Constraining Neutrino interaction uncertainties with the SAND detector at DUNE

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Outline

In this presentation:

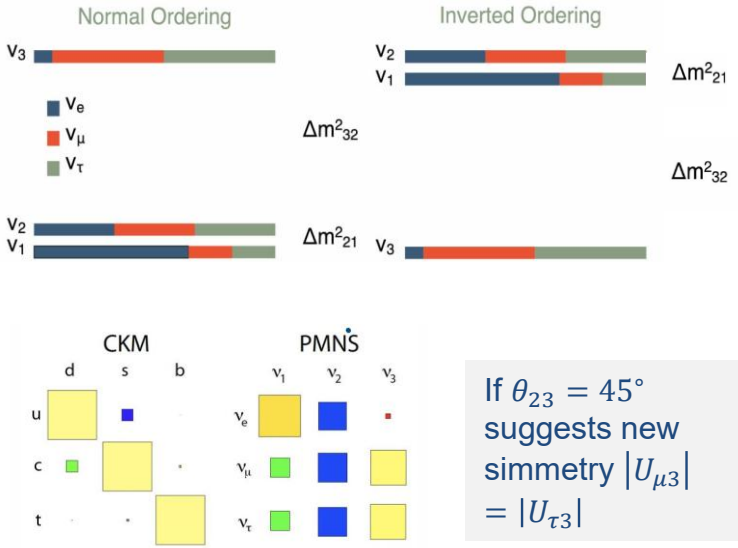
- Overview of the **DUNE experiment**, its physics goals, scope and composition
- Overview of the **SAND Near Detector**
- Introduction to the '**Solid Hydrogen**' technique in SAND: obtain a sample of neutrino interactions on hydrogen, devoid of nuclear effect systematics, by statistical subtraction
- Preliminary results from a 'Solid Hydrogen' **flux measurement study** in the $\bar{\nu}_\mu$ **CCQE channel**

Neutrino physics: Open questions

- Mass-less in the Standard Model
- Evidence of flavour oscillations

→ **Mass** **Mixing**

- Many **open questions** still exist:
  - What is the neutrino mass ordering?
  - Is there leptonic CP violation?
  - Is θ_{23} mixing maximal?
  - Is the PMNS matrix unitary?
  - What is the neutrino absolute mass scale?
  - Are neutrinos Majorana particles?

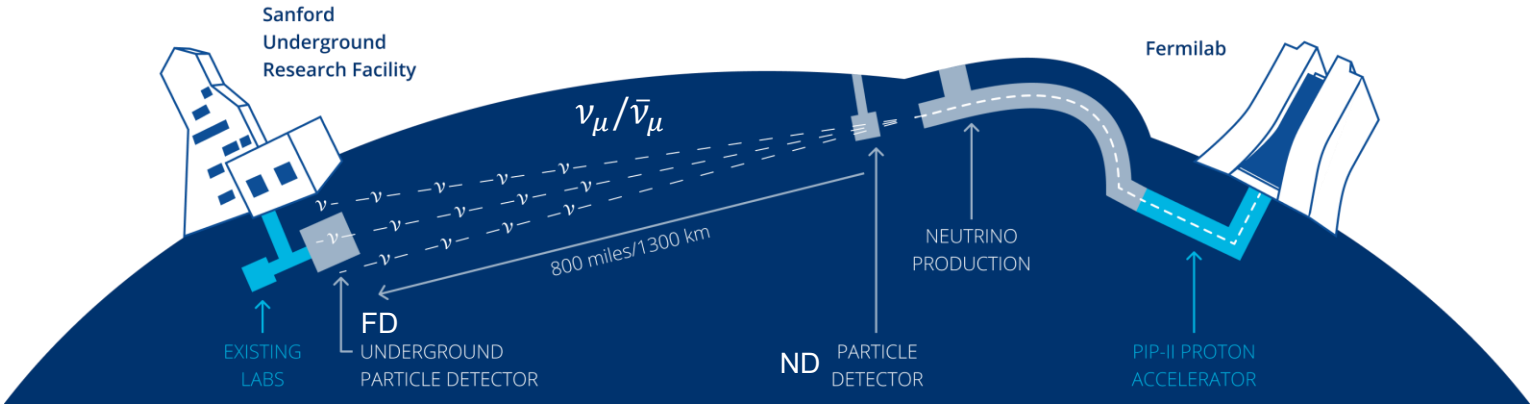


If $\theta_{23} = 45°$ suggests new simmetry $|U_{\mu 3}| = |U_{\tau 3}|$

Can be investigated in oscillation experiments

Need other dedicated experiments

The Deep Underground Neutrino Experiment



A new generation Long Baseline – 1300 km – neutrino oscillation experiment based on:

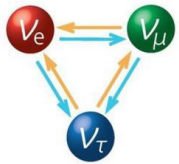
- a wide band high intensity (1.2 MW upgradable to 2.4 MW) $\nu/\bar{\nu}$ neutrino beam produced at Fermilab
- a large total mass (~70 kton) Far Detector at the Sanford Underground Neutrino Facility (SURF) 1.5 km underground exploiting the Liquid Argon Time Projection Chamber (LArTPC) technology
- a Near Detector complex (ND) at Fermilab providing control of systematic uncertainties, enabling a rich physics program

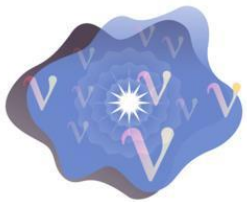
DEEP UNDERGROUND NEUTRINO EXPERIMENT

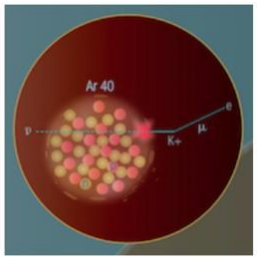
- 1300+ collaborators
- 36 countries
- 200+ institutions including CERN

DUNE Collaboration Meeting, CERN January 2023

DUNE's Physics program







Long-baseline wide-band neutrino beam

- Measurement of CP violation phase, mixing angles and neutrino mass ordering in a single experiment using spectral information

Underground location → access to astrophysical neutrinos

- Supernova neutrino burst detection–sensitive to the ν_e component
- Atmospheric neutrino – capability of ν_τ identification
- Solar neutrinos – potential for detection of hep flux

Massive detectors with tracking and calorimetric information

- Search for baryon number violating processes – $p \to \nu K^+, n\bar{n}$

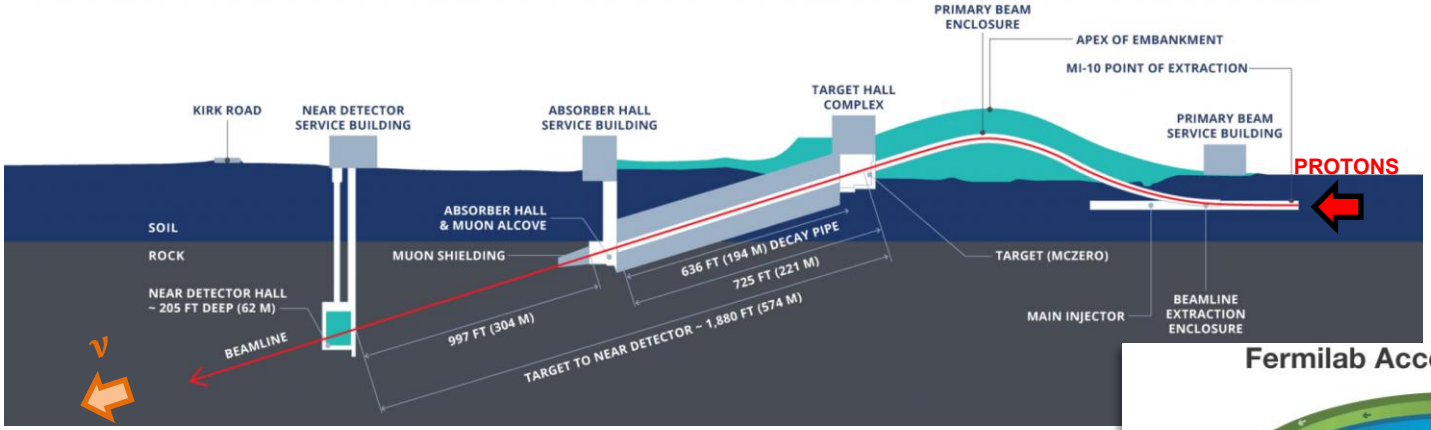
Long baseline + higher energy neutrino beam

