Physics case for ν_τ detection

Toshihiko Ota

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
München Germany

Outline

1. Standard oscillation search
   - Solve the parameter degeneracy
   - Special attention to large theta13 case
2. **New physics search**
   - **High energy origin**

     Non-standard interaction (NSI), Non-unitarity (NU)
   - **Low energy origin**

     Sterile neutrino, Long range force
3. Summary

1. Standard oscillation search
   - Parameter degeneracy
   - Large theta13 case

ν_τ detection in standard oscillation search

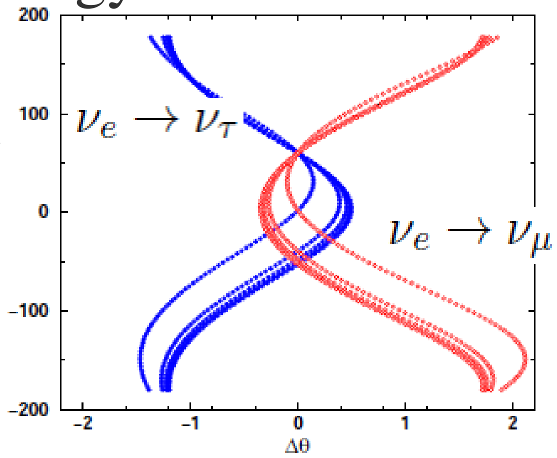
Discussion so far

1. CP violating phase search at lepton sector: Golden channel $\nu_e \to \nu_\mu$
   L=3,000 km (Matter oscillation dominant)+High energy
2. θ_{13}-δ correlation

   Two choices to solves it

   ✓ Add 2nd detector for Silver channel $\nu_e \to \nu_\tau$

Donini Meloni Migliozzi
NP**B646** (2002) 321



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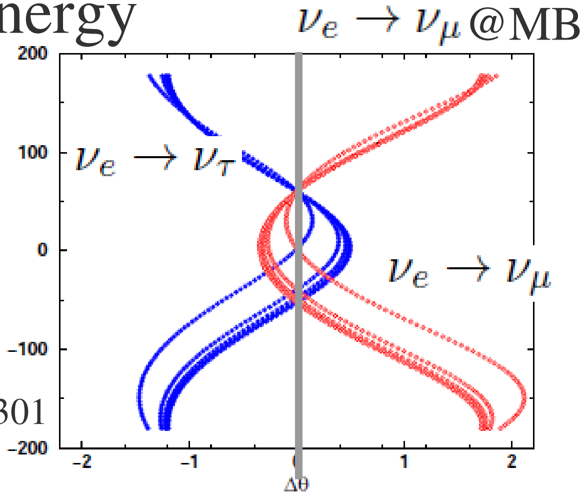
Huber Winter
PR**D68** (2003) 037301



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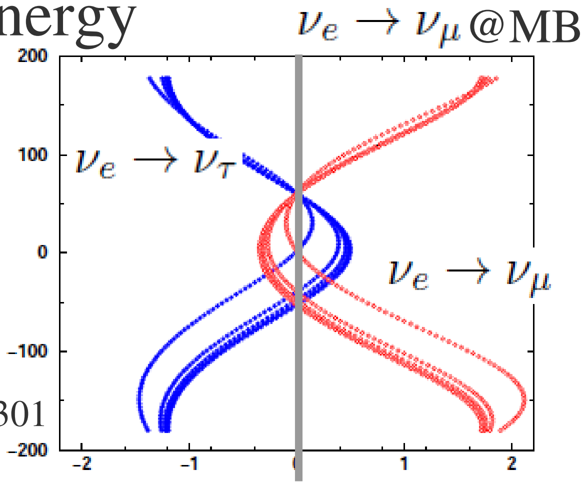
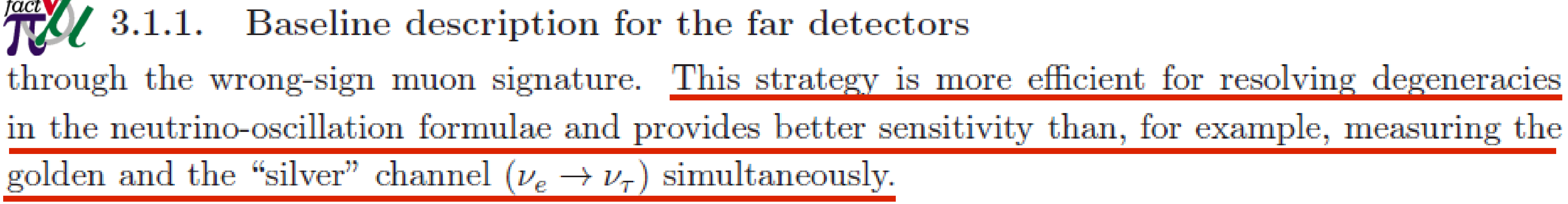


After optimisation studies (ISS,IDS),

Current IDS-NF setup contains two baselines

- MIND at L=4,000 km (Matter oscillation dominant)
- MIND at L=7,500 km (Magic baseline)

IDS-NF



3.1.1. Baseline description for the far detectors

through the wrong-sign muon signature. This strategy is more efficient for resolving degeneracies in the neutrino-oscillation formulae and provides better sensitivity than, for example, measuring the golden and the "silver" channel ($\nu_e \to \nu_\tau$) simultaneously.

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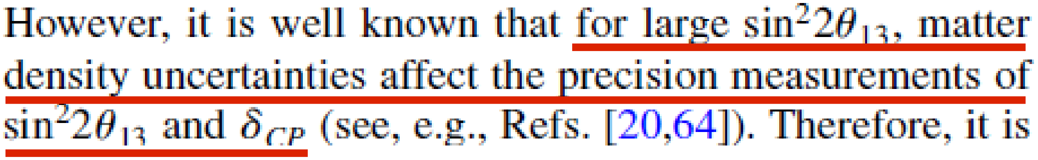
- Large θ_{13} enhances the matter density uncertainty

Huber Lindner Rolinec Winter PR**D74** (2006) 073003



However, it is well known that for large $\sin^2 2\theta_{13}$, matter density uncertainties affect the precision measurements of $\sin^2 2\theta_{13}$ and δ_{CP} (see, e.g., Refs. [20,64]). Therefore, it is

1 Special attention to large θ_{13}

Recently T2K and MINOS (also global fit of solar and KamLand) suggest large value of θ_{13} . How does this change the optimal setup?

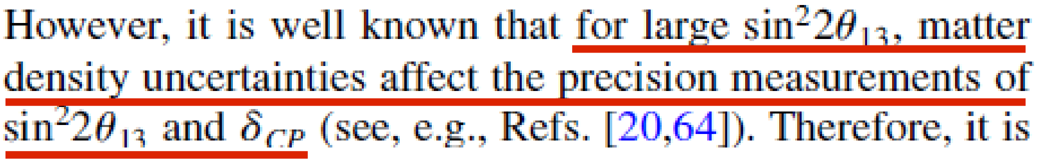
- Large θ_{13} enhances the matter density uncertainty
- Longer baseline and higher energy are not advantageous.
- Low Energy Neutrino Factory with TASD detector

E_μ =4 GeV $L =$ 1,100-1,400 km

Too low energy for efficient tau production

More on LENF → Talk by Ballett

Huber Lindner Rolinec Winter PR**D74** (2006) 073003



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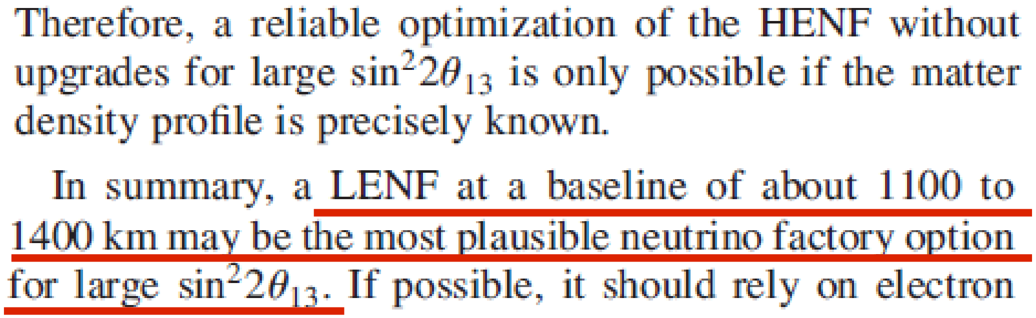
Tang Winter PR**D81** (2010) 033005



Therefore, a reliable optimization of the HENF without upgrades for large $\sin^2 2\theta_{13}$ is only possible if the matter density profile is precisely known.

In summary, a LENF at a baseline of about 1100 to 1400 km may be the most plausible neutrino factory option for large $\sin^2 2\theta_{13}$. If possible, it should rely on electron

Discussion including the other options (beta beam and superbeam) is necessary. Staging is also important subject.

More on optimization → Talk by Agarwalla

2 New Physics Search

High energy origin
(NSI and NU)

Motivation
NSI (and NU) in oscillation experiments
Constraints

Expected sensitivity in future experiments
Merit of tau detector

New physics from high energy scale

- *Theoretical motivation*

  Effective Lagrangian at the EW scale after integrating out the heavy d.o.f,

$$\mathscr{L}_{\mathsf{eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\mathrm{NP}}^3}\mathcal{O}^{d=7} + \cdots$$

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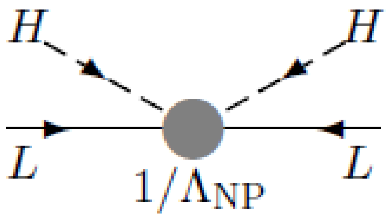
Weinberg op.

$$\mathcal{O}^{d=5} = (\overline{L^c} \mathrm{i}\tau^2 H)(H^{\mathsf{T}} \mathrm{i}\tau^2 L)$$



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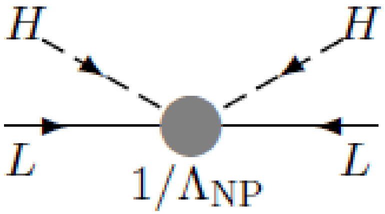

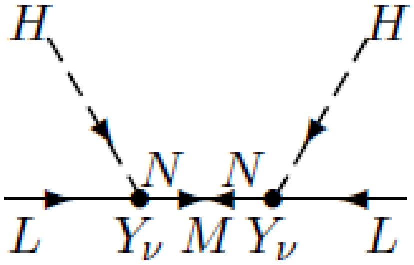

SM singlet fermion

$N(1_0^R)$

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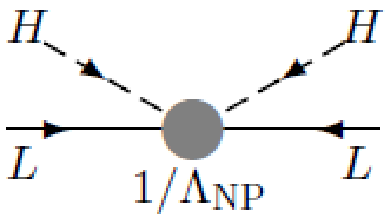

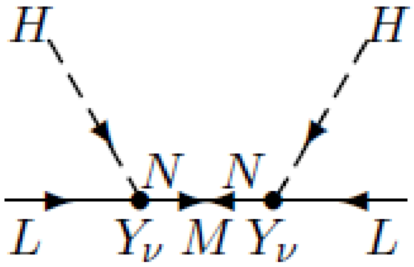

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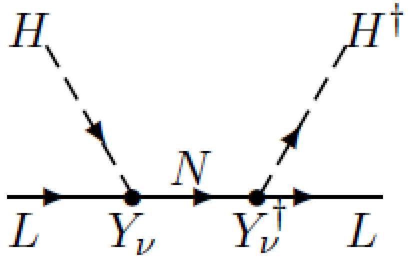

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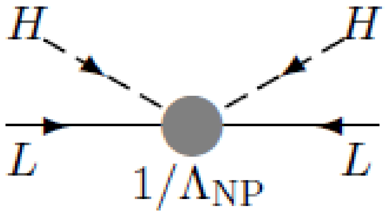

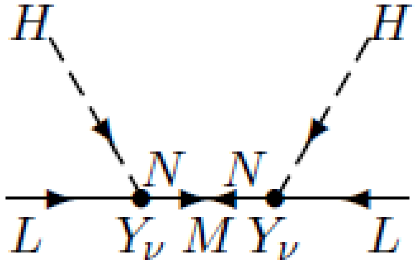

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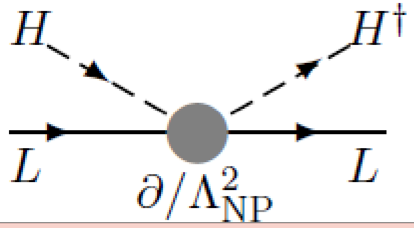
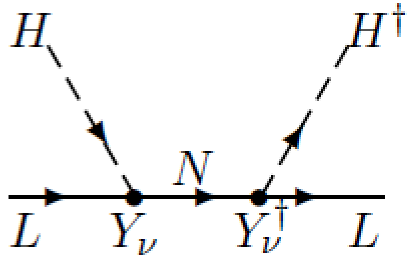


$$\xleftarrow{\Lambda_{\text{EW}}\longleftarrow\Lambda_{\text{NP}}}$$



$\Lambda_{\text{NP}} \sim 1$ TeV

→ Talk by Ibarra

$$\boxed{\mathcal{O}^{d=6} = (\bar{L} i\tau^2 H^*) i\partial_\rho \gamma^\rho (H i\tau^2 L)}$$

→ Non-unitary (NU) lepton mixing matrix

Footprint of new physics @high E

Another realization of non-unitarity (+charged LFV) = 4th generation → Talk by Herrero-Garcia

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4-Fermi interactions

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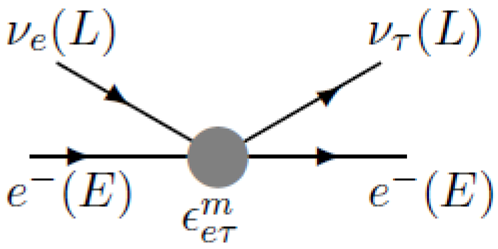

