ICECUBE
South Pole Neutrino Observatory

Search for NSI in neutrino propagation with IceCube DeepCore

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PPNT | Uppsala | 8 October 2019

JG|U

PRISMA+

Credit: Martin Wolf, IceCube/NSF

NSI $\subset$ General Neutrino Interactions

- if SM is effective low-energy theory, with new physics at high energy scale Λ:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{O}_5}{\Lambda^1} + \frac{\mathcal{O}_6}{\Lambda^2} + \cdots + \text{h.c.}$$

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after EWSB: Majorana neutrino mass

Weinberg (1979)

NSI $\subset$ General Neutrino Interactions

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$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{O_5}{\Lambda^1} + \boxed{\frac{O_6}{\Lambda^2} + \cdots} + \text{h.c.}$$

- $d \geq 6$ operators can give rise to **general neutrino interactions**
- strongest low-energy effects typically expected for $d = 6$

Bischer, Rodejohann (2019)

  - 10 possible operators for both NC and CC interactions; 2 usually considered as NSI

propagation

$(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)\,(\bar{f}\gamma^\mu P_{L,R} f)$

NSI

production, detection

$(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)\,(\bar{q}\gamma^\mu P_{L,R} q')$

- neutrino propagation only sensitive to vector-type interactions

Bergmann, Grossmann, Nardi (1999)

Why consider NC (propagation) NSI?

- **in principle:**

gauge invariance

$\Downarrow$

strong constraints on NC NSI from non-observation of charged lepton flavour violation

Gavela, Hernandez, Ota, Winter (2009), Antusch, Baumann, Fernández-Martínez (2009)

- **but:**

models with neutral light new mediators able to avoid these bounds

$\mathcal{O}$**(10 MeV)**

Farzan, Tórtola (2018)

ν oscillations: effective approach still valid

relaxed limits from (incoherent) ν scattering experiments

- **also:**

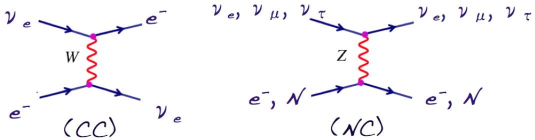
NC NSI from **CC NSI** via Fierz transformation

Bischer, Rodejohann, Xu (2018)

difficult to obtain large NSI (ν production, detection)

Neutrino propagation in standard matter

- flavour-asymmetric matter ⇒ flavour-dependent index of refraction in **coherent neutrino scattering**



interaction Hamiltonian:

$$H_I = H_Z^n + H_Z^p + H_Z^e + H_W^e$$

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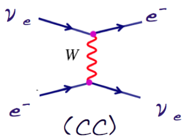

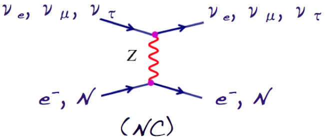

interaction Hamiltonian:

$$H_I = \underbrace{H_Z^n + H_Z^p + H_Z^e}_{=0} + H_W^e$$

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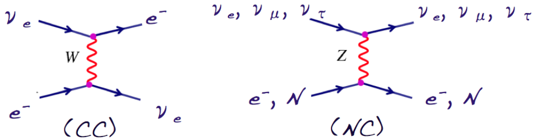

interaction Hamiltonian:

$$H_I = \underbrace{H_Z^n}_{\text{unobservable}} + H_W^e$$

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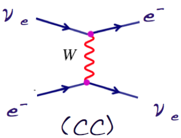

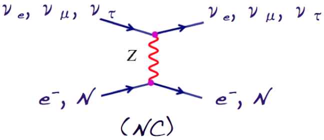

interaction Hamiltonian:

$$H_I = H_W^e = \mathrm{diag}(\sqrt{2}G_F N_e, 0, 0)$$

(responsible for MSW & parametric enhancement)

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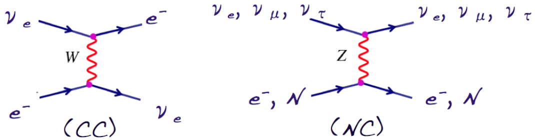
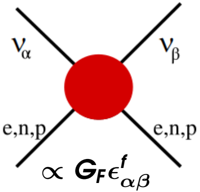


interaction Hamiltonian:

$$H_I = H_W^e = \mathrm{diag}(\sqrt{2}G_F N_e, 0, 0)$$

(responsible for MSW & parametric enhancement)

- NSI introduce additional potential $\boldsymbol{H_{\mathrm{NSI}}(x) = \sqrt{2}G_F \sum_{f=e,n,p} N_f(x)\epsilon^f_{\alpha\beta}}$



