Heavy Neutral Leptons at Short-Baseline Neutrino Detectors

Joachim Kopp (CERN & JGU Mainz)
FIPS 2022 Workshop | October 17–21, 2022

CERN

Neutrino PLATFORM

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Table of Contents

General Considerations

CERN

Neutrino PLATFORM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

the Neutrino Portal

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

the Neutrino Portal

SM lepton doublet

SM Higgs doublet

SM singlet fermion
(HNL)

$$\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$$

the Neutrino Portal

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

leads to mixing between ν and N

➠ any process that makes ν in the SM can also make N
(suppressed by a mixing angle)

➠ meson decays!

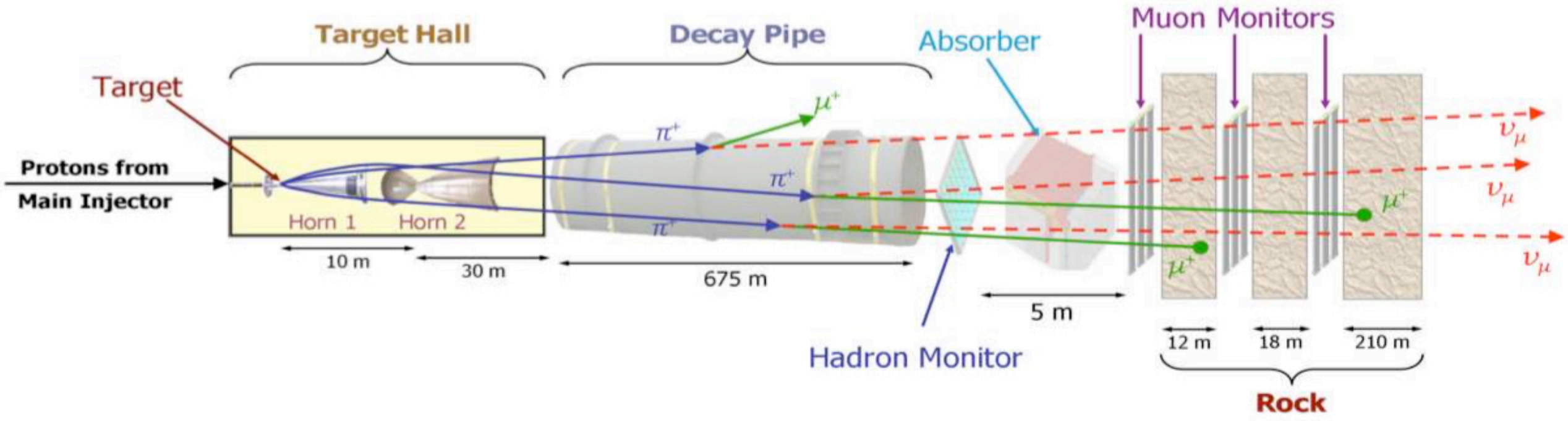
the Neutrino Portal

$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

leads to mixing between ν and N

➠ any process that makes ν in the SM can also make N
(suppressed by a mixing angle)

➠ meson decays!



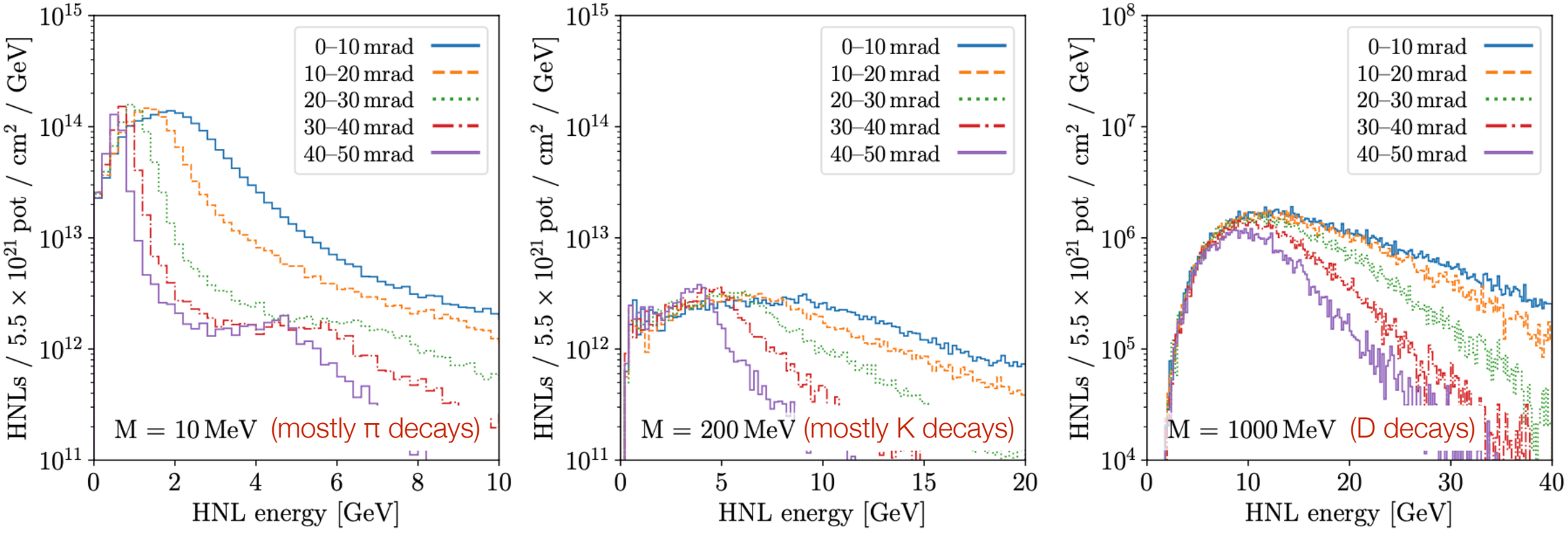
the Neutrino Portal

$$\mathcal{L} \supset y \, \bar{L} \, (i\sigma^2 H^*) \, N$$

leads to mixing between ν and N

➠ any process that makes ν in the SM can also make N
(suppressed by a mixing angle)

➠ meson decays!



the Neutrino Portal

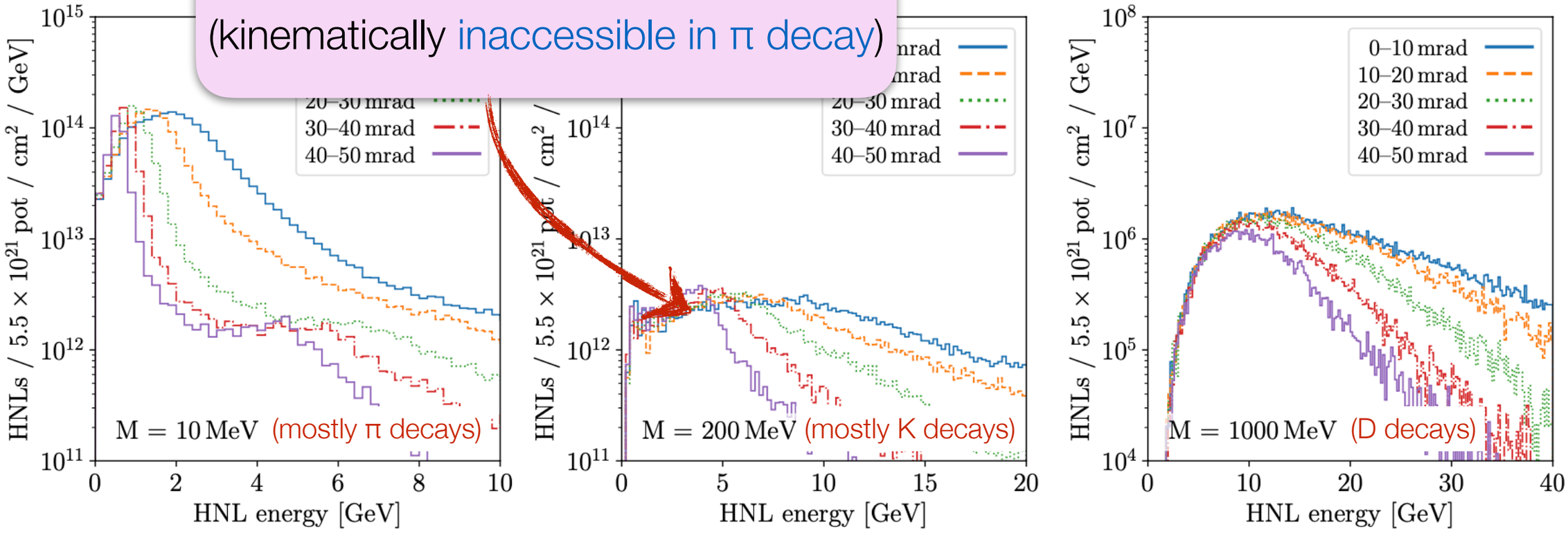
$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

leads to mixing between ν and N

➠ any process that makes ν in the SM can also make N

production of heavier HNLs suppressed

(kinematically inaccessible in π decay)



the Neutrino Portal

$$\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$$

leads to mixing between ν and N

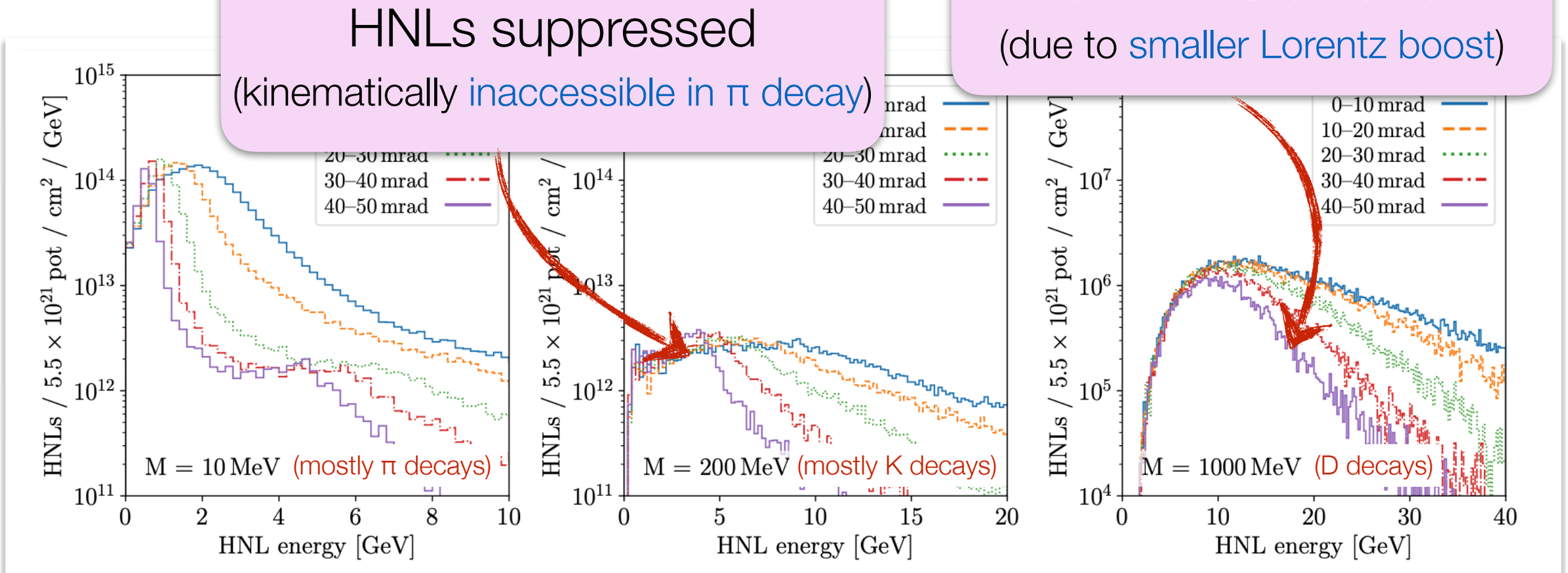
➠ any process that makes ν in the SM can also make N

production of heavier HNLs suppressed

(kinematically inaccessible in π decay)

but more off-axis

(due to smaller Lorentz boost)



