FERMILAB-SLIDES-24-0143-T

How Matter Matters:

The Story of Time Invariance Violation in Neutrino Oscillations

Olivia Meredith Bitter

New Perspectives 2024

Neutrino pictures: https://www.particlezoo.net/

Motivation from the CPT symmetry story

If we follow that CPT is a
fundamental symmetry.

C P T

- ✓ Charge conjugation
- ✓ Parity
- ✓ Time reversal

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Charge parity transform (CP) alone is violated in the weak sector.

CPT + ~~CP~~

- ✓ Charge conjugation
- ✓ Parity
- ✓ Time reversal

Motivation from the CPT symmetry story

If we follow that CPT is a fundamental symmetry.

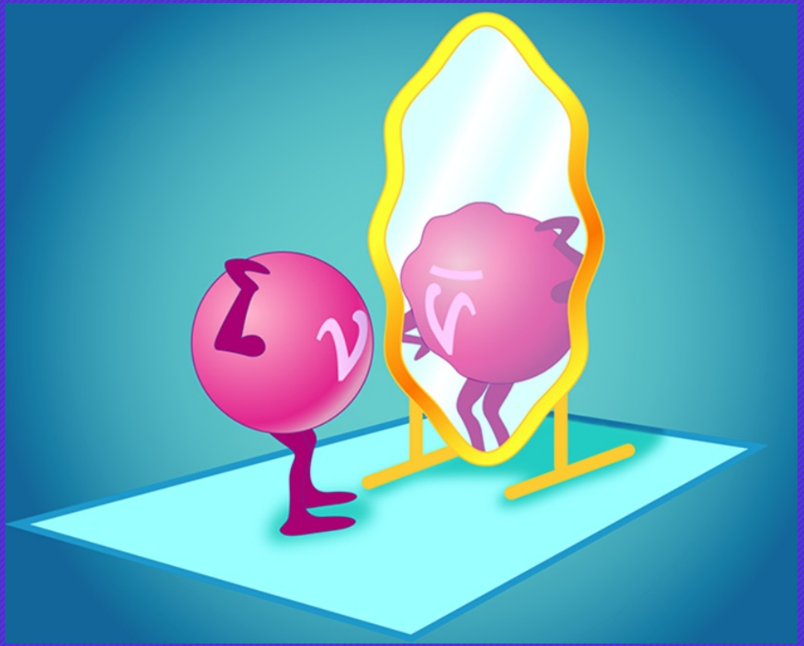
Charge parity transform (CP) alone is violated in the weak sector.

Time reversal transforms alone should also be violated in weak interactions, to preserve such an overall symmetry.

- ✓ Charge conjugation
- ✓ Parity
- ✓ Time reversal

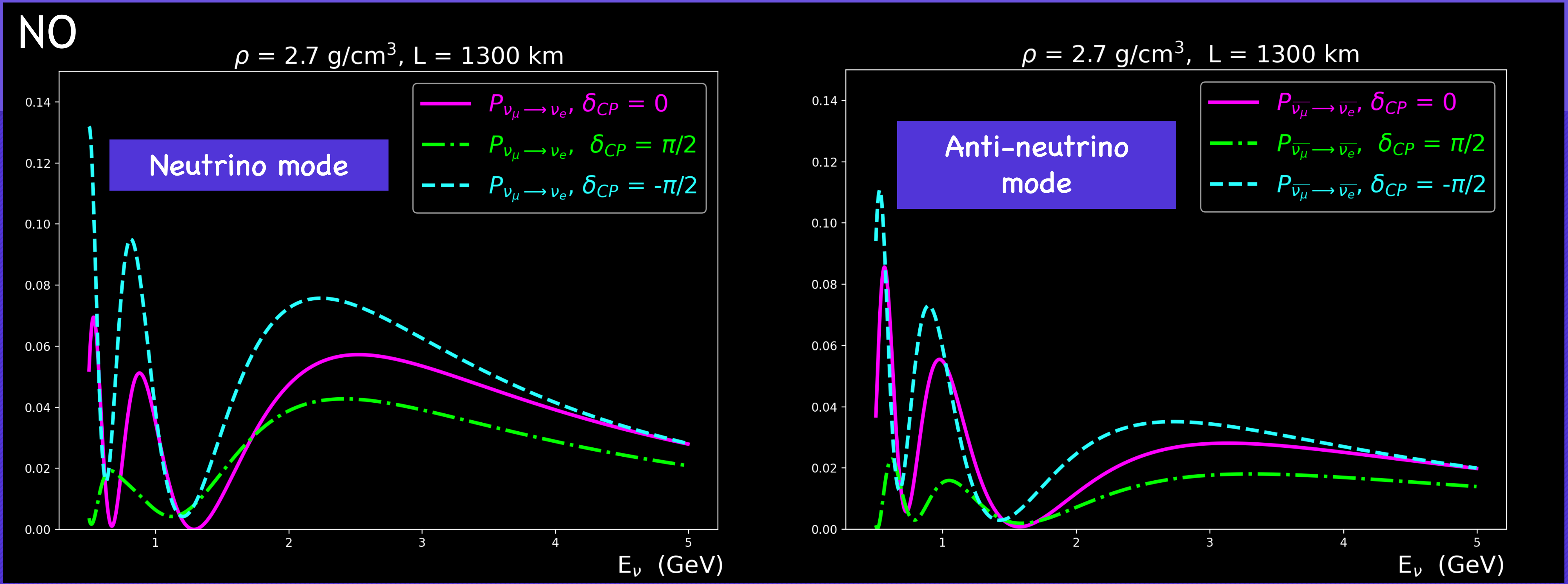
Motivation from the CPT symmetry story

- ✓ Neutrino physics is a well motivated probe for CP violation, but we are limited to an improper test due to living in a matter dominated universe.
- ✓ Let us then consider to what extent time invariance violation occurs within the neutrino sector.
- ✓ Why? New physics may not impact both CP and time reversal in the same way.



Source:https://physics.aps.org/articles/v15/120
Credit:APS/Carin Cain

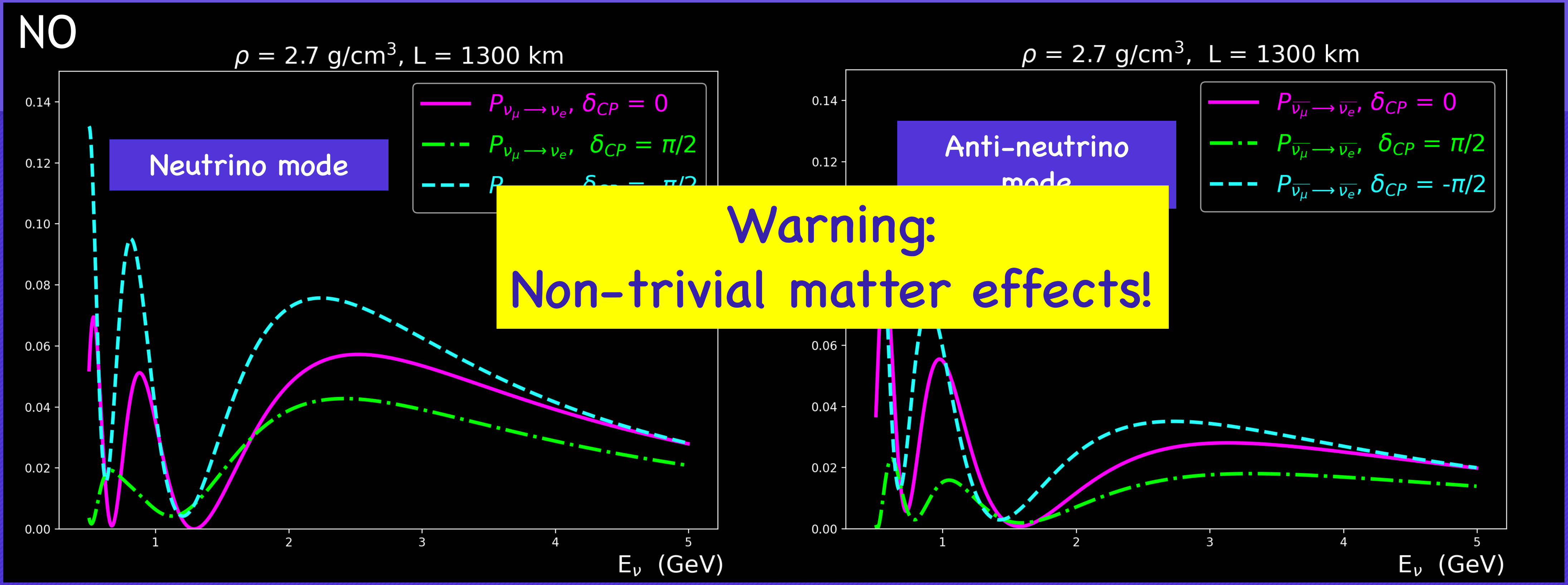
Motivation from experiments story



density $\Longleftrightarrow$ Earth's crust

CP conjugate channels are the *most common probes,* as they are more accessible to experiments like long baselines.

Motivation from experiments story



density $\Longleftrightarrow$ Earth's crust

CP conjugate channels are the *most common probes,* as they are more accessible to experiments like long baselines.

Motivation from experiments story

What else can we do?

Motivation from experiments story

Time Invariance Tests

Source: (Time-turner) https://tenor.com/view/time-turner-harry-potter-moving-spinning-gif-16031036

Motivation from experiments story

Time Invariance Tests

✓ Time invariance violation tests give relatively clearer ways to aid in our understanding of how different matter profiles can affect neutrino oscillations

(i.e. distinguishing between intrinsic & induced time invariance violation)

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Motivation from experiments story

Time Invariance Tests

- ✓ Time invariance violation tests give relatively clearer ways to aid in our understanding of how different matter profiles can affect neutrino oscillations

(i.e. distinguishing between intrinsic & induced time invariance violation)

NOTE: time invariance probability tests require comparing

$$P_{\nu_\mu \to \nu_e} \quad \text{vs} \quad P_{\nu_e \to \nu_\mu}$$

(or anti-neutrino versions)

We assume that a new beam capable of producing high energy ν_e's exists (i.e. muon storage rings).

Recalling 3-Flavor Neutrino Oscillations with charge-current matter effects

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

(PMNS matrix)

$$H = \frac{1}{2E_\nu} U M^2 U^\dagger + A$$

Sources: https://neutrino.syr.edu/research/neutrino-oscillations/ & https://neutrino-history.in2p3.fr/neutrino-oscillation/

$$M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \qquad A = \begin{pmatrix} \sqrt{2}G_F N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

+/- for neutrinos/antineutrinos

Defining time invariance measures

To clarify what "comparison" we are making in looking for time invariance violation effects, we've specified two distinct measures:

1. proper time invariance: (aka: true time invariance violation)

   - Not a good observable, but certainly no harder to calculate than CP conjugate channels.

   - Requires comparing probabilities with final states exchanged and <u>swapping the detector with source.</u>

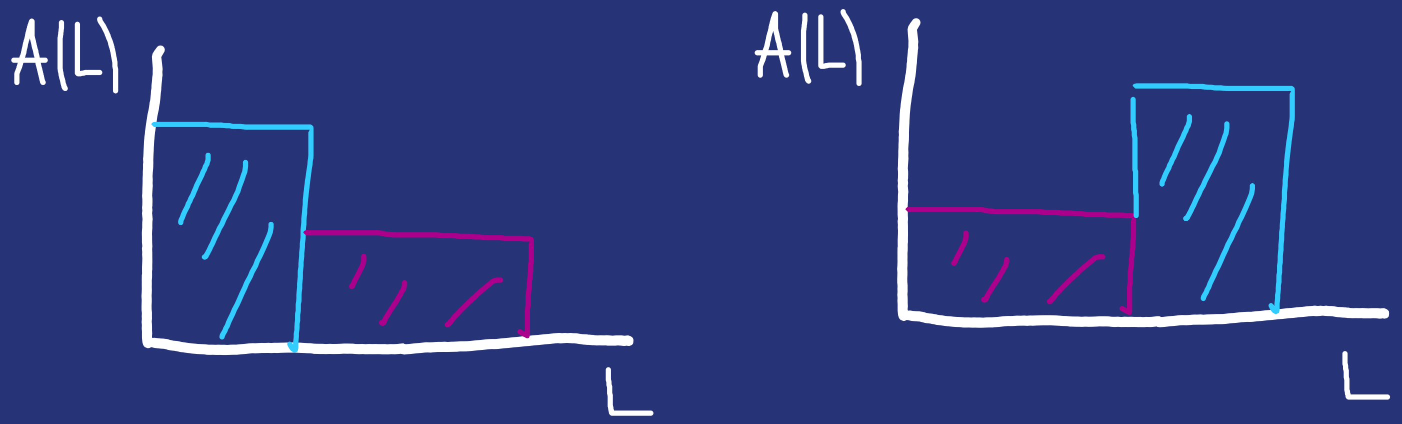
Defining time invariance measures

To clarify what "comparison" we are making in looking for time invariance violation effects, we've specified two distinct measures:

1. proper time invariance: (aka: true time invariance violation)

$$P_{\nu_e \to \nu_\mu} \quad vs \quad P_{\nu_\mu \to \nu_e}$$

(decreasing potential) (increasing potential)



ex: 2-step piece-wise constant matter profiles
A_{00} = A(L) = $\sqrt{2}G_F N_e$

N_e changes depending on density

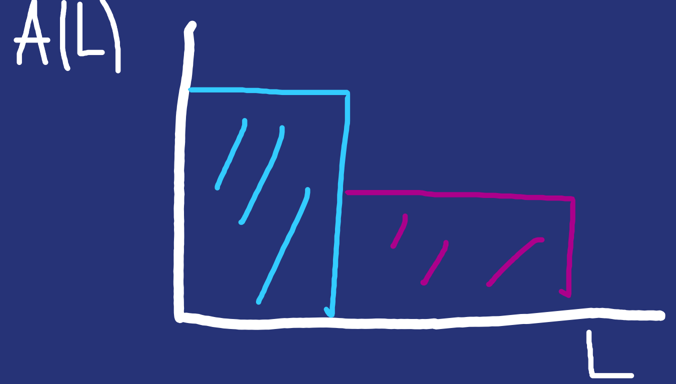
Defining time invariance measures

2. improper time invariance: (next best thing!)

- Compares probabilities with only the final states exchanged.

$P_{v_e \to v_\mu}$ vs $P_{v_\mu \to v_e}$

(decreasing potential) (decreasing potential)



This is what an experiment can measure!

Modeling Matter Effects for 3-Flavors

✓ For the purposes of our study, we separately two types of matter potential profiles.

Symmetric: vacuum or single step constant matter potential profile

Non-symmetric: piece-wise matter potential profiles (increasing or decreasing)

Modeling Matter Effects for 3-Flavors

- ✓ For the purposes of our study, we separately two types of matter potential profiles.

