Neutrino interactions in ‘Solid’ hydrogen at the DUNE near site

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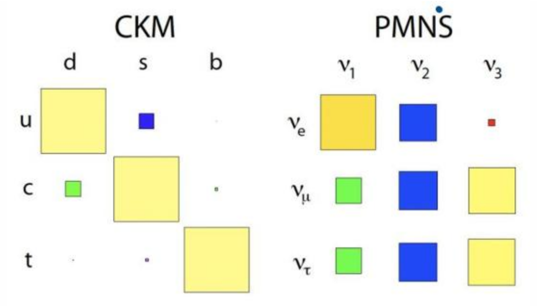
Outline

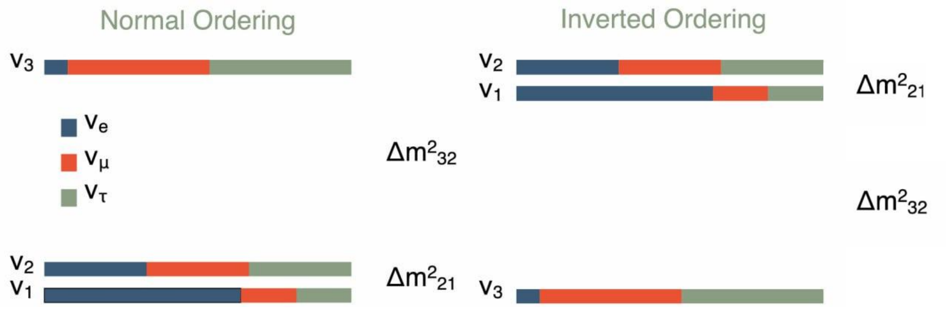
Overview:

- Neutrino Oscillations
- The DUNE experiment
- The SAND detector at the DUNE near site
- Constraining systematics: the ‘solid’ hydrogen concept

Neutrino oscillations



- Most abundant known particles in the Universe
- Massless in the Standard Model
- Evidence of flavour oscillations → **Mass** **Mixing**
- Many oscillation parameters have been measured but 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?



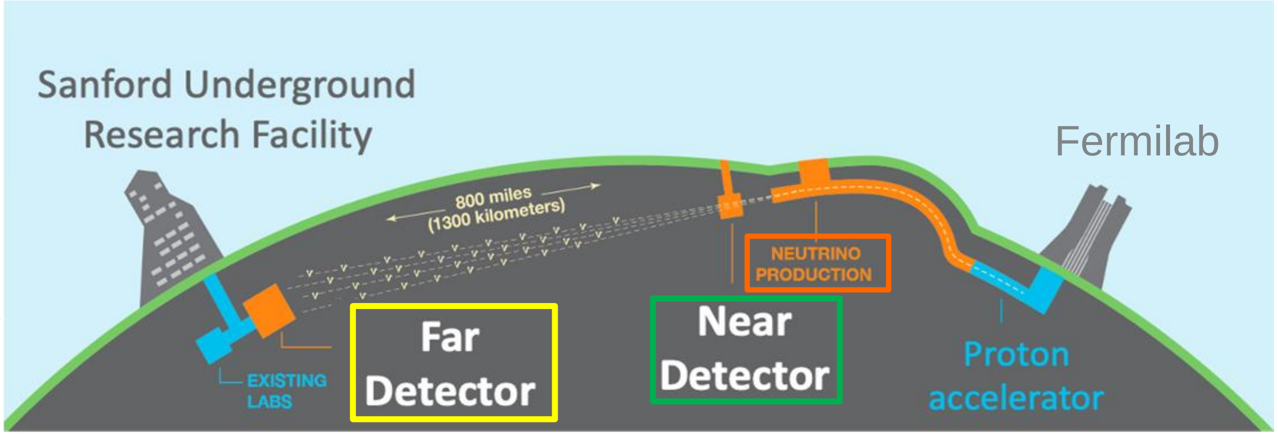
A next-generation long baseline neutrino oscillation experiment:

- **Deep Underground Neutrino Experiment** (DUNE)

The DUNE experiment

Physics goals:

- Mass ordering
- CP violating phase
- Mixing angles
- Supernova, solar, atmospheric neutrinos
- Physics beyond the Standard Model