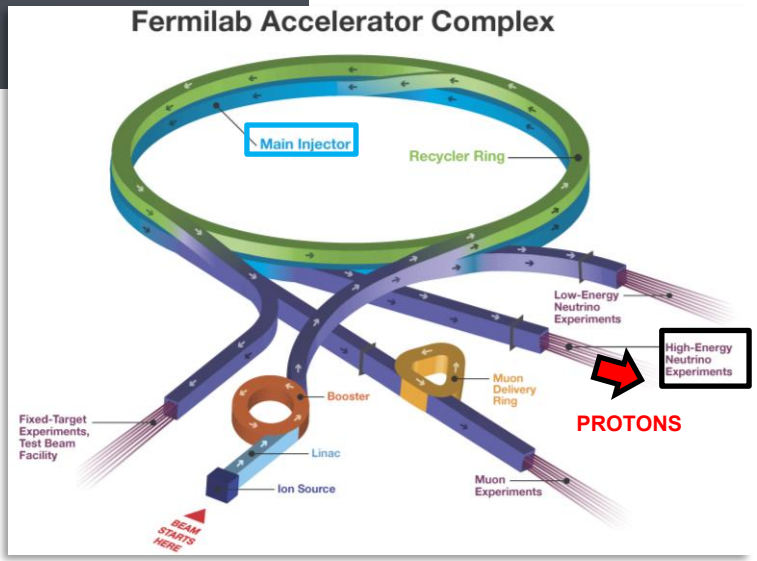
- ν_τ appearance, NSI searches

Capable Near Detector Complex

- Precise neutrino physics (cross sections, nuclear effects)
- BSM searches

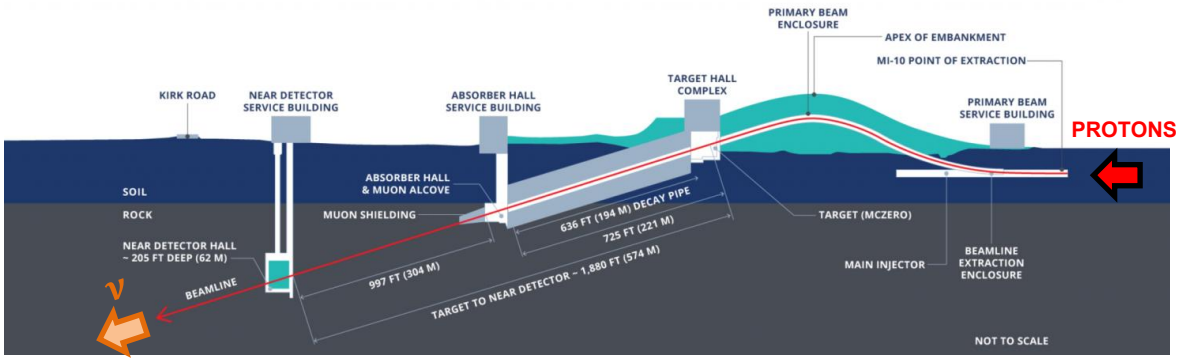
The LBNF beam

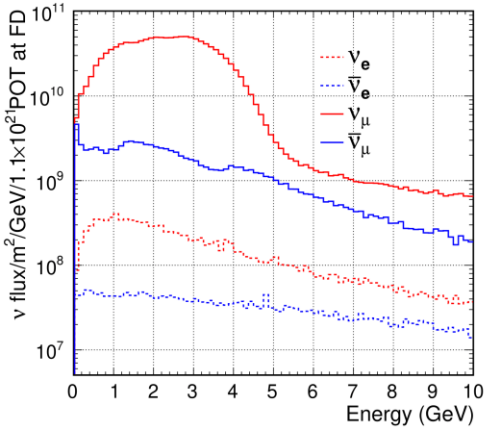




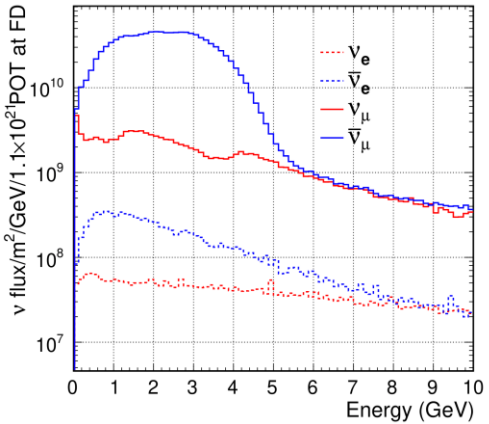
- LBNF will use accelerated protons from the Main Injector: start at 1.2 MW (Phase I) and then upgraded to 2.4 MW (Phase II)
- Primary proton beam (60-120 GeV) on a graphite target at 5.8° slope: $(1.1 - 1.9)10^{21}\frac{pot}{yr}$

The LBNF beam





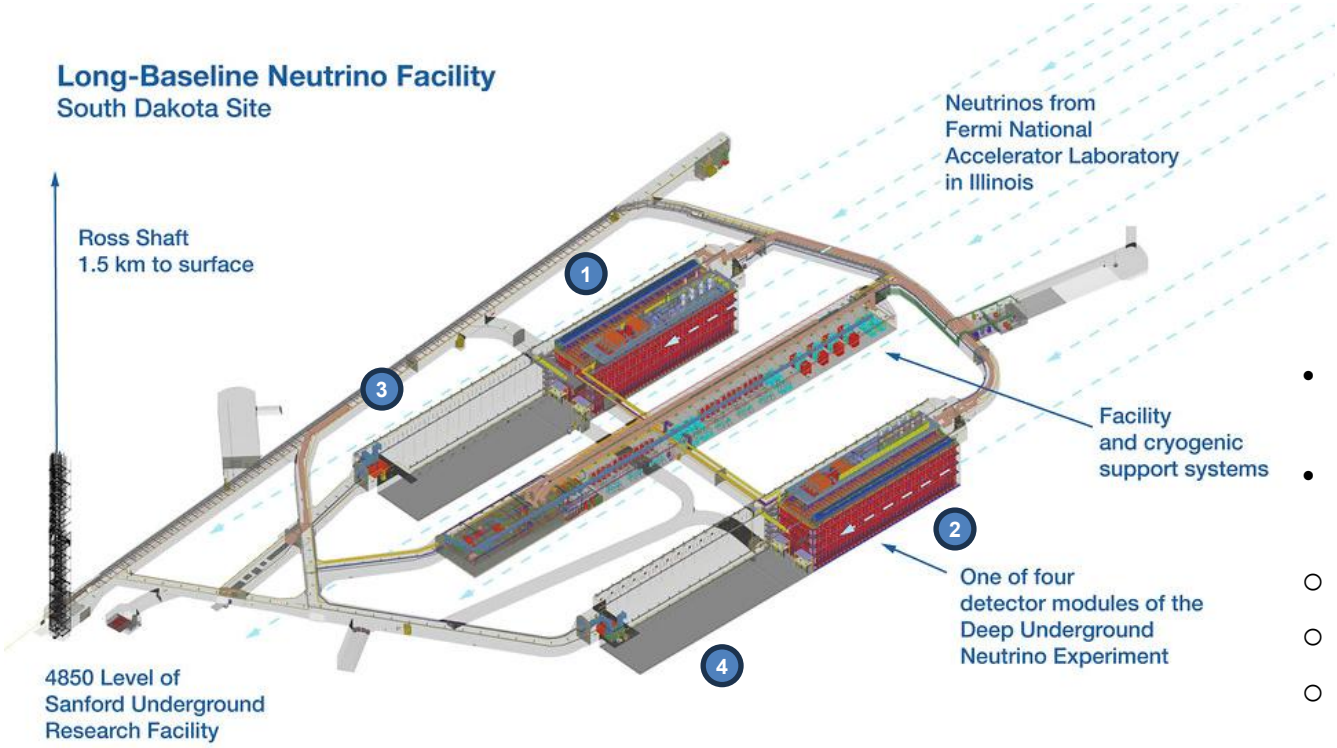
FHC
ν-mode

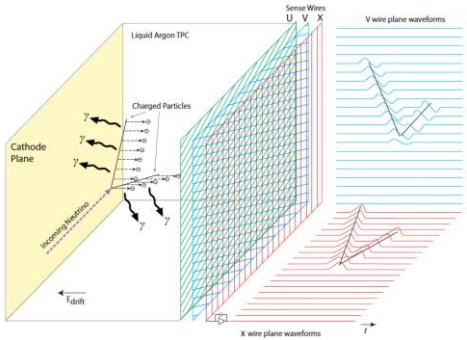


RHC
$\bar{\nu}$-mode

- LBNF will use accelerated protons from the Main Injector: start at 1.2 MW (Phase I) and then upgraded to 2.4 MW (Phase II)
- Primary proton beam (60-120 GeV) on a graphite target at 5.8° slope: $(1.1 - 1.9)10^{21}\frac{pot}{yr}$
- Forward Horn Current (FHC): neutrino enhanced
- Reverse Horn Current (RHC): antineutrino-enhanced

The Far Detector Complex at SURF





LArTPC: best particle imaging at kton scale

- Sanford Underground Research Facility in Lead, South Dakota
- 4 x 17-kt LAr TPC modules, located 1.48 km underground
  - **FD1** – Horizontal Drift LArTPC
  - **FD2** – Vertical Drift LArTPC
  - Phase-2 - **FD3** (decision 2027) - **FD4** module of opportunity (decision 2028)

The Far Detector Complex at SURF

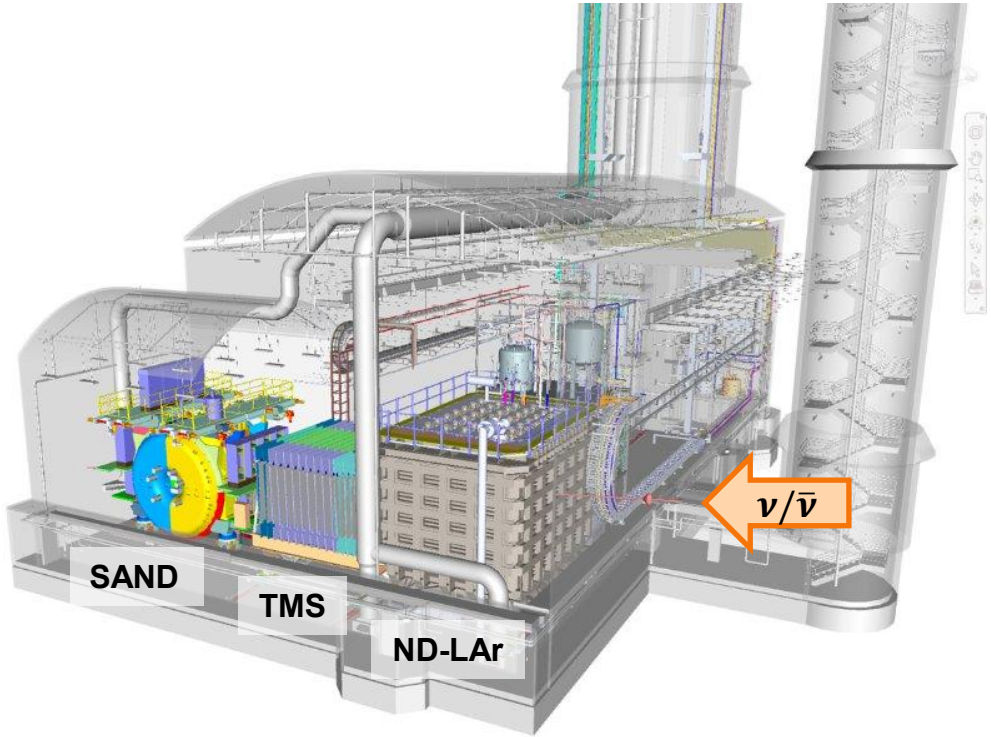
Caverns excavations completed in 2024 on budget and on-schedule!

