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Horizon 2020
European Union funding
for Research & Innovation

Light sterile neutrinos: the current picture from neutrino oscillations

TAUP 2019, Toyama (JP), 8–14/09/2019

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase $\delta_{\rm CP}$

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

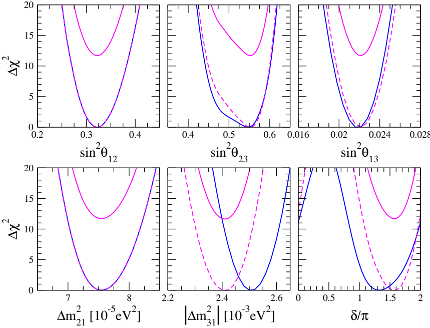
NO: Normal Ordering, $m_1 < m_2 < m_3$

IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \text{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \text{eV}^2\ (\text{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \text{eV}^2\ (\text{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\text{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\text{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\text{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\text{IO})
\end{aligned}$$

First hints for $\delta_{\rm CP} \simeq 3/2\pi$



see also: http://globalfit.astroparticles.es

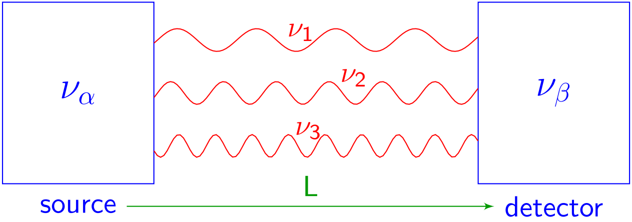
Two types of neutrinos

flavor neutrinos ν_α

$|\nu_\alpha\rangle = U_{\alpha k}|\nu_k\rangle$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$E_k^2 = p^2 + m_k^2 \longleftarrow$ define $\longrightarrow t = L$

$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\alpha|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

A large family

In principle, previous discussion is valid for N neutrinos

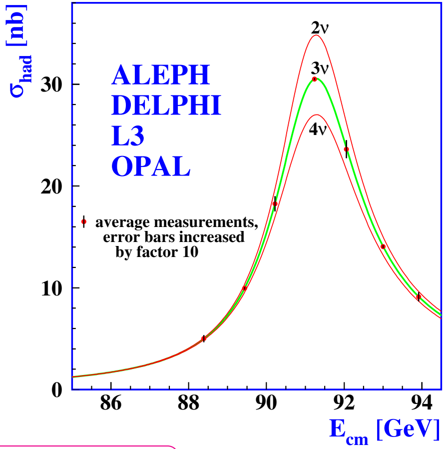
only constraint: there are exactly three flavor neutrinos in the SM

[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$N_\nu^{(Z)} = 2.9840 \pm 0.0082$$

through the measurement of the Z resonance

$$e^+ e^- \longrightarrow Z \longrightarrow \sum_{a=e,\mu,\tau} \nu_a \bar{\nu}_a$$



neutrinos $\alpha > 3$ must be sterile

sterile neutrino = SM singlet: no couplings with other SM particles

A large family

In principle, previous discussion is valid for N neutrinos

$N \times N$ mixing matrix, N flavor neutrinos, N massive neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s_1}\rangle \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \\ \cdots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \cdots \end{pmatrix}$$

A large family

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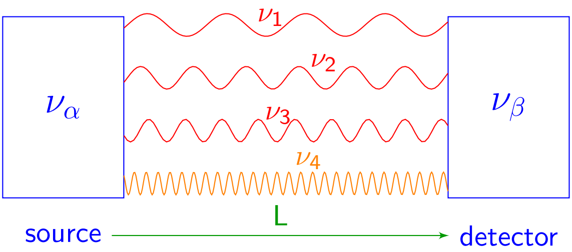
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$
$\ell = 1, 2, 3$

$\Delta m^2_{41} \simeq 1\ \mathrm{eV}^2$
$\simeq \Delta m^2_{42}$
$\simeq \Delta m^2_{43}$



6 angles

3 Dirac CP phases

3 Majorana CP phases

Short BaseLine (SBL)

$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\alpha|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

If $m_4 \gg m_\ell$, faster oscillations

ν_4 oscillations are averaged in most neutrino oscillation experiments

Effect of 4th neutrino only visible as global normalization

Short BaseLine (SBL) oscillations: $\frac{\Delta m^2_{41} L}{E} \simeq 1$

At SBL, oscillations due to Δm^2_{21} and $|\Delta m^2_{31}|$ do not develop

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APPearance ($\alpha \neq \beta$)

source of $\overset{(-)}{\nu}_\alpha$

detect different flavor $\overset{(-)}{\nu}_\beta$

Short BaseLine (SBL)

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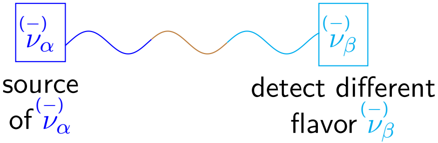
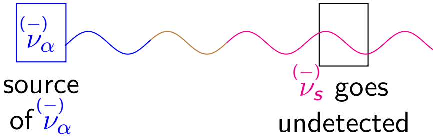
DISappearance





Short BaseLine (SBL)

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APPearance ($\alpha \neq \beta$)

DISappearance

CP violation cannot be observed in SBL experiments!

New mixings in the 3+1 scenario

$$4 \times 4 \text{ mixing matrix: } \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

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DISappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

reactor

gallium

$$|U_{e4}|^2 = \sin^2 \vartheta_{14}$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

accelerator

atmospheric

$$|U_{\mu 4}|^2 = \cos^2 \vartheta_{14} \sin^2 \vartheta_{24}$$

New mixings in the 3+1 scenario

4 × 4 mixing matrix: $\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$ ϑ_{14} ϑ_{24} ϑ_{34}

DISappearance

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$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ reactor gallium

$$|U_{e4}|^2 = \sin^2 \vartheta_{14}$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ accelerator atmospheric

$$|U_{\mu4}|^2 = \cos^2 \vartheta_{14} \sin^2 \vartheta_{24}$$

APPearance

$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

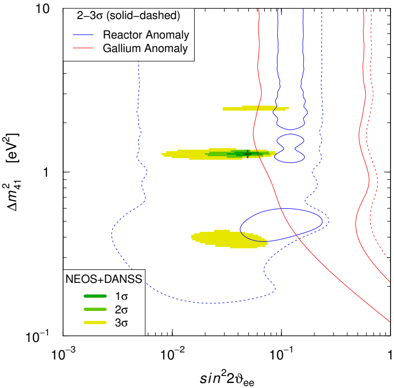
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ LSND MiniBooNE KARMEN OPERA ...

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$$

quadratically suppressed!

for small $|U_{e4}|^2$, $|U_{\mu4}|^2$


2–3σ (solid–dashed)
Reactor Anomaly
Gallium Anomaly
NEOS+DANSS
1σ
2σ
3σ
10
1
10^{-1}
Δm^2_{41} [eV^2]
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{ee}$

Gallium anomaly

[SAGE, 2006][Laveder, 2007][Giunti&Laveder, 2011]

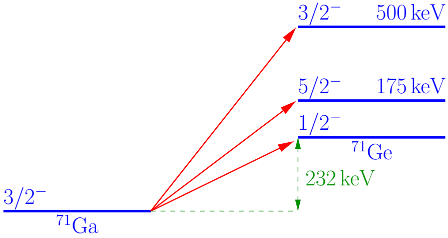
$L \simeq 1.9$ m $\quad$ $L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

ν_e sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75$ MeV $\qquad$ $E \simeq 0.81$ MeV

In the detector: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$



cross sections of
the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

[Frekers et al., PLB 706 (2011) 134]

