The measurement of the solar neutrino fluxes from the pp-chain with Borexino detector

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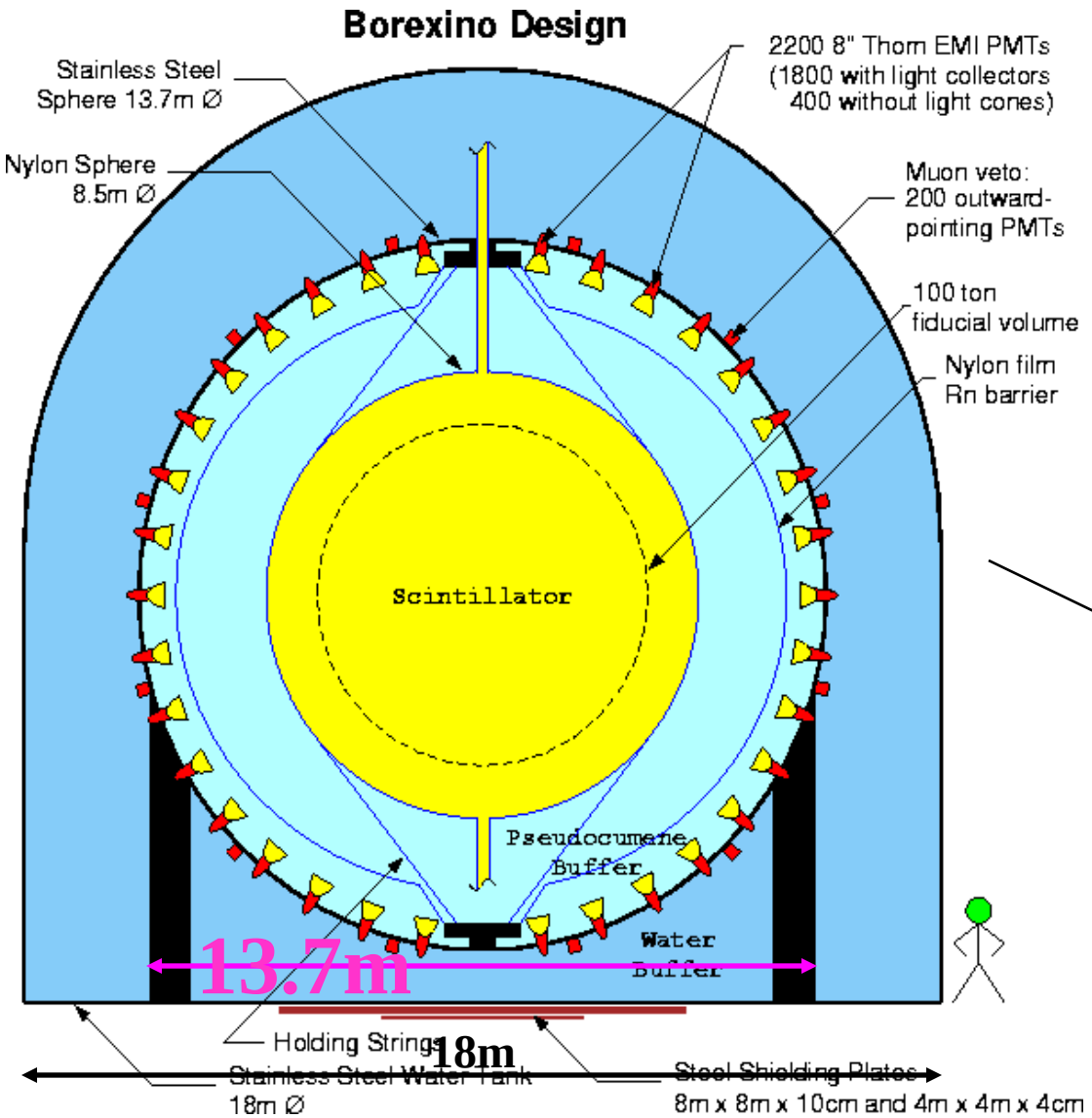
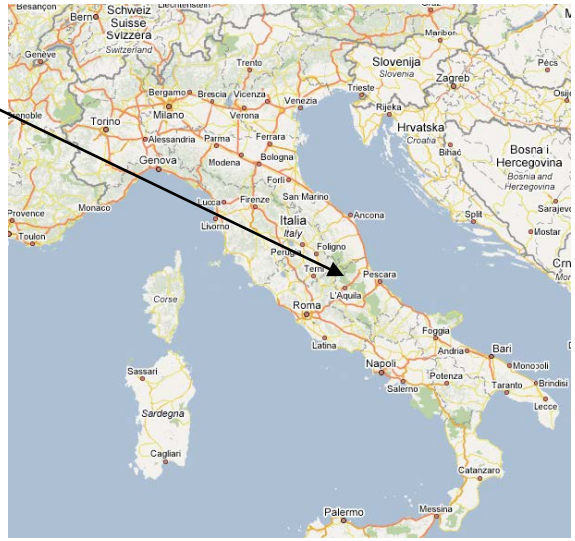
on behalf of Borexino collaboration

LNGS, November 24, 2015

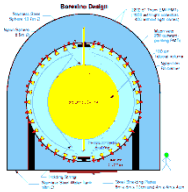
BOREXINO *(in operation from May,2007)*



- **278 t of liquid organic scintillator PC + PPO (1.5 g/l)**
- **(ν,e)-scattering with low threshold (~200 keV)**
- **Outer muon detector**



pp-chain



2014

pp

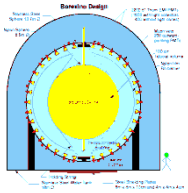
$p + p \rightarrow {}^{2}H + e^{+} + \nu$

99.76%

0.24%

pep

$p + e^{-} + p \rightarrow {}^{2}H + \nu$



2012

83.30%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

16.70%

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

0.12%

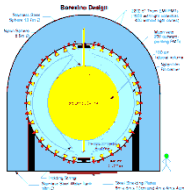
${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

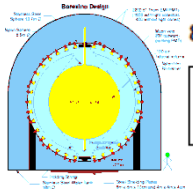
99.88%

${}^{7}Be$

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$



2007,2008,2011
2012 (d/n)
2014 (seasonal)



