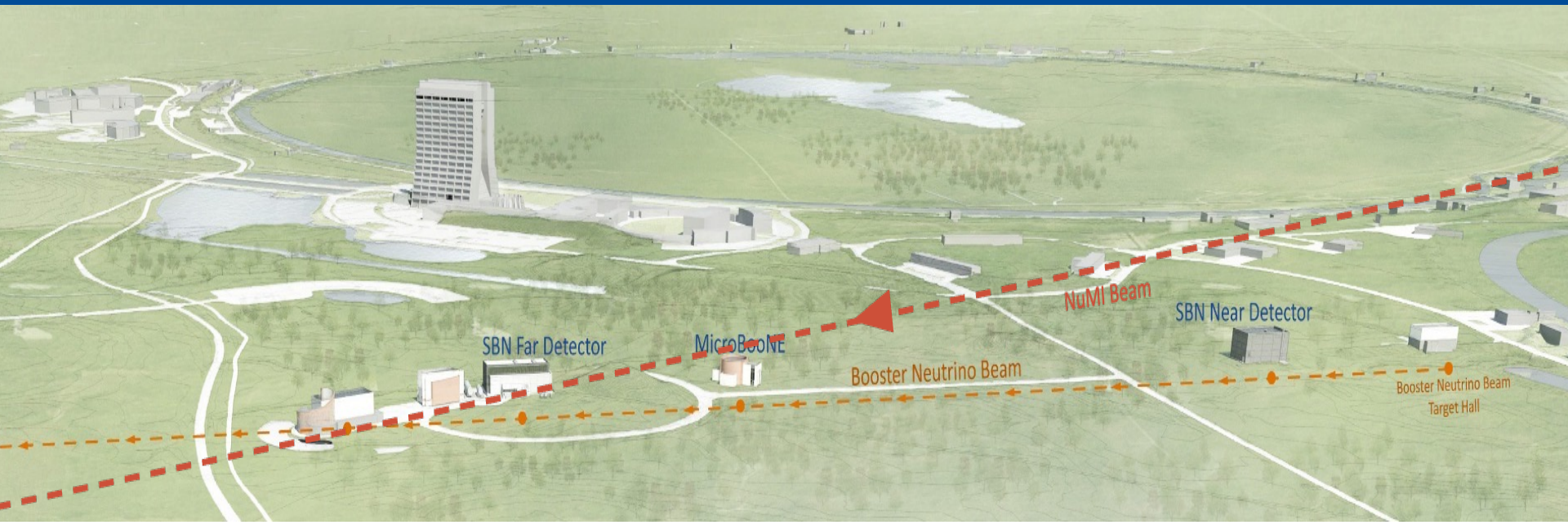


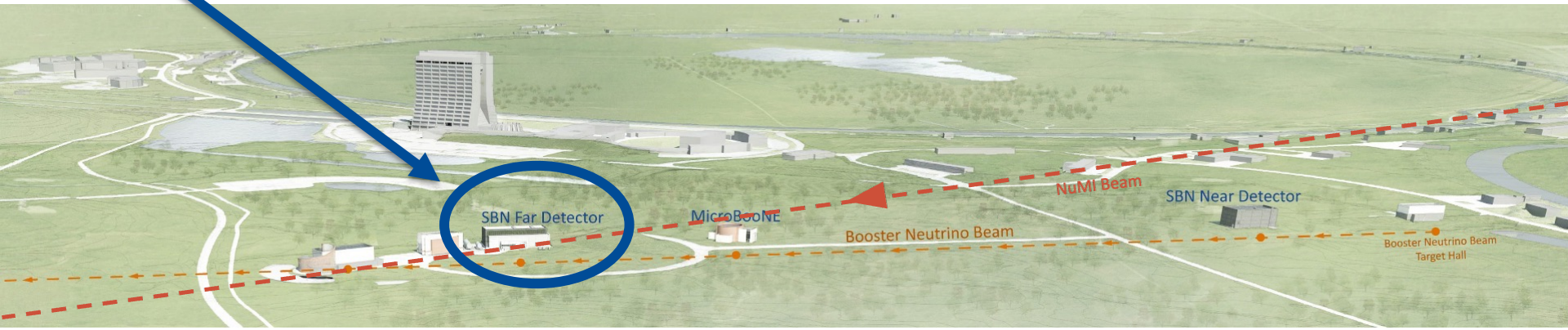
BSM Physics at ICARUS: Status and Plans

Jamie Dyer (Colorado State University)
on behalf of the ICARUS Collaboration

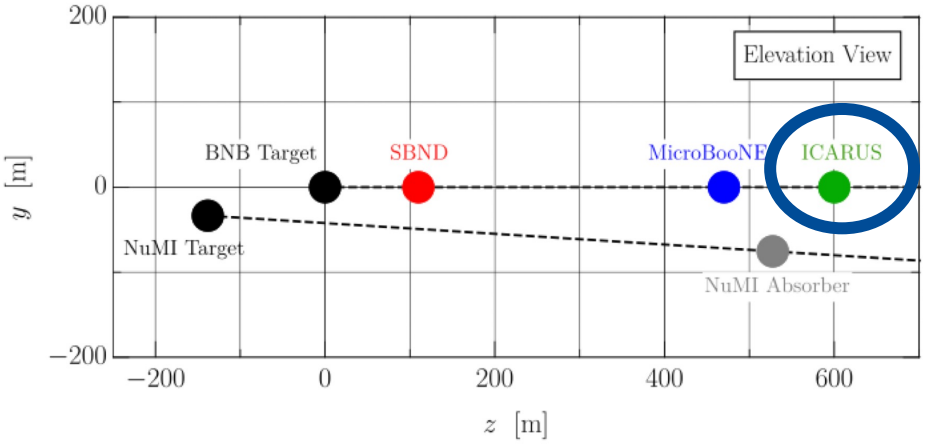
2nd Short-Baseline Experiment-Theory Workshop
Los Alamos National Laboratory | April 2-5, 2024

In partnership with:

ICARUS within SBN



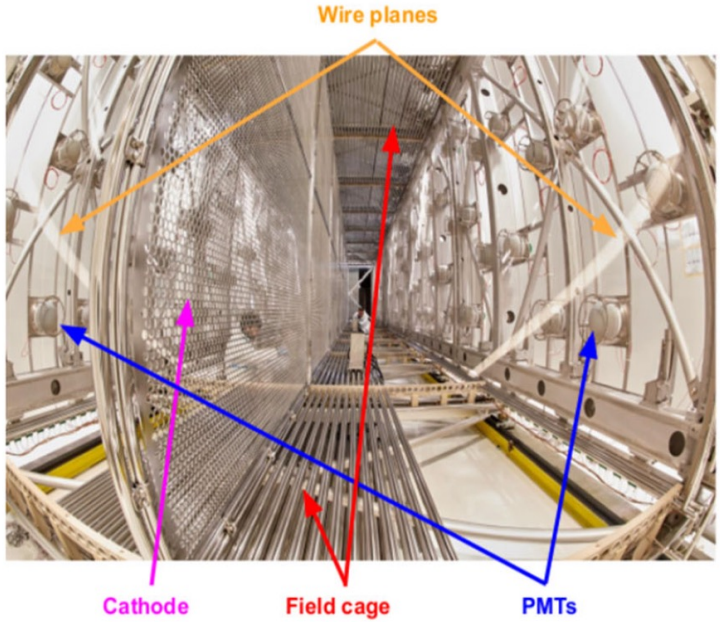
- On-axis exposure to BNB enables neutrino oscillation measurements
- **5.75° off-axis exposure to NuMI beam** facilitates neutrino cross section measurements + searches for exotic physics originating from heavy mesons.



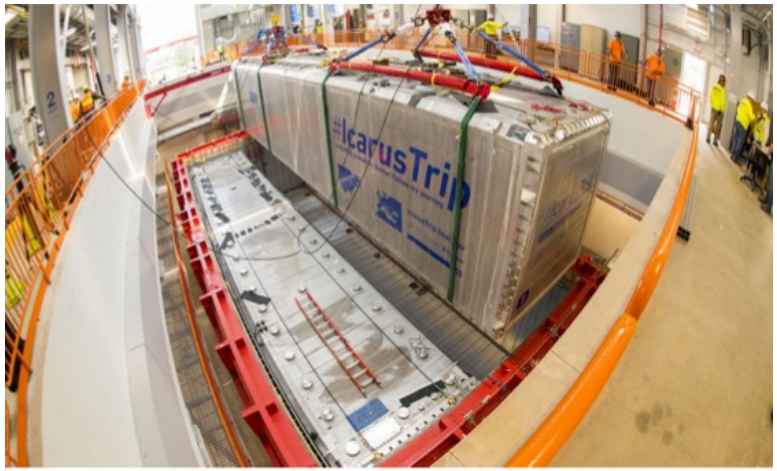
Elevation view of SBN experiments wrt BNB and NuMI beamlines.
B. Batell, J. Berger,and A. Ismail, Phys. Rev. D 100, 115039 (2019)

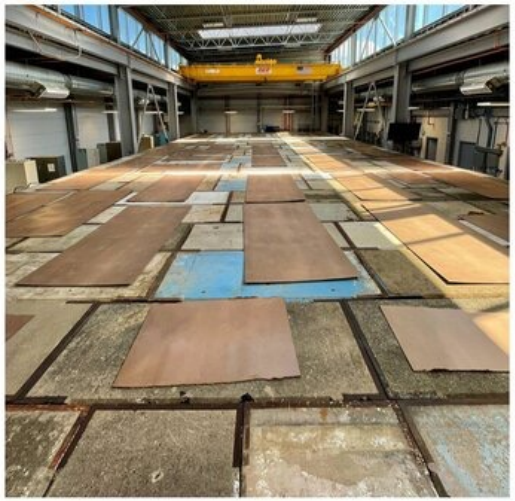
Detector Overview

- 2 cryostats each with two TPCs separated by cathode plane, for a total of 760 tons LAr in active volume.
- 360 PMTs cover anode planes for ~ns timing res.
- 3m concrete overburden above detector reduces cosmic activity from above
- Scintillator material surrounding ICARUS (CRT subsystem) tags throughgoing cosmic rays that enter and exit the detector.
- See Minerba's and Alice's talks for more detail.



