Dark sector searches @neutrino experiments

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Vikram Discussions on Neutrino Astrophysics, PRL,March 21, 2025

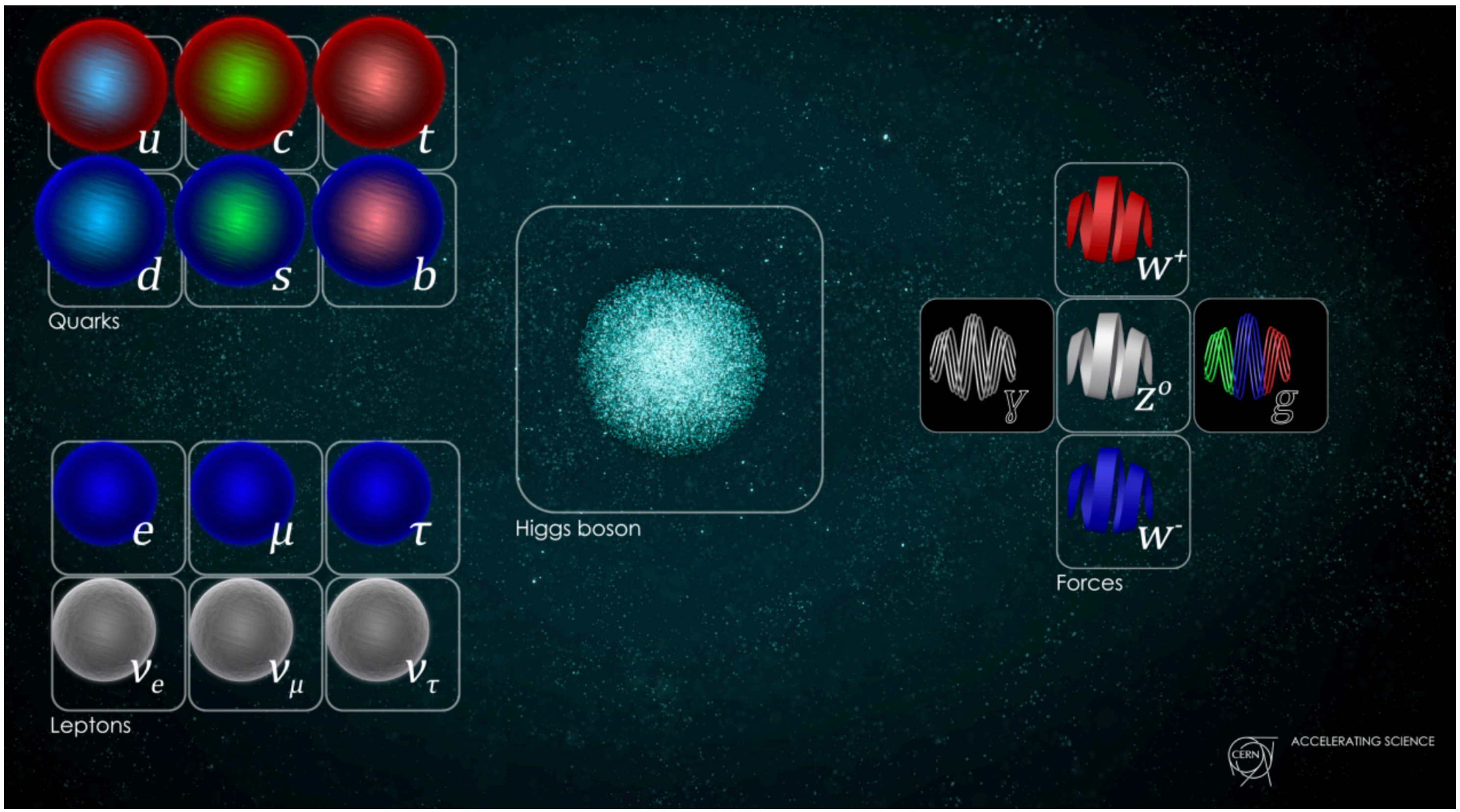
Outline

- Motivation: Dark sector searches with Neutrino experiments

- The search : Phenomenology & analysis results: ongoing Neutrino experiments
  - Sub-GeV dark matter search @MiniBooNE (Phys.Rev.Lett. 118 (2017) 22, 221803, Phys.Rev.D 98 (2018) 11, 112004)
  - "First" physics result @ICARUS (arXiv: 2411.02727 [hep-ex], accepted in PRL)
  - HNL searches @ICARUS (Eur. Phys. J. C **85**, 195 (2025))
- Future : BSM searches @protoDUNE using SPS beam @CERN

The Standard Model

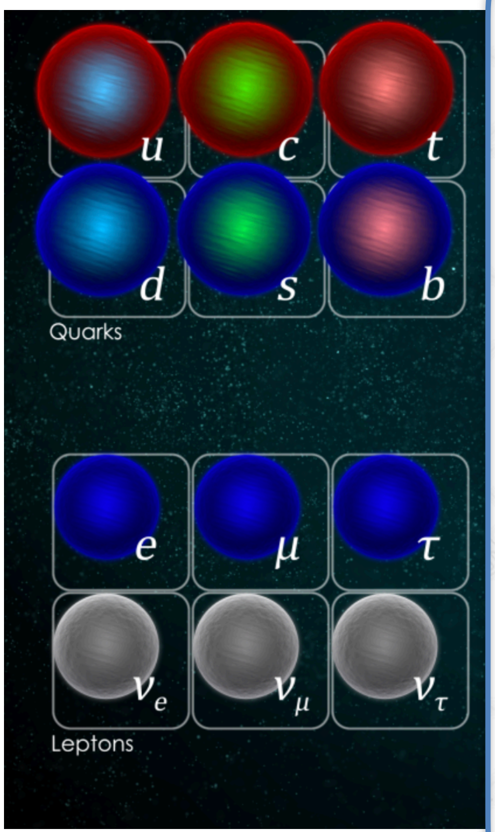
- Particle physics has a Standard Model of particles and their interactions



- Point-like particles
- Force carriers communicate between particles
- The Higgs particle completes the Standard Model

The Standard Model

- Particle physics has a Standard Model of particles and their interactions



ke particles

- Force carriers communicate between particles
- The Higgs particle completes the Standard Model

What about the Neutrinos ?

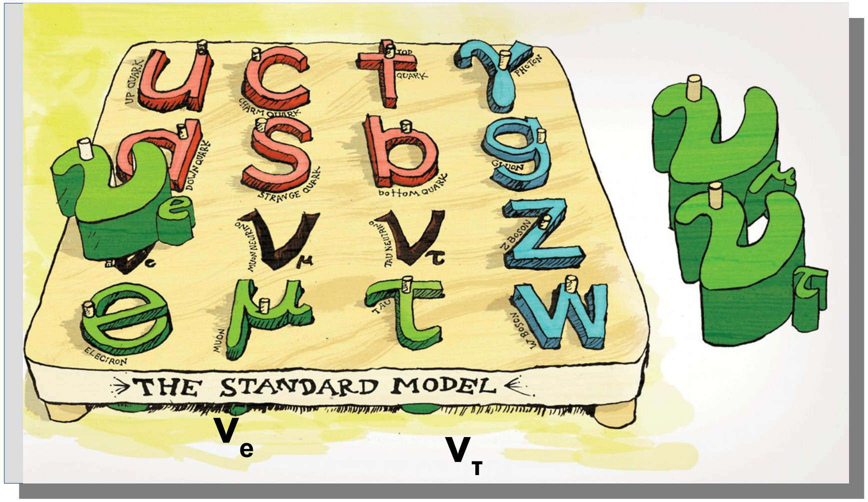
- In the Standard model neutrinos are neutral leptons that only interact via the weak force

- Three flavors of neutrinos (experimentally observed)

- Neutrinos oscillate between one flavor to another flavor, call neutrino oscillations

- Neutrino oscillation brings neutrino mass

- Standard model can not explain the existence of Neutrino mass



Need to go beyond standard model !

Where is BSM/New Physics ?

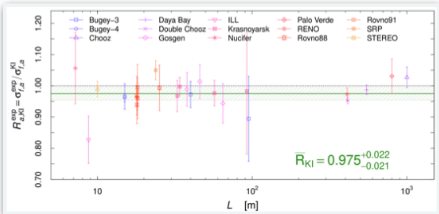
White Paper on New Opportunities at the Next-Generation Neutrino Experiments
(Part 1: BSM Neutrino Physics and Dark Matter)

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]

Naturalness? Baryon Asymmetry? Strong CP? Neutrino Mass? Flavor Puzzle? Dark Matter? Unification? Inflation? Quantum Gravity? ...

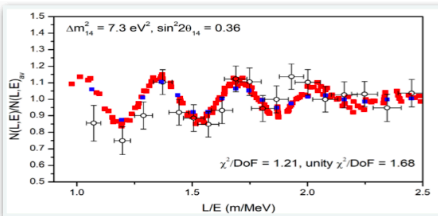
Where is BSM/ New physics ?

One of the motivation: Short Baseline Anomaly



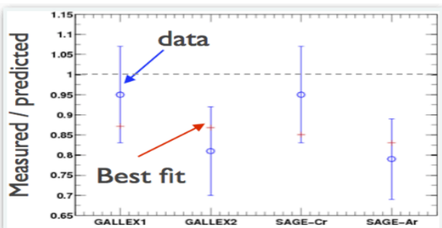
reactor flux anomaly
resolved with new input data
to flux calculation

✔



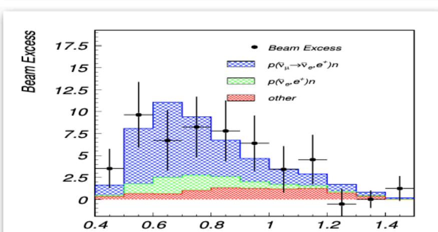
reactor spectra
is there really an anomaly?

?



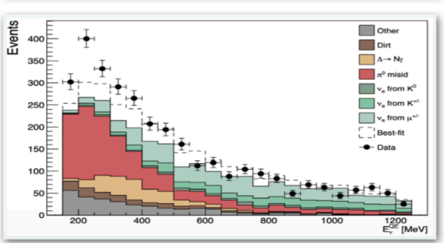
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



MiniBooNE
unresolved

?

