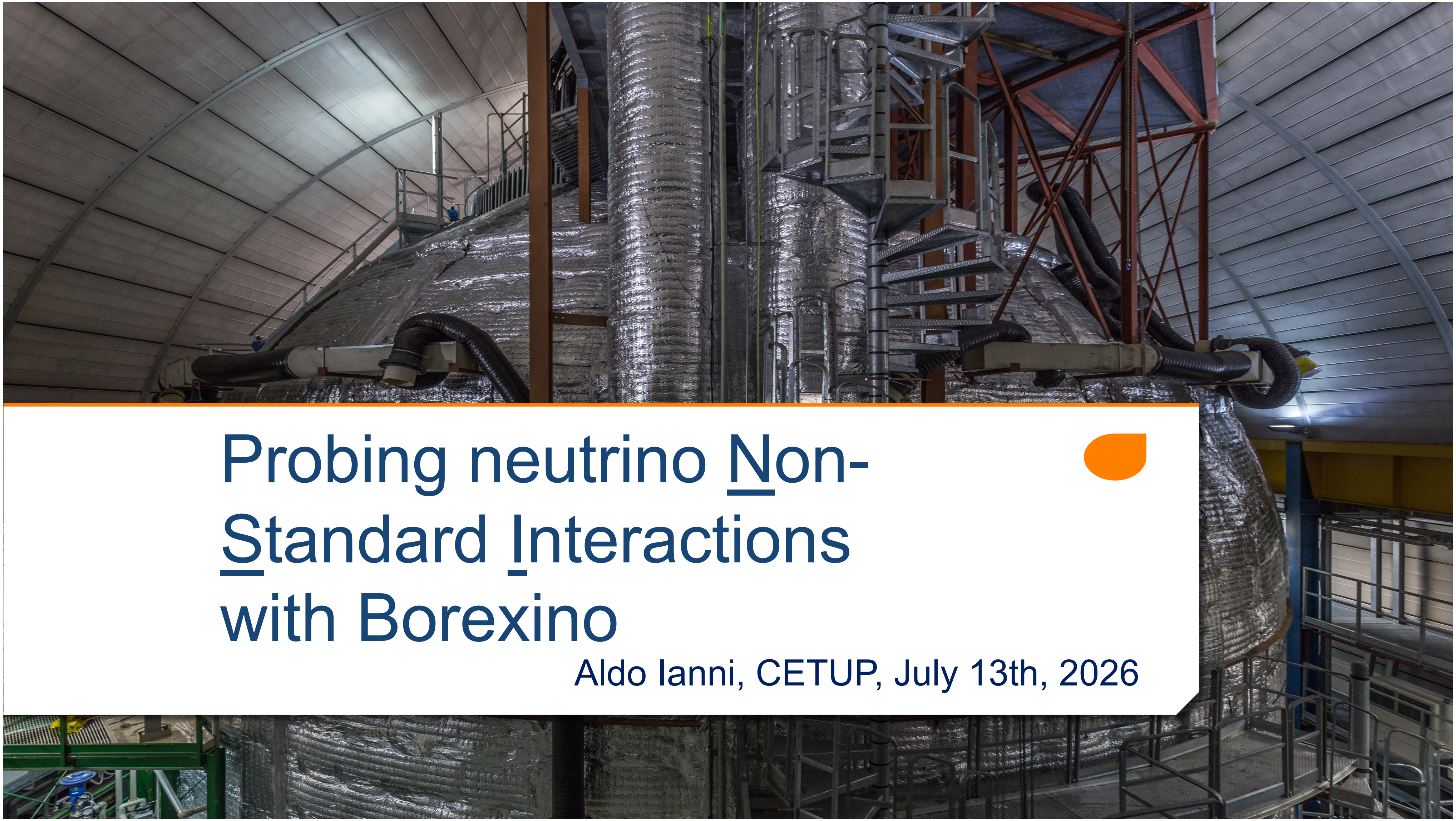


Probing neutrino Non-Standard Interactions with Borexino

Aldo Ianni, CETUP, July 13th, 2026

A few preliminary considerations

- The **Solar Neutrino Problem** and the **Atmospheric Neutrino Anomaly** solved with neutrino oscillations and the MSW-LMA theory
- Neutrino masses implies physics BSM (as of today the only robust evidence)
- If SM is a low energy effective theory we can predict both neutrino masses and neutrino Non-Standard Interactions (NSI) by *basic* modifications
- These NSI involve new couplings for neutrinos beyond the standard weak interaction
- At present improved experimental precision can probe physics BSM with solar, atmospheric, beam neutrinos, and with CEνNS
- Borexino turns to be very sensitive to some NSI (through the neutrino-electron ES) due to its radiopurity and to the high rate from the monocromatic ^{7}Be solar neutrinos. This is the main topic of the talk.

On neutrino NSI

- We distinguish between CC and NC NSI
  - CC affects production and detection: wrong flavour production, modifies detection cross section, produces zero-distance transition
  - NC affects propagation: modify oscillations and detection
- In presence of NC NSI the propagation of neutrinos through matter is modified by a non-standard potential:
  - The potential is proportional to $G_F\ \varepsilon_{\alpha\beta}\ N_f$ implying $\boldsymbol{\nu_\alpha + f \longrightarrow \nu_\beta + f}$ with f = e, u, d
- NC NSI can be split into a vector NSI and an axial-vector NSI
  - In matter the potential depends only on $\varepsilon_{\alpha\beta}{}^V$
- For neutrino-electron ES we could have
  - $\nu_e + e \longrightarrow \nu_{\mu,\tau} + e$
  - There is a shift in the NC cross section amplitute
  - Both $\varepsilon_{\alpha\beta}{}^V$ and $\varepsilon_{\alpha\beta}{}^A$ modify the recoil spectrum

A few remarks on NSI

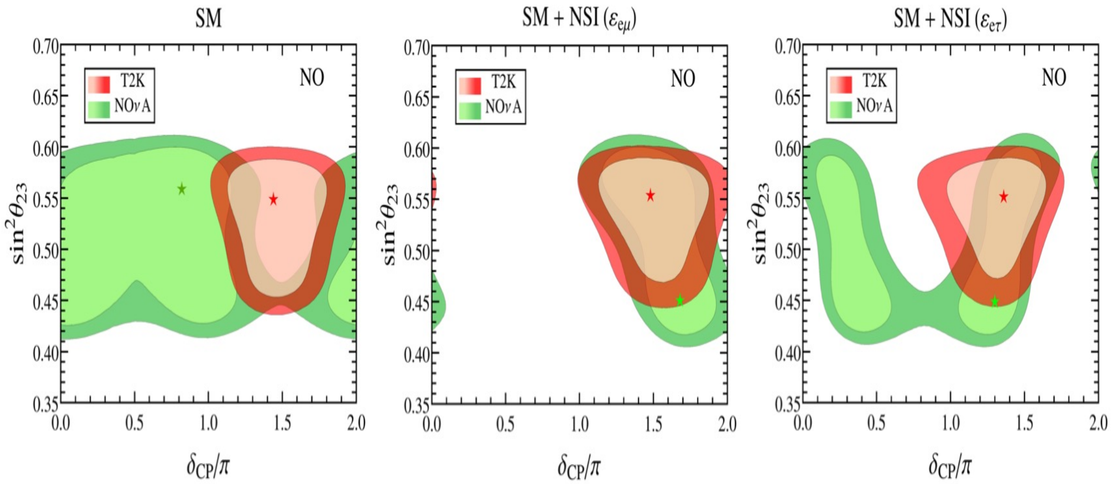
- Guzzo, Masiero, and Petcov **1991**: FCNC to probe **solar neutrino anomaly** even with massless neutrinos as an alternative to matter-enchanced neutrino oscillations
  - matter-enchanced neutrino oscillations require m_2^2-$m_1^2 \neq 0$ and $\sin 2\theta_{12} \neq 0$
  - FCNC such as ν_e + f ––> ν_τ + f can provide a solution even with no mixing (no vacuum oscillations)
  - the interaction strength is normalized to G_F within an effective theory at low energy
  - prior to SNO and KamLAND NSI were a viable solution
- Gonzalez-Garcia et al. **1999**, Fornengo et al. **2003**: probing **atmospheric neutrino anomaly** with NSI
  - atmospheric neutrino anomaly tested against ν_μ ––> ν_τ oscillations and FC NSI, ν_μ + f ––> ν_τ + f
  - $P_{\nu_\mu \to \nu_\tau} = sin^2(2\varphi) sin^2(\alpha F L)\ with\ \alpha = \sqrt{2} G_F \langle N_f \rangle$ with L the baseline and φ, F effective variables of the theory
- Masud and Mehta **2016**: NSI as subleading effect impacting **CP violation measurement** in DUNE by changing $P_{\mu\mu}$ and $P_{\mu e}$
- Coloma et al. **2023**: global fit (solar, atmospheric, accelerators, reactors, and CEνNS) to constrain neutrino NSI

