Opportunity to search for the BSM physics at the ICARUS detector

Animesh Chatterjee

LLP13 Workshop, June 19-23,2023

LLP in SM

Long-Lived Particles (LLP) can travel macroscopic distances before decaying

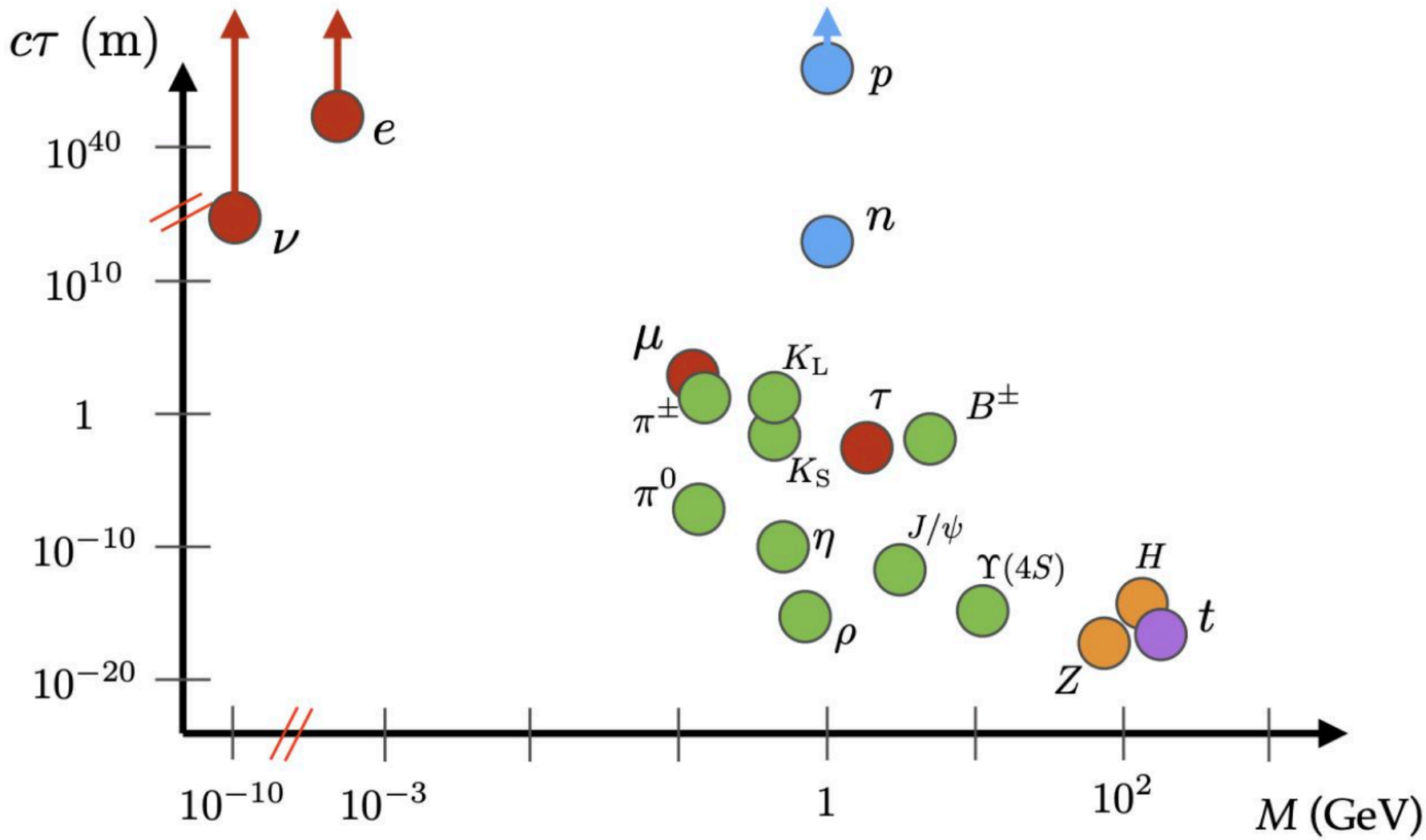


Image taken from arXiv: 1903.04497

Their presence comes from conserved symmetries, feebly couplings, heavy mediators/hierarchy of mass scale, small phase space.

LLP in BSM

LLP in BSM can arise from many well motivated classes of theories

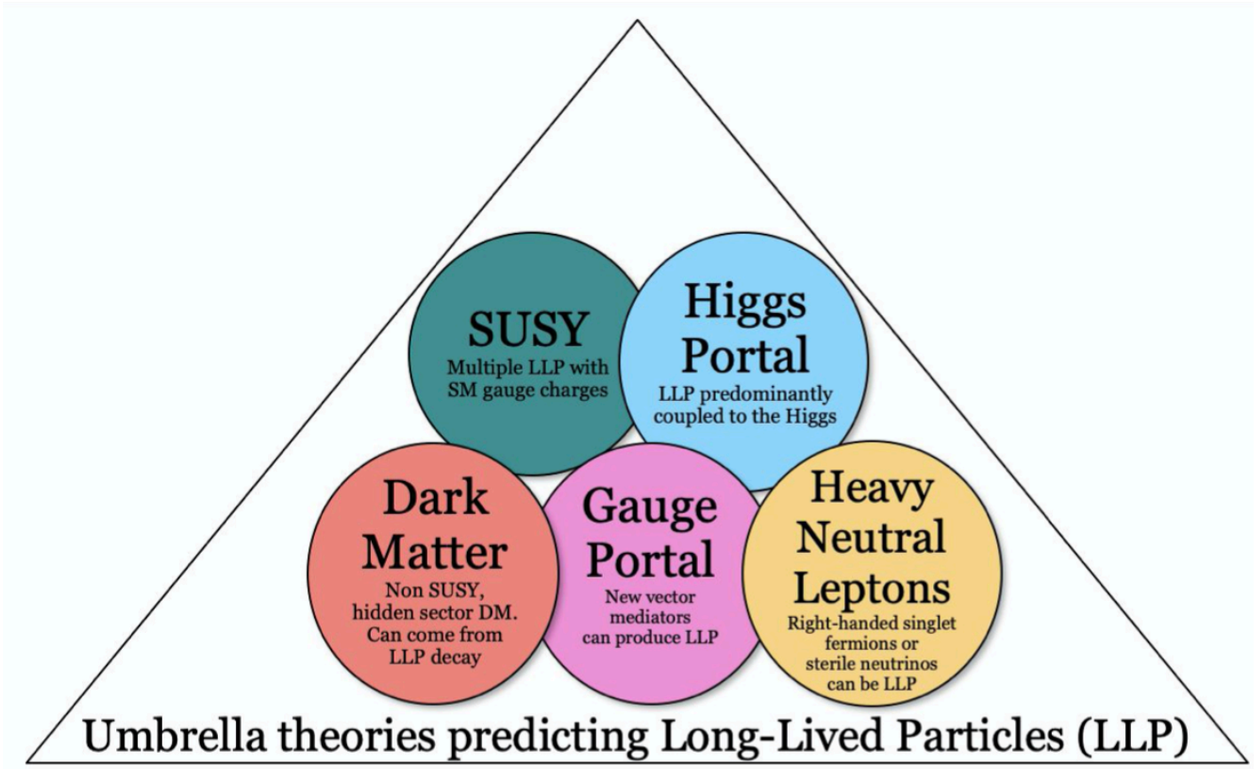


Image from : arXiv:1903.04497, 1806.07396

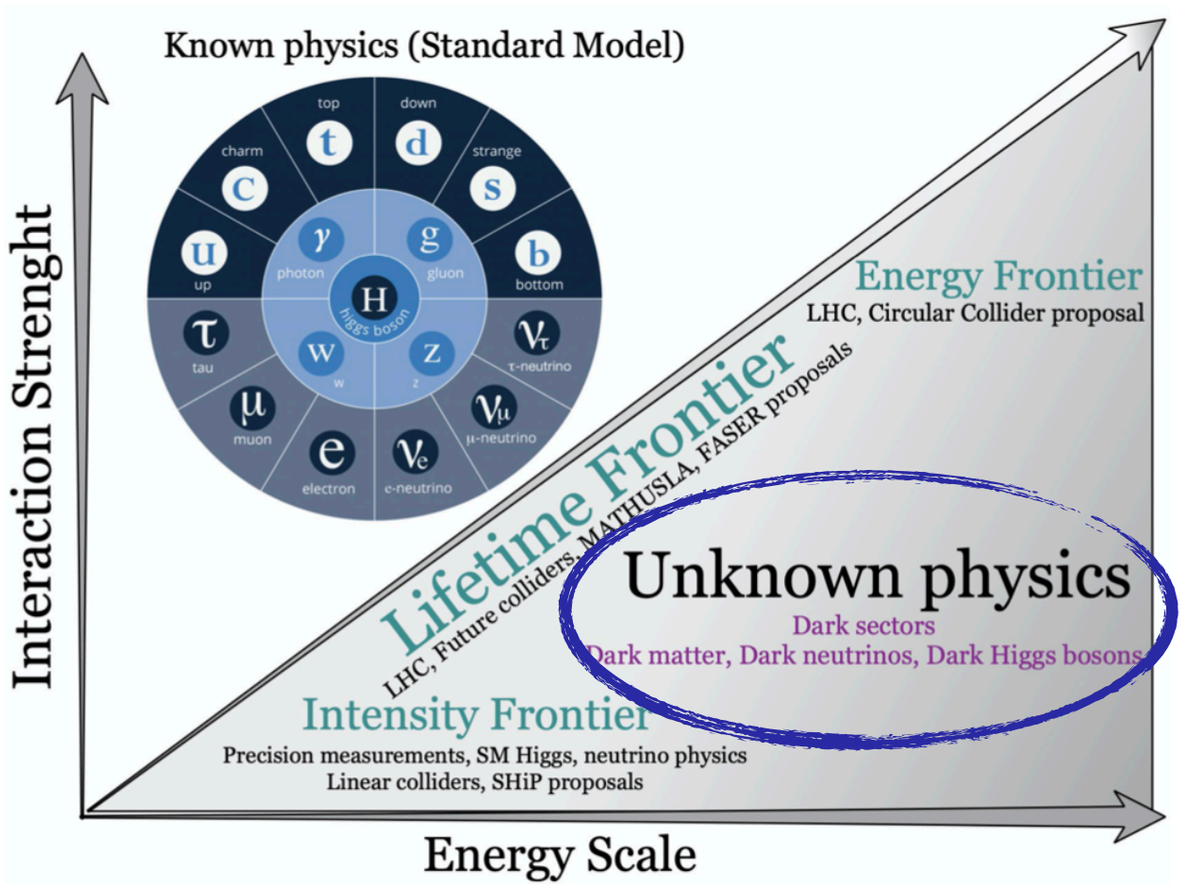


Image @CERN, ATLAS web

Need dedicated experiment to search for the long-lived particles to understand Unknown physics (BSM).

Why BSM ?

WHITE PAPER ON NEW OPPORTUNITIES AT THE NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

C.A. ARGÜELLES[1], A.J. AURISANO[2], B. BATELL[3], J. BERGER[3], M. BISHAI[4], T. BOSCHI[5], N. BYRNES[6], A. CHATTERJEE[6], A. CHODOS[6], T. COAN[7], Y. CUI[8], A. DE GOUVÊA[* 9], P.B. DENTON[4], A. DE ROECK[* 10], W. FLANAGAN[11], D.V. FORERO[12], R.P. GANDRAJULA[13], A. HATZIKOUTELIS[14], M. HOSTERT[15], B. JONES[6], B.J. KAYSER[16], K.J. KELLY[16], D. KIM[17], J. KOPP[10,18], A. KUBIK[19], K. LANG[20], I. LEPETIC[21], P.A.N. MACHADO[16], C.A. MOURA[22], F. OLNESS[6], J.C. PARK[23], S. PASCOLI[15], S. PRAKASH[12], L. ROGERS[6], I. SAFA[24], A. SCHNEIDER[24], K. SCHOLBERG[25], S. SHIN[26,27], I.M. SHOEMAKER[28], G. SINEV[25], B. SMITHERS[6], A. SOUSA[* 2], Y. SUI[29], V. TAKHISTOV[30], J. THOMAS[31], J. TODD[2], Y.-D. TSAI[16,32], Y.-T. TSAI[33], J. YU[* 6], AND C. ZHANG[4]

[1907.08311]

* **Experimental evidence :**
  - ☑ **Dark matter**
  - ☑ **Neutrino masses**
  - ☑ **Short-baseline anomalies**
  - ☑ **Matter-antimatter asymmetry**
  - ☑ **Gravitational interaction e.t.c.**

* **Theoretical motivation :**
  - ☑ **Hierarchy problem**
  - ☑ **Flavor puzzle**
  - ☑ **Nature of neutrinos (Dirac or Majorana)**
  - ☑ **Strong CP Problem**
  - ☑ **Dark sector e.tc.**

Why BSM ?

