Reconstruction studies of $1\mu 1p$ fully contained $\nu_\mu CC$ events from the Booster neutrino beam with the ICARUS detector

Imaging Cosmic And Rare Underground Signals

INTENSE Meeting

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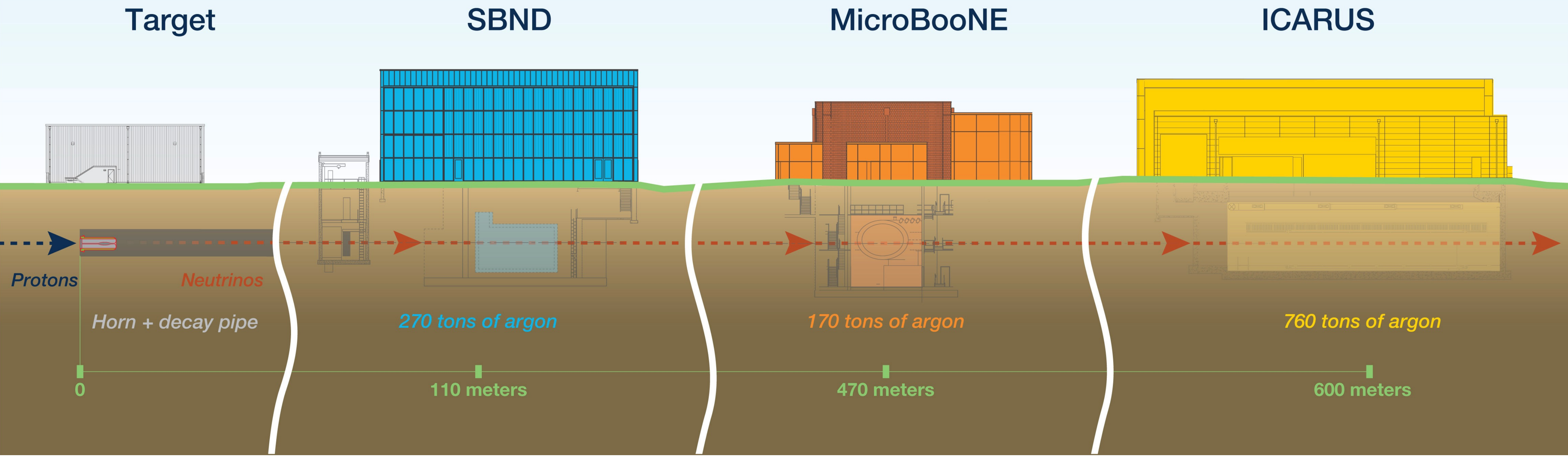
Short-Baseline Neutrino Program at Fermilab

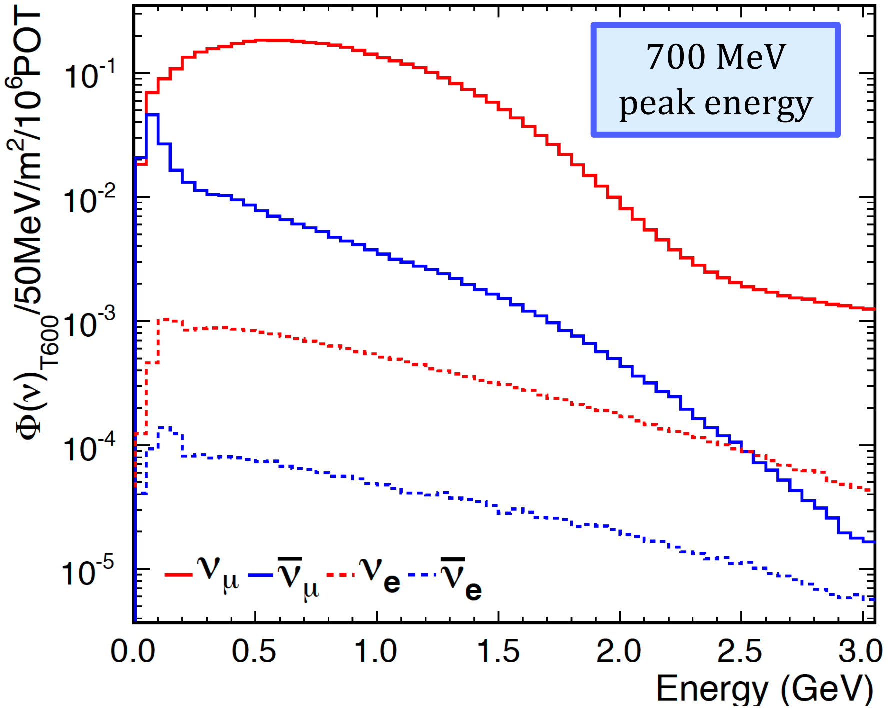


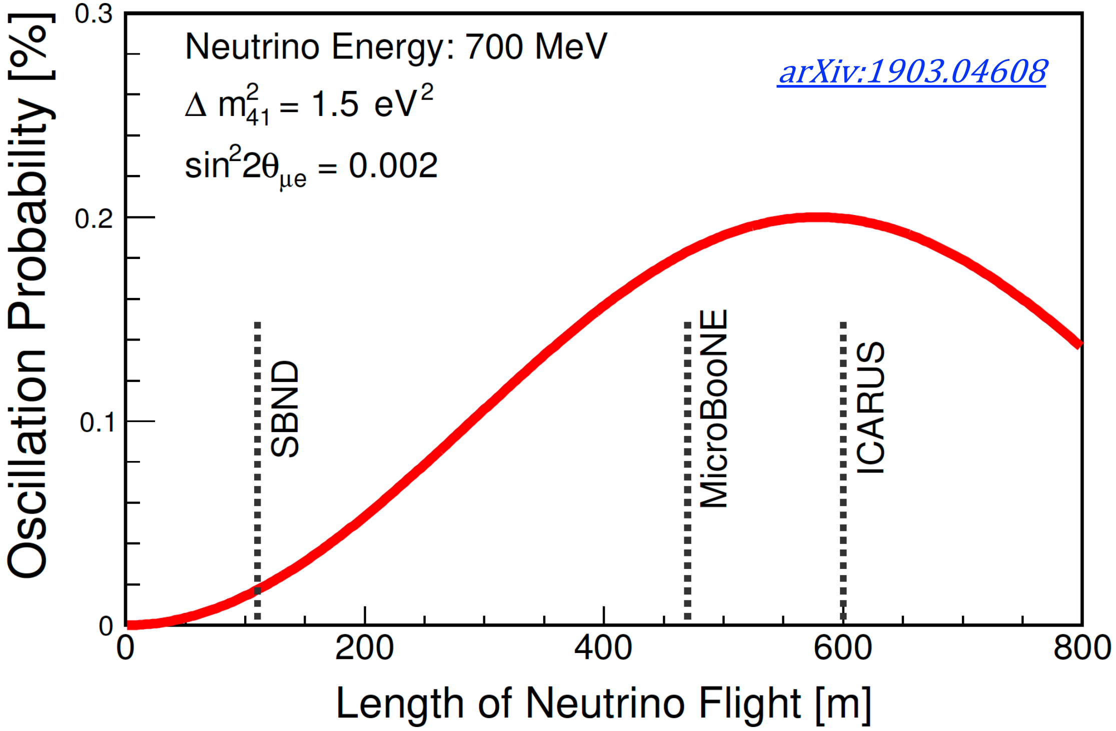
- Several anomalies have been observed in neutrino oscillation experiments, some of them can be explained by introducing an additional sterile neutrino state (ν_s)
- Short Baseline Neutrino (SBN) program should clarify this question by exploiting the BNB beam and comparing the neutrino interactions observed at different distances along the baseline by **ICARUS** and SBND (LArTPC detectors)

SBN at Fermilab

- BNB is a well characterized ν_μ-beam, able to produce ν and $\bar{\nu}$ beams with low ν_e contamination

(0.5 % ν_e content)





$\vec{p}$ ~8.9 GeV proton beam on Be target

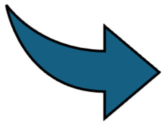
*Using best fit values

Multi detector design

- Combined analysis of near (SBND) and far (ICARUS) detector data will cover the currently allowed LSND parameter region with 5σ both in appearance and disappearance channels

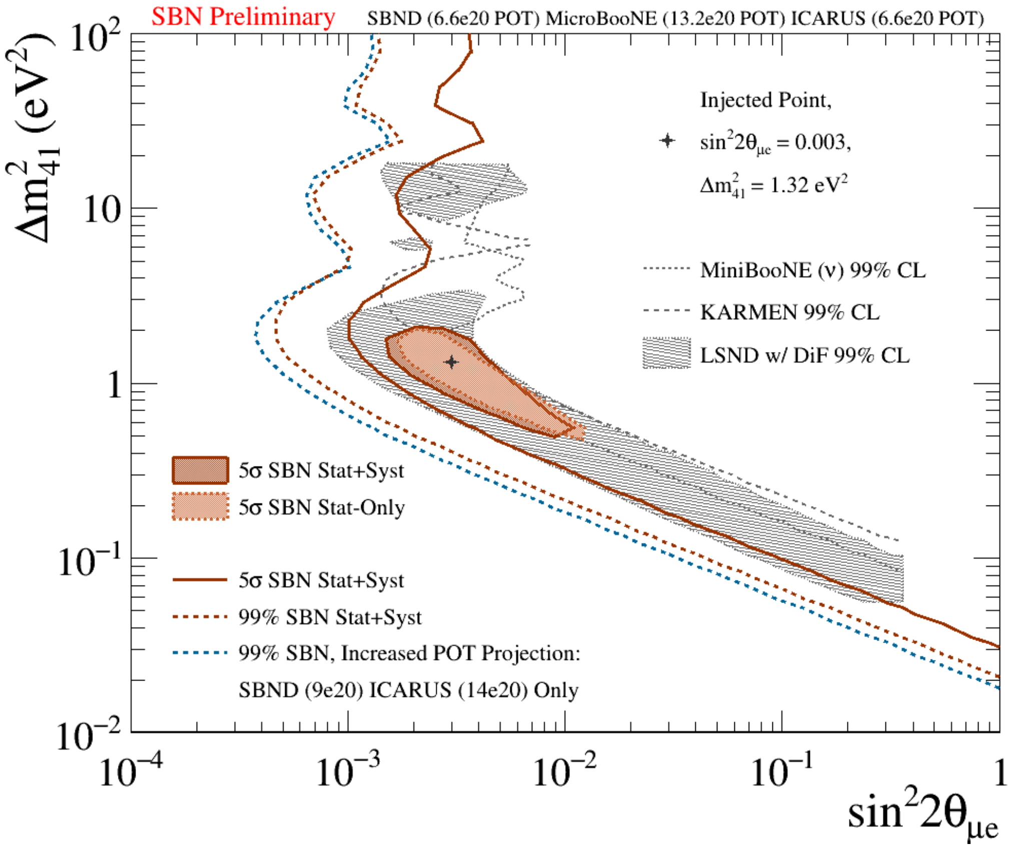
3 years of data taking (6.6×10^{20} POT)

- The shared detector technology, nuclear target and beam is expected to reduce the systematic uncertainties to % level



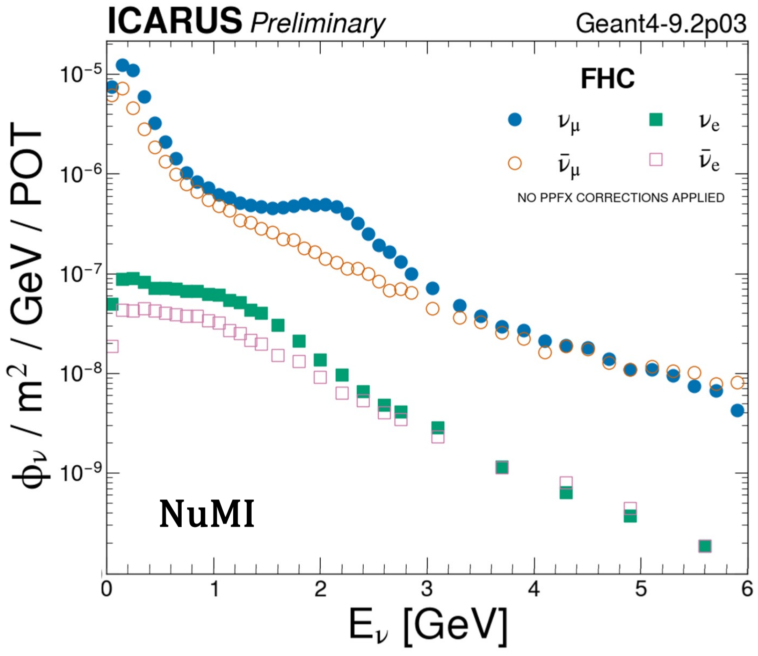
BNB beam composition and energy spectrum constrained by the near detector

