Neutrino and Beyond Standard Model Physics Searches at the CERN ProtoDUNE Detectors

Ciaran Hasnip, CERN
On behalf of the *DUNE Collaboration*
NuTel 2025
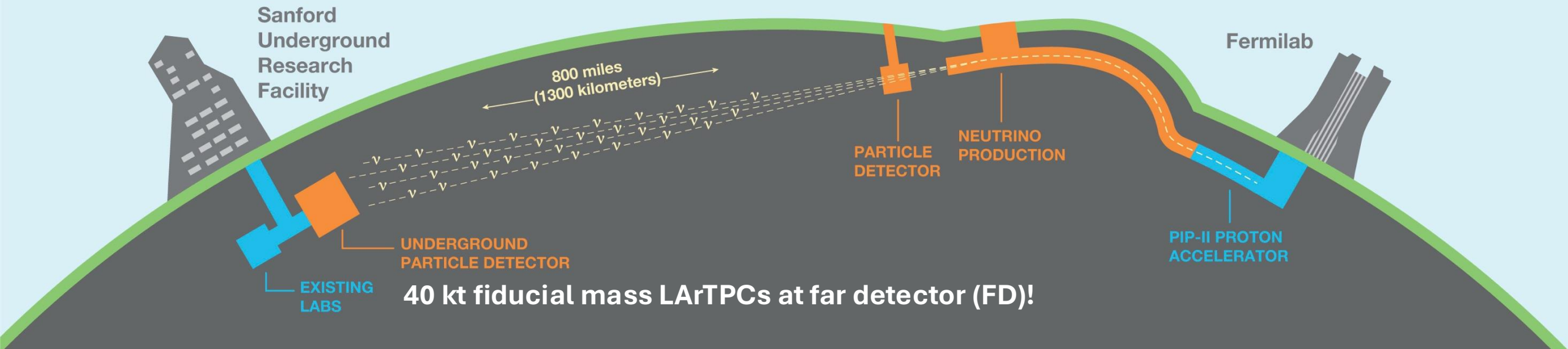**30/09/2025**

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Deep Underground Neutrino Experiment (DUNE)

- See DUNE plenary talk by David Rivera on Thursday for more details

Observe $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

Measure δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}, mass ordering

**40 kt fiducial mass LArTPCs at far detector (FD)!**

ProtoDUNE at CERN Neutrino Platform

- Two large **prototypes** of the DUNE FD at **CERN Neutrino Platform**

- Built to **test LArTPC detector technology** for the DUNE FD and measure hadron-Ar cross section measurements

ProtoDUNE-HD

ProtoDUNE-VD

DEEP UNDERGROUND NEUTRINO EXPERIMENT
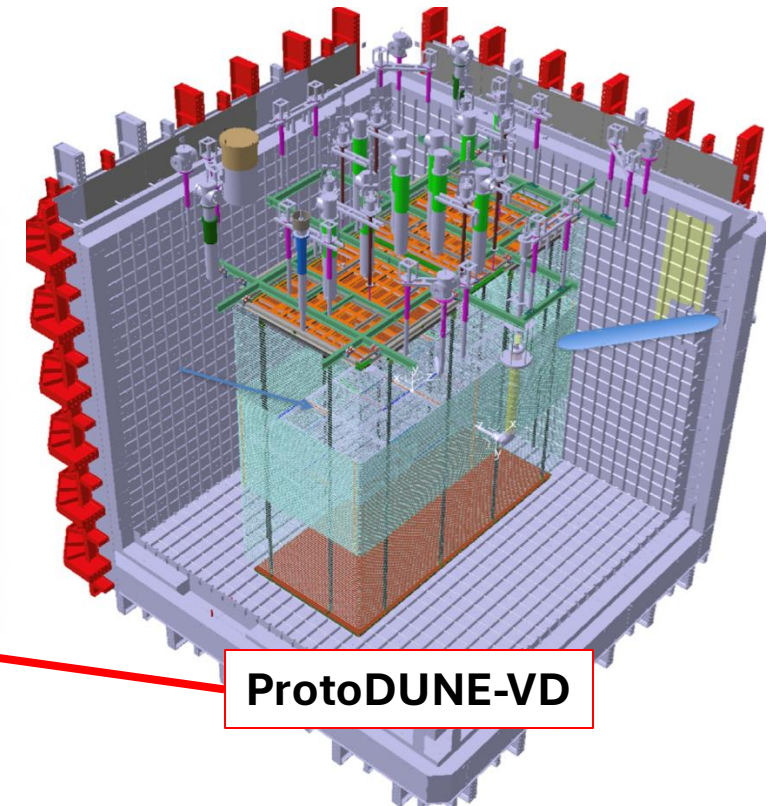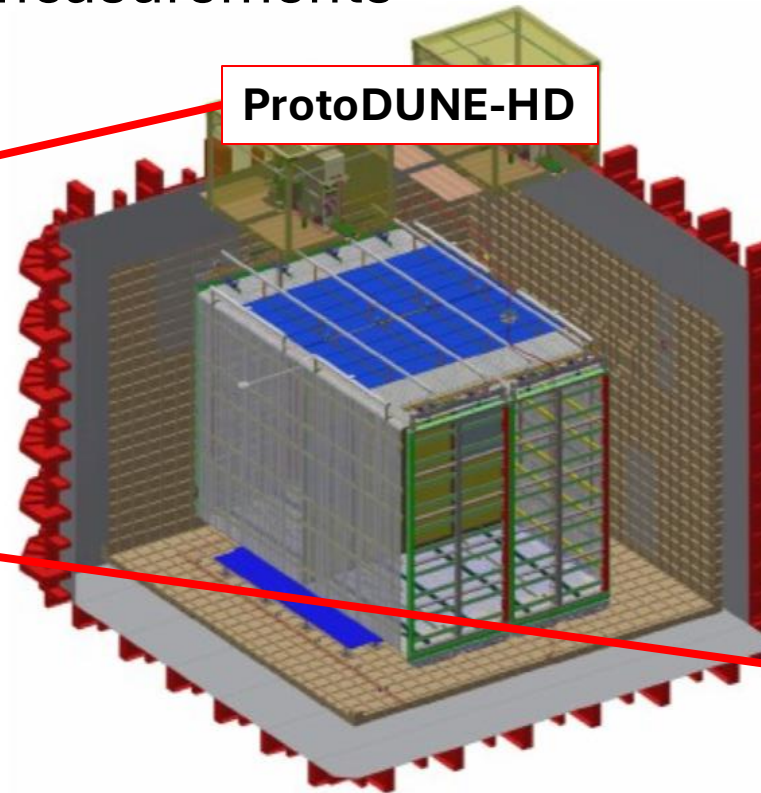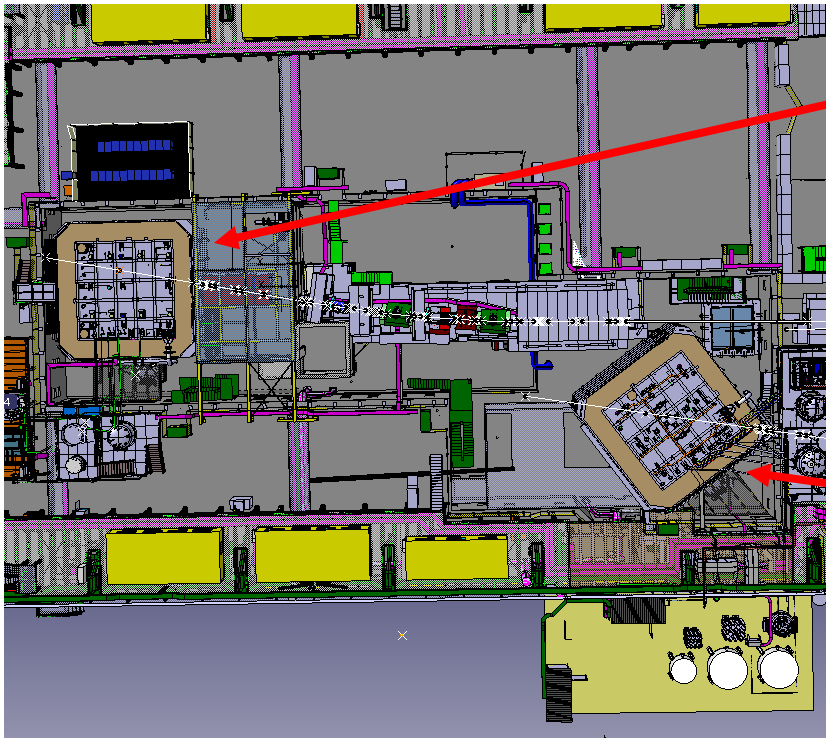
Neutrinos and BSM Physics in ProtoDUNE

- New idea: search for **neutrinos** and **beyond-standard model (BSM)** particles at **ProtoDUNE** from the **CERN Super Proton Synchrotron (SPS)**

- Details of proposal and estimated physics sensitivity of a ProtoDUNE BSM search published: J. High Energ. Phys. 2024, 134 (2024)

- ProtoDUNE becomes a beam-dump experiment – common way to search for weakly interacting long-lived particles or neutrinos
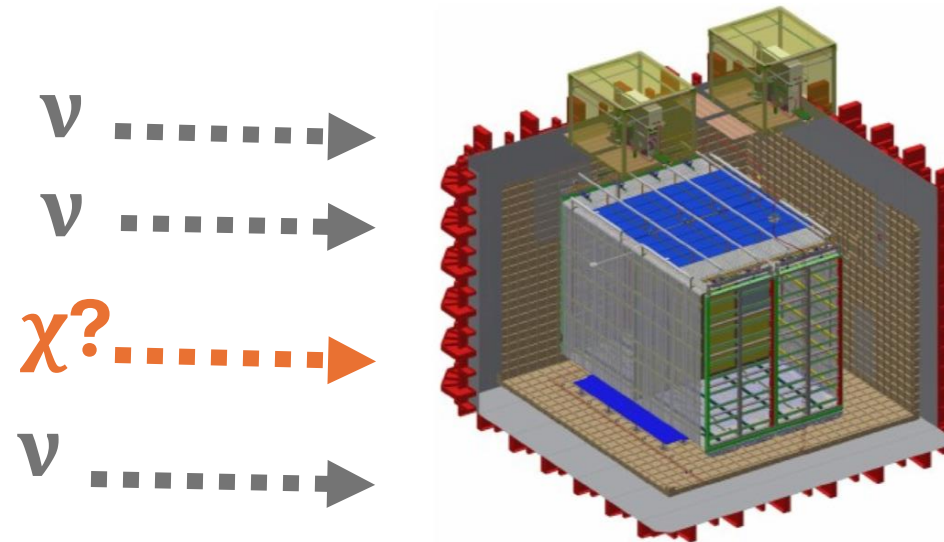
Beam-Dump Experiment

- A beam (usually protons) hitting a **fixed target** is a common way to produce **neutrinos** – or possibly something more exotic (e.g. Heavy Neutral Lepton)

- Pions, kaons etc. are produced in the target – **decay downstream** to neutrinos/BSM

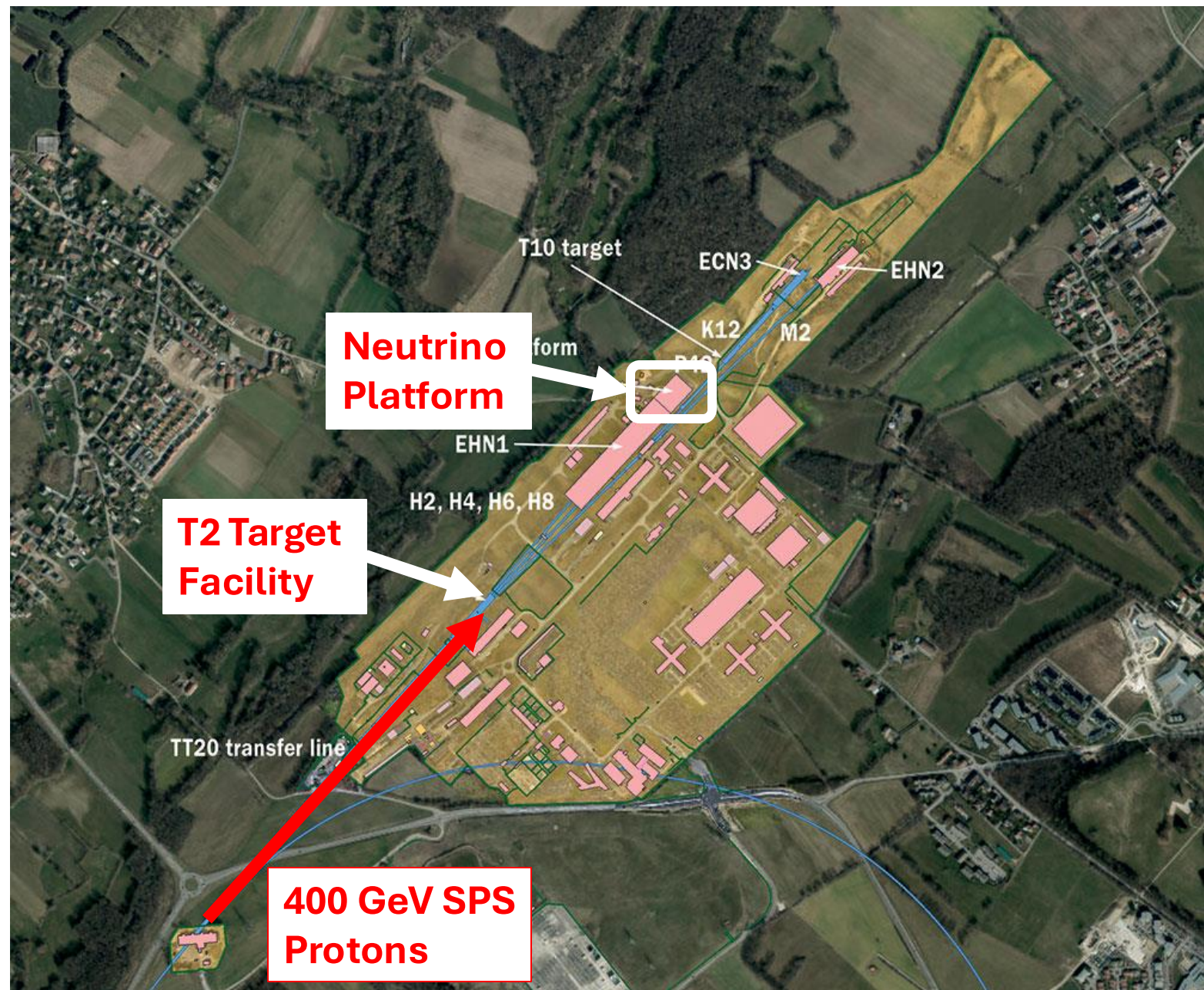- Place a detector in path of the neutrinos/BSM to try and observe them
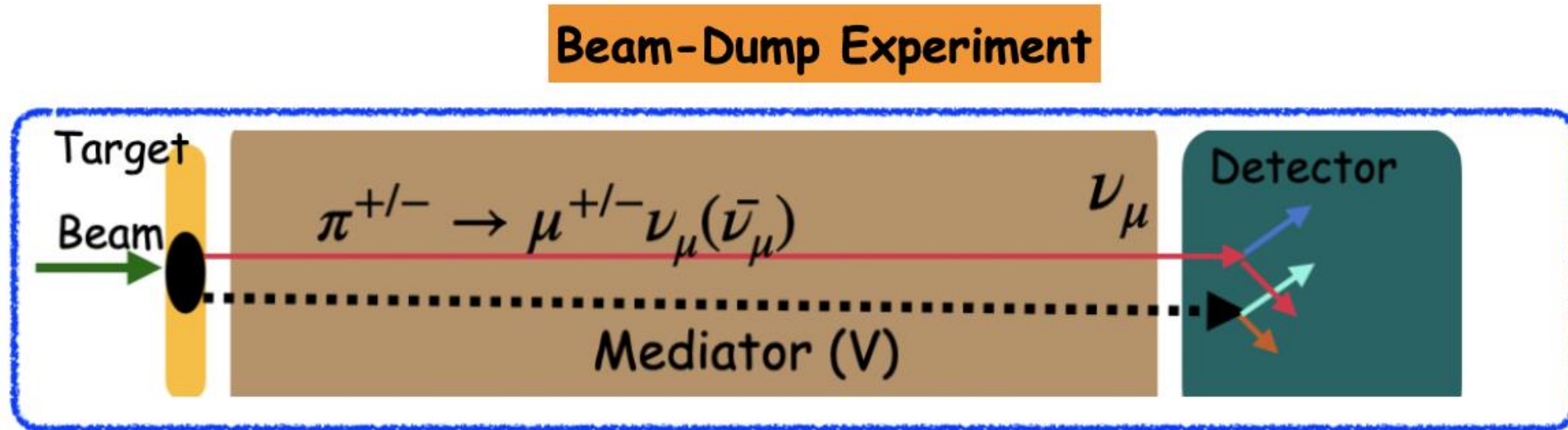
How can the ProtoDUNE detectors be a beam-dump experiment?