The Near Detector Complex

ND Hall : 574 m from LBNF target
60 m underground

Configuration (Phase I):

- **ND-LAr:** 7 x 5 array of modular 1x1x3 m^3 LArTPC with pixel readout
- **TMS:** Magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
- **DUNE-PRISM: ND-LAr + TMS** move up to 28.5 m off-axis to access narrow neutrino spectrum
- **SAND:** On-axis magnetized neutrino detector

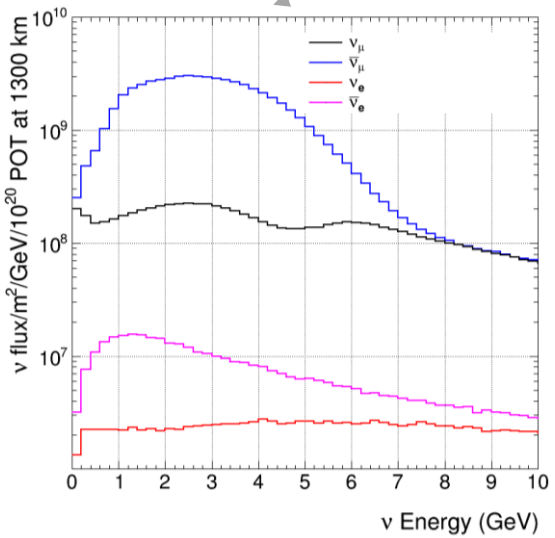


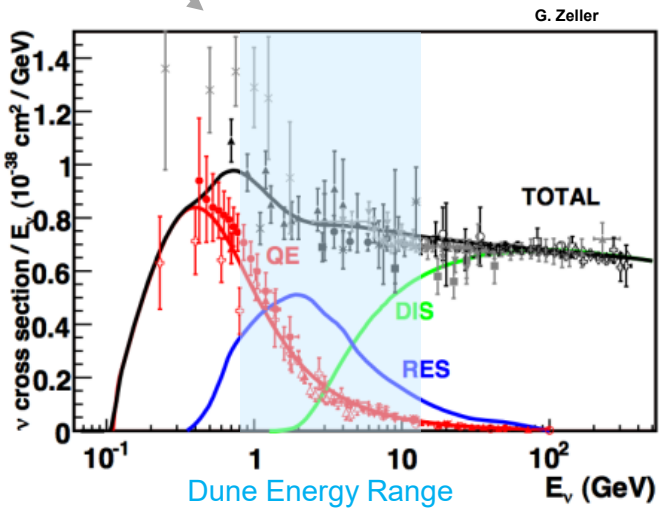
What do we actually measure?

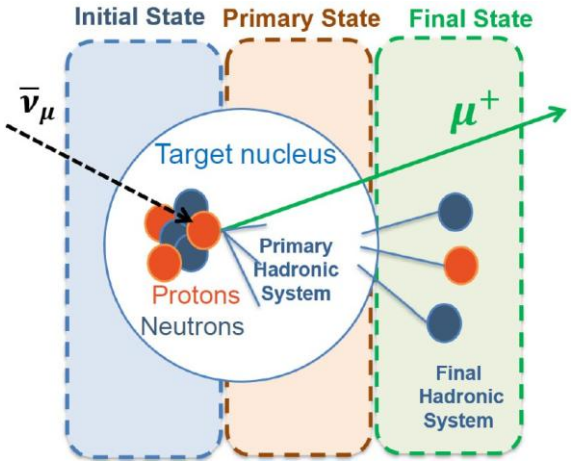
The **number of events N_x** at the Near/Far Detector for a process x, which is given by:

$$N_x(E_\nu) = \int P_{osc}(E_\nu)\, \Phi_{\bar{\nu}}\, \sigma_x(E_\nu)\, R_{phys}(E_\nu, E_{vis})\, \underline{R_{det}\,(E_{vis}, E_{rec})}\, \underline{\epsilon_x\,(E_{rec})}\, dE_\nu$$

Neutrino **flux** | **cross section** | **nuclear smearing** | **detector response** | **selection efficiency**







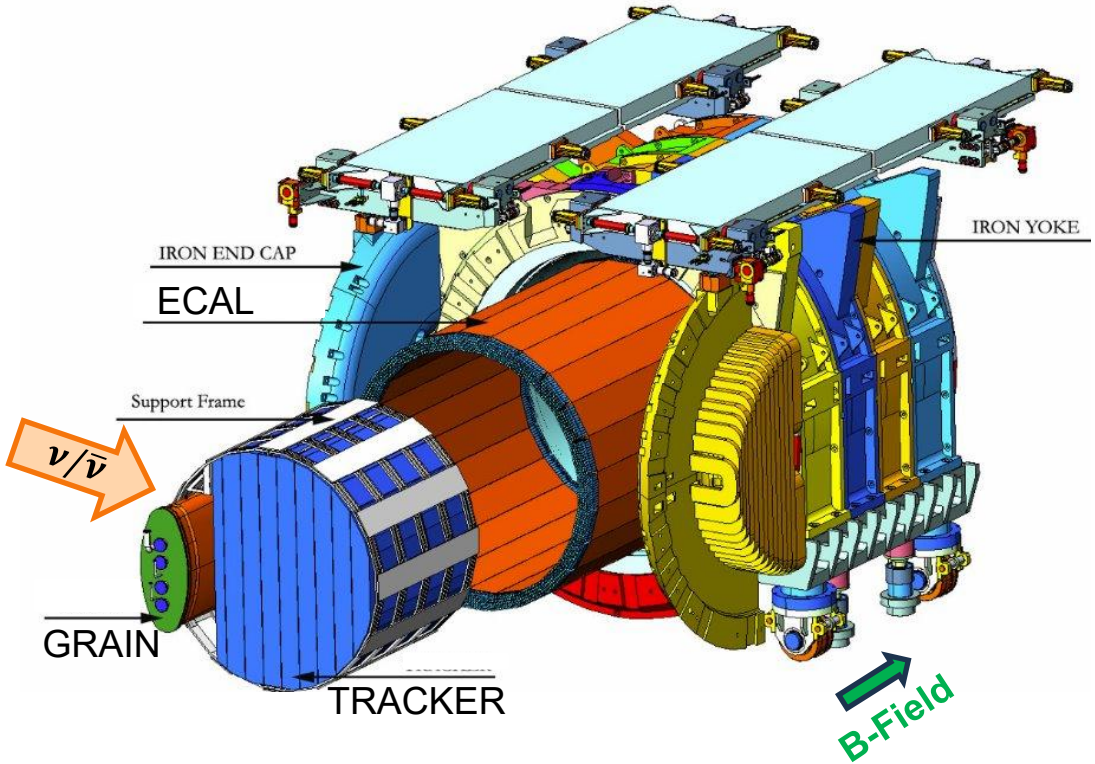
‘Solid’ hydrogen concept

- Neutrino-hydrogen interactions are **free from nuclear effects** and thus are devoid of a major source of systematic uncertanties: $R_{phys}(E_\nu, E_{vis}) \equiv 1$
- It has been proposed that by using a neutrino detector that **alternates dedicated targets** of graphite (C) and polypropylene (C_3H_6), a sample of interactions on hydrogen can be obtained by **statistical subtraction**.
  - *“A Novel Approach to Neutrino-Hydrogen Measurements” H. Duyang, B. Guo, S.R. Mishra and R. Petti, https://doi.org/10.48550/arXiv.1809.08752*
- Selecting for a channel on Hydrogen for which the cross section is know, it should be possible to produce a **flux measurement unaffected by nuclear effect systematics**

The SAND detector tracker has been specifically designed to take advantage of this technique

The SAND (System for on-Axis Neutrino Detection)

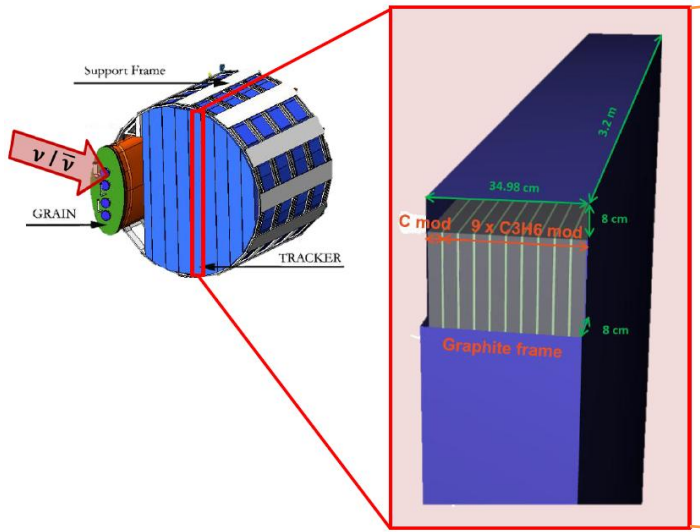
- Solenoidal cryogenic magnet
  - Yoke of 475 t
  - **B field** of 0.6 T
- **Electromagnetic sampling calorimeter:**
  - 24 barrels modules of scintillating fibers and lead reused from KLOE
- Tracking system:
  - **Modular** and **low density** of about 5 t mass with overall 1 radiation length
- GRAIN (GRanular Argon for Interactions of Neutrinos)
  - 1 t liquid **argon** active target