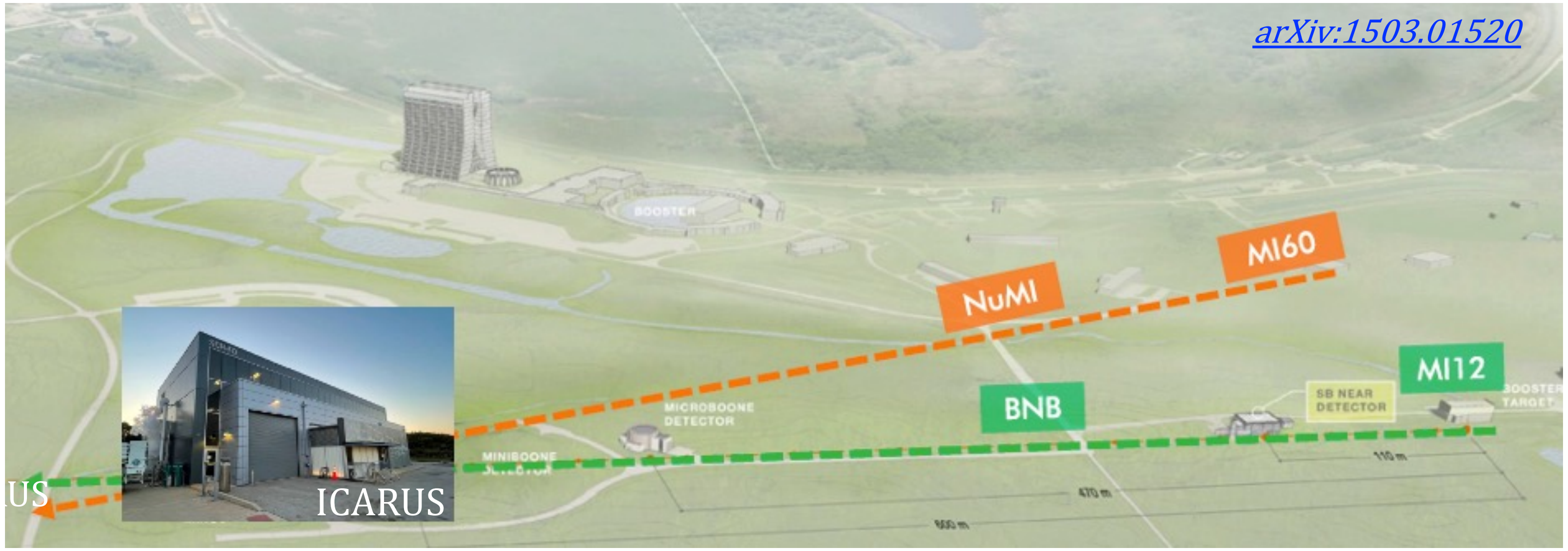
SBN ν_e appearance sensitivity



ICARUS at Fermilab

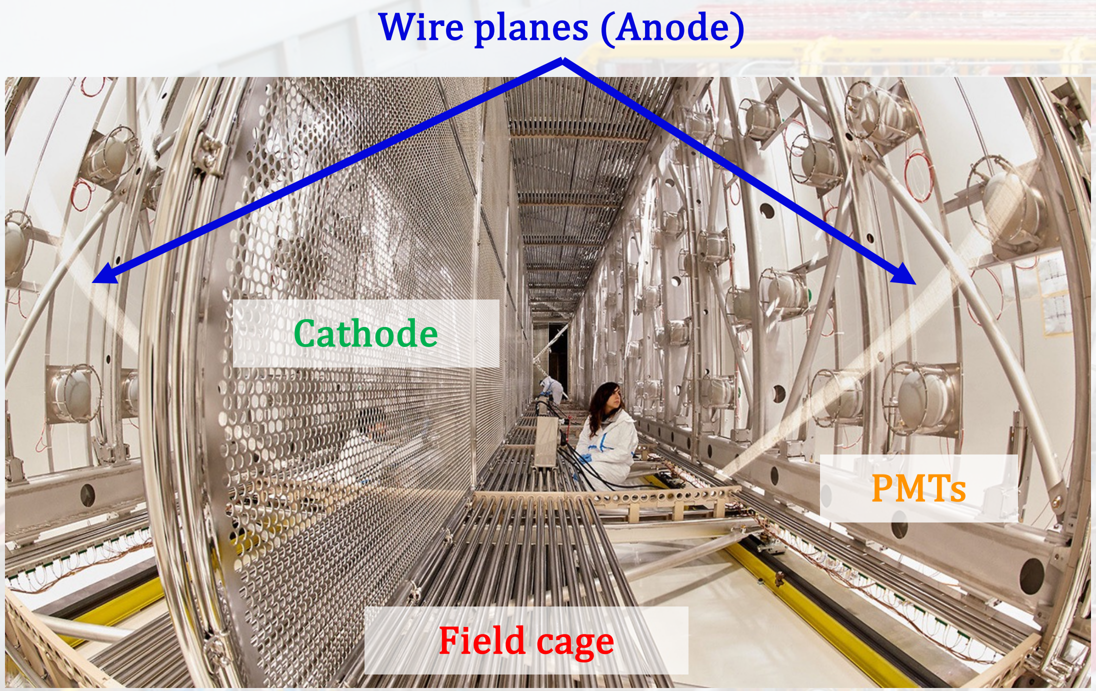
- ICARUS is also exposed ~ 6° off-axis to the NuMI beam and can access the ν_e rich component of the spectrum
- Both ν_e appearance and ν_μ disappearance channels can be observed, granting access to study the nature of the observed anomalies and shed light on the existence of sterile neutrinos





120 GeV proton beam on graphite target

The ICARUS detector



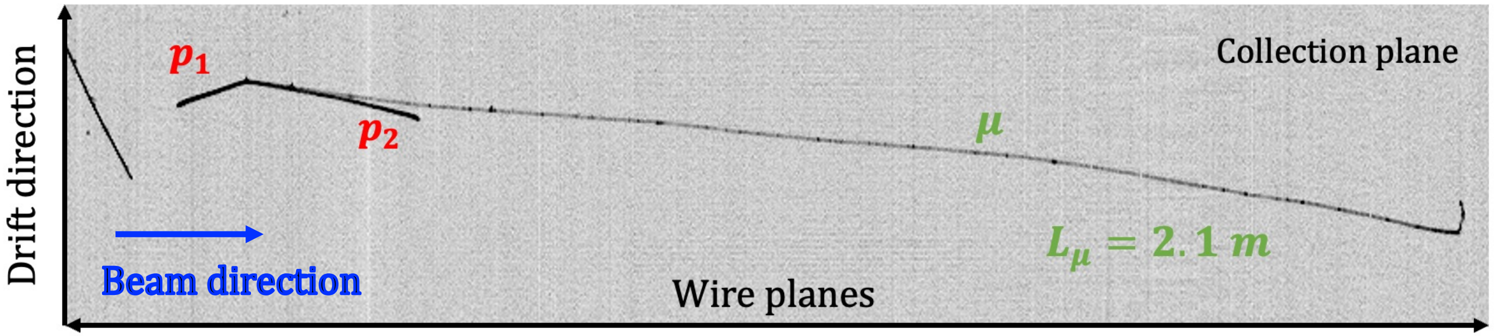
Inside ICARUS: internal view of one cryostat

- Uniform Liquid Argon time-projection chamber (LArTPC) detector
- First large LArTPC, still one of the largest in operation
  - 2 Identical modules with 476 *t* total active mass
- Self-triggering detector, with precise 3D imaging and calorimetric capabilities
- Previous operation at LNGS, ICARUS moved to FNAL after overhauling phase at CERN and INFN Labs

Ongoing physics analysis

- The near detector is getting ready to join the SBN program, in the meanwhile ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation hypothesis in the same L/E range (~ 1-3 m/MeV), but collecting $\sim \times 100$ more energetic events
  - ν_e disappearance channel from NuMI: selecting contained EM showers from quasi-elastic ν_e CC interactions
  - ν_μ disappearance channel from BNB: focusing on contained quasi-elastic ν_μ CC interactions

- BNB studies are performed on ν_μCC fully contained events with a single muon and at least a proton in the final state



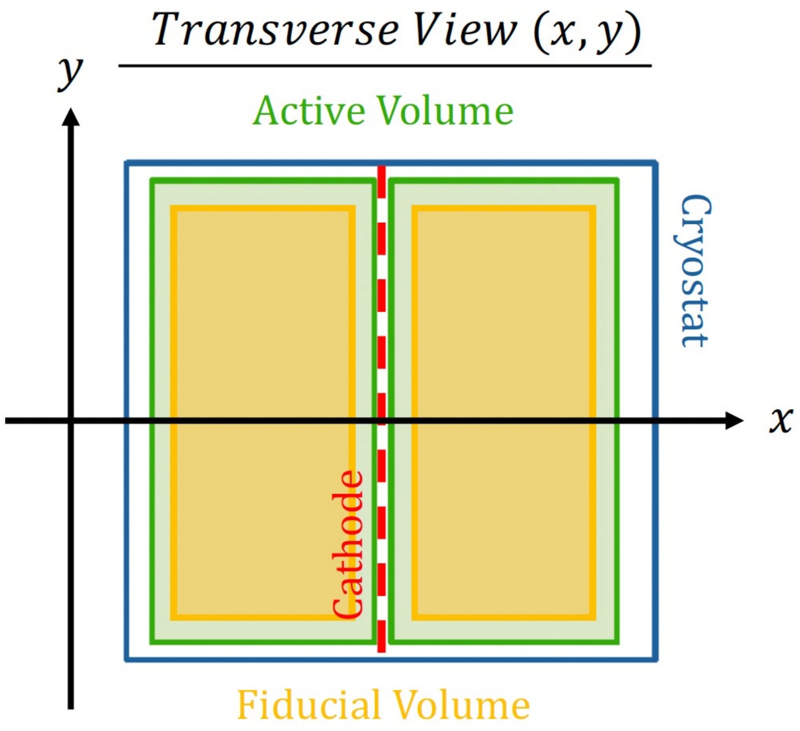
BNB neutrino event selection

- A first step towards this goal is to select events which:

    1. ν **vertex** should be inside the fiducial volume i.e., 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls
    2. **Fully contained** interactions i.e., no signal in the last 5 cm of the LAr active volume
    3. Stopping muon of $L_\mu > 50$ cm

- To further simplify, consider $\mathbf{1\mu 1p}$ candidates

    4. Only 1 proton $L_p > 1$ cm produced at the primary vertex



Automatic selection

- Due to the large number of collected events an automatic procedure to select $1\mu1$p candidates is mandatory
- Using the experience gained with previous analysis, a first test was performed on simulated events