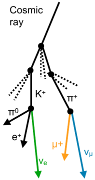
$$H_{\mathrm{mat}}(x) = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + (\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu})(x) & \epsilon^{\oplus}_{e\mu}(x) & \epsilon^{\oplus}_{e\tau}(x) \\ \epsilon^{\oplus *}_{e\mu}(x) & 0 & \epsilon^{\oplus}_{\mu\tau}(x) \\ \epsilon^{\oplus *}_{e\tau}(x) & \epsilon^{\oplus *}_{\mu\tau}(x) & (\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu})(x) \end{pmatrix}$$

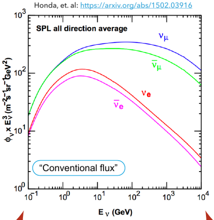
- **in Earth, $\epsilon^{\oplus}_{\alpha\beta}$ can be taken as constant:** $\boldsymbol{\epsilon^{\oplus}_{\alpha\beta}(x) \approx \epsilon^{\oplus}_{\alpha\beta} = \epsilon^e_{\alpha\beta} + \epsilon^p_{\alpha\beta} + 1.051\epsilon^n_{\alpha\beta}}$

Esteban et al. (2018)

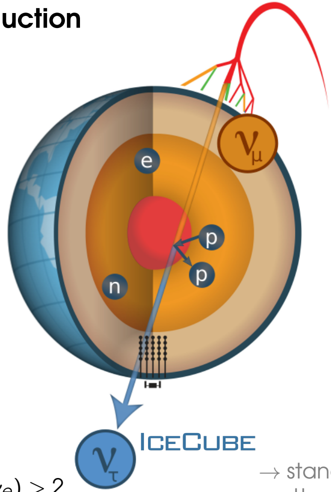
Physics with atmospheric ν's in IceCube DeepCore

1. atmospheric neutrino production





$\Phi(\nu_\mu)/\Phi(\nu_e) = 2$ $\Phi(\nu_\mu)/\Phi(\nu_e) > 2$



2. neutrino oscillation

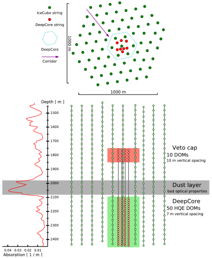
$$i\frac{\mathrm{d}}{\mathrm{d}x}|\nu\rangle = \left(U\frac{M_D^2}{2E}U^\dagger + H_{\mathrm{mat}}(x)\right)|\nu\rangle$$

baselines between 20 km and 12 700 km

→ standard & nonstandard matter effects

→ sterile neutrinos

3. neutrino detection



- 8 dedicated densely instrumented DeepCore strings
- sensitivity to $\mathcal{O}(10\,\mathrm{GeV})$ $\nu + \bar{\nu}$
- rich physics potential

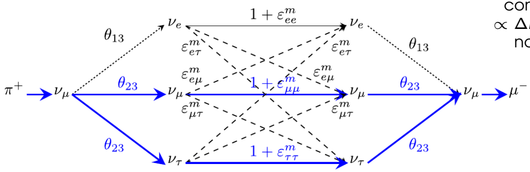
→ $\nu_\mu + \bar{\nu}_\mu$ disappearance

→ $\nu_\tau + \bar{\nu}_\tau$ appearance

→ decoherence

NSI in atmospheric neutrino oscillations

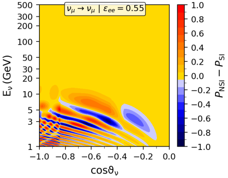
- here: effects of NSI couplings on ν_μ survival probability
- (observed: superposition of $\nu_{e,\mu} \to \nu_{e,\mu,\tau}$ & $\bar{\nu}_{e,\mu} \to \bar{\nu}_{e,\mu,\tau}$)

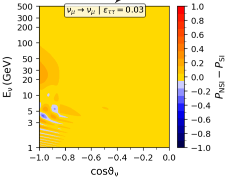


contributions $\propto \Delta m^2_{21} / \Delta m^2_{31}$ not shown

Kopp, Lindner, Ota, Sato (2008)

