

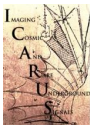
Analysis of Rock Events from NuMI in the Icarus Detector at Fermilab

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Fermi National Accelerator Laboratory

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U.S. DEPARTMENT OF
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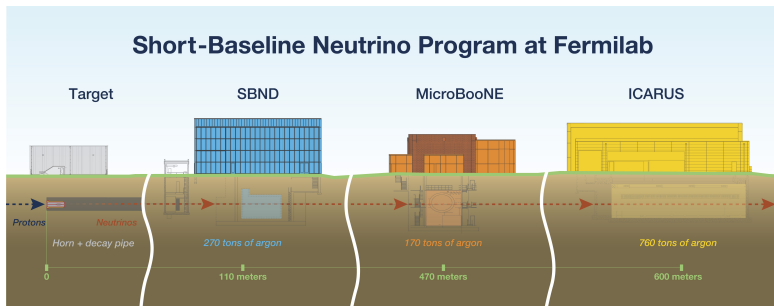


1 SBN Program

2 Rock Muon Analysis



Goal → solve neutrino oscillation anomalies (sterile neutrino?)



- 3 LArTPC detectors (100 m, 500 m, 600 m)
 - Increase ν (flavour) identification
 - Reduction of systematics to % scale
- ν from BNB (SBN) and off-axis NuMI (Icarus)

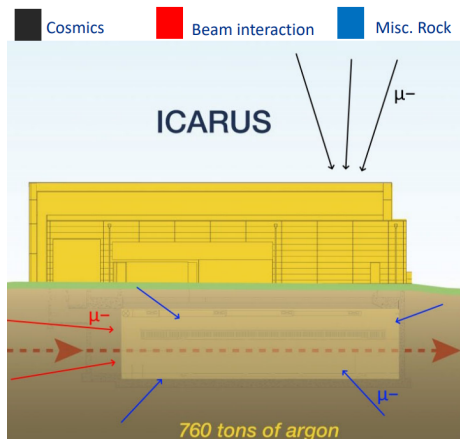


- $3.6 \times 3.9 \times 19.9 \text{ m}^3$ LArTPC
(Active volume $\approx 470 \text{ t}$)
- First used in the CNGS (@ LNGS),
moved to CERN for refurbishment.
From 2017 @FNAL. Data taking started
in 2021.
- SBN goals required moving detector to
surface \rightarrow Relevant CR bkg (11 kHz)
 \rightarrow Introduction of Cosmic Rays Tagging
(CRT)



Focus of the activity:

- Looking at μ tracks in the detector
- Trying to separate cosmogenic and beam-induced background

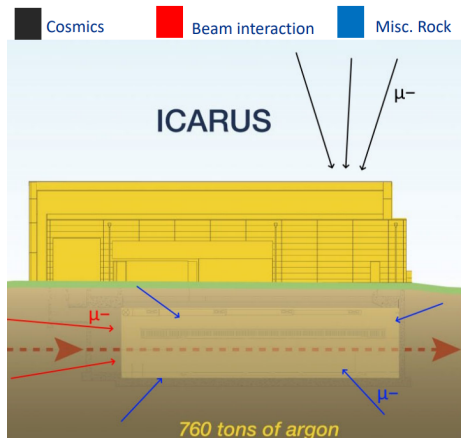


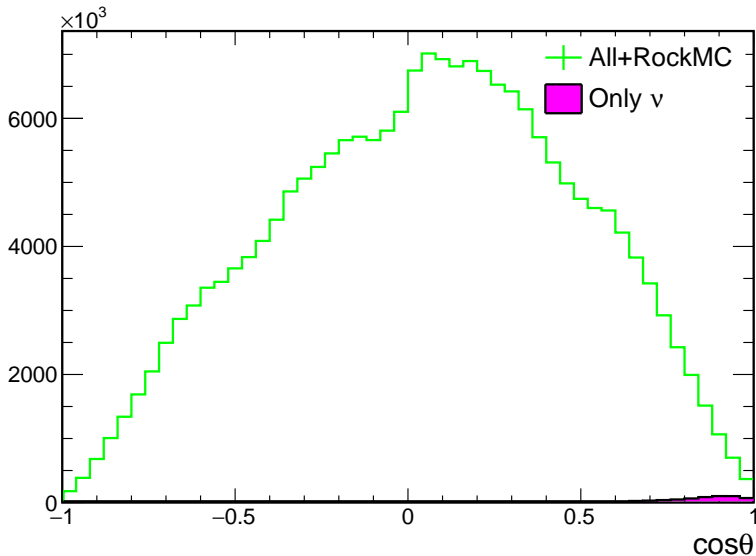
Working with 3 datasets

- **All MC**
Includes Beam interaction and Cosmics
- **Rock MC**
Includes Beam interaction and Cosmics and **Misc. Rock**
- **Data from Run1**

Investigating cuts for optimal selection of events.

Looking at geometrical distributions of the tracks.





On top of that MCs include information about the origin of the track

- ν events \rightarrow tracks originating from neutrino events
- μ events \rightarrow non-neutrino initiated tracks

Attention

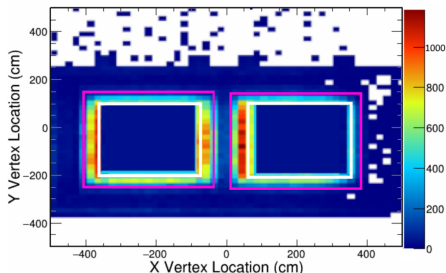
- MC tag on plots indicates Monte Carlo samples
- Data vs MC comparisons are POT normalised



Looking at interactions outside of the detector $\rightarrow \nu$ interacting with the nuclei of the rock between the beam production point and the detector.

Expected events \rightarrow need to be outside of the **Fiducial Volume (FV)**

-Track Vertex



Reconstructed vertex of rock μ

- Pink \rightarrow TPC boundaries
- White \rightarrow FV

-Track end

Extra requirement:

End of track containment.

Less information for exiting tracks (Momentum?)

End of track within 10 cm of TPC borders.

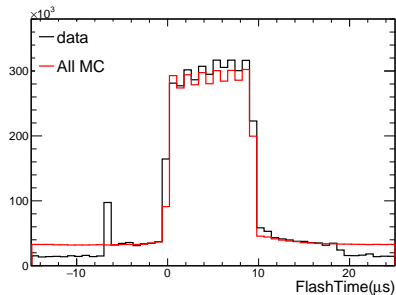
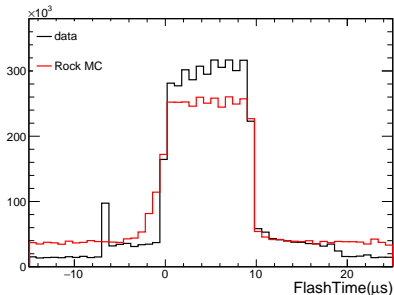


Beam induced muons arrive in time with the beam. It is possible to reduce the cosmic muons by selecting a proper time window ($-0.2 \rightarrow 9.8 \mu\text{s}$) with respect to the beam spill.

- Not too big of an impact on statistics
- Very helpful in reducing cosmics \rightarrow out of time wrt to the spill

Cutting at $-0.1 \rightarrow 9.7 \mu\text{s}$





Flash time for each Monte Carlo with respect to data (Area normalised)

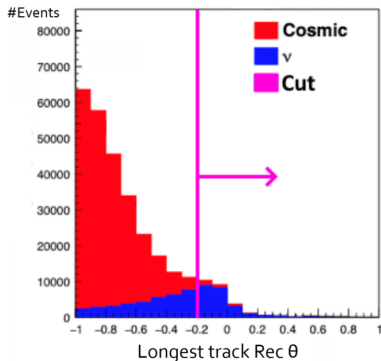


Y direction of the longest track in a slice (typically a muon) gives information about the nature the event.

(...slc->nuid.crlongtrkdiry)

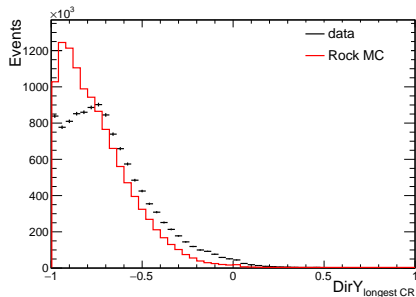
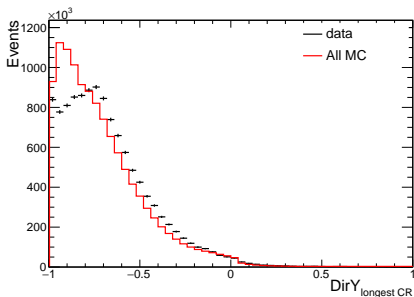
- Vertical and down-going
→ Most likely a cosmic
- Horizontal
→ Most likely beam-induced

Cut selected at -0.2



Monte Carlo for the All events dataset. The cut selects a high purity beam-induced sample.



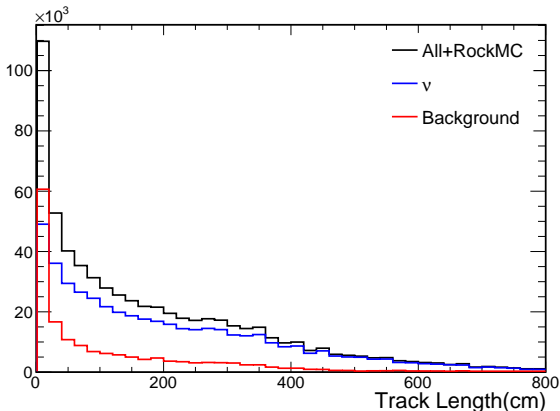


Area normalised comparison of data and Monte Carlo distributions of Data vs Monte Carlo Y direction distribution.
 (Confirms trend observed by David Wells)



After all other cuts many cosmics can still be removed.

Beam-induced events are more energetic, resulting in longer muon tracks.

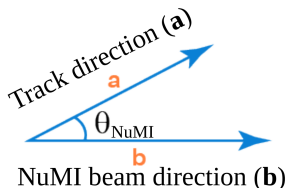


Cutting at 20 cm \rightarrow Effect of cut can be seen from second bin
(Plot already includes track direction and flash constraints)



Variables

- Vertex Positions
- Energy Loss (& Residual Range of Tracks) → Sanity Check
- Track Length
- $\cos \theta_{\text{NuMI}}$ → track angle wrt NuMI beam (off axis)
- ϕ → azimuthal angle of the track wrt z axis
- $\cos \theta$ → track angle wrt z axis



$$\cos \theta_{\text{NuMI}} = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}| |\vec{b}|}$$

$$\cos \theta = \frac{\vec{a} \cdot \vec{z}}{|\vec{a}| |\vec{z}|}$$



All the plots in the following pages have been produced with these cuts

- Track vertex outside the fiducial volume
- Track end inside the detector
Exclude from 10 cm inside the detector border
- Track direction constraint
- Track length above 20 cm
- Spill on time with the NuMI beam spill



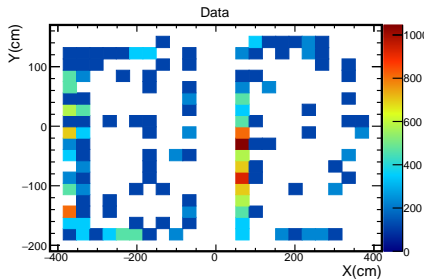
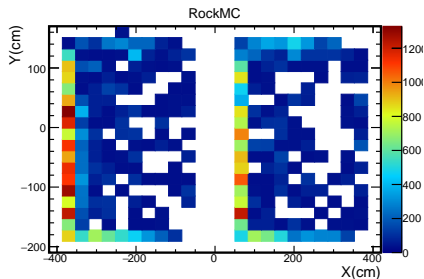
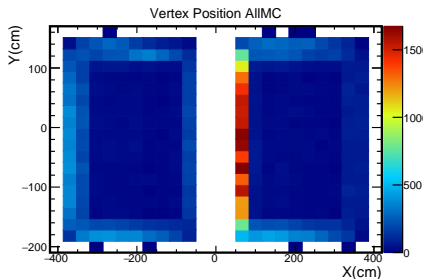
Inclusion of systematic effects on the Monte Carlo samples

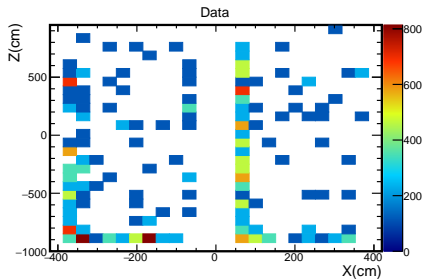
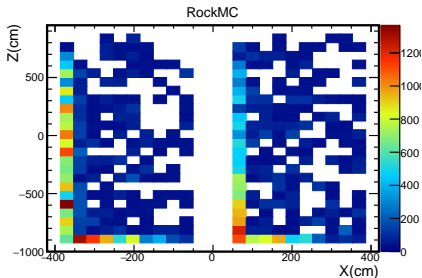
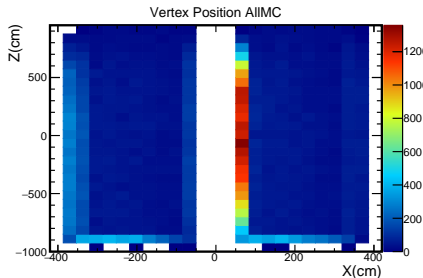
- NuMI Flux
- GENIE (has 2 components MultiSim and MultiSigma)
(see backup slides for list of components)
- GEANT4 (only for Rock Monte Carlo)

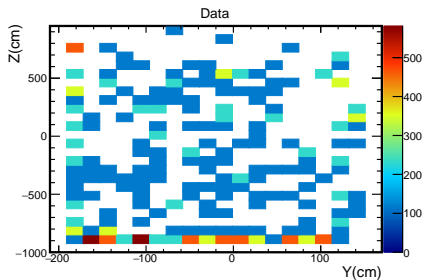
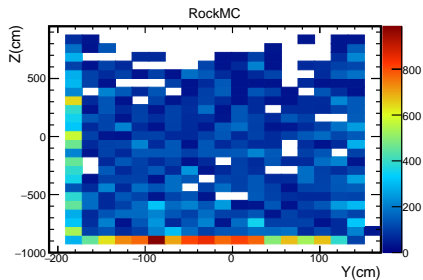
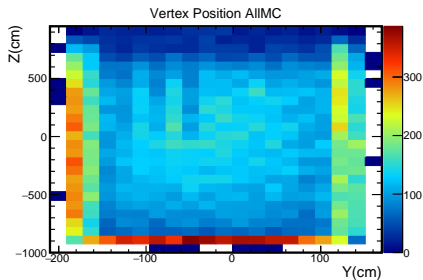
Systematic contributions

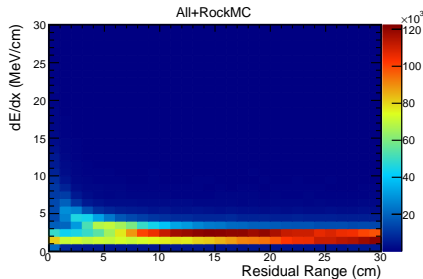
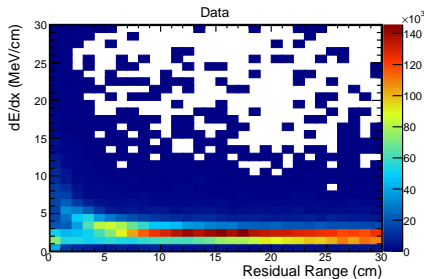
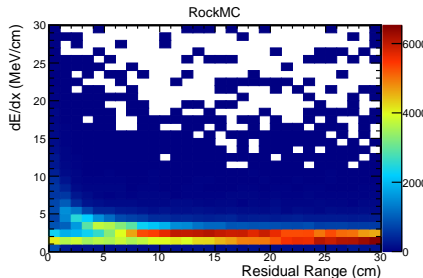
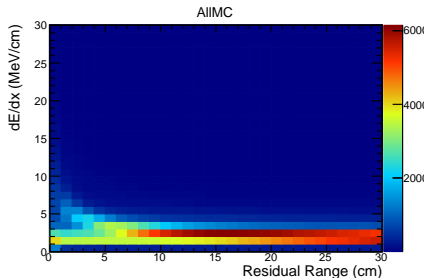
- defined as a deviation from the reference spectrum (reference)
- summed in quadrature
(more careful analysis in the future \rightarrow correlation effects)
- simplified to have all effects at 1σ
(when effects are well understood add weight with entity of deviation)

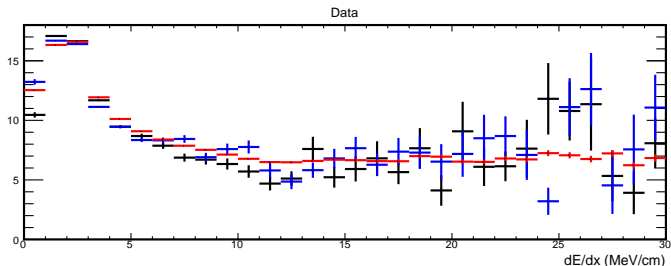
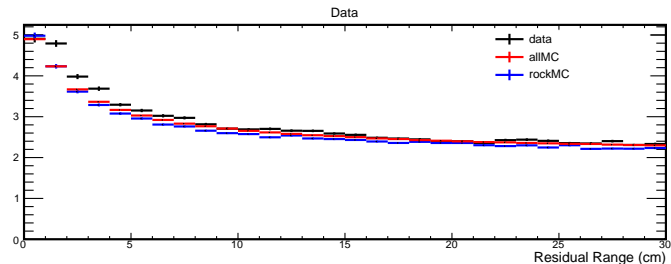


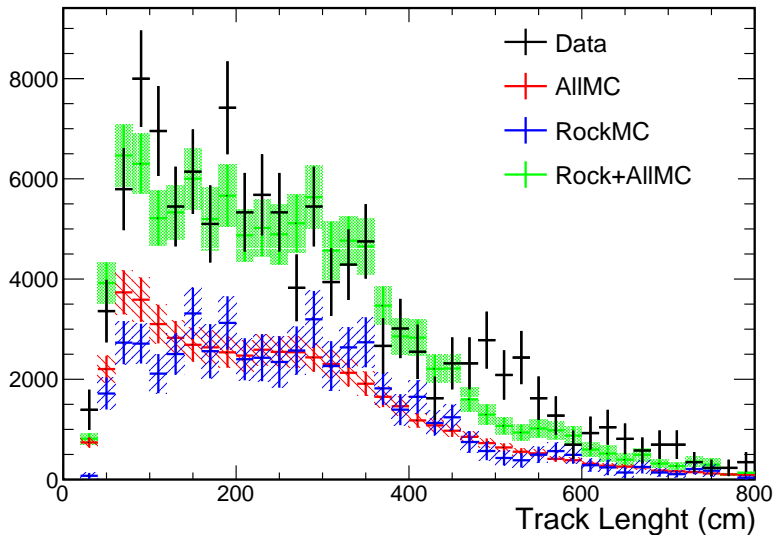




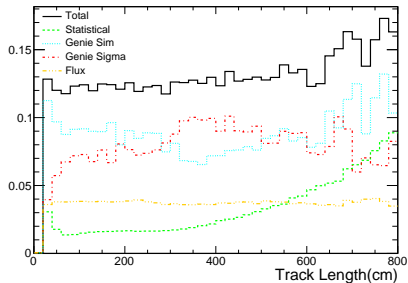




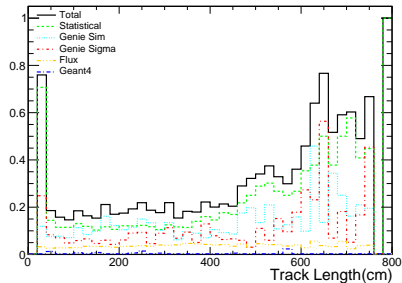


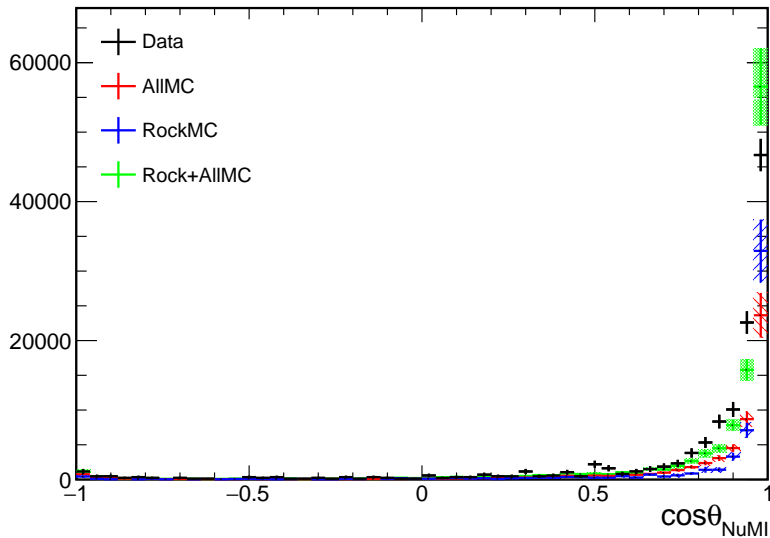


AllMC Error Components

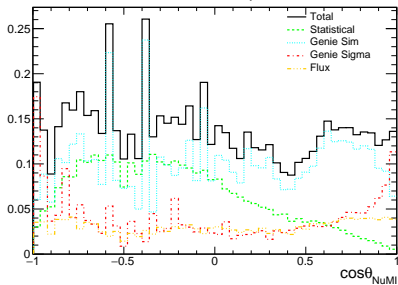


RockMC Error Components

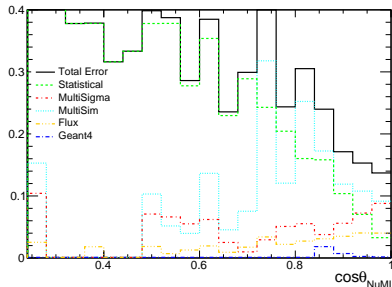
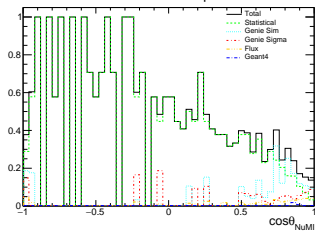


