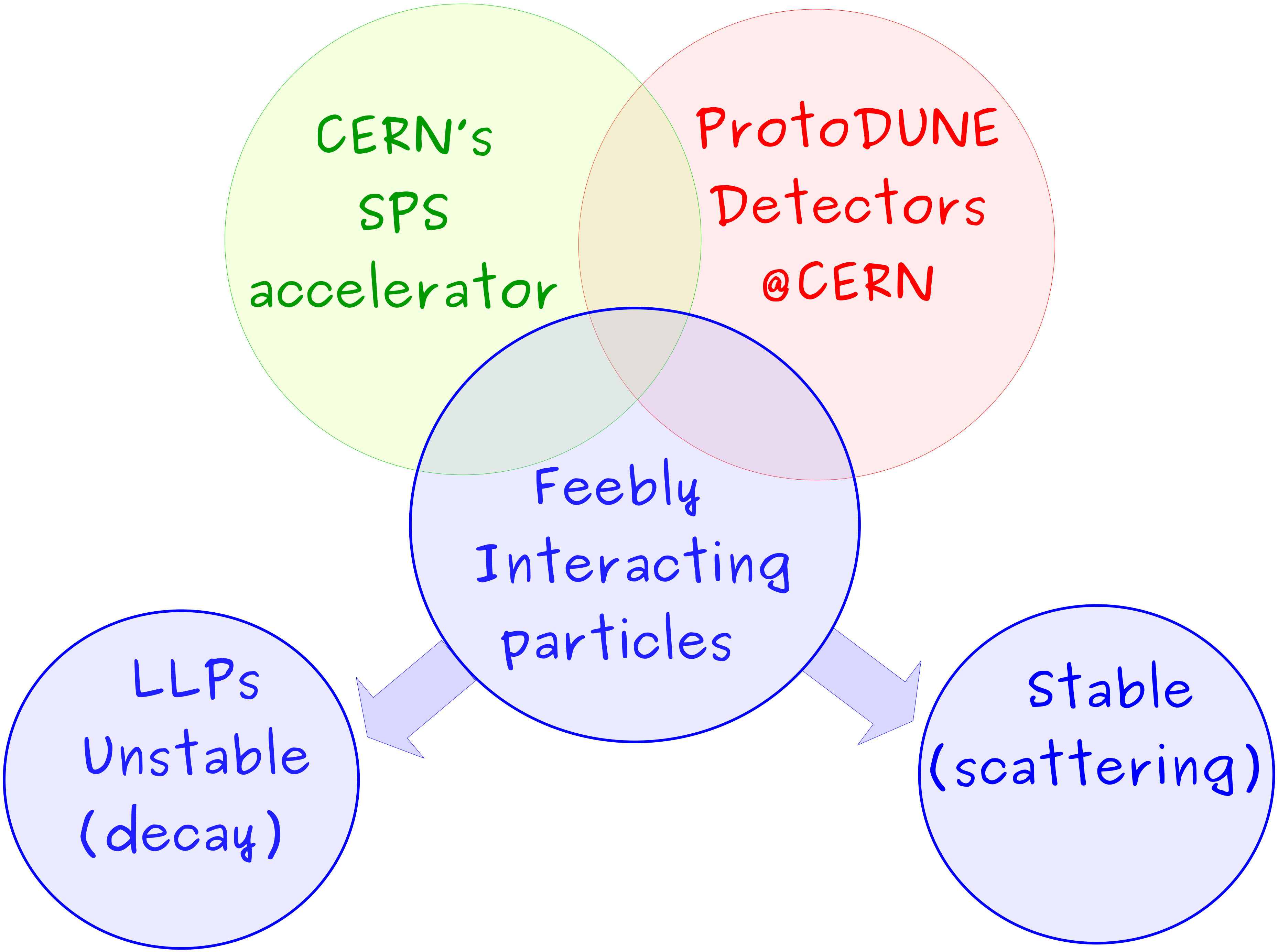
New Physics searches using ProtoDUNE & the SPS accelerator

Jacobo López-Pavón

Based on a collaboration with
Pilar Coloma, Laura Molina-Bueno, Salvador Urrea
https://arxiv.org/pdf/2304.06765.pdf

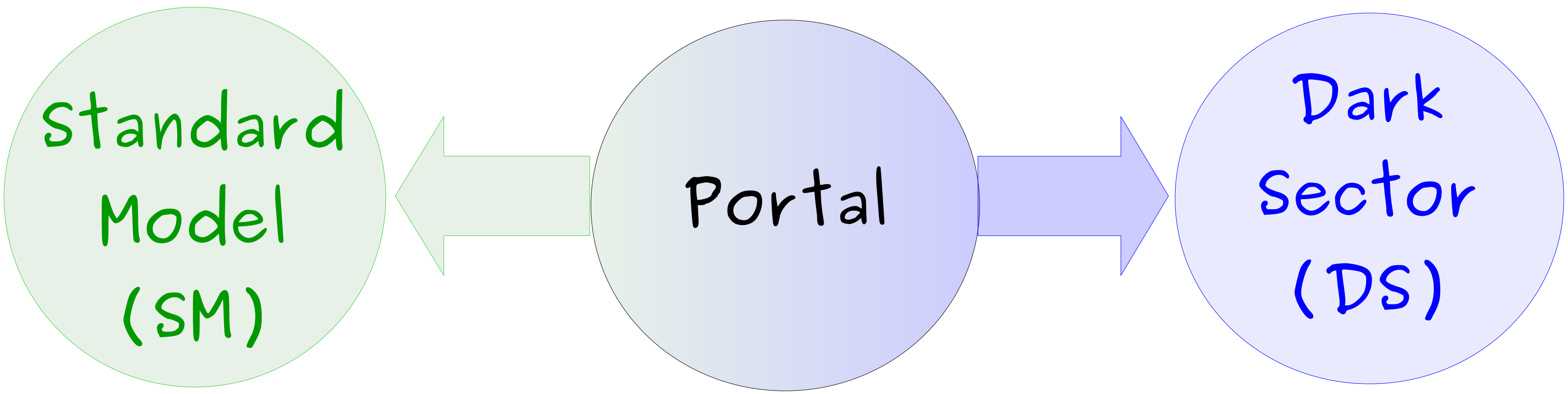
Workshop on the Standard Model & Beyond | CORFU 2023

CIDEGENT/2018/019


CERN's
SPS
accelerator
ProtoDUNE
Detectors
@CERN
Feebly
Interacting
particles
LLPs
Unstable
(decay)
Stable
(scattering)

Motivation: Feebly-interacting particles

New Physics at low energy scales might be the key to explain open questions as the **Dark Matter** problem or the **origin of neutrino masses** and **baryon asymmetry**.

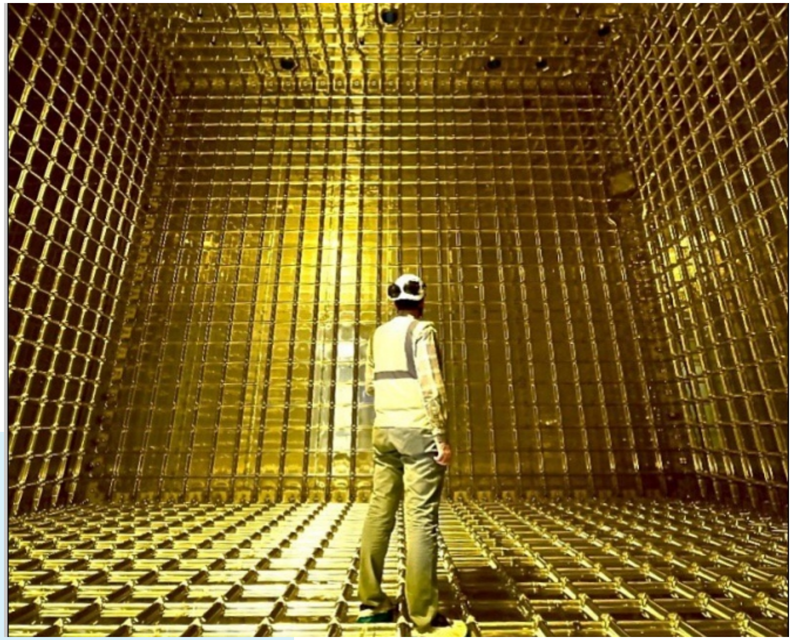


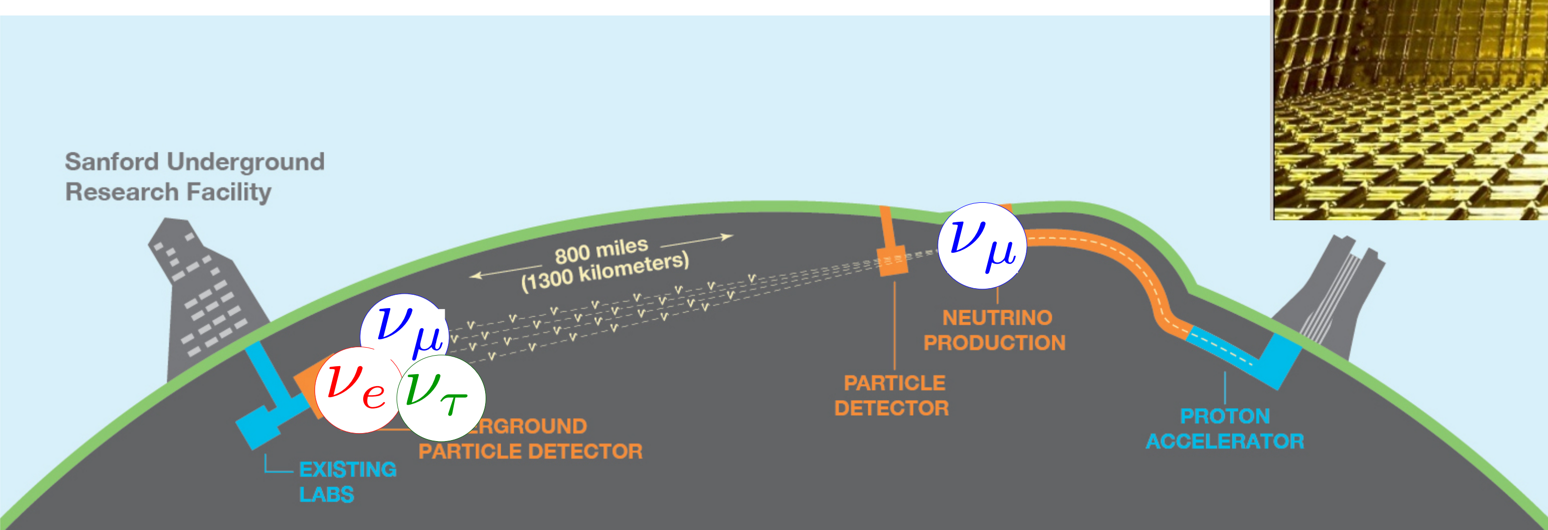
Vector: **Dark Photon**
Scalar: **Dark Higgs**
Pseudo-scalar: **ALPs**
Fermion: **Heavy Neutral Leptons** (HNLs)

See for instance FIPs workshop reports 2102.12143 and 2305.01715

Motivation

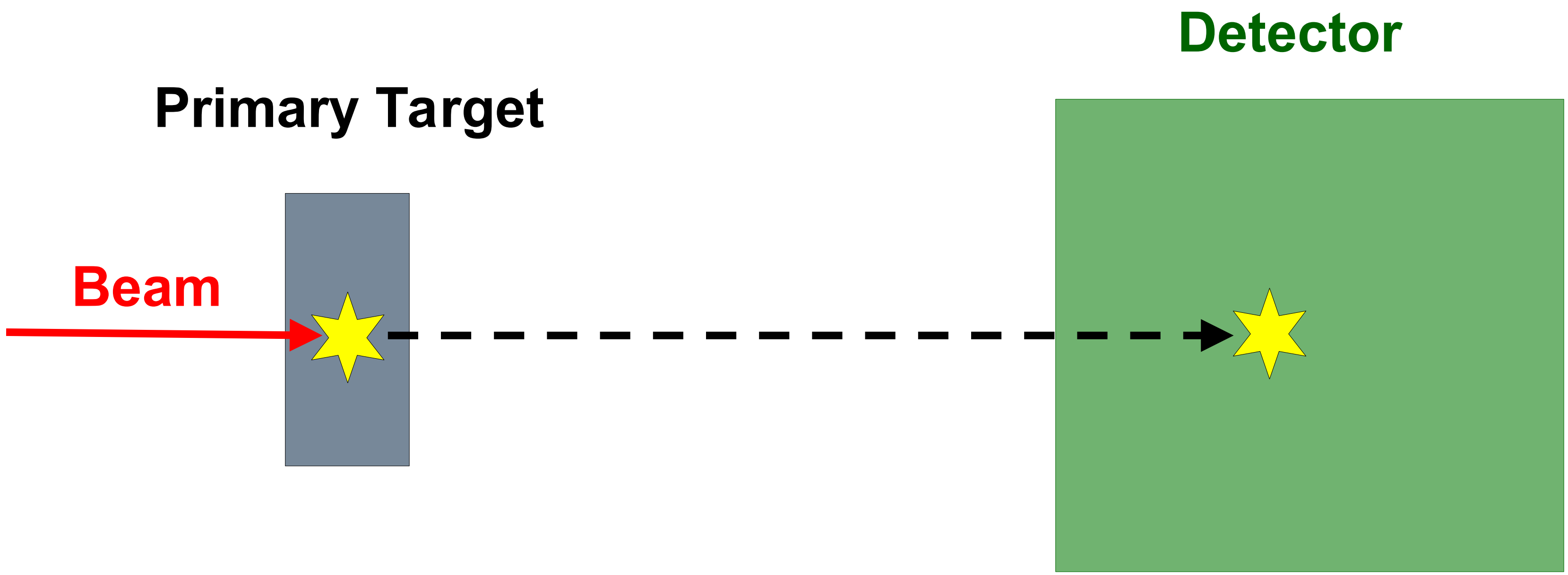
ProtoDUNE detectors, already located at CERN, are two kiloton-scale liquid Argon Time Projection Chambers (LArTPCs) constructed to prototype and consolidate the technology of the DUNE Far Detector





