Dark Matter and Physics Beyond the Standard Model at DUNE

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for the DUNE collaboration

International Conference on Neutrinos and Dark Matter

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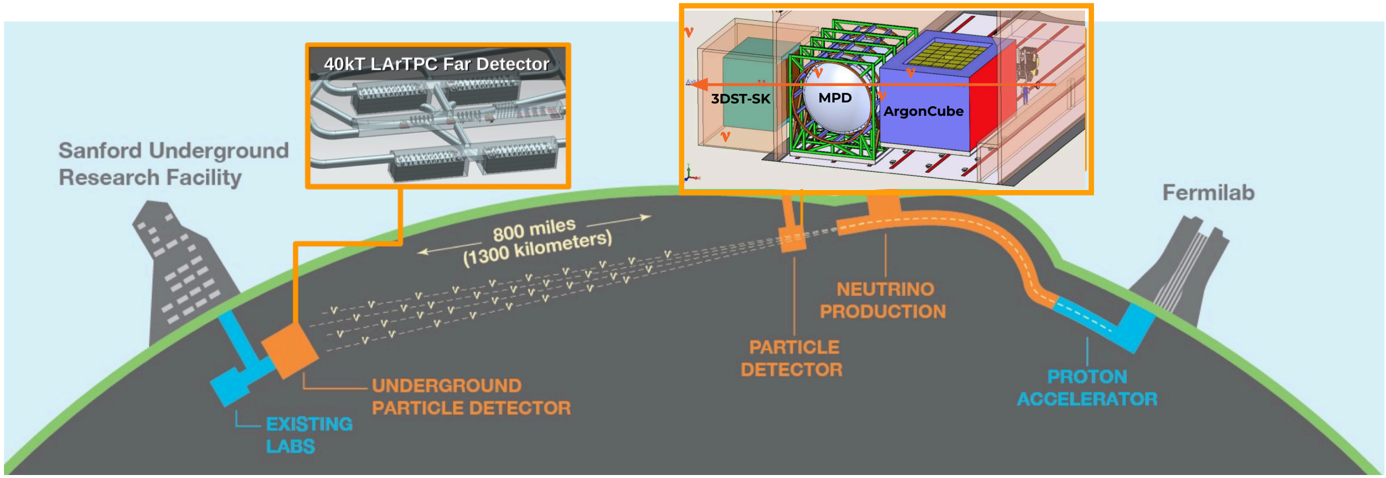
The Deep Underground Neutrino Experiment

- The Deep Underground Neutrino Experiment (DUNE) is the next generation long baseline neutrino experiment to provide a broad neutrino physics programme. It will consist of:
  - Far Detector: 40 kton (fiducial) liquid argon time-projection chamber (LArTPC) installed (on-axis) 1475 meters underground at the Sanford Underground Research Facility in Lead, South Dakota, 1300 km away from the source.
  - Hybrid Near Detector: integrated system composed of multiple detectors placed at a distance of ~574 m from the beam line. LArTPC and MPD (GAr TPC) designed to be moved for off-axis measurements.
- Fermilab's Main Injector accelerator as a powerful 60-120 GeV proton beam (1.2MW upgradeable to 2.4MW) to make highest energy neutrino beam.
- DUNE is currently made up of over 1000 collaborators from over 180 institutions in over 30 countries plus CERN.
- Start of physics operations in mid-2020s.



BSM searches @ DUNE

The unique combination of the high-intensity neutrino beam with DUNE's near detector and massive LArTPC far detector enables a variety of probes of BSM physics, either novel or with unprecedented sensitivity.

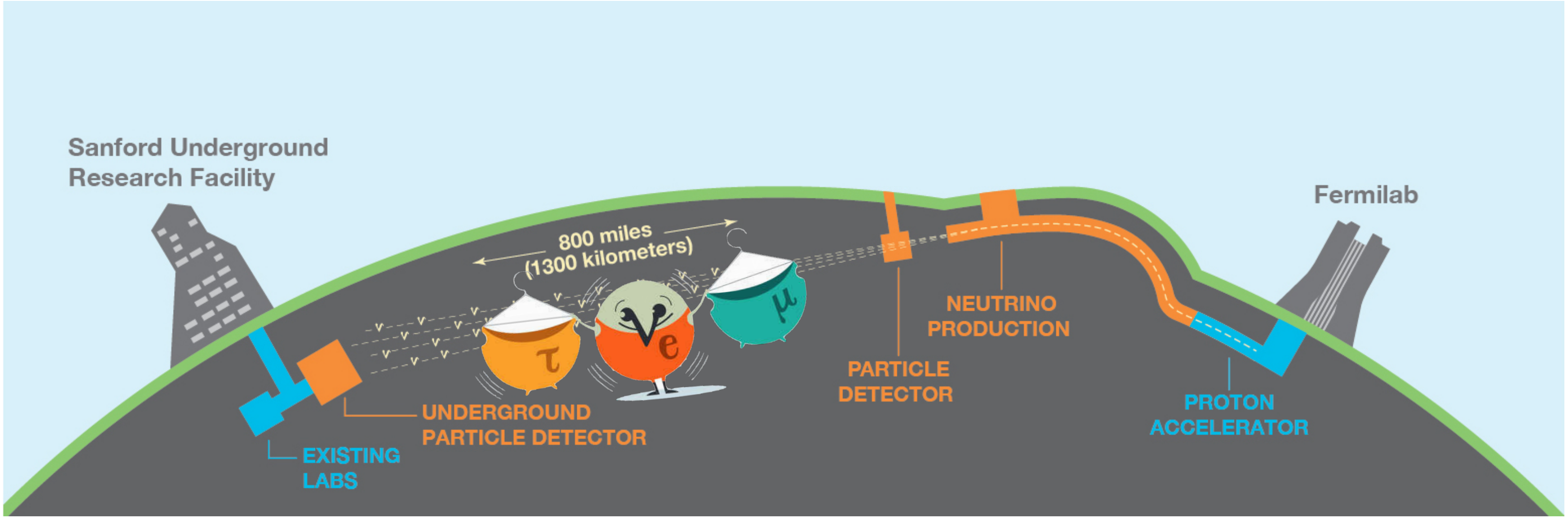
- Searches beyond the standard three-neutrino-flavour paradigm (FD and ND):
  - active-sterile neutrino mixing;
  - non-unitarity of the leptonic mixing matrix;
  - non-standard neutrino interactions (NSI);
  - violation of Charge, Parity, and Time reversal symmetry (CPT);
- Searches for new physics at the ND:
  - light-mass dark matter;
  - new physics via neutrino trident production;
  - heavy neutral leptons;
- Searches for new phenomena at the FD benefitting from its

large mass and resolution:

  - boosted dark matter;
  - nucleon decay.

