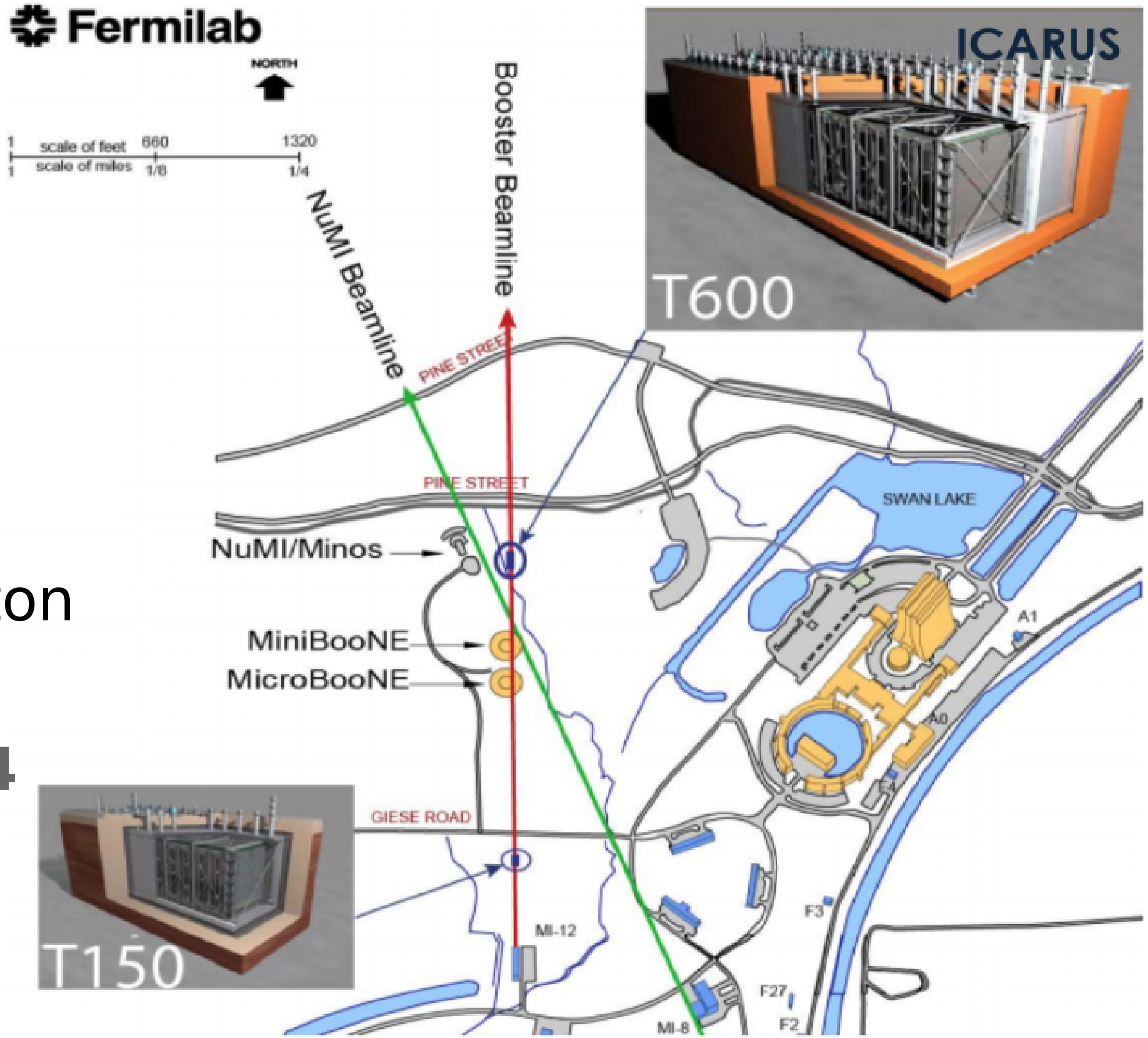
NuMI @ ICARUS:
Flux, Cross Sections, and BSM Physics

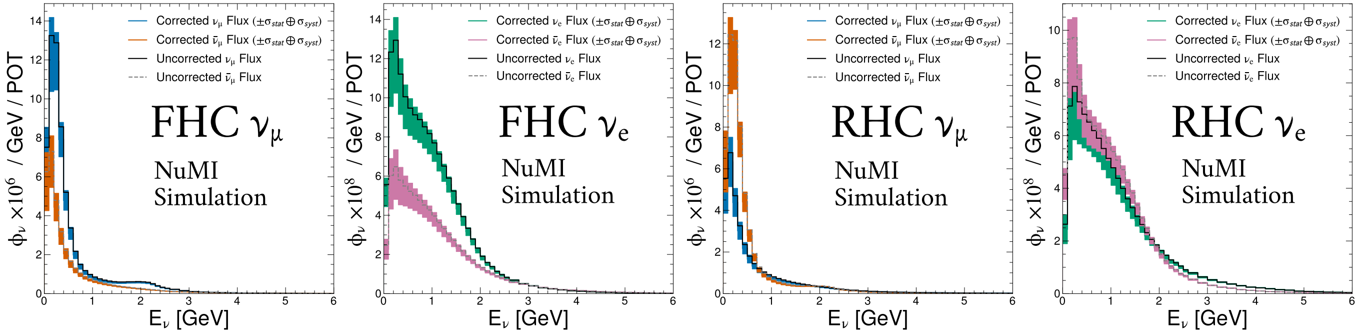
Daniel Cherdack, University of Houston
on behalf of the ICARUS Collaboration

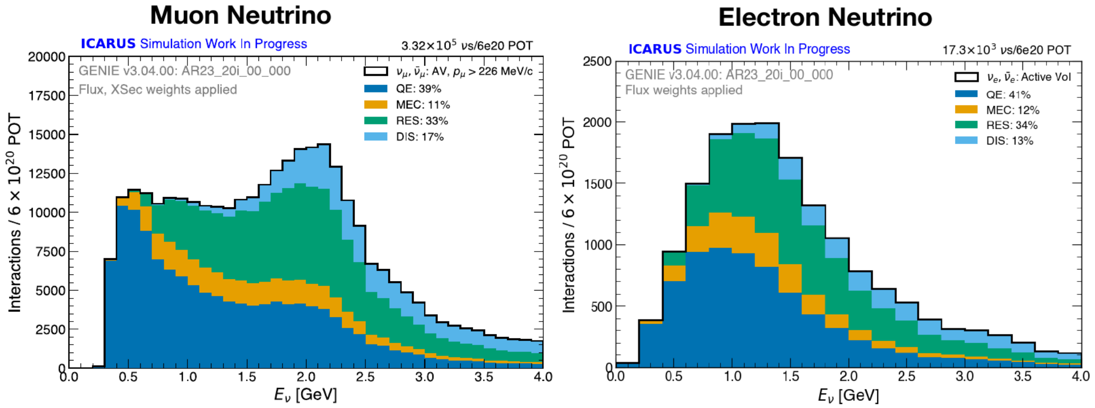
ICHEP 2024, Prague CZ, July 17 – 24, 2024

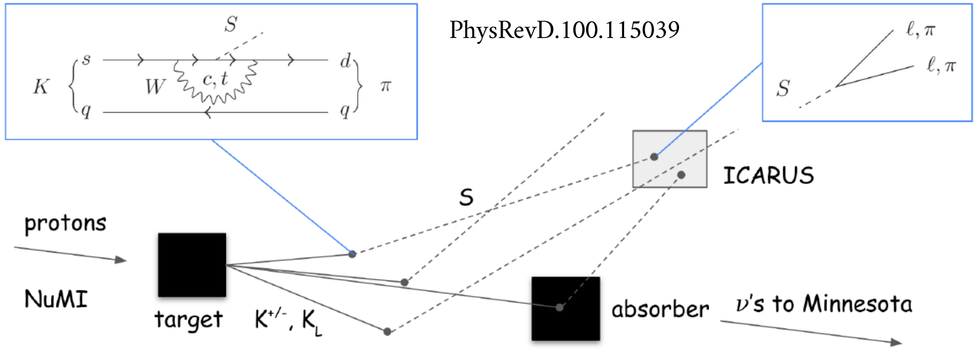


Outline

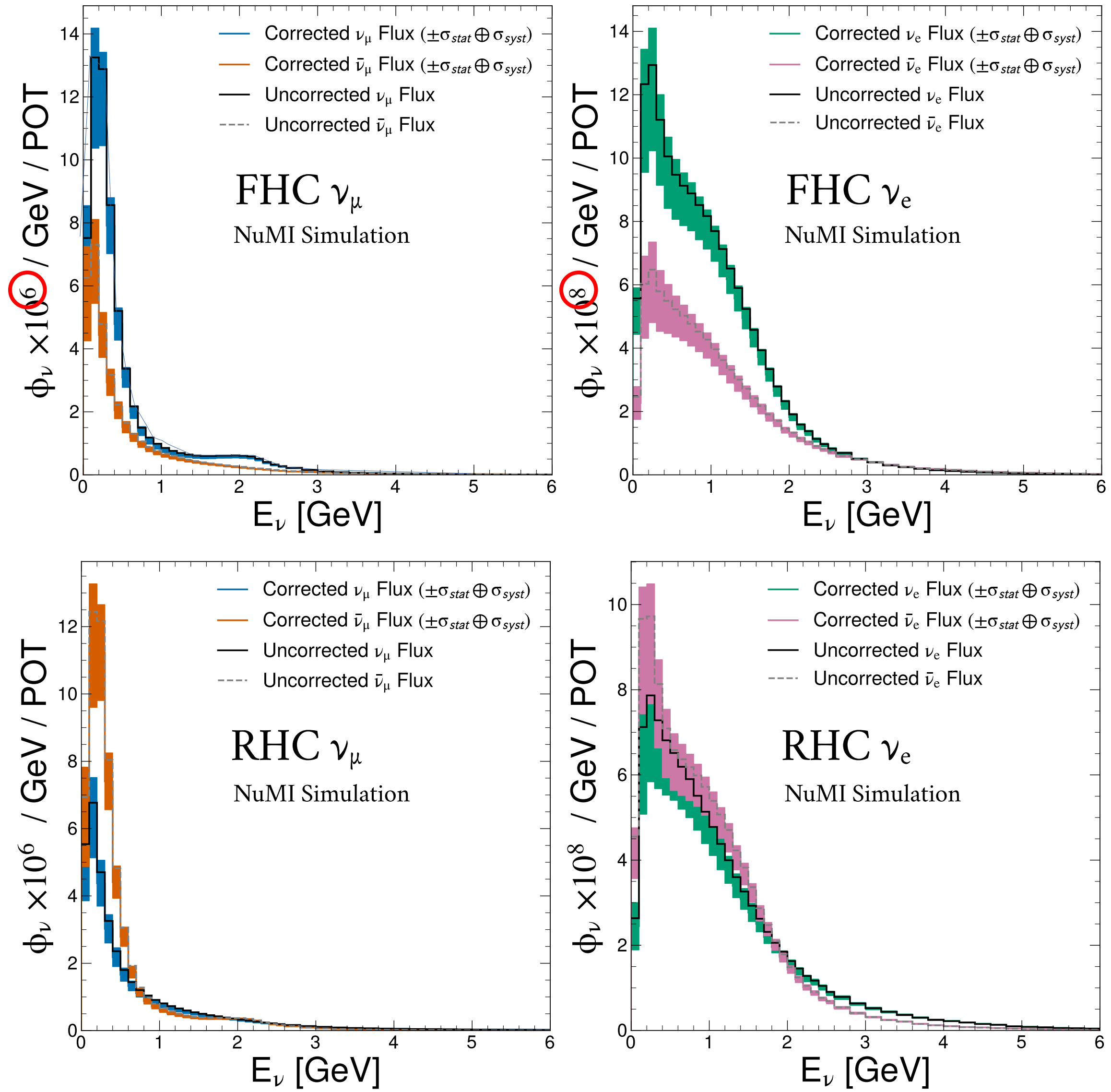
- The NuMI flux at ICARUS
  - Flavor, energy, and run mode
  - The impact of being 5.75° off-axis
  - Understanding uncertainties
  - Recent updates
- Cross Sections
  - Physics potential
  - Progress towards a first result
- Exotic Signals
  - BSM model sensitivity
  - Results of a first-pass di-muon search





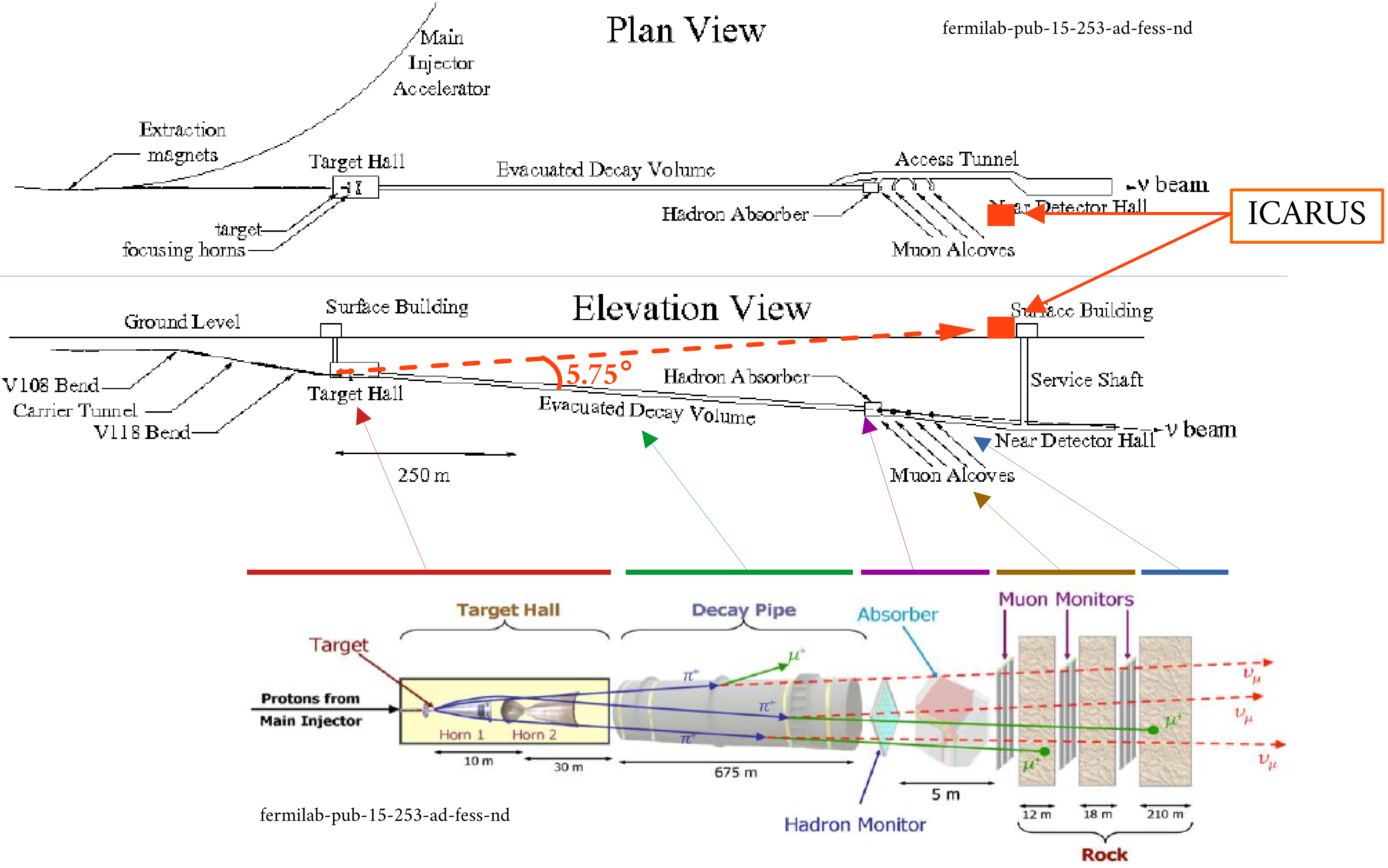


The NuMI Flux at ICARUS



- Very high flux below E_ν of 0.5 GeV
- Significant flux for $0.5 < E_\nu < 3.5$
- FHC: Forward horn Current / ν dominated
- RHC: Reverse horn Current / $\bar{\nu}$ dominated
- Large wrong sign contamination
- Contamination stronger in RHC, esp. ν_e
- ν_e flux is large enough for relatively high statistics measurements
  - 2 orders of magnitude less than ν_μ flux
  - Much wider peak structure
- Corrections and error band from PPFX
  - Hadron production data for p-C
  - Propagate large uncertainties otherwise

