Report on the SBN Analysis Working Group

PAC Meeting
Fermilab, January 15th 2020

Daniele Gibin, Ornella Palamara

Outline

- The SBN Analysis Group, scope, organization and deliverables
- Oscillation sensitivities studies
- Event simulations
- Progress on detector systematics
- Progress on event selection and reconstruction, and background rejection
- Conclusions

SBN oscillation analysis

- The successful exploitation of the SBN program relies on an accurate comparison between the event spectra measured at different distances along the beam line
- The oscillation analysis requires
  - Common tools for efficient selection of the neutrino events and for background rejection validated with real data
  - Detailed understanding of the detector performance and cross-calibration tools to minimize systematic effects
  - A common analysis strategy to compare measurements and extract oscillation parameters

Approaching real data...

- The time scale for the oscillation analysis is determined by smooth and well understood operation of Near and Far detectors
- Real data are fundamental to assess the detector performance and understanding and quantifying the experimental systematics
- We are approaching a turning point for the SBN program with the start of the operation of the Far detector
  - The commissioning of the detector and then the collection of the neutrino interactions from the neutrino beams will have priority
  - The selection and reconstruction of the neutrino interaction will be pursued with real data, driving and tuning the tools currently being developed on MC simulations
- The Near detector will become available in the following year

SBN Analysis Group

- The SBN Analysis Group is responsible for all the aspects of the combined, multi-detector physics analysis for sterile neutrino oscillation searches with Booster beam in neutrino mode
- *Scope:* Explore how the combined SBN physics analysis for sterile neutrino oscillation searches can be most effectively performed
- *Goal*: Develop simulation/reconstruction/analysis methods and tools to perform the SBN oscillation analyses
- Work focuses on
  - Implementing a multi-detector simulation.
  - Building reconstruction and analysis tools within a common framework (LArSoft).
  - Developing an end-to-end common analysis scheme in preparation for real data exploitation.
- Developments are shared between the detectors: tools originally developed and tuned for one detector are promptly exploited also by the other

SBN Oscillation Analysis Group Organizational Chart

SBN Analysis Working Group

Convener: Daniele Gibin
Convener: Ornella Palamara

Neutrino Event Generators
(Simulation and Tuning on SBN data)
Convener: Jarek Nowak
Convener: Marco Roda

MC production
(Consistent generation of different type of events)
Convener: Maya Wospakrik
Convener: Dom Brailsford

Track reconstruction in TPC
(Consistent clustering, vertexing, track reconstr.)
Convener: Tracy Usher
Convener: Jonathan Asaadi

Shower reconstruction in TPC
(Consistent shower id, vertexing, and reconstr.)
Convener: Yun Tse Tsai
Convener: Dom Brailsford

TPC simulation and Calibration
(Consistent Charge reconstruction, dQ/dx->dE/dx, Lifetime, Space Charge)
Convener: Filippo Varanini
Convener Mike Mooney
Commissioning liasons: Angela Fava, Michelle Stancari

CRT simulation & reconstruction
(CRT signals, timing, CRT-TPC matching)
Convener: Umut Kose

Light Detection Systems simulation & reconstruction
(LDS signals, timing, LDS-TPC matching)
Convener: Alessandro Menegolli
Convener: Diego Garcia Gamez

sbncode
(General tool for event selection and access to reconstruct. quantities)
Convener: Andy Mastbaum

Event Selection, Cosmic ID and rejection
(consistent combination of TPC, CRT PDS, PID, and cross-validation on exclusive channels)
Convener: Christian Farnese
Convener: Michelle Stancari

Systematics and Oscillation Sensitivities
(Consistent evaluation of flux, cross-sections and detector systematics, common tools to evaluate oscillation sensitivities)
Convener: Daniele Gibin
Convener: Costas Andreopoulos

SBN Analysis subgroups

- The mission of each subgroup, within its proper domain, includes:
  - Ensure the closest possible commonality in simulation, reconstruction and analysis between the detectors.
  - Develop procedures to cross-calibrate and cross-check the efficiencies and backgrounds in the Near and Far detectors.
  - Check that the differences between the detectors and their running condition (systematics) are properly understood and handled.
- Sub-groups have defined milestones and timescales relative to their specific domains and have regular meetings.
- SBN Analysis Group wiki page https://cdcvs.fnal.gov/redmine/projects/sbn-analysis-group/wiki

Modus operandi

- The SBN Analysis Group meets biweekly since September 2016
- Parallel meeting of the various subgroups, reporting the progress at the biweekly SBN Analysis meetings
- SBN Analysis workshops to facilitate discussions, to favor the sharing of expertise/tools and permit hands-on side-by-side work of SBN collaborators ("work-together" scheme)
  - *Fermilab, October 2017*
  - *Padova, March 2018*
  - *Oxford, April 2019*
  - *Fermilab, September 2019*
  - *Planning to have the next workshop in March 2020 at CERN*
- SBN Analysis Software workshop/hackathon at Fermilab (December 4-5 2018), and special SBN software training sessions in preparation of each workshop.

SBN Analysis Group - Deliverables

- Implement a **multi-detector** **simulation**, implement **reconstruction** algorithms/tools and **analysis tools**.
- **Oscillation Analysis:** proceed in three (parallel) intermediate steps
  I. Consistency check - **reproduce the SBN proposal-era oscillation sensitivities** with 3 new oscillation fitting frameworks, using truth-level information and the same inputs for beam, reconstruction efficiencies, backgrounds and systematic uncertainties.
  II. Update the oscillation sensitivities - still using truth-level information, and exploiting **updated inputs** for efficiencies/backgrounds and systematic effects (accounting for the available/developed SBN event reconstruction and recent results from other LAr experiments).
  III. Oscillation physics sensitivity results based on full event simulation and full event reconstruction.

SBN Fermilab

O. Palamara | PAC meeting 20

FROM January 16th 2019 presentation

Oscillation sensitivity studies

SBN analysis paradigm

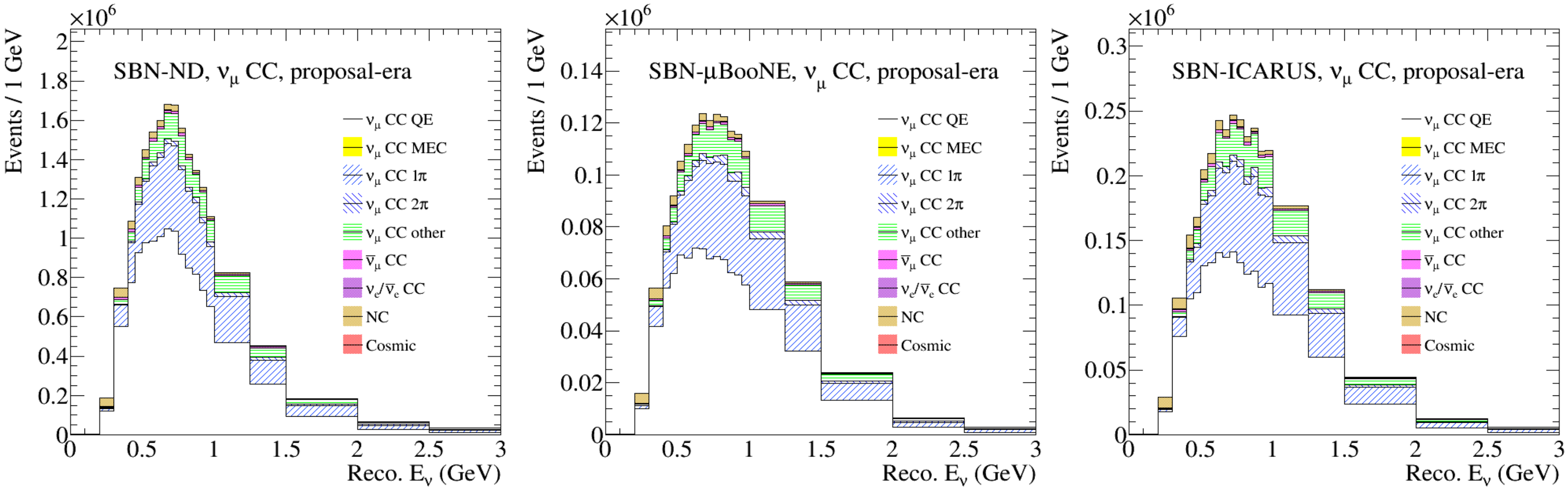
- The joint SBN fit is obtained with three independently developed frameworks to fit oscillation
  - CAFAna: Framework used in various NOvA analyses (including sterile and cross-section) and by the DUNE long-baseline group for the TDR sensitivities.
  - SBNFit: Framework designed to run multi-channel, multi-detector and multi-running-mode fits (based on MiniBooNE's covariance matrix approach). Now being used in the MicroBooNE low energy excess analysis.
  - VALOR: Fitting framework used for T2K oscillation analyses and DUNE oscillation sensitivities.
- All fitter frameworks access through common SBN code the **same** MC/data event samples, with the same SBN event selection, physics and detector systematics.
- **The exploitation of different fitters permits to cross-check and validate all the steps of the analysis enforcing the robustness and correctness of the procedure**

Sensitivities to oscillation

- Sizeable MC neutrino and cosmic event samples have been generated for the Near and Far detectors
- Oscillation sensitivities have been computed for both $\nu\mu$ disappearance and νe appearance, selecting events based on truth level quantities and including:
  - BNB neutrino fluxes and flux uncertainties over the different detectors
  - the same exposure as the proposal
  - the same hypotheses as the proposal for the signal efficiencies and background rejection.
- A first exercise (*Proposal era comparison*) was performed adopting the GENIE v2.12 interaction model and uncertainties as in the proposal (GENIE v2.8)
- Sensitivities have also been studied with an updated neutrino interaction model (GENIE v3.0.6).

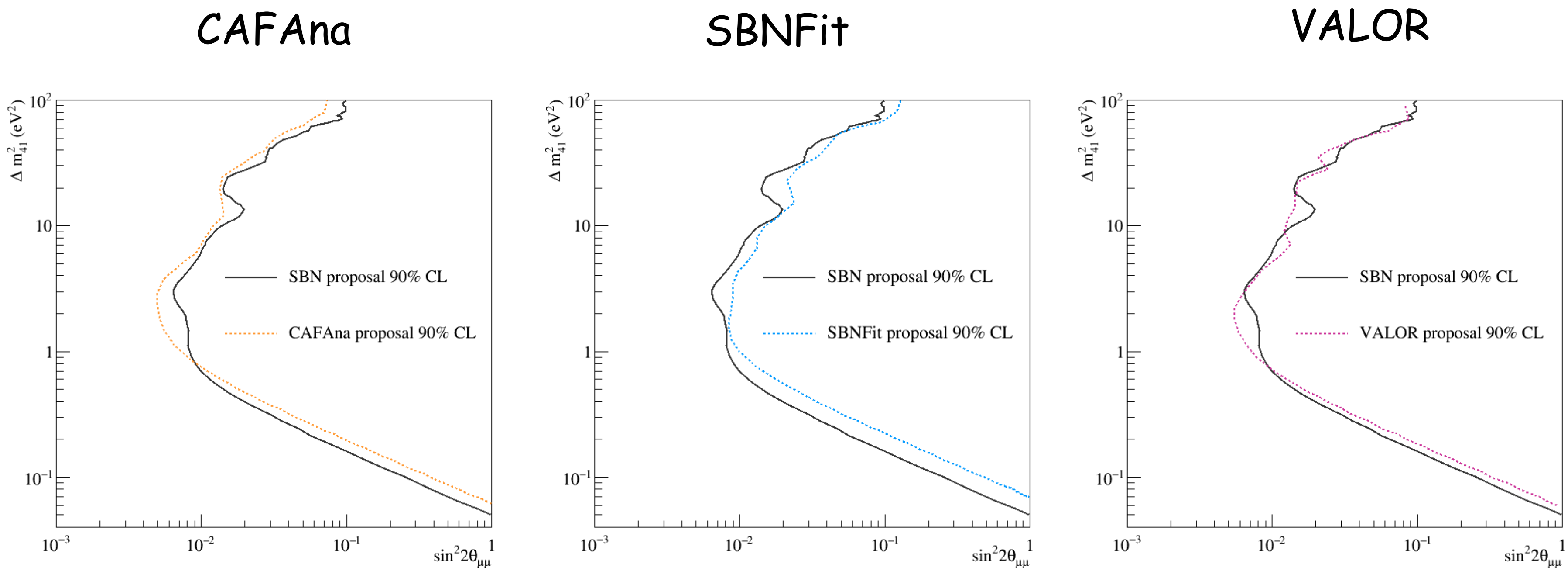
GENIE v2.12 $\nu\mu$CC Event spectra

- Total exposure as in the proposal of 6.6×10^{20} pot for ICARUS and SBND corresponding to 6×10^{6} and 5×10^{5} $\nu\mu$CC interactions respectively (13.2×10^{20} pot for μBooNE)



