NuFact 2010, Mumbai

LSND and MiniBooNE within (3+1) plus NSI

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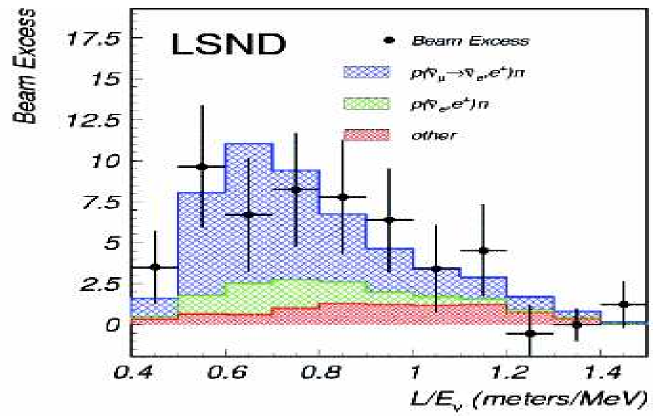
E. Akhmedov, T. Schwetz, 1007.4171

$\nu_\mu \to \nu_e$ ***data at the*** $E/L \sim 1$ ***eV^2 scale***

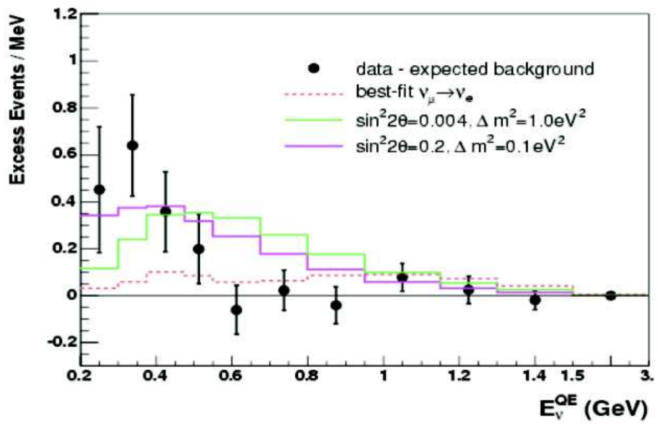


LSND $\bar\nu_\mu \to \bar\nu_e$

$87.9 \pm 22.4 \pm 6.0$ excess events

$P = (0.264 \pm 0.067 \pm 0.045)\%$

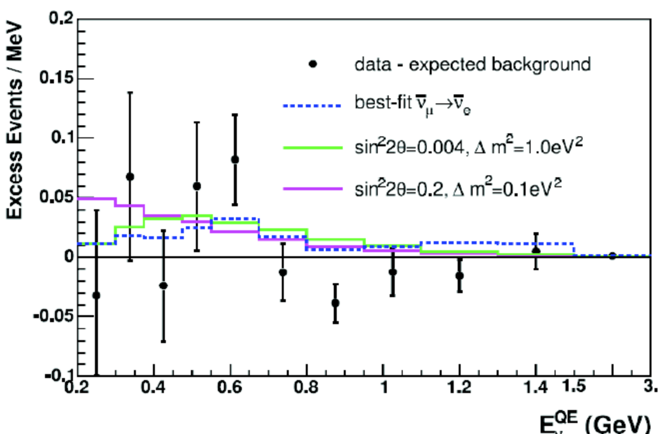
$\sim 3.8\sigma$ away from zero



MiniBooNE $\nu_\mu \to \nu_e$

$E > 475$: no excess

$E < 475$: $\sim 3\sigma$ excess



MiniBooNE $\bar\nu_\mu \to \bar\nu_e$

$\sim 2\sigma$ excess, consistent with LSND

in 2ν framework

(3+1) neutrino oscillations?

(3+1) oscillations

In (3+1) schemes the SBL appearance probability is effectively 2-ν oscillations:

$$P_{\mu e} = \sin^2 2\theta_{\rm SBL} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

