Discovery Reach for Non-Standard Interactions in a Neutrino Factory

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Contents

Introduction

References: P. Huber and J. W. F. Valle, Phys. Lett. **B523** (2001) 151. P. Huber, T. Schwetz, J. W. F. Valle, Phys. Rev. **D66** (2002) 013006. A. M. Gago, M. M. Guzzo, H. Nunokawa, W. J. C. Teves, and R. Zukanovich Funchal Phys. Rev. **D64** (2001) 073003. Y. Grossman, Phys. Lett. **B359** (1995) 141. M. C. Gonzalez-Garcia, Y. Grossman, A. Gusso, and Y. Nir, Phys. Rev. **D64** (2001) 096006. G. L. Fogli, E. Lisi, A. Mirizzi, and D. Montanino, Phys. Rev. **D66** (2002) 013009. T. O, J. Sato, and N. Yamashita, Phys. Rev. **D65** (2002) 093015. S. Davidson, C. Peña-Garay, N. Rius, and A. Santamaria, JHEP **0303** (2003) 011. M. Blennow, T. Ohlsson, and W. Winter, hep-ph/0508175. M. Honda, N. Okamura, and T. Takeuchi, hep-ph/0603268. N. Kitazawa, H. Sugiyama, and O. Yasuda hep-ph/0606013. A. Friedland and C. Lunardini, Phys. Rev. **D74** (2006) 033012.

Introduction — Motivation

- The aim of future neutrino experiments is the precision measurement of the oscillation parameters such as θ_{13} and $\delta_{\rm CP}$
  - Osc. probabilities will be measured with $\mathcal{O}$(1-0.1)% or higher accuracy.
  - We have a good chance to observe not only the standard oscillation phenomena but also the sub-leading effects induced by non-standard interactions (NSIs).

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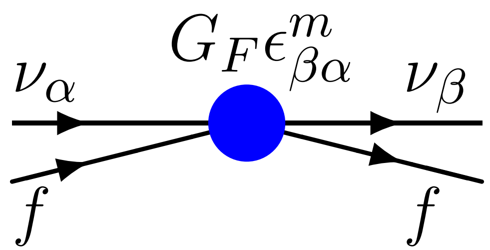
- NSIs — Flavour violating interactions with neutrinos such as $\nu_\alpha f \to \nu_\beta f$, $\ell_\alpha^- \to \nu_\beta e^- \bar{\nu}_e$...
  - It can be written as eff. 4-Fermi int. as

$$-\mathcal{L}_{\rm NSI} = 2\sqrt{2} G_F \epsilon^m_{\beta\alpha} (\bar{\nu}_\beta \gamma^\rho P_L \nu_\alpha)(\bar{f} \gamma_\rho P_{L/R} f)$$



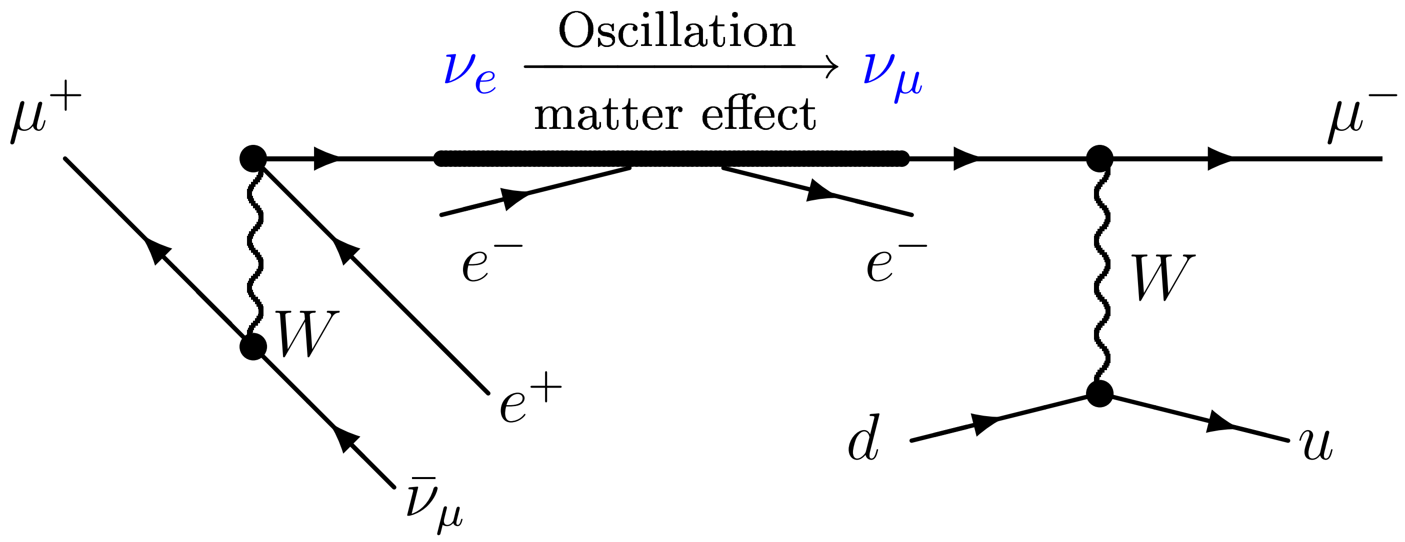
— We study the discovery reach of the NSIs in the osc. exp.

Introduction — Standard oscillation

- A long baseline exp. can be described diagrammatically as

$$\mathcal{A}(\nu_\mu N \to \mu^- X)\langle \nu_\mu | \mathrm{e}^{-\mathrm{i}HL} | \nu_e \rangle \mathcal{A}(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e)$$

$$||$$



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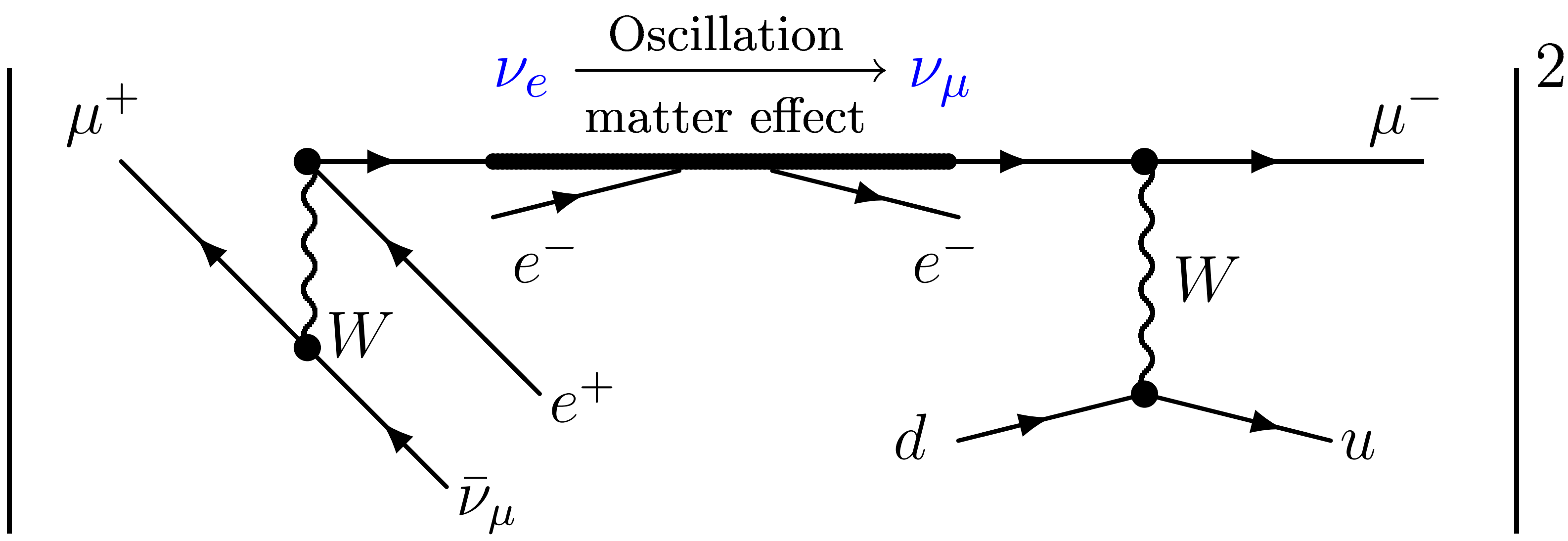
$$\left|\mathcal{A}(\nu_\mu N \to \mu^- X)\langle\nu_\mu|\mathrm{e}^{-\mathrm{i}HL}|\nu_e\rangle\mathcal{A}(\mu^+ \to e^+\bar{\nu}_\mu\nu_e)\right|^2$$

$$\|$$



Introduction — Standard oscillation

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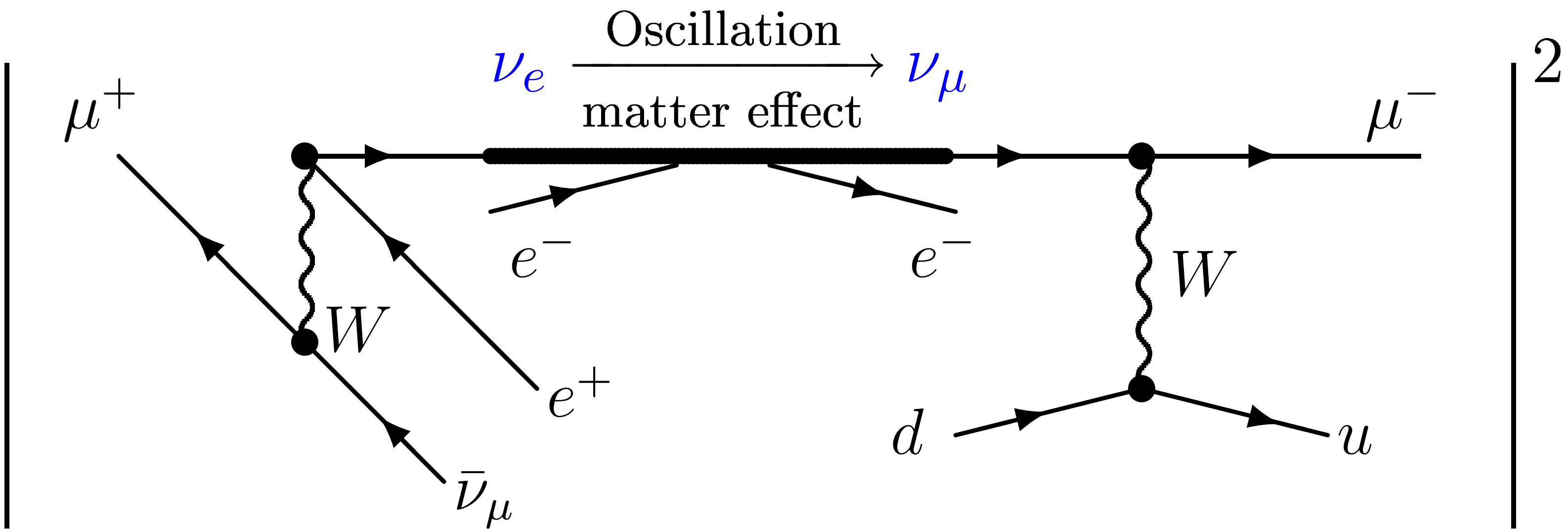
$$\sigma(\nu_\mu N \to \mu^- X) \times P_{\nu_e \to \nu_\mu} \times \Gamma(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e)$$