Beam-Dump Experiment
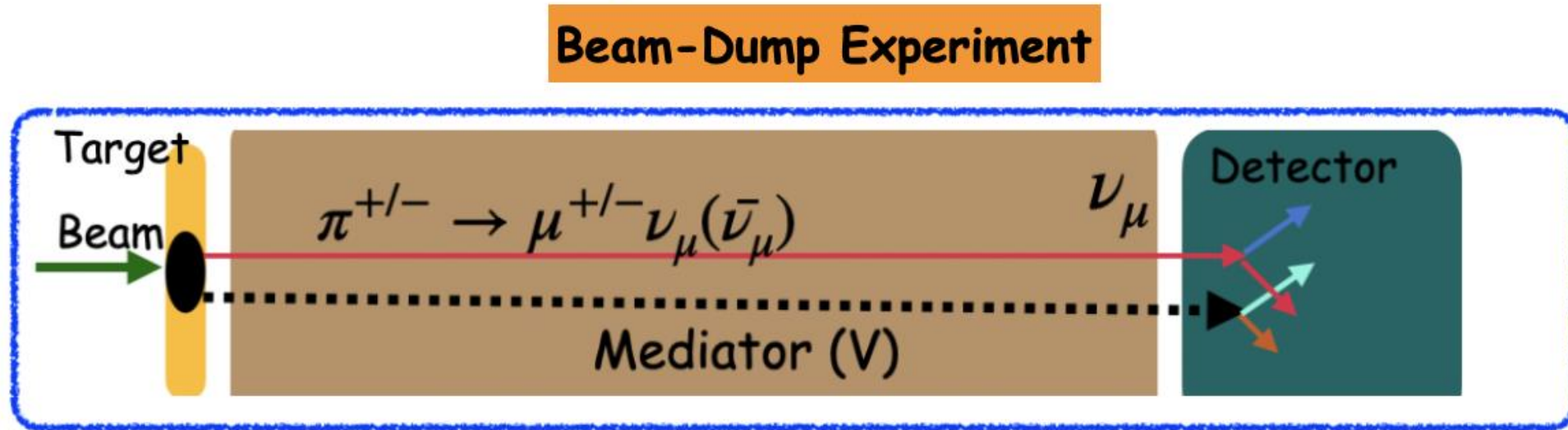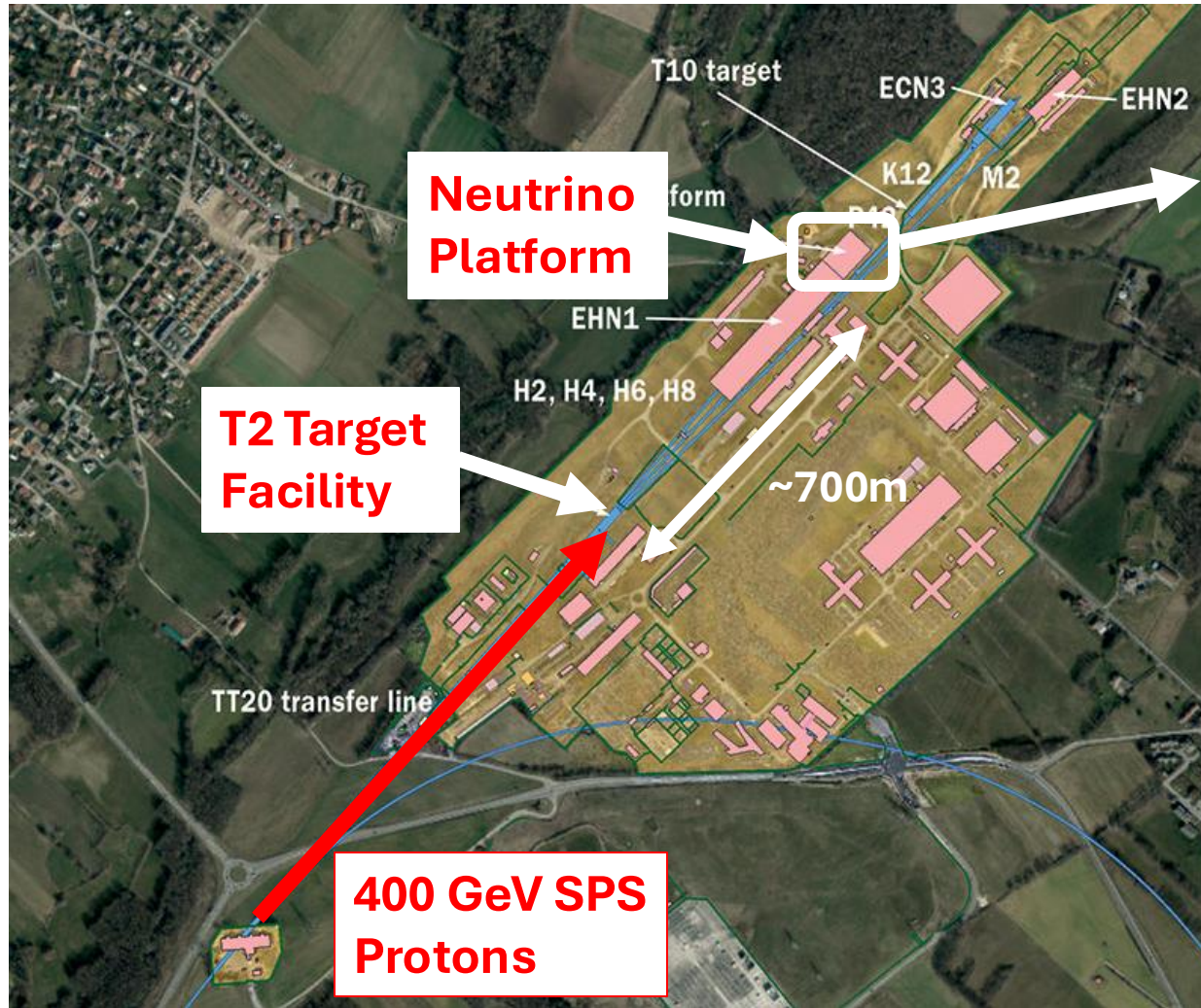
CERN SPS and Neutrino Platform

- CERN SPS beam accelerates protons to **400 GeV**

- SPS protons hit the **"T2" target**

- Protons hitting T2 are **aligned in the direction of the Neutrino Platform**

Neutrino Platform

T2 Target Facility

400 GeV SPS Protons

T10 target
ECN3
EHN2
K12
M2
...form
EHN1
H2, H4, H6, H8
TT20 transfer line

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The T2 Beamline

Neutrino Platform Top View

Neutrino Platform

T2 Target Facility

~700m

400 GeV SPS Protons

T2 Beamline

NP04/ProtoDUNE-HD

NP02/ProtoDUNE-VD

DEEP UNDERGROUND NEUTRINO EXPERIMENT
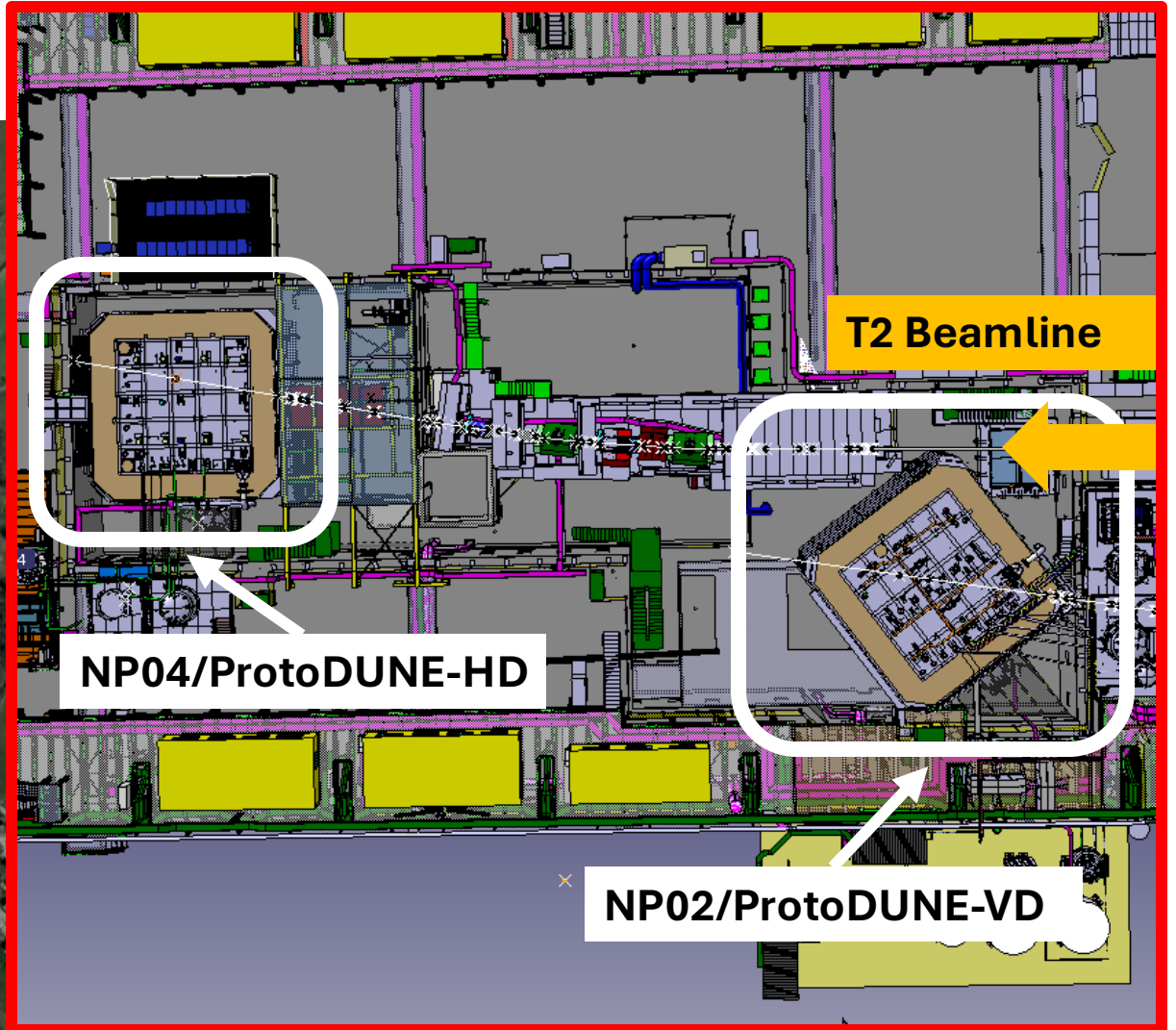
The T2 beamline

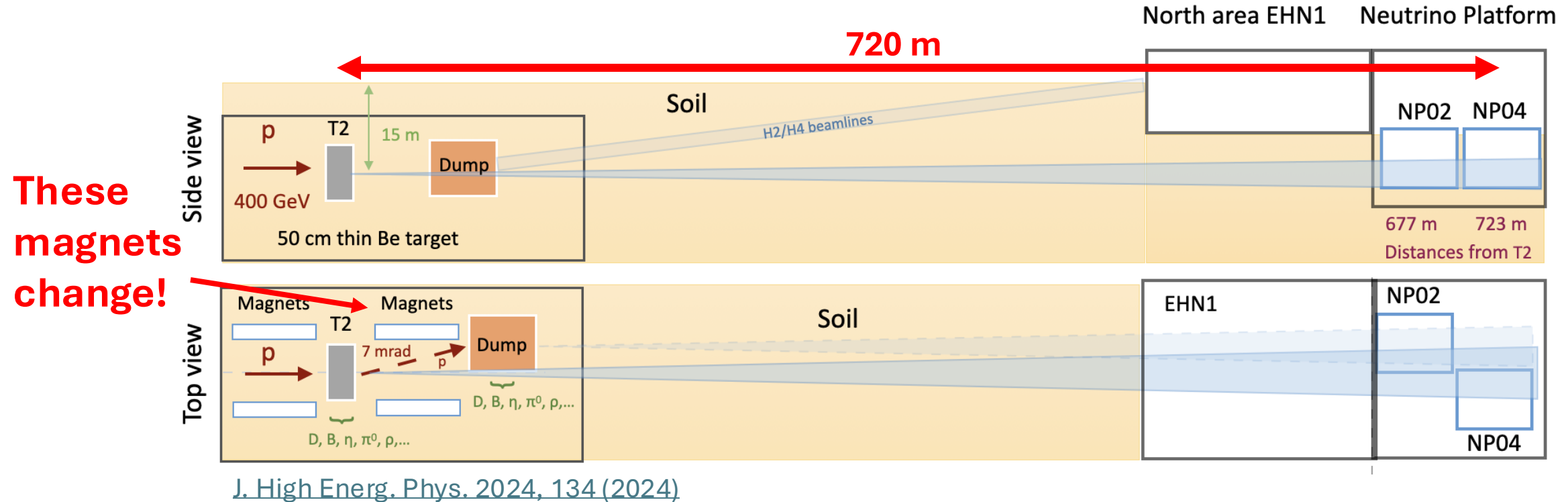- We have a **670-720m beamline (VD or HD ProtoDUNE)** – neutrinos/BSM produced in T2 or downstream dump (TAX)

