Baseline effects for a sterile at DUNE

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in collaboration with J. Pulido

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FCT Fundação para a Ciência e a Tecnologia

DF Departamento de Física Técnico Lisboa

CFTP Centro de Física Teórica de Partículas

European Union

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COMPETE

Phase II ND Workshop

Imperial College London,
20 June 2023

Sterile neutrinos

- We are entering an era of **precision** for Neutrino Physics
- Hints of deviations from LSND, MiniBooNE, the Gallium anomaly (and BEST), and the reactor $\bar{\nu}$ anomaly
- Could be explained in a 3+1 oscillation scenario, with

$$\Delta m_{41}^2 \sim \mathcal{O}(\mathrm{eV}^2)\,, \qquad \sin^2\theta_{14} \sim 0.01 - 0.1$$

[see e.g. 1901.08330, 1906.01739, 2106.05913 for reviews]

- So far, no coherent picture has emerged...

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...and there are tensions that need to be addressed

  - Appearance-disappearance tension

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee}\ \sin^2 2\theta_{\mu\mu}$$

  - Large sterile mixing must be reconciled with Cosmology (e.g. via secret ν interactions [1310.5926, 1806.10629])

DUNE

DUNE's driving and main ancillary science goals include:

- Probe and test the 3ν oscillation paradigm, aiming to determine the CPV phase, mass ordering, and the octant of θ_{23}
- Detect supernova ν_e flux (if we are lucky)
- Measure atmospheric neutrino oscillations
- Measure ν cross sections and study nuclear effects
- Search for proton decay, dark matter and **other BSM phenomena**

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The near detector (ND) will play several roles in the oscillation programme [see CDR 2103.13910], including:

- High-statistics beam characterisation and monitoring
- Help tune the neutrino interaction model
- Allow to deconvolve beam and x-section models (moving off-axis)

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DUNE will contribute to clarifying the sterile neutrino situation

Outline

1. How to account for baseline effects in sterile ν searches?
2. Our path, an outsider's perspective
3. Comments on phase II ND impact on sterile searches

   (see also BSM talks tomorrow afternoon)

A sterile at DUNE

Meson decays $\Rightarrow$ mostly ν_μ (FHC) or mostly $\bar{\nu}_\mu$ (RHC)

Note: simplified ND complex, only LAr TPC (50 ton fiducial vol.) scaled-down version of the FD

No oscillations up to the ND in the 3+0 case

A sterile at DUNE

Meson decays $\Rightarrow$ mostly ν_μ (FHC) or mostly $\bar{\nu}_\mu$ (RHC)

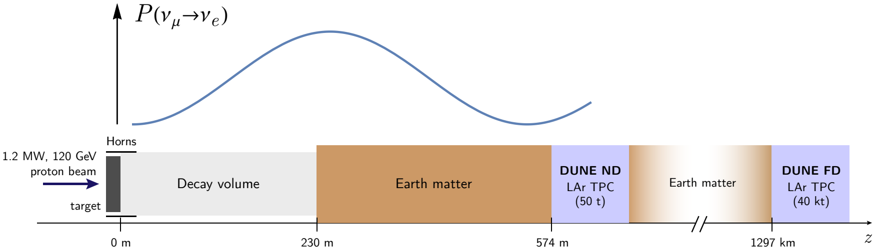
Sterile neutrinos giving signals at the DUNE ND have been studied before [1604.04731, 1609.08637, 1708.04909, 1802.02133, 2008.12769, 2105.11466, 2110.05767]

Sterile-induced oscillations at the ND

$$P^{\text{SBL}}_{\nu_\alpha \to \nu_\beta}(L, E) \simeq \delta_{\alpha\beta} - 2|U_{\alpha 4}|^2 (\delta_{\alpha\beta} - |U_{\beta 4}|^2) \Bigg[1 - \underbrace{\cos\left(\frac{\Delta m^2_{41} L}{2E}\right)}_{\text{killed by fast osc.}} \Bigg]$$