Constraints to consider when probing neutrino NSI with Borexino/SK/SNO with ES

- **CHARM II** experiment at CERN (1986-1991)
  - Instrumented calorimeter (692 t of glass) with a muon spectrometer
  - Exposed to ν_μ and anti- ν_μ beam from SPS (450 GeV protons) with mean energy of 23.8 and 19.3 GeV, respectively
  - Measurement of ν_μ and anti- ν_μ interactions with electrons (purely leptonic interactions) provided crucial results on $g_{\nu L/R}$
- **TEXONO** - Taiwan EXperiment On NeutrinO (2001-2023)
  - Reactor anti-neutrinos
  - Detector at 28 m from core #1 inside a neutron and gamma shielding
  - NaI(Tl) and CsI(Tl) detectors
- **LSND** (Liquid Scintillator Neutrino Detector) 1993-1998
  - 167 t of mineral oil liquid scintillator at 30 m from beam damp producing from pion decays neutrinos, mainly anti- ν_μ at Los Alamos Meson Physics Facility (E_{max} = 52.8 MeV)
  - Mainly famous for anti- ν_μ —> anti- ν_e oscillations
- **LEP** e^+e^- —> $\nu\bar{\nu}\gamma$

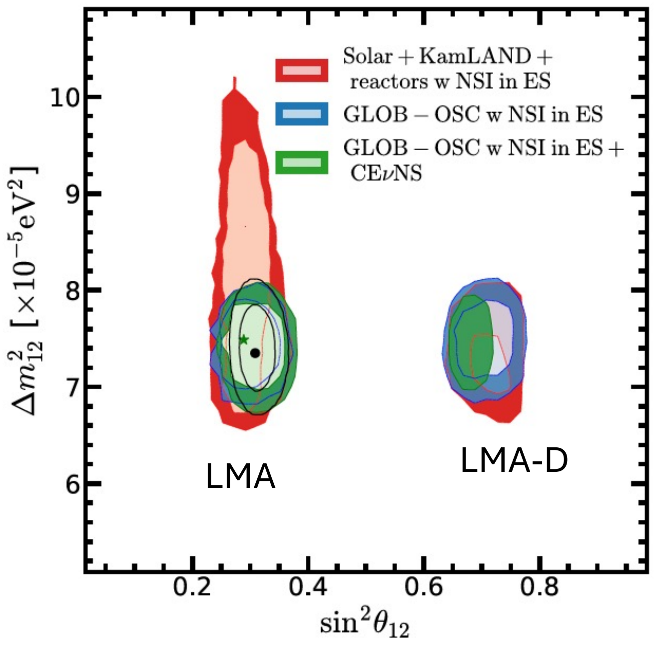
NSI and oscillation data

With NSI mitigation of T2K and NOνA tension, Chatterjee and Palazzo 2021



Marginalizing out oscillation parameters and NSI coupling (propagation and detection) to quarks and electrons in a global fit including Borexino and CEνNS. Solid black line w/o NSI. Coloma et al., 2023

90% and 3σ CL

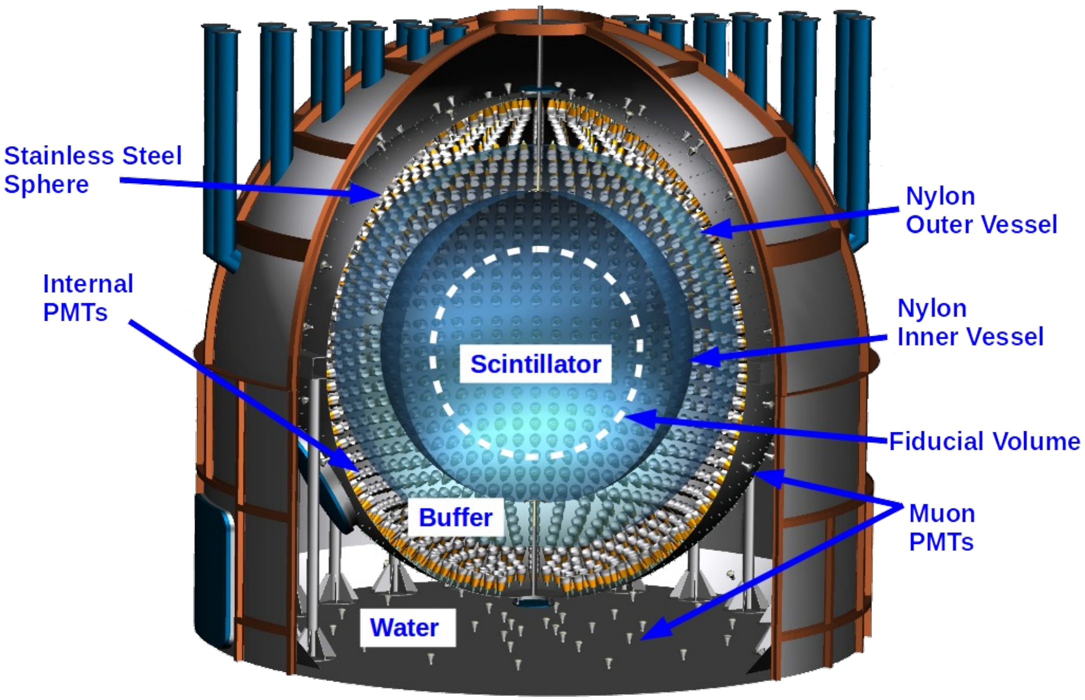


The Borexino detector

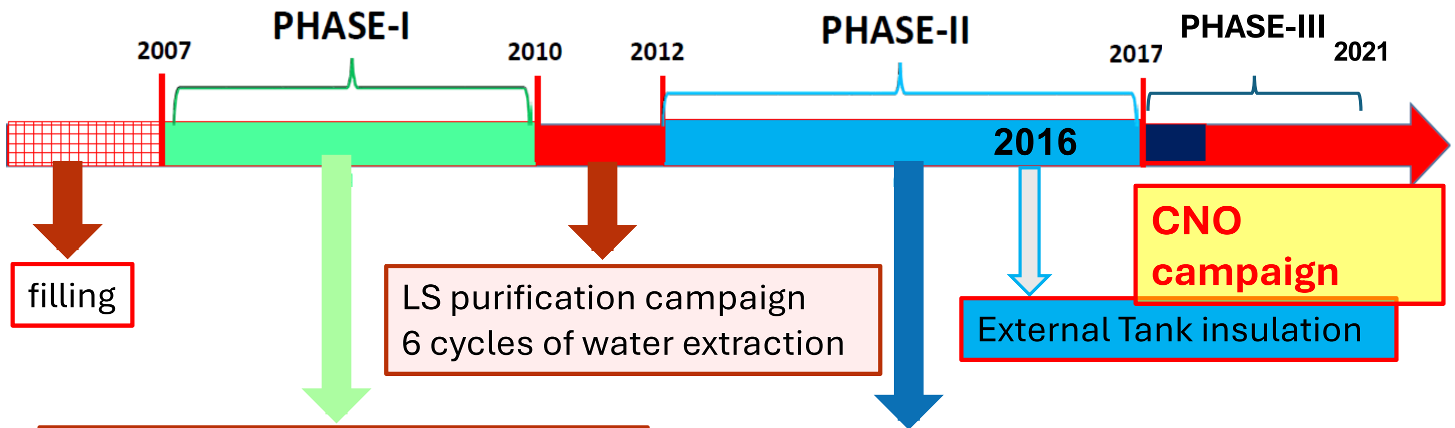
2200 8-inch PMTs
1800 PMTs with ligh cones

208 PMTs in water Cherenkov

278 tons of LS in Inner Vessel



Borexino data taking



- R(^7Be) + D/N
- R(pep) – first observation
- R(^8B)– first with LS
- R(CNO) – limit

geo- ν – first robust observation
cosmic muons flux studies
rare processes

- R(pp) *first in real time*
- Seasonal variations of R(^{7}Be)
- Simultaneous spectroscopy of pp, ^{7}Be and pep ν
- R(^8B)–improved
- geo- ν
- ν magnetic moment