with

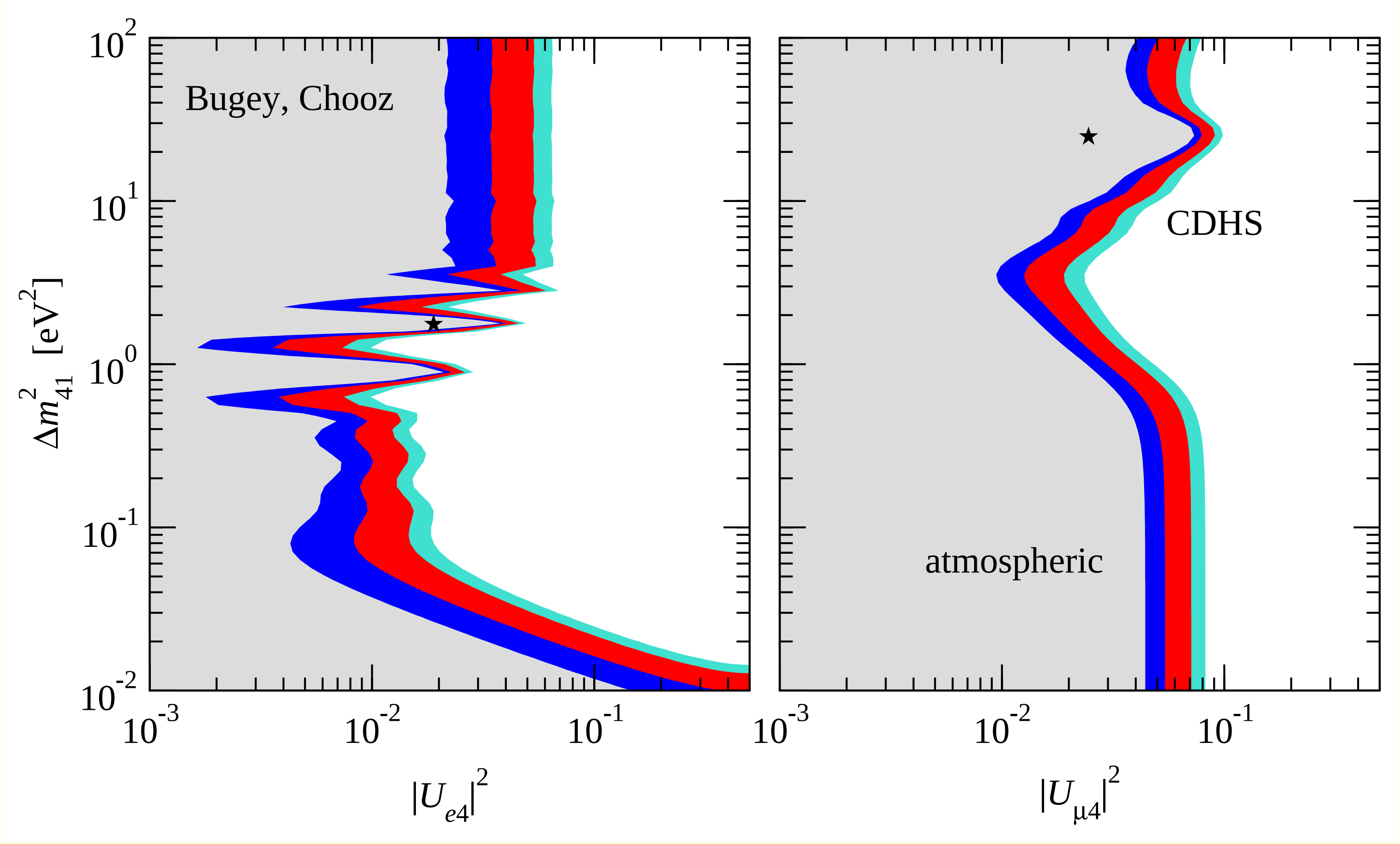
$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

(no CP violation)

Appearance vs disappearance in (3+1)

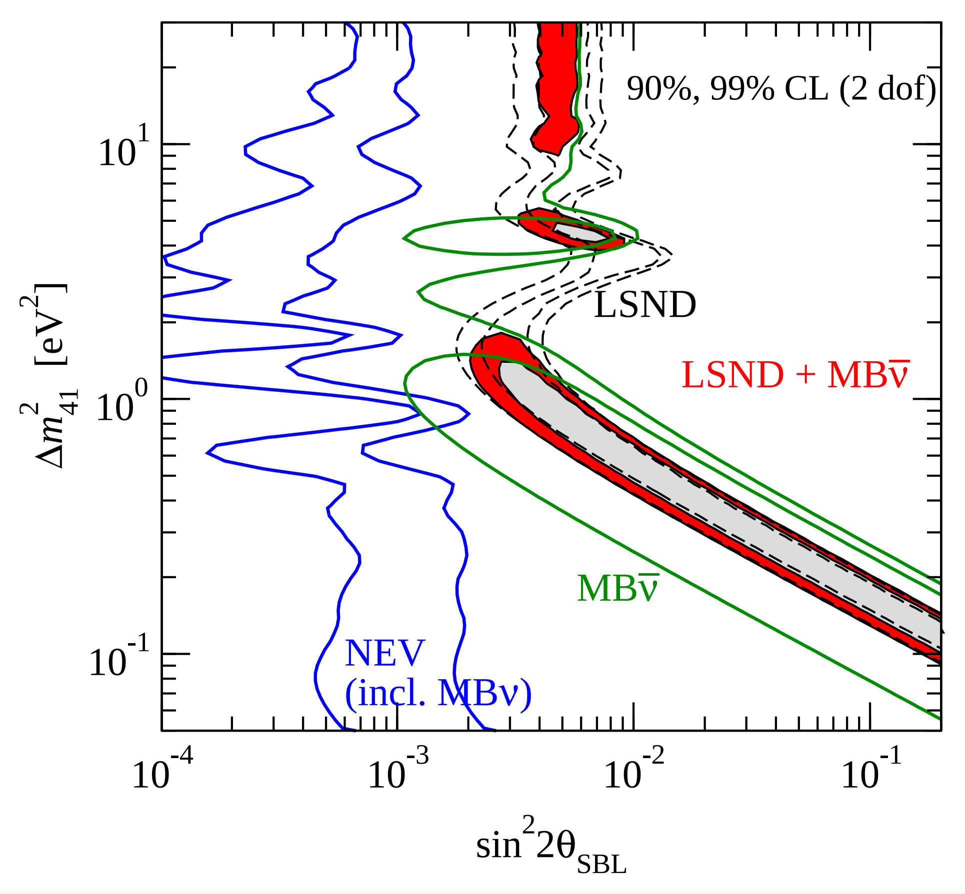
appearance amplitude $\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$

$\Leftrightarrow$ disapp. exps. constrain $|U_{e4}|^2$ and $|U_{\mu 4}|^2$



(3+1) global

strong disagreement between LSND/MB$\bar{\nu}$ and null-result exps.



regions touch each other at $\Delta\chi^2 = 12.7$ (99.8% CL for 2 dof)

More sterile neutrinos?