J. High Energ. Phys. 2024, 134 (2024)

# T2 Target Area G4 Simulation

- A full **Geant4 model** of the **target facility** around T2 has been created

- Simulate 400 GeV SPS protons hitting this facility and the subsequent hadrons produced

- Produce fluxes of BSM particles, such as Heavy Neutral Leptons (HNLs)

- Dump, magnets and ~500m of soil absorb remaining hadrons

T2 Target

Wobbling Magnets

Downstream Dump

~100m
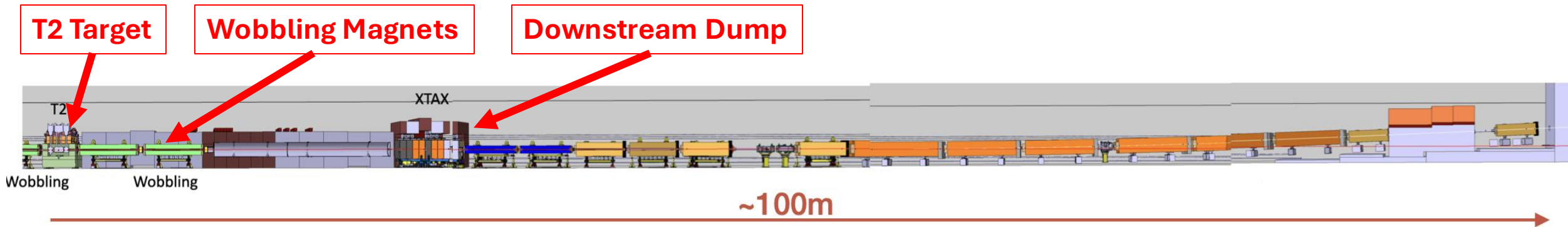
Potential Sensitivity of ProtoDUNE BSM Program

- Sensitivity for HNL benchmark model: J. High Energ. Phys. 2024, 134 (2024)

Decays considered: $N \rightarrow \nu ee, \nu \mu\mu, \nu e\mu, e\pi, \mu\pi, \nu\pi^0$
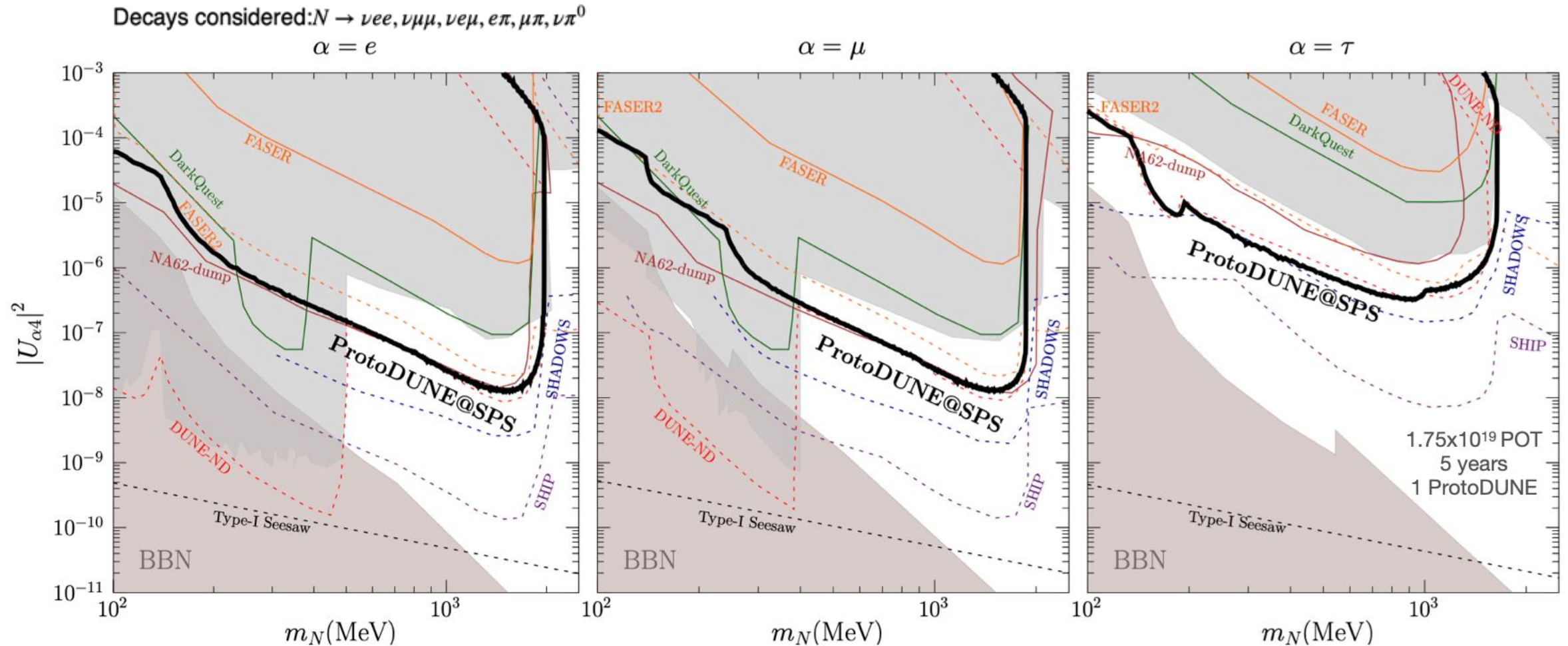
Proof of Principle – Observing Neutrinos at ProtoDUNE

- The aim is to do a **BSM search at ProtoDUNE**

- First search for something that **exists** – **neutrinos**!

- Proof of concept: observation of **neutrinos** from the **T2 target** – becomes background in BSM search

- A sample of neutrinos in a FD-like LArTPC will be useful – **test energy reconstruction methods** or possibly a cross-section measurement

T2 Beamline

NP04/ProtoDUNE-HD

NP02/ProtoDUNE-VD

DEEP UNDERGROUND NEUTRINO EXPERIMENT
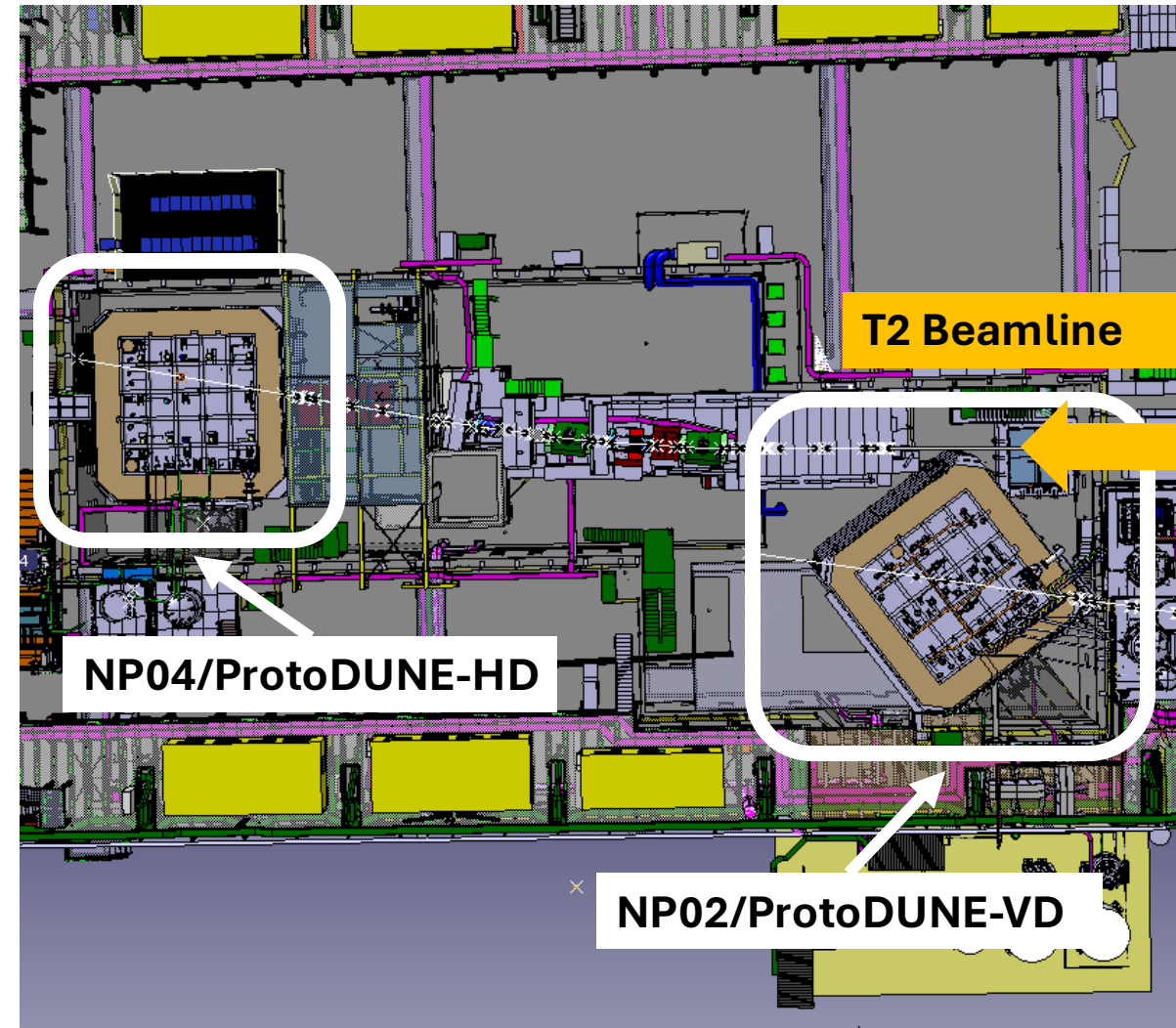
What is the Neutrino Flux?

- Geant4 simulation of SPS protons hitting T2 target area and downstream facilities
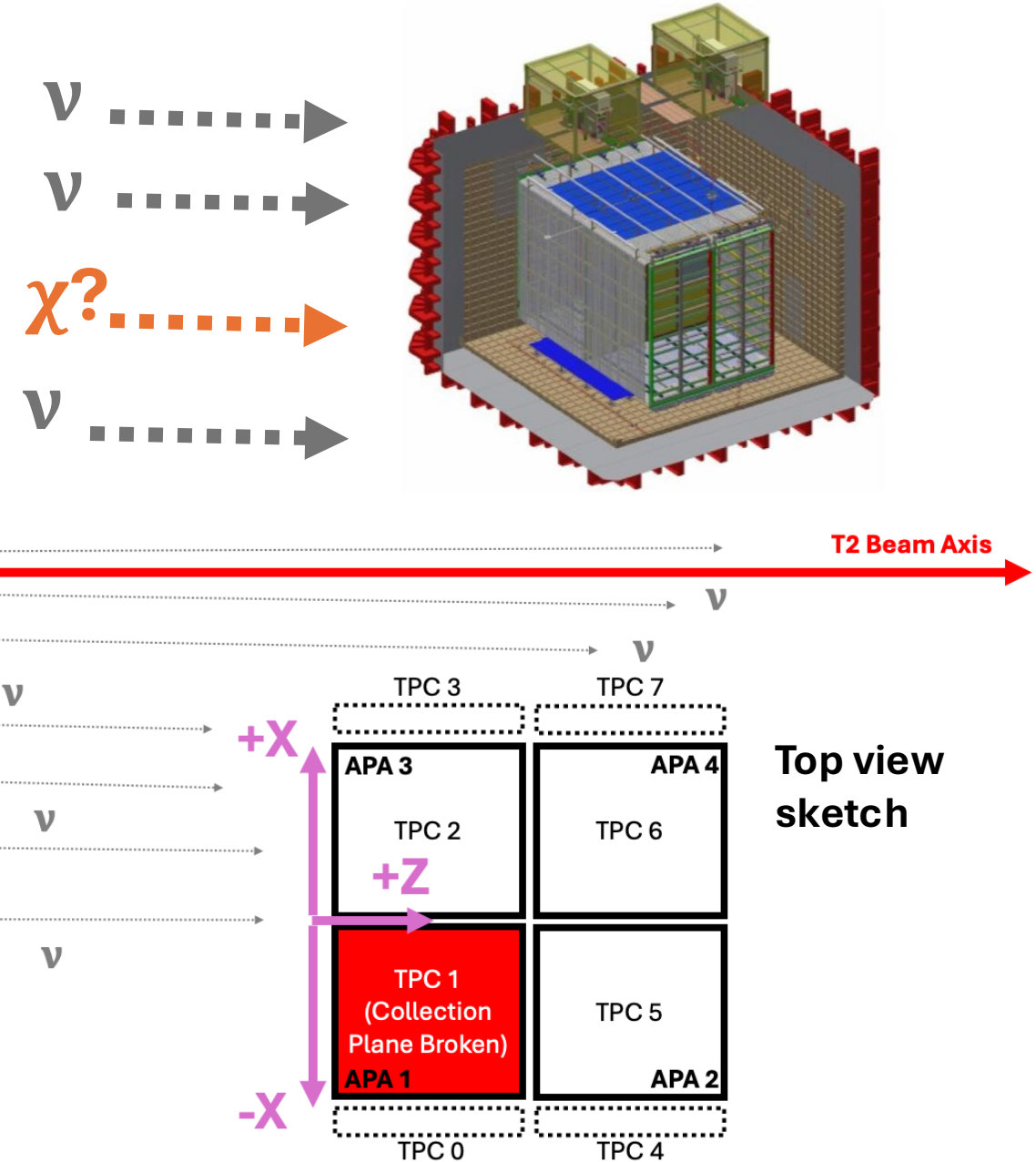
- Flux peaks at **0-10 GeV** and long tail to **more than 100 GeV**

- Very **high-energy** neutrinos!

