Status of the SBN Analysis Working Group

Fermilab PAC Meeting
June 8th, 2021

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Outline

1. Introductory remarks
2. Overburden studies
3. Update on SBN Analysis WG activities
4. Software infrastructures and computing resources

1. Introductory remarks

- The SBN Analysis Group is requested to provide all the common tools for the sterile neutrino oscillation searches at SBN that will enable exploring LSND allowed oscillation parameter region with 5σ sensitivity.
- The international SBN program received the scientific and formal approval by the major European and US Funding Agencies which also provided the required resources according to an established common agreement.
- Furthermore during its first year of operation, ICARUS will also investigate the present NEUTRINO-4 results with both BNB and NuMI off-axis beams (see ICARUS presentation). The data taking is expected to start in the fall collecting a large number of events which have to be promptly analyzed.
- As already pointed out in https://arxiv.org/abs/1408.6431, due to the large expected statistics it will be virtually impossible to analyze visually all the extremely complex events, following for each of them an elaborated procedure. A sophisticated automatic and very efficient method is therefore necessary.
- The automatic methods must be compared to a smaller sample of visually analyzed events to ensure the correct operation of the automatic procedure.

Introductory remarks, cont'd

- Present PAC Charge: *"We ask the committee to review the status of the SBN analysis group activity, the status of the recommendation (see below) from the December 2020 PAC meeting and the outcome of the studies of sensitivity for the SBND and ICARUS detector with the two possible overburden configurations."*

  "The PAC recommends the SBN analysis working group support the ICARUS collaboration in using the common tools developed in SBN to quantify the sensitivity of running ICARUS in the single-detector mode, as is planned in the current timeline, and to assess computing needs."

- The SBN Analysis working group has continued the effort for the complete event reconstruction. All the developed tools will be also exploited by ICARUS during its initial standalone data taking searching for the NEUTRINO-4 signal.

- Moreover a joint effort has been devoted to study in detail the role of the overburden for SBND and ICARUS.

- In parallel all the necessary software infrastructure and the optimization of computing resources necessary for the initial ICARUS data taking and then for SBND are being prepared and shared within the common Analysis Infrastructure group.

2. Overburden studies

- The exploitation of LAr-TPC detector to perform a sensitive search for neutrino anomalies at shallow depth with the FNAL BNB neutrino beam was discussed in a seminal paper in 2014 (https://arxiv.org/abs/1408.6431), proposing to protect the liquid argon TPC (LAr-TPC) against cosmic rays with both a passive layer and an active surrounding detector.
- This cosmic rays mitigation strategy was endorsed in the subsequent SBN proposal (https://arxiv.org/abs/1503.01520).
- An overburden together with a Cosmic Ray Tagger (CRT) system surrounding each detector are included in *the SBN project for both ICARUS and SBND* in their shallow depth operation at FNAL, as a fundamental element to reduce the event background from cosmic rays.
- Following the request from the PAC new sets of detailed simulations were recently performed to quantify the impact of the overburden on the cosmic rays and the associated background events.

Neutrino and cosmic ray rates at SBN

- Due to different mass and distance from the neutrino source the expected rates of neutrino interactions and cosmic rays (CR) inside 1.6 μs BNB beam spill, are largely different in SBND and ICARUS. **With the overburden:**

SBND

- A neutrino interaction every 20 spills;
- An in-spill cosmic muon every 190 spills;
- 4 "out-of-spill" cosmic muons during each TPC drift time (1.25 μs);

ICARUS

- A neutrino interaction every 180 spills;
- An in-spill cosmic muon every 44 spills;
- 14 "out-of-spill" cosmic muons during each TPC drift time (.96 μs);

According to the proposal the total expected intrinsic νeCC in the fiducial LAr volume of SBND and ICARUS is ~20000 and ~1900 respectively

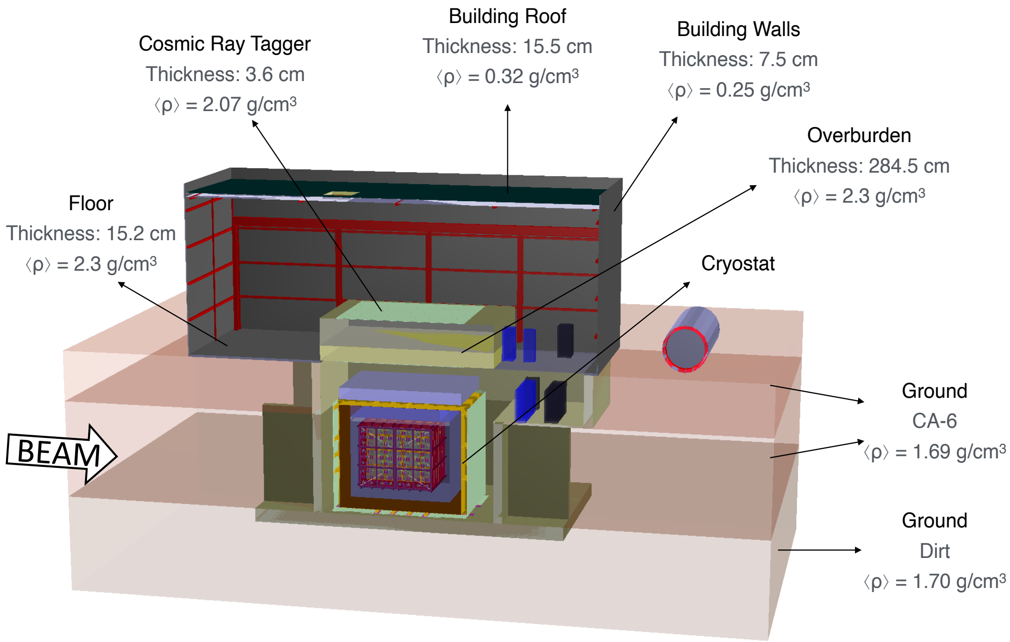
Very different neutrino/cosmics rates in the two detectors:

$$\frac{ICARUS\left(\nu/\text{in-spill CR}\right)}{SBND\left(\nu/\text{in-spill CR}\right)} \sim \frac{1}{40} \qquad \frac{ICARUS\left(\text{out-of-spill CR}\right)}{SBND\left(\text{out-of-spill CR}\right)} \sim 3.5$$

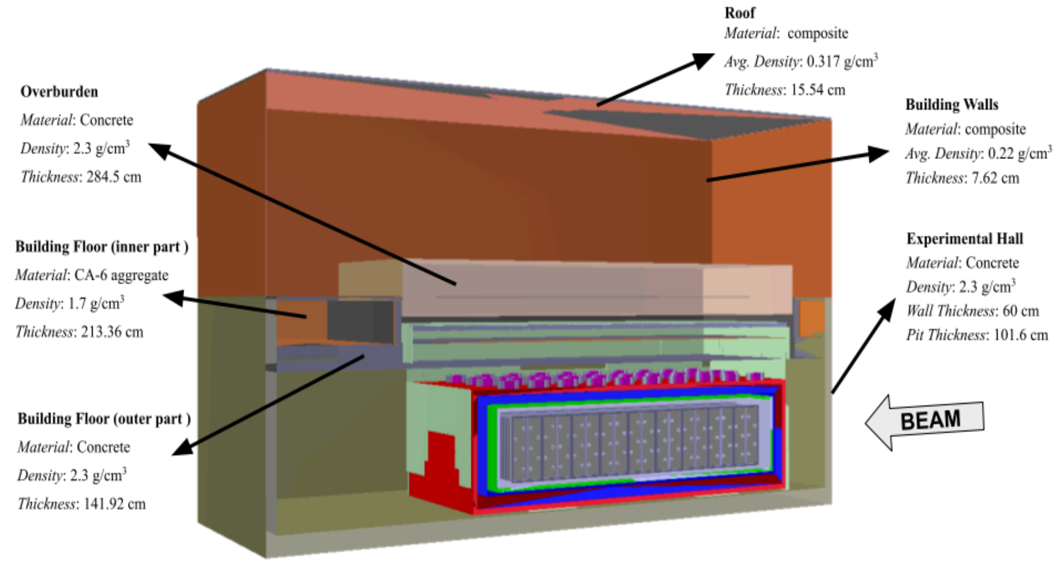
In ICARUS neutrino signal/cosmic background ratio is 40 times more unfavorable with in addition a >3 times larger out-of-spill comics rate.

