Heavy Neutral Leptons

At DUNE-ND

P. Barham Alzás on behalf of the BSM group

08/08

NDGAr Group Meeting

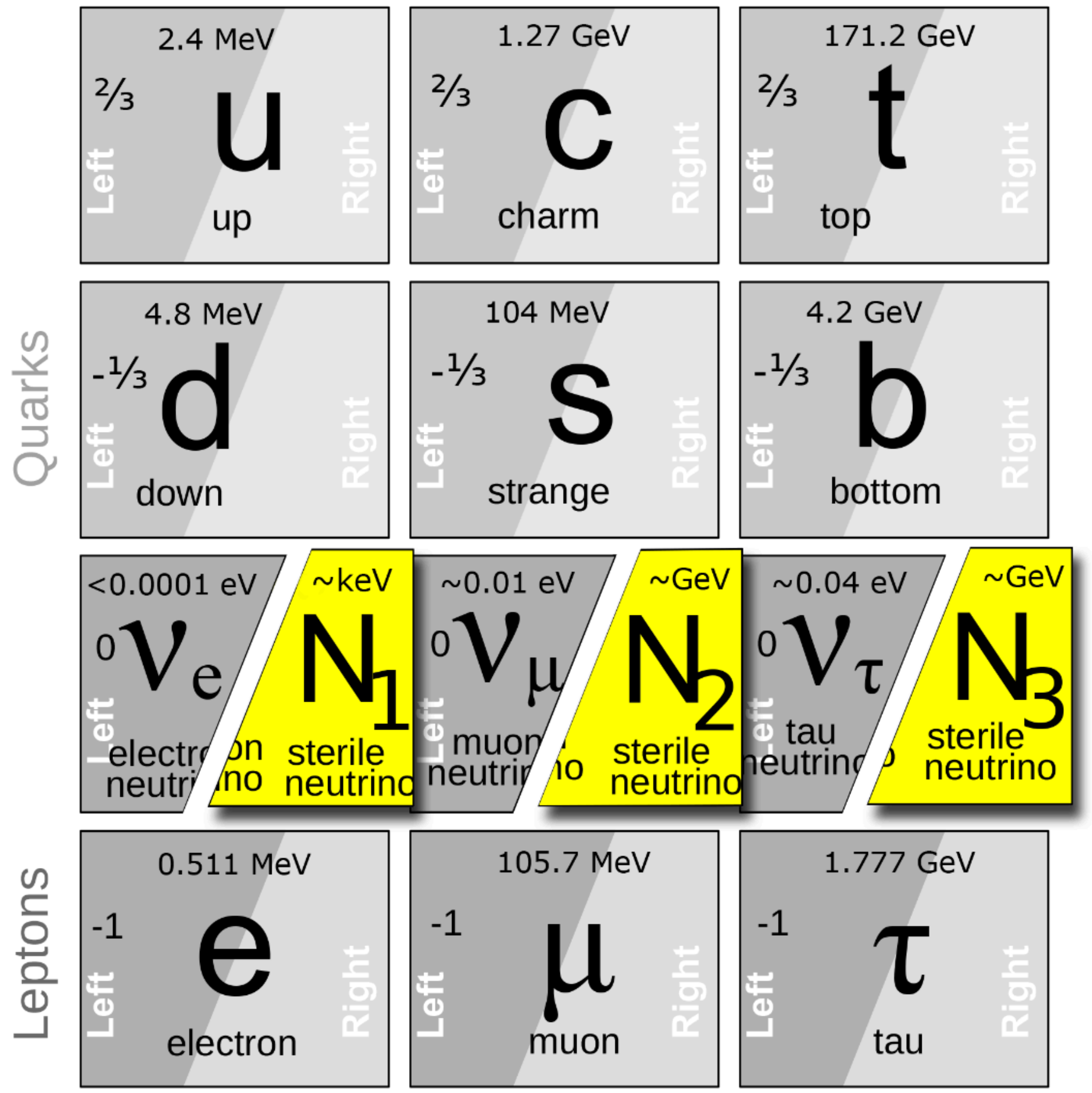
Heavy Neutral Leptons - Reminder

Heavy neutral leptons: hypothetical particles that are full fermion singlets of the SM gauge group.

They are right handed counterparts of the known active, left handed neutrinos.

Only couple to the SM via neutrino mixing —> production and decay $\propto |U_{\alpha 4}|^2$ —> extremely hard to produce and detect.

Theoretically interesting as a SM extension for several reasons.



"Neutrino Minimal" Standard Model

Heavy Neutral Leptons - Production and detection

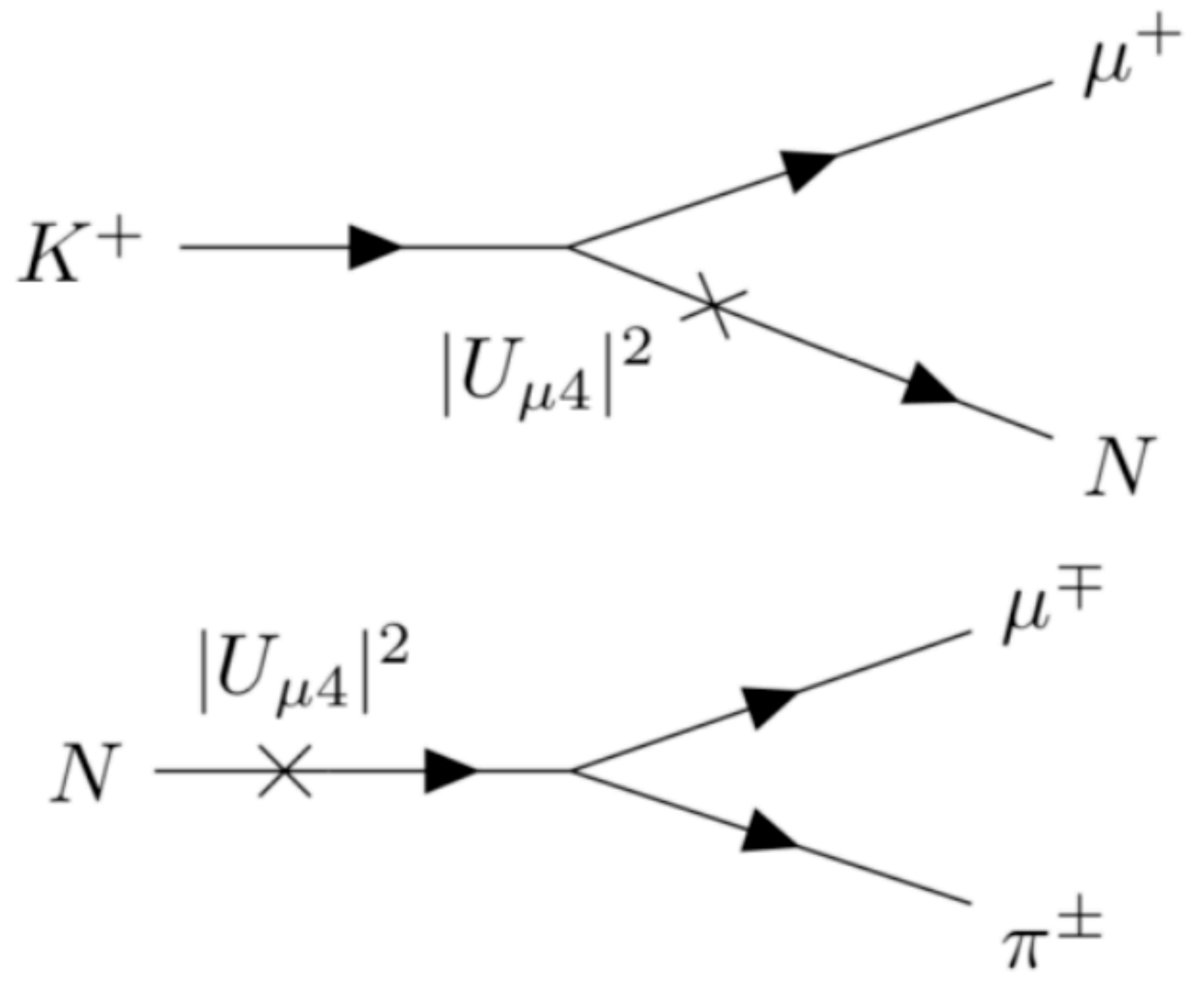
At DUNE, HNLs will be produced at the 120 GeV proton beam graphite target:

- Light and heavy mesons (pions, kaons, D, Ds…) and tau leptons are produced when protons impact on the target.
- These particles decay into HNLs instead of regular neutrinos with probability $\propto |U_{\alpha 4}|^2$.

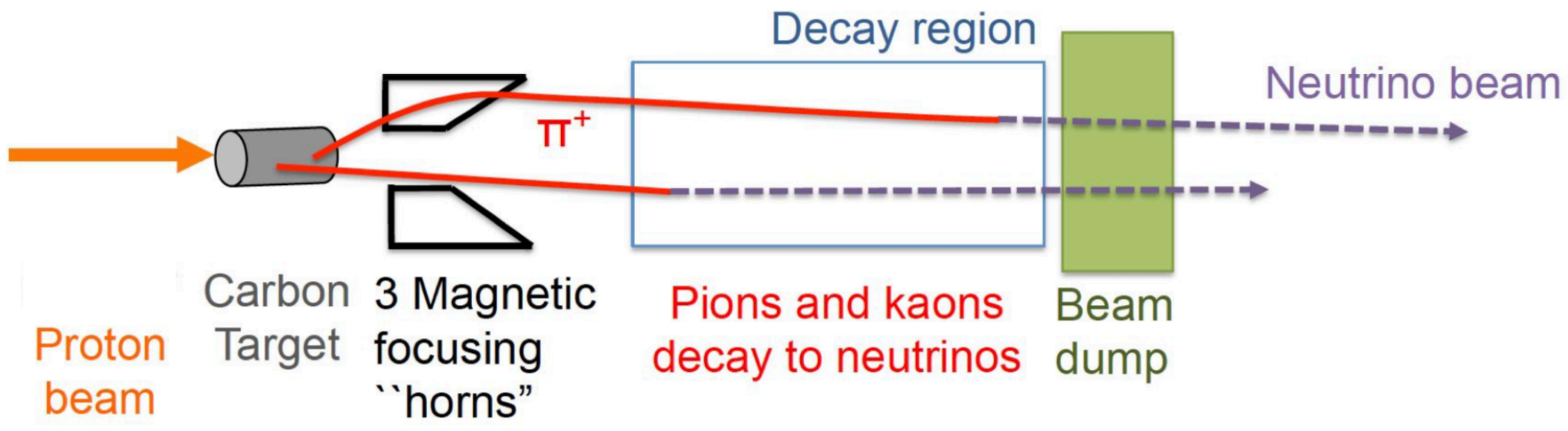
—> DUNE will be sensitive to HNLs in the MeV to GeV range.

