BSM Physics Opportunities @ DUNE - Direct Detection Searches

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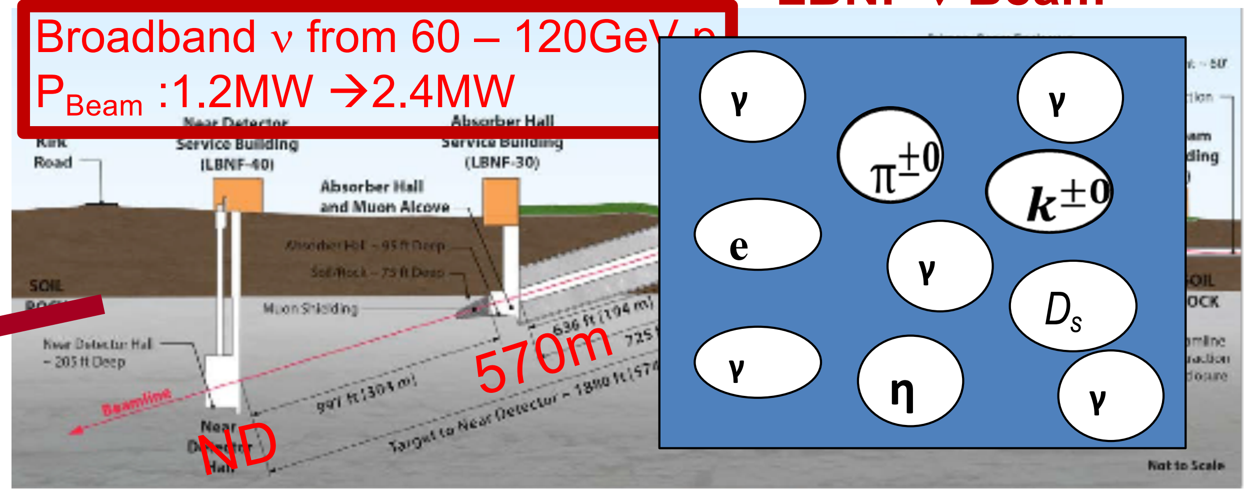
Introduction

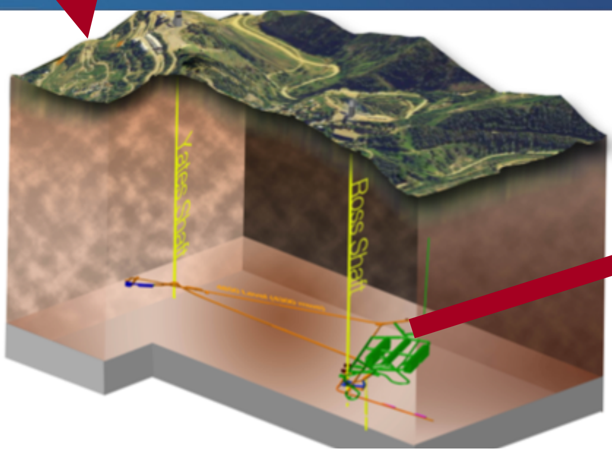
- ν flavor oscillation is a firmly established phenomena
  - Flavor and mass eigenstates differ (prob α θ_{ij}, Δm^2 & L/E_ν)
- The neutrino sector in SM (m_ν=0) needs a modification to reflect m_ν!
  - Precision measurements of the oscillation parameters
    - Mixing angles and mass hierarchy
  - Studying 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

Anatomy of DUNE

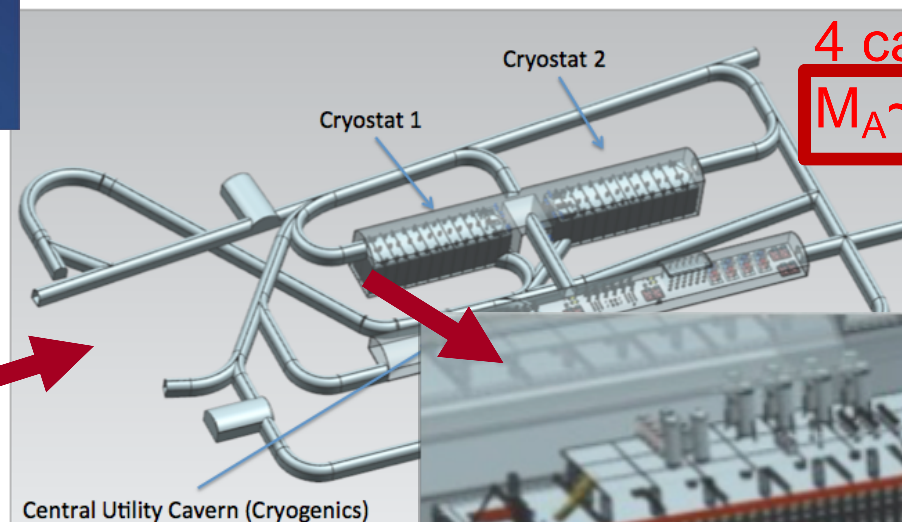
LBNF ν Beam

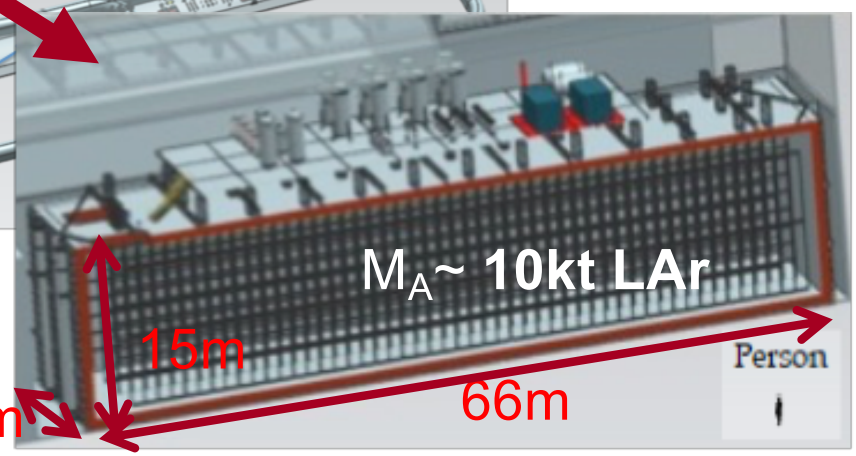
Broadband ν from 60 – 120GeV p
P_{Beam} :1.2MW →2.4MW





4 caverns for
M_A~ 40kt LAr





LBNF Far Detector Site, SURF

1500m underground

Producing new states @ Neutrino Experiments

Variety of mechanisms possible to produce new particles → Access to new physics

(1) Charged meson decays
➔ Horn focussing enhances acceptance of charged mesons

$$M^{\pm} \to \ell^{\pm} N$$
$$M^{+} \to \ell^{+} \nu X$$

3-body decays not helicity suppressed.

(2) Neutral meson decays

$$M^{0} \to \gamma X$$
$$M \to \gamma X X$$

(3) Secondaries production (p → secondaries): $\gamma N \to XN$

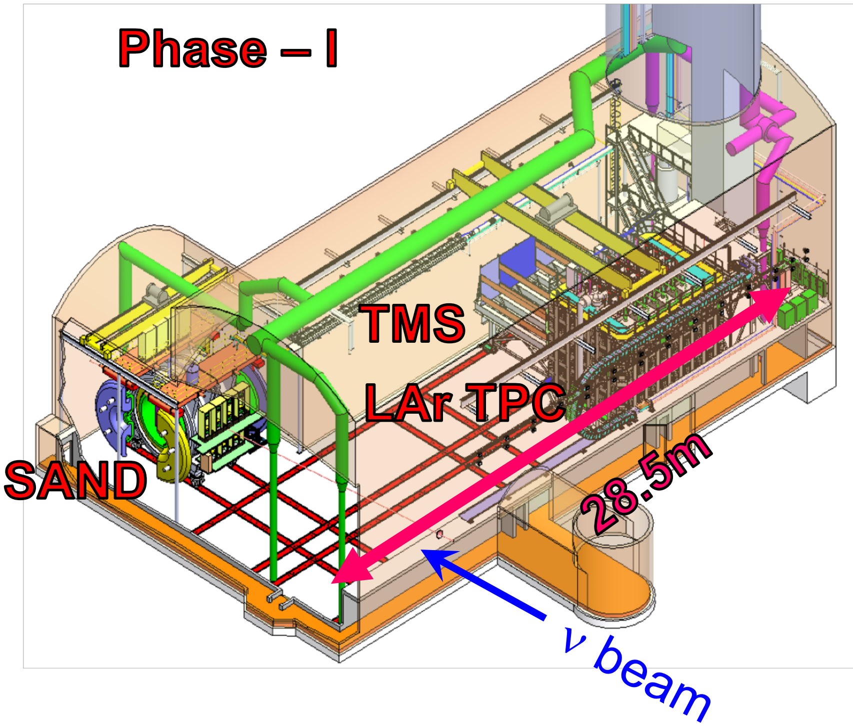
(4) Resonance & Compton productions : $e^+e^- \to X$, $e^+e^- \to \nu\nu_s$, $e+\gamma \to e+X$, etc.

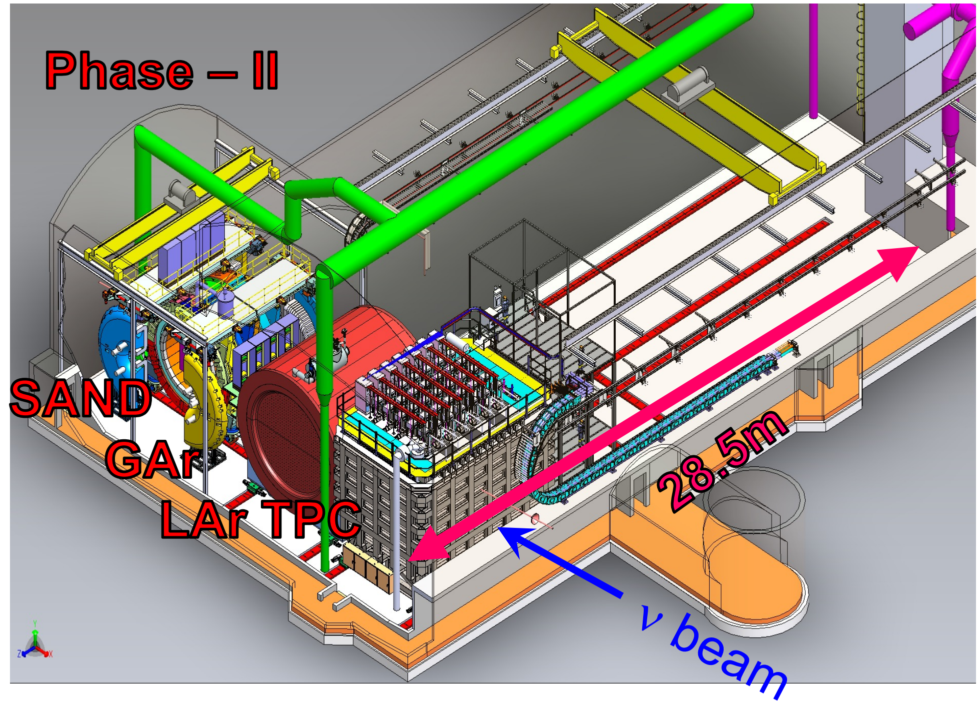
(5) DY, brem, scalar meson decays, etc : $pp \to ppX$

(6) And many more

Close collaborations of theorists & experimentalists continue expanding this list!!

DUNE Near Detector Complex





- **Phase I ND** consists of [LAr TPC (M_A=150t, V_A=105m^3) – TMS, making up the PRISM] – SAND
- **Phase II Full Suite ND consists** of [LArTPC - Magnetized (0.5T) large volume HPGAr TPC (10atm – M_A=1t, V_A=108m^3) w/ ECAL, making up the PRISM] – SAND

BSM@ν Signature Categories

- Direct Observation Signatures from the beams
  - High beam flux
  - Large mass, high density for scattering signatures
  - Large volume, low density for decay signatures
  - Capable near detector complex
  - Low threshold energy
  - Low background from cosmic sources
- 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

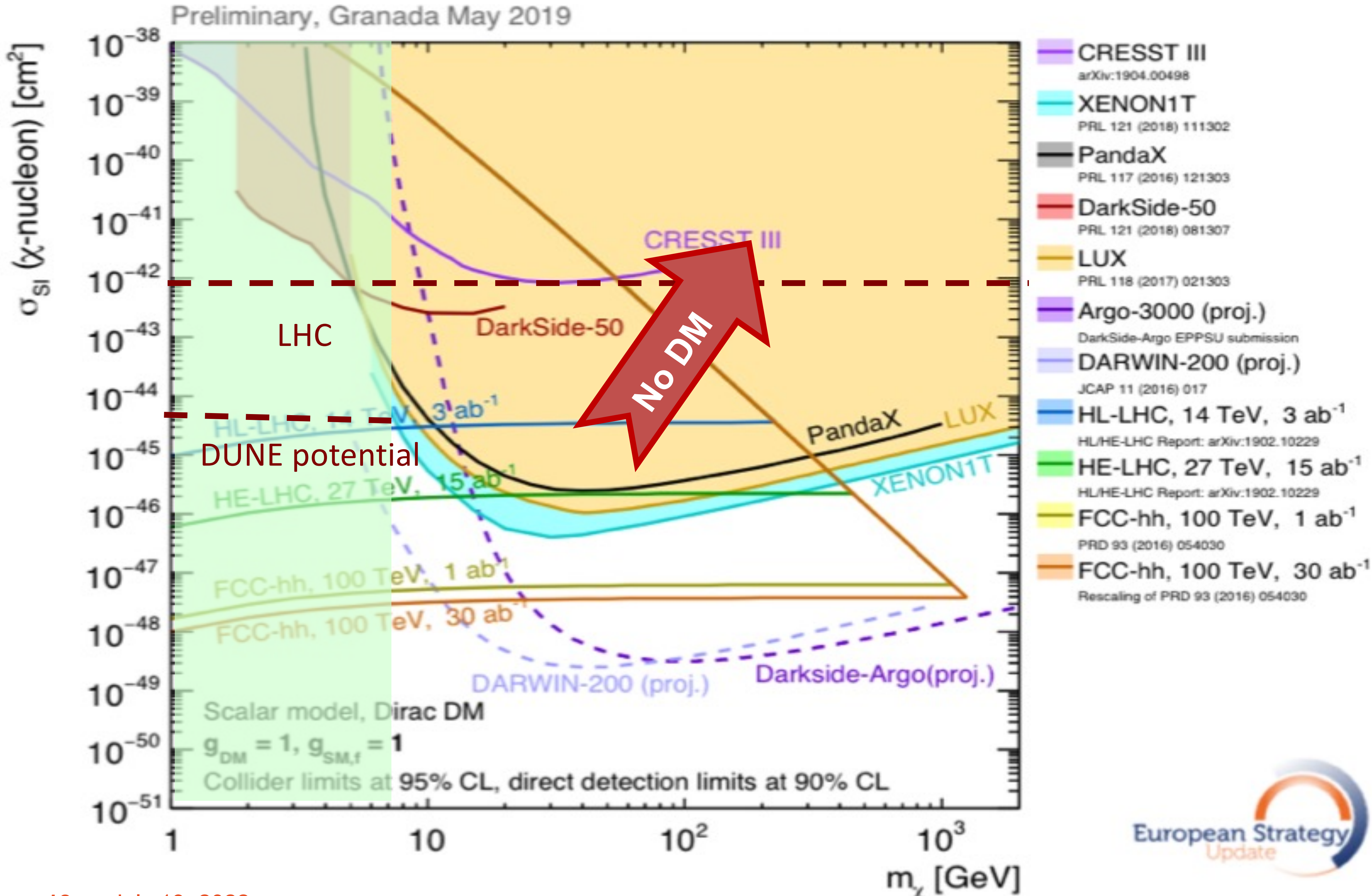
What makes DUNE good for BSM@ν?