Off-Axis Neutrino Detectors

Interesting to look for HNLs **off-axis**

- ★ signal remains sizeable
- ★ background from SM ν significantly reduced

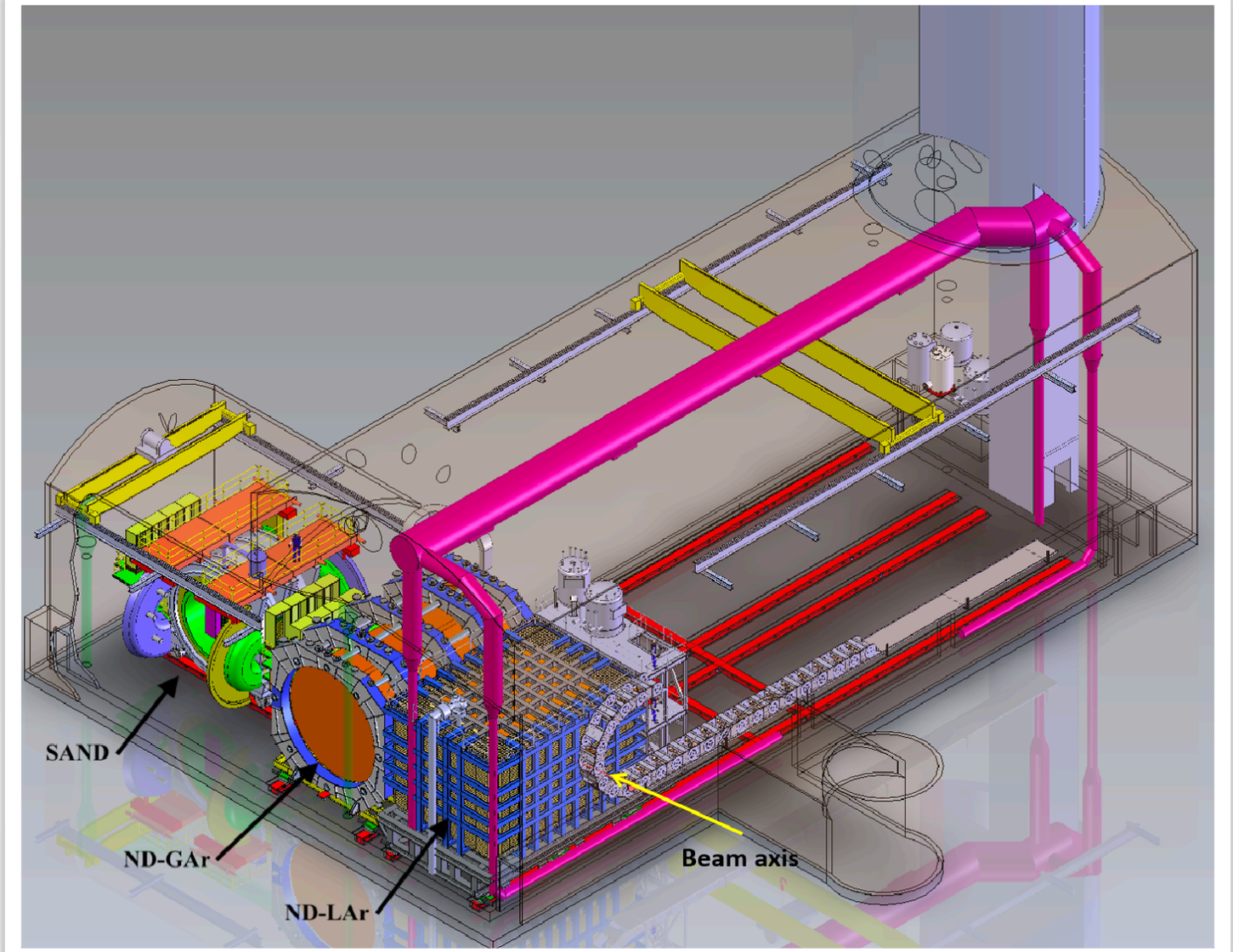
DUNE

CERN

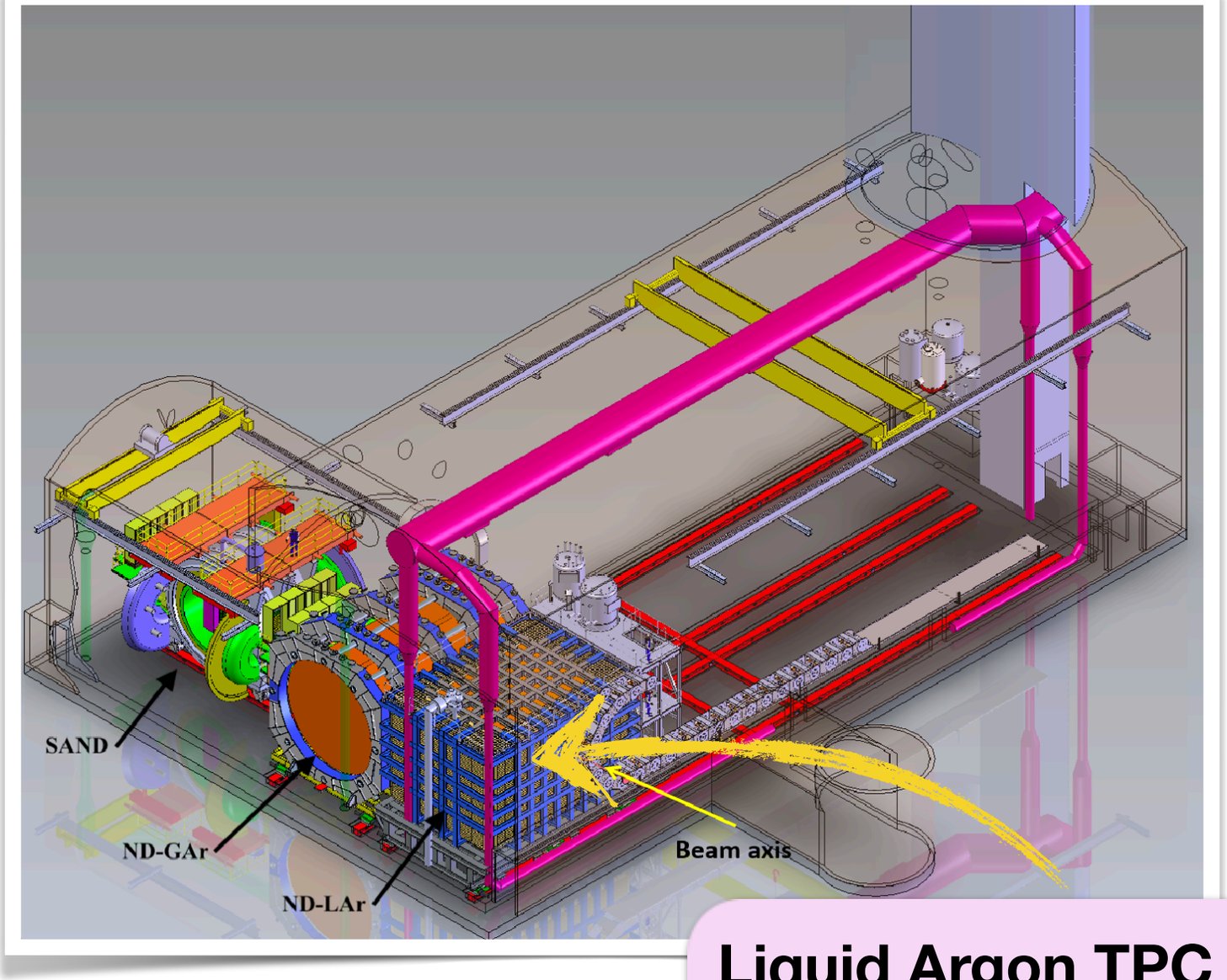
Neutrino PLATFORM

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Example: DUNE Near Detectors



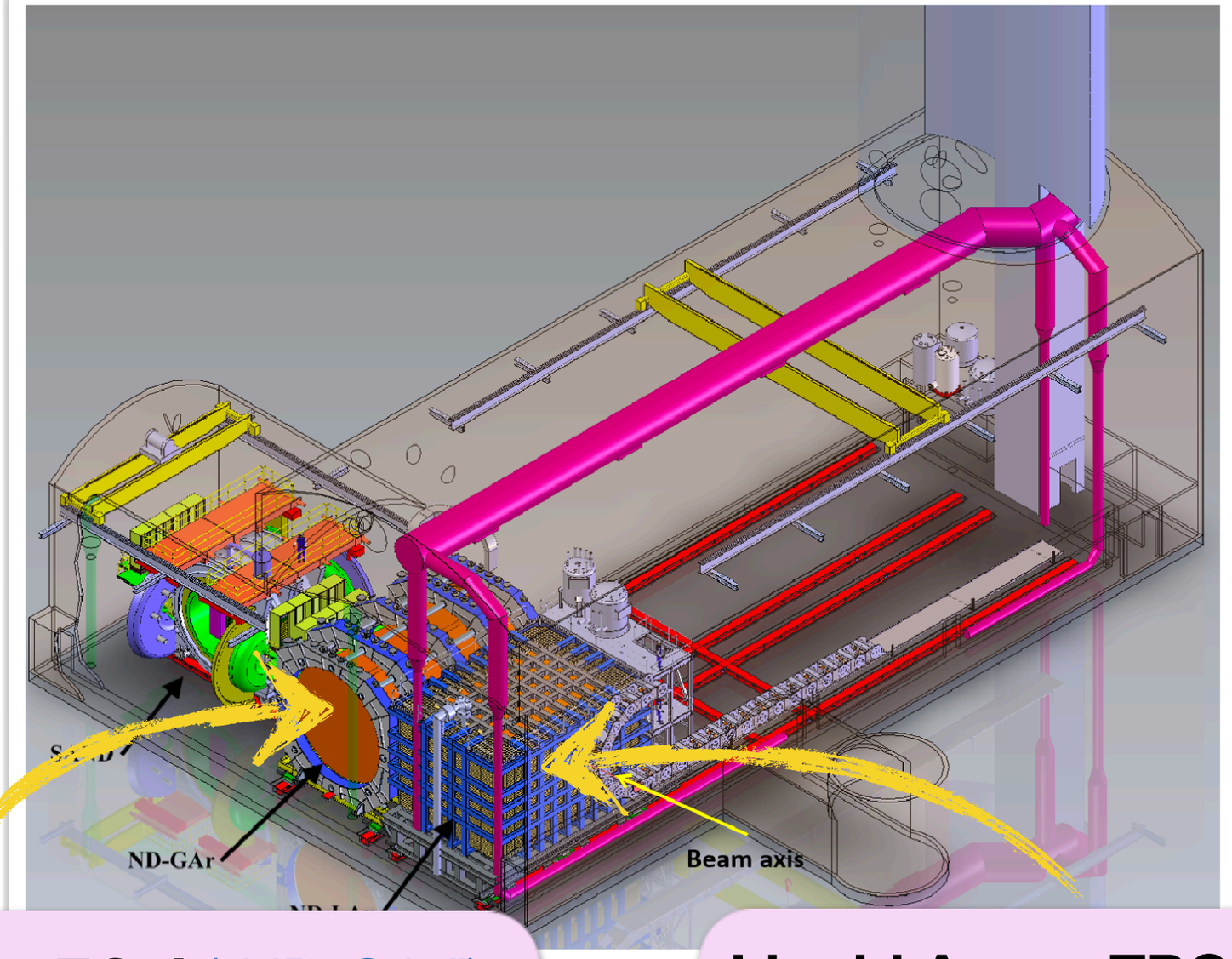
Example: DUNE Near Detectors



Liquid Argon TPC (“ND-LAr”)

- similar to far detector

Example: DUNE Near Detectors



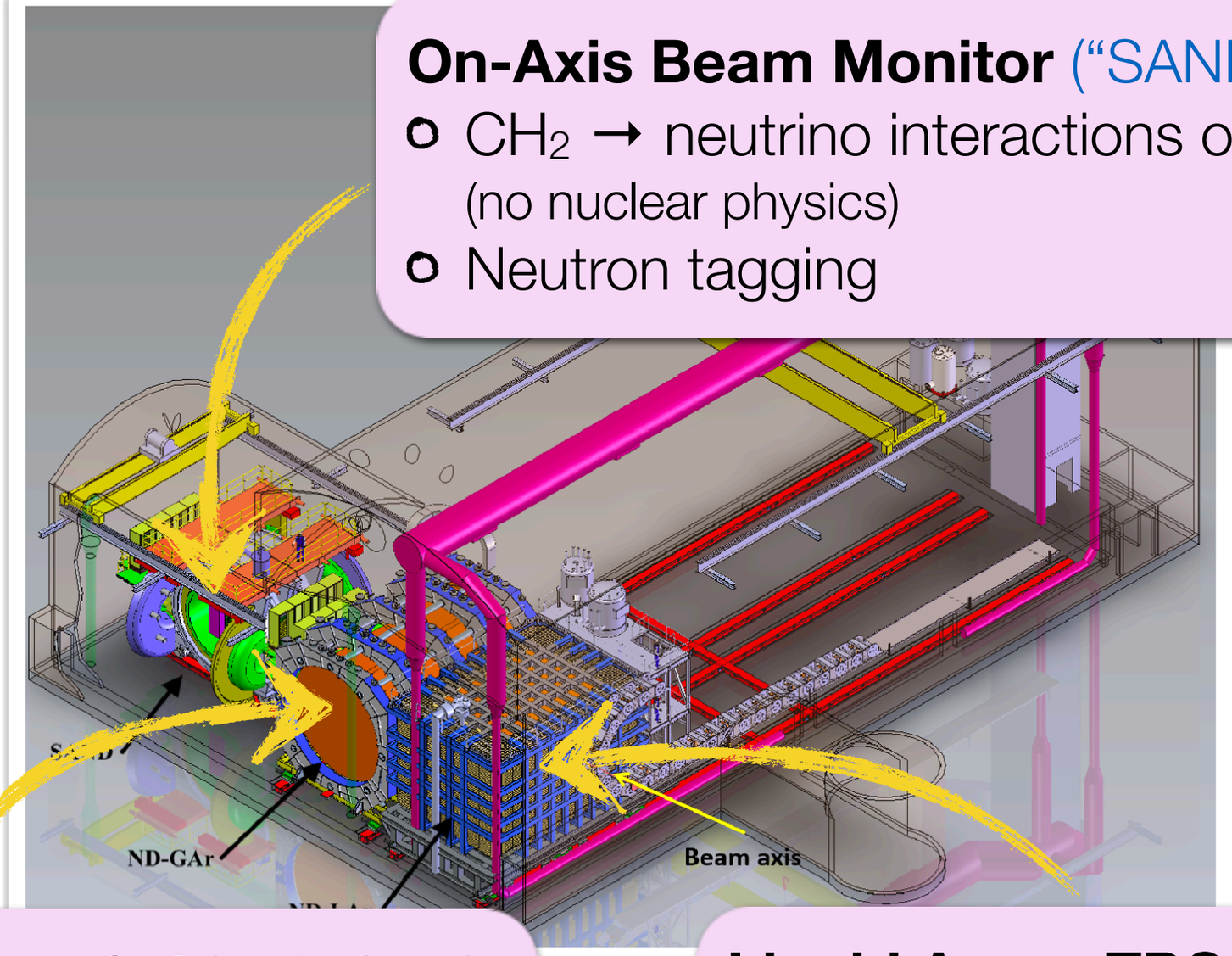
HP Gas TPC + ECal (“ND-GAr”)

- excellent event reconstruction
- magnetic field

Liquid Argon TPC (“ND-LAr”)

- similar to far detector

Example: DUNE Near Detectors



On-Axis Beam Monitor (“SAND”)

- CH_2 → neutrino interactions on free protons (no nuclear physics)
- Neutron tagging

HP Gas TPC + ECal (“ND-GAr”)

- excellent event reconstruction
- magnetic field

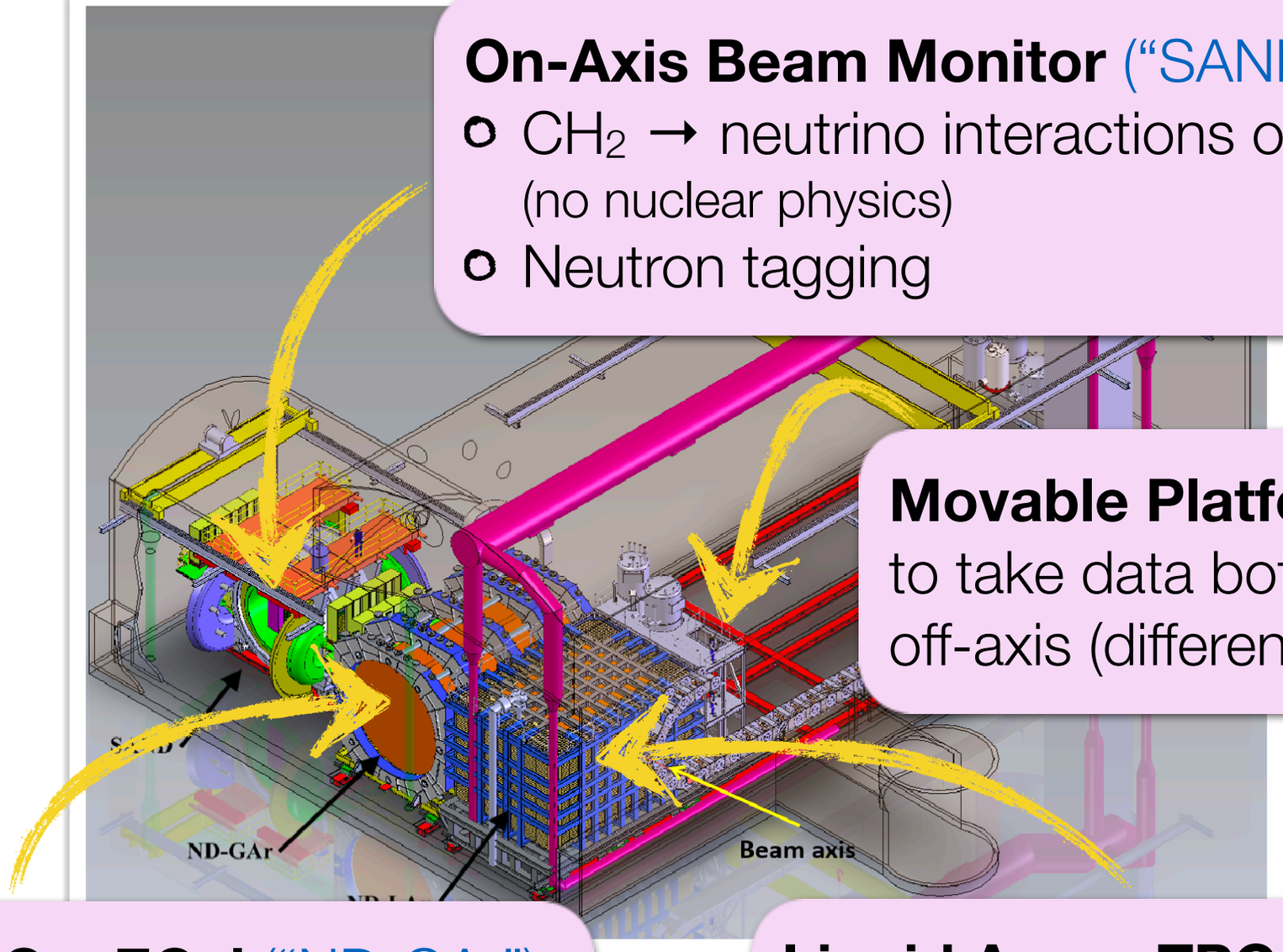
Liquid Argon TPC (“ND-LAr”)