Credit to R. Thompson www.nytimes.com

NON-STANDARD NEUTRINO OSCILLATIONS



Neutrino Non Standard Interactions

- Neutrino non-standard interactions (NSI) are parametrised in a model-independent and phenomenological way:

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{ff'X}(\overline{\nu}_\alpha \gamma^\mu P_L l_\beta)(\overline{f'}\gamma_\mu P^X f)$$

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fX}(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\overline{f}\gamma_\mu P^X f)$$

- CC-NSI affect the production and detection of neutrinos
- NC-NSI affect the propagation of neutrinos in matter (in DUNE)

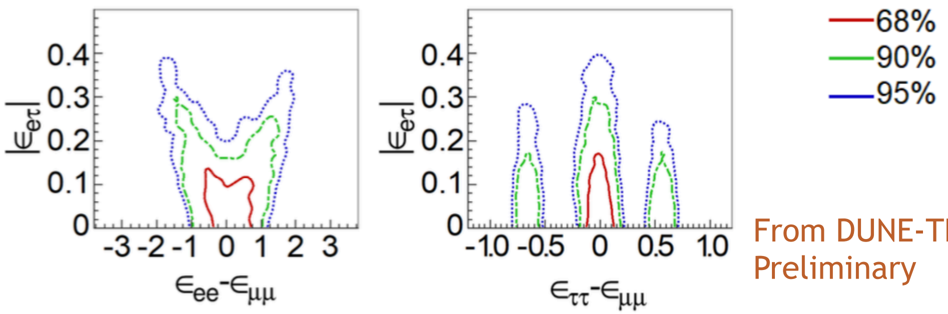
NC-NSI can be studied at the DUNE FD. They can be parametrised as new contributions to the MSW matrix in the neutrino-propagation Hamiltonian and understood as non-standard matter effects:

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

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

Coloma JHEP 1603 (2016) 016
Blennow et al. JHEP 08 (2016) 090
Bakhti et al. J. Phys. G44 no. 12, (2017) 125001
Y. Farzan, M. Tórtola Front. in Phys. 6 (2018) 10
Masud et al. Sci.Rep. 9 (2019) no.1, 352

Neutrino Non Standard Interactions



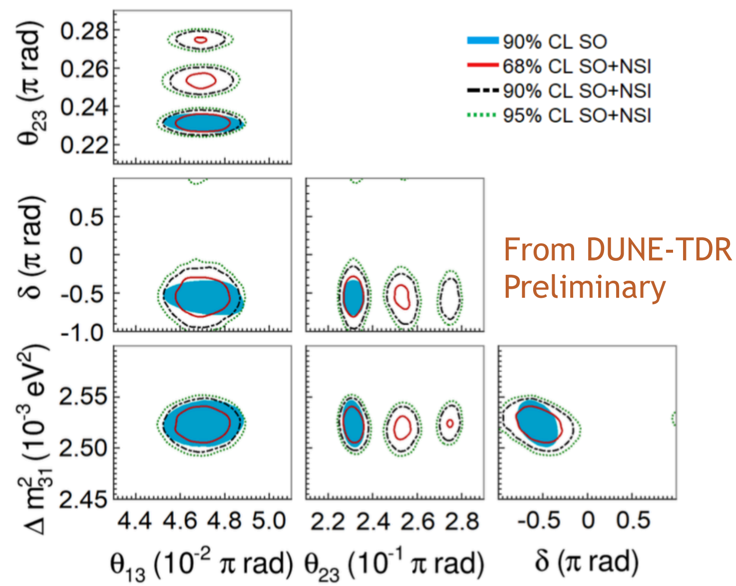
From DUNE-TDR Preliminary

Allowed regions of the non-standard oscillation parameters with important degeneracies.

DUNE may improve present constraints on $|\varepsilon_{e\mu}|$ and on $|\varepsilon_{e\tau}|$ by at least a factor 2.

Projections of the standard oscillation parameters with nonzero NSI.

- An important degeneracy appears in the measurement of the mixing angle θ_{23}.
- The sensitivity of the CP phase is strongly affected.



From DUNE-TDR Preliminary

Quasi-Dirac neutrino oscillations

A pair of quasi-Dirac neutrinos is a pair of Majorana neutrinos with a small mass splitting and a relative CP-sign between the two states.

We begin with a pair of active-sterile neutrinos.

This pair has mass matrix:

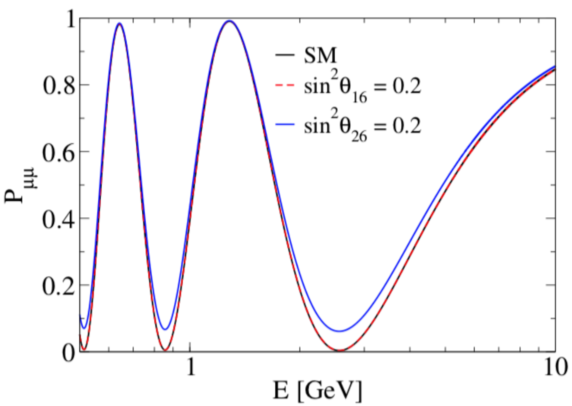
$$m_\nu = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

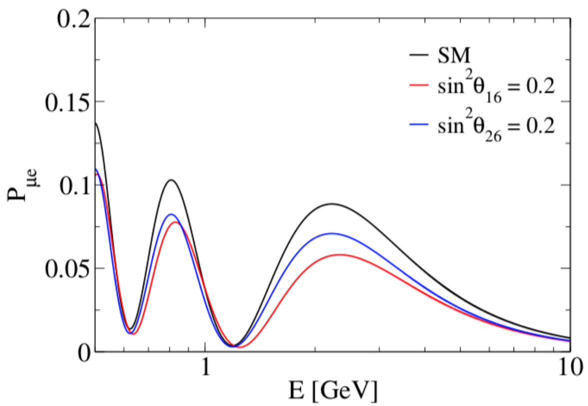
If these are zero, neutrinos are Dirac particles.