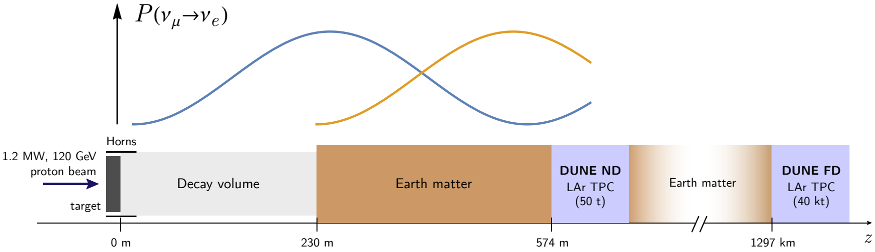
We consider both ND and FD events w/ exact 3+1 oscillation formulae in matter, **ND baseline effects** and the latest configurations [2103.04797]

Baseline effects at the ND



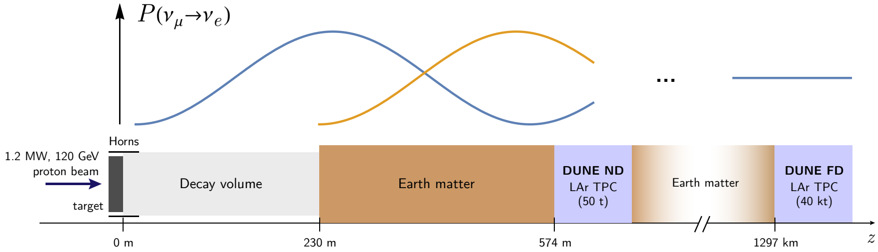
$\Delta m^2_{41} \sim \mathcal{O}(\text{eV}^2)$ and $E \sim \text{GeV} \quad \Rightarrow \quad$ osc. length $\sim$ decay pipe length

Baseline effects at the ND



$$\Delta m^2_{41} \sim \mathcal{O}(\text{eV}^2) \text{ and } E \sim \text{GeV} \quad \Rightarrow \quad \text{osc. length} \sim \text{decay pipe length}$$

Baseline effects at the ND



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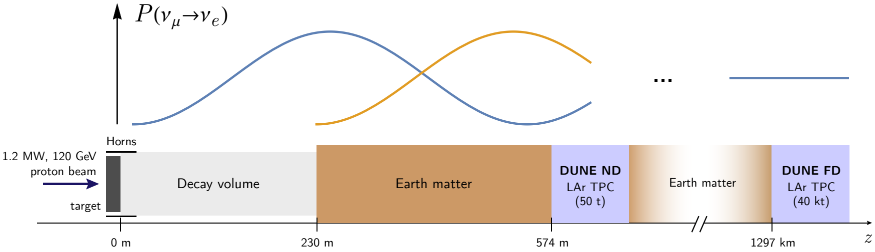


$\Delta m^2_{41} \sim \mathcal{O}(\text{eV}^2)$ and $E \sim \text{GeV} \quad \Rightarrow \quad$ osc. length $\sim$ decay pipe length

- replaced by a 20% energy smearing in 2008.12769 (DUNE BSM)
- goes beyond the usual geometric integration of fluxes (also in 3+0)
- need to pass the event-dependent baseline L to the probabilities

