Status of the ICARUS reconstruction and analysis

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1. Neutrino anomalies and ICARUS research program;
2. Event reconstruction tools;
3. Event selection and analysis;
4. Conclusion.

Neutrino related anomalies ?

From Carlo presentation

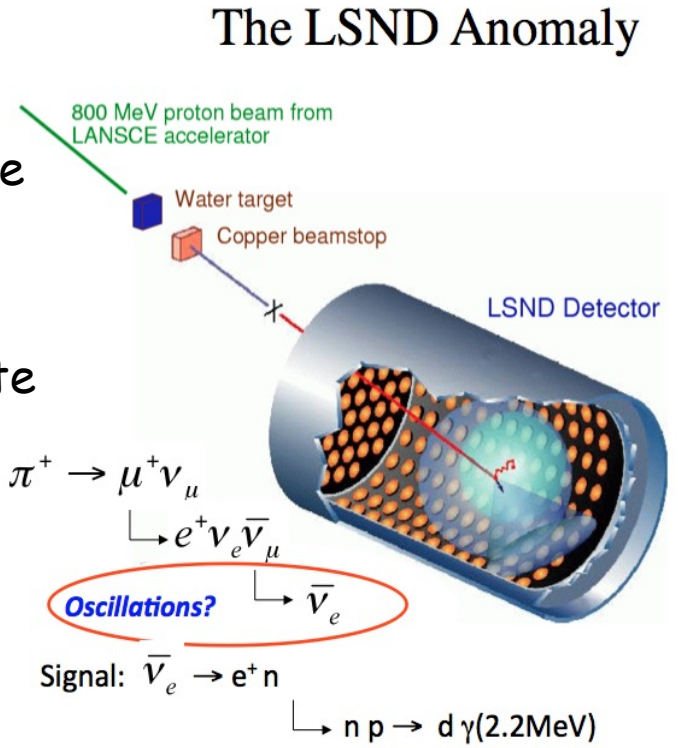
- For several decades, many anomalies beyond an ordinary 3-flavour mixing picture have been collected in the neutrino sector, suggesting the existence of some additional new related physics:

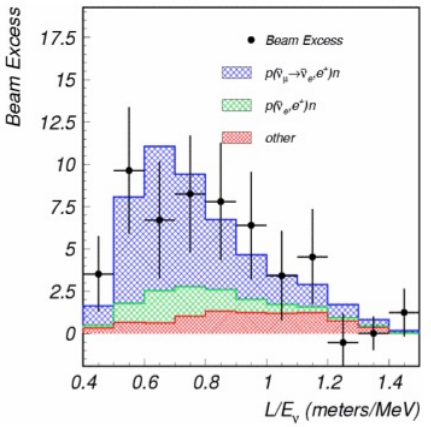
  - anti–ν_e appearance: anti-ν_μ in the accelerator LSND experiment; Reaction is anti ν_e to e^++n with n captured by a p; n + p into d + γ.

  - ν_e disappearance: SAGE, GALLEX experiments with Mega-Curie sources and observed/predicted rate R = 0.84±0.05;

  - anti-ν_e disappearance of near-by nuclear Reactor experiments and rate R = 0.934±0.024

  - recent observation of sterile neutrino oscillations by the Neutrino-4 experiments.





Saw an excess of $\bar{\nu}_e$: 87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

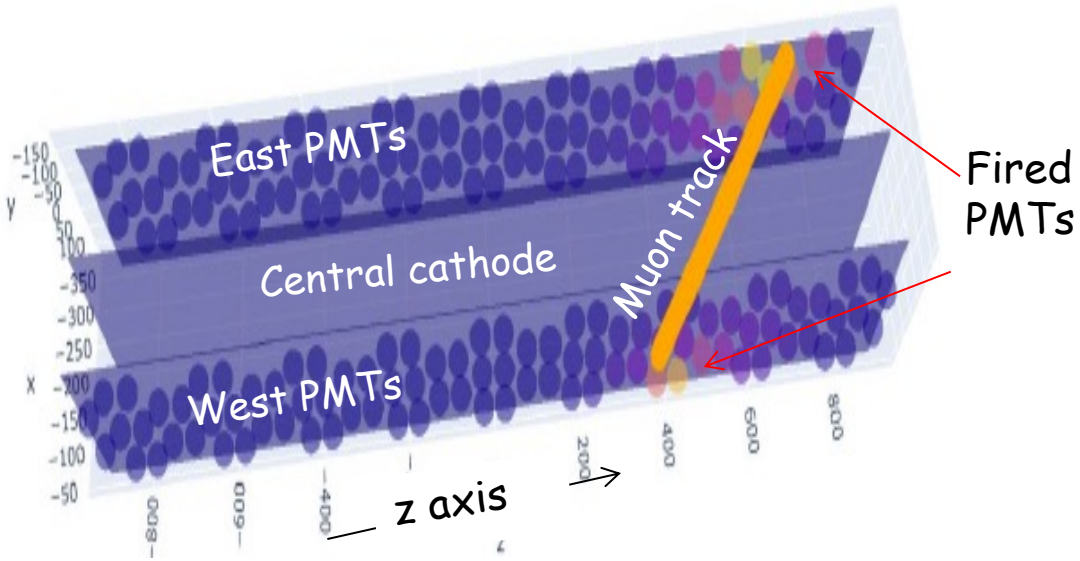
3.8 σ evidence for oscillation.

