Non-Oscillation Searches at DUNE ND

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Path to Dark Sector Discoveries at Neutrino Experiments
Colorado State University
5th June 2023

Outline

- Introduction
- Deep Underground Neutrino Experiment (DUNE)
- DUNE Near Detector Complex
- DUNE ND BSM Physics Topics
  - Light Dark Matter
  - Axion-like Particles
  - Neutrino Trident
  - Heavy Neutral Lepton
- Summary

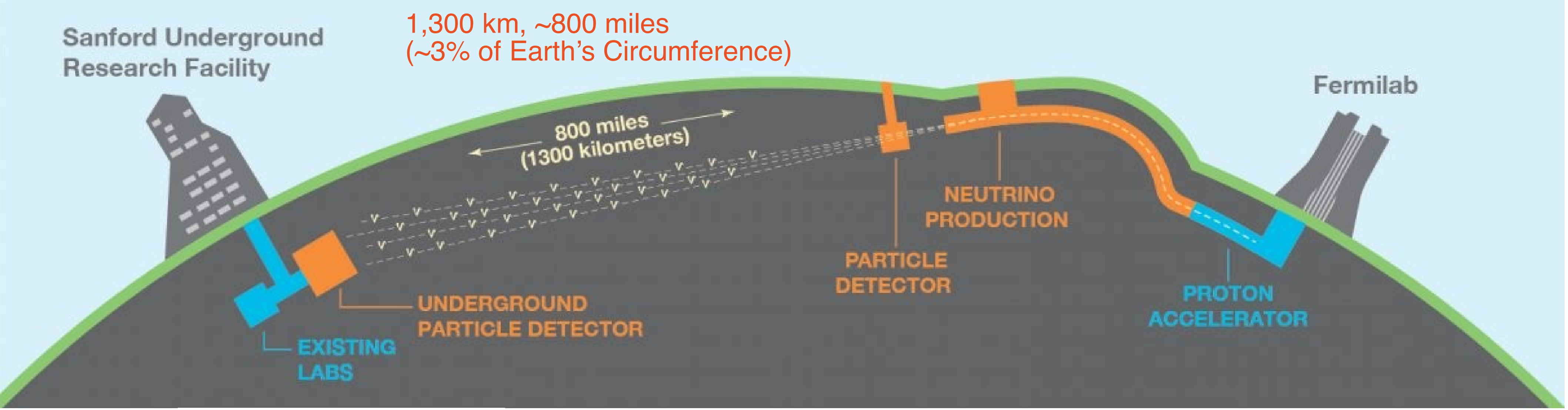
Quick introduction of ND subdetectors, and will point out what makes it good for dark sector or Non-oscillation studies

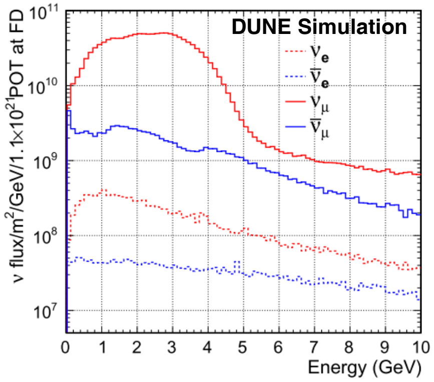
Not going to address all the details but will focus on:
1) Signatures of Signals/Backgrounds
2) Tools and simulation workflow
3) Currently expected sensitivity

Introduction

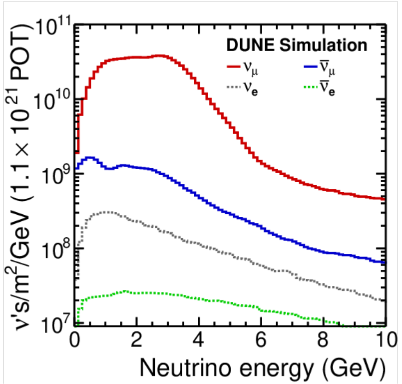
- 1998, neutrino oscillation phenomenon discovered:
  - Neutrino oscillation revealed that $m_\nu \neq 0$.
  - This is apparently contrary to the assumption of the Standard Model (SM).
  - Therefore, this means that now neutrino physics entered the into the realm of **Beyond Standard Model (BSM)** physics.
- This demands the precision measurement of **neutrino oscillation parameters**.
- In experimental particle physics, the word 'precision' often related to high statistics.
  - Large mass, high precision detectors and high intensity neutrino beam with **long-baseline**.
  - This makes cutting-edge neutrino experiments as a **general purpose** particle physics machine.

Deep Underground Neutrino Experiment





DUNE FD TDR Vol. II [arXiv:2002.03010]



Comparing two measurements
→ neutrino oscillations
→ BSM physics?
sterile neutrino,
non-standard interaction

DUNE ND CDR [arXiv:2002.03010]

The LBNF Beam

- The new PIP-II accelerator will provide **120 GeV** proton beam to DUNE through the Main Injector.
- The Phase-I operating beam power is **1.2 MW** and it can be upgraded up to **2.4 MW**.

Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

Day-1 configuration (row 120 GeV, 1.20 MW)

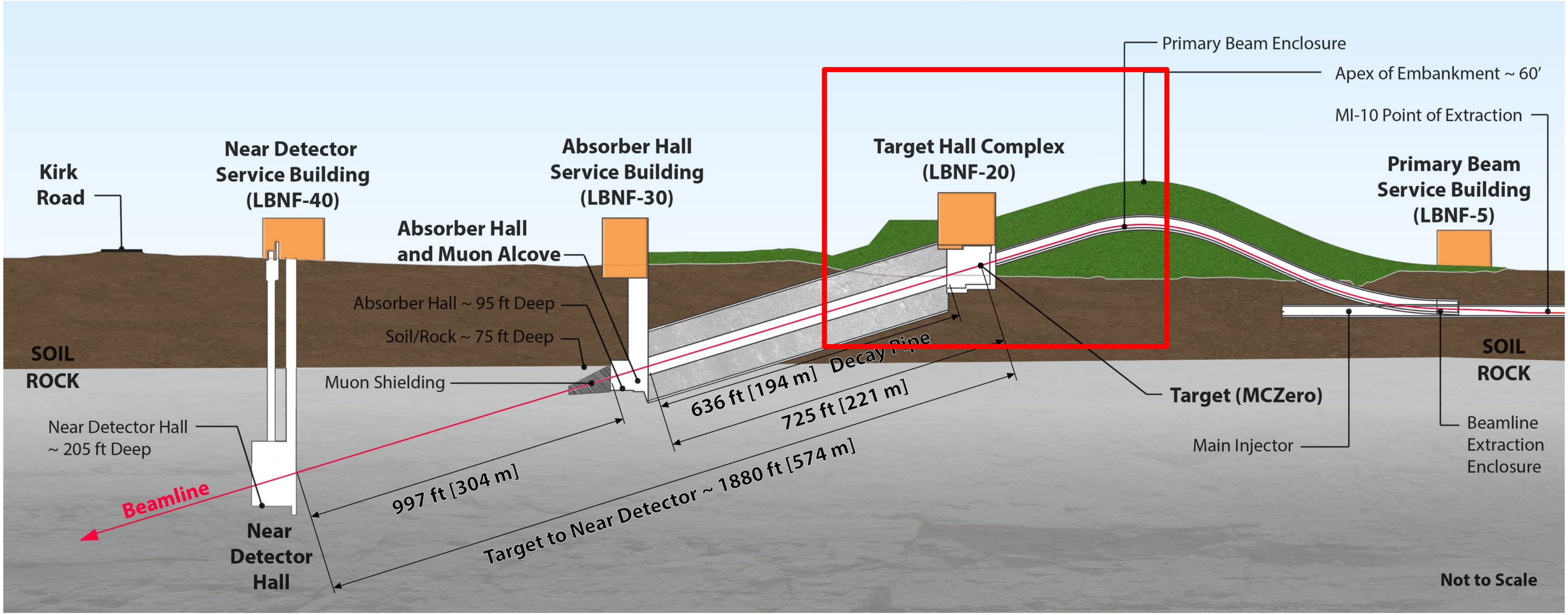
Phase-II (row 120 GeV, 2.40 MW)

[Heidi Schellman, ICHEP 2018]

Fermilab Accelerator Complex

University of Texas Arlington DUNE

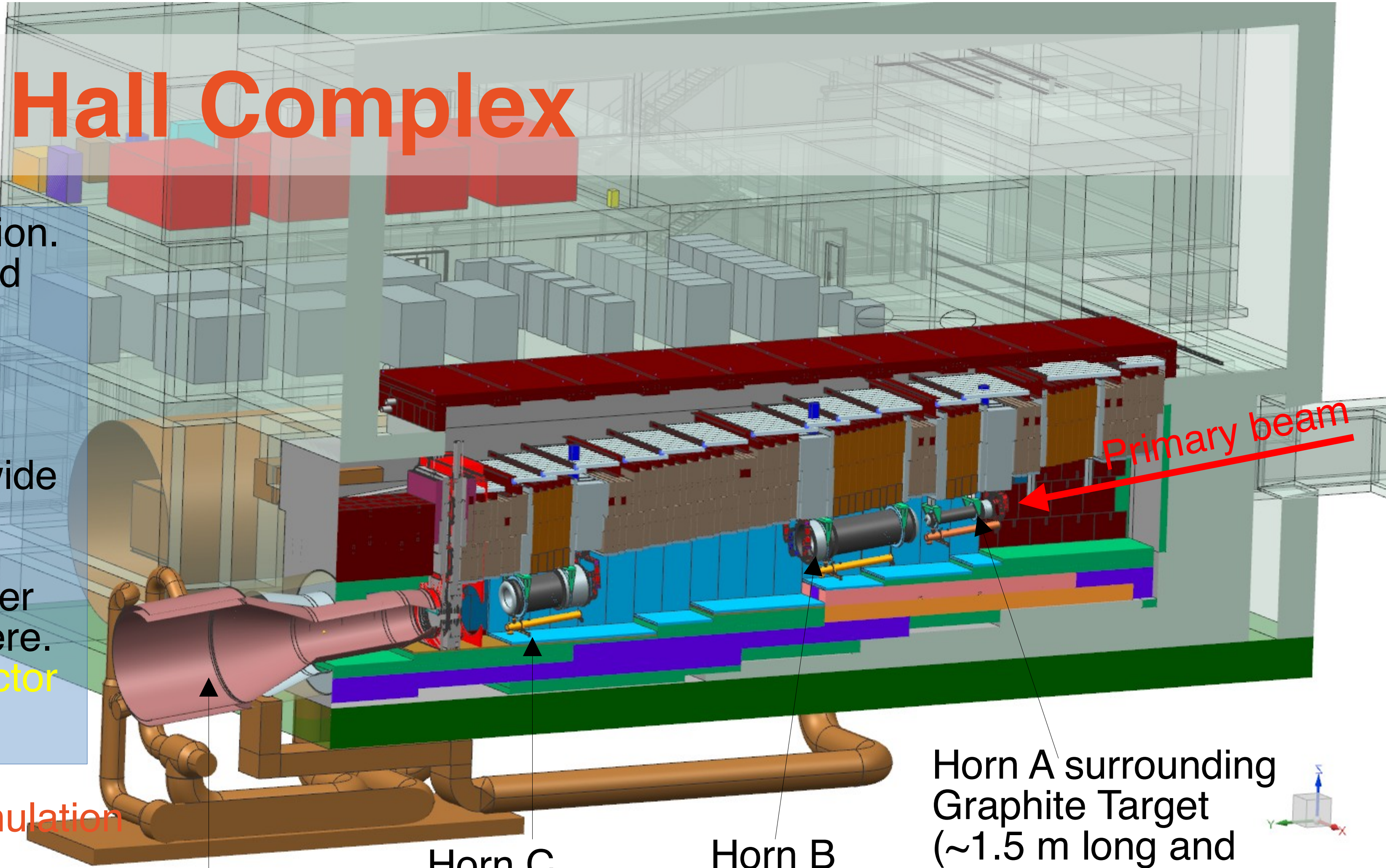
Target / Hadron Absorber / ND



Target Hall Complex

- Neutrino production.
- Collimate charged mesons using 3 steps of focusing horns system to focus neutrino beams and get wide bandwidth of neutrino energy.
- ~52% beam power will be used in here.
- Produce dark sector particles?

