The NuMI Flux at ICARUS



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NuFACT 2023 Seoul National University, Seoul, South Korea August 21 – 27, 2023

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Why Do We Care?

- NuMI neutrinos at ICARUS provide unique opportunity to measure cross sections on Ar in the ~1-3 GeV range
 - Both FHC and RHC contain significant ν and $\overline{\nu}$
 - The v_e to v_{μ} cross section ratio between 1-3 GeV is ~5-9%
- Inputs for DUNE:
 - DUNE will have a peak energy in the 1-3 GeV region
 - The DUNE ND will measure these processes with high statistics
 - Models constrain $\overline{\nu}/\nu$ and ν_e/ν_{μ} ratios
 - Data based measurements and uncertainties will provide useful priors
- Understanding the flux reduces error on background subtraction and cross section extraction
- The NuMI flux and uncertainties have not been studied in detail at 5.75° off-axis

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Neutrino Flux at ICARUS



- Large low energy v_{μ} peak
- Useful "shoulder" at to ~2.5 GeV
- Large wrong-sign contamination
- Relatively high v_e to v_{μ} ratio

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FHC Neutrino Flux at ICARUS







Cross Section Shifts Energy Peak



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Location of Hadronic Interactions (Not to scale) 1.53 0.3 y [m] larget ICARUS preliminary Fe other Location 0.2 0 nteraction 50 100 Interaction Location z [m]

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Energy vs Off-axis Angle



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Energy vs Off-axis Angle



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ν_e to ν_μ Ratio



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Interactions per Neutrino



- Includes primary pC interaction
- More interactions per neutrino
- What are projectiles and targets?
- 7 hadrons projectiles
- Nuclei that compose
 - Target
 - Horns
 - Target chase
 - Decay pipe

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Interactions per Neutrino

- ← On axis | Off axis →
 - Many more interactions on $A \neq C^{12}$
 - Many more meson projectiles
 - Target/projectiles combinations as function of E_v

other 0.03 0.01 0.01 0.00 K_{L}^{0} 0.01 0.01 0.01 0.00 K^{*} 0.02 0.02 0.02 0.01 π^{*} 0.03 0.03 0.02 0.00 π^{*} 0.08 0.09 0.09 0.02 -0.1 n 0.09 0.03 0.06 0.01 p 1.27 0.06 0.16 0.05 C AI Fe other target nucleus V_{e} ICARUS FHC ICARUS preliminary other 0.03 0.01 0.01 0.00 K_{L}^{0} 0.01 0.02 0.02 0.00 K^{0} 0.01 0.02 0.02 0.00 K^{*} 0.00 0.01 0.01 0.00 K^{*} 0.00 0.01 0.01 0.00 π^{*} 0.02 0.02 0.02 0.00 π^{*} 0.04 0.03 0.05 0.01 -0.1 n 0.09 0.03 0.06 0.01 p 1.26 0.05 0.16 0.05 C AI Fe other	v_{μ} ICARUS FHC ICARUS preliminary							
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Decay z-Position



- Most ICARUS v come from target region
 - High energy tail from target
 - Lowest energies from decay pipe
- On-axis v come from decay pipe
 - Kaon decays near target
 - Decays of $\pi^{\pm}(\nu_{\mu})$ and $\mu(\nu_{e})$ along decay pipe.

Decay z-Position (Cumulative)



Hadron Contributions by Decay Angle



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Hadron Contributions by Decay Angle



- Along dotted line:
 - θ = 5.75° → meson points to ICARUS
- $\theta < 5.75^{\circ}$
 - more forward going meson
 - higher angle decay
- $\theta > 5.75^{\circ}$
 - reinteraction in decay pipe
 - low energy meson pointing back to ICARUS
- Pions point to ICARUS
- Forward going Kaons with wide decay kinematics
- K's point to ICARUS \rightarrow Higher energy v



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x_F Bug in PPFX

Bug Fixed





- Bug: hard code $m_{targ.} = m_{proj.}$ in x_F calculation
- Breaks for incoming mesons
- With bug: correlated errors inflate total uncertainty
- Fixed Bug: introduces more shape uncertainty
- <u>Small effect on axis!</u>

Baseline (L) vs Energy & Angle



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Hadron Production Uncertainties



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PPFX Corrections and Uncertainties



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Meson Inclusive Breakdown - ν_{μ}



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Meson Inclusive Breakdown - v_e





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Physics vs. PCA Comparisons - ν_{μ}



- Variances, so components add
- Physics channels: correlated
- PCs: independent
- Hashed: total of unshown channels
- RHS white space:
 - Impact of correlations
 - Correlated components do not add quadratically

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Physics vs. PCA Comparisons - v_e



- Variances, so components add
- Physics channels: correlated
- PCs: independent
- Hashed: total of unshown channels
- RHS white space:
 - Impact of correlations
 - Correlated components do not add quadratically

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Covariance Matrices



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Bug Fix: Impact on Uncertainties



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Bug Fix: Impact on Correlations

Post Bug Fix







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PPFX Corrections and Total Errors



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Summary & Outlook

- Ongoing cross section and exotics program using NuMI @ ICARUS
 - Many exciting potential measurements on the horizon
 - Lots of ongoing work on reconstruction, event selection, and systematics
 - Accumulated: ~3×10²⁰ POT FHC
 - Start RHC running this Fall
- NuMI flux fully characterized at ICARUS 5.75° off-axis position
 - Beamline and focusing uncertainties
 - PPFX hadron production uncertainty corrections and error bars
 - Leading uncertainties: meson interactions (2^{nd} is pA for non C nuclei)
 - Fully implemented into analysis software
- NuMI upgraded to 1MW
 - Currently using flux ratio as correction (NOvA) / uncertainty (ICARUS)
 - Next step: regenerate all beamline systematic alterations at high statistics this Fall & rerun

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New data

PPFX

samples in