Solar neutrinos: overview and new Borexino results

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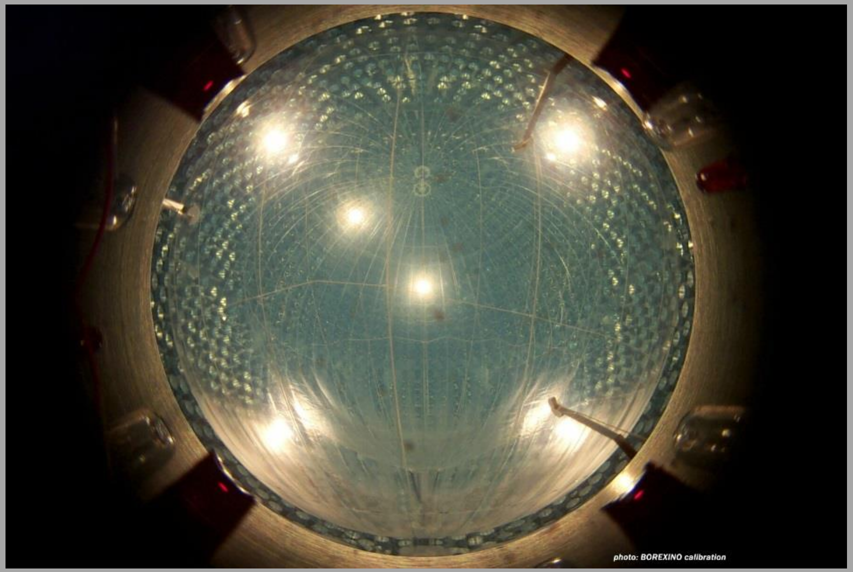
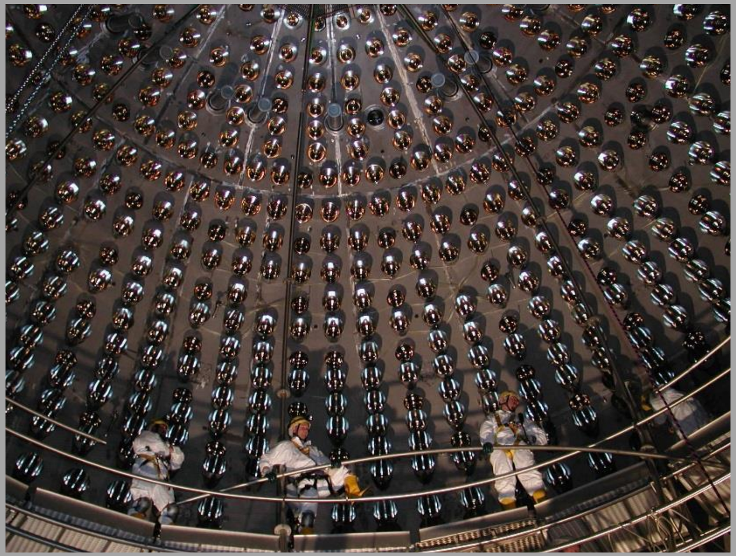
On behalf of the Borexino Collaboration

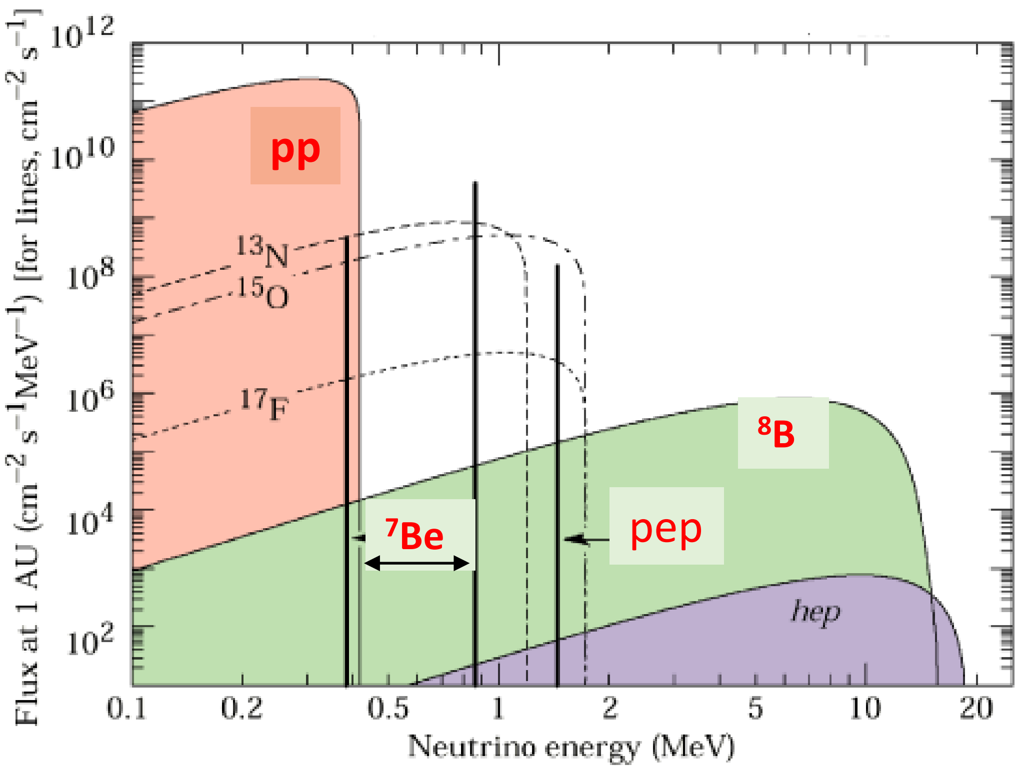


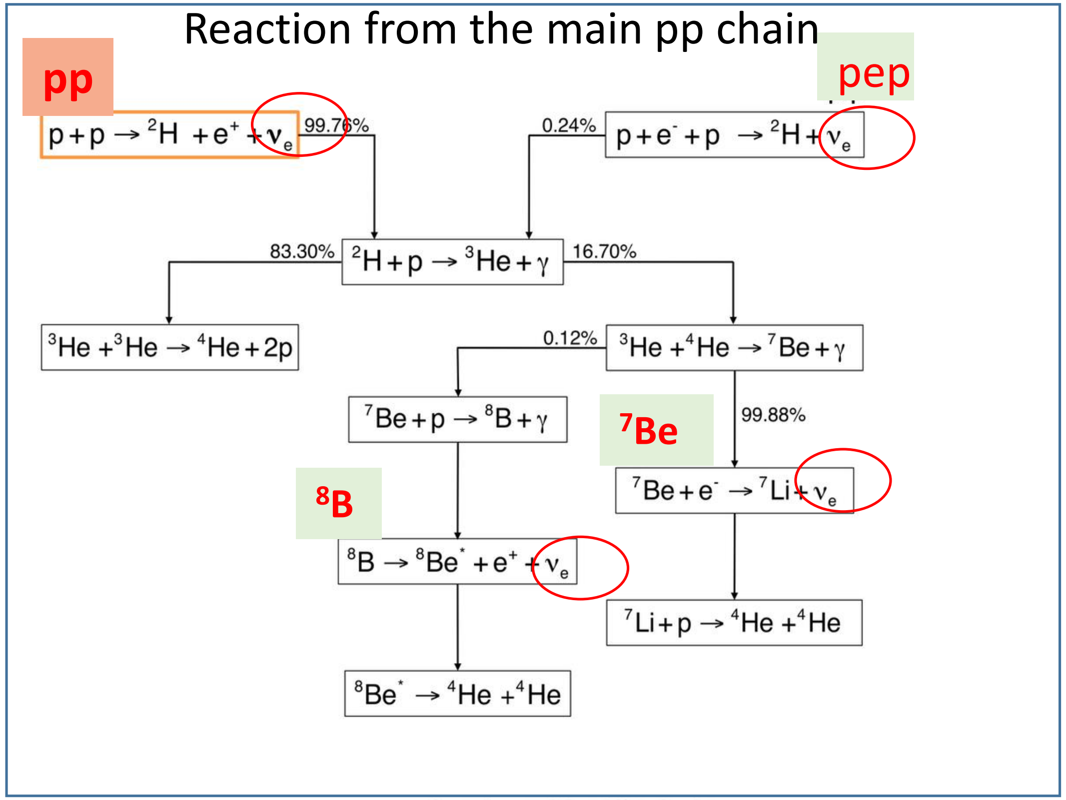
The Borexino nylon vessel filled with the scintillator
(picture of few days ago)



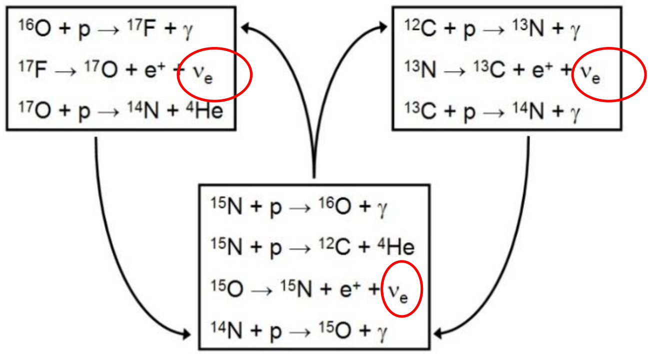
Inside view of the Borexino sphere holding the Photomultipliers

Solar Neutrinos





Reactions of the CNO Cycle



- Fusion reactions in the core of the Sun
- pp dominant in the SUN (99% of the energy and ν production))
- CNO important for larger mass stars

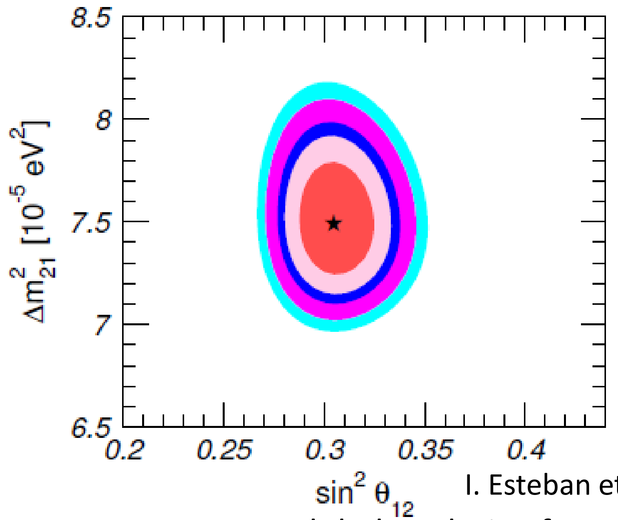
$$4H + 2e^- \rightarrow {}^4He + 2e^+ + 2\upsilon_e + 26.7 \quad MeV$$

About 50 years of solar ν: from the solar ν problem to ν oscillation: LMA-MSW

		ν detected	Signal	Signal/SSM
Radiochemical	Homestake	^{7}Be, pep, CNO, ^{8}B	256 ± 0.23 SNU	0.32 ± 0.05
Radiochemical	Gallex/GNO /SAGE	pp,^{7}Be, pep,CNO,^{8}B	66.2 ± 3.1 SNU	0.52 ± 0.03
Water Cherenkov	SK I+II+III+IV	^{8}B	Φ_{8B}=2.345±0.039 10^6 cm^{-2} s^{-1}	0.42 ± 0.06
Water Cherenkov	SNO	^{8}B	Φ_{ES}=2.04±0.18 10^6 cm^{-2} s^{-1} Φ_{CC}=1.67±0.07 10^6 cm^{-2} s^{-1} Φ_{nc}=5.25±0.20 10^6 cm^{-2} s^{-1}	0.36 ± 0.06 0.30 ± 0.04 0.94 ± 0.14
Scintillator	Kamland	^{7}Be ^{8}B	58.2± 9.4 cpd/100t 0.15 ± 0.02 cpd/100t	0.66 ± 0.11
Scintillator	Borexino Phase I (new Phase II not included here)	pp (Phase II) ^{7}Be pep CNO ^{8}B	144 ± 16 cpd/100t 46.0± 2.2 cpd/100t 3.1 ± 0.7 cpd/100t 0.22 ± 0.04 cpd/100t <7.9 95% CL cpd/100t	0.75 ± 0.08 0.63 ± 0.05 0.70 ± 0.15 0.43 ± 0.10

- Evidence of ν oscillations
- Interaction of ν with matter MSW

Kamland reactor results + solar
(before Borexino&Kamland solar) : LMA-MSW (year 2002)



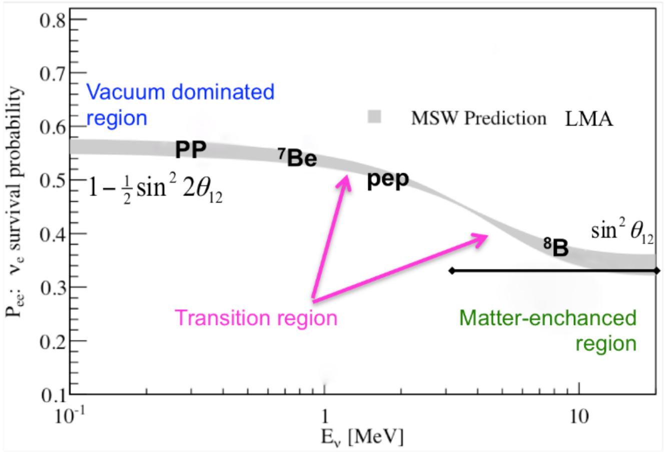
I. Esteban et al, JHEP 01 (2017).
Global analysis of oscillation data