Accessing baseline information

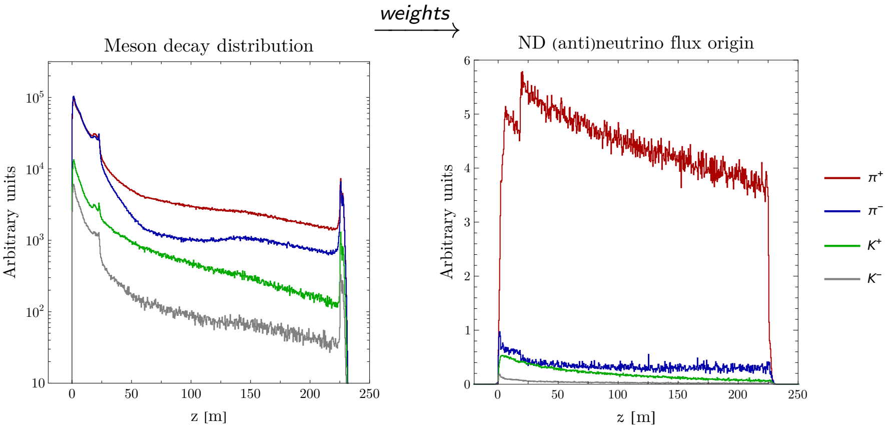
Challenge #1

Have full control of the flux simulation to study BSM scenarios

We recompute the fluxes, **keeping track of where the ν are produced**

- macro file publicly available at the time
- version `v3r5p7` of `g4lbne`, built against Geant `4.10.3.p03`
- 1.5 m long, 1.6 cm in diameter cylindrical target
- 1.2 MW, 120 GeV proton beam (1.1×10^{21} POT/y)
- 3-horn focusing system at $\pm$300 kA [see also 2103.04797]
- 10^7 protons simulated for each mode (FHC, RHC)

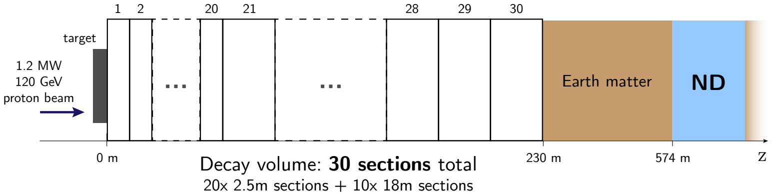
Accessing baseline information: results (FHC)



On the right: neutrinos actually arriving at the ND

Passing baseline information

- GLoBES: each experiment $\leftrightarrow$ single baseline L passed to $P_{\nu_\alpha \to \nu_\beta}$
  $\leftrightarrow$ single unoscillated flux file
- Our solution: section the production region into point-like sources, each an independent GLoBES "experiment" (max. $\sim$ 30)



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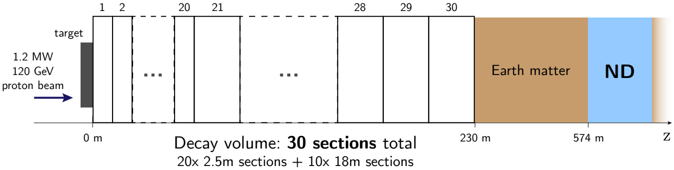

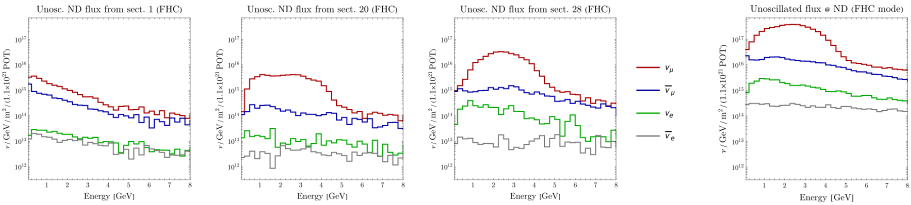

GLoBES setup

- 3.5 years FHC + 3.5 years RHC
- include low-pass filter to average out fast osc. [see also 2105.11466]
- "experiments" are not actually independent: must modify GLoBES source code and internal functions to sum the number of ND events before computing the χ^2 (there are only 2 experiments/detectors)
- `.glb` and related files obtained from ancillary material of 2103.04797 ("Experiment Simulation Configurations", prev. 1606.09550) include:
  - cross-sections for ν interactions in Ar (GENIE `v2.12.10`)
  - efficiencies and smearing matrices
  - rules (at the heart of the analysis, next slide)
  - systematics (in a couple of slides)