Some HNLs will decay inside the Near Detector: we look for their decay products as signature (mainly leptons, pions and other light mesons).

We have a chance of observing these extremely rare events thanks to DUNE's very high intensity beam and excellent Near Detector capabilities.



Production and decay examples at DUNE-ND.



DUNE-ND will be at ~600 m from beam target.

DUNE sensitivity: history since 2019

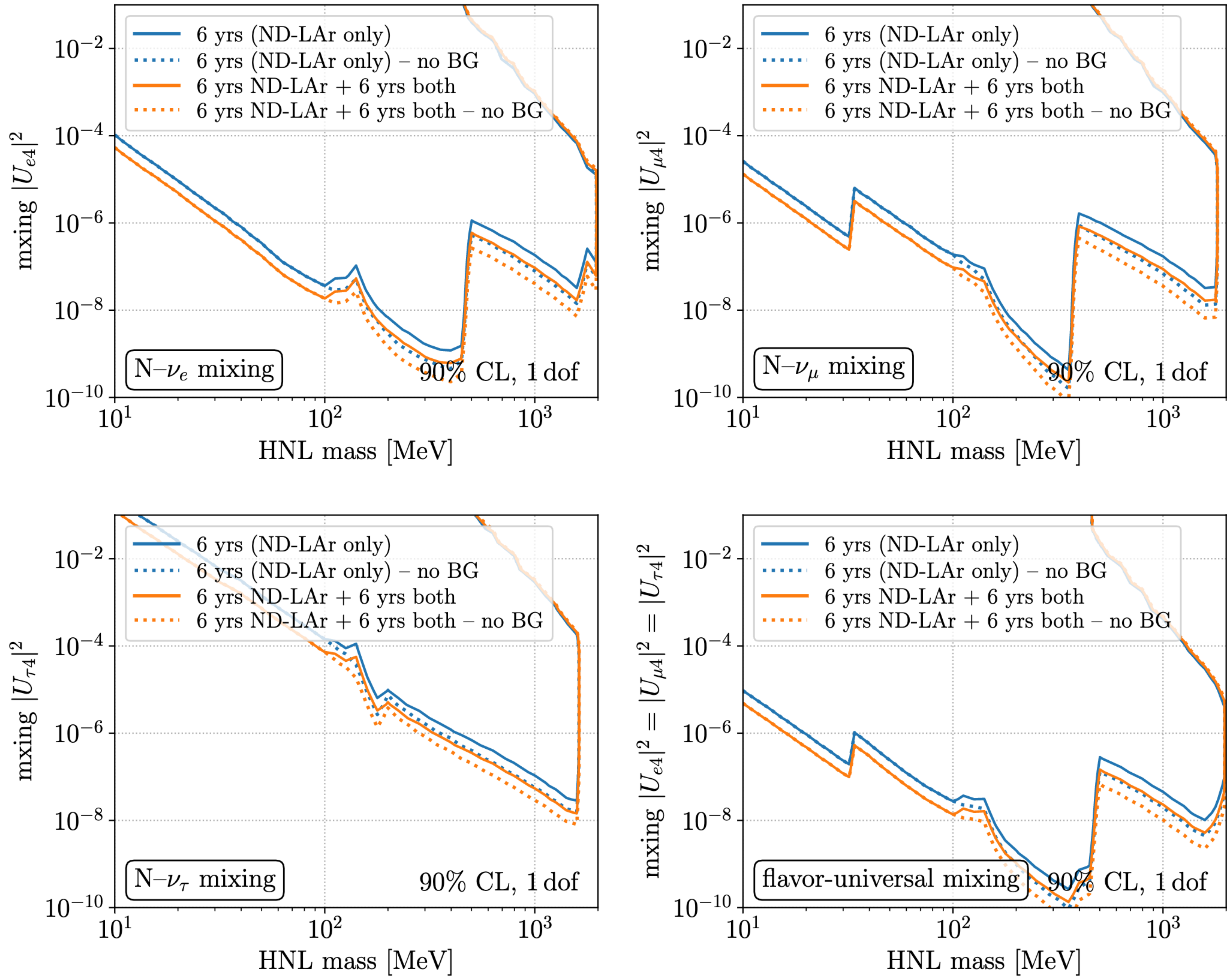
- Several phenomenology papers since 2019 have appeared studying DUNE's sensitivity to HNLs (sensitivities only for ND-LAr and ND-GAr):
  - P0 arXiv:1902.06099
  - P1 Pascolli et al. arXiv:1905.00284
  - P2 Sfar, Christodoulou and ADR (in CDR arXiv:2103.13910)
  - P3 Kelly et al. arXiv:1912.07622
  - P4 Coloma, Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia and Pavlovic arXiv:2007.03701
  - P5 Kopp et al. arXiv:2102.03383

- P4 and P5 have provided the most advanced sensitivity estimates.

- Some confusion as to what the DUNE sensitivity is with these different studies (all cited).

- All agree on: the region with least expected competition is the low mass region (because of the low beam energy, high intensity). The ~GeV region is also interesting (less competitive vs not approved experiments).

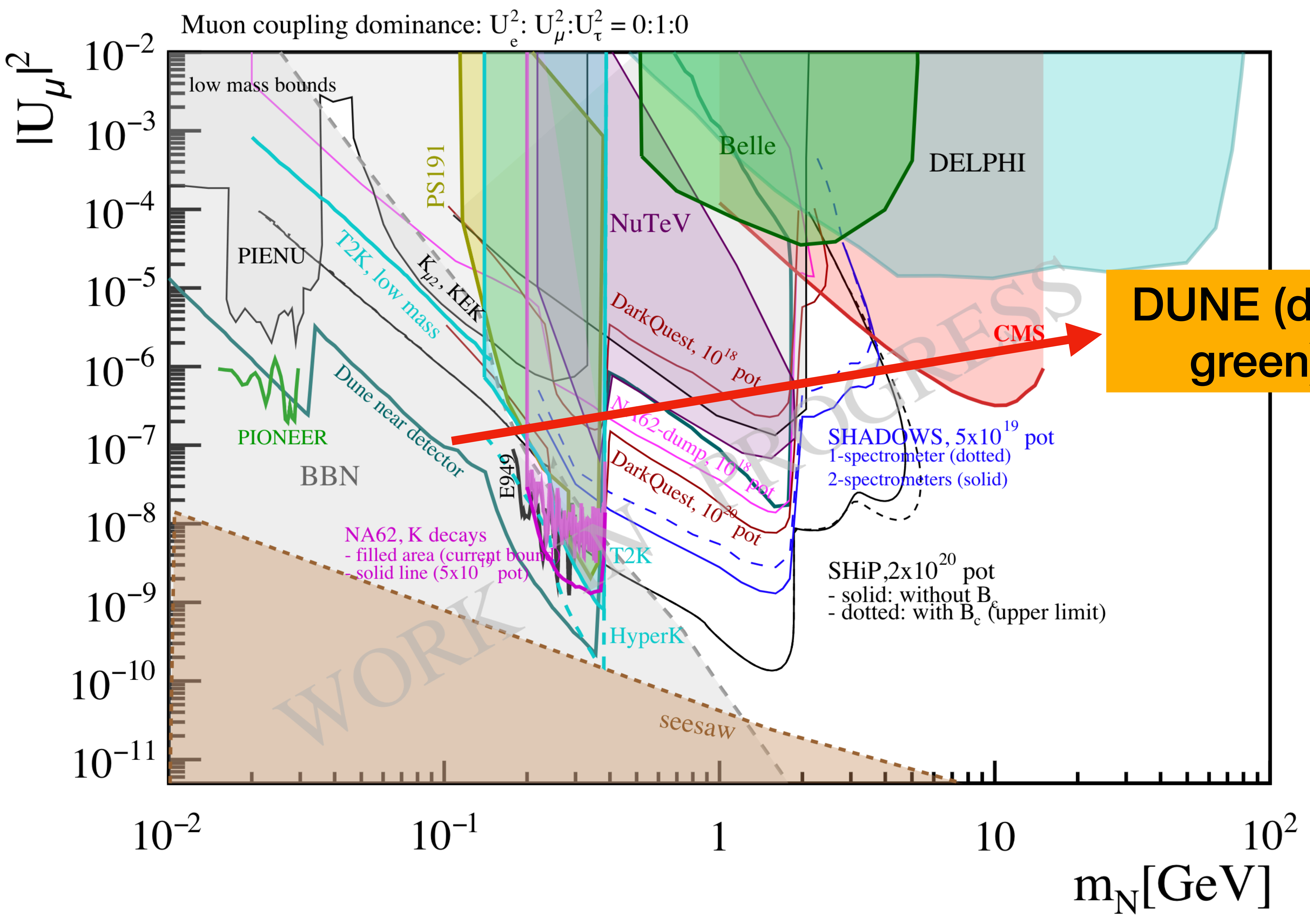
Snowmass results (March 22')



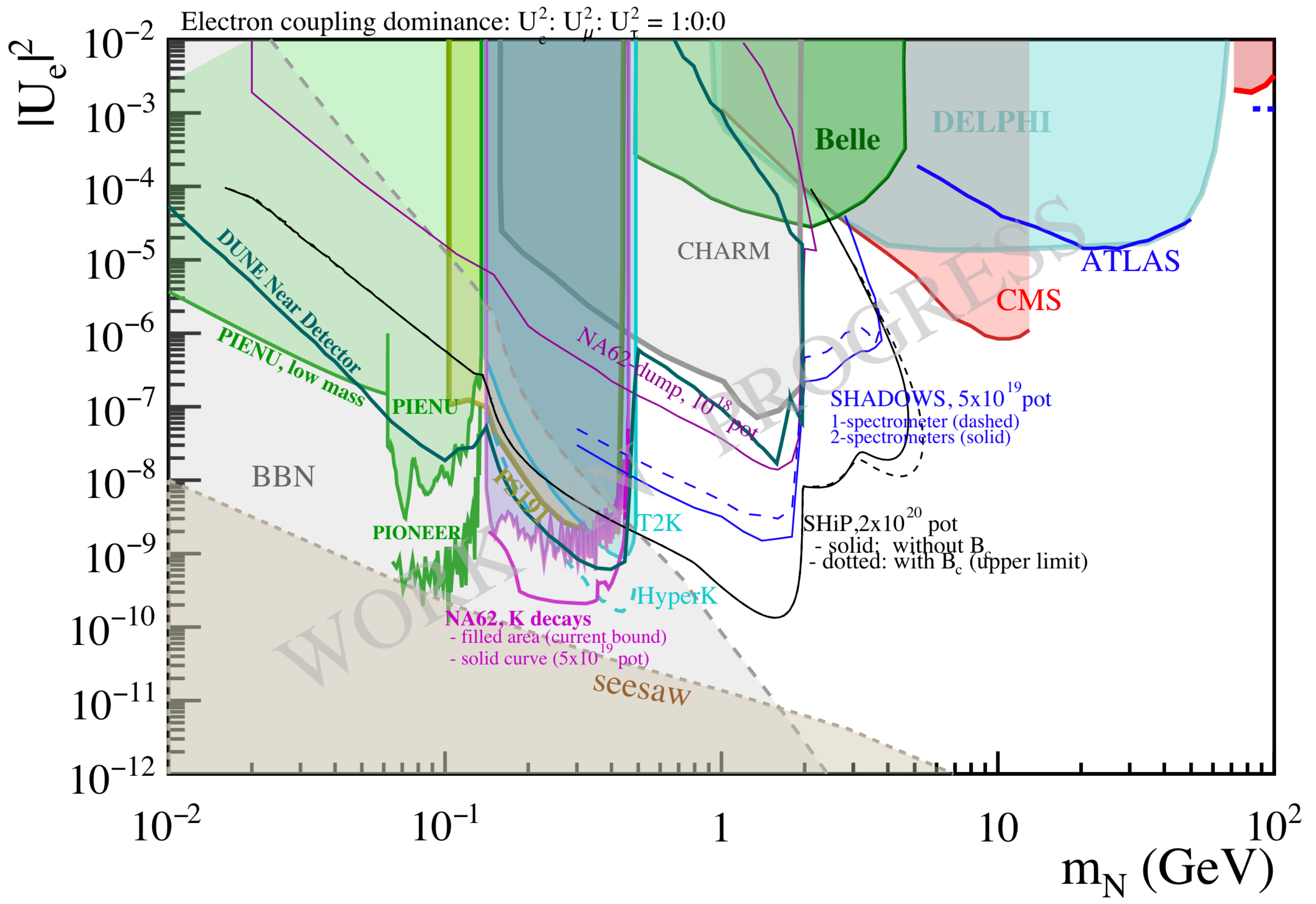
DUNE results reported in HNL whitepaper for Snowmass (J. Kopp, P. Barham, A. de Roeck), based on Kopp et al. (P5).

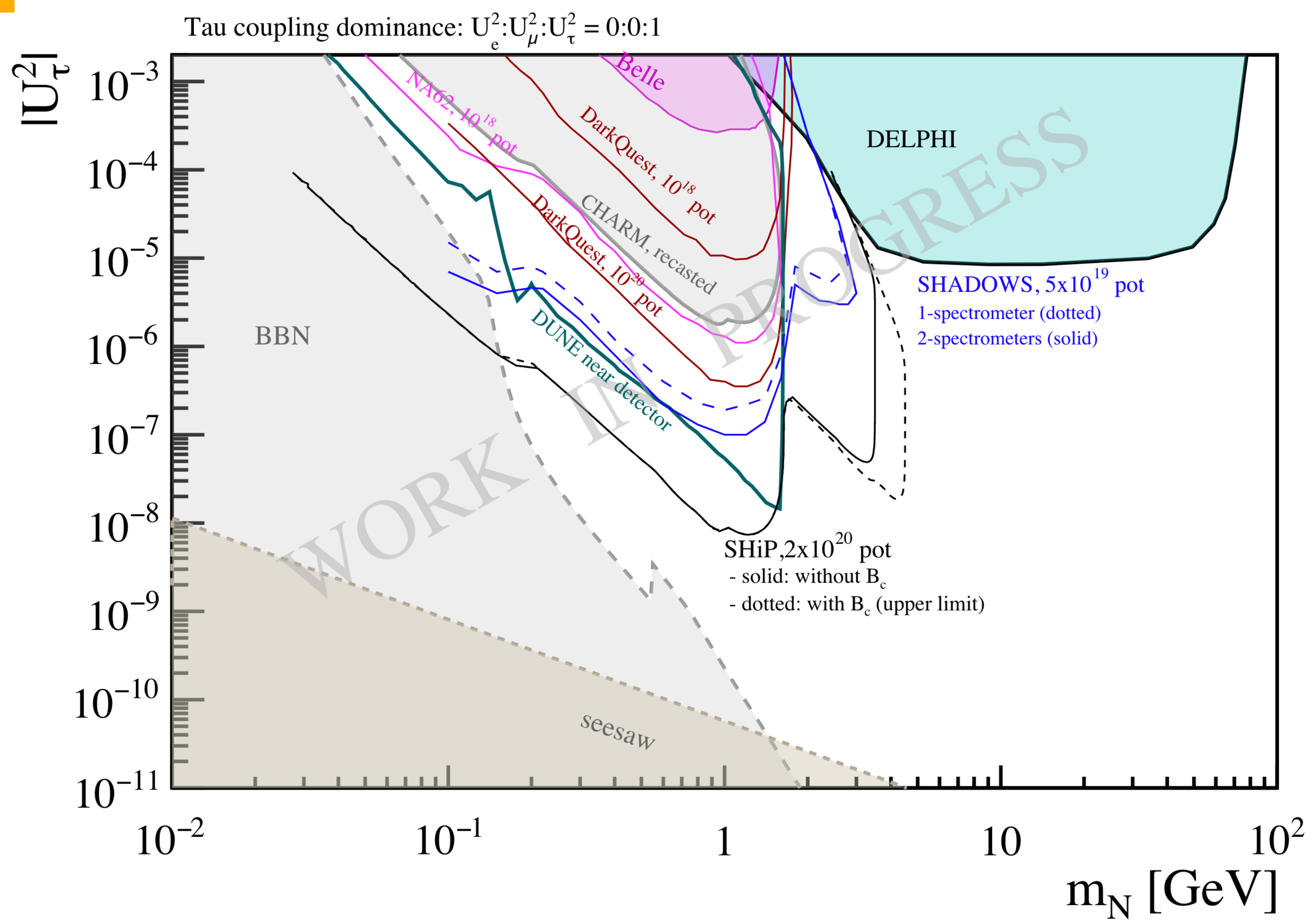
- Sensitivity for all decay channels combined, for the 12 year running scenario (details later).
- Off-axis study: improved signal-to-background ratio, but limited statistics —> similar sensitivity results.
- Basic smearing and cuts.
- No-BG scenario included as there is potential to improve the signal-background distinction in future studies (e.g. via precise timing).

Snowmass results



DUNE (dark green)





Most competitive bounds for second generation mixing.

New results since Snowmass

Updated Snowmass results with more accurate fluxes and detector response.

New fluxes provided by J. Hernández, based on P4 approach (most complete treatment of flux correction). Kinematics changes due to non-zero HNL masses taken into account. **Adapted to most recent ND-LAr and ND-GAr geometries.**

- Backgrounds based on Kopp et al. (P5) study (NuShock generated). **New antineutrino mode backgrounds** available and used.
- **Running conditions adapted to realistic DUNE scenarios:**
  - 120 GeV proton beam.
  - 6 years of LBNF with 1.2 MW followed by 6 years with 2.4 MW, corresponding to a total of 2 x 10^{22} PoT for ND-LAr (12 years running) and 1.4 x 10^{22} PoT for ND-GAr (later 6 years running).
  - 50% neutrino mode, 50% antineutrino mode (all previous studies only in neutrino mode).
- **Mixing** of one flavour at a time.