NSI probed with Phase II and Phase III

Borexino radio-purity

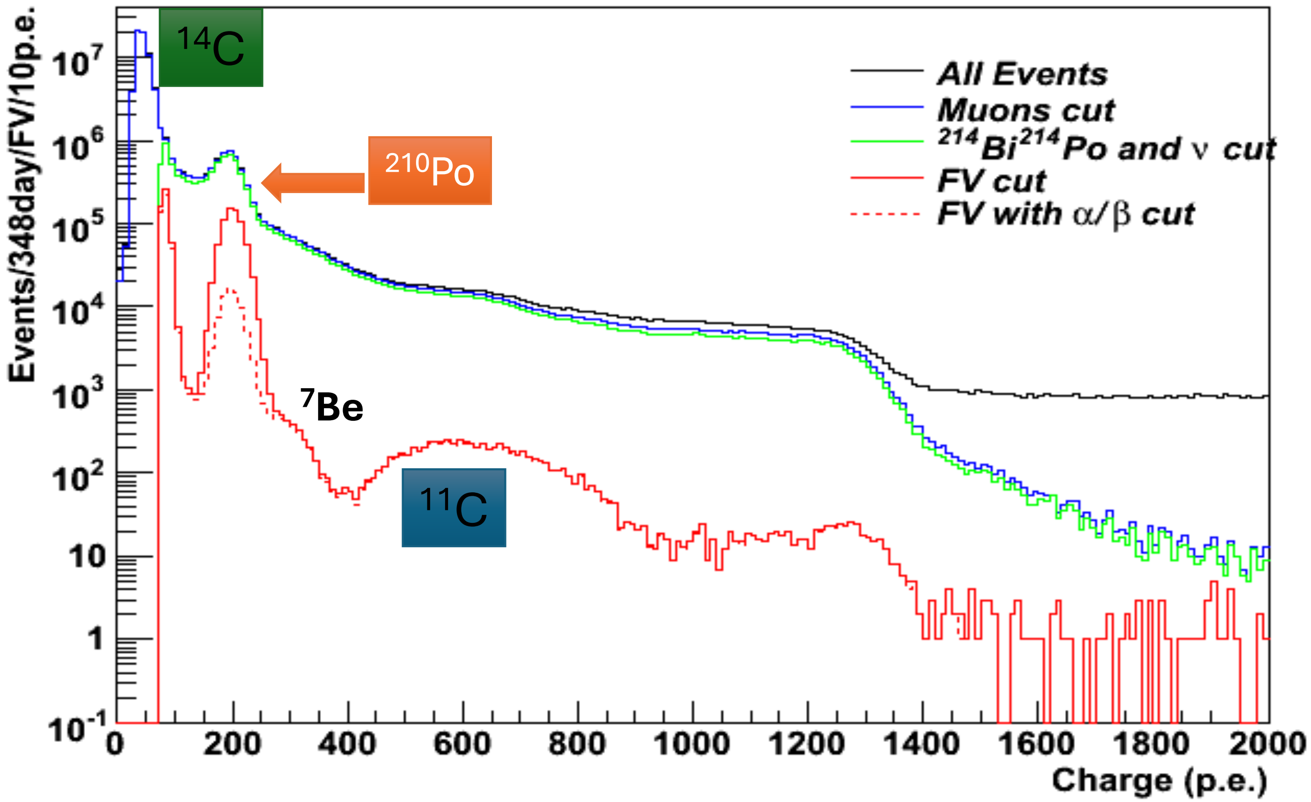
Isotope	Spec. in LS	After filling	After purification
^{238}U	≤ 10^{-16} g/g	(5.3±0.3) 10^{-18} g/g	≤ 9.4 10^{-20} g/g
^{232}Th	≤ 10^{-16} g/g	(3.8±0.8) 10^{-18} g/g	< 5.7 10^{-19} g/g
$^{14}C/^{12}C$	≤ 10^{-18}	(2.7±0.1) 10^{-18} g/g	no change
^{40}K	≤ 10^{-18} g/g	≤ 0.4 10^{-18} g/g	
^{85}Kr	≤ 1 cpd/100ton	30± 5 cpd/100ton	≤ 5 cpd/100ton
^{39}Ar	≤ 1 cpd/100ton	<< ^{85}Kr	<< ^{85}Kr
^{210}Po	not specified	~ 8000 cpd/100ton	no change
^{210}Bi	not specified	~ 20-70 cpd/100ton	20±5 cpd/100ton