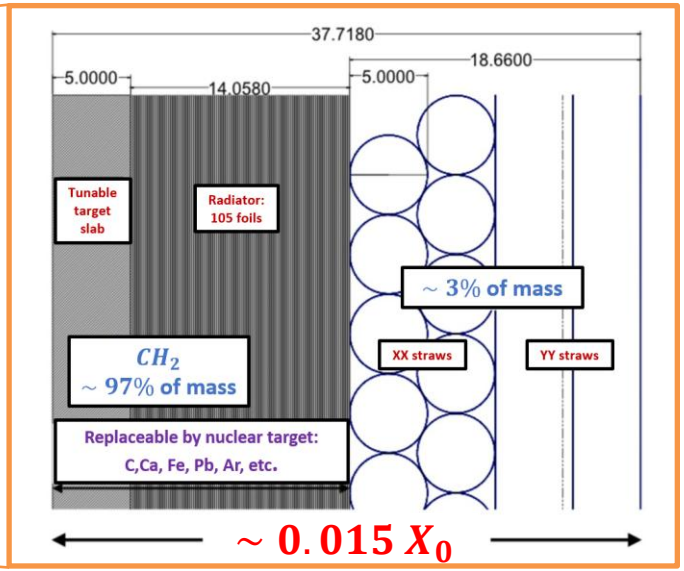
The SAND tracker - Straw Tube Tracker

Straw Tube Tracker (baseline design) **:**

- composed by a series of **passive target** slabs, and **active straw tube layers**
- 1 graphite target (pure C) for every 9 plastic (C_3H_6) targets
- Overall target mass: 4.7 t of plastic and 0.7 t graphite → **0.7 t of Hydrogen by subtraction!**



Module

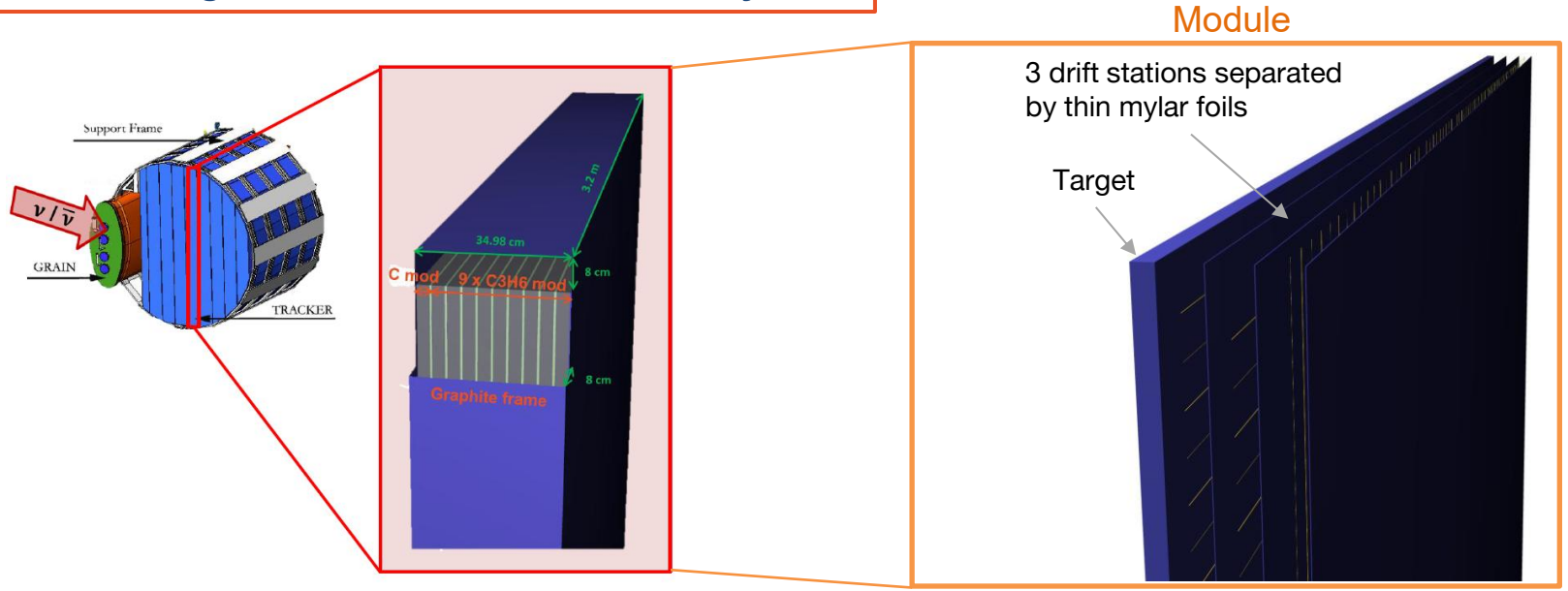


The SAND tracker - Drift Chamber Tracker

Drift Chamber Tracker (alternative design) **:**

- composed by a series of **passive target** slabs, and **multi-wire drift chamber**
- Same proportion of graphite and plastic targets

This is the configuration considered in our study



Solid Hydrogen Study

CCQE Interaction

$$\bar{\nu}_\mu + H \rightarrow \mu^+ + n$$

- Thesis work by G. Ingratta 'Study of Neutrino interactions on Hydrogen in the SAND detector of DUNE'

Motivation:

- This is the simplest reaction in DUNE energy range for which we have a **theoretical parametrization** of the cross-section
- The main source of theoretical **uncertainty** in the cross-section is given by the value of the axial mass *
  (Bernard et al 2002, global average is MA = 1.026 ± 0.021 GeV)

* N.B. : This is only true at very low Q^2 , where the dependecy of the axial mass factor on it can be ignored. This has not been taken into account in this preliminary study, due to the lack of available statistics

Selection of $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$ in SAND

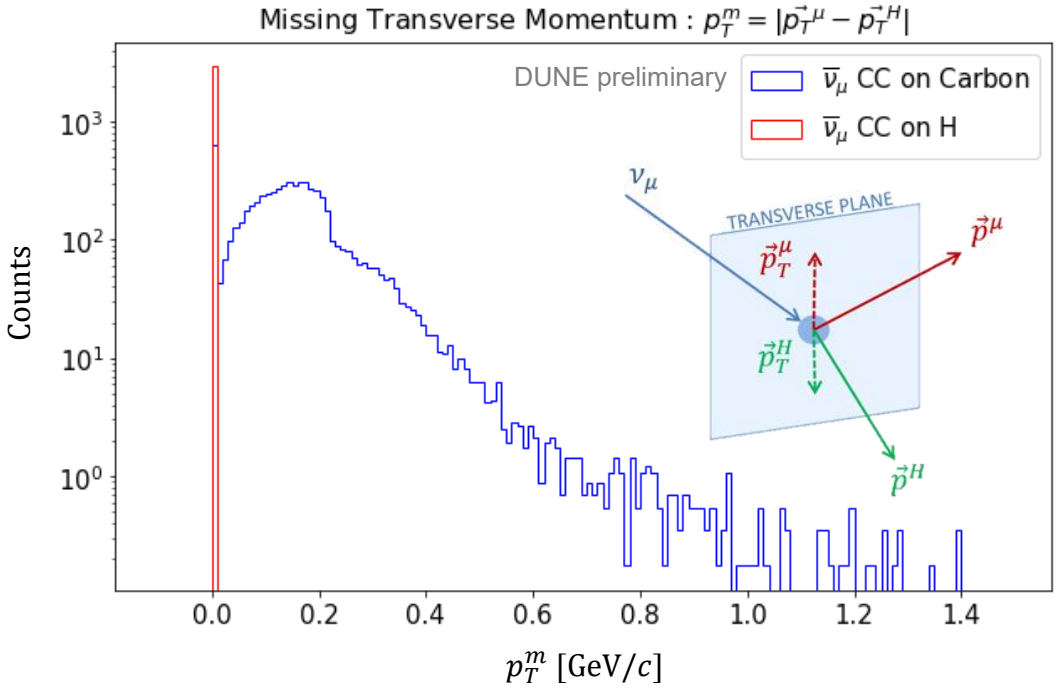
Selection method:

- ν interactions on H are expected to be perfectly balanced on a plane transverse to the neutrino direction
- Once μ+ is reconstructed:

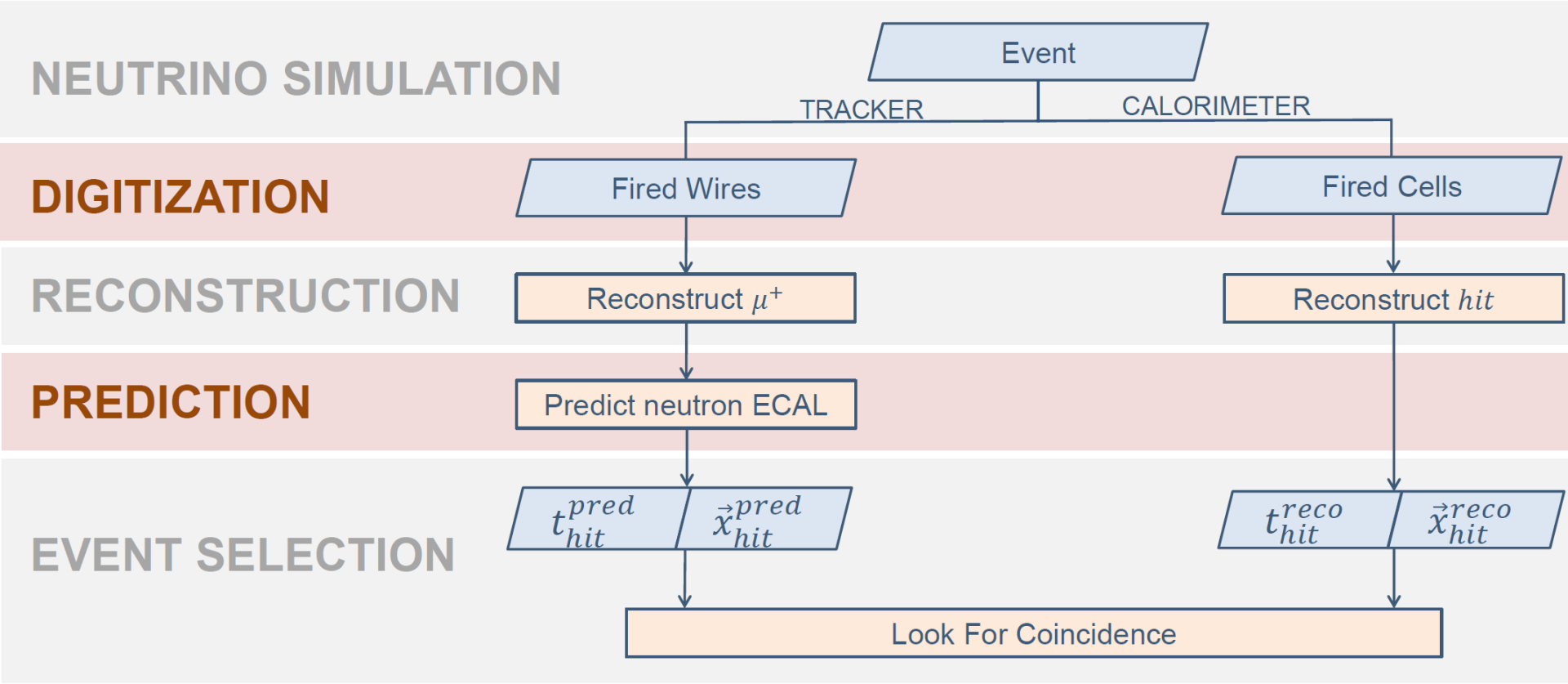
$$E_{\bar{\nu}}^{\text{reco}} = \frac{M_n^2 - m_\mu^2 - M_p^2 + 2M_p E_\mu^{reco}}{2\left(M_p - E_\mu^{reco} + p_\mu^{reco}\cos\theta_\mu^{reco}\right)}$$

$$E_n^{\text{expected}} = E_{\bar{\nu}}^{reco} + M_p - E_\mu^{reco}$$

- Neutron is tagged in ECAL from its time of flight to the calorimeter

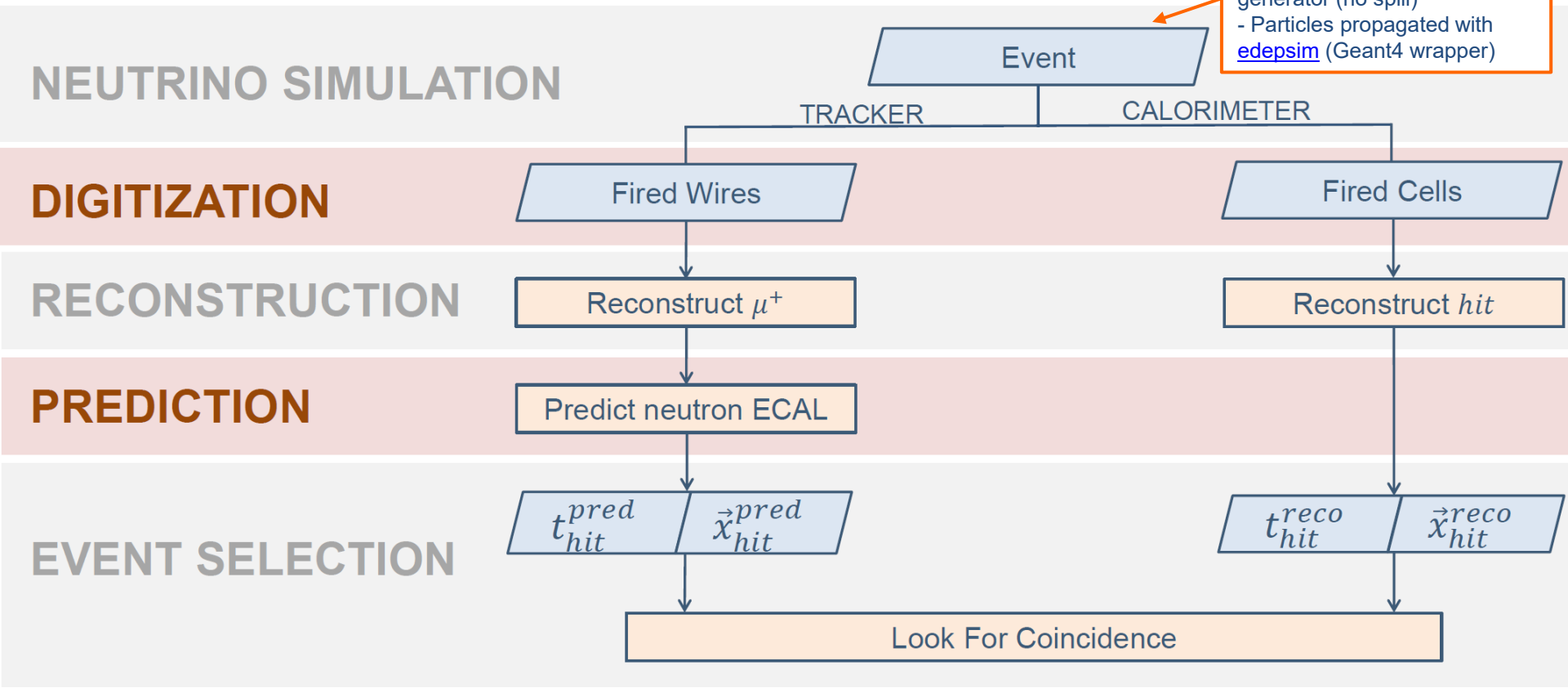


Simulation workflow



Simulation workflow

- Single neutrino interactions simulated with GENIE MC generator (no spill) *
- Particles propagated with edepsim (Geant4 wrapper)



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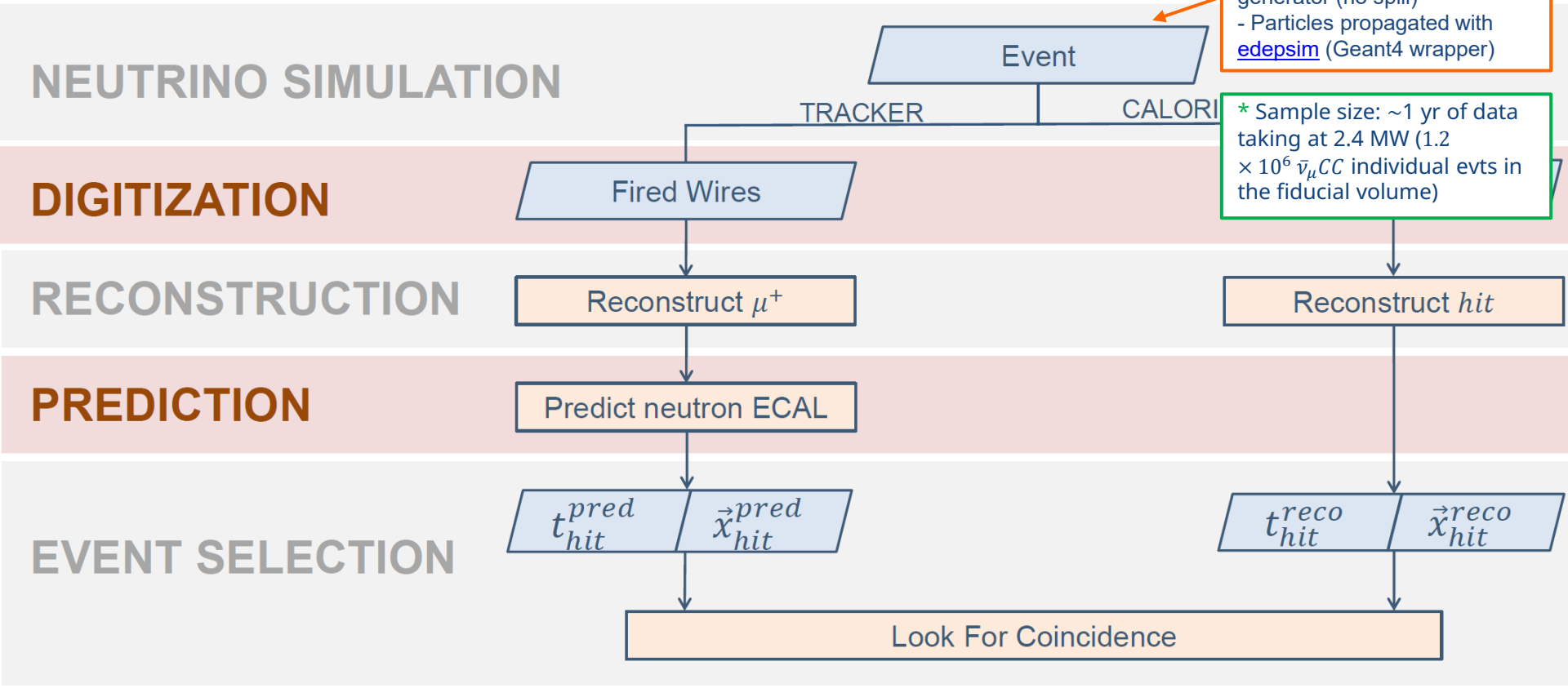

