A modern look at the oscillation physics case for a neutrino factory

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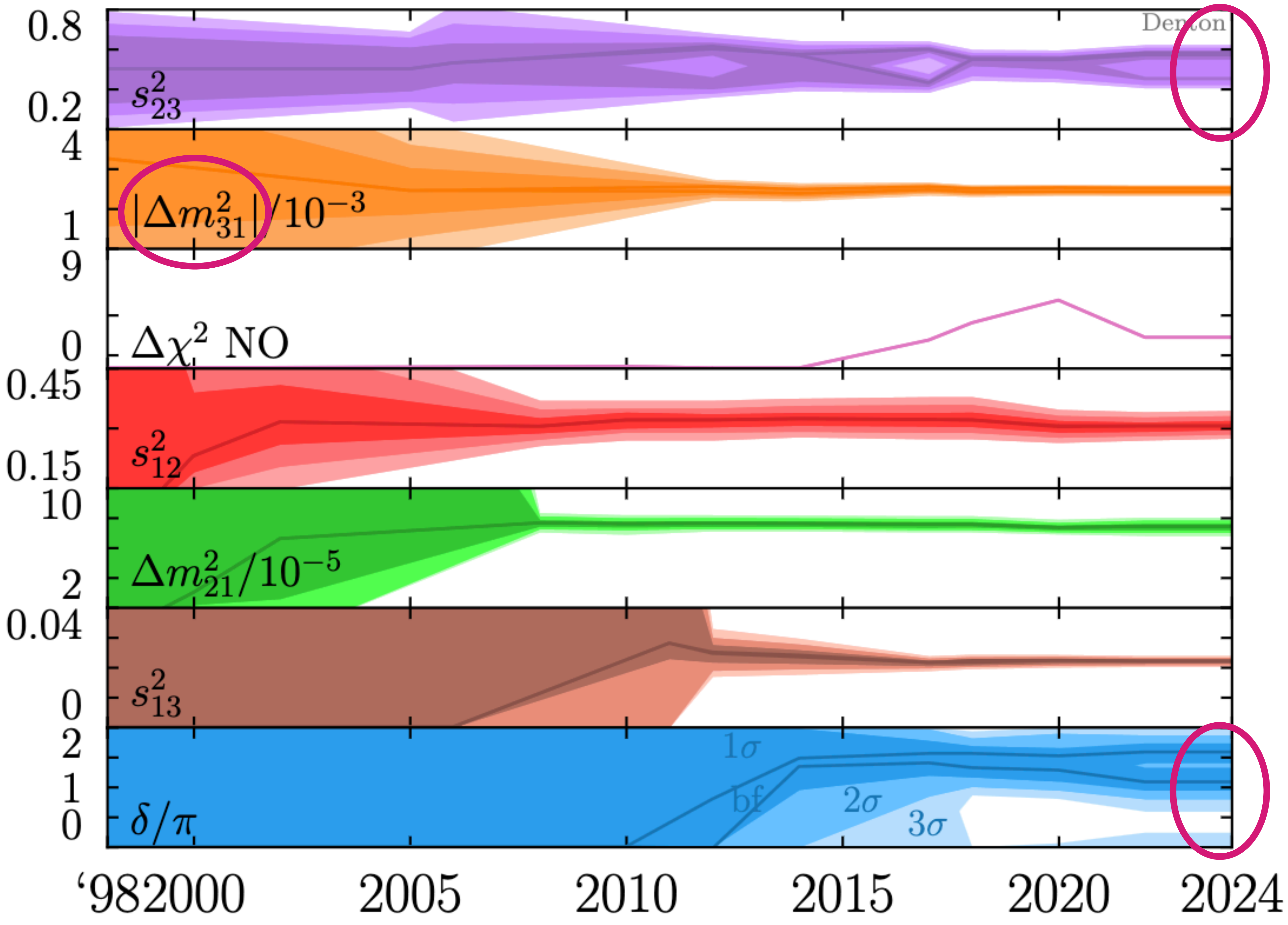
Neutrino oscillations

Where do we stand?



[update from Denton et al 2212.00809]

Neutrino oscillations

Where are we going?

Long baseline (300 km, 1300 km) accelerator neutrino experiments:

Hyper-Kamiokande, DUNE

$\rightarrow$ CP phase, octant of θ_{23}, Δm^2_{31}, mass ordering

Medium baseline (~50 km) reactor neutrino experiment:

JUNO

$\rightarrow \theta_{12}, \Delta m^2_{21},$ mass ordering

Atmospheric neutrino experiments:

HK, IceCube-Gen2, KM3NeT-ORCA

$\rightarrow \theta_{23}, \Delta m^2_{31}$, mass ordering

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?

Neutrino factory

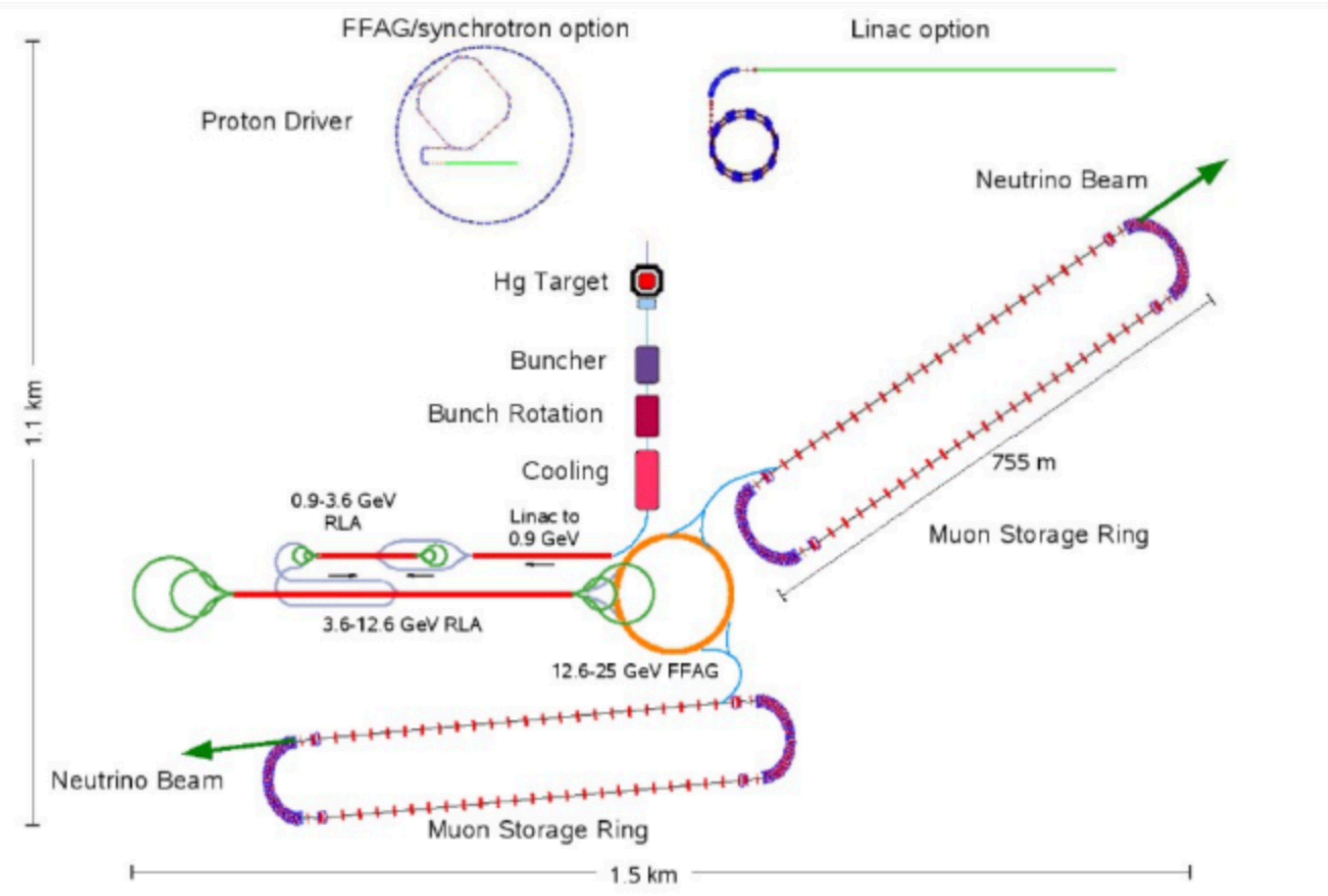
With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal

[P5 2407.19176]

Recent P5 report mentions muon collider as possible future collider

Neutrino factory could be a possible first step towards this goal

Neutrino factory



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

Neutrino factory

Has been considered in early 2000's to measure CPV for $\theta_{13} < 1°$

[De Rujula, Gavela, Hernandez 9811390]

However we now know that $\theta_{13} \approx 8.5°$

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

[2407.02572]

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*

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

Neutrino factory

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*
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[2407.02572]

Goal of NF is not discovery of CPV but

- precise measurements of mixing parameters and/or
- potentially resolve any discrepancies identified in previous measurements

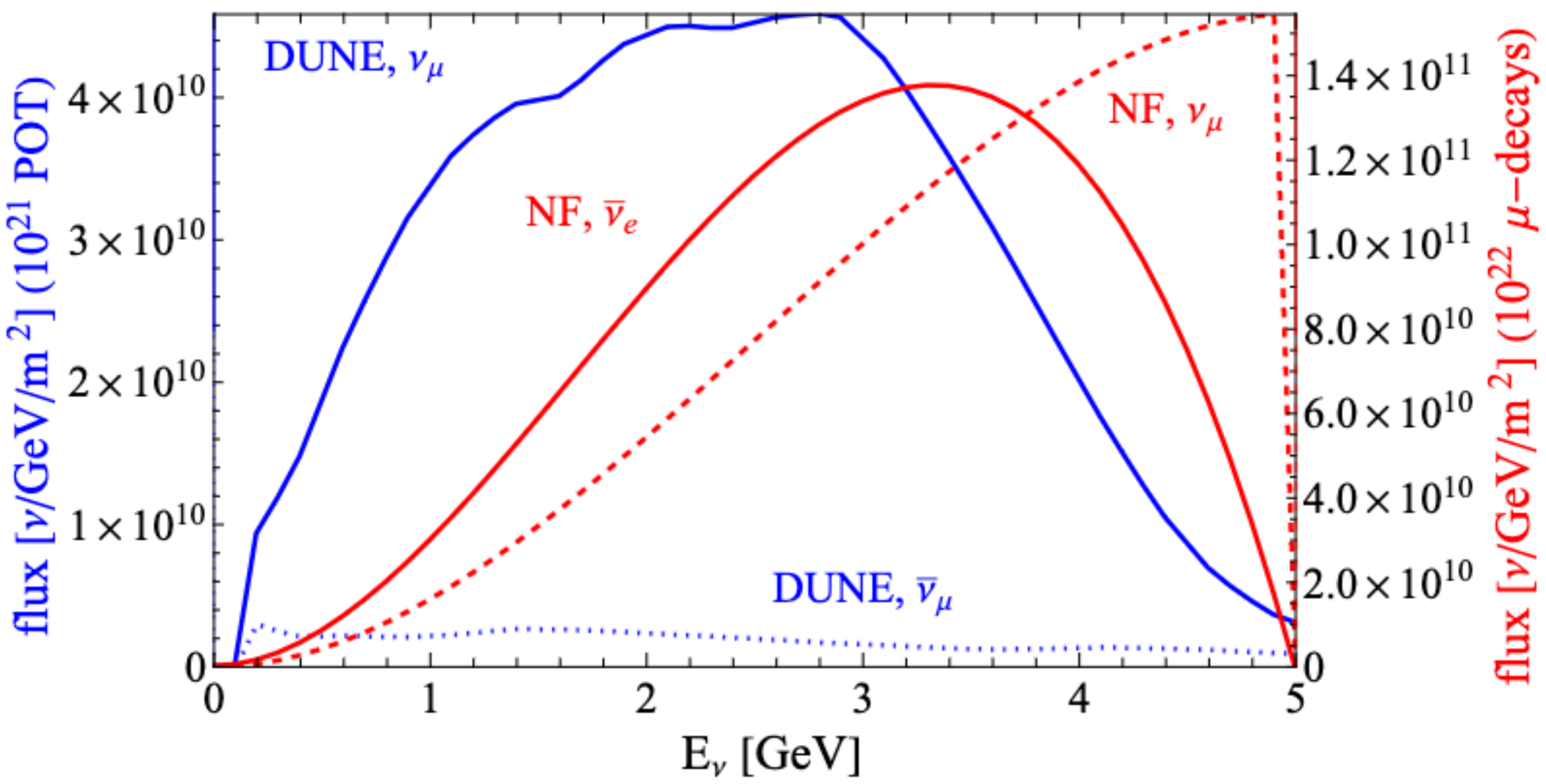
Assume DUNE+HK are successful

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

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

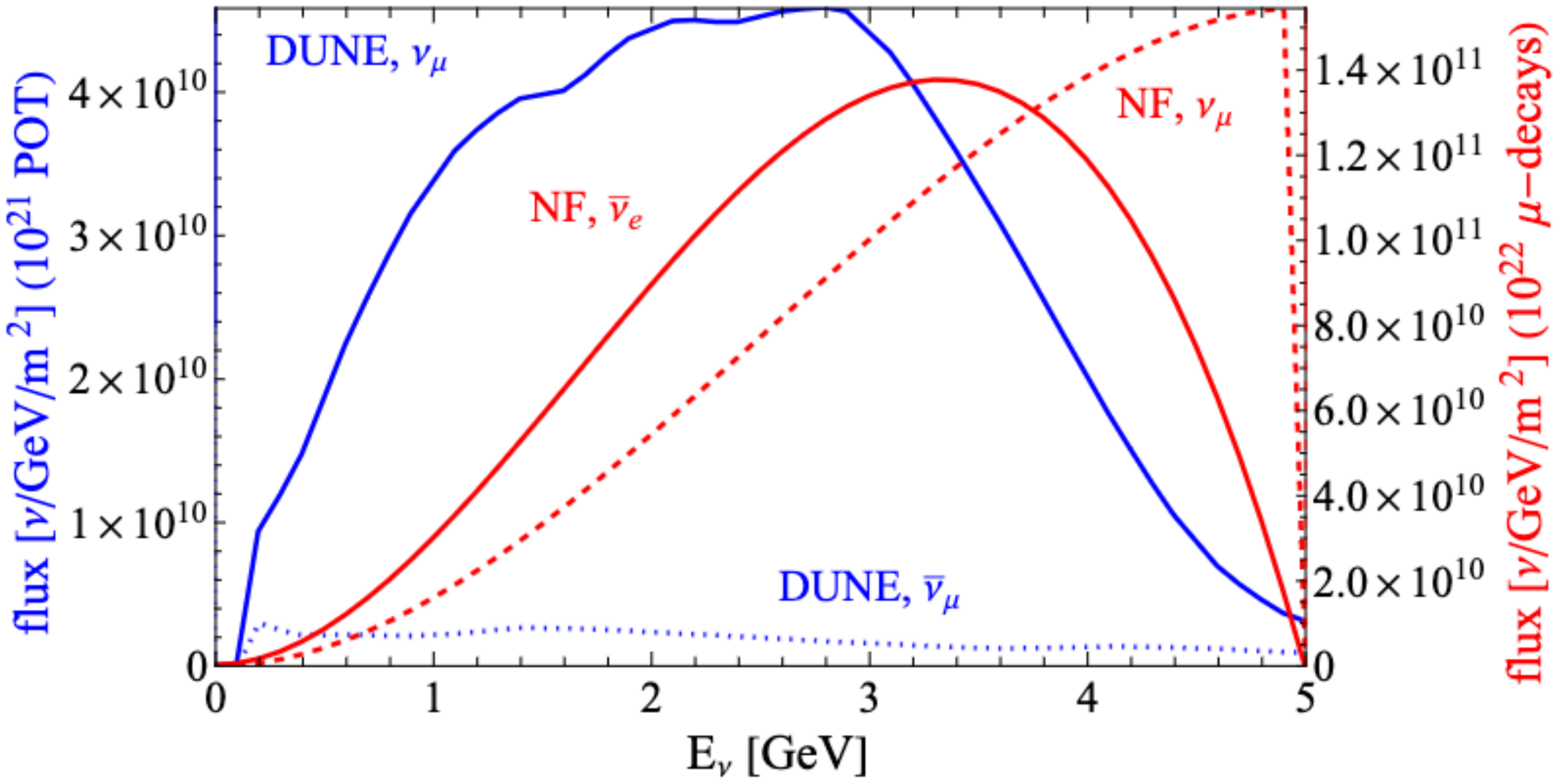


[JG, Denton 2407.02572]

Neutrino factory

NF vs neutrino beams from fixed target experiments:

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

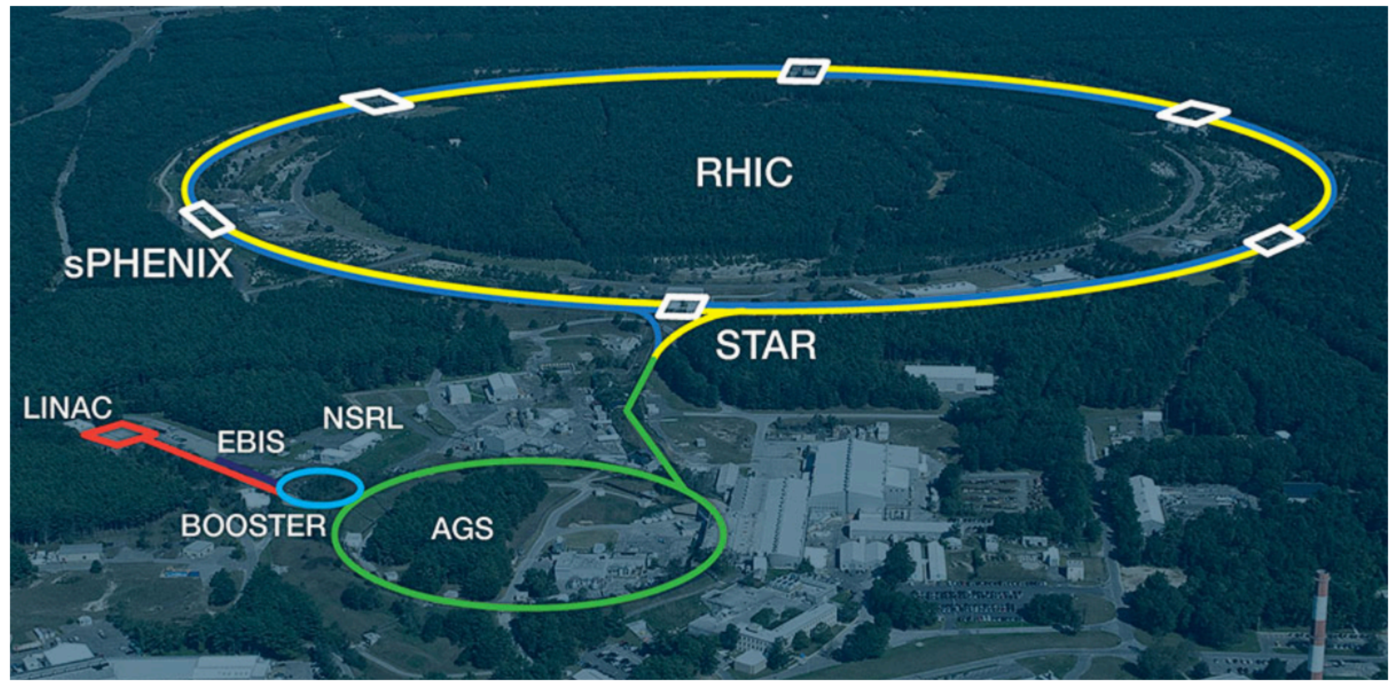


[JG, Denton 2407.02572]

Neutrino factory
Setup

Study two setups:

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



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

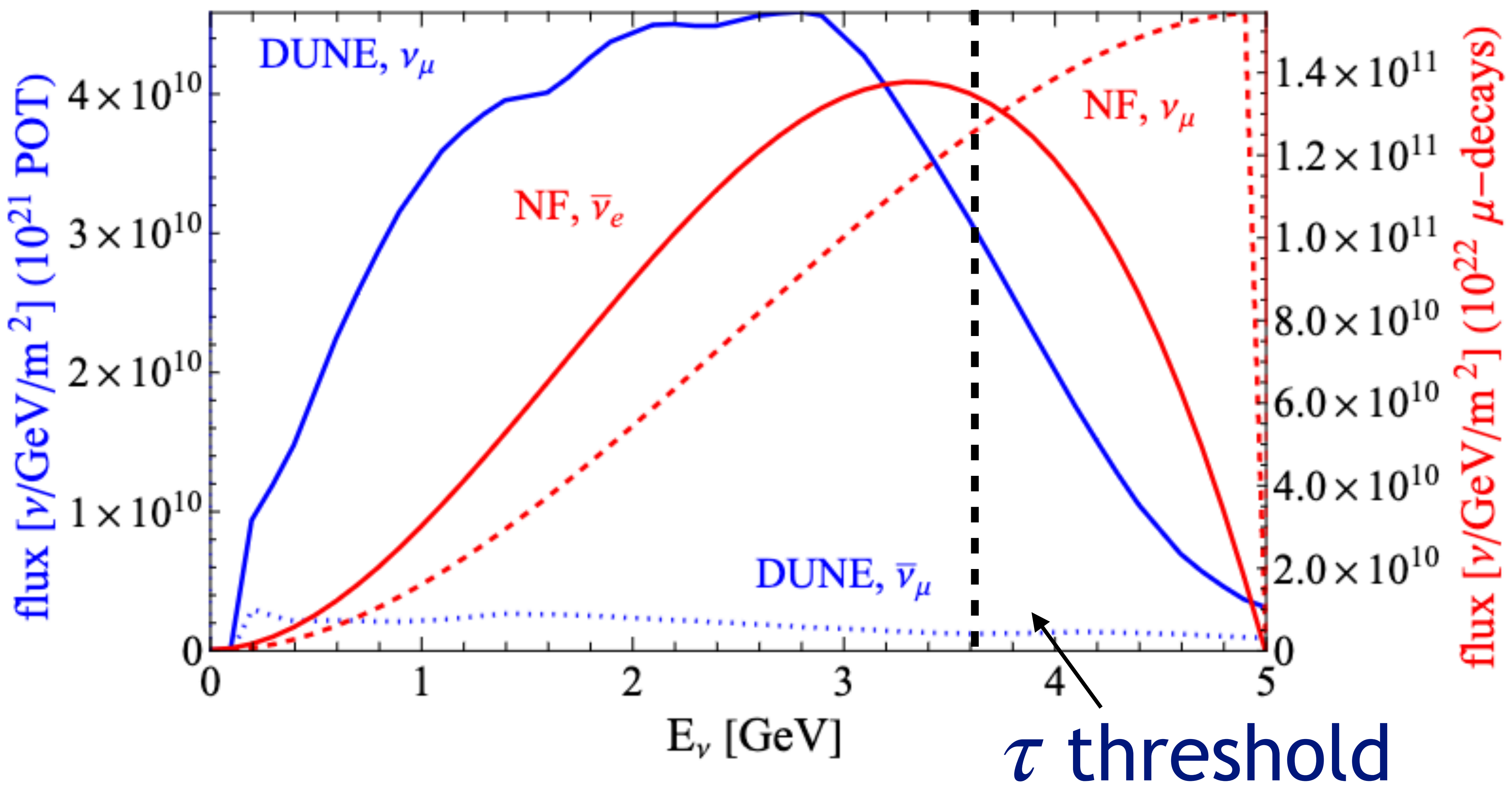
Talk on NF at J-PARC focused on T-violation by Sho Sugama on Thursday afternoon

Neutrino factory
Setup

[JG, Denton 2407.02572]

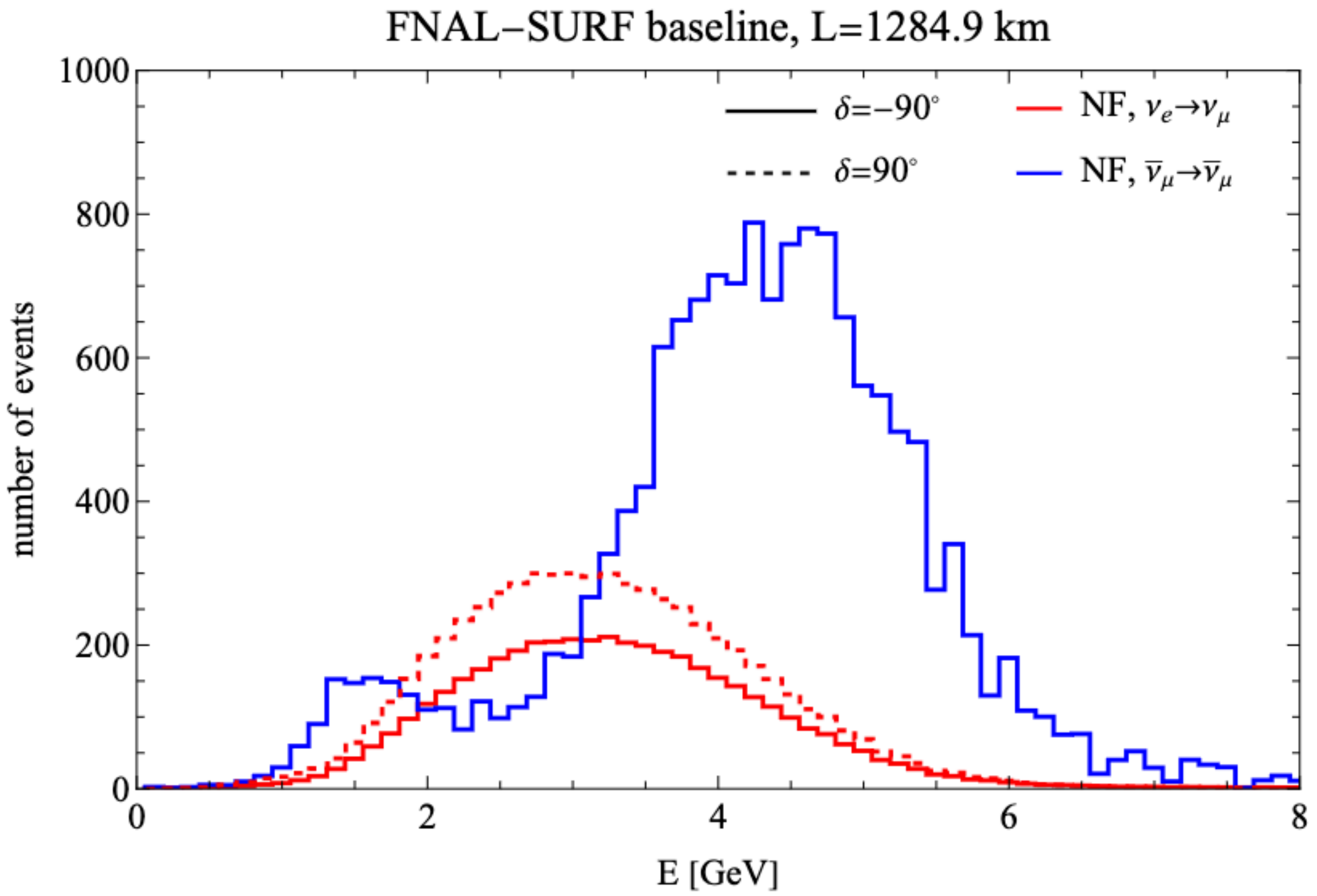
- Far detector: LArTPC, total fiducial target mass of 40 kT
- 2.5% normalization uncertainty on ν_e, ν_μ flux (DUNE: $\sigma_{\phi_{\nu_e}} = 2\,\%$, $\sigma_{\phi_{\nu_\mu}} = 5\,\%$)

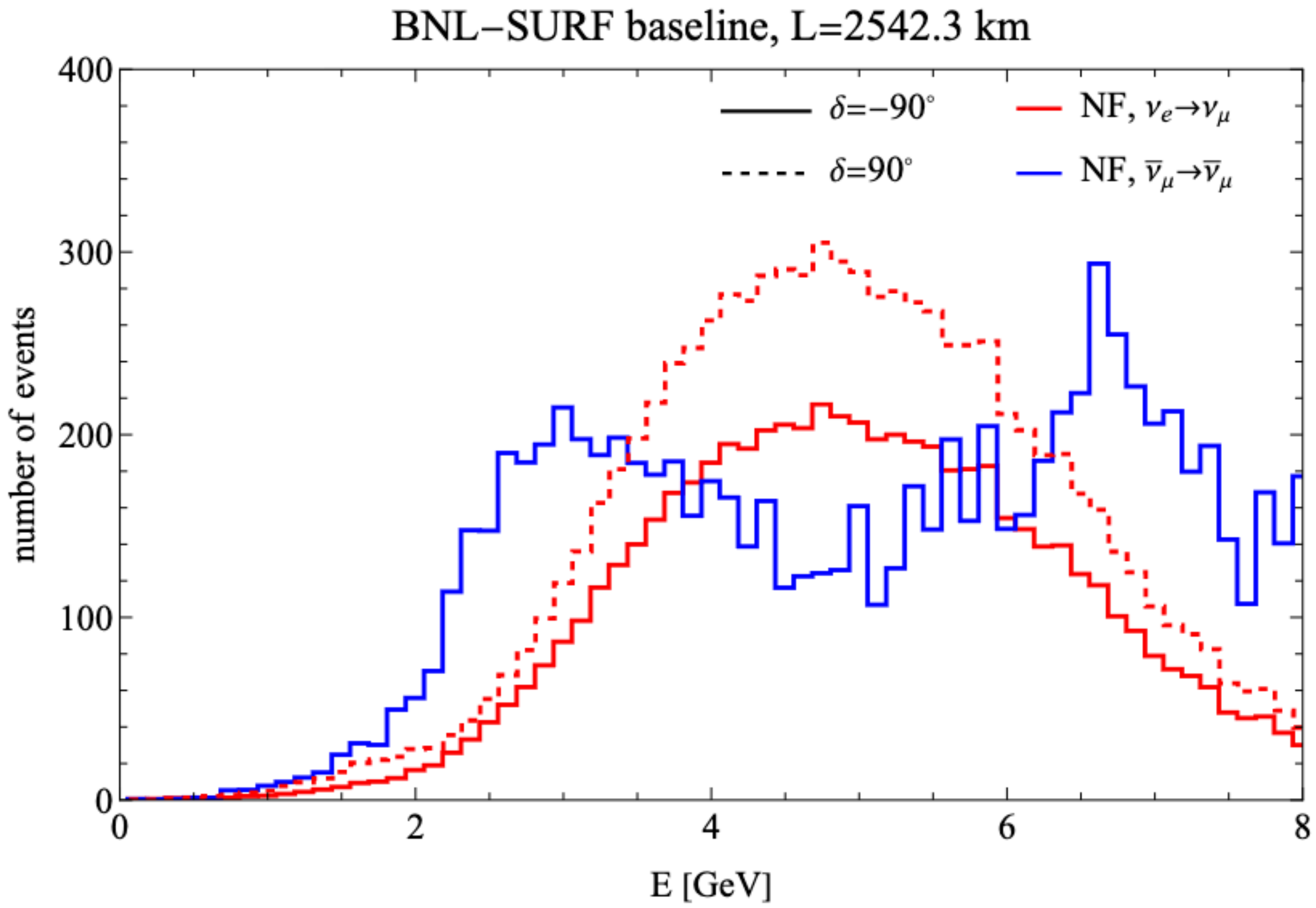
Tau neutrino appearance as background



Neutrino factory
Results

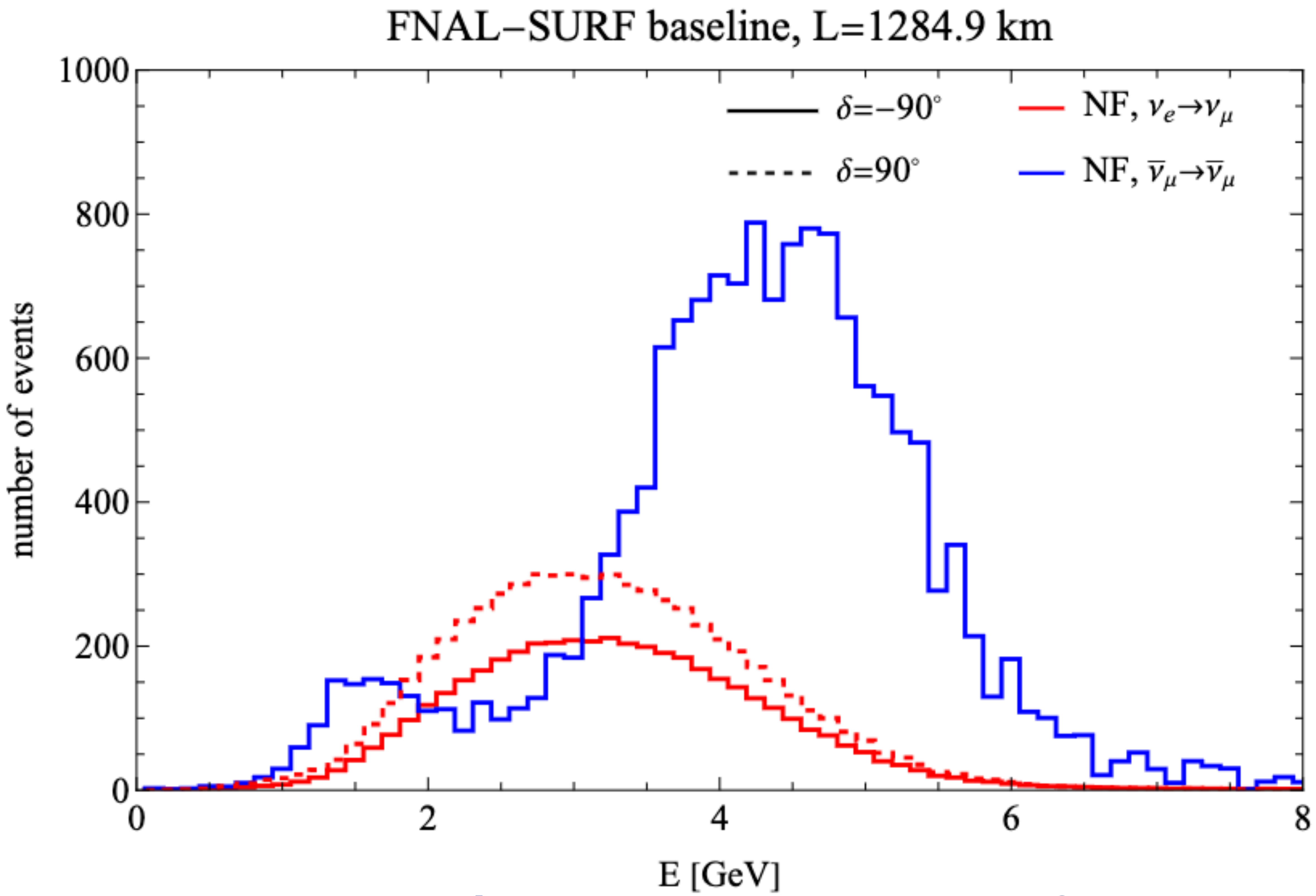
[JG, Denton 2407.02572]

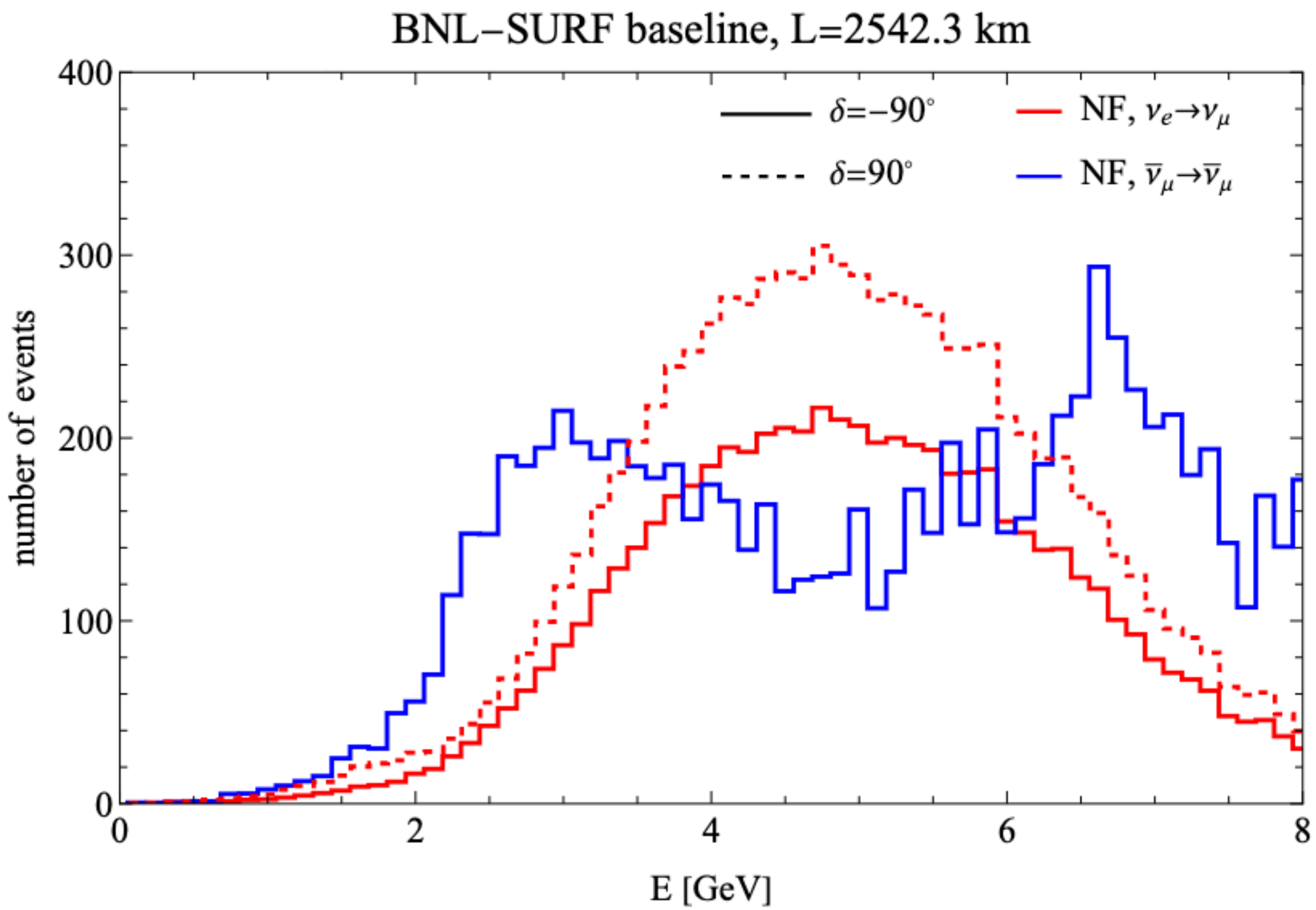




Neutrino factory
Results

[JG, Denton 2407.02572]





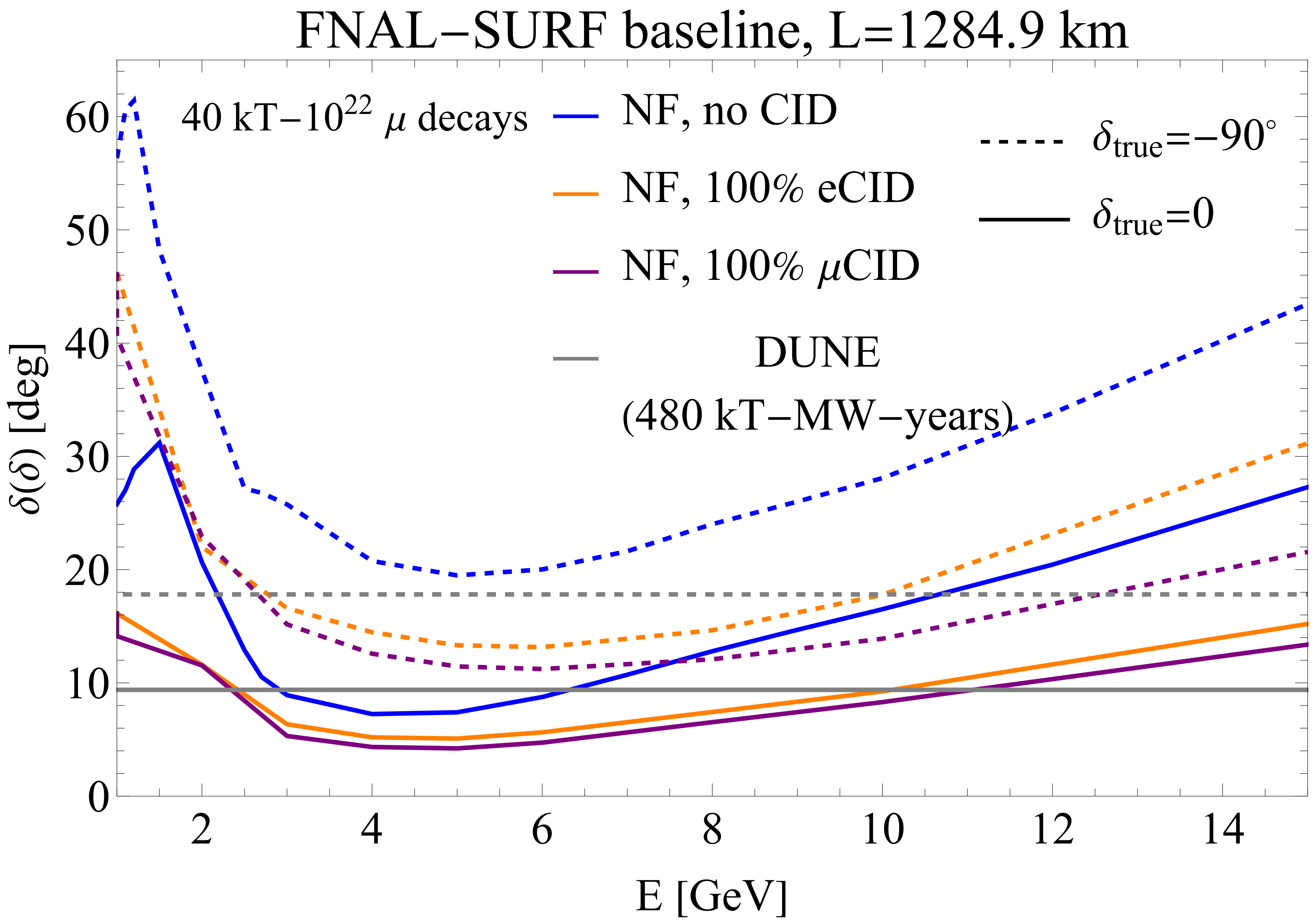
Distinguish ν_μ appearance from ν_μ disappearance using charge identification (CID)

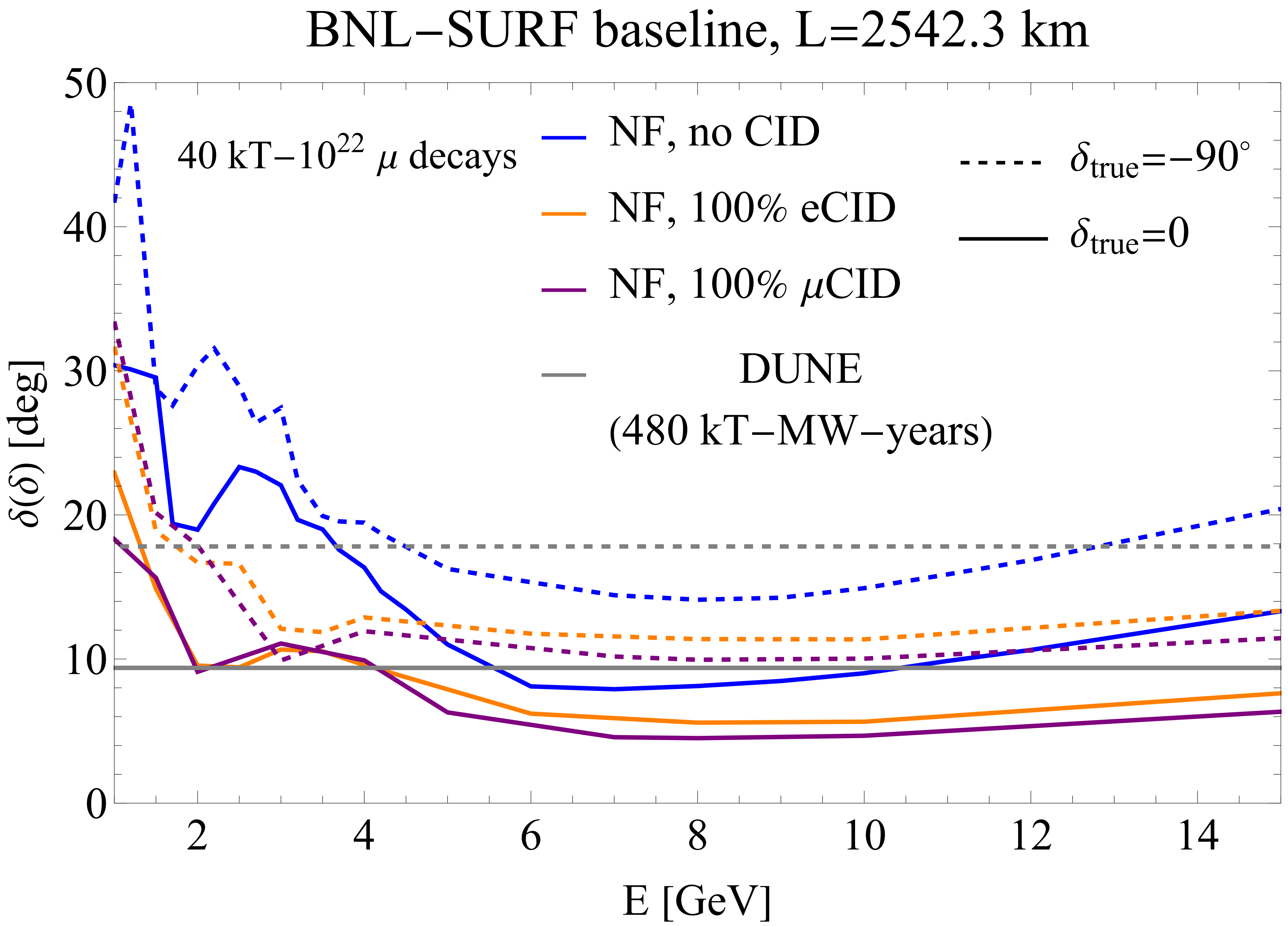
Appearance peaks in disappearance dip for BNL configuration
→ CID less relevant

Neutrino factory

[JG, Denton 2407.02572]

Results





Optimal muon energy to maximize precision of δ

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

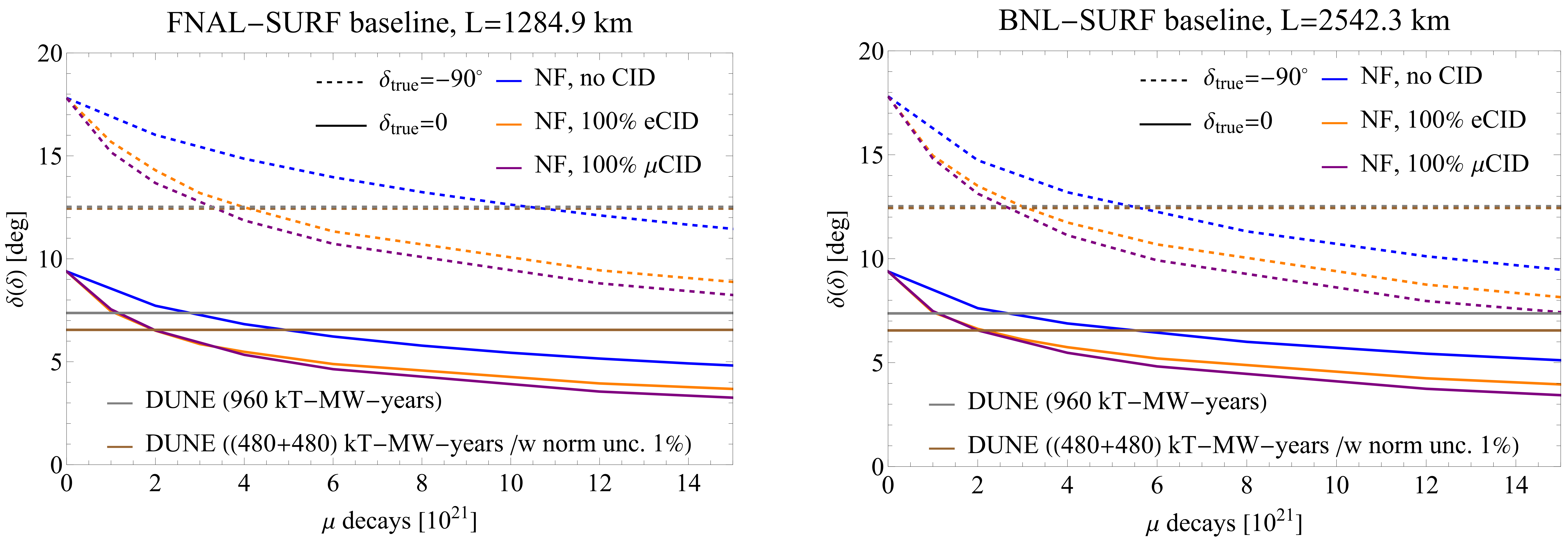
Running time neutrino: antineutrino 1:1

Depending on physics case these values might slightly change

Neutrino factory

Results

[JG, Denton 2407.02572]



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

(depending on true value and setup)

Neutrino factory
Results

CP phase predicted in flavor models

$\rightarrow$ Measurement of δ can distinguish different flavor models

Example:

Neutrino mixing matrix predicted by discrete flavor symmetries

Charged lepton mixing matrix non-diagonal

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

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

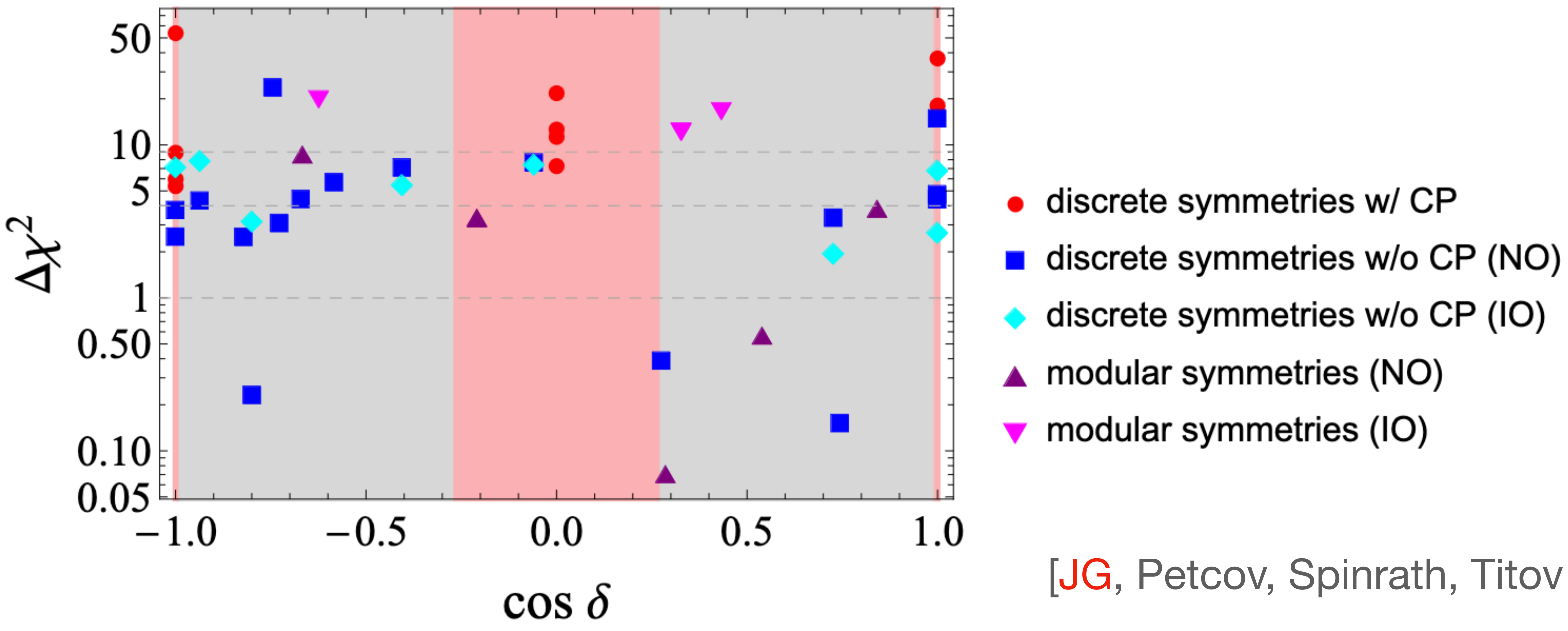
Neutrino factory

Results

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]

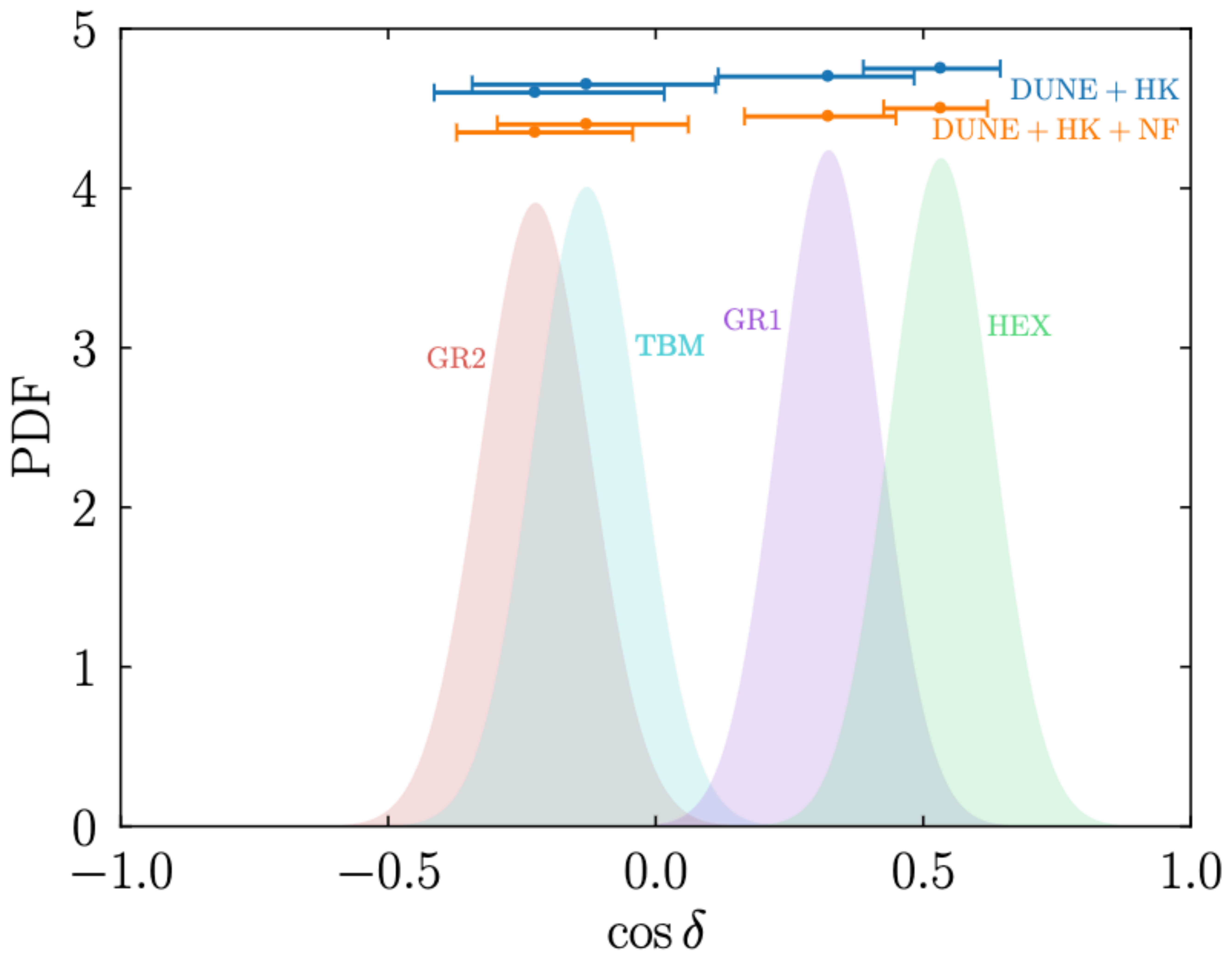
Other parameters, neutrino mass and $0\nu\beta\beta$ can also probe flavor models

[JG, Denton 2308.09737]

Neutrino factory

Results

[JG, Denton 2407.02572]



→ improved distinction power of models when including NF

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

Neutrino factory

Results

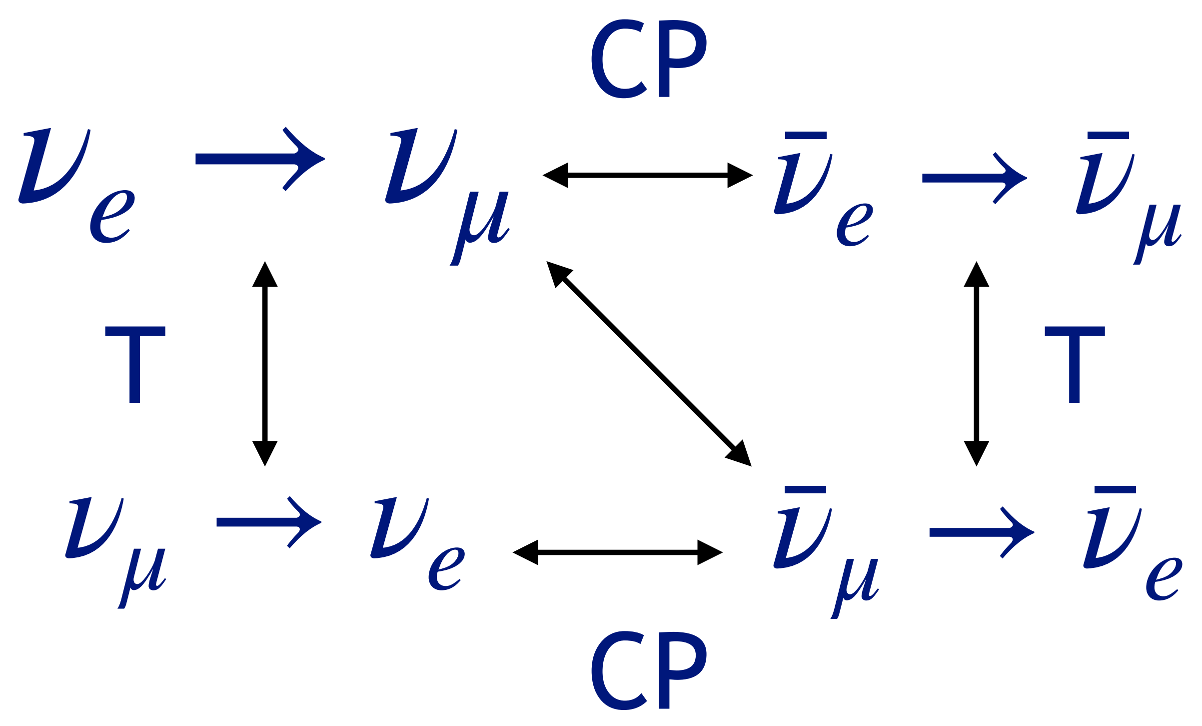
Sensitivity to δ mostly comes

from $\nu_e \to \nu_\mu$ (“golden channel”)

$\leftrightarrow$ unlike at DUNE, HK which rely on

$\nu_\mu \to \nu_e$ channel

Channels related by $\delta \to -\delta$



Probe of CPT invariance: NF has 4 different oscillation channels which are is CP, T, and CPT conjugates of each other

Combine with DUNE, HK to test CPT invariance

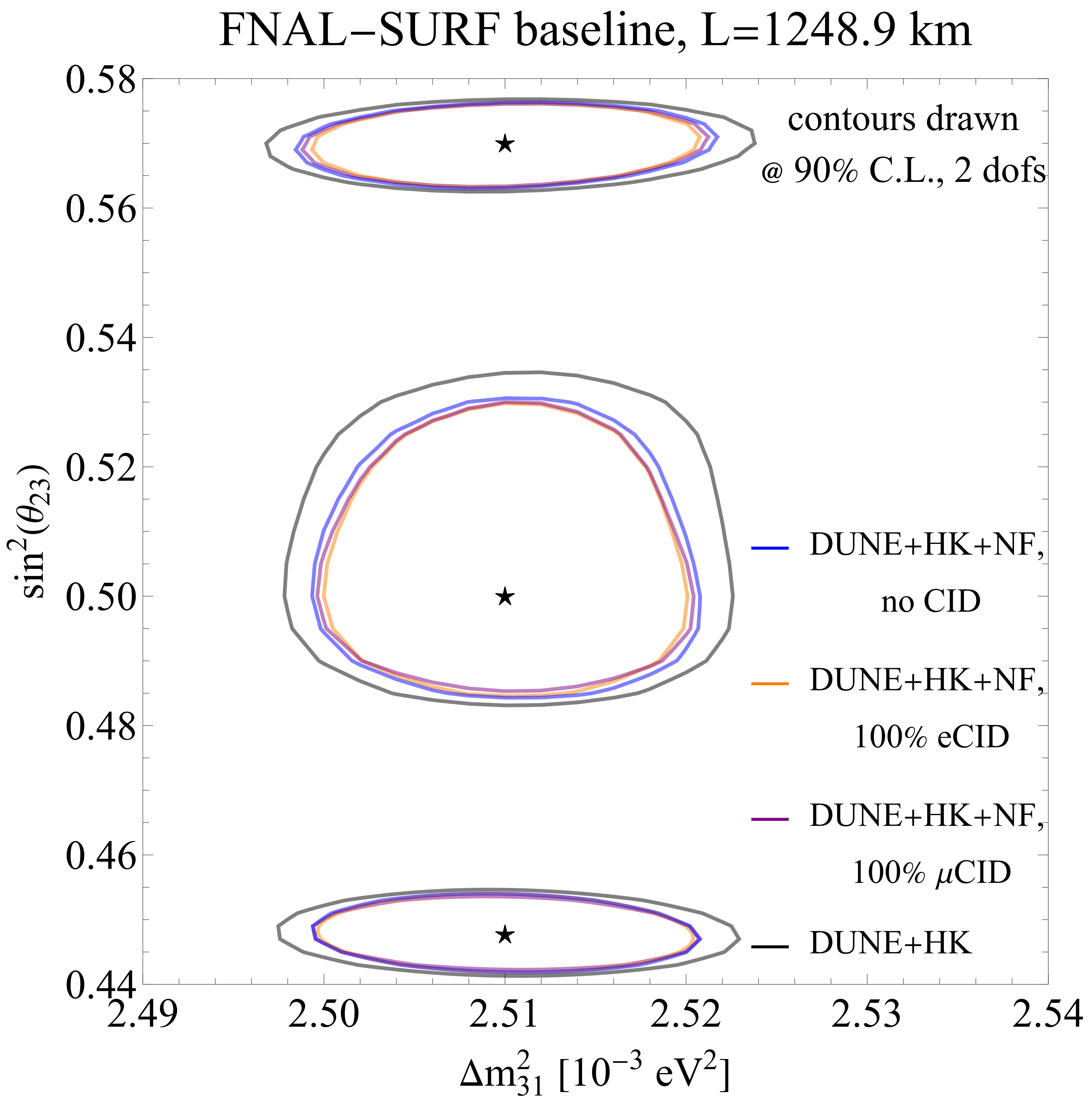
Neutrino factory

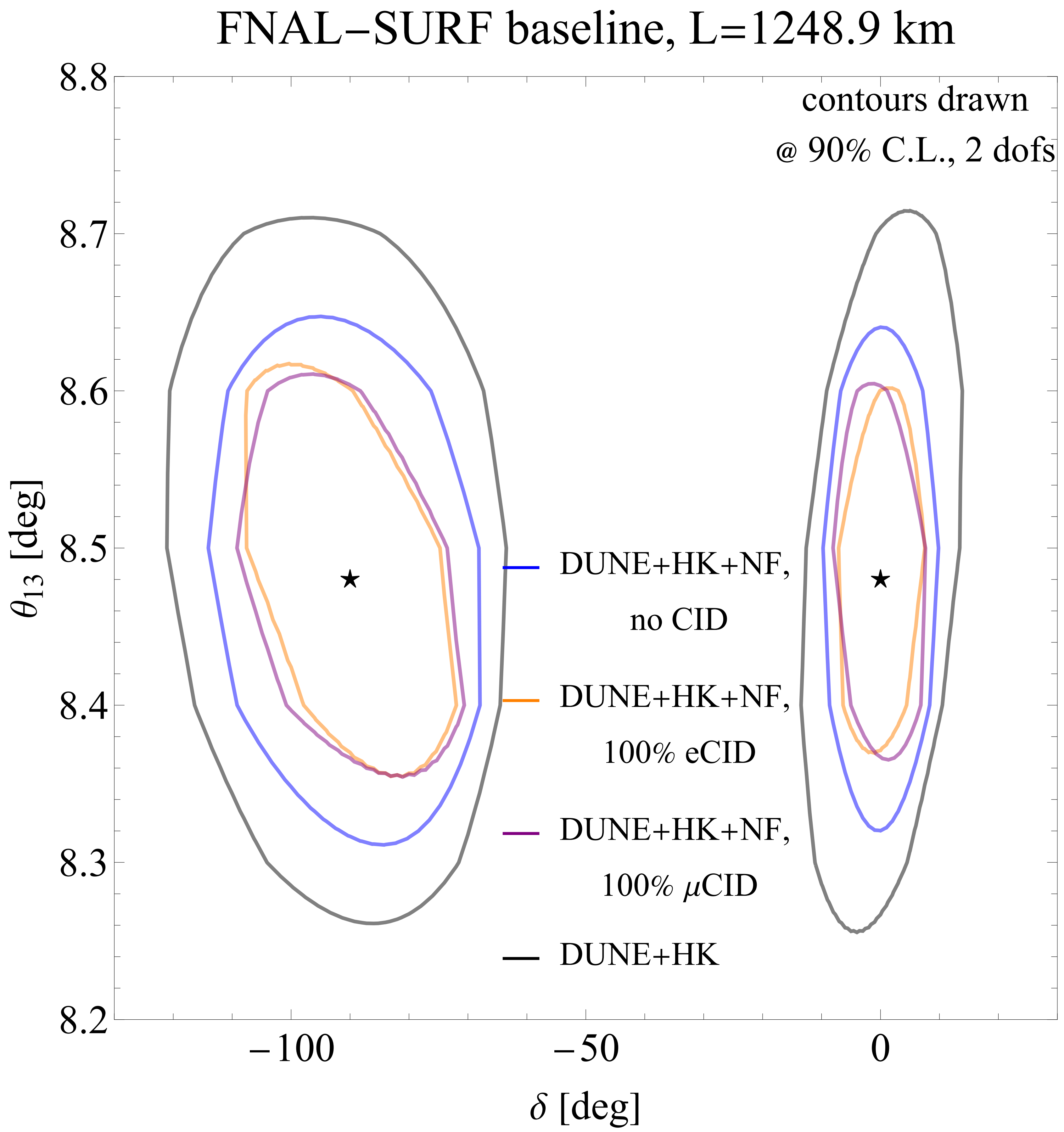
Results

[JG, Denton 2407.02572]

Results for a total of

40 kT – 10^{22} μ decays





- DUNE, HK will improve over current constraints
- NF will reduce uncertainties even more
- Results potentially even better due to improvements in LAr technology

Neutrino factory

Results

[JG, Denton 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

Conclusions

NF interesting possibility as a future oscillation experiment

- Improved precision on several fundamental parameters including the amount of CP violation
- Improved flavor model differentiation capabilities
- A technological stepping stone on the way to a high
- energy muon collider
- Possible improvements in BSM physics (steriles, NSI, non-unitarity)
- ND physics

Thanks for your attention!

Appendix: Neutrino factory

Results

- 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

[JG, Denton 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

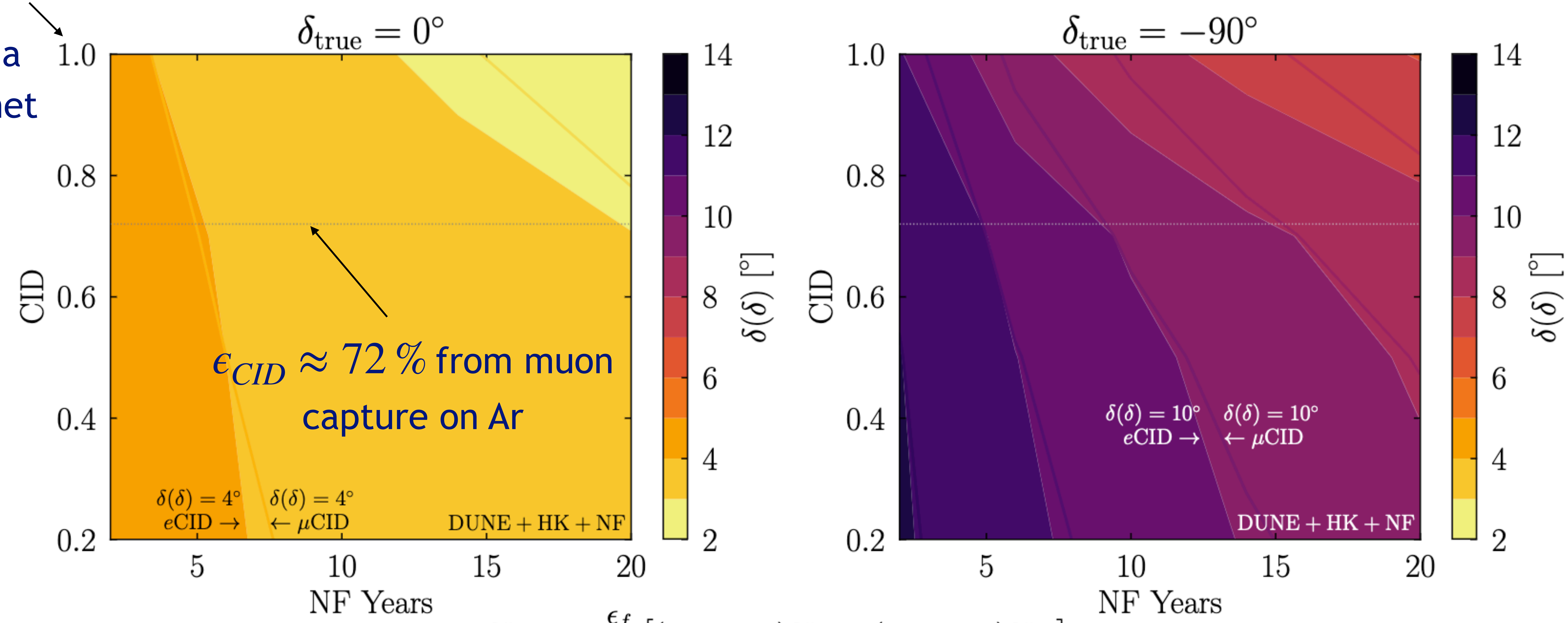
[JG, Denton 2302.08513]

Appendix: Neutrino factory

Results

[JG, Denton 2407.02572]

Use a magnet



$\epsilon_{CID} \approx 72\,\%$ from muon capture on Ar

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

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

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

Appendix: Neutrino factory

Results

[JG, Denton 2407.02572]

Results for a total of

40 kT $- 10^{22}$ μ decays

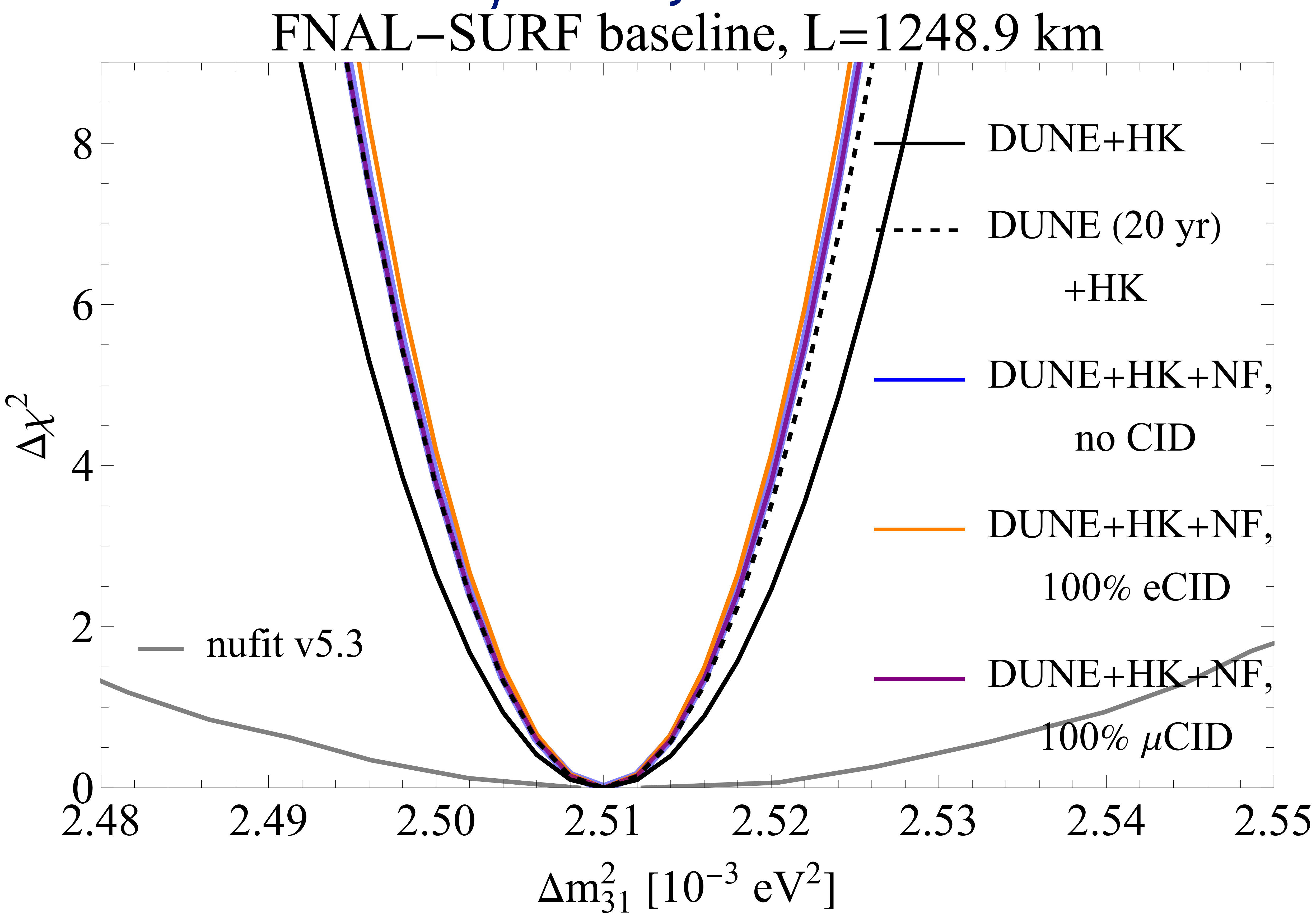
Appendix: Neutrino factory

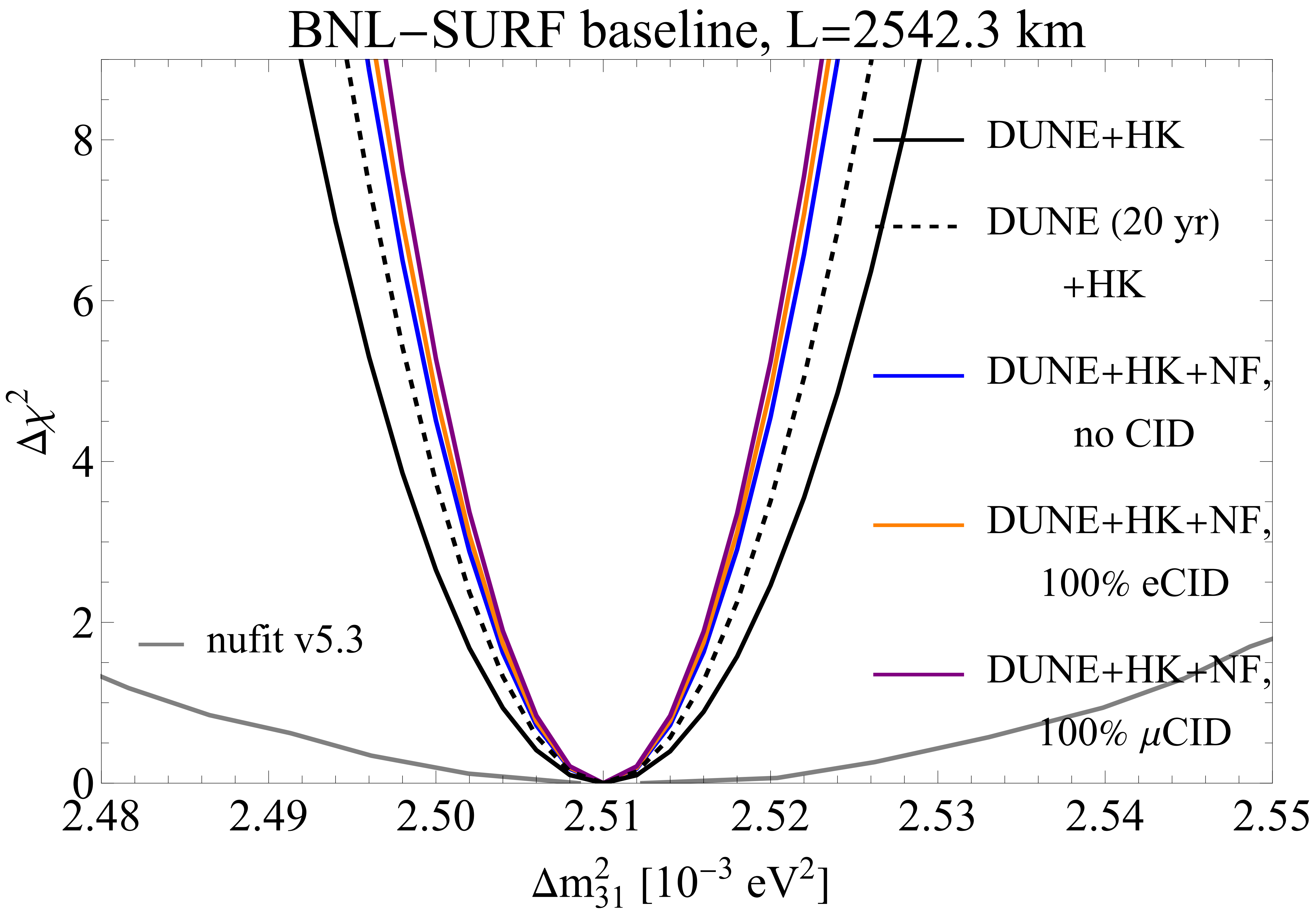
Results

Results for a total of

40 kT – 10^{22} μ decays

[JG, Denton 2407.02572]