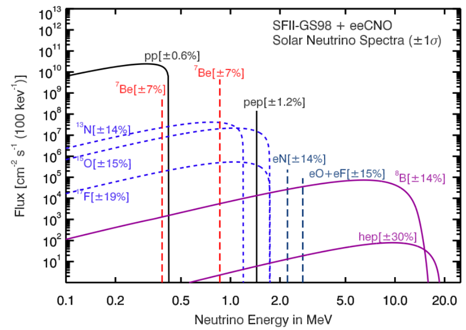
A_{BX} ~ 40 cpd/100ton in ^{7}Be ROI

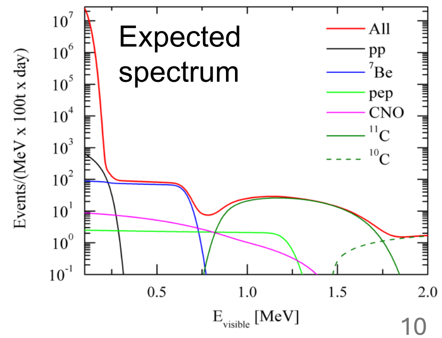
A_{BX} ~ $5x10^{-9}$ Bq/kg

Impacting accuracy of ^{7}Be spectrum measurement

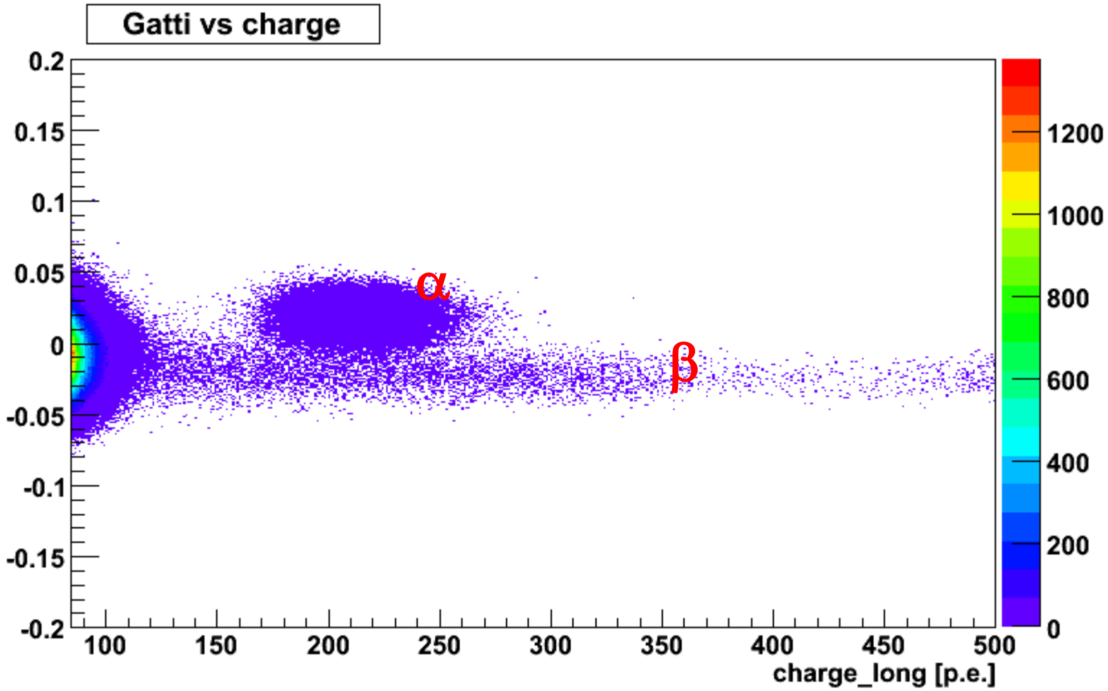
Early Borexino data







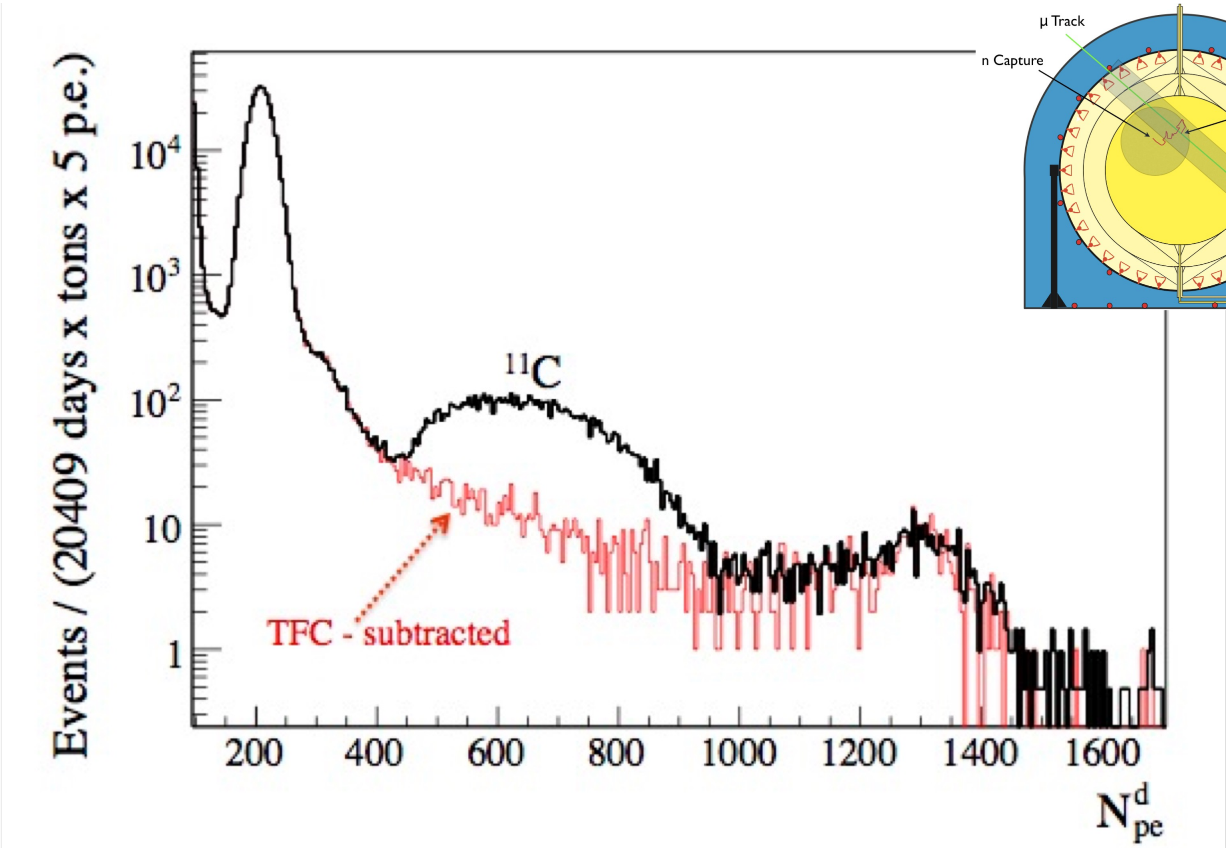
Pulse Shape Discrimination



Used to remove ^{210}Po

Better sensitivity to ^{7}Be recoiled electron spectrum

Three-fold Coincidence (TFC)



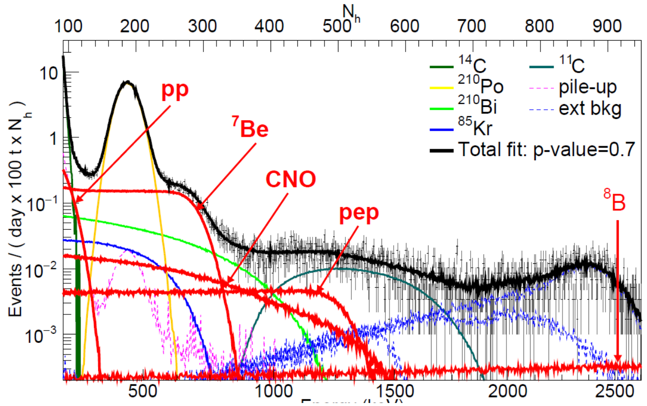
Used to remove ^{11}C

Better sensitivity to
pep and CNO neutrinos

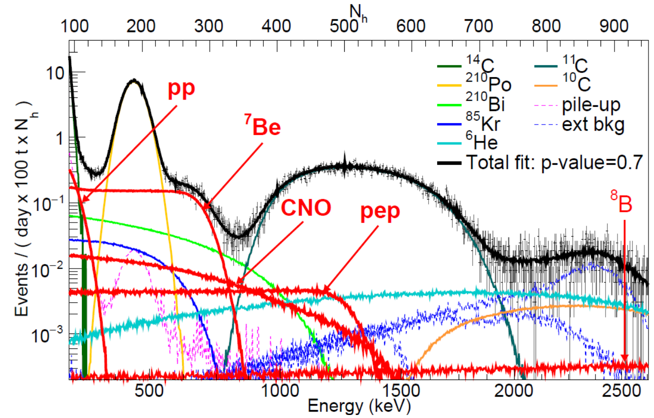
50% reduction of exposure

Multivariate fit example

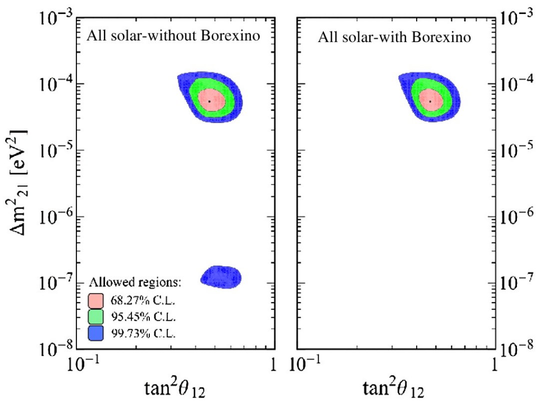
L($^{11}C_{sub}$)

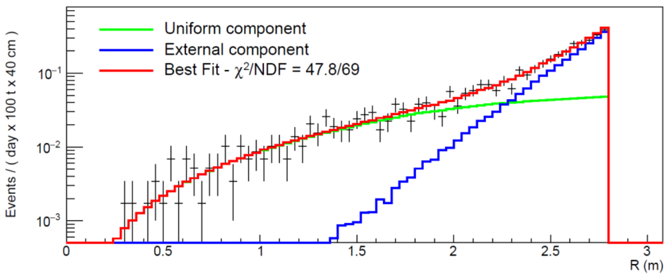


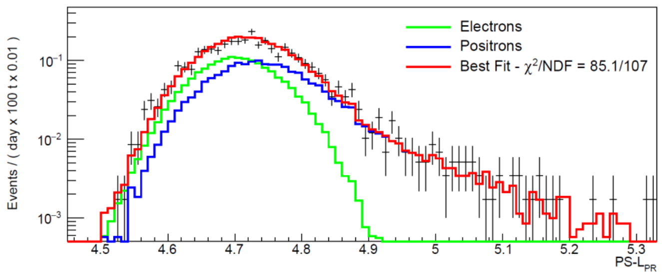
L($^{11}C_{tag}$)



Only solar neutrinos







L(Rad)

L(PS)

Background from nylon vessel

Both ^{210}Bi and ^{210}Po produced by ^{210}Pb (long lived)

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{years}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,\mathrm{days}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}$$

Convective currents can carry radioactive isotopes from the nylon vessel into the Fiducial Mass

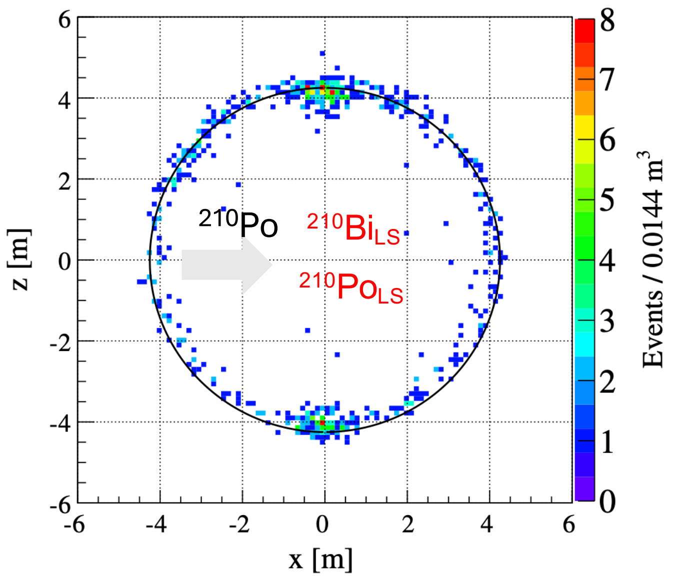
Nylon vessel has ppt level of U, Th plus out-of-equilibrium ^{210}Pb and surface ^{210}Po contamination

Some isotopes can leach off the surface and move to the FM

^{210}Po in LS has two components:

1. Intrinsic (supported by ^{210}Pb)
2. Due to convection

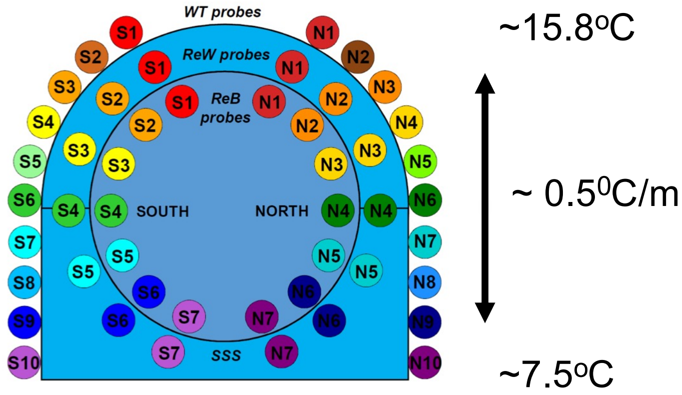
Stopping convection, reduced ^{210}Po moving toward the FV