White Paper on New Opportunities at the Next-Generation Neutrino Experiments
(Part 1: BSM Neutrino Physics and Dark Matter)

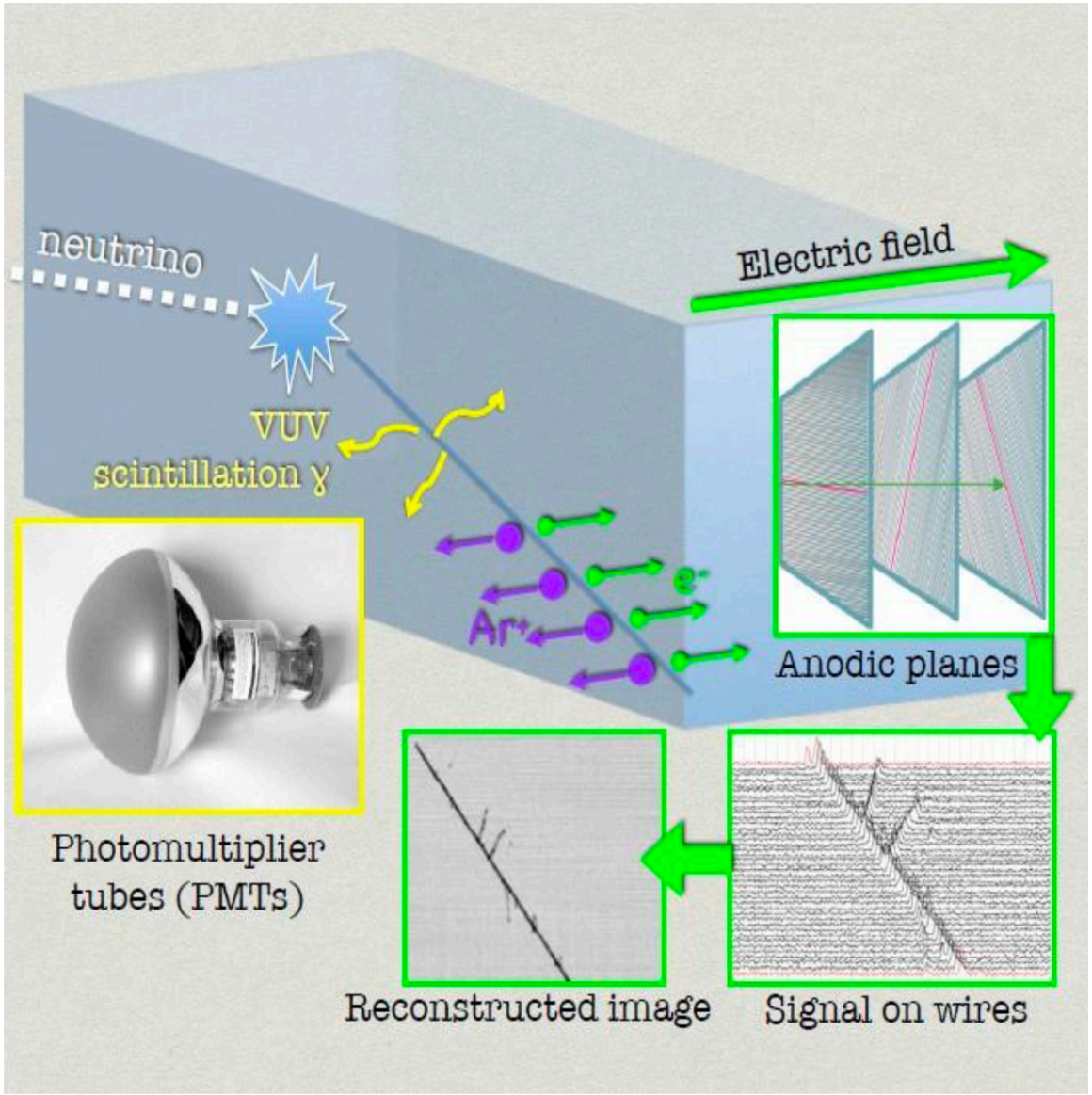
C.A. Argüelles[1], A.J. Aurisano[2], B. Batell[3], J. Berger[3], M. Bishai[4], T. Boschi[5], N. Byrnes[6], A. Chatterjee[6], A. Chodos[6], T. Coan[7], Y. Cui[8], A. de Gouvêa[* 9], P.B. Denton[4], A. De Roeck[* 10], W. Flanagan[11], D.V. Forero[12], R.P. Gandrajula[13], A. Hatzikoutelis[14], M. Hostert[15], B. Jones[6], B.J. Kayser[16], K.J. Kelly[16], D. Kim[17], J. Kopp[10,18], A. Kubik[19], K. Lang[20], I. Lepetic[21], P.A.N. Machado[16], C.A. Moura[22], F. Olness[6], J.C. Park[23], S. Pascoli[15], S. Prakash[12], L. Rogers[6], I. Safa[24], A. Schneider[24], K. Scholberg[25], S. Shin[26,27], I.M. Shoemaker[28], G. Sinev[25], B. Smithers[6], A. Sousa[* 2], Y. Sui[29], V. Takhistov[30], J. Thomas[31], J. Todd[2], Y.-D. Tsai[16,32], Y.-T. Tsai[33], J. Yu[* 6], and C. Zhang[4]

[1907.08311]

BSM searches with the Liquid Argon TPC based neutrino experiments

* Experimental evidence :
  - ☑ Dark matter
  - ☑ Neutrino masses
  - ☑ Short-ba
  - ☑ Gravitational interaction e.t.c.
* Theoreti
  - ☑ puzzle
  - ☑ Nature of neutrinos (Dirac or Majorana)
  - ☑ Strong CP Problem
  - ☑ Dark sector e.tc.

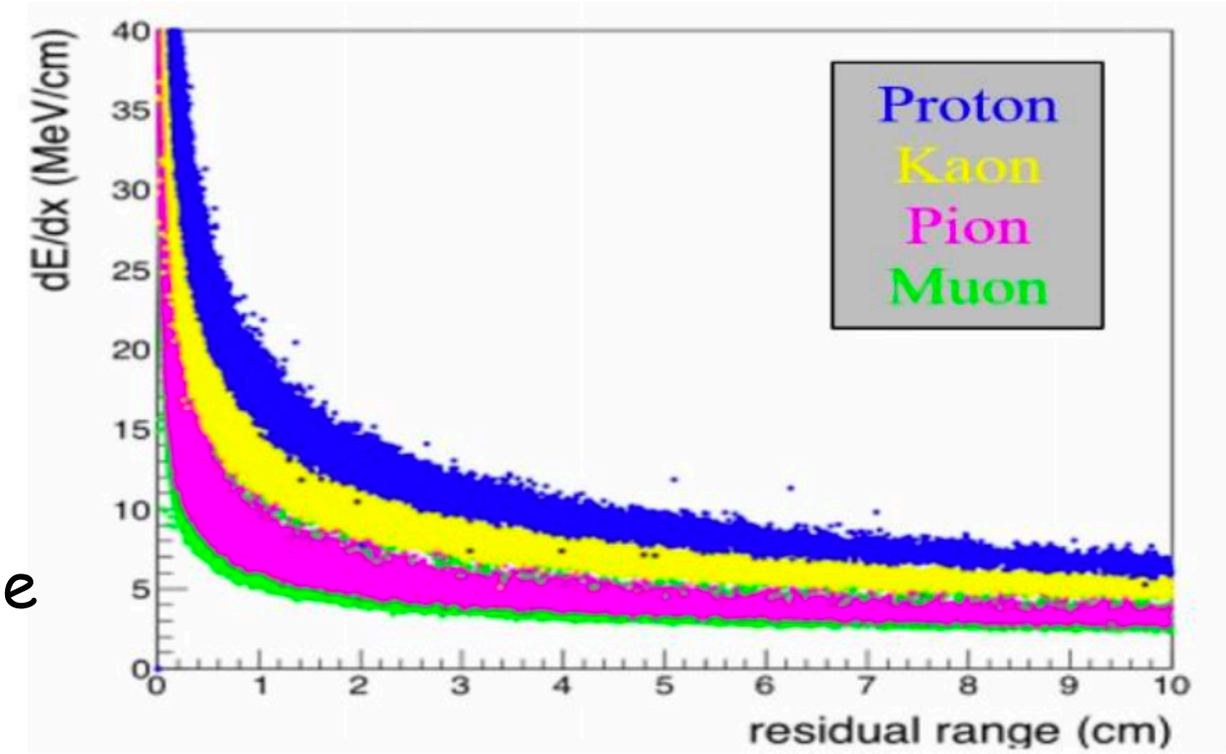
Why Liquid Argon TPC (LArTPC)?



* Neutrino (or any energetic particle) interaction i n LAr produces ionization and scintillation light

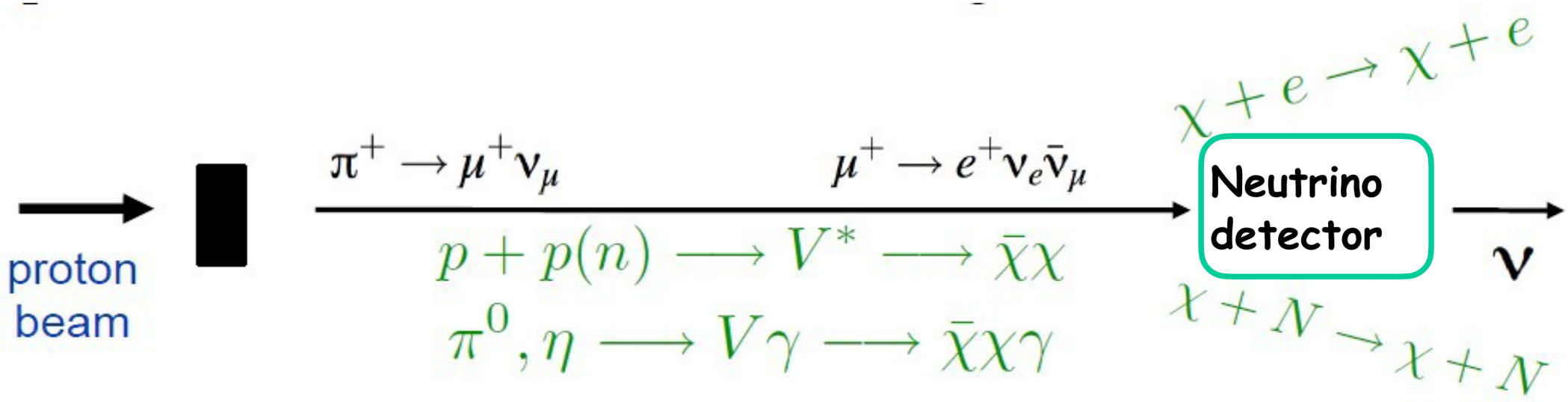
*3D image reconstruction is obtained from full drift recording, by combining coordinates on different wire planes

* Particle identification via dE/dX



* Transparent to its own scintillation light(no absorption)
* Timing information from PMTs will be very useful tool for heavy particle searches

How to detect LLP/BSM in LArTPC ?



