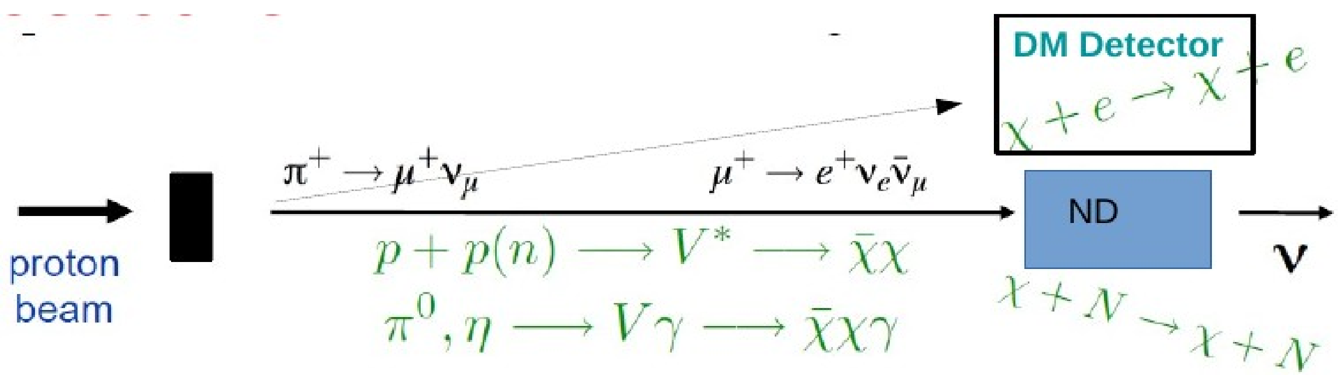
“Path to Dark Sector Discoveries at Neutrino Experiments”

COLORADO STATE UNIVERSITY

SBN Program

Overview: Status of non-oscillation Searches at the SBN Program



Vittorio Paolone (University of Pittsburgh)

Motivation

- **Exploit intense proton beams of the short baseline neutrino (SBN) experiments**
- **The excellent reconstruction capabilities of liquid argon time-projection chambers (LArTPCs)**
- **The SBN experiments are sensitive to dark sector models with masses in the 100s of MeV/c^2 mass range.**
- **The dark sector particles can be copiously produced in SBN beams, propagate into the detectors, and decay or scatter into visible signals.**

Quick Review: Dark Sector Models

- Simplest way dark sector particles interaction with the standard model are via portal interactions:

  → The dark sector particle mixes with a SM particle – usually neutral

- These portals fall into these general categories.

  → Higgs portal model: Scalar dark sector particles - interactions by mixing with the Higgs boson

  → Heavy Neutral Lepton (HNL) models: Fermionic particles - interactions by mixing with neutrinos

  → Heavy QCD axion models: Pseudoscalar particles - interactions by mixing with pseudo-scalar mesons

  → Vector portal: Vector particles – interactions by mixing with the photon

Quick Review: Dark Sector Models cont.

- **Higgs Portal Model:**

→ Mediator between the SM and dark sector model:singlet scalar particle (S) mixes with the Higgs boson.

→ Characterized by the mass of the scalar m_S and the mixing angle with the Higgs θ.

→ Mixing angles down to order 10^{-4} can be probed by the SBN LArTPCs.

→ In particular, scalars produced from NuMI kaons and decaying to e, μ, or pion pairs in ICARUS have the greatest projected sensitivity in the range $m_S \approx 40 - 360$ MeV

- **Vector Portal:**

→ Typically produced in proton beam dump:

→ Pseudoscalar meson decay: Low mass dark photons may be efficiently produced through the decays of π^0 , η, $\eta^0 \to \gamma V$ or Proton bremsstrahlung: directly produced via bremsstrahlung, $pp \to pV X$,

→ Detected via scattering in detector: Cross section (10^{-34} cm^2), masses (few 100 MeVs)

Quick Review: Dark Sector Models cont.

- **HNL Model:**

→ HNLs could couple to the other neutrinos through an extension of the PMNS matrix.

→ The SBN program can search for HNLs in a variety of masses from 20-30 MeV up to 388 MeV.

→ HNLs can be coupled to all SM neutrinos: $U_{\alpha 4}$ (α= neutrino flavor)

→ The main contributing decay channels for the sensitivity to $U_{\mu 4}$ coupled HNLs are:

→ The $e+e-\nu$ channel for the (20,150 MeV) mass region

→ The $\nu\pi^0$ channel for intermediate masses

→ The $\mu\pi$ channel for the upper mass (~250 MeV to 388 MeV), including the di-muon channel $\mu+\mu-\nu$.

Quick Review: Dark Sector Models cont.

- **Axion Model:**

→ Decays of heavy (M_a ~ GeV) These QCD axions are not dark matter candidates but could solve the Strong CP problem

→ In SBN, axions with a gluonic coupling would be produced by mixing with psuedoscalar mesons.

→ Axions would decay to a variety of final states: γγ, πππ, ππγ, as well as μ and e pairs if it has leptonic couplings.

→ Axions can also interact with electrons in the detector.

→ The axion has a mass m_a and a decay constant f_a , both are free parameters.

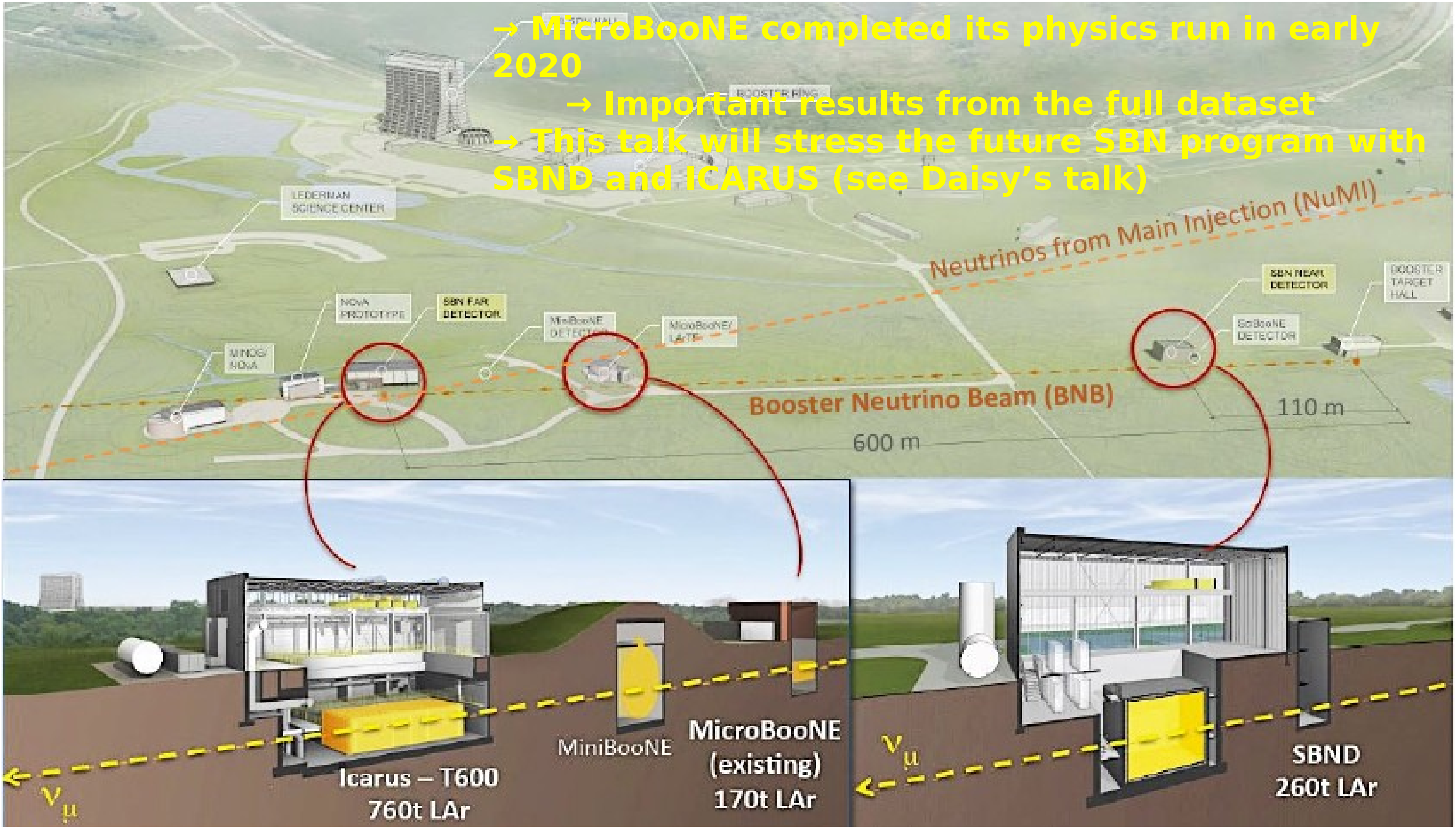
→ SBN will explore phase space where the mixing between the axion and SM particles is small, therefore they are long lived

