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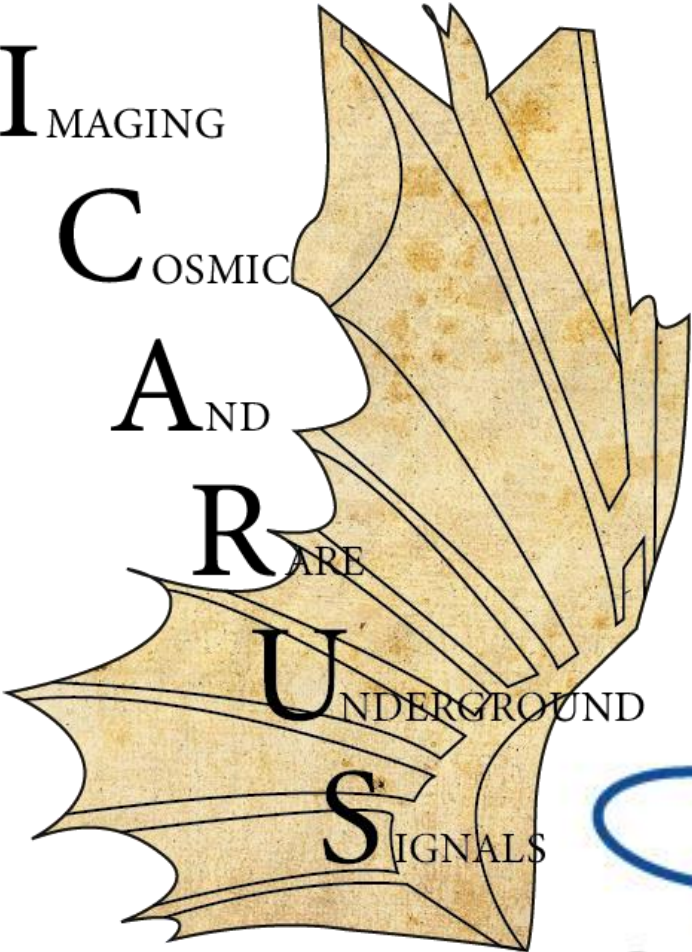
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SBN



Searches for New Physics with the NuMI Beam at ICARUS

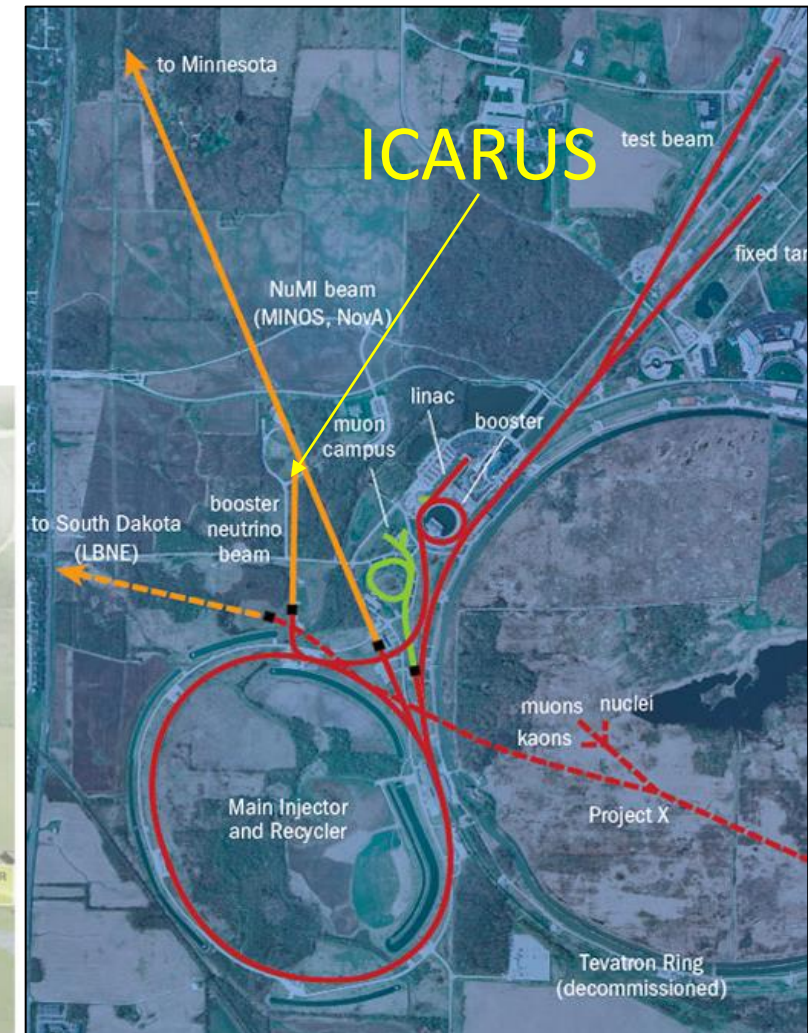
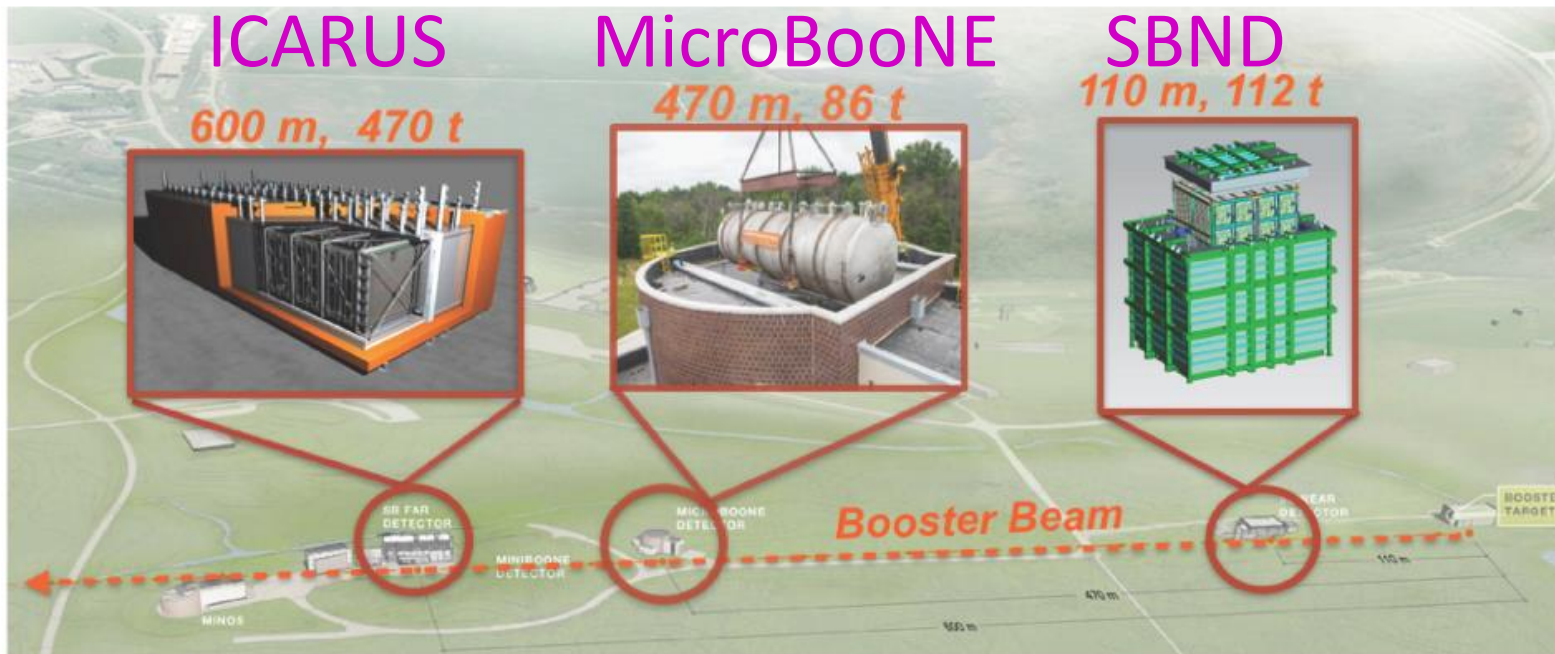
GRAY PUTNAM

UNIVERSITY OF CHICAGO



ICARUS and SBN at Fermilab

- ICARUS is the Far Detector in the Short-Baseline Neutrino (SBN) program
- SBN program physics:
 - eV-scale sterile neutrino search
 - GeV-scale neutrino cross section measurements
 - **Single Detector BSM physics searches**



The ICARUS Detector at Fermilab

TPC



Top
CRT



Side
CRT



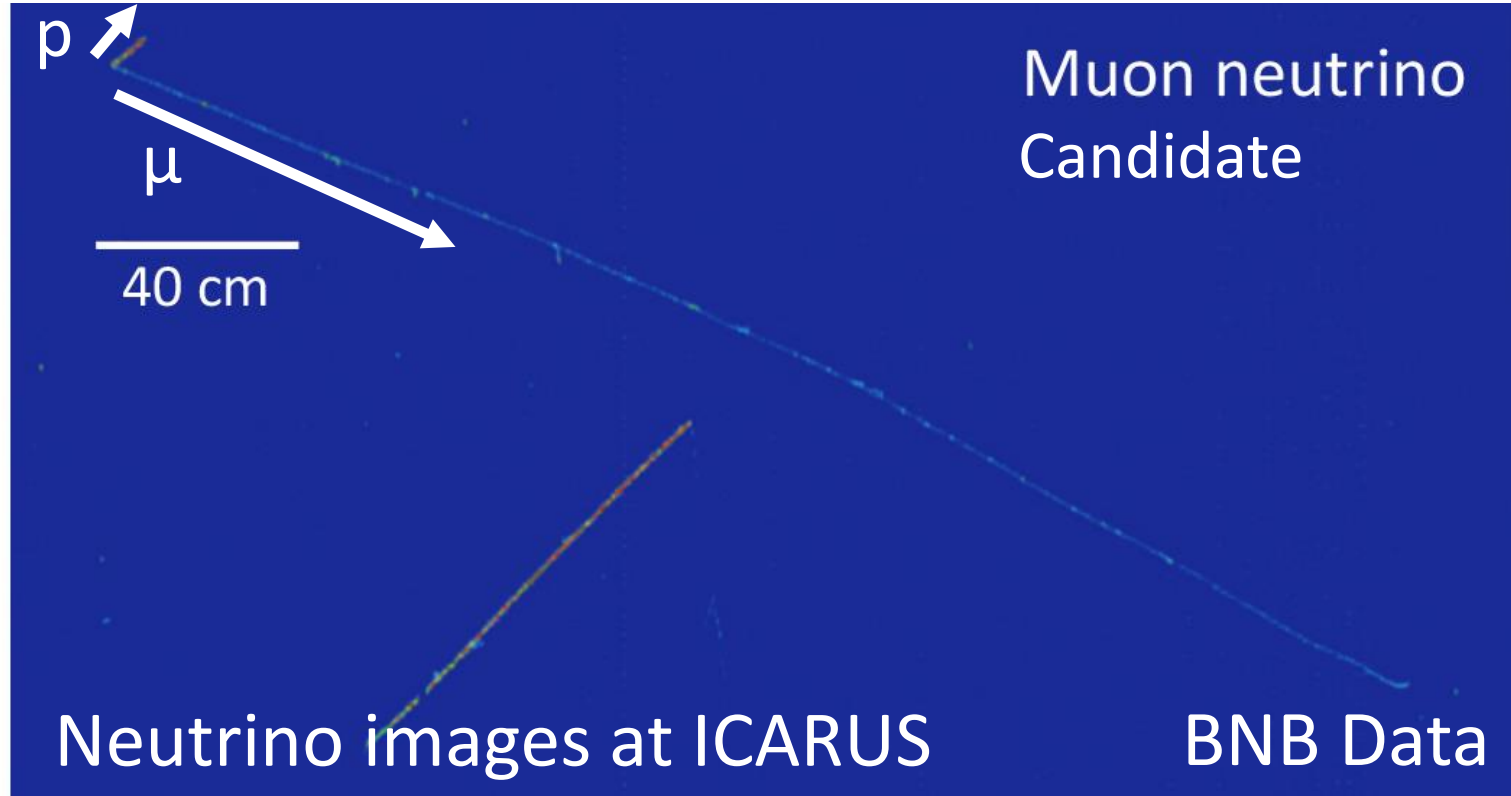
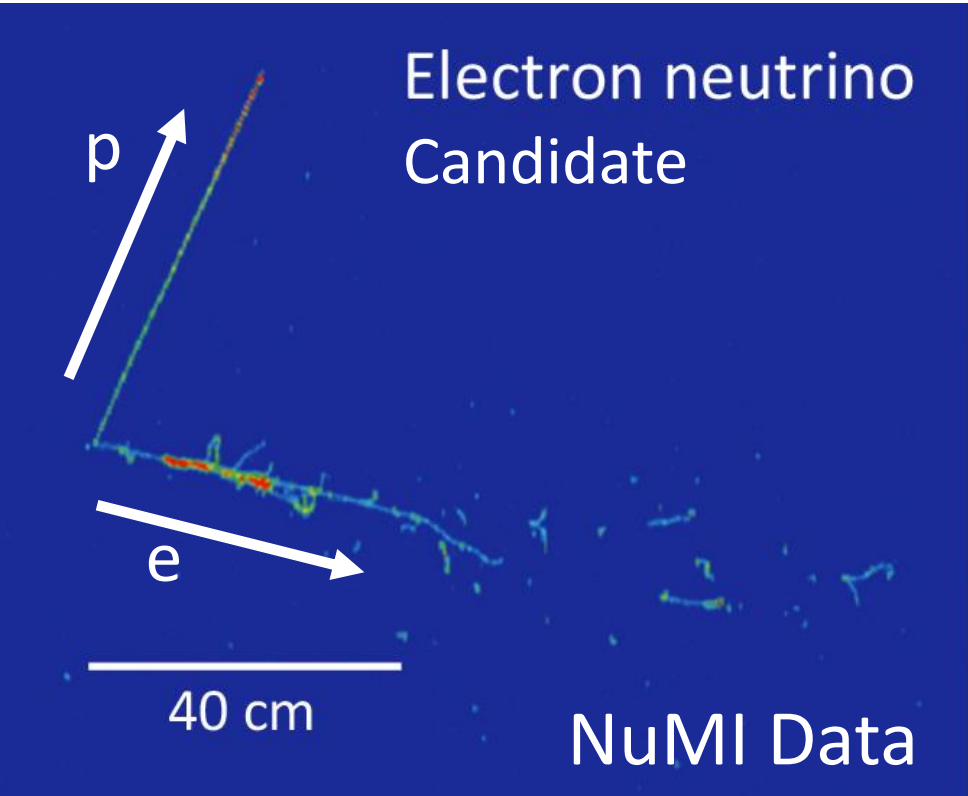
Cryostat before overburden, CRT installation

PMTs



- 2 modules each with two TPCs, 1.5 m / 1 ms drift
- 3 readout wire planes, ~54k wires
- 360 8" PMTs
- Cosmic ray tagger: scintillator strips read out by SiPMs

Neutrino Images in ICARUS



<https://news.fnal.gov/2021/05/icarus-gets-ready-to-fly>

- ICARUS is now taking neutrino beam data

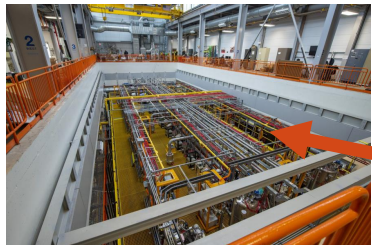


Image from one TPC inside each cryostat

ICARUS Detector Operation

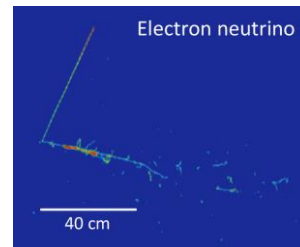
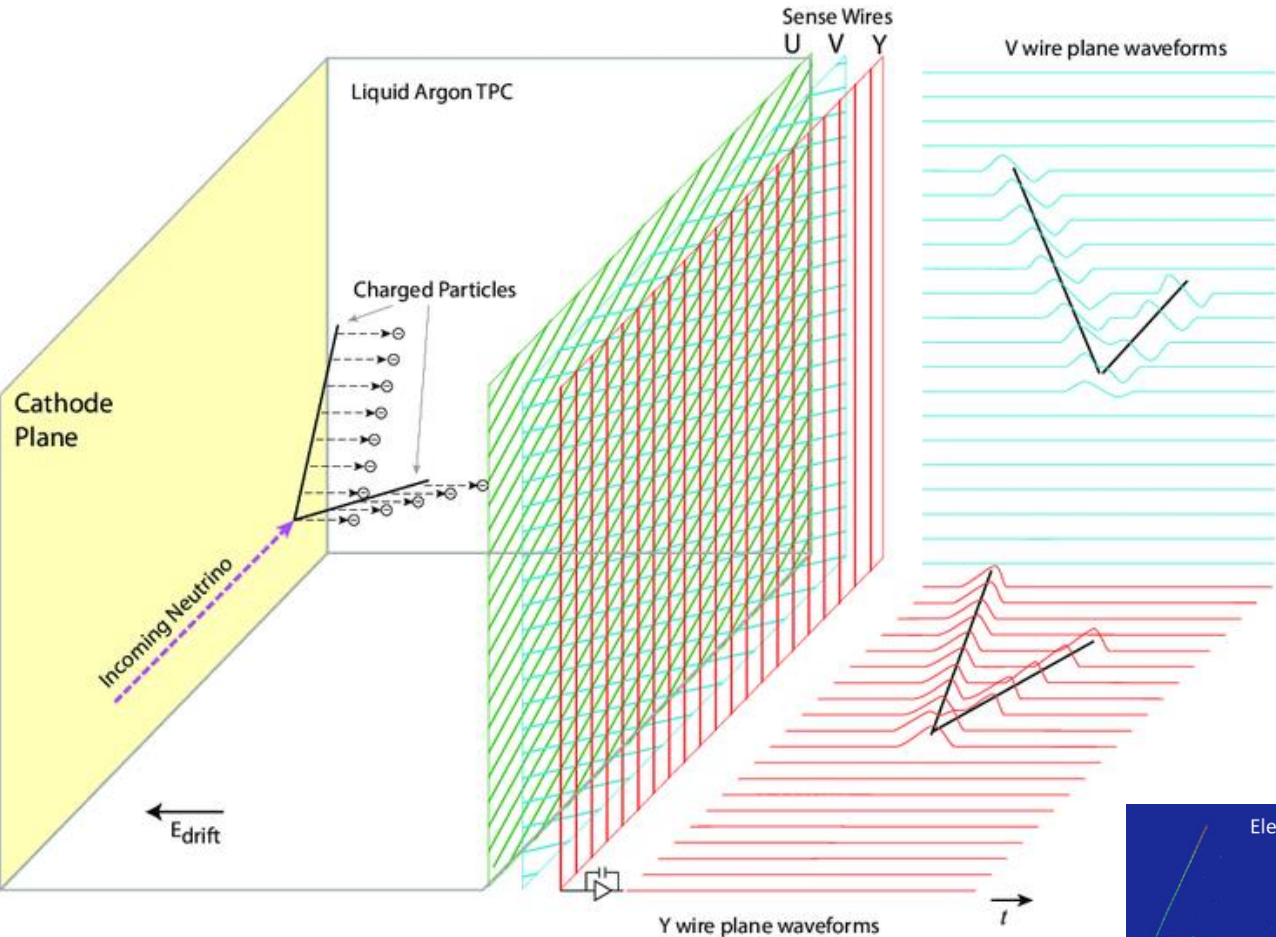
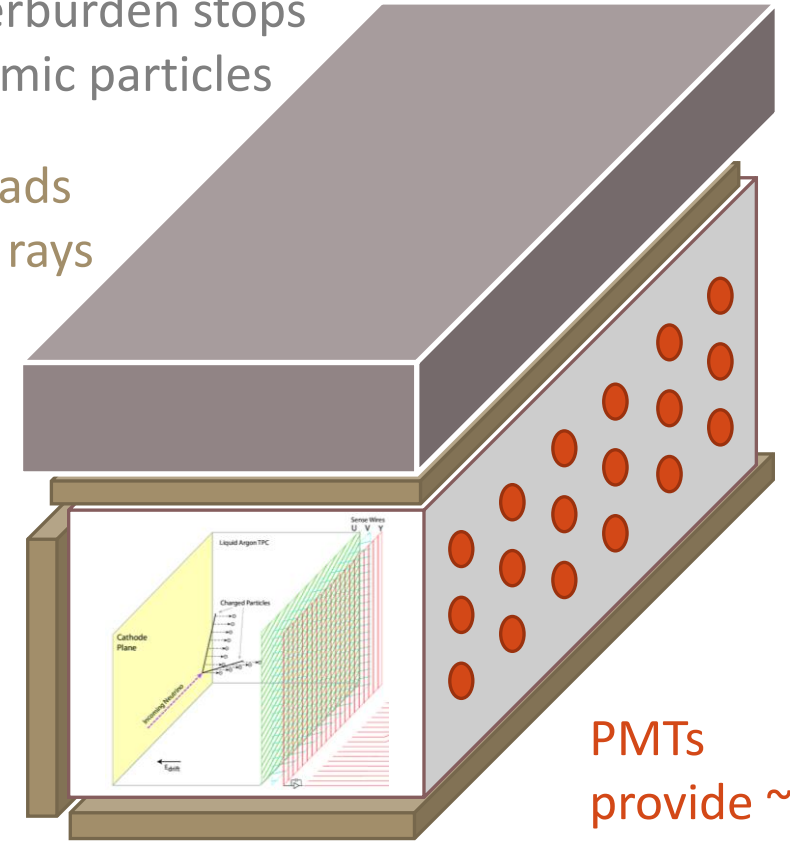
3m concrete overburden stops cosmic particles

Scintillator pads track cosmic rays (CRT)

Time projection chamber tracks particles with ~mm resolution

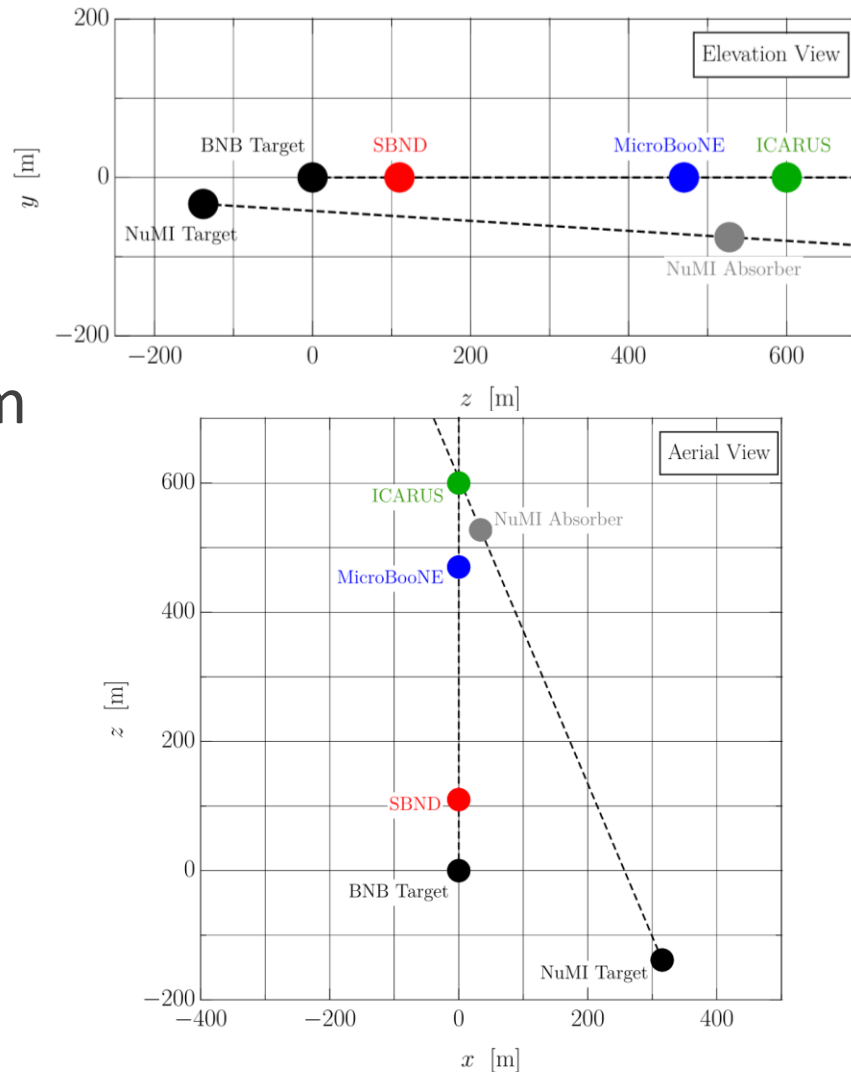
PMTs provide ~ns timing resolution

1 ICARUS Cryostat / Module

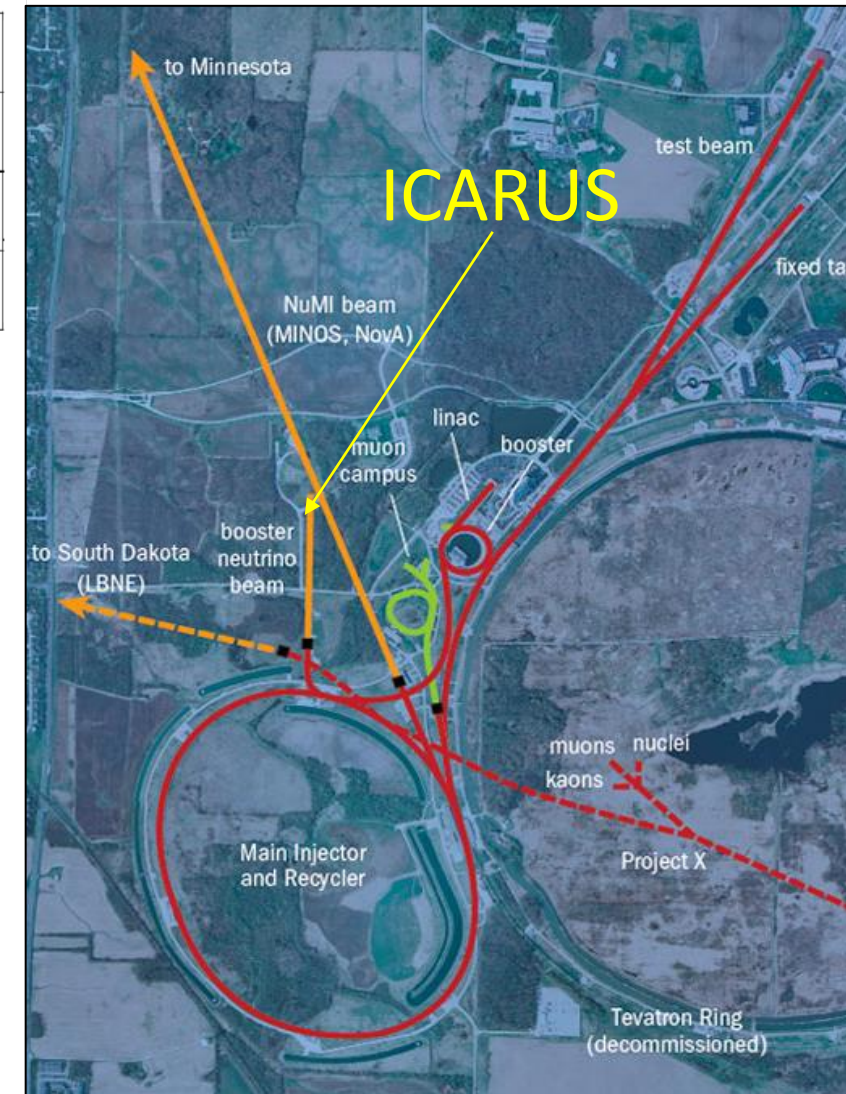


Two Neutrino Beams: NuMI and BNB

- ICARUS sits at the confluence of **two** neutrino beams!
- The Booster Neutrino Beam (BNB) enables the eV-scale sterile search
- The Neutrinos at the Main Injector (NuMI) beam is a higher energy + intensity beam slightly off-axis to ICARUS



Schematic View: Phys. Rev. D 100, 115039



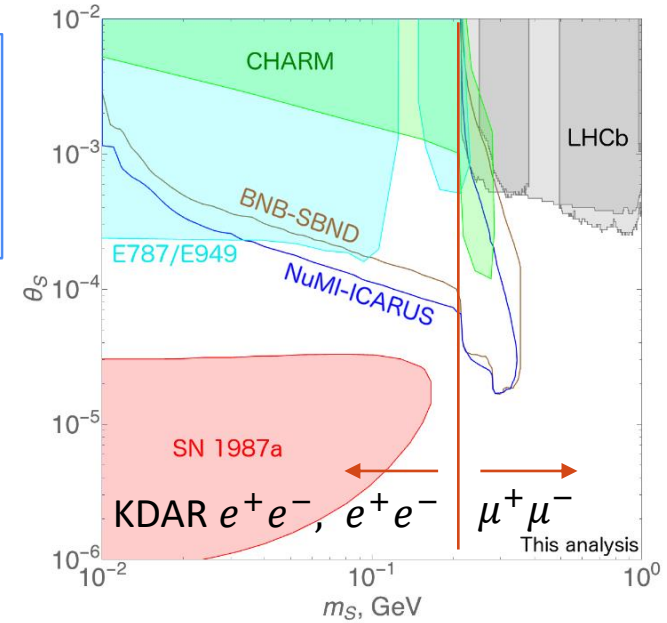
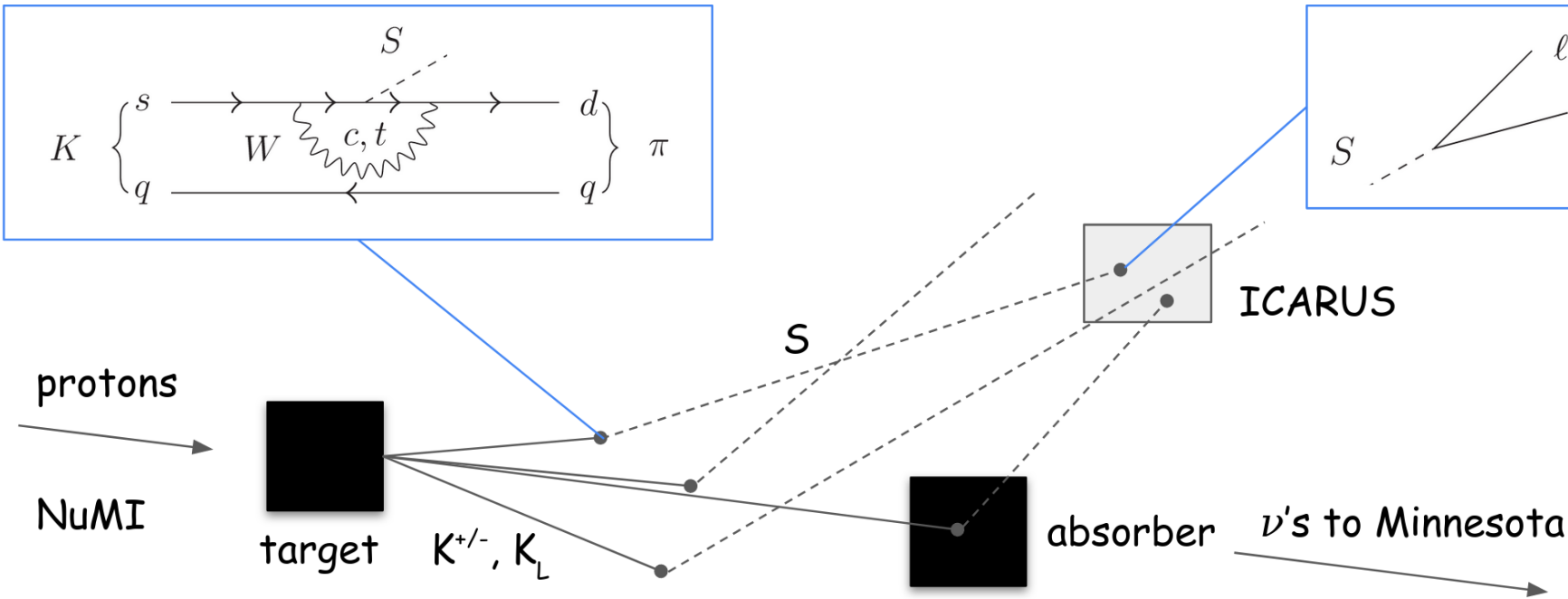
Searches for New Physics at ICARUS

- A few single-detector searches are being developed at ICARUS, focused on the NuMI beam

Final State	Sensitive Physics
$\mu^+ \mu^-$	Scalar Portal / Dark Higgs, others
$e^+ e^-$	
KDAR $e^+ e^-$	
Forward e	Vector Portal / Dark Photon DM

- In this talk I will cover the analyses that are currently being pursued and the event generation tools developed to support them

BSM Physics: Scalar / Higgs Portal

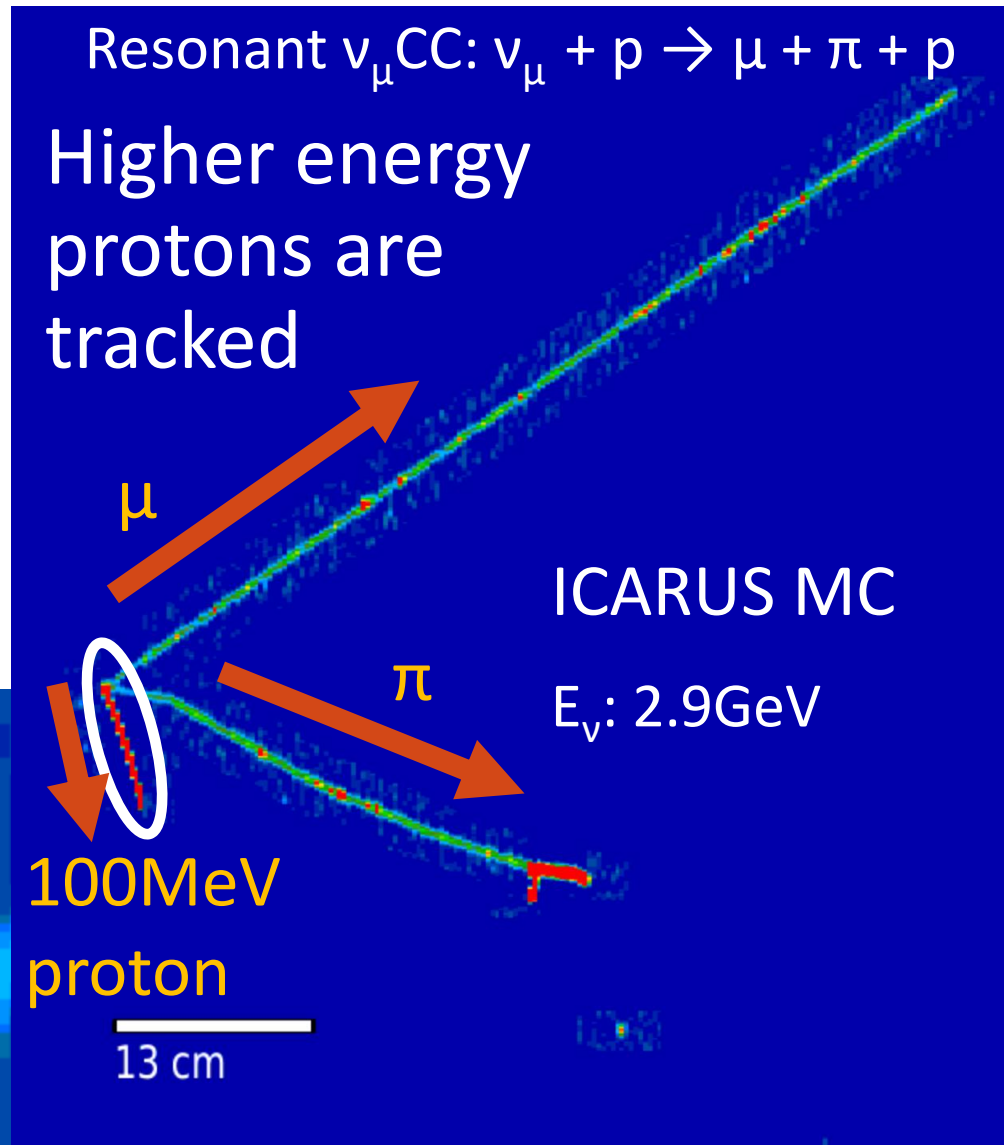
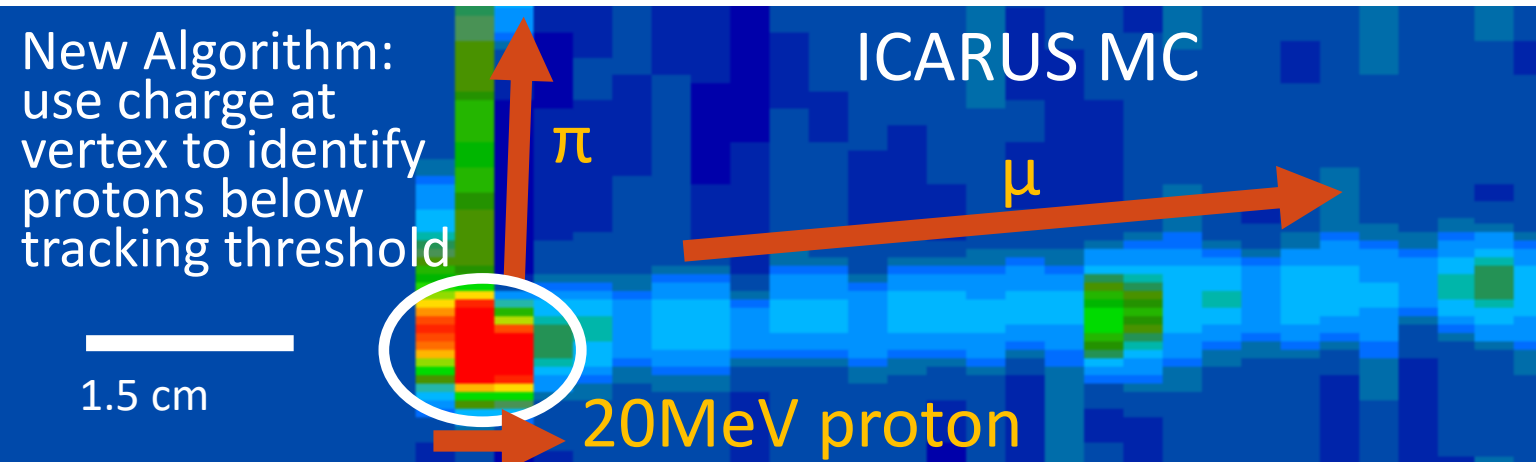


Estimated sensitivity from:
Phys. Rev. D 100, 115039

- In the Higgs Portal, there is a new scalar with couplings to the SM through a small mixing with the SM Higgs
- This scalar would be produced in Kaon decay when $M_s < m_K - m_\pi$

$\mu^+ \mu^-$: Rejecting the Neutrino Background

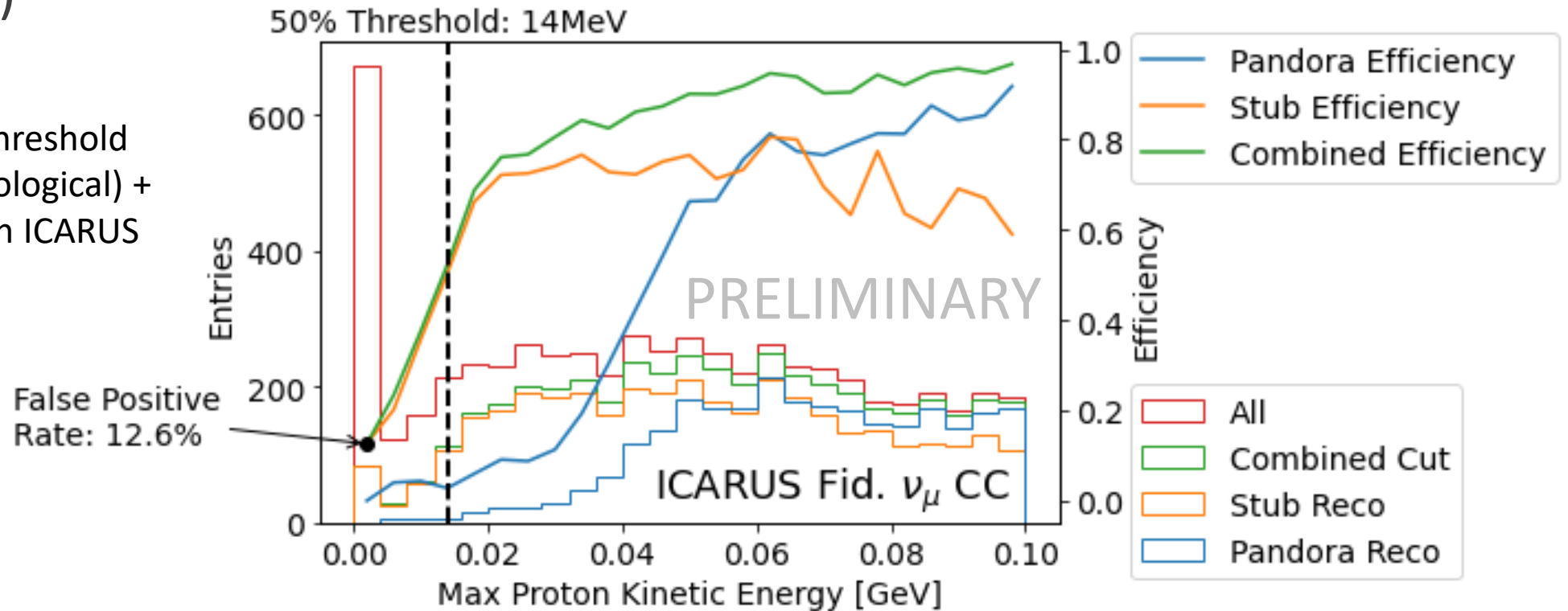
- Neutrino interactions with a pion and a muon represent a background
 - It is not possible to tell apart muons from pions in LAr in all cases
- Most such interactions also produce a proton
 - Protons are tracked down to about 50 MeV
 - Flagging charge at vertex lowers this to ~ 15 MeV



Low Energy Proton Identification w/ Charge

Performance on ICARUS MC demonstrates a much lower proton identification energy threshold than topological reconstruction (Pandora)

Proton identification threshold applying Pandora (topological) + Stubs (charge-based) in ICARUS on BNB neutrino MC



$\mu^+ \mu^-$: Rejecting the Neutrino Background

- But a few such neutrino interactions do not produce a proton
- Many of these can be rejected from scalar kinematics

Coherent-Pion ν_μ CC: $\nu_\mu + \text{Ar} \rightarrow \mu + \pi + \text{Ar}$

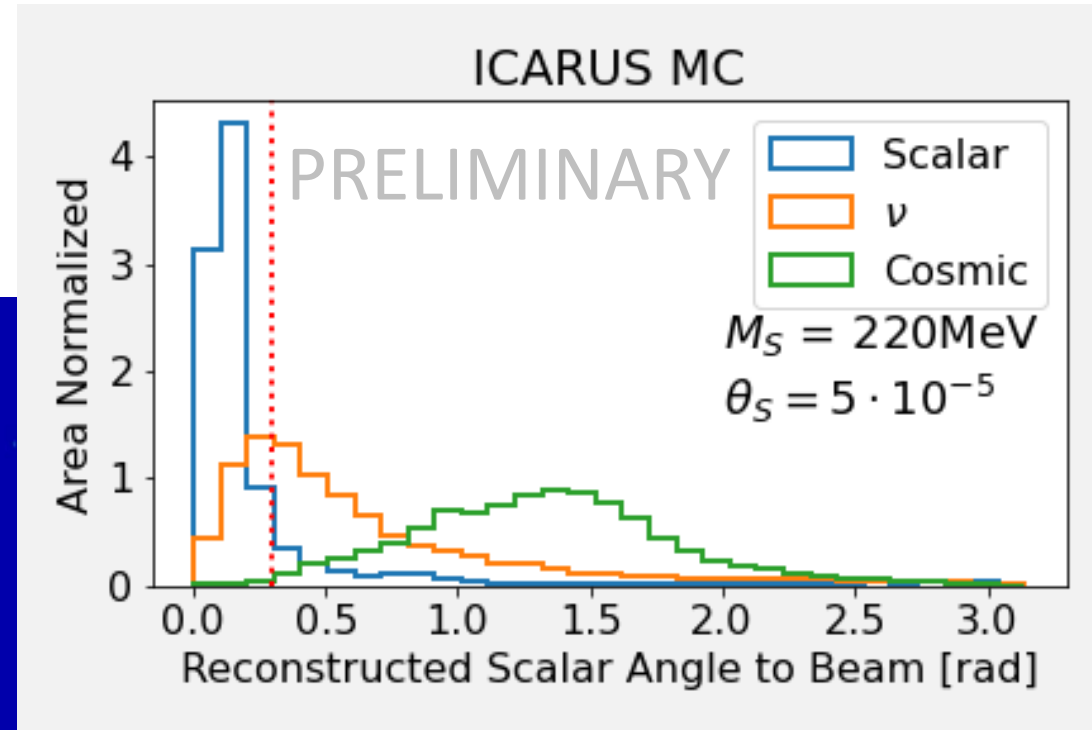
ICARUS MC

$E_\nu: 2.7\text{GeV}$

π

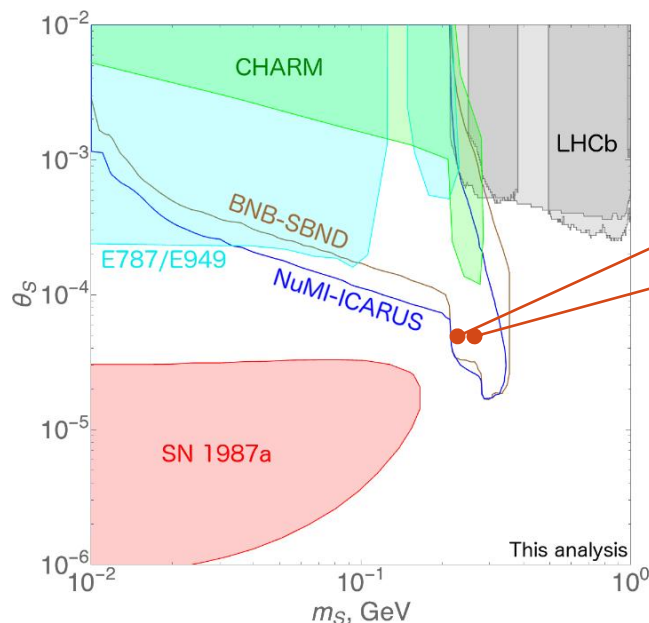
μ

30 cm

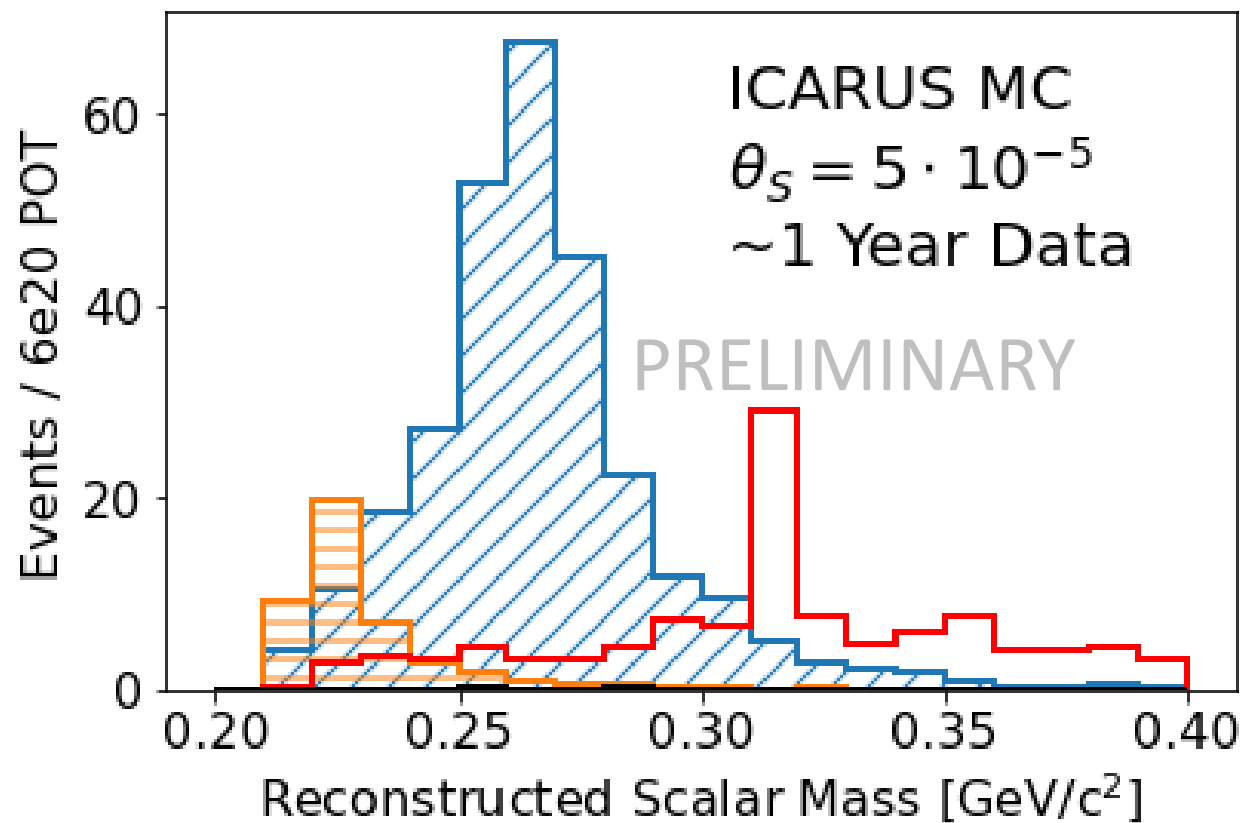
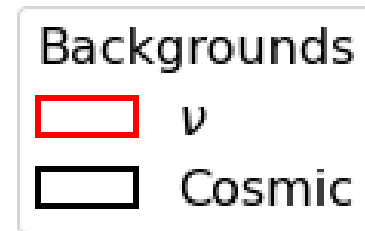
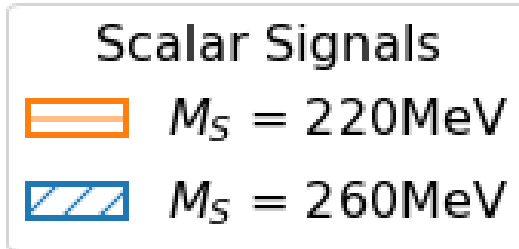


Nucleon fermi momentum and mis-reconstruction smears the reconstructed neutrino direction to beam.

Scalar Portal $\mu^+ \mu^-$ Analysis



Estimated sensitivity from:
Phys. Rev. D 100, 115039

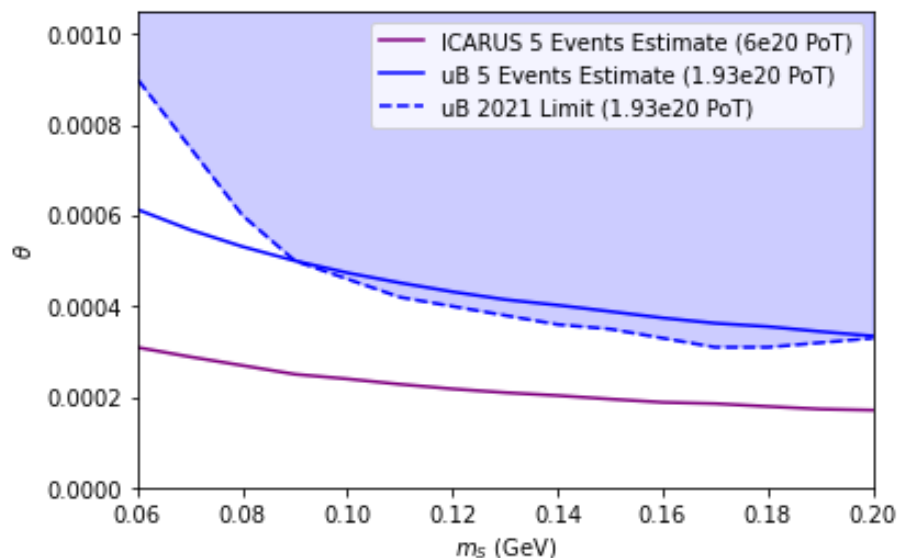


- Early indication from simulation:
 - 100% cosmic rejection
 - >99% neutrino rejection
 - ~40% signal efficiency above 1GeV

Scalar Portal: e^+e^- Analyses

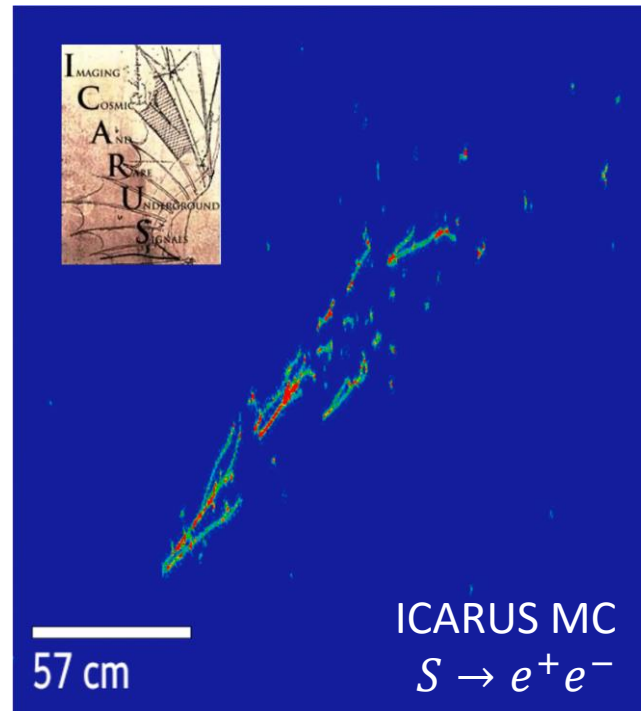
KDAR (Kaon-Decay-At-Rest) Signal:

- Distinctive mono-energetic signal of scalars from at rest Kaons in the NuMI absorber
- Previous uB analysis
 - *Phys.Rev.Lett.* 127 (2021) 15, 151803
- ICARUS should improve due to larger size, possible run time



KDIF (Kaon-Decay-In-Flight) Signal:

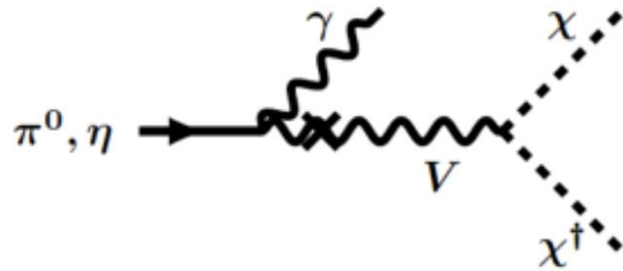
- Example event display:



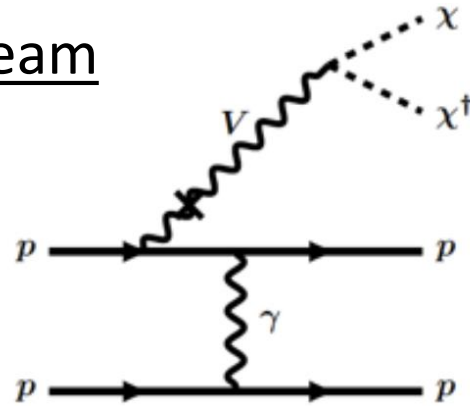
- ML based reconstruction techniques are being pursued to identify columnated shower pairs

Vector Portal: Forward e

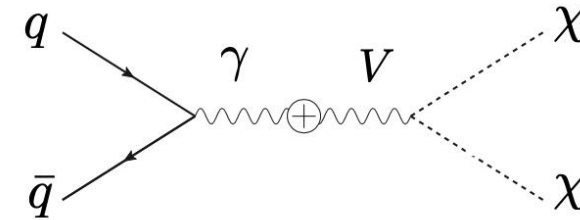
Production of Dark Matter Beam



Neutral mesons decays



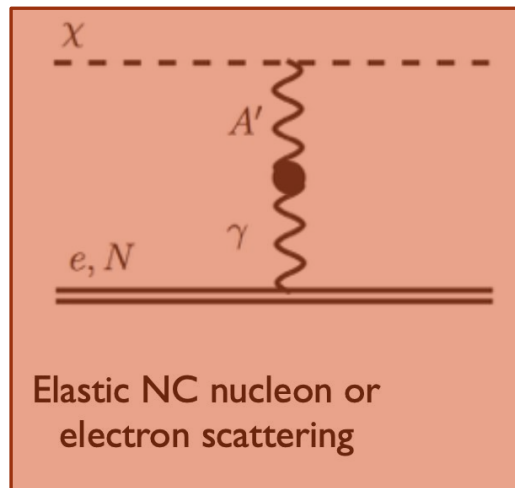
Bremsstrahlung + vector meson mixing



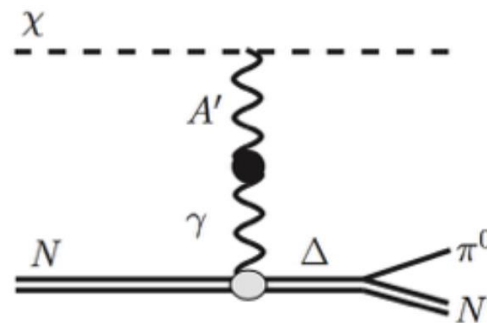
Direct production

Scattering in Detector

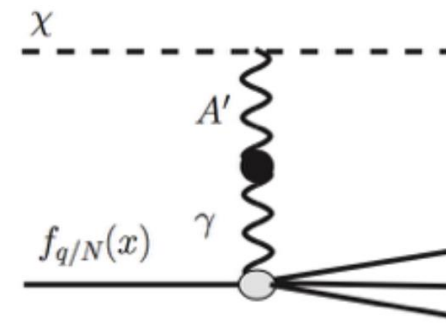
Elastic scattering off electrons is a promising low background channel.



Elastic NC nucleon or electron scattering



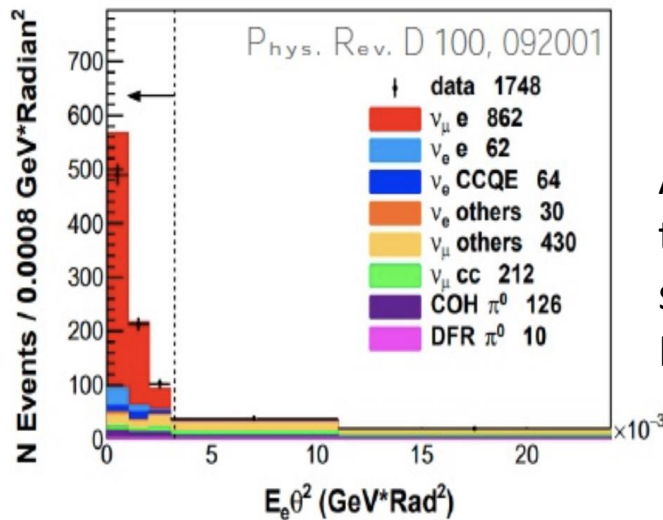
Inelastic NC neutral pion-like scattering



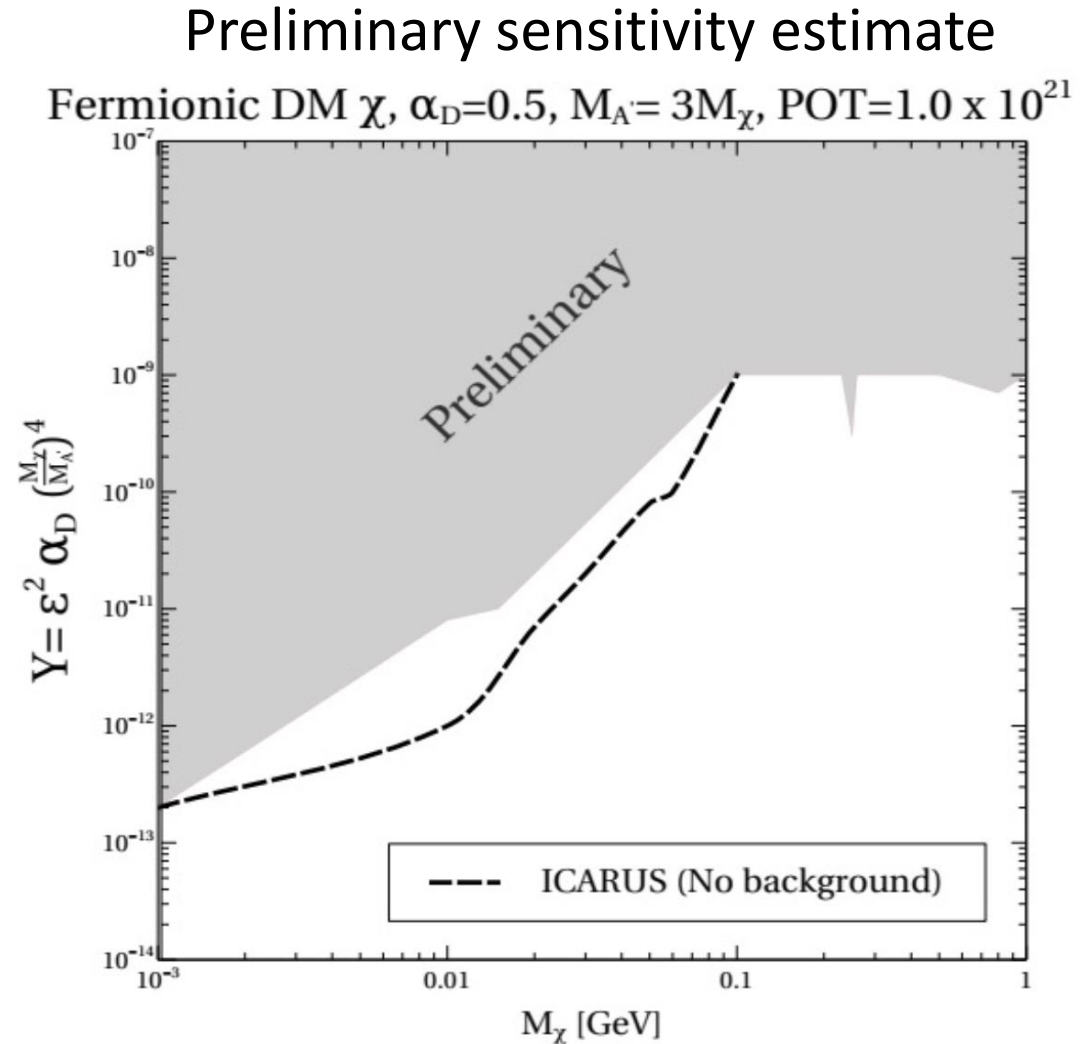
Deep Inelastic scattering

Vector Portal: Forward e

- Work ongoing to understand / mitigate neutrino background
- Timing is a very promising handle (1-2 ns resolution expected from PMTs)
- Can also apply kinematics, use techniques from $\nu - e$ scattering (such as $E_e \theta^2$)



Application of $E_e \theta^2$ to select for $\nu - e$ scattering events in MINERvA



Outlook

- ICARUS is a large (~ 500 t) detector taking data now with the (120 GeV) NuMI beam
- This physics data will be sensitive to a variety of new physics models
- Currently we are focusing on the e^+e^- , forward e , and $\mu^+\mu^-$ channels for new physics
- Searching for new physics in these channels requires / spurs development of new experimental techniques
 - Ex: low-energy proton ID
 - Something we are considering now: how to identify new physics when the neutrino background is small but non-zero?

Generation Tools

Generation Tools at ICARUS

- Getting events from new physics models into detector MC is a necessary step in analysis
- Generation tools should:
 - Generate on command
 - Make unweighted events
 - Re-use existing code where possible (modular)

Detector Monte-Carlo Generation Stages



- Solution we have on ICARUS (and SBND) to support a few analyses: MeVPrtl generator
 - <https://github.com/SBNSoftware/sbncode/tree/develop/sbncode/EventGenerator/MeVPrtl>

MeVPrtl: Modular Event Generation

Step

Example Implementations

MesonGen: Get meson

NuMIKaonGen

BNBKaonGen

NuMIEtaGen

Per-beam,
Per-particle

MeVPrtlFlux: Decay meson
into “portal” particle

Kaon2Scalar

Tau2HNL

...others

Per-model

RayTrace: Transport particle
to detector

WeightedRayTrace

Universal

MeVPrtlDecay: decay back
to SM

MakeScalarDecay

MakeHNLDecay

Per-model

MeVPrtl: Ray Trace Weighting

- Naively weighting the (massive) “portal” particle to hit the detector can lead to singular weights in the Monte-Carlo

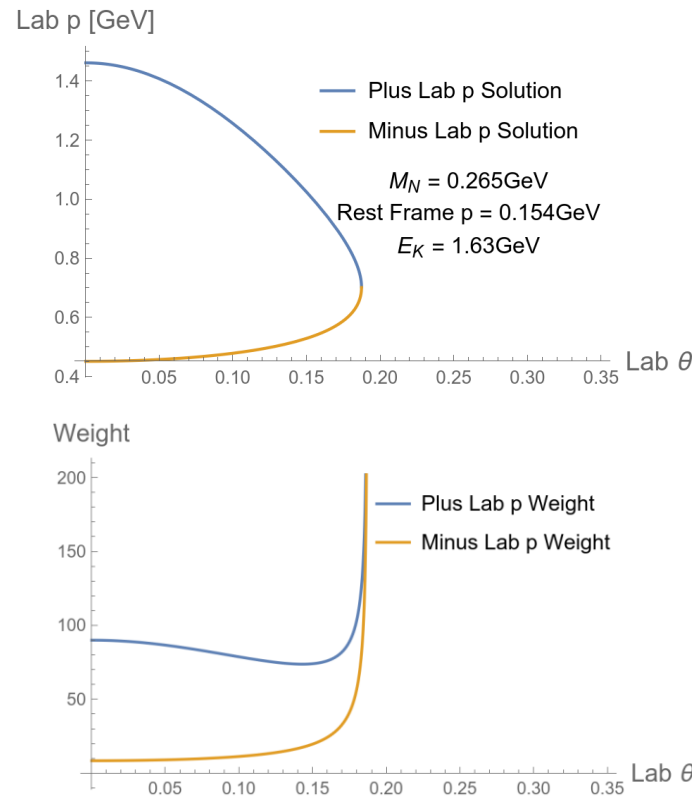
Intersection probability: $p_{int} = \frac{1}{4\pi} \int_D d\Omega'$



Pick (θ, ϕ) for “portal” particle

$$\int_D d\Omega' \rightarrow \int_D \frac{d\Omega'}{d\Omega} d\Omega$$

Singularity when the meson lab frame velocity is faster than the “portal” velocity in the meson rest frame



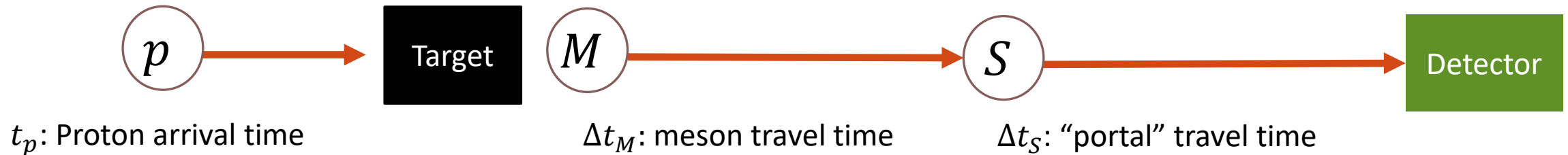
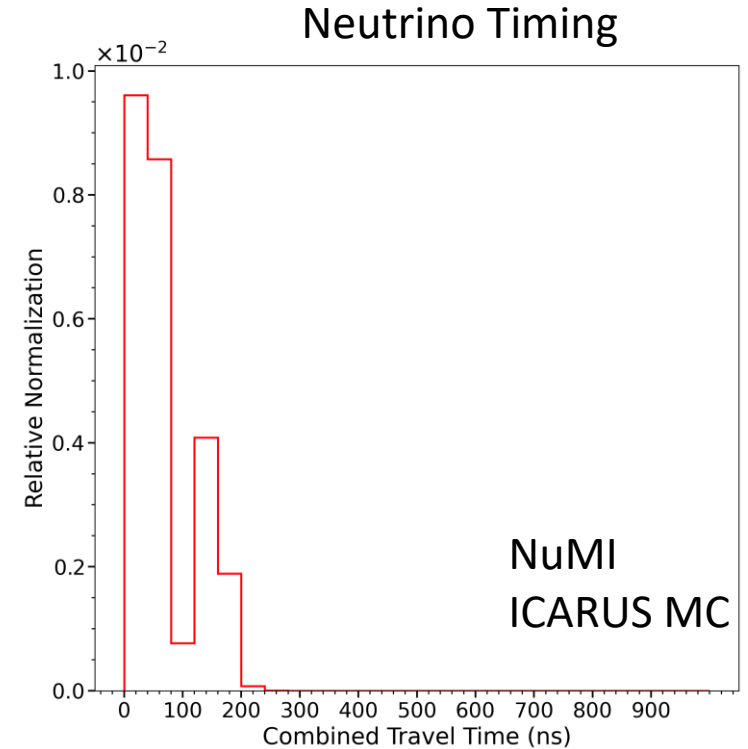
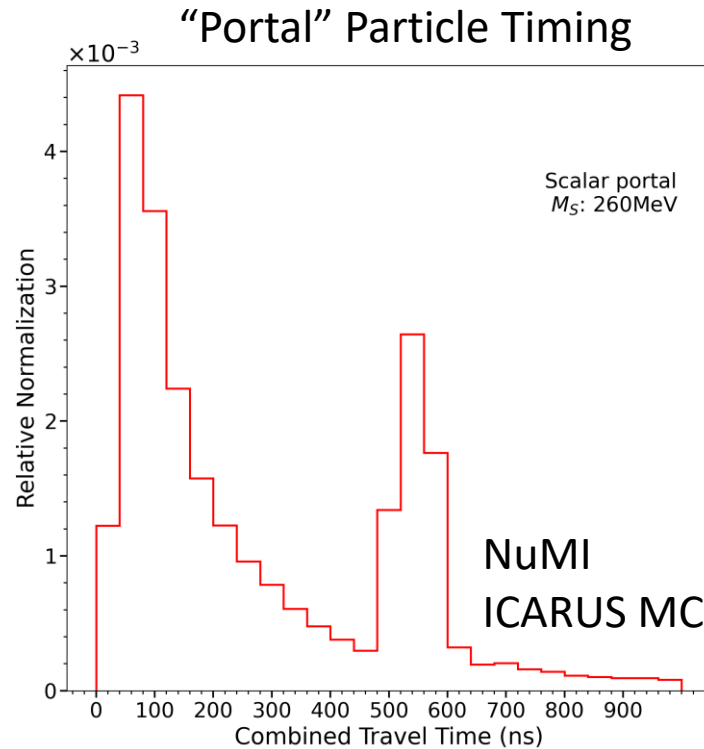
Pick (θ', ϕ) for “portal” particle

$$\int_D d\Omega' \rightarrow \int_D \frac{d\phi'}{d\phi} d\phi d\theta'$$

No singularity

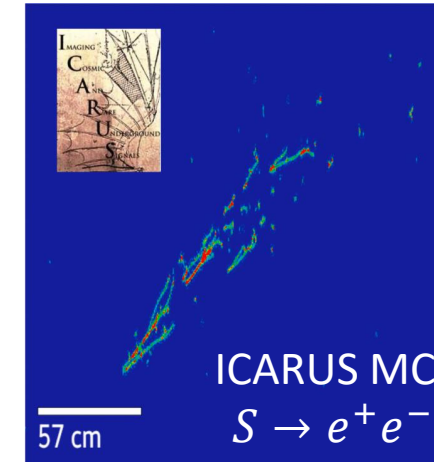
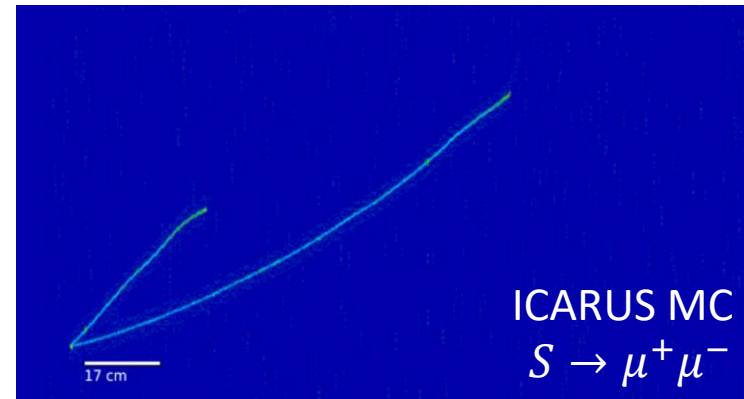
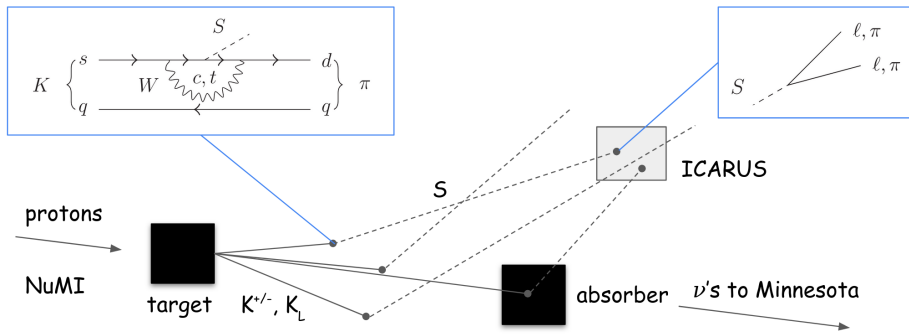
MeVPrtl: Event Timing

- Event timing is a promising handle to select for heavy particle interactions against the neutrino background
- To simulate this correctly, it is necessary to go from the proton arrival time to the particle travel time

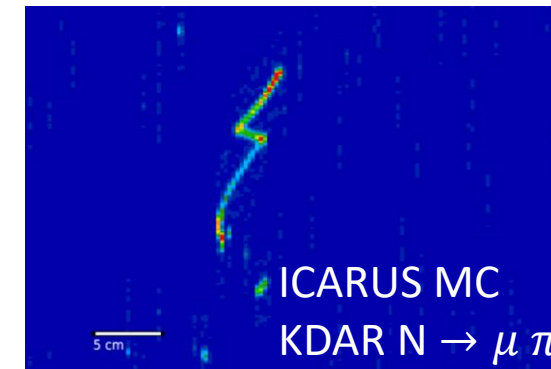
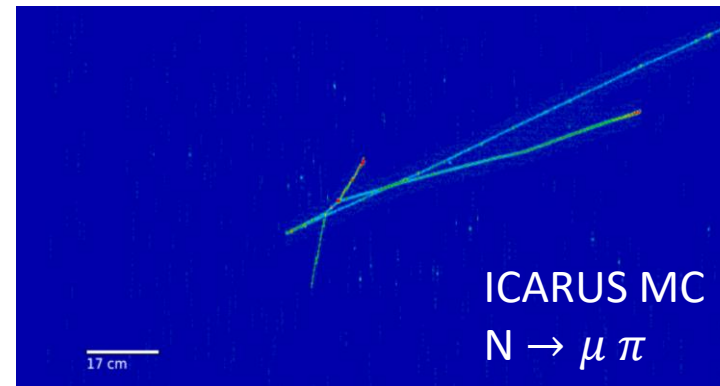
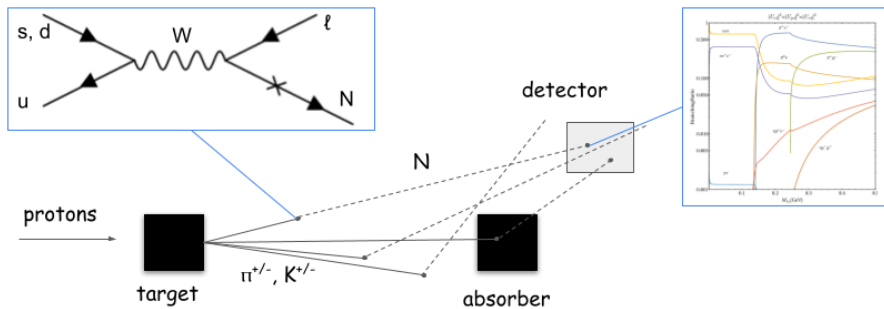


Example Models in MeVPrtl

Higgs Portal



Heavy Neutral Lepton

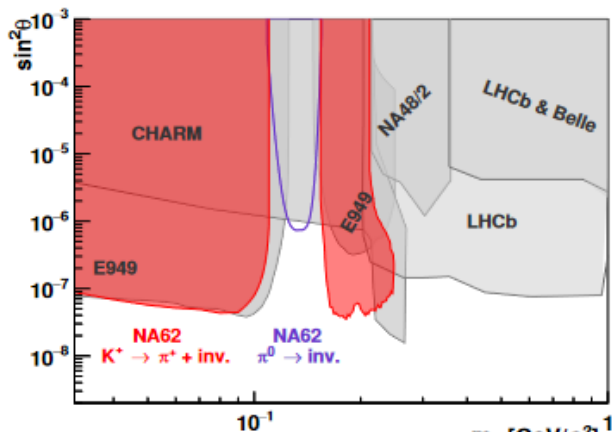


- We are also looking into integrating other models such as the heavy QCD axion

Conclusion

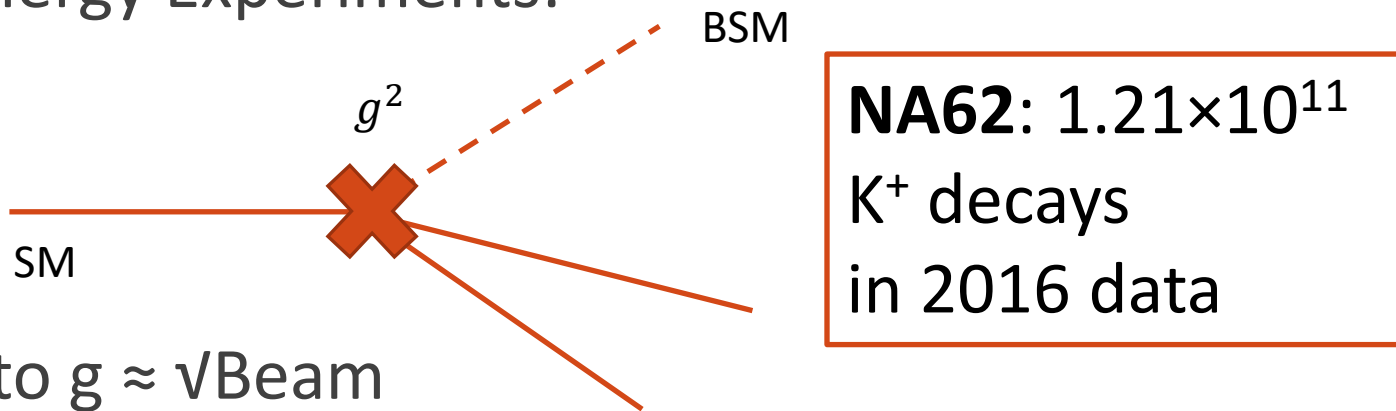
- ICARUS is a large (~ 500 t) detector taking data now with the (120 GeV) NuMI beam
- This physics data will be sensitive to a variety of new physics models
 - Many considerations can be taken from DUNE
- Currently we are focusing on the e^+e^- , forward e , and $\mu^+\mu^-$ channels for new physics
- These analyses are enabled by the “MeVPrtl” event generation tool

How Can ICARUS Compete with Kaon Decay Experiments?