[G4LBNE] is the simulation tool for this study.



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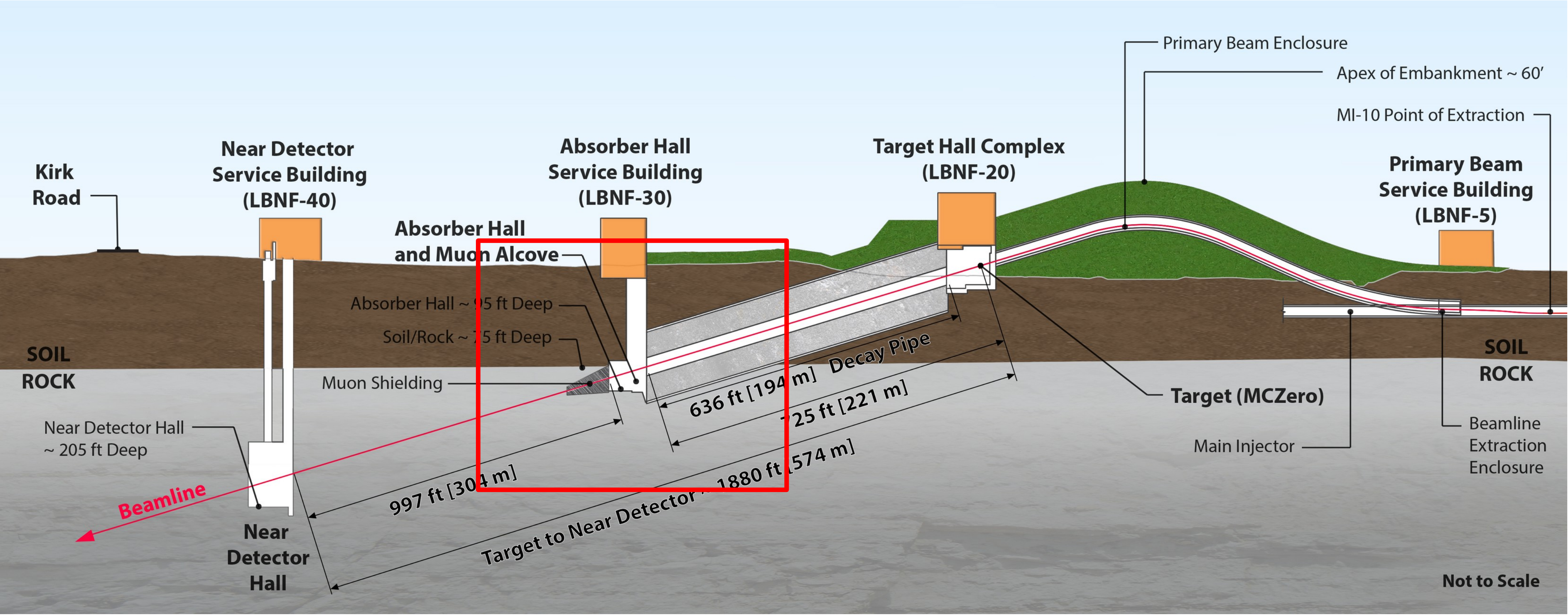
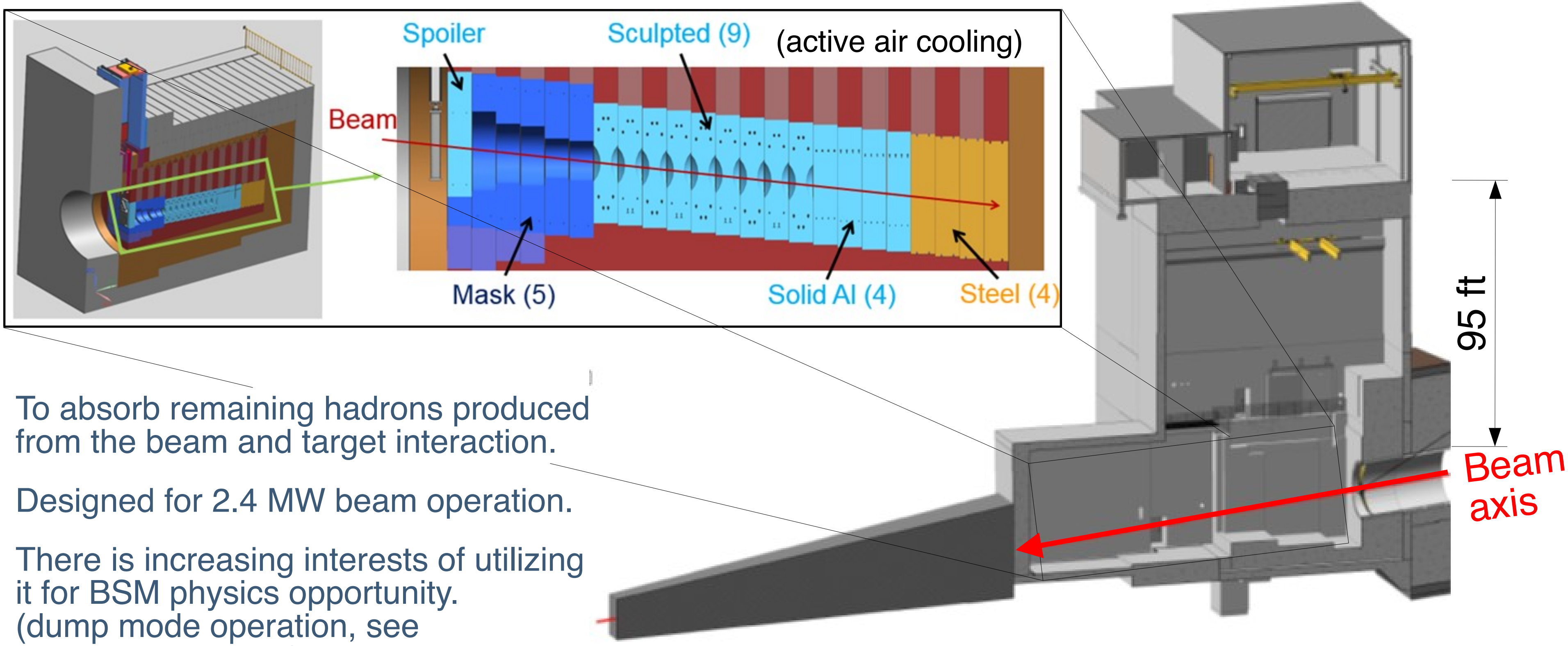
Target / Hadron Absorber / ND



Hadron Absorber

[B. Hartsell, et. al. 10.18429/JACoW-IPAC2015-WEPTY025]
[Heidi Schellman, ICHEP 2018]



- To absorb remaining hadrons produced from the beam and target interaction.
- Designed for 2.4 MW beam operation.
- There is increasing interests of utilizing it for BSM physics opportunity. (dump mode operation, see Zahra Tabrizi's talk)

~17% beam power will be absorbed

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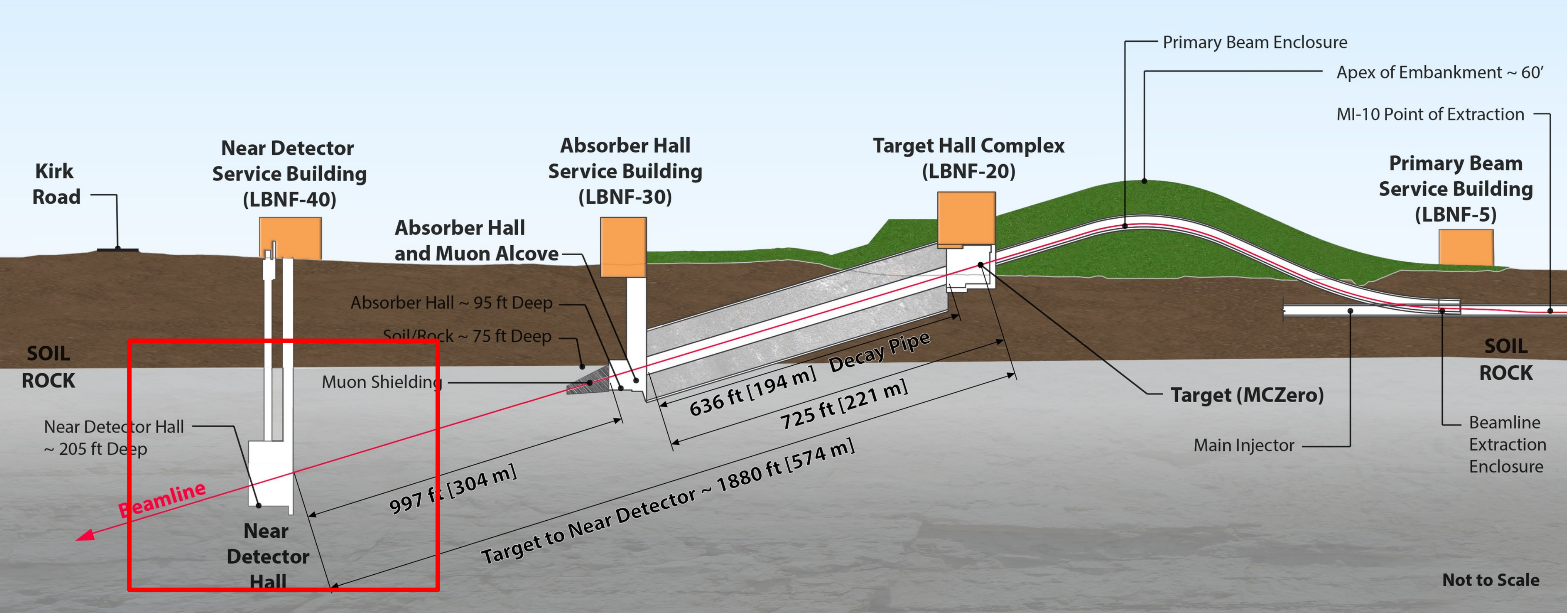
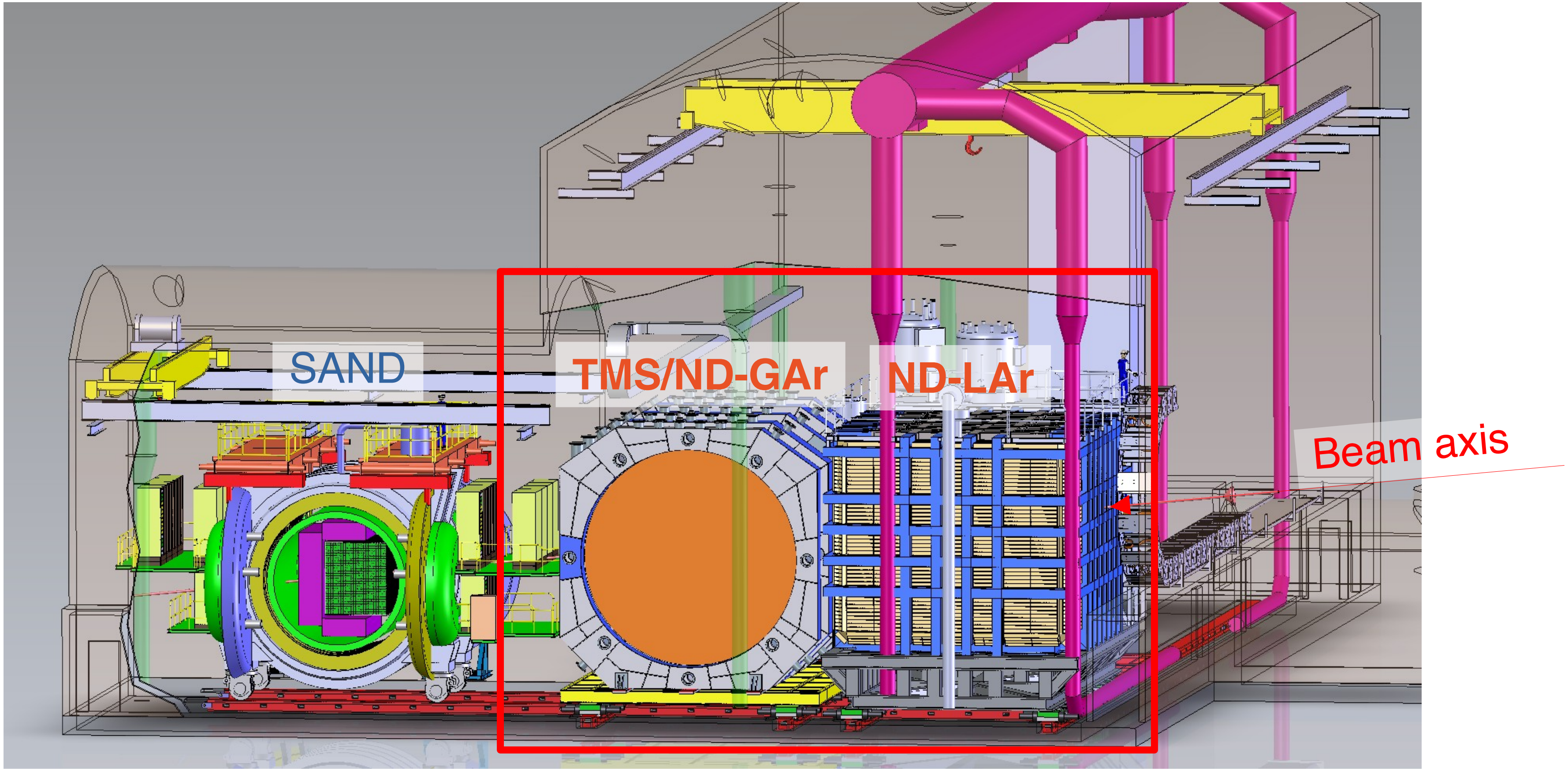
Target / Hadron Absorber / ND