$\nu +$ cosmics MC production with $\sim 2.88 \times 10^{20}$ POT

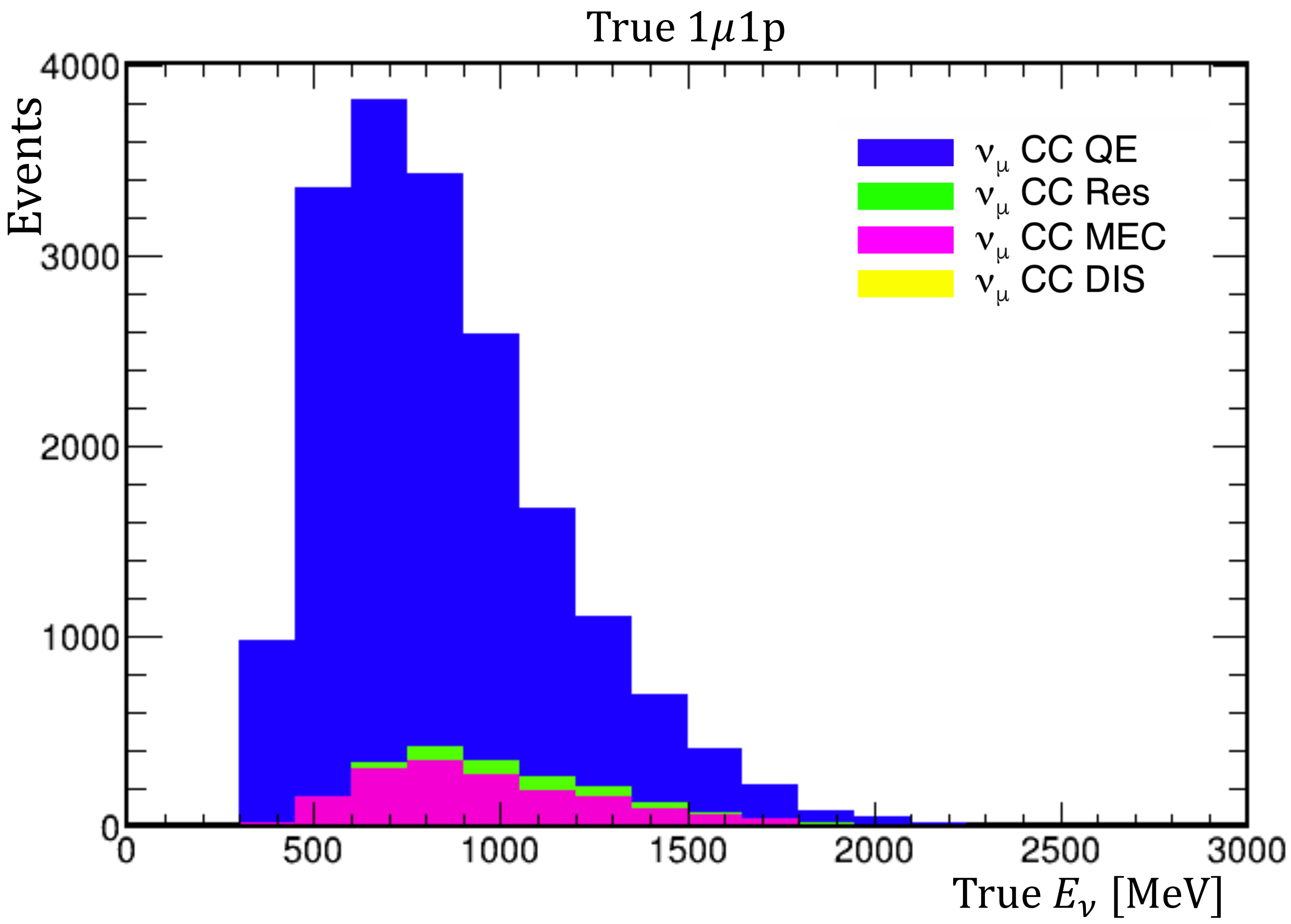
- **Truth** level definition of $1\mu1$p events
  - $\nu_\mu CC$ events with the interaction vertex inside the fiducial volume
  - 1 muon of at least 50 cm length
  - 1 proton with deposited energy $E_{dep} > 50$ MeV
  - **All** charged primary and secondary particles contained within 5 cm from the active TPC borders
  - No other particles with $E_{dep} > 25$ MeV

*50 MeV proton ≈ 2.3 cm length

Signal definition – truth level

- Using the previous definition and considering a MC exposure of $\mathbf{2.5{\times}10^{20}}$ **POT** (~ total data collected POT Run 1+2), ~18.5k **$1\mu1p$** signal events are expected with the following true energy spectrum

Contribution	2.5×10^{20} POT
$\nu_\mu CC$ QE	16440 (89.0%)
$\nu_\mu CC$ Res	375 (2.0 %)
$\nu_\mu CC$ MEC	1646 (8.9%)
$\nu_\mu CC$ DIS	16 (0.1%)
Total events	18477



Automatic event selection – $1\mu 1$p

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill

   To strongly reduce events whose trigger is produced by in-spill cosmics or not contained ν interactions

Automatic event selection – $1\mu 1$p

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill
2. Events with reconstructed vertex inside fiducial volume

   To have a better control of the event reconstruction

Automatic event selection – $1\mu 1$p

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill
2. Events with reconstructed vertex inside fiducial volume
3. TPC-PMT matching: require charge z-barycenter of interaction in the TPC to be within 1 m from the light z-barycenter of the triggering flash

To define the region of interest where the event is located, effectively rejecting out of spill cosmic events

Automatic event selection – $1\mu 1$p

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill
2. Events with reconstructed vertex inside fiducial volume
3. TPC-PMT matching: require charge z-barycenter of interaction in the TPC to be within 1 m from the light z-barycenter of the triggering flash
4. **All reconstructed** objects inside the slice need to be contained within 5 cm from the active TPC borders

   To select contained events and avoid space charge effect distortions

Automatic event selection – 1μ1p

1. CRT Veto: no CRT-PMT in-time matching inside the 1.6 μs beam spill
2. Events with reconstructed vertex inside fiducial volume
3. TPC-PMT matching: require charge z-barycenter of interaction in the TPC to be within 1 m from the light z-barycenter of the triggering flash
4. **All reconstructed** objects inside the slice need to be contained within 5 cm from the active TPC borders
5. Muon identification corresponding to the longest track in the slice satisfying
    - Start point within 10 cm from the reconstructed vertex
    - Length of at least 50 cm
    - Tagged as primary track
    - Track score ≥ 0.5
    - $\chi^2_\mu < 30$ and $\chi^2_p > 60$

- Track score: to distinguish between track and shower objects
- Custom version of χ^2: only using hits with dE/dx $\in$ (0.5, 100) MeV/cm
- Using plane with most hits between Induction 2 and Collection

Automatic event selection – $1\mu 1$p

6. 0 reconstructed pions: excluding the already identified muon, no reconstructed primary tracks fulfilling all the following requirements
   - Track score ≥ 0.5
   - within 50 cm from the interaction vertex, either the start or end point
   - $\chi_p^2 > 100$
   - Kinetic energy greater than 25 MeV, from track range under the pion hypothesis

To avoid distant primary tracks

Automatic event selection – 1μ1p

6. 0 reconstructed pions: excluding the already identified muon, no reconstructed primary tracks fulfilling all the following requirements
   - Track score ≥ 0.5
   - within 50 cm from the interaction vertex, either the start or end point
   - $\chi_p^2 > 100$
   - Kinetic energy greater than 25 MeV, from track range under the pion hypothesis

To avoid distant primary tracks

7. Only 2 visible primary PFPs: exactly 2 primary PFPs with more than 25 MeV of kinetic energy, where one of which needs to be the muon candidate. Only primary tracks within 50 cm from the reconstructed vertex are considered

PFPs: Reconstructed objects, either tracks or showers

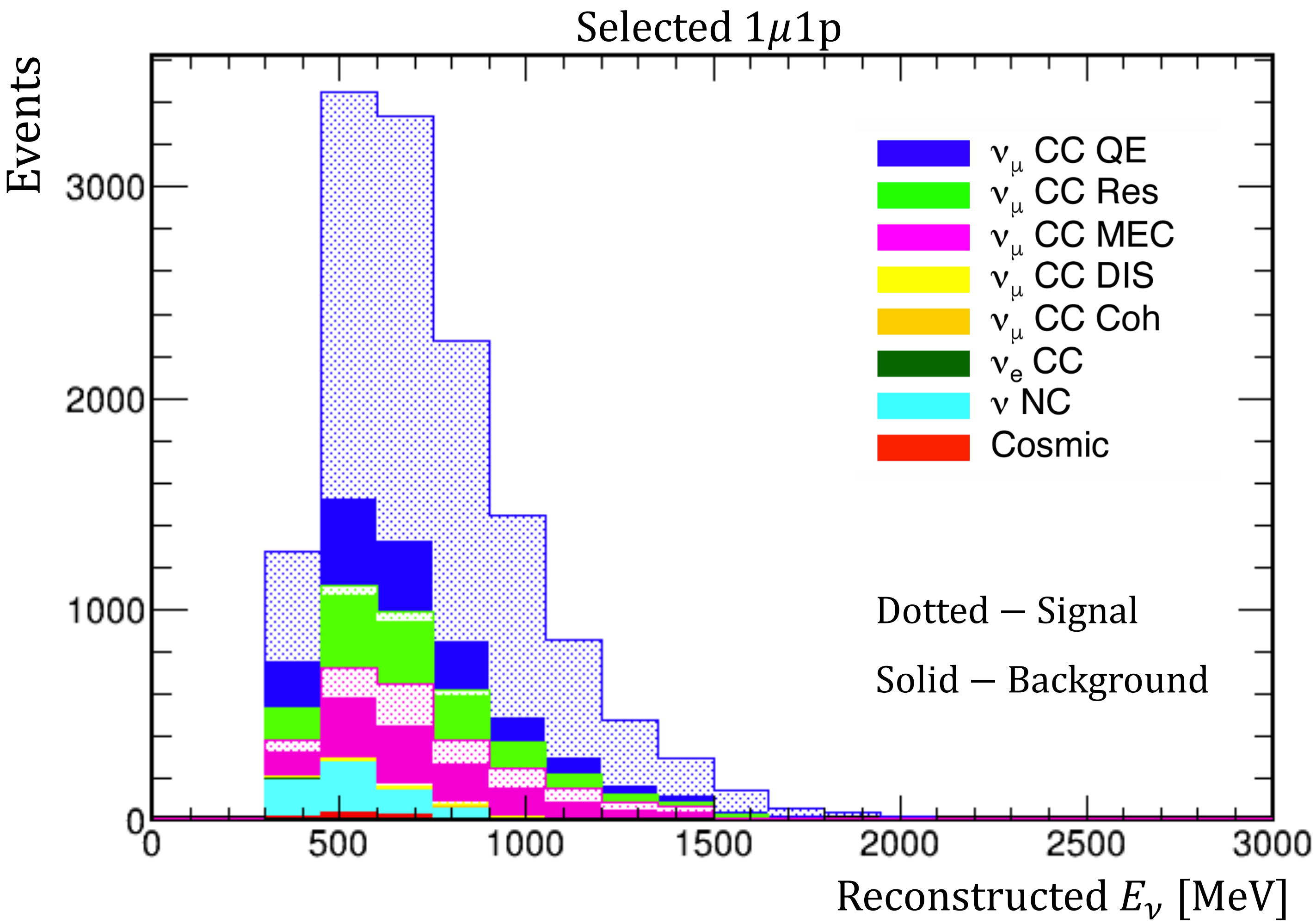
Automatic event selection – $1\mu 1$p

6. 0 reconstructed pions: excluding the already identified muon, no reconstructed primary tracks fulfilling all the following requirements
   - Track score ≥ 0.5
   - within 50 cm from the interaction vertex, either the start or end point
   - $\chi_p^2 > 100$
   - Kinetic energy greater than 25 MeV, from track range under the pion hypothesis

To avoid distant primary tracks

7. Only 2 visible primary PFPs: exactly 2 primary PFPs with more than 25 MeV of kinetic energy, where one of which needs to be the muon candidate. Only primary tracks within 50 cm from the reconstructed vertex are considered
8. Proton identification: the remaining PFP needs to be tagged as a proton candidate
   - Start point within 10 cm from the reconstructed vertex
   - Tagged as primary track
   - Track score ≥ 0.4
   - At least 50 MeV of kinetic energy, range-based measurement
   - $\chi_p^2 < 100$

Automatic event selection – $1\mu 1$p



*No Intime cosmics simulated. Preliminary studies showed that when included, cosmic contribution is ~ 1% of the total selected

$\mathbf{2.5 \times 10^{20}}$ POT

Contribution	Signal (%)	Bkg (%)
$\nu_\mu CC$ QE	59.1	10.8
$\nu_\mu CC$ Res	1.2	9.1
$\nu_\mu CC$ MEC	5.4	8.6
$\nu_\mu CC$ DIS	<0.1	0.6
$\nu_\mu CC$ Coh		0.1
$\nu_e CC$		<0.1
ν NC		4.2
cosmic		0.8
Total selected	8990	4692