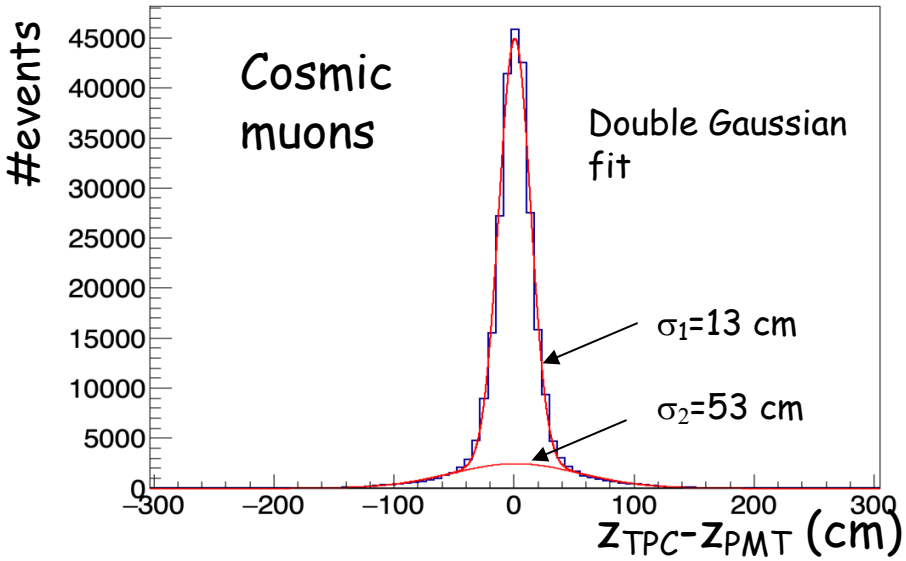
ICARUS Research Program

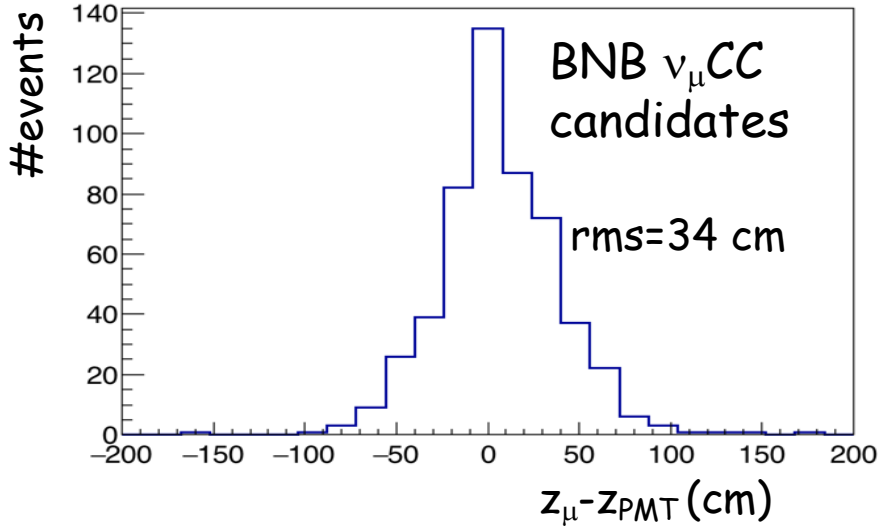
- The SBN program should clarify the question of the sterile neutrino exploiting the BNB beam and comparing the ν_e and ν_μ interactions observed at different distances along the BNB beam by ICARUS and SBND.
- However, as pointed out by Carlo Rubbia, the Neutrino-4 measurement is a very exciting new result that could change all the sterile neutrino anomaly story, related also to dark matter puzzle. Data collected by ICARUS from the Booster and NuMI beams is sufficient to address the Neutrino-4 claim.
  - Before the joint operation with SBND, ICARUS is initially focused on studying ν_μCC quasi elastic interactions with BNB. A similar study of ν_eCC quasi elastic interactions with the NuMI beam will be then performed.
- In parallel, the study of ν_e, ν_μ events from NuMI will also allow to measure ν-Ar cross sections and optimize ν reconstruction/identification in an energy range of interest for DUNE. The NuMI beam will allow an initial search for sub-GeV Dark Matter.
- Event reconstruction and analysis tools developed for these single detector analyses will be exploited in the next stage for the joint SBN program.
- The status of the event reconstruction and selection is presented in the following.

2. Event reconstruction tools: event localization with scintill. light

- The simple algorithm comparing the track and the light barycenter (z_{TPC}, z_{PMT}) has been validated with cosmic muons and with a set of visually identified BNB ν_μCC candidates with Lμ>50 cm







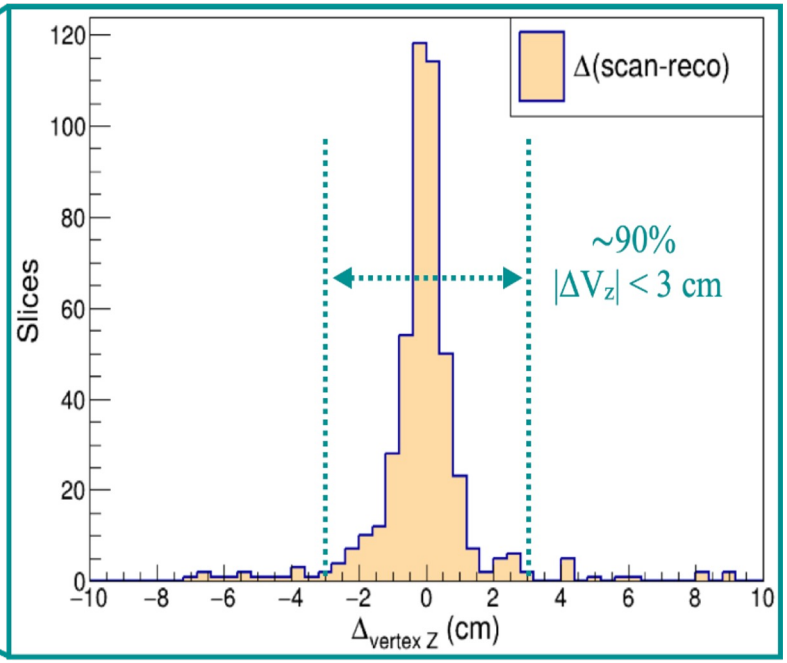
- A more sophisticated algorithm to match TPC events with the light is available within SBN, relying on MC simulation: need for an improved model of the scintillation light detected by the PMTs.

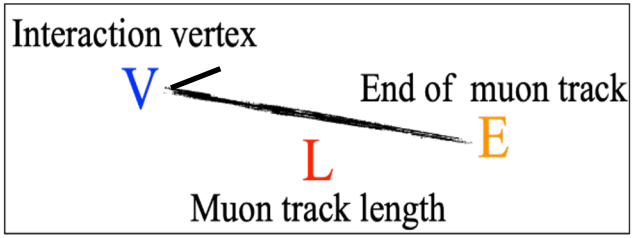
Validation of the automatic TPC event reconstruction of BNB ν events

- Comparison of the automatic event reconstruction with visual scanning results, for a sample of 553 ν_μ CC candidate events from commissioning runs.