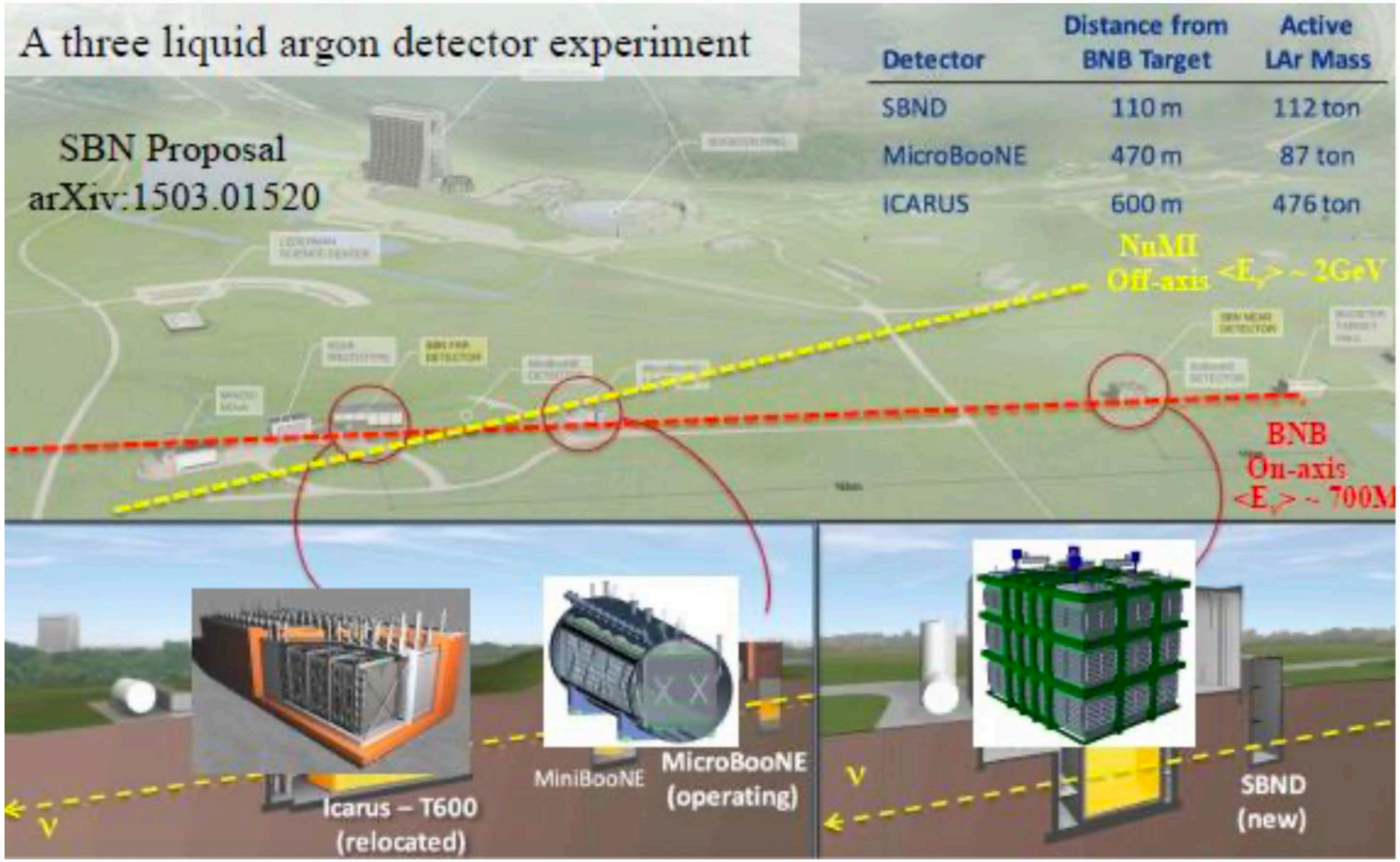
We can use the neutrino detector for BSM/LLP searches, looking for decay/ recoil signature with the accelerator-based proton beam.

MiniBooNE
8GeV BNB Beam
540m to the mineral oil detector

SBN (ICARUS)
8.9 GeV BNB and 120 GeV NuMI Beam, 3 LArTPC detector

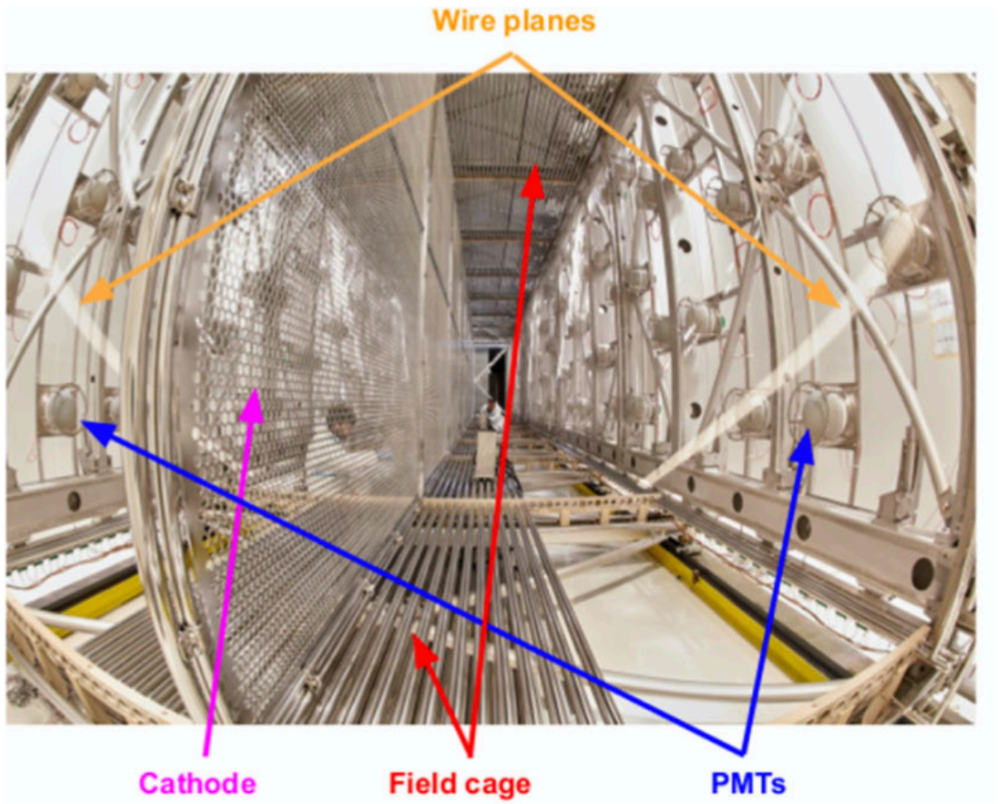
DUNE Near detector
120 GeV LBNF Beam
Multipurpose near detector

Short Baseline Neutrino Program (SBN)



- ☑ The SBN Program is composed of three LArTPC detectors with the goal of definitively addressing the hints of eV-scale sterile neutrinos, can be used for BSM searches

Imaging Cosmic And Rare Underground Signals (ICARUS) in a nutshell

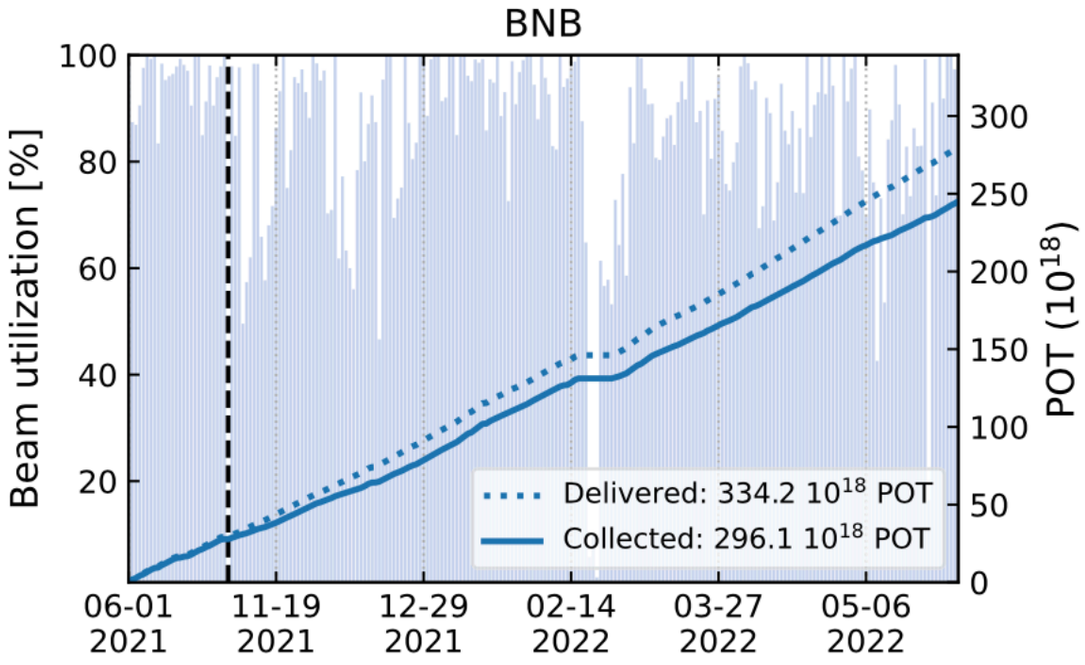


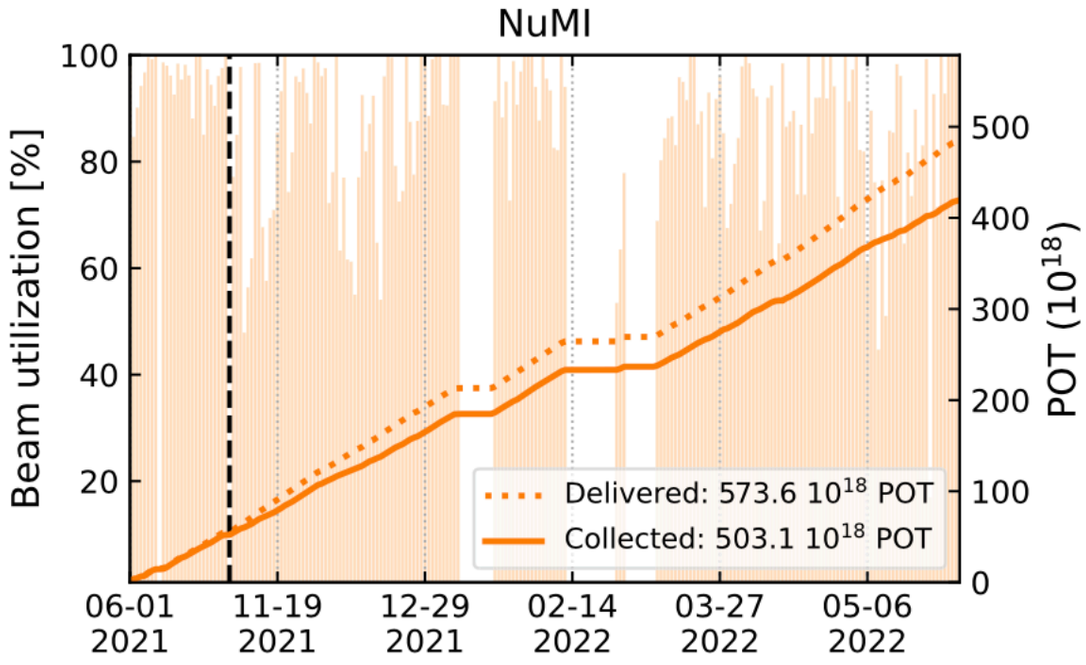
- ICARUS-T600 was the first large LArTPC detector
- Two identical modules (T300) each 19.6 x 3.6 x 3.9 m^3.
- ICARUS-T600 Liquid argon mass: total 760 t; active 476 t
- Drift distance 1.5 m. Electric field 500 V/cm (75 kV) -> drift time ~1ms
- 3 signal wire planes (2 induction + 1 collection)
- Pitch and inter-plane distances: 3 mm; 400 ns sampling time
- ~54,000 channels

ICARUS started "Physics data" both with NuMI and BNB beam!

