LLPs at the Neutrino Frontier

llp11

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*Jaehoon Yu**

University of Texas at Arlington

Outline

- Neutrino Experiment Physics Motivation
- Why are future ν experiments good for LLPs & BSM?
  - A case study – DUNE
- BSM Physics Topics @ the ν Frontier
- LLP Signals and Backgrounds
- Conclusions

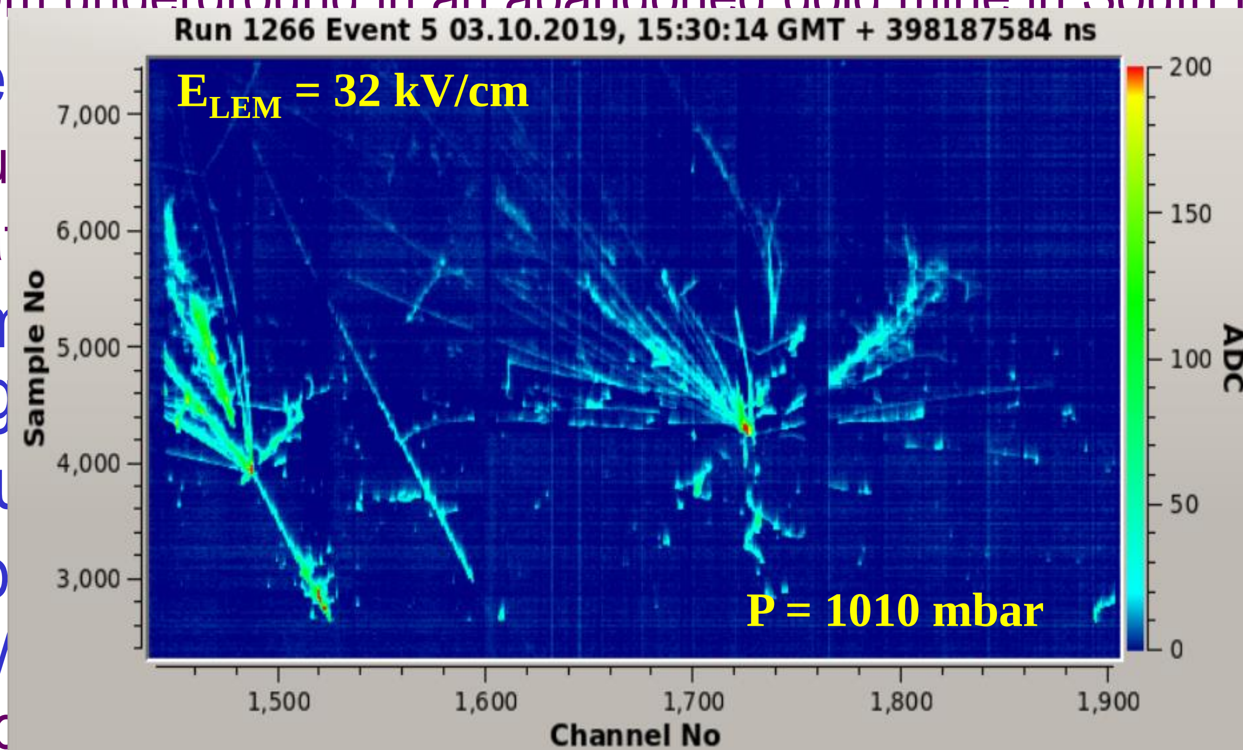
* *For the Snowmass 2021 NF03 Conveners: P. Coloma, L. Koerner, I. Shoemaker*

ν Experiment Physics Motivation

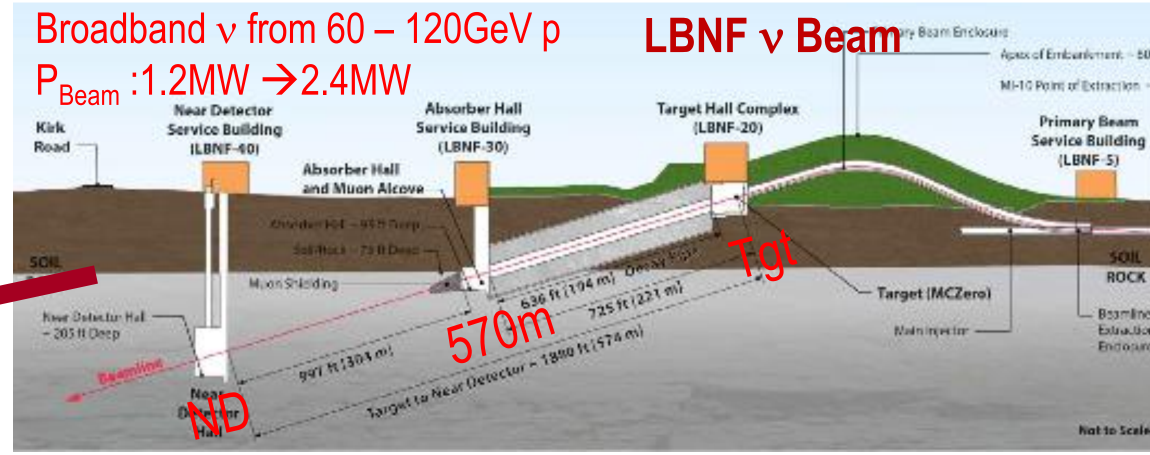
- ν flavor oscillation is a firmly established phenomena
  - Happens because flavor and mass eigenstates differ (probability α θ_{ij}, Δm^2 & L/E_ν)
- The neutrino sector in SM ($m_\nu=0$) needs a modification to reflect m_ν!
  - Precision measurements of the oscillation parameters
    - Mixing angles and mass hierarchy
  - Studying the CPV in ν sector and precisely measuring the CP phase
    - Do neutrinos and anti-neutrinos oscillate the same way?
- These could lead to a new symmetry
- The question of the grand unification
  - Energy scale of the unification and discovery of nucleon decay
- Understanding particles of astrophysical origin
  - Supernova ν, blackhole formation, relic neutrinos, dark matter, etc
- These require high statistics samples
  - Large mass, large volume and highly capable (near and far) detectors
  - **High intensity neutrino beam facility** with a long baseline