SBN Overview

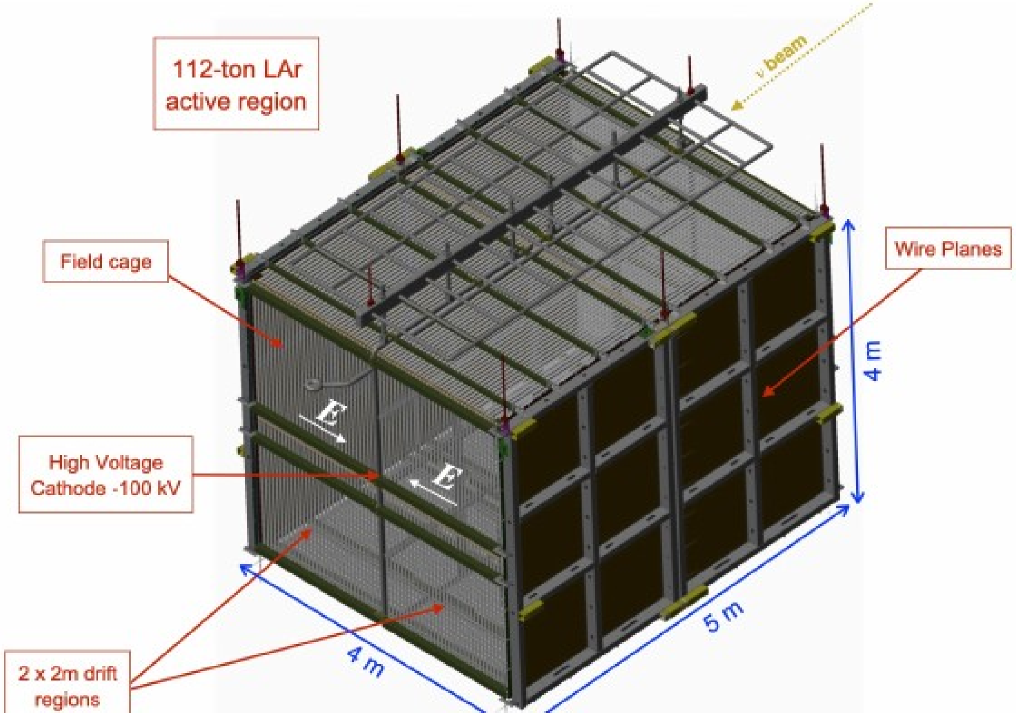
→ MicroBooNE completed its physics run in early 2020

→ Important results from the full dataset

→ This talk will stress the future SBN program with SBND and ICARUS (see Daisy's talk)

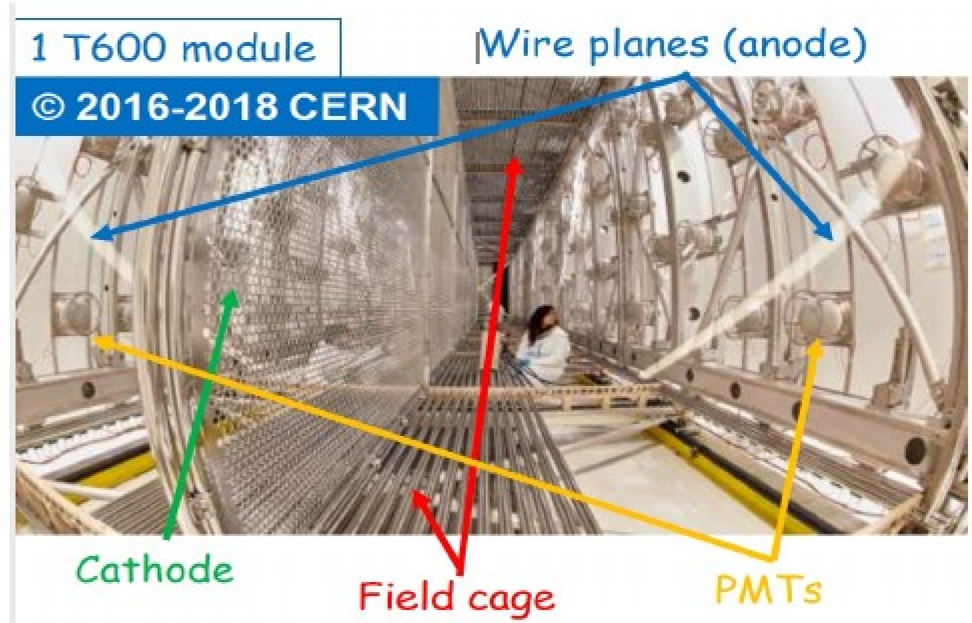


SBND Detector: LArTPC



→ New detector: 4 x 4 x 5m^3, 112 t active mass LAr
→ 2-m drift, 120 PMTs, 196 X-Arapuca photon detectors (precision timing)
→ Installation complete and expected to be ready for filling in July 2023
→ Expect to be operational in late 2023

ICARUS Detector: LArTPC

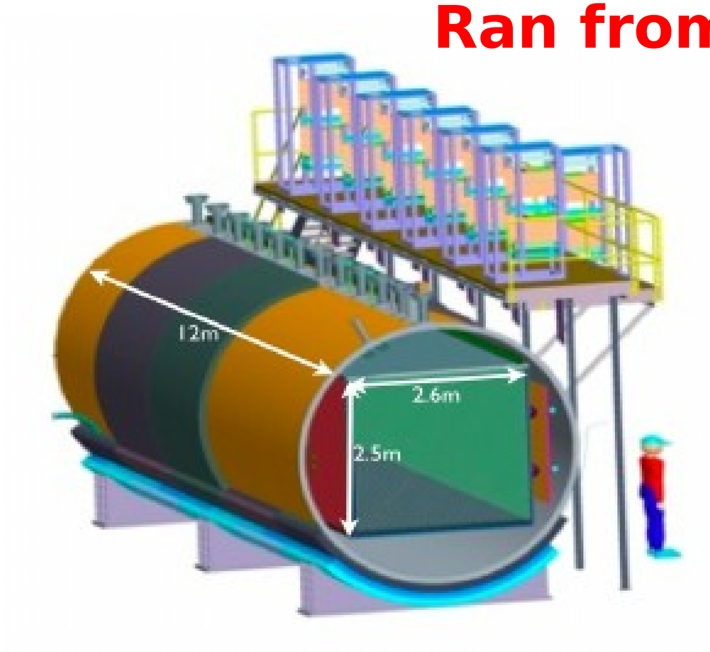


Steady data taking with BNB, NuMI beams from March 2021

→ Two modules (T300) each is 19.6 x 3.6 x 3.9 m^3; total(active) LAr mass 760t(476t)
→ Drift distance 1.5 m. Electric field 500 V/cm -> drift time ~1 ms
→ 3 signal wire planes (2 induction + 1 collection); total 53,248 wires
→ Pitch and inter-plane distances: 3 mm; 400 ns sampling time
→ Photon detector system: 360 TPB-coated PMTs: Precise timing (~1ns)
→ Cosmic Ray Tagger: Close to ~4p coverage, 1100 m^2 plastic scintillator