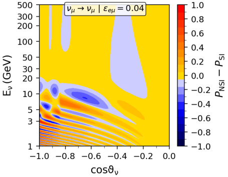
ϵ^d

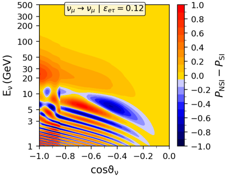


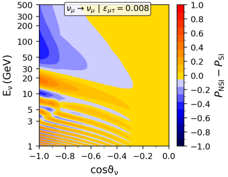


flavour-diagonal couplings

(note the different NSI coupling magnitudes)







flavour-changing couplings

First low-energy DeepCore NSI search: physics

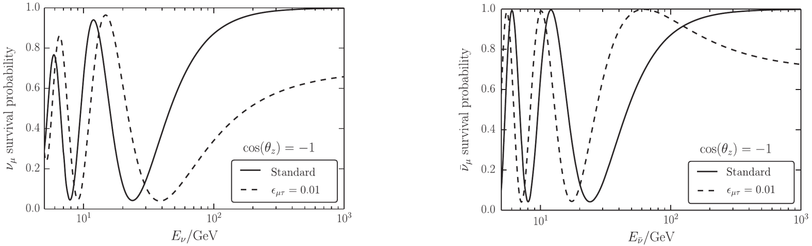
PRD97 072009 (2018)

- **assumption:**

$$H_{\mathrm{mat}}(x) = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 3\epsilon^d_{\mu\tau} \\ 0 & 3\epsilon^d_{\mu\tau} & 0 \end{pmatrix}$$

Esmaili, Smirnov (2013)

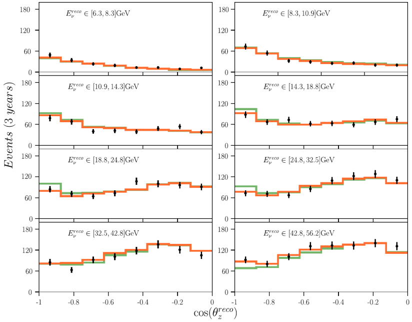
- 2ν system of $\nu_\mu \rightleftarrows \nu_\tau$ approximately realised for $\epsilon_{e\beta} \ll 1$, $E_\nu \gtrsim 20\,\mathrm{GeV}$
- solely $\epsilon_{\mu\tau}$ determines high-energy behaviour of 2ν system
- assuming NSI universality ($\epsilon_{\tau\tau} = \epsilon_{\mu\mu}$) $\Rightarrow$ strongest constraints on $\epsilon_{\mu\tau}$

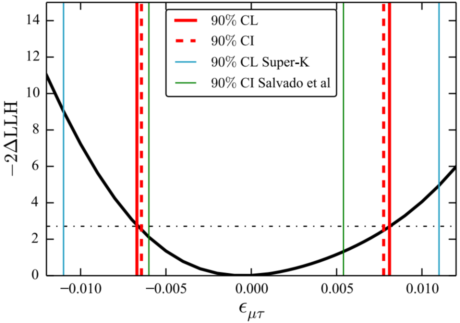


PRD97 072009 (2018)

First low-energy DeepCore NSI search: sample & results

- 3-year sample of $\sim$ 5k upgoing events
- high purity of $\nu_\mu + \bar{\nu}_\mu$ CC: $\sim 70\,\%$
- atm. μ background < 1% level





@ 90 % C.L. (Wilks):

$$-6.7 \times 10^{-3} < \epsilon^{d}_{\mu\tau} < 8.1 \times 10^{-3}$$

$$\Leftrightarrow -2.1 \times 10^{-2} < \epsilon^{\oplus}_{\mu\tau} < 2.4 \times 10^{-2}$$

All-flavour low-energy search for NSI with DeepCore

event selection: medium-statistics osc. sample extended to $E_{\mathrm{reco,max}} = 100\,\mathrm{GeV}$

data taking period: three years, 2012–2015 ⇒ 45k atm. ν's + $\bar{\nu}$'s

cf. PRD99 032007 (2019)

- 5 **one-at-a-time** (model-dependent) searches:
  - 2 searches for **non-universal** interactions: $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$ and $\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$
  - 3 searches for **flavour-changing** interactions:

$$\epsilon^{\oplus}_{e\mu} = |\epsilon^{\oplus}_{e\mu}|e^{i\delta_{e\mu}},\ \epsilon^{\oplus}_{e\tau} = |\epsilon^{\oplus}_{e\tau}|e^{i\delta_{e\tau}},\ \epsilon^{\oplus}_{\mu\tau} = |\epsilon^{\oplus}_{\mu\tau}|e^{i\delta_{\mu\tau}}$$