Future ν Experiments – a case study, DUNE

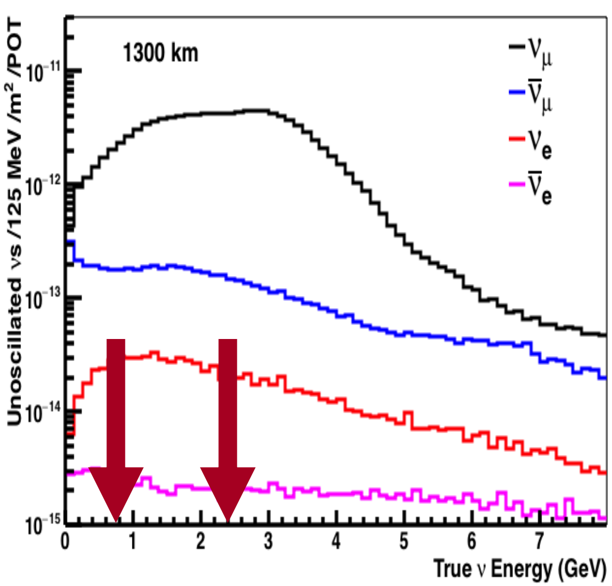
- Stands for Deep Underground Neutrino Experiment
- The US flagship long baseline (1300km) { experiment
  - 1500m underground in an abandoned gold mine in South Dakota
- With ve… MW!)
  - Resu…
  - Grea…
- Large m… LArTPC 3D imaging … th
- Powerfu… tematics
- Was bo… ation! A seven y…
  - Unific… (EU) – as a result of the 2013 US Snowmass Community Strategy Studies
- 1347 collaborators from ~204 institutes in 33 countries

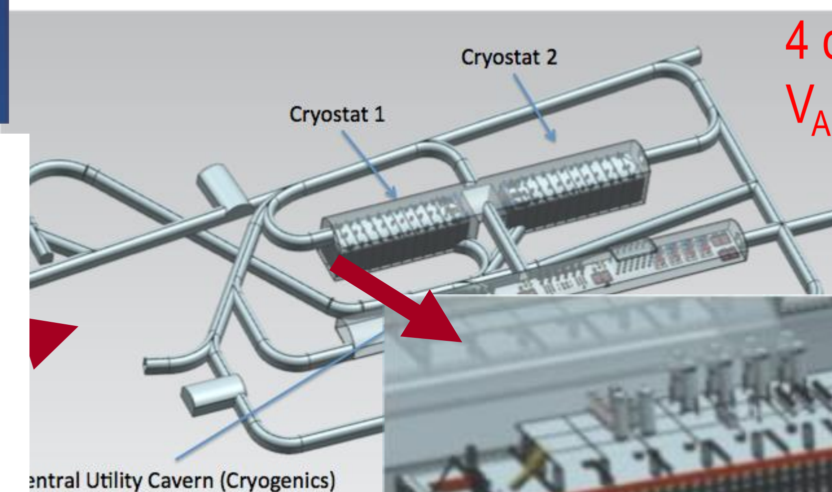


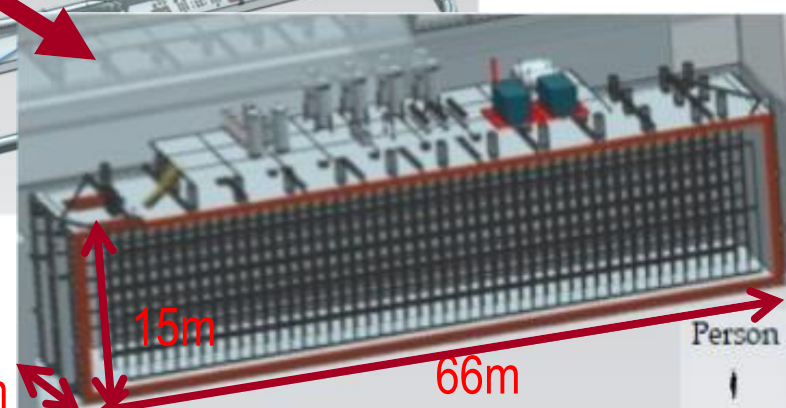
Anatomy of DUNE



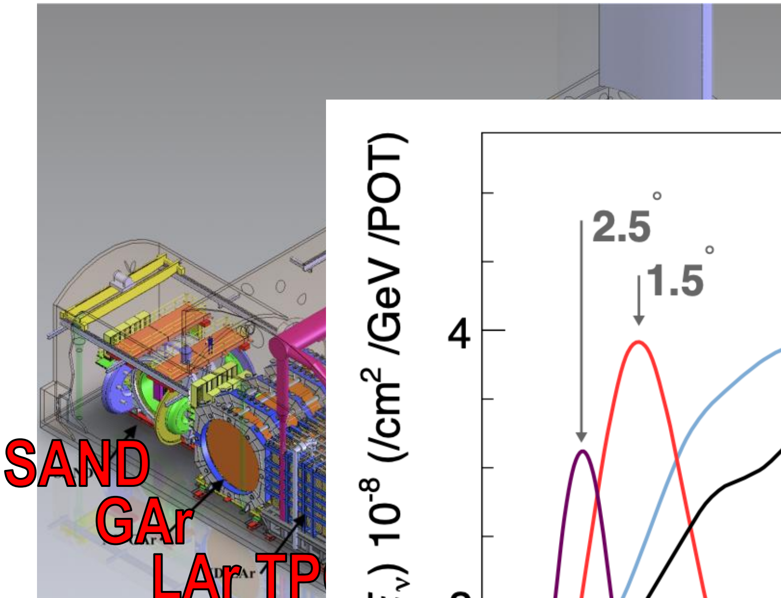
4 caverns w/ active V_A~ **10kt LAr** each