MicroBooNE Detector: LArTPC

Ran from 2015-2020



MicroBooNE Detector

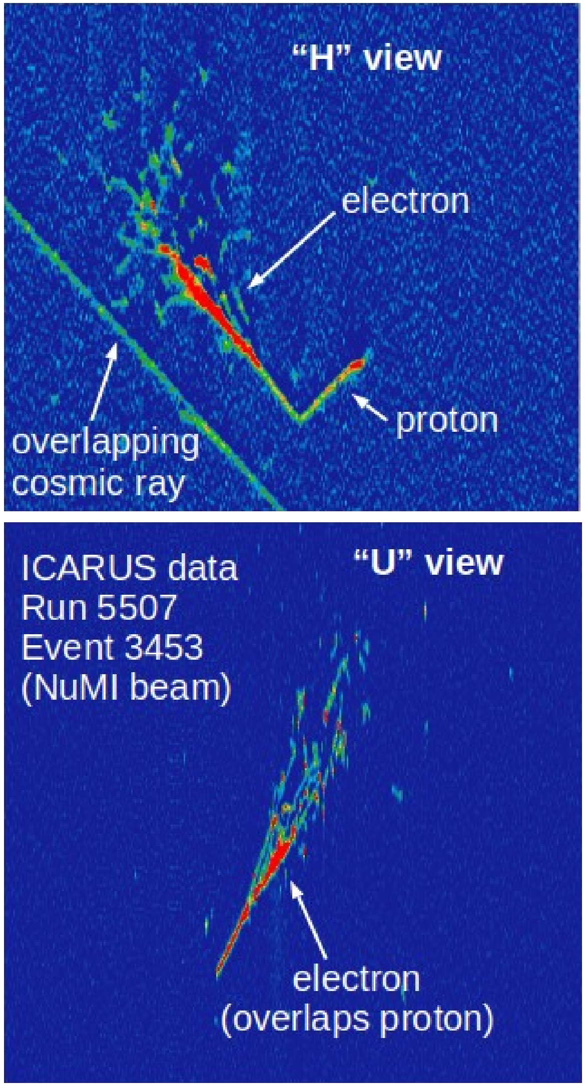
Cyrostat

→ Active volume 85 tons of liquid argon: 2.6 x 2.3 10.4 m^3

→ 3 planes of wires with 3mm pitch

→ 32 PMTs for light readout

LArTPC Capabilities

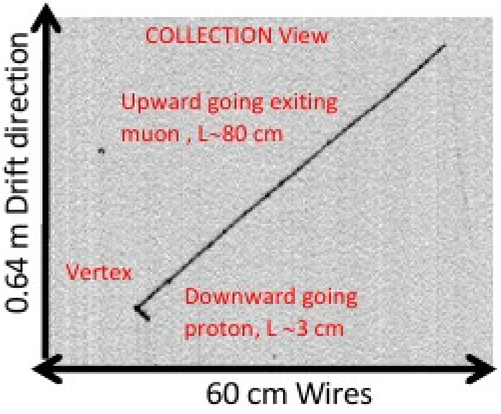


3D imaging charged particles:
Spatial resolution ~ 1 mm^3

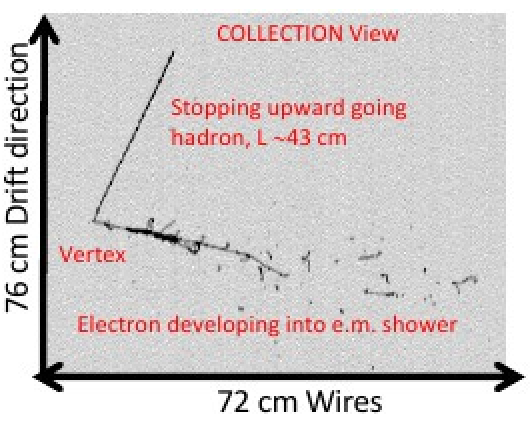
Excellent EM energy resolution:

Many BSM signatures involve EM final states

BNB CC QE ν_μ Candidate

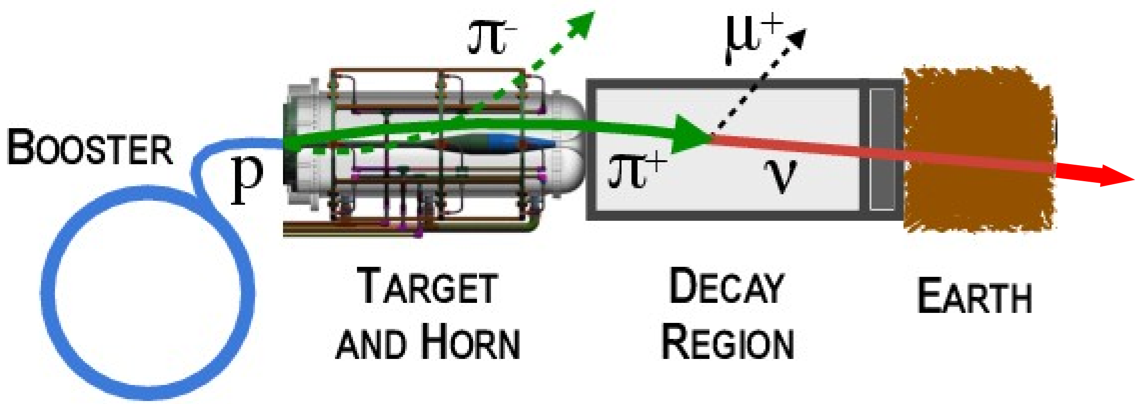


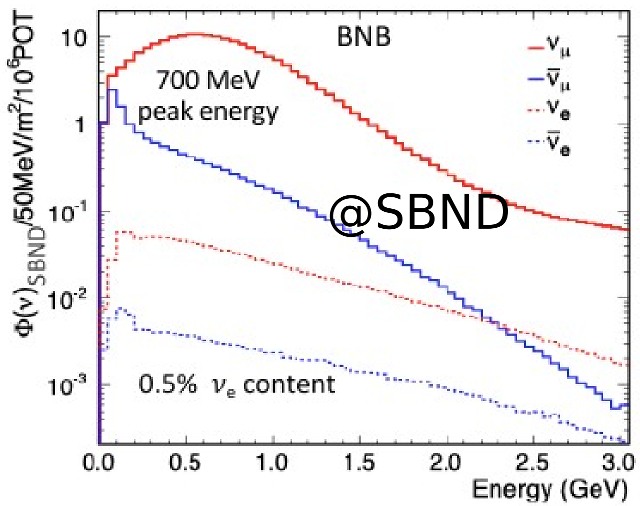
NuMI CC QE ν_ε Candidate



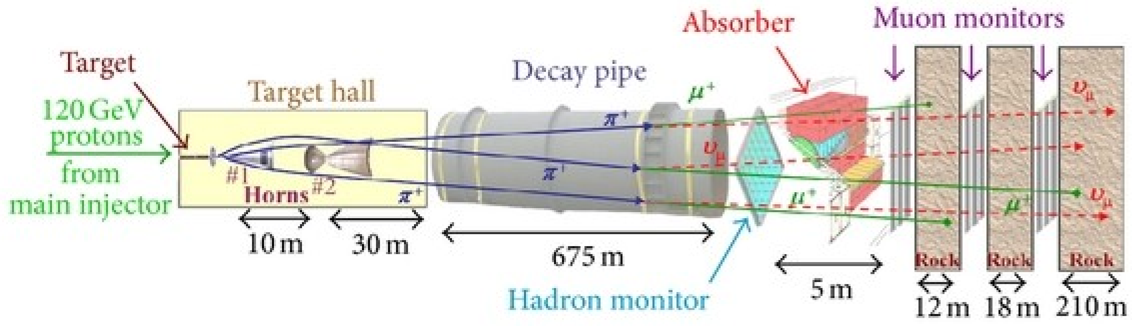
SBN: Access to both BNB (on-axis) and NuMI (off-axis) Beams