Category	# events
Agreement between visual and automatic reconstruction on the position of the vertex $\|\Delta V_{scan\text{-}reco}\| < 15$ cm, the end position of the muon track $\|\Delta E_{scan\text{-}reco}\| < 15$ cm and the length of the muon track $\|\Delta L_{scan\text{-}reco}\| < 30$ cm	**336**
Agreement between visual and automatic reconstruction only on the position of the vertex $\|\Delta V_{scan\text{-}reco}\| < 15$ cm not on the muon track	**140**
No agreement between visual and automatic reconstruction for any of the spatial parameters	77
All scanned ν_μ CCQE candidates available	553

476 (86%)



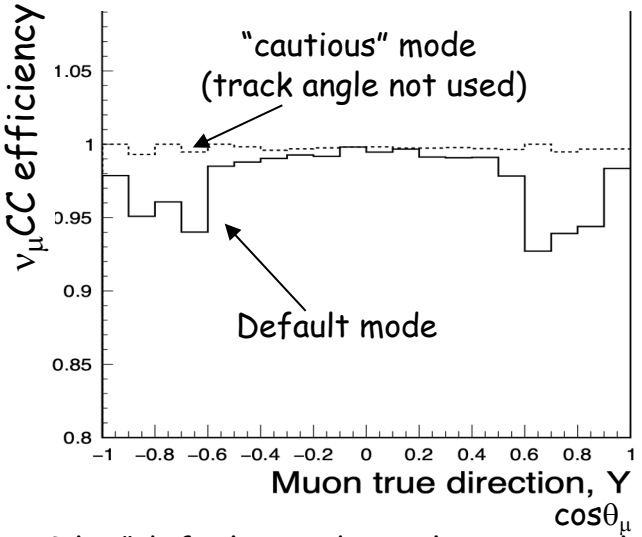


- The same analysis has been performed on a 83 protons sample from ν_μ CCQE candidate: 44% of the events fall in the 1st category of the table above and 3% in the 2nd category.

Progress & efforts with Pandora-based TPC Reco (with SBND)

- The goal is to improve the reconstruction to match the requirements of the high level event analysis groups;
- Several recent updates:
  - improved νμCC selection efficiency by a "cautious" mode to tag clear-cosmics with TPC only;
  - Mitigation of incomplete track reconstruction;
  - Saving of additional reconstructed variables to allow for track-shower re-classification at analysis stage;
  - ICARUS tuning of the track shower classification originally optimized by SBND.

Pandora clear cosmic rejection



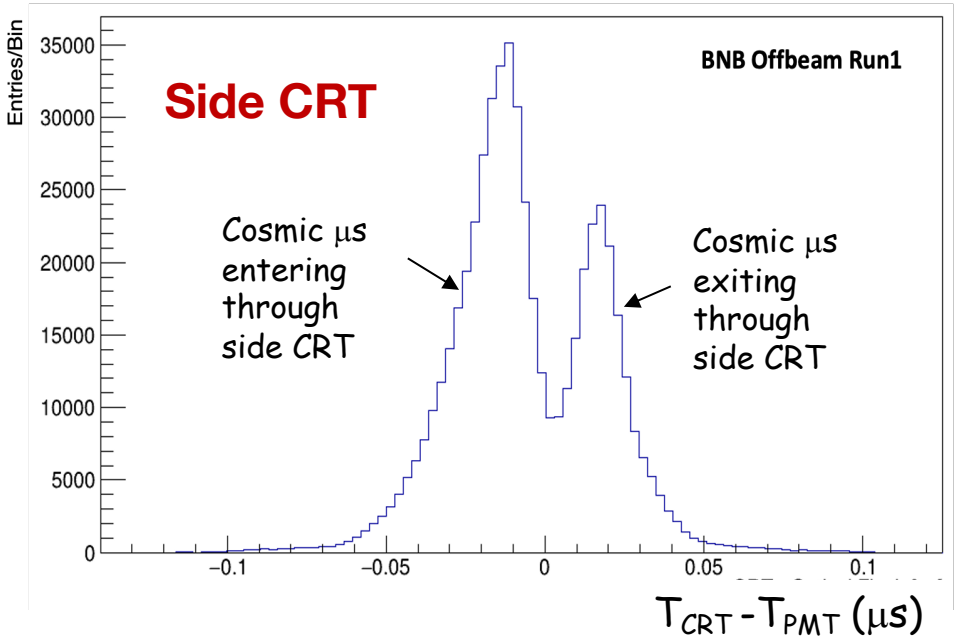
The "default" mode exploits several reconstructed physical quantities, including the angle θ_μ between the μ track and the vertical direction to tag cosmics.

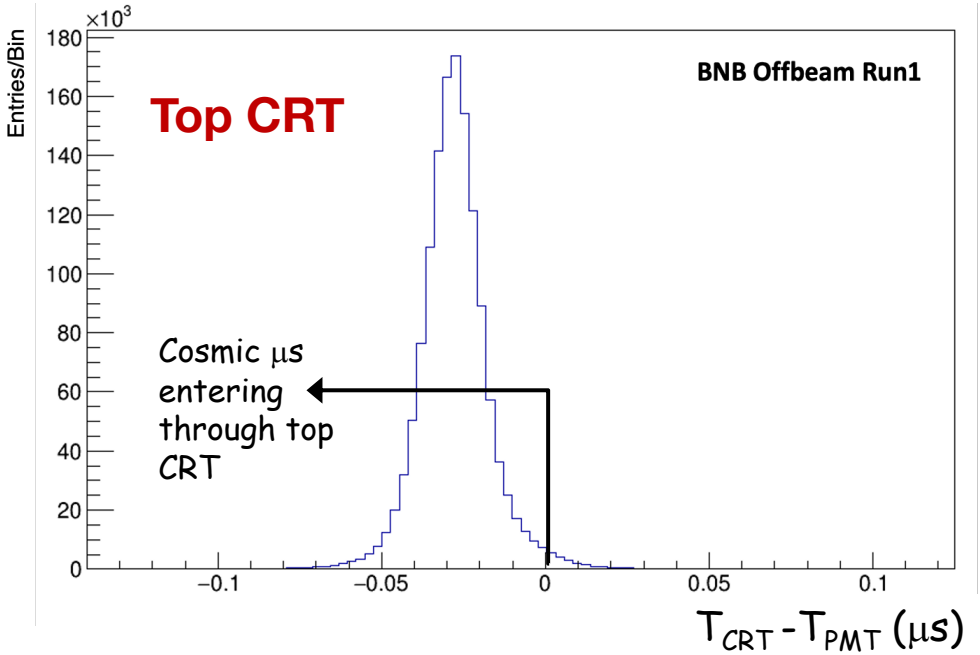
- The performance of the updated event reconstruction is assessed with a sample of visually selected/measured ν events and with MC studies;
- Progress also in the physical description in the simulation by:
  - Including MC emulation of trigger;
  - Moving to 2D drift model to better describe the wire signals.

Exploiting the CRT-PMT time information

- The CRT - PMT matching in time is being developed (with beam and off-beam data);
- CRT hits and fired PMTs are synchronized with Global Trigger signal, accounting for:
  - Electronic signals propagation time;
  - Propagation of scintillation light in the wavelength shifter fibers of the CRT bars;
  - PMT transit time, as measured with laser and cosmic muons.