Description of the experimental setups

SBND

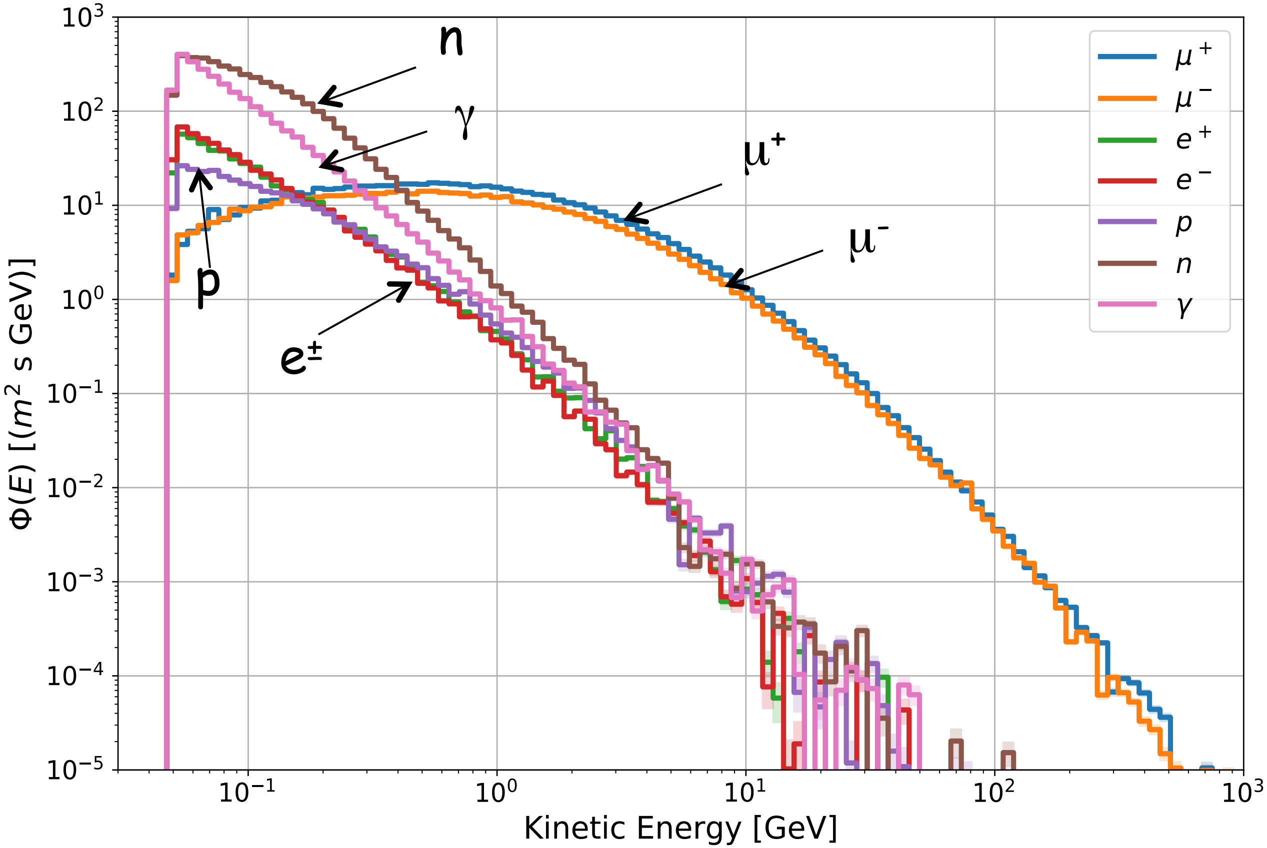


ICARUS



- Accurate description of geometry and composition of the two experimental setups used for MC simulations and data reconstruction (recently revised in detail).
- SBND and ICARUS share several materials and building components for which the code uses identical material and composition.
- Relevant differences include the material budget above the active LAr, pit geometry and implementation of the overburden, only partially closing the aperture above the detector in SBND and completely sealing it in ICARUS.

MC simulation of cosmic rays



Cosmic particle fluxes at 226 m above sea level (smaller contributions from K/π are not shown)

- Primary cosmic rays impinging on the detector are sampled from a set of atmospheric showers pre-simulated by CORSIKA version 7.4003 (proton-only model).
- Primary particles E_K > 50 MeV kinetic energy are simulated.
- Primary cosmic particles are then propagated with GEANT4 through the experimental setups down to 1 MeV of energy.

Cosmic rays simulation in SBND and ICARUS setups

- The common cosmic ray SBND/ICARUS simulations through the detectors have been performed in different geometrical configurations, introducing step by step various part of the experimental setups to understand their role in the reduction of the cosmic rays reaching the active detectors. In particular:
  1) "LAr only", i.e. including only the liquid argon volume and without anything else (i.e. without building, pit, the cryostat, etc);
  2) "no overburden", adding to 1) the detector infrastructures, the pit, the surrounding dirt and the materials of the experimental hall;
  3) "overburden" i.e. 2) plus the 285 cm thick overburden.
- For each configuration an event statistics corresponding to the total 211 s expected BNB exposure (6.6×10^{20} pot delivered statistics) of in-spill cosmic rays has been simulated, recording the particles reaching the active liquid argon. Out of spill cosmics are not included.
- The study is focusing on backgrounds to νeCC appearance signal.
- E.m. showers with E>200 MeV are considered, using MC "true" variables without a complete event reconstruction; e-γ separation is not applied; simple π^0 rejection based on the presence of a second γ with E>100 MeV (as in the Proposal).

Effect of overburden on primary fluxes

- Shielding effect of the materials of cryostats, buildings and detector location in a pit and overburden (OB) on the rate of primary cosmics reaching the Active Volume (AV):

Particle	Detector	without OB (Hz)	with OB (Hz)	without OB/ with OB
μ	SBND	3928	3144	1.25
	ICARUS	17117	12761	1.34
n	SBND	256	11.2	23
	ICARUS	1426	6.8	210
γ	SBND	16	0.19	83
	ICARUS	116	0.03	3542
p	SBND	9	0.18	48
	ICARUS	54	0.10	533

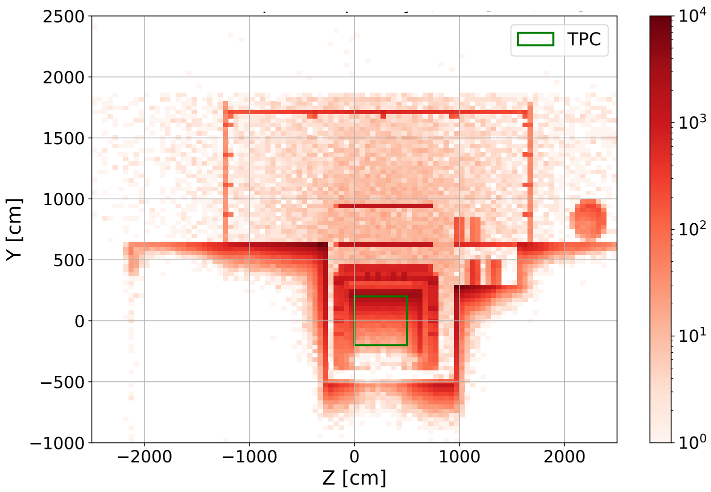
Rate (Hz) of primary cosmics E_k>50 MeV entering AV *without and with overburden.*

Surrounding materials produce similar effects for SBND and ICARUS.

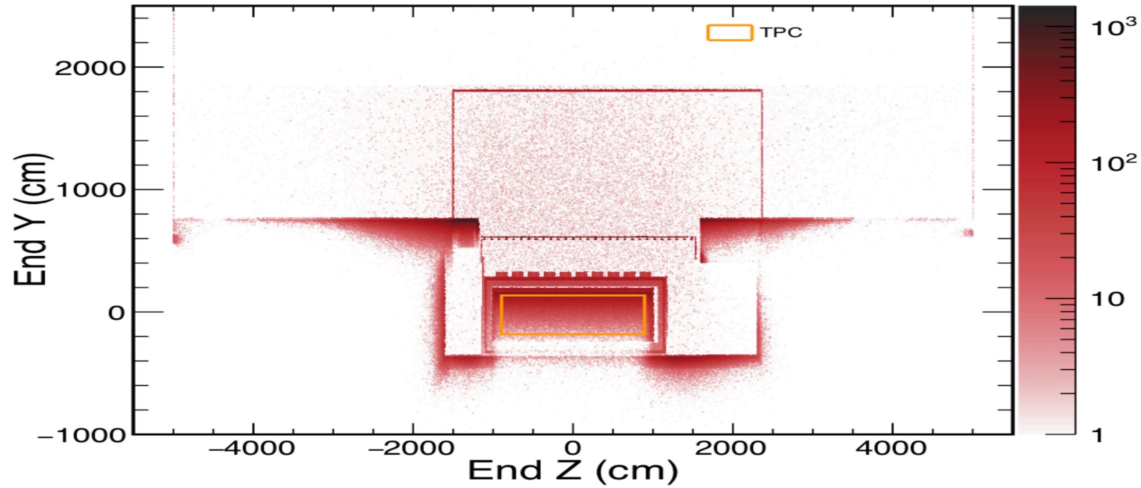
- *Fundamental role of overburden in suppressing the most challenging neutral particles "invisible" to CRT. Beside the general reduction of cosmic flux, neutrons and photons can be strongly suppressed only by the overburden:*
  - Primary neutrons are suppressed by a factor ~20 in SBND and ~200 in ICARUS where the overburden completely closes the pit aperture.
  - Primary γ are suppressed by a factor ~80 in SBND while almost fully removed in ICARUS