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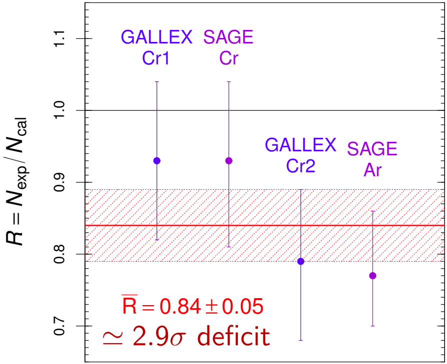
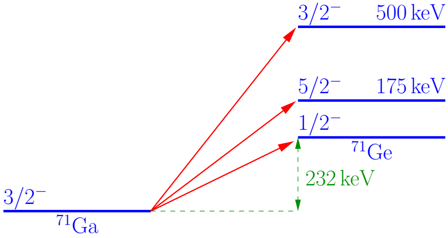
Test detection of solar ν_e





cross sections of the transitions from

[Krofcheck et al., PRL 55 (1985) 1051]

[Frekers et al., PLB 706 (2011) 134]

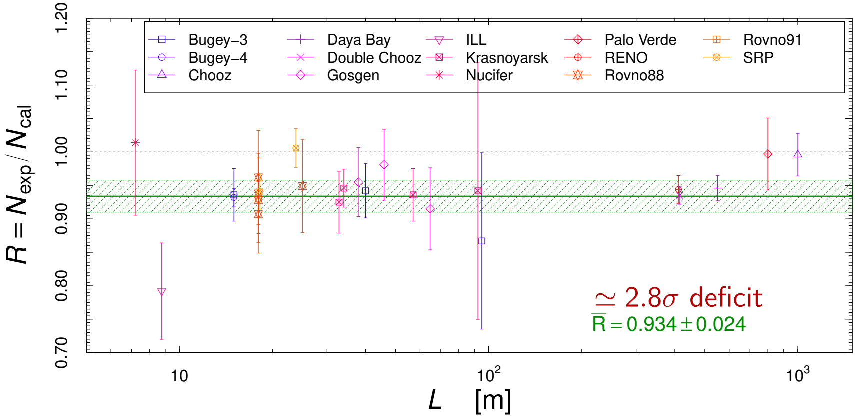
Reactor Antineutrino Anomaly (RAA)

[PRD 83 (2011) 073006]

2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller+ (HM)

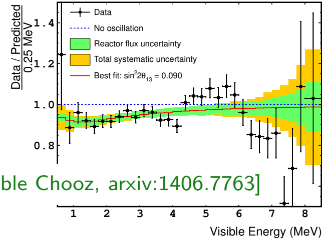
[Huber, PRC 84 (2011) 024617] [Mueller et al., PRC 83 (2011) 054615]

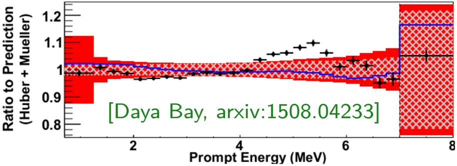
Previous reactor rates evaluated with new fluxes ⇒ deficit

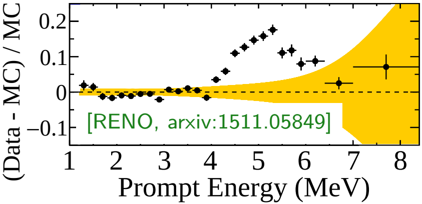


Suppression at detector due to active-sterile oscillations?

Can we trust the HM fluxes?







2014:

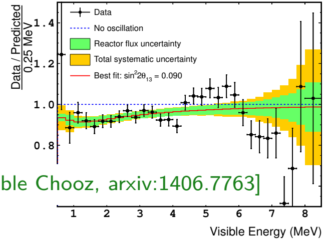
bump in the spectrum around 5 MeV!

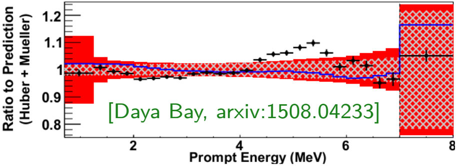
cannot be explained by SBL oscillations

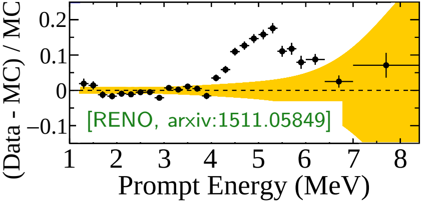
(averaged at the observed distances)

many attempts of possible explanations,
how to clarify the issue?

Can we trust the HM fluxes?







2014:

bump in the spectrum around 5 MeV!

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(averaged at the observed distances)

many attempts of possible explanations, how to clarify the issue?

Model independent information!

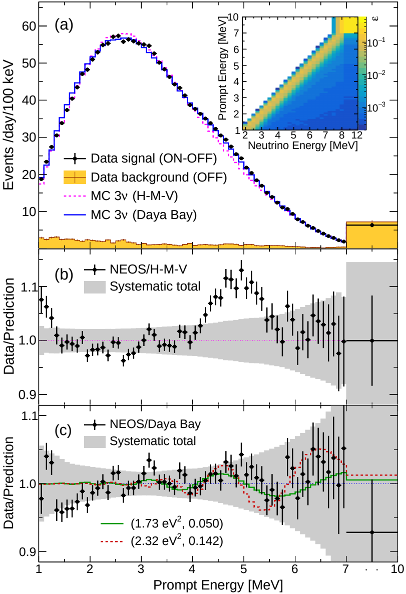
(i.e. take ratio of spectra at different distances)

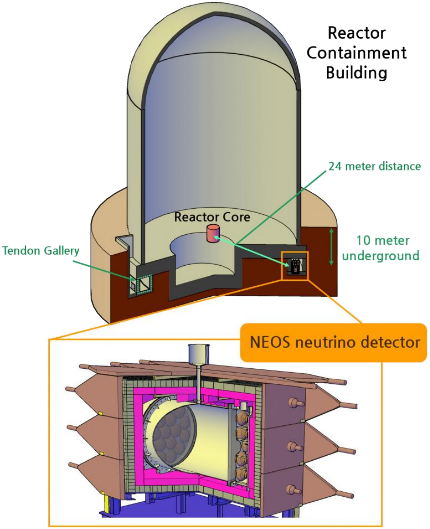
$$\Phi_1 = \Phi_0(E) f(L_1, E) \quad \Phi_2 = \Phi_0(E) f(L_2, E)$$

$$\Phi_1 / \Phi_2 = f(L_1, E) / f(L_2, E)$$

NEOS

Single detector experiment



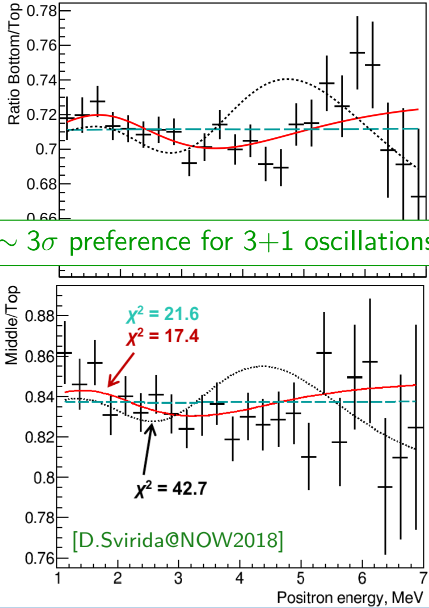


Ratio to DayaBay measurement to be model independent

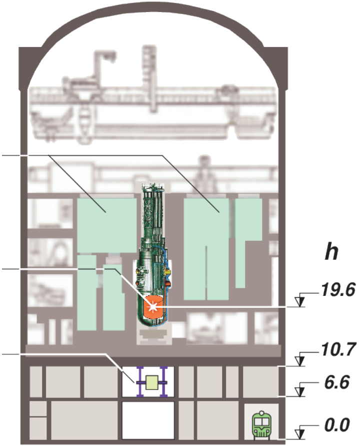
DANSS

[PLB 787 (2018) 56]

Single movable detector



$\sim 3\sigma$ preference for 3+1 oscillations

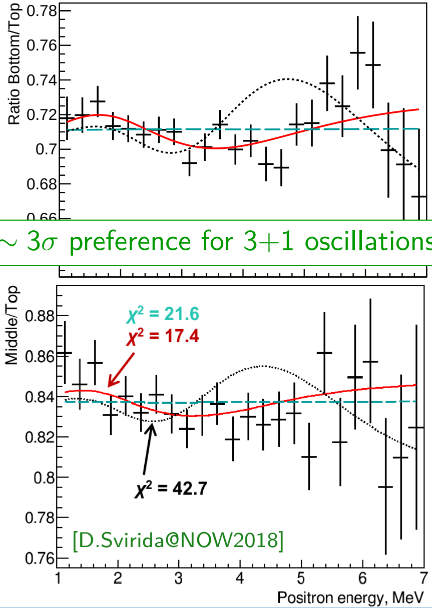


Detector can be at $\sim$ 10.5, $\sim$ 11.5 or $\sim$ 12.5 m from reactor core

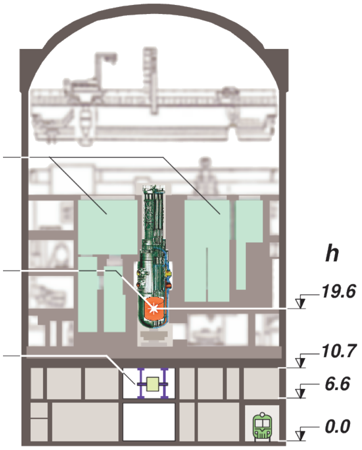
DANSS

[PLB 787 (2018) 56]

Single movable detector



~ 3σ preference for 3+1 oscillations

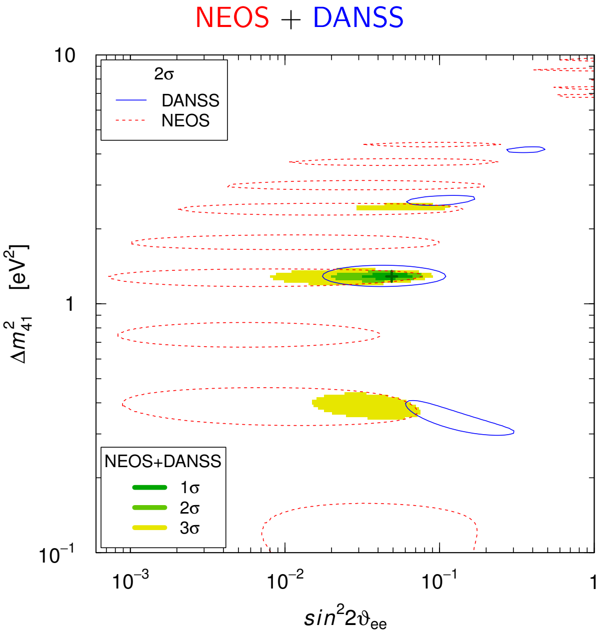


Detector can be at ~ 10.5, ~ 11.5 or ~ 12.5 m from reactor core

see later for 2019 update!

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]



The NEOS and DANSS region perfectly overlap at

$\Delta m^2_{41} \simeq 1.3 \text{ eV}^2$

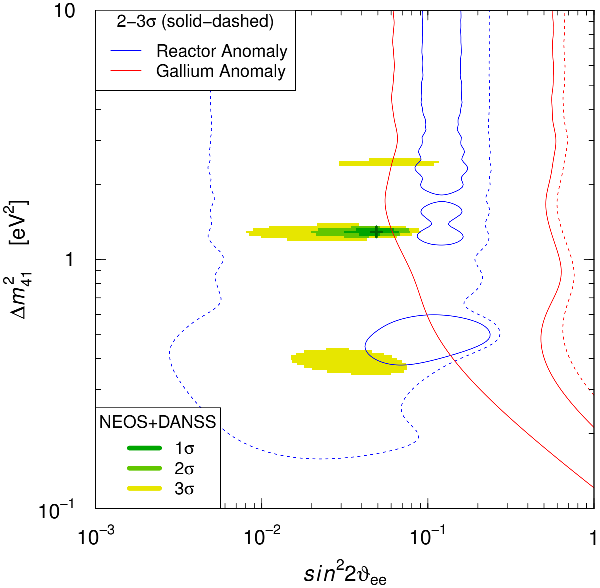
$\sin^2 2\vartheta_{ee} \simeq 0.05$

$\sin^2 \vartheta_{14} \simeq 0.01$

Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]

DANSS + NEOS + RAA + Gallium

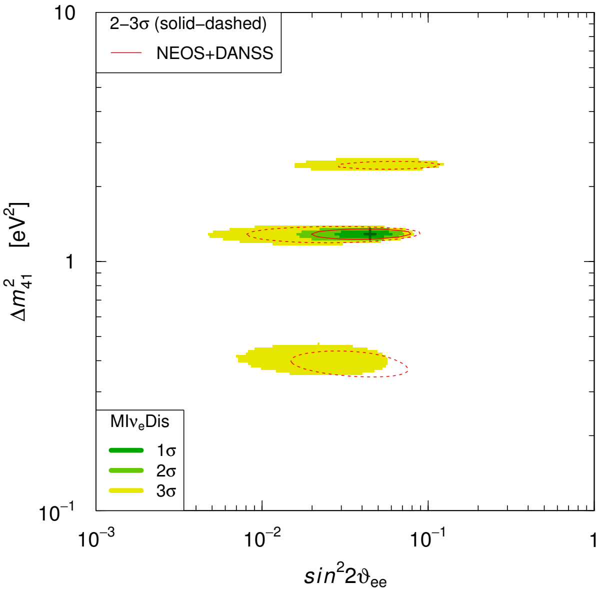


DANSS + NEOS
do not agree with
Gallium and RAA

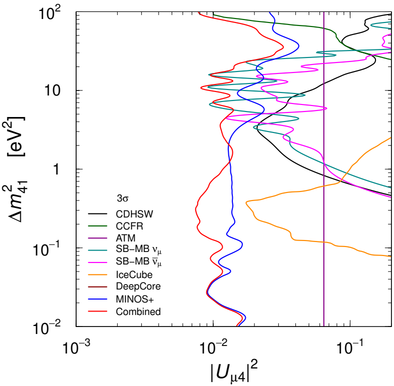
Model-independent fit of $\overset{(-)}{\nu}_e$ DIS (2018)

[SG+, PLB 782 (2018) 13]

All data:



Fit dominated by DANSS + NEOS


3σ
CDHSW
CCFR
ATM
SB–MB ν_μ
SB–MB $\bar{\nu}_\mu$
IceCube
DeepCore
MINOS+
Combined
Δm^2_{41} [eV^2]
$|U_{\mu4}|^2$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}

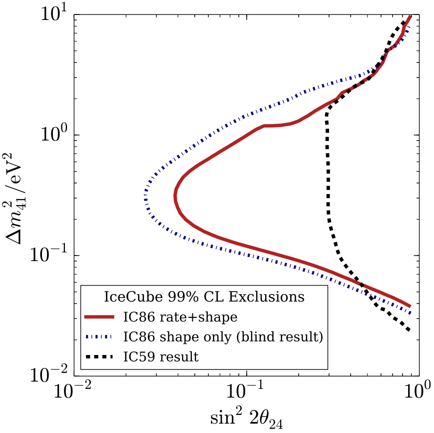
IceCube and DeepCore

IceCube

$\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$

$\sim 2 \times 10^4$ High energy μ events

320 GeV $<$ E $<$ 20 TeV



[PRL 117 (2016) 071801]

IceCube and DeepCore

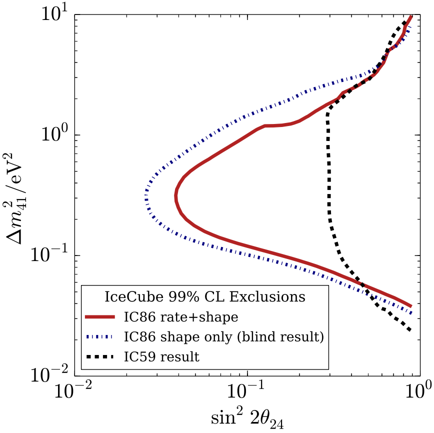
IceCube

$\mathcal{O}(10\ \text{km}) \lesssim L \lesssim \mathcal{O}(10^4\ \text{km})$

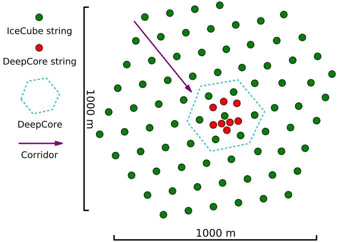
DeepCore

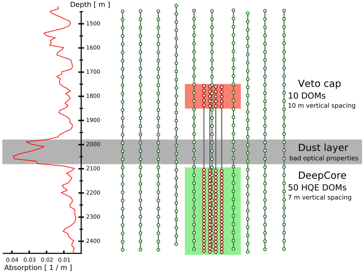
$\sim 2 \times 10^4$ High energy μ events

$320\ \text{GeV} < E < 20\ \text{TeV}$



[PRL 117 (2016) 071801]



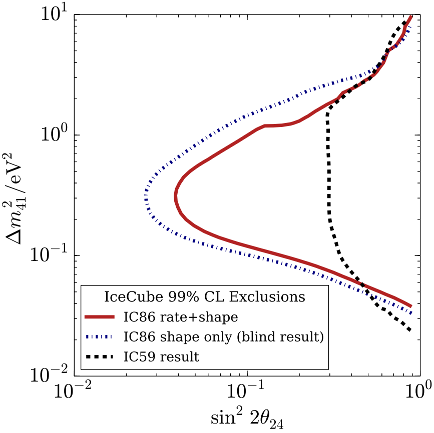


IceCube and DeepCore

IceCube $\mathcal{O}(10\text{ km}) \lesssim L \lesssim \mathcal{O}(10^4\text{ km})$ DeepCore

$\sim 2 \times 10^4$ High energy μ events

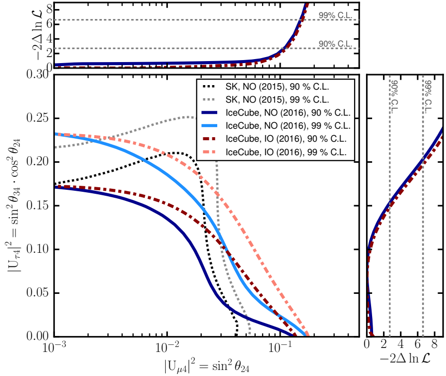
320 GeV $< E <$ 20 TeV



[PRL 117 (2016) 071801]

$\sim 5 \times 10^3$ tracklike events

6 GeV $\lesssim E \lesssim$ 60 GeV



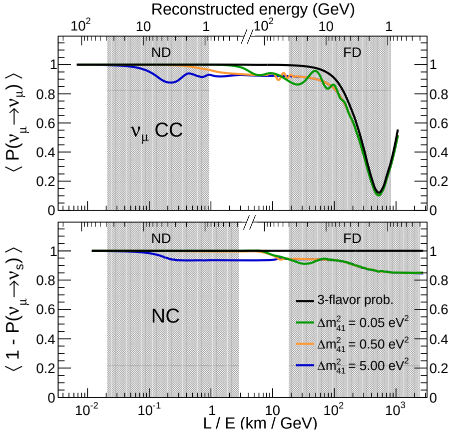
[PRD 95 (2017) 112002]

Both also constrain $|U_{\tau 4}|^2$

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

$1\text{ GeV} \lesssim E \lesssim 40\text{ GeV}$, peak at 3 GeV



[PRL 117 (2016) 151803]:

far-to-near ratio

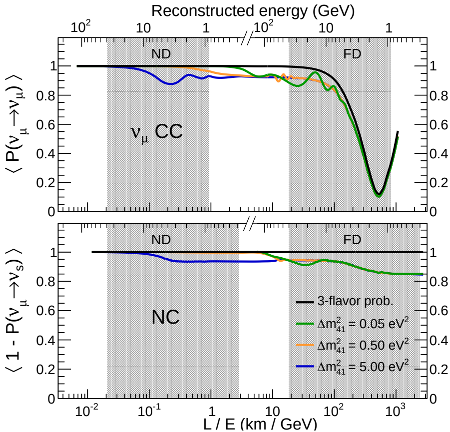
[PRL 122 (2019) 091803]:

full two-detectors fit

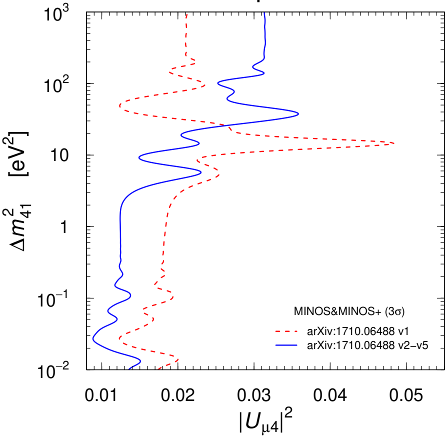
MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

$1\text{ GeV} \lesssim E \lesssim 40\text{ GeV}$, peak at 3 GeV



MINOS+ update:



[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

[SG+, in preparation]

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

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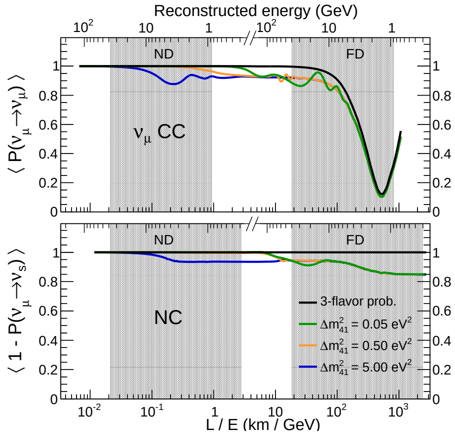
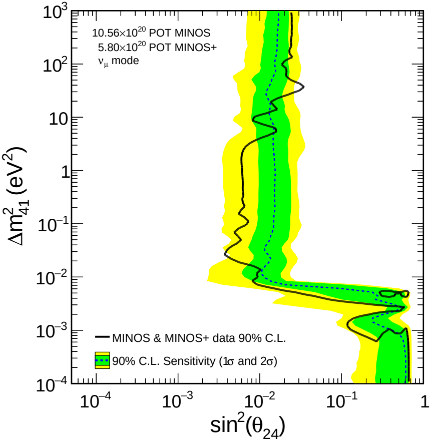


Sensitivity and exclusion limit:



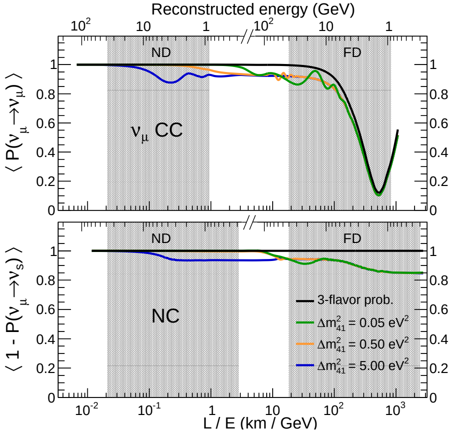
[PRL 117 (2016) 151803]: far-to-near ratio

[PRL 122 (2019) 091803]: full two-detectors fit

[PRL 122 (2019) 091803]

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector



[PRL 117 (2016) 151803]:

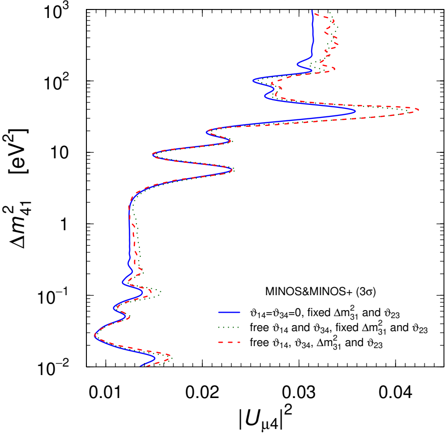
far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

1 GeV $\lesssim E \lesssim$ 40 GeV, peak at 3 GeV

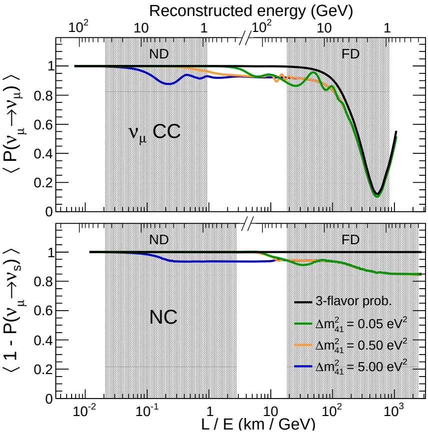
Marginalize over mixing parameters:



[SG+, in preparation]

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector



[PRL 117 (2016) 151803]:

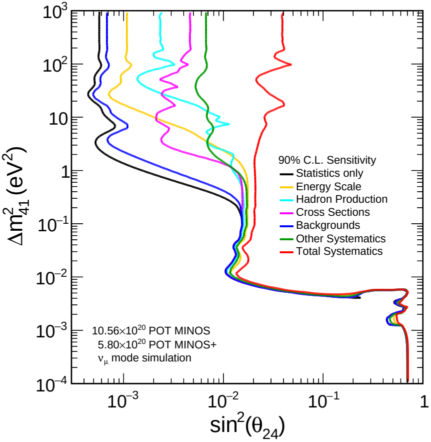
far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

1 GeV $\lesssim E \lesssim$ 40 GeV, peak at 3 GeV

Systematics:



[PRL 122 (2019) 091803]

MINOS & MINOS+

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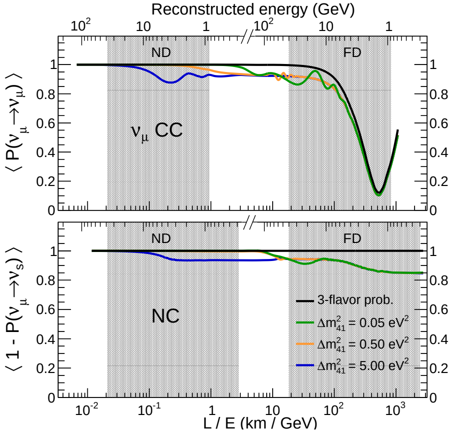
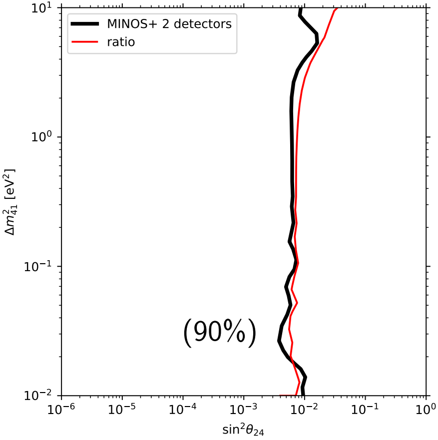


Two detectors vs ratio fit:



[PRL 117 (2016) 151803]:

far-to-near ratio

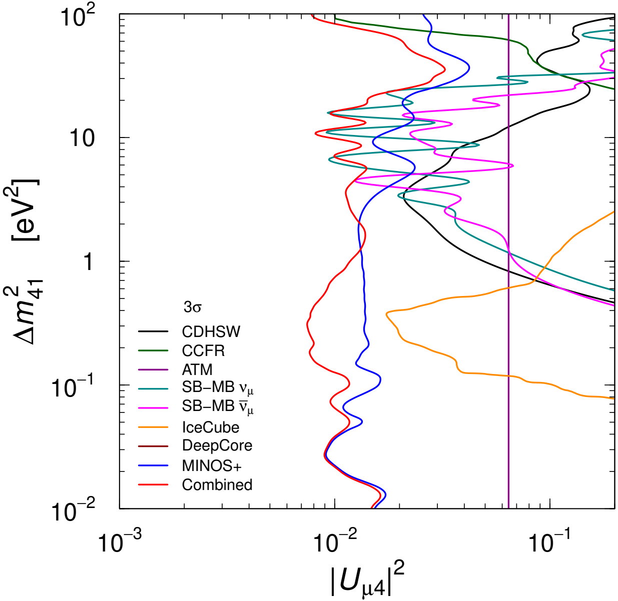
[PRL 122 (2019) 091803]:

full two-detectors fit

[SG+, in preparation]

Global fit of $\overset{(-)}{\nu}_\mu$ DIS

[SG+, in preparation]

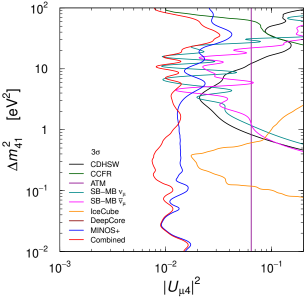


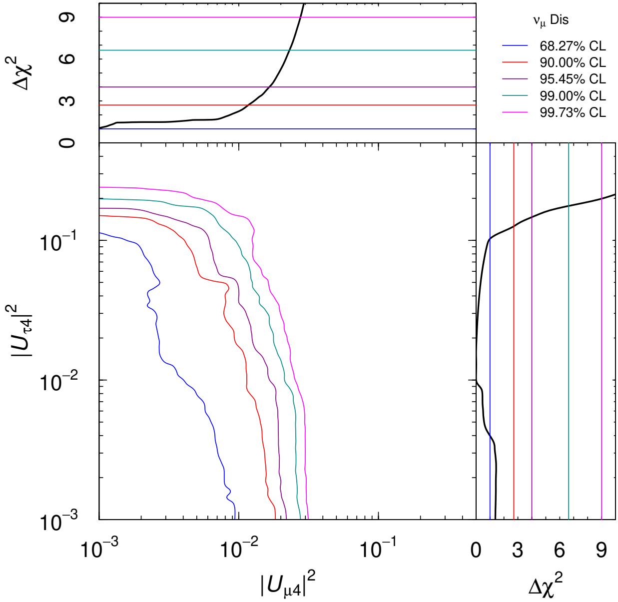
MINOS+ dominates at small Δm^2_{41}

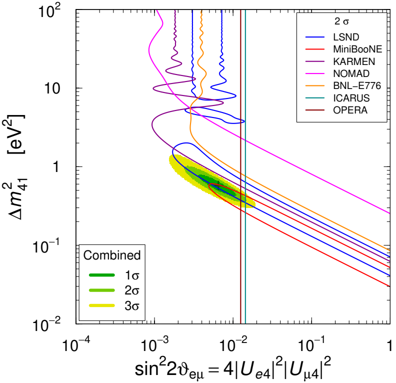
IceCube important at $\Delta m^2_{41} \simeq 0.2$ eV^2

Global fit of $\overset{(-)}{\nu}_\mu$ DIS

[SG+, in preparation]





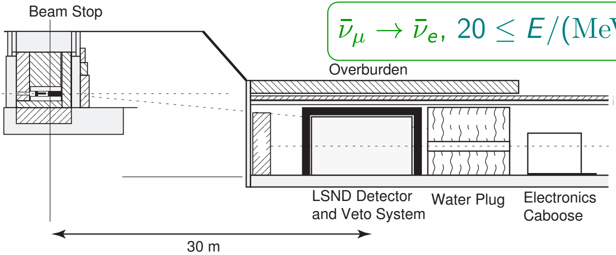


2 σ
LSND
MiniBooNE
KARMEN
NOMAD
BNL–E776
ICARUS
OPERA
Combined
1σ
2σ
3σ
Δm^2_{41} [eV^2]
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$

LSND

[PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$, $20 \leq E/(\mathrm{MeV}) \leq 52.8$



well known source of $\bar{\nu}_\mu$:

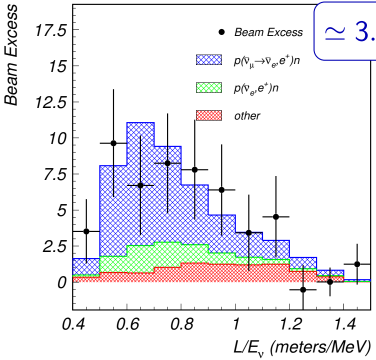
$$p + \mathrm{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow{\text{at rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30$ m

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

$\simeq 3.8\sigma$



No signal seen in KARMEN ($L \simeq 18$ m)

[PRD 65 (2002) 112001]

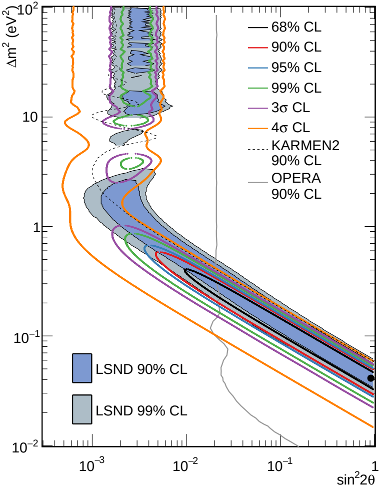
MiniBooNE

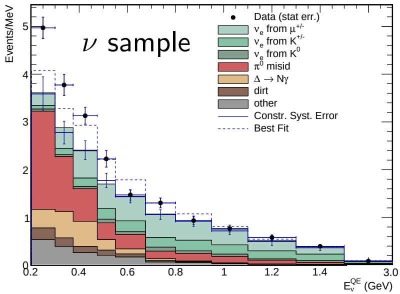
[PRL 121 (2018) 221801]

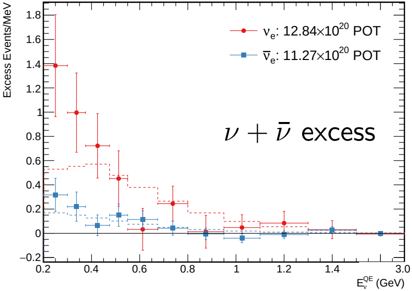
purpose: check LSND signal

$L \simeq 541$ m, 200 MeV $\leq E \lesssim 3$ GeV

no money, no near detector







MiniBooNE

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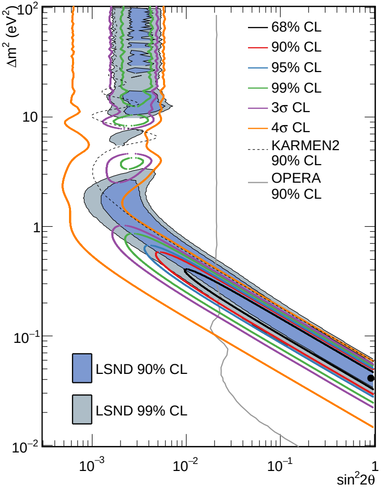
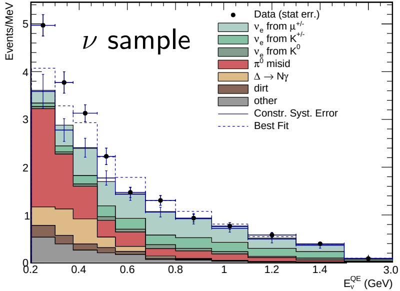
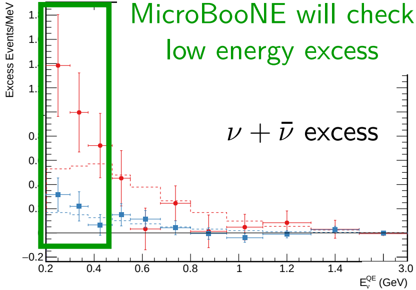


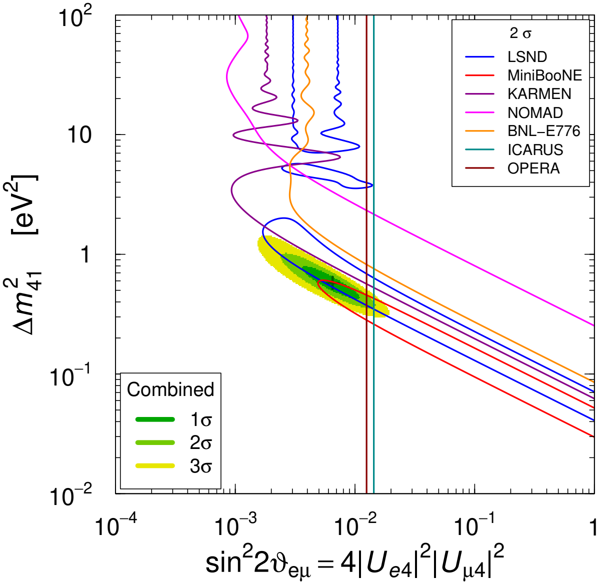




MicroBooNE will check low energy excess

Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, in preparation]



with full MiniBooNE data

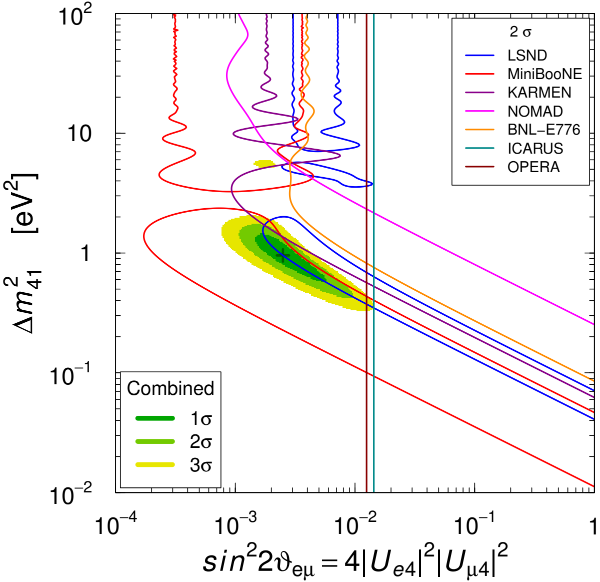
ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

KARMEN cuts part of LSND region

Global fit of $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ APP

[SG+, in preparation]

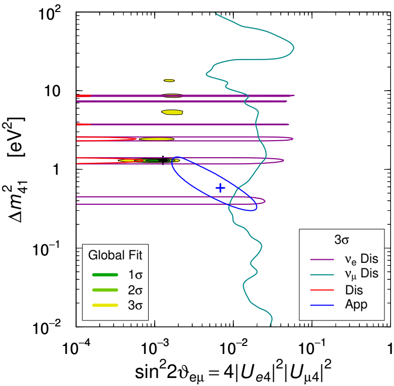


without MiniBooNE low energy bins

ICARUS and OPERA exclude MiniBooNE best fit

LSND and MiniBooNE only partially in agreement

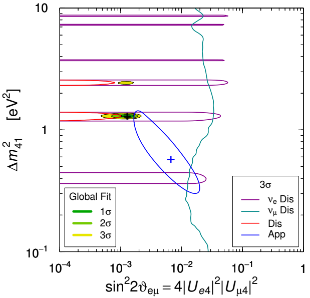
KARMEN cuts part of LSND region


10^2
10
1
10^{-1}
10^{-2}
Δm^2_{41} [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$
Global Fit
1σ
2σ
3σ
3σ
ν_e Dis
ν_μ Dis
Dis
App