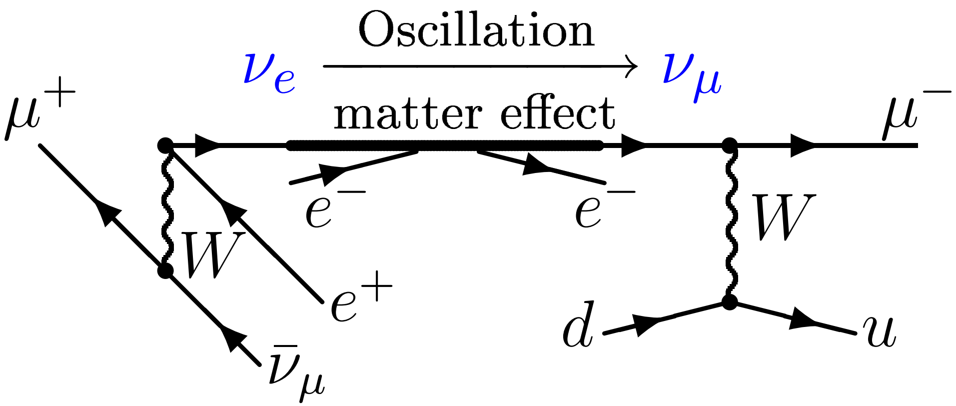
$$\|$$



Introduction — Oscillation enhanced search for NSIs

- ν osci. $=$ Flavour changing process

$$\ell_\alpha^- \xrightarrow{\text{CC}} \nu_\alpha \xrightarrow{\text{osc}} \nu_\beta \xrightarrow{\text{CC}} \ell_\beta^-$$



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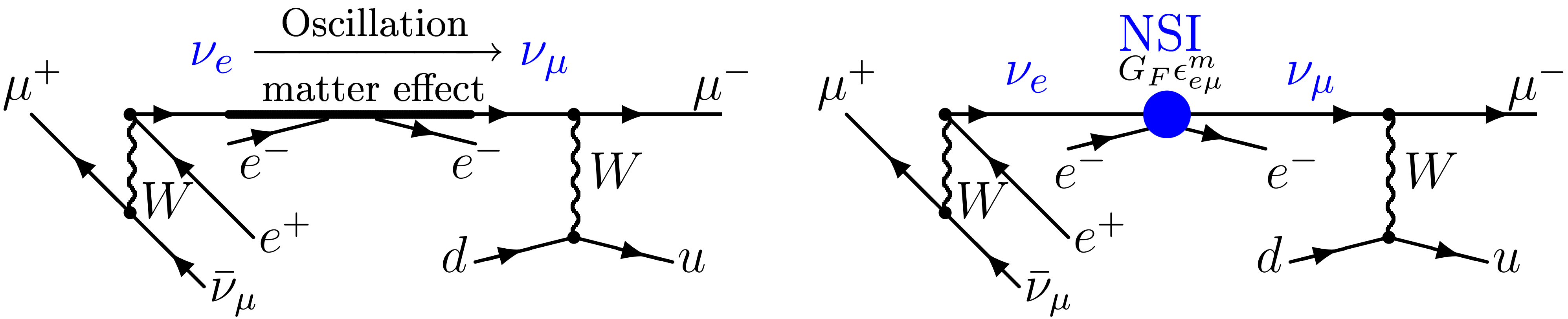

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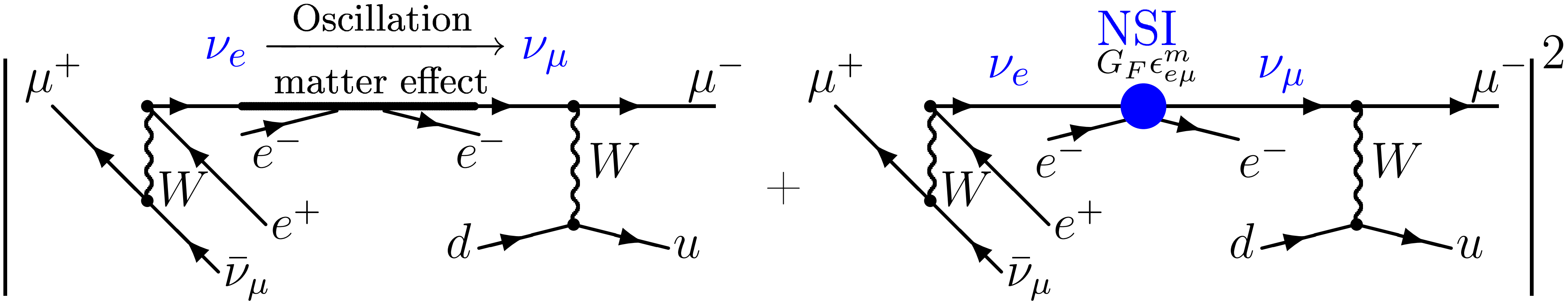
$$\ell_\alpha^- \xrightarrow{\text{CC}} \nu_\alpha \xrightarrow{\text{NSI}} \nu_\beta \xrightarrow{\text{CC}} \ell_\beta^-$$

— They interfere with each other.



- The signals of NSI appear in the osc. probability at $\mathcal{O}(\epsilon_{e\mu}^m)$.
  — This is quite different from the charged lepton LFV process.
  e.g., $\text{Br}(\mu \to 3e)$ is proportional to $|\epsilon_{e\mu}^m|^2$.

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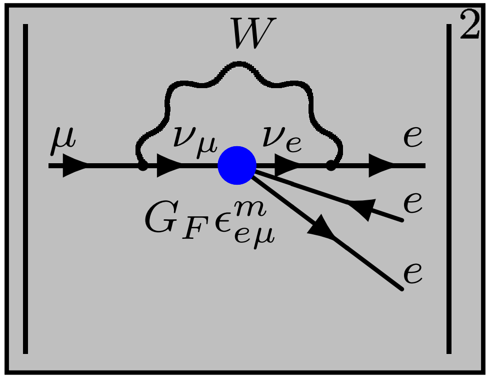
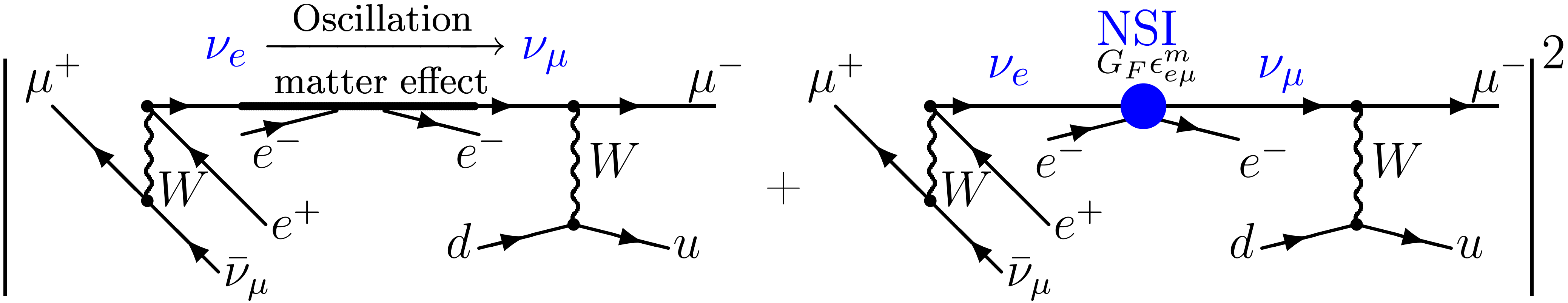




- The signals of NSI appear in the osc. probability at $\mathcal{O}(\epsilon^m_{e\mu})$.
  — This is quite different from the charged lepton LFV process.
  e.g., $\mathrm{Br}(\mu \to 3e)$ is proportional to $|\epsilon^m_{e\mu}|^2$.

Introduction — NSIs in matter

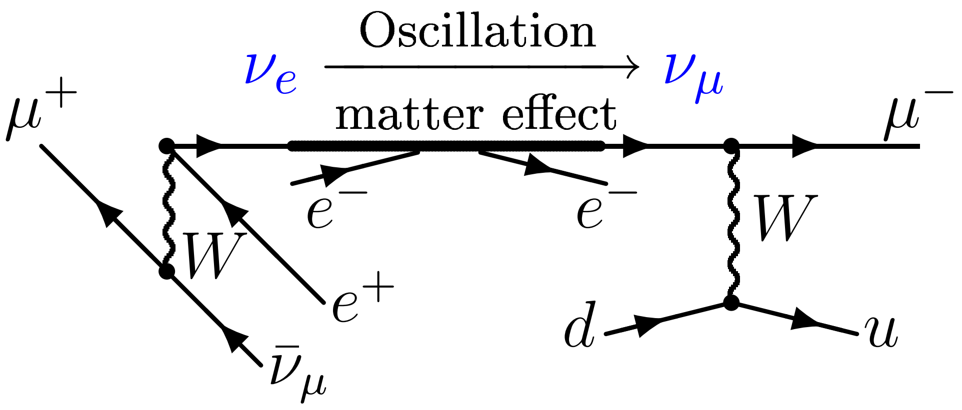
- NSIs in matter can be described by extra potential terms — We parametrize them as

$$H_{\beta\alpha} = \frac{1}{2E_\nu}\left\{ U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} a_{\rm CC} & & \\ & 0 & \\ & & 0 \end{pmatrix} + (V_{\rm NSI})_{\beta\alpha} \right\},$$

$$(V_{\rm NSI})_{\beta\alpha} = a_{\rm CC} \begin{pmatrix} \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ (\epsilon^m_{e\mu})^* & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ (\epsilon^m_{e\tau})^* & (\epsilon^m_{\mu\tau})^* & \epsilon^m_{\tau\tau}. \end{pmatrix}$$

- In general, each off-diagonal (flavour violating) element has a complex phase.

Introduction — NSI in beam source



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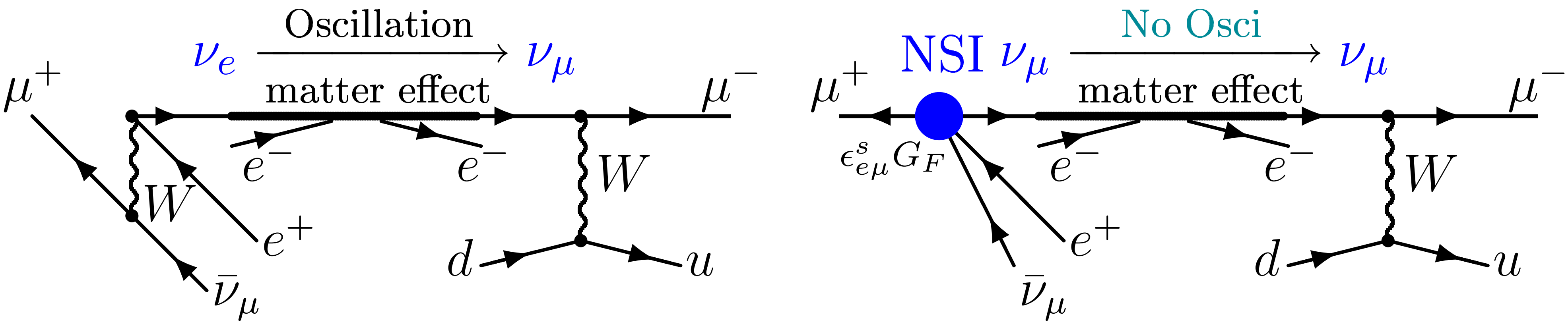
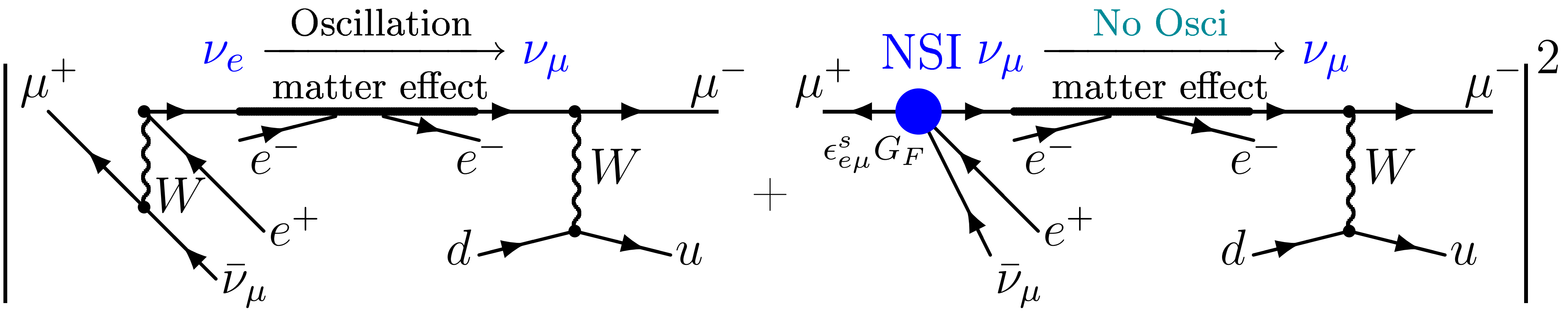


- NSIs in beam source can be treated by a flavour mixture state

$$|\nu_e^{(s)}\rangle = |\nu_e\rangle + \epsilon^s_{e\mu}|\nu_\mu\rangle.$$

Introduction — NSI in beam source



- NSIs in beam source can be treated by a flavour mixture state

$$|\nu_e^{(s)}\rangle = |\nu_e\rangle + \epsilon^s_{e\mu}|\nu_\mu\rangle.$$

- The oscillation probability is calculated with the *source state* as

$$P_{\nu_e\to\nu_\mu} = \left|\langle\nu_\mu|\mathrm{e}^{-\mathrm{i}HL}|\nu_e^{(s)}\rangle\right|^2 = \left|\langle\nu_\mu|\mathrm{e}^{-\mathrm{i}HL}|\nu_e\rangle + \epsilon^s_{e\mu}\langle\nu_\mu|\mathrm{e}^{-\mathrm{i}HL}|\nu_\mu\rangle\right|^2$$

— Interferece between Osc. Amp. and NSI. Amp.