If they are not zero, but very small we are left with a pair of quasi-Dirac neutrinos.

The charged current SM Lagrangian is modified and a new mass term is allowed.

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^- \sum_{l=1}^{3} \sum_{j=1}^{6} \mathbf{V}_{lj} \bar{\ell}_l \gamma^\mu P_L \nu_j + \text{h.c.} \qquad \mathcal{L}_{\text{mass}} = \frac{1}{2} \bar{\nu}_\alpha M_{\alpha\beta} \nu_\beta + \text{h.c.}$$

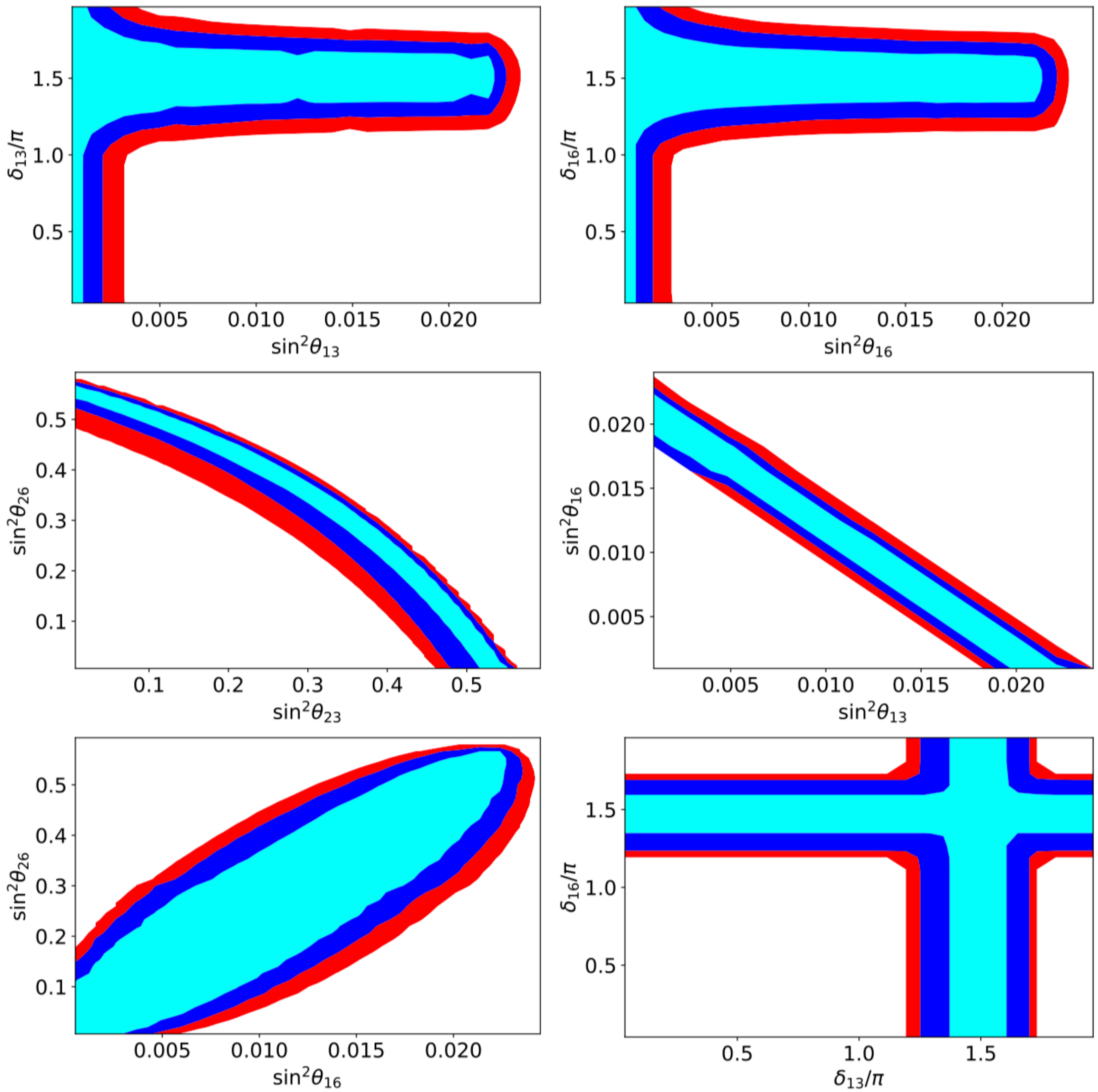




Oscillation probabilities at the DUNE FD

Anamiati, VDR, Hirsch, Ternes, Tortola
Phys.Rev. D100 (2019) no.3, 035032

Quasi-Dirac neutrino oscillations



We assume DUNE to run 3.5 years in neutrino mode and other 3.5 years in antineutrino mode.

Total exposure of 300 kton-MW-years (equivalent to 1.47×10^{21} POT per year).