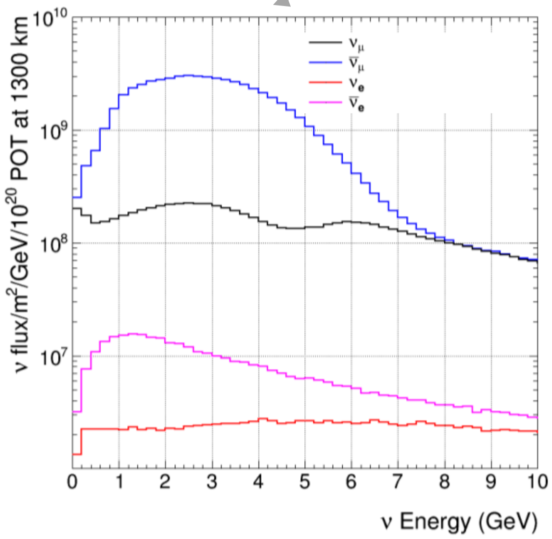
FAR DETECTOR	NEAR DETECTORS	BEAM
Four Liquid Argon Time Projection Chambers (LArTPC) modules 17 kt each Measure the oscillated neutrino spectrum, perform astroparticle physics and BSM searches	Three subdetectors: SAND, ND-LAr, TMS Measure the unoscillated neutrino flux Constrain systematic uncertainties on the neutrino flux and cross section	Most intense wide-band beam of (anti)ν_μ • energy peaked at 2.5 GeV • 1.2 MW power upgradable to 2.4 MW

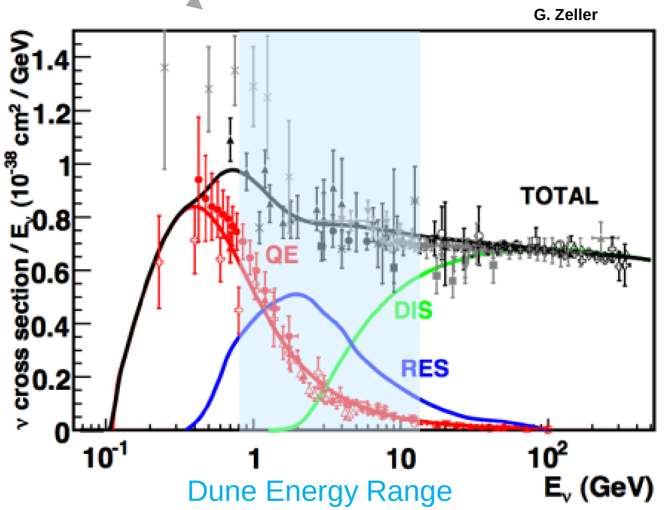
What do we measure?

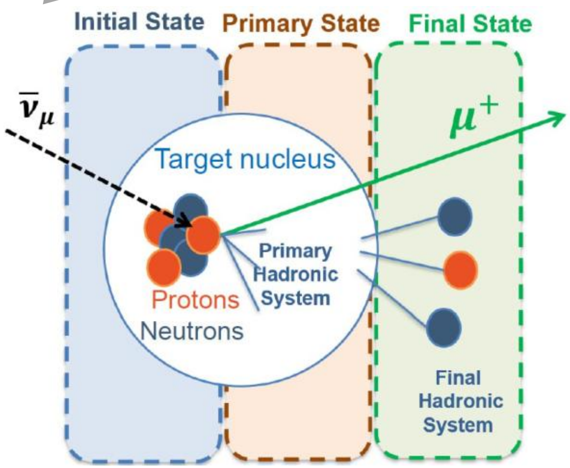
The **number of events** N_x at the Near/Far Detector for a process x is given by:

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

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







‘Solid’ hydrogen target

The **number of events** $\boldsymbol{N_x}$ at the Near/Far Detector for a process $\boldsymbol{x}$ is given by:

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

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

- **Neutrino-hydrogen** interactions are **free from nuclear effects** and thus would be devoid of major source of systematic uncertanties:

$$R_{phys}(E_\nu, E_{vis}) \equiv 1$$

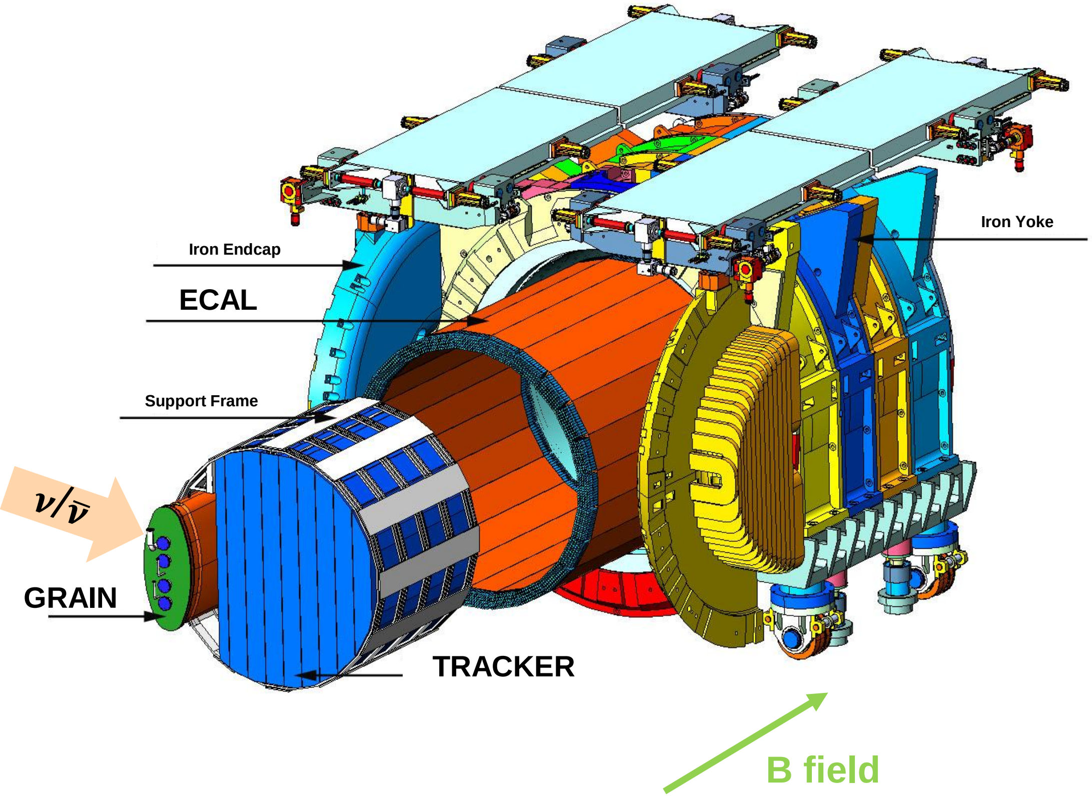
- It has been proposed that by using a neutrino detector that **alternates dedicated targets** of graphite (C) and polypropylene (C_3H_6), a sample of interactions on hydrogen can be obtained by **statistical subtraction**. [*H. Duyang et al. arXiv.1809.08752*]

- **SAND** detector is designed to have a about **0.7 t** of **Hydrogen target**.

The SAND (System for on-Axis Neutrino Detection)

Physics goals:

- On-axis beam monitoring to detect time-dependent energy spectrum changes on a weekly basis
- **Reduction of systematic uncertainties and nuclear smearing effects on the reconstructed neutrino energy**
- **Precise absolute and relative flux measurements of $\bar{\nu}_\mu$,ν_μ , $\bar{\nu}_e$,ν_e**
- Short-baseline physics studies

