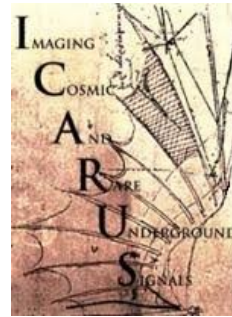


ICARUS NuMI BSM Searches



Vittorio Paolone

(on behalf of the ICARUS Collaboration)

ICARUS BSM Program Overview

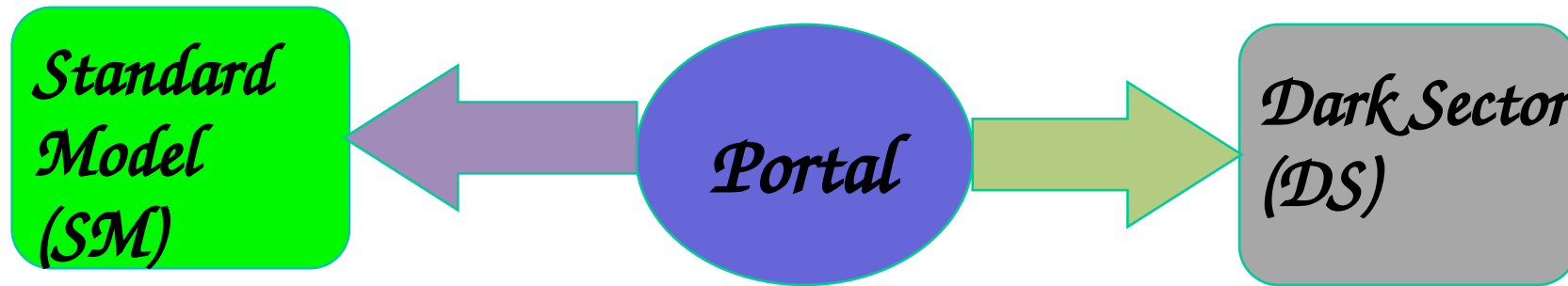
MicroBooNE Collaboration Meeting

26-29 May, 2026



Motivation: ICARUS BSM searches

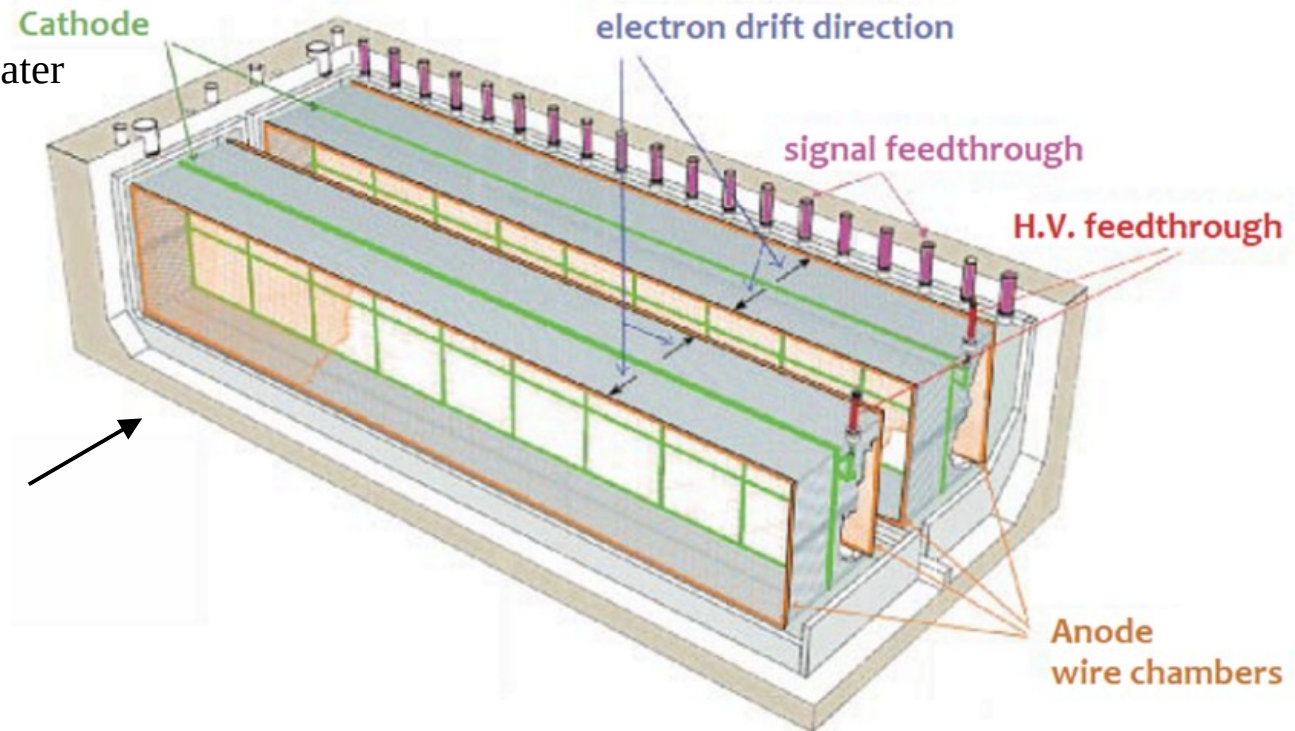
Simplest link to LLP/BSM physics is through *portal* in which a *dark sector* particle mixes with an *SM* particle.



- ✓ *Scalar (Dark Higgs)* : Scalar dark sector particles - interactions by mixing with the Higgs boson
- ✓ *Vector (Dark Photon)* : Couple to SM via kinematic mixing of SM- and dark-sector photons
- ✓ *Pseudo-scalar (ALPs)* : Heavy particles couples to SM via gluonic mixing
- ✓ *Fermion ($\mathcal{HN}(\mathcal{L})$)* : Fermionic particles - interactions by mixing with neutrinos

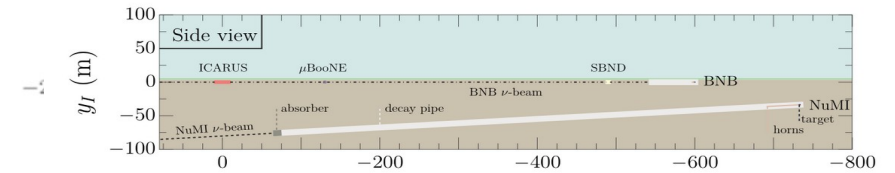
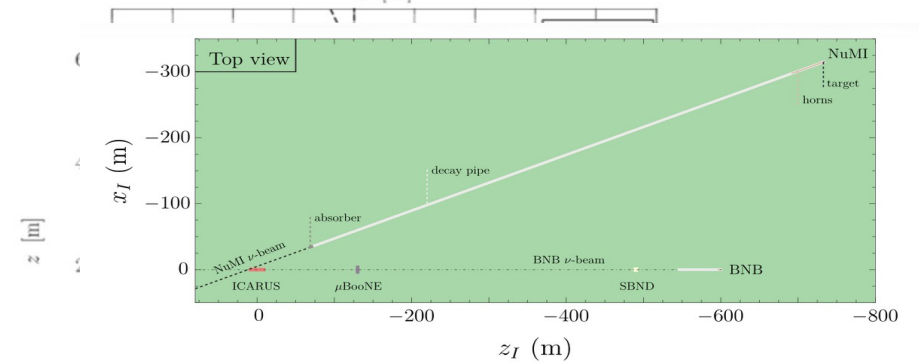
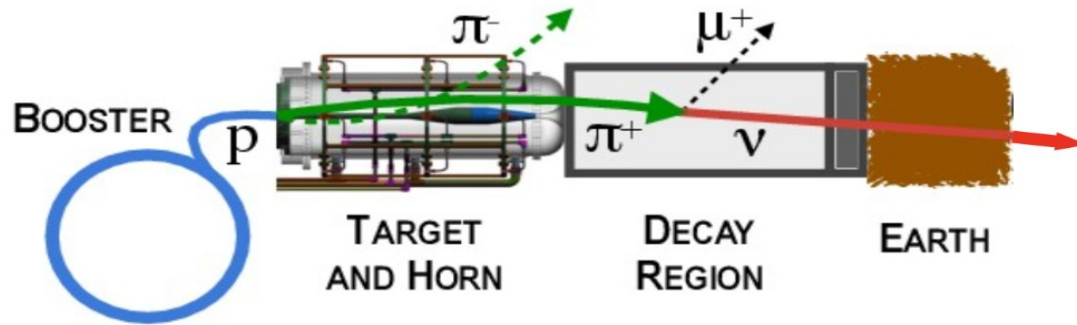
ICARUS Detector Summary