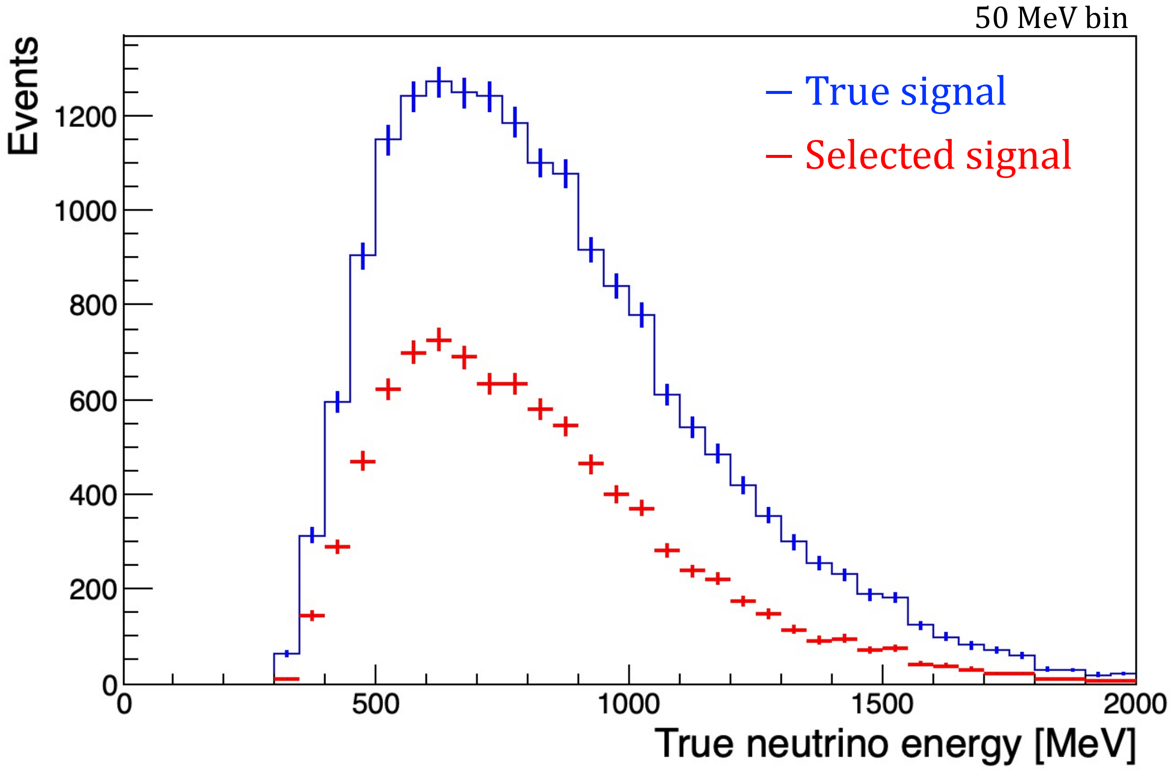
*% wrt total selected: 13682

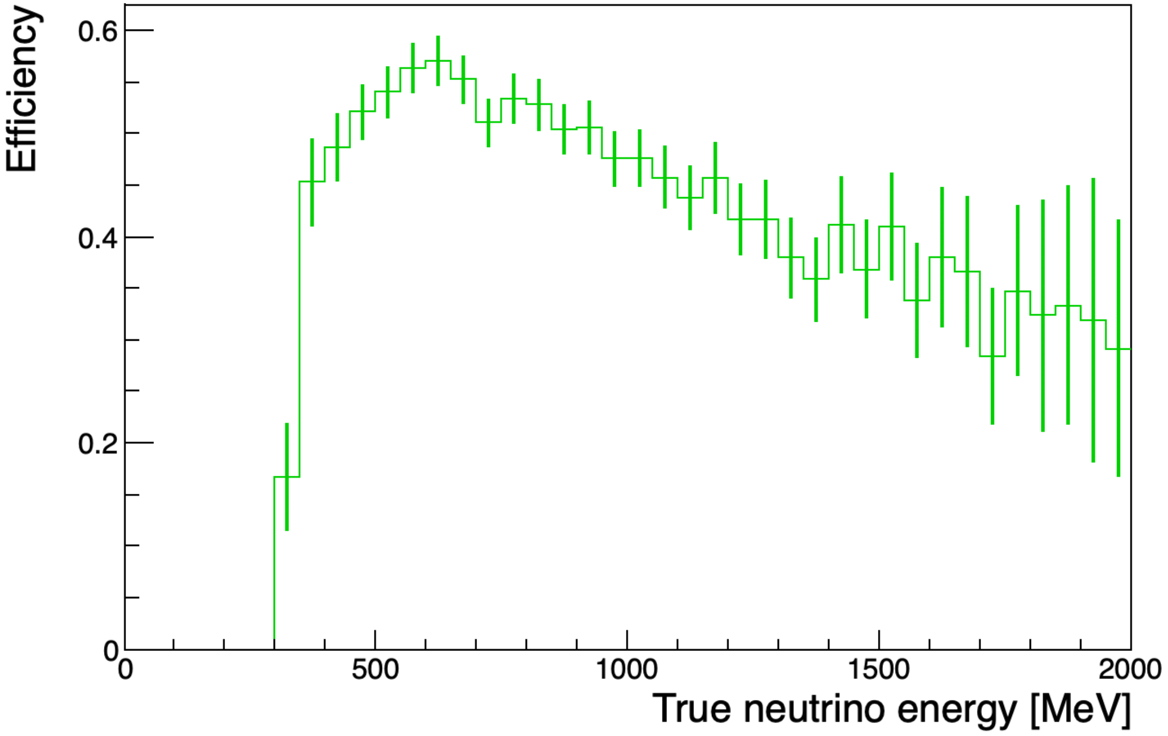
Automatic event selection – $1\mu1p$

- Efficiency of the **$1\mu1p$** selection as a function of the neutrino true energy

$$\text{Efficiency} = \frac{\textit{Selected signal}}{\textit{True signal}} \approx 49\%$$

$$\text{Purity} = \frac{\textit{Selected signal}}{\textit{All selected}} \approx 66\%$$



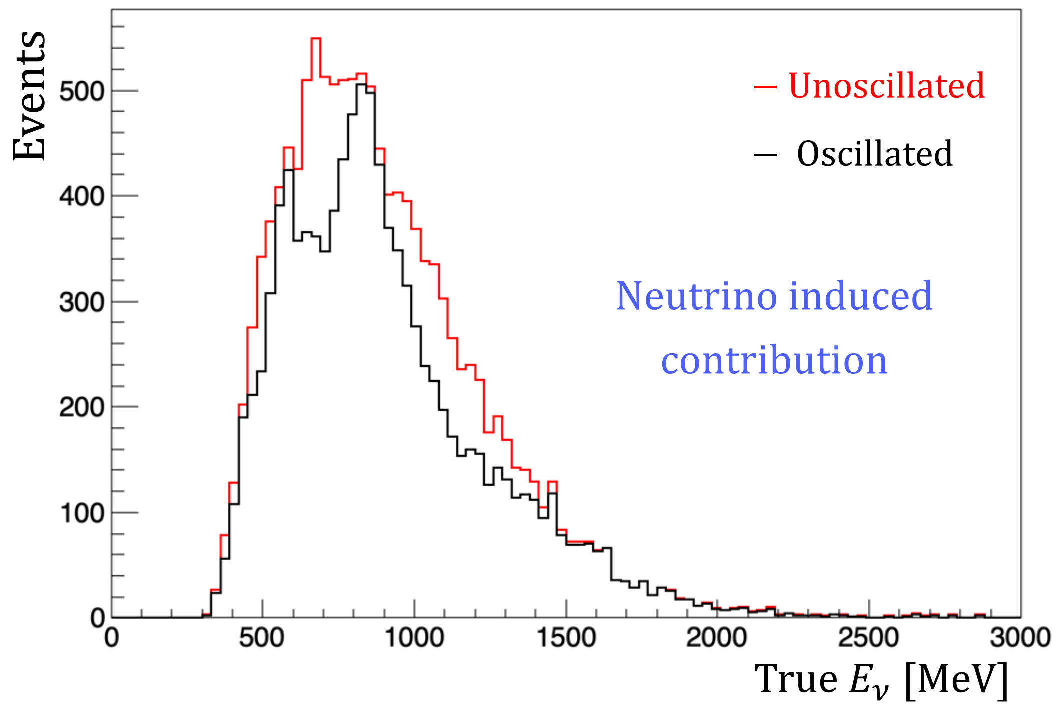


Oscillation hypothesis

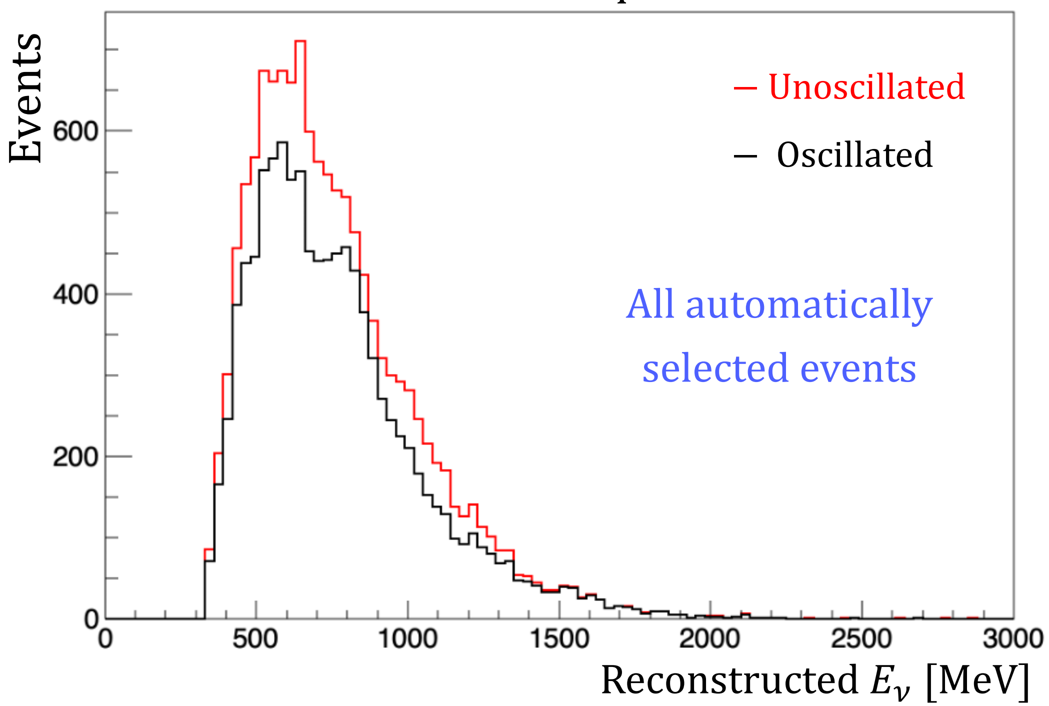
- The ultimate goal of the event selection is to provide an oscillation measurement
- Example of a **hypothetical** ν_μ disappearance assuming the Neutrino-4 $\bar{\nu_e}$ amplitude and Δm^2

$P(\nu_\mu \longrightarrow \nu_\mu)_{SBL} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 1.27 \frac{\Delta m^2_{41} L}{E_{\nu_\mu,true}}$ with $\sin^2 2\theta_{\mu\mu} = 0.36$, $\Delta m^2_{41} = 7.3$ eV^2, $E_{\nu_\mu,true}$ and L the true baseline