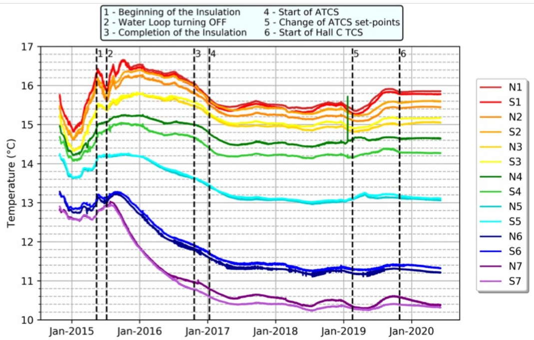


Thermal insulation and temperature control

Borexino Water Tank with insulation

Deployment of T probes

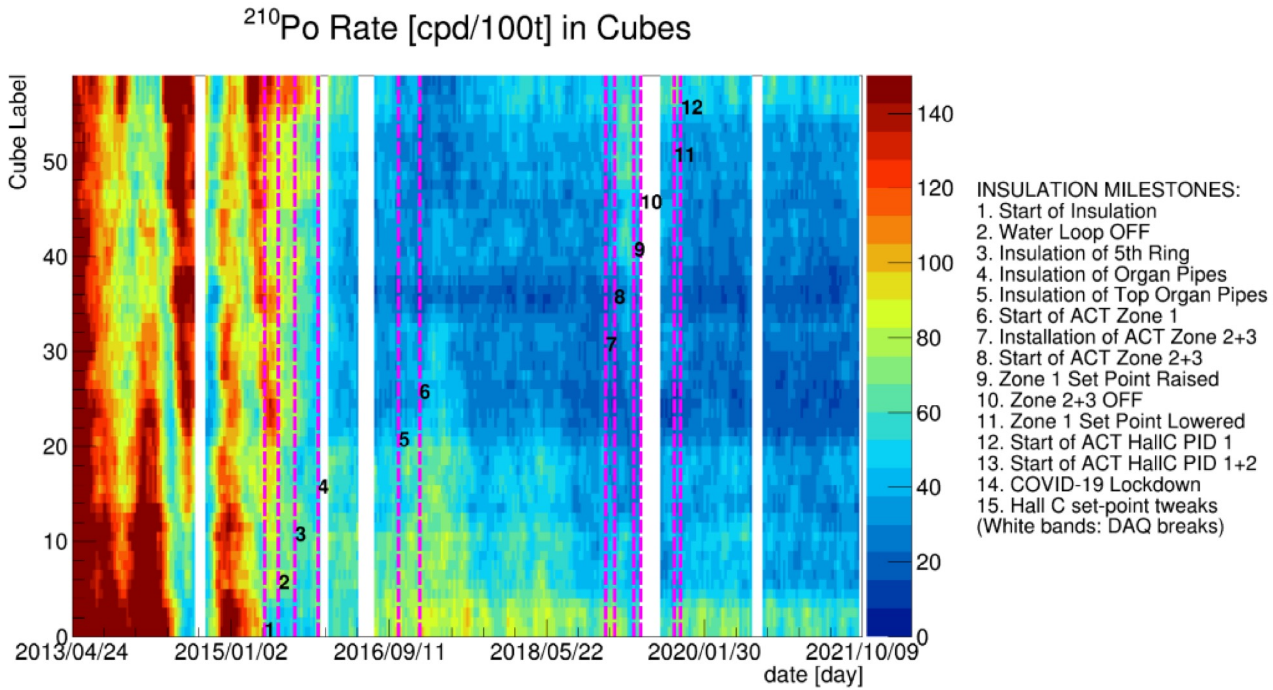




Temperature as a function of time in different volumes of the detector

Goal: reduce seasonal and external activity effects to avoid convective currents

^{210}Po activity vs time by PSD tagging



Reduction of ^{210}Po from the vessel allows to determined intrinsic contamination of ^{210}Bi

Enhancement sensitivity for pep and CNO neutrinos

NSI formalism in the framework of Borexino

In the SM the neutrino-electron scattering at low energy is described by:

$$\mathcal{L}_{\mathrm{SM}} = -2\sqrt{2}G_F(\overline{\nu}_\alpha\gamma^\mu P_L\nu_\alpha)\left[\, g_R(\overline{e}\gamma_\mu P_R e) + g_L(\overline{e}\gamma_\mu P_L e)\,\right]$$

Assuming extra weak-strength interactions:

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\substack{\alpha,\beta \\ l,l',X}} \varepsilon_{\alpha\beta}^{ll'X}\,(\overline{\nu}_\alpha\gamma_\mu P_L\nu_\beta)\left(\overline{l}\gamma^\mu P_X l'\right)$$

with X = L, R

In Borexino l' = l = e: same lepton in the initial and final state

Probe only $\varepsilon_{\alpha\beta}^{L/R}$: **12 parameters**

Possible rearrangement: $\varepsilon_{\alpha\beta}^{V/A} = \frac{1}{2}\left(\varepsilon_{\alpha\beta}^{R} \pm \varepsilon_{\alpha\beta}^{L}\right)$

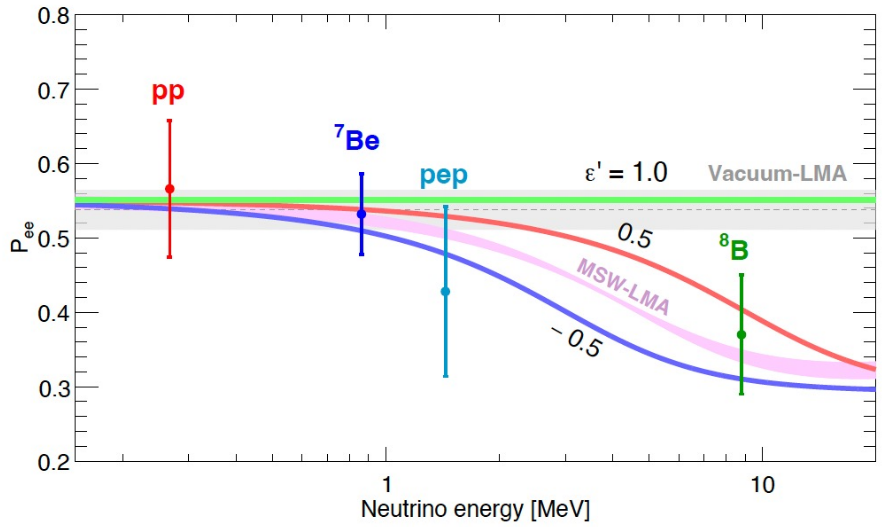
$$\varepsilon_{\alpha\beta} = \varepsilon_{\alpha\beta}^{L} + \varepsilon_{\alpha\beta}^{R}$$

NSI and neutrino propagation

- With NSI neutrino propagation is affected by a shift in the matter-effect potential, leading to a modification of the electron neutrino survival probability, P_{ee}

NSI affect the resonance energy

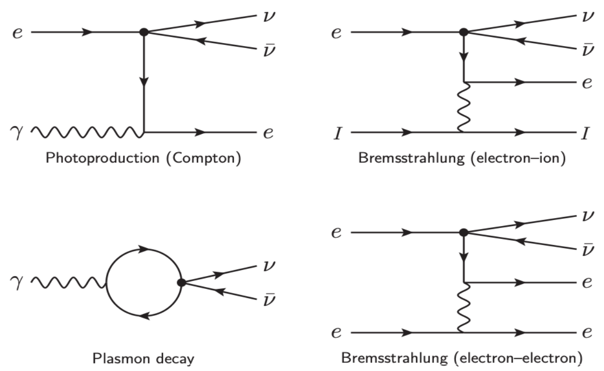
- $E_{res}^{\odot}(0) \sim \frac{2\ MeV}{1-\varepsilon'}$
- $E_{res}^{\oplus}(0) \sim \frac{30\ MeV}{1-\varepsilon'}$ Earth matter effect small



$with\ \varepsilon' = \varepsilon_{\tau\tau}^{V} sin^2\theta_{23} + \varepsilon_{\mu\mu}^{V} cos^2\theta_{23} - \varepsilon_{ee}^{V}$ and $V_{matt}(x) = \sqrt{2}\, G_F N_e(x) \rightarrow (1-\varepsilon')\sqrt{2}\, G_F N_e(x)$

Remark

- Solar neutrinos pruduced by Hydrogen to Helium conversion with a flux of 6.6×10^{10} $cm^{-2}s^{-1}$
- NSI can affect neutrino production (E. Vitigliano et al. JCAP 1712 (2017) 010)



- These processes affect the neutrino spectrum below 100 keV where Borexino is not sensitive.
- The predicted flux < 10^6 $cm^{-2}s^{-1}$
- No effect at production is included in probing NSI with Borexino