APP – DIS tension in 2019

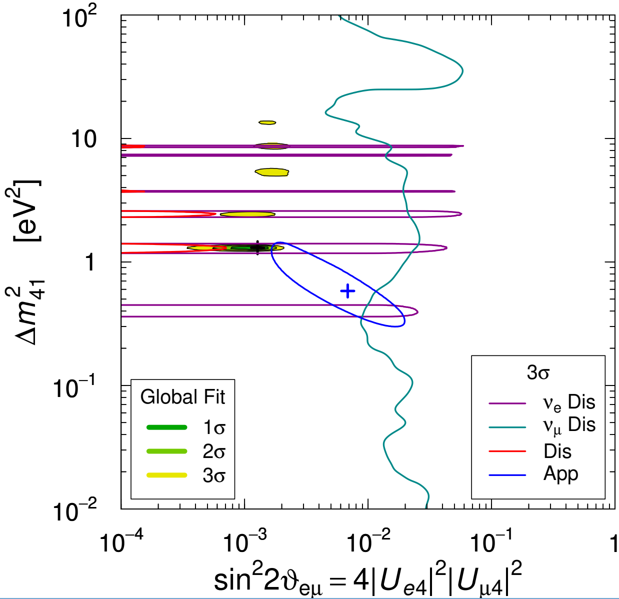
[SG+, in preparation]

Status just after Neutrino 2018:



MINOS+ update, new data including MiniBooNE (all bins)

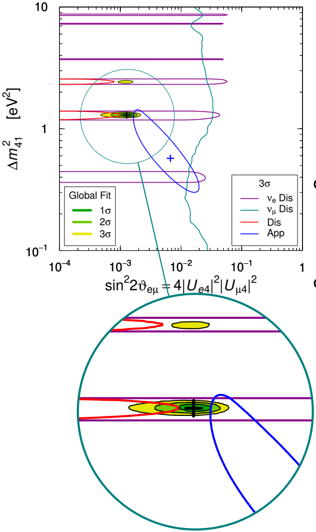
Status in early 2019



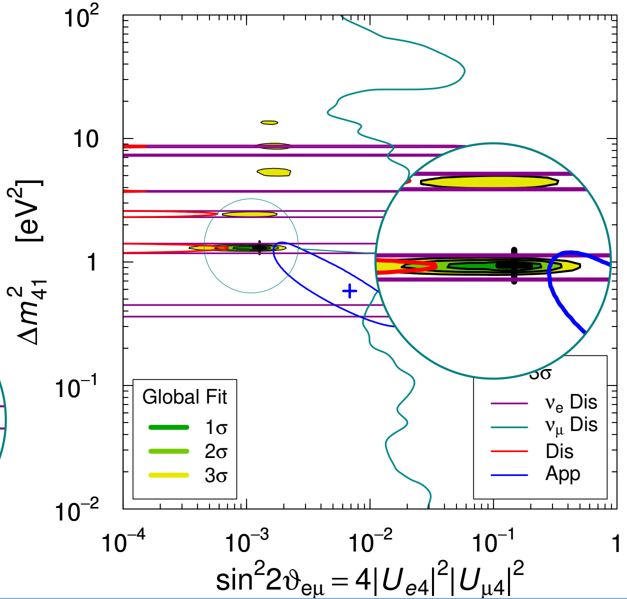
APP – DIS tension in 2019

[SG+, in preparation]

Status just after Neutrino 2018:

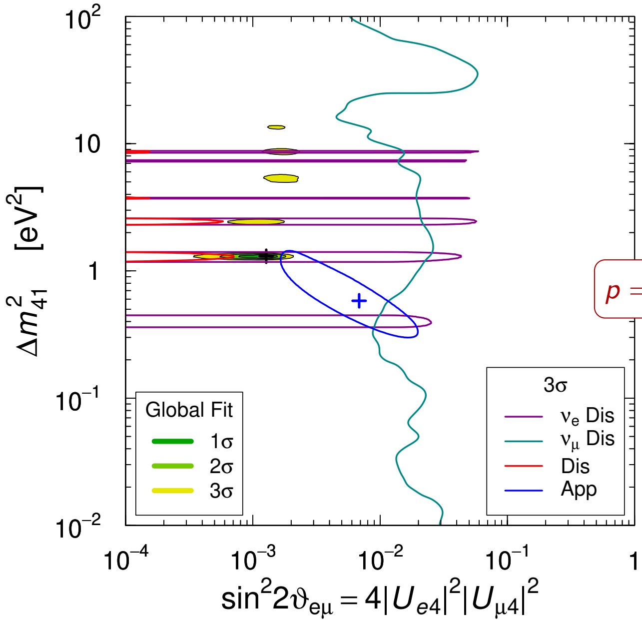


Status in early 2019



APP – DIS tension in 2019

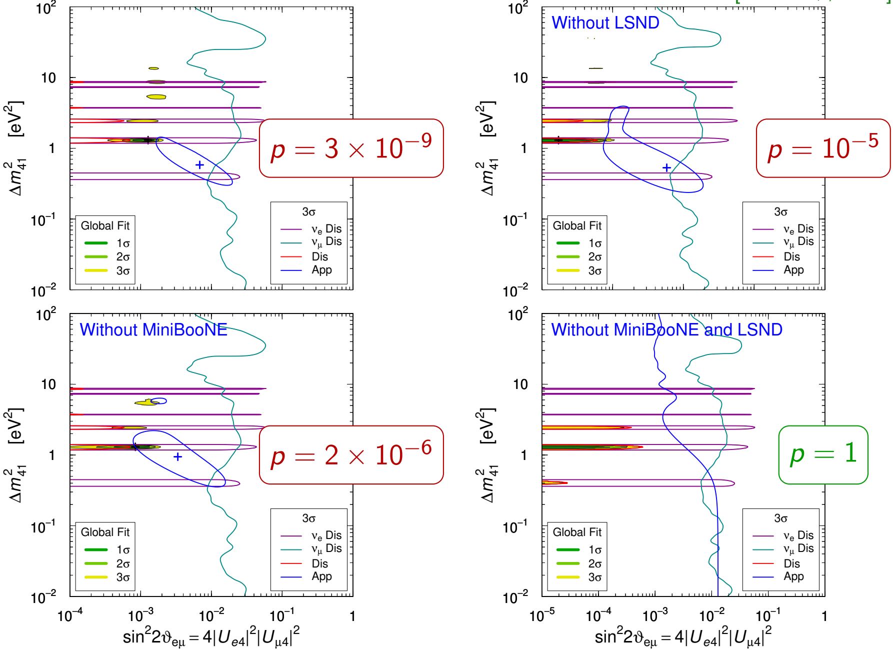
[SG+, in preparation]



$p = 3 \times 10^{-9}$

APP – DIS tension in 2019

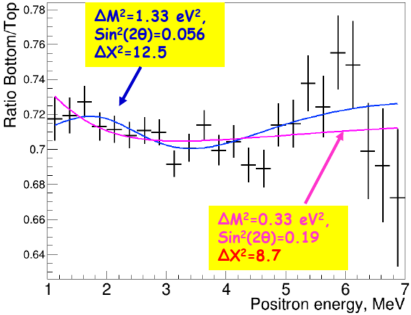
[SG+, in preparation]
see also [Dentler+, 2018]



DANSS in 2019

[Danilov@EPS-HEP, 2019]

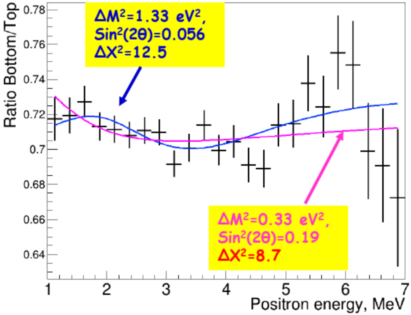
old data



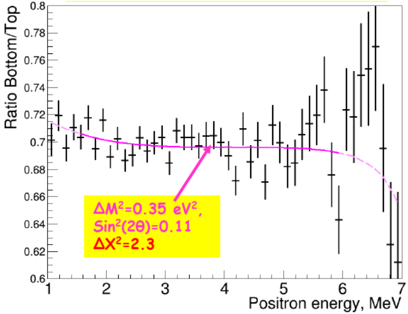
DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data



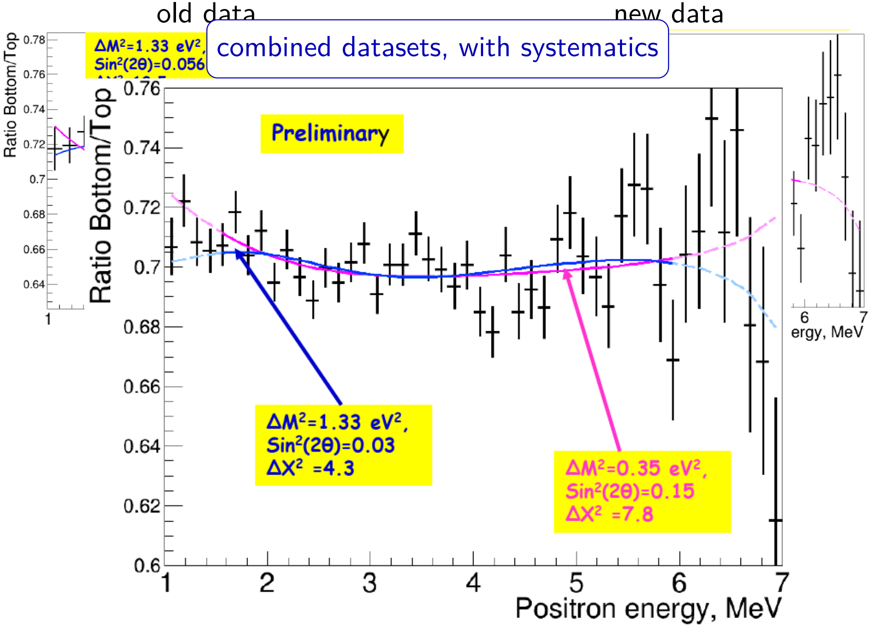
new data



New analysis also considers systematics!

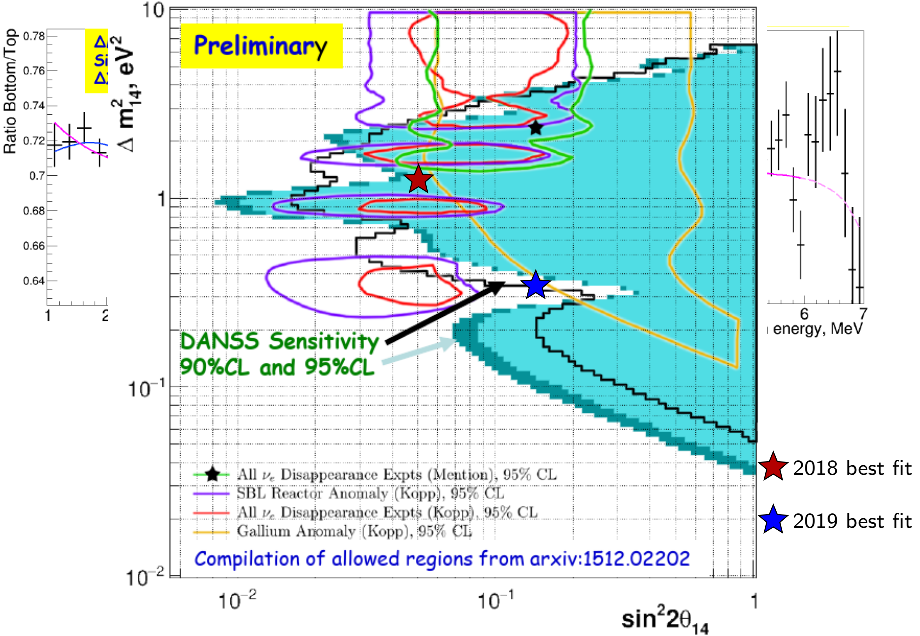
DANSS in 2019

[Danilov@EPS-HEP, 2019]



DANSS in 2019

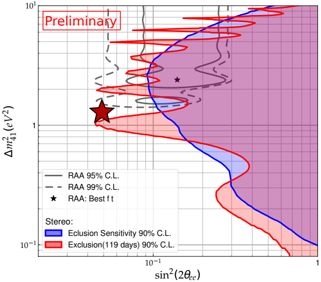
[Danilov@EPS-HEP, 2019]



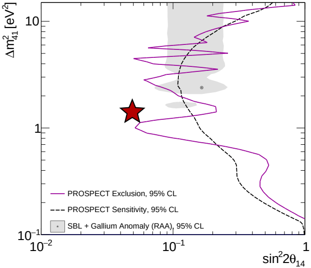
More to come...

★ = 2018 DANSS+NEOS best fit
[SG et al., PLB 782 (2018) 13]

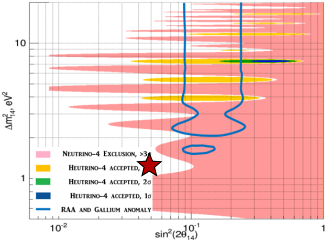
[STEREO, arxiv:1905.11896]



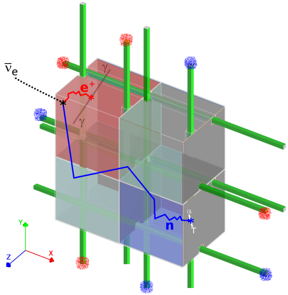
[PROSPECT, PRL 121 (2018) 251802]



[Neutrino-4, PZETF 109 (2019) 209-218]

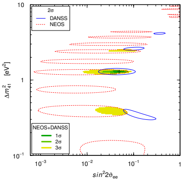


[SoLiD, JINST 13 (2018) P09005]

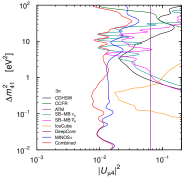


Conclusions

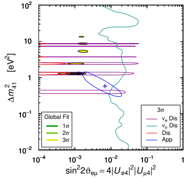
1. Unclear model-independent results from $\overset{(-)}{\nu}_e$ DIS, plus discrepancy with Gallium anomaly and RAA



2. nothing seen in $\overset{(-)}{\nu}_\mu$ DIS
strong upper bounds on $|U_{\mu 4}|^2$,
but also first constraints on $|U_{\tau 4}|^2$



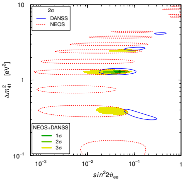
3. strong APP-DIS tension
What are LSND/MiniBooNE observing?
Systematics or LSν or new physics?



Conclusions

1

Unclear model-independent results from $\overset{(-)}{\nu}_e$ DIS, plus discrepancy with Gallium anomaly and RAA

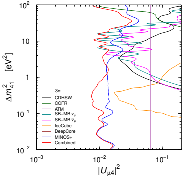


2

nothing seen in $\overset{(-)}{\nu}_\mu$ DIS

strong upper bounds on $|U_{\mu 4}|^2$,

but also first constraints on $|U_{\tau 4}|^2$

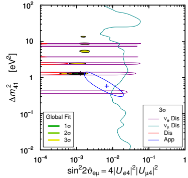


3

strong APP-DIS tension

What are LSND/MiniBooNE observing?

Systematics or LSν or new physics?



Thank you for the attention!