Before reconstruction effect

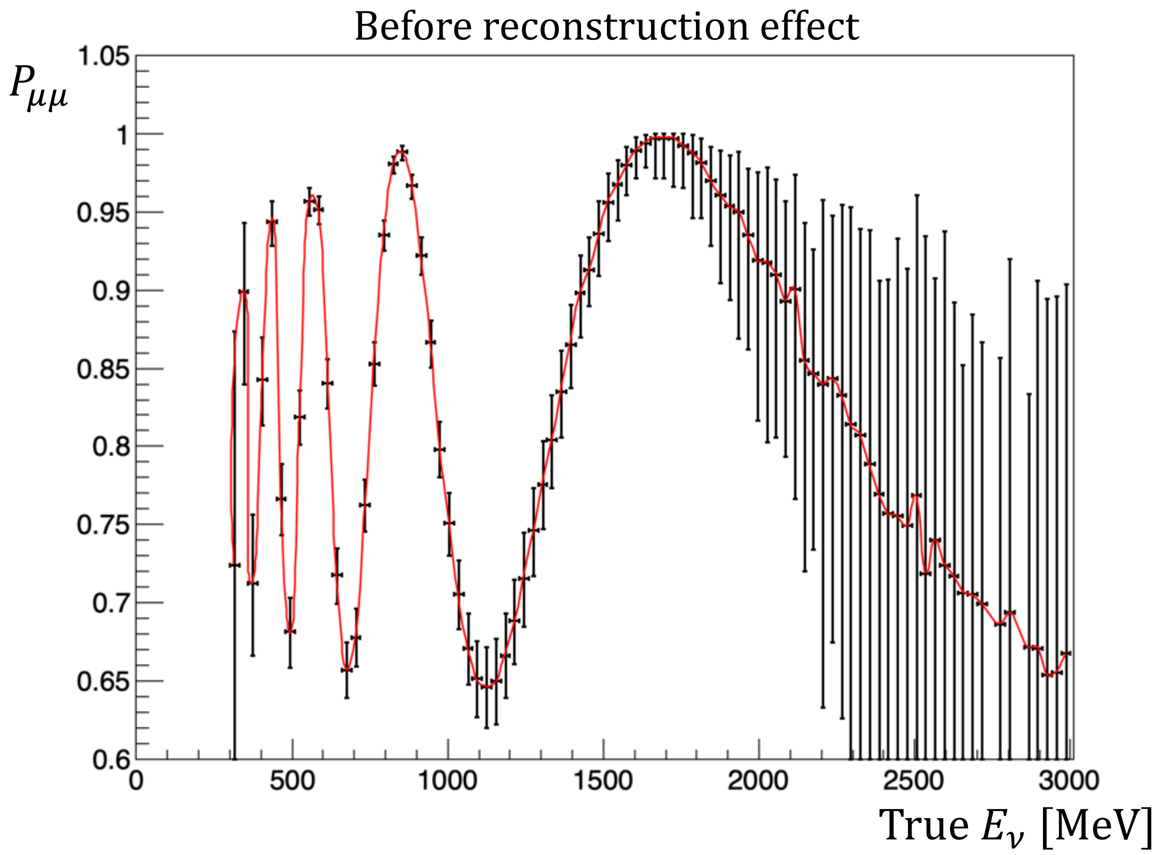


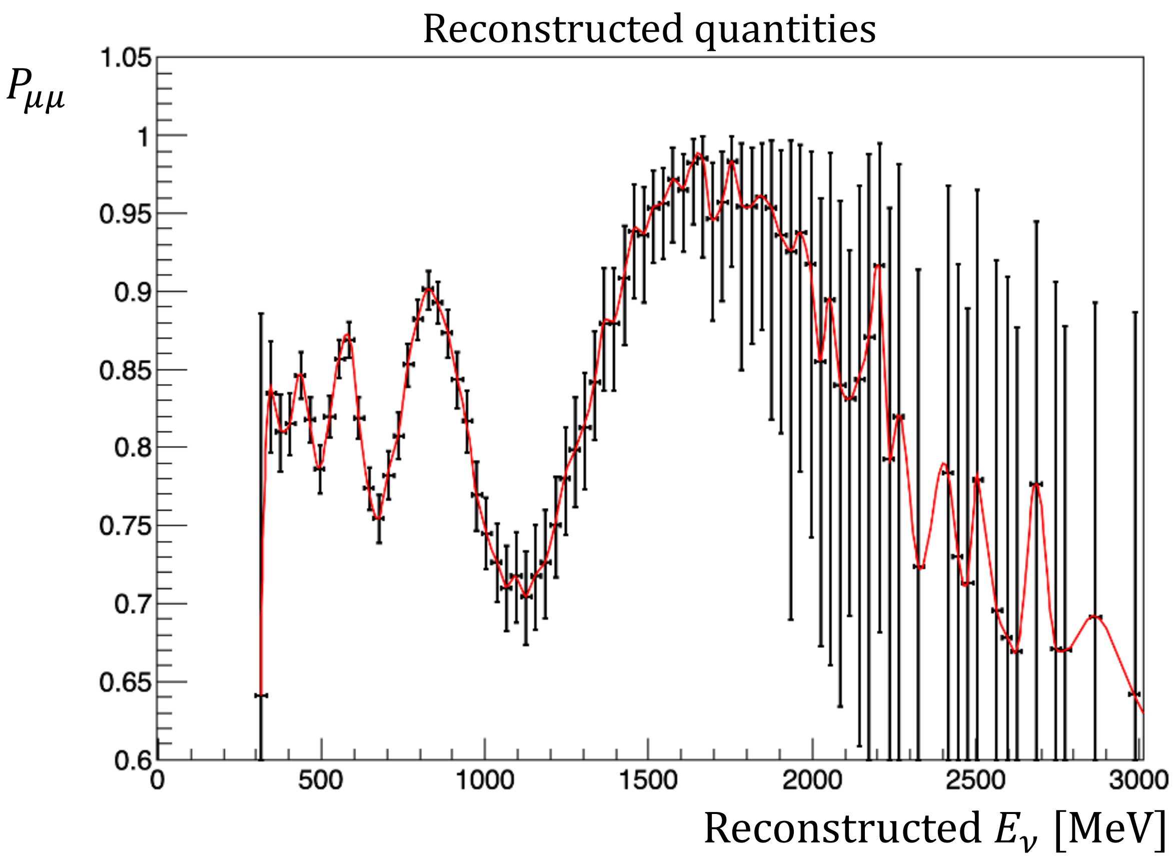
Reconstructed quantities



Oscillation hypothesis

- The survival probability is obtained dividing the oscillated energy spectrum with respect to the unoscillated one



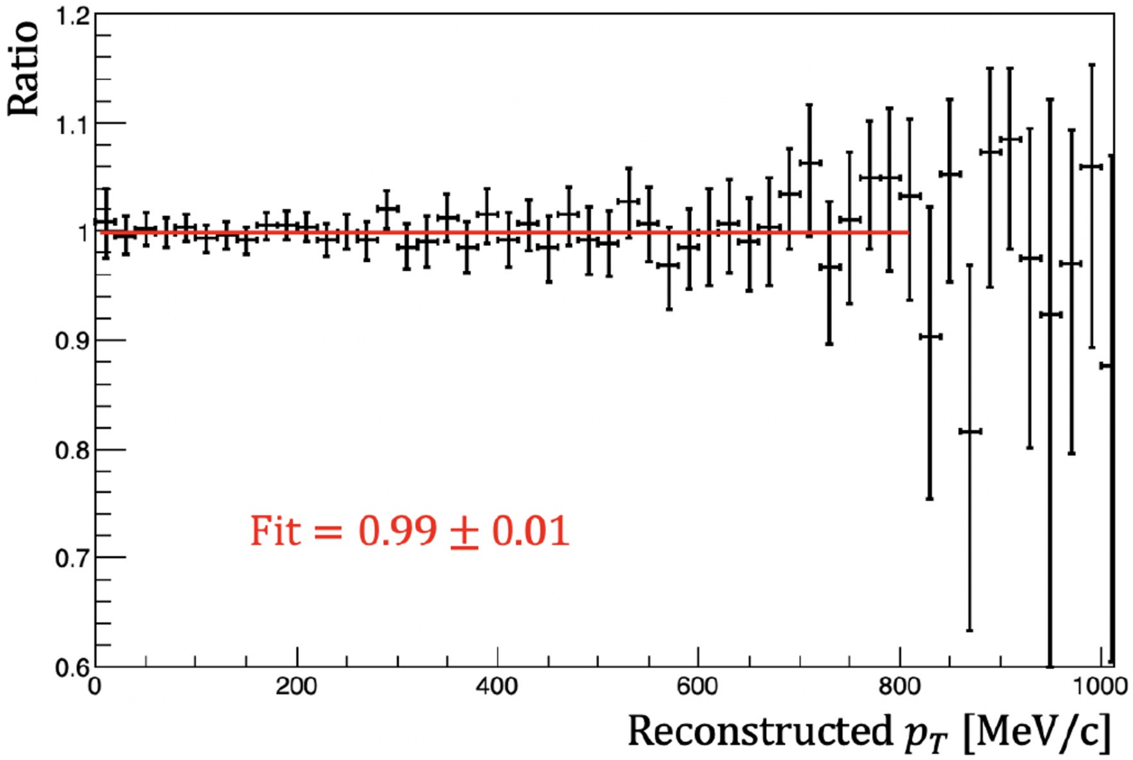


*Only statistical errors are shown

Oscillation hypothesis

- The transverse momenta was also studied showing that it is **not** affected by the mixing of sterile-active neutrino

Can be exploited without inferring any neutrino oscillation property



*Only statistical errors are shown

Data – MC Comparison

- Data efficiency and purity were evaluated using Run 9435 ($\sim 2\times10^{18}$ POT), where 143 1μ1p candidates were selected. These were classified as:
  - 109 1μ1p
  - 17 1μ2p
  - 10 other interactions
  - 7 not contained

- 76% of Purity was found while a 47% Efficiency was evaluated from 100 events (flat scan)
- Visual scanning of MC events showed that the method tend to overestimate the purity, hence obtaining compatible results with simulation values, given also the small data statistics
  - MC study: 66% Purity and 49% Efficiency

Data – MC Comparison

- The statistics used to produce the following Data – MC absolute comparison for the **$1\mu 1p$** selection are:
  - Data sample, which corresponds to 2.24×10^{19} POT (~10% of total Run2 POT)

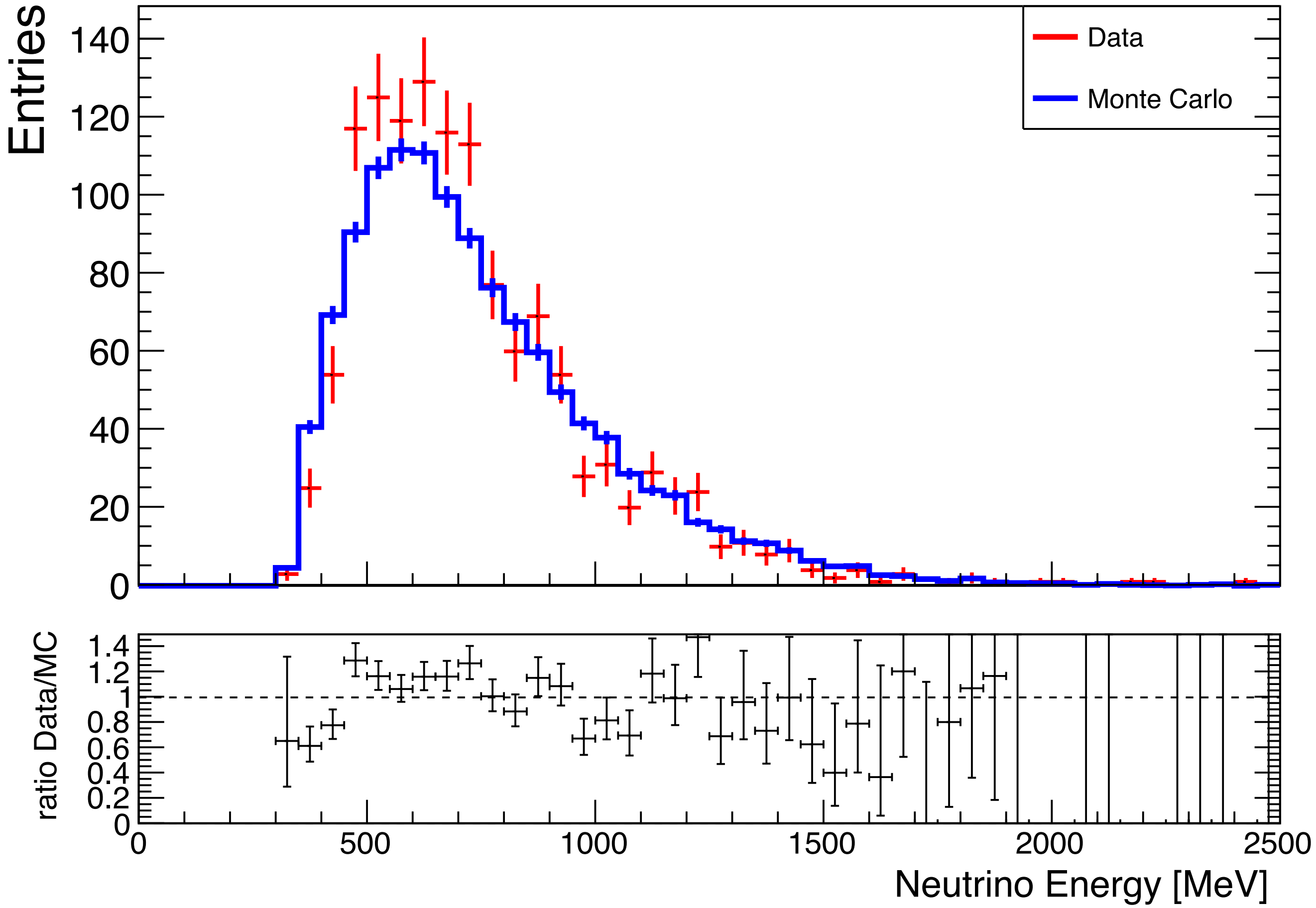
    → 1277 **$1\mu 1p$** selected candidates
  - Full MC simulation (2.88×10^{20} POT), scaled down to the Data POT (2.24×10^{19} POT)

    → 1226 **$1\mu 1p$** selected candidates (15782 events considering all statistics)

- MC has been divided into signal and background components and also broken down by interaction channels
- Only statistic errors will be shown, however huge effort is ongoing to include full systematic uncertainties soon