Rules and statistical analysis

Challenge #2

Base our BSM study on validated rules

$$\text{Rule} \equiv \{\text{signal and background channels with systematics}\}$$
$$\leftrightarrow \ 1 \text{ independent } \Delta\chi^2 \text{ contribution to the total } \chi^2$$

In our case, only CC rules were available [2103.04797] and thus considered:

- $\nu_e + \bar{\nu}_e$ appearance in FHC mode
- $\nu_e + \bar{\nu}_e$ appearance in RHC mode
- $\nu_\mu + \bar{\nu}_\mu$ disappearance in FHC mode
- $\nu_\mu + \bar{\nu}_\mu$ disappearance in RHC mode

NC channels are included as background to CC events (misid.) $\rightarrow$ affected by sterile mixing and have to be unfolded in flavour (cannot use `NOSC_`)

Systematics

Type	Description	σ	Det.	Rules	Channels
Normalization (ζ_k)	ND fiducial volume	1%	ND	all	all
	FD fiducial volume	1%	FD	all	all
	flux for FHC signal channels	8%	both	$1, 3$	sig.
	flux for RHC signal channels	8%	both	$2, 4$	sig.
	flux for FHC background channels	15%	both	$1, 3$	bkg.
	flux for RHC background channels	15%	both	$2, 4$	bkg.
	flux for FHC sig. (ND/FD diff.)	0.4%	ND	$1, 3$	sig.
	flux for RHC sig. (ND/FD diff.)	0.4%	ND	$2, 4$	sig.
	flux for FHC bkg. (ND/FD diff.)	2%	ND	$1, 3$	bkg.
	flux for RHC bkg. (ND/FD diff.)	2%	ND	$2, 4$	bkg.
	CC cross sections for $\overset{(-)}{\nu}_\alpha$ (6 syst.)	15%	both	all	all $\overset{(-)}{\nu}_\alpha$
	CC xsec. (ND/FD diff., 6 syst.)	2%	ND	all	all $\overset{(-)}{\nu}_\alpha$
	NC cross sections for $\overset{(-)}{\nu}$ (2 syst.)	25%	both	all	NC bkg.
	NC xsec. (ND/FD diff, 2 syst.)	2%	ND	all	NC bkg.
Shape ($\zeta'_{r,i}$) (bin-to-bin uncorrelated)	FHC $\overset{(-)}{\nu}_e$ app. dominant (60 syst.)	5%	both	1	bkg.
	RHC $\overset{(-)}{\nu}_e$ app. dominant (60 syst.)			2	bkg.
	FHC $\overset{(-)}{\nu}_\mu$ dis. dominant (60 syst.)			3	sig.
	RHC $\overset{(-)}{\nu}_\mu$ dis. dominant (60 syst.)			4	sig.