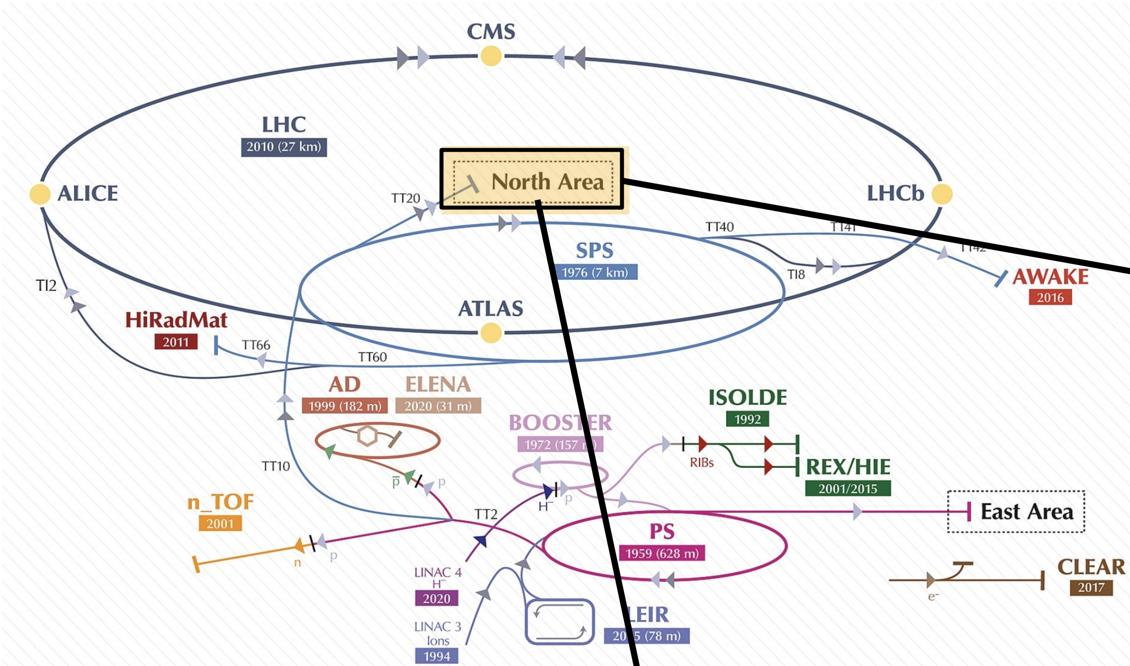
Motivation

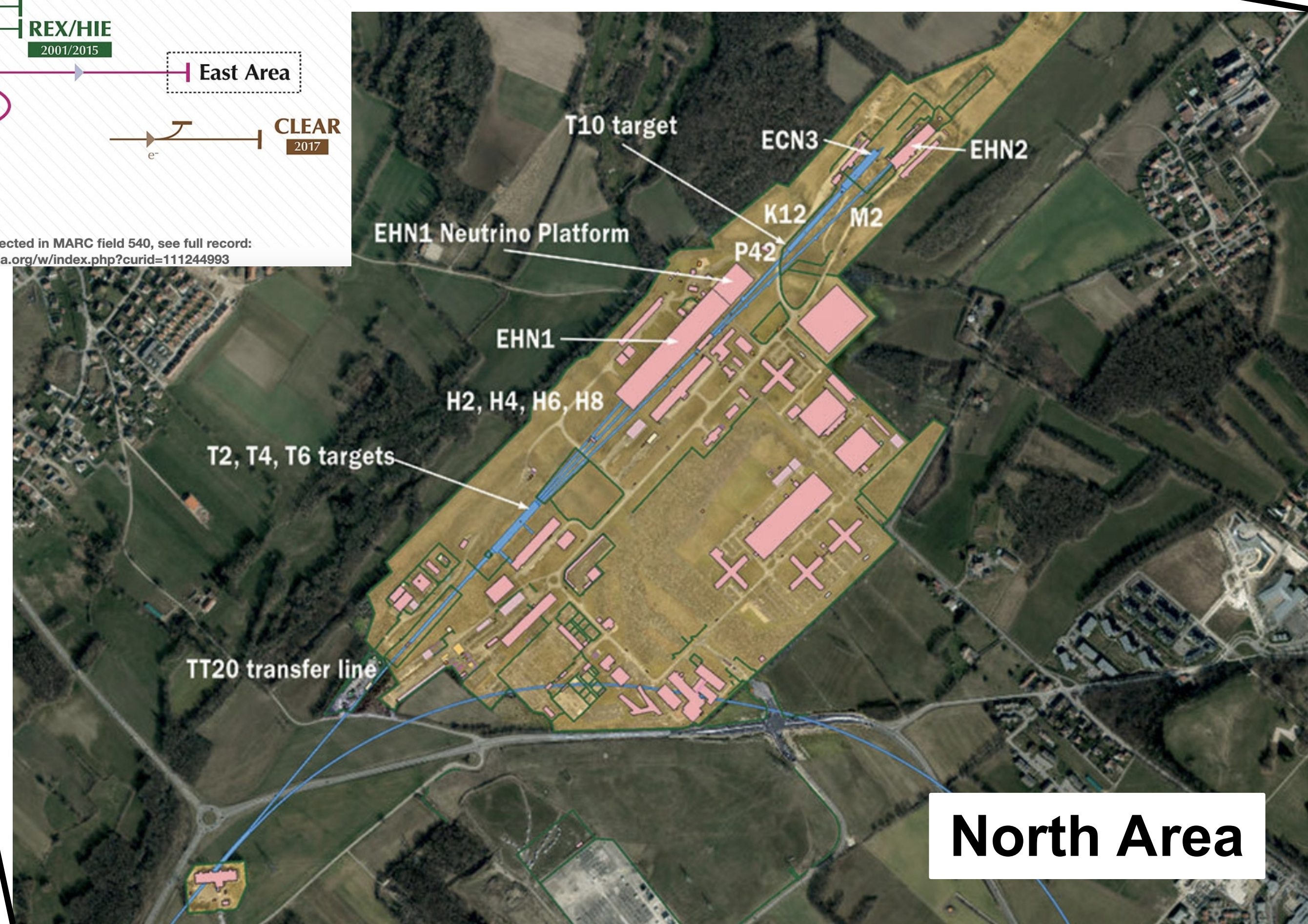
Can ProtoDUNE detectors be used as a beam dump facility to search for new feebly interacting particles?



Some examples: NA62, FASER, DUNE near detector, HIKE, SHADOWS, SHiP...

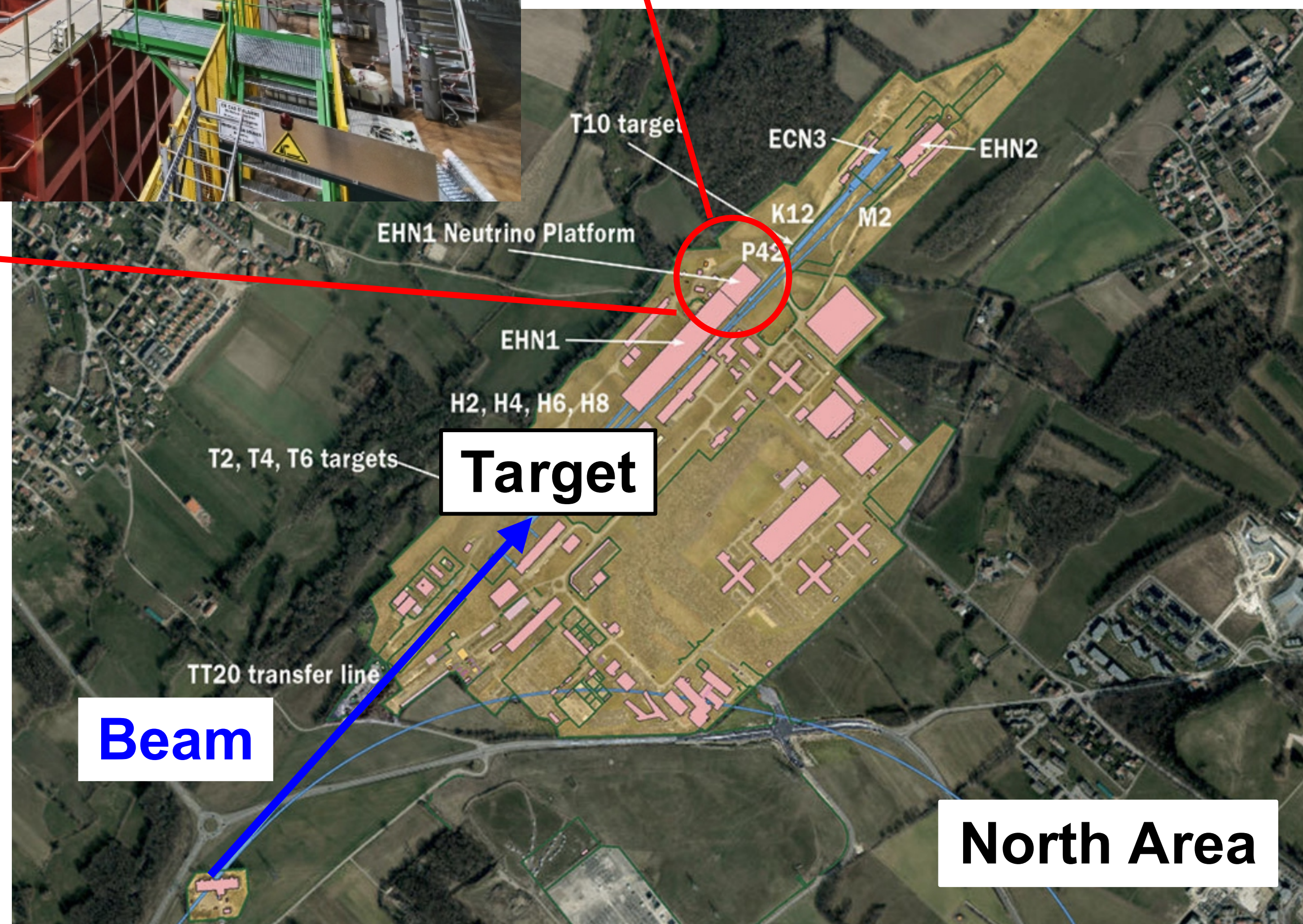
North Area & SPS acclerator @CERN



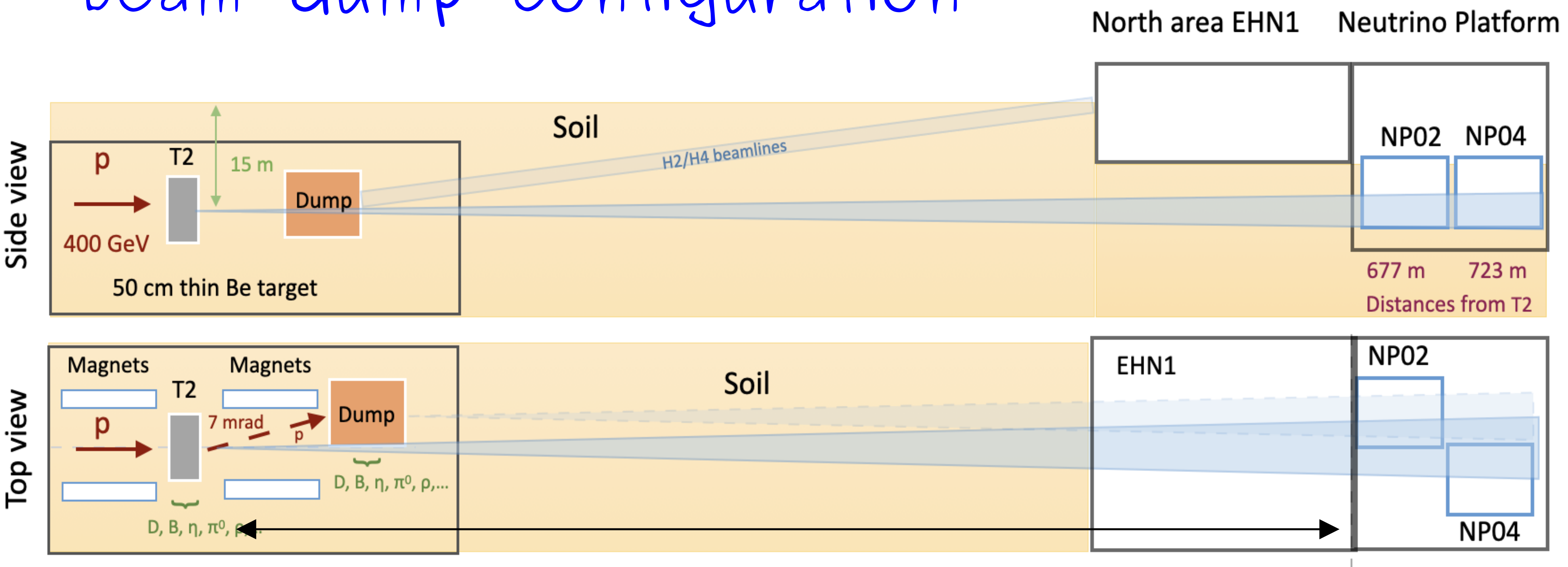


North Area & SPS acclerator @CERN

CERN Neutrino Platform
(**ProtoDUNE** detectors)