Understanding the flux at 5.75°



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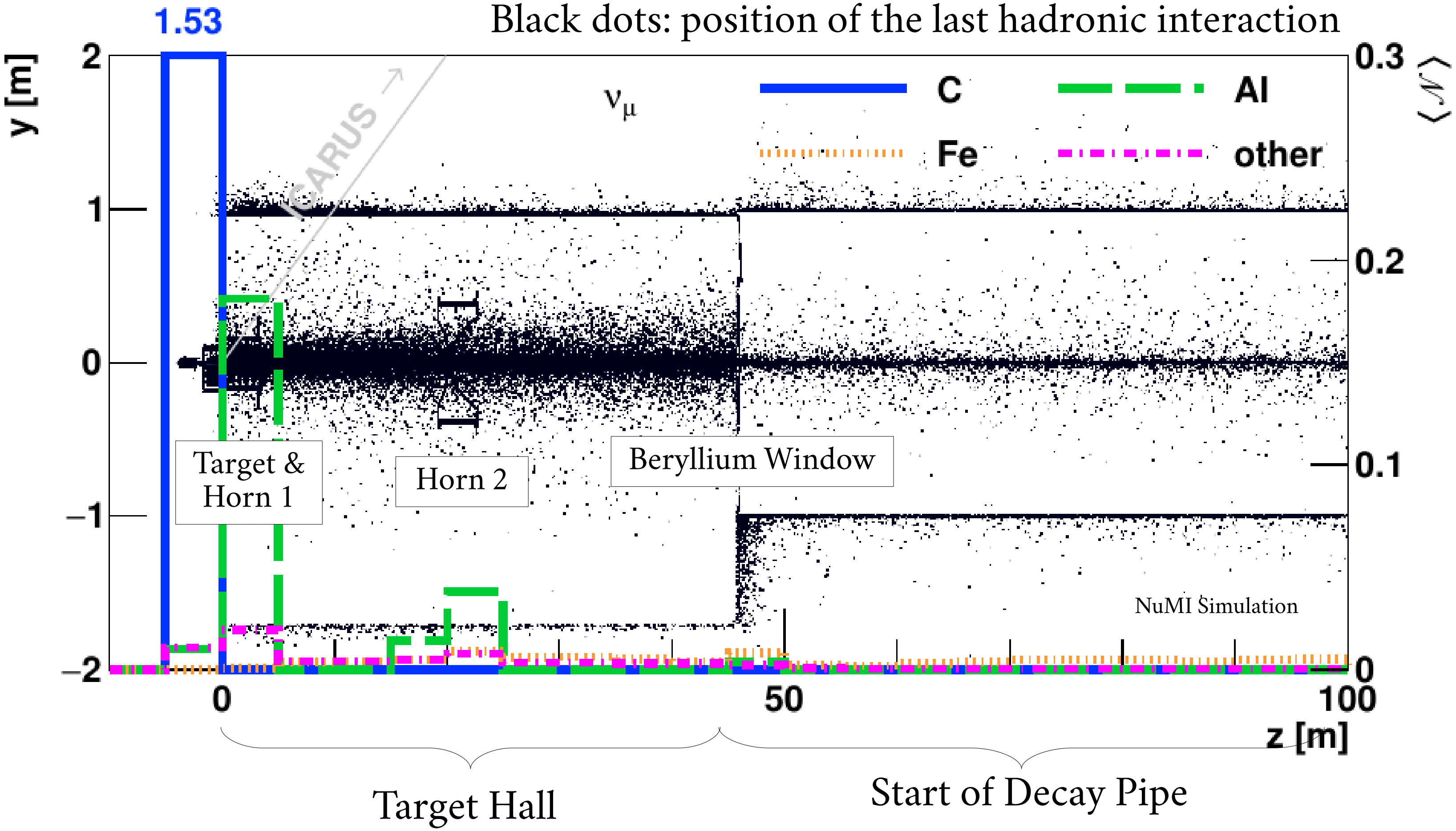
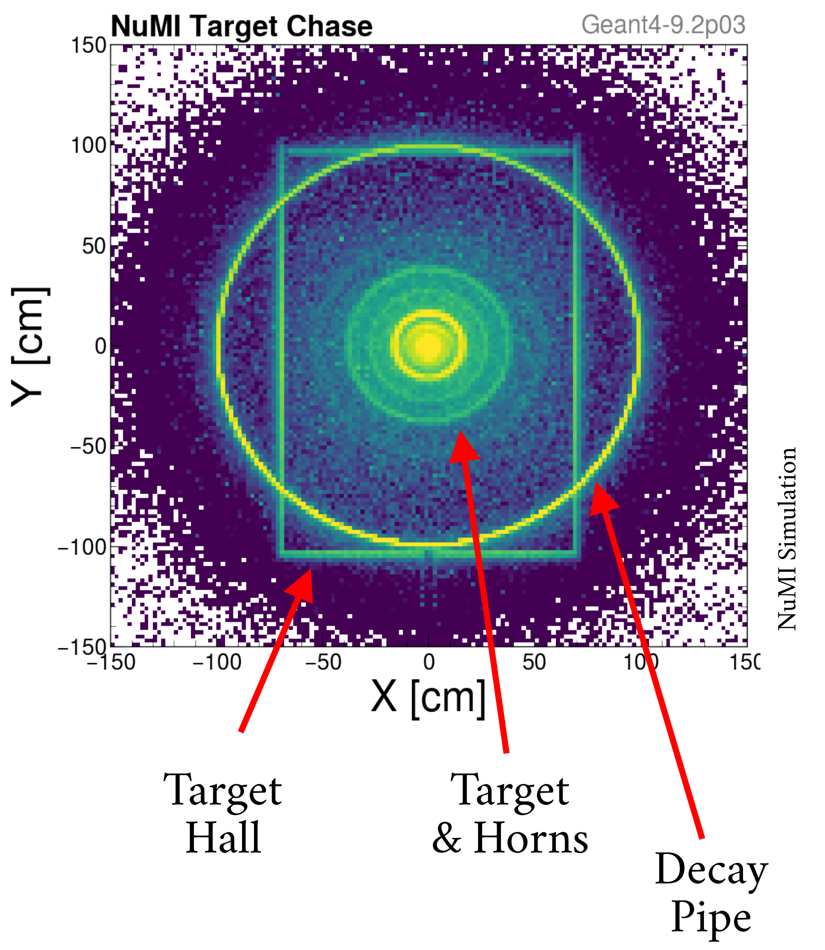
Understanding the flux at 5.75°

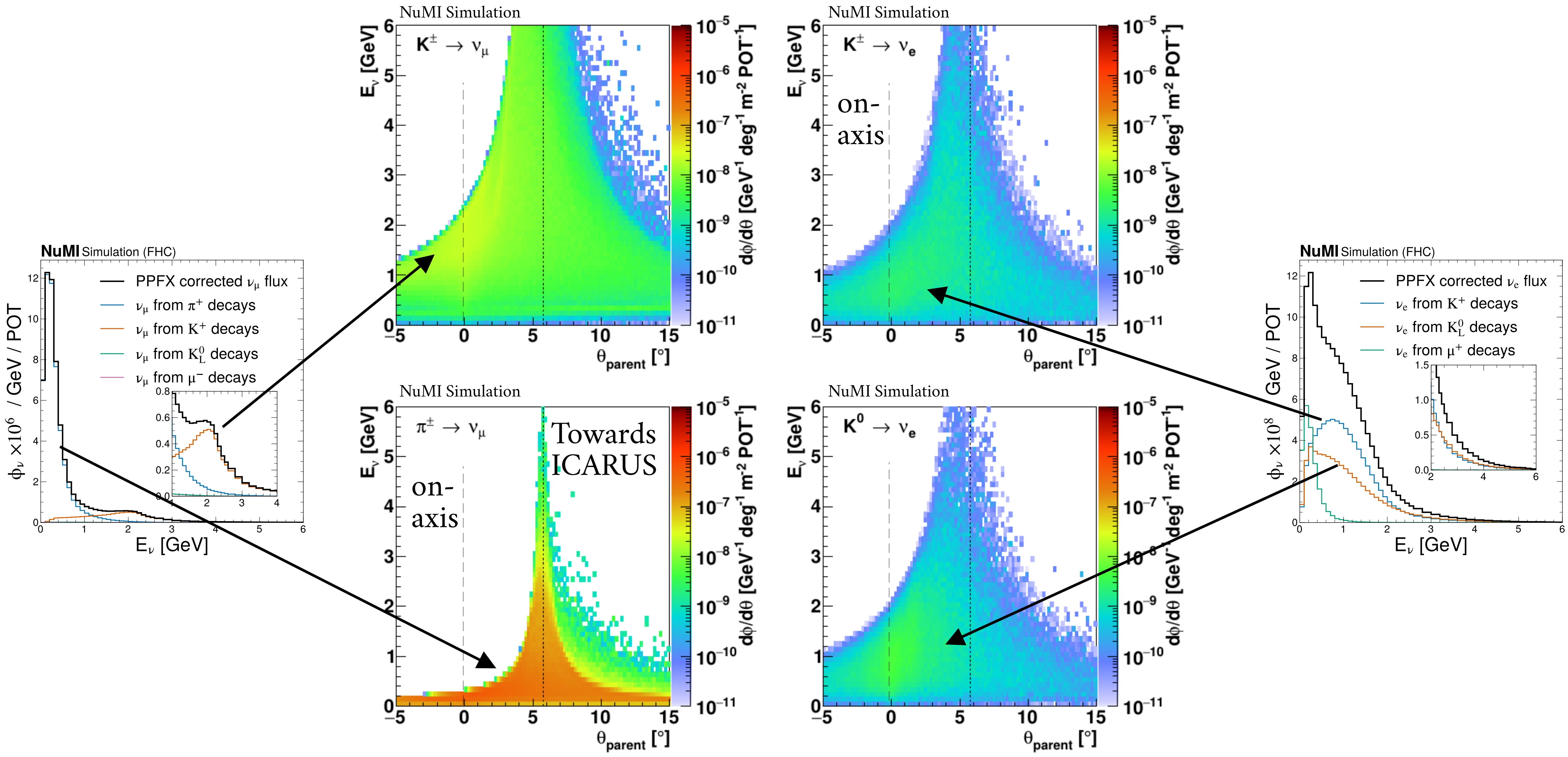
Black dots: position of the last hadronic interaction



Color scale: position of decay to ν



Understanding the flux at 5.75°



Flux Updates - Geomentry

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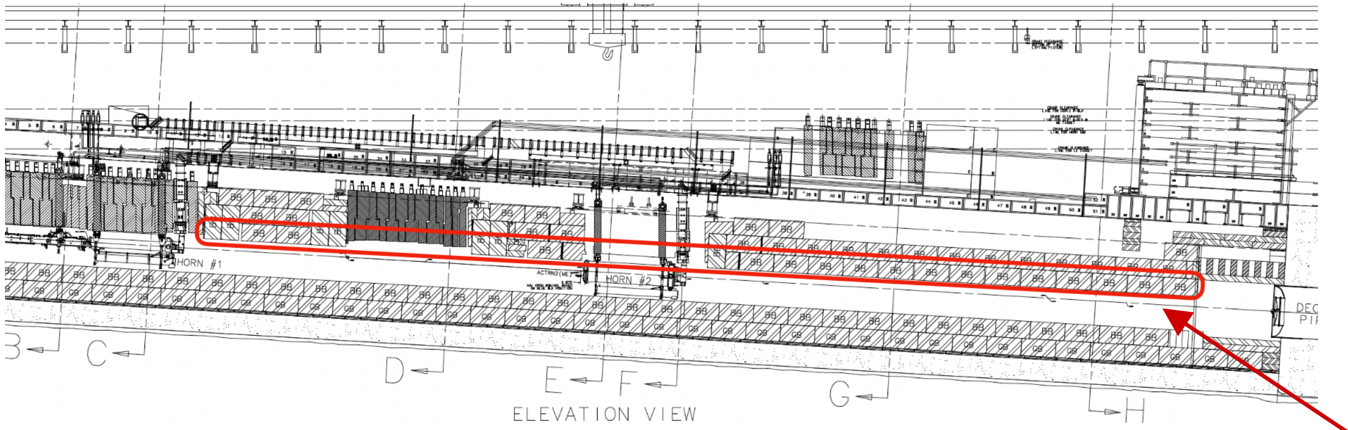
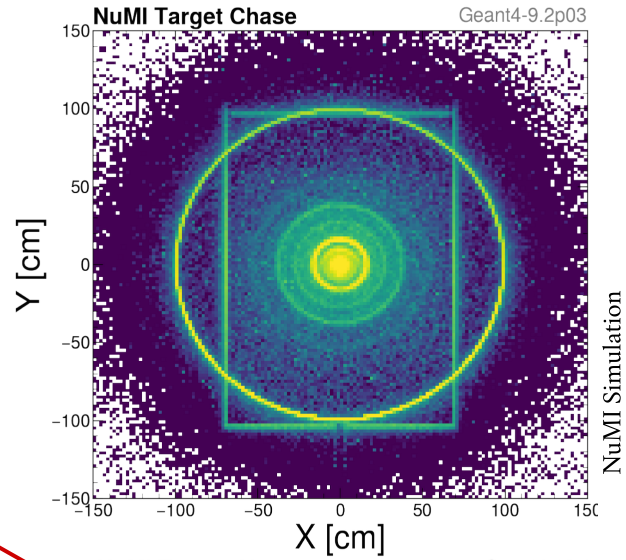
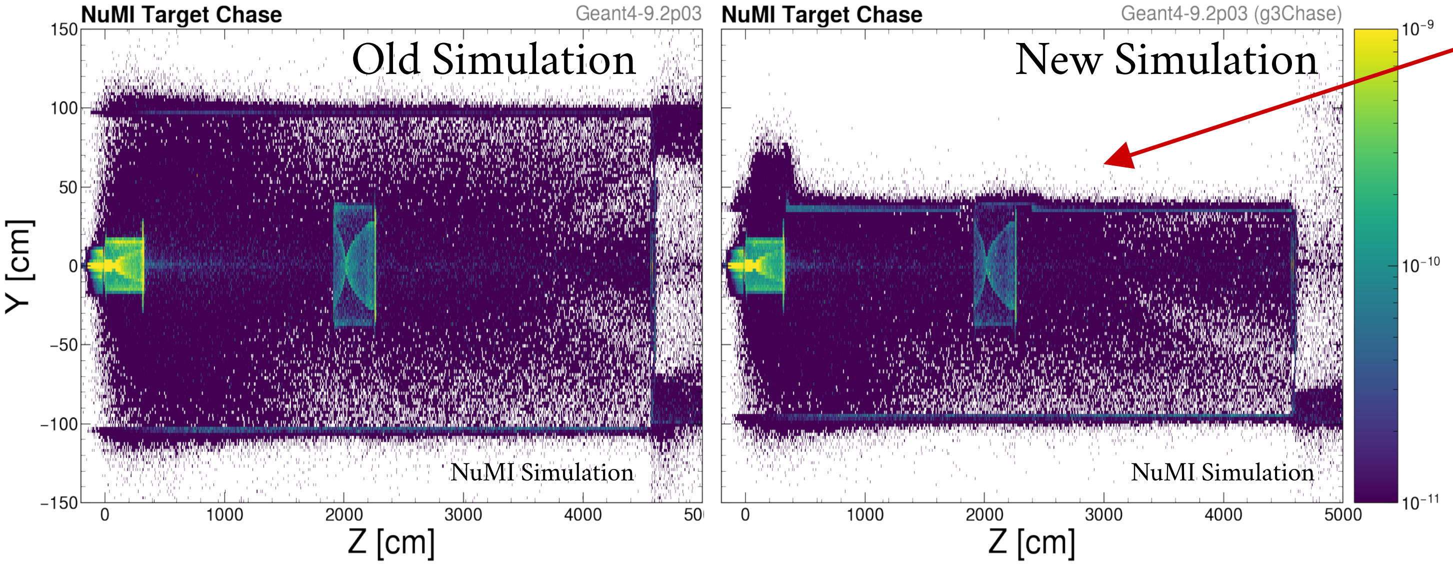
MicroBooNE-NOTE-1129-PUB