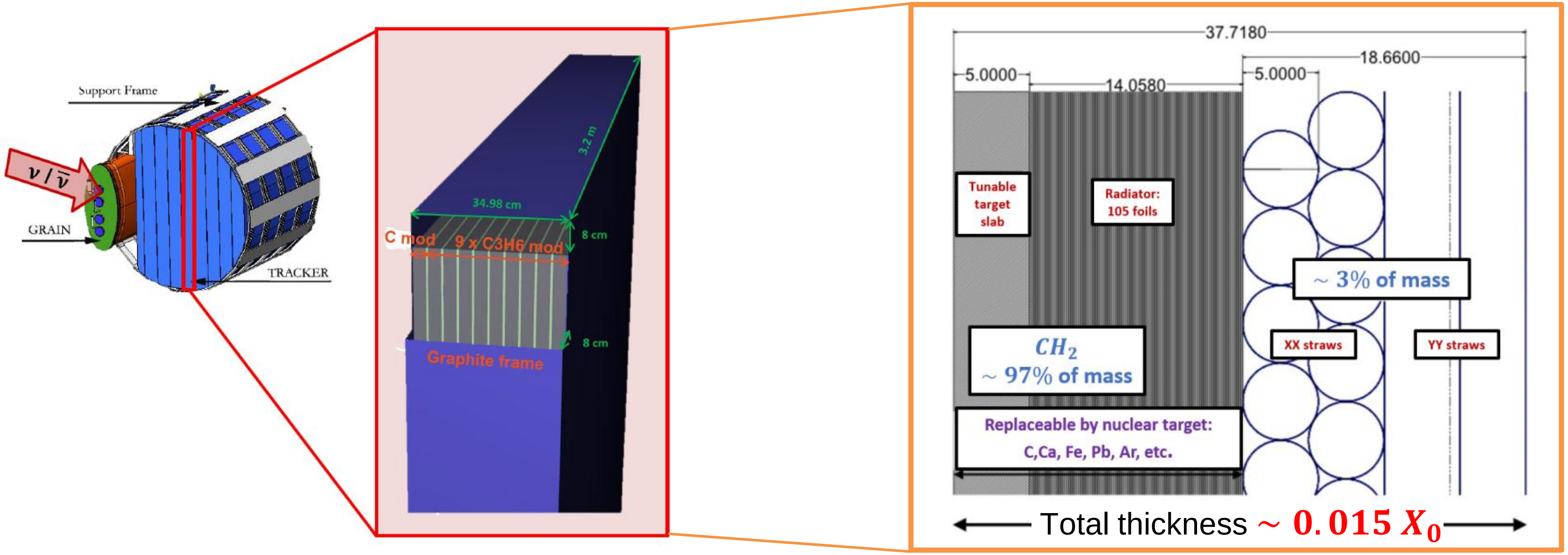


The SAND tracker - Straw Tube Tracker

Straw Tube Tracker (reference choice) **:**

- 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

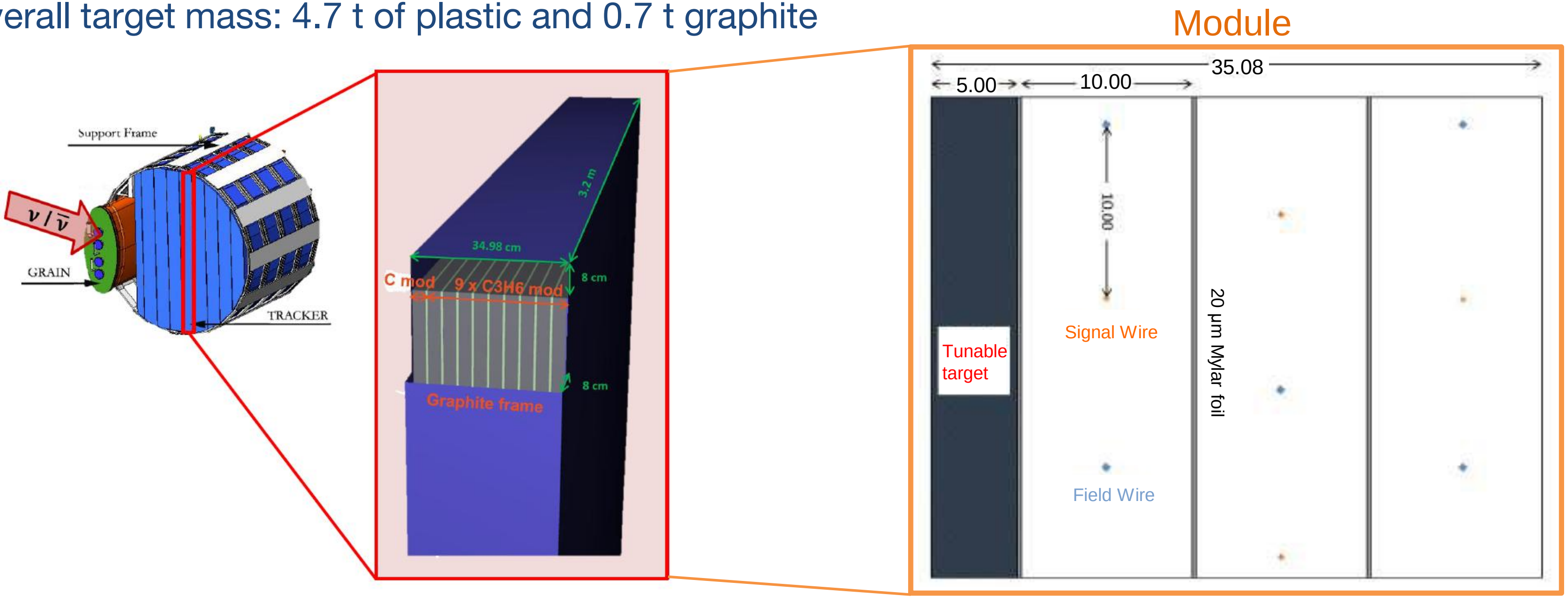
Module



The SAND tracker - Drift Chamber Tracker

Drift Chamber Tracker (alternative design) :

- composed by a series of **passive target** slabs, and **multiwire drift chambers**
- 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



