# Tools for BSM@nu – What do we need for experiments?

*NuTools for BSM@ν Workshop*
*PittPACC*
*University of Pittsburg*
***Dec. 14 – 16, 2022***

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# Outline

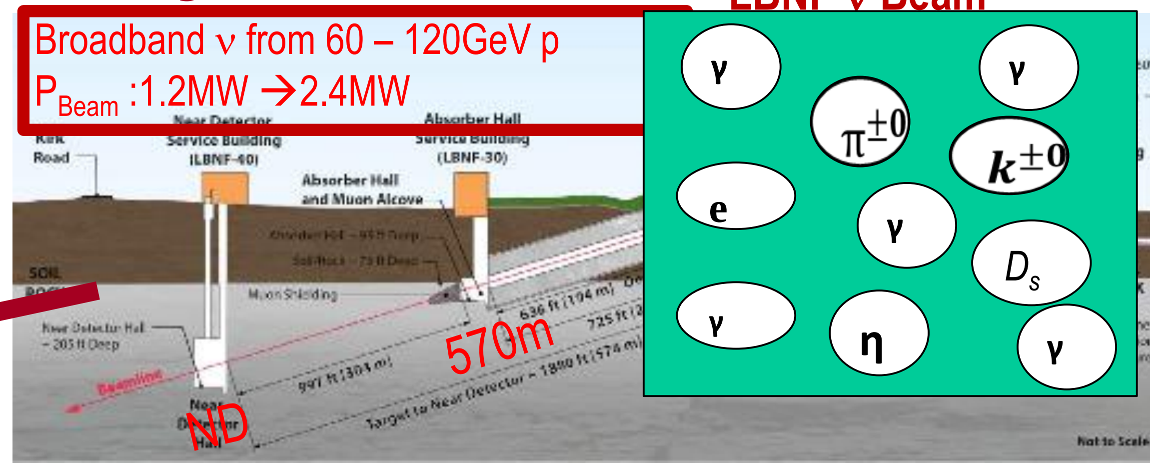
- Introduction
- BSM Opportunities at $\nu$ exp, why & how?
- Conditions for BSM
- A few example cases on DUNE
- Considerations for $\nu$ exp
- Outcomes wish list
- Conclusions

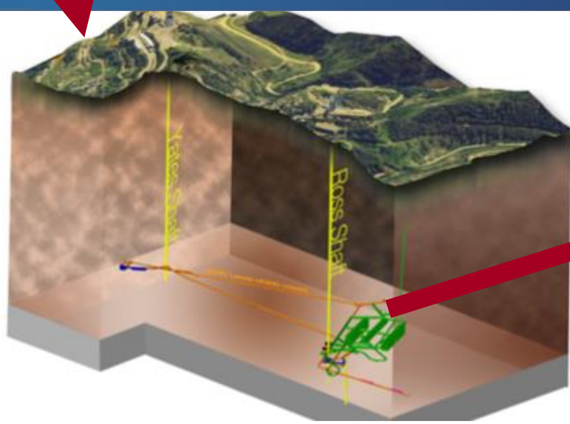
# Introduction

- High intensity proton beams and large active mass FD with precision 3D imaging capability, along with the powerful ND complex make it possible to contemplate BSM physics traditionally inaccessible to $\nu$ experiments
- Most next gen $\nu$-experiments design solely focused on the B&B $\nu$ oscillation parameter measurements, CPV and p decays
- Some detectors have capabilities to fit BSM measurements
  - The strengths of LArTPC offer breaths & depths of BSM physics ➔ resulted in BSM as a core physics program of DUNE
  - SBN experiments are to be fully operational with high flux proton beams soon!!
- Must take full advantage of these facilities