Symmetric: vacuum or single step constant matter potential profile

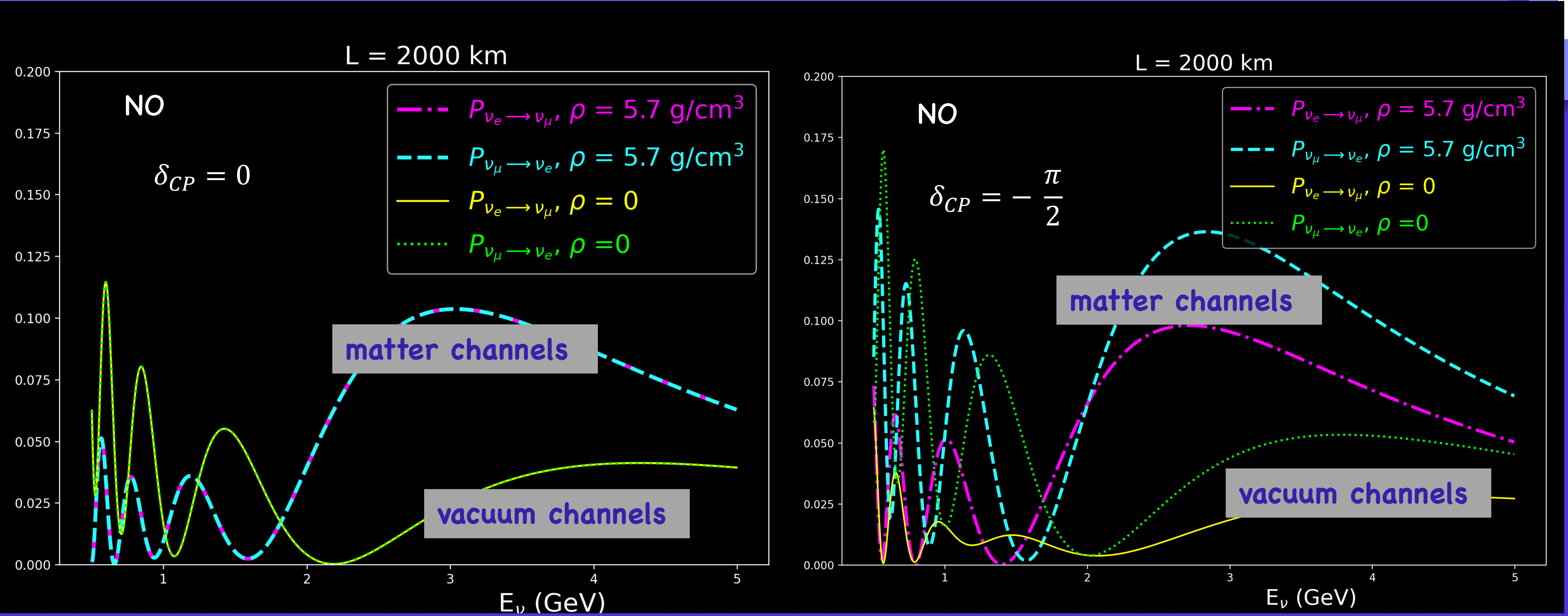
Non-symmetric: piece-wise matter potential profiles (increasing or decreasing)

All mixing parameters (apart from δ_{CP}) have been drawn from NuFIT 2024 global fits: (arXiv:2007.14792 & NuFIT 5.3 (2024), www.nu-fit.org)

Disclaimer!

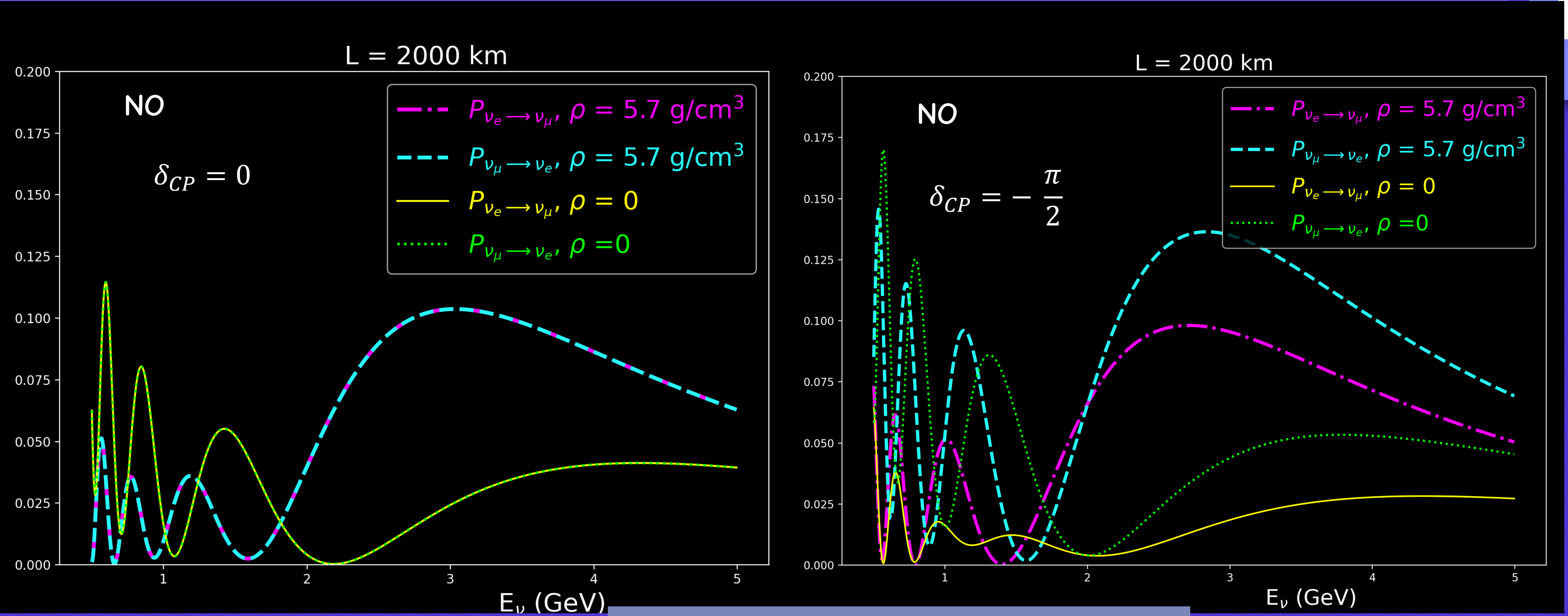
The following <u>preliminary</u> analysis is done with hypothetical/fictious matter effects, to get a general sense of how intrinsic versus induced time invariance violation behave with matter effects in cases that the have stronger oscillation differences.

Symmetric matter effects for 3-Flavors



Constant matter potential:
1.1×10^{-3} eV^2/GeV
(5.7 g/cm^3)

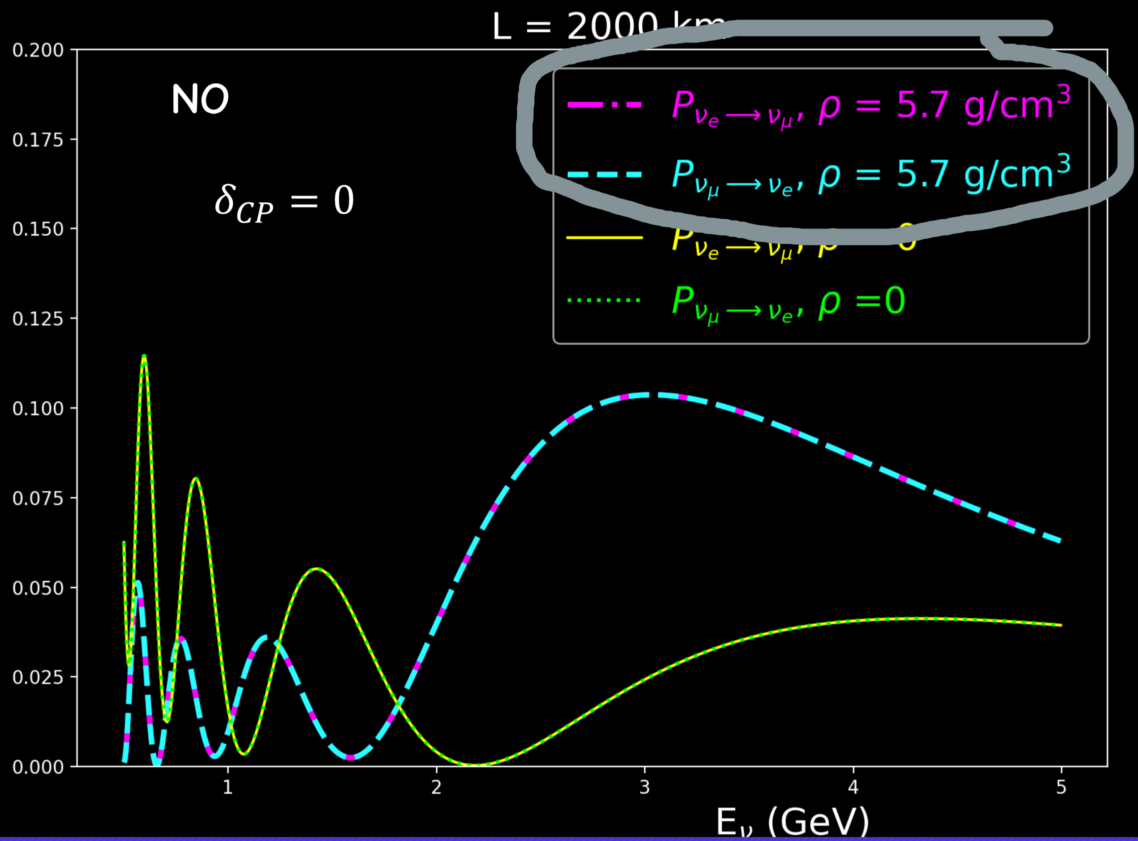
Symmetric matter effects for 3-Flavors

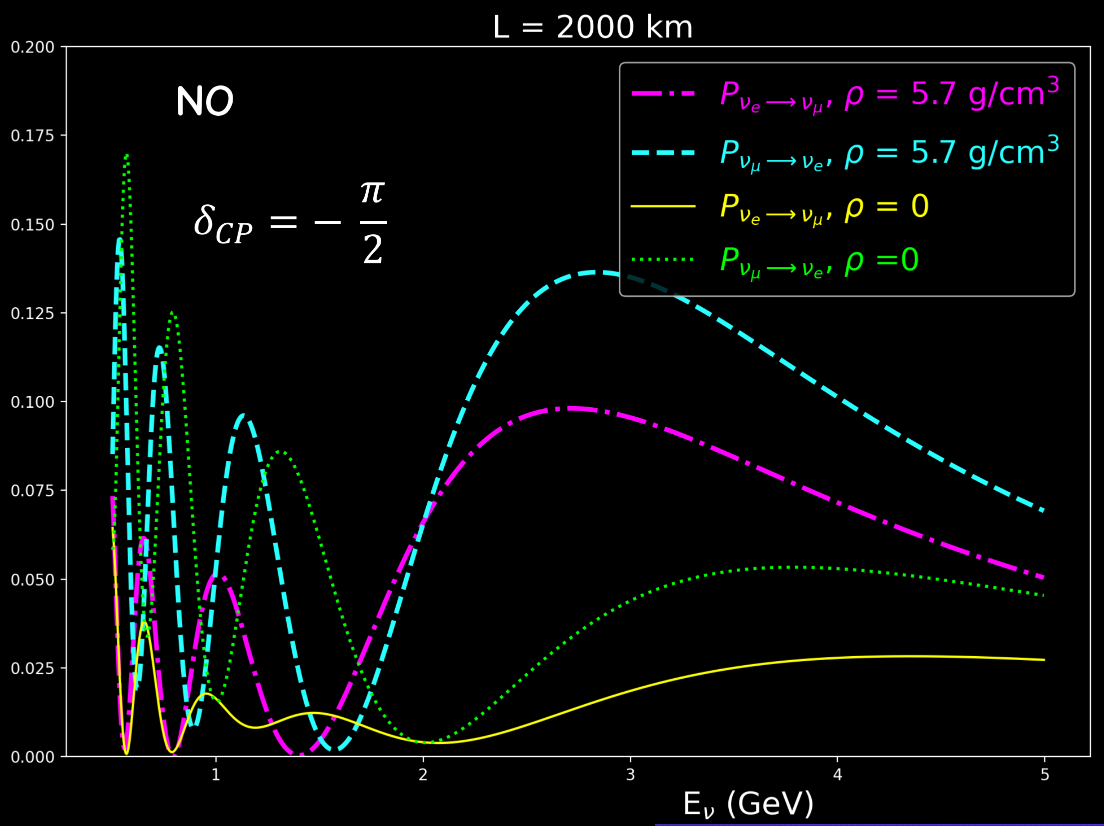


1. Symmetric matter potentials *cannot induce time invariance violation.*

2. If there is intrinsic time invariance from δ_{CP}, then the matter potential simply *changes the degree of the effects.*

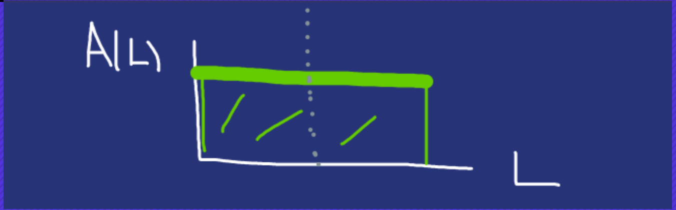
Symmetric matter effects for 3-Flavors



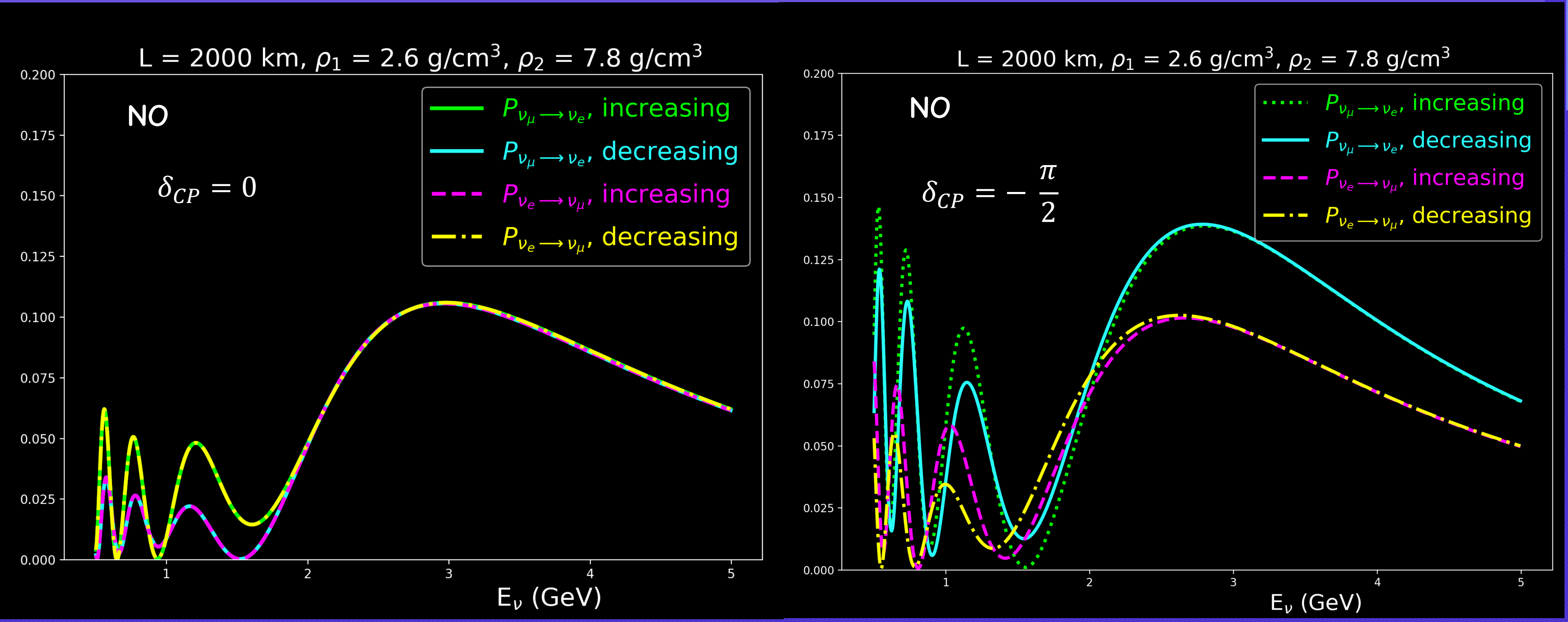


If we exchange final states, same matter potential profile.

