Oscillation physics case for a neutrino factory

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COLORADO STATE UNIVERSITY

Neutrinos and a muon collider

What can a muon collider do for neutrino physics?

What can neutrino physics do for a muon collider?

Neutrinos and a muon collider

What can a muon collider do for neutrino physics?

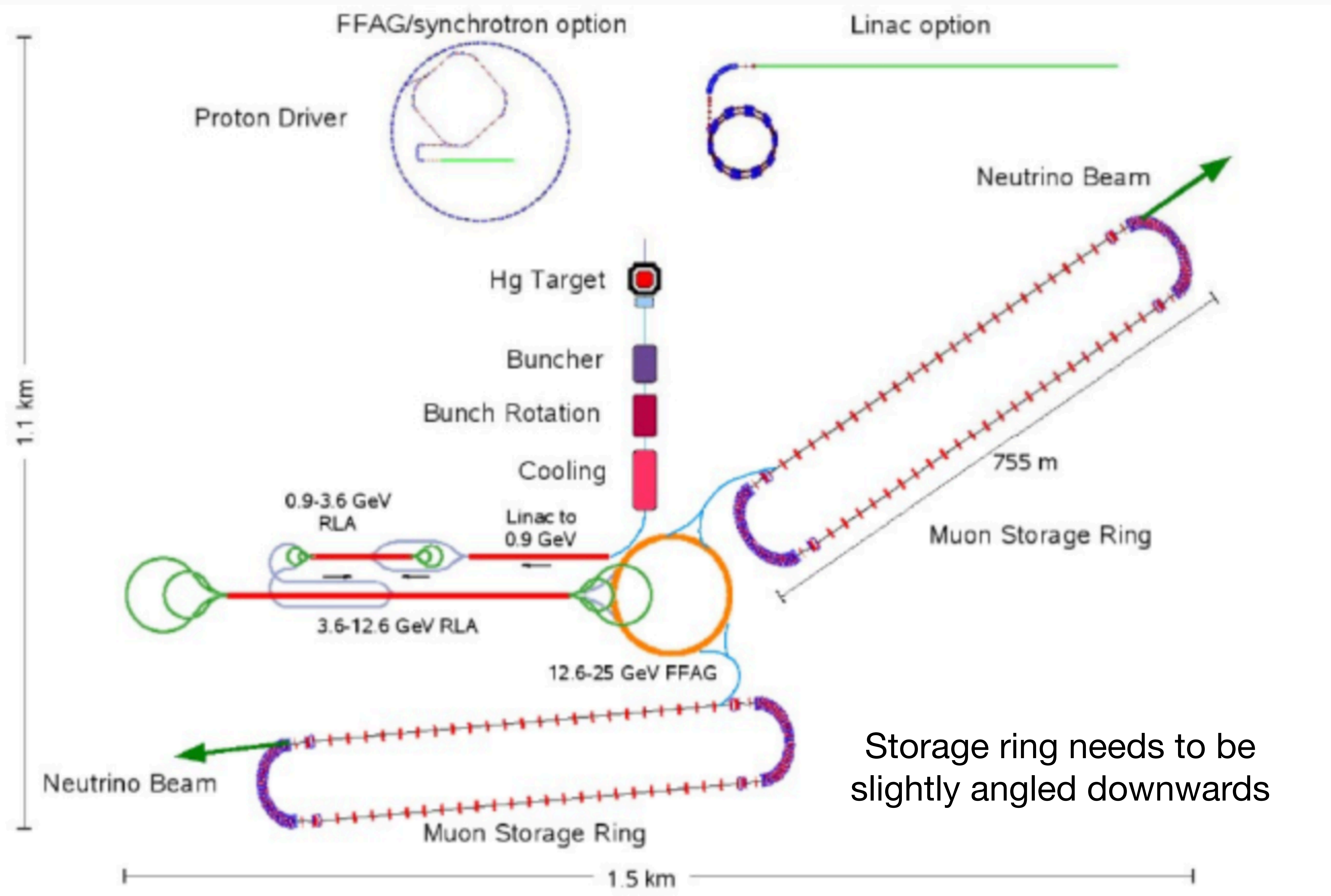
See talks by A. Thompson, M. Hostert

What can neutrino physics do for a muon collider?

This talk!

Motivate a neutrino factory as a possible first stage of a muon collider

Neutrino factory



Storage ring needs to be slightly angled downwards

- Neutrino production from (anti-)muon decays: $\mu^- \rightarrow \nu_\mu \bar{\nu}_e e^-$
- Muons decay along straight line of race track design → very collimated neutrino beam of known composition
- ν_e, ν_μ, ν_τ appearance & ν_e, ν_μ disappearance searches possible
- Beam of equally many neutrinos as anti-neutrinos (albeit of different flavor)

Neutrino factory

Has been considered in early 2000's to measure CPV for $\theta_{13} < 1^\circ$
Distinction between neutrinos and anti neutrinos (CID) was found to be important

[De Rujula, Gavela, Hernandez 9811390]

renewed interest in muon colliders & current knowledge of oscillation physics
$\Rightarrow$ modern study timely

A Modern Look at the Oscillation Physics Case for a Neutrino Factory

Peter B. Denton[1,*] and Julia Gehrlein[2,†]

[1] *High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[2] *Physics Department, Colorado State University, Fort Collins, CO 80523, USA*

[2407.02572]

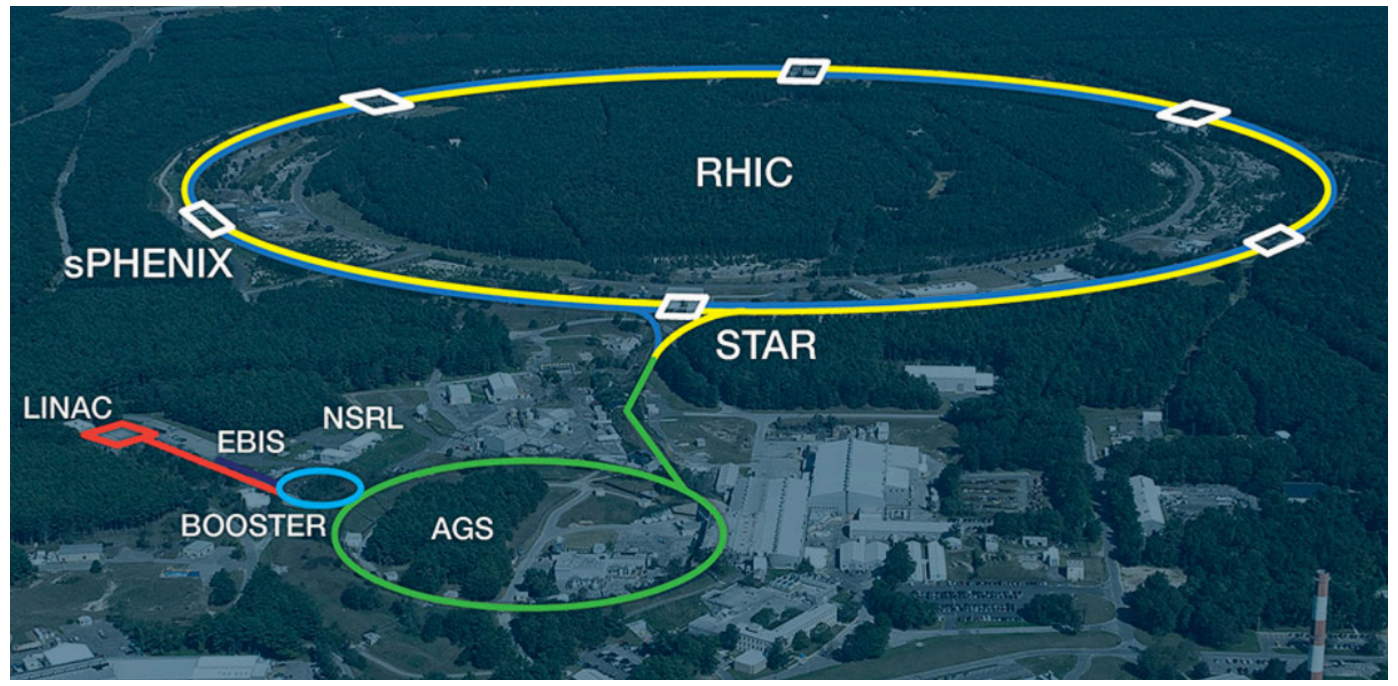
Published in NPB

Non-oscillation case recently studied in [Bogacz et al 2203.08094]

Neutrino factory
Setup

Study two setups:

- neutrino source at Fermilab, 40 kT LAr far detector at SURF → baseline: 1284.9 km



- neutrino source at Brookhaven (AGS/RHIC/EIC), 40 kT LAr far detector at SURF → baseline: 2542.3 km

Study of NF at J-PARC [Kitano, Sato, Sugama 2407.05807]

Assume DUNE+HK are successful → Study precision on oscillation parameters combining DUNE+HK+NF

Neutrino factory
Results

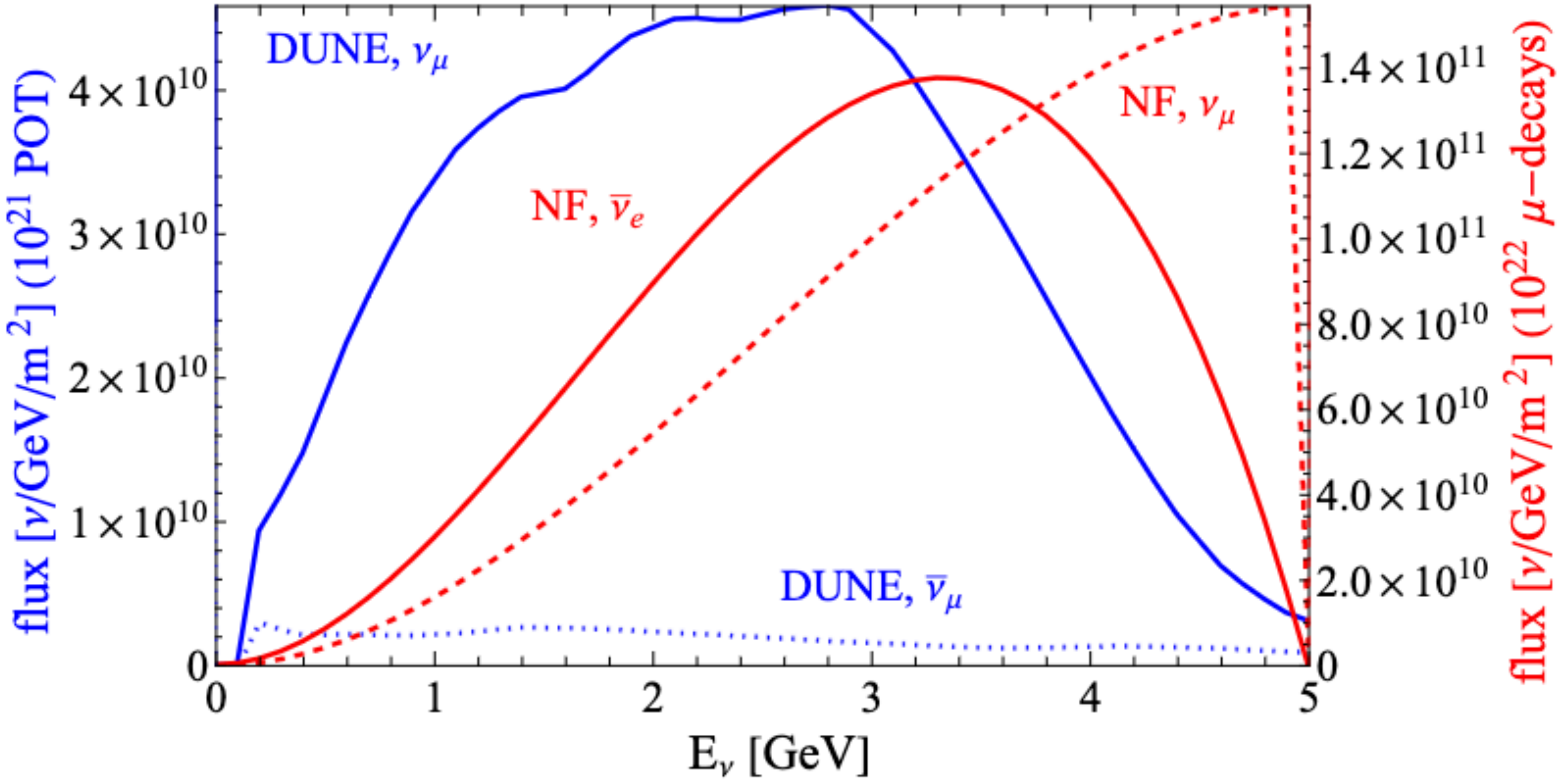
[Denton, JG, 2407.02572]

Optimal muon energy to maximize precision of δ

$E_\mu \approx 5$ GeV (FNAL-SURF), $E_\mu \approx 8$ GeV (BNL-SURF)

Running time neutrino: antineutrino 1:1

Depending on physics case these values might slightly change



→ lower muon energy required at a neutrino factory than at a muon collider

⇒ NF can act as a first lower energy stage of a high-energy muon collider

Neutrino factory

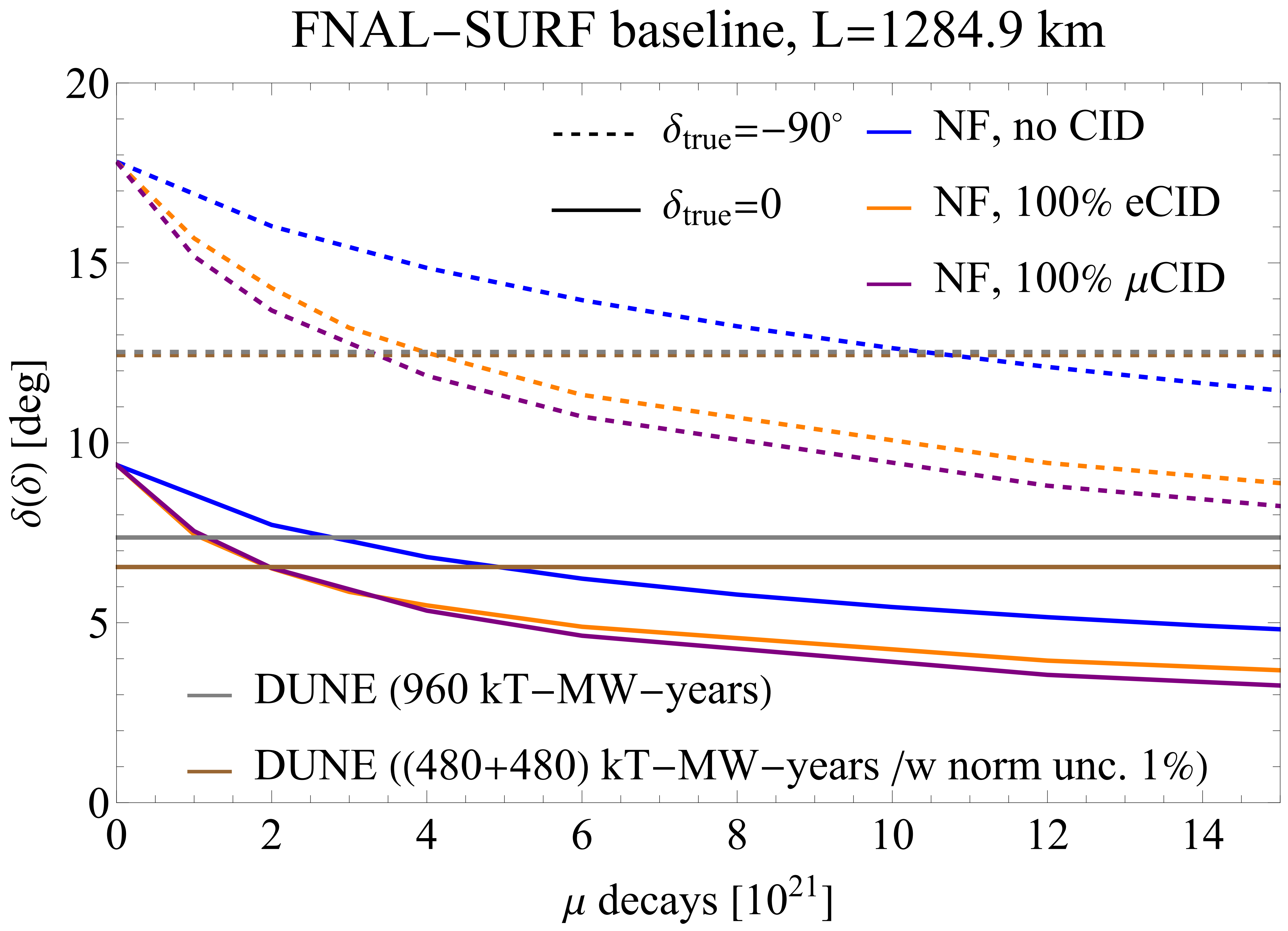
Results

[Denton, JG, 2407.02572]

~10^{22} μ decays required to improve precision of δ (depending on true value and setup) compared to doubling the running time of DUNE

Use as benchmarks

- DUNE (10 yr)+HK (10 yr)
- DUNE (10 yr)+HK (10 yr)+NF (10 yr)