Considered channels:

- $N \to \nu e e$
- $N \to \nu e \mu$
- $N \to \nu \mu \mu$
- $N \to e \pi$
- $N \to \mu \pi$
- $N \to \nu \pi^0$

New results

- **Add parametrized detector effects**:

  1. Reconstruction efficiencies.

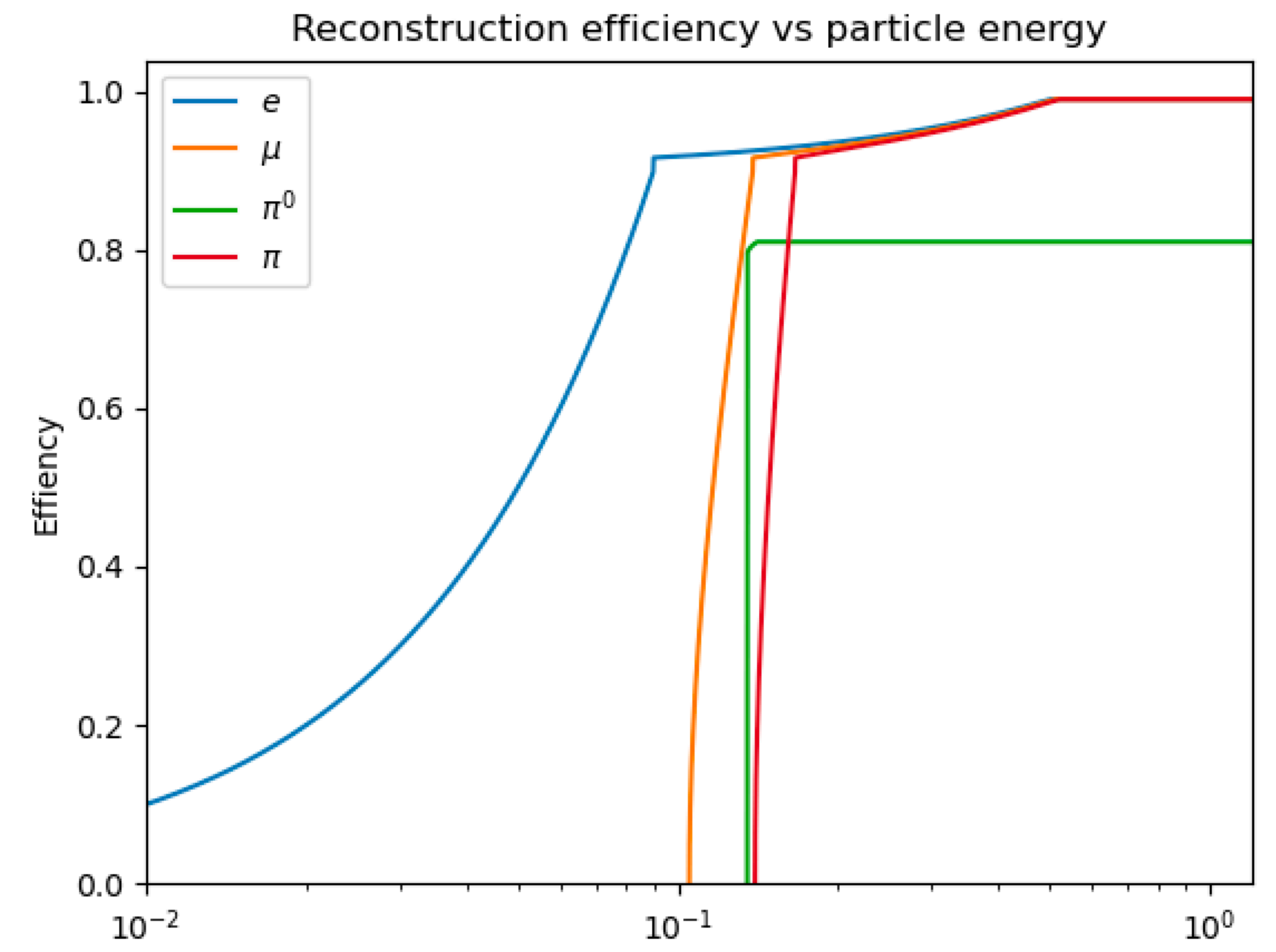
  2. Energy and angular resolutions for different particles —> accurate smearing of the fluxes and accurate histogram bin sizing for background comparison.

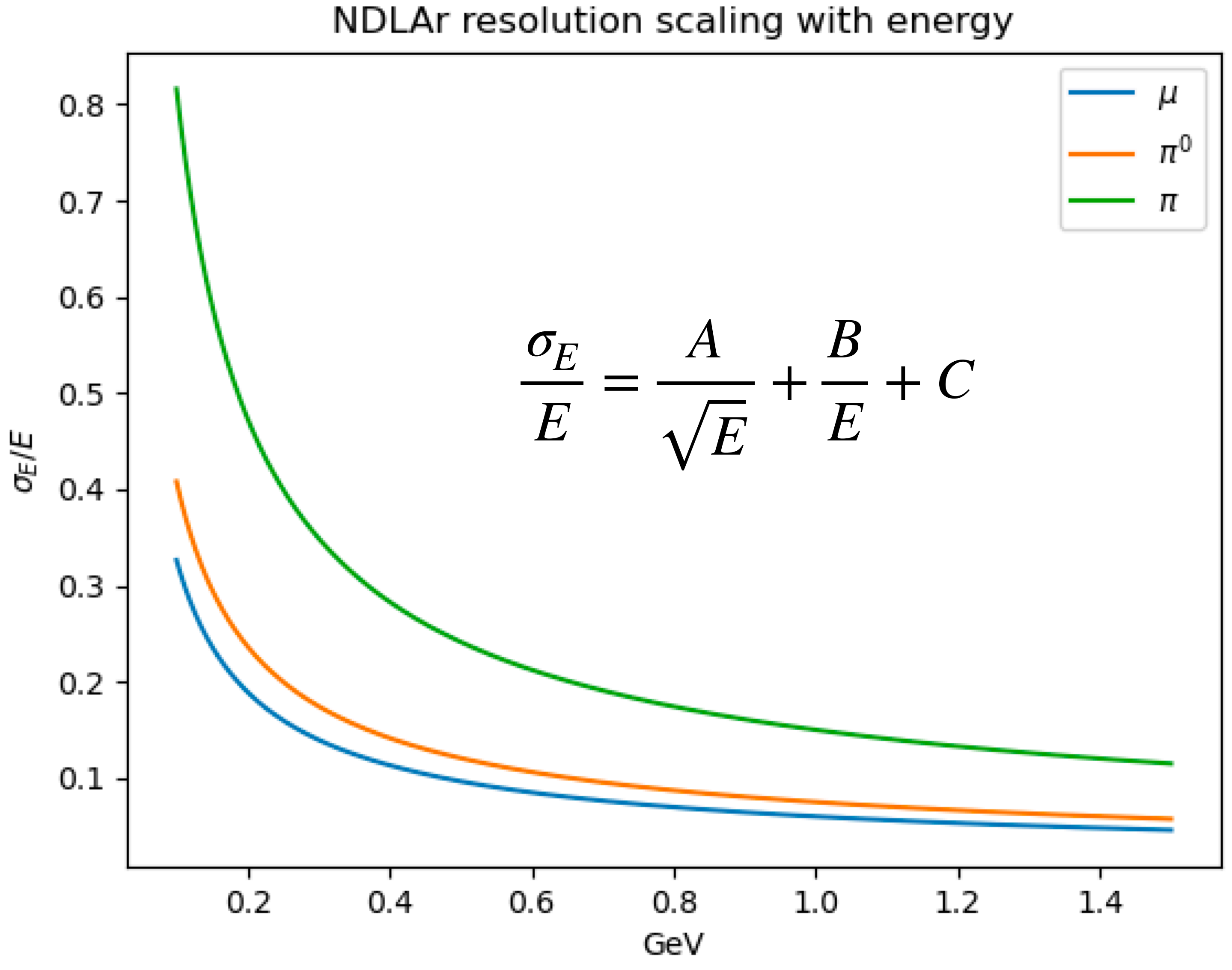
  3. Energy and angular cuts.

- **Following ND CDR info:**

  4. Most info available for ND-GAr in the CDR.

  5. Information lacking for ND-LAr: provisional info for resolutions and efficiencies taken from far detector TDR (single phase technology): arXiv:2002.03005 [hep-ex].





$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} + \frac{B}{E} + C$$

Reconstruction efficiencies (ND-GAr) and resolution scaling for different particles (ND-LAr).

New results (ND-GAr details)

Some examples:

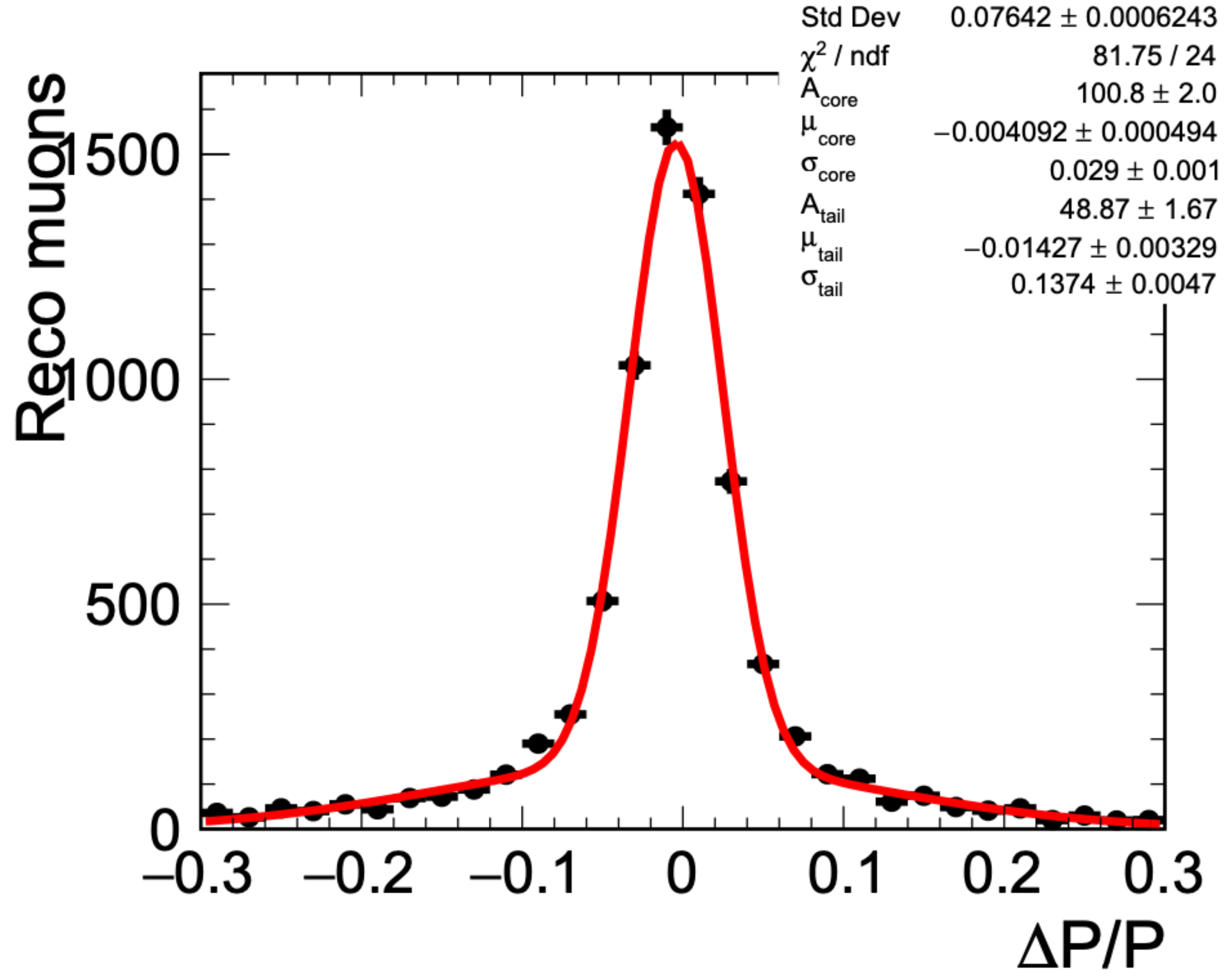
- Muon momentum resolution:

  Gaussian 'core' of $\Delta p/p$ = 2.7%, tails = 12%.

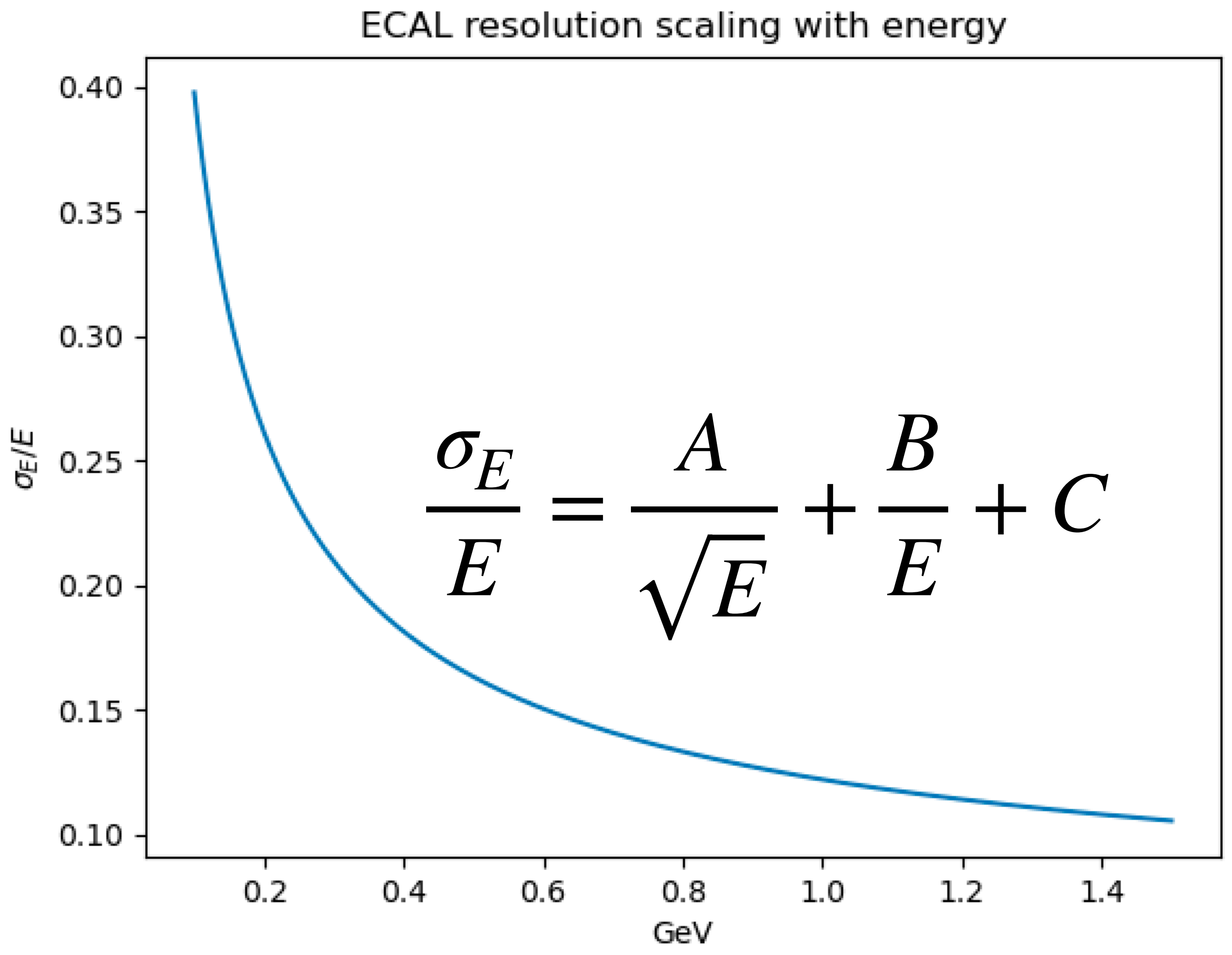
- Neutral pion energy resolution:

  π^0 decays ~98% to $\gamma\gamma$ —> Use ECAL energy resolution for two photons to get the pion resolution.

Similar procedure for ρ, ρ^0, ϕ… but not included in decay channel list.

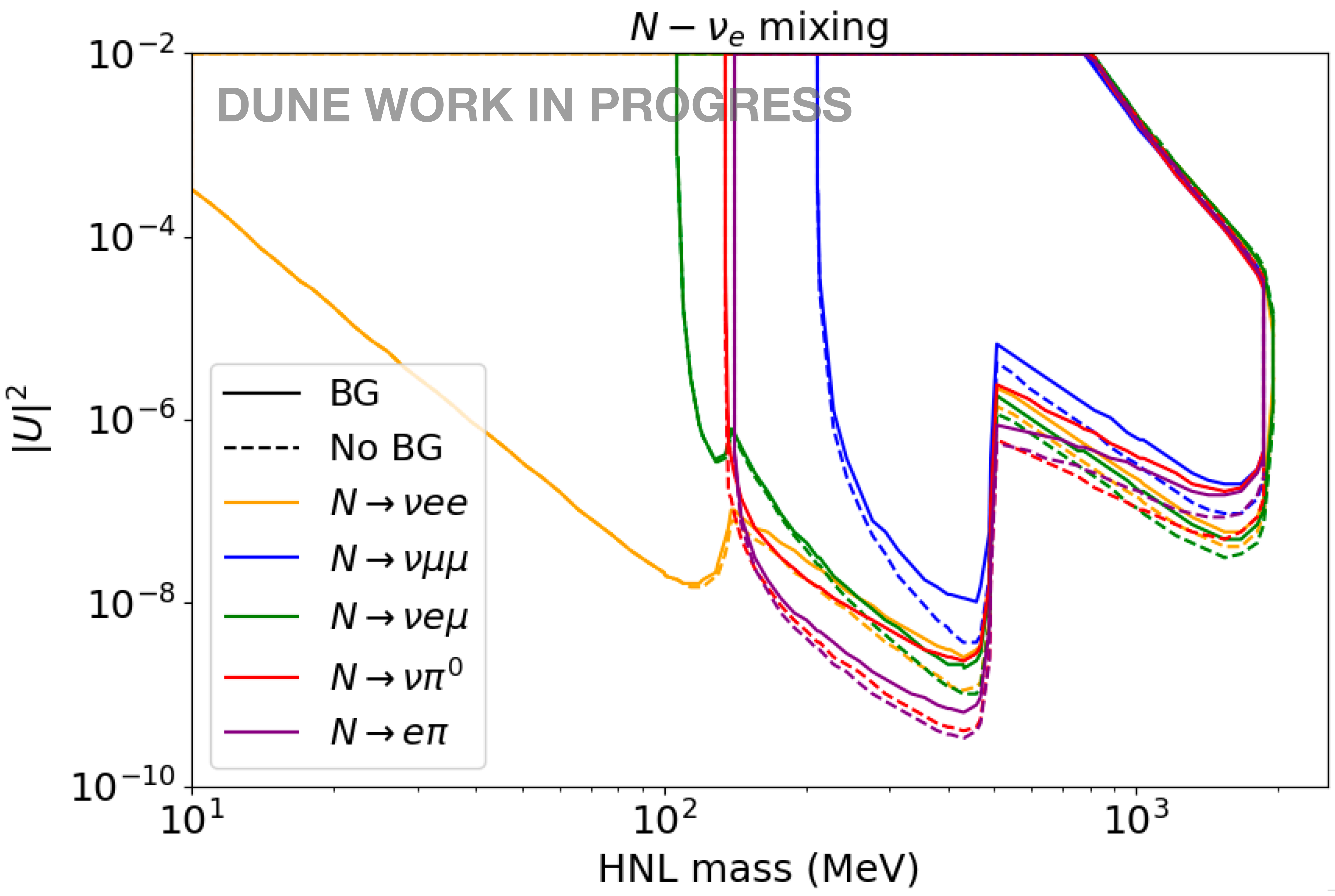


Muon momentum resolution (Fig 3.23 ND CRD)

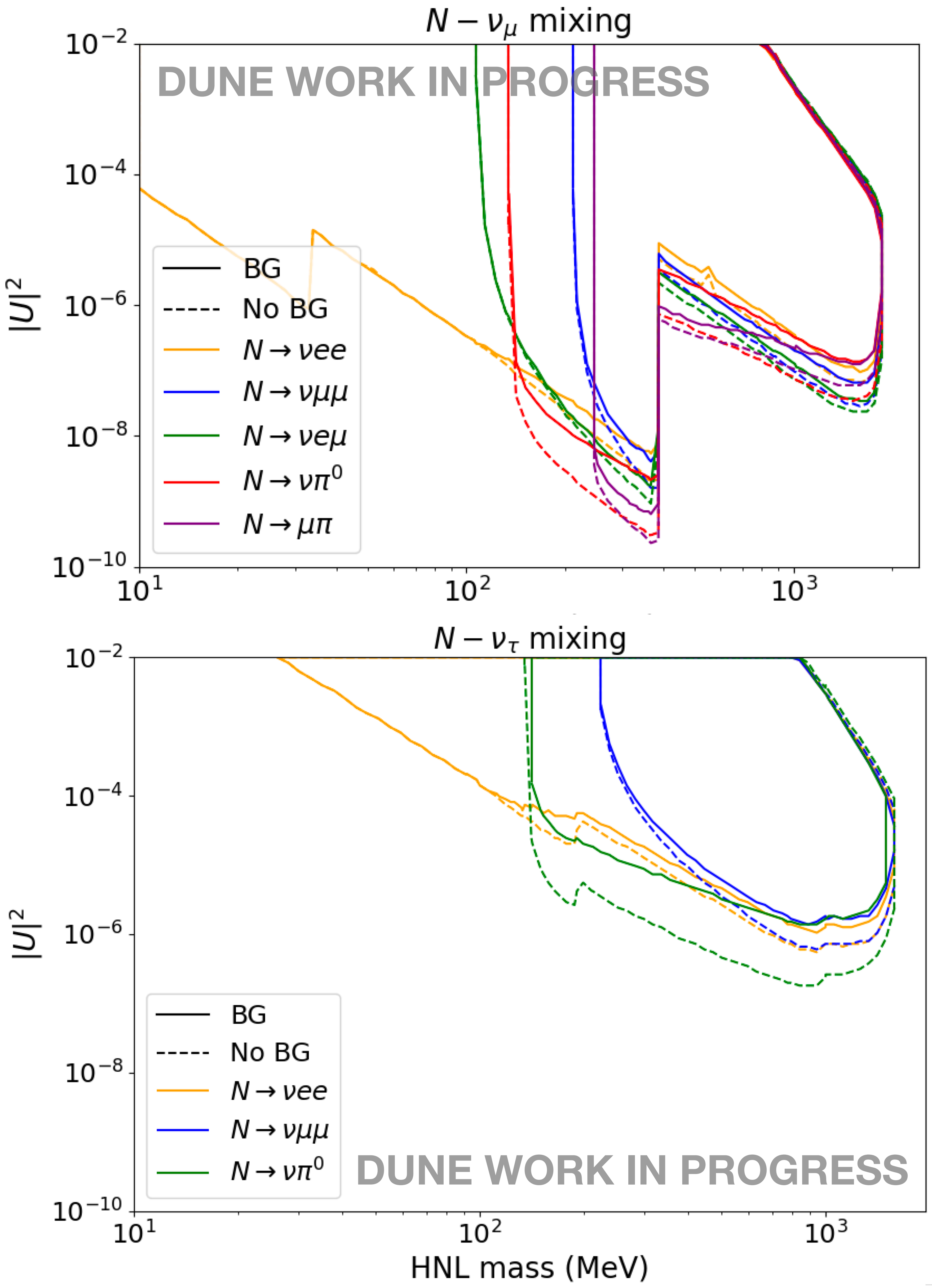


A = 6%, B = 1.6%, C = 4%.

New results: ND-GAr 6 y.

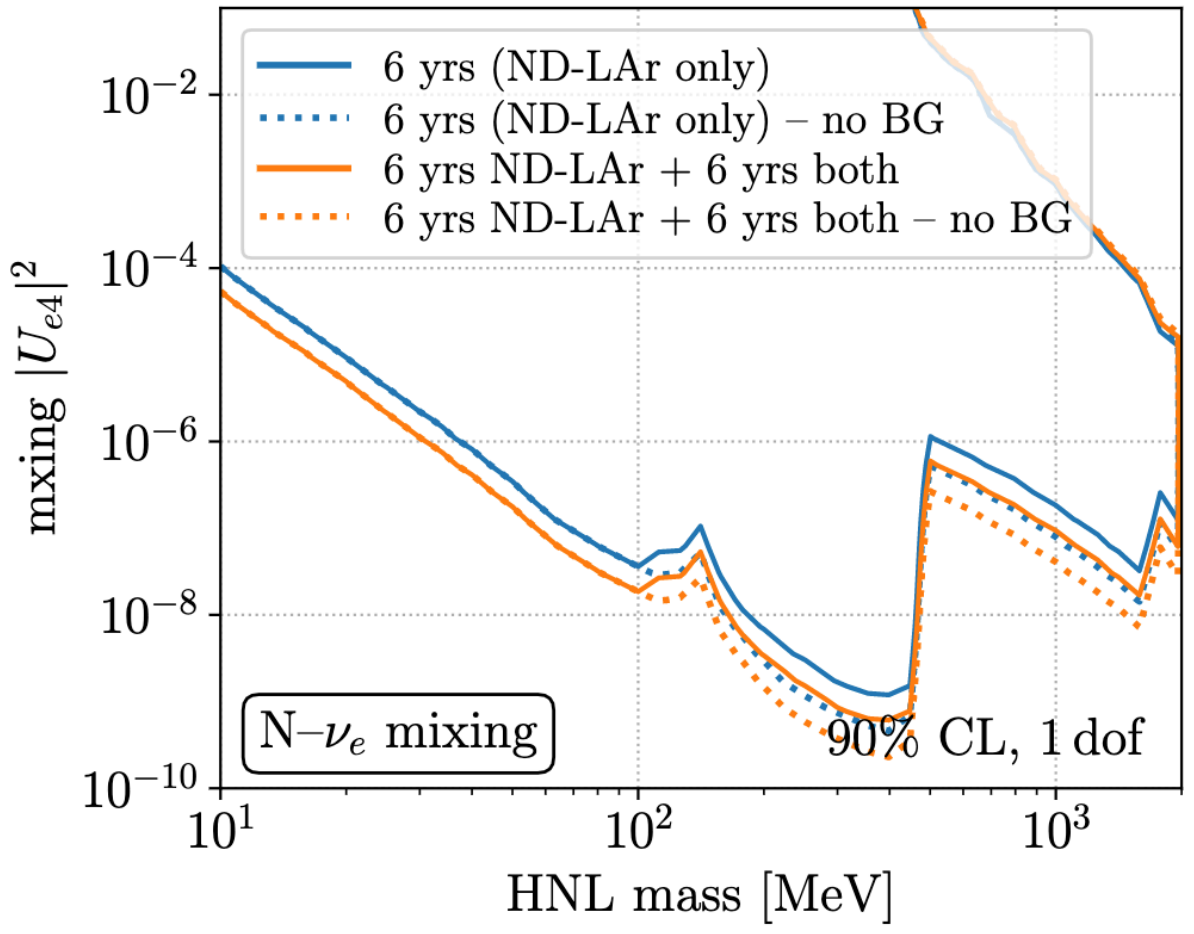


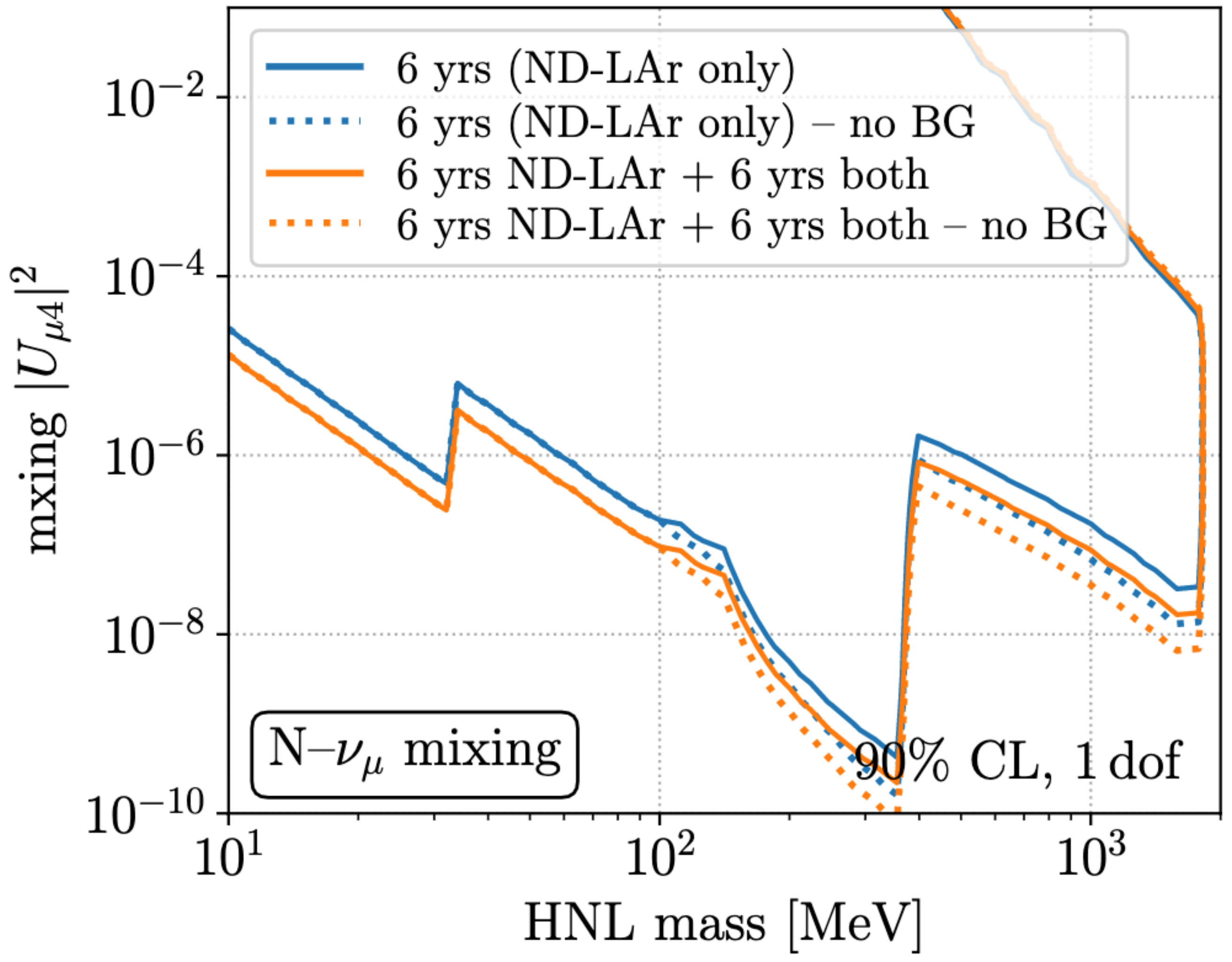
Electron neutrino mixing. All channels.