- Simulate separate **flux** for **each T2 magnet configuration**
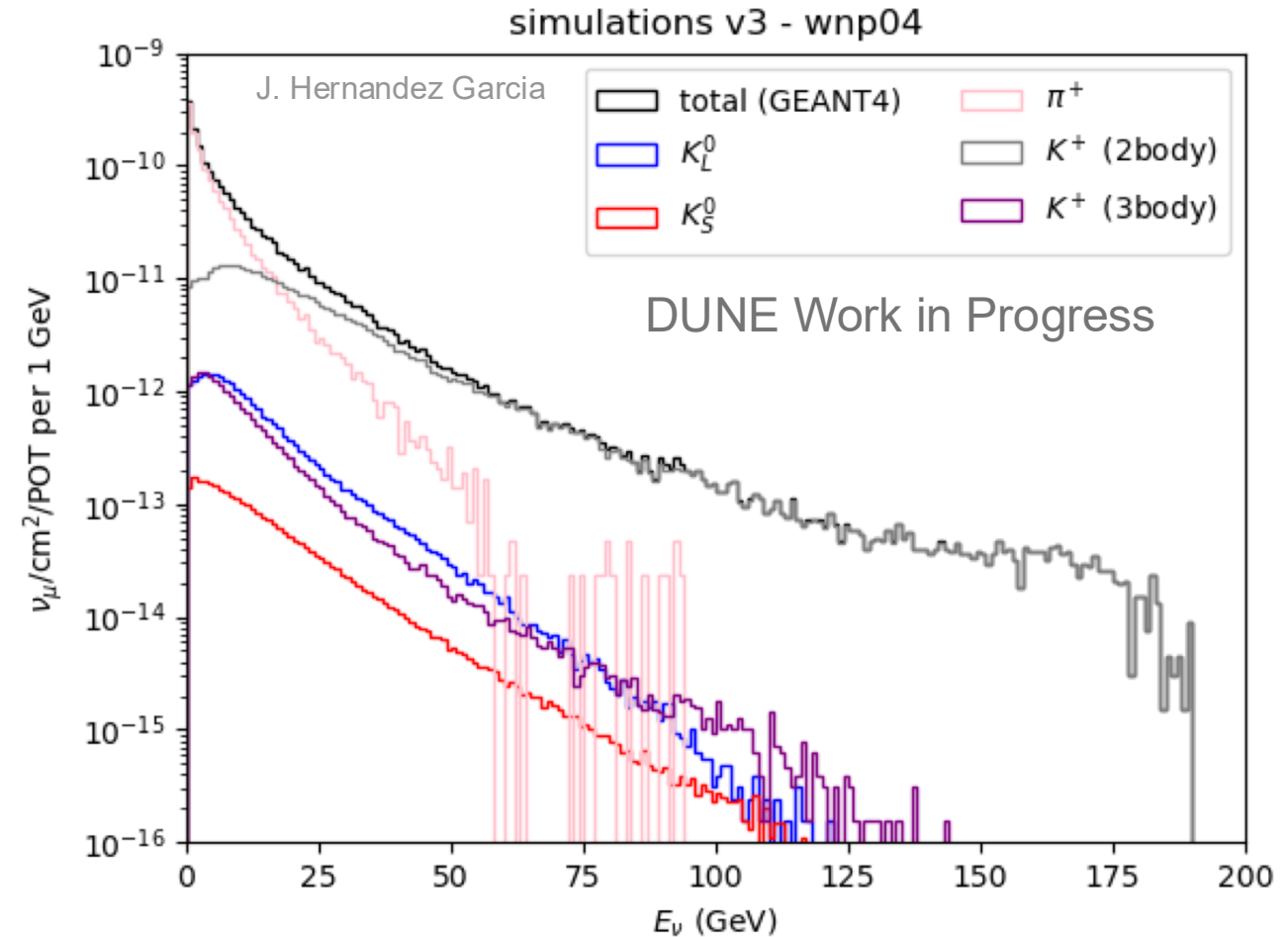
ProtoDUNE-HD (NP04)

- Horizontal drift configuration

- 4 drift volumes – 2 wire planes either side of cathode

- We are **~720m** downstream from T2 and only **~7m** off the central axis of the beam

- Neutrinos (or BSM particles) are moving **totally parallel** to the **central cathode**

- **Many of them very high energy**

T2 Beam Axis

Top view sketch

TPC 3   TPC 7

+X   APA 3   APA 4

TPC 2   TPC 6
+Z

TPC 1
(Collection
Plane Broken)   TPC 5

APA 1   APA 2
-X

TPC 0   TPC 4

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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Data Overview at ProtoDUNE-HD

- Collected **~1 week of data**

- Trigger algorithm that selects **high energy events parallel to the cathode**

- Need to self-trigger detector – **rare events** and long **4.8s beam spill**

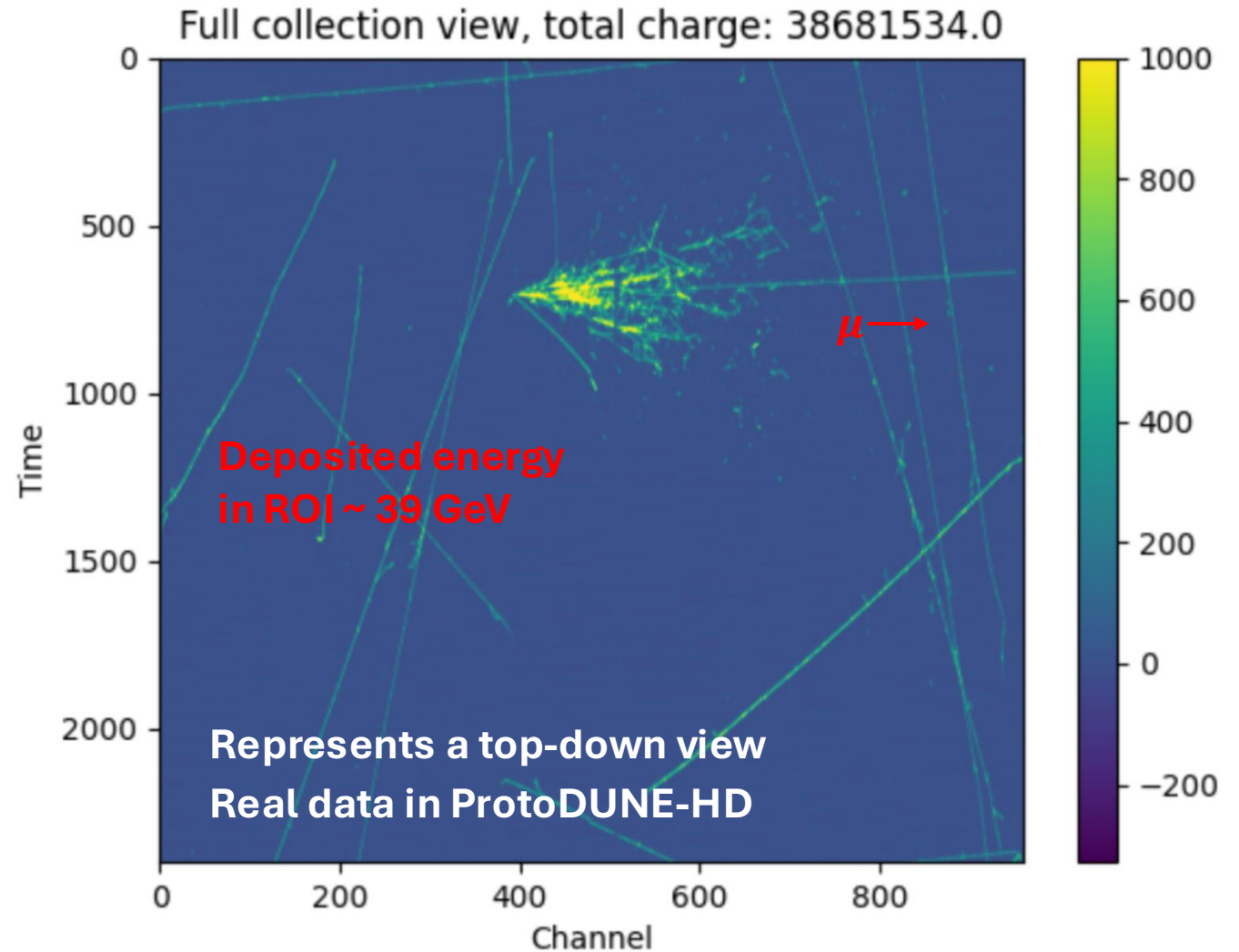- Data taken non-intrusively – no effect on other CERN operations

Run 29416, Trigger 401, APA2 Plane 2
Trigger Type (Supernova), 2024-10-03 12:30:14+02:00 (CERN)

Non-active channels this side
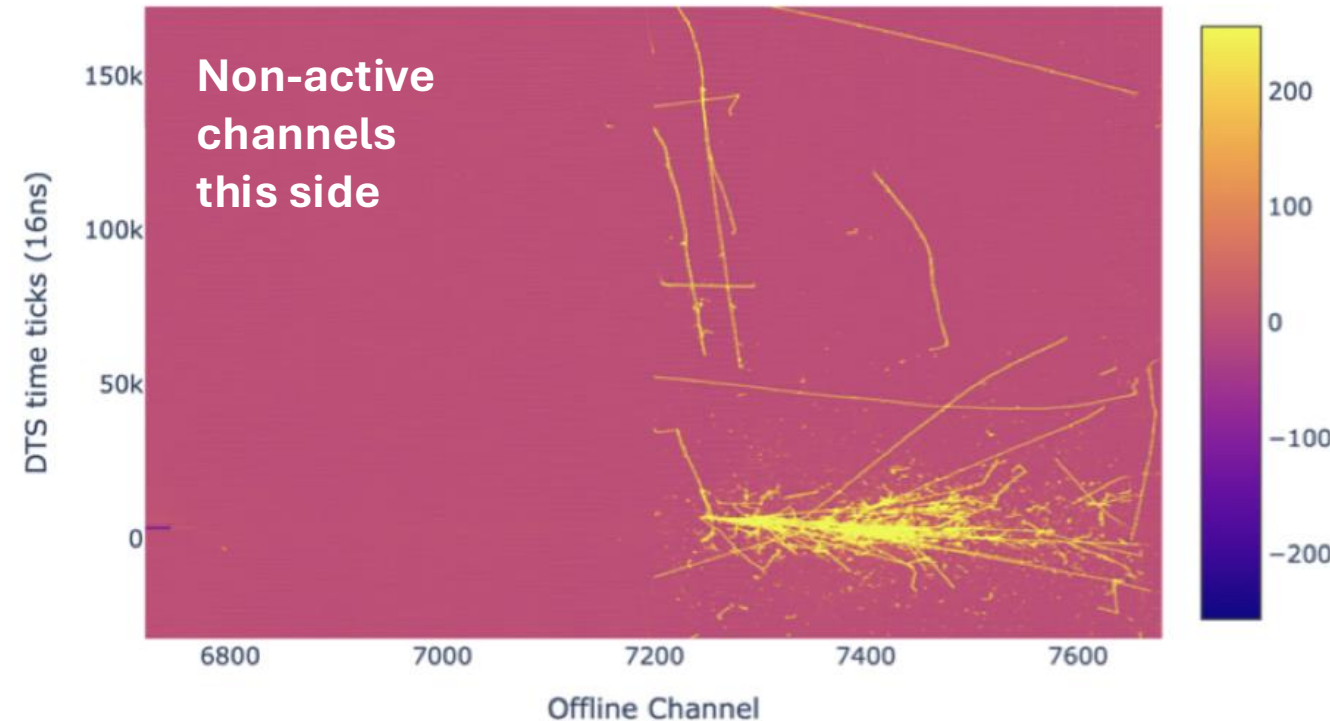
First Neutrino Candidates in Data

- Here is an identified **neutrino candidate**

- Identified by initial eye-scanning process by CERN Student Dario Pullia

- **Real data taken when the SPS beam spill was on**

- Forward-going shower with vertex within fiducial volume

Full collection view, total charge: 38681534.0

Deposited energy in ROI ~ 39 GeV

μ→

Represents a top-down view
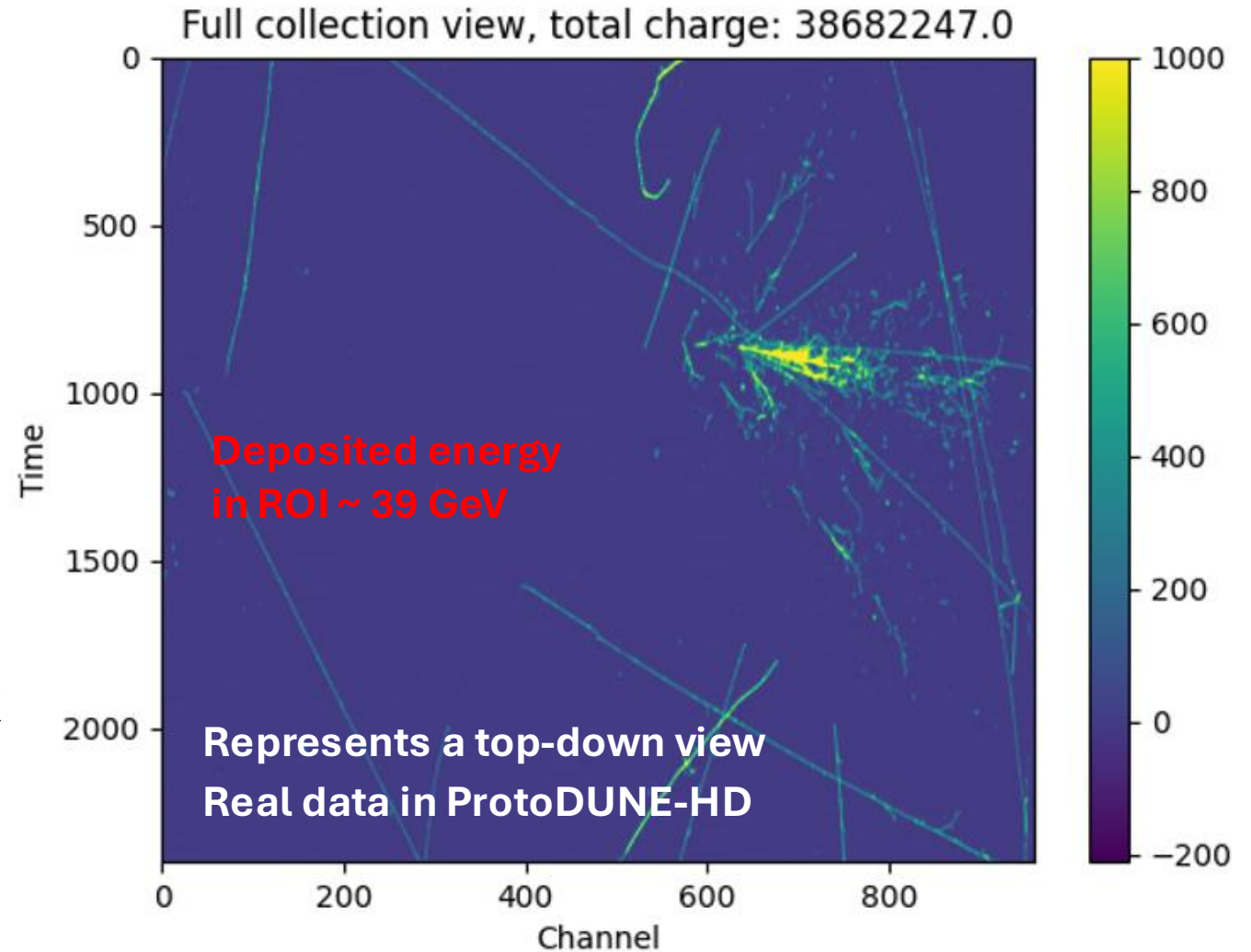Real data in ProtoDUNE-HD