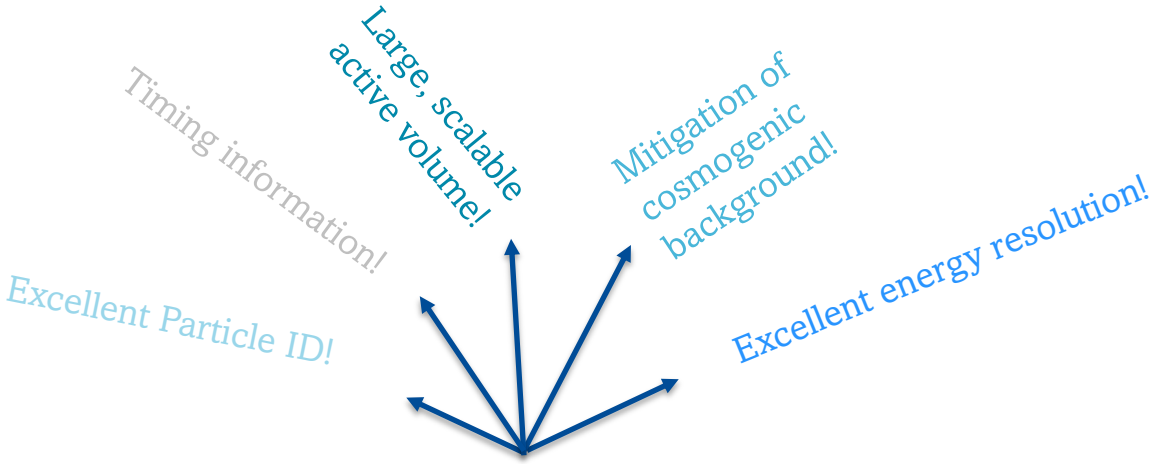
DOI: http://doi.org/10.1140/epjc/s10052-023-11610-y

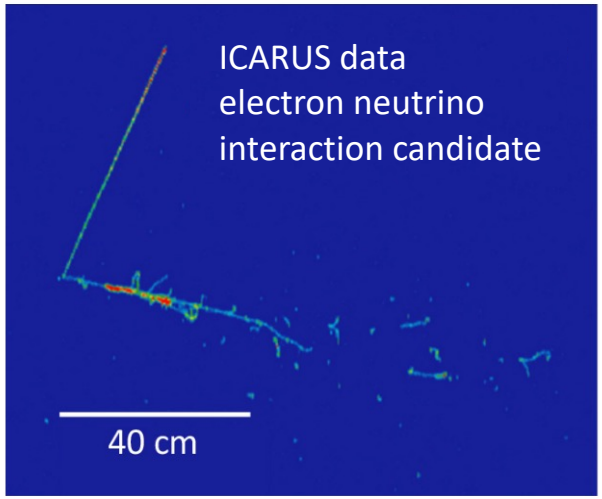




3 X 10^20 NuMI POT data collected in Runs 1 and 2.

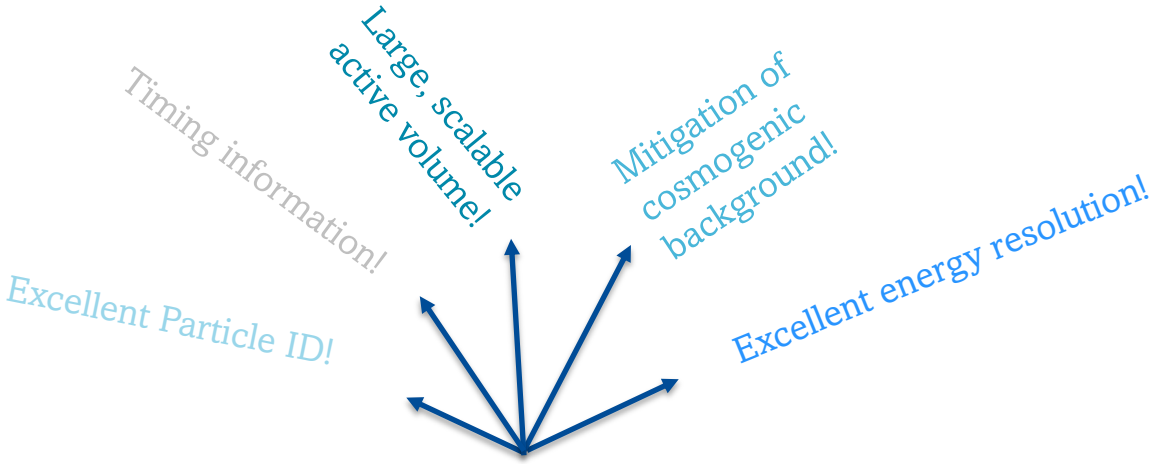
ICARUS as an Opportunity for Discovery!

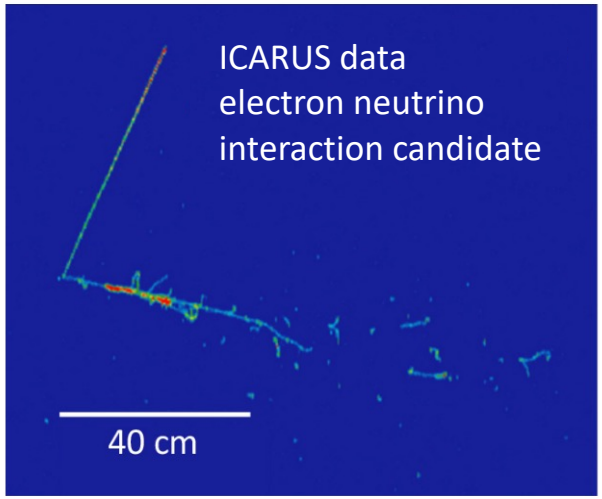




The same characteristics that make **LArTPCs/ICARUS great for studying** neutrino physics…

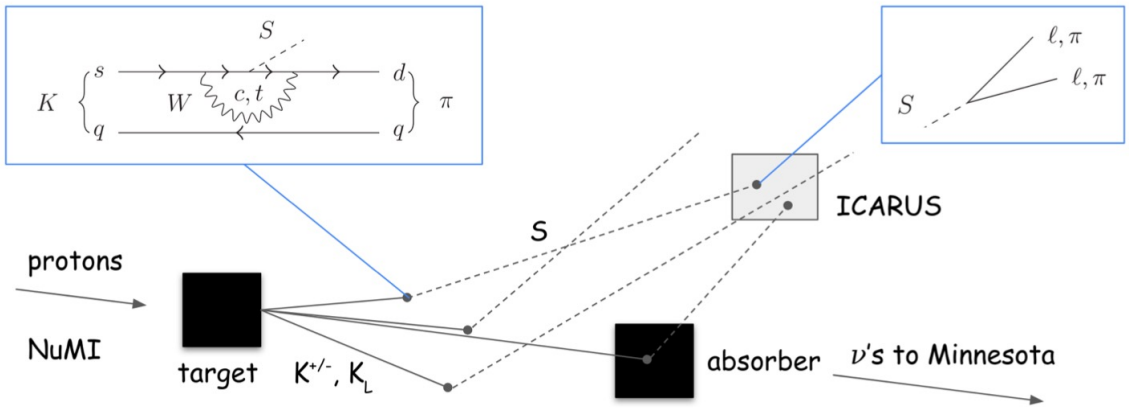
ICARUS as an Opportunity for Discovery!





The same characteristics that make **LArTPCs/ICARUS great for studying** neutrino physics…

… also make it great for studying **ANY physics process** that results in SM final state particles inside the active volume.