Observable: recoiled electron spectrum

$$\frac{dR_\nu}{dT} = N_e \Phi_\nu \int dE_\nu \frac{d\lambda_\nu}{dE} \left[P_{ee} \frac{d\sigma_e}{dT} + P_{e\mu} \frac{d\sigma_\mu}{dT} + P_{e\tau} \frac{d\sigma_\tau}{dT} \right]$$

$$\frac{dR_\nu}{dT} = N_e \phi_\nu \int dE_\nu \frac{d\lambda}{dE_\nu} \left[P_{ee} \frac{d\sigma_e}{dT} + (1 - P_{ee}) \left(c_{23}^2 \frac{d\sigma_\mu}{dT} + s_{23}^2 \frac{d\sigma_\tau}{dT} \right) \right] \quad with\ \theta_{13} \sim 0$$

$$\frac{d\sigma_\alpha(E,T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_{\alpha L}^2 + g_{\alpha R}^2 \left(1 - \frac{T}{E}\right)^2 - g_{\alpha L} g_{\alpha R} \frac{m_e T}{E^2} \right]$$

$$g_{\alpha L} = \begin{cases} g_{LL}^{\nu e} + 1 & \text{for } \alpha = e, \\ g_{LL}^{\nu e} & \text{for } \alpha = \mu, \tau, \end{cases}$$

$$g_{\alpha R} = g_{LR}^{\nu e} \quad \text{for } \alpha = e, \mu, \tau.$$

$$\begin{aligned} g_{LV}^{\nu e} &= -\frac{1}{2} + 2\sin^2\theta_W\ , \\ g_{LA}^{\nu e} &= -\frac{1}{2}\ , \\ g_{LL}^{\nu e} &= \frac{1}{2}(g_{LV}^{\nu e} + g_{LA}^{\nu e}) = -\frac{1}{2} + \sin^2\theta_W\ , \\ g_{LR}^{\nu e} &= \frac{1}{2}(g_{LV}^{\nu e} - g_{LA}^{\nu e}) = \sin^2\theta_W\ . \end{aligned}$$

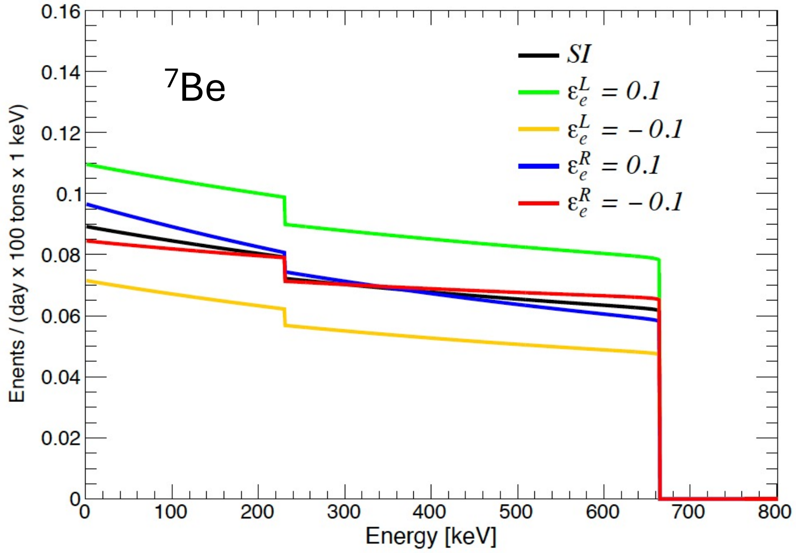
$$R_\nu = \int \frac{dR_\nu}{dT} dT = N_e \Phi_\nu \langle \sigma_\nu \rangle$$

NSI :

$$\begin{aligned} g_{\alpha R} &\rightarrow \tilde{g}_{\alpha R} = g_{\alpha R} + \varepsilon_\alpha^R\ , \\ g_{\alpha L} &\rightarrow \tilde{g}_{\alpha L} = g_{\alpha L} + \varepsilon_\alpha^L\ . \end{aligned}$$

NSI and detection channel

- With NSI the detection channel is affected by a change in the couplings, leading to a change in the electron recoil spectrum: normalization and spectral shape
- Due to the ^{7}Be monocromatic line Borexino is specially sensitive to these modifications provided S/B >>1



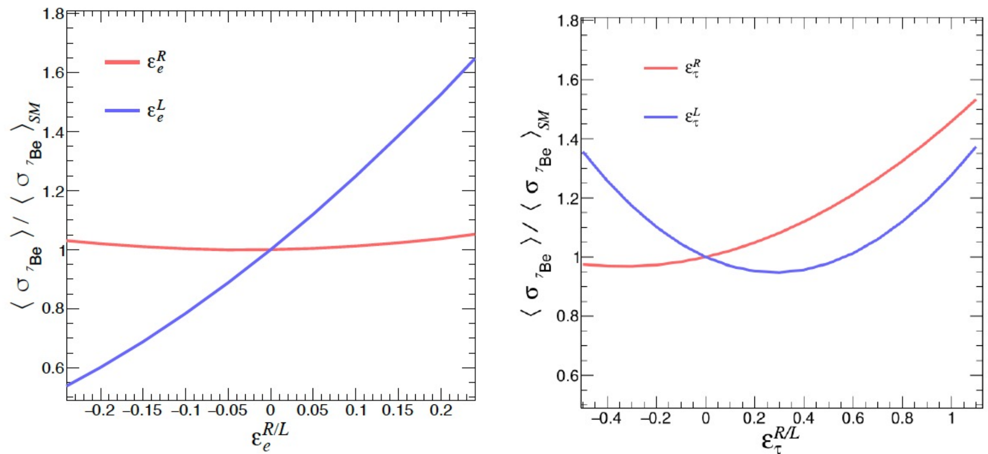
Total rate

Propagation Detection

$$\frac{dR_\nu}{dT} = N_e \Phi_\nu \int dE_\nu \frac{d\lambda_\nu}{dE} \left[P_{ee} \frac{d\sigma_e}{dT} + P_{e\mu} \frac{d\sigma_\mu}{dT} + P_{e\tau} \frac{d\sigma_\tau}{dT} \right]$$

$$R_\nu = \int \frac{dR_\nu}{dT} dT = N_e \Phi_\nu \langle \sigma_\nu \rangle$$

- NSI effects at propagation and detection are both included in $\langle\sigma_\nu\rangle$
- In Borexino the best sensitivity is obtained from the monoenergetic ^{7}Be solar neutrinos
- ε_e^L is constrained by the normalization of the cross section, while ε_e^R by the spectral shape of recoil e^-



Fit method

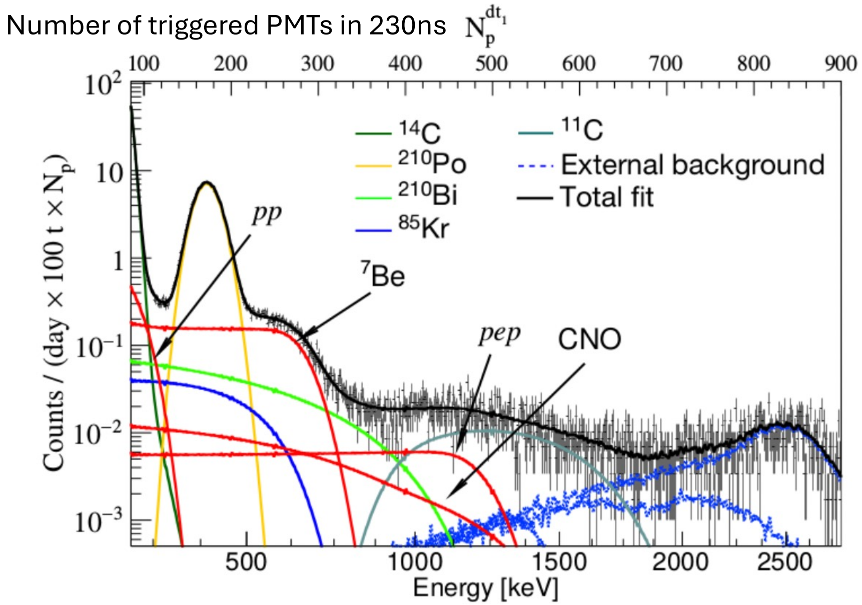
- Due to the large number of parameters a new analysis method was exploited
- Detector response function was not calculated for all NSI parameters (12 with off-diagonal terms)
- Method:
  - Determine MC PDF response S_{MC} as a function of the energy estimator Q, Nhits
  - Use electron recoil spectrum S_0 (no NSI) and detector response and resolution G
  - Perform deconvolution to calculate response function G_{RW}
  - Use G_{RW} to determine PDF with NSI
- Validation with solar neutrino fit

$$S_{MC}(Q) = S_0\big(E_R(Q)\big) \otimes G(Q)$$

$$G_{RW}(Q) = S_0(E_R(Q))^{-1} \otimes S_{MC}(Q)$$

$$S_{RW}(Q) = S_{NSI}\big(E_R(Q)\big) \otimes G_{RW}(Q)$$

Data selection and fit



- Phase-III data (2016-2021)
- Exposure 1500 days x 70 tons
- 2 ms rejection after cosmic muons
- Fiducial Volume: r < 2.8 m and -1.8 < z < 2.2 m
- Floating parameters: light yield, energy resolution parameters (2), ^{210}Po peak width (2), ^{11}C e$^+$ quenching
- Neutrino oscillation parameters fixed to global fit best values with penalties
- Solar neutrino fluxes from SSM (HZ, LZ)
- Fit: multivariate likelihood + penalty terms