Muon/tau neutrino mixing. All channels.

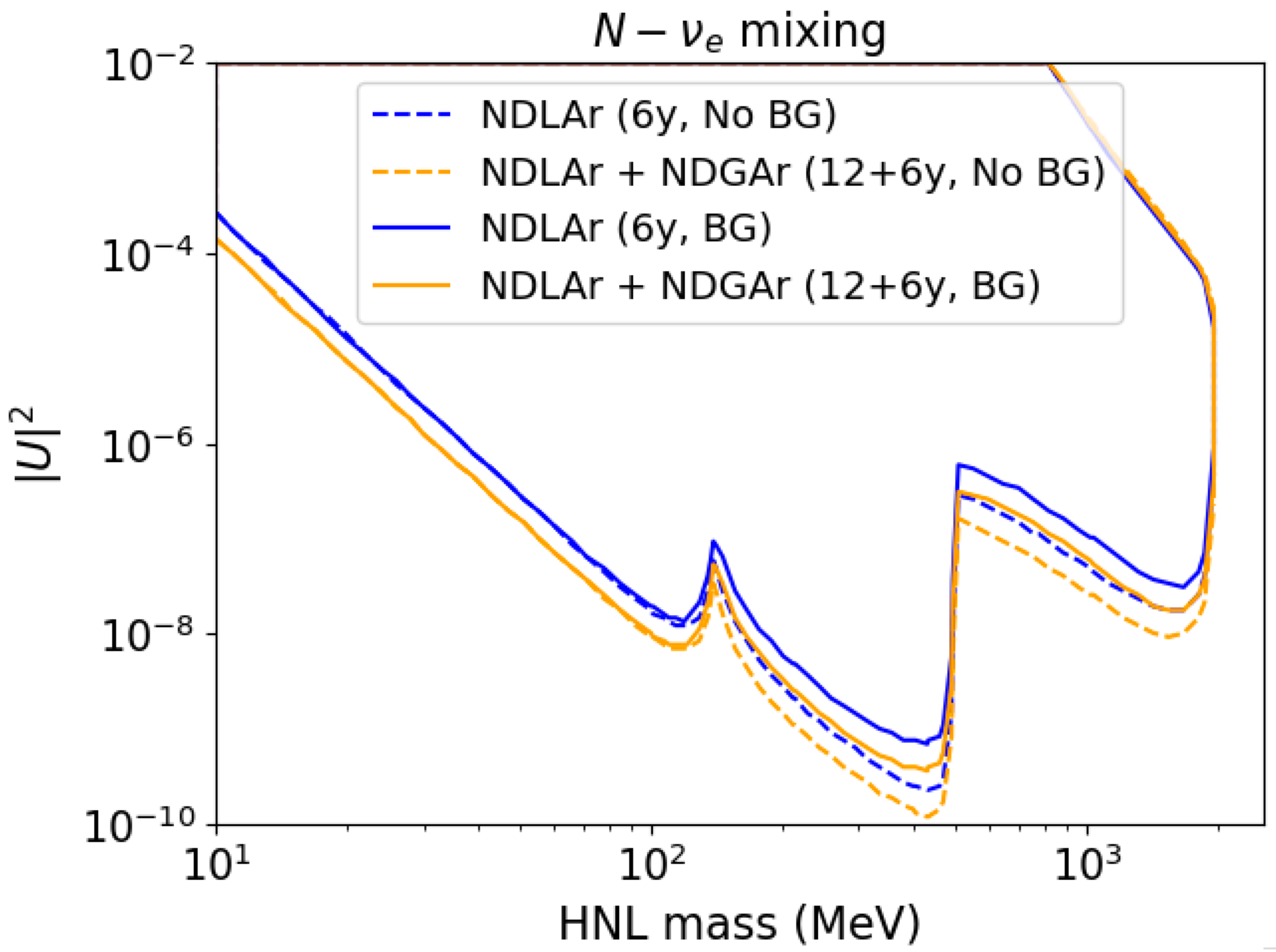
Where we left… Phenomenological studies

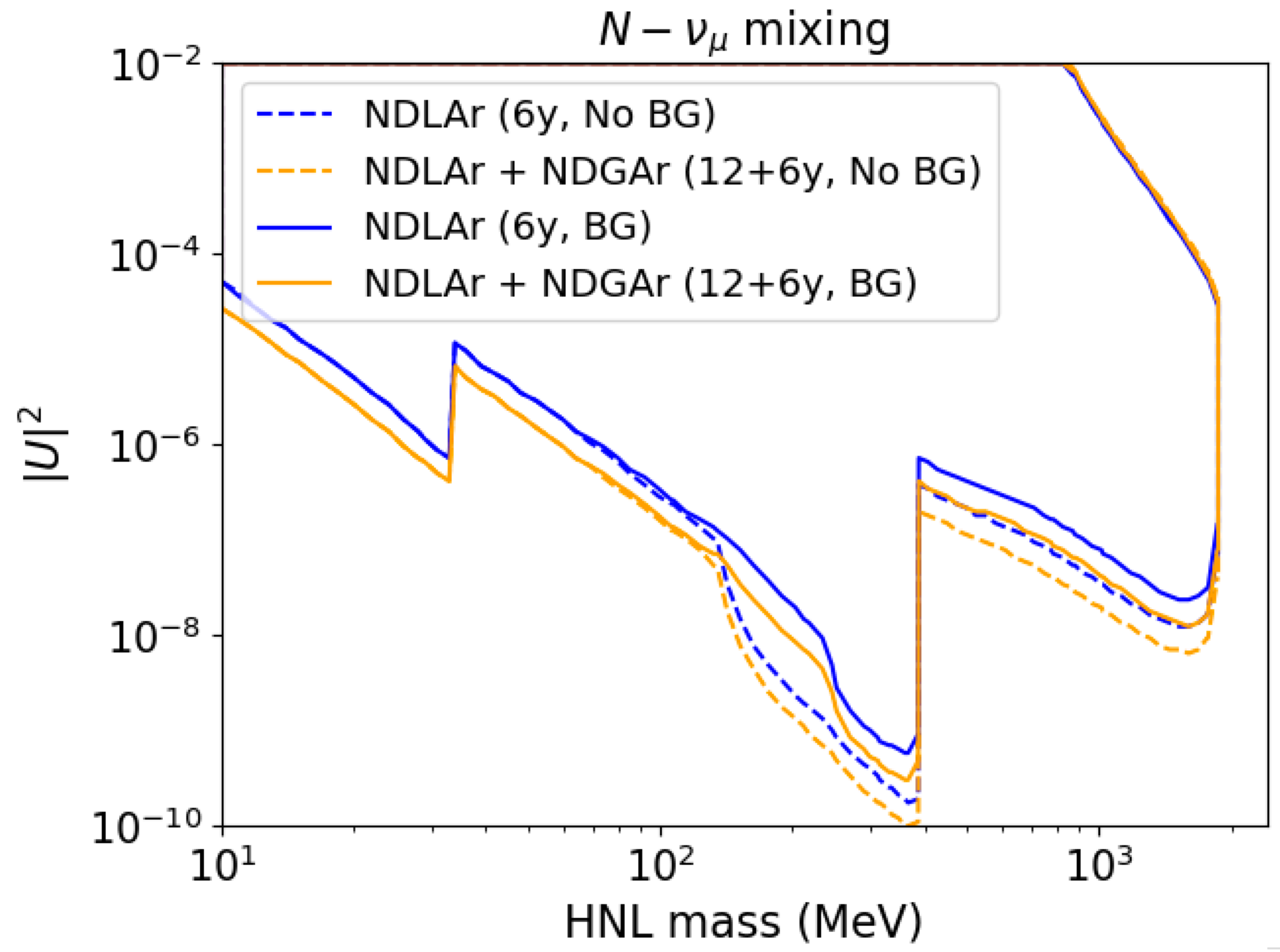




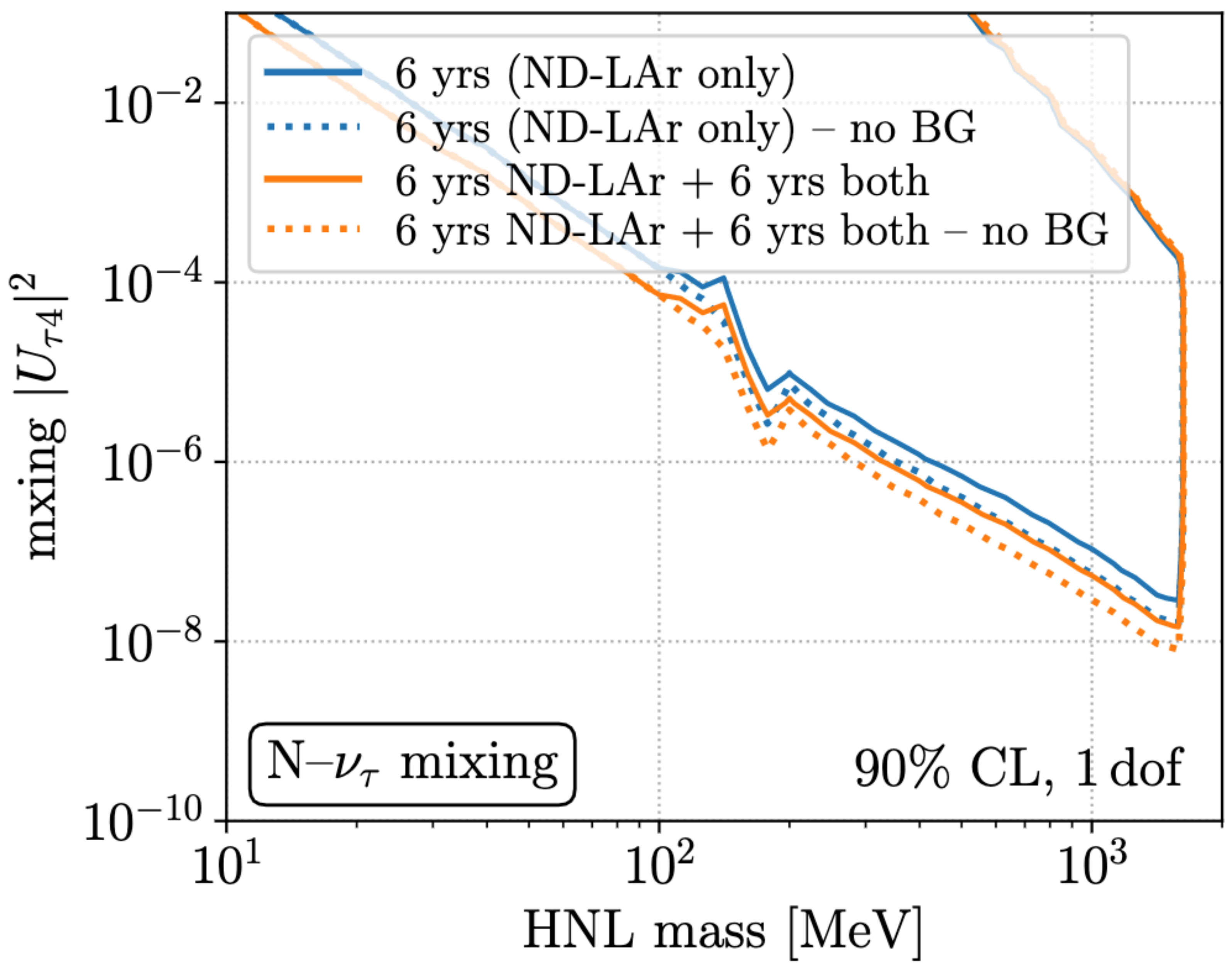
Snowmass vs. New results

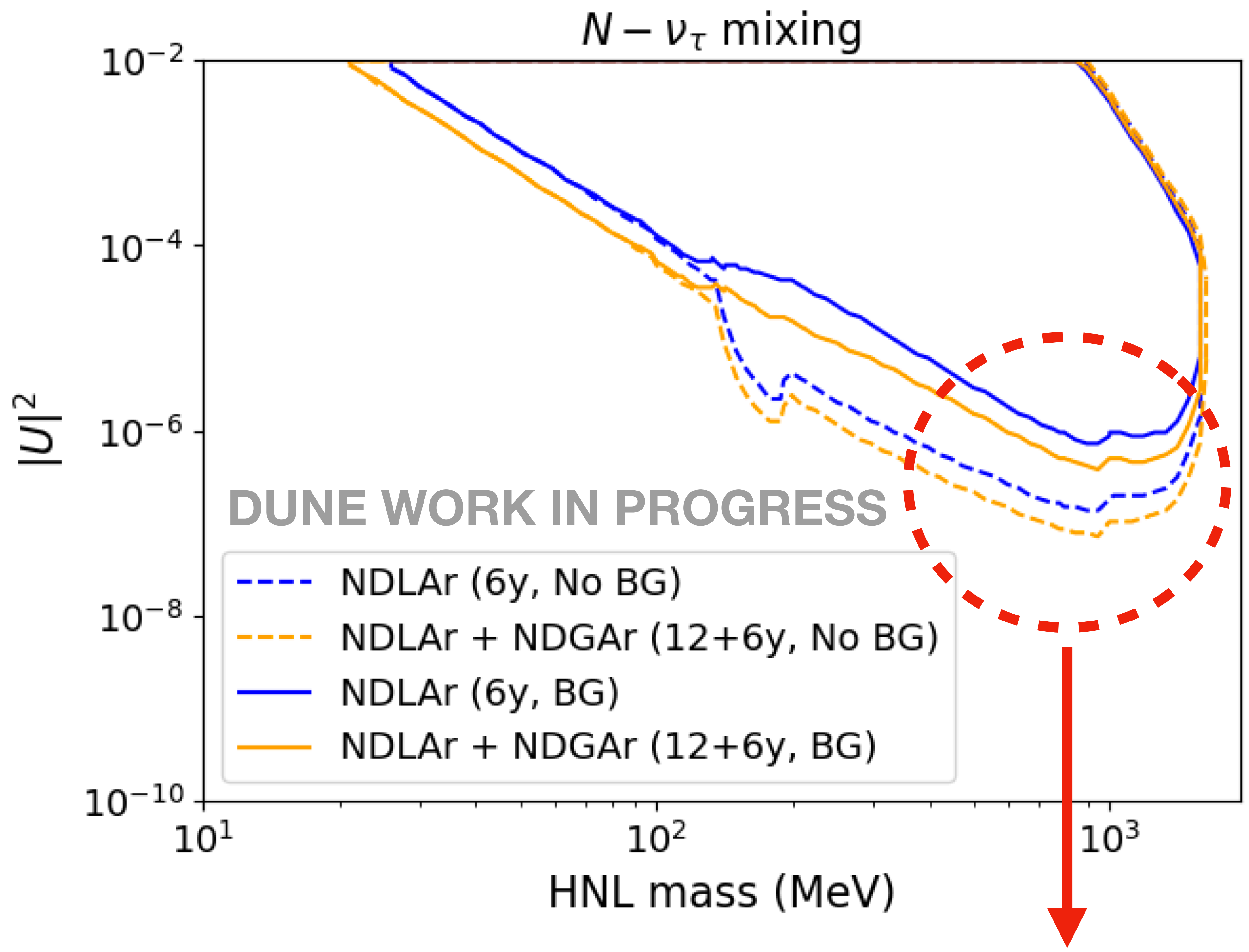
DUNE WORK IN PROGRESS





New results: full sensitivity





D/Ds region:
kinematic error fixed

Takeaway: results remain similar to those reported to Snowmass.

Conclusions and outlook

In conclusion…

- DUNE will have an excellent sensitivity to study HNLs in the MeV to GeV range for a wide range of mixing parameters, which will be unique in some regions.

- ND-GAr and ND-LAr by themselves seem to have a similar sensitivity, *without taking into account ND-GAr's charge tagging capabilities*.

Next steps:

  - Re-estimate the sensitivities phenomenologically with new flux version (preserving correlation between initial and final spin). —> We expect the results to vary little.