Anamiati, VDR, Hirsch, Ternes, Tortola
Phys.Rev. D100 (2019) no.3, 035032

Sensitivity to CPT violation

Assume that neutrinos oscillate with parameters $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta$
while the antineutrinos oscillate with a new set of parameters $\Delta \overline{m}^2_{21}, \Delta \overline{m}^2_{31}, \overline{\theta}_{12}, \overline{\theta}_{13}, \overline{\theta}_{23}, \overline{\delta}$

To prove the CPT-theorem of QFT one needs:

- Hermiticity of the Hamiltonian
- Locality
- Lorentz invariance

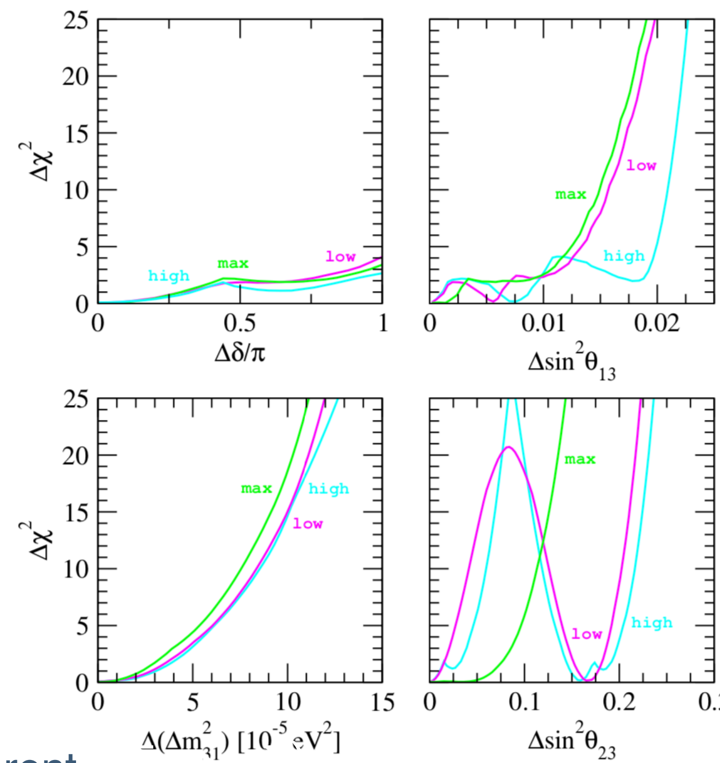
If CPT is violated, one of the three ingredients above must be violated.

$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow$ CP violation (if δ → - δ)

$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow$ CPT violation

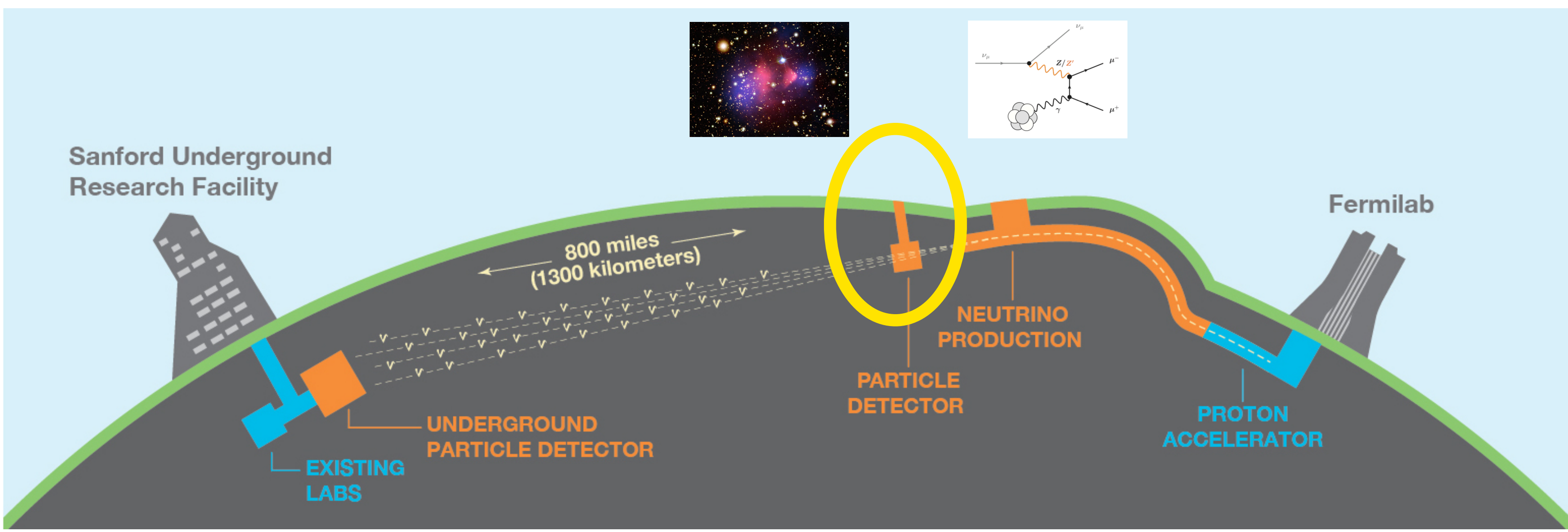
DUNE has great sensitivity to $\Delta(\Delta m_{31}^2)$.

Projected sensitivities of DUNE to the difference of neutrino and antineutrino parameters and three different values of the θ23 mixing angle: maximal mixing (green), lower octant (magenta) and upper octant (blue).



Barenboim et al. Phys.Lett. B780 (2018) 631-637

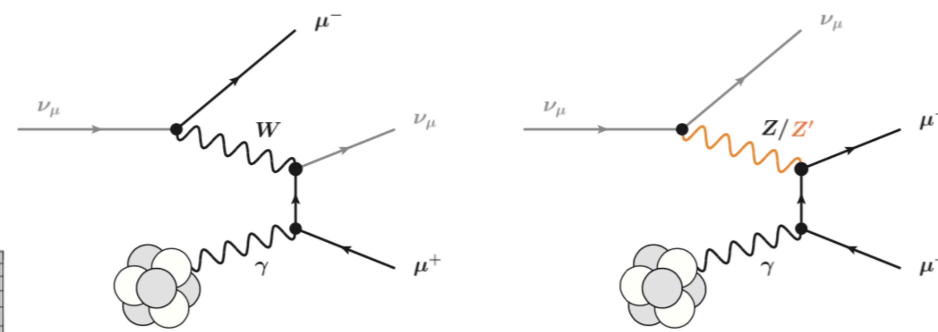
SEARCHES FOR NEW PHYSICS AT THE NEAR DETECTOR