TOF(*) Side -Top CRT: T_{CRT}-T_{PMT}



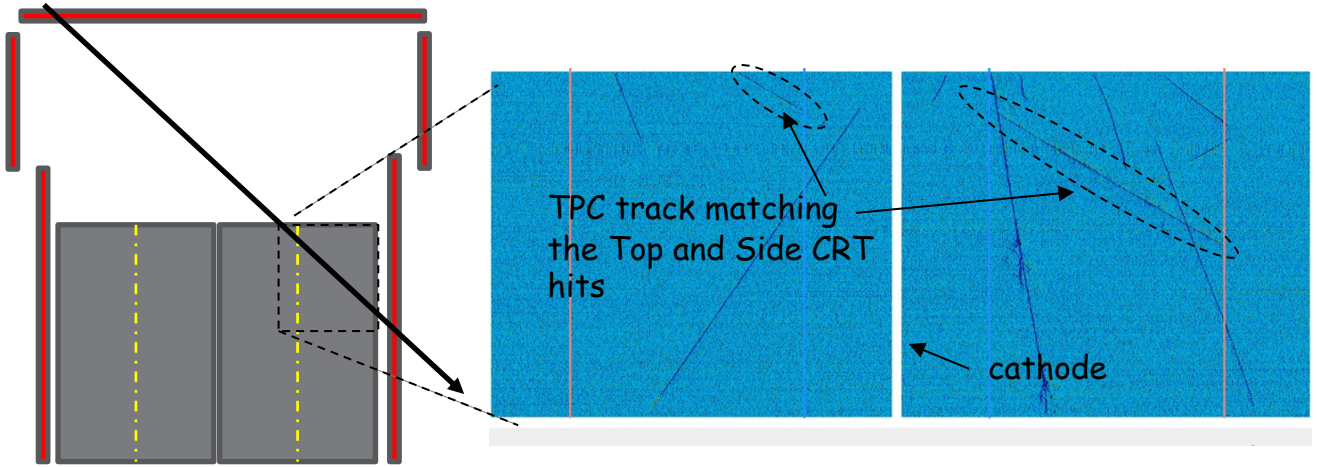


- The double peak structure observed in the side CRT is due to entering/exiting muons.

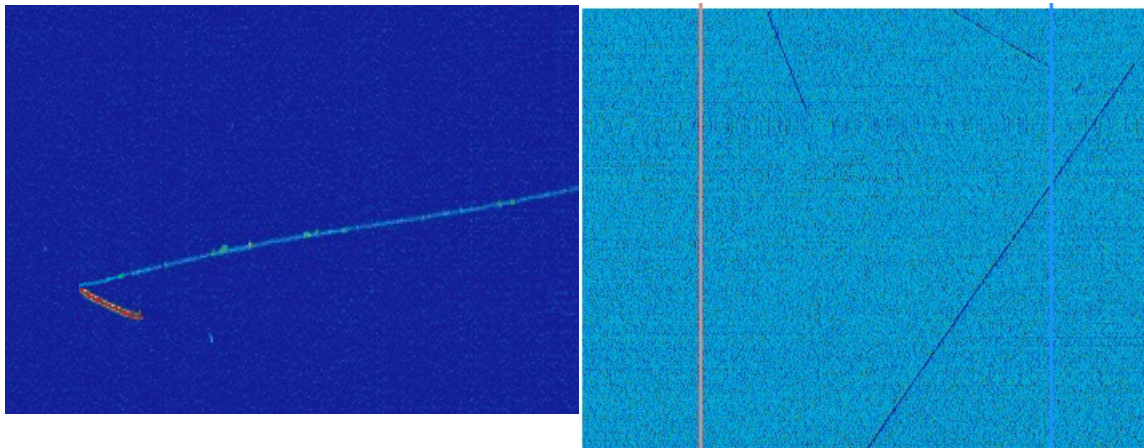
Cosmic Background Rejection/neutrino selection with CRT-PMT

- Event selection based on CRT-PMT matching under study → possible event pre-selection to reject cosmic rays without TPC event reconstruction:
  - Selection of PMT signals generating the Global Trigger during the beam spills (1.6 μs/9.6 μs for BNB/NuMI);
  - Event classification based on CRT hit – PMT time difference.

- Cosmic muon event matched with one Top (entering) and one Side (exiting) CRT hit;

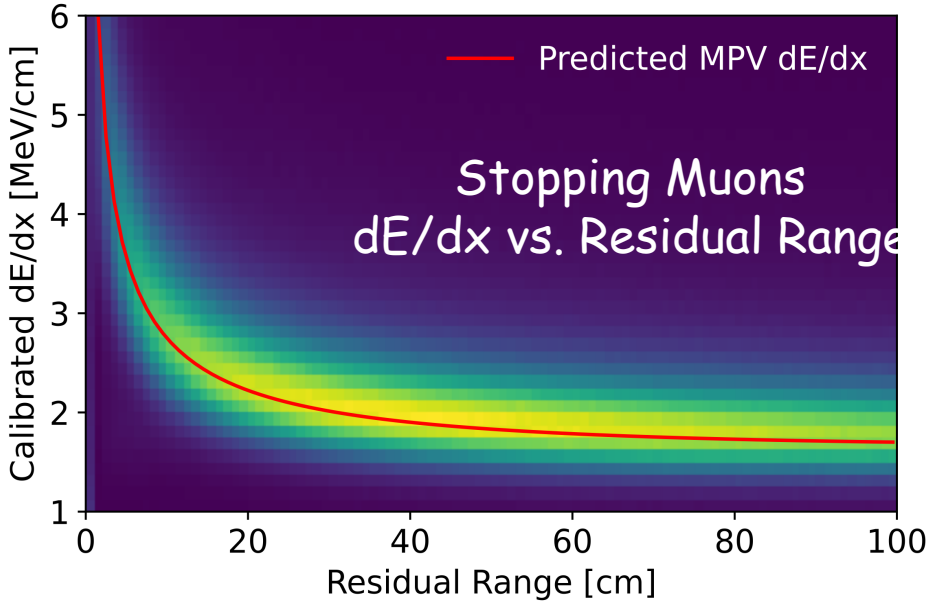


- Contained neutrino event with PMT light not associated with any CRT hit.