  - Estimate sensitivities with a full Near Detector simulation (when ready).

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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```
E_thr = {
u.pdg_gamma : 0.03, # Photon
u.pdg_e : 0.03, # Electron
u.pdg_pip : 0.10, # Pion
u.pdg_mu : 0.03 # Muon
}
```

Energy threshold in GeV

Angular cut: $\theta < \frac{M}{(E_1 + E_2)}$

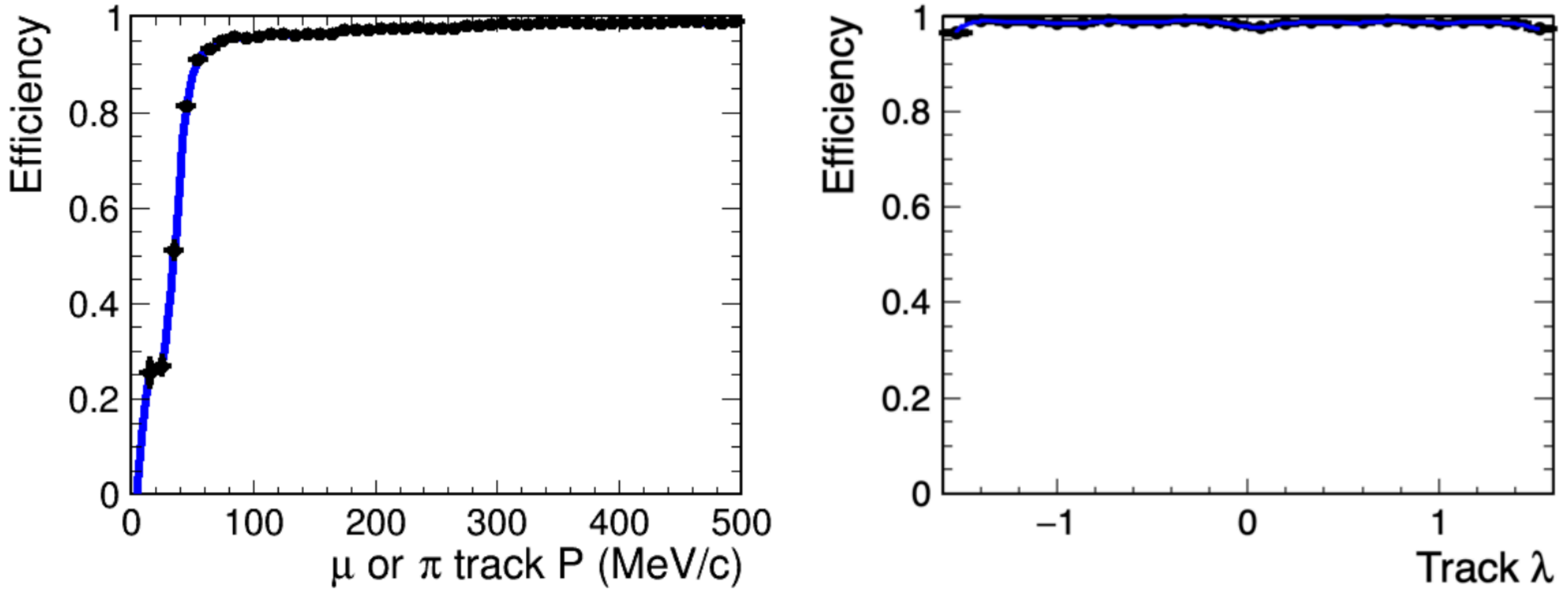

Figure 3.19: (Left) The efficiency to find tracks in the HPgTPC as a function of momentum, p, for tracks in a sample of Generates Events for Neutrino Interaction Experiments (GENIE) events simulating 2 GeV ν_μ interactions in the gas, using GArSoft. (Right) The efficiency to find tracks as a function of λ, the angle with respect to the center plane, for tracks with $p > 200$ MeV/c.