- The ICARUS detector is composed of two semi-independent modules filled with liquid argon,
 - Each are approximately 3.6 meters high, 3.9 meters wide and 19.9 meters long.
- The read-out chambers (two TPCs for each half-vessel)
 - The FV corresponding to about 480 tons.
 - The read-out consists of three parallel planes of wires (horizontal, +60 and -60 degrees).
 - Read-out by electric charge induction on the first two readout planes and by electric charge collection on the last readout plane.
- PMT scintillation light system – more later

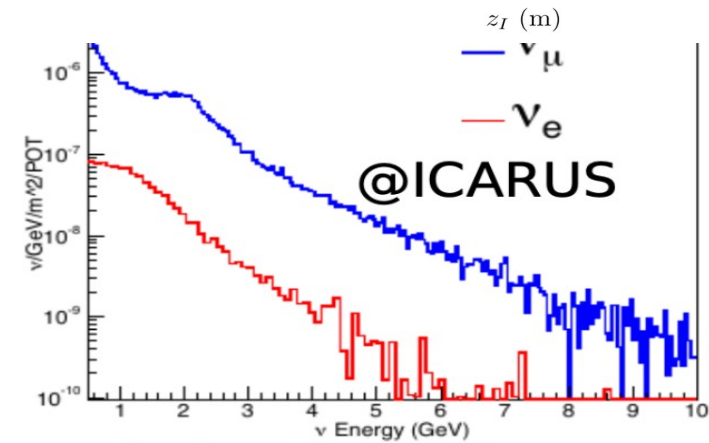
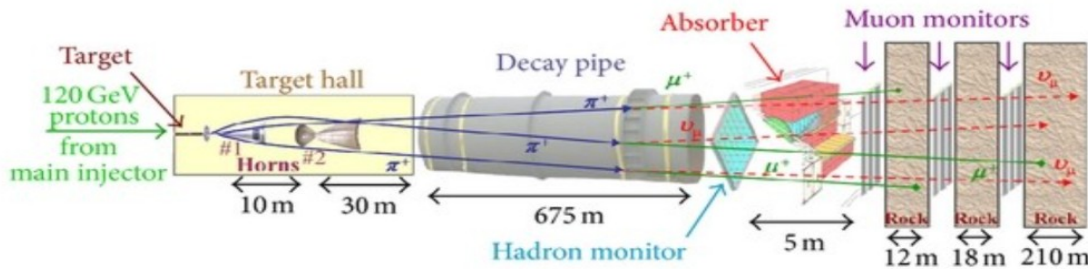


Why ICARUS for BSM searches ?

BNB Beam (On-axis @0°)

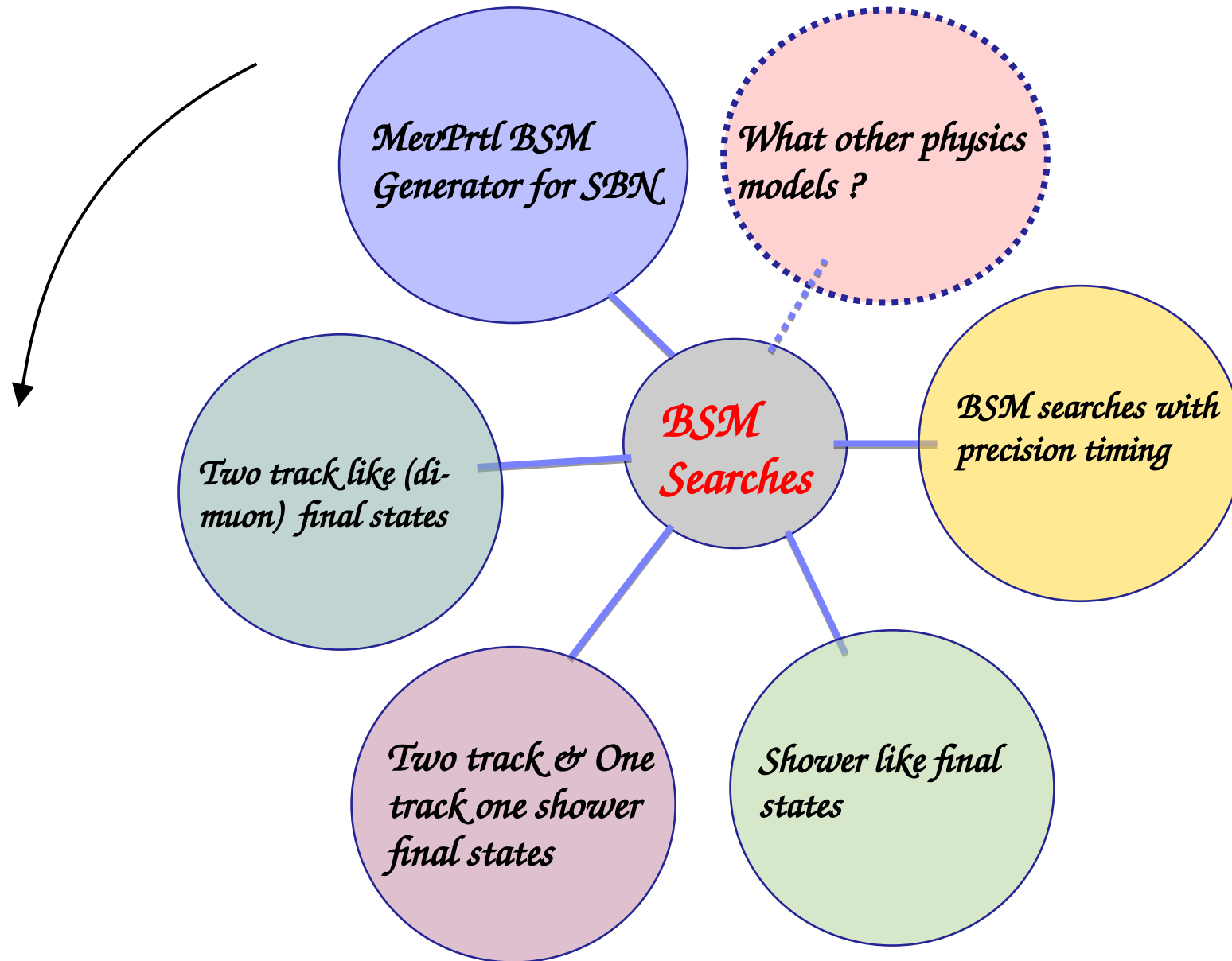


NuMI Beam (Off-axis @5.7°)



Both BNB beam (SBND, on axis) and NuMI off-axis (reduced neutrino background) at ICARUS will be excellent setup for BSM/LLP searches.