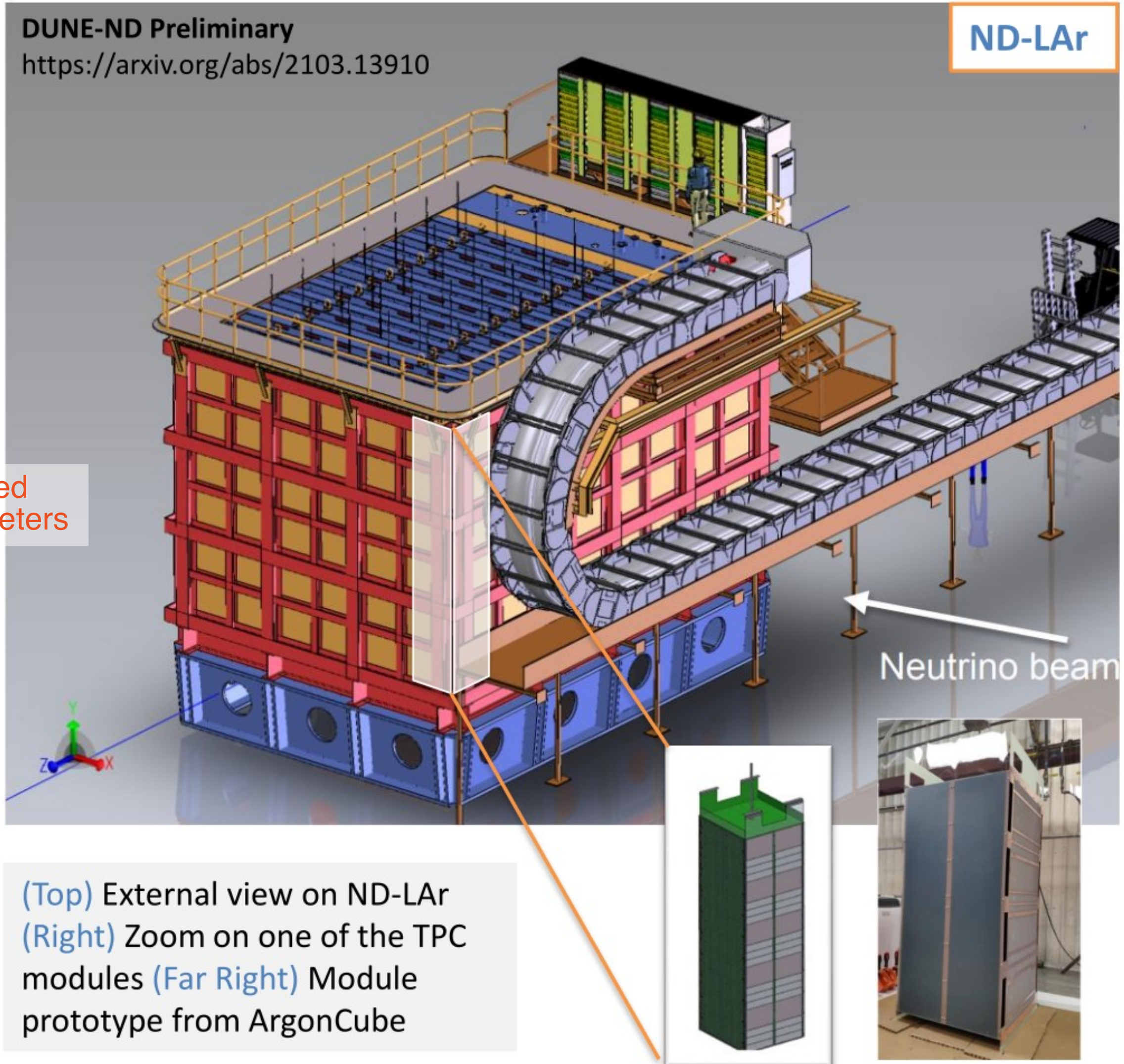
DUNE Near Detector Complex



DUNE ND-LAr

- LArTPC provides excellent charged particle measurement and will be used to measure neutrino fluxes precisely.
  - Spatial resolution ~ 1 mm^3
  - Angular resolution ~ 5 mrad
  - Energy resolution ~ 5%
- ~150 t active material mass
  - Modular design
- 4 m × 3 m × 5 m Active Vol. (3 m × 2 m × 3 m Fiducial V.)
- Detector movable Off-Axis (max ~30 m)

Day-1 expected design parameters

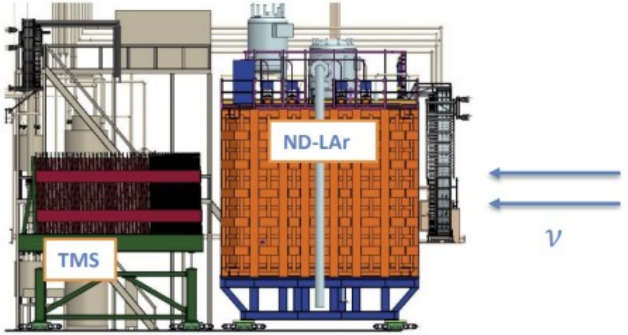


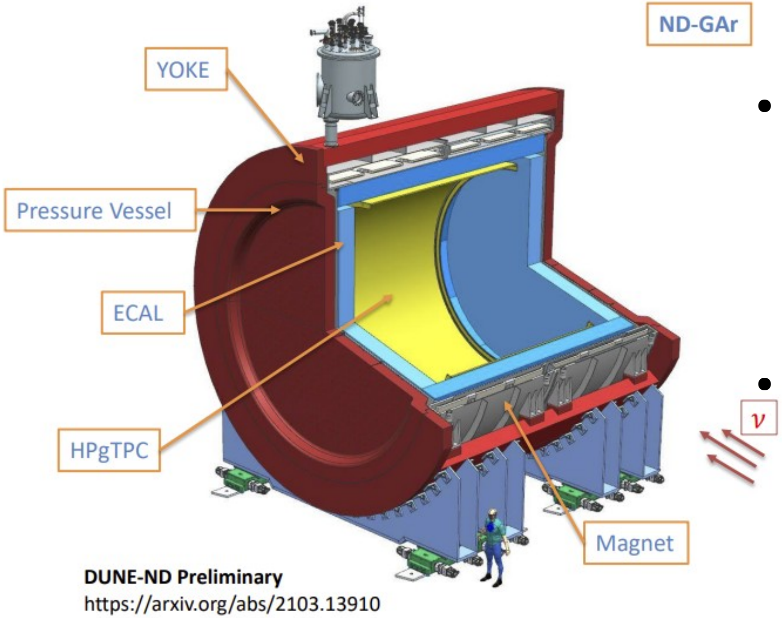
(Top) External view on ND-LAr (Right) Zoom on one of the TPC modules (Far Right) Module prototype from ArgonCube

[Federico Battisti, ICHEP 2022]

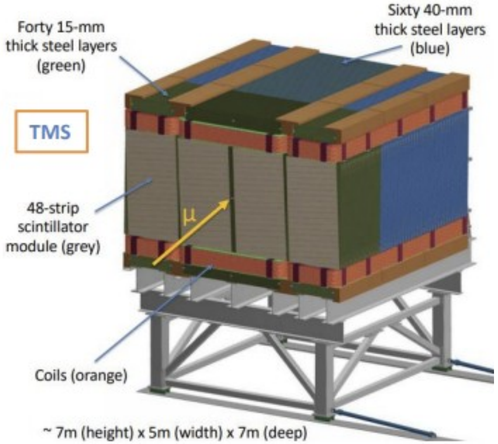
DUNE ND-GAr / ND-TMS

- Allows ND provides excellent momentum resolution for charged particle tracks (μ, p) that were produced in ND-LAr and through interplay with ND-LAr it will provide precise neutrino flux measurement at ND site.
- ND-TMS will likely to be the DUNE day-1 configuration and will be upgraded to ND-GAr in DUNE Phase-II.