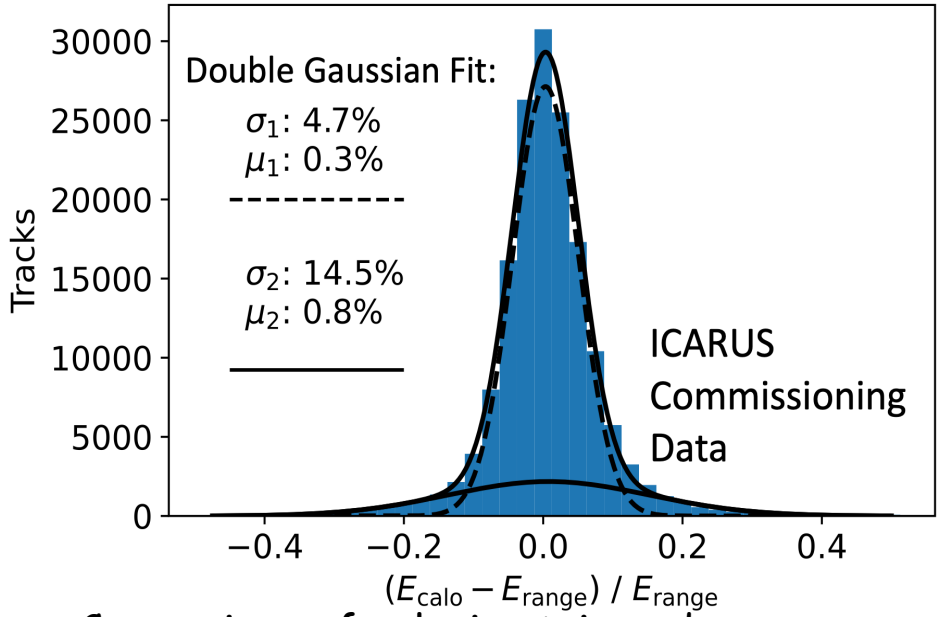


TPC wire signal calibration with stopping muons

- The measured ionization density dQ/dx is studied in bins of residual range, track angle and drift time for cosmic μs stopping/decaying in the LAr
- The full calibration has been developed, including: measurement of the drift velocity, equalization of electronic channels and detector response across the wire plane.



Profile of dE/dx v Residual Range for μs after equalization + gain calibration

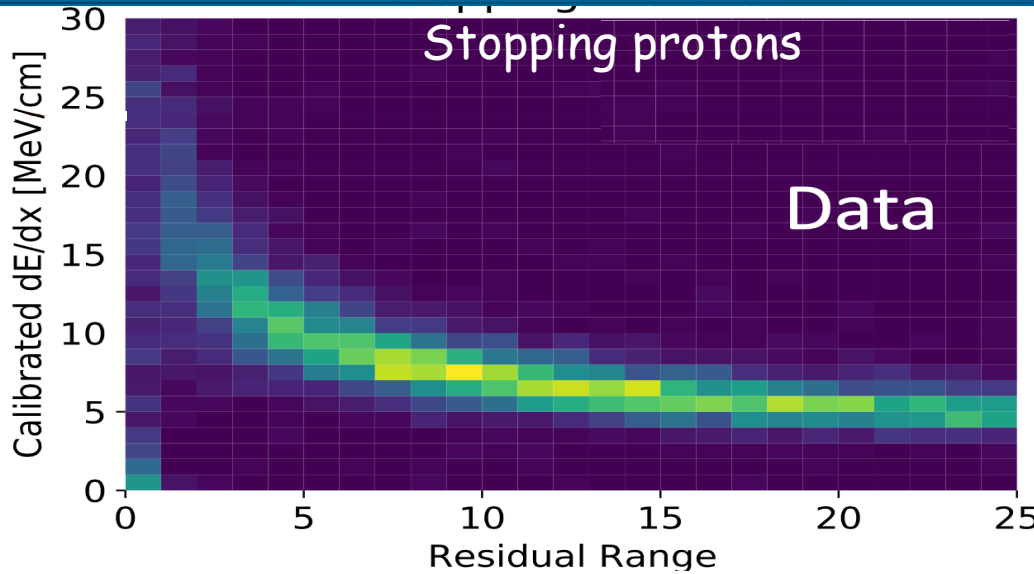


Comparison of calorimetric and range energy measurements for ms in the calibration dataset

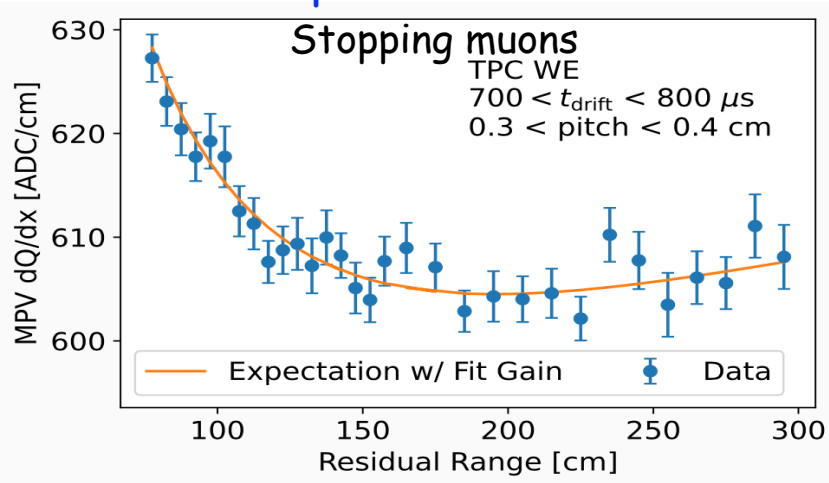
- The procedure includes a parameterization of the uncertainty on dE/dx measurement;
- Possibility to validate the PID algorithm based on dE/dx Vs range for stopping particles.

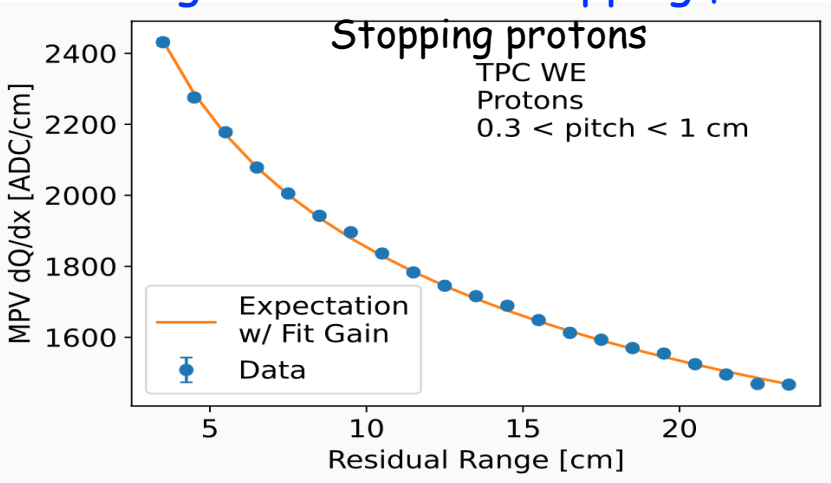
Extended TPC wire signal calibration

- Stopping protons were selected in data for calibration purposes;
- The dE/dx versus residual range profile indicates a disagreement between p and μ data (reconstruction/detector effects?);
- The disagreement is fixed by simultaneous fit of stopping μ/p data and of recombination parameters.