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

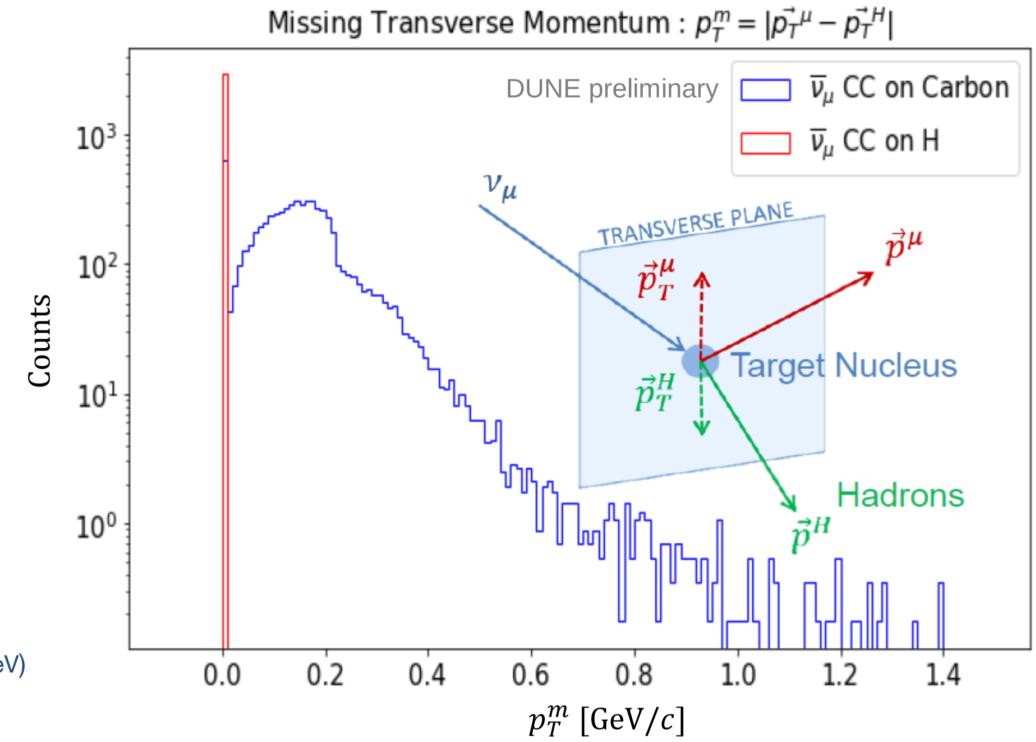
- Thesis work by G. Ingratta 'Study of Neutrino interactions on Hydrogen in the SAND detector of DUNE'

- Considered interaction:
  $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$

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)



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Selection method:

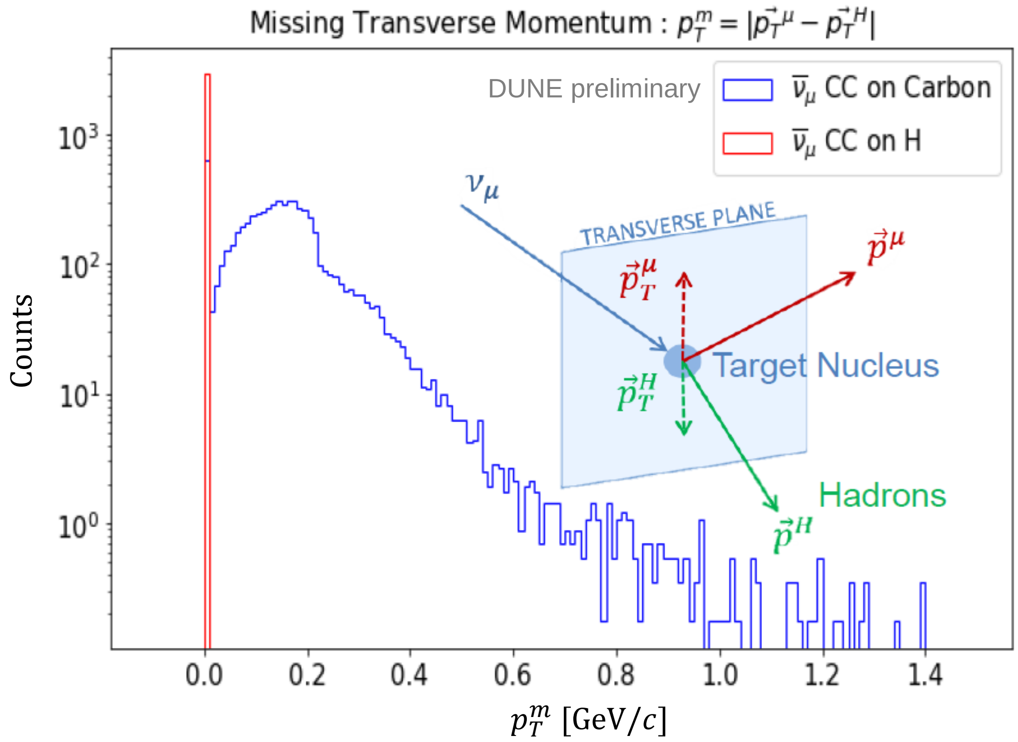
- ν interactions on H are expected to be perfectly balanced on a plane transverse to the neutrino direction