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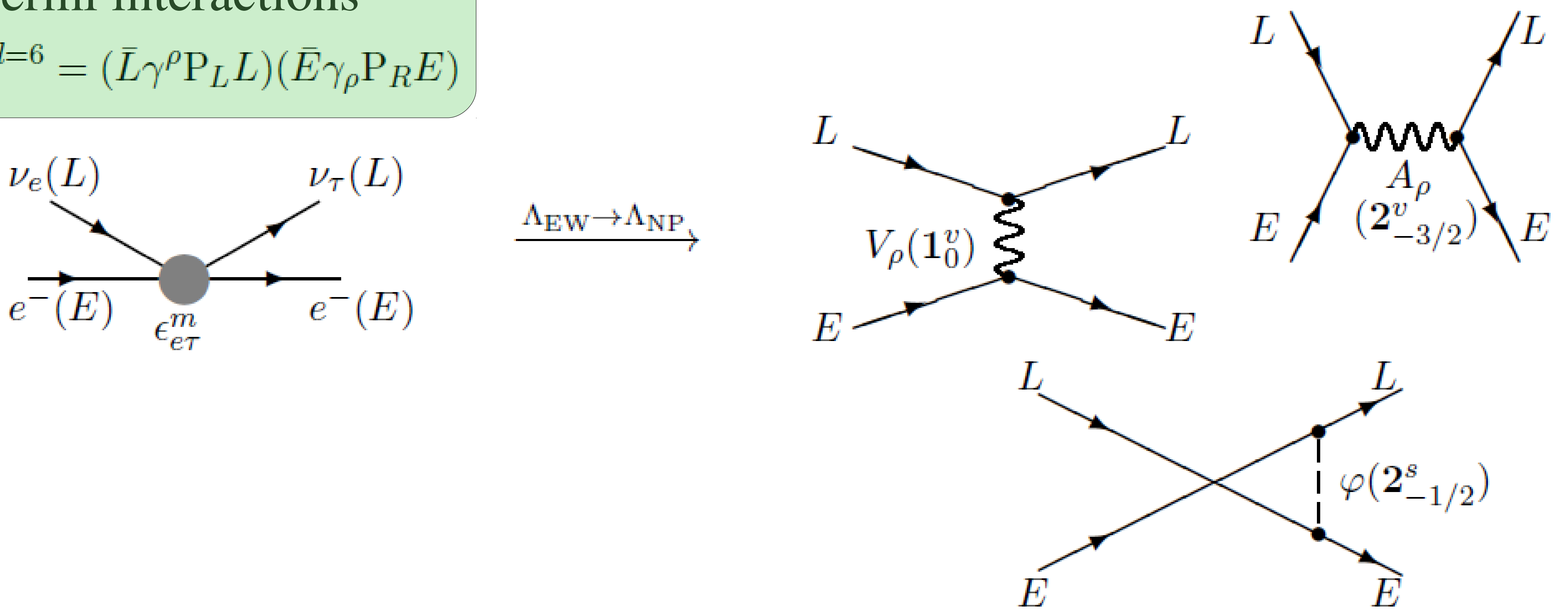

Footprint of new physics @high E

New physics from high energy scale

- *Signal at neutrino oscillation experiments*

  Standard oscillation

$$P_{\nu_\alpha \to \nu_\beta} = |\langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle|^2$$

Modified by NSI (and NU)

NU: NSIs with particular relations

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- CC type NSI — flavour mixture states at source and detection
  Grossman PLB359 (1995) 141.

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$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma} |\nu_\gamma\rangle, \qquad \text{e.g., } \pi^+ \xrightarrow{\epsilon^s_{\mu e}} \mu^+ \nu_e$$

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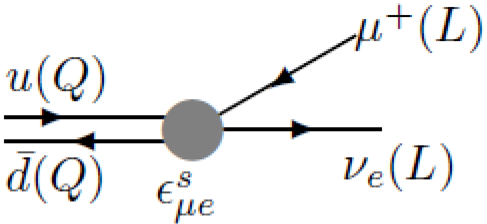

at superbeam

Another non-standard effect at near detector = Heavy sterile decay → Talk by Gninenko

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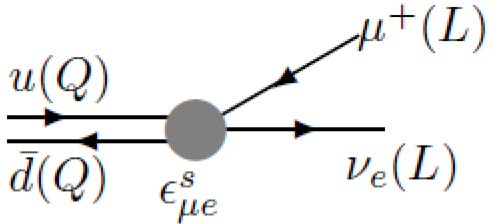


at superbeam

Another non-standard effect at near detector = Heavy sterile decay → Talk by Gninenko

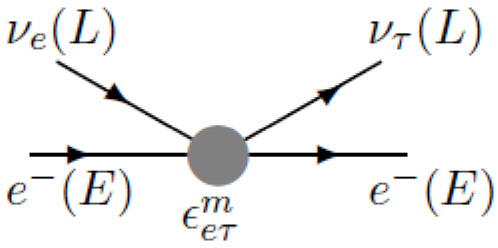
- NC type NSI — extra matter effect in propagation

e.g., Wolfenstein PRD**17** (1978) 2369. Valle PLB**199** (1987) 432. Guzzo Masiero Petcov PLB**260** (1991) 154.
Roulet PRD**44** (1991) R935.

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}(H+V_{\mathrm{NSI}})L} | \nu_\alpha \rangle \right|^2$$

$$(V_{\mathrm{NSI}})_{\beta\alpha} = \sqrt{2} G_F N_e \begin{pmatrix} \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix},$$

e.g., $\nu_e \xrightarrow{\epsilon^m_{e\tau}} \nu_\tau$
in propagation

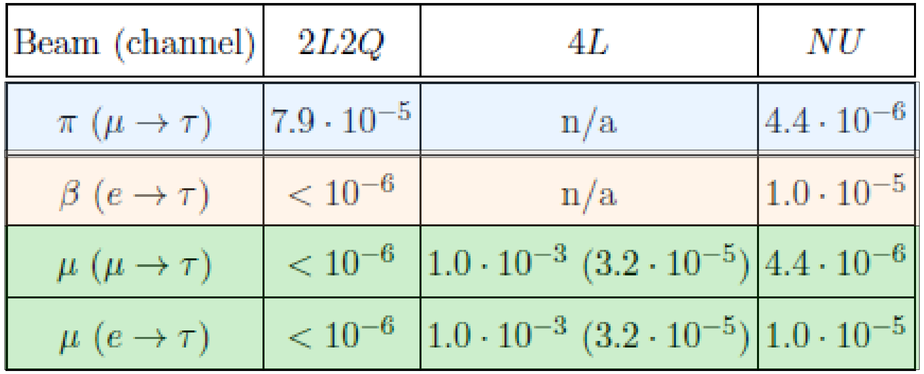


Constraint from charged lepton sector

Talk by Davidson, Fernandez-Martinez

- *Source and detection effect*

  Signal tau event/SM process $|\epsilon^s_{\alpha\tau}|^2$



	Beam (channel)	$2L2Q$	$4L$	NU
Conventional beam	π ($\mu \to \tau$)	$7.9 \cdot 10^{-5}$	n/a	$4.4 \cdot 10^{-6}$
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Antusch Blennow Fernandez-Martinez O
JHEP **1006** (2010) 0756

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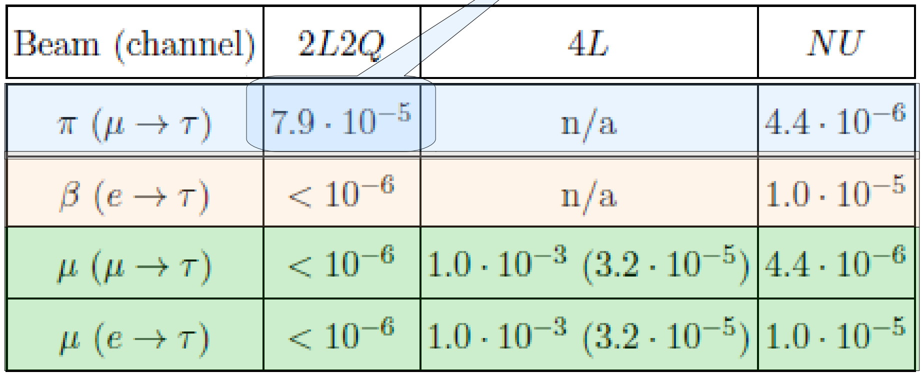
Chiral enhancement $\epsilon^s_{\mu\tau} = (\mathcal{C}^\dagger_{ED} - \mathcal{C}^\dagger_{EU}) \times \omega_\mu$

$$\omega_\mu = \frac{m_\pi}{m_\mu}\frac{m_\pi}{m_u + m_d} \sim 20$$



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Neutrino factory	$\mu\ (\mu\to\tau)$	$< 10^{-6}$	$1.0\cdot10^{-3}\ (3.2\cdot10^{-5})$	$4.4\cdot10^{-6}$
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$$\mathscr{L}_{\text{eff}} = 2\sqrt{2}G_F\mathcal{C}^\dagger_{ED}(\overline{\mu}L_\tau)(\overline{Q}d_R) + 2\sqrt{2}G_F\mathcal{C}^\dagger_{EU}(\overline{\mu}L_\tau)\mathrm{i}\tau^2(\overline{u_R}Q)$$

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JHEP **1006** (2010) 0756

- *NSI in propagation*

Biggio Blennow Fernandez-Martinez
JHEP 0908 (2009) 090

$$|\epsilon^m_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

[Note] Model independent bounds require a lot to models.

To avoid the loop cLFV bounds
1) Dim.8 NSI without dim.6 ops.
2) TeV scale cut-off,
3) Fine-tuning of TeV completion.

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Conventional beam	$\pi\ (\mu \to \tau)$	$7.9 \cdot 10^{-5}$	n/a	$4.4 \cdot 10^{-6}$
Beta beam	$\beta\ (e \to \tau)$	$< 10^{-6}$	n/a	$1.0 \cdot 10^{-5}$
Neutrino factory	$\mu\ (\mu \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}\ (3.2 \cdot 10^{-5})$	$4.4 \cdot 10^{-6}$
	$\mu\ (e \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}\ (3.2 \cdot 10^{-5})$	$1.0 \cdot 10^{-5}$

$$\mathcal{L}_{\text{eff}} = 2\sqrt{2}G_F\mathcal{C}^\dagger_{ED}(\overline{\mu}L_\tau)(\overline{Q}d_R) + 2\sqrt{2}G_F\mathcal{C}^\dagger_{EU}(\overline{\mu}L_\tau)i\tau^2(\overline{u_R}Q)$$

Antusch Blennow Fernandez-Martinez O
JHEP **1006** (2010) 0756

- *NSI in propagation*

Biggio Blennow Fernandez-Martinez
JHEP 0908 (2009) 090

$$|\epsilon^m_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

[Note] Model independent bounds require a lot to models.

To avoid the loop cLFV bounds

1) Dim.8 NSI without dim.6 ops.
2) TeV scale cut-off,
3) Fine-tuning of TeV completion.

- Typical size of non-standard effect motivated by high energy models

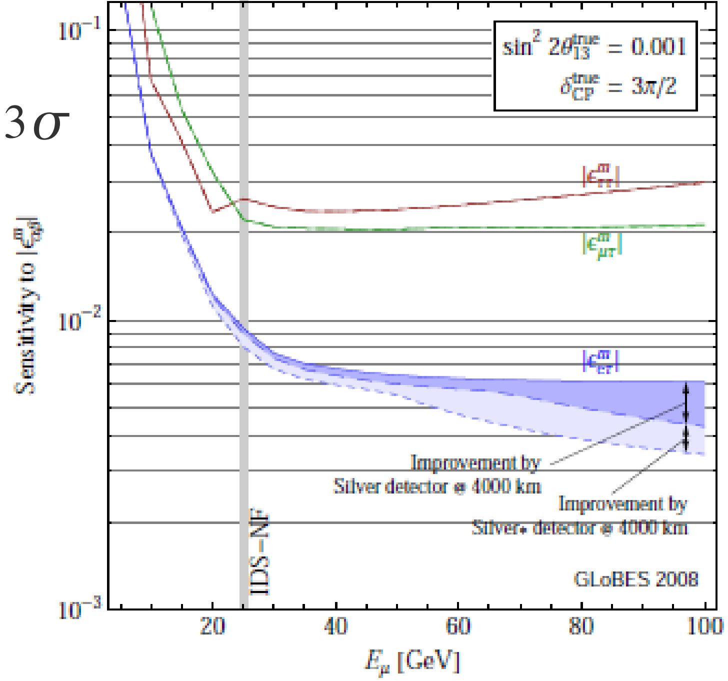
MSSM $\epsilon^s_{\mu\tau}$ (at nufact)$= |\varepsilon^{box}_{\mu\tau}| \approx 10^{-3}\sqrt{\frac{\mathrm{BR}(\tau \to \mu\gamma)}{10^{-7}}}$

Bellazzini Grossman Nachshon Paradisi
JHEP **1106** (2011) 104 Talk by Paradisi

Sensitivity in future experiment

Ribeiro Minakata Nunokawa Uchinami Zukanovich-Funchal
JHEP **0712** (2007) 002
Coloma Donini Lopez-Pavon Minakata arXiv:1105.5936

Kopp O Winter PR**D78** (2008) 053007



- Based on IDS-NF setup
  Impact of the silver channel to search for $\epsilon^m_{\alpha\tau}$ with 10 kt ECC

✓ Optimum baseline $L \sim 4,000$ km

✓ Silver channel is only relevant to $\epsilon^m_{e\tau}$ at high energy regime ($E \gtrsim 50$ GeV)

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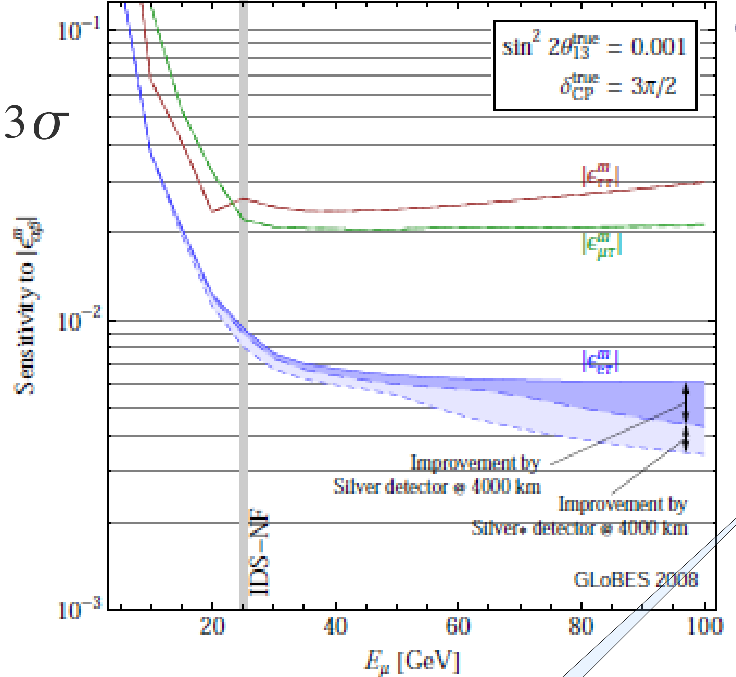

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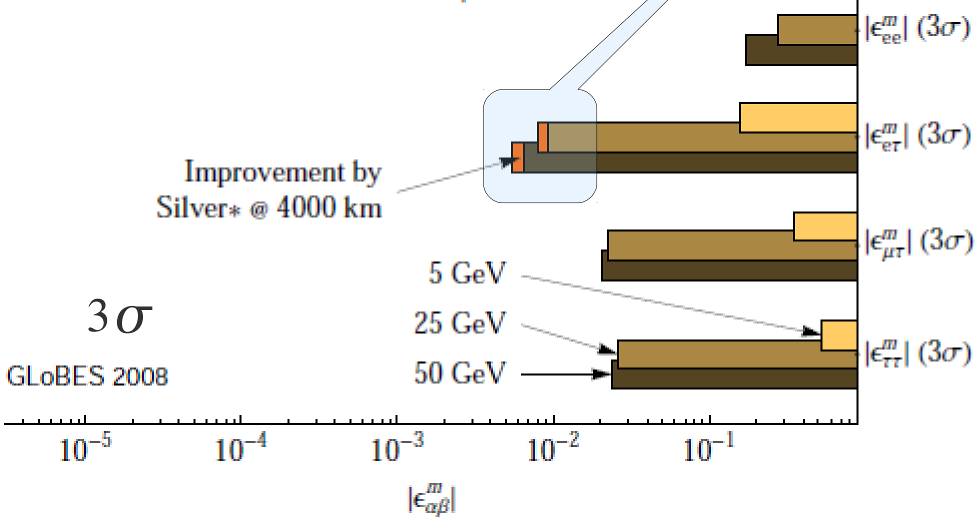

- Expected sensitivity at best

  ✓ NSI in propagation

  $\epsilon^m_{e\tau} > \mathcal{O}(10^{-3})$

Sensitivity in future experiment

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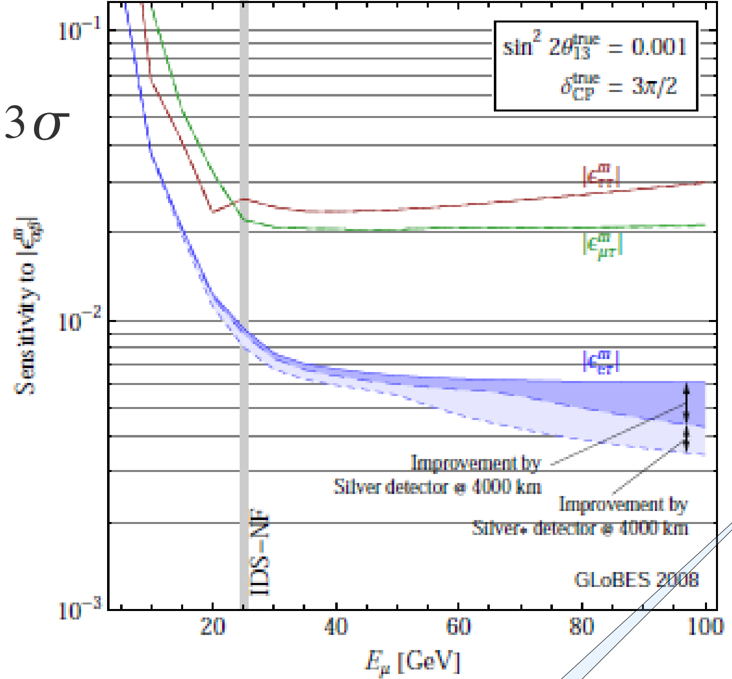

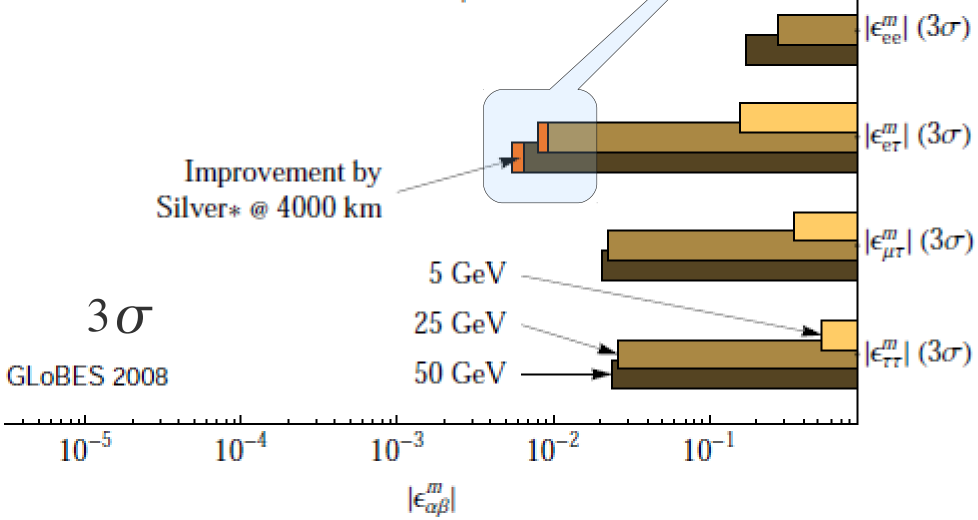

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- Expected sensitivity at best
  - ✓ NSI in propagation

    $\epsilon^m_{e\tau} > \mathcal{O}(10^{-3})$
  - ✓ NSI at source with tau near detector

    $|\epsilon^s_{\mu\tau}|^2$ =Tau signal/SM>$\mathcal{O}(10^{-6})$

    MINSIS workshop arXiv:1009.0476

2 New Physics Search

Low energy origin
(Sterile neutrino)

Motivation
MiniBooNE/LSND results

Expected sensitivity in future experiments
Merit of tau detector

Another possibility of NP at low energy scale = Long range force → Talk by Hye-Sung

New physics at low energy: Sterile neutrino

Talk by Giunti, Halzen

- *Motivations*
  - ✓ Long standing LSND/MiniBooNE signals
  - ✓ Recent reactor flux re-calculation ✓ Ga neutrino experiment
  - ✓ Extra radiation suggested by cosmological observations

  - ✓ KK modes in large extra dimension Talk by Machado
  - ✓ Neutrino mass models with steriles Talk by Hernandez, Zhang

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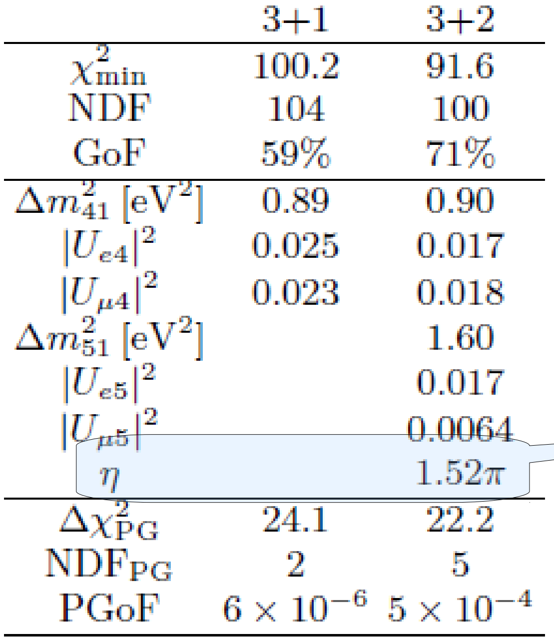
- *Best-fit for LSND/MiniBooNE*



	3+1	3+2
$\chi^2_{\rm min}$	100.2	91.6
NDF	104	100
GoF	59%	71%
Δm^2_{41} [eV^2]	0.89	0.90
$\lvert U_{e4}\rvert^2$	0.025	0.017
$\lvert U_{\mu 4}\rvert^2$	0.023	0.018
Δm^2_{51} [eV^2]		1.60
$\lvert U_{e5}\rvert^2$		0.017
$\lvert U_{\mu 5}\rvert^2$		0.0064
η		1.52π
$\Delta\chi^2_{\rm PG}$	24.1	22.2
NDF$_{\rm PG}$	2	5
PGoF	6×10^{-6}	5×10^{-4}

Giunti Laveder arXiv.1107.1452v2

✓ Anti-neutrino appearance signal suggests

$$\Delta m_s^2 \sim 1\ \mathrm{eV}^2$$

→ 4th neutrino mass eigenstate

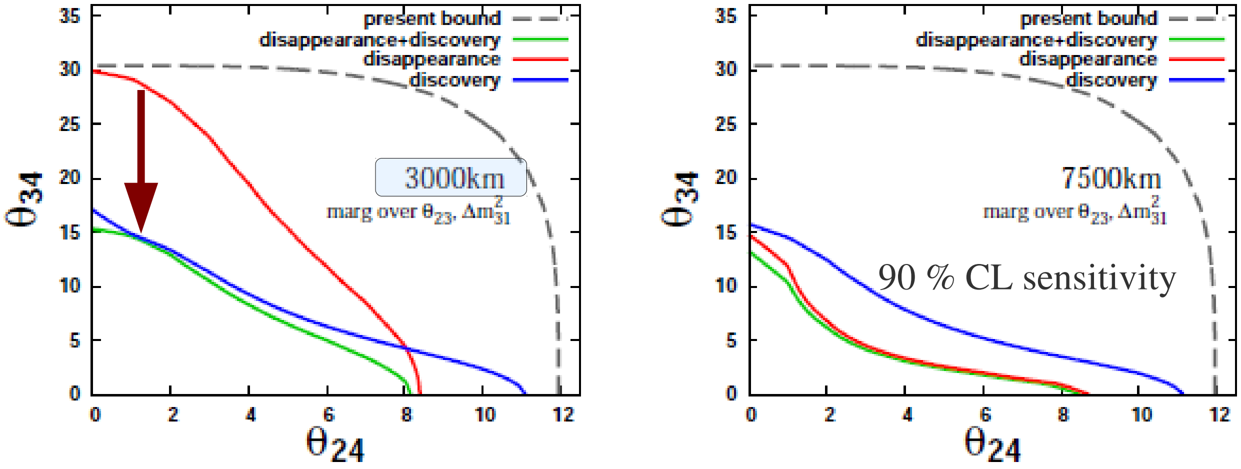
✓ No appearance signal in neutrino events
→ (3+2) and large CPV
→ (3+1)+NSI Akhmedov Schwetz JHEP **1010** (2010) 115

[Note] Tension with disapp. exps. is still left
[Note] 3+2 is cosmologically disfavoured

Long baseline setup for sterileν search

Donini Fuki Lopez-Pavon Meloni Yasuda
JHEP **0908** (2009) 041

Discovery channel with Magnetised ECC (4 kton)



90 % CL sensitivity

Improved by
discovery channel

Long baseline setup for sterile ν search

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JHEP **0908** (2009) 041

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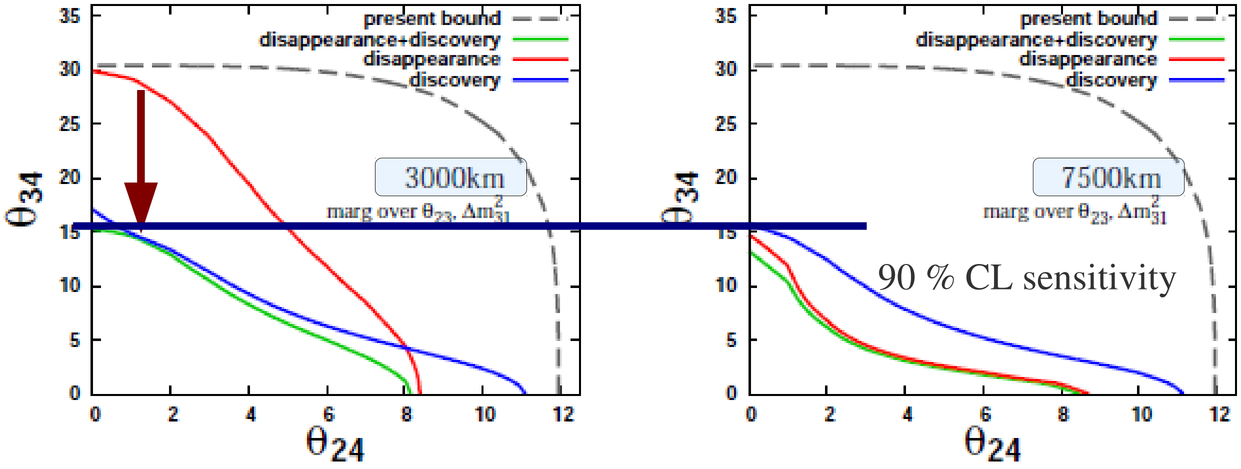

If two MINDs are placed at IDS-NF, the additional discovery channel does not so much improve the sensitivities to the mixing angles with the sterile state.

Improved by discovery channel

Discovery channel sensitivity is equivalent to disapp.@MB

Long baseline setup for sterile ν search

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JHEP **0908** (2009) 041

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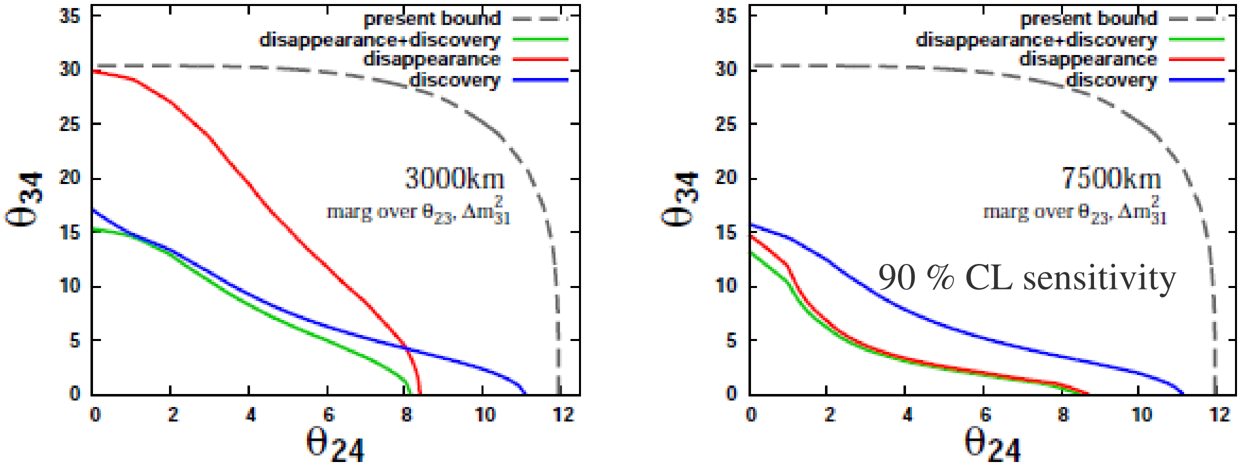

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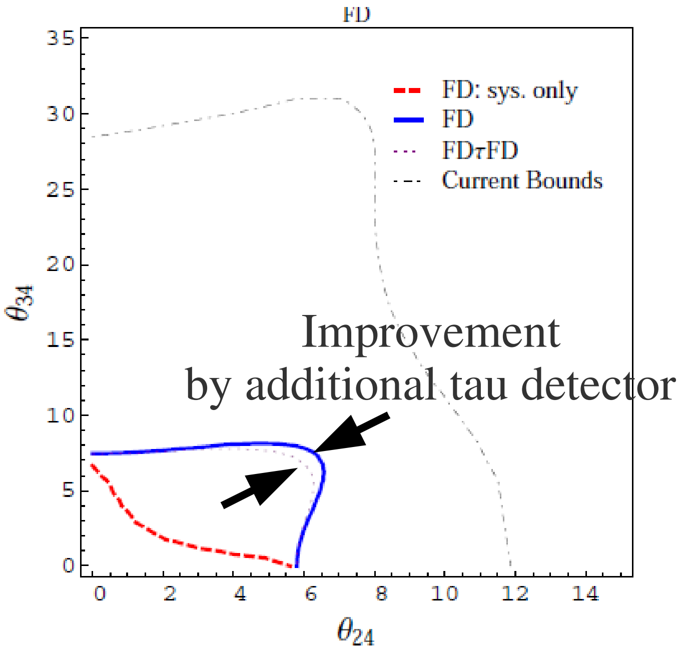
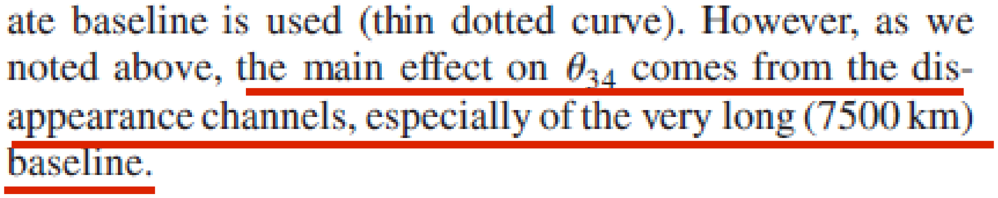


Improvement
by additional tau detector

Meloni Tang Winter
PR**D82** (2010) 093008

IDS-NF setup +
OPERA-inspired ECC (10kton)
@L=4,000 km


ate baseline is used (thin dotted curve). However, as we noted above, the main effect on θ_{34} comes from the disappearance channels, especially of the very long (7500 km) baseline.

Long baseline setup for sterile ν search

Donini Fuki Lopez-Pavon Meloni Yasuda
JHEP **0908** (2009) 041

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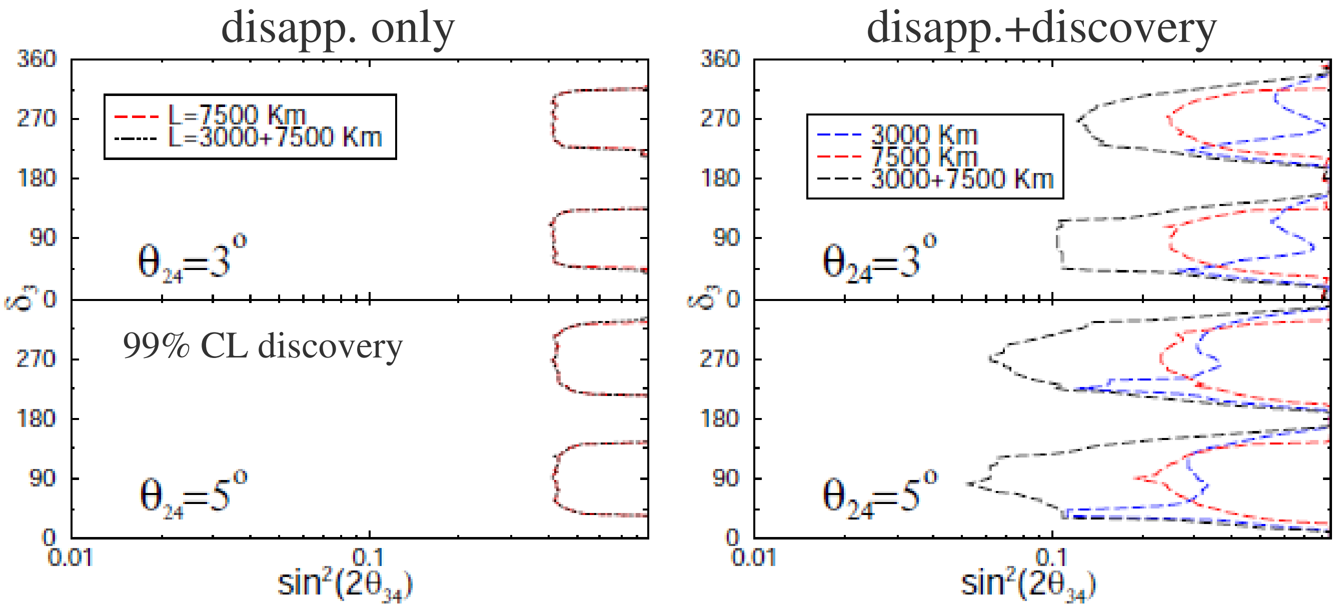
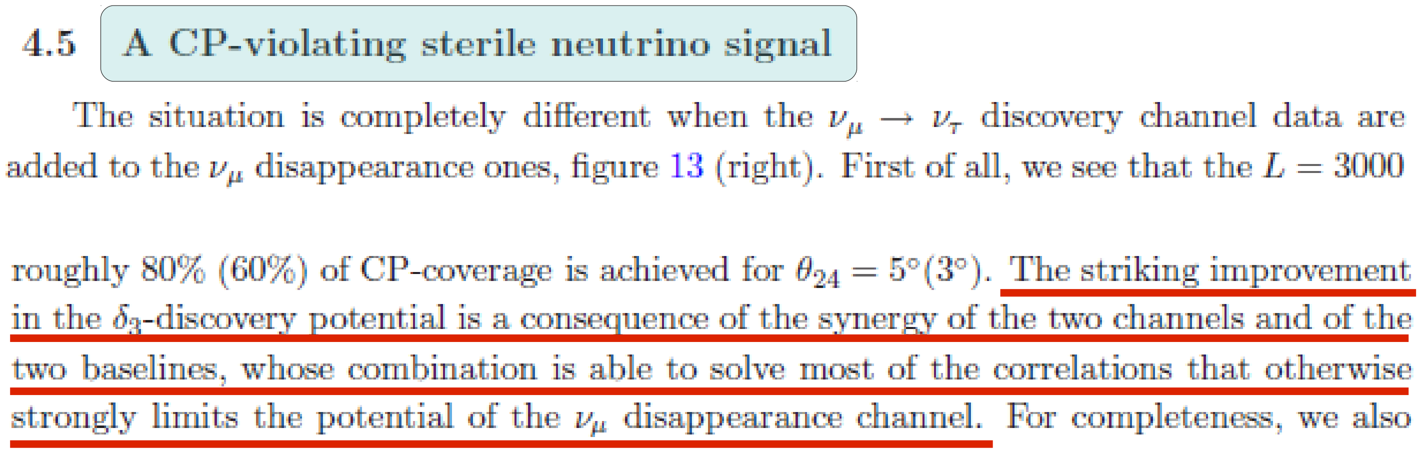

disapp. only

disapp.+discovery



4.5 A CP-violating sterile neutrino signal

The situation is completely different when the $\nu_\mu \to \nu_\tau$ discovery channel data are added to the ν_μ disappearance ones, figure 13 (right). First of all, we see that the $L = 3000$

roughly 80% (60%) of CP-coverage is achieved for $\theta_{24} = 5^\circ (3^\circ)$. The striking improvement in the δ_3-discovery potential is a consequence of the synergy of the two channels and of the two baselines, whose combination is able to solve most of the correlations that otherwise strongly limits the potential of the ν_μ disappearance channel. For completeness, we also

3 Summary

Summary and personal remark

3 Summary

- ***Standard oscillation parameters***

  Golden channel @L=4000 km suffers degeneracy →

  MIND@MB is more efficient than Silver det. (5-10 kt) @L=4,000 km

  BG in golden/disapp. channel from $\nu_e \to \nu_\tau$ can be correctly counted without tau detector

  Indumathi Sinha PR**D80** (2009) 113012 Donini Gomez-Cadenas Meloni JHEP **1102** (2011) 095
  Agarwalla Huber Tang Winter JHEP **1101** (2011) 120

- ***NSI (NU)*** 5-10 kt OPERA-like Silver det.

  $\epsilon^m_{\mu\tau}$ $\epsilon^m_{\tau\tau}$ Disapp. channel is sensitive

  $\epsilon^m_{e\tau}$ Golden channel @MB is sensitive

  They are statistically advantageous than silver channel

  Near tau detector @superbeam (MINSIS)

  $|\epsilon^s_{\mu\tau}|^2$ from chiral-enhanced operator

  Current bound from cLFV< $7.9 \cdot 10^{-5}$

  Expected sensitivity < $\mathcal{O}(10^{-6})$

- ***Sterile neutrino*** Discovery channel with 4 kt MECC

  Additional mixing angle θ_{34} — MIND@MB is competitive with MECC

  Additional CP phase — Discovery channel can be a powerful tool

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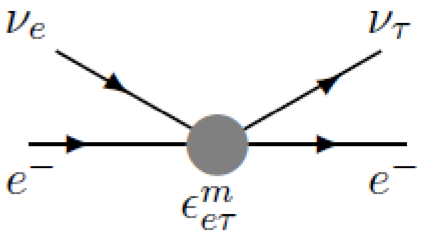
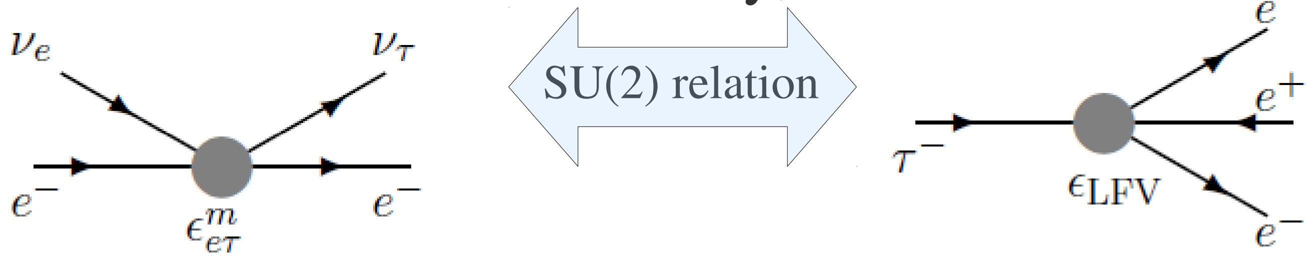
Personal remark



Personal remark

Naively,



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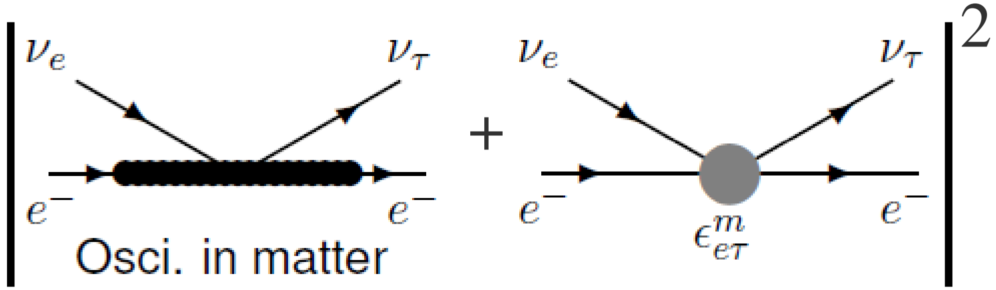
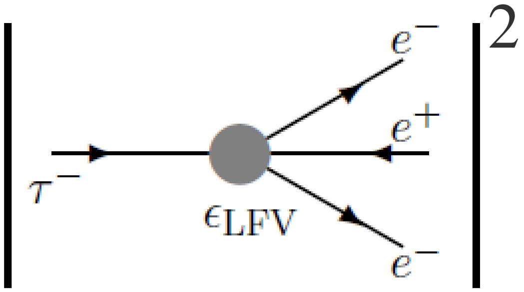


Naively,

SU(2) relation

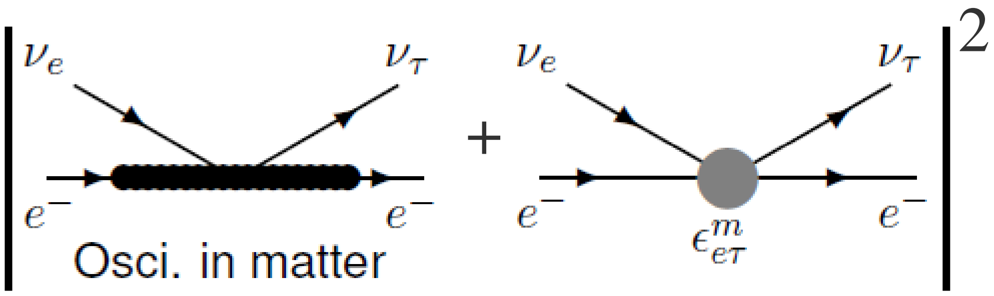


$$P^{\rm SO}_{\nu_e \to \nu_\tau} + \underline{\underline{\mathcal{O}(\epsilon^m_{e\tau})}}$$

Oscillation enhancement

$$\mathrm{Br}(\tau \to 3e) = |\epsilon_{\rm LFV}|^2$$

Personal remark



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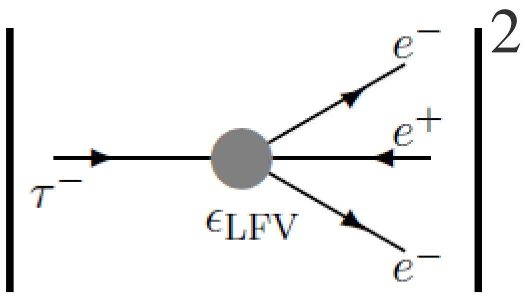

$$P^{\mathrm{SO}}_{\nu_e\to\nu_\tau} + \underline{\underline{\mathcal{O}(\epsilon^m_{e\tau})}}$$

Oscillation enhancement

$$\mathrm{Br}(\tau \to 3e) = |\epsilon_{\mathrm{LFV}}|^2 < \mathcal{O}(10^{-8})$$

To compete with charged LFV search
in sensitivity to New Physics @high E,

we want to have the precision

$$|\epsilon^m_{e\tau}| < \mathcal{O}(10^{-4})$$

Exception: Chiral enhancement takes place in the pion decay and does not in the rare tau decay to pion.
Therefore, $|\epsilon^s_{\mu\tau}| \gg |\epsilon_{\mathrm{LFV}}|$.