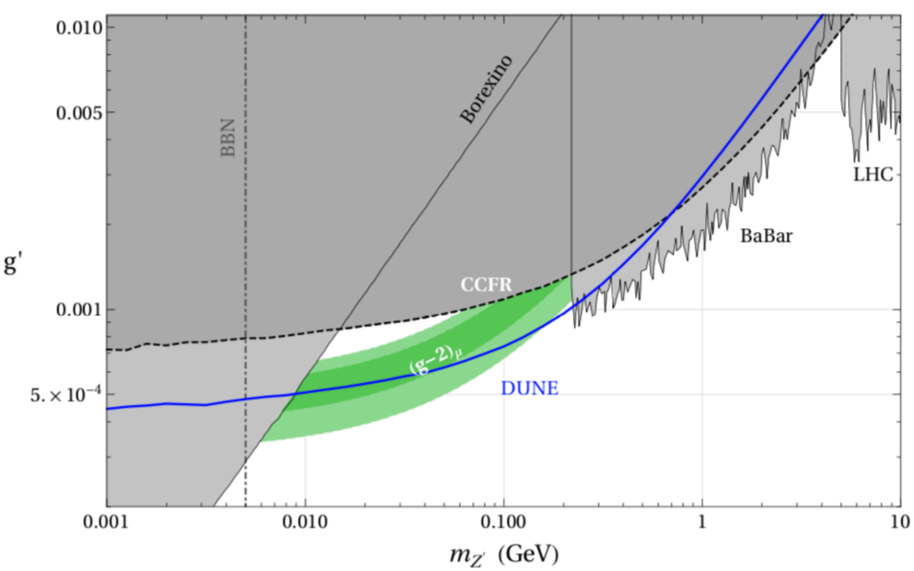


NEUTRINO TRIDENTS

Neutrino trident scattering is a rare SM weak process in which a neutrino, scattering off the Coulomb field of a heavy nucleus, generates a pair of charged leptons.

- Its cross section is ~7 orders of magnitude smaller than the CC one.
- Only a few tens of events observed in previous experiments (DIS).





Altmannshofer et al. Phys. Rev. Lett. 113, 091801 (2014)
Ballett et al. JHEP01(2019)119
Altmannshofer et al. arXiv:1902.06765

- Trident rate sensitive to the existence of new forces mediated by a light vector boson that could explain the muon g–2 anomaly.
- Example model: to gauge an anomaly-free global symmetry of the SM such as the difference of muon-number and tau-number.
- Existing constraints and projected DUNE sensitivity in the $L_\mu - L_\tau$ parameter space.

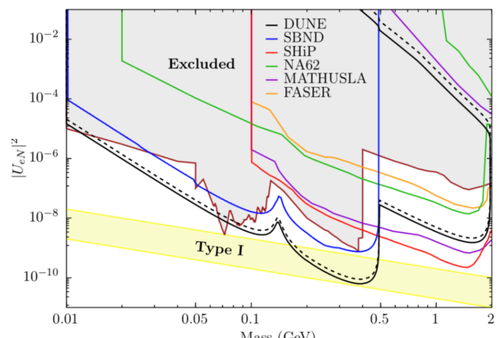
Heavy Neutral Leptons

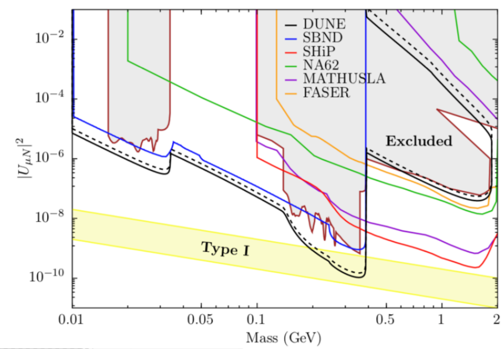
The high intensity of the neutrino beam enables DUNE to search for weakly interacting heavy neutral leptons (HNLs), such as heavy nearly-sterile neutrinos.

Thanks to small mixing angles, the HNLs can be stable enough to decay inside the ND.

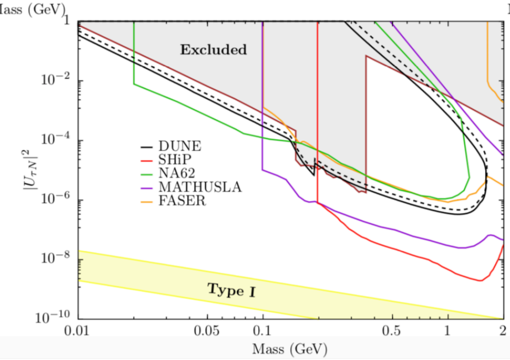
Typical decay channels are two-body decays into a charged lepton and a pseudo-scalar meson (or a vector meson), two-body decays into neutral mesons, and three-body leptonic decays.

Different phenomenology if the decaying HNL is a Majorana or a Dirac fermion.





- DUNE ND has exceptional sensitivity to discovery of HNLs.
- Current limits improved and regions of theoretical interest reached.
- After discovery, the nature of HNL could be determined.