ν_μ disappearance (comparison with proposal)

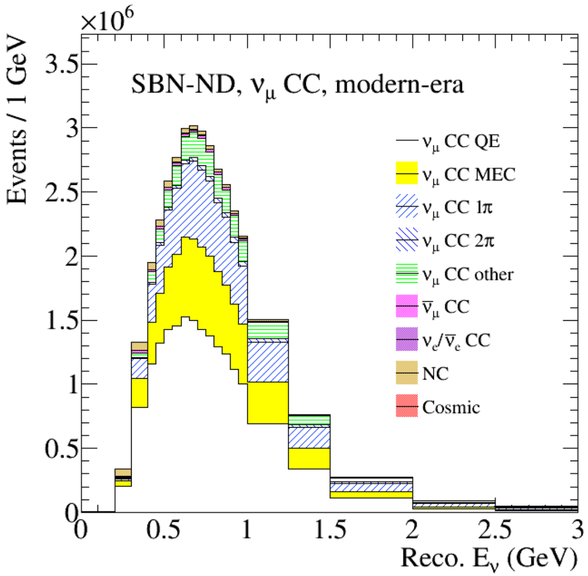
- Results obtained for the proposal era GENIE neutrino interaction model for the three fitters

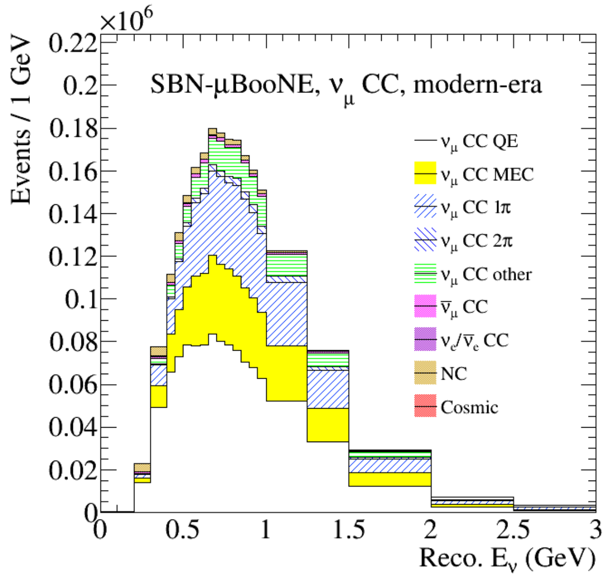


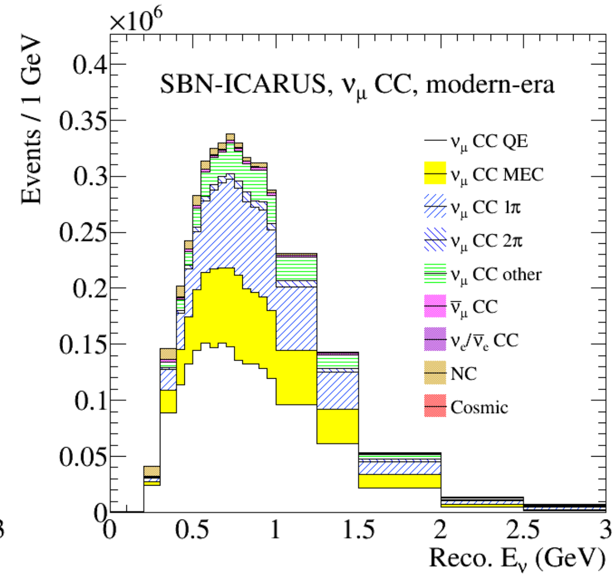
- Cross-comparison between different fitters proved to be very effective to identify errors and pin down the approximations adopted for the treatment of systematic effects
- Still some level of difference between the fitters being addressed

Alternative interaction model

- New interaction model new GENIE v3.0.6 (including additional MEC channel) has been introduced

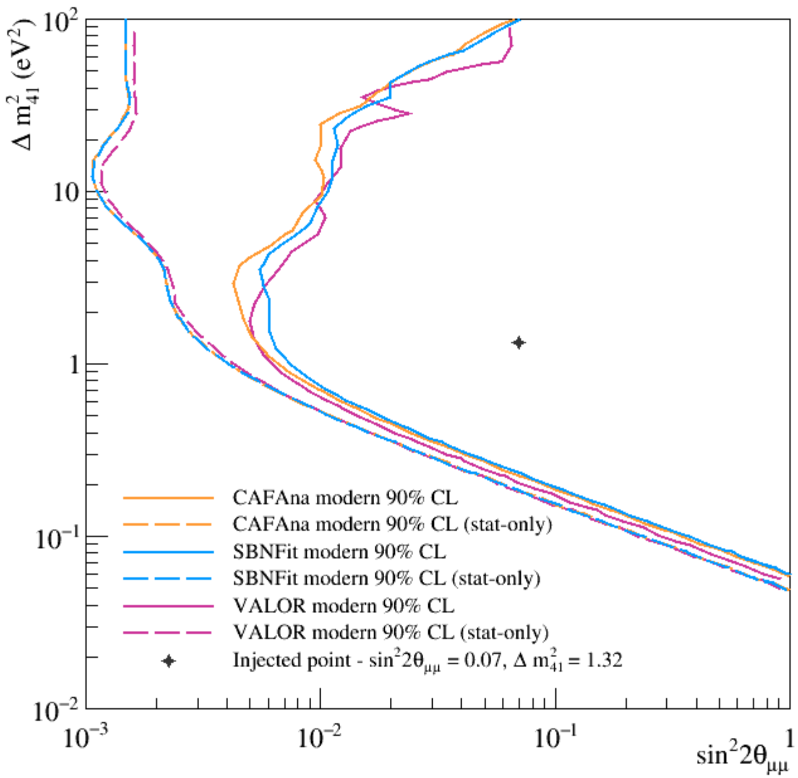




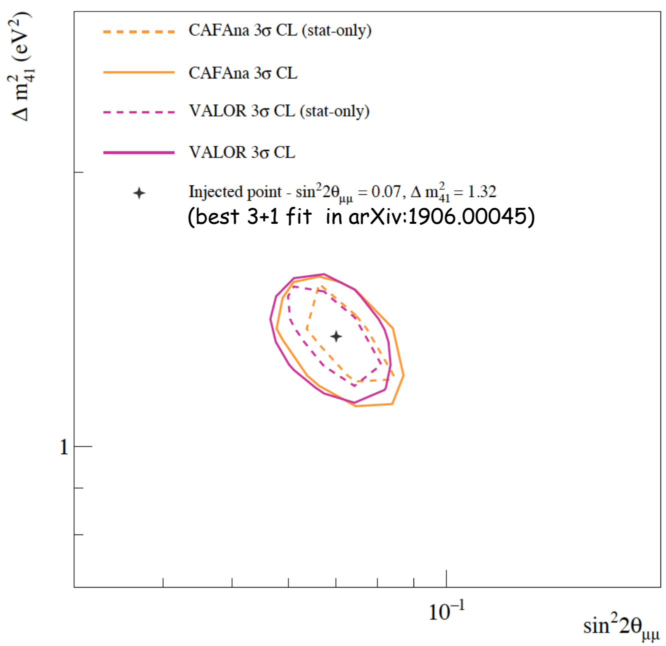


νμ disappearance with the alternative interaction model

- Sensitivity has been computed for the new GENIE version and for the three fitters
- Missing systematics on the additional MEC events
- Still some level of difference between the fitters being addressed

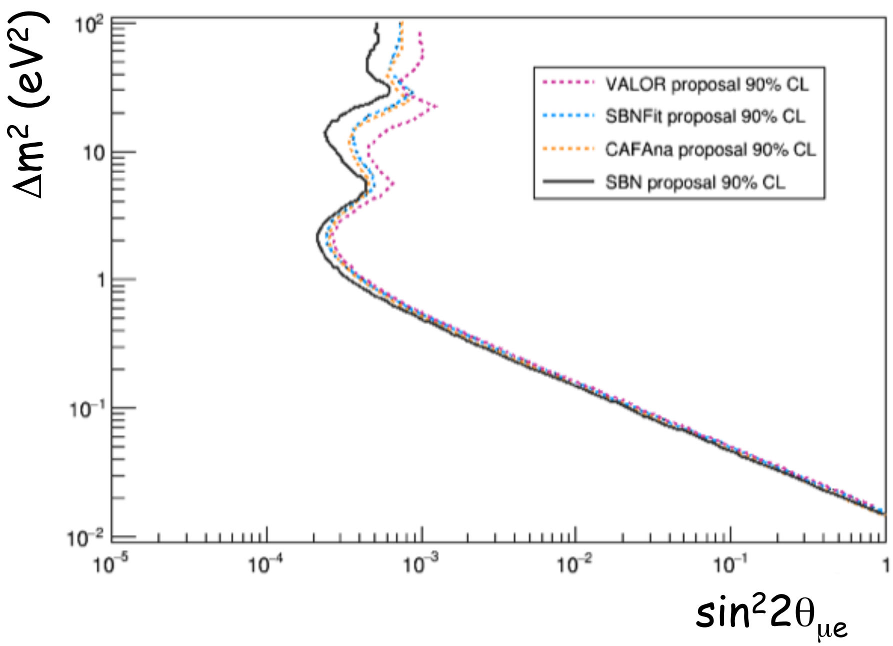


- Sensitivity to an injected oscillation signal



Comparison with proposal for the νe appearance

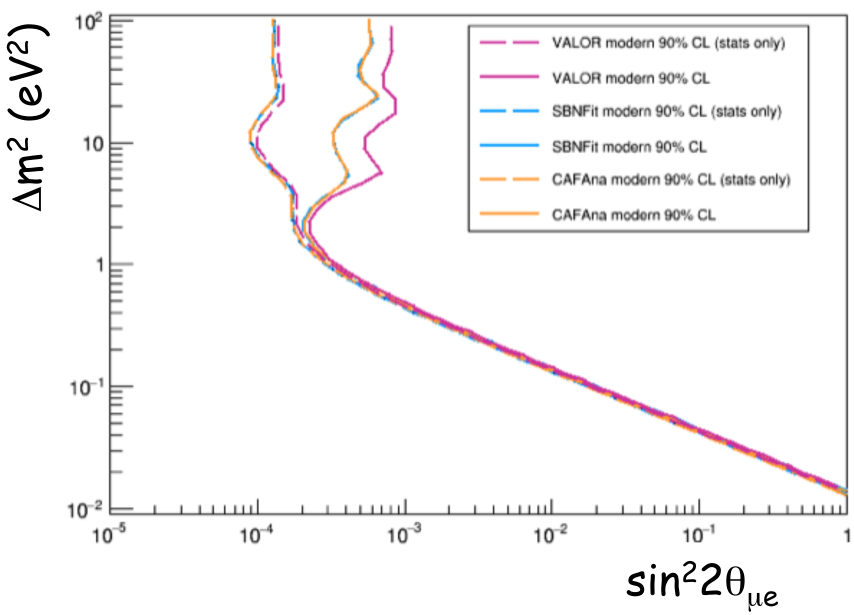
- Similar study has been performed at the truth level for the νe appearance channel, under the same assumptions of the proposal and with the GENIE v2.12