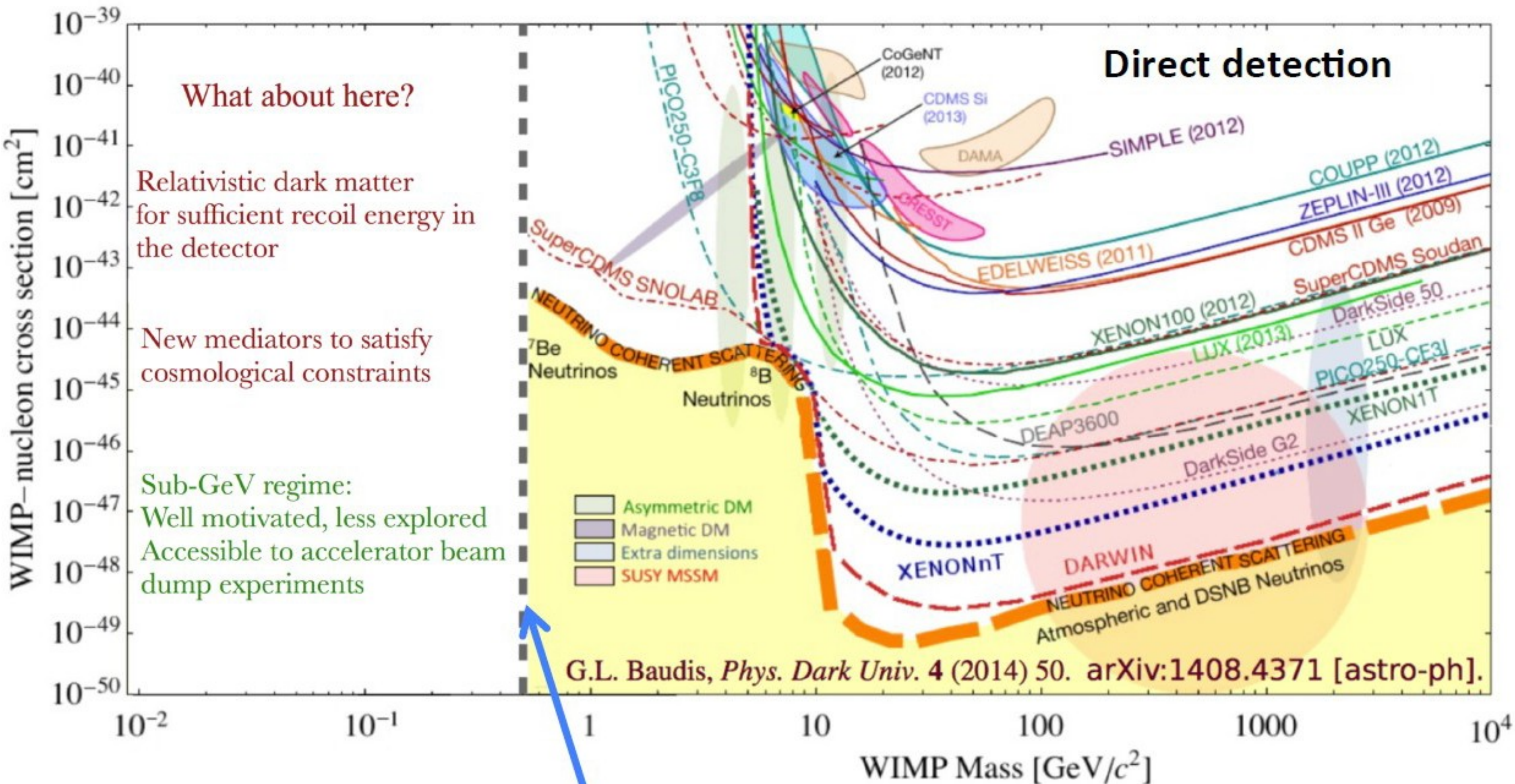
Detailed talk by Prof. Raj Gandhi

One of the motivation: Is there a common explanation for all the anomalies ?

- Flavor conversion : Inclusion of a new light sterile neutrino
- Inclusion of dark sectors: Dark matter particles, dark neutrinos, Long lived Heavy Neutrinos etc.
- Conventional explanation : Single photon production, reactor flux modeling etc.

And many more theoretical models ...

Second motivation: Experimental motivation for searching Dark Sector using Neutrino detectors



- *Direct detection ~GeV threshold limit*
- *Accelerator based fixed target experiment has experienced much recent theoretical and experimental activity below GeV range.*

Second motivation: Experimental motivation for searching DS using Neutrino detectors

* Opportunities to probe hidden sectors experimentally arise in particular when states exist with a mass scale of a GeV or less and a lifetime longer than the mesons decay due to weak interactions
* Such light, long-lived hidden sector states can be searched for at high-intensity fixed target experiments
* A rough comparison between the collider and fixed target reach for "new light states" in Dark sector:

* Assuming the interaction between SM and DS is mediated by operators of dimension 4+n , with n>=0, the production cross-section typically can be written as

$$\boxed{\sigma \sim \frac{\kappa^2}{E^2}\left(\frac{E}{\Lambda}\right)^{2n}}$$

Where κ is a dimensionless coupling constant and Λ ~ TeV

arXiv:0906.5614, 2207.06898

Second motivation:Comparison between Collider and Fixed Target Exp

* Integrated luminosity of collider (LHC) ~ 10^{41} cm^{-2}.
* The analogue of integrated luminosity for a fixed target of length 1m with 10^{21} POT is $10^{21} \times 10^{24} \times 10^{2}$ cm^{-2} ~ 10^{47} cm^{-2}
* With these numbers, one can derive and compare the production rates for neutral ~ GeV scale states at collider and FT

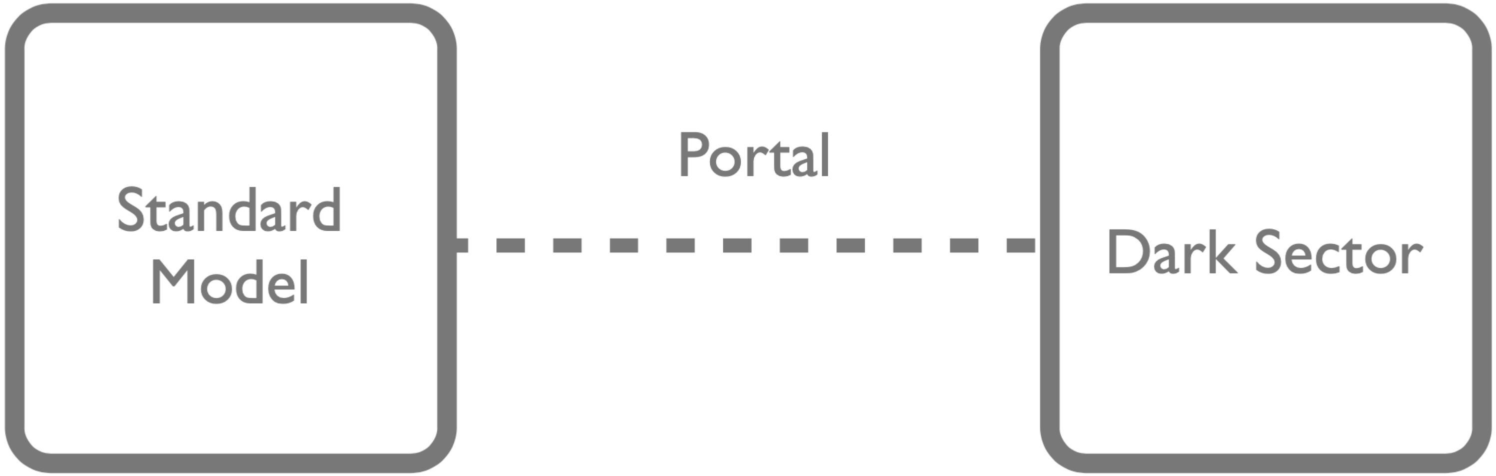
$$\boxed{\frac{N_{\text{collider}}}{N_{\text{target}}} \sim 10^{-6} \times \left(\frac{E_c}{E_t}\right)^{2n-2}}$$

Now, if we use $E_{\text{c}}/E_{\text{t}} = E_{\text{c}}/\sqrt{2m_p E_{\text{lab}}}$, and E_c=14 TeV, E_{lab}=100GeV, then

$$\boxed{\frac{N_{\text{collider}}}{N_{\text{target}}} \sim 10^{-12+6n}}$$

* For low ("portal") n=0,1, clearly the production rate at fixed targets is advantageous and at n=2 it is comparable to colliders. However, this does not imply that the signals would be necessarily be larger at FT due to detector geometry acceptance and other factors.

The dark sector paradigm



"New particles" with the following properties …

- A mediator may connect the visible and dark sectors through a "portal"
- Gauge singlets - not charged under SM gauge symmetries
- May be very light, well below weak scale ~100 GeV
- Dark Matter, Sterile (heavy) neutrino, axions, … could be part of the sector.

This talk will be mostly based on exploring different DS portal using data from fixed target accelerator based neutrino experiments.

Dark sector models looking @ν-Experiment

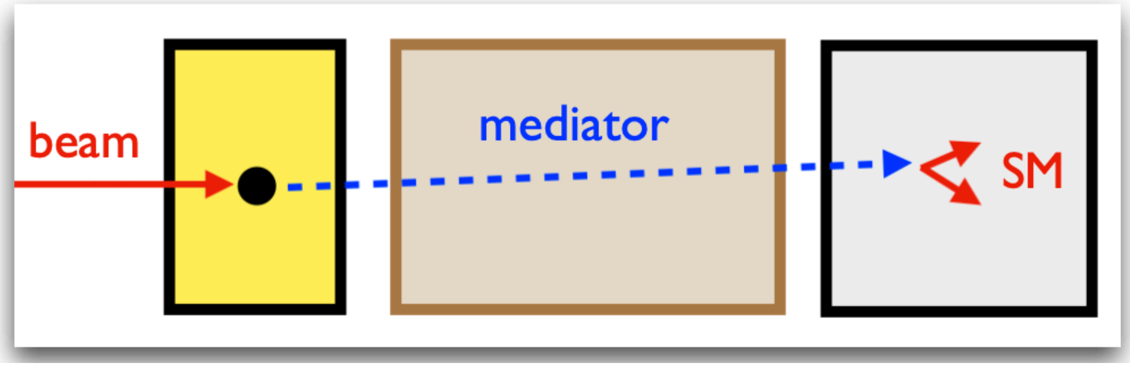
* Simplest way dark sector particles interaction with the standard model are via "portal" (operators of lowest dimension):

* These portals fall into different general categories :

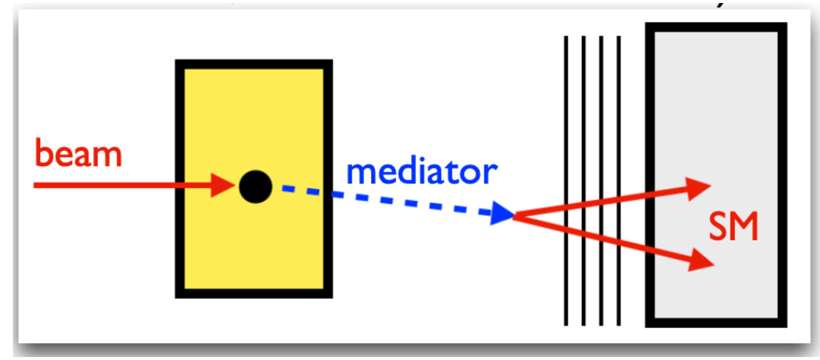
- ☑ Vector Portal (dark photon) : dark sector photons couple to SM via kinematic mixing ($F'^{\mu\nu}$)
- ☑ Higgs portal (HPS) : Scalar dark sector particles - interactions through the coupling with the Higgs ($H^\dagger H$)
- ☑ Neutrino Portal (HNL) : Fermionic particles - interactions by mixing with neutrinos (LH)
- ☑ Axion Portal : Axion like particles (ALPs) may couple to the SM through various higher dimensional operators.

Experimental techniques

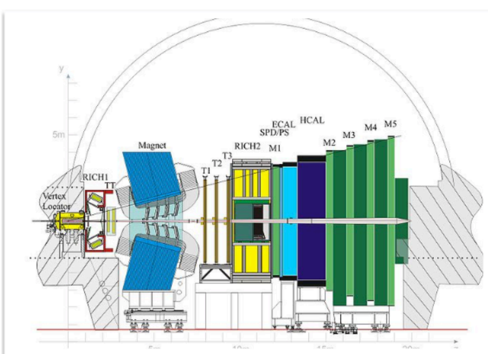
Beam Dump (MiniBooNE, ICARUS, SBND, DUNE, SHADOWS ..)

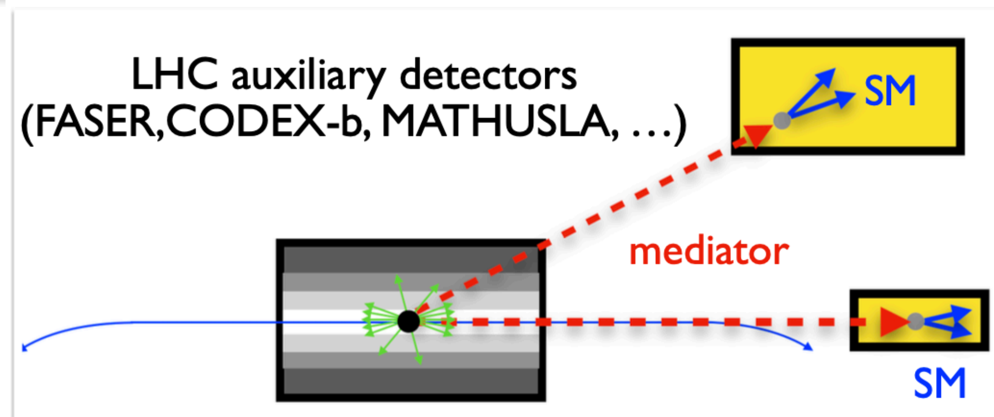


Fixed target spectrometer (DarkQuest, HPS,NA64 ...)