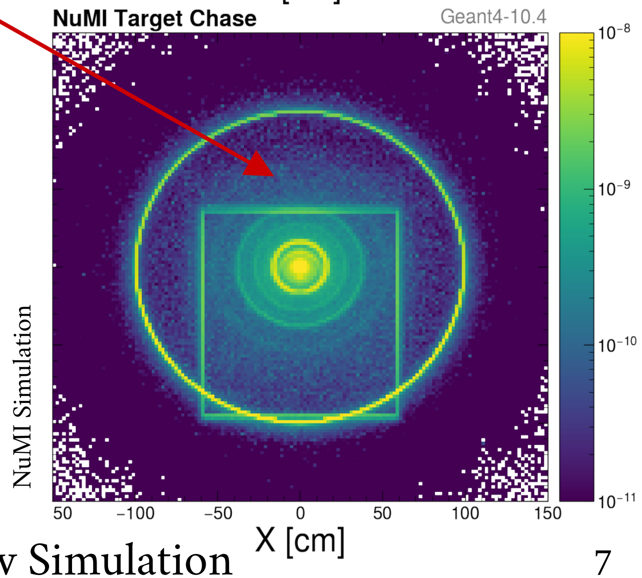


Old Simulation



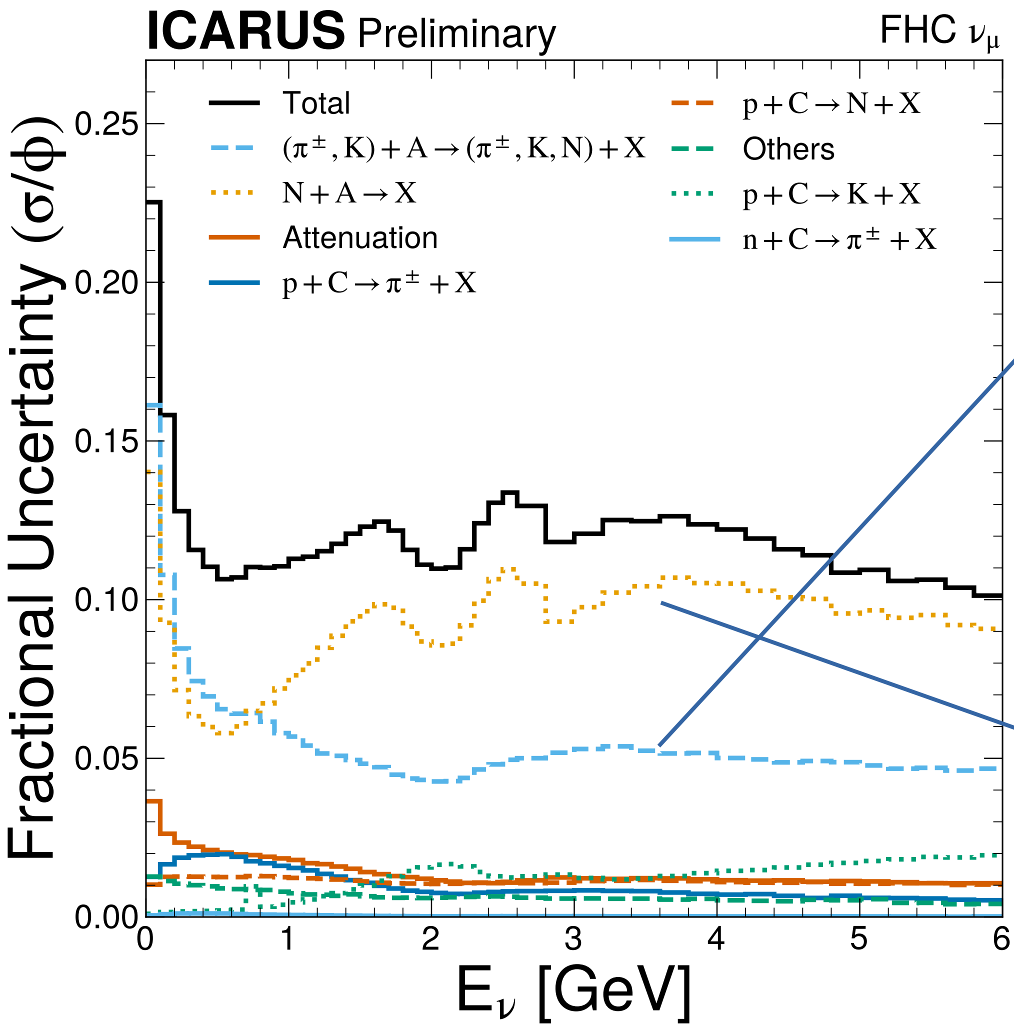
Missing Steel Blocks

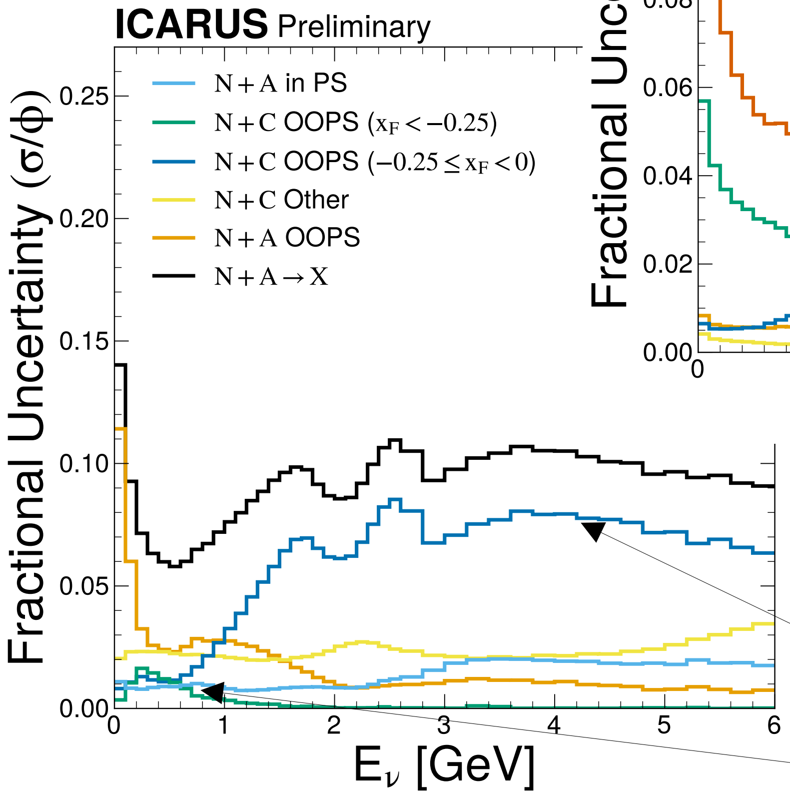


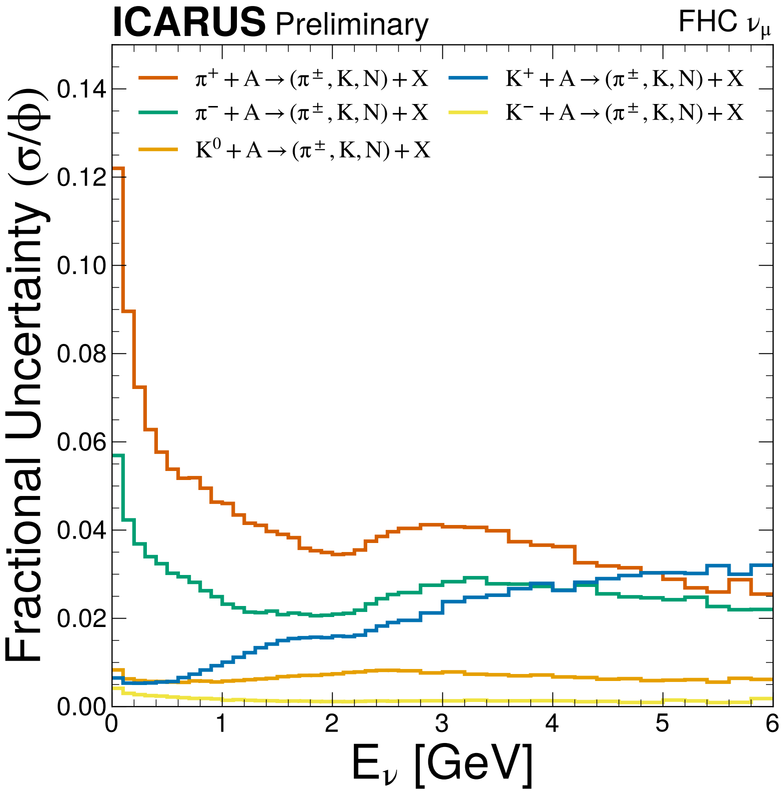


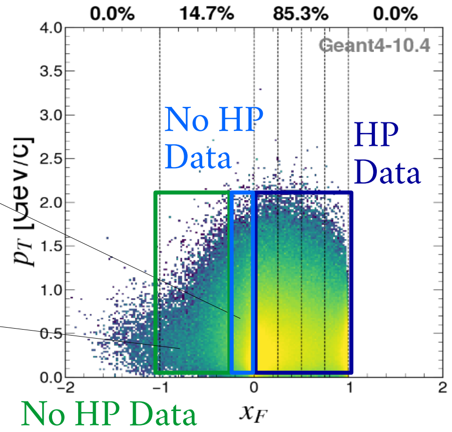
New Simulation

Flux Uncertainties: Contributions

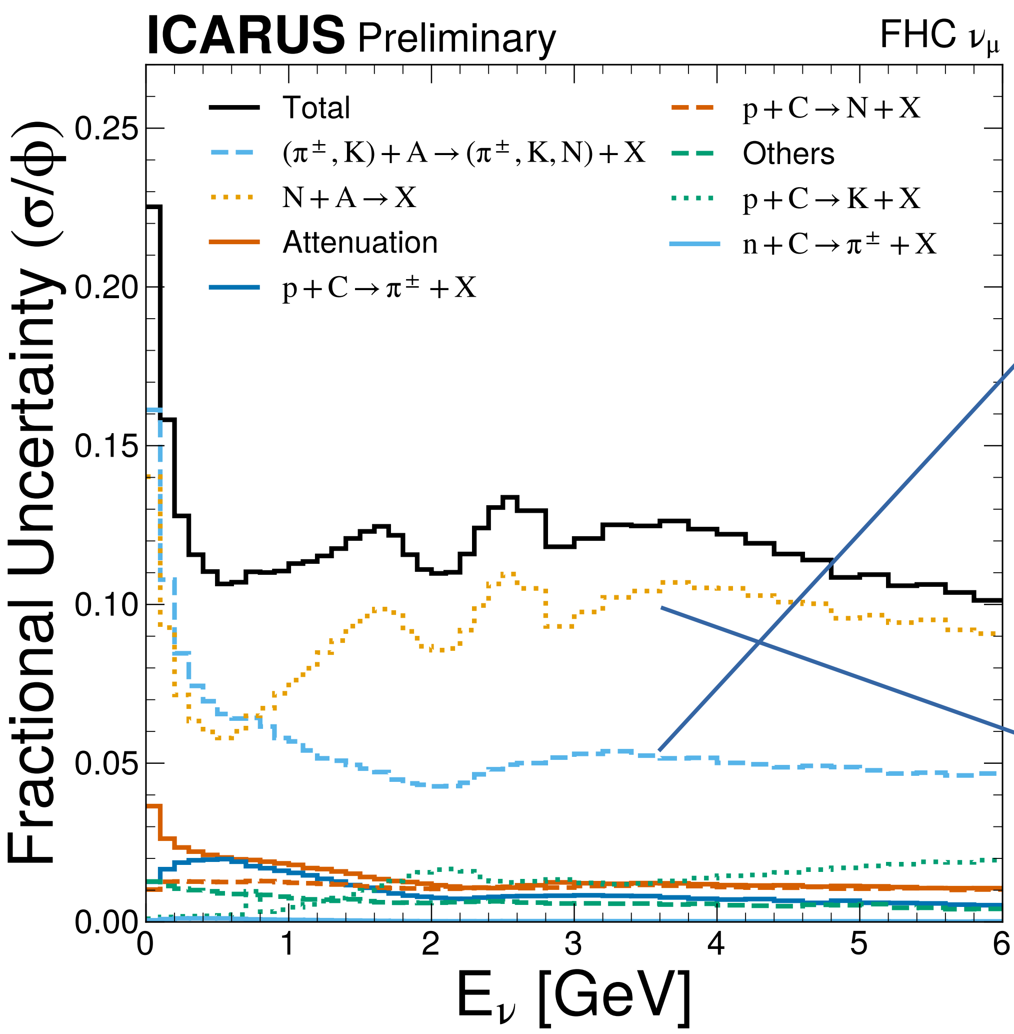


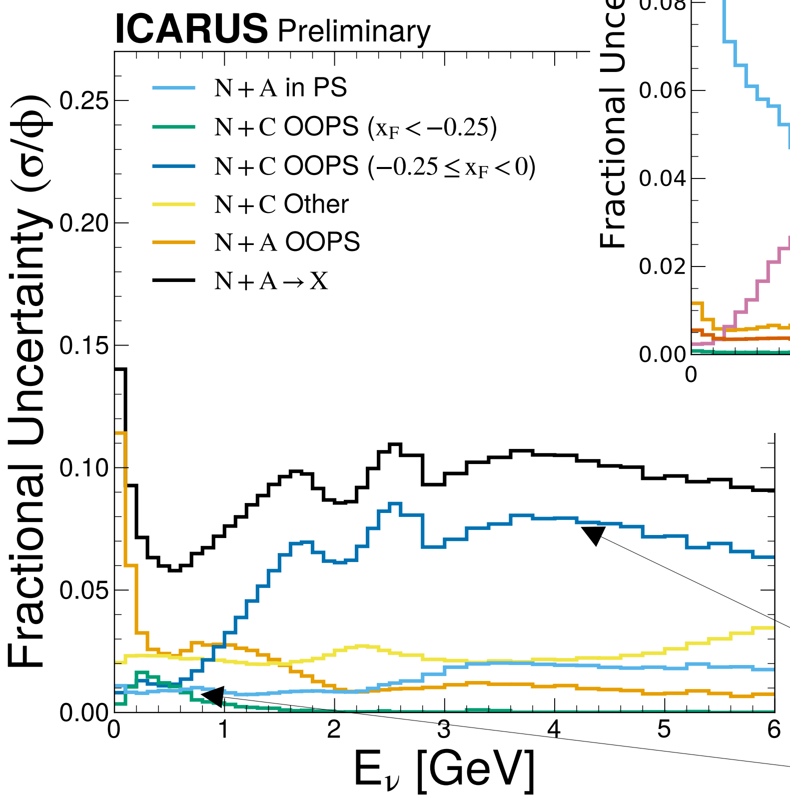


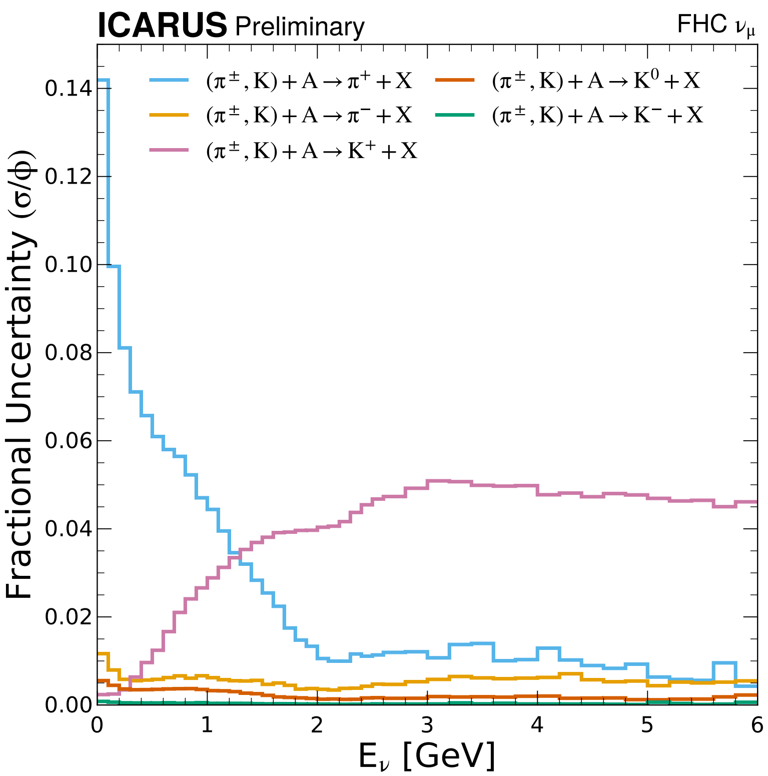


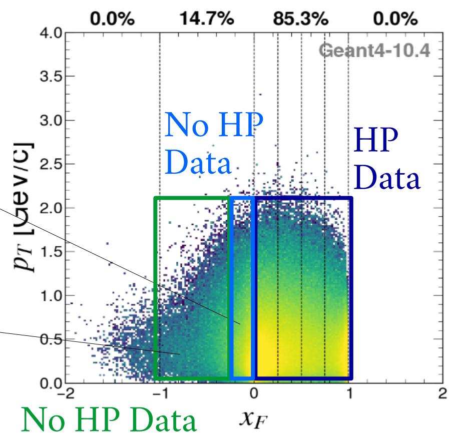


Flux Uncertainties: Contributions

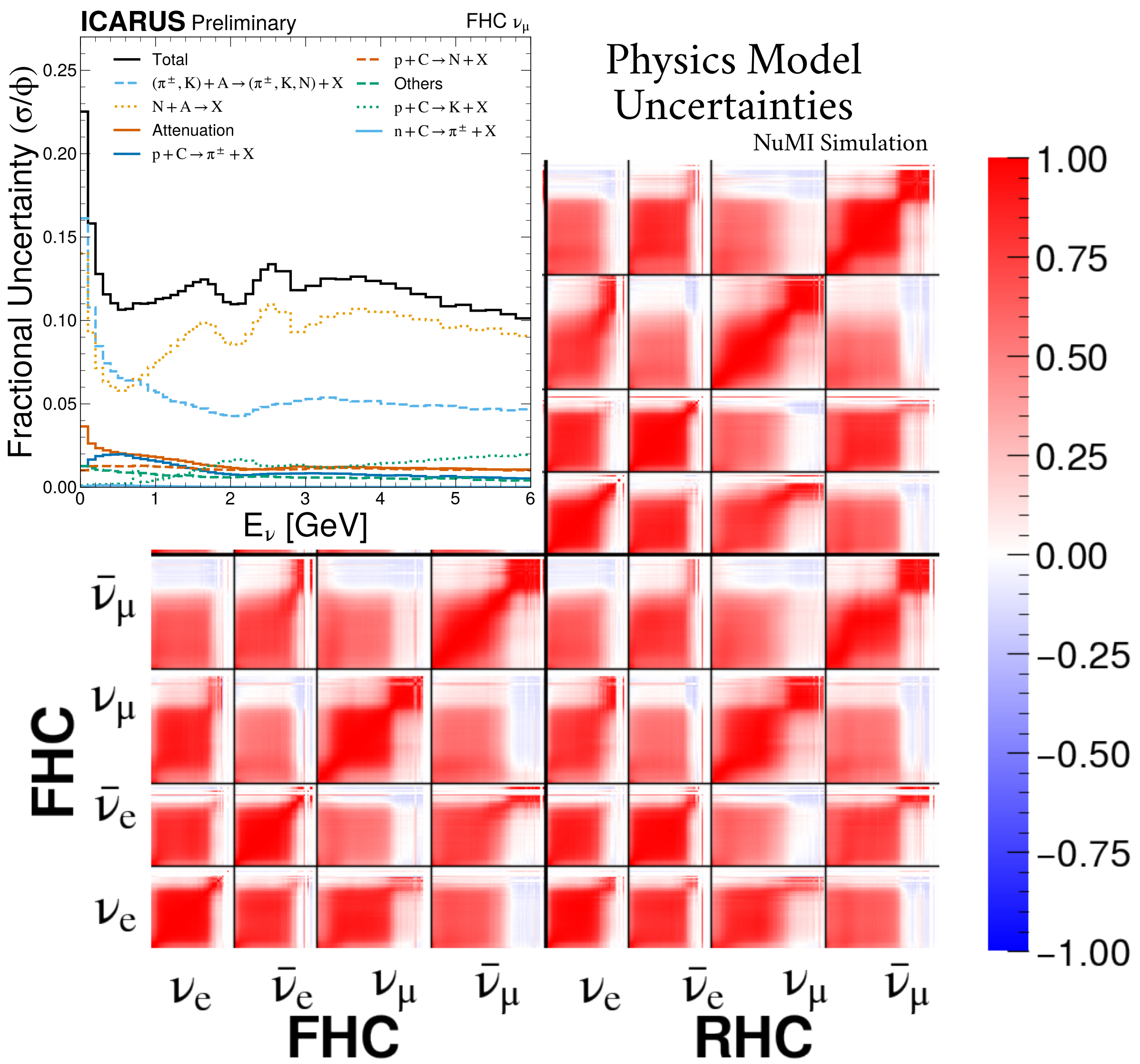


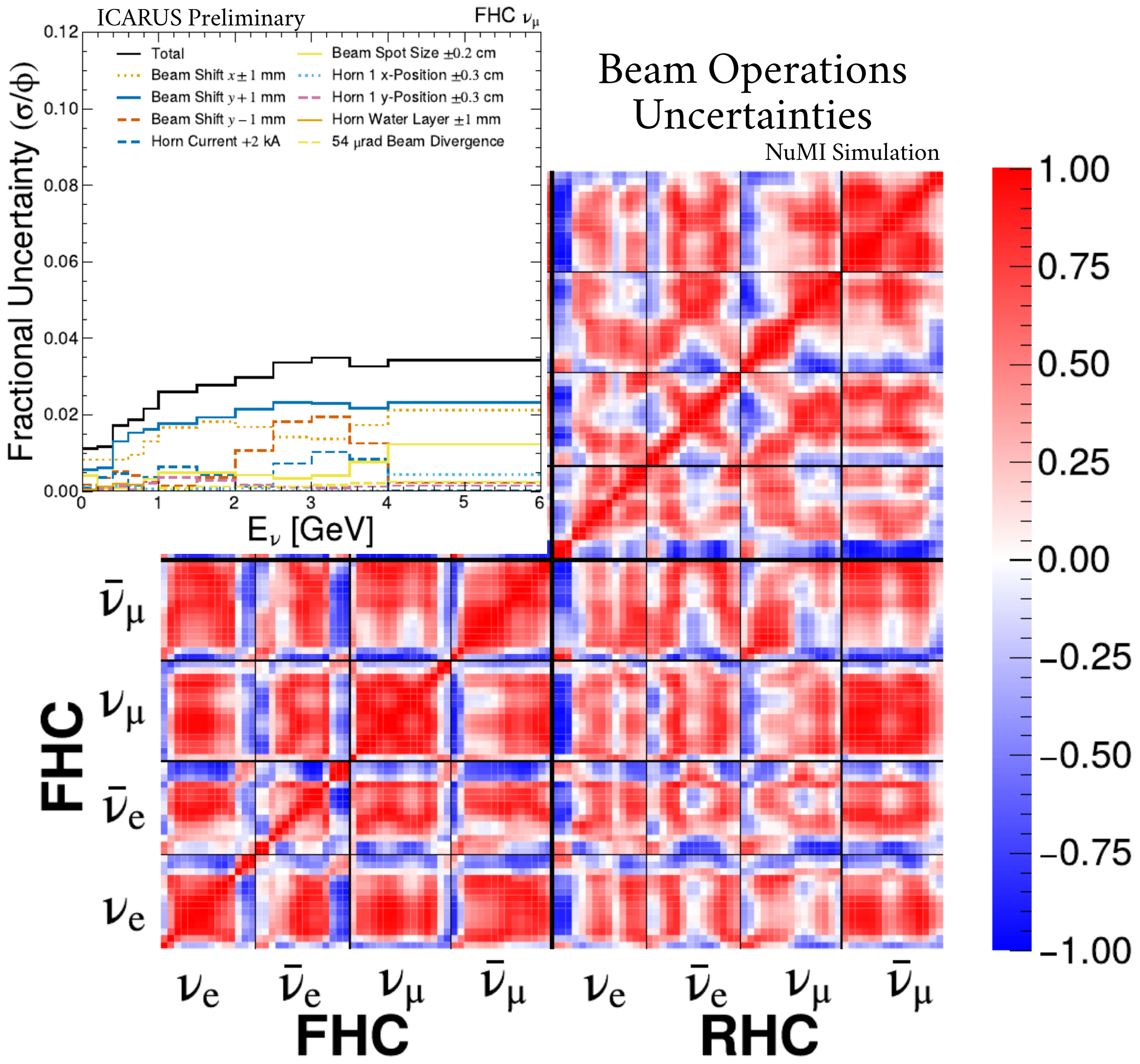






Flux Uncertainties: Correlations





Cross Section Opportunities

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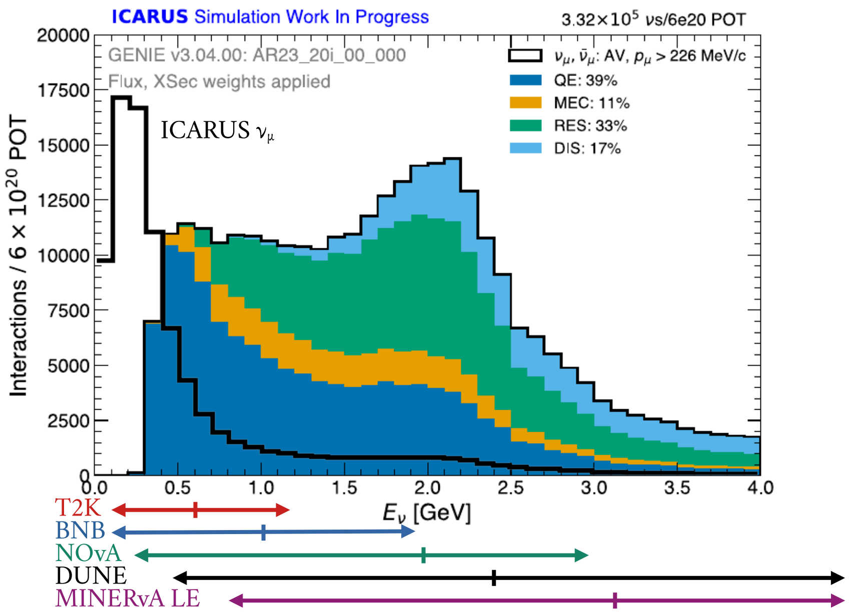
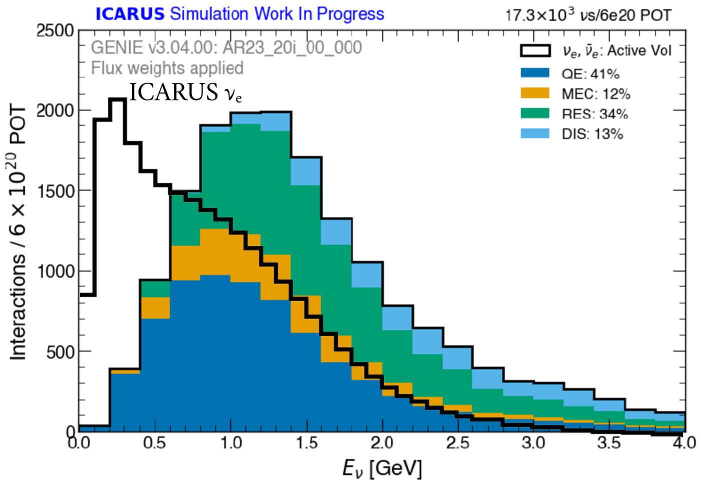
- Cross Section Measurements for DUNE
  - Similar measurements
    - Flux covers lower half of DUNE energy range
    - Same nucleus - argon
    - Same detector technology - LArTPC
  - Similar models
    - Current DUNE GENIE version
    - Current DUNE uncertainty model
  - Goal: inform DUNE x-sec uncertainty model
    - Processes that elucidate the hadronic system
    - Production and reinteraction of pions
    - Differences between ν_e and ν_μ, and $\bar{\nu}$ and ν processes
    - Develop uncertainties for unbiased analyses and to cover data