- Once μ+ four-momentum is reconstructed:

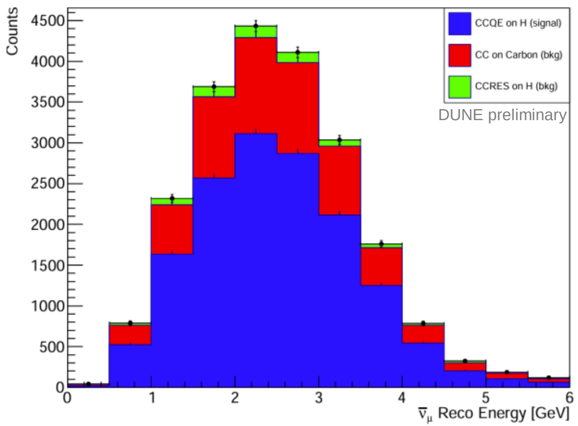
$$E_{\bar{\nu}}^{\text{reco}} = \frac{M_n^2 - m_\mu^2 - M_p^2 + 2M_p E_\mu^{reco}}{2\left(M_p - E_\mu^{reco} + p_\mu^{reco}\cos\theta_\mu^{reco}\right)}$$

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

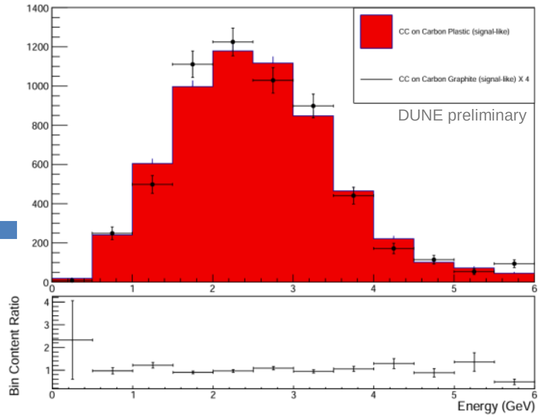
- Neutron is tagged in ECAL from its time of flight to the calorimeter



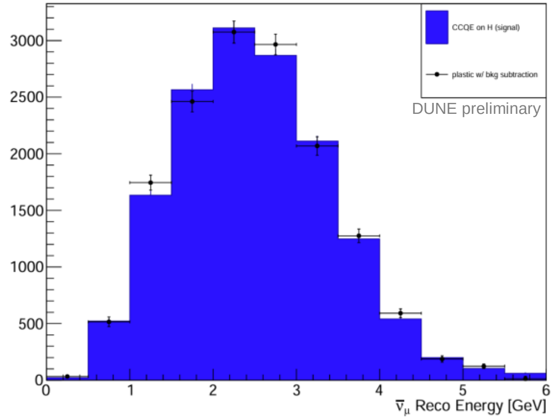
Statistical Subtraction



C_3H_6



C



'Solid' hydrogen

Unfolding of the event rate on Hydrogen

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

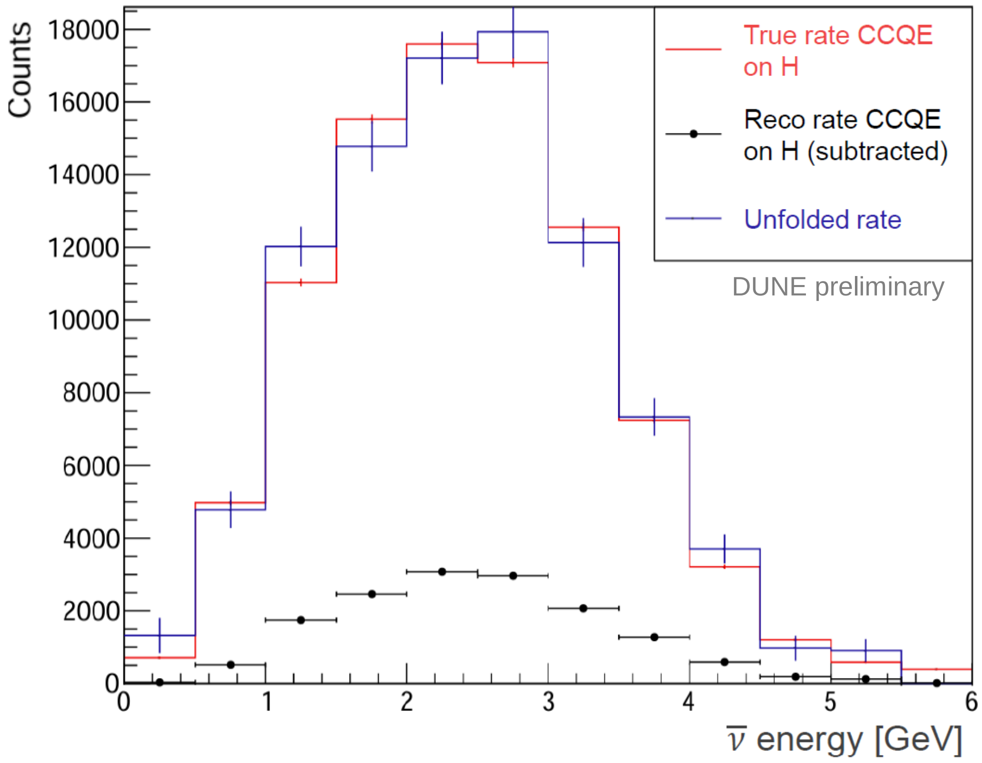
$$x_{reco} \sim \Phi \otimes \sigma \otimes \epsilon \otimes R$$