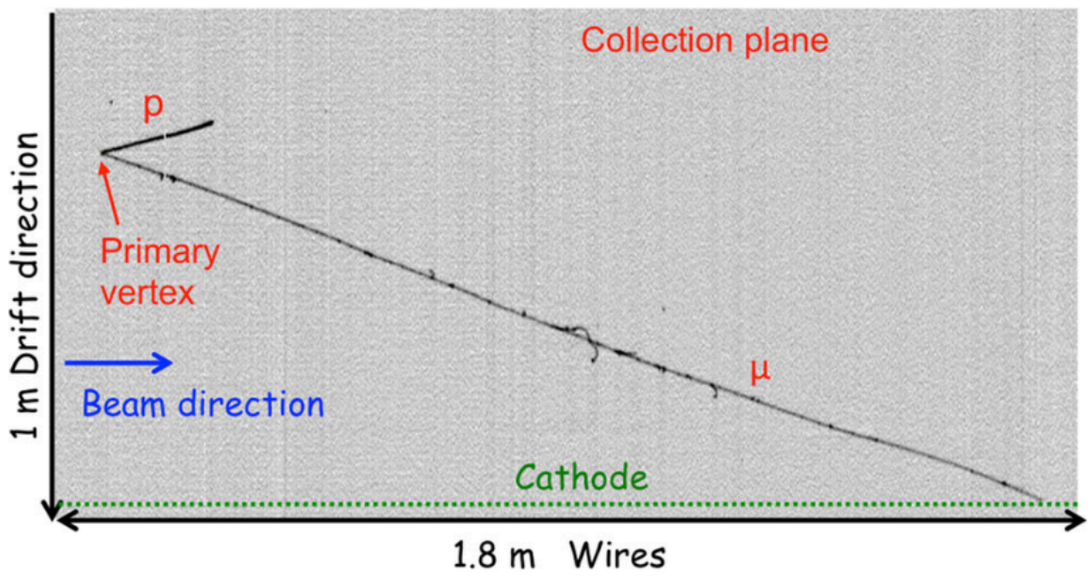
ICARUS first operation at SBN

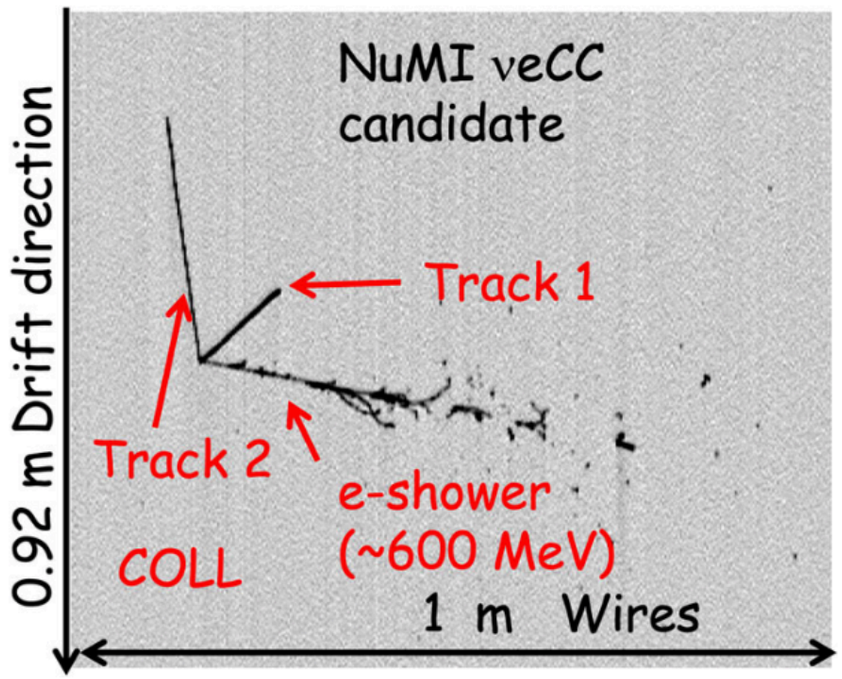
Eur. Phys. J. C **83**, 467 (2023)





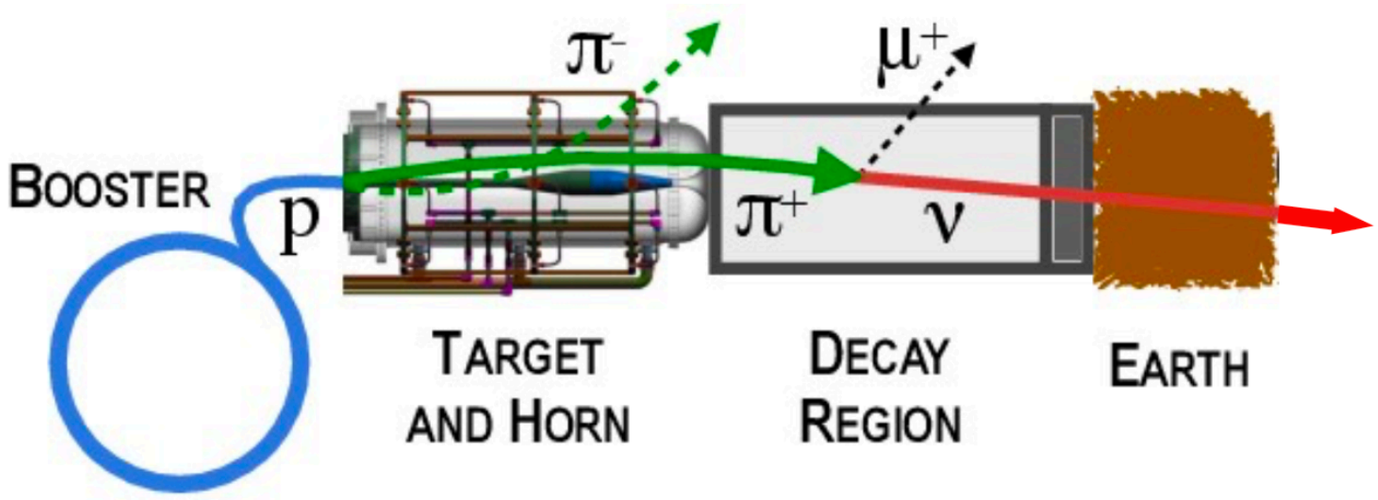
νμCC candidate from the BNB beam

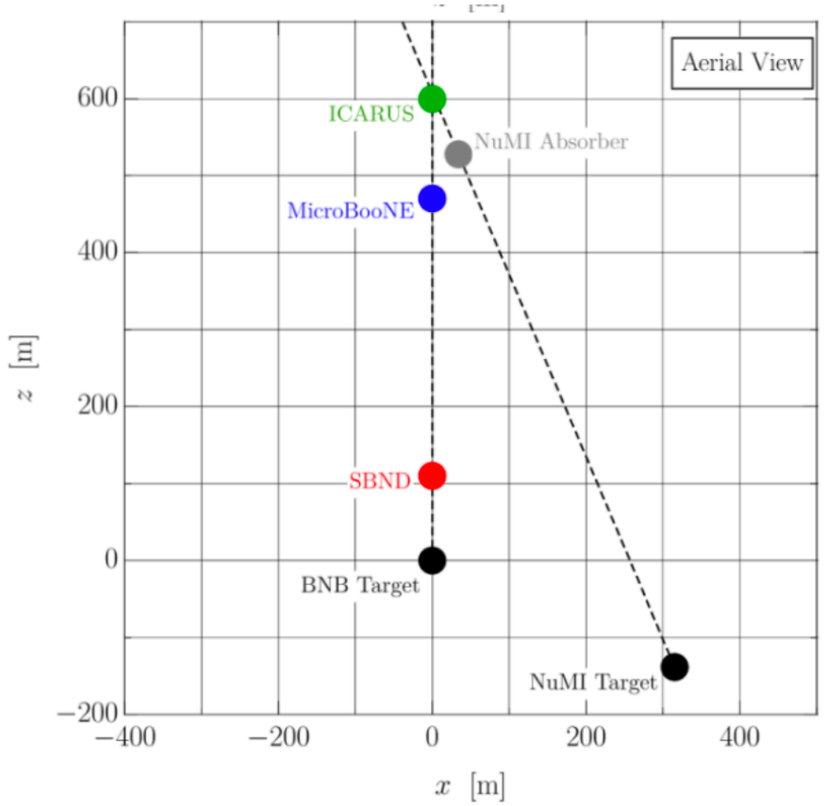




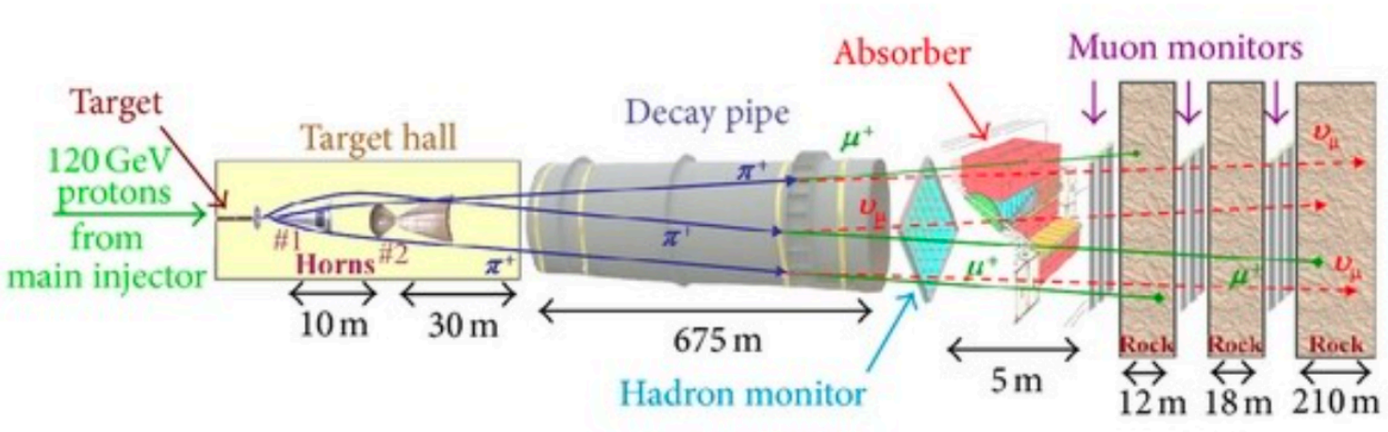
Why ICARUS for BSM searches ?

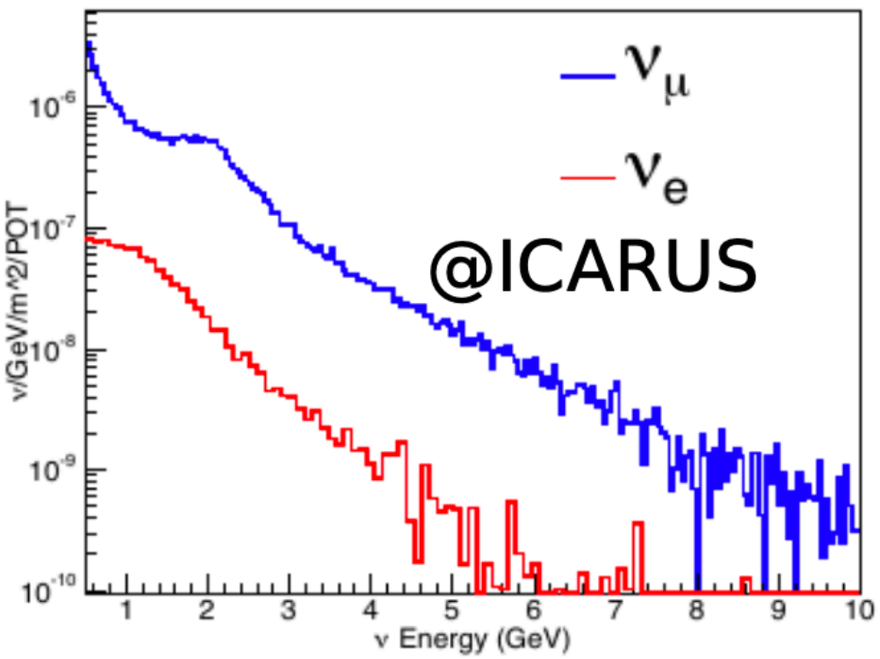
BNB Beam (On-axis @0°)





NuMI Beam (Off-axis @5.7°)





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

Dark sector models looking @ICARUS

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

- These portals fall into three general categories :

  - ☑ Higgs portal Scalar (HPS) : Scalar dark sector particles - interactions by mixing with the Higgs boson
  - ☑ Vector Portal : Vector particles – interactions by mixing with the photon
  - ☑ Heavy Neutral Lepton (HNL) : Fermionic particles - interactions by mixing with neutrinos
  - ☑ Heavy QCD axion (ALP) : Pseudoscalar particles - interactions by mixing with pseudo-scalar mesons