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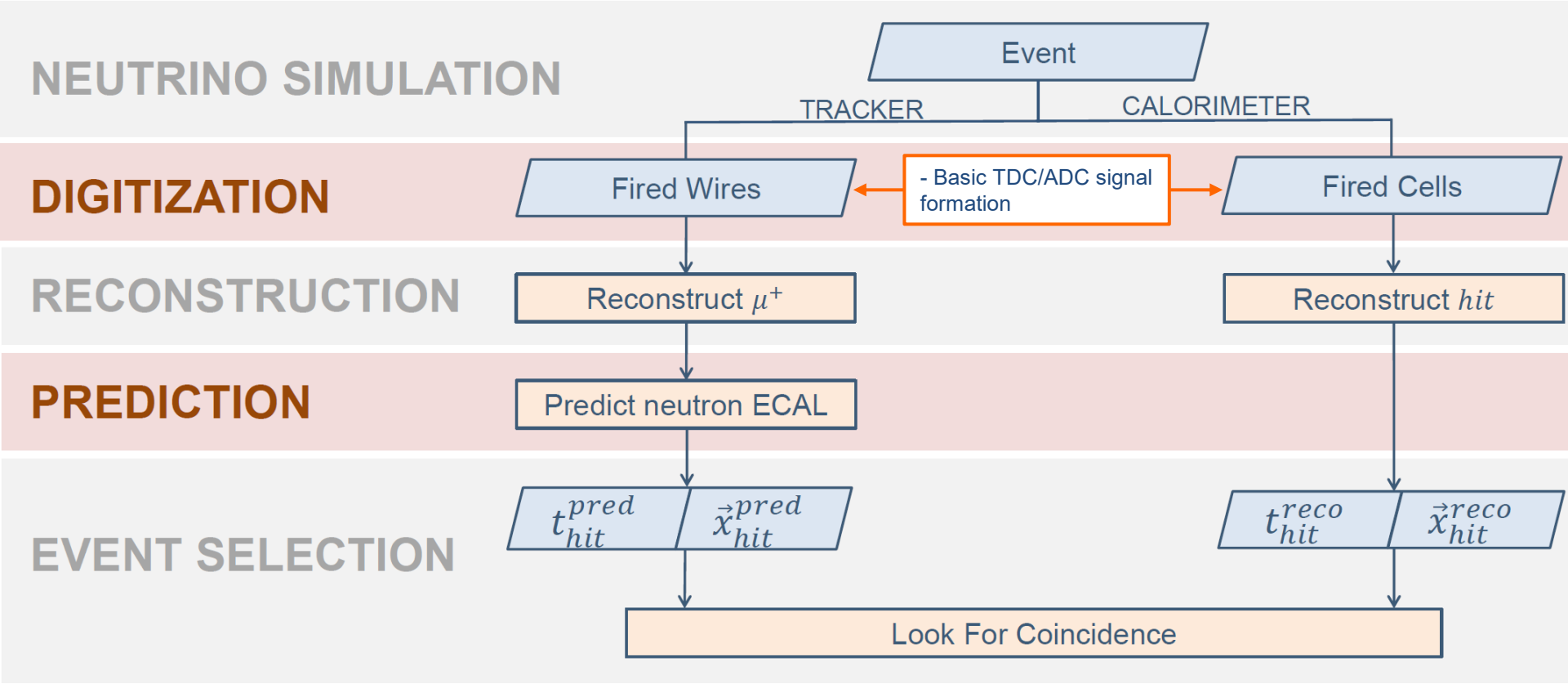

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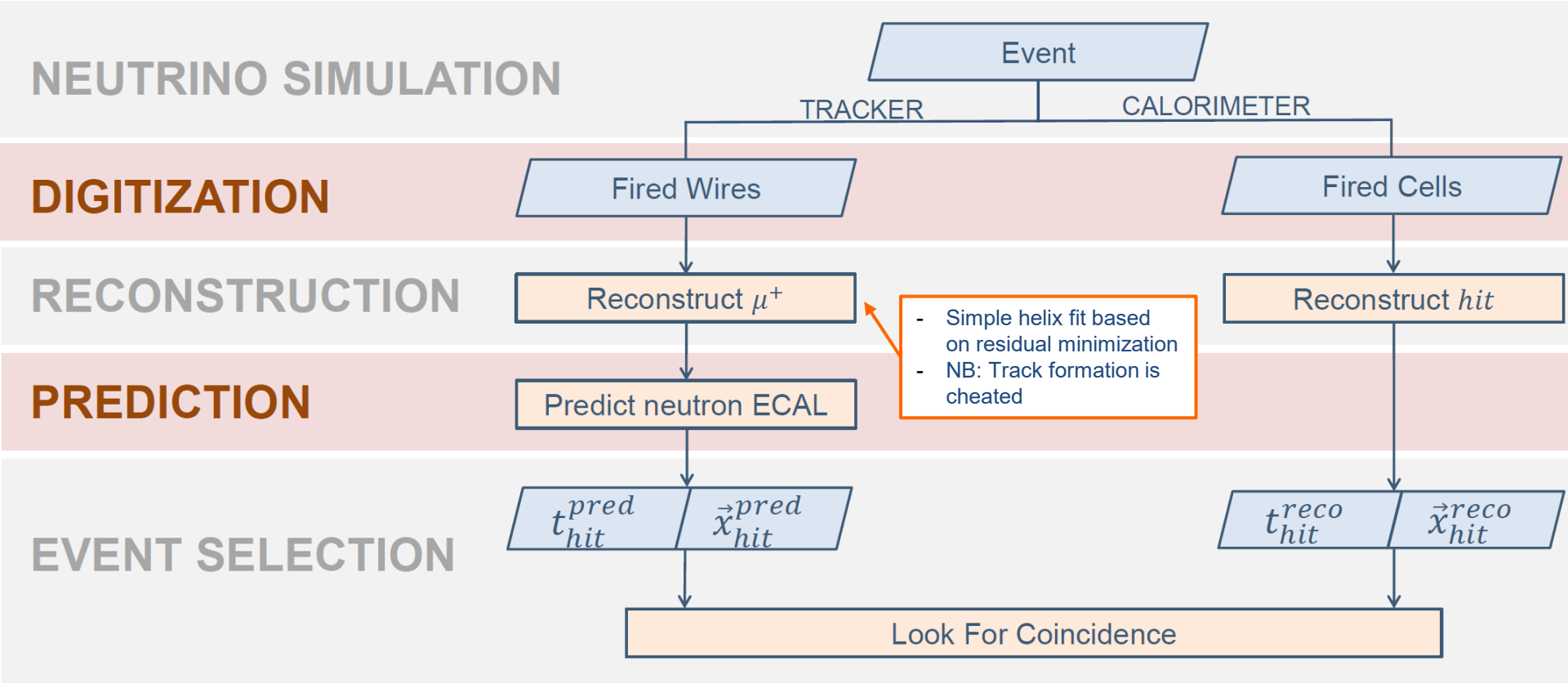
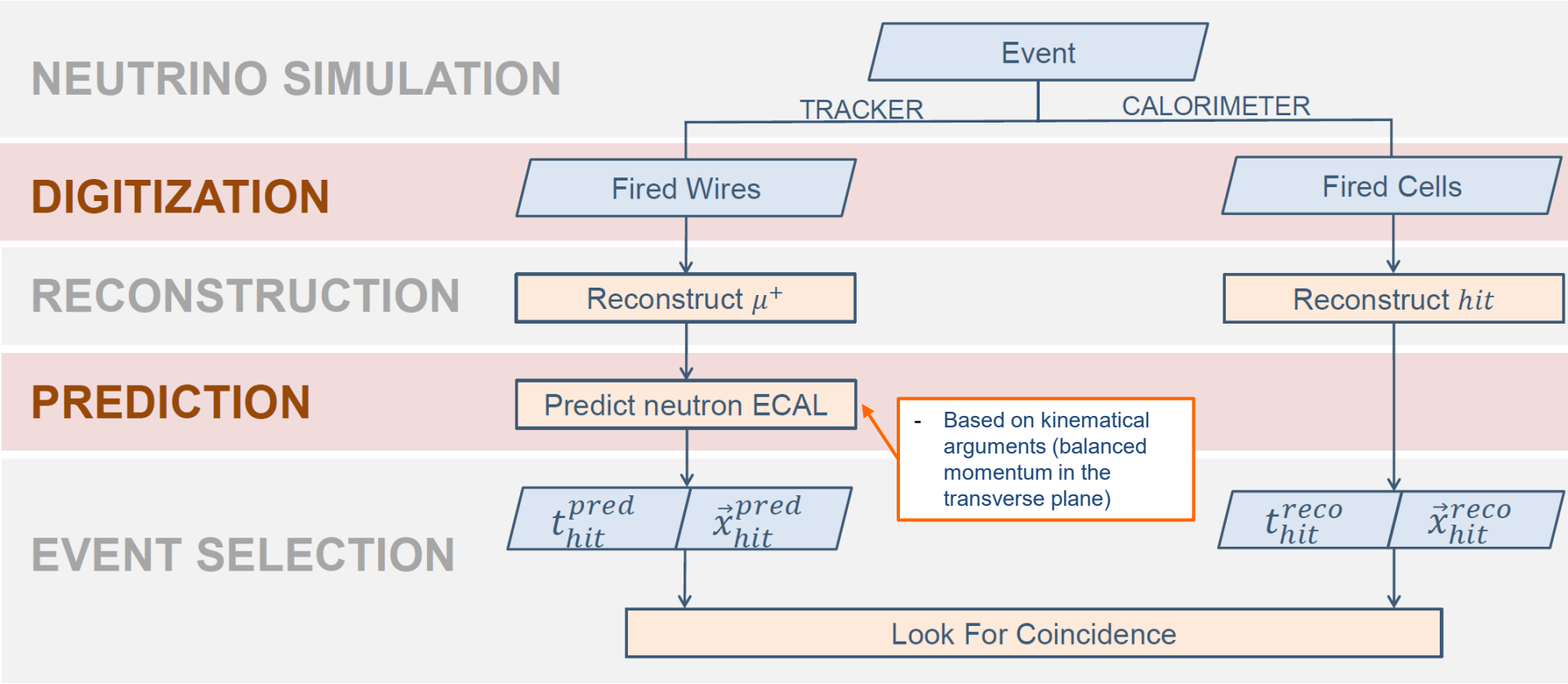