This extended procedure calibrates the TPC wire signals for both stopping μ and p.





- Michel electrons from μ decay and photons from π^0 decay are being studied as additional calibration samples.

3. Event selection and analysis: Neutrino selection

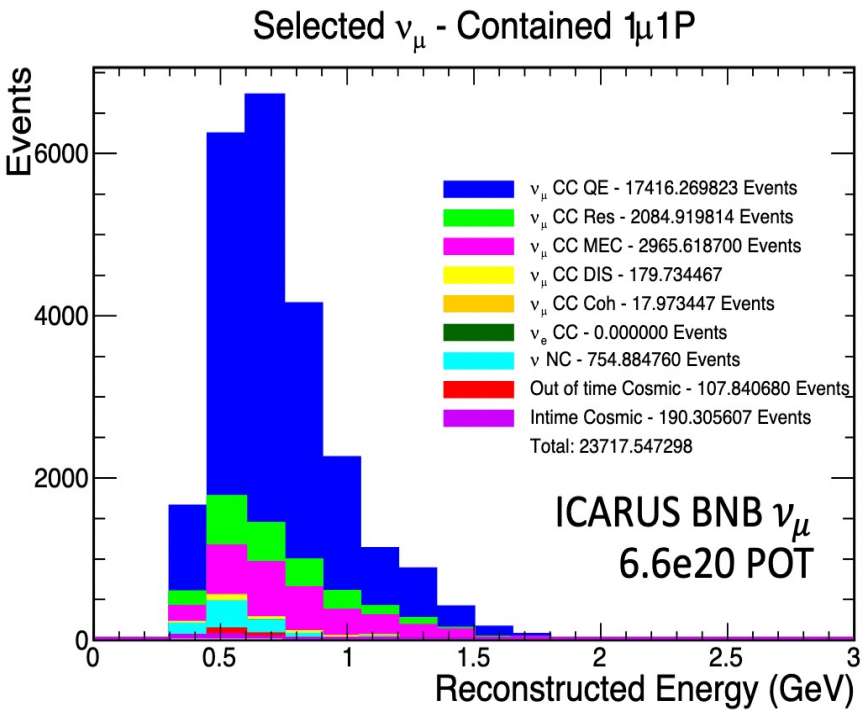
- Two separate analysis streams: LArSoft/Pandora-based and Machine Learning-based; Work largely independent, but communication between groups is good. The goal is to share the same output file format for the analysis;
- Current focus is on νμCC even if a nominal selection exists also for ν_eCC events;
- Event selection procedures are currently being used for:
  - MC study of the event reconstruction performance (feedback for improvements);
  - Preliminary MC studies of selection efficiency/purity at the different stages of procedure and test workflows;
  - Initial input to neutrino oscillation sensitivity studies (MC);
  - Selecting collected events for input to visual scanning;
  - Data/MC comparisons, including visual scan results to check both reconstruction/selection and correct classification of the automatic procedure.
- A first blinding procedure was adopted, hiding some relevant quantities from analyzers and scaling the exposure (in POT) by an unknown offset up to ±30%. The data will be fully disclosed only after proving the reliability of the analysis.

LArSoft-Based event Selection (BNB)

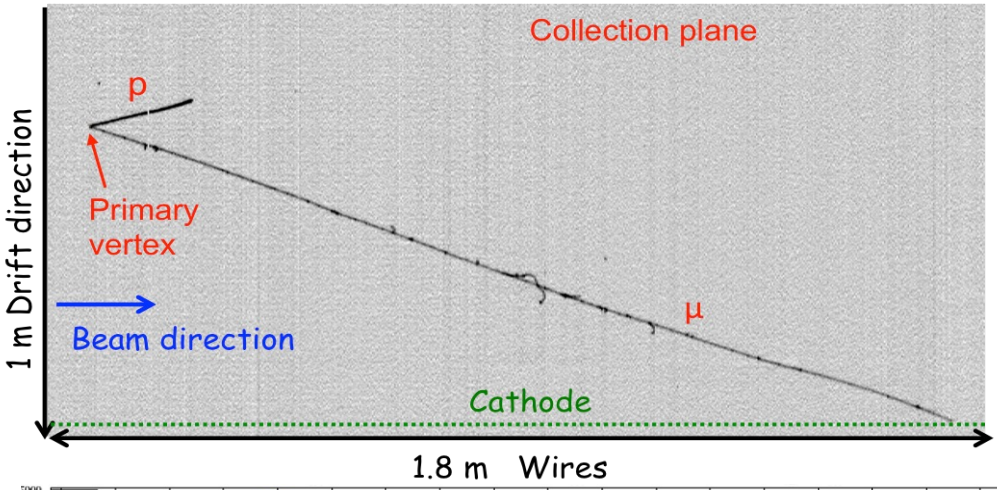
- General strategy: identify a clean, well-reconstructed sample of QE-like ν_μCC events (no attempt at the moment to optimize the selection efficiency):
  - Cosmics rejected by PMT signal (addition of CRT in progress – very promising);
  - All tracks must be contained in the fiducial volume;
  - Only 1 reconstructed μ and 1 reconstructed proton (no extra tracks or showers);

- Cosmic rejection factor >99.7%, with a residual contamination <1% in MC, even if with a reduced ν event selection efficiency (to be optimized); expected improvements on signal efficiency by:
  - PMT-CRT based cosmic rejection to relax or remove less efficient cosmic rejection criteria;
  - Recent more accurate signal calibration for a better PID ;
  - Upgraded event reconstruction, which will allow us to accept a more inclusive event sample.