Muon Neutrino



Electron Neutrino



Track Reconstruction and PID

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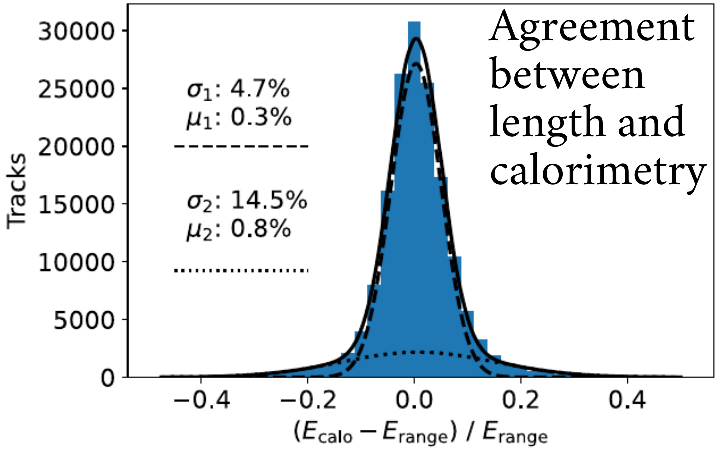
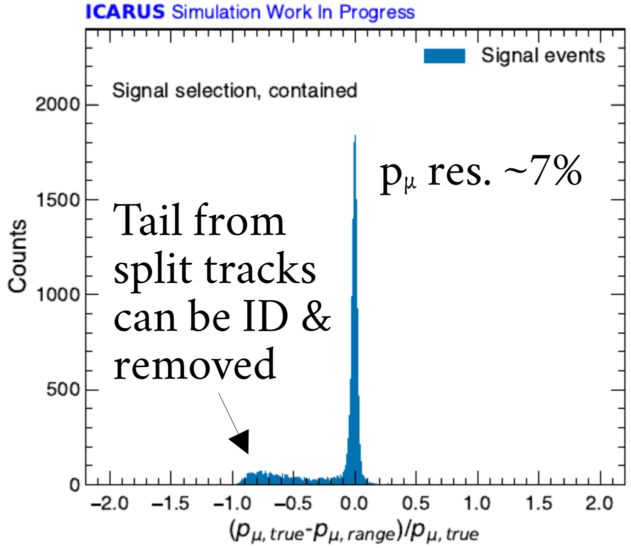
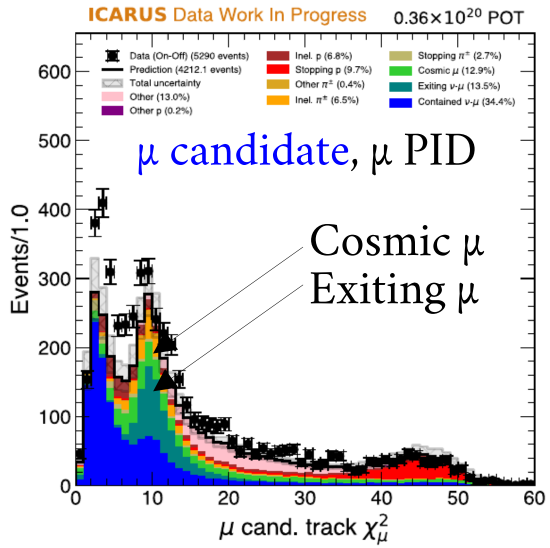
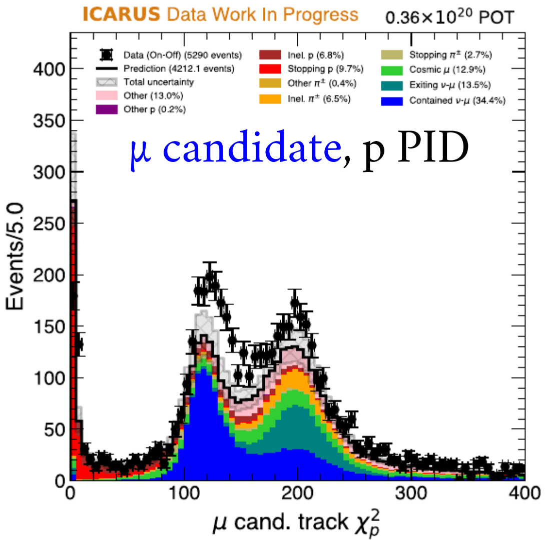




15% of available data





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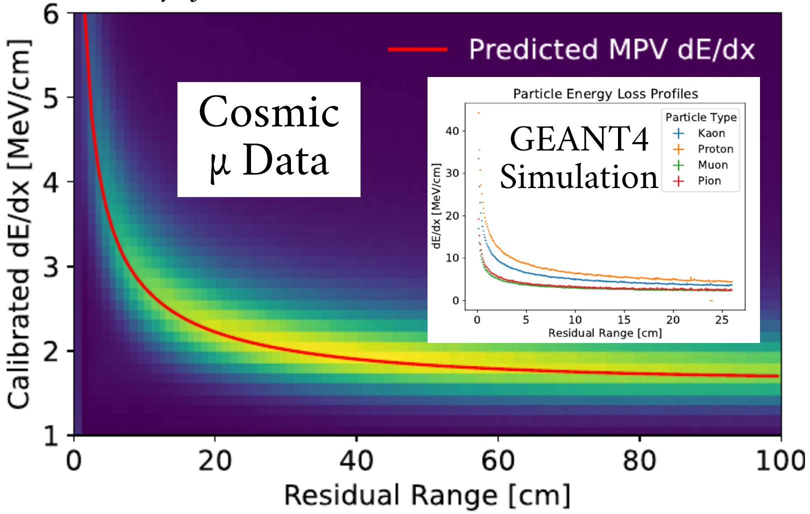
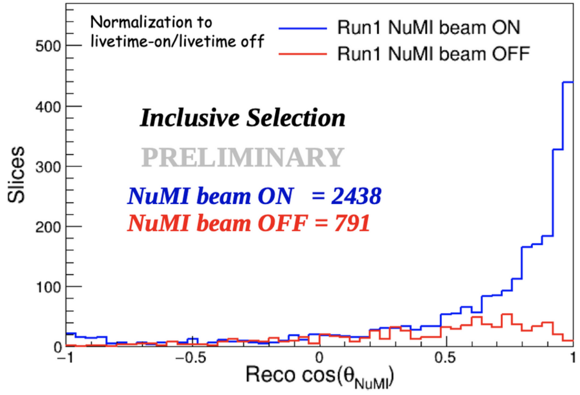
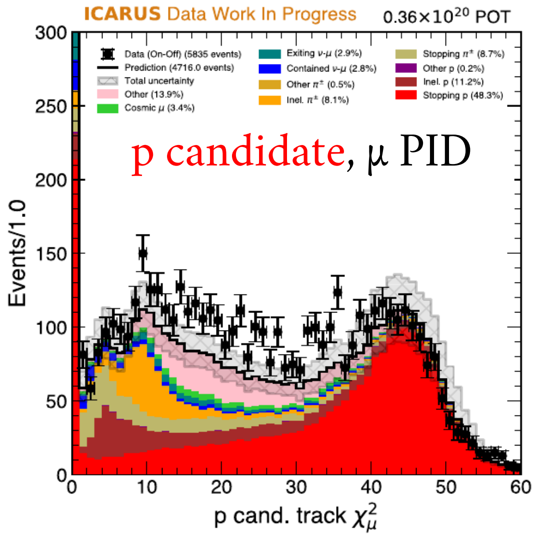
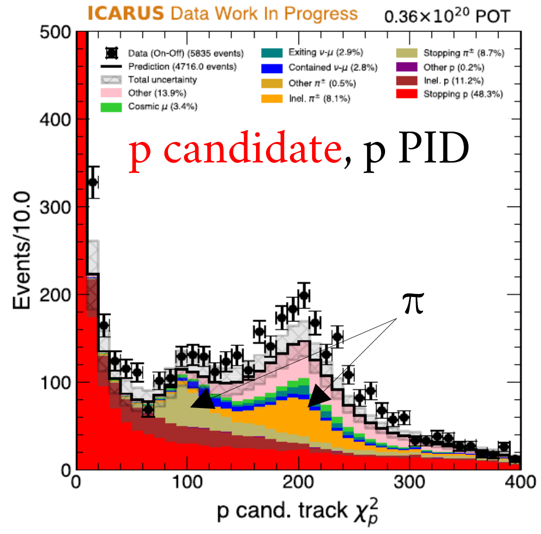


Cosmic Rejection

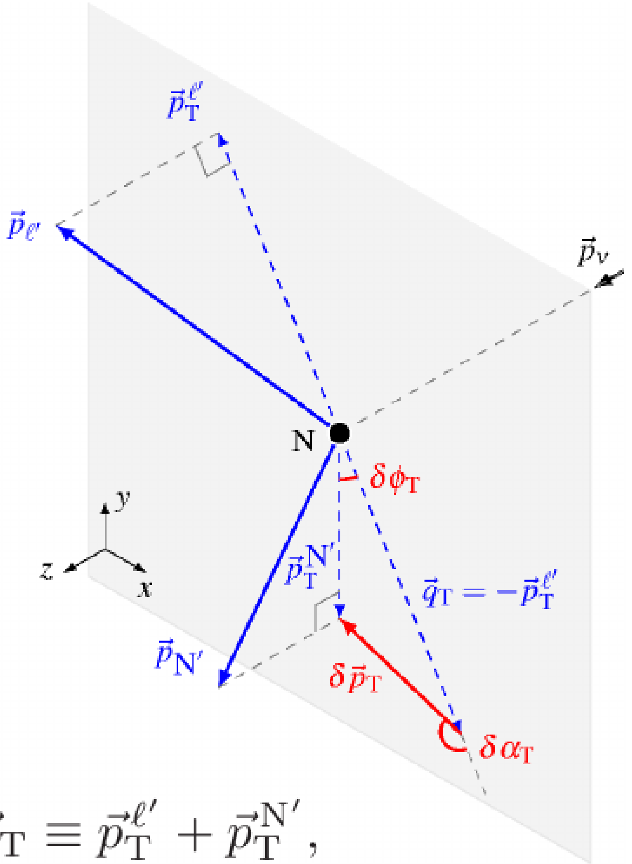






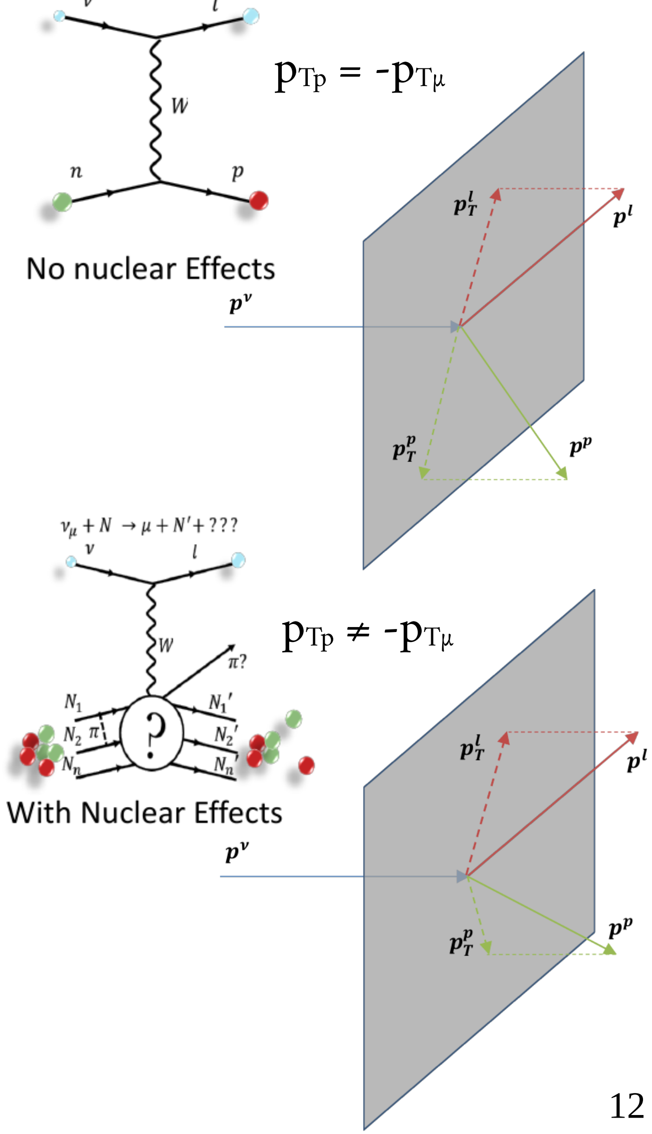
TKI Measurement

- Transverse Kinematic Imbalance (TKI)
  - Define transverse plane as ⊥ to ν dir.
  - Project $\overline{p}_{\mu}$ on to transverse plane: $p_{T\mu}$
  - For a target nucleon at rest $p_{Tp} = -p_{T\mu}$
- Understanding the hadronic system
  - Initial $\overline{p}_{N}$ adds momentum to the FS
  - FSI slows and redirects the primary p
  - FSI can alter the event topology
- $\delta\phi_T$ is sensitive to p_{Tp} direction
- $\delta\alpha_T$ is sensitive to p_{Tp} magnitude
- δp_T is sensitive to p_{Tp} both
- Measuring all 3 helps break degeneracies



$$\delta\vec{p}_T \equiv \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'},$$