- the 6th fit allows for **more freedom in the NSI flavour structure**:

$$H_{\mathrm{mat}}(x) = R_{12}(\varphi_{12})R_{13}(\varphi_{13})\sqrt{2}G_F N_e(x)\mathrm{diag}(\epsilon_{\oplus}, 0, 0)R^{\dagger}_{13}(\varphi_{13})R^{\dagger}_{12}(\varphi_{12})$$

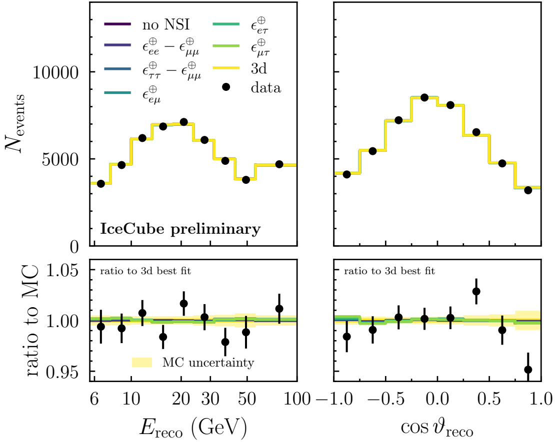
Euler rotation angles (φ_{12}, φ_{13})

overall matter potential strength ($\epsilon_{\oplus}$)

Esteban et al. (2018)

All-flavour low-energy search for NSI with DeepCore

- rather weak deviations between the seven fits (including no NSI)
  - goodness of fit (trials) approx. 20 % in all cases



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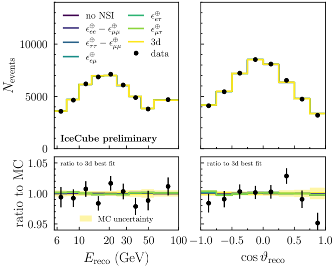
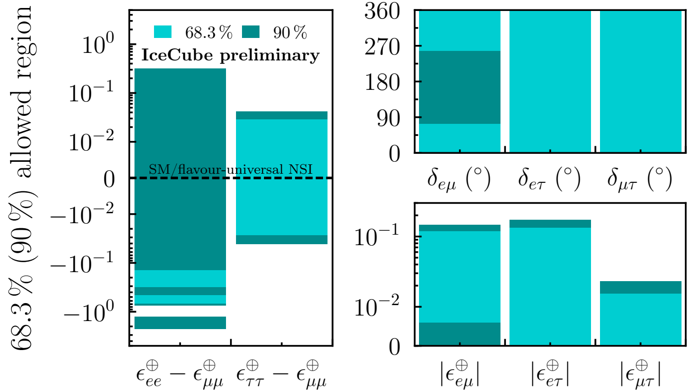


- **@ 90 % C.L. (Wilks):**

all fits compatible with either flavour-universal NSI or no NSI

normal ordering (NO) assumed



DeepCore NSI search: $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$

- NSI $e - \mu$ non-universality rescales Wolfenstein's SM matter potential:

$$V_{\rm CC} \rightarrow V_{\rm CC} \times \left(1 + \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}\right)$$

- degenerate with mass ordering (lacking sensitivity to θ_{12} & $\delta_{\rm CP}$):

$$\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} \leftrightarrow -\left(\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}\right) - 2$$
$$\iff \Delta m^2_{31} \leftrightarrow -\Delta m^2_{32}$$

Coloma, Schwetz (2016)

DeepCore NSI search: $\epsilon_{ee}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}$

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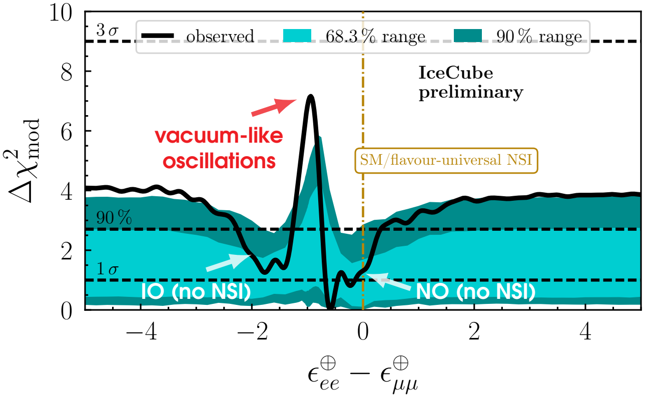
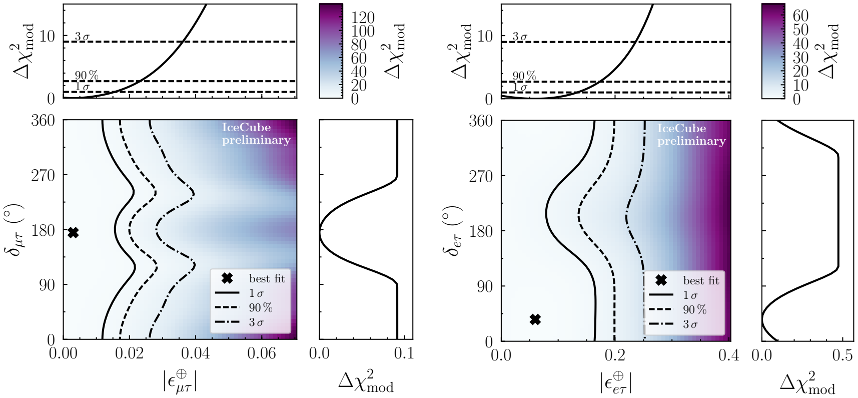
$$\Longleftrightarrow \Delta m_{31}^2 \leftrightarrow -\Delta m_{32}^2$$