Discovery reach for NSIs in neutrino factory

Reference: P. Huber, M. Lindner, and W. Winter, Comput. Phys. Commun. **167** (2005) 195.

Discovery reach for NSIs in neutrino factory

- Discovery reach for $\epsilon^m_{e\mu}$ in neutrino factory
  — how small $|\epsilon^m_{e\mu}|$ can be found in the neutrino factory.
- We introduce a NSI as the complex parameter
  - There is no reason to consider it is a real parameter.
  - The discovery reach strongly depends on the phase.
- We turn off all NSIs other than the NSI which we study.
- Modified GLoBES software is used.
- The following values are adopted as the true value of the standard oscillation parameters

powered by GLoBES

$$\sin^2 2\theta_{12}^{\rm true} = 0.83, \quad \sin^2 2\theta_{13}^{\rm true} = 0.01, \quad \sin^2 2\theta_{23}^{\rm true} = 1.0,$$
$$(\Delta m^2_{21})^{\rm true} = 8.2 \times 10^{-5}\ [\mathrm{eV}^2], \quad (\Delta m^2_{31})^{\rm true} = 2.5 \times 10^{-3}\ [\mathrm{eV}^2].$$

Discovery reach for NSIs in neutrino factory

- Discovery reach for $|(\epsilon^m_{e\mu})^{\rm true}|$ is determined by[a]

$$\chi^2 \equiv \min_{\lambda} \sum_i^{\rm bin} \left| N_i\left(\lambda^{\rm true}, (\epsilon^m_{e\mu})^{\rm true}\right) - N_i\left(\lambda, \epsilon^m_{e\mu} = 0\right) \right|^2 \Big/ V_i,$$

where $\lambda \in \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\rm CP}, \Delta m^2_{21}, \Delta m^2_{31}, a_{\rm CC}\}$.

- If $\chi^2 > \chi^2_{3\sigma}$, the effect induced by the NSI with the value of $|(\epsilon^m_{e\mu})^{\rm true}|$ will be discovered at the 3σ level.

- Undetermined parameters: $\delta^{\rm true}_{\rm CP}$ and $\arg[(\epsilon^m_{e\mu})^{\rm true}]$
— We scan the value of χ^2 on the $\delta^{\rm true}_{\rm CP}$-$\arg[(\epsilon^m_{e\mu})^{\rm true}]$ plane for the fixed $|(\epsilon^m_{e\mu})^{\rm true}|$.

[a] In the numerical calculation, we use the χ^2 function for the Poisson distribution.

Discovery reach for $\epsilon^m_{e\mu}$ in neutrino factory

- In the case $|(\epsilon^m_{e\mu})^{\mathrm{true}}| = 5 \times 10^{-4}$,
- $|\epsilon^m_{e\mu}|$ is too small

  ↓

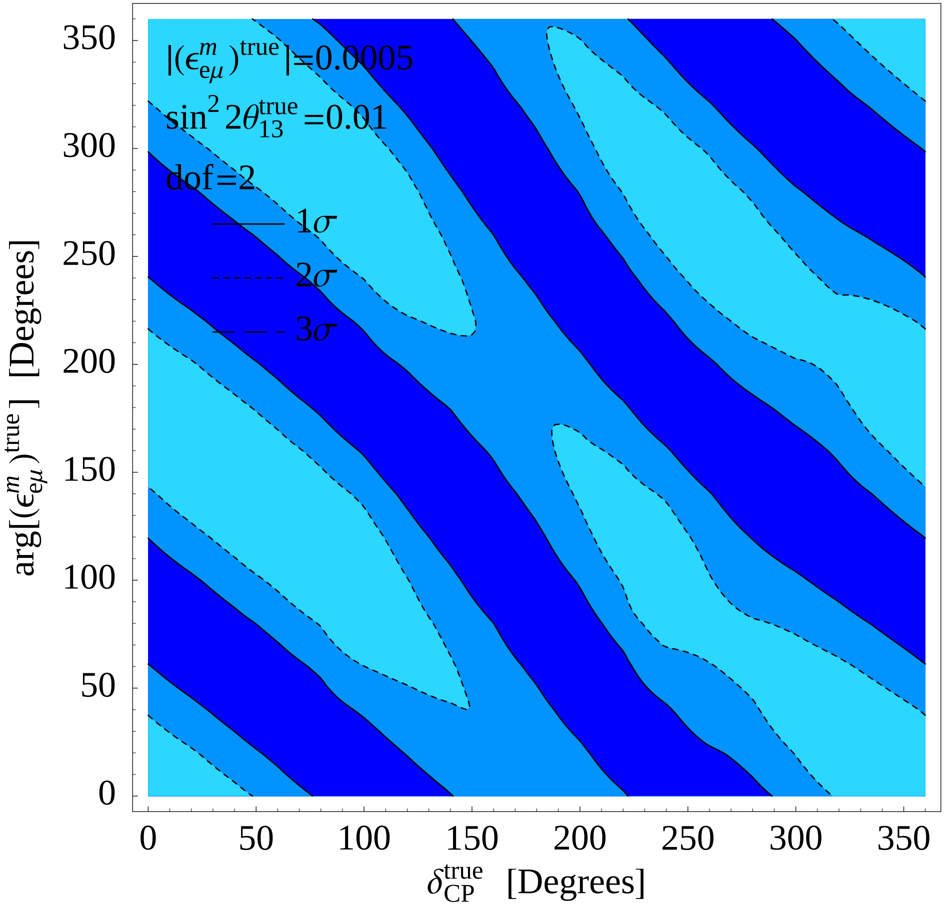
  χ^2 cannot exceed 3σ on the whole parameter plane. (Under the sea)

  ↓

  The deviation from the standard oscillation is not significant

  ↓

  No chance to discover!



Discovery reach for $\epsilon^m_{e\mu}$ in neutrino factory

- In the case $|(\epsilon^m_{e\mu})^{\text{true}}| = 6 \times 10^{-4}$,
- $|\epsilon^m_{e\mu}|$ becomes larger

  ↓

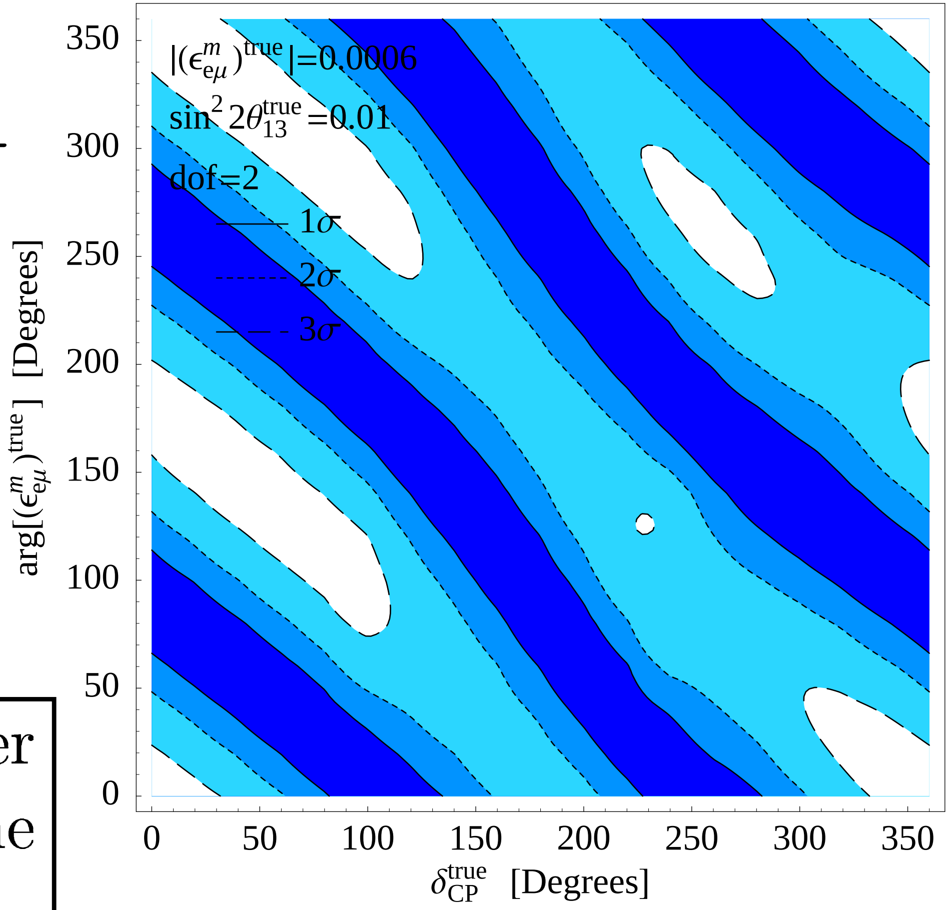
  In some regions χ^2 exceeds 3σ (Islands appear)

  ↓

  The deviation from the standard oscillation is significant at 3σ

  ↓

  We have a chance to discover NSI effect depending on the phases



Discovery reach for $\epsilon^m_{e\mu}$ in neutrino factory

- In the case $|(\epsilon^m_{e\mu})^{\text{true}}| = 1 \times 10^{-3}$,
- $|\epsilon^m_{e\mu}|$ becomes larger

  $\downarrow$

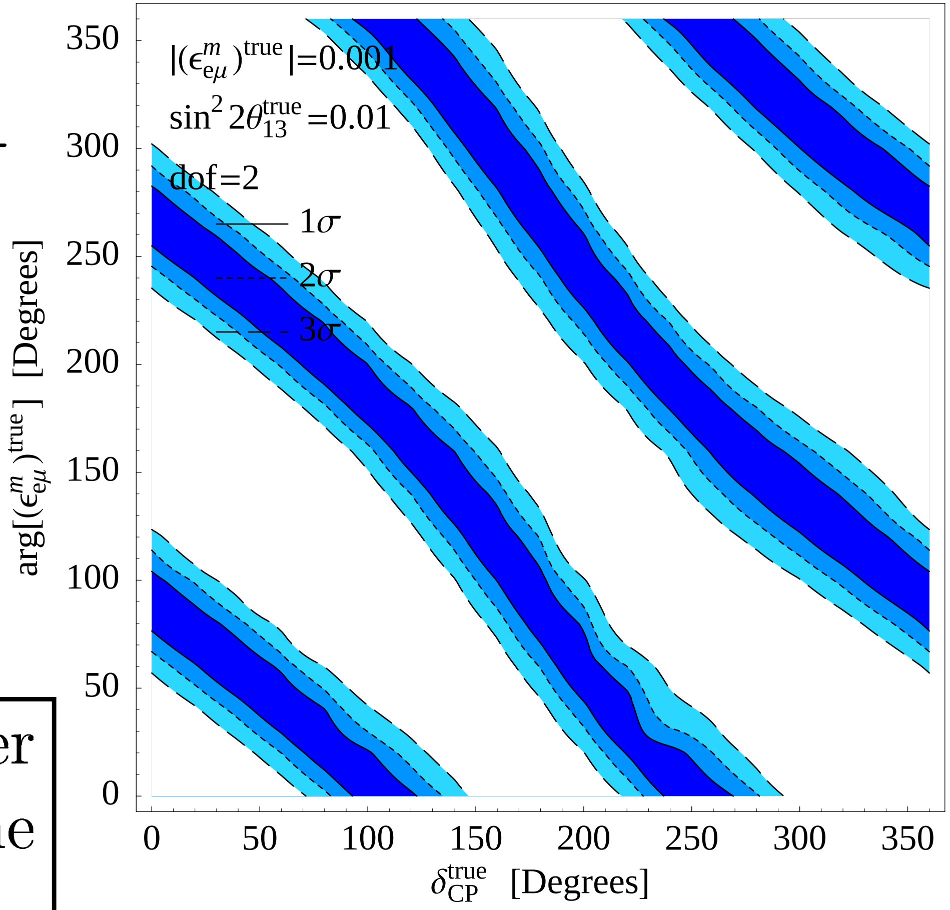
  In some regions χ^2 exceeds 3σ (Islands appear)