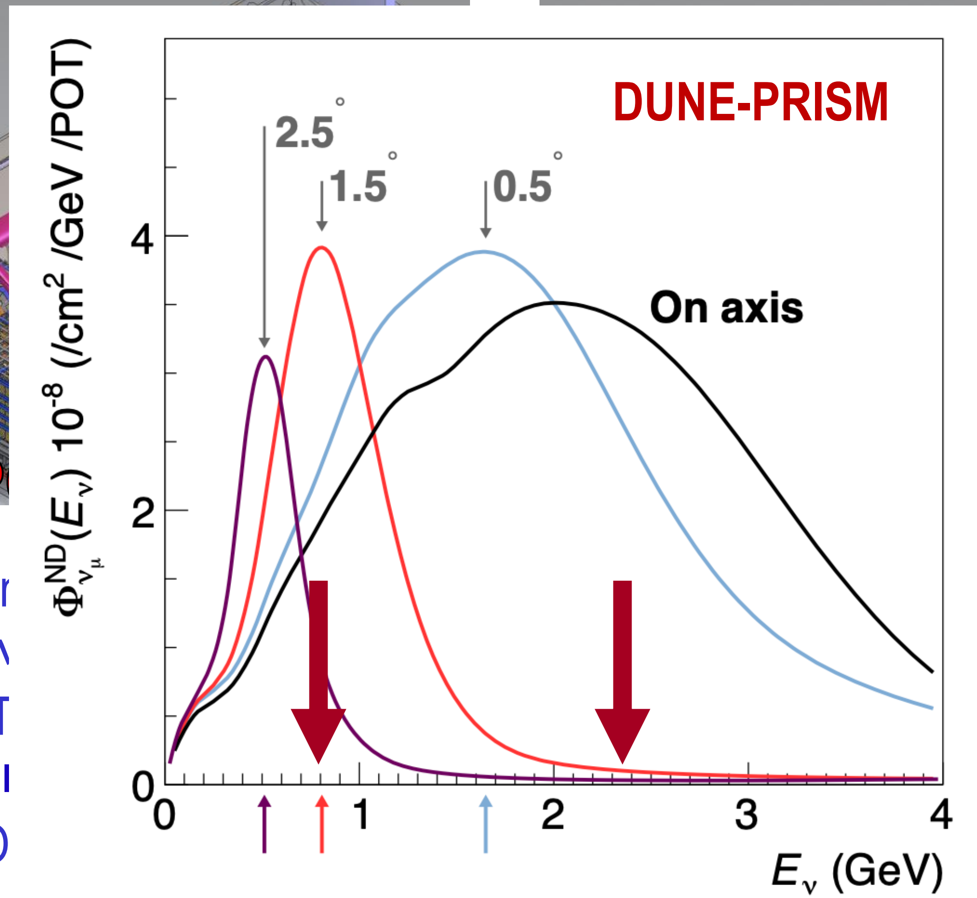


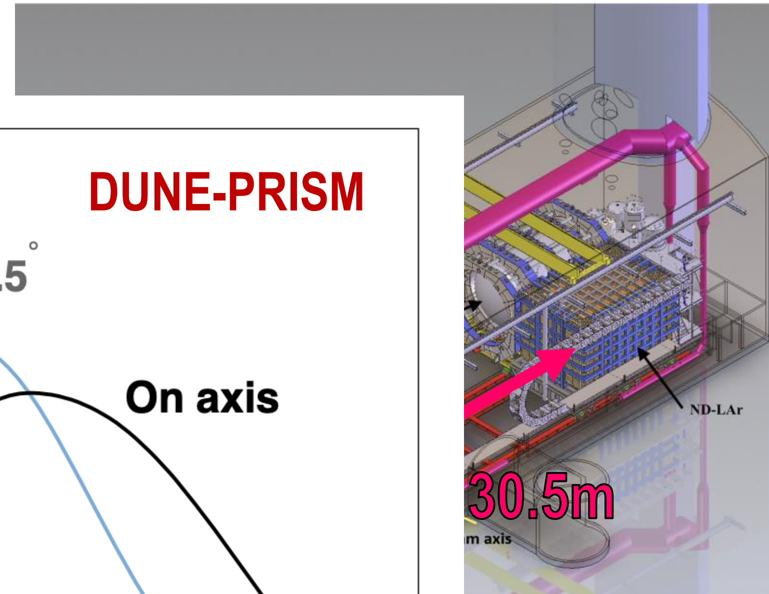




DUNE Near Detector Complex







- LAr TPC: The sa ... om different nuclear effects than FD; ... n-axis (~1Hz)
- Magnetized (0.5T ... events with **low-threshold tracki** ... **r** on-axis
- DUNE-PRISM: O ... nd ND-GAr from on axis up to **30.5m**
- SAND(**S**ystem for **O**n-**A**xis neutrino **D**etection): Monitors on-axis ν beam flux to the FD; Consists of a straw tube tracker + ECAL equipped with a 0.6T magnet

BSM@ν, the Genesis

- BSM@ν picked up steam after the 2013 US Snowmass exercise
- The science drivers of P5 clearly lists strategic opportunities
- Must leverage the neutrino facility capabilities for precision oscillation measurements to the next step
- Need to further increase community interests on BSM opportunities and complement those in the EF regime
- Leadership needed in expanding physics opportunities
- Theory and experiment groups have been working together closely and playing the necessary leadership roles!
- A paper on ROP covers some of these opportunities (Argüelles *et al*., ROP 83, 124201, 2020), an outcome of the 1st workshop @ U. Texas Arlington, April 2019
  - 2nd at U.Pitt. Feb. 2022 for BSM@ν in Snowmass 2021 (NF03)➔ 6 WP
  - 3rd will be at SLAC in March 2023 ➔ Announcement to follow shortly

Science Driver 2013 – ν

- **Under the 2014 P5 Science Driver: Pursue the physics associated with neutrino mass**:
- Neutrino community put forward the following six questions to pursue
  - What is the origin of neutrino mass?
  - How are the masses ordered?
  - What are the masses?
  - Do neutrinos and antineutrinos oscillate differently?
  - Are there additional neutrino types or interactions?
  - Are neutrinos their own antiparticles?

