Charged pion production from neutron background in ICARUS

- Cosmic neutron interactions in LAr producing one charged π and at least 1 proton are a possible source of background events, since pions in the TPC can be misidentified as muons and mimick contained QE νμCC.
- 20k vertical neutrons at fixed kinetic energy T have been simulated to evaluate the probability to observe an interaction producing a single contained charged pion together with at least one proton.
- The starting point of the simulated neutrons is the top of the LAr active volume, at the center of one TPC along the longitudinal and drift direction.

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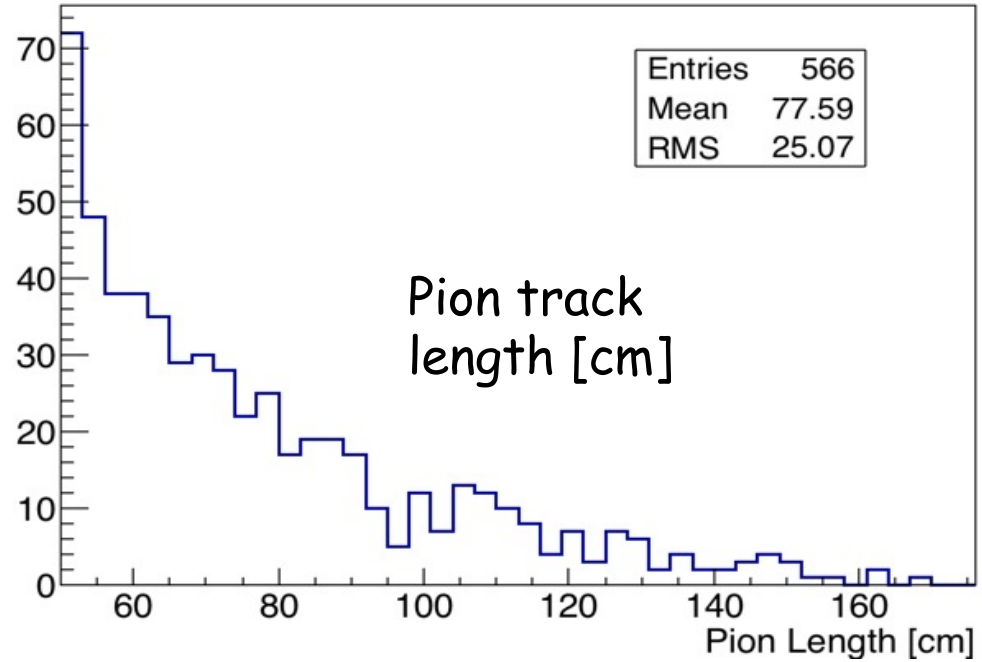
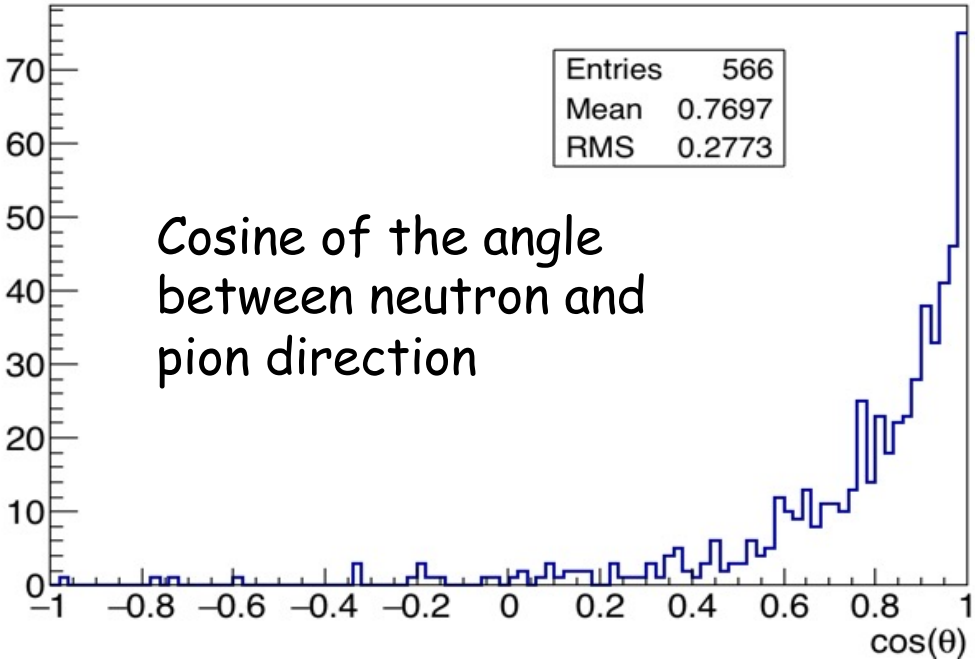
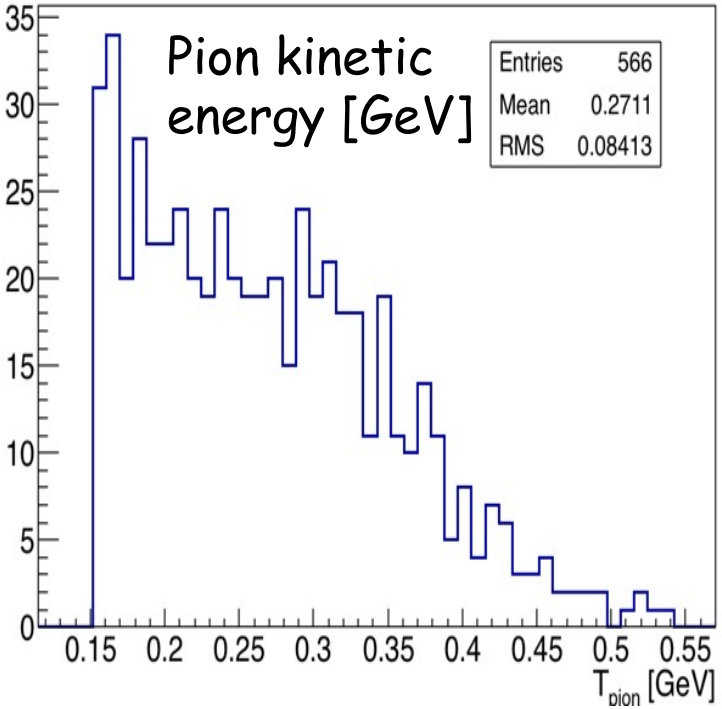
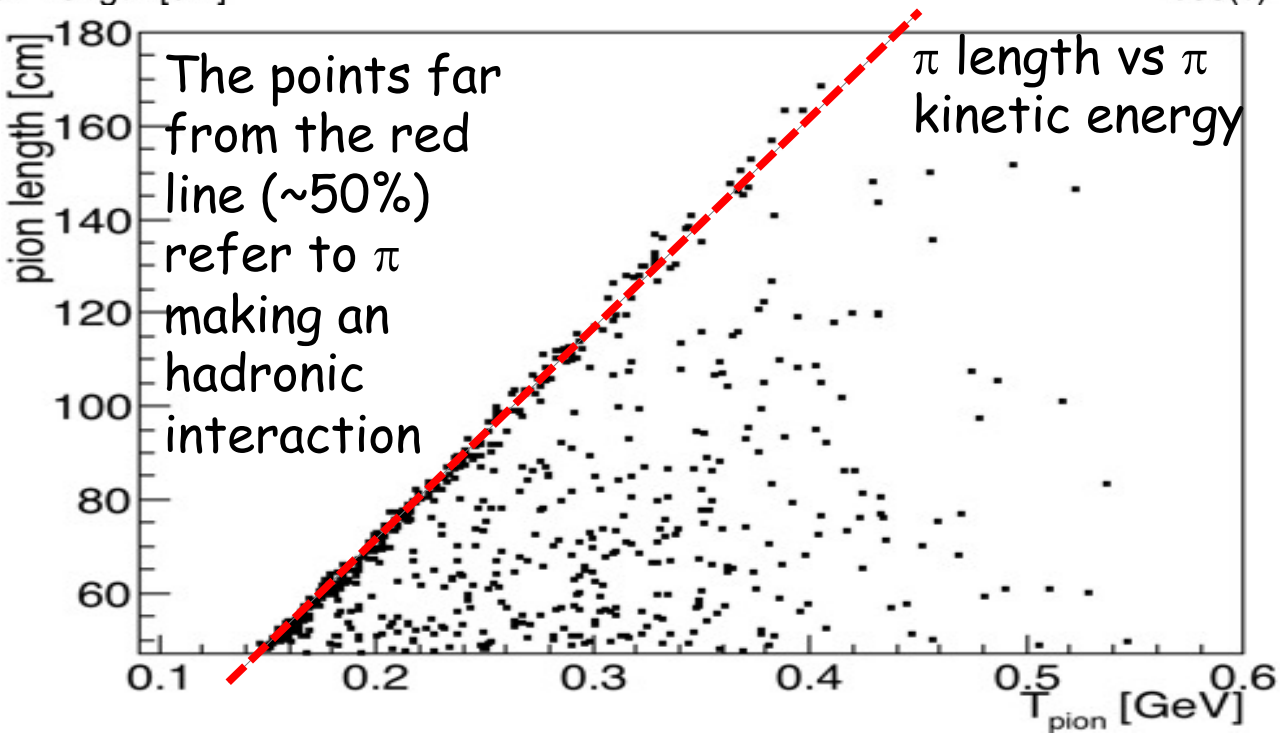
	T=300 MeV	T=450 MeV	T=600 MeV	T=800 MeV
Number of interactions	81	781	2197	4031
Interaction Probability	0.4 %	3.9 %	11 %	20.2 %
Number of interactions with a pion longer than 50 cm	0	7	94	566
Interaction probability (pion longer than 50 cm)	0 %	0.04 %	0.5 %	2.8 %

