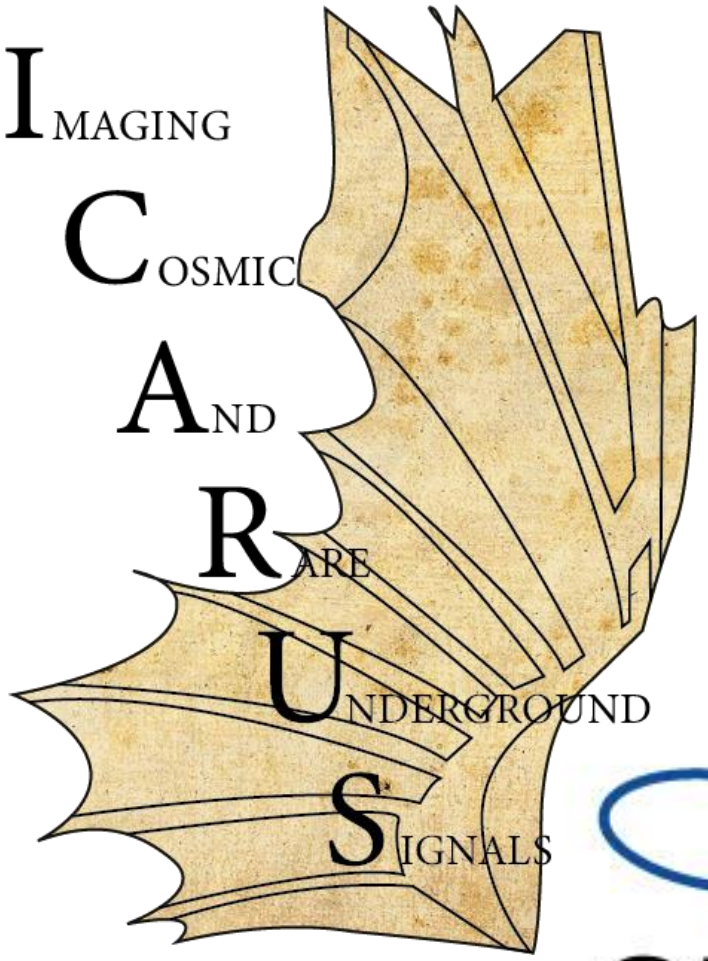


Tooling for BSM Searches at ICARUS and SBN

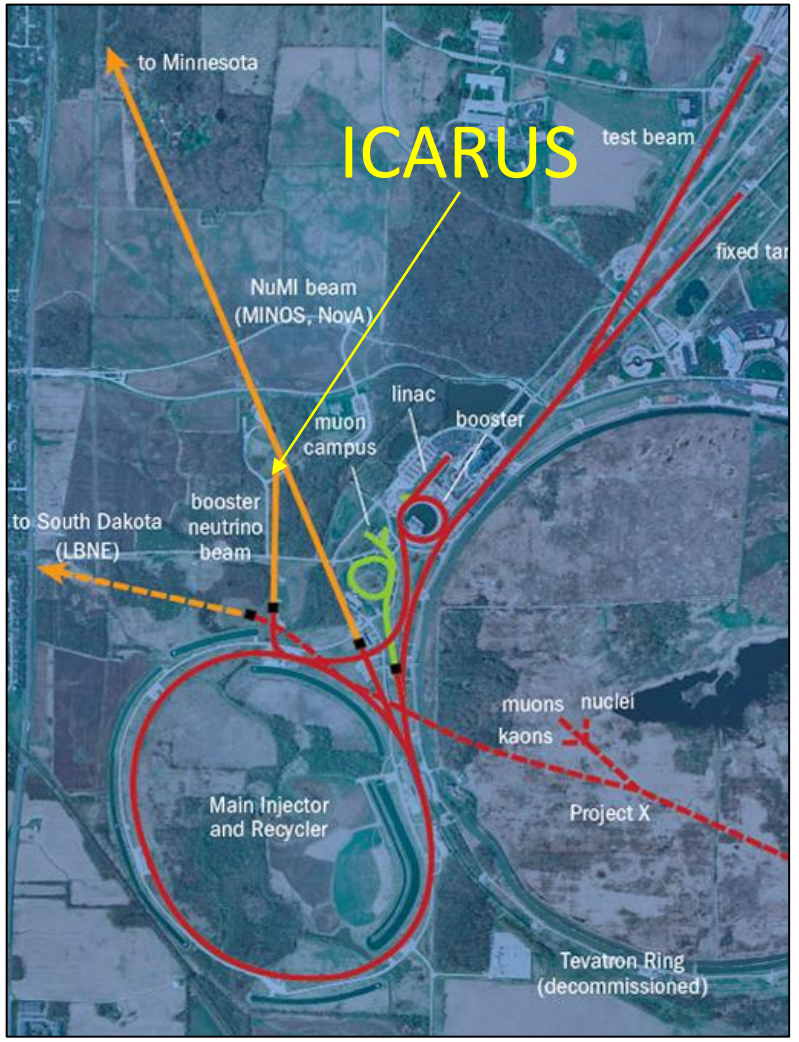
GRAY PUTNAM

UNIVERSITY OF CHICAGO

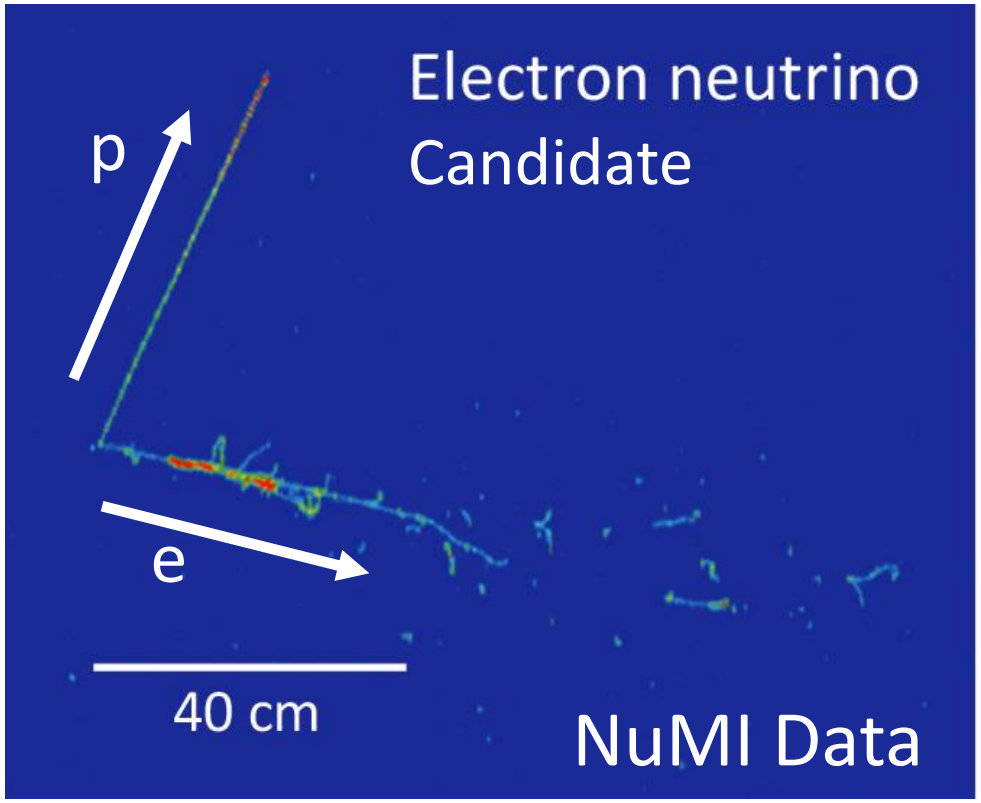
ICARUS Experiment

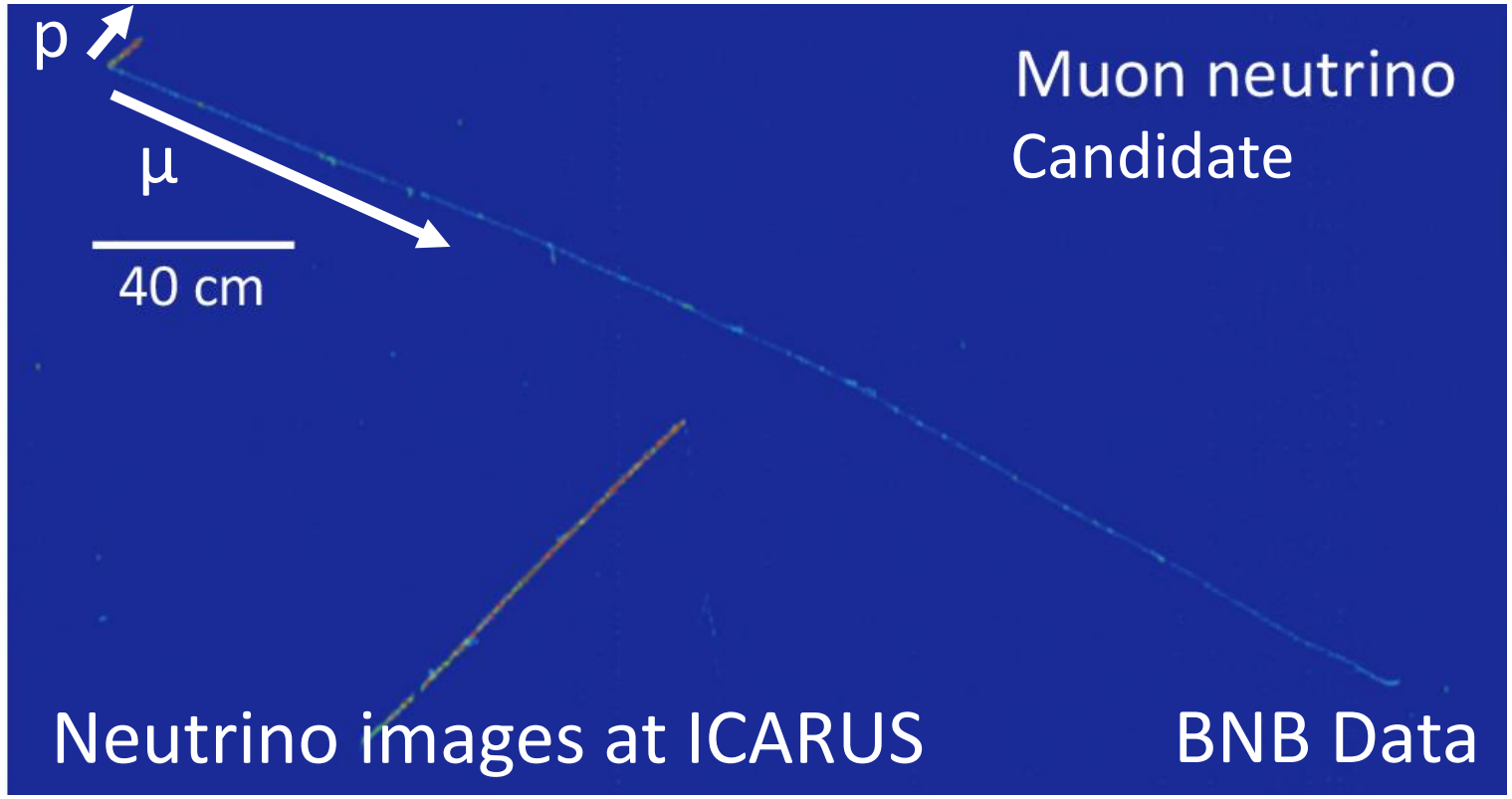
ICARUS and SBN at Fermilab

- 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**

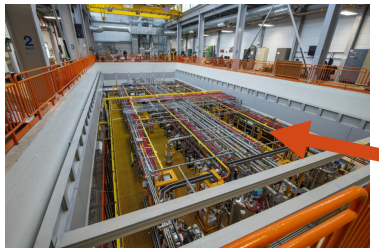


Neutrino Images in ICARUS





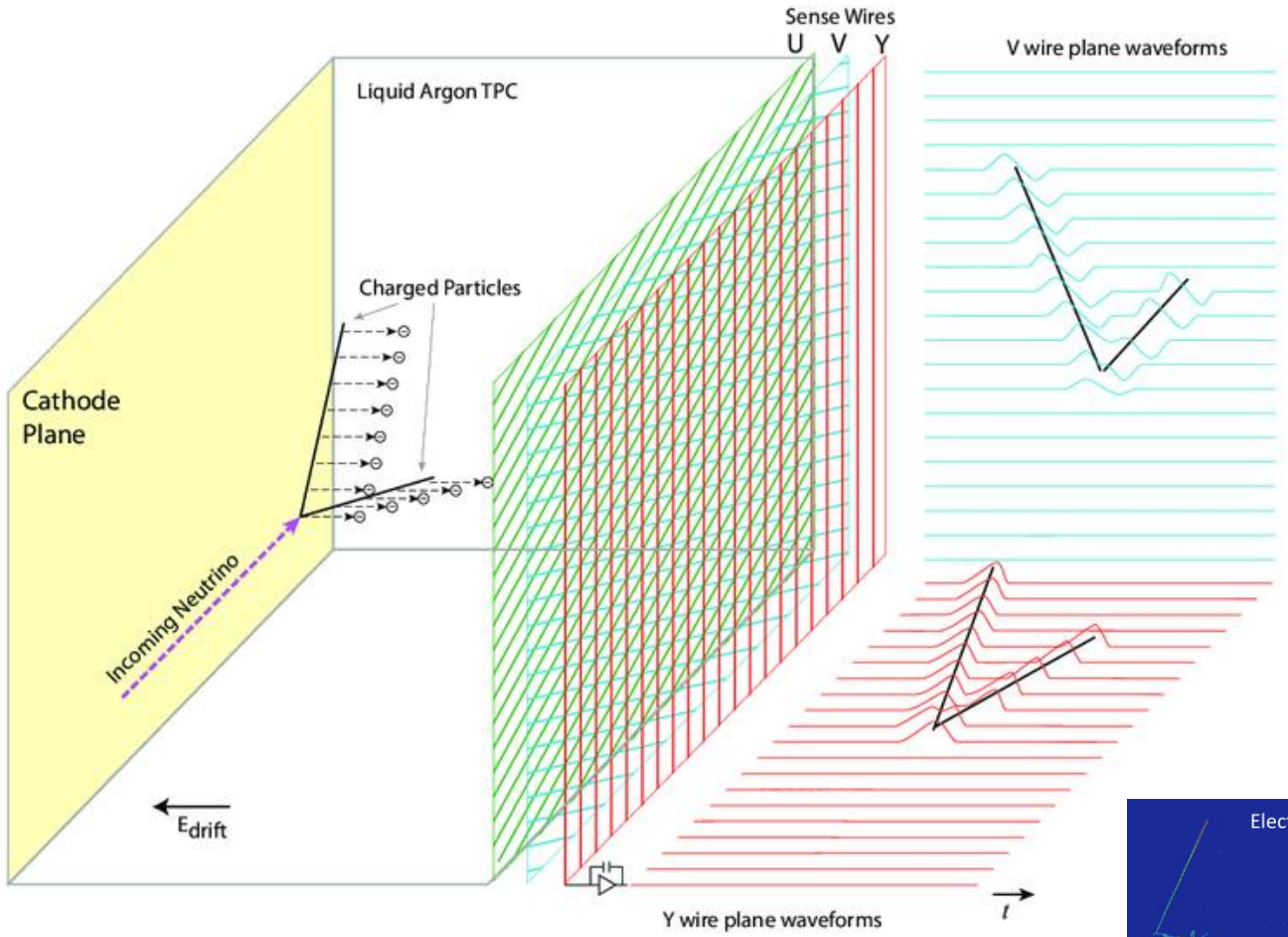
https://news.fnal.gov/2021/05/icarus-gets-ready-to-fly



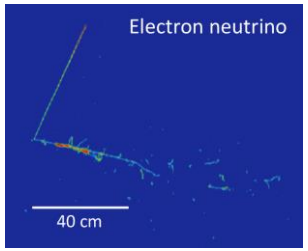
- ICARUS is now taking neutrino beam data

Image from one TPC inside each cryostat

ICARUS Detector Operation

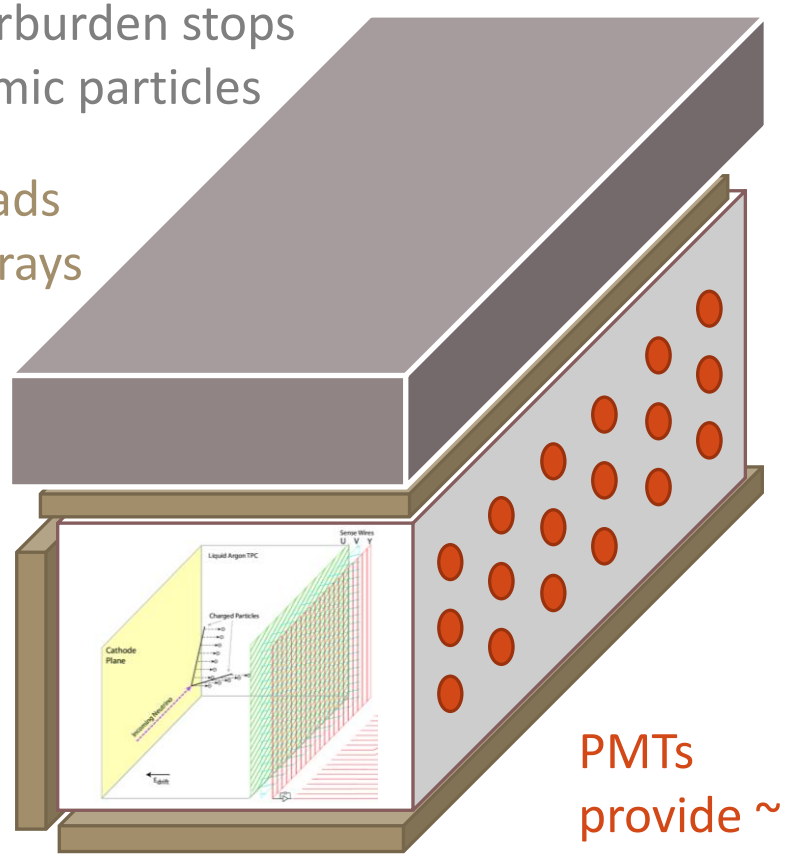


Time projection chamber tracks particles with ~mm resolution



3m concrete overburden stops cosmic particles

Scintillator pads track cosmic rays (CRT)

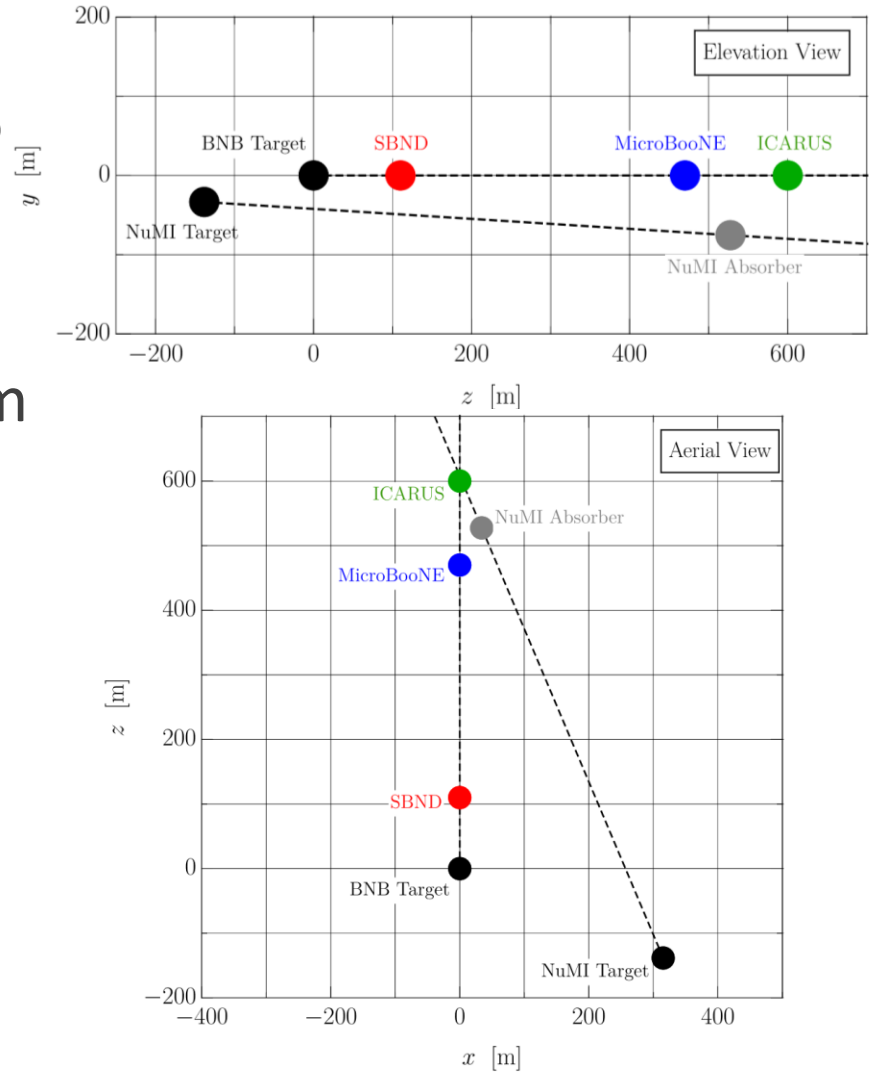


PMTs provide ~ns timing resolution

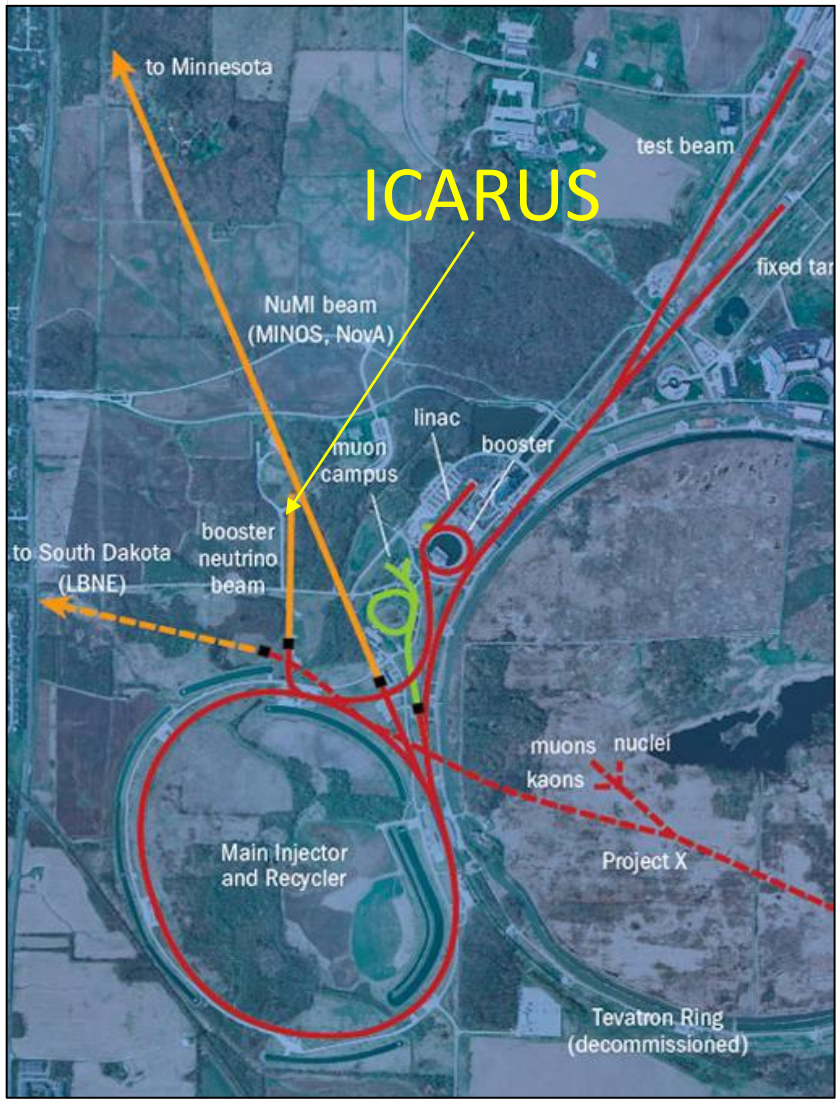
1 ICARUS Cryostat / Module

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

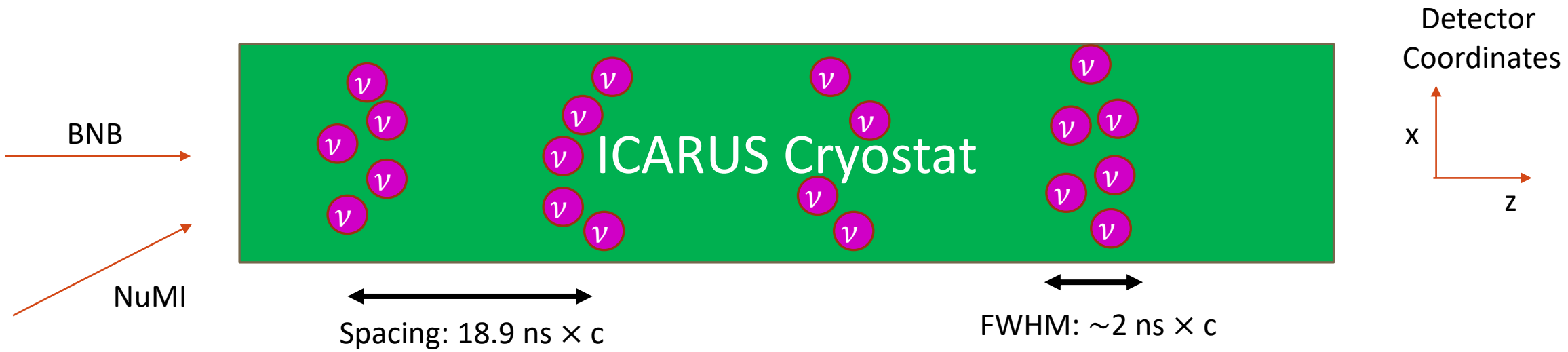
- A few single-detector searches are being developed at ICARUS, focused on the NuMI beam

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

- We are developing techniques to identify these events and select for them against the neutrino background

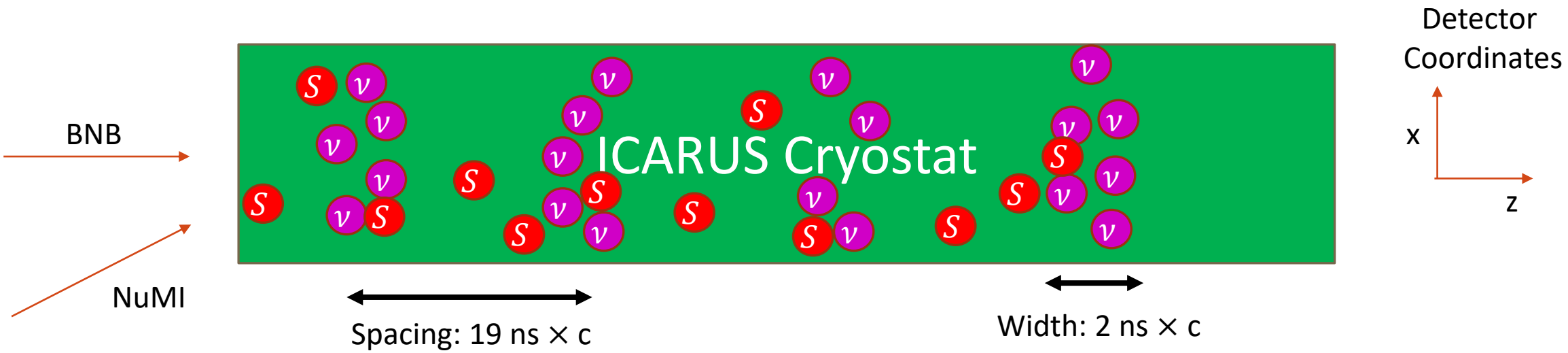
Scalar Portal theory-based sensitivity estimate: Phys. Rev. D 100, 115039
QCD Axion theory-based sensitivity estimate: *JHEP* 02 (2023) 111

Event Timing is Useful to Select BSM Events



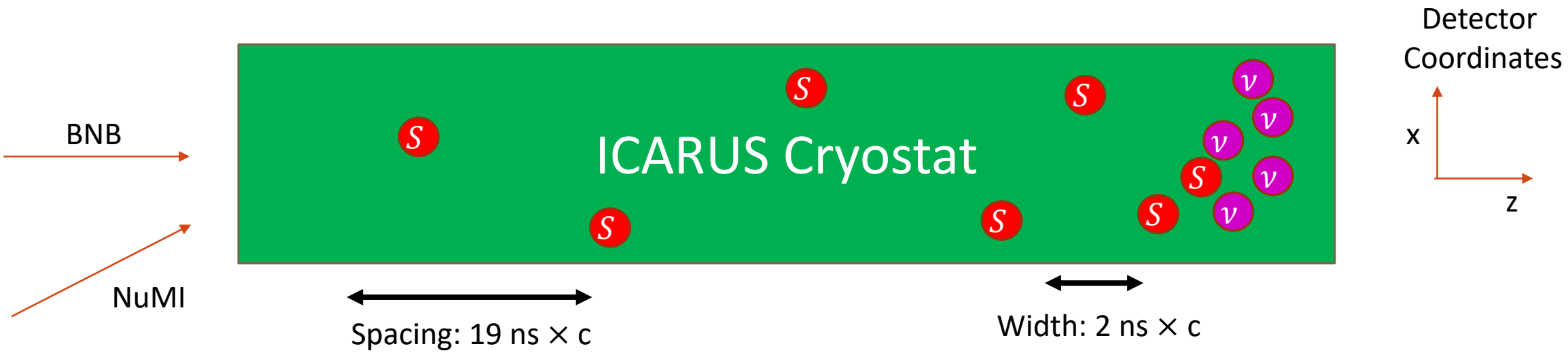
- The FNAL ν beams (BNB and NuMI) split each beam spill in a series of **bunches**
- ICARUS (and SBND) should be able to attain the PMT timing resolution necessary to resolve these

Event Timing is Useful to Select BSM Events



- The FNAL ν beams (BNB and NuMI) split each beam spill in a series of **bunches**
- Massive BSM particles would arrive in the detector in-between the neutrino spill (in its spatial-temporal interaction point)

Event Timing is Useful to Select BSM Events



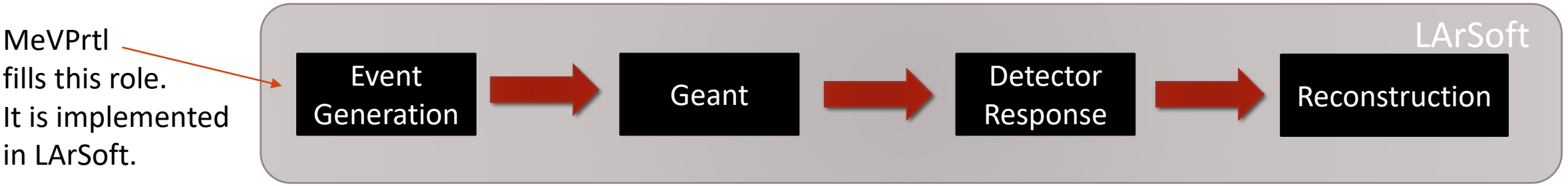
- The FNAL ν beams (BNB and NuMI) split each beam spill in a series of **bunches**
- Massive BSM particles would arrive in the detector in-between the neutrino spill (in its spatial-temporal interaction point)
- With a tail of events past the end of the neutrino spill

Event Generation Tooling: **MeVPrtl**

Generation Tools at ICARUS: **MeVPrtl**

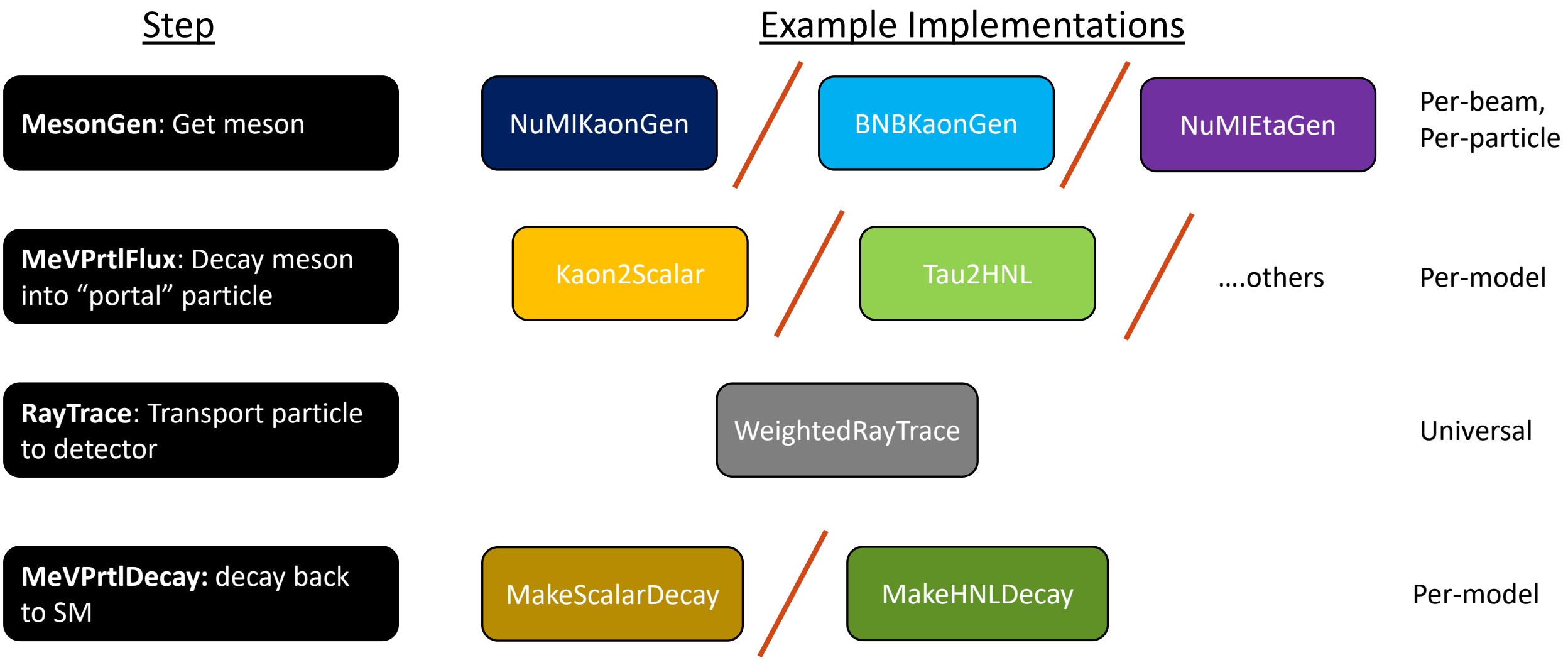
- Getting events from new physics models into detector MC is a necessary step in analysis
- Generation tools should:
  - Generate on command
  - Make unweighted events
  - Re-use existing code where possible
  - Simulate detailed effects like timing

Detector Monte-Carlo Generation Stages



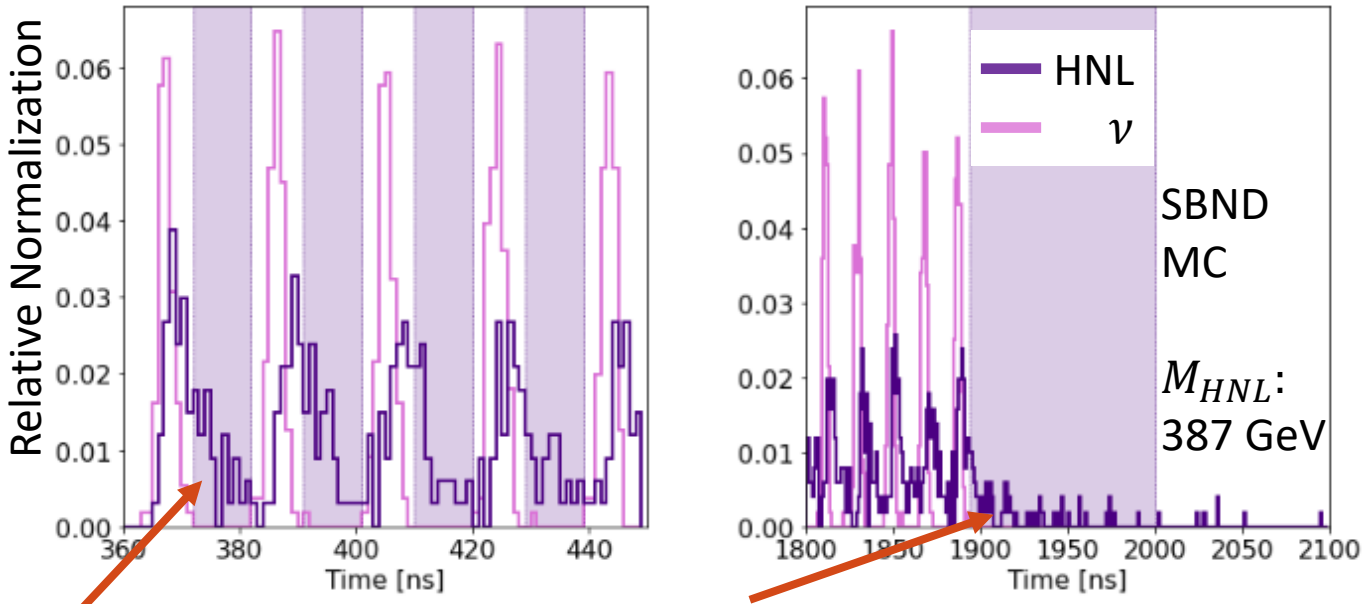
- Solution we have on ICARUS and SBND to support a few analyses: MeVPrtl generator
  - https://github.com/SBNSoftware/sbncode/tree/develop/sbncode/EventGenerator/MeVPrtl

MeVPrtl: Modular Event Generation



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



Massive Heavy Neutral Leptons arrive outside the beam bunches and past the beam spill

Credit: Lan Nguyen, Luis Pelegrina Gutiérrez, **SBND**

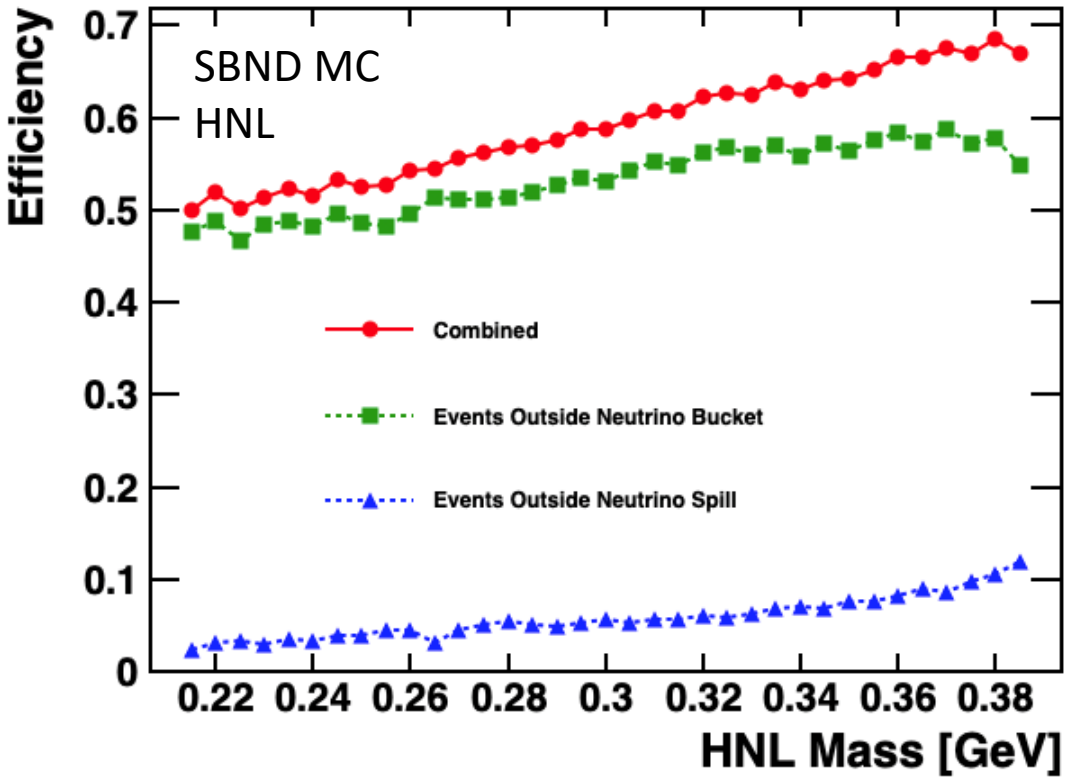
t_p: Proton arrival time

Δt_M: meson travel time

Δt_S: "portal" travel time

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



Credit:
Lan Nguyen, Luis Pelegrina Gutiérrez, **SBND**

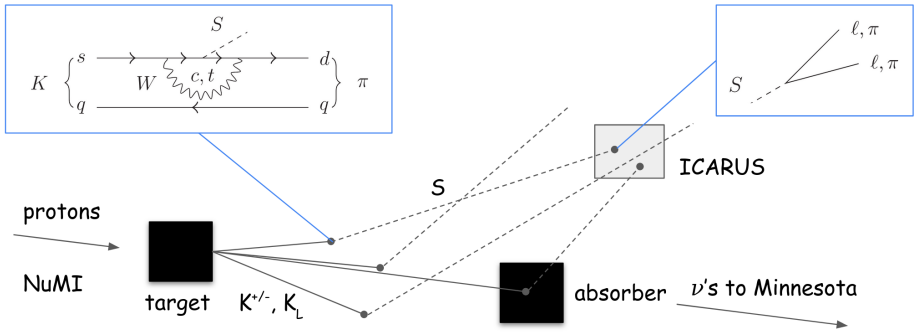
t_p: Proton arrival time

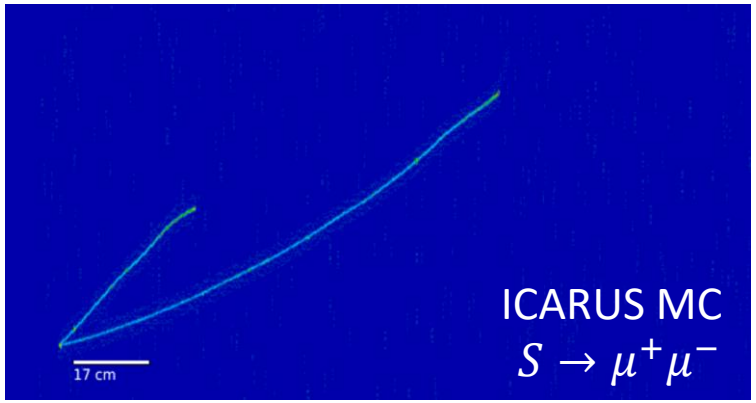
Δt_M: meson travel time

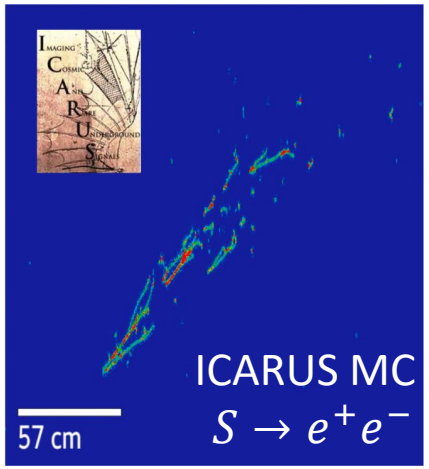
Δt_S: "portal" travel time

Example Models in MeVPrtl

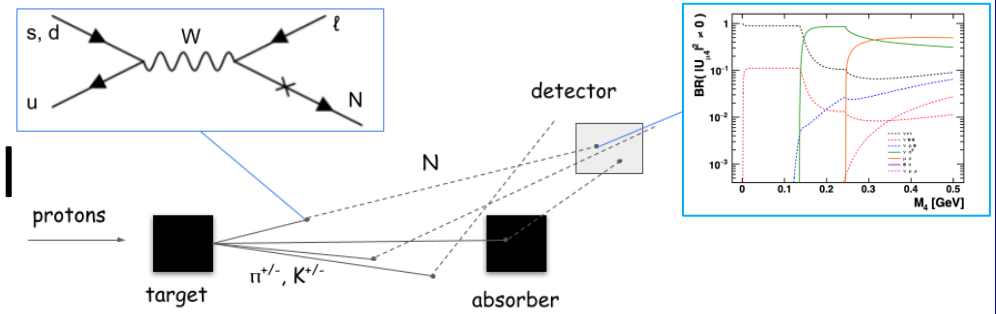
Higgs Portal

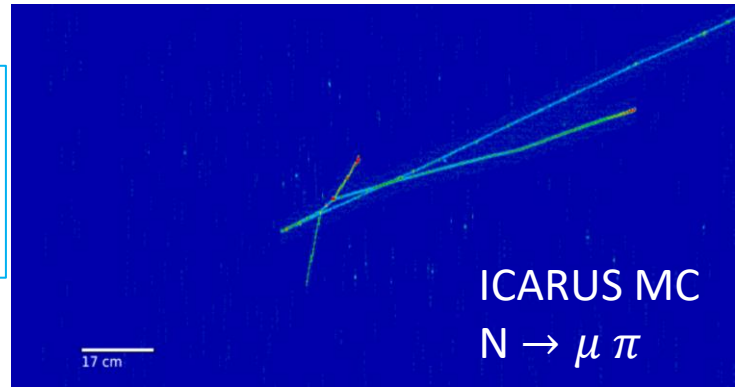


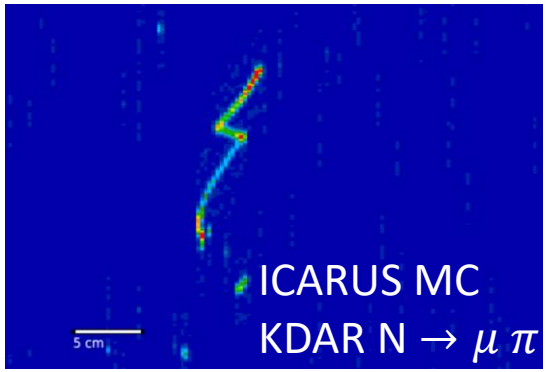




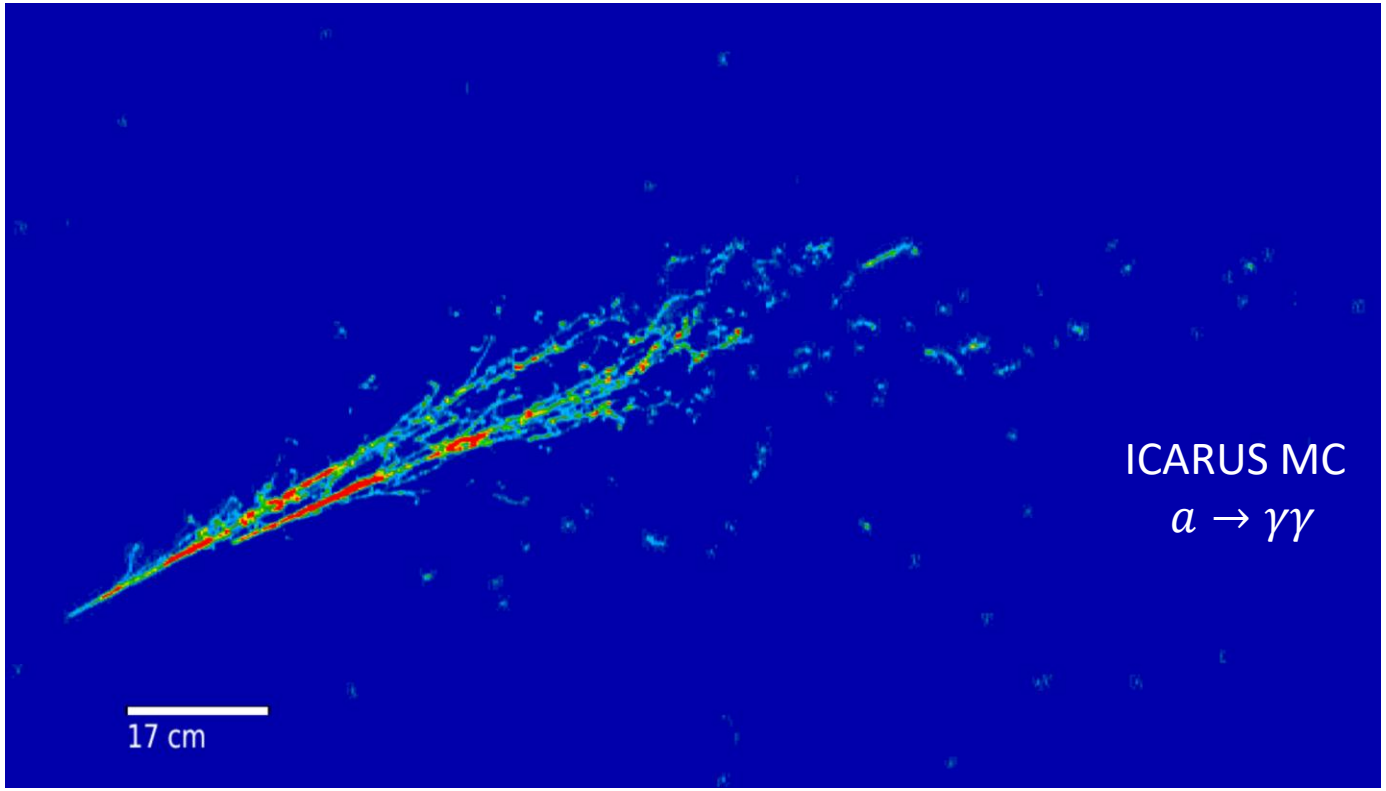
Heavy Neutral Lepton



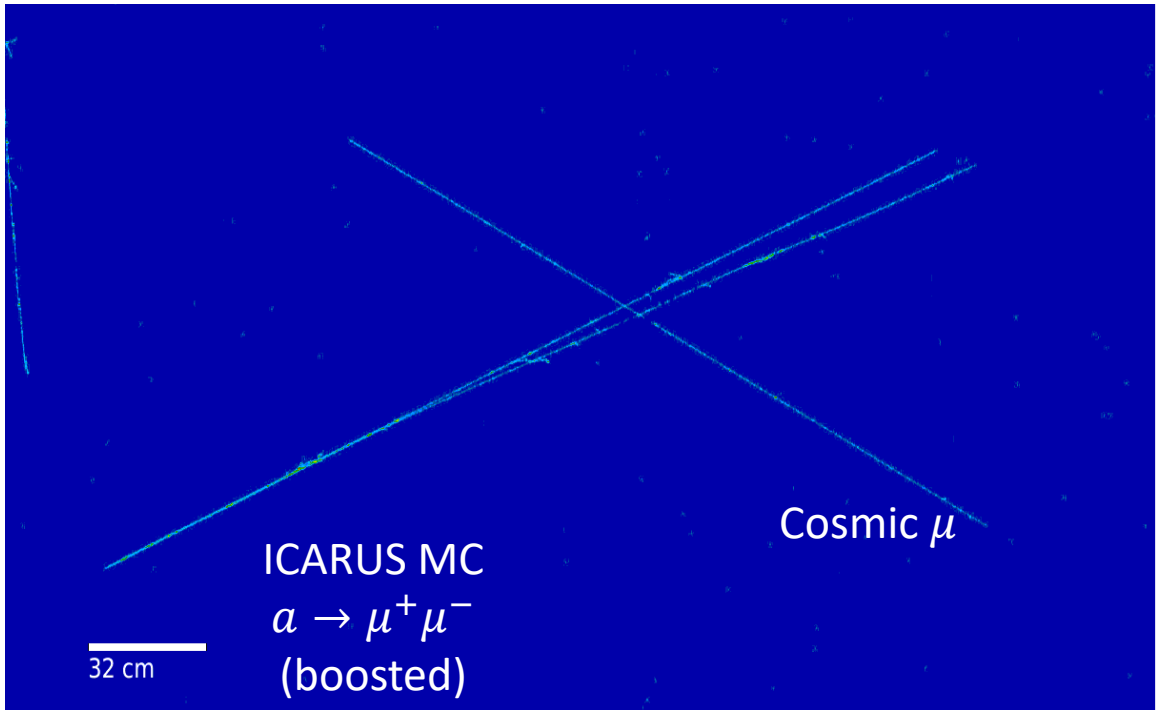




Example Models in MeVPrtl



Heavy QCD Axion



My Perspective on How to Progress From Here

- MeVPrtl was written to solve a specific problem for SBN – how to simulate the response of BSM physics models in the detector
- How do we scale this?
  - Make it easier for theorists to contribute new models
  - Make it easier to simulate complex physics (angular correlations, busy decays, interactions)
- There's tooling from the collider world that lets you simulate physics from a Lagrangian (FeynRules, UFO, Sherpa, MadGraph, …) – we should use these, but:
  - Many of these existing tools assume collider-like physics – our simulation needs are different
  - Oftentimes models operate on effective degrees of freedom (mesons, etc.) which have complicated interactions

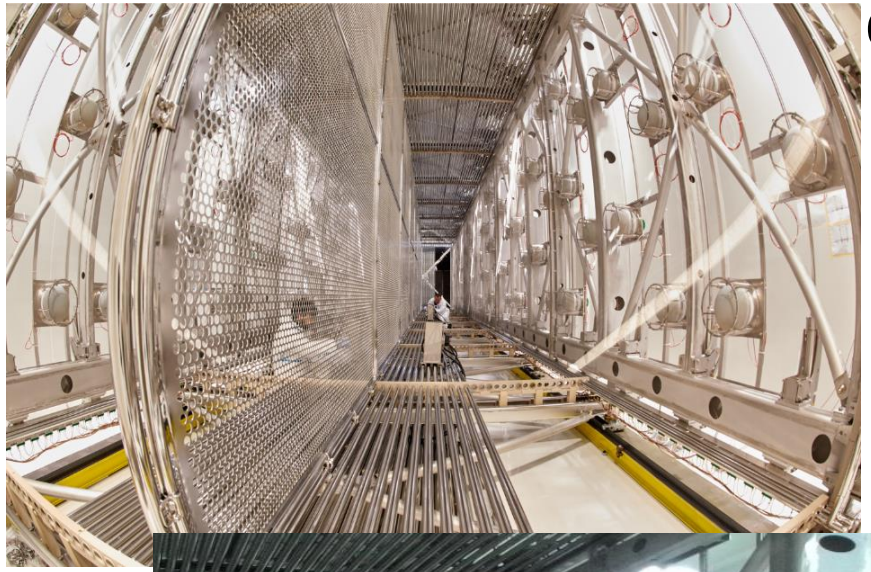
Conclusion

- 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
  - Looking ahead, the tool is also being used to develop SBND analyses

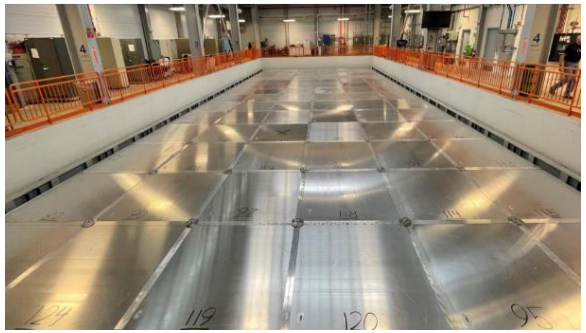
Backup Slides

The ICARUS Detector at Fermilab

TPC



Top CRT



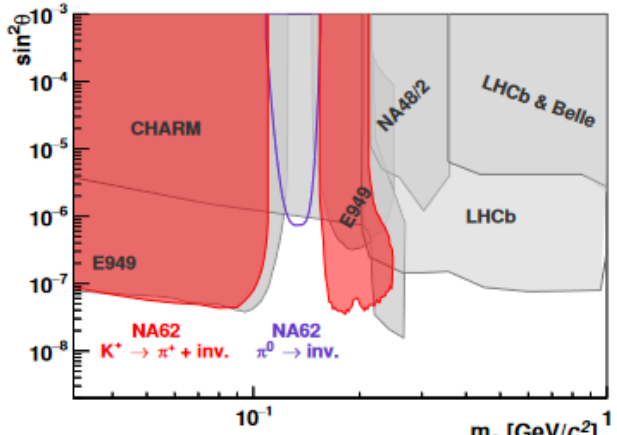
Side CRT

Cryostat before overburden, CRT installation

PMTs

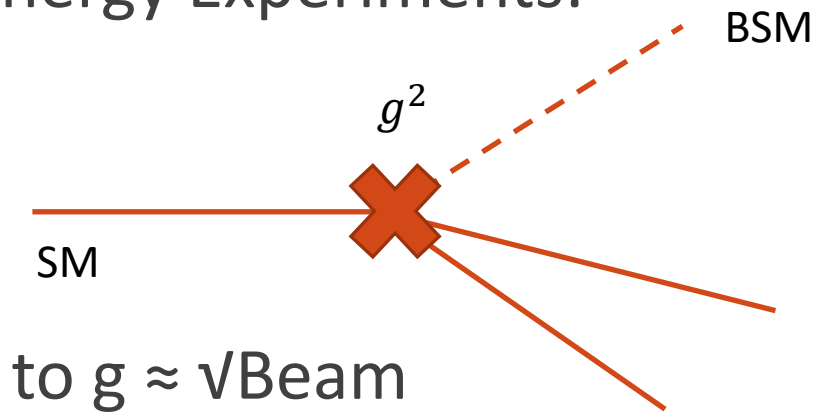
- 2 modules each with two TPCs, 1.5 m / 1 ms drift
- 3 readout wire planes, ~54k wires
- 360 8” PMTs
- Cosmic ray tagger: scintillator strips read out by SiPMs

How Can ICARUS Compete with Kaon Decay Experiments?



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

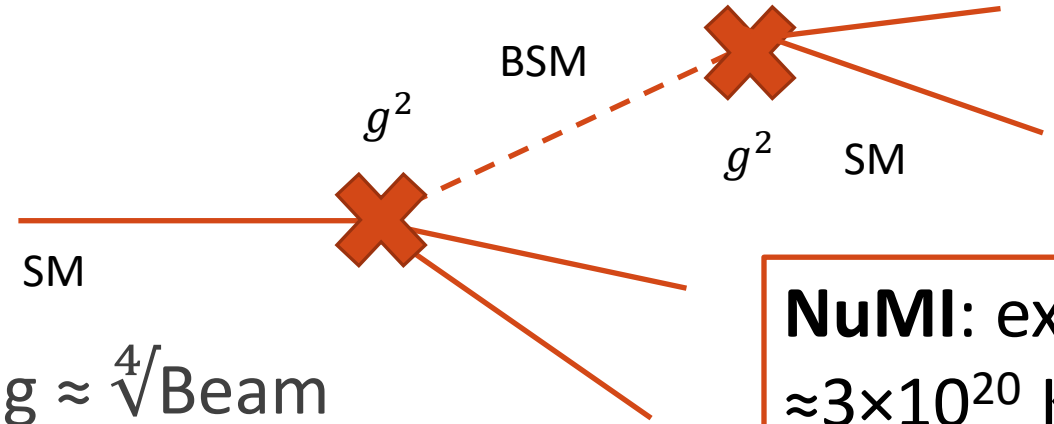
Missing Energy Experiments:



Sensitivity to g ≈ √Beam

NA62: 1.21×10^{11} K^+ decays in 2016 data

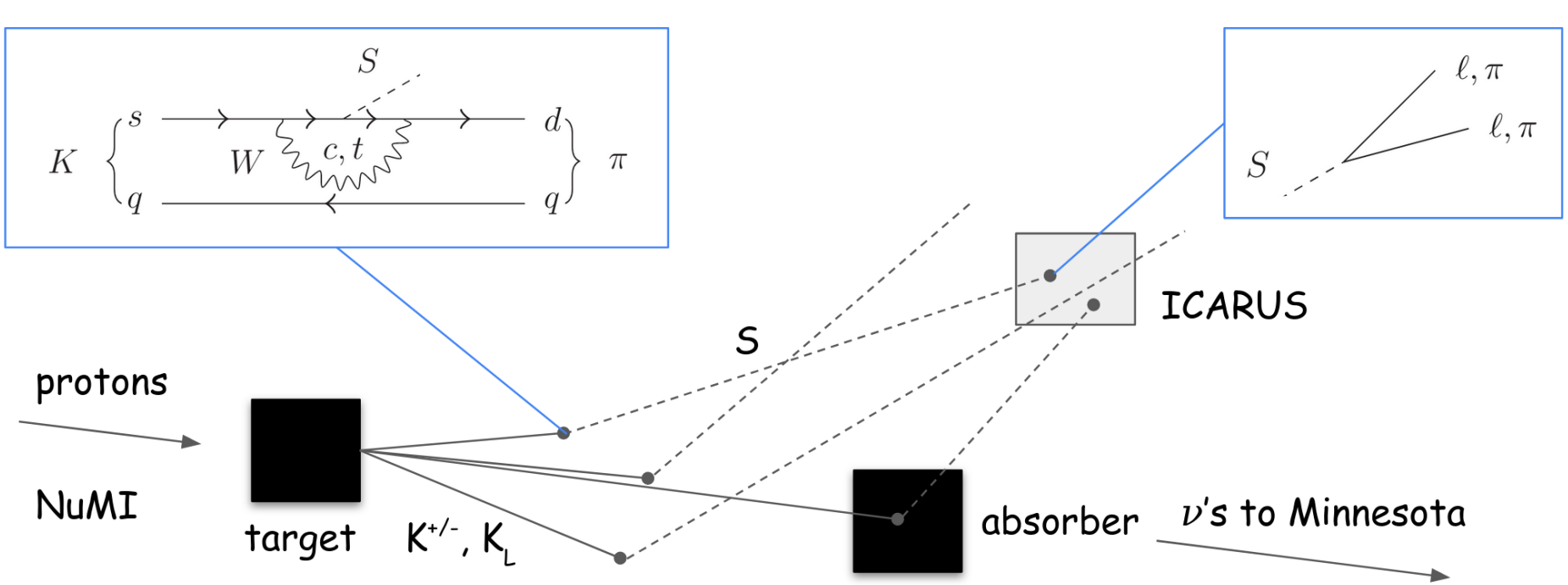
Delayed Decay Experiments:

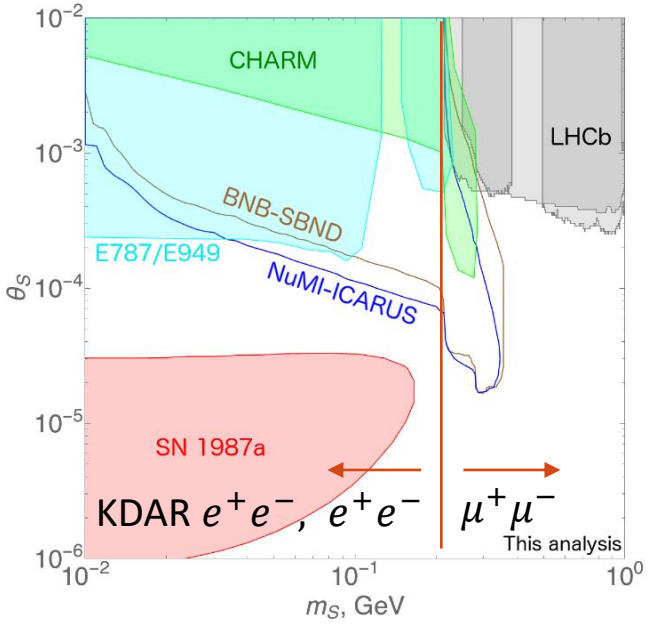


Sensitivity to g ≈ $\sqrt[4]{}$Beam

NuMI: expect ≈3×10^{20} K^+, K^-, K_L decays per year

BSM Physics: Scalar / Higgs Portal



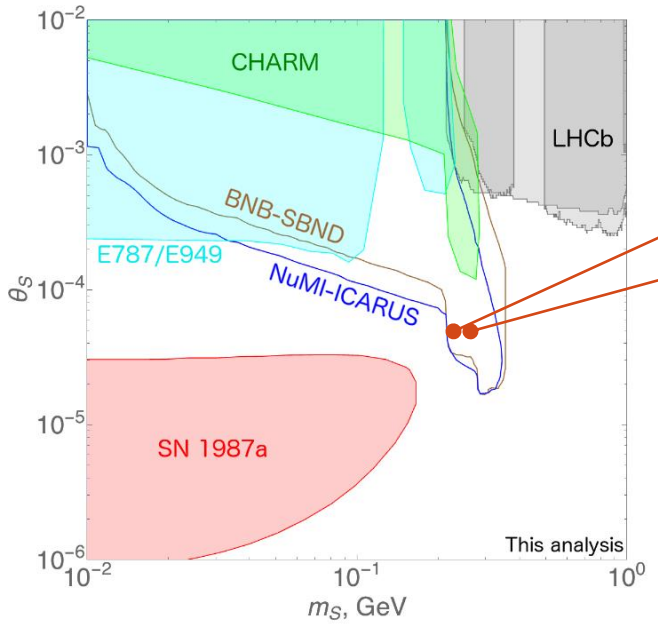


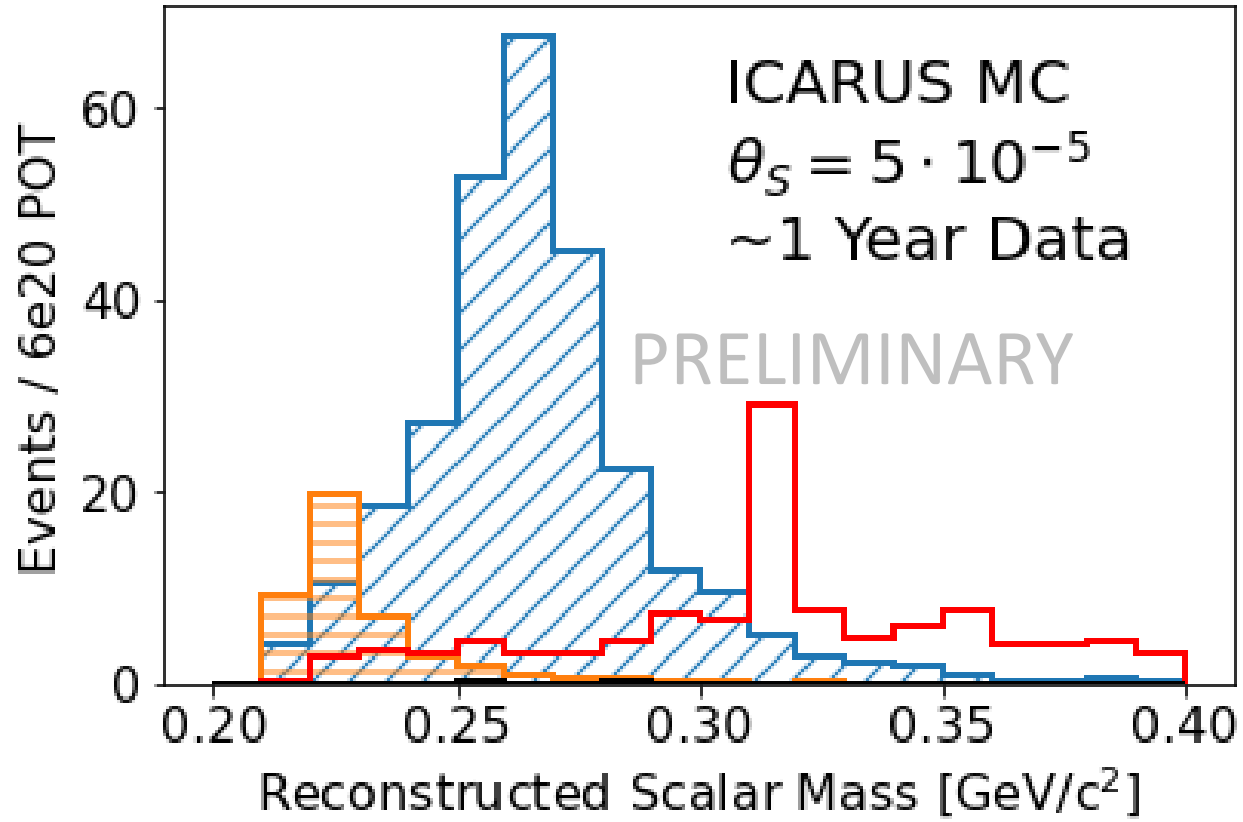
Estimated sensitivity from:
Phys. Rev. D 100, 115039

- 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 $M_s < m_K - m_\pi$

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

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



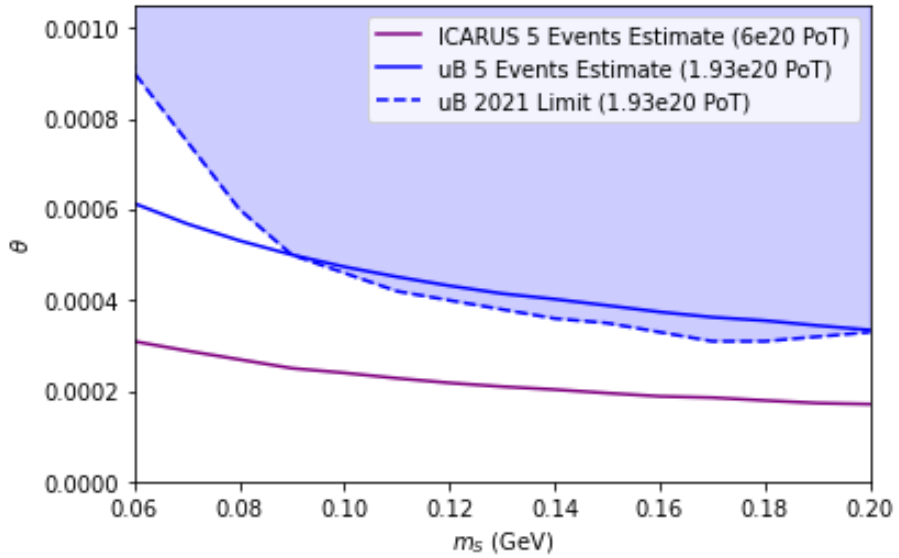


- Early indication from simulation:
  - 100% cosmic rejection
  - >99% neutrino rejection
  - ~40% signal efficiency above 1GeV

Scalar Portal: e^+e^- Analyses

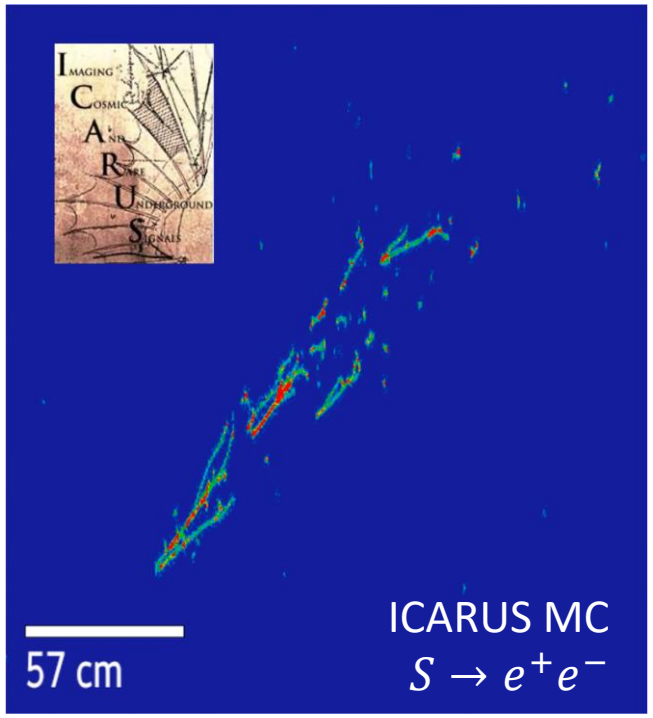
KDAR (Kaon-Decay-At-Rest) Signal:

- 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:

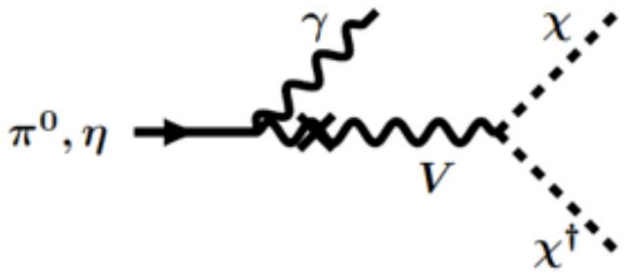
- Example event display:



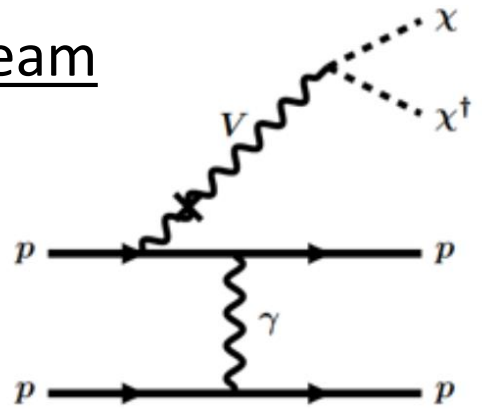
- ML based reconstruction techniques are being pursued to identify columnated shower pairs

Vector Portal: Forward e

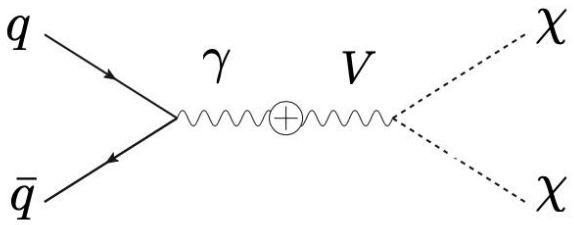
Production of Dark Matter Beam



Neutral mesons decays



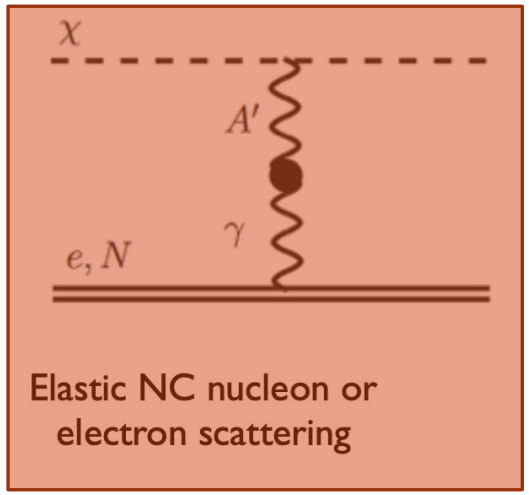
Bremsstrahlung + vector meson mixing



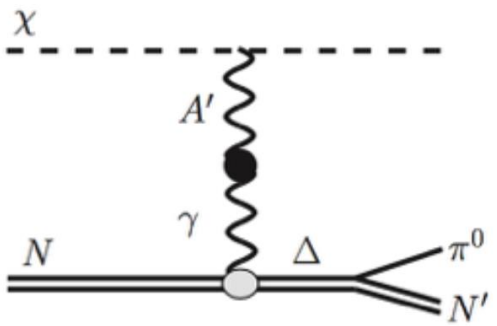
Direct production

Scattering in Detector

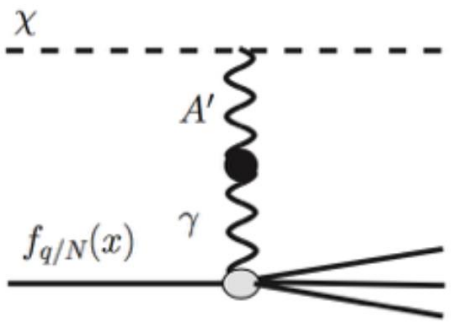
Elastic scattering off electrons is a promising low background channel.



Elastic NC nucleon or electron scattering



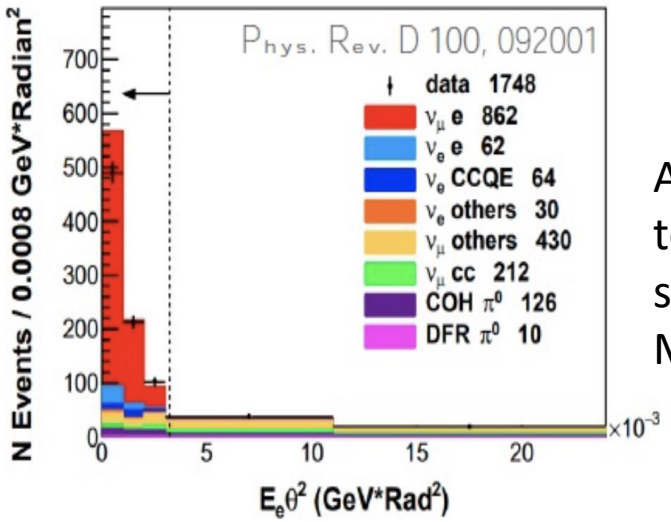
Inelastic NC neutral pion - like scattering



Deep Inelastic scattering

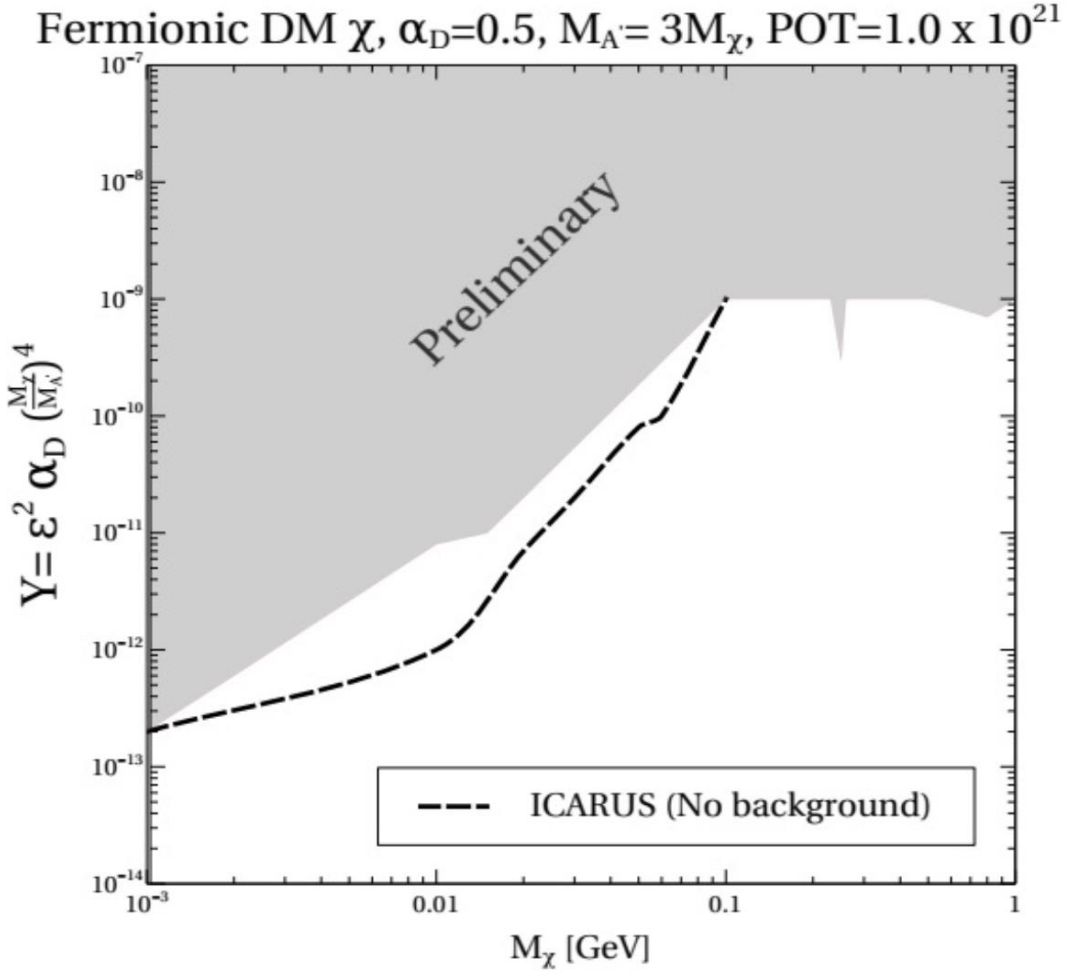
Vector Portal: Forward e

- 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

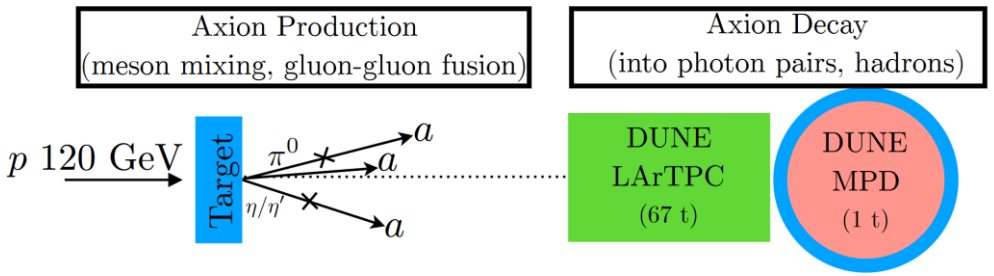
Preliminary sensitivity estimate

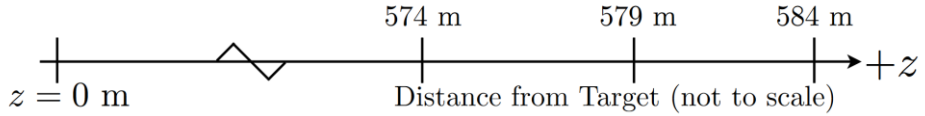


Outlook

- 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: intra-spill event timing

Other Models Under Consideration

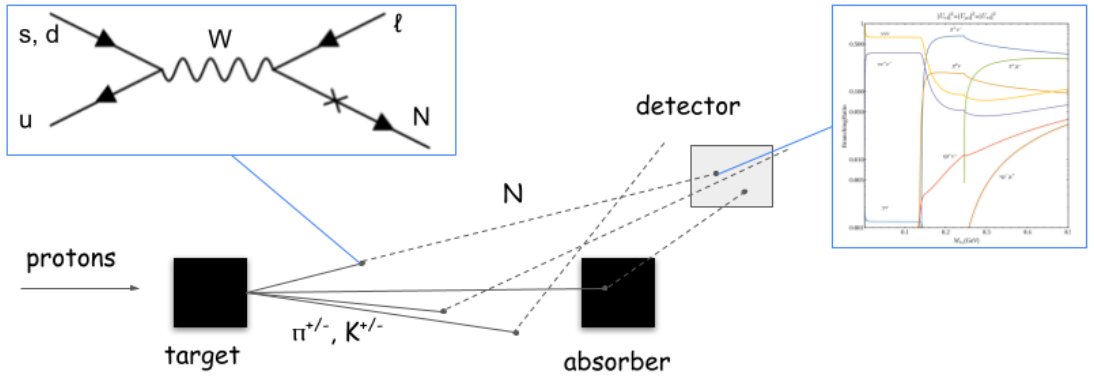




Kelly, Kumar, and Liu, *Phys.Rev.D* 103 (2021) 9, 095002

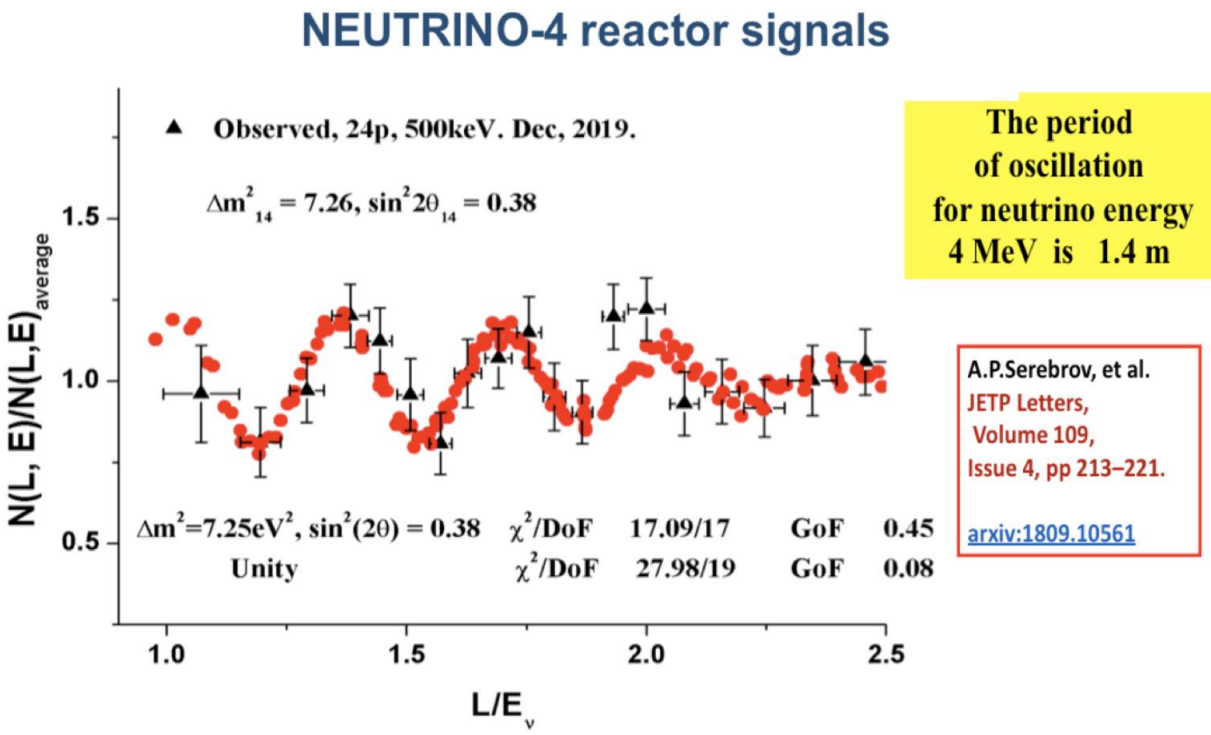
Heavy QCD Axion

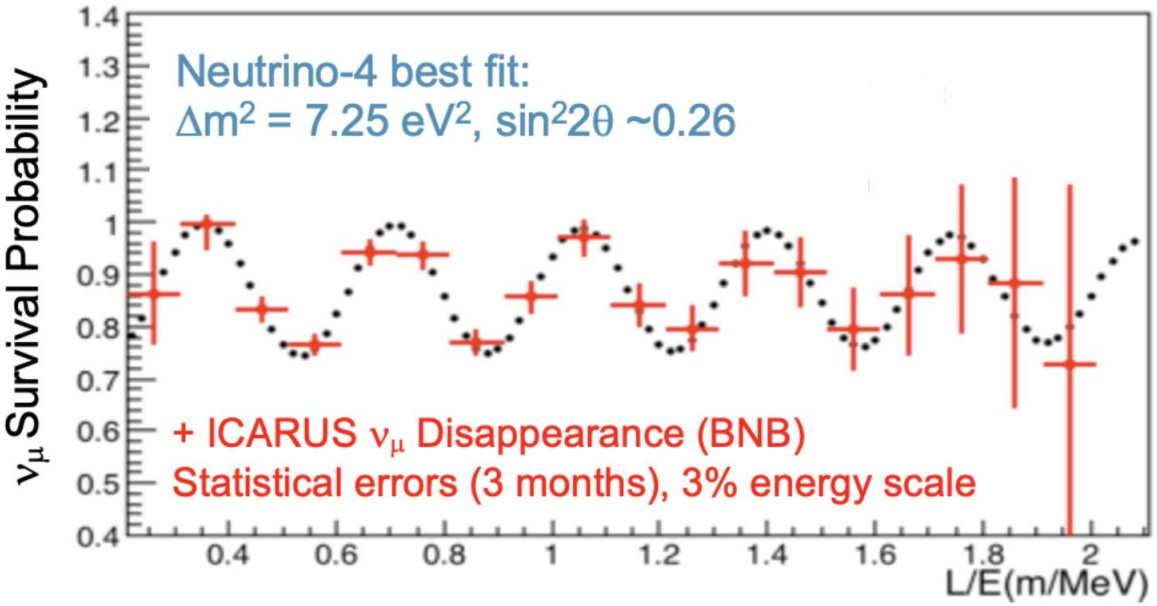
Heavy Neutral Lepton



- 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



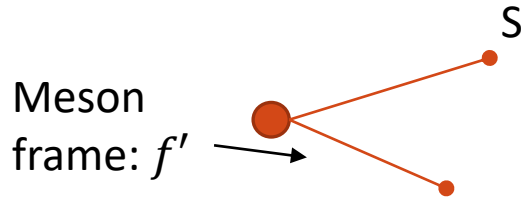


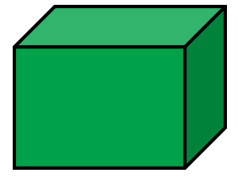
- Work is ongoing to understand the sensitivity of an ICARUS-only analysis to sterile neutrino oscillations
- Somewhat higher Δm^2 -- motivated by Neutrino 4 / BEST anomalies

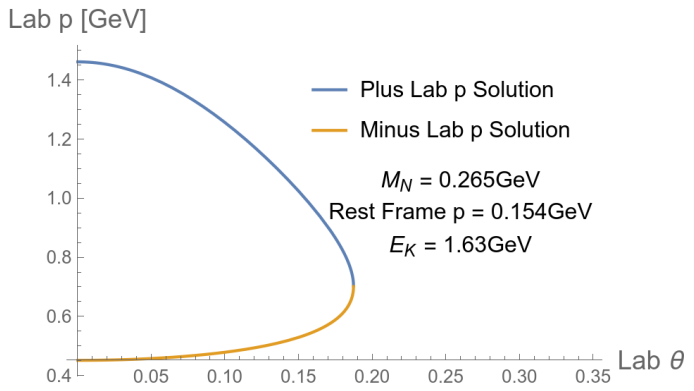
MeVPrtl: Ray Trace Weighting

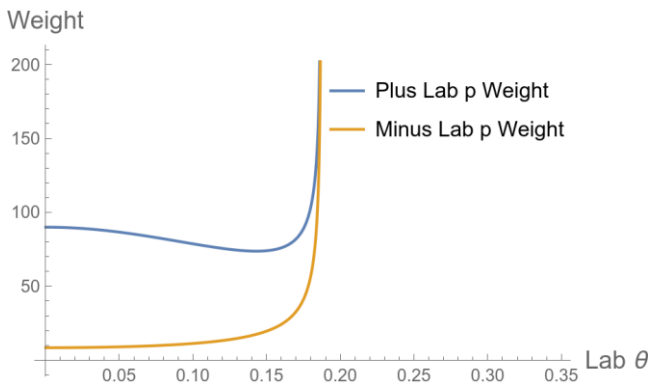
- Naively weighting the (massive) "portal" particle to hit the detector can lead to singular weights in the Monte-Carlo