3. Improper and proper comparisons are the same if the *matter potential is symmetric.*



Non-symmetric matter effects for 3-Flavors

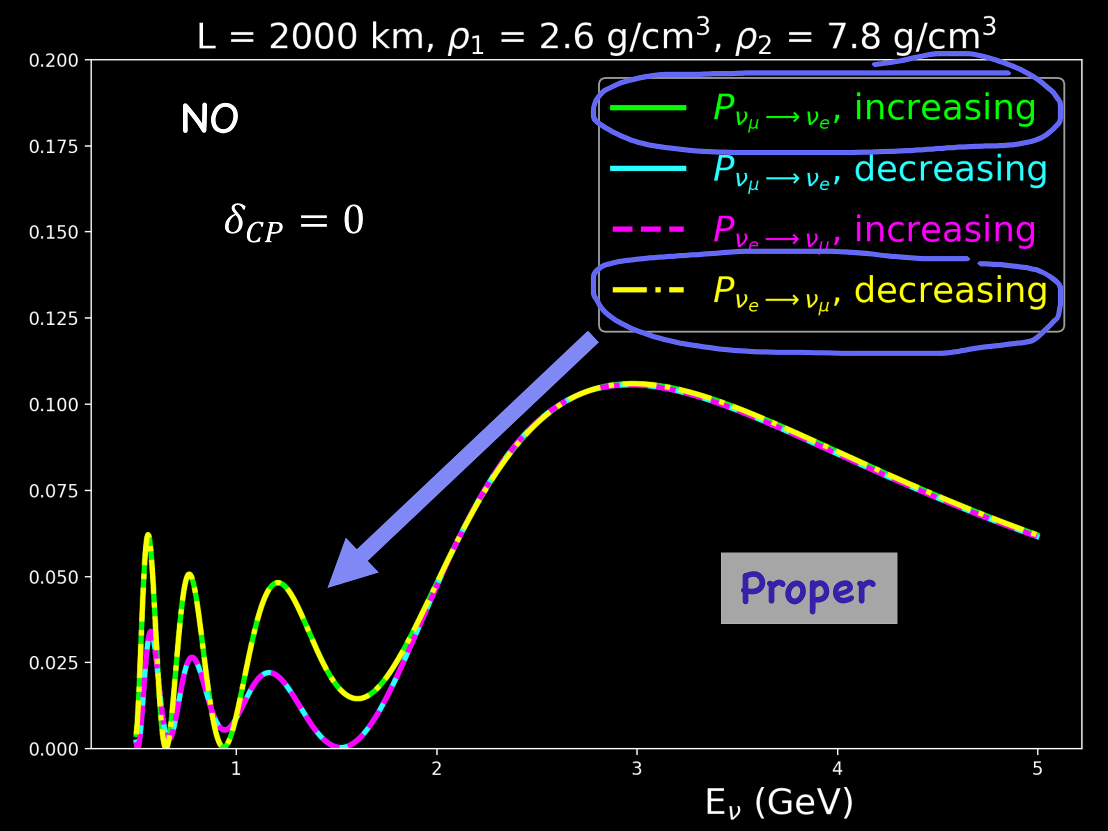


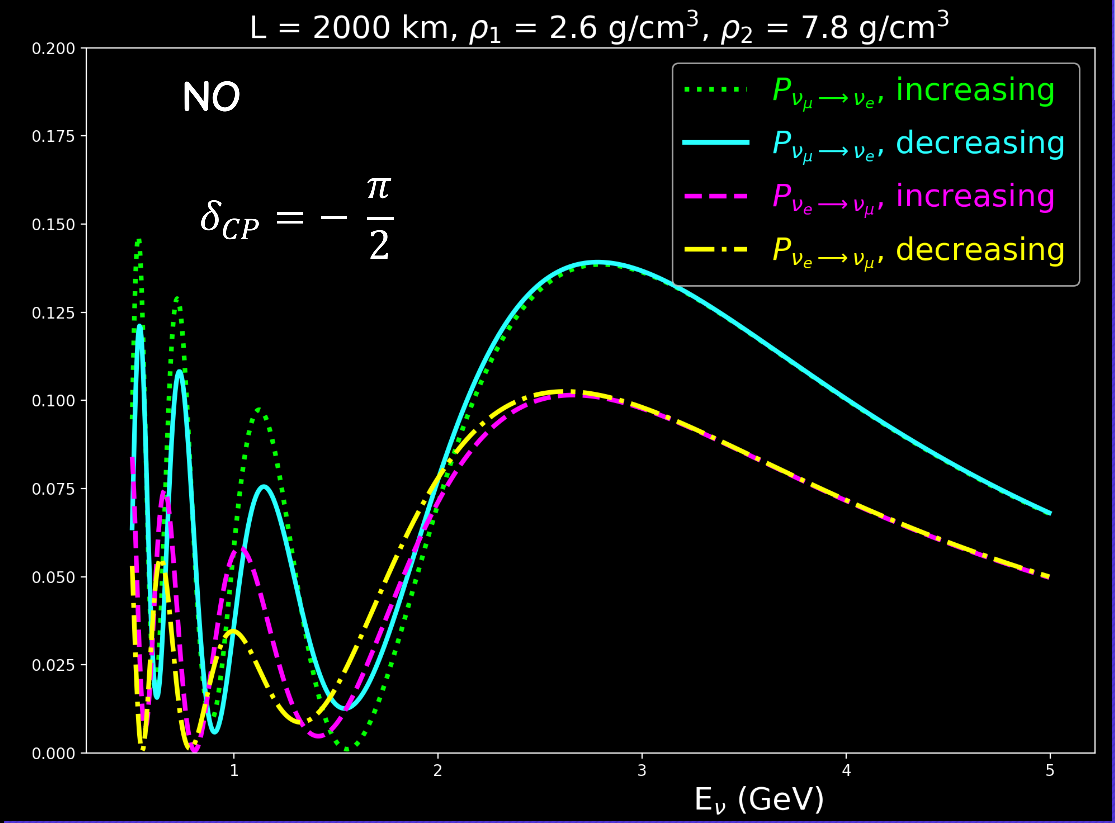
Piecewise matter potential (2 steps):

$A_1 = 5\times10^{-4}$ eV^2/GeV (2.6 g/cm^3)

$A_2 = 1.5\times10^{-3}$ eV^2/GeV (7.8 g/cm^3)

Non-symmetric matter effects for 3-Flavors

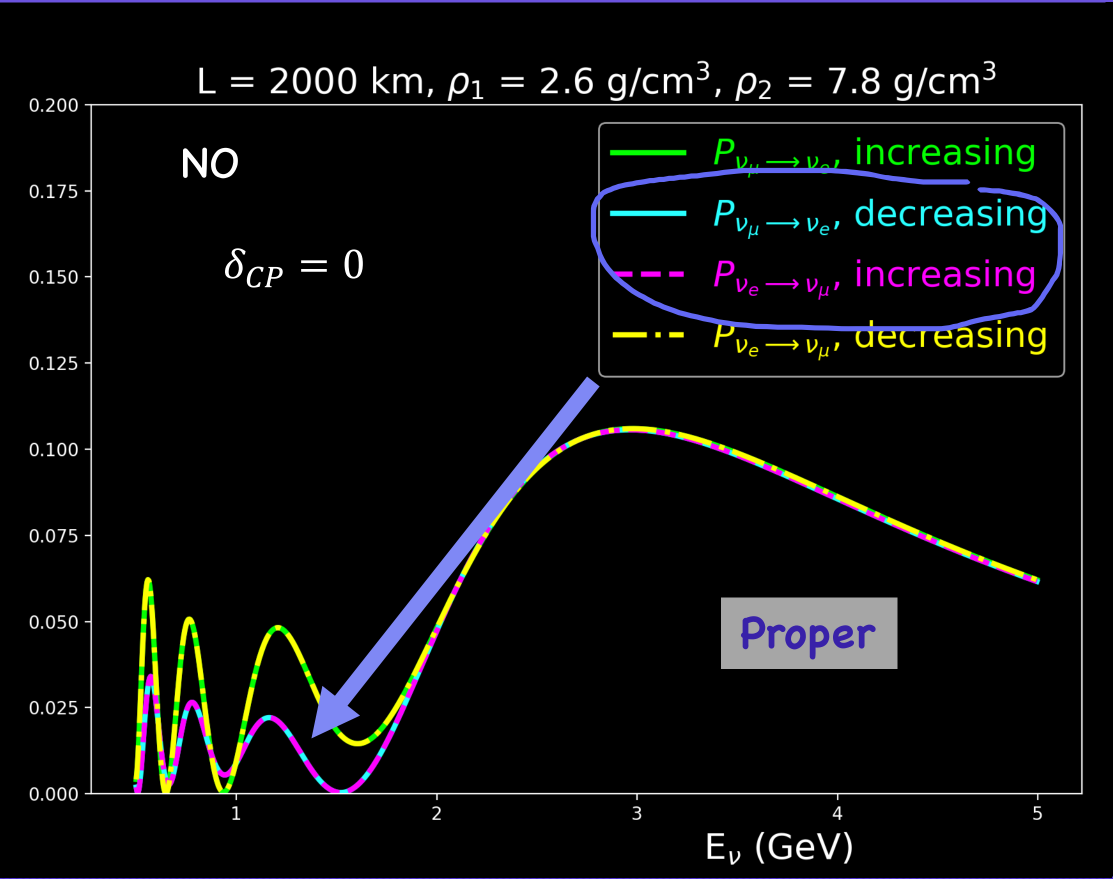


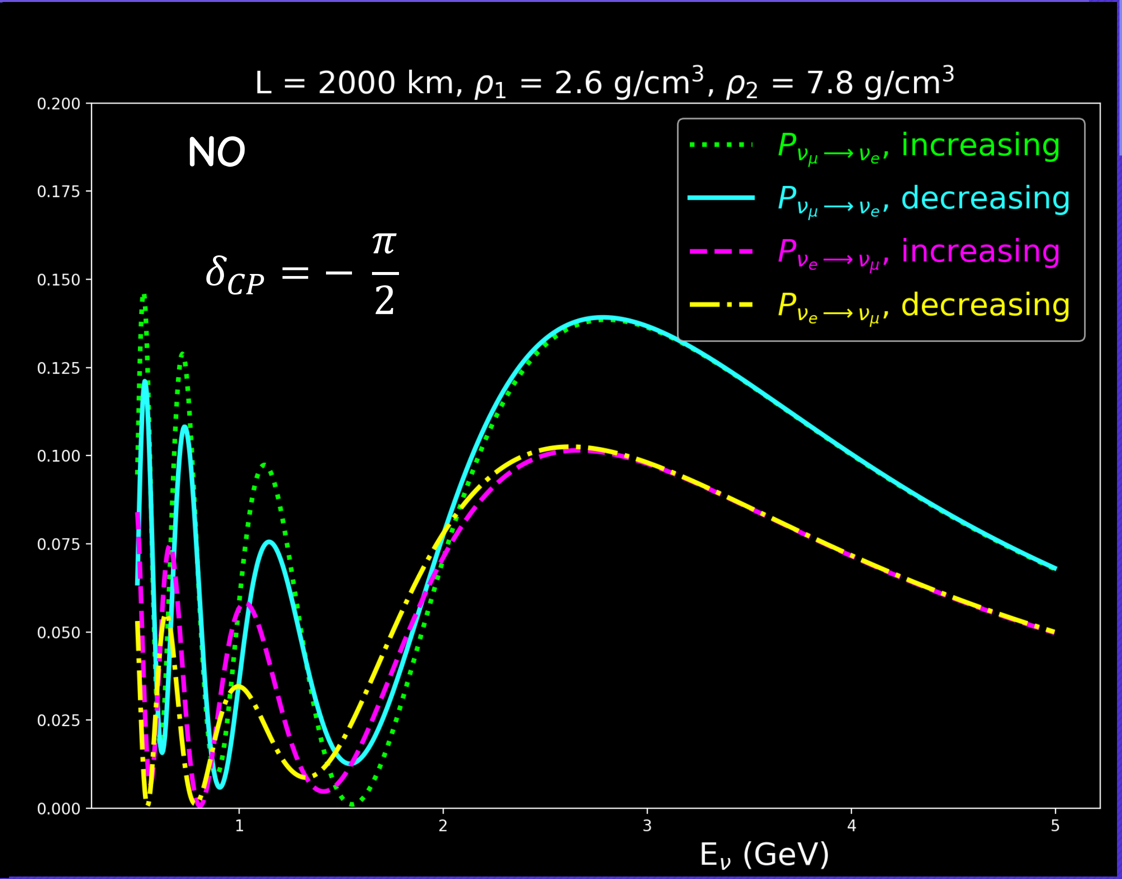


1. Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

2. Proper time *remains invariant,* but improper channels are *different.*

Non-symmetric matter effects for 3-Flavors





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New Perspectives, 2024

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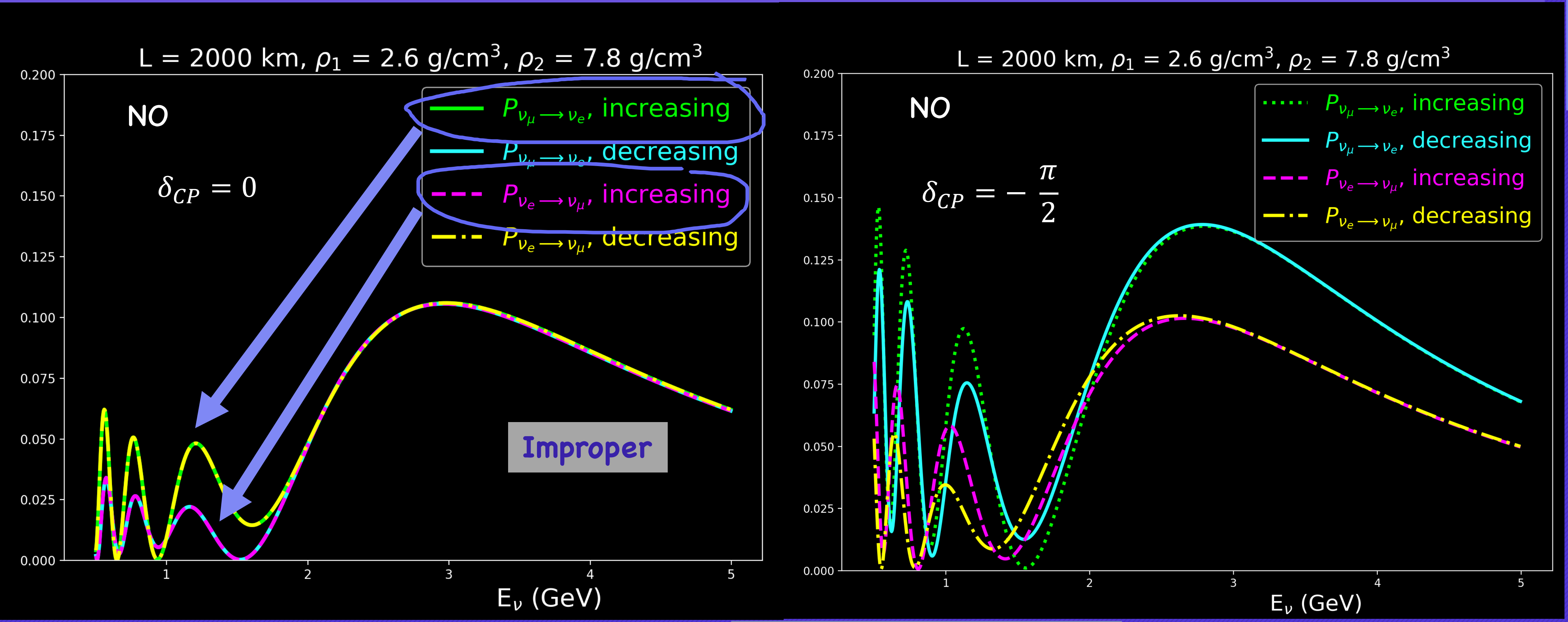