Primary neutron (E_k>50 MeV) suppression by overburden

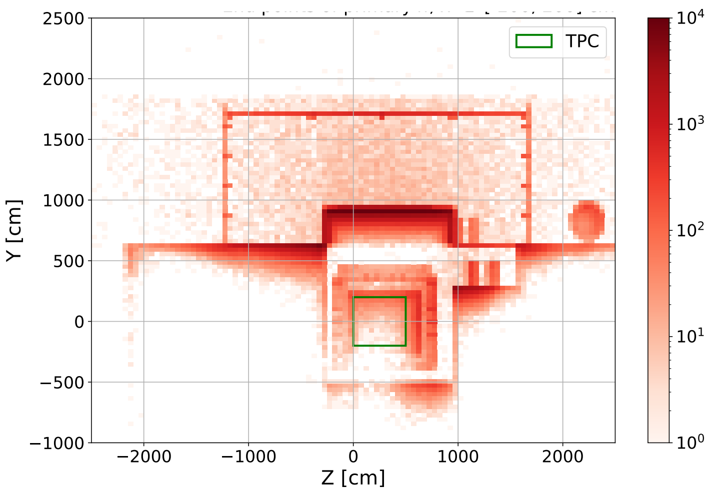
SBND without OB



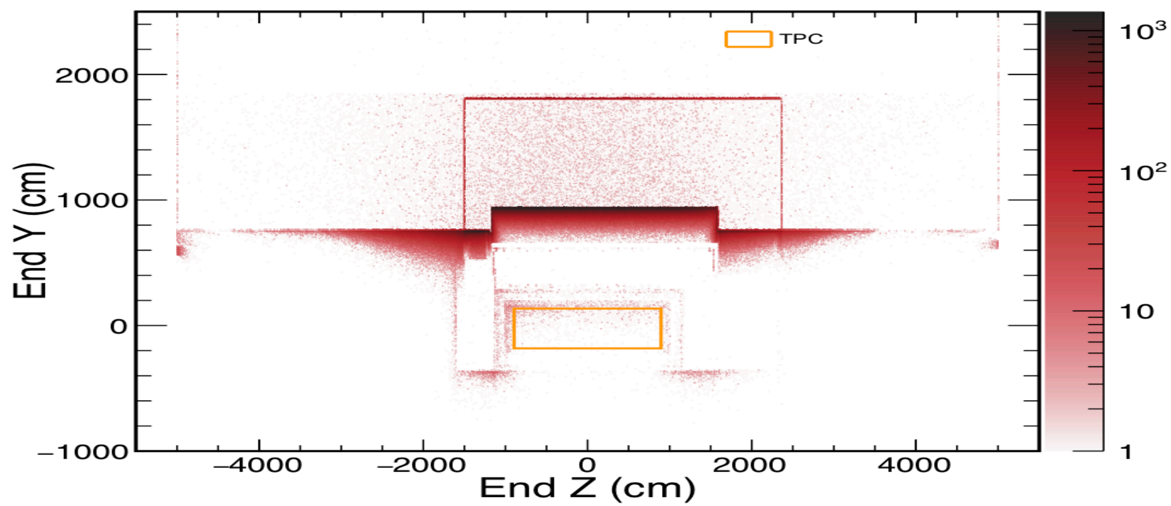
ICARUS without OB



SBND with OB



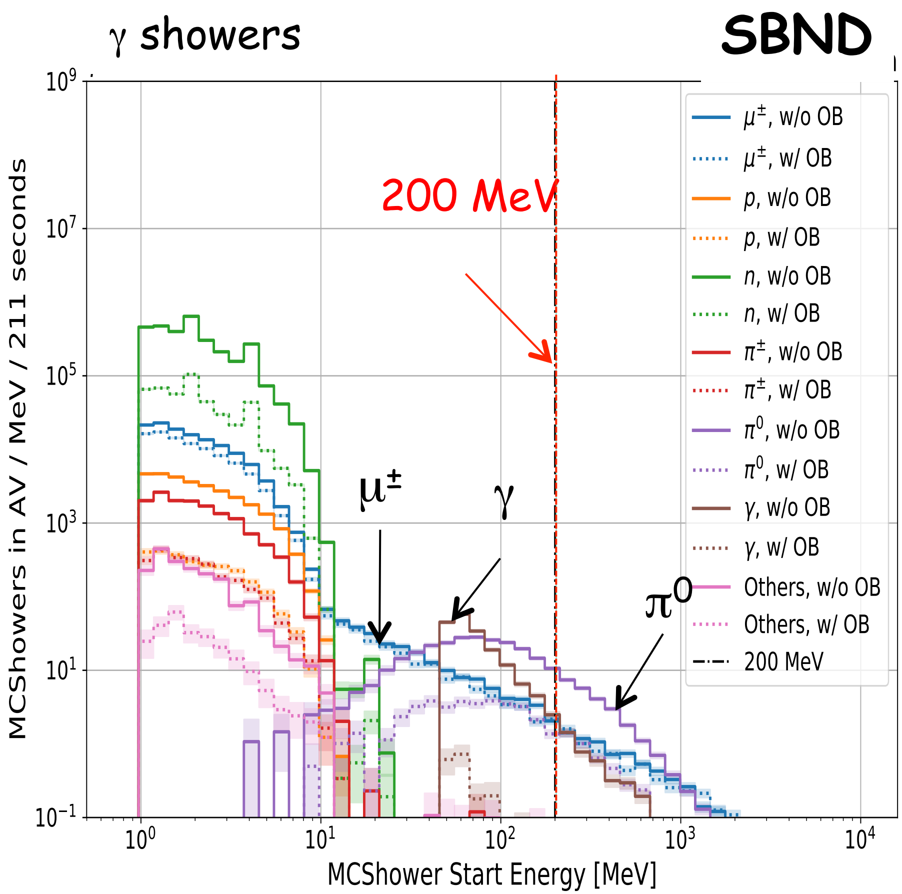
ICARUS with OB

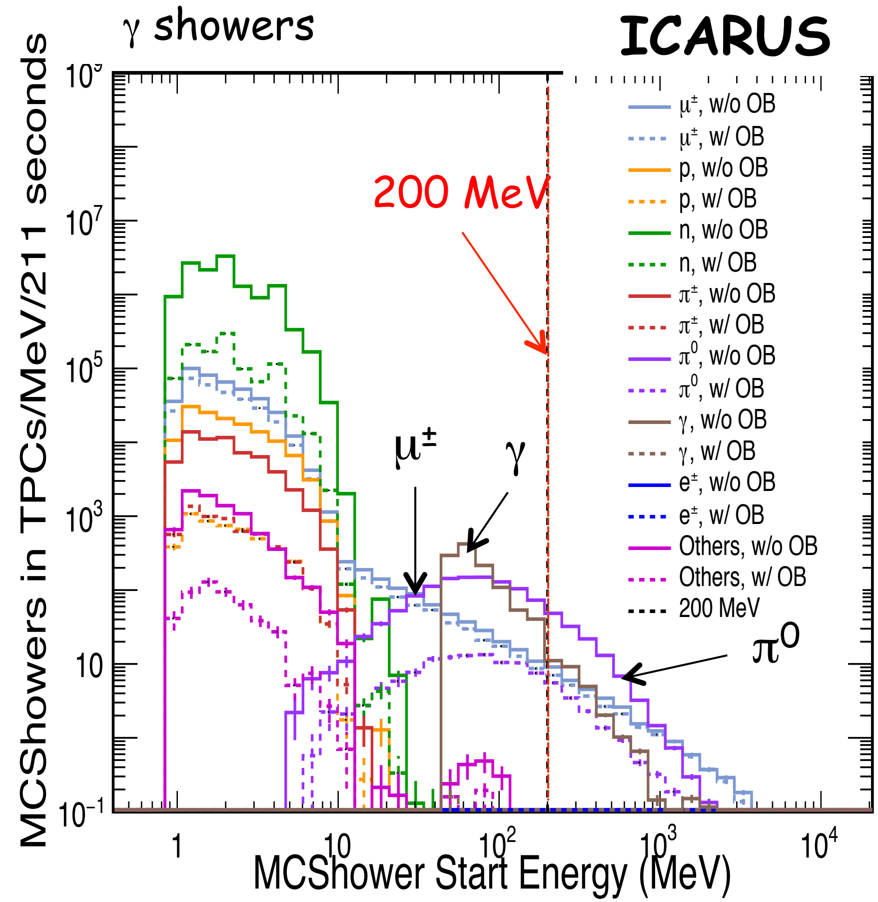


- The overburden completely seals the pit for ICARUS and only partially for SBND

e.m. showers from cosmic rays

- $e^{\pm}$ initiated showers clearly branch off their parent μ and do not represent a background.
- Overburden reduces the most serious background due to γ initiated showers >200 MeV.





γ initiated showers in active volume (211 s): without (solid lines) and with OB (dashed lines) classified based on shower mother particle

γ initiated showers: effect of the overburden

- 3 main mechanisms are involved in the production of γ showers (E>200 MeV) in the LAr

Example: the ICARUS case

	γ from π^0		γ from μ brems	Primary γ
Primary cosmic	**hadrons**	μ	μ	γ
(Without OB)	**(86%)**	(14%)		
With OB	5%	**95%**		
	π^0			
Total in 211 s in active LAr	(12290 γ) 989 γ		(3630 brem γ) 3270 brem γ	(2231 primary γ) negligible

- π^0 decay: dominant channel with large fraction from untagged neutrons without OB.
- OB strongly suppress hadrons and removes primary γ and associated showers
  - The residual contribution from muons (through bremsstrahlung or π^0 nuclear photo-production) can be further rejected exploiting the CRT signal and by their small distance from the muon (as quoted in the Proposal).

Comparing γ initiated showers from different sources

- Cosmogenic γ showers from present study (after rejecting π^0 with γ_1>200 MeV γ_2>100 Mev):

e.m. E>200 MeV in FV	SBND		ICARUS	
	without OB	with OB	Without OB	With OB
events with π^0	297	44	2059	174
Primary γ	45	0	501	0

- As a comparison, e.m. showers by BNB ν NC interactions in LAr producing a single π^0 and by BNB ν interacting outside the active volume result (after π^0 rejection):

e.m. E>200 MeV in FV	SBND	ICARUS
ν NC interactions in LAr with 1 π^0	45932	6585
Events with 1 π^0 from ν in "Dirt"	2791	630

- Note that the contribution from ν interactions in the overburden are negligible.
- These tables include all γ initiated showers in the fiducial volume (FV) generated by different sources and corresponding to events with different topologies.
- The studies focus on counting of γ-showers with simple π^0 identification criteria. In the actual data analysis each background source has to be addressed separately by exploiting all the event features like vertex reconstruction when present, e-γ identification by dE/dx, conversion distance from vertex and proper π^0 identification.

Summary on the overburden study

- For the SBN "definitive" sterile neutrino search we must remove as many controllable backgrounds as possible in the experiment setup.
- We have quantified, with accurate description of the geometry and composition of the experimental setups, the different impact of the overburden for SBND and ICARUS, due to their different distance from the neutrino source, LAr mass and geometrical configuration.
- For SBND the improvements that the overburden would bring to the main physics analysis appear to be marginal.
- Even if π^0's from beam neutrino neutral current interactions remain the primary signal background, the important role of the overburden in reducing cosmogenic background in ICARUS and its contribution to reduce the associated systematic uncertainties is confirmed by the new detailed MC calculations.
- The overburden is an essential component for the ICARUS detector due to neutrino over cosmic ratio ~40 times less favorable compared to SBND.
- In addition, in ICARUS, the overburden will significantly reduce the amount of data collected (~25% less cosmic muons in time with the beam) and the subsequent effort and time required for the analysis.