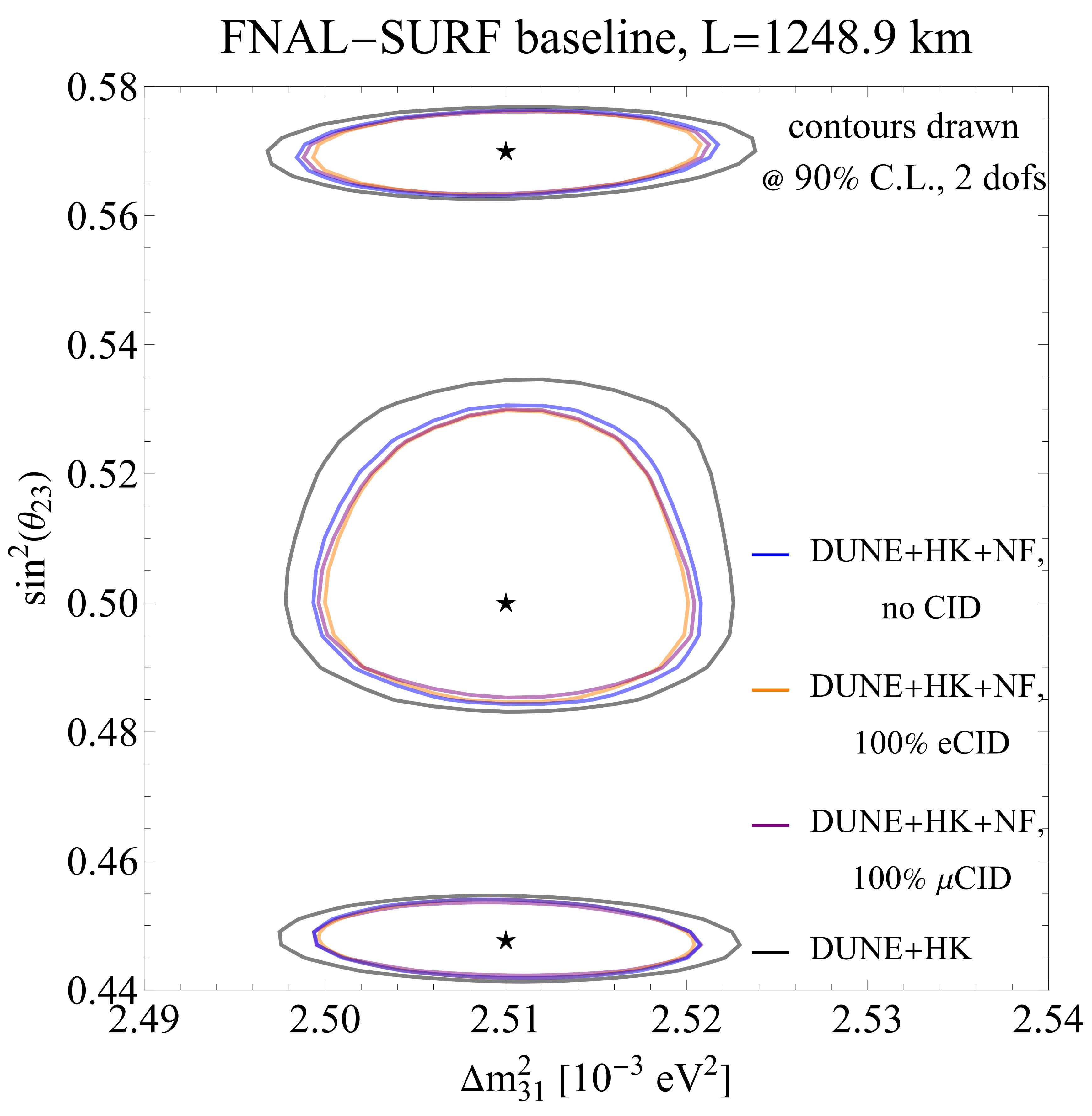
Neutrino factory

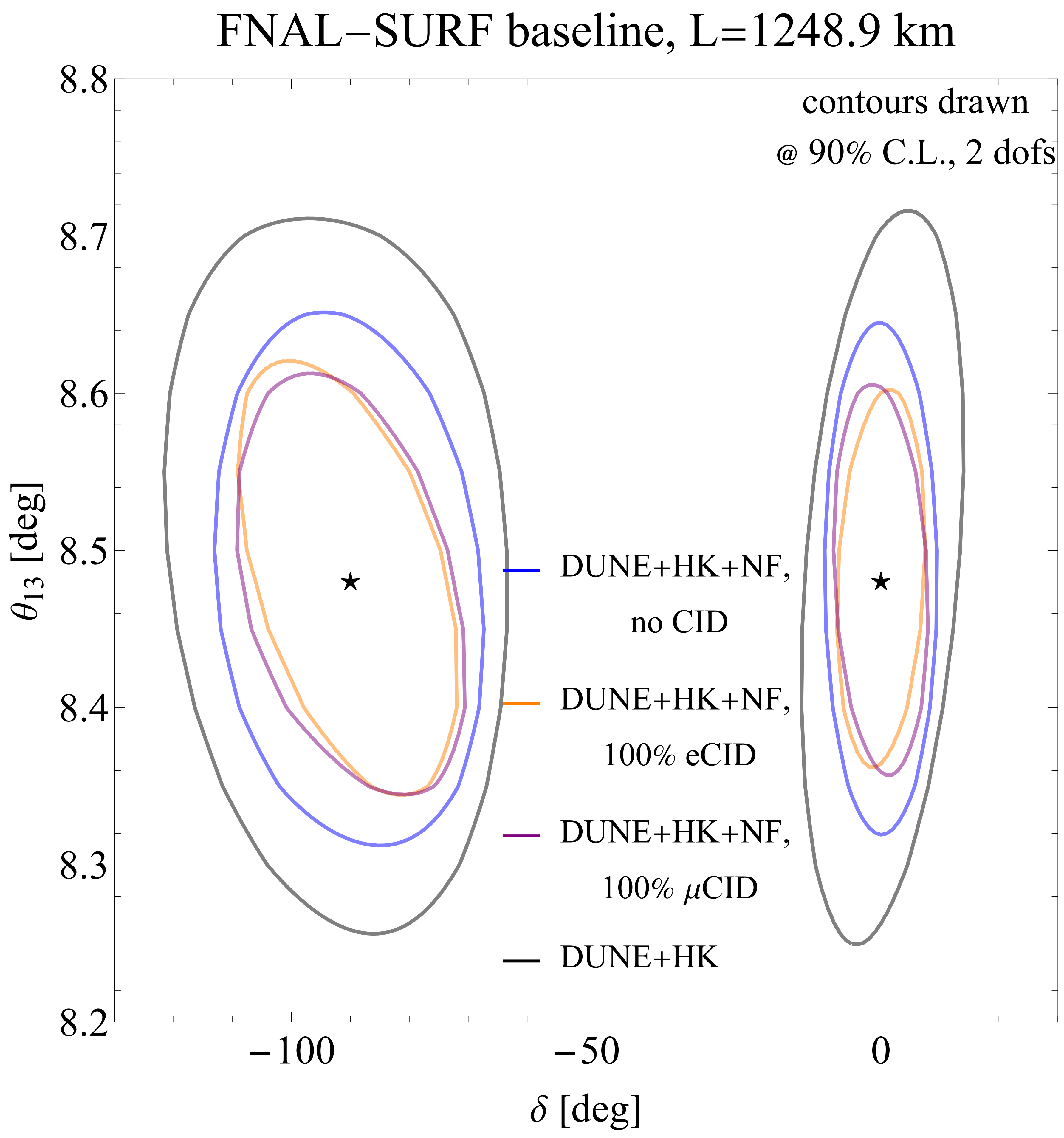
Results

Results for a total of

40 kT – 10^{22} μ decays

[Denton, JG, 2407.02572]





- DUNE, HK will improve over current constraints
- NF will reduce uncertainties even more
- Results potentially even better due to improvements in LAr technology
- CID not as important

Neutrino factory

Benefit for standard oscillation physics

[Denton, JG, 2407.02572]

NF appealing possible option should the results of HK and DUNE disagree and further oscillation studies are required

NF provides:

- higher neutrino energy
- longer baseline
- overall smaller flux uncertainty
- tunable energy
- 6 oscillation channels and their CP conjugate ones with similar large number of events

Neutrino factory
Results: BSM

NF has four different oscillation channels which are is CP, T, and CPT conjugates of each other

⇒ Probe of CPT invariance

Testing New Physics in Oscillations at a Neutrino Factory

[2502.14027]

Peter B. Denton,[1] Julia Gehrlein,[2] and Chui-Fan Kong[3,4]

Neutrino factory

Results: CPT

[Denton, JG, Kong 2502.14027]

treat mixing parameters of neutrinos and anti-neutrinos separately

$$\chi^2 \equiv \chi^2_\nu(x) + \chi^2_{\bar{\nu}}(\bar{x})$$

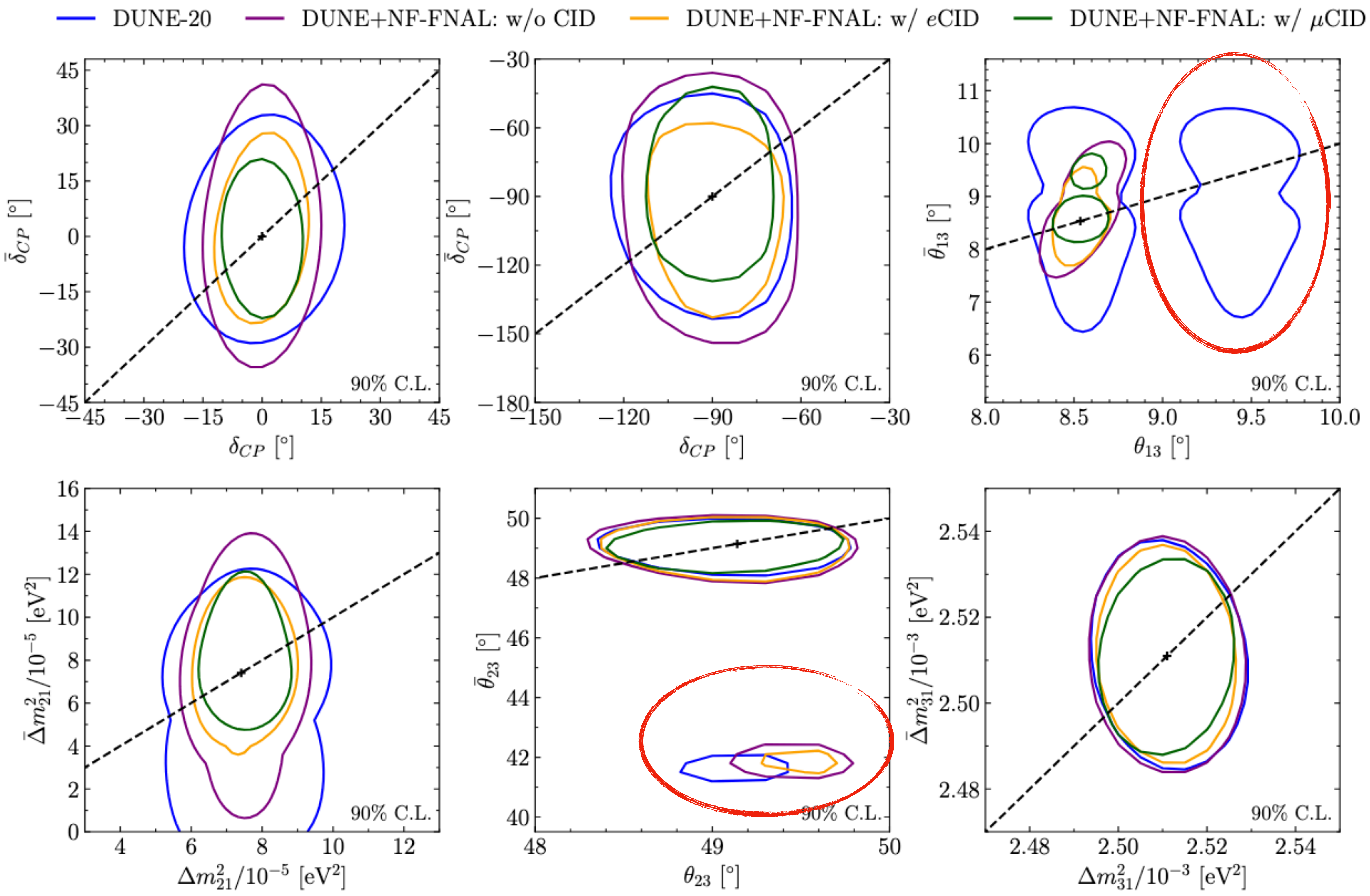
Similar approach as in [Barenboim, Ternes, Tortola 1712.01714, 2005.05975], [Barenboim, Martinez-Mirave, Ternes, Tortola 2305.06384]

Consider benchmarks

- DUNE (10 yr)
- DUNE (20 yr)
- DUNE (10 yr)+NF (10 yr)

Neutrino factory
Results: CPT

[Denton, JG, Kong 2502.14027]



- Addition of NF improves constraints
- Excludes degeneracies present for DUNE thanks to presence of ν_e dis and ν_μ app channels

Neutrino factory
Results: NSI

[Denton, JG, Kong 2502.14027]

$$\mathscr{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,\alpha,\beta} \epsilon_{\alpha\beta}^{f,V} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)\,,$$

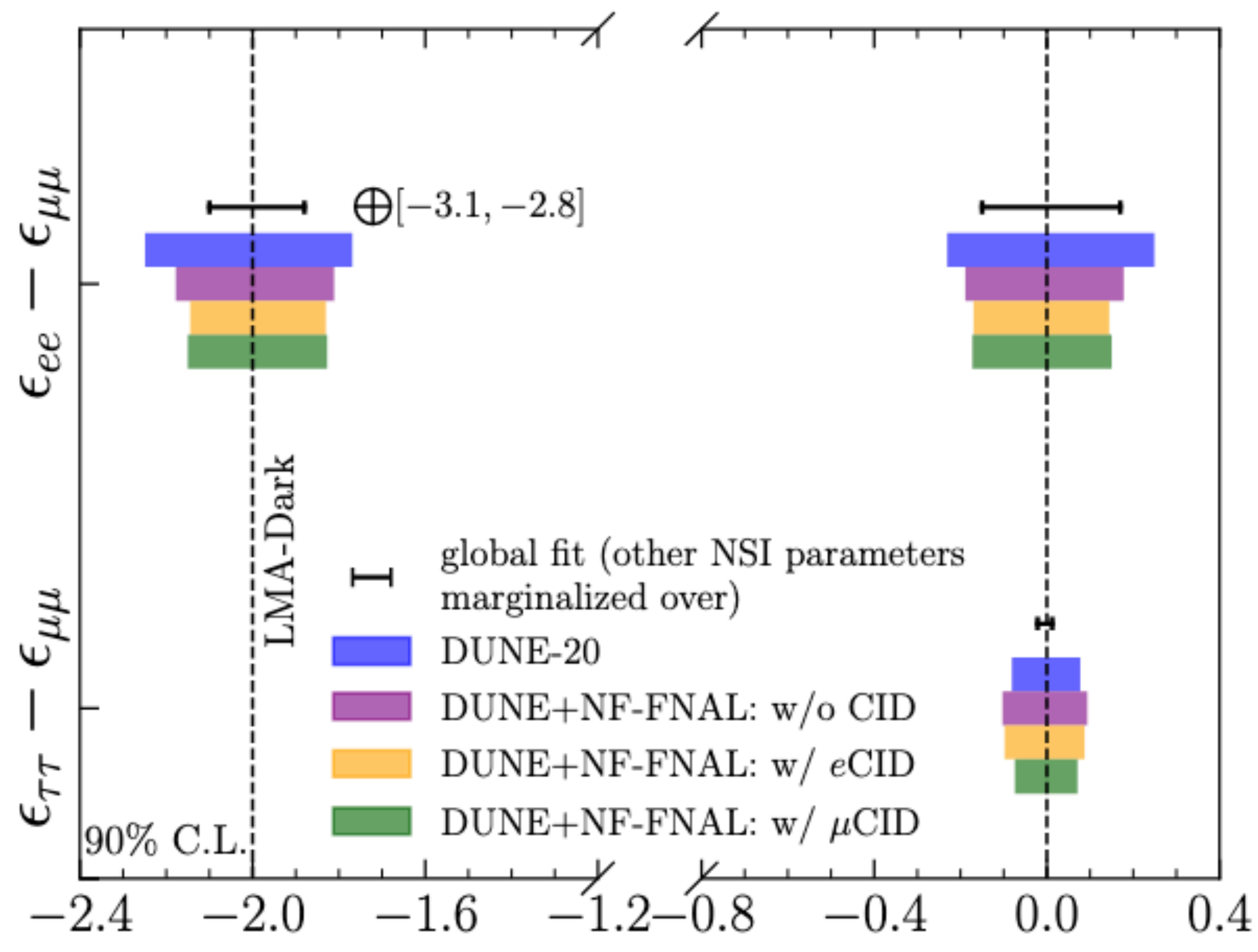
Five NSI parameters: diagonal parameters are real, off-diagonal parameters can be complex

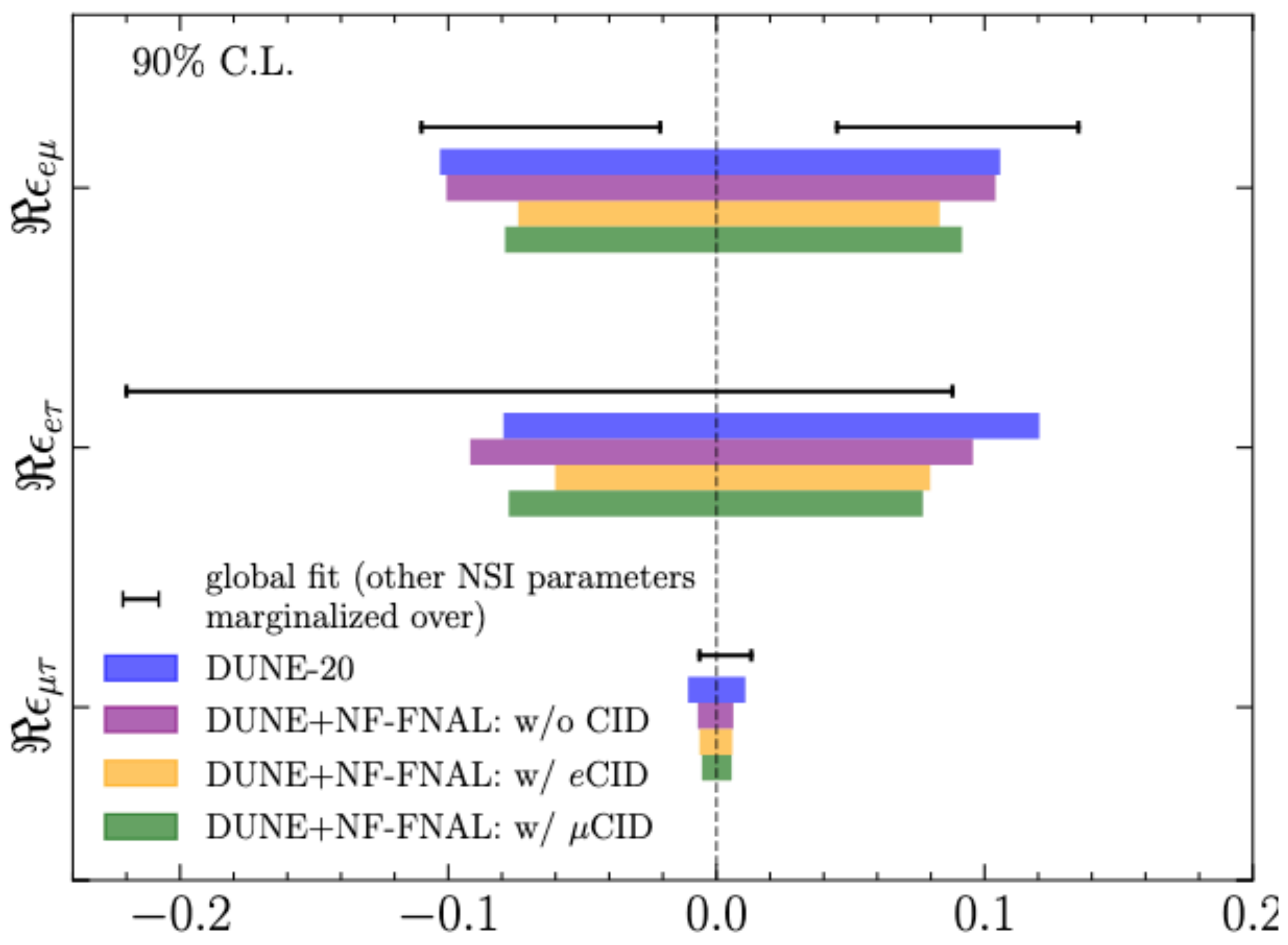
Study constraints on

- one parameter at a time
- two parameters at a time

Neutrino factory
Results: NSI

[Denton, JG, Kong 2502.14027]

