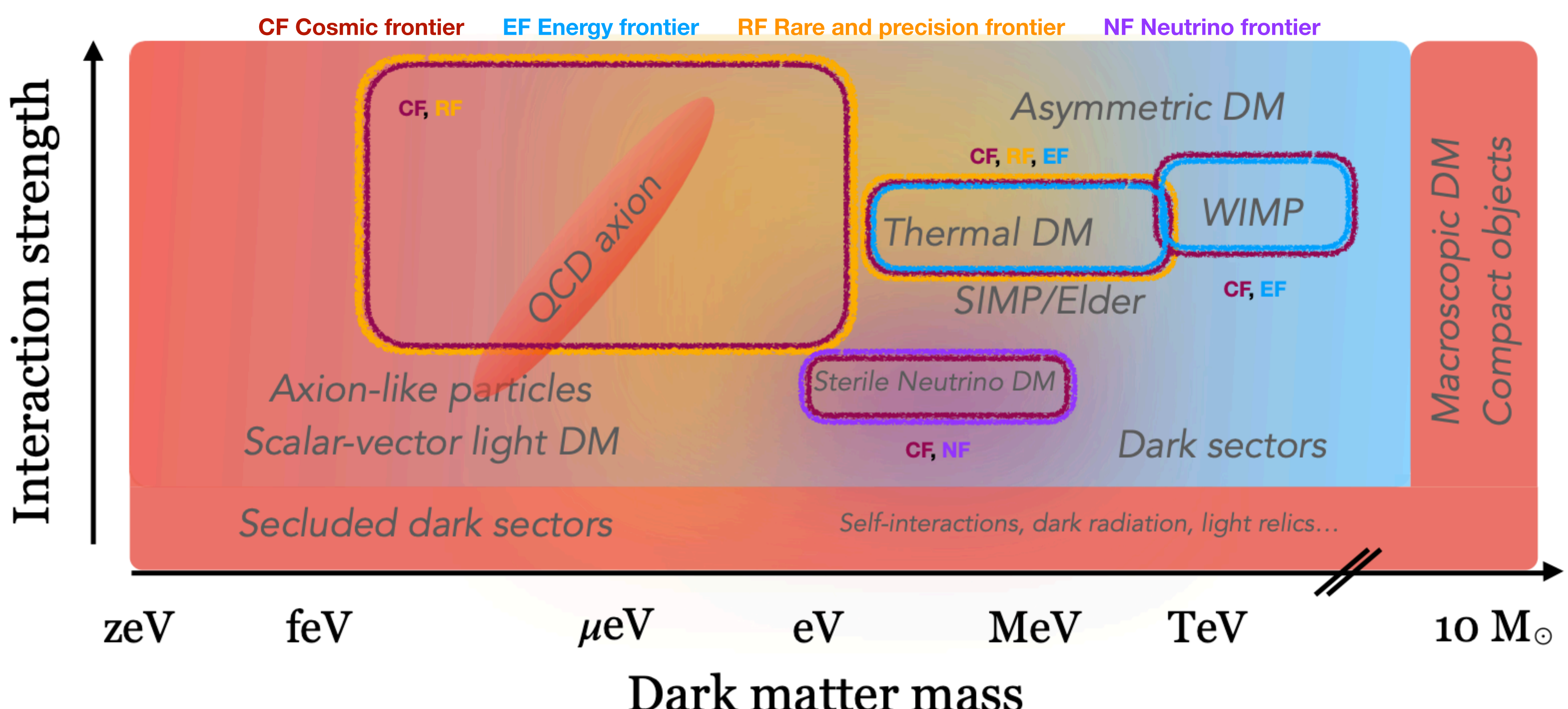


They can solve some of the most pressing questions in particle physics: *the **origin of neutrino masses**, the **baryon asymmetry of the universe*** and the ***Dark Matter origin***.

$$L_{Total} = L_{SM} + L_{DS} + L_{Portal}$$

G. Lanfranchi et al. Annual Review of Nuclear and Particle Science (2021) 71:1, 279-313

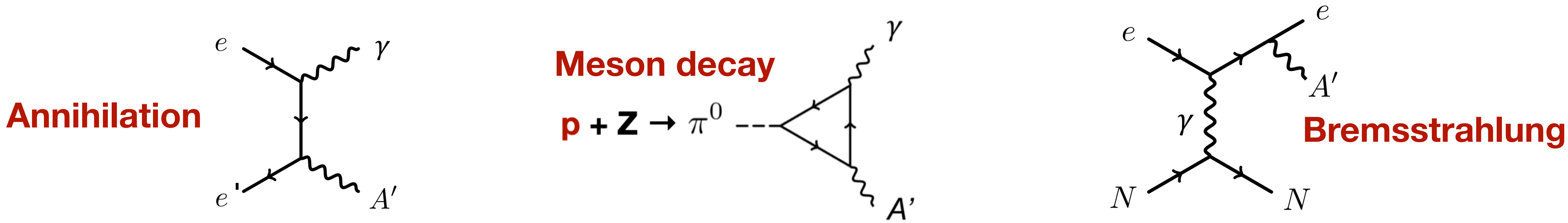
Vector (***Dark Photon***), Scalar (***Dark Higgs***), Fermion (***Heavy neutral lepton***), Pseudo-scalar (***Axion***)

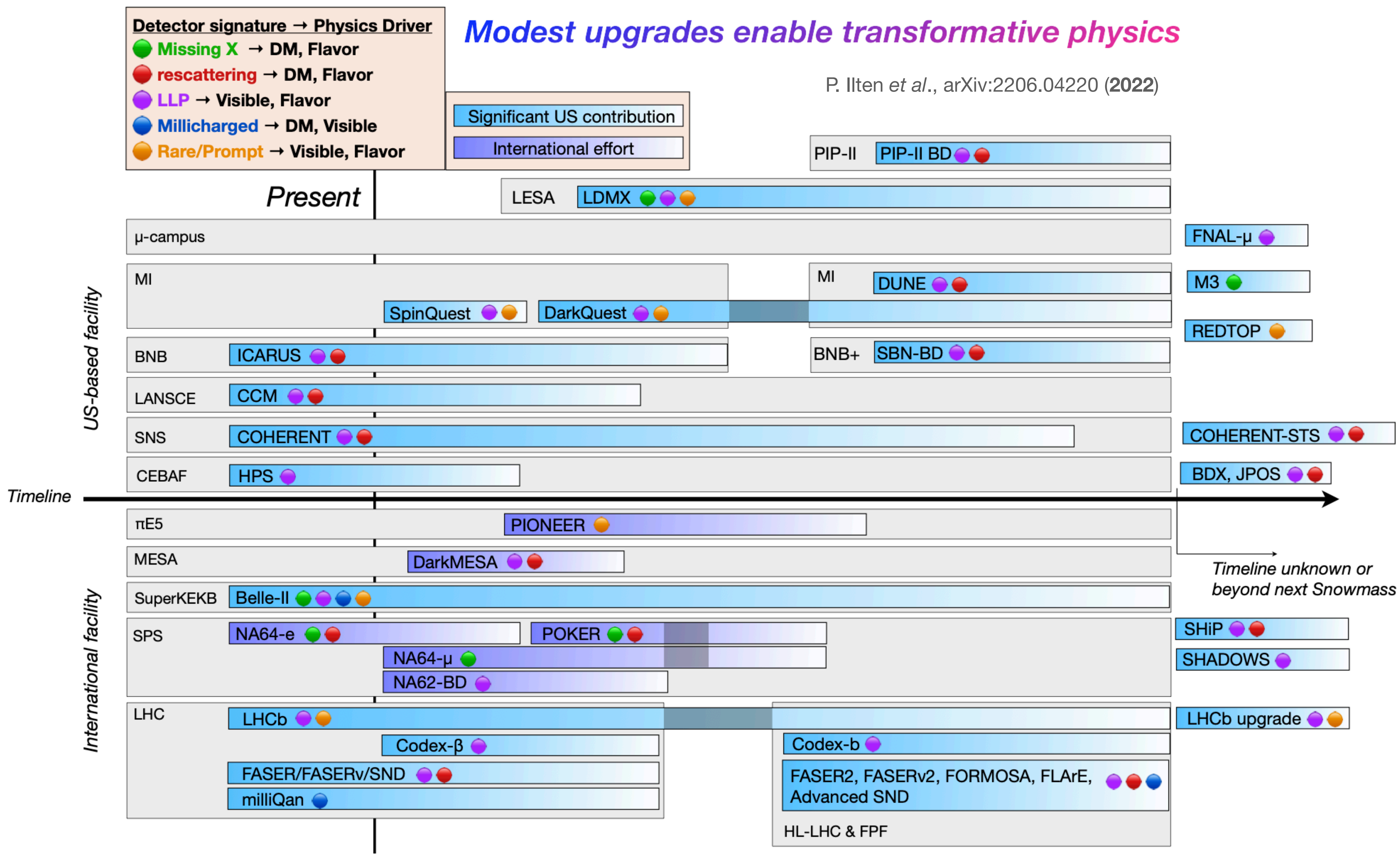


A. Boveia *et al.*, arXiv:2211.07027(**2022**)

Summary of accelerator-based facilities

From e^+e^- *collider*, *beam dump* and *kaon factories*, *p, e⁻/e⁺ and μ fixed target*:





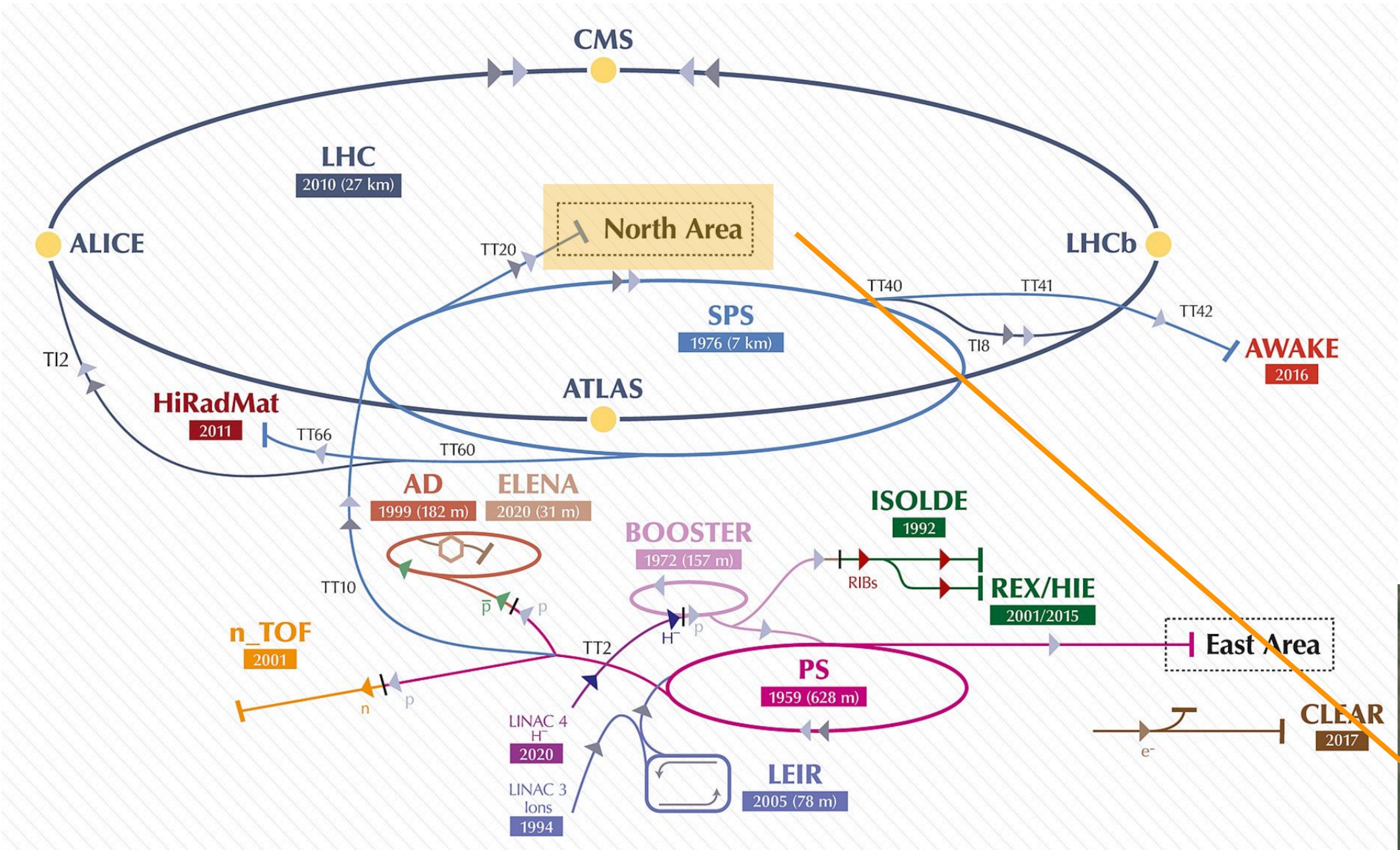
Motivation

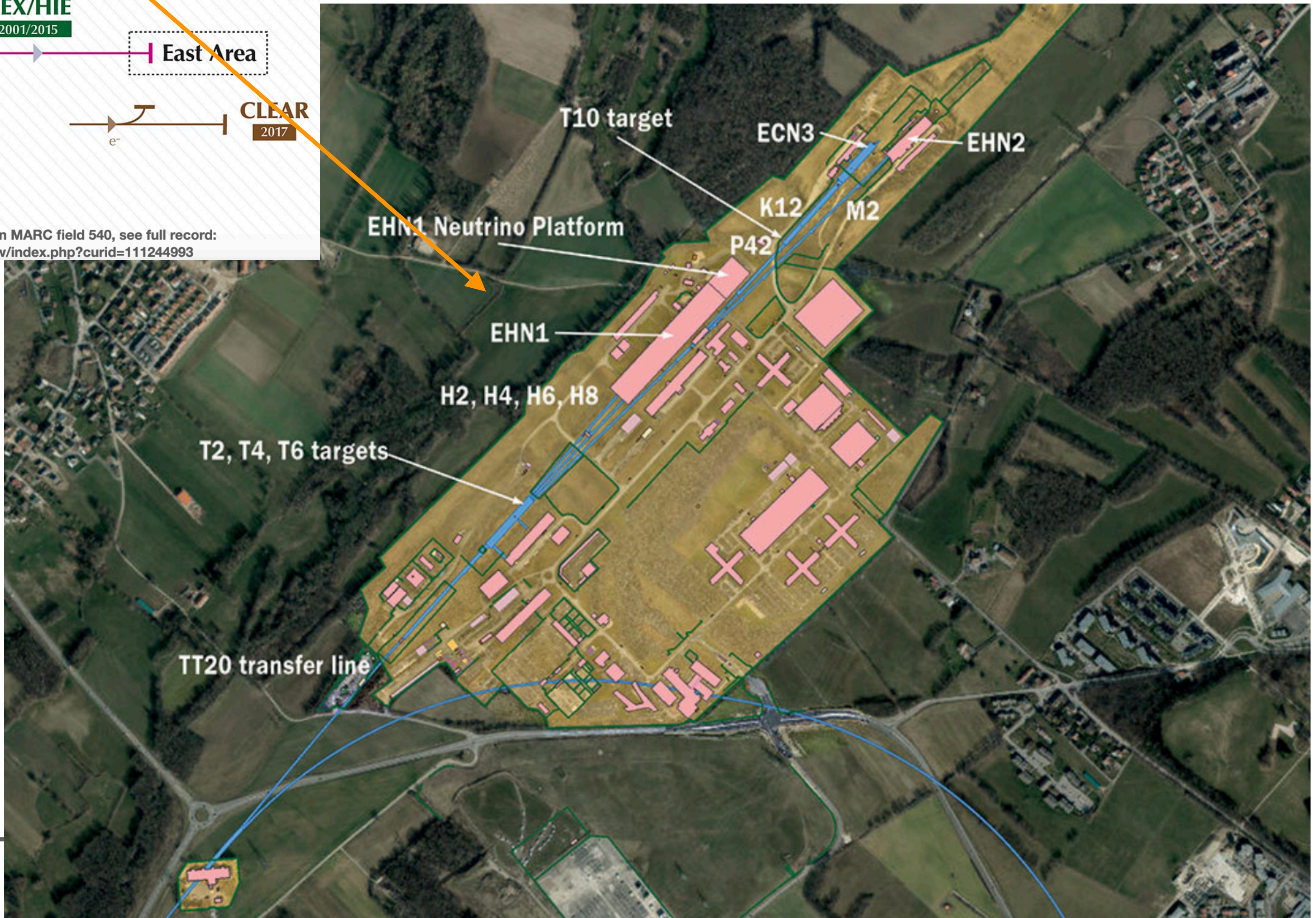
Can we use the existing ProtoDUNE detectors as a beam-dump facility to search for new weakly interacting particles?