- similar to far detector

Example: DUNE Near Detectors

On-Axis Beam Monitor (“SAND”)

- CH_2 → neutrino interactions on free protons (no nuclear physics)
- Neutron tagging



Movable Platform (“PRISM”) to take data both on-axis and off-axis (different beam spectra)

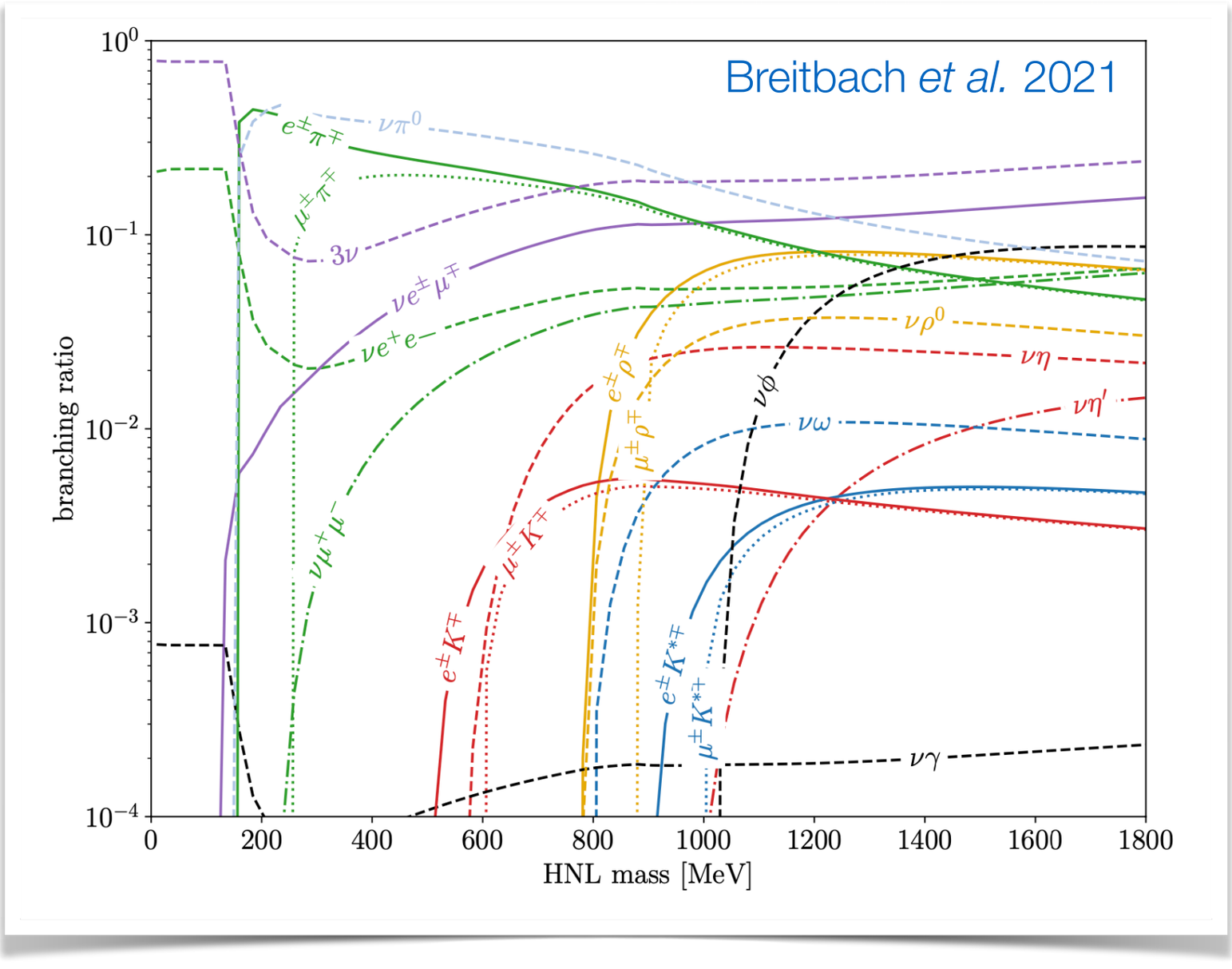
HP Gas TPC + ECal (“ND-GAr”)

- excellent event reconstruction
- magnetic field

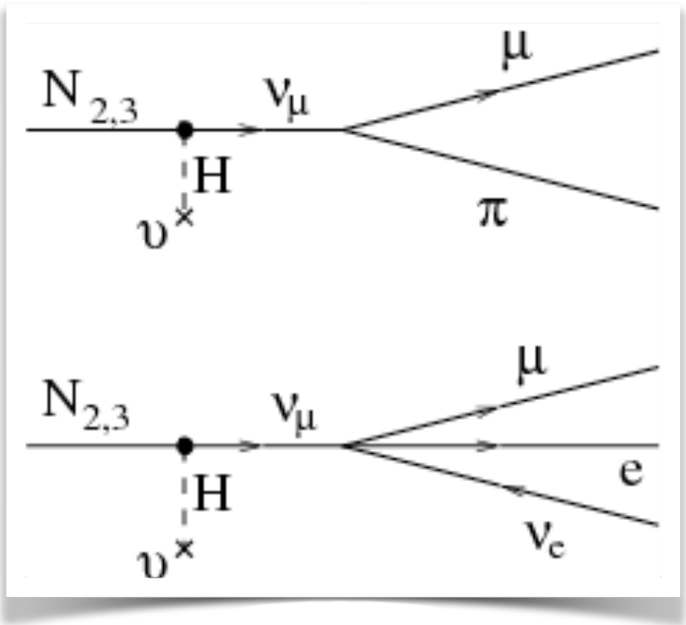
Liquid Argon TPC (“ND-LAr”)

- similar to far detector

HNL Decay

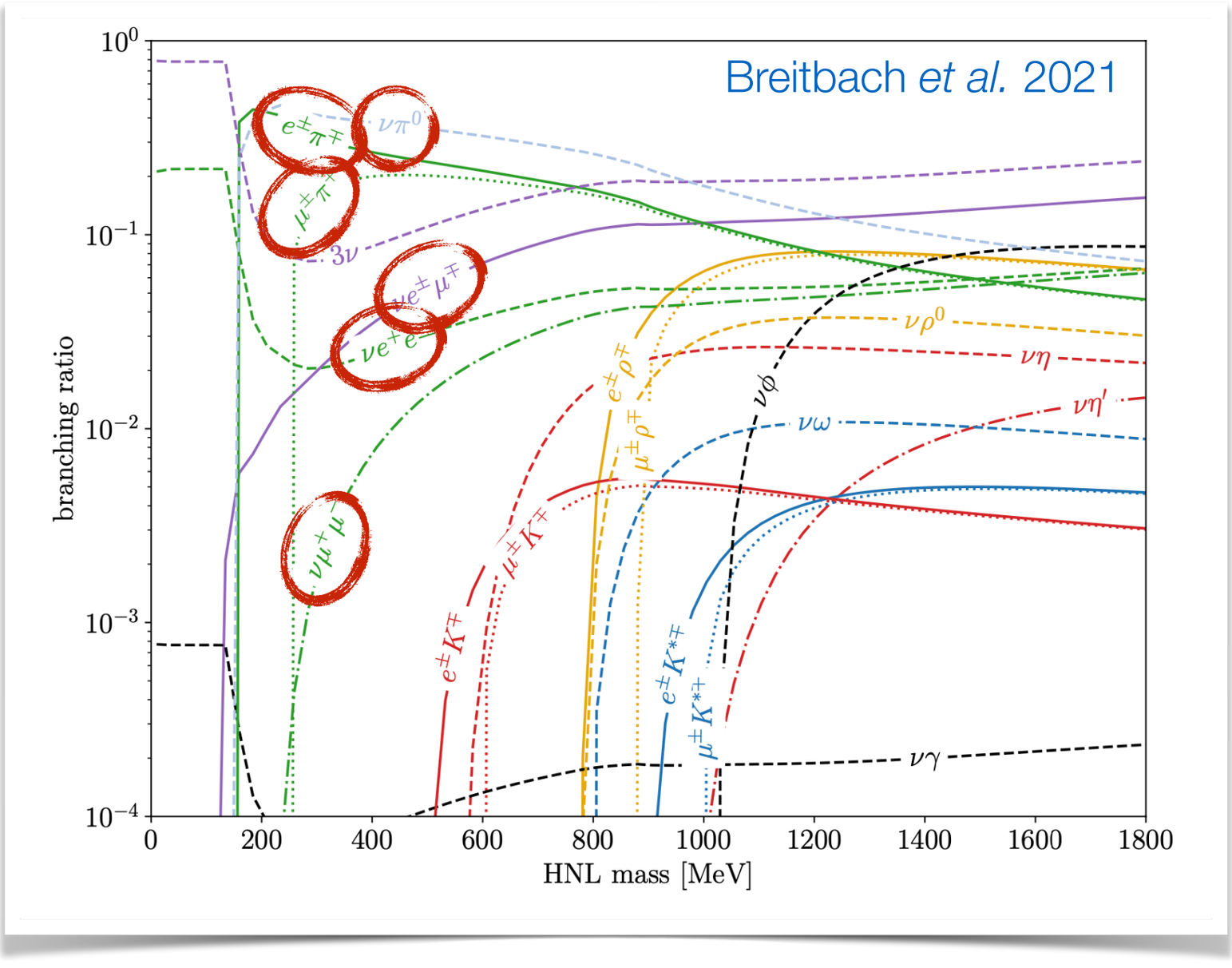


$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$

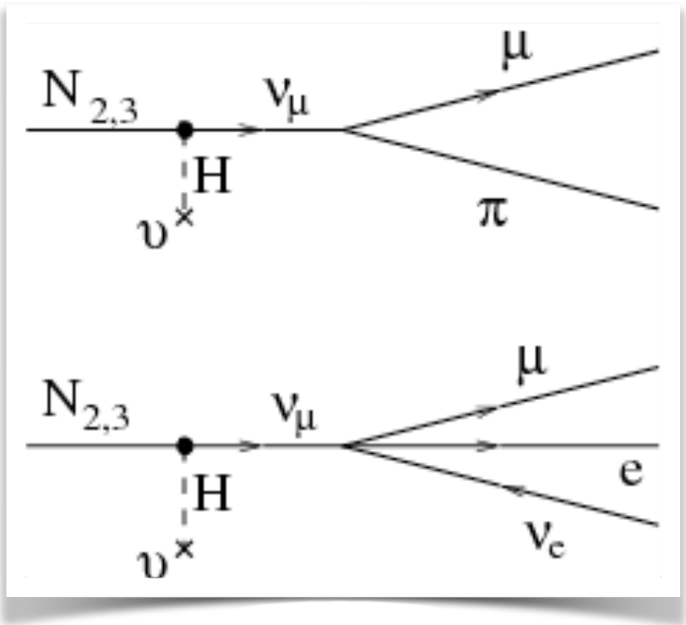


Ballett Boschi Pascoli
arXiv:1905.00284

HNL Decay



$$\mathcal{L} \supset y\,\bar{L}\,(i\sigma^2 H^*)\,N$$



Ballett Boschi Pascoli
arXiv:1905.00284

Off-Axis Neutrino Detectors

Interesting to look for HNLs **off-axis**

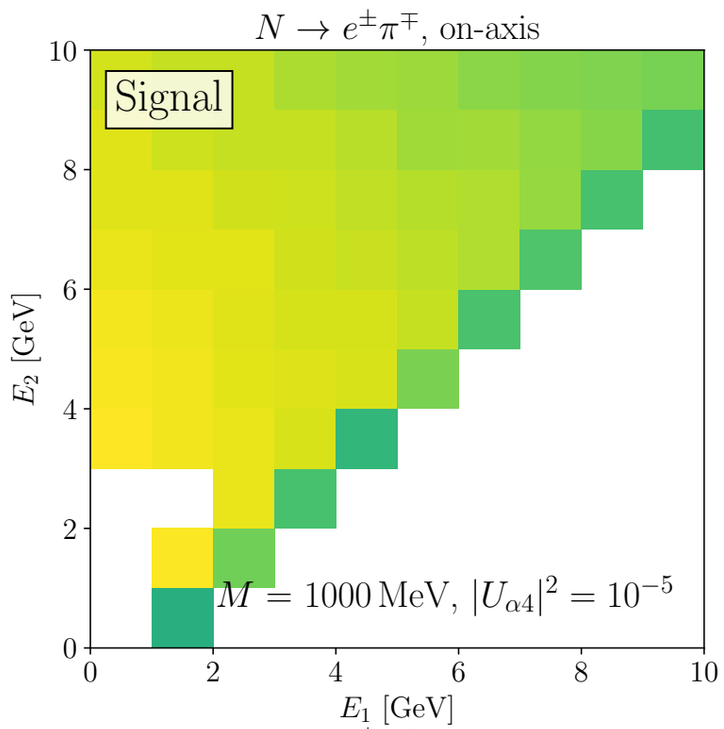
- ★ signal remains sizeable
- ★ background from SM ν significantly reduced

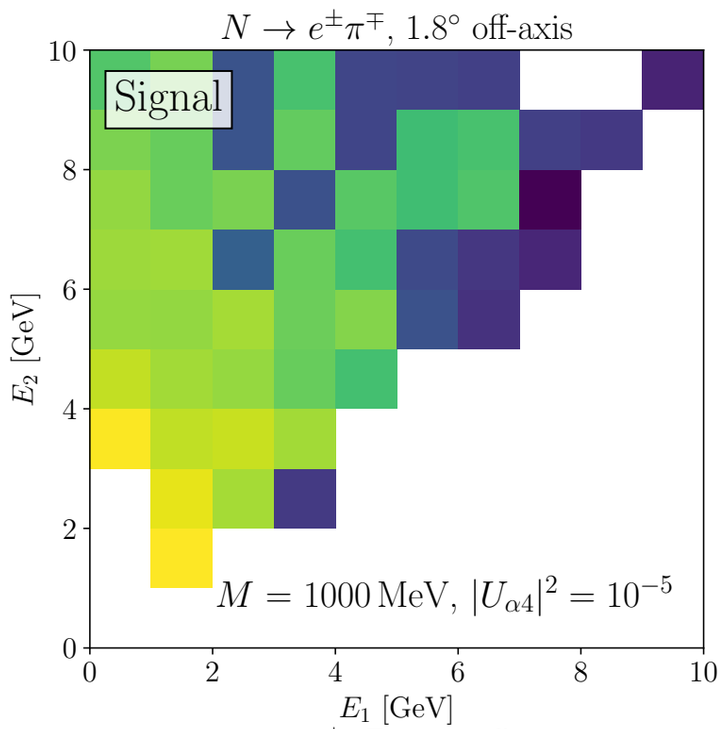
Off-Axis Neutrino Detectors

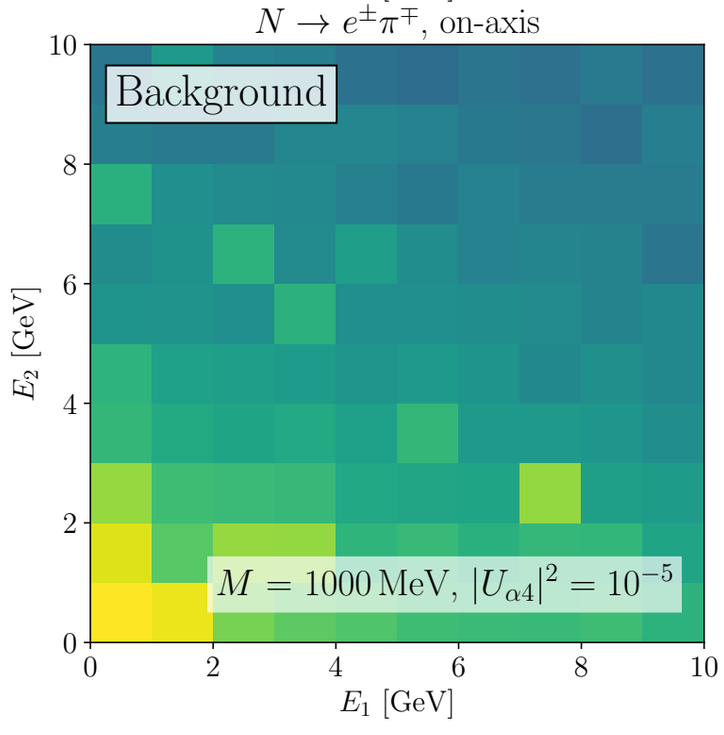
Interesting to look for HNLs **off-axis**