Challenge #3

Working with acceptable and properly correlated systematical uncertainties

Type	Description	σ	Det.	Rules	Channels
Normalization (ζ_k)	ND fiducial volume	1%	ND	all	all
	FD fiducial volume	1%	FD	all	all
	flux for FHC signal channels	8%	both	$1,3$	sig.
	flux for RHC signal channels	8%	both	$2,4$	sig.
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	CC xsec. (ND/FD diff., 6 syst.)	2%	ND	all	all $\overset{(-)}{\nu}_\alpha$
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	FHC $\overset{(-)}{\nu}_\mu$ dis. dominant (60 syst.)			3	sig.
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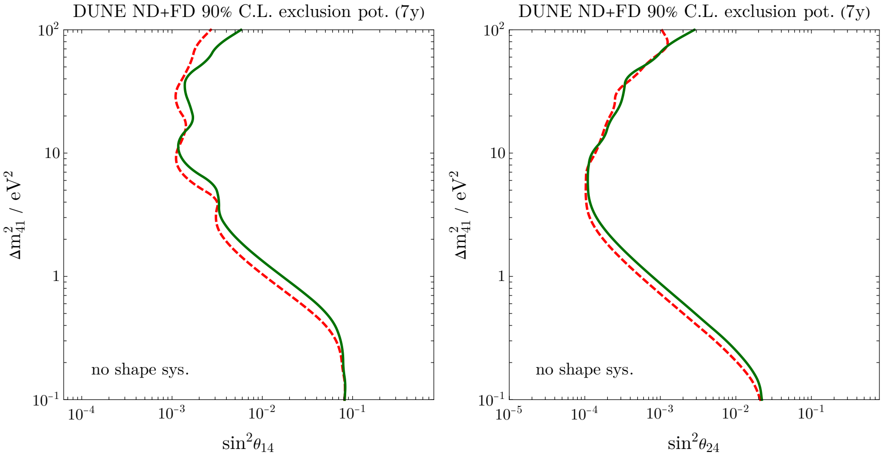
Systematics are correlated across indicated detectors, rules, channels

normalisation: 2008.12769, *shape*: inspired by 2105.11466

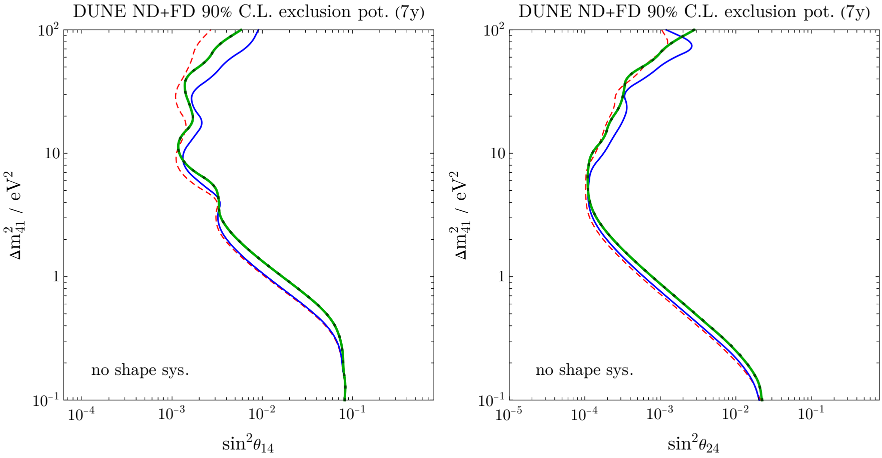
Results: no shape systematics



Red: fixed $L = 574$ m for ND events, Green: w/ ND baseline effects

Overall, slightly reduced sensitivity to a sterile neutrino

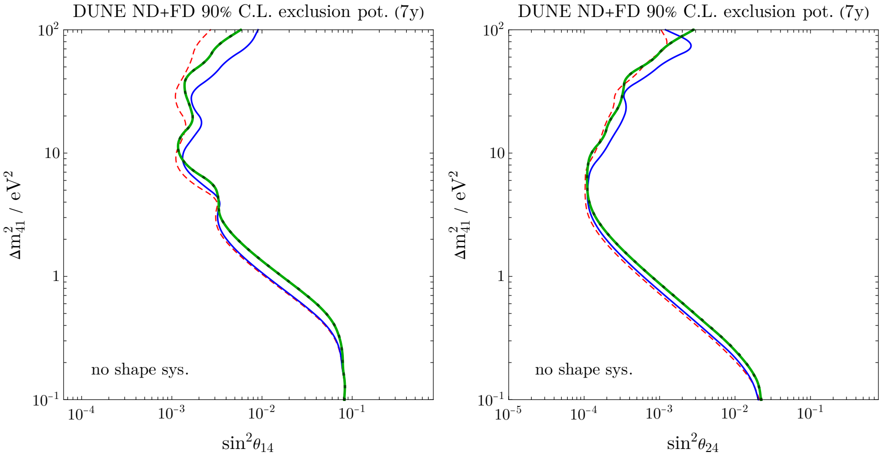
Results: no shape systematics (vs. 20% E smearing)



