A modern look at the oscillation case at a neutrino factory

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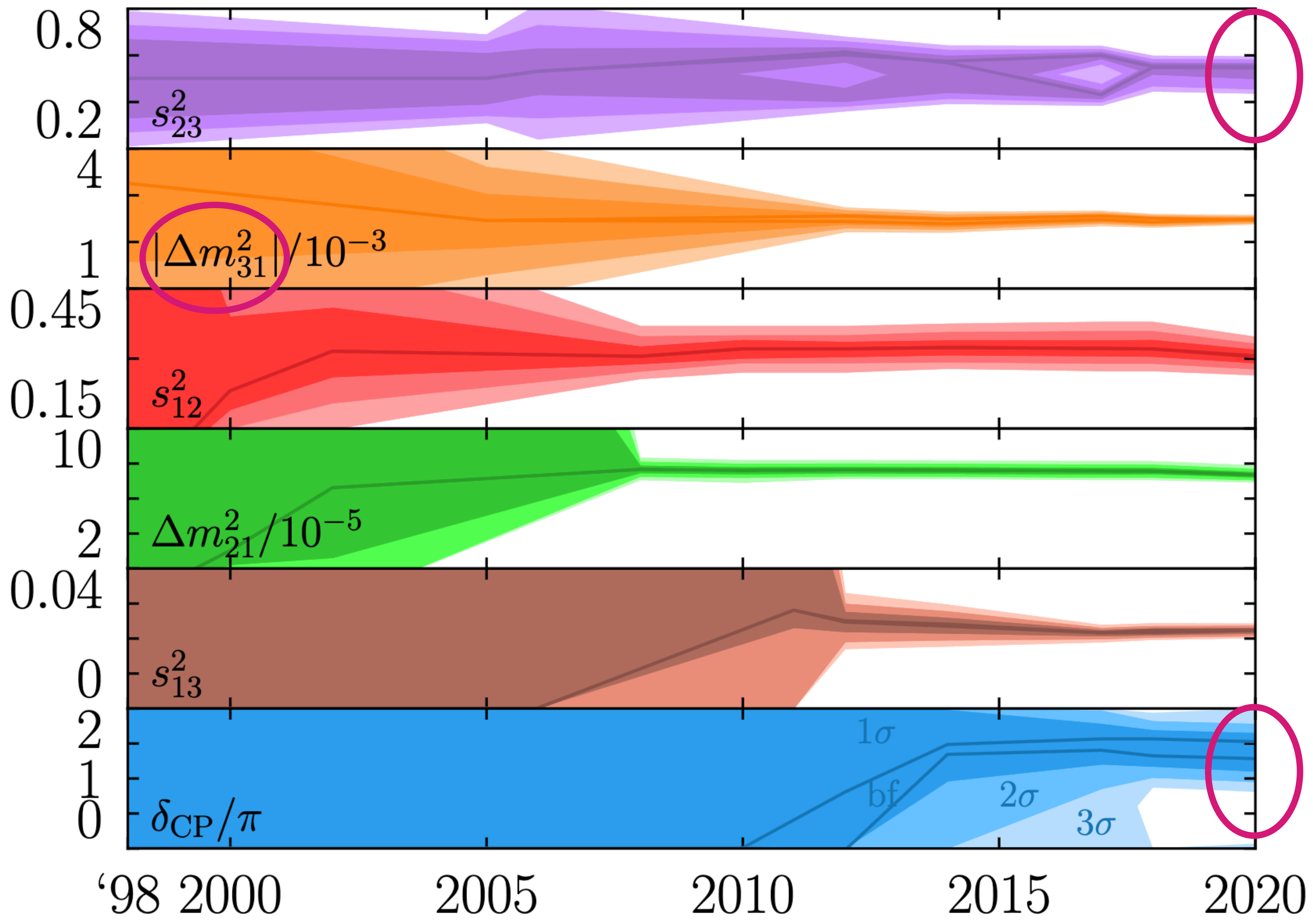
Neutrinos
Where do we stand?

Oscillations:

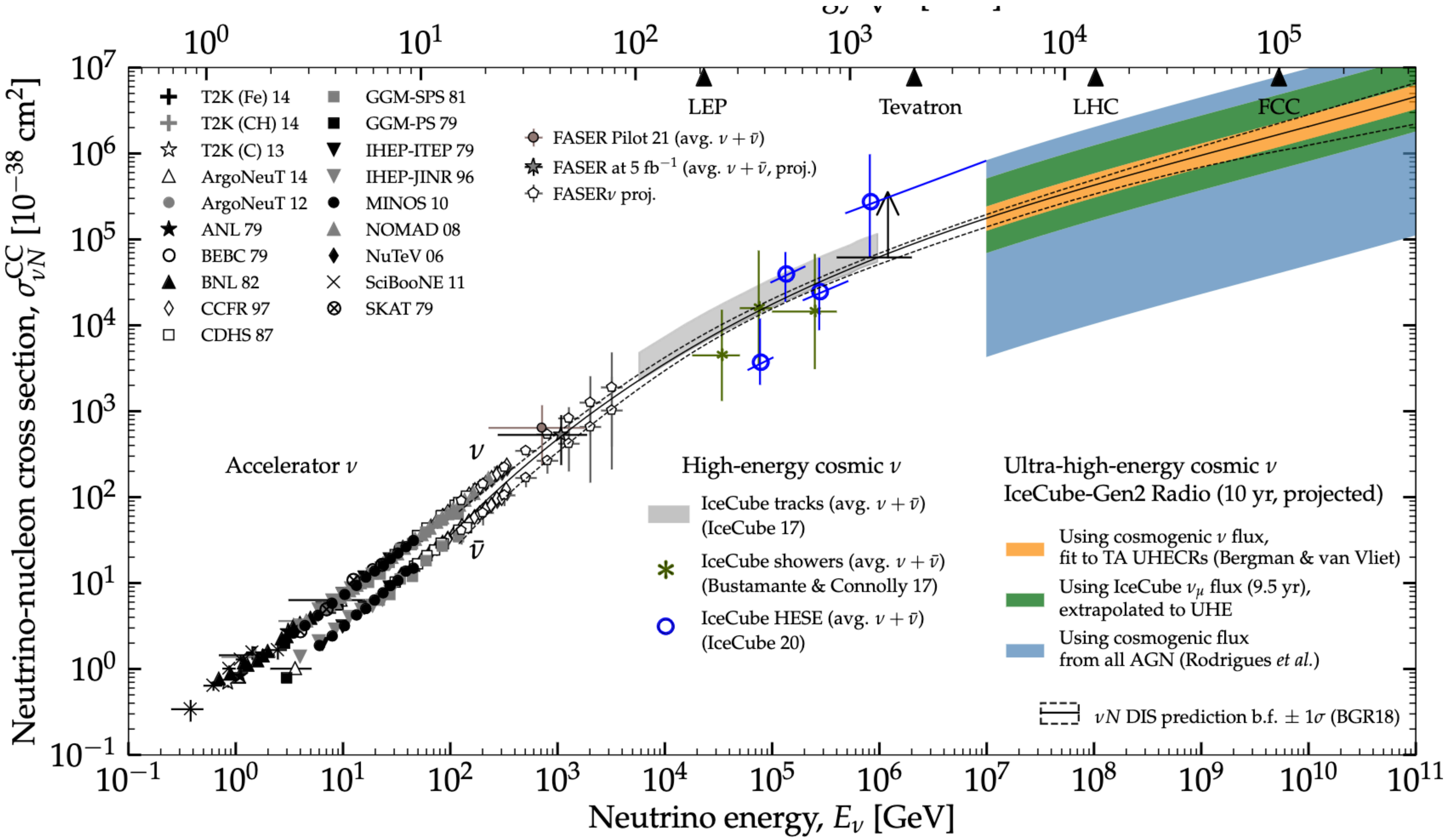


[Denton et al 2212.00809]

Neutrinos
Where do we stand?

Scattering:

CEvNS on its way to precision physics



xsec uncertainty: limiting factor for future accelerator experiments

[Ackerman et al 2203.08096]

Neutrinos

Where do we stand?

BSM physics:

Neutrino portal

$y\bar{L}_L\tilde{H}N_R$

→ sterile neutrinos

Scalar or vector portal

$\lambda(H^\dagger H)(S^*S)$ or $\varepsilon B_{\mu\nu}B'^{\mu\nu}$

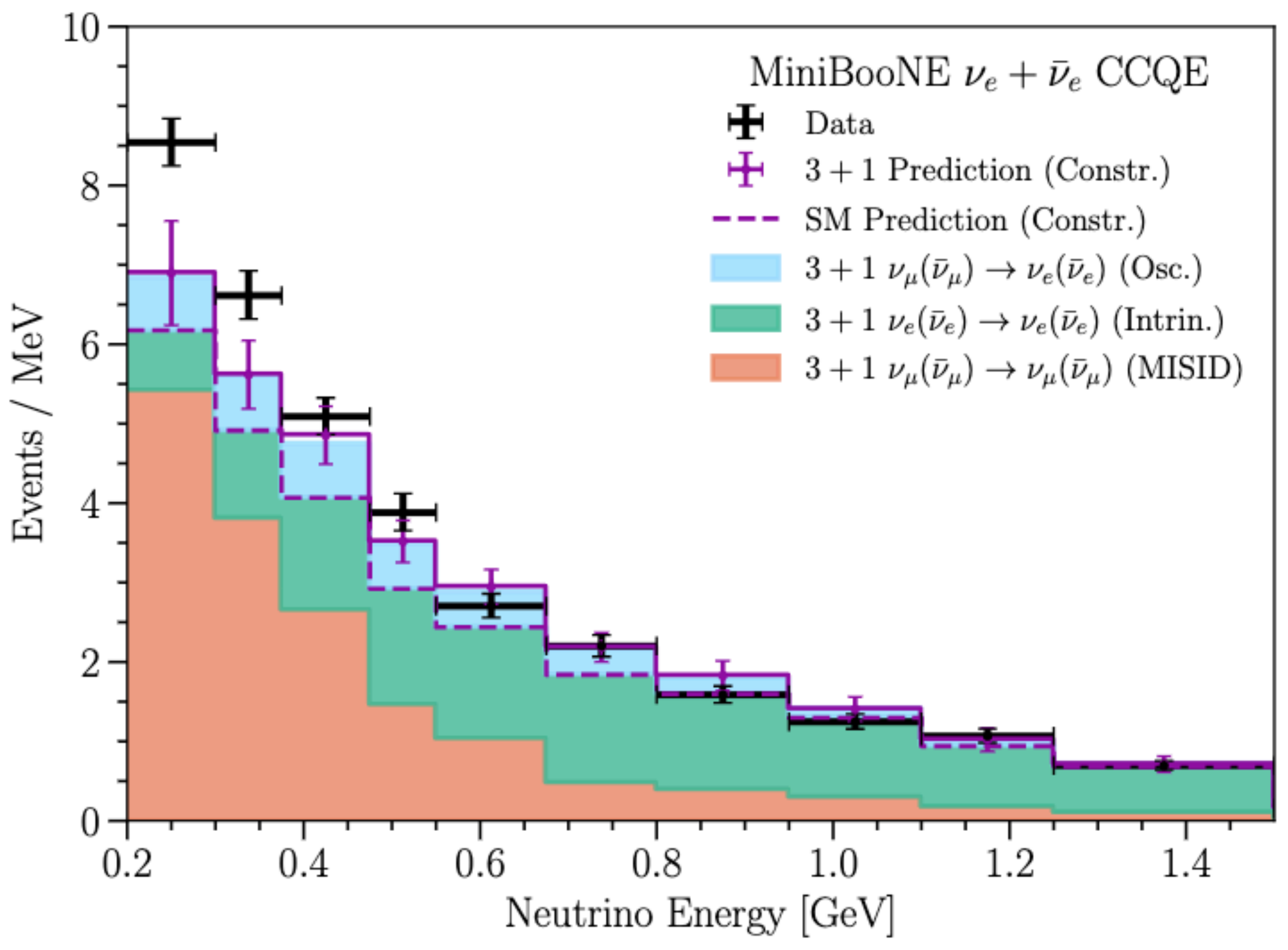
→ new neutrino interactions

Massive neutrinos are new physics!

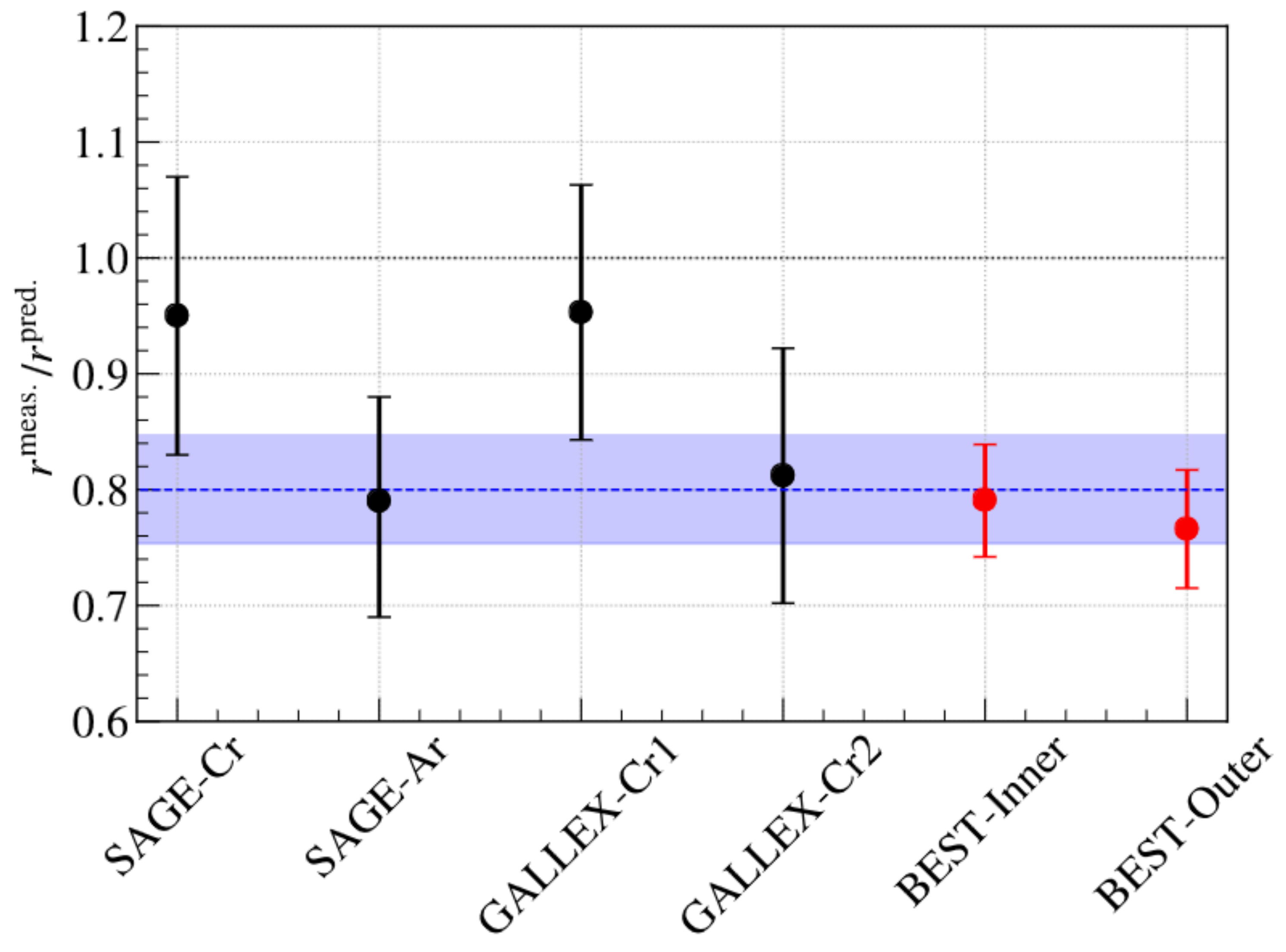
Some (persistent) anomalies in neutrino physics

Vanilla sterile neutrino explanation not a good global fit!

So far no convincing SM explanation either [Brdar, JG, Kopp 2303.05528]



[MiniBooNE+MicroBooNE 2201.01724]

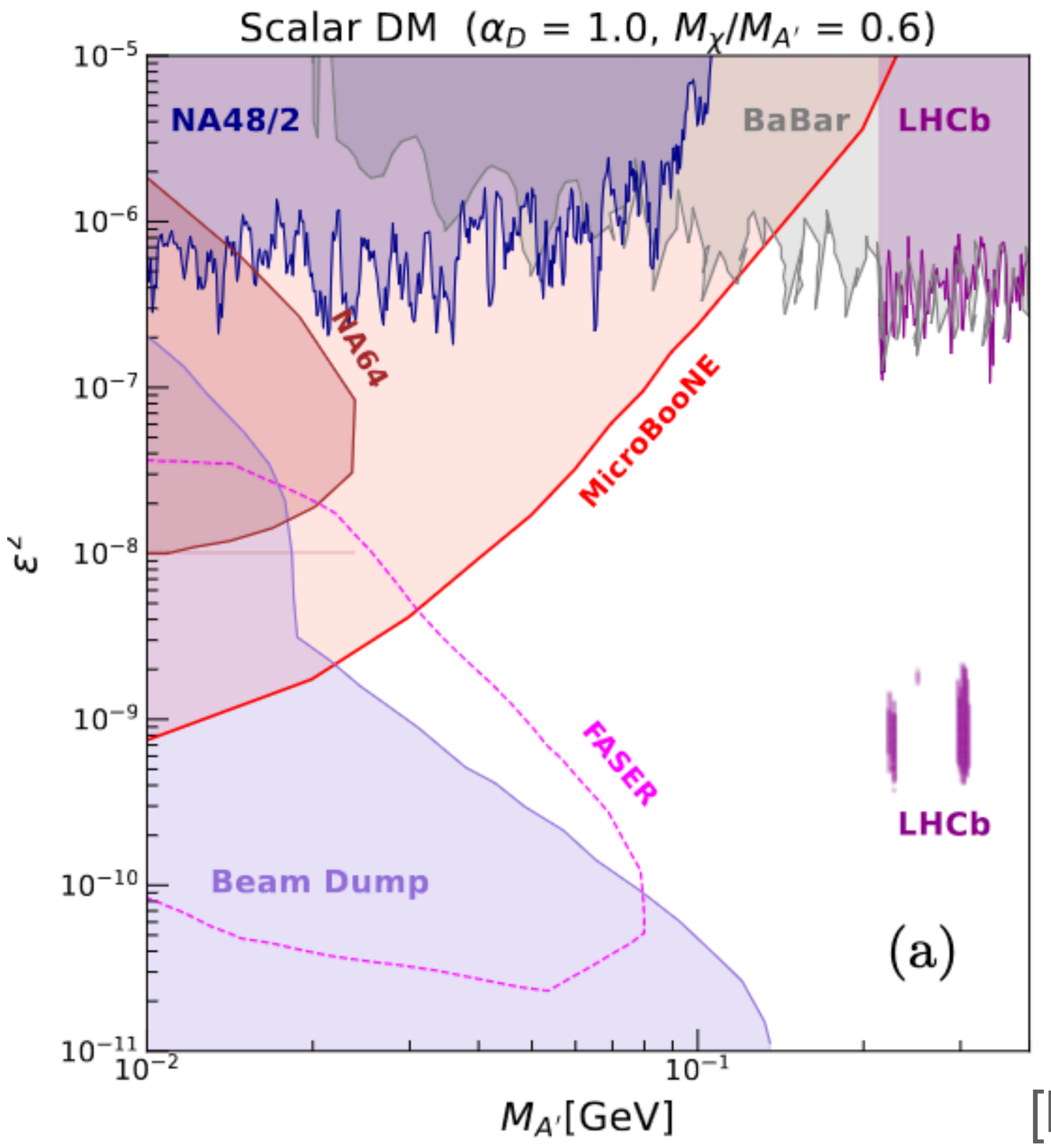


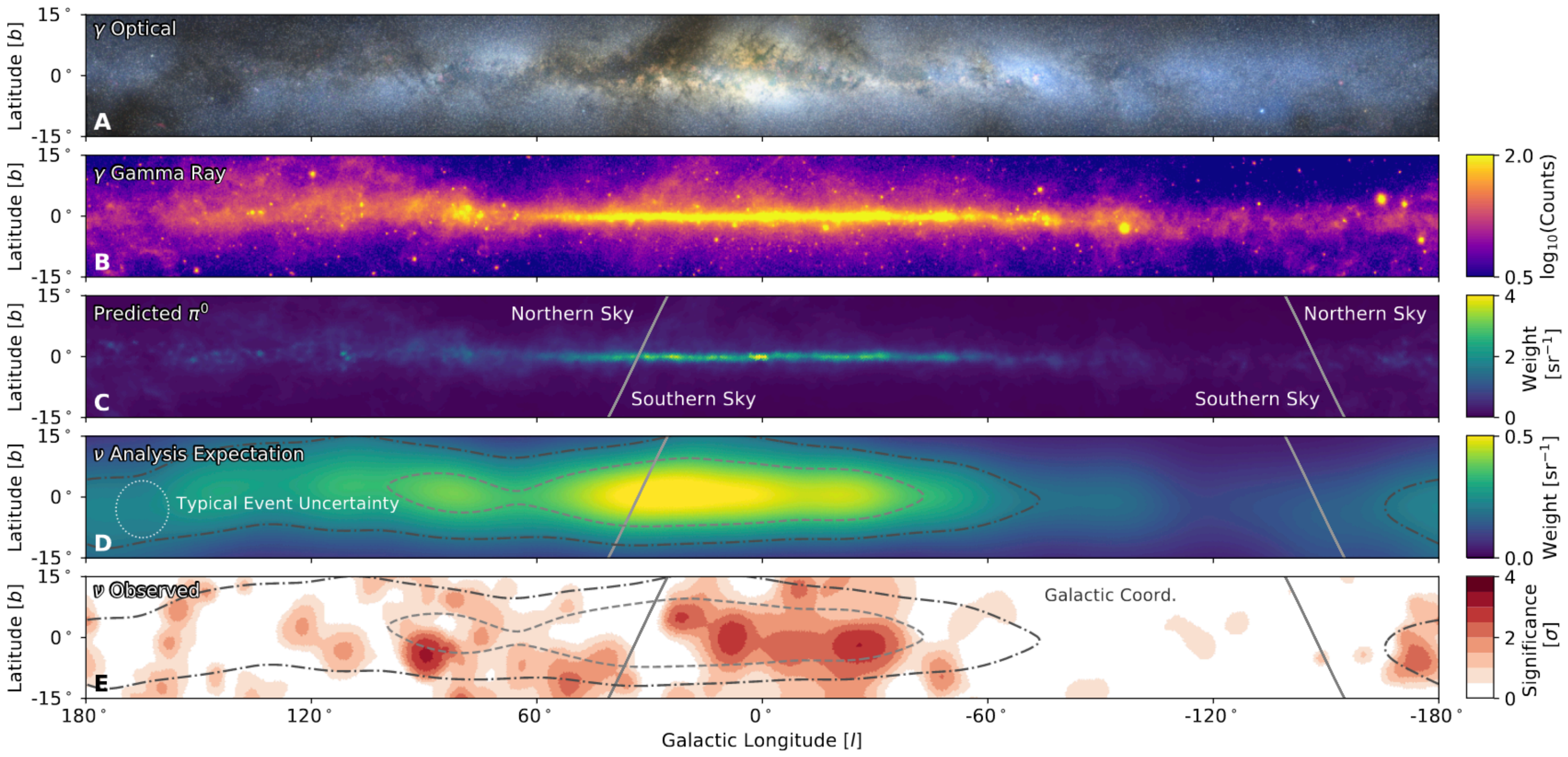
[BEST 2201.07364]

Neutrinos

Where do we stand?

Benefit of neutrino experiments for DM, axion searches, astrophysics,…





[MicroBooNE 2312.13945]

[IceCube 2307.04427]

Neutrinos

Where are we going?

Oscillations:

Long baseline (300 km, 1300 km) accelerator neutrino experiments:
Hyper-Kamiokande, DUNE
$\rightarrow$ CP phase, octant of θ_{23}, 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
$\rightarrow \theta_{23}$, mass ordering

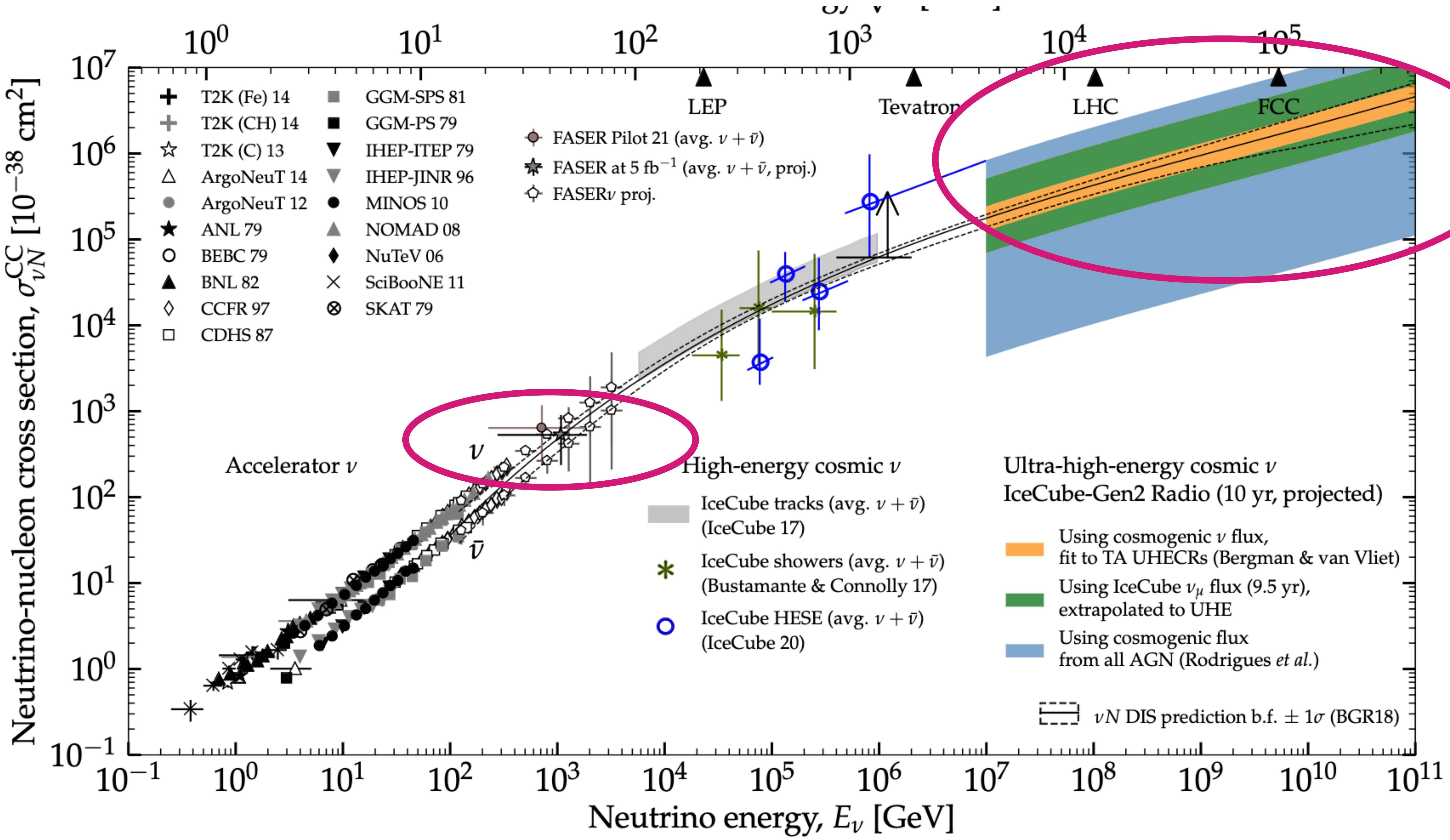
Neutrinos

Where are we going?

Scattering:

FASER: xsec at TeV energies

SHIP: measurement of ν_τ xsec



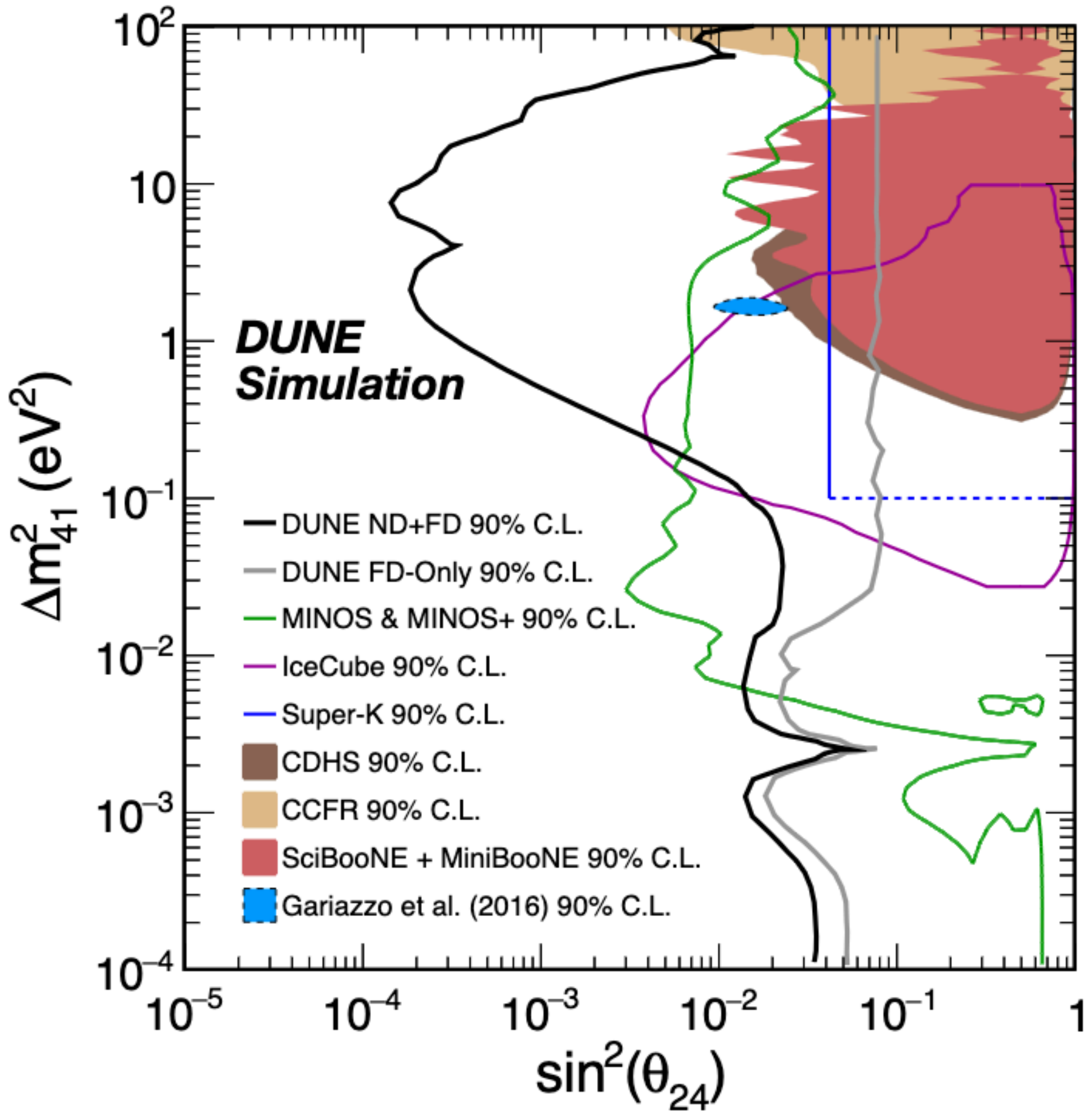
IceCube-Gen2: UHE cosmic νs

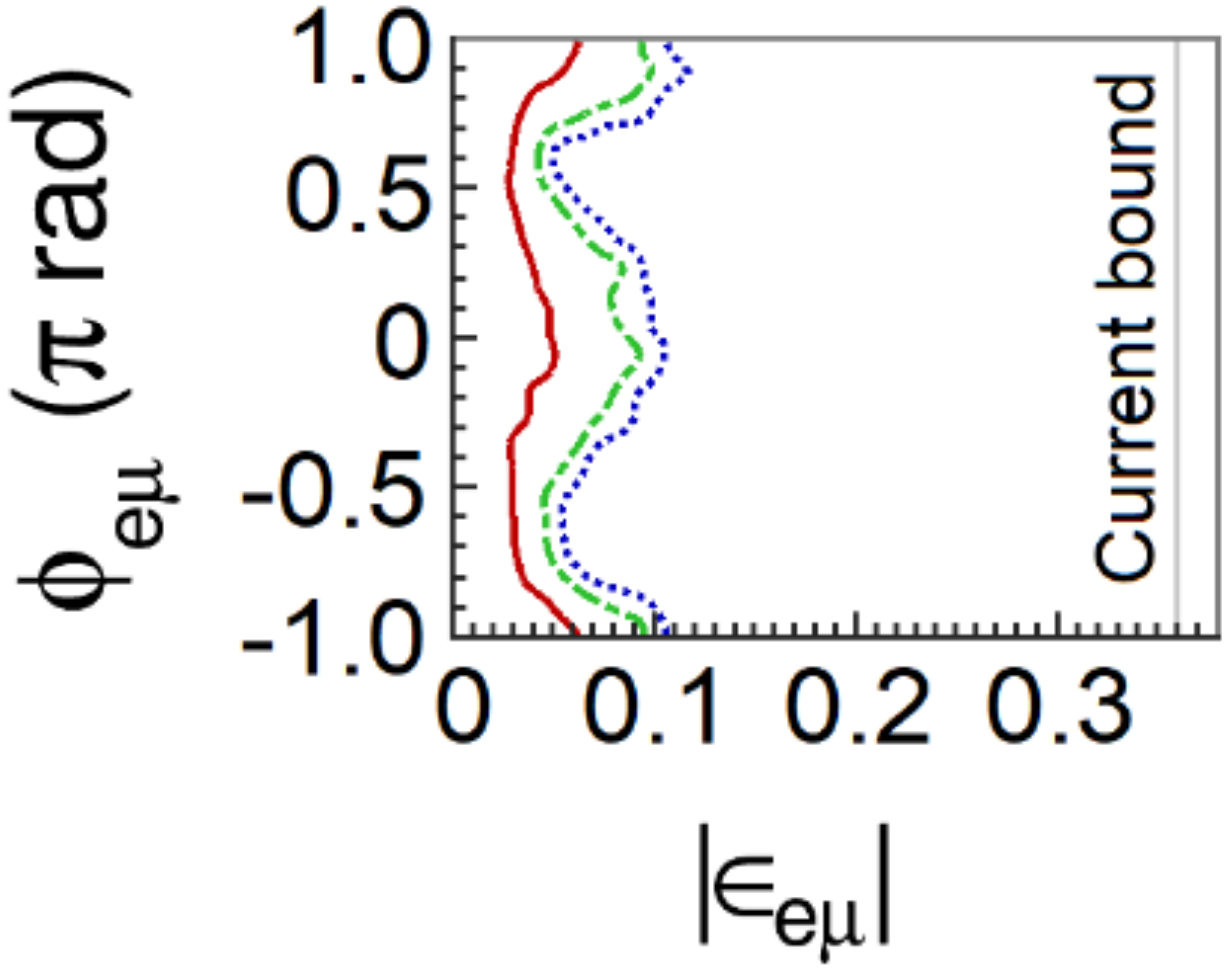
Neutrinos
Where are we going?

BSM physics:

Upcoming oscillation experiments will probe BSM physics

SBL experiments to test anomalies





[DUNE 2002.03005]

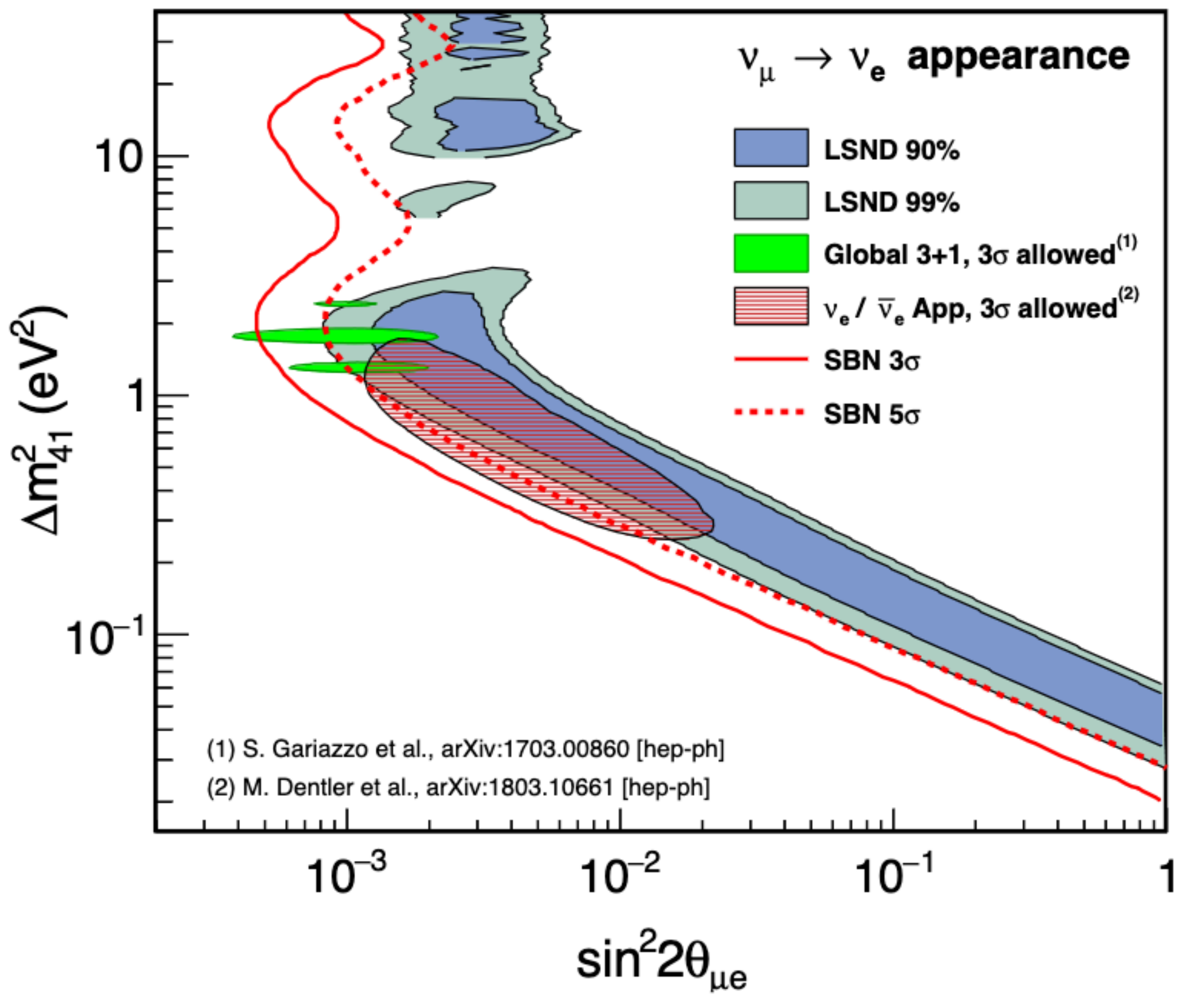


Figure 7

[Machado, Palamara, Schmitz 1903.04608]

Neutrinos
What's next?

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?

Neutrinos

What’s next?

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

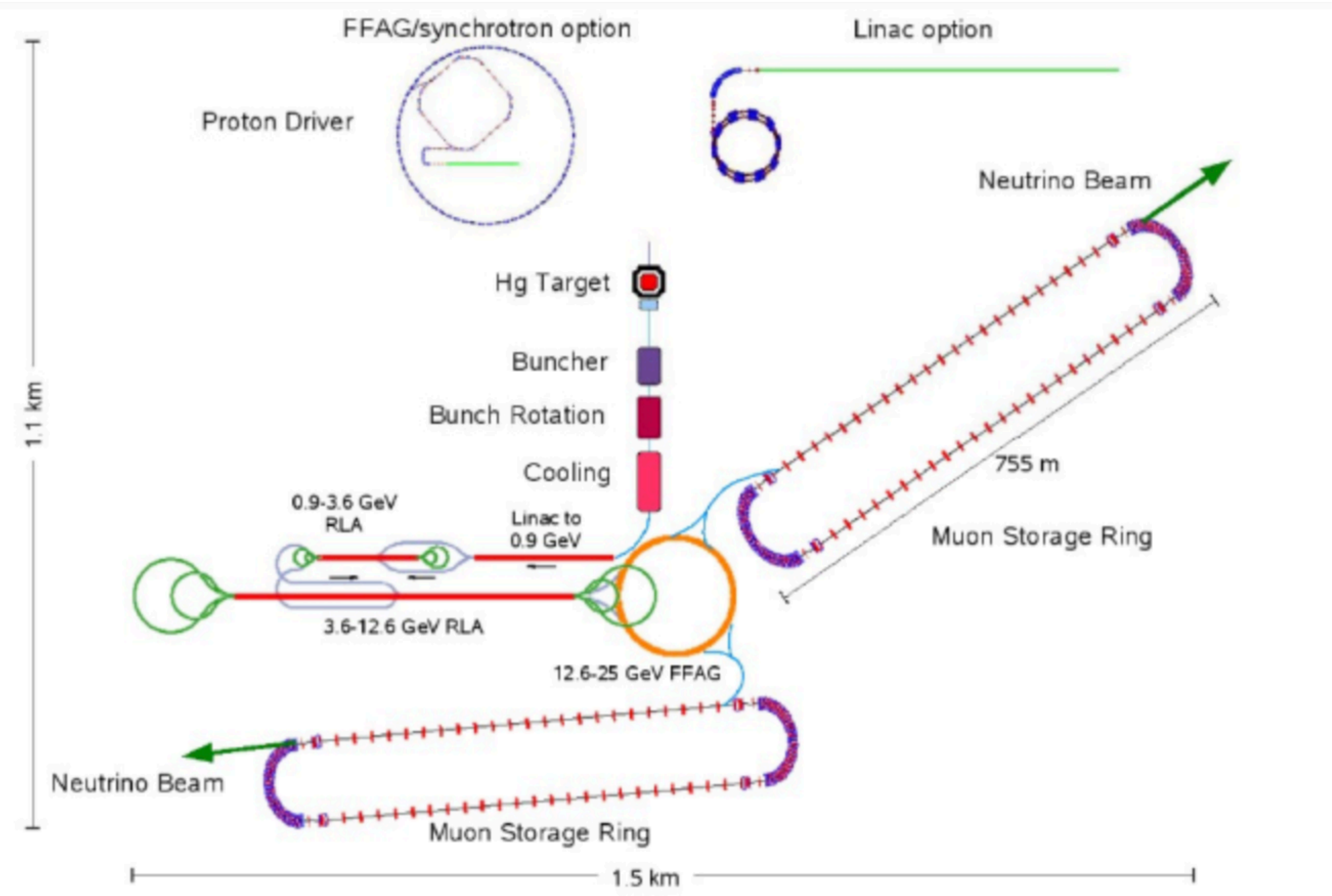
Neutrino factory

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

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 $\theta_{13} < 1^\circ$

[De Rujula, Gavela, Hernandez 9811390]

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

renewed interest in muon colliders & current knowledge of oscillation physics

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

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]

Neutrino factory

renewed interest in muon colliders & current knowledge of oscillation physics

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[2407.02572]

- Goal of NF is not discovery of CPV but precise measurements and/or
- potentially resolve any discrepancies identified in previous measurements

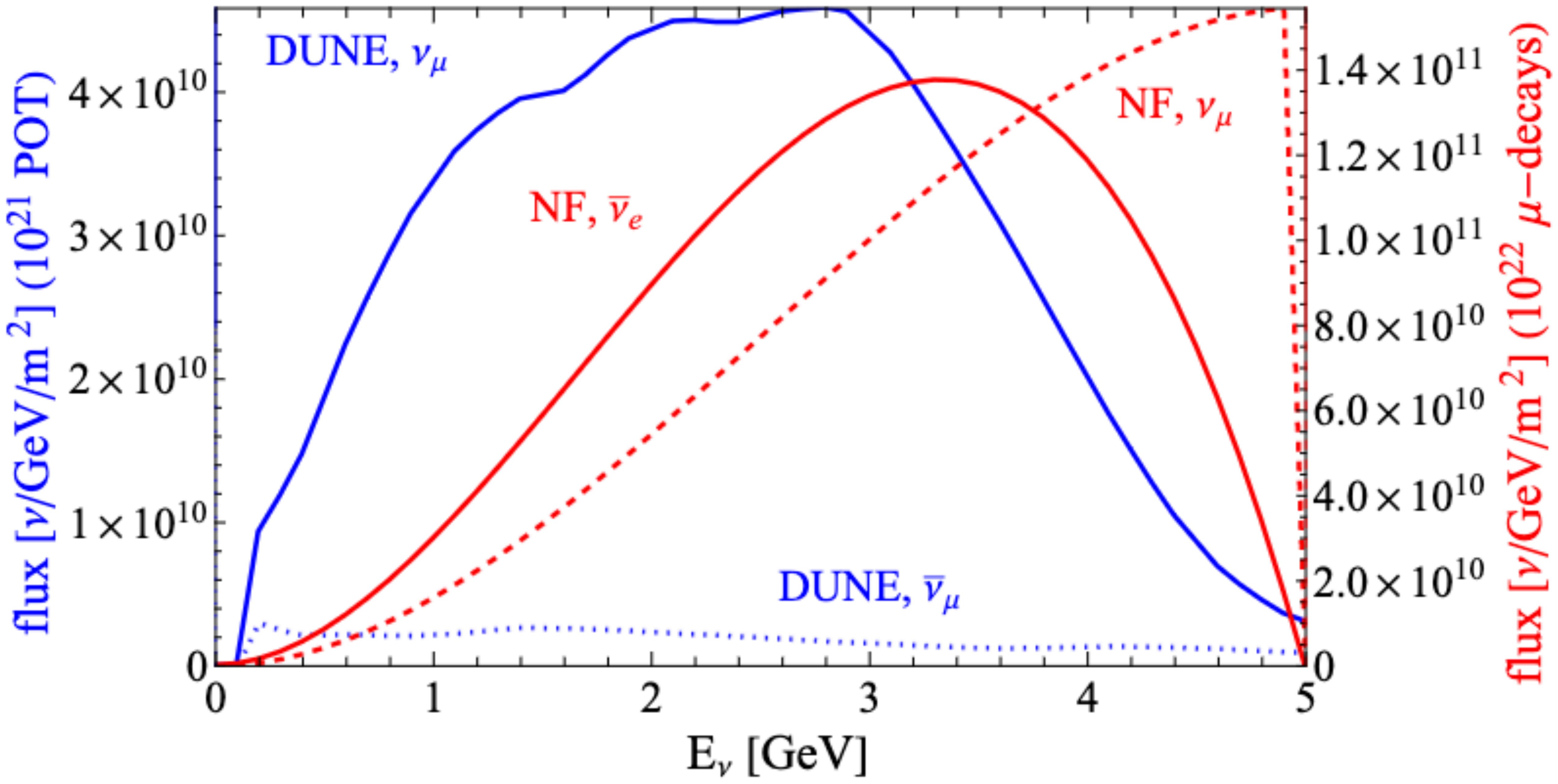
Assume DUNE+HK are successful

$\rightarrow$ Study precision on δ combining DUNE+HK+NF

Neutrino factory

NF vs neutrino beams from fixed target experiments:

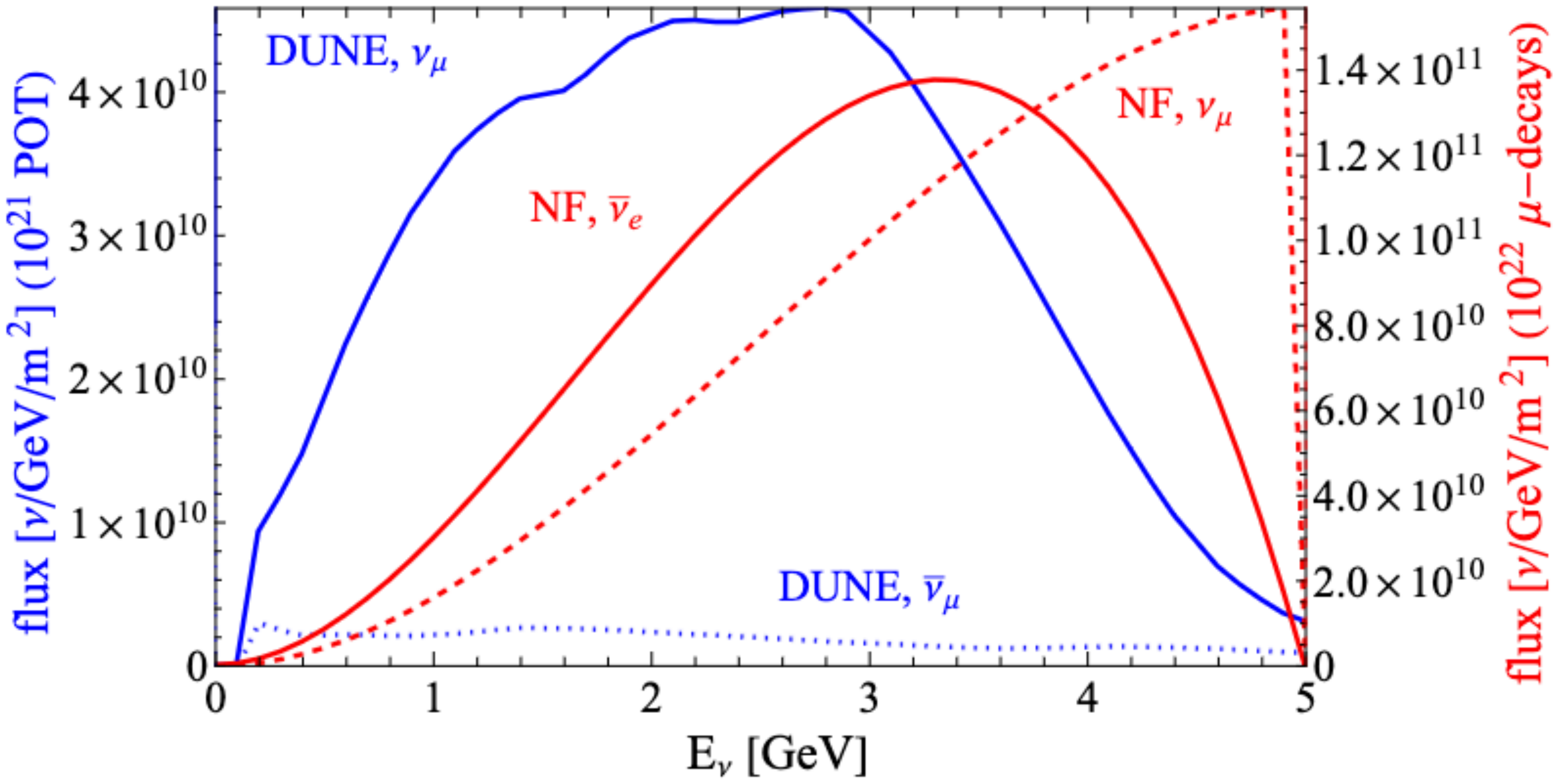
- achievable maximal neutrino energy is higher at a neutrino factory
- composition and the expected energy of the neutrino beam is well known
- equally many neutrinos as anti-neutrinos



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

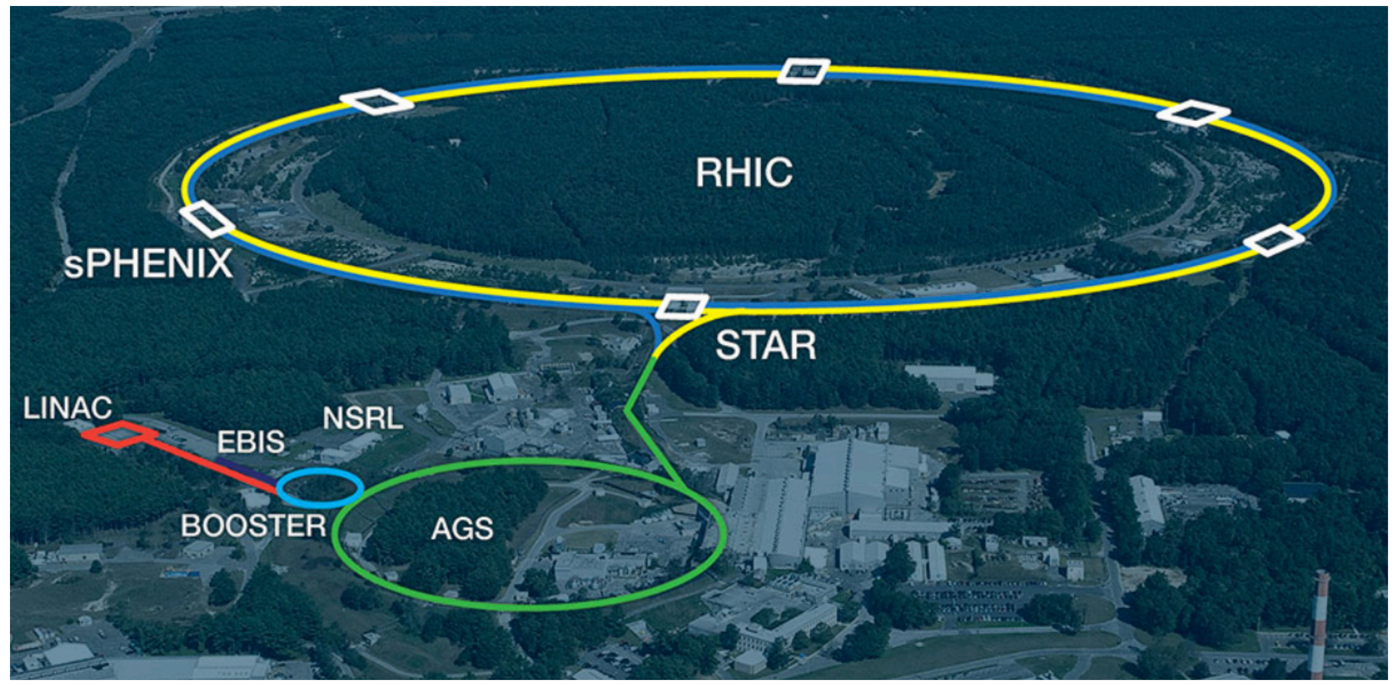


Neutrino factory
Setup

Study two setups:

- neutrino source at Fermilab, far detector at SURF $\rightarrow$ baseline: 1284.9 km

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



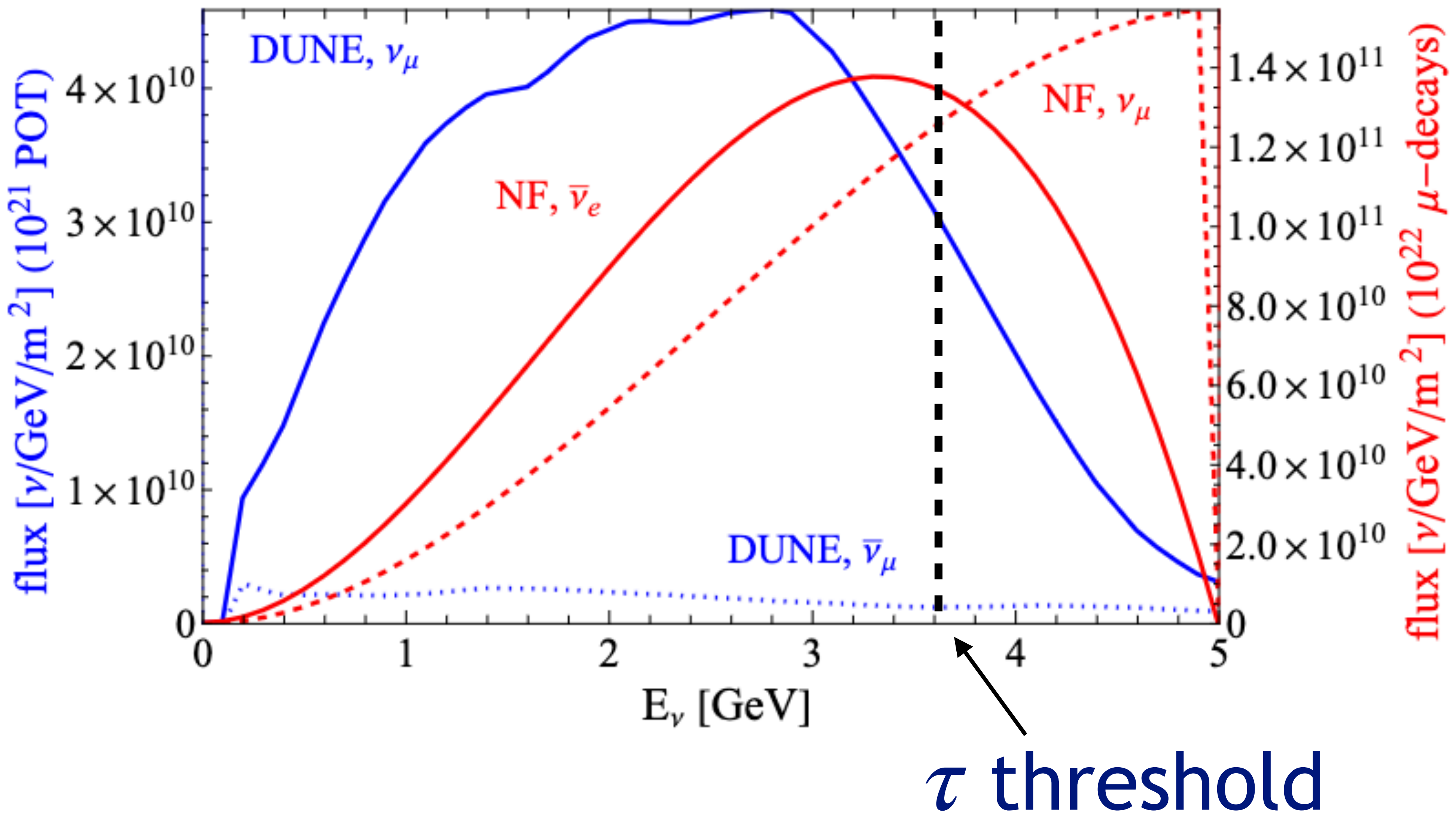
Neutrino factory
Setup

Far detector:

- LArTPC, total fiducial target mass of 40 kT
- assume 10^{21} muon (or anti-muon) decays per year

Tau neutrino appearance as background

Fix MO to NO



Neutrino factory
Results

Optimal muon energy to maximize sensitivity to δ

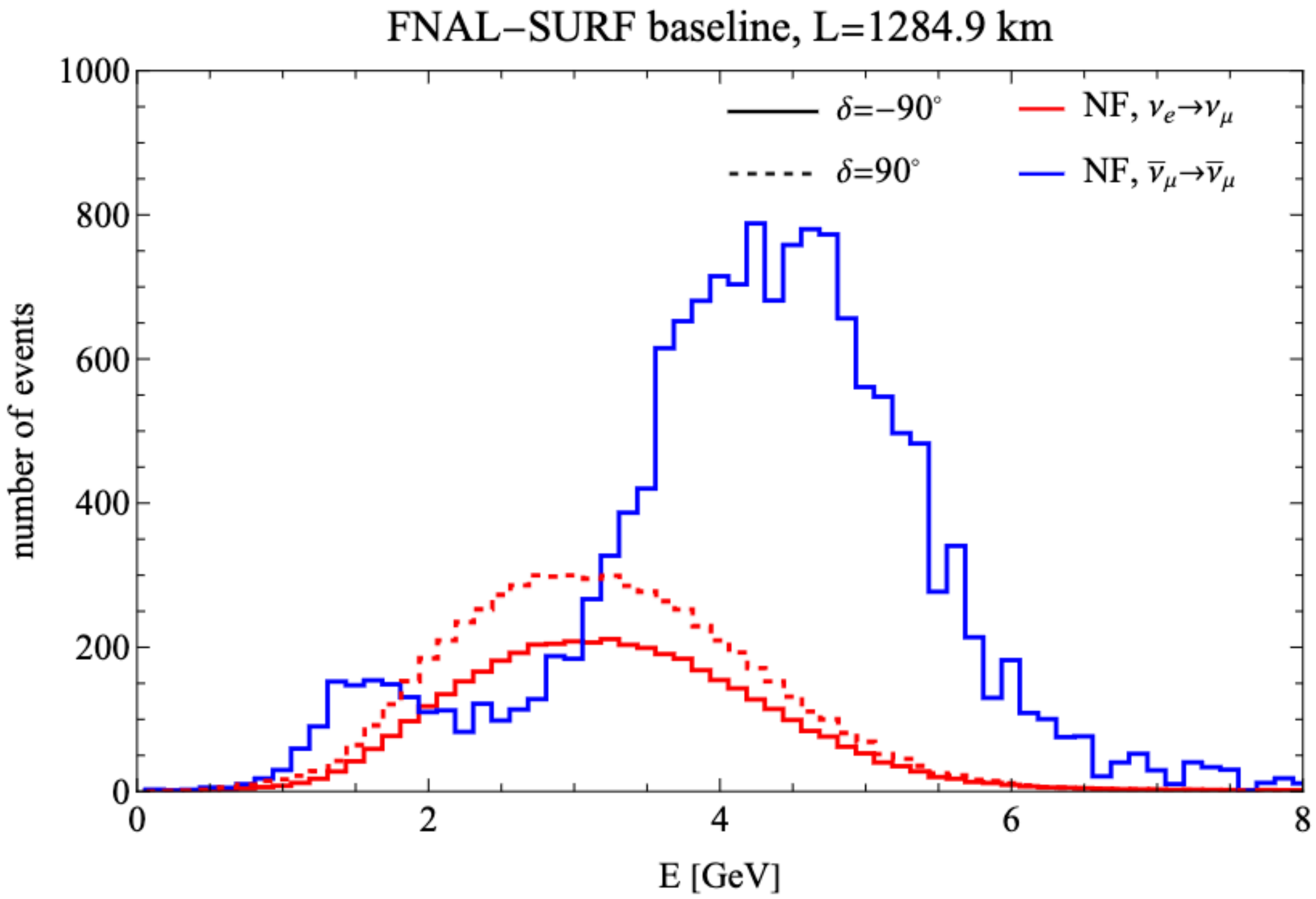
$$E_\mu = 5 \text{ GeV (FNAL-SURF)}$$

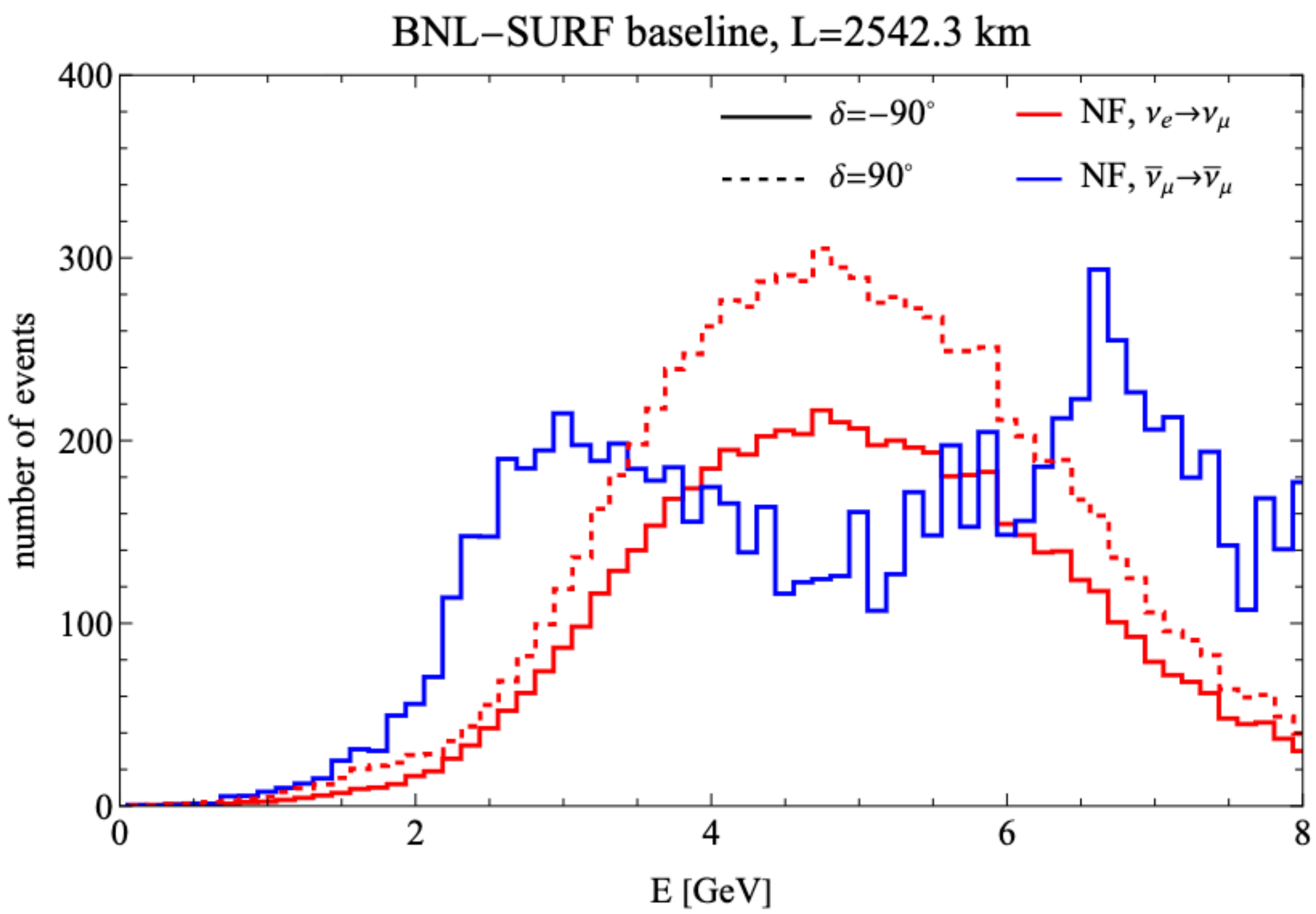
$$E_\mu = 8 \text{ GeV (BNL-SURF)}$$

Running time neutrino: antineutrino 1:1

Depending on physics case these values might slightly change

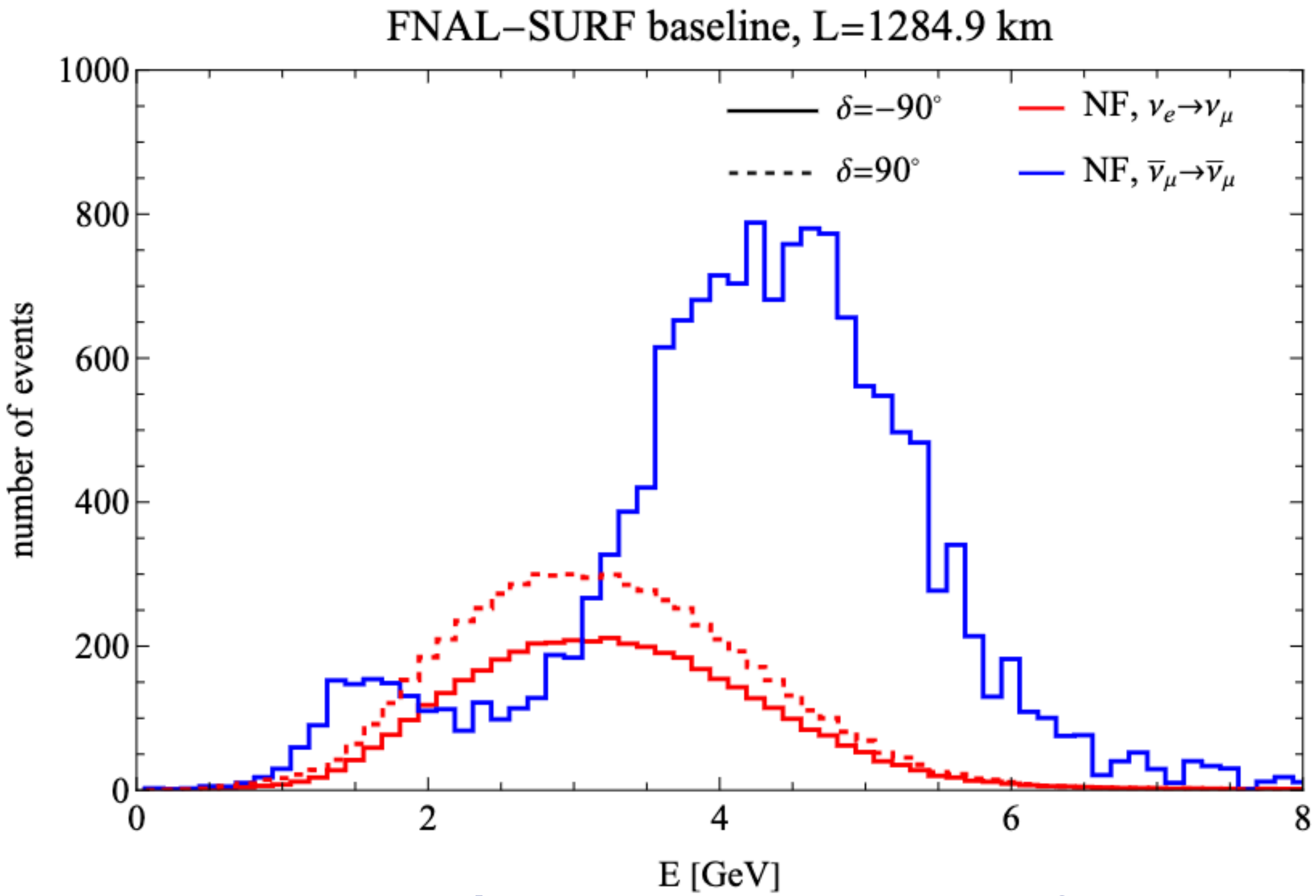
Neutrino factory
Results

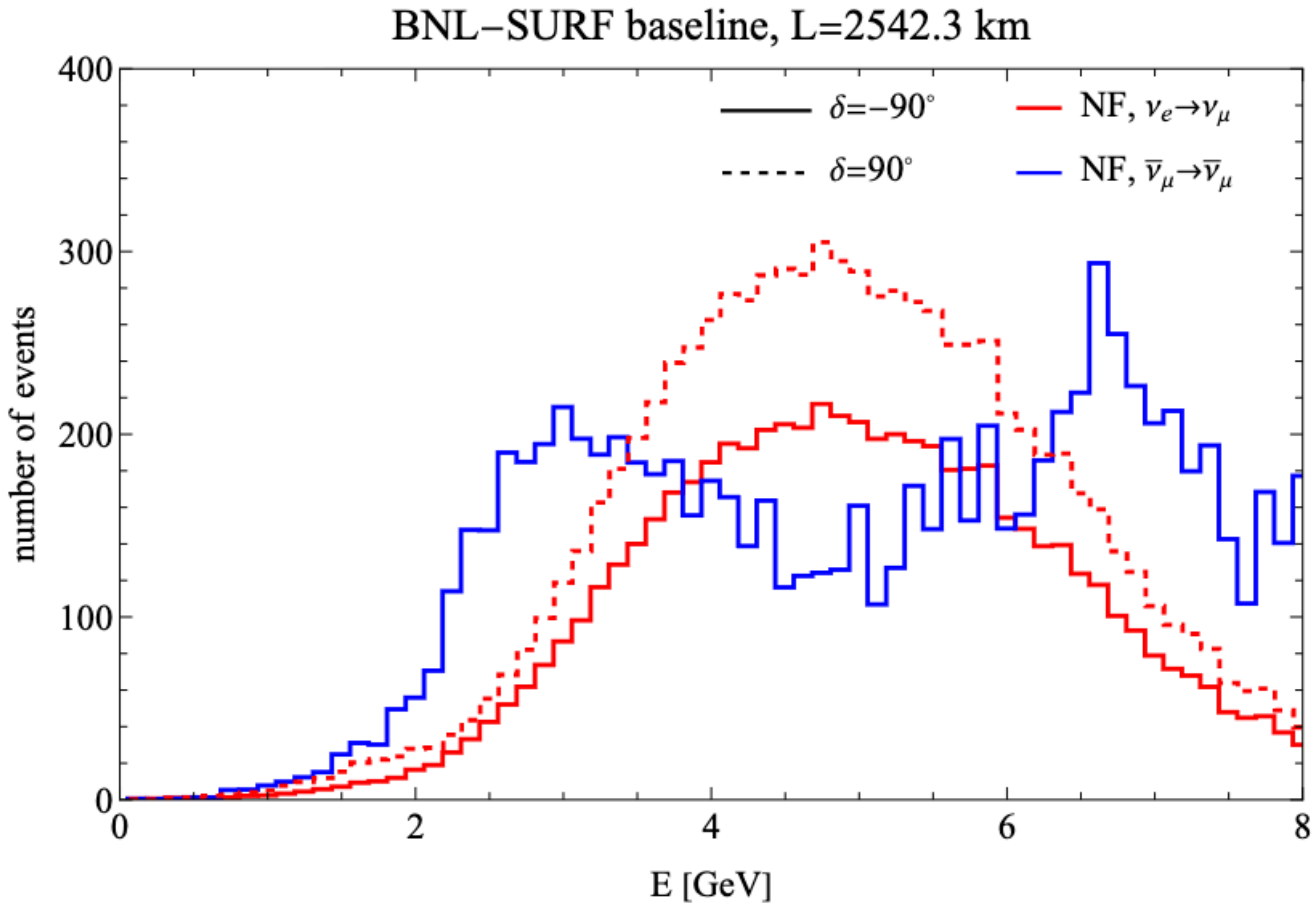




Neutrino factory

Results





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

Appearance peaks in disappearance dip for BNL configuration $\to$ CID less relevant

Neutrino factory
Results

Study precision of δ using the combination of DUNE+HK+NF

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

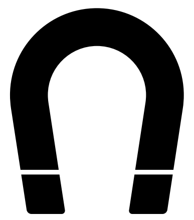
HK: 190 kT water detector, 1.3 MW beam running for 10 years with

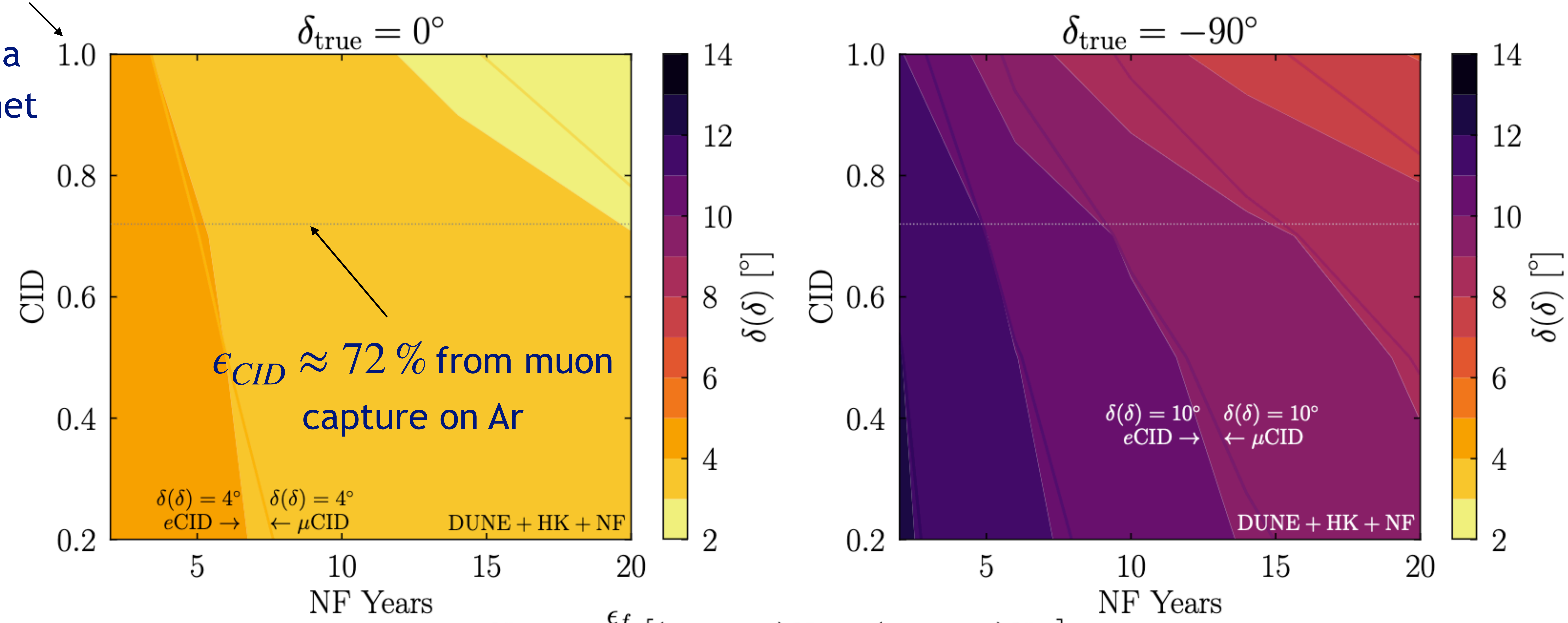
$$\nu : \bar{\nu} = 1 : 3$$

Neutrino factory

Results

Use a magnet

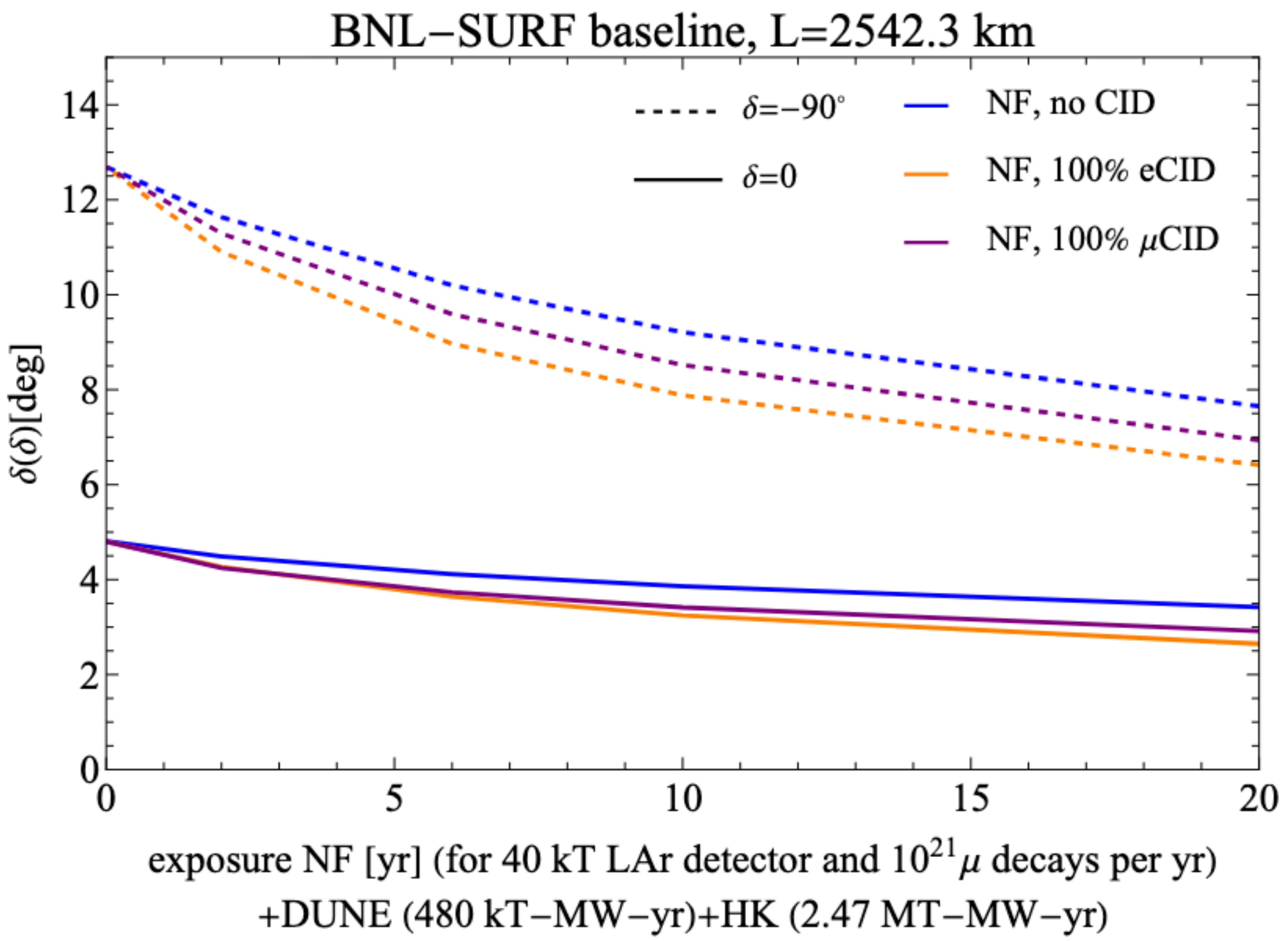




$$N_{\nu_{\rm f,obs}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\nu_f} + (1-\epsilon_{CID})N_{\bar{\nu}_f}\right]$$

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

Neutrino factory
Results



- CID can improve the precision on δ by 15-20%
- Slightly more precision at BNL setup due to more matter effects which increases probability

Neutrino factory
Results

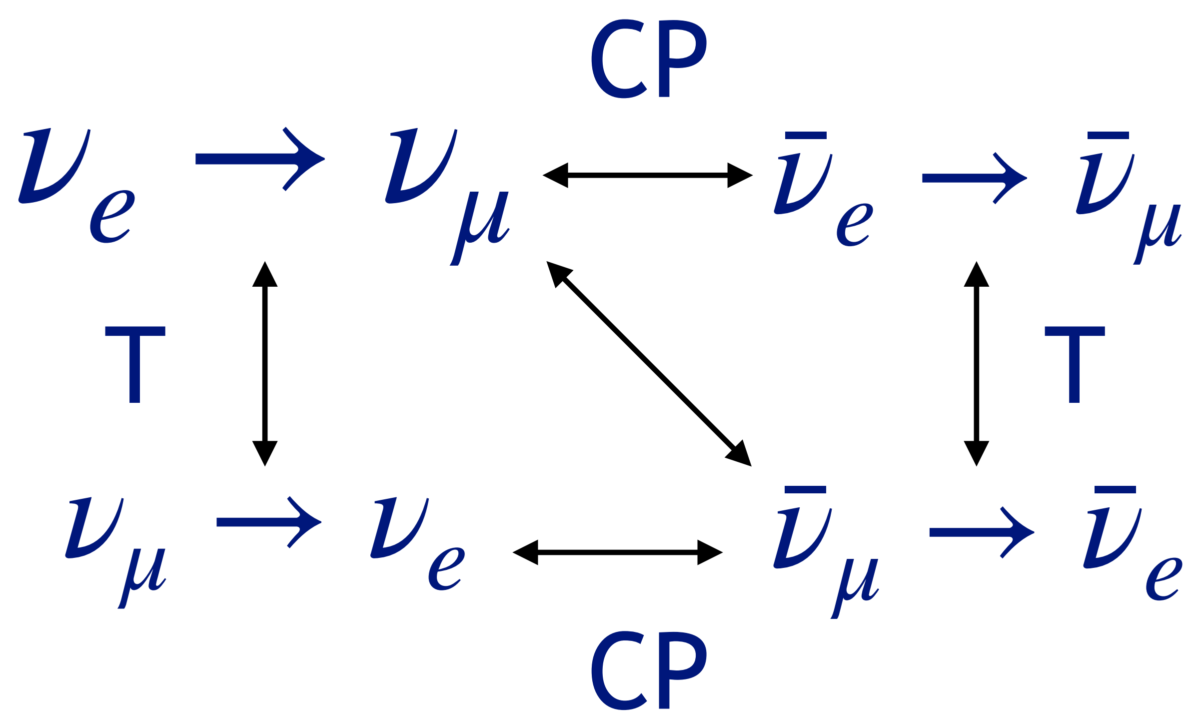
Sensitivity to δ mostly comes

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

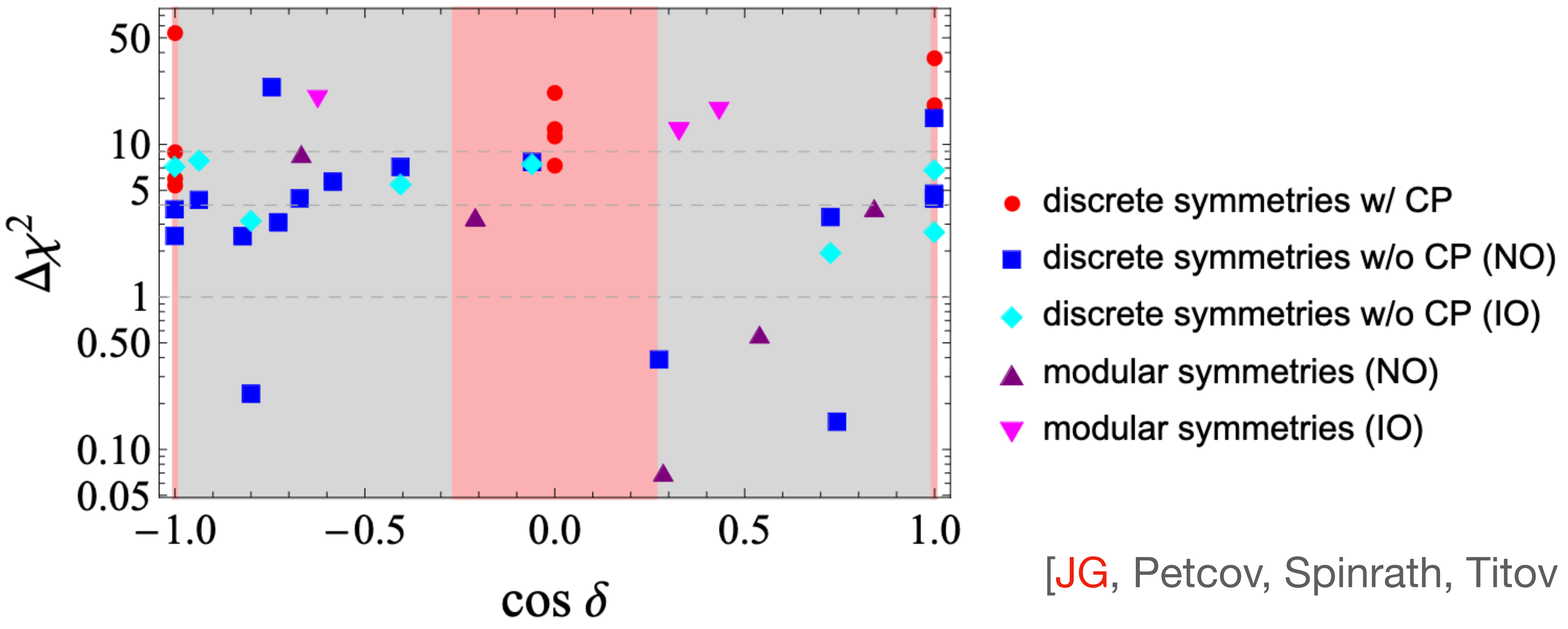
Combine with DUNE, HK to test CPT invariance

Neutrino factory
Results

CP phase predicted in flavor models

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

$\Rightarrow$ 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

CP phase predicted in flavor models

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

Example:

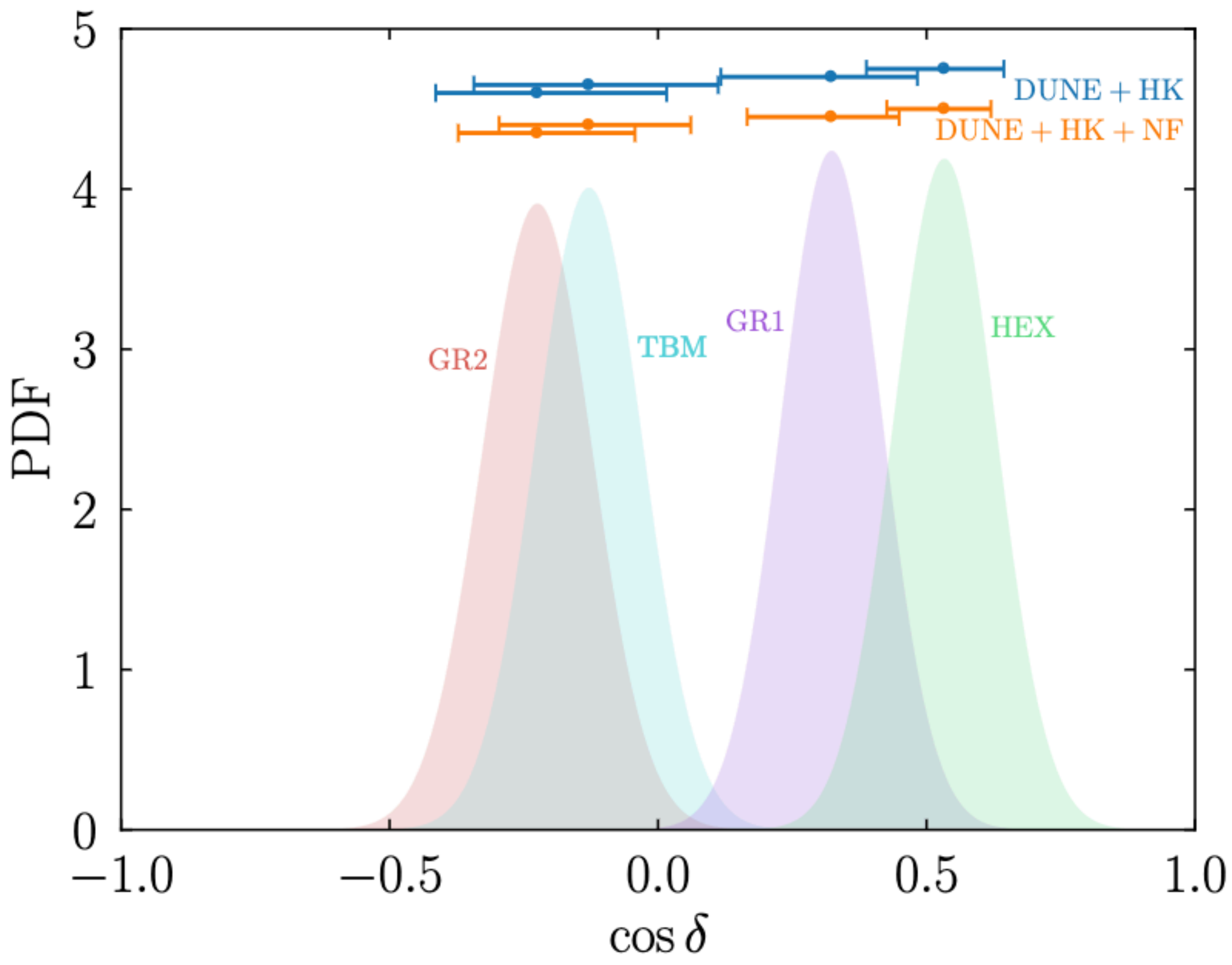
Neutrino mixing matrix predicted by discrete flavor symmetries

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



→ improved distinction power of models when including NF

Neutrino factory

Results

$\delta = (-90°,\ 0)$	no CID	100% eCID	100% μCID
HK	$(20.8°, 5.6°)$	–	–
DUNE	$(17.7°, 9.3°)$	–	–
DUNE+HK	$(13.9°, 4.8°)$	–	–
DUNE+HK+NF(FNAL)	$(10.6°, 3.8°)$	$(8.3°, 3.1°)$	$(8.9°, 3.3°)$
DUNE+HK+NF(BNL)	$(9.2°, 3.9°)$	$(7.9°, 3.3°)$	$(8.5°, 3.4°)$

CID increases precision on δ however not as essential as emphasized in the literature >10 years ago due to good energy resolution of LAr

Neutrino factory
Results

- NF improves 1σ uncertainty on θ_{23}
  by factor of two (three) from 480 kT-MW-yr of DUNE
  with a total exposure of 80×10^{23} μ-kT-year for a baseline FNAL(BNL)-SURF

- NF has only limited sensitivity to the solar parameters, just like DUNE
  $\rightarrow$ solar priors important

[JG, Denton 2302.08513]

Results could even be even better due to future improvement in LAr technology!

Neutrino factory
Results

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

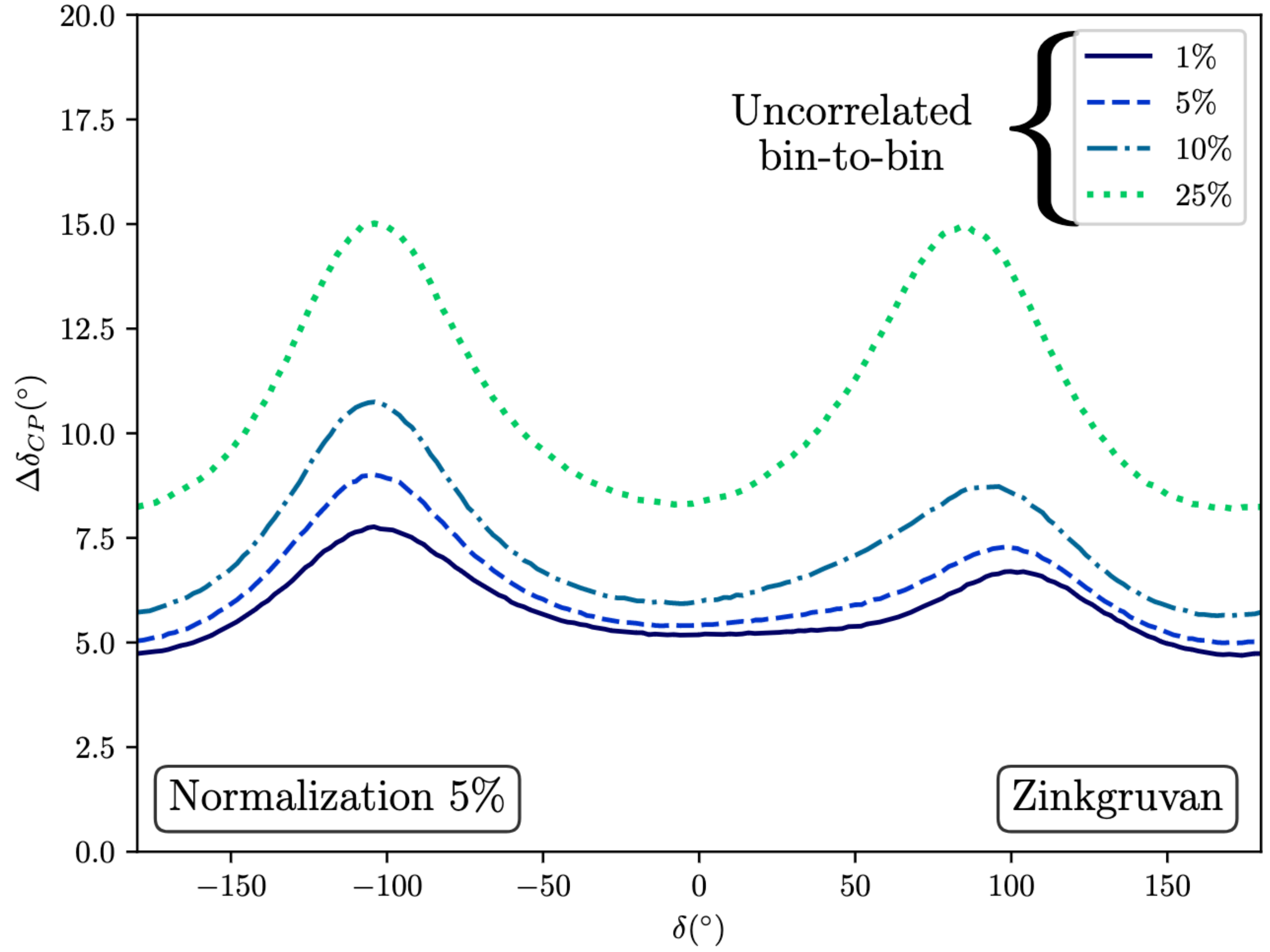
NF interesting possibility as a future oscillation experiment

- 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!

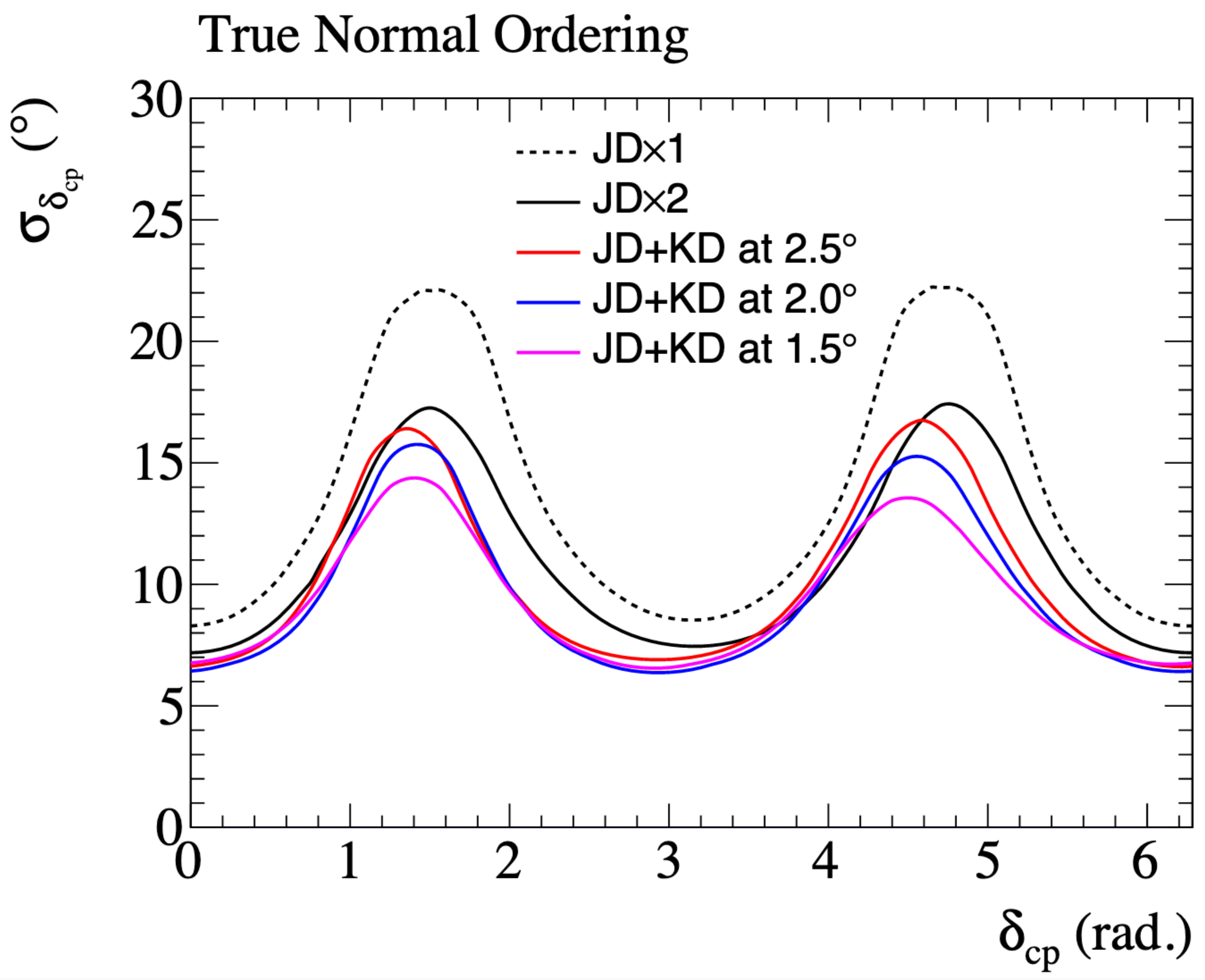
Appendix

- ESSnuSB



[ESSnuSB 2303.17356]

- T2HKK



[HK 1611.06118]

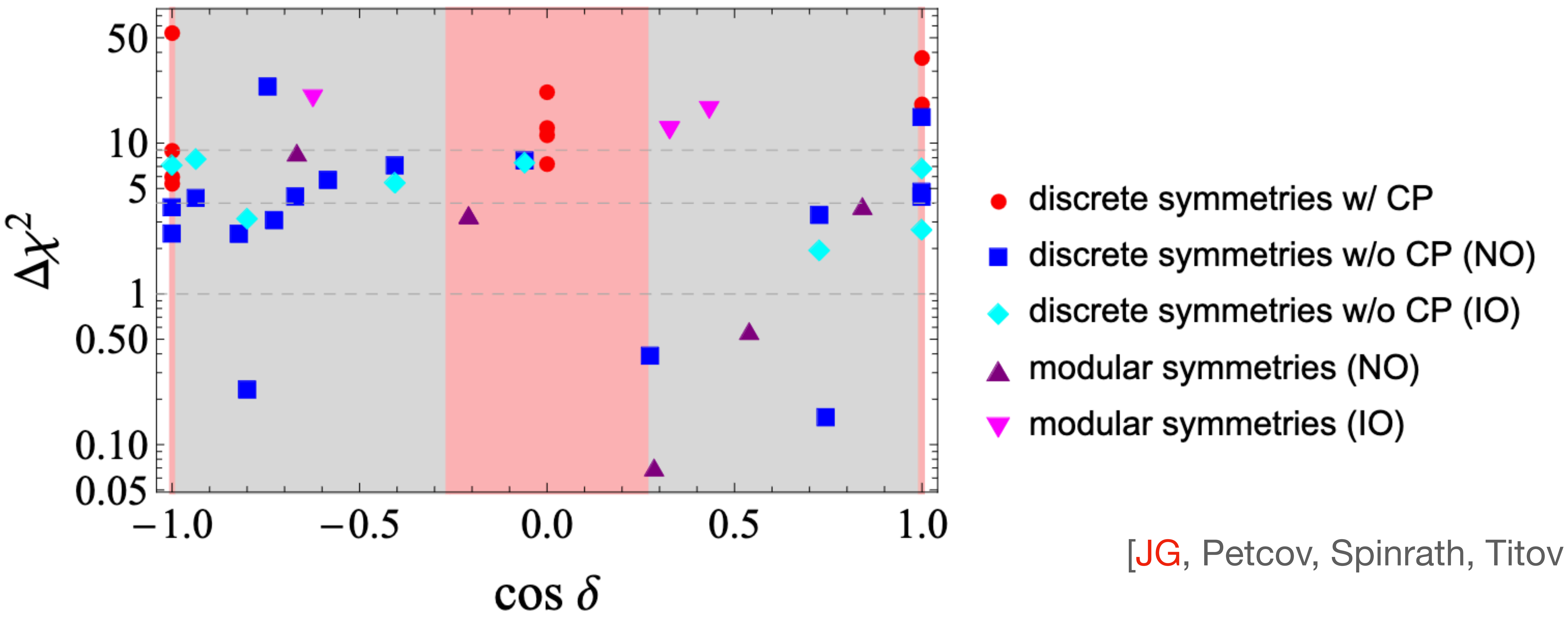
Future of oscillation physics

- 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]

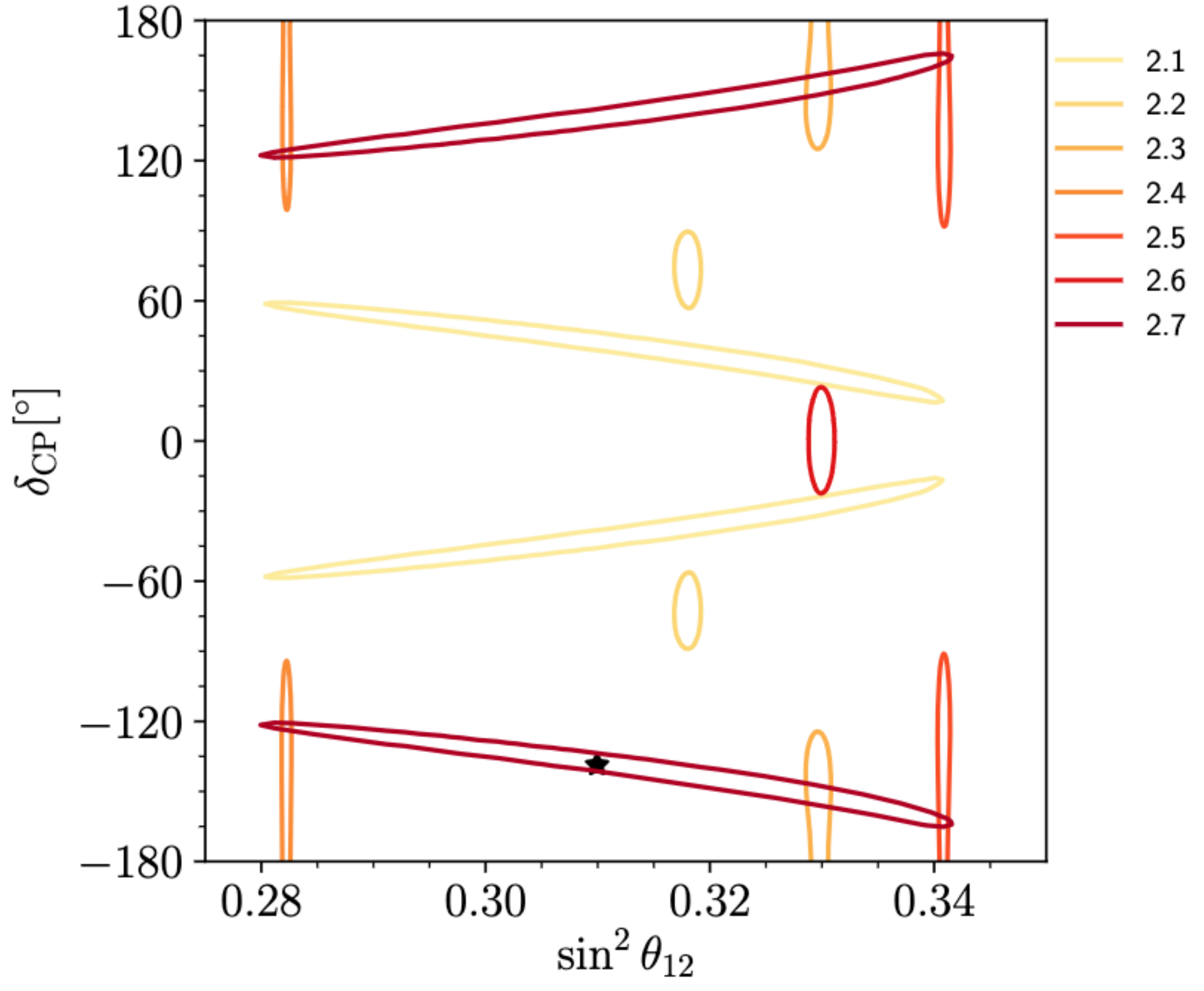
Future of oscillation physics

- Distinguish different flavor models with precision oscillation measurements

Sum rules can be used to distinguish different mixing pattern

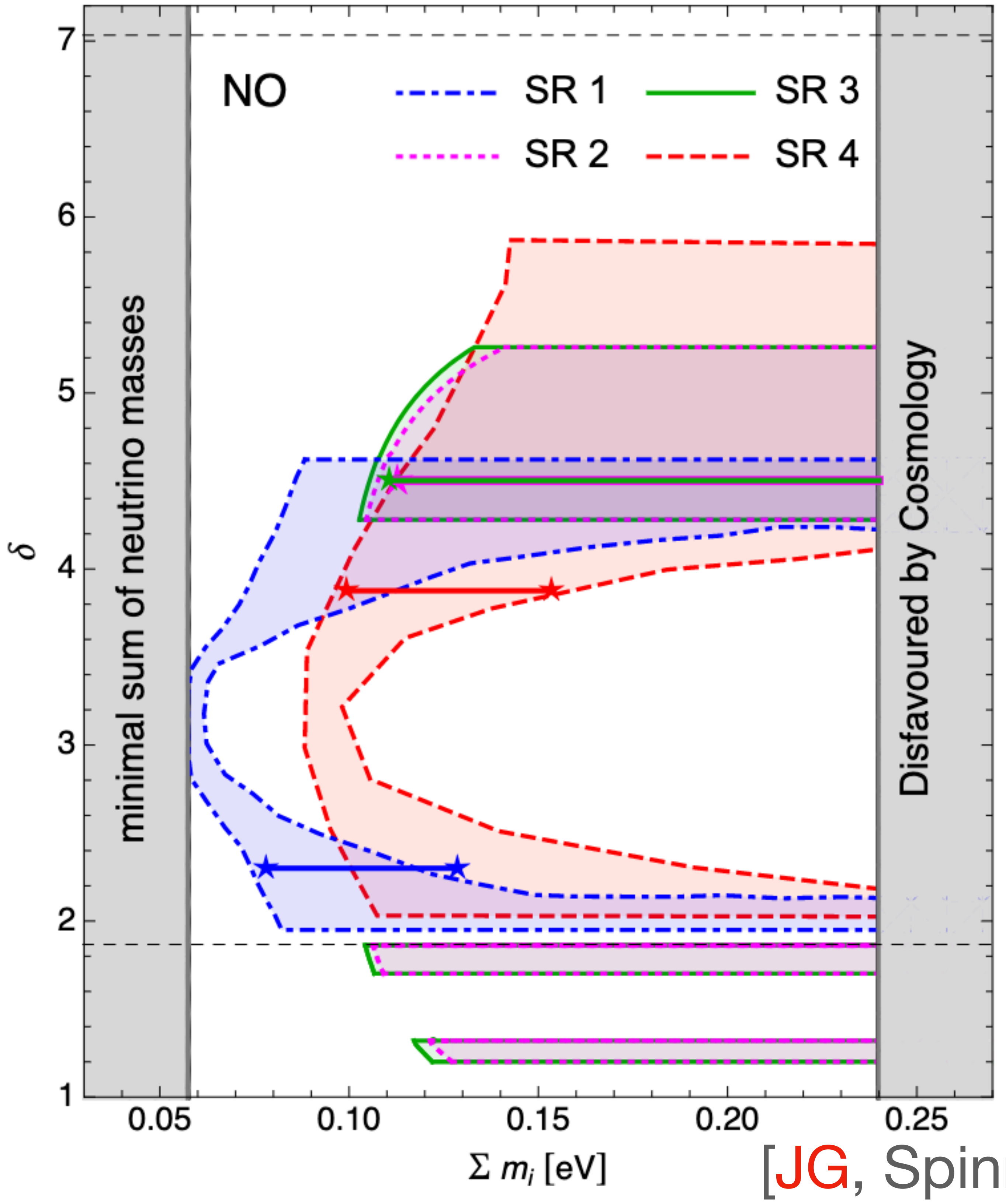
Future experiments can disentangle different models

at $>5\sigma$!



[Blennow, Ghosh, Ohlsson, Titov 2004.00017]

Correlations can be probed!

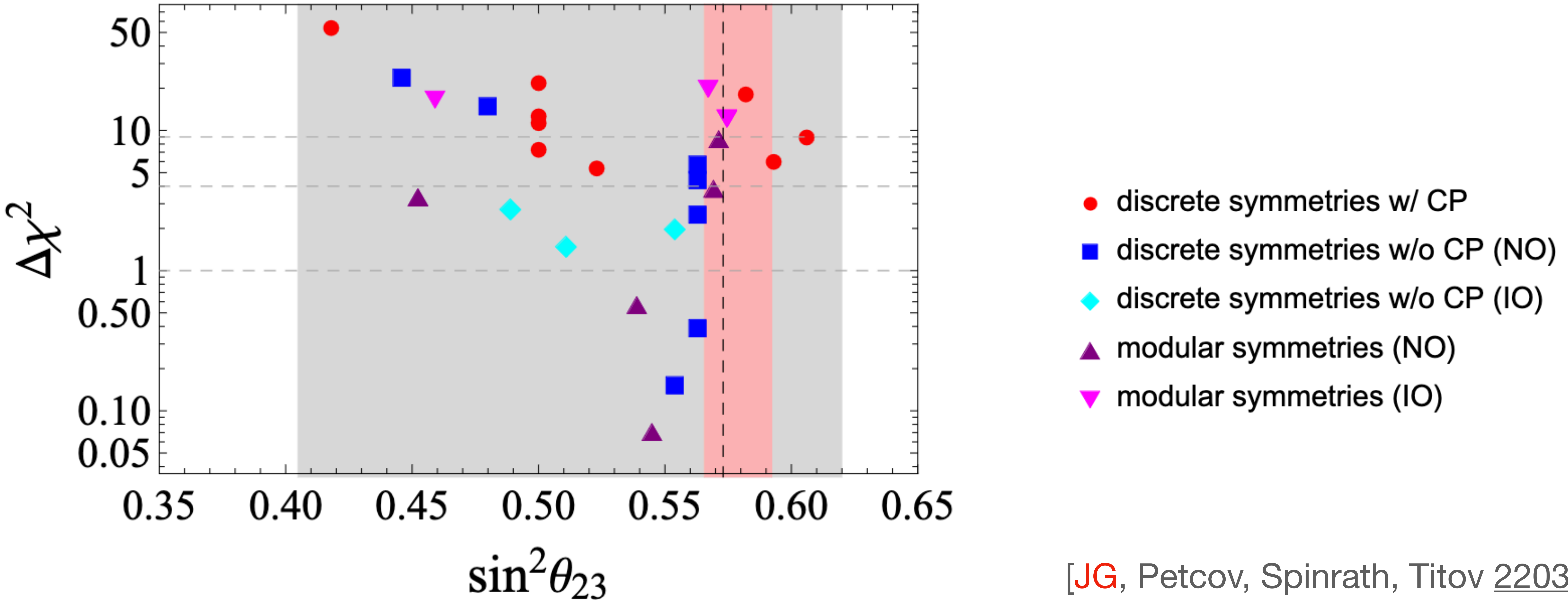


[JG, Spinrath 2012.04131]

Appendix: Mixing sum rules

Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models

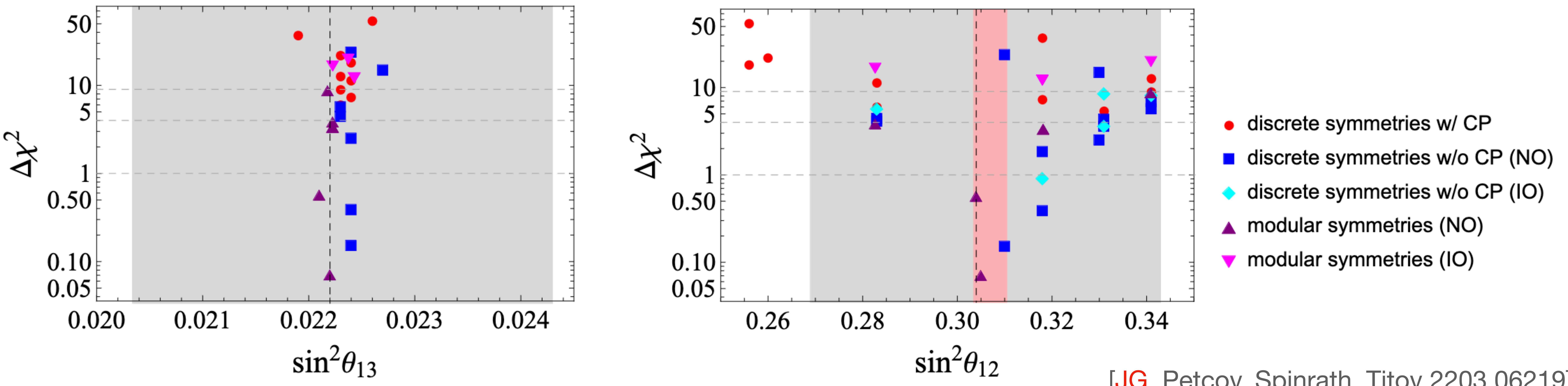


[JG, Petcov, Spinrath, Titov 2203.06219]

Appendix: Mixing sum rules

Sum rules can be used to distinguish different mixing pattern

Future experiments can disentangle different models



[JG, Petcov, Spinrath, Titov 2203.06219]