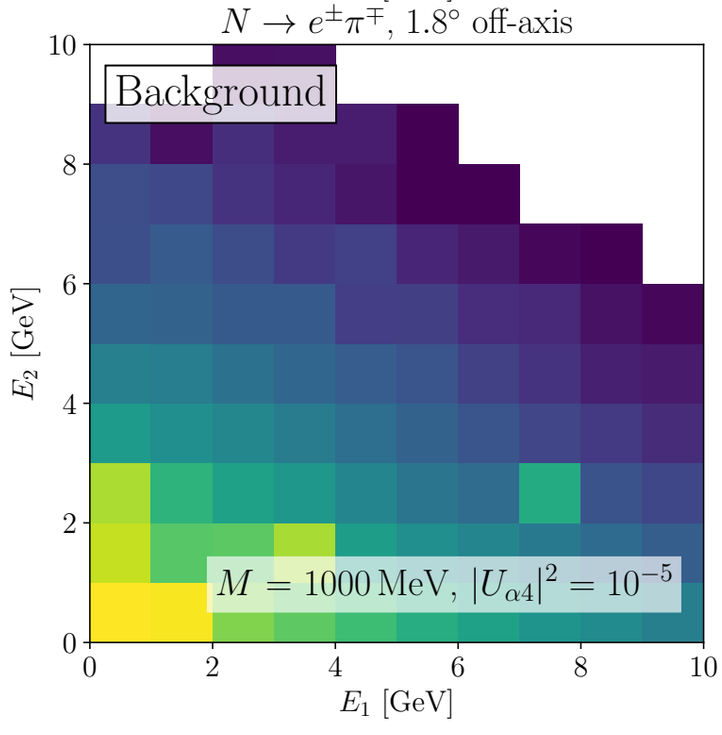
- ★ signal remains sizeable
- ★ background from SM ν significantly reduced
- ★ but cuts (especially angle w.r.t. beam axis)
  very efficient at suppressing BG, too

HNL Events Rates – Signal vs. Background





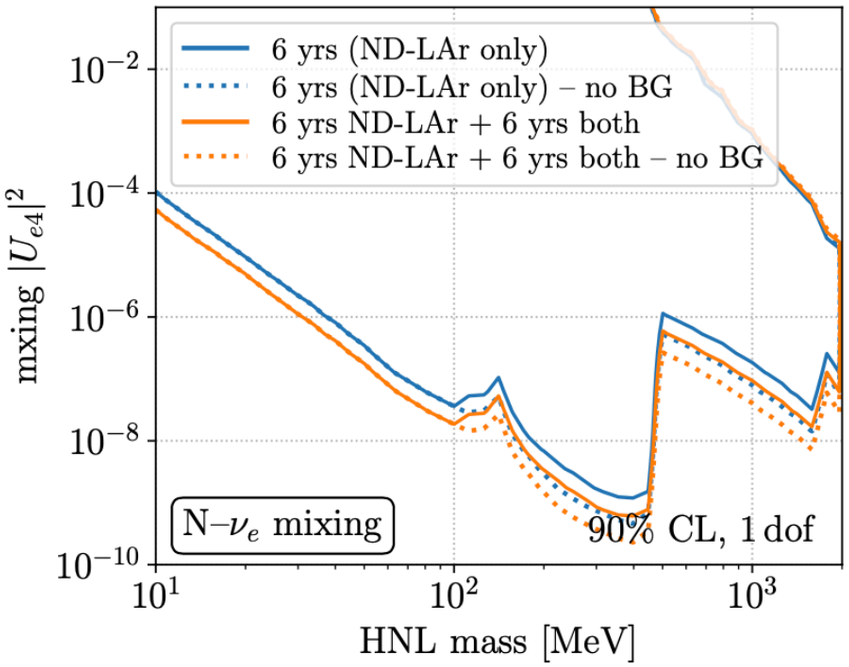


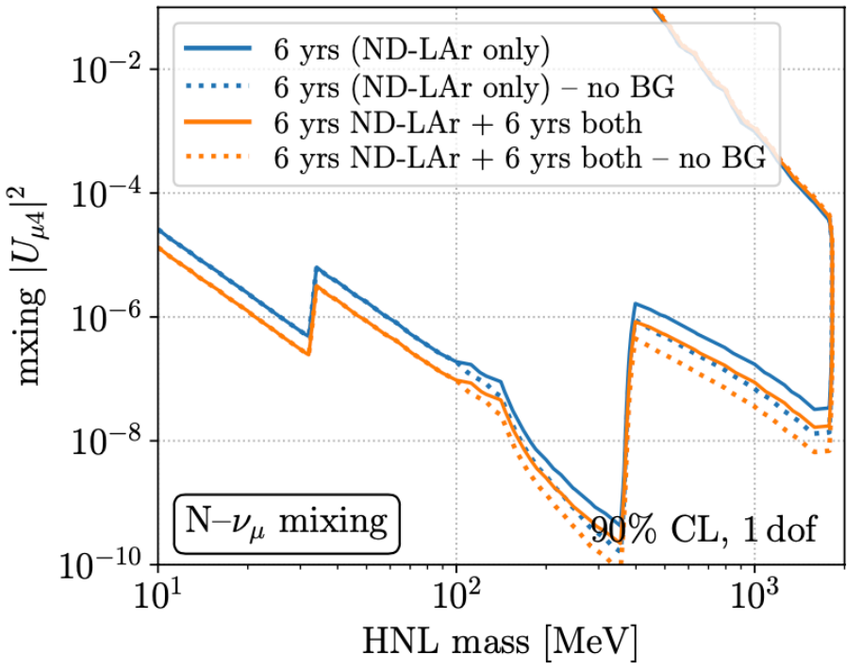


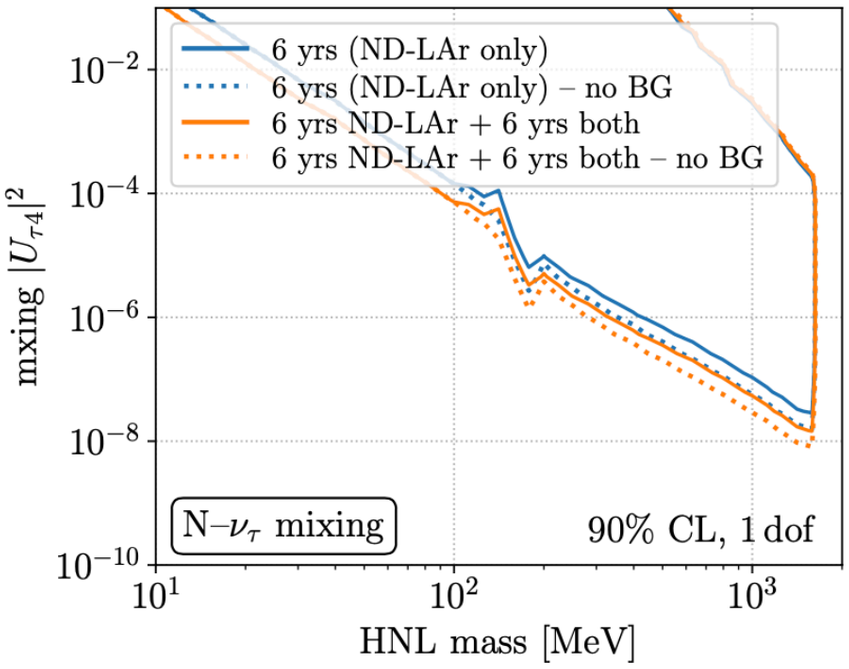
Breitbach *et al.* 2021

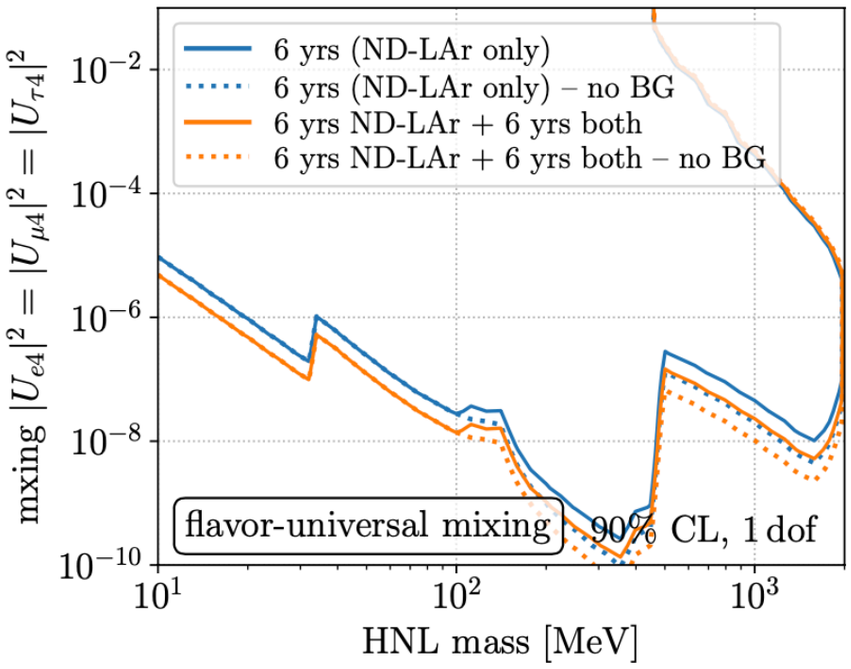
HNLs: Importance of ND-GAr

Abdullahi *et al.* 2022







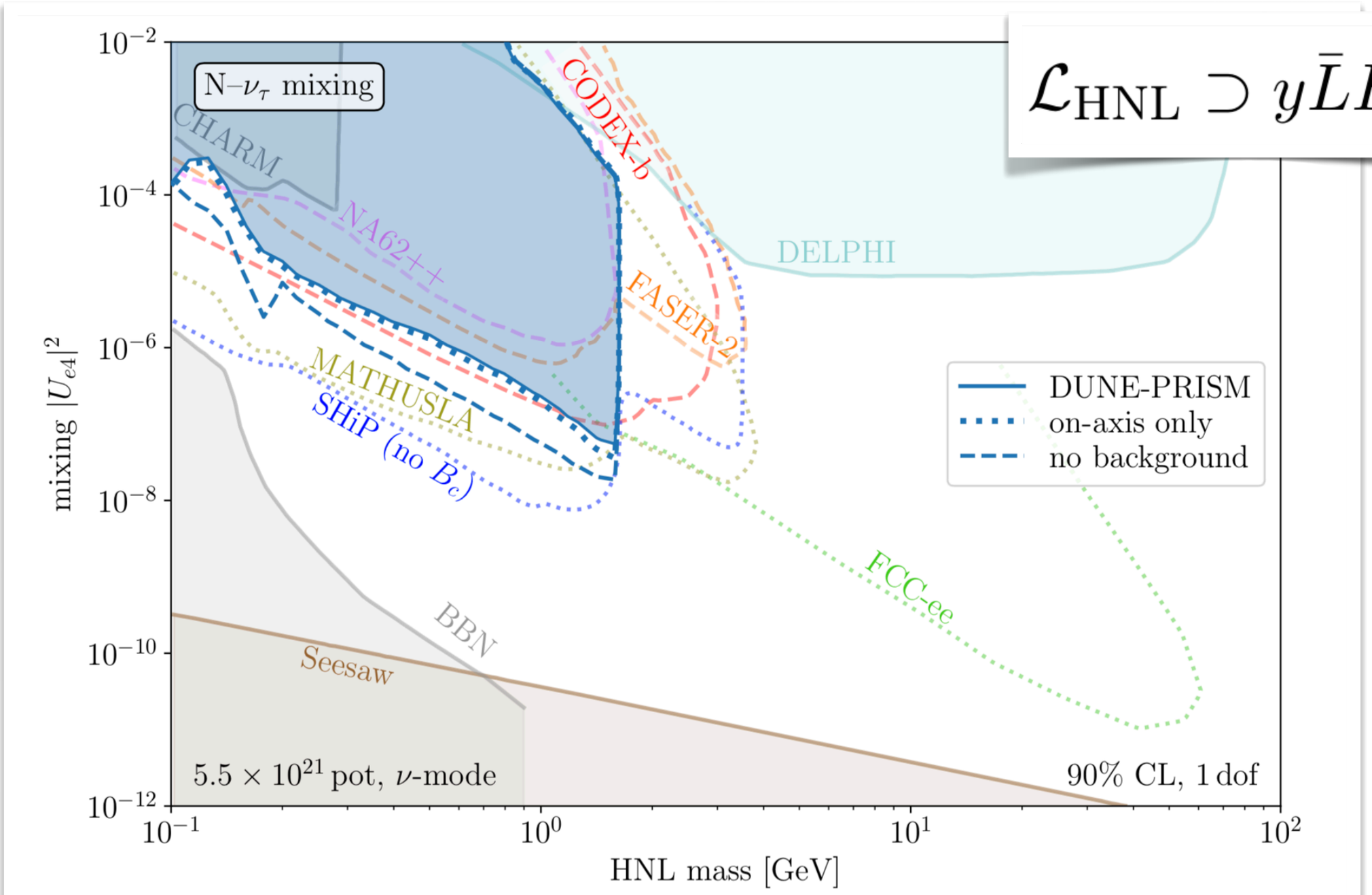


HNL Backgrounds: Key Points

- ★ low-density detector (like ND-GAr) is beneficial
- ★ off-axis: better S/B ratio, but less statistics
  - ➠ HNL sensitivity relatively independent of PRISM run strategy
- ★ for well-understood detectors, backgrounds can be brought under control
  (thanks to very different kinematic distributions)