- In the viewpoint of dark sector study, we expect opportunities to catch the decays of long-lived unstable dark sector particles.
- Detector movable Off-Axis as well as ND-LAr



[Federico Battisti, ICHEP 2022]

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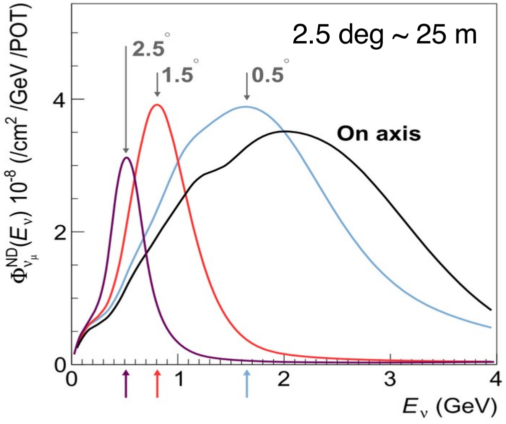
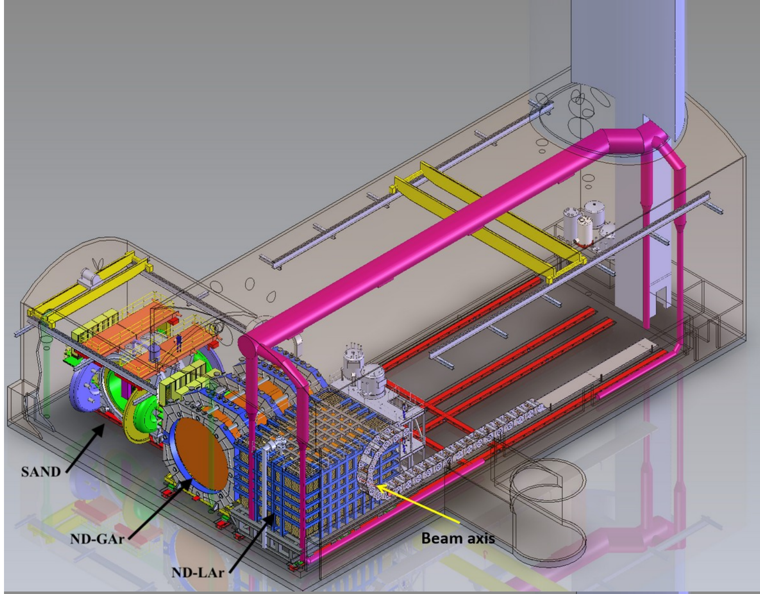
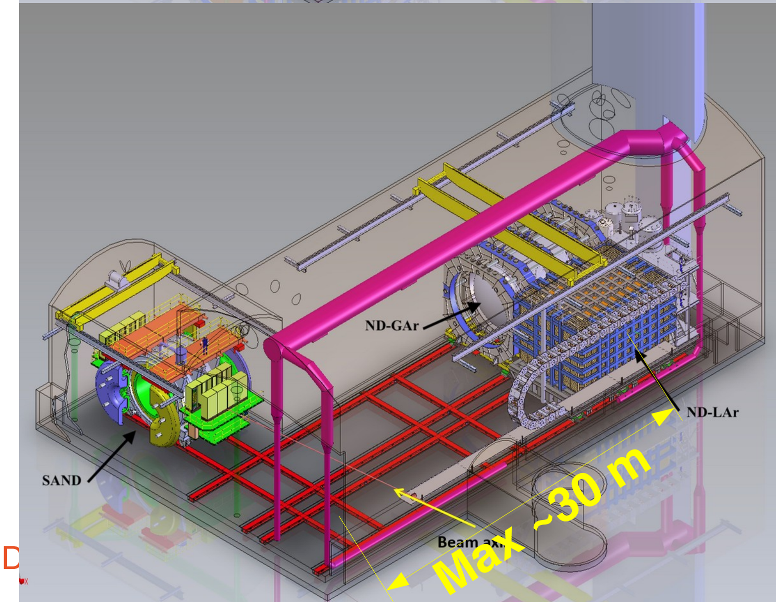
DUNE ND PRISM

- The main purpose of the PRISM system is to control systematic uncertainties of neutrino fluxes originated from materials along the neutrino pathways.
- By locating ND subdetectors to the Off-Axis position, this decreases neutrino flux and it plays a role in reducing backgrounds in **BSM** studies.
- Movable up to **~30 m**.

DUNE ND CDR [arXiv:2002.03010]







What Makes DUNE ND Well-Suited for BSM Study?

- **Direct Observation Signature from the Beams**
  - Require high beam flux → **P_{beam} = 1.2 – 2.4 MW**
  - Large mass, high density for scattering signatures → **ND LAr w/M_A = 150 t, fine segmentation**
  - Large volume, low density for decay signatures → **ND-GAr ND w/ECAL and magnetized precision tracking**
  - Capable near detector complex → **Combinations of ND-LAr + ND-GAr on PRISM + SAND for fine tracking & beam monitoring**
  - Low threshold energy → **Both ND and FD TPC threshold ALA few MeV**
- **What do we need to know?**
  - Signal flux and realistic behaviors in the detector
  - Neutrino flux and their interactions in the detector as bck → **ND Sub-detectors with PRISM**

[Jae Yu, Snowmass CSS 2022]

Selected BSM Topics at DUNE ND

- High beam power, large detector mass + highly capable, precision near and far detectors with low E threshold make **DUNE a BSM machine**
  - Recall the signal to background ratio grows by the sqrt of the beam power
  - Near Detector Searches è Take advantage of high beam power•
    - **Axion-like Particles (ALP)**
    - **Low mass Dark Matter (LDM)**
    - **Heavy Neutral Leptons (HNL)**
    - **Neutrino Trident**
    - Dark Photon
    - Milli-charge Particles (mCP)
    - And many many more..

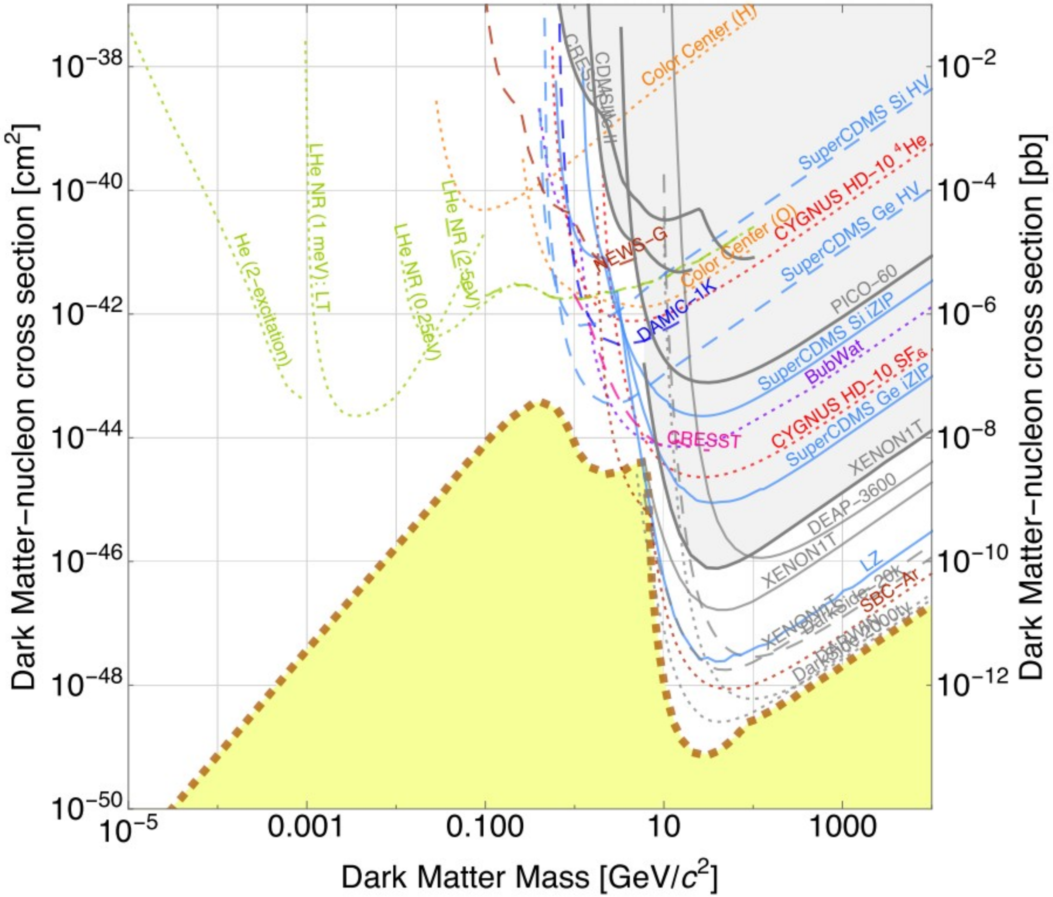
Topics I will cover today.

Please check arXiv:2103.13910 and EPJ C.81, 322 (2021) for more physics.

  - Far Detector Searches take advantage of ND, large VA FD & long baseline
    - Sterile neutrino searches
    - Non-standard Interactions, Non-Unitarity, CPT violation
    - Large Extra Dimensions (LED)
    - Boosted Dark Matter (BDM) & Inelastic Boosted Dark Matter (iBDM)
    - And many many more…
- Strong collaboration of theorists and experimentalists essential
- Some of these topics covered in EPJ C.81, 322 (2021)

[Jae Yu, Snowmass CSS 2022]

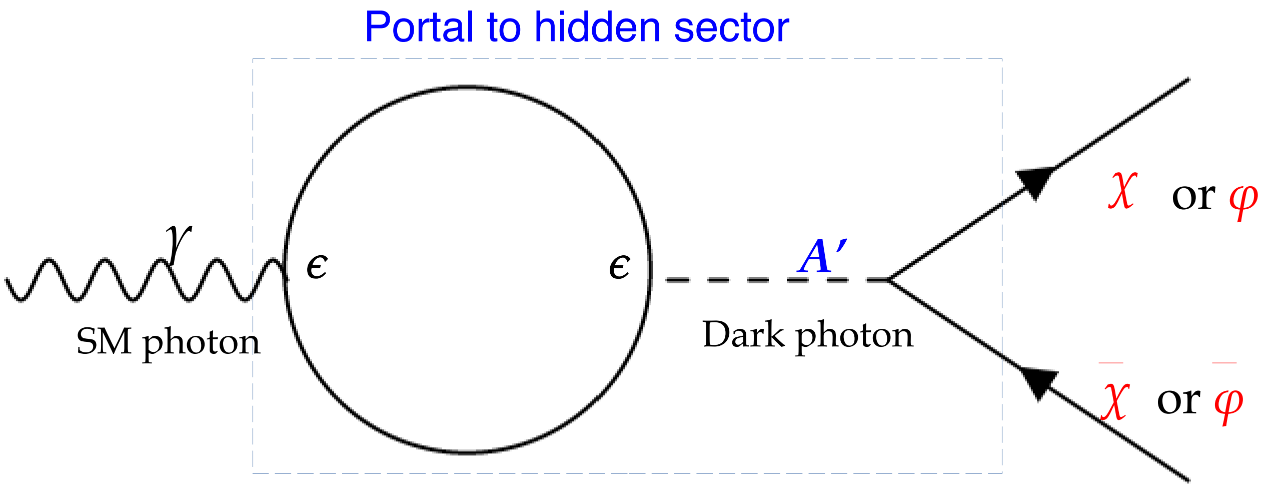
Light Dark Matter

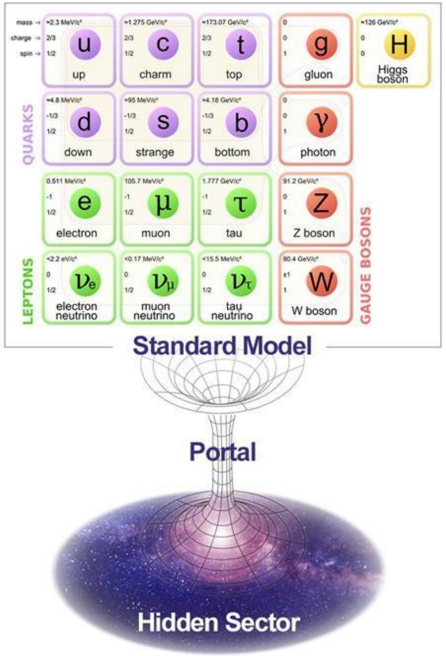


- Phase space for WIMP searches.
- ~1 GeV, a threshold to capture DM-nucleon scattering event in LXe/LAr/Ge/GHe detectors.
- Sub-GeV territory is remain unexplored.
- Many new ideas other than WIMP
  - WIMP mass lower than 2 GeV can not explain dark matter relic abundance.
  - Hidden sector or portal interaction scenario.