Beam dump configuration

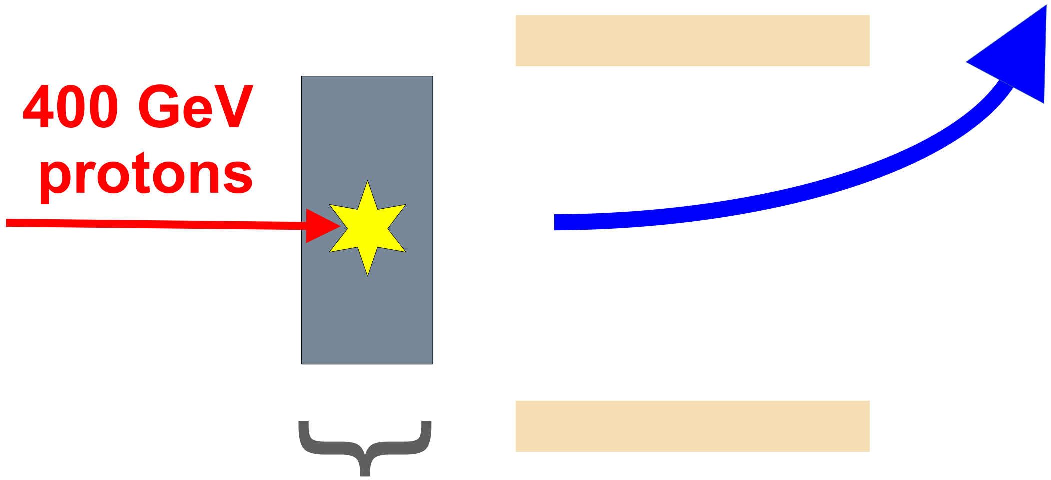


$$l_{det} \sim 700\,m$$

- Proton energy: 400 GeV (instead of 80-120 GeV as in neutrino experiments)
- ~5-7x10^{12} protons/spill with a spill duration of 4.8 s →3-5x10^{18}PoT/year
- *No decay volume*
- *ProtoDUNE detectors:* Liquid Argon Time Projection Chambers with large fiducial volume and excellent imaging capabilities to identify decay products
- Detectors at the surface. Cosmic-rays expected dominant background source.

Production

Primary Target T2
(50 cm Beryllium target)



Charged kaons and pions deviated with magnets

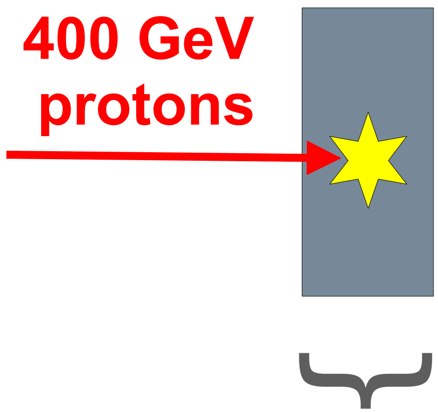
SM neutrino background significantly reduced.

Products from proton interactions with a target (only **neutral and short-lived mesons M** can be in principle exploited)

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

Production

Primary Target T2
(50 cm Beryllium target)



Meson production yield Y_M (normalised per PoT)

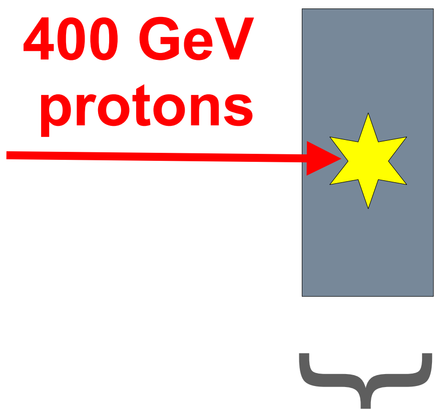
π^0	η	η'	D	D_s	τ
4.03	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$
ρ	ω	ϕ	J/ψ	B	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$

Products from proton interactions with a target (only **neutral and short-lived mesons M** can be in principle exploited)

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

1) Long Lived Particles (LLPs)

Primary Target T2
(50 cm Beryllium target)



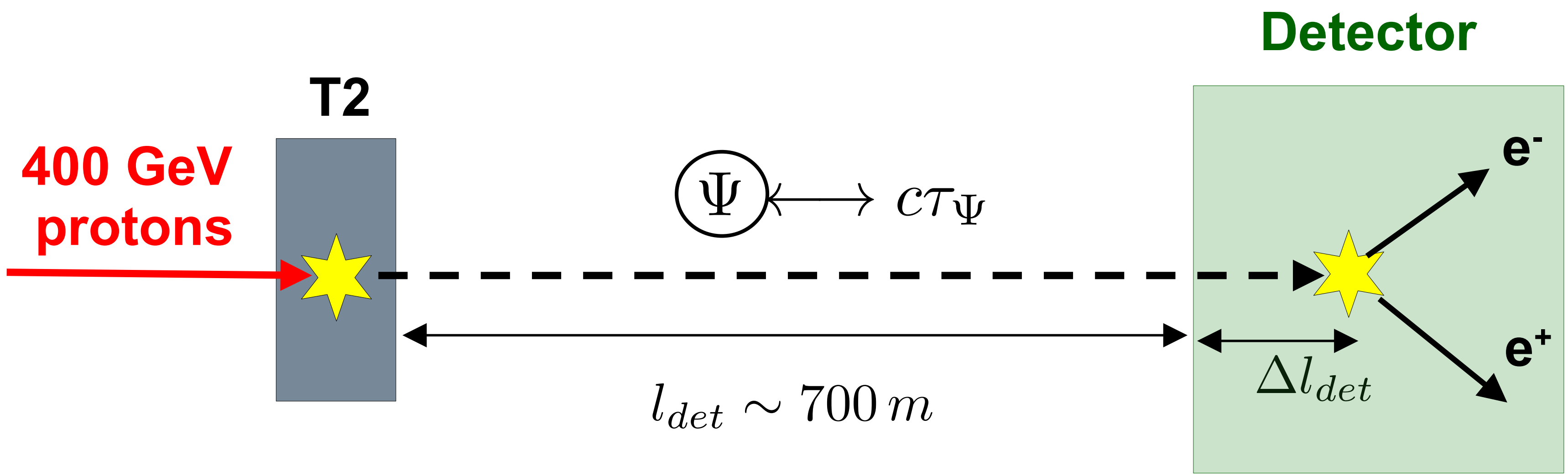
These mesons can decay in new unstable light particles Ψ generating an intense flux of LLPs

$$\mathrm{BR}\left(M \to \Psi + \ldots\right)$$

Products from proton interactions with a target (only **neutral and short-lived mesons M** can be in principle exploited)

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

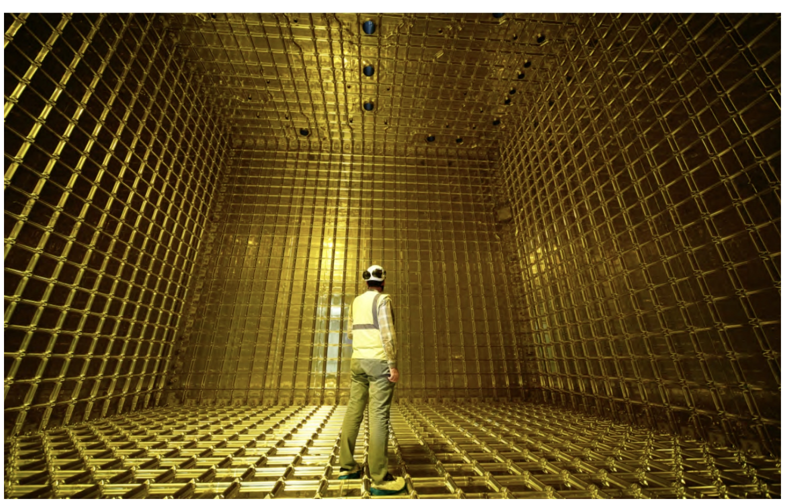
1) LLPs: Model independent approach



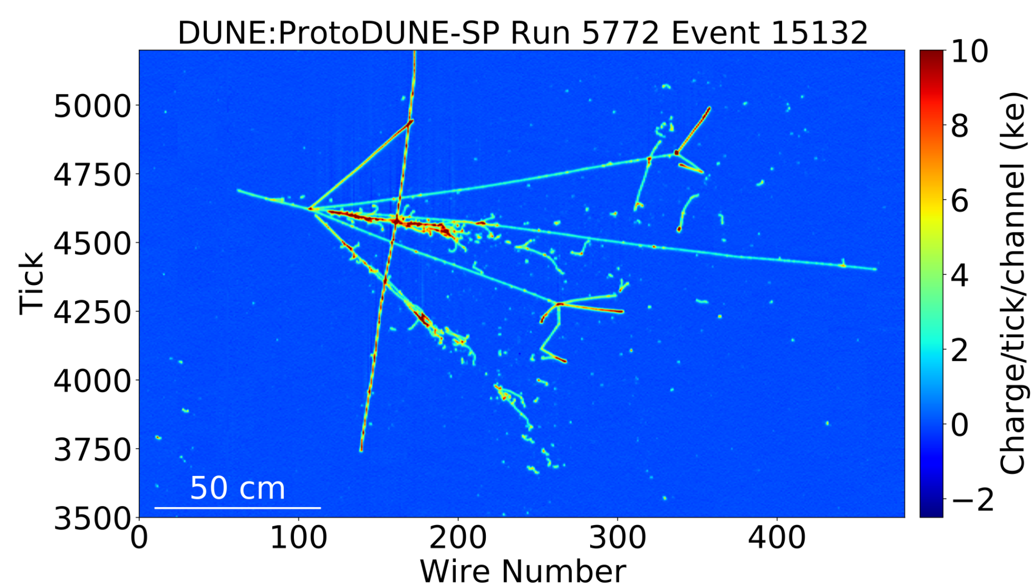
$\mathrm{BR}\,(M \to \Psi)$

$\mathrm{BR}\,(\Psi \to visible)\,\epsilon_{det}$

We considered only one detector



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



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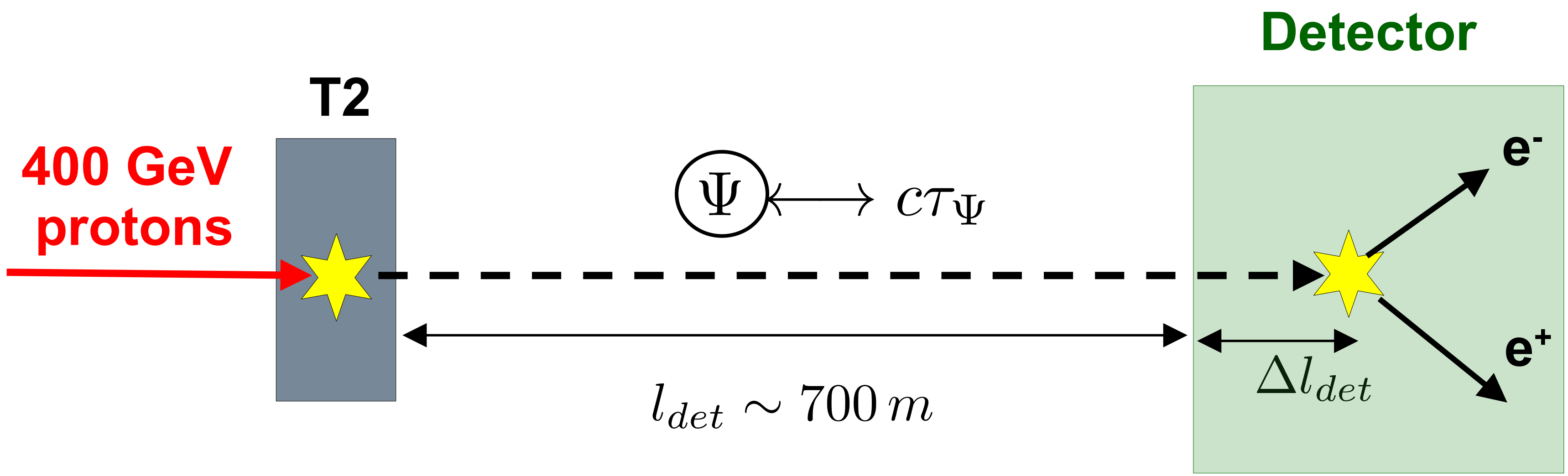
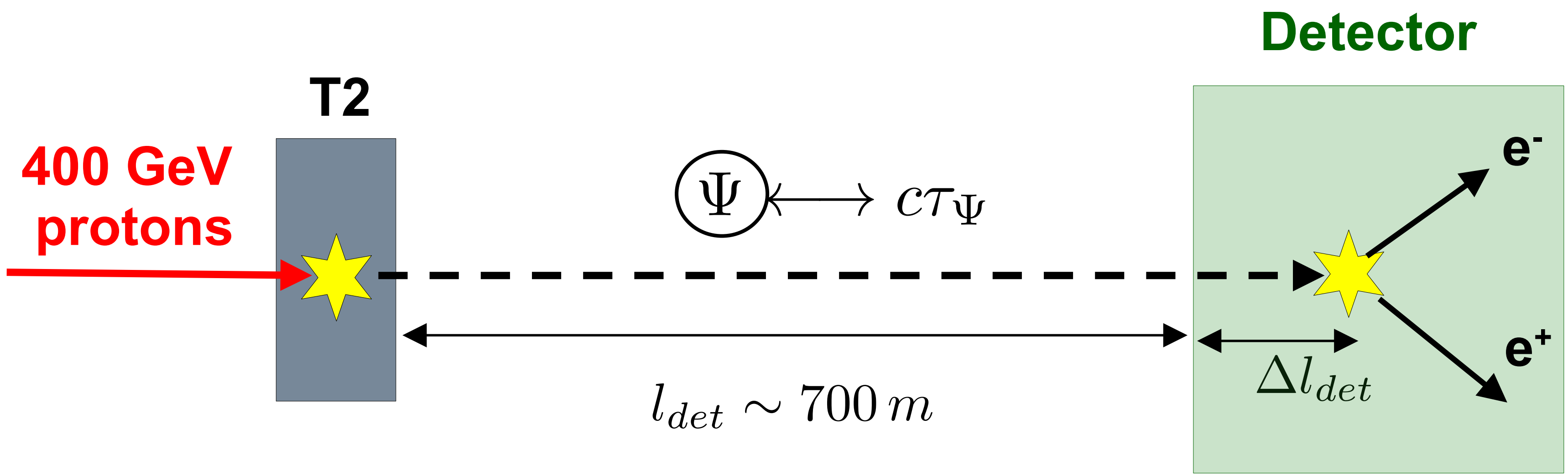


$$N_{dec} = N_{dec}^{M} \mathrm{BR}\left(\Psi \to visible\right) \epsilon_{det}$$

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

$$\mathcal{P} = e^{\frac{-\ell_{det}}{L_\Psi}} \left(1 - e^{\frac{-\Delta\ell_{det}}{L_\Psi}}\right) \leftrightarrow L_\Psi = \gamma_\Psi \beta_\Psi c\tau_\Psi \simeq c\tau_\Psi E_\Psi/m_\Psi$$

1) LLPs: Model independent approach



$$N_{dec} = N^M_{dec} \mathrm{BR}\left(\Psi \to visible\right) \epsilon_{det}$$

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

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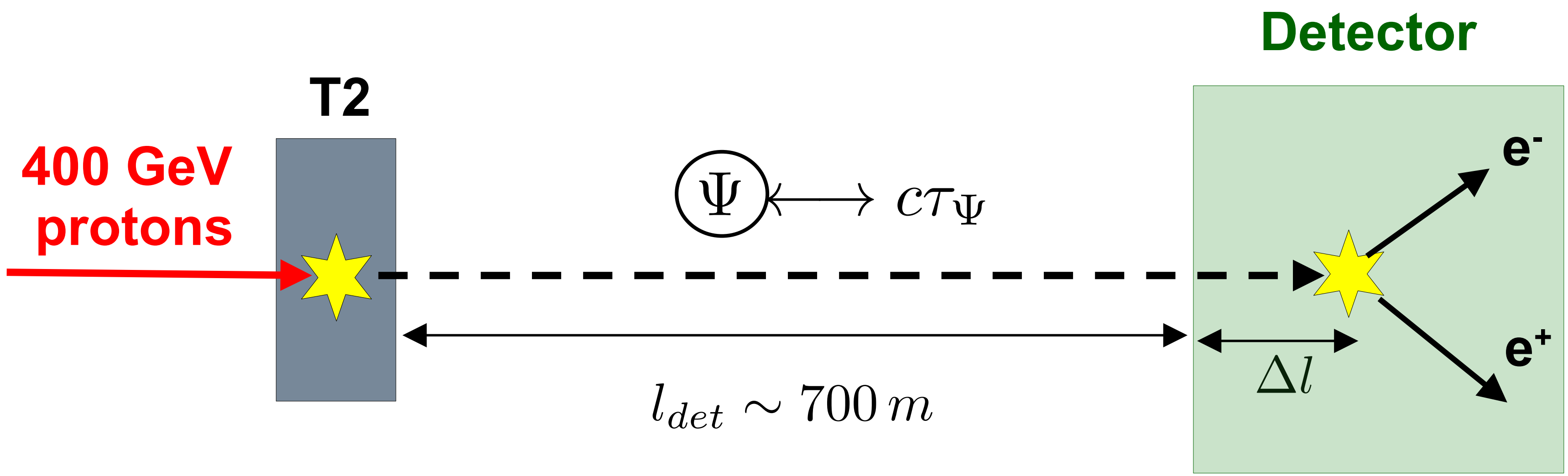
1) LLPs: Model independent approach



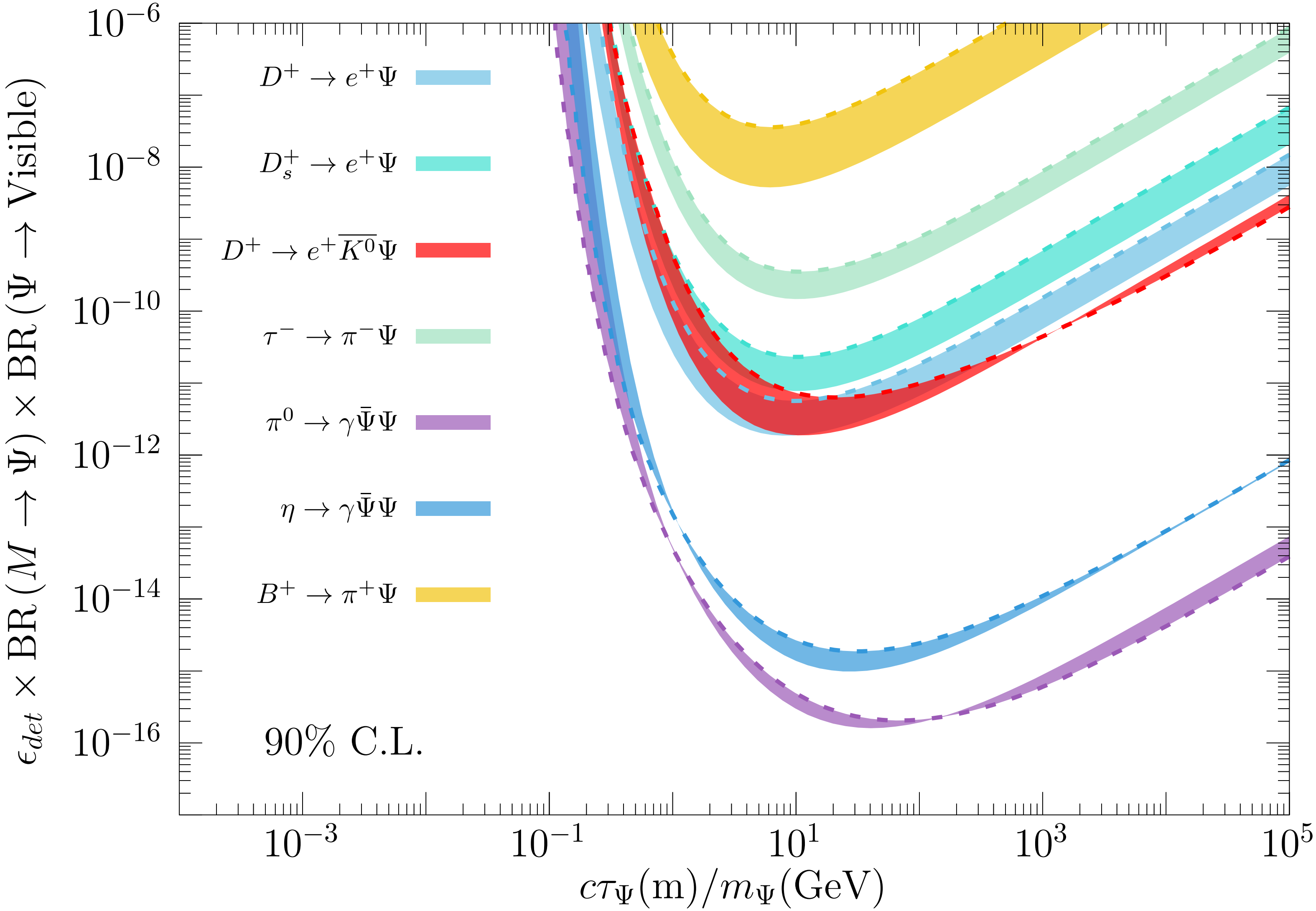
$$N_{dec} = N_{dec}\left(\mathrm{BR}\left(M \to \Psi\right)\mathrm{BR}\left(\Psi \to visible\right), c\tau_\Psi/m_\Psi\right)$$

- Note that in the small coupling limit we have:

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

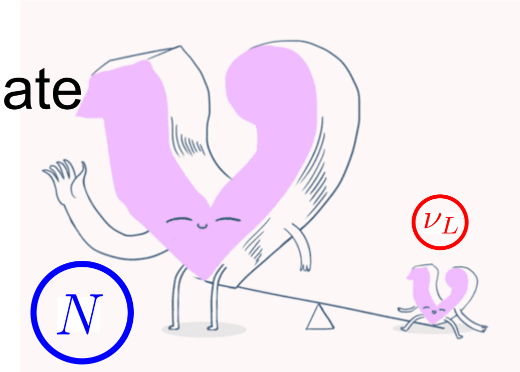
1) LLPs: Model independent approach

$$N_{dec} = N_{dec}\left(\mathrm{BR}\left(M \to \Psi\right)\mathrm{BR}\left(\Psi \to visible\right)\epsilon_{det}, c\tau_\Psi/m_\Psi\right)$$



1) LLPs: Heavy Neutral Leptons

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



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

Minkowski 77; Gell-Mann, Ramond, Slansky 79, Yanagida 79; Mohapatra, Senjanovic 80
Fukujita, Yanagida 1986
Mohapatra, Valle 86; Bernabeu, Santamaria, Vidal, Mendez, Valle 87; Malinsky, Romao, Valle 05.
Akhmedov, Rubakov, Smirnov (ARS), Asaka, Shaposnikov

- We consider a simplified scenario: one HNL mixing exclusively with one neutrino flavor. As a better approximation to neutrino mass models pheno, two additional benchmarks have been recently proposed in 2207.02742

- Production branching ratios and decay widths from Coloma *et al* 2007.03701

- A complete summary of the current experimental constraints can be found in https://github.com/mhostert/Heavy-Neutrino-Limits
  Fernández-Martínez, González-López, Hernández-García, Hostert, JLP 2304.06772

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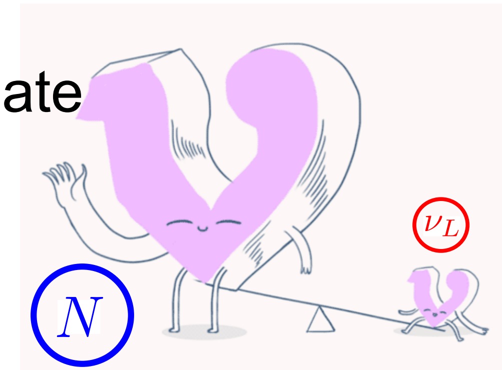
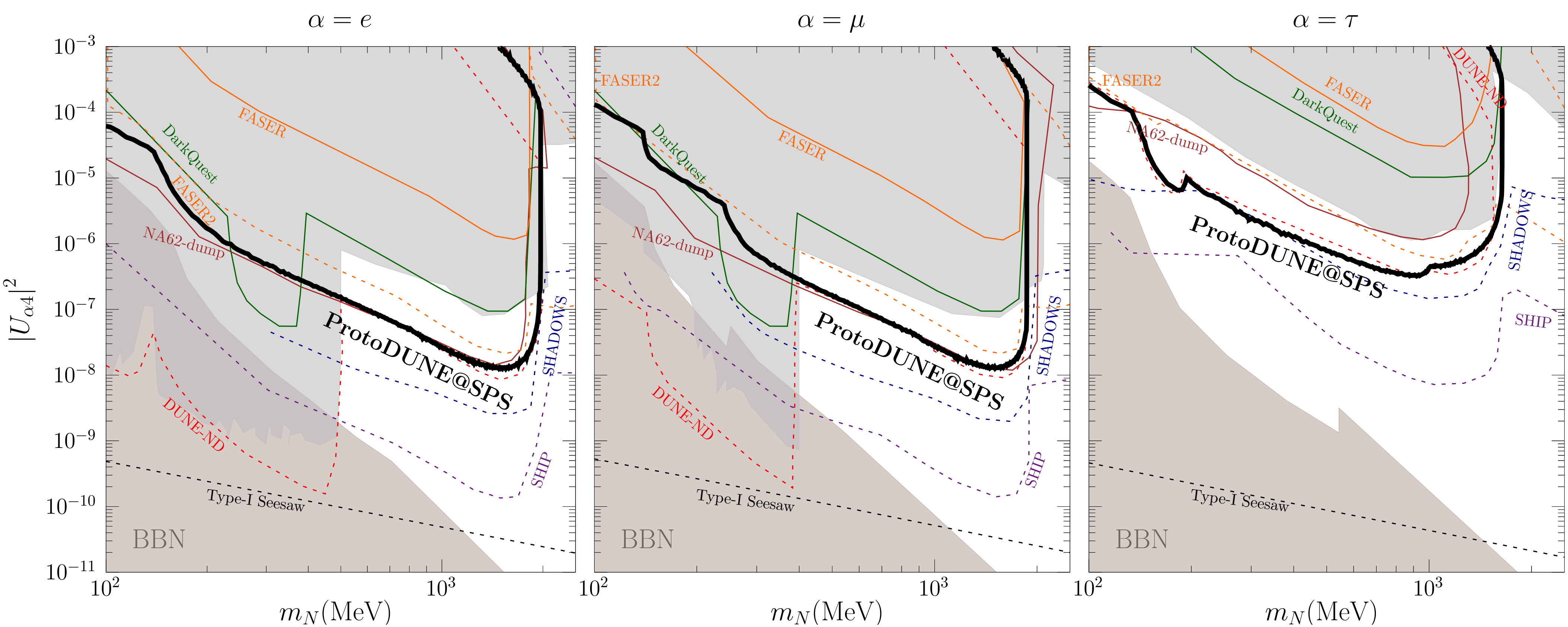
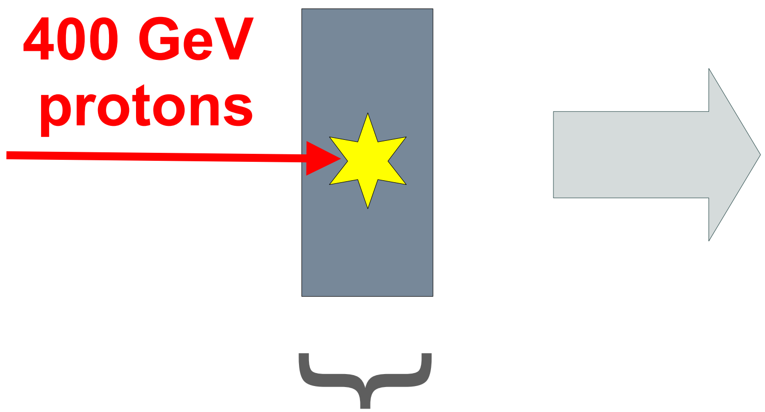


$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}U^*_{\alpha 4}\gamma^\mu l_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}U^*_{\alpha 4}\gamma^\mu \nu_{L\alpha}Z_\mu$$



2) Stable Particles

Primary Target T2
(50 cm Beryllium target)



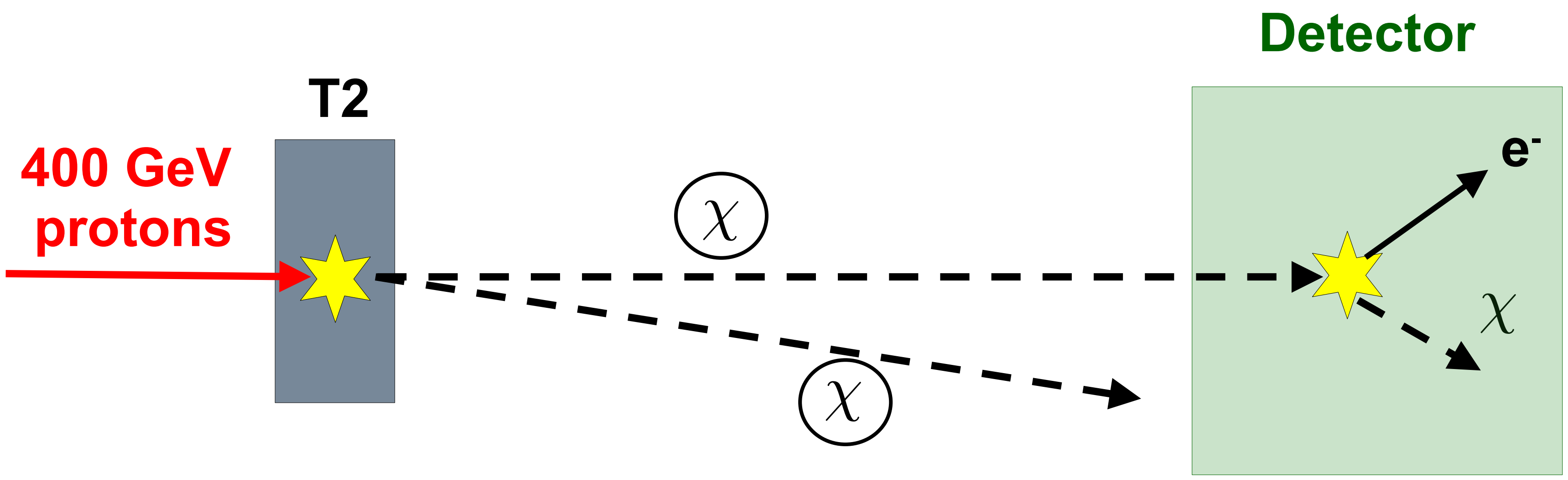
These mesons can also decay in new stable light particles χ

$$\mathrm{BR}\left(M \to \chi\overline{\chi} + \ldots\right)$$

Products from proton interactions with a target (only **neutral and short-lived mesons M** can be in principle exploited)

(D, D_s, B, Y, J/Ψ, η, η’, π^0, ρ, …)

2) Stable Particles (model independent)



$\mathrm{BR}\,(M \to \chi\overline{\chi})$

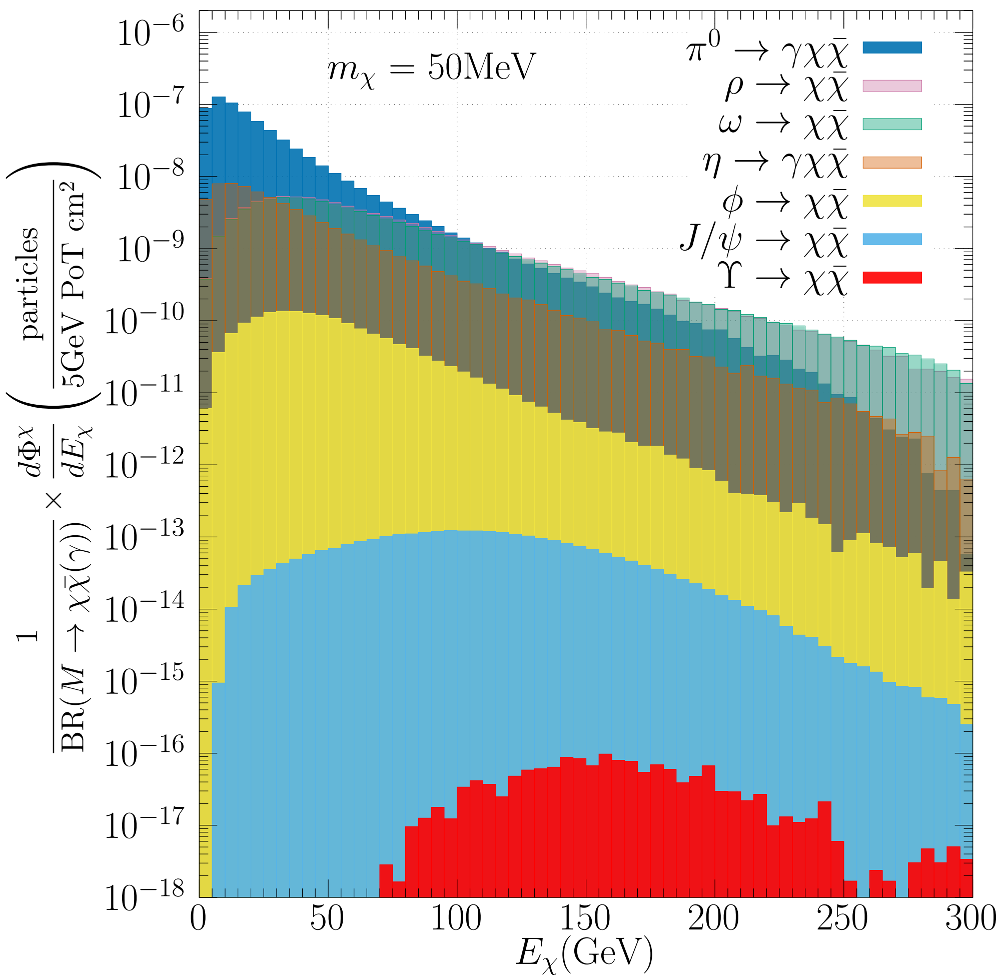
$\chi\, e^-$ scattering

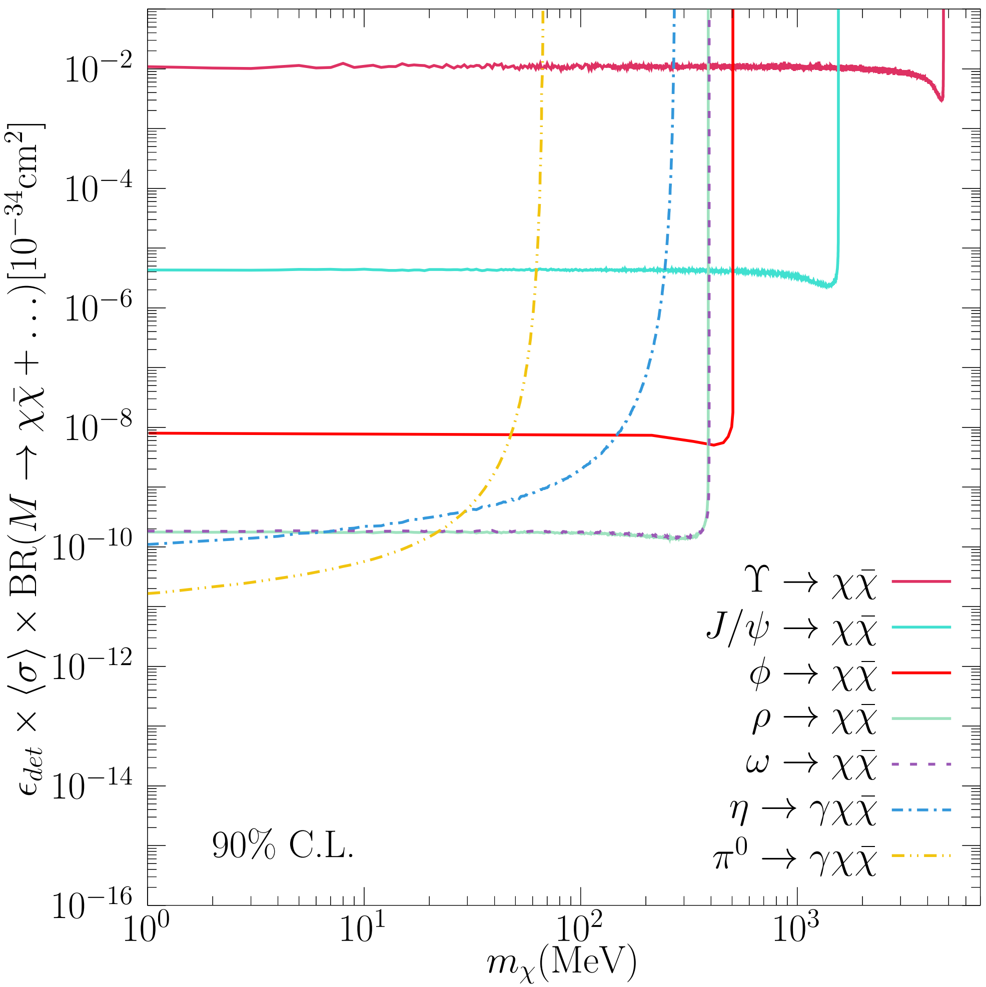
$$\langle\sigma\rangle = \frac{1}{\Phi^\chi}\int_0^\infty \int_{T^{\min}}^{T^{\max}} \frac{d\sigma}{dT}\,(E_\chi, \{X\})\,\frac{d\Phi^\chi}{dE_\chi} dT dE_\chi$$

$$\boxed{N_{ev} = \epsilon_{det}\, N_{trg}\, \langle\sigma\rangle\, \Phi^\chi\, N_{\mathrm{PoT}} \propto \langle\sigma\rangle \mathrm{BR}\,(M \to \chi\overline{\chi})}$$

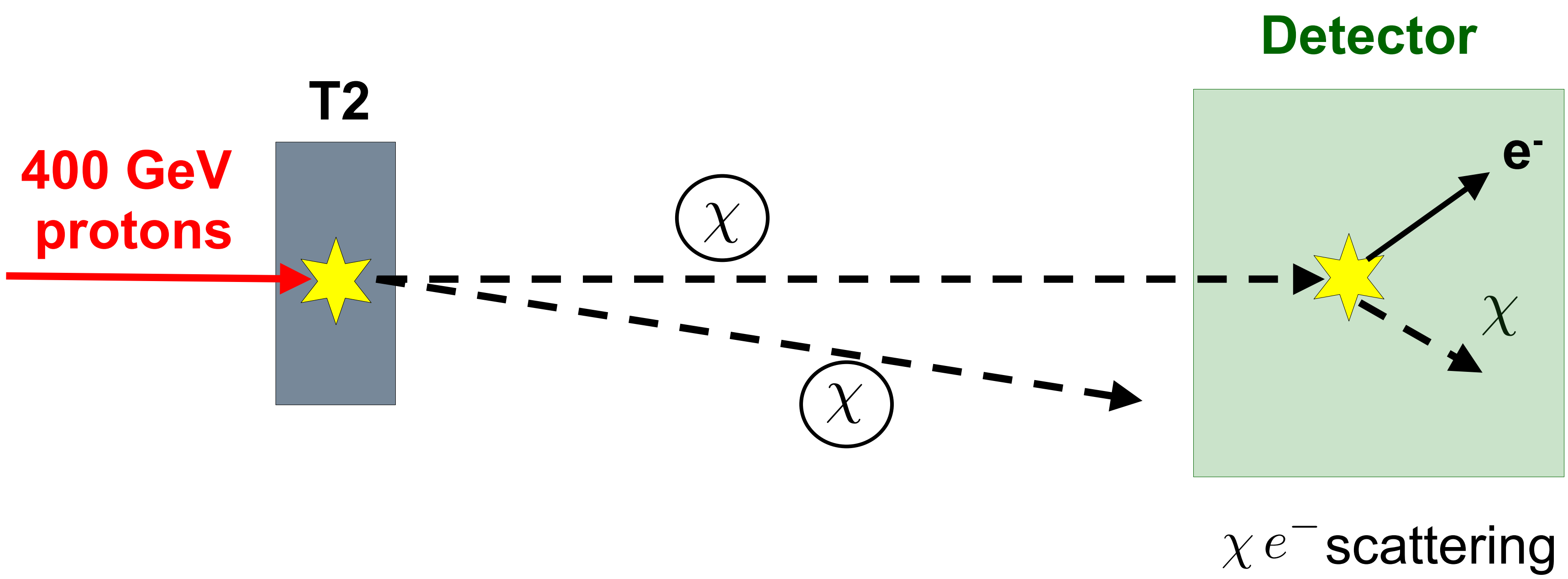
2) Stable Particles (model independent)

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





2) Stable Particles: Millicharged Particles

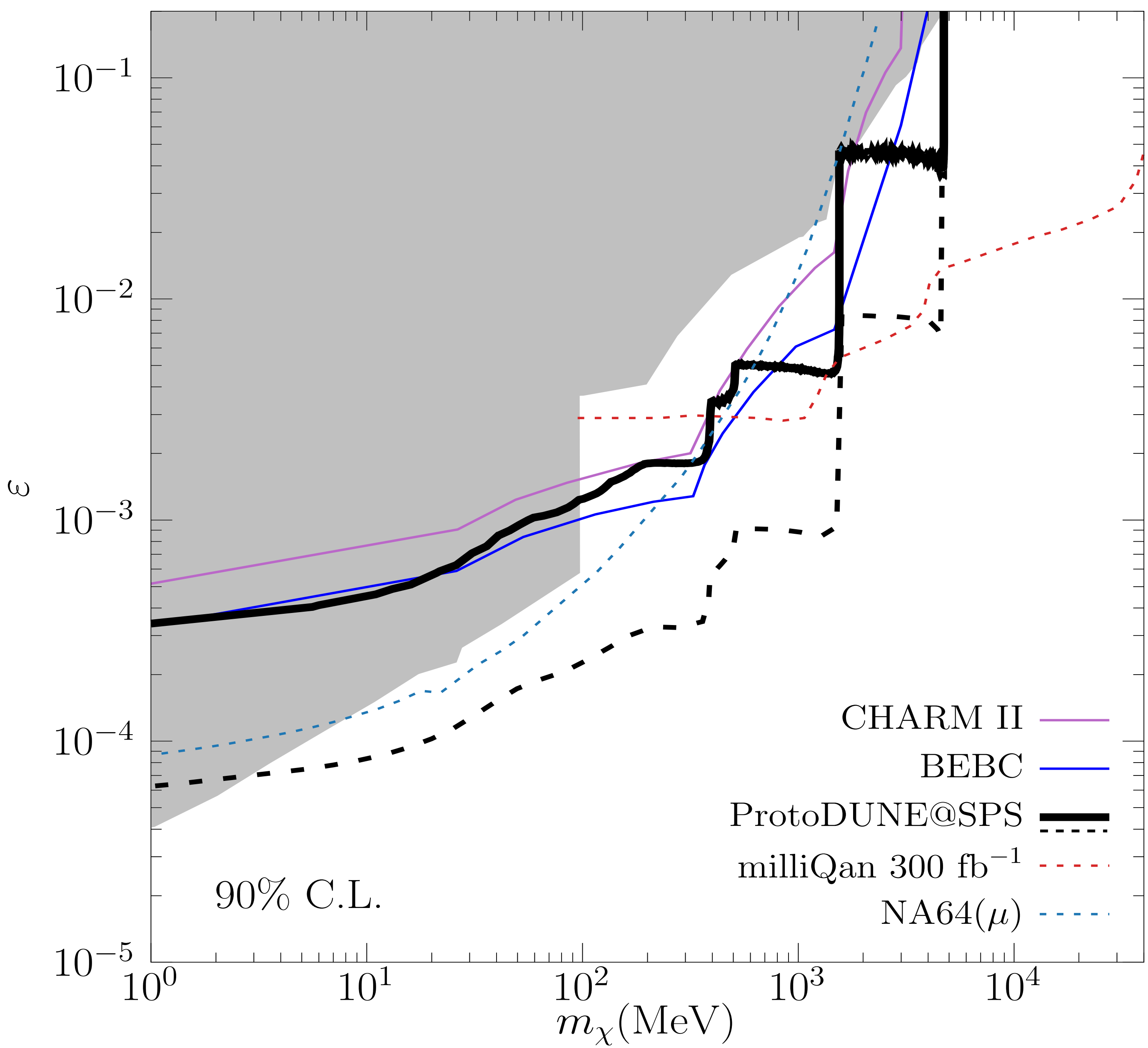


- **Millicharged particles (MCPs)**: fermions with an effective charge **eε**, arising from the mixing of the SM photon and a massless Dark Photon

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

Harnik, Liu, and Palamar 1902.03246

2) Stable Particles: Millicharged Particles



Conclusions

- Given its location at CERN, ProtoDUNE may be exposed to a flux of new particles generated after the collision of 400 GeV protons, extracted from the SPS accelerator, on a target. Their excellent imaging capabilities and large fiducial volume makes them ideal to search for weakly interacting massive particles in BSM scenarios.

- 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 (HNLs and MCPs) but this setup offers many other possibilities such as dark photons, dark scalars, ALPs, or light dark matter.

- The expected sensitivity using a model-independent approach is also computed . This can be easily recasted to particular NP models.

- **The set up has the potential to improve over current bounds within a short timescale, using facilities that are already in place at CERN, and without interfering with the experimental program in the North Area**.

- *A dedicated analysis is required to determine the expected background levels and detector efficiencies, as well as the development of a new trigger optimized for the beam-dump approach* (a working group in collaboration with the CERN Neutrino Platform has been created to study the feasibility of the proposal).

Thank you!

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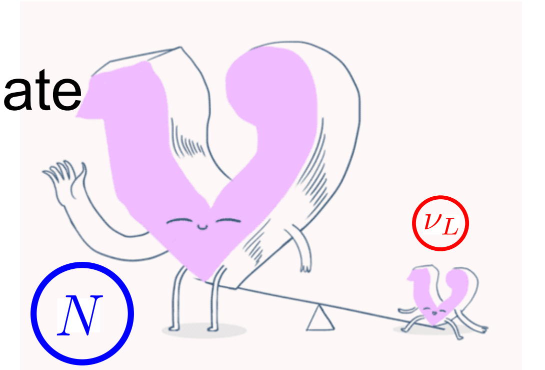
HNLs arising in low-scale seesaw models can accommodate **the origin of neutrino masses** and **baryon asymmetry**



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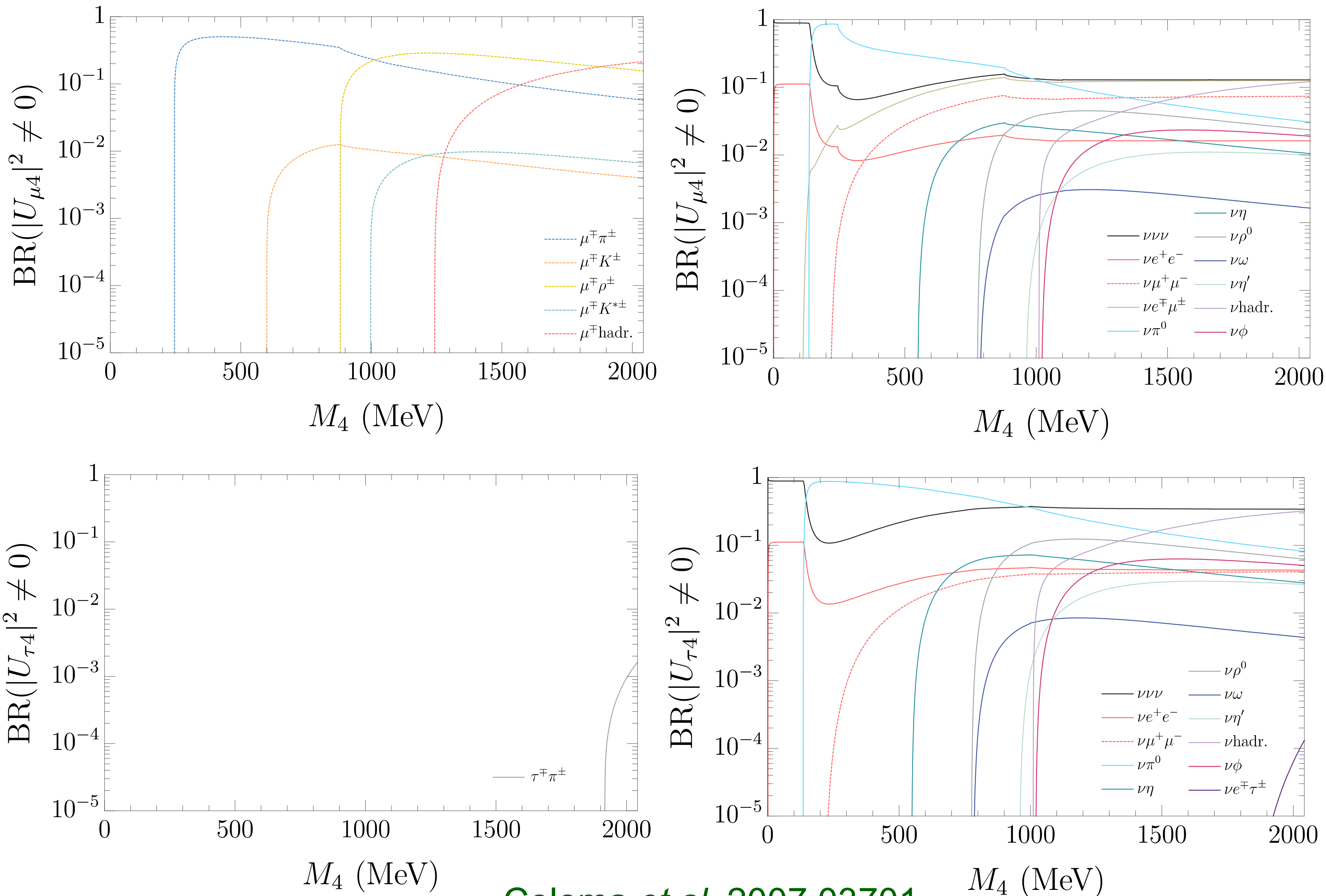
Parent	2-body decay	3-body decay
$\pi^+ \to$	e^+N_4	—
	μ^+N_4	
$K^+ \to$	e^+N_4	$\pi^0e^+N_4$
	μ^+N_4	$\pi^0\mu^+N_4$
$\tau^- \to$	π^-N_4	$e^-\overline{\nu}N_4$
	ρ^-N_4	$\mu^-\overline{\nu}N_4$

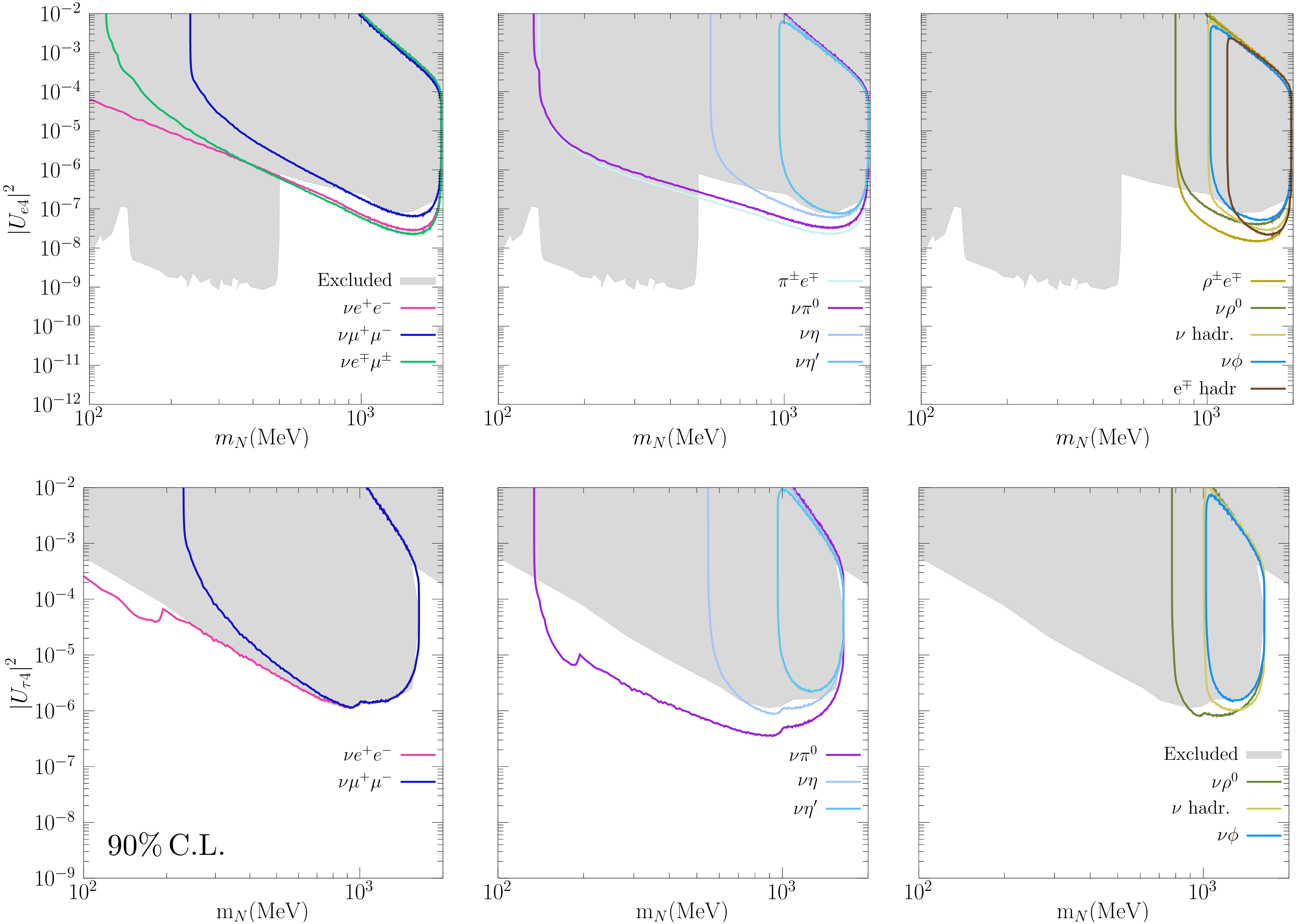
Parent	2-body decay	3-body decay
$D^+ \to$	e^+N_4	$e^+\overline{K^0}N_4$
	μ^+N_4	$\mu^+\overline{K^0}N_4$
	τ^+N_4	
$D_s^+ \to$	e^+N_4	—
	μ^+N_4	
	τ^+N_4	

HNL production branching ratios and decay widths from Coloma *et al.* 2007.03701

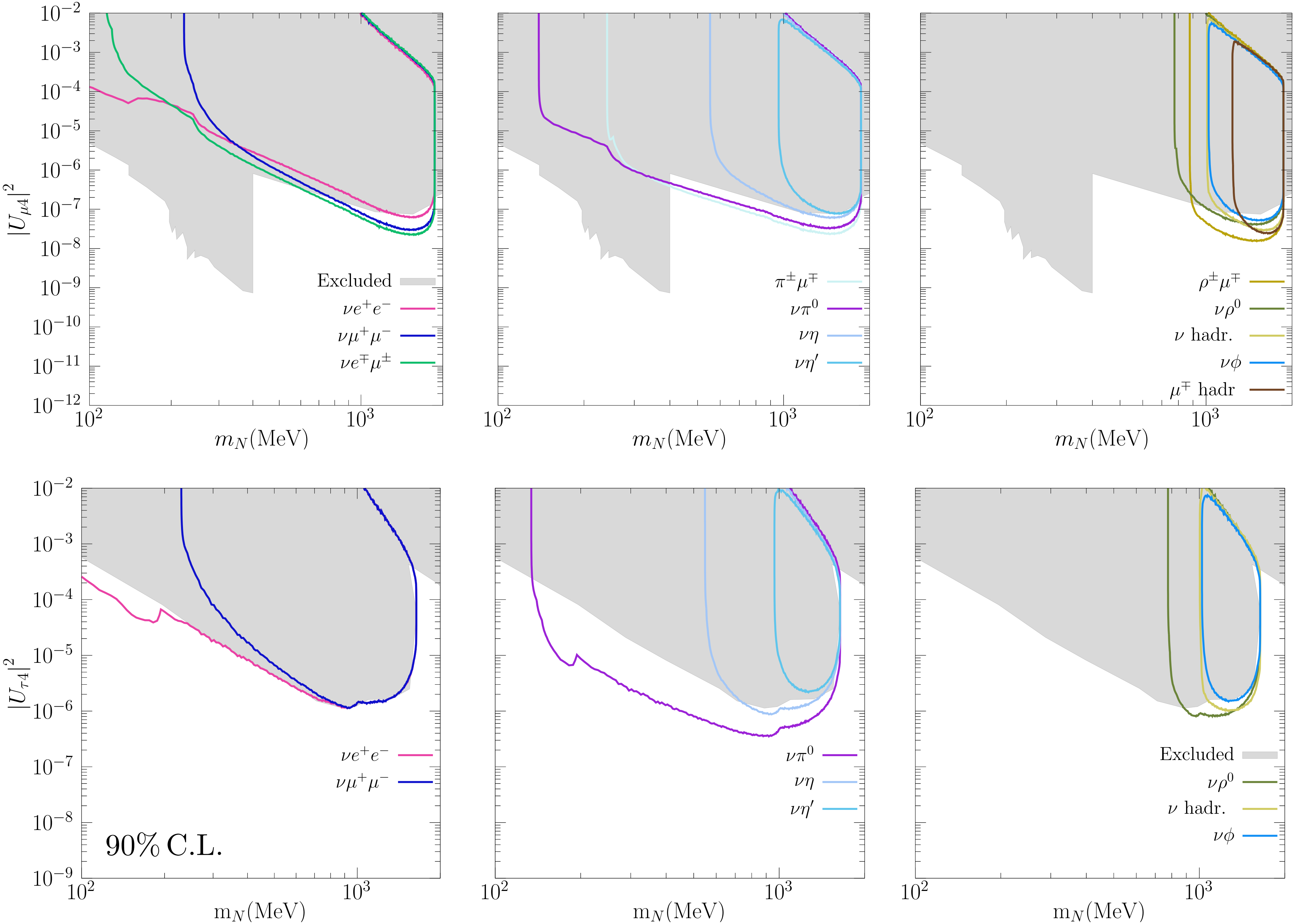
Production of HNLs



Coloma *et al.* 2007.03701

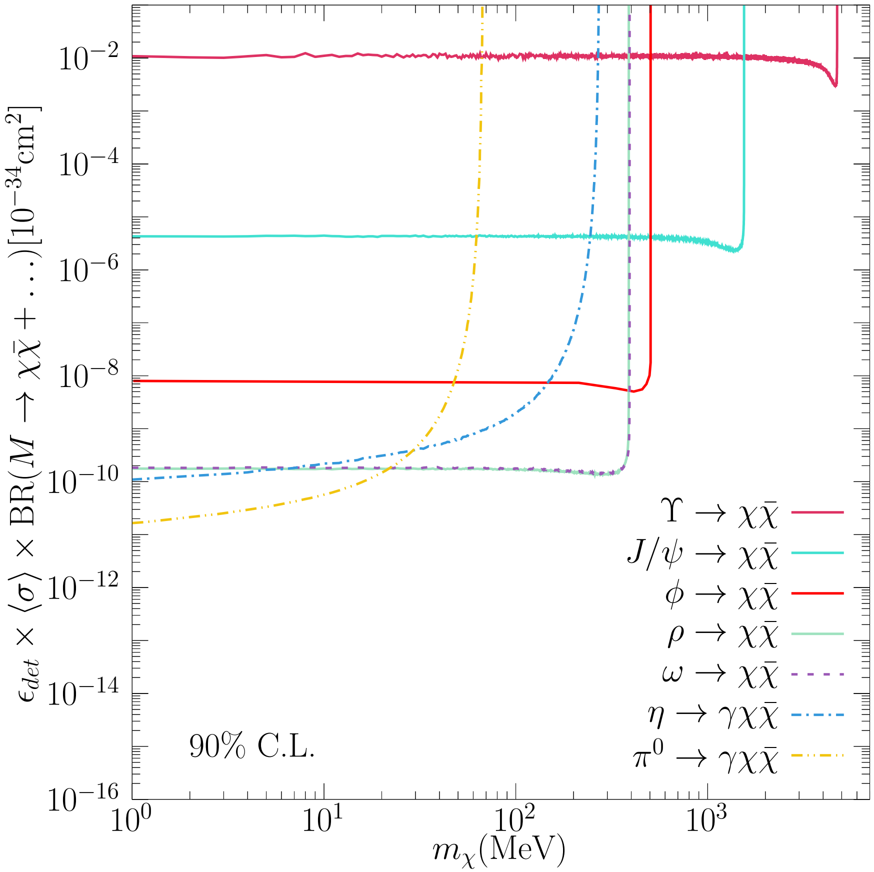


$|U_{e4}|^2$
m_N(MeV)
Excluded
νe^+e^-
$\nu\mu^+\mu^-$
$\nu e^\mp\mu^\pm$
$\pi^\pm e^\mp$
$\nu\pi^0$
$\nu\eta$
$\nu\eta'$
$\rho^\pm e^\mp$
$\nu\rho^0$
ν hadr.
$\nu\phi$
e$^\mp$ hadr
$|U_{\tau 4}|^2$
m$_N$(MeV)
90% C.L.



$|U_{\mu4}|^2$
m_N(MeV)
Excluded
$\nu e^+ e^-$
$\nu \mu^+ \mu^-$
$\nu e^\mp \mu^\pm$
$\pi^\pm \mu^\mp$
$\nu \pi^0$
$\nu \eta$
$\nu \eta'$
$\rho^\pm \mu^\mp$
$\nu \rho^0$
ν hadr.
$\nu \phi$
$\mu^\mp$ hadr
$|U_{\tau4}|^2$
m$_N$(MeV)
90% C.L.

Recasting model independent bound: toy example



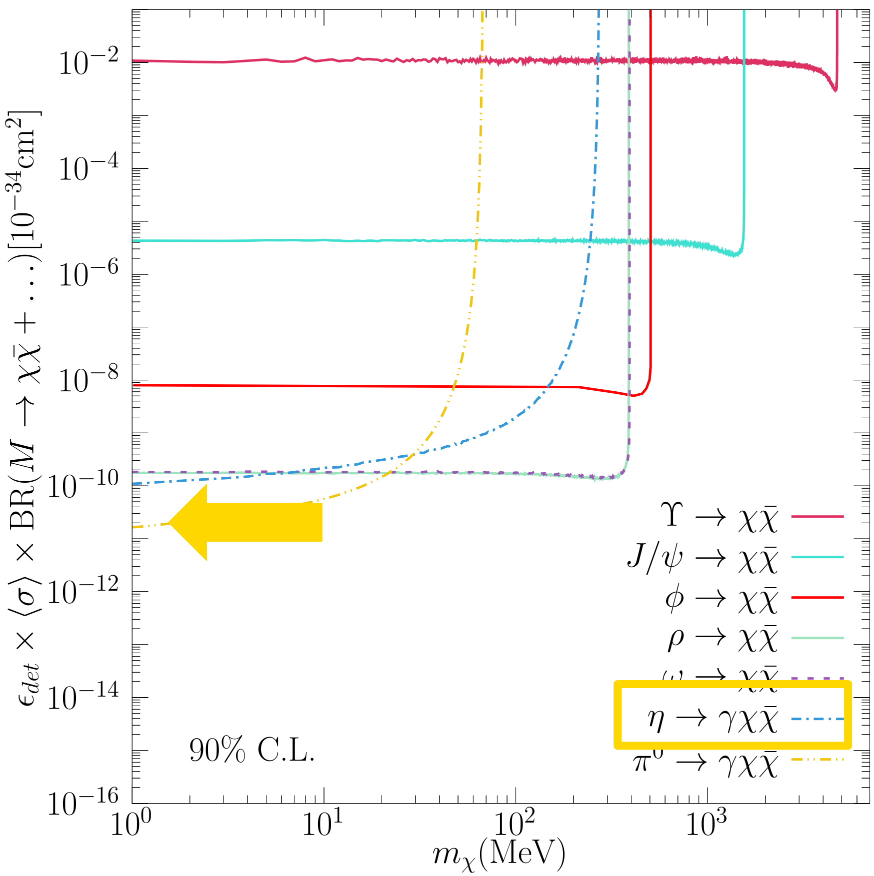
- For small MCP masses with $E_\chi \gg T, m_e, m_\chi$

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

$$\Downarrow$$

$$\frac{\langle\sigma\rangle \times \mathrm{BR}}{10^{-26}\ \mathrm{cm}^2} \sim \underbrace{\mathrm{BR}(\pi^0 \to \gamma e^- e^+)}_{1.175 \times 10^{-2}} \varepsilon^4 \left(\frac{30\ \mathrm{MeV}}{T_{\min}}\right)$$

Recasting model independent bound: toy example



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$$\Downarrow$$

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$$\Downarrow$$

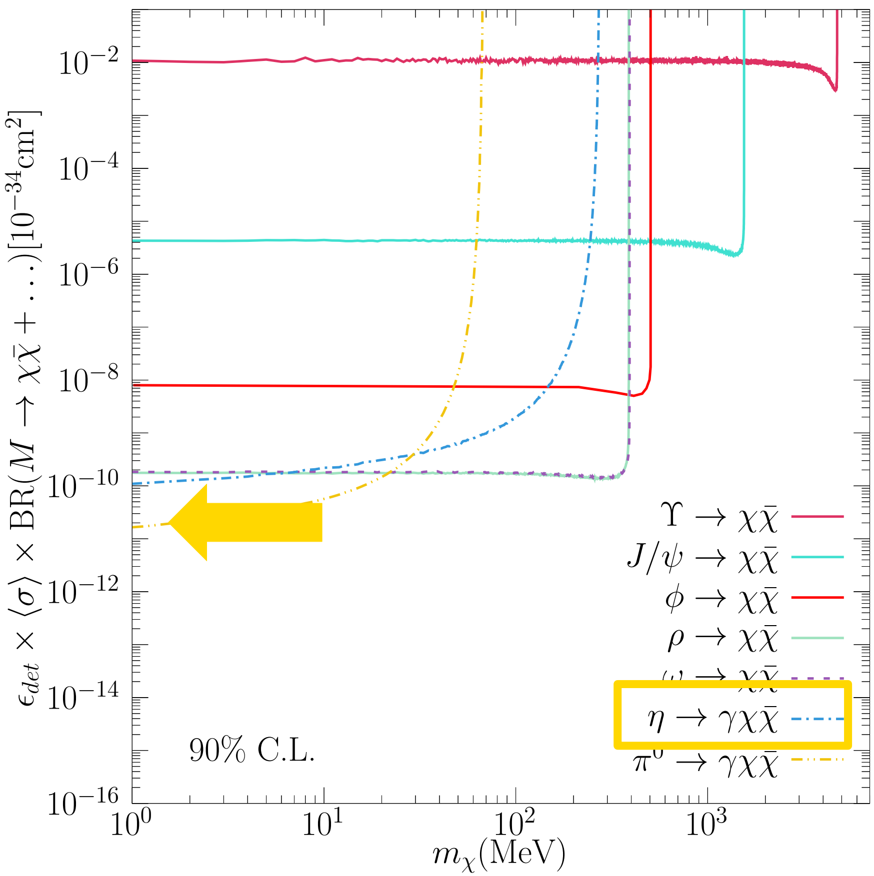
$$10^{-19}$$

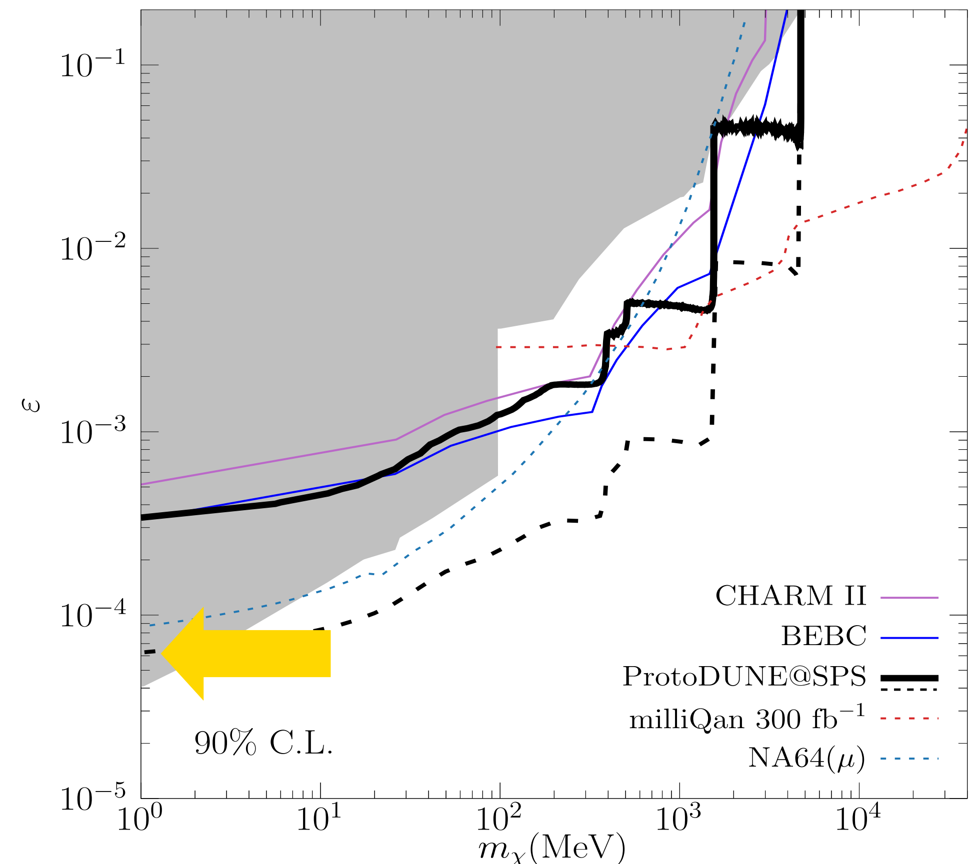
$$\Downarrow$$

- Sensitivity for small MCP masses $\boxed{\varepsilon \sim 5 \times 10^{-5}}$

Recasting model independent bound: toy example

- For small MCP masses with $E_\chi \gg T, m_e, m_\chi$

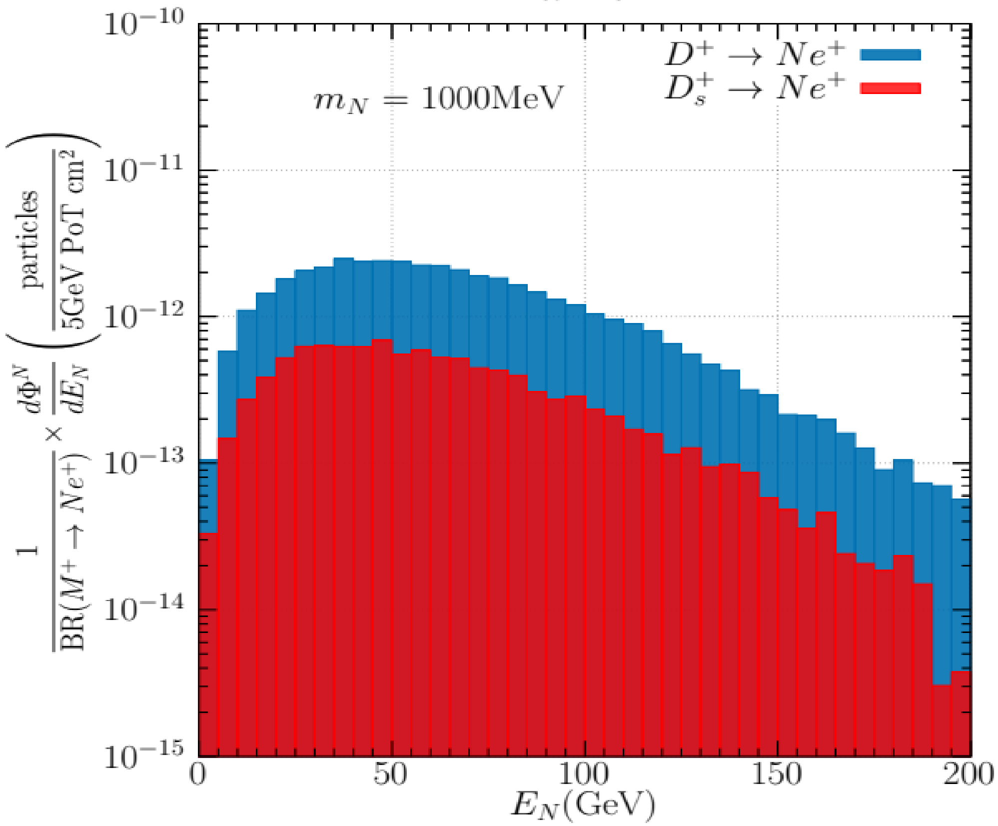




- Sensitivity for small MCP masses $\varepsilon \sim 5 \times 10^{-5}$

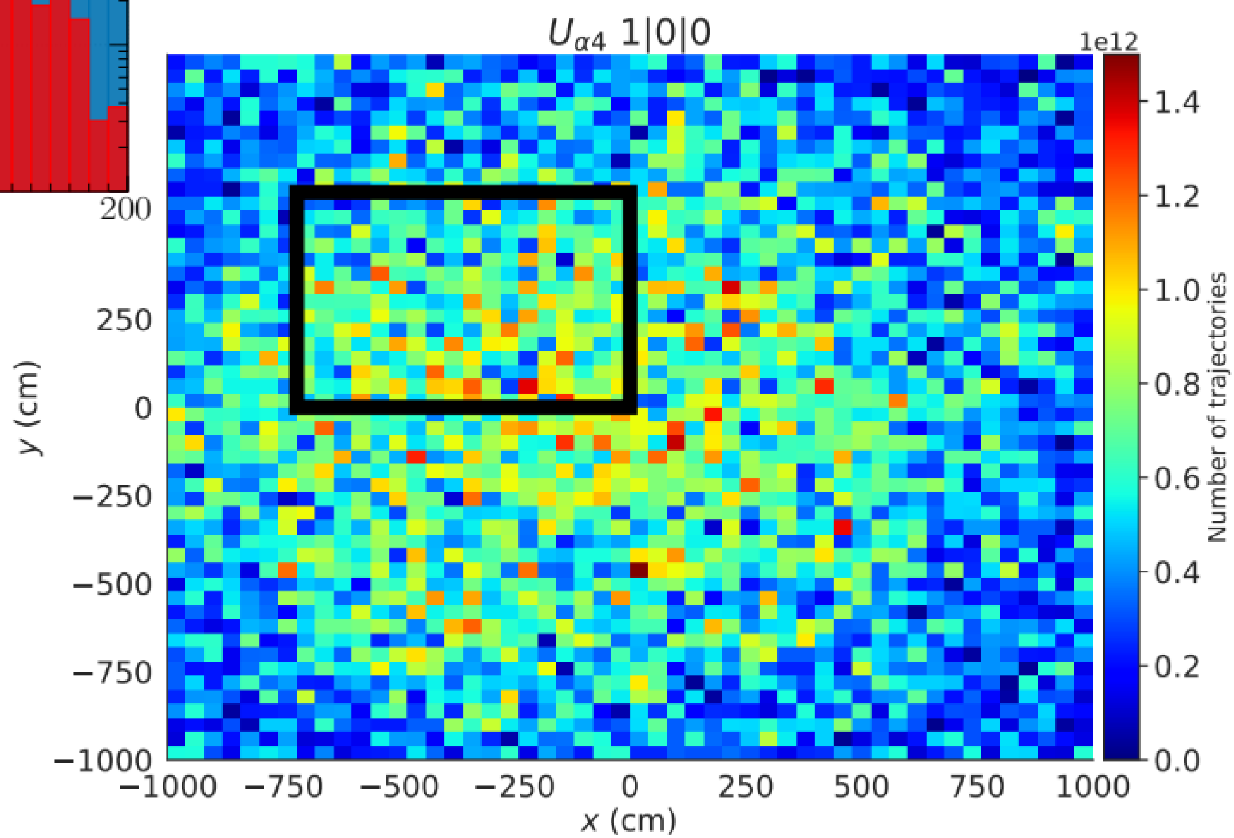
HNL Fluxes

HNL intersecting the detector



- Quite energetic HNL beam

HNL at z=677 m (# of trajectories)



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

Simple example of recasting model independent bound

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

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

- Note that in the small MCP masses with $E_\chi \gg T, m_e, m_\chi$

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

$$\Downarrow$$

$$\frac{\langle\sigma\rangle \times \mathrm{BR}}{10^{-26}\ \mathrm{cm}^2} \sim \underbrace{\mathrm{BR}(\pi^0 \to \gamma e^- e^+)}_{1.175 \times 10^{-2}} \varepsilon^4 \left(\frac{30\ \mathrm{MeV}}{T_{\mathrm{min}}}\right)$$