Data – MC Comparison

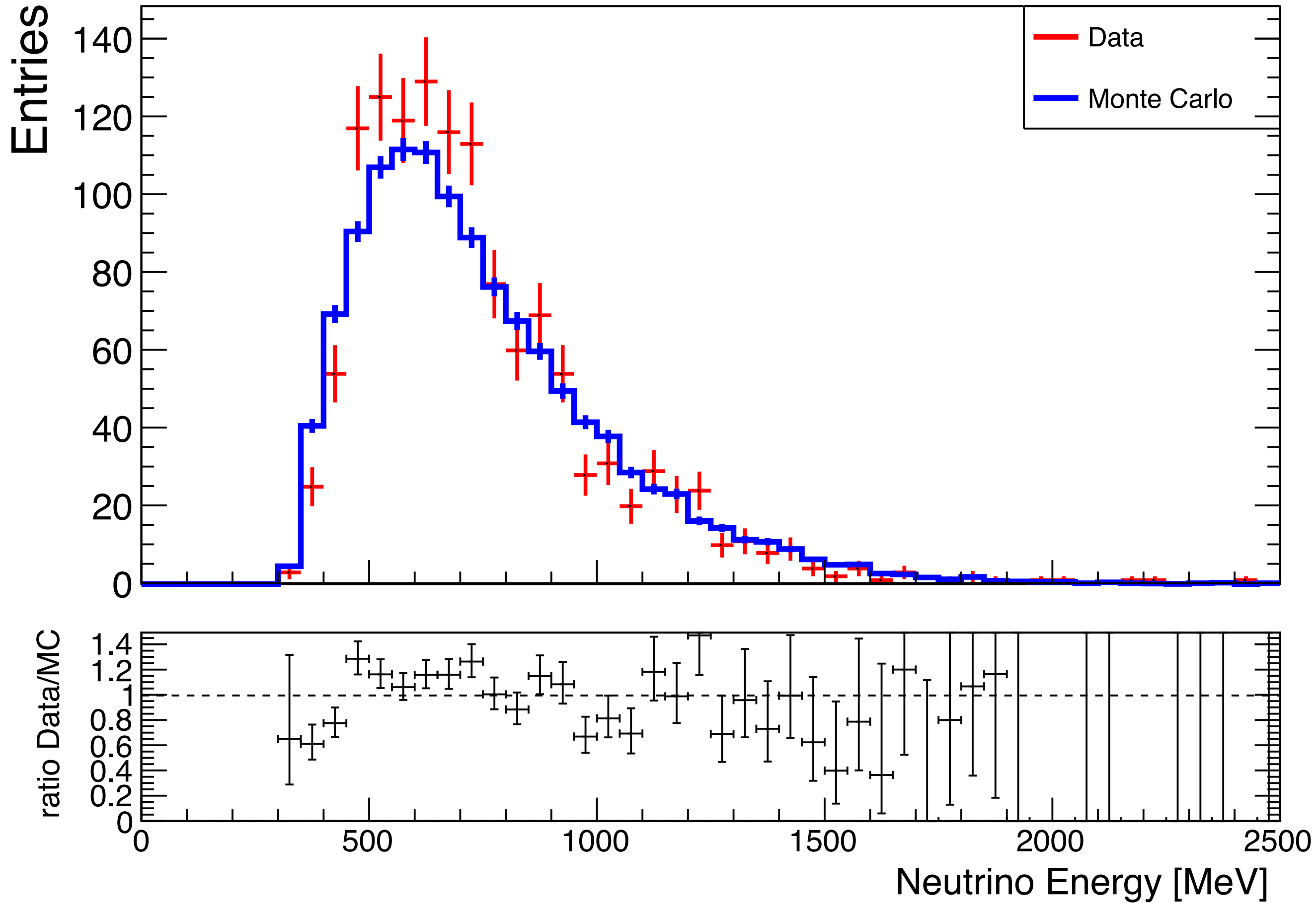
- Reconstructed neutrino energy following the method proposed in [Physical Review C 95.6 (2017): 065501]

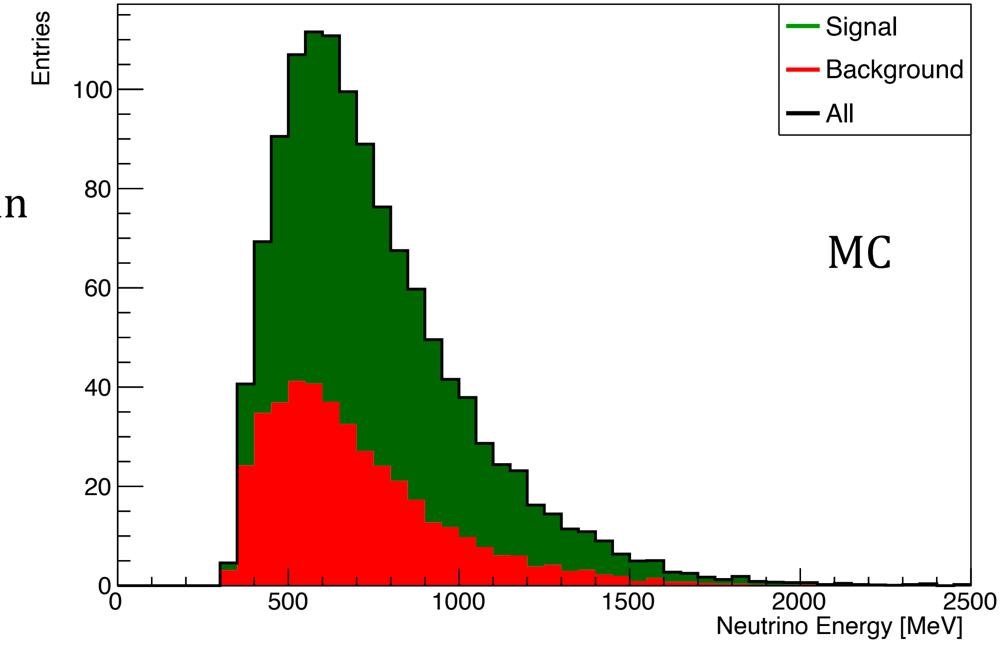


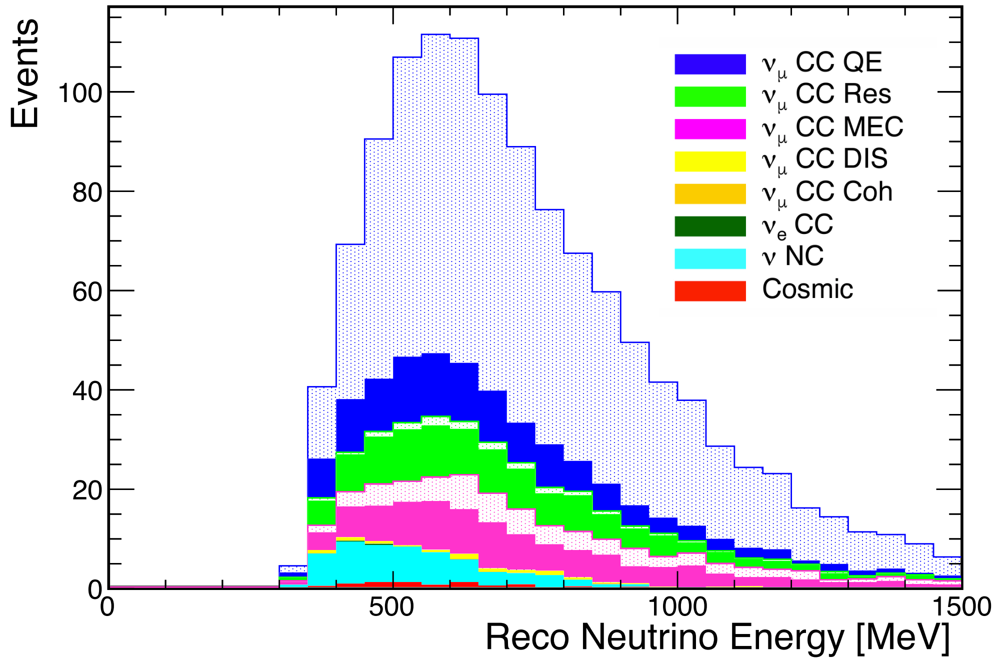
- Muon and proton energies are calculated from the measured range-based momentum
- Assuming a QE-like interaction and accounting for the Fermi motion of the struck nucleon
- In this case a constant binding energy was used ($E_b = 21.8$ MeV)

Data – MC Comparison

- Reconstructed neutrino energy following the method proposed in [Physical Review C 95.6 (2017): 065501]