Presently:
- SuperK
- Borexino

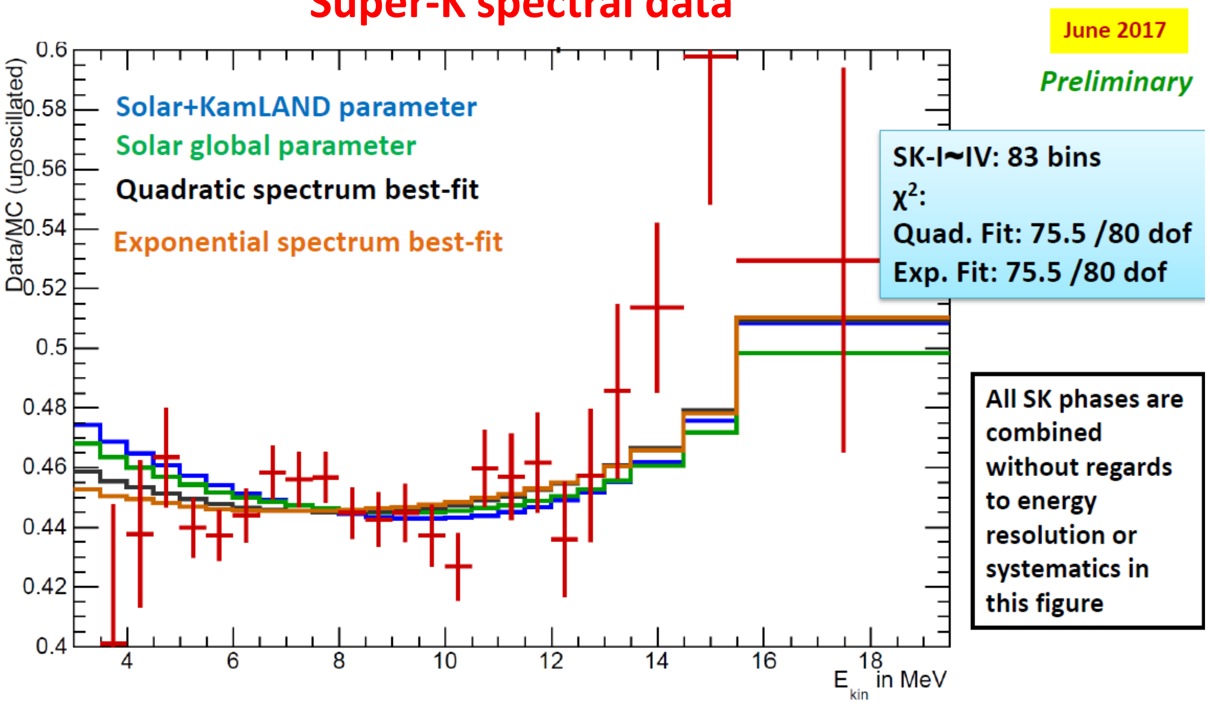
Adapted from A. Ianni Prog. Part. Nucl. Phys. 94 257 (2017)

Why do we still measure solar ν? 1) Precision meas. to confirm LMA-MSW prediction

- Pee should show a vacuum to matter transition
- Non Standard Interactions modify Pee
- Precise flux meas. of single spectral component
- Measure ^{8}B with low threshold
- Have good accuracy for the lowest ^{8}B energy bin



Super-K spectral data

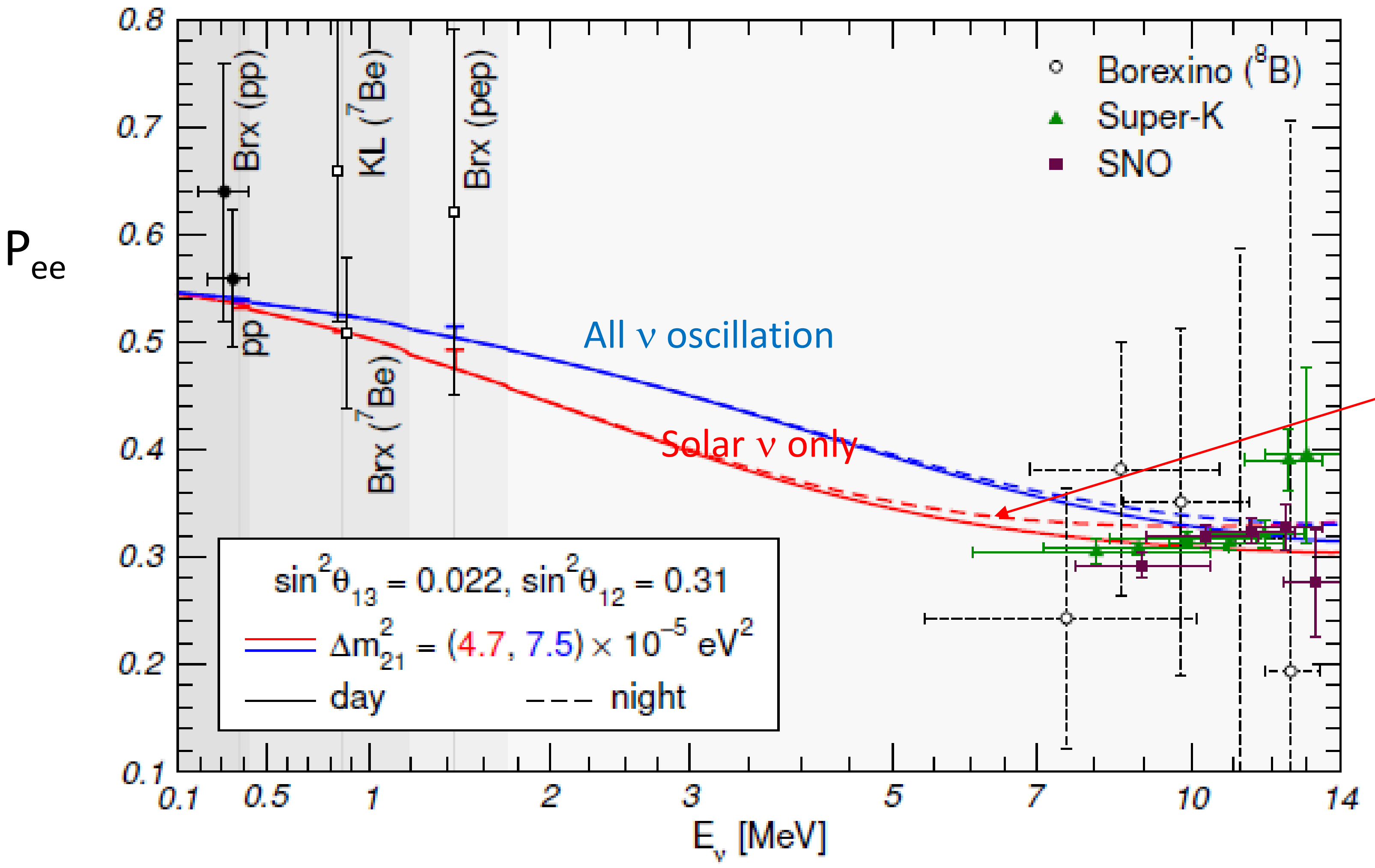


All SK phases are combined without regards to energy resolution or systematics in this figure

Plot from Yasuo Takeuchi
(Kamland Coll, Quy Nhon 18-July 2017)
Preliminary

SK spectrum is consistent within
1 σ with the MSW upturn obtained
with Osc. Param from solar
2 σ with MSW upturn obtained
with Osc Param. from solar+Kamland

Pee vs energy: the importance of the precision spectroscopy



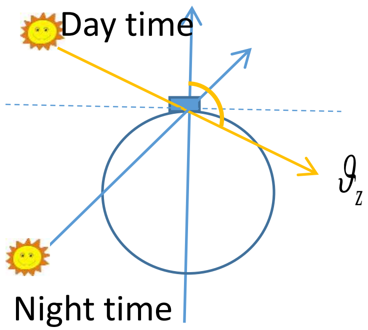
LMA-MSW

- Matter effect in the Earth:
- Day-Night flux asymmetry
- Only at high energy

Maltoni & Smirnov,Eur.Phys.J.2016

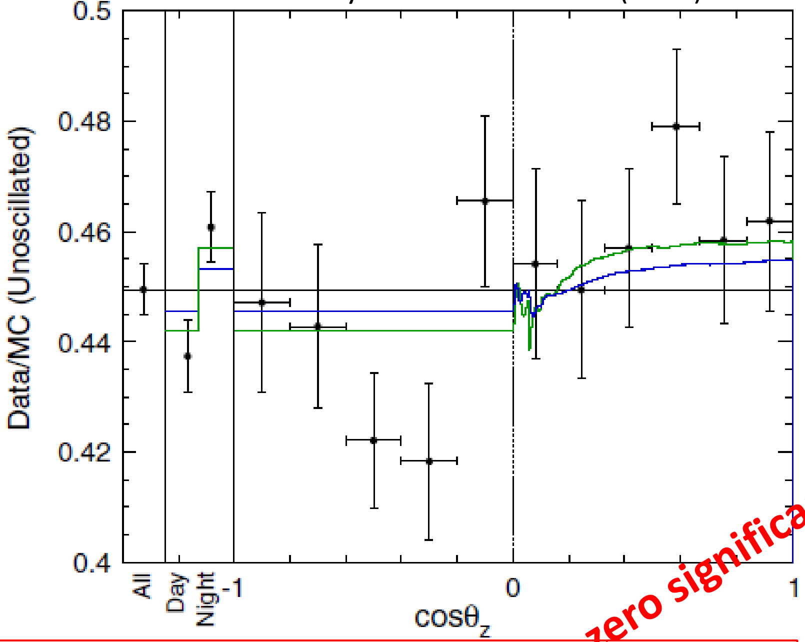
Why do we still measure solar n? 1) Confirm LMA-MSW prediction

- Matter effect in ν oscillation
- Regeneration effect during night (ν traverse the Earth)
- LMA-MSW: no effect for ^{7}Be, measurable effect for ^{8}B



SuperKamiokande ^{8}B E>4.5 MeV

SK Coll. Phys. Rev. D 94 052010 (2016)

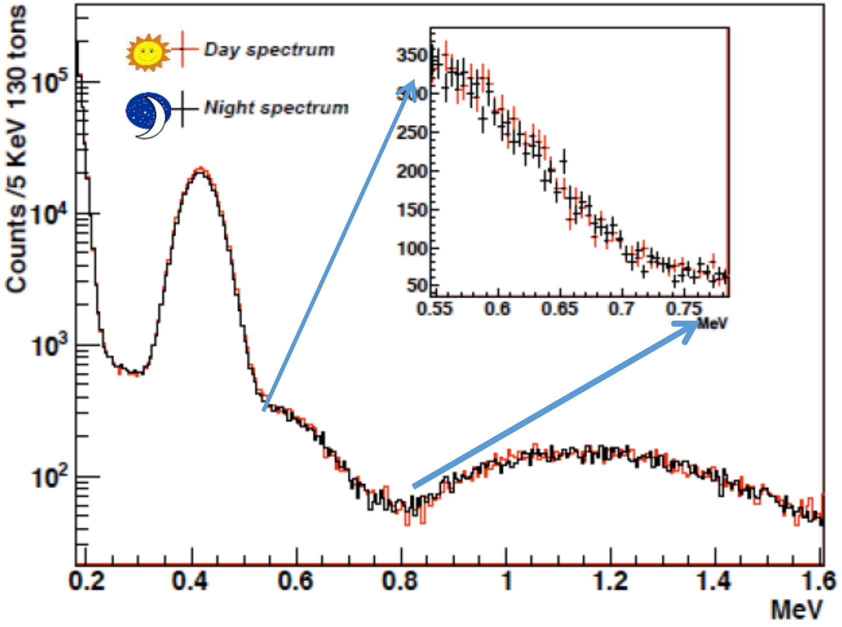


Non zero significance 3σ !!!

$$A_{DN}^{8B} = \frac{D-N}{(N+D)/2} = (-3.3 \pm 1.0 \pm 0.5)\%$$

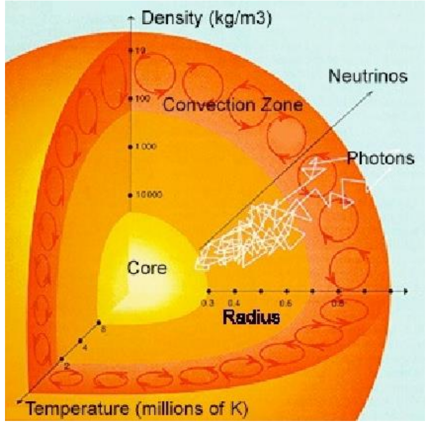
Borexino Phase I : ^{7}Be

Borexino Coll., Phys. Lett. B707 (2012) 22.