3. Update on SBN Analysis WG activities

- Since our last presentation in December 2020, we have
  - Maintained regular meetings
  - Organized one (online) Workshop - **VI SBN Analysis Workshop** – Tuesday Apr. 6th – Monday April 12th, with contributions from the different SBN Analysis subgroups:
    - Plenary Sessions:
      - Status of reconstruction and event selection;
      - Status of oscillation sensitivities;
      - Status of detector systematics evaluation and impact on oscillation sensitivities;
      - Status of SBN Analysis Infrastructures;
      - Use of Machine Learning tools for SBN;
      - "Looking forward" sessions to discuss improvements and next steps.
    - Parallel working sessions: for different subgroups to meet and discuss results and plan future activities.
  - Organized tutorials on SBN software tools
  - Continued comparisons between ICARUS data and Monte Carlo simulations

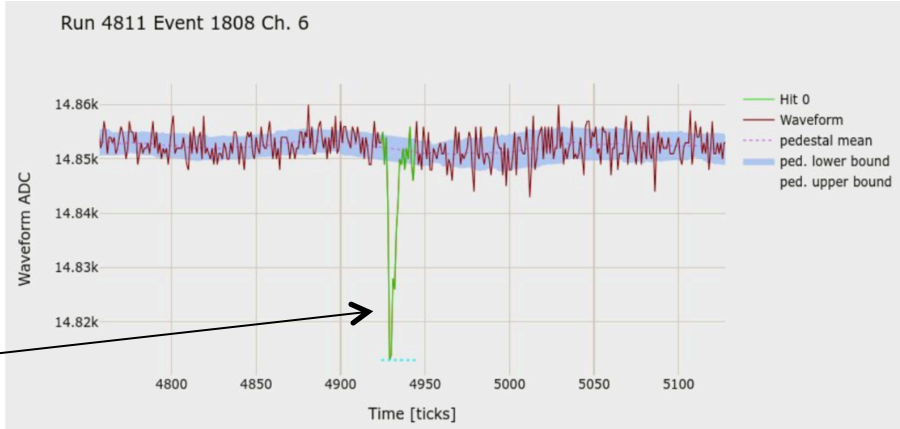
Snapshots of some of the current activities in the next slides

TPC Simulation and Reconstruction

- Continue refining TPC simulation (e.g. 1D→2D wire field response)
- Study of detector effects using first ICARUS data and folding of studies into data-driven simulations.
- Estimate impact of detector systematics on SBN oscillation analyses.
- Addressing/fixing the efficiency of the current ν_e event selection, in particular by improving the vertex reconstruction. Current efforts are focused on improving the precision of the reconstructed vertices:
  - Ongoing efforts to retrain/reweight/add new variables to the vertex selection Multi Variate Analyses (MVA) in Pandora.
- Effort in shower reconstruction:
  - Improving shower energy reconstruction by utilizing a method developed by ArgoNeuT.
  - Improving e-γ separation via dE/dx by studying the performance of the initial track stub identification
- Effort for muon-pion separation.
- Analysis of ICARUS commissioning data is using the current version of the SBN reconstruction tools (Pandora-based reconstruction). The SBN Analysis TPC reconstruction group continues to provide support/advice/tooling in that effort.

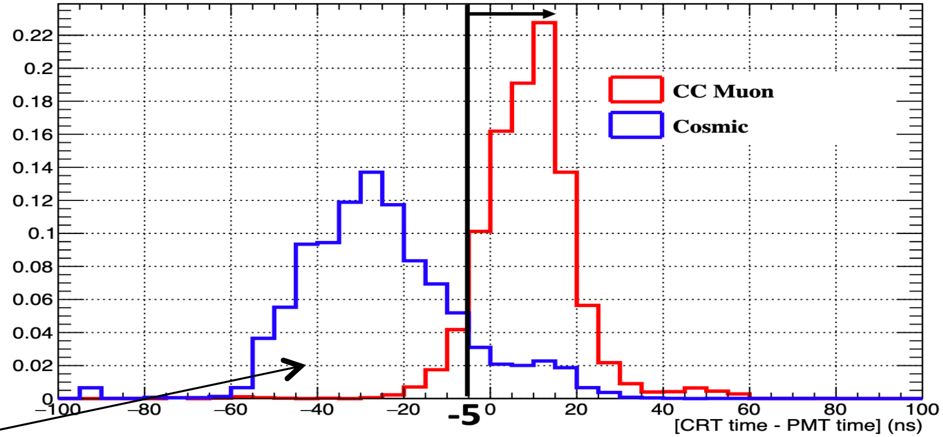
PMT and CRT reconstruction

- The simulations are being updated using PMT-system performance results.
  - An updated Flash-matching algorithm is being tested and tuned for SBND with the measured SER signals.
- First use of Optical Reconstruction with ICARUS data:
  - PMT pulse (Optical Hit) finder used to reconstruct the local pedestal and identify pulses on the waveform and reconstruct pulse start time



- ICARUS simulations demonstrated the possibility to distinguish incoming cosmic rays from exiting muons from a neutrino interaction in the active LAr exploiting the time difference between the CRT and the inner PMT signals.
- SBND is now validating the same method.

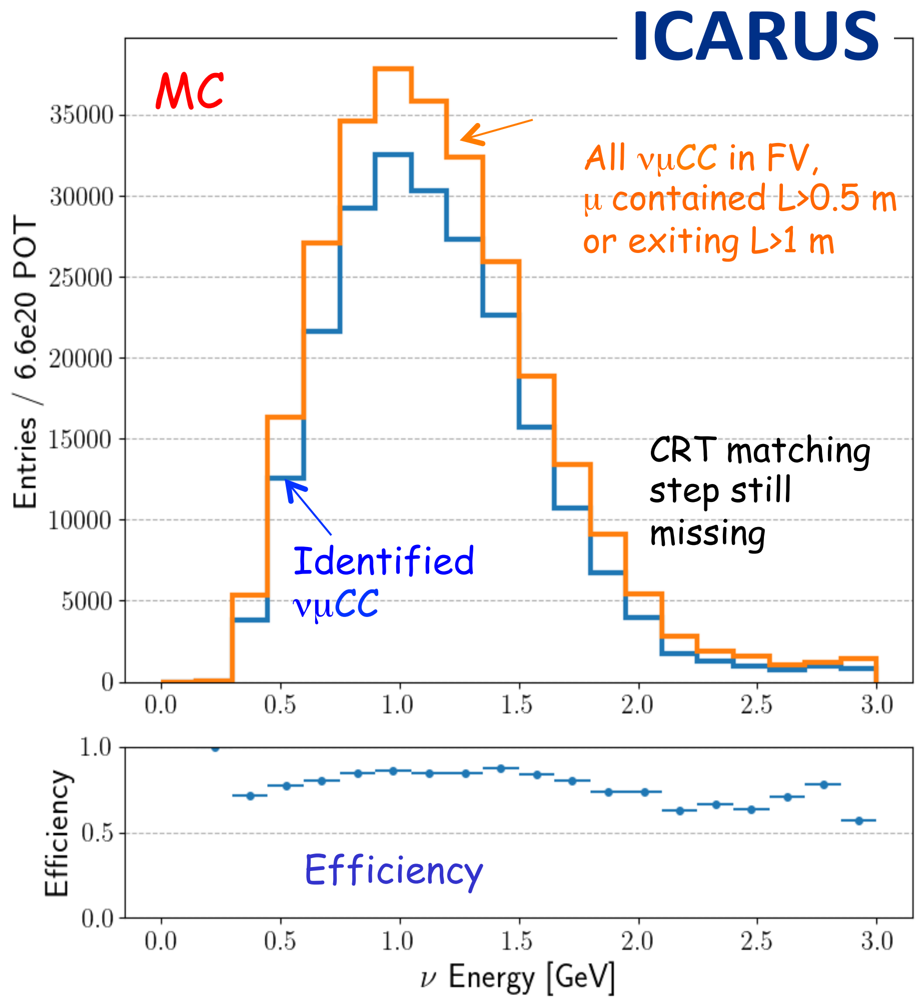
Using minimum optical hit time



Sample	# tagged as Nu	# tagged as Cosmic	Total	(%)
Neutrino	3290	256	3546	92.78
Cosmic	8221	57611	65832	87.51

Present status of the MC νμCC event selection

- The νμCC event selection is based on:
  - ✓ The μ track exiting the interaction vertex with μ identified by the characteristic dE/dx mip signal and a track length >50 cm if contained or >100 cm if exiting;
  - ✓ TPC-CRT track matching to further reject cosmic backgrounds (this final step is still under development in ICARUS).

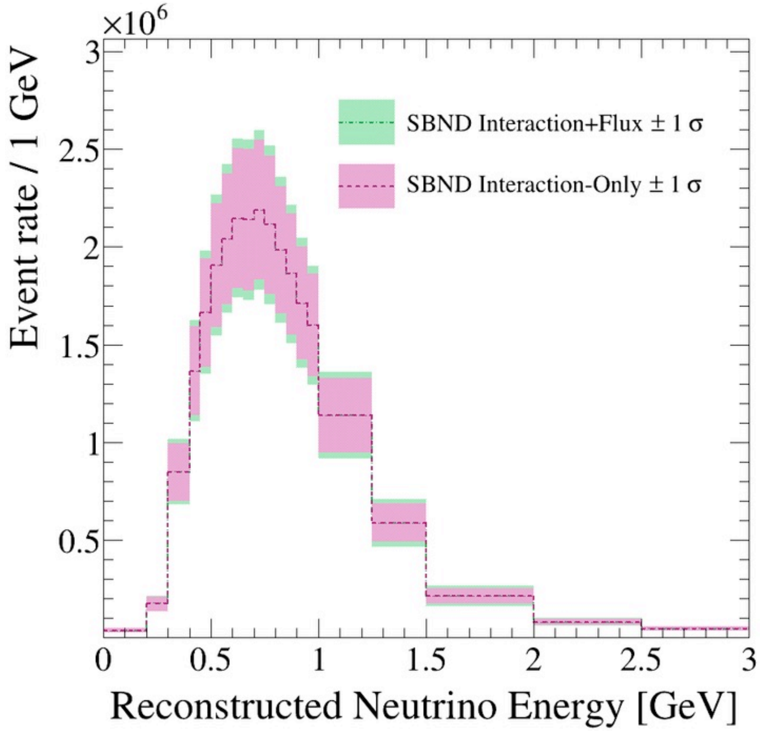


- This νμCC event selection procedure was discussed at the last December PAC meeting in particular for SBND, showing a 83.4% efficiency for events inside the fiducial volume (FV).
- The same procedure has been recently applied also to ICARUS showing νμ CC id efficiency > 82% before CRT-TPC matching.
- Strong rejection of cosmics and NC background could be obtained by joint exploitation of TPC, PMT, CRT signals in both detectors.

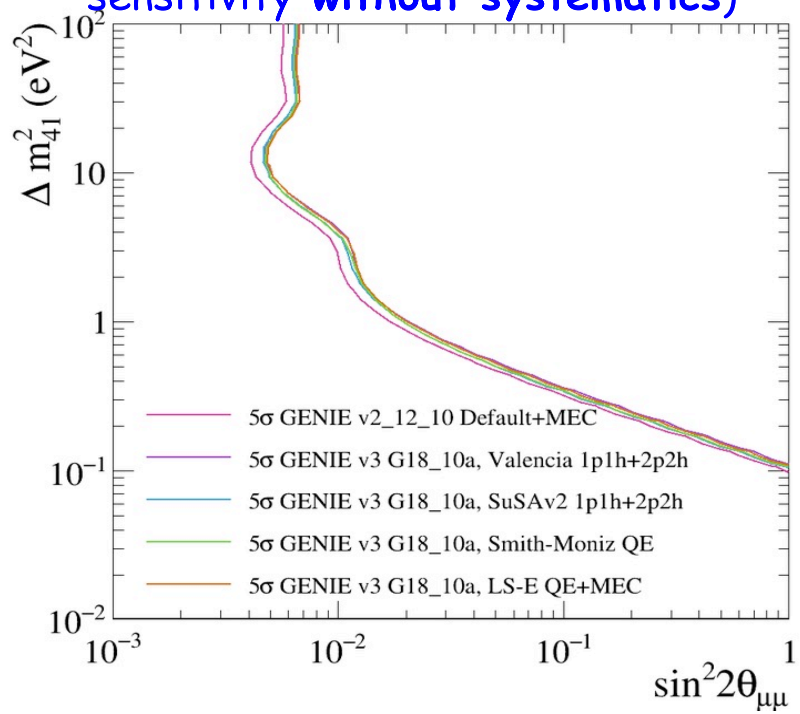
Flux, cross-section and interaction model systematics

- Extensive set of physics modeling uncertainties on the default interaction model are already included in sensitivity calculations.