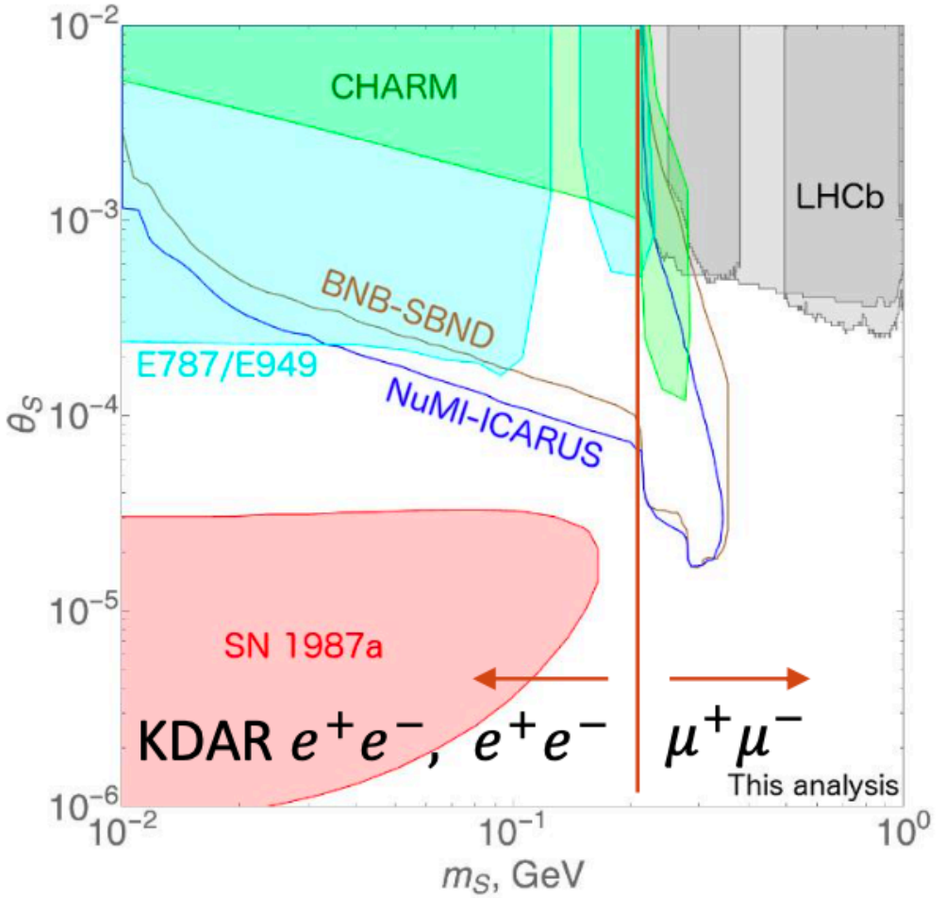
Search for these dark sector models @ICARUS using NuMI beam ongoing

Higgs Portal Scalar (HPS) @ICARUS

✱ Higgs Portal :

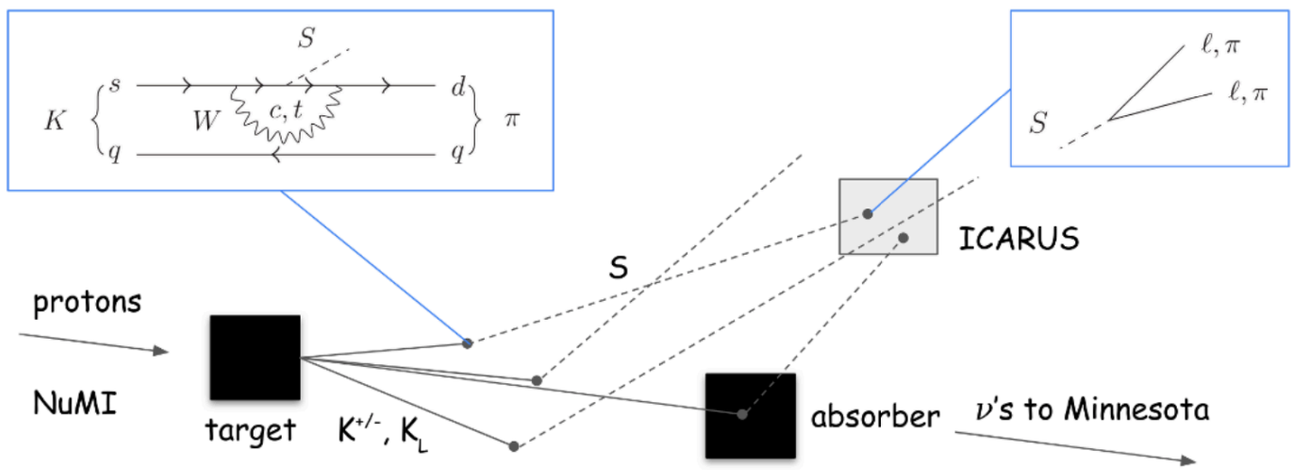
SM ⟷ $\mathcal{L} \supset -(AS + \lambda S^2)H^\dagger H$ ⟷ Higgs scalar

- ☑ In the Minimal model, the new scalar S couples to the Higgs via portal coupling
- ☑ 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 ICARUS LArTPC