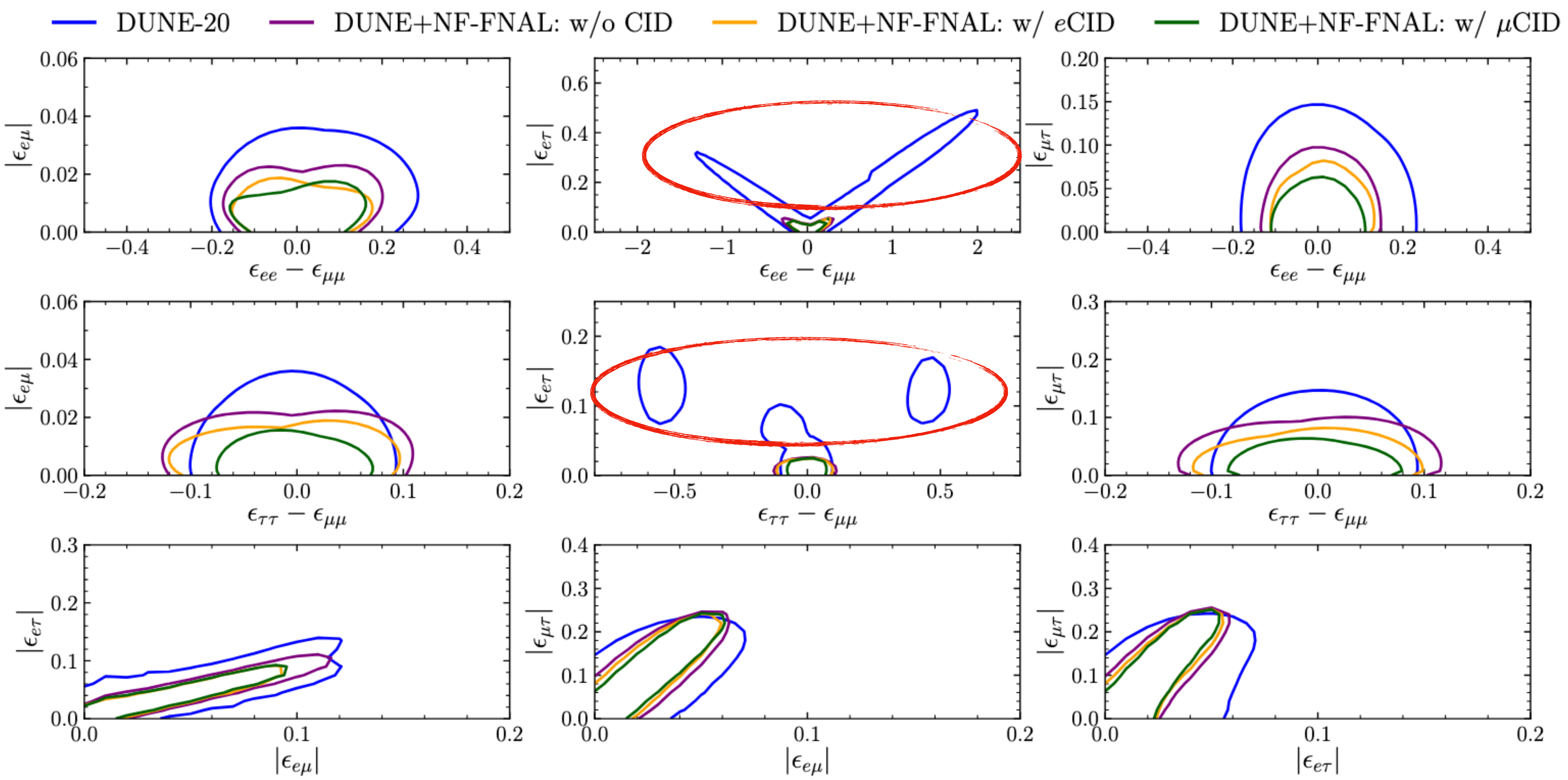




DUNE+NF: improvement of constraints on one non-zero NSI parameter at a time due to additional oscillation channels compared to DUNE alone

Neutrino factory
Results: NSI

[Denton, JG, Kong 2502.14027]



Addition of NF excludes degeneracies present in DUNE only thanks to presence of ν_e dis and ν_μ app channels

Neutrino factory

Conclusions

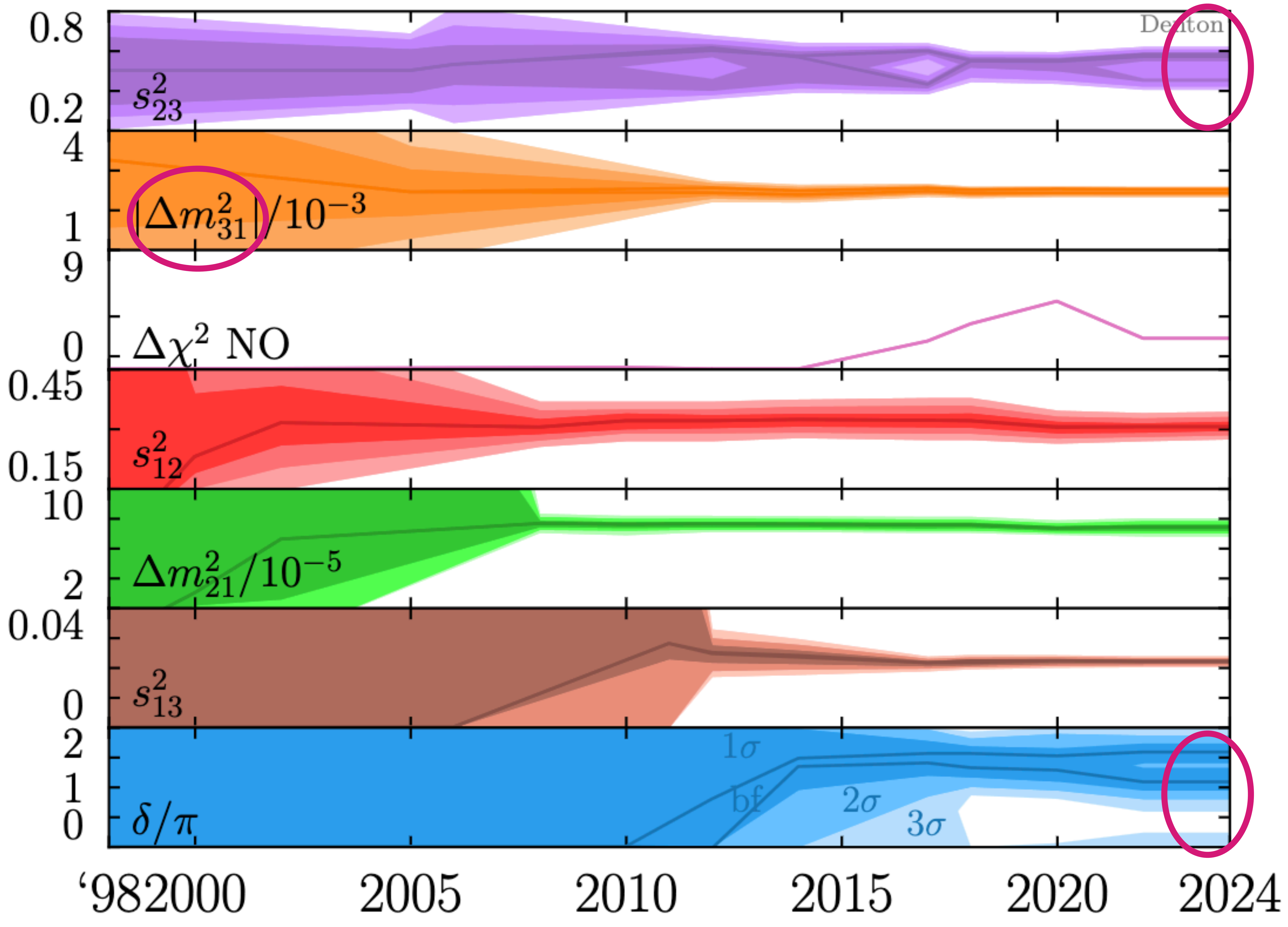
NF interesting possibility as a future oscillation experiment

- Expected improved precision on several fundamental parameters including the amount of CP violation
- expected improved constraints on CPT violation and NSI and exclusion of degeneracies
- A technological stepping stone on the way to a high energy muon collider

Thanks for your attention!

Appendix: Neutrino oscillations

Where do we stand?



[update from
Denton et al 2212.00809]

Appendix: Neutrino oscillations

Where are we going?

Long baseline (300 km, 1300 km) accelerator neutrino experiments:
Hyper-Kamiokande, DUNE
→ CP phase, octant of θ_{23}, Δm^2_{31}, mass ordering

Medium baseline (~50 km) reactor neutrino experiment:
JUNO
→ $\theta_{12}, \Delta m^2_{21},$ mass ordering

Atmospheric neutrino experiments:
HK, IceCube-Gen2, KM3NeT-ORCA
→ θ_{23}, Δm^2_{31}, mass ordering

Appendix: Neutrino oscillations

Where are we going?

What do we want to do after the next generation of neutrino oscillation experiments?

Answer depends on the outcome of these experiments

- If new physics is found
- If their results agree or disagree
- General landscape of particle physics

What do we want to learn about?

Appendix: Neutrino factory

- Goal of future NF is not discovery of CPV but precise measurements of mixing parameters and/or
- potentially resolve any discrepancies identified in previous measurements
- Resolve degeneracies between standard oscillation parameters and new physics

Assume DUNE+HK are successful

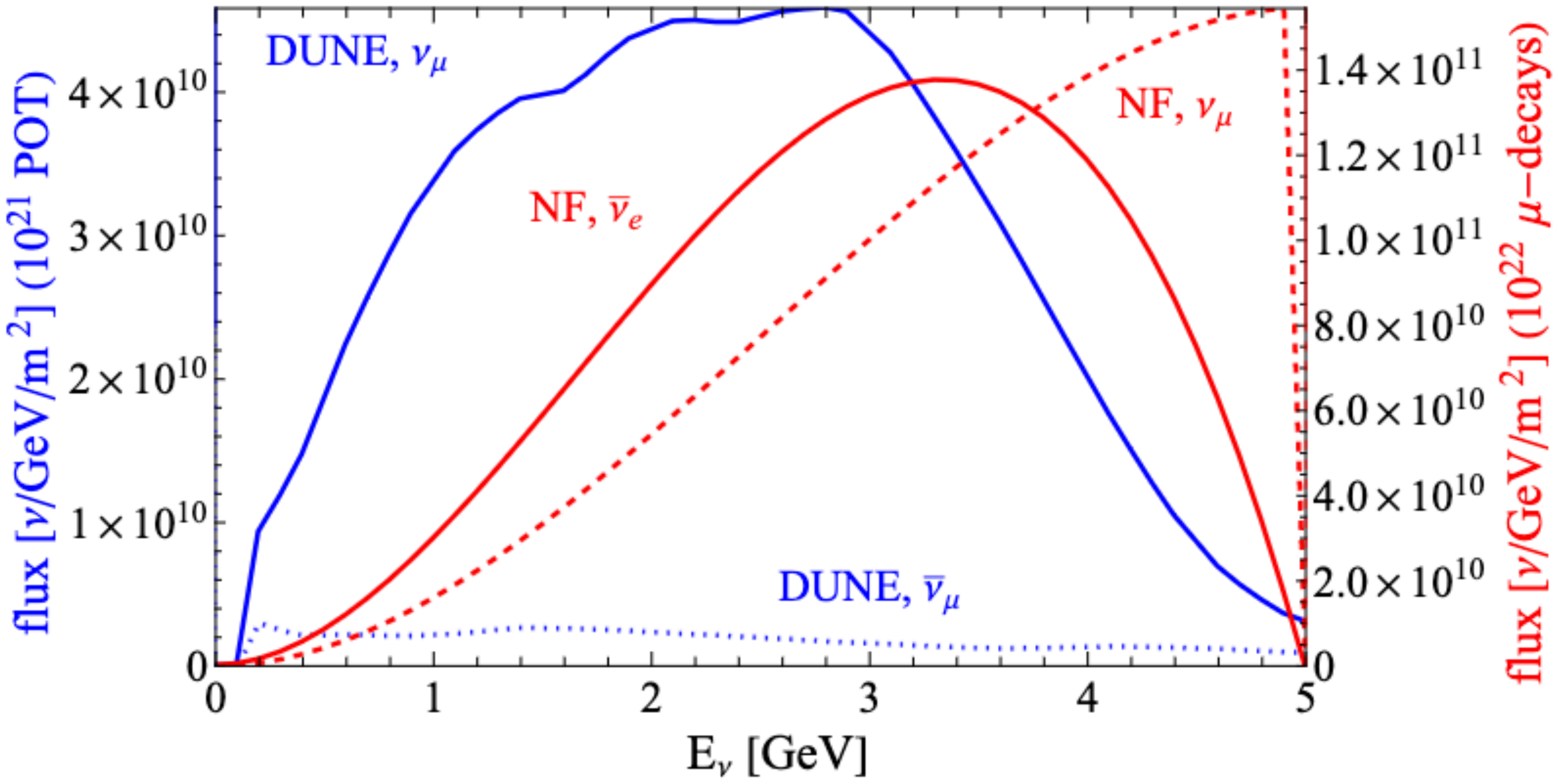
→ Study precision on oscillation parameters combining DUNE+HK+NF

→ Study expected constraints on new physics scenarios using DUNE+NF

Appendix: Neutrino factory

NF vs neutrino beams from fixed target experiments:

- achievable maximal neutrino energy is higher at a neutrino factory
- composition and the expected energy of the neutrino beam is well known
- equally many neutrinos as anti-neutrinos



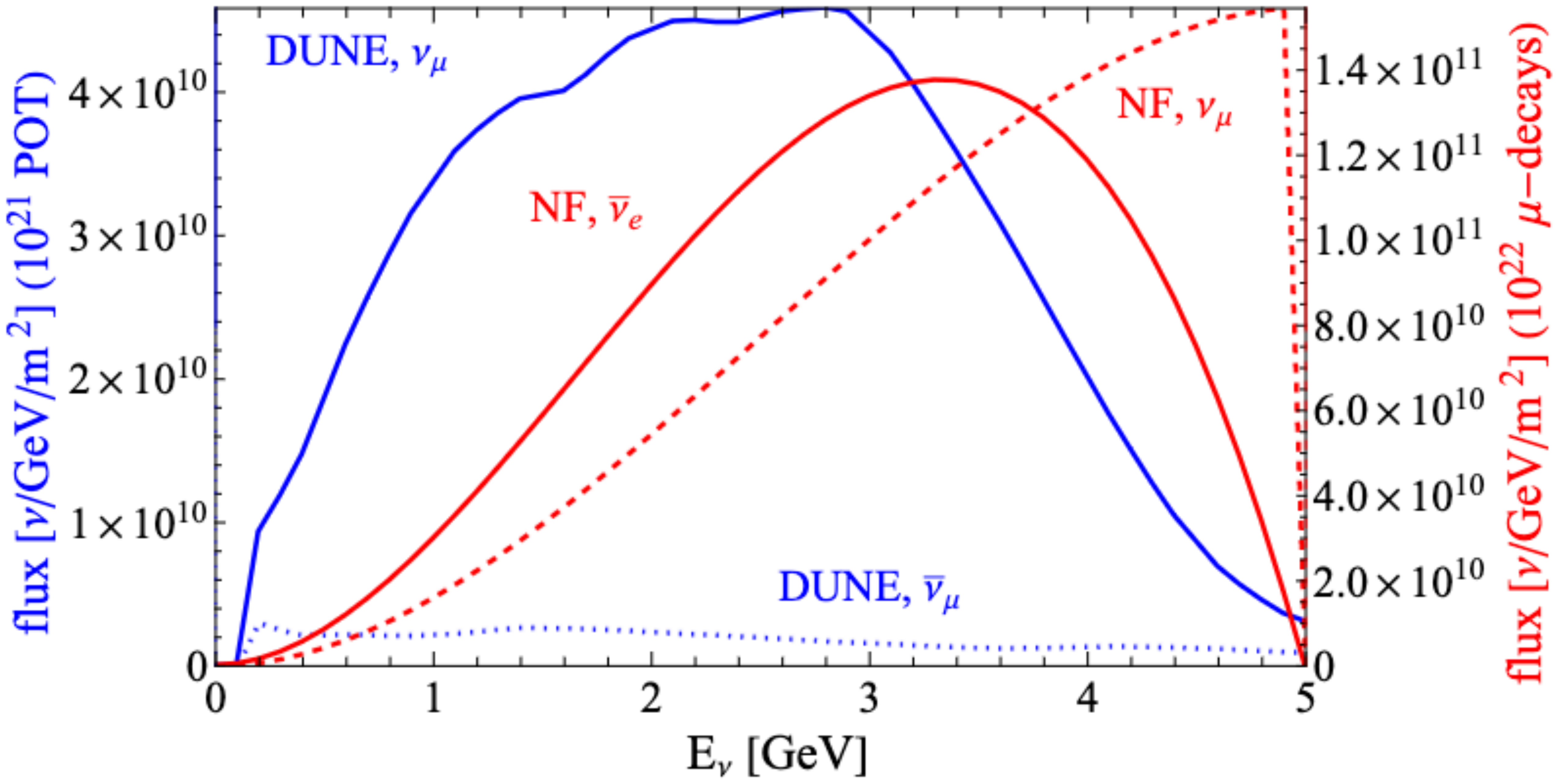
Neutrino production: $\mu^- \to \nu_\mu \bar{\nu}_e e^-$

[Denton,JG, 2407.02572]

Appendix: Neutrino factory

NF vs neutrino beams from fixed target experiments:

- ν_e in source
  $\rightarrow \nu_\mu$ appearance searches
- no ν_τ in source
  $\rightarrow \nu_\tau$ appearance searches
- neutrino energy is tunable and flexible



Neutrino production: $\mu^- \rightarrow \nu_\mu \bar{\nu}_e e^-$

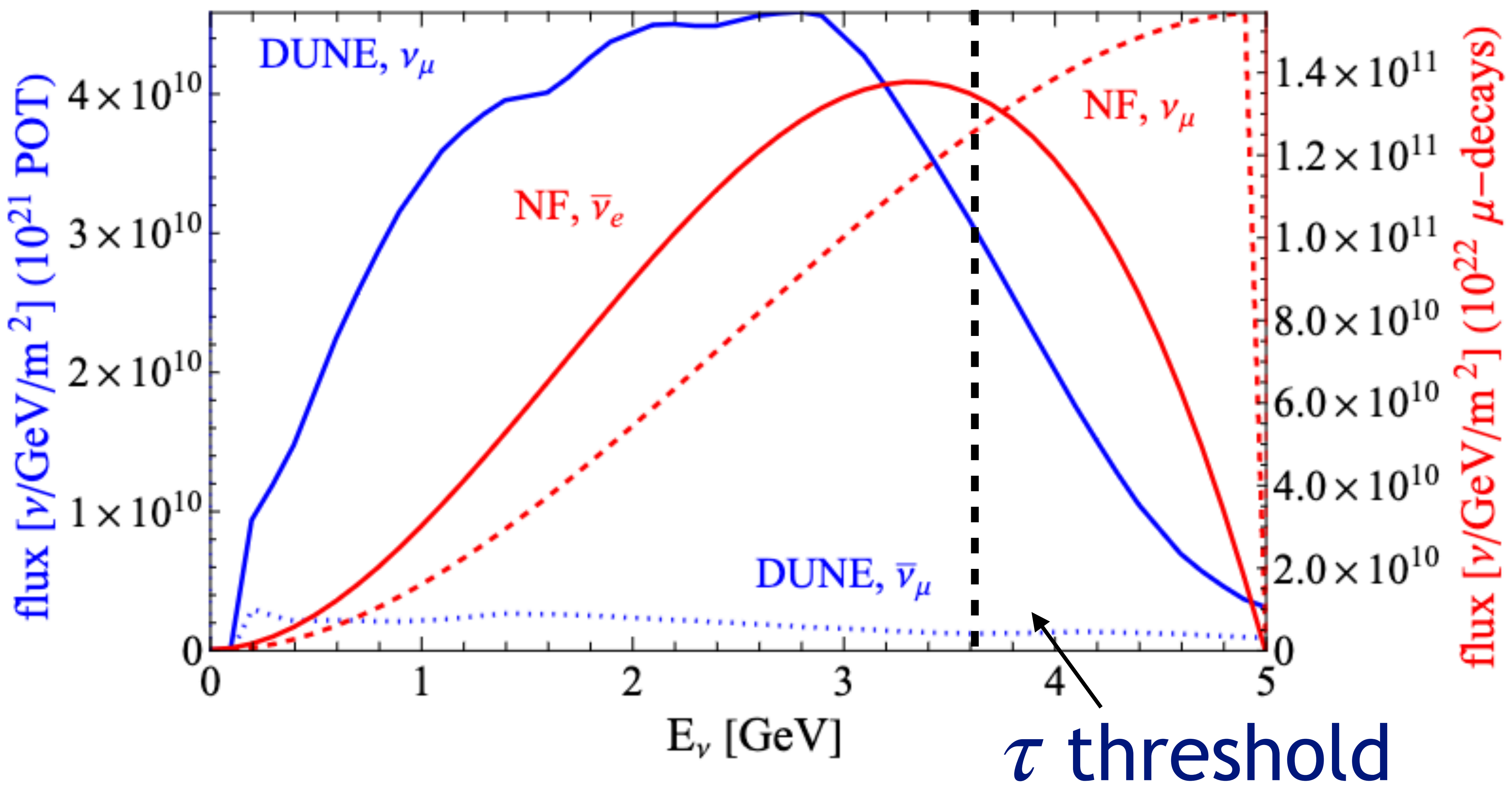
[Denton,JG, 2407.02572]

Appendix: Neutrino factory
Setup

[Denton, JG, 2407.02572]

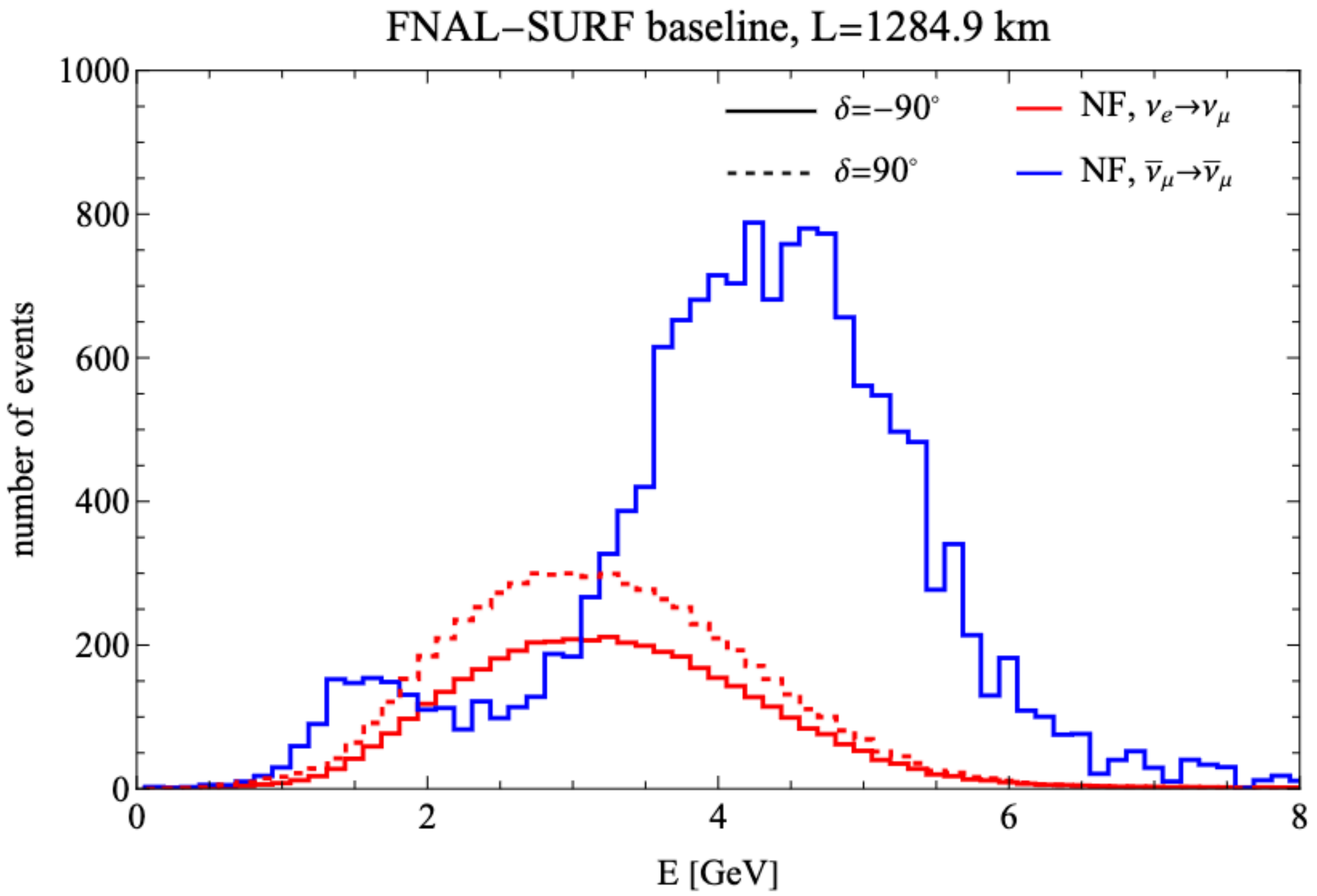
- Far detector: LArTPC, total fiducial target mass of 40 kT
- 2.5% normalization uncertainty on ν_e, ν_μ flux

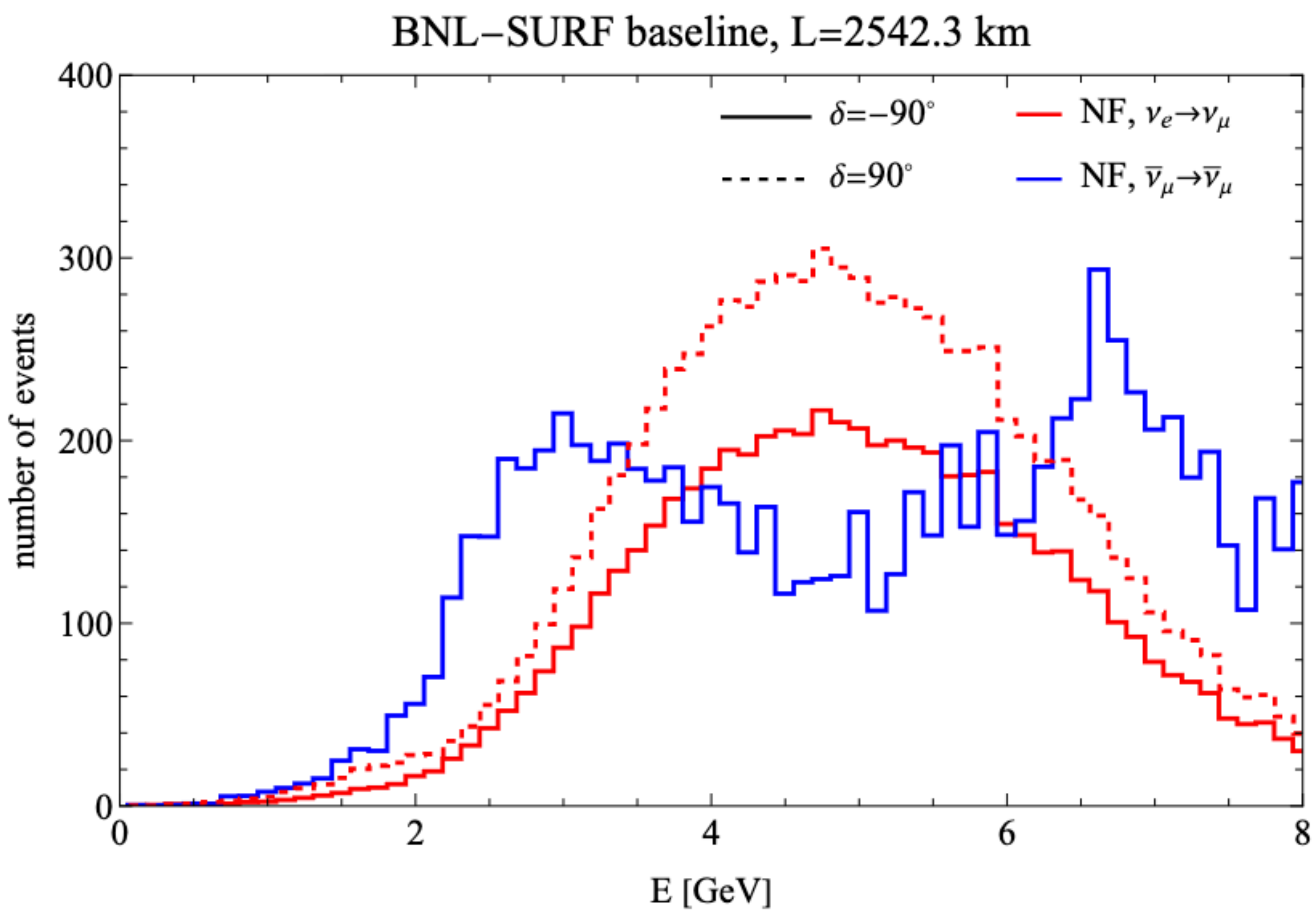
Tau neutrino appearance as background



Appendix: Neutrino factory
Results

[Denton, JG, 2407.02572]

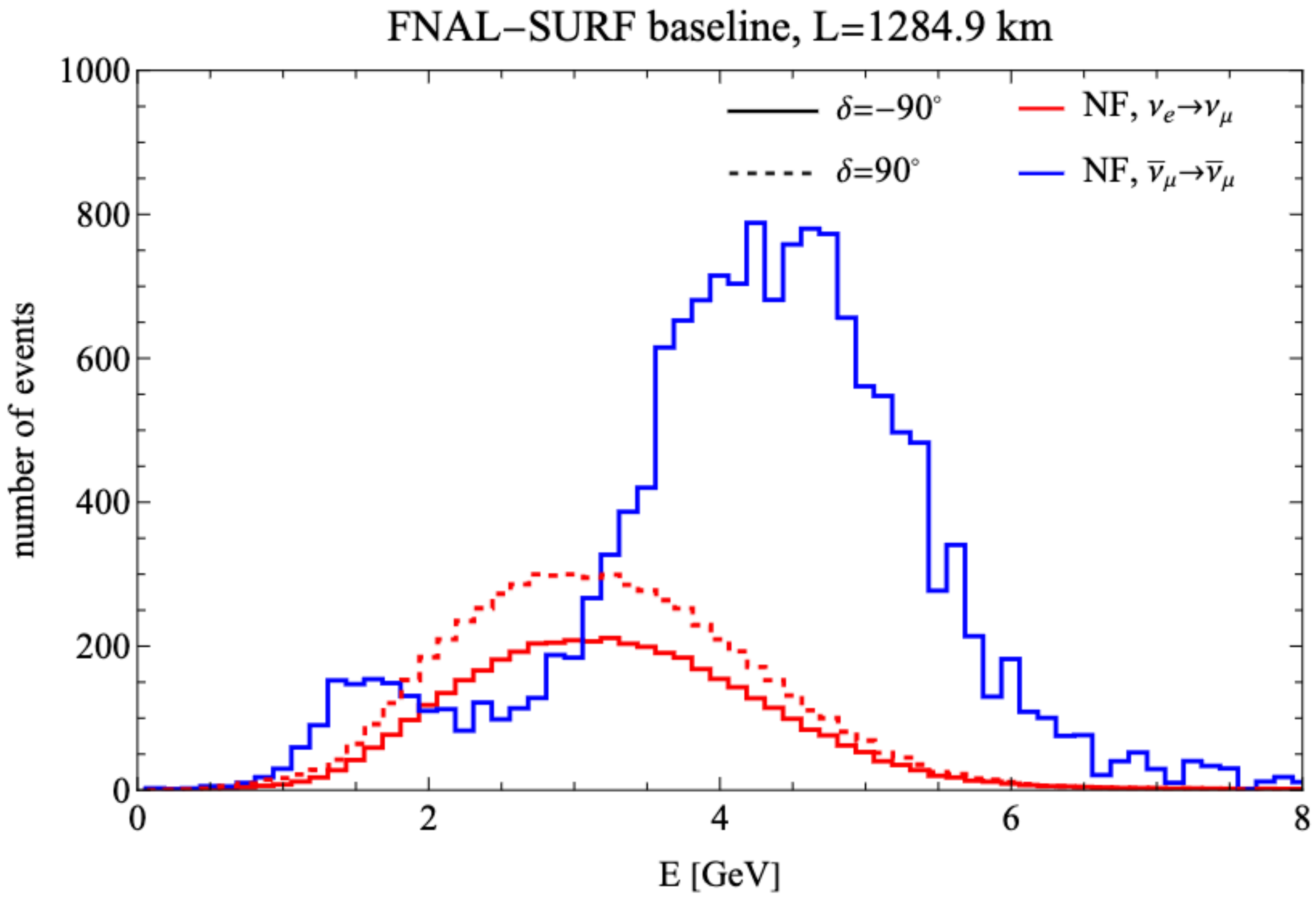




Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]



Distinguish ν_μ appearance from $\bar{\nu}_\mu$ disappearance using charge identification (CID)

Appendix: Neutrino factory
Results

CP phase predicted in flavor models

→ Measurement of δ can distinguish different flavor models

Example:

Neutrino mixing matrix predicted by discrete flavor symmetries

Charged lepton mixing matrix non-diagonal

$$U_{PMNS} = U_e^\dagger U_\nu$$

$$\rightarrow \theta_i(\theta_{12}^\nu, \theta_{23}^\nu, \theta_{12}^e)$$

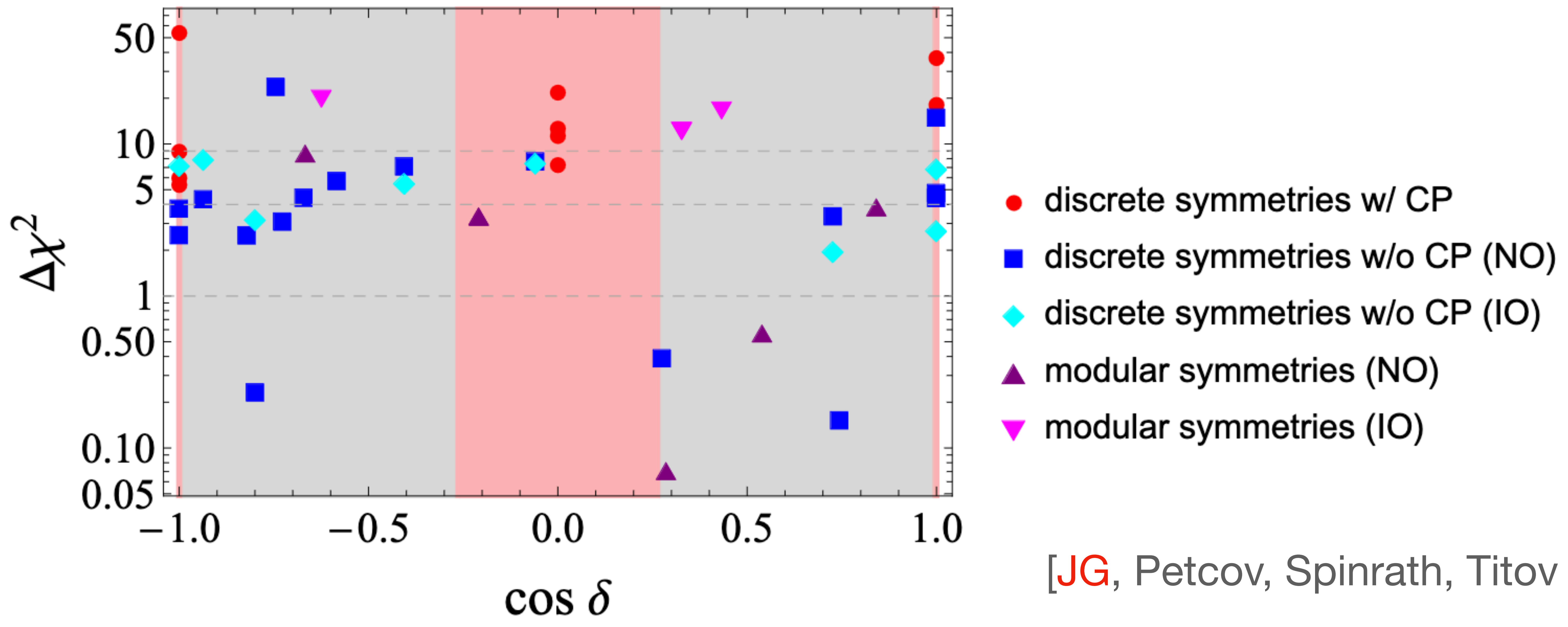
Appendix: Neutrino factory

Results: three flavor

CP phase predicted in flavor models

→ Measurement of δ can distinguish different flavor models

⇒ provides target precision for upcoming experiments



[JG, Petcov, Spinrath, Titov 2203.06219]

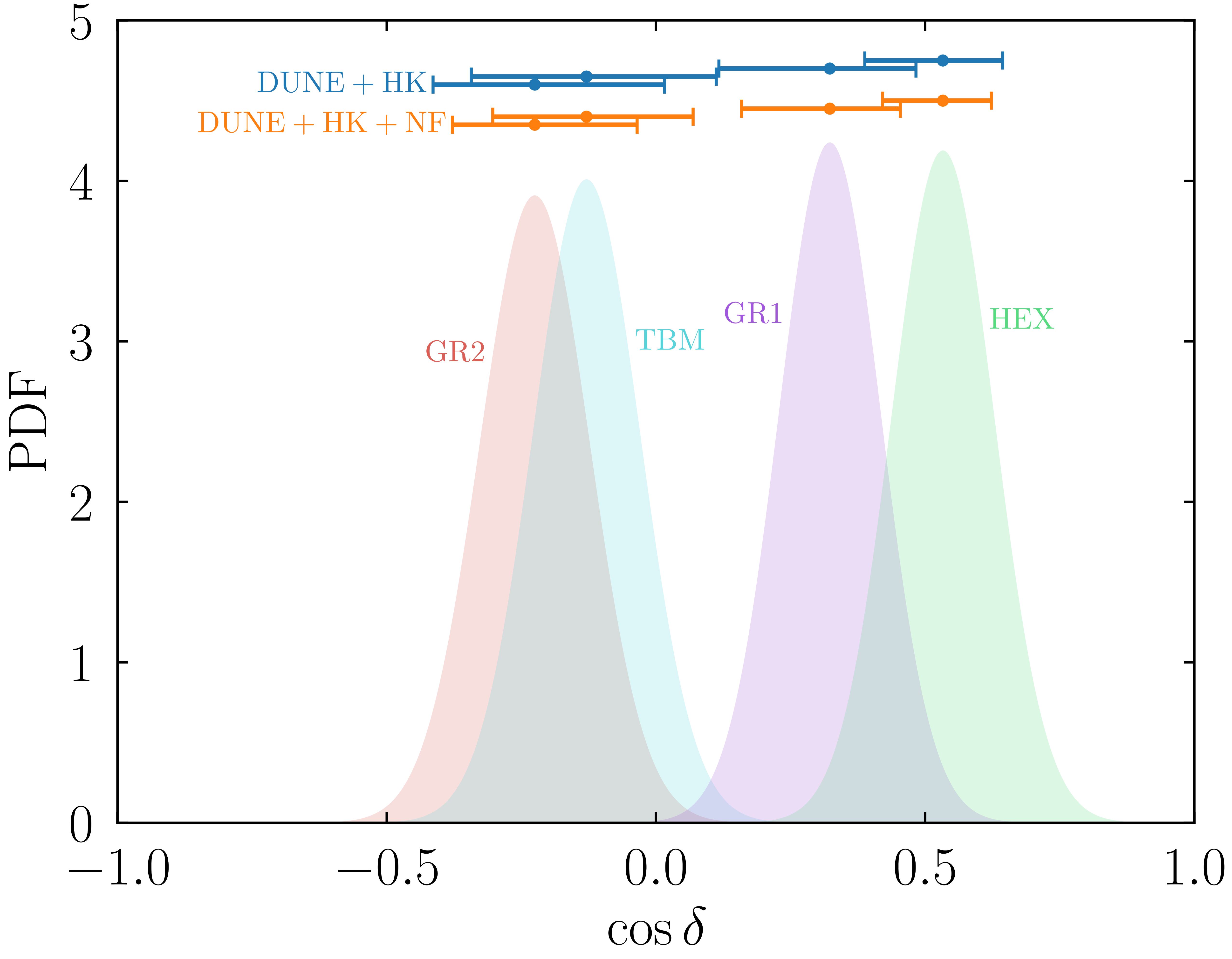
Other parameters, neutrino mass and $0\nu\beta\beta$ can also probe flavor models

[Denton, JG 2308.09737]

Appendix: Neutrino factory

Results: three-flavor

[Denton, JG, 2407.02572]

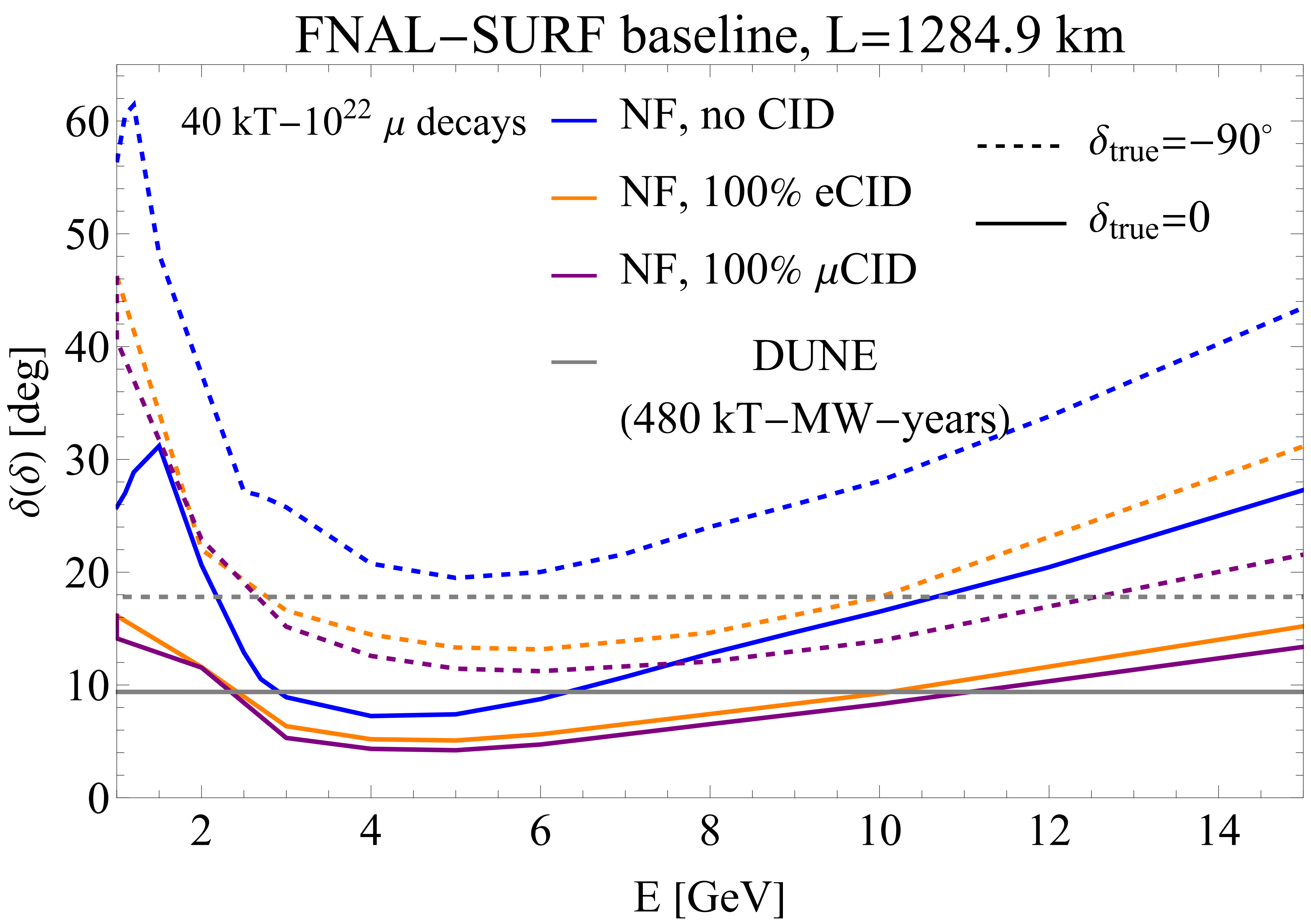


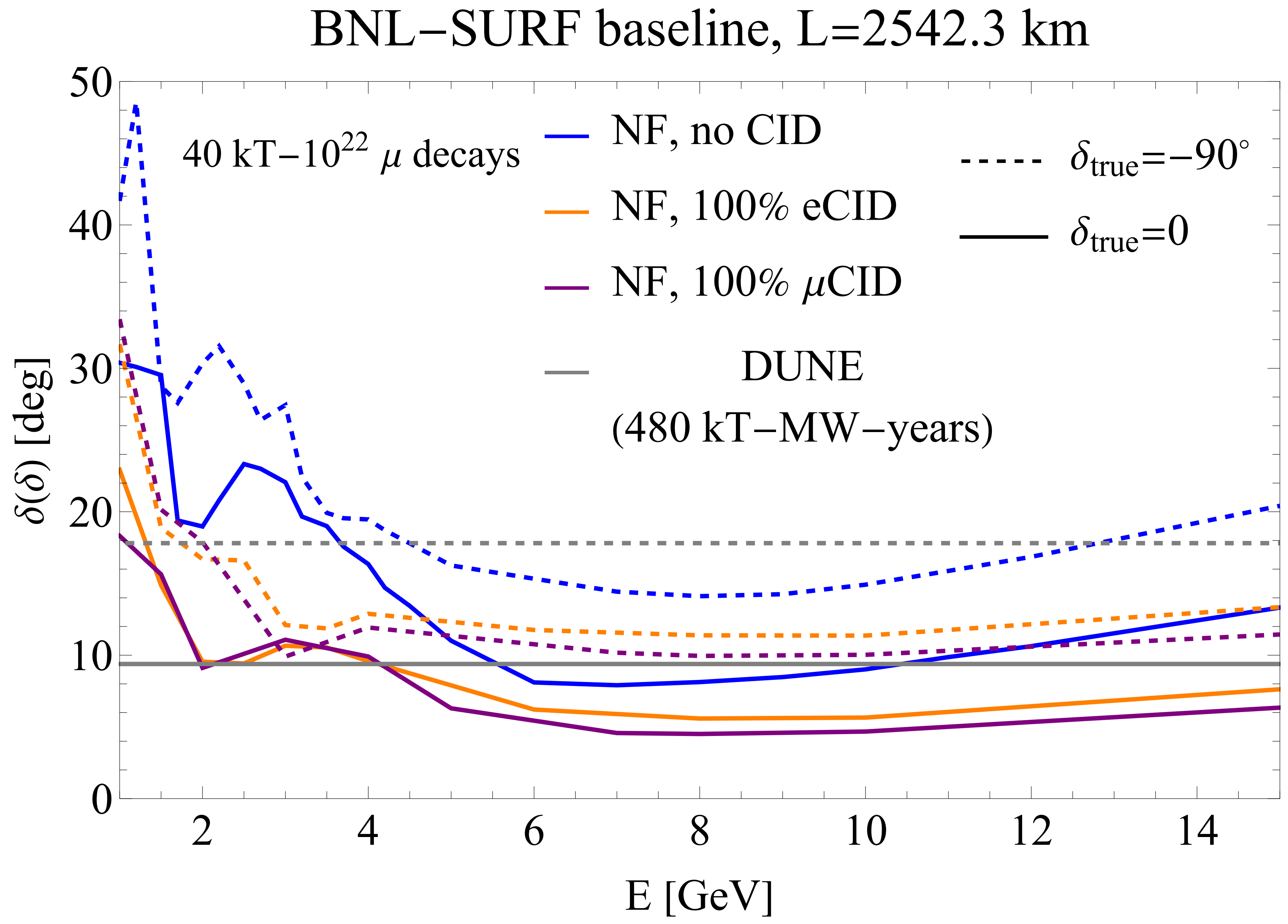
→ improved distinction power of models when including NF

Assuming a total of 40 kT – 10^{22} μ decays

Appendix: Neutrino factory

[Denton, JG, 2407.02572]





Optimal muon energy to maximize precision of δ

$E_\mu \approx$ 5 GeV (FNAL-SURF), $E_\mu \approx$ 8 GeV (BNL-SURF)

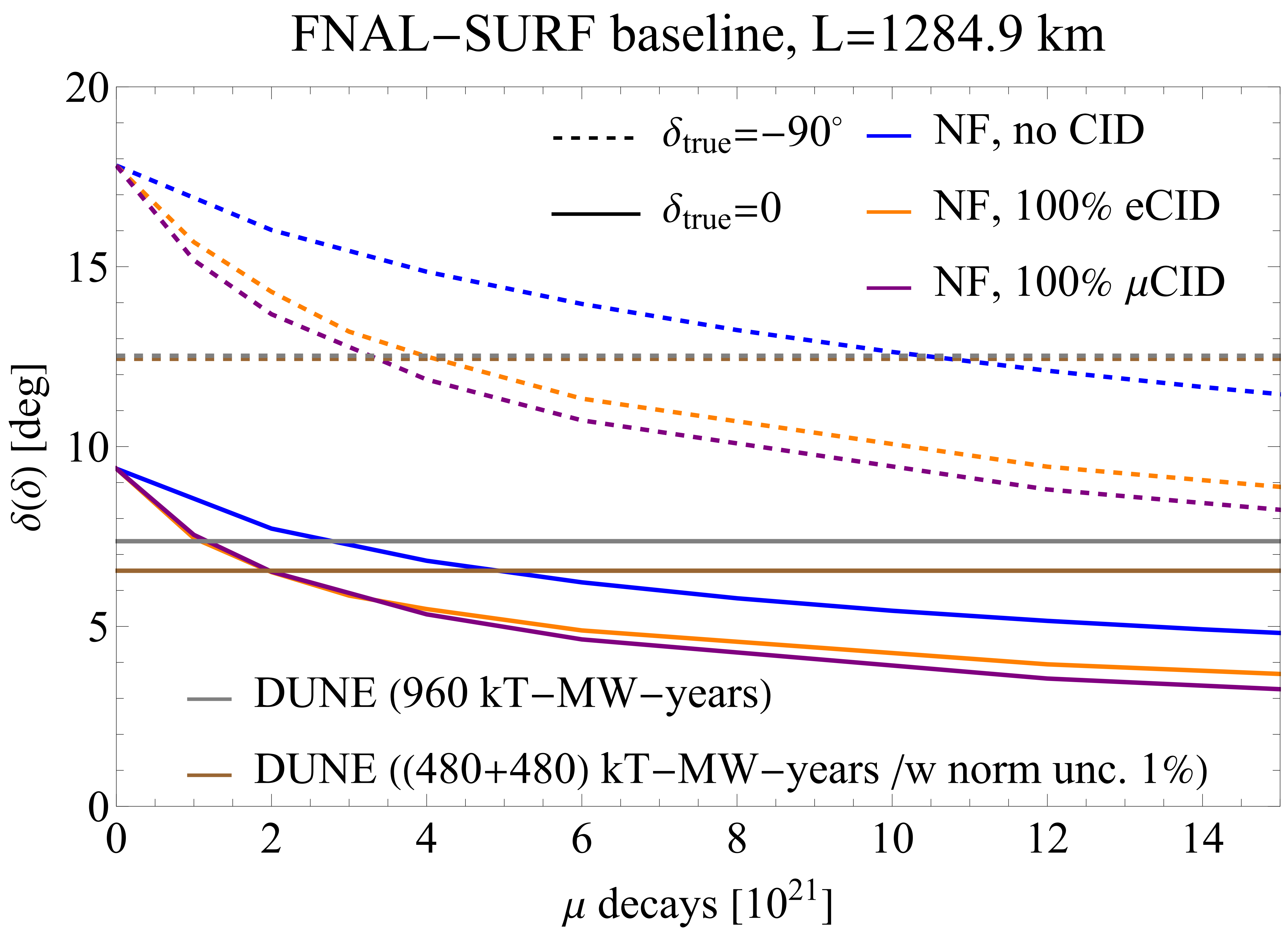
Running time neutrino: antineutrino 1:1

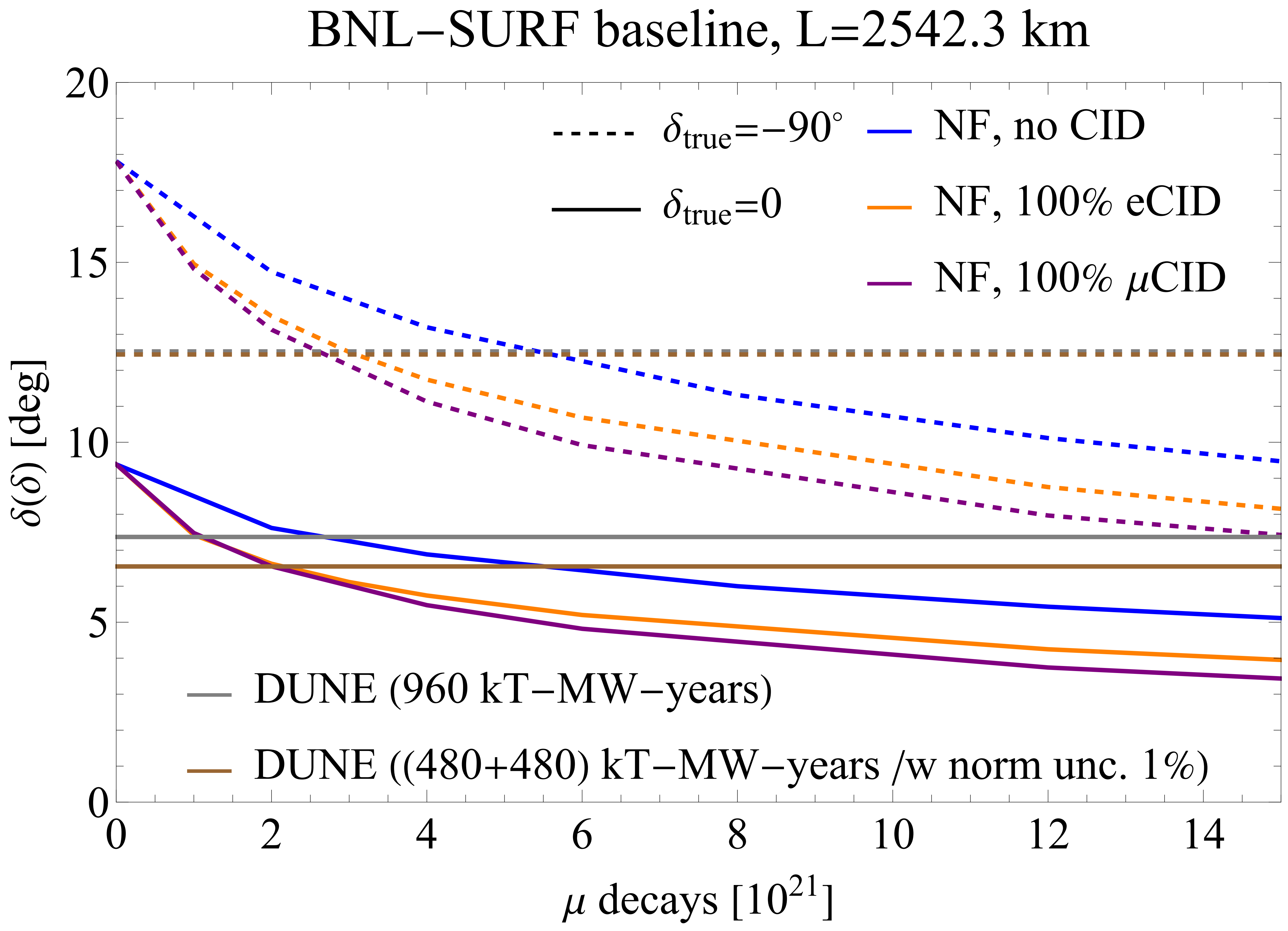
Depending on physics case these values might slightly change

Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]





~10^{22} μ decays required to improve precision of δ

(depending on true value and setup)

Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]

- DUNE: 480 kT-MW-year
  5 years of each neutrino running and anti-neutrino with 1.2 MW proton beam and with a total fiducial volume of 40 kT of LAr
- HK: 190 kT water detector, 1.3 MW beam running for 10 years with $\nu : \bar{\nu} = 1 : 3$

Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]

Results for a total of
40 kT – 10^{22} μ decays

$\delta = (-90°,\ 0)$	no CID	100% eCID	100% μCID
HK	$(20.8°, 5.6°)$	–	–
DUNE	$(17.8°, 9.4°)$	–	–
DUNE+HK	$(13.9°, 4.8°)$	–	–
DUNE (20 yr)+HK	$(11.0°, 4.5°)$	–	–
DUNE+HK+NF(FNAL)	$(11.2°, 3.9°)$	$(8.5°, 3.2°)$	$(9.0°, 3.3°)$
DUNE+HK+NF(BNL)	$(9.3°, 3.9°)$	$(8.0°, 3.3°)$	$(8.6°, 3.4°)$

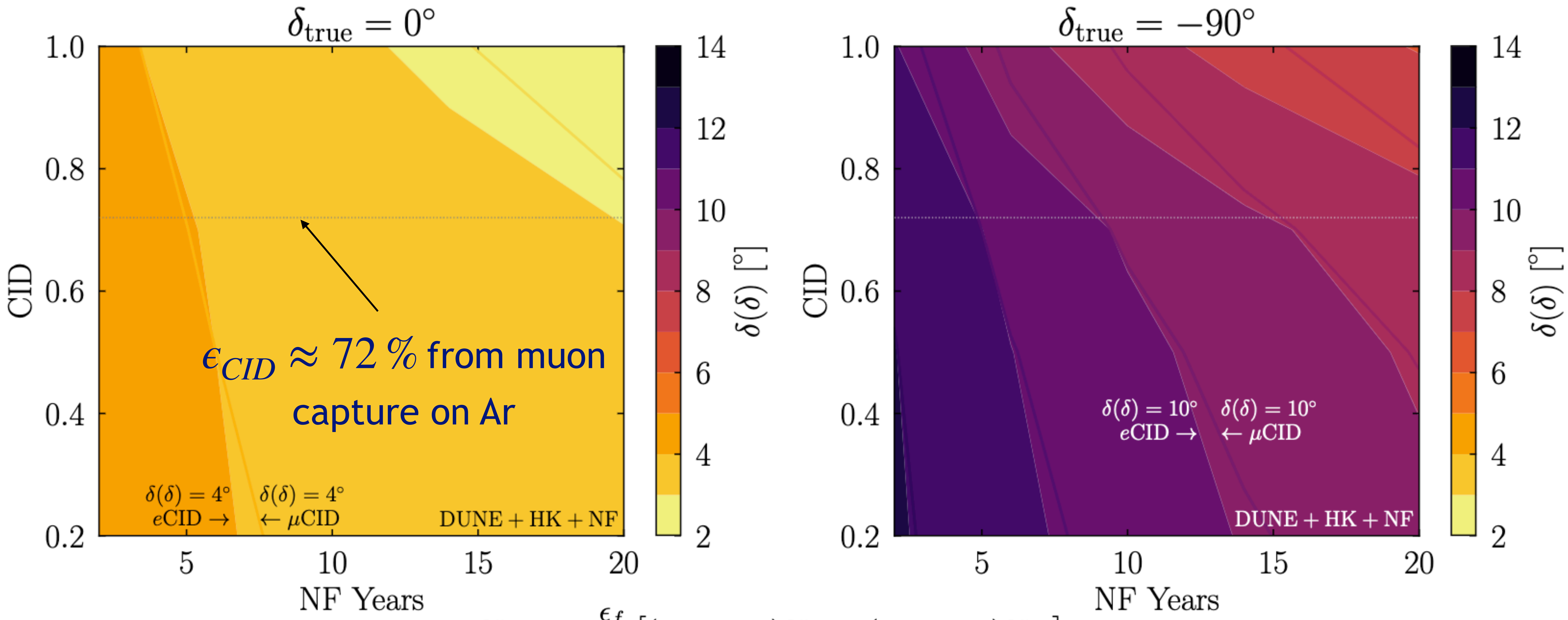
- CID increases precision on δ however not as essential as emphasized in the literature >10 years ago due to good energy resolution of LAr
- NF has only limited sensitivity to the solar parameters, just like DUNE
  $\rightarrow$ solar priors important

[JG, Denton 2302.08513]

Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]



$$N_{\nu_{\rm f,obs}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\nu_f} + (1-\epsilon_{CID})N_{\bar{\nu}_f}\right]$$

$$N_{\bar{\nu}_{\rm f,obs}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\bar{\nu}_f} + (1-\epsilon_{CID})N_{\nu_f}\right]$$

Results for a total of 40 kT – 10^{22} μ decays

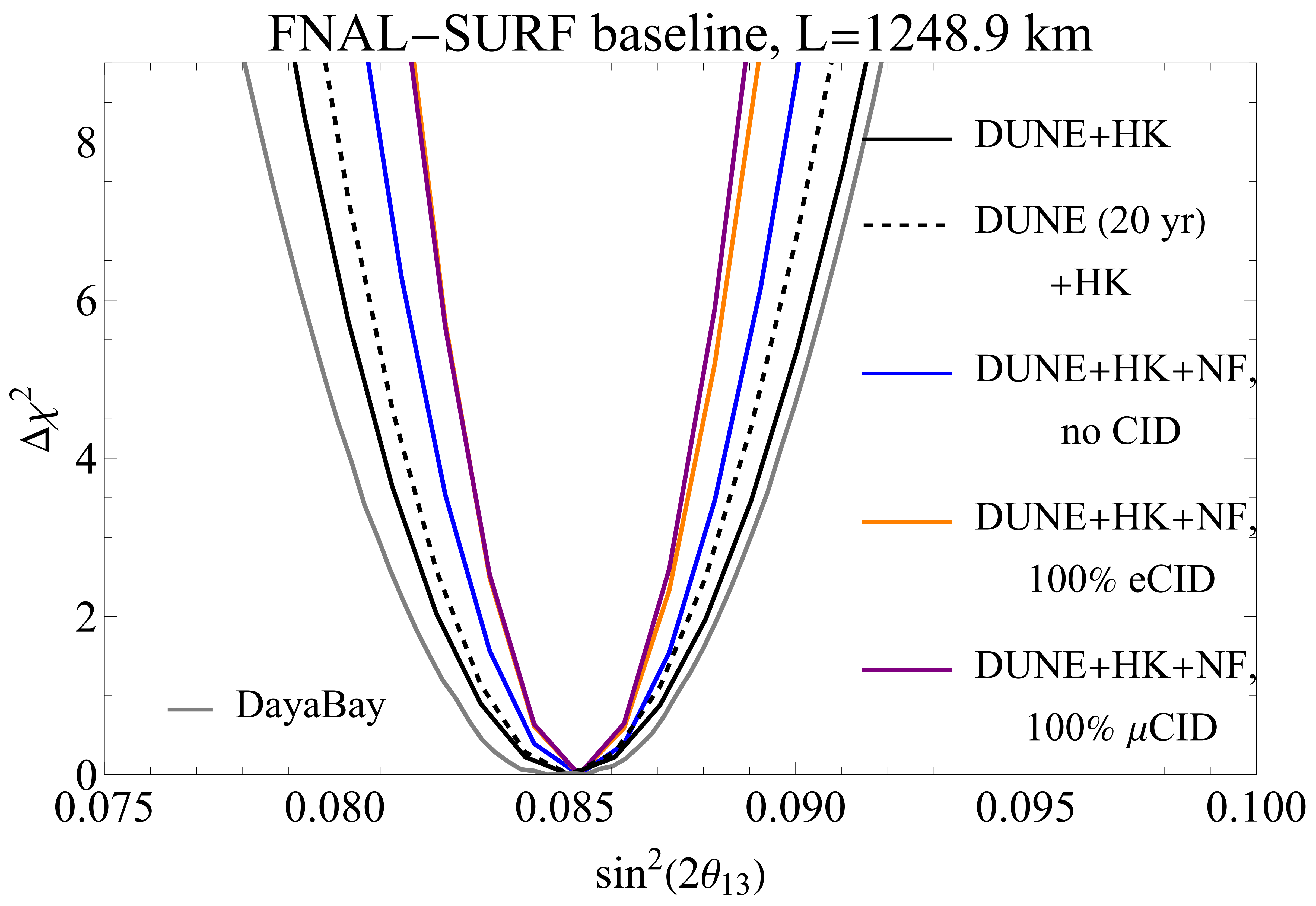
Appendix: Neutrino factory

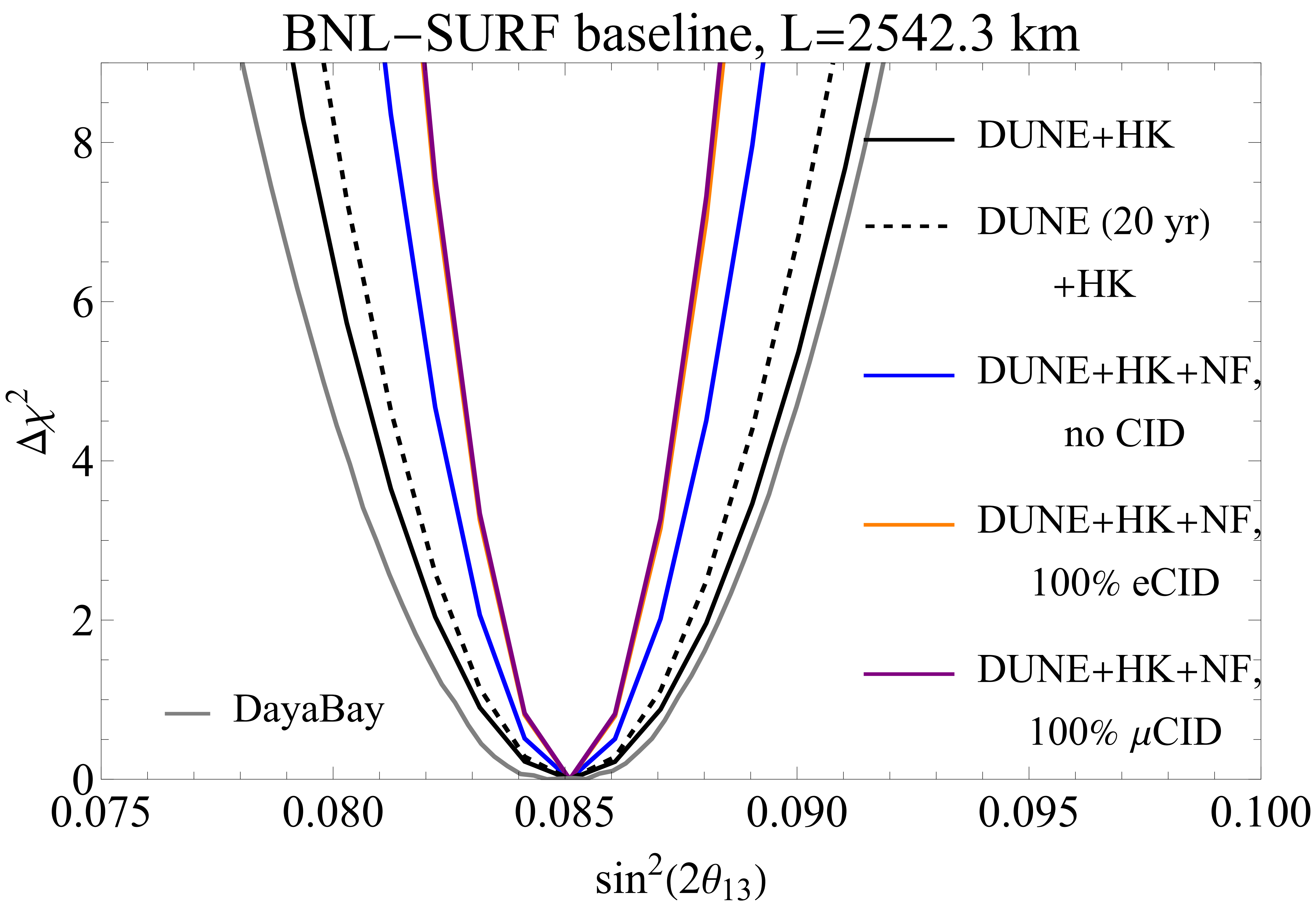
Results

Results for a total of

40 kT $-$ 10^{22} μ decays

[Denton, JG, 2407.02572]





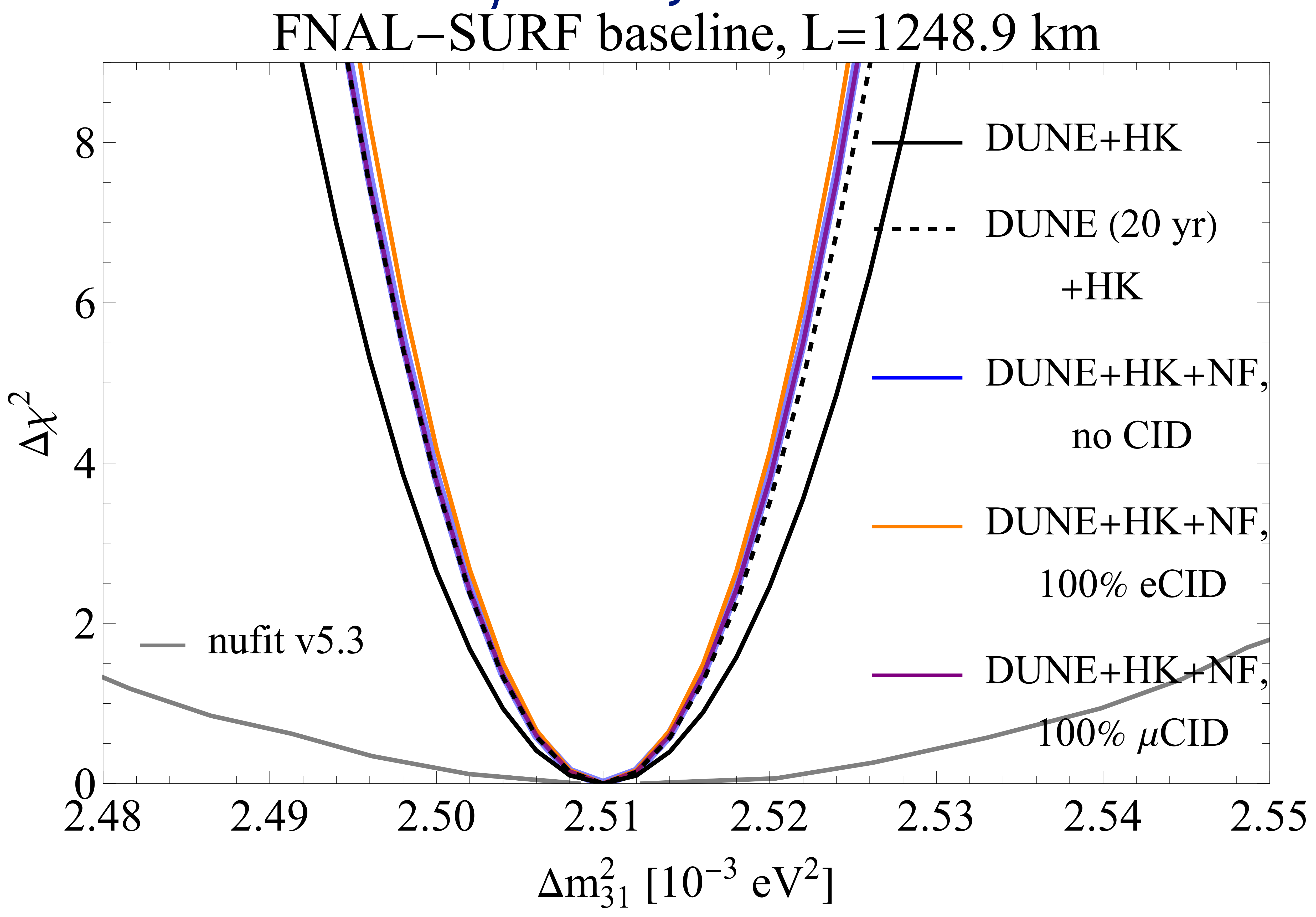
Appendix: Neutrino factory

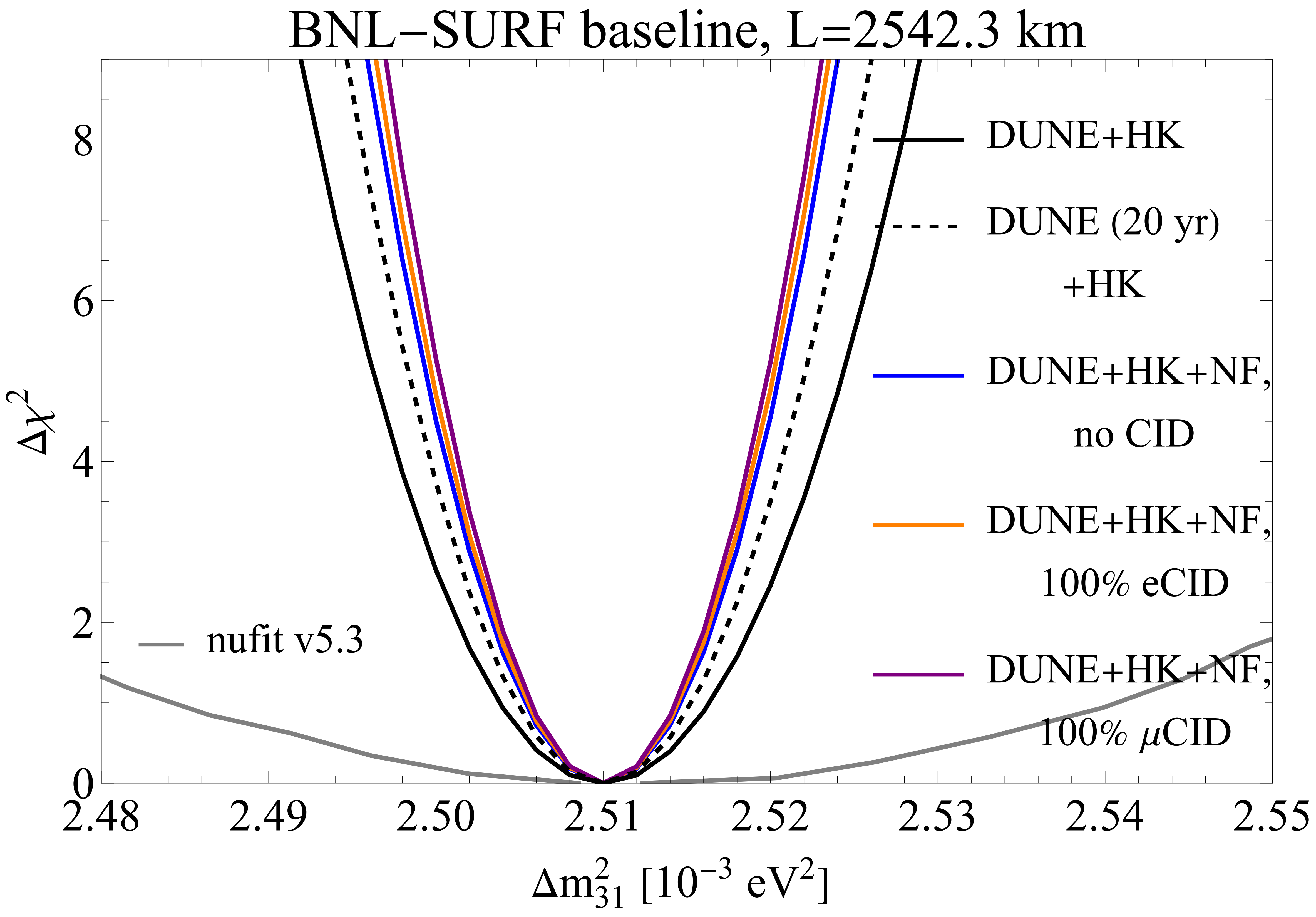
Results

Results for a total of

40 kT – 10^{22} μ decays

[Denton, JG, 2407.02572]





Appendix: Neutrino factory

Results

[Denton, JG, 2407.02572]

Results for a total of

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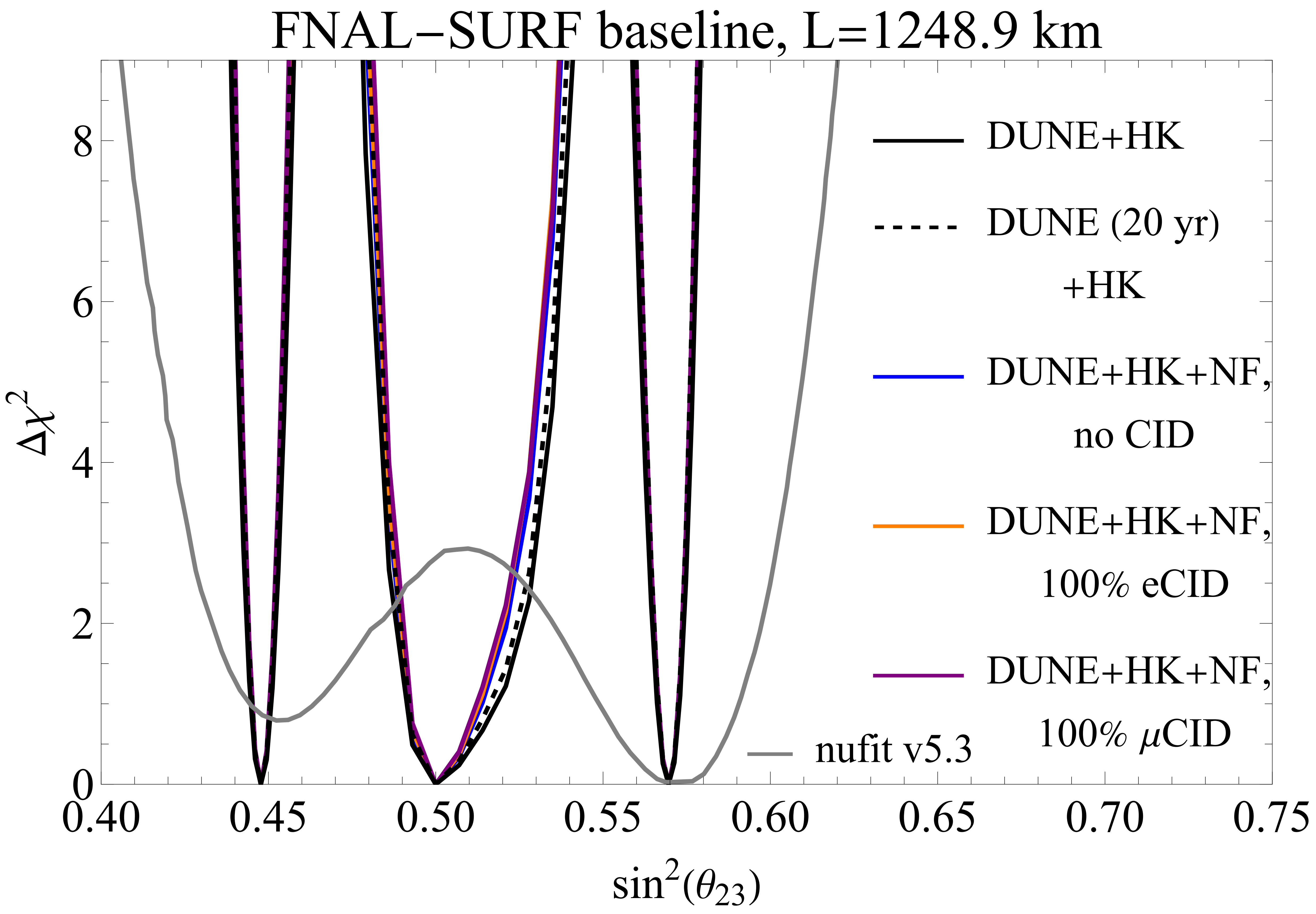
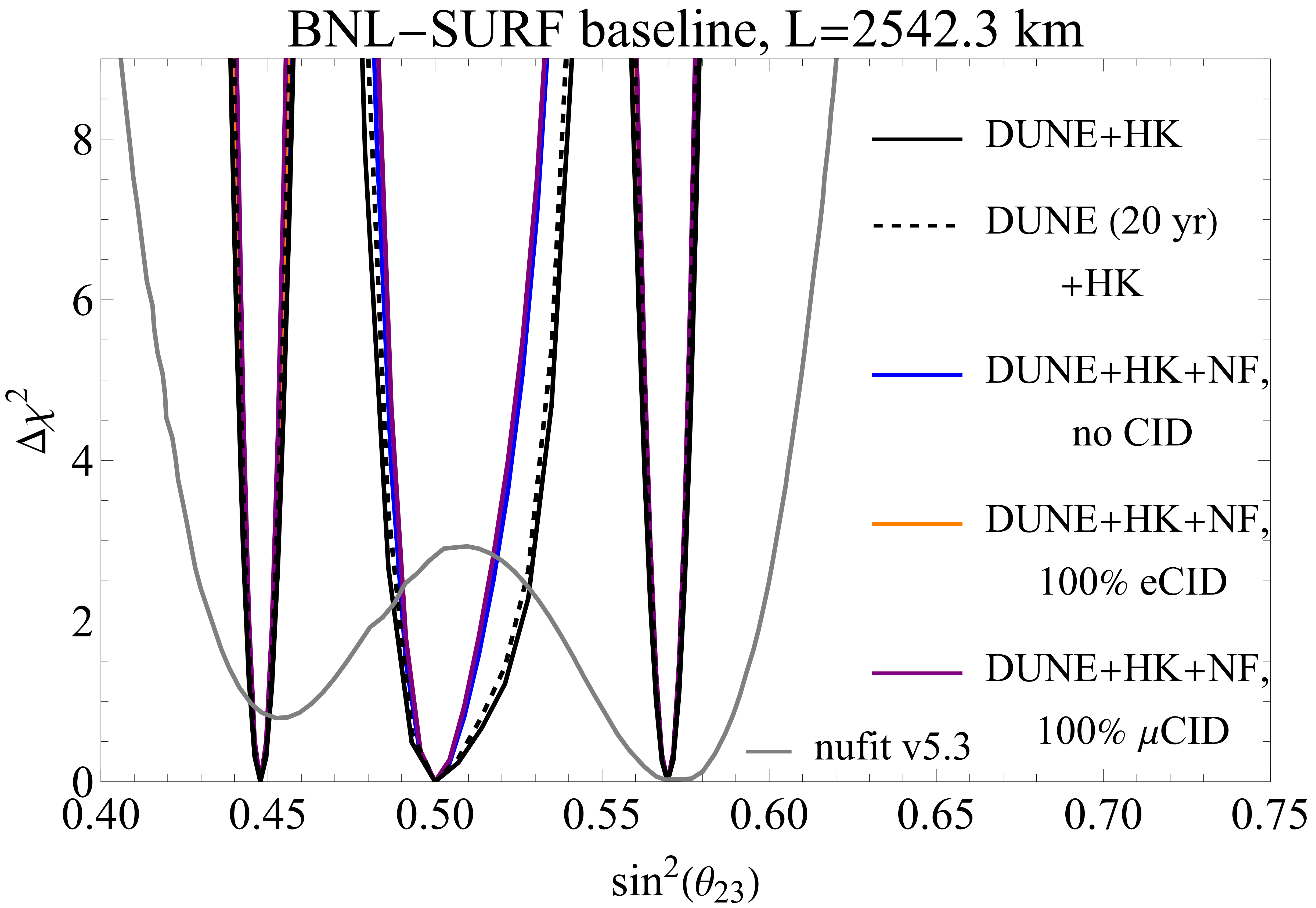




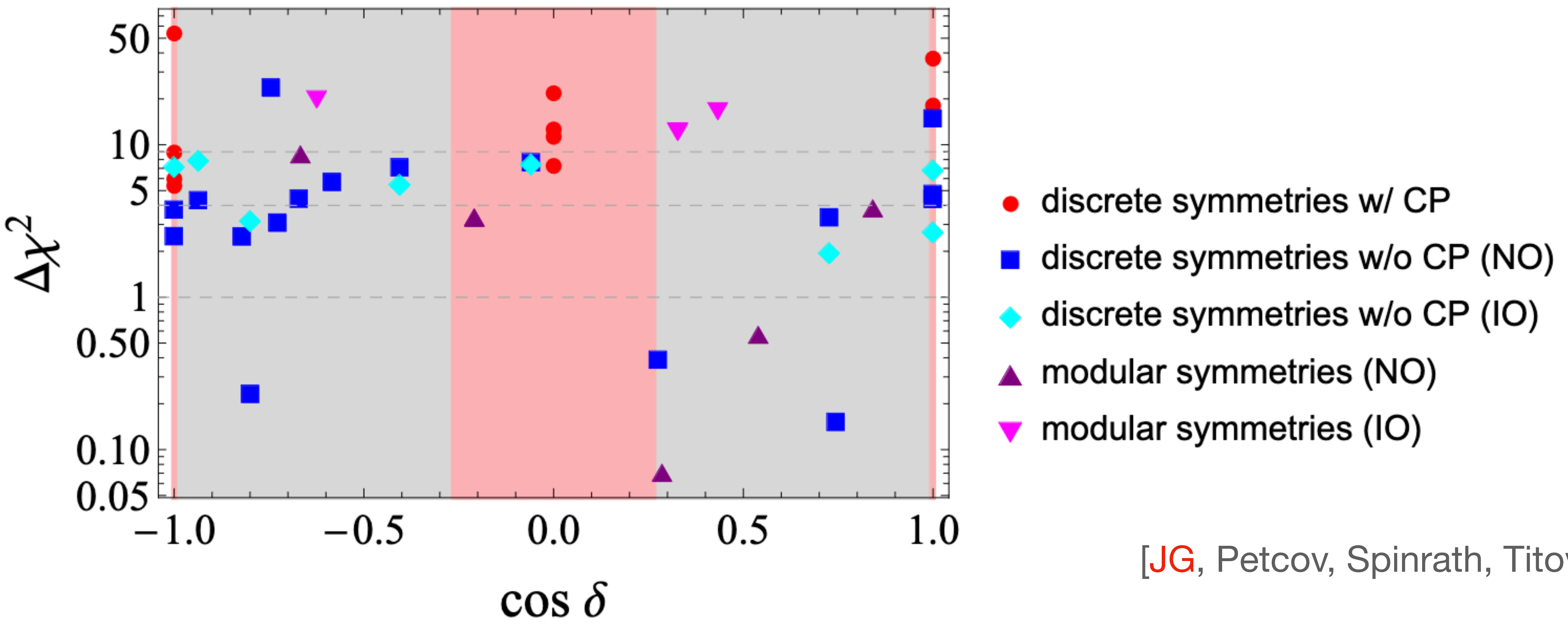
Appendix: Flavor models

- Distinguish different flavor models with precision oscillation measurements

Most predictive flavor models predict relations between mixing parameter like

$$\theta_{12}^{\text{PMNS}} - \theta_{12}^{\nu} \approx \theta_{13}^{\text{PMNS}} \cos\delta$$

Can be used to distinguish different mixing pattern



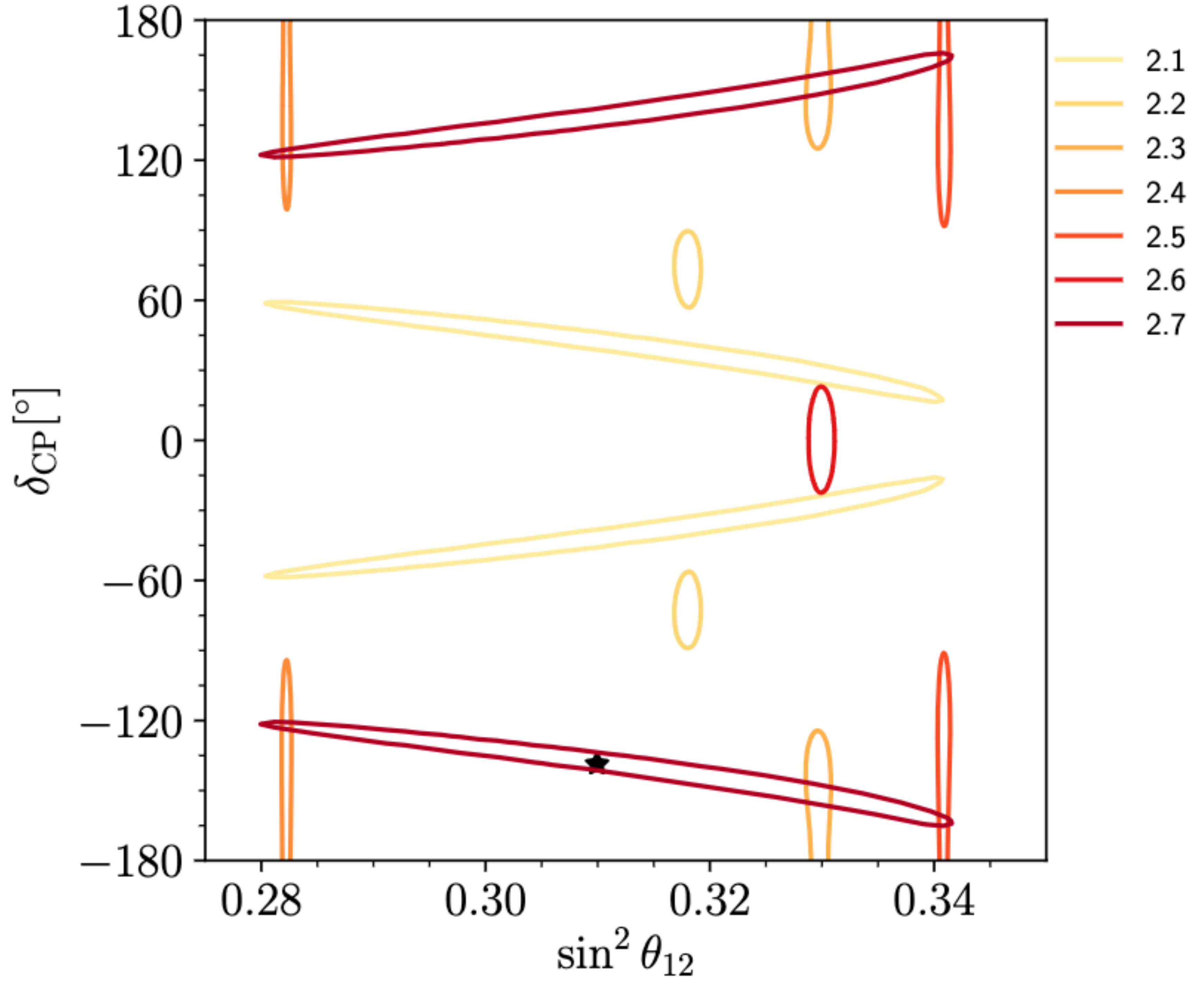
[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: Flavor models

- Distinguish different flavor models with precision oscillation measurements

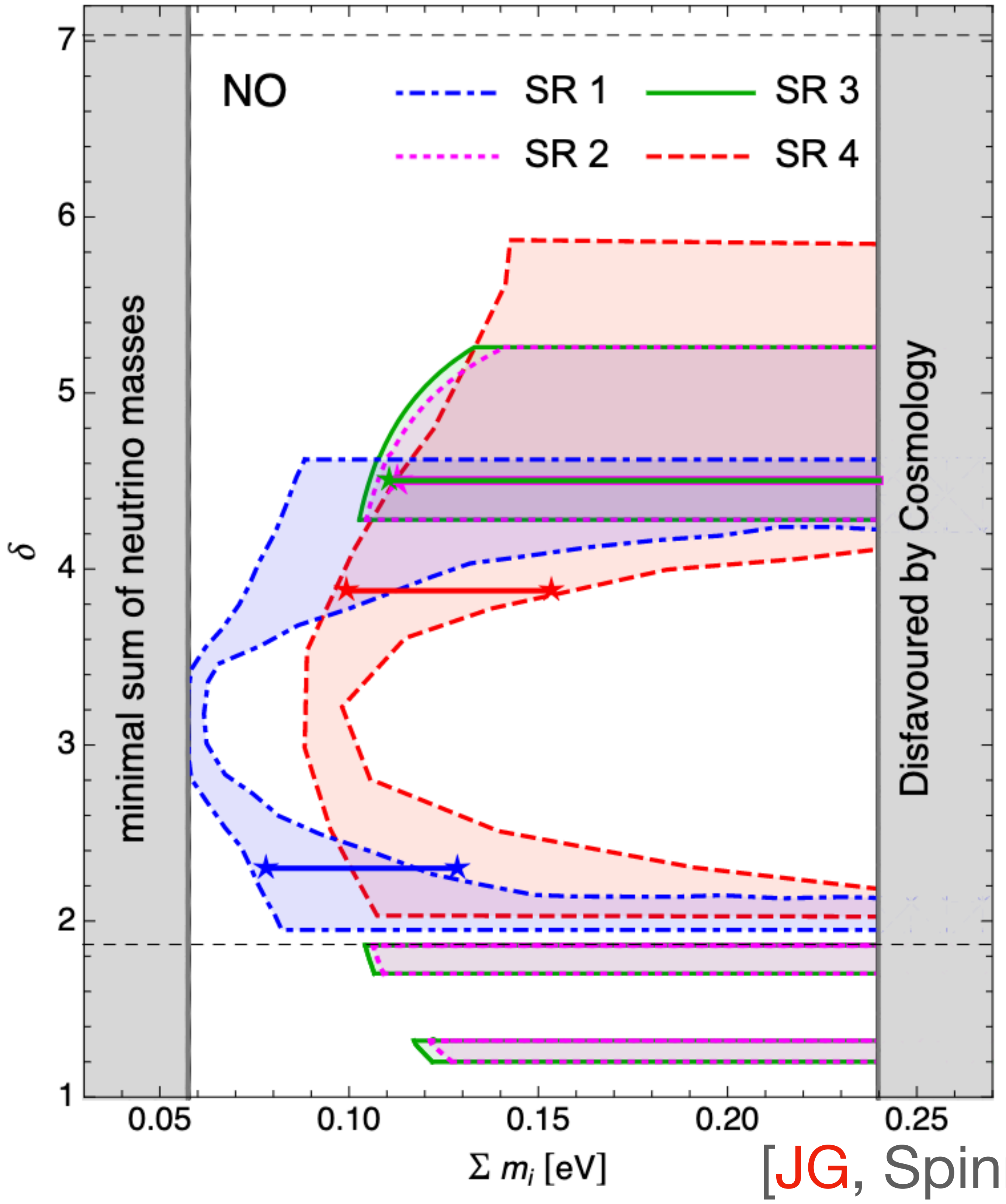
Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models at >5σ!



[Blennow, Ghosh, Ohlsson, Titov 2004.00017]

Correlations can be probed!

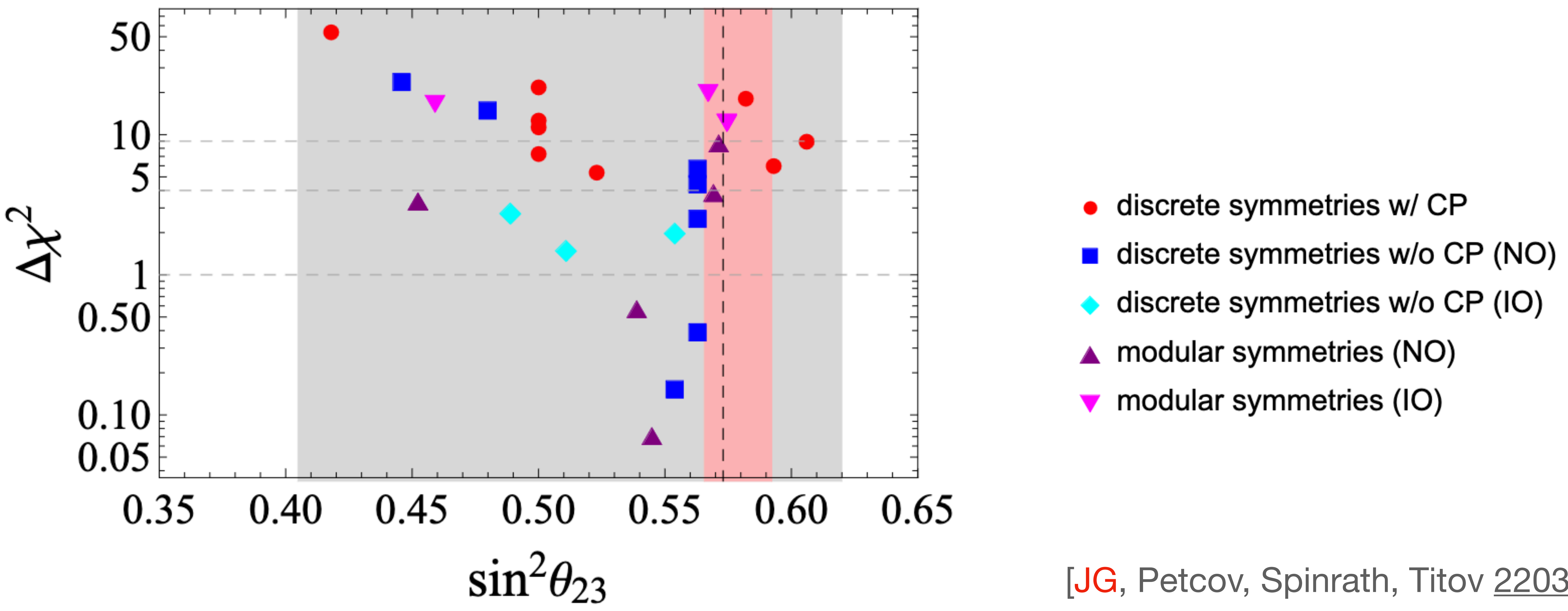


[JG, Spinrath 2012.04131]

Appendix: Flavor models

Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models

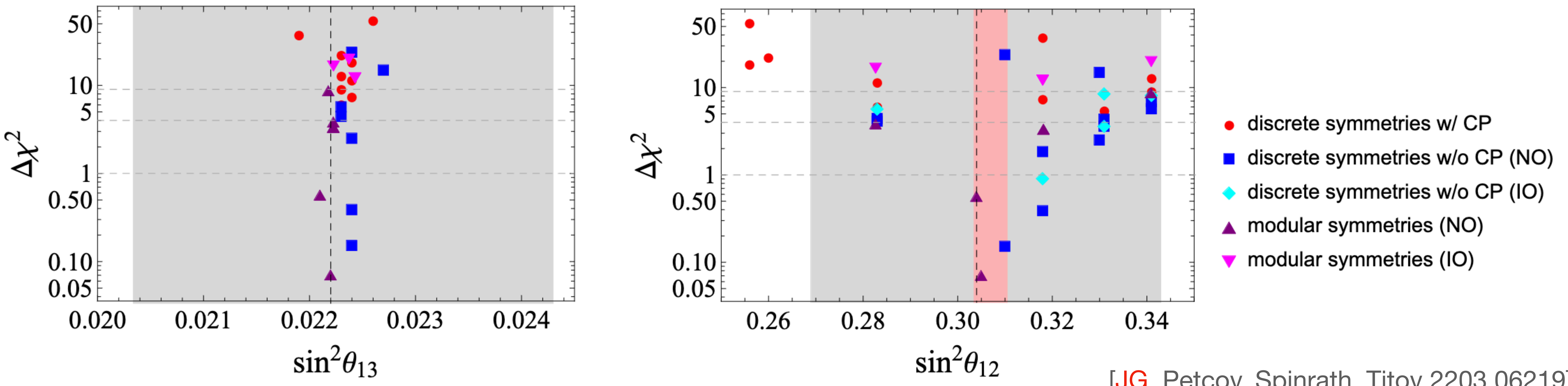


[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: Flavor models

Sum rules can be used to distinguish different mixing pattern

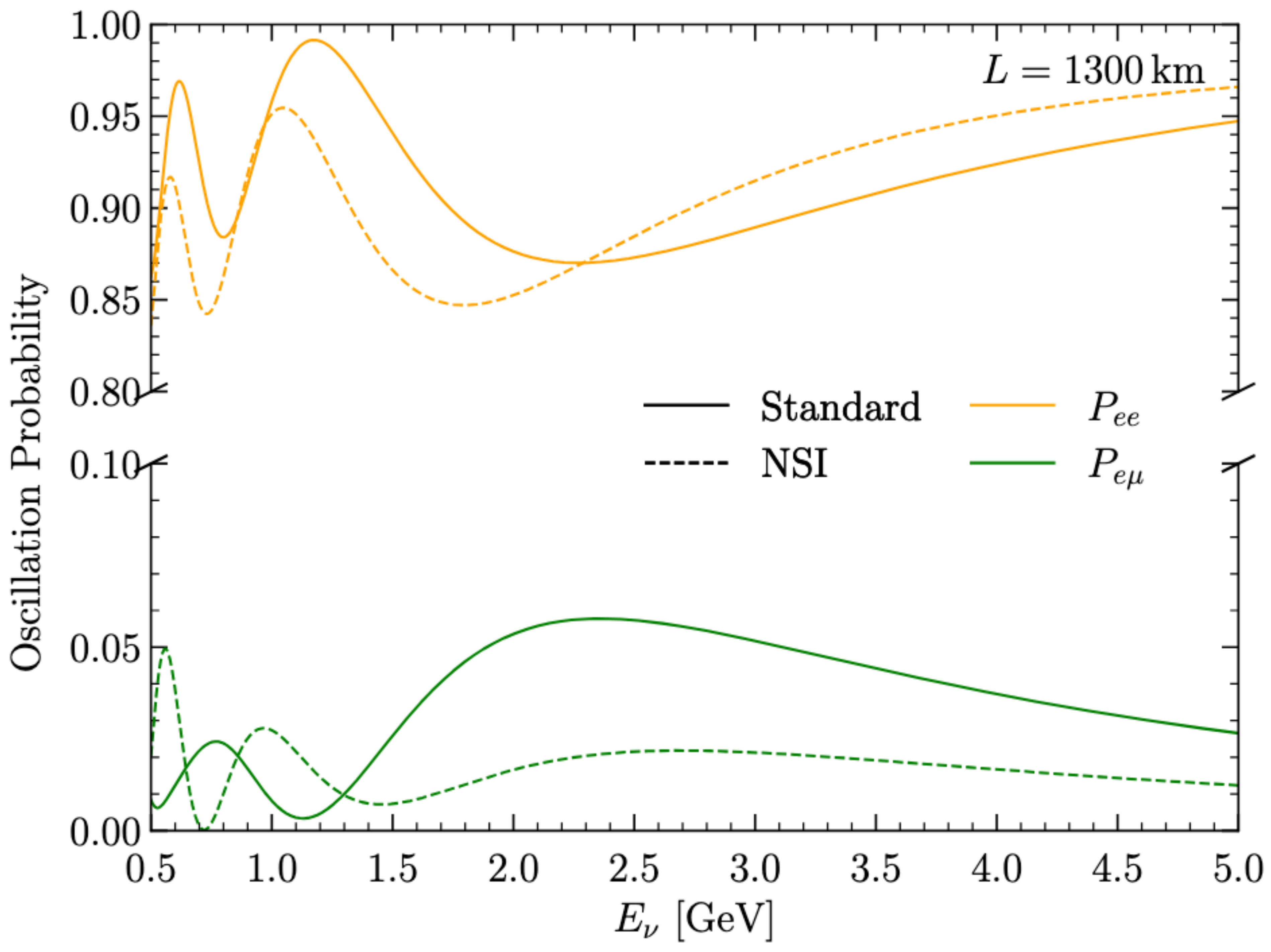
Future experiments can disentangle different models



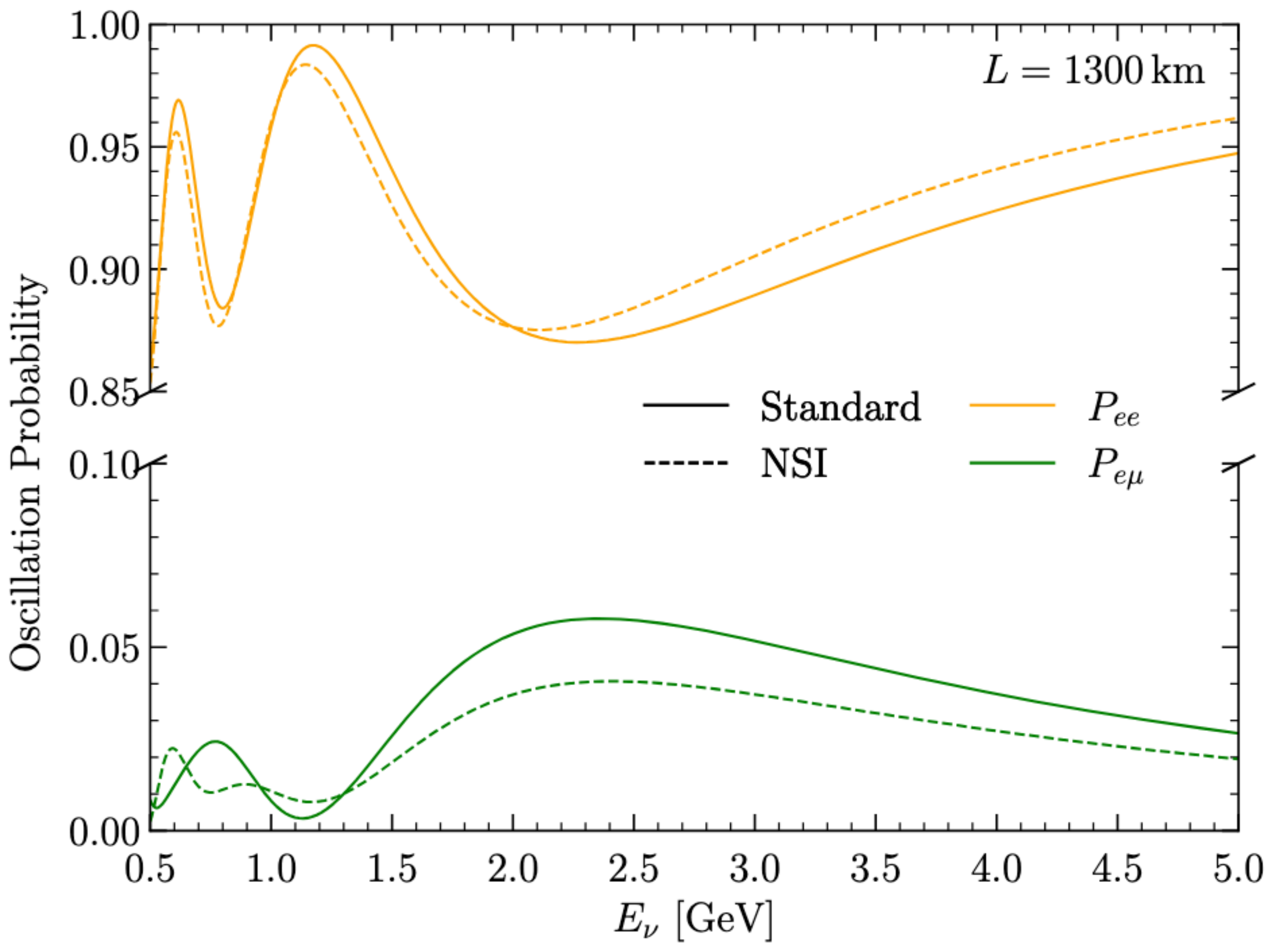
[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: NF BSM

[Denton, JG, Kong 2502.14027]



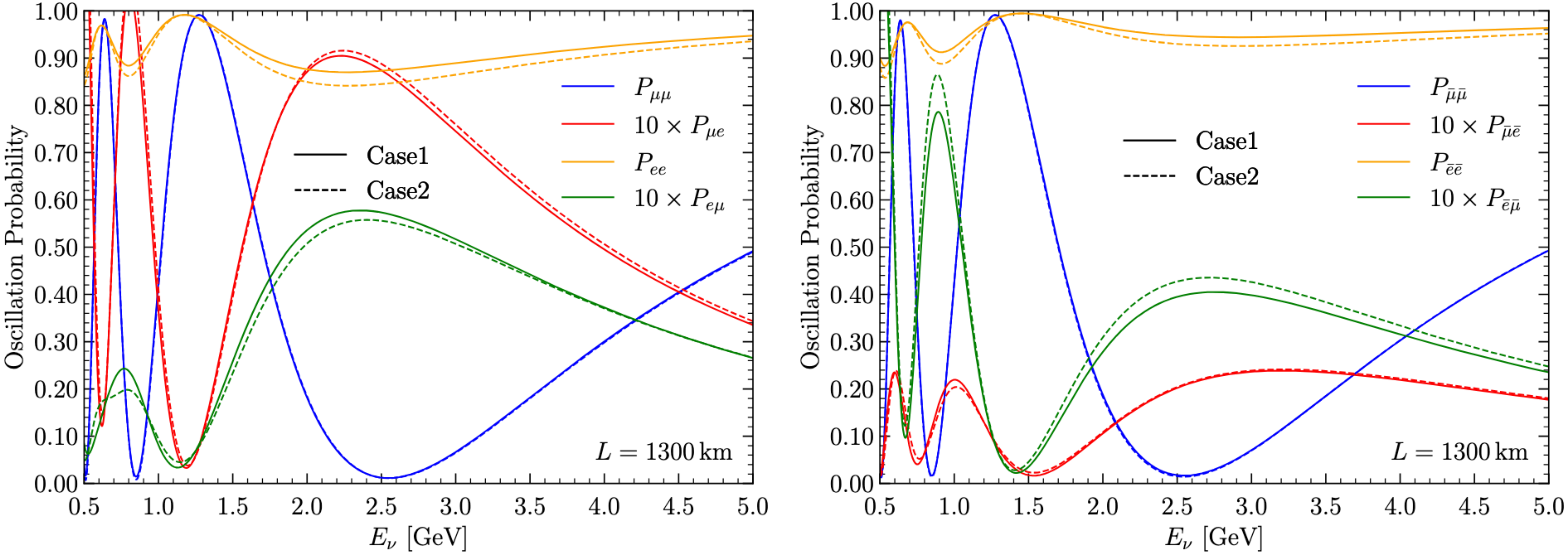
$$\epsilon_{ee} - \epsilon_{\mu\mu} = 1.2, |\epsilon_{e\tau}| = 0.3, \phi_{e\tau} = -152^\circ$$
$$\theta_{23} = 42^\circ, \delta_{CP} = -53^\circ$$



$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} = -0.55, |\epsilon_{e\tau}| = 0.125, \phi_{e\tau} = -133^\circ$$
$$\theta_{23} = 45^\circ, \delta_{CP} = -74^\circ$$

Appendix: NF BSM

[Denton, JG, Kong 2502.14027]



Case 1: $\theta_{13} = 8.5^\circ, \theta_{23} = 44.7^\circ, \delta_{CP} = -90^\circ$
Case 2: $\theta_{13} = 9.5^\circ, \theta_{23} = 43^\circ, \delta_{CP} = -83^\circ$

Case1: $\bar{\theta}_{23} = 44.7^\circ, \bar{\theta}_{13} = 8.5^\circ, \bar{\delta}_{CP} = -90^\circ$
Case 2: $\bar{\theta}_{23} = 42^\circ, \bar{\theta}_{13} = 9.9^\circ, \bar{\delta}_{CP} = -94^\circ$