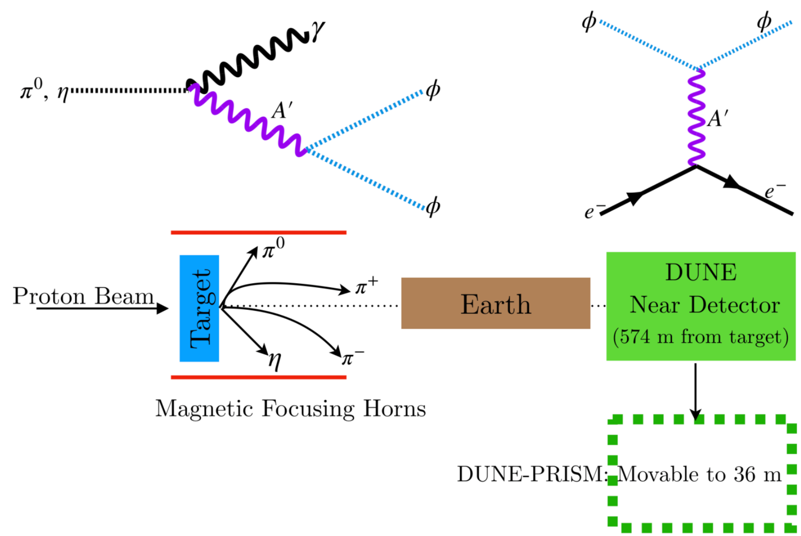
solid: Majorana HNL
dashed: Dirac HNL

From DUNE-TDR. Adapted from Ballett et al. arXiv: 1905.00284

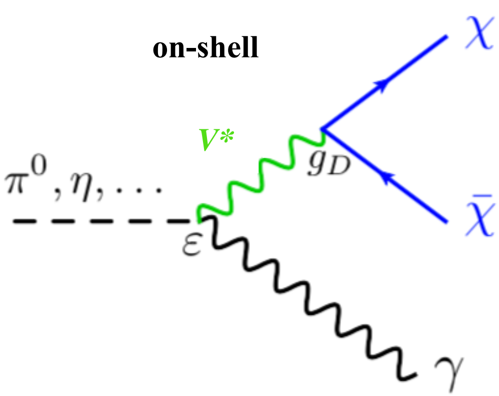
Light dark matter

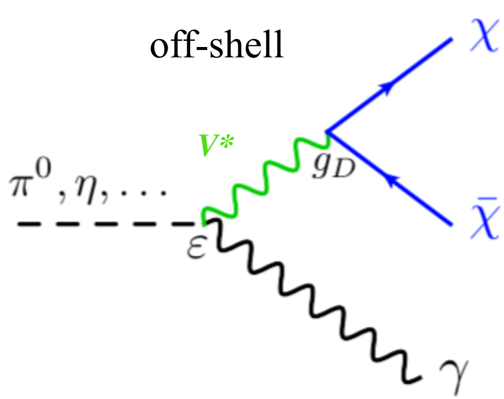
VDR, K. Kelly and P. Machado
Phys.Rev. D100 (2019) no.9, 095010

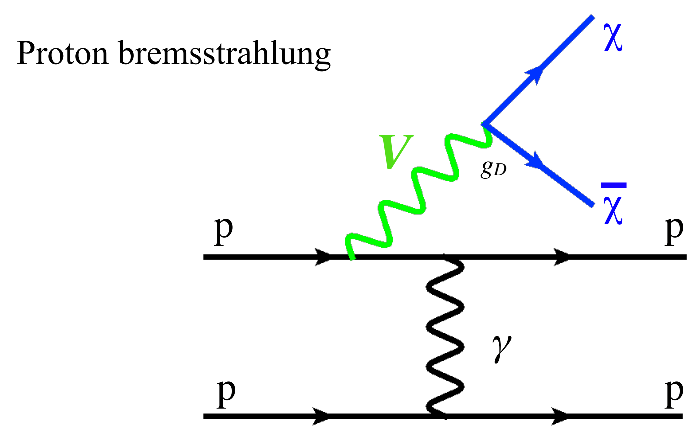
DUNE near detector can perform as a high intensity beam dump experiment.



- High luminosity available (10^{21} POT/year)
- Allows for the production of a sizeable relativistic DM beam.
- DM produced in the radiative decay of neutral hadrons, proton bremsstrahlung processes or direct parton-level production.

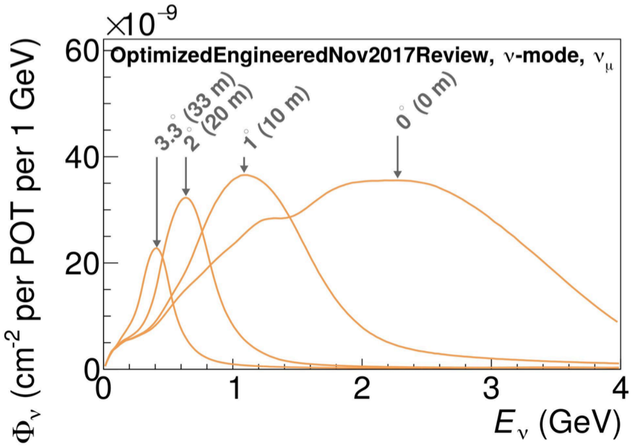






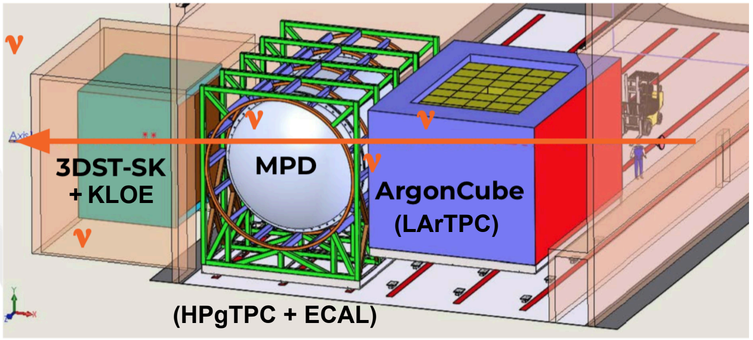
DUNE PRISM

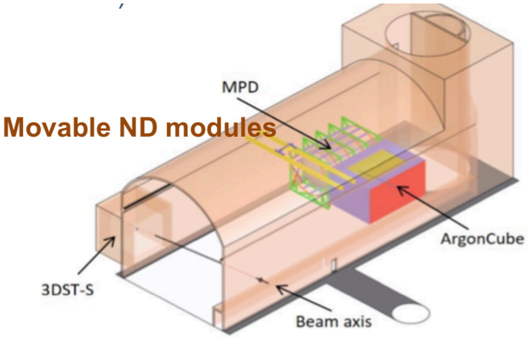
- The DUNE PRISM concept proposes to move the near detector between 0 and 36 m transverse to the beam direction.
- By moving the detector off-axis, can measure increasingly lower Ev spectra.
  - Advantage: reduce systematic uncertainties related to neutrino cross sections.
  - Interaction observed at different off-axis angles can be combined to mimic what would be observed with a different Ev spectrum.



credit: L. Pickering and M. Wilking, DUNE PRISM design group

- DM beam is broader than the neutrino beam: detectors located away from the proton beam axis will have larger signal to background ratio.