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

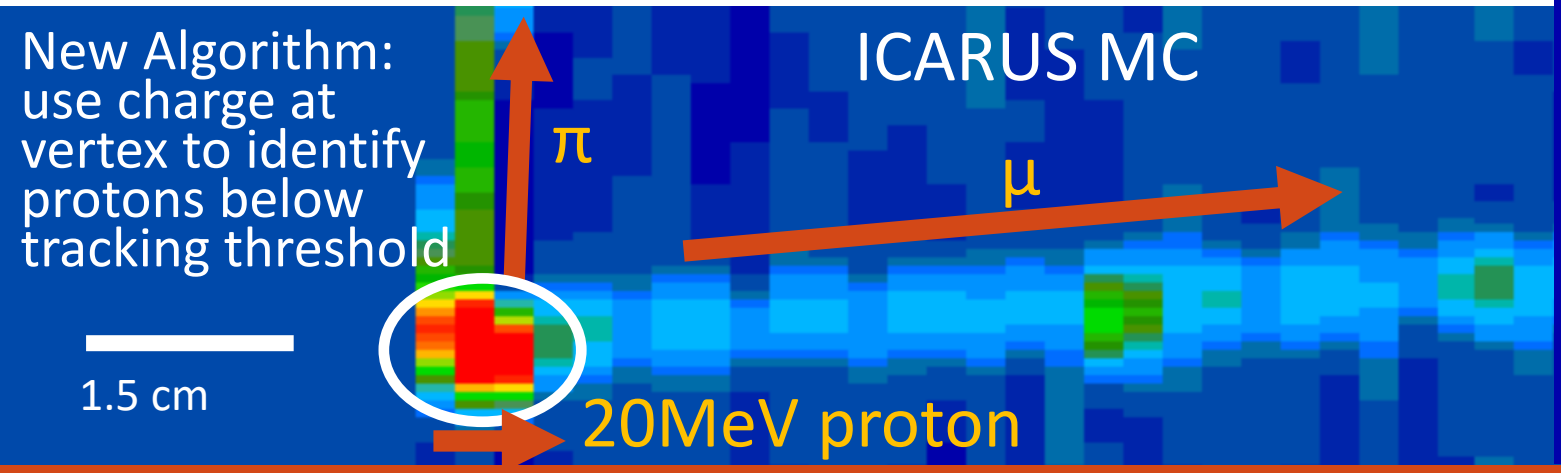
Pick (θ', ϕ) for "portal" particle

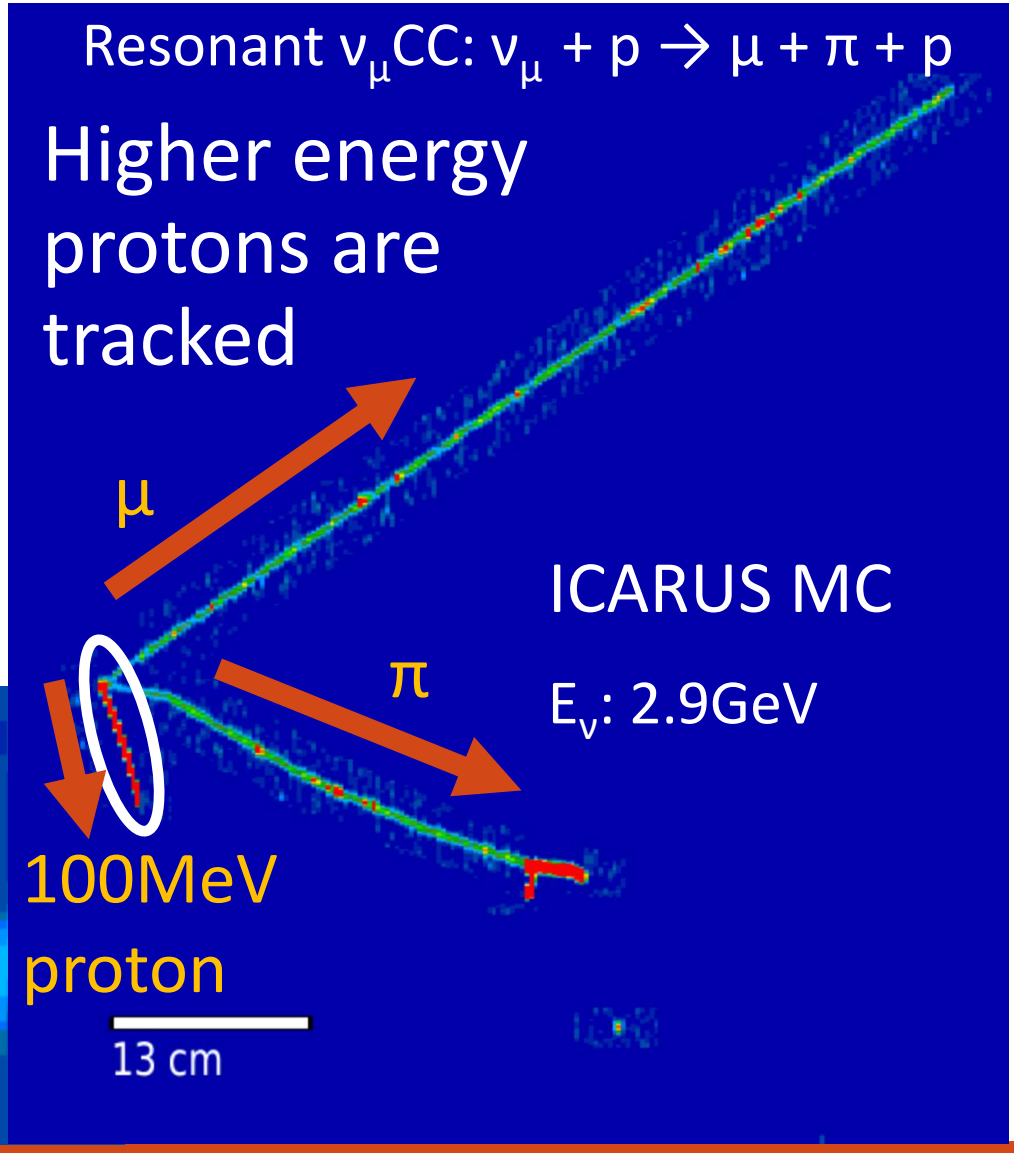
$$\int_D d\Omega' \rightarrow \int_D \frac{d\phi'}{d\phi} d\phi d\theta'$$

No singularity

$\mu^+\mu^-$: 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 ~15MeV

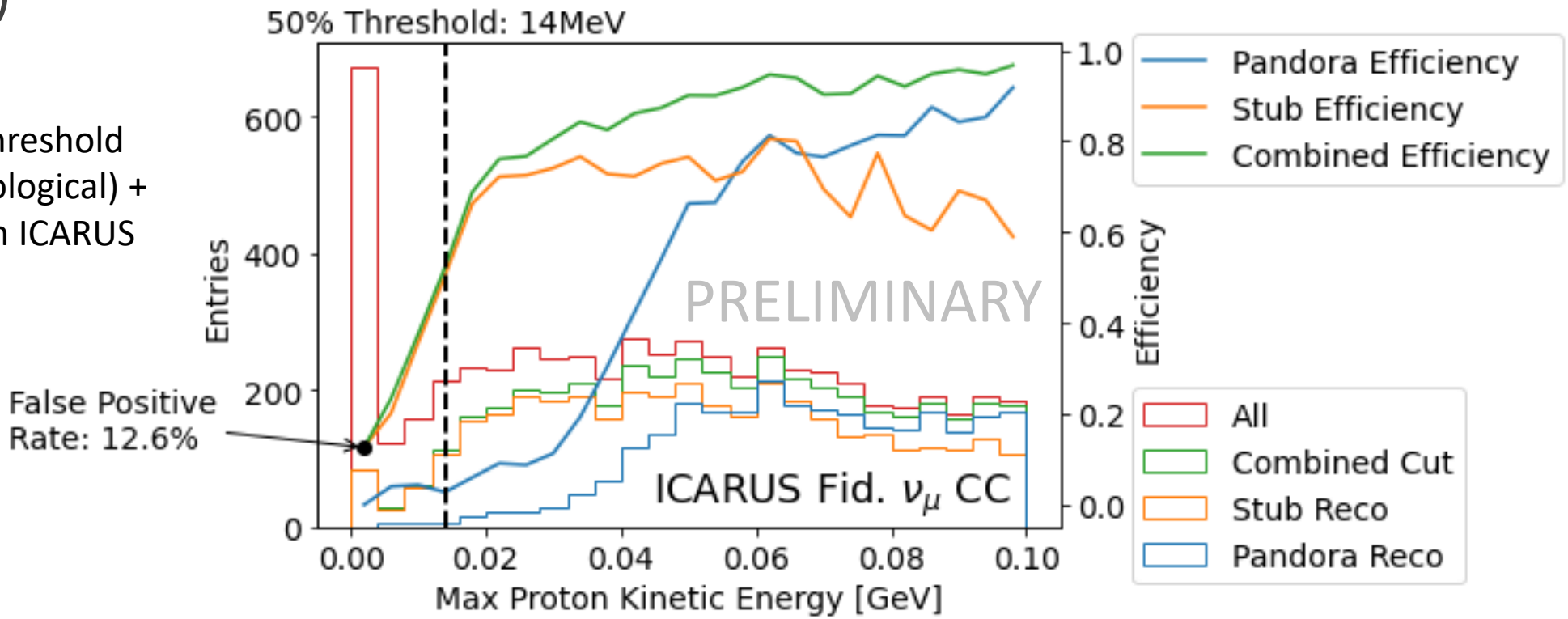




Low Energy Proton Identification w/ Charge

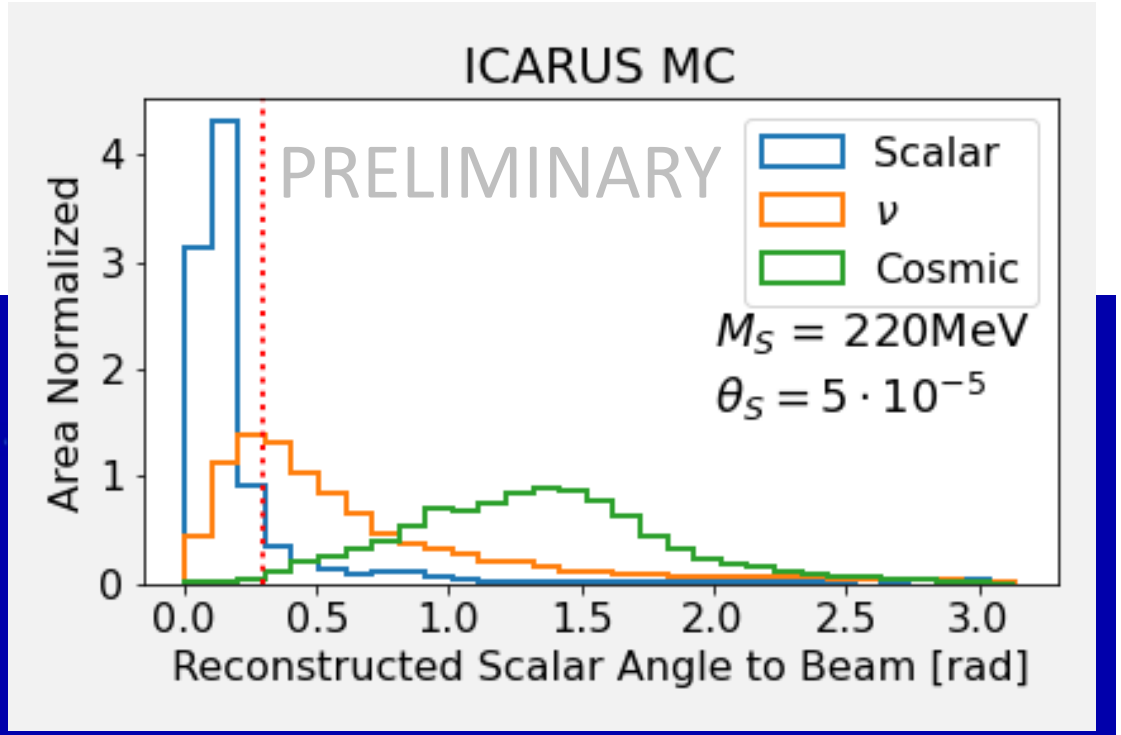
Performance on ICARUS MC demonstrates a much lower proton identification energy threshold than topological reconstruction (Pandora)

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



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