HNLs: DUNE Sensitivities

$$\mathcal{L}_{\text{HNL}} \supset y \bar{L} \tilde{H} N$$

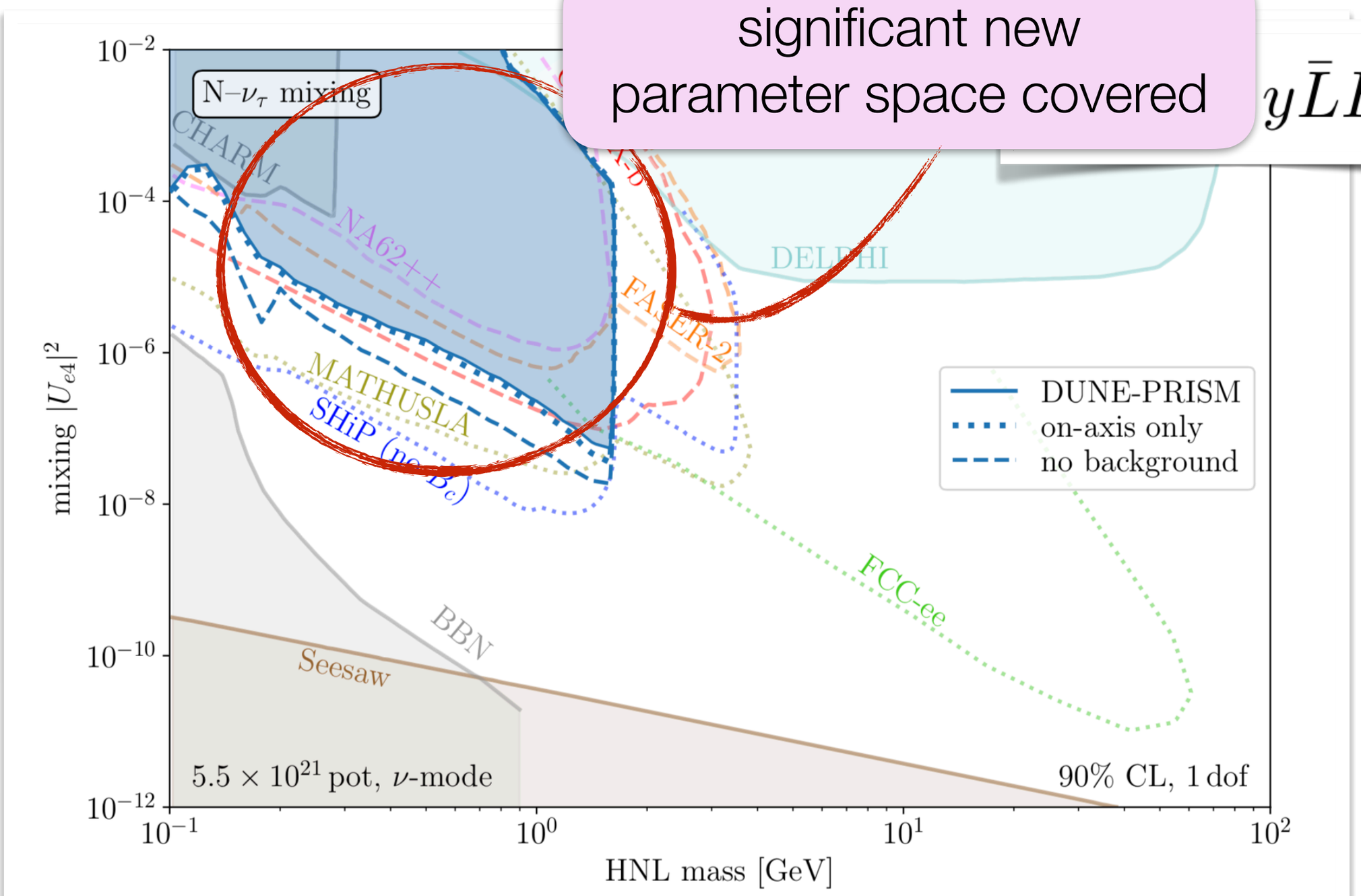


Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic

HNLs: DUNE Sensitivities

significant new
parameter space covered

$y\bar{L}\tilde{H}N$

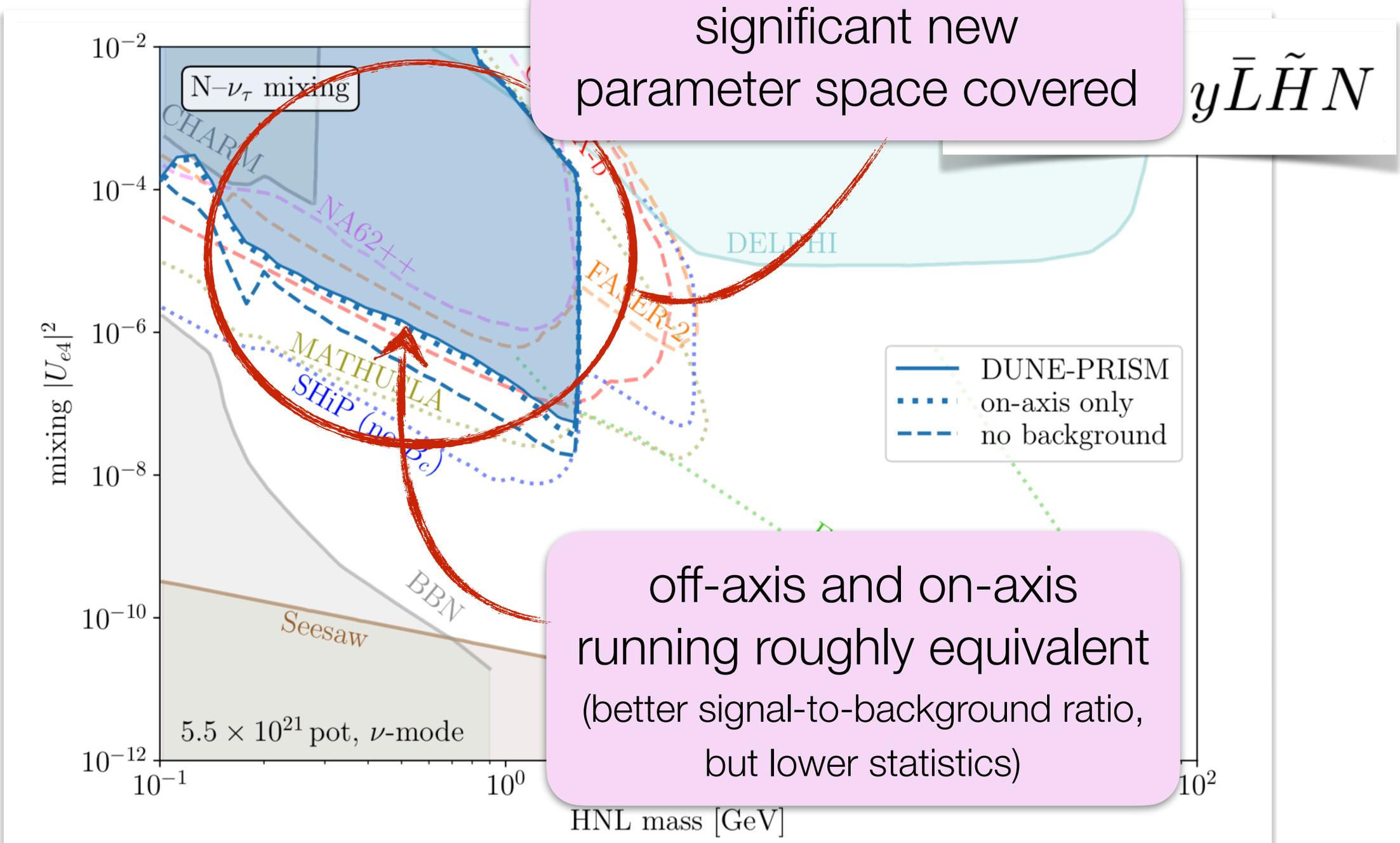


Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic

HNLs: DUNE Sensitivities

significant new parameter space covered

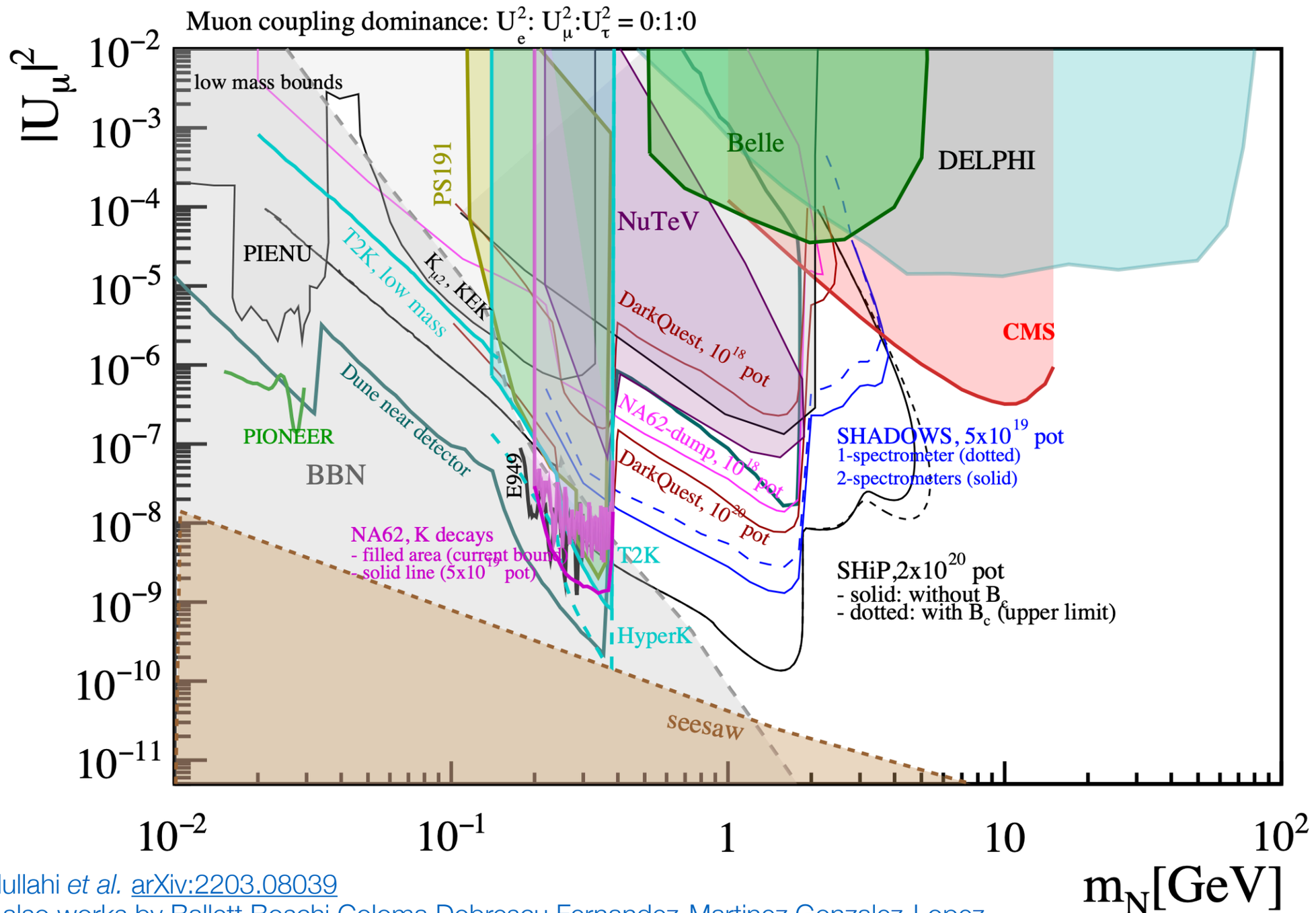
$y\bar{L}\tilde{H}N$



off-axis and on-axis running roughly equivalent
(better signal-to-background ratio, but lower statistics)

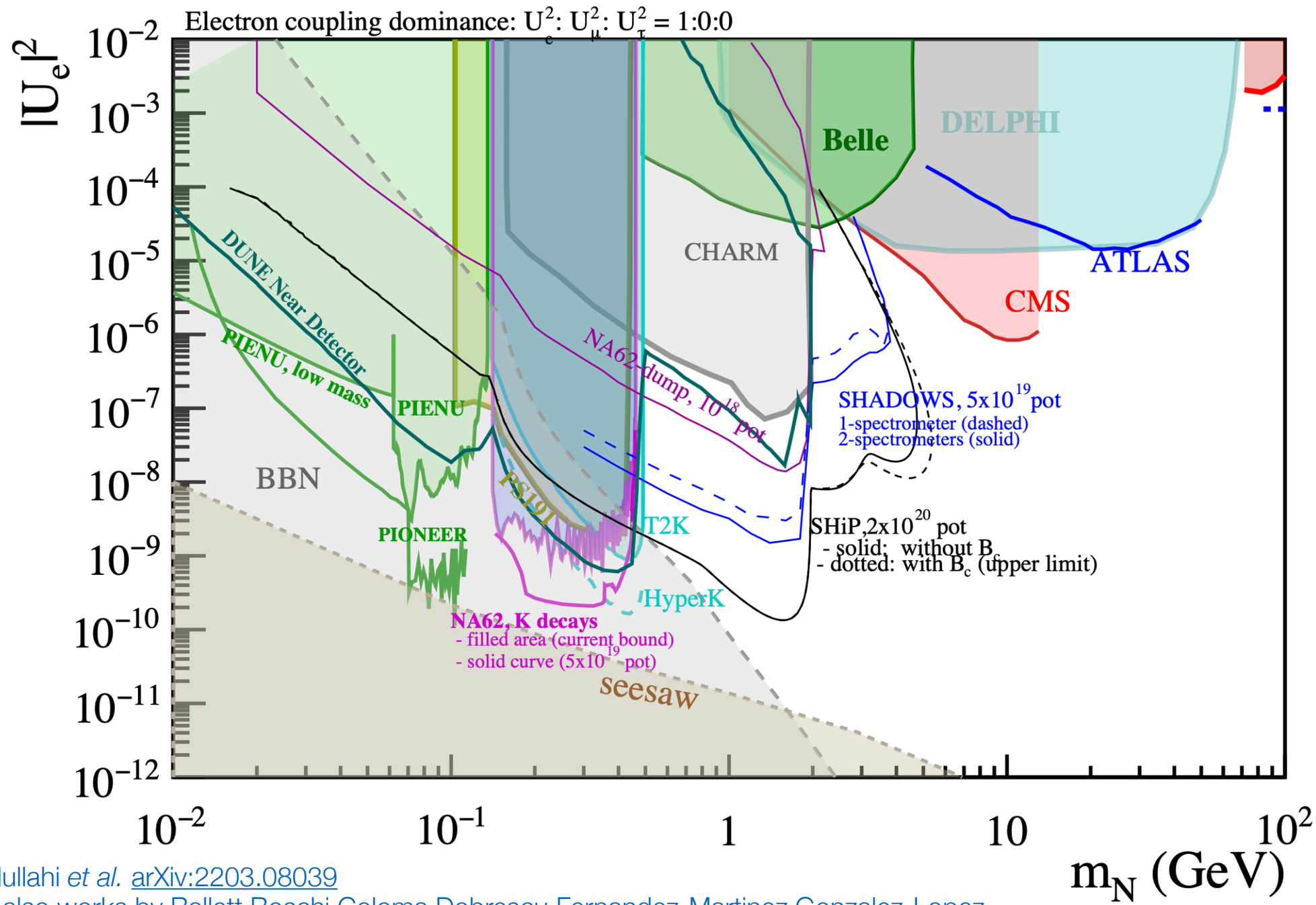
Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic

HNLs: Sensitivities



Abdullahi *et al.* arXiv:2203.08039
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic Breitbach Buonocore Frugiuele JK Mittnacht

HNLs: Sensitivities



Abdullahi *et al.* arXiv:2203.08039
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic Breitbach Buonocore Frugiuele JK Mittnacht