Beam-dump experiment

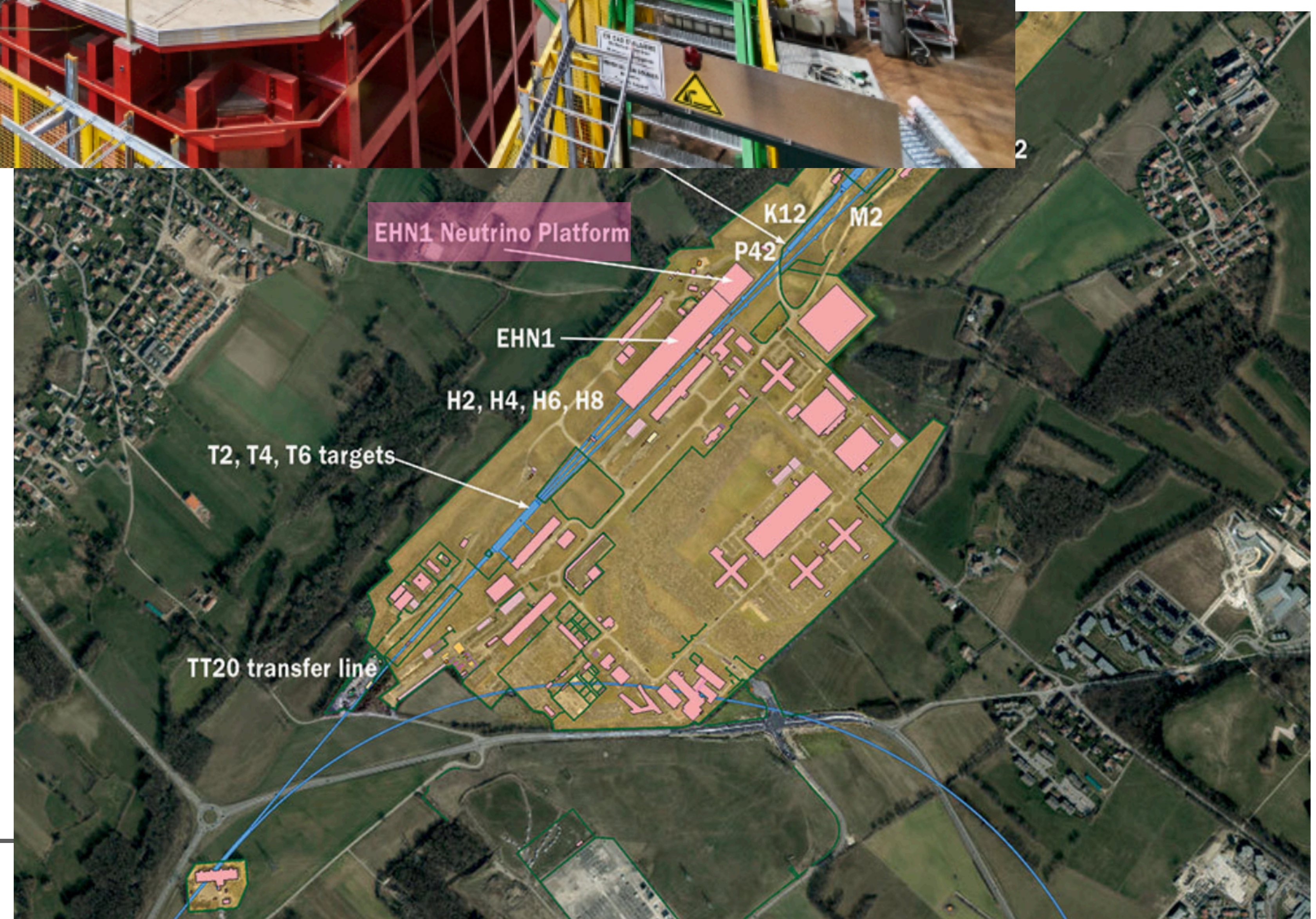
(Many present and future facilities: MiniBooNE, LSND, NA62,SHIP, T2K, SBND, DUNE...)

The SPS accelerator

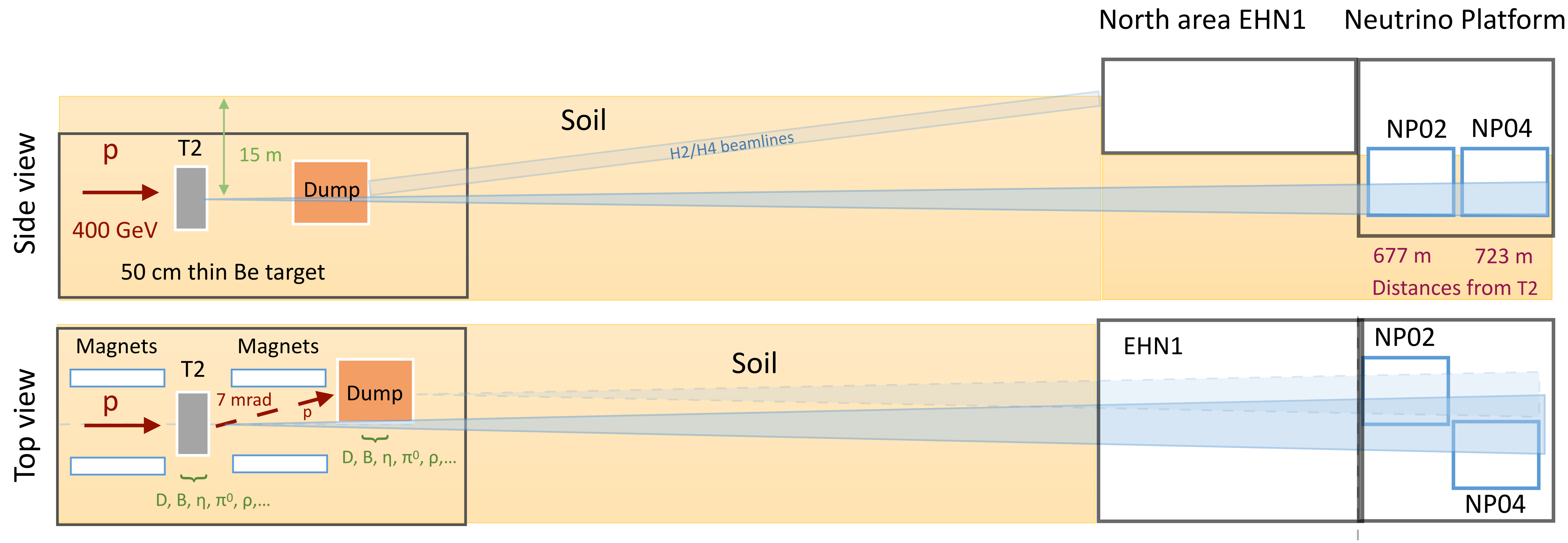





From https://neutrino-secretariat.web.cern.ch/visits


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

The experimental setup



Key aspects:

1) *Proton initial momentum*: 400 GeV (instead to 80-120 GeV as in neutrino experiments)

2) ~5-7x10^{12} protons/spill with a spill duration of 4.8 s →3.5x10^{18}PoT/year

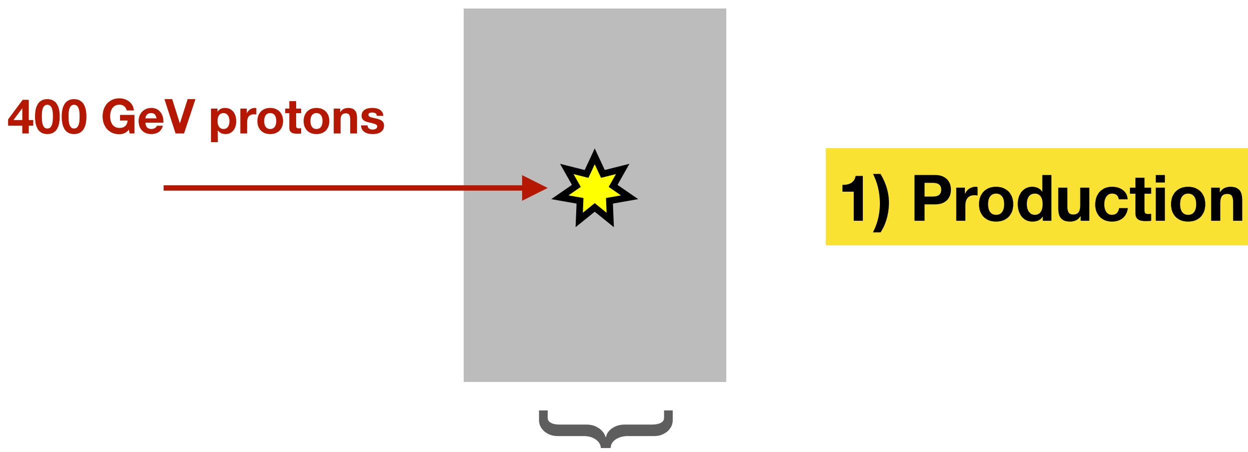
3) *No decay volume*

4) *ProtoDUNE detectors:* Liquid Argon Time Projection Chambers with large fiducial volume and excellent imaging capabilities to identify the decay products

- The detectors are at the surface. Cosmic-rays are the expected dominant background source.

Beam dump approach: *production*

Primary Target T2
(50 cm Beryllium target)



Products from the result of proton interactions with a target (focus on short-lived mesons ,M))

(D, D_s, B, Y, J/Ψ, η, η', π^0, ρ, …)

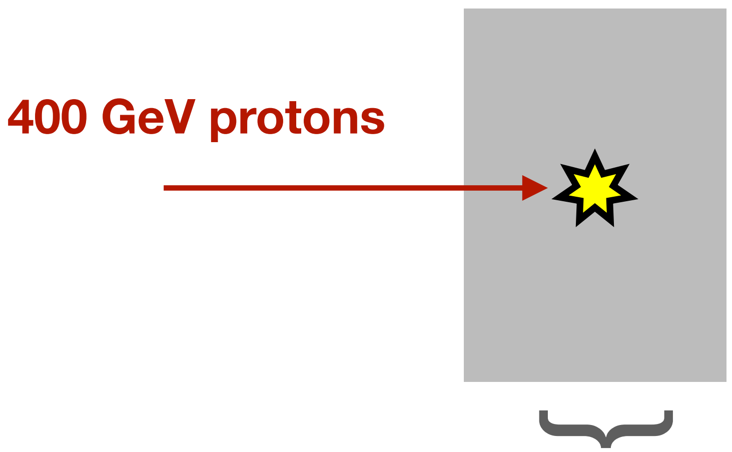
Meson production yield Y_M (normalised per PoT)

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*

Beam dump approach: *LLPs scenarios*

Primary Target T2



Products from the result of proton interactions with a target (focus on short-lived mesons ,M))