What is missing? Exploration of BSM physics, utilizing the ν facility

BSM@ν Signature Categories

- Direct Observation Signatures
  - Requires high beam flux
  - Sufficiently large mass for scattering signatures
  - Sufficiently large volume for decay signatures
- Inferred Observation Signatures from both beam and cosmogenic sources
  - Leverage oscillatory behaviors
  - Large target mass FD for interactions
- What do we need to know?
  - Signal flux and realistic behaviors in the detector
  - Neutrino flux and their interactions in the detector as bck

Some BSM Physics Topics at ν Experiments

- High beam power, large detector mass + highly capable, precision near and far detectors with low E threshold make BSM physics viable
  - Signal to background ratio grows by the sqrt of the beam power
  - Near Detector Searches ➔ Take advantage of high beam power
    - Low mass Dark Matter (LDM)
    - Heavy Neutral Leptons (HNL)
    - Axion-like Particles (ALP)
    - Dark Photons
    - Milli-charge Particles (mCP)
    - Neutrino Trident
  - Far Detector Searches ➔ Take advantage of ND, large V_A FD and 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)
- Promote strong collaboration between theorists and experimentalists
- Some of these topics covered in EPJ C.81, 322 (2021)

BSM@ν (NF03) Sub-topical Groups and the WPs

- Sub-topical groups formed based on submitted LOI's @ https://www.snowmass21.org/neutrino/bsm/start

1. Heavy Neutral Leptons: I. Shoemaker, A. de Roeck
   - Coordinate with NF02
2. Coherent Elastic Neutrino-Nucleus Scattering: L. Strigari, P. Barbeau, R. Strauss
3. BSM searches within neutrino oscillations: P. Coloma, D. Forero, T. Katori
   - Covers Large Extra Dimension searches, Lorentz and CPT symmetry, Non-unitarity of the neutrino mixing matrix, Non-standard interactions, etc
   - Coordinate with NF01 & NF02
4. Baryon number violation: B. Dev, L. Koerner
   - Coordinate with RF04 and any related CPM groups
5. Cosmogenic dark matter and exotic particle searches: D. Kim, Y. Tsai
   - Coordinate with CPM97
6. Beam-originating dark sector particle (DSP) searches: B. Batell, J. Yu
   - Coordinate with CPM108

NF03 Summary Report to be available for final set of comments

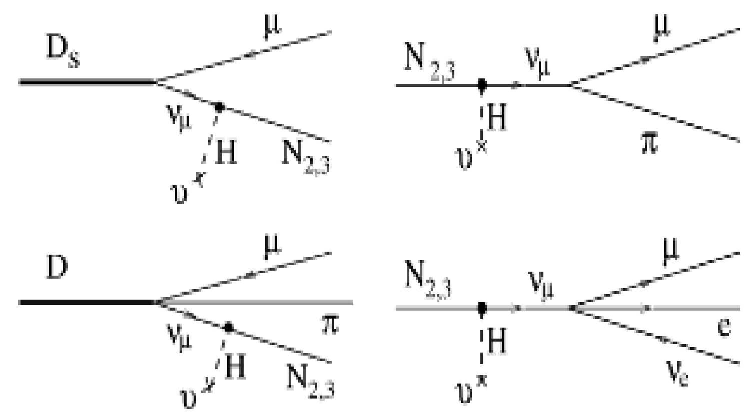
BSM Scenario	Sources	Signatures	Example Experiments
HNL [1]	Colliders Nuclear decays Fixed target	HNL decay Nuclear decay kinematics HNL decay	ATLAS, CMS, FASER, Belle II, ... KATRIN/TRISTAN, HUNTER ... DUNE ND, SHiP, ICARUS, ...
	Atm. & solar νs	Distorted recoil spectrum HNL decay, double bangs	DUNE, HK, IceCube/DeepCore, ...
	Early Universe	Cosmological parameters ($N_{\rm eff}$)	Simons Observatory, CMB-S4, ...
Non-unitarity [2]	Beam & Atm. νs	Deviations from 3-ν mixing (ND & FD)	DUNE, ESSνSB, HK, ...
LED [2]	Reactor νs Beam νs	Distortion of oscillated spectra (FD & ND)	JUNO, TAO,... DUNE, ...
	Atm. νs	Anomalous matter effects	Icecube, KM3NeT, ...
NSI & light mediators [2, 4]	Reactor & Spallation sources Solar, Beam, Atm & SN νs Beam νs Collider νs	Distortion of CEνNS rate Anomalous matter effects Anomalous appearance, $\nu - e^-$ scattering, tridents Distortion of CC spectrum	COHERENT, CONNIE, CONUS, ... DARWIN, DUNE, T2HKK, HK, IceCube, ... DUNE ND, T2HK ND, IsoDAR, ... FASERν, ...
Long-range forces [2]	Solar & Atm ν UHE Astrophysical nus	Anomalous matter potential Distorted flavor ratios	HK, JUNO, DUNE, ... HE Neutrino Telescopes
ν-DM interact. [2]	Reactor & solar νs Beam ν UHE Astrophysical νs	Distorted oscillated spectra, or time-dependent oscillation params. Distorted flavor ratios & spectra	JUNO, ... DUNE, ... HE & UHE Neutrino Telescopes
ν self interact. [3, 12]	SN νs UHE Astrophysical νs Early Universe Beam & Collider νs	SN extra energy loss, distortion in neutrino spectra Distorted spectra Effects on CMB, BBN, & structure formation Missing energy & p_T in ν scattering	DUNE, HK, JUNO, ... HE & UHE ν telescopes CORE, PICO, CMB-S4 DUNE ND, Forward Physics Facility, ...
ν decay [2]	Reactor νs Beam νs Atm. νs	Distortion of oscillated spectra	JUNO, ... DUNE, MOMENT, ESSνSB, HK, ... INO-ICAL, KM3NeT-ORCA, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
CPT violation [2]	Beam νs Atm. νs	Different ν and $\bar{\nu}$ osc. params.	DUNE, ESSνSB, HK, ... IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
Lorentz violation [2]	Beam νs Atm. νs	Sidereal modulation of event rate	DUNE, ESSνSB, HK, ... IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra, velocity dispersion	HE & UHE Neutrino Telescopes
Quantum decoh. [2]	Beam νs Atm. νs	Distortion of oscillated spectra	DUNE, ... KM3NeT, IceCube, HK, ...
	UHE Astrophysical νs	Distorted flavor ratios	HE Neutrino Telescopes
B violation [5]	Detector mass	Nucleon decay, $n - \bar{n}$ oscillations	DUNE, HK, JUNO, ...
Dark Matter [6, 7]	DM annihilation, DM decay Boosted DM, slow-moving DM	Excess of νs from Sun or Earth Scattering, or up-scattering & decay	HK, DUNE, IceCube ...
	Fixed target	Decay Scattering, or up-scattering & decay	DUNE, T2HK, SBN, FASERν, ...
Milli-charged particles [7]	Fixed target Atmosphere	Scattering	DUNE ND, T2HK ND, ... DUNE, HK, JUNO, ...