T2K / T2HK

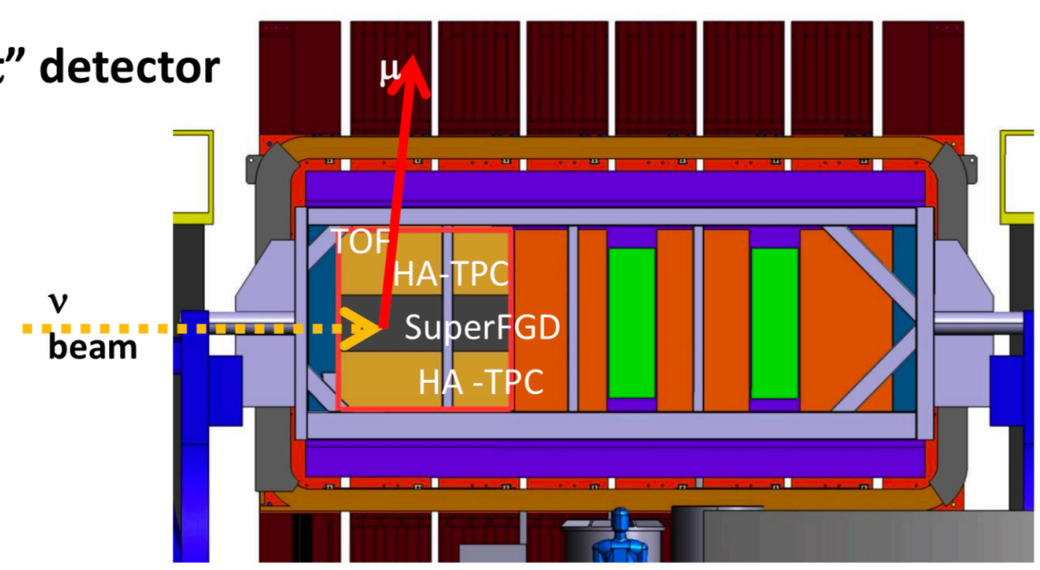
CERN

Neutrino PLATFORM

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

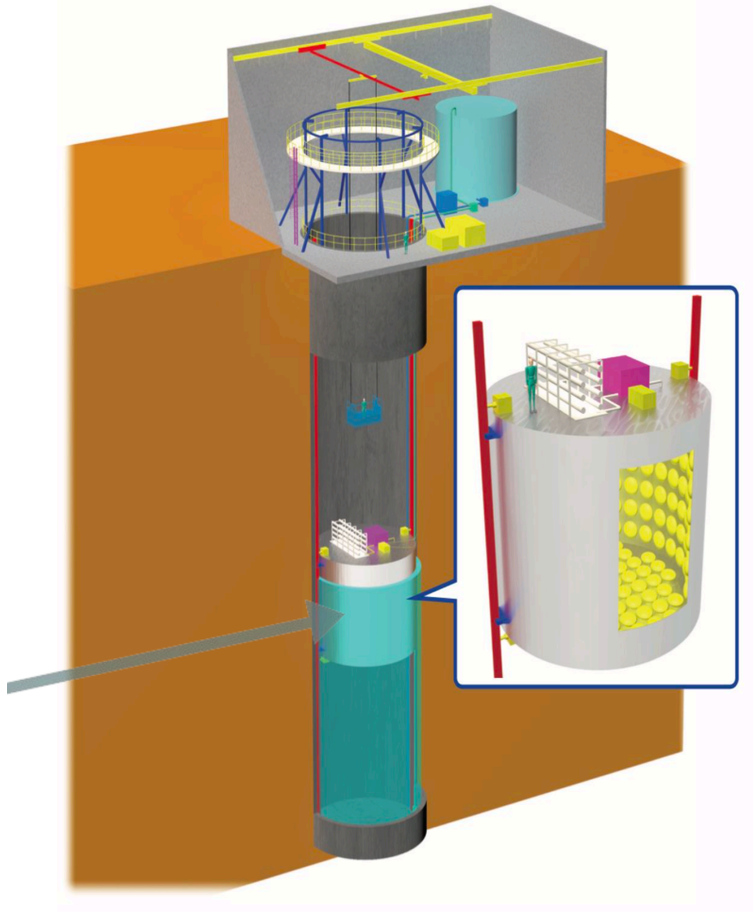
Towards T2HK

Upgraded ND-280
(2.2 tons ➟ 4.2 tons)



CERN-SPSC-P357

Movable WC Detector
(sub-kton, 1–4° off-axis)



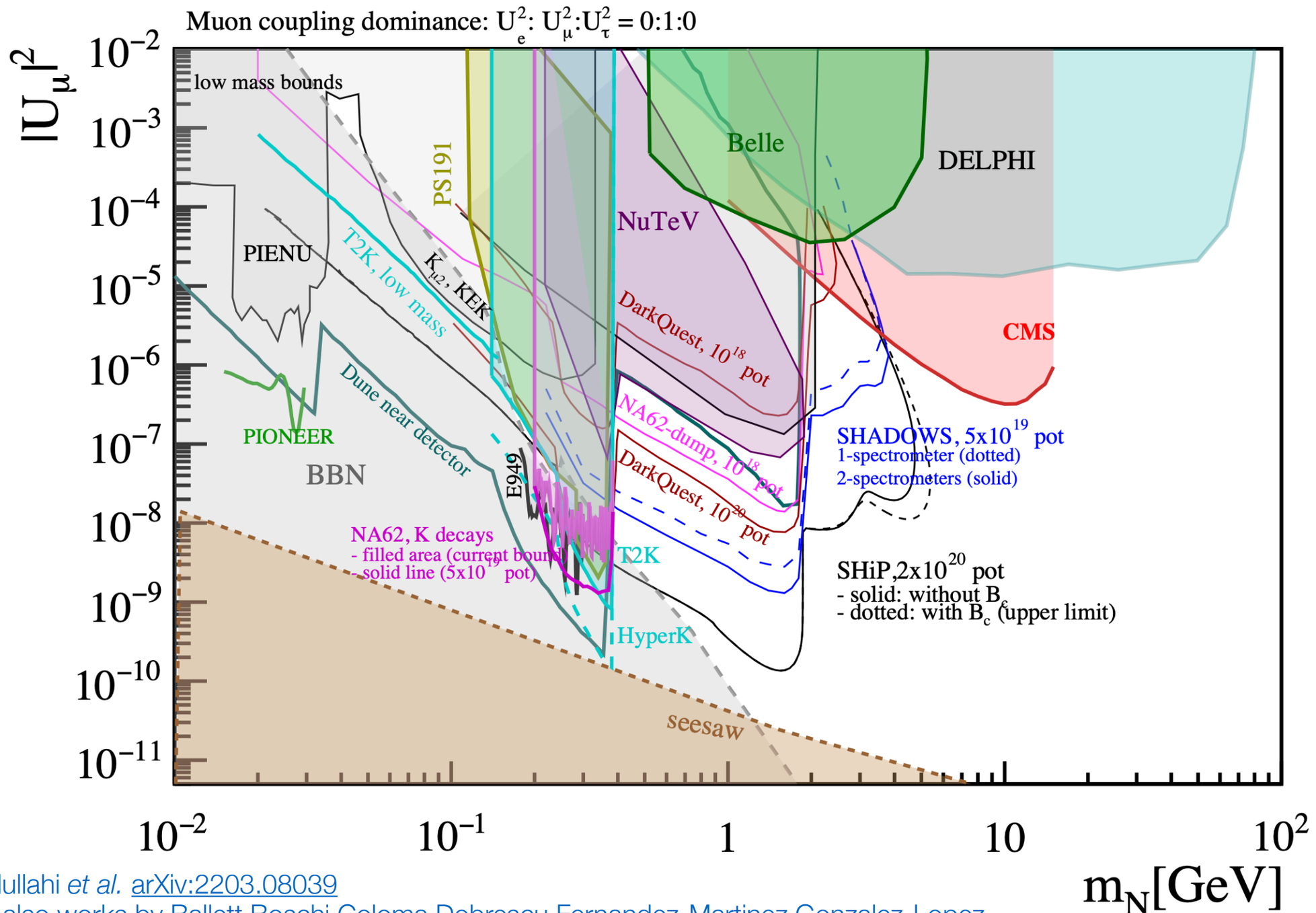
from a talk by Thorsten Lux

cf. DUNE: 0–3.5° off-axis

ND-LAr: 67 tons, ~100 m^3 – liquid, large BG for HNLs

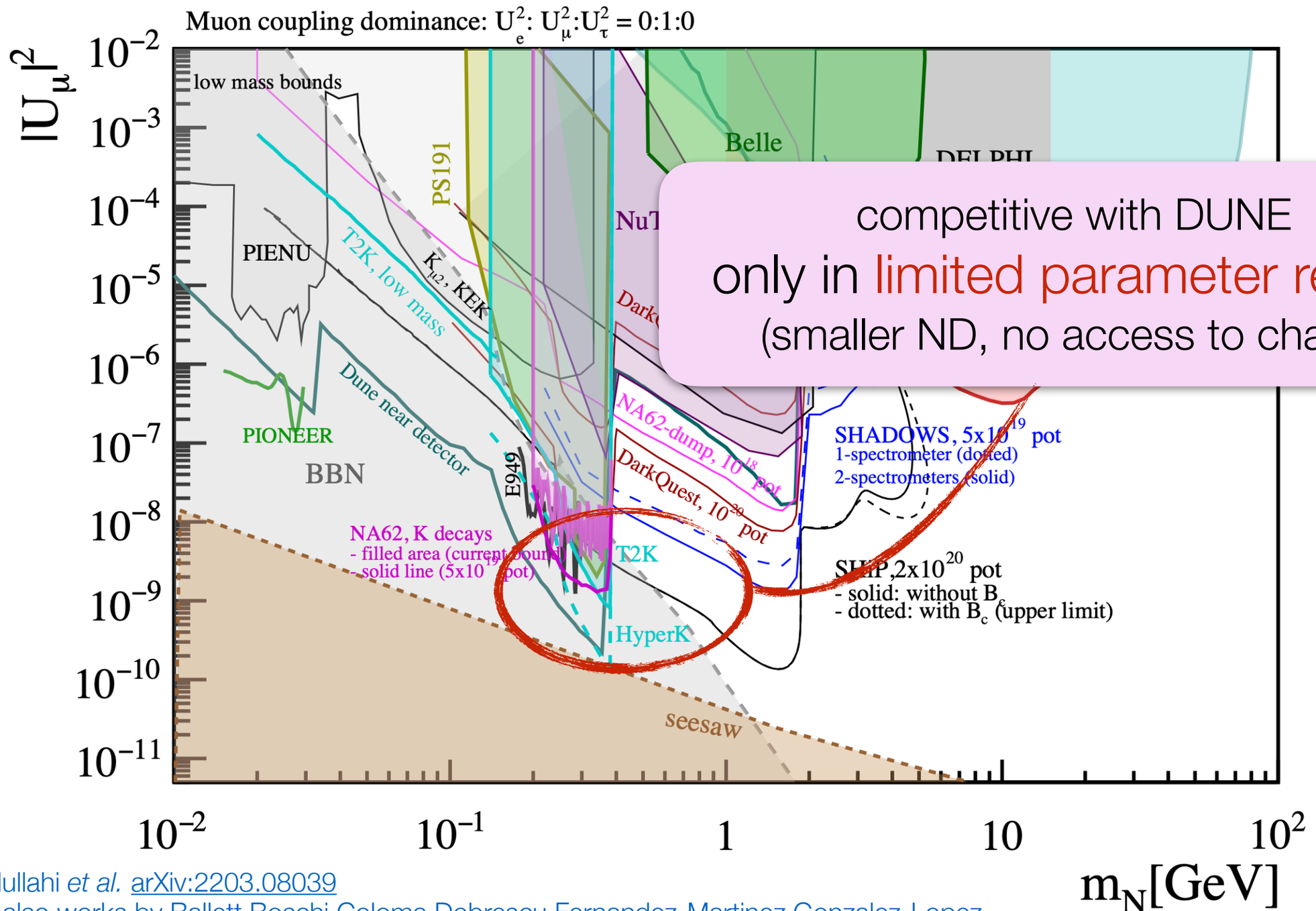
ND-GAr: 1 ton, ~100 m^3 – gaseous, low BG for HNLs

HNLs: Sensitivities



Abdullahi *et al.* arXiv:2203.08039
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic Breitbach Buonocore Frugiuele JK Mittnacht

HNLs: Sensitivities



competitive with DUNE

only in limited parameter region

(smaller ND, no access to charm)

Abdullahi *et al.* arXiv:2203.08039

see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic Breitbach Buonocore Frugiuele JK Mittnacht

Other Opportunities

CERN

Neutrino PLATFORM

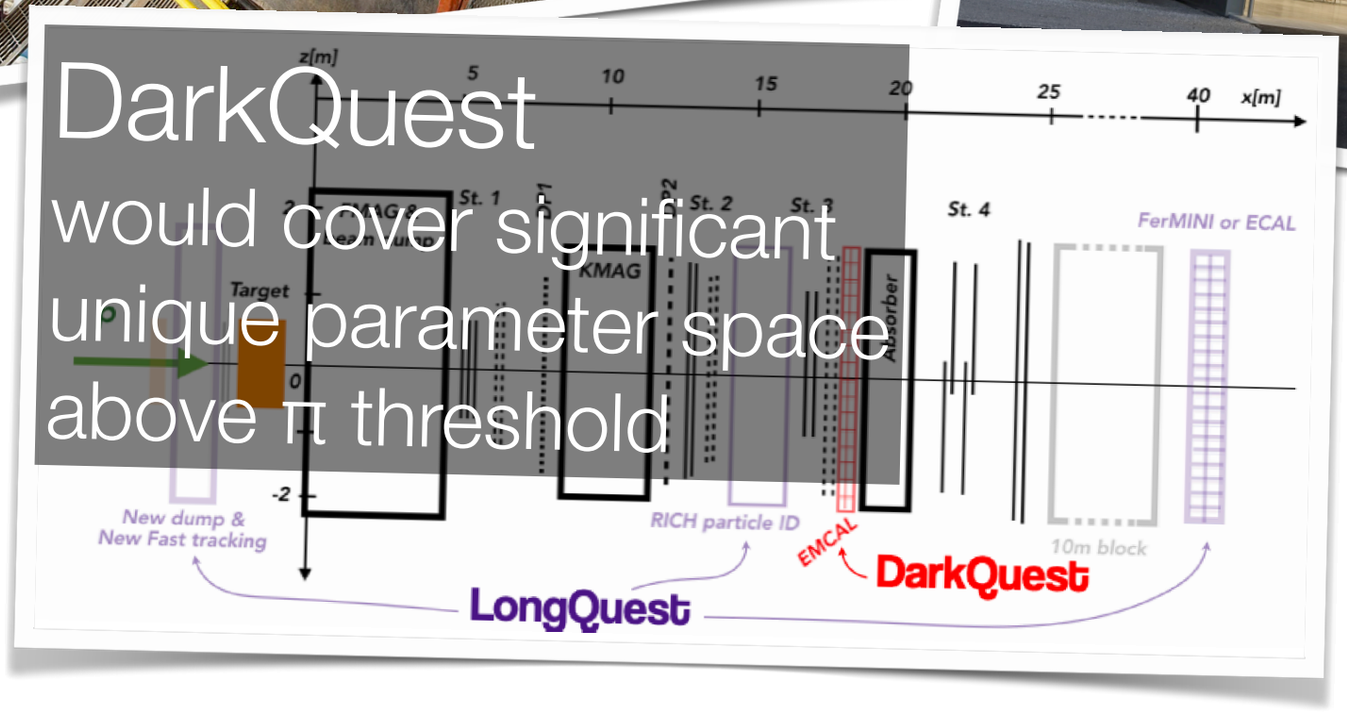
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Table of Contents