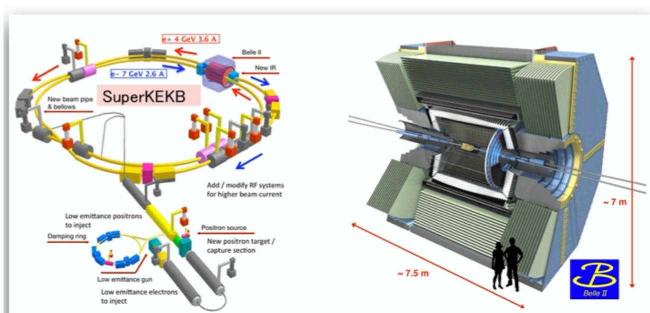


LHC (CMS, ATLAS, LHCb)

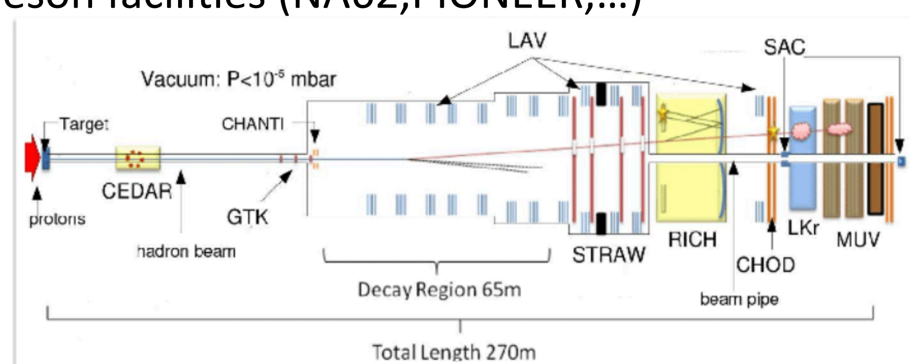




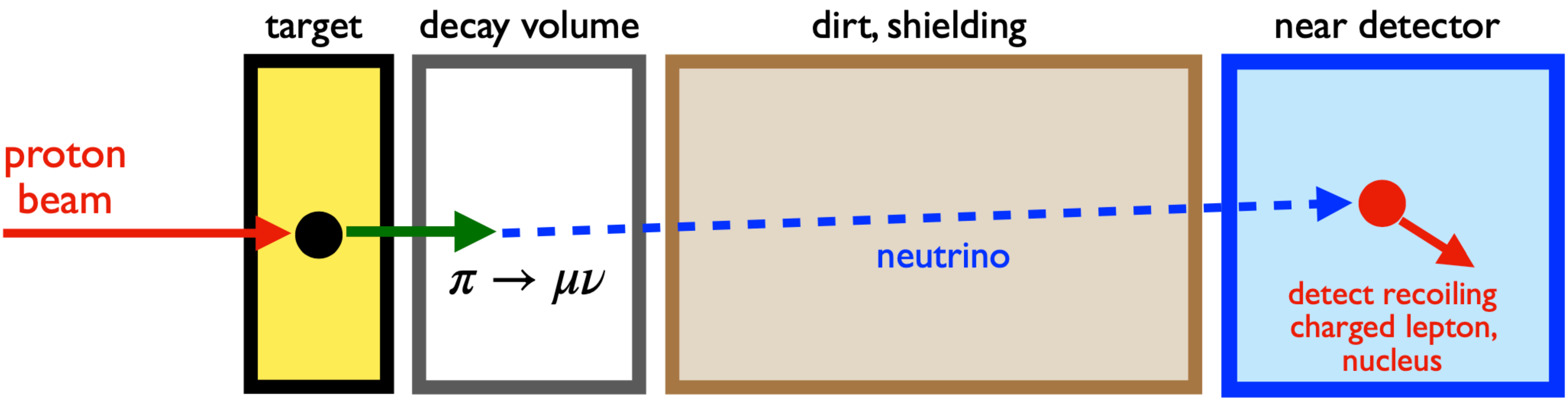
e+ e- colliders (Belle II, ...)



Meson facilities (NA62,PIONEER,...)

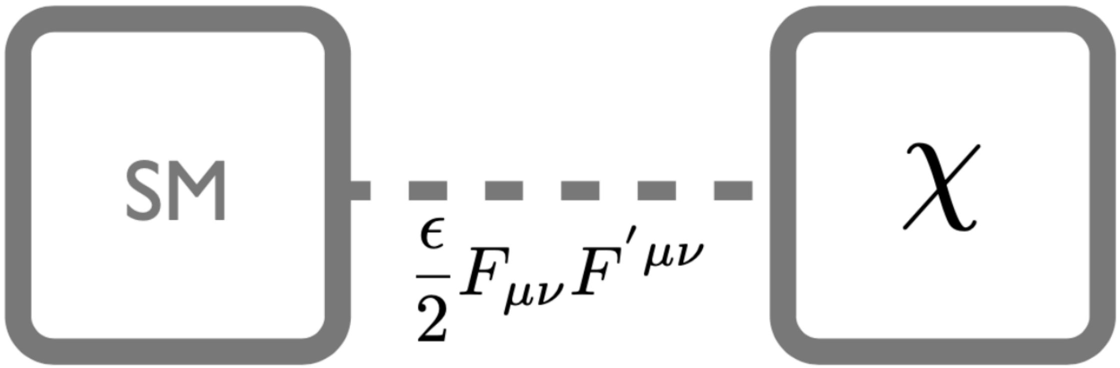


How to search Dark sector particles in neutrino experiment



- High intensity proton beam - fixed target experiment
- Large acceptance due to forward kinematics, short baselines, large volume detectors
- Less SM background compared to collider.
- Advanced neutrino detectors with excellent particle ID and energy reconstruction are suitable for BSM searches

DS model # 1: Vector portal

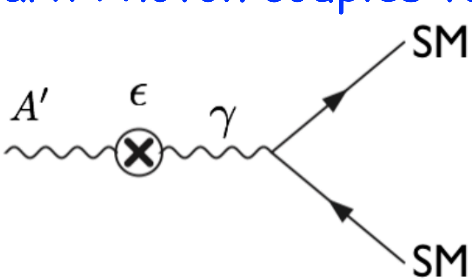


[Holdom]
[Pospelov, Ritz, Voloshin]
[Hooper, Zurek]
[Arkani-Hamed, et al]

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

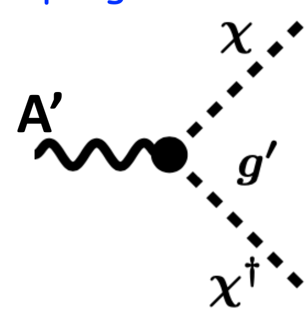
* Dark photon (A') mediates interaction between DM and SM
* 4 new parameters; $m_\chi, m_{A'}, \alpha_D, \epsilon$

Dark-Photon couples to SM :



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

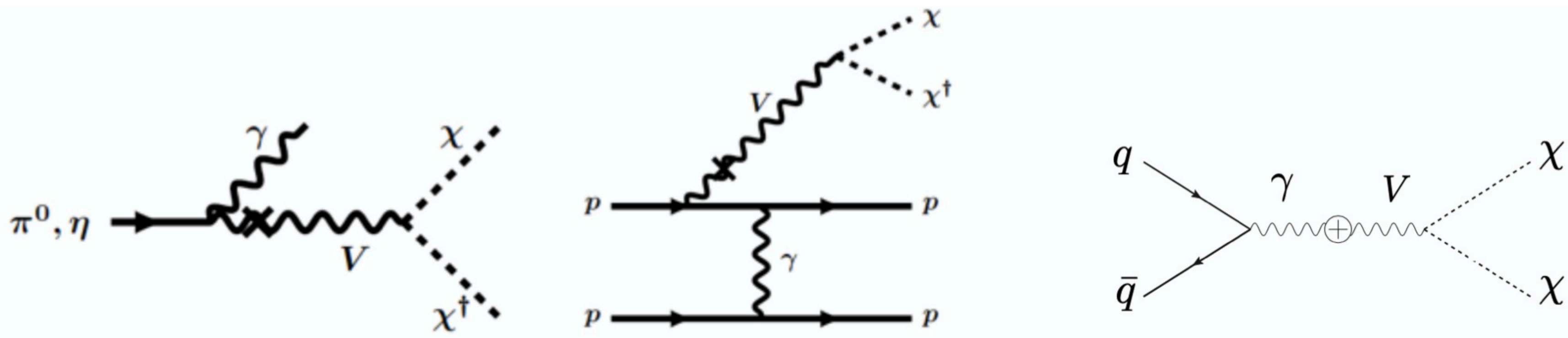
Coupling between mediator and particle



$$\alpha' = \frac{g'^2}{4\pi}$$

DS model # 1: Vector portal

❖ Production of DM beam:

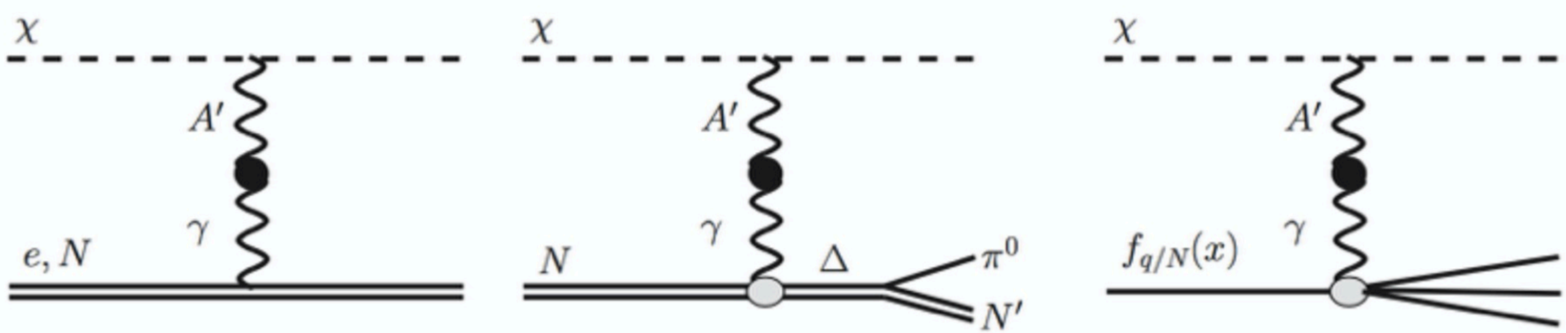


Neutral mesons decays

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

DS model # 1: Vector portal : How to estimate signal events in a detector

$$N_{\text{event}} = N_{\text{POT}}\, X_{A'}\, \text{Br}(A' \to \text{vis})\, \epsilon_{\text{det}}$$

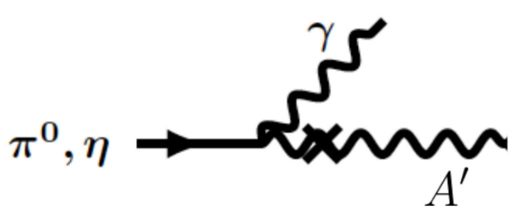
Where , N_{POT} = Number of protons on target

$X_{A'} = \dfrac{\sigma_{A'}}{\sigma_{\text{tot}}}$ Production fraction of A' per POT