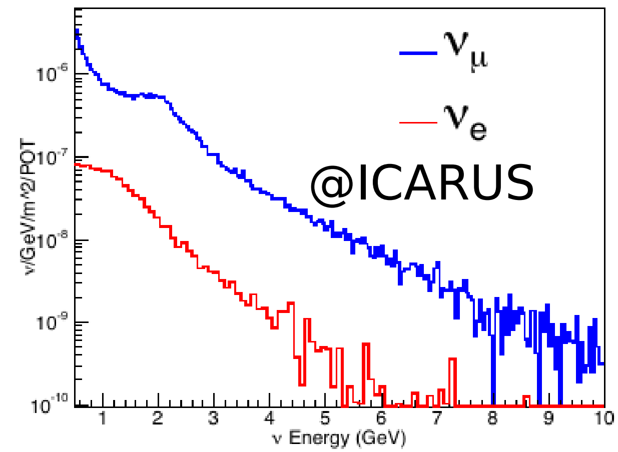
- **BNB Beam (on-axis@0º):**



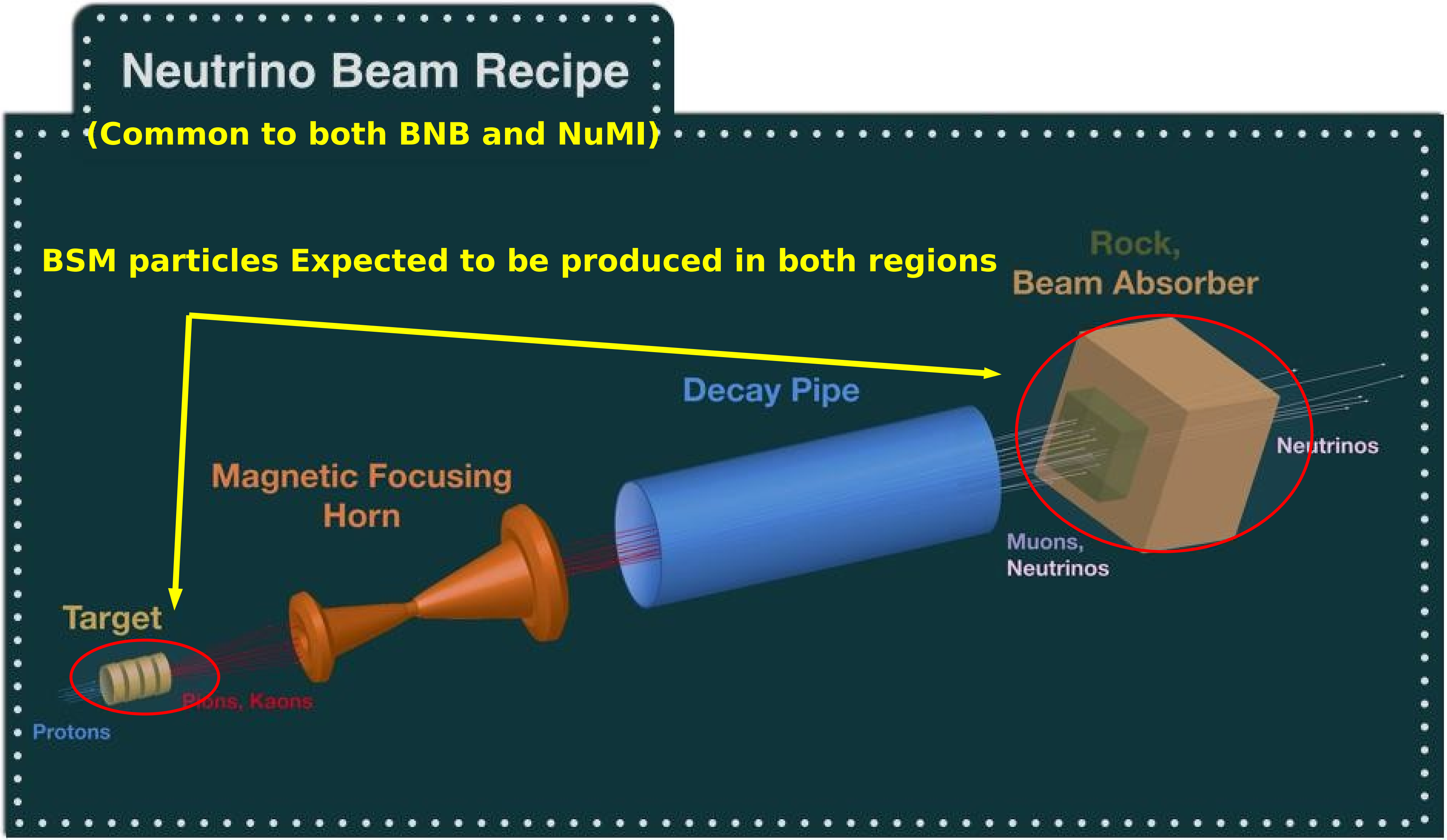


- **NuMI Beam (off-axis@5.7⁰):**



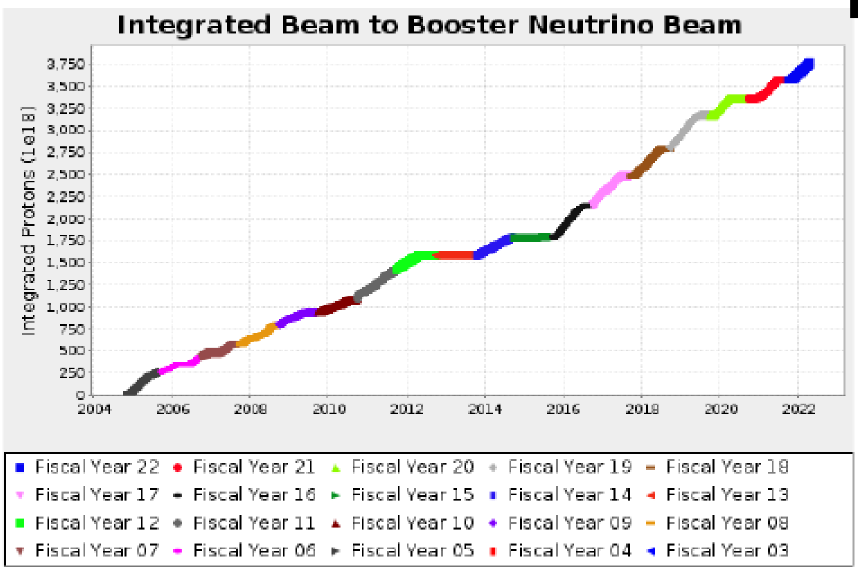


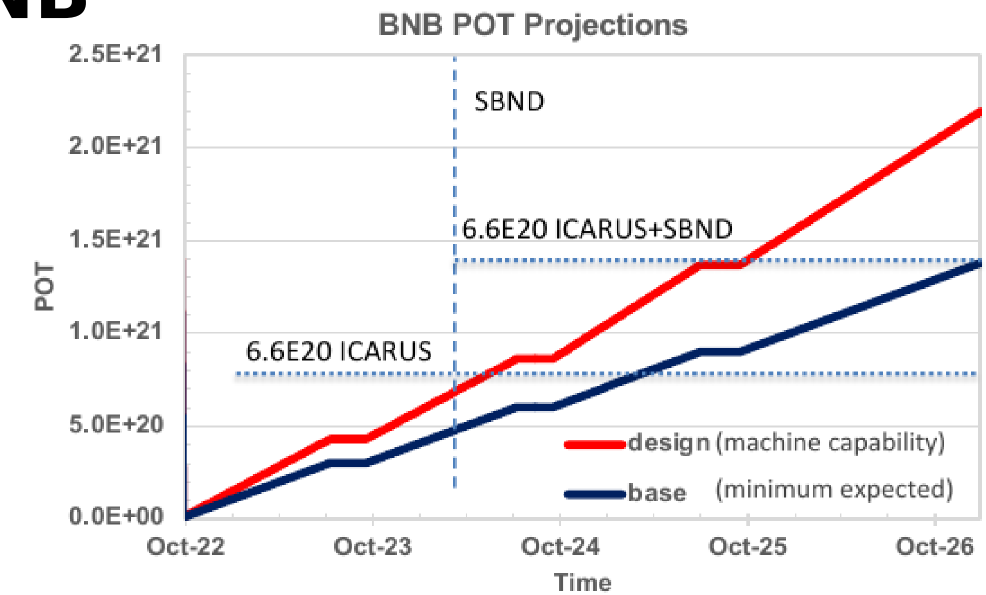
Sources of BSM particles in Neutrino Beams



Expected Beam Exposure

BNB





SBN Proposal: 6.6 x 10^{20} POT BNB

→ BNB will operate till LBNF long-shutdown ~Jan. 2027. Assuming design POT:

→ ICARUS > 3X original SBN proposal

→ ICARUS+SBND > 2X original SBN proposal

NuMI: SBN runs parasitically off of NOvA

→ ~900 kW recently

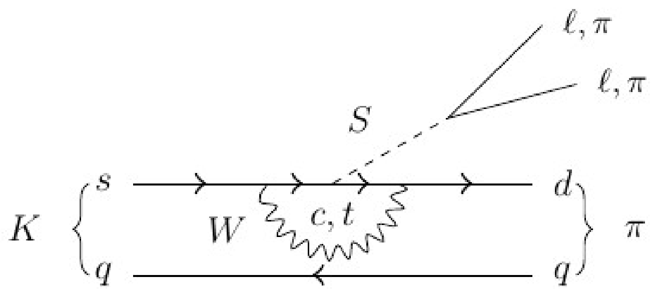
→ ~8x10^{20} POT/year

Dark Sector Particle Production

- **The BSM particles are generated from mixing or decays with standard model particles:**

  → Mainly mesons – generated in neutrino beams.