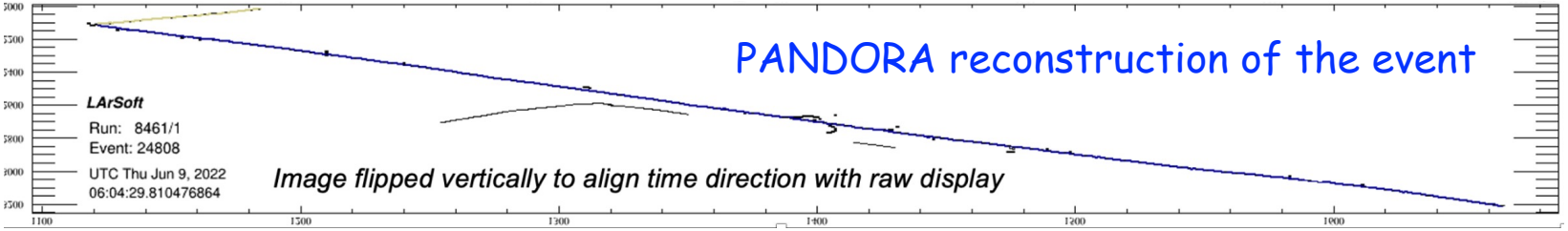
Contained 1Mu1P (ICARUS MC)



An example of automatically selected ν_μCCQE like candidate in BNB

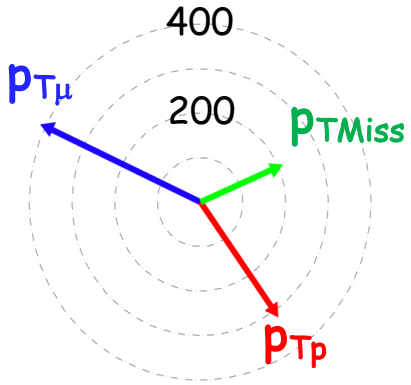


- 3.8 m long stopping muon;
- ~20 cm long stopping proton;
- Total deposited energy ~1.1 GeV;
- Total momentum $\overrightarrow{p_{tot}} = \overrightarrow{p_\mu} + \overrightarrow{p_p}$ at 8^0 from the beam axis;
- Total transverse momentum ~200 MeV/c.

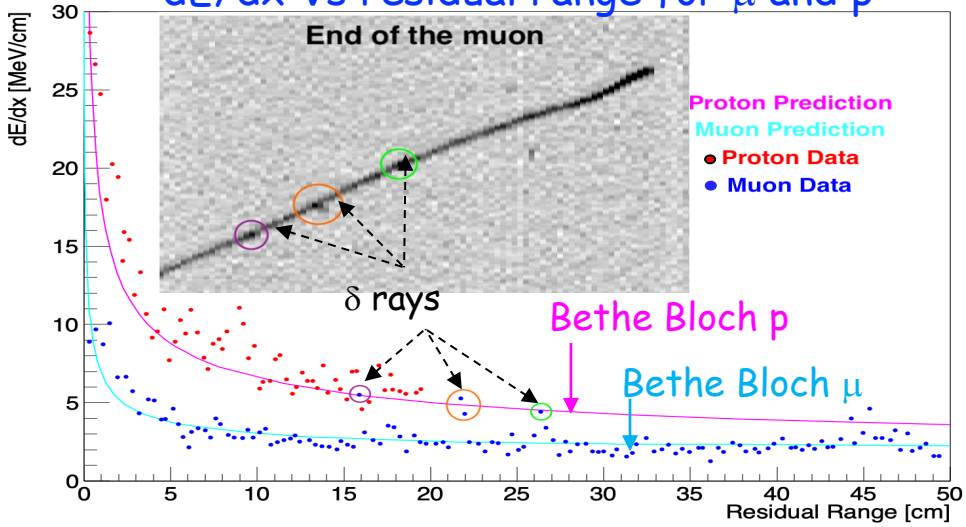


PANDORA reconstruction of the event

Momenta in the transverse plane (MeV/c)



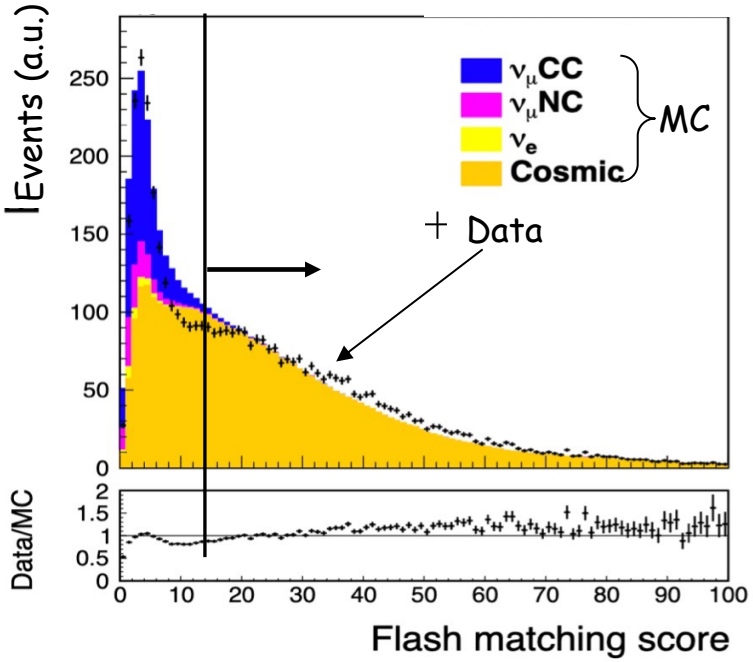
dE/dx Vs residual range for μ and p



Neutrino cross section measurement with NuMI

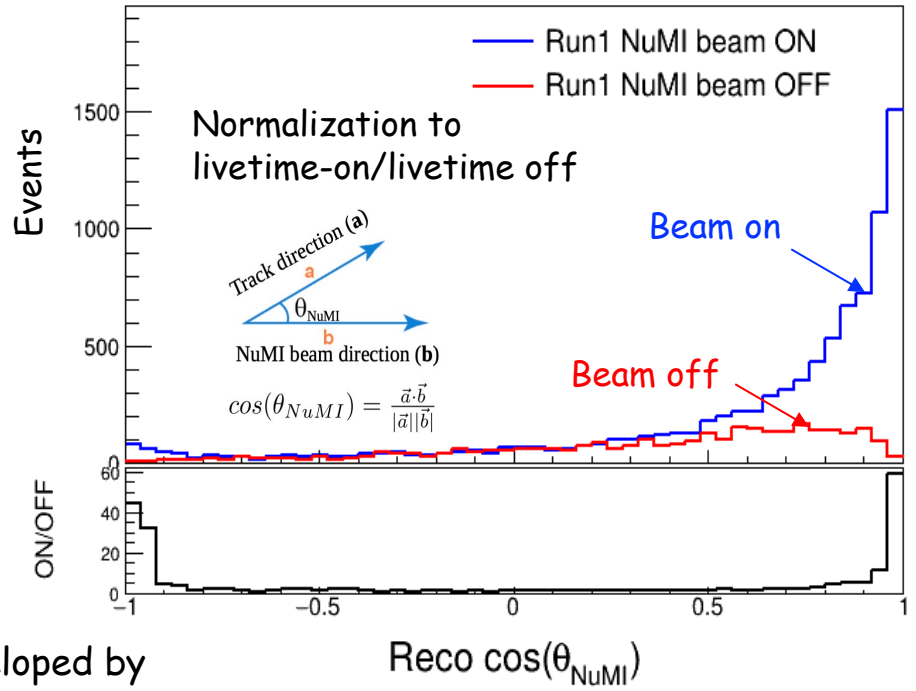
- Cross section analyses are performed within the SBN framework:
  - Muon and electron neutrino event selections are being developed and optimized;
  - The cross-section extraction tools are being developed together with the evaluation of systematic uncertainties;
- Currently the collected NuMI neutrino and cosmic data are being analysed, focusing on ν_μCC event selection.