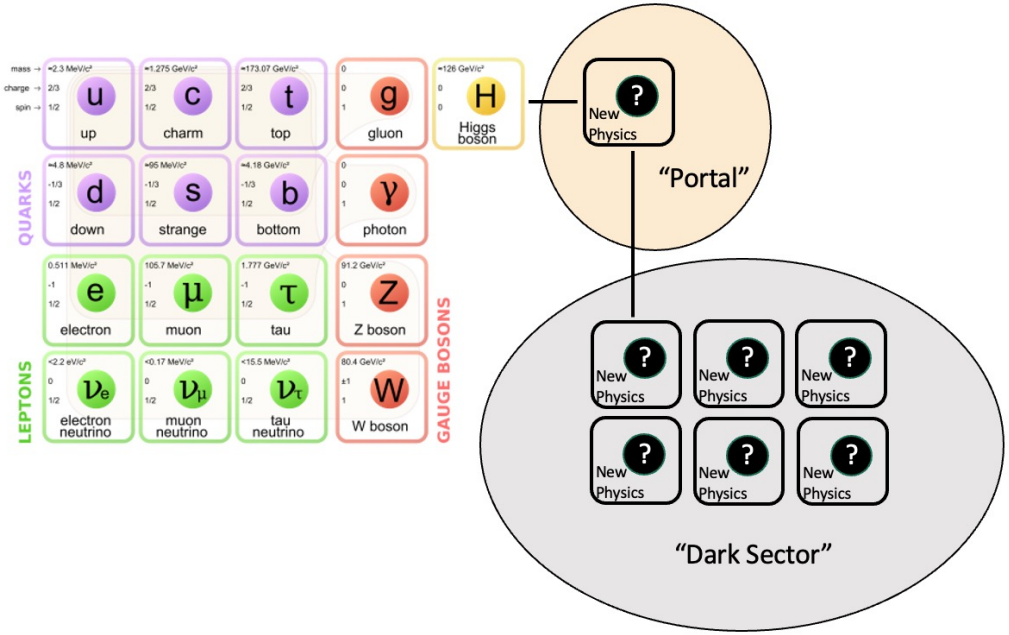


Fermilab

~~Probable~~ Probe-able Dark Sector Models at ICARUS

- Simplest link to BSM physics is through portal in which a dark sector particle mixes with an SM particle.

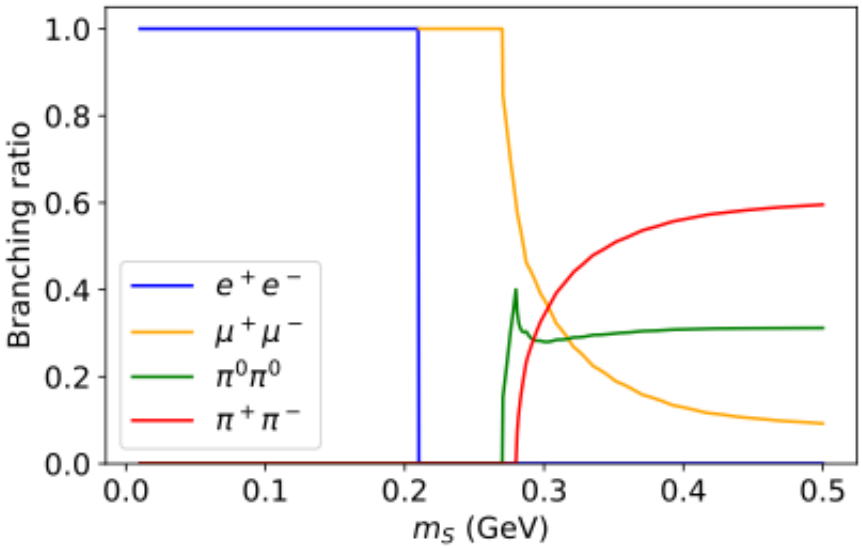
- ICARUS can be used to search for 100s MeV mass portal particles belonging to the following classes of models:

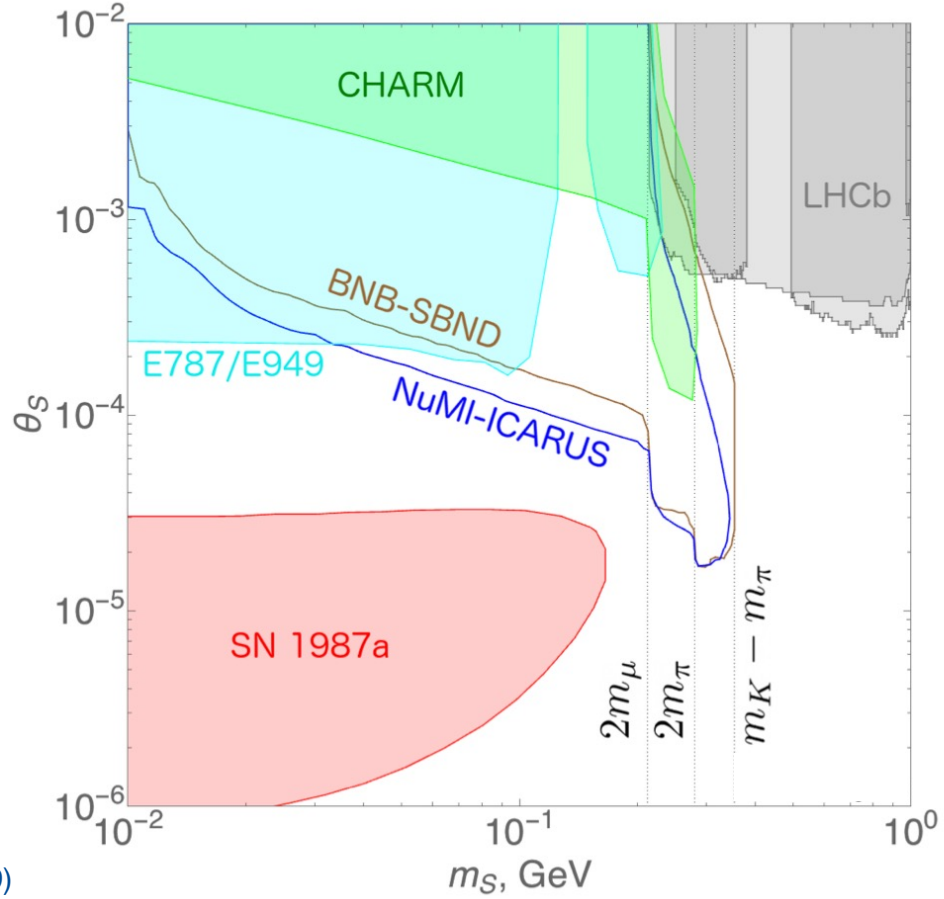


  - **Higgs Portal Scalar (HPS)**: dark scalar mixes with the Higgs boson
  - **Heavy QCD Axion Model**: Heavy particle couples to SM via gluonic mixing
  - **Heavy Neutral Lepton (HNL):** dark fermionic particles mix with SM neutrinos through extension of PMNS matrix
  - **Vector Portal DM**: dark sector fermions couple to SM via kinematic mixing of SM- and dark-sector photons

Higgs Portal Scalar (HPS)

- Dark scalar particle (**S**) mixes with the Higgs boson via angle $\boldsymbol{\theta}$
- **Production at ICARUS**: $K_{NuMI} \rightarrow \pi S$
- **Decay**: $S \rightarrow e^- e^+, \mu^- \mu^+, \pi\pi$

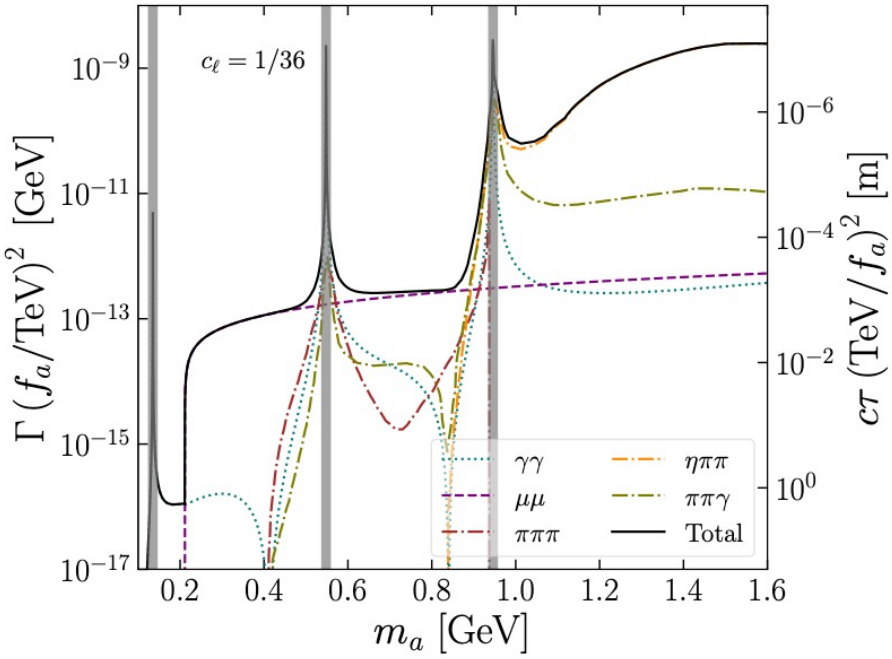


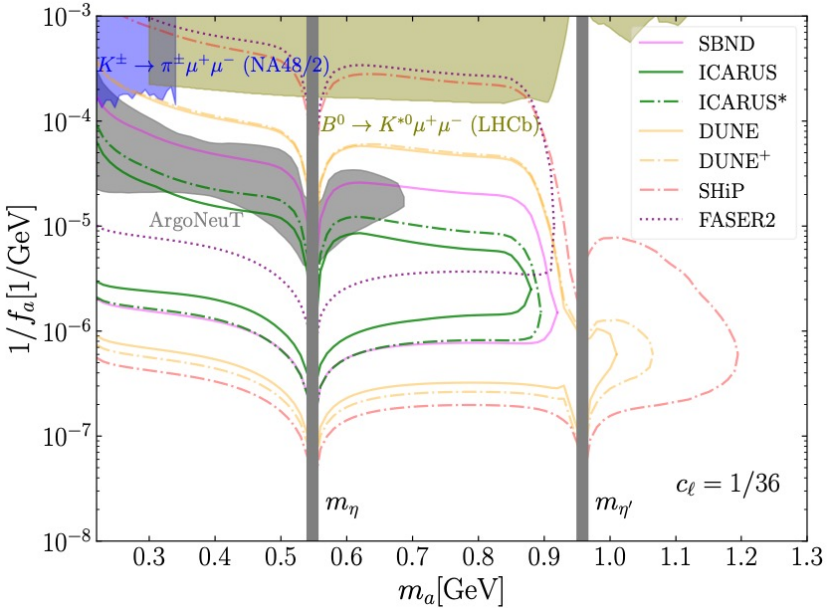


HPS branching ratio and phenomenological projection plots:
B. Batell, J. Berger,and A. Ismail, Phys. Rev. D 100, 115039 (2019)

Heavy QCD Axions

- Alleviates strong CP problem via gluonic coupling to SM.
- Leptonic coupling (c_l) allowed, as well as other gauge couplings.
- Axion couplings to all SM fields depend on the axion decay constant f_a.
- **Production at ICARUS**: mixing with pseudoscalar mesons in NuMI (eg π^0, η, η')
- **Decay at ICARUS**: $a \rightarrow \mu^- \mu^+$

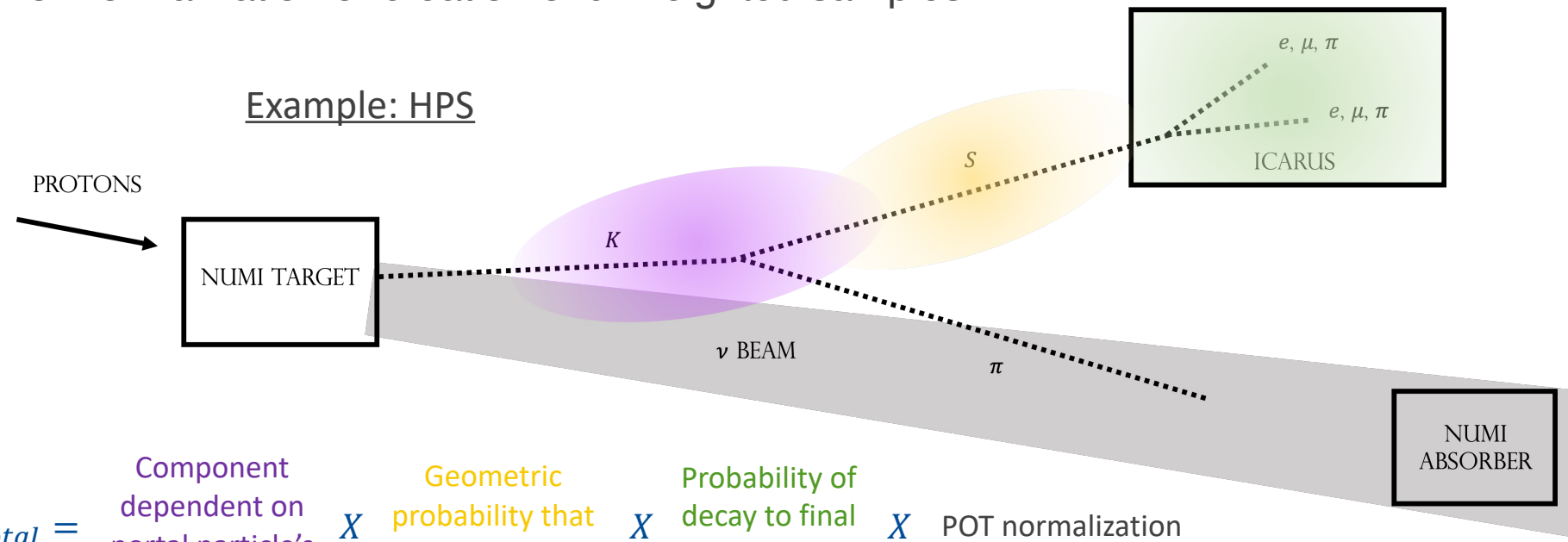




Plots:
R.T. Co, S. Kumar, and Z. Liu. *Searches for heavy QCD axions via dimuon final states.* Journal of High Energy Physics, 2023(2).

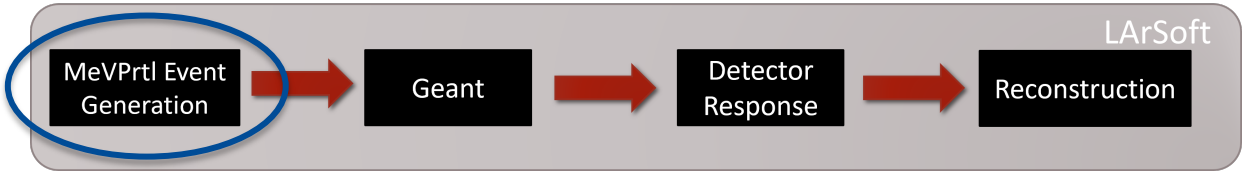
BSM Event Generation at ICARUS

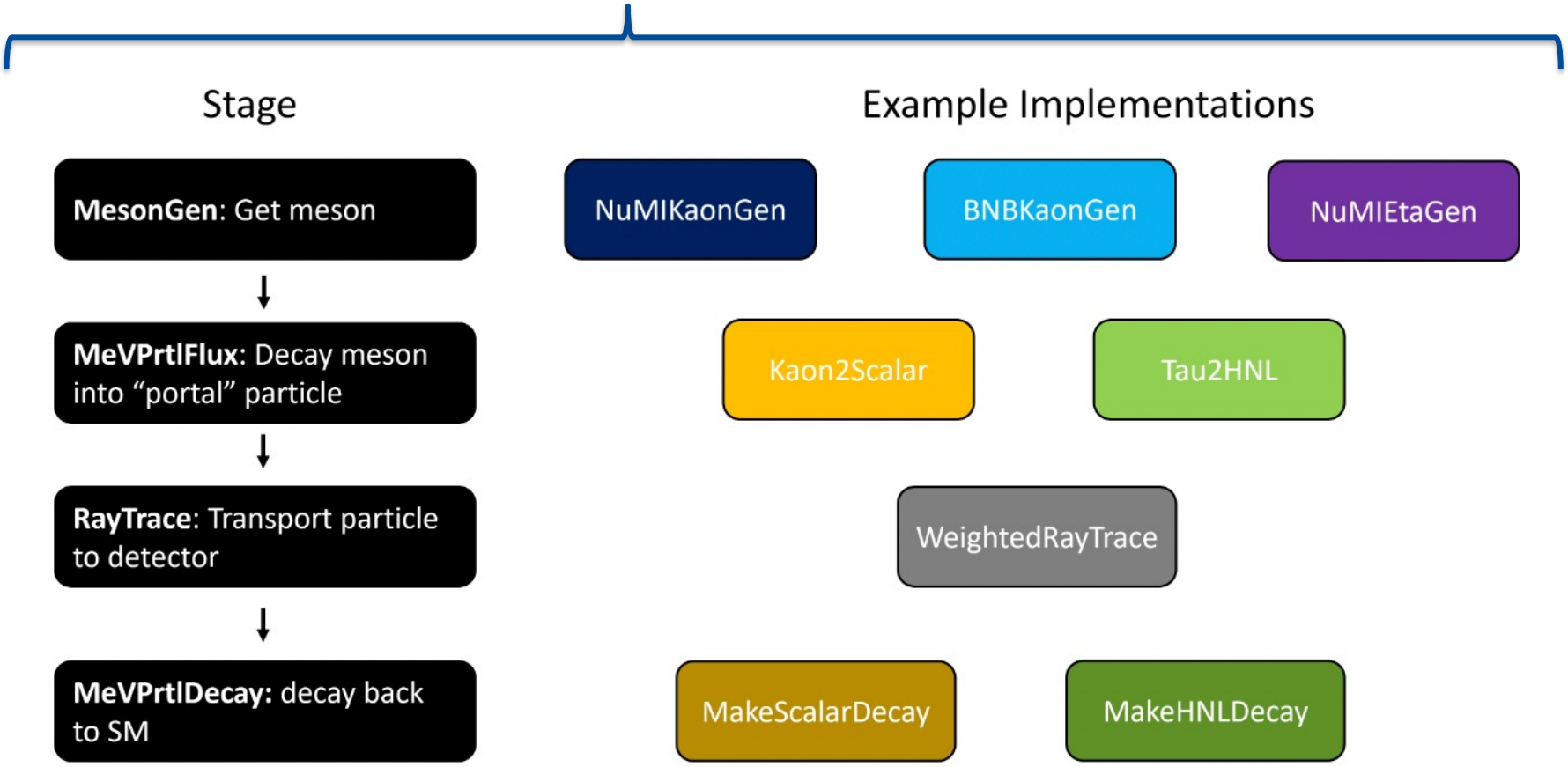
- Ongoing ICARUS BSM analyses use ***MeVPrtl*** for Monte Carlo event generation, which has been developed by SBN collaborators for the SBN program.
- ***MeVPrtl*** is configurable for any combination of beam (BNB or NuMI), detector (SBND or ICARUS), and model (HPS, Heavy QCD axion, HNL).
- It generates the kinematics of desired events, as well as event weights to be used for normalization or creation of unweighted samples.



$W_{total} =$ Component dependent on portal particle's parent X Geometric probability that BSM particle impinges detector X Probability of decay to final state inside detector X POT normalization

MeVPrtl Generator





- ***MeVPrtl*** github repository: https://github.com/SBNSoftware/sbncode/tree/develop/sbncode/EventGenerator/MeVPrtl
- Internal tech note for generator available to SBN collaborators; public version in progress

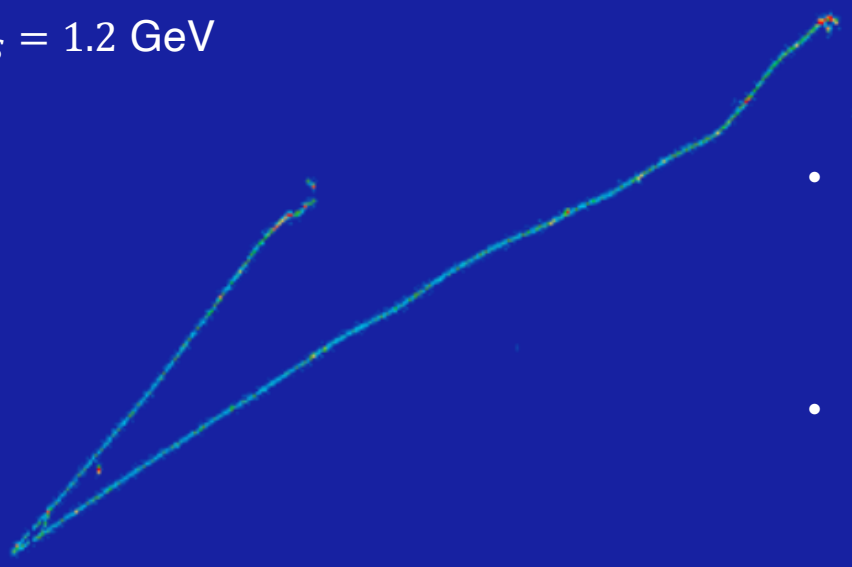
ICARUS's first iteration of BSM analyses hone *Dimuon Final State*

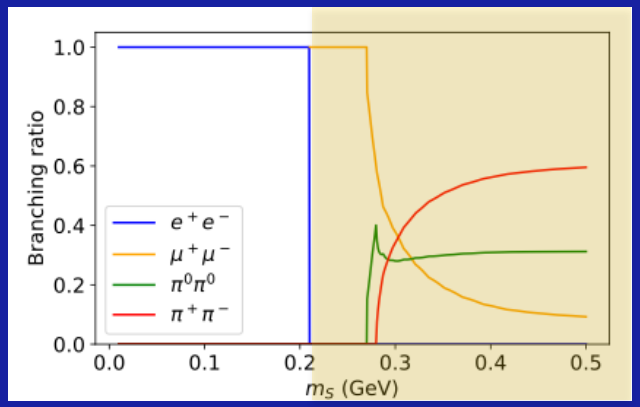
ICARUS Monte Carlo

$S \rightarrow \mu\mu$

$m_S = 260$ MeV

$E_S = 1.2$ GeV





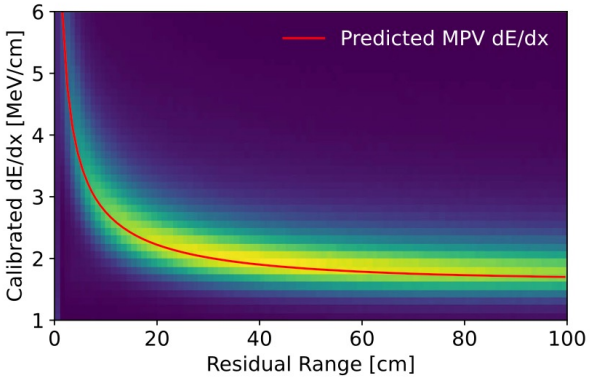
B. Batell, J. Berger,and A. Ismail, Phys. Rev. D 100, 115039 (2019)

- Dimuon final states from BSM particle decays produce clear topological signature in TPC readout.
- Background:
  - cosmic muons (subleading)
  - ν_μ events, primarily ones that have a muon and pion in the final state (leading)
- Analysis with fully contained tracks is very mature, complimentary analysis for partially contained tracks rapidly progressing.

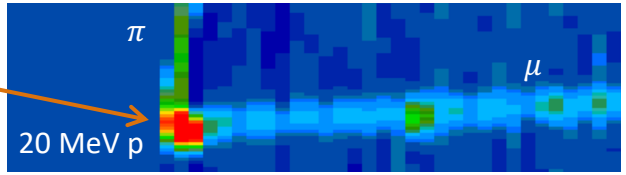
Contained Dimuon Final State Analysis: Event Selection

Selection criteria

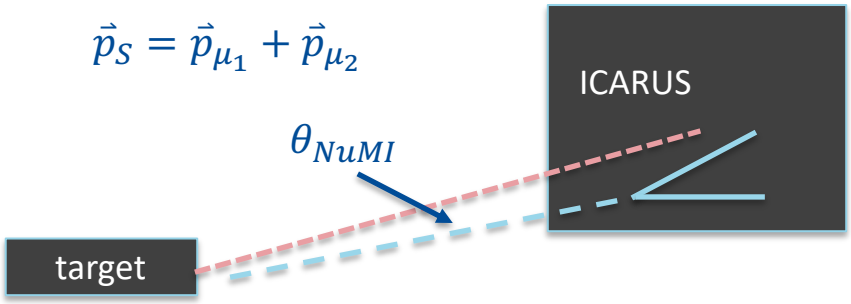
- **Preselection**: events with two fully contained tracks connected at vertex
- **Object cuts**: remove events with significant showers or extra tracks
- **Muon ID**: enforce track calorimetry consistent w/ muon expectation
- Remove interactions with low-energy protons by identifying extra charge near vertex, aka "**stub**"
- **Kinematics**: require small θ_{NuMI}



Calibrated collection plane dE/dx for sample of stopping muons in ICARUS
DOI:10.1140/epjc/s10052-023-11610-y

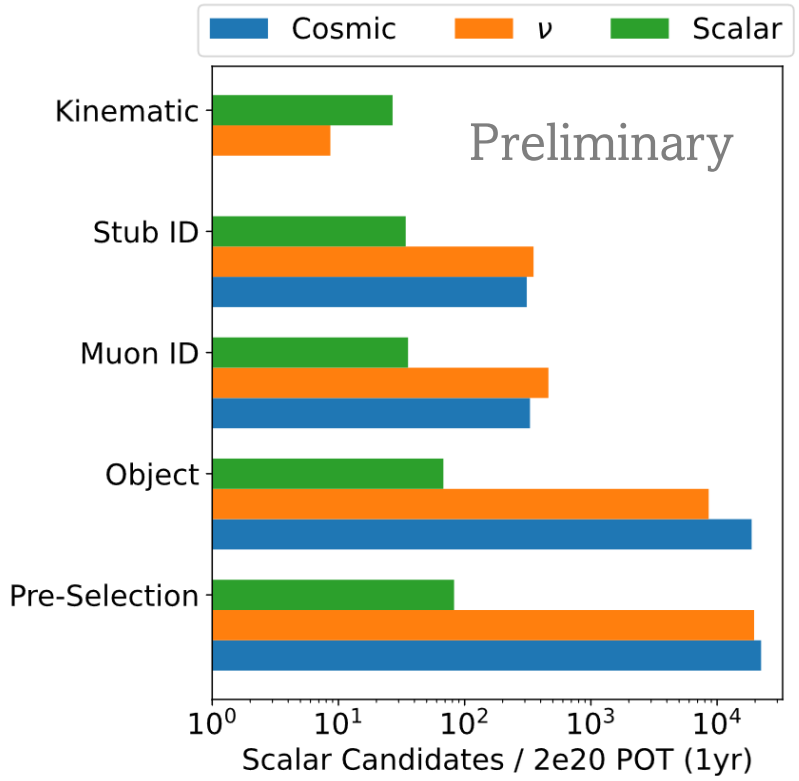


$\vec{p}_S = \vec{p}_{\mu_1} + \vec{p}_{\mu_2}$



reconstructed incident neutrino direction is complicated due to "missing" visible energy of final state neutrino, smearing from Fermi momentum of nucleon.

Contained Dimuon Final State Analysis: Event Selection



Selection efficiency for HPS model benchmark $m_S = 260$ MeV, $\theta = 5e-5$

After event selection…

- ~all cosmic background is eliminated
- **The dominant background is charged current neutrino interactions undergoing coherent pion production**:

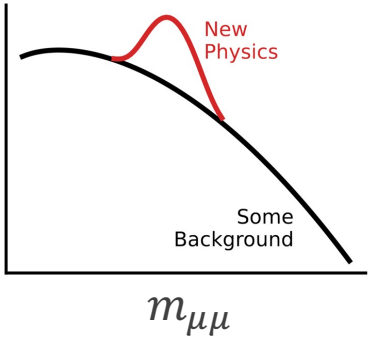
Argon nucleus

$$\upsilon_\mu + A \rightarrow \mu + \pi + A$$

  - charged pions are calorimetrically difficult to distinguish from muons
  - small energy transfer from υ to A means visible momentum is oriented along $\vec{p}_\upsilon$

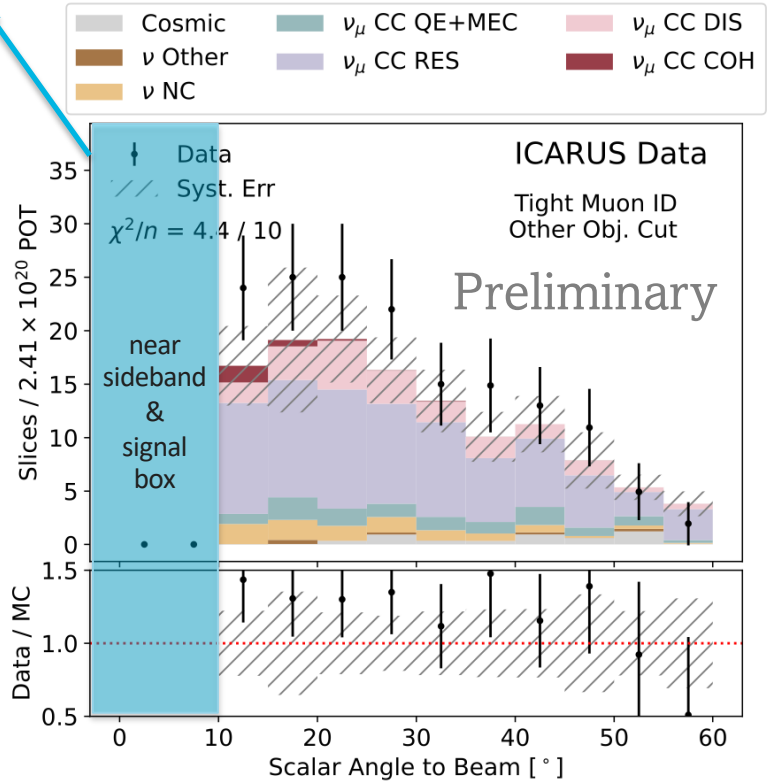
Fermilab

Contained Dimuon Final State Analysis: Search Strategy



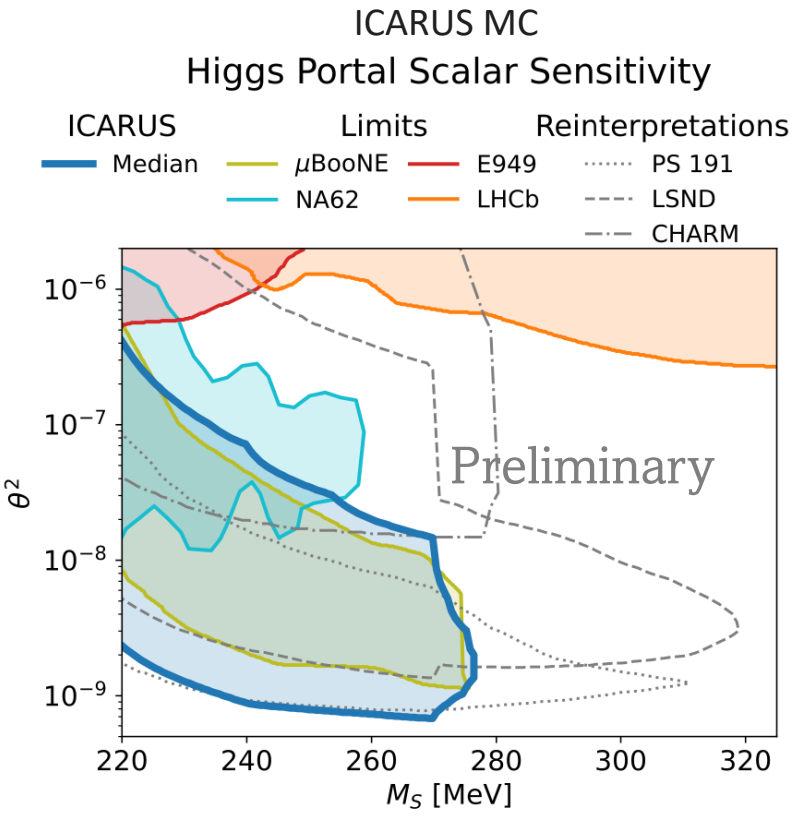
- Perform a **bump hunt** for the dimuon invariant mass with selected events. Signal box is defined by small $\boldsymbol{\theta_{NuMI}}$ (after application of other cuts).

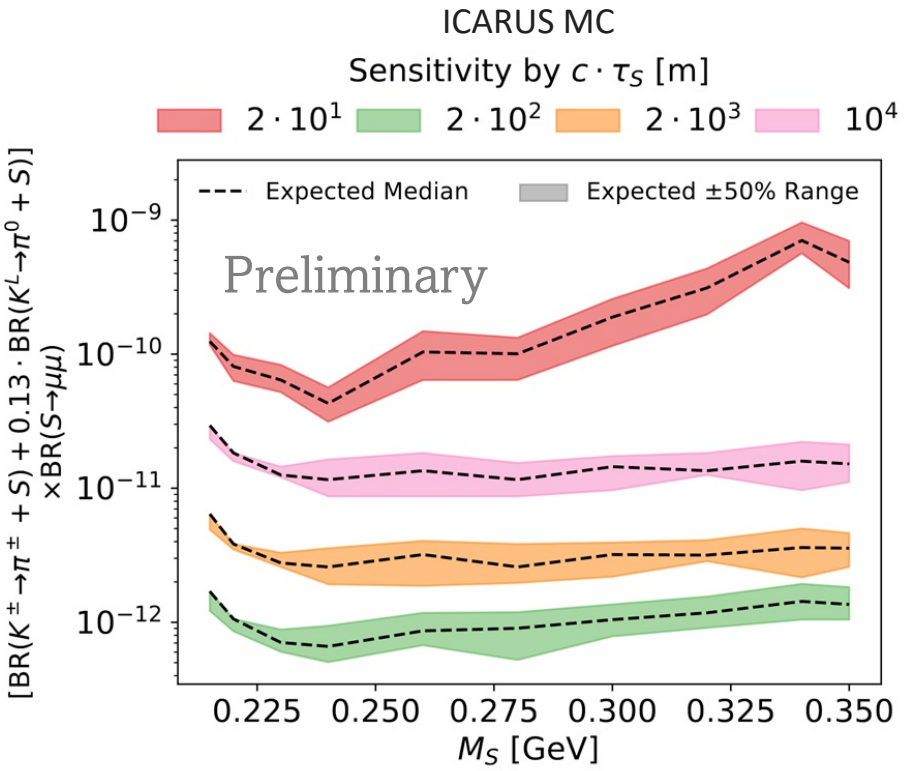
- Both the event selection and our understanding of the coherent pion background have been validated with data/MC comparisons in sideband regions.



Fermilab

Contained Dimuon Final State Analysis: Projected Sensitivities





- HPS sensitivity in (θ, m_S) can be recast to model independent sensitivity
- Contours show 90% confidence limit

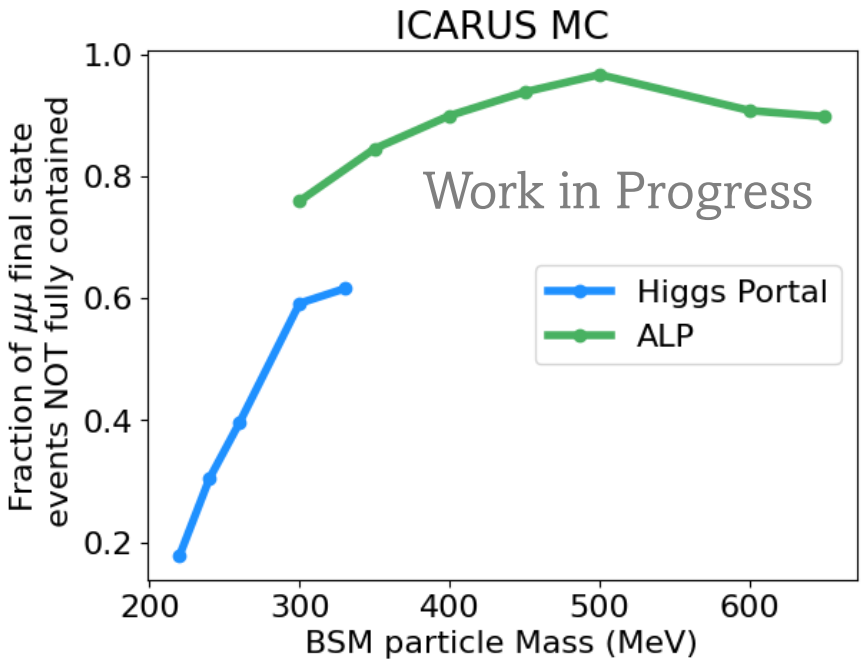
A Complimentary Search: Uncontained Dimuon Final States

- The previous analysis utilizes dimuon final states fully contained in the ICARUS fiducial volume. However, sensitivity to HPS is increased with complimentary event selection for exiting muons.
- Furthermore, a selection for exiting muons also gains us sensitivity to Heavy QCD Axions originating through mixing with π^0, η, η', which tend to be more energetic.

Simulated sample model benchmarks:

Model	Mass (MeV)	θ_S (HPS) or f_a (axion)
HPS	220, 240, 260	5e-5
	300	3e-5
	330	2e-5
Heavy QCD axion	300, 350, 400, 450, 500	e5
	600, 650	e6

(All axion samples generated with c_l= 1/100)



Uncontained Dimuon Final States: Event Selection

Selection criteria

- Preselection
- Object cuts
- Muon calorimetric ID for both tracks
- Stub ID
- Kinematics
  - θ_{NuMI}

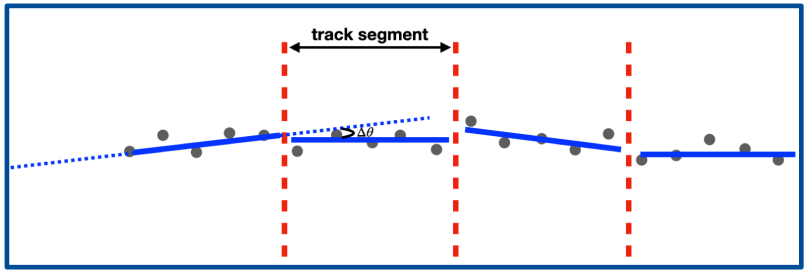
Uncontained Dimuon Final States: Event Selection

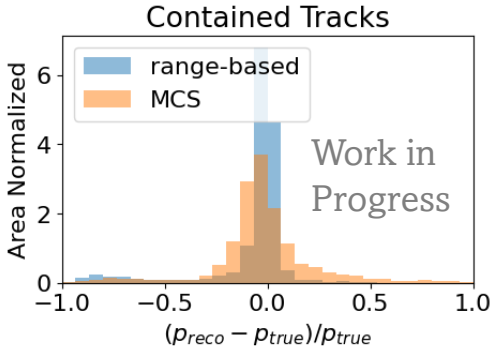
Selection criteria
(differences from contained dimuon selection in orange)

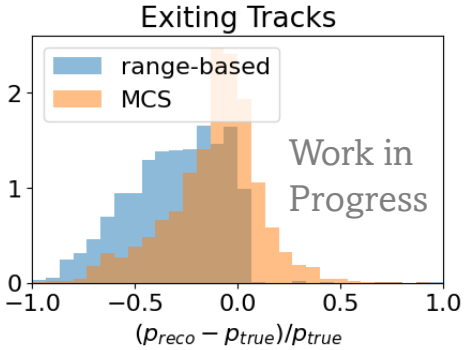
- Preselection
- Object cuts
- Muon calorimetric ID for both tracks
- Stub ID
- Kinematics
  - θ_{NuMI}

  *__Multiple Coulomb Scattering__ is used to reconstruct track momentum, instead of range-based momentum reconstruction.

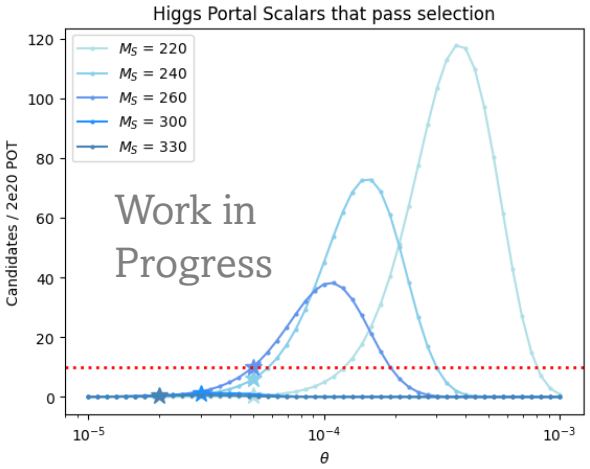
  - $\theta_{\mu\mu}$ (require small)
- Require that both tracks are long ($\gtrsim$ 1m)
  - goal with this cut is to eliminate persistent $1\mu1\pi$ background.

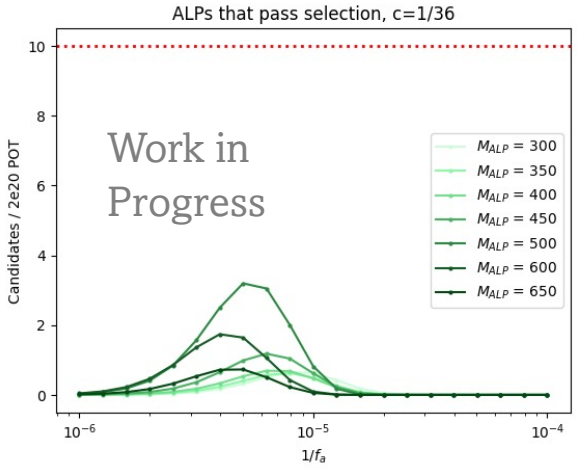


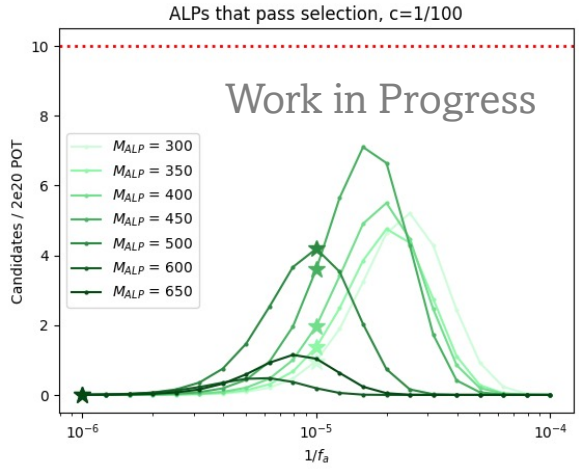


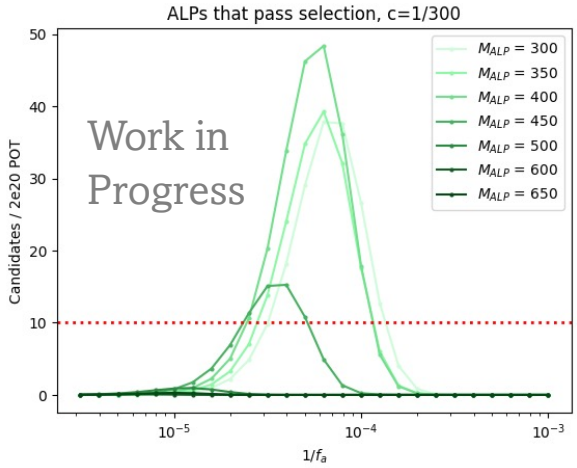


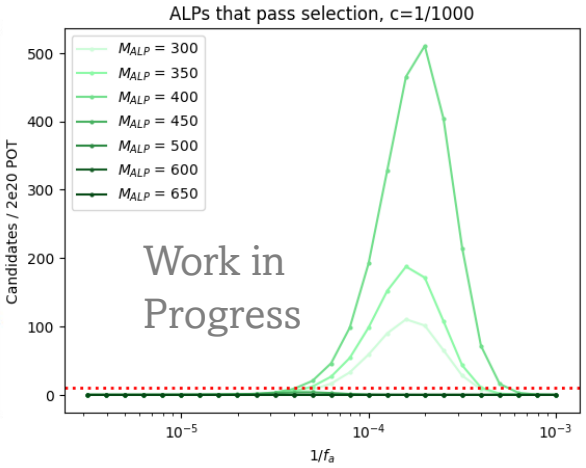
Uncontained Dimuon Final States: Monte Carlo Projections











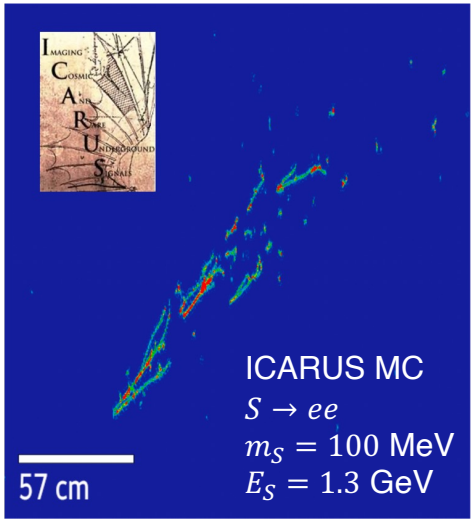
- Stars mark benchmarks used for MC simulation.
- We can expect sensitivity to Higgs Portal scalars with $m_S \lesssim 260$ MeV.
- We can expect sensitivity to heavy QCD axions with $m_{ALP} \lesssim 450$ MeV, with small c_1.