Example: T = 800 MeV neutron interactions and > 50 cm pion









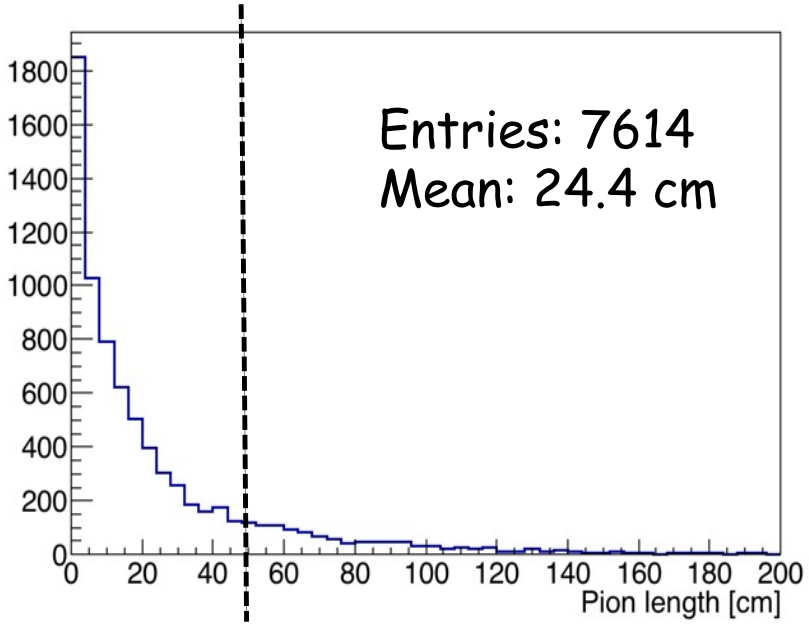
Pion production from cosmic neutrons with "no overburden"