Simulation workflow



Sample selection

SELECTION CRITERIA

- Neutrino vertex in the **fiducial volume**
- μ+ **reconstructed** in the tracker with >70 wires
- 1 charged particle associated with the neutrino vertex
- >1 ECAL hit consistent with the expected **neutron in time and position**

SELECTED SAMPLE

Sample on plastic C_3H_6 targets :

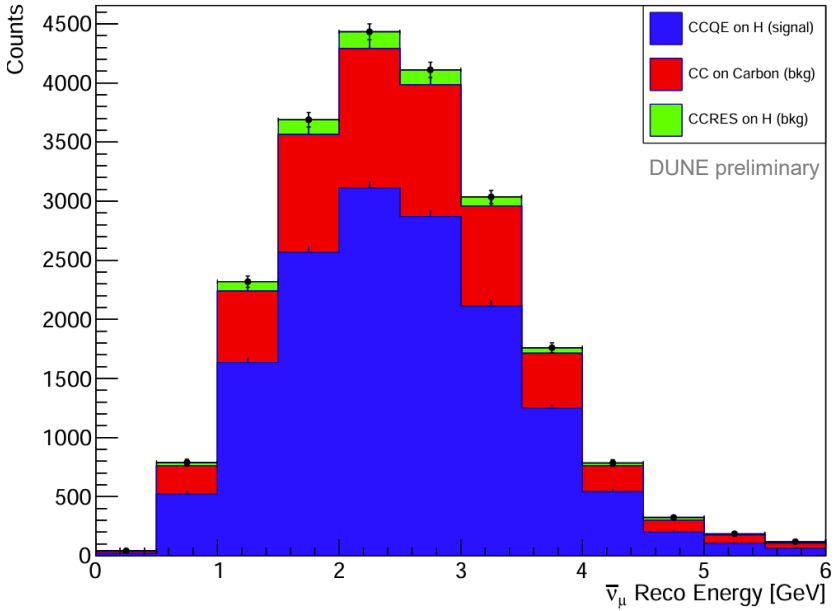
- **Signal:** - CCQE on H: $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$
- **Bkg:** - CCQE on C: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - CCRES on C: $\bar{\nu}_\mu + p(n) \rightarrow \mu^+ + n + \pi^0(\pi^-)$
  - CCRES on H: $\bar{\nu}_\mu + H \rightarrow \mu^+ + n + \pi^0$

Control sample on graphite C targets:

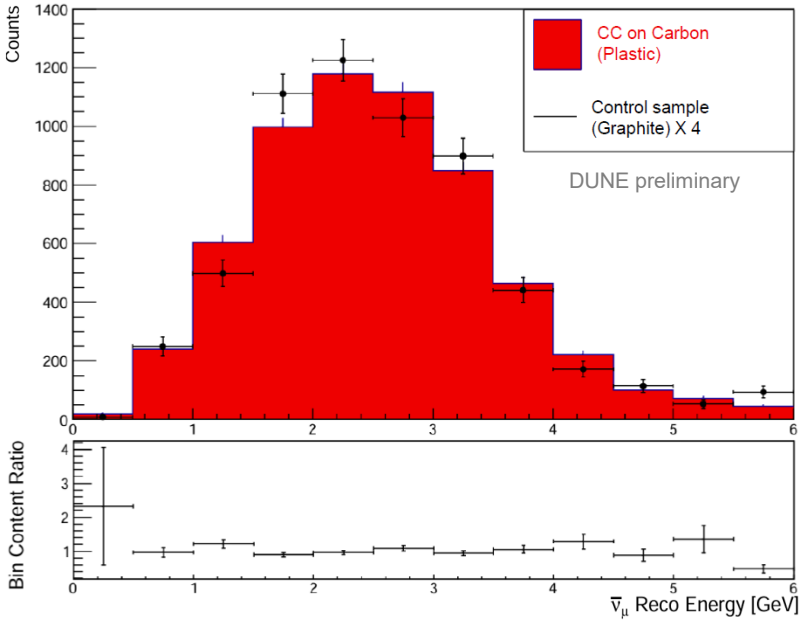
- **Signal:** - CCQE on C: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - CCRES on C: $\bar{\nu}_\mu + p(n) \rightarrow \mu^+ + n + \pi^0(\pi^-)$

Statistical Subtraction

Total selected sample on C_3H_6



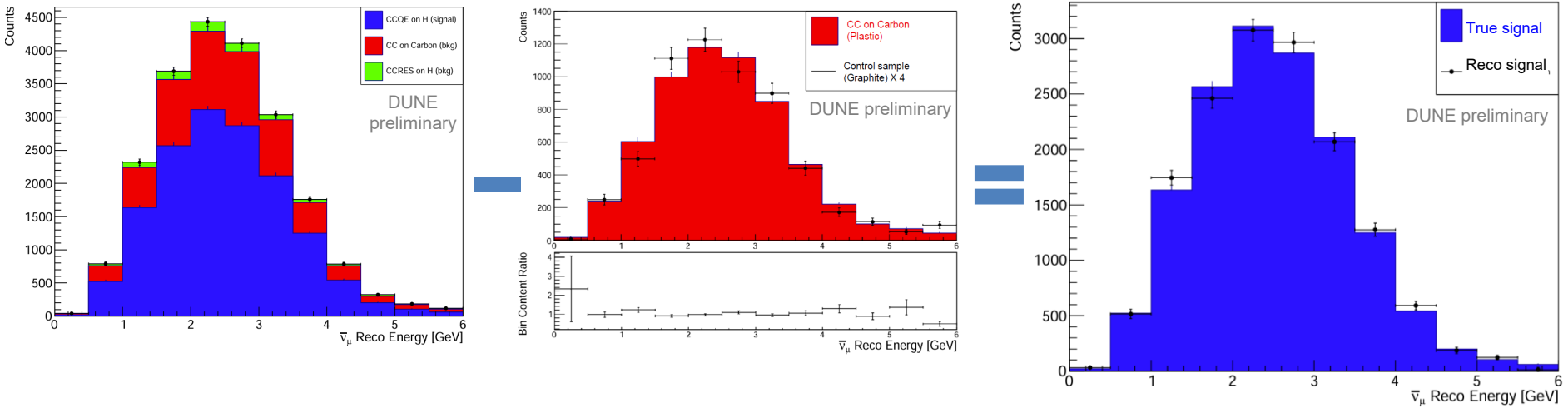
Bkg on C_3H_6 VS control sample on C



$$E_{\bar{\nu}}^{\text{reco}} = \frac{M_n^2 - m_\mu^2 - M_p^2 + 2M_p E_\mu^{reco}}{2\left(M_p - E_\mu^{reco} + p_\mu^{reco}\cos\theta_\mu^{reco}\right)}$$

Statistical Subtraction

- **Solid Hydrogen technique:** the **reconstructed signal rate** as function of the **neutrino reconstructed energy,** is obtained from a **statical subtraction** of the measured background giving the (nearly) same detector acceptances.



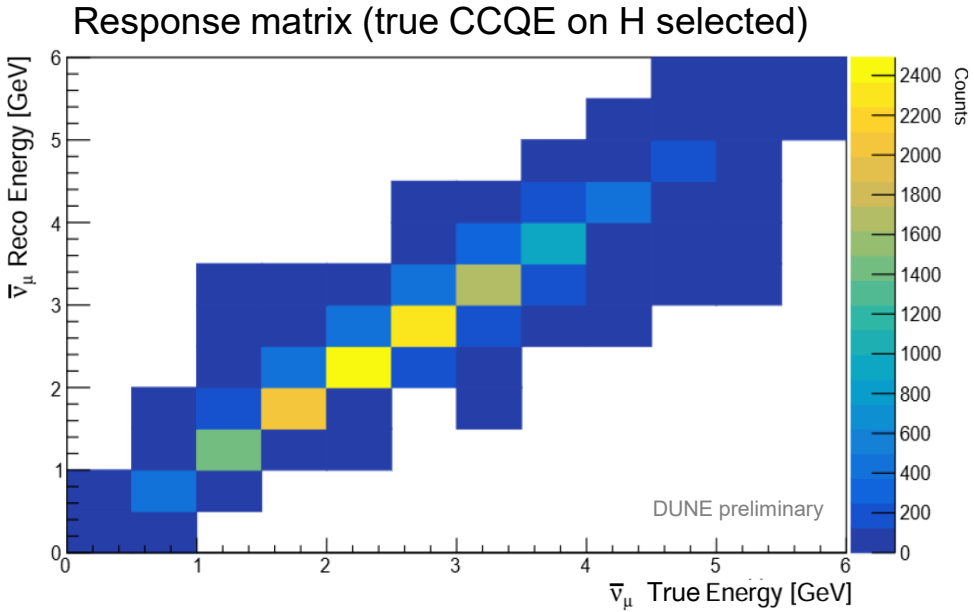
Unfolding – response matrix CCQE on H selected

- The **reconstructed** signal rate differs from the **true** rate by the convoluted effect of the **detector resolution** and signal selection **efficiency.**

$$x_{reco} \sim \Phi \otimes \sigma \otimes \epsilon \otimes R$$

flux · cross section · selection efficiency · detector response

- The true rate is obtained using an **unfolding** technique implemented in the ROOT analysis framework with *RooUnfold*