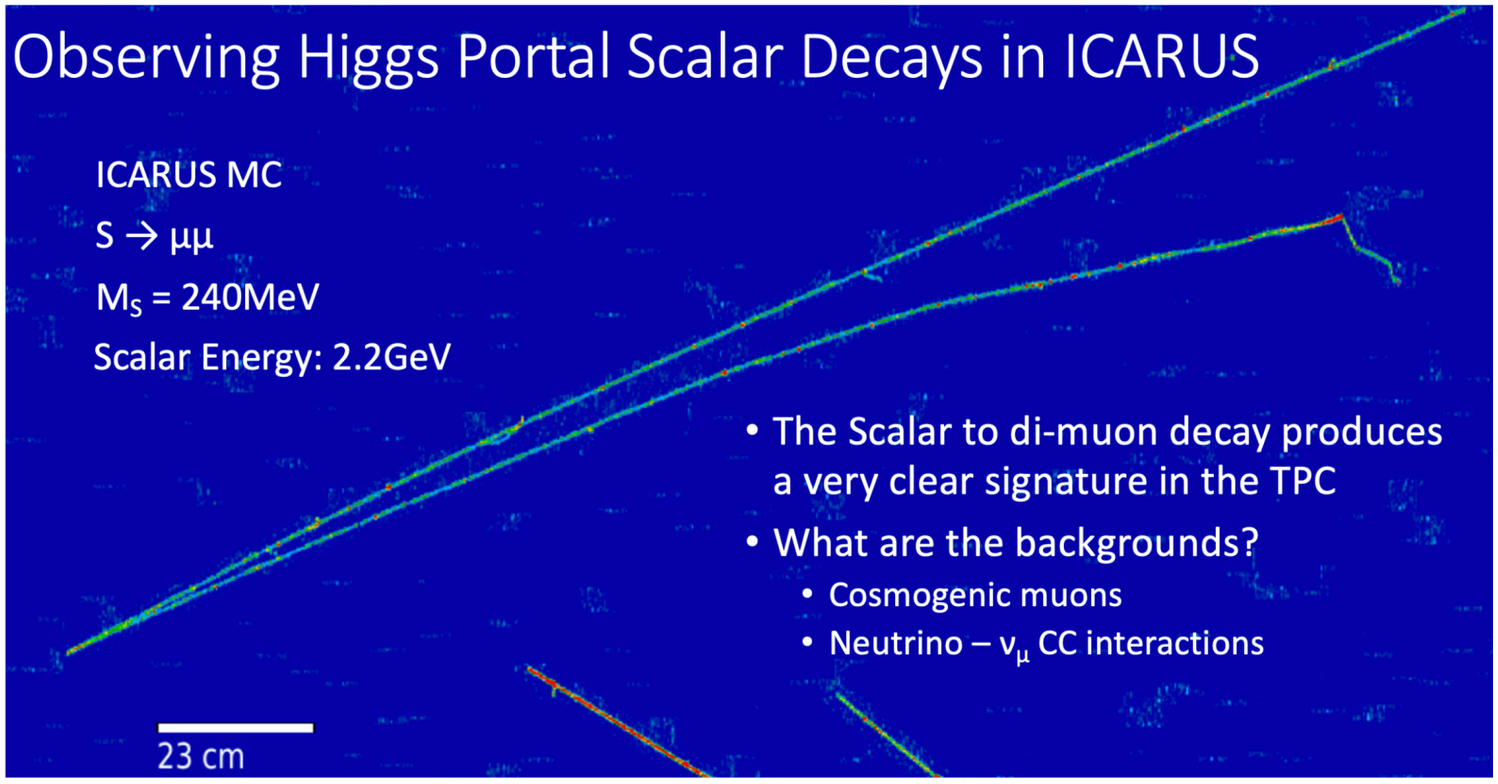


Estimated sensitivity from: Phys. Rev. D 100, 115039

HPS production and detection @ICARUS

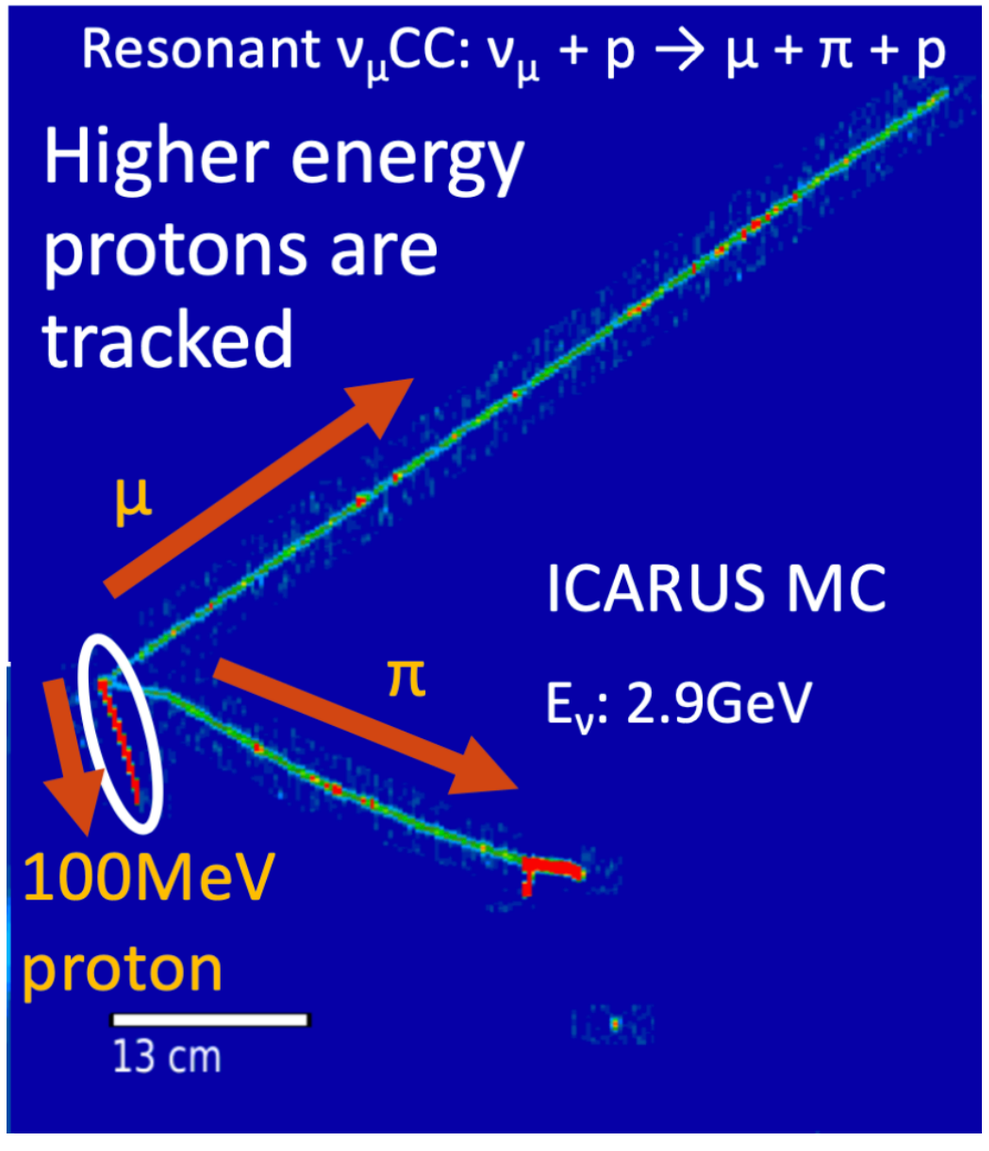


HPS decay to di-muon final state

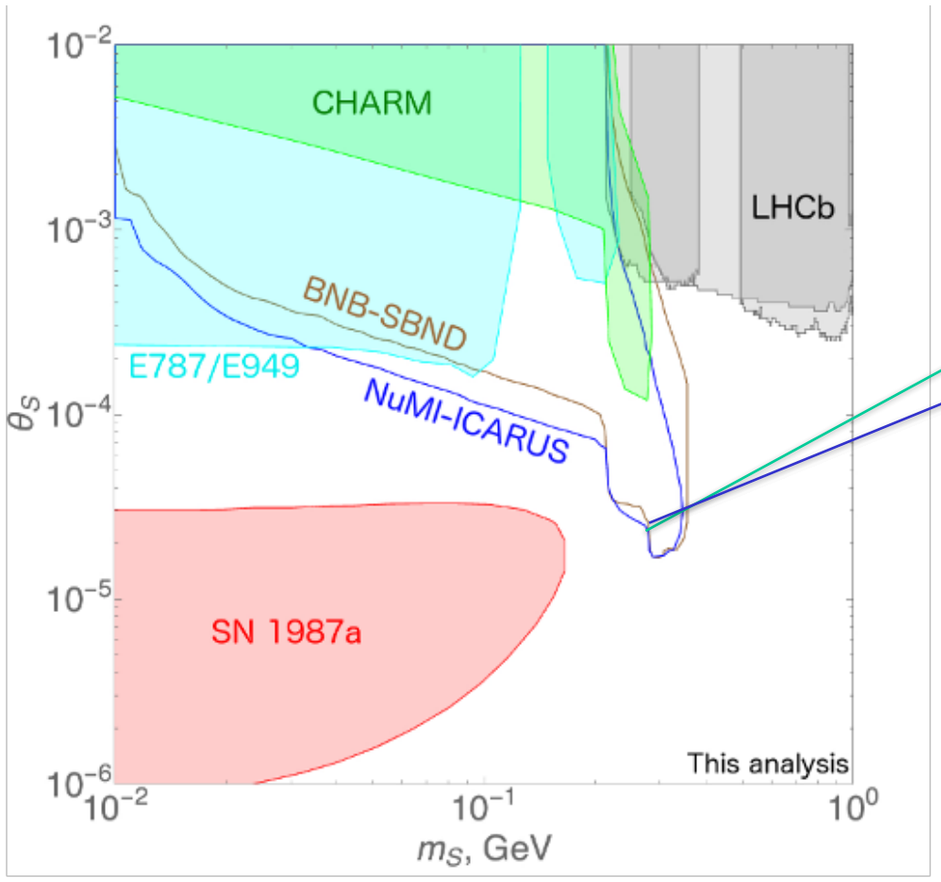


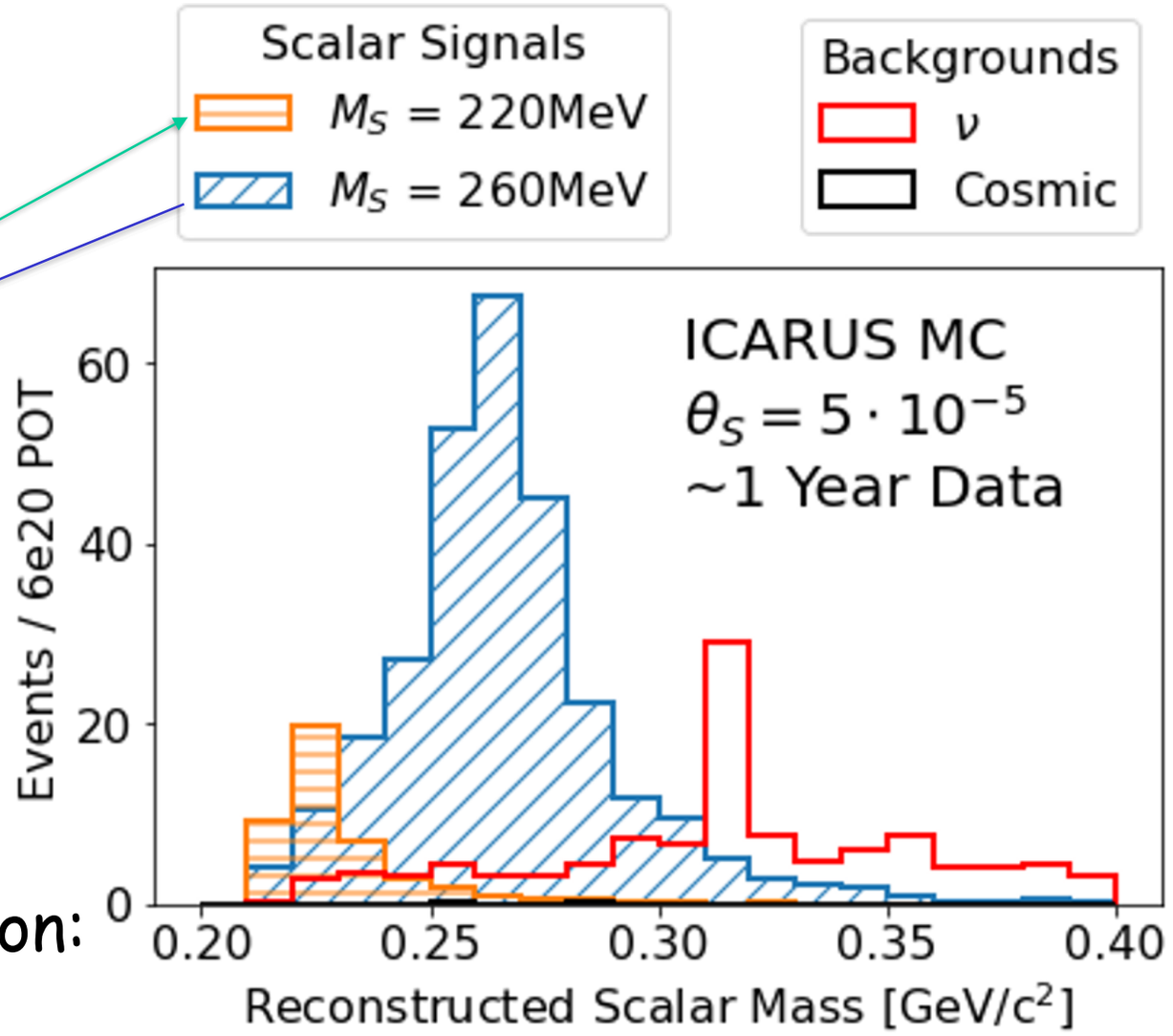
* Neutrino interactions with a final state pion and a muon is the major background

* Such interactions also produces protons
  - Protons are tracked down to about 50MeV
  - Flagging charge at vertex lowers this to ~15MeV



HPS decay to di-muon final state



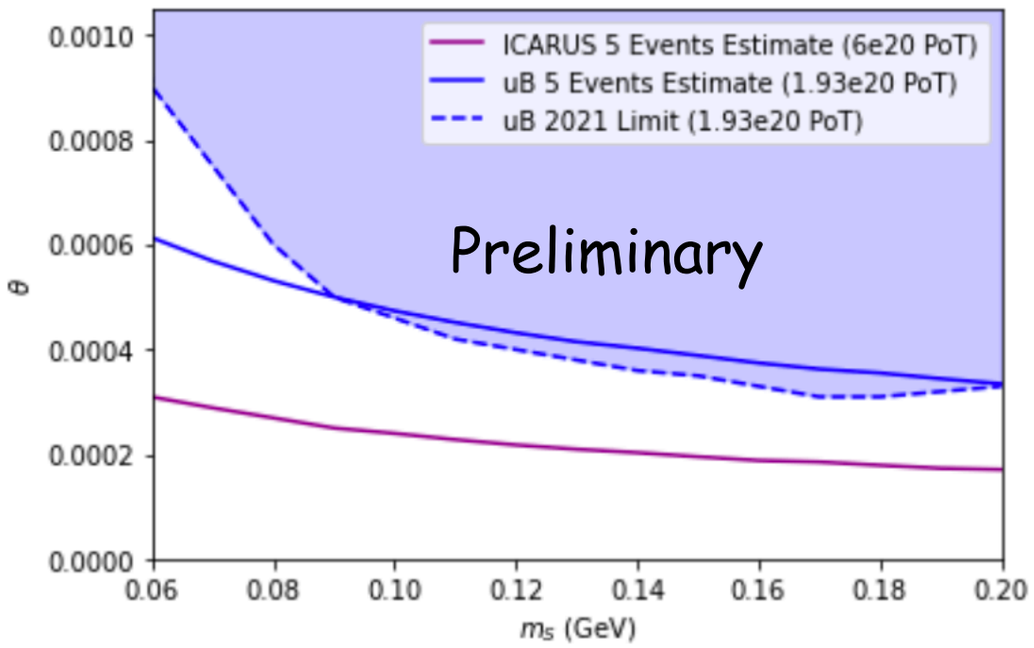


- Preliminary estimate from simulation:
  - ☑ 100% cosmic rejection
  - ☑ > 99% neutrino rejection
  - ☑ ~40% signal efficiency

HPS to di-muon searches is in mature state and in on a timeline to complete a result this calendar year

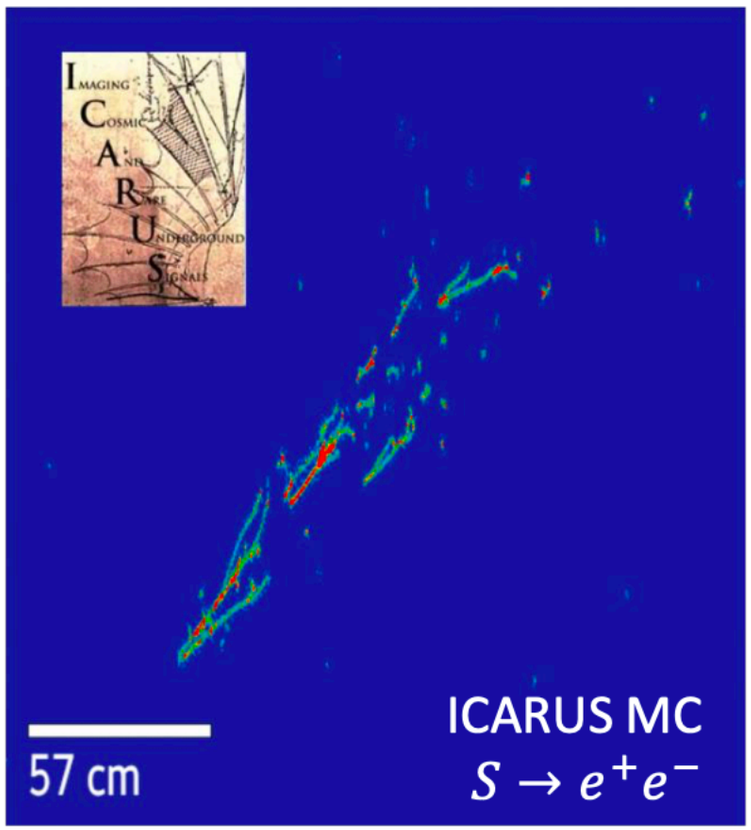
HPS decay to e^+ e^- final state

* 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)



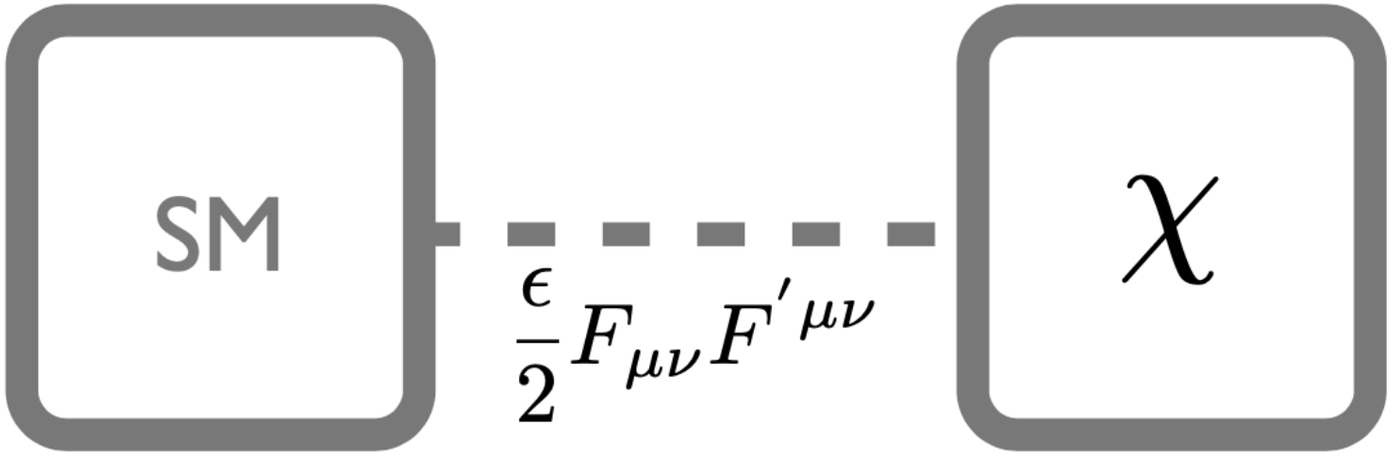
* KDIF (Kaon-Decay-in-Flight)
  Signal:

Example event display:



Work ongoing, expect better sensitivity due to larger detector volume compared to MicroBooNE.