Light dark matter: dark photon portal

Extend the SM gauge group by including a new $U(1)_D$, spontaneously broken in a hidden sector. A dark matter particle χ (or Φ) interacts with the SM particles through a massive dark photon A' and its kinetic mixing with the photon.

- DM is a light WIMP
- stable because new interactions are such that the DM can only be pair produced.

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M^2_{A'}}{2} A'_\mu A'^\mu + \overline{\chi} i \gamma^\mu \left(\partial_\mu - i g_D A'_\mu\right) \chi - M_\chi \overline{\chi} \chi$$

Fermionic DM

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M^2_{A'}}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M^2_\phi \, |\phi|^2$$

Scalar DM

- ε kinetic mixing parameter between the SM $U(1)_Y$ and the new $U(1)_D$
- g_D gauge coupling associated to the dark $U(1)_D$
- $\alpha_D \equiv g_D^2 /(4\pi)$, dark fine structure constant

Okun Sov. Phys JTEP 56, 502
Holdom PLB 166 196
Pospelov et al. Phys. Lett. B662 (2008) 53-61
Pospelov Phys. Rev. D80 (2009) 095002

Light dark matter

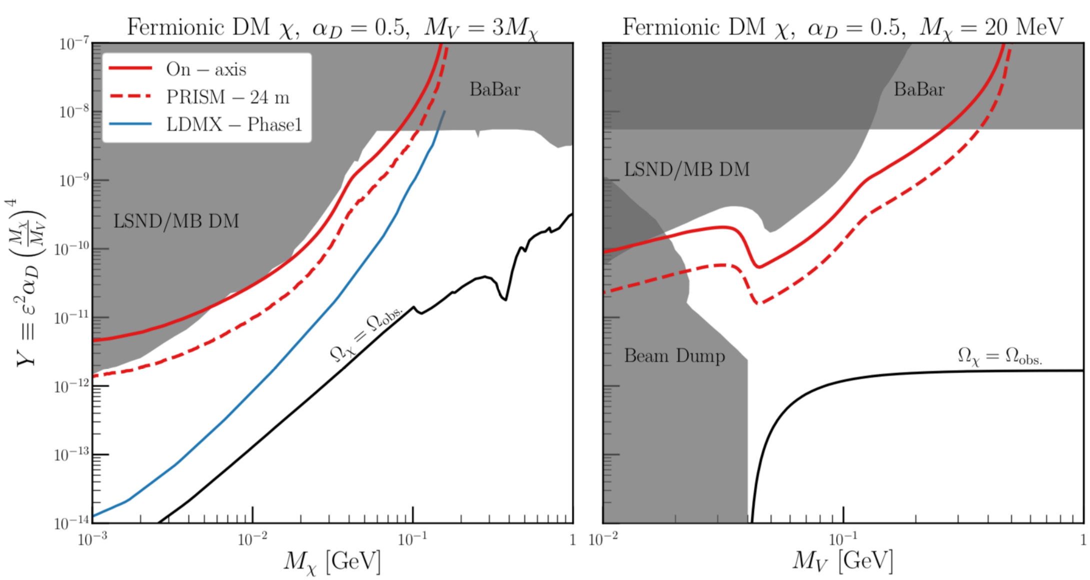
We focus on scattering off electrons. Main backgrounds:

- neutrino-electron scattering (NC) $\nu_\mu e^- \rightarrow \nu_\mu e^-$
- neutrino-nucleon scattering (CC) $\nu_e n \rightarrow e^- p$

Sensitivity can be improved by including information about the final-state electron kinematics for the signal and background distributions.

DUNE can significantly improve the constraints from LSND, MiniBooNE-DM and BABAR.

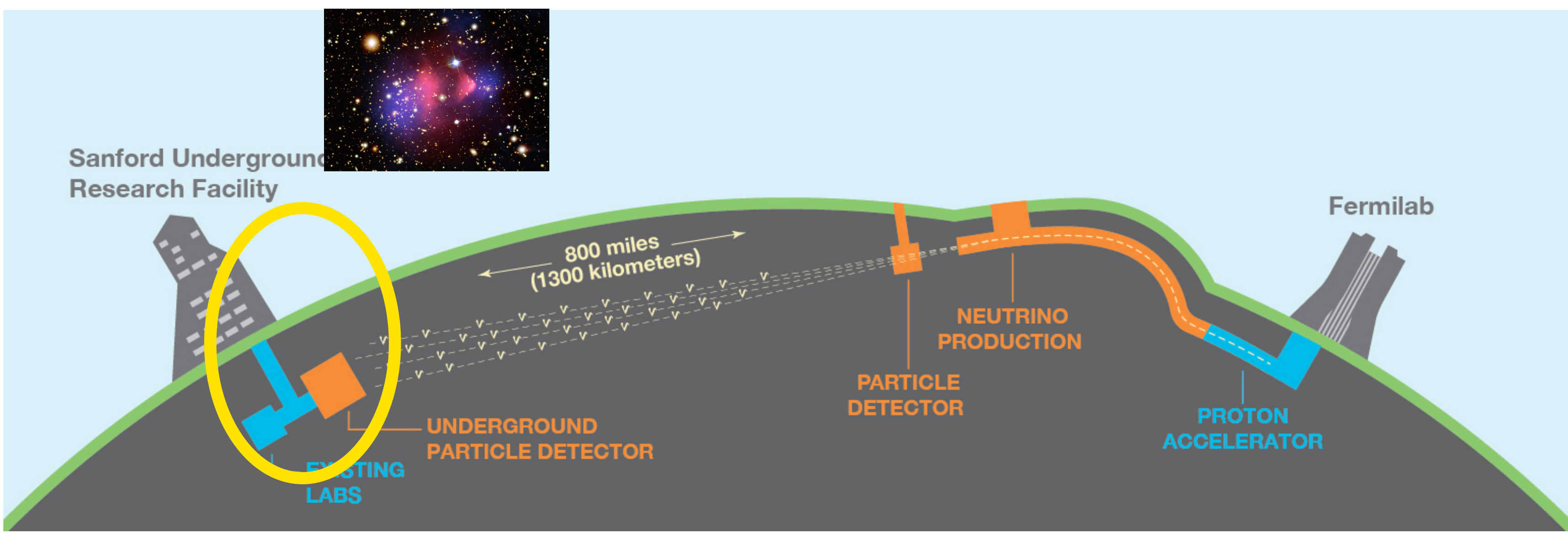
Competitive with dedicated experiments in probing light dark matter scenarios.