Coloma, Schwetz (2016)



90 % C.L.: $[-2.26, -1.27] \oplus [-0.74, 0.32]$

DeepCore NSI search: τ flavour-changing NSI



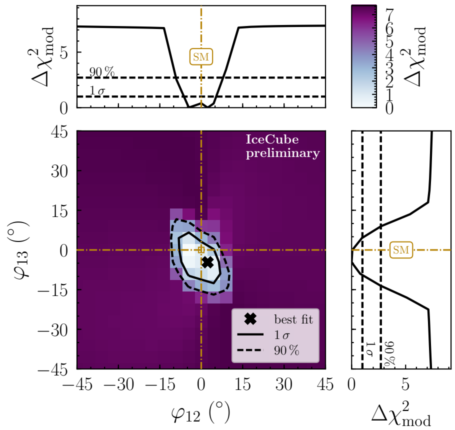
90 % limits:

- $|\epsilon^{\oplus}_{\mu\tau}| \leq 0.023$
- $|\epsilon^{\oplus}_{e\tau}| \leq 0.17$

- correlated effects of magnitudes and complex phases
  - complex phases unconstrained

DeepCore NSI search: flavour structure

projection of 3d profile onto $(\varphi_{12}, \varphi_{13})$, i.e., minimised over $\epsilon_{\oplus}$



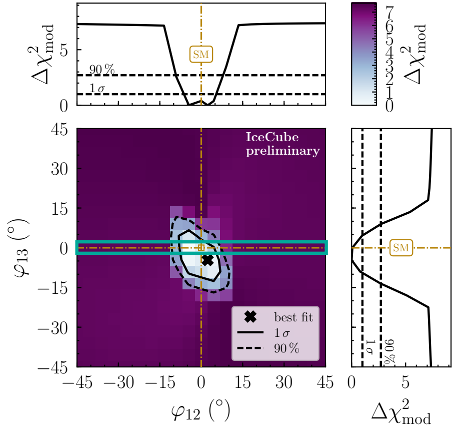
- $\mathcal{O}(10^5)$ points tested; refined projections onto subdimensions
- at 90 % C.L., data pins down both matter potential's strength ($\epsilon_{\oplus}$) and flavour projection angles ($\varphi_{12}, \varphi_{13}$)

  (for two degenerate matter-potential eigenvalues, CP-conserving NSI, cf. Esteban et al. (2018))
- not shown:

  @ 90 %: $\epsilon_{\oplus} \in [-1.2, -0.3] \oplus [0.2, 1.4]$

DeepCore NSI search: flavour structure

projection of 3d profile onto ($\varphi_{12}, \varphi_{13}$), i.e., minimised over $\epsilon_{\oplus}$

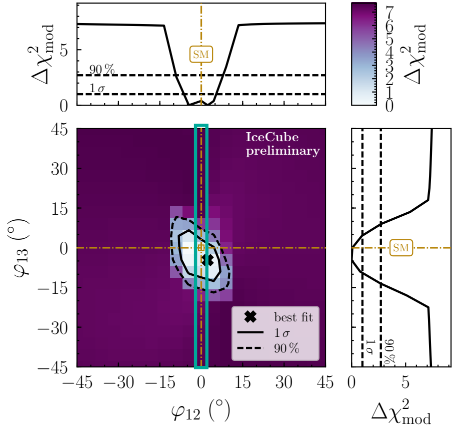


$\varphi_{13} = 0$:

$\Rightarrow$ no flavour-changing τ NSI

DeepCore NSI search: flavour structure

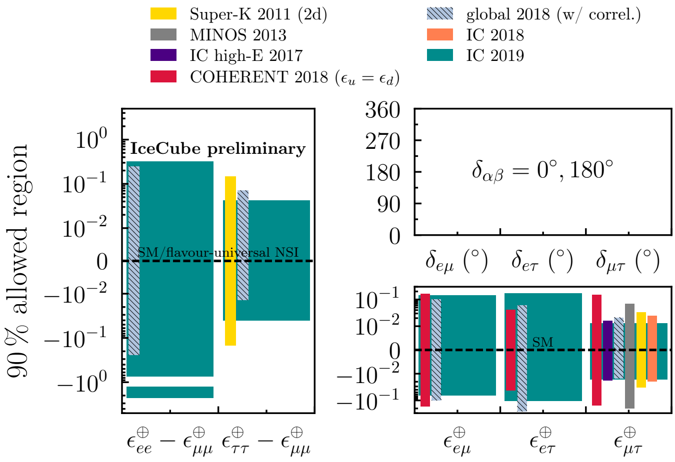
projection of 3d profile onto ($\varphi_{12}, \varphi_{13}$), i.e., minimised over $\epsilon_\oplus$



$\varphi_{12} = 0$:

$\Rightarrow$ no flavour-changing μ NSI

DeepCore NSI search: limit comparison



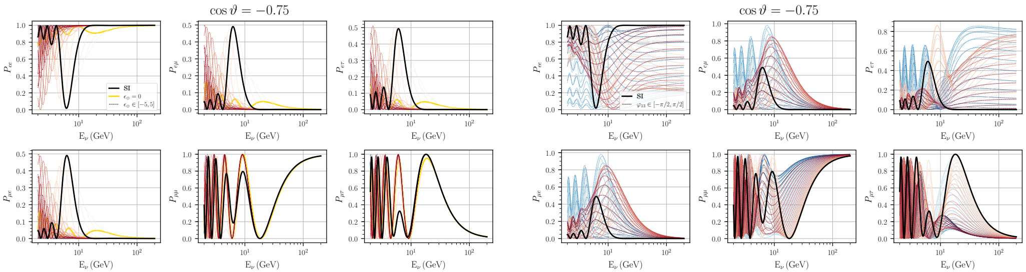
References:

- "Super-K 2011"
- "MINOS 2013"
- "IC high-E 2017"
- "COHERENT 2018"
- "global 2018"
- "IC 2018"
- "IC 2019": this work

- most common assumption: real NSI (= no new sources of CPV)

Toward the next IceCube NSI search

- broad NSI impact on atmospheric neutrinos
  - signals in all oscillation channels & across wide range of energies: from GeV to TeV



$\Rightarrow$ **promising search strategy:**

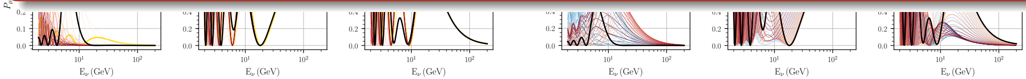
- use standard matter effects at few GeV as "anchor"
- look for incompatibility with high-energy data
- also reduce summation over $\nu + \bar{\nu}$

Toward the next IceCube NSI search

- broad NSI impact on atmospheric neutrinos
  - signals in all oscillation channels & across wide range of energies: from GeV to TeV

⇒ need unified low- (DeepCore) + high-energy (IceCube) event sample

- **technically challenging, but generally beneficial to BSM searches**
  - **active topic within IceCube**



⇒ promising search strategy:

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Summary

- IceCube offers wide range of possibilities to search for new neutrino interactions
  - focus so far on **propagation (matter effects)**

well-motivated theoretically

constraints independent of new-physics scale

- DeepCore 2nd generation NSI analysis performed
  - 10× statistics increase — extended energy range — all neutrino flavours

$\Rightarrow$ set limits on all effective NSI couplings for Earth matter

+ tested NSI flavour structure in three-dim. parameter space

- work toward next-generation IceCube & DeepCore NSI analyses ongoing
  - model assumptions
  - statistical approach
  - event selection
  - systematics

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Thank you!

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  - statistical approach
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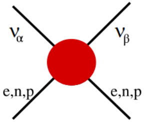
backup

Generating NSI

- a common approach: invoke scalar extensions of the SM

after integrating out new (heavy) scalar boson ϕ



valid for $M_\phi^2 \gg Q^2$ †

analogous to Fermi 4-point interaction

- BSM theories yield effective coupling parameters:

$$\mathcal{L}_{\rm NSI}^{\rm eff} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{ff',C} \left(\overline{\nu}_\alpha \gamma^\mu \nu_\beta\right) \left(\bar{f} \gamma_\mu P_C f'\right)$$

$$\alpha, \beta = e, \mu, \tau$$
$$f, f' = e, u, d$$
$$C = L, R$$

NC-like: $f = f'$

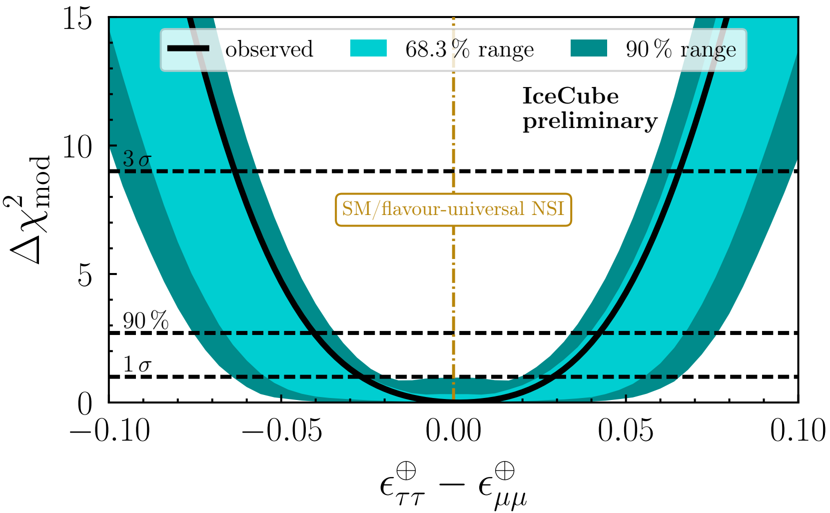
- in the following:

$$\epsilon_{\alpha\beta}^{f} \equiv \epsilon^{ff,V} = \epsilon^{ff,L} + \epsilon^{ff,R}$$

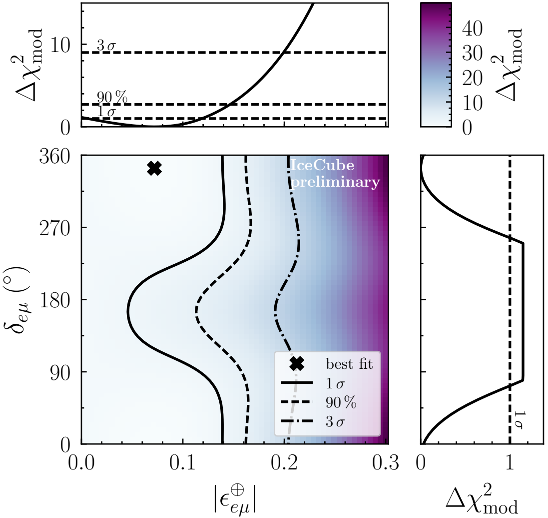
(vector interaction)

† $Q^2 = 0$ in coherent forward scattering $\Rightarrow$ sensitivity independent of new physics scale

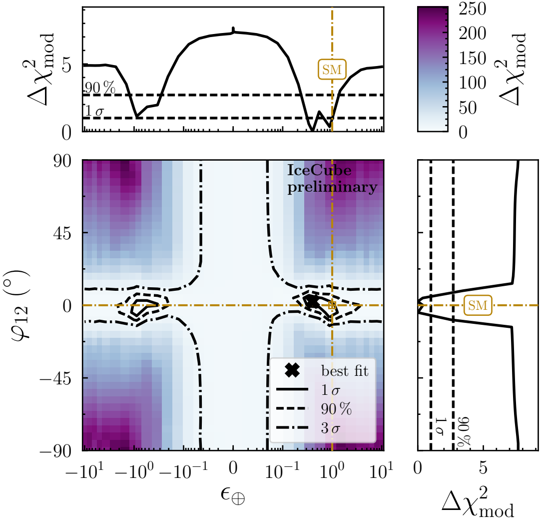
DeepCore NSI search: $\epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}$