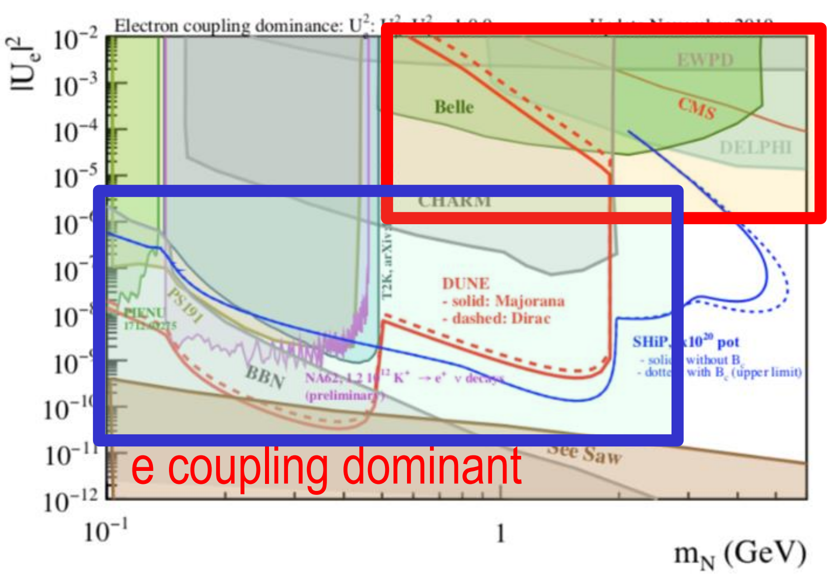
Table 1: Summary of the most significant experimental signatures for the BSM scenarios covered in this document. Example experiments sensitive to each scenario are also provided (see references for the full list). Abbreviations: Atm.=Atmospheric, B=Baryon number, CC=Charged Current, CEνNS=Coherent Elastic ν-Nucleus Scattering, DM=Dark Matter, FD=Far Detector, HE=High Energy, LED=Large Extra Dimensions, ND=Near Detector, NSI=Non-Standard Interactions, SN=Supernovae, UHE=Ultra-High Energy.

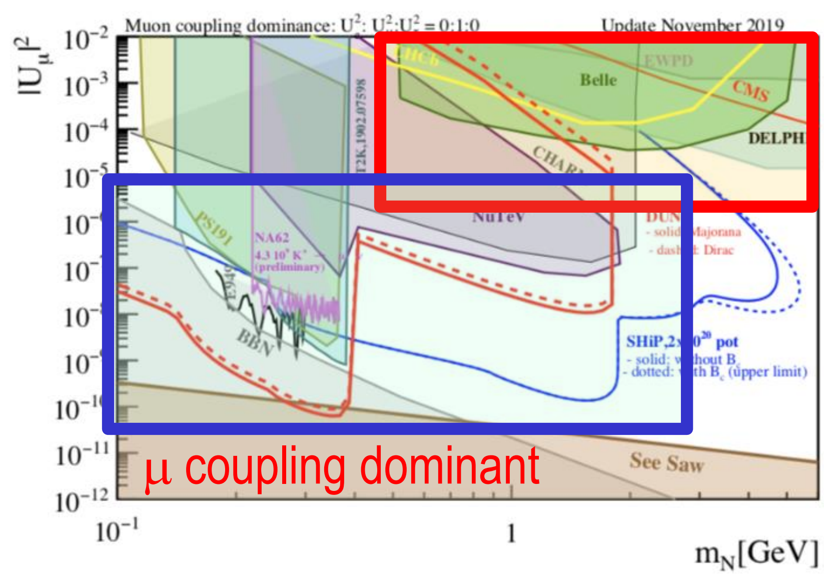
HNL Searches @ DUNE ND

- High intensity proton beams produce heavy neutral leptons from the decays of heavy mesons in the ν-production target ➔ complementary to colliders
- HNL then decays into charged leptons and lighter mesons in the DUNE ND complex ➔ a charge lepton + a meson, 2 charged leptons + ν
  - Vertex requirements would help
- Multiple production and decay channels are available for searches
  - Coloma *et al.*, (2007.03701)
- See Albert's talk tomorrow