- Direct Observation Signatures from the beams
  - Requires high beam flux ➔ **P_{Beam}= 1.2 – 2.4MW**
  - Large mass, high density for scattering signatures ➔ **ND LAr w/ M_A=150t, 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 plus SAND for fine tracking & beam monitoring**
  - Low threshold energy ➔ **Both ND and FD TPC threshold ALA few MeV**
  - Low bck from cosmic sources ➔ **1500m underground FD**
- Inferred Observation Signatures from both beam and cosmogenic sources
  - Leverage oscillatory behaviors ➔ **ND and FD combinations**
  - Large target mass FD for interactions ➔ **FD M_A=40kt**
- 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 Complex with PRISM**

Selected BSM Topics @ DUNE

- 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 ➔ Take advantage of high beam power
    - Axion-like Particles (ALP)
    - Low mass Dark Matter (LDM)
    - Heavy Neutral Leptons (HNL)
    - Dark Photon
    - Neutrino Trident
    - Milli-charge Particles (mCP)
    - **And many many more..**
  - Far Detector Searches ➔ Take advantage of ND, large V_A 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)

Dark Matter Search Motivation

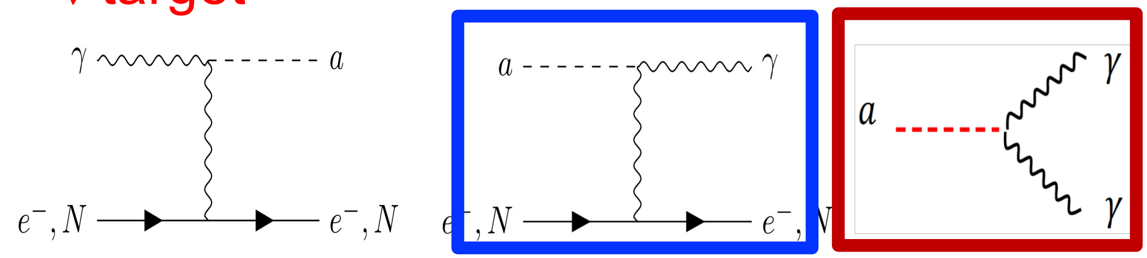


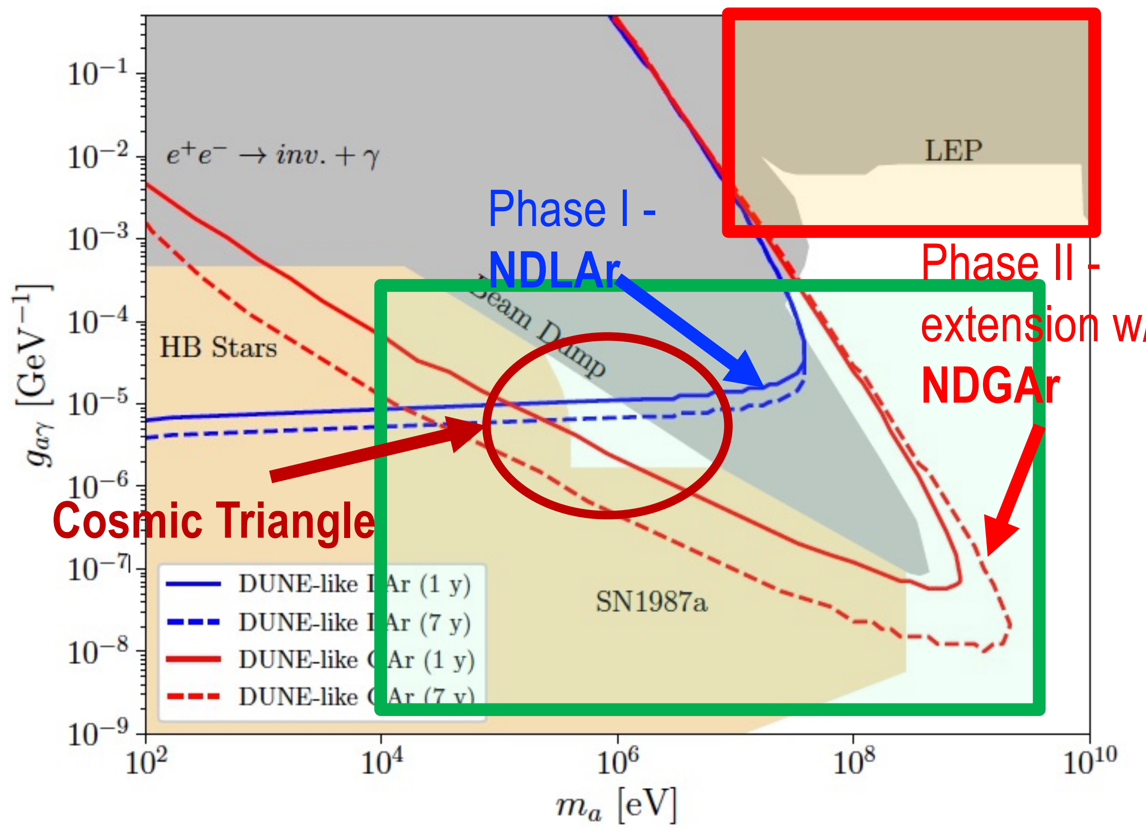
ALP Searches @ DUNE ND

- Axion-like particles (ALP) can be produced via the Primakoff process in high intensity proton beams in the neutrino target
- Detection through a scattering with e/N + γ or decays of the ALP to two γ
- Other axion coupling, e.g. g_{ae} is accessible, as well
- DUNE ND Phase II enables complete closure of the Cosmic Triangle!!
  - Brdar *et al*., PRL126, 201801 (2021)

Production in ν target

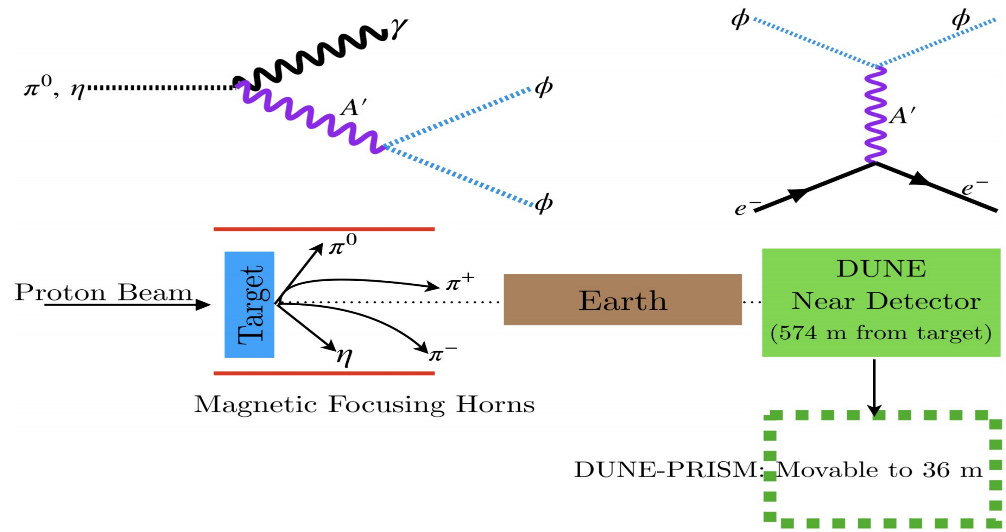
Detection

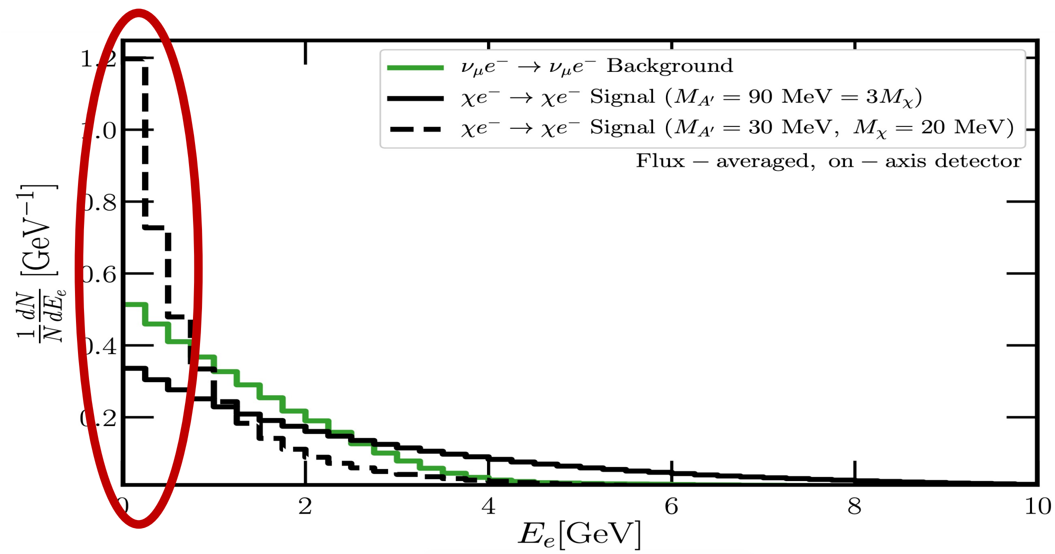




Light Dark Matter (LDM) Search

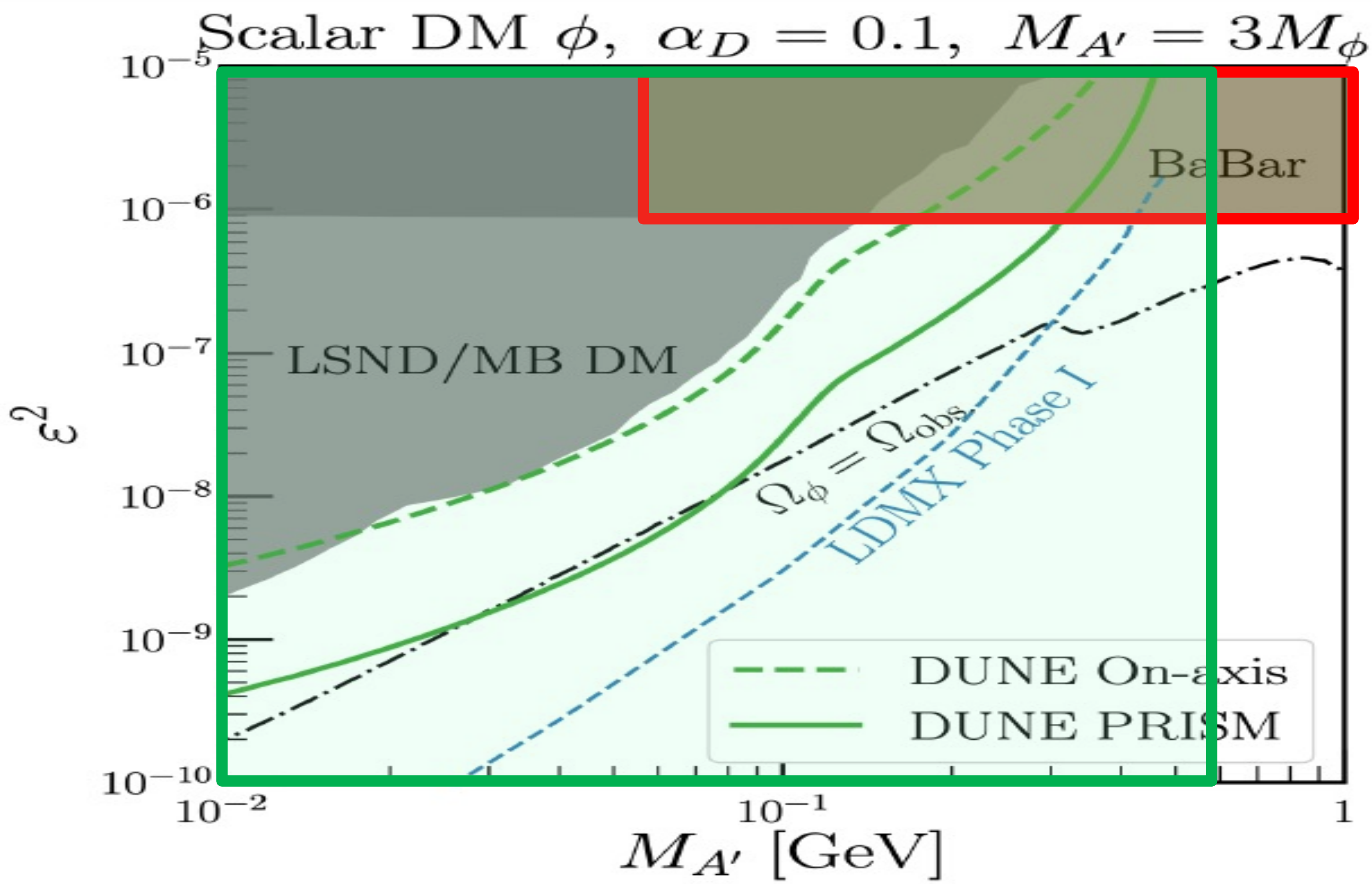
- LDM's produced in the target via coupling of dark photon with a SM γ from brem, scalar meson decays or direct DY
- Identify the signal using e^- or nucleon recoil by LDM via dark photon kinetic coupling with SM γ
  - Batell *et al.* [0906.5614],
  - deNiverville *et al.* [1205.3499]
  - Coloma *et al.* [1512.03852]
- Ability to identify e^- recoil w/ low E threshold key
  - Expands the LDM mass coverage
  - Recoil E_e peaks at low E for low LDM mass
  - Significant background from ν_μ scattering off e^-





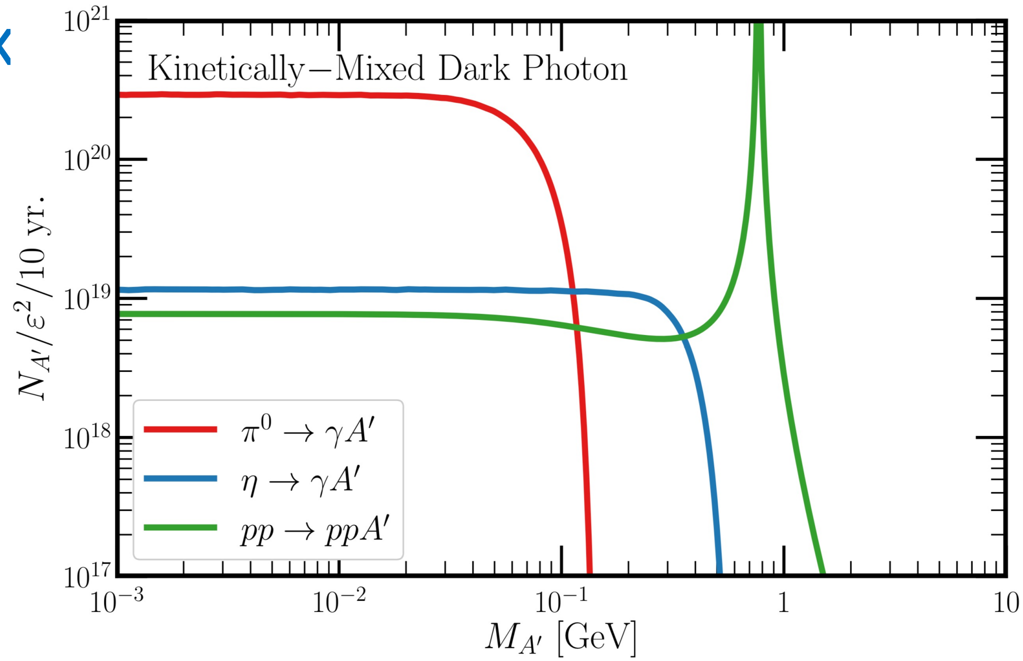
LDM Search Sensitivity

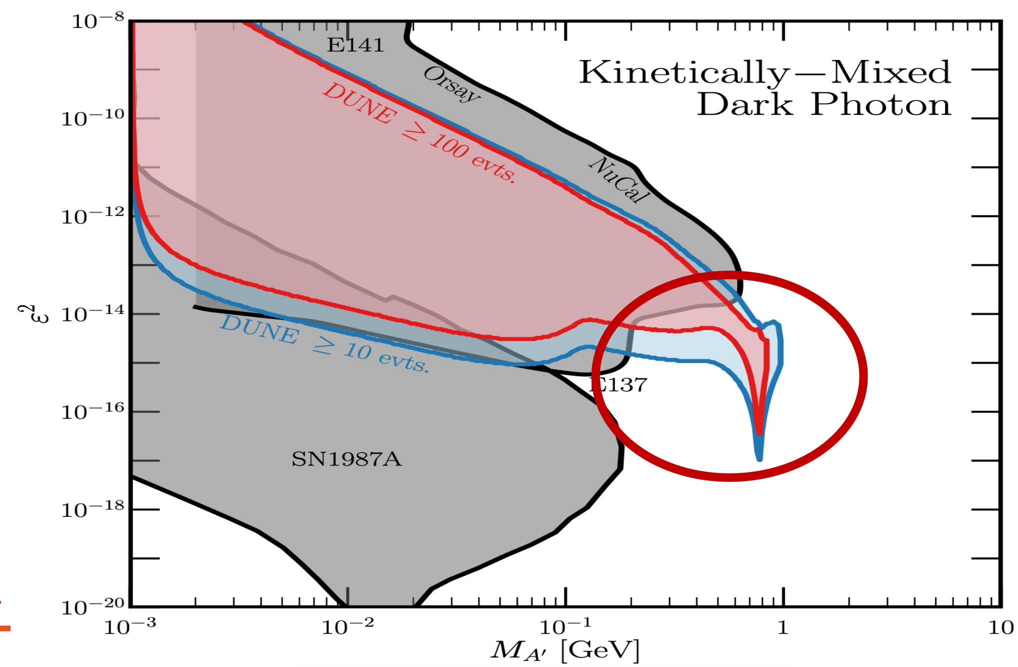
- Search benefits from DUNE PRISM for neutral meson induced LDM
  - Leverage more rapid reduction of ν_μ flux than the signal off-axis (De Romeri *et al*., [PRD**100**, 095010, 2019](#))



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^-, $\mu^+\mu^-$
  - Many more final states..
  - Cleaner signature
  - Low E thre. for higher ε_A'
  - Low energy ν-N interactions essential for backgrounds

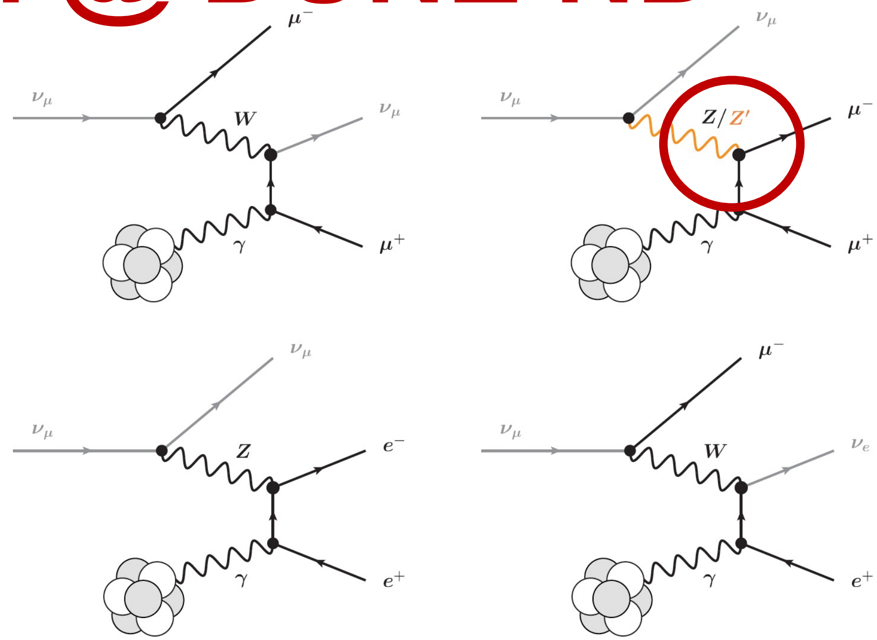


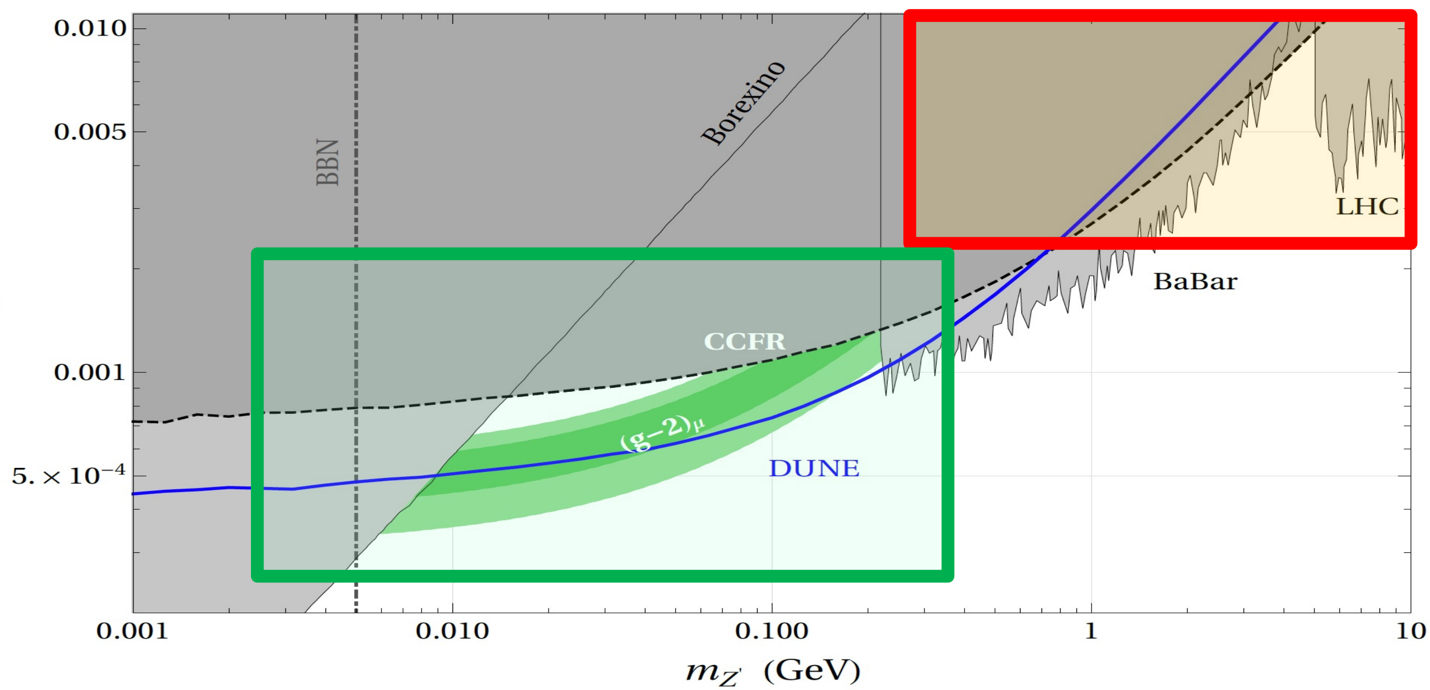


Dev, et al., JHEP07, 166 (2021)

ν-Trident Search @ DUNE ND

- SM predicts the neutrino tridents through rare weak processes ➔ produces a pair of charged leptons.
- **Unknown gauge boson couplings** could cause deviations in the SM predicted signal yields
- DUNE sensitive in the region where $(g-2)_\mu$ anomaly can be explained at the 1σ and 2σ level

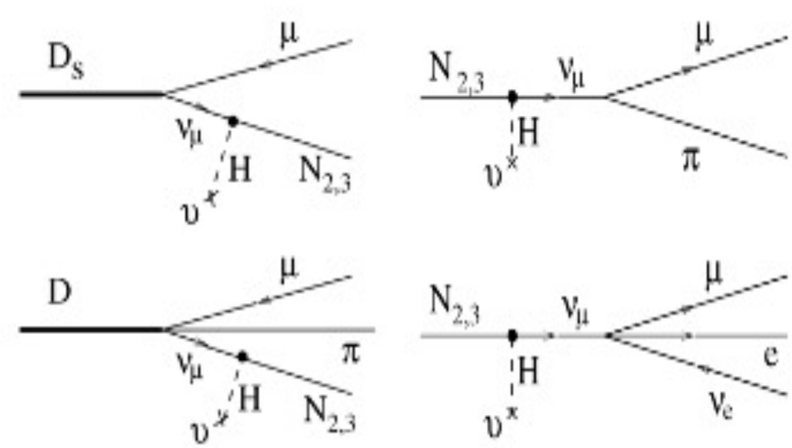


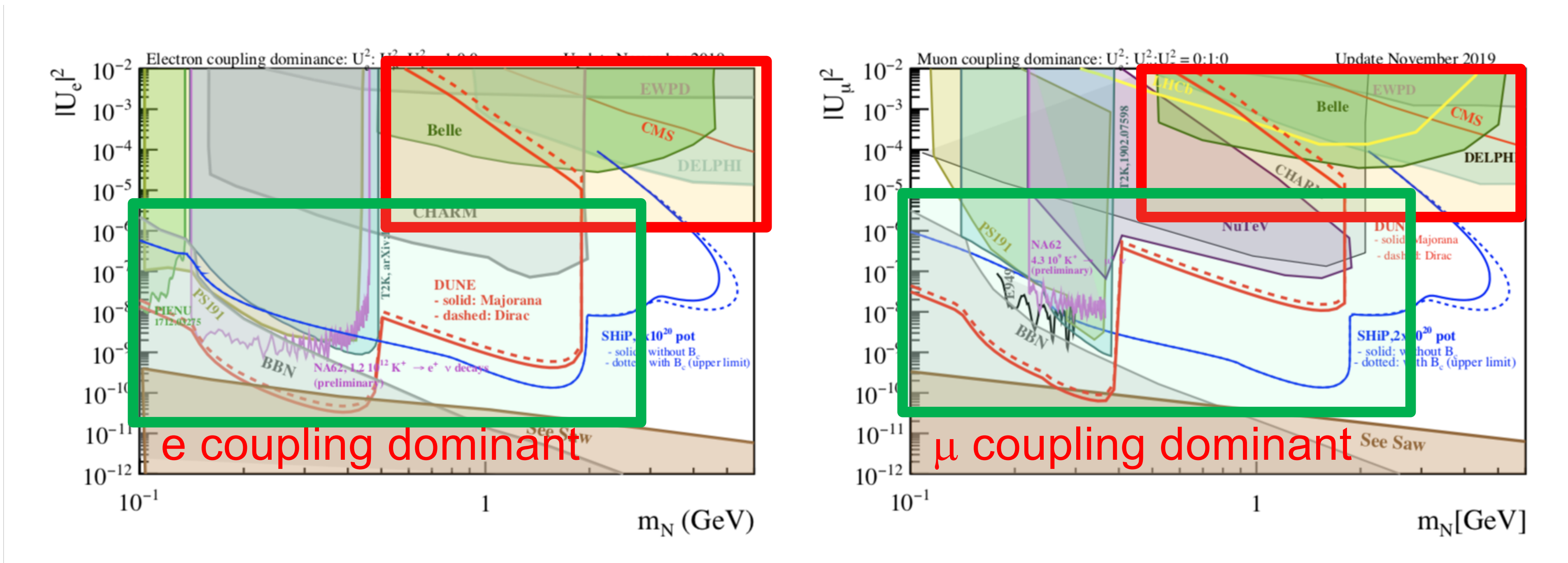


HNL Searches @ DUNE ND

- High intensity proton beams produce HNL from the decays of heavy mesons
  ➔ complementary to colliders
- HNL decays to charged leptons and lighter mesons in the DUNE ND complex
  ➔ a charge lepton + a meson, 2 charged leptons + ν
  - Coloma *et al.*, (2007.03701)
- Clear demonstration of complementarity to the LHC

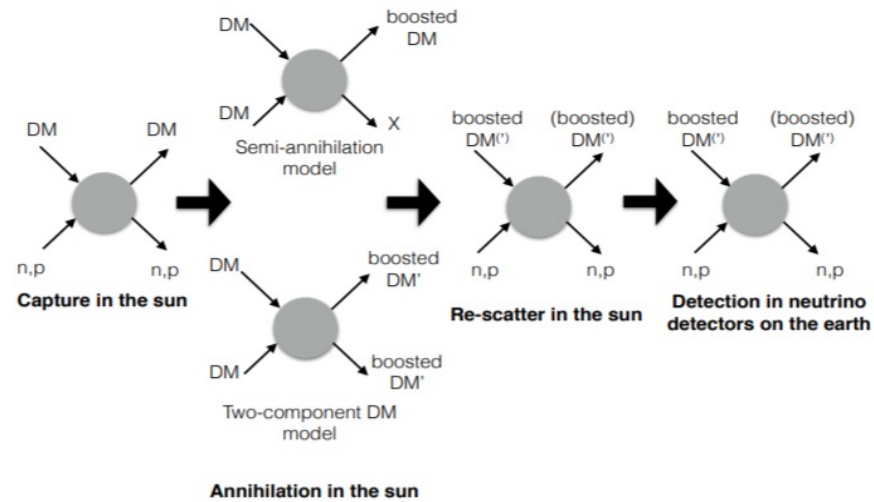
Production **Detection in ND**

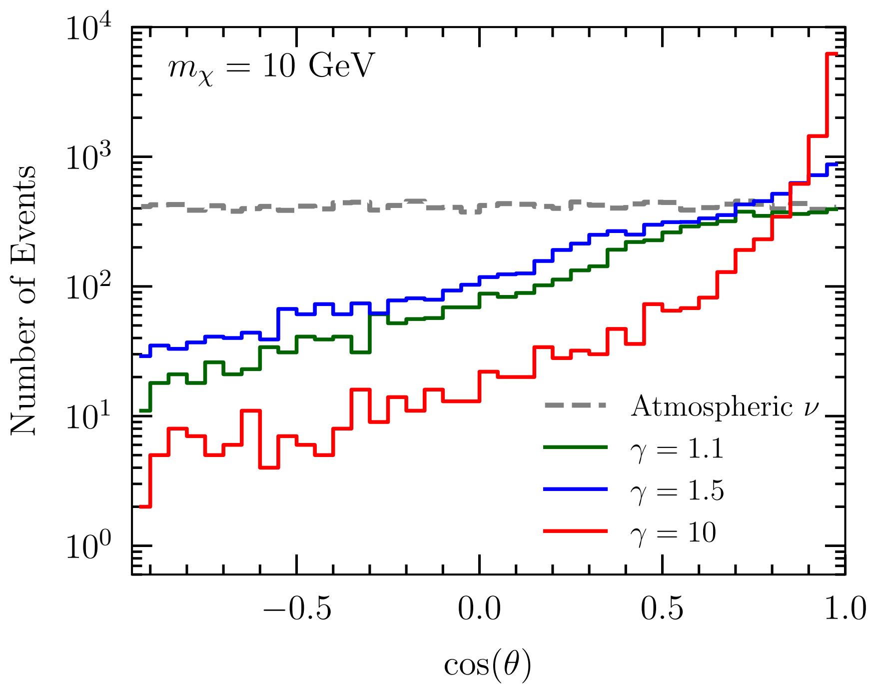


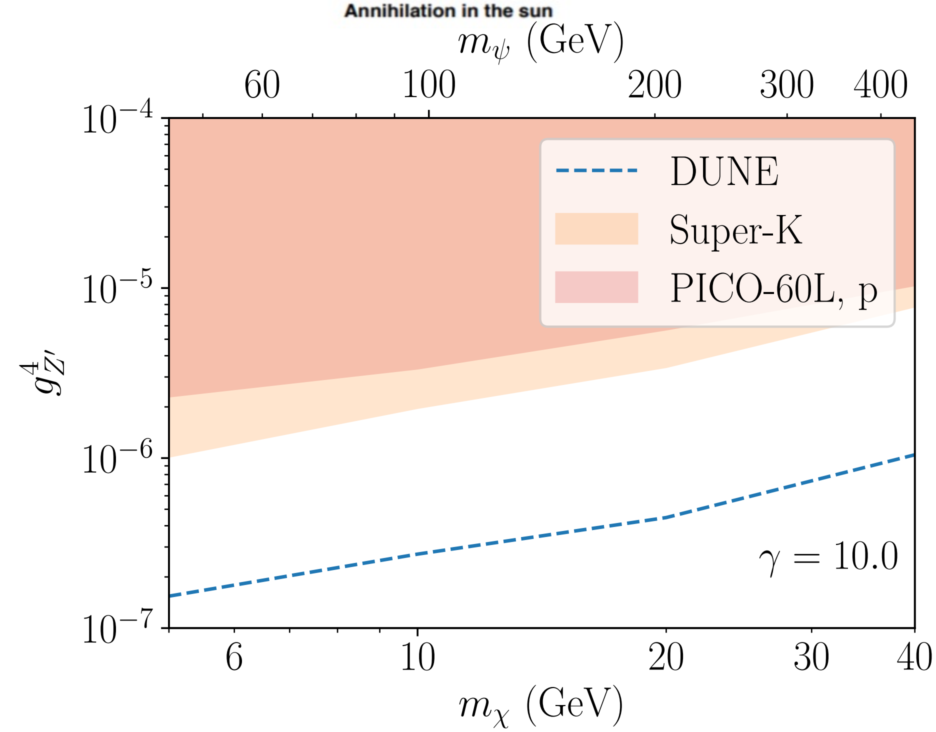


BDM Searches @ DUNE FD

- DM's captured in the Sun could be boosted in it and enter the detector (BDM)
- Potential of searching for BDM in its elastic scattering in detector via nucleon or e recoil
- Large volume LAr TPC FDs' precision tracking and vertexing w/ low E threshold capability enables detection of BDM
- Backgrounds from ν-N interaction challenging



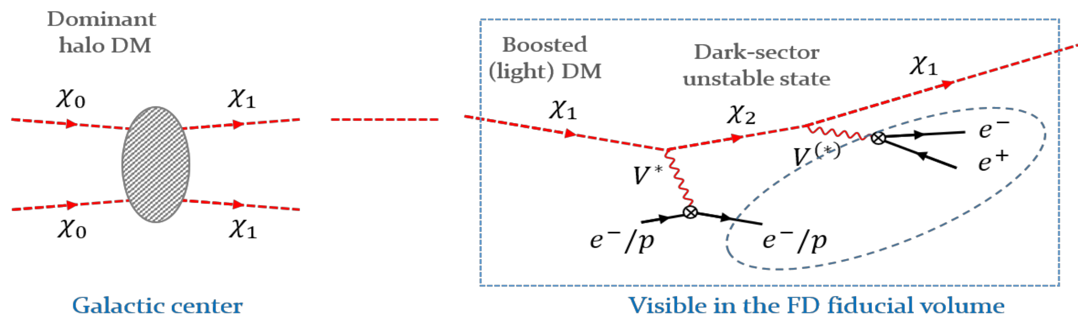


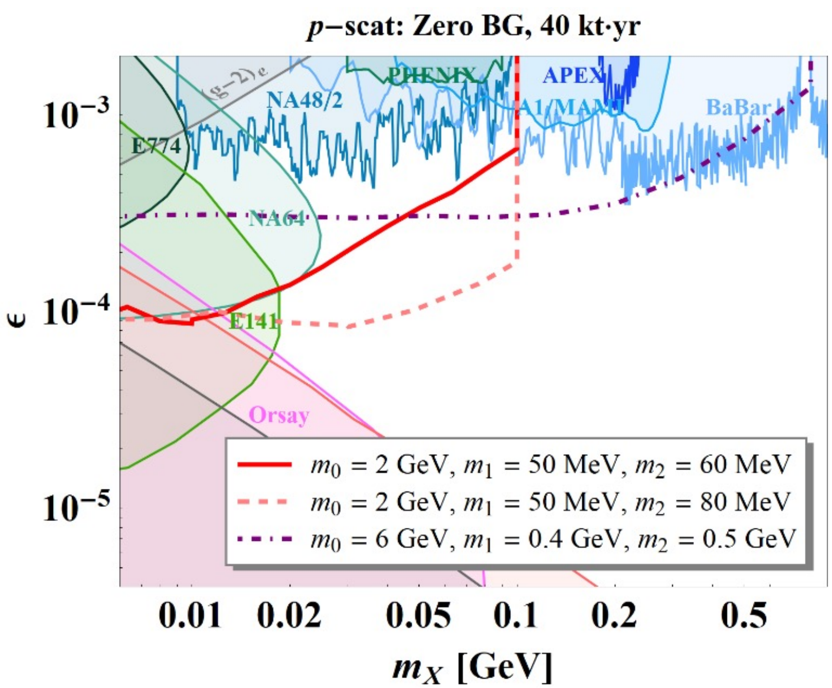


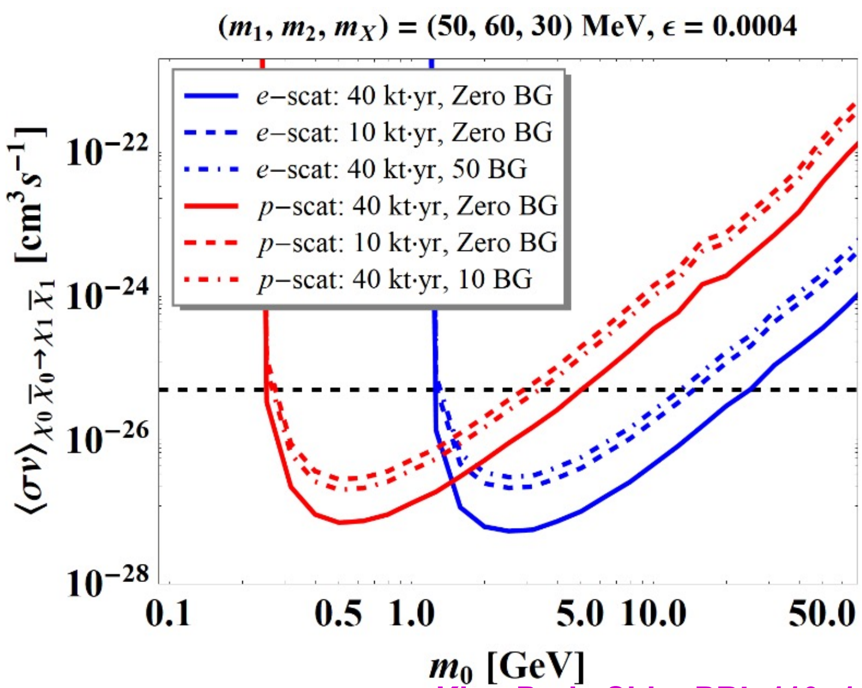
Berger *et al.*, PRD103, 095012, 2021

iBDM Searches @ DUNE FD

- DM annihilation in the galactic center produces boosted dark matter (BDM)
- Potential of searching for relativistic BDM in its inelastic scattering in the detector ➔ Distinctive signature of 3 leptons + missing energy final states helps overcome backgrounds
- Large volume, high density, underground FDs' w/ precision tracking and vertexing w/ low E threshold key