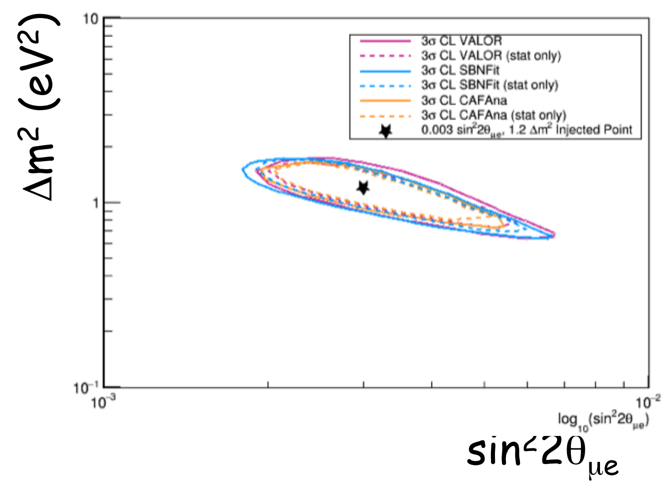
- The comparison between the three fitters show differences which are being addressed

New Genie sensitivities for the νe appearance

- Similar study has been performed at the truth level for the νe appearance channel with the new Genie v3.0.6 interaction model
- Still some systematics of the new model are missing
- Again the exploitation of different fitters is invaluable to improve the correctness of the procedure; the residual difference are being addressed



- Sensitivity to an injected oscillation signal corresponding to the LSND best fit point



Testing the fitters

- To exercise the reliability of the oscillation analysis, a so called "mock data challenge" has been devised:
  - Produced a set of MC simulations including known (but hidden to the analysis) systematic and oscillation effects
  - Pass them through the fit procedure and
  - Verify if the fitters can disentangle the effects and provide the correct answer

- The outcome of this exercise will provide invaluable information about
  - the correctness of the fitter procedure
  - the reliability and resilience of the fitters to different inputs

MC simulation for the event reconstruction

Event Simulation for selection and reconstruction studies

- Full MC simulation is available for the Near and Far detectors, including detailed simulation of:
  - the charge deposit in the TPC and modeling of the wire response
  - the scintillation light, including the photo-detector response
  - the CRT signals, including modeling of the detector response
- Sizeable samples of MC events have been generated and reconstructed for both SBND and ICARUS
  - $\nu\mu$: BNB neutrino + cosmic "overlay" sample + cosmic-only sample
  - νe: BNB νe "oscillated" sample (i.e. with the spectrum of BNB $\nu\mu$) + BNB $\nu\mu$ sample (to study fake νe from mis-id $\nu\mu$ interactions)
  - Single particle samples for developments and systematic studies

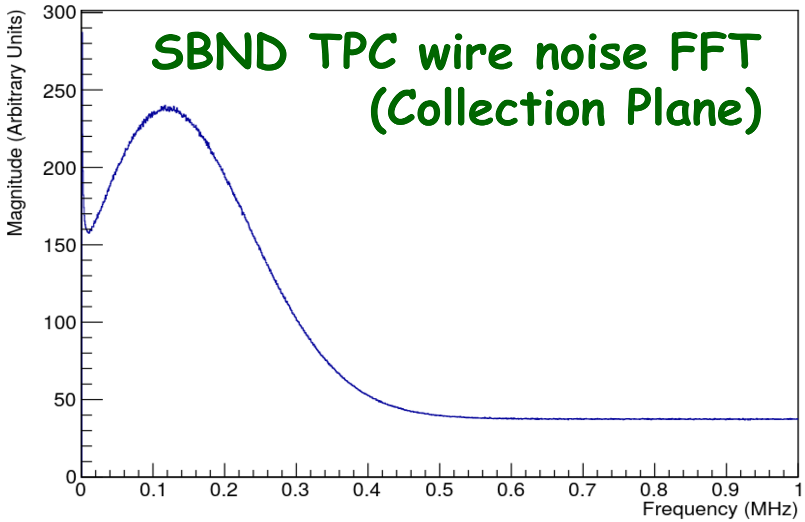
Detector	N spills per ν	N spills per Cosmic μ in spill	Total cosmic μ per drift
SBND	25	300	5
ICARUS	250	50	10

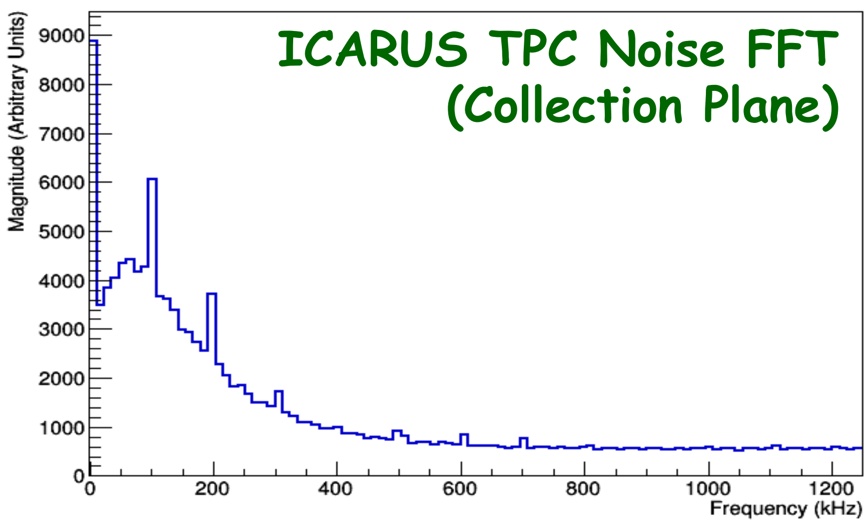
Progress on detector systematics

Addressing detector systematics

- The understanding of actual detector systematics will be based on experimental measurements
- First studies of possible detector systematic have been performed with MC simulation, exploiting the same tools for both SBND and ICARUS
- In particular difference between detectors have been addressed by studying the major possible sources:
  - different noise condition and wire geometry
  - space charge effects

Improving low-level detector simulation: electronic noise





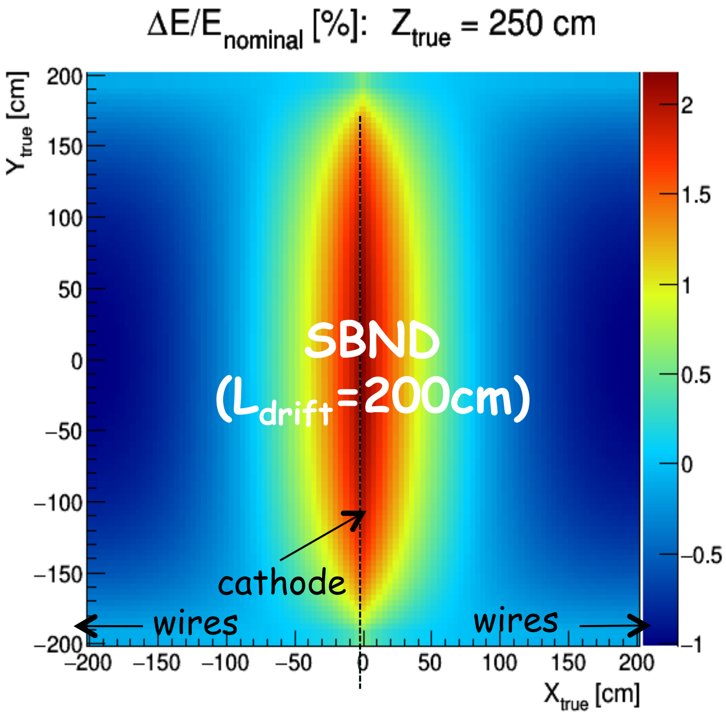
- Both detectors are now using data-driven models for the simulation of the electronic noise for the TPC wire signals:
  - SBND data-driven model extrapolated from MicroBooNE
  - ICARUS data-driven model from TPC noise measurements at LNGS

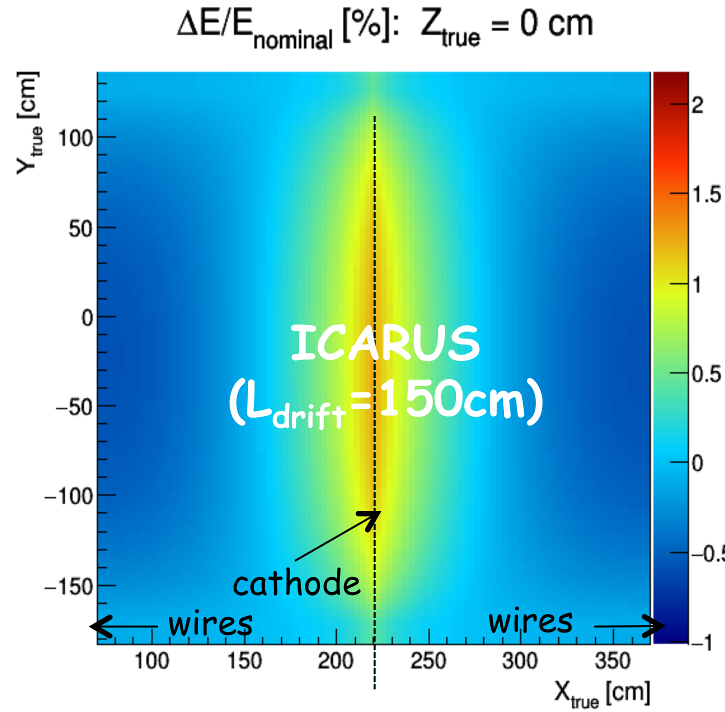
- Very limited impact on the hit identification after optimization of hit finding algorithm

- First study on simulated isotropic muons in the two detectors indicate hit efficiency in excess of ~98% for both detectors

Space Charge effect

Map of the $\Delta E/E$ induced by SCE (middle cross section)

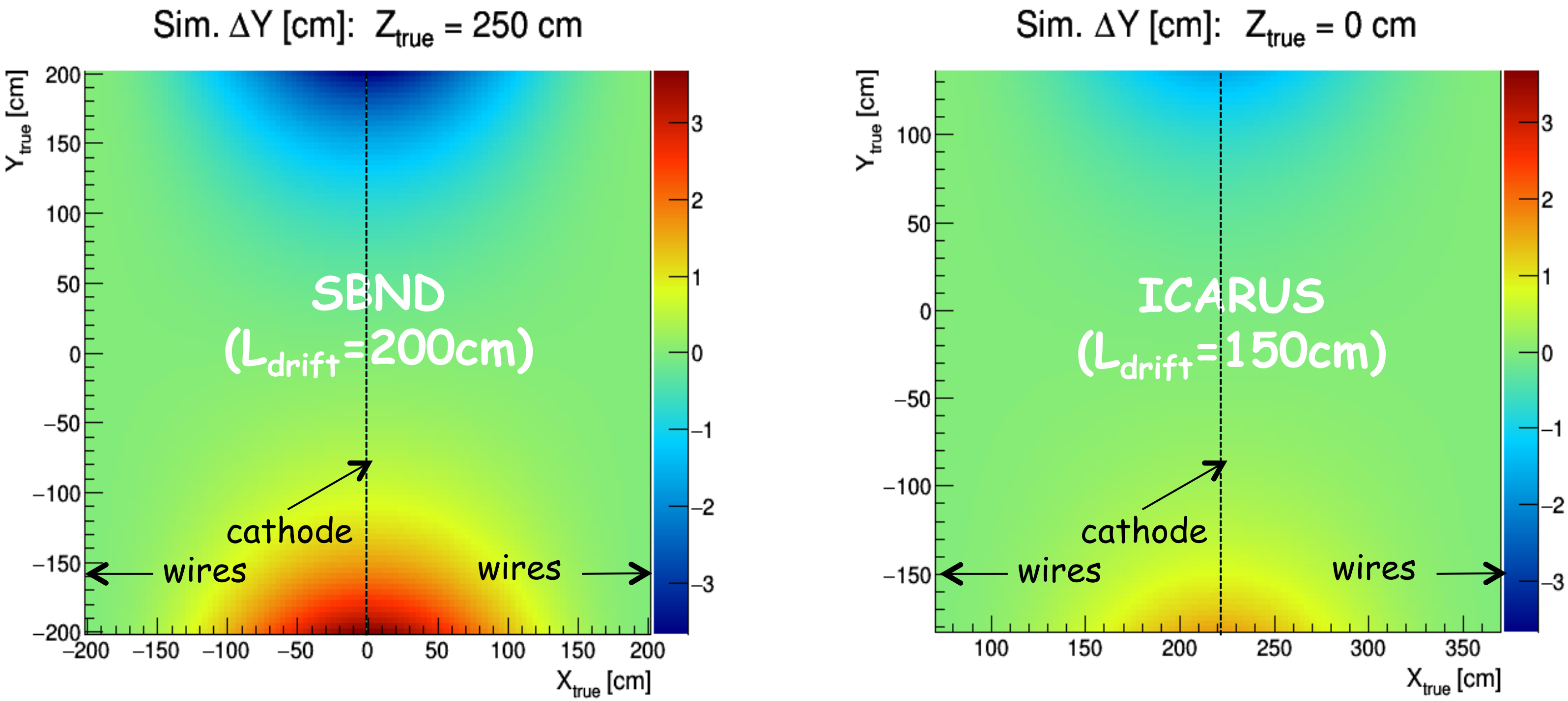




- Space charge effects by build-of positive argon ions by cosmic rays in near-surface LArTPCs ➔ Electric field distortions impacting both spatial position and collected charge - through e^--ion recombination
- Developed stand-alone SCE simulation for SBND and ICARUS
- SCE Simulation implemented in **LArSoft** for both detectors
- Implementation of correction of SCE is in progress
- SCE not yet adopted in the standard SBND and ICARUS simulations