Table of Contents

Table of Contents

Table of Contents



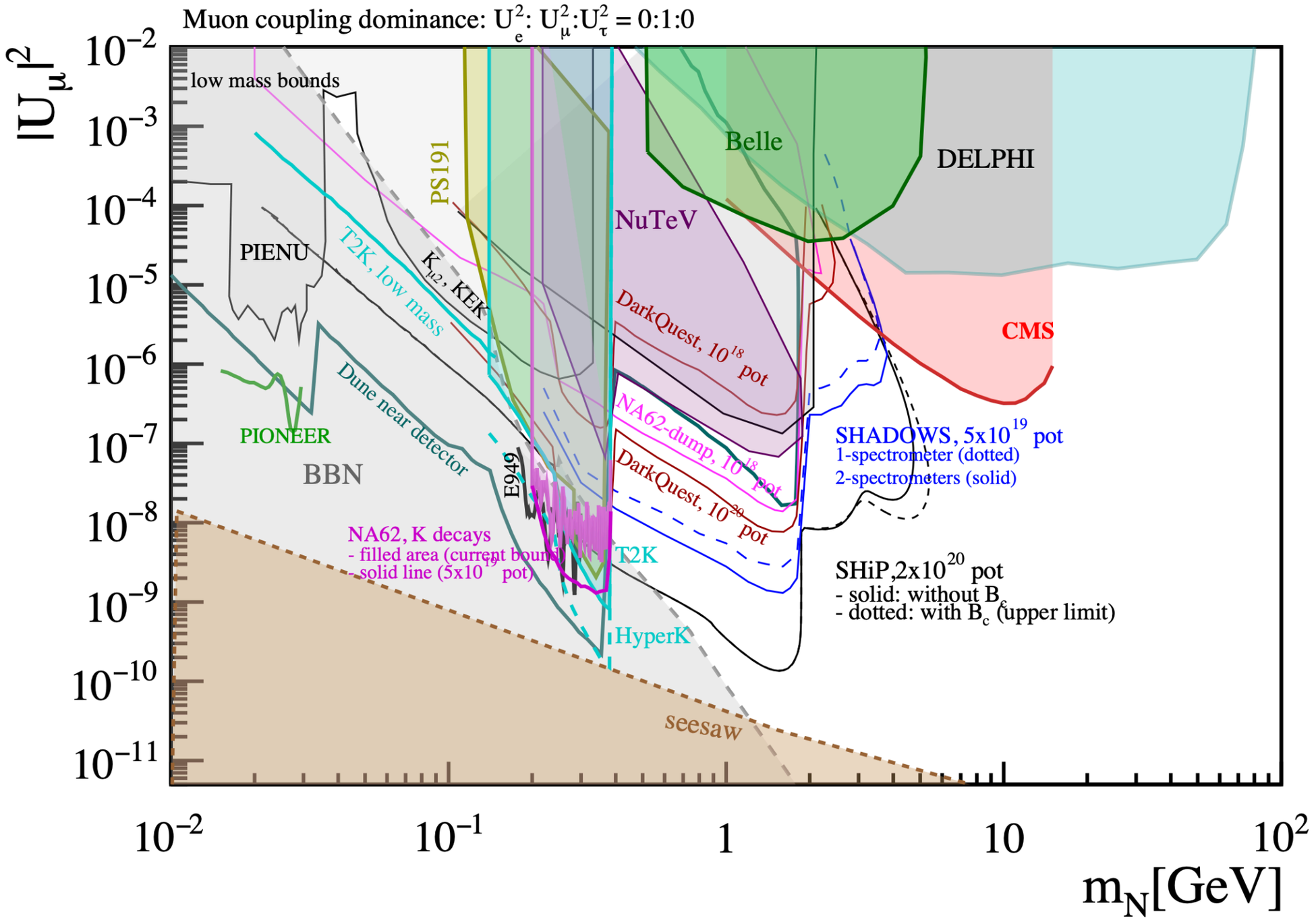
Summary

CERN

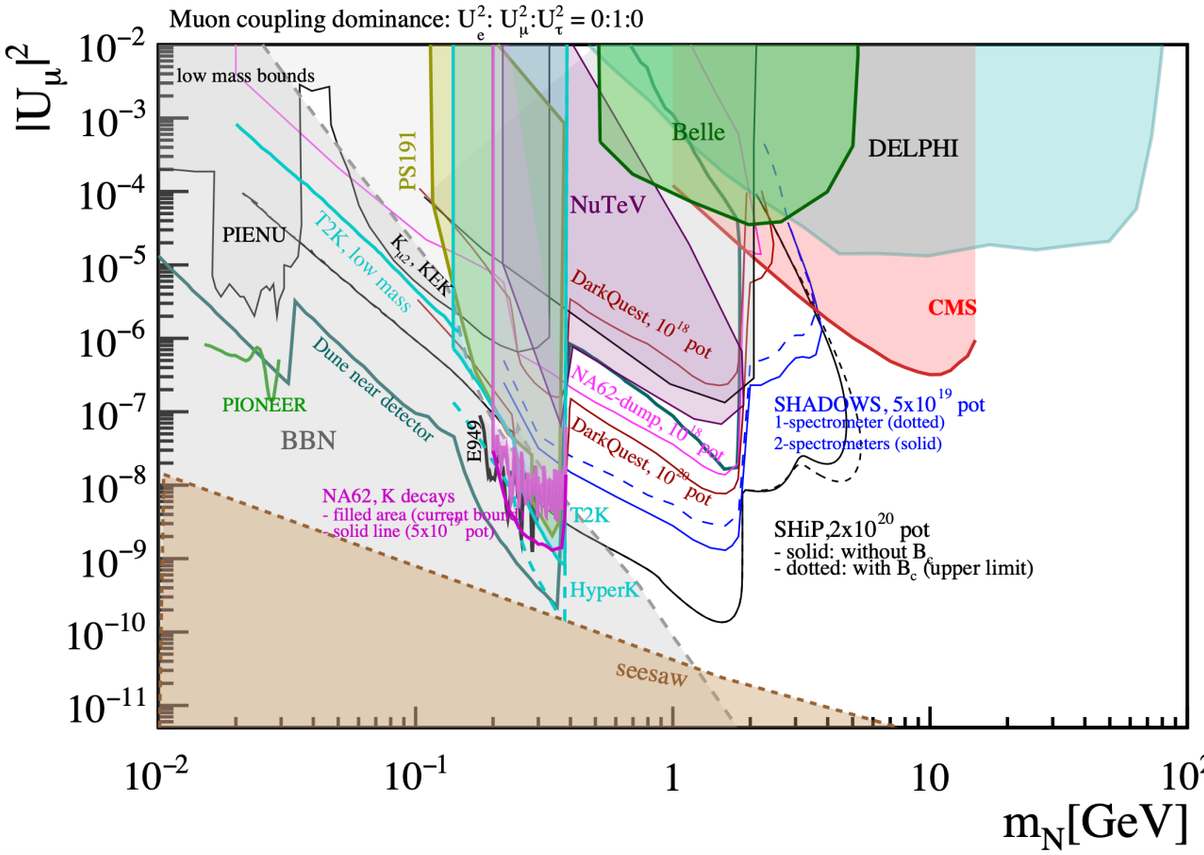
Neutrino PLATFORM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Summary


Muon coupling dominance: U_e^2: U_μ^2:U_τ^2 = 0:1:0
$|U_\mu|^2$
low mass bounds
PIENU
PS191
$K_{\mu 2}$, KEK
T2K, low mass
Belle
DELPHI
NuTeV
DarkQuest, 10^{18} pot
CMS
NA62-dump, 10^{18} pot
DarkQuest, 10^{20} pot
SHADOWS, 5×10^{19} pot
1-spectrometer (dotted)
2-spectrometers (solid)
PIONEER
BBN
Dune near detector
E949
NA62, K decays
- filled area (current bound)
- solid line (5×10^{19} pot)
T2K
HyperK
SHiP,2×10^{20} pot
- solid: without B_c
- dotted: with B_c (upper limit)
seesaw
m_N[GeV]

Summary



Theorist's Wish List

- ★ Collaborations: make results accessible to theorists
- ★ Funding Agencies: take BSM program seriously
- ★ Everyone: find common name for sterile ν / RH ν / HNL / NHL

Thank You!

CERN

Neutrino PLATFORM

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Bonus Slides

CERN

Neutrino PLATFORM

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Simulation / Analysis Pipeline

☑ HNL Production

- DUNE beam line simulation
  - ➠ remove neutrinos, re-decay parent mesons to HNLs
- simple estimates for charm decay
  (not included in DUNE simulation)

☑ HNL Decay

☑ Backgrounds: from GENIE

☑ simple *E* smearing and particle mis-ID; no charge ID

Ballett Boschi Pascoli
arXiv:1905.00284

☑ angular cut $\theta < M_N / (E_1 + E_2)$

☑ 2-dimensional binning in E_1 and E_2

Simulation / Analysis Pipeline

☑ HNL Production

- DUNE beam line simulation
  - ➠ remove neutrinos, re-decay parent mesons to HNLs
- simple estimates for charm decay
  (not included in DUNE simulation)

☑ HNL Decay

☑ Backgrounds: from GENIE

☑ simple *E* sm … particle … ID

… scoli
… 0284

HNL mass

total energy
of HNL decay products

mean angle
of HNL decay products
w.r.t beam axis

$\theta < M_N / (E_1 + E_2)$

… nal binning in E_1 and E_2

Simulation / Analysis Pipeline

☑ HNL Production

- DUNE beam line simulation
  - ➠ remove neutrinos, re-decay parent mesons to HNLs
- simple estimates for charm decay
  (not included in DUNE simulation)

☑ HNL Decay

☑ Backgrounds: from GENIE

☑ simple *E* smearing and particle mis-ID; no charge ID

Ballett Boschi Pascoli
arXiv:1905.00284

☑ angular cut $\theta < M_N / (E_1 + E_2)$

☑ 2-dimensional binning in E_1 and E_2

Simulation / Analysis Pipeline

☑ HNL Production

- DUNE beam line simulation
  - ➠ remove neutrinos, re-decay parent mesons to HNLs
- simple estimates for charm decay (not included in DUNE simulation)

☑ HNL Decay

☑ Backgrounds: from GENIE

☑ simple *E* smearing and particle mis-ID; no charge ID

Ballett Boschi Pascoli
arXiv:1905.00284

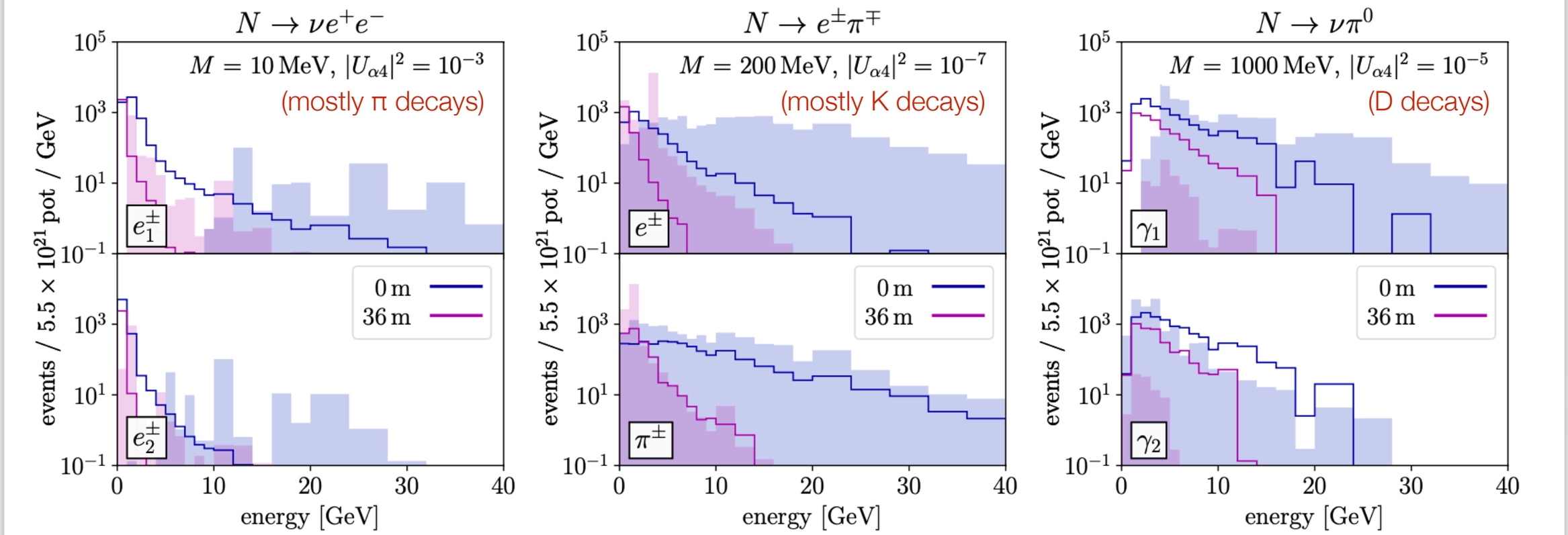
☑ angular cut $\theta < M_N / (E_1 + E_2)$

☑ 2-dimensional binning in E_1 and E_2

} efficient BG suppression

HNL Event Rates

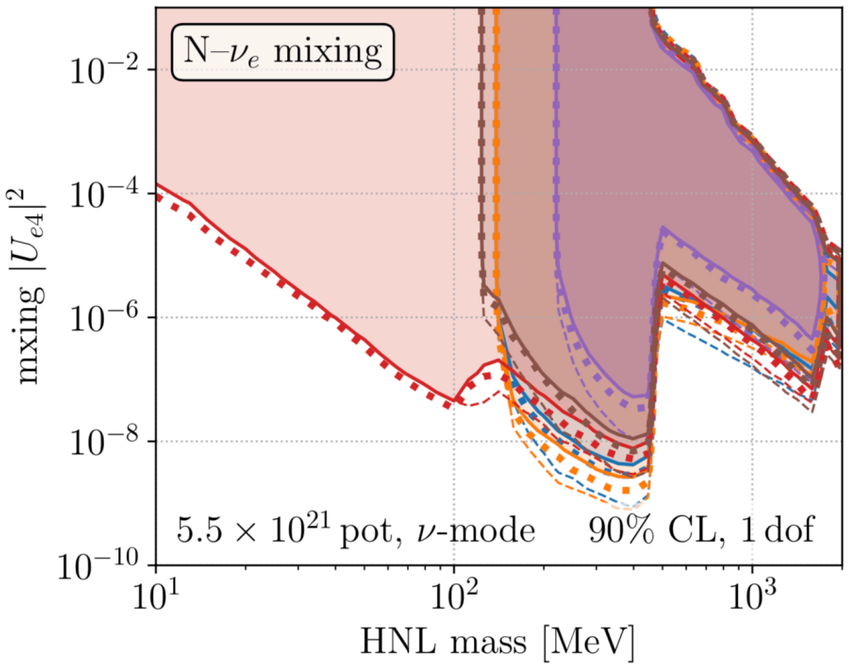
Breitbach *et al.* 2021

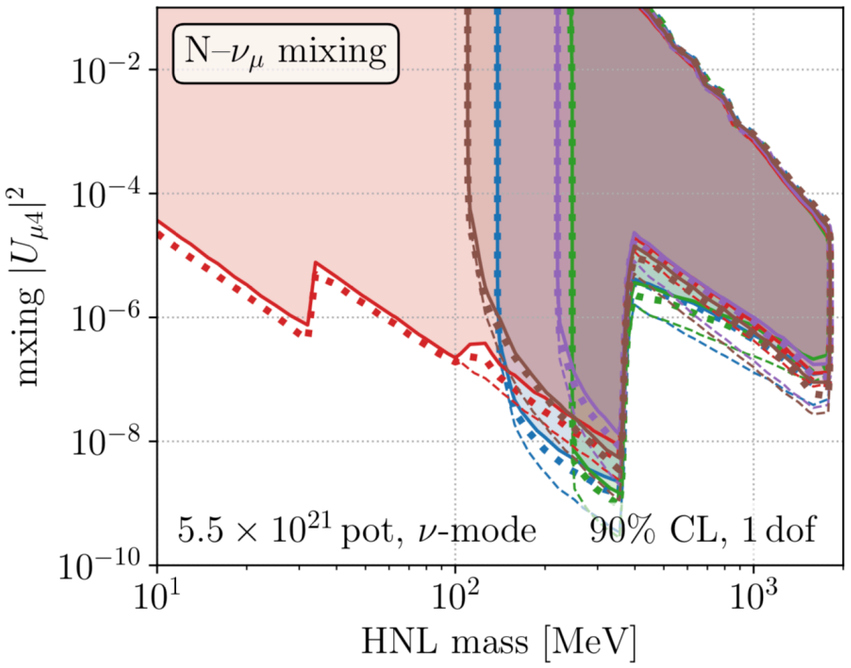


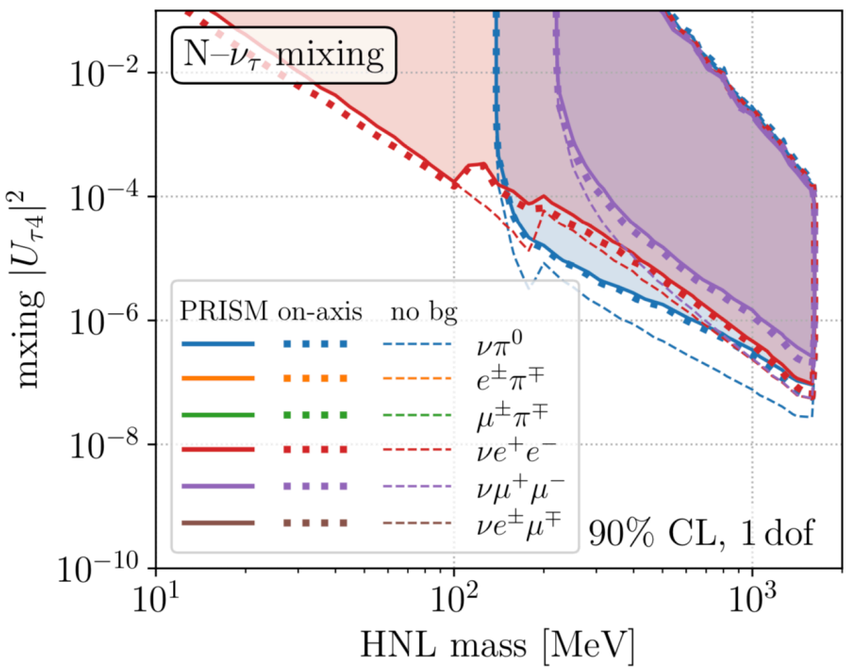
- ☑ off-axis: improved signal-to-background ratio, especially in 2D plane
- ☑ but cuts (especially on angle w.r.t. beam axis) very efficient at suppressing backgrounds, too.