# Anatomy of DUNE


LBNF ν Beam



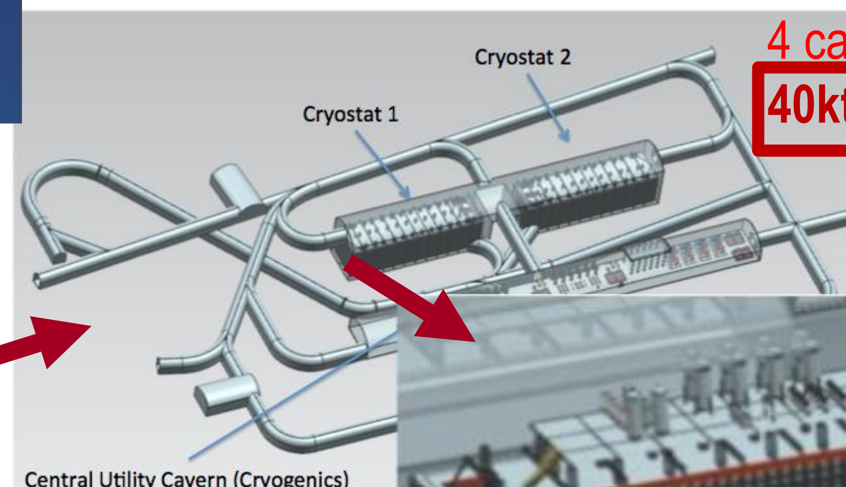



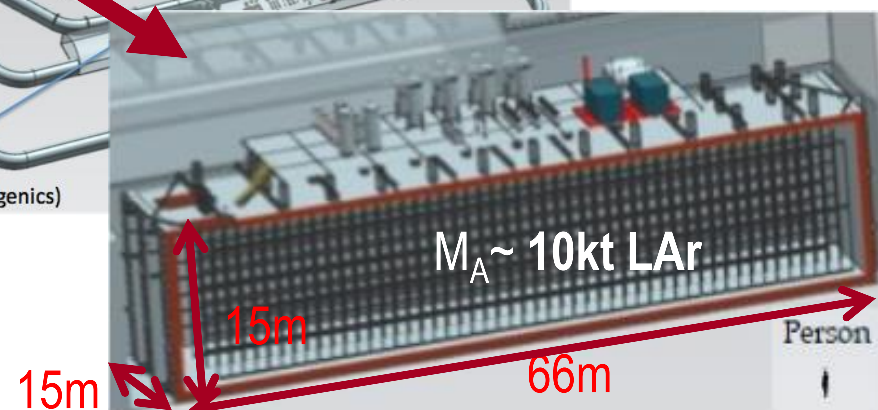

LBNF Far Detector Site, SURF

**1500m underground**

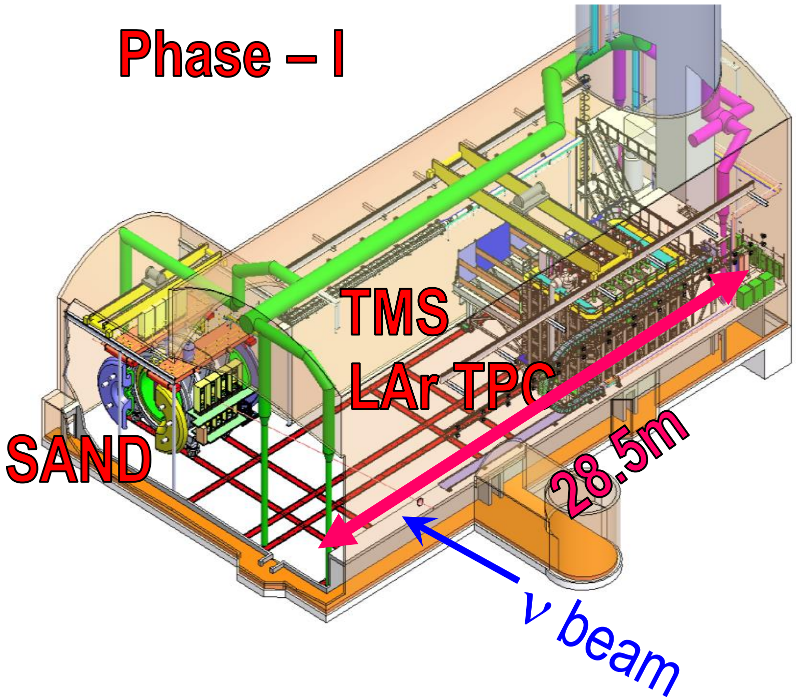
4 caverns for $M_A$~

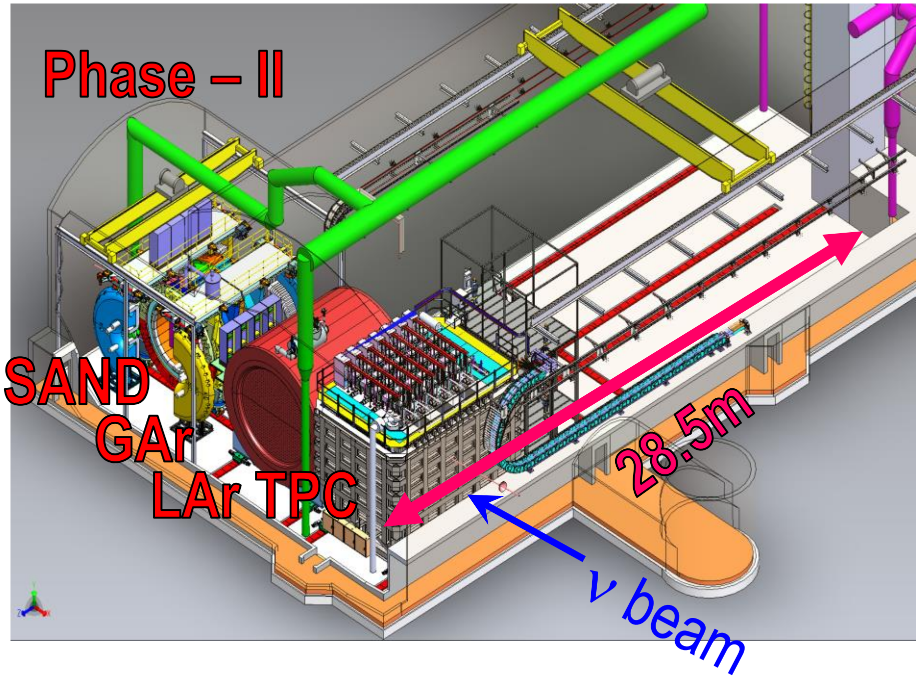
**40kt LAr**



# 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

# Snowmass 2021 NF Science Driver

- How are the neutrino masses ordered?
- What are the values of the neutrino masses?
- What is the origin of the neutrino masses?
- Are neutrinos their own anti-particles?
- Do neutrinos and antineutrinos oscillate differently?
- Is the three-flavor picture of neutrino oscillation complete?
- Do neutrinos interact in novel ways, or with new and so-far undiscovered particles?
- Using neutrinos as a window on the universe, what will we see?

# BSM@ν Signature Categories & Needs

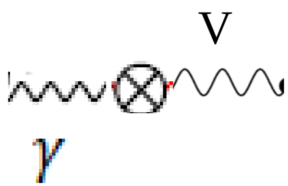
- Direct Observation Signatures from the beams leverage
  - High beam flux
  - Large mass, high density for scattering signatures
  - Large volume, low density for decay signatures
  - Capable near detector complex
  - Low threshold energy
  - Low background from cosmic sources
- Inferred Observation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

# BSM Physics Topics at $\nu$ exp

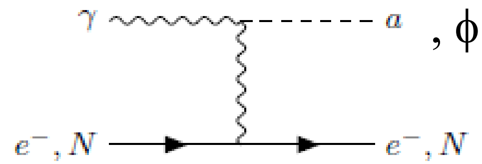
- High beam power, large detector mass + highly capable, precision near and far detectors with low E thresholds make BSM physics viable
  - Signal to background ratio grows by the sqrt of the beam power
  - Near Detector Searches → Take advantage of high beam power
    - Dark sector particles – beam originating : Low mass Dark Matter (LDM), Pseudo-scalar/ scalar Axion-like Particles (ALP), Light Mediators (a,$\phi$,V), dark photons, erc
    - Heavy Neutral Leptons (HNL)
    - Milli-charge Particles (mCP)
    - Neutrino Trident …

# New Physics @ The beam

## Varieties of mechanisms possible to produce new particles ➔ Access to new physics

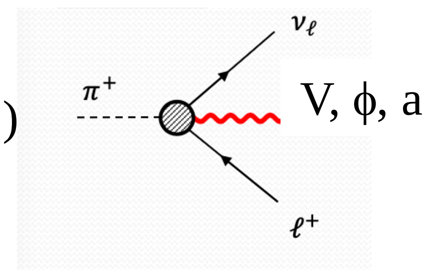
(1) 


Kinetic mixing

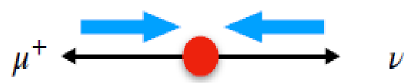



: Primakoff

V: Vector
ϕ=scalar
a=pseudo-scalar

(2) 


3-body is not helicity suppressed.
For 2-body decay mode of the charged pion :




(3) $\pi^0 \to \gamma$ V

(4) $e^+e^- \to V, \phi, a$ Resonance production, Compton productions, DY, *Bremsstrahlung*

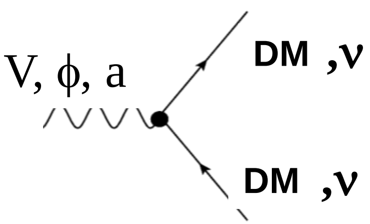
*Many more*

# New Physics @ the Detector

## Look for both decay products and scattering in ND for beam originating BSM signatures

Decays

(1) V, ϕ, a Short-lived,

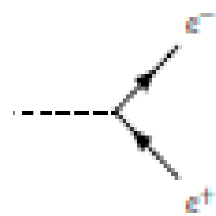


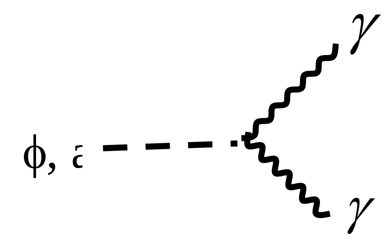

DM, ν produces nuclear/electron recoil

DM up-scattering

(2) V, ϕ, a Long-lived,

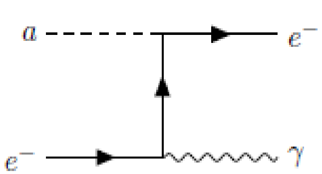
V, ϕ, a



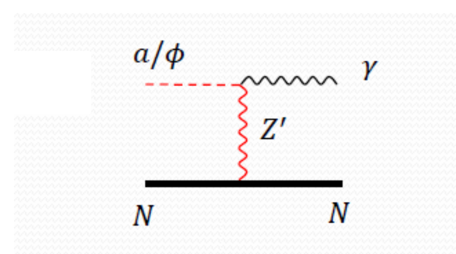




Scattering

V, ϕ, a




V



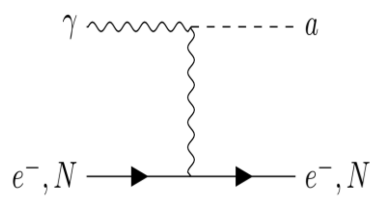
# Selected BSM Topics @ DUNE

- 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)

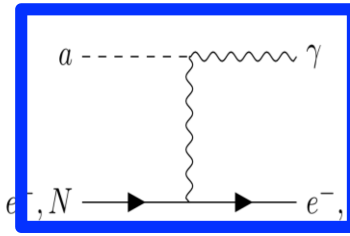
# ALP Searches @ DUNE ND

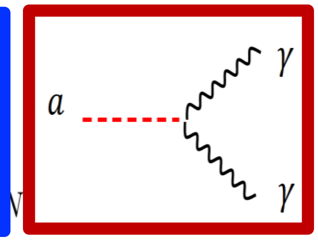
- Axion-like particles (ALP) can be produced via the Primakoff process in high intensity proton beams in the neutrino target
- Detection through a scattering with e/N + γ or decays of the ALP to two γ
- Other axion coupling, e.g. $g_{ae}$ is accessible, as well
- DUNE ND Phase II enables complete closure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

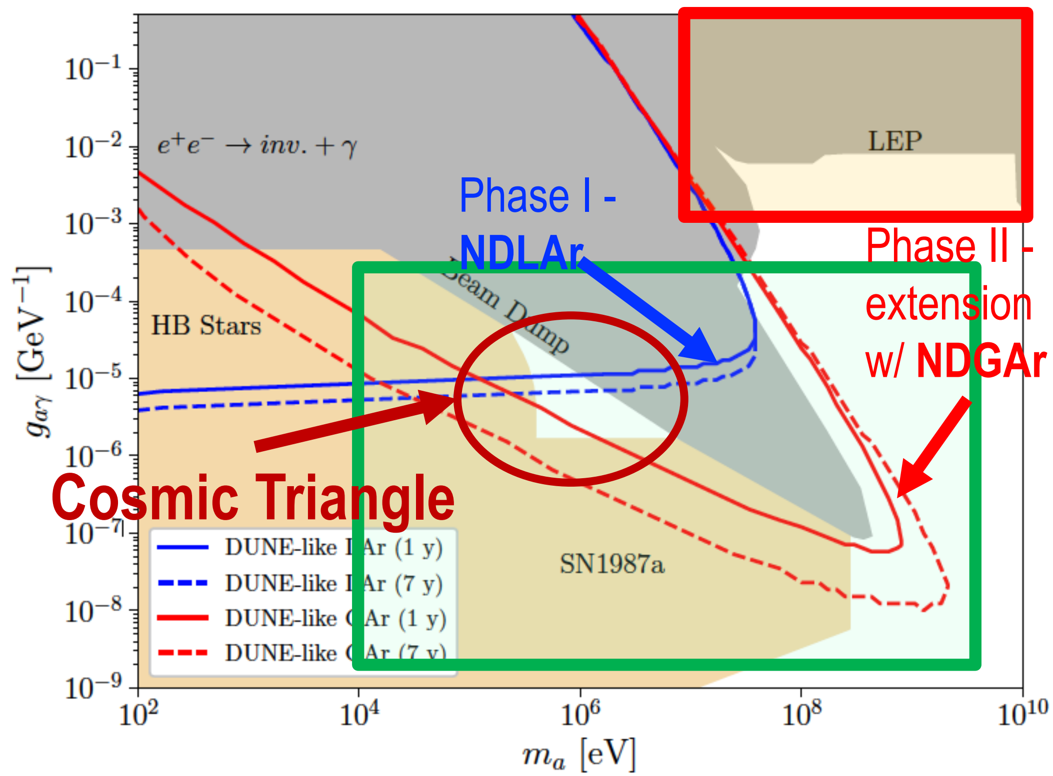
Production in ν target




Detection

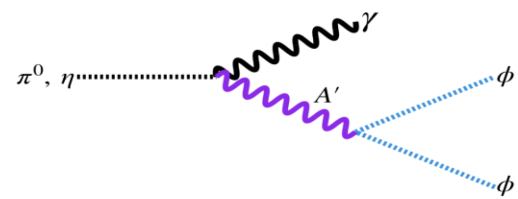


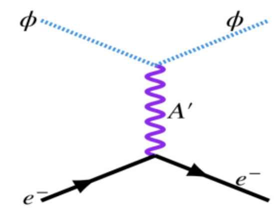



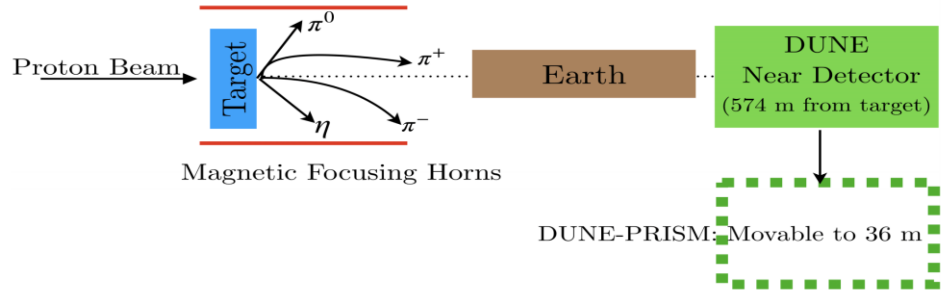



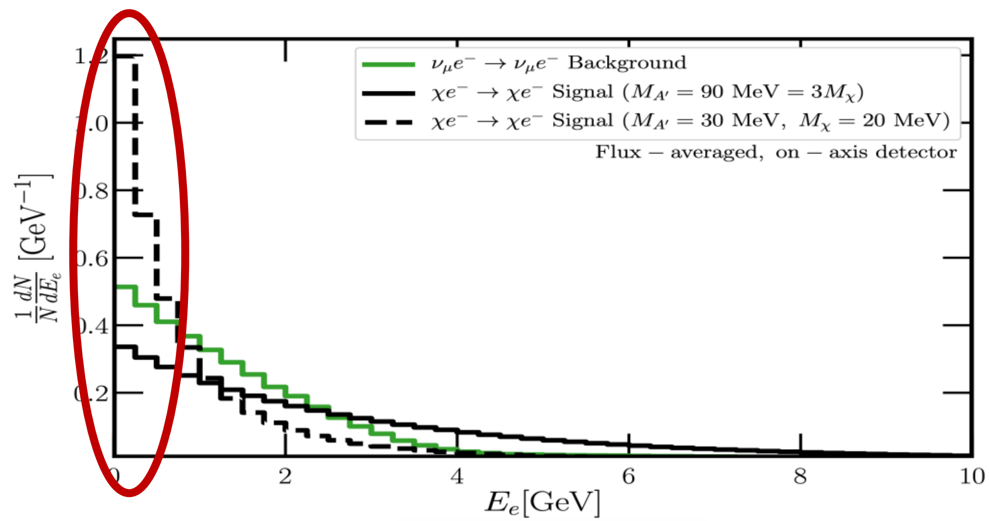
# Light Dark Matter (LDM) Search

- LDM's produced in the target via coupling of dark photon with a SM $\gamma$ 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 $\gamma$
  - 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 $\nu_\mu$ scattering off $e^-$