flux — cross section — selection efficiency — detector response

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

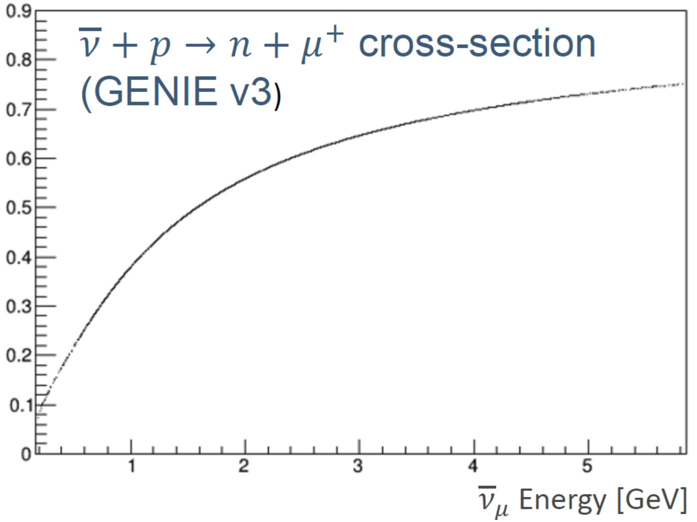
$$x_{unfolded} \sim R\, x_{reco} \sim \Phi \otimes \sigma$$

Response matrix

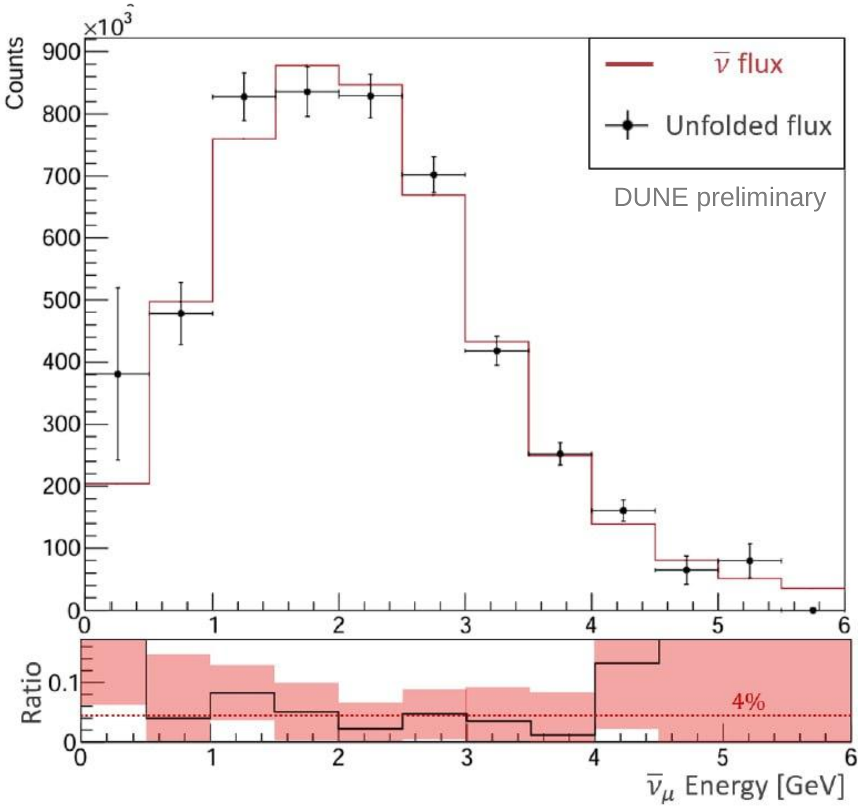


Absolute $\bar{\nu}$ flux

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



(C.H. Llewellyn Smith, Phys. Rept. 3C, 261 (1972))