ν_μCC flux/cross section uncertainties



Impact of different interaction models on ν_μ CC collected event statistics (plot shows **statistics only** sensitivity **without systematics**)



- Mock data studies of alternative models to test/improve: 1) uncertainty for default model; 2) SBND to ICARUS extrapolation; 3) impact on sensitivity.
- Simulation / analysis framework can handle alternative models for cross-section & nuclear re-interaction models as well as interface alternative MC generators.

4. Software Infrastructures and computing resources

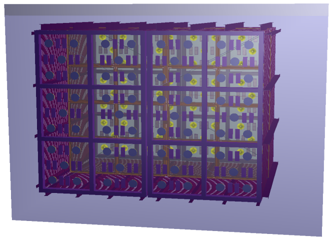
- The SBN requested resources for storage and CPU were prepared by the SBN Analysis Infrastructure WG and presented jointly, along with a breakdown for the individual detectors.
- Awaiting final report but received good responses from Fermilab Computing Resource Scrutiny Group review.
- Actively working with experiment and lab experts to address computing bottlenecks and improve computing efficiency, particularly data I/O.

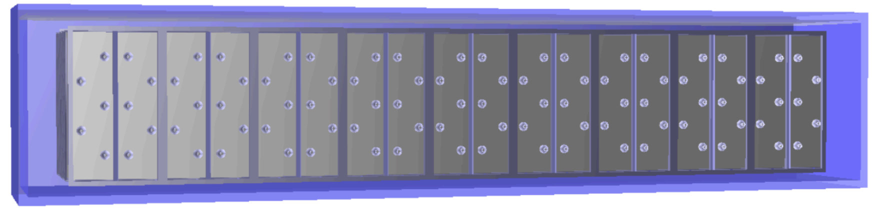
Detectors		2021	2022	2023
ICARUS	Cumulative Data Storage Needs [PB]	13.7	17.7	24.2
	Grid Computing Needs [CPU MHr]	14.3	20.8	29.1
SBND	Cumulative Data Storage Needs [PB]	1.0	4.6	7.4
	Grid Computing Needs [CPU MHr]	4.0	11.8	19.0

BACKUP

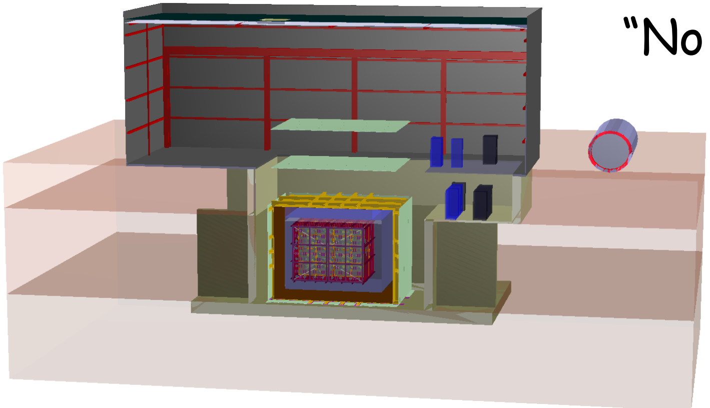
The three simulated configurations

SBND | **ICARUS**

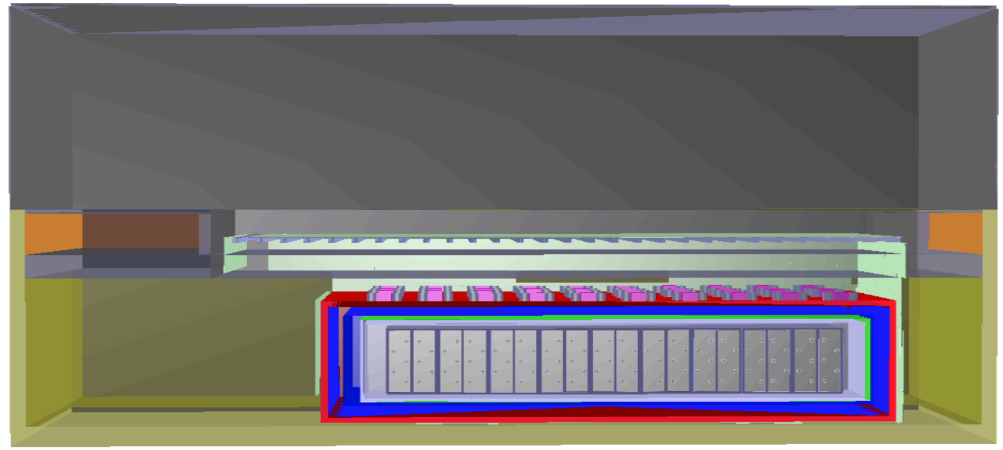


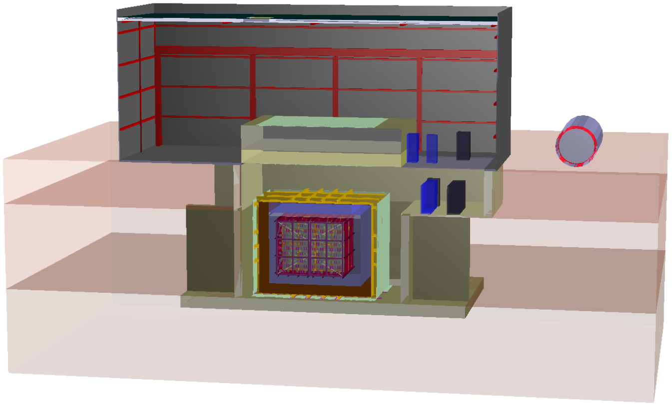


"LAr only"

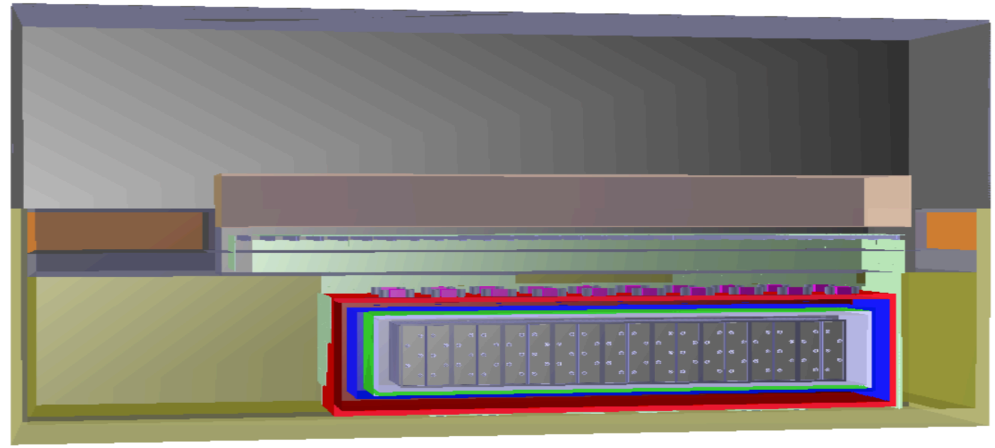


"No overburden"