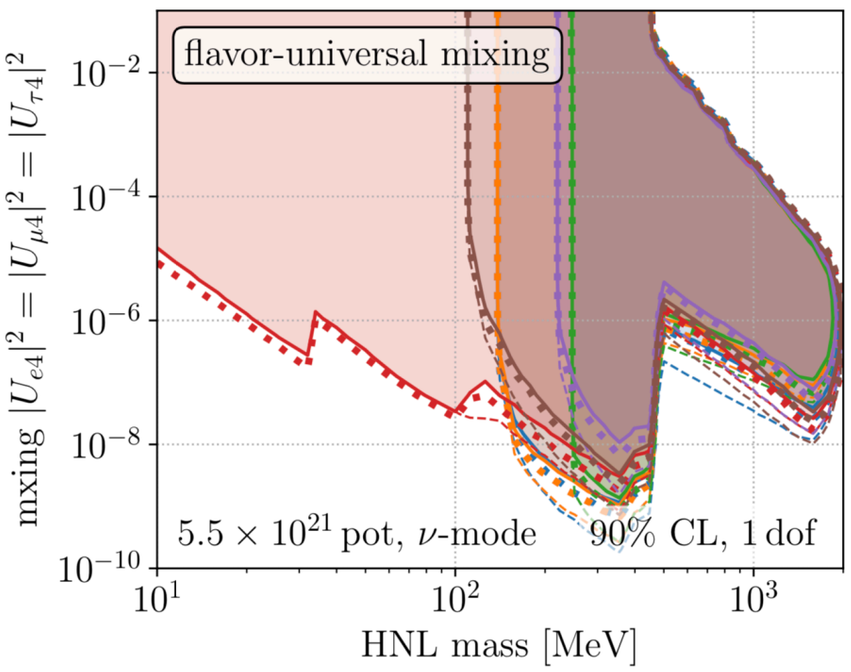
HNLs: Interplay of Decay Channels

Breitbach *et al.* 2021

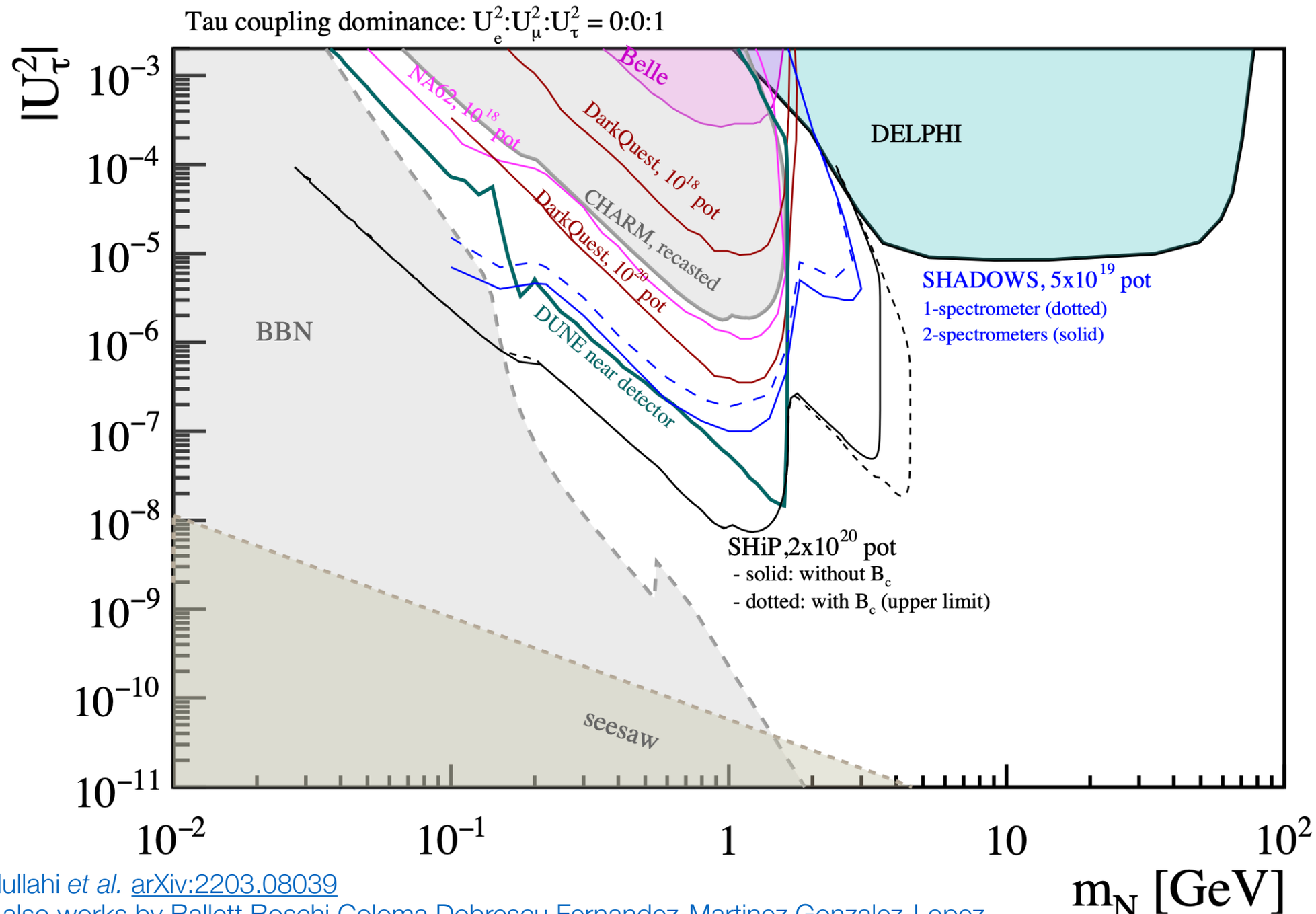






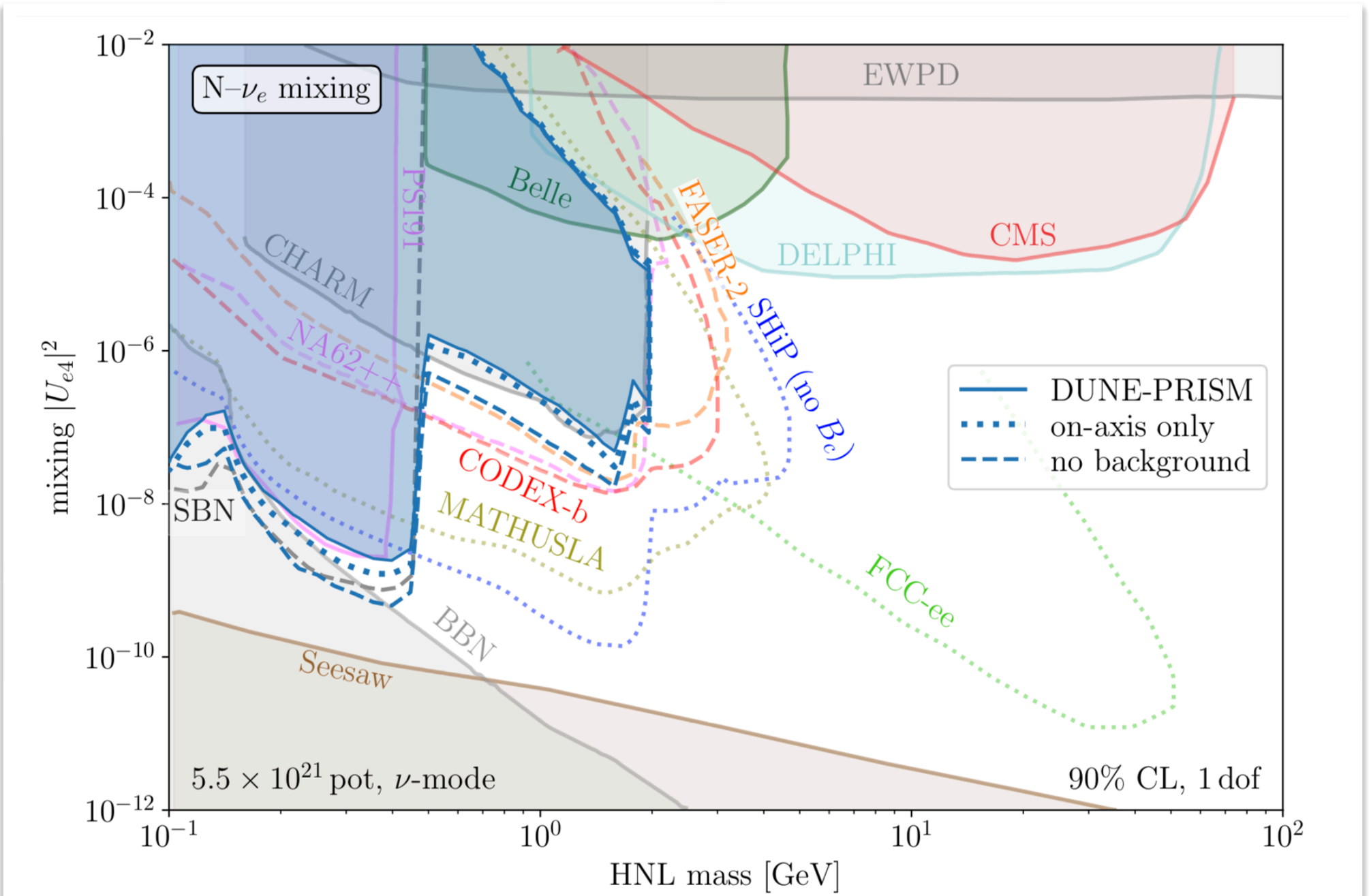


HNLs: Sensitivities



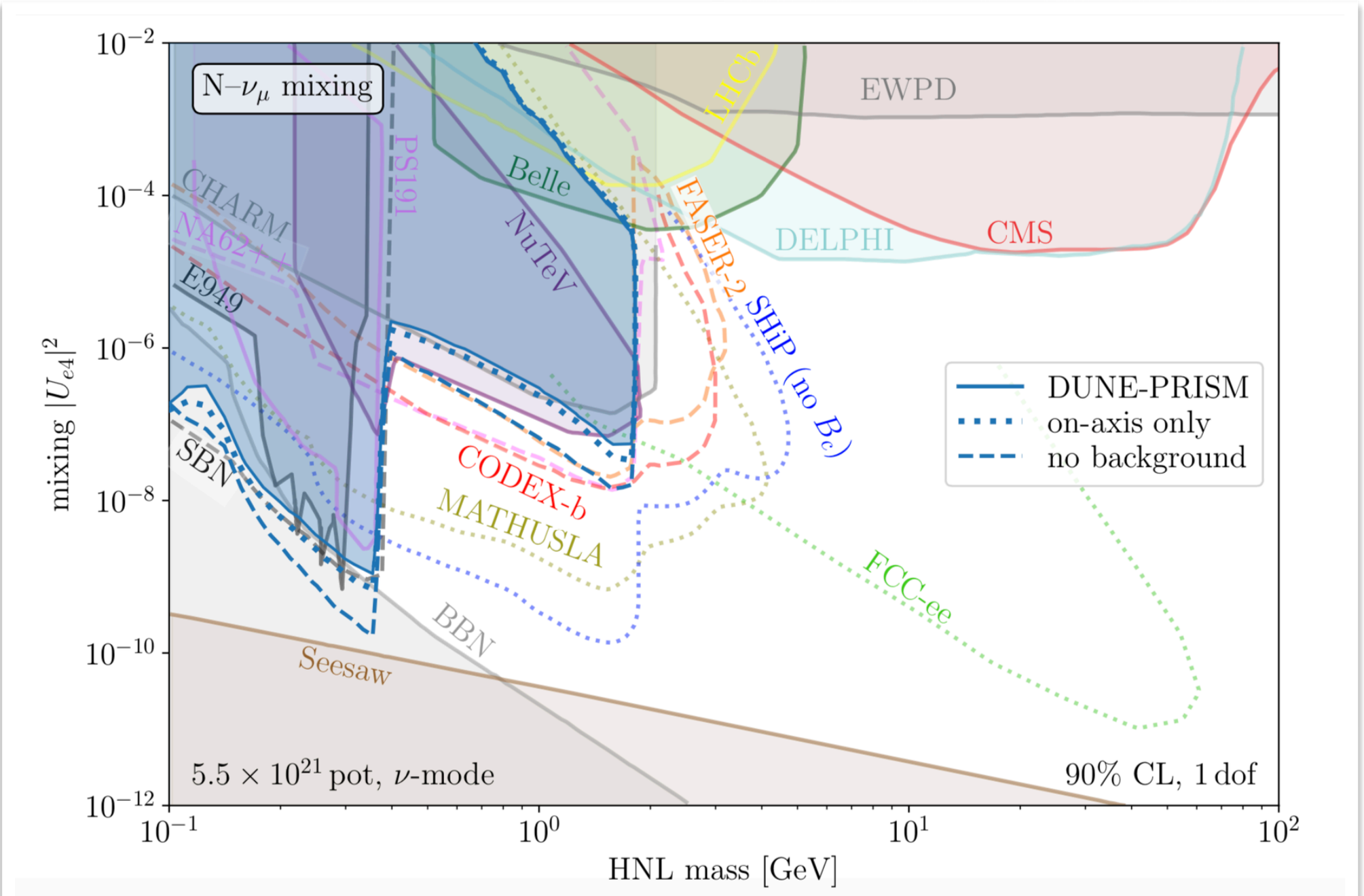
Abdullahi *et al.* arXiv:2203.08039
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic Breitbach Buonocore Frugiuele JK Mittnacht

HNLs: DUNE Sensitivities



Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic

HNLs: DUNE Sensitivities



Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic