NuFACT 2017
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Beyond Standard Neutrino Theory

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I am expected to talk about “Exotics”...

...What kind of monster should I talk about?

eV sterile neutrinos → Pallavicini,

Heavy neutrinos → Wynne,

Complementarity w. other exps → Antusch, Tang, Teixeira

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Let me try to focus on the following items...

- Nonstandard neutrino interactions,
- Non-unitarity PMNS matrix,
- Secret neutrino interactions (nu-nu, nu-invisible)

* Materials are mainly taken from the papers 2015-

- NP in $0\nu\beta\beta$, cosmological bounds to m_ν ...

- Non-standard neutrino interactions

Non-standard neutrino interactions

NSIs – NP parametrized with four-Fermi interactions

e.g., $-\mathscr{L} = 2\sqrt{2} G_F \epsilon^m_{\alpha\beta} [\overline{\nu}_\alpha \gamma^\rho \mathrm{P}_L \nu_\beta][\overline{e}\gamma_\rho \mathrm{P}_L e] + \mathrm{H.c.}$ $\qquad a = 2\sqrt{2} G_F N_e E$

$$\langle \nu_\alpha | H | \nu_\beta \rangle = \frac{1}{2E} \left[U_{\alpha i} \Delta m^2_{i1} U^\dagger_{i\beta} + a \begin{pmatrix} 1 + \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ (\epsilon^m_{e\mu})^* & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ (\epsilon^m_{e\tau})^* & (\epsilon^m_{\mu\tau})^* & \epsilon^m_{\tau\tau} \end{pmatrix} \right]$$

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e.g., $-\mathscr{L} = 2\sqrt{2}G_F\epsilon^s_{\mu\alpha}[\overline{\nu}_\alpha\gamma^\rho \mathrm{P}_L\mu][\overline{d}\gamma_\rho \mathrm{P}_L u] + \mathrm{H.c.}$

$|\nu^s_\mu\rangle = |\nu_\mu\rangle + \epsilon^s_{\mu\alpha}|\nu_\alpha\rangle$ in $\pi^+ \to \mu^+ + \nu_\alpha$

* also affects the detection process as $\epsilon^{d*}_{\alpha\mu}$ in $\nu_\alpha N \to \mu^- X$

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Current bounds at 90%CL, Choubey et al., JHEP 12 (2015) 126

$|\epsilon^m_{ee} - \epsilon^m_{\mu\mu}| < 4.2$ $\quad |\epsilon^m_{\tau\tau} - \epsilon^m_{\mu\mu}| < 0.05$ $\quad |\epsilon^m_{e\mu}| < 0.3$ $\quad |\epsilon^m_{e\tau}| < 3.0$ $\quad |\epsilon^m_{\mu\tau}| < 0.01$

$|\epsilon^s_{\mu e}| < 0.026$ $\quad |\epsilon^s_{\mu\mu}| < 0.078$ $\quad |\epsilon^s_{\mu\tau}| < 0.013$

* see also the global fit by Gonzalez-Garcia Maltoni, JHEP1309 (2013)152

$|\epsilon^m_{\mu\tau}| < 0.005$

New

From IceCube high *E* atmos, Salvado, et al., JHEP1701 (2017) 141

Non-standard neutrino interactions

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New

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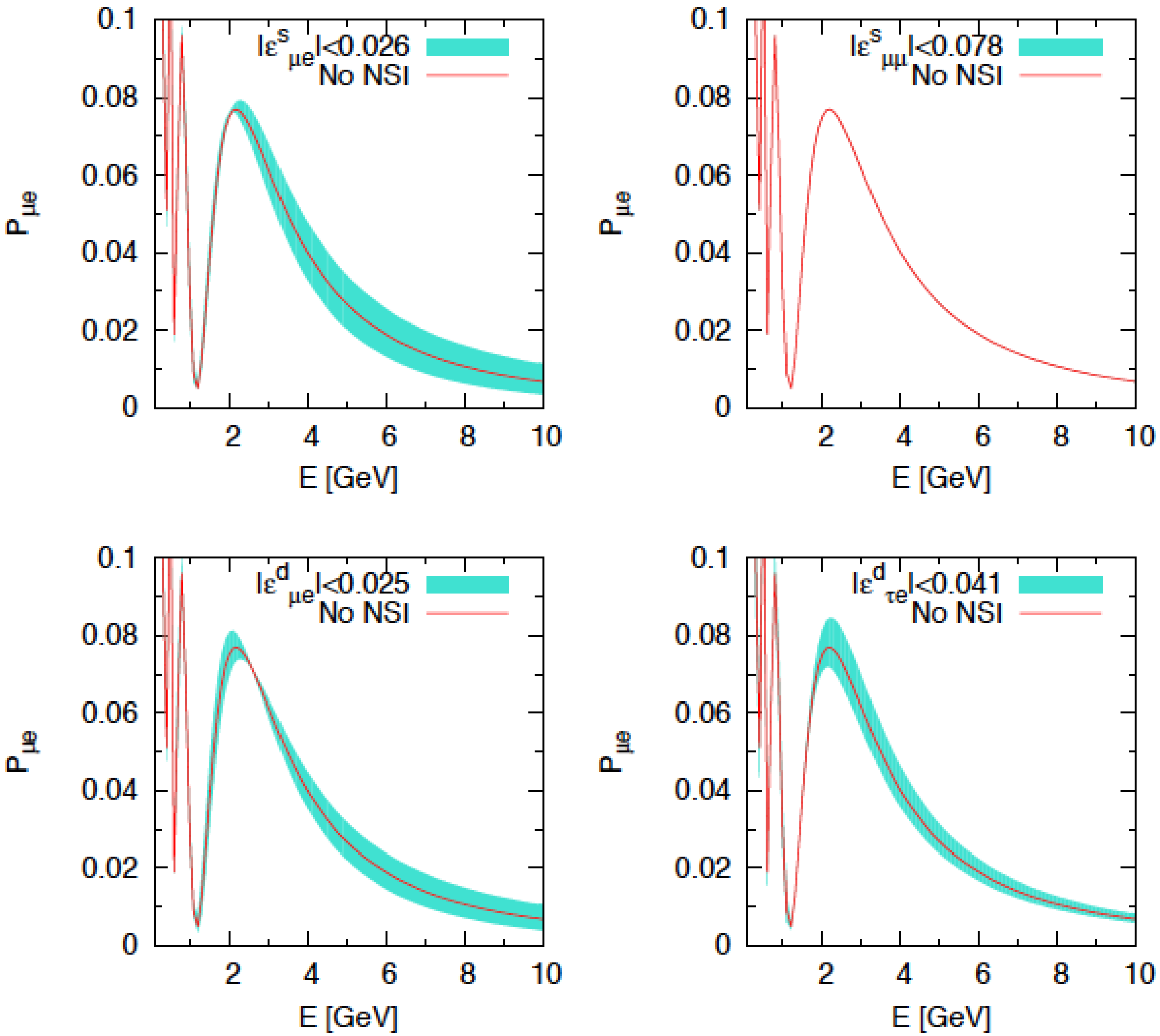
It is not easy to realize the NSIs with their upper limits (→ we will see), but we should keep the possibilities phenomenologically allowed in mind

Non-standard neutrino interactions

Impact of NSIs on the oscillation probability for $\nu_\mu \to \nu_e$

Blennow et al., JHEP 1608 (2016) 090



NSIs in source/detection

The standard osc params are set to be their best fits

$\delta_{\rm CP}$ is fixed at $-\pi/2$

$L = 1{,}300$ km (DUNE)

NSI parameters are varied in their allowed regions

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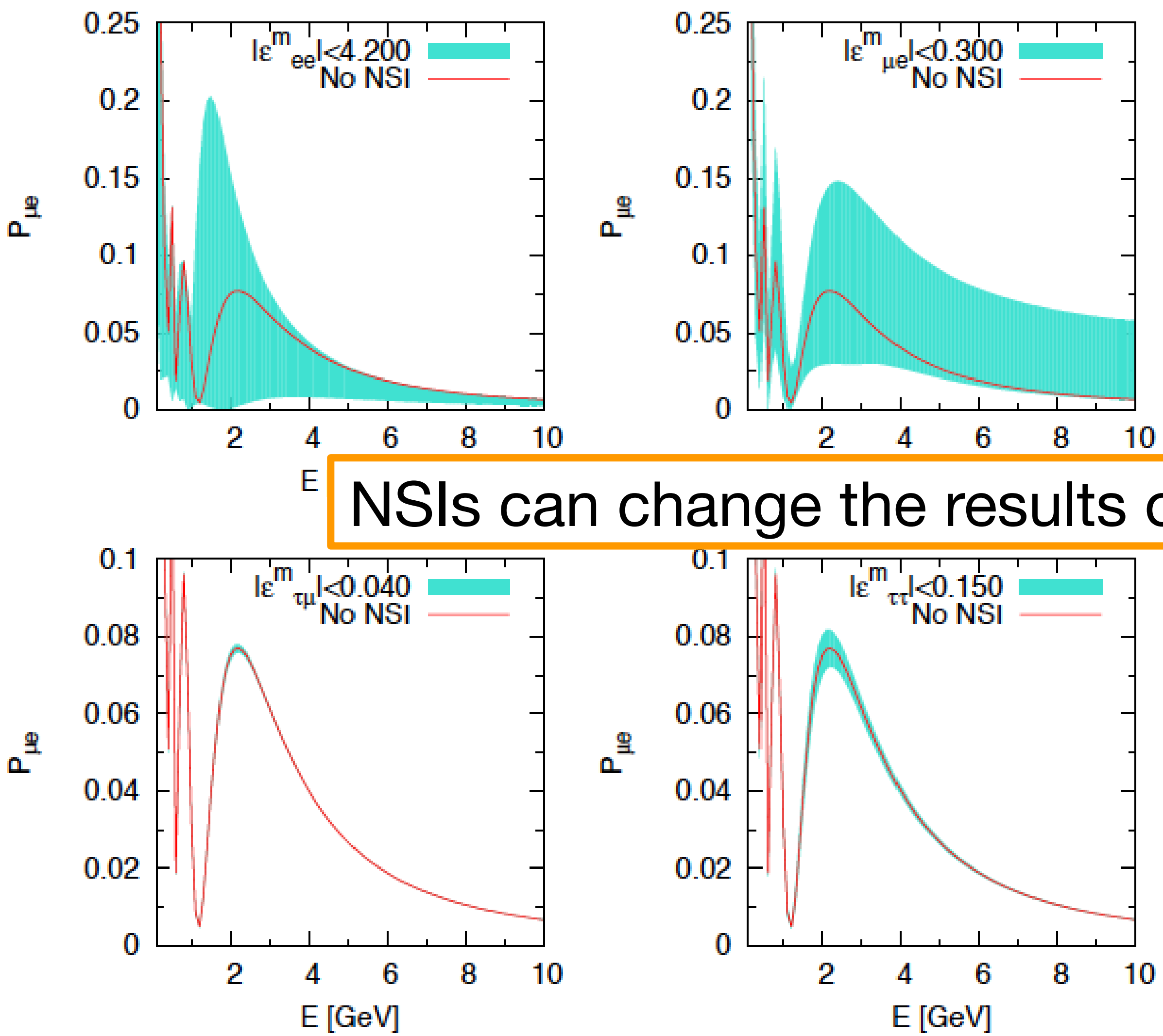

NSIs can change the results of DUNE a lot!

NSIs in propagation

The standard osc params are set to be their best fits

$\delta_{\rm CP}$ is fixed at $-\pi/2$

$L = 1{,}300$ km (DUNE)

NSI parameters are varied in their allowed regions

NSIs in future experiments

* Check the talk by Raut

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NSIs as noise

NSIs in the context of the parameter determination in future experiments

NSIs in future experiments

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NSIs as noise

NSIs in the context of the parameter determination in future experiments

NSIs as signals

High precision experiments may also be sensitive to New Physics

* Check the talk by Raut

NSIs as noise

NSIs in the context of the parameter determination in future experiments

NSIs as noise

NSIs disturb the determination of the standard oscillation parameters.

* Degeneracies with NSIs at LBL experiments, see e.g., Liao et al., PRD93 (2016) 093016

NSI-δ_{CP}

Masud et al., J. Phys. G43 (2016) 095005

Masud Mehta, PRD94 (2016) 013014

Rout et al., PRD95 (2017) 075035

Miranda et al., PRL (2017) 117 061804

de Gouvea Kelly 1605.099376

Ge Smirnov JHEP 10 (2016) 138

Dutta Ghoshal JHEP 09 (2016) 110

NSI-Mass Hierarchy (MH)

Masud Mehta, PRD94 (2016) 053007

Dutta et al., NPB920 (2017) 385

Deepthi et al., 1612.00784

* source/detection NSI effects in MH determination at JUNO, Ohlsson et al. PLB728 (2014) 148

NSI-θ_{23} octant

Agarwalla et al., PLB762 (2016) 64

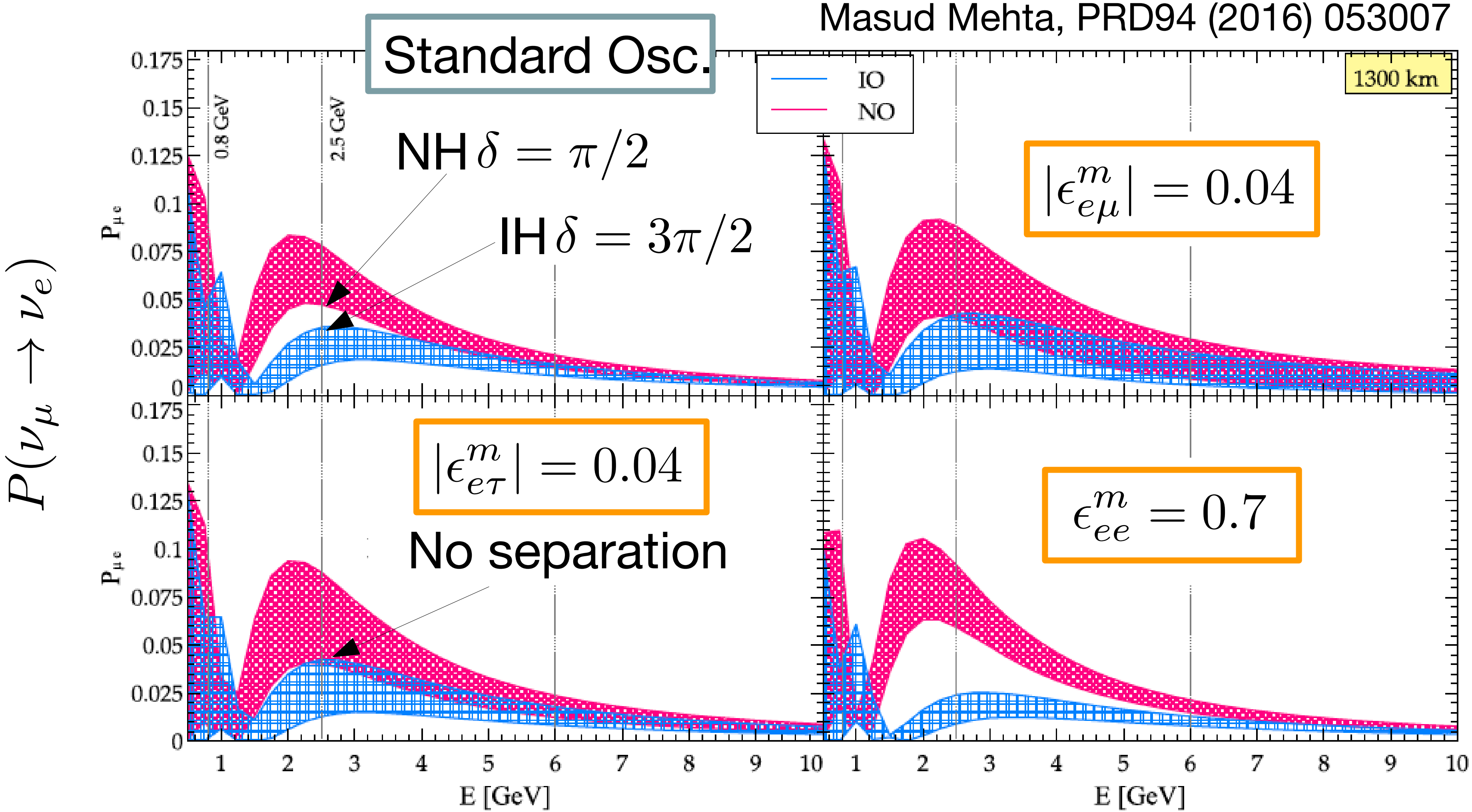
Dutta et al., PRD 95 (2017) 095007

Das et al., 1708.05182

NSIs disturb the determination of the standard oscillation parameters.

NSI-MH at DUNE ($L = 1300$ km)

Masud Mehta, PRD94 (2016) 053007



With NSIs, osc. probs. with NH overlaps with those with IH.

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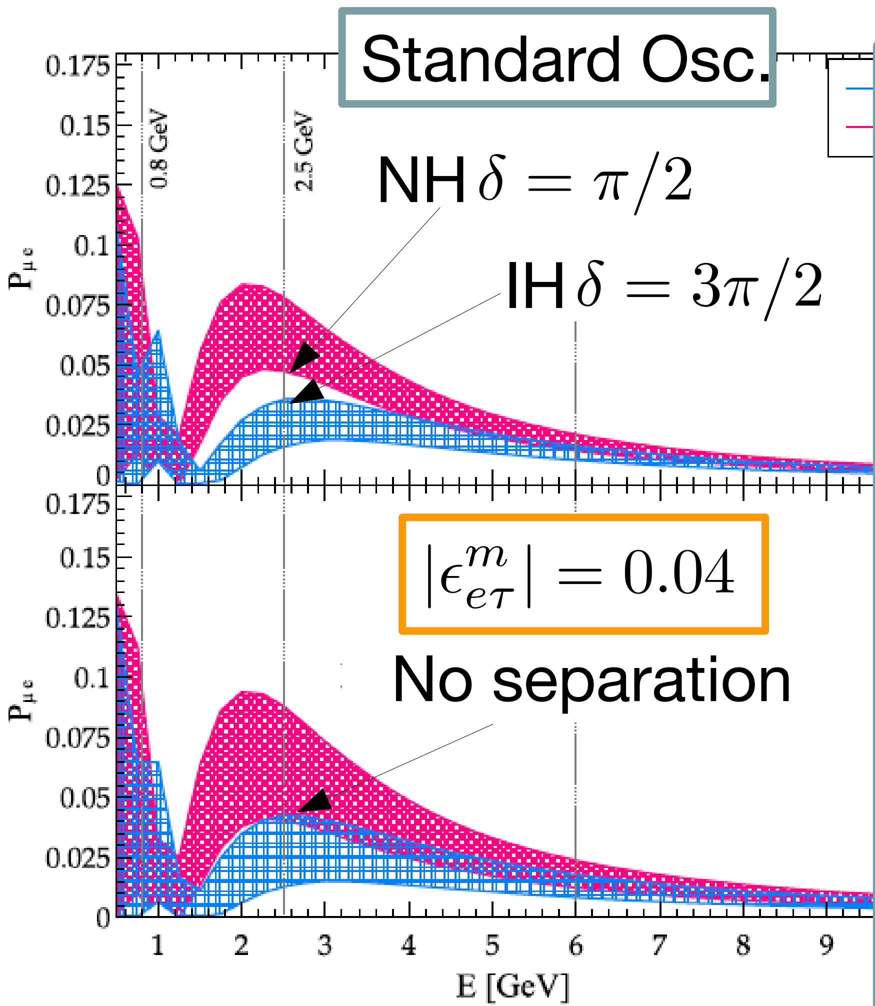

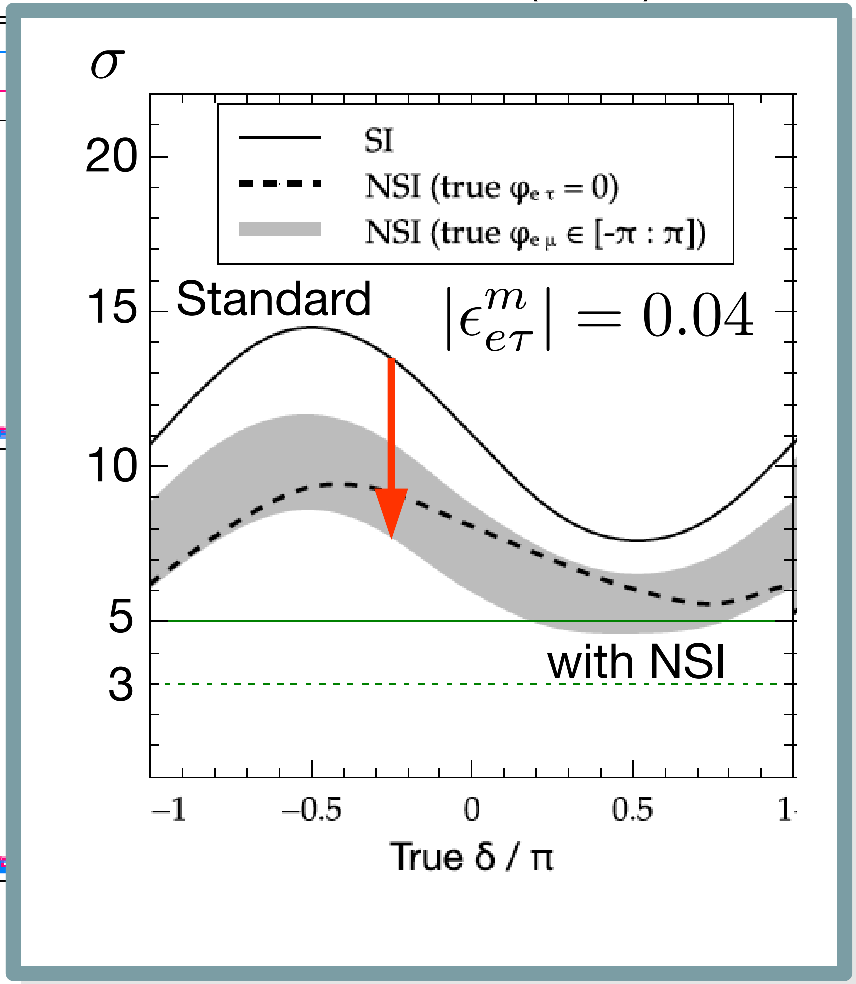

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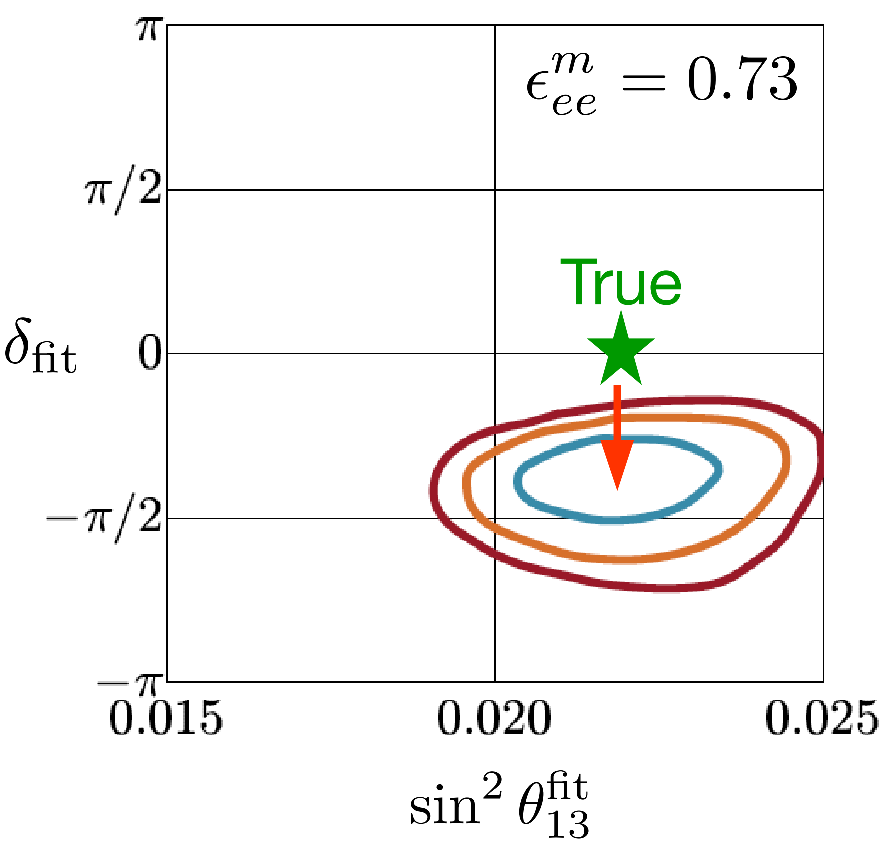
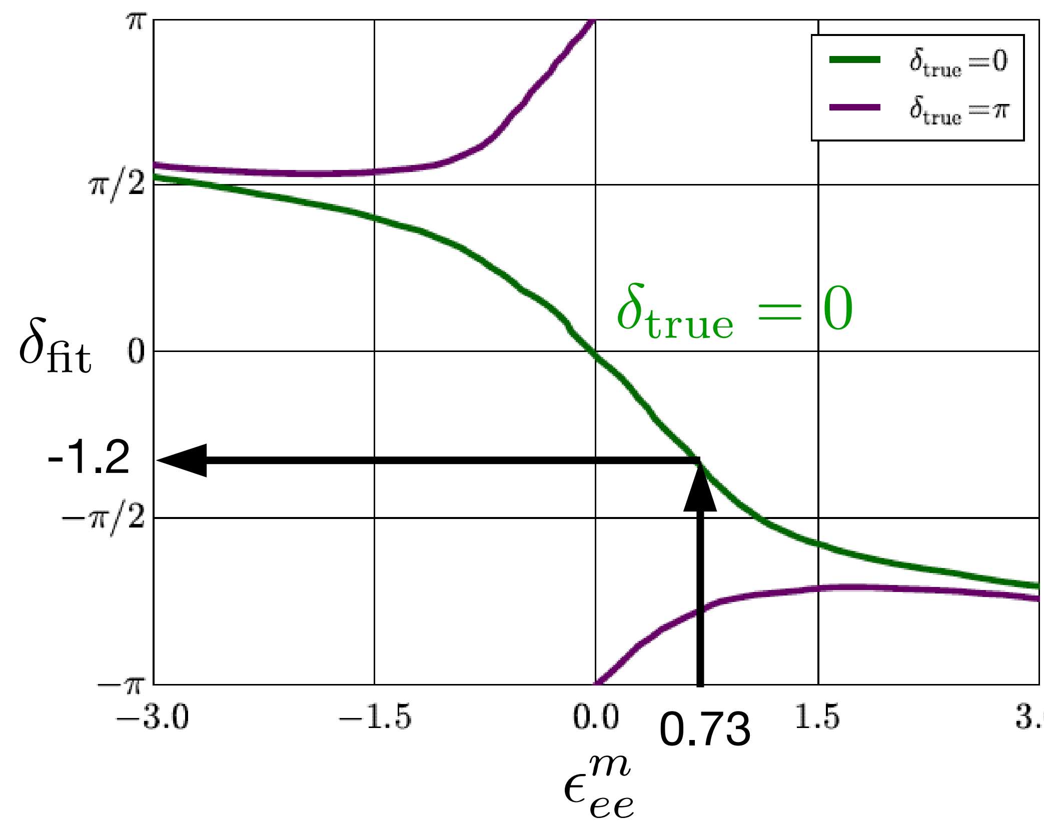
NSI-δ_{CP} at DUNE

de Gouvea Kelly 1605.099376



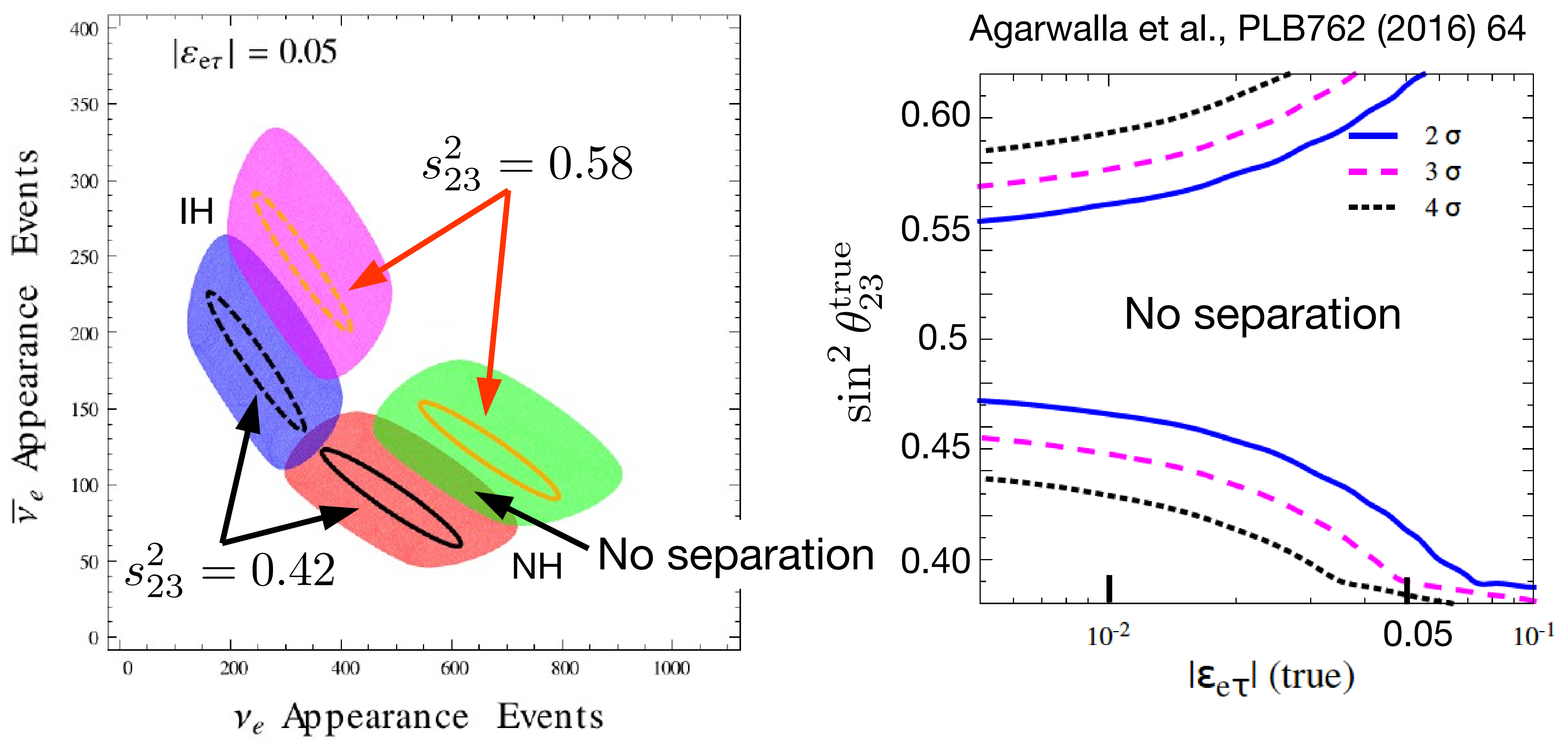


NSIs confuses the determination of δ

– Although the fit is good, the best-fit point suggests the wrong δ

NSIs disturb the determination of the standard oscillation parameters.

NSI-θ_{23} octant at DUNE



With NSIs, the ellipses of LO overlap with those of HO.

NSIs as noise

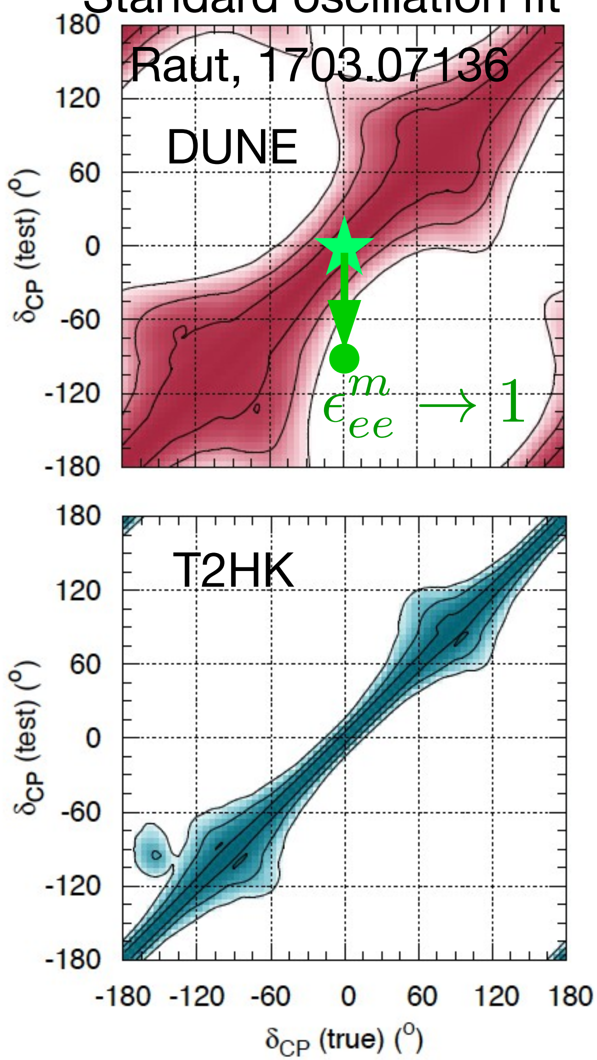
NSIs in the context of the parameter determination in future experiments

To reduce the noise...

How to reduce the NSI noise in the determination of the SO params.

Synergy between DUNE and T2HK (clean from matter related effects)

Standard oscillation fit



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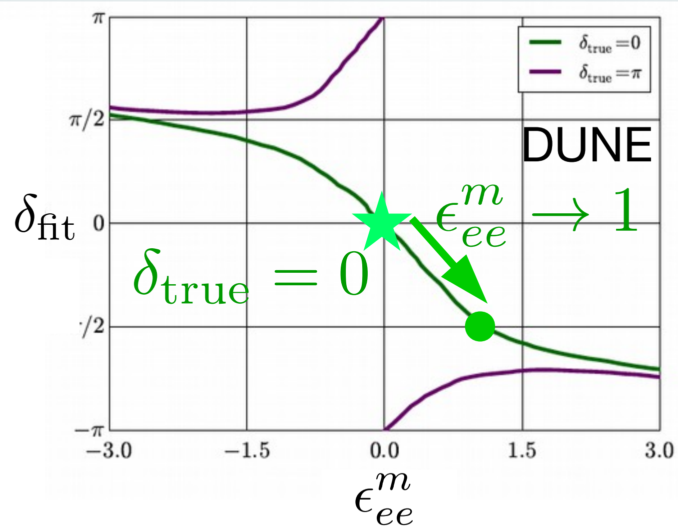

The best fit of δ at DUNE can be greatly shifted by matter NSI effects.

* For standard oscillation fit at DUNE+T2HK, see also Fukasawa Yasuda NPB918 (2017) 337

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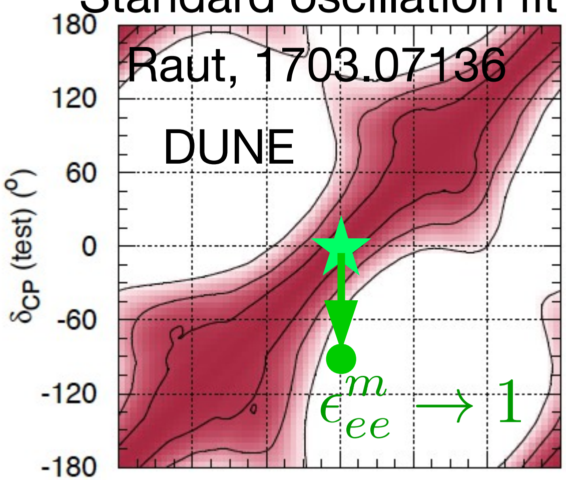

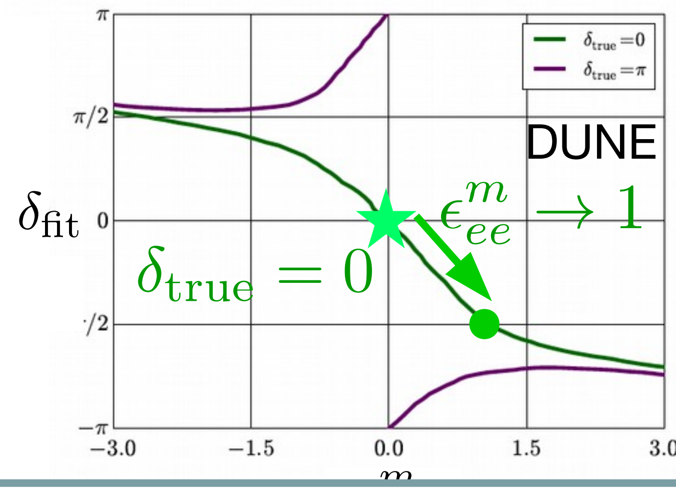

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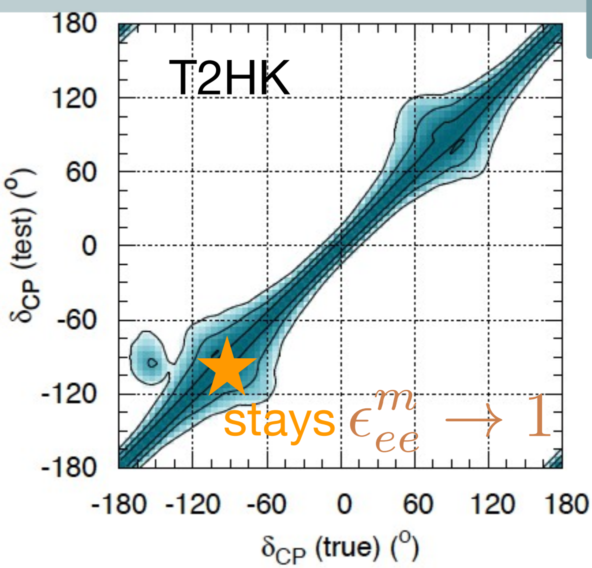
The best fit of δ at DUNE can be greatly shifted by matter NSI effects.

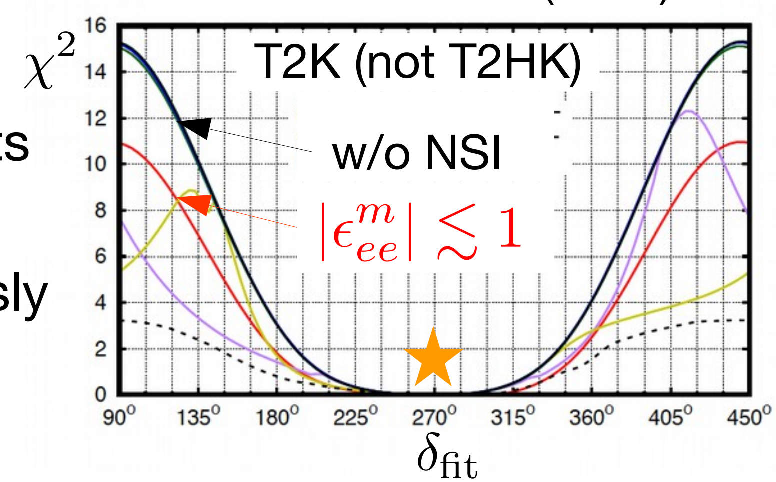
T2(H)K: shorter *L*, lower *E*



…does not so much suffer from the matter related effects

…can determine δ regardlessly of the matter NSIs

Ge Smirnov JHEP 10 (2016) 138



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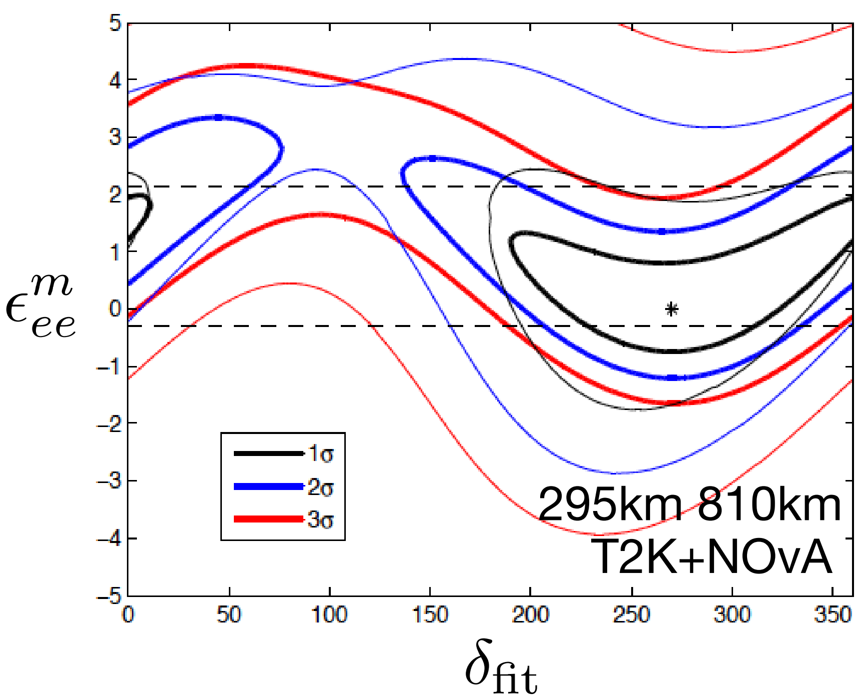
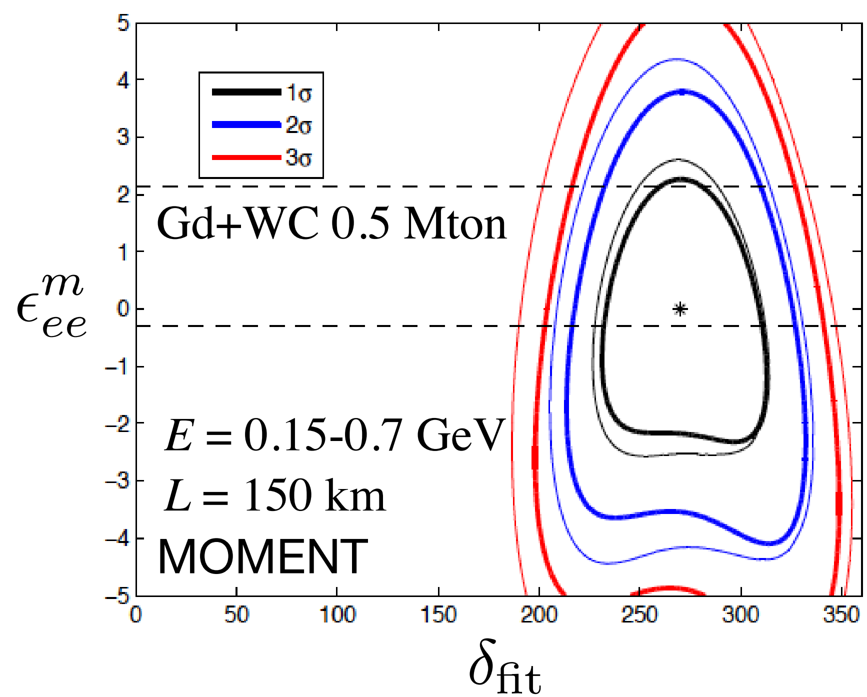
How to reduce the NSI noise in the determination of the SO params.

- Go shorter baseline (than T2(H)K) with a good profile/intense beam



Bakhti Farzan JHEP 1607 (2016) 109



No disturbance from matter NSIs

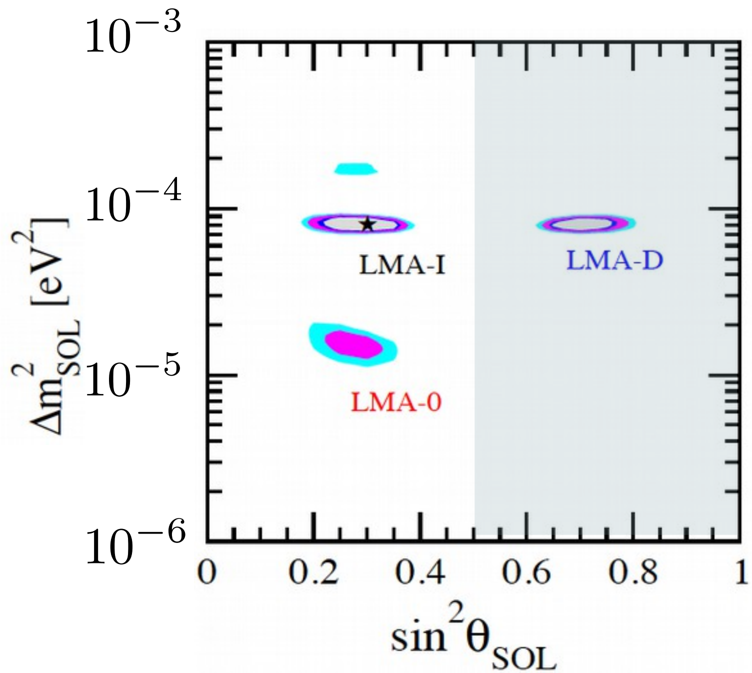
Future beams: ESSnSB (conventional high intensity beam, 0.2-0.6GeV) MOMENT (mu DIF), DAEdALUS (mu DAR), NuSTORM (mu storage ring)...

How to reduce the NSI noise in the determination of the SO params.

- Ask for help to non-oscillation experiments

e.g., Dark solar solution (LMA-D) vs COHERENT Akimov et al., 1708.01294

Miranda et al., JHEP 10 (2006) 008



LMA-D $s_{12}^2 \sim 0.7$

$$\epsilon_{ee}^{\odot} - \epsilon_{\mu\mu}^{\odot} \sim -2$$

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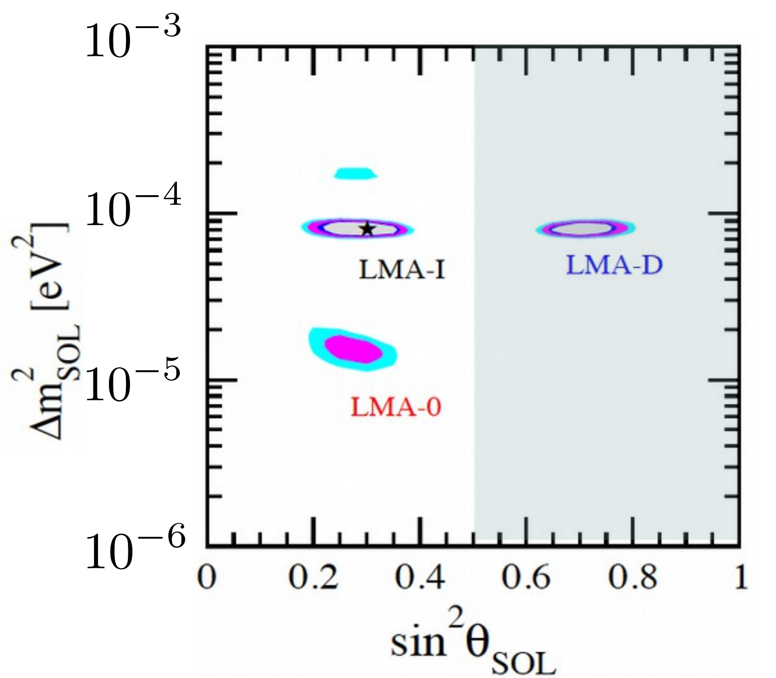
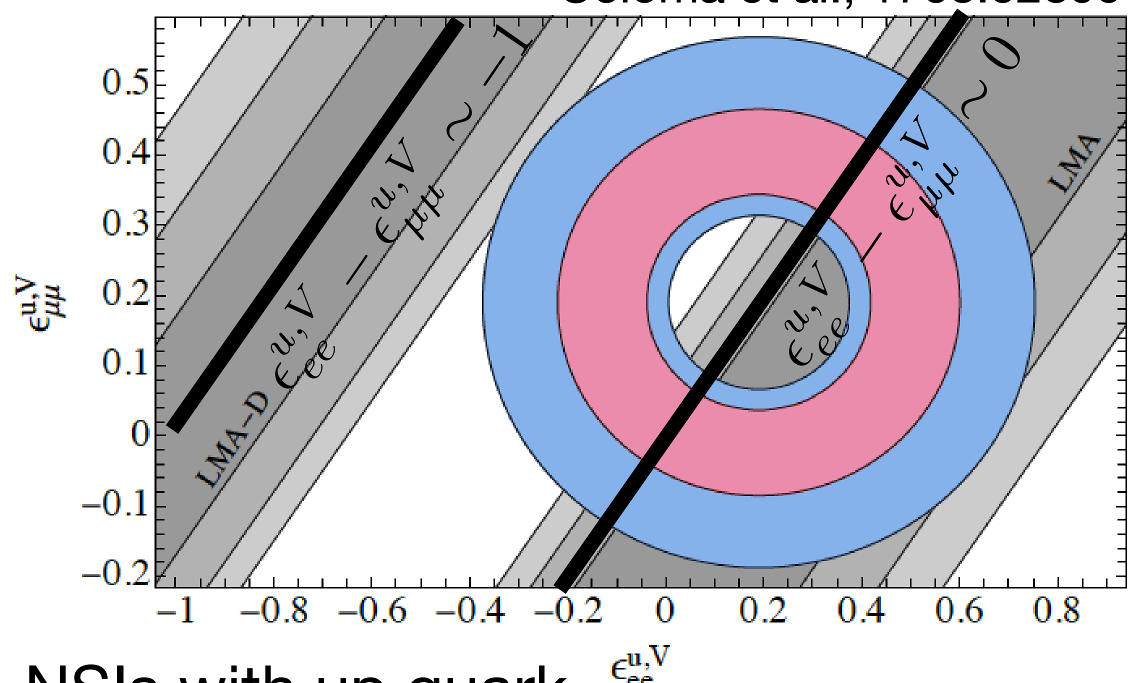


Coloma et al., 1708.02899



LMA-D $s^2_{12} \sim 0.7$

$$\epsilon^{\odot}_{ee} - \epsilon^{\odot}_{\mu\mu} \sim -2$$

NSIs with up quark

$$-\mathscr{L} = 2\sqrt{2}G_F \epsilon^{u,V}_{\alpha\alpha}[\overline{\nu}_\alpha \gamma^\rho P_L \nu_\alpha][\overline{u}\gamma_\rho u]$$

*Discussion on light mediators, Liao Marfatia, 1708.04255

*For sensitivity to NSIs at COHERENT, see also,
Lindner et al., JHEP 1703 (2017) 097 Shoemaker, PRD95 (2017) 115028

NSIs as noise

How to reduce the NSI noise in the determination of the SO params.

Energy dependence - Wide band, More channels

$$P(\nu_\mu \to \nu_e) = 4s_{13}^2 s_{23}^2 \mathcal{F}_1^2 + 4\left[\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right]^2 s_{12}^2 c_{12}^2 c_{23}^2 \left[\frac{\Delta m_{31}^2}{a}\mathcal{F}_2\right]^2 \qquad \mathcal{F}_1 \equiv \frac{\sin\frac{[\Delta m_{31}^2 - a]L}{4E}}{1 - a/\Delta m_{31}^2}$$

$$+8\left[\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right] s_{12}c_{12}s_{23}c_{23}s_{13}c_\delta \left[\frac{\Delta m_{31}^2}{a}\mathcal{F}_1\mathcal{F}_2 \cos\frac{\Delta m_{31}^2 L}{4E}\right] \qquad \mathcal{F}_2 \equiv \sin\frac{aL}{4E}$$

Standard Osc.

$$-8\left[\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right] s_{12}c_{12}s_{23}c_{23}s_{13}s_\delta \left[\frac{\Delta m_{31}^2}{a}\mathcal{F}_1\mathcal{F}_2 \sin\frac{\Delta m_{31}^2 L}{4E}\right]$$

NSI contributions

$$+8s_{23}c_{23}s_{13}\left[|\epsilon_{e\mu}^m| c_{23} c_{\delta+\phi_{e\mu}^m} - |\epsilon_{e\tau}^m| s_{23} c_{\delta+\phi_{e\tau}^m}\right]\left[\mathcal{F}_1\mathcal{F}_2\cos\frac{\Delta m_{31}^2 L}{4E}\right]$$

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$$+\mathcal{O}(\Delta m_{21}^2 \epsilon)$$

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$$+\mathcal{O}(\Delta m_{21}^2 \epsilon)$$

In high energy limit

NSIs as noise

How to reduce the NSI noise in the determination of the SO params.

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$$-8s_{23}c_{23}s_{13}\left[|\epsilon_{e\mu}^m| c_{23} s_{\delta+\phi_{e\mu}^m} - |\epsilon_{e\tau}^m| s_{23} s_{\delta+\phi_{e\tau}^m}\right]\left[\mathcal{F}_1\mathcal{F}_2\sin\frac{\Delta m_{31}^2 L}{4E}\right] \qquad 1/E^2$$

$$+8s_{23}^2 s_{13}\left[|\epsilon_{e\mu}^m| s_{23} c_{\delta+\phi_{e\mu}^m} \cancel{+ |\epsilon_{e\tau}^m| c_{23} c_{\delta+\phi_{e\tau}^m}}\right]\left[\frac{a}{\Delta m_{31}^2}\mathcal{F}_1^2\right] \qquad 1/E$$

$$+\mathcal{O}(\Delta m_{21}^2 \epsilon)$$

In high energy limit

NSIs as signals

High precision experiments may also be sensitive to New Physics

Sensitivities to NSIs at the forthcoming experiments.

DUNE

Blennow et al., JHEP 08 (2016) 090
Coloma, JHEP 03 (2016) 016
de Gouvea Kelly, NPB908 (2016) 318
Liao et al., JHEP 01 (2017) 071

Cosmic neutrinos at IceCube

Rasmussen et al., 1707.07684
Gonzalez-Garcia et al., Astropart Phys. 84 (2016) 15
Bustamante et al., PRL 115 (2015) 161302
Shoemaker Murase PRD 93 (2016) 085004

T2HK

Fukasawa et al., PRD95 (2017) 055005
Kelly, PRD95 (2017) 115009
Liao et al., JHEP 01 (2017) 071

* source/detection NSIs at ESSvSB
Blennow et al., JHEP 1412 (2014) 120

Cosmology

Archidiacono Hannestad, JCAP 1407 (2014) 046

* source/detection NSIs at MOMENT
Tang Zhang, 1705.09500

Atmospheric neutrinos

at IceCube

Salvado et al., JHEP 01 (2017) 141
Mocioiu Wright, NPB893 (2015) 376
Choubey Ohlsson PLB739 (2014) 357
Esmaili Smirnov, JHEP 06 (2013) 026
Ohlsson et al., PRD88 (2013) 013001

SK official

Mitsuka et al., PRD84 (2011) 113008

Set the bounds from real data

at HK

Kelly, PRD95 (2017) 115009
Fukasawa Yasuda, NPB914 (2017) 99

at KM3NeT

Coelho 1702.04508

at INO

Choubey et al., JHEP 12 (2015) 126

NSIs as signals

Sensitivities to NSIs at DUNE + T2HK

Coloma, JHEP 03 (2016) 016

- Synergy between DUNE + T2HK

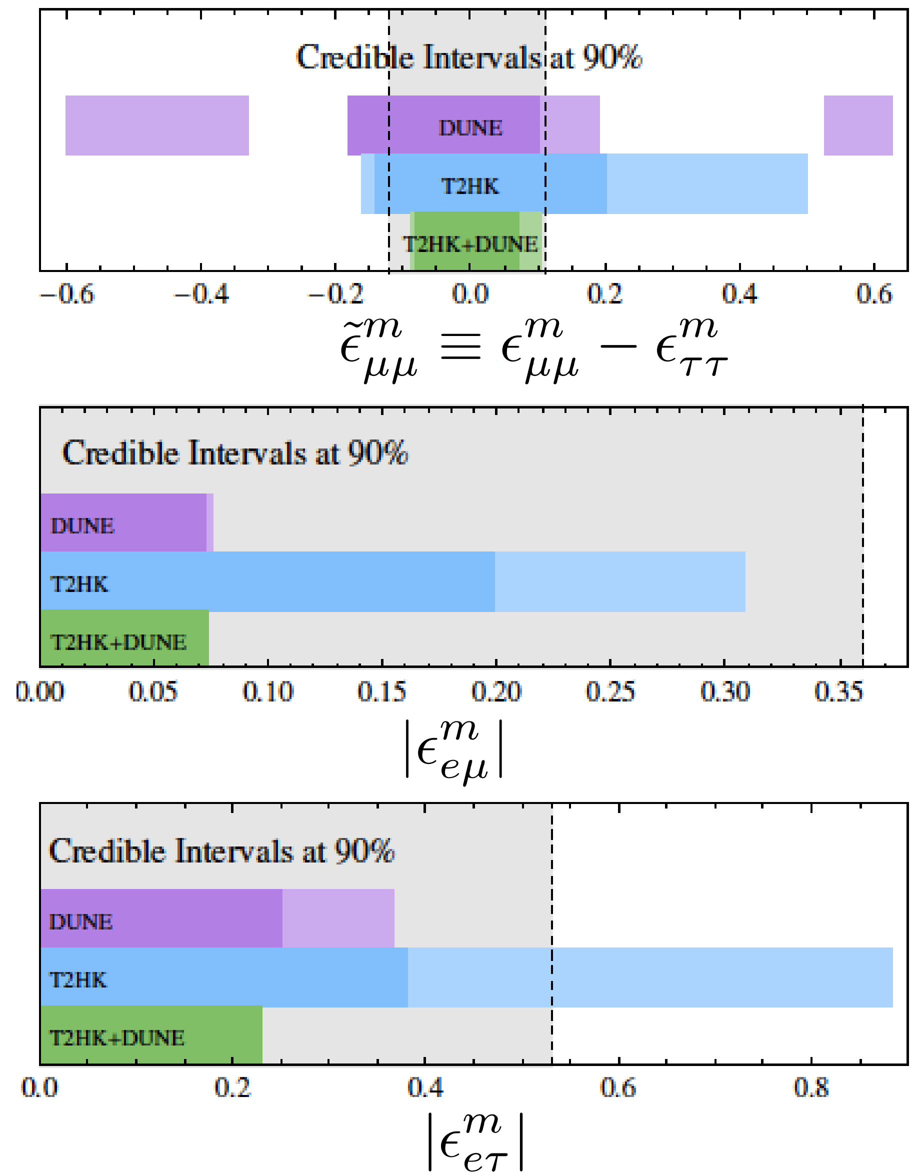
  Degeneracies in $\tilde{\epsilon}^m_{\mu\mu}$ at DUNE is solved with T2HK

  Inclusion of the priors improves the sensitivity to $\epsilon^m_{e\tau}$ (solve the degeneracy with $\tilde{\epsilon}^m_{ee}$)

  Determinations of the standard osc. parameters are also important

- Typical sensitivities ~0.1-0.05

- Sensitivities to matter NSIs at NuFACT ~ O(0.001)



* Check the talk by Rius

How to get large NSIs?

$$|\epsilon| \sim \mathcal{O}(1) - \mathcal{O}(10^{-2})$$

Currently allowed → Sensitivity reach at the forthcoming experiments

Large NSIs in theory

O(1) NSIs are currently allowed and phenomenologically motivated by...

- Weak tension between...

Solar vs KamLAND in Δm^2_{21}

Liao et al., PLB771 (2017) 247

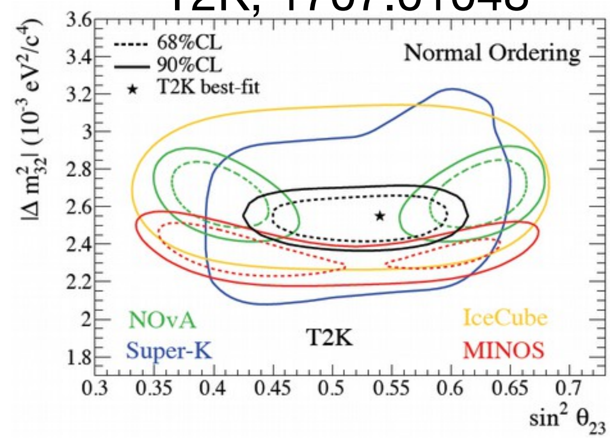
$$\epsilon^m_{ee} \sim 0.5$$

T2K vs NOvA in θ_{23}

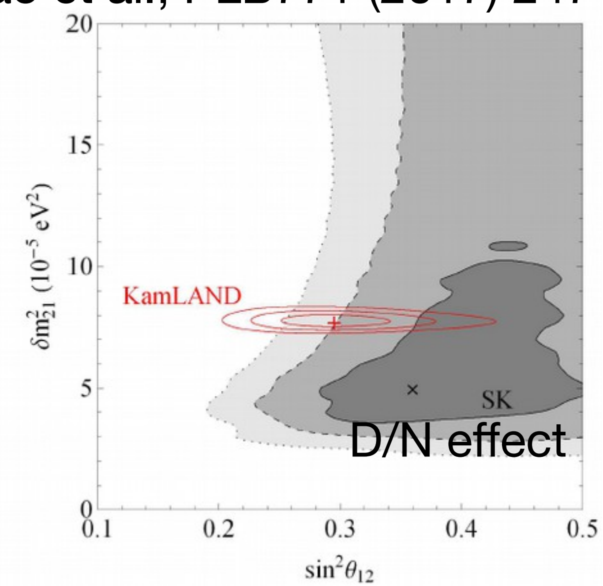
Liao et al., PLB767 (2017) 350

$$\epsilon^m_{\tau\tau} \sim 0.5 \quad \epsilon^m_{e\tau} \sim 1$$

T2K, 1707.01048



Liao et al., PLB771 (2017) 247



see also Fukasawa et al., 1609.04204, Ghosh Yasuda 1709.08264

- To test the robustness of the standard oscillation fits

– e.g., Dark solar solution –

Miranda et al., JHEP 10 (2006) 008

Maltoni Smirnov, EPJ A52 (2016) 87

Coloma et al., JHEP 04 (2017) 116

$$\epsilon^{\odot}_{\mu\mu} \sim 2$$
$$s^2_{12} \sim 0.7$$

vs COHERENT

Rate: Coloma et al., 1708.02899

Shape: Liao Marfatia, 1708.04255

- We should not exclude the possibilities allowed phenomenologically...

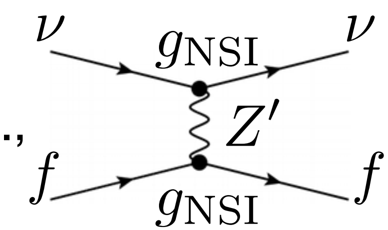
Large NSIs in theory

It is not easy to accommodate with such a large NSI in a model...

Naive expectation...

$$\epsilon = \frac{g_{\mathrm{NSI}}^2}{2\sqrt{2}G_F\Lambda^2} = 3 \cdot 10^{-2} \left[\frac{g_{\mathrm{NSI}}}{1.0}\right]^2 \left[\frac{1.0[\mathrm{TeV}]}{\Lambda}\right]^2$$

e.g.,



...suggests New Physics (Leptoquarks, Z' etc.) at LHC.

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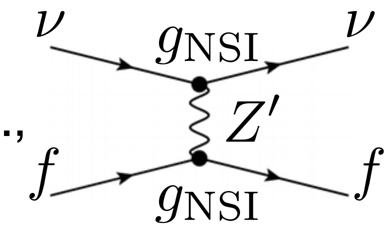
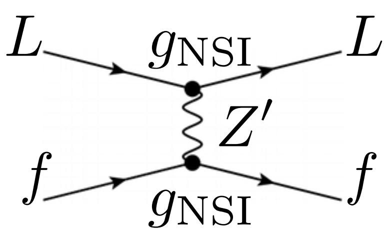


...suggests New Physics (Leptoquarks, Z' etc.) at LHC.

NSIs appears with charged lepton SU(2) counter processes.

$$\mathscr{L} = 2\sqrt{2}G_F\epsilon\left[\overline{L}\gamma^\rho L\right]\left[\overline{f}\gamma_\rho f\right] = 2\sqrt{2}G_F\epsilon\left[\overline{\nu}\gamma^\rho \mathrm{P}_L\nu + \overline{\ell}\gamma^\rho \mathrm{P}_L\ell\right]\left[\overline{f}\gamma_\rho f\right]$$



Bound from counter processes

$$\epsilon \lesssim \mathcal{O}(10^{-3})$$

Grossman, PLB359 (1995) 141
Bergmann Grossman, PRD59 (1999) 093005
Bergmann et al., PRD60 (1999) 093008
Bergmann et al., PRD61 (2000) 053005

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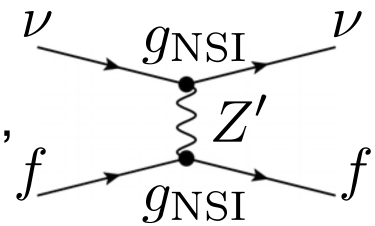

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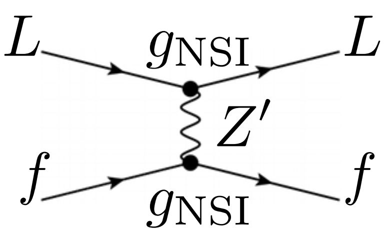

Bound from counter processes

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Grossman, PLB359 (1995) 141
Bergmann Grossman, PRD59 (1999) 093005
Bergmann et al., PRD60 (1999) 093008
Bergmann et al., PRD61 (2000) 053005

To avoid the counter, use of d=8 operators with Higgs fields. e.g.,

$$\mathscr{L} = (2\sqrt{2}G_F)^2\epsilon\left[\overline{L}\mathrm{i}\tau^2 H^*\gamma^\rho H^\top \mathrm{i}\tau^2 L\right]\left[\overline{f}\gamma_\rho f\right] = 2\sqrt{2}G_F\epsilon[\overline{\nu}\gamma^\rho \mathrm{P}_L\nu][\overline{f}\gamma_\rho f]$$

$$+(2\sqrt{2}G_F)^2\epsilon(\overline{\ell}\ell\overline{f}fH^+H^-)+\cdots$$

Berezhiani Rossi, PLB535 (2002) 207
Davidson et al., JHEP 03 (2003) 011

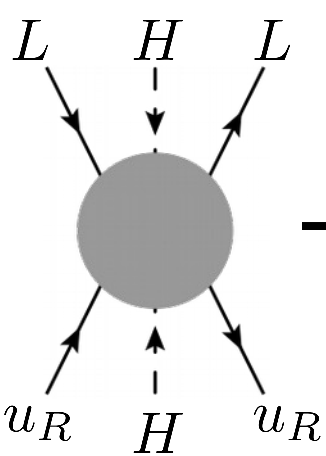
NSIs from d=8 ops look free from the bounds to the counter processes...

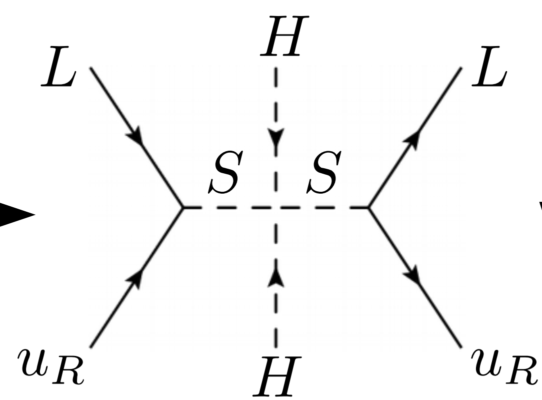
Tree-level decompositions of d=8 ops are accompanied by...

d=6 ops of NSIs + counter processes

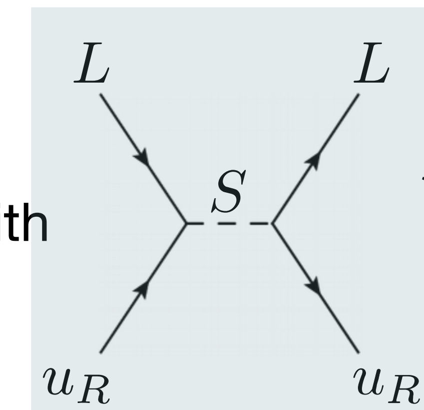
Antusch et al., NPB810 (2009) 369
Gavela et al., PRD79 (2009) 013007

d=8 NSI op





with



d=6 NSI

* *S*: Leptoquark,
Pair-produced at
LHC through gluon

Large NSIs in theory

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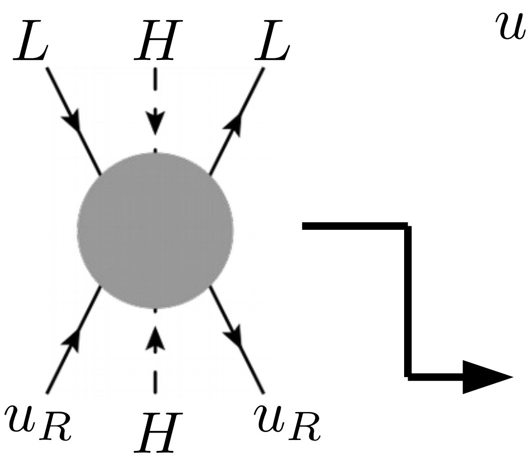
- Tree-level decompositions of d=8 ops are accompanied by...

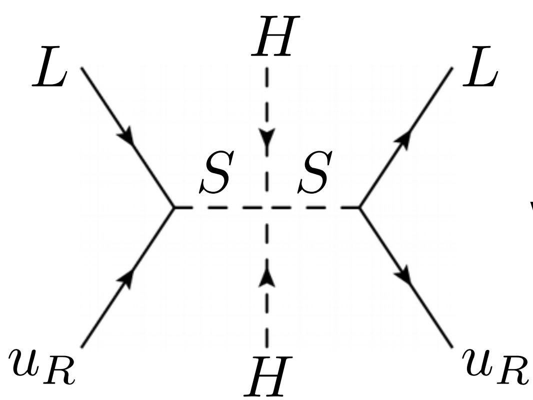
d=6 ops of NSIs + counter processes

Antusch et al., NPB810 (2009) 369
Gavela et al., PRD79 (2009) 013007

d=6 ops of the non-Unitarity (MUV)

d=8 NSI op





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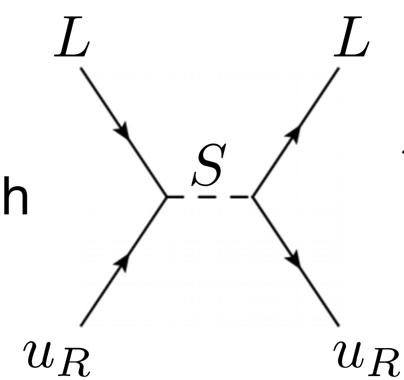
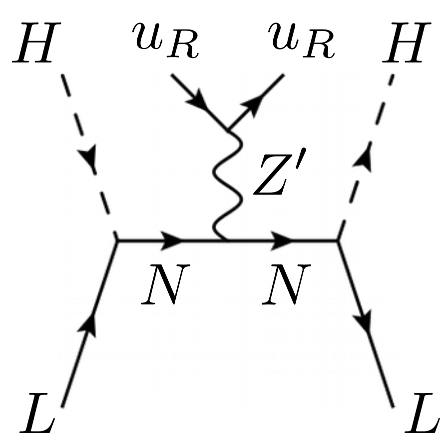
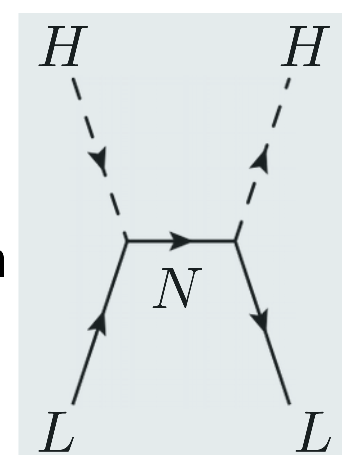


d=6 NSI

* S: Leptoquark, Pair-produced at LHC through gluon



with



d=6 Non-Uni.

behaves as NSIs in osc.

* Z' makes a di-jet resonance at LHC

Large NSIs in theory

NSIs from d=8 ops look free from the bounds to the counter processes...

Tree-level decompositions of d=8 ops are accompanied by...

d=6 ops of NSIs + counter processes

Antusch et al., NPB810 (2009) 369
Gavela et al., PRD79 (2009) 013007

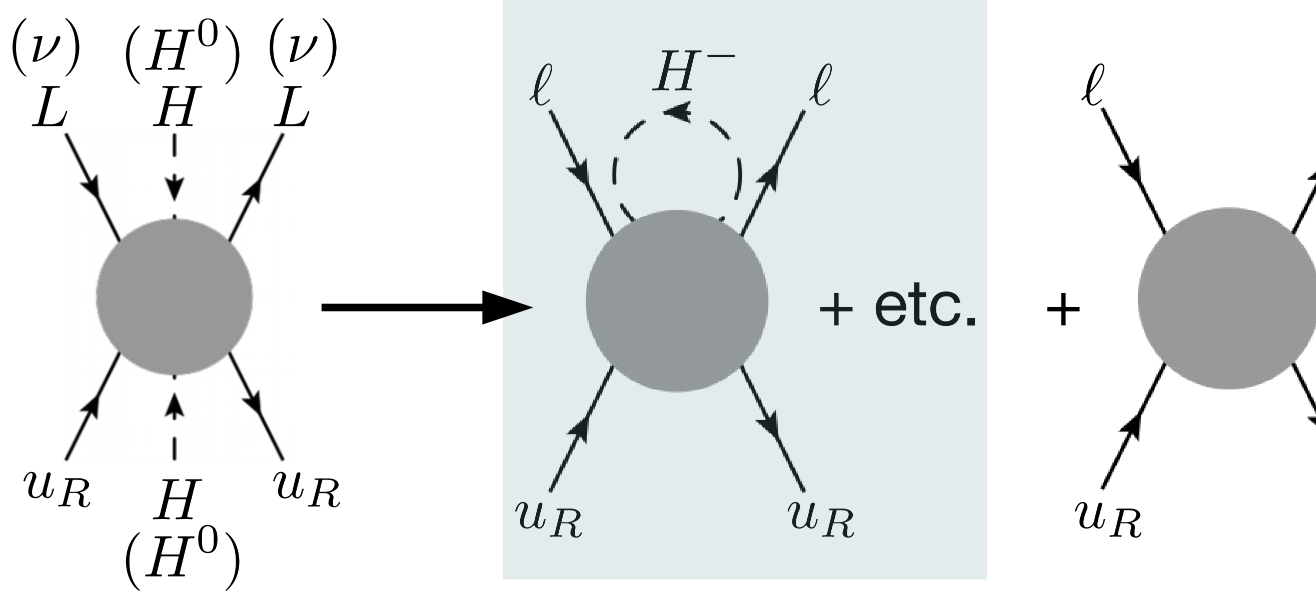
d=6 ops of the non-Unitarity (MUV)

→ $\boxed{\text{d=6 NSI/non-Uni models}}$

At the loop level...

They are quadratical divergent.

Biggio et al., JHEP 03 (2009) 139
Biggio et al., JHEP 08 (2009) 090



d=6 counter terms

→ $\boxed{\text{d=6 NSI models}}$

Large NSIs in theory

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→ d=6 NSI/non-Uni models

- At the loop level...

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Biggio et al., JHEP 03 (2009) 139
Biggio et al., JHEP 08 (2009) 090

To cancel/regularize them, d=6 ops (counter terms) are necessary.

→ d=6 NSI models

- It may be possible, but cancellations/fine-tunings are necessary

"Pure NSIs from d=8" require the dedicated construction at the d=6 level.

- A new trend

→ NSIs mediated by a light mediator

Large NSIs in theory

NSIs mediated by light fields

- Forward scattering → mediator is not necessarily heavier than EW

$$\epsilon = \frac{g_{\rm NSI}^2}{2\sqrt{2}G_F\Lambda^2} = 3\cdot 10^{-2}\left[\frac{g_{\rm NSI}}{10^{-5}}\right]^2\left[\frac{10[\rm MeV]}{\Lambda}\right]^2$$

→ Faint interactions mediated by a MeV mediator

- GeV right-hand nus + New U(1) with MeV scale breaking → O(1) NSI

$$\mathscr{L} = y\overline{L}i\tau^2 H'^{*}{\rm P}_R\Psi + M_\Psi\overline{\Psi}\Psi$$

$$\mathscr{L}_{\rm NSI} = \boxed{\frac{g_f g_\Psi \kappa_\alpha^* \kappa_\beta}{M_{Z'}^2}}[\overline{\nu}_\alpha\gamma^\rho {\rm P}_L\nu_\beta][\overline{f}\gamma_\rho f]$$

$$\equiv 2\sqrt{2}G_F\epsilon_{\alpha\beta}$$

$M_{Z'} \simeq 10[\rm MeV]$ $\quad M_\Psi \simeq 1[\rm GeV]$

$g_q \sim 10^{-4}$

$g_\Psi \sim 0.05$

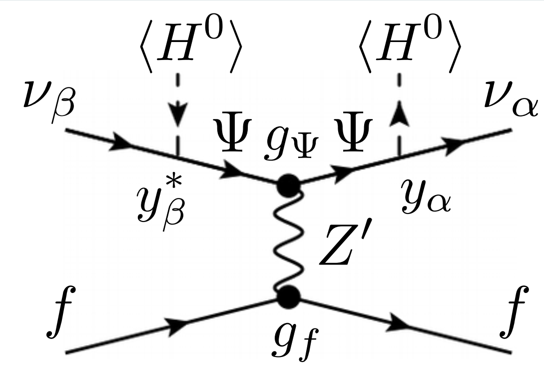
$y \sim 1$

mixing btw nu-Psi

$\kappa_e \simeq y_e^*\langle H'\rangle/M_\Psi$

$\langle H'\rangle = M_{Z'}/(\sqrt{2}g_\Psi)$

$\epsilon_{ee}^m \sim 1$



Farzan, PLB748 (2015) 311
Farzan Heeck, PRD94 (2016) 053010
Farzan Shoemaker, JHEP 07 (2016) 033
Machado, AIPConf. 1743 (2016) 030005
Babu et al., 1705.01822

- MeV mediator is a trend → Cosmic Nu, muon g-2, LUV in B-phys. etc.

Non-unitary PMNS matrix

- Unitarity violation

Violation of the conservation of

probability and energy

Non-unitary PMNS matrix

Unitarity is violated in effective theories in general. For example,...

Mix with light sterile neutrinos

→ Talk by Pallavicini, Ko, Aurisano, Blake, Ghosh, Vanegas Forero

$$U_{\alpha i} = \begin{pmatrix} \boxed{N_{3\times 3}} & \cdots \\ \vdots & \ddots \end{pmatrix}$$

Extra osc. driven by Δm^2_{41} etc.

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j}^{N} \mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\frac{\Delta m^2_{ji}L}{4E} + 2\sum_{i<j}^{N} \mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\frac{\Delta m^2_{ji}L}{2E}$$

Mix with heavy neutral fields = “Minimal Unitarity Violation”

see e.g., Antusch et al., JHEP10 (2006) 84

$\langle\nu_4|\nu_\alpha\rangle \neq 0$ $|\nu_4\rangle$ Too heavy to participate in the propagation non-unitary

$$P(\nu_\alpha \to \nu_\beta) = \left|\sum_{i,j=1}^{3} \langle\nu_\beta|\nu_j\rangle\langle\nu_j|\mathrm{e}^{-\mathrm{i}HL}|\nu_i\rangle\langle\nu_i|\nu_\alpha\rangle\right|^2 = \left|\sum_{i=1}^{3} N_{\beta i}\mathrm{e}^{-\mathrm{i}\frac{\Delta m^2_{i1}L}{2E}}N^\dagger_{i\alpha}\right|^2$$

* One must be further careful about the normalization factor, cf.,Langacker London, PRD38 (1988) 907

Neutrino decay

See e.g., Berryman et al., PLB742 (2015) 74
Coloma Peres, 1705.03599 Choubey et al., 1705.05820

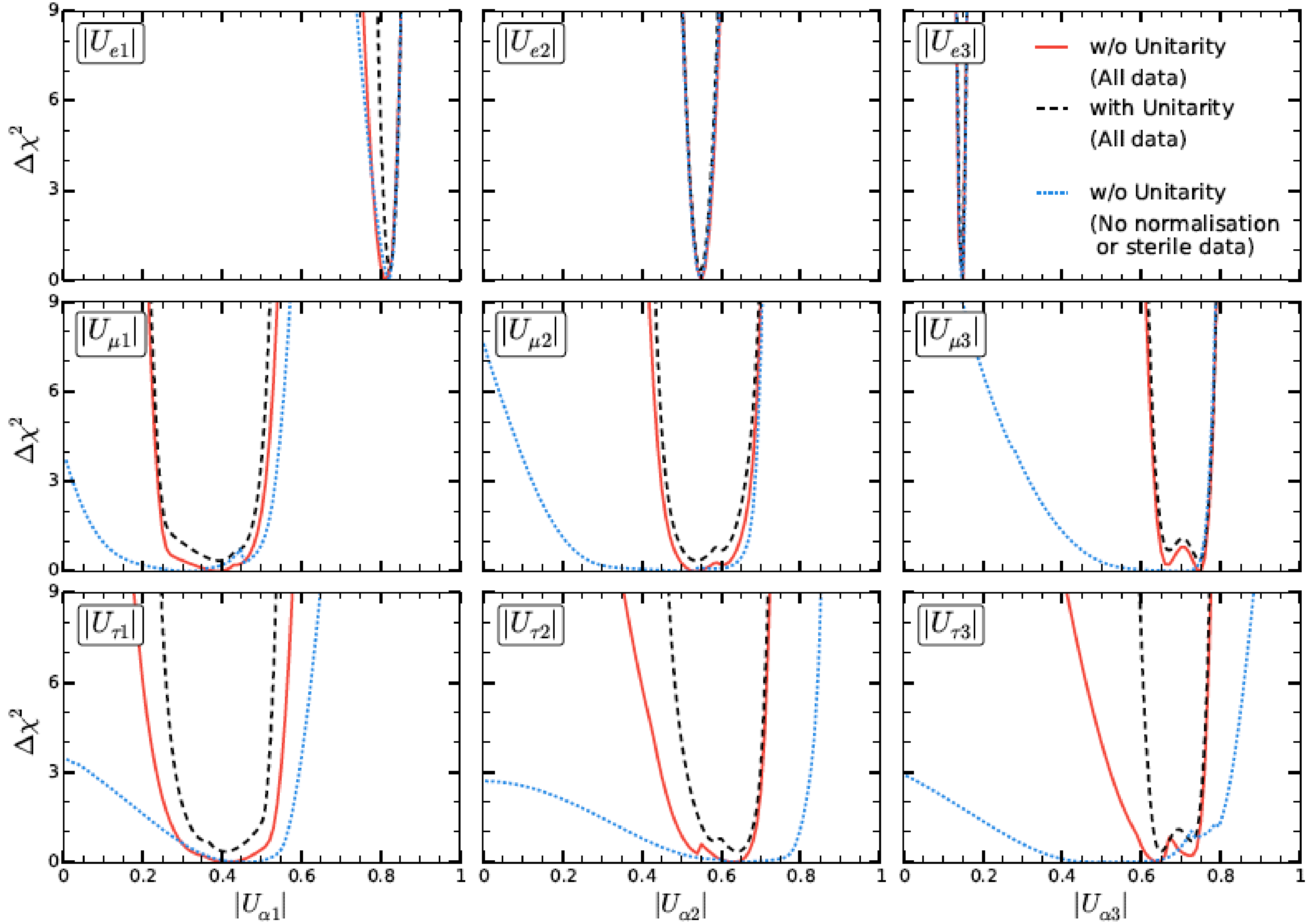
Non-hermitian Hamiltonian

$$\langle\nu_i|H_{\mathrm{vac}}|\nu_i\rangle = \frac{m_i^2}{2E} - \mathrm{i}\frac{\Gamma_i}{2}$$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3}|\nu_i\rangle\langle\nu_i|\nu_\alpha\rangle = \sum_{i=1}^{3}|\nu_i\rangle N^\dagger_{i\alpha}$$

Fitting the PMNS to oscillation experiments without assuming unitarity

Parke Ross-Lonergan, PRD93 (2016) 113009



Non-unitary PMNS matrix

Current bounds in MUV (Mix with heavy neutrals)

Fernandez-Martinez et al., JHEP 03 (2016) 033

See also, Antusch Fischer, JHEP 10 (2014) 094
Escrihuela et al., 1612.07377
Blennow et al., JHEP 04 (2017) 153

Observable	SM prediction	Experimental value
$M_W \simeq M_W^{\rm SM}\,(1+0.20\,(\eta_{ee}+\eta_{\mu\mu}))$	(80.363 ± 0.006) GeV	(80.385 ± 0.015) GeV
$s^{2\,\rm lep}_{\rm W\,eff} \simeq s^{2\,\rm lep\,SM}_{\rm W\,eff}\,(1-1.30\,(\eta_{ee}+\eta_{\mu\mu}))$	0.23152 ± 0.00010	0.23113 ± 0.00021
$s^{2\,\rm had}_{\rm W\,eff} \simeq s^{2\,\rm had\,SM}_{\rm W\,eff}\,(1-1.30\,(\eta_{ee}+\eta_{\mu\mu}))$	0.23152 ± 0.00010	0.23222 ± 0.00027
$R_l \simeq R_l^{\rm SM}\,(1+0.18\,(\eta_{ee}+\eta_{\mu\mu}))$	20.740 ± 0.010	20.804 ± 0.050
$R_c \simeq R_c^{\rm SM}\,(1+0.11\,(\eta_{ee}+\eta_{\mu\mu}))$	0.17226 ± 0.00003	0.1721 ± 0.0030
$R_b \simeq R_b^{\rm SM}\,(1-0.06\,(\eta_{ee}+\eta_{\mu\mu}))$	0.21576 ± 0.00003	0.21629 ± 0.00066
$\sigma^0_{\rm had} \simeq \sigma^{0\,\rm SM}_{\rm had}\,(1+0.55\,(\eta_{ee}+\eta_{\mu\mu})+0.53\eta_{\tau\tau})$	(41.479 ± 0.008) nb	(41.541 ± 0.037) nb
$\Gamma_{\rm inv} \simeq \Gamma^{\rm SM}_{\rm inv}\,(1-0.33\,(\eta_{ee}+\eta_{\mu\mu})-1.32\eta_{\tau\tau})$	(0.50166 ± 0.00005) GeV	(0.4990 ± 0.0015) GeV
$R^\pi_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0042 ± 0.0022
$R^\pi_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	0.9941 ± 0.0059
$R^W_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	0.992 ± 0.020
$R^W_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	1.071 ± 0.025
$R^K_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	0.9956 ± 0.0040
$R^K_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	0.978 ± 0.014
$R^l_{\mu e} \simeq (1-(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0040 ± 0.0032
$R^l_{\tau\mu} \simeq (1-(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	1.0029 ± 0.0029
$\left\lvert V^\beta_{ud}\right\rvert \simeq \sqrt{1-\lvert V_{us}\rvert^2}(1+\eta_{\mu\mu})$	$\sqrt{1-\lvert V_{us}\rvert^2}$	0.97417 ± 0.00021
$\left\lvert V^{\tau\to K\nu_\tau}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee}+\eta_{\mu\mu}-\eta_{\tau\tau})$	$\lvert V_{us}\rvert$	0.2212 ± 0.0020
$\left\lvert V^{\tau\to K,\pi}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2232 ± 0.0019
$\left\lvert V^{K_L\to\pi e\overline{\nu}_e}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2237 ± 0.0011
$\left\lvert V^{K_L\to\pi\mu\overline{\nu}_\mu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2240 ± 0.0011
$\left\lvert V^{K_S\to\pi e\overline{\nu}_e}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2229 ± 0.0016
$\left\lvert V^{K^\pm\to\pi e\overline{\nu}_e}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2247 ± 0.0012
$\left\lvert V^{K^\pm\to\pi\mu\overline{\nu}_\mu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{ee})$	$\lvert V_{us}\rvert$	0.2245 ± 0.0014
$\left\lvert V^{K,\pi\to\mu\nu}_{us}\right\rvert \simeq \lvert V_{us}\rvert\,(1+\eta_{\mu\mu})$	$\lvert V_{us}\rvert$	0.2315 ± 0.0010

$\eta_{\alpha\beta}$ in non-oscillation observables

The PMNS matrix N is parametrized as

$$N_{\alpha i} \equiv [\delta_{\alpha\beta} - \eta_{\alpha\beta}]\,\mathcal{U}_{\beta i}$$

3*3 unitary matrix

Deviation from unitarity is parametrized with a 3*3 hermitian matrix

* Unitarity condition of the full mixing matrix

$$U = \begin{pmatrix} N_{3\times 3} & \Theta \\ R & S \end{pmatrix} \xrightarrow{UU^\dagger = \mathbf{1}} \eta = \frac{1}{2}\Theta\Theta^\dagger$$

* Parametrization with a 3*3 lower triangular matrix
Escrihuela et al., PRD92 (2015) 053009
Blennow et al., JHEP 04 (2017) 153

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Fernandez-Martinez et al., JHEP 03 (2016) 033

See also, Antusch Fischer, JHEP 10 (2014) 094
Escrihuela et al., 1612.07377
Blennow et al., JHEP 04 (2017) 153

		G-SS	
		LFC	LFV
$\sqrt{2\eta_{ee}}$, $\lvert\theta_e\rvert$	1σ	$0.031^{+0.010}_{-0.020}$	–
	2σ	< 0.050	–
$\sqrt{2\eta_{\mu\mu}}$, $\lvert\theta_\mu\rvert$	1σ	< 0.011	–
	2σ	< 0.021	–
$\sqrt{2\eta_{\tau\tau}}$, $\lvert\theta_\mu\rvert$	1σ	$0.044^{+0.019}_{-0.027}$	–
	2σ	< 0.075	–
$\sqrt{2\eta_{e\mu}}$, $\sqrt{\lvert\theta_e\theta_\mu\rvert}$	1σ	< 0.018	$< 4.1 \cdot 10^{-3}$
	2σ	< 0.026	$< 4.9 \cdot 10^{-3}$
$\sqrt{2\eta_{e\tau}}$, $\sqrt{\lvert\theta_e\theta_\tau\rvert}$	1σ	< 0.045	< 0.107
	2σ	< 0.052	< 0.127
$\sqrt{2\eta_{\mu\tau}}$, $\sqrt{\lvert\theta_\mu\theta_\tau\rvert}$	1σ	< 0.024	< 0.115
	2σ	< 0.035	< 0.137

The PMNS matrix *N* is parametrized as

$$N_{\alpha i} \equiv [\delta_{\alpha\beta} - \eta_{\alpha\beta}]\,\mathcal{U}_{\beta i}$$

3*3 unitary matrix

Deviation from unitarity is parametrized with a 3*3 hermitian matrix

Current bounds $\eta < \mathcal{O}(10^{-3})$

We can constrain the deviation from unitarity, but...

Can we “test” the unitarity in oscillations? – In principle, Yes.

Non-unitary PMNS matrix

Unitarity check in $\nu_\mu \to \nu_e$

Sato, hep-ph/0008056, proc. of NuFACT00
Paes Sicking, PRD95 (2017) 075004

Oscillation probability at $(\Delta m^2_{21})^2, \Delta m^2_{21}|U_{e3}|, |U_{e3}|^2,$

Different *E* dependences
They can be separated, in principle

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} = {} & 4|U_{\mu 3}U^*_{e3}|^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
& + 4\mathrm{Re}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right] \left[\frac{\Delta m^2_{21} L}{4E}\right] \sin \frac{\Delta m^2_{31} L}{2E} \\
& - 8\mathrm{Im}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right] \left[\frac{\Delta m^2_{21} L}{4E}\right] \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
& + 4\left|U_{\mu 2}U^*_{e2}\right|^2 \left[\frac{\Delta m^2_{21} L}{4E}\right]^2 + \mathcal{O}\left[(\Delta m^2_{21})^2 |U_{e3}|\right]
\end{aligned}
$$

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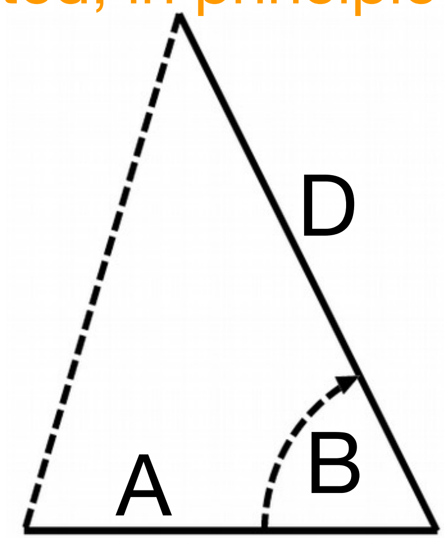
$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} = {} & 4\underbrace{|U_{\mu 3}U^*_{e3}|^2}_{\text{coeff. A}} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
& + 4\underbrace{\mathrm{Re}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right]}_{\text{coeff. B}} \left[\frac{\Delta m^2_{21} L}{4E}\right] \sin \frac{\Delta m^2_{31} L}{2E} \\
& - 8\underbrace{\mathrm{Im}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right]}_{\text{coeff. C}} \left[\frac{\Delta m^2_{21} L}{4E}\right] \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
& + 4\underbrace{\left|U_{\mu 2}U^*_{e2}\right|^2}_{\text{coeff. D}} \left[\frac{\Delta m^2_{21} L}{4E}\right]^2 + \mathcal{O}\left[(\Delta m^2_{21})^2 |U_{e3}|\right]
\end{aligned}
$$



- If *U* is unitary, we can determine a triangle only with A, B, and D

Non-unitary PMNS matrix

Unitarity check in $\nu_\mu \to \nu_e$

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Oscillation probability at $(\Delta m^2_{21})^2, \Delta m^2_{21}|U_{e3}|, |U_{e3}|^2,$

Different E dependences
They can be separated, in principle

coeff. A

$$P_{\nu_\mu\to\nu_e} = 4|U_{\mu 3}U^*_{e3}|^2 \sin^2\frac{\Delta m^2_{31}L}{4E}$$

$$+4\mathrm{Re}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right]\left[\frac{\Delta m^2_{21}L}{4E}\right]\sin\frac{\Delta m^2_{31}L}{2E}$$

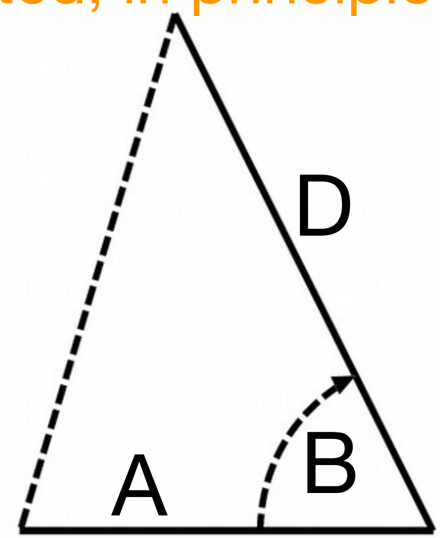
coeff. B

$$-8\mathrm{Im}\left[U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3}\right]\left[\frac{\Delta m^2_{21}L}{4E}\right]\sin^2\frac{\Delta m^2_{31}L}{4E}$$

coeff. C

$$+4\left|U_{\mu 2}U^*_{e2}\right|^2\left[\frac{\Delta m^2_{21}L}{4E}\right]^2 + \mathcal{O}\left[(\Delta m^2_{21})^2|U_{e3}|\right]$$

coeff. D



- If U is unitary, we can determine a triangle only with A, B, and D
- C is Jarlskog's invariant = Area of the triangle

Jarlskog, PRL55 (1985) 1039,
PRD36 (1987) 2127

Unitarity of U is tested by checking...

Area of the triangle suggested by A, B, and D $\stackrel{?}{=}$ C/2

Secret neutrino interactions

- Interactions between neutrinos and invisibles (incl. neutrinos)

Secret neutrino interactions

Neutrino-neutrino interactions (a kind of NSIs), Neutrino-DM interactions

Sterile matter effect to avoid the bound from $N_{\rm eff}$

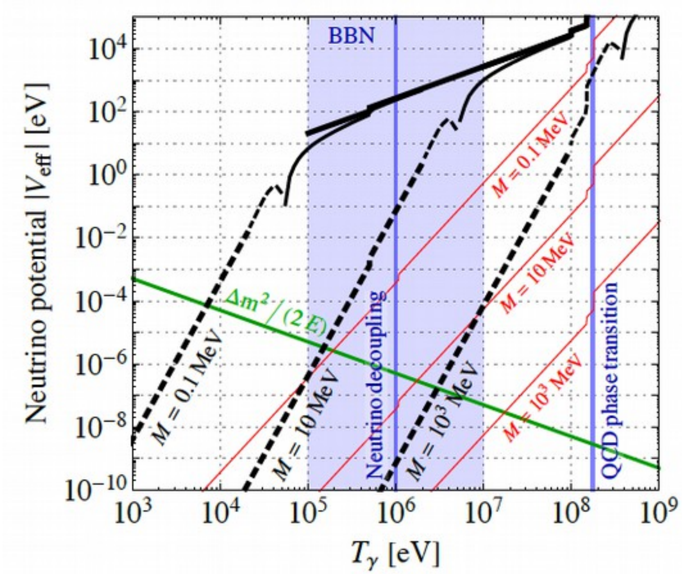
Chu et al., JCAP 1510 (2015) 011
Cherry et al., 1605.06506

Dasgupta Kopp, PRL112 (2014) 031803

MSW effect with thermal potential mediated by a new gauge boson with a mass around MeV

$$\sin^2 2\tilde{\theta}_{\text{a-s}} = \frac{\sin 2\theta_{\text{a-s}}}{(\cos 2\theta_{\text{a-s}} + \frac{2E}{\Delta m^2} V_{\rm eff})^2 + \sin^2 2\theta_{\text{a-s}}}$$

Sterile decouples before/during BBN, if $V_{\rm eff} \gg \dfrac{\Delta m^2}{2E}$



Neutrino annihilation to avoid cosmological bound on $\sum m_\nu$

Farzan Hannestad, JCAP 1602 (2016) 058

Dark matter effect with sterile neutrino

Capozzi et al., JCAP 1707 (2017) 021

Fuzzy DM (very light DM)-nu interaction

Berlin, PRL 117 (2016) 231801 Krnjaic et al., 1705.06740 Brdar et al., 1705.09455

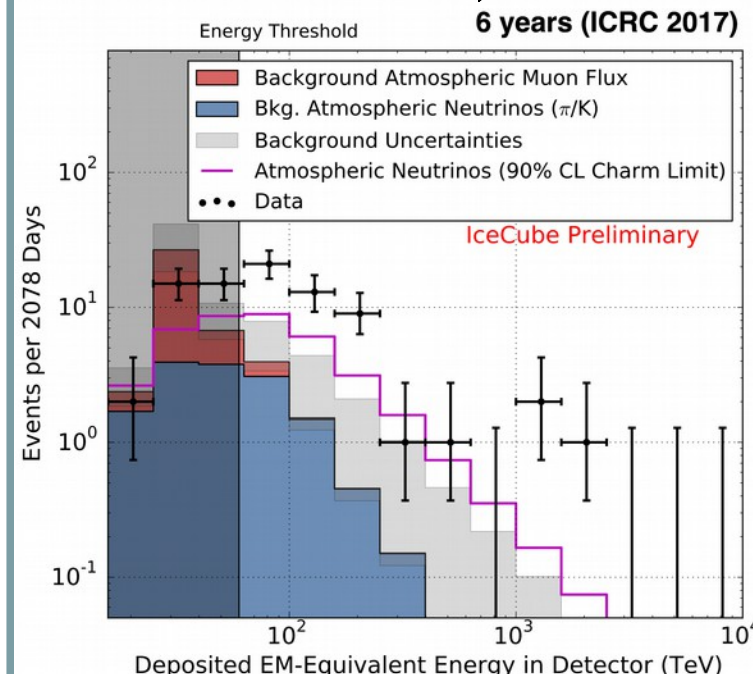
Secret neutrino interactions

Neutrino-neutrino interactions (a kind of NSIs), Neutrino-DM interactions

Cosmic neutrinos as a probe to secret neutrino interactions

Deviation from a power-law spectrum?

IceCube, van Santen



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Deviation from a power-law spectrum?

DM decay as the source?

→ Talk by Heeck

Secret int with DM

$$\chi \to \phi\nu \qquad M_\chi \sim E_{\nu_{\mathrm{Cosmo}}}$$

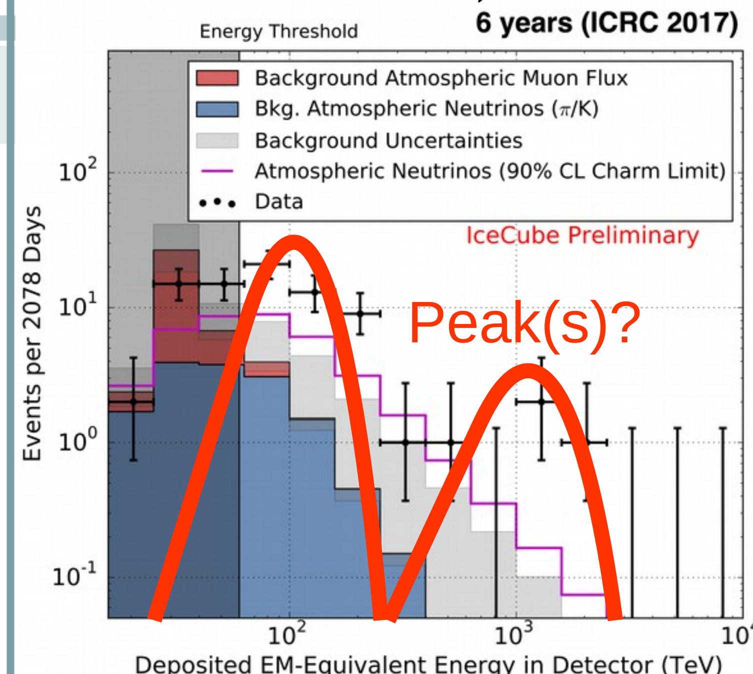
Peak around M_χ

See e.g.,

Feldstein et al., PRD88 (2013) 015004
Esmaili Serpico., JCAP 1311 (2013) 054
Cohen et al., PRL 119 (2017) 021102
Chianese Merle, JCAP 1704 (2017) 017
El Aisati et al, JCAP 1707 (2017) 027
Hiroshima et al., 1705.04419 Chianese et al., 1707.05241

DM+astro?
2 DMs?

IceCube, van Santen



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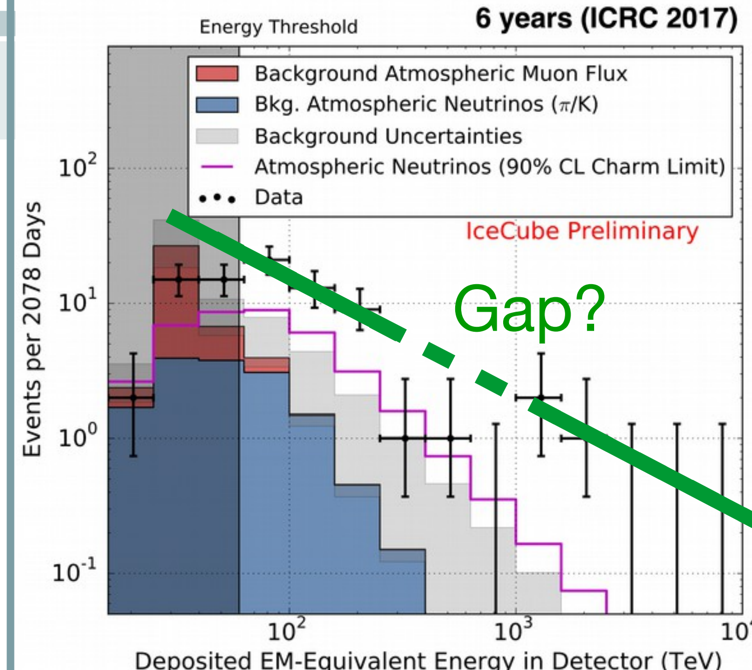


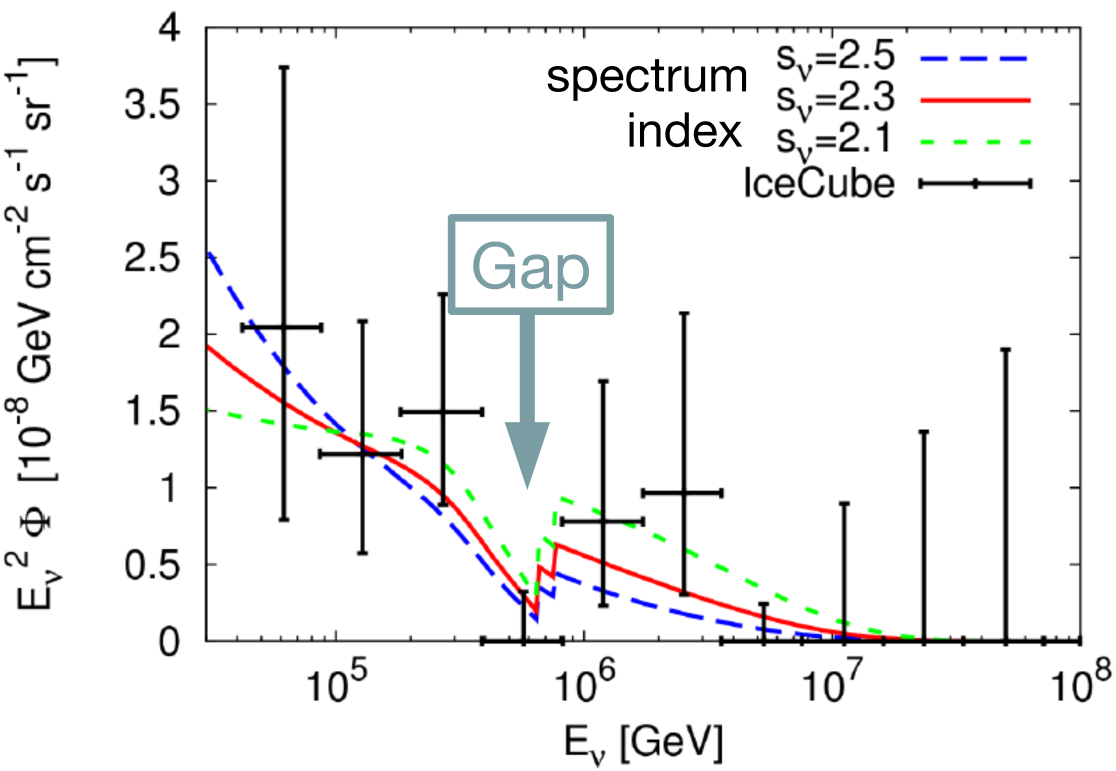
Resonant scattering in propagation, mediated by a secret nu-nu int.?

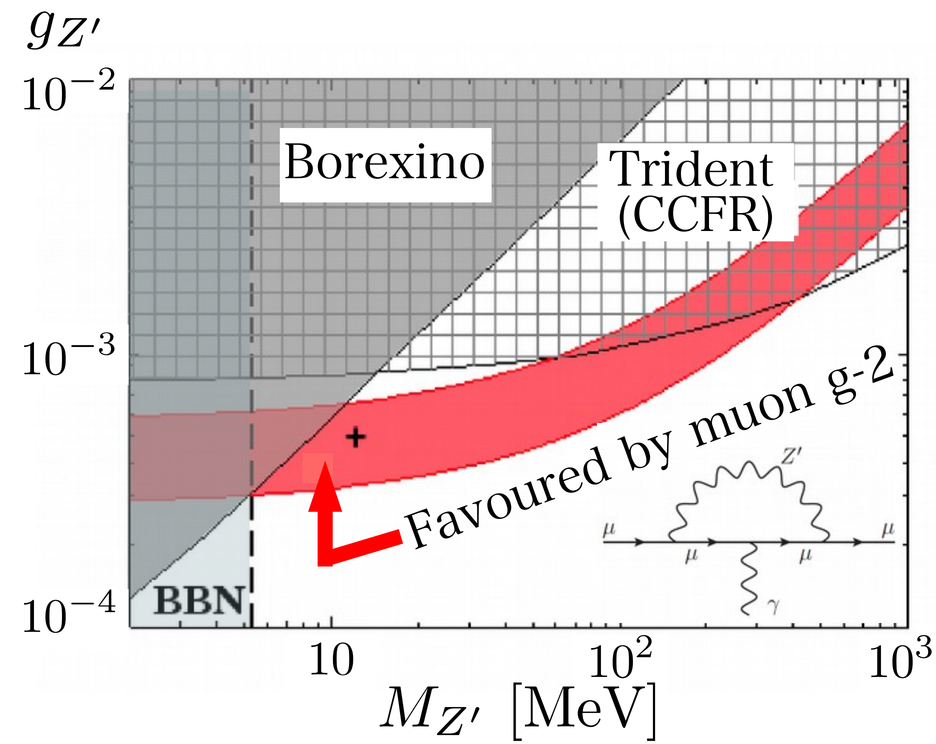
Ioka Murase, PTEP 2014 (2014) 061E01
Ng Beacom PRD90 (2014) 065035
Ibe Kaneta PRD90 (2014) 053011
Blum et al., 1408.3799
Araki et al., PRD91 (2015) 037301
Kamada Yu, PRD92 (2015) 113004
DiFranzo Hooper PRD92 (2015) 095002
Araki et al., PRD93 (2016) 013014

Gap at resonance?

Cosmic neutrino spectrum with the $L_\mu - L_\tau$ interaction

Araki et al., PRD93 (2016) 013014





$L_\mu - L_\tau$ gauge interaction

$$\mathscr{L} = g_{Z'}\left[\overline{\mu}\gamma^\rho\mu - \overline{\tau}\gamma^\rho\tau + \overline{\nu}_\mu\gamma^\rho \mathrm{P}_L\nu_\mu - \overline{\nu}_\tau\gamma^\rho \mathrm{P}_L\nu_\tau\right] Z'_\rho + (M^2_{Z'}/2)Z'_\rho Z'^\rho$$

+ $M_{Z'} = 11\text{MeV}$
  $g_{Z'} = 5\cdot 10^{-4}$

Contribution to muon g-2 is $a_\mu^{Z'} = 24.2\cdot 10^{-10}$

Gap should not be deep → $L_\mu - L_\tau$ will be tested

Summary

Summary

- NSIs with O(0.1-1) are phenomenologically allowed

It is possible for NSIs with O(0.01) to disturb the parameter determinations at the forthcoming experiments.

- It may be time to "think freely and rightly" on future plans...

→ Check the talk by Raut

Low energy
Short baseline

but High intensity
High resolution

Low "noise",
"Unitarity check"

ESSνSB, NuSTORM,
MOMENT, DAEdALUS etc...

Think freely is great
but think rightly is greater

Original NuFact

High energy
Long baseline

Discovery of "signals"
of non-standard effects

Wide band beams

→ Trace out the oscillation pattern over a wide energy range
→ Separate the standard osc. effects from exotics

- A new trend – Secret neutrino interactions with light mediators

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For other uses, see

The (鵺, 鵼, 恠鳥, or 奴延鳥) is a legendary Japanese yōkai or mononoke.

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"Kyoto Taibi (The End)" (京都 鵺 大尾) (among The Sixty-nine Stations of the Kiso Kaidō one that is by Utagawa Kuniyoshi, in Kaei 5 (1852), October)

Appearance [edit]

In the *Heike Monogatari*, it is described as having the face of a monkey, the legs of a tiger, the body of a tanuki (Japanese raccoon dog) and the front half of a snake for a tail. In other writings nothing is stated about its torso, so it is sometimes depicted to have the

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Nue

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For other uses, see NUE (disambiguation).

The **Nue** (鵺, 鵼, 恠鳥, or 奴延鳥) is a legendary Japanese yōkai or mononoke.

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Thank you very much for your kind attention

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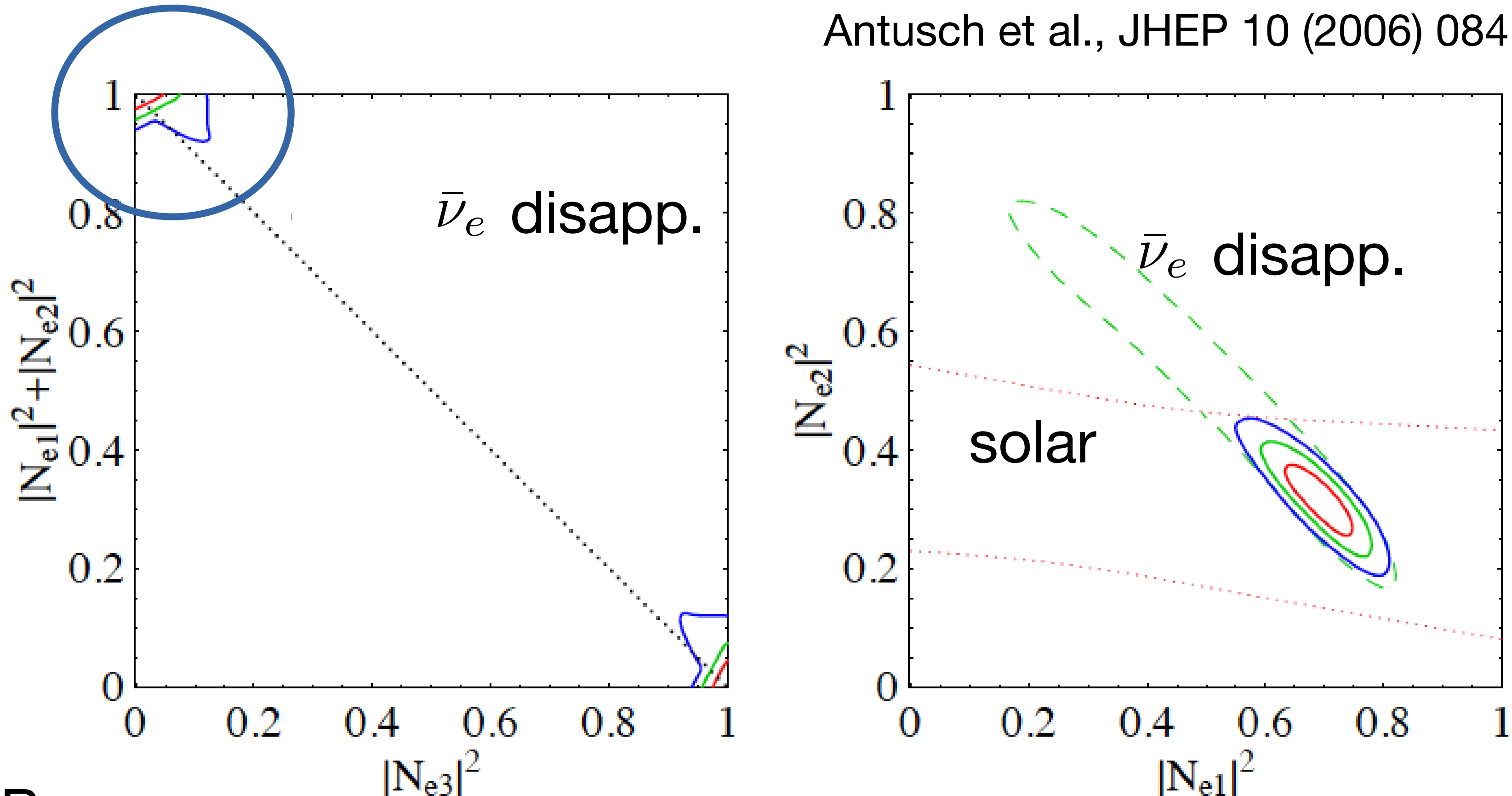
Backups

Non-unitary PMNS matrix

PMNS elements constrained from oscillation experiments

Antusch et al., JHEP 10 (2006) 084



Daya Bay

$$4|N_{e3}|^2(|N_{e1}|^2+|N_{e2}|^2)=0.084$$

$$|N_{e2}|^2=0.3$$

$$|N_{e1}|^2+|N_{e2}|^2+|N_{e3}|^2=(NN^\dagger)_{ee}\simeq 1$$ ← No osc. in short baseline

Non-unitary PMNS matrix

Relation between non-unitarity η and NSI ϵ

Non-unitarity appears in osc. as "correlated NSIs"

$$N_{\alpha i} \equiv [\delta_{\alpha\beta} - \eta_{\alpha\beta}]\mathcal{U}_{\beta i}$$

$$\eta_{ee} = -\epsilon^m_{ee} \quad \eta_{\mu\mu} = \epsilon^m_{\mu\mu} \quad \eta_{\tau\tau} = \epsilon^m_{\tau\tau} \quad \eta_{\mu\tau} = \epsilon^m_{\mu\tau} \quad \epsilon^m_{e\mu} = \epsilon^m_{e\tau} = 0 \quad \eta_{\alpha\beta} = -\epsilon^{s,d}_{\beta\alpha}$$

at the first order of η

Meloni et al., JHEP1004 (2010) 041
Blennow et al., JHEP 04 (2017) 153

Sensitivities to η at forthcoming LBLs are $\mathcal{O}(10^{-2})$
except $\eta_{e\mu}$ and $\eta_{e\tau}$

The other parametrization method of the non-unitary PMNS

Escrihuela et al., 1612.07377

$$N_{\alpha i} \equiv [\delta_{\alpha\beta} - \alpha_{\alpha\beta}]\,\mathcal{V}_{\beta i}$$

$$\alpha = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Blennow et al., JHEP 04 (2017) 153

	Non-Unitarity	Averaged-out sterile
α_{ee}	$1.3 \cdot 10^{-3}$	$2.6 \cdot 10^{-2}$
$\alpha_{\mu\mu}$	$2.0 \cdot 10^{-4}$	$4.5 \cdot 10^{-2}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	10^{-1}
$\alpha_{\mu e}$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$4.8 \cdot 10^{-2}$
$\alpha_{\tau e}$	$2.7 \cdot 10^{-3}$	$7.2 \cdot 10^{-2}$
$\alpha_{\tau\mu}$	$1.2 \cdot 10^{-3}$	$9.5 \cdot 10^{-2}$

Secret neutrino interactions

Gap in the spectrum – Secret interaction between Cosmic nu and CnuB?

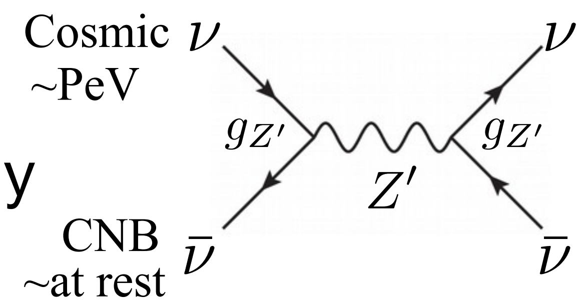
Resonance condition

$$s \simeq 2E_{\nu_{\rm Cosmic}} m_{\nu_{\rm C\nu B}} \overset{!}{=} M_{Z'}^2$$

~Gap (sub-PeV) **~0.1eV**

$$\boxed{M_{Z'} \sim \mathrm{MeV}}$$

so that cosmic nu.s with a particular energy lose their energies



Condition to mean free path

$$\lambda \simeq 1/n_{\rm C\nu B}\sigma_{\rm @Res} \overset{!}{\lesssim} \mathrm{Gpc}$$

so that cosmic neutrinos from extra galactic sources get the scattering

$$\sigma_{\rm @Res} \gtrsim 10^{-30}[\mathrm{cm}^2]$$

$$n_{\rm C\nu B} = 56.8[/\mathrm{cm}^3] \text{ for each dof} \gg n_{\rm Baryon}$$

$L_\mu - L_\tau$ model

$$\mathscr{L} = g_{Z'}\left[\bar{\mu}\gamma^\rho\mu - \bar{\tau}\gamma^\rho\tau + \bar{\nu}_\mu\gamma^\rho \mathrm{P}_L\nu_\mu - \bar{\nu}_\tau\gamma^\rho \mathrm{P}_L\nu_\tau\right] Z'_\rho$$

$$\boxed{g_{Z'} > 10^{-4}}$$

$$\sigma(\nu_i\bar{\nu}_j \to \nu\bar{\nu}) = \frac{|g_{ji}|^2 g_{Z'}^2}{6\pi}\frac{s}{(s-M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2}$$

$$g_{ji} = g_{Z'}\sum_\alpha U^\dagger_{j\alpha}\mathrm{diag}(0,1,-1)_\alpha U_{\alpha i}$$