First Neutrino Candidates in Data

- Here is another identified **neutrino candidate**

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- **Real data taken when the SPS beam spill was on**

- Forward-going shower with vertex within fiducial volume

Full collection view, total charge: 38682247.0

Deposited energy in ROI ~ 39 GeV

Represents a top-down view
Real data in ProtoDUNE-HD
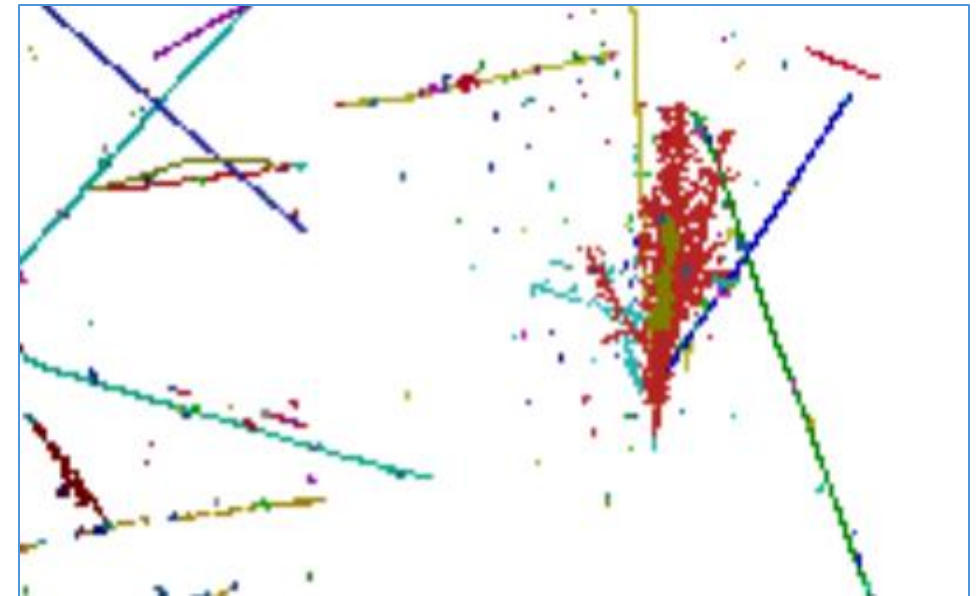
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Data Processing to Reconstruction

- End-to-end **data processing implemented**

- Data has been **reconstructed with Pandora** – analysis with cut-based neutrino selection near completion
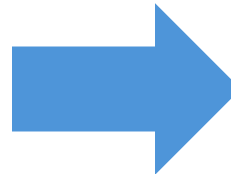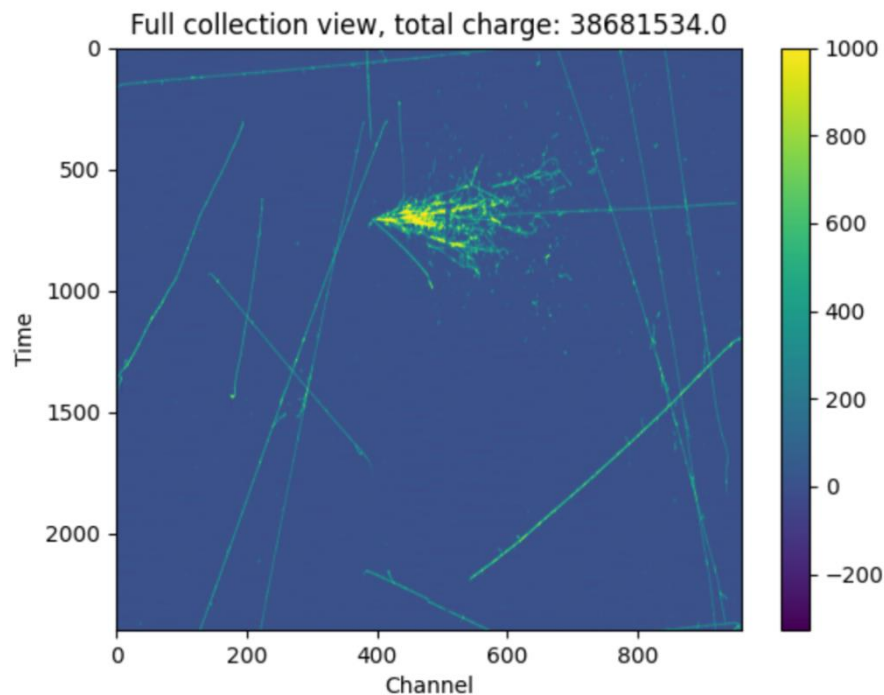
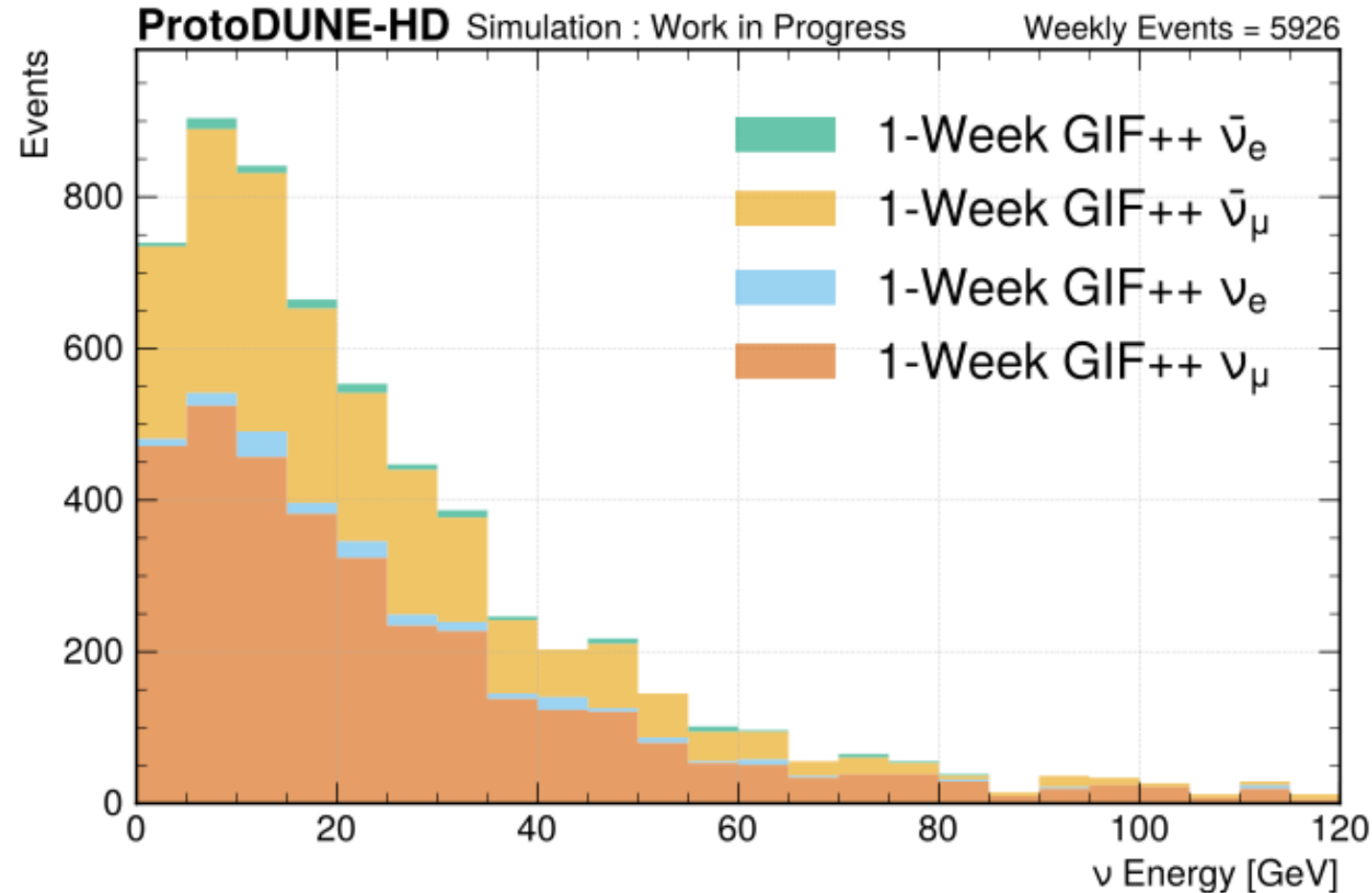

Real Pandora Reconstructed Data

Neutrino MC Event Simulation

- Neutrino flux passed to **GENIE** - neutrino interactions in a G4 model of ProtoDUNE-HD

- **Thousands of interactions in active volume per week**

	Weekly interactions		
Magnet Conf.	w000	w133	wNP04
ν_μ-^{40}Ar $-$ CC	2983	464	2597
ν_μ-^{40}Ar $-$ NC	955	150	823
$\overline{\nu_\mu}$-^{40}Ar $-$ CC	1248	305	1574
$\overline{\nu_\mu}$-^{40}Ar $-$ NC	495	121	615
Total	5681	1040	5609

J. Hernandez Garcia

Neutrino MC Event Simulation

- Neutrino flux passed to GENIE - neutrino interactions in a G4 model of ProtoDUNE-HD

- Simulated neutrinos with cosmic overlay **reconstructed with Pandora**
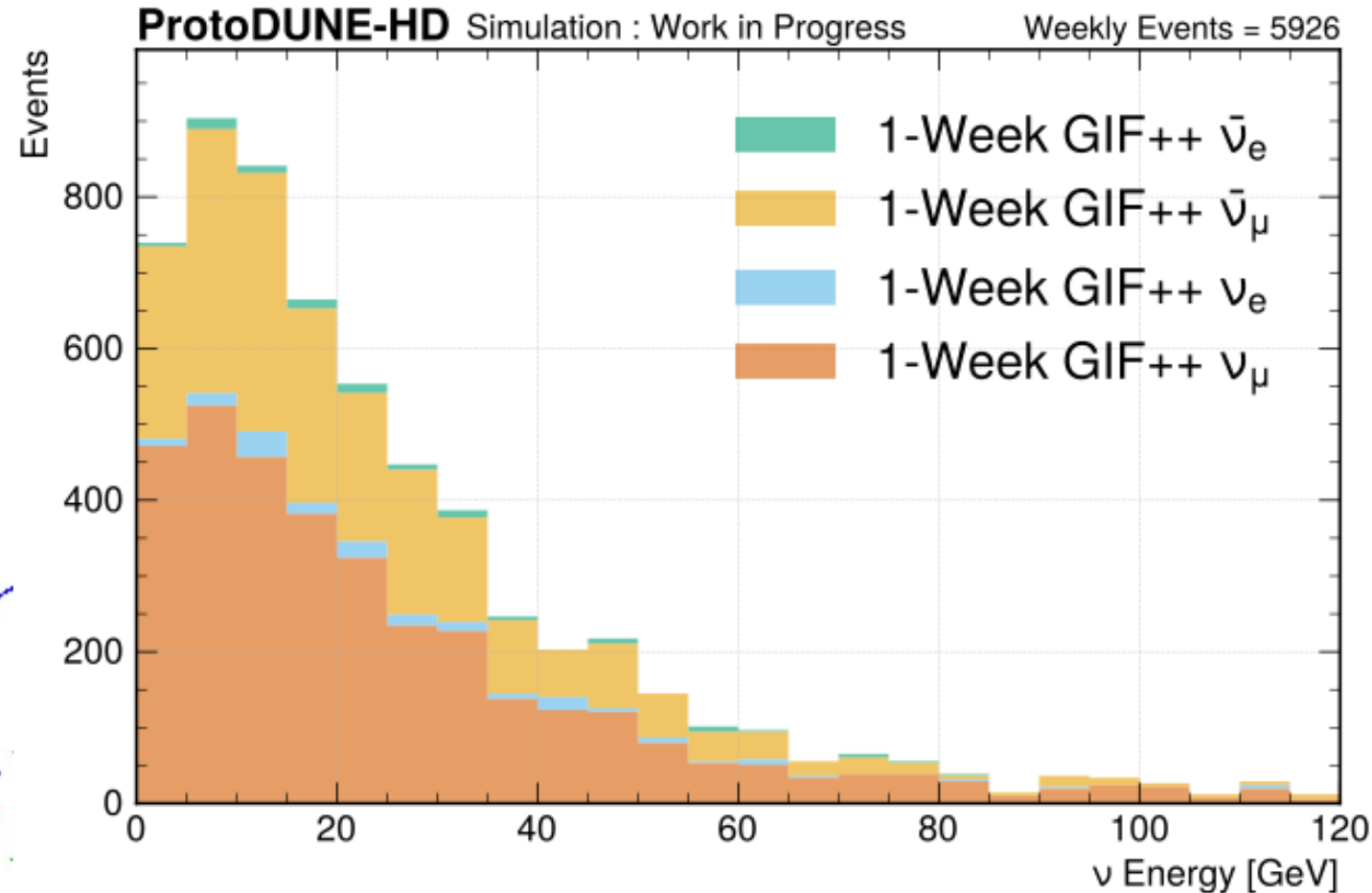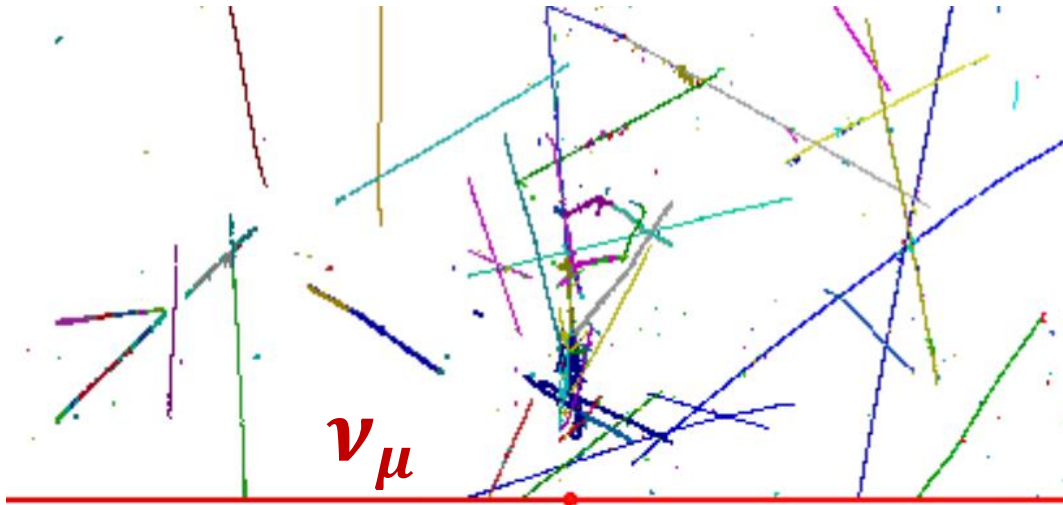
Estimate Rate of Triggering Neutrinos with Simulation