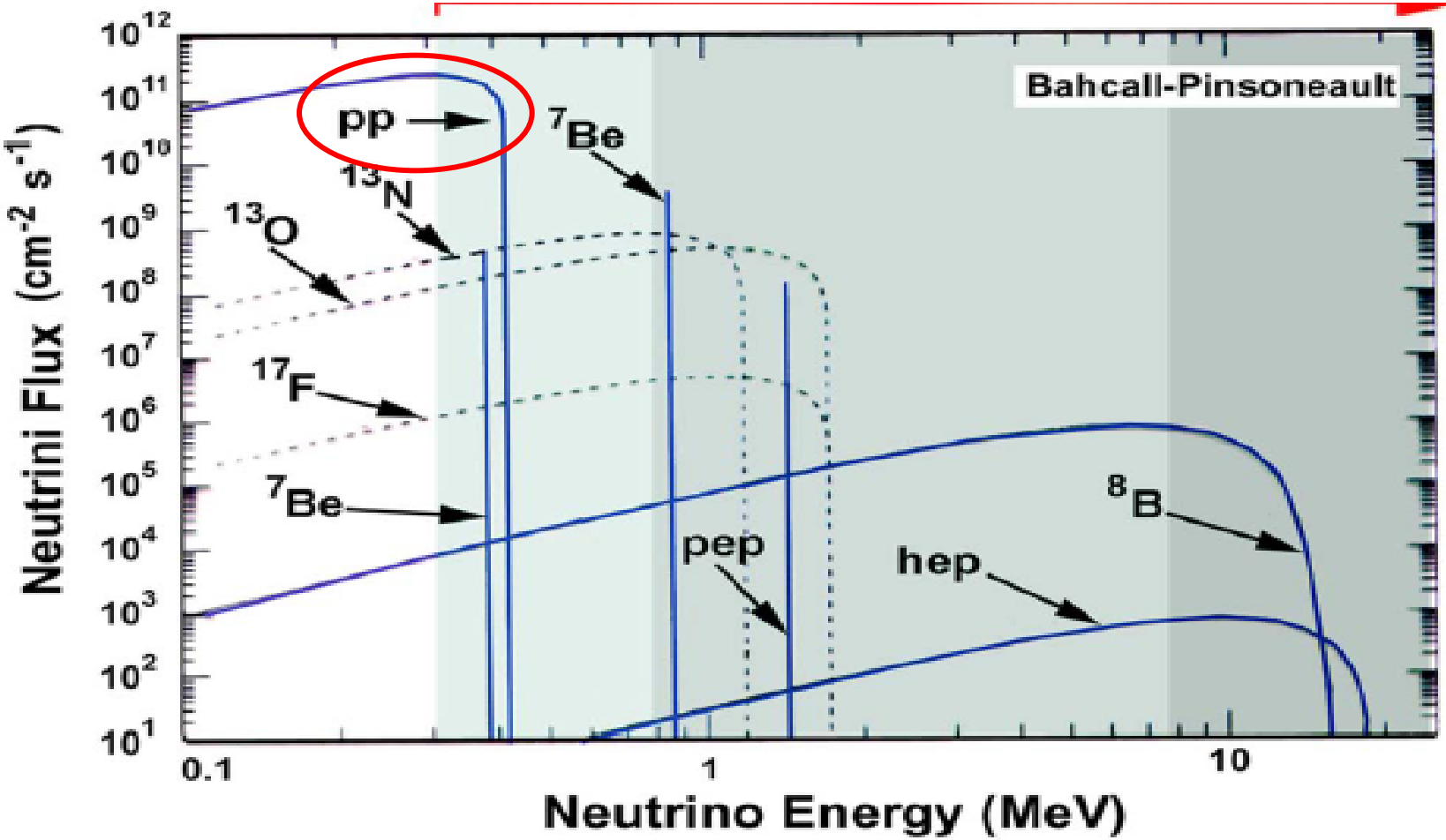
${}^{8}B$

$${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$$

2010

${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

${}^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$



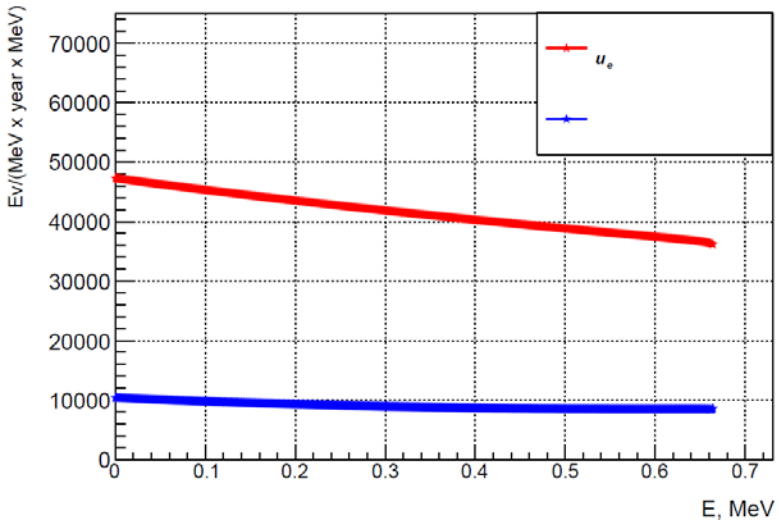
SSM pp neutrino flux ~$6 \cdot 10^{10}$ $cm^{-2}s^{-1}$ (>90% of all solar neutrinos)

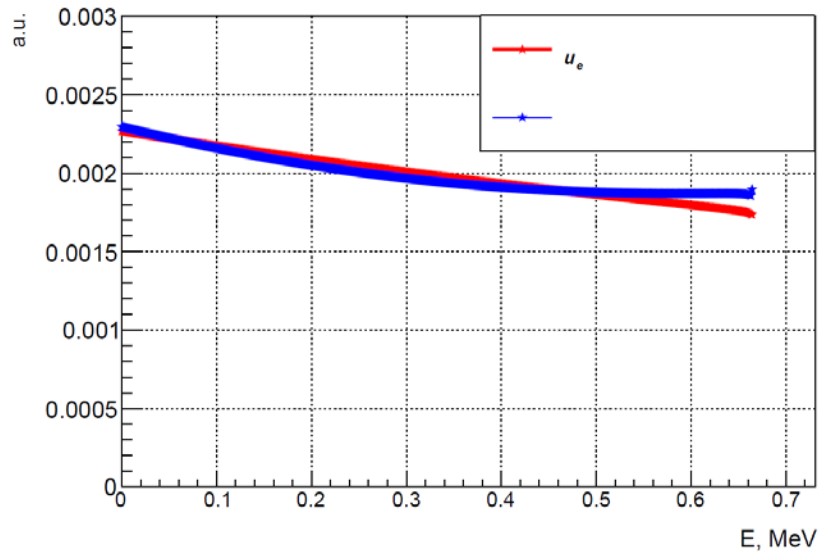
^{7}Be $5 \cdot 10^{9}$ $cm^{-2}s^{-1}$ (~10%)