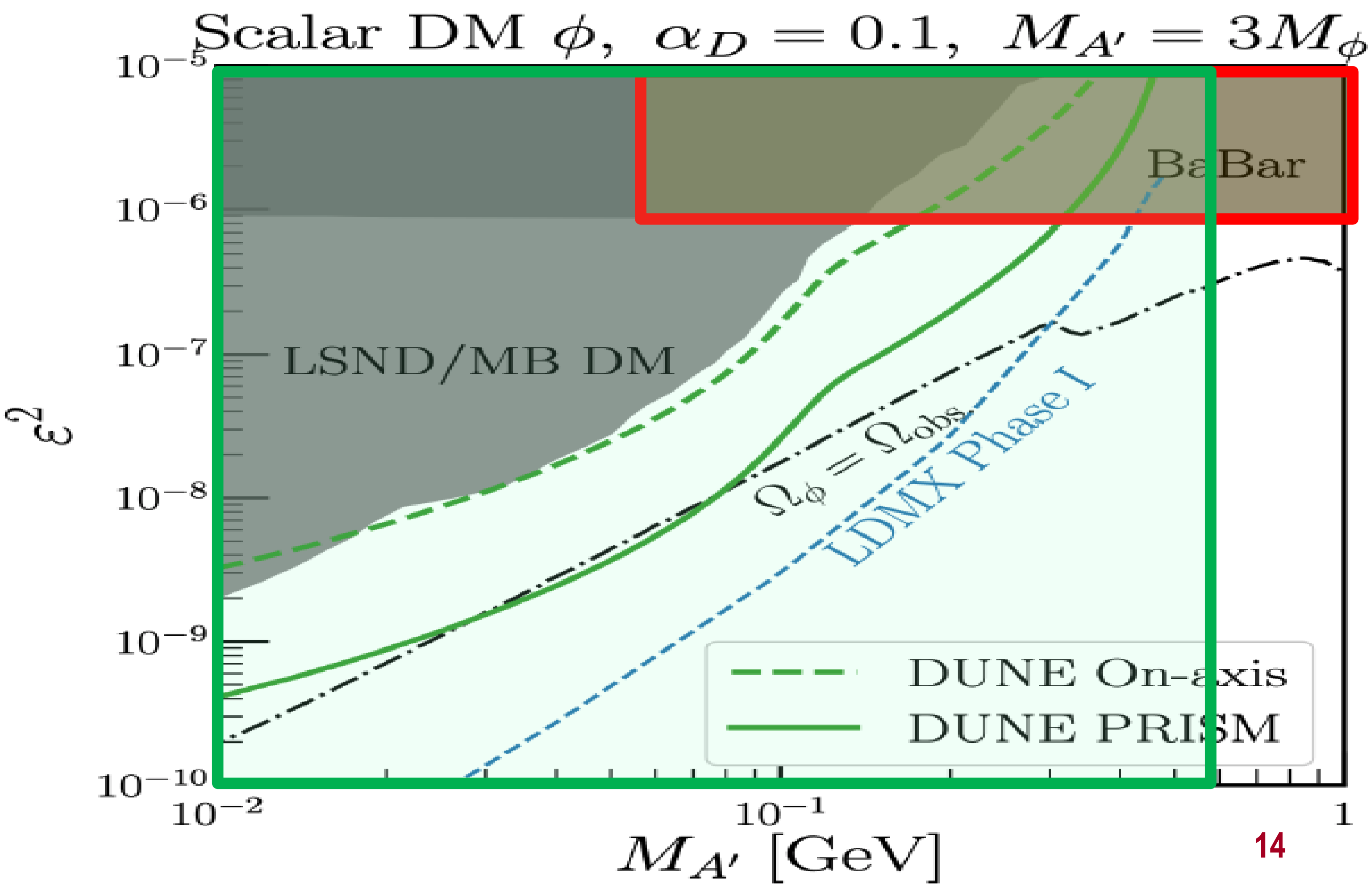



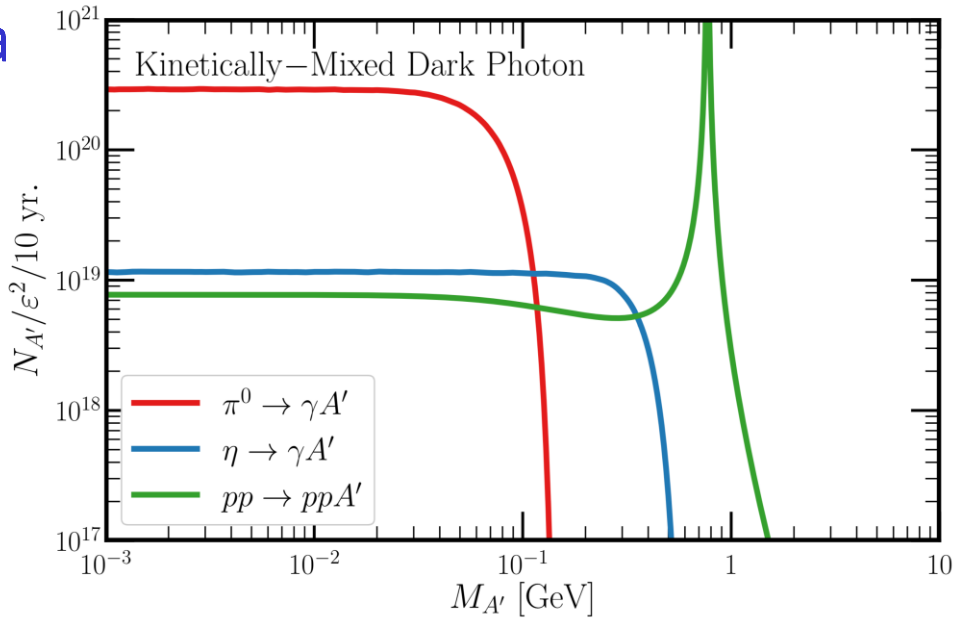
# LDM Search Sensitivity

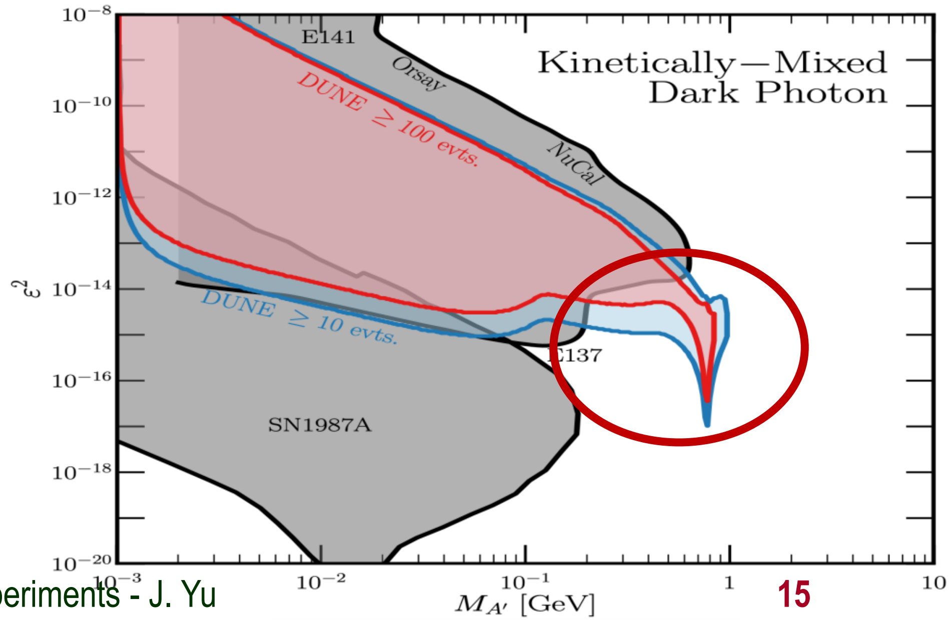
- Search benefits from DUNE PRISM for neutral meson induced LDM
  - Leverage more rapid reduction of $\nu_\mu$ flux than the signal off-axis (De Romeri *et al.*, PRD**100**, 095010, 2019)



# Dark Photon Searches

- New U(1) could kinetically mix with a SM $\gamma$ 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 $\varepsilon_A$'
  - Low energy ν-N interactions essential for backgrounds



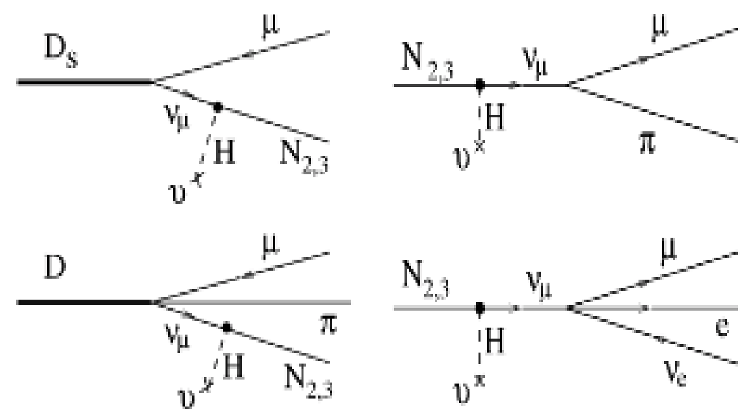



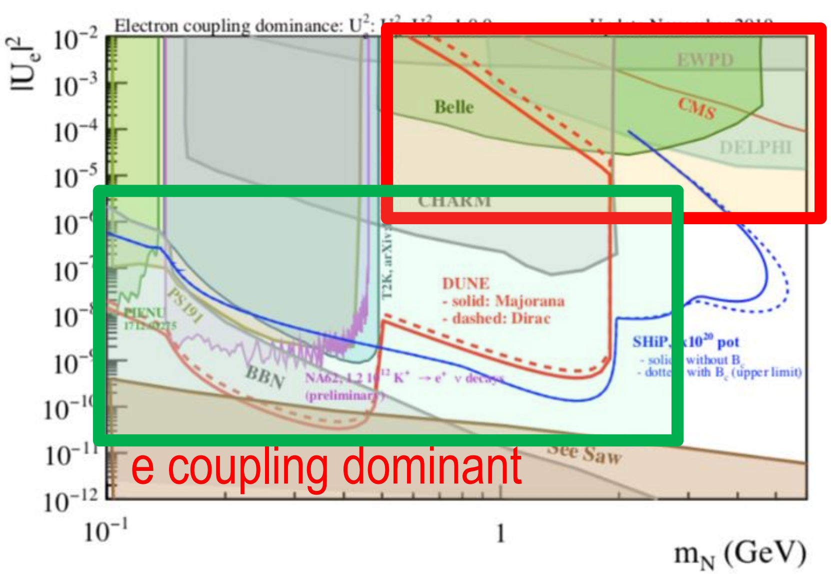

Dev, et al., JHEP07, 166 (2021)

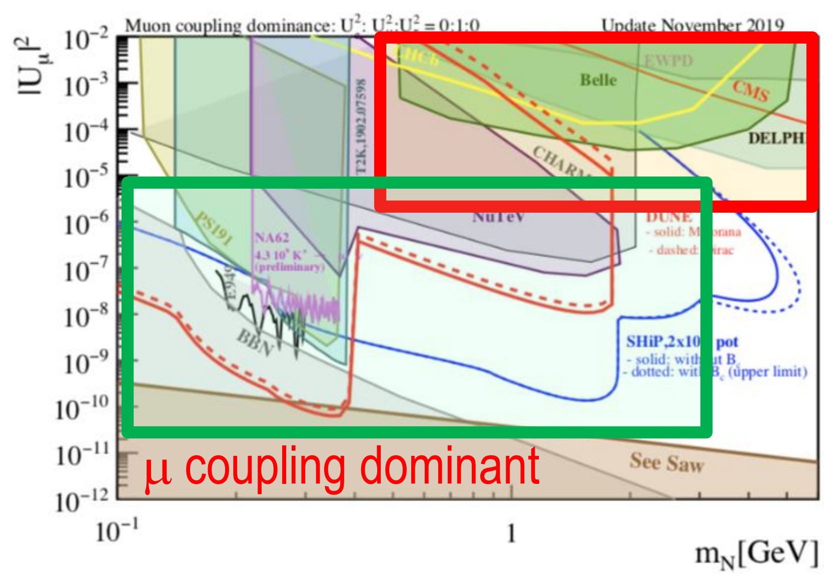
# HNL Searches @ DUNE ND

- 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**

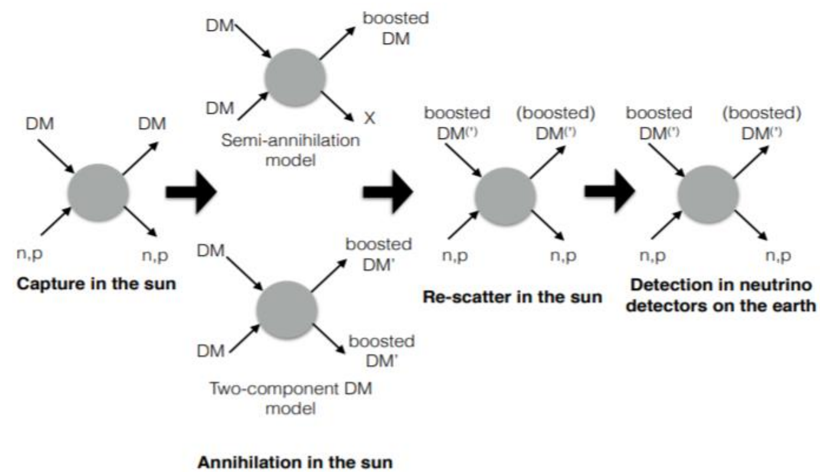


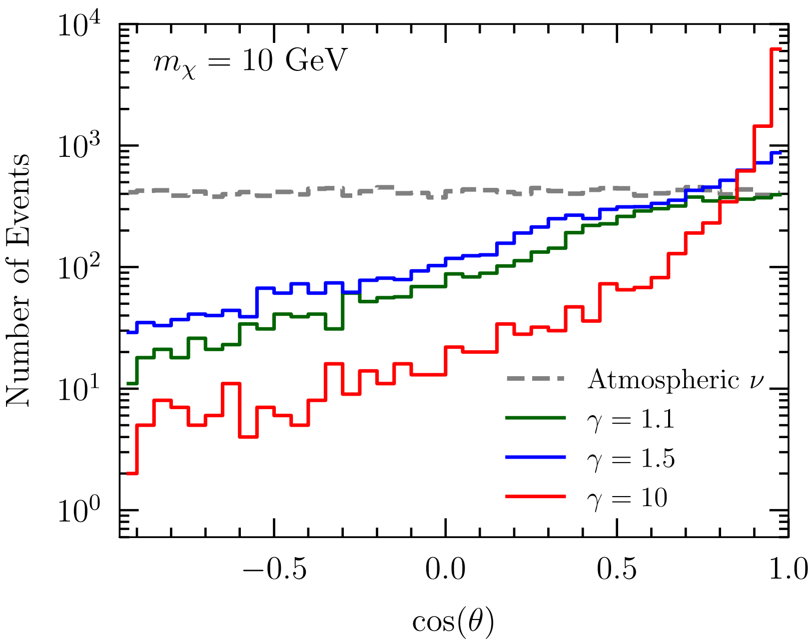



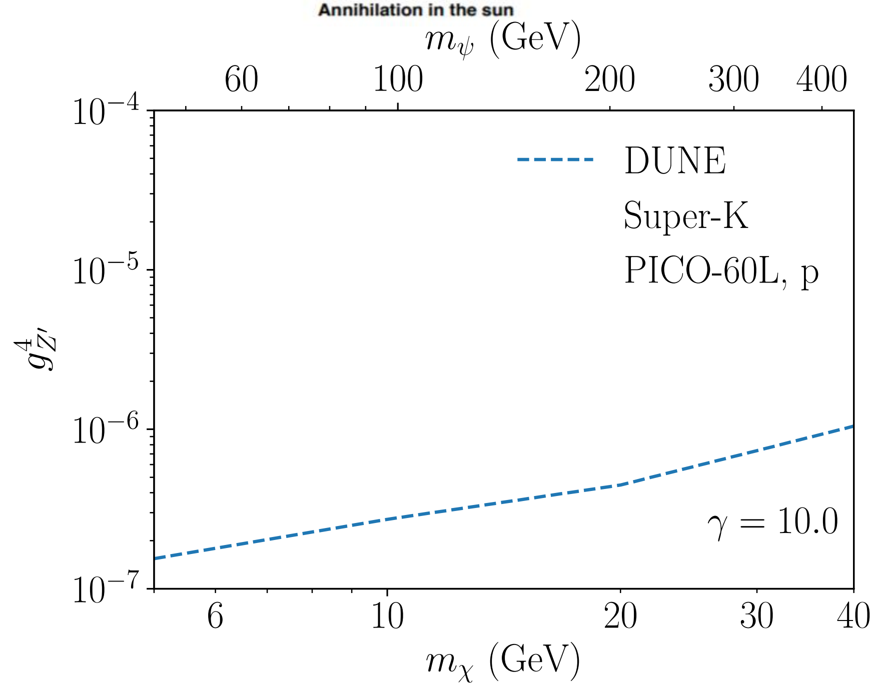



# BDM Searches @ DUNE FD

- 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 n-N interaction challenging

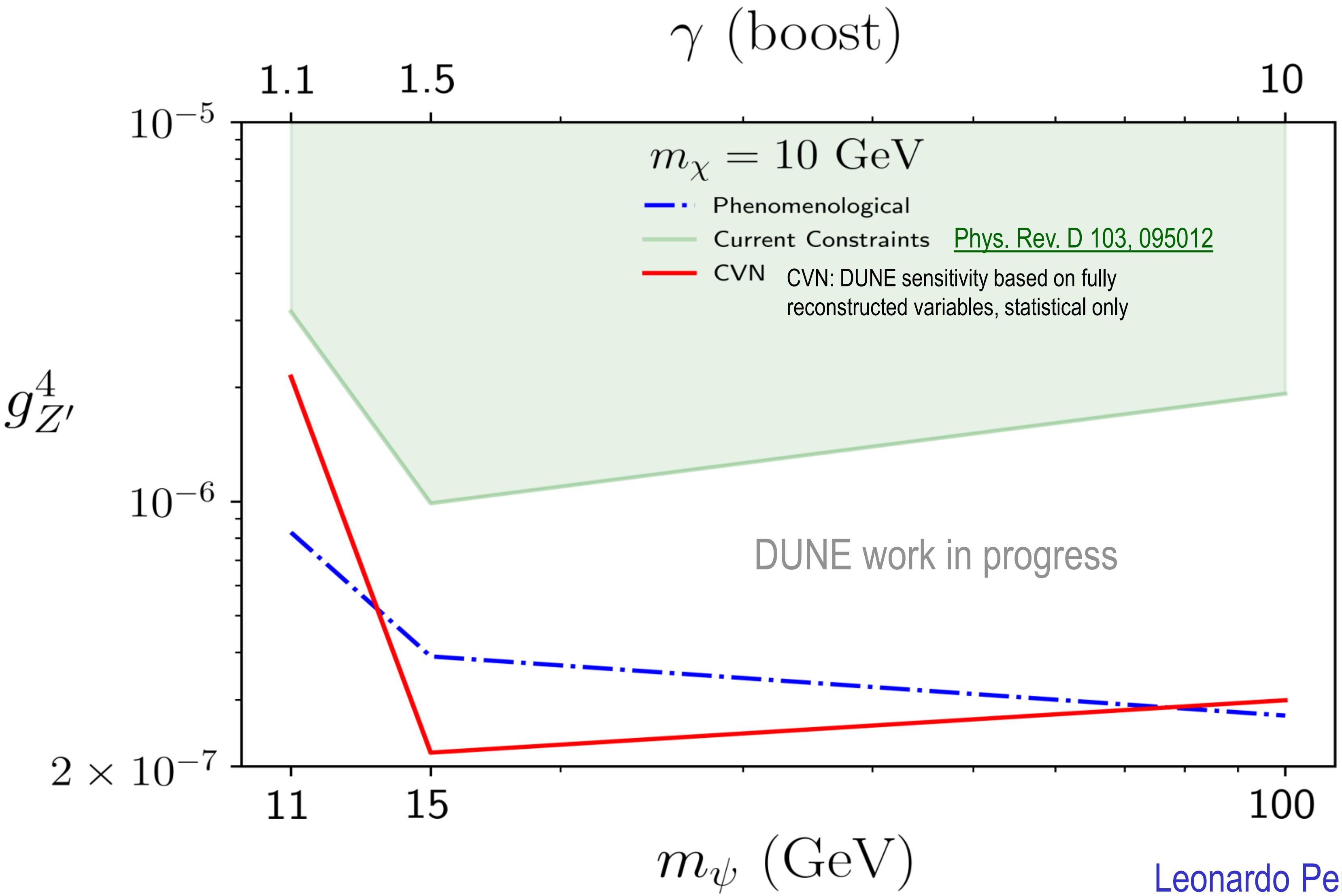



Berger *et al.*, PRD103, 095012, 2021

# BDM Sensitivity Reach



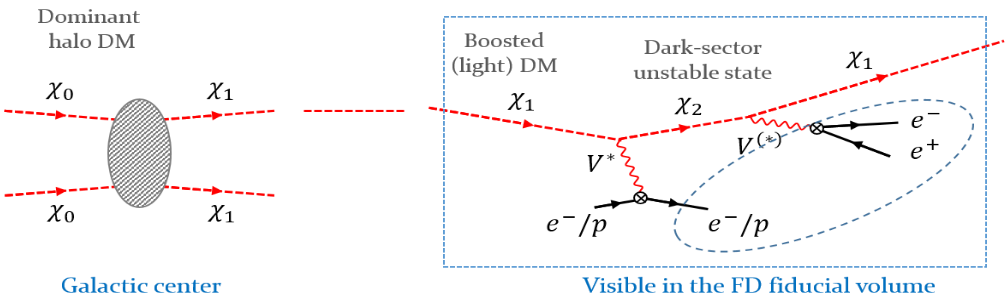

Leonardo Peres

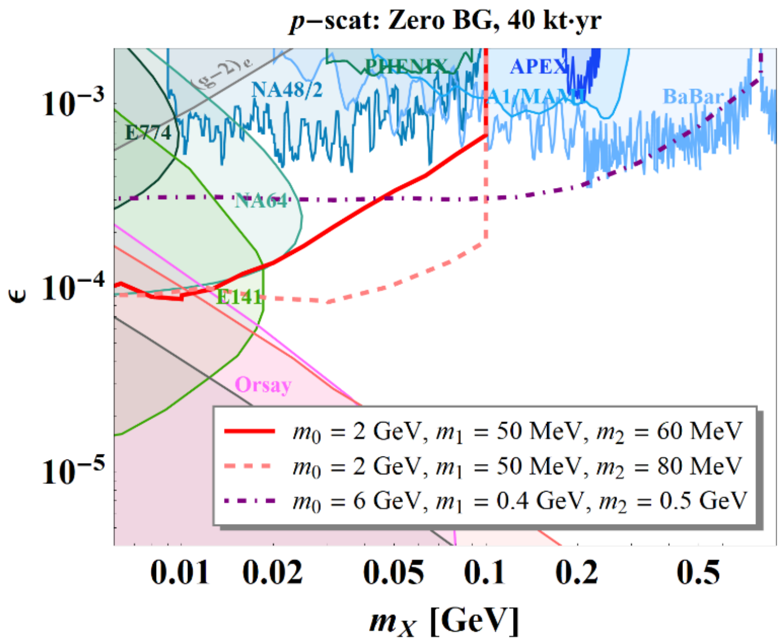


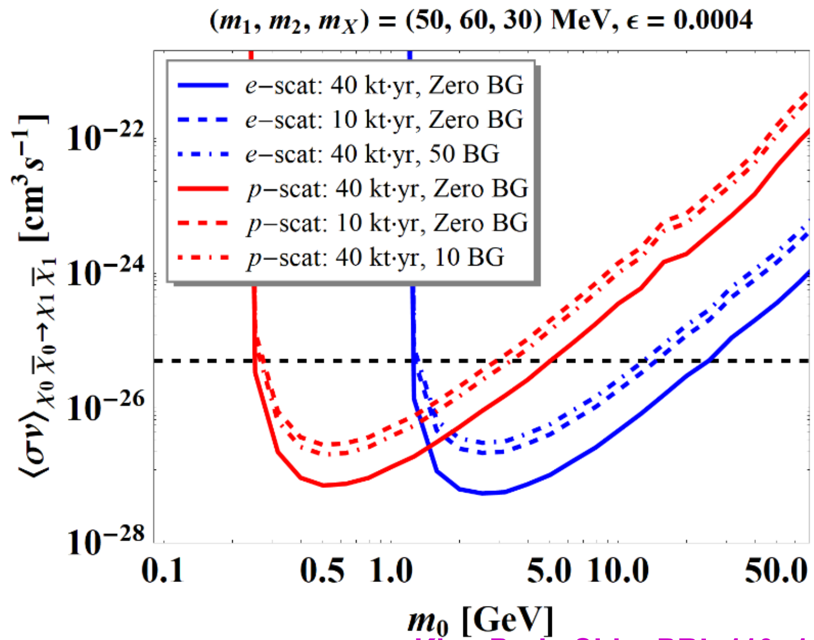
Y. Tsai

# 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

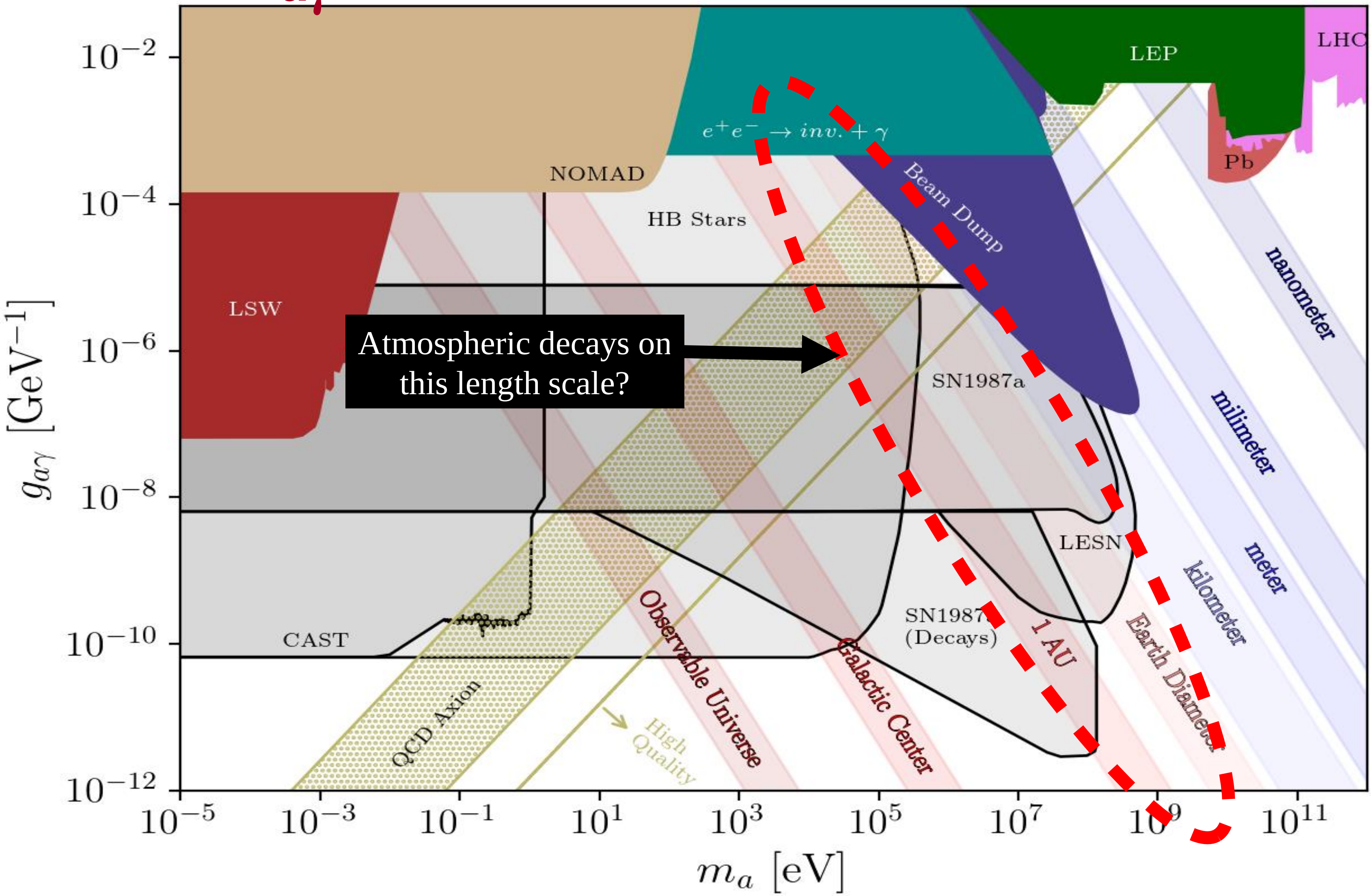



Kim, Park, Shin, PRL 119, 161801, 2017

# ALP $g_{a\gamma}$ Sensitivity Coverage Potential




A. Thomson

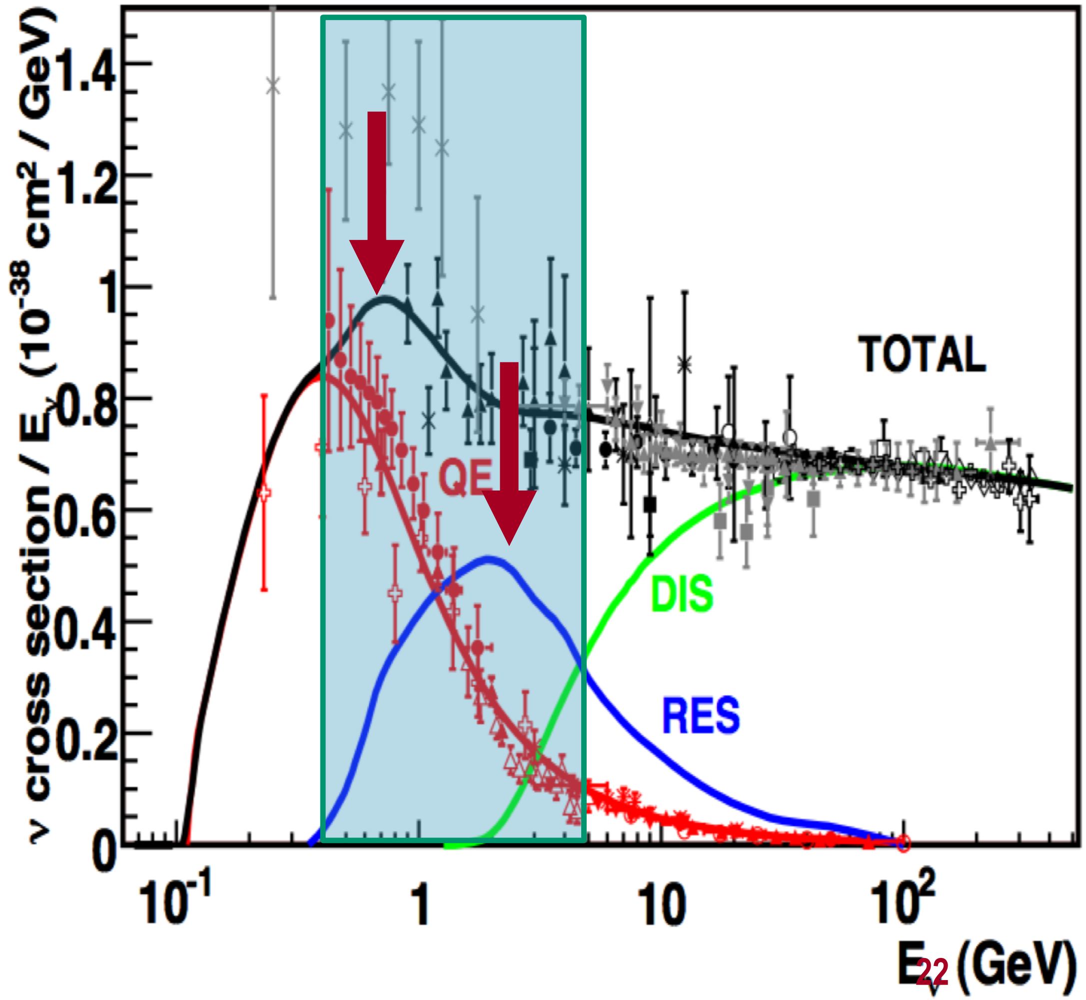
# Signature & Backgrounds of BSM@$\nu$

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

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

# Low E ν Interactions

- QE & RES dominates ν-N interactions in $E_\nu$ 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, 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 $\nu$–N have been in existence and continue improving (and new ones appearing – ACHILLES) ➔ but they still have sizeable uncertainties within each and between themselves
- Generators begin to incorporate BSM processes but could take a long time to implement due to insufficient resources ➔ need further strengthening the efforts

# Very different challenges and strategies

- Detector technology
  - LArTPC, Water Cerenkov, Emulsions, etc
- Detector locations
  - Underground versus surface
- Detector dimension parameters
  - Target density, mass, geometric size, etc
- Performance parameters
  - Position resolutions, angular resolutions, vertex resolutions, energy resolutions, energy thresholds, etc
- These determine various experimental strategies
  - Triggering
  - Computing, including data storage and reco & sim

# Considerations for BSM at ND

- Dominant physics would be beam originating BSM
- Large amount of beam $\nu$ backgrounds
- Different cosmic background considerations
  - Underground: cosmic background less of a concern
  - Beam neutrino background interaction in the rocks give backgrounds
  - Shallow depth detectors suffer from cosmic ray bck
    - Could focus on beam originating signatures, reducing the impact
  - Solar & atm $\nu$ interactions still contribute as bck but would be negligible

# Considerations for BSM at FD

- Dominant physics would be oscillatory behavior based BSM & non-beam related BSM, such as cosmogenic DSPs
- Very little beam $\nu$ backgrounds other than those from $\nu$-rock interactions
- Deep underground location helps to keep most cosmic ray backgrounds away
  - Solar and atm $\nu$ interactions still contribute as bck
- Some terrestrial backgrounds which can be rejected, except for neutrons and backgrounds from radioactive impurities
- Need to be able to trigger on the signal by itself

# Critical Capabilities for BSM Signatures

- Identification of low E electron and nucleon recoil ➔ low E threshold
- Ability to resolve two EM particles ➔ good angular resolution
- Ability to identify and correlate a low E electron or nucleon recoil with a vertex of an EM shower pair ➔ High position and vertex resolution
- Increase the number of interactions ➔ Higher target mass

# Considerations for BSM @ $\nu$-exp

- Need to perform detailed studies to provide information for improvements and their impacts to the BSM physics such as
  - Energy thresholds of 10 MeV , 1MeV, 100keV & 10keV
  - Position resolution of 1mm, 0.1mm, 0.01mm (can we do this leveraging the multiple pixel energy deposit pattern?)
  - Angular resolution of 1degree, 0.5 degrees, 0.1 degrees
  - Energy/ dE/dx resolution
  - Vertex resolution
  - Active mass of 1*LAr (10kt), 3*LAr and 5*LAr- the cavern dimension is fixed ➔ increasing the mass means that the detector will have to use denser materials than the first two detectors ➔ e.g. multiple layers of thin plates of W sandwiched w/ Lar
  - Leverage directional information of the sources ➔ New readout chips, such as QPiX or LArPix help in event-by-event bases?

# General BSM@ν Search Strategy?

- Continue developing phenomenology and expanding the potential kinematic ranges to search BSM physics
  - Can we explore everything the EF and CF search in the phase space that are yet to be covered?
  - Can we do SUSY particle searches? Are there phase space that can be complimented by fixed target experiments?
- Integrate and reflect the new signatures into the tools and allow more realistic studies in experiments
  - Need strong final supports to increase the resources adequately for a timely experimental reflections
- Test it at the experiments through measurements
- Feedback to the theory community

# Upcoming LArTPC $\nu$-exp

- In the next few years in LArTPC?
  - ProtoDUNE HD and VD : fall 2023 through end of 2024
    - ~300t and ~200t, respectively ➔ ~ 500 t total
  - SBND: Detector completion expected 2023 ➔ Start taking data in 2024 ➔ $V_A$~ 112t ➔ Focus on beam originating BSM
  - ICARUS: Has been taking data, $V_A$~470t, can see both BNB and NuMI beams ($6^o$ off-axis) ➔ Can do oscillatory behavior and cosmogenic BSM searches + beam originating BSM
  - DUNE FD : Construction completed by 2029 – 2030, Two FD's of 10kt each ➔ Oscillatory behavior and cosmogenic BSM
  - DUNE ND: Construction completed by 2030 - 2031, $V_A$~ 150t ➔ Focus on beam originating BSM

# Upcoming LArTPC ν-exp

| Exp | Depth | VA | d_tgt | Main bck |
|---|---|---|---|---|
| ProtoDUNEs | Surface | ~500t total | NA | Cosmic ray |
| SBND | Surface | ~112t | 100m | Beam ν + Cosmic ray |
| ICARUS | Surface w/ a 3m concrete overburden | ~470t | 600m | Beam ν + reduced Cosmic ray |
| DUNE LArND | ~100m underground | ~150t | ~540m | Beam ν |
| DUNE FD | 1500m underground | 10kt + 10kt | $1.3 \times 10^6$ m | Terrestrial + Impurities |

# Experimental Considerations

- Signal handling → Trigger development
  - Backgrounds affect the total acceptable rates
  - For cosmogenic signatures, the data size could be large → lowering the rates critical
- Reconstruction algorithm development
- Analysis strategy for strengthening the signature while suppressing backgrounds
- Ensuring the signal over data tuning for oscillation analyses
- Systematic uncertainty handling
- Model independent result presentations

# What is needed of tools?

- Rapid phase space scanning capabilities
- Ability to feed the output of a new physics calculations into the detailed detector simulation w/ greatly reduced efforts
- Ability to rapidly double-check the accuracy
  - Tools must be able to reproduce the SM physics and link it with the BSM
- Rapid data analysis and feedback chain
  - More on the experiments' responsibilities
- Ability to vary experiment-relevant quantities and generate realistic simulated events fast!!