Cosmic rejection using TPC-PMT matching



"flash matching score" based on TPC-PMT matching developed by the SBND collaborators and shared within the SBN framework

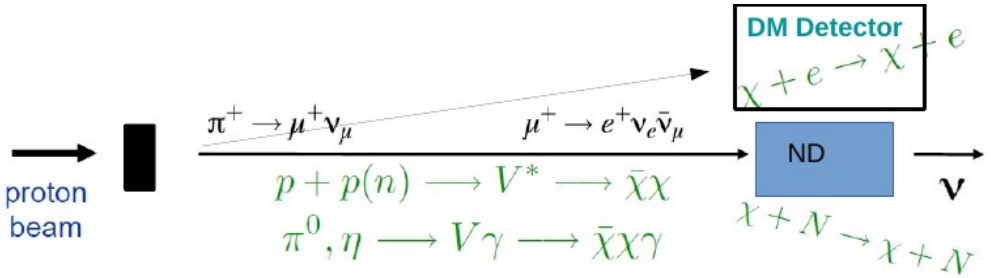
Angle with respect the beam direction after cosmic background rejection cuts



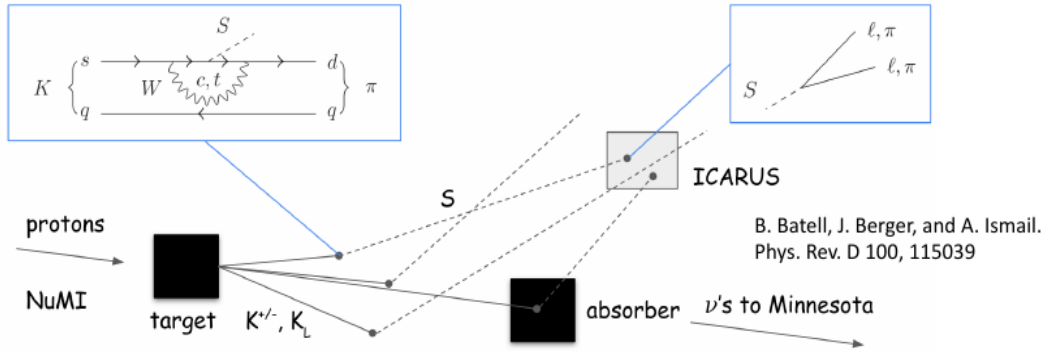
Beyond Standard Model (BSM) physics with the NuMI beam (off-axis)

- Direct detection ~< 1 GeV threshold:
  - High intensity NuMI beam has the potential for generating rare processes such as the production (via decays) of DM particles (portal);
  - Off-axis ➔ reduced backgrounds from standard neutrino interactions.

- Vector Portal to the dark sector:
  - p+p(n)→XX:
    - DM detection channel: X e→X e



- Search for Higgs Portal Dark Scalar :
  - Dark Scalars from Kaon Decay at Rest (KDAR) and Kaon decay in flight (KDIF)
  - Detection channel:
    - KDAR: decays to e-e+;
    - KDIF: decays to di-muon.



- A suitable MC event generation tool ("MeVPrtl") is available to simulate BSM events;
- Event selections tuned with MC to reject cosmics and ν events are ready to be validated with collected data ;
- Further searches include heavy neutral leptons, millicharged and axion like particles.

4. Conclusions

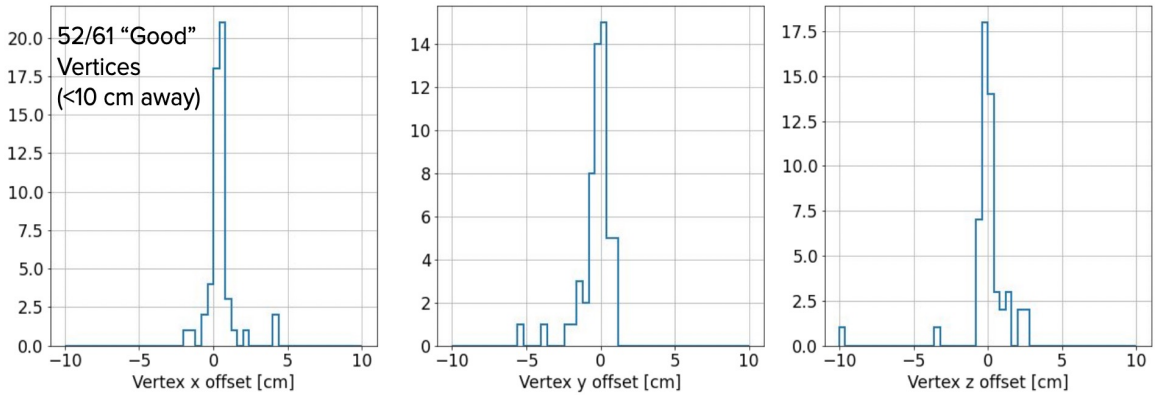
- ICARUS has started collecting physics quality data with BNB and NuMI beams;
- ICARUS Collaboration is initially focusing on single detector physics, selecting a clean and pure sample of neutrino interactions from BNB beam, to address the Neutrino-4 claim;
- A first detector calibration scheme has been developed, allowing the accurate reconstruction of the signals from the TPC, PMT and CRT;
- The event reconstruction/selection is progressing, driven by real events collected by the detector and by MC studies;
- Current production is planning to make available to the event analysis a large statistics of reconstructed data and corresponding simulated data by the end of April;
- The goal is to present/release work in progress and possibly preliminary results in time for Summer 2023 conferences;
- The experience gained during the single detector operation will be directly exploited and propagated to the joint SBN program;
- Effective synergy is in place within SBN, sharing software and tools.

BACKUP

Machine Learning (ML)-Based Analysis

- Fully ML-based workflow, starting from 3D spacepoints: fake candidates de-ghosting, semantic segmentation, clustering, aggregation, PID, vertexing, …
- Several physics analyses in progress using this workflow, including ν_μCC QE-like selection;
- Good performance for most of the reconstruction workflow, with improvements needed (and expected) in particle ID and vertexing;
- Analyses not yet including cosmic background.

Vertex Reconstruction in Data:
ML Reco Compared to Visual Scan



ν_μCC Reconstruction in MC: