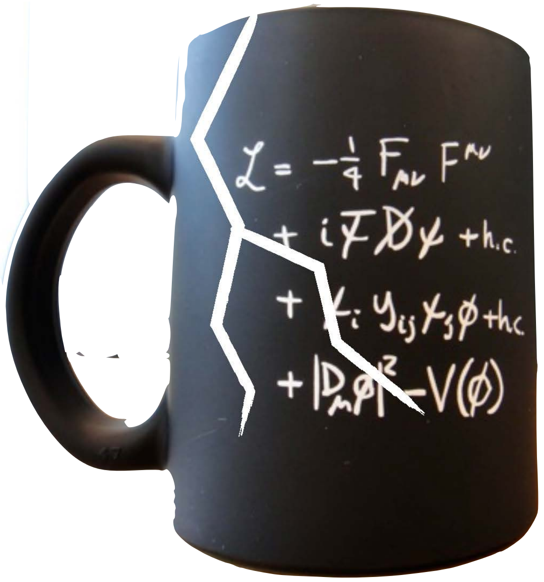
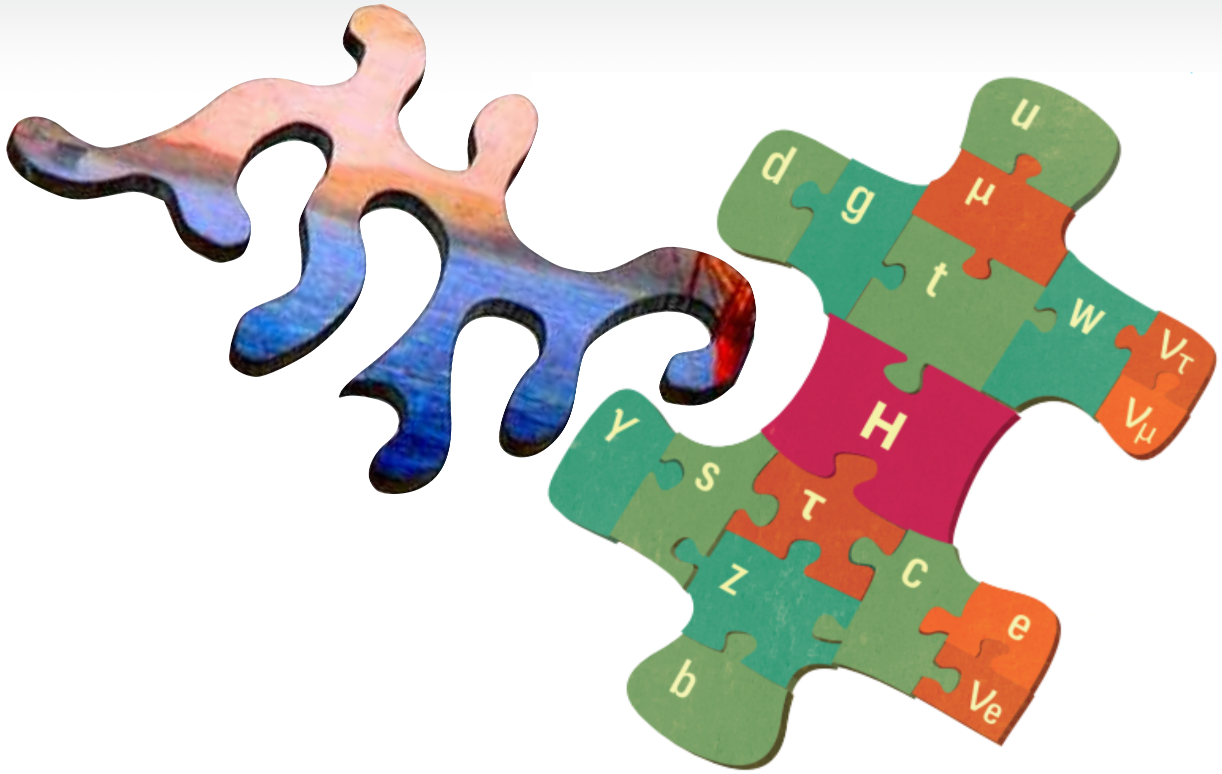


Beyond the Standard Model Physics Group
- Tech Note Review -



Alex Sousa and Jaehoon Yu

for the BSM Physics Working Group

DUNE Collaboration Call

December 14, 2018

BSM Topics and Sub-Group Leaders

- BSM Physics Group Coordination - Jae Yu and Alex Sousa
- **Light Sterile Neutrinos** - Alex Sousa
  - Tech Note Ready
- **Non-Standard ν Interactions/Non-Unitarity/CPT Violation** - Célio Moura
  - Tech Note Ready
- **Low-Mass Dark Matter / Inelastic Boosted Dark Matter** - Animesh Chatterjee and Doojin Kim
  - Tech Note Ready
- **Boosted Dark Matter from the Sun** - Yun-Tse Tsai
  - Tech Note Ready
- **Neutrino Tridents** - Justo Martín-Albo
  - Tech Note Ready
- **ν_τ Physics Opportunities** - Adam Aurisano
  - Work started recently (Spring 2018) - Contributed TDR sub-section
- Tech Notes essential in preparing first draft of BSM Physics TDR section
  - 42 pages not including overhead and references
- Seeking Collaboration input on Tech Notes in preparation for second TDR draft

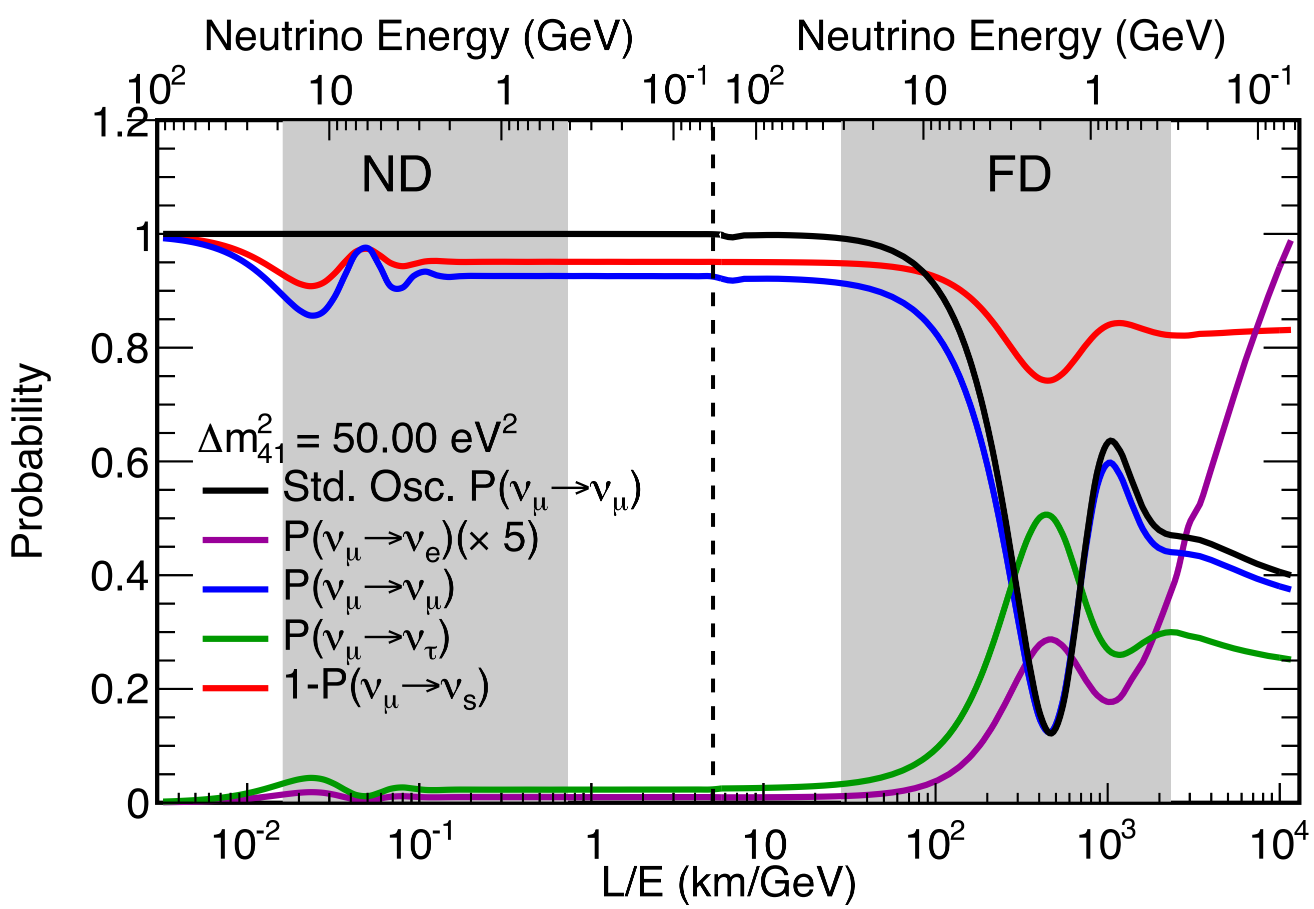
Light Sterile Neutrinos

- Like other current LBL experiments, DUNE will be able to probe active-to-sterile neutrino mixing:
  - **Look for CC and NC disappearance between ND and FD** (and anomalous FD ν_e appearance)
  - **Sensitivity to ν_μ disappearance and ν_e appearance at the ND baselines**

Search for Sterile Neutrinos in DUNE - BSM Physics Tech Note

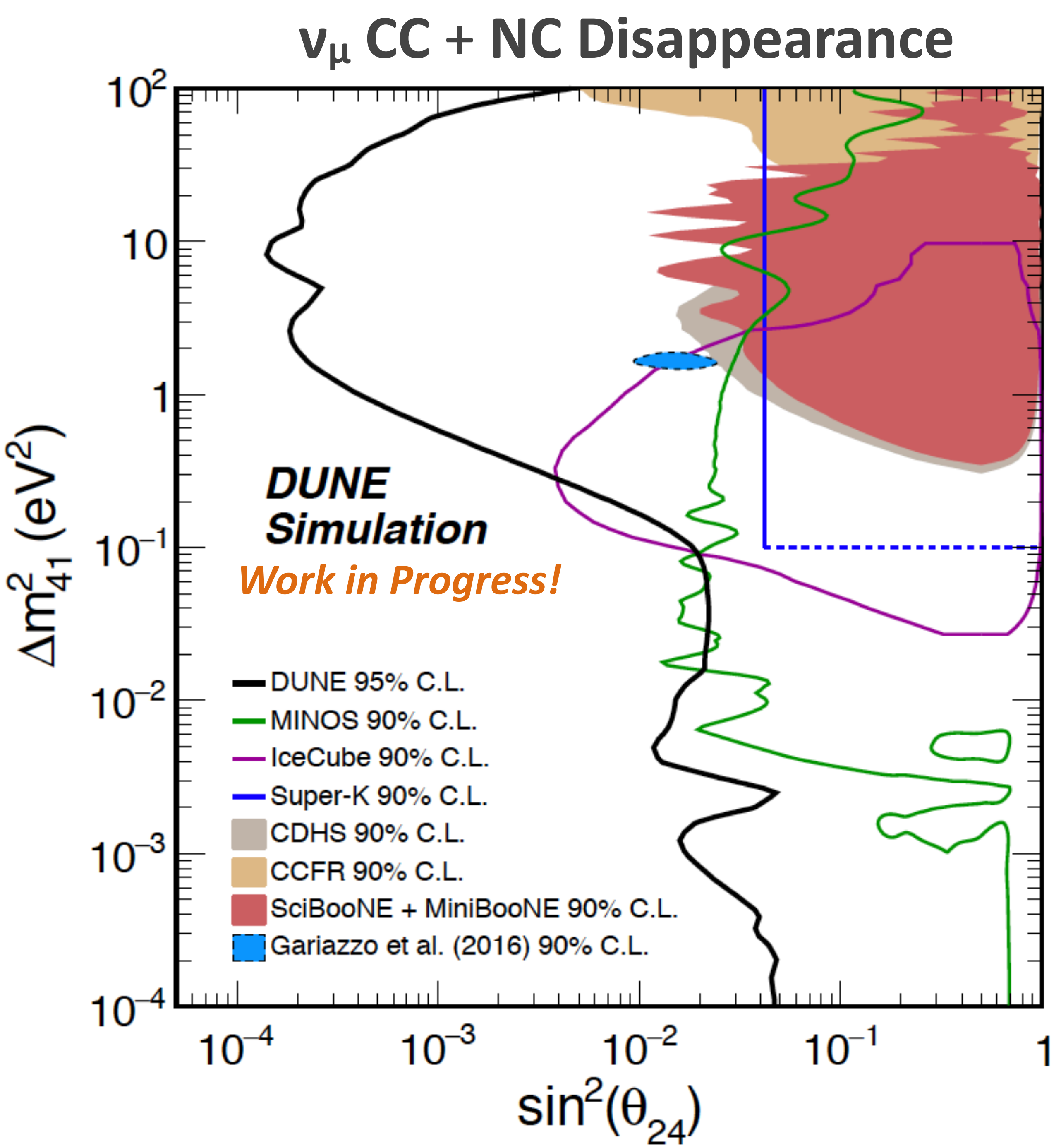
M. Blennow,[1,2] E. Fernandez-Martinez,[1] S. Rosauro-Alcaraz,[1] A. Sousa,[3] and J. Todd[3]
(for the DUNE BSM Physics Group)
[1] *Instituto de Física Teórica UAM/CSIC, Calle Nicolás Cabrera 13-15, Cantoblanco E-28049 Madrid, Spain*
[2] *Department of Physics, School of Engineering Sciences, KTH Royal Institute of Technology, AlbaNova University Center, 106 91 Stockholm, Sweden*
[3] *Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221, USA*

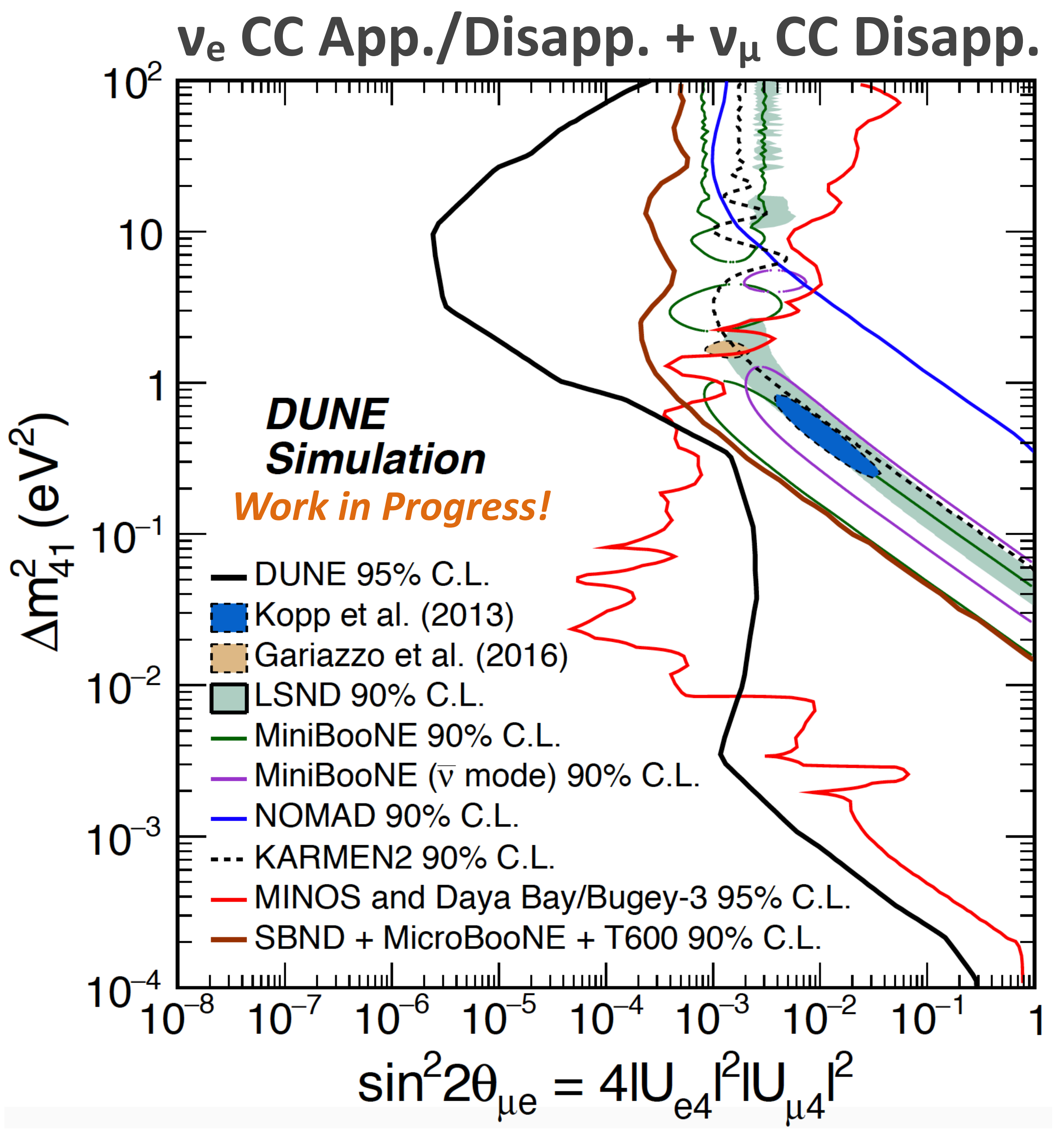
DUNE will be sensitive to active to sterile neutrino oscillations over a broad range of potential sterile neutrino mass splittings. Probing sterile neutrino mixing with DUNE is accomplished by looking for disappearance of charged-current and neutral-current interactions over the long baseline separating the Near and Far detectors, as well as over the short baseline of the Near detector. Additionally, DUNE will also be sensitive to nonstandard disappearance of electron (anti)neutrinos over the Near and Far detector baselines. This note presents the DUNE physics reach for discovering or constraining active neutrino mixing with sterile species obtained using a simultaneous fit to the Far and Near detectors in a GLoBES framework. The contents of this note will be condensed in the BSM Physics section of the DUNE Technical Design Report.



- GLoBES simultaneous fit of Near and Far detectors ($4\times3\times5$ m^3, 83.76 ton LArTPC ND @ 574 m, to be updated)
- 300 Kt.MW.years CDR exposure, 80 GeV reference beam flux as in CDR (to be updated)
- Same reconstruction efficiencies as in CDR
- More realistic systematics with respect to those considered in the CDR
- Account for uncertainty in neutrino production point (or pion decay point) between target and ND

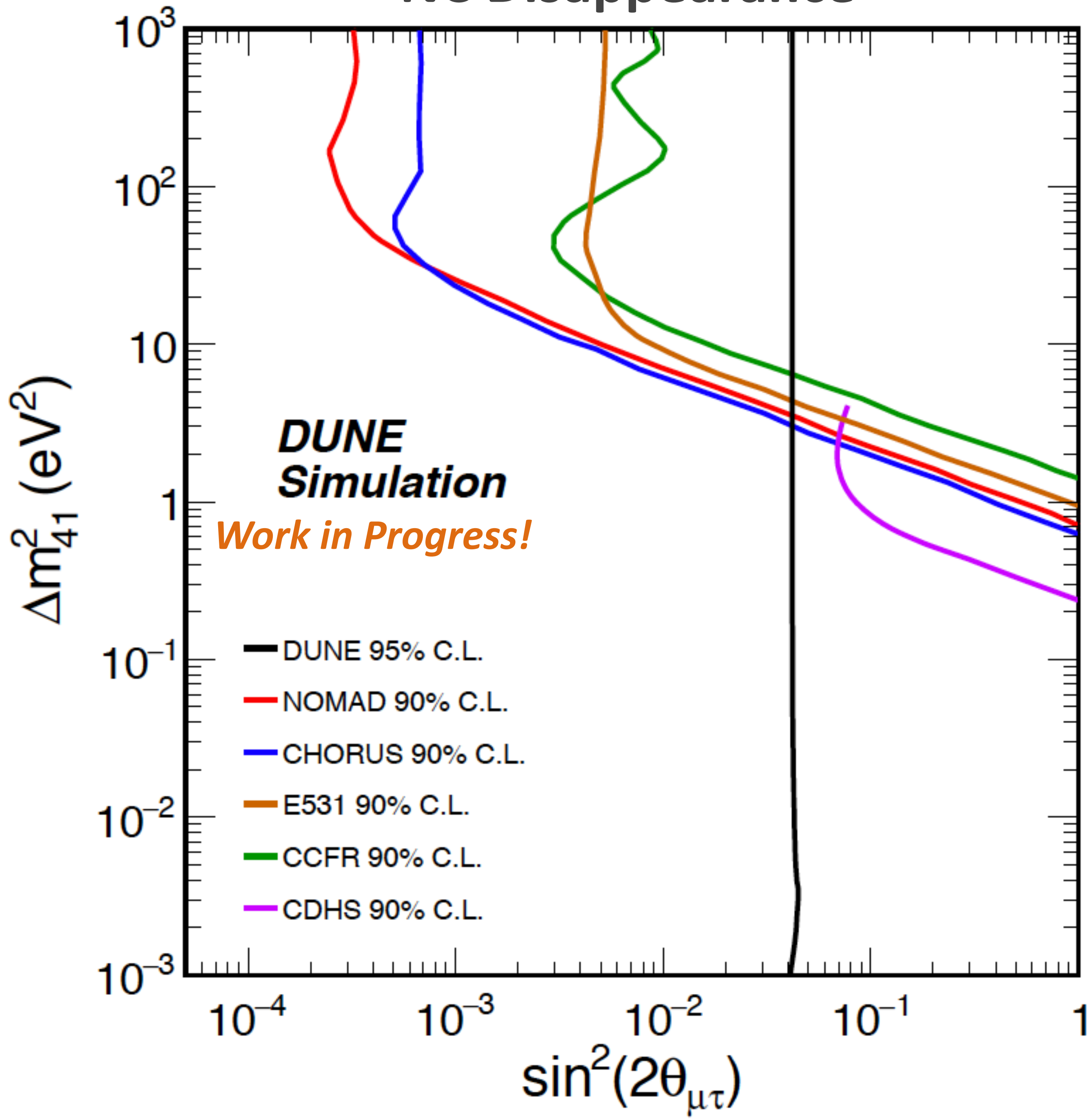
Light Sterile Neutrino Results





Light Sterile Neutrino Results

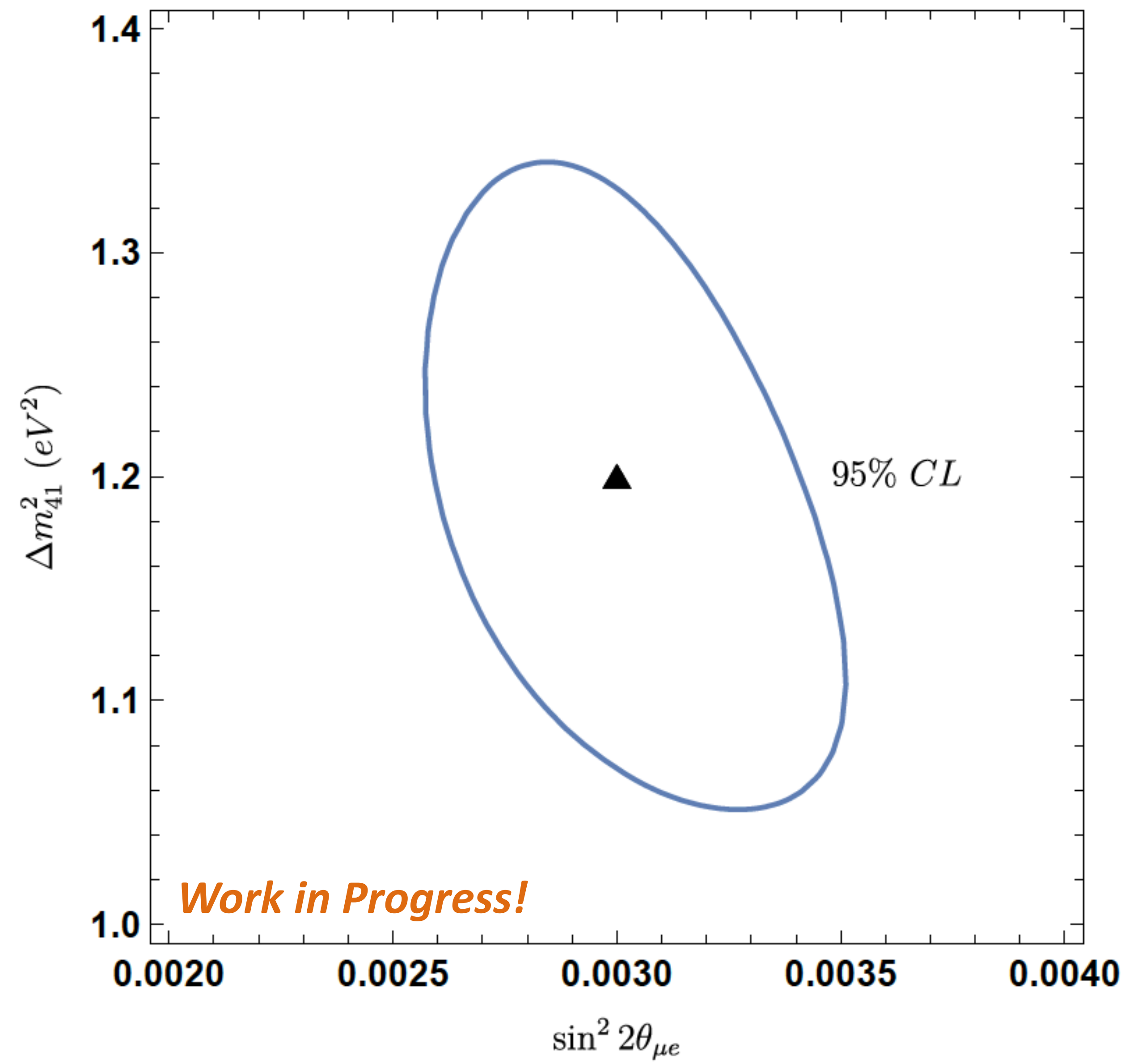
NC Disappearance



$$\sin^2 2\theta_{\mu\tau} \equiv 4|U_{\tau 4}|^2|U_{\mu 4}|^2 = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}$$

Discovery Potential at LSND best fit

$$(\Delta m^2_{14} = 1.2\ \mathrm{eV}^2;\ \sin^2 2\theta_{\mu e} = 0.003)$$



NSI/Non-Unitarity/CPT Violation

- NSI and NU are GLoBES analyses with minimizer replaced by MonteCUBES plugin, which uses Markov Chain Monte Carlo to handle higher-dimensional parameter space
  - *M. Blennow and E. Fernandez-Martinez, arXiv: 0903.3985*

- 300 Kt.MW.years CDR exposure, 80 GeV reference beam flux as in CDR

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

CC NSI
production, detection

$$\mathcal{L}_{NC} = (\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

NC NSI
propagation

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

1

Beyond Standard Model Physics Prospects at DUNE: Searches for NSI, Non-Unitarity, and CPT Symmetry Violation Tech Note

G. Barenboim,[2,5] A. Chatterjee,[4] E. Fernandez-Martinez,[3] D.V. Forero,[6] M.M. Guzzo,[6] F. Kamiya,[7] O.G. Miranda,[1] C.A. Moura,[7] O.L.G. Peres,[6] C.A. Ternes,[5] and M. Tórtola[5]

(For the DUNE BSM Physics Working Group)

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[4] *Department of Physics, University of Texas (Arlington), Arlington, TX 76019, USA*
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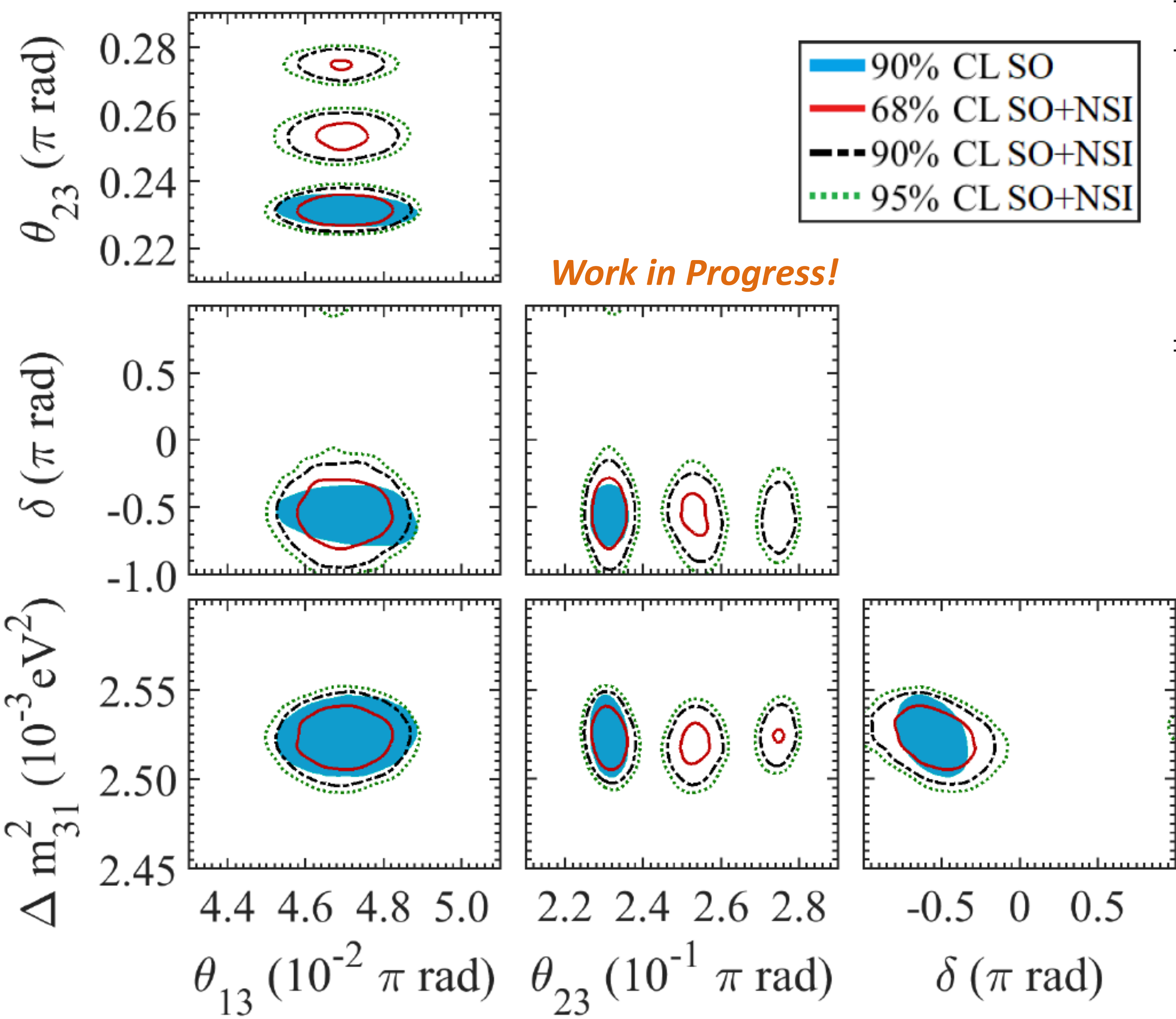
NSI: Non-standard neutrino interactions can significantly modify the data to be collected by DUNE as long as the new physics parameters are large enough. NSI may impact the determination of current unknowns such as CP violation [1, 2], mass hierarchy [3] and octant of θ_{23} [4]. If the DUNE data are consistent with the standard oscillation for three massive neutrinos, interaction effects of order 0.1 G_F, affecting neutrino propagation through the Earth, can be ruled out at DUNE [5, 6]. We notice that DUNE might improve current constraints on $|\epsilon^m_{e\tau}|$ and $|\epsilon^m_{e\mu}|$ by a factor 2-5 [7–9]. **NU:** A generic characteristic of most models explaining the neutrino mass pattern is the presence of heavy neutrino states, beyond the three light states of the Standard Model of particle physics [10–13]. This implies a deviation from unitarity of the 3×3 PMNS matrix, which can be particularly sizable the lower the mass of the extra states are [14–17]. For values of non-unitarity parameter deviations of order 10^{-2}, this would decrease the expected reach of DUNE to the standard parameters, although stronger bounds existing from charged leptons would be able to restore its expected performance [18, 19]. **CPT:** CPT symmetry, the combination of Charge Conjugation, Parity and Time reversal, is a corner-stone of our model building strategy and therefore the repercussions of its potential violation would severely threaten the standard model of particle physics. DUNE can improve the present limits on Lorentz and CPT violation by several orders of magnitude [20–25], contributing as very important experiment to test one of the deepest results of quantum field theory.

- If new heavy states mix with active neutrinos (*e.g.* if neutrinos acquire mass through a type I seesaw mechanism), the mixing matrix need not be unitary

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U^{3\times 3}$$

NSI Searches

- Projected DUNE measurements of Std. Osc. parameters with and without NSI



Parameter	Nominal	1σ range ($\pm$)
θ_{12}	0.19π rad	2.29%
$\sin^2(2\theta_{13})$	0.08470	0.00292
$\sin^2(2\theta_{23})$	0.9860	0.0123
Δm^2_{21}	$7.5\times10^{-5}\mathrm{eV}^2$	2.53%
Δm^2_{31}	$2.524\times10^{-3}\mathrm{eV}^2$	free
δ_{CP}	1.45π rad	free

- DUNE may potentially improve present constraints on $|\varepsilon_{e\tau}|$ and $|\varepsilon_{e\mu}|$ by at least a factor of **2**:
  - *T. Ohlsson, arXiv:1209.2710*
  - *O. G. Miranda and H. Nunokawa, arXiv:1505.06254*
  - *Y. Farzan and M. Tortola, arXiv: 1710.09360*

Non-Unitary Mixing

- If new heavy states mix with active neutrinos (*e.g.* if neutrinos acquire mass through a type I seesaw mechanism), the mixing matrix need not be unitary

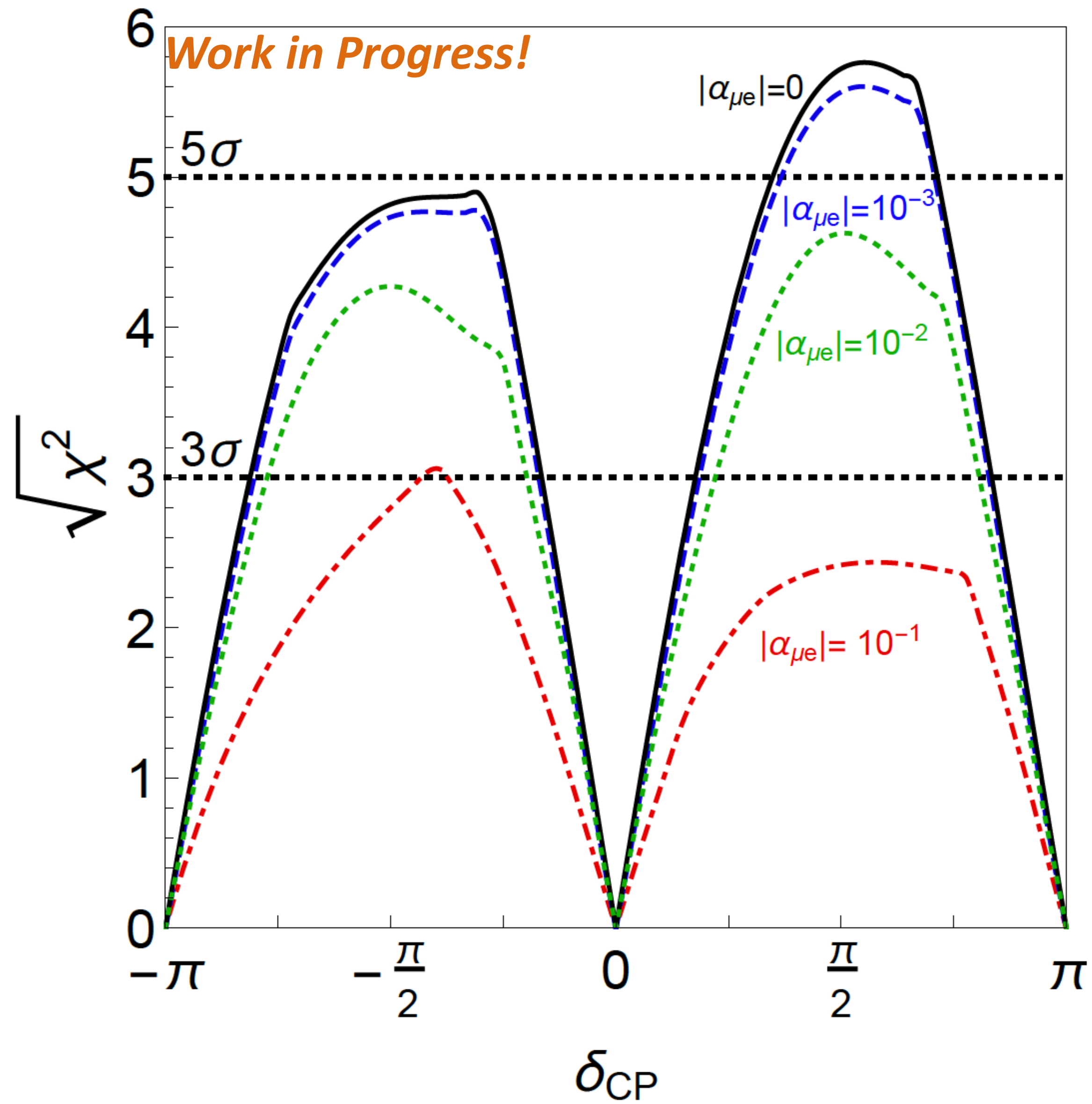
$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U^{3\times 3}$$

90% CL constraints on the non-unitarity parameters

α_{ee}	0.3	$\alpha_{\mu e}$	0.04
$\alpha_{\mu\mu}$	0.2	$\alpha_{\tau e}$	0.7
$\alpha_{\tau\tau}$	0.8	$\alpha_{\tau\mu}$	0.2

Work in Progress!

- bounds comparable with constraints from present oscillation experiments, but are not competitive with those obtained from flavor and electroweak precision data.



- Impact of non-unitarity on the DUNE CP violation discovery potential

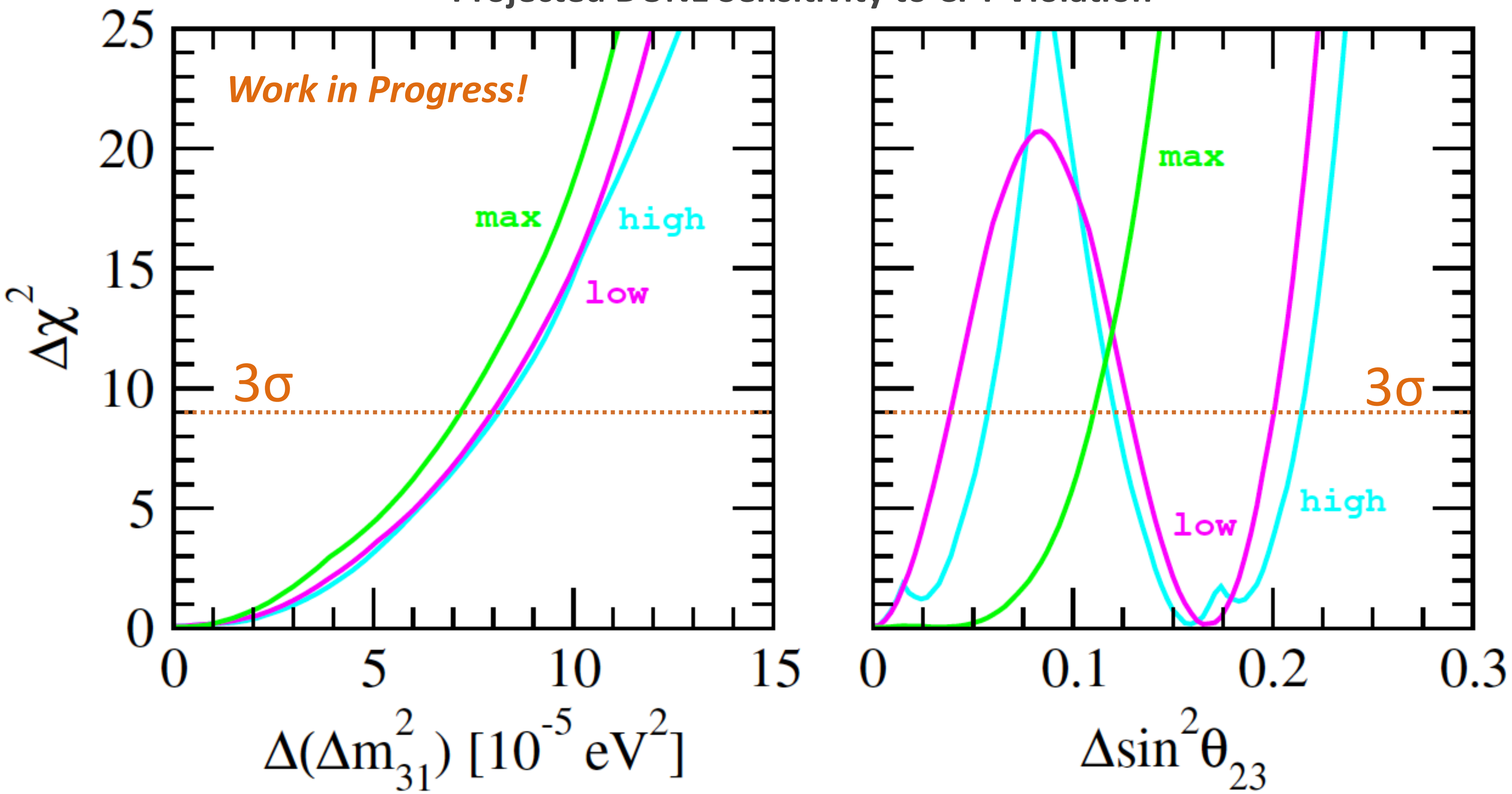
CPT Violation

- Present 3σ bounds on CPT Violation from neutrino oscillation experiments

$$|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| < 4.7 \times 10^{-5}\,\mathrm{eV}^2$$
$$|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| < 3.7 \times 10^{-4}\,\mathrm{eV}^2$$

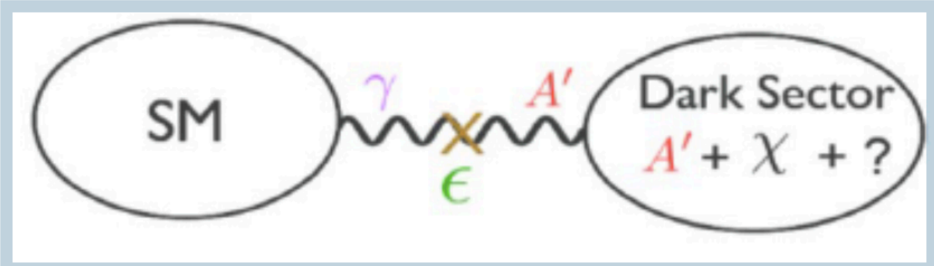
$$|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| < 0.14$$
$$|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| < 0.03$$
$$|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| < 0.32$$

Projected DUNE Sensitivity to CPT Violation

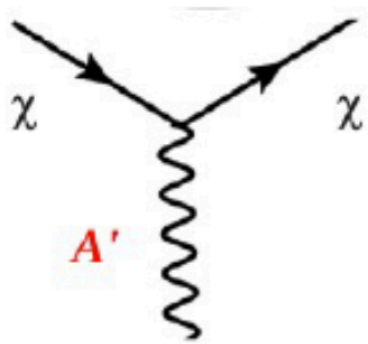


- Different lines show maximal mixing, and upper and higher octants of θ_{23}
- DUNE can improve current limit on $\Delta(\Delta m^2_{31})$ by almost one order of magnitude

Low-Mass Dark Matter



- **Minimal model**
- A′ interacts with γ through kinetic mixing
- Dark matter particle χ interact with A′ with coupling α



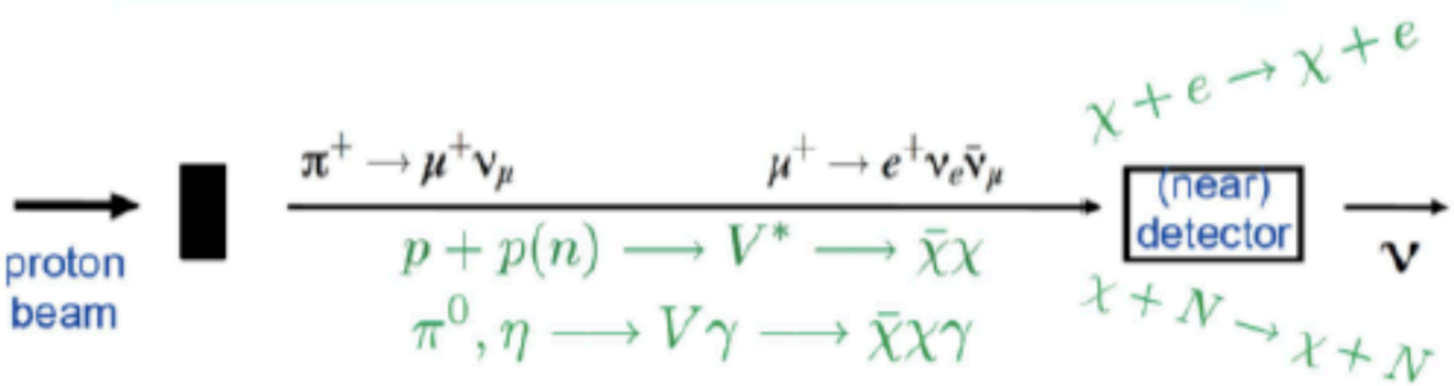
A' production: $\sigma \propto \varepsilon^2$

Searching for Low-mass Dark Matter at the DUNE Near Detector and Inelastic Boosted Dark Matter at the DUNE Far Detectors

Garrett Brown, Animesh Chatterjee, Doojin Kim, Jong-Chul Park,
Seodong Shin and Jaehoon Yu

The null observation of dark matter signatures at direct/indirect detection and the LHC experiments (mostly aiming at WIMPs) is motivating to contemplate alternative approaches. Of them, the search for dark matter with mass being much smaller than the electroweak scale (e.g., below the GeV level) has received rising attention. The detector technologies adopted in the DUNE experiment makes it possible to have sensitivity to relevant signals. In this context, we investigate the detection prospects for such dark matter at DUNE near and far detectors. Regarding the near detector, we assume that dark matter is created via the proton beam and scatters elastically off an electron in detector material. For the far detectors, we consider the situation that boosted dark matter, which often arises in two-component dark matter scenarios, comes from the galactic halo, and up-scatters to a heavier dark-sector state which subsequently disintegrates to additional visible particle(s) (a.k.a *in*elastic boosted dark matter). The interactions between such light dark matter and Standard Model particles are described by a vector "portal" scenario, and we find that DUNE can probe a broad range of unexplored parameter space.

- **Dark matter production at fixed target experiment**



- Look for elastic electron scattering signal

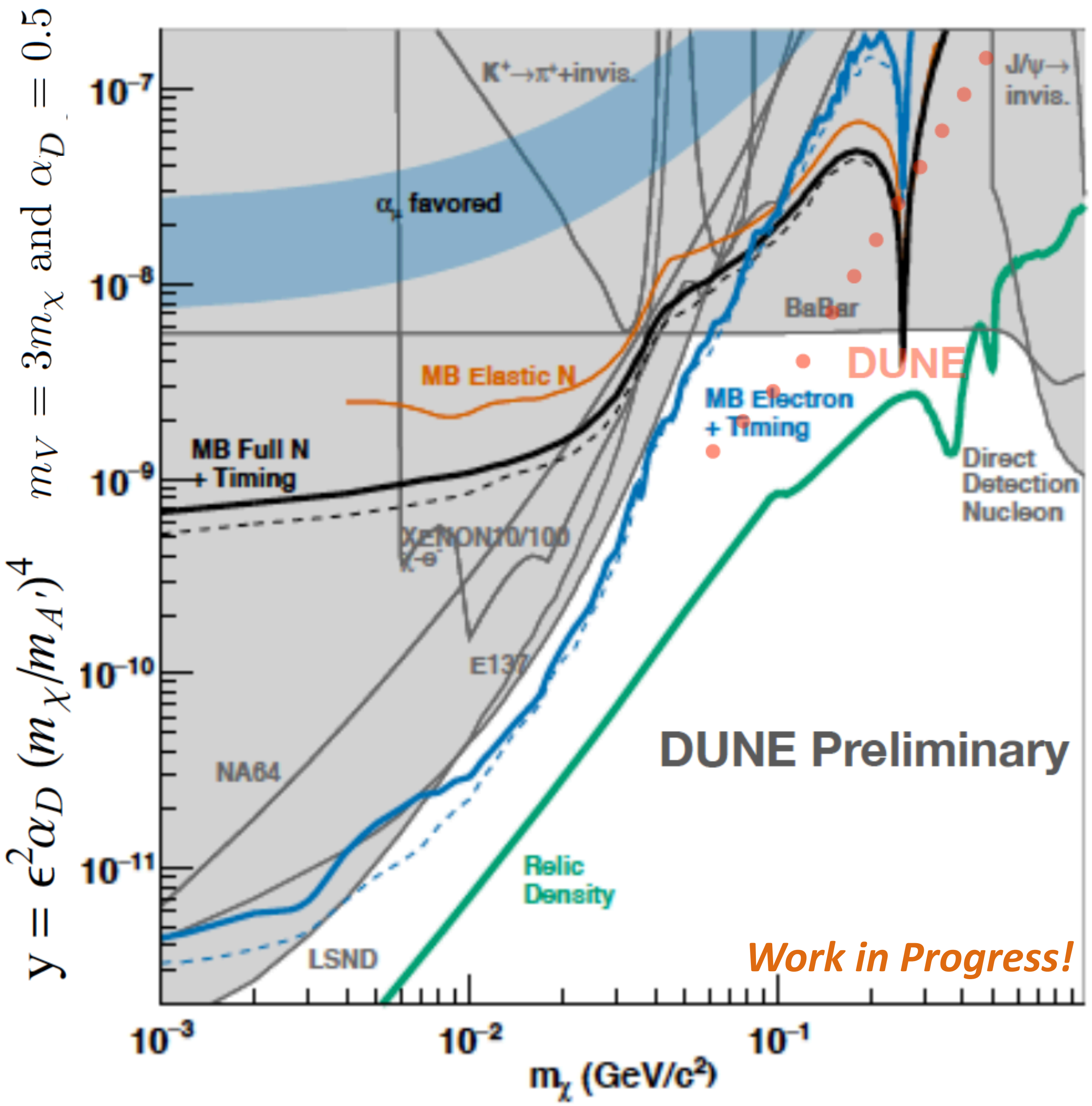
- Generate 50 million DM events for each set of DM parameters using MadGraph5 in fixed target mode
- The Near Detector is located at a distance of 570 m from the target
- ND fiducial volume of 4m(W) x 3m(H) x 5m (L), mass of 85 ton
- Considering DM-electron scattering. Look for electron recoils. Main bkg. from beam ν - electron scattering
- Selection uses recoil energy and angle kinematic variables

Low-Mass DM Results

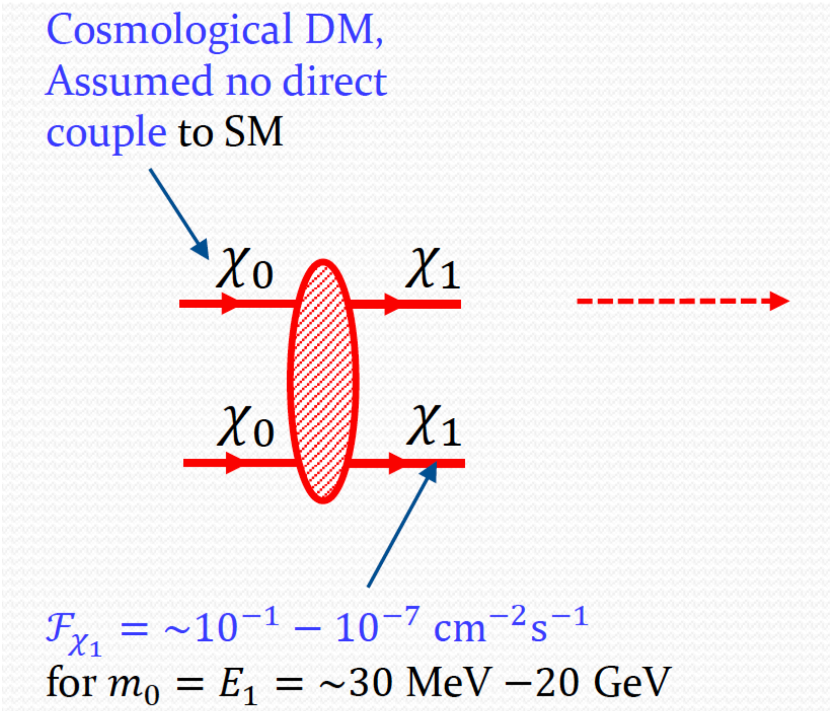
- The analysis done with 1.2 MW of beam power with 50% duty cycle
- 3.5 Years of data

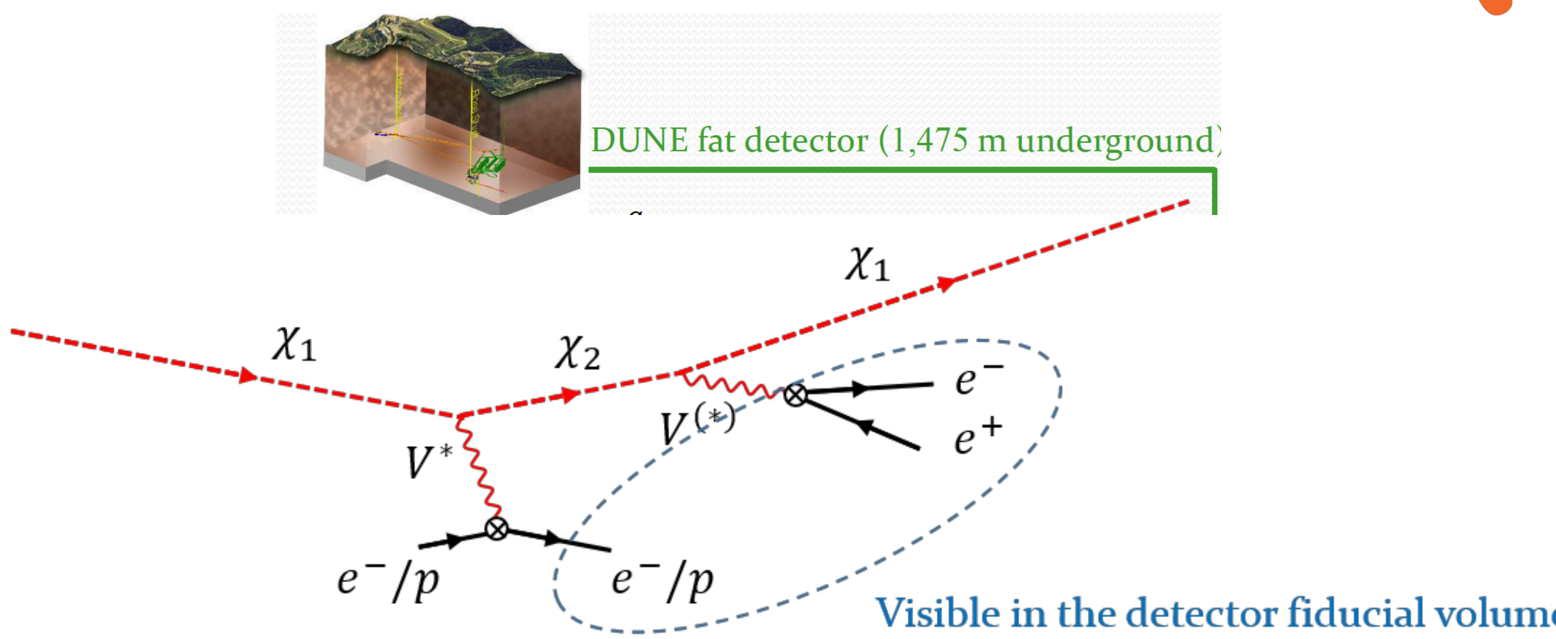
- **Uncertainties used:**
- Flux =20%
- Cross-section = 10%
- Scattering angle of electron = 5%
- Detector sys = 5%

- **Detector properties :**
- **Efficiency 80%**
- **$\sigma = 5\%/\sqrt{E}$**



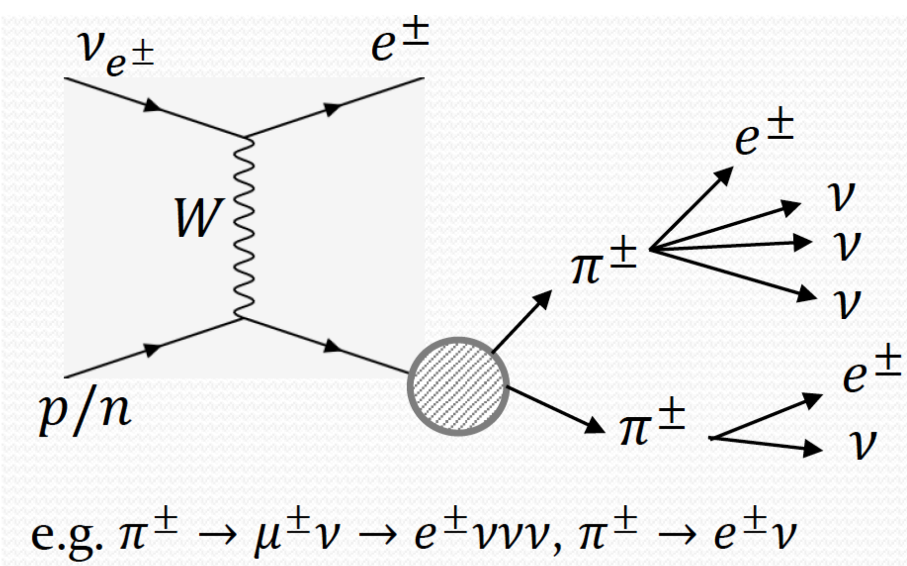
Inelastic Boosted Dark Matter

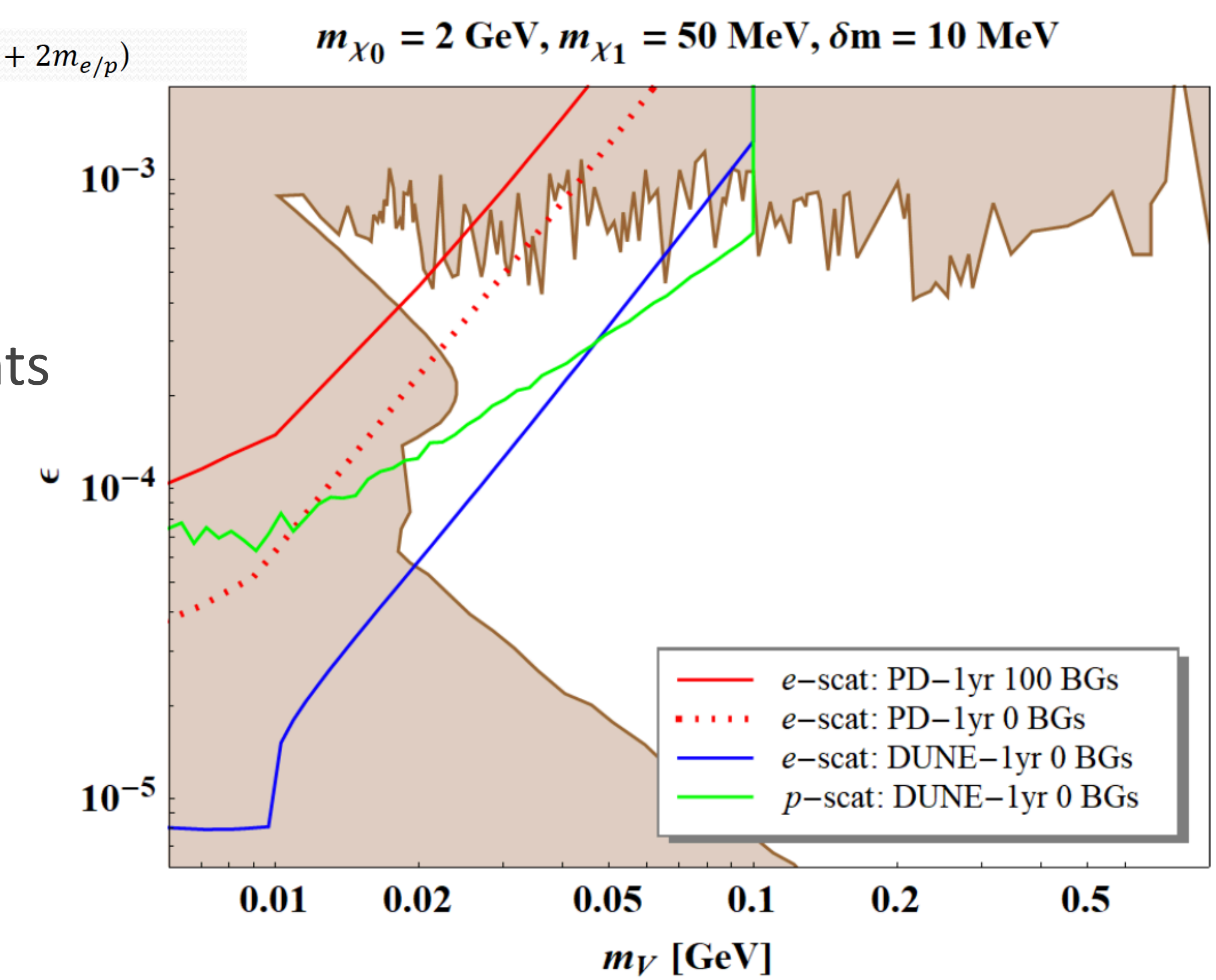




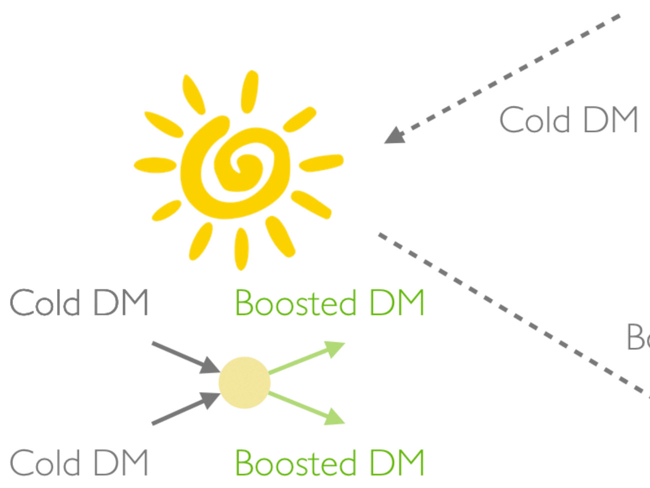
❑ Dark photon (X) scenario as a benchmark model, inelastic scattering of χ_1 (i.e., $m_2 > m_1 + 2m_{e/p}$)

- Main bg. from ν_e CC-induced multi-track events





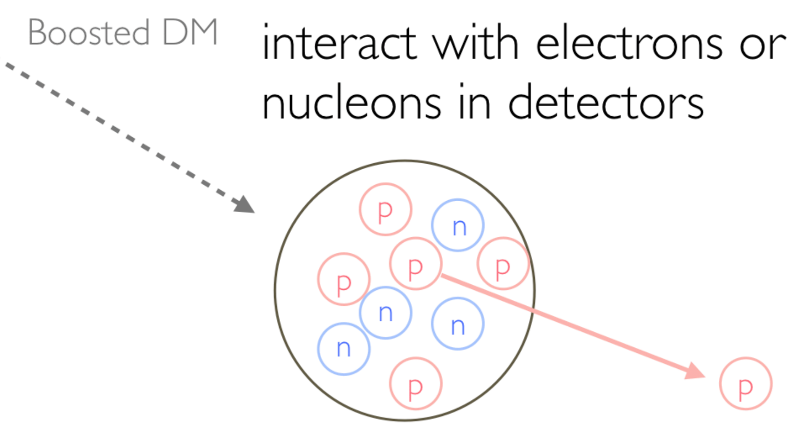
Boosted Dark Matter from the Sun



1. Cold dark matter captured by dark matter concentrated region, such as the Sun or Galaxy Center

2. Produce lighter, boosted dark matter via annihilation or decay

3. Boosted dark matter interact with electrons or nucleons in detectors



4. Look for scattered electrons or recoil protons

Refs: J. Berger's Talk, JCAP 1502 (2015) 005

Search for Boosted Dark Matter in DUNE

Josh Berger
Physics Department, University of Pittsburg

Yun-Tse Tsai, Gianluca Petrillo, Dane Stocks, Mathew Graham, and Mark Convery
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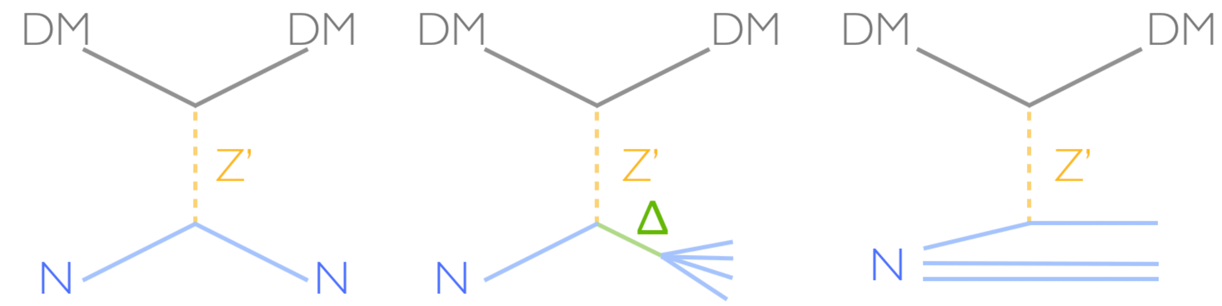
Jonathan Assadi
University of Texas at Arlington, Arlington, Texas 76019, USA

Detection



Main background events: NC atmospheric νs

845 NC events in 10k ton LAr per year

Analysis Strategy

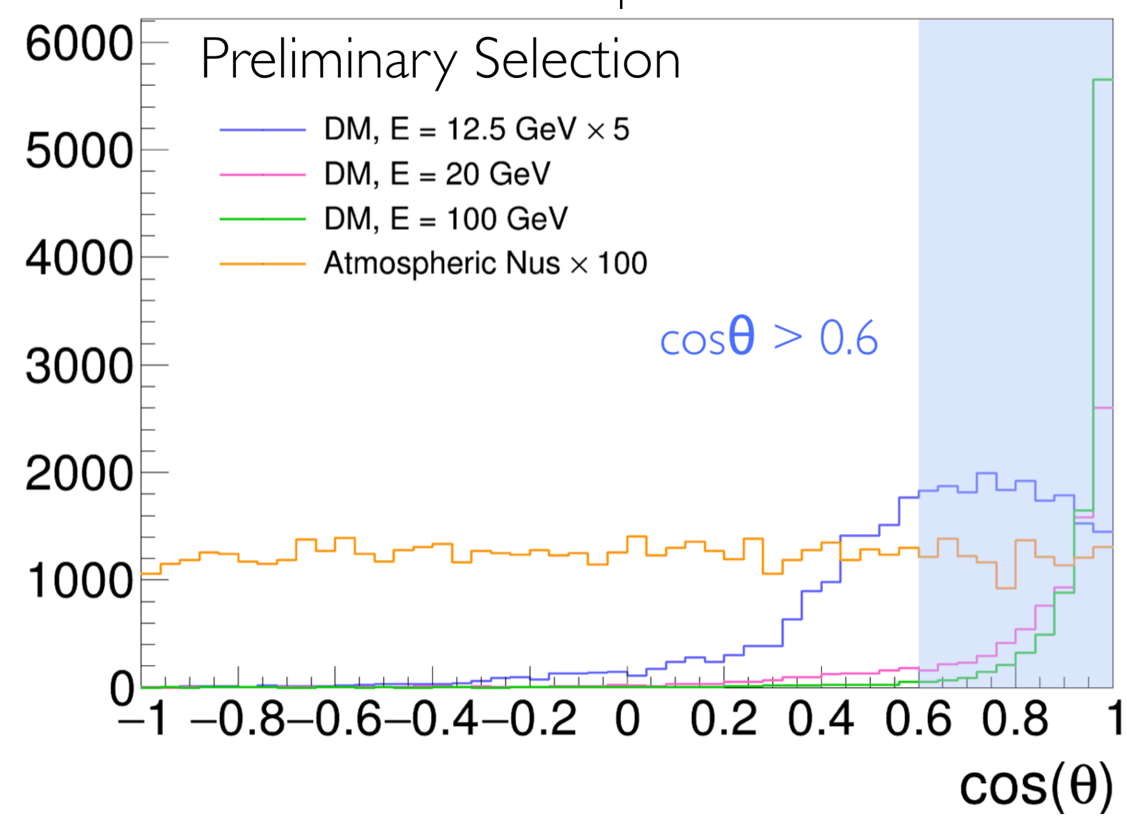
- Scan over the parameter space of DM mass and mediator mass
- Mono-energetic boosted DM flux coming from the Sun direction
- DM-Ar interactions provided by J. Berger
  - Validated analytically and via MadGraph
  - Included in official GENIE v3
- GENIE takes care of the final state interactions
  - GENIE default FSI model: HAIntranuke model
- GEANT4 detector material (LAr) simulation

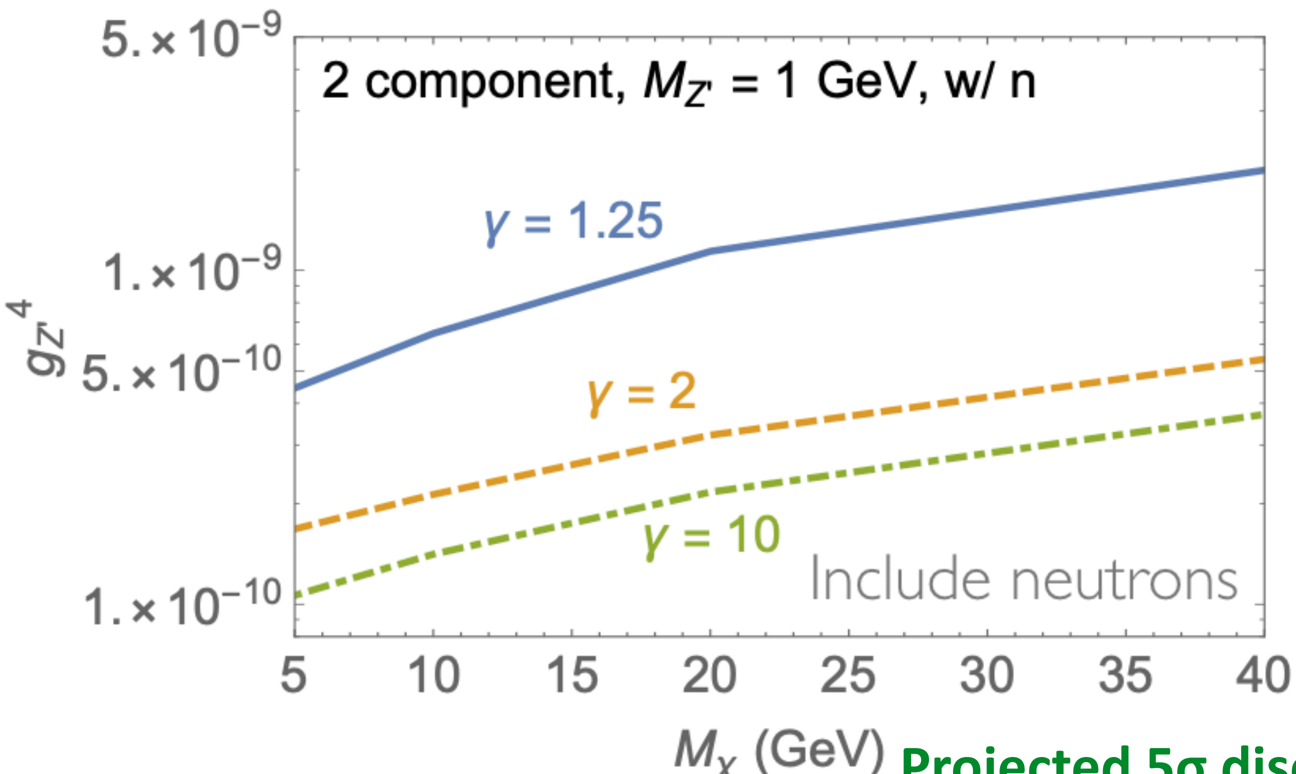
Boosted Dark Matter from the Sun

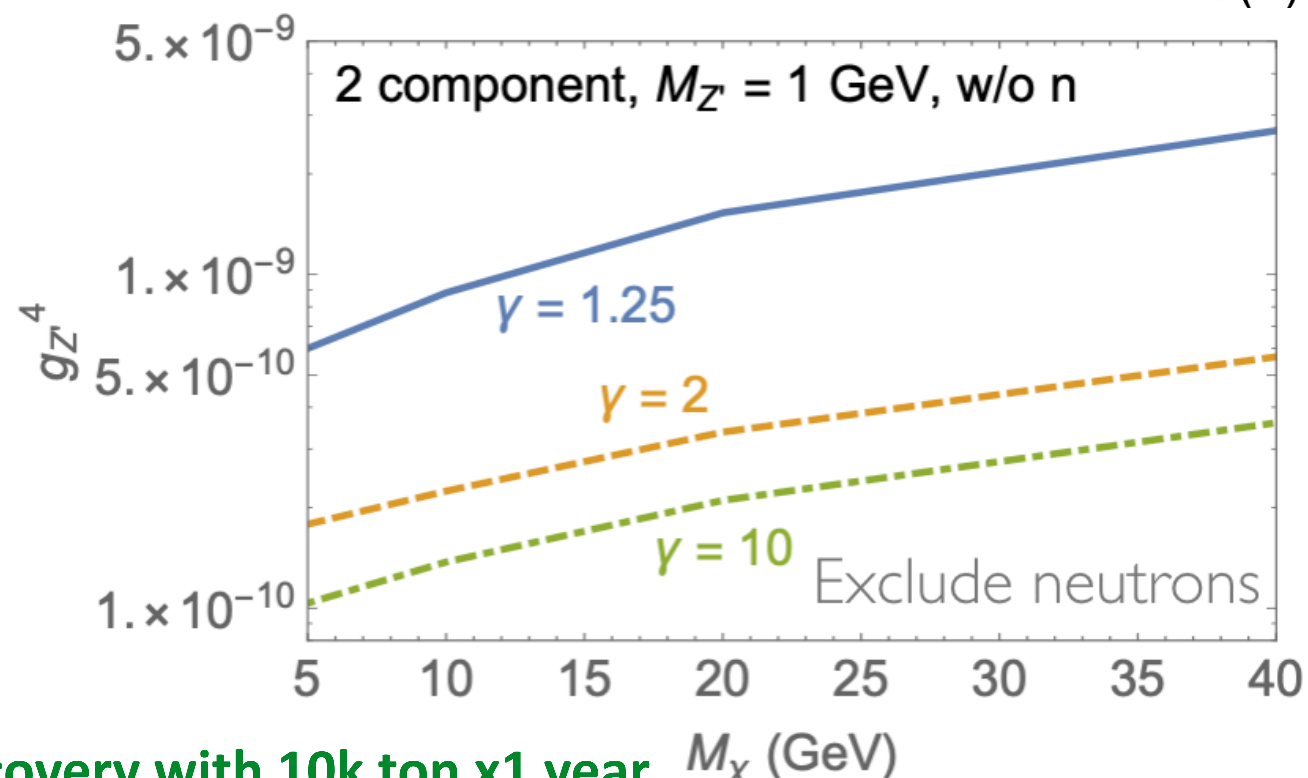
Assumed Detector Response (CDR)

	Angular resolution	Energy/Momentum resolution	KE Threshold [MeV]
p	5°	p<400 MeV/c: 10% p>400 MeV/c: 5%⊕30%/√E [GeV]	50
n	5°	40%/√E [GeV]	50
π	1°	μ-like contained: track length π-like contained: 5% Shower or exiting: 30%	100
e/γ	1°	2%⊕15%√E [GeV]	30
μ	1°	Contained: track length Exiting: 30%	30

θ = angle between Sun direction and summed momentum of visible particles in final state







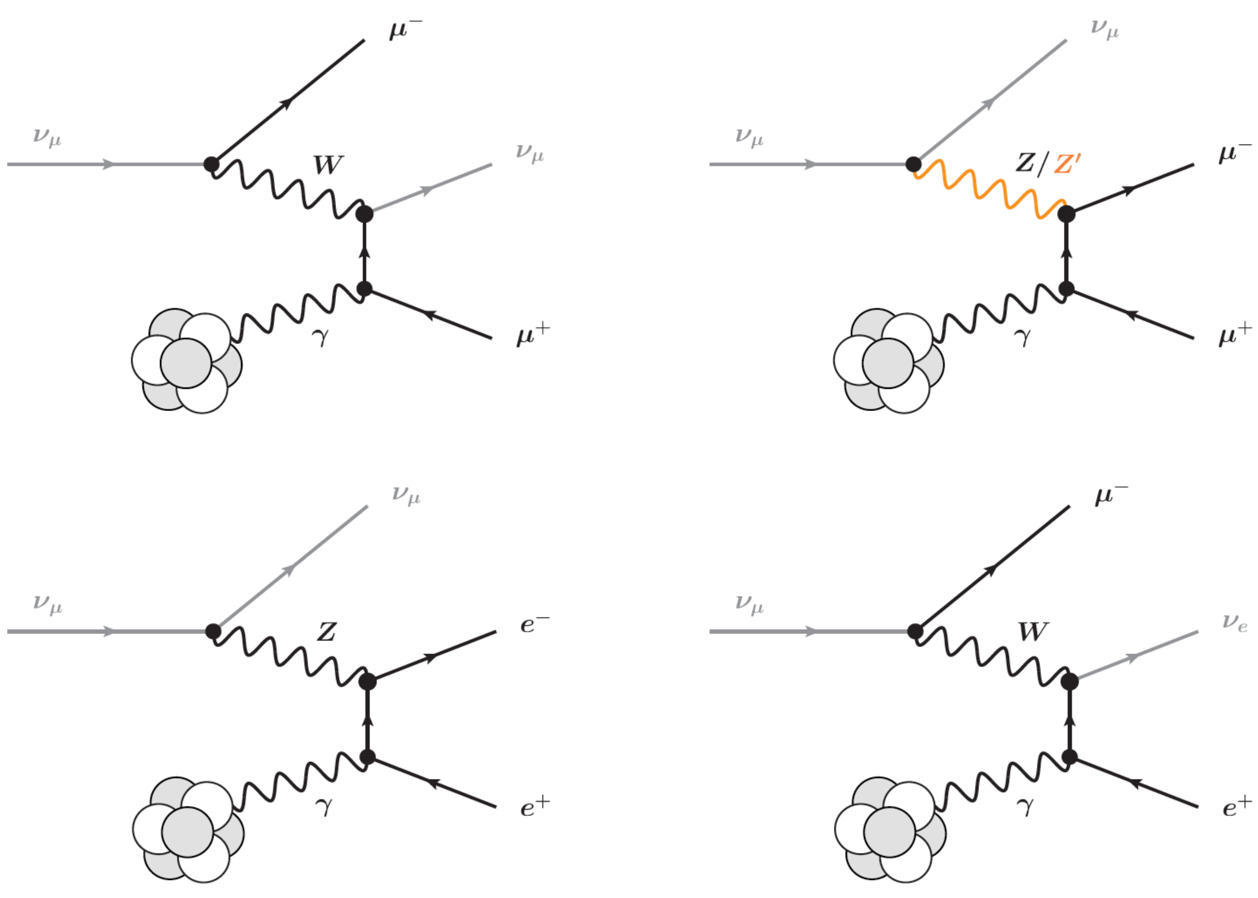
Projected 5σ discovery with 10k ton x1 year

Neutrino Tridents

- Rare SM process. Has been observed with measured cross section in good agreement with SM

$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm exp}}{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm SM}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$

WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801



- Strong probe of potential new Z’ boson advanced as explanation for (g-2) anomaly
  - Z’ couples to muons, but also to muon neutrinos. Enhances production w.r.t. SM
- Associated paper in DocDB-10890 reviewed by Collaboration, finalizing responses before submission

BSM Physics with DUNE: Search for Neutrino Tridents at the Near Detector

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[b] *Department of Physics, Harvard University 17 Oxford St, Cambridge, MA 01238, USA*

[c] *Department of Physics, University of Cincinnati Cincinnati, Ohio 45221, USA*

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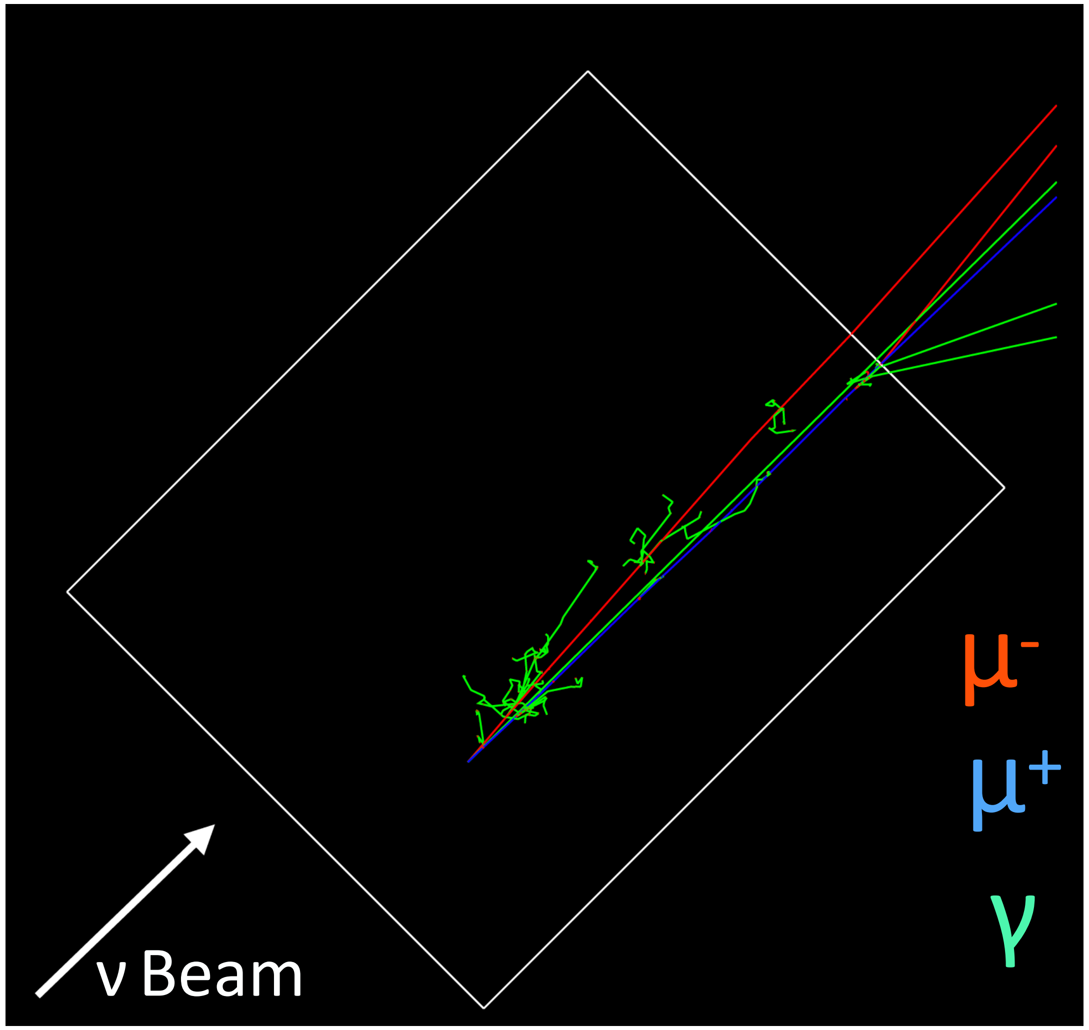
ABSTRACT: The DUNE near detector will collect an unprecedented large number of neutrino interactions, allowing the precise measurement of rare processes such as neutrino trident production, i.e. the generation of a lepton-antilepton pair through the scattering of a neutrino off a heavy nucleus. This process' event rate is a powerful probe to a well-motivated parameter space for new physics beyond the Standard Model. Here, we study the sensitivity of the DUNE near detector to neutrino tridents. We provide predictions for the Standard Model cross sections and corresponding event rates at the near detector for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu \mu^+\mu^-$, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu e^+e^-$, and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e e^\pm\mu^\mp$ trident interactions, also discussing their uncertainties. We perform a detailed study of all relevant backgrounds and identify a set of selection cuts that would allow the DUNE near detector to measure the $\nu_\mu \to \nu_\mu\mu^+\mu^-$ cross section with a 25% accuracy after running in neutrino and anti-neutrino modes for 3 years each. We show that this measurement would be highly sensitive to new physics, and, in particular, we find that the parameter space of models with gauged $L_\mu - L_\tau$ that can explain the $(g-2)_\mu$ anomaly could be covered almost entirely.

Neutrino Tridents in ND

	reference beam 80 GeV		optimized beam 80 GeV	
	coherent	incoherent	coherent	incoherent
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	2.05 ± 0.12	0.87 ± 0.27	1.24 ± 0.07	0.56 ± 0.17
$\nu_\mu \to \nu_\mu e^+ e^-$	4.92 ± 0.29	0.32 ± 0.10	3.84 ± 0.23	0.23 ± 0.07
$\nu_\mu \to \nu_e e^+ \mu^-$	17.4 ± 1.0	2.2 ± 0.7	12.1 ± 0.7	1.5 ± 0.5
$\nu_\mu \to \nu_e \mu^+ e^-$	0	0	0	0
$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	1.54 ± 0.09	0.67 ± 0.21	0.93 ± 0.06	0.43 ± 0.13
$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	4.03 ± 0.24	0.26 ± 0.08	3.19 ± 0.19	0.18 ± 0.06
$\bar{\nu}_\mu \to \bar{\nu}_e e^+ \mu^-$	0	0	0	0
$\bar{\nu}_\mu \to \bar{\nu}_e \mu^+ e^-$	13.8 ± 0.8	1.7 ± 0.5	9.7 ± 0.6	1.2 ± 0.4

Event rates per year (1.5E21 POT) and tonne of argon.

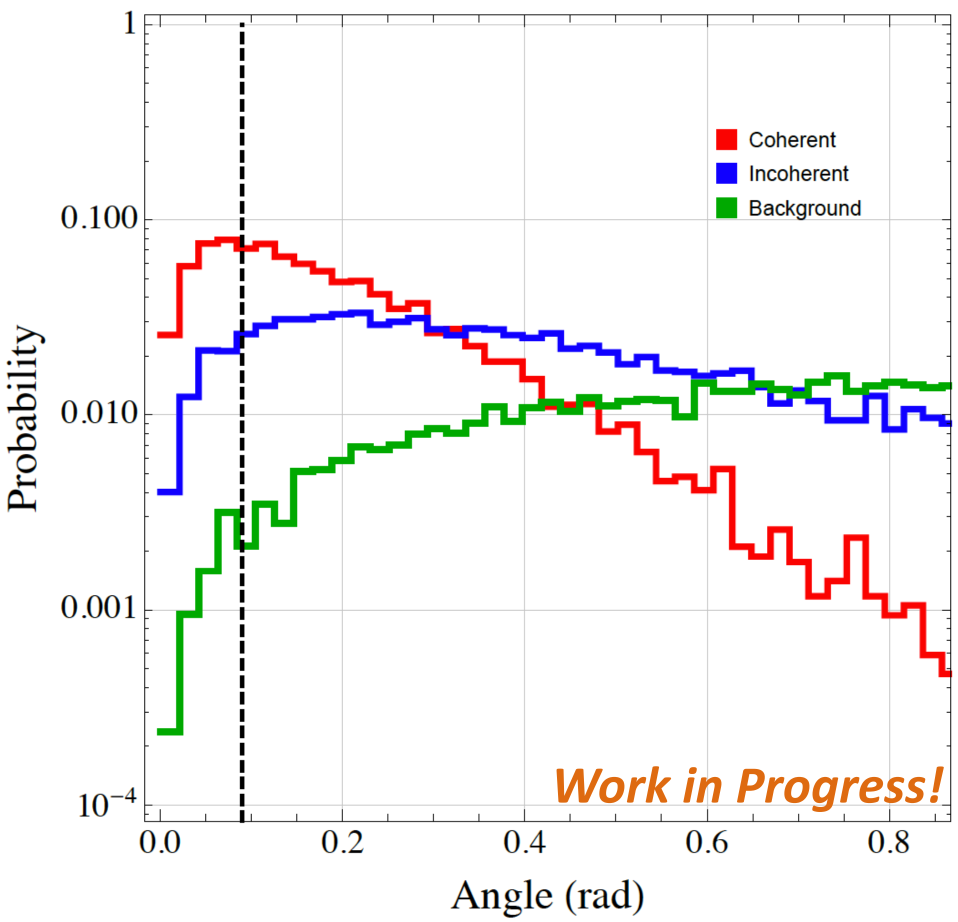


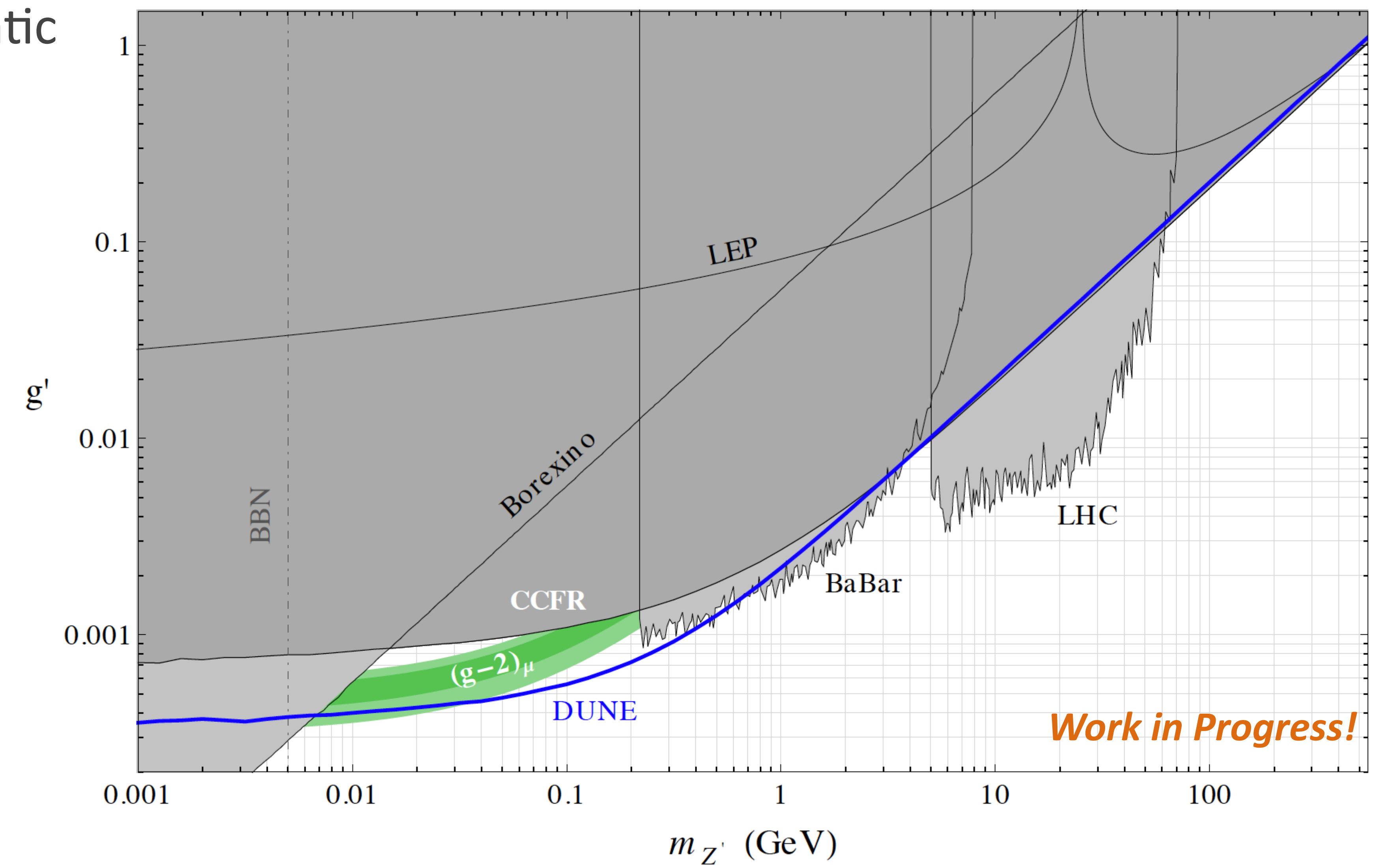
- New MC event generator of neutrino trident events (in argon or iron) written. Code publicly available

- Backgrounds (CC interactions in ND LArTPC) generated using GENIE neutrino generator
- Signal and backgrounds run through simulation of the DUNE ND.
  - Dimensions of LArTPC: 4×3×5 m³ (~84 tonnes), working on updating to new ND dimensions, flux

Neutrino Tridents in ND

- Event selection through kinematic variables





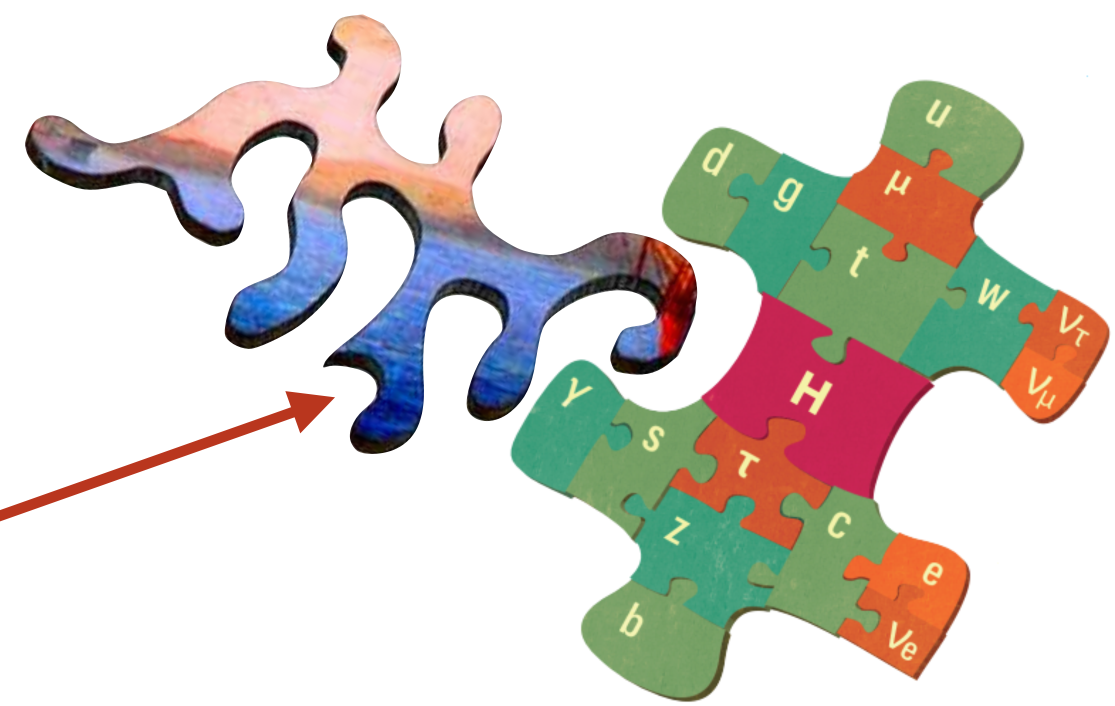
- Opening angle between two tracks. Events with 0.5° < θ < 5.5° are accepted. Achieved 10^7 bkg rejection
- Existing constraints and projected DUNE ND sensitivity in the L_μ–L_τ parameter space (light Z' boson model)

Tech Note Review

- 5 Tech Notes on DocDB; Please use provided spreadsheets (specific to each Note) to submit comments; Please append <YourName>, or your institution's name, to spreadsheet file, and send comments to each sub-group leader
- **Light Sterile Neutrinos** - DocDB-12067 - Link to Spreadsheet
  - **Send comments to** Alex Sousa
- **NSI/Non-Unitarity/CPT Violation** - DocDB-12109 - Link to Spreadsheet
  - **Send comments to** Célio Moura
- **Low-Mass DM / Inelastic Boosted DM** - DocDB-12103 - Link to Spreadsheet
  - **Send comments to** Animesh Chatterjee **and** Doojin Kim
- **Boosted DM from the Sun** - DocDB-12097 - Link to Spreadsheet
  - **Send comments to** Yun-Tse Tsai
- **Neutrino Tridents** - DocDB-12112 - Link to Spreadsheet
  - **Send comments to** Justo Martín-Albo
- Please provide comments by **11:59 PM CST, Friday, January 4, 2019**
- Looking forward to your input, thanks!

Outlook

- Many thanks to all that are contributing to the work in the BSM Physics group!
- Excellent space for development of collaborations between theorists/ phenomenologists and experimentalists
- Currently thinking about post-TDR work and reviewing organization of the working group - New ideas welcome!



Your favorite model here

- Please come to our bi-weekly meetings, Tuesdays, 9 am Fermi time, and join our mailing list:
  e-mail listserv.fnal.gov with message body:
  subscribe DUNE-PHYSICS-BSM <firstname> <lastname>
- Slack: *#bsm-physics*
- DUNE BSM Wiki: https://cdcvs.fnal.gov/redmine/projects/dunebsm/wiki