Unfolding of the absolute flux

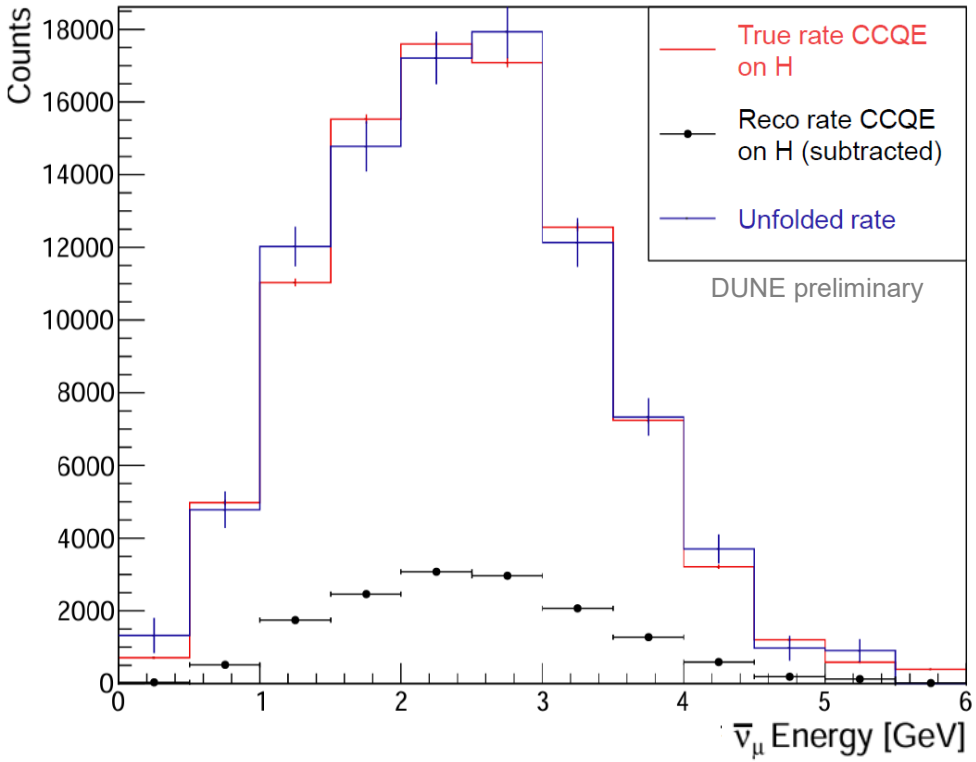
- The unfolding procedure **corrects the reconstructed signal** rate for the effect of the detector response and efficiencies

$$x_{reco} \sim \Phi \otimes \sigma \otimes \epsilon \otimes R$$

flux · cross section · selection efficiency · detector response

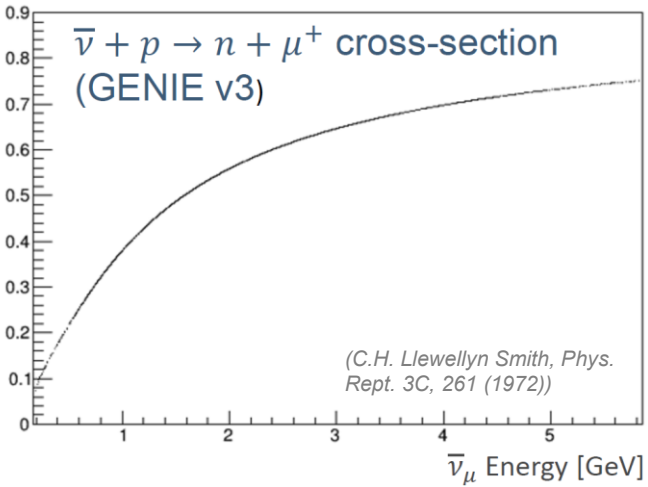
$$x_{unfolded} \sim R\, x_{reco} \sim \Phi \otimes \sigma$$

Response matrix

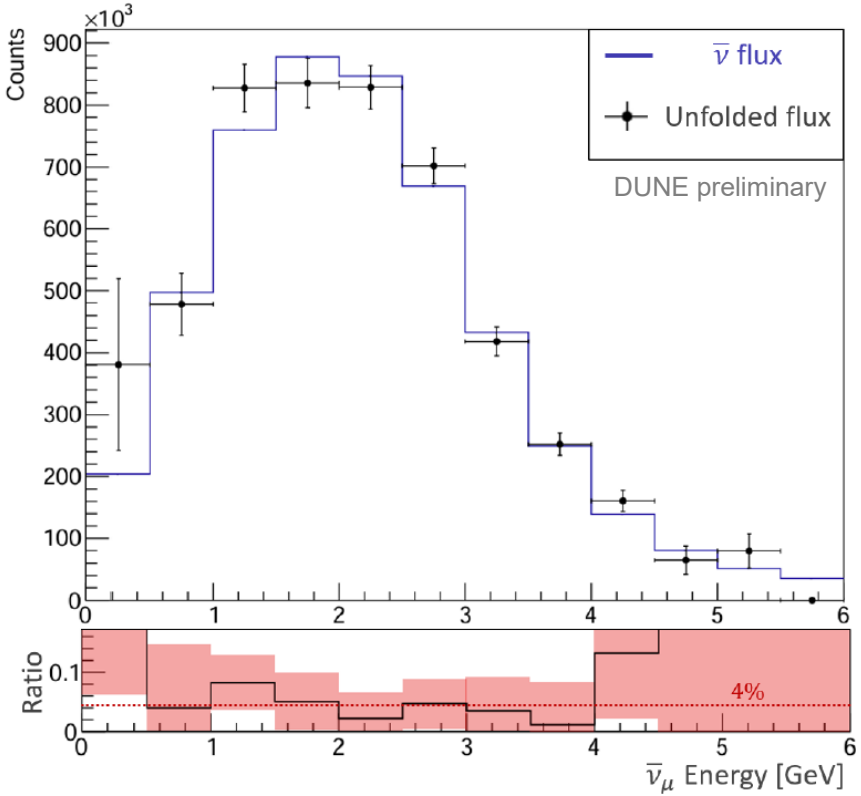


Absolute $\bar{\nu}$ flux

- The **absolute flux** is obtained by dividing the unfolded signal rate by the nominal value of the ν on H cross section



N.B. : cross section uncertainty Q^2 dependency has been ignored in this study



Conclusions and Outlooks

Summary

Simulated 1.2×10^6 $\bar{\nu}_\mu CC$ neutrino events in SAND's drift chamber tracker fiducial volume ~**1 year of data taking at 2.4 MW** (Genie+edep-sim)

- Applied complete detector response simulation and track reconstruction
- **Selection $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$ interaction channel with the solid hydrogen technique**
- Preliminary evaluation on uncertainties for flux estimate at ~4%, ignoring uncertainty on cross section Q^2 dependency

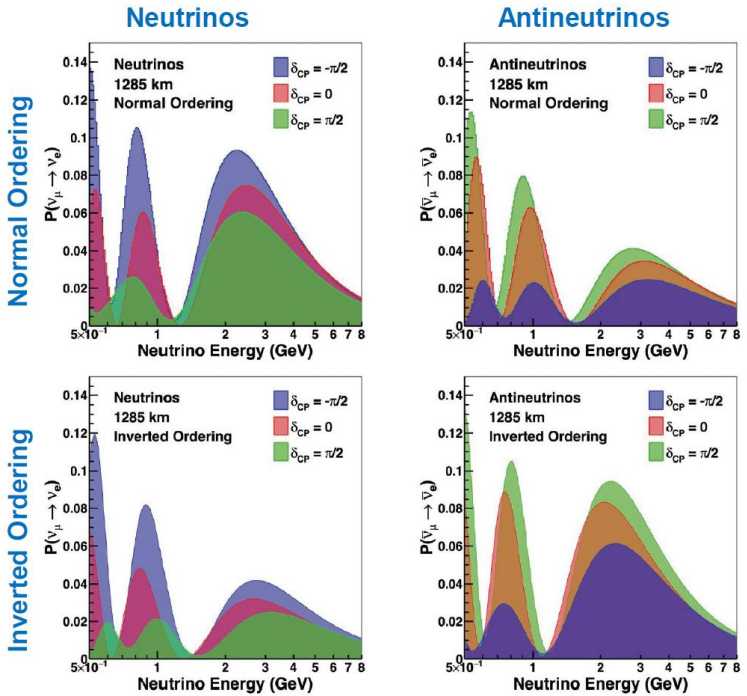
Outlook & Conclusions

- **Current ~4% flux uncertainty is not sufficient, but the estimate is limited in statistics**: with 5 years of data, uncertainties should improve by a few percent
- **Several steps can and will be improved**, this is only to be taken as a **proof of concept** (better muon reconstruction, enhanced hit reconstruction on the calorimeter, better selection methods etc.)

Thank you !

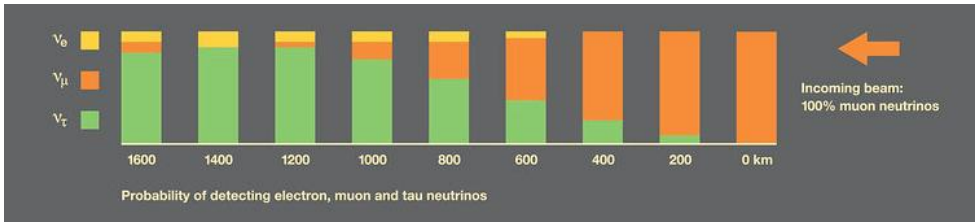
backup

The oscillation measurement



$\nu_e/\bar{\nu}_e$ **oscillation shapes**

$P(\nu_\mu \to \nu_e)$ **VS** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



- Mass ordering and CP violation induce **different shapes in $\nu_e/\bar{\nu}_e$ oscillation probabilities**
- **DUNE's unique capability** : with a **wide band beam** measures these shapes over more than a full period resolving degeneracies. Not simply a counting experiment!

Mass ordering + CP violation + θ_{23} octant in a single experiment