Production **Detection in ND**

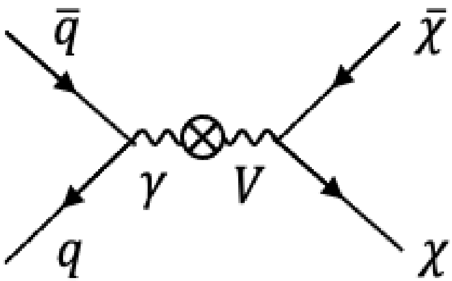


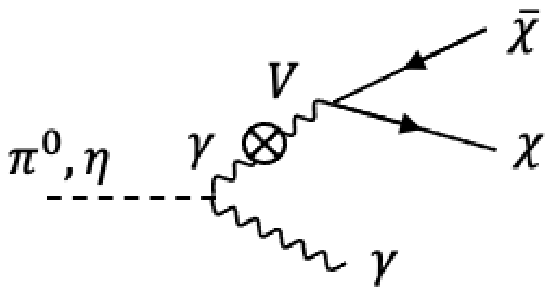


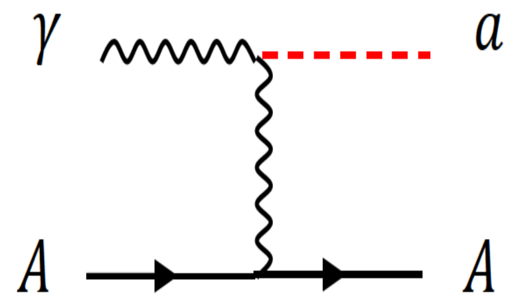


BSM@ν Dark Sector Particle Signatures at ND

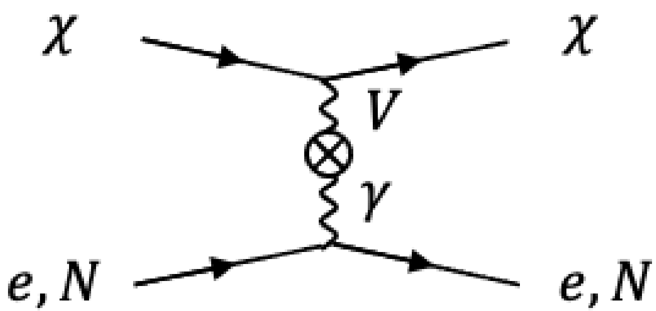
- High intensity proton beams produce large number of photons from brem, DY and neutral mesons decays ➔ Make it possible to contemplate couplings of new U(1) gauge to SM γ