Others – much less

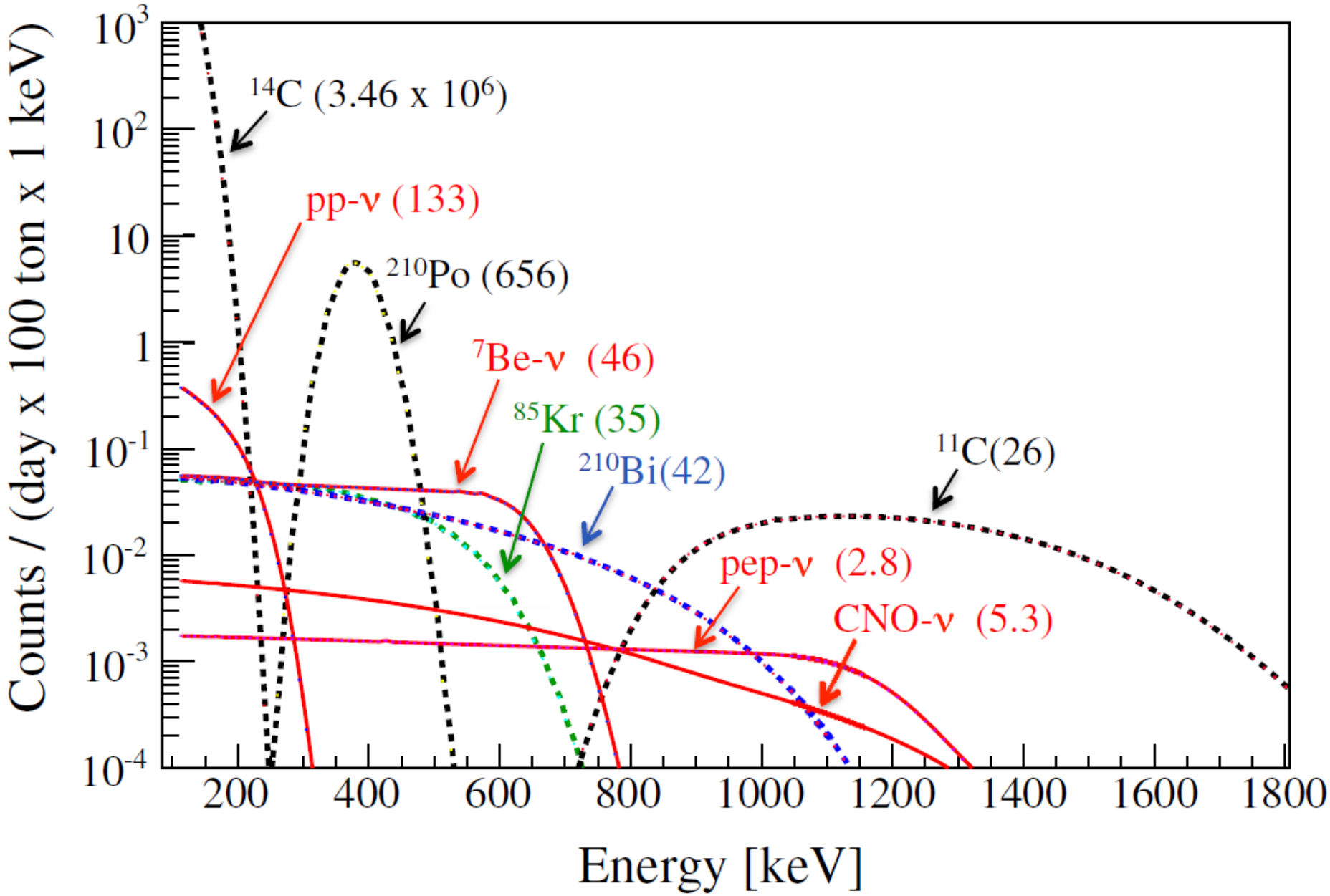
Detection

- Neutrino elastic scattering on electrons $\nu + e^- \rightarrow \nu + e^-$
- Both electron and non-electron flavours are detected (with $\sigma(\upsilon_e) \approx 6\,\sigma(\upsilon_{\mu,\tau})$. Detected signal contains a mixure of both contributions : $P_{ee}\sigma(\upsilon_e) + (1 - P_{ee})\,\sigma(\upsilon_{\mu,\tau})$
- Elastic scattering cross section for monoenergetic ν has "step-like" form (quasi-Compton) with $T_{max} = \frac{E_\upsilon}{1+\frac{m_e}{2E_\nu}}$

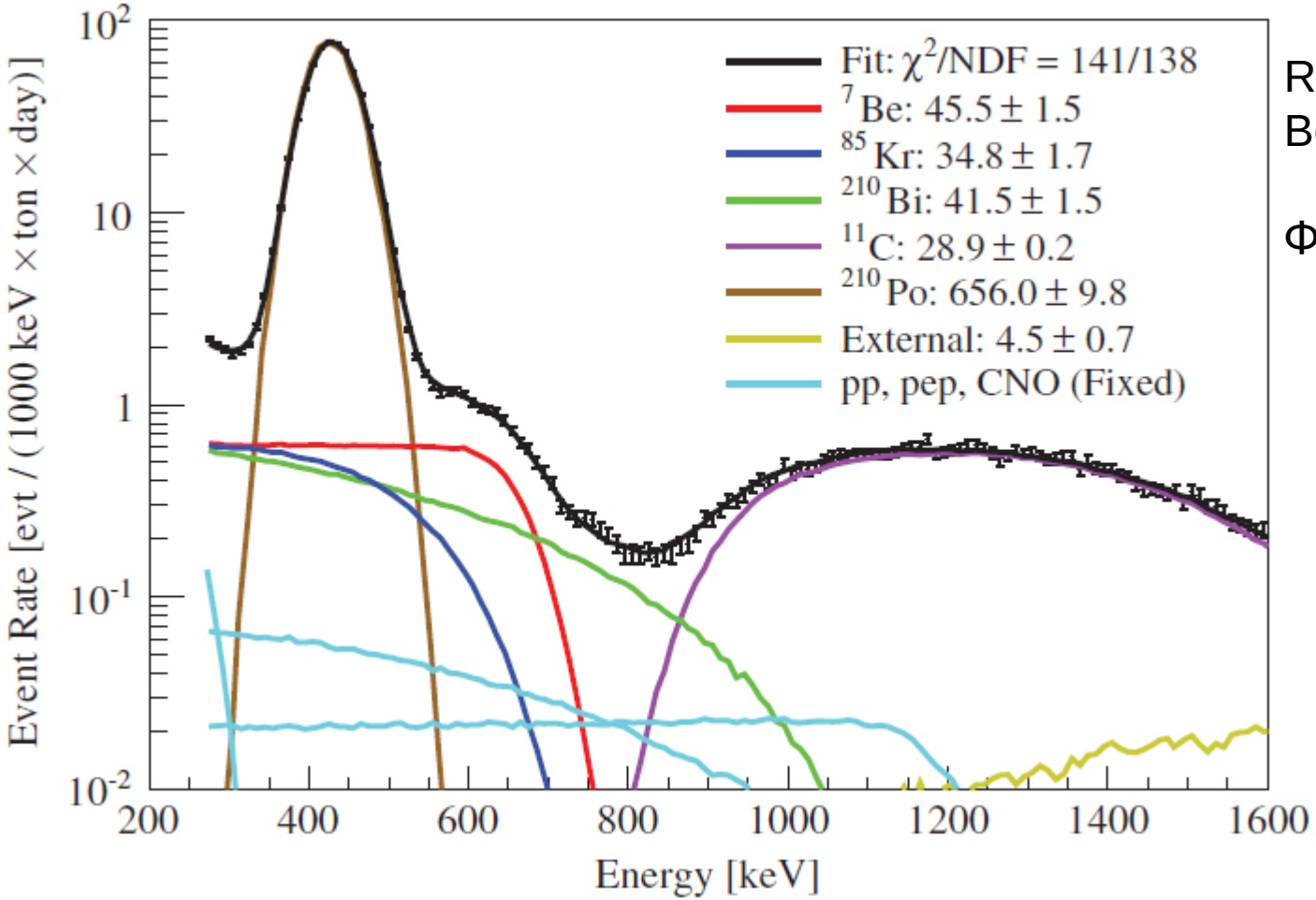




Spectral contributions in the Borexino data



^{7}Be neutrino study : above ^{14}C end-point



Radiochemical+ Borexino ^{7}Be:

Φ(pp)= $(6.14\pm0.61)10^{10}$ $cm^{-2}s^{-1}$

"Precision Measurement of the ^{7}Be Solar Neutrino Interaction Rate in Borexino"
PRL 107, 141302 (2011)

Main components of ^{7}Be analysis: data selections

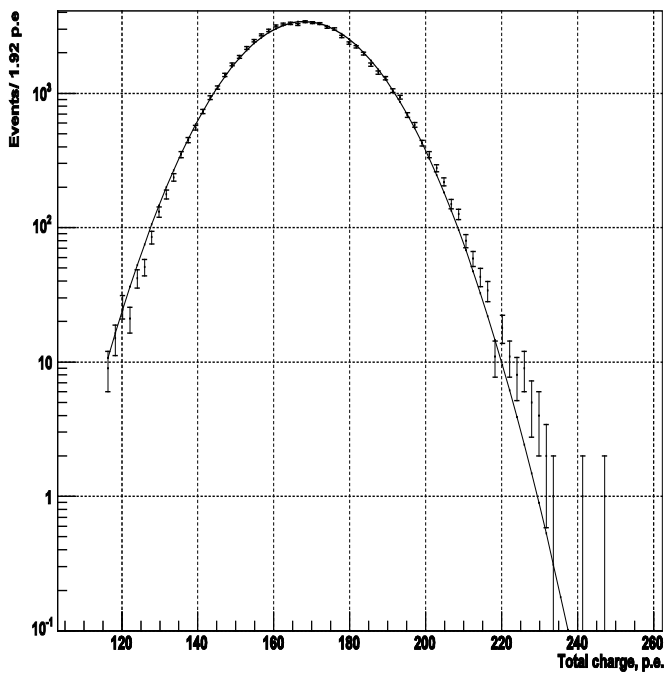
- FV cut removes external background (R<3 m) and events associated with radon on the top of the IV (|Z|<1.67)
- Muon cut (dT<2 ms & dT<2 s) – removes events associated with cosmic muons (software and hardware muon definition)
- Data quality cuts – remove electronics noise
- Data selections include “mild” α/β cut to clean valley between ^{14}C and ^{210}Po from “stray” α’s

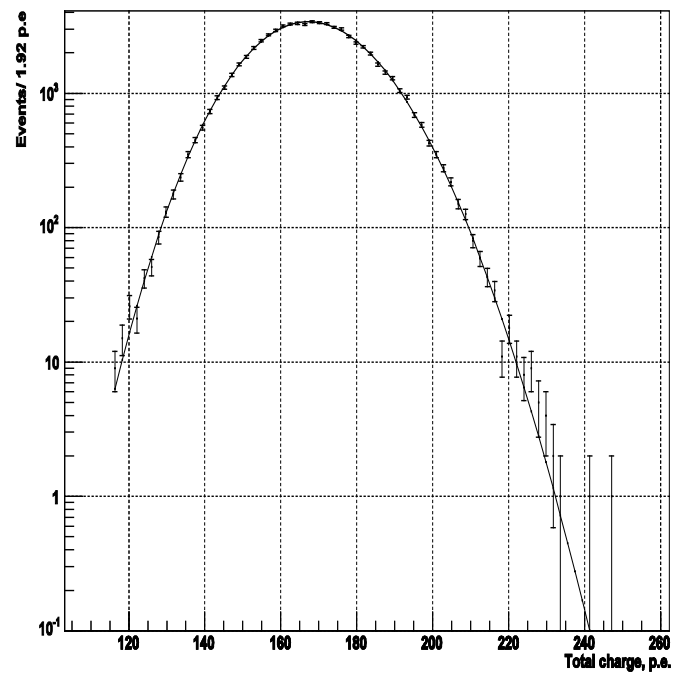
^{7}Be analysis

- Spectral components are constructed (analytical and MC method). Some contributions are free in fit, others are fixed (namely, CNO and other Solar neutrino fluxes).
- Fit is performed with free energy scale (MC) and free energy resolution parameters (analytical). In addition, in analytical fit the position of the ^{11}C (β^{+}) spectrum starting point is free.
- Energy scale is modeled taking into account non-linearities (ionization quenching and Cherenkov light production)
- The scintillatio) is carefully modeled to fit the high statistics ^{210}Po peak
- Independent measurement of ^{85}Kr count is available, but ^{85}Kr count was not constrained (the sensitivity of the fit is comparable to the precision of the measurement)
- Systematics: FV (1.5% from calibrations) and energy scale

Comparison of two response models (Gaussian and Generalized Gamma) with CTF data

(monoenergetic α with E=7.68 MeV were selected at the detector's center r<60 cm)