ICARUS BSM Searches at a glance



MeVPrtl: Dark Sector Event Generator for SBN

Simulating the full chain from beam to detector for new physics searches

KEY IDEA

- Modular MC generator for BSM particles in SBN
- Simulates Production->propagation-> decay (scattering)-> detector signal

CORE FEATURES

- Integrated with larsoft + Geant4
- Supports: Higgs Portal Scalar, Heavy Neutral Lepton, QCD axions

MeVPrtl: An Event Generator for Dark Sector Particles in the Short-Baseline Neutrino Program

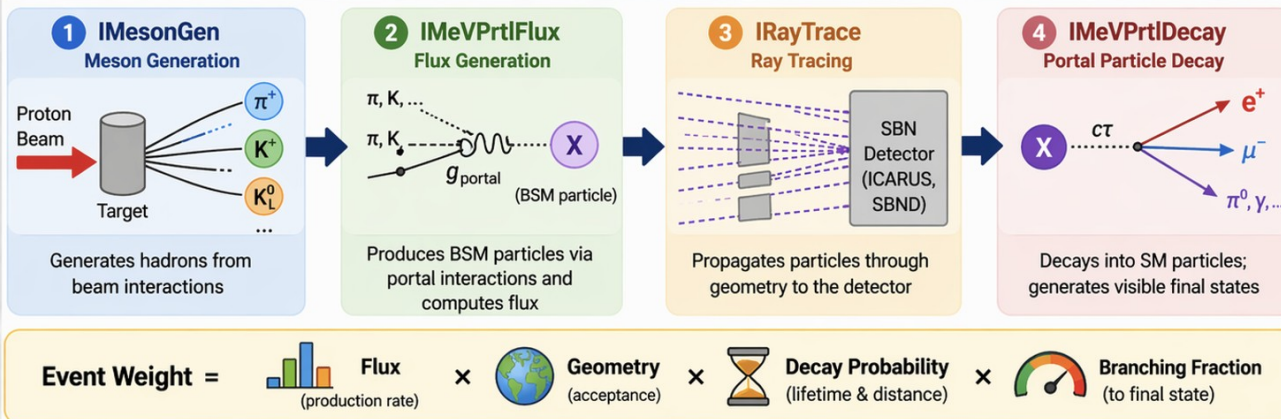
ICARUS Collaboration, SBND Collaboration, P. Abratenko^a, N. Abrego-Martinez^b, R. Acciarri^a, A. Aduszkiewicz^d, F. Akbar^a, D. Andrade Aldana^f, L. Aliaga-Soplín^g, F. Abd Alrahman^h, R. Alvarez-Garrote^h, C. Andreopoulosⁱ, A. Antonakis^j, J. Asadi^k, W. F. Badgett^l, S. Yebes Baena^m, B. Baibussinovⁿ, S. Balasubramanian^o, A. Barnard^p, V. Basque^q, J. Bateman^r, A. Beever^s, B. Behara^t, E. Belchior^u, V. Bellini^v, R. Benocci^w, J. Berger^x, S. Bertolucci^y, M. Betancourt^z, A. Bhat^{aa}, M. Bishai^{ab}, A. Blake^{ac}, A. Blanchet^{ad}, F. Boffelli^{ae}, B. Bogart^{af}, M. Bonasini^{ag}, T. Boone^{ah}, B. Bottino^{ai}, A. Braggiotti^{aj}, D. Brailsford^{ak}, A. Brandt^{al}, S. J. Brice^{am}, S. Brickner^{an}, V. Brin^{ao}, A. Brizzolari^{ap}, M. B. Brunetti^{aq}, H. S. Budd^{ar}, L. Camilleri^{as}, A. Campa^{at}, R. Capozzi^{au}, D. Caratelli^{av}, D. Carber^{aw}, B. Carlson^{ax}, M. F. Carneiro^{ay}, H. Caron^{az}, R. Castillo^{ba}, F. Cavanna^{bb}, S. Centro^{bc}, G. Cerati^{bd}, A. Chappell^{be}, S. Chatterjee^{bf}, H. Chen^{bg}, D. Cherdack^{bh}, S. Cherubini^{bi}, N. Chithirasreemadan^{bj}, S. Chung^{bk}, M. F. Cicala^{bl}, M. Ciccheria^{bm}, R. Coakley^{bn}, T. E. Coan^{bo}, A. Cozzani^{bp}, M. R. Convery^{bq}, L. Cooper-Troendle^{br}, S. Copello^{bs}, C. Cuestas^{bt}, S. D. Curi^{bu}, O. Dalager^{bv}, M. Dall'Olio^{bw}, M. Dallolio^{bx}, A. A. Dange^{by}, S. Kr Das^{bz}, M. Diwan^{ca}, Z. Djuricic^{cb}, S. Dolan^{cc}, S. Dominguez Adame^{cd}, S. Di Domizio^{ce}, S. Donati^{cf}, F. Drielsma^{cg}, M. Dubnowski^{ch}, K. Duffy^{ci}, J. E. Dyer^{cj}, S. Dytmann^{ck}, A. Ereditato^{cl}, J. J. Evans^{cm}, A. Ezeribe^{cn}, A. Falcone^{co}, C. Fan^{cp}, C. Farnese^{cq}, A. Fava^{cr}, D. Di Ferdinando^{cs}, F. Castillo Fernandez^{ct}, A. Filkins^{cu}, B. Fleming^{cv}, W. Foreman^{cw}, D. Franco^{cx}, G. Fricano^{cy}, I. Furic^{cz}, A. Furmanski^{da}, N. Gallice^{db}, S. Gao^{dc}, D. Garcia-Gamez^{dd}, S. Gardiner^{de}, C. Gatto^{df}, D. Gibin^{dg}, I. Gil-Botella^{dh}, A. Gioiosa^{di}, S. Gollapinni^{dj}, G. Moreno Granados^{dk}, P. Green^{dl}, W. C. Griffith^{dm}, W. Gu^{dn}, A. Guglielmi^{do}, G. Guring^{dp}, L. Pelegrina Gutiérrez^{dq}, L. Hageman^{dr}, P. Hamilton^{ds}, K. Hassini^{dt}, H. Hauser^{du}, A. Heggestuen^{dv}, A. Hergenhan^{dw}, M. Hernandez-Morquecho^{dx}, P. Holanda^{dy}, B. Howard^{dz}, R. Howell^{ea}, Z. Hulcher^{eb}, I. Ingrassia^{ec}, M. S. Ismail^{ed}, C. James^{ee}, W. Jang^{ef}, R. S. Jones^{eg}, M. Jung^{eh}, T. Junk^{ei}, Y.-J. Jwa^{ej}, D. Kalra^{ek}, G. Karagiorgi^{el}, L. Kashur^{em}, K. J. Kelly^{en}, W. Ketchum^{eo}

* Paper draft review completed within ICARUS/SBND collaboration

* Paper uploaded to arXiv

<https://arxiv.org/abs/2605.11321>

SIMULATION WORKFLOW: 4-STAGE PIPELINE



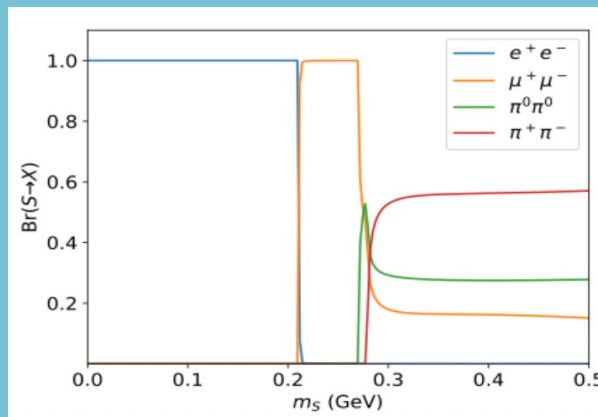
Di-muon Final States Search

Contained search published: Phys.Rev.Lett. 134 (2025) 15, 151801, un-contained (exiting muon) search extension presently in collaboration review