$\text{Br}(A' \to \text{vis})$ Branching fraction of A' decays to dark matter

ϵ_{det} Probability of A' decaying inside the detector and detector efficiencies

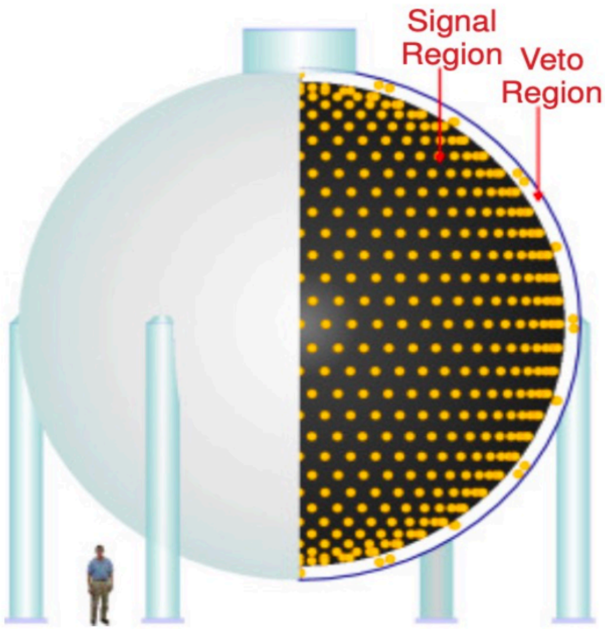
One example of production : A' from π^0

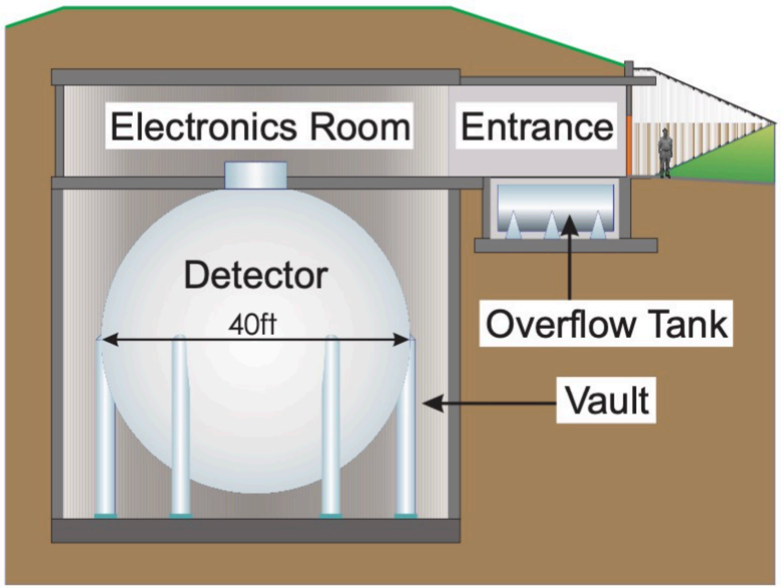


$$X_{A'} = X_{\pi^0}\, \text{Br}(\pi^0 \to \gamma A')$$

$$\text{Br}(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3$$

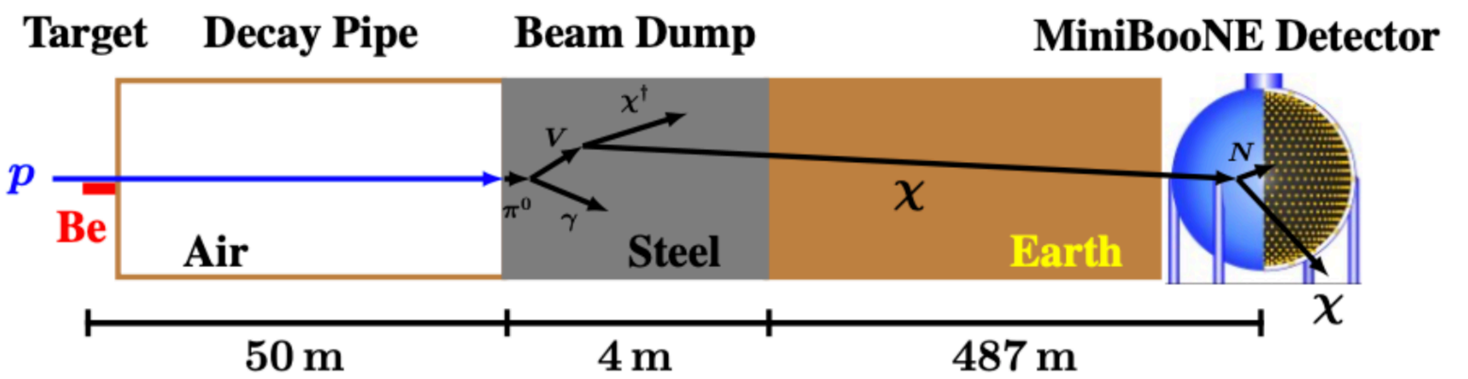
Dark Matter search@MiniBooNE Detector





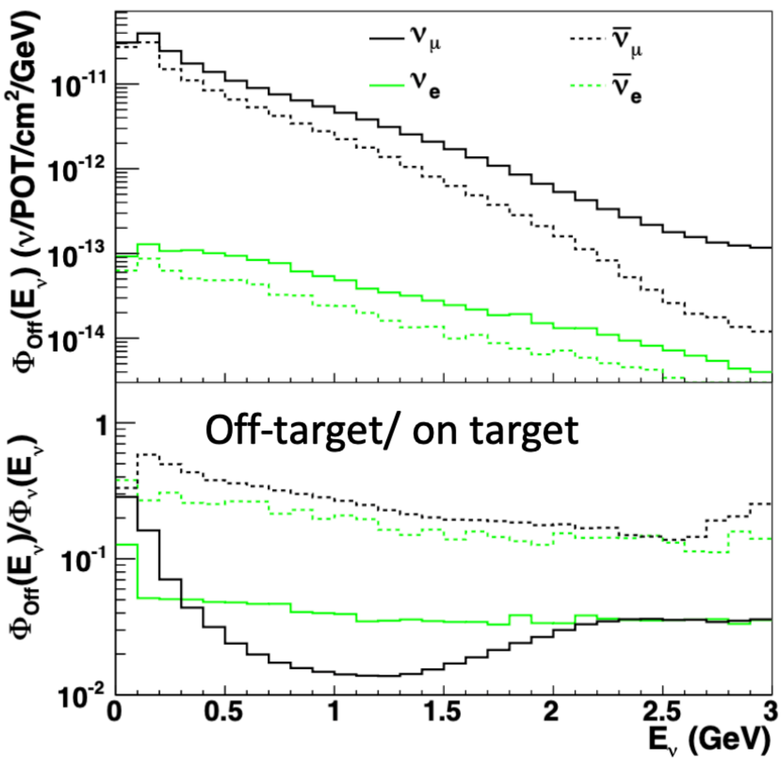
- The MiniBooNE detector is a 818 tons of mineral oil (CH_2) Cherenkov detector, oil sits inside a 610 cm radius sphere.
- The inner signal region consists of 1280 inward facing PMTs and the veto region consists of 240 PMTs.
- PMT timing resolution is 1 ns

MiniBooNE-DM Setup



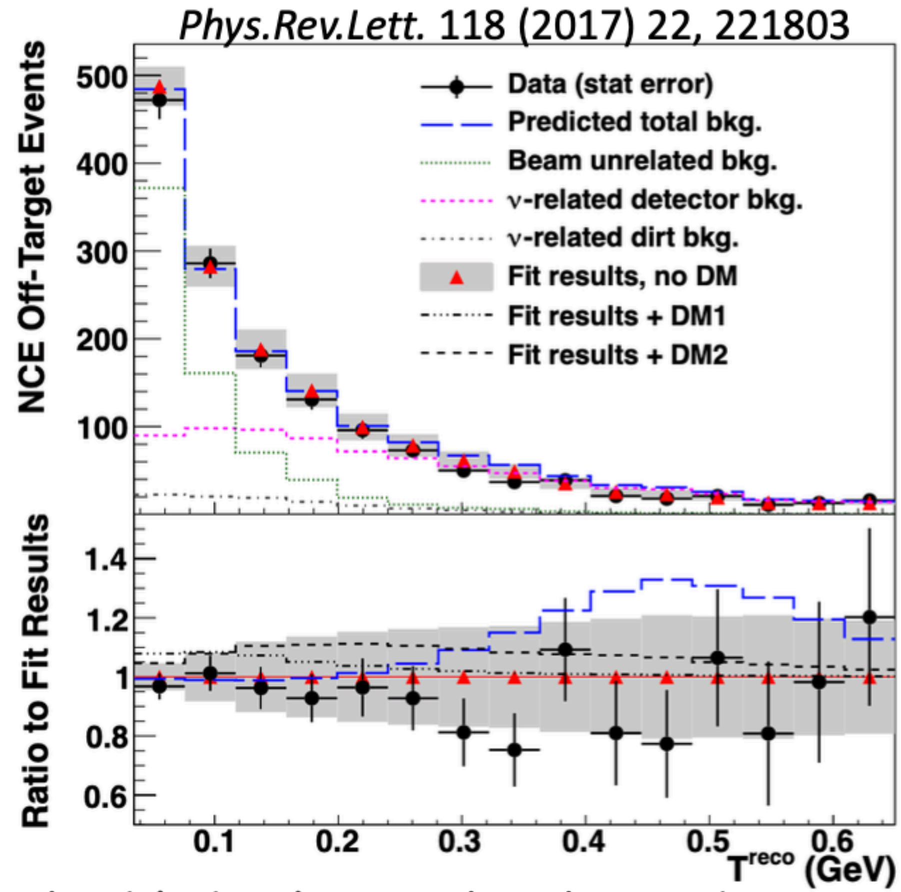
- For the Dark Matter (DM) search, the beamline was configured in "off-target" mode, which reduce a lot of neutrino background.
- To understand the neutrino background in detail, first neutrino flux calculated for CCQE-μ channel (as the dominant channel).
- 900 CCQE-μ off-target data are first identified (using previous selection of MB neutrino data sets)
- This not only validate the off-target MC model but also shows the reduction of the neutrino background in the off-target mode (1/27).

Predicted flux in off-target mode



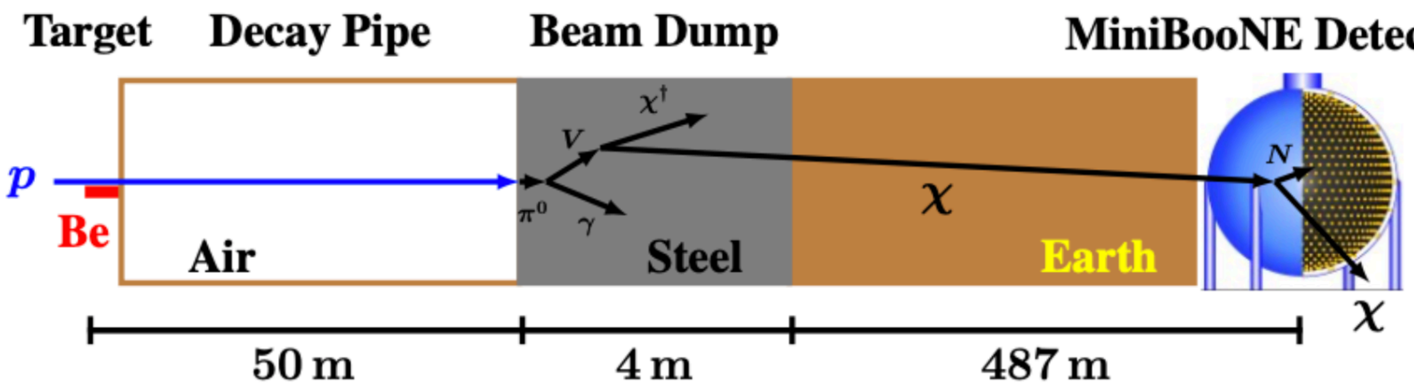
MiniBooNE-DM Setup

- ❖ The signature of the χ N scattering events is a pattern consistent with a proton/neutron of a few hundred of MeV
- ❖ First, a DM-candidate event sample selected from the off-target data using previous neutrino-NCE scattering with a cut 35<T<600MeV
- ❖ This selection along with the requirement of no-activity in the veto, minimizes beam-unrelated background (cosmic) and non-NCE beam related background.