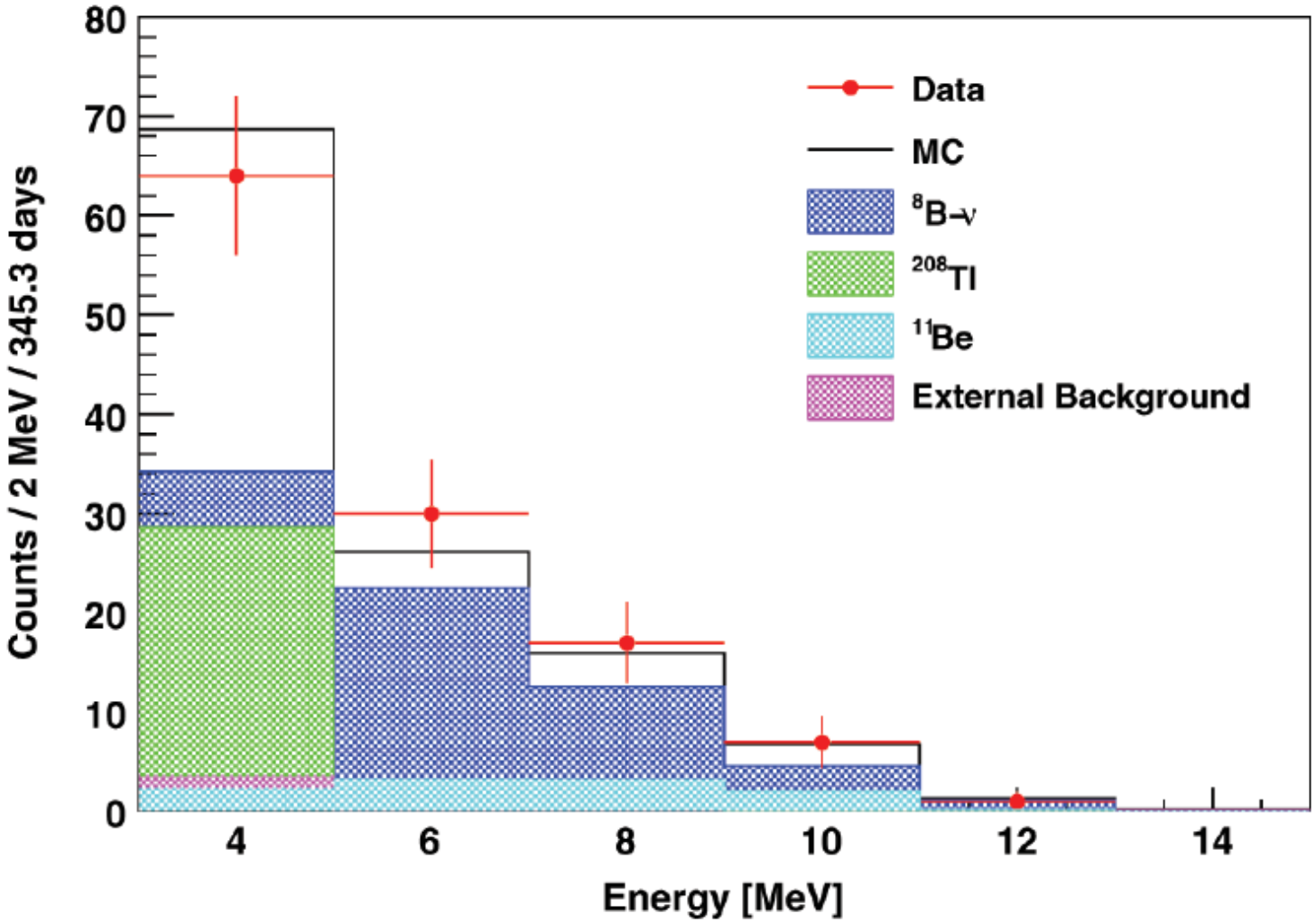
Gauss: χ^2=174.7/67

Gen. Gamma: χ^2=68.8/67

$$\frac{\chi_1^2}{\chi_2^2} = F(p, 67, 67)$$

p>99.99%

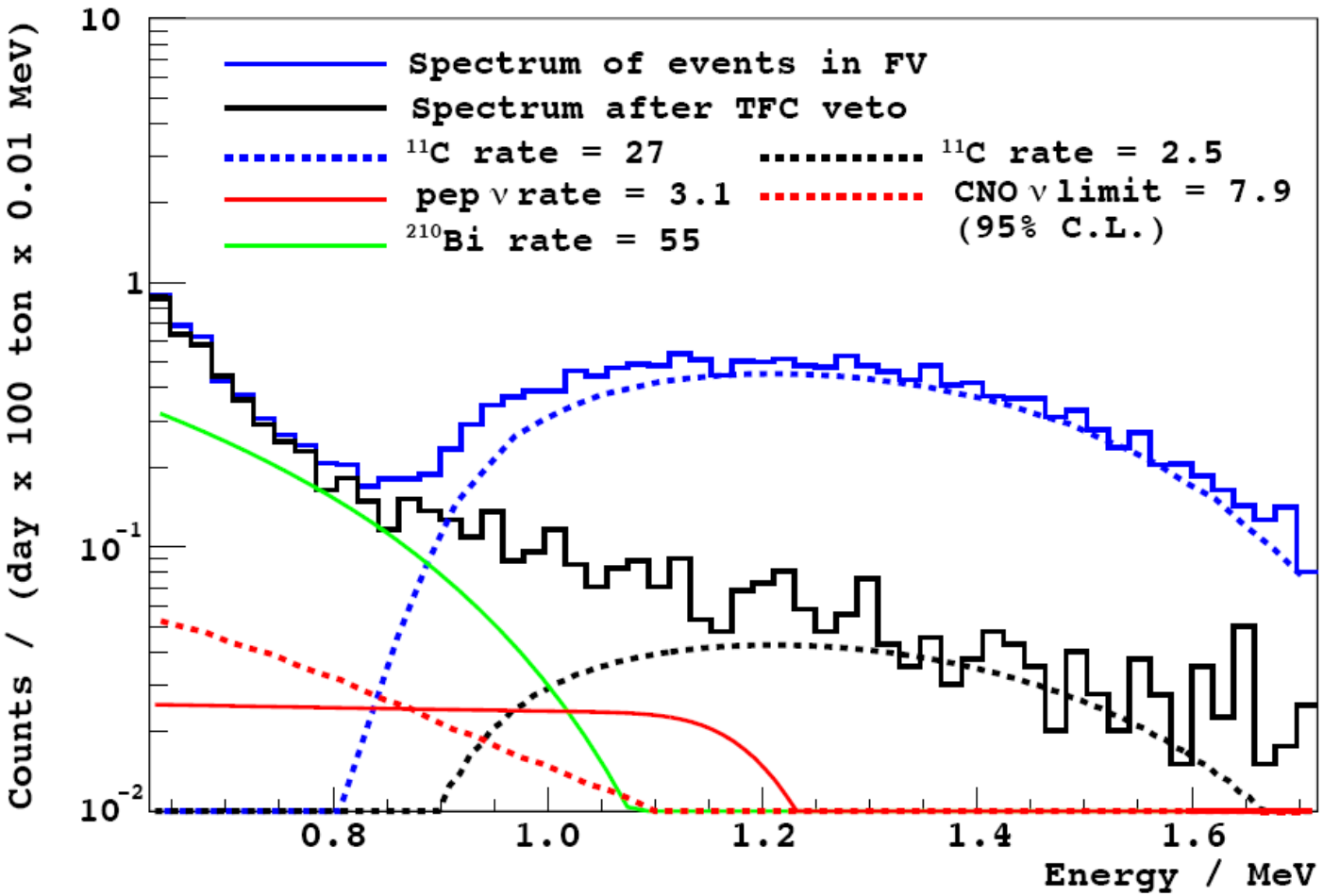
^{8}B neutrino study : above ^{208}Tl



Main components of ^{8}B analysis

- FV cut removes external background (R<3 m) : 100 tonnes.
- Muon cut (dT<6.5 s; 30% of live-time loss) – removes events associated with long-lived isotopes produced in interactions with cosmic muons (software and hardware muon definition)
- Neutrons cut (dT<2 ms) for muons in the buffer
- ^{10}C removal (tagging by coincidence with μ+n)
- ^{214}Bi removal (tagging by Bi-Po coincidence)
- ^{208}Tl subtraction (estimated by 212Bi-Po coincidence)
- ^{11}Be subtraction (estimated from events with dT<240 s and dR<2 m from the muon track)

pep-neutrino study: above ^{210}Po peak



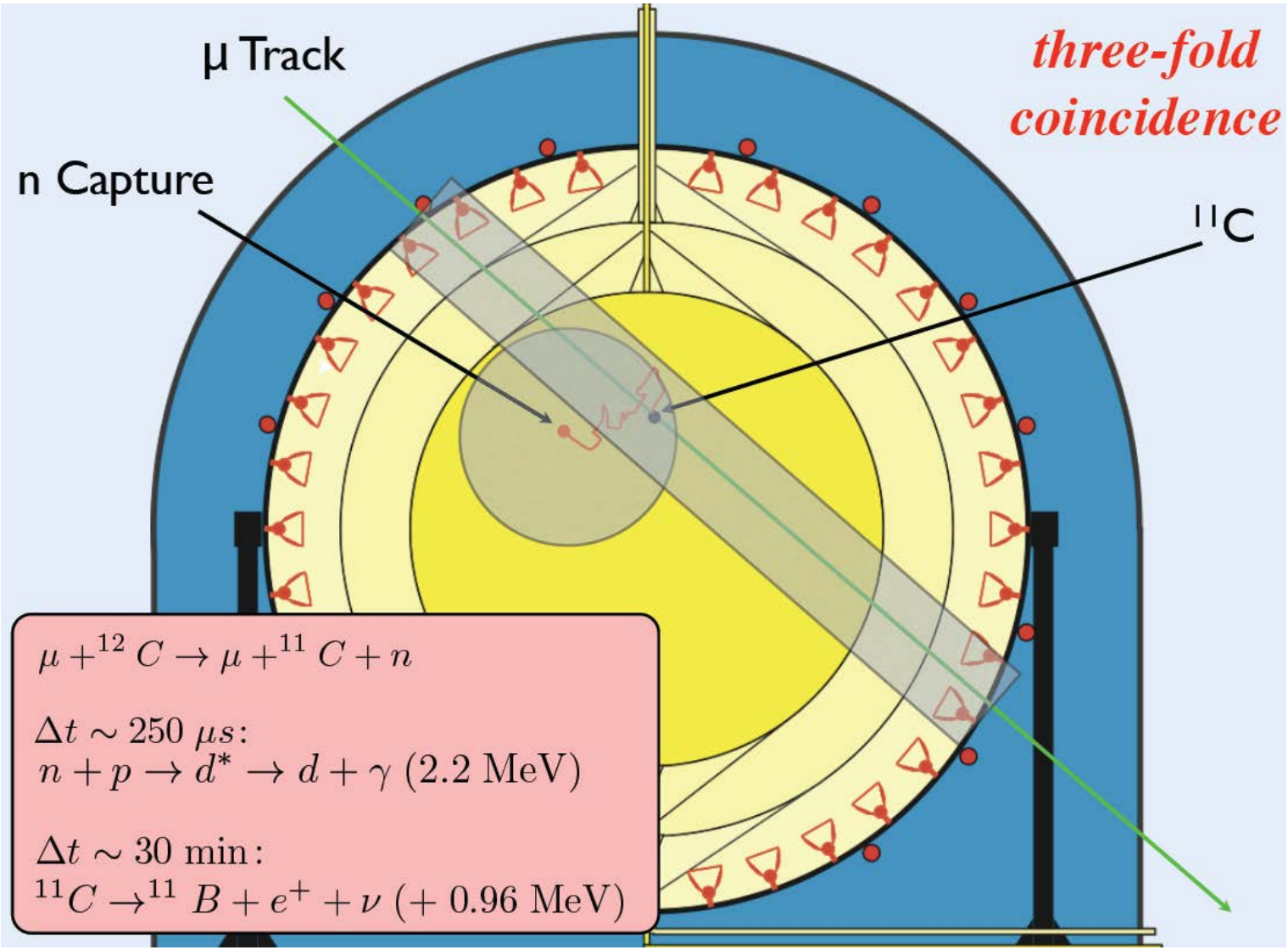
Background reduction in ^{11}C - 91%
with 51.5% live-time loss

Main components of pep analysis: data selections

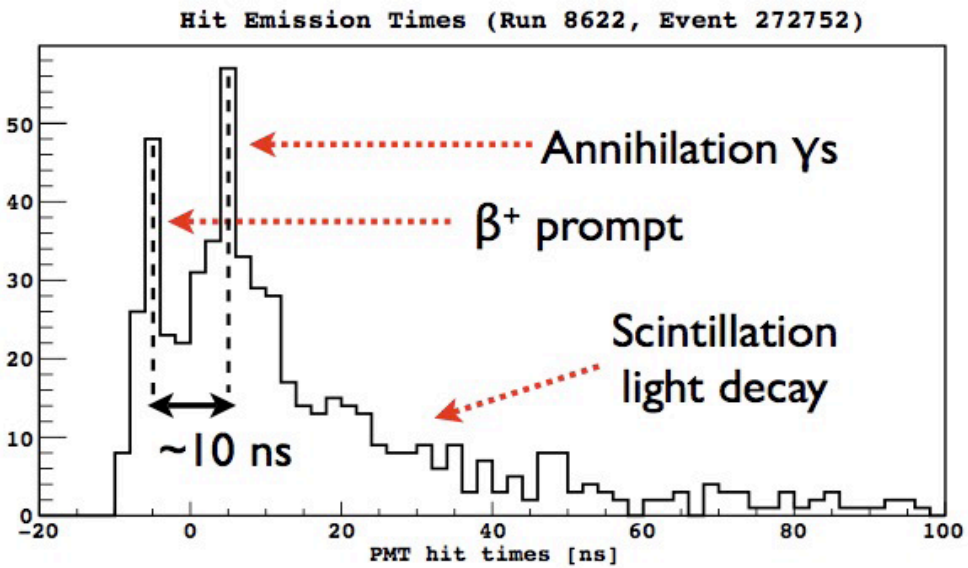
- FV cut removes external background (R<2.8 m and -1.8 <Z< 2.2 m) : 100 tonnes.
- ^{11}C removal (tagging by TFC)
- Multivariate analysis, together with the “mai” spectral fit the following fits are performed :

1. spectral fit of “after TFC” spectrum;
2. the fit on the PSD in the ^{11}C energy region;
3. the fit on the radial distribution of events

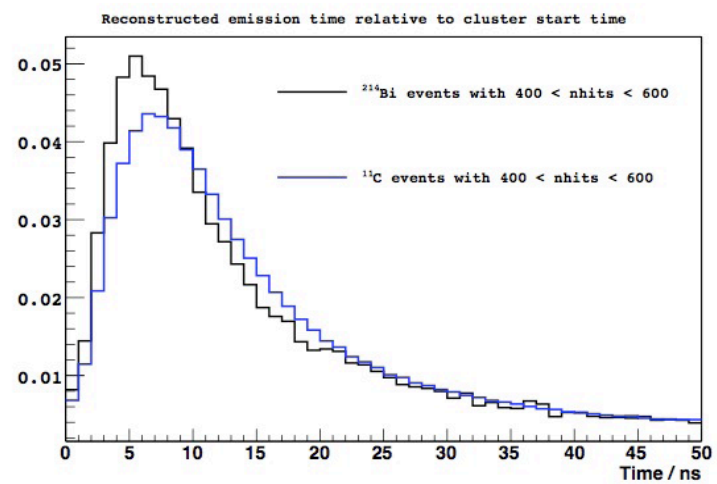
Threefold coincidences (TFC)

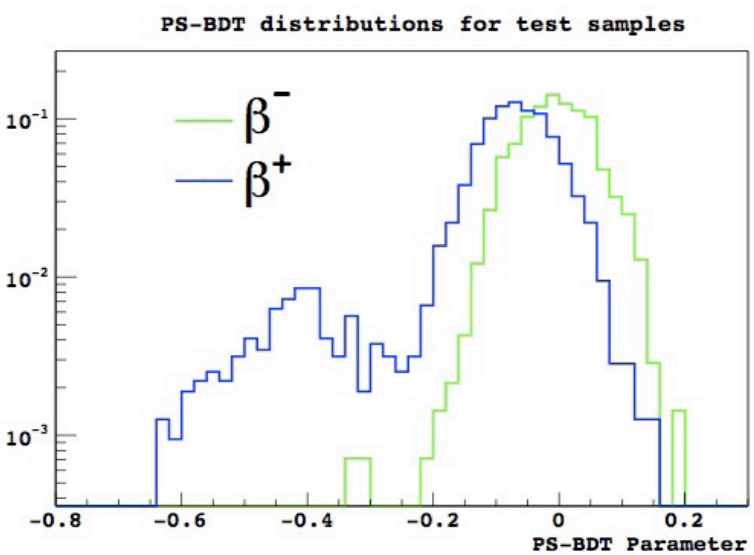


e^+/e^- discrimination



50% of β^+ decays give *ortho*-positronium ($t_{1/2}$ = 3 ns).

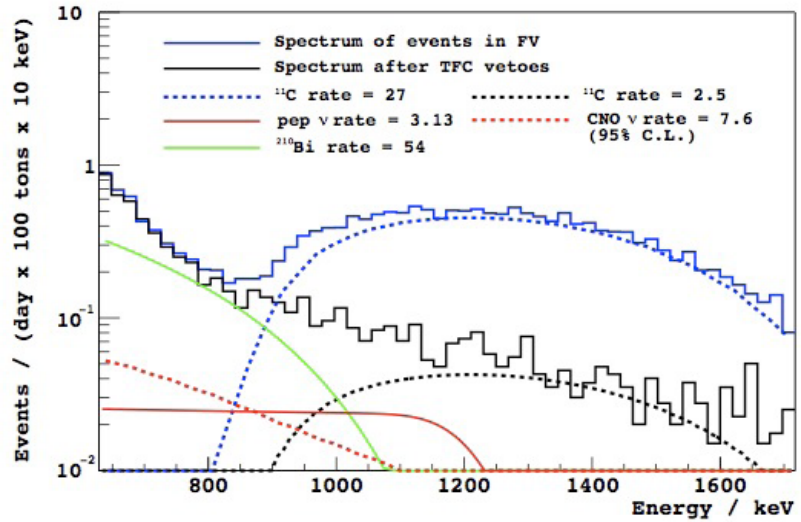


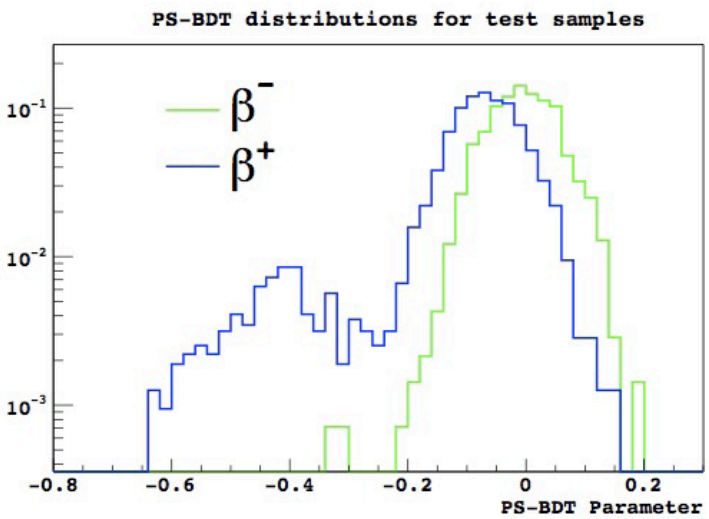


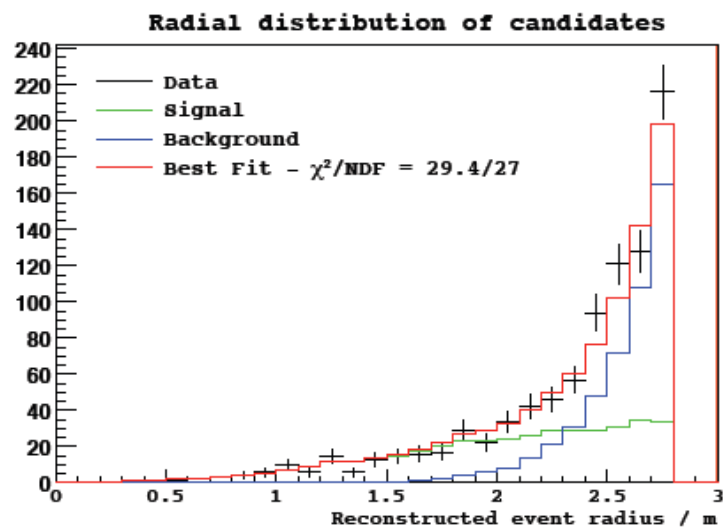
- Use boosted decision tree to optimize discrimination.
- Train, test, and build PDF with events cut by TFC.

Multivariate fit

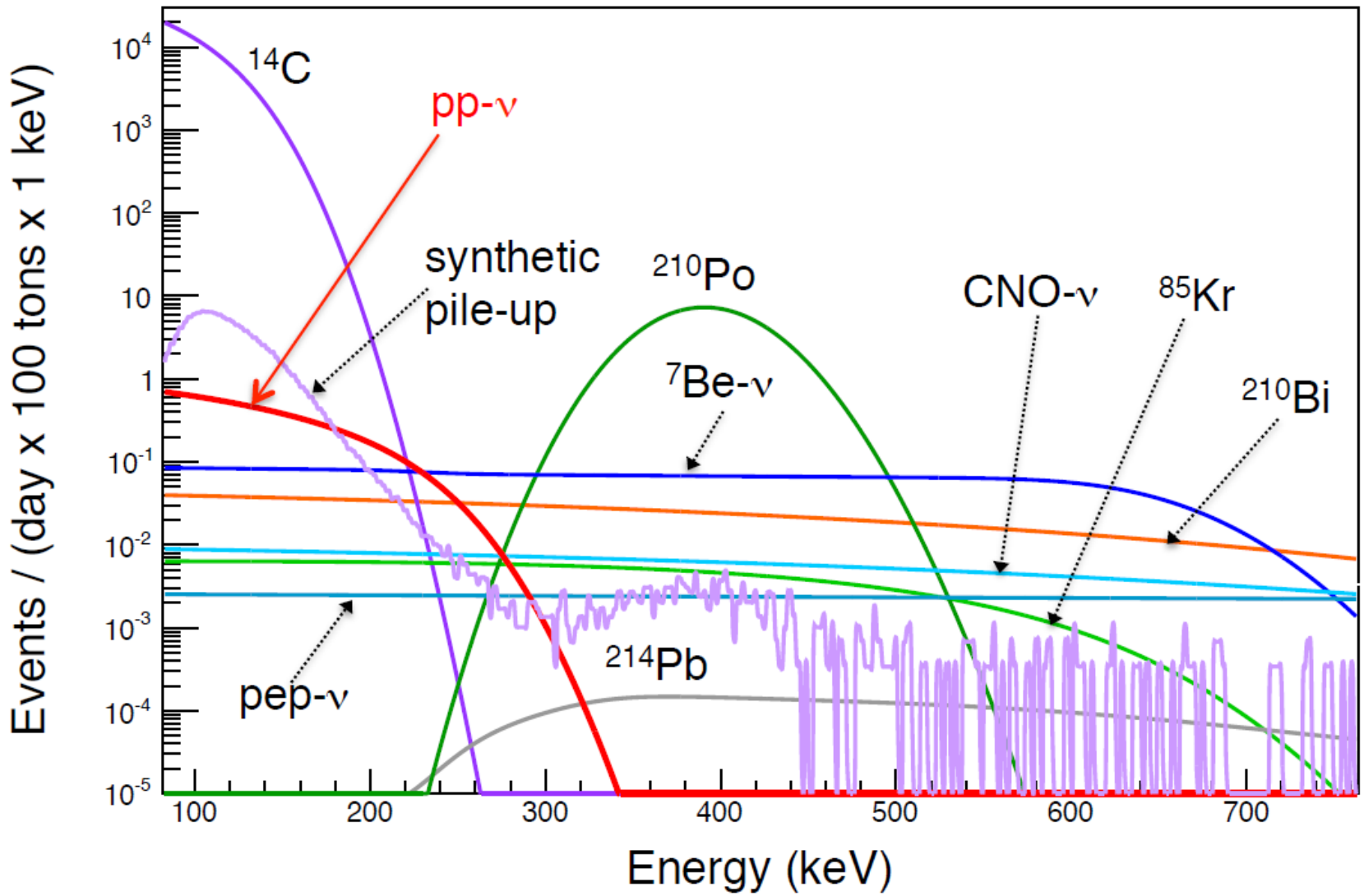
- Binned likelihood fits in energy, radius, and BDT
- 2D energy-radius and energy-BDT PDFs
- Simultaneous fits to TFC accepted and rejected spectra (double background statistics).







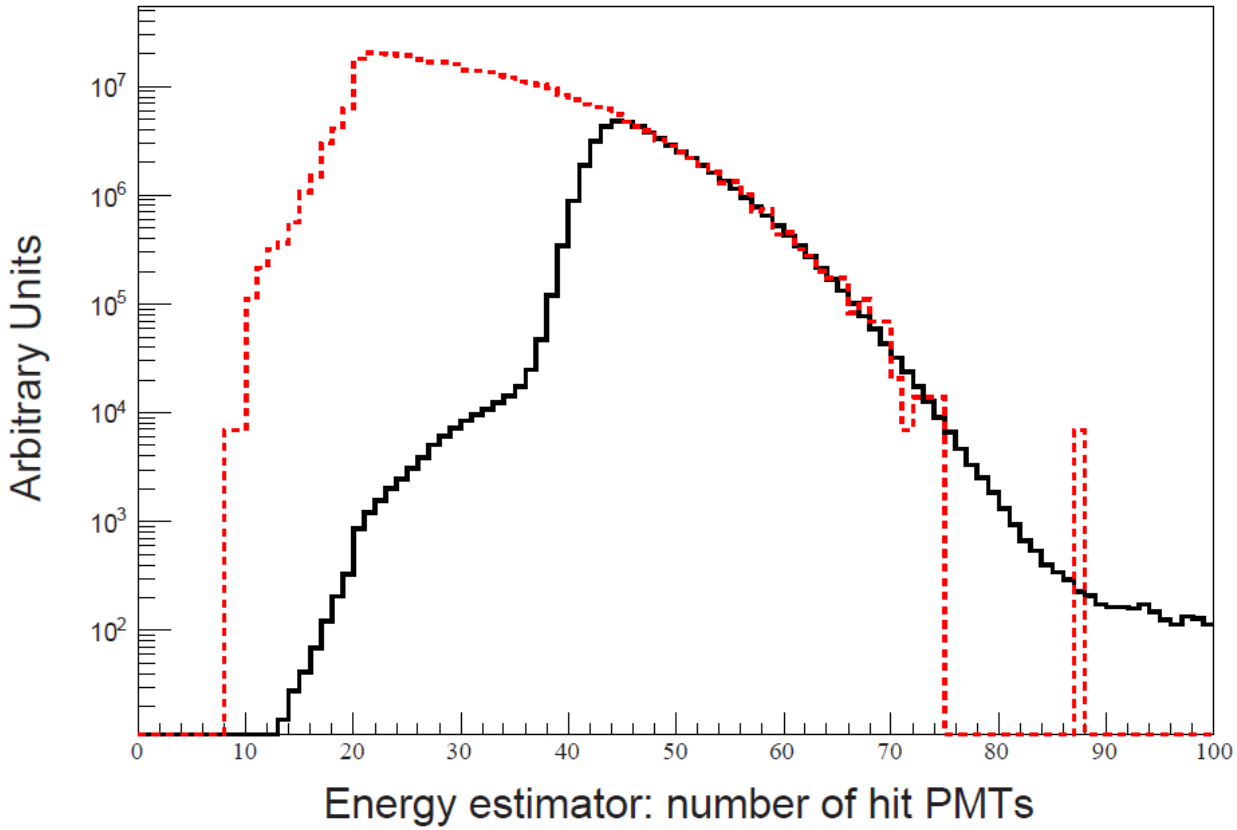
pp-neutrino study: includes ^{14}C and ^{210}Po (Phase II measurement)