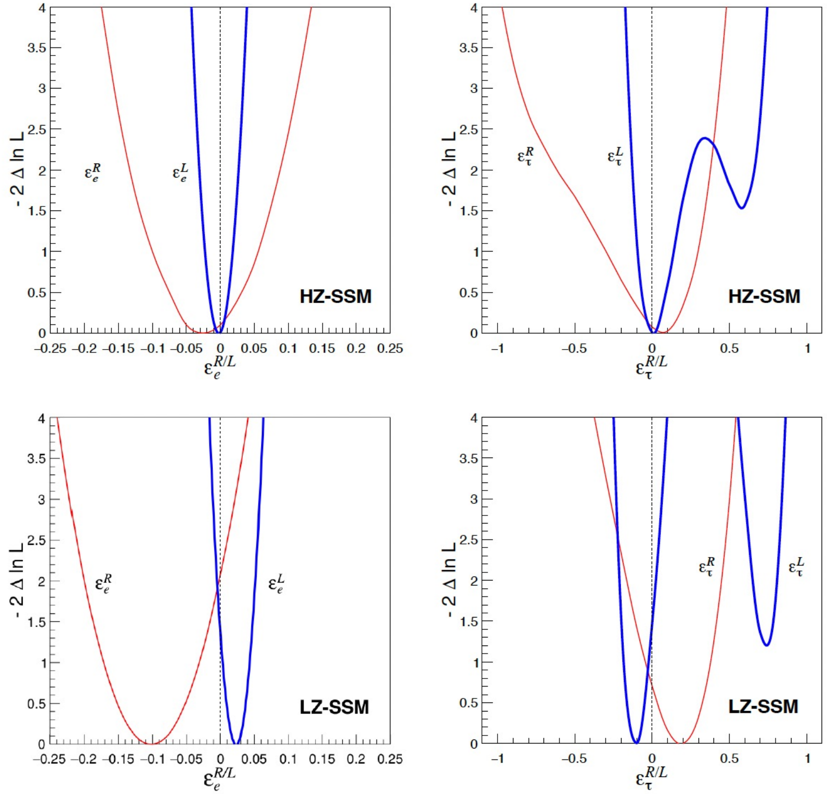
$$\mathcal{L}(\vec{k}\,|\varepsilon,\vec{\theta}) \;=\; \mathcal{L}_{sub}^{TFC}(\vec{k}\,|\varepsilon,\vec{\theta}) \cdot \mathcal{L}_{tag}^{TFC}(\vec{k}\,|\varepsilon,\vec{\theta}) \cdot \mathcal{L}_P(\vec{k}\,|\vec{\theta}) \cdot \mathcal{L}_R(\vec{k}\,|\vec{\theta})$$

Backgrounds in Borexino

	Phase-I	Phase-II	Phase-III
^{210}Bi	$\sim$ 42 cpd/100t	$\sim$ 18 cpd/100t	$\sim$ 11 cpd/100t
^{210}Po	$\sim$ 700 cpd/100t	$\sim$ 250 cpd/100t	$<$ 20 cpd/100t
^{85}Kr	$\sim$ 35 cpd/100t	$<$ 6.8 cpd/100t (95% CL)	$<$ 11 cpd/100t (95% CL)
^{238}U	$(5.3 \pm 0.5) \times 10^{-18}$ g/g	$< 9.4 \times 10^{-20}$ (95% CL)	$(6.5 \pm 2.2) \times 10^{-20}$
^{232}Th	$(3.8 \pm 0.8) \times 10^{-18}$ g/g	$< 5.7 \times 10^{-19}$ (95% CL)	$< 2.8 \times 10^{-19}$ (95% CL)

Bound on NSI parameters

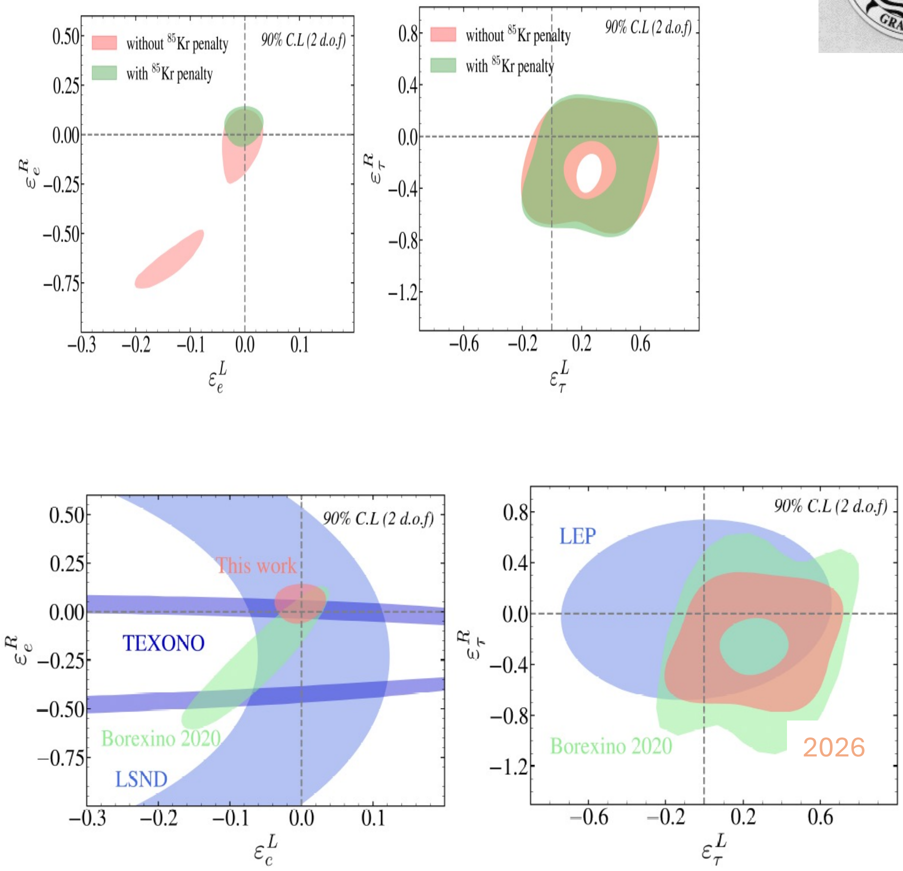
- One ε at a time
- Better sensitivity on ε_e^L depends on sensitivity on normalization of neutrino rates
- On the contrary the shape is affected by background compoments such as ^{85}Kr
- Shifts for LZ-SSM is due to a lower ^{7}Be flux



Results from Borexino [1]

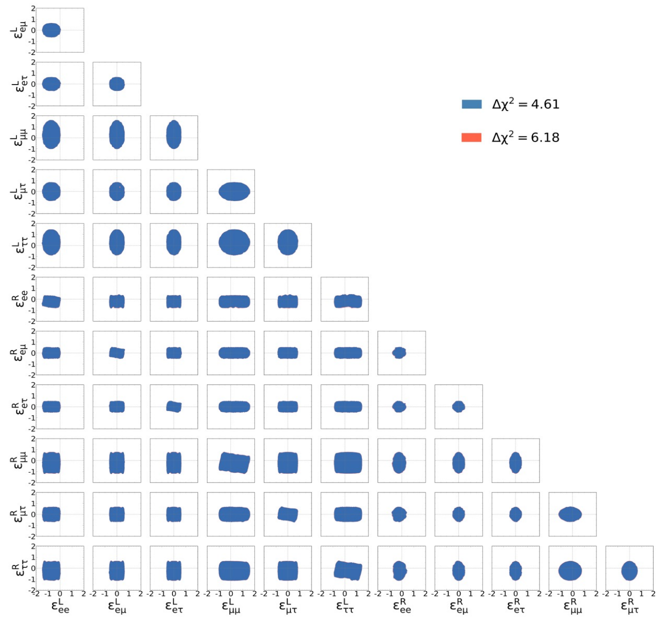
	90% C.L. region		90% C.L. region
ε_e^L	[-1.47, 0.04]	ε_e^R	[-0.73, 0.33]
$\varepsilon_{e\mu}^L$	[-0.63, 0.63]	$\varepsilon_{e\mu}^R$	[-0.53, 0.53]
$\varepsilon_{e\tau}^L$	[-0.62, 0.62]	$\varepsilon_{e\tau}^R$	[-0.52, 0.52]
ε_{μ}^L	[-1.01, 1.61]	ε_{μ}^R	[-1.13, 0.66]
$\varepsilon_{\mu\tau}^L$	[-0.84, 0.84]	$\varepsilon_{\mu\tau}^R$	[-0.63, 0.63]
ε_{τ}^L	[-0.86, 1.45]	ε_{τ}^R	[-1.07, 0.57]