Red: fixed $L = 574$ m for ND events, Green: w/ ND baseline effects

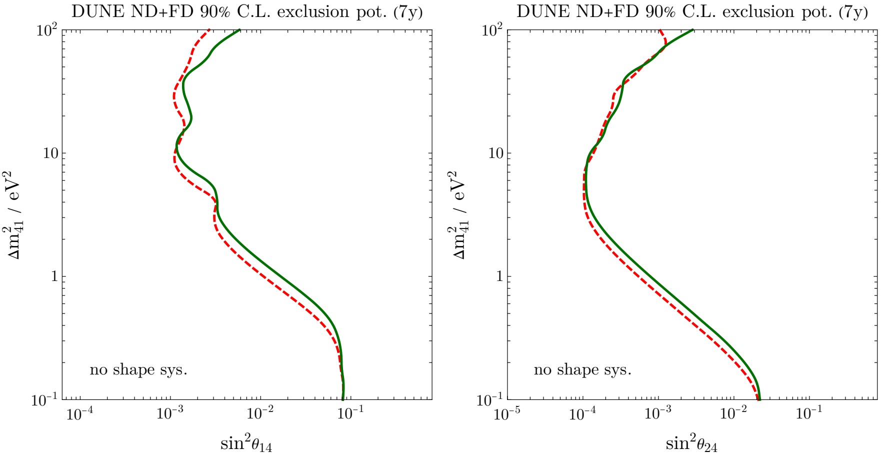
Blue: 20% energy smearing [as in 2008.12769]

Results: no shape systematics (vs. 20% E smearing)



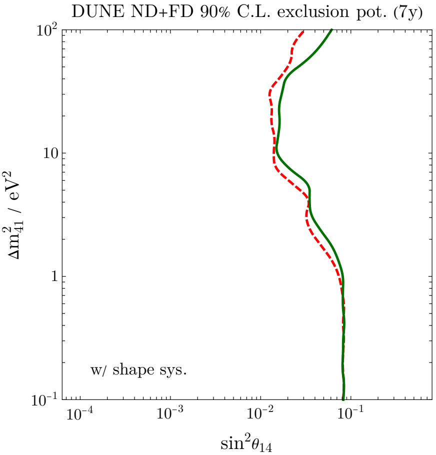
Matter effects and exact oscillation formulae for ND events are not important (matter effects mandatory for FD)