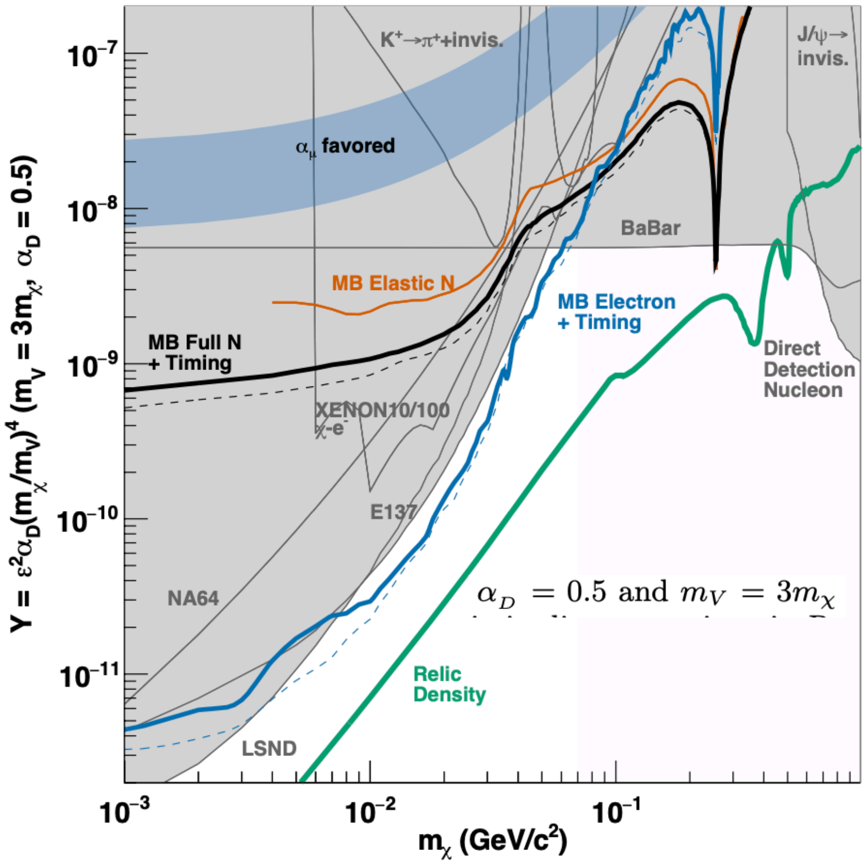
- ❖ Neutrino induced NCE events are an irreducible background and must be subtracted.
- ❖ NCE sample from previous neutrino run was selected and MC modified to generate NCE events in off-target mode.
- ❖ DM-N NCE events are generated and simulated through the same detector simulation as of neutrino (in off-target mode) with proper re-weight.
- ❖ No excess of events observed and put constraints of the DM Parameter space.

DS model # 1: Vector portal@MiniBooNE



* First Dark matter search result in beam-dump mode in neutrino experiment and constraints are more stringent than existing experimental results.

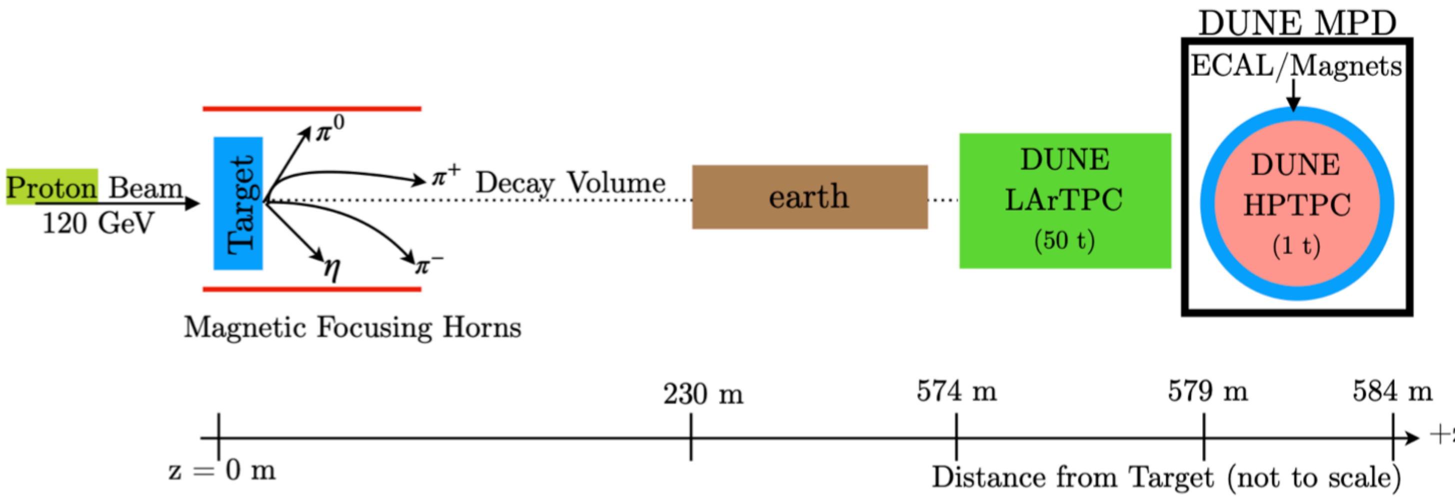
90% C.L. on vector portal,1.86x10[20] POT

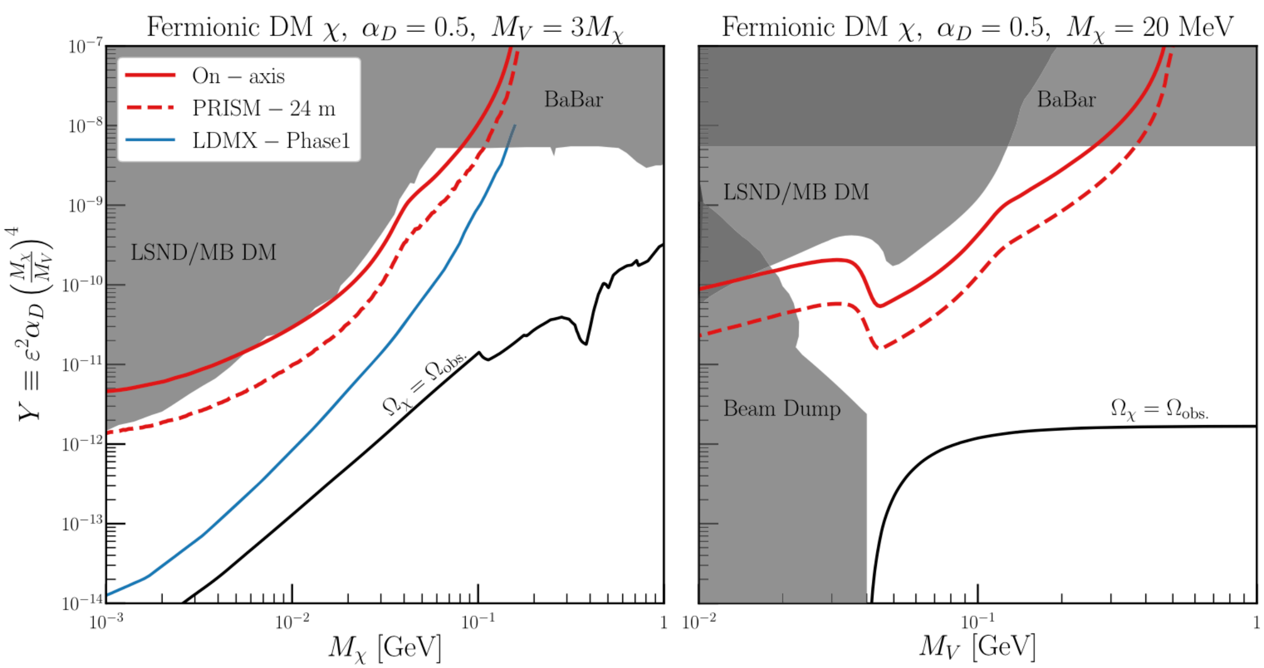


* The MiniBooNE-DM collaboration searched for vector-boson mediated production of dark matter using the Fermilab 8 GeV Booster proton beam to a steel beam dump.
* First analysis performed with DM-Nucleon Elastic scattering(Phys.Rev.Lett. 118 (2017) 22, 221803) and full analysis with DM-electron scattering using timing info (Phys.Rev.D 98 (2018) 11, 112004)
* No significant excess over background was observed and a 90% confidence limit (CL) was placed on the vector portal light dark matter (LDM) model using a frequentist approach

PRL 118(2017) 22,221803, PRD98(2018) 11,112004
A.Chatterjee et.al., MiniBooNE-DM collaboration

DS model # 1: Vector portal@DUNE





- Expected DUNE on-axis and PRISM sensitivity to $\chi\, e^- \to \chi\, e^-$ scattering
- Simulation uses full DUNE detector simulation and sensitivity performed at the LArTPC detector due to the high density.

Eur.Phys.J.C 81 (2021) 4, 322
A.Chatterjee et.al., DUNE Collaboration

DS portal # 2: Higgs portal

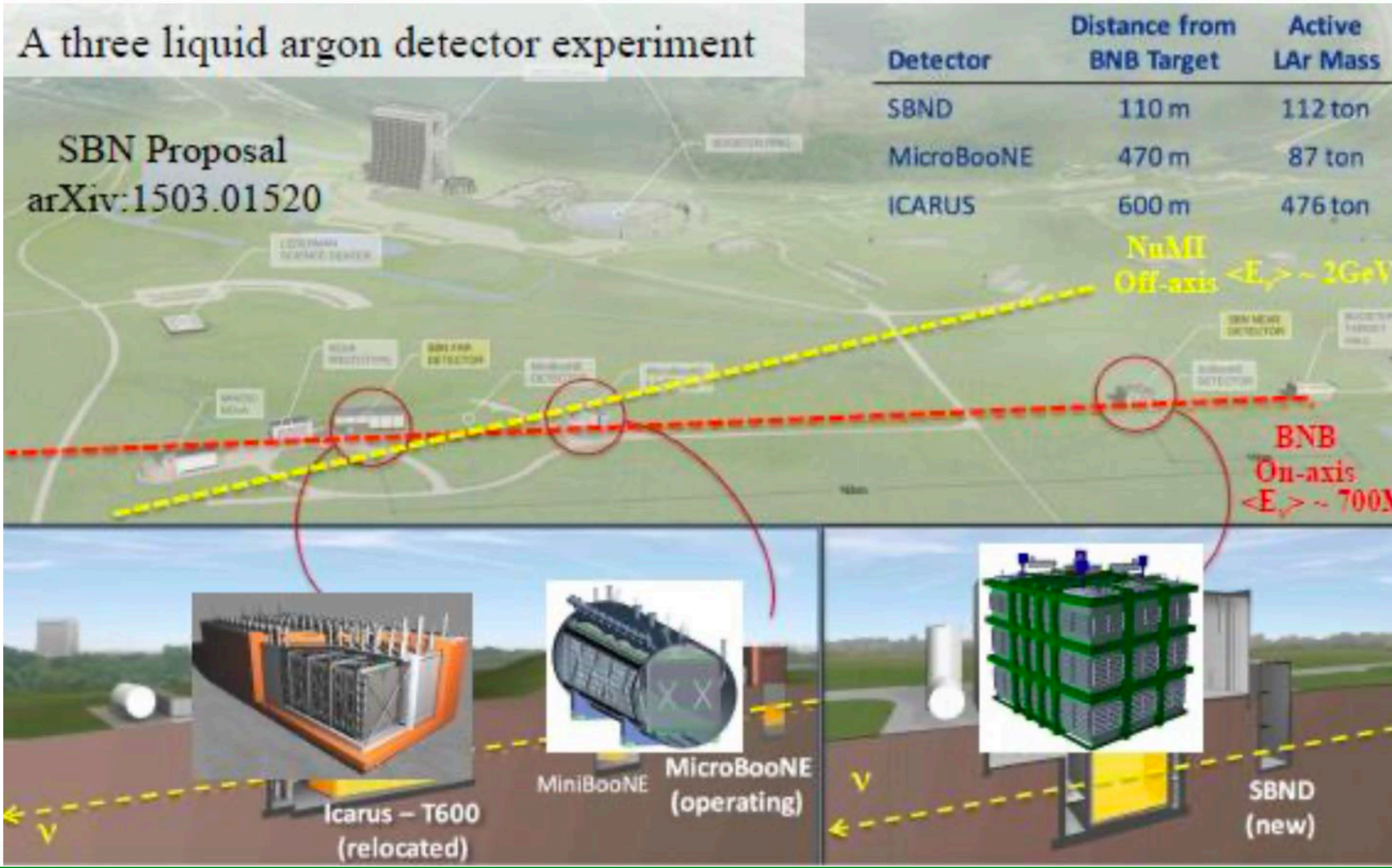
Hidden sector particle decay to di-muon final state searches @ICARUS

arXiv: 2411.02727 [hep-ex]

Accepted in PRL

- First "Physics" result from ICARUS/SBN experiment
- 4 members analysis team (A.Chatterjee (coordinator, analysis supervisor), G.Putnam (Ph.D student, U-Chicago), N.Row (Postdoc, U-Chicago), H.Hausner (postdoc, Fermilab))

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

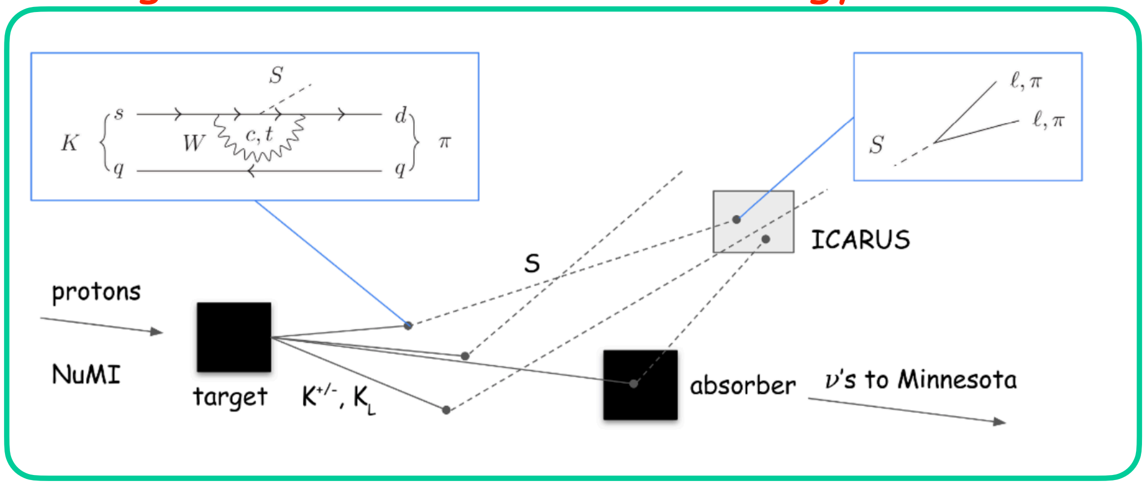
Motivation: Search for Higgs Portal scalar with two muons

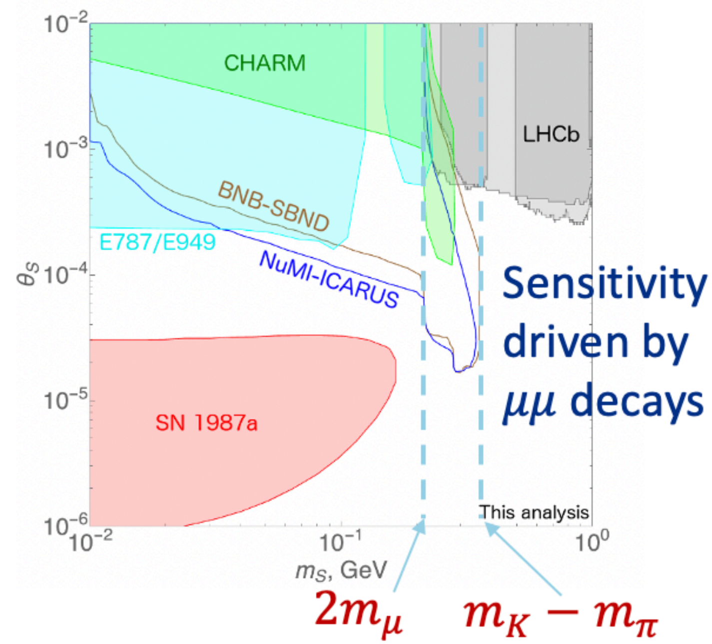
✱ Motivation: Higgs Portal Scalar – a BSM scalar decays in ICARUS to 2 muons

SM $\longleftrightarrow$ Higgs scalar

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

Diagram of the HPS Phenomenology @ICARUS



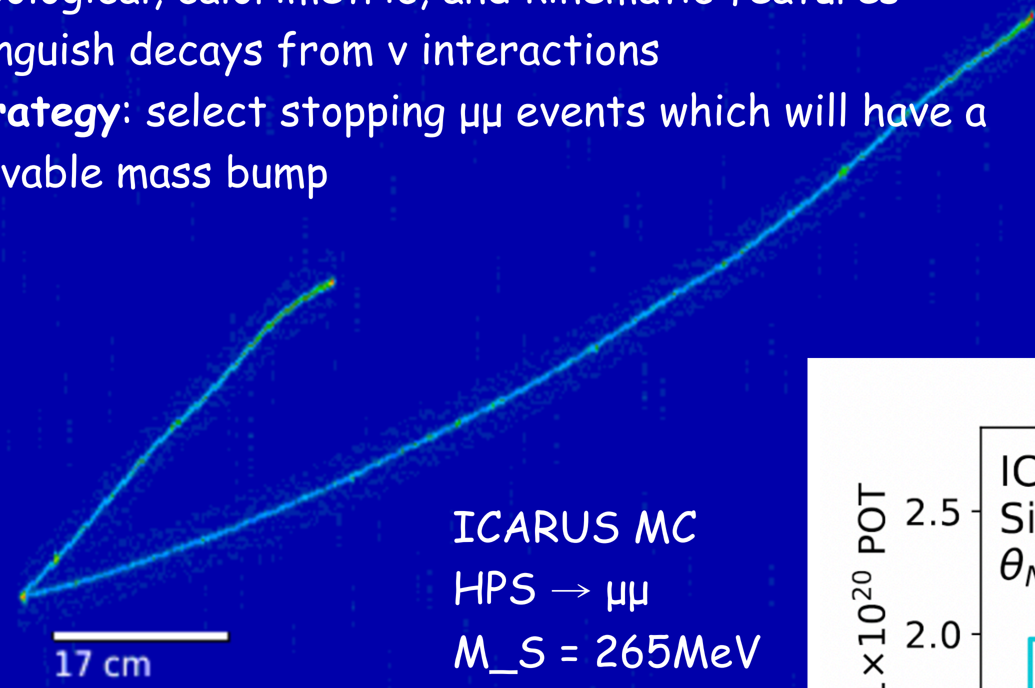


B. Batell, et.al. Phys. Rev. D 100, 115039

- ☑ 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 Θ with the Higgs
- ☑ Production in NuMI is via Kaon decay ($K_{NuMI} \rightarrow \pi S$)
- ☑ Once produced, the scalar can decay to dilepton or pion pairs: $S \rightarrow e^-e^+, \mu^-\mu^+, \pi\pi$

The Result: di-muon final state

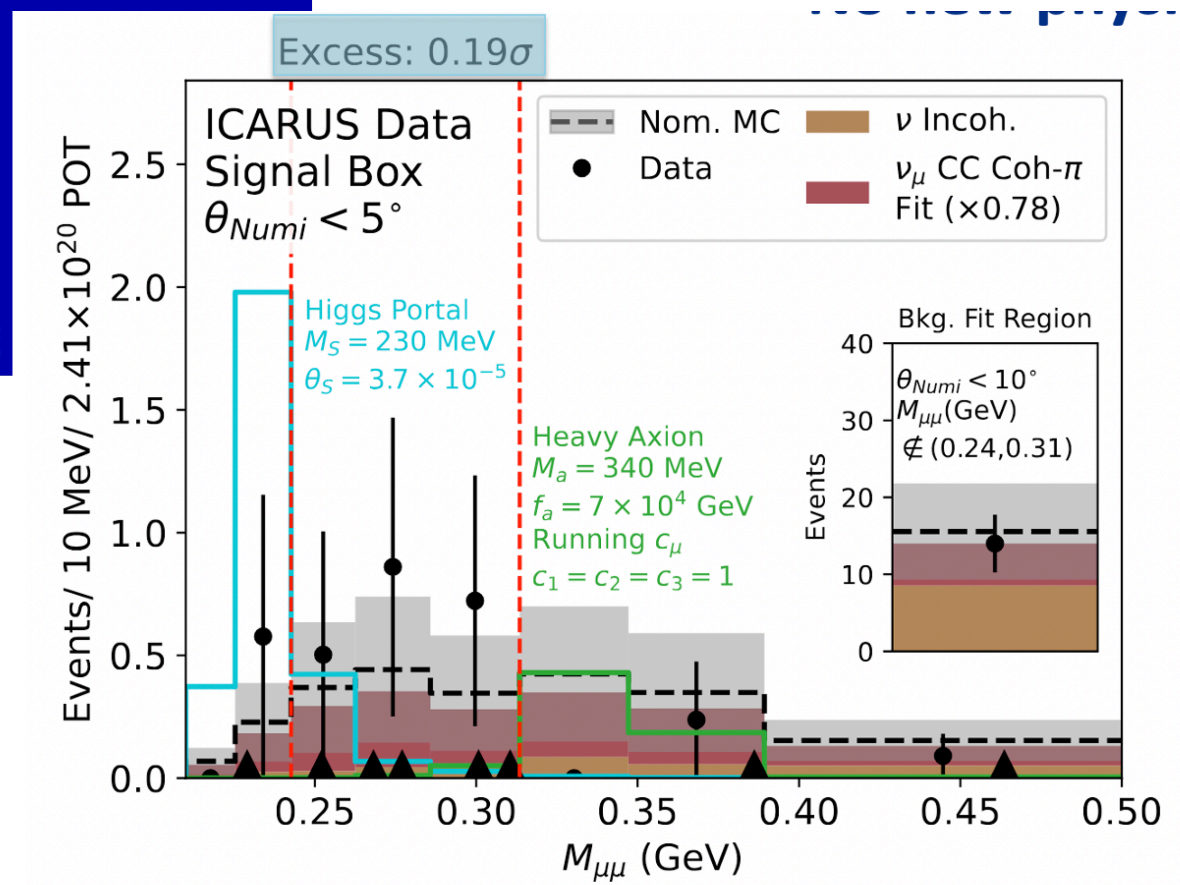
- 2μ is a clear and easy to reconstruct final state in the detector
- Topological, calorimetric, and kinematic features distinguish decays from ν interactions
- **Strategy**: select stopping μμ events which will have a resolvable mass bump



- **Strategy**: fit ν_μ CC Coh-π scale factor to data, look for bumps

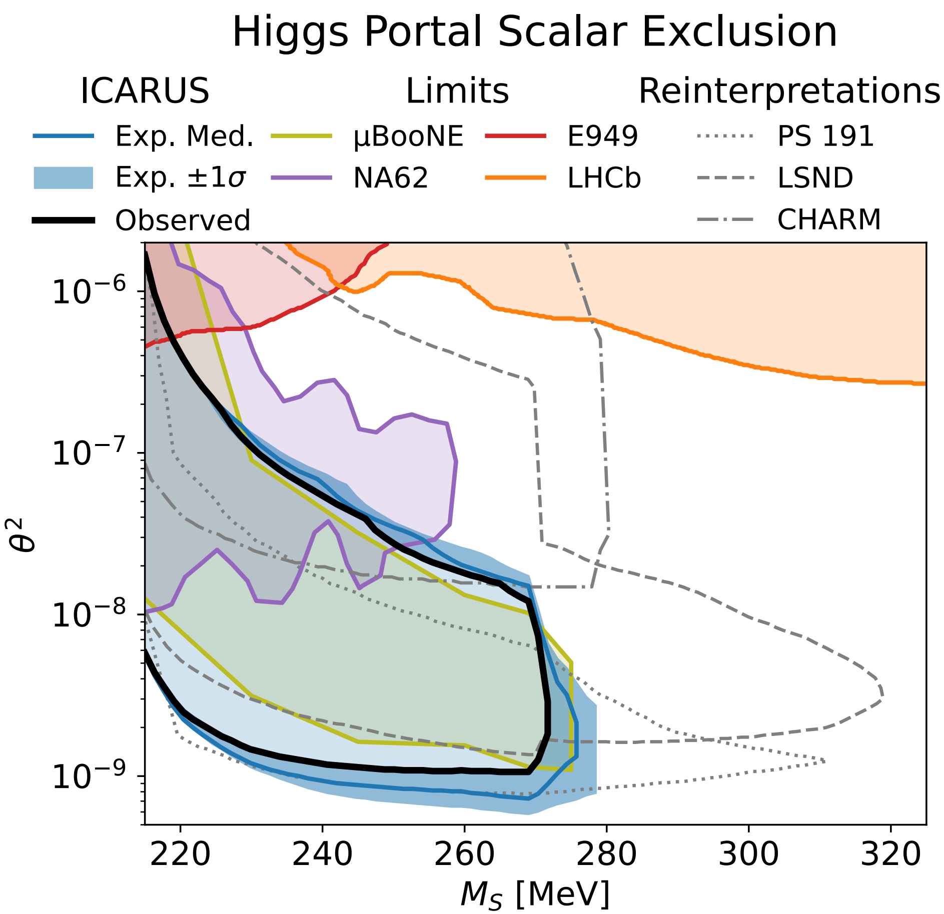
- Scalar decays create a resonance in the di-muon mass

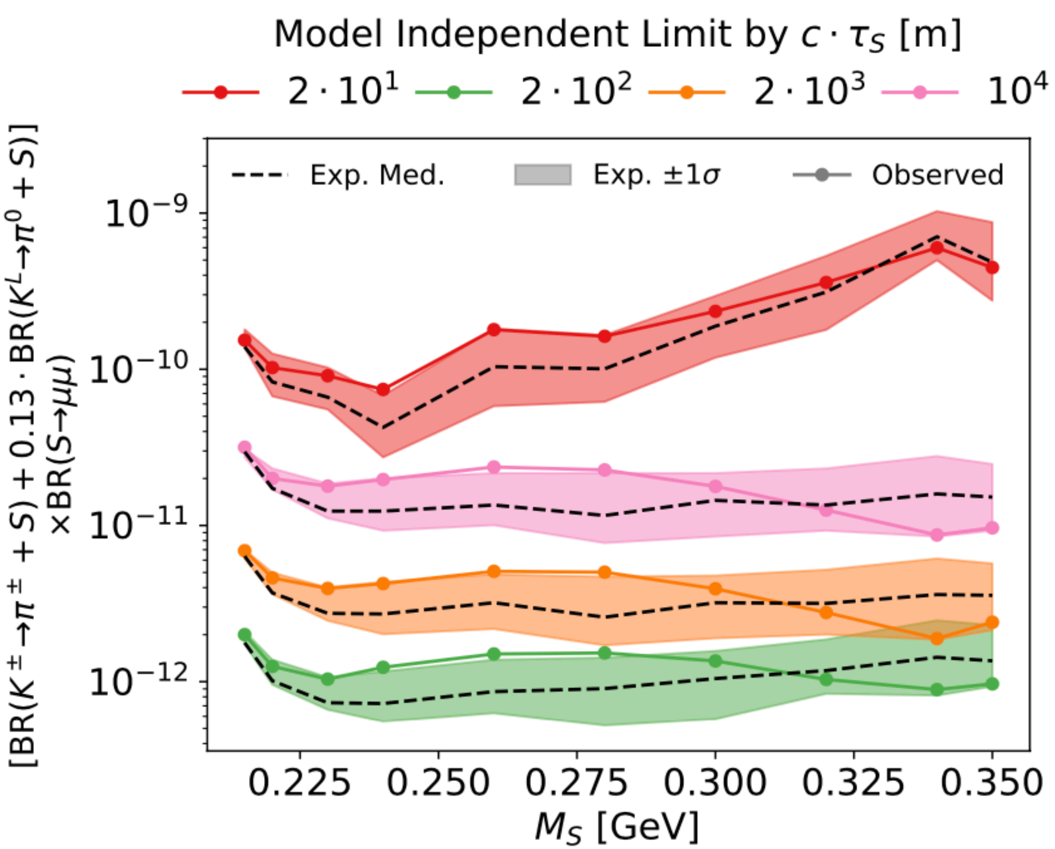
No New Physics!



Limits on HPS

arXiv: 2411.02727 [hep-ex]





- First study of HPS and model independent limit from fixed target neutrino experiments
- 90% C.L. limits computed

DS model #3 : Heavy Neutral Lepton searches@ICARUS-SBN (Pheno-study)

* HNLs arise in simple SM extensions (type-I Seesaw) to explain the origin of neutrino masses
* The HNL mixes with the active neutrinos

Fig. from Khalil, Moretti

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha N}N$$

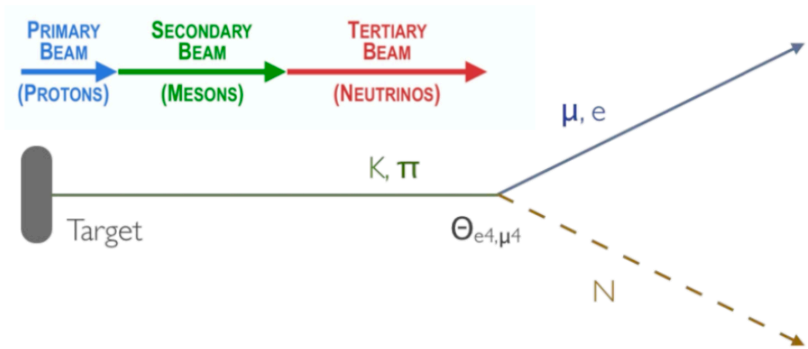
* Interaction Lagrangian : $\mathcal{L} \supset -y_\nu^{\alpha i}\left(L_\alpha H\right)N_i,$

Gauge singlet fermions Ni interact with SM fields via Yukawa interactions,

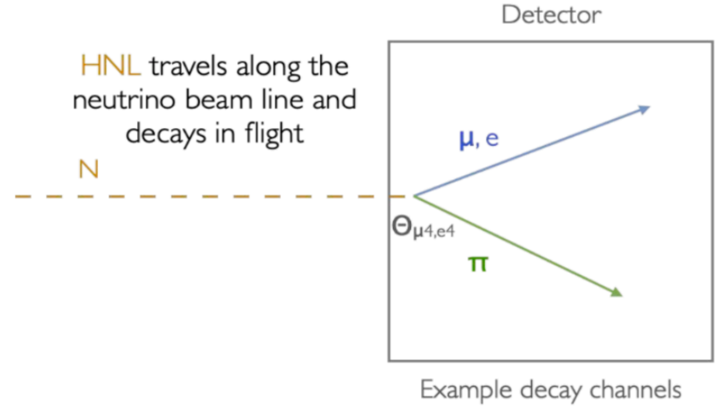
A.Chatterjee, A.De.Roeck. J.G.Garcia (Eur. Phys. J. C **85**, 195 (2025),*arxiv: 2408.03383*)

DS model #4 : Heavy Neutral Lepton

- **Production**



Detection :



List of decay modes to HNL

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

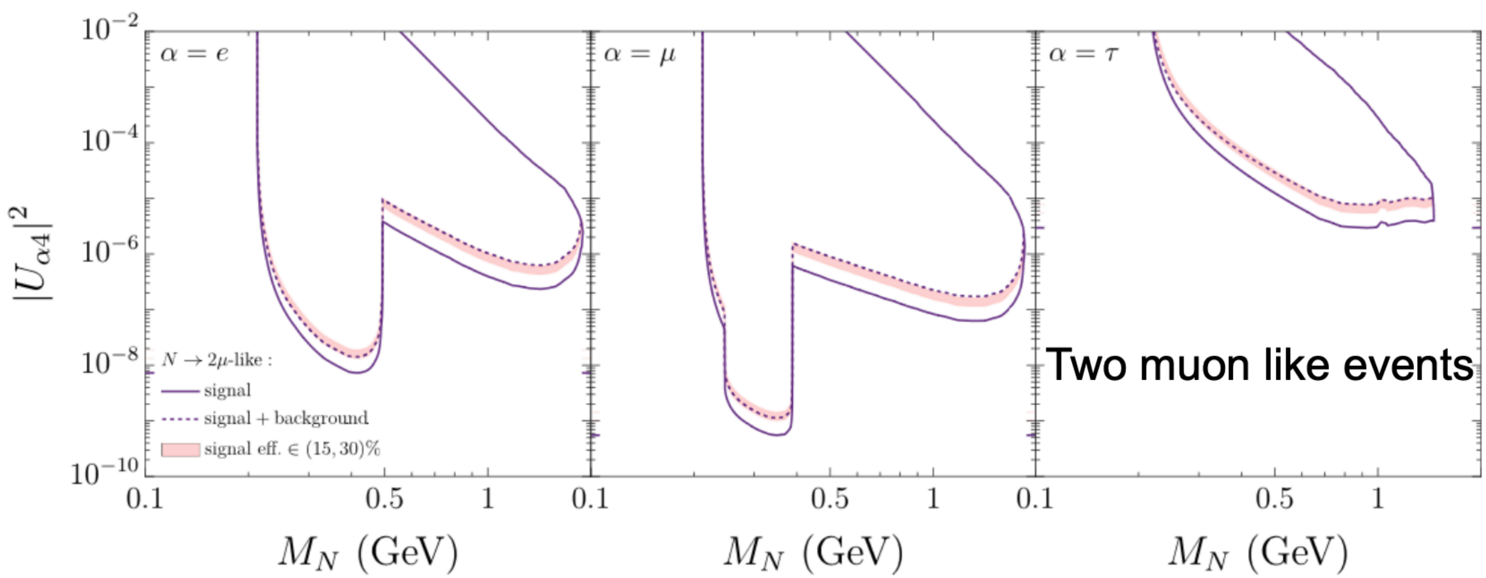
HNL decay modes

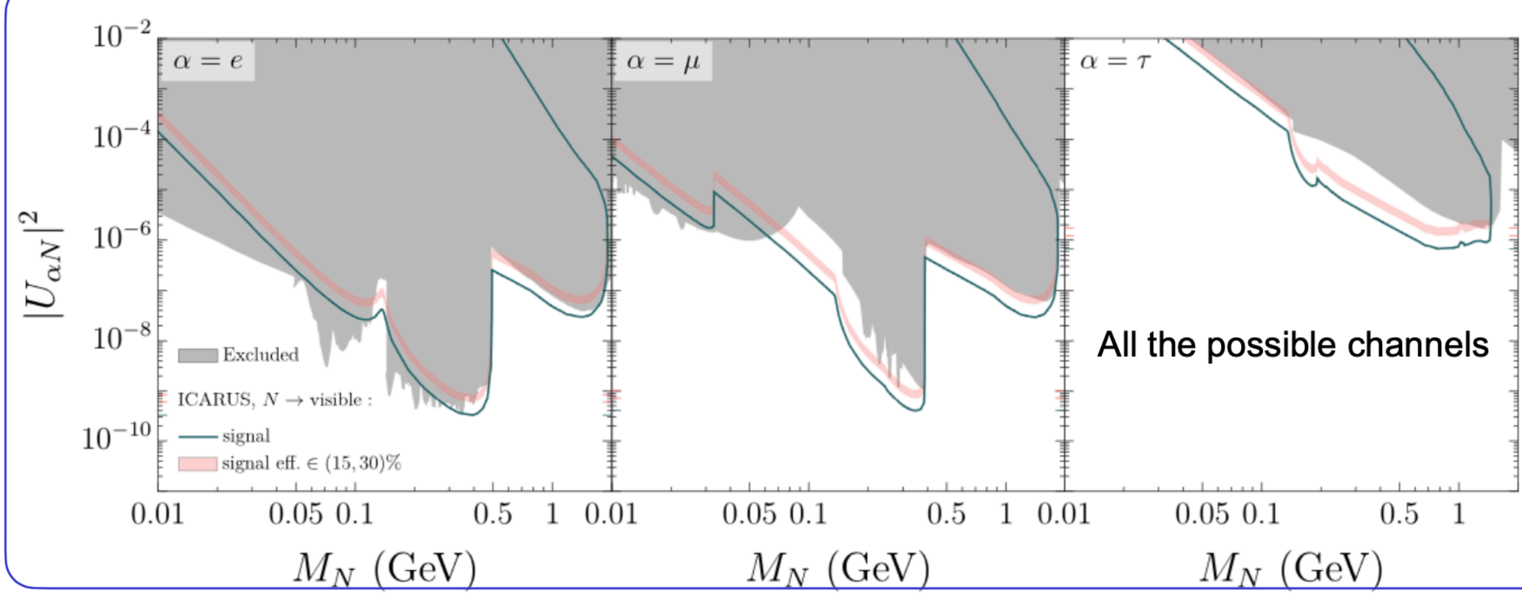
	$N \to$				
$\lvert U_{eN}\rvert^2$	$ee\nu$	$\mu\mu\nu$	$e\mu\nu$	e hadr.	ν hadr.
	$\nu\pi^0$	$e\pi$	$e\rho$	—	
$\lvert U_{\mu N}\rvert^2$	$ee\nu$	$\mu\mu\nu$	$e\mu\nu$	μ hadr.	ν hadr.
	$\nu\pi^0$	$\mu\pi$	$\mu\rho$	—	
$\lvert U_{\tau N}\rvert^2$	$ee\nu$	$\mu\mu\nu$	—	—	ν hadr.
	$\nu\pi^0$	—	—	$\nu\rho^0$	