# Outcomes wish list – 1

- An overarching strategy to support BSM@$\nu$ activities in a timely and sustainable manner
- A good plan with a clear timeline and milestones to accomplish the established strategy
  - To test and improve the accuracy of the tools → minimize systematic uncertainties on tools
  - To improve performance of the tools, e.g. speed
  - Strategy for theorists and experimentalists to work together for physics from day 1
  - To ensure BSM signatures don't get washed off
  - To ensure sufficient funding supports for tools development

# Outcomes wish list – 2

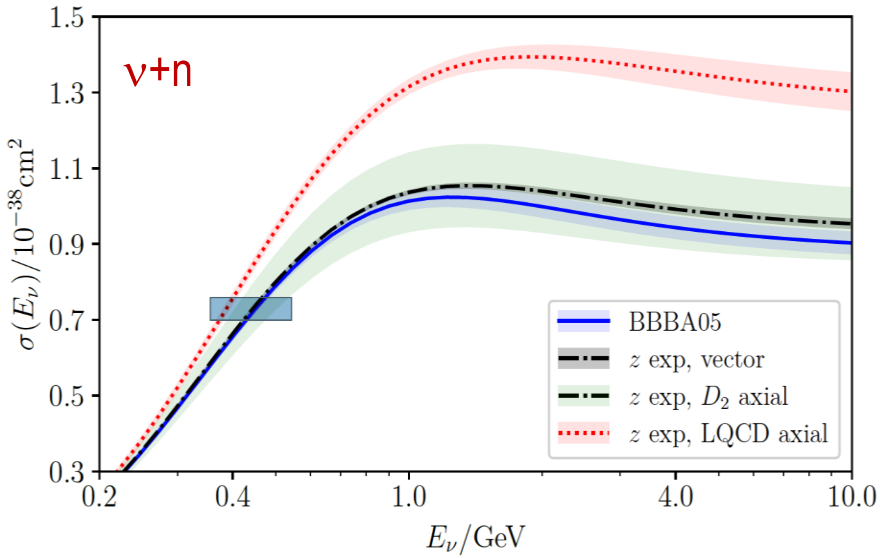
- Plan for using ProtoDUNEs as a testing ground for developing tools and extracting physics
  - ProtoDUNE detectors have a capability trigger on cosmogenic BSM signatures
- Apply the tools and algorithms to SBND for 8GeV beam originating BSM and ICARUS for 120GeV off-axis BSM + cosmogenic searches
- Implement to DUNE and improve for day 1 physics
- Propose a new experiment to strengthen the BSM in fixed target experiments or in a muon collider

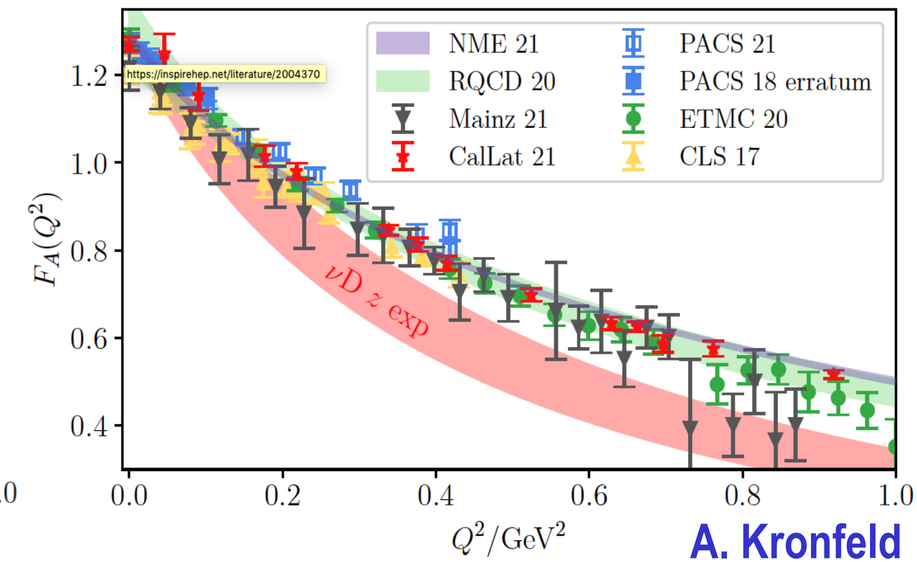
# Conclusions

- $\nu$ experiments have excellent and complimentary BSM capabilities
  - LArTPC detectors (SBN and DUNE) in particular provide the precision and low E thresholds necessary for BSM
- SBN experiments and ProtoDUNEs provide early opportunities to explore BSM@$\nu$ before DUNE and HK
- DUNE Phase – I detector suite already pushes the boundary of BSM in the phase space out of EF & CF but need good tools
- Future detectors like DUNE's MsoO present a great opportunity to make it a even more powerful BSM discovery machine
  - Need to input physics requirements to detector designs NOW
- Tools are essential for timely realistic studies and capturing the signal ➔ Should be thoroughly tested in ProtoDUNE & SBN

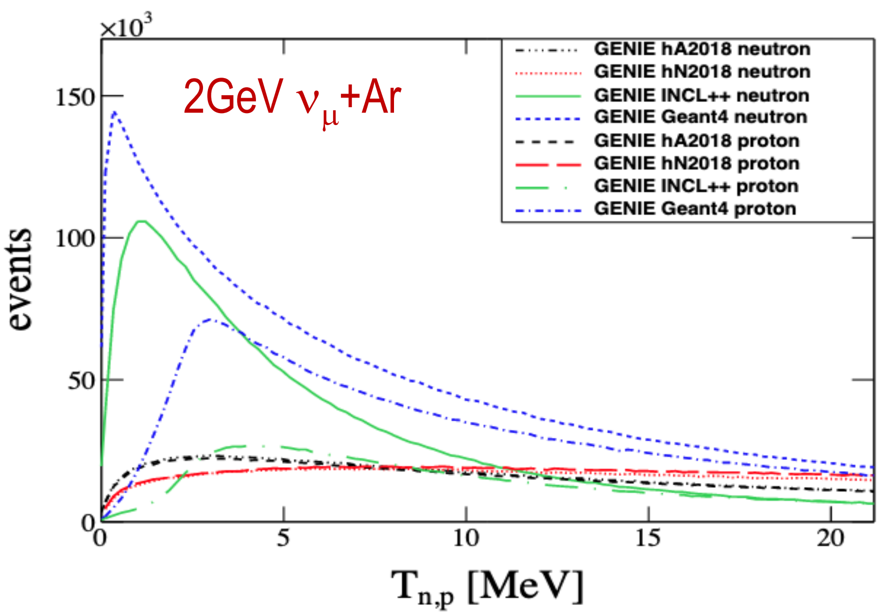
# Additional slides

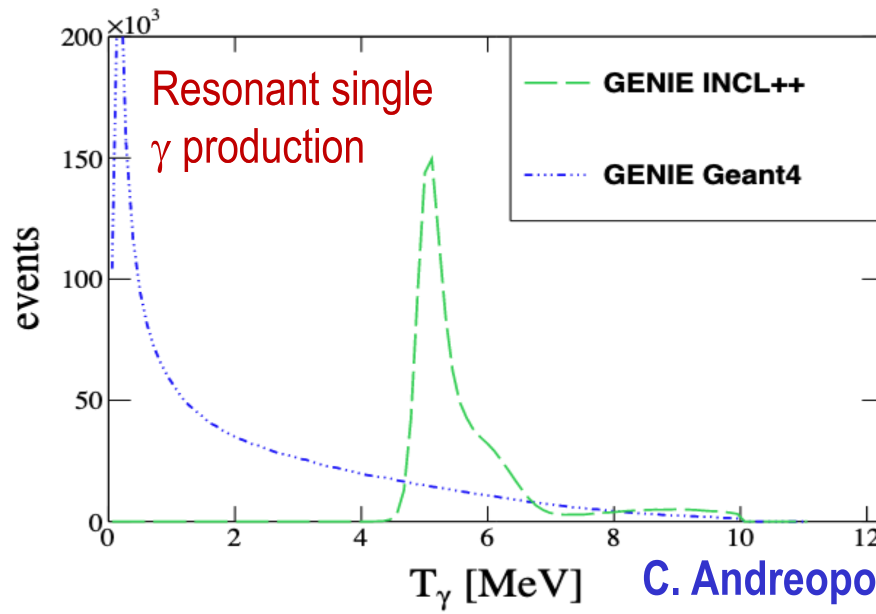
# At the CERN ν-N Interactions workshop..




A. Kronfeld




C. Andreopoulos

# Discussion Points – I

- Signature handling
  - Need simulation tools for signal generations and to perform more realistic studies of the signal
    - Essential for capturing the signal events
- Realistic background estimates and mitigation
  - □ $\nu$ are the primary backgrounds, what does cosmic ray do to DUNE ND BSM physics?
    - Can we cut on $\pi^0$ mass region? What is the impact of such cut?
  - What can we do to help reducing the $\nu$-N interaction modeling in a timely fashion?  When is this become "timely"?
  - Are there anything we can do to mitigate background from the beam?

# Discussion Points – II

- Systematic uncertainties
  - What are the sources of the biggest systematic uncertainties and how do we reduce them? ➔ e.g. $\nu$ flux uncertainty directly impacts the sensitivity
- Detectors and triggers
  - What is the BSM trigger in next gen exp and beyond?
    - Beam based signatures and cosmogenic signatures will require different triggers and background rate handling
  - What capabilities should be incorporated to further enhance BSM opportunities and discovery potential?
- What needs to be done to keep the interests and engagement and testing the whole analysis chain?