BSM Models

Higgs Portal Scalar

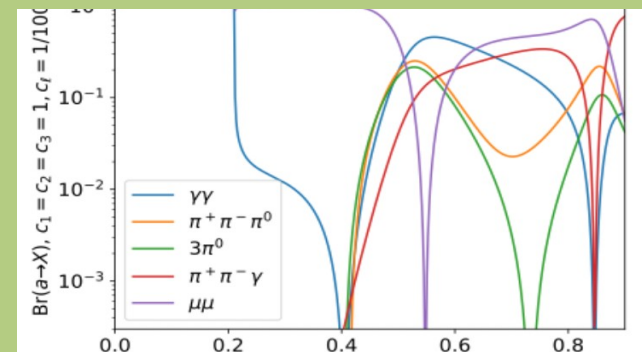
- * Portal particle connecting SM to the Dark sector
- * 2 parameter model mass (m_s), mixing angle with Higgs (θ_s)
- * Produced from Kaon decay
- * Decay modes:



Caption

Heavy QCD Axions

- * Portal particle connecting SM particle with gluonic coupling to solve strong CP problem.
- * 3 model parameters: axion mass (m_a), axion coupling to SM (muons) c_μ , axion decay constant f_a
- * Produced from Kaon or pseudo scalar mesons decay

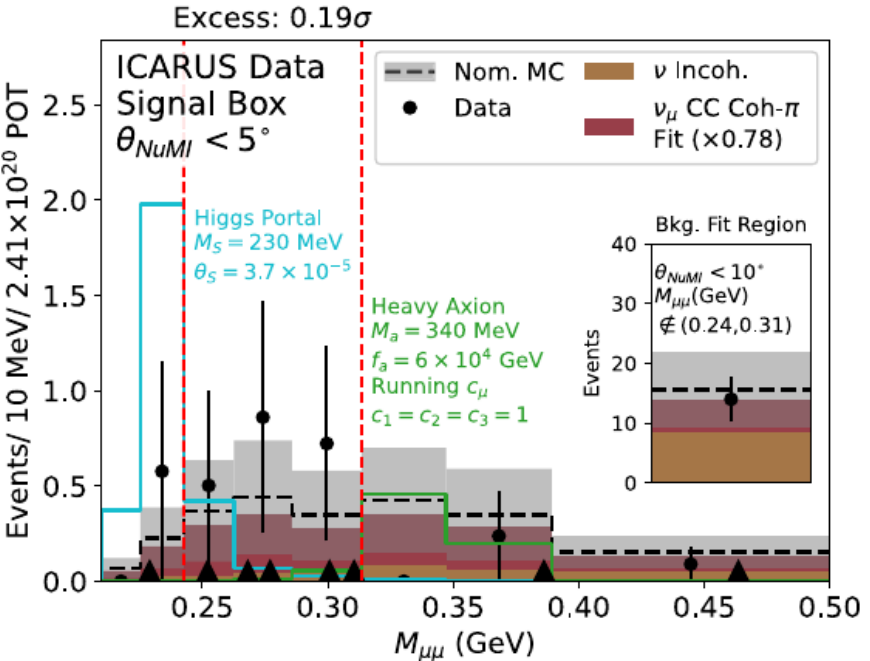


Caption

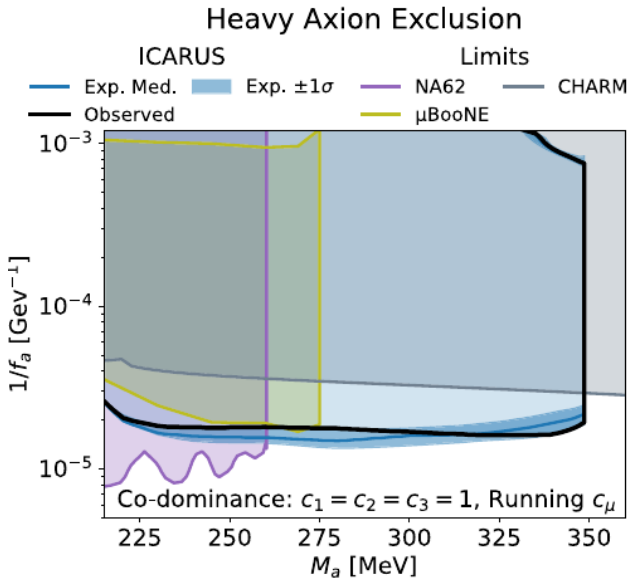
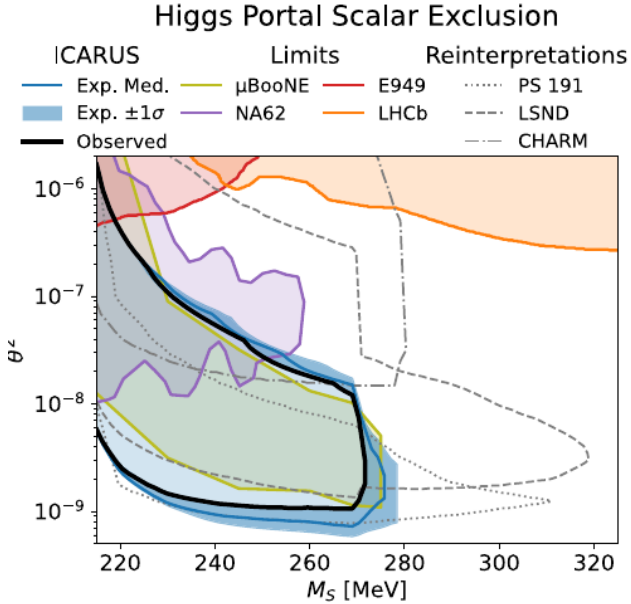
Search for a Hidden Sector Scalar from Kaon Decay in the Dimuon Final State at ICARUS

(PHYSICAL REVIEW LETTERS 134, 151801 (2025))

A search for long-lived particles (LLPs), produced in kaon decays, the subsequently decay into two muons contained inside the ICARUS neutrino detector was performed:

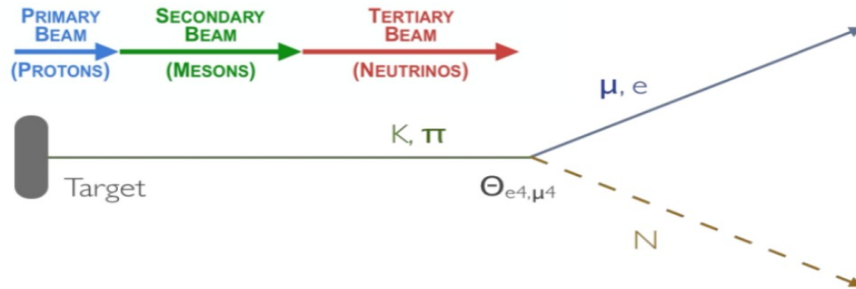


(Exclusions are computed at the 90% CL.)