  $\downarrow$

  The deviation from the standard oscillation is significant at 3σ

  $\downarrow$

  We have a chance to discover NSI effect depending on the phases



Discovery reach for $\epsilon_{e\mu}^m$ in neutrino factory

- In the case $|(\epsilon_{e\mu}^m)^{\text{true}}| = 2 \times 10^{-3}$,
- $|\epsilon_{e\mu}^m|$ becomes larger

  $\downarrow$

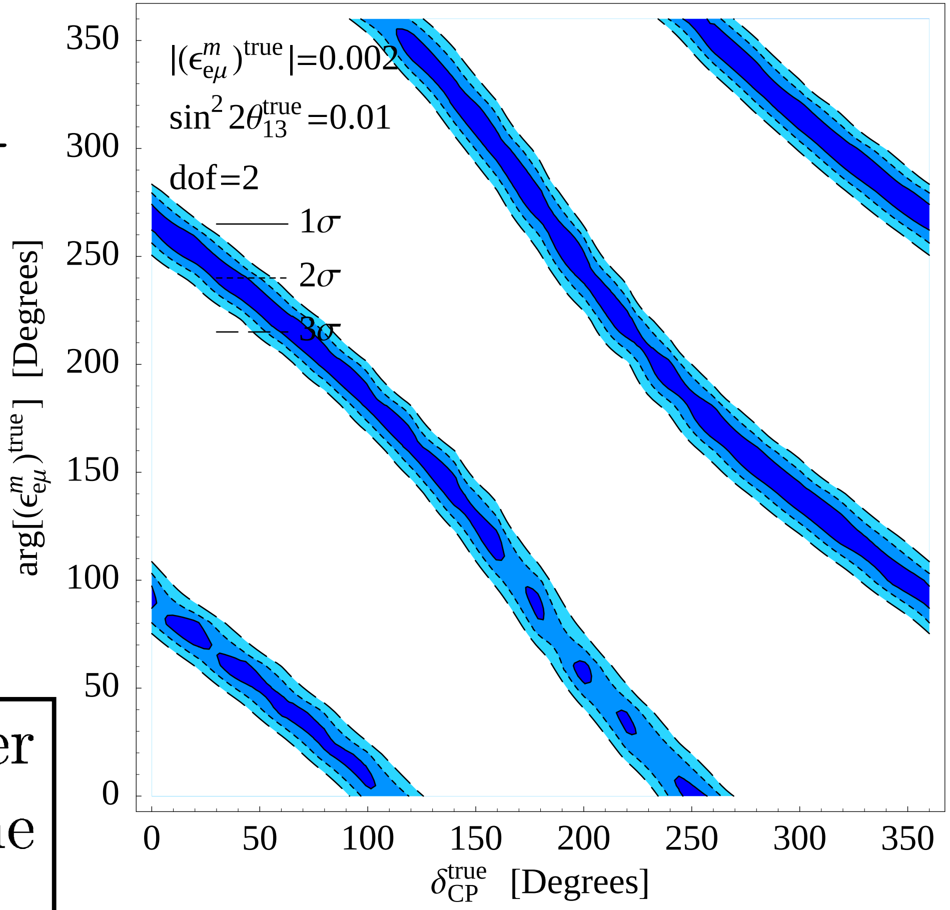
  In some regions χ^2 exceeds 3σ (Islands appear)

  $\downarrow$

  The deviation from the standard oscillation is significant at 3σ

  $\downarrow$

  We have a chance to discover NSI effect depending on the phases



Discovery reach for $\epsilon_{e\mu}^{m}$ in neutrino factory

- In the case $|(\epsilon_{e\mu}^{m})^{\rm true}| = 4 \times 10^{-3}$,
- $|\epsilon_{e\mu}^{m}|$ becomes larger

  ↓

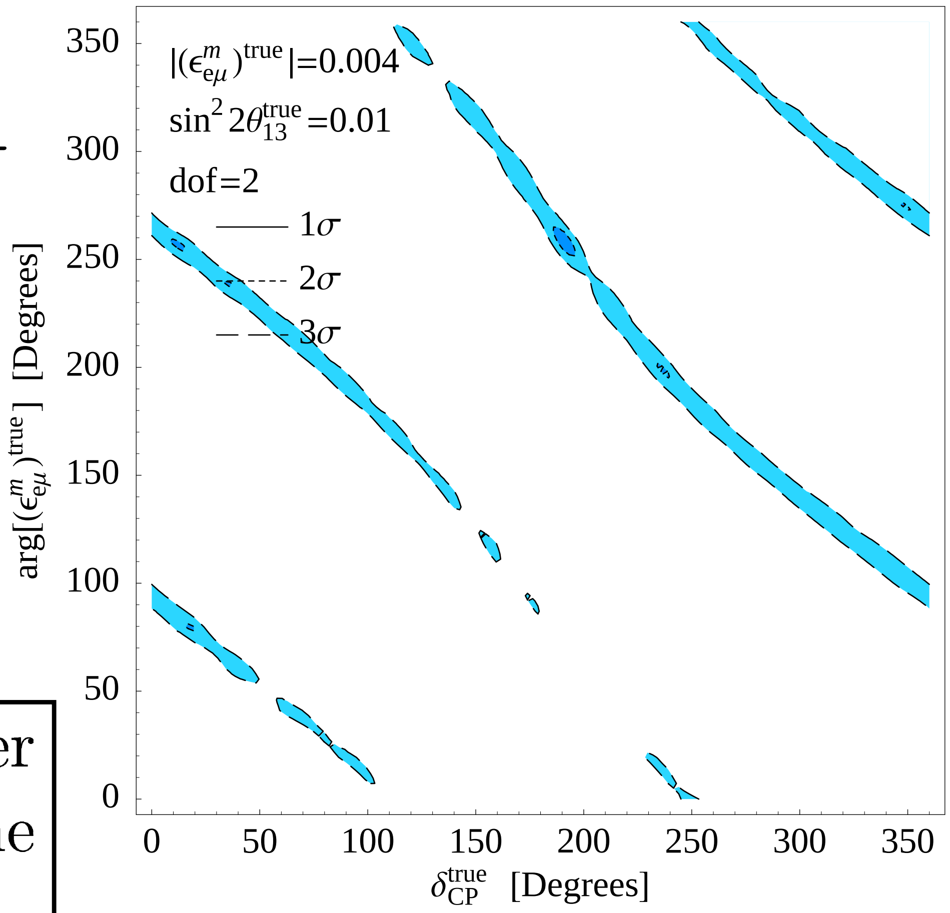
  In some regions χ^2 exceeds 3σ (Islands appear)

  ↓

  The deviation from the standard oscillation is significant at 3σ

  ↓

  We have a chance to discover NSI effect depending on the phases



Discovery reach for $\epsilon_{e\mu}^m$ in neutrino factory

- In the case $|(\epsilon_{e\mu}^m)^{\rm true}| = 5 \times 10^{-3}$,
- $|\epsilon_{e\mu}^m|$ is large enough

$\downarrow$

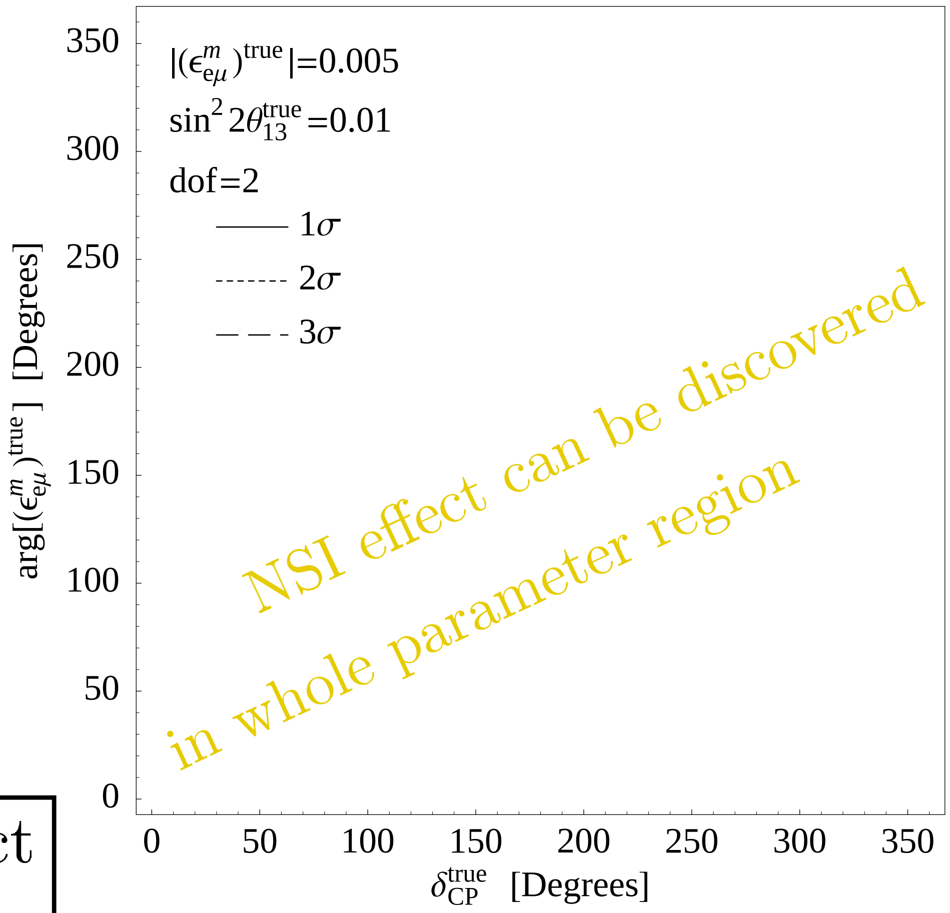
χ^2 exceeds 3σ on the whole parameter plane (The sea disappears)

$\downarrow$

The deviation from the standard oscillation is significant at 3σ

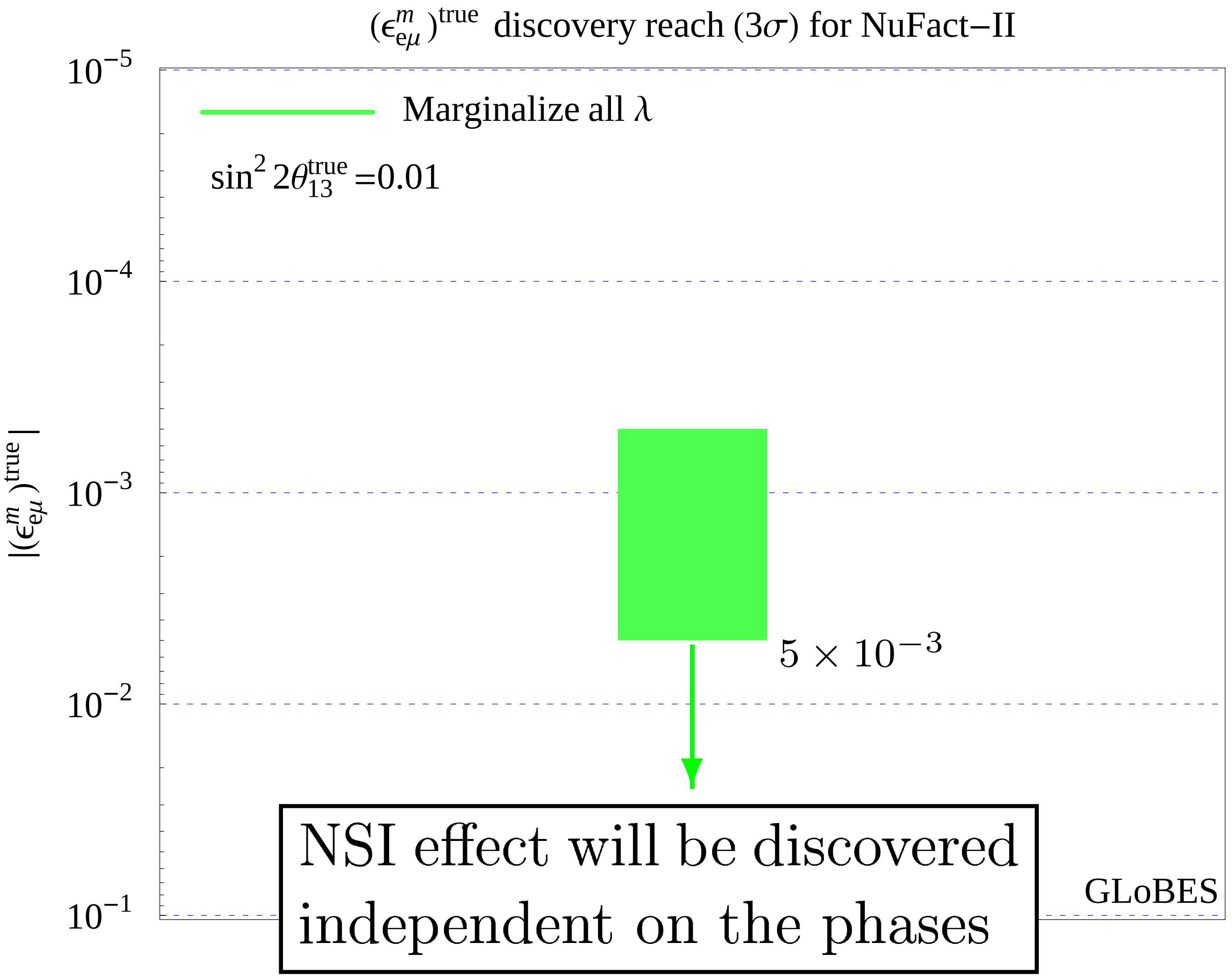
$\downarrow$

We can observe the NSI effect with any values of phases.



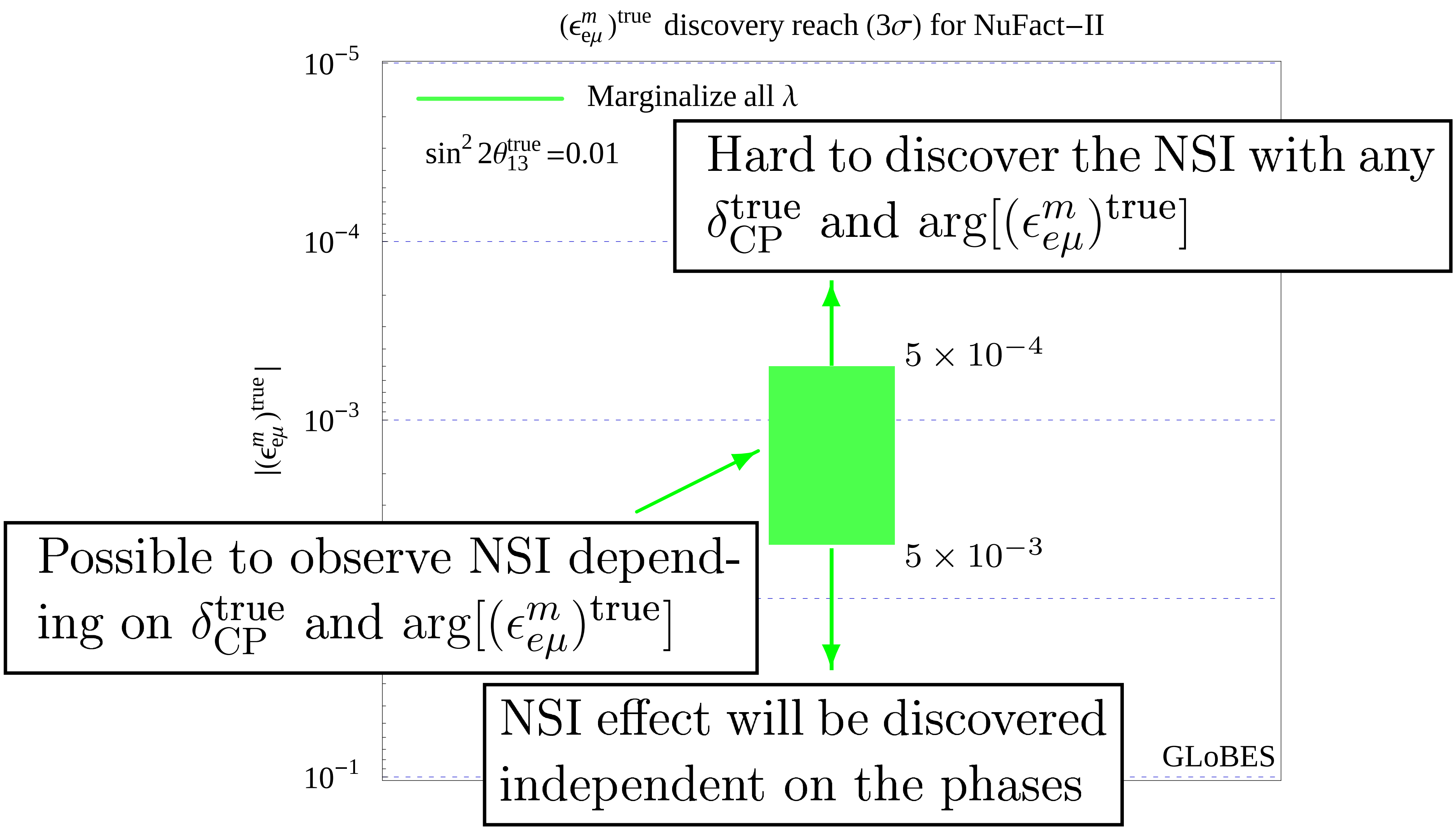
Discovery reach for NSIs in neutrino factory

- Summary plot for the discovery reach of $\epsilon_{e\mu}^{m}$



Discovery reach for NSIs in neutrino factory

- Summary plot for the discovery reach of $\epsilon^m_{e\mu}$



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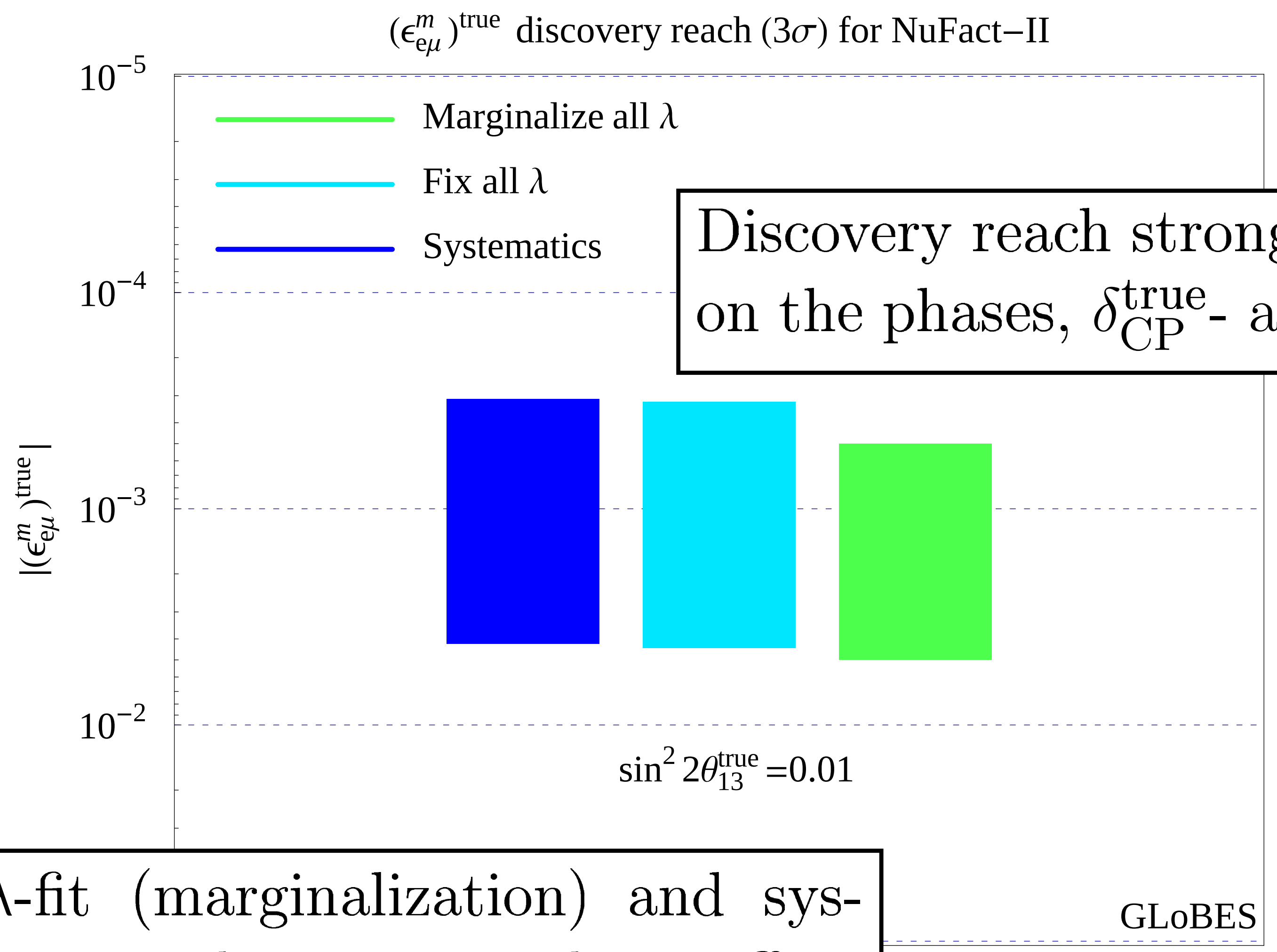
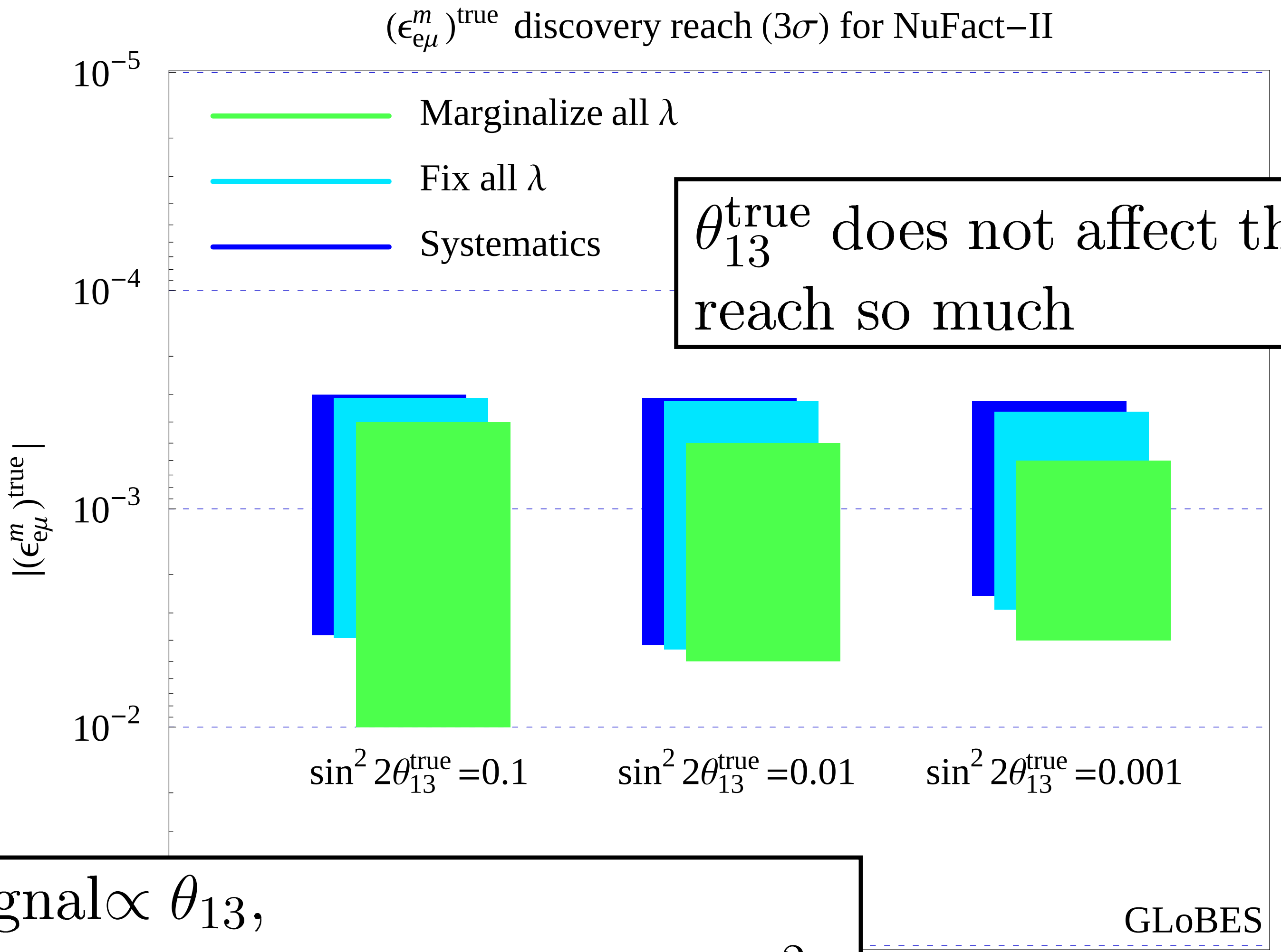


Discovery reach strongly depends on the phases, δ_{CP}^{true}- $\arg[(\epsilon^m_{e\mu})^{true}]$

λ-fit (marginalization) and systematic do not give a large effect

Discovery reach for NSIs in neutrino factory

- Summary plot for the discovery reach of $\epsilon^m_{e\mu}$

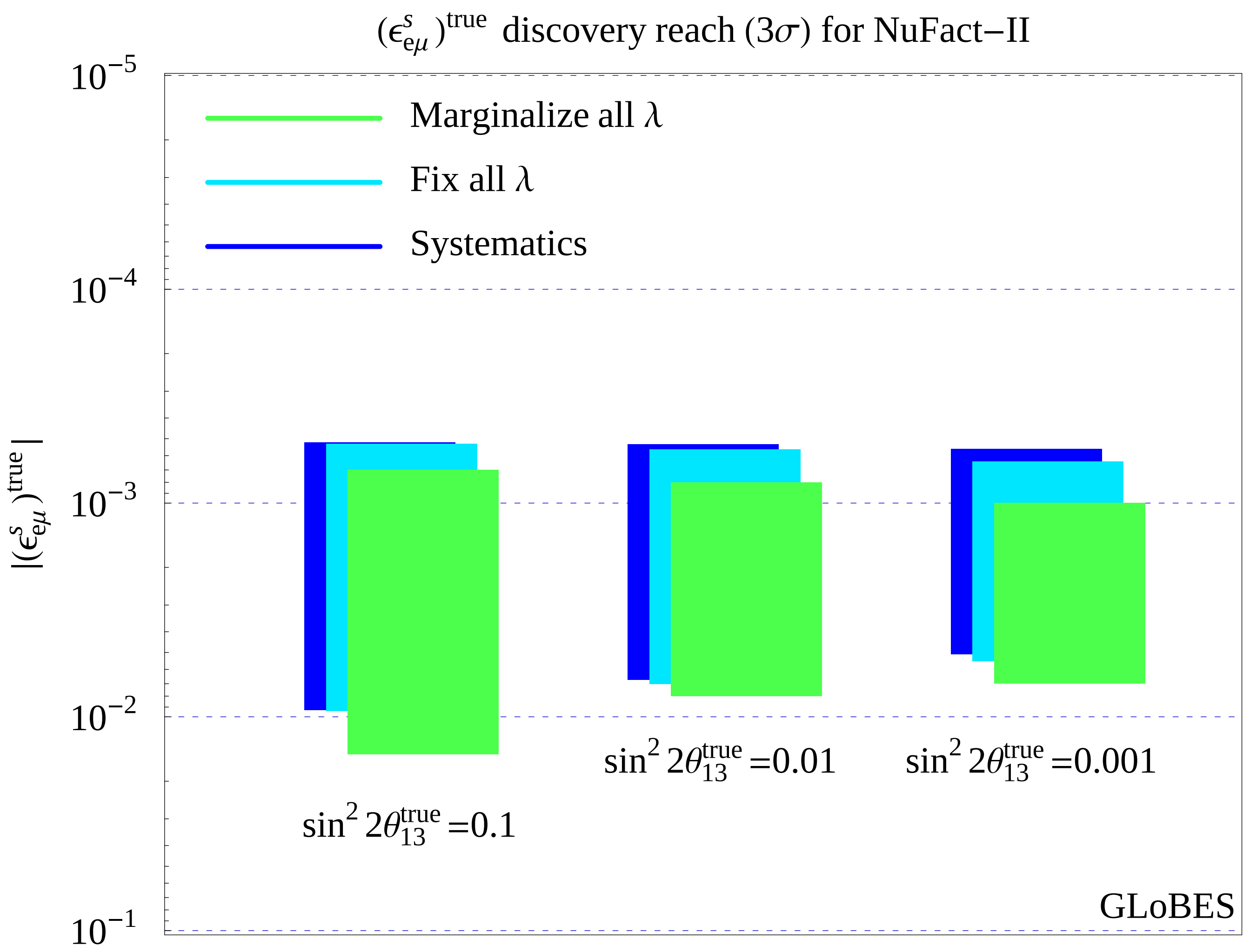


$\theta_{13}^{\text{true}}$ does not affect the discovery reach so much

signal$\propto \theta_{13}$,
background (standard osc.)$\propto \theta_{13}^2$

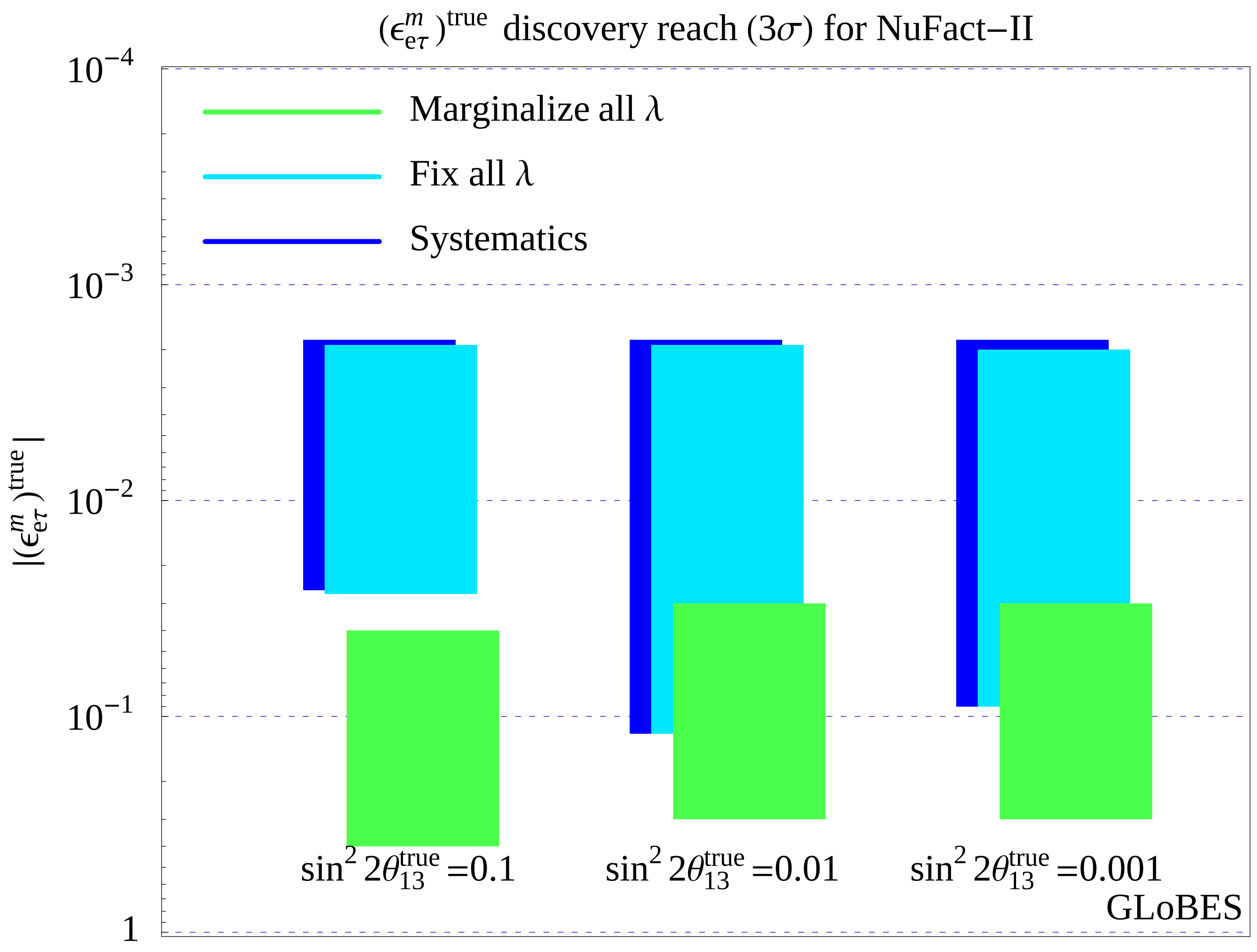
Discovery reach for NSIs in neutrino factory

- Similar plot for the discovery reach of $\epsilon^s_{e\mu}$

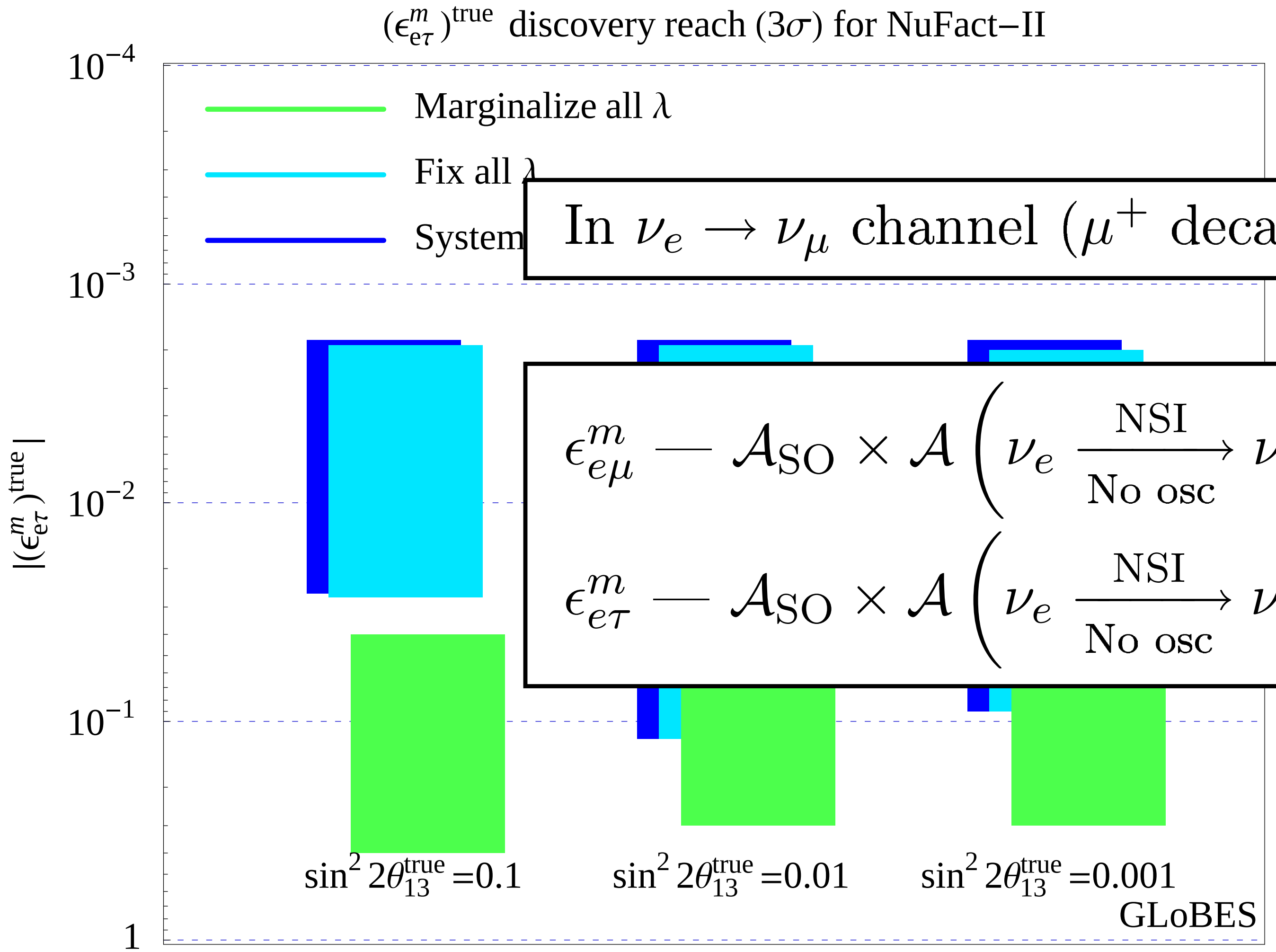


Discovery reach for NSIs in neutrino factory

- Similar plot for the discovery reach of $\epsilon^m_{e\tau}$



- Similar plot for the discovery reach of $\epsilon^m_{e\tau}$



In $\nu_e \to \nu_\mu$ channel (μ^+ decay μ^- detection)

$$\epsilon^m_{e\mu} \text{ — } \mathcal{A}_{\rm SO} \times \mathcal{A}\left(\nu_e \xrightarrow[\text{No osc}]{\text{NSI}} \nu_\mu\right)$$

$$\epsilon^m_{e\tau} \text{ — } \mathcal{A}_{\rm SO} \times \mathcal{A}\left(\nu_e \xrightarrow[\text{No osc}]{\text{NSI}} \nu_\tau \xrightarrow[\text{Osc}]{} \nu_\mu\right)$$

Implementation of NSIs to GLoBES

- For NSIs in matter effect, e.g., $\epsilon^m_{e\mu}$,

$$H_{\alpha\beta} = H_{\rm SO} + H_{\rm NSI}, \quad \begin{cases} 2E(H_{\rm SO})_{\alpha\beta} = U_{\alpha i} \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger_{i\beta} + \begin{pmatrix} a_{\rm CC} & & \\ & 0 & \\ & & 0 \end{pmatrix}, \\ 2E(H_{\rm NSI})_{\alpha\beta} = \begin{pmatrix} 0 & a_{\rm CC}|\epsilon^m_{e\mu}|{\rm e}^{{\rm i}\,\arg[\epsilon^m_{e\mu}]} & \\ a_{\rm CC}|\epsilon^m_{e\mu}|{\rm e}^{-{\rm i}\,\arg[\epsilon^m_{e\mu}]} & 0 & \\ & & 0 \end{pmatrix}. \end{cases}$$

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```
static int ComputeMixingMatrix()
{
...
md[0][0] += msw;

// two extra-parameters: //
// abs(epsilon) = nsparams[0], arg(epsilon)=nsparams[1] //

md[0][1] += msw * nsparams[0] * exp(complex<FLOAT>(0,1) * nsparams[1]);
md[1][0] += msw * nsparams[0] * exp(complex<FLOAT>(0,-1) * nsparams[1]);
...
}
```

Implementation of NSIs to GLoBES

- For NSIs at the source and detection, e.g., $\epsilon^s_{e\mu}$,
  - The initial source state is a mixture of the flavour state

$$|\nu_e^{(s)}\rangle = |\nu_e\rangle + |\nu_\mu\rangle \epsilon^s_{e\mu}.$$

  - The oscillation probability for $\nu_e^{(s)} \to \nu_\beta$ is calculated to be

$$P_{\nu_e^s \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_e^{(s)} \rangle \right|^2 = \left| S_{\beta e} + \epsilon^s_{e\mu} S_{\beta\mu} \right|^2$$

$$= \left| \left\{ \begin{pmatrix} S_{ee} & S_{e\mu} & S_{e\tau} \\ S_{\mu e} & S_{\mu\mu} & S_{\mu\tau} \\ S_{\tau e} & S_{\tau\mu} & S_{\tau\tau} \end{pmatrix} \begin{pmatrix} 1 & & \\ |\epsilon^s_{e\mu}| \mathrm{e}^{\mathrm{i}\arg[\epsilon^s_{e\mu}]} & 1 & \\ & & 1 \end{pmatrix} \right\}_{\beta e} \right|^2,$$

where $S_{\beta\alpha}$ is the standard oscillation amplitudes, i.e.,

$$S_{\beta\alpha} = \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle.$$

Implementation of NSIs to GLoBES

- For NSIs at the source and detection, e.g., $\epsilon^s_{e\mu}$,

$$P_{\nu^s_\alpha \to \nu_\beta} = \left| \left\{ \begin{pmatrix} S_{ee} & S_{e\mu} & S_{e\tau} \\ S_{\mu e} & S_{\mu\mu} & S_{\mu\tau} \\ S_{\tau e} & S_{\tau\mu} & S_{\tau\tau} \end{pmatrix} \begin{pmatrix} 1 & & \\ |\epsilon^s_{e\mu}| \mathrm{e}^{\mathrm{i}\,\arg[\epsilon^s_{e\mu}]} & 1 & \\ & & 1 \end{pmatrix} \right\}_{\beta\alpha} \right|^2$$

Implementation of NSIs to GLoBES

- For NSIs at the source and detection, e.g., $\epsilon^s_{e\mu}$,

$$P_{\nu^s_\alpha \to \nu_\beta} = \left| \left\{ \begin{pmatrix} S_{ee} & S_{e\mu} & S_{e\tau} \\ S_{\mu e} & S_{\mu\mu} & S_{\mu\tau} \\ S_{\tau e} & S_{\tau\mu} & S_{\tau\tau} \end{pmatrix} \begin{pmatrix} 1 & & \\ |\epsilon^s_{e\mu}| \mathrm{e}^{\mathrm{i}\,\arg[\epsilon^s_{e\mu}]} & 1 & \\ & & 1 \end{pmatrix} \right\}_{\beta\alpha} \right|^2$$

