BSM Physics Opportunities at DUNE

Workshop on Neutrino-Nucleus Interactions in the Standard Model and Beyond

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Outline

- Introduction
- What makes DUNE good for BSM?
- BSM Physics Topics at DUNE
- Backgrounds to BSM
- Conclusions

DUNE Physics Motivation

- The neutrino sector in SM 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 nucleon decay
- Understanding particles of astrophysical origin
  - Supernova, 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

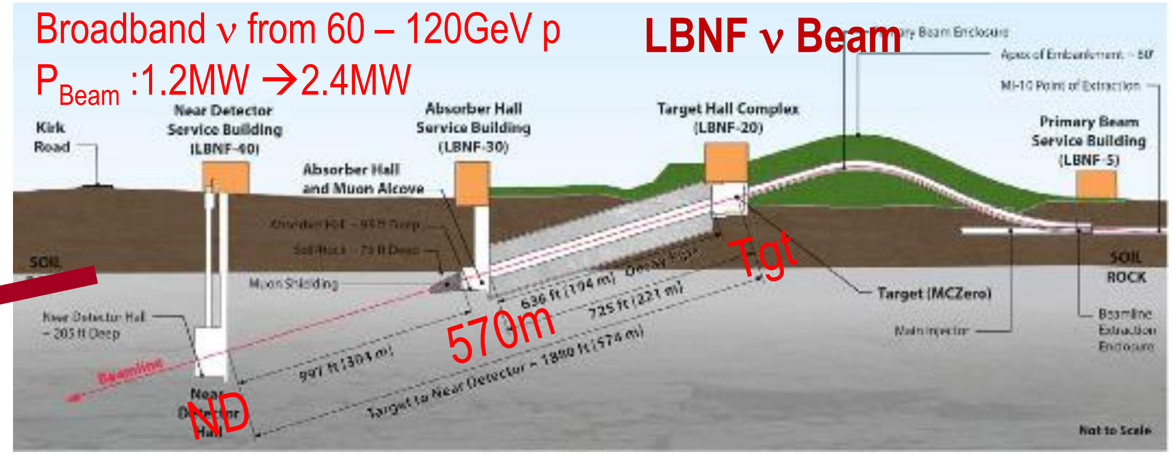
BSM@nu, the genesis

- BSM@nu picked up steam after the 2013 U.S. Snowmass exercise
- 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
- Need a strategic plan to strengthen the fundamental measurements, such as ν-N xsec, to support precision measurements
- Need to think about managing and mitigating background from "neutrino interactions"
- Important to play a leadership role in expanding physics opportunities
- Low E capabilities of the detectors could expand BSM kinematic reach
- A paper on ROP covers some of these opportunities (Argüelles *et al.*, https://iopscience.iop.org/article/10.1088/1361-6633/ab9d12)

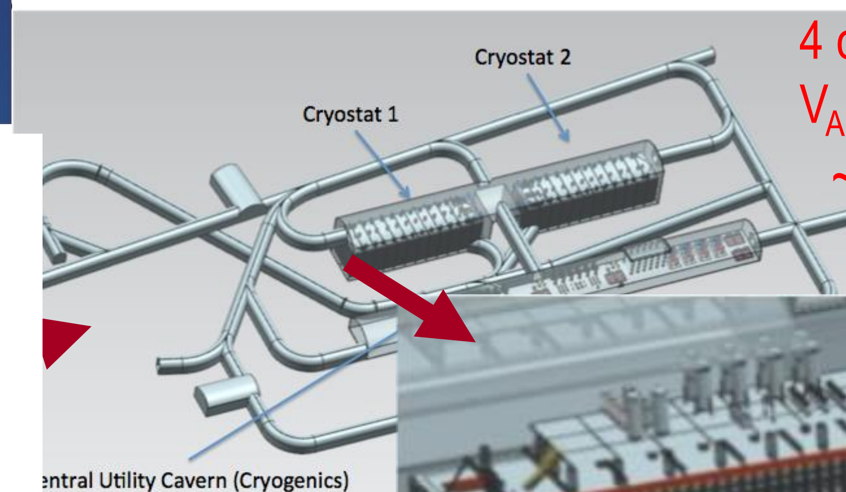
Deep Underground Neutrino Experiment (DUNE)

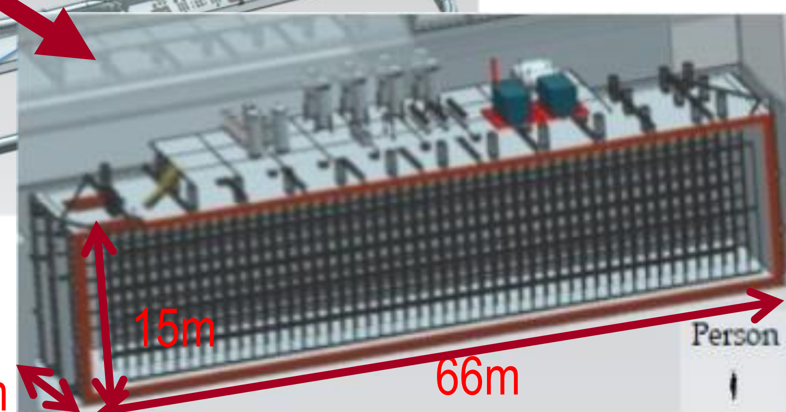
- Per the 2013 – 2014 strategic planning of the communities in the three regions, an effort of building a next generation international neutrino experiment is in progress in the U.S.
- Joint efforts of teams from all three regions – Americas, Europe and Asia – US flagship hosted by Fermilab
- DUNE far detector TDR completed and published in 2020
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08008;
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08009;
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/08/T08010
- LAr TPC precision 3D imaging detectors → Potential to employ multiple technologies within one experiment, systematic x-check
- LBNF (Long Baseline Neutrino Facility) far site construction approved by US DOE in Sept. 2016
  - Fundamental safety and construction infrastructure completed in 2021
  - A full-fledged cavern excavation ongoing!

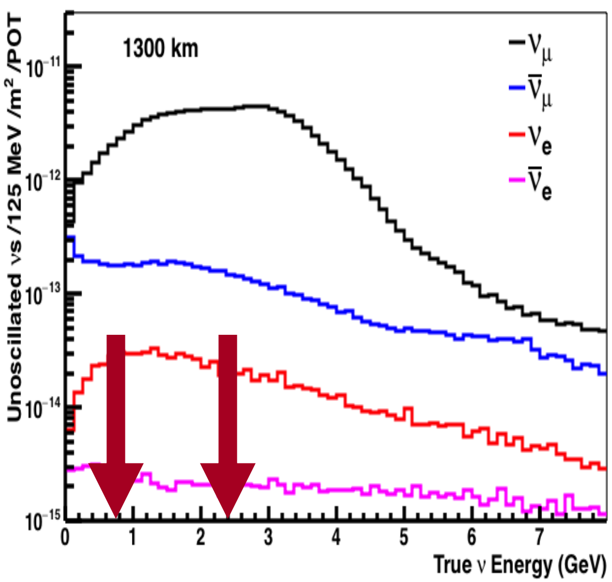
Anatomy of DUNE



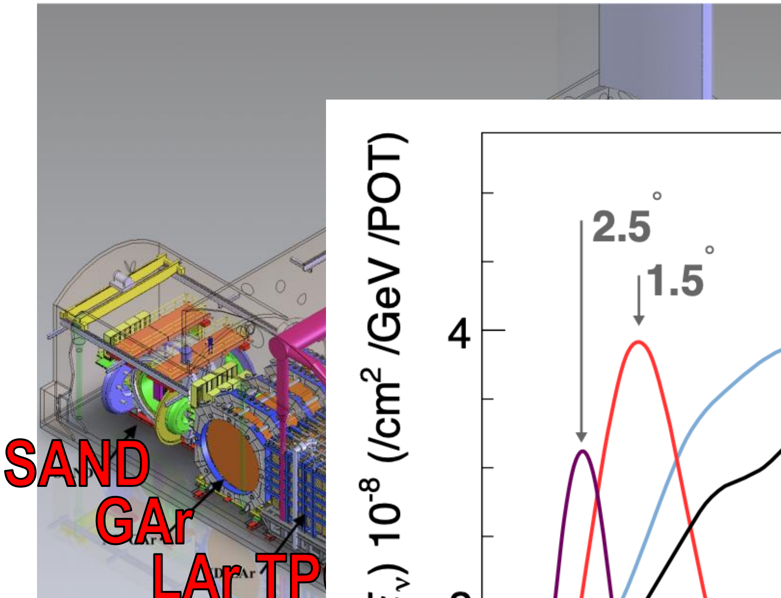
4 caverns w/ fiducial V_A~ **10kt LAr** each
~30xICARUS