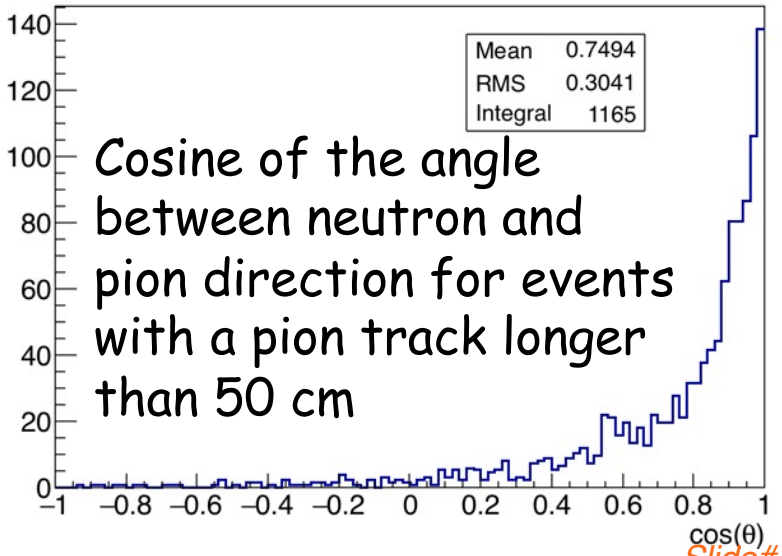
- The analysis has been performed using the configuration "no overburden" (corresponding to the nominal geometry including all the experimental setup but removing the overburden).
- A total exposure of 211 s has been fully simulated through the experimental setup tagging the particles reaching the active LAr.
- In the following table, the number of primary cosmic neutrons reaching the active LAr is evaluated for different kinetic energy thresholds.
- For comparison in the last rows the number for the "overburden" case and the ratio "overburden"/"no overburden" are also reported;

	T>50 MeV	T>200 MeV	T>400 MeV	T>600 MeV
Number of primary neutrons in 211 s	$3.0*10^5$	$1.0*10^5$	$3.3*10^4$	$1.7*10^4$
Rate (Hz)	$1.4*10^3$	460	155	80
Neutrons in 1 drift window (0.96 ms)	1.3	0.44	0.15	0.077
Neutrons in 1 drift window (0.96 ms) OVB case	$6.6*10^{-3}$	$2.5*10^{-3}$	$5.4*10^{-4}$	$2.5*10^{-4}$
Ratio NO OVB/OVB	197	176	278	308

Pion production from cosmic neutrons: “no overburden”

- The interactions from primary and secondary cosmic neutrons in the active LAr have been studied to select events where a single contained charged pion is produced together with at least one proton.
- Cosmic ray fluxes have been simulated with the CORSIKA code and then propagated with GEANT4 through the ICARUS experimental setup, together with all their secondaries, down to 1 MeV threshold
- In the studied statistics of 211s, 7614 interactions have been recognized (stopping π s through hadronic interactions are included).
- The additional request that π track > 50 cm reduces the number of interactions to 1165
- The comparison with the results obtained in the “overburden” case shows that it reduces this background by a factor ~60 (1165 with respect to 20 strongly suppressing the contribution from primary hadrons)