$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\delta p_T},$$



Courtesy Stephen Dolan

Selecting a 1μNp Sample

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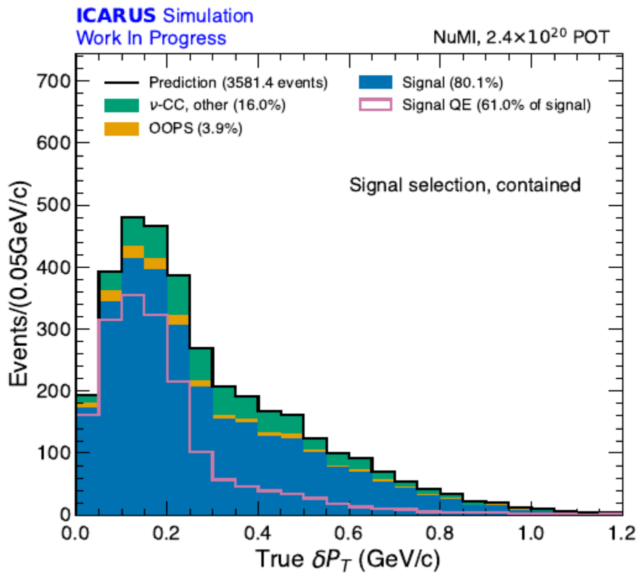
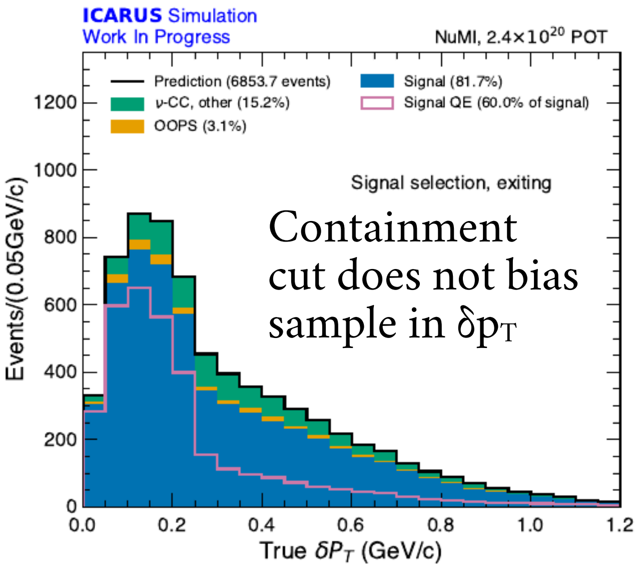
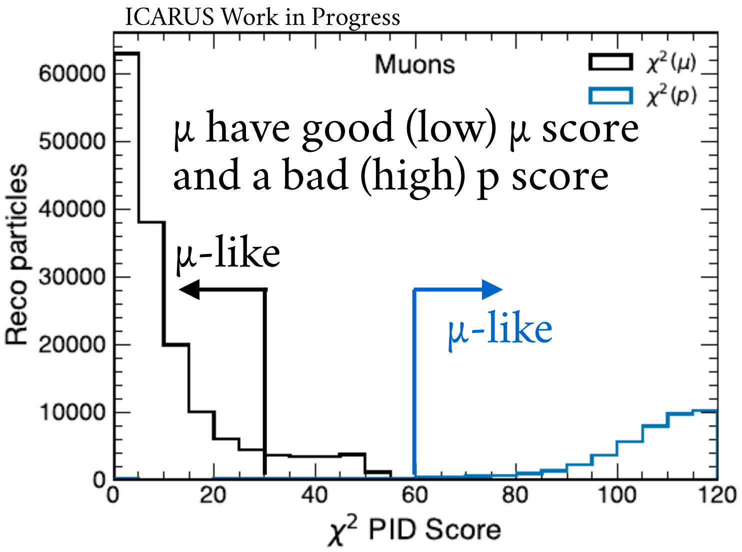
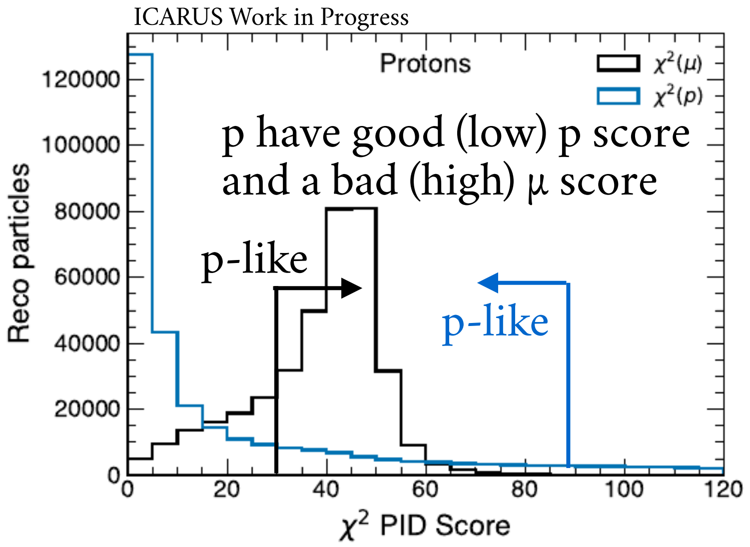
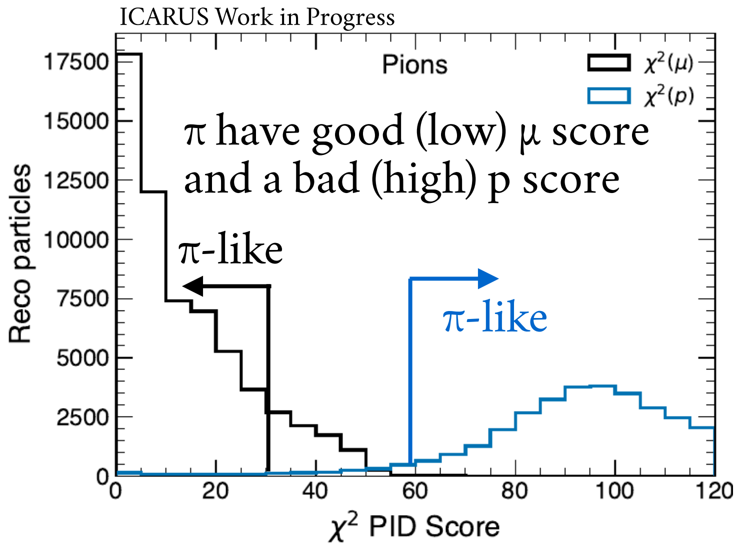
- Vertex in the fiducial volume
- Not a “clear cosmic”
- Require at least 2 tracks
  - 1 μ-like track
    - Length > 50 cm
    - Fully contained
  - 1 p-like track
  - 0 π-like tracks



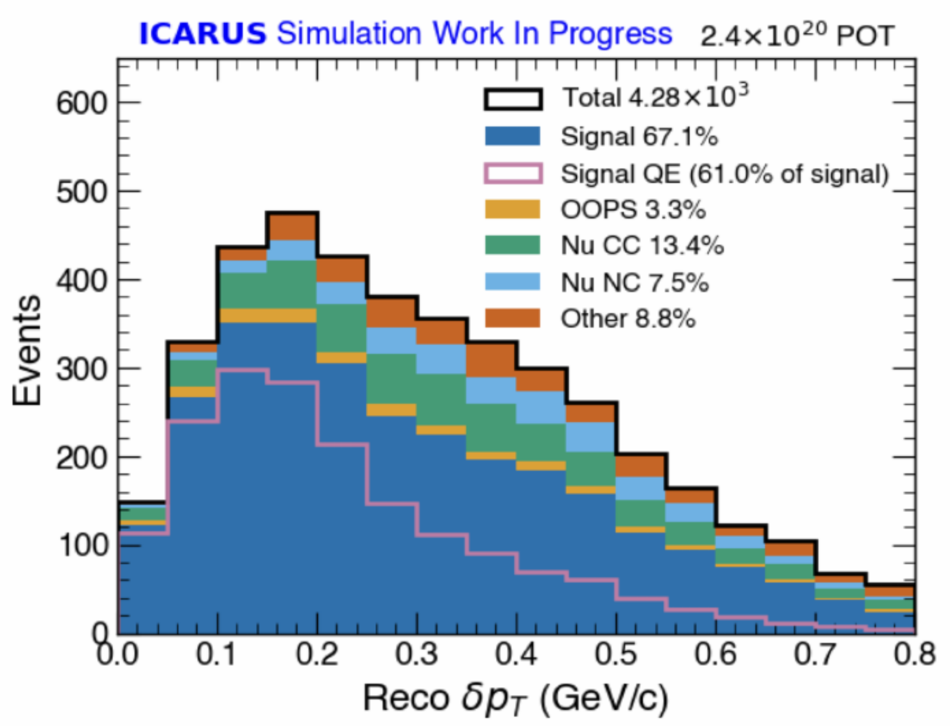


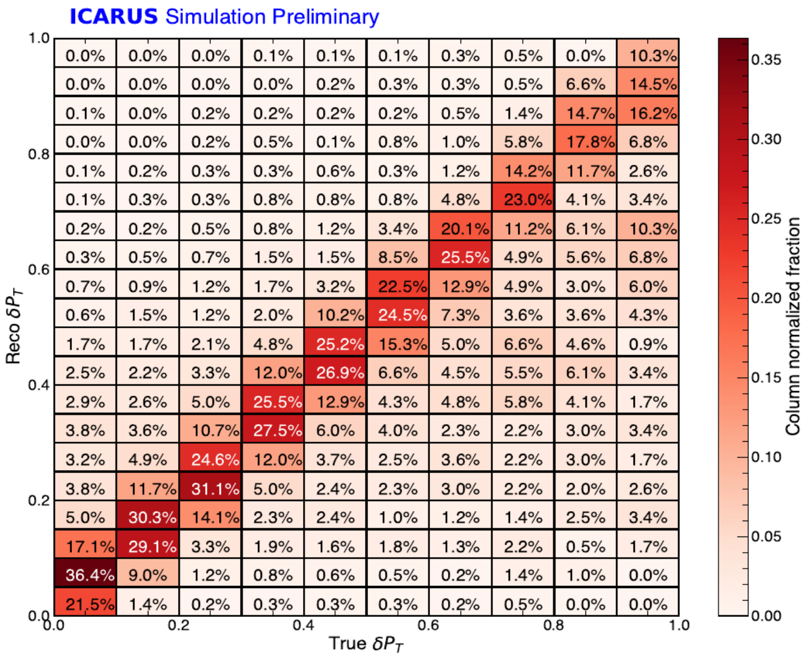


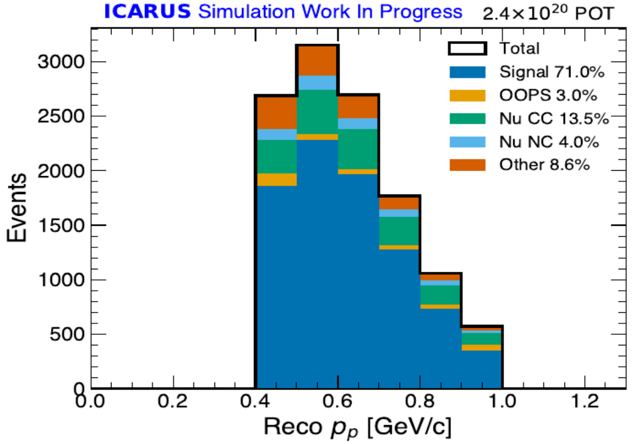


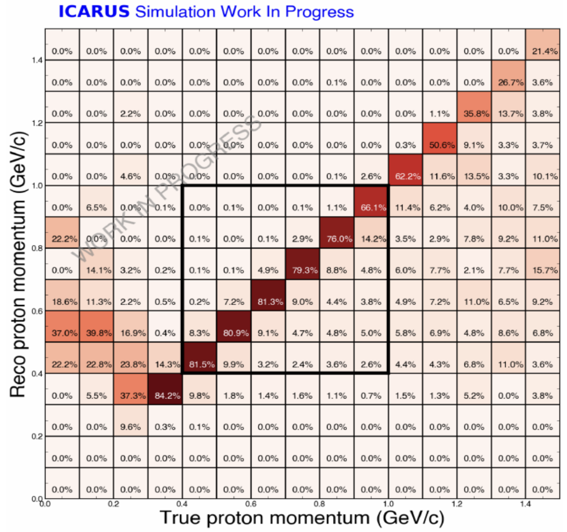


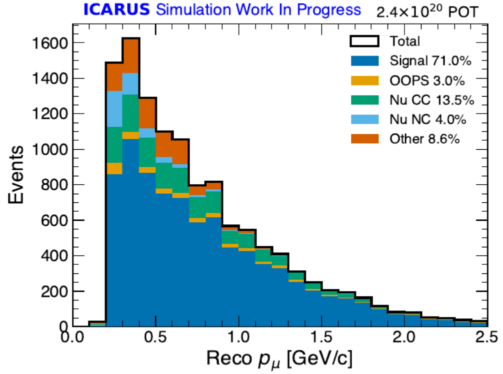
The Selected Sample

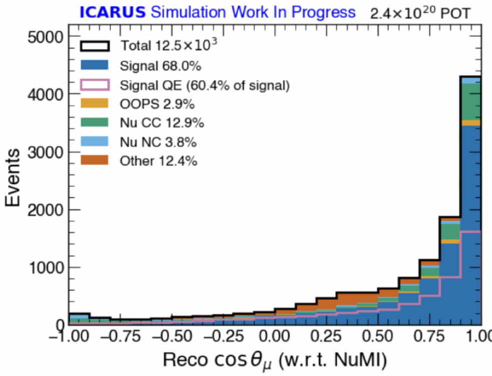


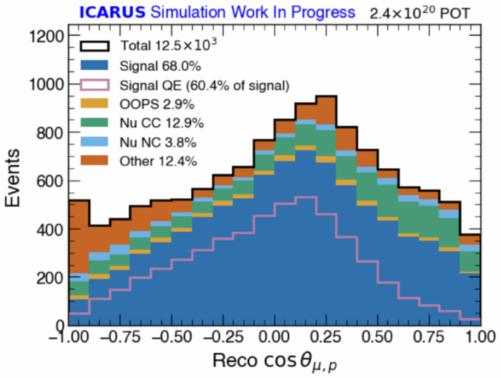




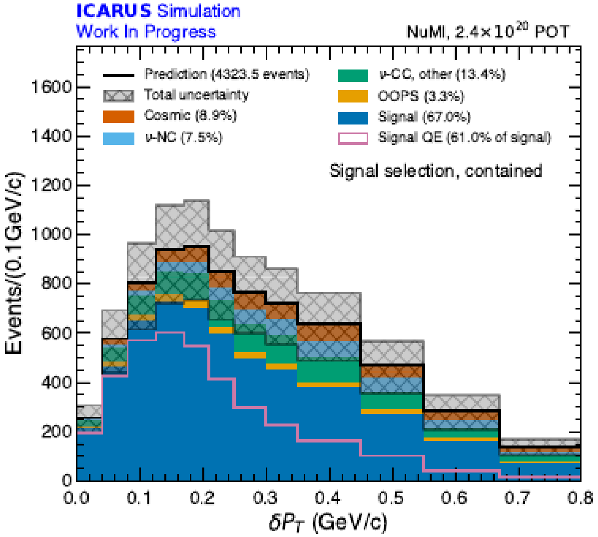


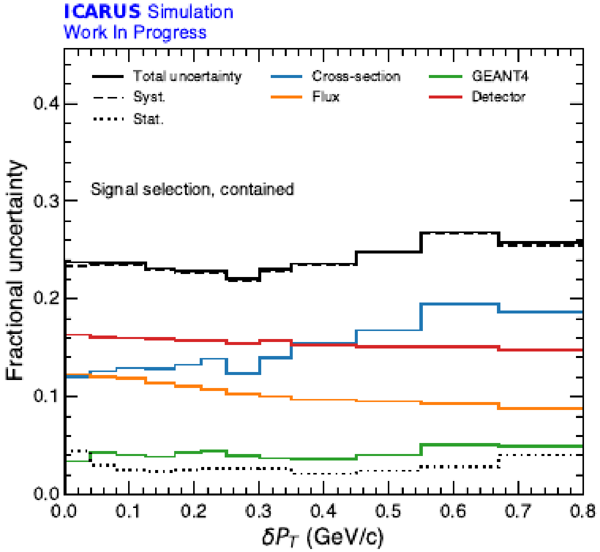


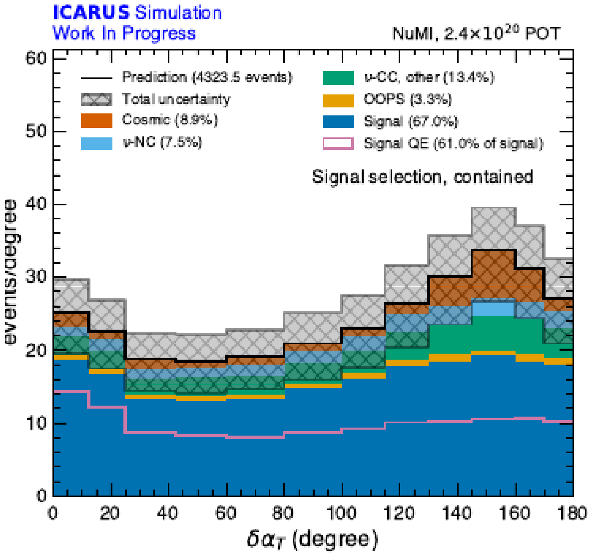


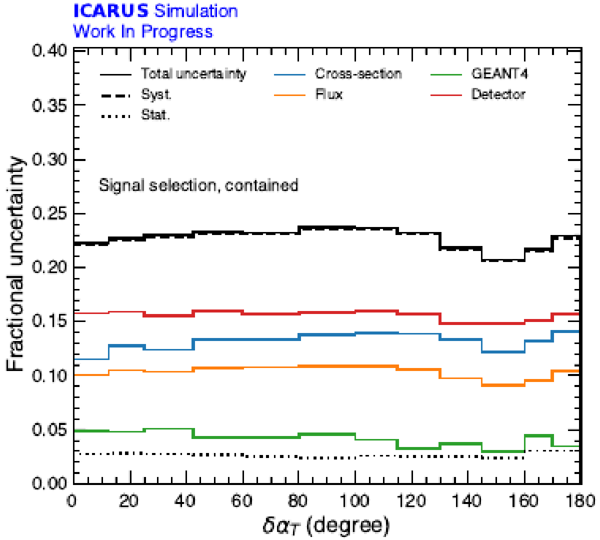


Backgrounds and Systematics









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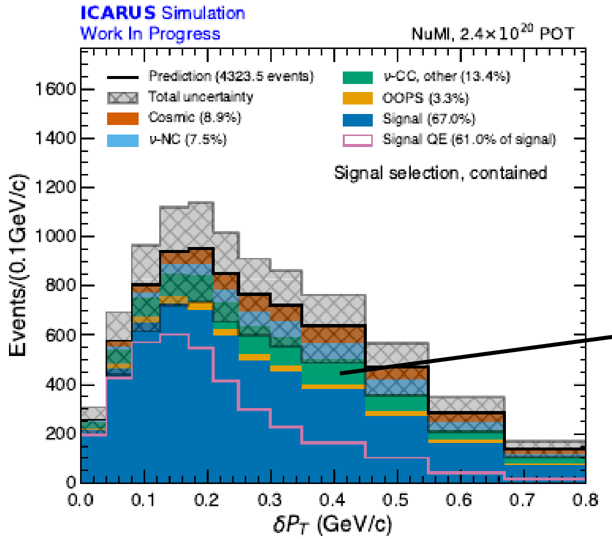

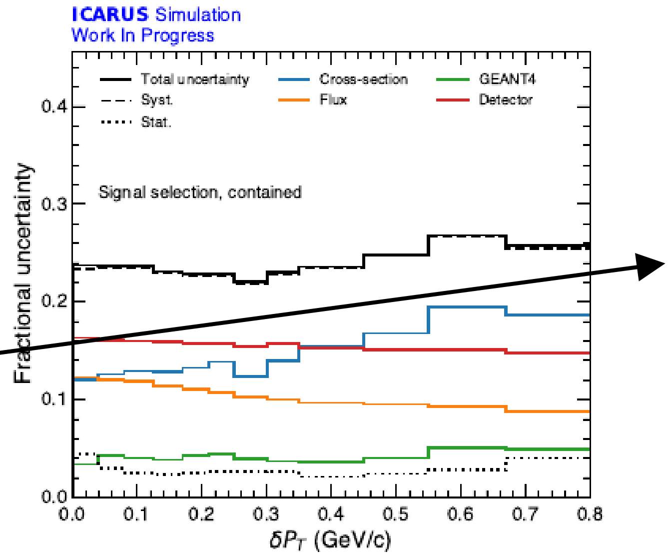

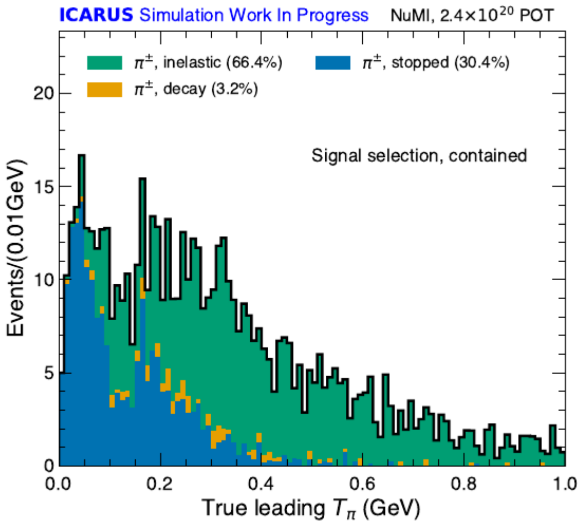

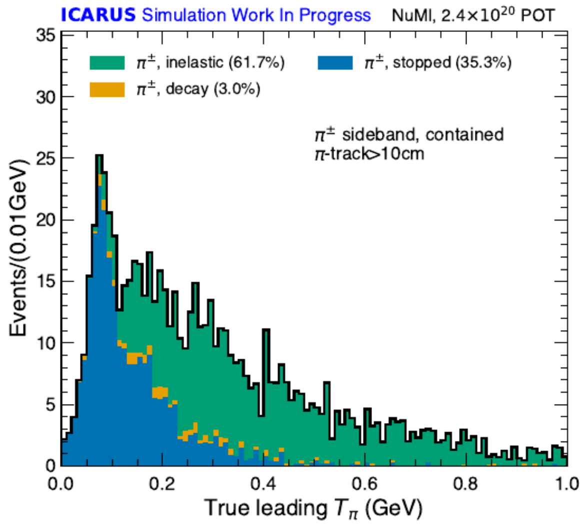

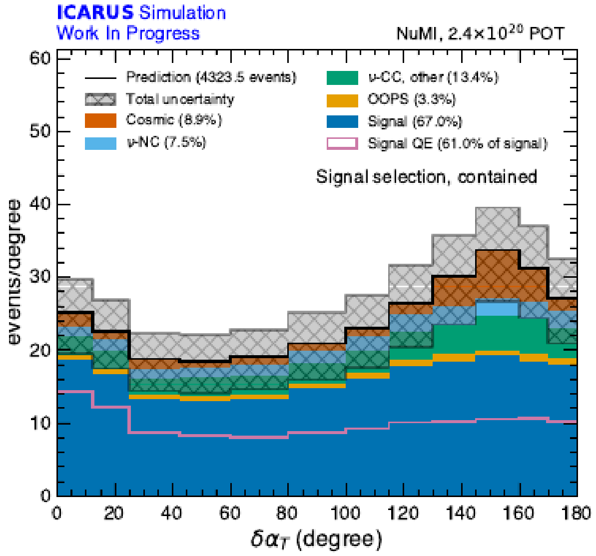

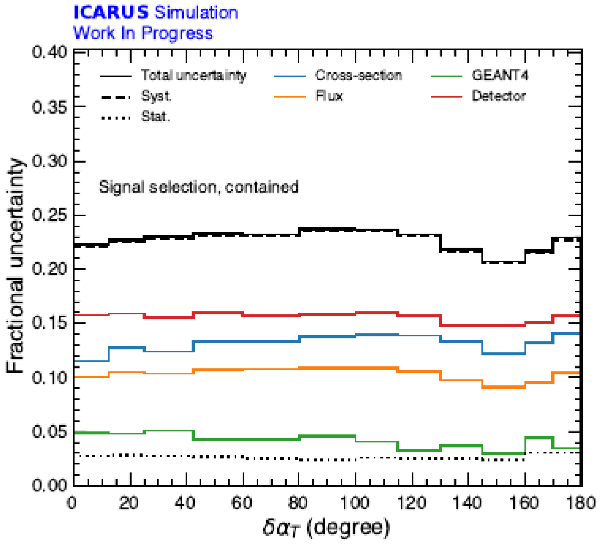

Backgrounds and Systematics

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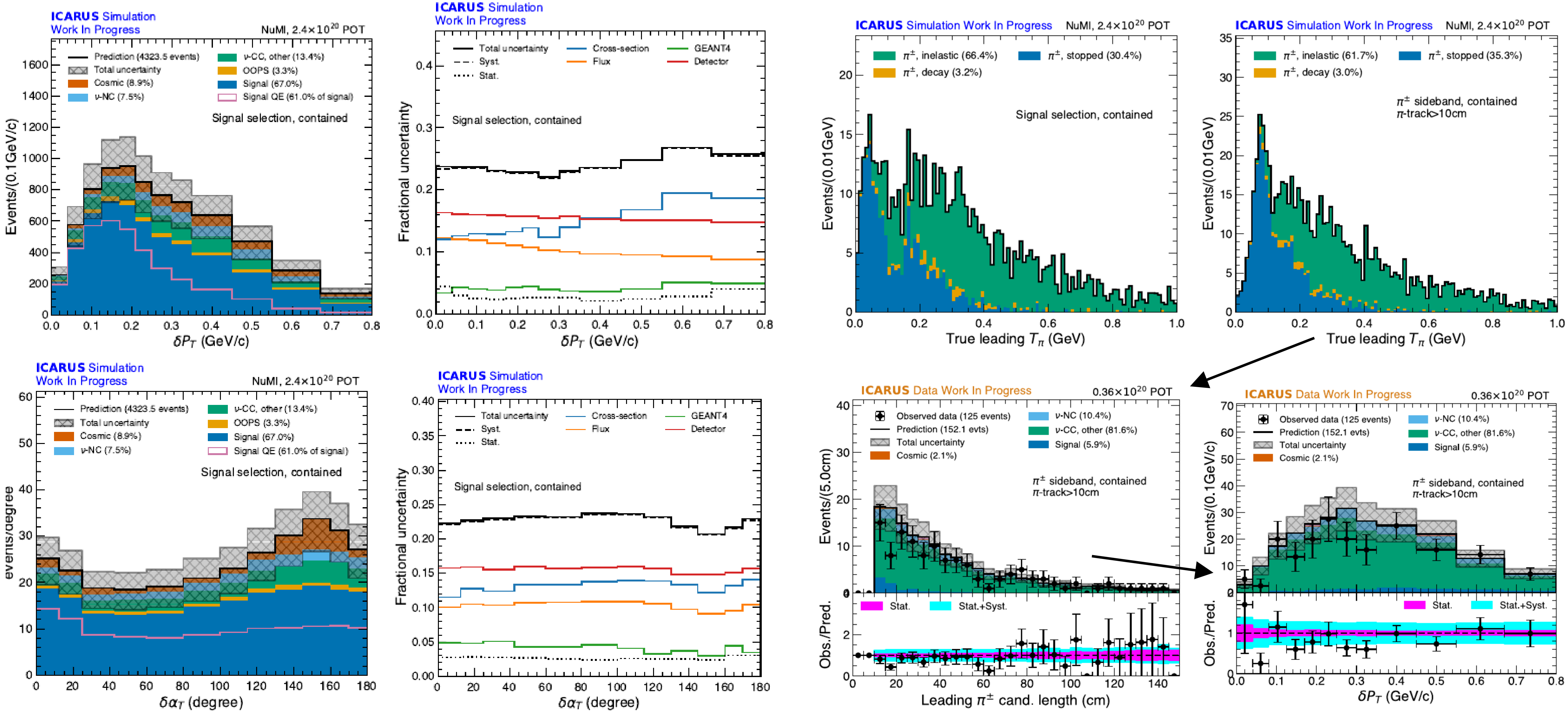
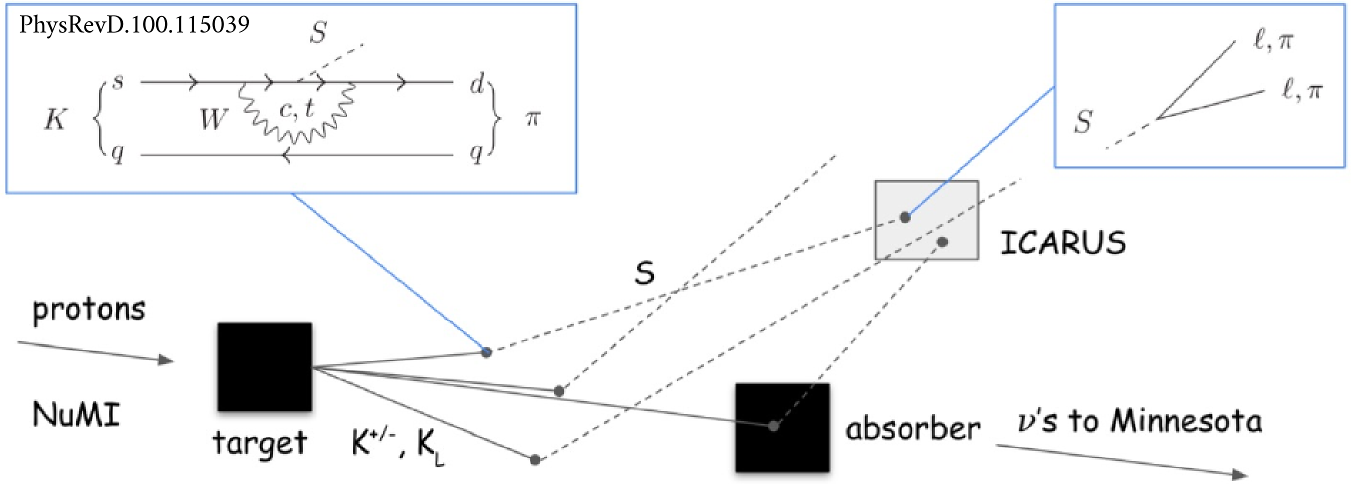
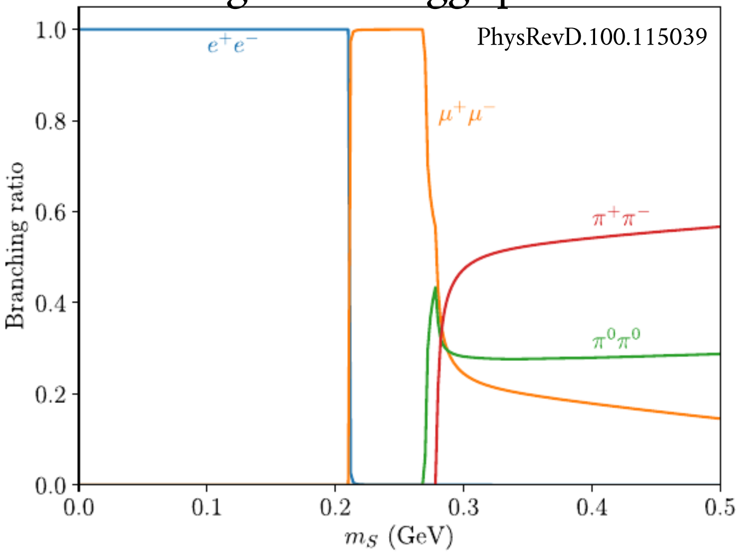


BSM Measurement Capabilities

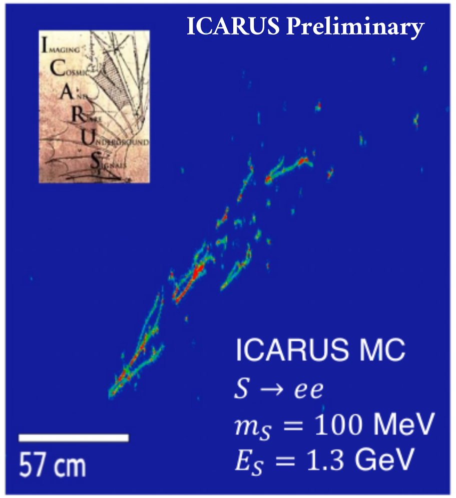
- A variety of BSM Physics models predict observable signal in ICARUS
  - Higgs portal scalar
  - Heavy QCD axion
  - Heavy neutral lepton
  - Vector portal dark matter
- Exotic particles created in NuMI beamline interactions or decays
  - Target region
  - Beam dump (KDAR)
- Particles travel to ICARUS and decay into observable particles
  - **Di-muon (μ^+/μ^- pair)**
  - e^+/e^-, π^+/π^-, or $\pi^0 \rightarrow \gamma\gamma$ pairs
  - Mono-energetic signal (KDAR)
  - Delayed timing w.r.t. standard beam window



Branching Ratio: Higgs portal scalar



Potential ICARUS Event



Di-muon Analysis Events

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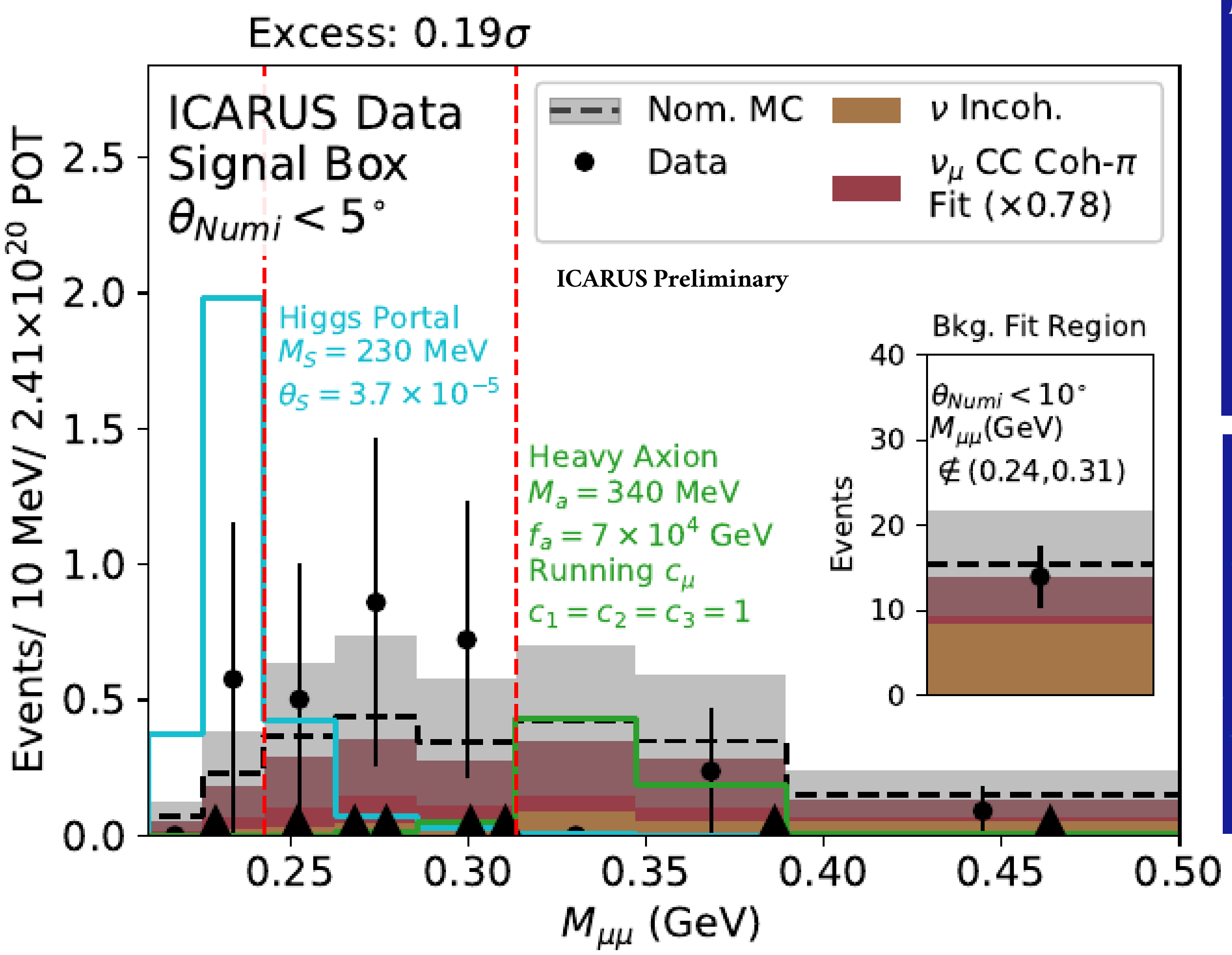
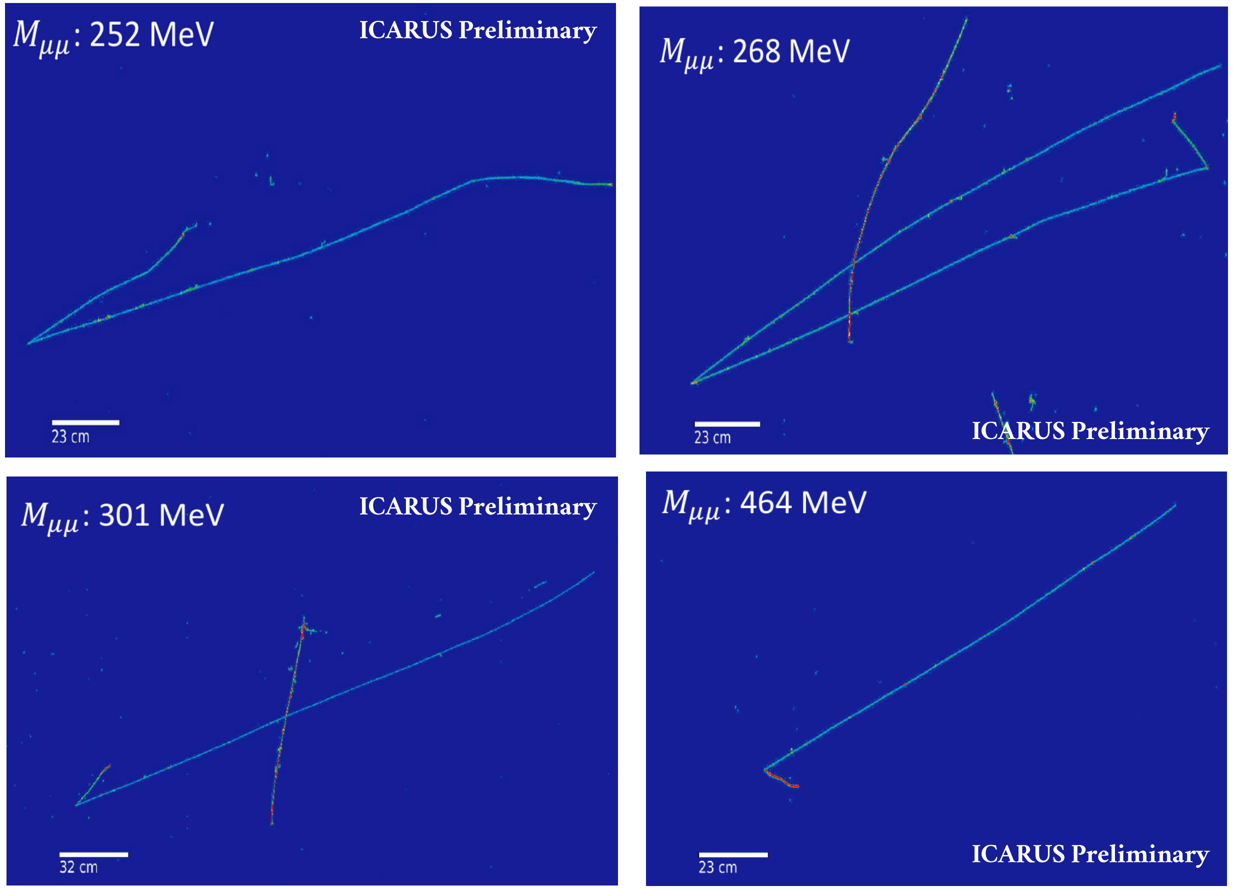
Paper in preparation

Run 1 Observed Data





Example selected data events

Di-muon Analysis Interpretation

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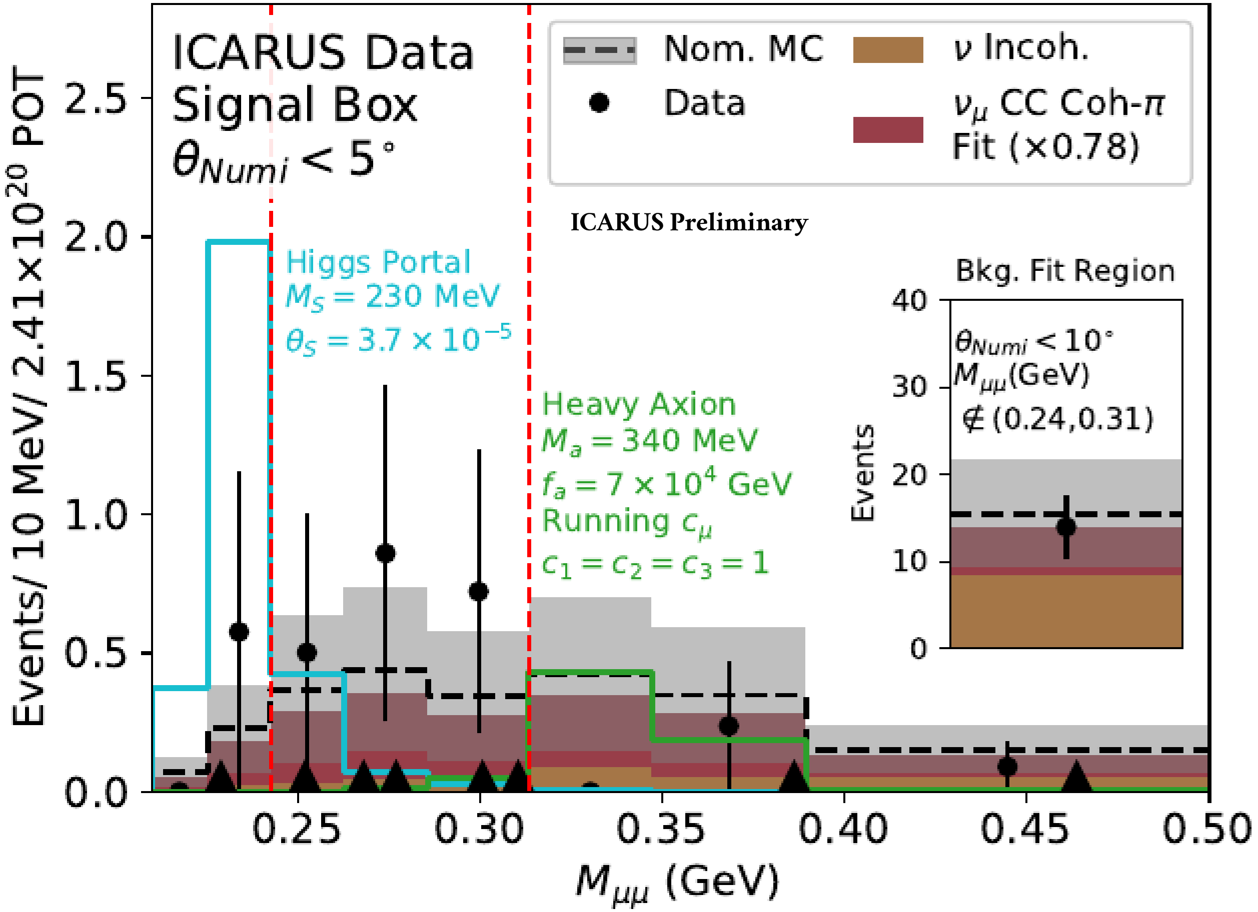
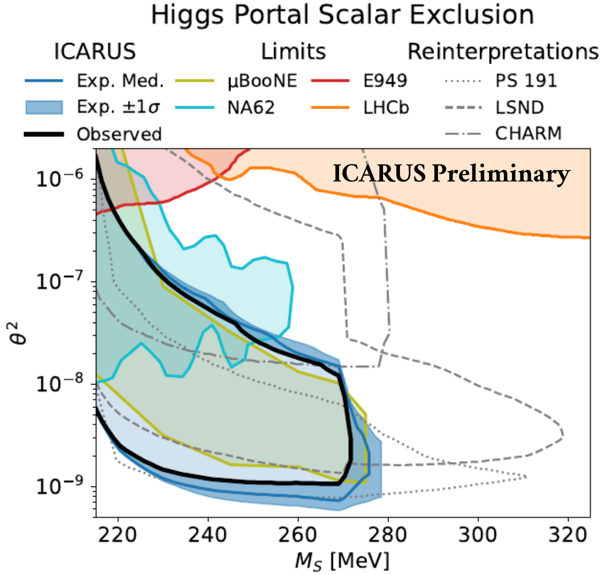
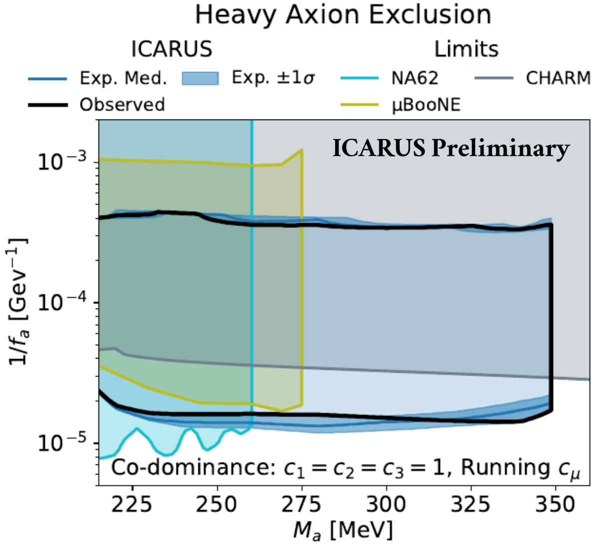
Paper in preparation

Run 1 Observed Data

Excess: 0.19σ



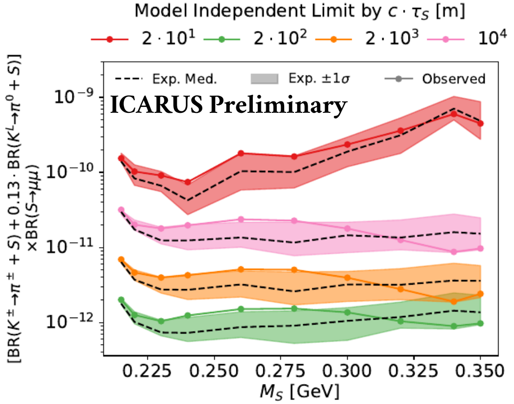




Higgs Portal Hypothesis

$$\Gamma(S \to \mu\mu) = \theta_S^2 \frac{m_\mu^2 m_S}{8\pi v^2}\left(1 - \frac{4m_\mu^2}{m_S^2}\right)^{3/2}$$

Model Independent Interpretation



Heavy Axion Hypothesis

$$\Gamma(a \to \mu\mu) = c_\mu^2 \frac{m_\mu^2 m_a}{8\pi f_a^2}\left(1 - \frac{4m_\mu^2}{m_a^2}\right)^{1/2}$$

Summary and Conclusions

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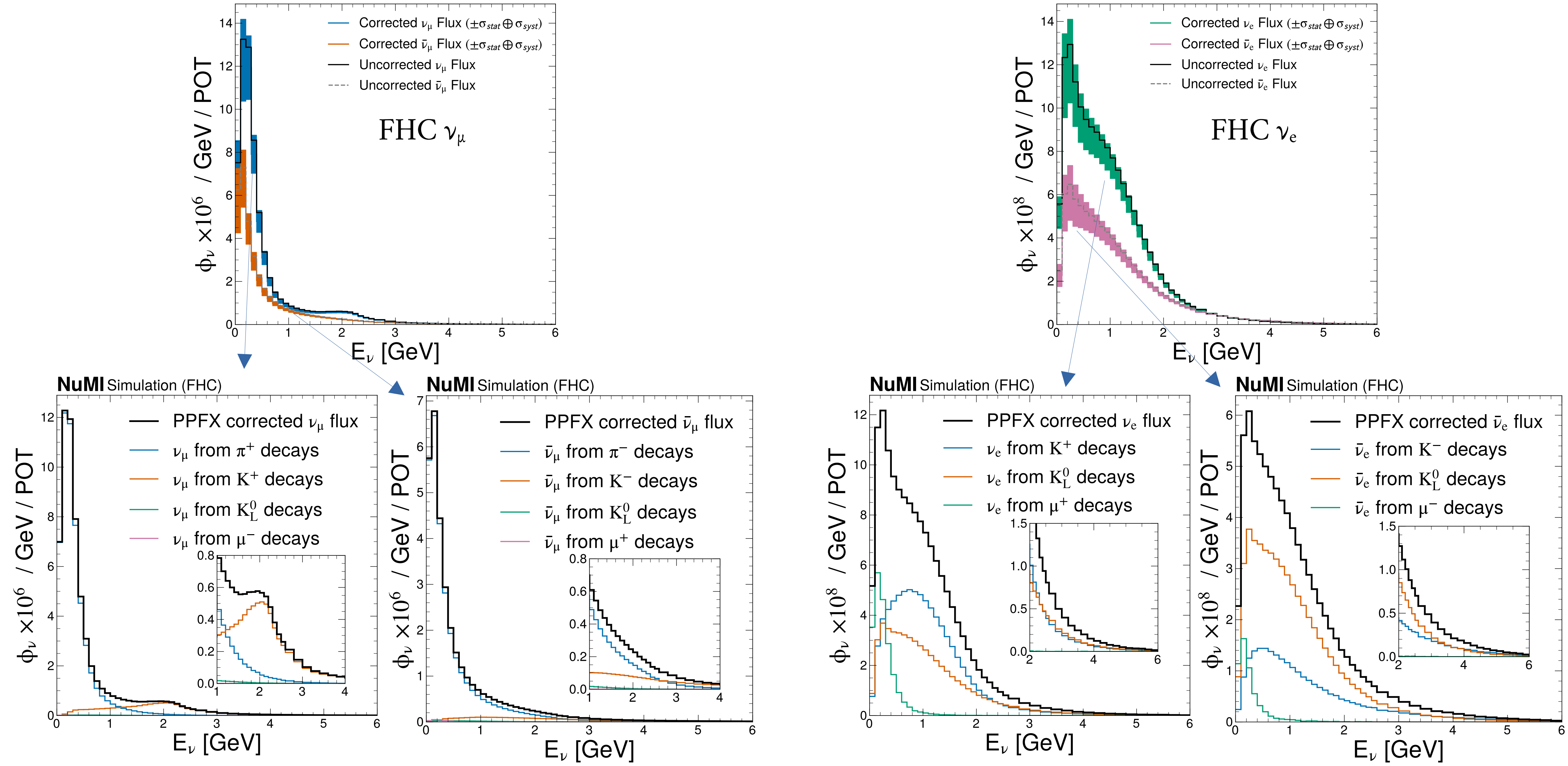
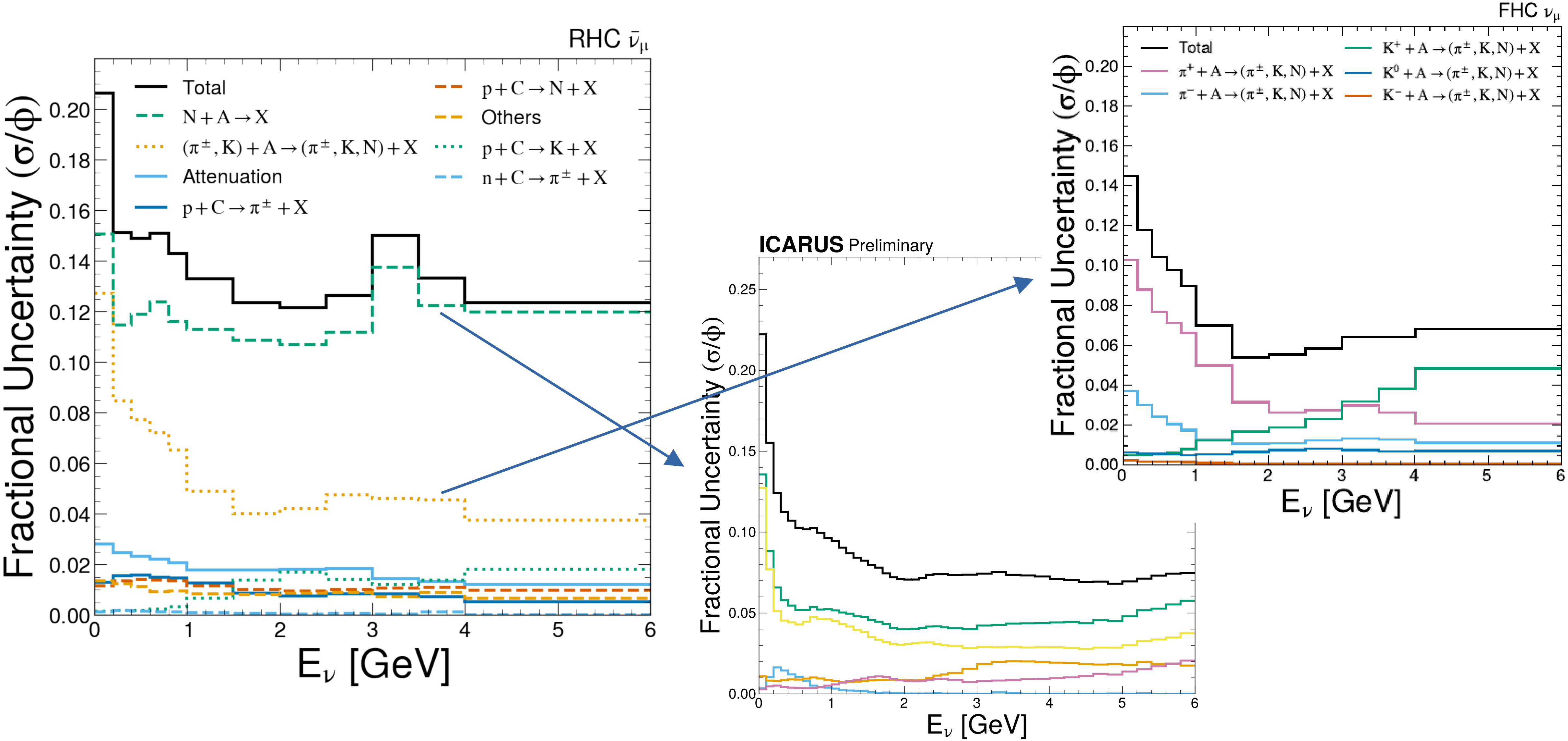
- ICARUS sits 5.75° off-axis of the NuMI Beam.
- NuMI neutrinos provide a unique opportunity to study and constrain ν-Ar interaction cross sections important for DUNE.
- The high off-axis angle also provides sensitivity to a variety of BSM model predictions.
- The NuMI beam and it's uncertainties have been well studied at 5.75°.
- ICARUS has collected 3.86×10^{20} POT in FHC (current analyses) and 3.42×10^{20} POT (recent runs) in RHC modes.
- An initial di-muon-based search for BSM physics has been completed.
- A first pass measurement of TKI in CCν_μ Np0π interactions is near completion.
- Many more measurements are underway along with a robust program aimed at improved reconstruction, calibration, and systematic uncertainty development.