Higgs portal example:



- **The flux of long lived mesons (pions and kaons) is “well” described by neutrino flux codes**
- **Other short lived mesons, such as η’s and π^0’s, are not considered by the neutrino flux but can also be a source new particles.**

  → These mesons are simpler to deal with because they do not propagate through the target or focusing horns, but estimates of their production are unconstrained by measurements.

  → Large flux errors

SBN Beam(s) Characteristics

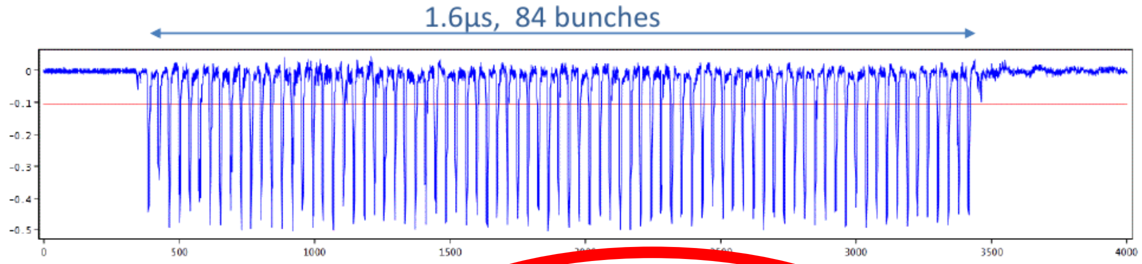
•8 GeV protons from Booster:

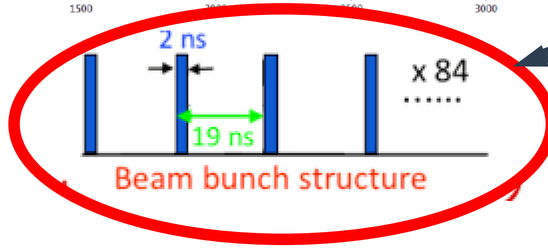
On-axis - Up to 5 Hz rep rate, 5 x 10^{12} protons/spill, 1.6 µs spill.

•Detector ν interaction rates:

SBND: 0.25 Hz ν, 0.03 Hz cosmic

ICARUS: 0.03 Hz ν, 0.14 Hz cosmic





Timing structure useful (See Xiao's talk)

•120 GeV protons from MI:

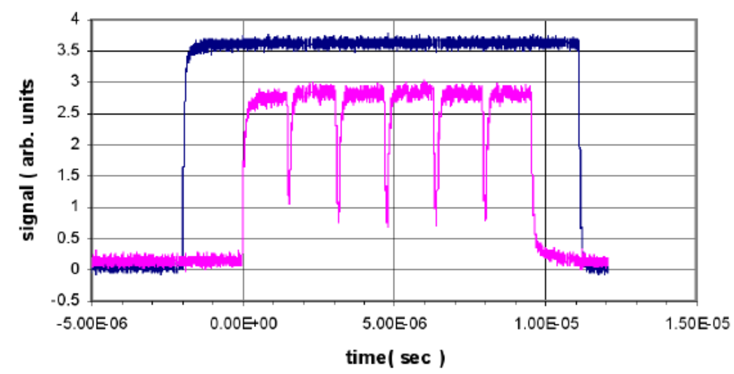
•NuMI off axis(@5.7°) at ICARUS

•In excess of 6 x 10^{13} pot/spill, ~10 µs spill,

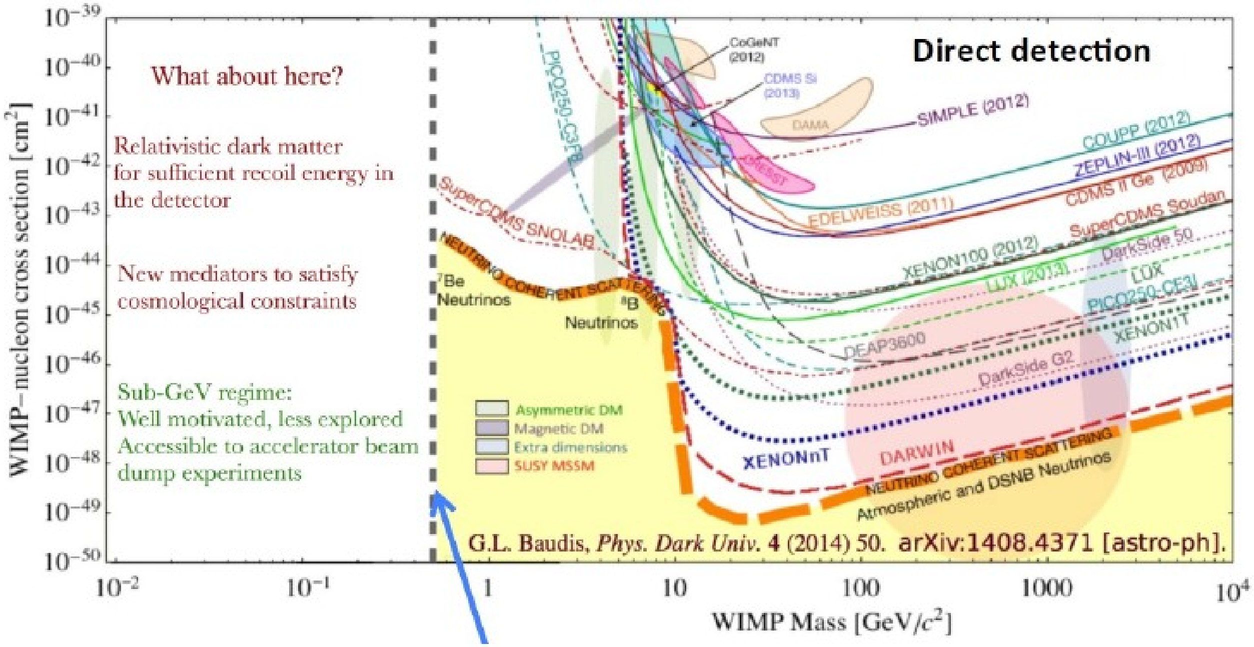
•0.75 Hz rep rate

ν interaction rate:

ICARUS: 0.014 Hz ν, 0.08 Hz cosmic



Why use these Beams for BSM searches?