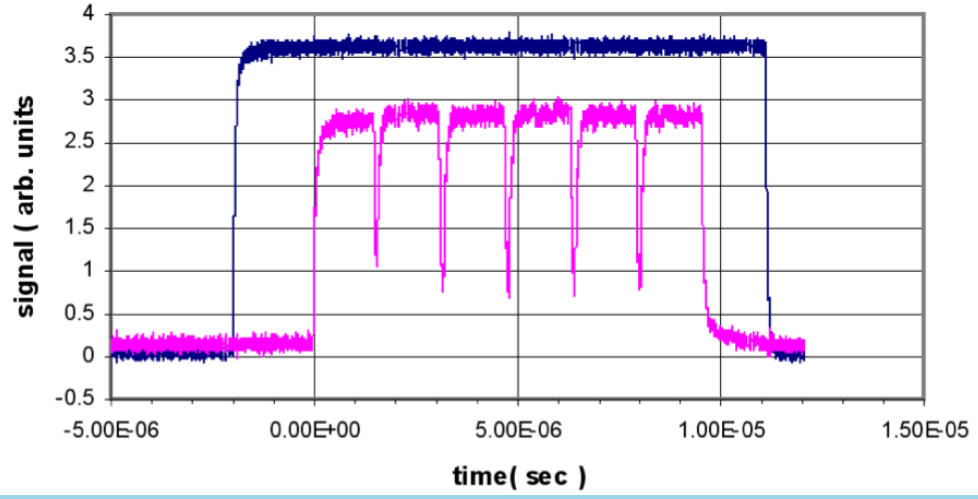
Further work for this analysis is in progress!

Further Opportunities for BSM Physics at Icarus

We can probe more models or push our sensitivity to HPS & Heavy QCD Axions with the following strategies:

- alternate final states, eg resulting in γ or e showers
- unique signature of physics originating in the absorber
  - "backward going" direction of final state particles
  - monoenergetic
- delayed timing of BSM signatures w.r.t. ν interactions for model independent search (ICARUS PMTs already demonstrate promising reconstruction ability in data!)





Left:
Pink: NuMI beam structure (oscilloscope trace of proton beam structure in NuMI Toroid)
Blue: beam trigger window

Blake, A.; Thomson, M. A.; Aurisanob, A.; Devan, A. V.; Kordosky, M.; Nelson, J. K.; Radovic, A.; Vahle, P.; and Yumiceva, F. X., *The NuMI neutrino beam (2016). Nuclear Instruments and Methods in Physics Research Section A-Accelerators Spectrometers Detectors and Associated Equipment*, 806, 279-306. 10.1016/j.nima.2015.08.063

Summary

- Positioned 6° off-axis the NuMI beam at FNAL, ICARUS is uniquely positioned to probe New Physics originating from heavy mesons.

- SBN has an in-house event generator, ***MeVPrtl***, whose modularity accommodates various BSM searches at ICARUS or SBND while eliminating unneeded redundancy of code.
  - Can be expanded to include more models, experiments (DUNE?).
  - Public description of tool is in draft.

- Advanced analyses leveraging the unique TPC topology of dimuon final states will soon discover or set limits on Higgs Portal Scalar and Heavy QCD Axion models.

- There is much more opportunity for discovery, leveraging alternate final state topologies, unique singals from meson decay-at-rest in the NuMI absorber, and timing with ~ns resolution from the PMT subsystem.

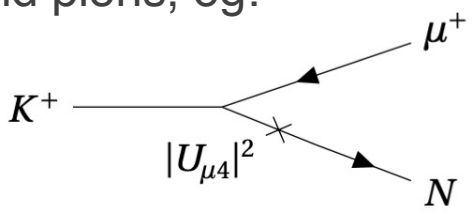
- Stay posted for a lot of exciting physics!

Thank you!

Backup

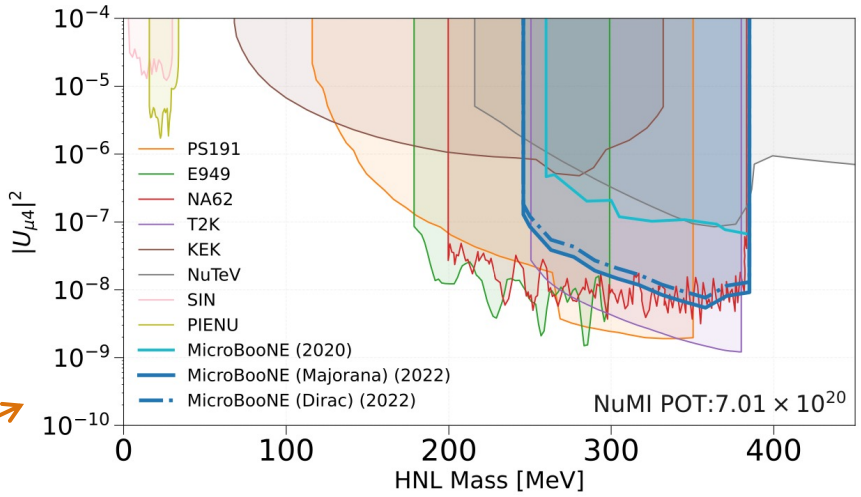
Heavy Neutral Leptons

- Dark fermionic particles mix with MS neutrinos through extension of the PMNS matrix.
- Can show up in place of neutrino in any interaction, so long as kinematically allowed
- Heavy mass allows them to be DM candidates, able to decay
- **Production at ICARUS**: produced in decay of charged kaons and pions, eg:



- **Decay at ICARUS:**

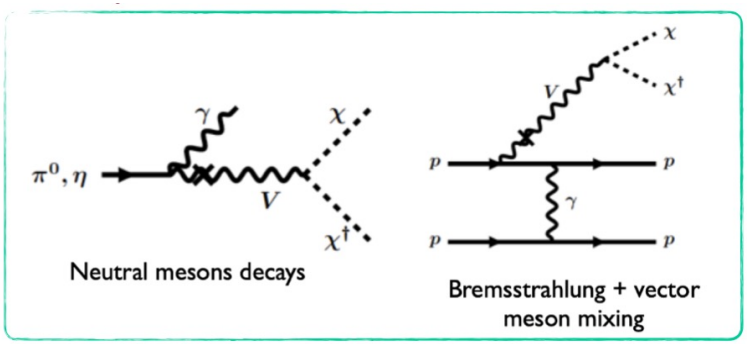
$$N \to e^- e^+ \nu \qquad N \to e^{\mp} \pi^{\pm}$$
$$N \to e^{\mp} \mu^{\pm} \nu \qquad N \to \mu^{\mp} \pi^{\pm}$$
$$N \to \mu^- \mu^+ \nu \qquad N \to \nu \pi^0$$

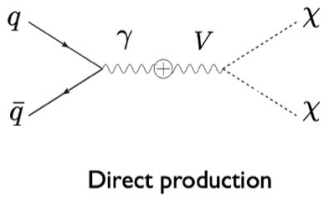


MicroBooNE result using $\mu^{\mp}\pi^{\pm}$ channel
DOI: https://doi.org/10.48550/arXiv.2207.03840

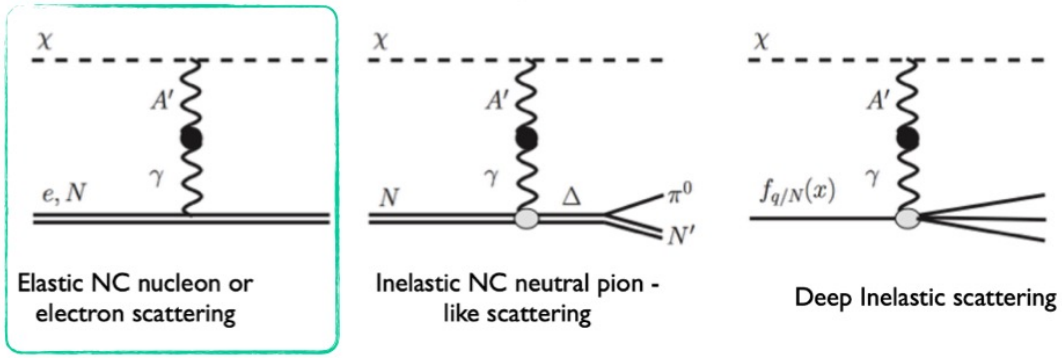
Vector Portal Dark Matter

- dark sector fermions couple to SM via kinematic mixing of SM- and dark-sector photons
- **Production at ICARUS**:





- **Detection via scattering**:



NuMI Neutrino Flux w.r.t. θ_{NuMI}, E_υ