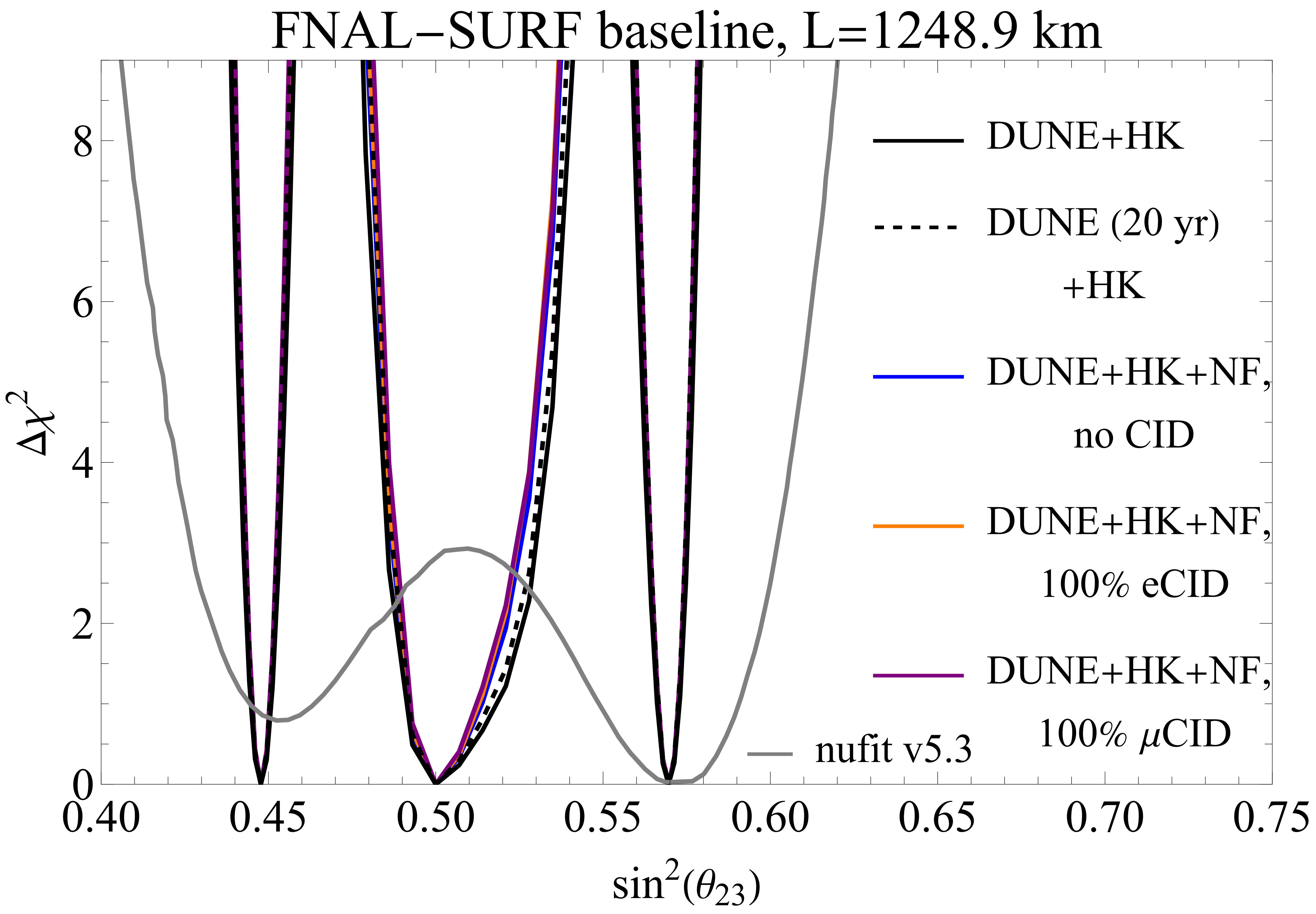
Appendix: Neutrino factory

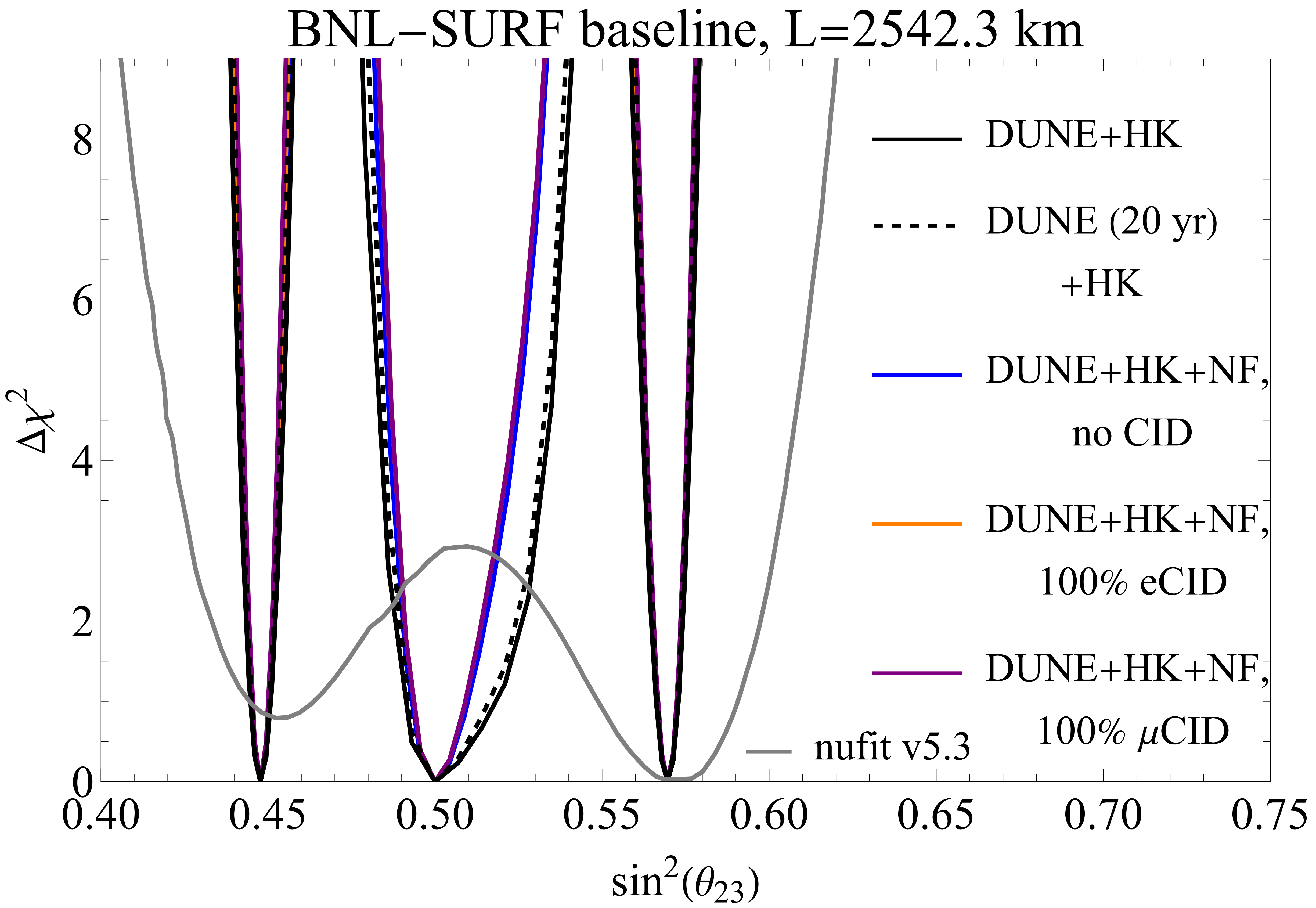
Results

[JG, Denton 2407.02572]

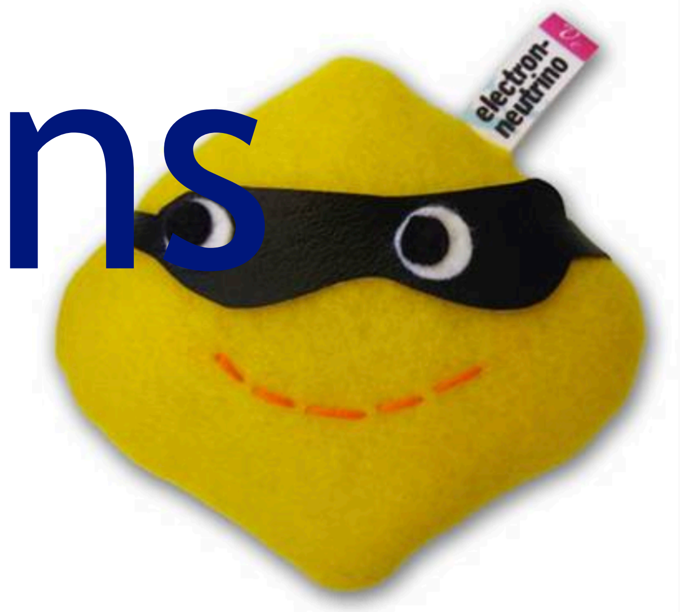
Results for a total of

40 kT $- 10^{22}$ μ decays





Appendix: Neutrino oscillations



Where are we going?

Proposed oscillation experiments

T2HKK

additional HK-like tank in Korea

[HK 1611.06118]

ESSnuSB

water Cherenkov detector in Sweden

[ESSnuSB 2107.07585]

THEIA

water-based liquid scintillator detector

4th DUNE module?

[THEIA 1911.03501]

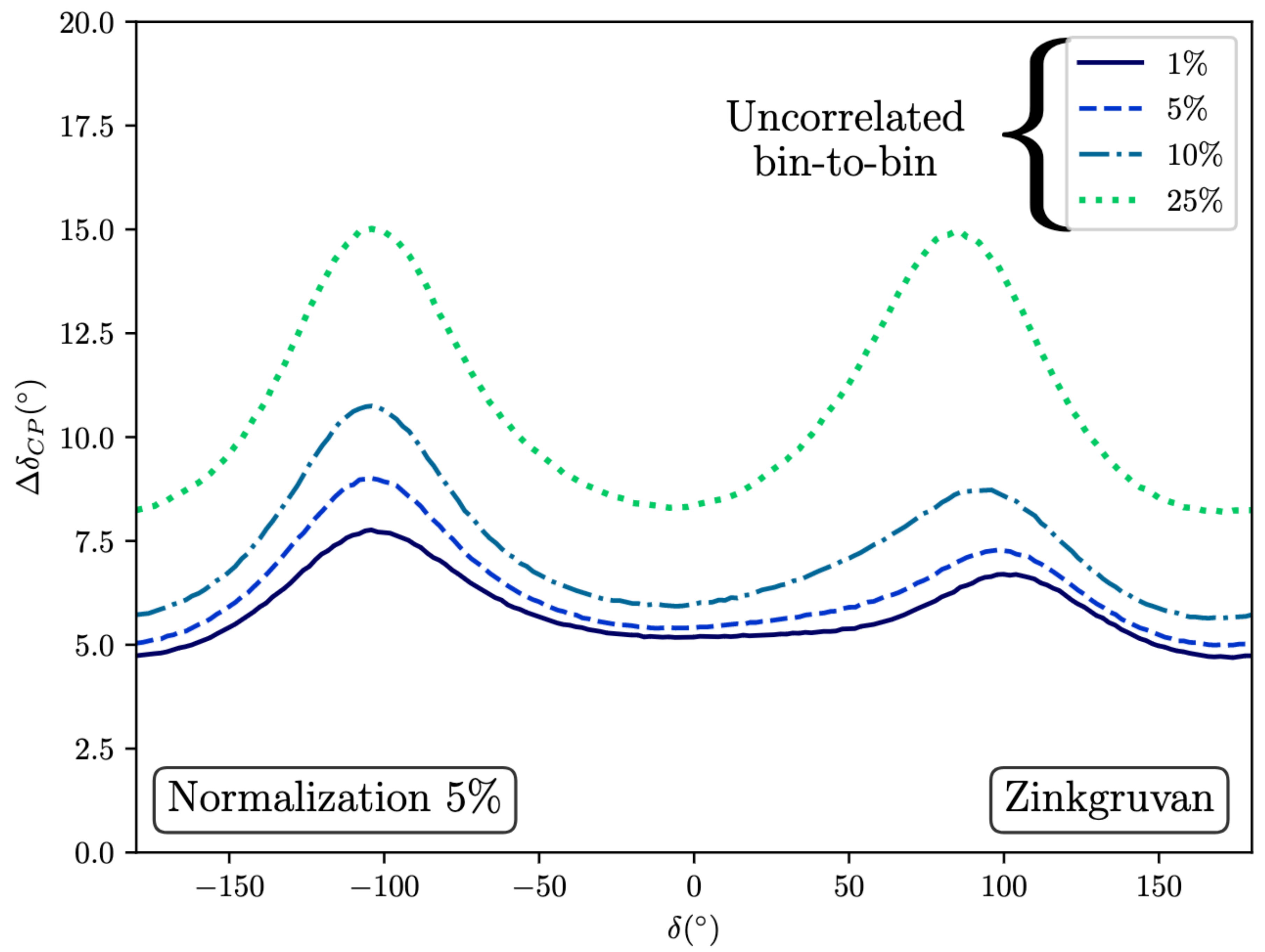
$\rightarrow$ second oscillation maximum

$\rightarrow$ Sensitive to low E ν physics

Appendix: Neutrino oscillations

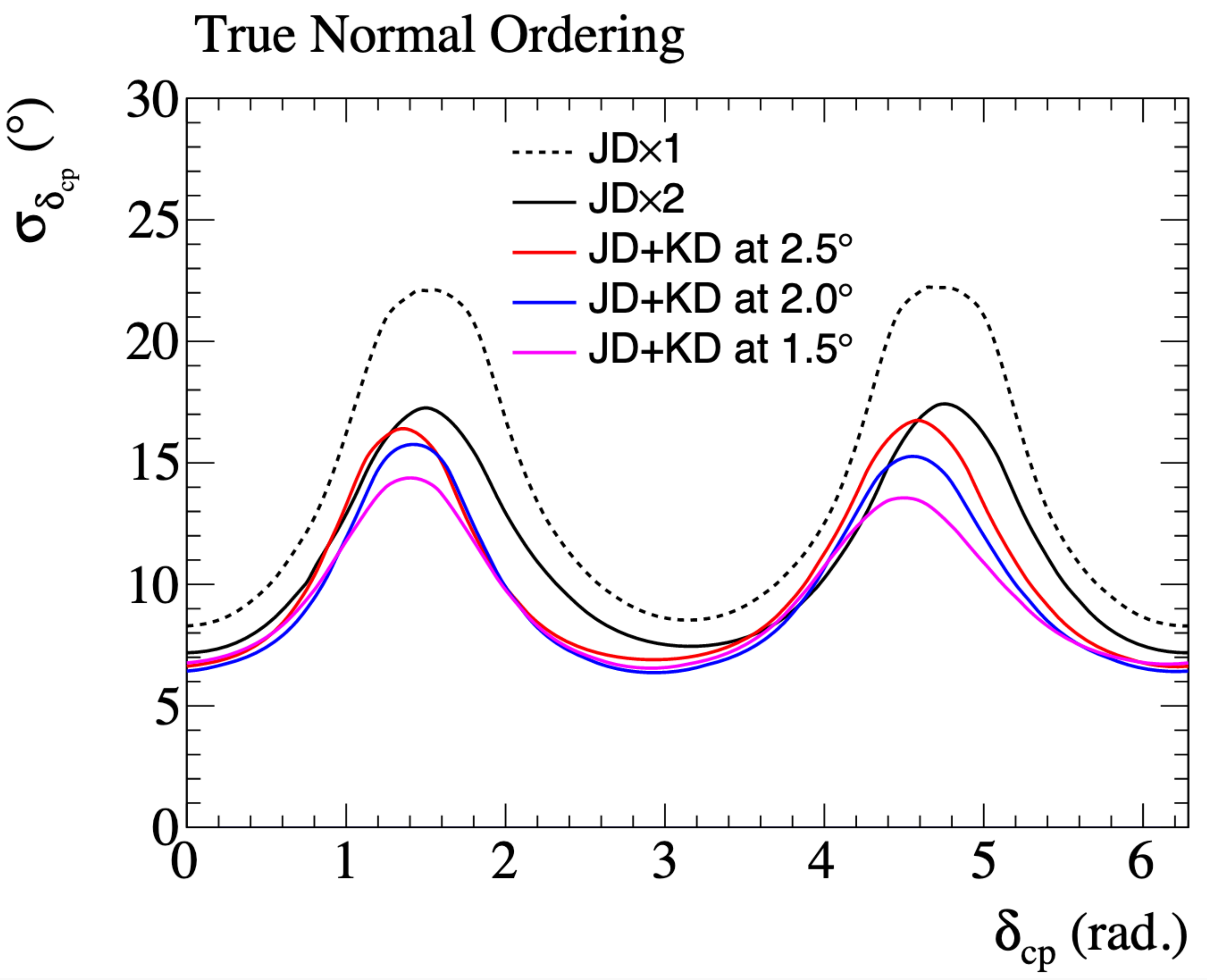
Where are we going?

- ESSnuSB



[ESSnuSB 2303.17356]

- T2HKK



[HK 1611.06118]

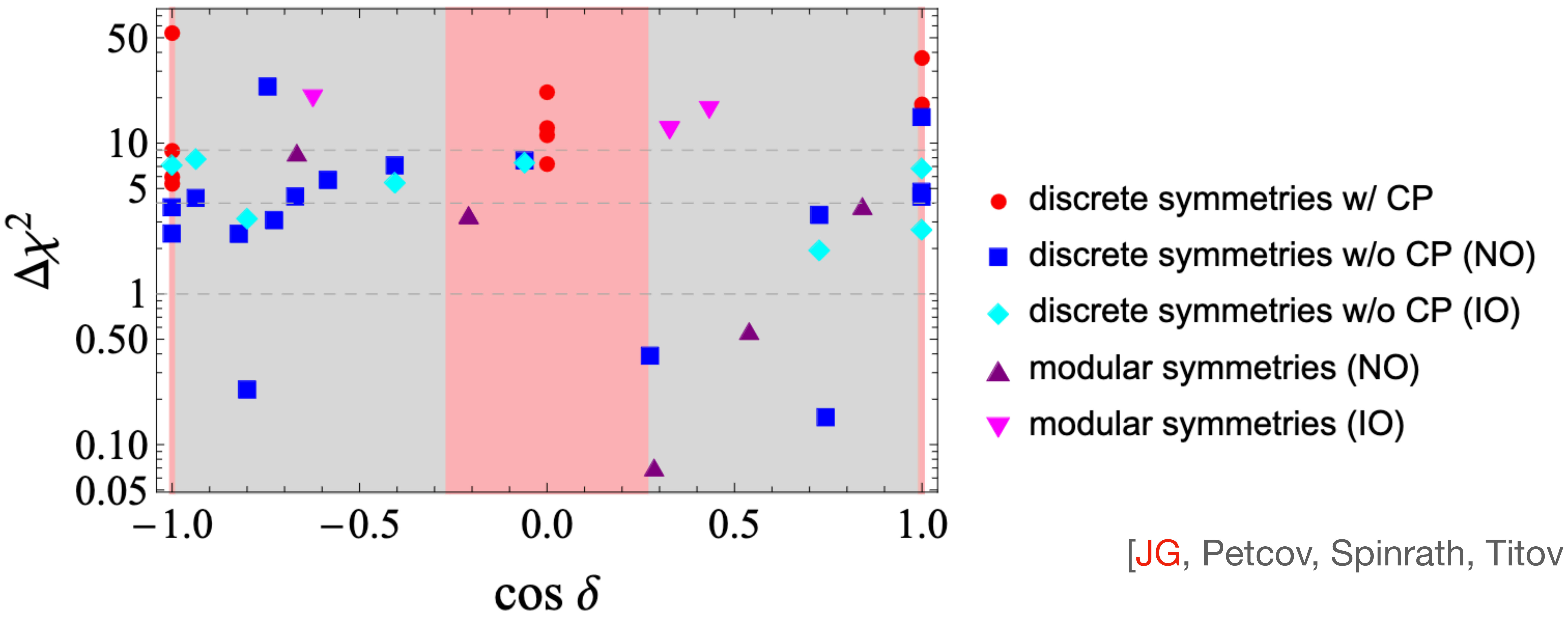
Appendix: Flavor models

- 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



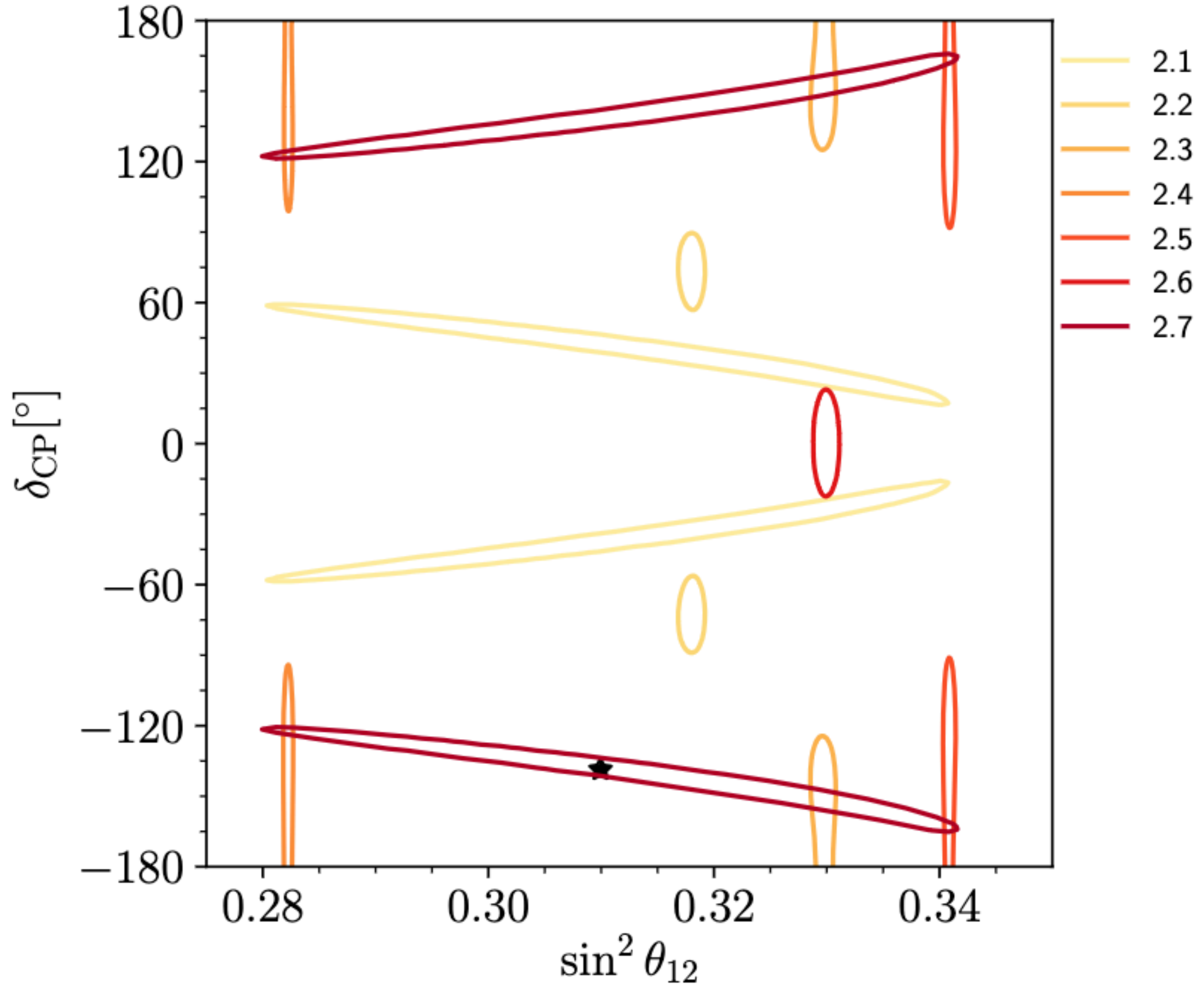
[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: Flavor models

- Distinguish different flavor models with precision oscillation measurements

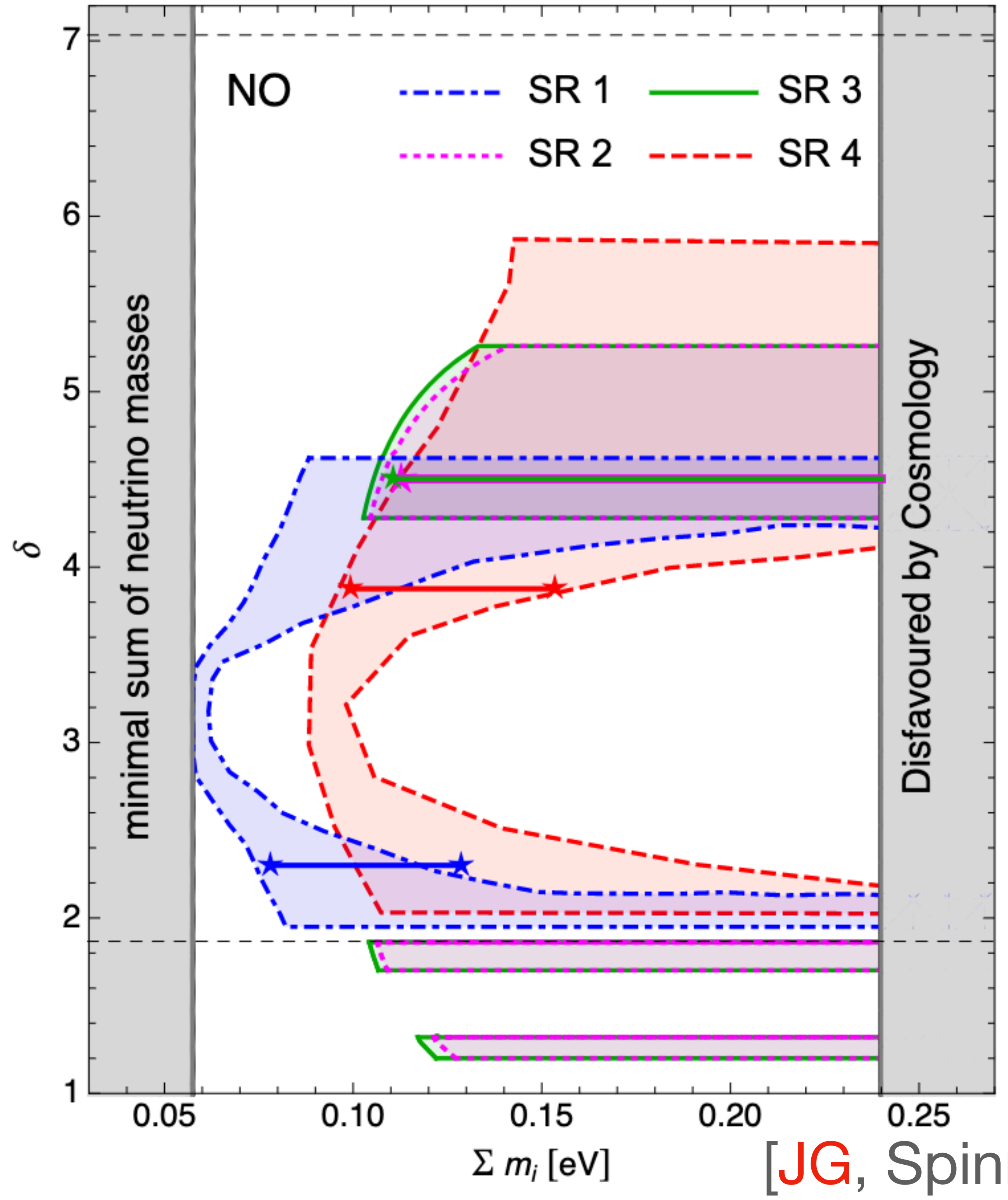
Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models at $>5\sigma$!



[Blennow, Ghosh, Ohlsson, Titov 2004.00017]

Correlations can be probed!

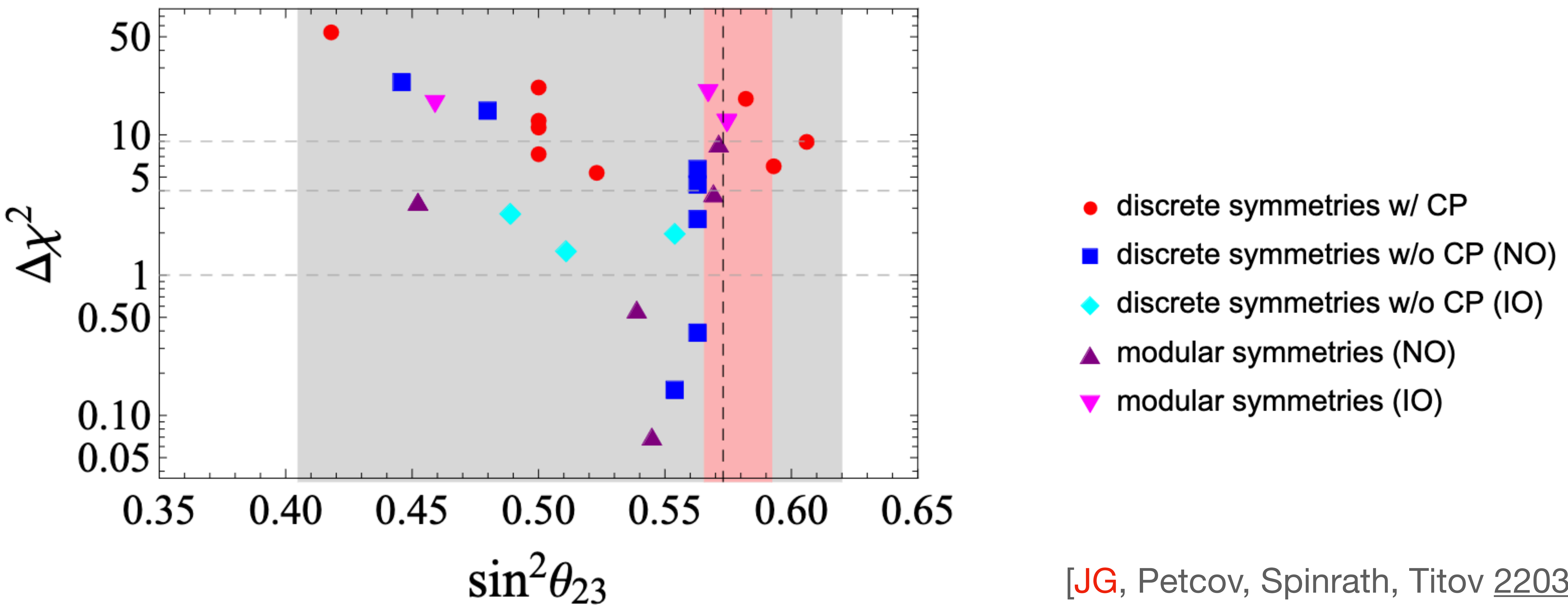


[JG, Spinrath 2012.04131]

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

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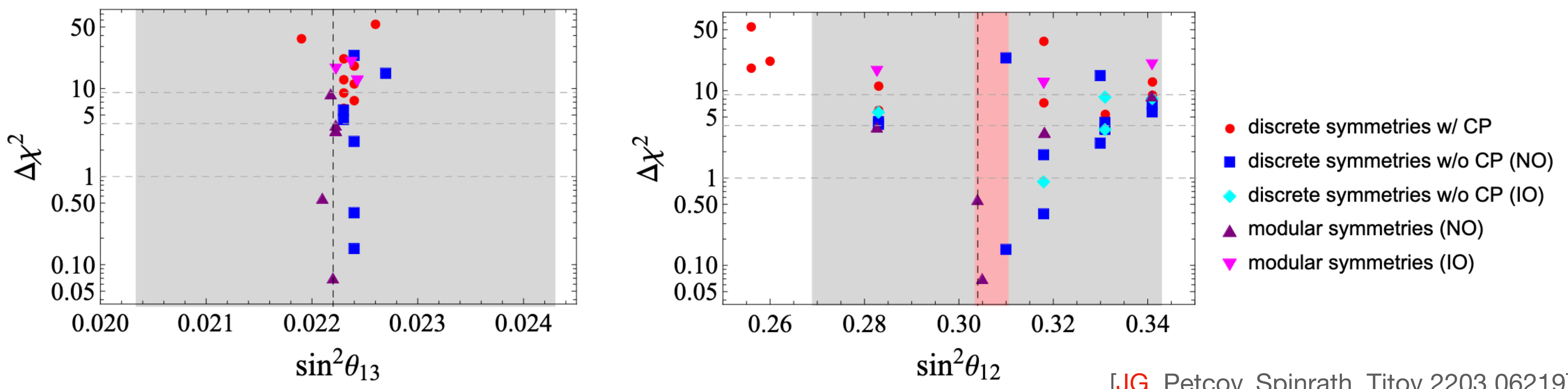

[JG, Petcov, Spinrath, Titov 2203.06219]