Backup Slides

The NuMI Flux at ICARUS

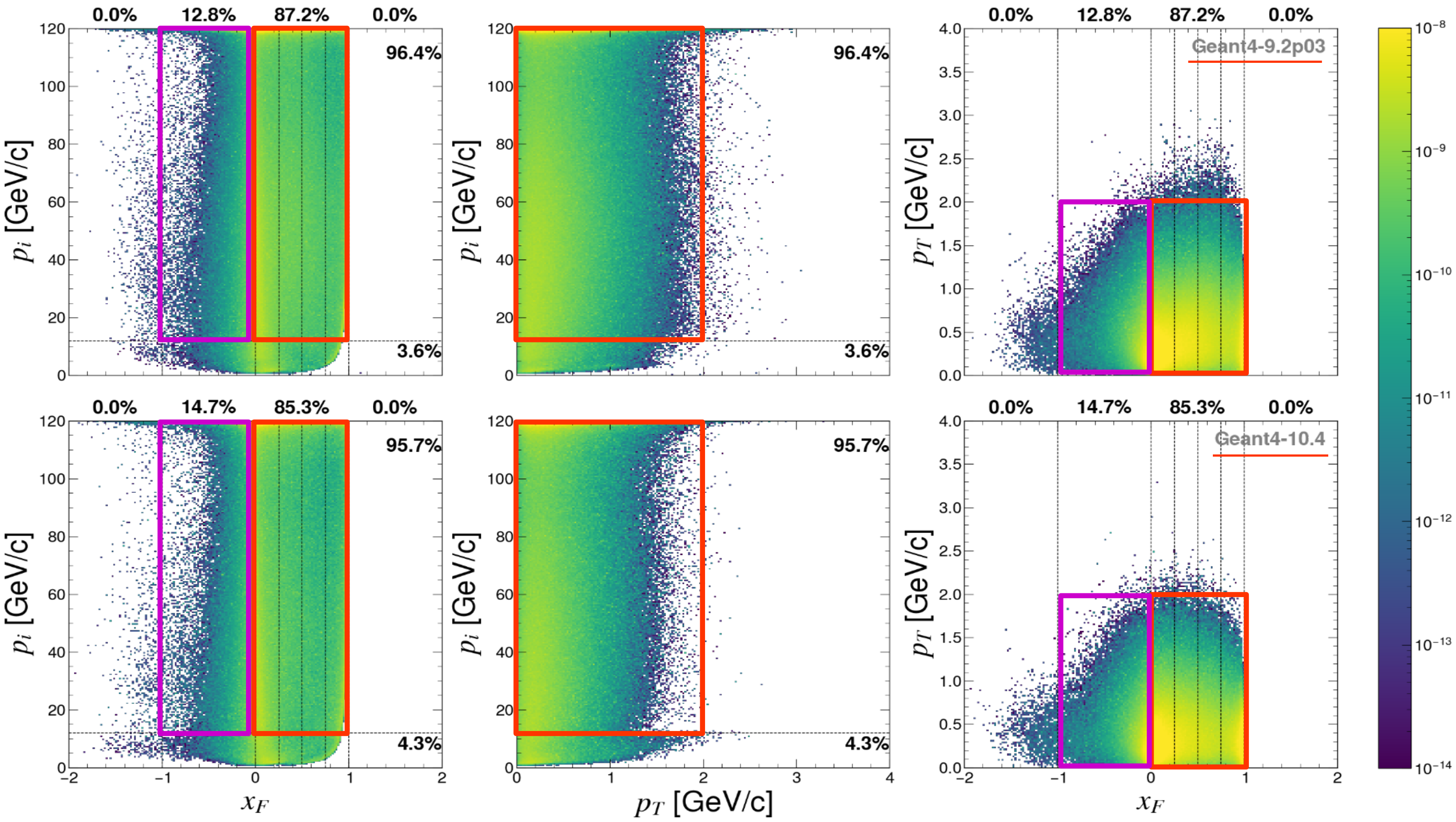


Flux Uncertainties



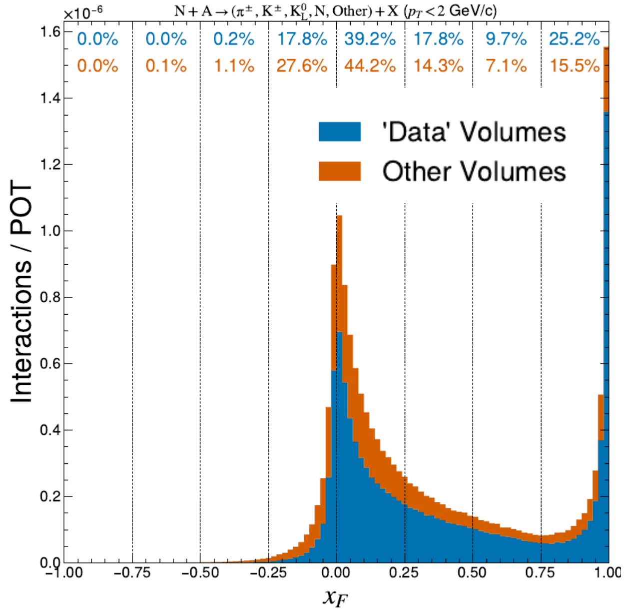
Flux Updates – GEANT4 Version

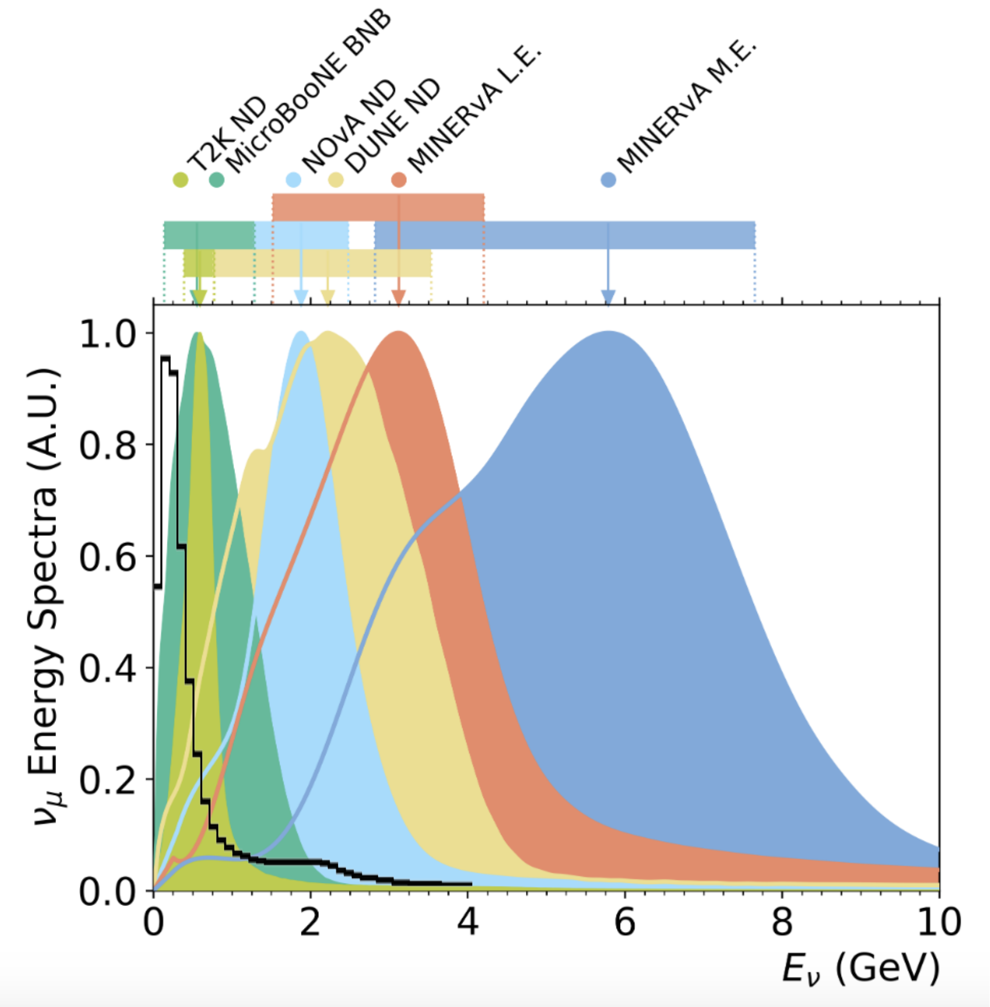
$N + A \rightarrow (N, \pi^{\pm}, K^{\pm}, \text{Other}) + X$ (All Volumes)



Data Coverage Regions

Previously Missing Uncertainties




T2K ND
MicroBooNE BNB
NOvA ND
DUNE ND
MINERvA L.E.
MINERvA M.E.
ν_μ Energy Spectra (A.U.)
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
E_ν (GeV)

Selecting a 1μNp Sample

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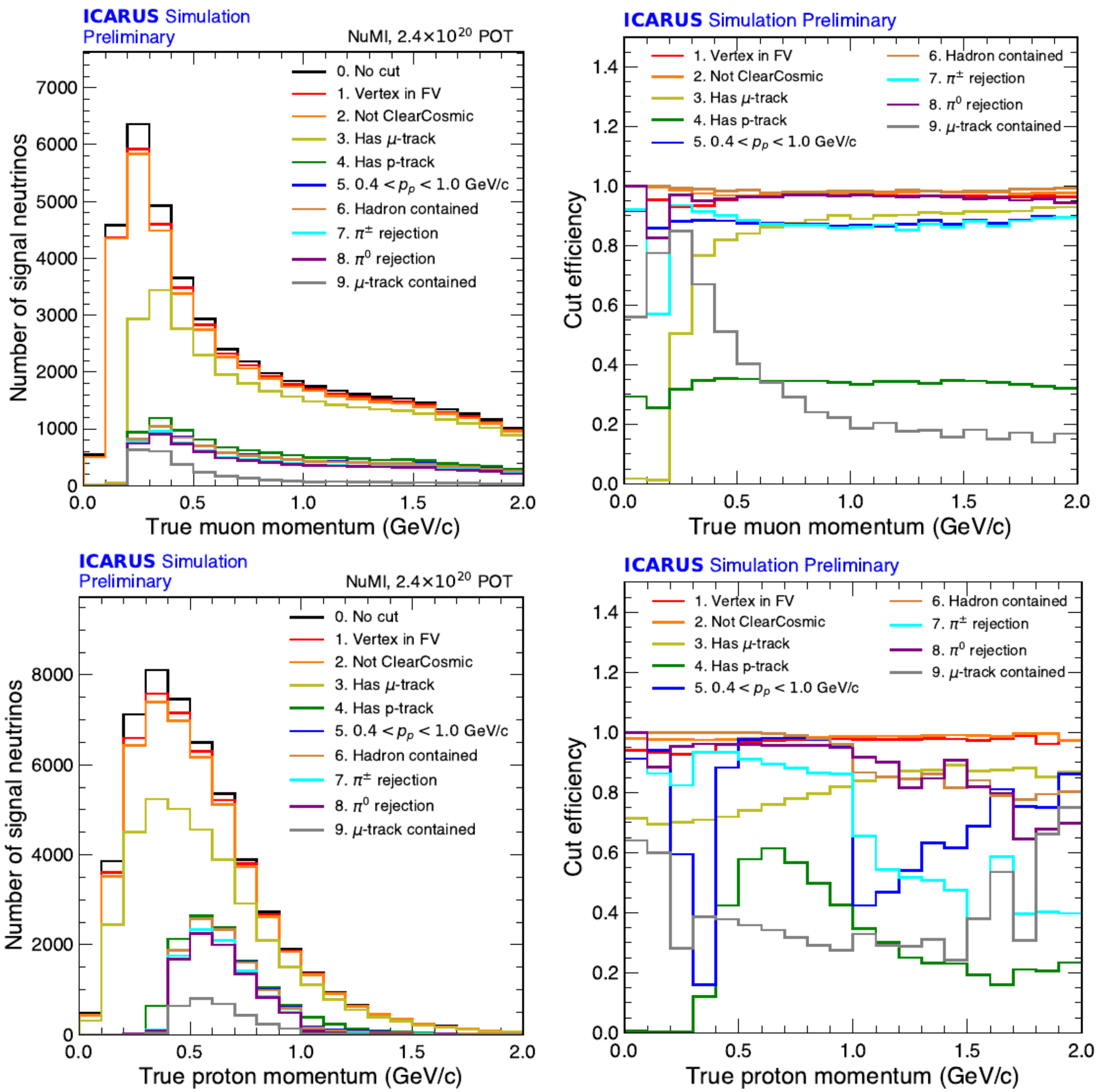

Signal phase space requirements:

- Charged current ν_μ
- Exactly 1true μ with
  - $P_\mu > 226$ MeV
- Any number of nucleons
- A 'leading' (post FSI) proton with
  - $p_p > 400$ MeV
  - $p_p < 1000$ MeV
- No (post FSI) mesons
- No FS photons > 10 MeV

Backgrounds and Systematics

- Detector Systematics
  - Front induction plane gain and noise
  - Front induction plane signal shape
  - Middle induction plane shape
  - Space-charge effects
  - Diffusion model parameter variations
  - Calibration
  - Particle reinteractions

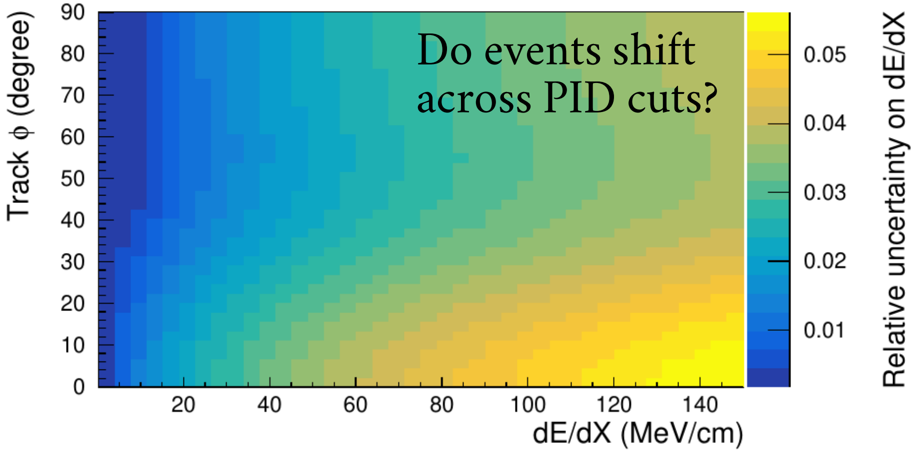

Table 1: List of GENIE dials used in the analysis.

Dial name	Short description	Central value	$+1\sigma$	-1σ
ZExpA1CCQE	$A1$ parameter of Z-expansion description of the axial-vector form factor on CCQE	2.30	14%	14%
ZExpA2CCQE	$A2$ parameter of Z-expansion description of the axial-vector form factor on CCQE	-0.6	67%	67%
ZExpA3CCQE	$A3$ parameter of Z-expansion description of the axial-vector form factor on CCQE	-3.8	100%	100%
ZExpA4CCQE	$A4$ parameter of Z-expansion description of the axial-vector form factor on CCQE	2.3	75%	75%
RPA_CCQE	RPA suppression is turned on (off) for dial=0 (1). Dials ouside $[0,1]$ is allowed.	—	—	—
CoulombCCQE	The strength of the electromagnetic potential for the Coulomb corrections on CCQE	1	20%	20%
VecFFCCQEshape	dial=1 for the reweight from BBBA07 to dipole.	—	—	—
NormCCMEC	Normalization of CC-MEC	1	50%	50%
NormNCMEC	Normalization of NC-MEC	1	50%	50%
DecayAngMEC	dial=1 gives an alternative distribution proportional to $\cos\theta^2$	—	—	—
MaCCRES	Axial-vector mass of the dipole form factor on CCRes	1.088962	20%	20%
MvCCRES	Vector mass of the dipole form factor on CCRes	0.840	10%	10%
MaNCRES	Axial-vector mass of the dipole form factor on NCRes	1.088962	20%	20%
MvNCRES	Vector mass of the dipole form factor on NCRes	0.840	10%	10%
RDecBR1gamma	Scale factor for the branching fraction of $X+\gamma$	1	50%	50%
RDecBR1eta	Scale factor for the branching fraction of $X+\eta$	1	50%	50%
Theta_Delta2Npi	dial=1 for the reweight from isotropic to R/S prediction for the π angular distribution from $\Delta\to N+\pi$	—	—	—
ThetaDelta2NRad	dial=1 for the reweight from isotropic to $\cos\theta^2$ for the γ angular distribution from $\Delta\to N+\gamma$	—	—	—
NonRESBGvpNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-p NC + 1π	1	50%	50%
NonRESBGvpNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-p NC + 2π	1	50%	50%
NonRESBGvpNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-p NC + 1π	1	50%	50%
NonRESBGvpNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-p NC + 2π	1	50%	50%
NonRESBGvnNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-n NC + 1π	1	50%	50%
NonRESBGvnNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-n NC + 2π	1	50%	50%
NonRESBGvnNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-n NC + 1π	1	50%	50%
NonRESBGvnNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of ν-n NC + 2π	1	50%	50%
NonRESBGvbarpNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-p NC + 1π	1	50%	50%
NonRESBGvbarpNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-p NC + 2π	1	50%	50%
NonRESBGvbarpNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-p NC + 1π	1	50%	50%
NonRESBGvbarpNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-p NC + 2π	1	50%	50%
NonRESBGvbarnNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-n NC + 1π	1	50%	50%
NonRESBGvbarnNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-n NC + 2π	1	50%	50%
NonRESBGvbarnNC1pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-n NC + 1π	1	50%	50%
NonRESBGvbarnNC2pi	Scale factor for the non-resonance background level ($W<2\,\mathrm{GeV}/c^2$) of $\bar{\nu}$-n NC + 2π	1	50%	50%
AhtBY	A_{HT} higher twist parameter in BY model scaling ξ_W	0.538	25%	25%
BhtBY	B_{HT} higher twist parameter in BY model scaling ξ_W	0.305	25%	25%
CV1uBY	$C_{\nu 1u}$ u valence GRV98 PDF correction parameter in BY model	0.291	30%	30%
CV2uBY	$C_{\nu 2u}$ u valence GRV98 PDF correction parameter in BY model	0.189	40%	40%
NormCCCOH	Normalization of CC-COH	1	100%	100%
NormNCCOH	Normalization of MC-COH	1	100%	100%
MFP_pi	Scale factor for the mean free path in the FSI of π	1	20%	20%
FrCEx_pi	Scale factor for the fraction of charge-exchange fate in the FSI of π	1	50%	50%
FrInel_pi	Scale factor for the fraction of inelastic scattered fate in the FSI of π	1	40%	40%
FrAbs_pi	Scale factor for the fraction of absorption fate in the FSI of π	1	30%	30%
FrPiProd_pi	Scale factor for the fraction of pion production fate in the FSI of π	1	20%	20%
MFP_N	Scale factor for the mean free path in the FSI of nucleon	1	20%	20%
FrCEx_N	Scale factor for the fraction of charge-exchange fate in the FSI of nucleon	1	50%	50%
FrInel_N	Scale factor for the fraction of inelastic scattered fate in the FSI of nucleon	1	40%	40%
FrAbs_N	Scale factor for the fraction of absorption fate in the FSI of nucleon	1	20%	20%
FrPiProd_N	Scale factor for the fraction of pion production fate in the FSI of nucleon	1	20%	20%
MaNCEL	Axial-vector mass of the dipole form factor on NCEL	0.994989	25%	25%
EtaNCEL	Strange axial-vector mass of the dipole form factor on NCEL	0.12	30%	30%