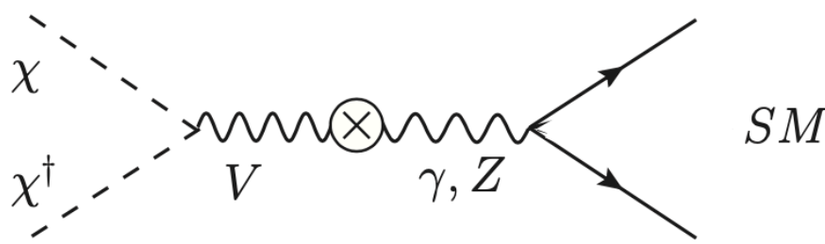
Vector portal dark matter @ICARUS



[Holdom]
[Pospelov, Ritz, Voloshin]
[Hooper, Zurek]
[Arkani-Hamed, et al]

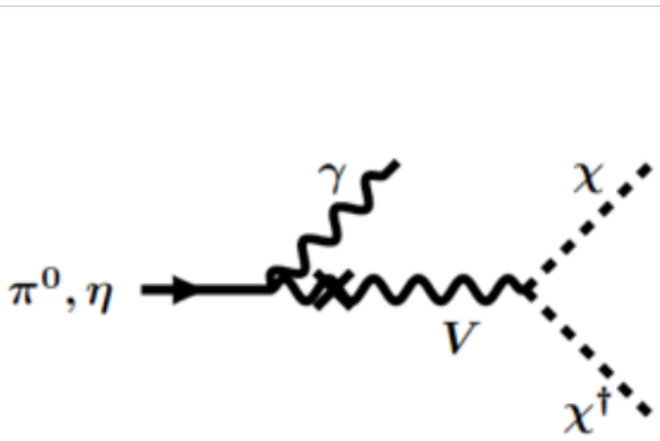
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \ldots$$

- Dark photon mediates interaction between DM and SM
- 4 new parameters; $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Can obtain correct relic abundance
- Coupling parameter space should not such that abundance is not too large and consistent with cosmology.

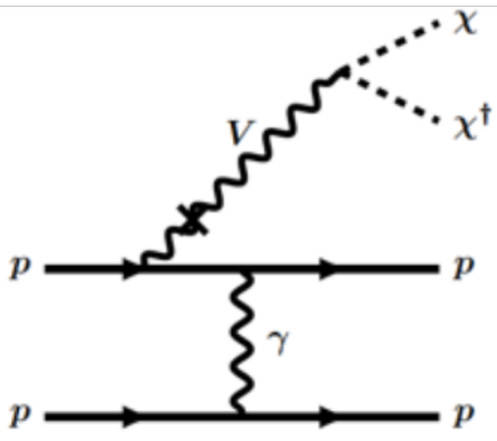


Vector portal dark matter: production & detection

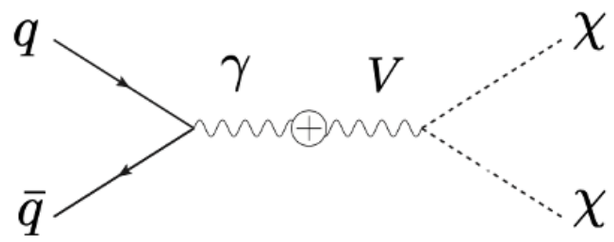
*Production of DM beam:



Neutral mesons decays

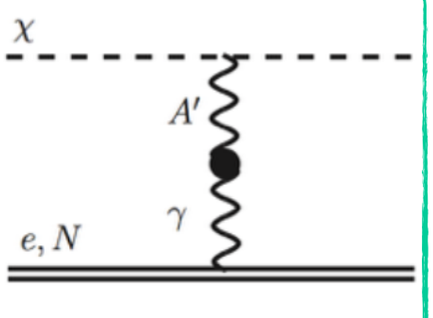


Bremsstrahlung + vector meson mixing

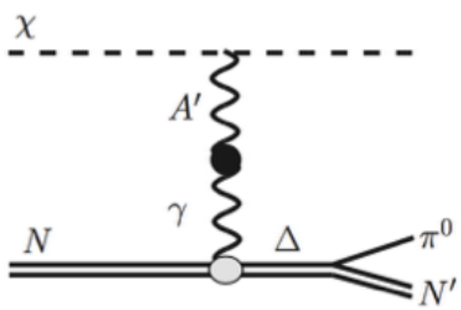


Direct production

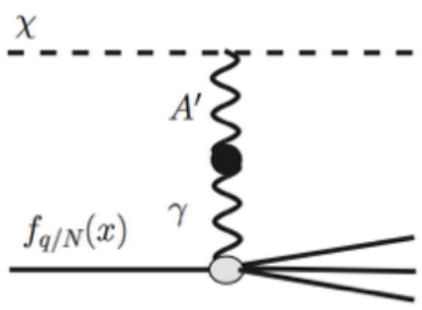
*Detection of DM via scattering:



Elastic NC nucleon or electron scattering



Inelastic NC neutral pion - like scattering

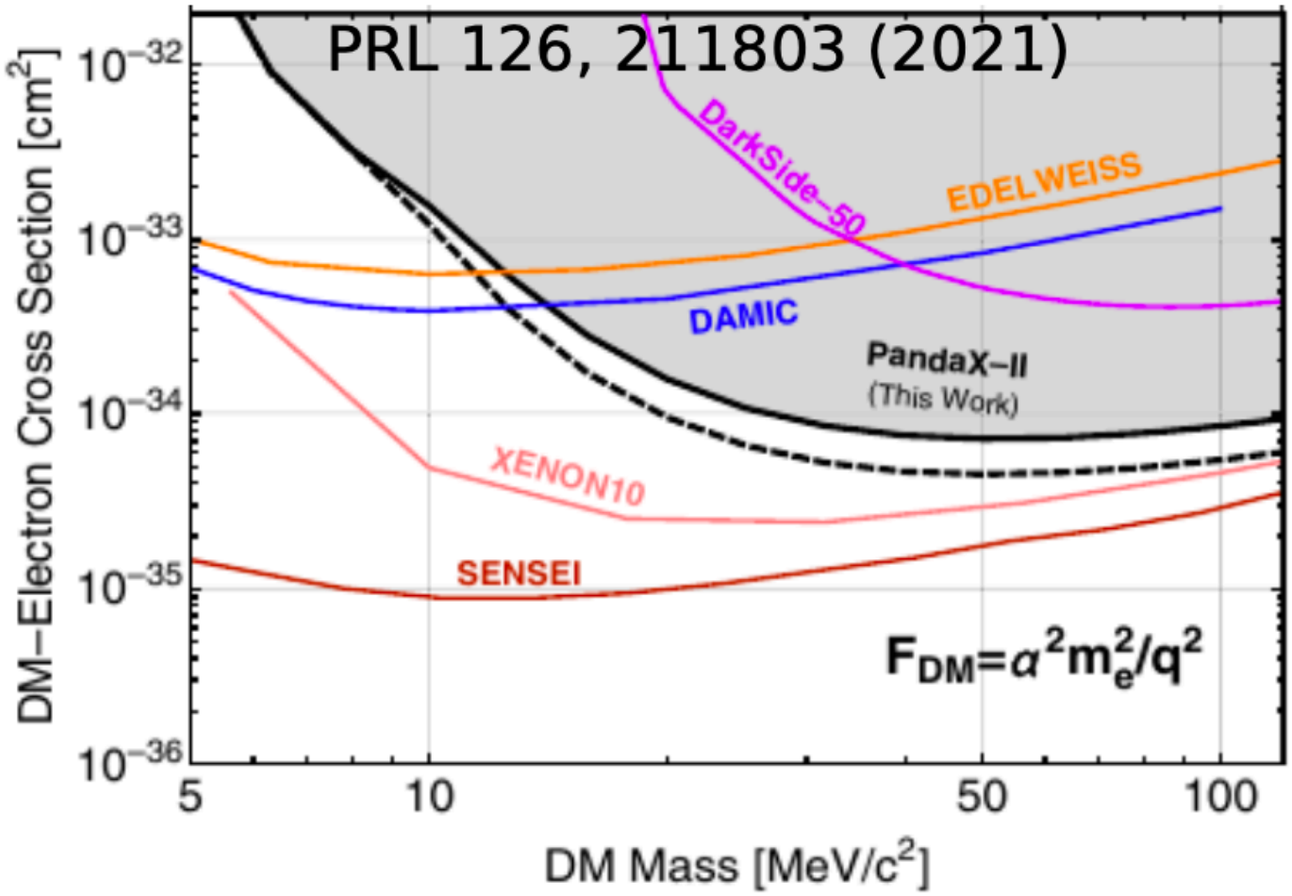


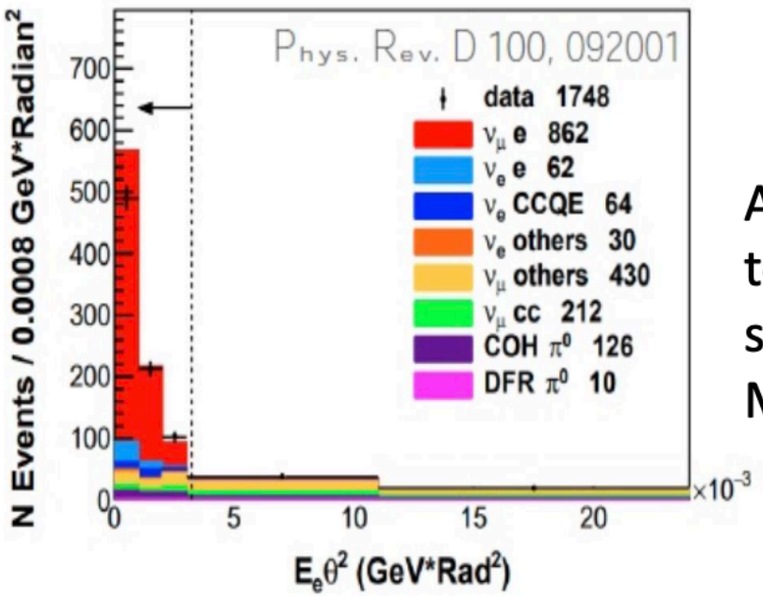
Deep Inelastic scattering

Elastic scattering off electrons is a promising low background channel.