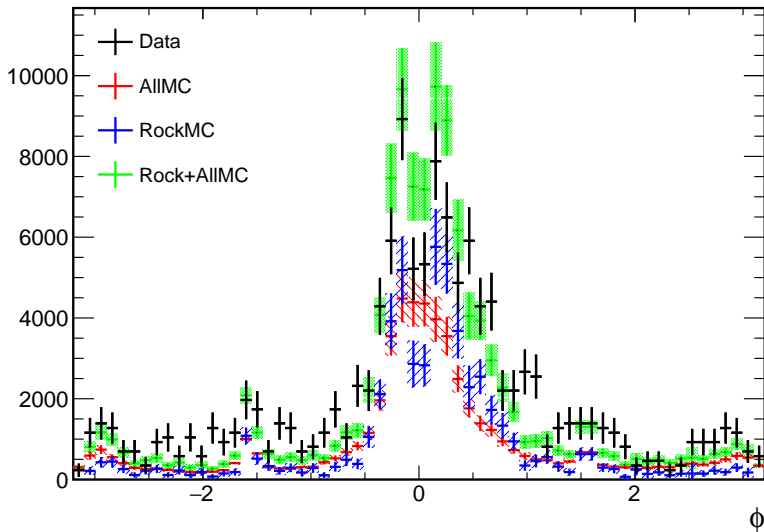


AllMC Error Components

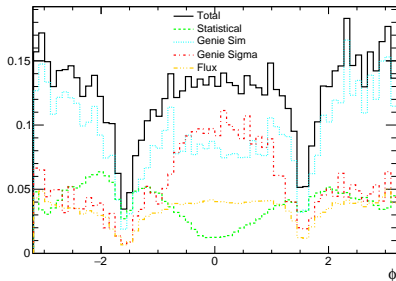


RockMC Error Components

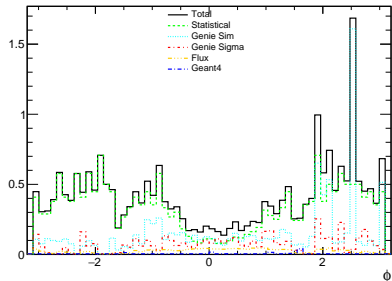


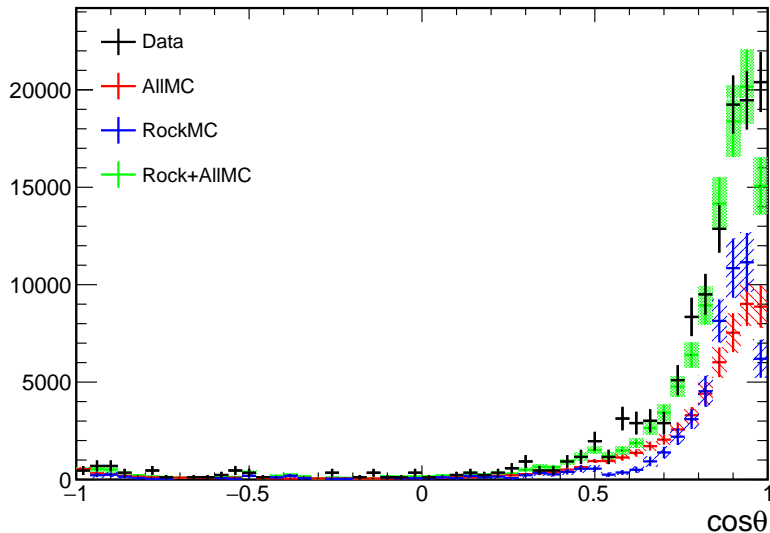


AllMC Error Components

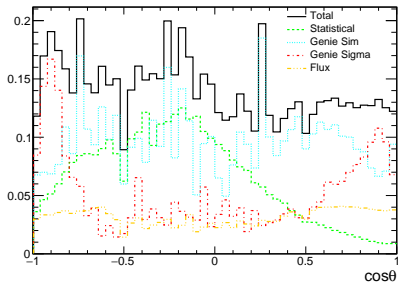


RockMC Error Components

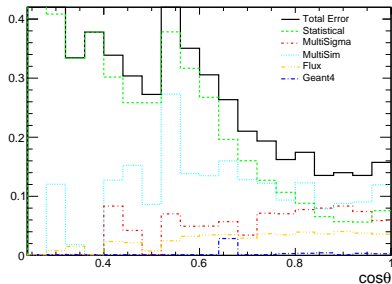
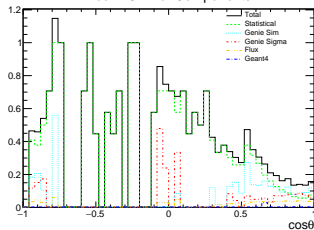




AIMC Error Components



RockMC Error Components



- A selection for Rock events has been developed
- General agreement between data and MC prediction (still some tensions need to be addressed)
- A internal report for the working group has been written

What to do in the future?

- Add in-time cosmic prediction (Could it fix disagreements in the plots?)
- Add detector systematic effects





- GENIEReWeight_ICARUS_v2_multisigma_RPA_CCQE
- GENIEReWeight_ICARUS_v2_multisigma_CoulombCCQE
- GENIEReWeight_ICARUS_v2_multisigma_NormCCMEC
- GENIEReWeight_ICARUS_v2_multisigma_NormNCMEC
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvpCC1pi
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvpCC2pi
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvpNC1pi
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvpNC2pi
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- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvnCC2pi
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvnNC1pi
- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvnNC2pi



- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvbarpCC1pi
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- GENIEReWeight_ICARUS_v2_multisigma_NonRESBGvbarnNC2pi
- GENIEReWeight_ICARUS_v2_multisigma_NormCCCOH
- GENIEReWeight_ICARUS_v2_multisigma_NormNCCOH



- GENIEReWeight_ICARUS_v2_multisim_ZExpAVariationResponse
- GENIEReWeight_ICARUS_v2_multisim_NCELVariationResponse
- GENIEReWeight_ICARUS_v2_multisim_CCRESVariationResponse
- GENIEReWeight_ICARUS_v2_multisim_NCRESVariationResponse
- GENIEReWeight_ICARUS_v2_multisim_DISBYVariationResponse
- GENIEReWeight_ICARUS_v2_multisim_FSI_pi_VariationResponse
- GENIEReWeight_ICARUS_v2_multisim_FSI_N_VariationResponse



(Rock MC only)

- reinteractions__piminus__Geant4
- reinteractions__piplus__Geant4
- reinteractions__proton__Geant4