Kim, Park, Shin, PRL 119, 161801, 2017

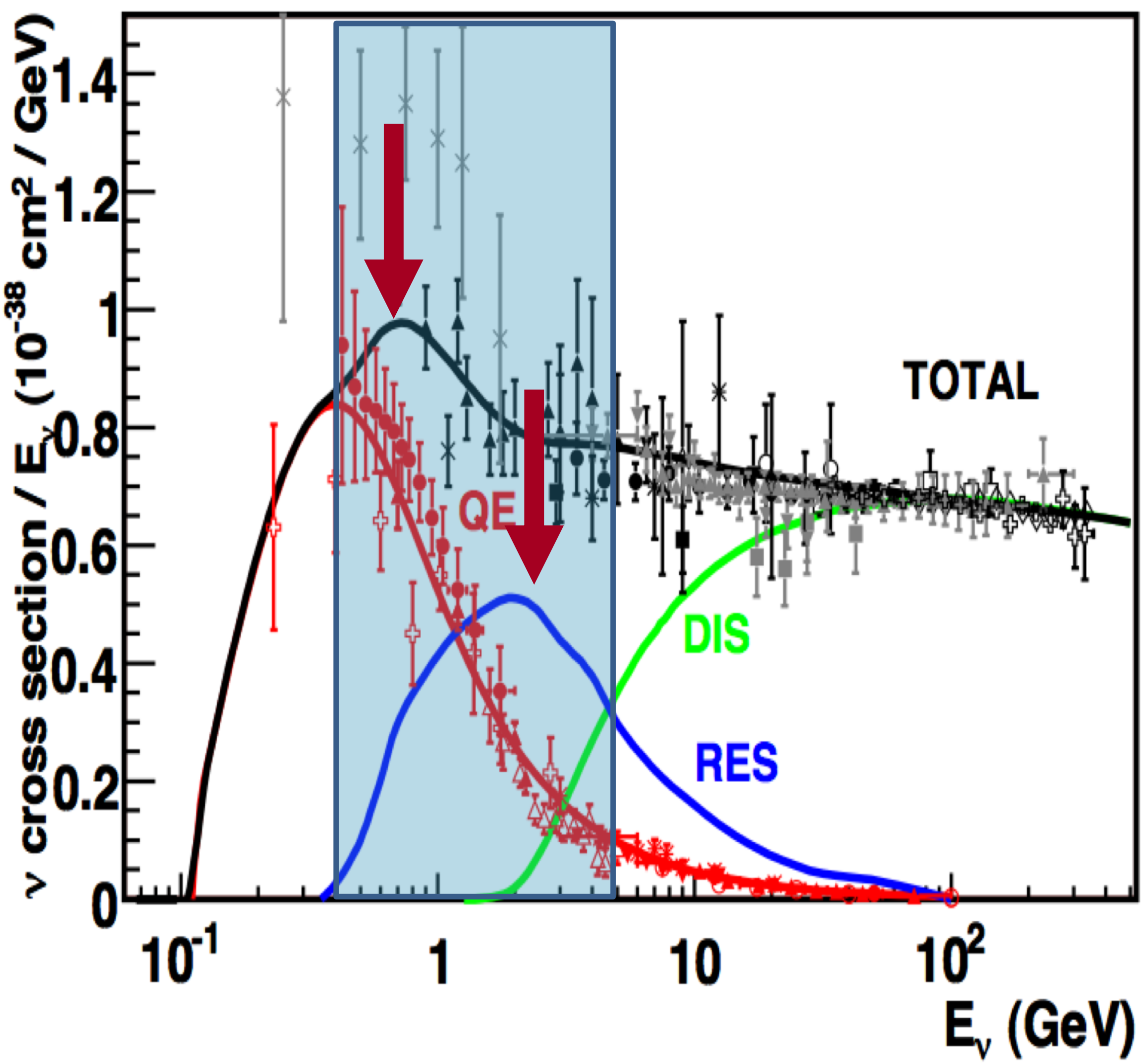
Signature & Backgrounds of BSM@ν

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

BSM Process	Selected signatures	Background
ALP	Scattering: γ+e, γ+N (n) Decay in flight : $\gamma\gamma$	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
LDM	$\chi e^- \rightarrow \chi e^-$, $\chi N \rightarrow \chi' N \rightarrow \chi e^- e^- N$, $\chi N \rightarrow \chi' N \rightarrow \chi \gamma N$,	NC w/ π^0, ν_e CC, QE, RES
mCP	Multiple e^- scatterings	ν_e CC w/ π^0
Dark Photon	$A \rightarrow e^- e^+$, $\mu^- \mu^+$, many more	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \rightarrow \nu e^- e^+$, $\nu \mu^- \mu^+$, $\nu\gamma$, $\nu e \mu$, $\nu \pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \rightarrow \nu e^- e^+$, $\nu \mu^- \mu^+$, $\nu e \mu$	$\nu_\mu N \rightarrow \nu_\mu \pi N'$ (ν CC)
BDM/ iBDM	$\chi N \rightarrow e^+ e^- e^- N$, $\chi N \rightarrow e^- N$, $\chi N \rightarrow nN$	ν coherent, NC w/ π^0, ν_e CC
Many more	Many many more	

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 backgrounds
- Large uncertainties for ν-N x-sec calculations
- DUNE can utilize its powerful ND complex to measure x-sec in-situ
- Collaboration between NP and HEP communities essential



Tails, tails and tails

- BSM 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
- Generator tools begin to incorporate BSM processes but could take a long time to implement due to insufficient resources → need further strengthening the efforts

Conclusions

- DUNE is a powerful experiment designed for precision ν property measurements
- DUNE's intense proton beams and superb detectors make it **uniquely capable** of probing wide breath of BSM physics
- DUNE can explore BSM physics in the kinematic regime **complementary to EF** experiments
- ν-N interactions critical backgrounds to BSM physics at DUNE ➔ Fundamental to improve on nuclear interaction modeling through a **close collaboration between HEP and NP communities**
- **DUNE made it possible to contemplate** many BSM topics at neutrino experiments
  - All NF03 physics topics list (grossly incomplete) are covered by DUNE

NF03 Physics Topics Table

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, ...

Take Home Messages

DUNE is a multi-purpose ν experiment best fit to explore rich BSM topics

DUNE compliments the Energy Frontier experiments on BSM physics

DUNE Phase – II with the full suite of detectors and doubled beam intensity are essential to fully exploit its BSM physics potential

Back Up Slides

Milli-Charged Particle Search

- mCP w/ charge < Q_{quark}
- Production via meson decays, DY
- Identify the signal using multiple e^- recoils by mCP and link them to point back to the source position & reject non-beam backgrounds
  - Tested with ArgoNEUT (~0.17m^3)
  - DUNE ND V~60m^3~350*$V_{ArgoNEUT}$
  - Difference in the beam E and large POT produce large number of mCP in a broad mCP mass range
  - 570m distance from target to ND could cause matter effect