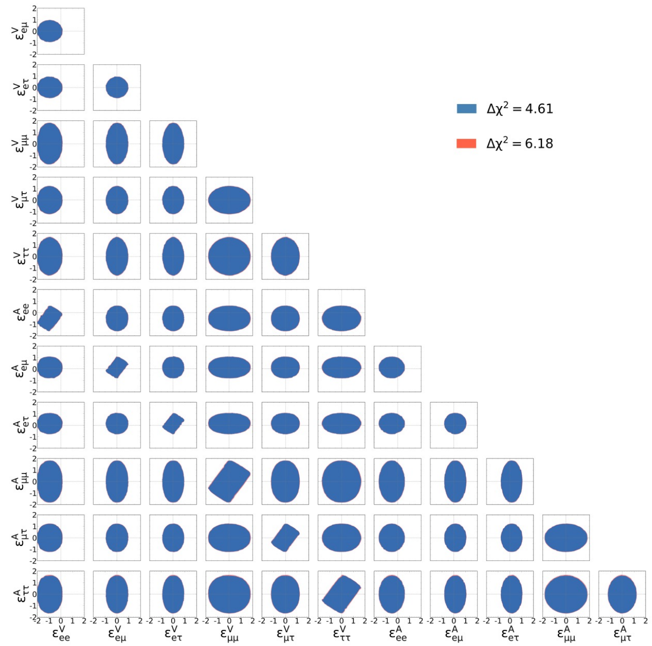
Neutrinos: ^{7}Be + pep + CNO



Results from Borexino [2]

	90% C.L. region		90% C.L. region
ε_e^V	[-1.97, 0.19]	ε_e^A	[-1.47, 0.48]
$\varepsilon_{e\mu}^V$	[-0.97, 0.97]	$\varepsilon_{e\mu}^A$	[-0.94, 0.85]
$\varepsilon_{e\tau}^V$	[-0.96, 0.96]	$\varepsilon_{e\tau}^A$	[-0.95, 0.83]
ε_μ^V	[-1.7, 1.96]	ε_μ^A	[-1.96, 1.96]
$\varepsilon_{\mu\tau}^V$	[-1.23, 1.23]	$\varepsilon_{\mu\tau}^A$	[-1.18, 1.18]
ε_τ^V	[-1.65, 1.67]	ε_τ^A	[-1.78, 1.78]





Results from global fit

- **Borexino Phase-II** data analysed by Coloma et al. JHEP 07 (2022) 138 and global fit JHEP 2023
- 22 uncorrelated pulls to include background uncertainties
- 5 correlated pulls for SSM priors
- 12 NSI parameters
- In order to reduce the number of parameters a few representative cases are selected
  - Purely vector case ($\varepsilon^L_{\alpha\beta} = \varepsilon^R_{\alpha\beta}$)
  - Purely axial case ($\varepsilon^L_{\alpha\beta} = -\varepsilon^R_{\alpha\beta}$)

effective coeff.

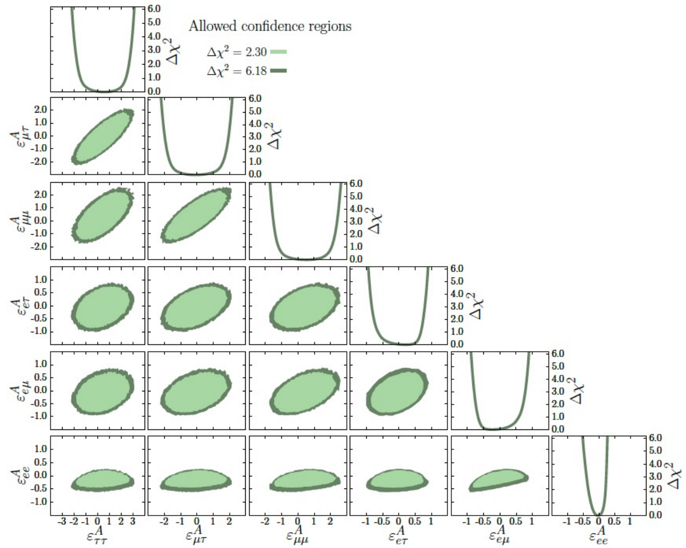
$$\mathcal{E}_{\alpha\beta}(x) = (\varepsilon^{e,V}_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}) + Y_n(x)\, \varepsilon^{n,V}_{\alpha\beta} \quad \text{with} \quad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)}$$

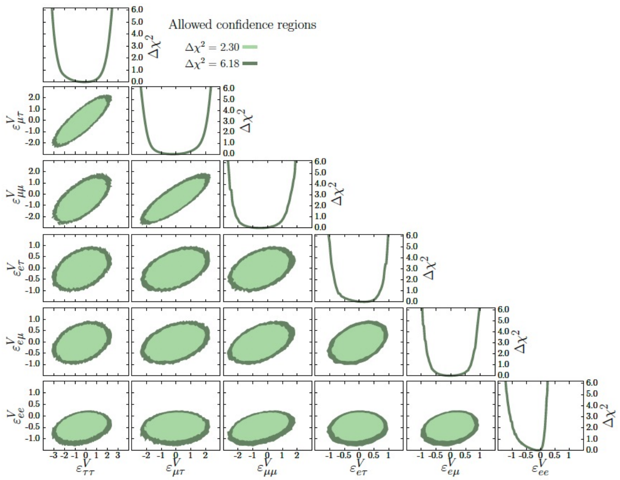
2022

	Allowed ranges at 90% CL (marginalized)			
	Vector ($X = V$)		Axial-vector ($X = A$)	
	Borexino	GLOB-OSC w NSI in ES	Borexino	GLOB-OSC w NSI in ES
$\varepsilon^{e,X}_{ee}$	$[-1.1, +0.17]$	$[-0.13, +0.10]$	$[-0.38, +0.24]$	$[-0.13, +0.11]$
$\varepsilon^{e,X}_{\mu\mu}$	$[-2.4, +1.5]$	$[-0.20, +0.10]$	$[-1.5, +2.4]$	$[-0.70, +1.2]$
$\varepsilon^{e,X}_{\tau\tau}$	$[-2.8, +2.1]$	$[-0.17, +0.093]$	$[-1.8, +2.8]$	$[-0.53, +1.0]$
$\varepsilon^{e,X}_{e\mu}$	$[-0.83, +0.84]$	$[-0.097, +0.011]$	$[-0.79, +0.76]$	$[-0.41, +0.40]$
$\varepsilon^{e,X}_{e\tau}$	$[-0.90, +0.85]$	$[-0.18, +0.080]$	$[-0.81, +0.78]$	$[-0.36, +0.36]$
$\varepsilon^{e,X}_{\mu\tau}$	$[-2.1, +2.1]$	$[-0.0063, +0.016]$	$[-1.9, +1.9]$	$[-0.79, +0.81]$

2023

	Allowed regions at 90% CL ($\Delta\chi^2 = 2.71$)			
	Vector		Axial Vector	
	1 Parameter	Marginalized	1 Parameter	Marginalized
ε_{ee}	$[-0.09, +0.14]$	$[-1.05, +0.17]$	$[-0.05, +0.10]$	$[-0.38, +0.24]$
$\varepsilon_{\mu\mu}$	$[-0.51, +0.35]$	$[-2.38, +1.54]$	$[-0.29, +0.19] \oplus [+0.68, +1.45]$	$[-1.47, +2.37]$
$\varepsilon_{\tau\tau}$	$[-0.66, +0.52]$	$[-2.85, +2.04]$	$[-0.40, +0.36] \oplus [+0.69, +1.44]$	$[-1.82, +2.81]$
$\varepsilon_{e\mu}$	$[-0.34, +0.61]$	$[-0.83, +0.84]$	$[-0.30, +0.43]$	$[-0.79, +0.76]$
$\varepsilon_{e\tau}$	$[-0.48, +0.47]$	$[-0.90, +0.85]$	$[-0.40, +0.38]$	$[-0.81, +0.78]$
$\varepsilon_{\mu\tau}$	$[-0.25, +0.36]$	$[-2.07, +2.06]$	$[-1.10, -0.75] \oplus [-0.13, +0.22]$	$[-1.95, +1.91]$





Conclusions

- From 2027 to 2021 Borexino has detected neutrino-electron ES of solar neutrinos performing precision spectroscopy of the solar neutrino spectrum
- The Borexino low background and high statistics spectral data allow to probe NSI and improve the global fit with NSI
- Understanding neutrino NSI is crucial for the correct interpretation of neutrino oscillation measurements
- Global fit improves significantly the sensitivity
- Probing NSI in the future will imply synergy between oscillation experiments and CEνNS
- Next-generation DM direct detection experiment are approaching the neutrino floor. NSI can produce significant deviations to expected results.
  - Increase of up to a factor of 5 wrt to the «standard» scenario (JHEP 07 (2018) 019)