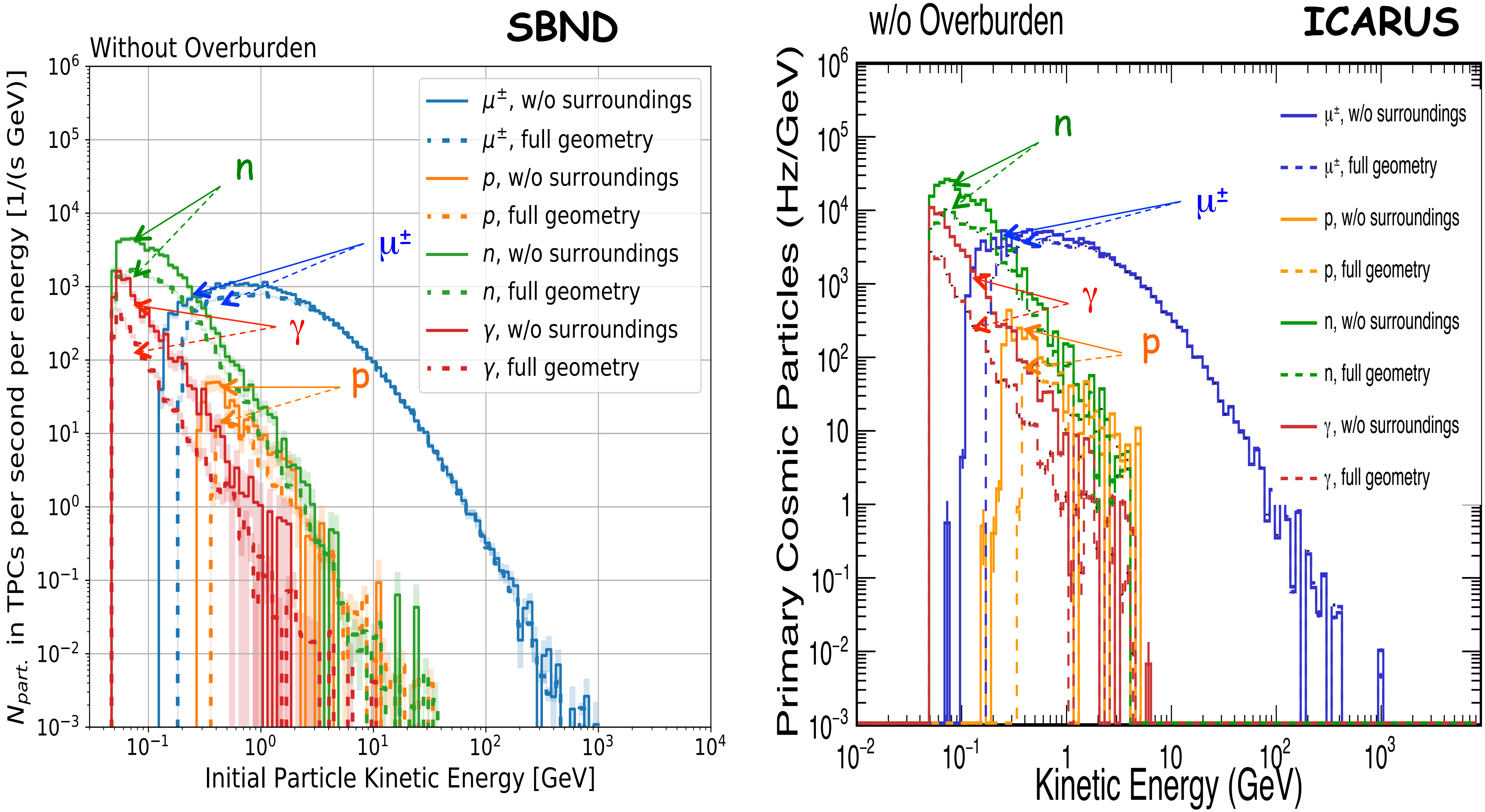




overburden

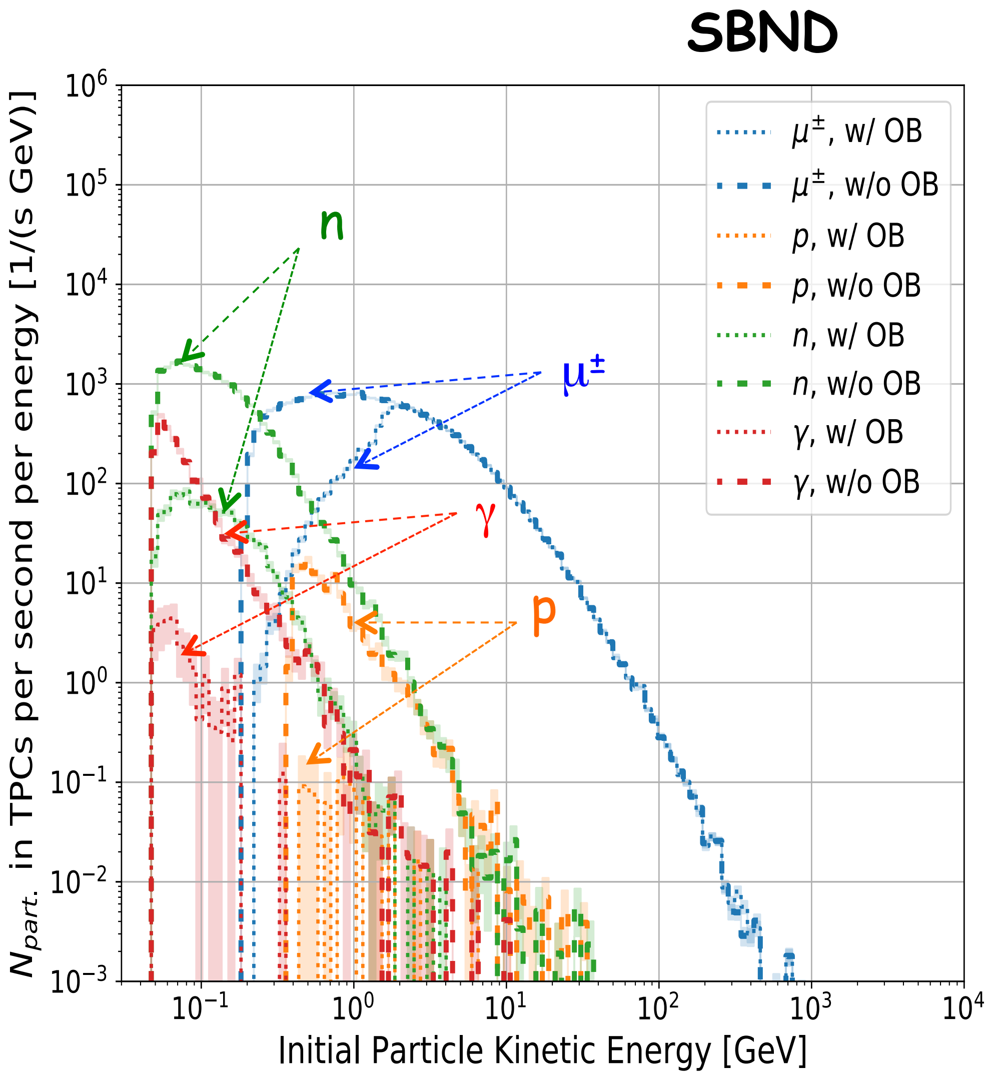


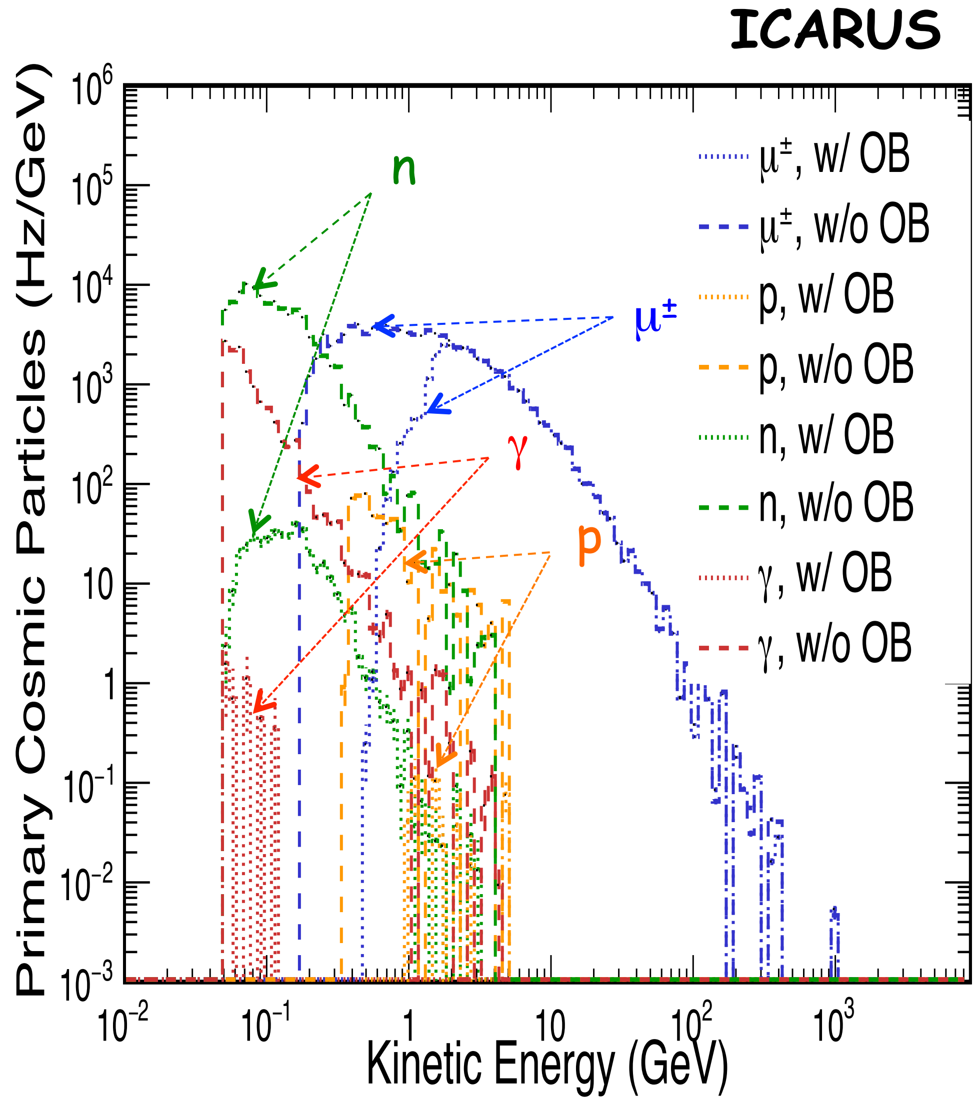
Effect of surrounding materials on primary cosmic flux



- The number of cosmic primaries inside the active volume for configuration 1 (with the LAr only, full lines) and configuration 2 (without overburden, dashed lines).

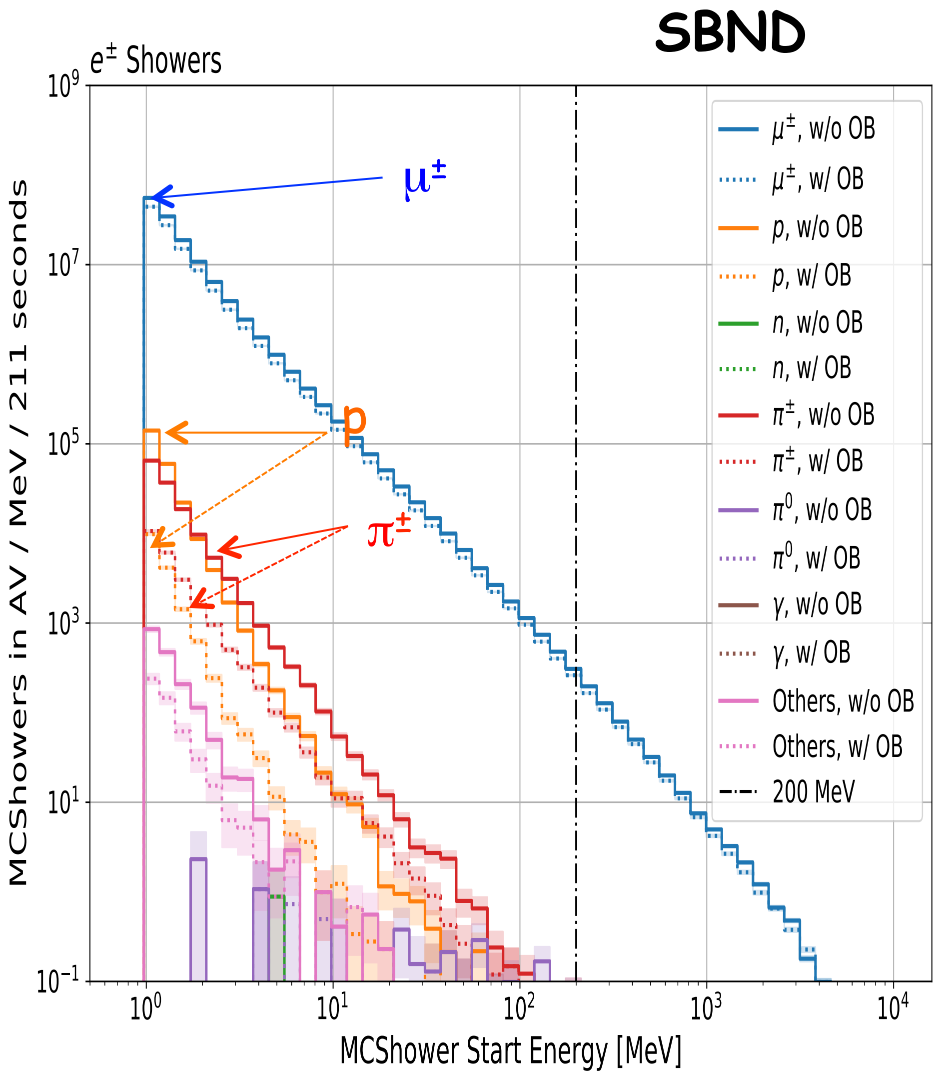
Effect of overburden on primary cosmic flux