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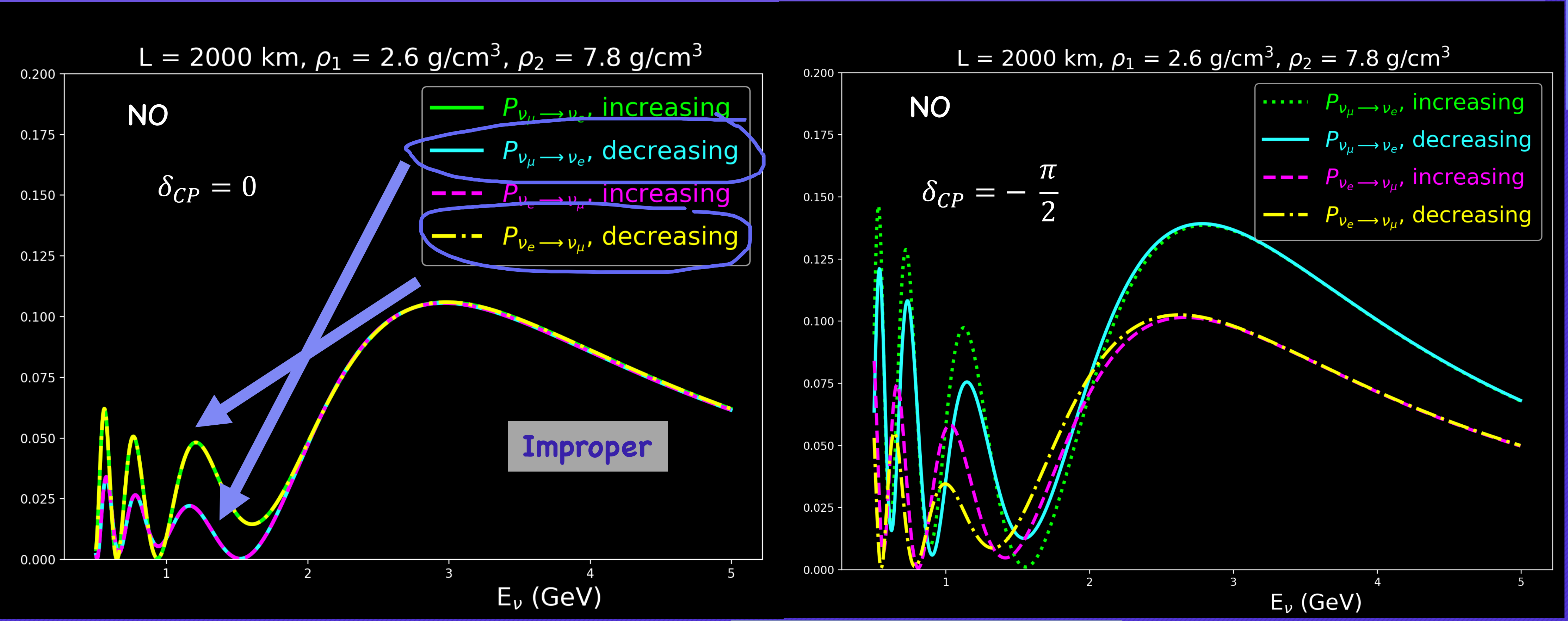

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New Perspectives, 2024

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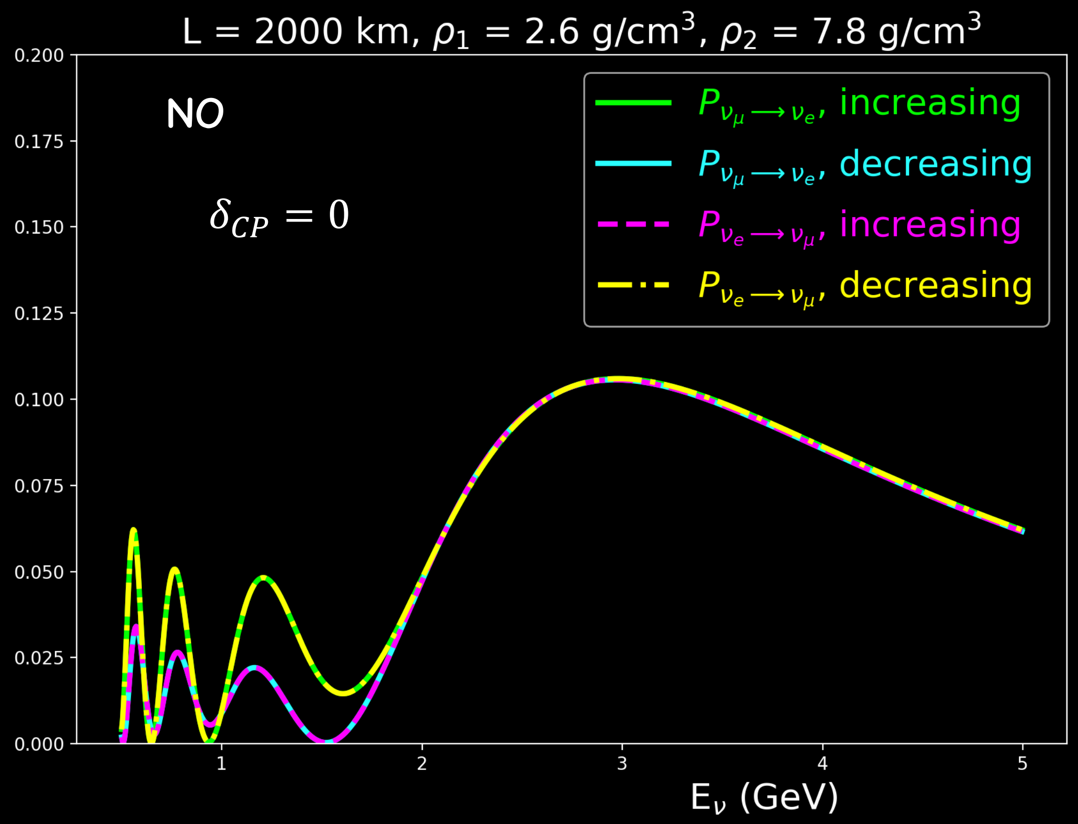
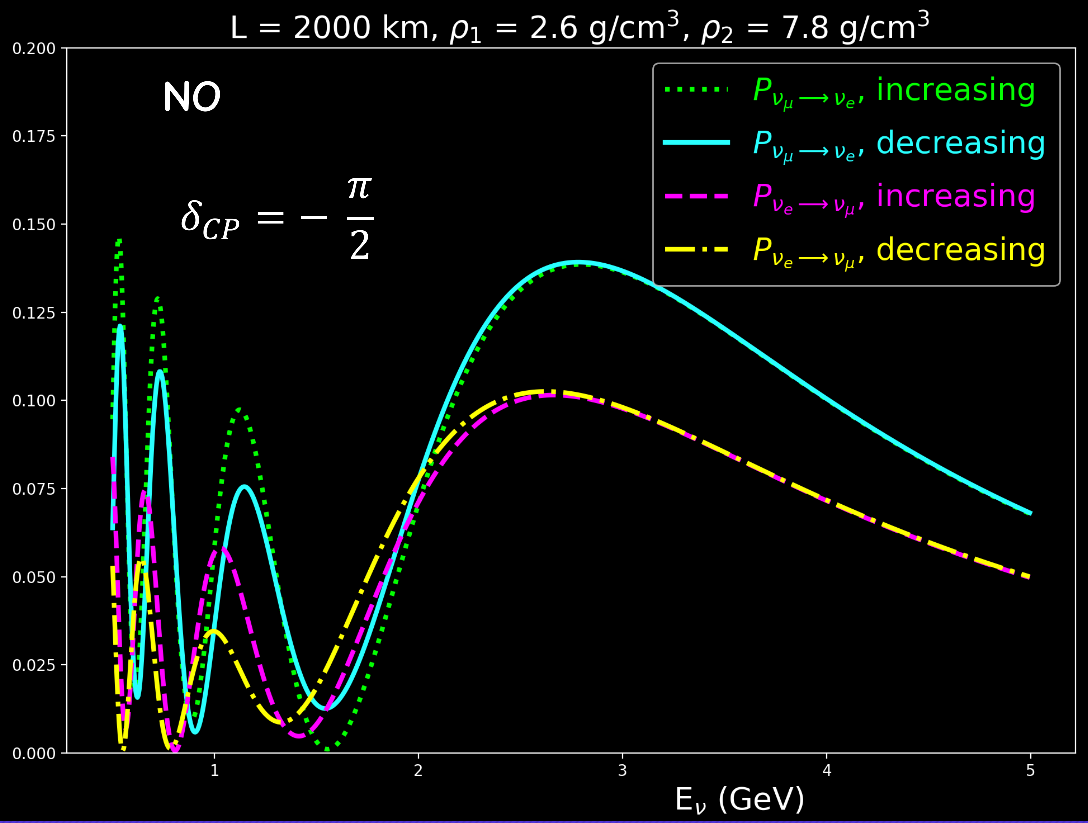


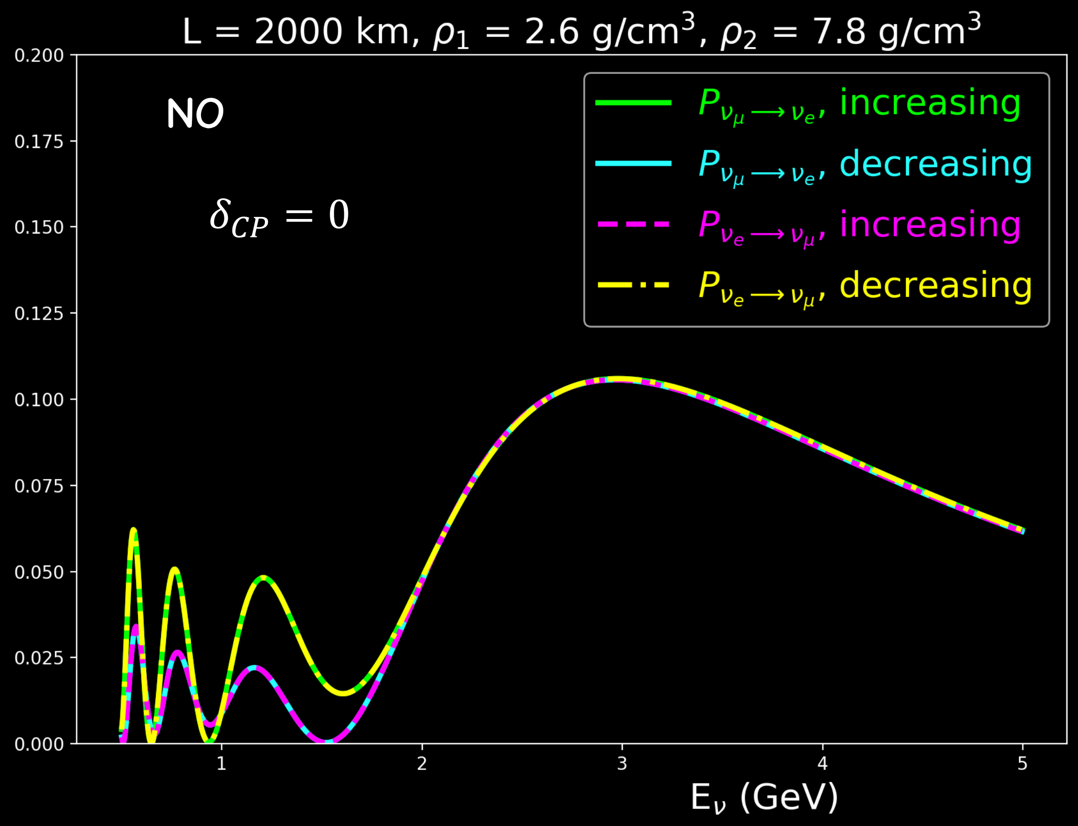


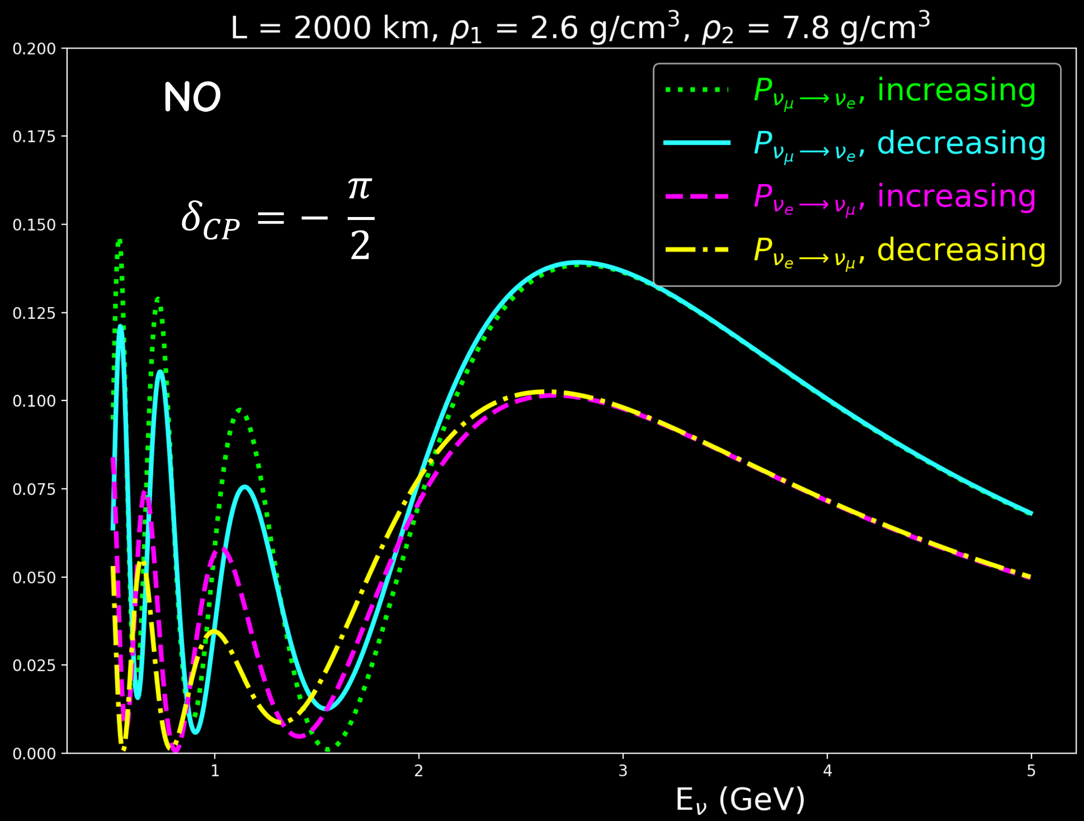
1. Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

2. Proper time *remains invariant*, but improper channels are *different*.

3. No intrinsic time invariance violation but *matter induced time invariance violation occurs*.

Non-symmetric matter effects for 3-Flavors





4. No longer pairwise degenerate if (δ_{CP}:- $\frac{\pi}{2}$).

5. Matter potential choice changes magnitude of oscillations:
All probabilities are different.

Main Takeaways

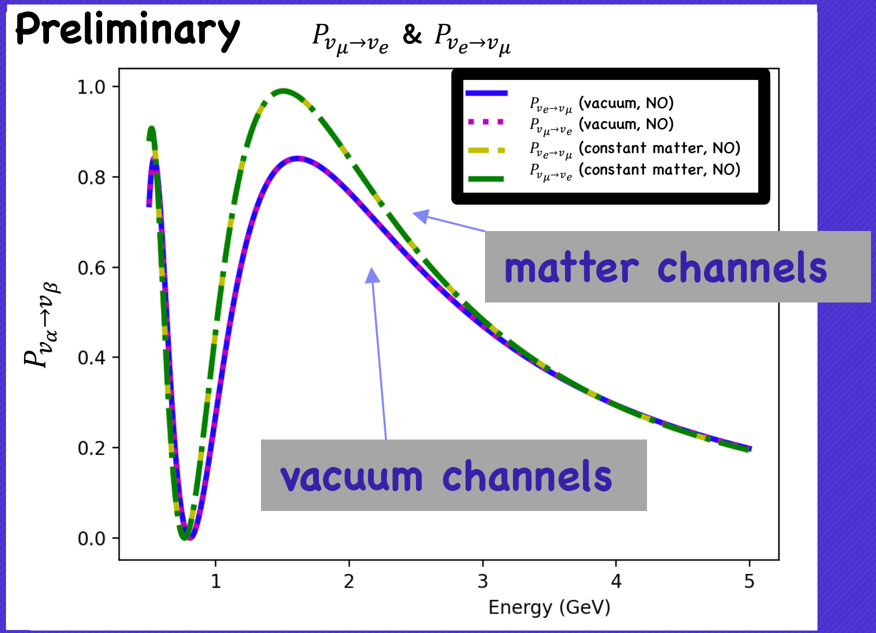
- This is an ongoing study into how much time invariance violation (if at all) can be observed in neutrino oscillations, and to what extent such observables can be differentiated in simple neutrino matter potential models.
- Symmetric potentials cannot induce time violation, but if time invariance is intrinsically non-conserved, the matter potential simply changes the degree of the observed effects.
- Symmetric potentials provide probes into checking proper time invariance, which could be accessible in the near future with new beams.
- Non-symmetric matter potentials can induce improper time violation, while proper time violation is more protected. More on this to come.
- Future studies: 2-flavor/3-flavor NSI and more realistic matter profiles just to name a few!

Thank you!

Backups

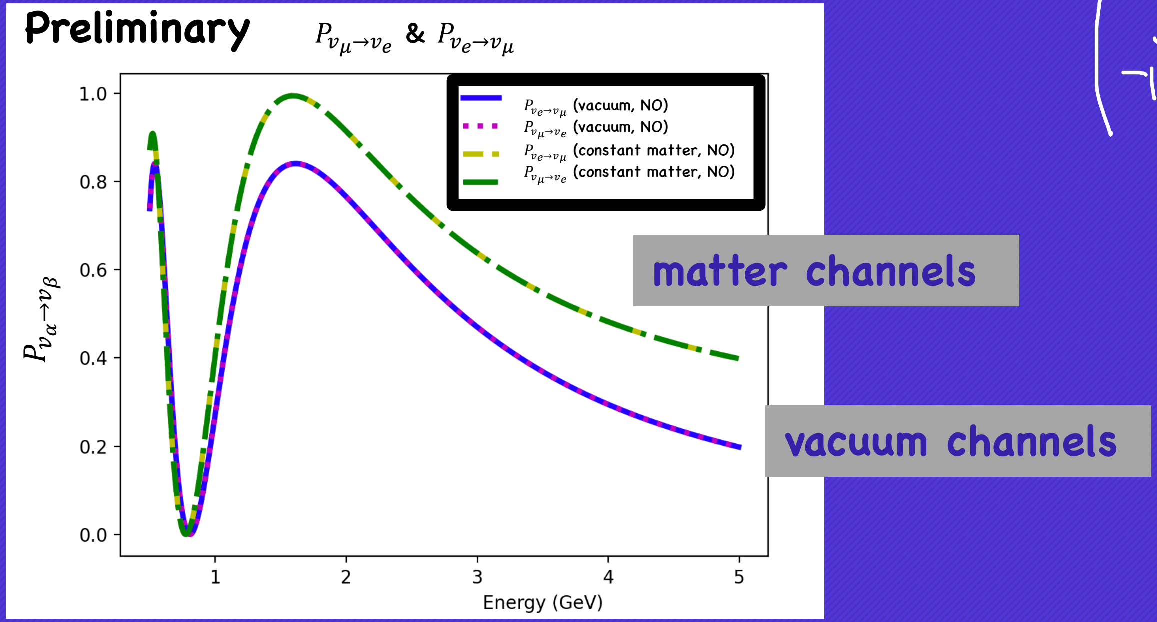
Symmetric matter effects for 2-Flavors
(Normal Ordering, Baseline: 2000 km)

constant matter potential:
$A \approx 5*10^{-4}\ eV^2/GeV$ (2.6 g/cm^3)



NSI + constant matter potential:
$A \approx 5*10^{-4}\ eV^2/GeV$ (2.6 g/cm^3)
$B \approx i * 2.5*10^{-4}\ eV^2/GeV$ (1.3 g/cm^3)

$$\begin{pmatrix} A & iB \\ -iB & 0 \end{pmatrix}$$

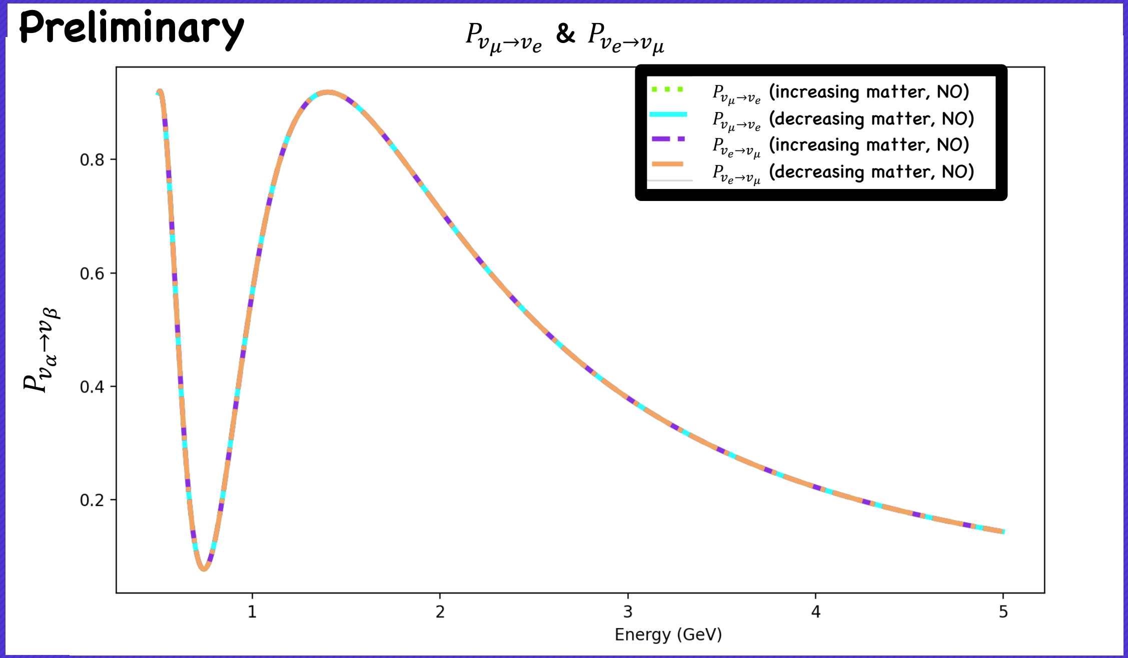


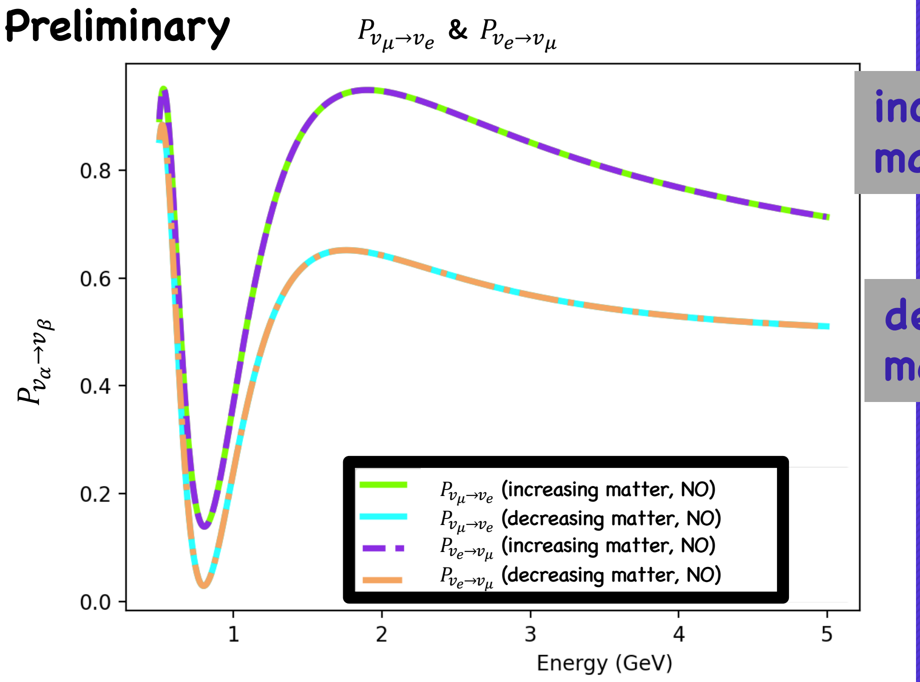
α, β -> $[\mu, e]$

Non-symmetric matter effects for 2-Flavors
(Normal Ordering, Baseline: 2000 km)

2 step constant matter potential:
A1 ≈ $5*10^{-4}$ eV^2/GeV (2.6 g/cm^3)
A2 ≈ $1.5*10^{-3}$ eV^2/GeV (7.8 g/cm^3)

NSI + 2 step constant matter potential:
A1 ≈ $5*10^{-4}$ eV^2/GeV (2.6 g/cm^3)
B1 ≈ i * $2.5*10^{-4}$ eV^2/GeV (1.3 g/cm^3)
A2 ≈ $1.5*10^{-3}$ eV^2/GeV (7.8 g/cm^3)
B2 ≈ i * $7.5*10^{-4}$ eV^2/GeV (3.9 g/cm^3)





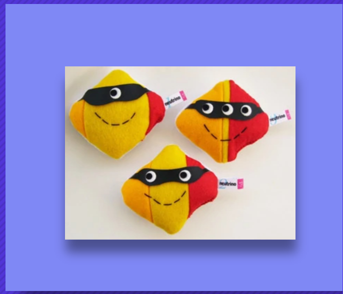
increasing matter

decreasing matter

α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors, 3-Steps

(Normal Ordering, Baseline: 2000 km)

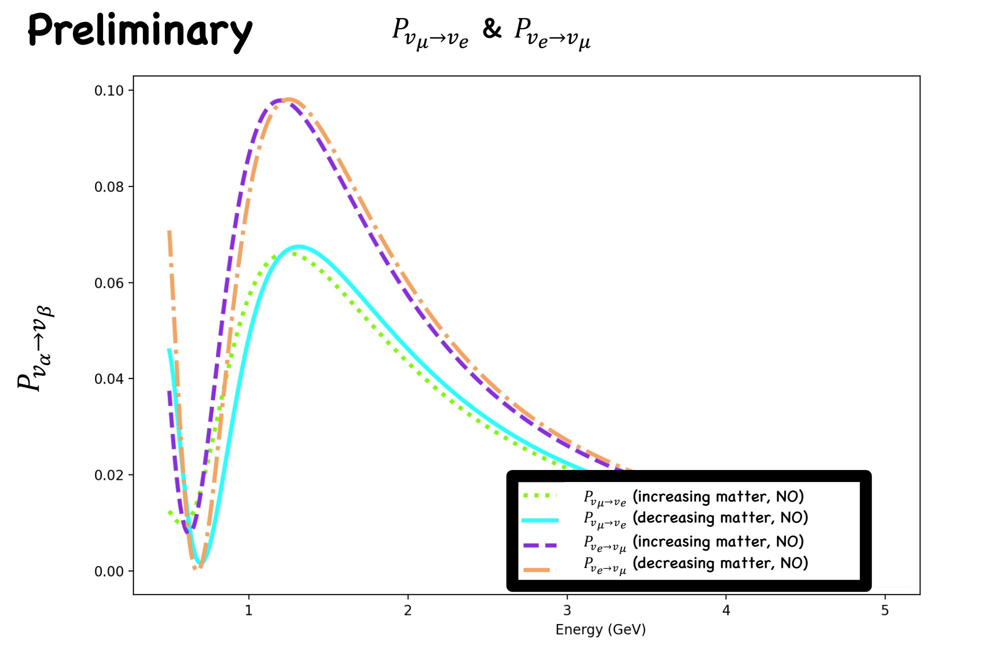


3 step constant matter potential:

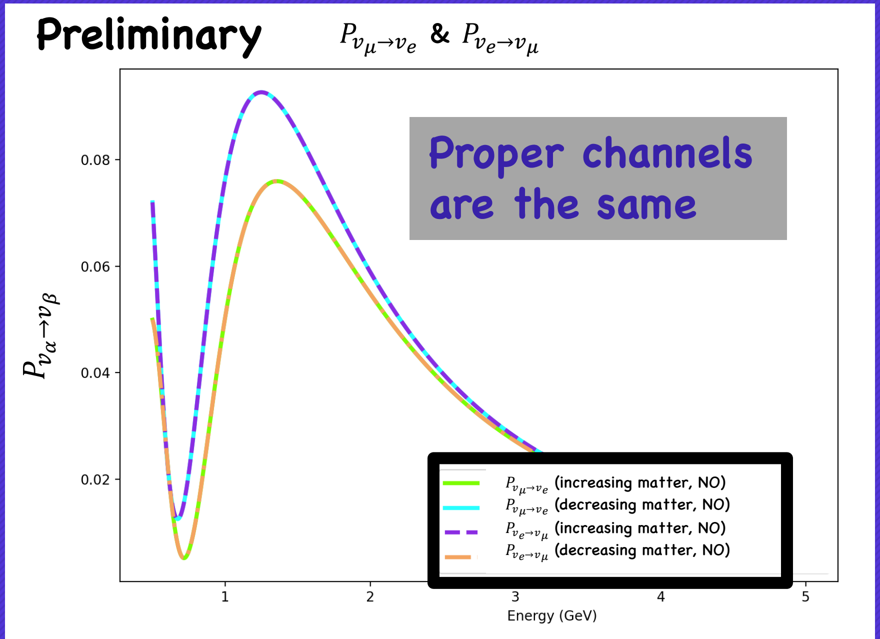
A1 ≈ $5.0*10^{-4}$ eV^2/GeV (2.6 g/cm^3)

A2 ≈ $1.5*10^{-3}$ eV^2/GeV (7.8 g/cm^3)

A3 ≈ $3.0*10^{-3}$ eV^2/GeV (15.6 g/cm^3)



δ_{CP} = 90



δ_{CP} = 0

α, β -> $[\mu, e]$

Recalling 3-Flavor Neutrino Oscillations with charge-current matter effects

We include matter effects explicitly from the following prescription for the probabilities (useful in the context of this study):

$$P_{v_\alpha \to v_\beta} = |< \mathbf{v}_\beta(0)|\mathbf{v}_\alpha(L) >|^2$$

where

$$|\mathbf{v}_\alpha(L) > = U\, |\mathbf{v}_\alpha(0) >$$

with $U = e^{-iLH}$ $(H = H_{vacuum} + H_{matter})$

Recalling 3-Flavor Neutrino Oscillations with charge-current matter effects

As an example for a Baseline L, let's break L up into 2 steps: L_1 and L_2, where each evolution U(L) will model different matter potentials A_1 and A_2 respectively.

Recalling 3-Flavor Neutrino Oscillations with charge-current matter effects

As an example for a Baseline L, let's break L up into 2 steps: L_1 and L_2, where each evolution U(L) will model different matter potentials A_1 and A_2 respectively.

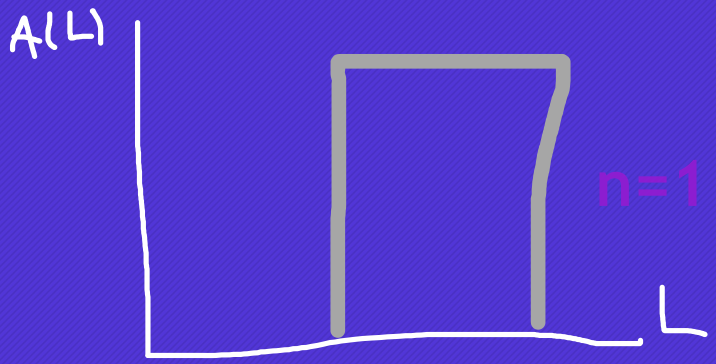
$U_1 = e^{-iL_1H_1}$ & $U_2 = e^{-iL_2H_2}$

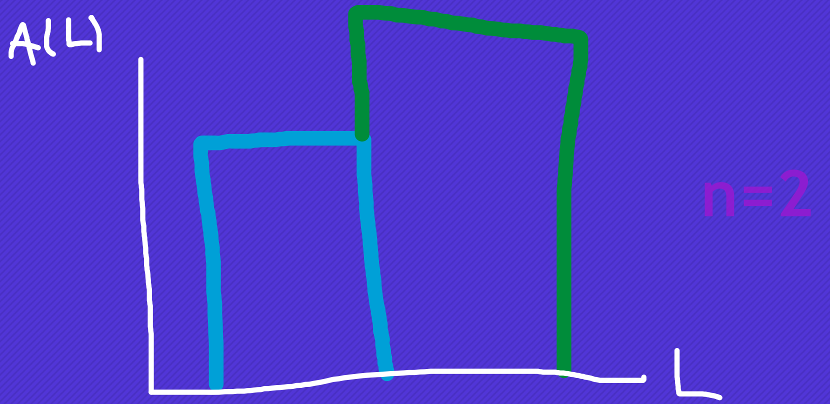
where H_i contain different matter effects in the form:

$A_i = \sqrt{2}G_F N_e$ -> constant

Recalling 3-Flavor Neutrino Oscillations with charge-current matter effects

In principle, one could consider an n multistep matter potential $A = \sum_{i=1}^{n} A_i$ where each step is itself a constant matter potential (piecewise constant).





Defining time invariance measures

To handle the difficulties of testing for time invariance violation effects in experiments, we've specified two distinct measures:

1. proper time invariance: (aka: true time invariance violation)

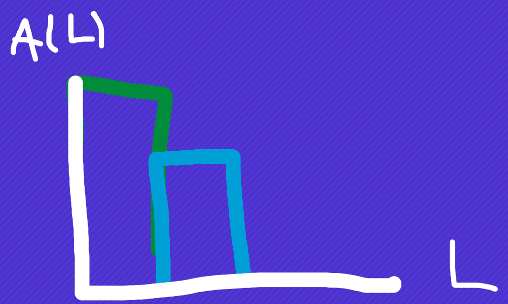
   - Not a good observable, but certainly no harder to calculate than CP conjugate channels.

   - Requires comparing probabilities with final states exchanged and <u>swapping the detector with source.</u>

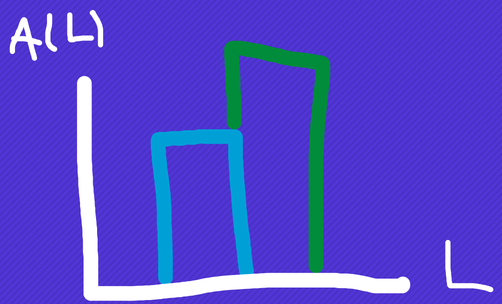
Defining time invariance measures

1. proper time invariance: (ex 2 steps)

(decreasing potential)



(increasing potential)



$P_{\nu_e \to \nu_\mu}$

for U = $U_1 U_2$

(decreasing potential)

vs

$P_{\nu_\mu \to \nu_e}$

for U = $U_2 U_1$

(increasing potential)

Defining time invariance measures

2. improper time invariance: (next best thing!)

- Compares probabilities with only the final states exchanged.

ex 2 steps:
(same potential)

$P_{\nu_e \rightarrow \nu_\mu}$

$U = U_2 U_1$

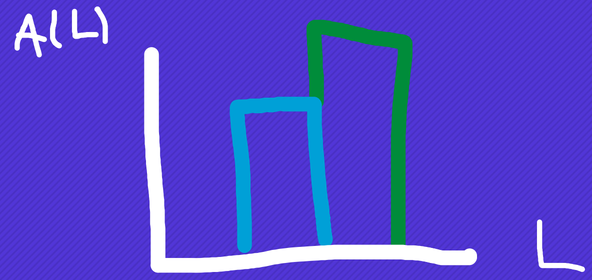
(increasing potential)

vs

$P_{\nu_\mu \rightarrow \nu_e}$

$U = U_2 U_1$

(increasing potential)



Defining time invariance measures

2. improper time invariance: (next best thing!)

- Compares probabilities with only the final states exchanged.

Improper time invariance violation has the potential to be observable in experiments.

ex 2 steps:
(same potential)

$$P_{v_e \rightarrow v_\mu}$$

$U = U_2 U_1$

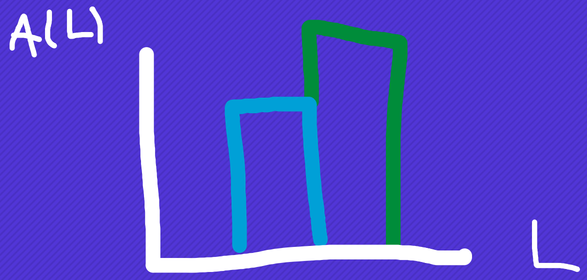
(increasing potential)

vs

$$P_{v_\mu \rightarrow v_e}$$

$U = U_2 U_1$

(increasing potential)



Modeling Matter Effects for 3-Flavors

- ✓ To make reasonable predictions that includes the role matter effects play in time invariance probes, it's important to keep in mind the characteristics of the matter potentials, as *these influence our results*.

- ✓ For the purposes of our study, we separately considered both symmetric and non-symmetric matter potential examples.

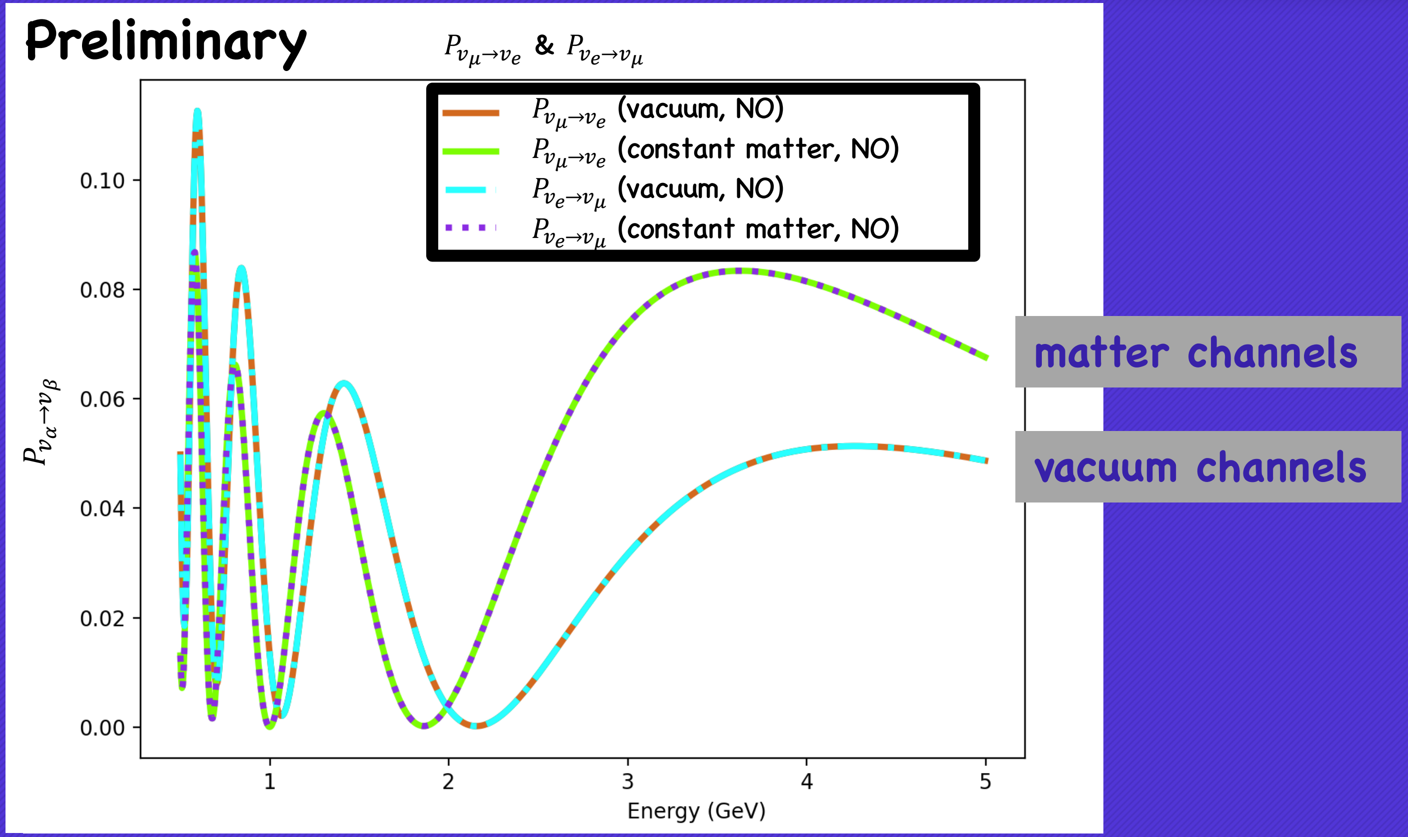
Modeling Matter Effects for 3-Flavors

The type of matter potential (symmetric/non-symmetric) provides a quick way to prove if there is matter induced time violation.

Symmetric: vacuum or single constant matter potential

Non-symmetric: piece-wise matter potentials (increasing or decreasing)

Symmetric matter effects for 3-Flavors

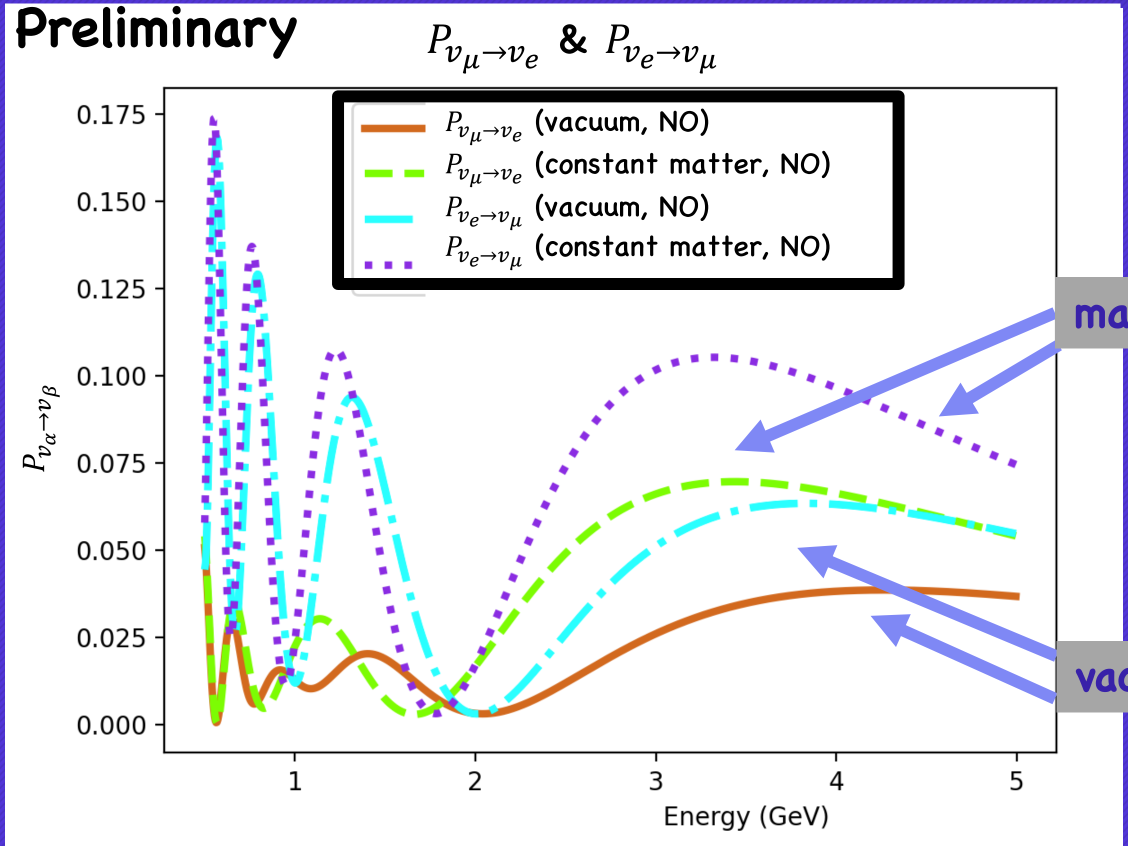


α, β -> $[\mu, e]$

$P_{\nu_\mu\to\nu_e}$ & $P_{\nu_e\to\nu_\mu}$ channels:

- ✓ Baseline: 2000 km
- ✓ Constant matter potential: $5\text{x}10^{-4}$ eV^2/GeV ($2.6\ g/cm^3$)
- ✓ δ_{CP}: 0
- ✓ Normal Ordering

Symmetric matter effects for 3-Flavors



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$P_{\nu_\mu \to \nu_e}$ & $P_{\nu_e \to \nu_\mu}$ channels:

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- ✓ δ_{CP}: $\frac{\pi}{2}$
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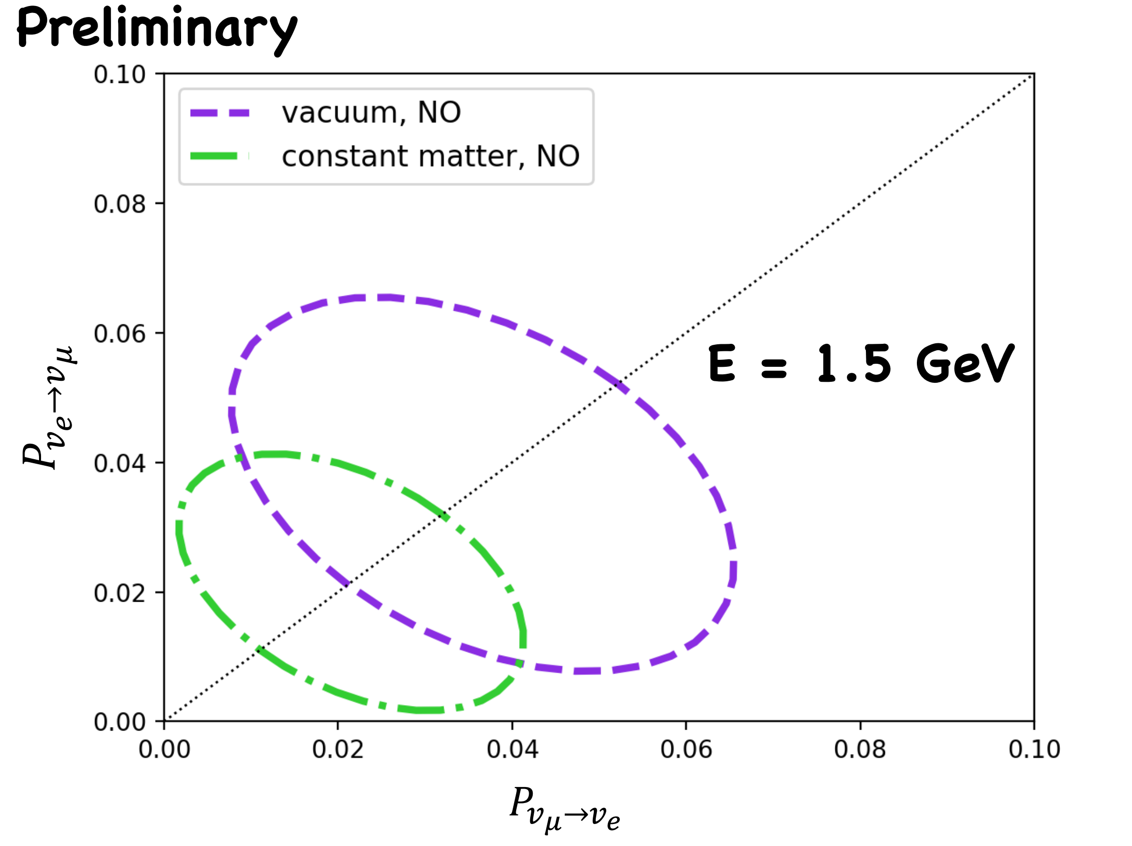
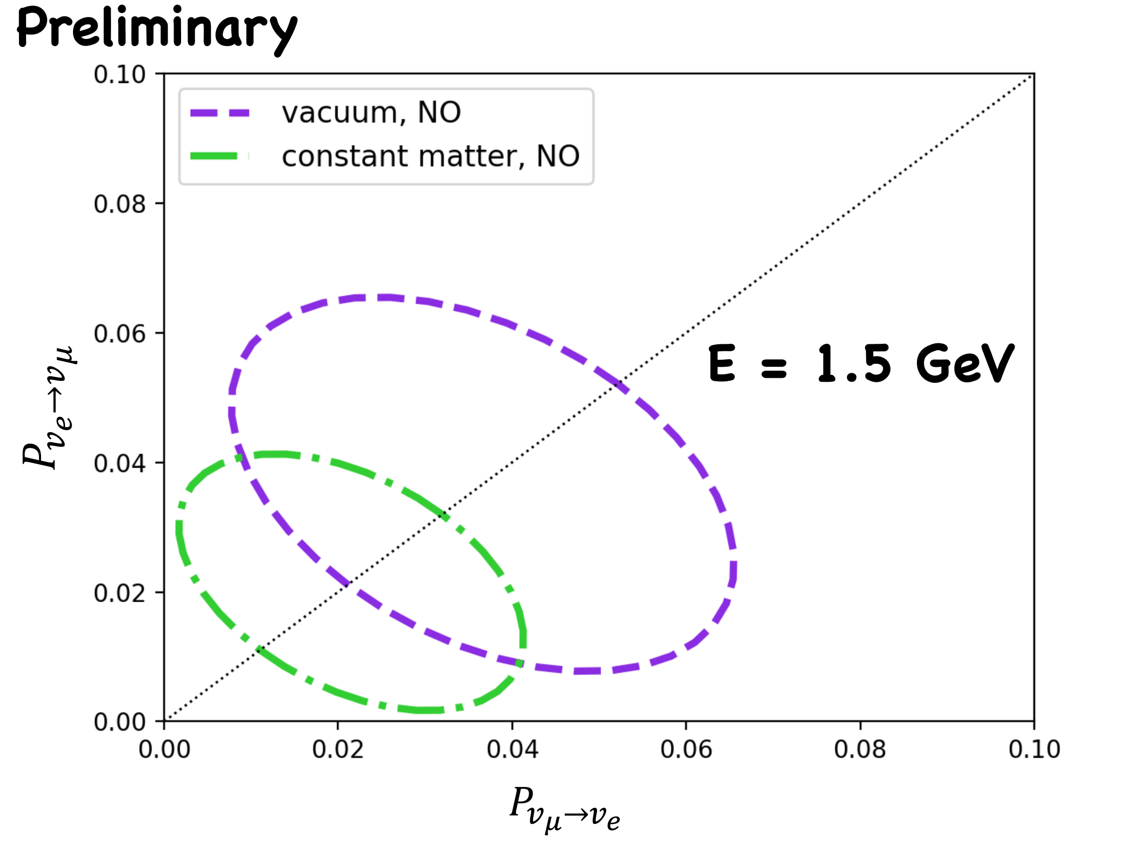
Symmetric matter effects for 3-Flavors



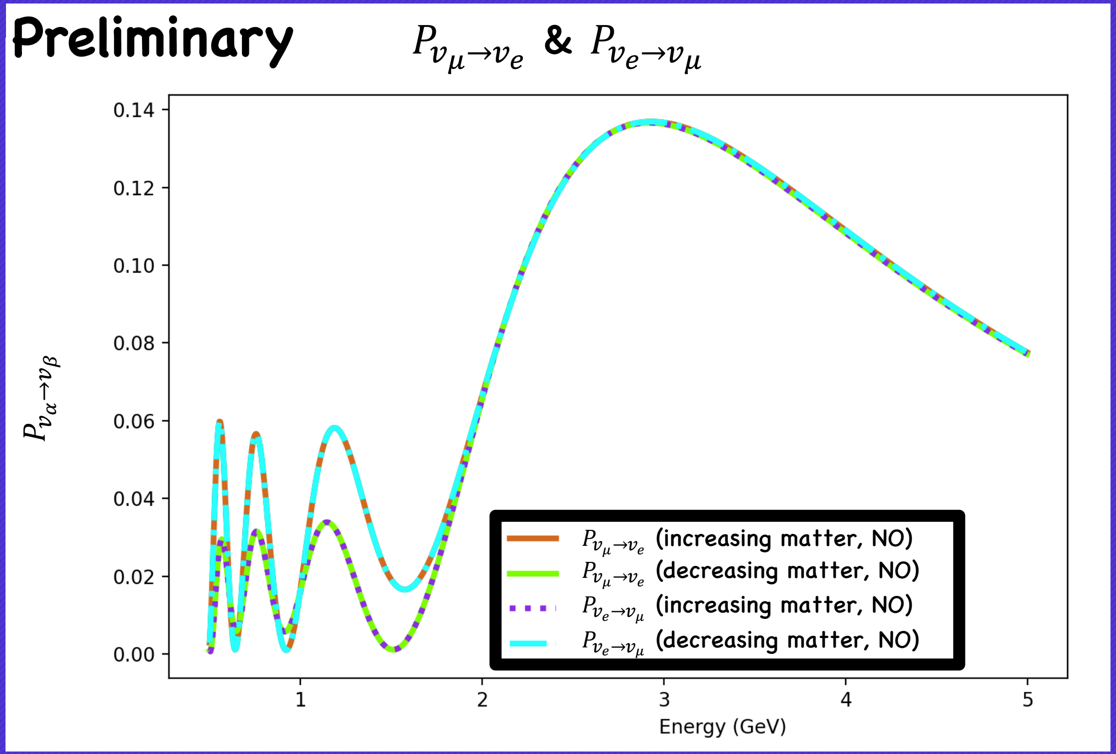
- ✓ Symmetric matter potentials *cannot induce time violation.*
- ✓ If there is intrinsic $P_{\nu_\mu \to \nu_e} \neq P_{\nu_e \to \nu_\mu}$ from δ_{CP}, then the matter potential simply *changes the degree of the observed effects.*

Symmetric matter effects for 3-Flavors



- ✓ Note: **Improper and proper comparisons are the same if the matter potential is symmetric.**
- ✓ *Why?*
  - ➔ A single constant matter potential is by construction symmetric.
  - ➔ We cannot tell the two measures apart if "exchanging source and detector" gives the *same results.*

Non-symmetric matter effects for 3-Flavors

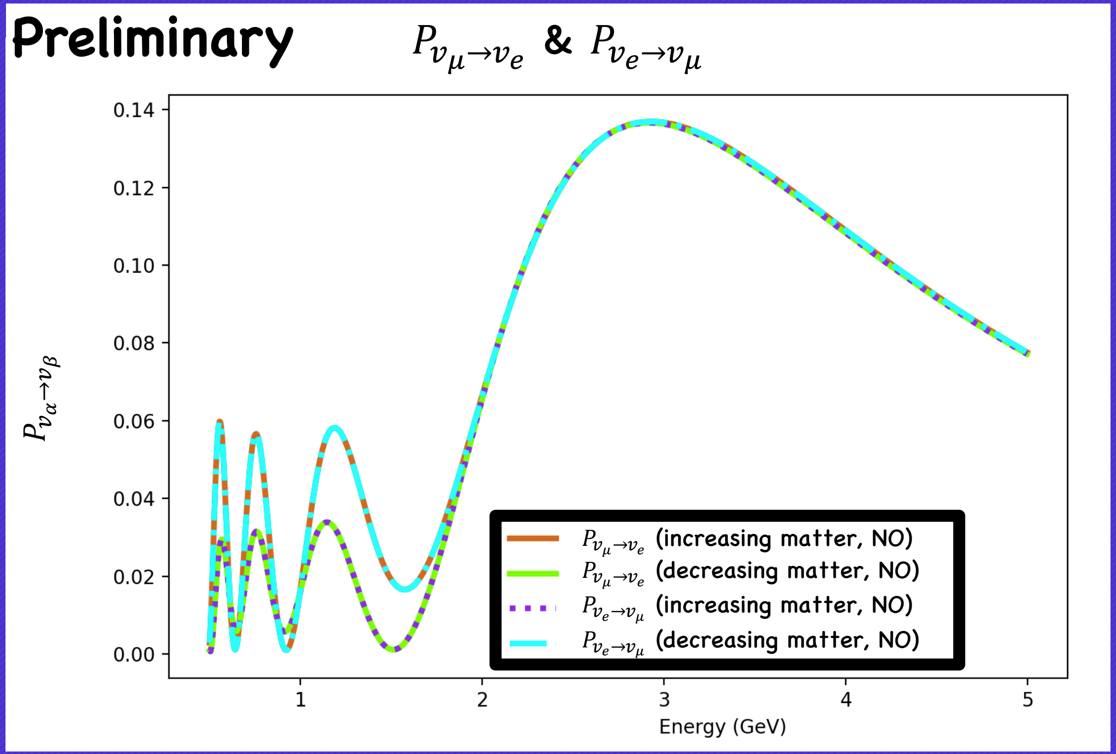


$P_{\nu_\mu \to \nu_e}$ & $P_{\nu_e \to \nu_\mu}$ channels:

- ✓ Baseline: 2000 km
- ✓ Piecewise matter potential (2 steps):
  - $A_1 = 5 \times 10^{-4}$ eV^2/GeV (2.6 g/cm^3)
  - $A_2 = 1.5 \times 10^{-3}$ eV^2/GeV (7.8 g/cm^3)
- ✓ δ_{CP}: 0
- ✓ Normal Ordering

α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors



✓ Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

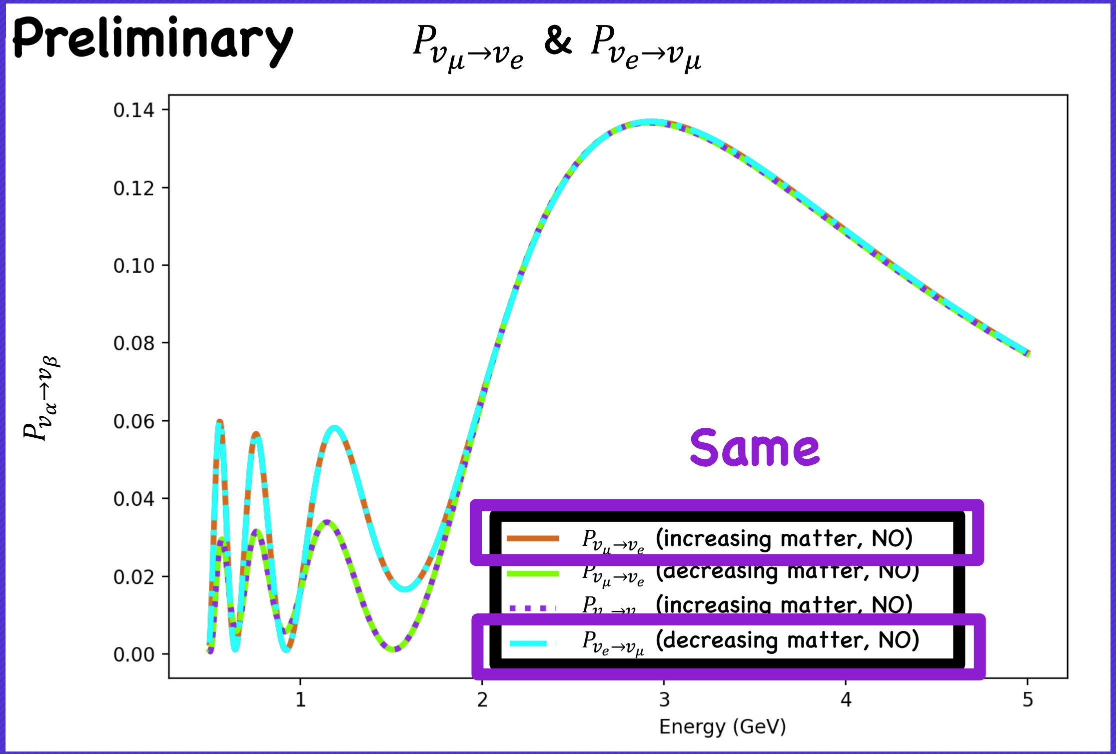
➔ Proper time invariance channels hold
➔ Improper are different

No intrinsic time invariance violation!

But matter induced time invariance violation can occur.

α, β -> [μ, e]

Non-symmetric matter effects for 3-Flavors

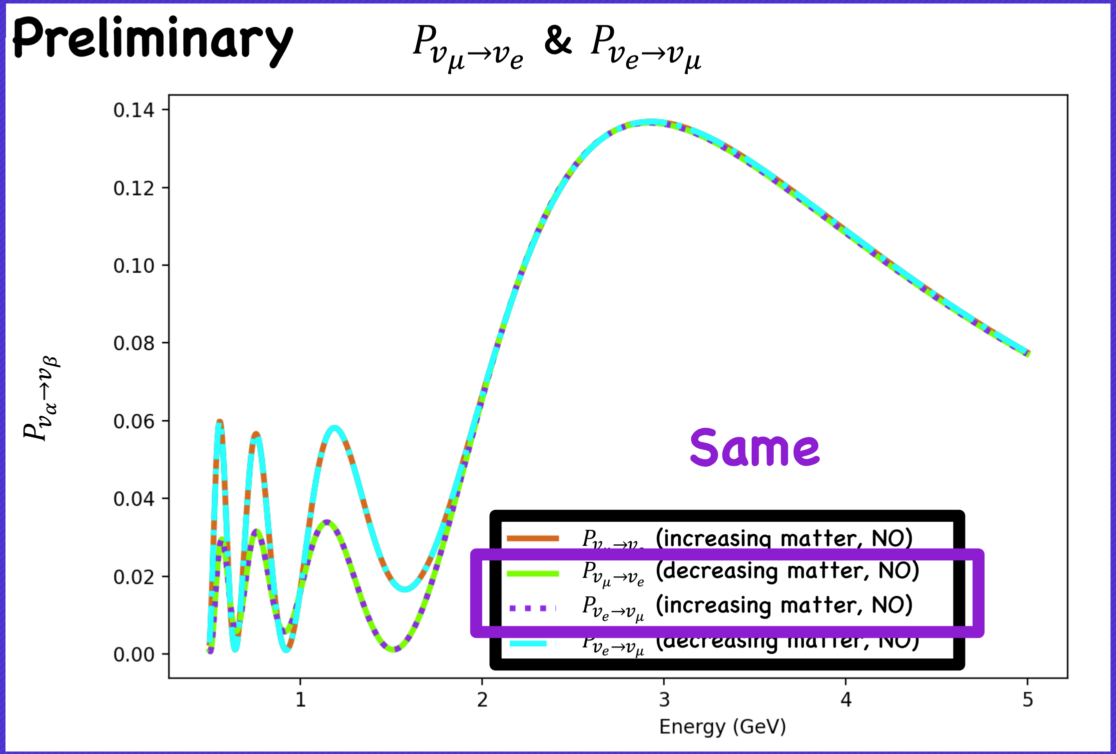


✓ Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

➔ Proper time invariance channels hold
➔ Improper are different

α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors



✓ Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

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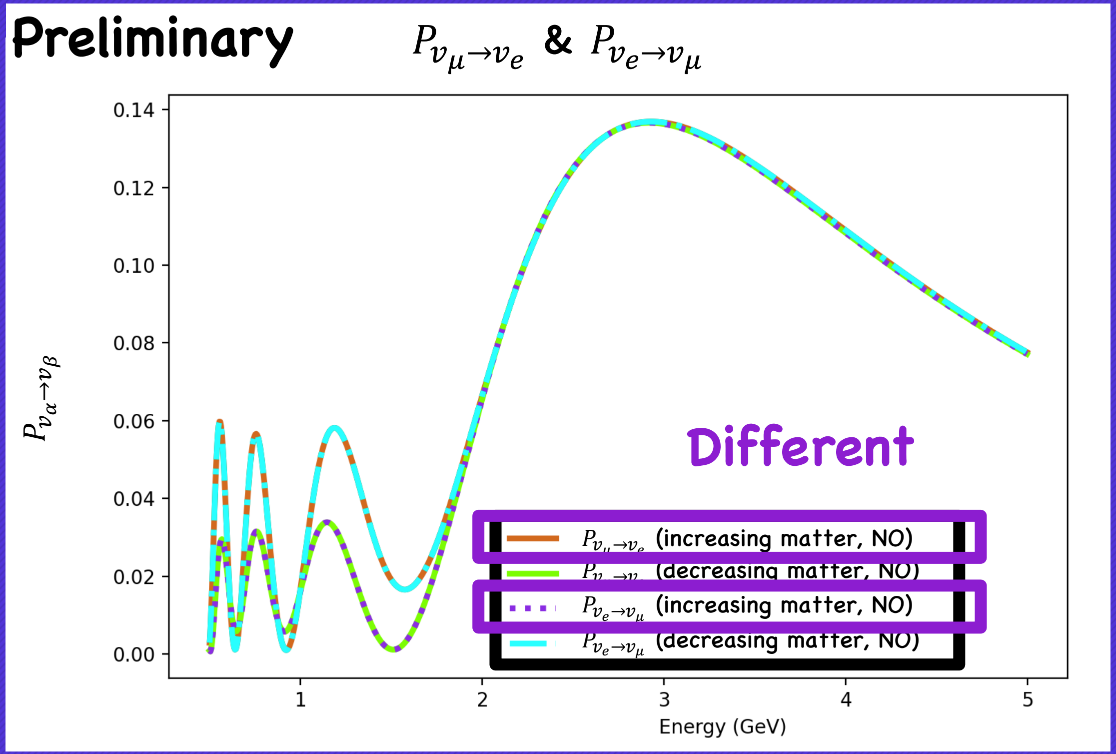
➔ Improper are different

α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors



✓ Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

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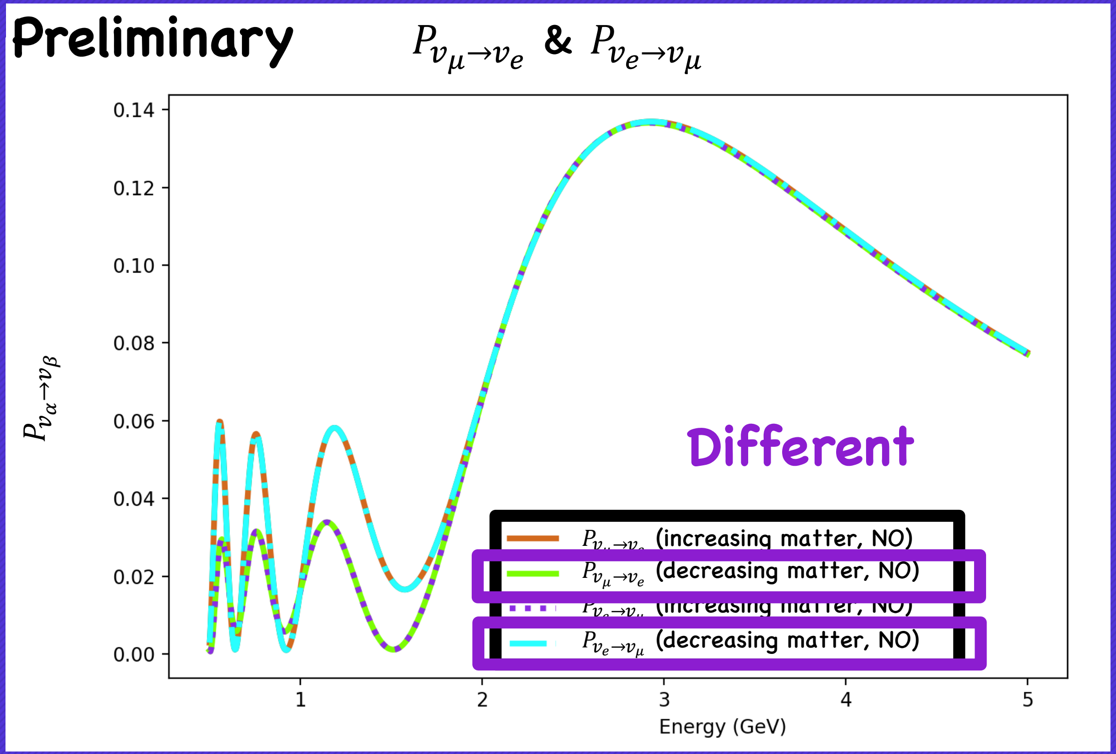
α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors



✓ Non-symmetric matter effects are pairwise degenerate (δ_{CP}: 0)

➔ Proper time invariance channels hold

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α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors

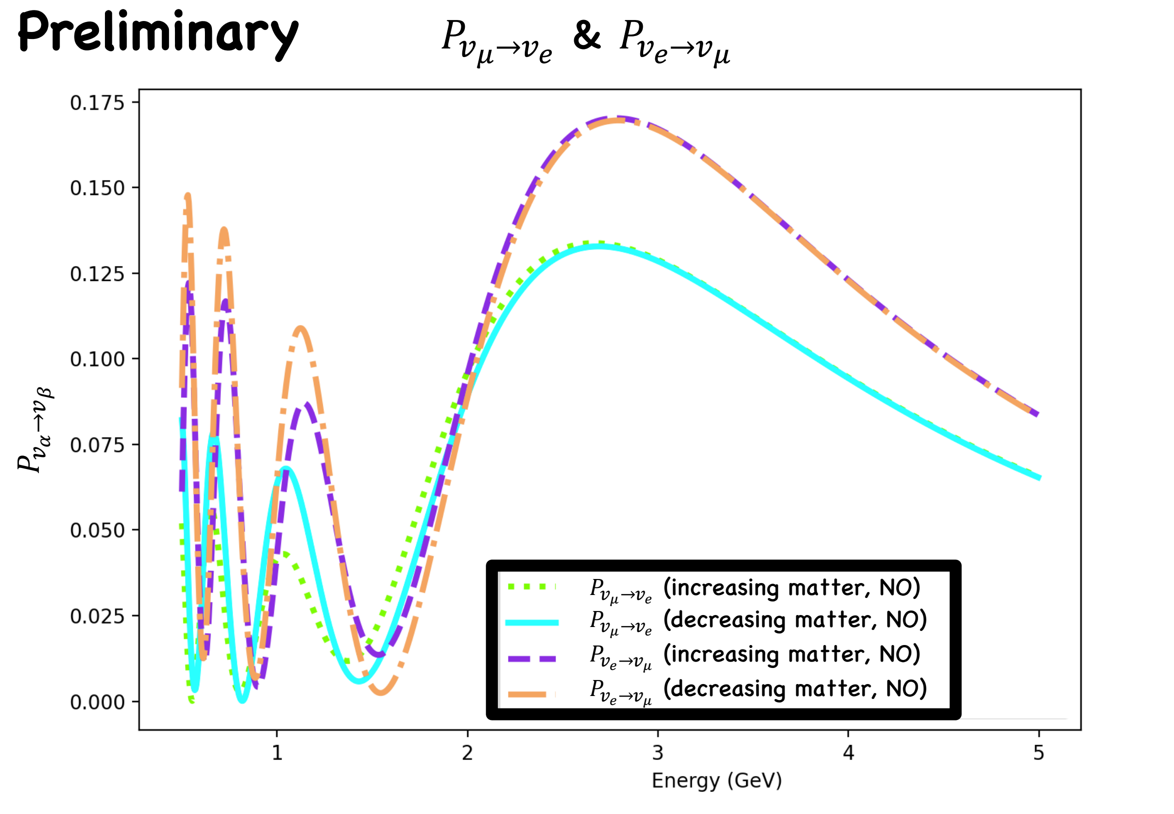
$P_{\nu_\mu \to \nu_e}$ & $P_{\nu_e \to \nu_\mu}$ channels:

- ✓ Baseline: 2000 km
- ✓ Piecewise matter potential (2 steps):

  $A_1 = 5x10^{-4}$ eV^2/GeV

  $A_2 = 1.5\ x10^{-3}$ eV^2/GeV

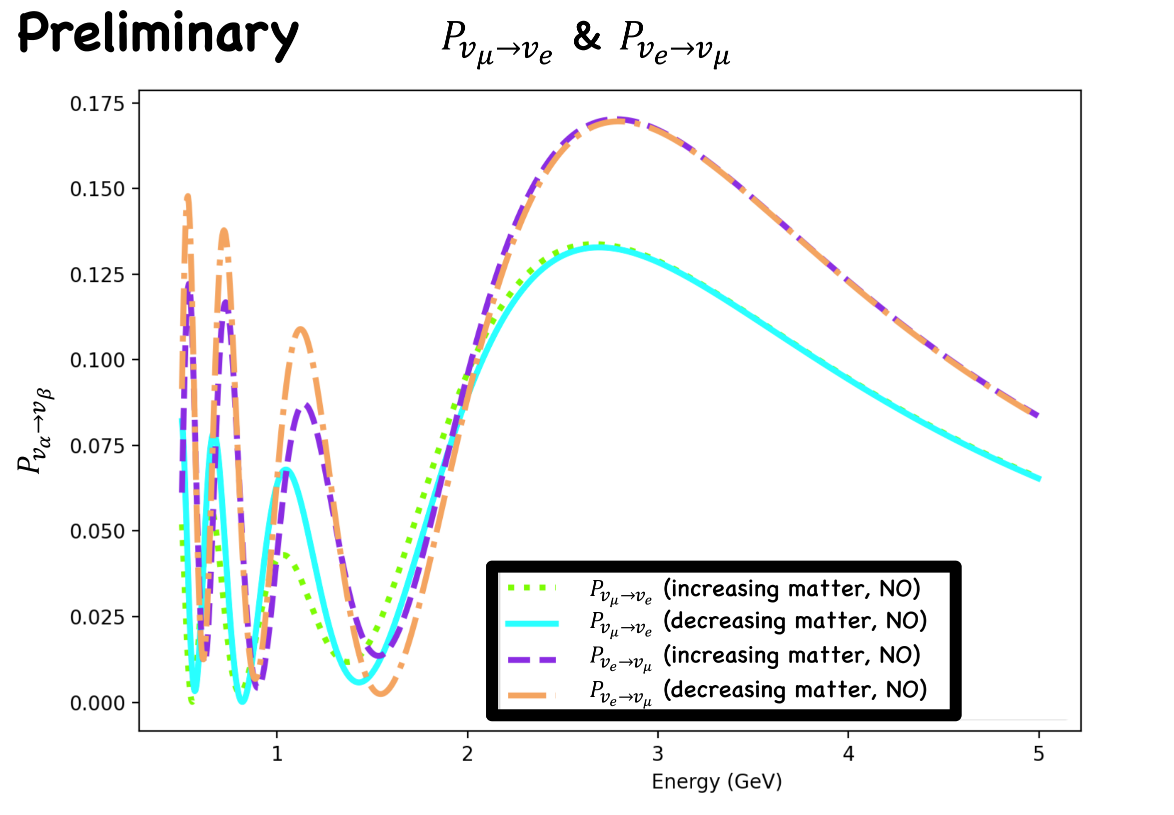
- ✓ $\delta_{CP}: \frac{\pi}{2}$
- ✓ Normal Ordering



α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors

- ✓ Non-symmetric matter effects (δ_{CP}: $\frac{\pi}{2}$)
- ✓ No longer pair-wise degenerate.
  (Intrinsic $P_{v_\mu \to v_e} \neq P_{v_e \to v_\mu}$)

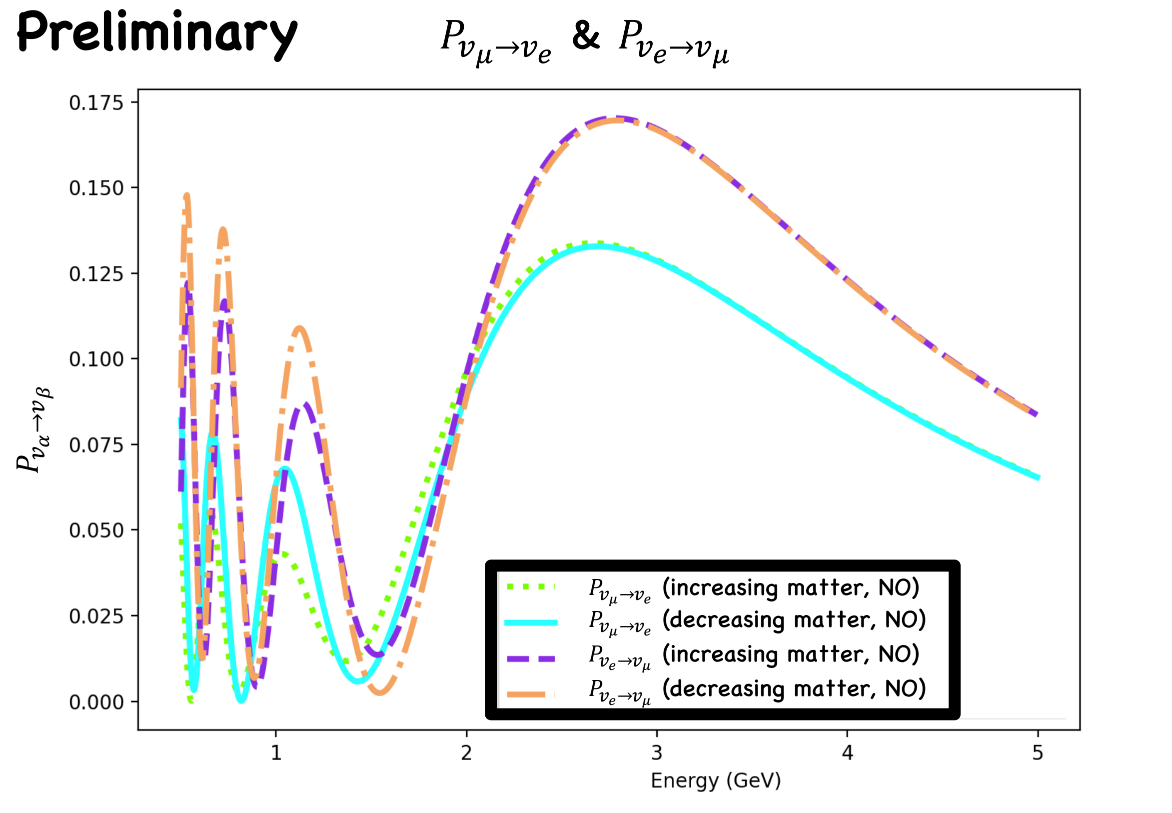


α, β -> $[\mu, e]$

Non-symmetric matter effects for 3-Flavors

- ✓ Non-symmetric matter effects (δ_{CP}: $\frac{\pi}{2}$)
- ✓ No longer pair-wise degenerate. (Intrinsic $P_{\nu_\mu \to \nu_e} \neq P_{\nu_e \to \nu_\mu}$)
- ✓ Matter potential choice changes magnitude of oscillations.

All probabilities are different.



α, β -> $[\mu, e]$

Future Studies

- ✓ Interesting probes in cases where matter induced time violation occurs and/or realistic models are non-symmetric:
  - Center of the Earth (annihilating dark matter to neutrinos scenario)
  - Geo neutrinos (properties/applications)
- ✓ Next steps include *NSI time invariance* probes applicable to DUNE, (a follow-up to previous work).