```
extern "C" void glb_probability_matrix(FLOAT prob[3][3], int panti, double pen)
{
...
for (int i=0; i<3; i++){
    for (int j=0; j<3; j++){
        amp[i][j] = complex<FLOAT>(0,0);
    }
}
for (int i=0; i<3; i++){
    amp[i][i]=complex<FLOAT>(1,0);
}
amp[1][0]= nsparams[0] * exp(complex<FLOAT>(0,1) * nsparams[1]);
...
for (int i=0; i<psteps; i++)
    MultiplyAmplitudeMatrix(amp,panti,length[i],pen,density[i]);
...
}
```

Summary

Summary

- We have studied the discovery reach for the NSIs in a neutrino factory.
- The undetermined parameters $\delta_{\rm CP}^{\rm true}$ and $\arg[\epsilon^{\rm true}]$ are scanned.

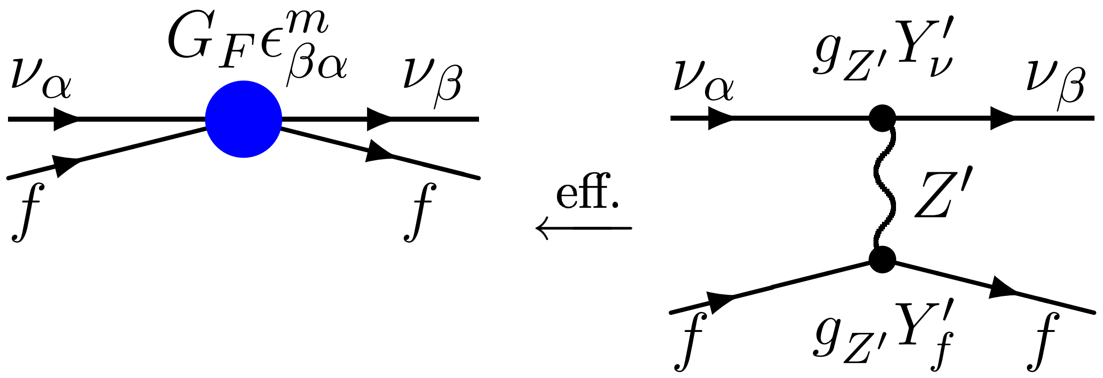
For $\epsilon_{e\mu}^m$, when $\sin^2 2\theta_{13}^{\rm true} = 0.01$

- With $|\epsilon_{e\mu}^m| \geq 5 \times 10^{-4}$, we have a chance to discover the effect at the 3σ level, depending on the phases.
- If $|\epsilon_{e\mu}^m| \geq 5 \times 10^{-3}$, it can be found in the ν factory regardless of the phases.

- Current bound from $\mu \to 3e$ is 5×10^{-4} at the 90% CL.
  — Comparable, depending on the phases

Summary

- The discovery reach for $\epsilon^m_{e\tau}$ and $\epsilon^s_{e\mu}$ has also studied.
  - $|\epsilon^s_{e\mu}| \sim \mathcal{O}(10^{-3,-4})$, $|\epsilon^m_{e\tau}| \sim \mathcal{O}(10^{-1,-2})$.
- The effective four-Fermi NSIs with $\epsilon \sim \mathcal{O}(10^{-2})$ may mean the TeV scale physics, i.e.,



  - If $g_{Z'}$ is the same as g_Z, $\epsilon^m_{\beta\alpha} = m_Z^2/m_{Z'}^2$.

- NSIs are not good signals for MSSM
  — They are strongly supressed

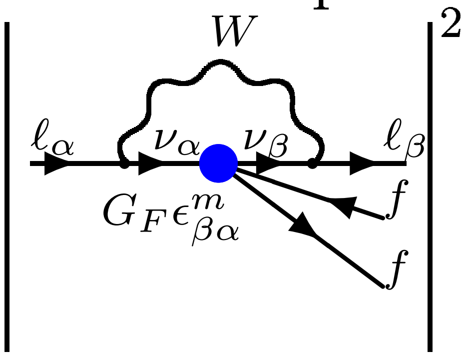
  — NSIs may be the signals for something else than MSSM

Discussion: NSIs in models

References : T. O and J. Sato, Phys. Rev. **D71** (2005) 096004.

NSIs in models

- We dealt with NSIs as effective 4-Fermi interactions so far.
- Current experimental bounds coming from the LFV process



$\epsilon^m_{e\mu}$ $(f=e)$	5×10^{-4} (90% CL)
$\epsilon^m_{e\tau}$ $(f=e)$	2.9 (90% CL)

Comparable with discovery reach in ν fact.

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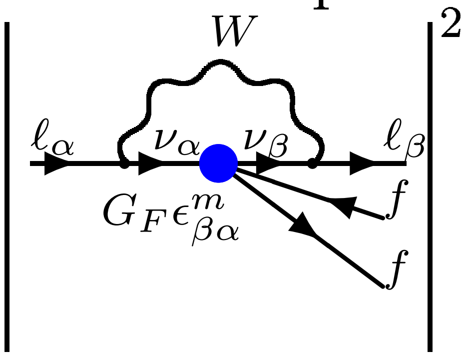

$\epsilon^m_{e\mu}$	$(f=e)$	5×10^{-4} (90% CL)
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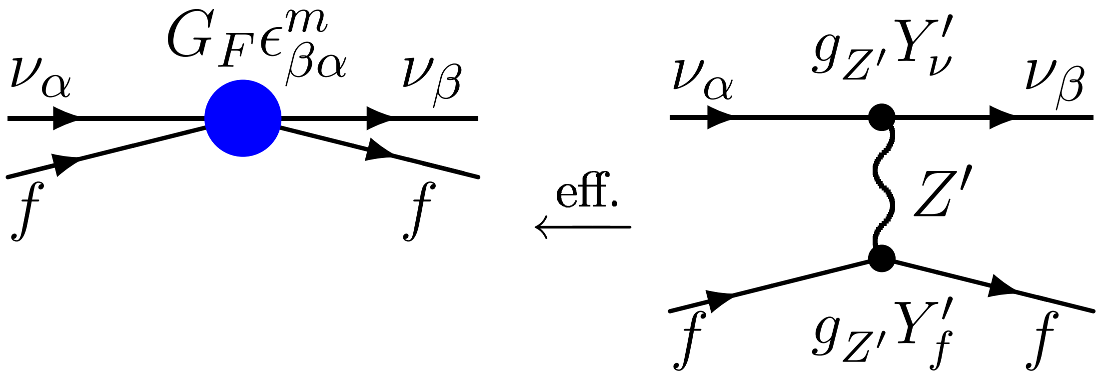
Comparable with discovery reach in ν fact.

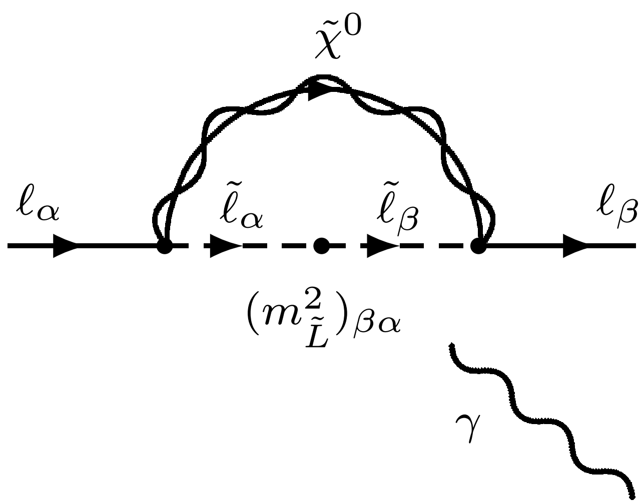
- These eff. int.s can be interpreted as *extra weak interactions*

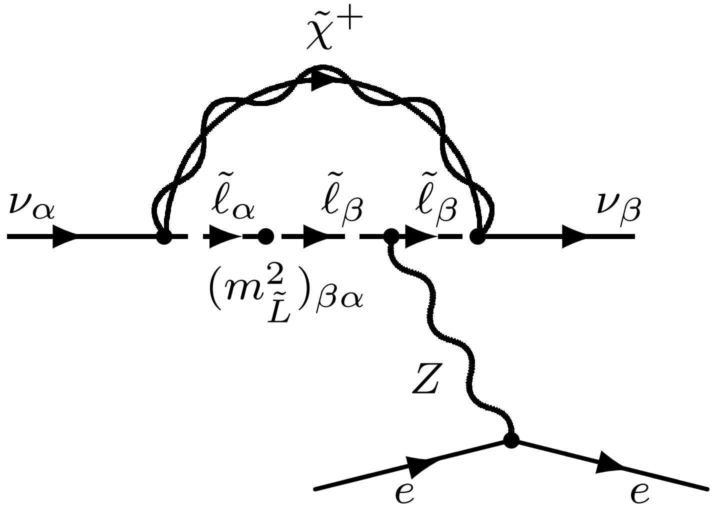


- If $g_{Z'}$ are the same as those of weak interaction, $\epsilon^m_{\beta\alpha}=m_Z^2/m_{Z'}^2$
- $\epsilon^m_{\alpha\beta}\sim\mathcal{O}(10^{-2})$ means *access to the TeV scale physics*

NSIs in models — MSSM with ν_R

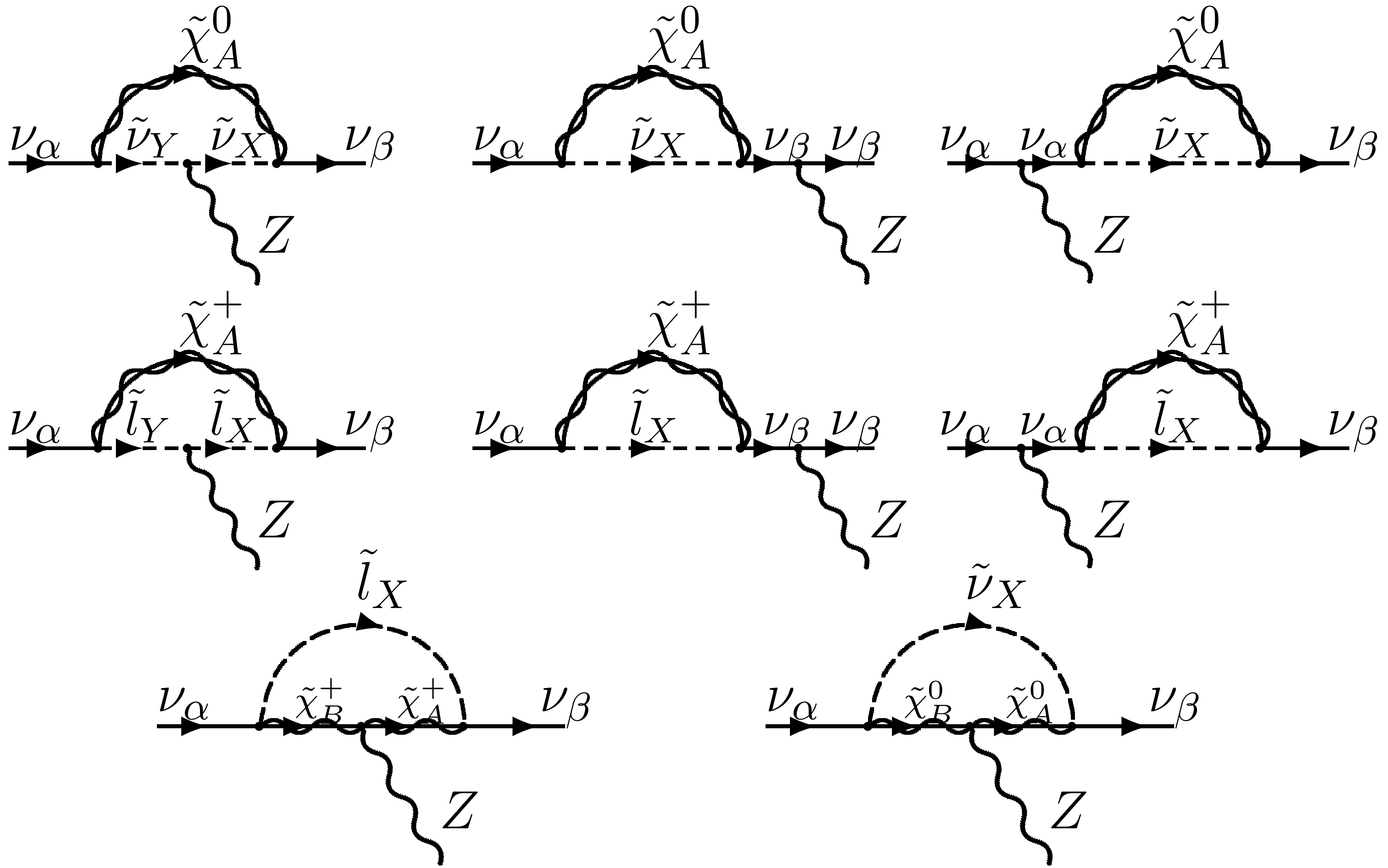
- In the MSSM, NSIs and $\ell_\beta \to \ell_\alpha \gamma$ are provided by similar one-loop diagrams with slepton mixings — they are correlated.





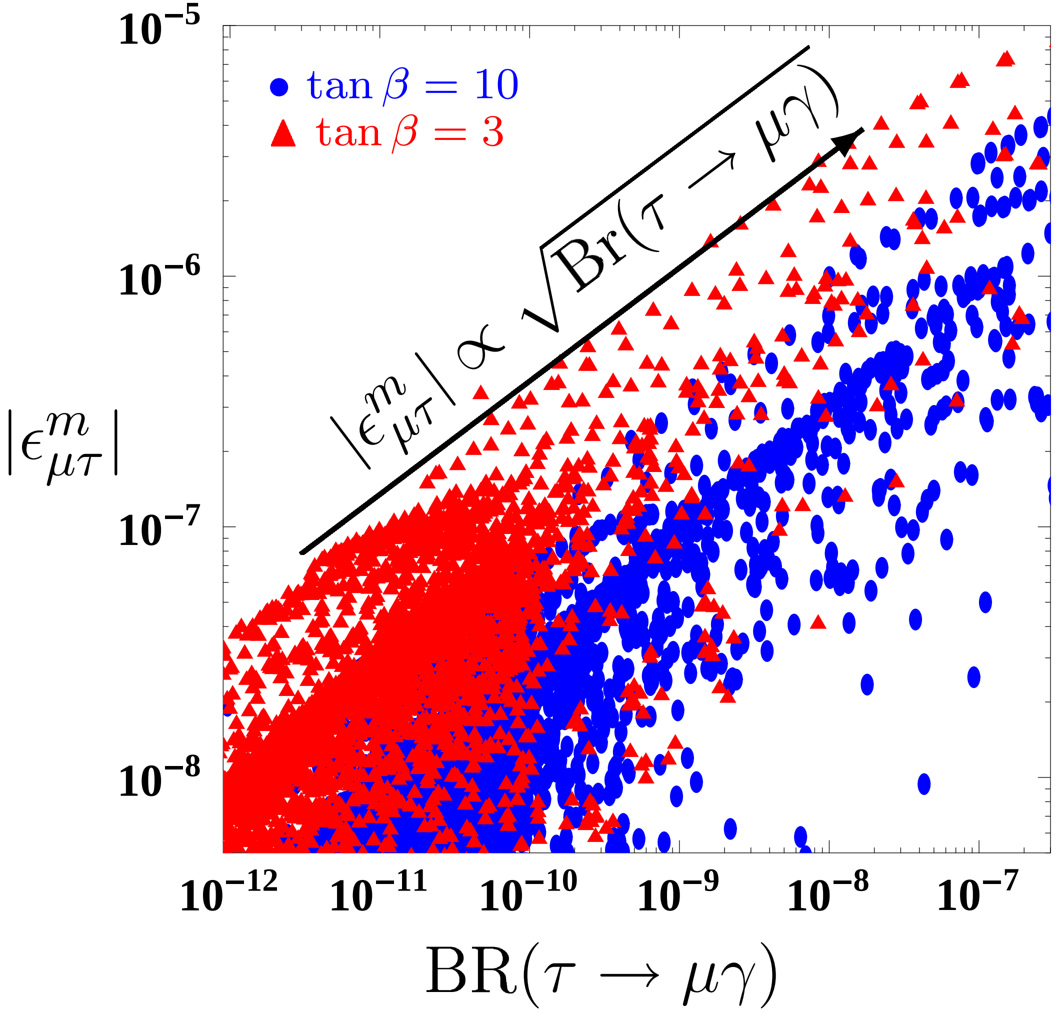
- Large slepton mixings are expected to be induced by the RGE effect associated with the neutrino Yukawa couplings.
- $\epsilon^{s,m}_{e\mu}$ is strongly suppressed, at least $\sqrt{\mathrm{Br}(\mu \to e\gamma)} = \mathcal{O}(10^{-5})$
- How about $\epsilon^m_{e\tau}$, $\epsilon^m_{\mu\tau}$?

NSIs in models — MSSM with ν_R



and box diagrams ...

NSIs in models — MSSM with ν_R



- Correlation between the NSI coupling $\epsilon^m_{\mu\tau}$ and LFV process $\tau \longrightarrow \mu\gamma$.
  - With some different Y_νs, we scan the m_0-$M_{1/2}$ space with $a_0 = 0$, $\tan\beta = 3, 10$, and $\mu > 0$.
- The parameter $\epsilon^m_{\mu\tau}$ is constrained at $\mathcal{O}(10^{-6})$ by the current bound of $\tau \longrightarrow \mu\gamma$.
- It is smaller than the naive estimation because of cancellation among diagrams.