# Long-lived BSM signatures @ProtoDUNE

H. Amar, A. Chatterjee, S. Bianco, P. Coloma, A. De Roeck, C. Hasnip, J. Hernández García, J. López-Pavón, J. Martin-Albo, L. Molina-Bueno, H. Sieber, S. Urrea


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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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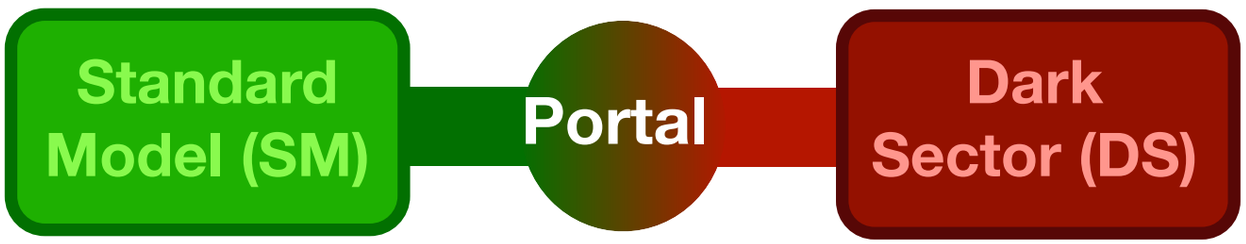
# **Motivation:** *Feebly interacting particles*

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



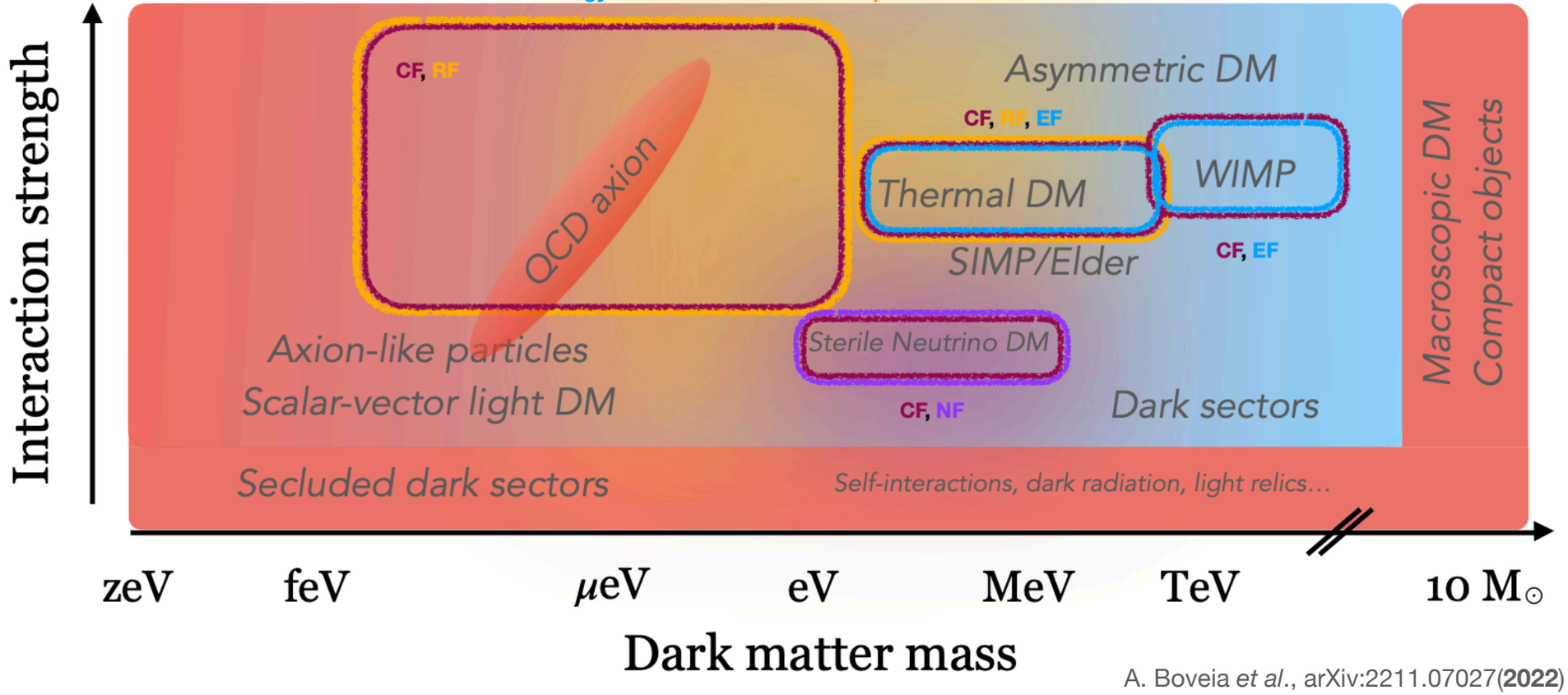

They can solve some of the most pressing questions in particle physics: *the* ***origin of neutrino masses****, the* ***baryon asymmetry of the universe*** and the ***Dark Matter origin***.

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

*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***)

CF Cosmic frontier EF Energy frontier RF Rare and precision frontier NF Neutrino frontier



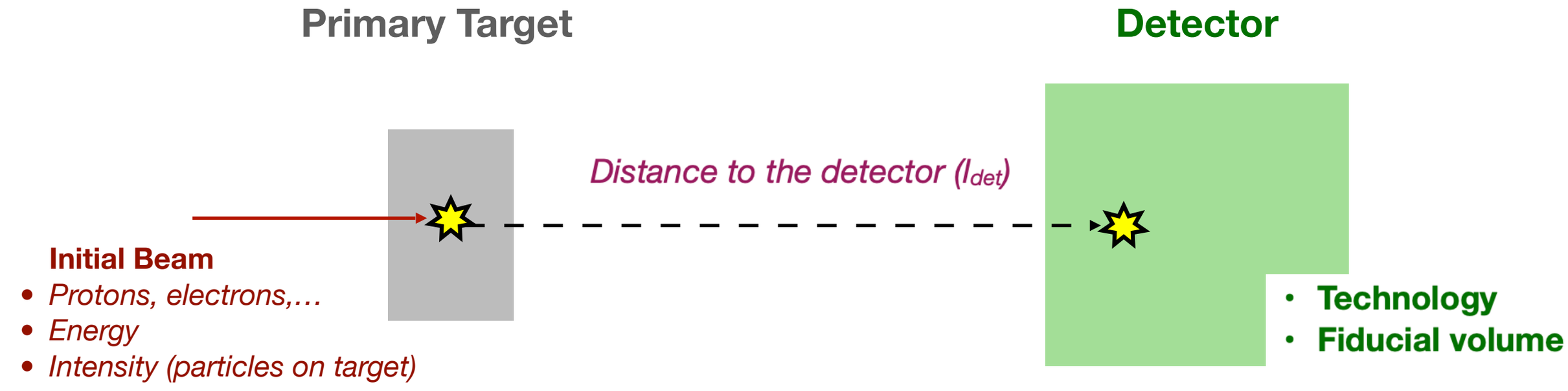

A. Boveia *et al.*, arXiv:2211.07027(**2022**)

# 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, ICARUS, DUNE…)**

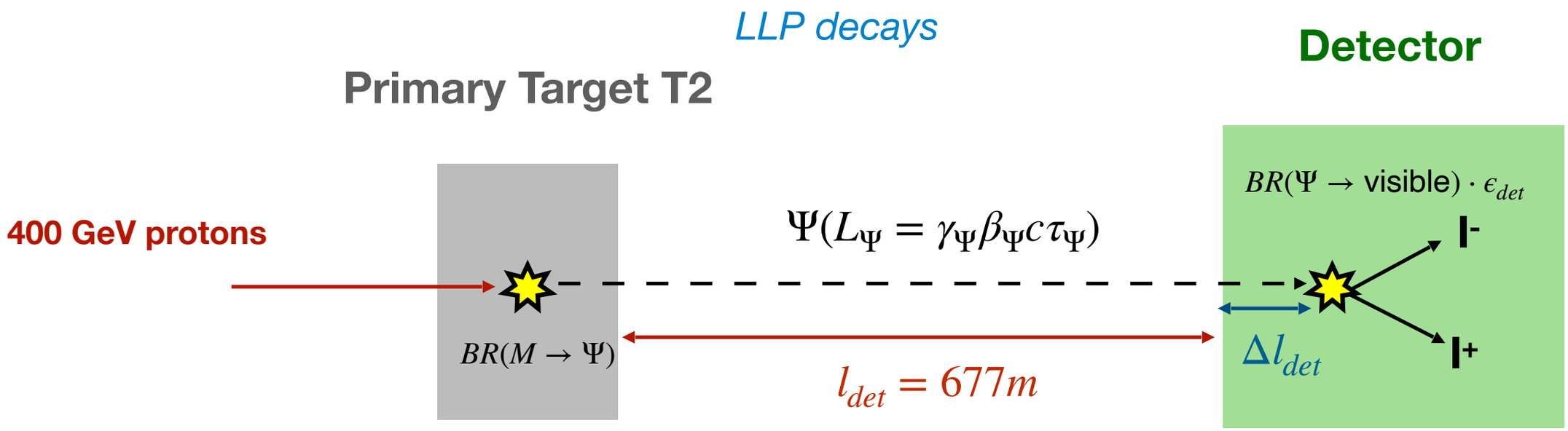



P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134
https://indico.cern.ch/event/1216822/contributions/5449234/attachments/2670524/4629251/molina_LLP2023_21062023.pdf

# Motivation

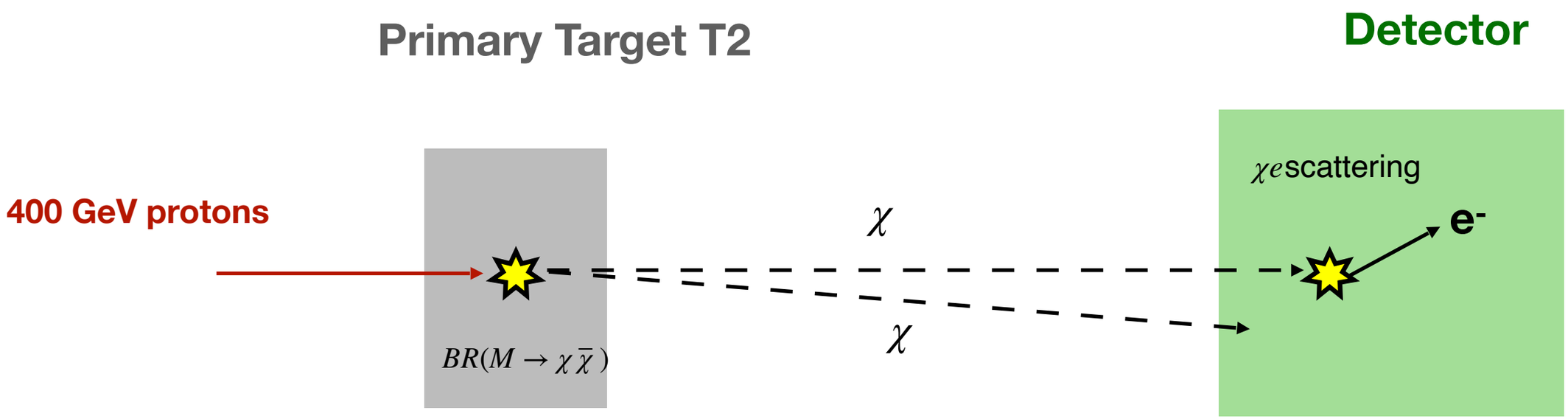
**It offers the possibility to exploit two signatures:**

*LLP decays*



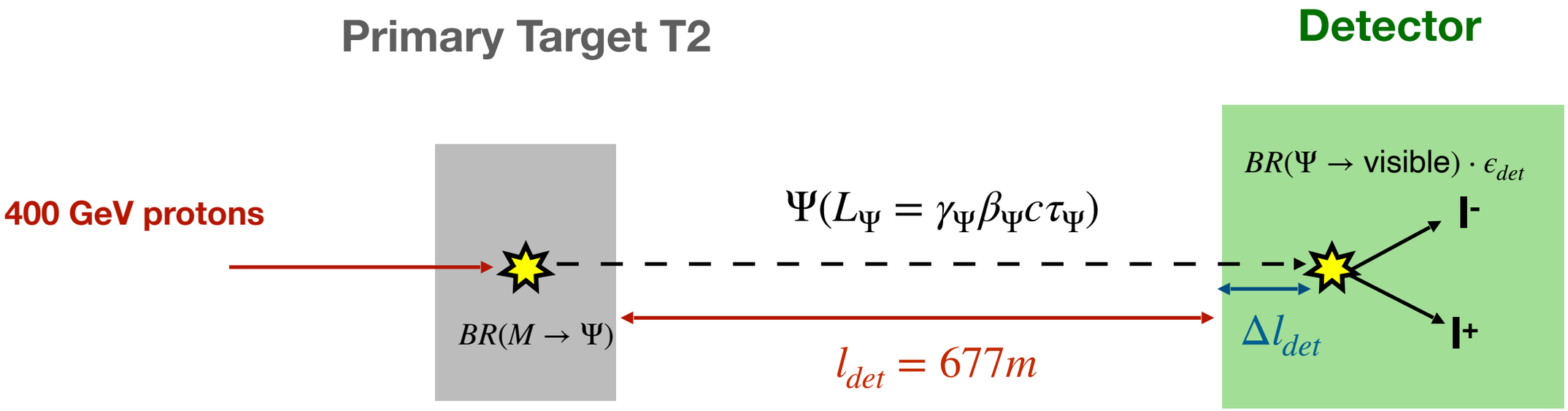

**In this study one ProtoDUNE detector considered**

*Scattering*



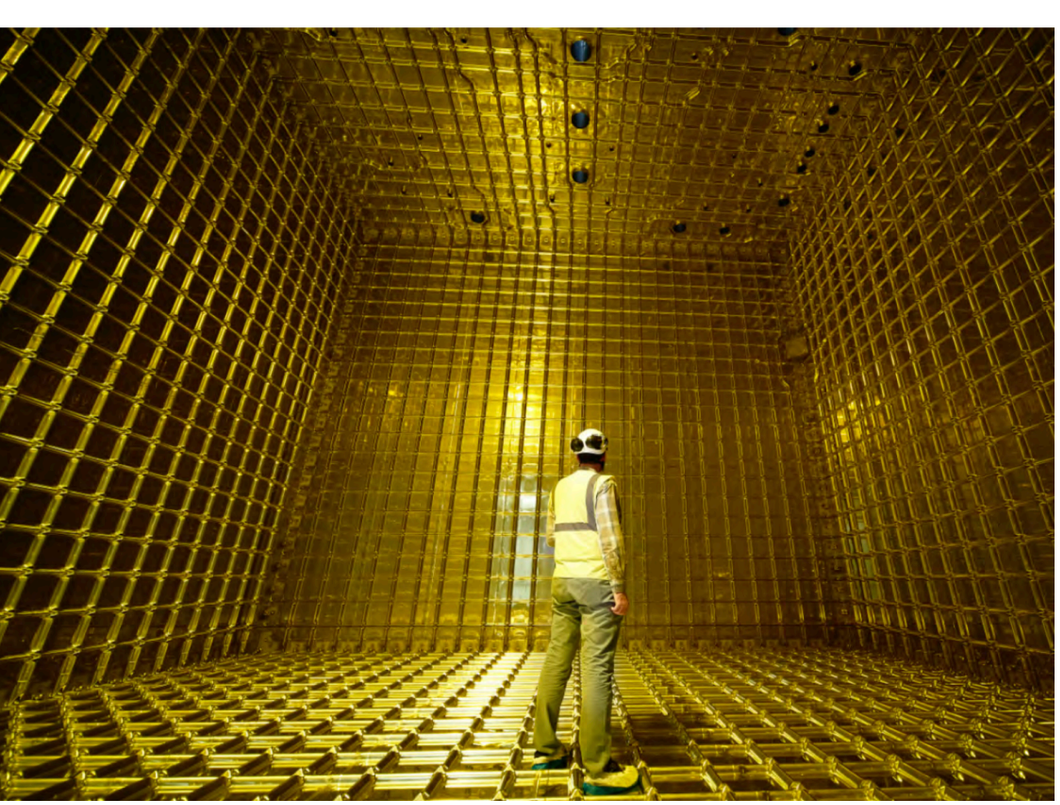

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134
https://indico.cern.ch/event/1216822/contributions/5449234/attachments/2670524/4629251/molina_LLP2023_21062023.pdf

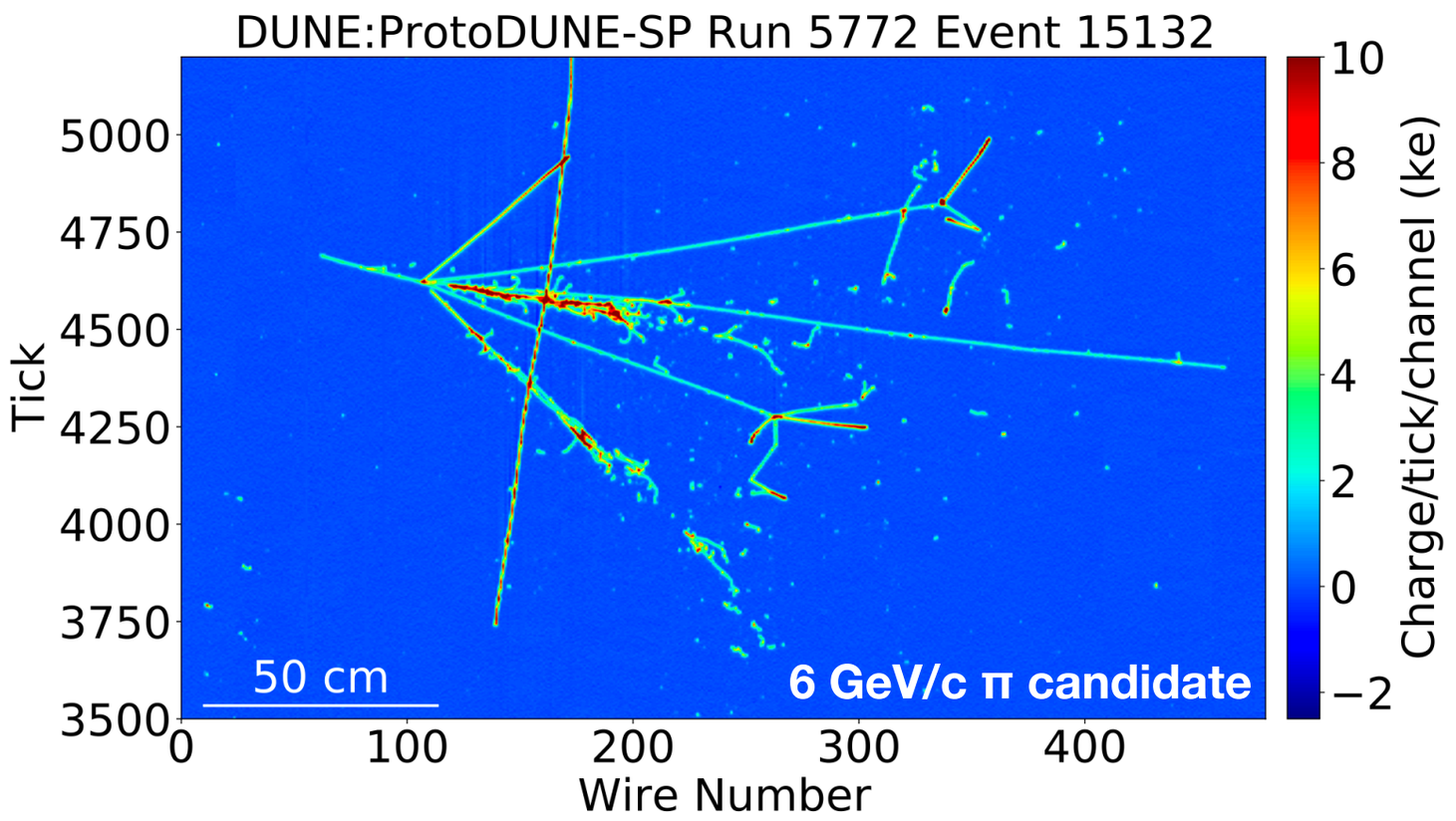
# Benchmark scenario: *LLPs scenarios*




**In this study one ProtoDUNE detector considered**

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



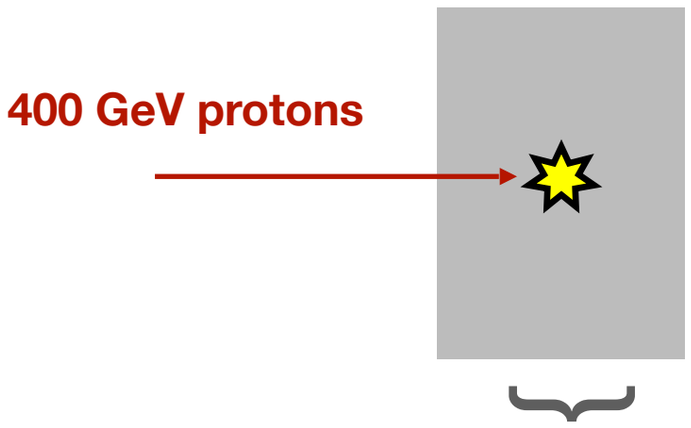



P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134

# LLP search: *production*

S. Urrea, J. Hernandez

**Primary Target T2**
(50 cm Beryllium target)




**1) Production**

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', $\pi^0$, ρ, …)

**Meson production yield $Y_M$ (normalised per PoT)**

New

| $K_L$ |
|---|
| 0.3 |

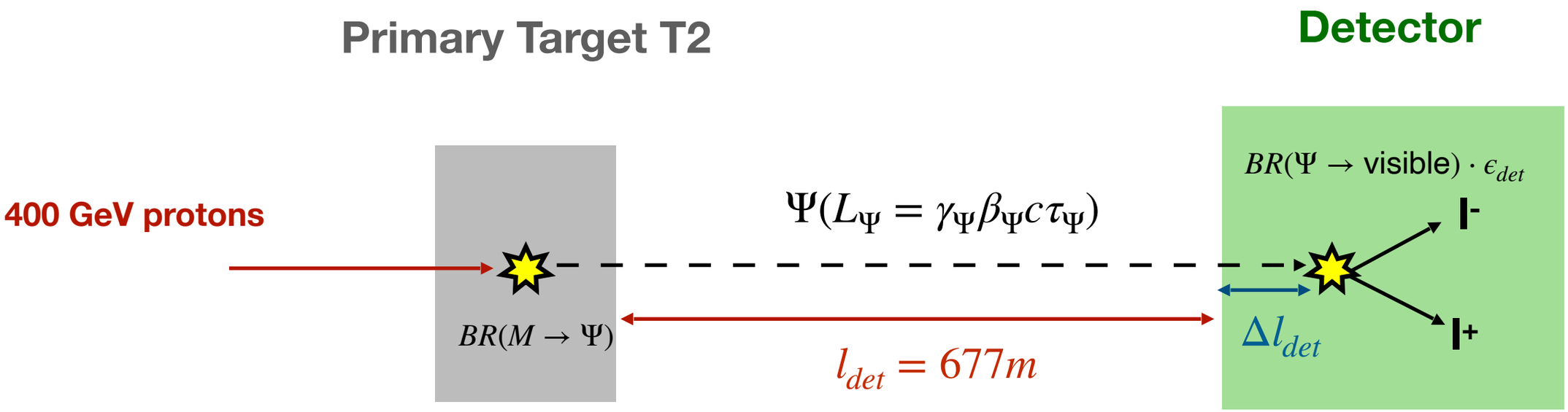
| $\pi^0$ | $\eta$ | $\eta'$ | $D$ | $D_s$ | $\tau$ |
|---|---|---|---|---|---|
| 4.03 | 0.46 | 0.05 | $4.8 \cdot 10^{-4}$ | $1.4 \cdot 10^{-4}$ | $7.4 \cdot 10^{-6}$ |

| $\rho$ | $\omega$ | $\phi$ | $J/\psi$ | $B$ | $\Upsilon$ |
|---|---|---|---|---|---|
| 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*

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134
https://indico.cern.ch/event/1216822/contributions/5449234/attachments/2670524/4629251/molina_LLP2023_21062023.pdf

# LLP search: *decay*



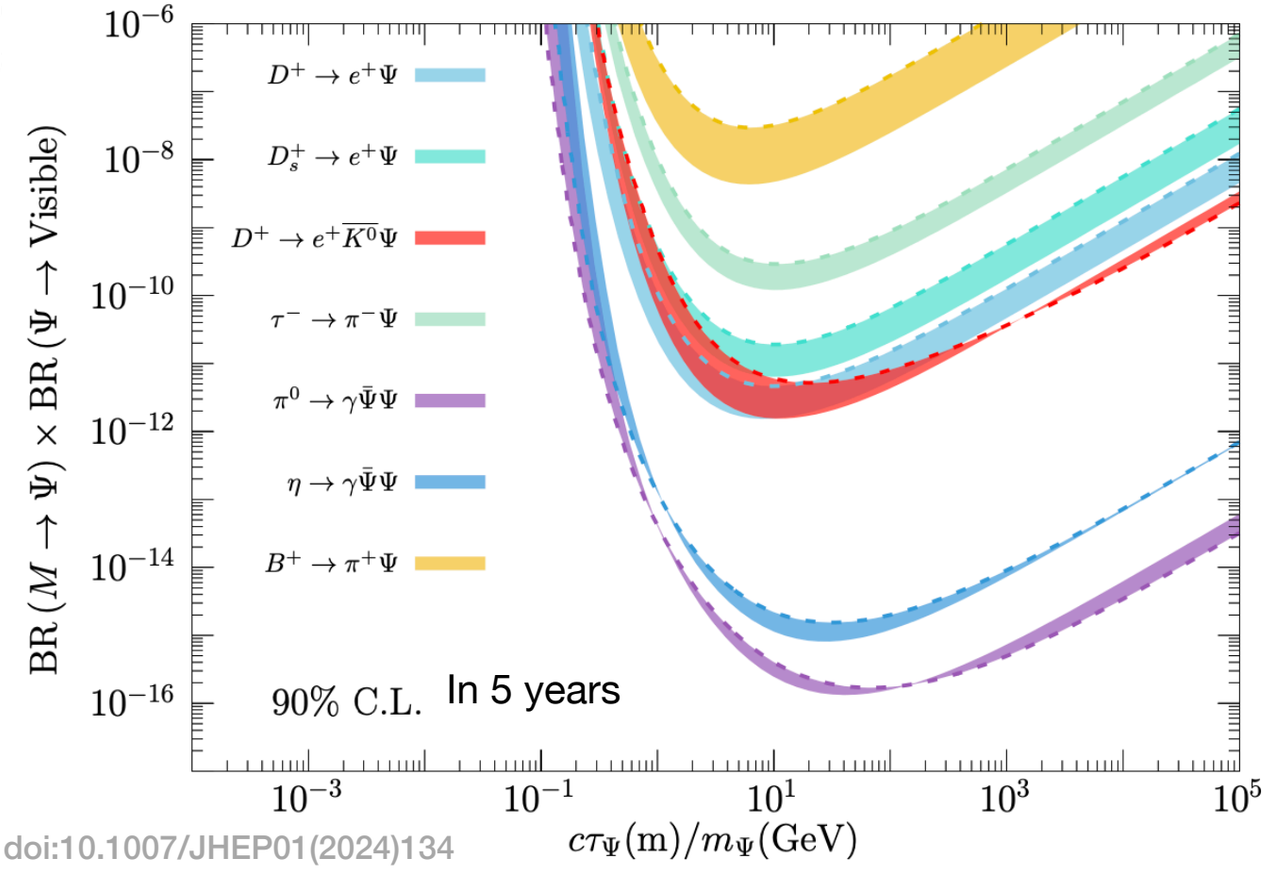

$$N_{dec} = N_{dec}^{M} \cdot BR(\Psi \to \text{visible}) \cdot \epsilon_{dec}$$

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

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

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

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




P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134

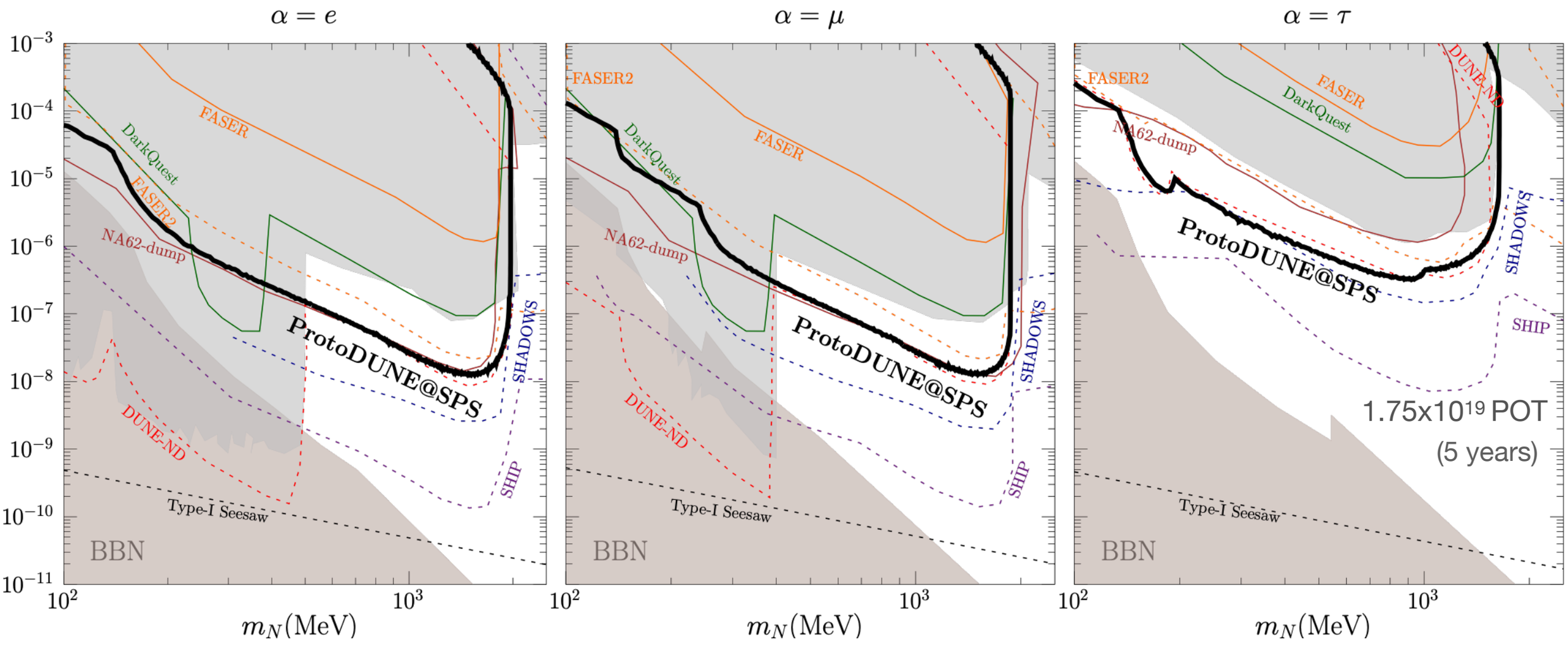
# **Benchmark model:** *Heavy neutral leptons (HNLs)*

P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134

*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*

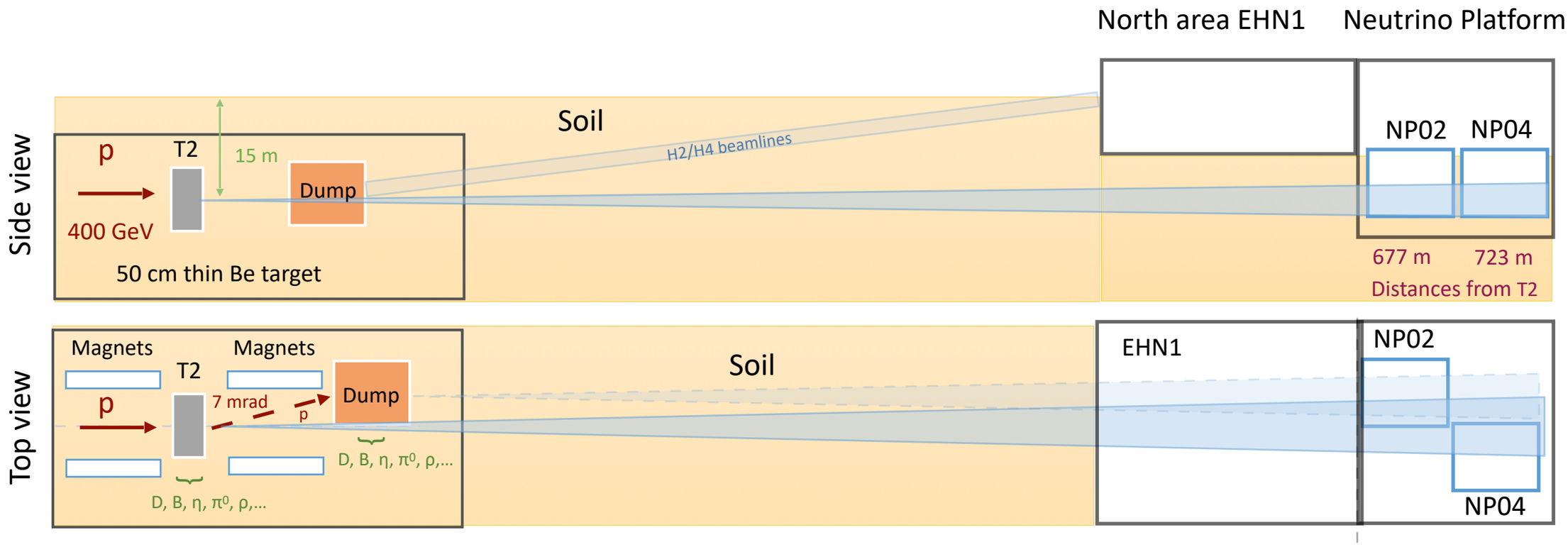
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}U^*_{\alpha 4}\gamma^\mu l_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}U^*_{\alpha 4}\gamma^\mu \nu_{L\alpha}Z_\mu$$




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).

# **Feasibility studies:** *LLP search at ProtoDUNE*




**Working group created last December to study the feasibility of the proposal with the main focus on:**

1. *Improve the signal simulation (previous study was a simplified simulation using Pythia):*

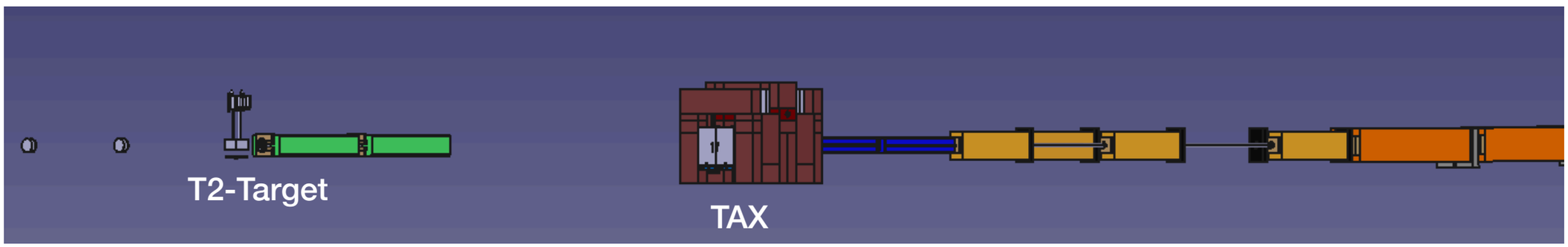
➡ *Full Geant4-based simulation including all T2 target area elements*

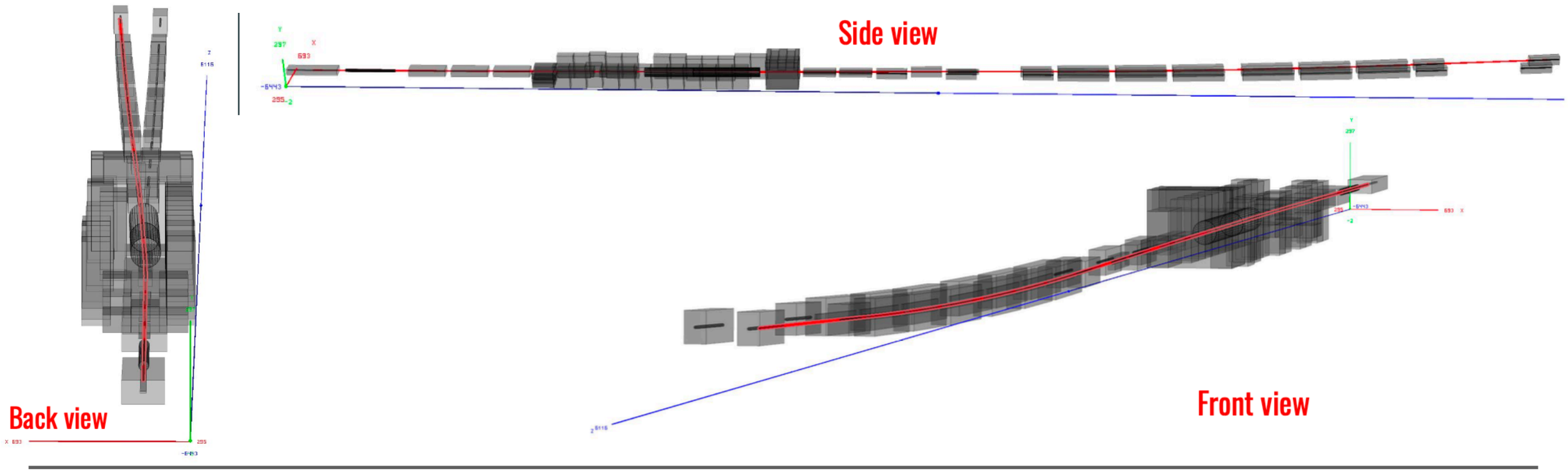
2. *Development of a dedicated trigger to search for LLP signatures*
3. *Estimate the main background sources (no background considered in the phenomenological study)*
4. *Full signal and background detector simulation developed using ProtoDUNE LArSoft framework*
5. *Exploit other LLP scenarios: axion-like particles, scalar, inelastic DM…*

# Beam simulation framework

H. Sieber

- New GEANT4-based simulation of the T2 target area including the main elements (target, tax, magnets). We want to thank the help of the BE-EA department: N. Charitonidis, S. Girod and B. Martinez Sutil.
- Meson fluxes produced in the target and the tax with the exact magnetic field settings considered. Previous results based on Pythia considering only the initial proton interaction were also validated and extended considering the target regeneration (still missing to include dedicated B and D production).

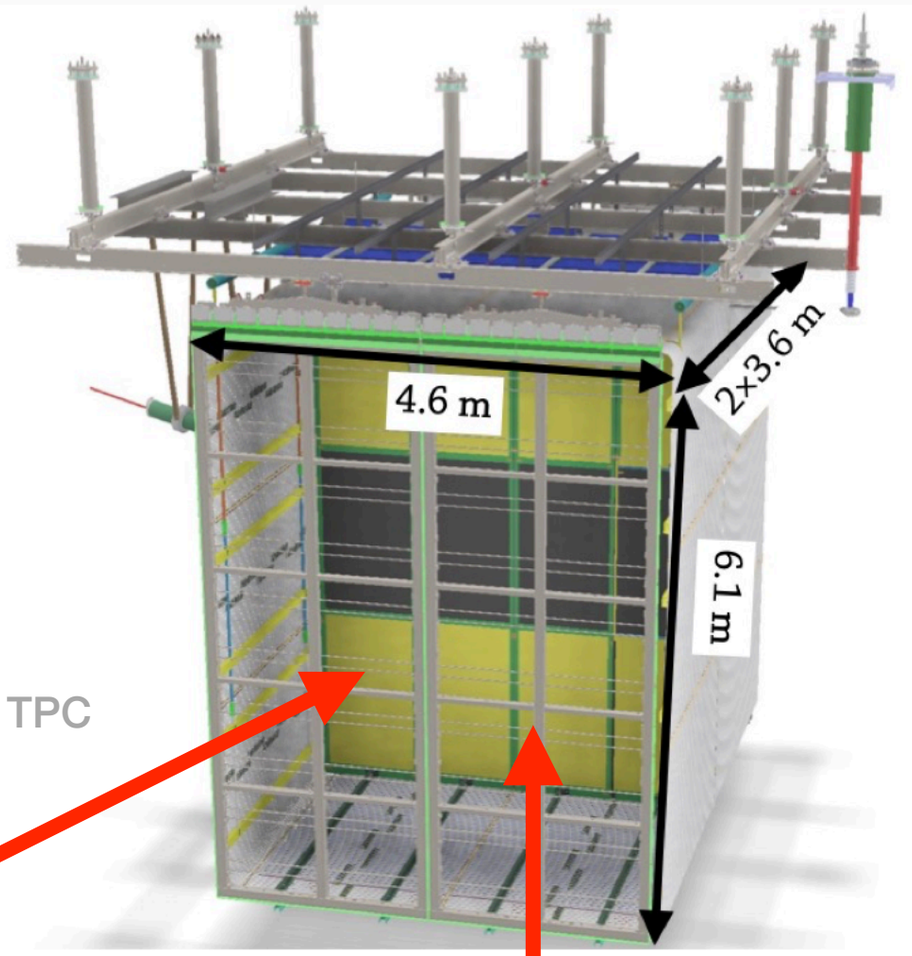


# Detector simulation framework

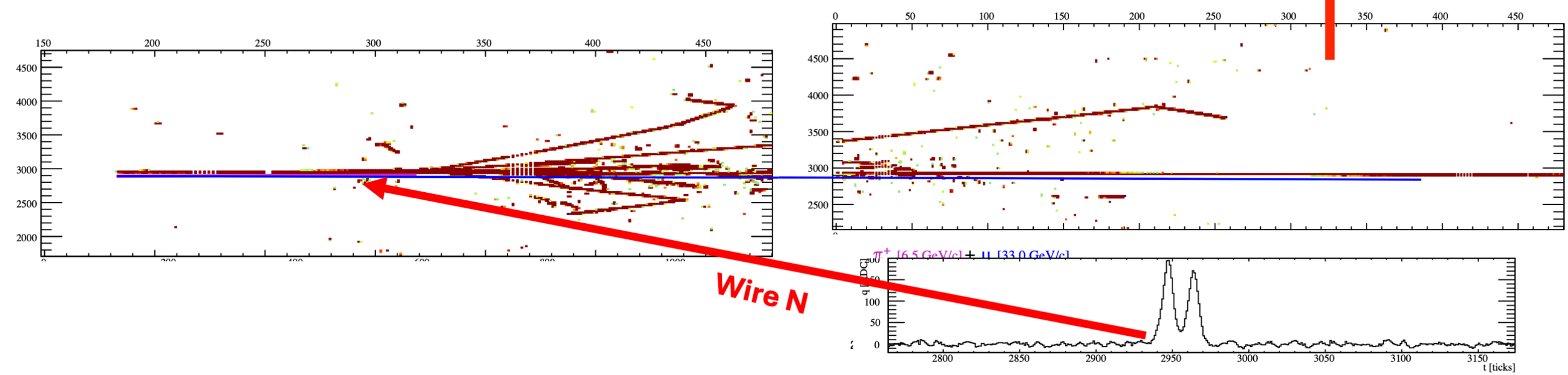
C. Hasnip, S. Urrea

- Signal simulation embedded inside the ProtoDUNE LArSoft framework. The decay of the LLP particles were propagated to the NP04 detector (we are currently considered this one as is the one filled with Argon and currently taking data).




Starting point: *Focus on the muon-like channels*

Example of a 1 GeV HNL decaying to a muon and a pion fully simulated in the TPC

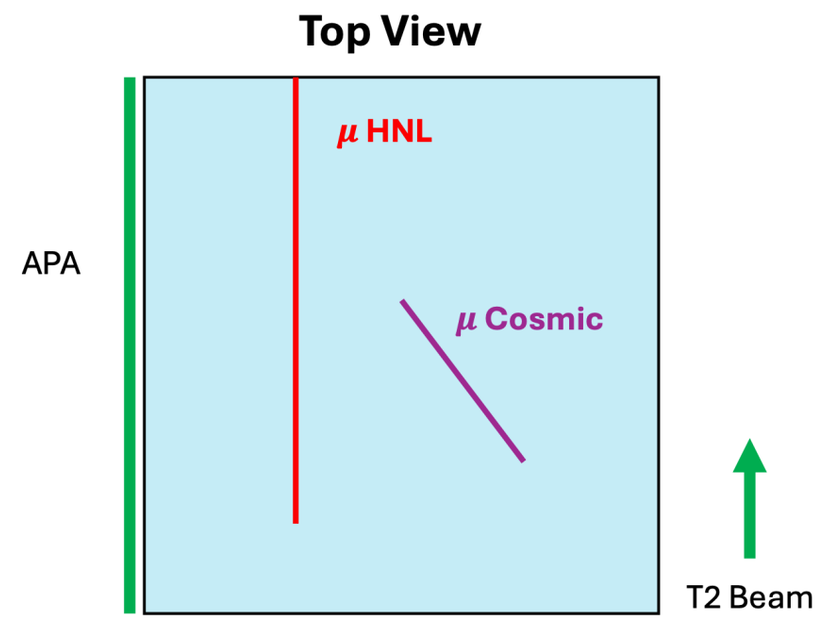


# Detector simulation framework

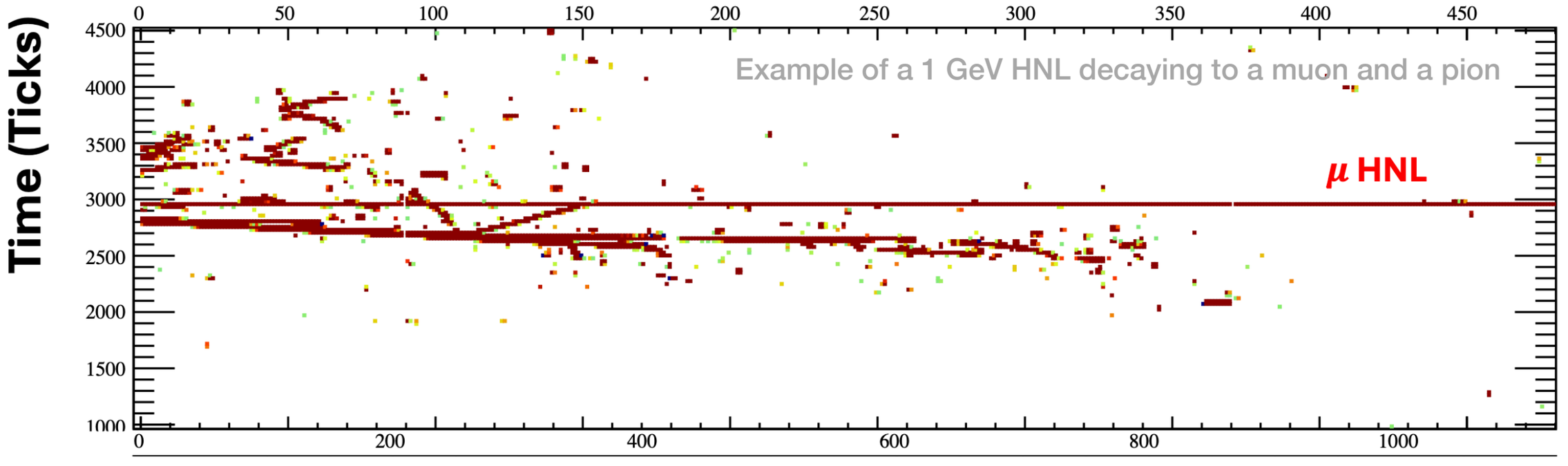
C. Hasnip, S. Urrea

- Develop the selection criteria to reject background events and to define the trigger algorithm settings (cut on the drift time difference and number of channels)

## Trigger Inputs: Ticks



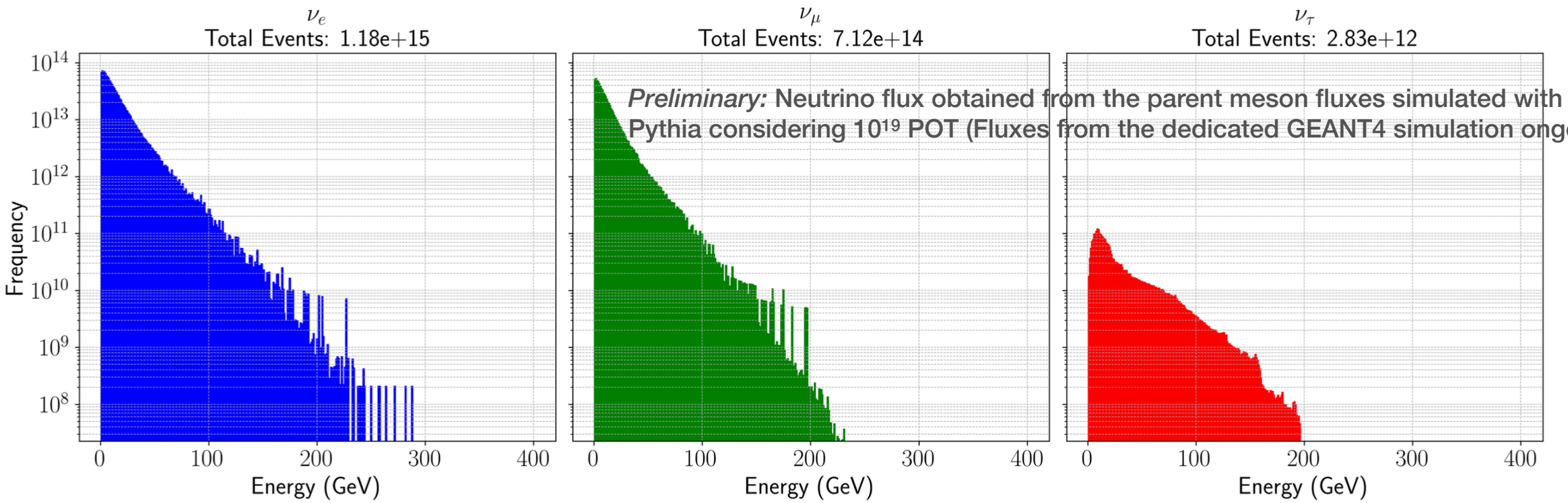

*Focus on the muon-like channels*



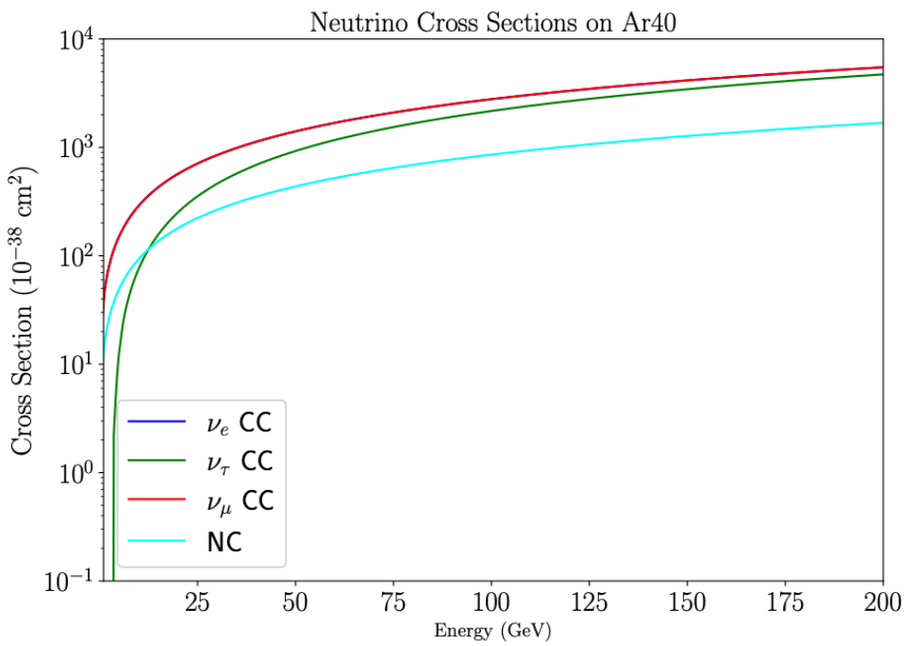
# Background studies

S. Urrea, J. Hernandez, J. Martin-Albo

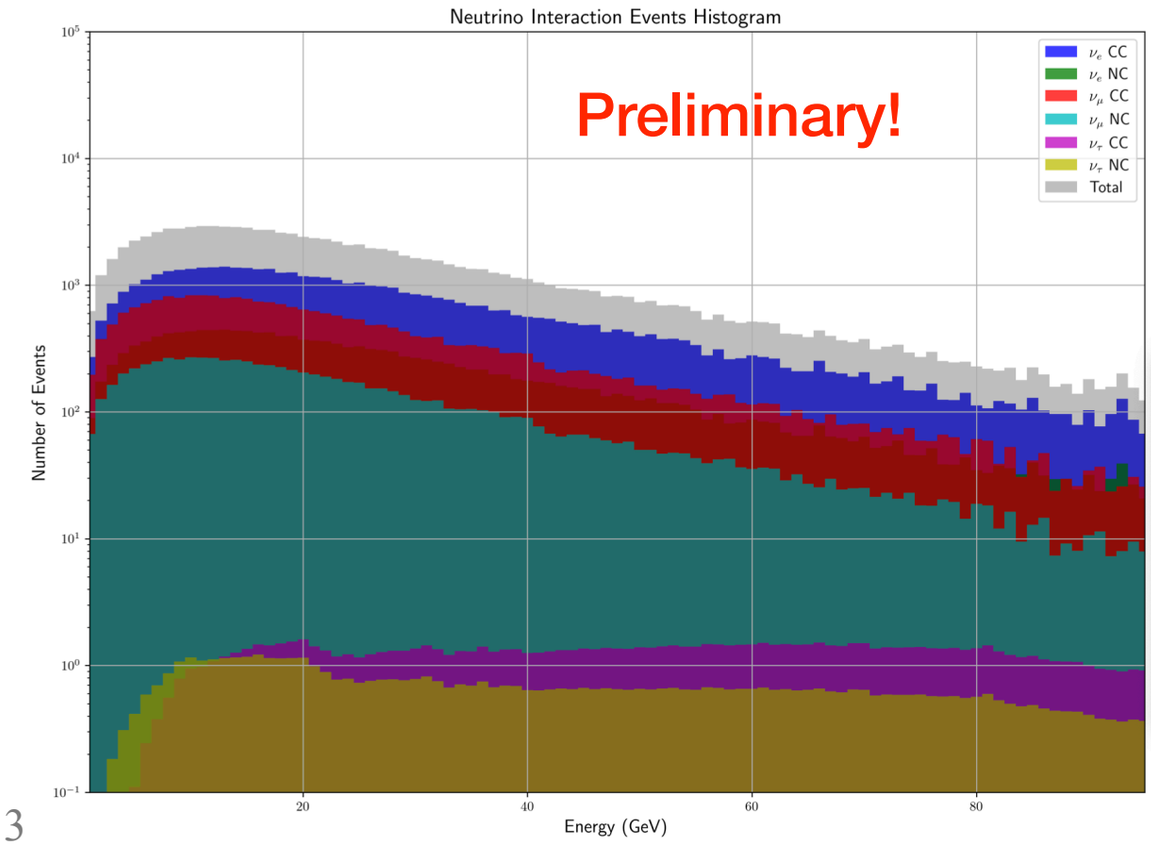
**Currently, the main background source are SM neutrinos produced in the decay of the mesons produced in the T2 target and TAX**




*Preliminary:* Neutrino flux obtained from the parent meson fluxes simulated with Pythia considering $10^{19}$ POT (Fluxes from the dedicated GEANT4 simulation ongoing)




Simulated using GENIE



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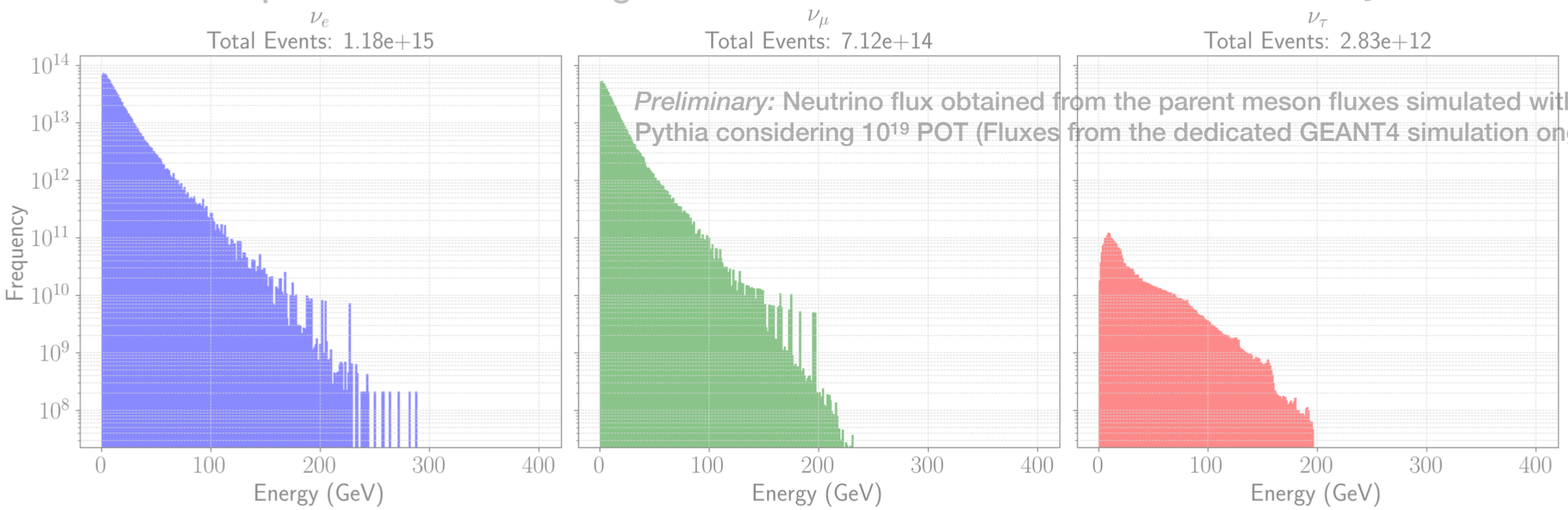
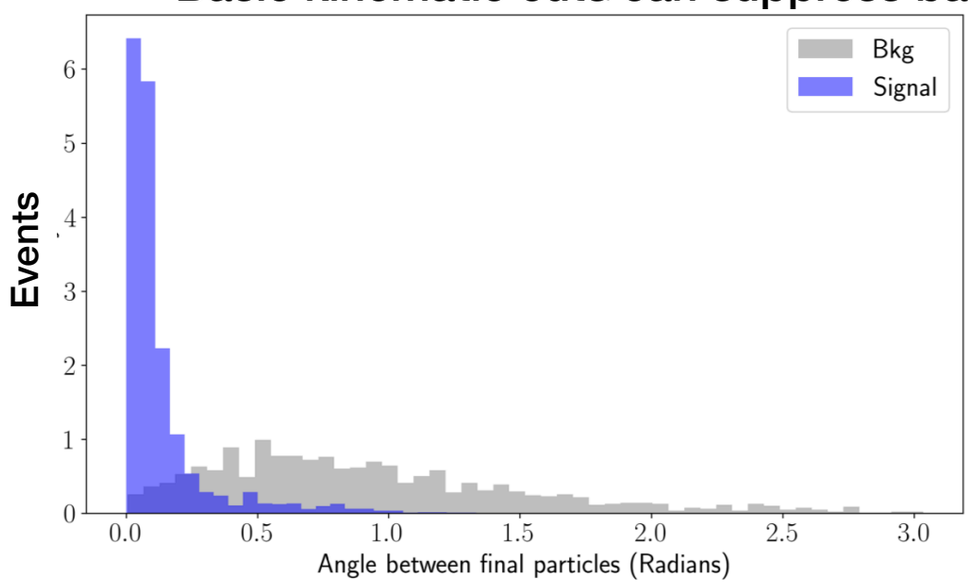


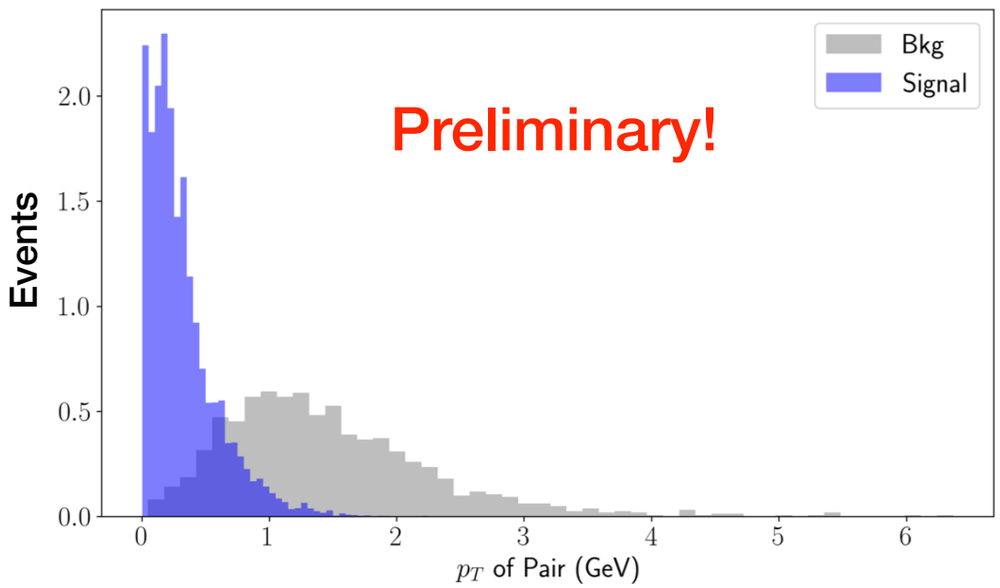

*Preliminary:* Neutrino flux obtained from the parent meson fluxes simulated with Pythia considering $10^{19}$ POT (Fluxes from the dedicated GEANT4 simulation ongoing)

**HNL decaying to:**

$\pi^{\pm}\mu^{\mp}$ or $\mu^{\pm}\mu^{\mp}$

**Basic kinematic cuts can suppress background events by 5 orders of magnitude**

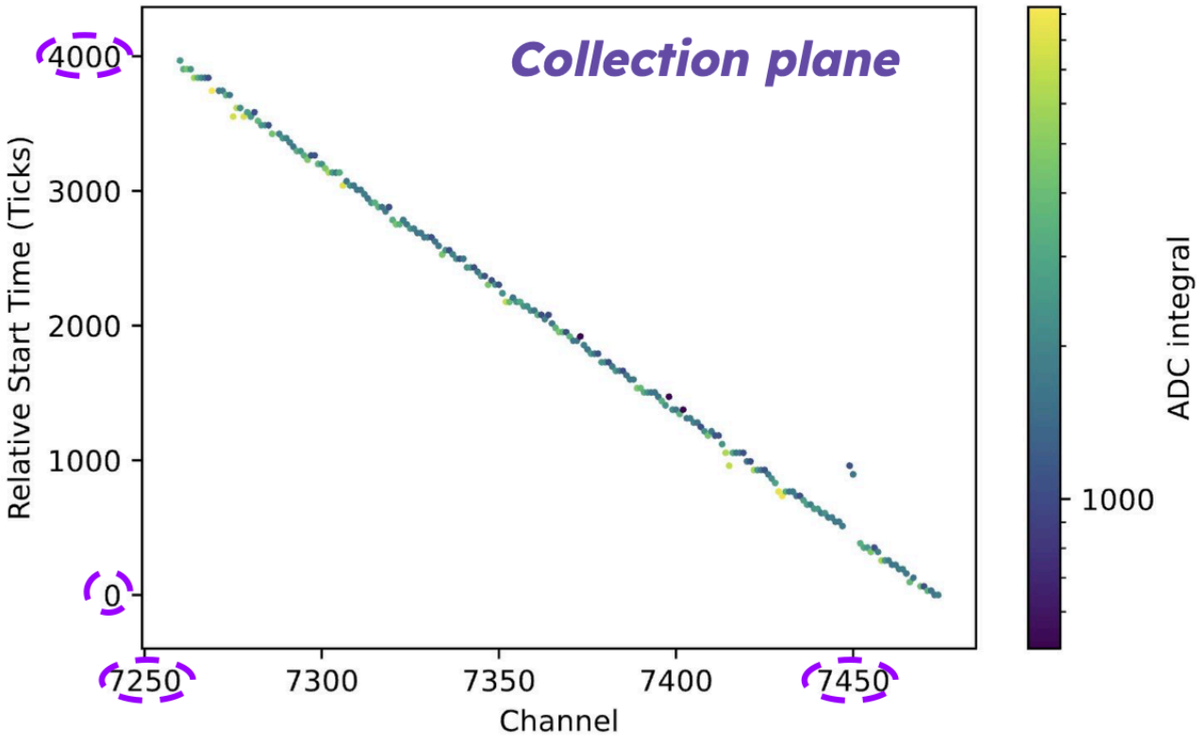


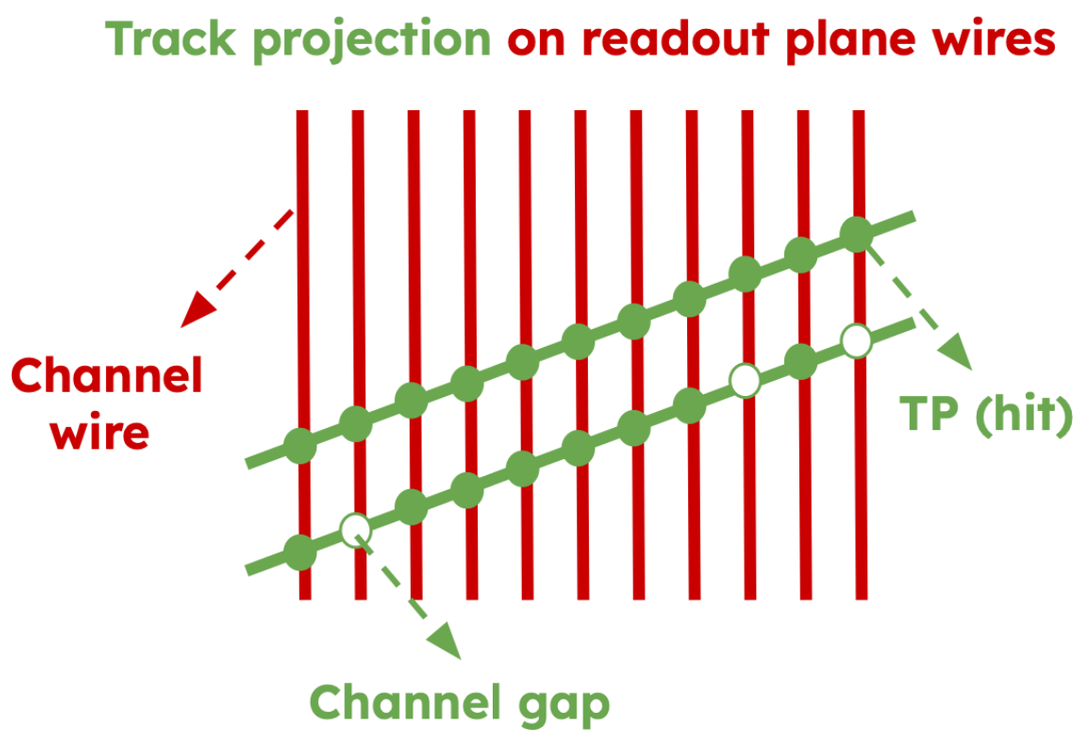



# Trigger and data reconstruction developments

H. Amar

- There was no dedicated trigger to search for LLP signatures: *main challenges were the time synchronisation with the spill and the rejection of cosmics.*
- *First step: select muon-like tracks traversing the TPC.* New trigger algorithm developed based on the drift time and the channel adjacency (developed in collaboration with the DUNE Data Acquisition System group).



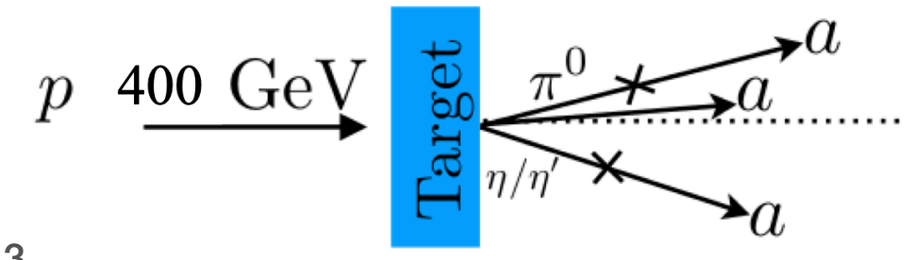

- NP04 started to collect data in June. We are currently analysing those runs to validate the algorithm and the time synchronisation between the TPC information and the spill.
- We plan to extend the algorithm to search for a decay vertex with two outgoing particles.

# Other LLP scenarios: *ALPs*

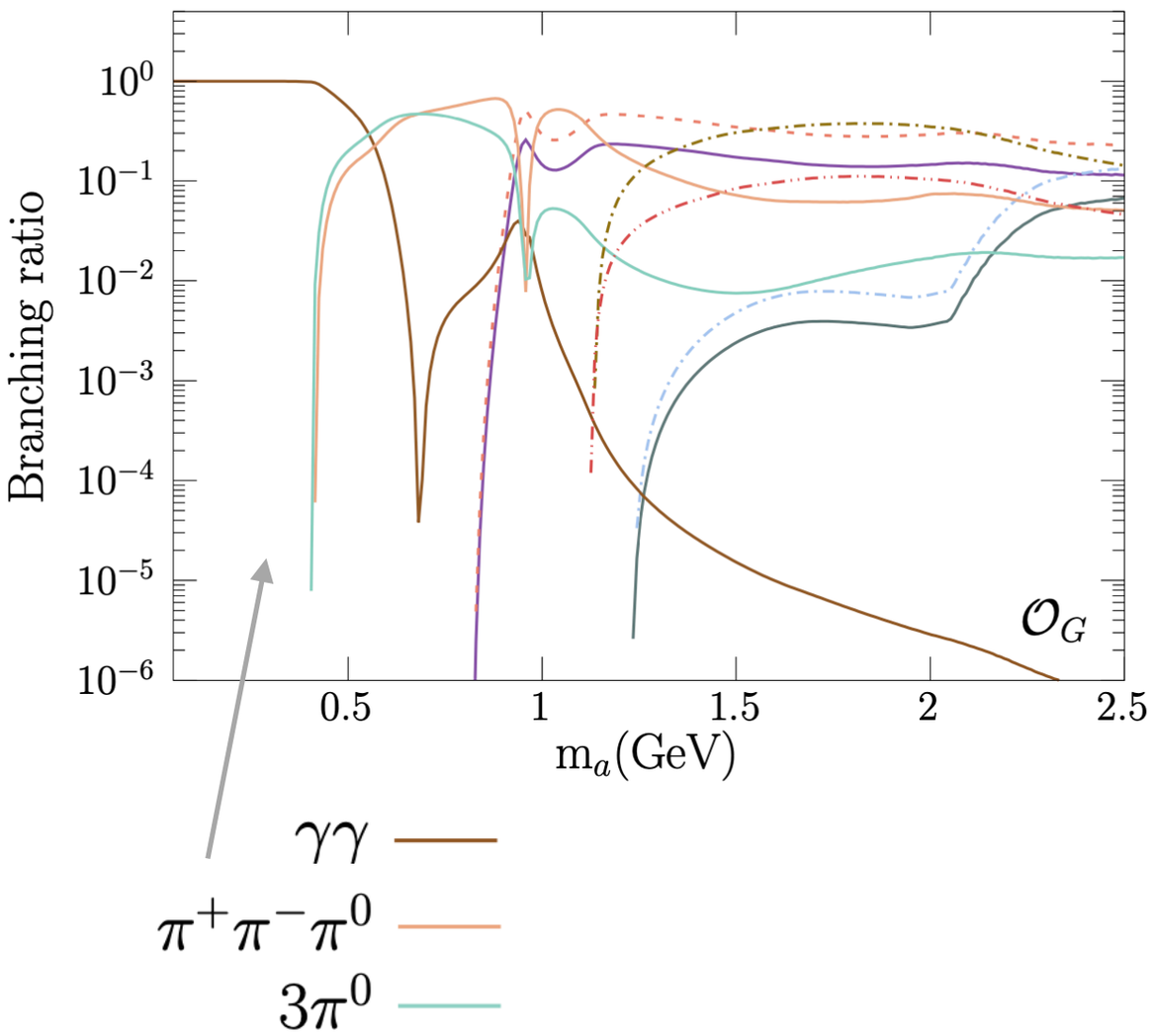
S.Urrea, P. Coloma, J. López-Pavón

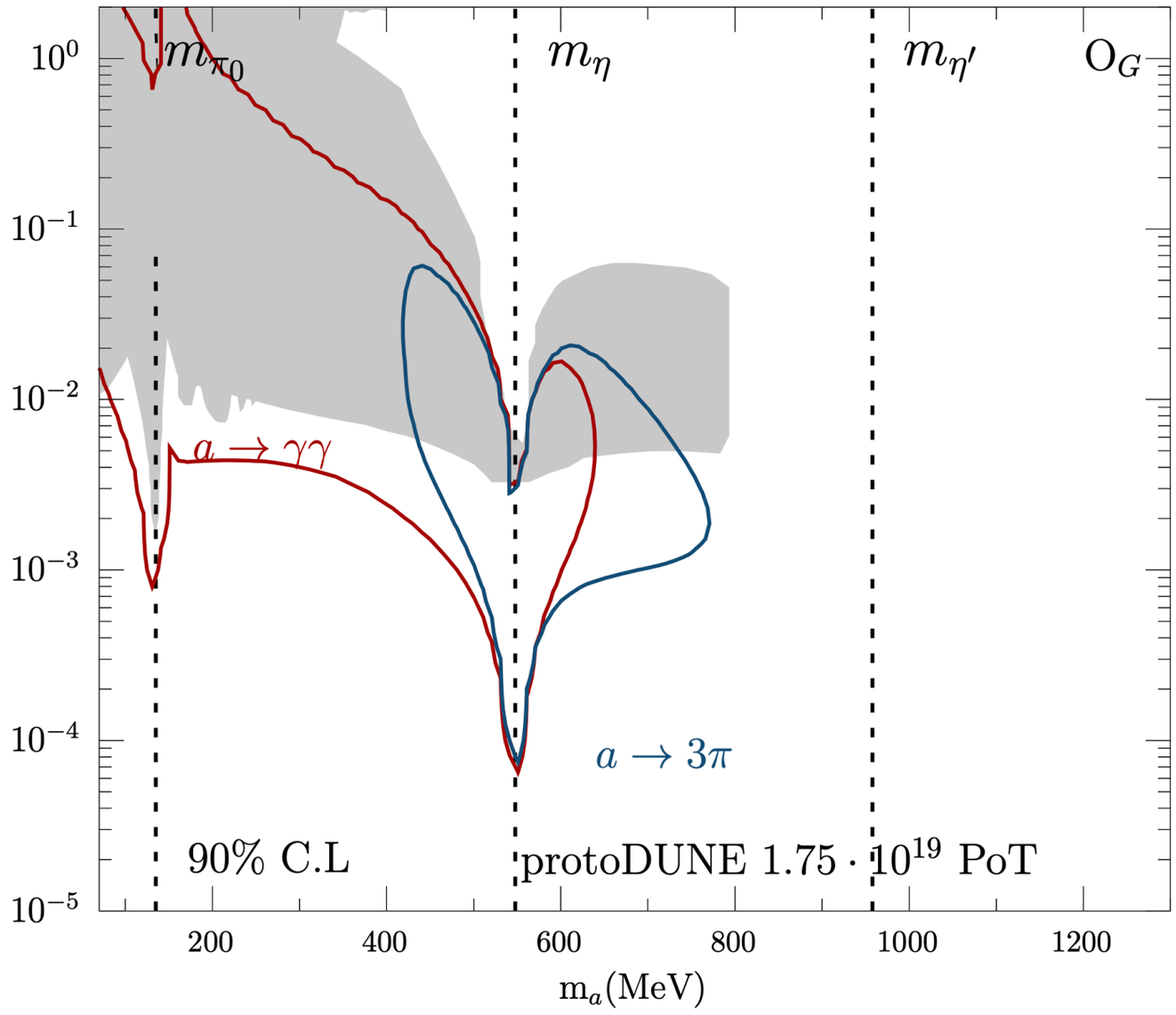
**Pseudo Nambu-Goldstone bosons motivated in many NP scenarios**
**( for example as a solution to DM origin)**

$$\delta\mathcal{L}_{a,int} = c_G\mathcal{O}_G = \frac{\alpha_s}{8\pi f_a} a G^b_{\mu\nu}\tilde{G}^{b\mu\nu}$$



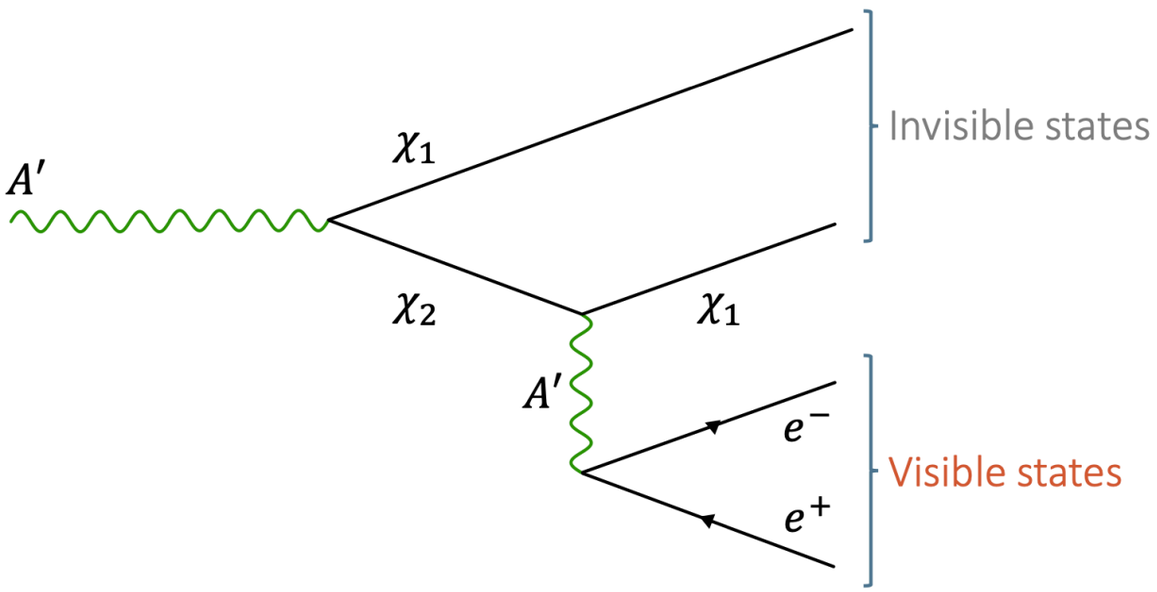

K. J. Kelly, S. Kumar and Z. Liu, Phys. Rev. D 103 (2021) no.9, 095002
P. Coloma, J. Martín-Albo and S. Urrea, Phys. Rev. D 109 (2024) no.3, 035013



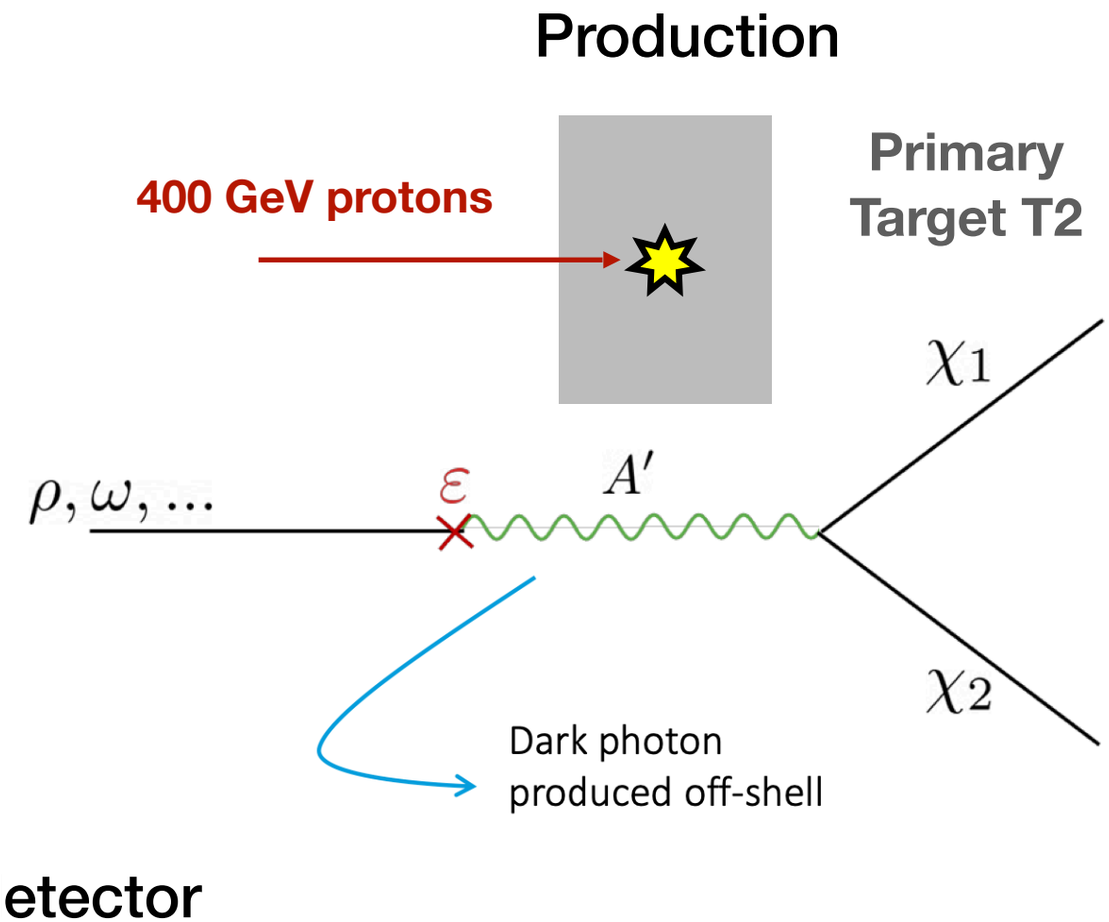



# Other LLP scenarios: *inelastic DM*

S. Bianco, P. Coloma

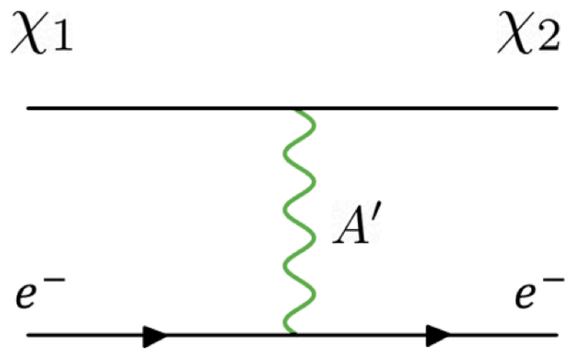



*M. Mongillo et al. Eur. Phys. J. C 83 (2023) no.5, 391*

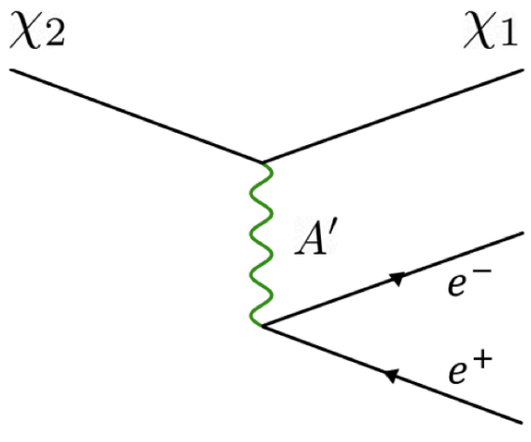



## Signature at the detector

Up-scattering of $\chi_1$



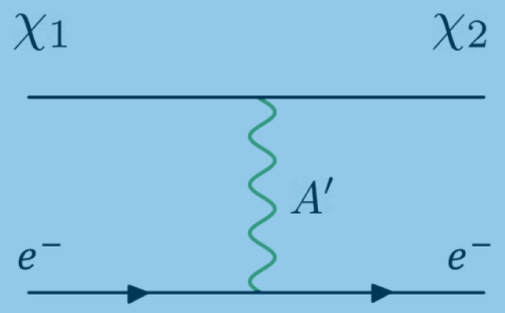

Decay of $\chi_2$



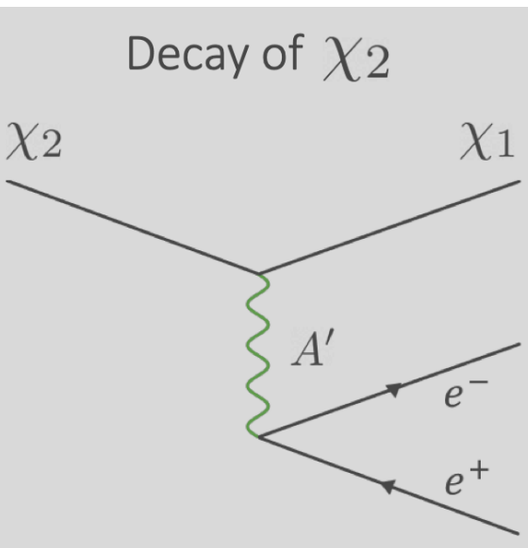
# Other LLP scenarios: *inelastic DM*

S. Bianco, P. Coloma

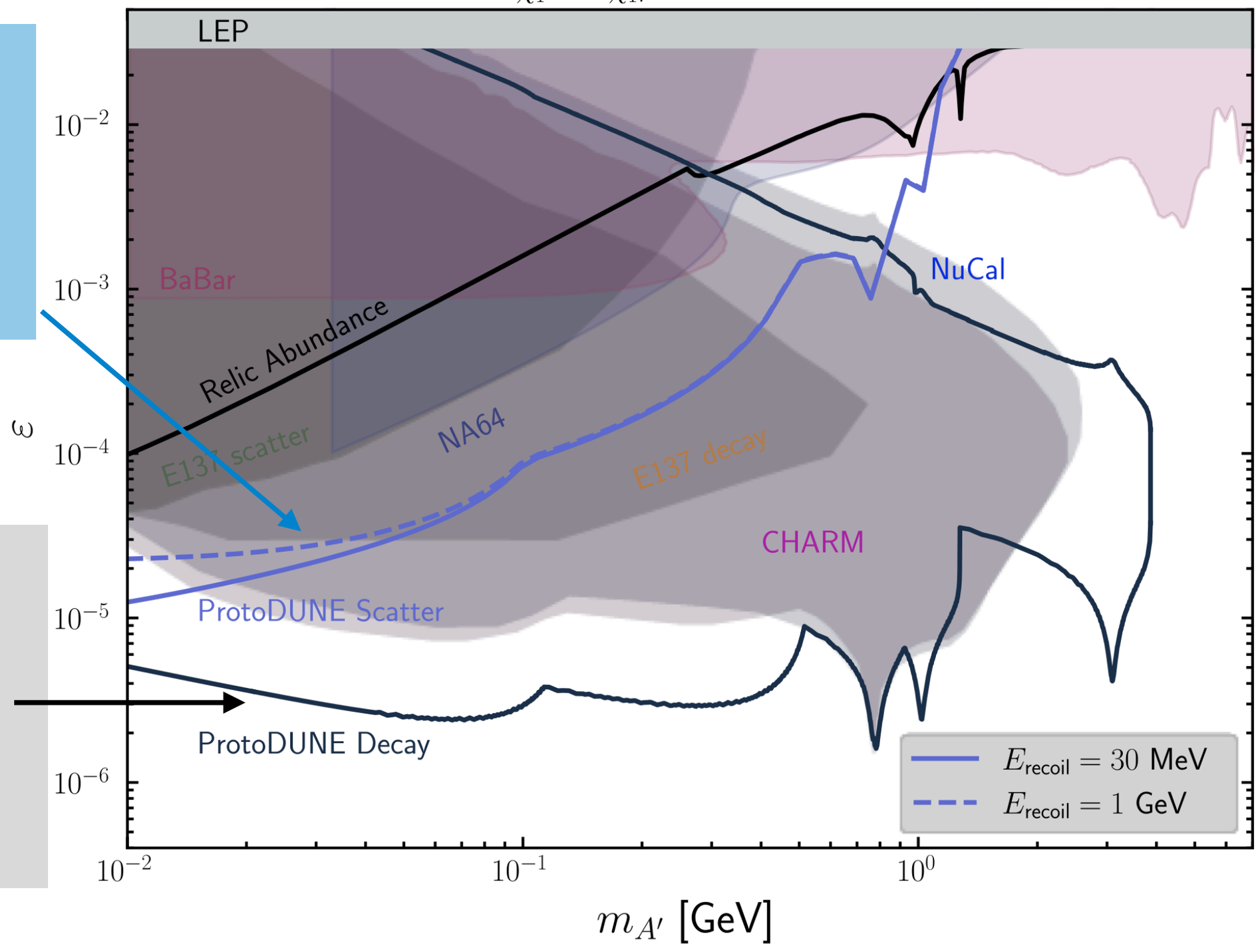
Up-scattering of $\chi_1$




Decay of $\chi_2$




$\Delta_{21} = 0.4\ m_{\chi_1},\ m_{\chi_1}/m_{A'} = 0.33,\ \alpha_D = 0.1$




*Bounds from M. Mongillo et al. Eur. Phys. J. C 83 (2023) no.5, 391*

# 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.
- Such a setup offers the possibility to search for both long lived unstable particles and stable particles. Currently, we are focused on carrying out the feasibility study to search for LLP decays, HNL in particular. Nevertheless, this setup offers many possibilities and we are already exploring ALPs, inelastic dark matter, dark scalar,…
- We have recently formed a working group to identify and work on the most important items to validate the proposal:
  - ✦We are developing a realistic simulation framework including the main beam elements and the ProtoDUNE detectors.
  - ✦A dedicated LLP trigger is under development and we plan to validate it with NP04 data this summer.
  - ✦We are also identifying the main background sources, focusing in the SM neutrinos as preliminary it seems the dominant one.
- We plan to complete the proof-of-principle studies this summer to demonstrate if this proposal is feasible.

# Thanks for your attention!

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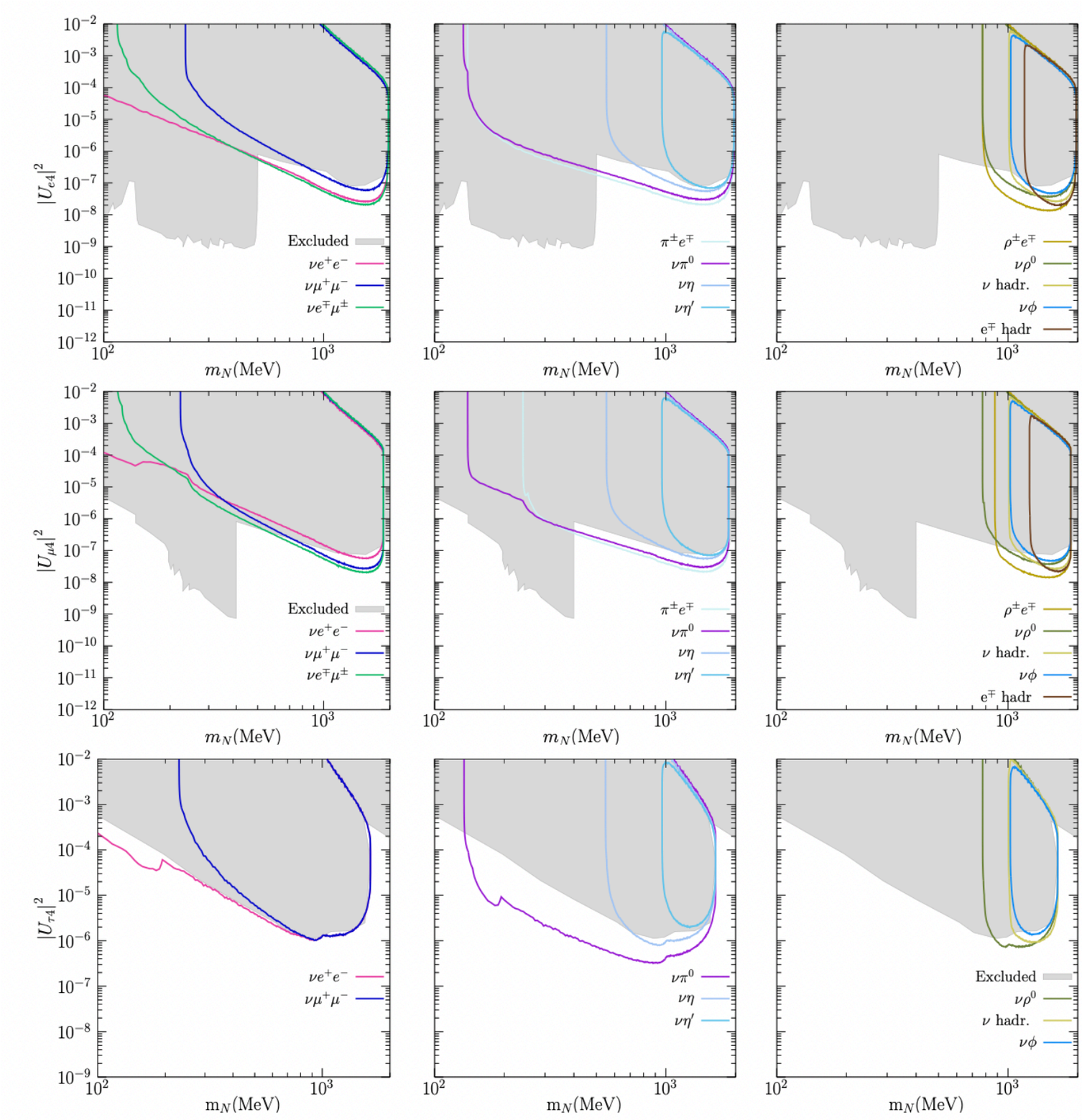
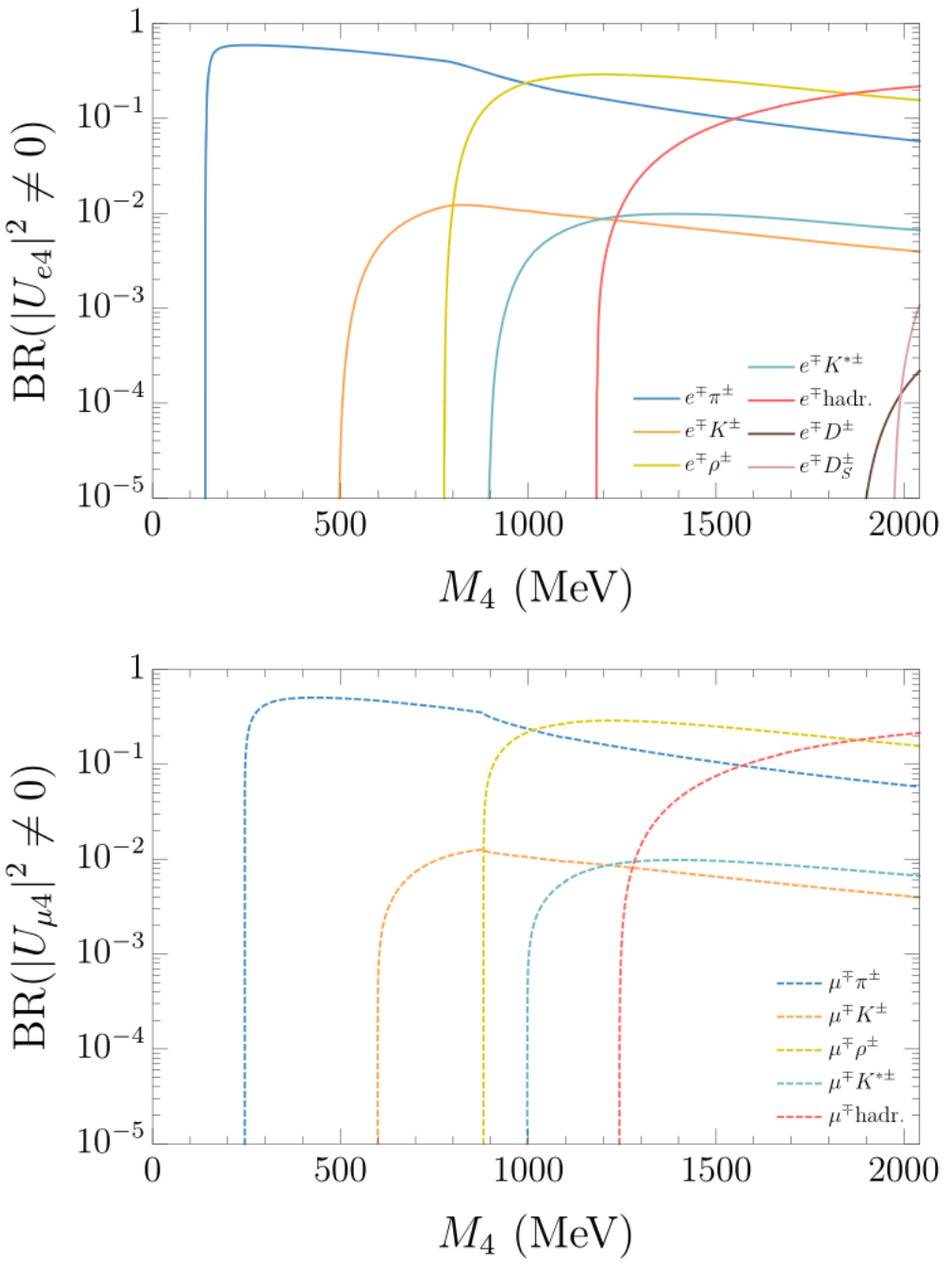
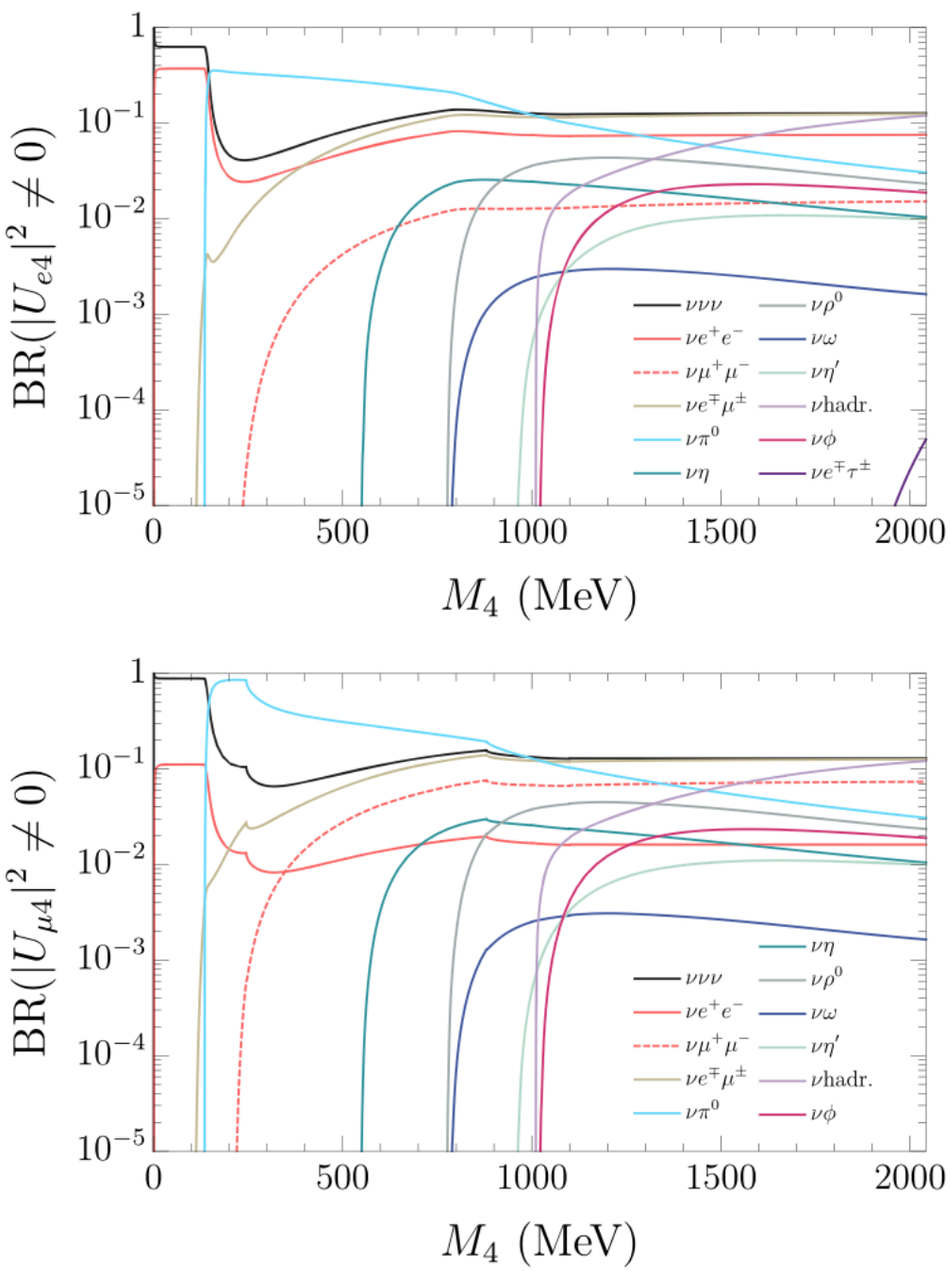
# Back-up

# HNL




P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134










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

# Detector simulation framework

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**Example of a generated event display:**

*1 GeV HNL*

*18 GeV pion*

*0.3 GeV muon*