- Simulation has realistic detector and trigger simulation

- Estimate **proportion of neutrinos we trigger for**

- Same trigger algorithm simulated as used for data

- Achieve **~24% trigger efficiency** for ν and **E > 10 GeV**

- ~1400 triggering neutrinos per week with this magnet configuration
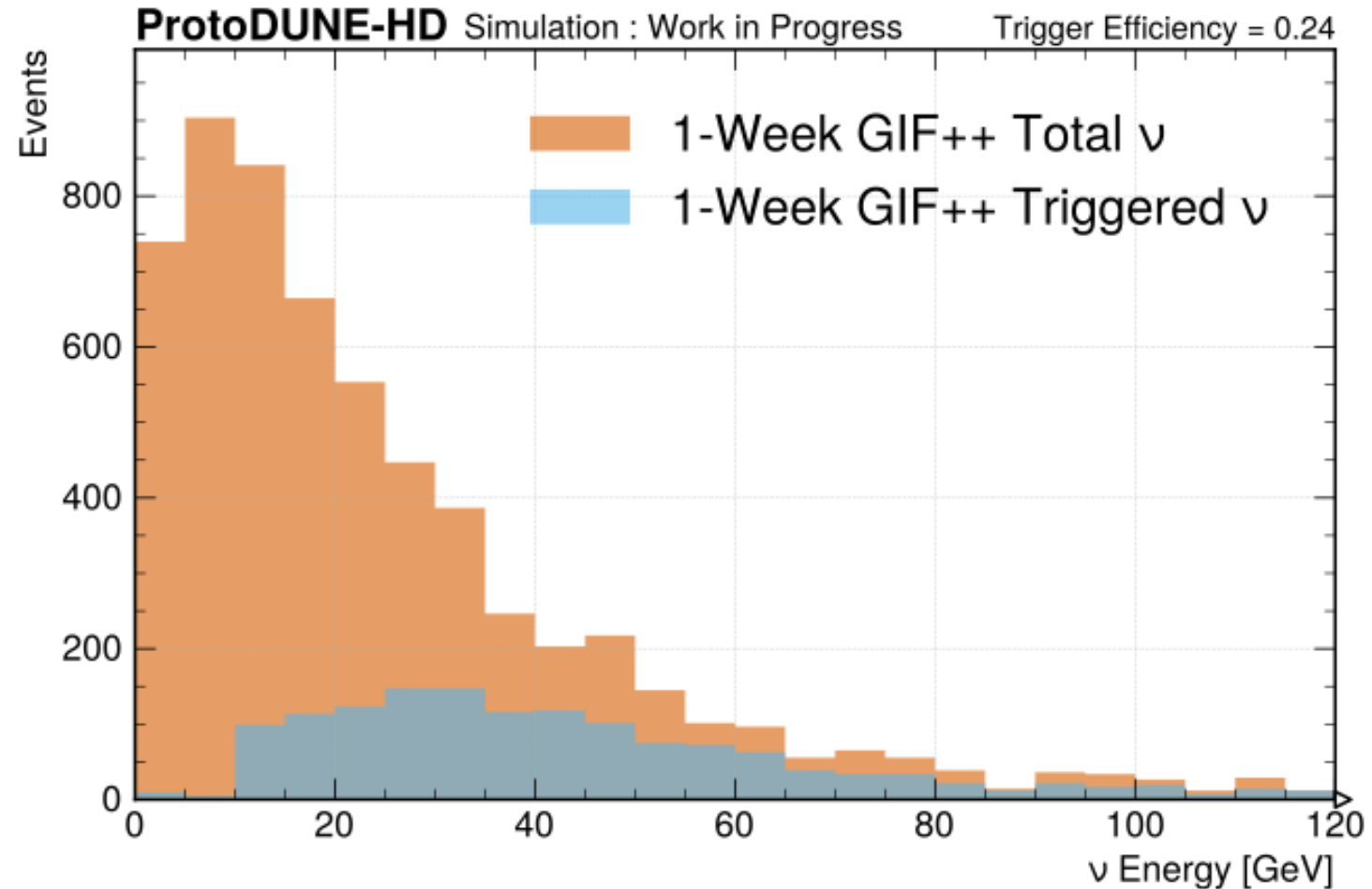
Analysis Strategy for ProtoDUNE-HD

- Trigger due to a cosmic muon **1-2 times per second**

- Trigger due to **neutrino once every few minutes** (depending on magnet configuration)
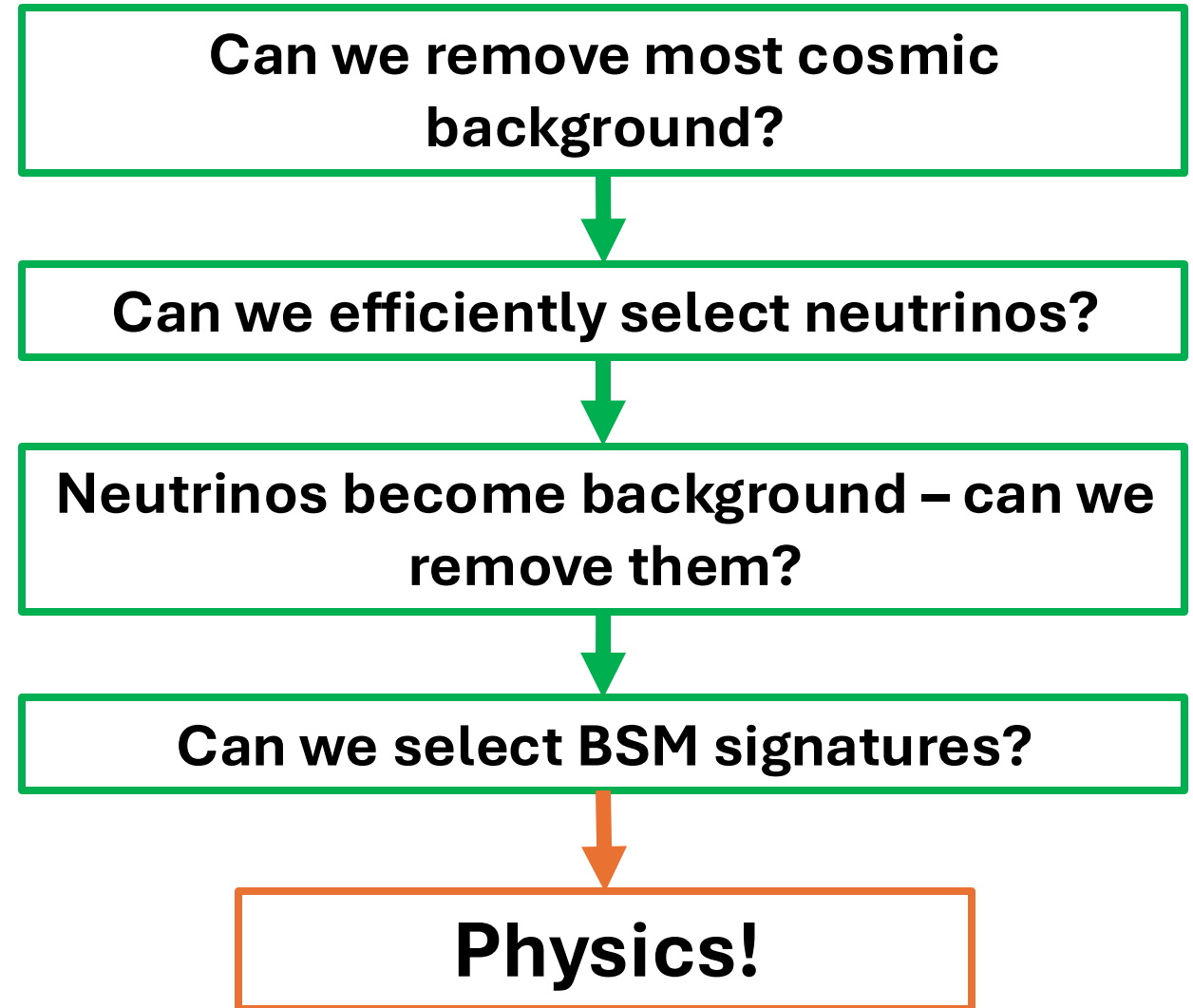
- First remove dominant cosmic background

- Measure our cosmic background rate from our **Spill OFF data**

Can we remove most cosmic background?

↓

Can we efficiently select neutrinos?

↓

Neutrinos become background – can we remove them?

↓

Can we select BSM signatures?

↓

Physics!

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Analysis Strategy for ProtoDUNE-HD

- Fortunately, neutrinos look quite **different from most cosmics**

- Event selection aims to show an **excess of beam-aligned high-energy showers** arising from a vertex

- Selection also under development to distinguish HNL decays from neutrinos

ν_μ

DEEP UNDERGROUND NEUTRINO EXPERIMENT
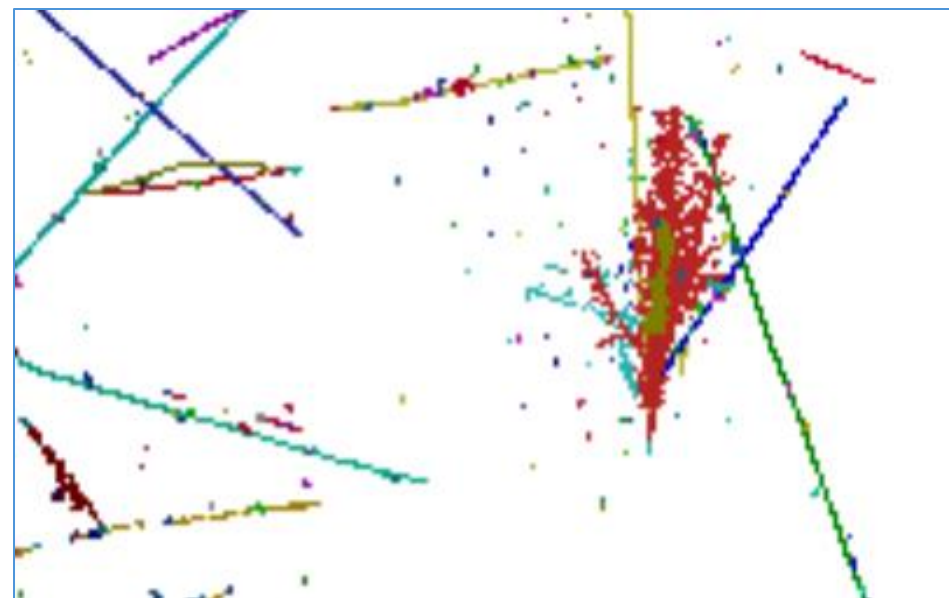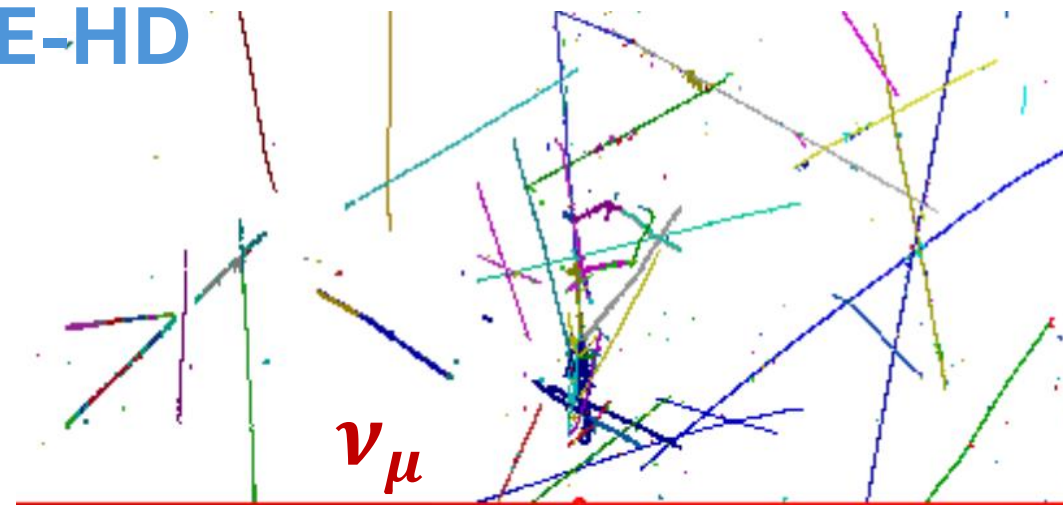
Looking to the Future – Vertical Drift

- Argon has been moved to **ProtoDUNE-VD** and is **taking data now**!

- Investigate searching for **neutrinos/BSM physics in NP02**

- Take data whilst the SPS is on

- Simulate neutrinos to estimate the rate

- Event selection to search for beam-aligned showers from a vertex

DEEP UNDERGROUND NEUTRINO EXPERIMENT
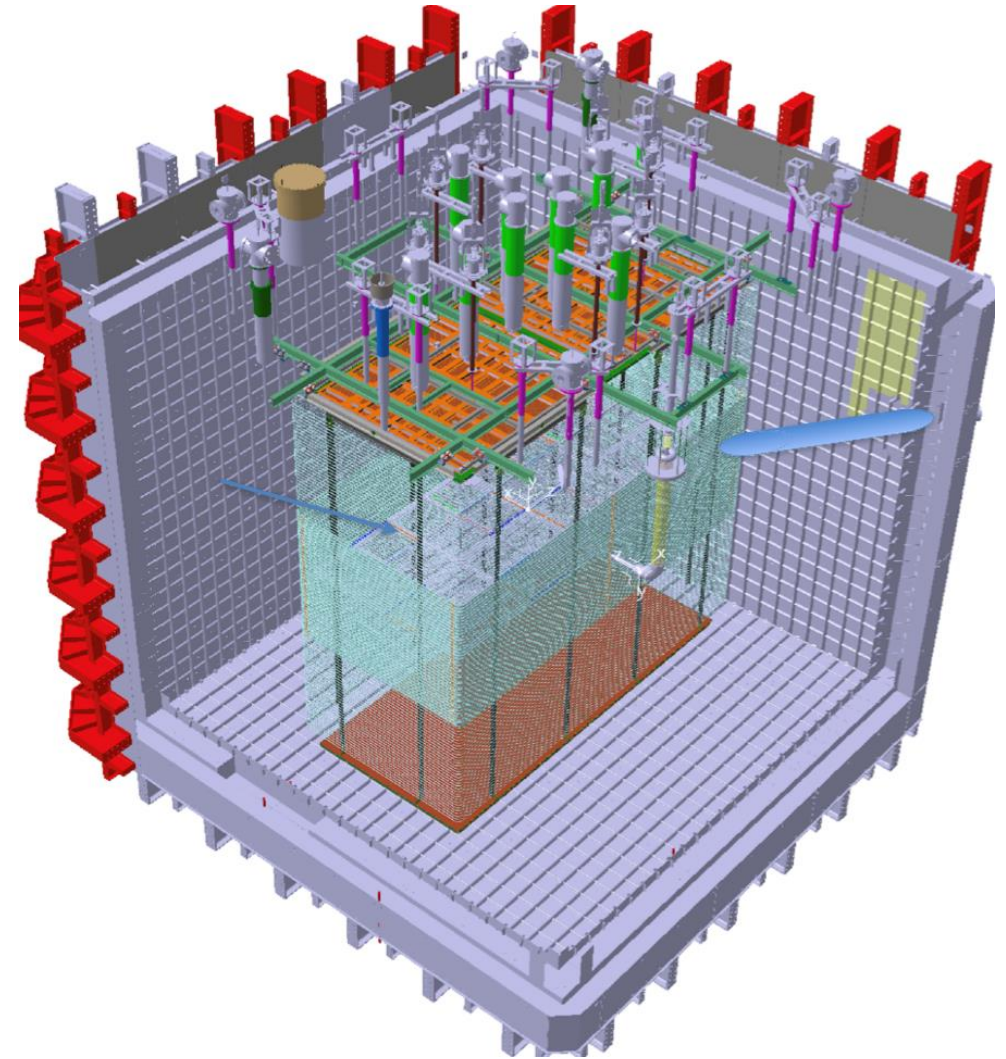
Looking to the Future – Vertical Drift

- Neutrino flux simulation repeated for ProtoDUNE-VD

- Similar position off-axis, but fiducial volume ~70% the size of ProtoDUNE-HD

- Still estimating **thousands of interaction in active detector volume per week of SPS beam**

- Expect similar trigger efficiency

- Developing an upgraded ML-based trigger algorithm
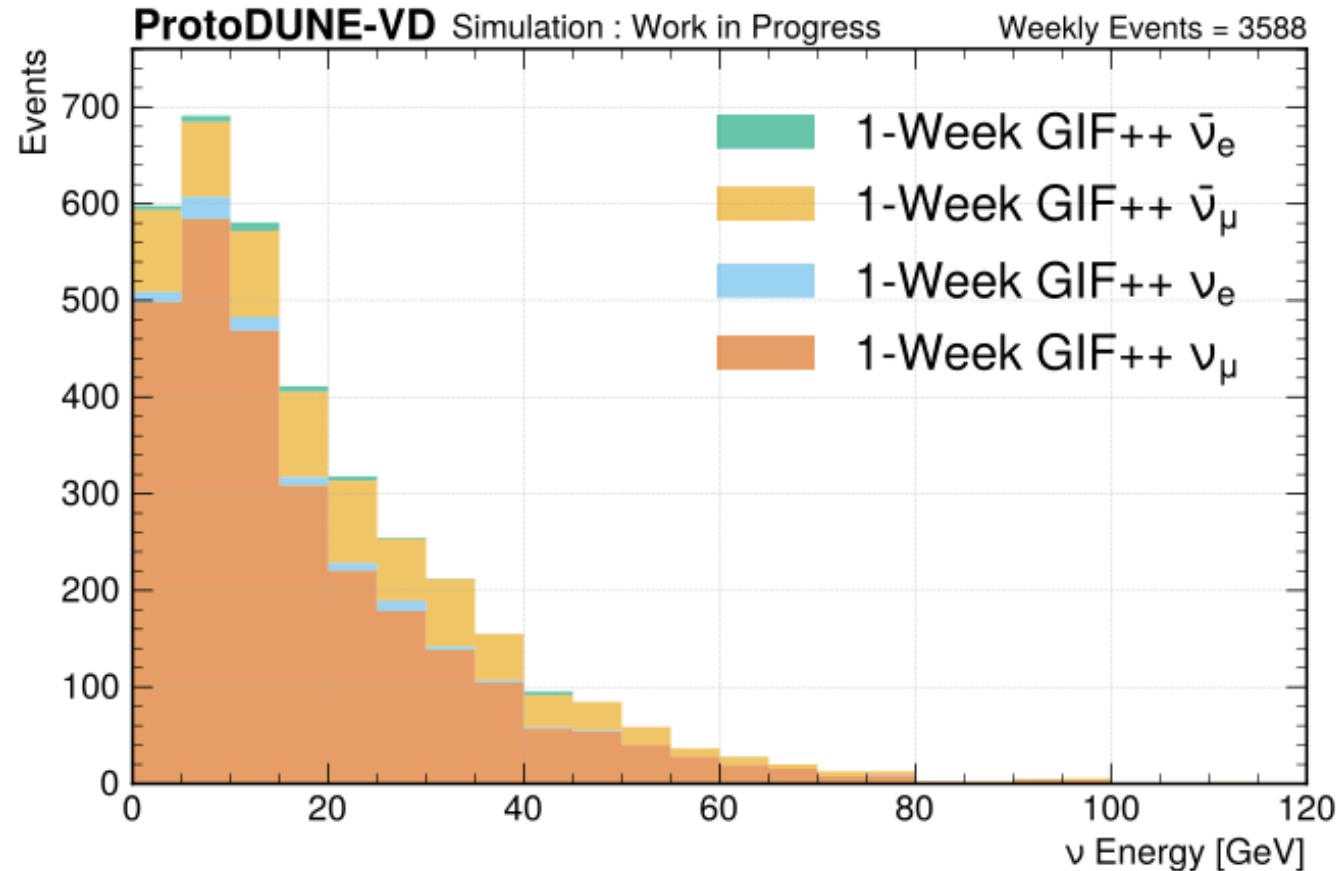
Conclusions

- Opportunity to search for neutrinos and BSM physics at ProtoDUNE detectors

- These searches can be run non-intrusively

- We have **~1 week of data** with at ProtoDUNE-HD – seen first neutrino candidates in ProtoDUNE!

- End-to-end **data processing for neutrino search complete**

- End-to-end **neutrino simulation complete**

- Aim to neutrino search analysis first as a **proof-of-principle of a future BSM program**

- Large sample of neutrinos in a DUNE FD-like detector very useful for testing energy reconstruction methods for the future FD

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

CERN

Thank you for listening!
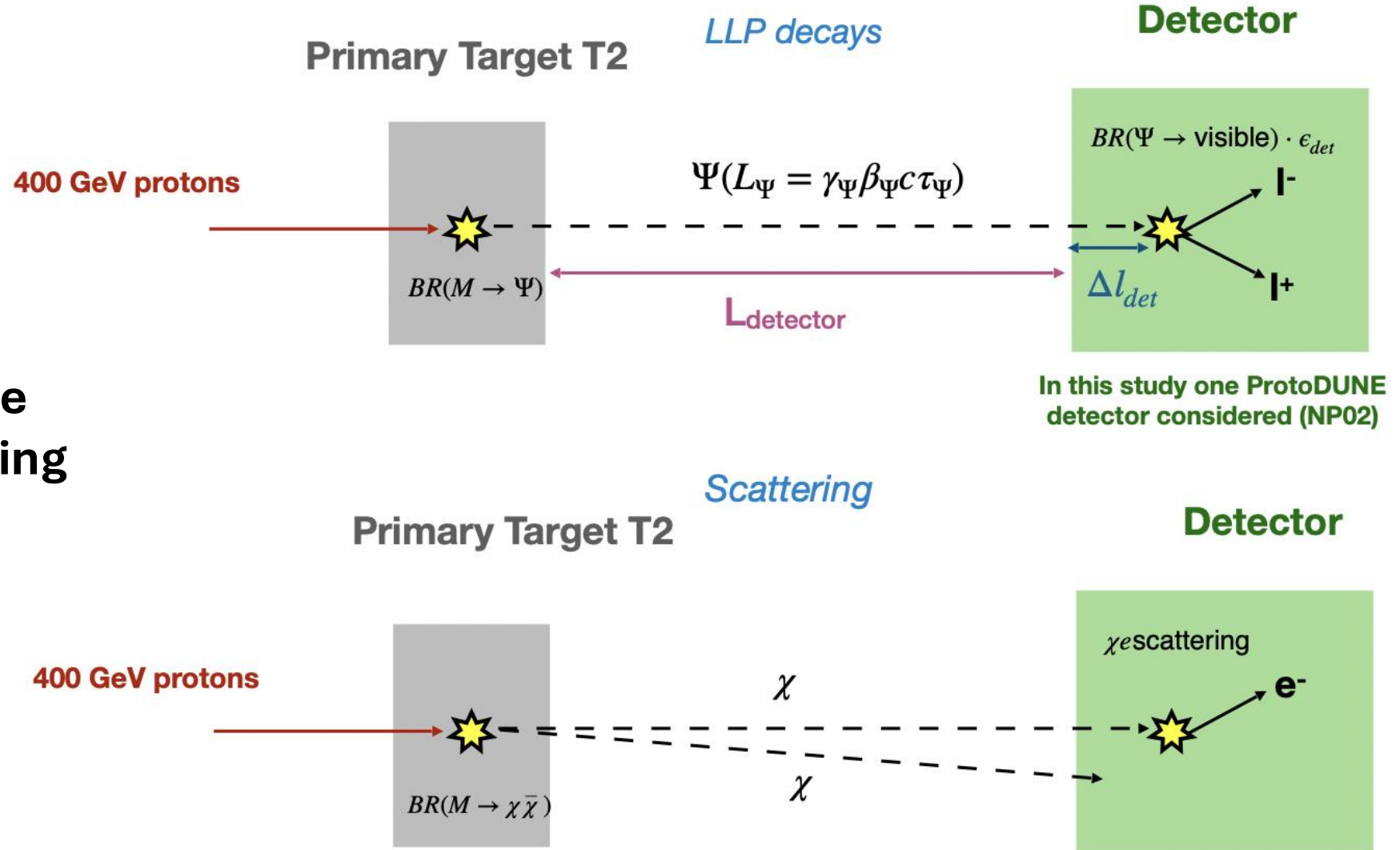
The ProtoDUNE-BSM Group:

H. Amar, C. Andreopoulos, A. Chatterjee, S. Bianco, E. van Campenhout, P. Coloma, A. De Roeck, G. Gurung, C. Hasnip, J. Hernández García, W. Ketchum, F. Lanni, J. López-Pavón, J. Martin-Albo, L. Molina-Bueno, O. Palamara, J. K. Plows, F. Pietropaolo, D. Pullia, F. Resnati, P. Sajitha, H. Sieber, C. Touramanis, S. Urrea

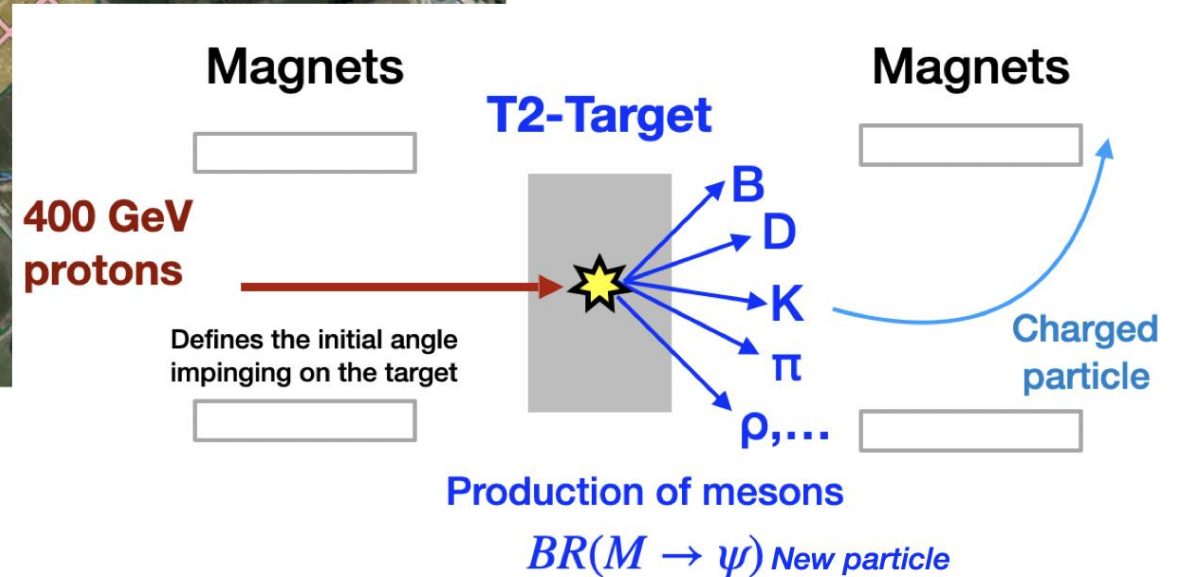DEEP UNDERGROUND
NEUTRINO EXPERIMENT

CERN

Backup

Could investigate decay or scattering channels

LLP decays

Primary Target T2

Detector

400 GeV protons

$\Psi(L_\Psi = \gamma_\Psi \beta_\Psi c \tau_\Psi)$

$BR(M \to \Psi)$

$BR(\Psi \to \text{visible}) \cdot \epsilon_{det}$

l⁻

l⁺

Δl_{det}

L$_{detector}$

In this study one ProtoDUNE detector considered (NP02)

Scattering

Primary Target T2
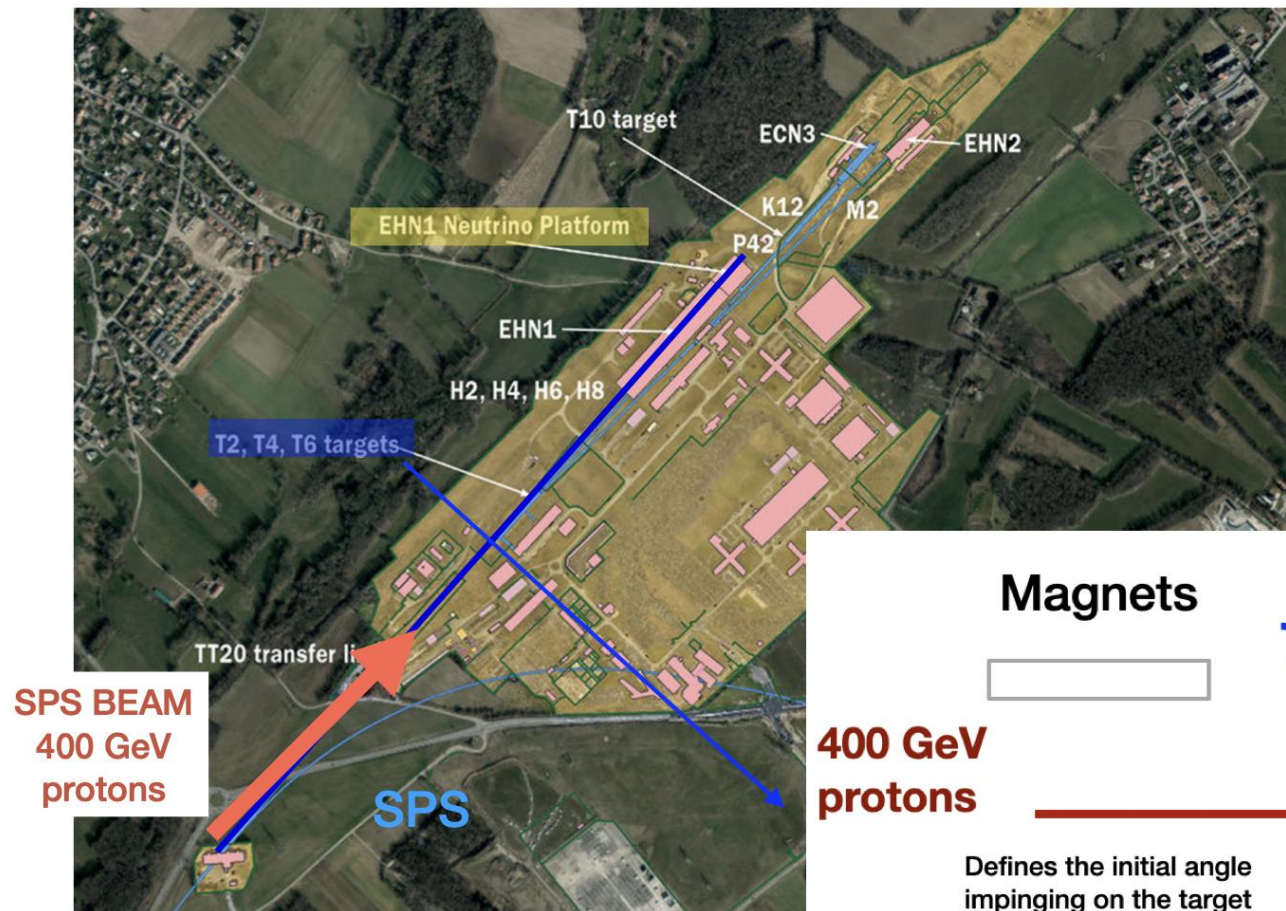
Detector

400 GeV protons

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

χ

χ

χescattering

e⁻

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

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Backup

Magnets

T2-Target

400 GeV protons

B

D

K

π

ρ,…

Charged particle

Magnets

Defines the initial angle impinging on the target

Production of mesons

$BR(M \rightarrow \psi)$ *New particle*

The current on these magnets depend on H4/H2 user
They are called "wobbling"

SPS BEAM 400 GeV protons

SPS

SPS BEAM 400 GeV protons

DEEP UNDERGROUND NEUTRINO EXPERIMENT

# Backup: Possible Schedule for BSM Program
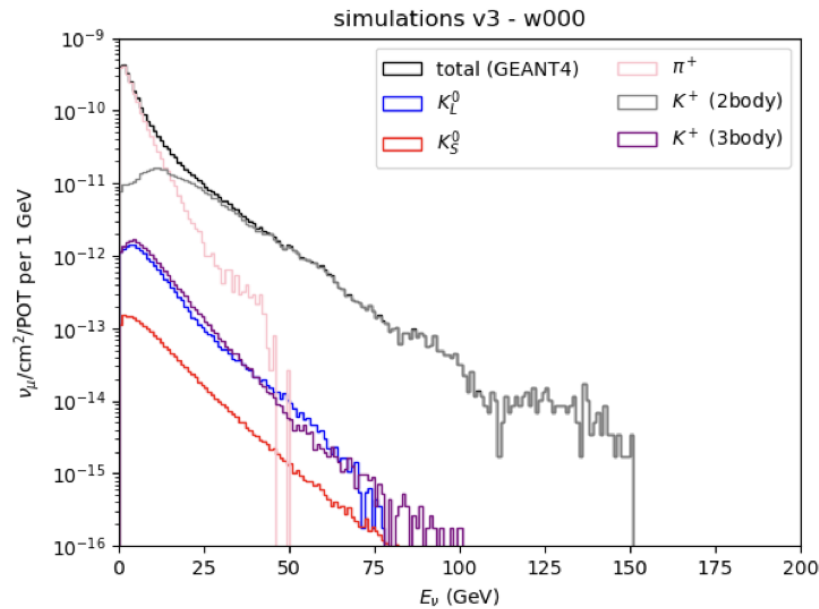
- Run parasitically at SPS (not interfering with other experiments at H4/H2)
- Proton run at SPS can be up to 6 months depending on the year
- We consider 5 years to collect 1.75×10^{19} POT

From: http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm
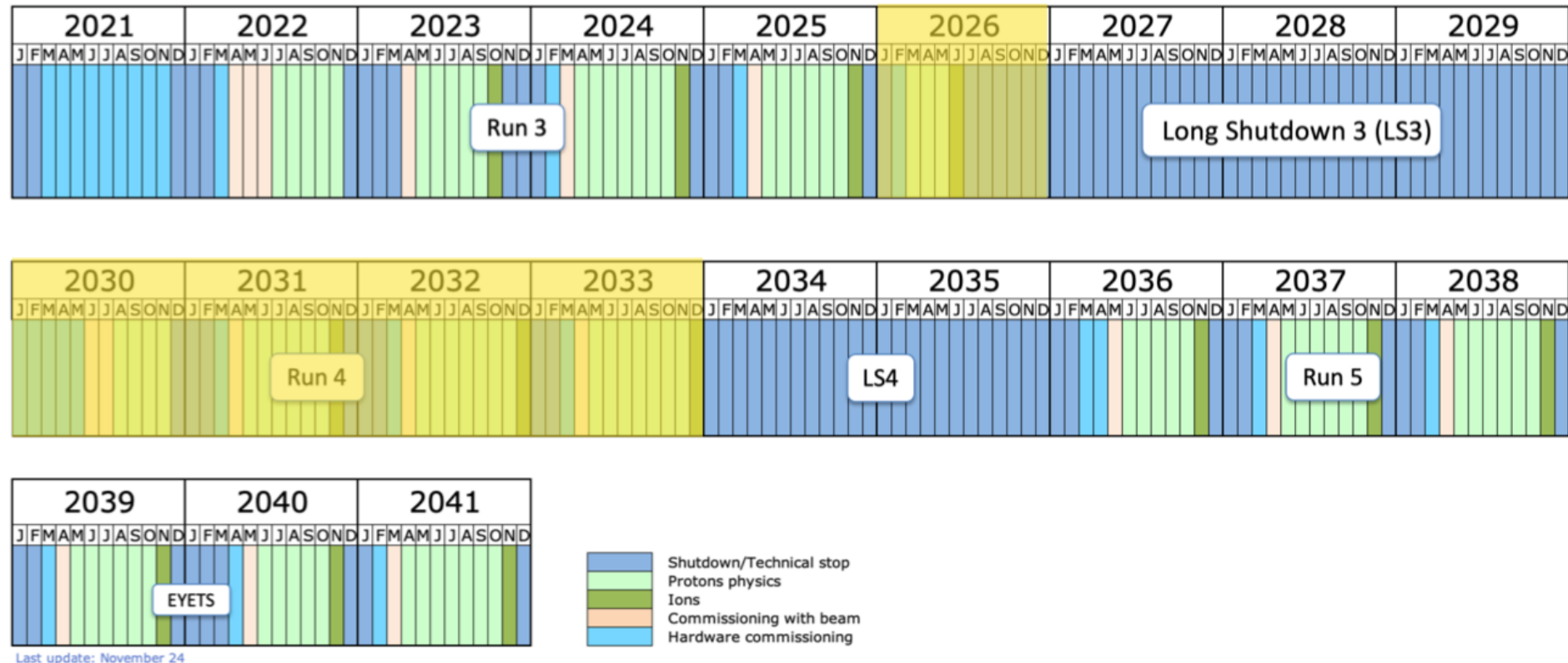
Backup: Possible Schedule for BSM Program

- Separate neutrino flux simulation for each magnet wobbling configuration
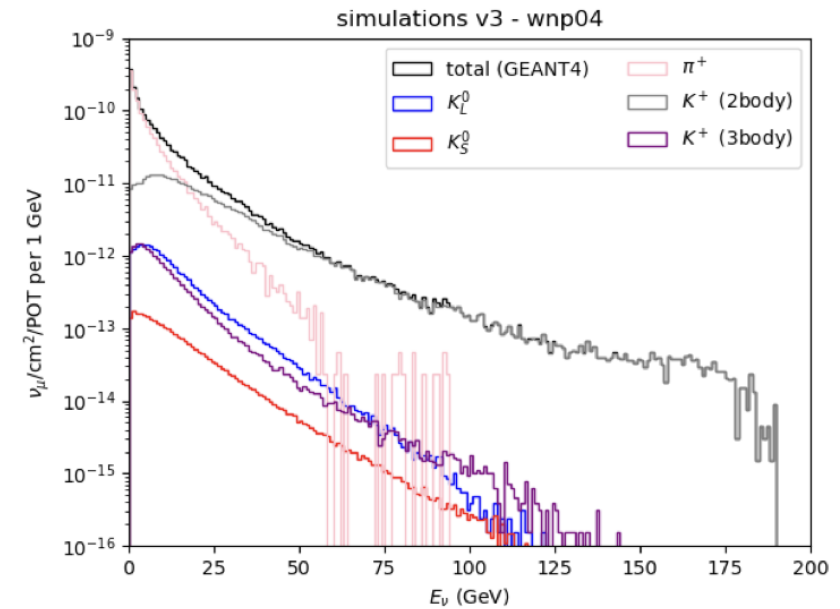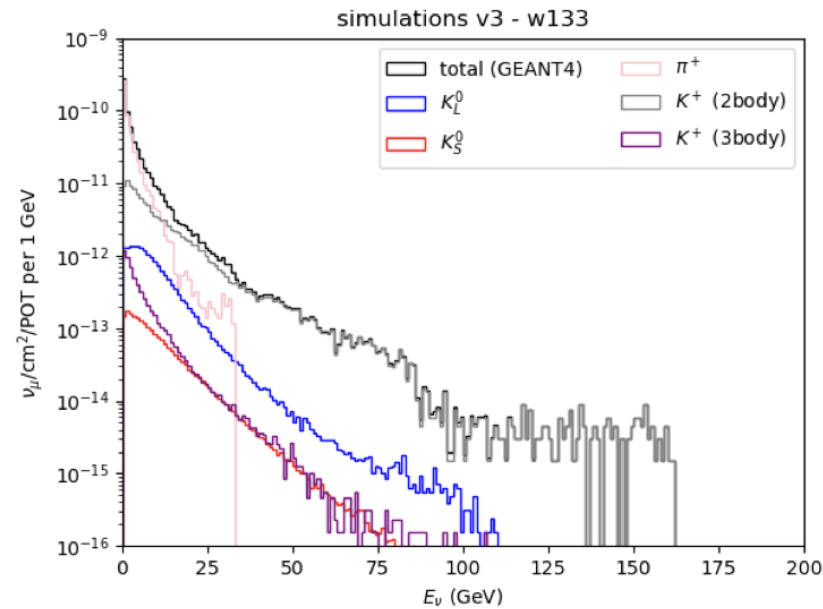
Data Processing Procedure

- End-to-end **data processing implemented** and running through to fully reconstructed events

- Reconstruction uses **FD neutrino pandora + PD-HD cosmic tagging**

- Produce a flag for whether SPS spill was ON/OFF

- Filter for **ground shake removal**

- 1 week of data processed to reconstruction and cut-based analysis on-going

Final

Raw Data

↓

Produce Boolean flag for Spill ON/OFF

↓

Trigger raw decoder (get TP/A/C in art format)

↓

Filter to remove ground shakes

↓

TPC raw decoder (get RawDigits)

↓

Timing raw decoder (get RDTimeStamps)

↓

Noise removal, hit finding, pandora ...

↓

Reconstructed Data

DEEP UNDERGROUND NEUTRINO EXPERIMENT