Conclusions and Perspectives

- To achieve DUNE's physics goals, SAND needs to **measure the neutrino flux** and **constrain the systematic uncertanties**
- To constrain systematic uncertanties SAND will use a **target of Hydrogen** which is **free from nuclear effects**
- This preliminary study achieved **4%** systematic uncertanties of the subtraction technique on the **absolute flux**
- Reduce the current ~4% flux uncertainty
- **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

Analysis Workflow

Production

Event Generation + Propagation in the detector

→

Digitization

ECAL: fired cells
Tracker: fired wires

→

Recostruction

ECAL: Reconstruct hit
Tracker: Reconstruct μ^+

→

ANALYSIS

Get quantities

E_n , $\vec{p}_n$ x_{ECAL}^{hit}
E_μ , $\vec{p}_\mu$ t_{ECAL}^{hit}
E_ν , $\vec{p}_\nu$ E_{ECAL}^{hit}

Event selection

To **identify signal** and background event

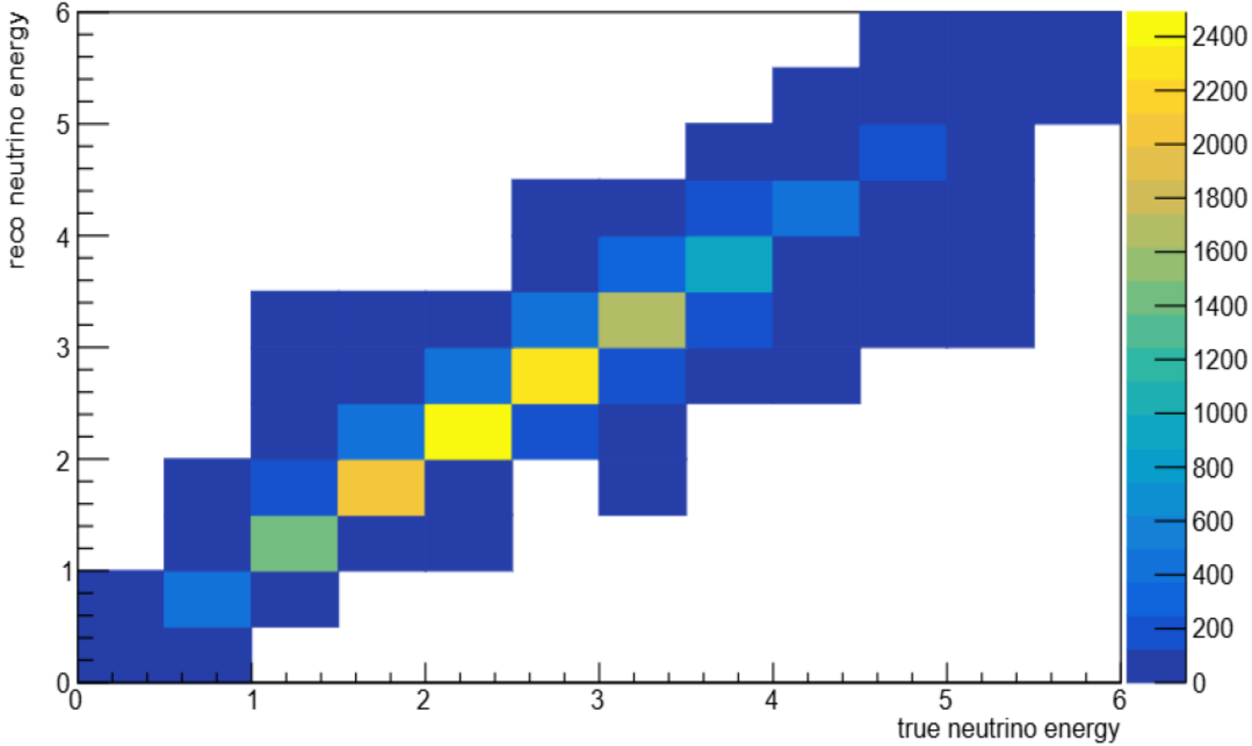
Statistical Subtraction

To obtain **reconstructed signal rate** as function of neutrino reconstructed energy

Unfolding

To obtain the **true rate** from the reconstructed signal convoluted with detector effects

Unfolding – response matrix CCQE on H selected



G. Ingratta for SAND software collaboration

Sample Selection

SELECTION CRITERIA	SELECTED SAMPLE

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: $\bar{\nu}_\mu + p(n) \rightarrow \mu^+ + n + \pi^0(\pi^-)$