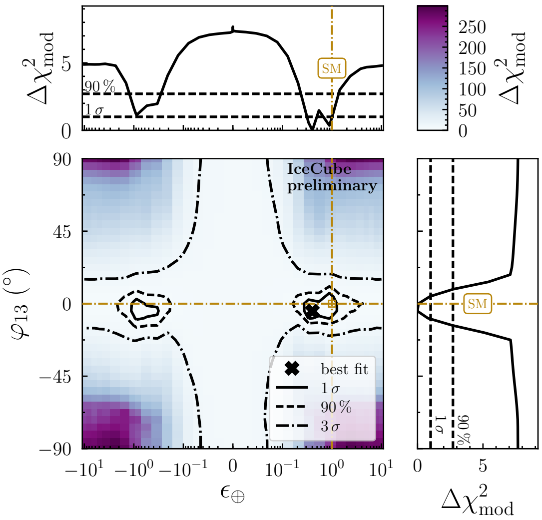


DeepCore NSI search: $\epsilon_{e\mu}^{\oplus}$



DeepCore NSI search: $\epsilon_\oplus$ and flavour structure





DeepCore NSI search: nuisance parameters

parameter	prior
neutrino flux and cross sections:	
ν_e/ν_μ ratio	1.0 ± 0.05
$\nu/\bar{\nu}$ ratio (σ)	0.0 ± 1.0
$\Delta\gamma_\nu$	0.0 ± 0.1
effective livetime (years)	...
M_A^{CCQE}(GeV)	$0.99^{+0.248}_{-0.149}$
M_A^{res}(GeV)	1.12 ± 0.22
NC normalisation	1.0 ± 0.2
oscillation:	
θ_{23}	...
Δm^2_{32}	...
detector:	
Optical Eff., Overall (%)	100 ± 10
Optical Eff., Lateral (σ)	0.0 ± 1.0
Optical Eff., Head-on	...
Bulk ice, scattering (%)	100 ± 10
Bulk ice, absorption (%)	100 ± 10

cf. PRD99 032007 (2019)

Previous NSI searches with IceCube

2018 low-energy

- **DeepCore** 3 year study using upgoing "golden" ν_μ CC only
  $\Rightarrow$ test only $\boldsymbol{\epsilon_{\mu\tau}}$:
  $-6.7 \times 10^{-3} < \epsilon^d_{\mu\tau} < 8.1 \times 10^{-3}$ (90 % C.L.) Phys.Rev. D97 (2018) no.7, 072009

2017 high-energy

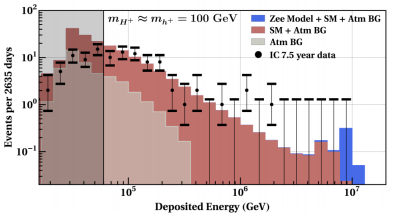
- **external** study using 1 year dataset of high-energy through-going muon tracks (0.3 TeV–20 TeV)
  $\Rightarrow$ limit on $\boldsymbol{\epsilon_{\mu\tau}}$, marginalised over $\boldsymbol{\epsilon_{\tau\tau} - \epsilon_{\mu\mu}}$:
  $-6 \times 10^{-3} < \epsilon^d_{\mu\tau} < 5.4 \times 10^{-3}$ (90% C.I.) JHEP 1701 (2017) 141

2013 high-energy+ low-energy

- **external** study using combination of 1 year high-energy (0.1 TeV–10 TeV) and 1 year low-energy (20 GeV–100 GeV) muon neutrinos
  $\Rightarrow$ constrain both $\boldsymbol{\epsilon_{\mu\tau}}$ and $\boldsymbol{\epsilon_{\tau\tau} - \epsilon_{\mu\mu}}$:
  $-6.1 \times 10^{-3} < \epsilon^d_{\mu\tau} < 5.6 \times 10^{-3}$ (90% C.I.)
  $-3.6 \times 10^{-2} < \epsilon^d_{\tau\tau} - \epsilon^d_{\mu\mu} < 3.1 \times 10^{-2}$ (90% C.I.) JHEP 1306 (2013) 026

Literature on high-energy NSI searches with IceCube

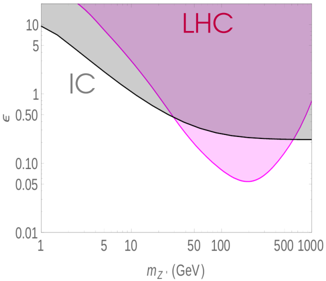
UHE resonance in $\bar{\nu}_\alpha e$ ("Zee burst")



arXiv:1908.02779

total νN cross section of high-energy astrophysical neutrinos from contained showers (6-year HESE)

$$\sigma_{\nu N}^{NSI} \lesssim \sigma_{\nu N}^{tot,cas} - \sigma_{\nu N}^{CC,IC} - \sigma_{\nu N}^{NC,SM}$$



arXiv:1907.07700

tree-level νq scattering through Z'