Light Dark Matter – Introduction

- In our light dark matter model, we assume that standard model photon is **kinetically mixed with 'dark photon'.**
- Dark matter particles can be produced by decay of dark photon through the '**portal interaction**'.





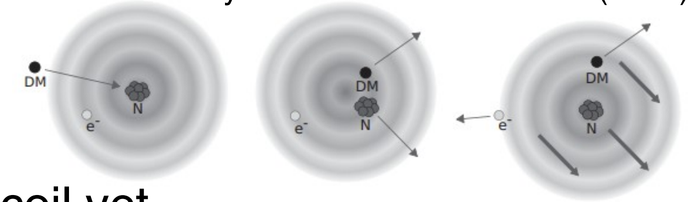
Beam intensity $\propto$ Photon flux $\propto$ **Dark matter flux**

DUNE, equipped with **high-intensity proton beam** provides a great opportunity to test this type of dark matter scenario.

Light Dark Matter – Event Generator

- **PYTHIA**: Neutral meson flux → Dark matter flux [Valentina De Romeri et. al. Phys. Rev. D **100** 095010]
  - Contribution from secondary interactions?
- Signal Event Generator – DMG4 [M. Bondi et. al. CPC **269** (2021) 108129]
  - Good
    - Versatility and detailed simulation powered by Geant4
  - Limitation
    - Programmed for electron beam dump experiment (NA64)
    - Supports DM production only through <u>bremsstrahlung</u> and e^-+ e^+ <u>annihilation.</u> π^0 decay is not supported.
- MadGraph
- BdNMC

[Matthew J. Dolan et al Phys. Rev. Lett. **121** 101801 (2018)]



We didn't had chance to simulate nucleon recoil yet...

Light Dark Matter – Simulation Flow

Signal

Dark matter event generator
(Pythia/Geant4/MadGraph/BdNMC)

GENIE MC – BDM module(Deveoped by J. Burger)
DM-LAr event generation
→ Recoiled electrons, ...

Event Generation Study
Detector Level Study

Detector simulation
- edep-sim (✓)
detector response, reconstruction
(LArSoft/larnd-sim/Pandora/MLReco) ...

Background

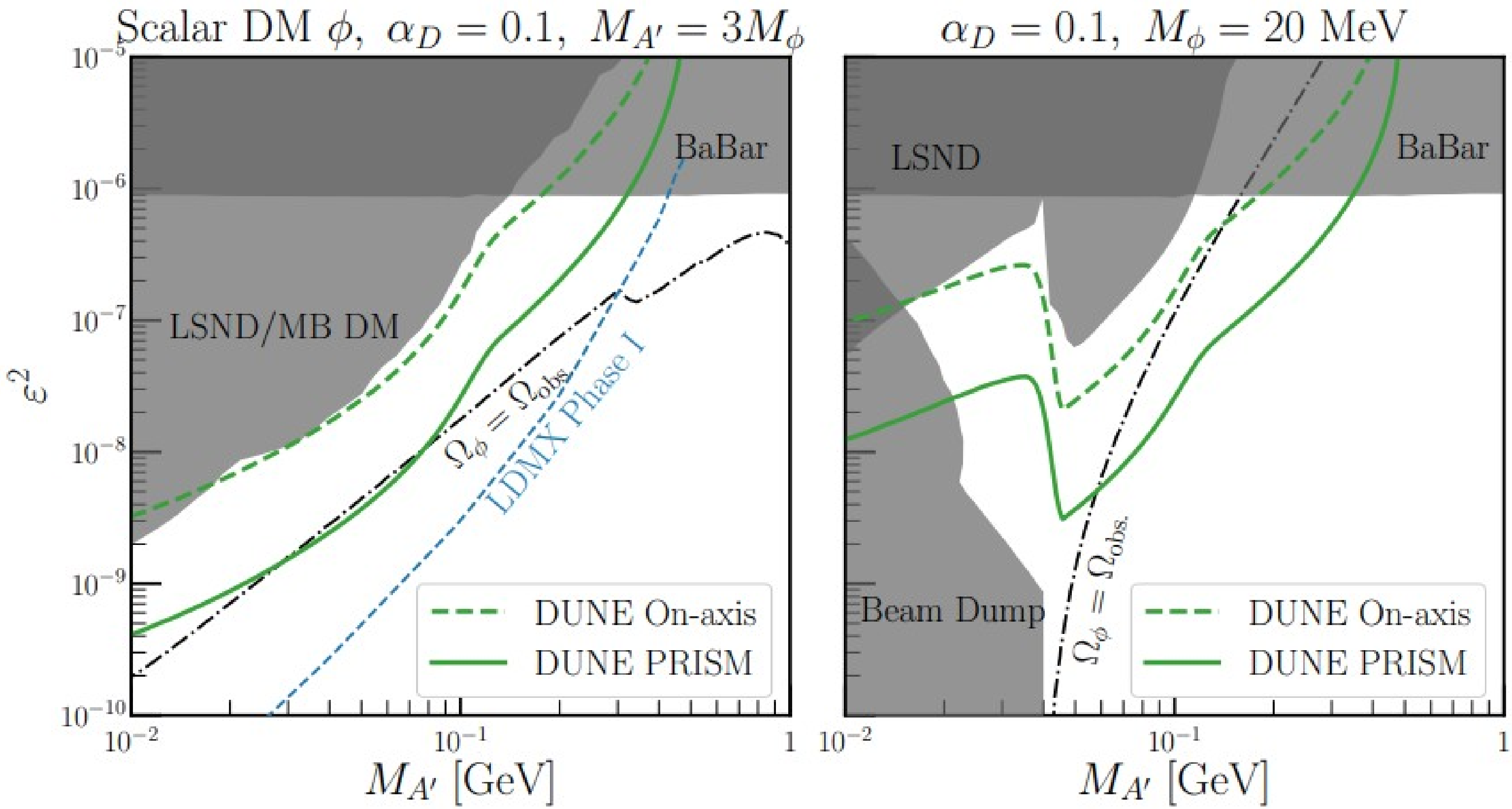
p-Target interaction
(G4LBNE simulation)
→ Neutrino flux

GENIE MC
ν-LAr event generation
→ Recoiled electrons, ...

Detector simulation
- edep-sim (✓)
detector response, reconstruction
(LArSoft/larnd-sim/Pandora/MLReco) ...

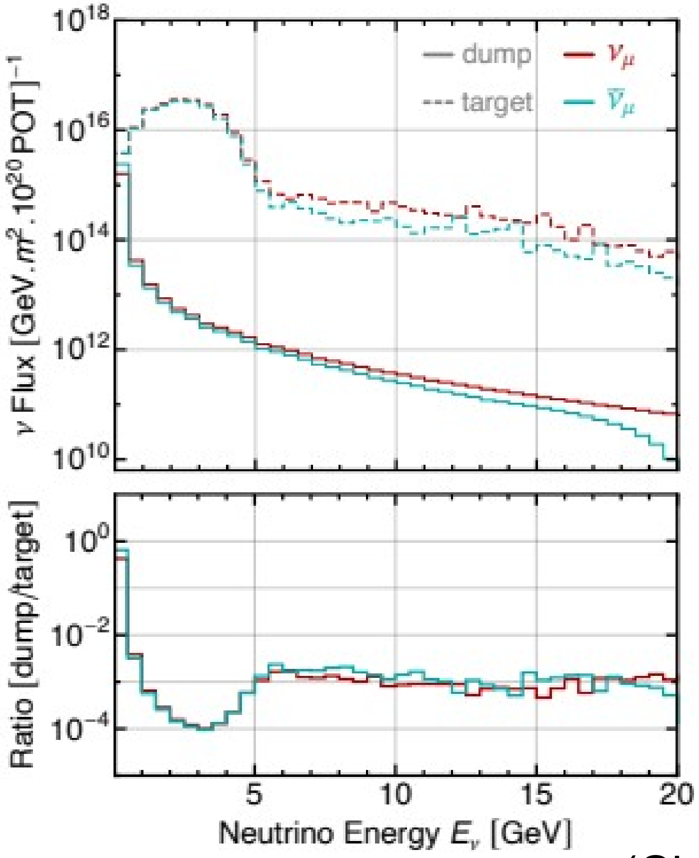
Sensitivity estimation taking into account **experimental details**

Light Dark Matter – Sensitivity

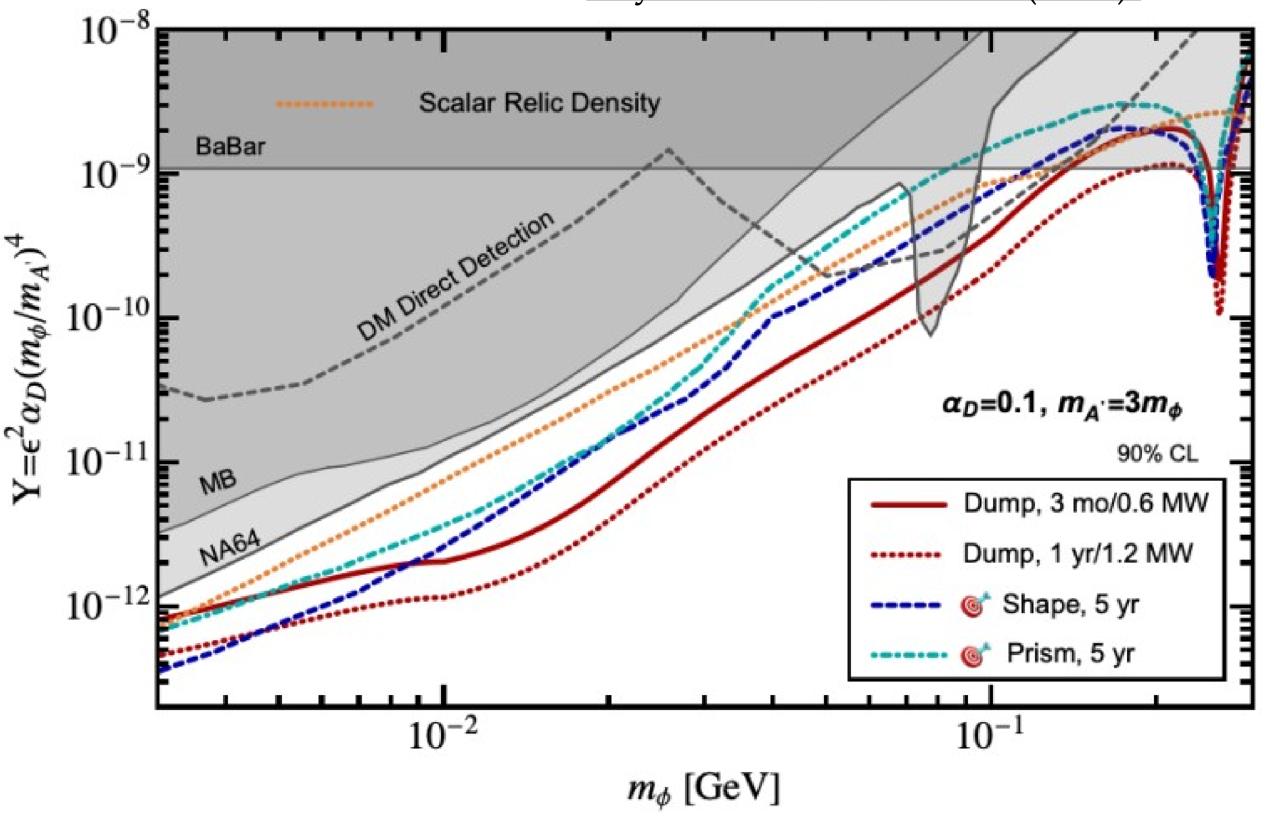


[Valentina De Romeri, Kevin Kelly, Pedro A.N. Machado. Phys. Rev. D **100** 095010]

Light Dark Matter – Sensitivity (cont'd)



Phys. Rev. D **107** 055043 (2023)

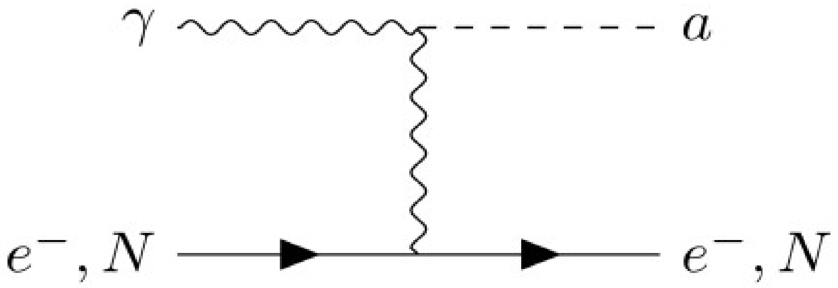


(Check details from Zahra Tabrizi's talk!)

Axion-like Particles

- ALPs are general extension of QCD axion to solve strong CP problem and at the same time an excellent dark matter candidate.

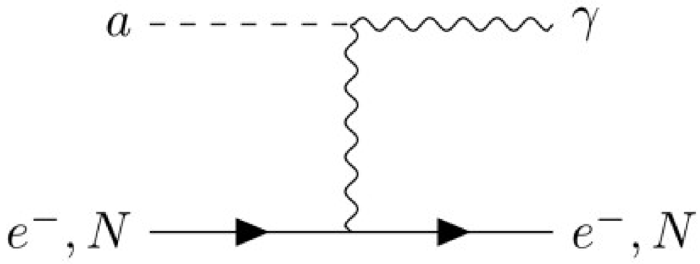
Production



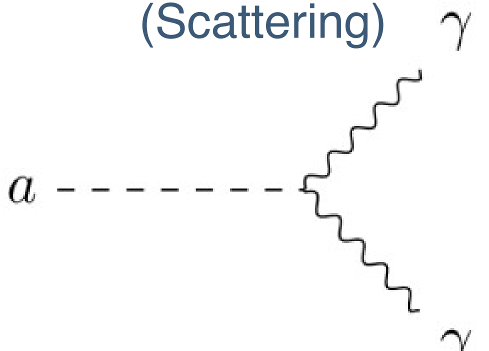
Primakoff Process

ALP flux ∝ Photon flux ∝ Beam intensity

Detection



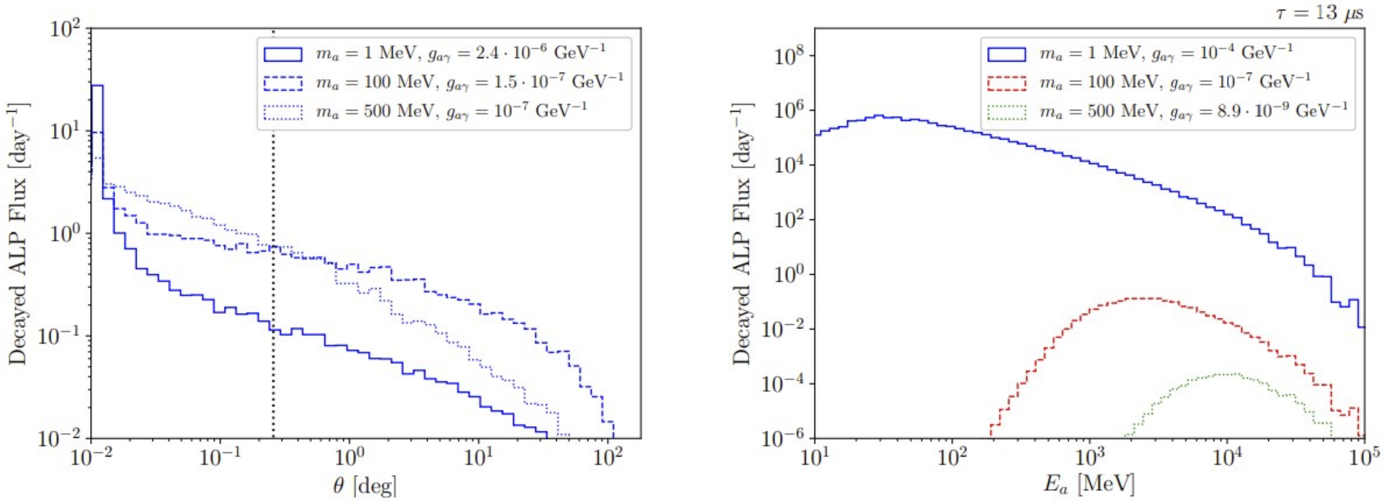
(Scattering)



(Decay/annihilation)

Axion-like Particles – Tools

- Standalone Geant4 simulation to obtain photon flux → Convert it to ALP

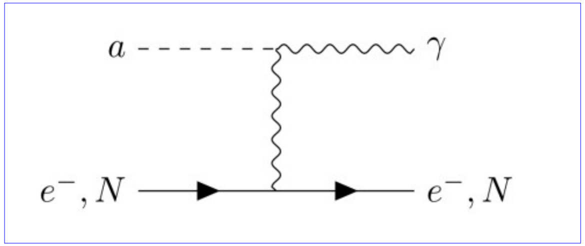


[Brdar et. al. Phys. Rev. Lett. 126, 201801 (2021)]

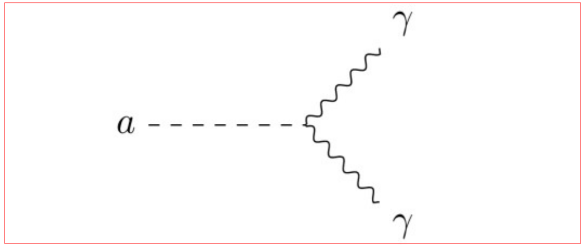
- DMG4 supports ALP production

Axion-like Particles – Sensitivity

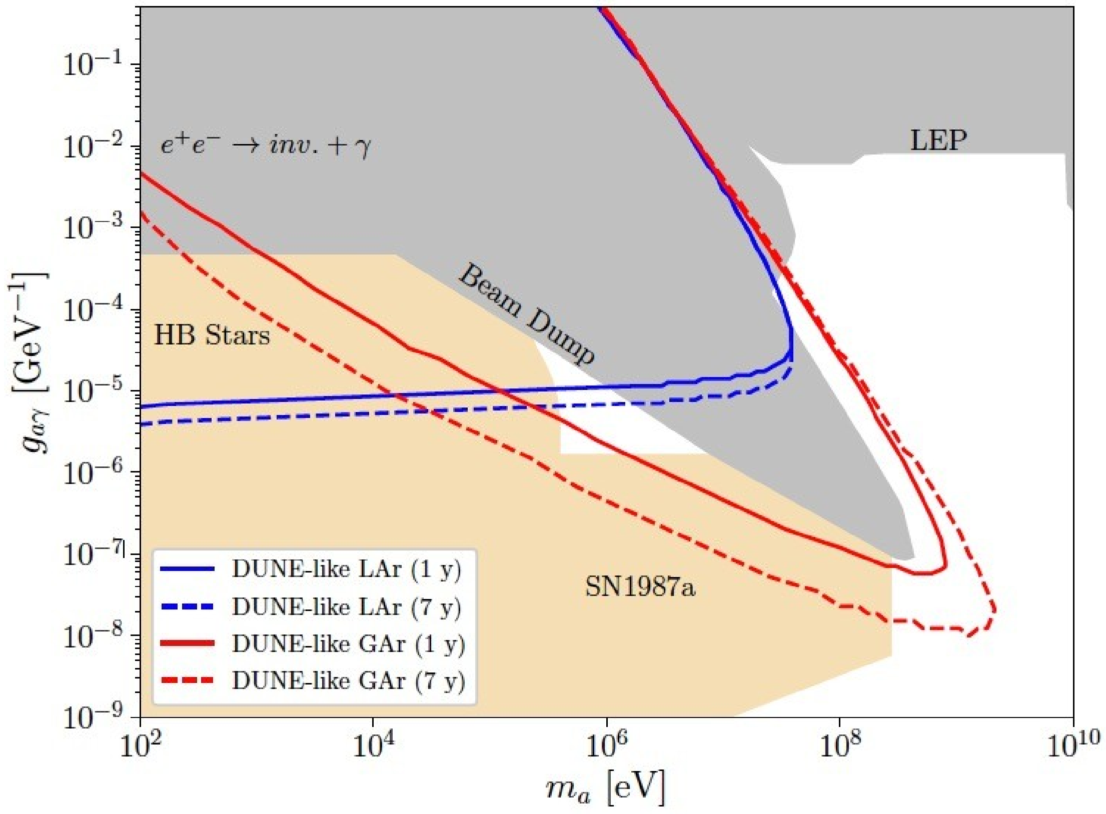
- Detection through scattering
  - ND-LAr



- Detection through decay
  - ND-GAr (Phase-II)



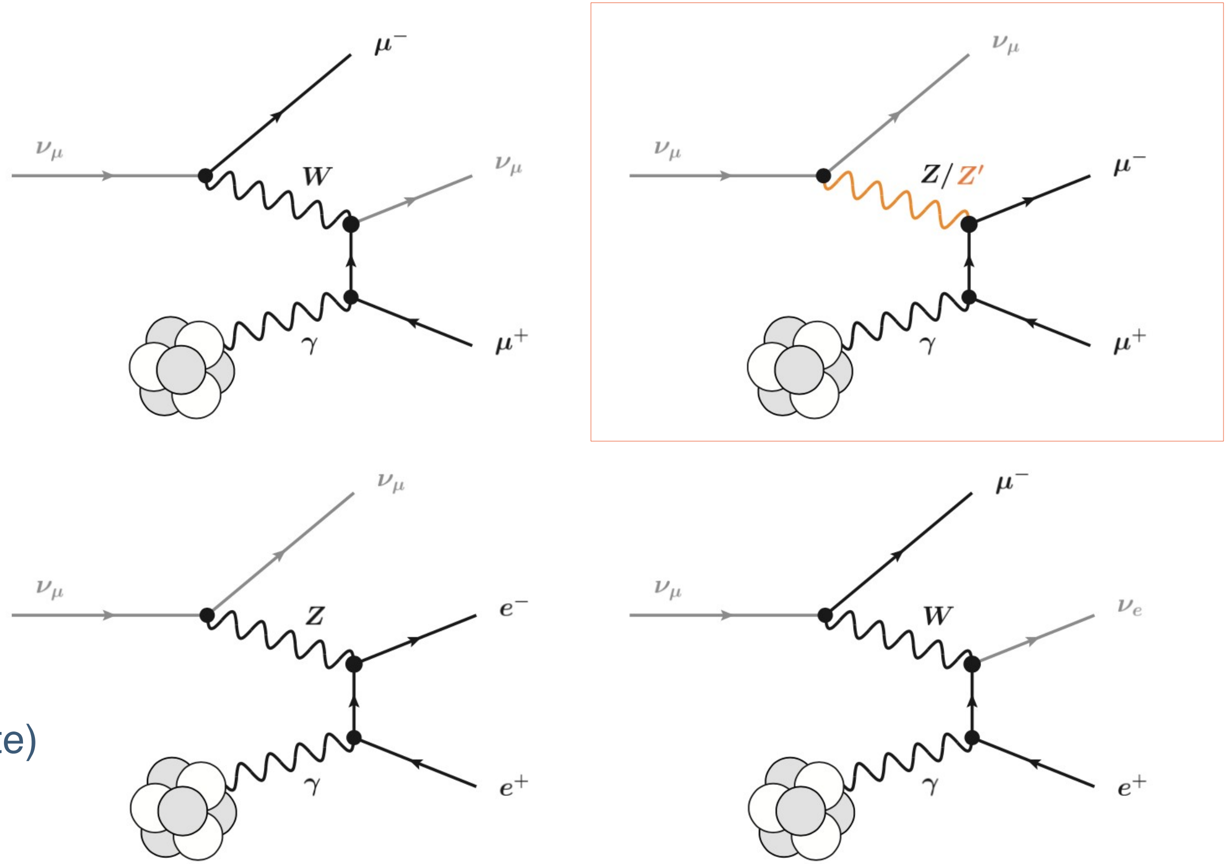
[Brdar et al., Phys. Rev. Lett. **126**, (2021) 201801]



Neutrino Trident

- Neutrino tridents - rare SM weak processes
- Signature: a pair of charged leptons
- Δ suggests unknown gauge boson (Z') couplings.

Δ=(SM expected rate – Observed event rate)



Neutrino Trident – Backgrounds

Backgrounds

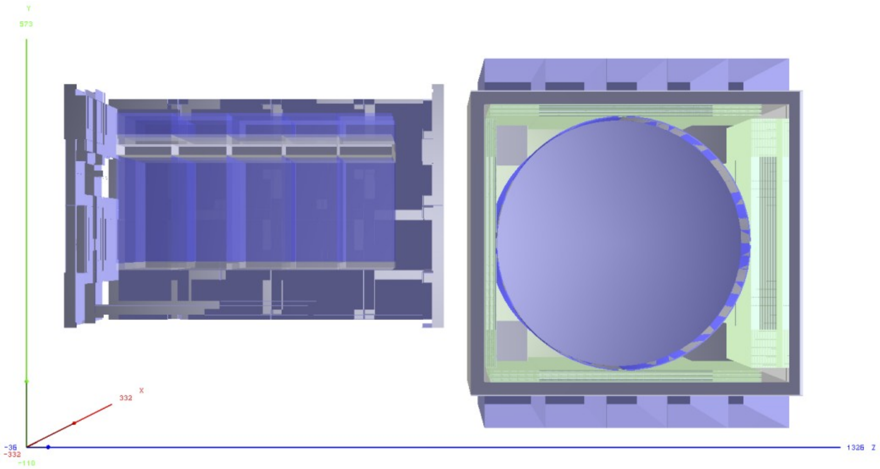
- Muon tridents main background: ν_μ CC $1\pi\,0p$
  - Difficult to distinguish pions and muons using calorimetry information, range etc.
  - Need to be identified from other event properties.
- Electron tridents main background: NC π^0
  - Photon showers from resulting pi-zero decay could mimic the expected two electron showers.
- Have started studying the muon trident backgrounds using initial ν_μ CC $1\pi\,0p$ events (some plots follow). Order of magnitude more stats on its way!

[M. Wallbank, DUNE BSM WG Meeting]

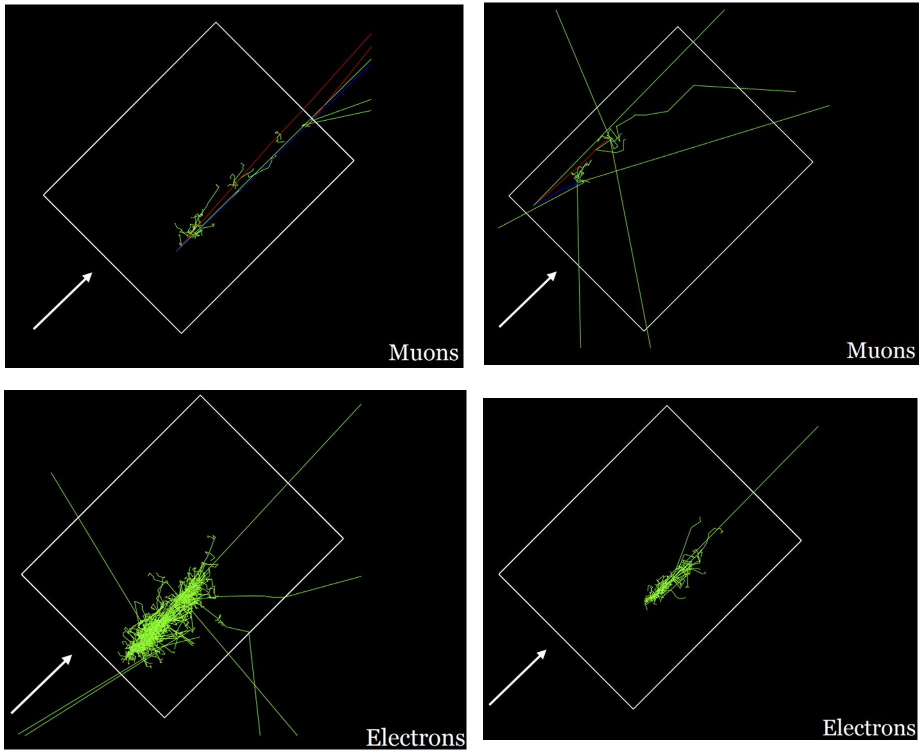
M Wallbank (Cincinnati) 5

Neutrino Trident – Tools

- Standalone Event Generator – Interfaced to Geant4
- Background simulation: GENIE



ND-LAr geometry (GDML based implement)



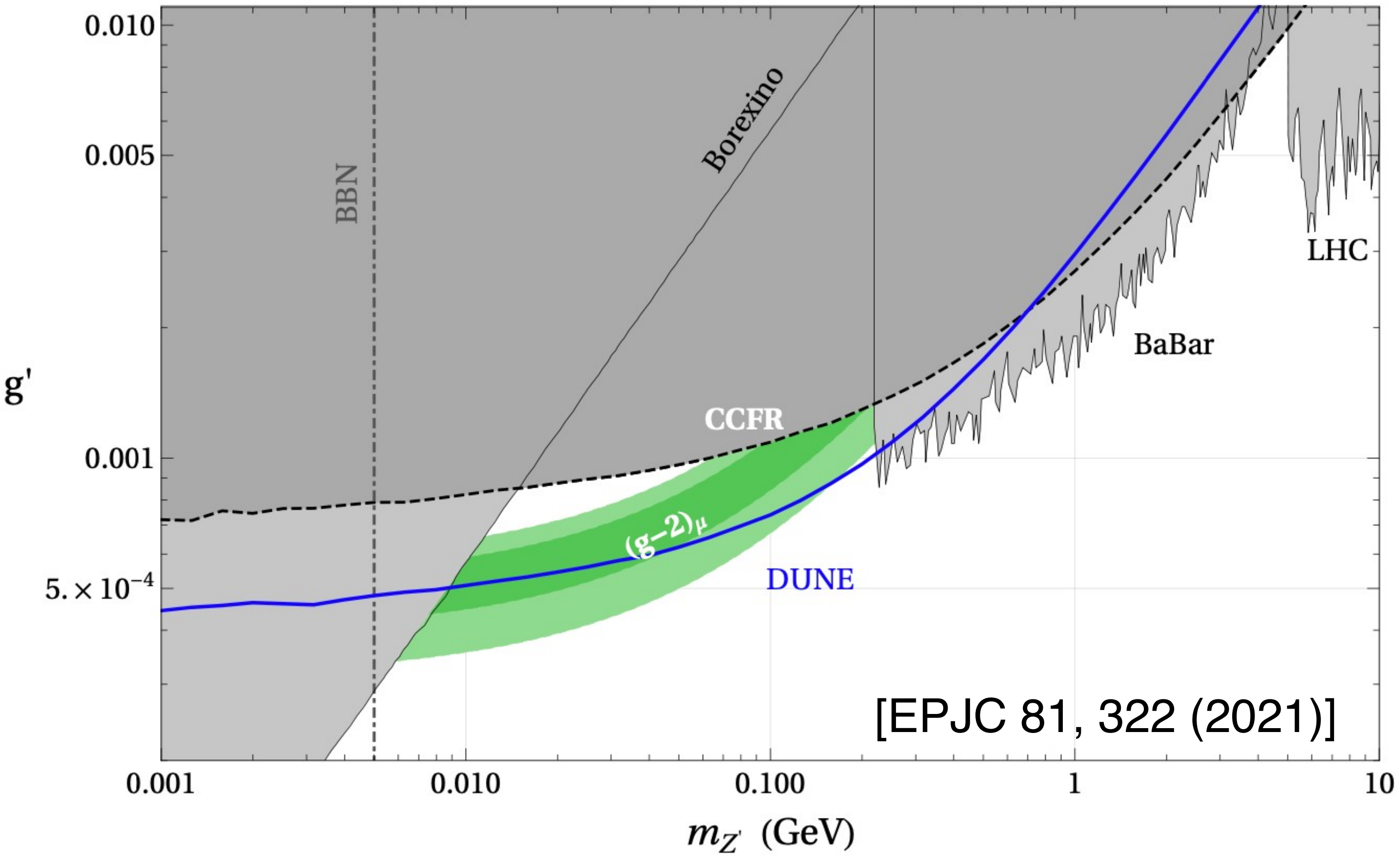
[Figures from J. Martín-Albo, DUNE CM Jan. 31. 2018]

Neutrino Trident – Sensitivity

DUNE is sensitive in the region where $(g\text{-}2)_\mu$ anomaly can be explained at 1σ and 2σ

Shaded in gray:
CMS($pp\rightarrow\mu^+\mu^-Z\rightarrow\mu^+\mu^-\mu^+\mu^-$)
BaBar($e^+e^-\rightarrow\mu^+\mu^-Z\rightarrow\mu^+\mu^-\mu^+\mu^-$)
Borexino(solar υ-e^- scattering)
CCFR(Tevatron trident meas.)

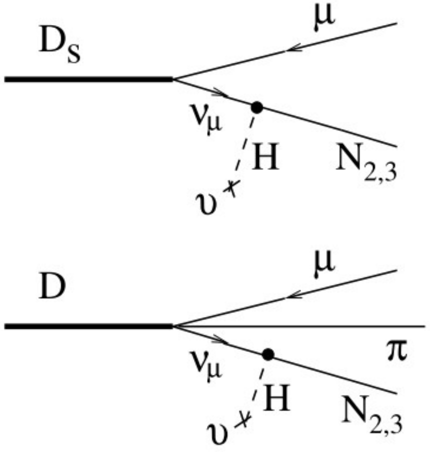
Theoretical constraints:
BBN



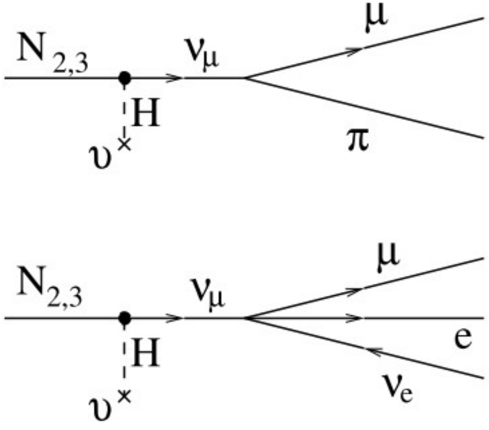
[EPJC 81, 322 (2021)]

Heavy Neutral Leptons

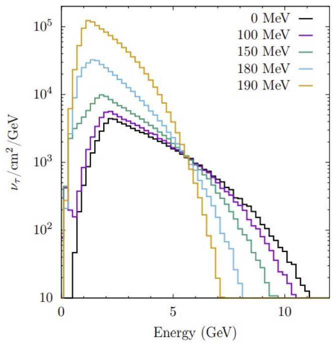
- Energetic collision of proton beam to the target often create heavy mesons such as D.
- Such heavy mesons could be a source of Heavy Neutral Leptons.
- HNLs are assumed to be stable enough to be able to stay alive until it fly ~500 m from the target to ND and then they decay-in-flight in the ND.
- HNL Signature:
  - Charged leptons + lighter mesons



Production



Detection in ND



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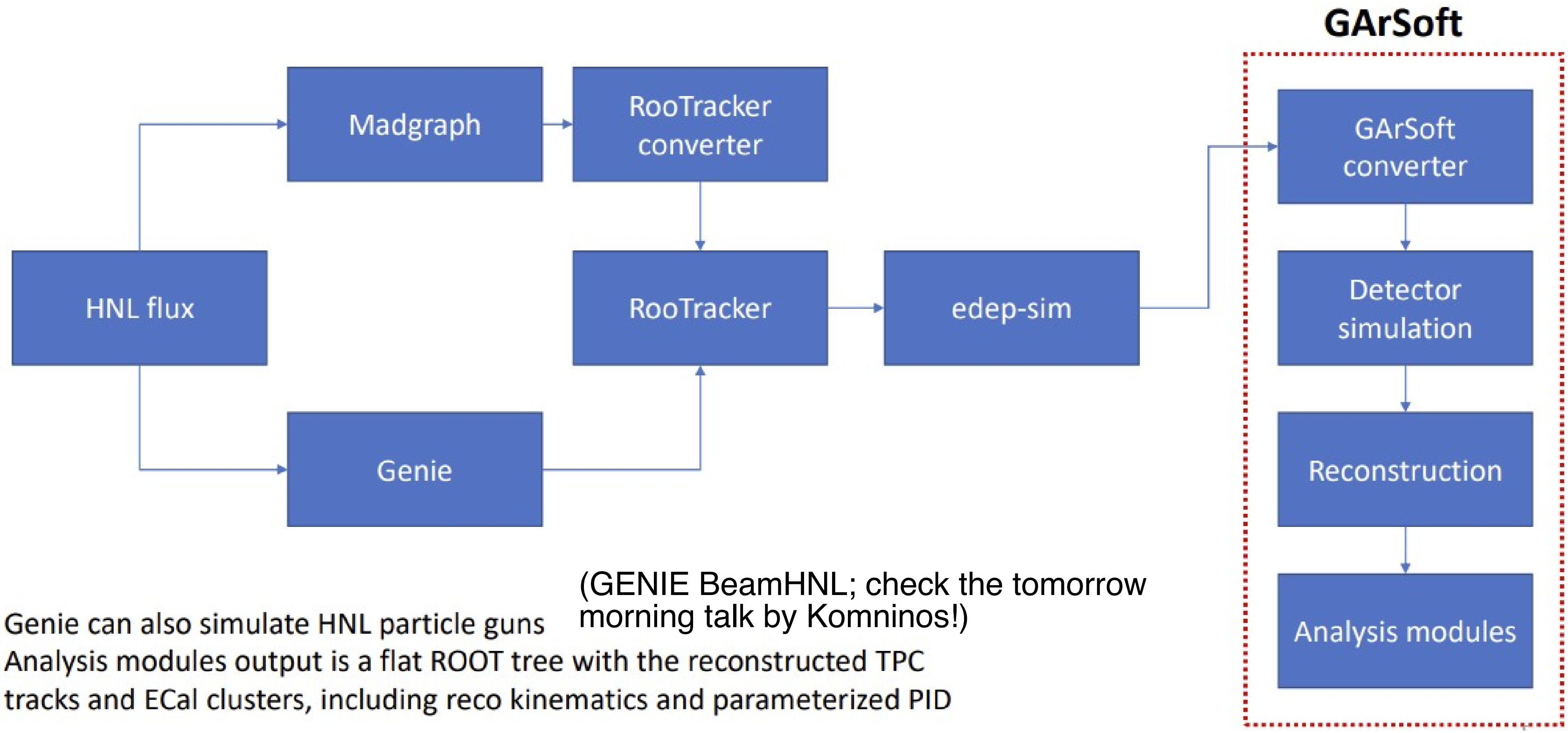
Heavy Neutral Leptons (2)

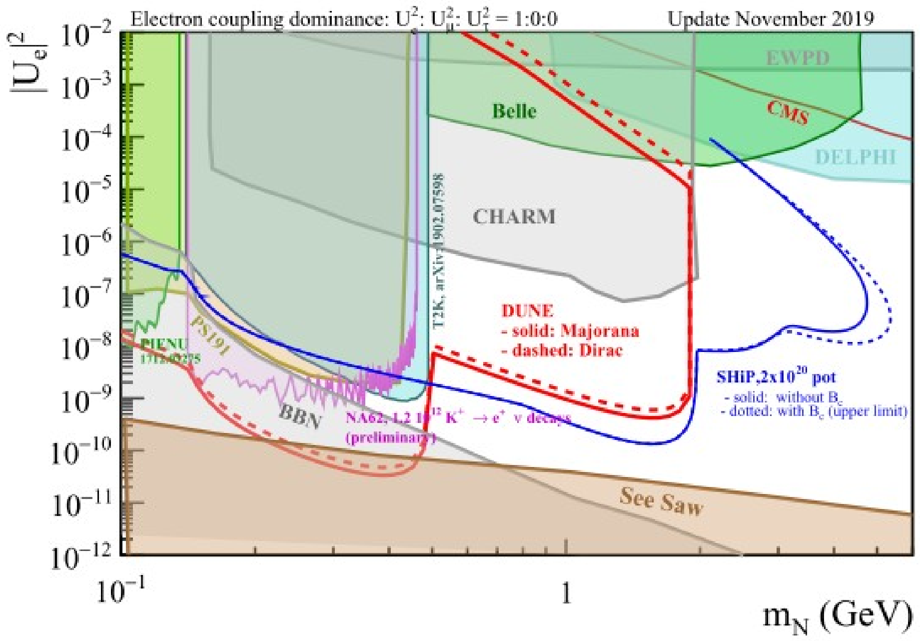


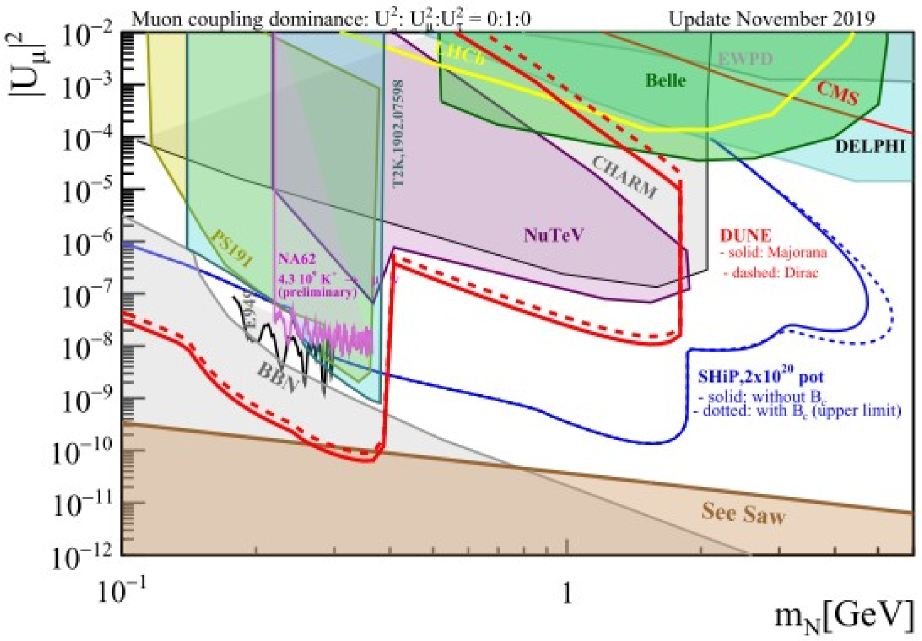
(GENIE BeamHNL; check the tomorrow morning talk by Komninos!)

Genie can also simulate HNL particle guns
Analysis modules output is a flat ROOT tree with the reconstructed TPC tracks and ECal clusters, including reco kinematics and parameterized PID

[Haifa Sfar, DUNE BSM WG Meeting]

Heavy Neutral Leptons (3)





90% CL sensitivity regions for dominant mixings $|U_{eN}|^2$ and $|U_{\mu N}|^2$ are presented for DUNE ND (red).
solid: Majorana neutrino / dashed: Dirac neutrino

Event Signatures and List of Tools

	Signal	Background	Evt. Gen.	Det. Sim.
LDM	$\boldsymbol{\chi e^- \to \chi e^-}$	$\upsilon_e e^- \to \upsilon_e e^-$	Pythia/Geant4/ MadGraph/BdNMC/ DMG4	Edep-Sim Larnd-sim
	$\chi N \to \chi N$	$\upsilon N \to \upsilon N$		
ALP	(S) $\boldsymbol{\gamma e, \gamma N}$	υ coherent, NC w/ π^0, υ_e CC w/ π^0, etc	Pythia/Geant4/DMG4	Edep-Sim Larnd-sim
	(D) $\boldsymbol{\gamma\gamma}$			
Trident	$\nu \to \nu e^- e^+$	$\upsilon_\mu N \to \upsilon_\mu \pi N'$ (υ CC) NC π^0	Geant4 (Standalone) GENIE	Edep-Sim Larnd-sim
	$\nu \to \nu \mu^- \mu^+$			
	$\nu \to \nu e \mu$			
HNL	$N \to \nu e^- e^+$	υ CC + mis-ID p, υe CC w/ π^0	Standalone HNL flux GENIE MadGraph5	Edep-Sim GArSoft
	$N \to \nu \mu^- \mu^+$			
	$N \to \nu \gamma$			
	$N \to \nu e \mu$			
	$N \to \nu \pi^0$			
	$\boldsymbol{N \to e \pi}$			
	$\boldsymbol{N \to \nu \pi}$			

Conclusion

- DUNE is a powerful BSM machine as well as it is excellent for neutrino physics.
- High-intensity proton beam and precision detectors of DUNE provides great opportunity to explore the dark sector or BSM physics.
- We have discussed the capabilities of DUNE ND subdetectors and a variety of Non-oscillatory physics topics that can be unveiled by utilizing them.
- Collaboration between theorist and experimentalist is essential to accomplish this.