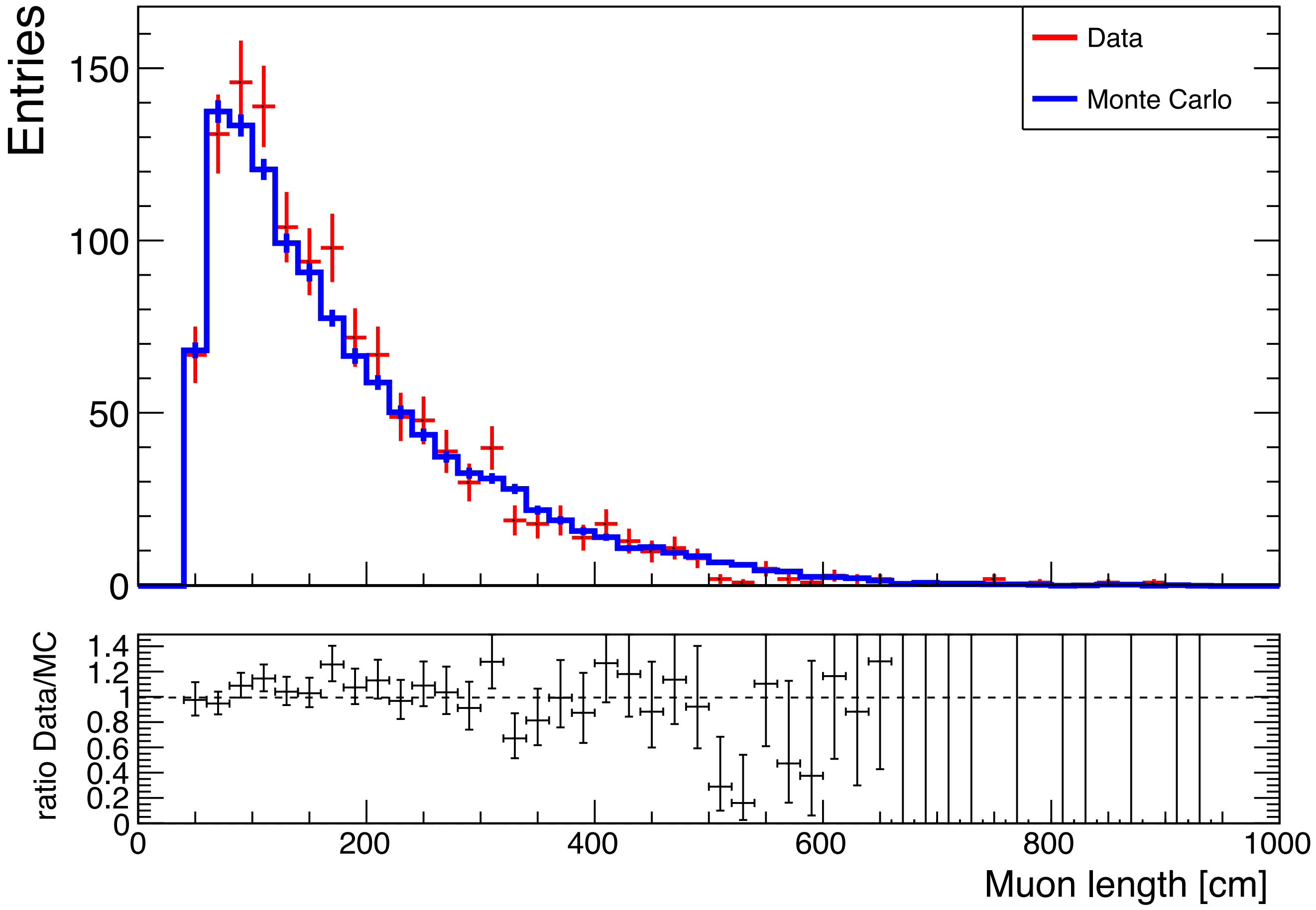


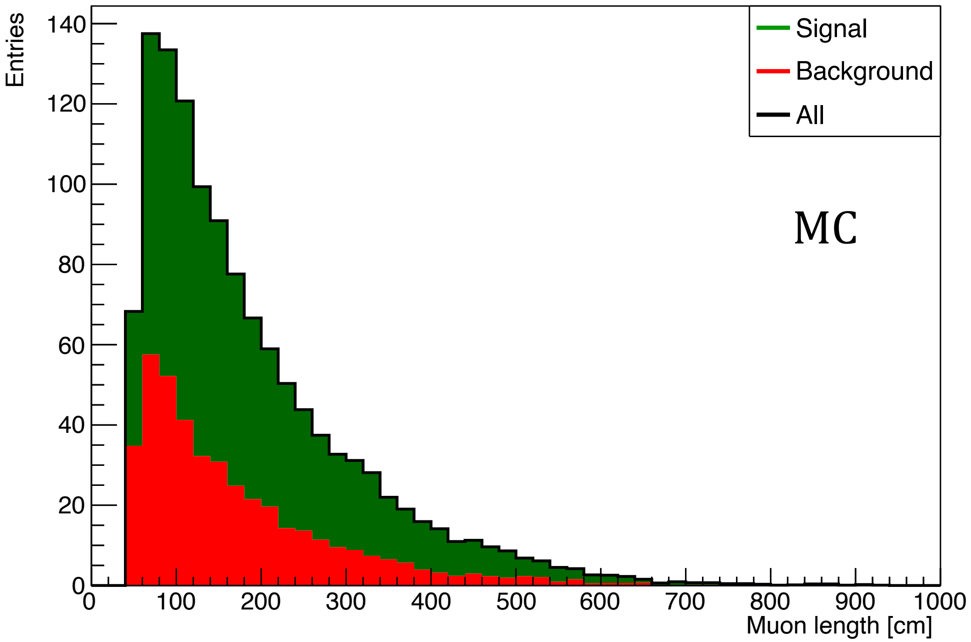


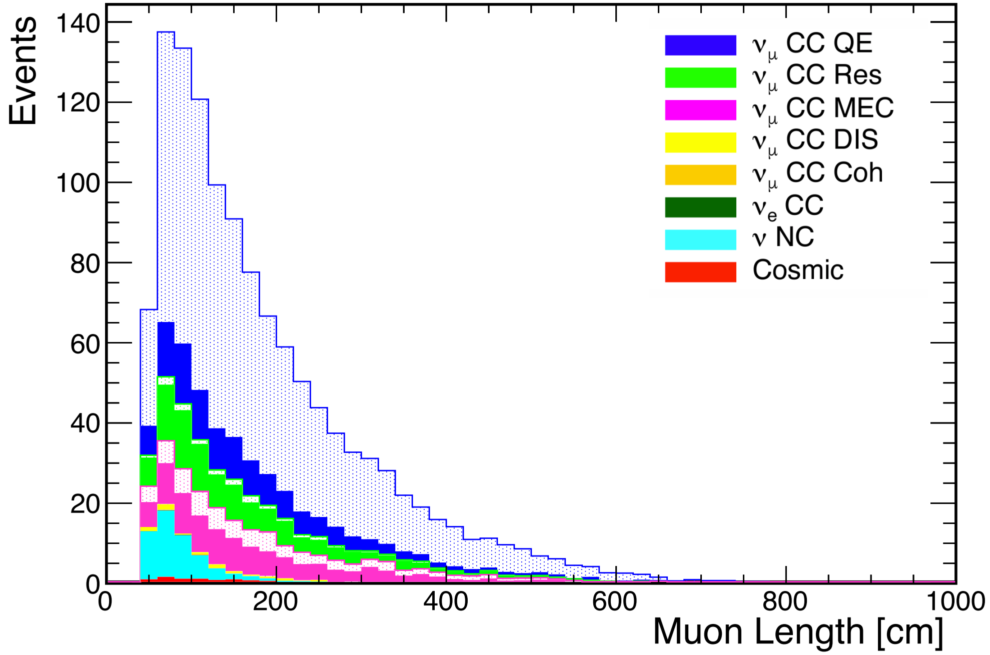


Data – MC Comparison

- Good agreement is observed in the reconstructed muon length

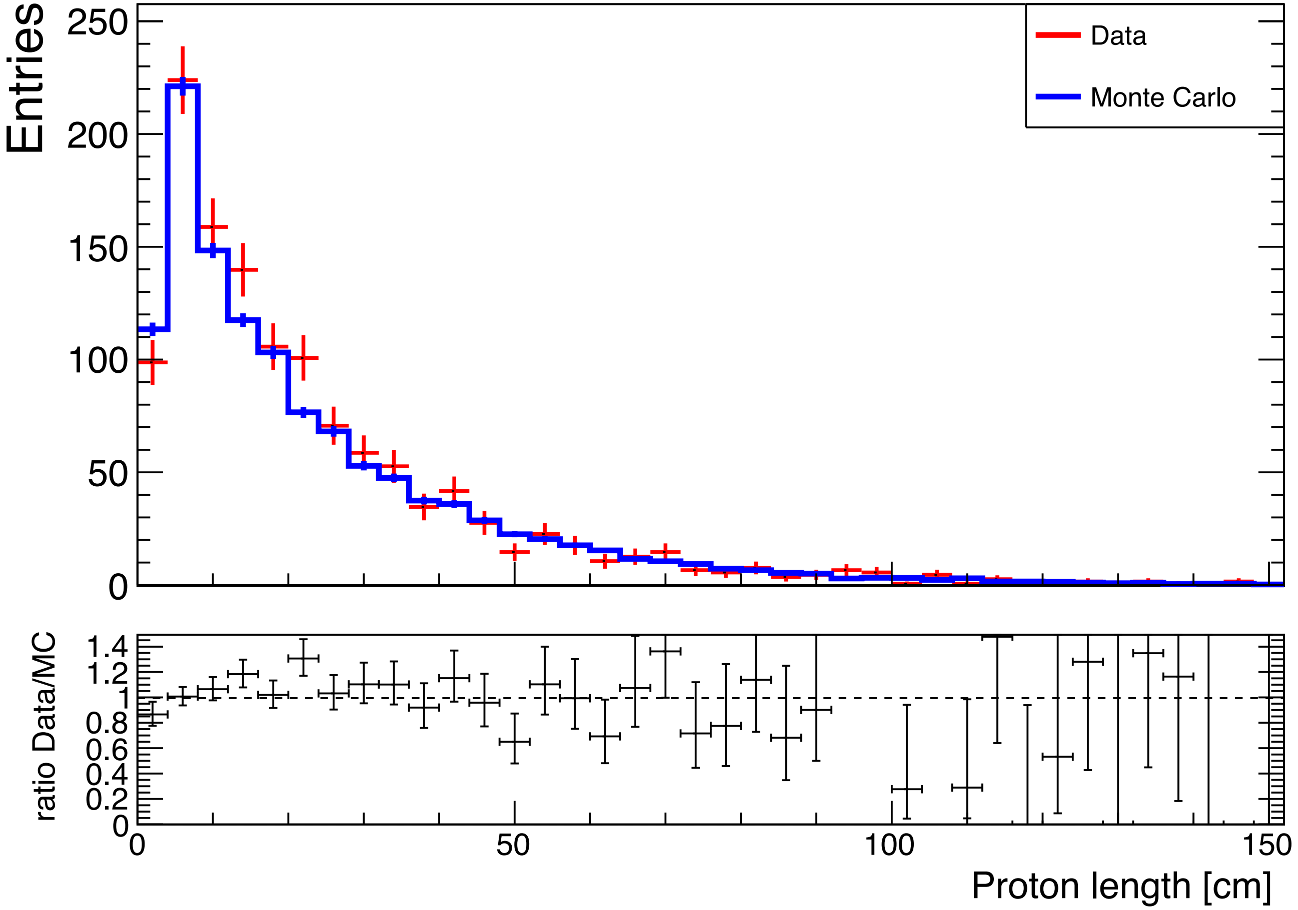


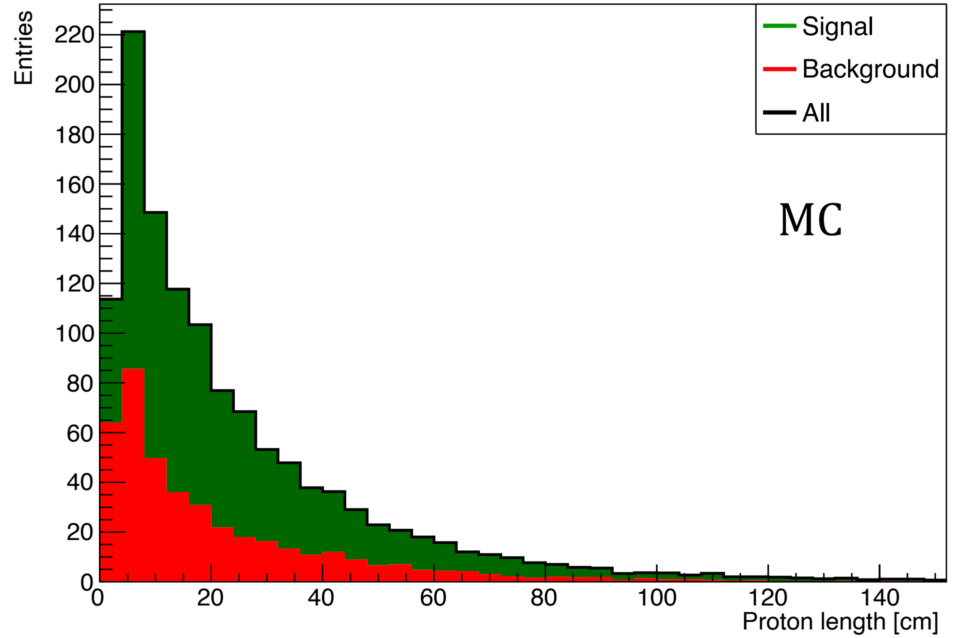


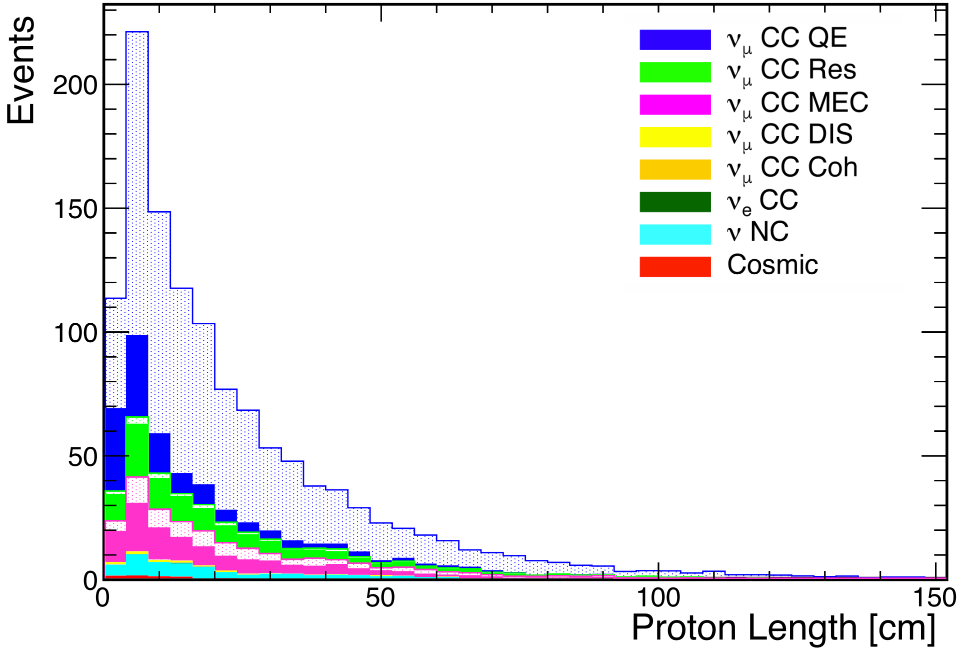


Data – MC Comparison

- Reconstructed length of the proton candidate

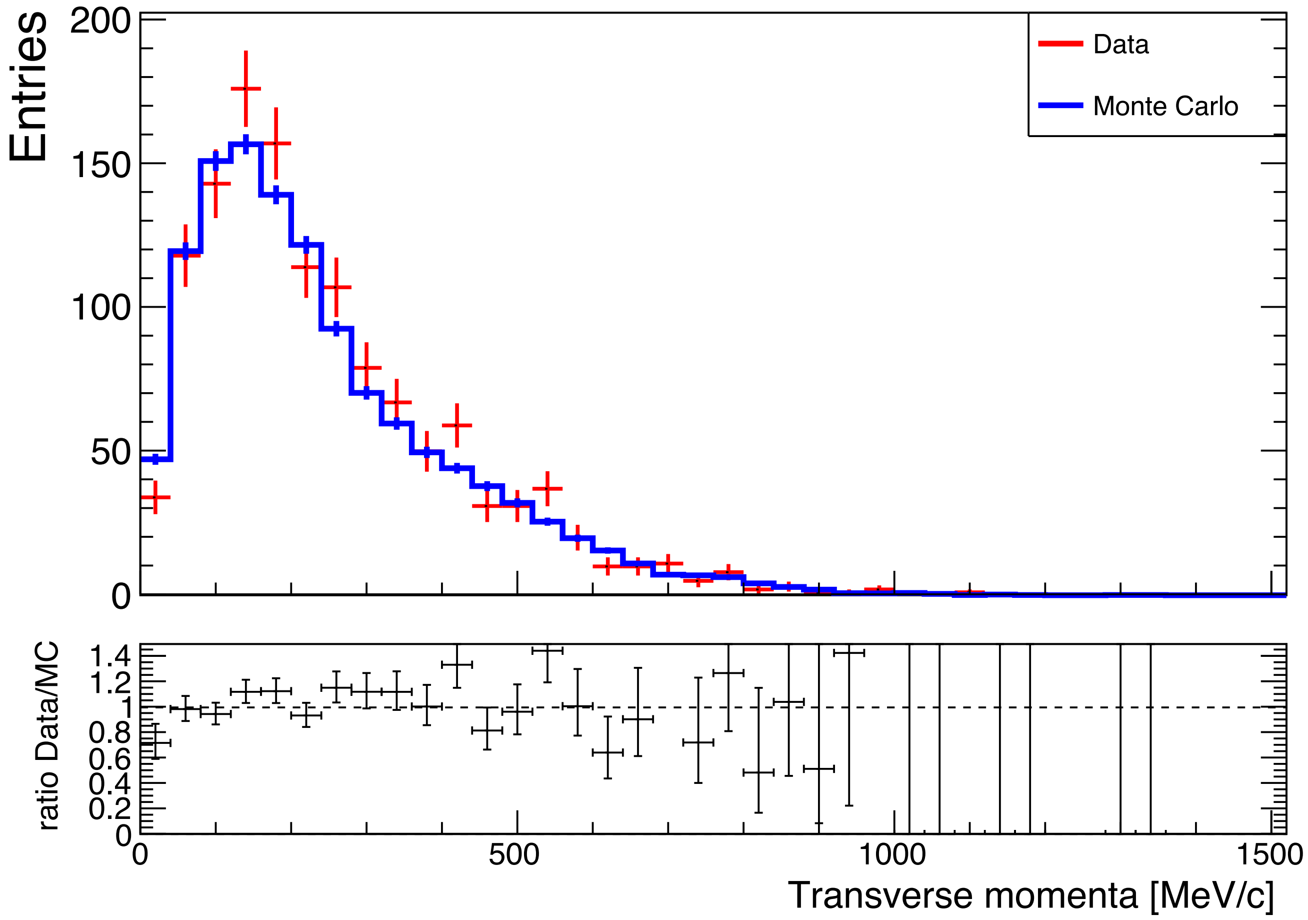


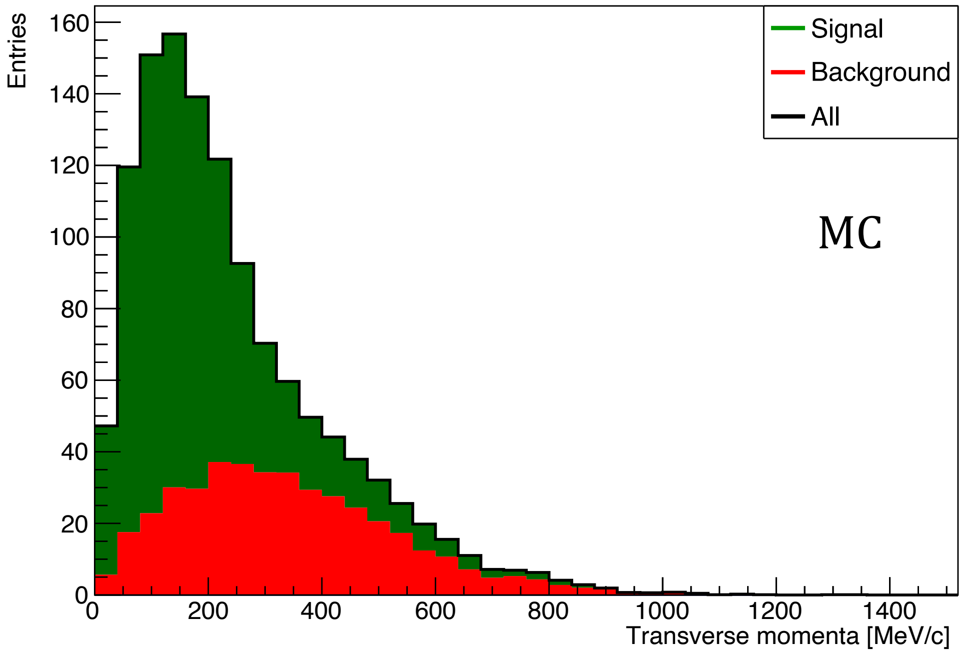


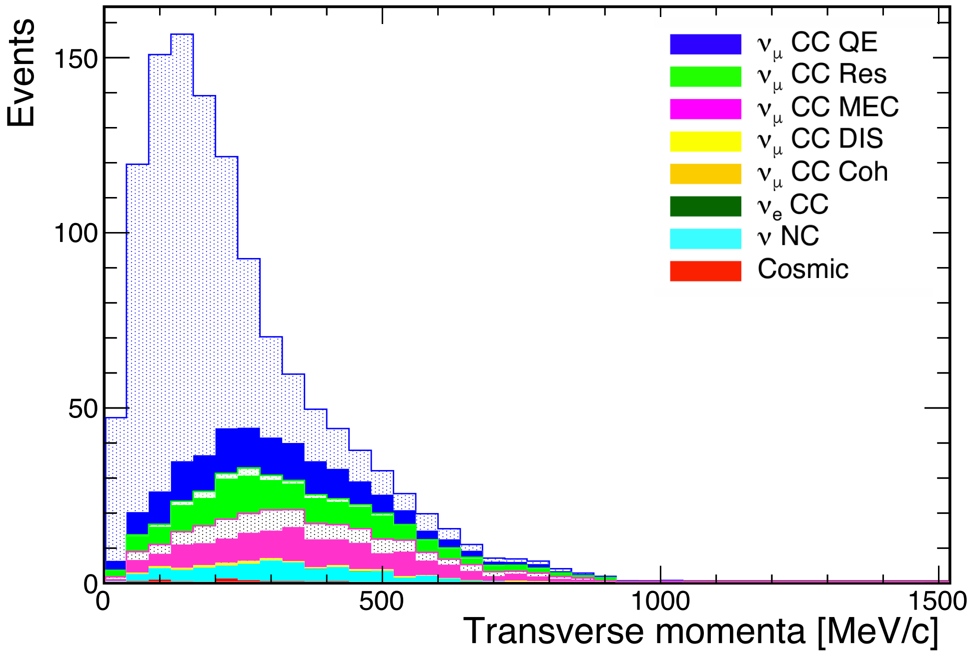


Data – MC Comparison

- Total transverse momentum of the neutrino interaction

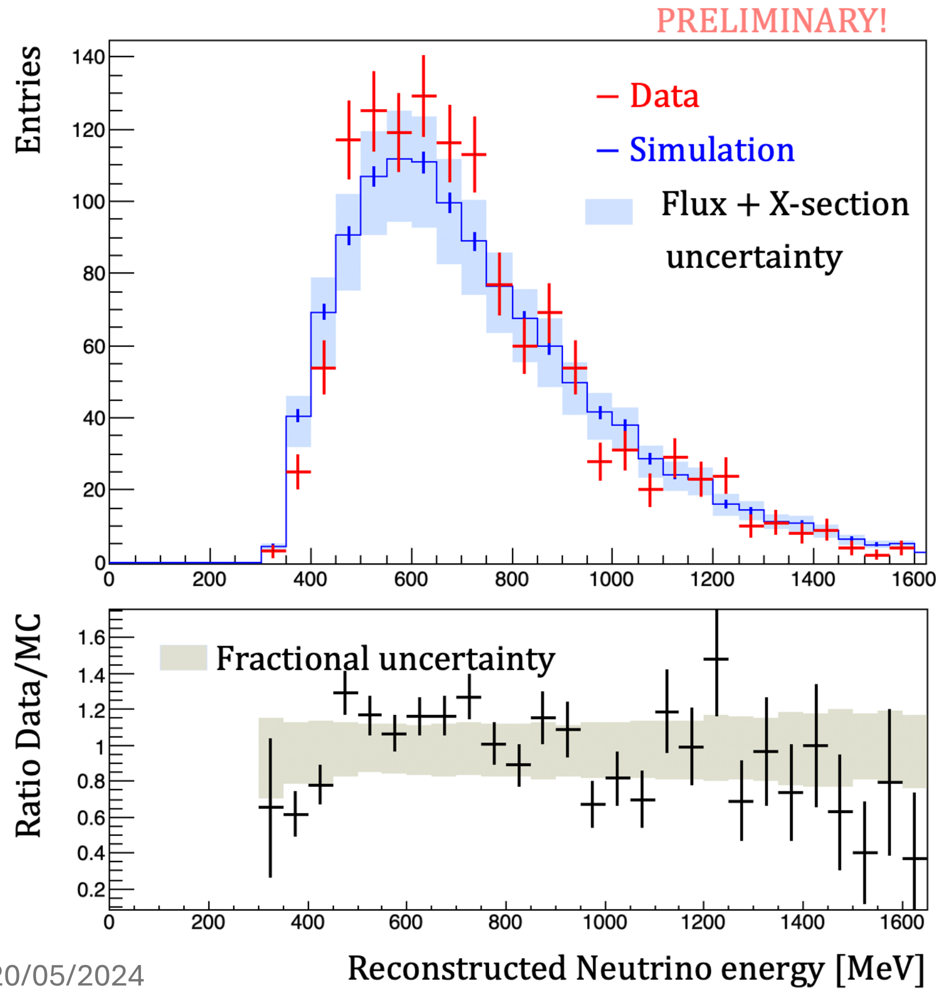


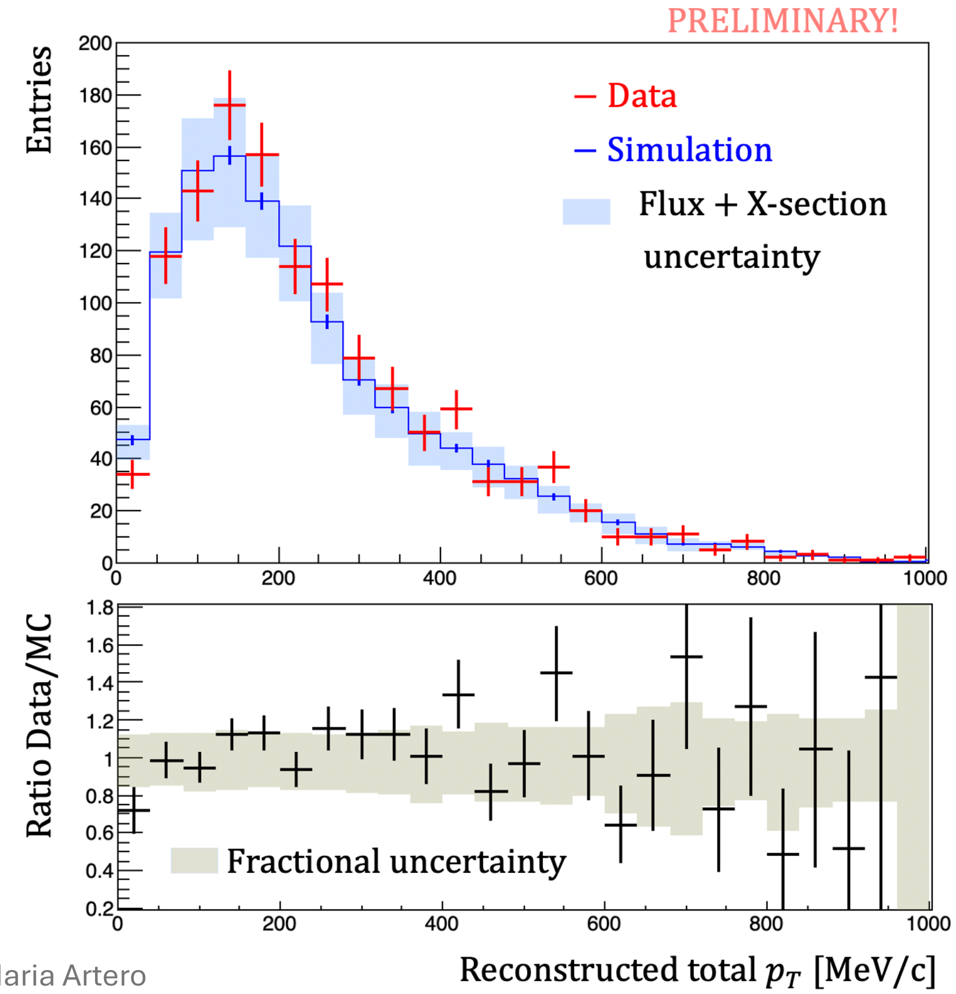




Systematics

- This is very preliminary and more work needs to be done, but the following systematics include **flux** and **cross section** uncertainties for the reconstructed neutrino energy and transverse momenta





Conclusions

- The $\boldsymbol{1\mu1p}$ selection is ready to be used
  - Reasonable agreement is seen between Data – MC, even when only statistical errors are considered
  - Possibility to further tune selection criteria, also profiting of transverse variables, to optimize the reconstruction performance and minimize systematic errors
  - Extend the selection to $1\mu Np$ sample and benefit from all the studies performed with the $1\mu1p$ sample
  - Still some work to be done to evaluate systematics for a more complete understanding of the current situation, f.i. detector systematics
  - Start thinking about possible side bands if we want to move forward with this selection
  - BNB and NuMI beams were back in March, so we are currently under Physics Run 3!

Backup slides

Neutrino Energy resolution

- Neutrino energy resolution for all neutrino interactions selected with the automatic selection