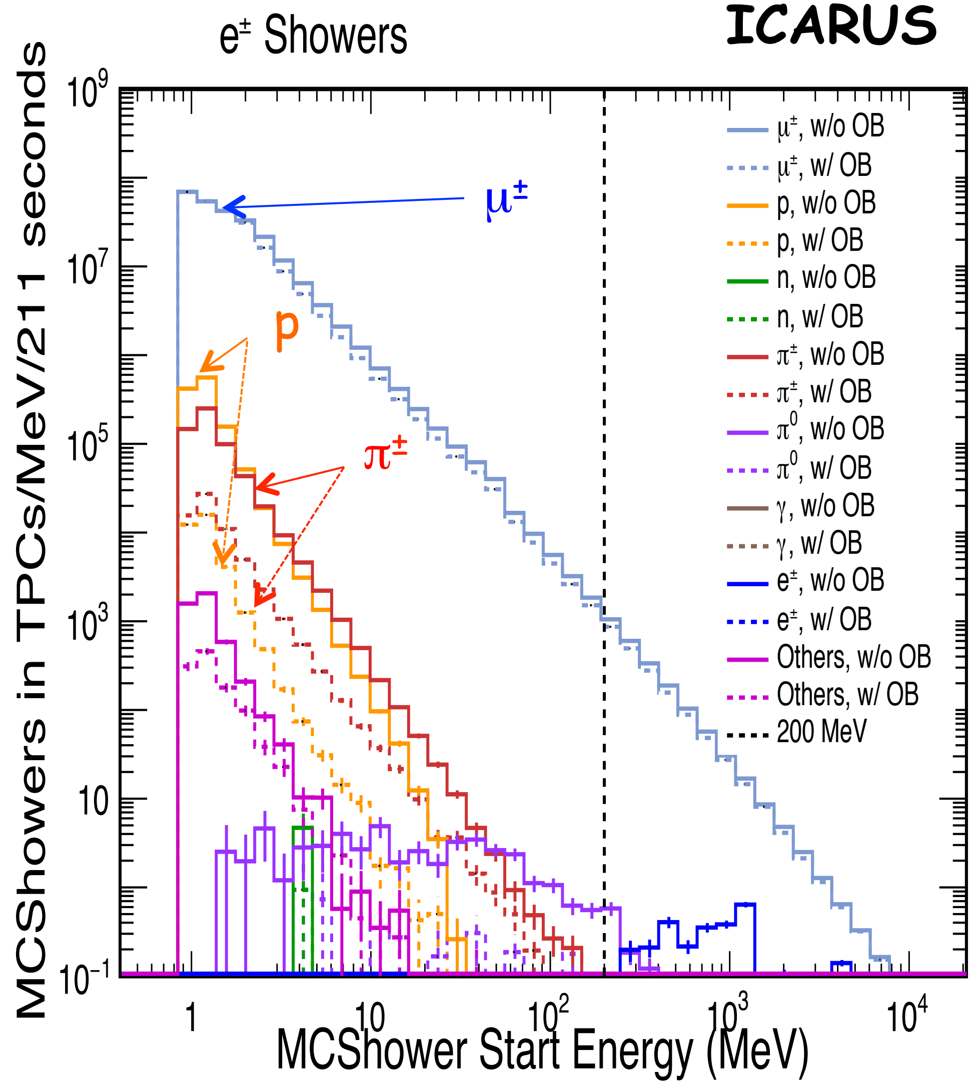




- The number of cosmic primaries inside the active volume for configuration 2 (without overburden, dashed lines) and configuration 3 (with overburden, dotted lines).

e.m. showers initiated by e±

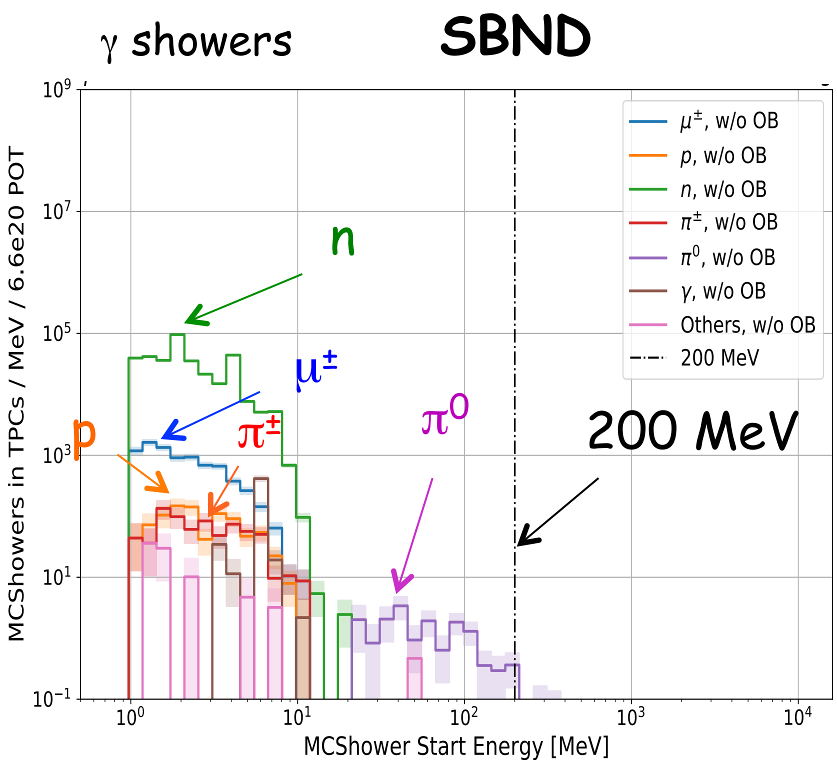


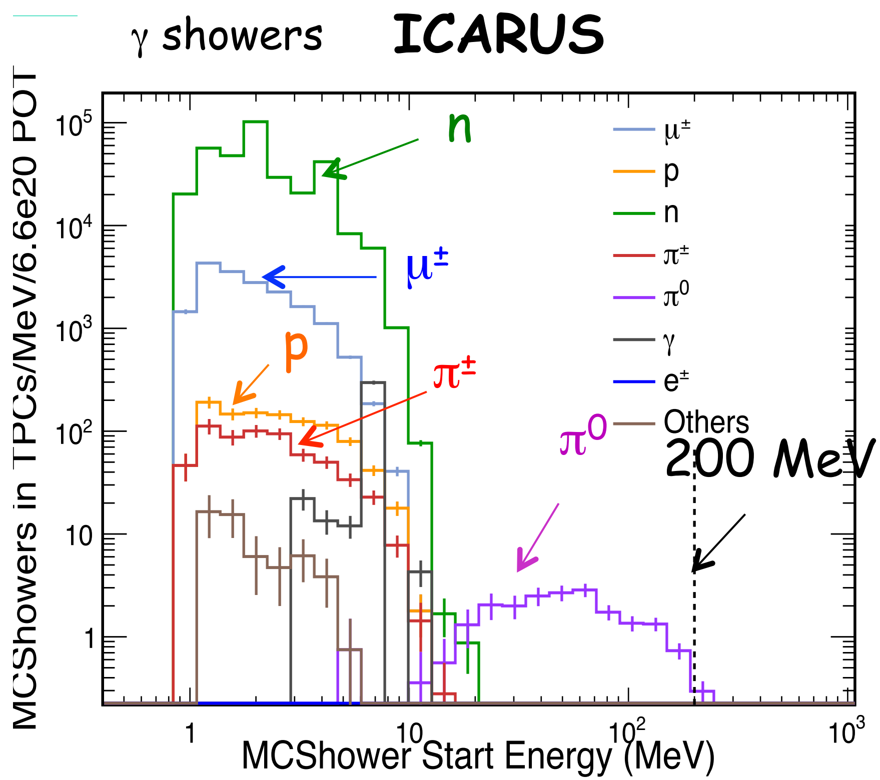


- The number of cosmogenic e± initiated e.m. showers in the active volume for configuration 2 (without overburden, full lines) and configuration 3 (with overburden, dotted lines), classified based on shower mother particle.