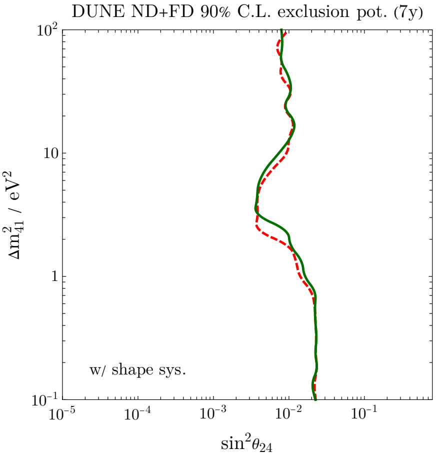
Results: no shape systematics



Red: fixed $L = 574$ m for ND events, Green: w/ ND baseline effects

Results: with 5% shape systematics





Red: fixed $L = 574$ m for ND events, Green: w/ ND baseline effects

Even with the inclusion of shape systematics, visible differences persist

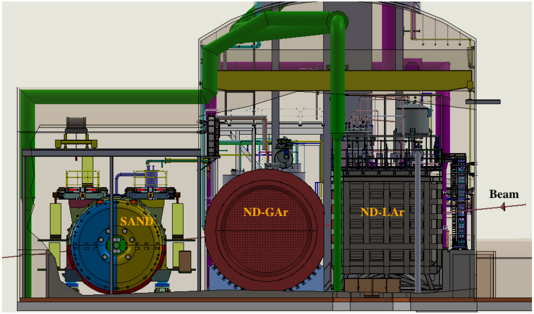
Challenges for independent BSM analyses

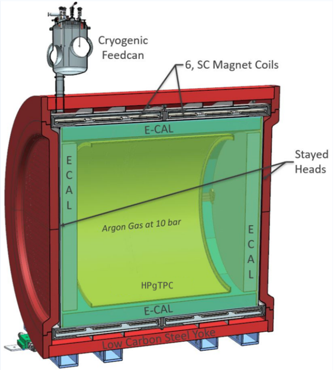
As outsiders, we relied on tools provided by the collaboration.

In summary:

1. We redid the flux simulation thanks to macro files which were publicly available (not anymore...)
2. We used and adapted only the rules (CC) given in the "Experiment Simulation Configurations" preprints [1606.09550, 2103.04797]
   - it could be valuable to have rules publicly available for all flavours (incl. τ) and all ND-complex detectors
3. We interpreted the (somewhat condensed) list of normalisation systematics in 2008.12769, and coded it into our `glb` files
   - it was not in the "Experiment Simulation Configurations"

Phase II ND upgrade





ND complex [2203.06281]: SAND (beam monitor) + ND-LAr
+ TMS (phase I) → **ND-GAr (phase II)**

Phase II ND upgrade

- ND-GAr can search for anomalous ν_τ interactions at the ND from SBL mixing with sterile neutrinos [2008.12769, 2203.06281 (DUNE)] (very low ν_τ beam background) $\rightarrow$ needs new rules!
- Searches for ν_τ appearance may improve the discovery potential for sterile neutrinos, NC NSI, non-unitarity, as well as contribute to general consistency tests of the 3ν paradigm [see also e.g. 2007.00015]
- According to 2203.06281, preliminary studies including ND-GAr estimate that DUNE's sensitivities to anomalous ν_τ app. may extend beyond previous ones (e.g. NOMAD, CHORUS)

  $\rightarrow$ see goal 4 in M. Bishai's talk this morning

Phase II ND upgrade

- τ lepton not directly observable at DUNE (lifetime 2.9×10^{-13} s)
- need incoming ν_τ with $E \gtrsim 3.5\,\text{GeV}$ (due to large m_τ)
- The products of τ decays are readily identifiable in the DUNE ND, given the excellent spatial and energy resolution of ND-GAr and the other ND instruments [2203.06281]
  - $\sim 65\%$ hadrons
  - $\sim 18\%$ $\nu_\tau + e^- + \bar{\nu}_e$
  - $\sim 17\%$ $\nu_\tau + \mu^- + \bar{\nu}_\mu$
- Excellent sensitivity of ND-GAr to this last $\tau \to \mu$ channel, with **high-energy muons**
  - ND-LAr limited to $p_\mu \lesssim 2\,\text{GeV}$ (no magnetic field)
  - TMS detector (phase I) is limited to $p_\mu \lesssim 6\,\text{GeV}$
  - **ND-GAr (phase II)** extends the range to $p_\mu \sim 15\,\text{GeV}$ (possibly beyond), thanks to the 0.5 T magnetic field

This extension will become even more valuable when operating in the high-energy tune [1904.07265, 2105.11466] peak ~ 4 GeV, $E_{\text{max}} \sim 15$ GeV

Summary

- The upcoming DUNE has a broad Physics reach and is sensitive to the BSM effects of sterile neutrinos
- Baseline effects should be accounted for in sterile precision studies
- We have identified challenges which may inhibit pheno analyses outside the collaboration
- The phase II ND upgrade is expected to enhance sensitivity to anomalous ν_τ appearance at the ND

Thank you!