(D, D_s, B, Y, J/Ψ, η, η’, π^0, ρ, …)

a) Long lived unstable particles

These mesons can decay to new light states (Ψ) generating an intense flux of long lived particles

$$BR(M \to \Psi \ldots)$$

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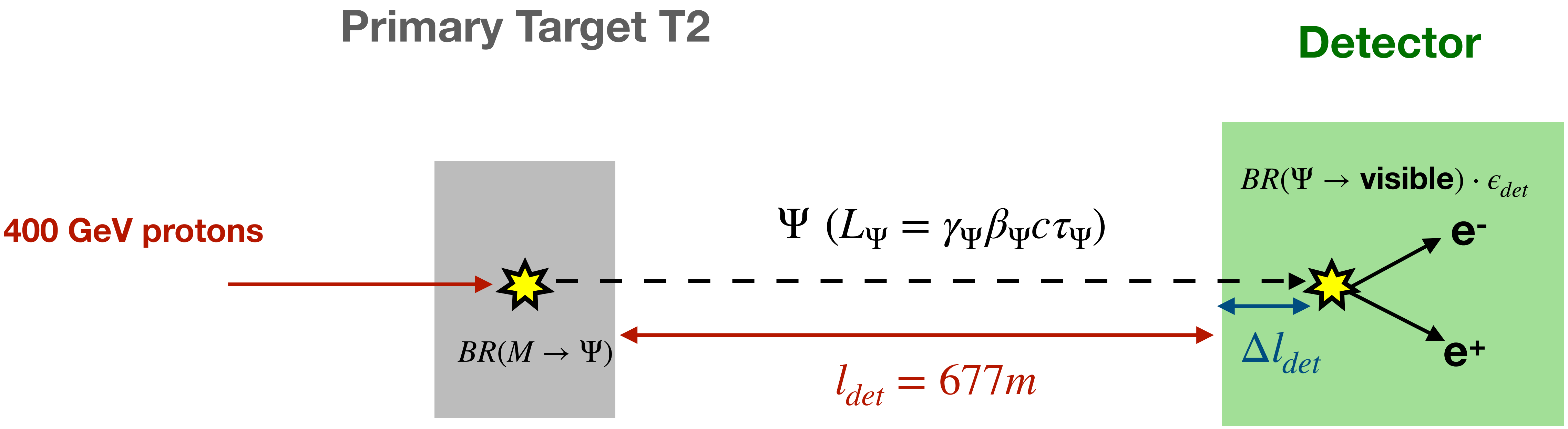
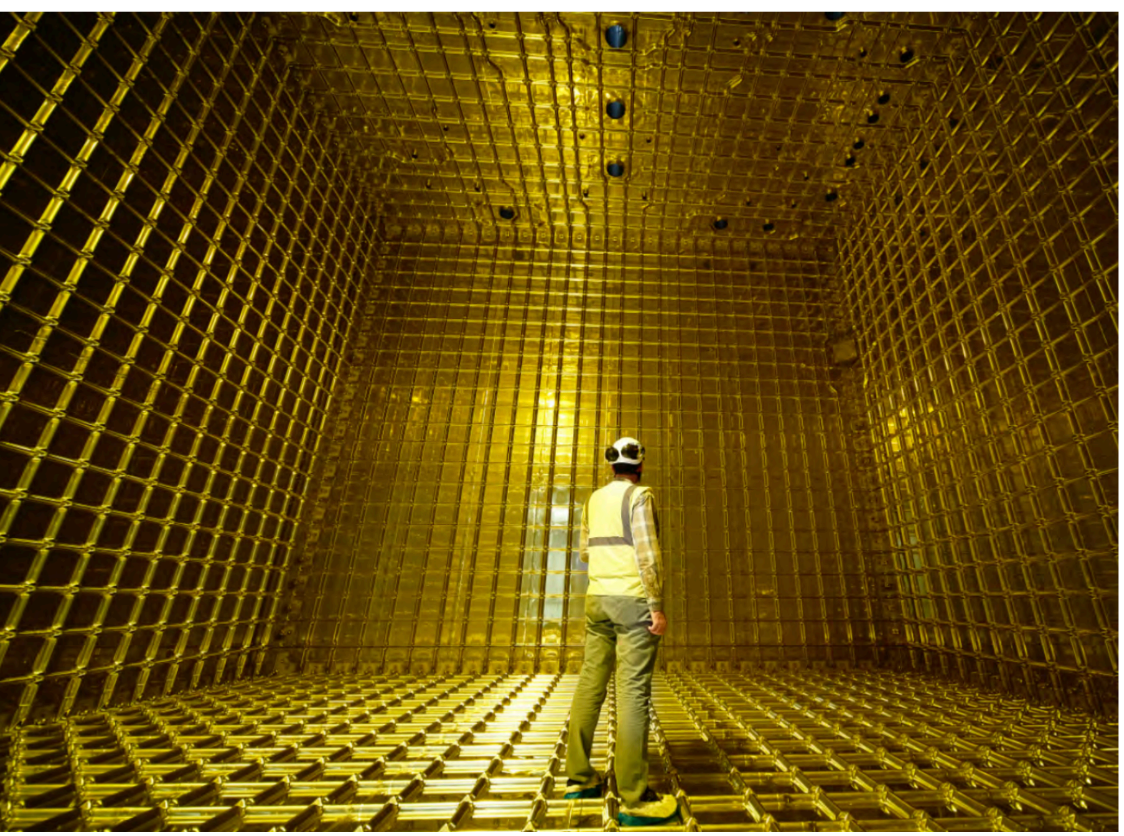
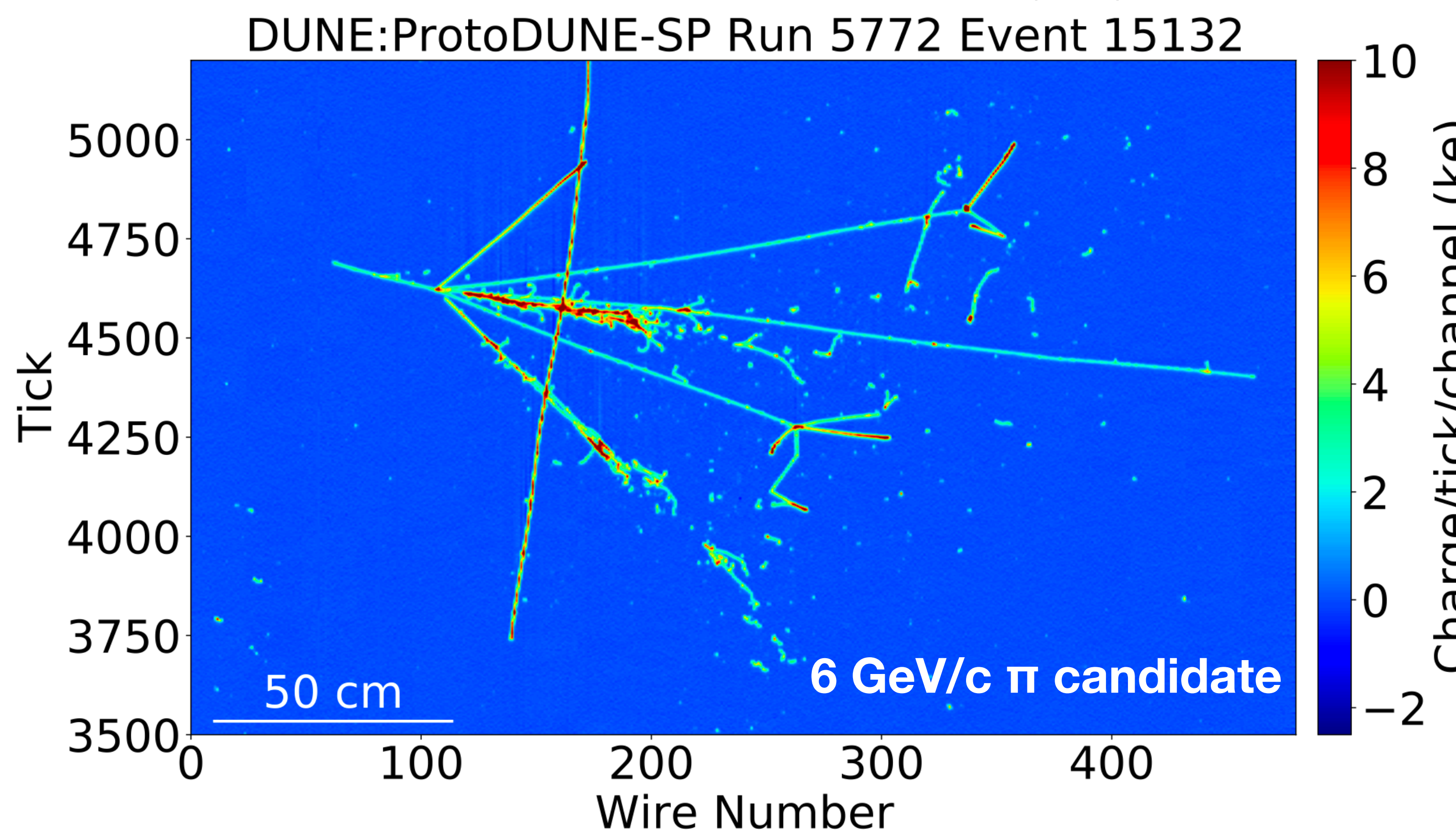
Beam dump approach: *LLPs scenarios*