DS model #4 : HNL sensitivity@ICARUS/SBN

90% C.L. limit for POT : 1.32X10^21 ~ 4 years of data taking

arXiv: 2408.03383 [hep-ph]





Dark Sector generator for Fixed-target experiments

Developed DS generator for fixed-target experiments @neutrino experiment
This will be public soon! Will be useful for DUNE@Fermilab and other DS search experiments like SHiP@CERN

`MeVPrtl`: An Event Generator for Dark Sector Particles in the Short Baseline Neutrino Experiments

ICARUS Collaboration, SBND Collaboration, J. Berger[a], A. Chatterjee[b], J. I. Crespo-Anadón[c], J. Dyer[a], R. Garrote[c], V. C. L. Nguyen[d], V. Paolone[e], L. Pelegrina-Gutiérrez[f] and G. Putnam[g]

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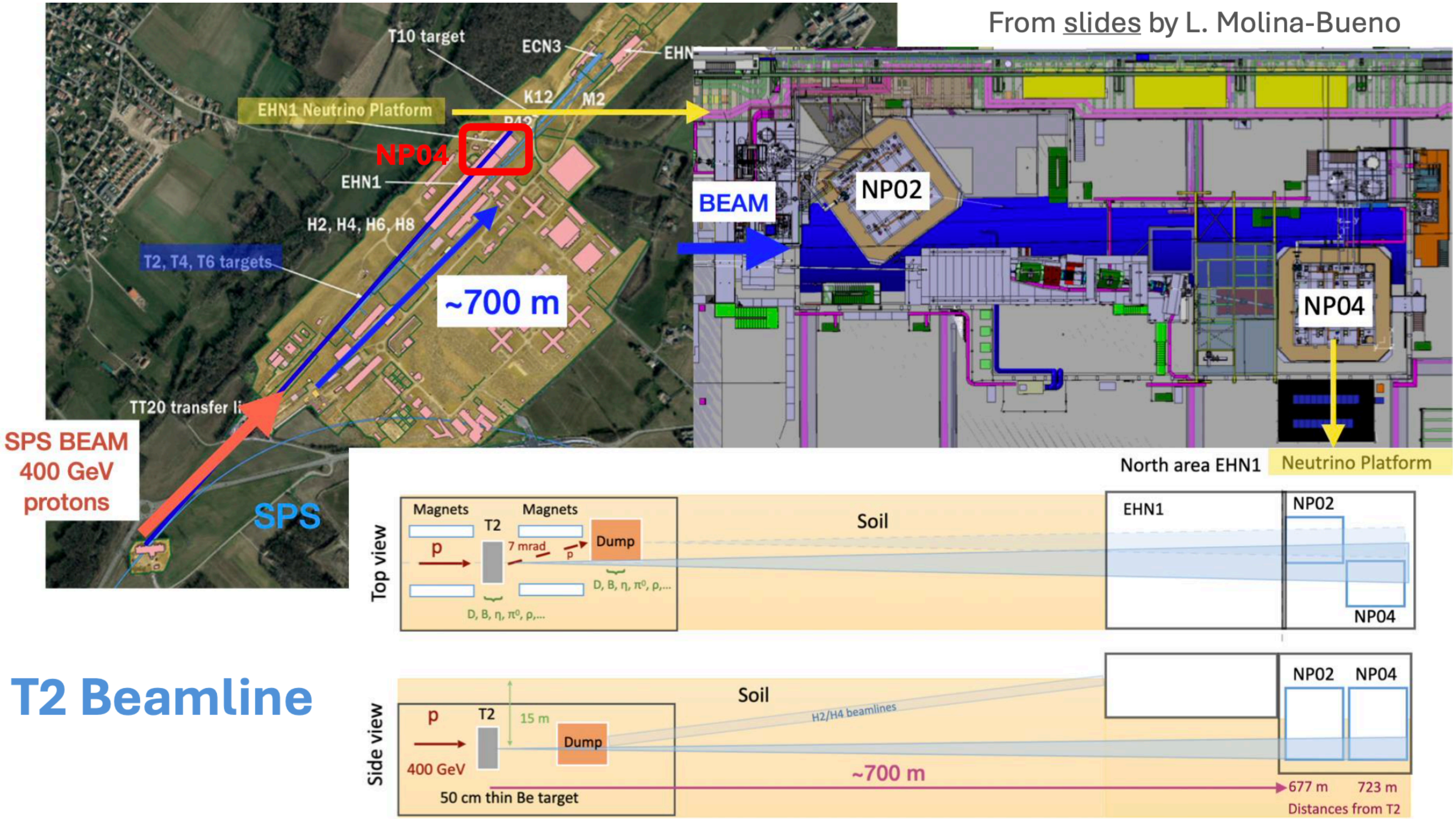
Abstract

MeVPrtlGen is a modular event generator of Beyond Standard Model (BSM) physics particles developed for use in the Short-Baseline Neutrino (SBN) program. A large class of BSM physics models predict that new particles could be produced in the intense BNB and NuMI neutrino beams, where they would travel to the SBN detectors and either interact with or decay into standard model particles. These new physics models are motivated by dark matter, the neutrino mass scale and a solution to the strong CP problem. MeVPrtl provides an interface to implement the overlapping phenomenology of these various models, and to connect them with meson flux inputs and object outputs used by the SBN `LArSoft`-based detector simulation. Implementations for the Higgs portal, heavy neutral lepton, and heavy QCD axion models exist within `MeVPrtl`. In this technote we specify these implementations and their validation, as well as details of the `MeVPrtl` interface.

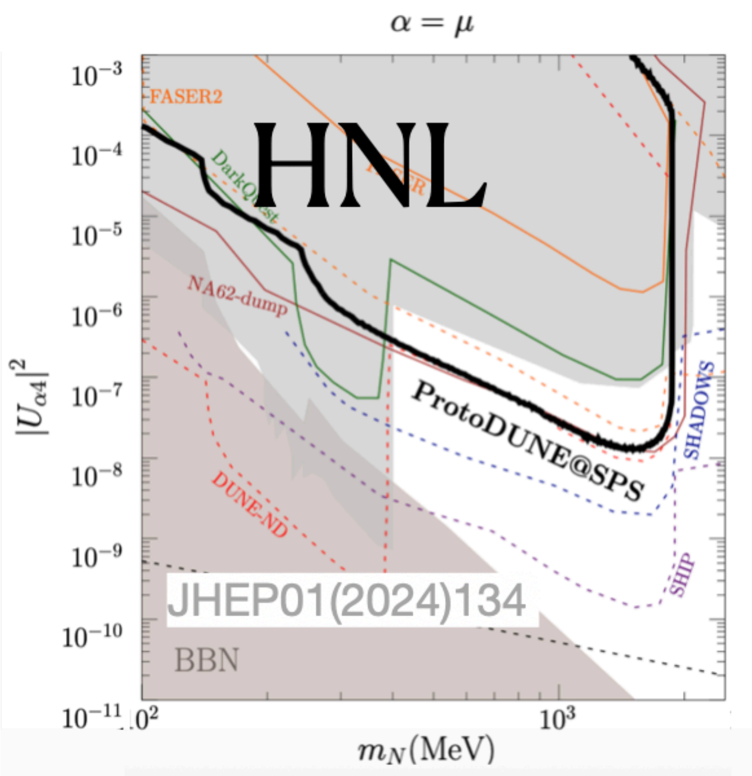
Future: BSM searches with LArTPC @CERN

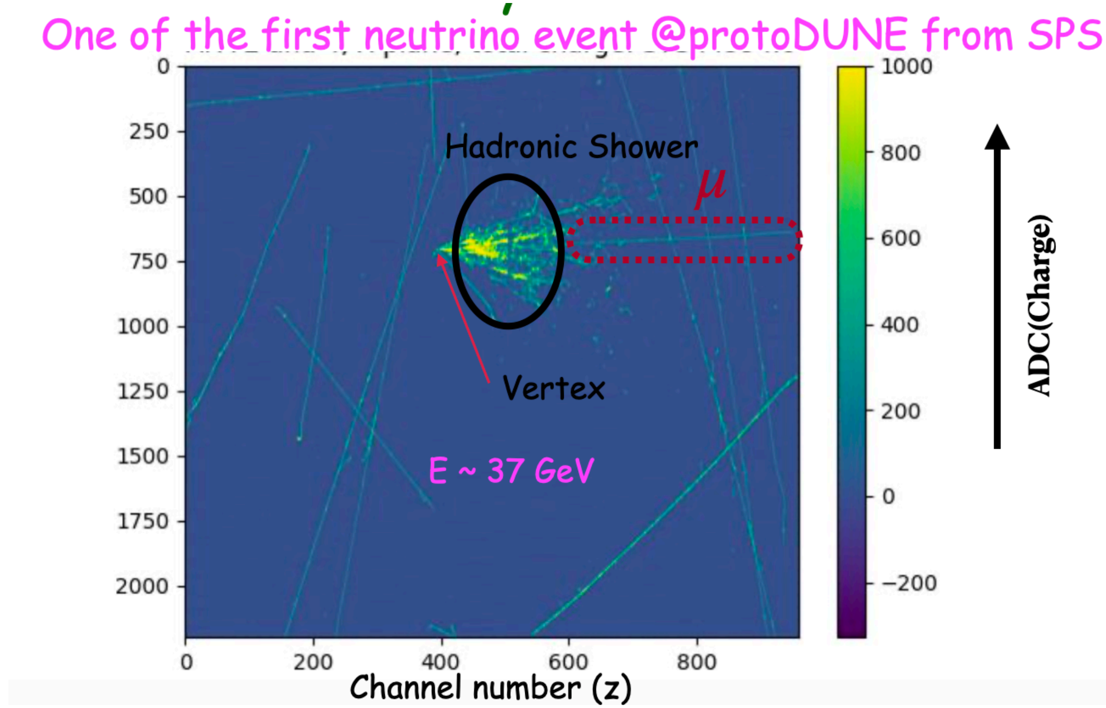
From slides by L. Molina-Bueno



The T2 Beamline

Future: BSM searches with LArTPC @CERN





- Recent study shows that ProtoDUNE detector with 400 GeV SPS beam at CERN will be excellent setup for BSM.
- Working group formed last year to study the feasibility of the proposal of a new experiment !
- We have developed experimental tools (software & hardware) to take small sample of data
- We have observed "neutrinos" from the data, which are background, to so the proof of principle.
- In process to analyze the data and submit proposal for running longer as Experiment.

Summary & Outlook

* Dark sector theories are motivated on several accounts, as they may address some of the outstanding mysteries in fundamental physics, including dark matter and neutrino masses, or explain certain experimental anomalies.

* A wide-ranging experimental program to probe the dark sector is emerging, and there has been a growing realization that neutrino beam experiments are a vital part of this.

* Substantial progress has been made in recent years in terms of the phenomenological and experimental developments needed to pursue a viable dark sector search program at neutrino beam facilities.

* We have performed both pheno and experimental data to search (or provide constraints) on the dark sector parameter space for different fixed target experiment

* Dark-sector MC generator for the fixed-target neutrino experiments will be released soon, this will helpful for future experiments.

* BSM search at CERN using prototypes of DUNE detectors will provide important information for proposed SHiP and FPF experiments.

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Thank you