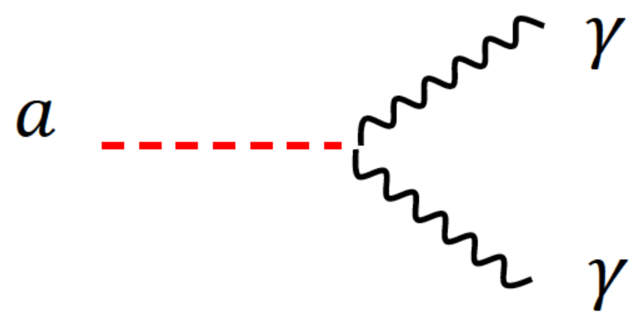






- Detection through an electron or N(n) recoil or 1, 2 γ final states

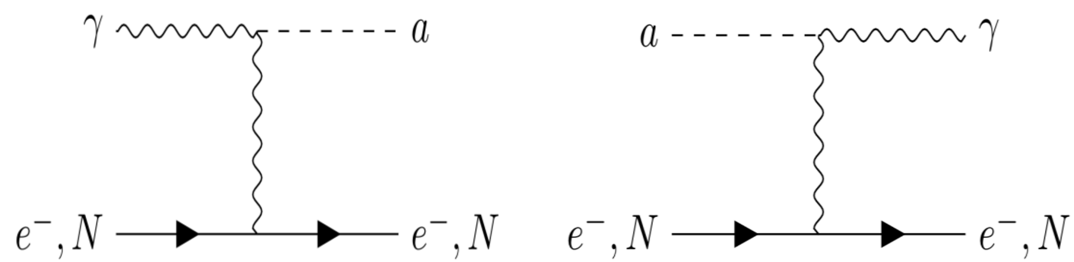


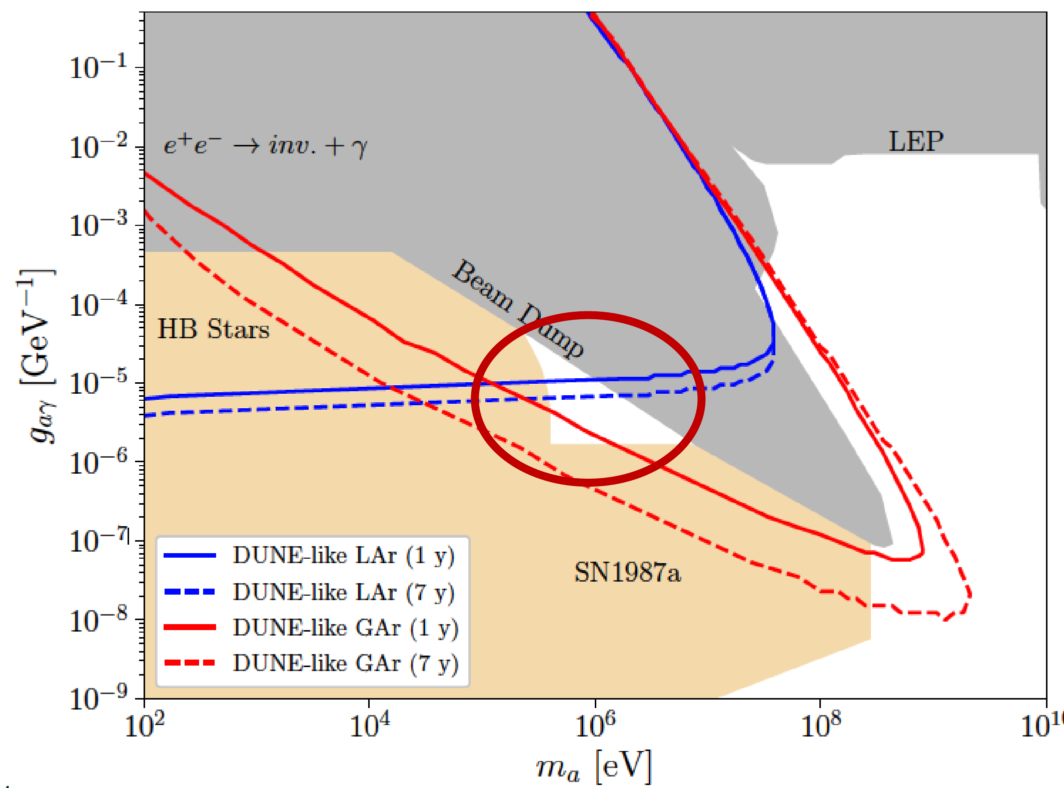


ALP Searches @ DUNE ND

- Axion-like particles can be produced via the Primakoff process in high intensity proton beams
- Detection via the inverse Primakoff process either in a scattering with e/N + γ or decays of the ALP to two γ
  - ν_e CC, NC backgrounds
  - ν_μ NC→ π^0 → $\gamma\gamma$ bck
- DUNE ND has a potential to fully close the cosmic triangle
- Brdar *et al*., PRL126, 201801 (2021)

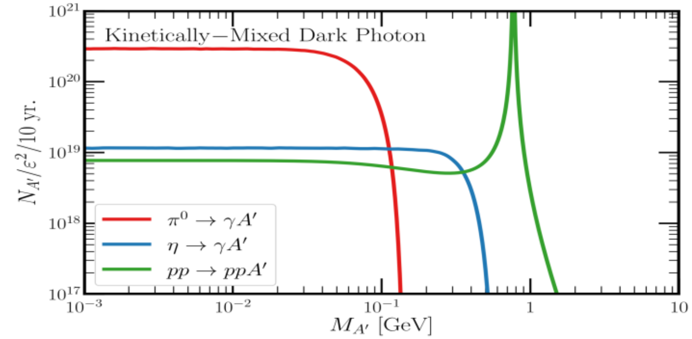
Production in ν target | Detection - scattering

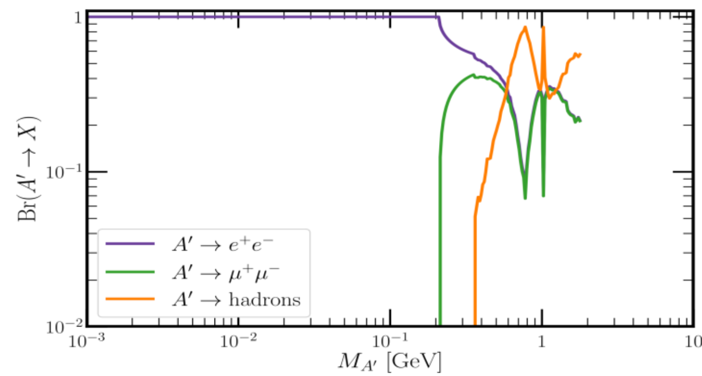


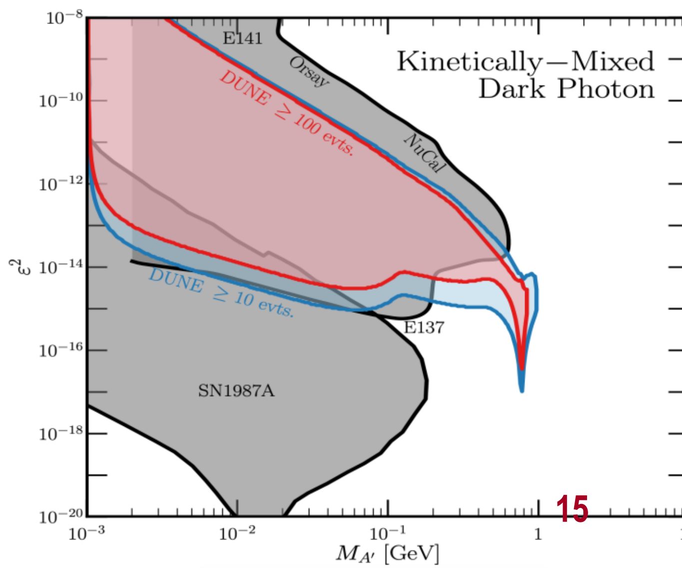


Dark Photon Searches

- New U(1) could kinetically mix with a SM γ from scalar meson decays or direct DY
- If these dark photons can live sufficiently long to reach the DUNE ND ➔ Look for their decays to a charged lepton pair
  - A' → e^+e^-
  - Primary background from $\pi^0 \rightarrow \gamma\gamma$
    - One of the γ mid-ID's as e and one missed
    - Could a magnet help?
  - A' → $\mu^+\mu^-$
    - Charged pion production from CC
    - Charged π decay product mixing with other low E hadronic activities
  - Low E threshold & precise understandings of ν CCQE and CCRES essential