In this study one ProtoDUNE detector considered



DUNE collaboration, JINST 15 (2020) no.12, P12004



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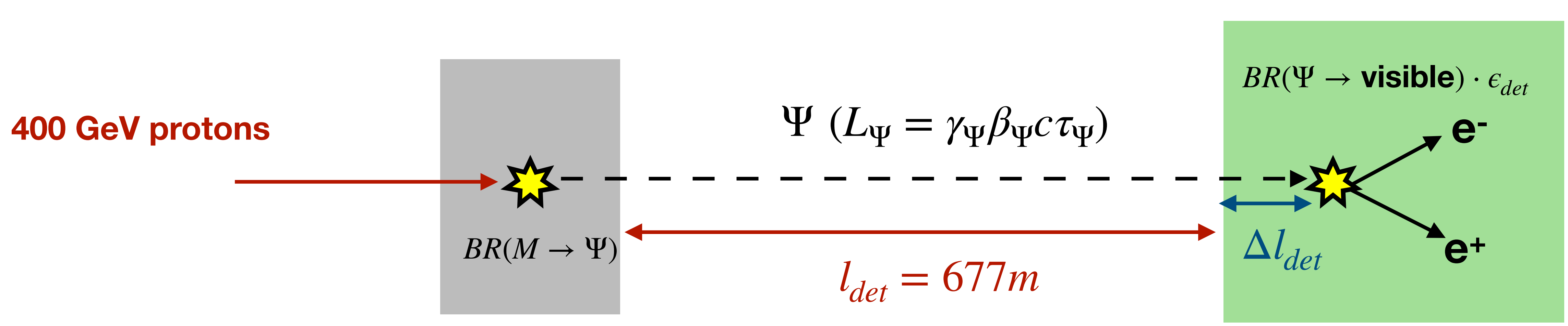
Beam dump approach: *LLPs scenarios*



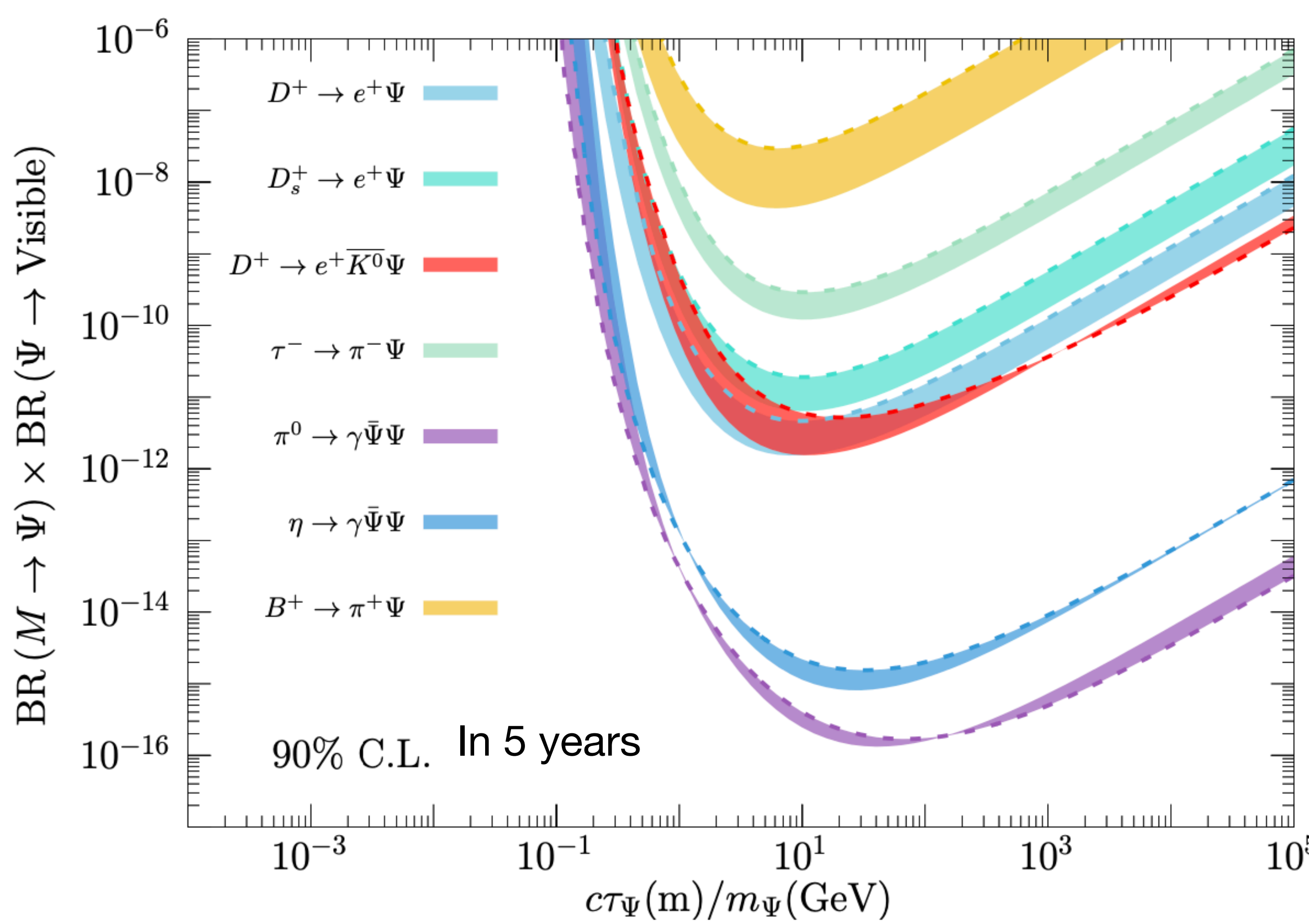
$$N_{dec} = N^M_{dec} \cdot BR(\Psi \to \textbf{visible}) \cdot \epsilon_{dec}$$

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

$$P_{dec} = e^{\frac{e^{-l_{det}}}{L_\psi}} \cdot \left(1 - e^{\frac{e^{-\Delta l_{det}}}{L_\psi}}\right)$$

In the limit of small couplings ($c\tau >> l_{det}, \Delta l_{det}$)

$$N^M_{dec} \simeq N_{\rm PoT}\, Y_M\, {\rm BR}(M \to \Psi) V_{det} \int \frac{dE_\Psi}{L_\Psi} \left\langle \frac{dn^{M\to\Psi}}{dE_\Psi dS} \right\rangle$$

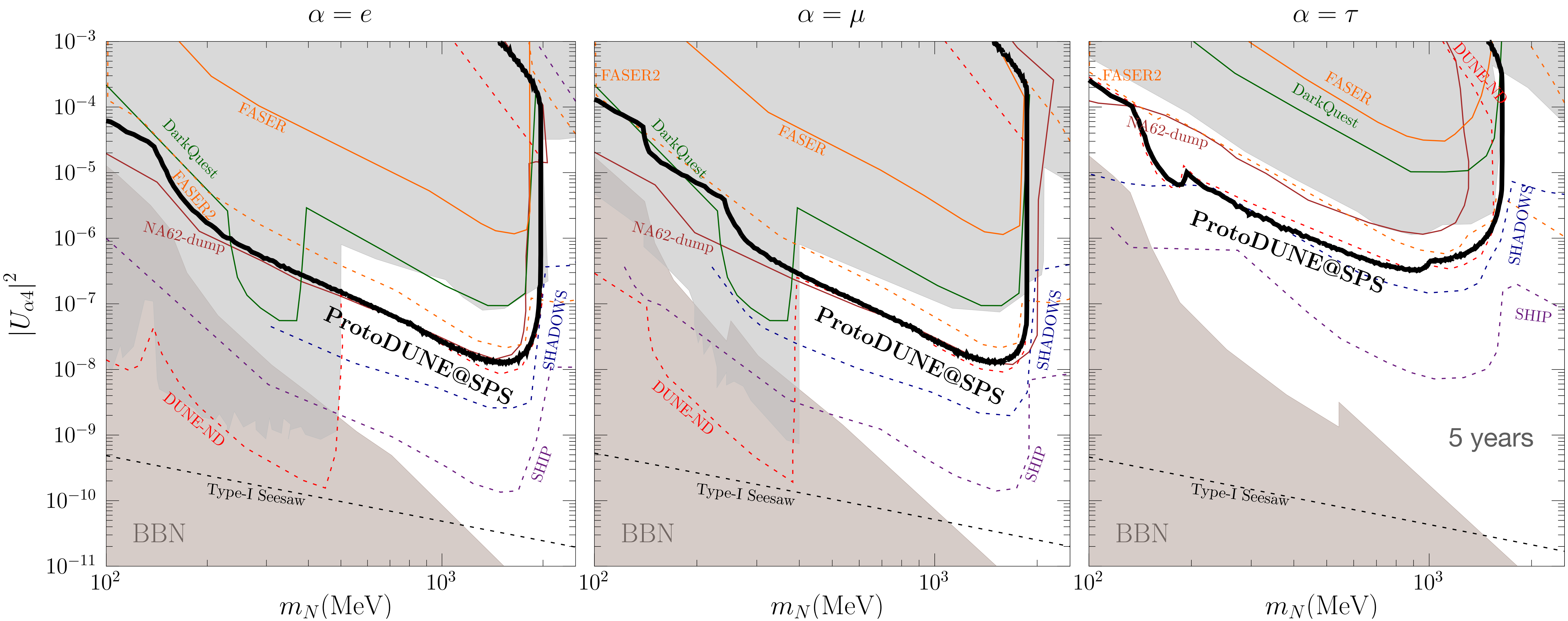


LLP scenarios: *Heavy neutral leptons (HNLs)*

HNLs arising in low-scale seesaw models can accommodate two fundamental questions: **the origin of neutrino masses** and **the baryon asymmetry**

Simplified scenario: *only one HNL (N) which mixes exclusively with one SM neutrino of a given flavour*

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



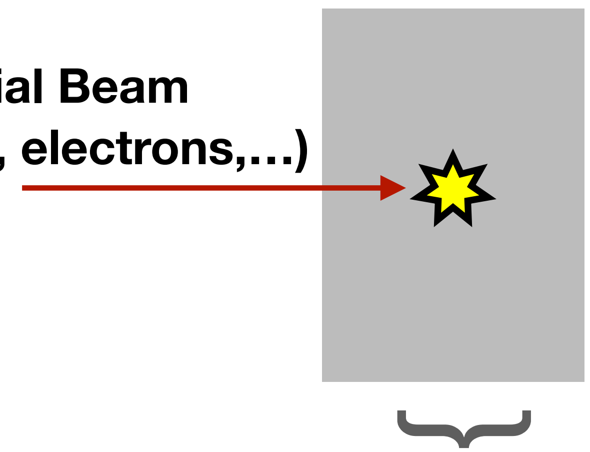
Decays considered: $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi, \nu\pi^0$

HNL production branching ratios and decay widths from P. Coloma *et al. Eur. Phys. J. C* **81**, 78 (2021).

Beam dump approach: *stable particles scenarios*

Primary Target T2

Initial Beam
(Protons, electrons,…)



Products from the result of proton interactions with a target (focus on short-lived mesons ,M))

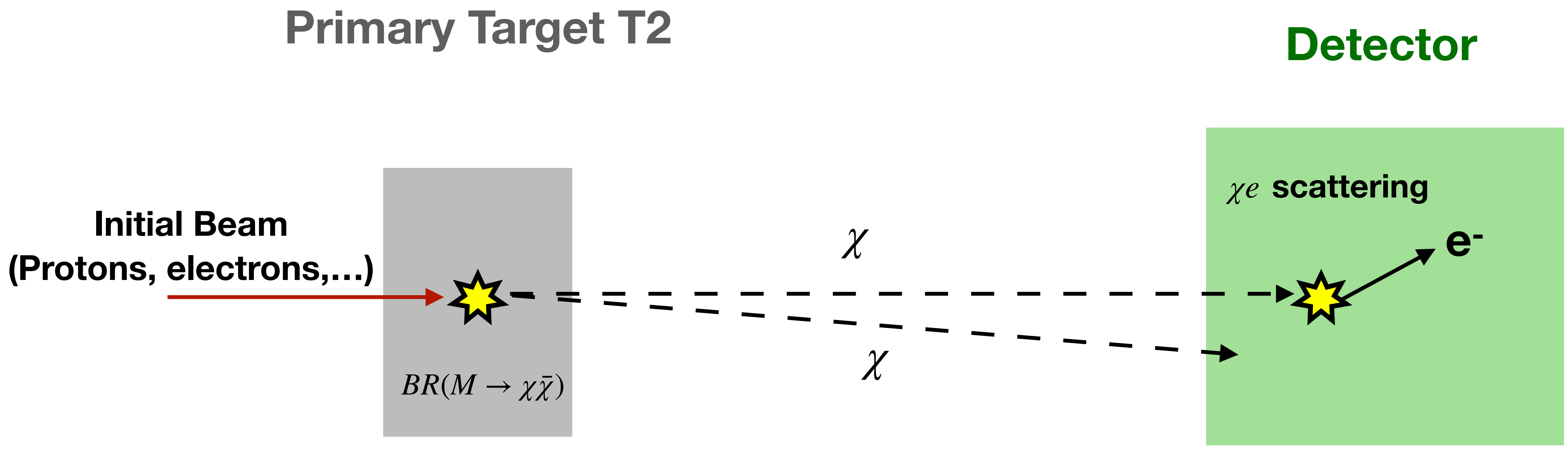
(D, D_s, B, Y, J/Ψ, η, η’, π^0, ρ, …)

b) Stable particles

These mesons can also decay to new light stable particles (χ)

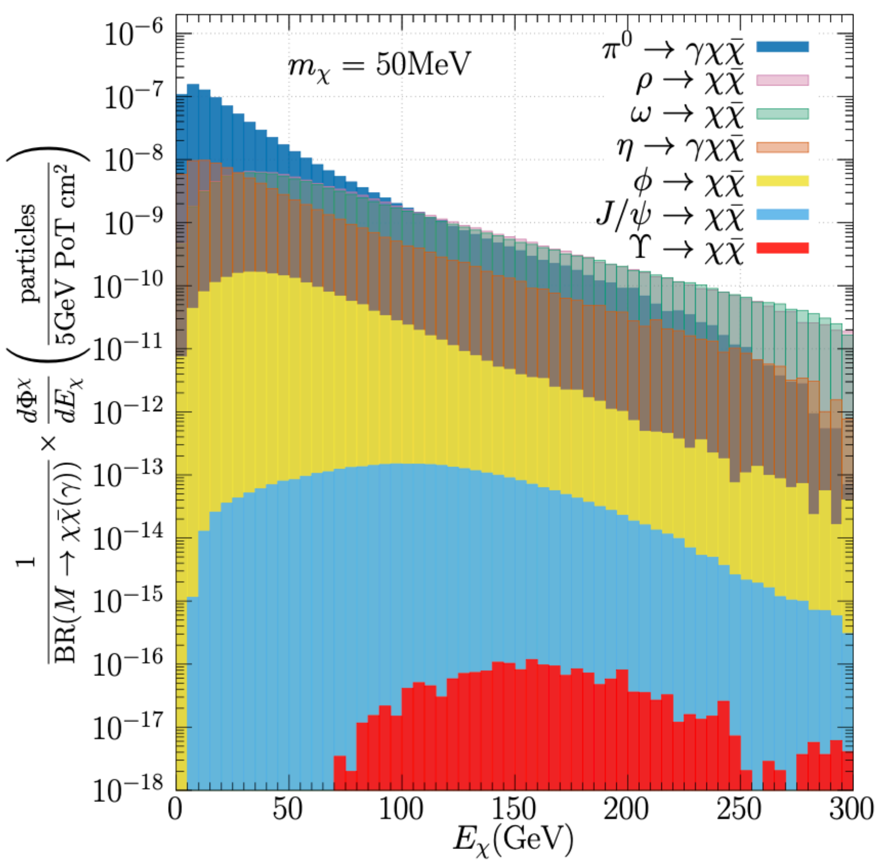
$$BR(M \to \chi\bar{\chi})$$

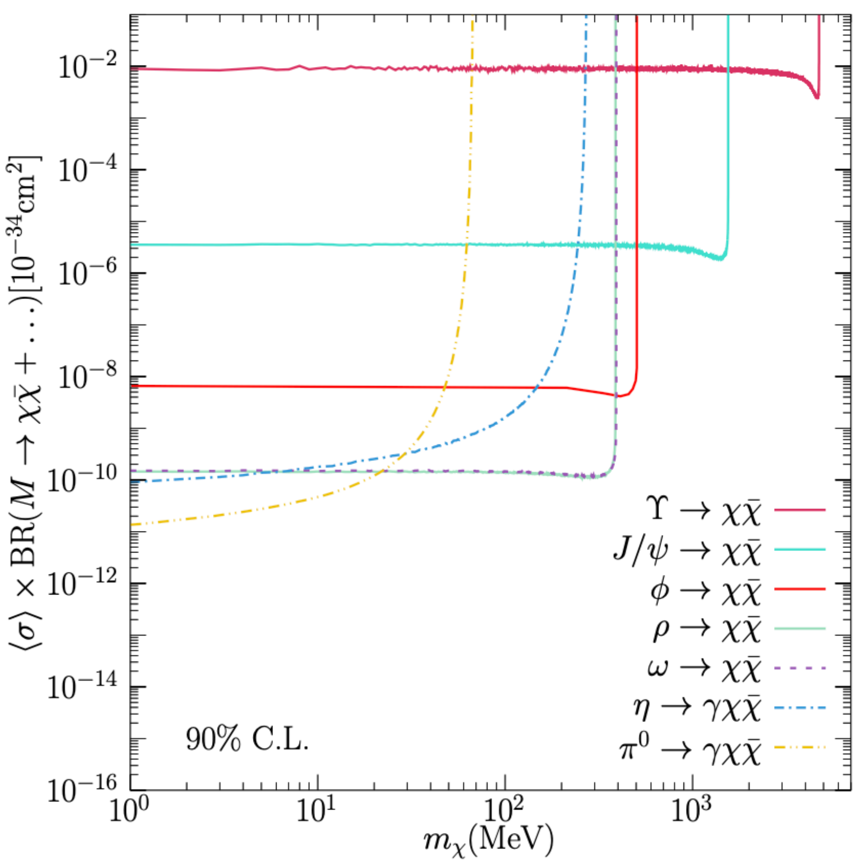
Beam dump approach: *stable particles scenarios*



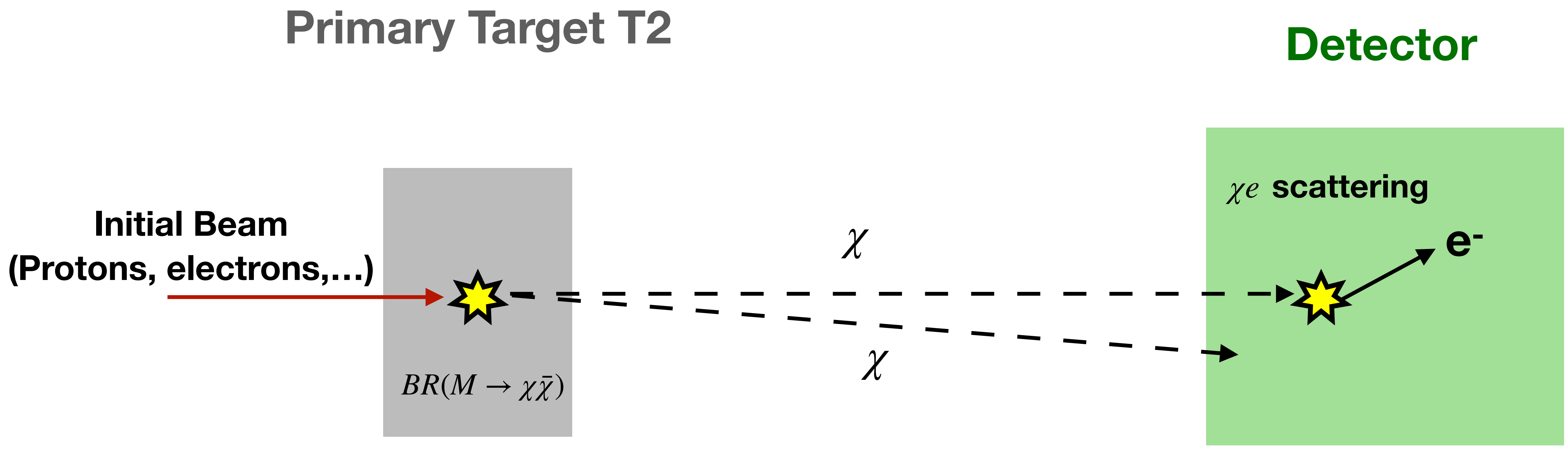
$$\langle\sigma\rangle = \frac{1}{\Phi^\chi}\int_0^\infty \int_{T^{\min}}^{T^{\max}} \frac{d\sigma}{dT}(E_\chi, \{X\})\,\frac{d\Phi^\chi}{dE_\chi}\,dT\,dE_\chi$$

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





Stable particle scenarios: *millicharged particles*



Millicharged particles (MCPs)**: fermions with an effective charge **eε.
They arise from the mixing of the SM photon and a massless Dark Photon

Differential electron scattering cross-section

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

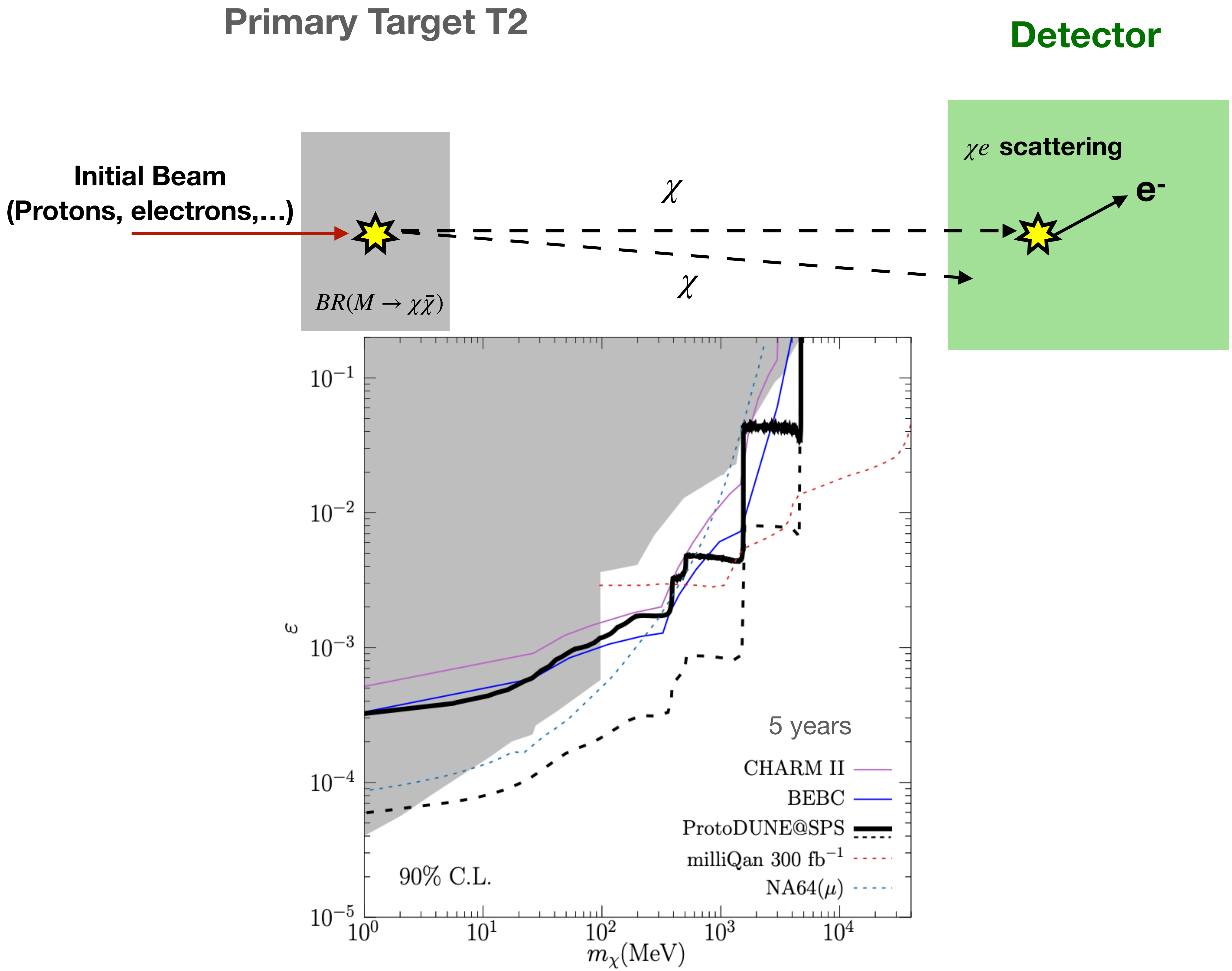
In the limit $E_\chi >> T, m_e, m_\chi$ and small MCP masses

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

$$\frac{\langle\sigma\rangle \times \mathrm{BR}}{10^{-26}\ \mathrm{cm}^2} \sim \mathrm{BR}(\pi^0 \to \gamma\chi\bar{\chi})\,\varepsilon^2 \left(\frac{30\ \mathrm{MeV}}{T_{\mathrm{min}}}\right)$$

$$\sim \mathrm{BR}(\pi^0 \to \gamma e^- e^+)\,\varepsilon^4 \left(\frac{30\ \mathrm{MeV}}{T_{\mathrm{min}}}\right)$$

Stable particle scenarios: *millicharged particles*



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Summary and outlook

➡The excellent imaging capabilities and the large fiducial volume of ProtoDUNE detectors make them ideal to search for weakly interacting massive particles in Beyond Standard Model scenarios.

- Given their location at CERN, the ProtoDUNE detectors may be exposed to a flux of new particles generated after the collision of 400 GeV protons, extracted from the SPS accelerator, with the T2 target.

➡We have exploited the possibility of using such a setup to search for both long lived unstable particles and stable particles. We have focused in two particular scenarios but this setup offers many other possibilities such as dark photons, dark scalars, axion-like particles, or light dark matter.

- We also show the expected sensitivity of the setup using a model-independent approach. This allows our results to be easily recasted to particular NP models involving either unstable or stable new states.

➡*A dedicated analysis is required in order to determine the expected background levels and detector efficiencies achievable for such a setup, as well as the development of a new trigger condition optimised for the beam-dump approach.*

➡A working group in collaboration with the Neutrino Platform has been created to study the feasibility of the proposal.

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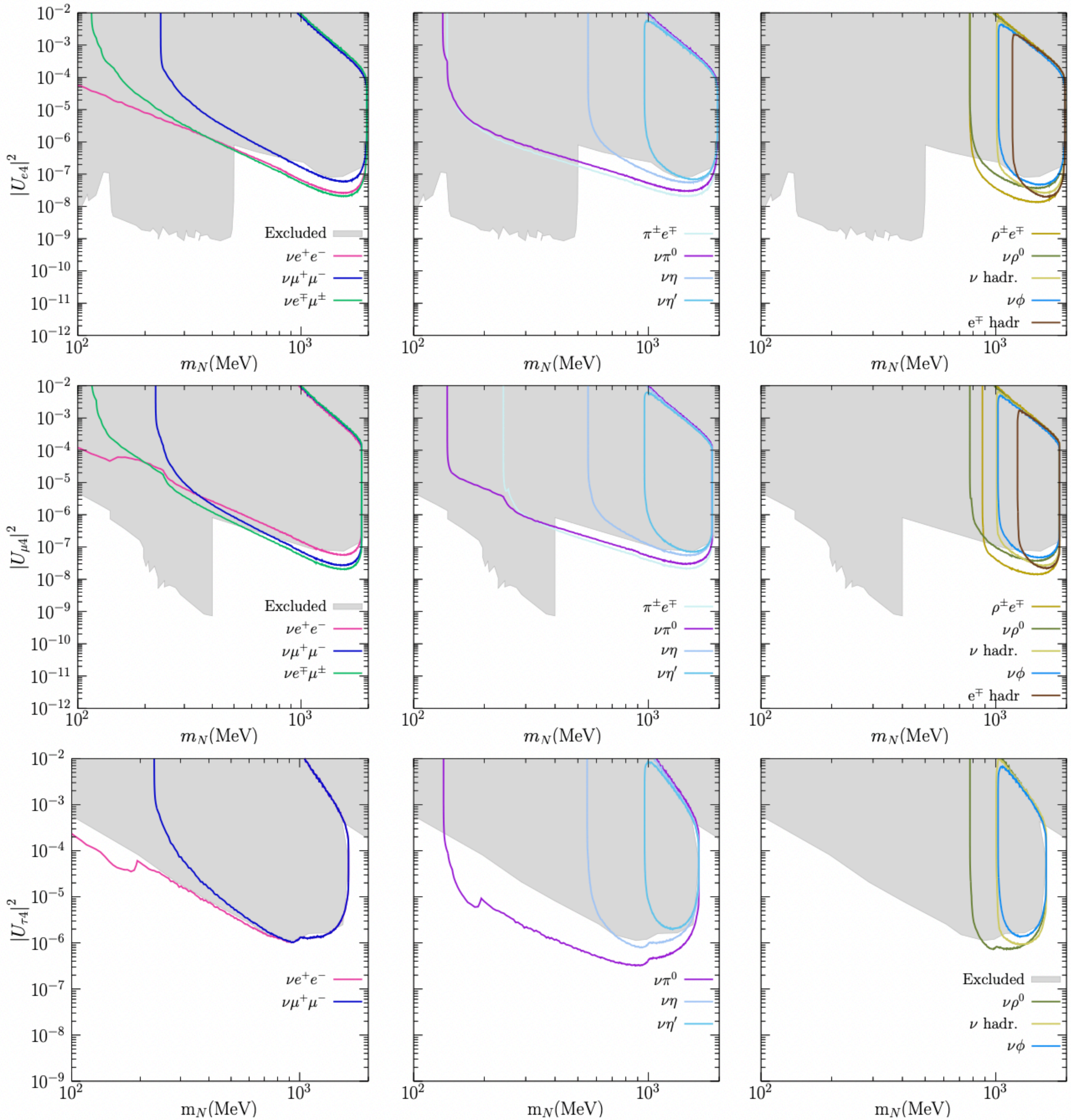
Thanks for your attention!

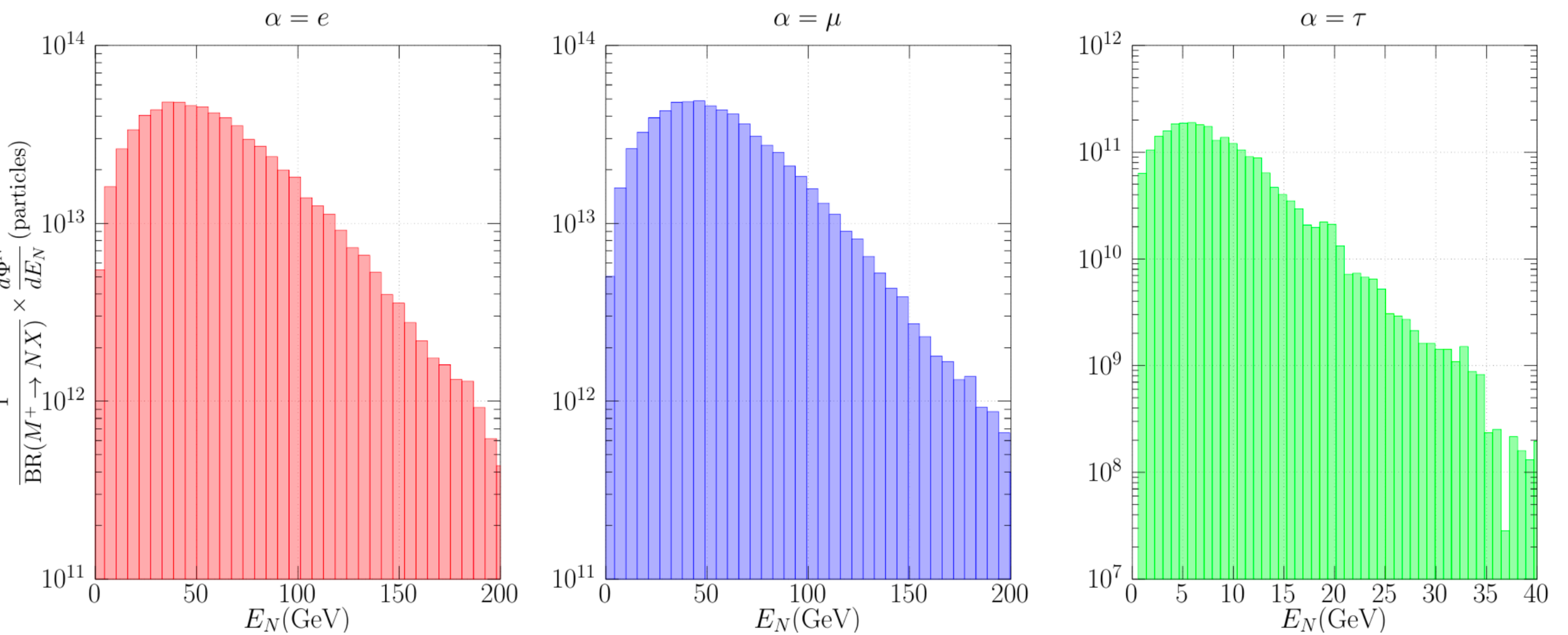
Back-up

HNL

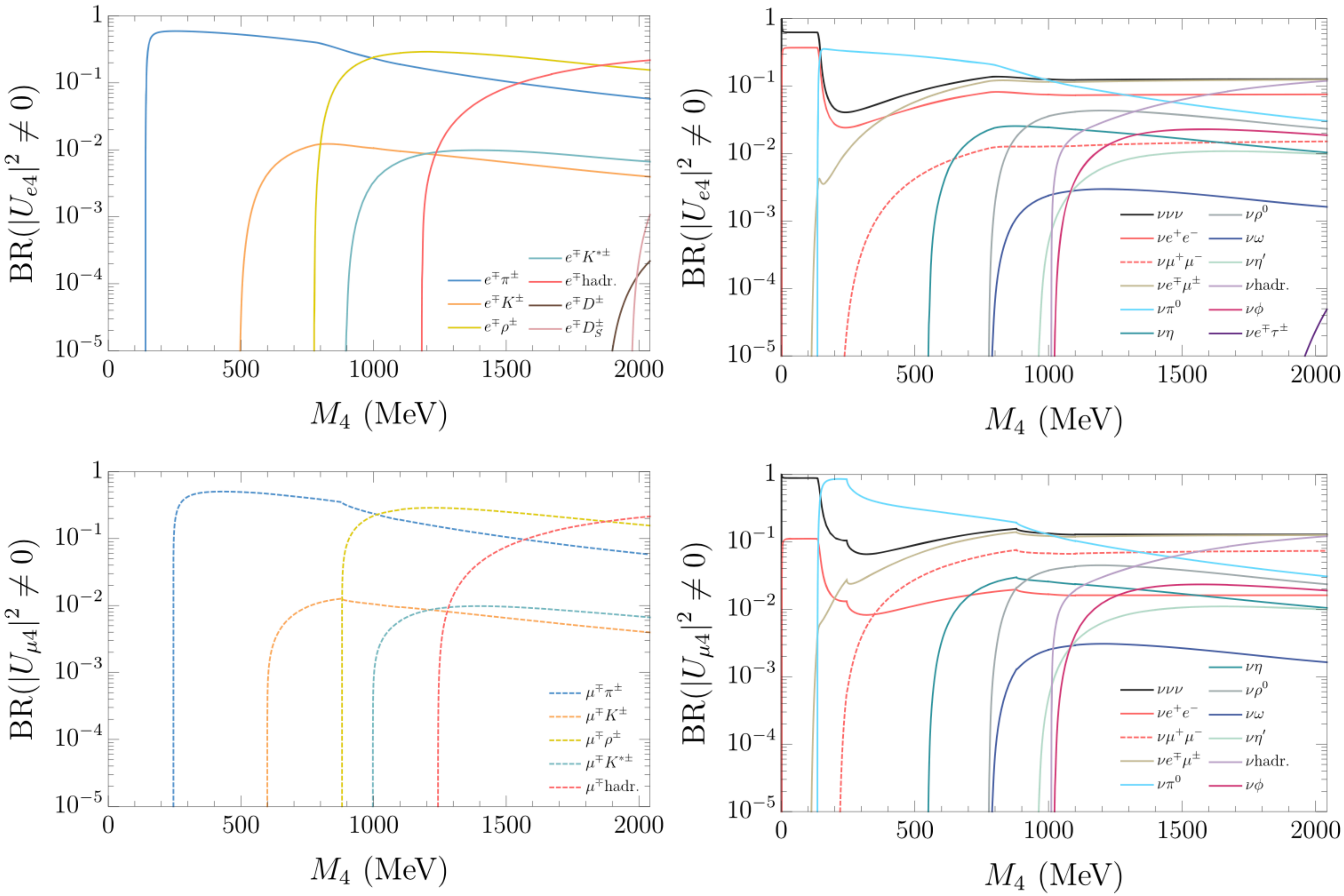


$|U_{e4}|^2$
$|U_{\mu4}|^2$
$|U_{\tau4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm e^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm e^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
$e^\mp$ hadr

HNL fluxes with detector acceptance



5 years



P. Coloma *et al. Eur. Phys. J. C* **81**, 78 (2021).