$$A_{DN}^{^{7}Be} = \frac{D-N}{(N+D)/2} = (-0.1 \pm 1.2 \pm 0.7)\%$$

Why do we still measure solar ν? 2) Solar models



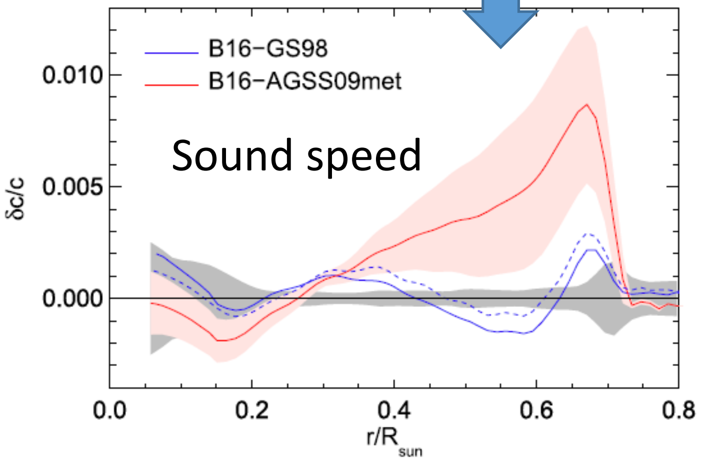
- Evolution of a star from beginning until now 4.57 10^9y
- Homogeneous mixture of H,He and heavy elements X_{ini}, Y_{ini}, Z_{ini}
- α_{MLT} : parameter entering in the description of the convection
- Cross sections for nuclear reactions (S factors)
- Opacity
- Equilibrium between gravitational force and outward force due to gradient of pressurre P(r)

Initial parameters adjusted to reproduce present days status:

Solar Luminosity L
Solar Radius
Z/X (abundance of metals) on the surface

Observables : elioseismology
solar neutrinos
……….

Since 2001: new analysis of spectroscopic data from photosphere, revision of surface solar metallicity, lower values (LZ)
But solar models reproducing these new LZ values **disagree with elioseismology data** (solar abundance problem)



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017)
Improoved model

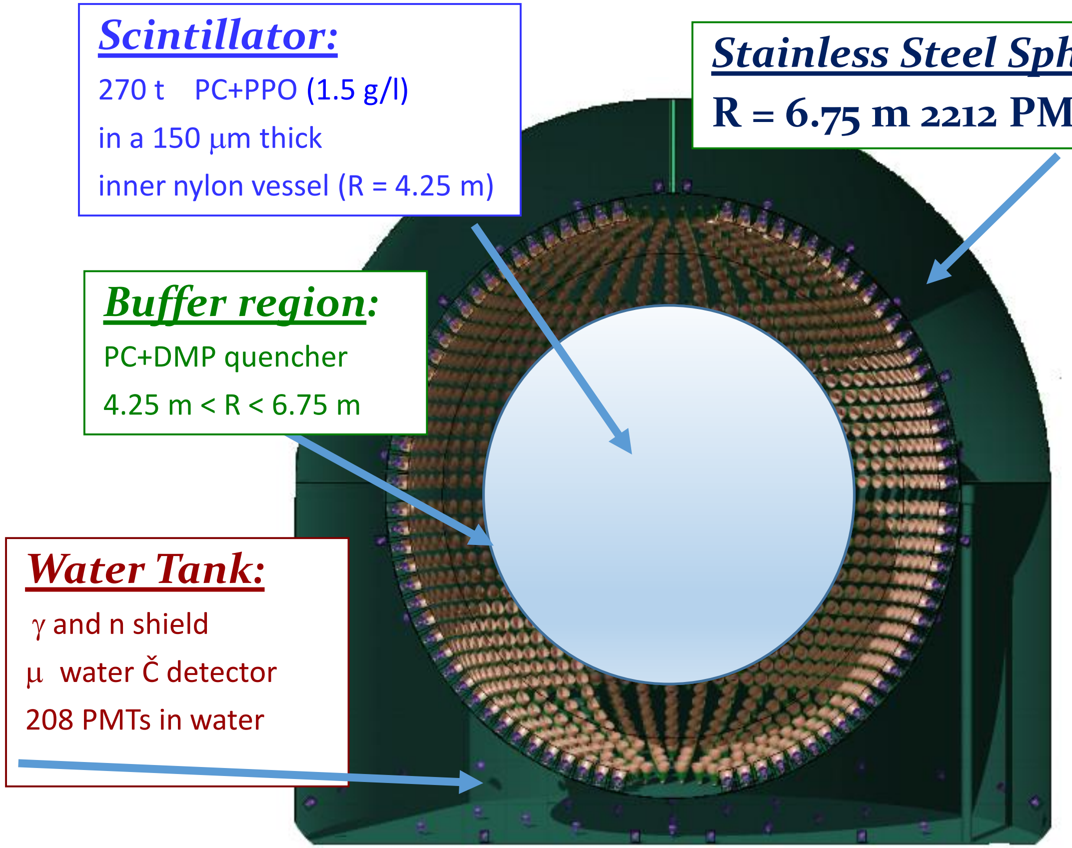
The prediction of solar ν flux is sensitive to the Sun metallicity

Flux	B16-GS98 HZ	B16-AGSS09met LZ
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
CNO $\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

Units:
pp: 10^{10} cm^{-2} s^{-1};
Be: 10^9 cm^{-2} s^{-1};
pep, N, O: 10^8 cm^{-2} s^{-1};
B, F: 10^6 cm^{-2} s^{-1};
hep: 10^3 cm^{-2} s^{-1}

^{7}Be: 8.7% diff
^{8}B: 17.6% diff
CNO: 40% diff

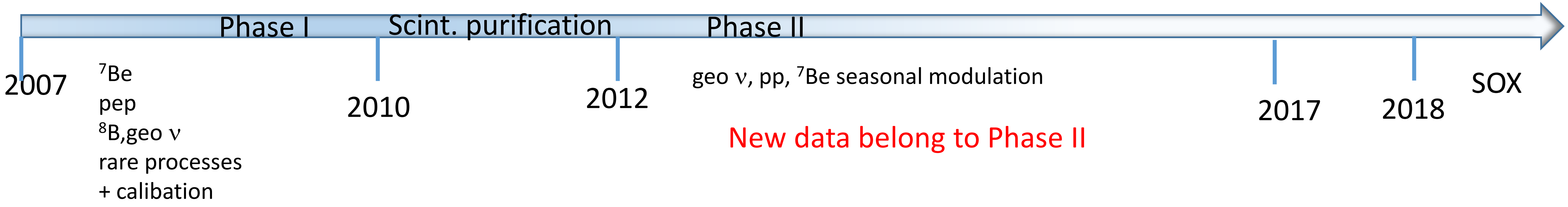
Borexino detector@LNGS



- **ν detection:** $\nu_x + e^- \rightarrow \nu_x + e^-$
- **Energy E:** N_p : Normalized number of hits PMts
  N_h : including multiple hits
  N_{pe}: number of phe (charge)
- **Position:** PMT hit time

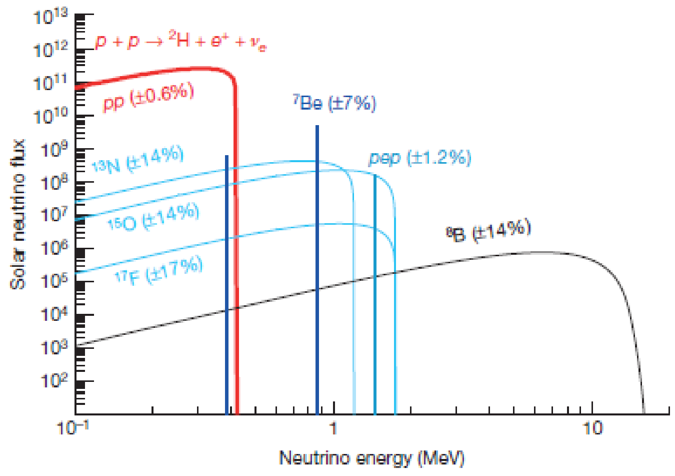
550 N_p @1MeV σ_E= 50 KeV@1MeV

$\sigma_{x,y,z}$ =10 cm@1MeV



New data belong to Phase II

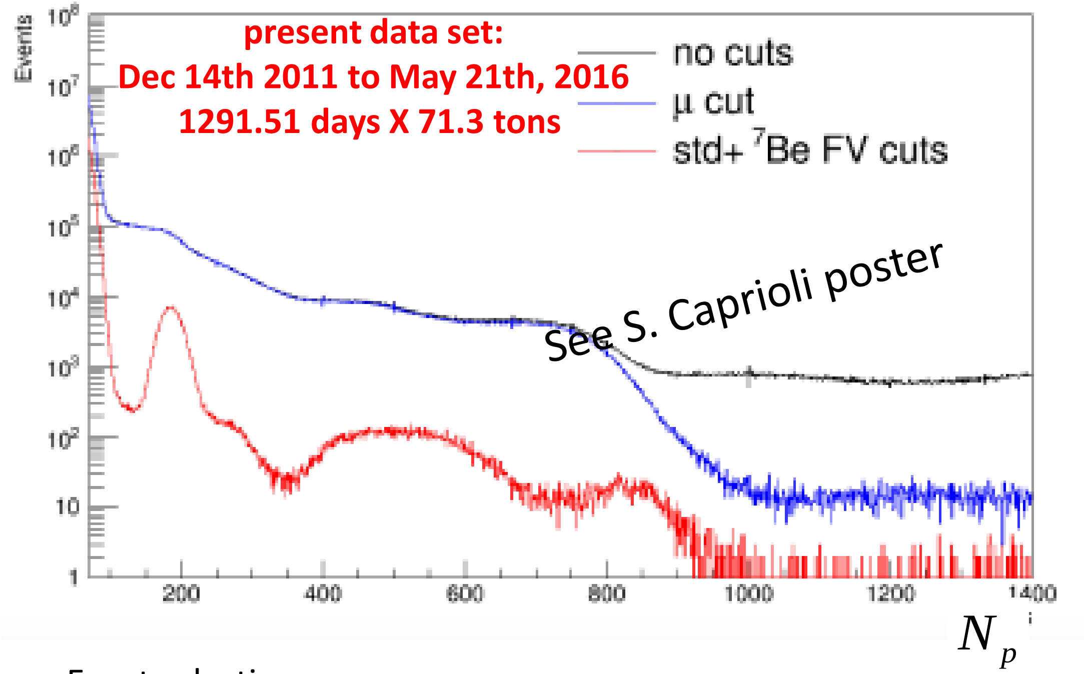
New Borexino results: first simultaneous precision spectroscopy of low energy solar ν with Phase II data



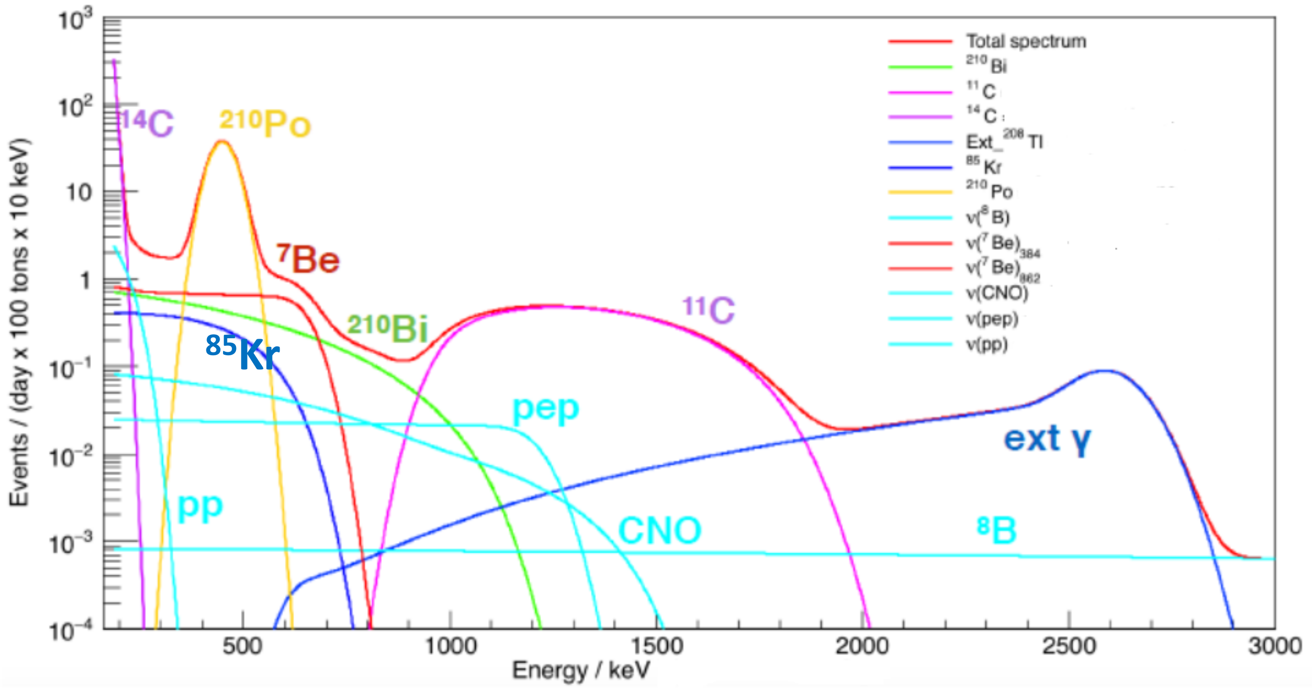
- Low energy
  - ➢ pp, ^{7}Be, pep interaction rates and fluxes (CNO limit)
- Precision
  - ➢ We increase the accuracy of our previous results
  - ➢ Increased exposure
  - ➢ Lower background
  - ➢ Improved models of the detector response functions
- First simultaneous
  - ➢ We analyze simultaneously all the energy spectrum from **0.186 to 2.97 MeV**
  - ➢ All ν obtained with a single analysis
  - ➢ Previous data were obtained analyzing selected regions of the spectrum