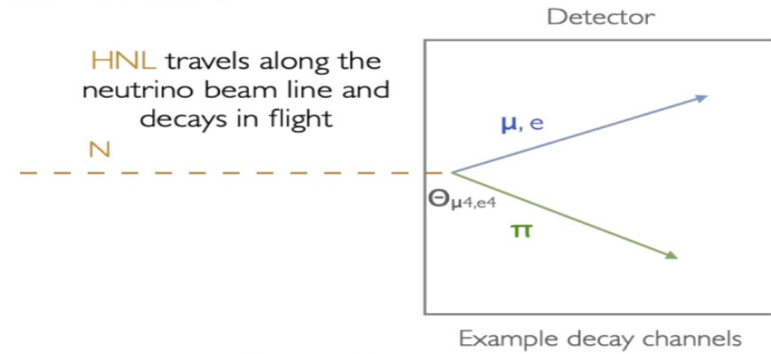


HNL searches using two tracks: Work in Progress

• Production



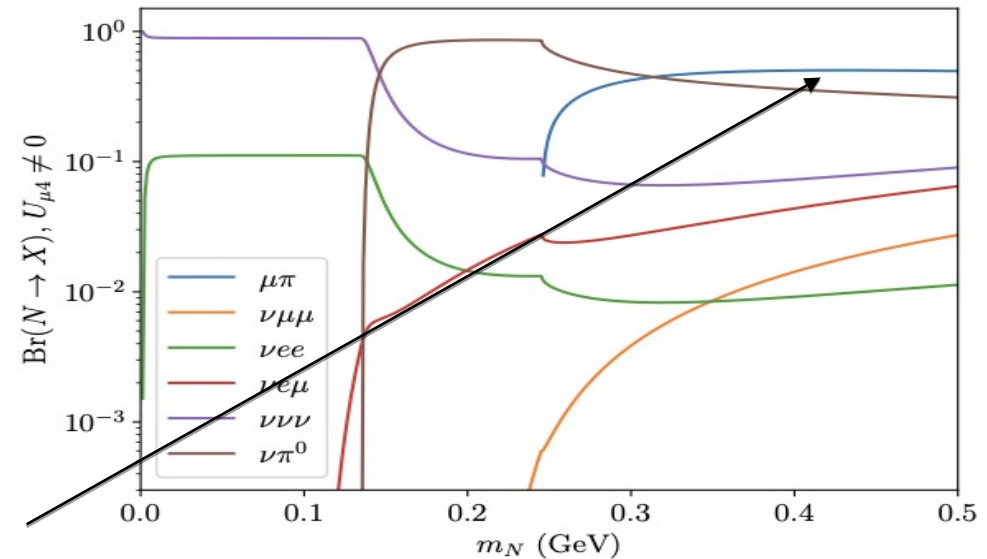
Detection :



List of decay modes to HNL

	$\pi \rightarrow$	$K \rightarrow$	$D \rightarrow$	$D_s \rightarrow$	$\tau \rightarrow$
$ U_{eN} ^2$	eN	eN	eN	eN	—
	—	$\pi^0 eN$	$K^0 eN$	—	—
$ U_{\mu N} ^2$	μN	μN	μN	μN	—
	—	$\pi^0 \mu N$	$K^0 \mu N$	—	—
$ U_{\tau N} ^2$	—	—	τN	τN	πN
	—	—	—	—	$\pi\pi^0 N$
	—	—	—	—	$e\nu N$
	—	—	—	—	$\mu\nu N$

HNL decay modes

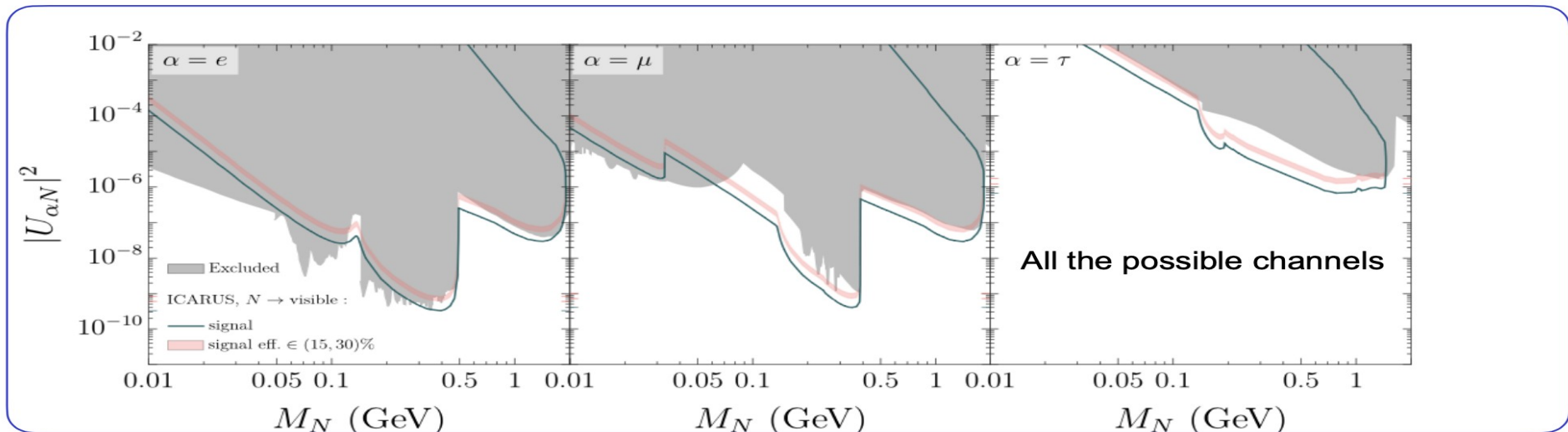
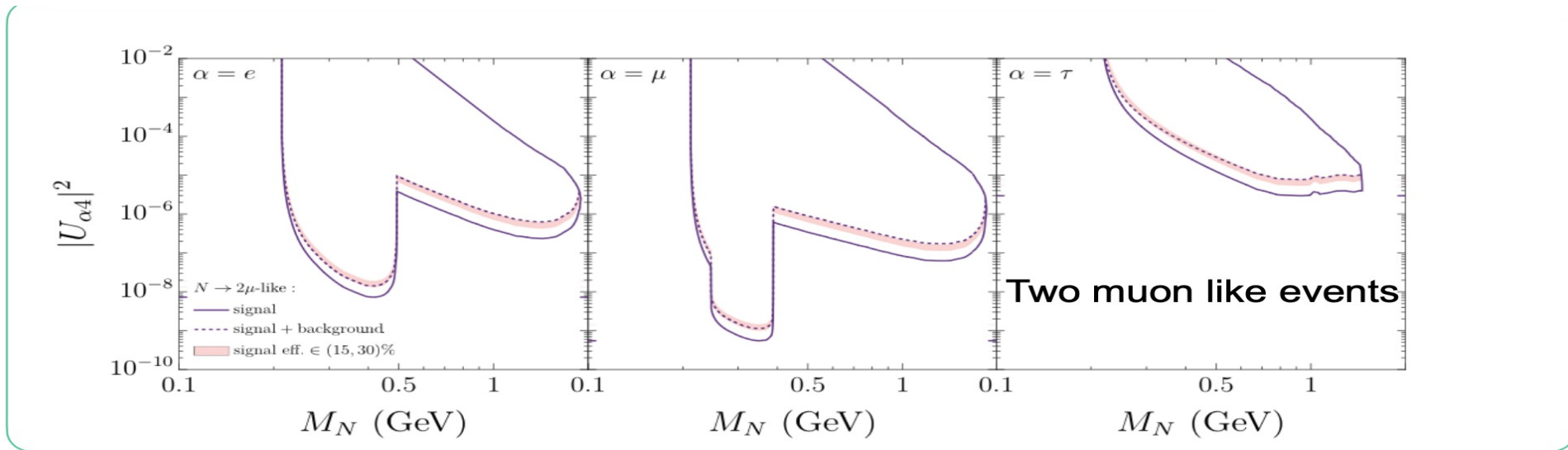