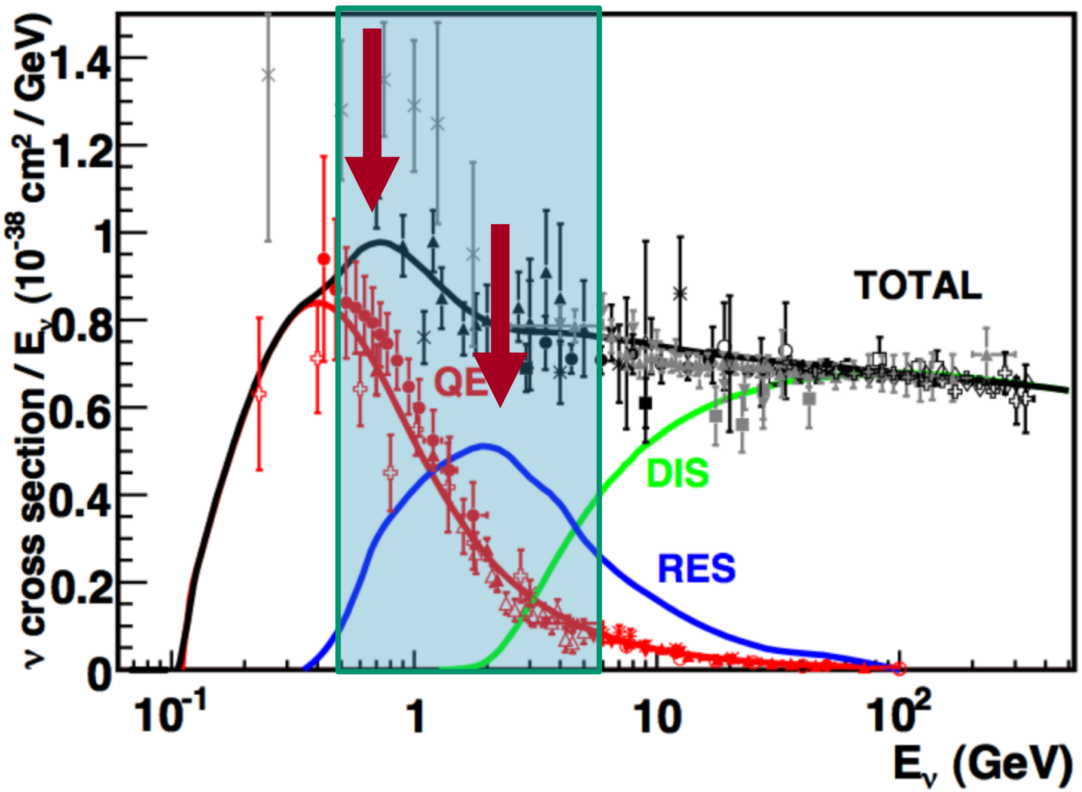
Signals & Backgrounds of BSM@ν

BSM signal final states include charged leptons (e+/-, μ+/-), photons and nucleus (nucleon) recoil → **ν-N interactions the primary background**

Process	Signatures	Background
HNL	$N \rightarrow \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ALP	Scattering: γ+e/ γ+N (n) Decay in flight : γγ	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
Dark Photon	$A \rightarrow e^- e^+$, $\mu^-\mu^+$, hadrons	ν CC + mis-ID π, Accidental overlap of CC & NC
iBDM	$\chi N \rightarrow e^- e^+ e^- N$	ν coherent, NC w/ π^0, ν_e CC

Low E ν Interactions

- QE & RES dominates ν-N interactions in E_ν range where the two oscillation maxima reside, for the case of DUNE ➔ critical to understanding ν background
- Large uncertainties for ν-N x-sec calculations
  - Planned measurement, such as at the e4ν collaboration could provide critical testing of nuclear interaction models
  - Clearly identify the list of measurements and prioritize them to target low hanging fruits first
- Collaboration between NP and HEP communities essential



Tails, tails and tails

- LLP production extremely rare and are in the tail ends of the SM processes → can easily be masked by SM fluctuations
- Many different theoretical predictions and generators for ν–N interactions have been in existence and continue improving → but they still have sizeable uncertainties within each and between themselves
  - Significantly reducing the uncertainties critical for B&B osc. physics
  - Essential for estimating backgrounds to LLP searches
- Generators begin to incorporate LLP processes but could take a long time to implement due to insufficient resources → need further strengthening the efforts
  - Strong collaborations between generator teams and experiments a way to mitigate the limited resource issue
  - NP and HEP communities must work together to understand low E processes
  - Need more concerted efforts and get them done in a timely fashion

Conclusions

- High intensity accelerators provide great opportunities to search for LLPs as a signature for BSM physics and dark sector particles
  - High power proton beams for next gen ν experiments enable expanding physics reach beyond that of neutrinos and the SM
- Large scale, precision detectors, such as DUNE capable of searching for LLP's and cover a broad scope of BSM physics
  - Large interests have been building up throughout the past several years
- ν-N interactions are critical backgrounds to LLP's and other BSM physics at the low kinematic phase space, relevant to ν experiments
  - Improvement in nuclear modeling requires a close collaboration between HEP and NP communities
- LLP's in the neutrino frontier complement that of the energy frontier → Ample opportunities to further develop BSM topics and leverage search strategies and techniques collaboratively

Science Driver Snowmass 2021 – ν

- **Under the P5 Science Driver: Pursue the physics associated with neutrino mass**
- Neutrino community put forward the following six questions to pursue
  - What is the origin of neutrino mass?
  - How are the masses ordered?
  - What are the masses?
  - Do neutrinos and antineutrinos oscillate differently?
  - Are there additional neutrino types or interactions?
  - Are neutrinos their own antiparticles?
  - What are the BSM signatures accessible at ν experiments?