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 $E\theta^2$)



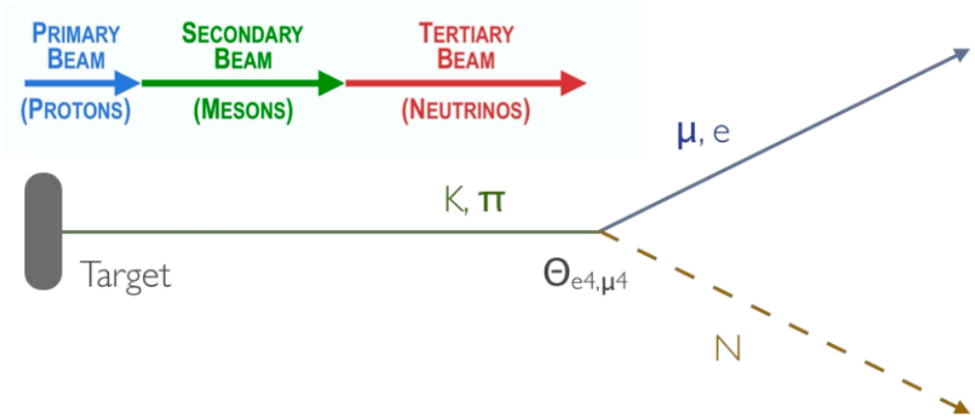


Application of $E_e\theta^2$ to select for $\nu - e$ scattering events in MINERvA

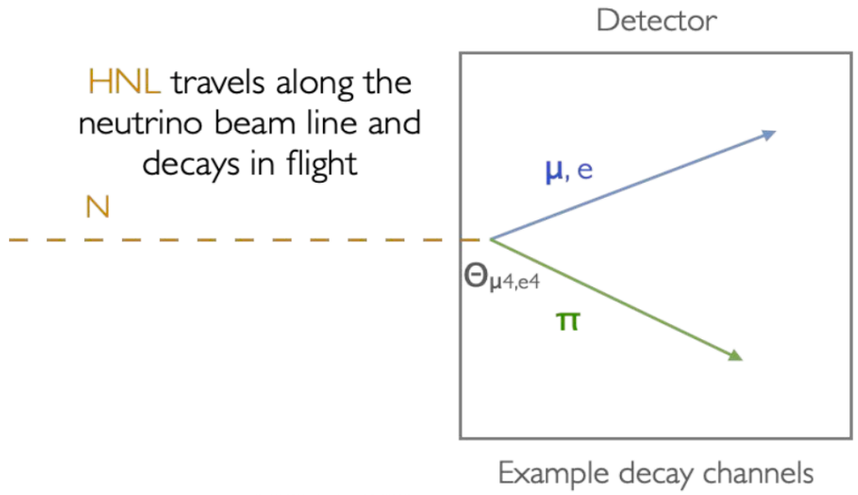
With the NuMI Off-axis beam and large LArTPC detector, ICARUS will provide be able explore more parameter space using forward e channel.

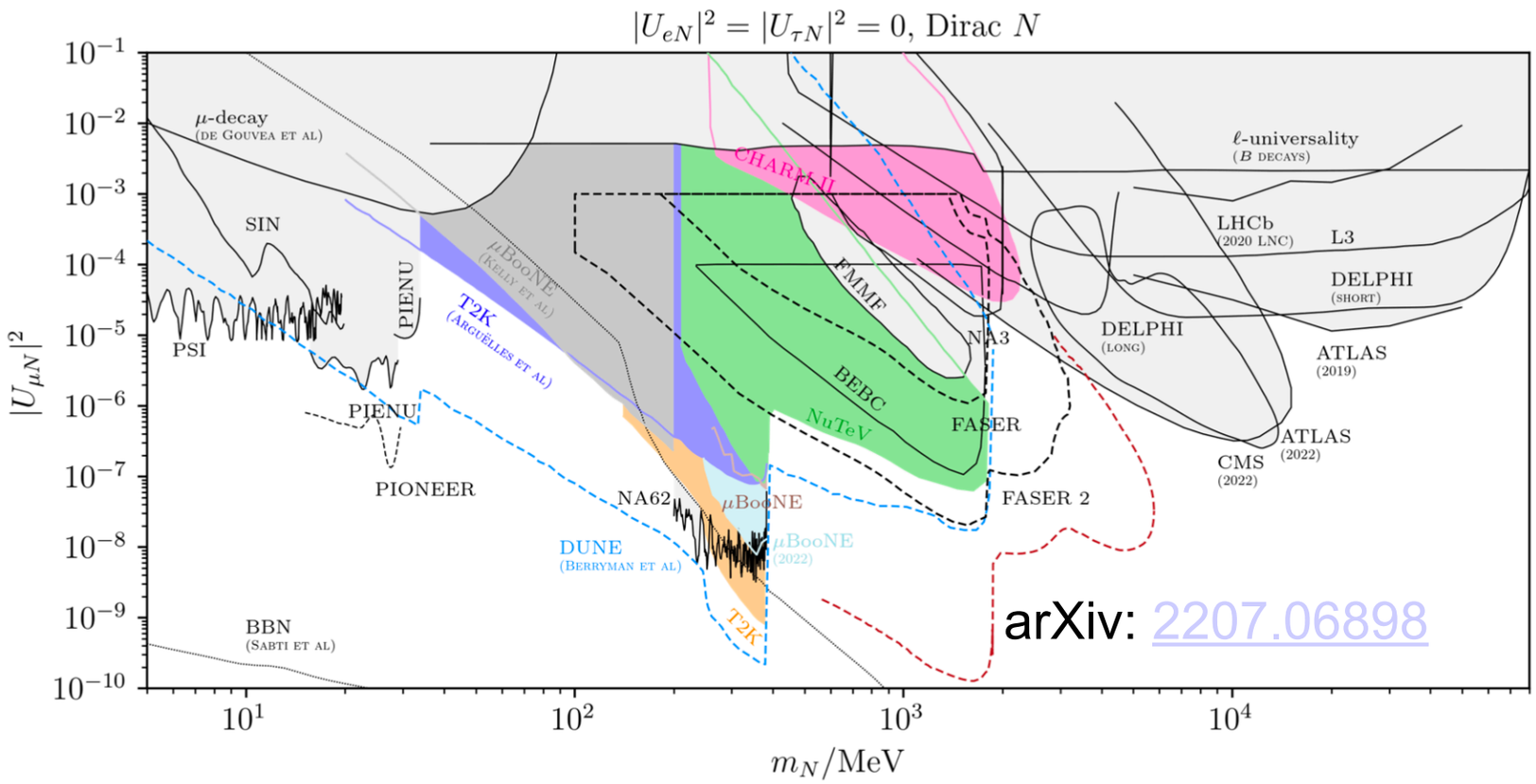
HNL searches @ICARUS

- Production



Detection :





arXiv: 2207.06898

- HNL decaying into two muons (pion) and a neutrino
- Other channel will also be interesting to search

- ICARUS will have great opportunity with two muon and electron channel and improve compared to MicroBooNE
- Work ongoing to understand the background and generate sensitivity .

Heavy QCD axion (ALP) searches @ICARUS

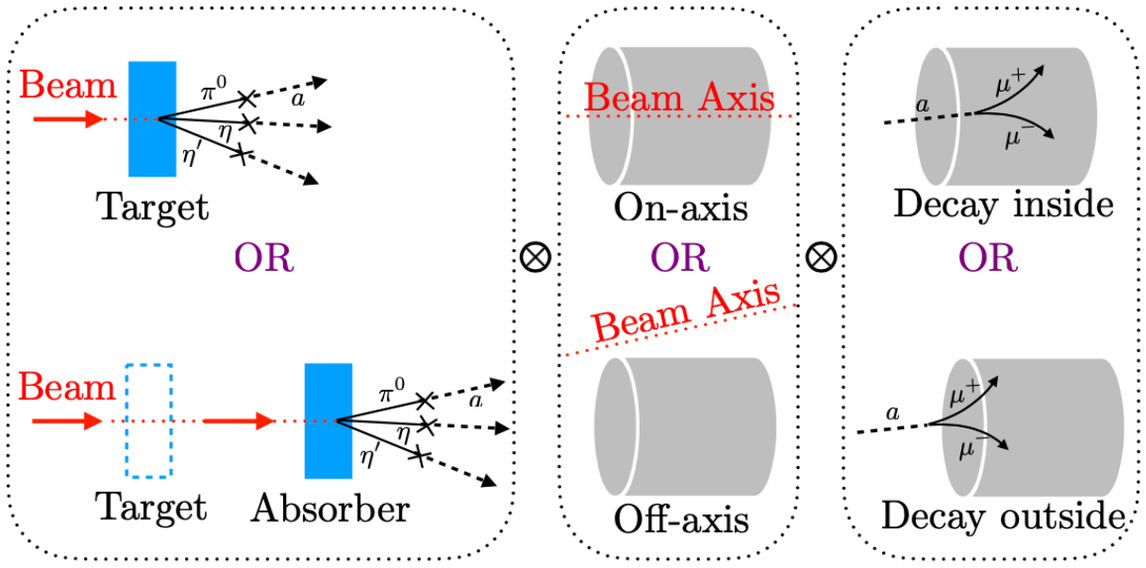
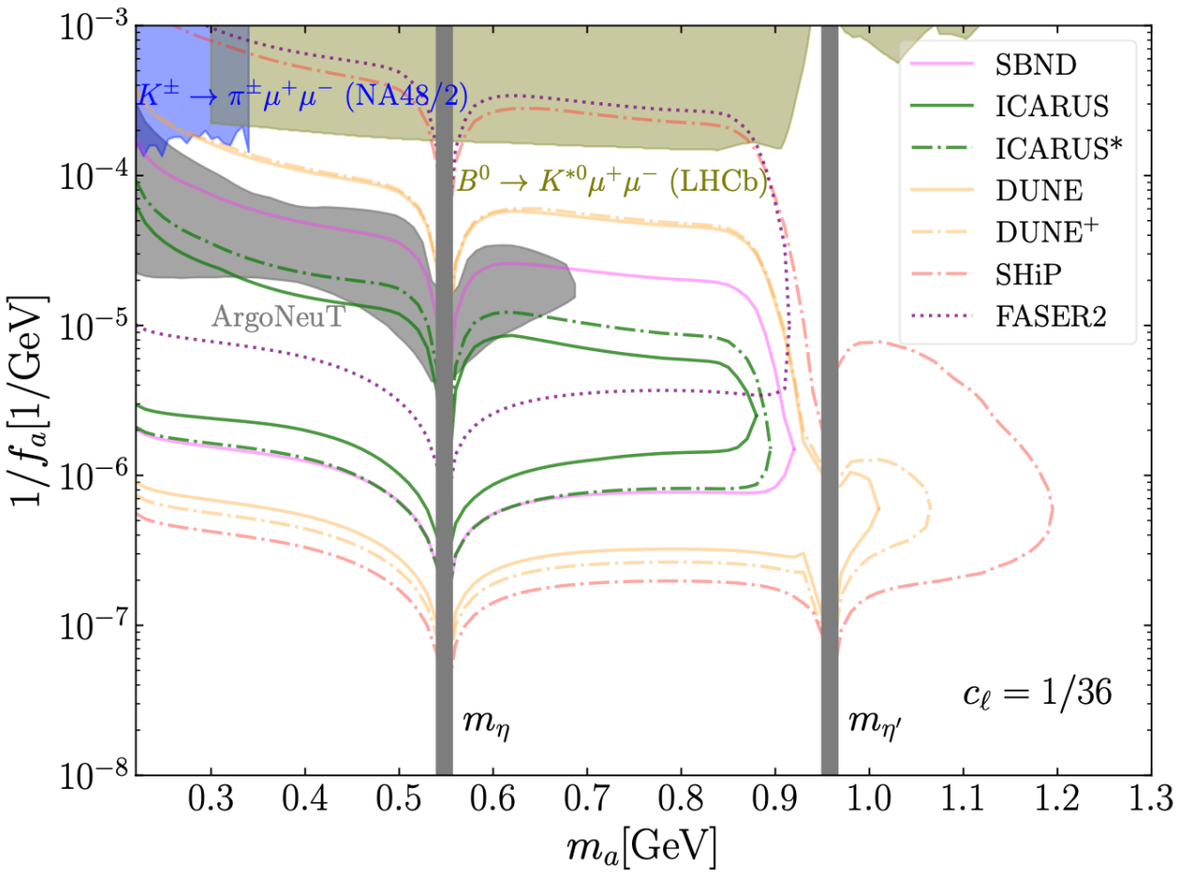


Image from arXiv:2210.02462

* The mixing production is primarily driven by axion mixing with the Standard Model mesons π, η, and η
* Di-muon final state will be the most significant final state to search for at ICARUS.

* The axion to di-muon decay channel not only has the feature of being clean and highly identifiable but also can allow for an enhancement in the decay volume
* ICARUS with large detector length will be able to put significant constraints on the mixing.

arXiv:2210.02462



Outlook

- BSM searches are an important effort of the ICARUS/SBN physics programs
- ICARUS is a large detector taking data now with both NuMI and BNB beam
- This physics data will be sensitive to a variety of new physics models
- Currently we are focusing on the Higgs portal scalar, vector portal and HNL searches.
- These measurements are expected to be competitive with other experiments
- In a stage to develop and mature software and analysis tools
- Results expected within this calendar year for few searches

Stay tuned!