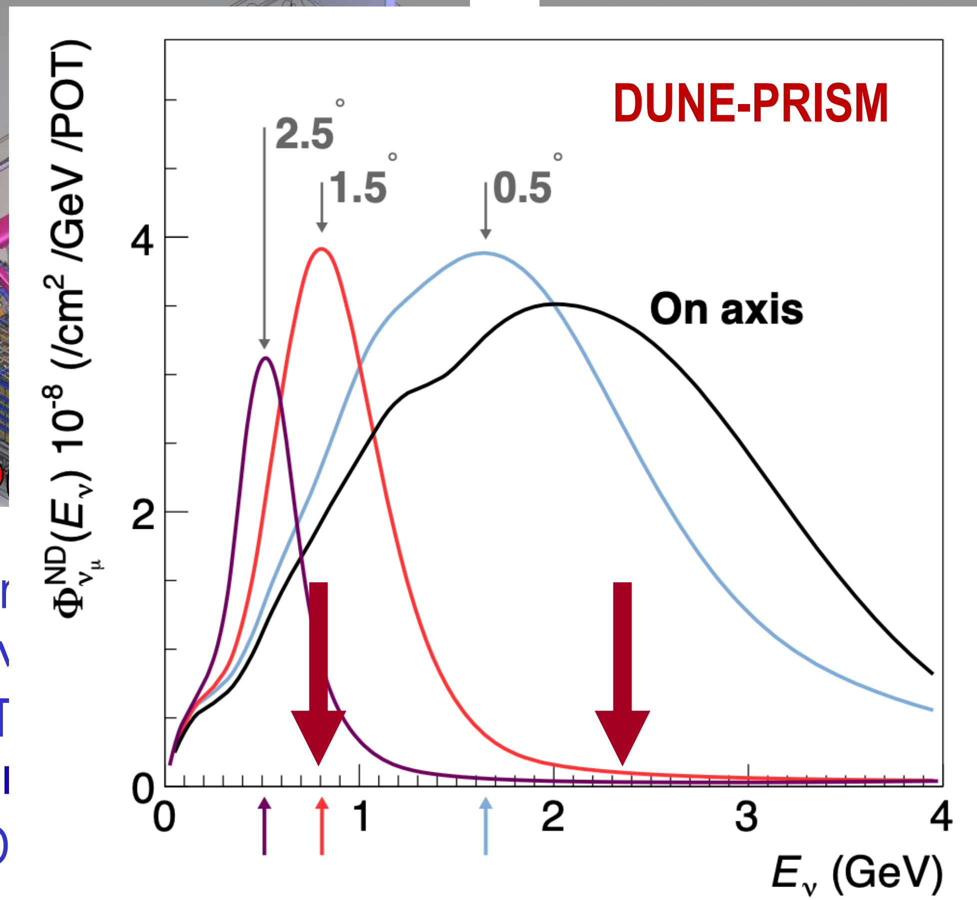


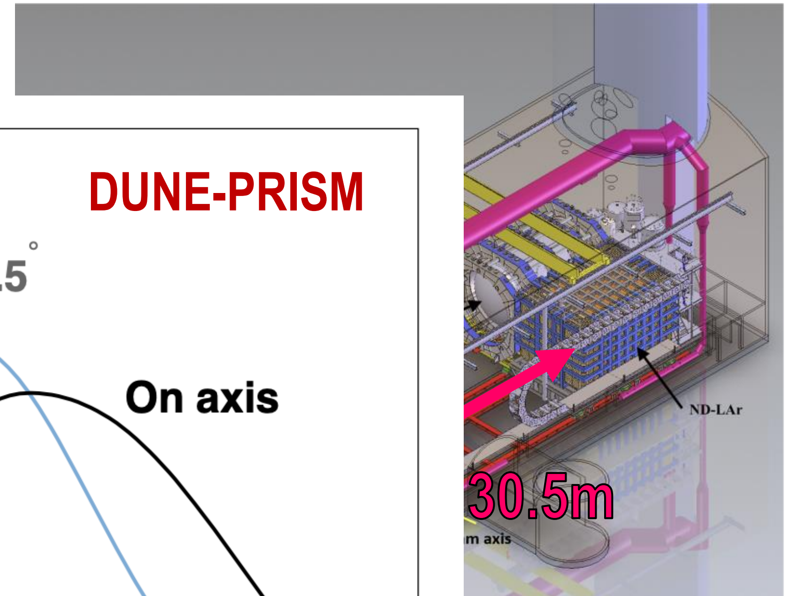




The DUNE Near Detector Complex Concept



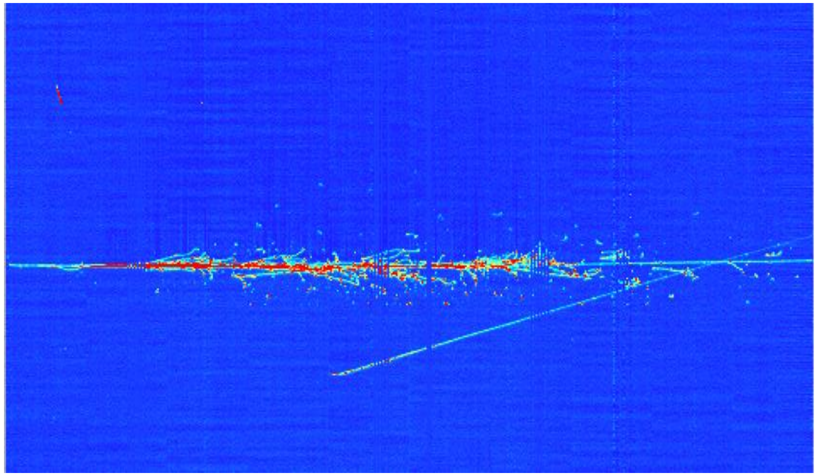




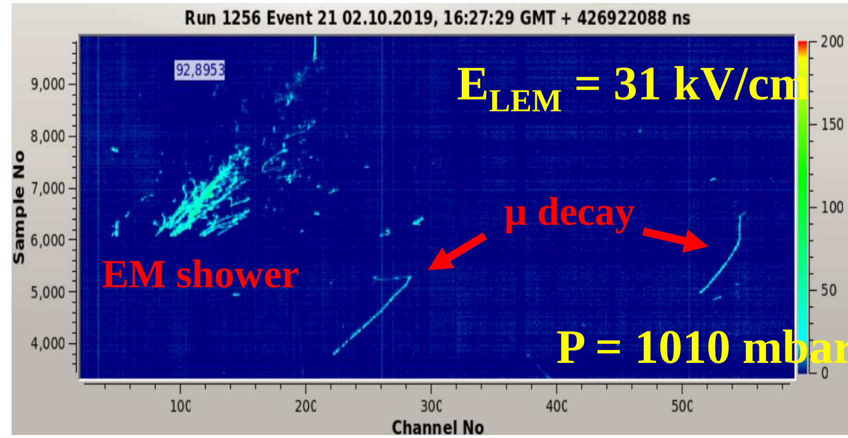
- LAr TPC: The sar … om different nuclear effects than FD; … n-axis (~1Hz)
- Magnetized (0.5T … r events with **low-threshold tracki** … **r** on-axis
- DUNE-PRISM: O … nd ND-GAr from on axis up to **30.5m**
- SAND(**S**ystem for **O**n-**A**xis neutrino **D**etection): Monitors on-axis ν beam flux to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

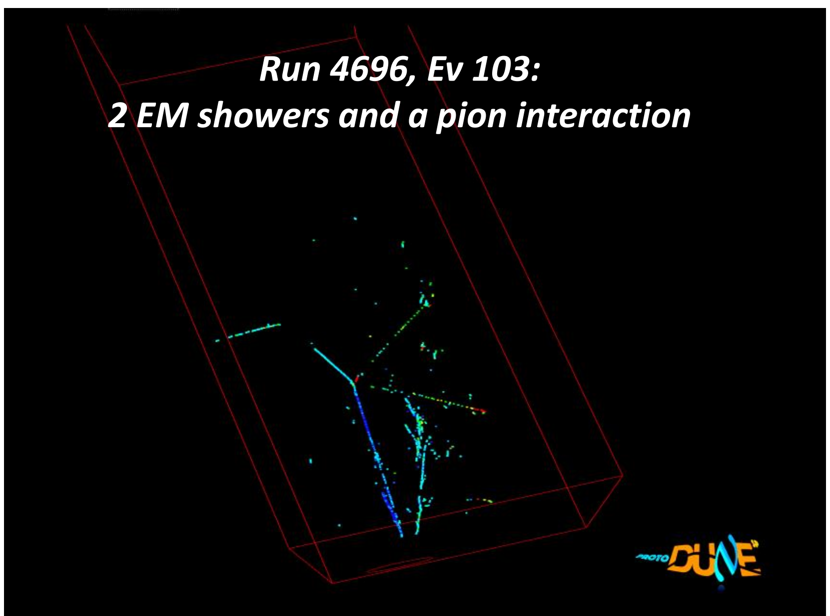
Images in DUNE LAr-TPC Prototypes

Throughgoing μ

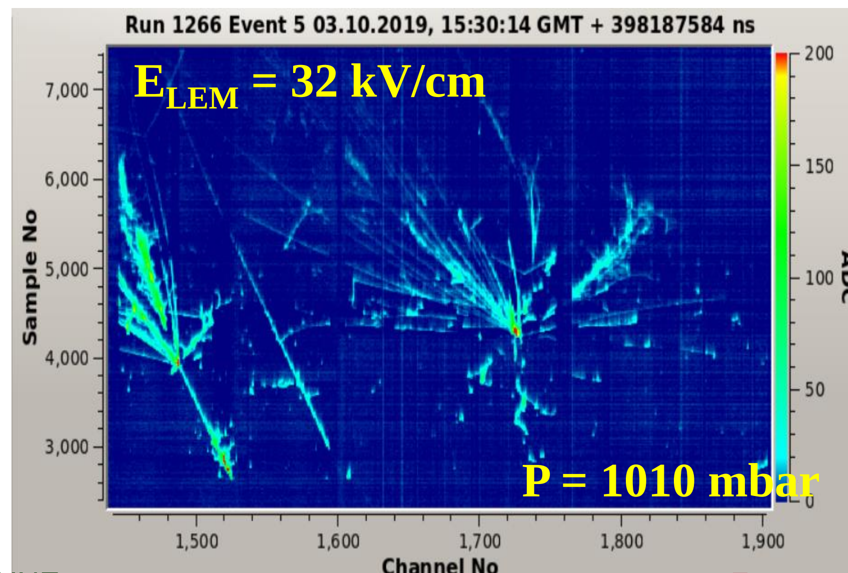


Electromagnetic shower + two muon decays





Multiple hadronic interactions in a shower

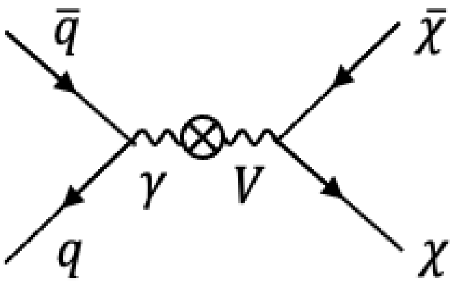


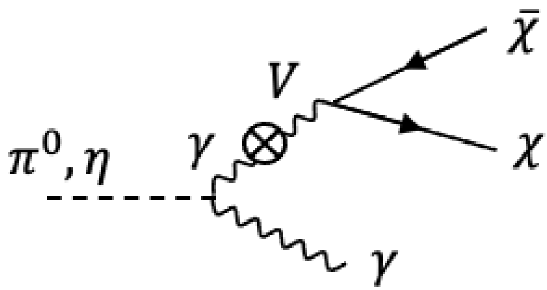
BSM Physics Topics at DUNE

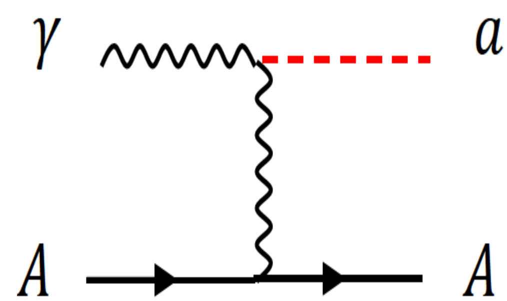
- High beam power, large detector mass + highly capable, precision near and far detectors with low E threshold make BSM physics viable
  - Signal to background ratio grows by the sqrt of the beam power
  - Near Detector Searches ➔ Take advantage of high beam power
    - Low mass Dark Matter (LDM)
  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

BSM@ν Physics Signatures at ND

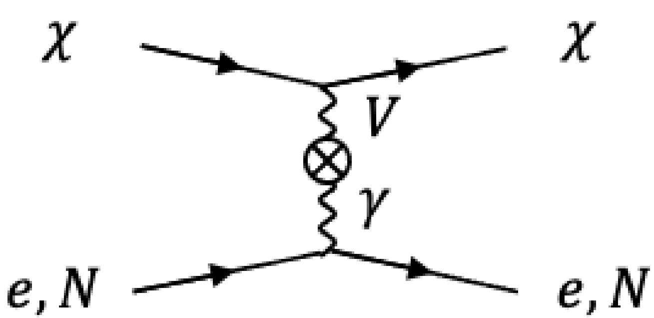
- High intensity proton beams produce large number of photons from brem, DY or neutral mesons decays ➔ Make it possible to contemplate couplings of new U(1) gauge to the SM γ

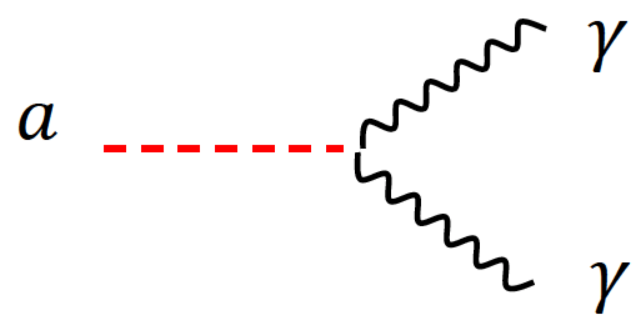






- Detection through an electron, μ, N(n) recoil or 1, 2 γ final states

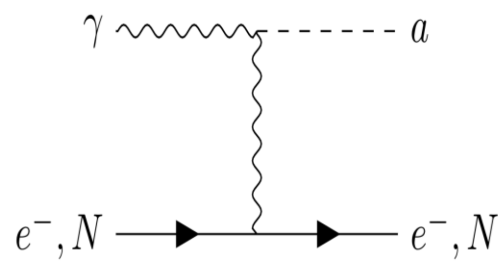




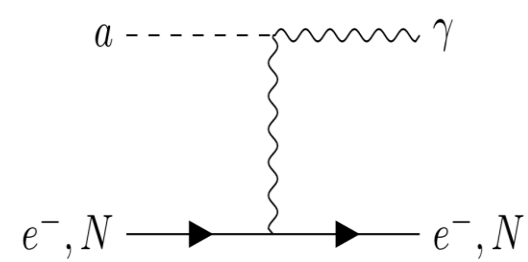
ALP Searches @ DUNE ND

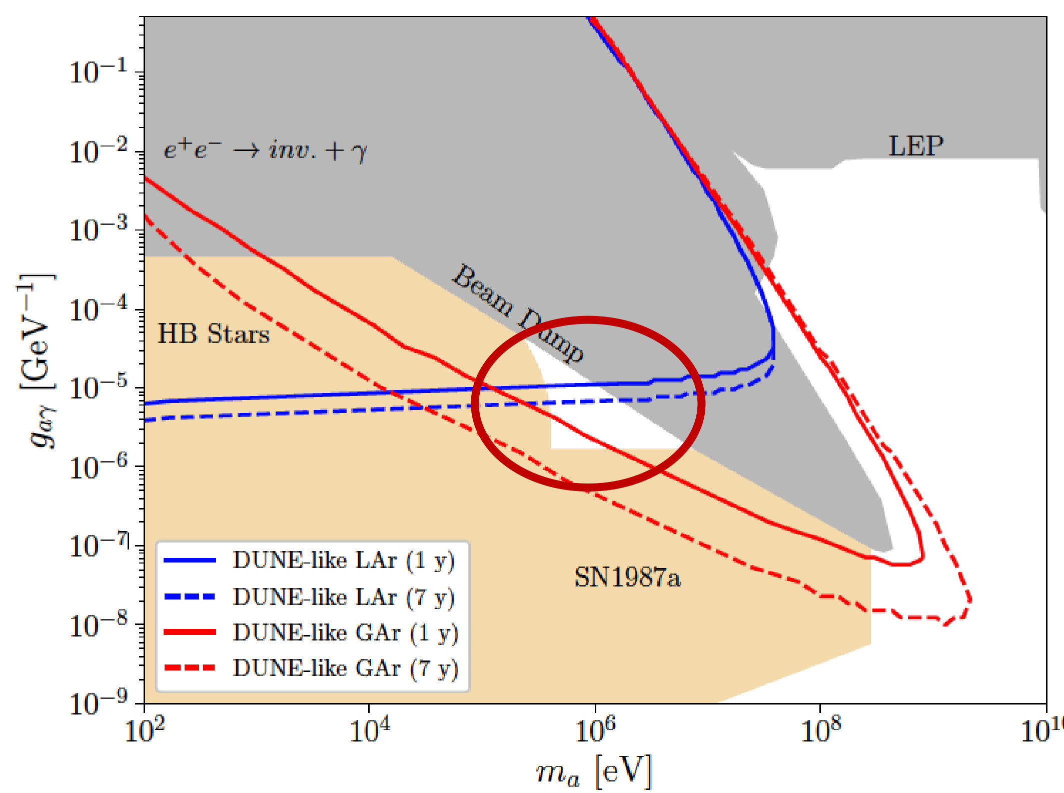
- Axion-like particles can be produced via the Primakoff process in high intensity proton beams
- Detection via the inverse Primakoff process either in a scattering with e/N + γ or decays of the ALP to two γ
  - ν_e CC, NC backgrounds
  - ν_μ NC→ π^0 → $\gamma\gamma$ bck
- DUNE ND has a potential to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

Production in ν target



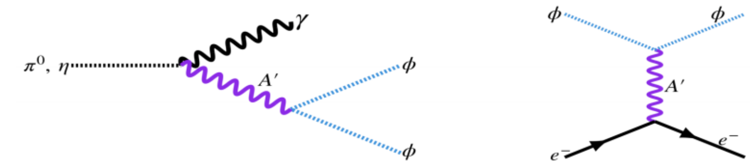
Detection - scattering

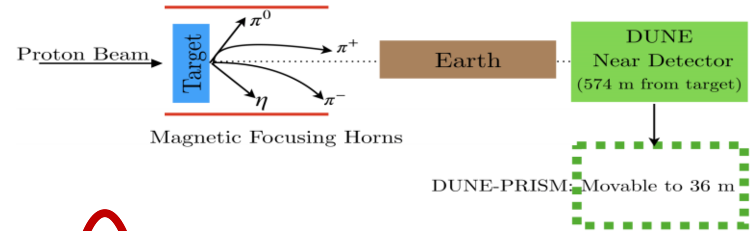


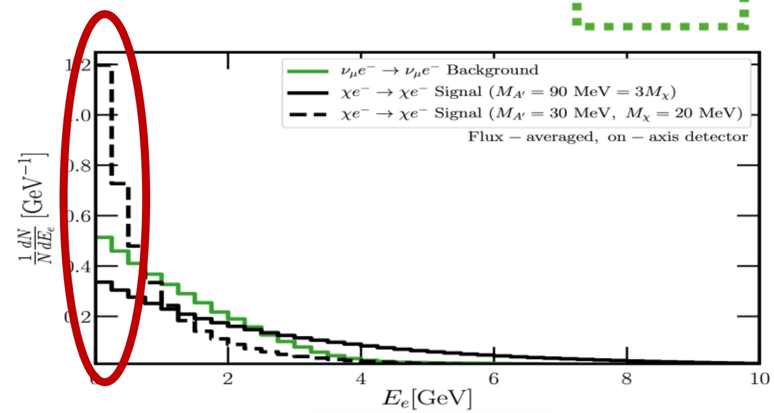


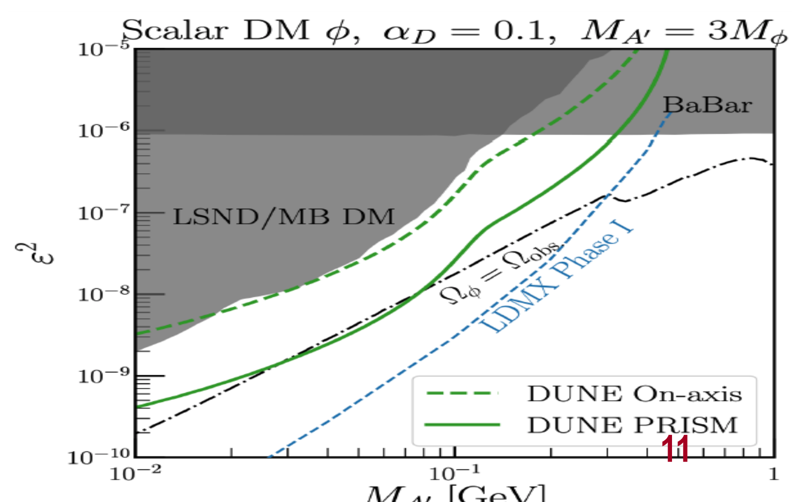
LDM Search and Low E Threshold

- 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^-
- Search benefits greatly 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)



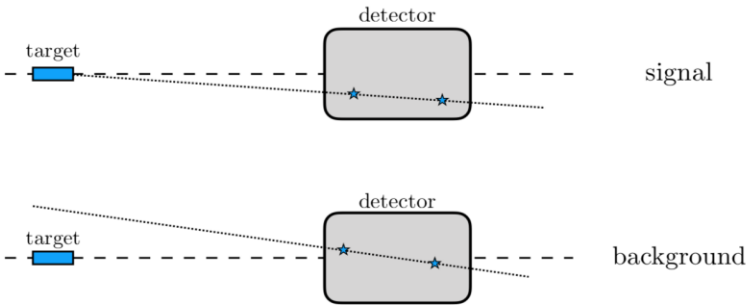


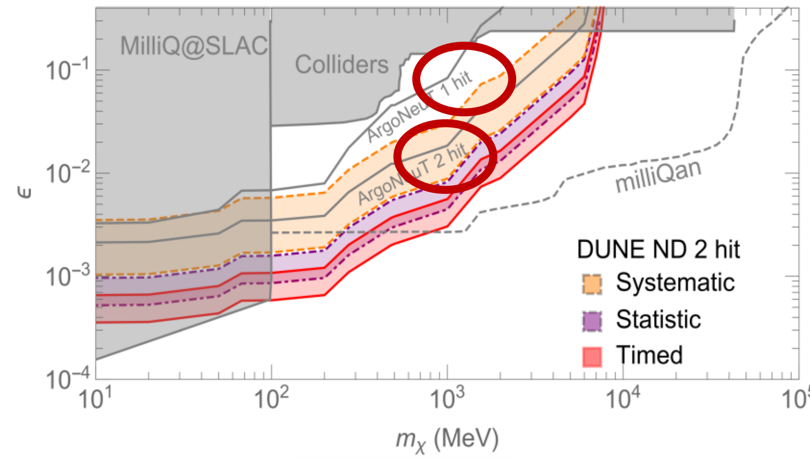


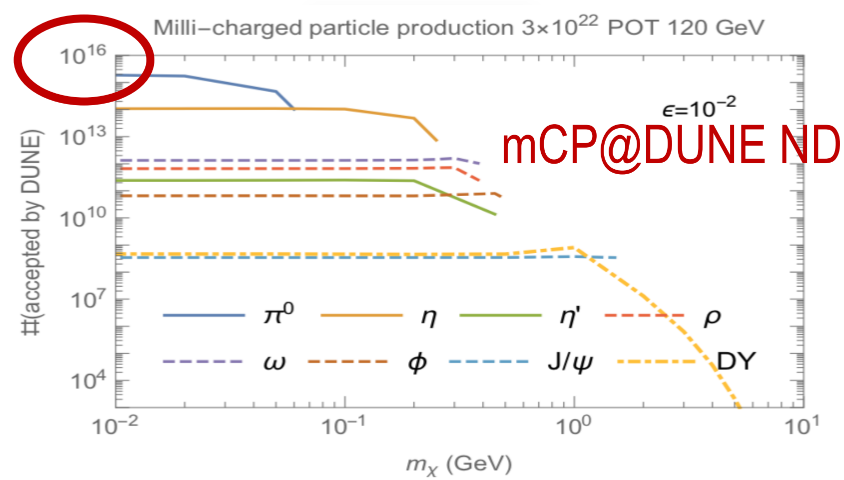


Milli-Charged Particle Search

- mCP w/ charge < Q_{quark}
- Production via meson decays or 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)
    - Ability to identify e^- recoil w/ ~<MeV E threshold enables this method possible
    - Enabling virtually background free search
  - 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

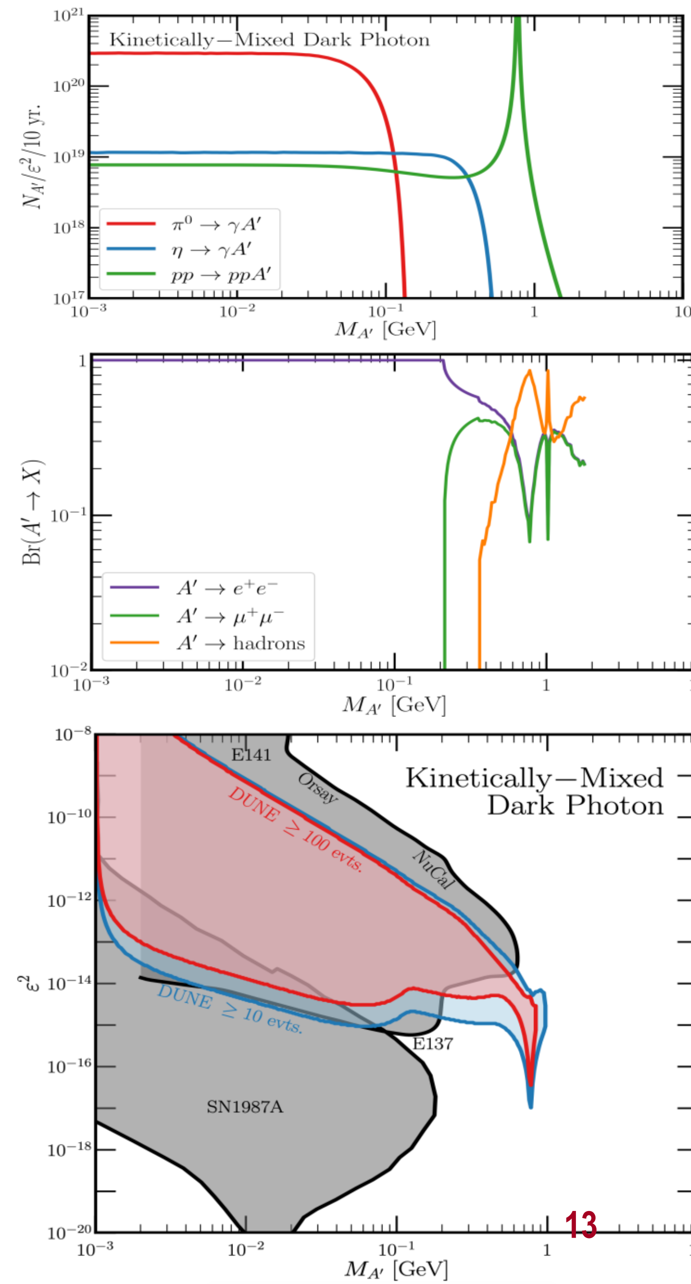






Dark Photon Search

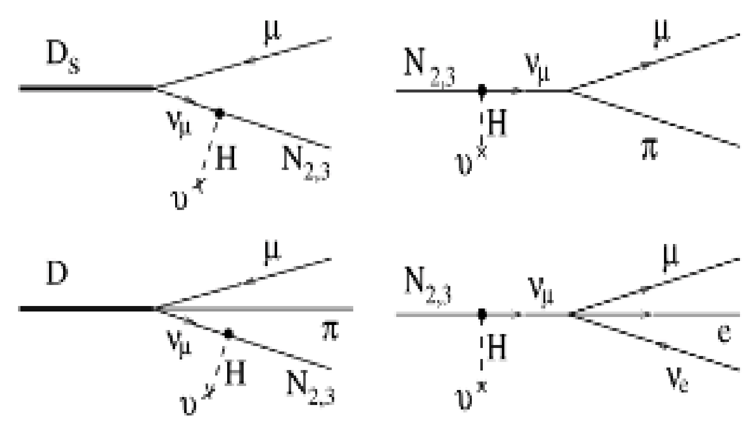
- New U(1) could kinetically mix with a SM γ from scalar meson decays or direct DY
- If these dark photons can live sufficiently long to reach the DUNE ND ➔ Look for their decays to a charged lepton pair
  - $A' \rightarrow e^+e^-$
  - Primary background from $\pi^0 \rightarrow \gamma\gamma$
    - One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

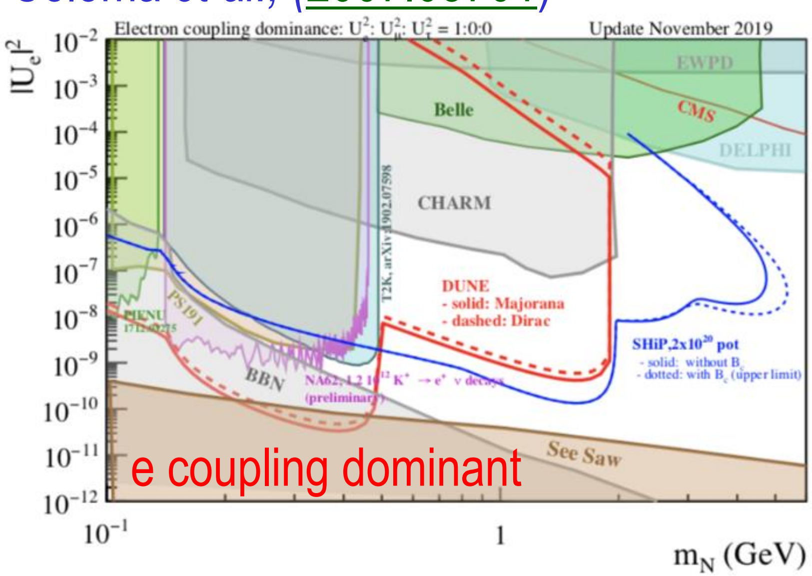


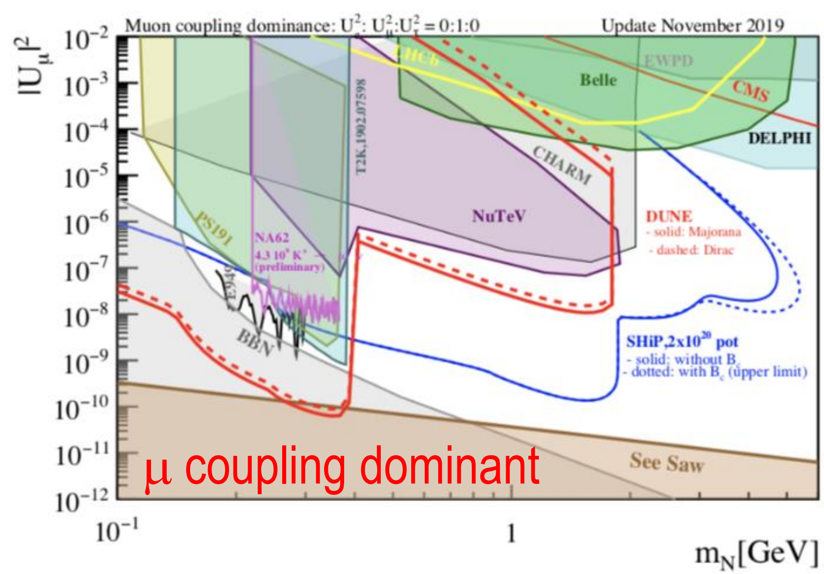
HNL Searches @ DUNE ND

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

Production **Decays in ND**







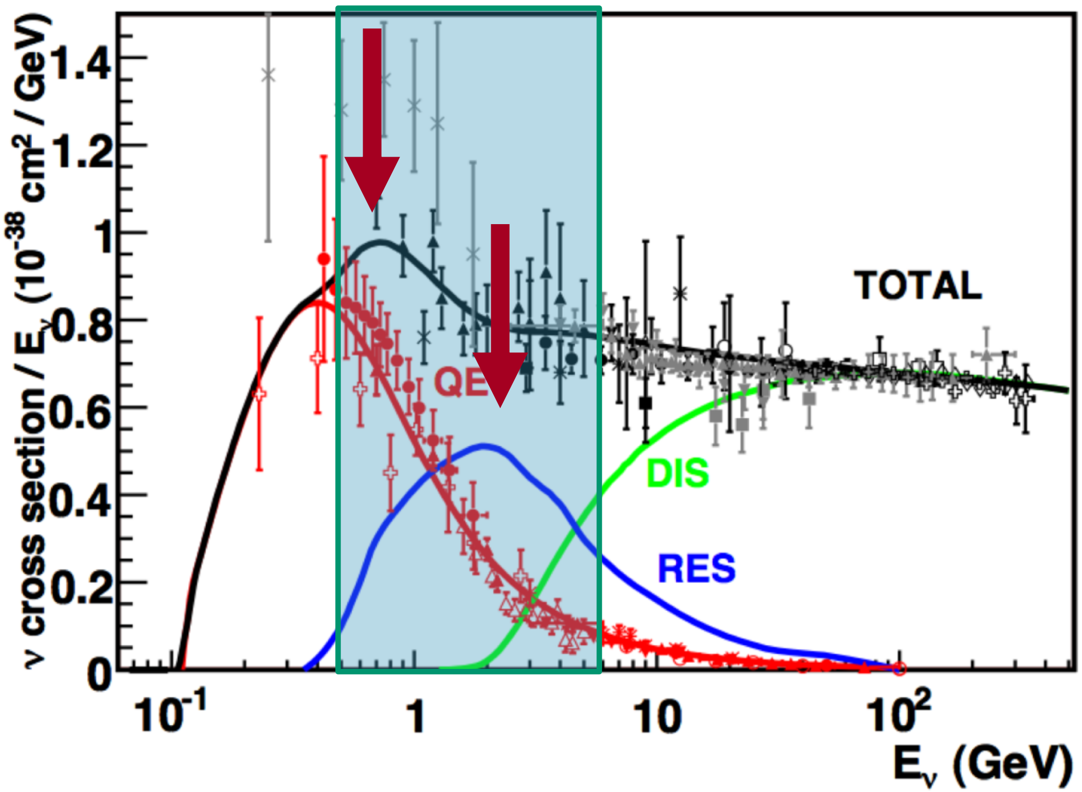
Signatures of BSM@ν

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

Process	Signatures	Background
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	$\chi e^- \to \chi e^-$, $\chi N \to N'n$	NC w/ π^0, ν_e CC, QE, RES
mCP	Multiple e^- scatterings	ν_e CC w/ π^0
Dark Photon	$A \to e^-e^+$, $\mu^-\mu^+$	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$	$\nu_\mu N \to \nu_\mu \pi N$□ ($\nu$ CC)
BDM/ iBDM	$\chi N \to e^- N$	ν coherent, NC w/ π^0, ν_e CC

Low Energy ν Interactions

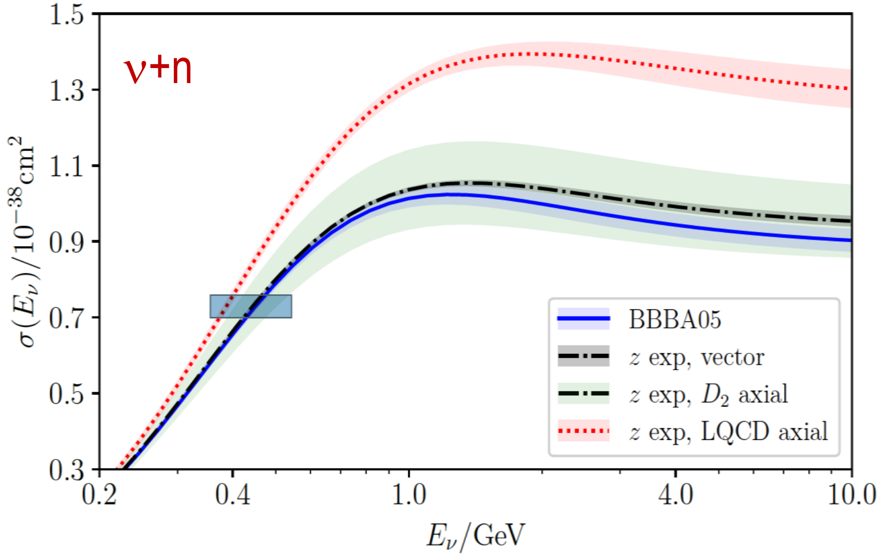
- QE and RES dominate ν-N interactions in DUNE E_ν range where the two oscillation maxima reside
- QE & RES critical to understanding background to BSM
- Large uncertainties for ν-N x-sec calculations in the critical region
  - Precision calculations w/ improved nuclear models and event generations essential for oscillation physics
  - Planned measurement, such as at e4ν collaboration could provide critical missing info
  - Need to clearly identify the list of measurements that can help improving calculations and prioritize them to target low hanging fruits first

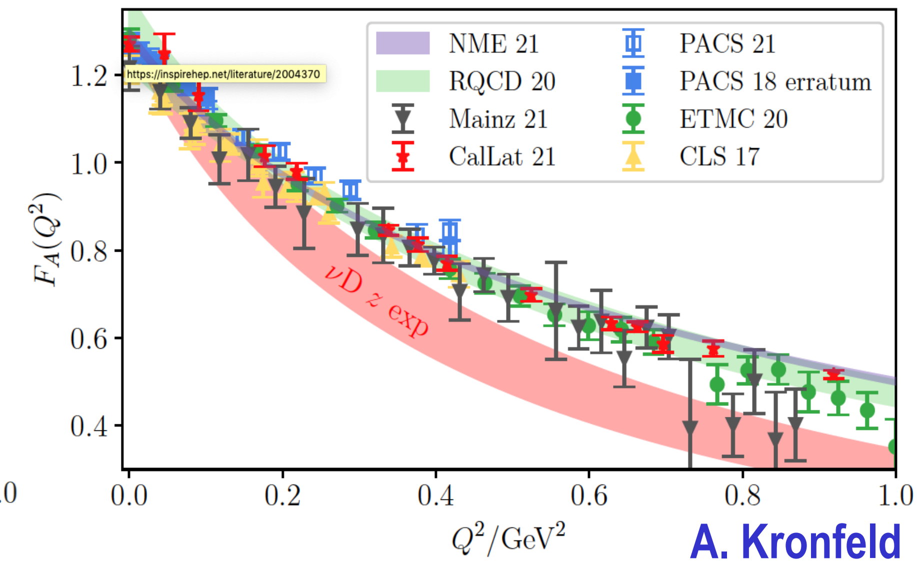


Tails, tails, tails

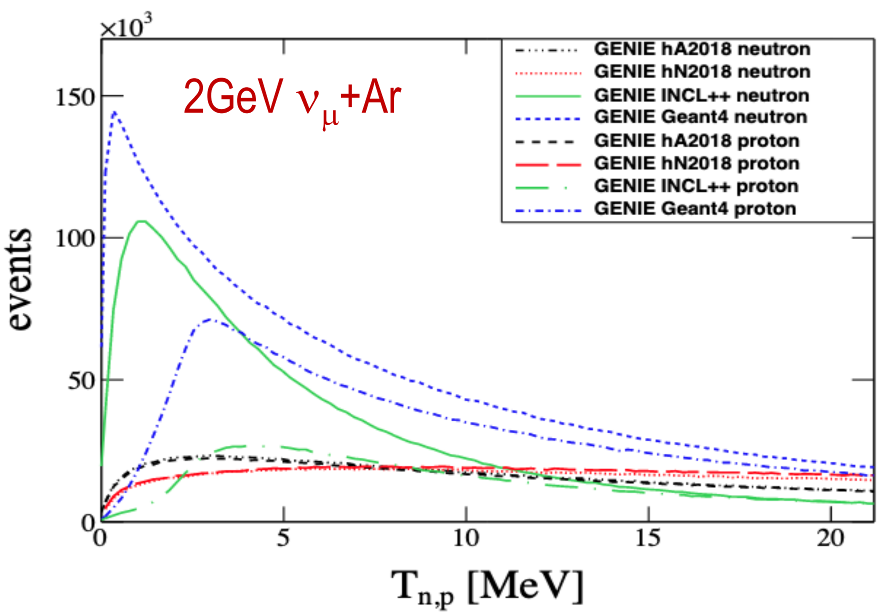
- BSM effects extremely rare and are in the tail ends of the SM processes ➔ can easily be masked by SM fluctuations
- Many theoretical predictions and generators for ν–N interactions have been in existence and continue making remarkable improvements ➔ but they still have sizeable uncertainties within each and between themselves

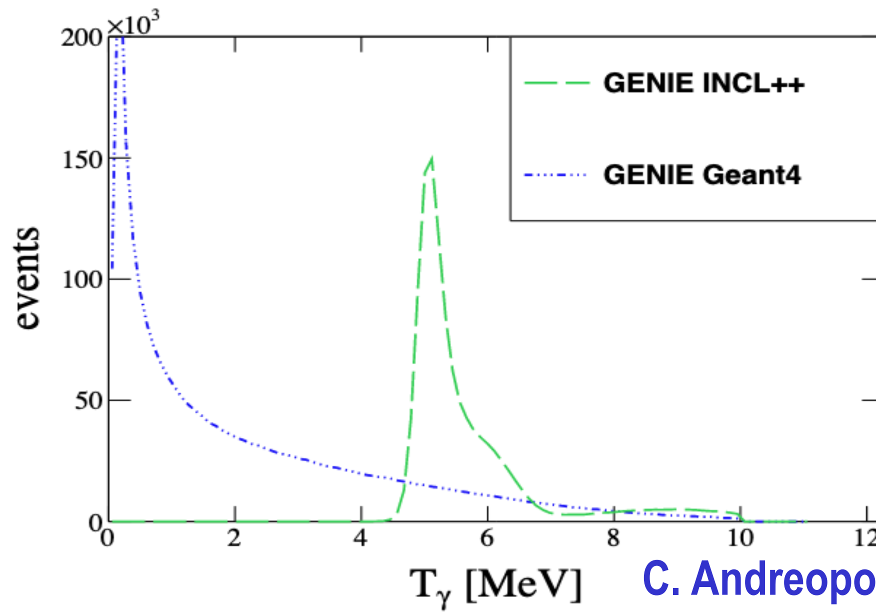
We learned at this workshop..





A. Kronfeld





C. Andreopoulos

Tails, tails, tails, and tails

- BSM effects 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 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 BSM searches
- Generators begin to incorporate BSM 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 boost
  - NP and HEP communities must work together to understand low E processes
  - In addition, we need more concerted efforts and get them done in a timely fashion

Conclusions

- The high intensity proton beams for next generation neutrino experiments enable expanding physics reach beyond that of neutrinos and the SM
- Large scale, precision 3D imaging capability DUNE detectors fit to probe a broad scope of BSM physics
  - Enormous opportunities to search for BSM signatures at DUNE ND and FD combinations
- Accessing yet-to-be-explored kinematic phase space requires precision detectors with as low E threshold as possible
  - Backgrounds from non-beam sources could be well rejected w/ low E electron detection capability and pointing back to the target
  - Neutrino interactions will be the significant background to BSM signatures
- In theory front, it is fundamental
  - To develop innovative tools for BSM signature calculations and generator
  - To significantly improve precision of the neutrino-Nucleus interactions