Space Charge effect

Map of the vertical distortion induced by SCE (middle cross-section)



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Progress on
Event selection and reconstruction
And Background rejection

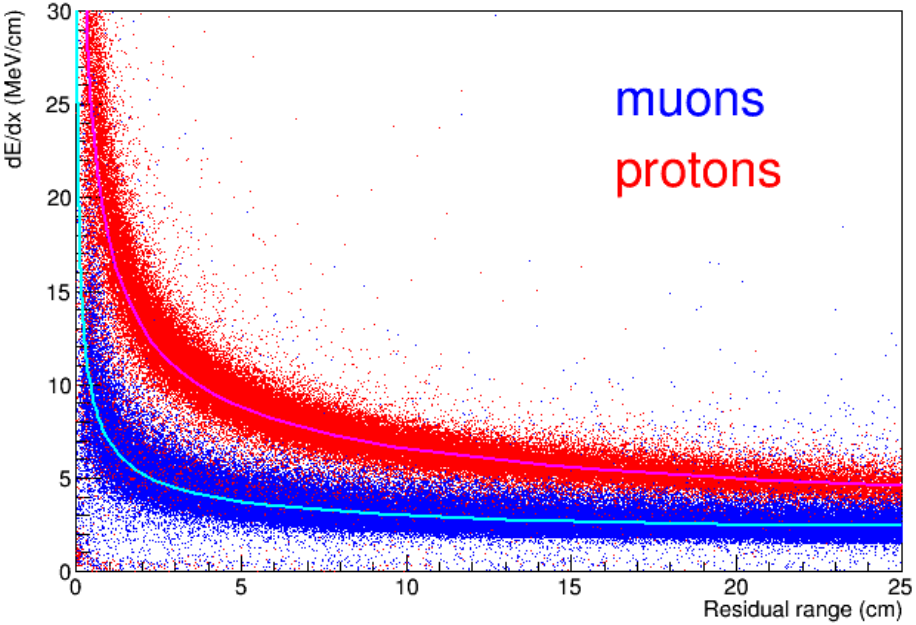
Event selection and reconstruction

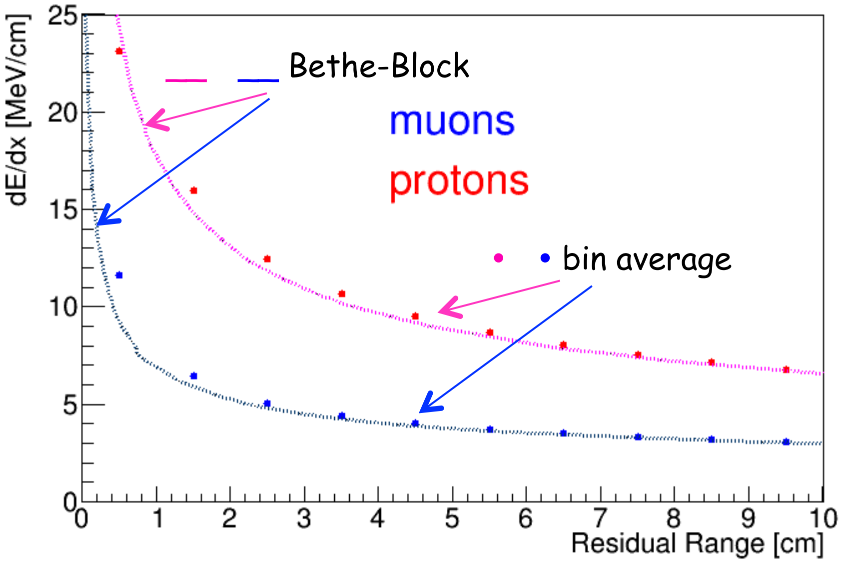
- The neutrino event selection and reconstruction is obtained with common tools for the TPC, the PMTs and the CRT, including backgrounds from cosmics and from the beam
- Results are preliminary and represent only an indication of the performance of SBN detectors
  - Pandora* reconstructs track and shower objects associated to the same interaction in the TPC, removing unambiguous cosmic rays
  - particle ID and calorimetry
  - PMT flash reconstruction
  - PMT flash matching with the TPC image
  - background rejection
    - Cosmic muons
    - electron-gamma separation
- Foreseen improvements include
  - PMT/CRT time matching
  - Exploitation of the accurate time information from the light system

*Pandora pattern-recognition algorithms, Eur. Phys. J. C75(9), 439 (2015), Eur. Phys. J. C 78, 82 (2018)

Calorimetry and particle ID for contained tracks

- In case of contained tracks calorimetric PID can be applied, exploiting dE/dx ionization versus residual range





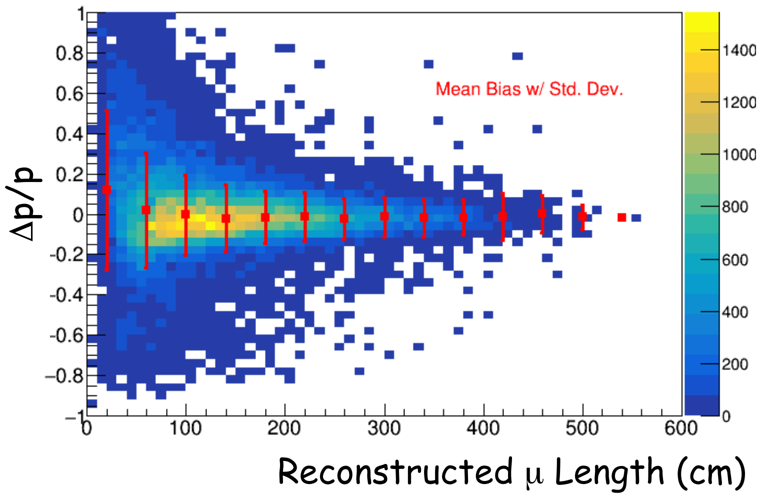
- For contained tracks the momentum can be obtained from range or/and from calorimetry

escaping muon momentum

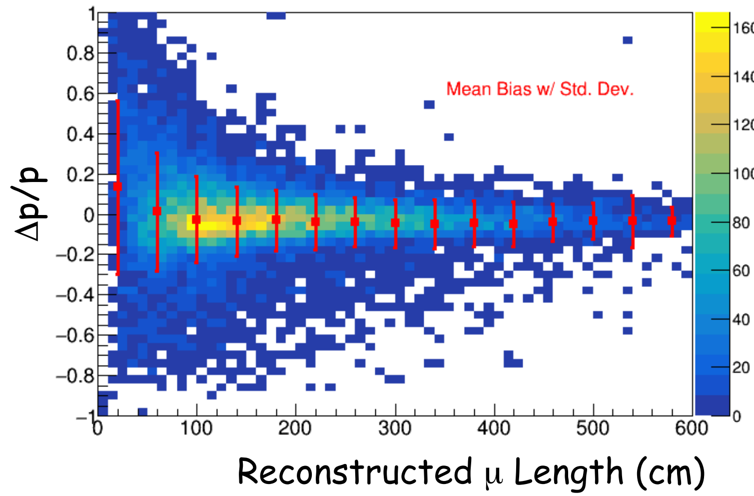
- The escaping muon (L_μ>100 cm) momentum is estimated with Multiple Coulomb scattering (MCS) in the liquid argon

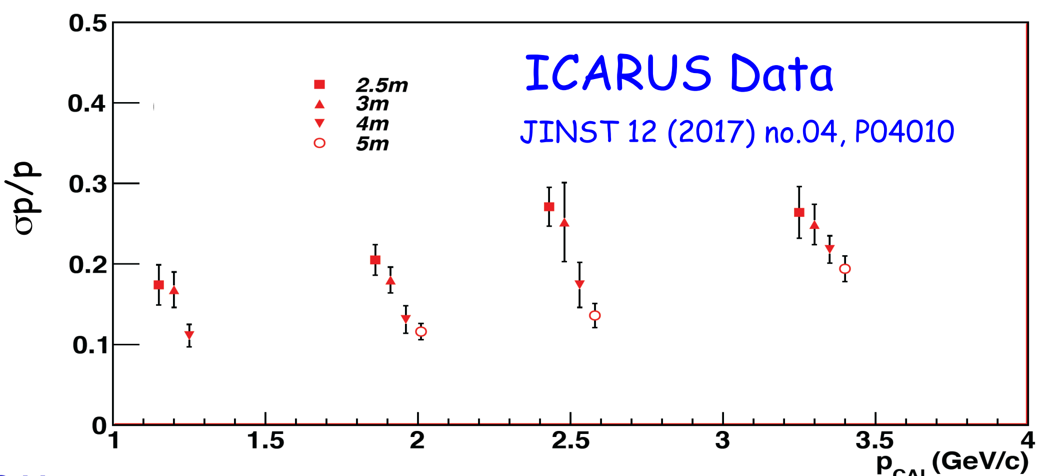
SBN simulation/reconstruction

SBND



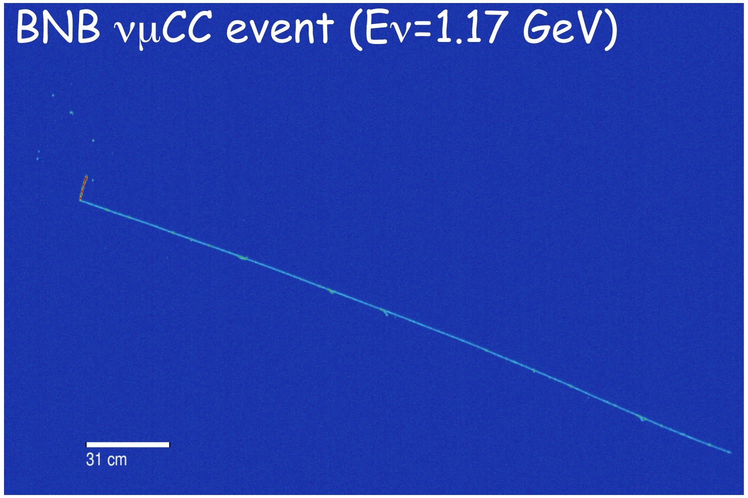
ICARUS

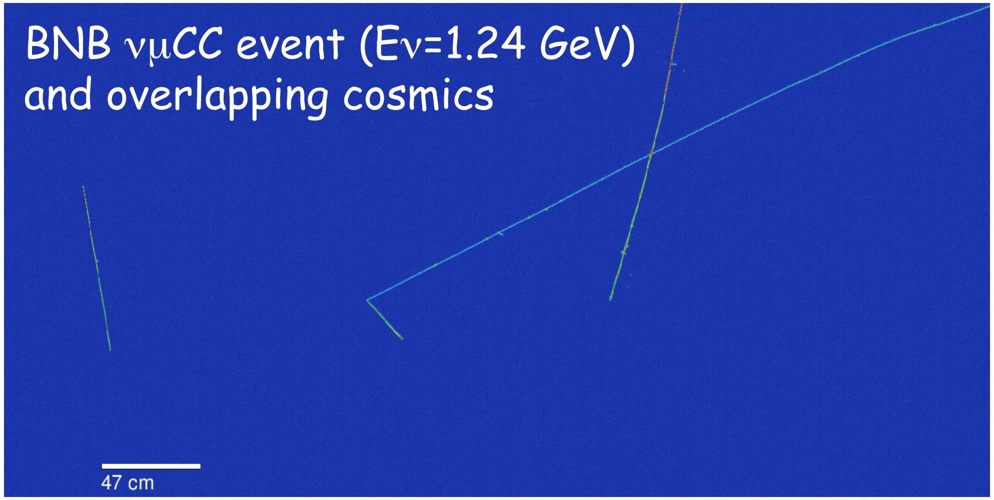




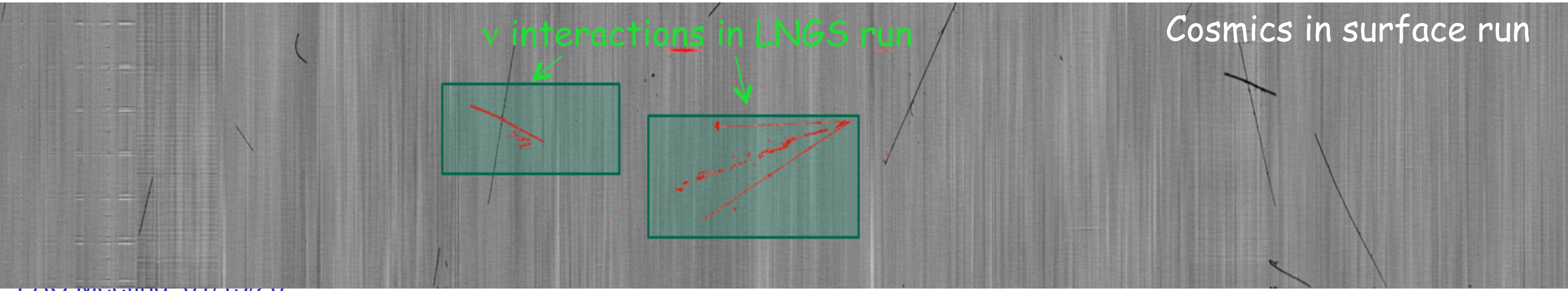
- Measurement on stopping μs @LNGS. Momentum p measured from MCS is compared with its calorimetric measurement p_{CAL}

Studies on νμ event



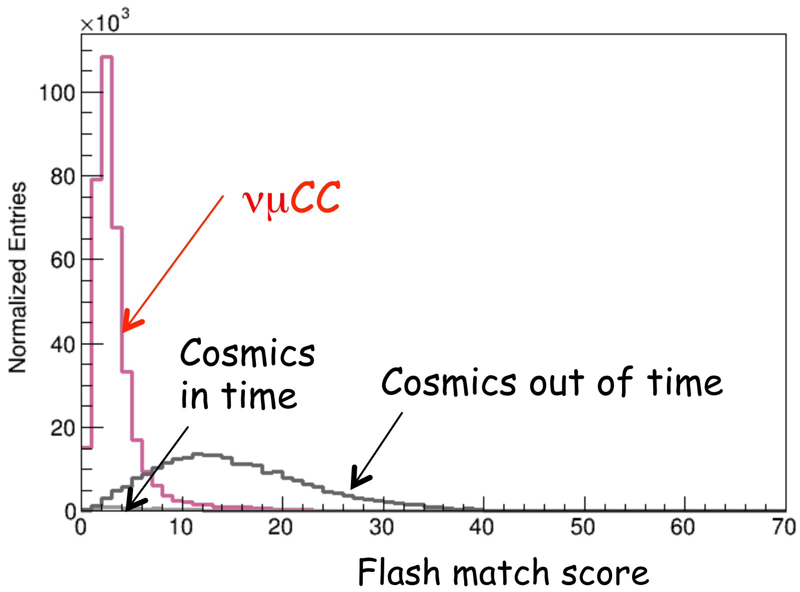


- Shallow depth operation: several out of time cosmic rays overlapping the ν event drift window
- ICARUS measured events: low energy CNGS ν events from LNGS run superimposed to an event from the surface test run in Pavia



Match of TPC image with the light flash

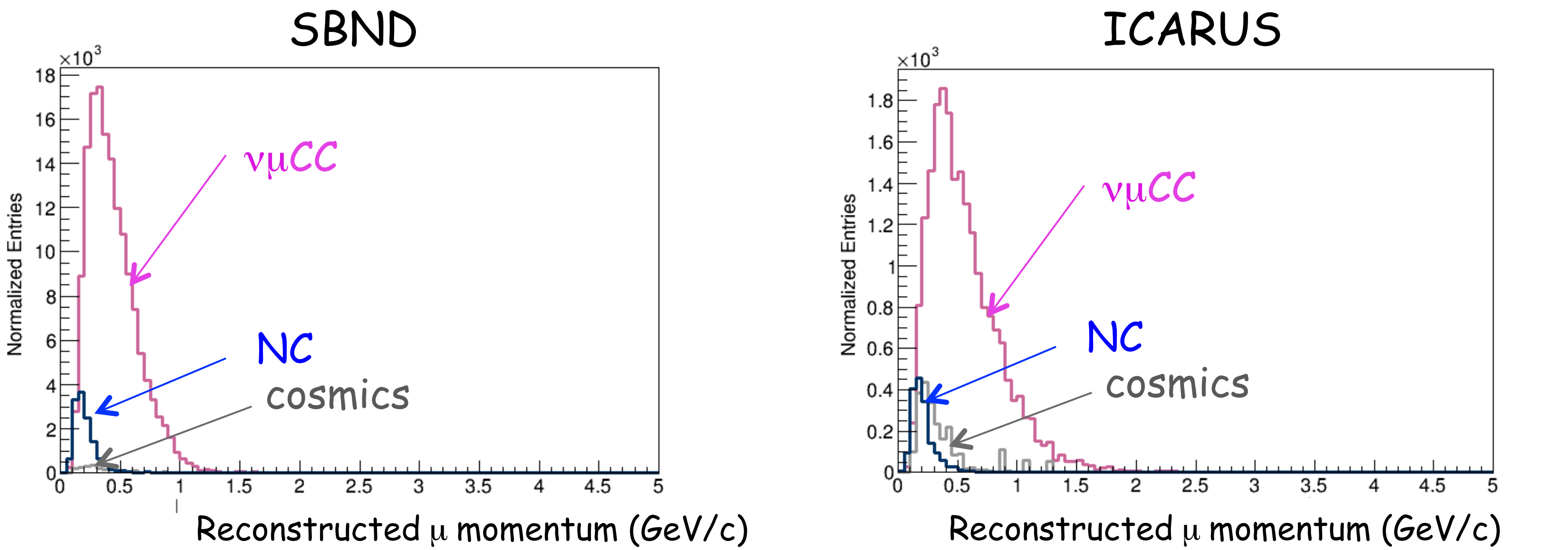
- Simple approach: match between charge and light image from comparison between the barycenter of the charge and the barycenter of the light signal
  - first identification of the interaction associated to the trigger



- Large improvements are expected from
  - χ^2 based comparison between charge and light
  - Exploitation of the timing information

Restricting to contained events...

- It is possible to ~get rid of cosmic backgrounds in both SBND and ICARUS by
  - Imposing a Veto condition on the CRT and
  - Considering only contained $\nu\mu$CC candidate events



- Significant improvements are expected from
  - A more sophisticated treatment of the scintillation light information (amplitude and time)
  - More refined exploitation of the CRT (including time information)

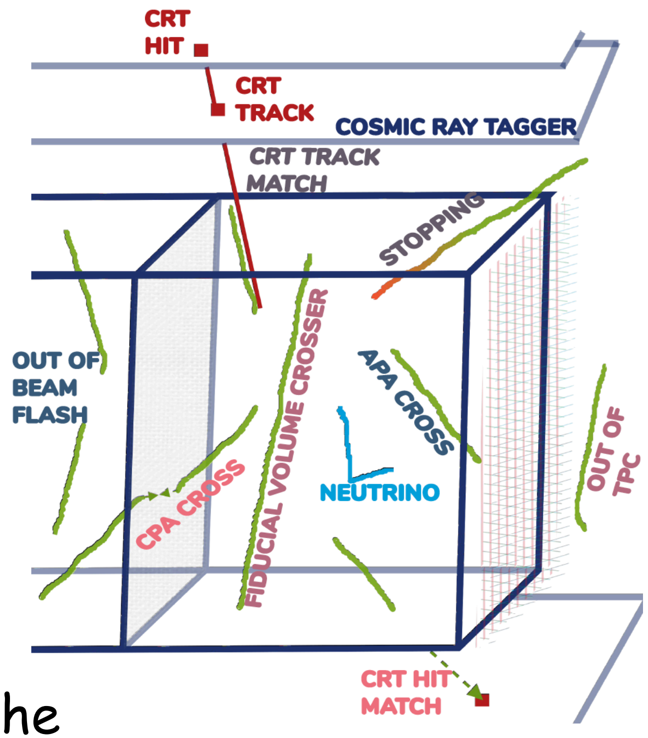
Rejection of cosmic with TPC and CRT: SBND case

- First stage Pandora: a topological event reconstruction in the TPC
- Second stage: CosmicID mixing TPC traking/calorimetry and CRT information

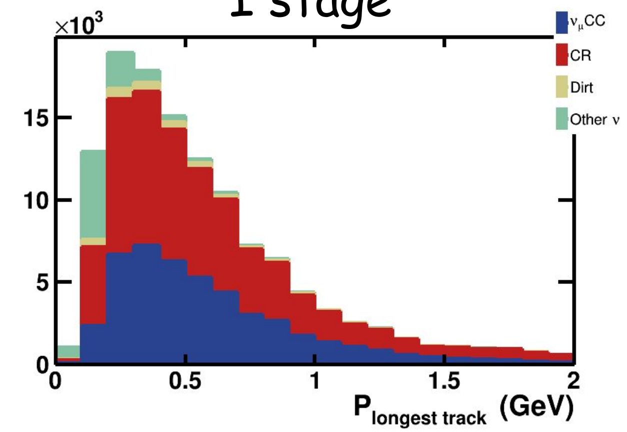
- 88% unambiguosly tagged as cosmic by Pandora

- of the remaining 96% rejected by CosmicID

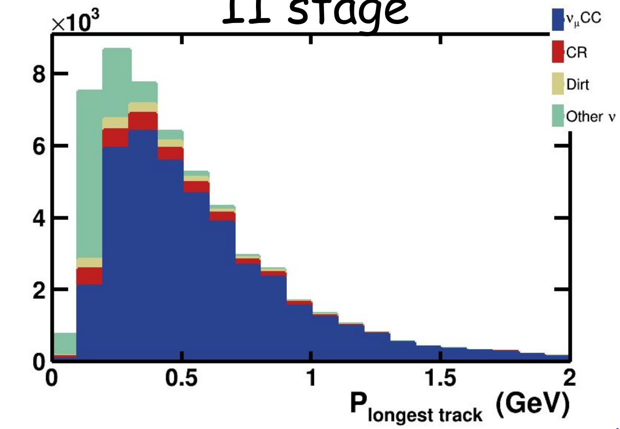
- In total 99.5% of the cosmic μ are rejected



I stage



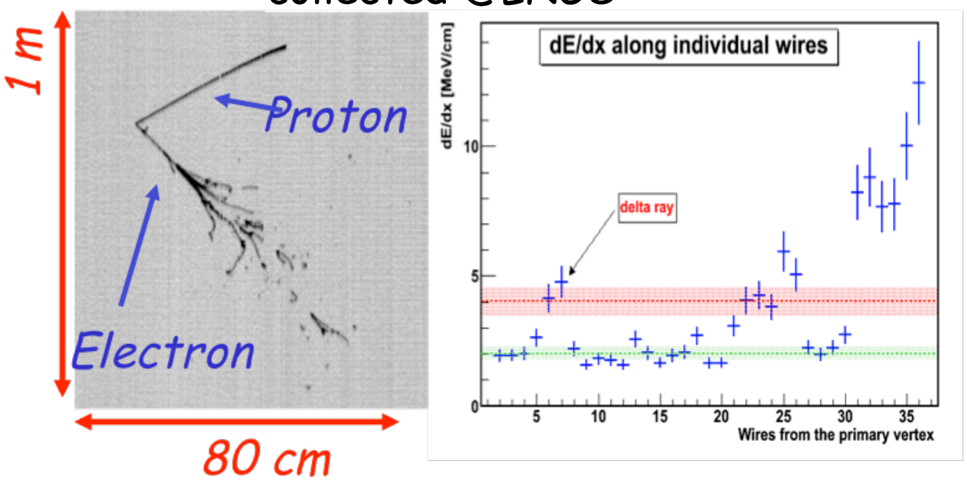
II stage



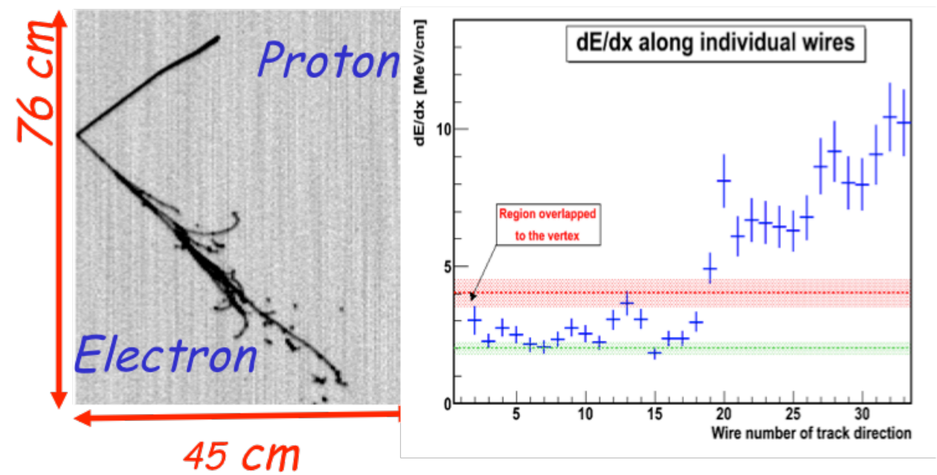
νe in LAr TPC

- LAr TPCs provide accurate tracking and calorimetric reconstruction and unique capability of e-γ separation
- Example of an atmospheric νe interaction in ICARUS collected during its underground run in Gran Sasso Laboratory, compared with a simulated quasi elastic νeCC

Atmospheric *νeCC* event collected @LNGS



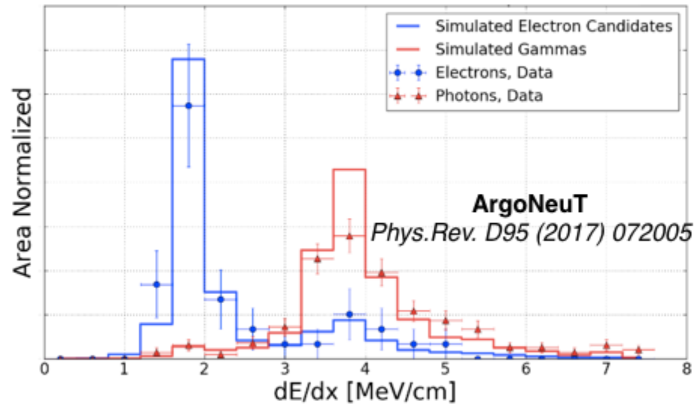
Simulated *νeCC* event



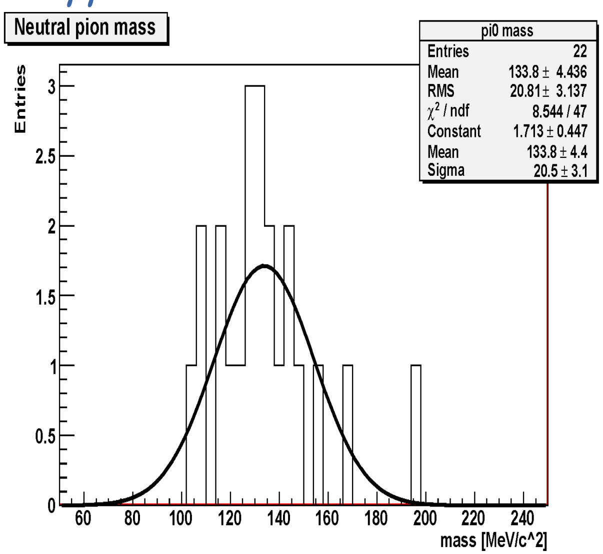
- *νeCC, E_{DEP}=0.9 GeV in ICARUS*
  - Proton identified by dE/dx;
  - Electron identified by single m.i.p. energy deposition before showering

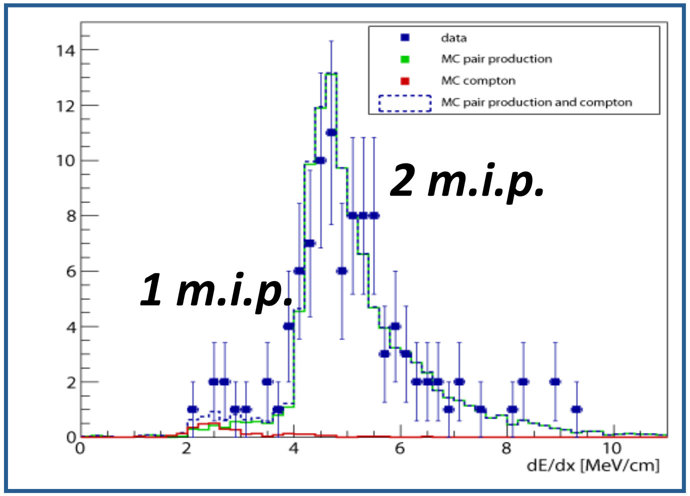
Unique feature of LAr-TPCs: e/γ separation, π^0 reconstruction

Three "handles" to separate e/γ:
- *invariant mass of π^0*
- *dE/dx: single vs. double m.i.p.*
- *photon conversion separated from primary vertex*

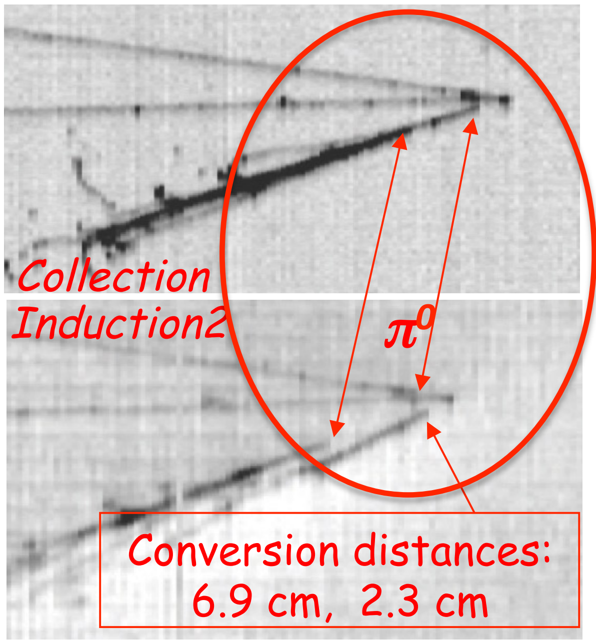


Mγγ: 133.8±4.4±4 MeV/c²



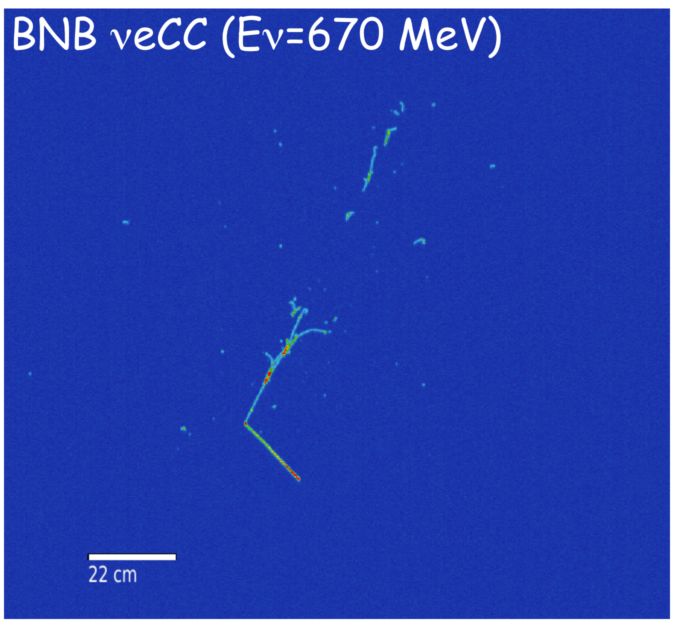


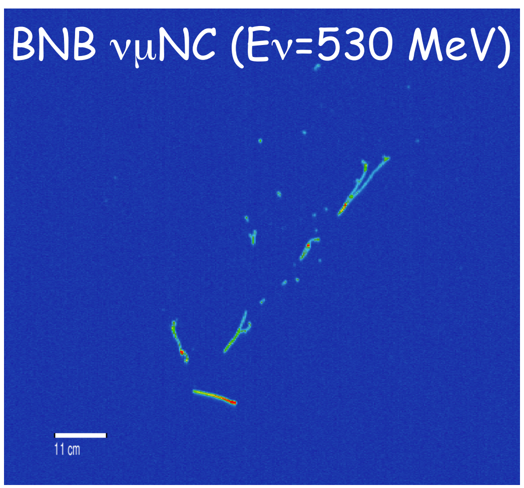
Crucial for NC rejection in νe-physics



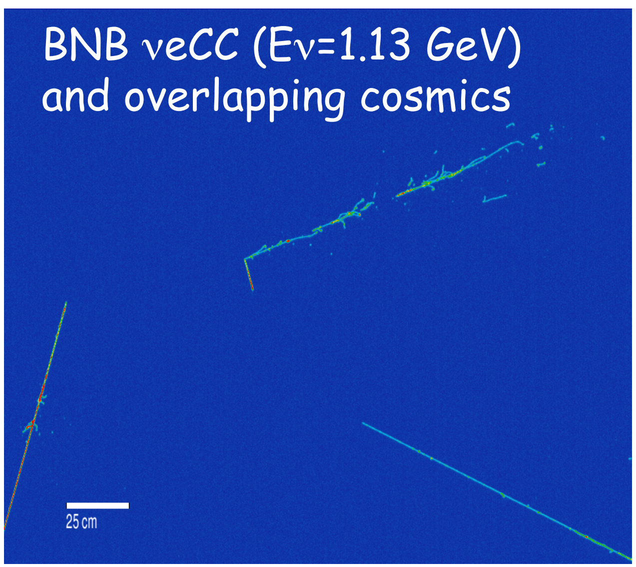
νe selection and reconstruction

- The selection and reconstruction of νe interaction is more challenging
  - Intrinsically more complex topology of the events
  - Potential background from misidentified γ–initiated showers generated by cosmics and by π^0 in NC neutrino events
- Good progress in the development and tuning of tools to select genuine νe interactions while rejecting backgrounds



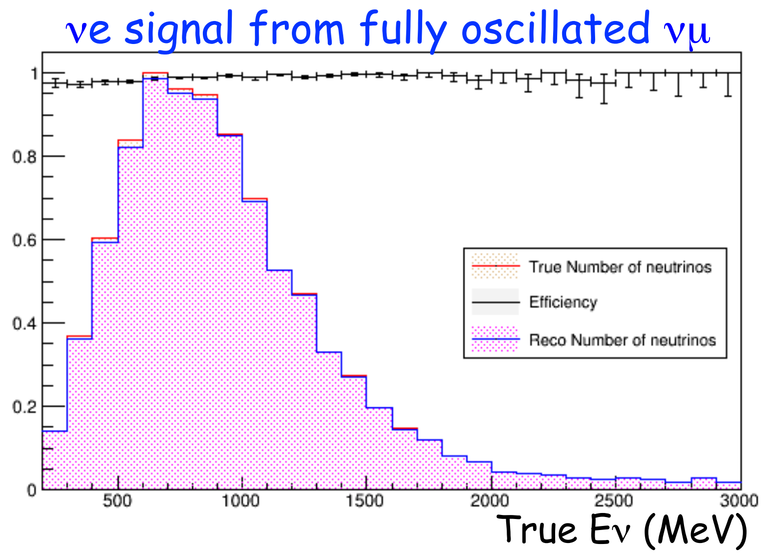


Present production

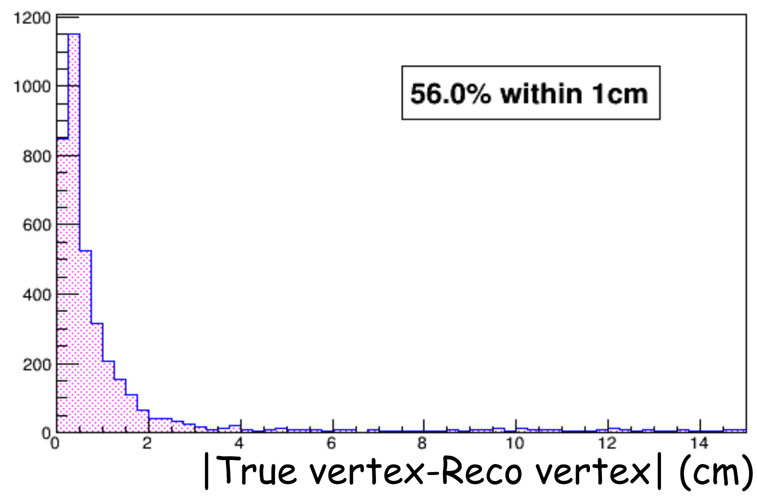


Tagging and reconstruction of νe events

- Pandora has an almost full efficiency to tag a νe neutrino interaction event



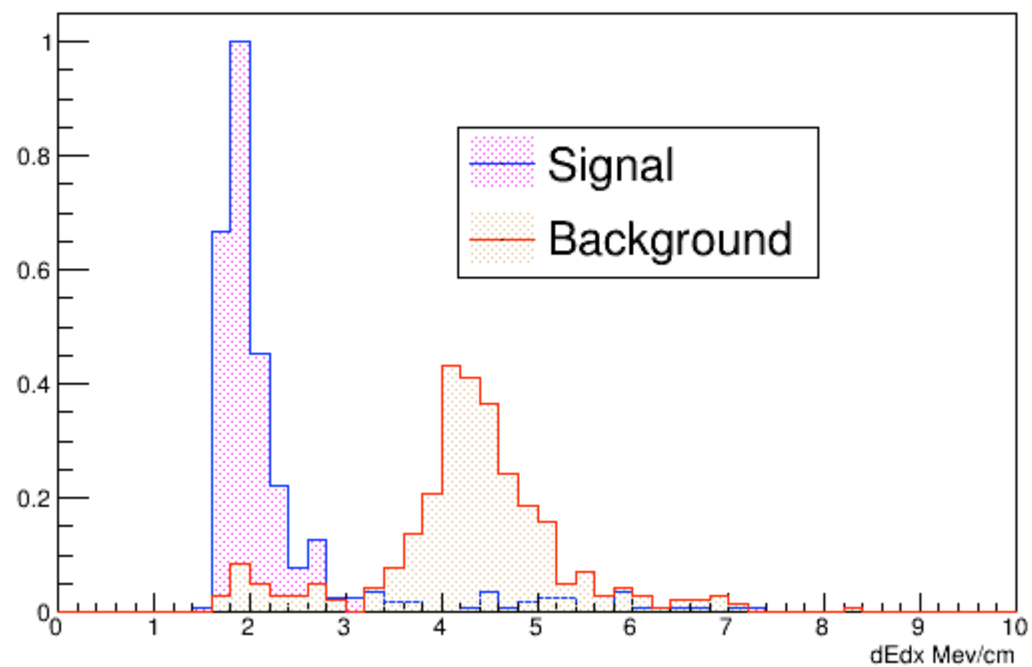
- At the present stage of the reconstruction the neutrino vertex is correctly reconstructed within 1-2 cm, with long tail…



e-γ separation

- e-γ separation based on the ionization density at the beginning of the shower (before the cascade onset)
  - e-showers are expected to start with 1 m.i.p. ionization density
  - γ-showers should start with 2 m.i.p. from pair-conversion
- Many aspects of the reconstruction are involved (primary vertex, shower identification, position and charge measurement in the vicinity of the primary vertex…)

- promising results with the present stage of the reconstruction tuning:
  ~90% electron efficiency
  ~90% γ rejection
  for well reconstructed ν vertex



Next steps

- Ongoing works to advance the reconstruction and analysis of the oscillation channels
  - Improve the $\nu\mu$ selection with more sophisticated usage of calorimetry, inner light and CRT information to reject cosmic background
  - Improve the νe selection efficiency and reconstruction and the rejection of NC background
- Exploit real data to measure detector performance and start addressing experimental systematics
  - Validate efficiency and background rejection with Far detector data
  - Exploit real data from the Near detector to measure its performance
  - Compare experimental performance of Near and Far detectors and study cancellation of common systematics exploiting standard candles
- In parallel proceed preparing a full oscillation analysis scheme to handle coherently near and far detectors data

Conclusions

- The work together scheme demonstrated very effective in
  - Exploiting synergies
  - Sharing expertise from the different groups
  - Reducing effort from single collaborations
  - Minimizing systematics which can impact the final oscillation analysis
- Progress since the last PAC presentation in the different activities of the group, including preparation of common tool for
  - Oscillation analysis
  - Detailed simulation of the events (including ν and cosmic background) including TPC, scintillation light and CRT
  - Promising first results on the event selection and background rejection. Optimization in progress
- A turning point with the actual detector data coming soon!

THANK YOU

BACKUP

PAC Recommendations/Charge

- Recommendations January 2019

  The PAC looks forward to the first deliverables, including, in March of 2019, the reproduction of the sensitivity of the appearance and disappearance oscillation channels reported in the SBN proposal, and,in the Summer of 2019, the first reassessment of the same sensitivities using more realistic estimates of backgrounds and systematics.

- Recommendations July 2019

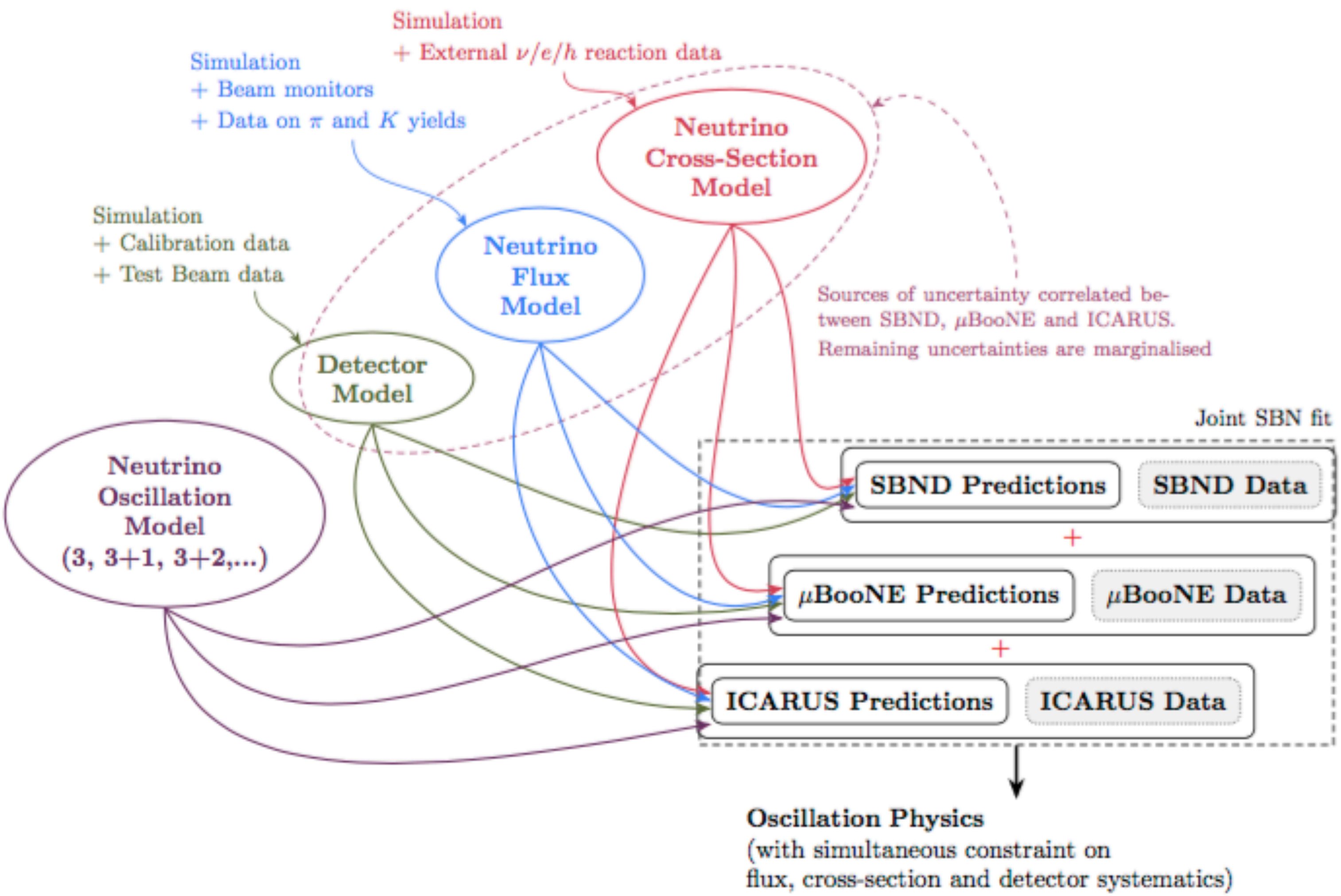
  The PAC is looking forward to hearing at the next PAC meeting updated information on the progress on realistic background and systematics estimations by the SBN Joint Working Groups and implementation of common reconstruction and analysis tools in preparation for the data exploitation

- SBN Charge:

  We ask the committee to assess the progress made by the analysis working groups towards an integrated SBN physics program. The committee will also review the status of the recommendations made at the January and July 2019 meeting. Suggestion to the speaker: In your presentation, you are invited to give a detailed update on the status of the various analysis efforts (e.g. simulation software, Monte Carlo production, reconstruction algorithms, and physics analyses).

SBN analysis paradigm

- The SBN oscillation analysis being implemented is based on extrapolation from SBND to ICARUS with SBND data driven physics systematics constraints as sketched below



GENIE neutrino interaction simulation

For the original SBN proposal studies, GENIE v2.8 was used.
To **replicate the SBN proposal sensitivities** we chose the most recent version of the GENIE v2 series (v2.12) available via LArSoft. *(The default comprehensive model and tune was unchanged throughout the v2 series)*

<u>Main features of the default GENIE v2.12 model:</u>

Initial state nuclear environment: *Fermi Gas model with N-N correlation tail by Bodek and Ritchie*

Neutrino-nucleus cross-section modelling:

- Quasi-elastic scattering: *Llewellyn Smith model with vector factors related, via CVC, to E/M form factors (BBA2005). Pseudo-scalar form factor has form suggested by PCAC. Dipole axial form factor with an axial mass of 0.99 GeV.*
- Multi-nucleon interactions: *(Optional) Empirical Dytman model motivated by the Lightbody model*
- Neutrino-production of baryon resonances*: Rein-Sehgal model with 16 unambiguous resonances, ignoring interferences. Dipole axial form factor with an axial mass of 1.12 GeV.*
- Non-resonance background / Shallow-inelastic scattering: *Legacy MINOS (neugen) resonance/DIS transition and tune by Andreopoulos, Gallagher – Inclusive inelastic model extrapolation down to threshold, decomposition of inclusive cross-section to 1-pion and 2-pion contributions, and tuning of non-resonance 1-pion and 2-pion backgrounds to bubble chamber inclusive and exclusive pion data.*
- Deep inelastic scattering: *Effective leading order model of Bodek and Yang with higher-twist and target mass corrections.*
- Coherent production of pions: *Rein-Sehgal model, with updates to account for lepton mass terms in the PCAC formula.*

Neutrino-induced hadronization: *Andreopoulos-Gallagher-Kehayias-Yang empirical low-W model, bridged to PYTHIA6*

Intranuclear hadron transport: *Effective INTRANUKE hA model*

Limitations of the GENIE v2 are understood – **Modern studies, beyond replication of proposal-era sensitivities, are based on v3.0.6** with a view to upgrading to v3.2.0 once it becomes available.

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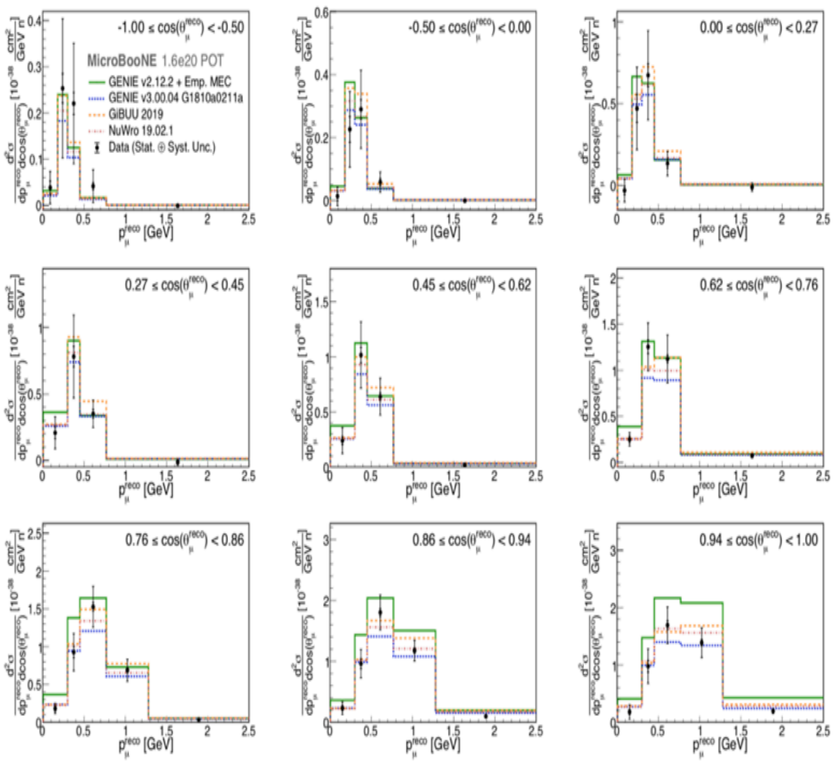


FIG. 2. ν_μ CC inclusive double-differential cross section on argon per nucleon n as a function of the measured muon momentum and cosine of the measured muon polar angle (angle with respect to the incoming neutrino direction). The data (black) is compared to a GENIE v2 with empirical MEC prediction (green), a GENIE v3 prediction (blue), a GiBUU prediction (orange), and a NuWro prediction (red), as described in the text. The vertical bars show statistical and systematic uncertainties.

arXiv:1905.09694

Modern versions of GENIE include both several comprehensive model configurations (both empirical and theory-driven) and tunes:

- Improved intranuclear INTRANUKE cascade models (hA, hN)
- Interfaces to new INCL and GEANT4/Bertini cascades (in v3.2)
- New improved free-nucleon cross-section tune and RES/DIS transition
- New improved hadronization tune (in v3.2)
- Several new cross-section models, in particular for QE, 2p2h and 1-pion

Current baseline tune is **G18_02a_02_11a** also tested in MicroBooNE

With respect to the default model in v2.12, the **G18_02a_02_11a tune in** v3.0.6 differs mainly in:

- the QE and 2p2h model (using Valencia calculation)
- the resonance neutrino-production model (Berger-Sehgal)
- the coherent pion-production model (Berger-Sehgal)
- the FSI model (updated INTRANUKE/hA)
- the resonance/DIS transition tune (new GENIE tune by Julia Tena Vidal)
- inclusion of missing rare processes (e.g. hyperon production, diffractive)

Treatment of systematics

CAFAna

Total oscillated predictions M_i for reconstructed bin i are obtained via $$M_i = \sum_{\alpha}^{e,\mu} \sum_{\beta}^{e,\mu,\tau} \sum_{j} P_{\alpha\beta}(E_j) M_{ij}^{\alpha\beta}$$

where $P_{\alpha\beta}$ are oscillation probabilities and $M_{ij}^{\alpha\beta}$ represent the number of selected events in a reconstructed bin i and true bin j, taken from a simulation. where neutrinos of flavor α from the beam have been replaced by equivalent neutrinos in flavor β. $M_{ij}^{\alpha\beta}$ is evaluated for a range of values of a systematic parameter x. Cubic interpolation is used. The prediction M_i is used to construct a log-likelihood ratio test statistic.

SBNFit

SBNFit constructs the test statistic $$\chi^2(\Delta m^2_{i1}, U_{\alpha i}) = \sum_{k=1}^{M} \sum_{l=1}^{M} \left[D_k - P_k^{osc}(\Delta m^2_{i1}, U_{\alpha i})\right] E_{kl}^{-1} \left[D_l - P_l^{osc}(\Delta m^2_{i1}, U_{\alpha i})\right]$$

where D_k represents the number of events in the k^{th} reconstructed energy bin, P_k^{osc} represents the number of oscillated events in the same bin, and $E_{k\ell}$ is a full covariance matrix containing the total statistical and systematic uncertainty between any two bins k and ℓ.

The covariance matrix $E_{k\ell}$ is constructed from weights corresponding to throws of the systematic parameters of the underlying model produced during the SBN MC production.

VALOR

An event rate prediction for a multi-dimensional reconstructed bin *r*, for a set of interesting physics parameters $\vec{\theta}$ and nuisance systematic parameters $\vec{f}$, for detector *d*, beam configuration *b*, and (selected) topological event sample *s*, is given by

$$n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) = \sum_{m} \sum_{t} P_{d;b;m}(t;\vec{\theta}) \cdot R_{d;b;s;m}(r,t;\vec{f}) \cdot T_{d;b;s;m}(r,t)$$

where $P_{d;b;m}(t,\vec{\theta})$ expresses oscillation or other new physics effects, $\mathrm{T}_{d;b;s;m}(r,t)$ are MC event rate templates constructed from the full simulation and reconstruction chain, representing the number of events in multi-dimensional reconstructed (true) bin *r (t)*, for detector *d*, beam configuration *b*, and topological event sample *s* and true reaction model m, and $R_{d;b;s;m}(r,t;\vec{f})$ express systematic effects on MC event template bins (can be either a normalisation or a non-linear systematic represented using an Akima spline). In the present iteration of VALOR/SBN sensitivity calculations, systematic parameter of the underlying flux and interaction models were mapped into a simple set of uncorrelated flux and cross-section normalisation parameters acting on reconstructed energy bins. Weights corresponding to throws of the systematic parameters of the underlying model, produced during the SBN MC production, were used to construct a pre-fit covariance matrix in the systematic parameter space chosen for the present iteration of VALOR studies.

The prediction $n^{pred}_{d,b,s}(r;\vec{\theta},\vec{f})$ is used to construct a log-likelihood ratio test statistic.

Treatment of variable baseline

CAFAna

MC templates are binned in true L/E

SBNFit

$$P^{3+N}_{\nu_\alpha \to \nu_\beta}(E_\nu, L_{osc}, \Delta m^2_{i1}, U_{\alpha i}) = \sum A(U_{\alpha i}) \sin^2\left(\frac{\Delta m^2_{i1} L_{osc}}{4E_\nu}\right) + \sum B(U_{\alpha i}) \sin\left(\frac{\Delta m^2_{i1} L_{osc}}{2E_\nu}\right)$$

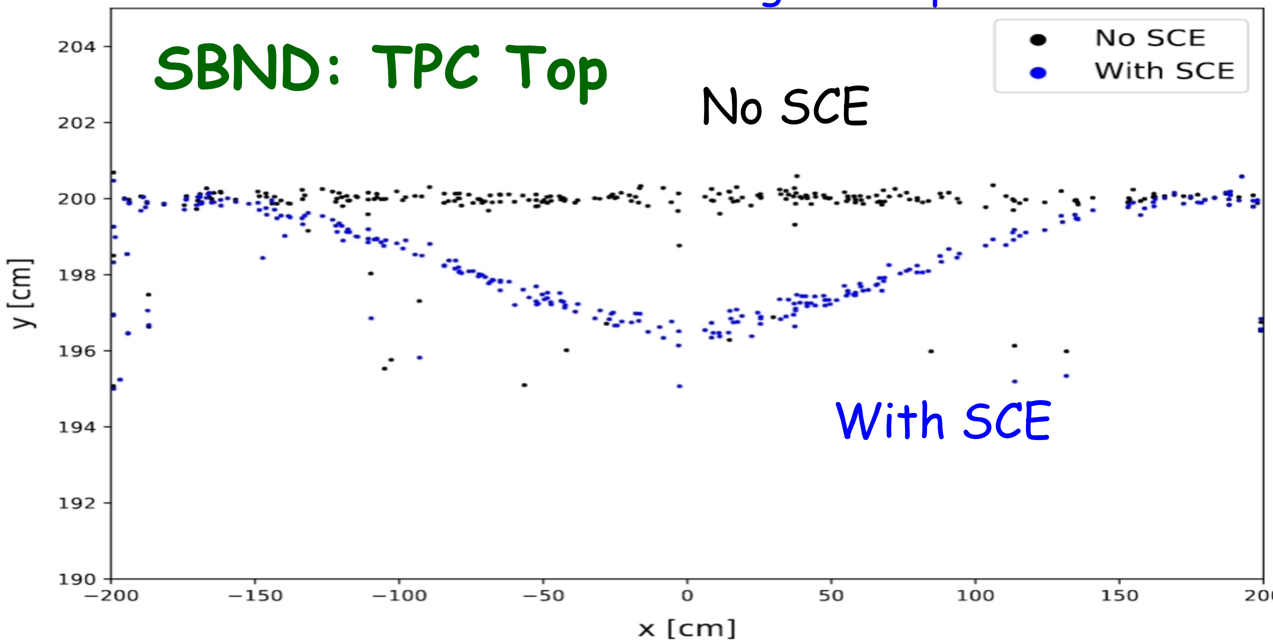
Pre-calculates (sin and $\sin^2$) frequency spectra for any given set of mass-splittings.

VALOR

Constructs a cubic spline, parameterising the distribution of baselines for each detector and, for each energy, averaged oscillation probabilities are calculated over the distribution of baselines.

SCE Implementation in LArSoft

x-y projection reconstructed entry points of simulated muons crossing the top of SBND



- Space charge effect simulation implemented in **LArSoft** for both detectors, including spatial and charge distortions:
- Implementation of correction of SCE and study of its impact on higher level physical analysis are in progress
- SCE not yet adopted in the standard SBND and ICARUS simulations