BNB ν interactions in the overburden

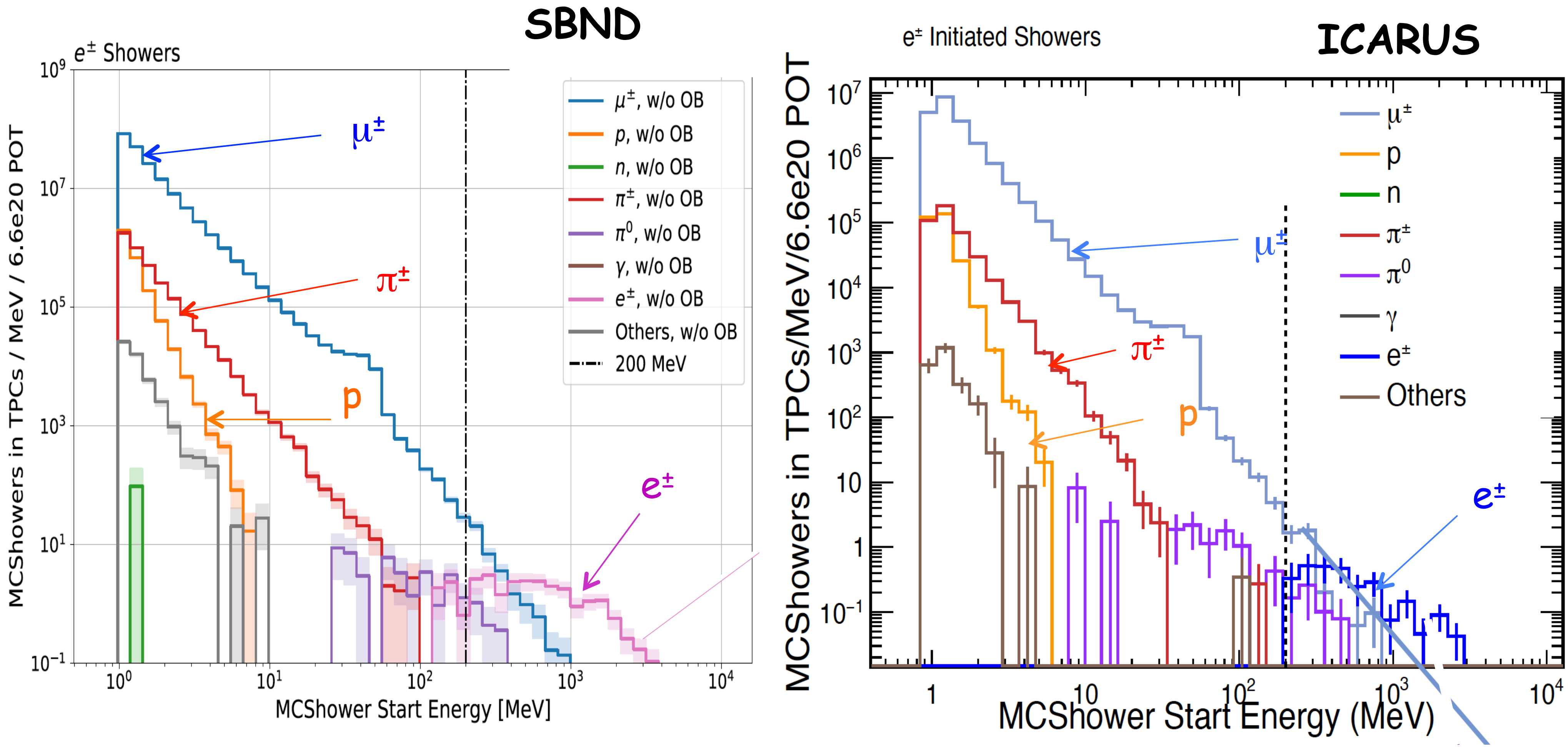
- Only 1507 and 6300 low energy neutrons enter SBND and ICARUS active LAr respectively, to be compared with ~50000 and ~300000 primary cosmic neutrons removed by the overburden.
- The e.m. shower background from π^0 produced in ν interactions in the overburden inside the SBND and ICARUS active LAr volume is negligible when the same selection used for cosmics is applied.





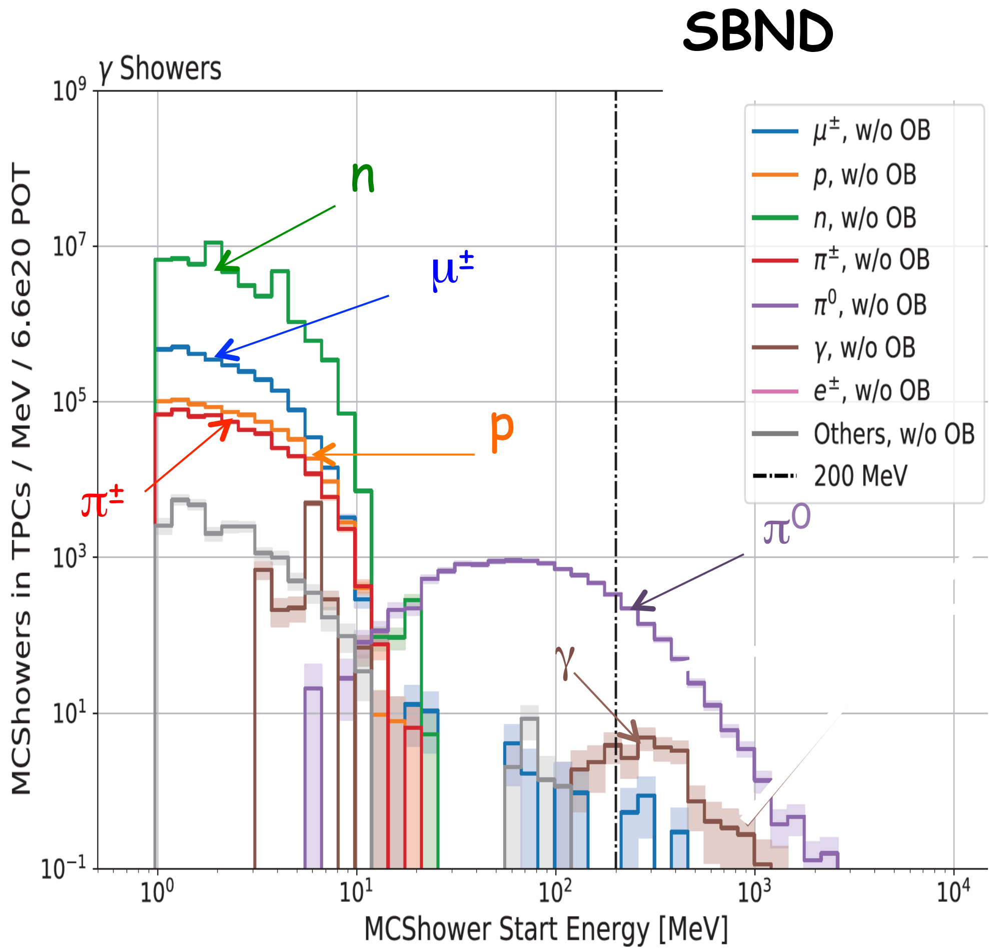
Number of γ initiated showers in active volume classified based on shower mother particle

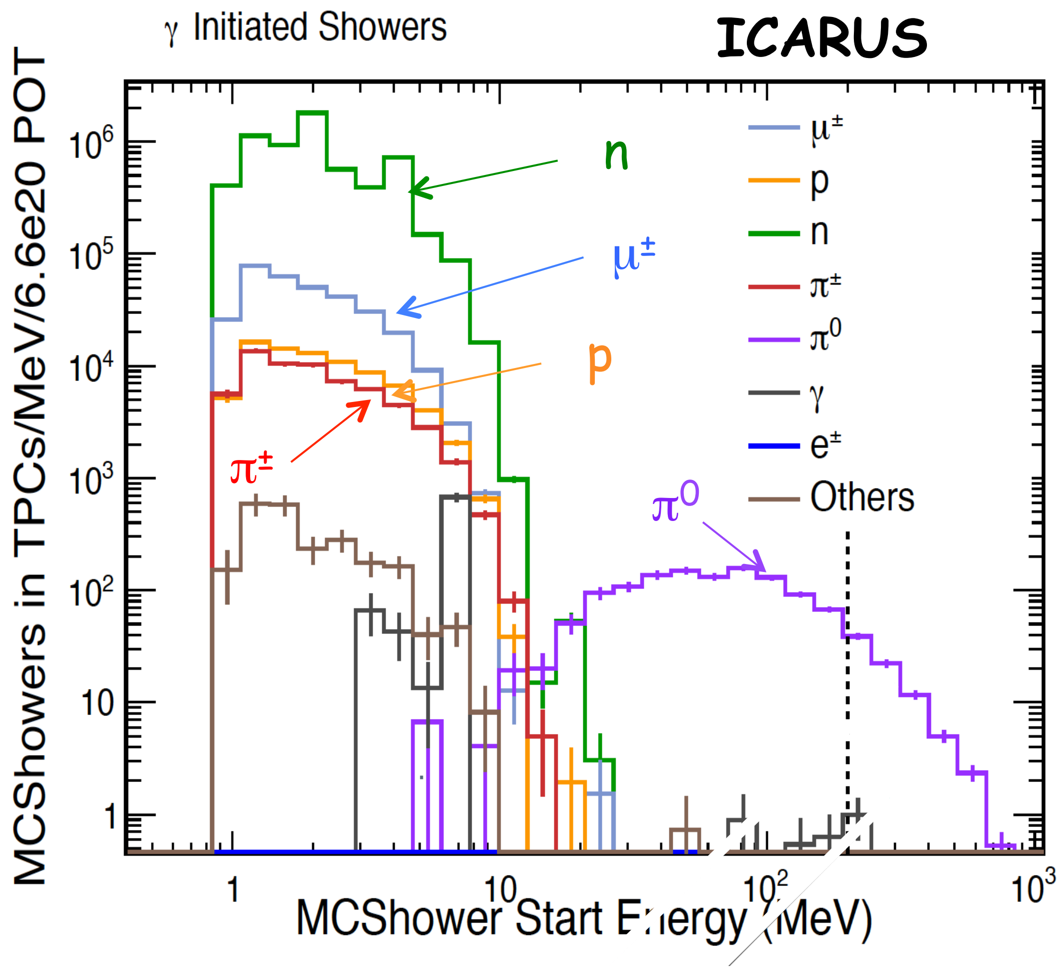
e± initiated showers by ν interactions in the surrounding materials



- The number of e± initiated e.m. showers in the active volume produced by BNB ν interacting in the surrounding materials, classified based on shower mother particle.

γ initiated showers by ν interactions in the surrounding materials





- The number of γ initiated e.m. showers in the active volume produced by BNB ν interacting in the surrounding materials, classified based on shower mother particle.

TPC-CRT track matching

- The signals collected on the CRT can be matched using the time information to create a "CRT track": in particular the CRT track is created using two hits on two CRT planes;
- The CRT tracks are then compared with the reconstructed tracks in the TPCs, taking into account the possible shifts along the drift direction due to an "out of time" track reconstructed in 3D with a wrong position;
- If a match between the CRT track and the TPC track is detected, the track can be considered as an incoming cosmic muon;