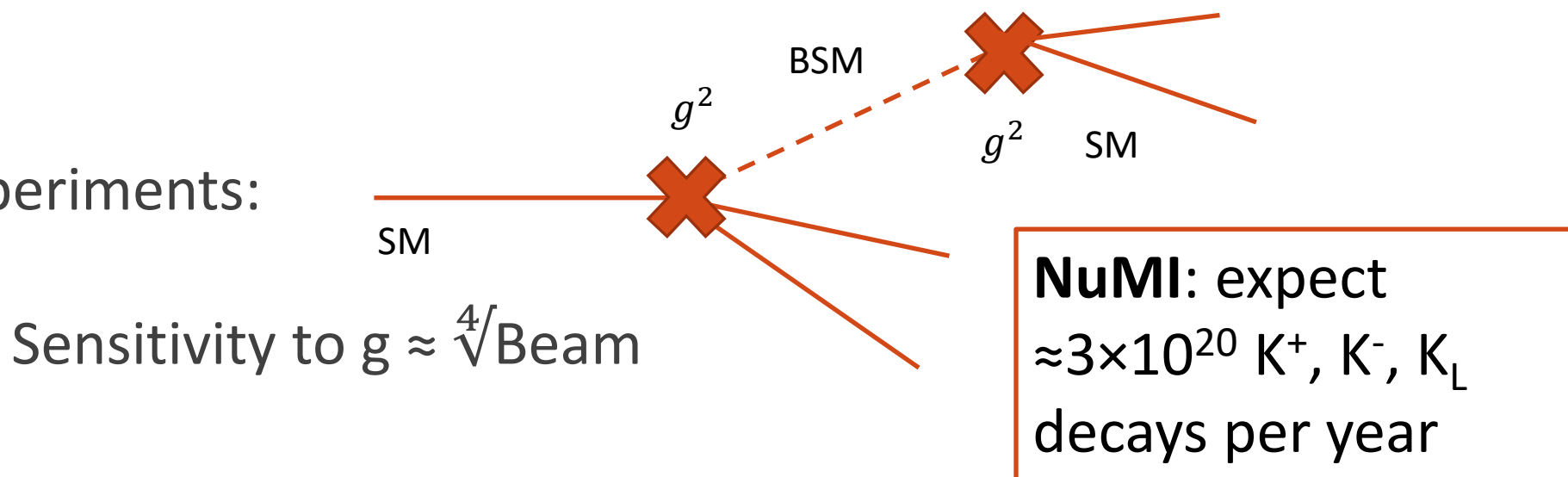


NA62 Collaboration (2020)
JHEP, 2103, 058. 14 p.

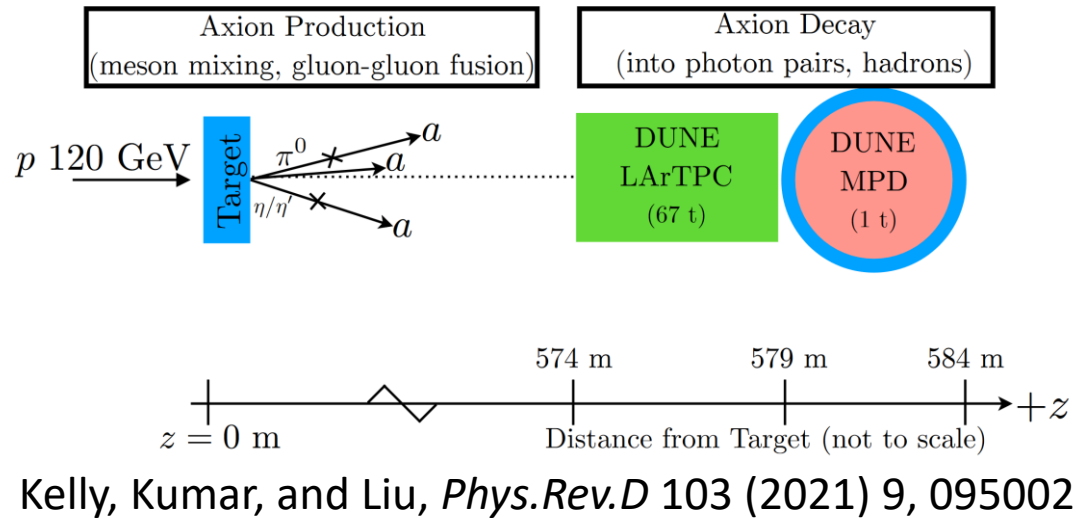
Missing Energy Experiments:



Delayed Decay Experiments:

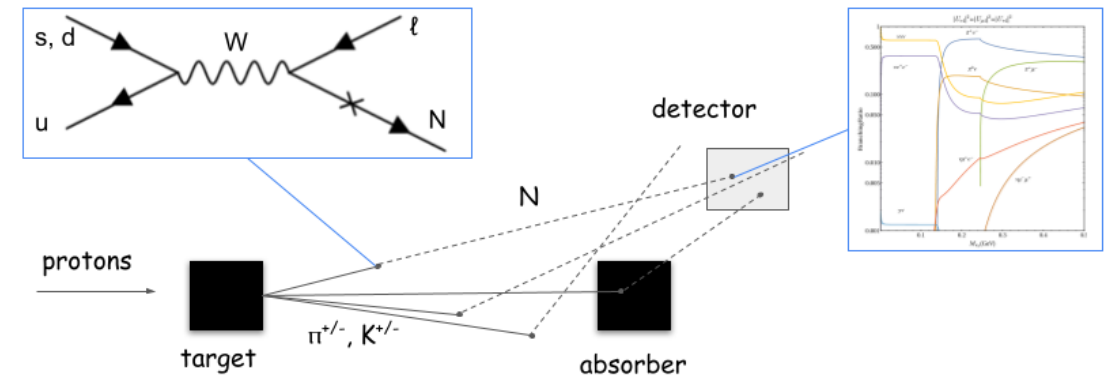


Other Models Under Consideration



Heavy QCD Axion

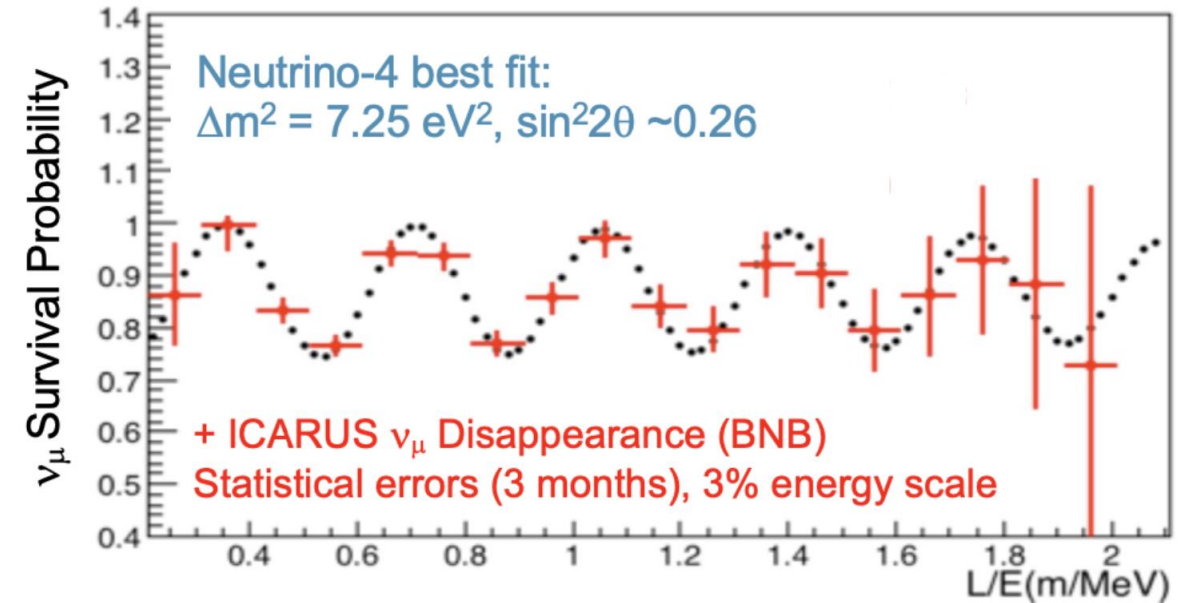
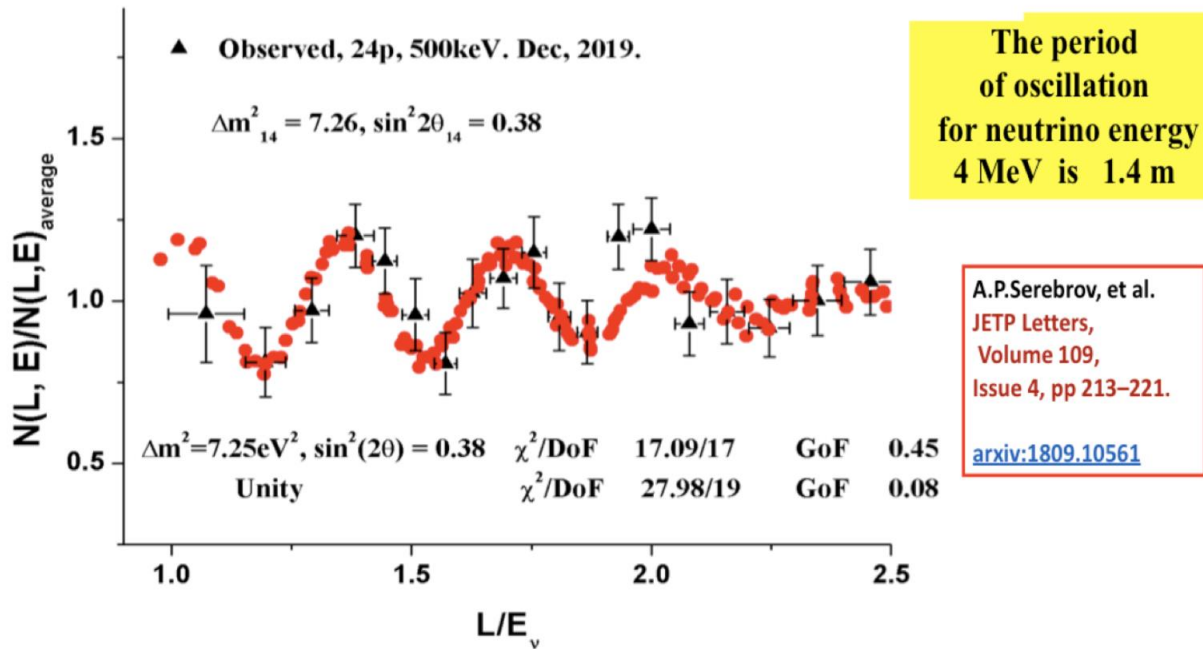
Heavy Neutral Lepton



- A variety of other models are also under consideration for NuMI@ICARUS
- We often can benefit from the work done understanding the new physics potential at DUNE

ICARUS Oscillation Search

NEUTRINO-4 reactor signals



- Work is ongoing to understand the sensitivity of an ICARUS-only analysis to sterile neutrino oscillations
- Somewhat higher Δm^2 -- motivated by Neutrino 4 / BEST anomalies