HNL decays to muon-pion (two tracks) for invariant mass measurement

HNL sensitivity@ICARUS/SBN

90% C.L. limit for POT : $1.32 \times 10^{21} \sim 4$ years of data taking

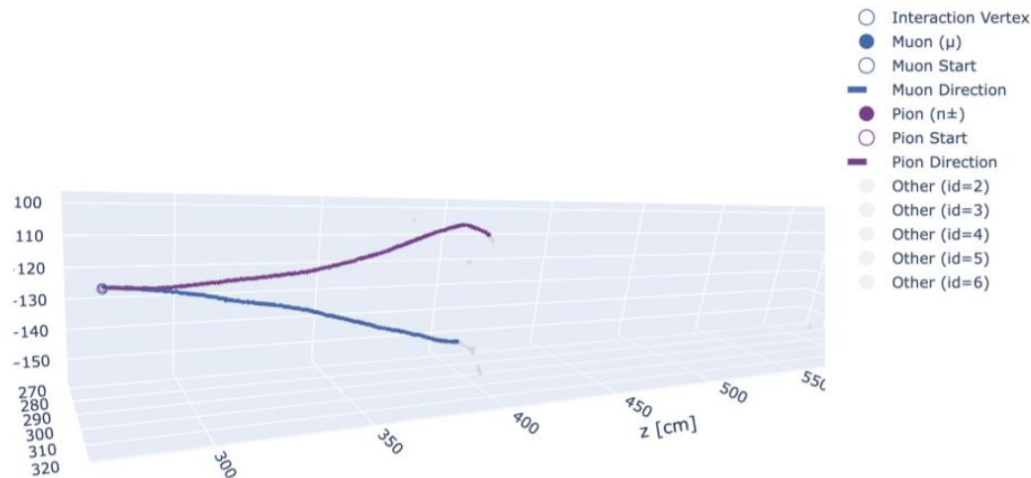
A.Chatterjee, A.De.Roeck, J.G.Garcia (Eur. Phys. J. C **85**, 195 (2025), arxiv: [2408.03383](https://arxiv.org/abs/2408.03383))



HNL-Two track : Simulation

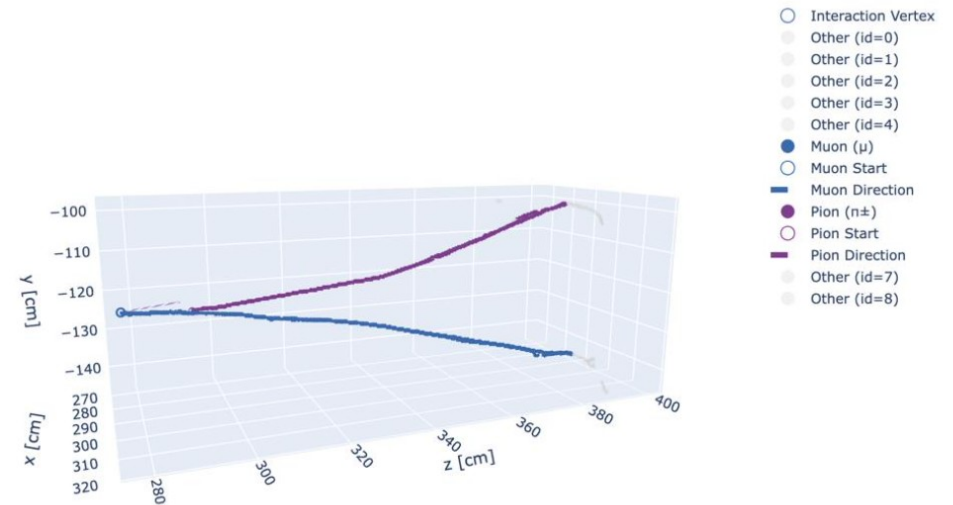
Event reconstructions using SPIN \mathcal{E}

1 μ 1 n Event Display



True simulated interaction

1 μ 1 n Event Display



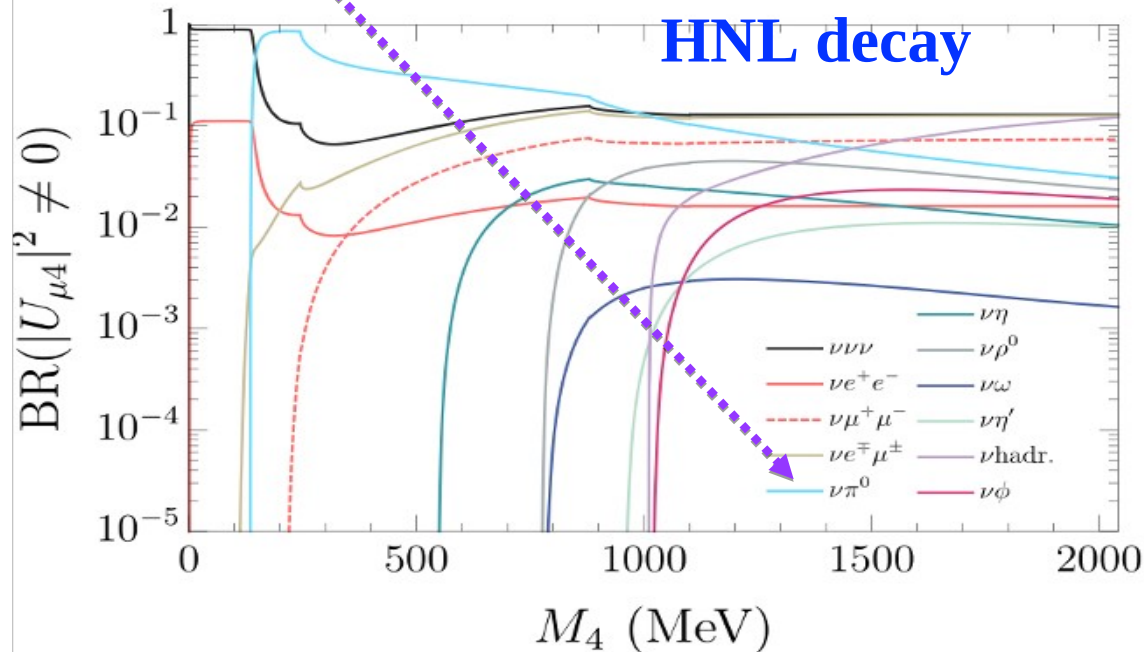
Reconstructed interaction

Presently working on:

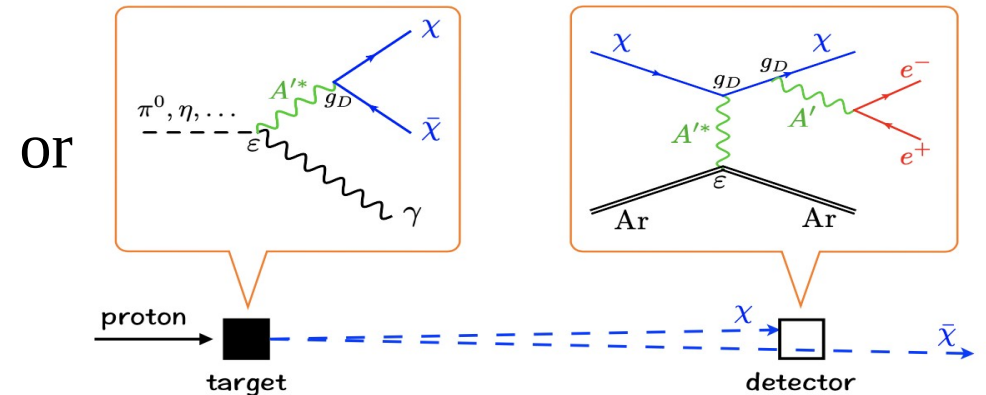
- * *Explore μ/π separation techniques*
- * *Selection cuts development for 1 μ 1 π topology*
- * *Background simulation: CC coh π , CC res π production*

Shower Final States Topology Searches

Motivation:



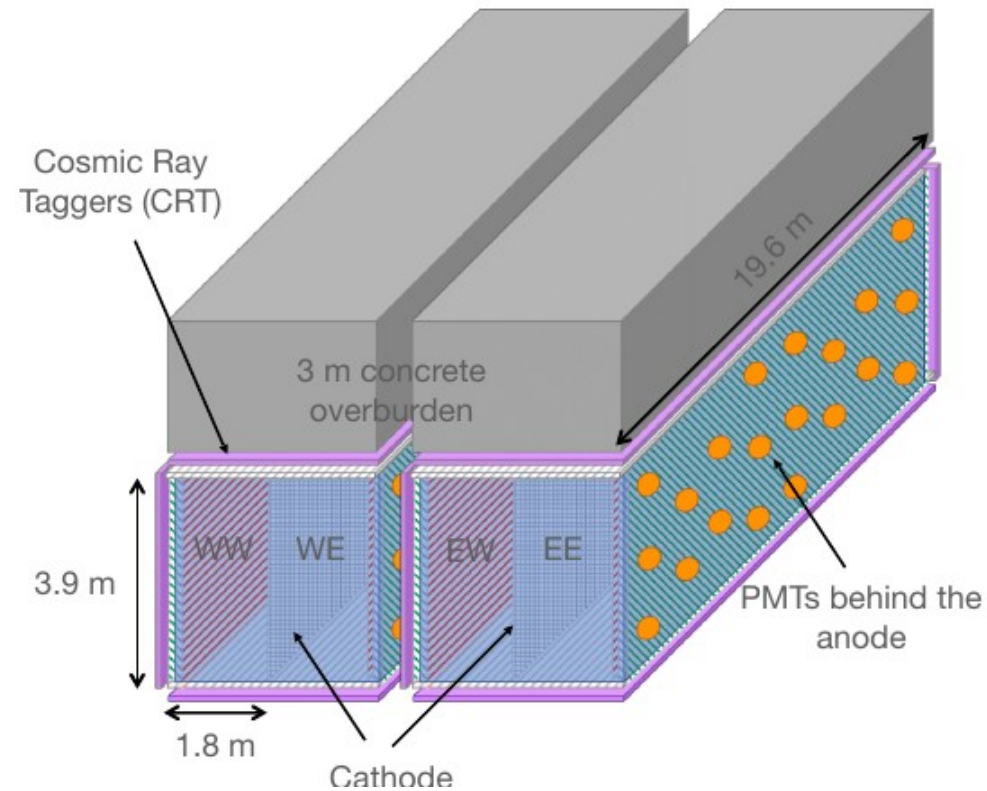
Dark tridents • JHEP 01 (2019) 001



- * *Two-shower based topology are particularly important for lower mass-region of the many BSM searches, and LArTPC are the key technology for the search.*
 - * *Show like topology for better signal yield, benefiting higher BR (HNL) and unique signature different BSM model (Dark Tridents, Low Mass Dark matter)*
 - * *Clean signature, less background, cover larger parameter space of the many BSM models*
- Studying performance of the two shower reconstruction of the NuMI beam using SPIN \mathcal{E} .*

ICARUS PMT Timing System

- The scintillation light is collected by 360 Hamamatsu R5912-MOD 8" PMTs
 - Sensitive to vacuum ultraviolet (VUV) photons using tetraphenyl butadiene coating deposited on their external window.
- The PMTs are installed behind the wire planes of each of the 4 TPCs
 - 90 PMTs per TPC



BSM Searches with PMT Timing

- * Any BSM(i.e. HNLs) may travel slower than neutrinos
- * Measure heavy neutral lepton (HNL) time-of-flight delay using the ICARUS Detector and NuMI Beam
- * **Core observable** : The delay with respect to neutrinos
- * **1. Heavy Neutral Lepton Time-of-Flight Delay:**

The time delay relative to a neutrino is

$$\Delta t_{\text{HNL}} = \frac{L}{c} \left(\frac{1}{\beta} - 1 \right) \quad \beta = \sqrt{1 - \frac{m_N^2}{E_N^2}}$$

2. Detector Timing Contributions:

The reconstructed time includes detector resolution:

$$\sigma_{\text{det}} = \sqrt{\sigma_{\text{PMT}}^2 + \sigma_{\text{electronics}}^2 + \sigma_{\text{photon}}^2}$$

Typical values:

Source	Contribution
PMT transit time spread	~1.5 ns
Electronics jitter	~0.5 ns
Photon propagation in LAr	~1 ns

- 3. **Beam timing uncertainty:** **bunch spacing:** $T_{\text{bunch}} = 18.8 \text{ ns}$
spill timing jitter: 0.8ns

4. Total Reconstructed Timing :

$$t_{\text{reco}} = \Delta t_{\text{HNL}} + \delta_{\text{det}} + \delta_{\text{beam}}$$

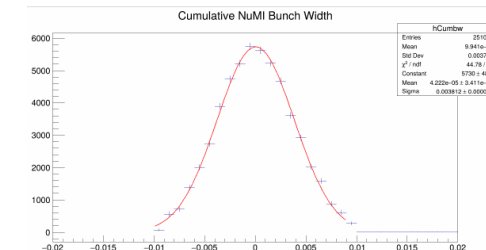
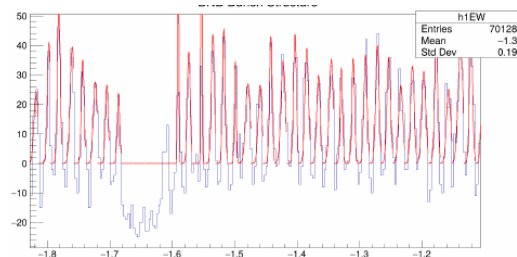
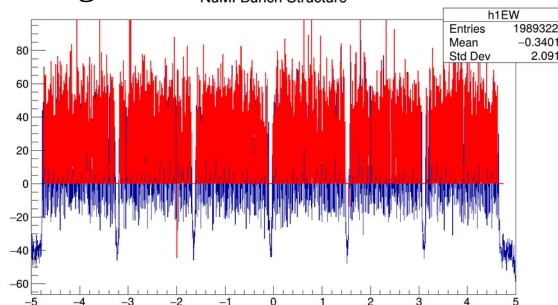
$$\delta_{\text{det}} \sim \mathcal{N}(0, \sigma_{\text{det}})$$

$$\delta_{\text{beam}} \sim \mathcal{N}(0, \sigma_{\text{beam}})$$

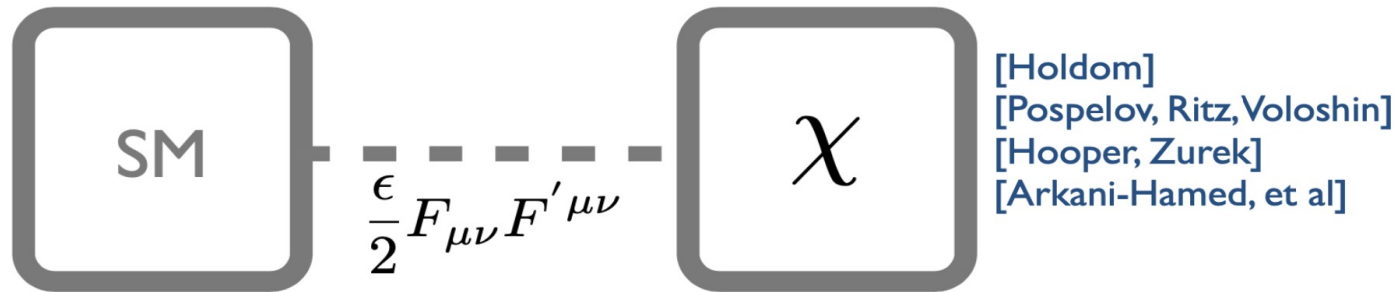
Work in Progress:

ICARUS CM meeting, 23 April, 2026, A.Chatterjee

NuMI Bunch Structure



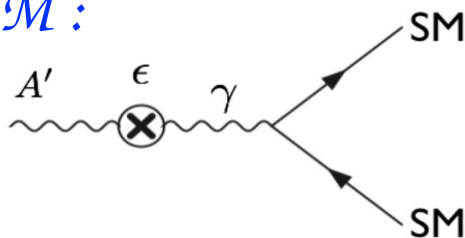
Vector Portal Model



$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} (F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \dots$$

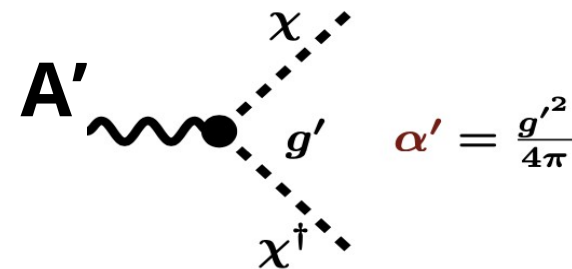
- * Dark photon (A') mediates interaction between DM and SM
- * 4 new parameters; $m_\chi, m_{A'}, \alpha_D, \epsilon$

Dark-Photon couples to SM:



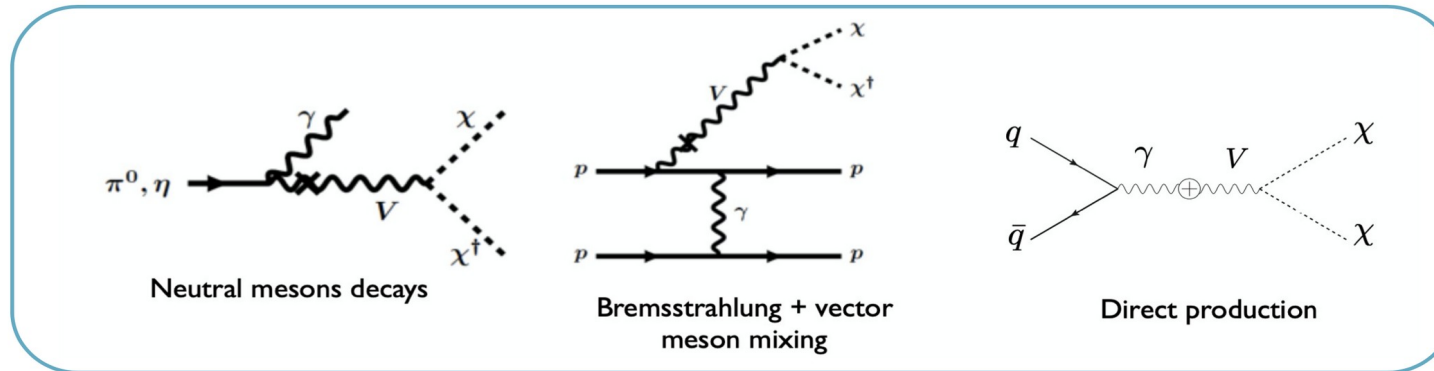
$$\Gamma_{A'} \sim \epsilon^2 \alpha m_{A'}$$

Coupling between mediator and particle

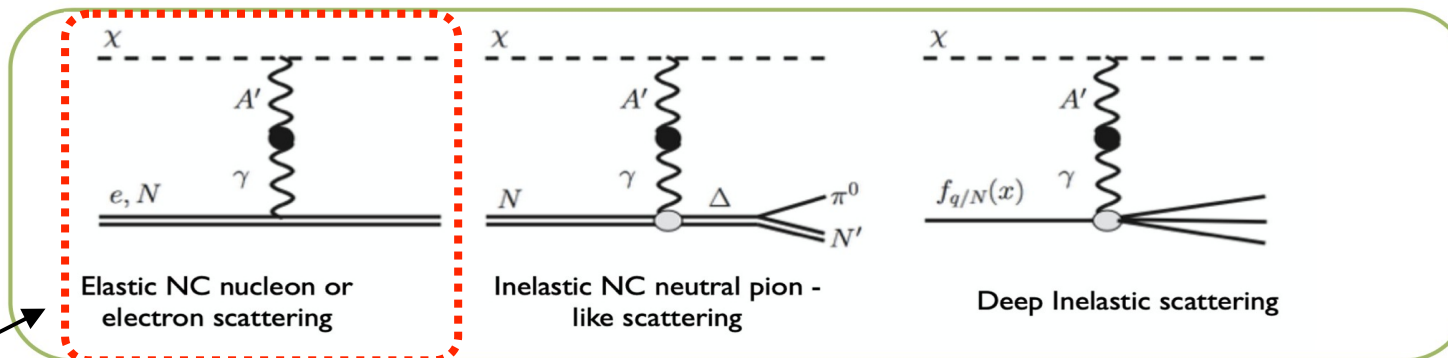


Vector Portal: Signal Characteristics

❖ Production of DM beam:



❖ Detection of DM via scattering :



- * DM-e elastic ($\chi e \rightarrow \chi e$) process is one of the golden channel to look for any scattering signature coming from heavy particle (sub-GeV DM)
 - * $E_e \theta_e^2$ is an important kinematical variable to separate neutrino-e background.
- Event timing relative to bunch center will be useful for background reduction



Milli-charge Particle Searches

- * Hypothetical particles with small electric charge: $Q_\chi = \epsilon e, \quad \epsilon \ll 1$

Production in NuMI beam

- * mCPs produced in proton–target interactions via:
 - π^0 / η decays $\rightarrow \gamma^* \rightarrow \chi\bar{\chi}$
 - Drell–Yan processes
 - off-shell photon radiation

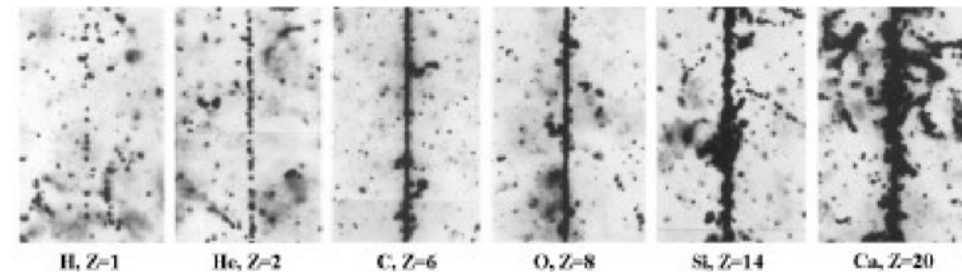
Detection signature

- * Very small ionization deposits (“blip-like” hits)
- * Multiple aligned low-energy hits along beam direction
- * No hadronic vertex activity

* Expected ICARUS sensitivity (NuMI mCP search)

- Mass range: ~ 10 MeV to 300 MeV
- Charge reach: $\epsilon \sim 10^{-4} - 10^{-3}$

$$\frac{dE}{dx} = \frac{n}{2\pi\mu E} \left(\frac{e^2}{\epsilon_0}\right)^2 \ln\left(\frac{4\mu E}{I}\right)$$



Summary

- * *ICARUS/SBN has a rich BSM physics program exploiting the potential of the NuMI beamline*
 - *MeV portal (MeVPrtl) publication has been uploaded to arXiv .*
 - *A di-muon final search has been published*
 - *The HNL analysis focusing on a two-track-like signature is currently in progress.*
 - *A shower-like final-state signature analysis has begun.*
 - *Additional BSM opportunities include sub-GeV dark matter searches, millicharged particles, and other beyond-the-Standard-Model scenarios.*