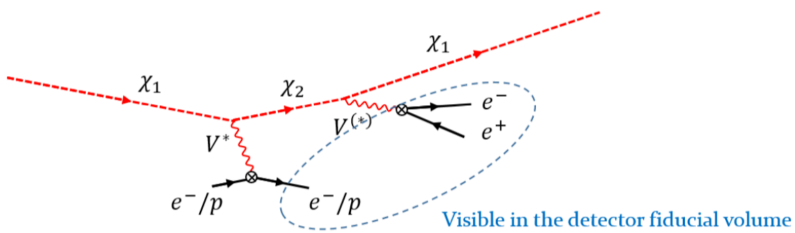
VDR, K. Kelly and P. Machado Phys.Rev. D100 (2019) no.9, 095010

LDMX collab. arXiv:1808.05219
Miniboone *Phys. Rev.* **D98** no. 11, (2018) 112004
deNiverville et al. *Phys. Rev.* **D99** no. 5, (2019) 051701

SEARCHES FOR NEW PHYSICS AT THE FAR DETECTOR

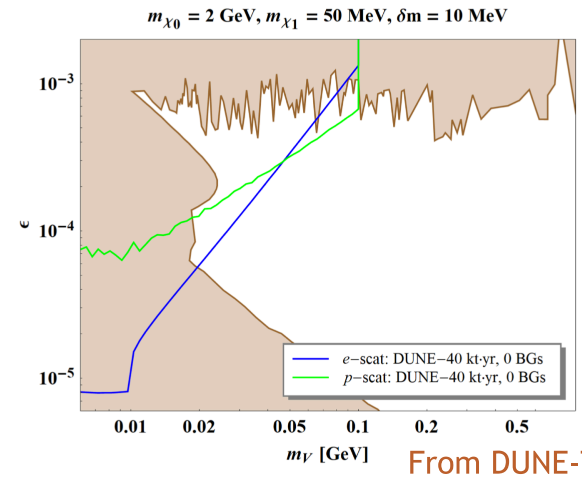


Boosted Dark Matter

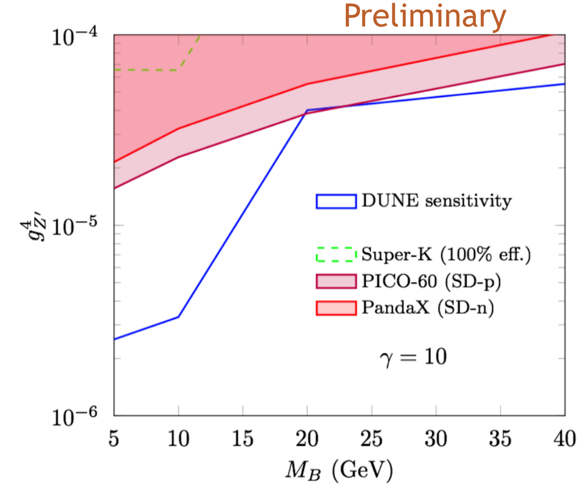


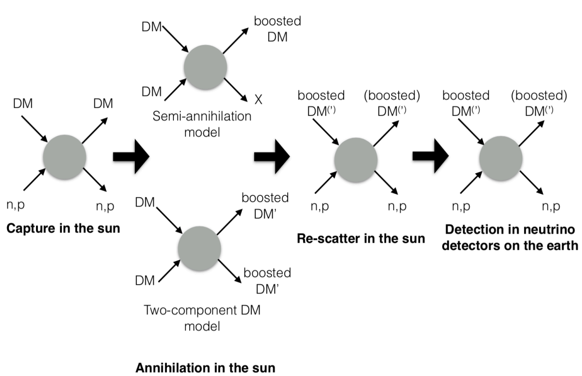
INELASTIC BOOSTED DM: Annihilating two-component DM scenario. Due to the large mass difference between the two DM components, the lighter one is produced relativistically.

The BDM reaches the DUNE FD and scatters off either electrons or protons energetically into a heavier unstable dark-sector state.



From DUNE-TDR Preliminary





ELASTIC BOOSTED DM: DM particles can be captured through their scattering with the nuclei within the Sun, mostly hydrogen and helium. The interactions are taken to be mediated by an axial, flavor-universal Z'

Chatterjee et al. arXiv:1803.03264
Berger et al. JCAP 1502 no. 02, (2015) 005
Kong et al. Phys. Lett. B743 (2015) 256-266
Kim et al. JHEP 08 (2018) 155

Conclusions

- The capable DUNE detectors and the highest energy neutrino beam enable a rich experimental programme of BSM physics searches such as:
  - non-standard short-baseline and long-baseline oscillation phenomena;
  - searches for new phenomena/particles at the ND;
  - searches for new phenomena at the FD benefitting from its large mass.
- DUNE will be a powerful discovery tool on a variety of BSM physics topics, including the potential discovery of new particles beyond the SM and precision neutrino measurements that may uncover deviations from the present three-flavor mixing paradigm and unveil new interactions and symmetries.
- DUNE will offer a long-term privileged and exciting setting for collaboration between experimentalists and theorists/phenomenologists.
- Look for results from finalised BSM studies in the upcoming DUNE Technical Design Report (TDR)!


Thank you!
DUNE