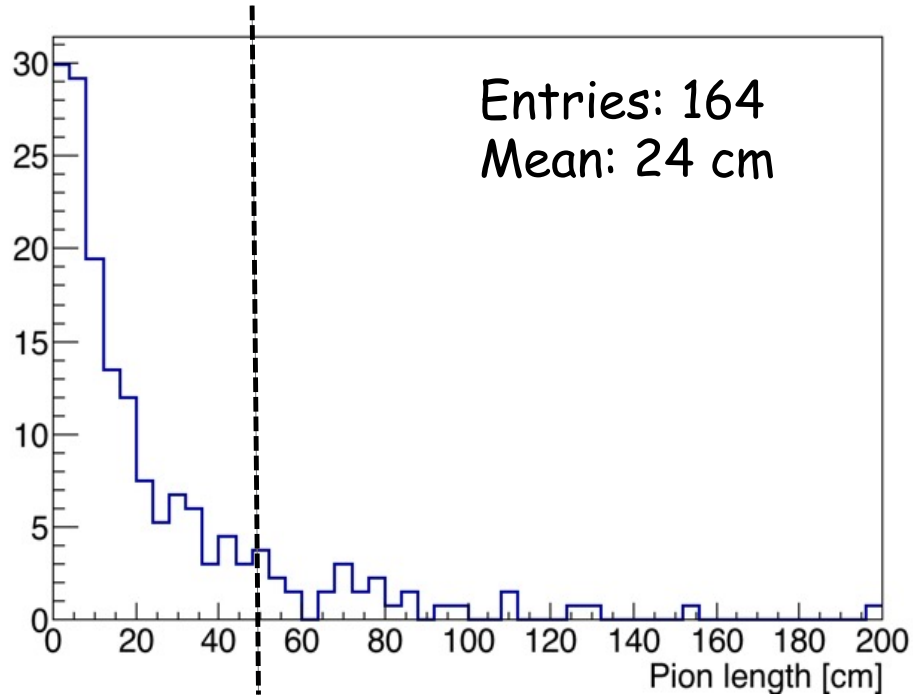
Pion production from cosmic neutrons “with overburden”

- The configuration “overburden” (corresponding to the nominal geometry including all the experimental setup with the overburden) is used. The most recent updates to the ICARUS geometry description are included: in particular the overburden thickness has been reduced from 3m to 2.845 m.
- A total exposure of 211s has been fully simulated through the experimental setup tagging the particles reaching the active LAr.
- In the following table, the number of primary cosmic neutrons reaching the active LAr is evaluated for different kinetic energy thresholds.

	T>50 MeV	T>200 MeV	T>400 MeV	T>600 MeV
Number of primary neutrons in 211 s	1458	550	119	54
Rate (Hz)	6.9	2.6	0.56	0.26
Neutrons in 1 drift window (0.96 ms)	$6.6*10^{-3}$	$2.5*10^{-3}$	$5.4*10^{-4}$	$2.5*10^{-4}$

Pion production from cosmic neutrons “with overburden”

- The interactions of the neutrons in the active LAr have been studied to select events where a single contained charged pion is produced together with at least one proton. All the neutrons are considered, both the primary and the secondaries produced by other cosmic particles interactions.
- In the studied statistics of 211s, 164 interactions have been recognized. The cases where the pion is stopping through hadronic interactions are included.
- The additional request to have a pion track >50 cm reduces the number of interactions to 20 (10 of which from primary μs) demonstrating that, in presence of the overburden, this background can be considered negligible;



- In this analysis the precision of this calculation is limited by the reduced available statistics for the primary cosmic particles in Corsika as implemented in LarSoft. This limitation is common to all the experiments exploiting LarSoft (ICARUS, SBND, DUNE …). The problem is under study.

Conclusion: benefits of the "overburden" for ICARUS

- The above detailed analysis on the identified events shows:
  - In the "no overburen" case, above events are estimated to be 7614, produced by primary neutrons for a π track > 50 cm they become 650.
  - Including secondary neutrons, the total becomes 1165 for a π track > 50 cm.
  - The addition of the "overburden" reduces the number of events originated by primary hadrons from 1156 to 10 events, by a factor ~120
  - Events originated by primary muons remain negligible

Events in 211 seconds and π track >50 cm	No overburden	Overburden
From primary neutrons	650	0
From secondary neutrons by primary hadrons	506	10
Total from hadrons	1156	10
From secondary neutrons produced by muons	9	10
Total Events	1165	20