Signal and background

Data energy spectrum
before and after cuts



Simulated energy spectrum
including solar ν and the main background components



Event selection

- removal μ and cosmogenics (1.5% dead time)
- removal of Bi-Po214
- noise events
- Fiducial Volume (R<2.8 m, -1.8 < z < 2.2m)
- 71.3 tons
- no αβ discrimination
- Fraction of good events removed by cuts <0.1%

Purification: reduction of ^{85}Kr, ^{210}B

^{232}Th (from ^{212}Bi-Po)

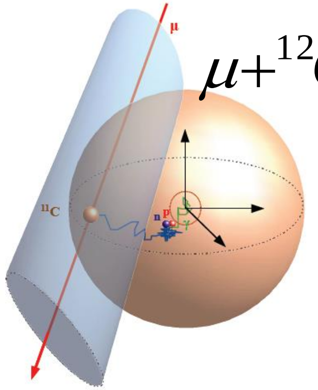
- < 5.7 10^{-19} g/g 95% C.L.
- PHASE 1: 3 10^{-18} g/g

^{238}U (from ^{214}Bi-Po)

- < 9.4 10^{-20} g/g 95% C.L.
- PHASE 1: 5 10^{-18} g/g

11C: Three Fold Coincidence and β+/β- discrimination

$$^{11}C \rightarrow \beta^{+}, \tau = 29 \quad \text{min}$$

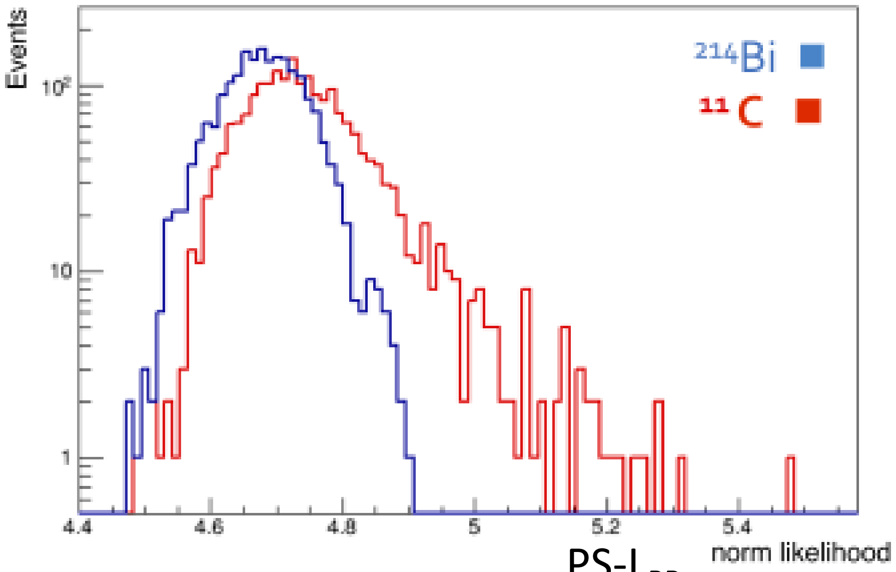


$$\mu + ^{12}C \rightarrow \mu + n + ^{11}C$$

- Identify μ and μ track
- Detect n (γ signal due to capture after themalization)
- Space time cuts around the μ track and n position: ^{11}C should be there
- Build a Likelihood function to evaluate if an event is a ^{11}C

Divide the exposure in 2 samples: ^{11}C subtracted & ^{11}C tagged

Performances: 92.4 +- 4 % tagging efficiency
exposure: 64% in the ^{11}C subtracted spectrum



PS-L_{PR}

Novel β+/β- pulse shape parameter:
Energy normalized likelihood of the position reconstruction

- Pdf of the position rec. assumes point like, prompt scintillation but:
  - e+ slows down, form O-Ps with few ns lifetime
  - Multiple interaction of 511 γ within about 20 cm
  - The max likelihhood assumes lower values for true β- events than for ^{11}C decay

Analysis method

Maximize a binned likelihood through a multivariate approach

$$L(\vartheta) = L_{sub}(\vartheta) \cdot L_{tag}(\vartheta) \cdot L_{rad}(\vartheta) \cdot L_{PS-L_{pr}}(\vartheta)$$

Monte Carlo

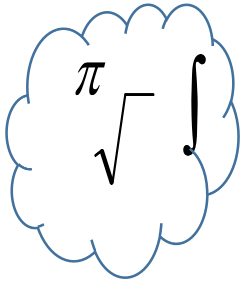
- Full simulation of energy loss&detector geometry
- Tracking of single scintill.& Cherenkov photons
- Absorption,re-emission, scattering..
- Detection on PMTs & electronics response simulation
- Tuned with calibration data taken during Phase 1
- Solar ν and back. simulated with known time variations of the detector
- Processed as real data
- Data analysis free fit parameters: solar ν and background rate
- If it works: MC well tuned & detector is stable

Borexino Monte Carlo: sub% accuracy

Borexino Coll. arXiv:1704.02291 (2017).

See S. Marcocci talk

Analytical



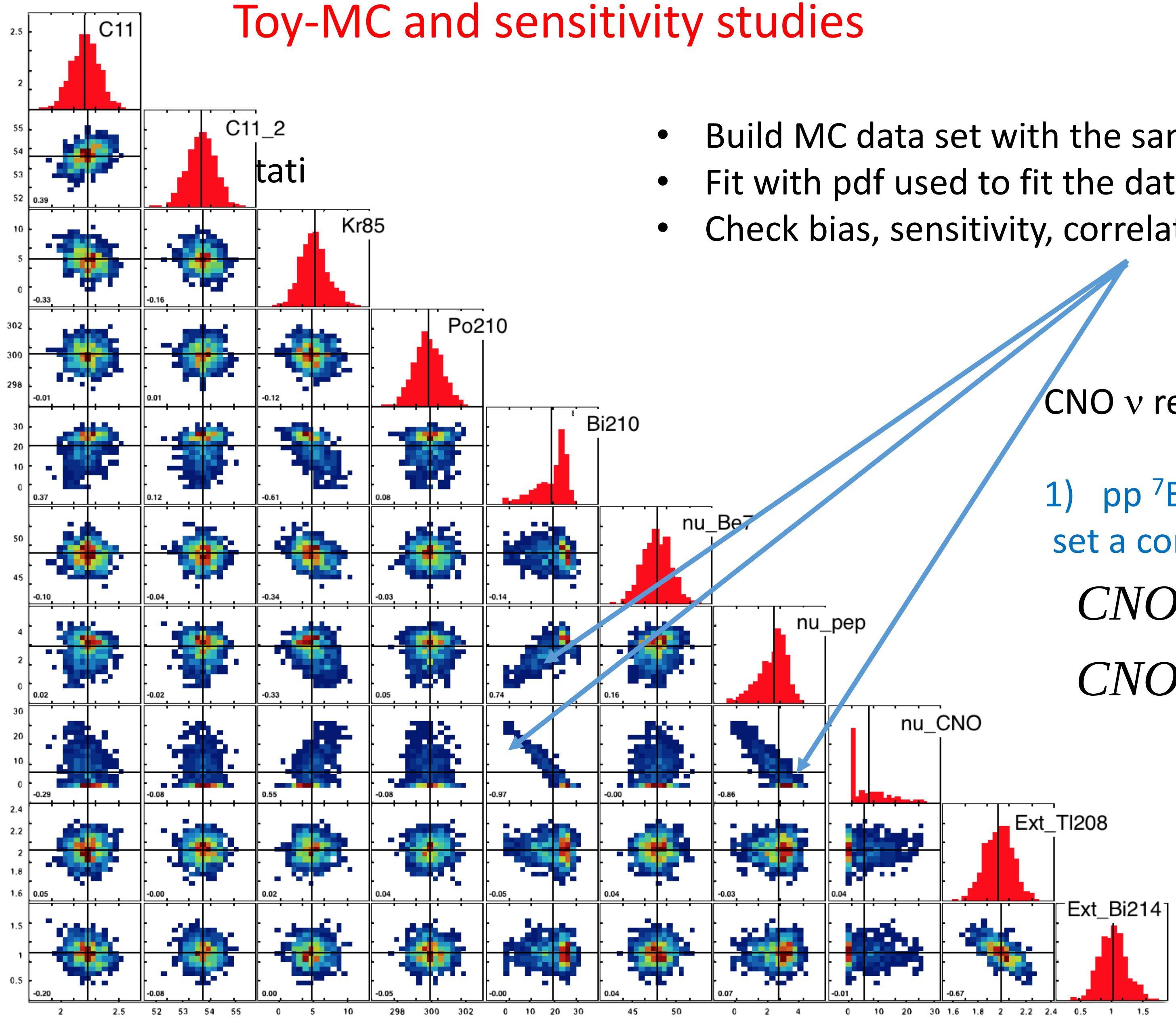
- Analytical model to link E to Np, Npe
- Including scintillation and Cerenkov Light
- Model to describe the E resolution
- Some model parameters fixed (comparison with MC or calib, data)
- Describe the energy response and resolution averaged in the FV
- Data Analysis free fit parameters:
  solar ν and background rate + 6 model parameters
  (Light Yield, 2 resolution param., position & width of 210Po peak, starting point of the 11C spectrum)
- Possibility to descrive unknown time variations
- Easy work at low energy (high rate 14C)

See Z. Bagdasarian poster

New computation tools based on parallel processing& GPU
See X. Ding poster

See X. Ding poster

Toy-MC and sensitivity studies



- Build MC data set with the same exposure as in the data
- Fit with pdf used to fit the data
- Check bias, sensitivity, correlations

Analysis strategy:

CNO ν recoil and ^{210}Bi: very similar energy spectrum

1) pp ^{7}Be pep flux measurement:
set a constraint of the CNO rate to the HZ and LZ values

$$CNO\ HZ \quad 4.92 \pm 0.56 \quad cpd/100t$$

$$CNO\ LZ \quad 3.52 \pm 0.37 \quad cpd/100t$$

2) Upper limit CNO ν flux:
we set a constraint on the ratio pp/pep

$$R(pp/pep) \quad 47.5 \pm 1.2$$

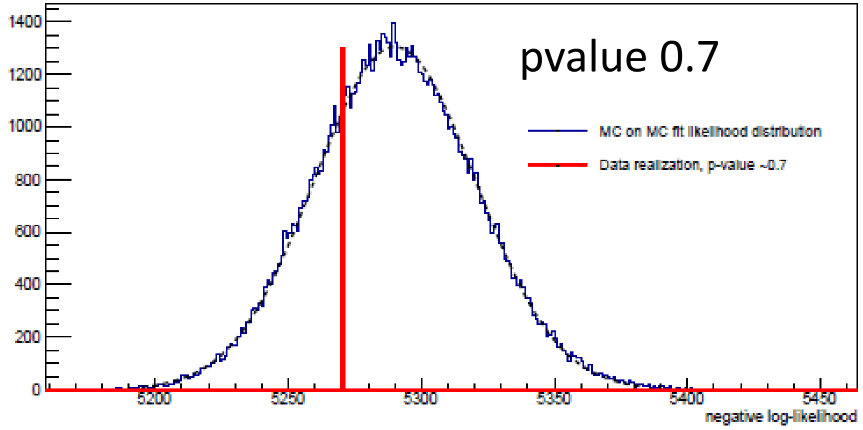
Results

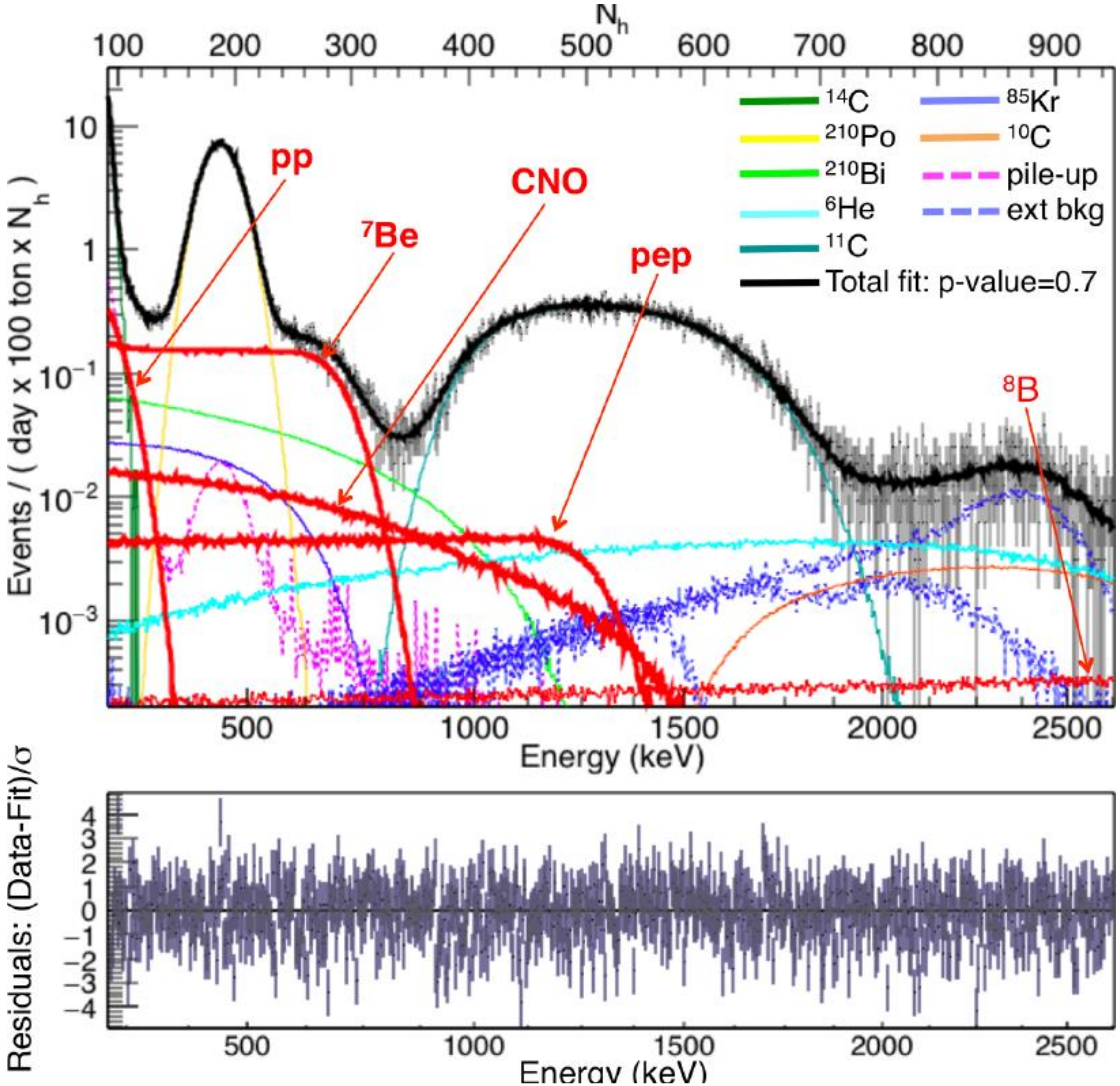
Example of multivariate fit of the data:

Energy spectrum ^{11}C tagged

N_h

Monte Carlo fit





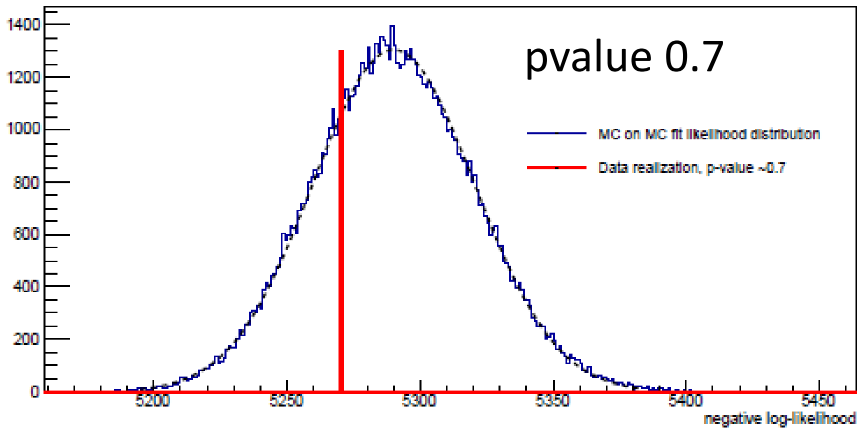
Results

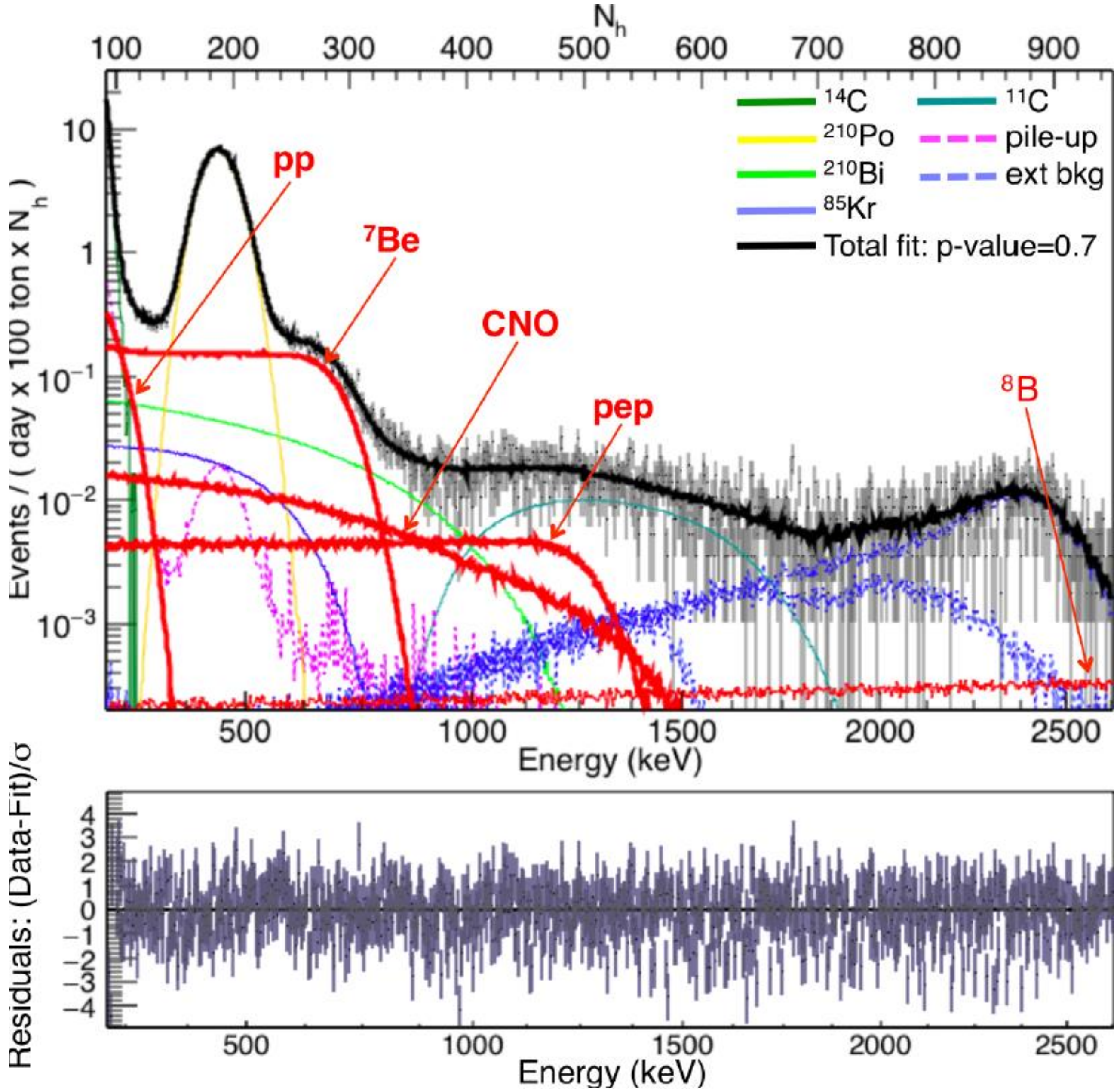
Example of multivariate fit of the data:

Energy spectrum ^{11}C subtracted

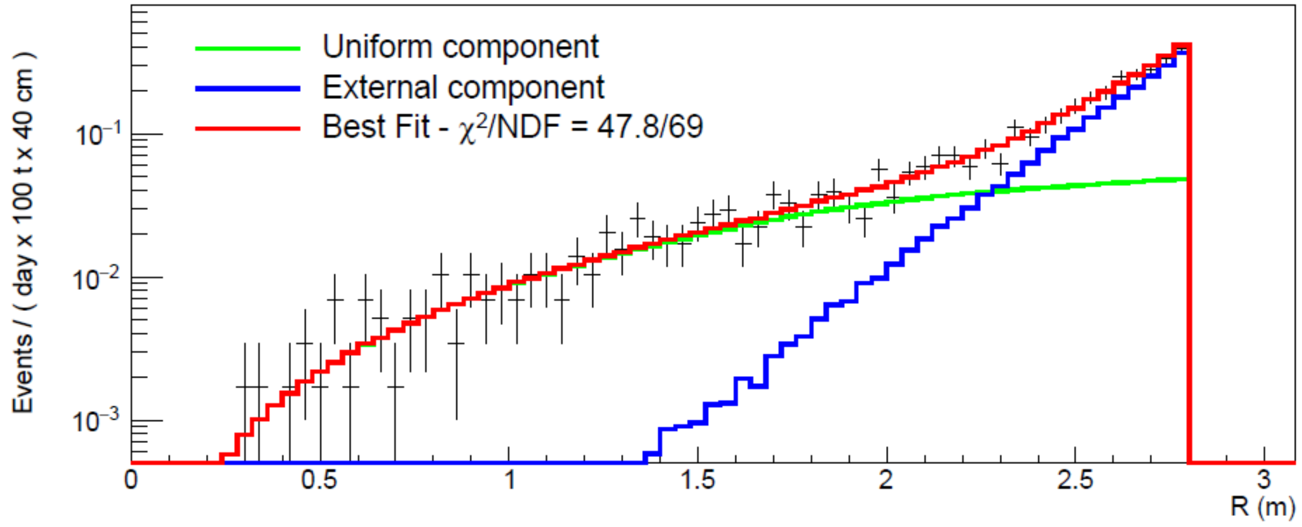
N_h

Monte Carlo fit





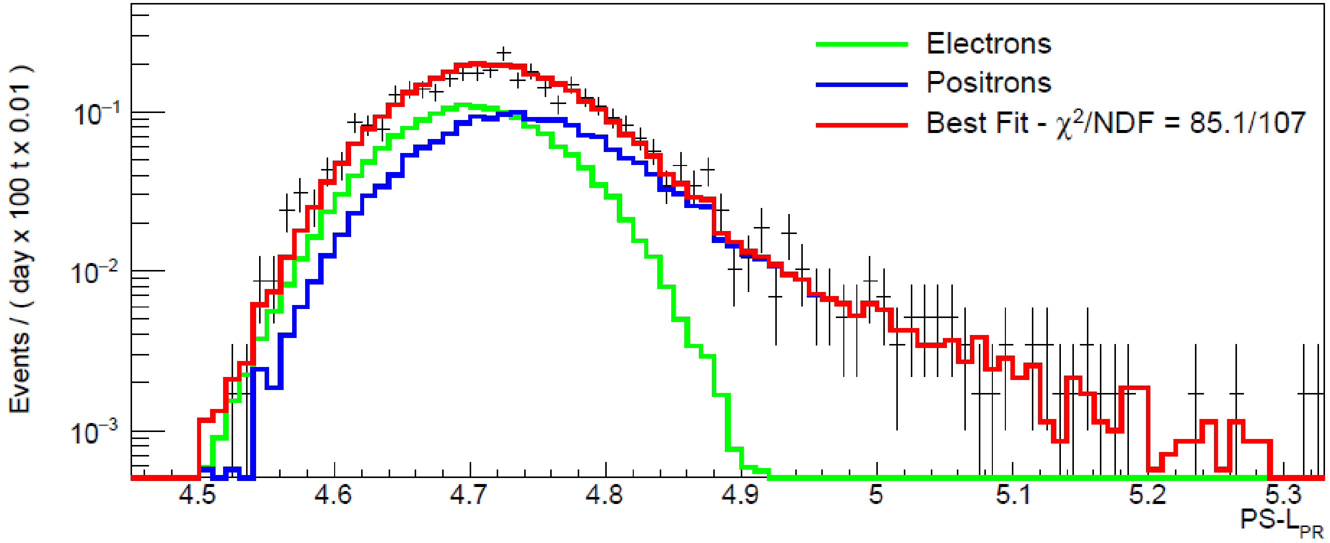
Fit results: radial distribution of the events and pulse shape parameter



fit of the radial distribution of the events

- Uniform component
- External background, exp decrease

(pdf from MC)

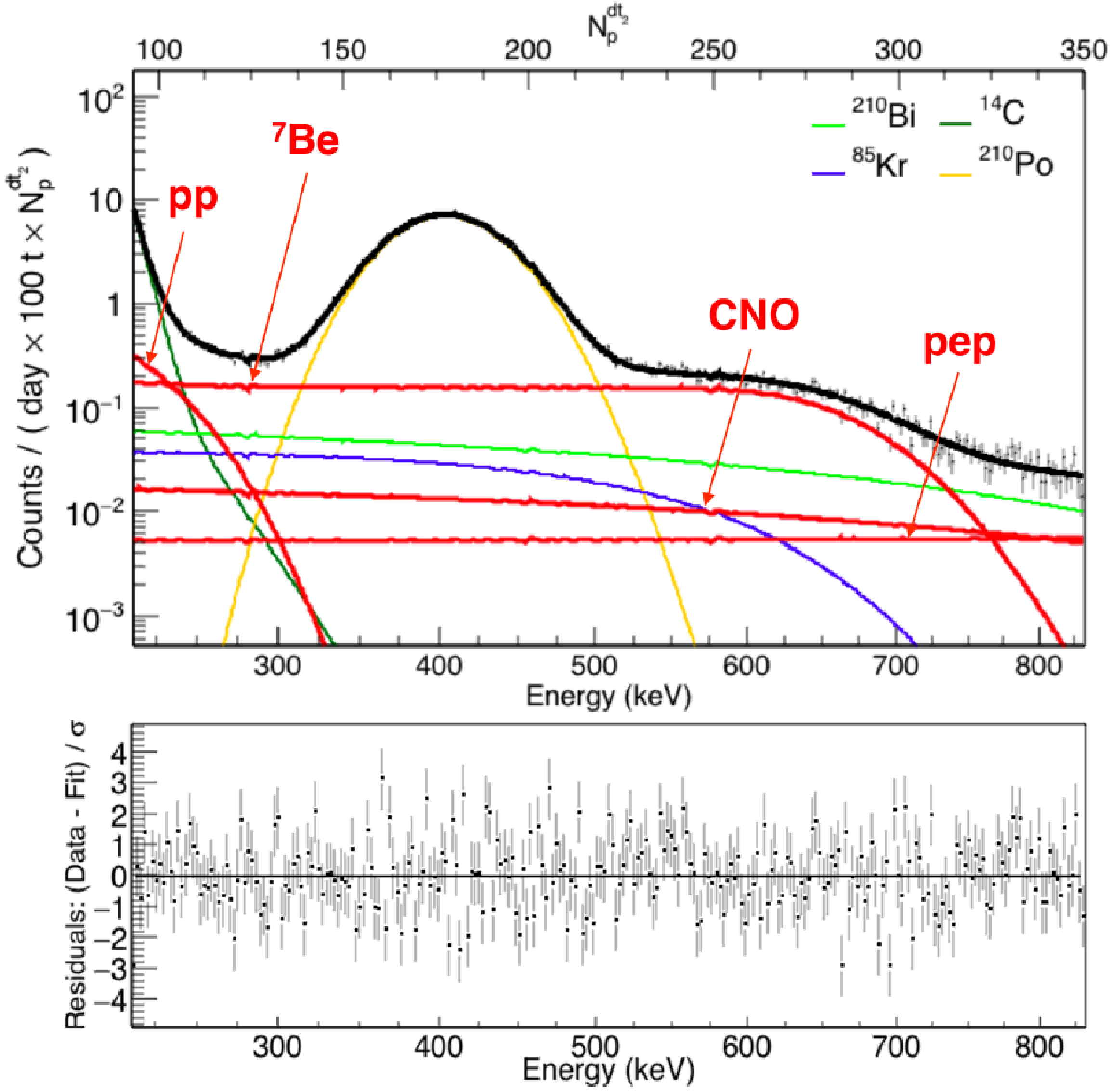


fit ofthe $\beta+/\beta-$ pulse shape parameter (pdf from data samples or from MC)

Fit Results: details of the low energy region

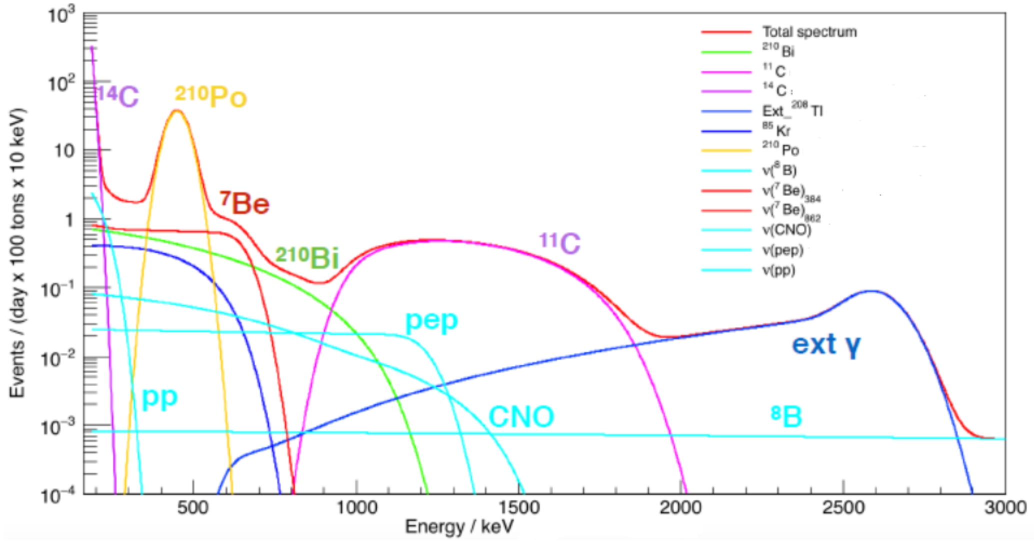
Example of multivariate fit of the data:

- Energy spectrum zoomed in the low energy region (200-830 KeV)
- N_p^{dt2}
- Analytical fit



Fit results: background

Background	Rate (cpd/100t)
^{14}C (Bq/100t)	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5± 1.9
^{11}C	26.8± 0.2
^{210}Po	260.0± 3.0
Ext ^{40}K	1.1± 0.6
Ext ^{214}Bi	1.9 ± 0.3
Ext ^{208}Tl	3.3 ± 0.1



Purification of the scintillator

6 cycles, closed loop

Reduction factors:

- 4.6 for ^{85}Kr
- 2.3 for ^{210}Bi

Fit results: systematics uncertainty

1) Systematic uncertainties

(N_p N_p^{dt2} N_h) → Choice of energy estimator

Energy scale
Not uniformity of the energy response
^{210}Bi spectral shape
→ Fit models (see text)

Source of uncertainty	*pp* −%	*pp* +%	^{7}Be −%	^{7}Be +%	*pep* −%	*pep* +%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6

New pp, ^{7}Be, pep results of the analysis of Phase II data

	Borexino results cpd/100t	expected HZ cpd/100t	expected LZ cpd/100t
pp	**$134 \pm 10^{+6}_{-10}$**	**131.0 ± 2.4**	**132.1 ± 2.4**
^{7}Be(862+384 KeV)	**$48.3 \pm 1.1^{+0.4}_{-0.7}$**	**47.8 ± 2.9**	**43.7 ± 2.6**
pep (HZ)	**$2.43 \pm 0.36^{+0.15}_{-0.22}$**	**2.74 ± 0.05**	**2.78 ± 0.05**
pep (LZ)	**$2.65 \pm 0.36^{+0.15}_{-0.24}$**	**2.74 ± 0.05**	**2.78 ± 0.05**

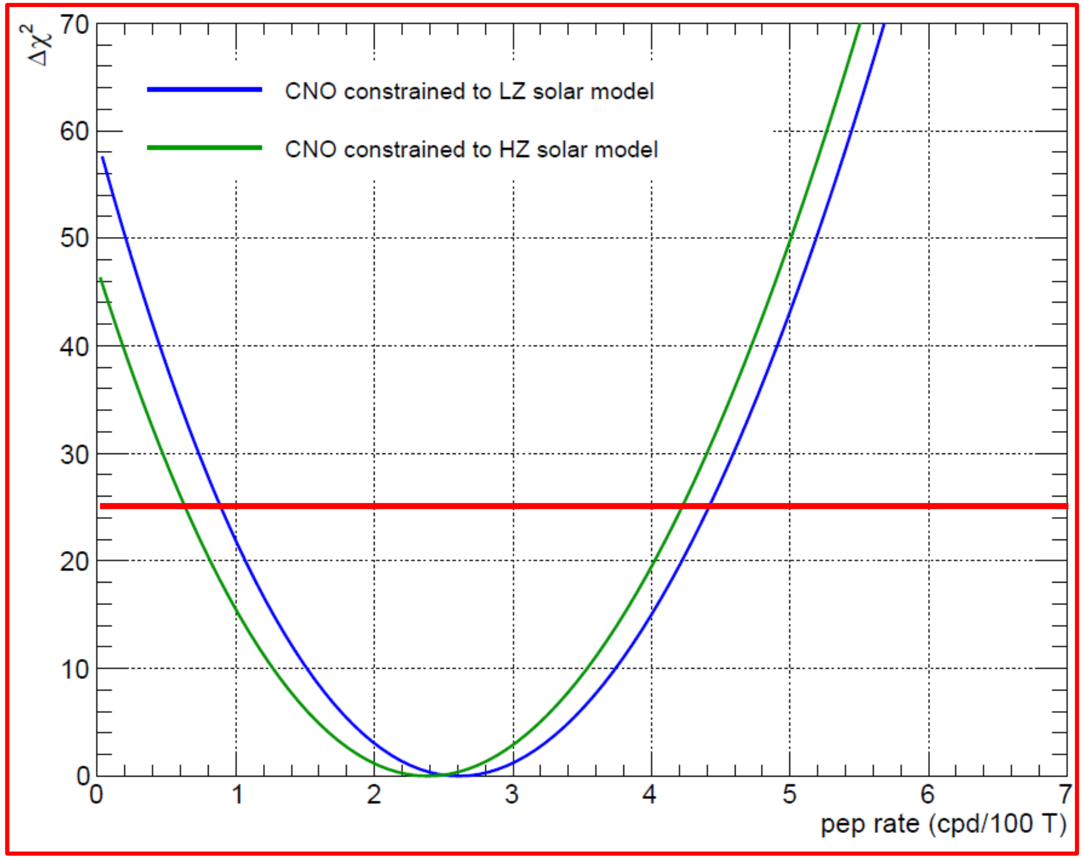
	Borexino results Flux ($cm^{-2}s^{-1}$)	expected HZ Flux ($cm^{-2}s^{-1}$)	expected LZ Flux ($cm^{-2}s^{-1}$)
pp	**$(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$**	**$5.98\ (1 \pm 0.006)\ 10^{10}$**	**$6.03\ (1 \pm 0.005)\ 10^{10}$**
^{7}Be(862+384 KeV)	**$(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$**	**$4.93\ (1 \pm 0.06)\ 10^{9}$**	**$4.50\ (1 \pm 0.06)\ 10^{9}$**
pep (HZ)	**$(1.27 \pm 0.19^{+0.08}_{-0.12})\ 10^{8}$**	**$1.44\ (1 \pm 0.009)\ 10^{8}$**	**$1.46\ (1 \pm 0.009)\ 10^{8}$**
pep (LZ)	**$(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$**	**$1.44\ (1 \pm 0.009)\ 10^{8}$**	**$1.46\ (1 \pm 0.009)\ 10^{8}$**

Comparison between Phase I and Phase II results

	Phase I	Phase II	Uncertainty reduction $\frac{Phase\ II}{Phase\ I}$
pp	$144 \pm 13 \pm 10$	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be(862KeV)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	0.57
pep	$3.1 \pm 0.6 \pm 0.3$	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61

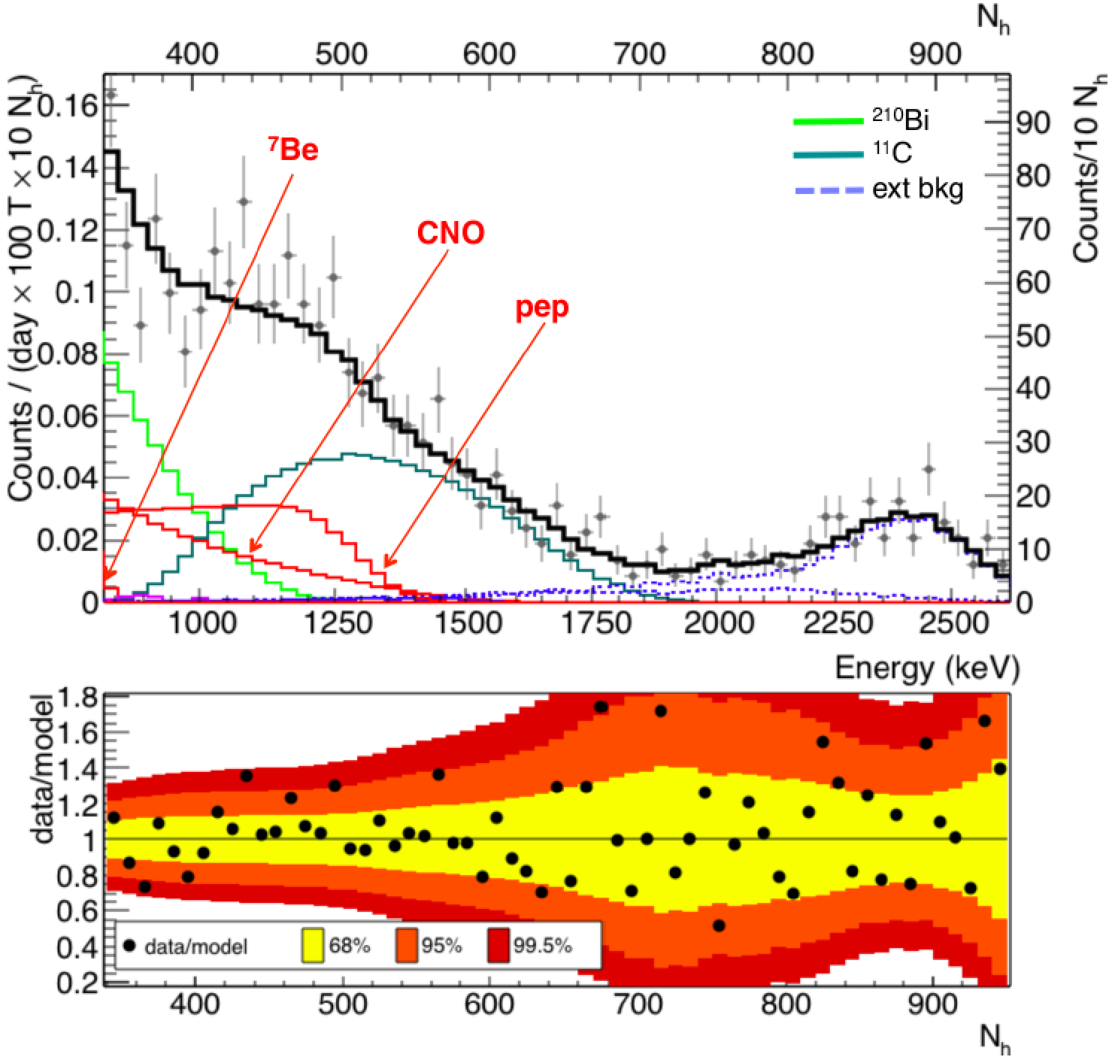
5 σ evidence of pep solar ν (including systematics uncertainties)

Likelihood profile resulting from the multivariate fit



Select innermost β- like events

Radius<2.4 PS-LPR<4.8



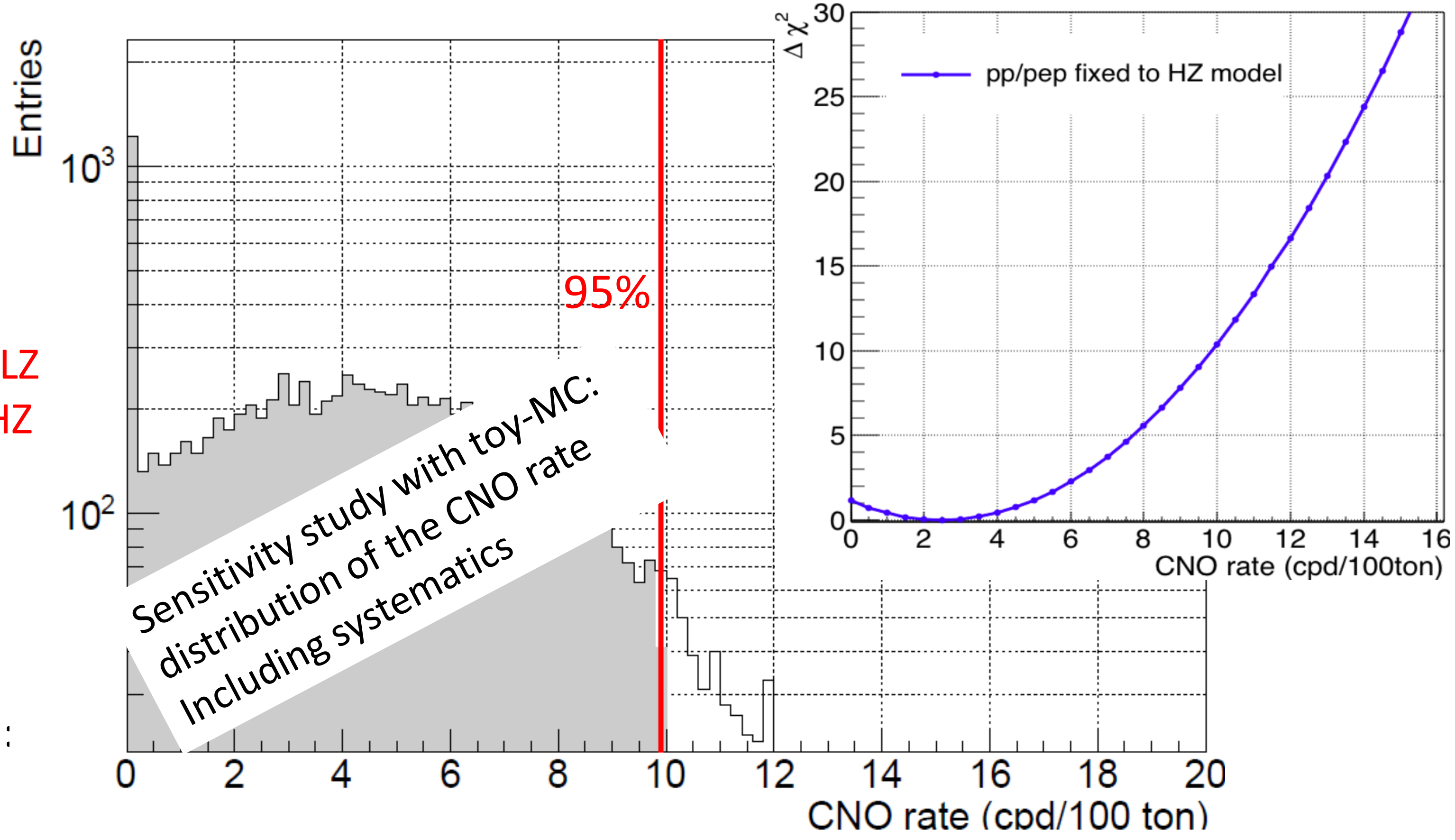
Upper limit on the CNO flux

- Set a constrain to the ratio pp/pep
- Very well know in the solar model
- Include oscillations LMA-MSW
- Toy MC study of the sensitivity :

the median 95% CL is 9 cpd/100t for LZ
10 cpd/100t for HZ

95% C.L. limit on the CNO n rate
8.1 cpd/100t
including systematics errors

Previous limit (set by Borexino Phase I):
7.9 cpd/100t



	Borexino result	Expected HZ	Expected LZ
CNO ν	**< 8.1 95%C.L cpd/100t**	**4.91 +-0.56 cpd/100t**	**3.62 +- 0.37 cpd/100t**

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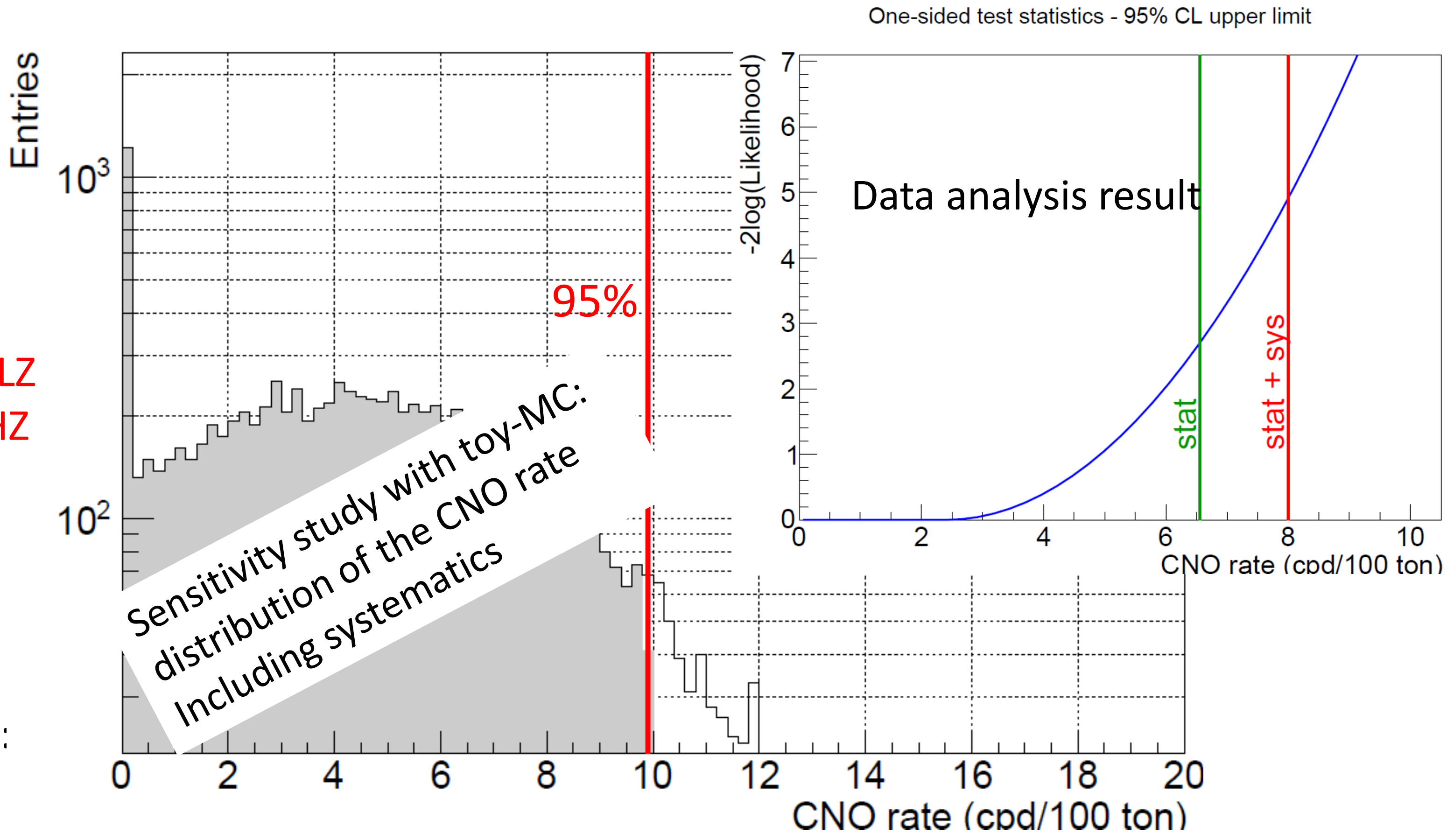

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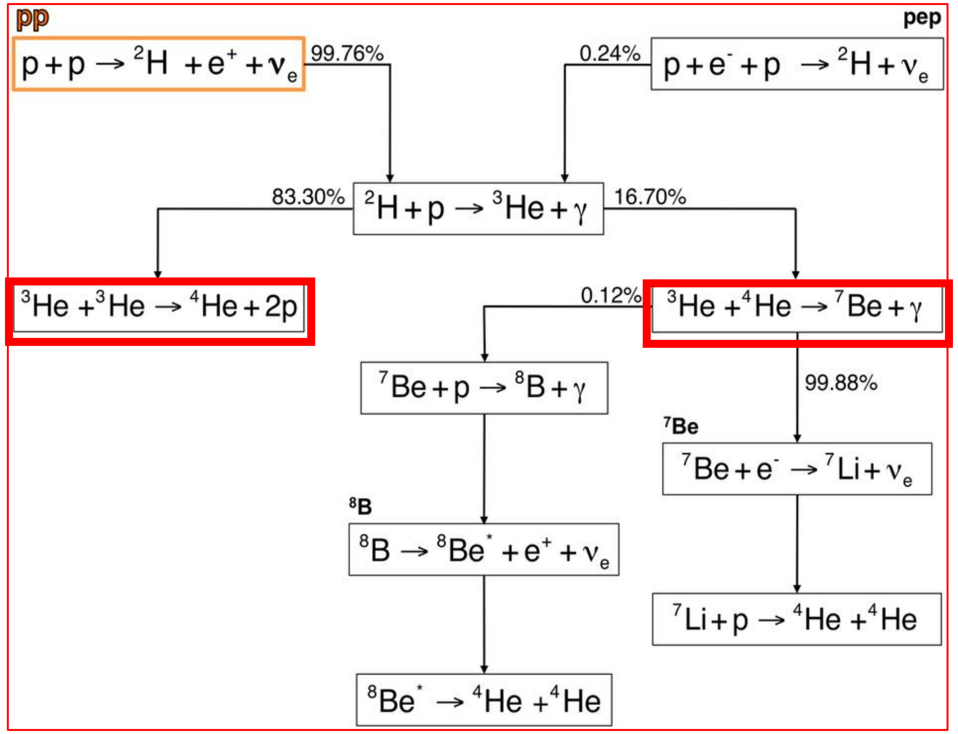
Implication of the results: probe solar fusion with R

$$R = \frac{Rate(^3He + ^3He)}{Rate(^3He + ^4He)}$$

Reaction from the main pp chain



$$R = \frac{2\,\Phi(^7Be)}{\Phi(pp) - \Phi(^7Be)}$$

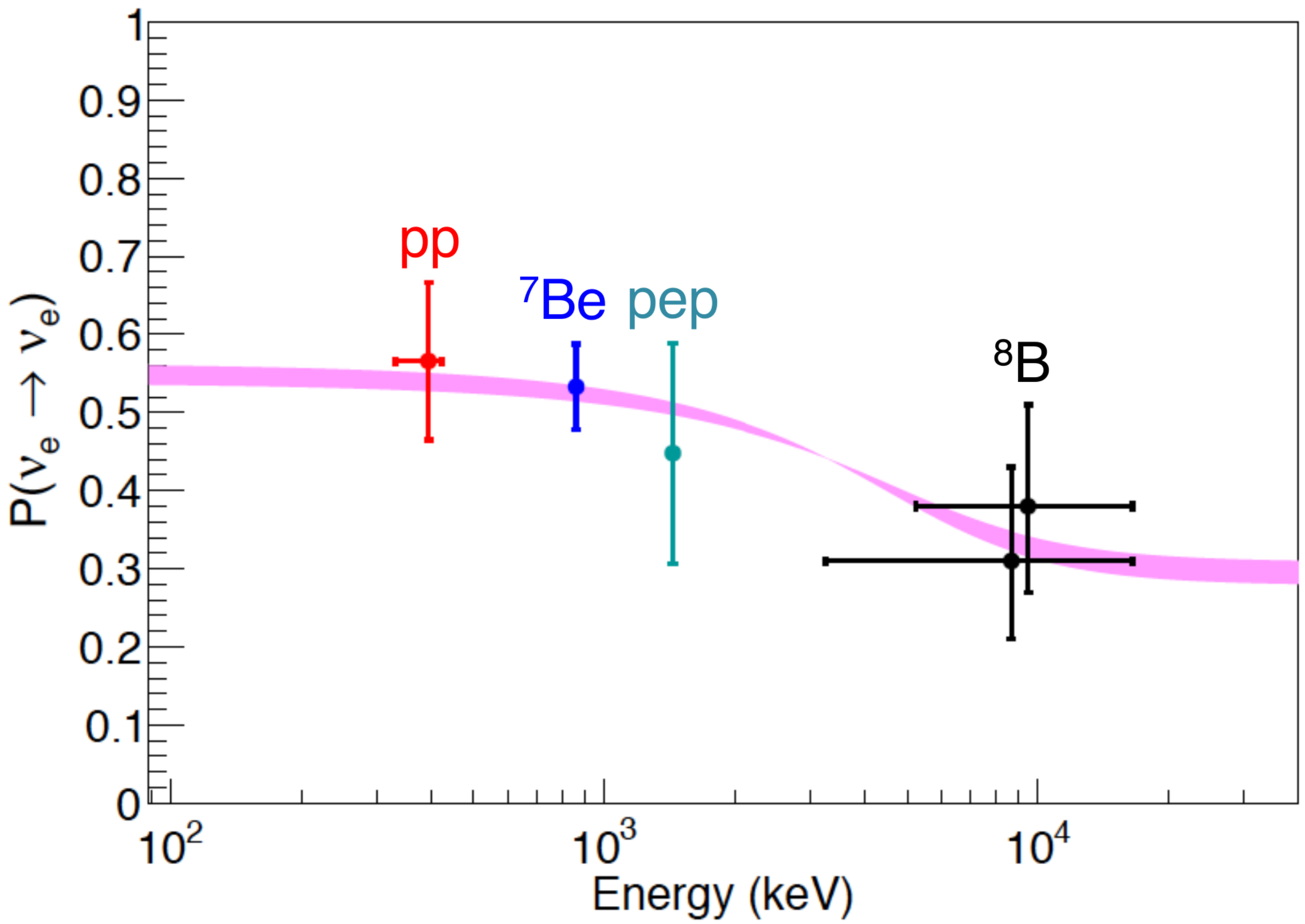
Expected values: (C. Pena Garay, private comm,)

$$R = 0.180 \pm 0.011 \quad HZ$$
$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

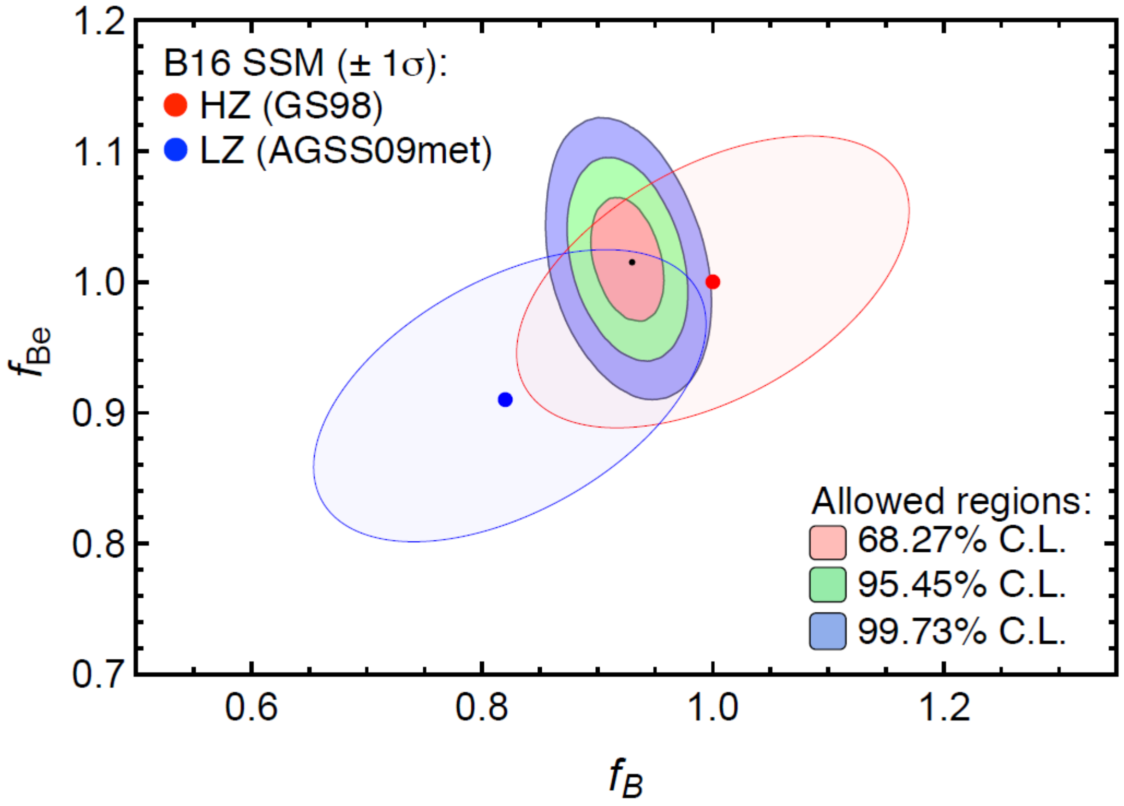
$$R = 0.18 \pm 0.02$$

Neutrino survival probability P_{ee} with the Borexino results



Neutrino survival probability with the new Phase II results and ^{8}B from Borexino (PRD 82 033006 (2010))

Implication of the results: towards probing HZ and LZ



Global fit of all solar, Kamland reactors with new Borexino results

$$f_B = \frac{\Phi(^8B)}{\Phi_{HZ}(^8B)} \qquad f_{B_e} = \frac{\Phi(^7Be)}{\Phi_{HZ}(^7Be)}$$

$$\Delta m^2_{12} \quad \sin^2(\theta_{12})$$

- hints towards High Metallicity???
- Note: only 1 σ theorethical uncertainty in the plot!
- Important to reduce the theorethical uncertainty

Conclusions

- Solar ν experiments (SK, Borexino) are running into a precision spectroscopy phase
- Validation of the MS-LMA model
- Testing solar models and helping to solve the metallicity issue
- New results from Borexino about pp, ^{7}Be, pep
- Simultaneous measurement of the 3 fluxes
- Improved accuracy compared to Phase I
- 5 σ evidence of pep ν
- ^{7}Be measured with 2.5% uncertainty (stat+sys)

➢ also new limit on the effective neutrino magnetic moment from Phase II Borexino data

$$\mu_{eff} < 2.8 \text{ X}10^{-11} \mu_B$$

(presented by L. Ludhova on Monday)

Borexino Collaboration

$$\mu^2_{eff} = P^{3\nu}\,\mu^2_e + (1 - P^{3\nu})\,(\cos^2\theta_{23}\,\mu^2_\mu + \sin^2\theta_{23}\,\mu^2_\tau)$$

$P_{ee} = P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}$

$P^{2\nu} = \sin^2\theta_{12}\,\sin^2(\Delta m^2_{12}\,L/4E)$

Assuming
LMA-MSW
$P^{2\nu}$ for pp- and ^{7}Be-ν is the same

(Dec 2011- May 2016)
1291 days

90% C.L.

from $\mu_{eff} < 2.8 \times 10^{-11}\mu_B$:

$\mu_e < 4.8 \times 10^{-11}\mu_B$

$\mu_\mu < 6.4 \times 10^{-11}\mu_B$

$\mu_\tau < 6.8 \times 10^{-11}\mu_B$

^{210}Bi independent constraint

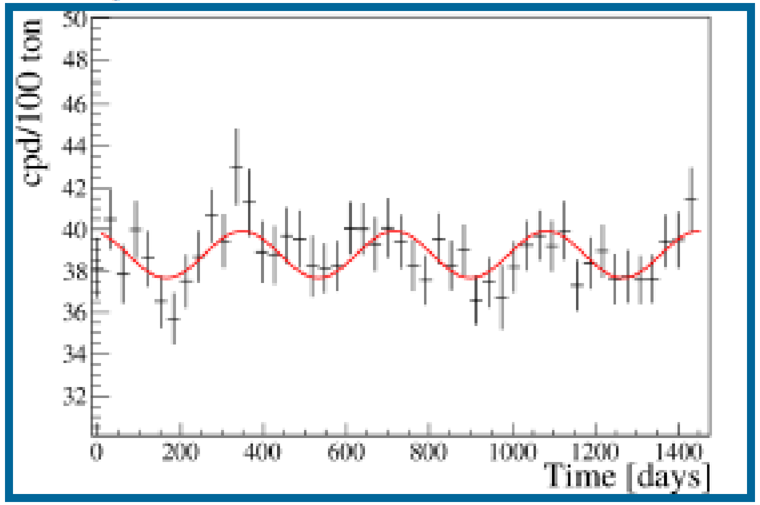
^{210}Pb (β^-, τ = 32y) → ^{210}Bi (β^-, τ = 7d) → ^{210}Po (α, τ = 200d)

- Assuming the secular equilibrium the ^{210}Bi rate can be determined by the ^{210}Po rate [F. Villante et al. Phys.Lett. B701 (2011) 336-341]:

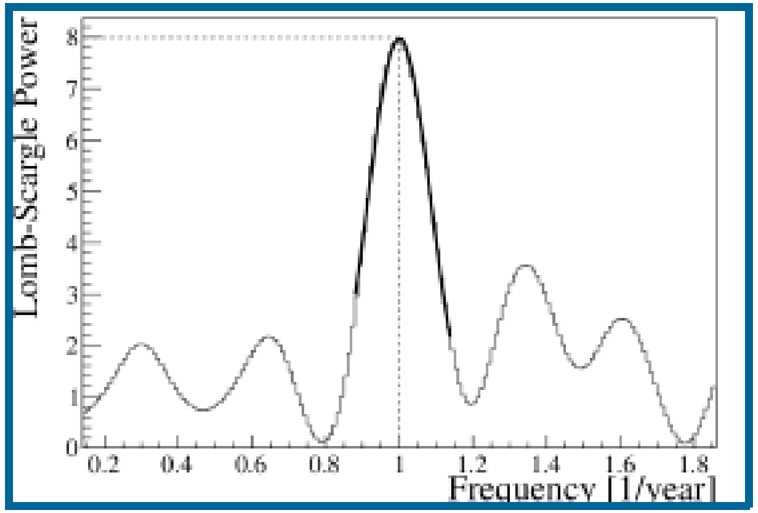
Before thermal insulation

After thermal insulation

I) Sinusoidal fit



2) Lomb-Scargle



The **period**, **amplitude**, and **phase** of the observed time evolution of the signal are **consistent with its solar origin**, and **the absence of an annual modulation is rejected at 99.99% C.L.**

	Simulated Data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

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