eV-scale sterile neutrino global fits & other hypotheses

European Neutrino "Town" meeting

Thomas Schwetz

Karlsruher Institut für Technologie

CERN, 22–24 Oct 2018

thanks to my collaborators:

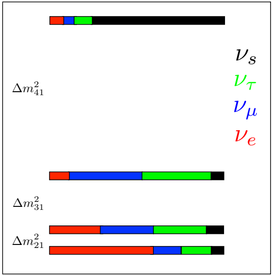
Dentler, Hernandez, Kopp, Maltoni, TS, 1709.04294

Dentler, Hernandez, Kopp, Machado, Maltoni, Martinez, TS, 1803.10661

Supported by the European Union's Horizon 2020 research and innovation programme
under the Marie Sklodowska-Curie grant agreement No 674896 (Elusives)

Hints for sterile neutrinos at the eV scale?

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
  - predicted vs measured rate
  - distance dependent spectral distortions
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)



ν_e disappearance: depends on $|U_{e4}| \to \theta_{ee}$

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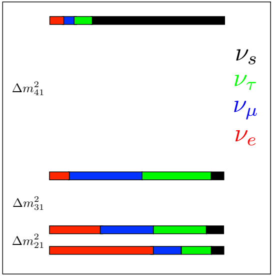
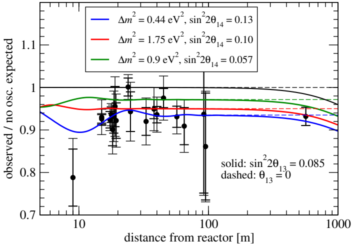


ν_e disappearance: depends on $|U_{e4}| \to \theta_{ee}$

Reactor anomaly – rate

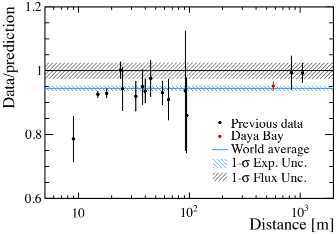
calculation of neutrino flux from nuclear reactors predict too many neutrinos Mueller et al., 1101.2663, P. Huber, 1106.0687



$f = 0.935 \pm 0.024$
(different from 1 @ 2.7σ)

Daya Bay 1808.10836

DayaBay ND flux weighted measurment (578 m), 1230-day



$f = 0.952 \pm 0.014 \pm 0.023$
(relativ to Huber-Mueller pred.)

can be explained by $\bar{\nu}_e$ disappearance at eV-scale Mention et al, 1101.2755

Reactor anomaly – rate

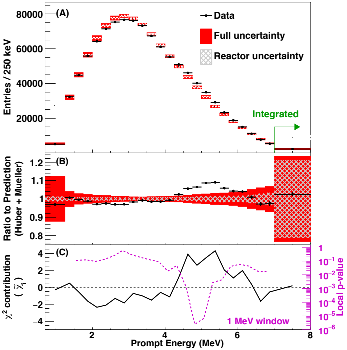
How reliable are the flux predictions and their uncertainty estimate?

Reactor anomaly – rate

How reliable are the flux predictions and their uncertainty estimate?

5 MeV bump:

- seen by RENO, DoubleChooz, DayaBay
- not present in DANSS data? (solid plastic scintillator)

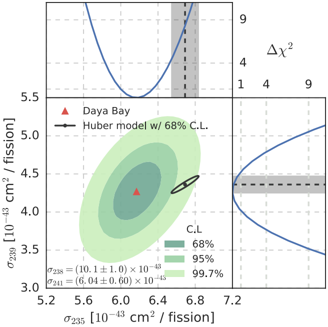


DayaBay, 1607.05378

DayaBay ^{235}U and ^{239}Pu flux determination 1704.01082

use fuel evolution and time dependence of observed neutrino rate:

- flux deficit in ^{235}U
  ^{239}Pu consistent with prediction



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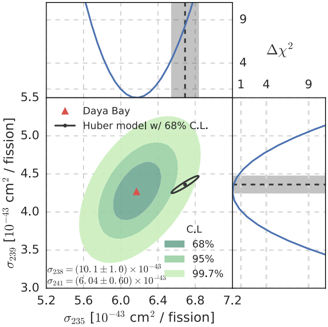


H_0: flux predictions correct (incl. errors) + sterile oscillations
H_1: no sterile neutrino, individual flux normalizations free

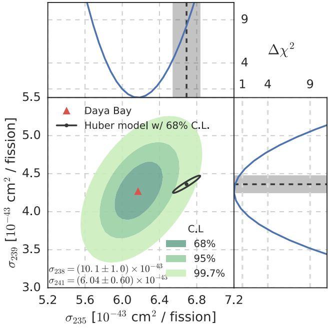
$$T = \chi^2_{\min}(H_0) - \chi^2_{\min}(H_1) \qquad T_{\rm obs} = 6.3\,(2.7\sigma)$$

Dentler, Hernandez, Kopp, Maltoni, TS, 1709.04294

DayaBay ^{235}U and ^{239}Pu flux determination 1704.01082

use fuel evolution and time dependence of observed neutrino rate:

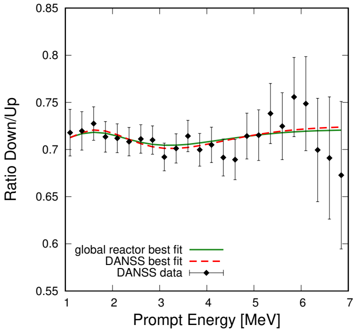
- flux deficit in ^{235}U
  ^{239}Pu consistent with prediction
- flux-free fit is preferred over sterile neutrino at 2.7σ
- but sterile neutrino osc gives also acceptable GOF: p-value = 18%

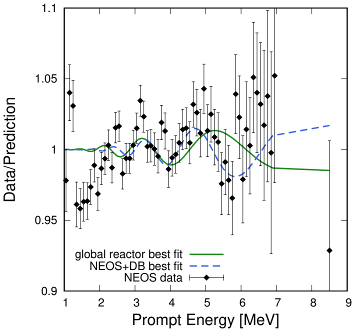


Analysis	$\chi^2_{\rm min}/\text{dof}$	gof	$\sin^2 2\theta_{14}^{\rm bfp}$	$\Delta\chi^2$(no osc)
fixed fluxes + ν_s	$9.8/(8-1)$	18%	0.11	3.9
free fluxes (no ν_s)	$3.6/(8-2)$	73%		

Dentler, Hernandez, Kopp, Maltoni, TS, 1709.04294

NEOS and DANSS spectral distortion Dentler et al, 1803.10661



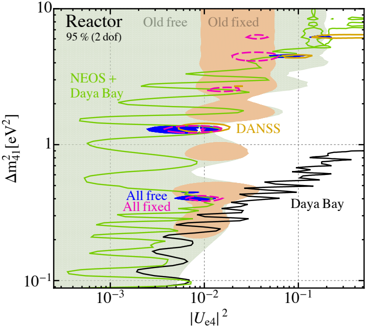


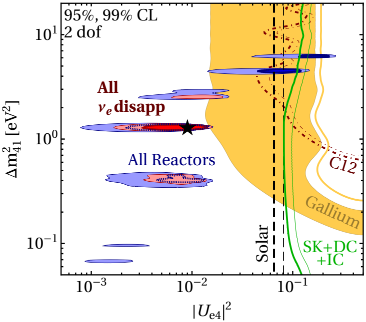
DANSS: relative spectra @ detector locations with $L = 10.7$ and 12.7 m

NEOS: spectrum at $L = 24$ m, relative to prediction based on Daya Bay near detector spectrum

Combined ν_e disappearance analysis Dentler et al, 1803.10661

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 − 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 − 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 − 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 − 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 − 6)	17.5	3.8σ





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- global ν_e disapp. data show indication for eV-scale oscillations at 3σ level, independent of reactor flux predictions
- taking into account also the H-M prediction (incl. uncert.), the significance is 3.8σ
- $\Delta m^2_{41} \simeq 1.3$ eV^2, $|U^2_{e4}| \simeq 0.01$

see also Gariazzo, Giunti, Laveder, Li, 1801.06467

Combined ν_e disappearance analysis Dentler et al, 1803.10661

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new constraints emerging from STEREO 1806.02096, PROSPECT 1806.02784
hint from Neutrino-4 @ $\Delta m^2_{41} \simeq 7.2$ eV^2 1809.10561, tension with other data

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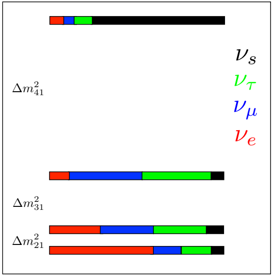

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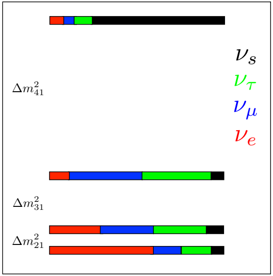
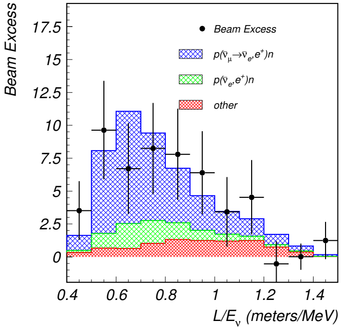


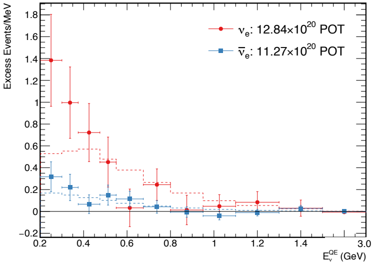
appearance data: depends on $|U_{e4} U_{\mu 4}| \to \theta_{\mu e}$

Hints for $\nu_\mu \to \nu_e$ appearance

LSND, 2001



MiniBooNE, 1805.12028

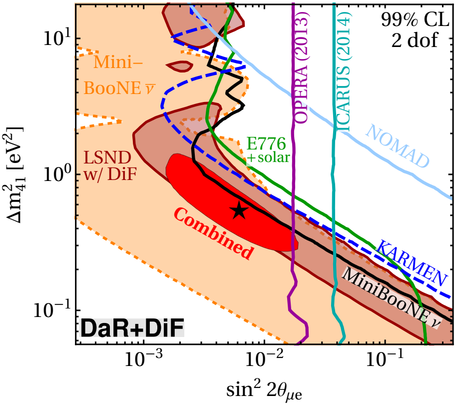


- signal for $\bar\nu_\mu \to \bar\nu_e$ transitions (3.8σ)

- neutrino mode excess: 381.2 ± 85.2 events (4.5σ)
- ν-$\bar\nu$ combined excess: 460.5 ± 95.8 events (4.8σ)

LSND and MiniBooNE data consistent within 2-flavour oscillations

Global data on SBL $\nu_\mu \to \nu_e$ appearance Dentler et al, 1803.10661



using pre-2018 MiniBooNE data, results quantitativley very similar

Can we explain all data together?

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

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Nuclear Physics B 643 (2002) 321–338

NUCLEAR PHYSICS B

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Ruling out four-neutrino oscillation interpretations of the LSND anomaly?

M. Maltoni [a], T. Schwetz [b], M.A. Tórtola [a], J.W.F. Valle [a]

[a] *Instituto de Física Corpuscular – C.S.I.C./Universitat de València Edificio Institutos de Paterna, Apt 22085, E-46071 Valencia, Spain*

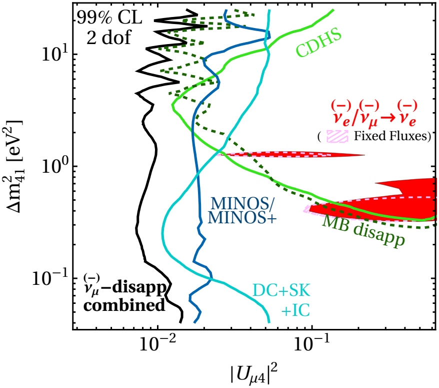
[b] *Institut für Theoretische Physik, Universität Wien Boltzmanngasse 5, A-1090 Wien, Austria*

Received 22 July 2002; accepted 14 August 2002

Abstract

Prompted by recent solar and atmospheric data, we re-analyze the four-neutrino oscillation description of current neutrino data, including the LSND evidence for oscillations. The higher degree of rejection for non-active solar and atmospheric oscillation solutions implied by the SNO neutral current result as well as by the latest 1489-day Super-K atmospheric neutrino data allows us to rule out $(2+2)$ oscillation schemes proposed to reconcile LSND with the rest of current neutrino oscillation data. Using an improved goodness of fit (g.o.f.) method especially sensitive to the combination of data sets we obtain a g.o.f. of only 1.6×10^{-6} for $(2+2)$ schemes. Further, we re-evaluate the status of $(3+1)$ oscillations using two different analyses of the LSND data sample. We find that also $(3+1)$ schemes are strongly disfavoured by the data. Depending on the LSND analysis we obtain a g.o.f. of 5.6×10^{-3} or 7.6×10^{-5}. This leads to the conclusion that all four-neutrino descriptions of the LSND anomaly, both in $(2+2)$ as well as $(3+1)$ realizations, are highly disfavoured. Our analysis brings the LSND hint to a more puzzling status.

Strong tension in global data Dentler et al, 1803.10661



non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

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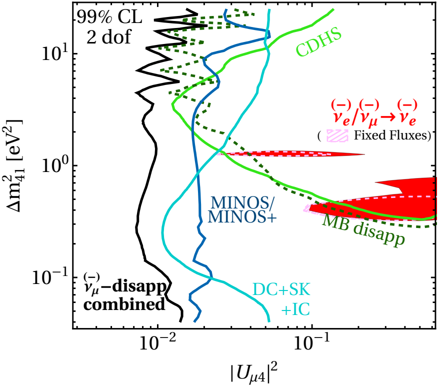

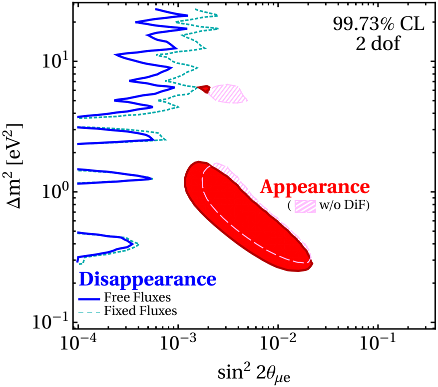

non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

consistency of appearance and disapp. data with a p-value $< 10^{-6}$

Robust tension between appearance and disapp. data

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

reactor flux-free analysis

Dentler et al, 1803.10661

results for 2018 MiniB very similar (tension gets slightly worse)

Summary eV-scale sterile neutrino oscillations

- ν_e disappearance data:
  signal for osc. with $\Delta m^2_{41} \simeq 1.3$ eV^2, $|U^2_{e4}| \simeq 0.01$ at $\gtrsim 3\sigma$
  supported by flux-prediction independent spectral distortions
  consistent with global data

- LSND and MiniBooNE $\nu_\mu \to \nu_e$ signals:
  strong tension with disappearance data
  explanation in terms of eV-scale oscillations very unlikely
  robust conclusion, indep. of reactor data
  does not rely on any single experiment
  adding more sterile neutrinos does not help eg. Kopp et al. 1303.3011

- eV-sterile neutrino explanations are in tension with cosmology
  eg. Gonzalez-Garcia, Salvado, Song, 1805.08218,

Other BSM explanations?

incomplete list:

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 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 et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05; Doring, Pas, Sicking, Weiler, 18
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10; Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

Comments on BSM explanations

- many of them are ruled out!
  (3 flavour neutrino oscillation data are very robust)
- many of them involve sterile neutrinos at some scale
- several of them address only one anomaly
  it is very hard to explain all with a single model

BSM example 1 – energy dependent quantum decoherence

Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15

- no sterile neutrino needed
- LSND signal controlled by the 1-3 mixing: $0.0014 < \sin^2\theta_{13} < 0.034$
- in order to be consistent with global data on oscillations, decoherence has to be confined to LSND energy range, 10 MeV $\lesssim E_\nu \lesssim$ 100 MeV
- no explanation for MiniBooNE, reactor and Gallium anomalies

$\Rightarrow$ very tailor-made explanation of LSND alone

BSM example 2 – sterile ν + non-standard interactions

Akhmedov,TS 10 see also Conrad,Karagiorgi,Shaevitz, 12; Liao,Marfatia,Whisnant 18

- 4th neutrino with $\Delta m^2_{41} \sim 1$ eV^2
- new type of CC-like interaction (4-Fermi like)
  can be different for LSND and other exps (leptonic vs hadronic)
- improves disapp/appear. tension (p-value $\approx 10\%$, 2010 data)
  reactor anomaly OK, MiniBooNE excess partially explained
- required NSI strength of few % is consistent with direct bounds:
  example point Akhmedov, TS 10:
  $|\varepsilon^{ud}_{\mu s}| \approx 0.05$, $|\varepsilon^{ud}_{e\mu}| \approx 0.011$, $|\varepsilon^{e\nu}_{\mu s}| \approx 0.03$, $|\varepsilon^{e\nu}_{\mu e}| \approx 0.01$
- validity with 2018 global data needs to be re-assessed
  Liao, Marfatia, Whisnant 18 require $\varepsilon \simeq \mathcal{O}(1)$
- gauge invariant UV completion difficult (LFV, collider constraints)
  Biggio etal 09, Gavela etal 08, Antusch etal 08, Davidson, Sanz, 11

BSM example 3a – sterile neutrino decay

possible explanations for LSND and MiniBooNE

- Palomares-Riuz, Pascoli, TS 05
  sterile neutrino N in the mass range 1 keV to 1 MeV
  produce N at source by mixing, $|U_{\mu 4}^2| \sim 0.01$
  decays before reaching the detector via $N \to \phi + \nu_e$
  can explain LSND, possibly MiniBooNE, but no reactor/Gallium
- Gninenko 09, 10
  sterile neutrino N in the mass range 40 to 80 MeV
  produced via scattering inside detector, $|U_{\mu 4}^2| \sim 0.001 - 0.01$
  fast decay via $N \to \gamma + \nu$, photon fakes e-like signal

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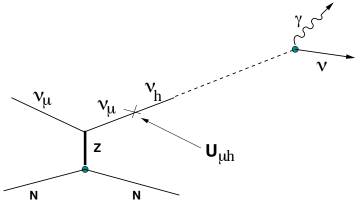

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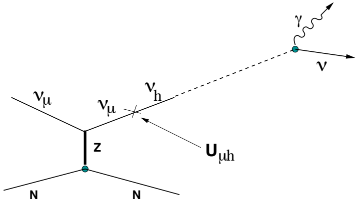
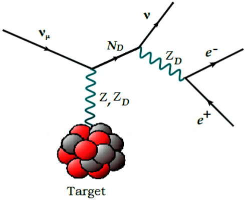
  produced via scattering inside detector, $|U_{\mu 4}^2| \sim 0.001 - 0.01$
  fast decay via $N \to \gamma + \nu$, photon fakes e-like signal



exluded by search for
$K^- \to \mu^- N (N \to \gamma\nu)$
ISTRA+ 1110.1610

BSM example 3b – sterile neutrino decay

Explaining the MiniBooNE excess



Bertuzzo, Jana, Machado, Zukanovich, 18

Ballett, Pascoli, Ross-Lonergan, 18

sterile neutrino masses 10 – few 100 MeV

N charged under a dark U(1), $m_{Z'} < 1$ GeV

production via Z' interaction in detector

decaying into a e^+e^- pair

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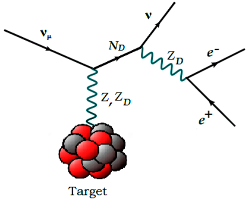
Explaining the MiniBooNE excess



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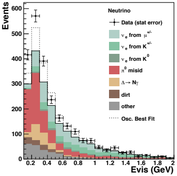
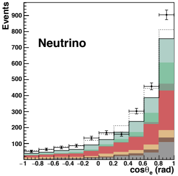
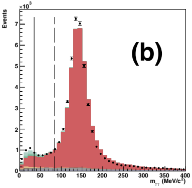
strong constraints on decay explanations Jordan,Kahn,Krnjaic,Moschella,Spitz,18

need to fit energy and angular distribution, as well as $\gamma\gamma$-invar. mass distr.

for neutrino and antineutrino mode, as well as for beam-dump mode







beam dump mode

1807.06137

assume excess $\propto$ POT:

expect.: 35.5 ± 7.4 ev

observed: -2.8 events

$\Rightarrow$ excess related to charged $\pi^\pm$, $K^\pm$

Summary

- persistent hint for eV-sterile neutrinos from ν_e disappearance data supported by spectral distortions at reactors
  - to be tested by upcoming reactor experiments (STEREO, PROSPECT, SOLID,...) and KATRIN
  - would imply interesting phenomenology for LBL oscillation experiments
    e.g., Blennow et al. 1609.08637; deGouvea, Kelly, 1605.09376
  - tension with cosmology?
- ν_e appearance signals very unlikely due to eV-scale oscillations
  - Is it even more exotic new physics?
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  - systematically explore possible more "mundane" explanations

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Thank you for your attention!