(3+2) appearance probability

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} \\ &+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2\phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\,, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right)\,.$$

(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

good fit to appearance exps (even MB low-E), BUT. . .

(3+2) disappearance data

$$P_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left(1 - \sum_{i=4,5}|U_{\alpha i}|^2\right)\sum_{i=4,5}|U_{\alpha i}|^2 \sin^2\phi_{i1}$$
$$- \; 4\,|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\phi_{54}$$

$\Rightarrow$ bound $|U_{ei}|$ and $|U_{\mu i}|$ ($i = 4, 5$), similar as in (3+1) to be reconciled with appearance amplitudes $|U_{ei}U_{\mu i}|$

(3+2) does not improve significantly wrt to (3+1)

Maltoni, TS, 0705.0107; Karagiorgi et al., 0906.1997; Akhmedov, TS, 1007.4171

$\chi^2_{\text{min,(3+1)osc}} - \chi^2_{\text{min,(3+2)osc}} = 5.0$ (4 dof) $\Rightarrow$ $71\%\text{CL}$

More ’exotic’ proposals?

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation
  Kostelecky, Mews, 04; Gouvea, Grossman, 06; Katori, Kostelecky, Tayloe, 06
- mass varying neutrinos
  Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions
  Paes, Pakvasa, Weiler 05
- 1 decaying sterile neutrino Palomares-Riuz, Pascoli, Schwetz 05
- 2 decaying sterile neutrinos with CPV
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KARMEN, TWIST

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KamLAND spectral data

energy dependence, MiniBooNE?

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  MiniBooNE $\bar{\nu}$?

and another exotic...

a sterile neutrino plus non-standard interactions

E. Akhmedov, TS, 1007.4171

(3+1) NSI

Assume

- a 4th neutrino with $\Delta m^2_{41} \sim 1$ eV^2
- a new type of CC-like interaction

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \sum_{\alpha,\beta} \varepsilon^{ff'}_{\alpha\beta} (\bar{f} P_{L,R} \gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.$$

f, f' fermions depending on production or detection process

(NC-like NSI will have no relevant effect in short-baseline experiments since matter effect is very small)

Transition amplitudes in (3+1) NSI

state appearing in a process at $X = S, D$ (source, detector):

$$|\nu_\alpha^X\rangle = C_\alpha^X \Big(|\nu_\alpha\rangle + \sum_\beta \varepsilon_{\alpha\beta}^X |\nu_\beta\rangle \Big) = \underbrace{C_\alpha^X \sum_i \Big(U_{\alpha i}^* + \sum_\beta \varepsilon_{\alpha\beta}^X U_{\beta i}^* \Big)}_{\equiv F_{\alpha i}^X} |\nu_i\rangle$$

transition amplitude

$$\mathcal{A}_{\alpha\beta}(L) = \sum_i F_{\alpha i}^S F_{\beta i}^{D*} e^{-iE_i L} \quad \stackrel{\mathrm{SBLlimit}}{\longrightarrow} \quad \alpha_{\alpha\beta}(e^{-i\Delta} - 1) + \beta_{\alpha\beta}$$

where

$$\Delta \equiv \frac{\Delta m_{41}^2 L}{2E}, \qquad \alpha_{\alpha\beta} = F_{\alpha 4}^S F_{\beta 4}^{D*}, \qquad \beta_{\alpha\beta} = \sum_i F_{\alpha i}^S F_{\beta i}^{D*}$$

Transition probability in (3+1) NSI

$$P_{\alpha\beta}(L) = \underbrace{4\left[|\alpha_{\alpha\beta}|^2 - \mathrm{Re}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\right]\sin^2(\Delta/2)}_{\text{similar to standard oscillations}}$$

$$+ \underbrace{|\beta_{\alpha\beta}|^2}_{\text{zero-distance effect}} + \underbrace{2\mathrm{Im}(\beta^*_{\alpha\beta}\alpha_{\alpha\beta})\sin\Delta}_{\text{NSI-osc interference} \to \text{CP viol}}$$

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disappearance experiments: $\beta_{\alpha\alpha} = \sum_i F^S_{\alpha i} F^{D*}_{\alpha i}$
if process at source and detector are the inverse of each other:

$$\beta_{\alpha\alpha} = 1 \quad \Rightarrow \quad P_{\alpha\alpha} = 1 - 4\alpha_\alpha(1-\alpha_\alpha)\sin^2(\Delta/2)$$

simliar to (3+1) oscillations with $\alpha_\alpha \to |U_{\alpha 4}|^2$
CP viol and zero-distance effects in disapp exps only for $S \neq D$

Source and detection processes

	source	detection
LSND/KARMEN	μ decay	ν-nucl CC (e)
MiniB/NOMAD	π decay	ν-nucl CC (e)
CDHS (atm)	π decay	ν-nucl CC (μ)
Bugey/Chooz	ν-nucl CC (e)	ν-nucl CC (e)

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Scenario 1: decouple LSND/KARMEN from the rest

$$|\alpha_{\mu e}^{\rm LK}|, |\beta_{\mu e}^{\rm LK}|, \delta^{\rm LK}$$

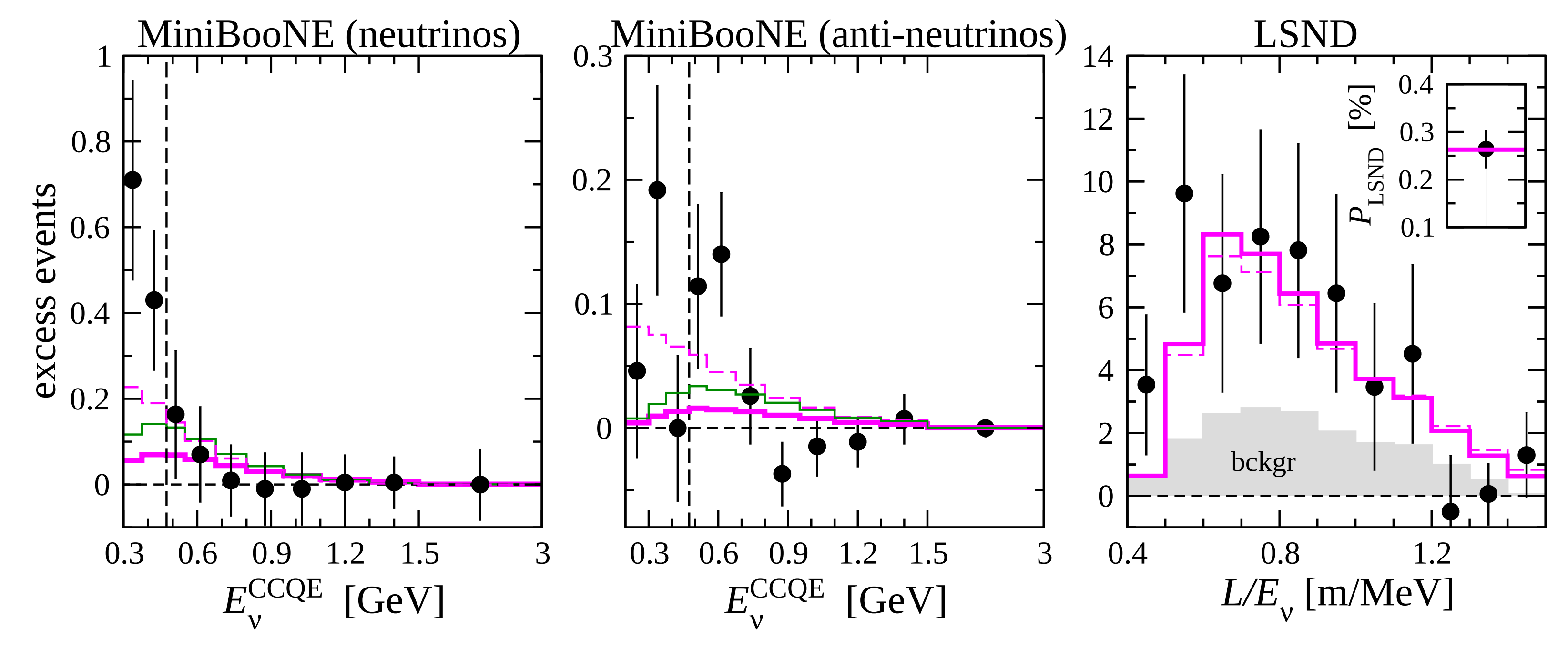
$$\alpha_e, \alpha_\mu, |\beta_{\mu e}|, \delta \; (|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu})$$

$$\Delta m^2_{41}$$

$\rightarrow$ 8 parameters: NSI^g

NSI^g fit results

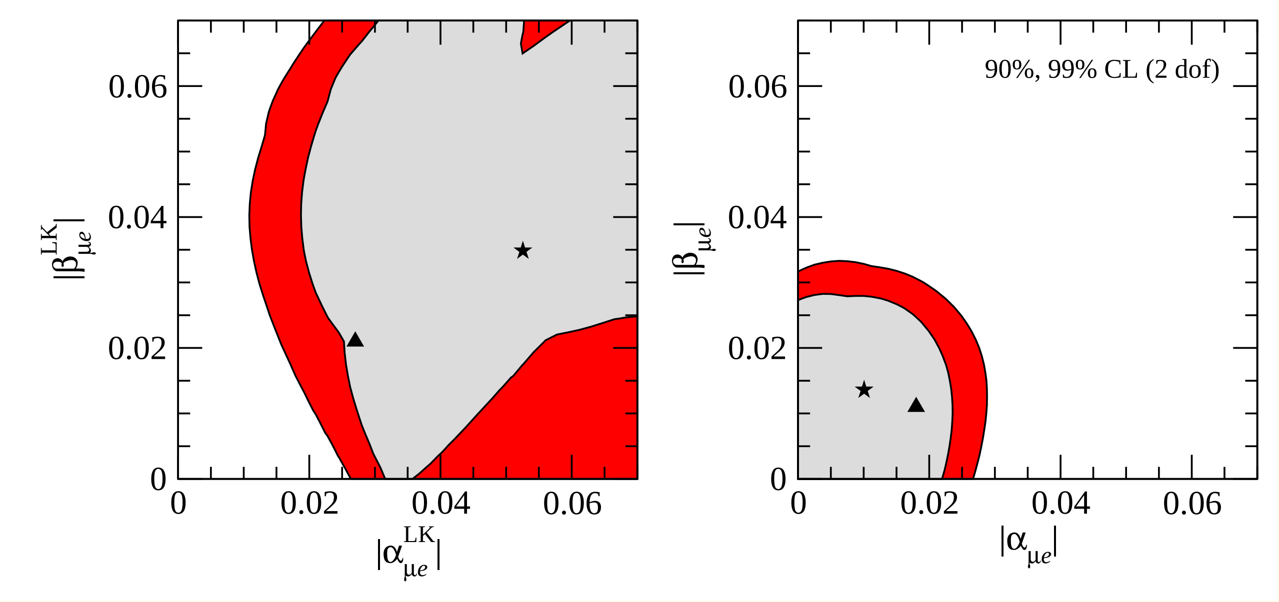
Data set	$\lvert\alpha_{\mu e}^{\rm LK}\rvert$	$\lvert\beta_{\mu e}^{\rm LK}\rvert$	$\delta^{\rm LK}$	$\lvert\alpha_{\mu e}\rvert$	$\lvert\beta_{\mu e}\rvert$	δ	Δm^2_{41}	χ^2/dof
Appearance	0.31	0.029	0.49π	0.15	0.011	1.5π	0.13 eV^2	$29.4/(37-7)$
Global	0.053	0.036	0.39π	0.010	0.013	1.2π	0.89 eV^2	$95.4/(115-8)$



$$\chi^2_{\text{min,(3+1)osc}} - \chi^2_{\text{min,(3+2)NSI}^g} = 18.5 \text{(5 dof)} \quad \Rightarrow \quad 99.76\%\text{CL}$$

appearance and disapp.: PG compatibility of 15%

NSI^g parameters



$$|U_{e4}| \approx 0.116,\ |U_{\mu 4}| \approx 0.205$$

$$|\varepsilon^{ud}_{\mu s}| \approx 0.05,\ |\varepsilon^{ud}_{e\mu}| \approx 0.011,\ |\varepsilon^{e\nu}_{\mu s}| \approx 0.03,\ |\varepsilon^{e\nu}_{\mu e}| \approx 0.01$$

in agreement with bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

$$|\alpha_{\mu e}| \approx (|U_{\mu 4}| - |\varepsilon^{ud}_{\mu s}|)|U_{e4}| \approx 0.018 \qquad |\beta_{\mu e}| \approx |\varepsilon^{ud}_{e\mu}| \approx 0.011$$

$$|\alpha^{LK}_{\mu e}| \approx (|U_{\mu 4}| + |\varepsilon^{e\nu}_{\mu s}|)|U_{e4}| \approx 0.027 \qquad |\beta^{LK}_{\mu e}| \approx |\varepsilon^{ud}_{e\mu}| + |\varepsilon^{\nu e}_{\mu e}| \approx 0.021$$

NSI^c

Scenario 2: "constrained" model

assume $\varepsilon^{S,D}_{\mu\alpha} \approx 0$

$$\alpha_e, \alpha_\mu, |\beta_{\mu e}|, \delta, \Delta m^2_{41} \quad (|\alpha_{\mu e}| = \sqrt{\alpha_e \alpha_\mu})$$

$\rightarrow$ 5 parameters: NSI^c

NSI^c

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$\rightarrow$ 5 parameters: NSI^c

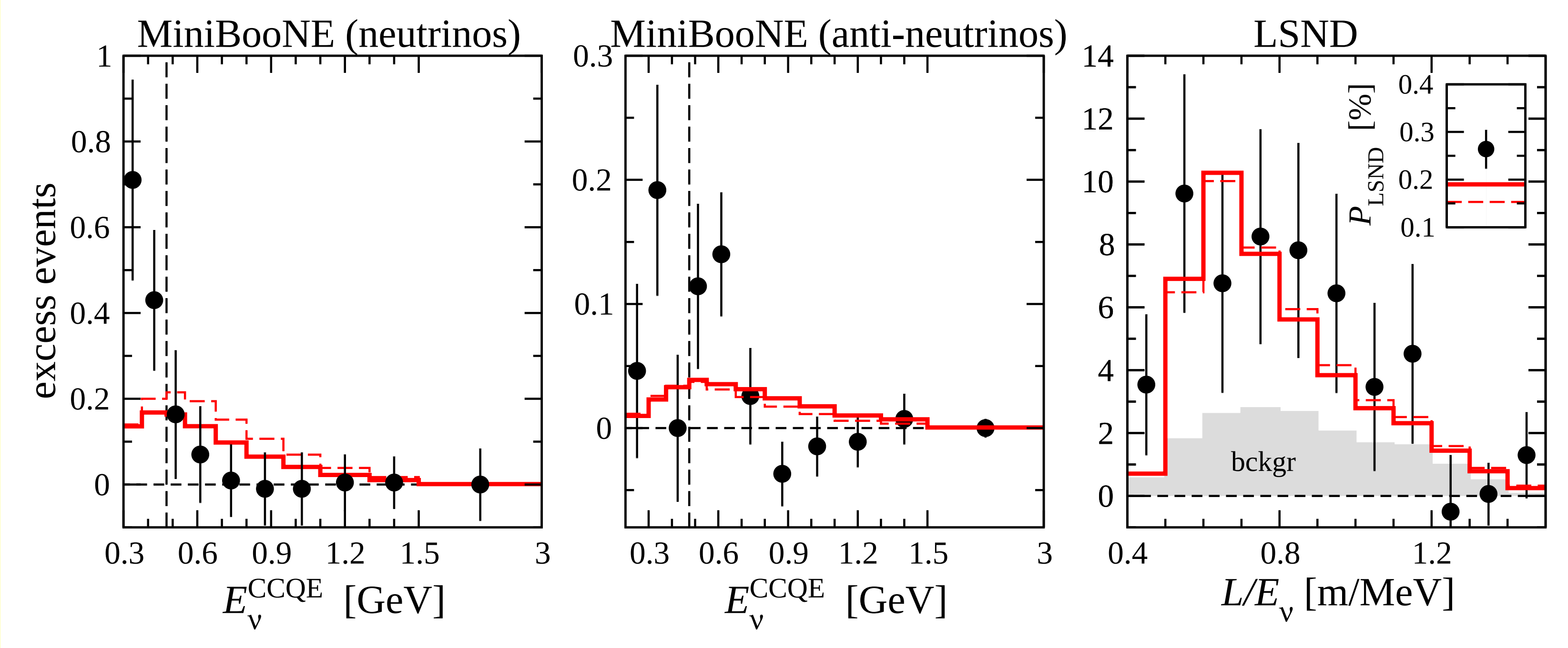
need only one non-zero NSI parameter: $\varepsilon^{ud}_{e\mu}$

$$\beta_{\mu e} = \varepsilon^{ud*}_{e\mu}\,, \quad \alpha_e = |U_{e4}|^2\,, \quad \alpha_\mu = |U_{\mu 4}|^2\,, \quad \delta = \mathrm{Arg}(U_{e4} U^*_{\mu 4} \varepsilon^{ud}_{e\mu})$$

with $|\varepsilon^{ud}_{e\mu}| \approx 0.017$

NSI^c fit results

Data set	$\lvert\alpha_{\mu e}\rvert$	$\lvert\beta_{\mu e}\rvert$	δ	Δm^2_{41}	χ^2/dof
Appearance	0.2075	0.0091	1.5π	0.1 eV^2	$33.5/(37-4)$
Global	0.019	0.017	1.3π	0.89 eV^2	$107/(115-5)$



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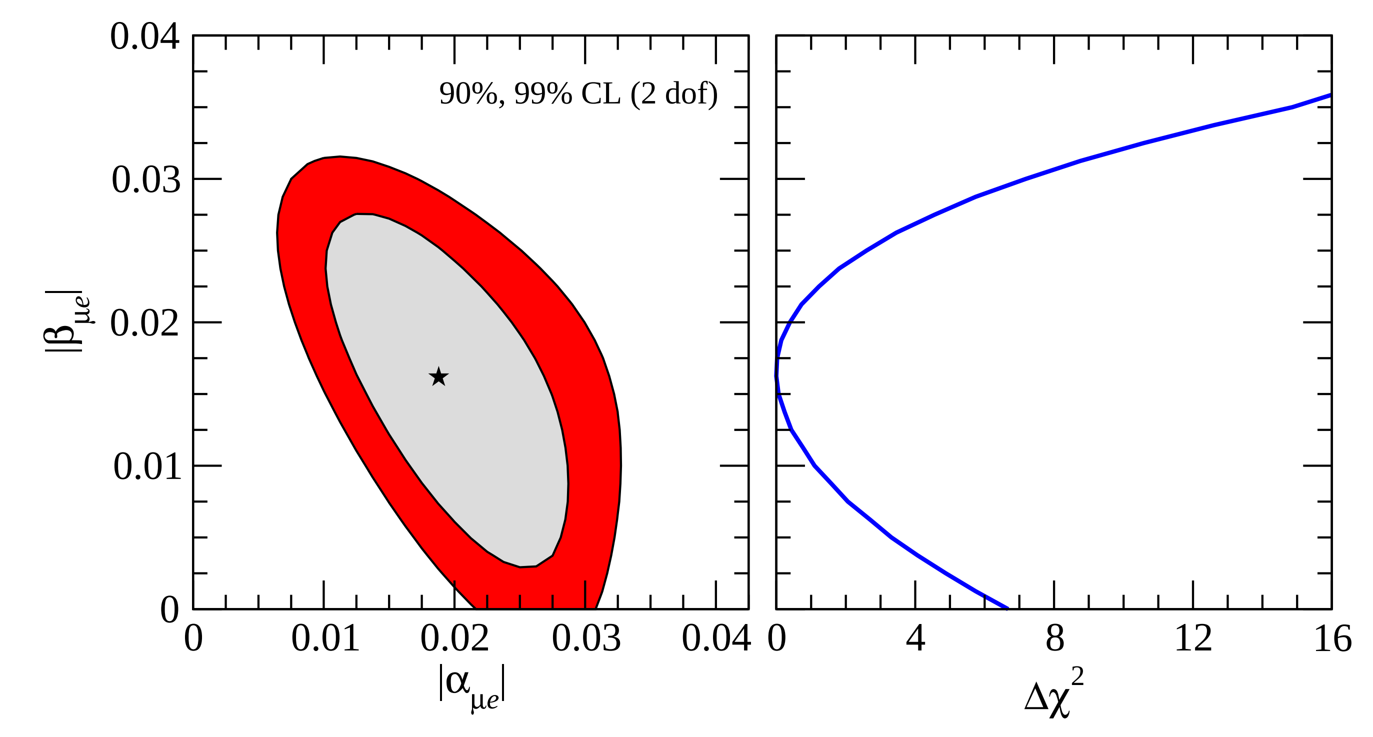

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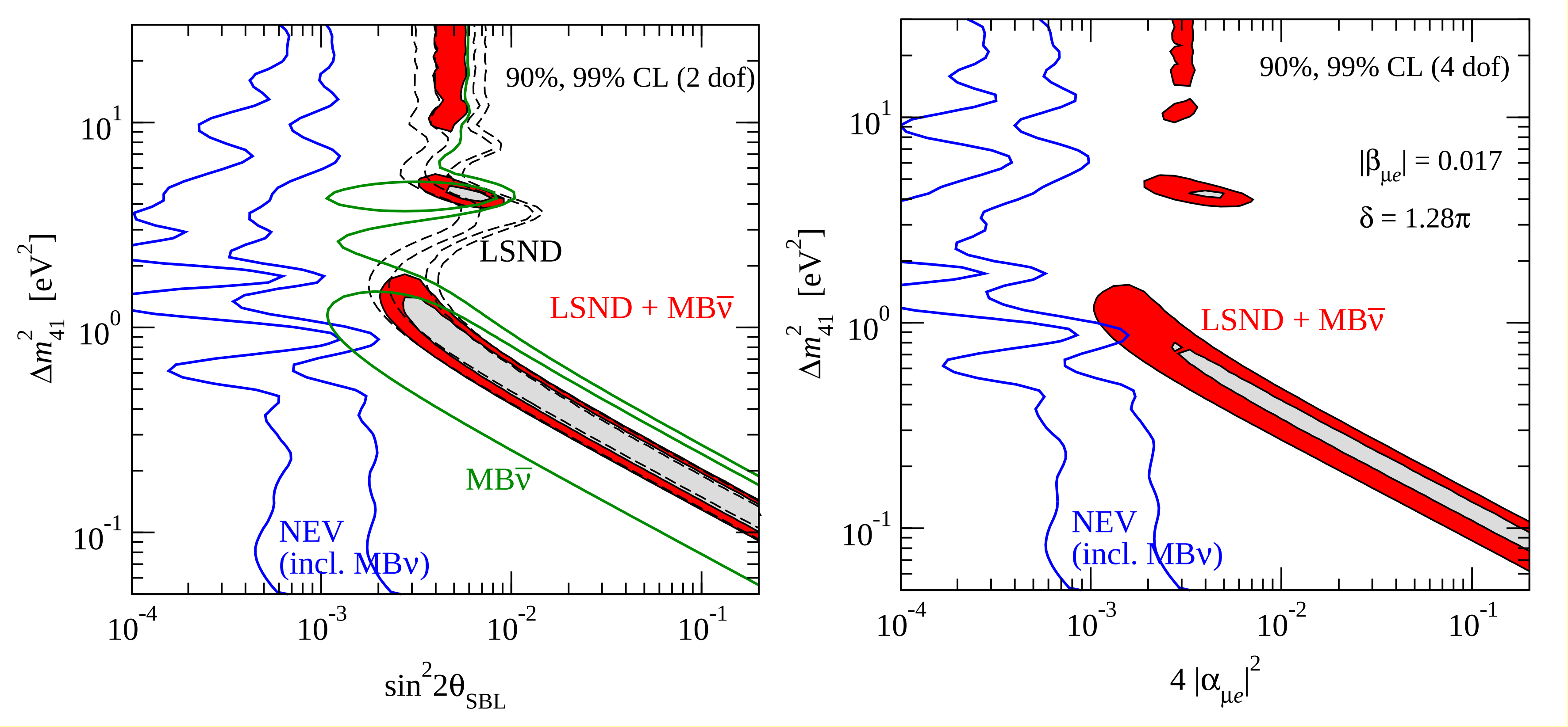
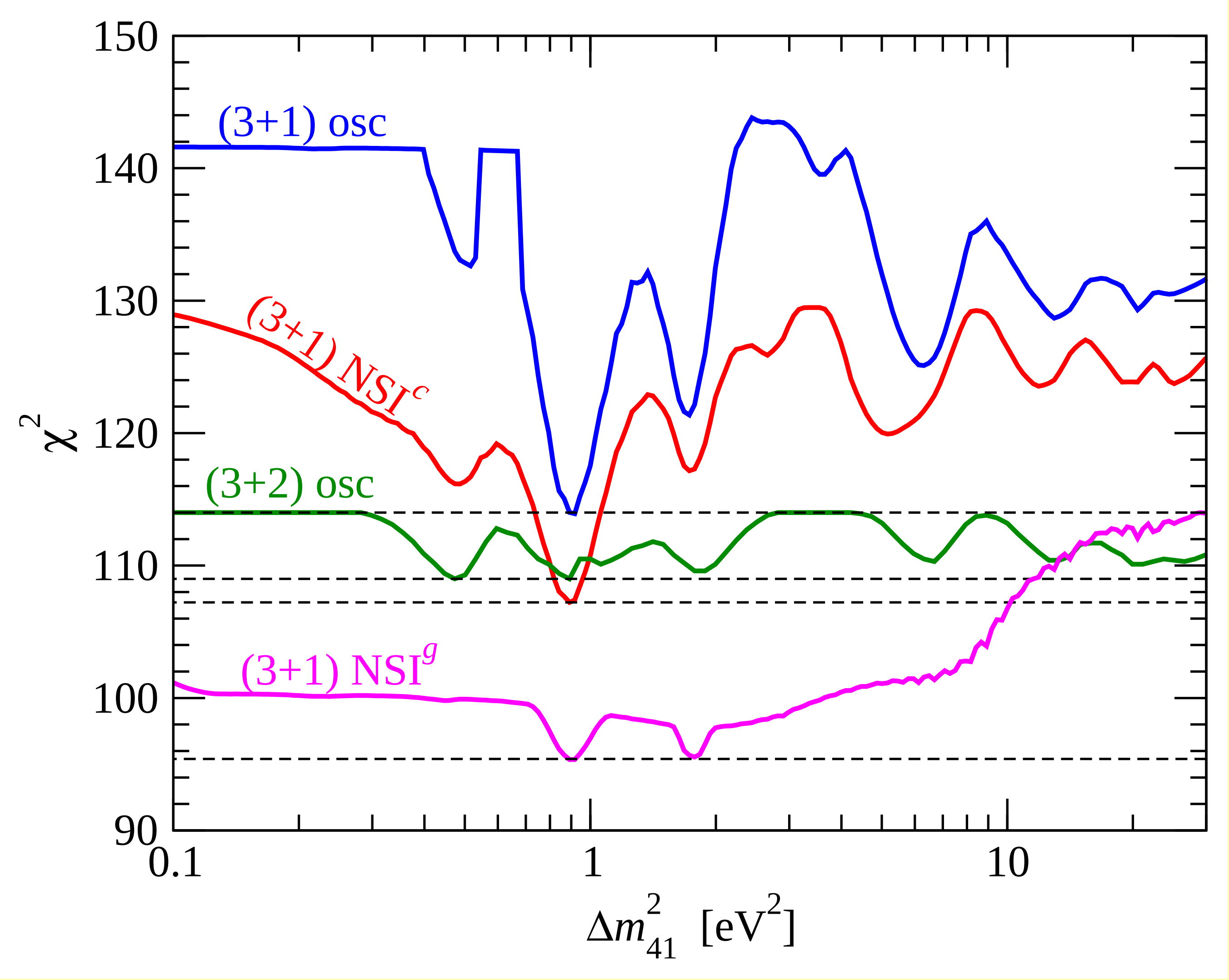
Appearance vs disappearance in NSI^c

Although the fit improves there is still tension



appearance and disapp.: PG compatibility of 0.3%

Comparison



150
140
130
120
110
100
90
0.1
1
10
χ^2
Δm^2_{41} [eV^2]
(3+1) osc
(3+1) NSI^c
(3+2) osc
(3+1) NSI^g

(3+1) and NSI – summary

eV-scale sterile neutrino + CC-like NSI

- offer CP violation by osc-NSI interference (LSND/MiniBooNE)
  in constrained version there is still some tension between appearance and disappearance
- allow to decouple LSND/KARMEN from all other data thanks to different production process $\rightarrow$ resolve tension between appearance and disappearance
- cannot explain low-energy excess in MiniBooNE

(3+1) and NSI – tests

tests of the idea:

- search for eV sterile neutrinos talks by P. Huber, J. Tang
  look for effects in SBL disappearance experiments!
- search for NSI
  talks by S. Parke, O. Yasuda, W. Rodejohann, M. Blennow, J. Lopez-Pavon
  zero-distance effects
- look for mediator particles at LHC

Can we get such NSI?

The strength of the new interactions we require are at the level of $\varepsilon \sim$ few % compared to G_F – in agreement with phenomenological bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

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if due to dim-6 operator $\varepsilon G_F(\bar{f} f')(\bar{\ell}\nu)$ expect a charged mediator with $m_\phi \sim m_W/\sqrt{\varepsilon} \sim$ TeV $\rightarrow$ excellent prospect at LHC

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BUT: seems difficult (impossible?) to obtain such operators at dim-6 in a gauge invariant way $\rightarrow$
go to dim-8 and involve some fine tuning

Gavela, Hernandez, Ota, Winter, 0809.3451; Antusch, Baumann, Fernandez, 0807.1003

Can we get such NSI?

The strength of the new interactions we require are at the level of $\varepsilon \sim$ few % compared to G_F – in agreement with phenomenological bounds Biggio, Blennow, Fernandez-Martinez, 0907.0097

if due to dim-6 operator $\varepsilon G_F(\bar{f} f')(\bar{\ell}\nu)$ expect a charged mediator with $m_\phi \sim m_W/\sqrt{\varepsilon} \sim$ TeV $\rightarrow$ excellent prospect at LHC

BUT: seems difficult (impossible?) to obtain such operators at dim-6 in a gauge invariant way $\rightarrow$
go to dim-8 and involve some fine tuning

Gavela, Hernandez, Ota, Winter, 0809.3451; Antusch, Baumann, Fernandez, 0807.1003

Thank you for your attention!