→ **Direct detection ~< 1 GeV threshold**

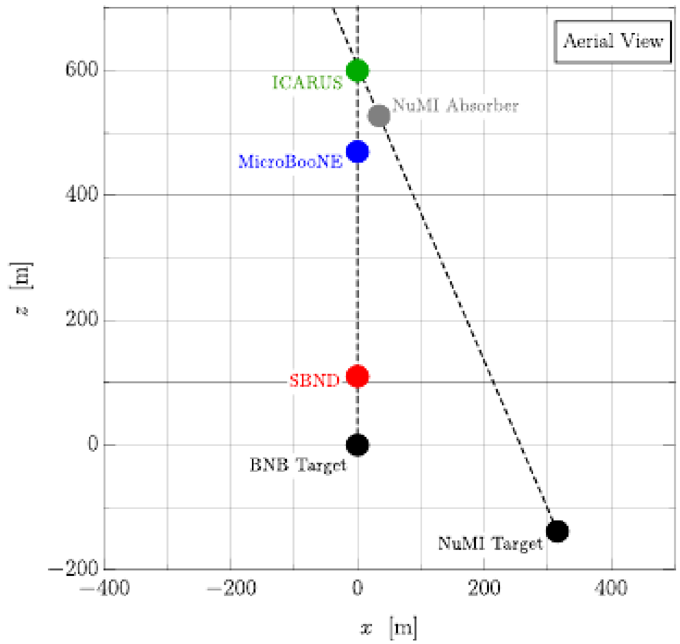
→ Accelerator based searches have experienced a lot of both theoretical and experimental activity recently

→ The high intensity SBN beams have the potential for generating rare processes such as the production (via decays) of DM particles (portal)

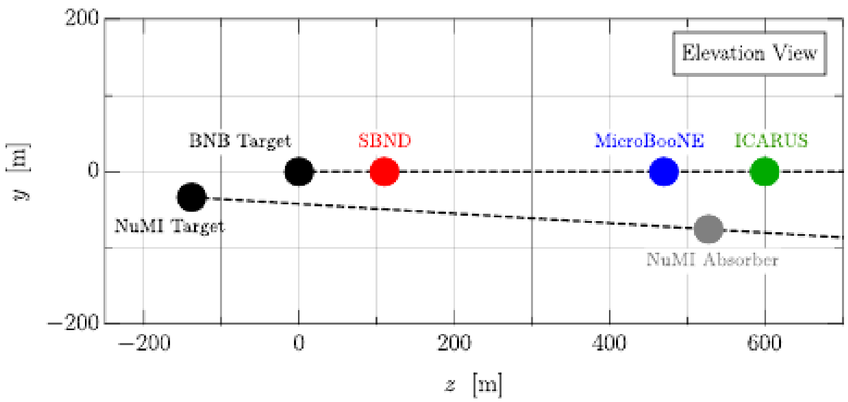
→ In NuMI case being off-axis reduces backgrounds from standard neutrino interactions - Large component of flux produced from Kaon decays

Complimentary searches using both SBND detectors (BNB beam) and ICARUS (off axis NuMI beam)

- **SBND –** Large acceptance to BNB Beam
- **ICARUS –** Large target mass, off-axis location reduces backgrounds from standard neutrino interactions and parents dominated by kaons and strategically located relative to the NuMI absorber (→ generates decays at rest (KDAR))



arXiv:1909.11670v3 [hep-ph]

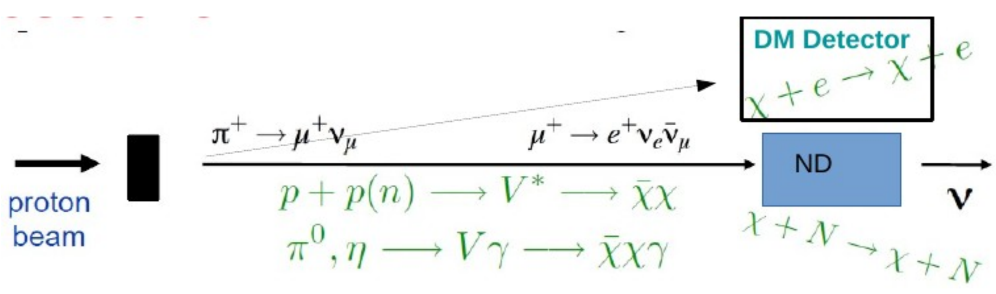


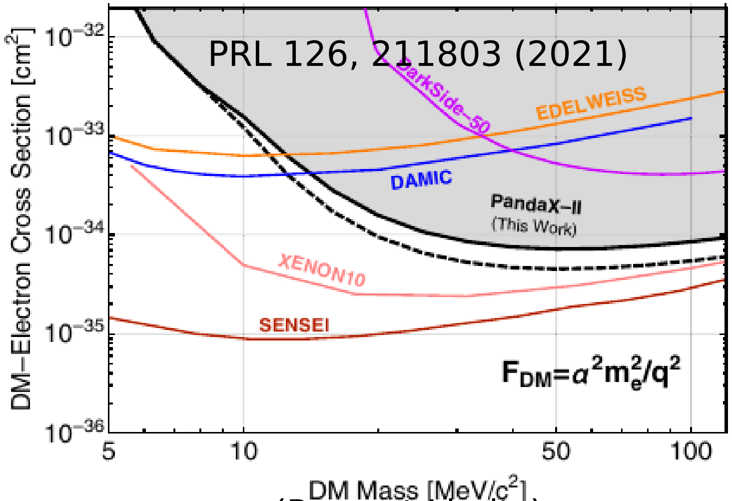
Some Selected BSM Searches in Progress

- Heavy neutral leptons (HNLs)
- Light dark matter (DM)
- Dark neutrinos
- Heavy axions
- Millicharged particles

ICARUS: Vector Portal to the dark sector

- **Production: p+p(n)→$\chi\chi$, Production dominated by neutral meson decay channel and bremsstrahlung**
- **DM detection channel (scattering off of target electrons) : χ e→χ e**





(Present Limits)

- **Event selection: Events with electron in final state with beam window and fiducial volume**

→ Use CRT cut to reject cosmic background

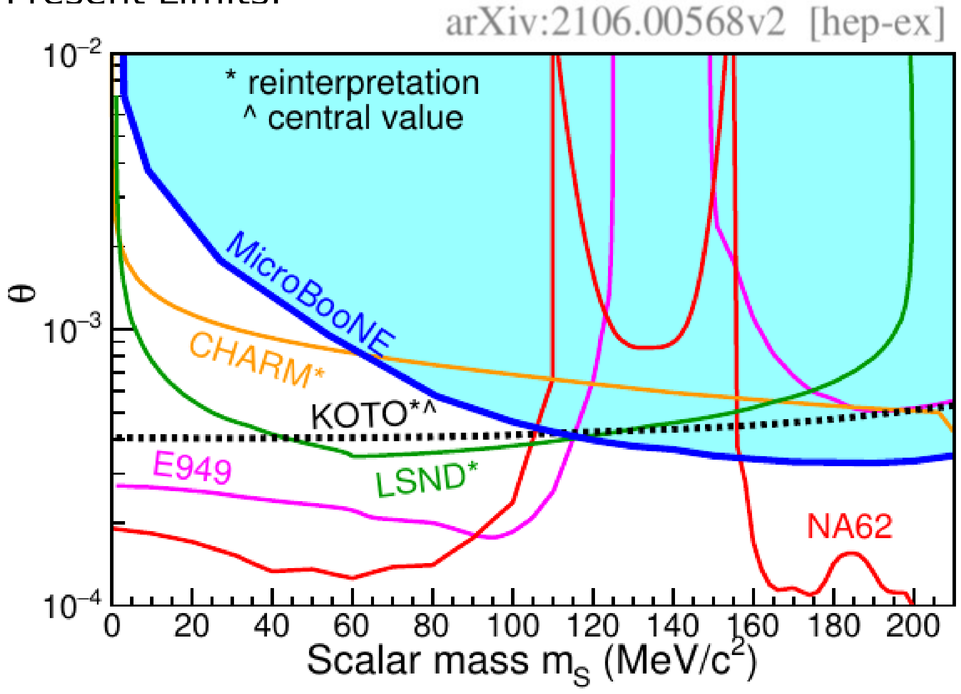
→ PMT-Timing analysis (σ_{PMT} ~1ns) - Measure event time wrt beam bunches: Look for out of time scatters. Most effective for heaviest/LE DM candidates – true for most searches

•

ICARUS: Search for Higgs Portal Dark Scalar

- **NuMI Production: Dark Scalars from Kaon Decay at Rest (KDAR) Signal and Kaon decay in flight (KDIF)**
- **Detection channel: KDAR, KDIF → Decays to e-e+**

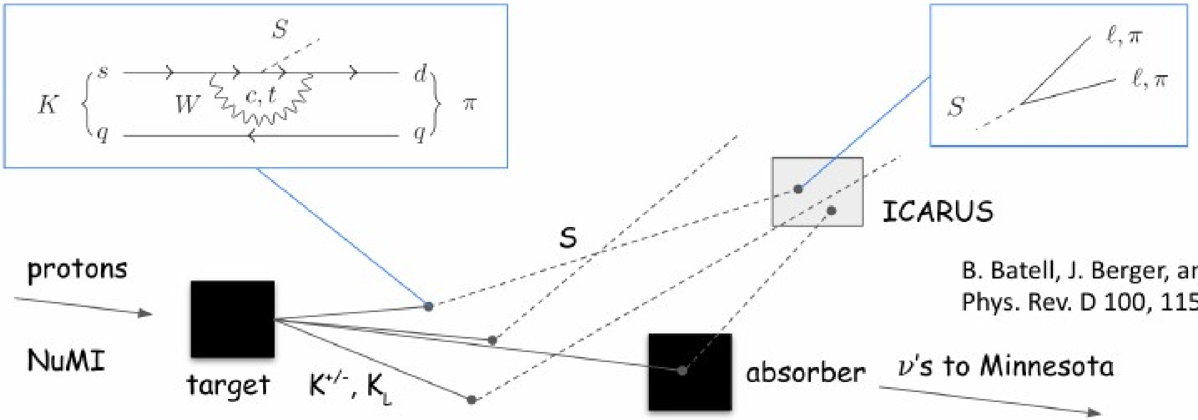
Present Limits:



→ Assuming 6×10^{20} POT (~ 1 year of running) and 14% detection efficiency with zero backgrounds expect a factor or 2 improvement

Search for Higgs Portal Dark Scalar

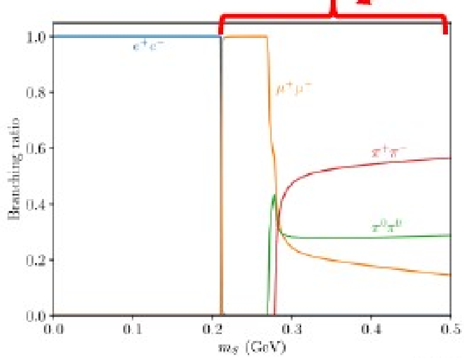
- Assuming 1.3×10^{21}POT for BNB
- Assuming $\sim3\times10^{21}$ POT for NuMI
- Could be achieved in 2-3 years of running



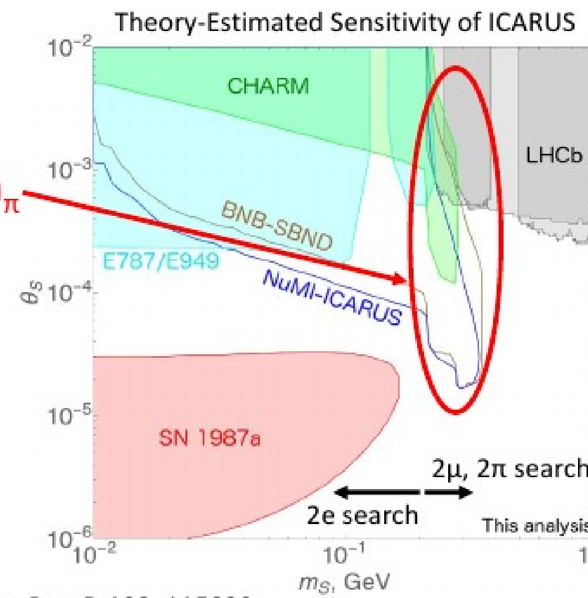
B. Batell, J. Berger, and A. Ismail. Phys. Rev. D 100, 115039

The **NuMI** beam at **ICARUS** can probe new parameter space of the Higgs Portal in the **decay to two muons**

$2m_\mu < M_s < m_K - m_\pi$



New parameter space from a 2μ search



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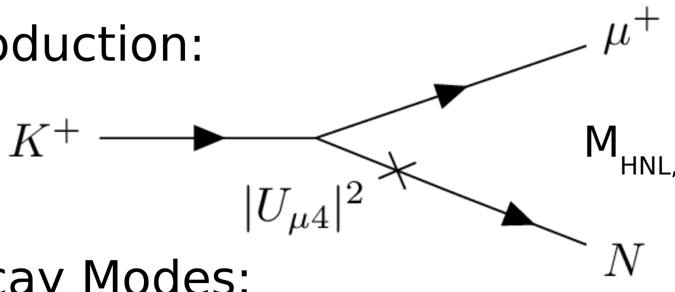
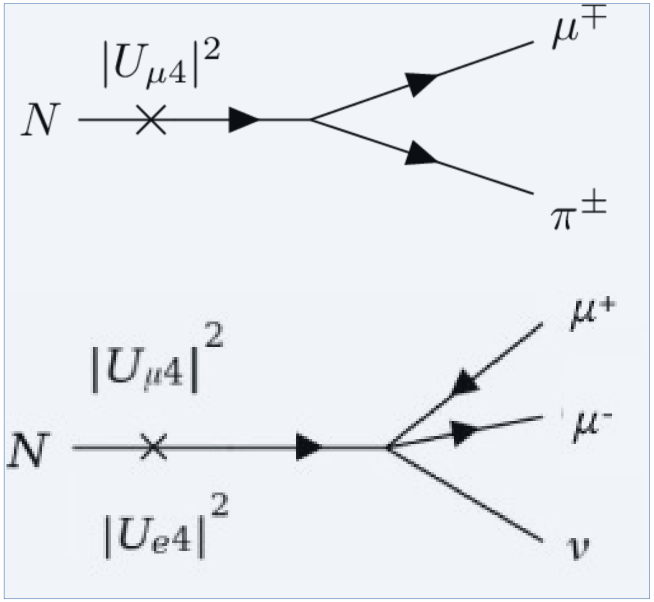
HNL Searches

Production:

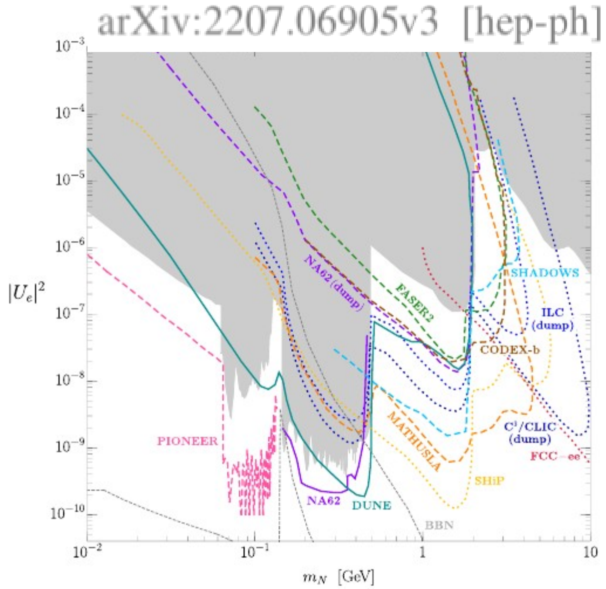


$M_{HNL,max} \approx 388$ MeV

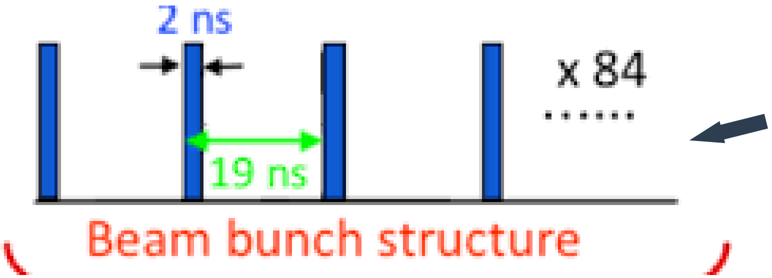
Decay Modes:



Electron mixing dominance.



HNL decaying into two muons (pion) (+/-) and a neutrino:
Limits HNL mass range from 211-388 MeV

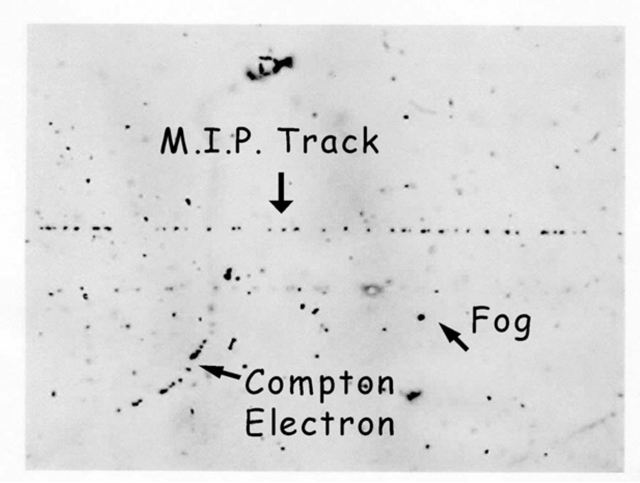


Look for events between bunches

Search for Millicharged particles

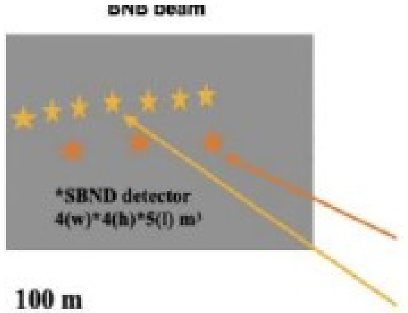
Production: Directly or decay particles produced from target or absorber
Detection method: Search for tracks with sub-MIP dE/dx deposition

Old technique – Emulsion example



$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e c^2 \beta^2}\, n \cdot \ln \frac{m_e c^2 \beta^2 \gamma^2}{2\pi \hbar \langle \nu_e \rangle}$$

LarTPCs: Modern Emulsion and Bubble chamber



Look for the “blips” signature :
as a result of hard scattering
Look for the “faint tracks”:
as a result of multiple soft scatterings.

(Amy Flather and Daisy Kalra @SBND)

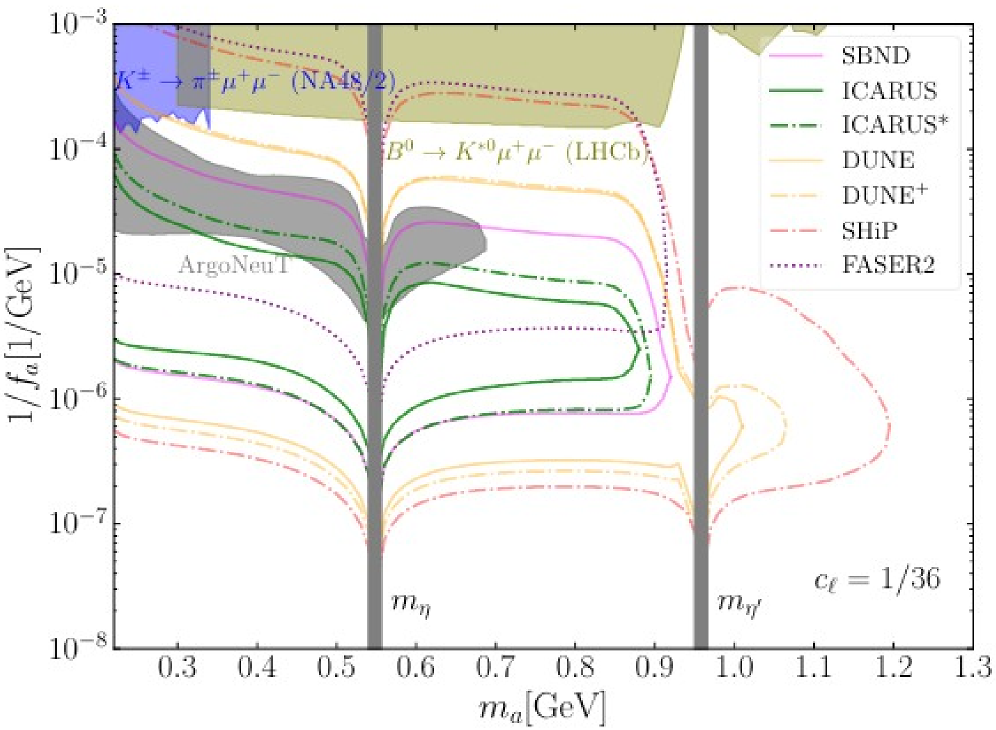
Search for Axion Like particles

- **Production: Decay particles produced from target or absorber**
  - **→ Axions in the BNB and NuMI beams are produced primarily by mixing with the psuedoscalar mesons π⁰, η, and η′**

→ Flux will not be well predicted: Production of neutral mesons not well measured

→ Axion decay modes – photonic, leptonic and hadronic

arXiv:2210.02462v1 [hep-ph]



$$\Gamma_{a\to\mu\mu} = \frac{c_\ell^2 m_a m_\mu^2}{8\pi f_a^2}\sqrt{1-\frac{4m_\mu^2}{m_a^2}}.$$

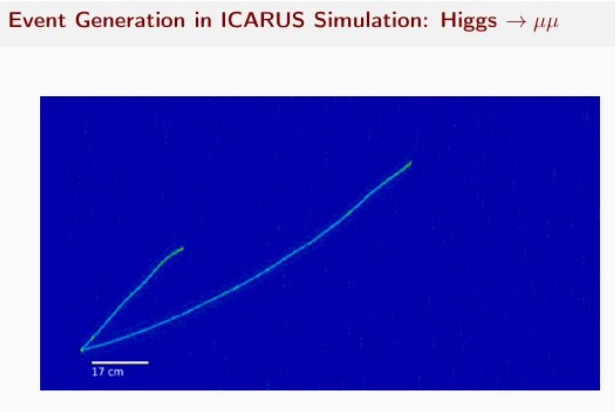
Path to Accurate BSM Search Sensitivities

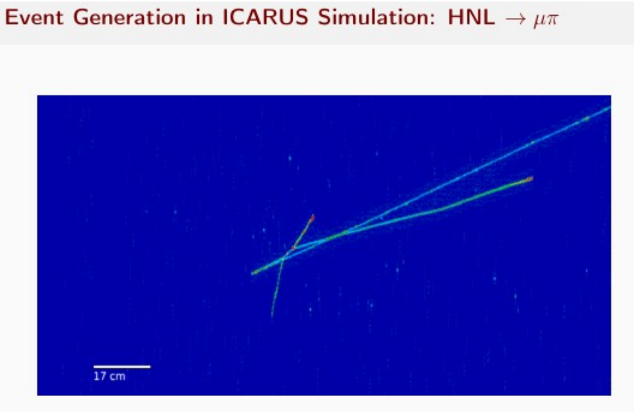
→ No detailed expected sensitivities for the searches discussed where shown – only rough estimates

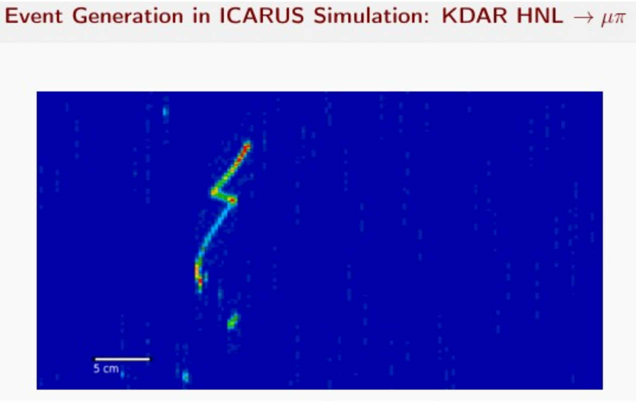
→ In general SBN is expected to be competitive In interesting phase regions

→ What is needed?

→ Event generator – basically in place: MeVPrtlGen generator is a modular event generator of Beyond Standard Model (BSM) for SBN







→ BSM tools integrated into the MC (detector simulation) production

→ MC production presently ongoing – almost completed (ICARUS)

→ Need to do the studies...

Summary

→ Many BSM searches using both BNB and NuMI off-axis beams are being implemented and studied

- → These measurements are expected to be competitive with other experiments
  - → In addition they are exploring less studied regions of BSM phase space
- → Significant progress on software and analyses plans have been made.
  - → Need to generate properly simulated sensitivity limits

→ BSM searches are an important effort of the SBN physics programs

- → BSM physics has to be somewhere…
  - → Need to look in every unexplored region of phase space