Main components of pp analysis

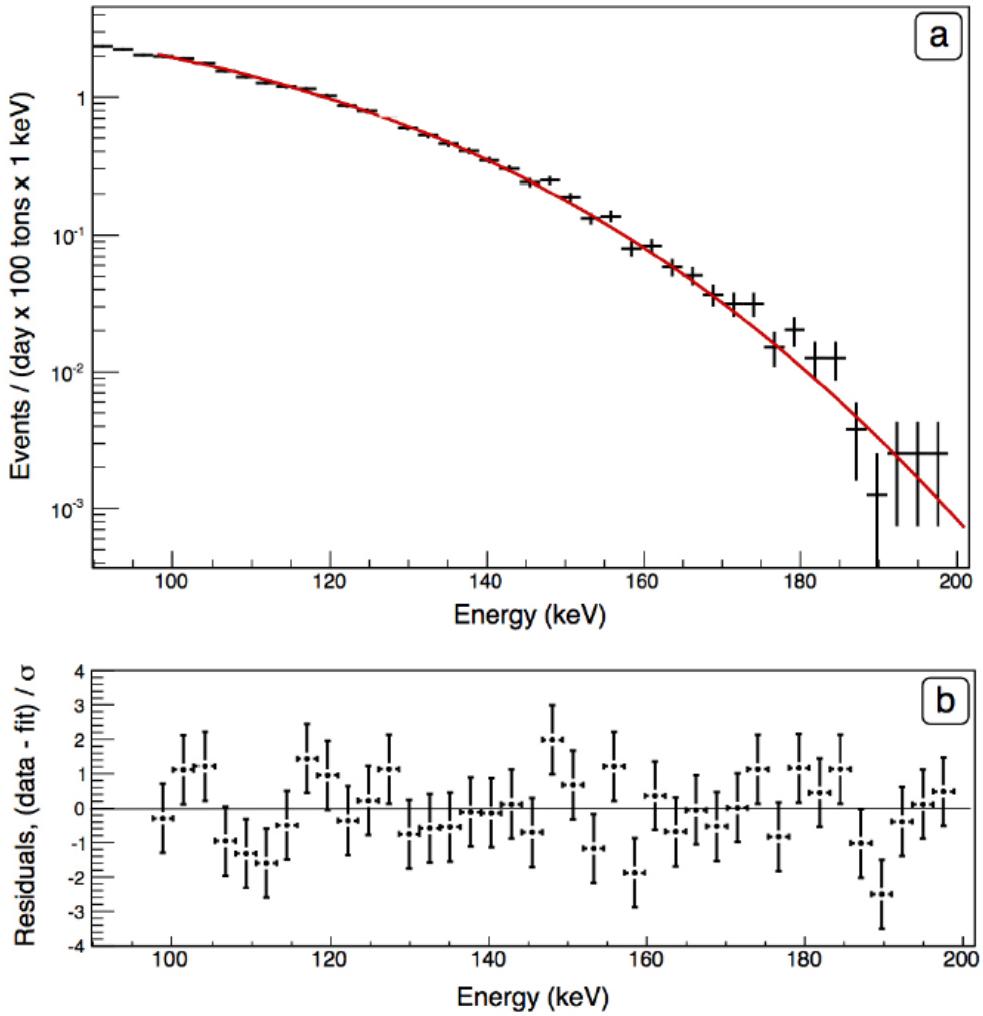
- Data selections: basically the same as for ^{7}Be analysis, but without any potentially energy-dependent cuts;
- Analytical method only (too high statistics for the MC), but MC was used to tune the method.
- Independent ^{14}C rate estimation;
- Pile-up events modeling (synthetic pile-up);
- Careful modeling of the energy response width;
- Careful modeling of the energy response shape

Independent ^{14}C rate estimation using second cluster events



The 14C rate was determined independently from the main analysis, by looking at a sample of data in which the event causing the trigger is followed by a second event (in red) within the acquisition time window of 16 μs. The main events spectrum are shown in the same scale in black.

^{14}C rate estimation using second cluster events



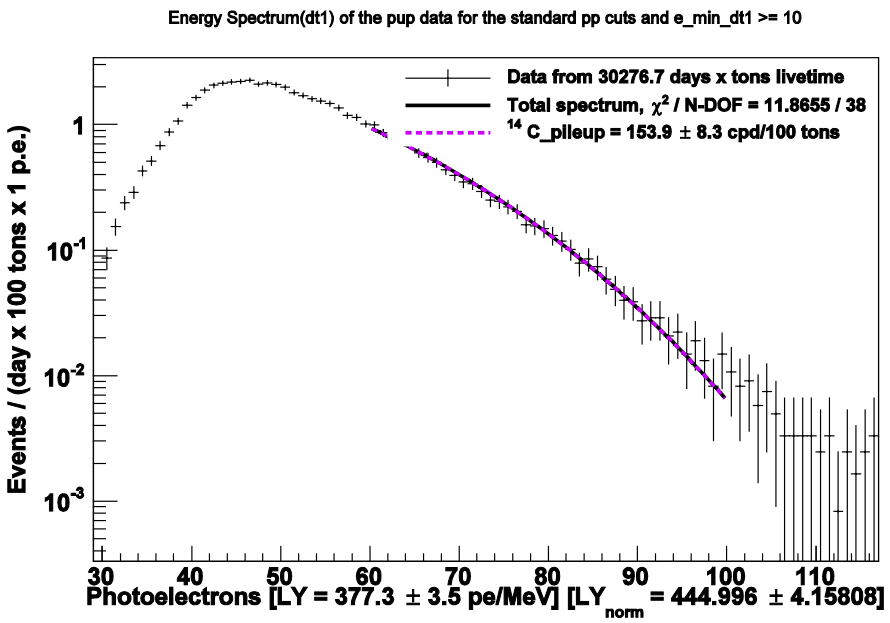
Time acquisition window is 16 ms. Only the data with ΔT>8 ms were used (to exclude PMTs afterpulses) Fitting the data with theoretical β-spectrum shape we obtained:
40±1 Bq/100 t rate.

The corresponding 14C/12C isotopical abundance is **$(2.7\pm0.1)\cdot10^{-18}$ g/g**

^{14}C β-spectrum has some deviations from the allowed shape parameterized as $S(E)=1+\alpha E$

Methods to construct pile-up

- Synthetic pile-up Data+Data
  - Real triggered events without any selection cuts are artificially overlapped with random data samples and processed with reconstruction code in a standard way



Fit of synth.pile-up with analytical function: 154±10 cpd/100 tones

Compatible with naïve rate estimation using ^{14}C counting rate only (40 Bq/100 t).

Energy scale

Energy estimator: number of triggered pmts (Npmts) - Integer

Conversion of energy to Npmts depends on:

- **Light yield (LY) – free**
- **Birks' parameter (k_B)- fixed at the value found from the calibration data (k_B=0.0109 cm/MeV)**
- **Average number of live PMTs (N_{Live}) – calculated for data set**
- **Geometric correction parameter (gc) fixed at value found with MC (no sensitivity in the low energy part)**

$$npmts = N_{Live} \cdot \frac{1 - e^{-\frac{Q(E)}{N_{Live}}}}{1 + gc \cdot \frac{Q(E)}{N_{Live}}}$$

$$Q(E) = LY \cdot E \cdot f(k_B, E)$$

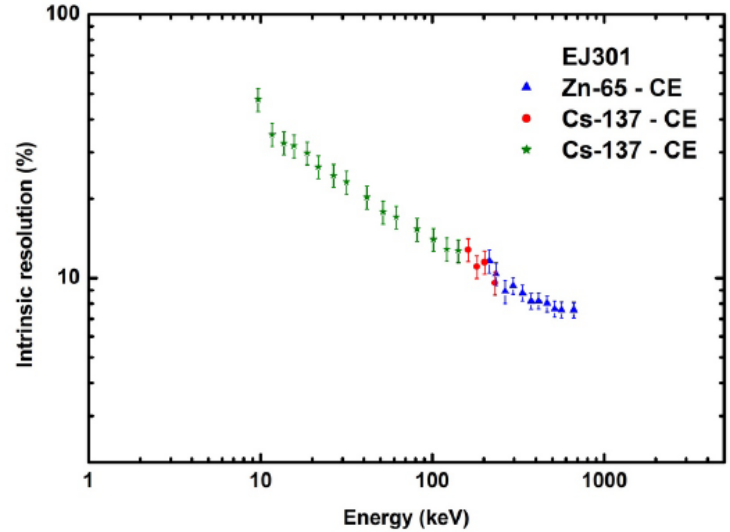
E→Q→Npmts conversion

The same as in ^{7}Be analysis

Energy resolution

energy resolution for npmt variable depends on: (2 free):

- **v_T – free.** Takes into account spatial non-uniformity of the light collection (basically ^{210}Po parameter because it has negligible contribution in the low energy part of the spectrum). The same for Po and ^{14}C
- **σ_{int} - free.** Intrinsic line width (extra width compared to sqrt($N_{photons}$)) for β-particles (absent or negligible for α).
- **v_f - fixed** at calculated value (variance of the number of live Pmts).
- **v_1=0.17 - fixed** at value found with MC (no sensitivity in the low energy part).



Intrinsic resolution measured for a EJ301 liquid scintillator. Various colours represent the data obtained with different radiation sources placed at various angles. (figure from 2012 JINST 7 P06011)

$$\sigma_N^2 = npmts \cdot \left(1 - \frac{npmts}{N_{Live}}(1+v_1)\right) + npmts^2 \cdot (v_T \cdot npmts \cdot (1+v_f) + v_f) + \sigma_{int}^2$$

The same as in ^{7}Be analysis

+Intrinsic line width

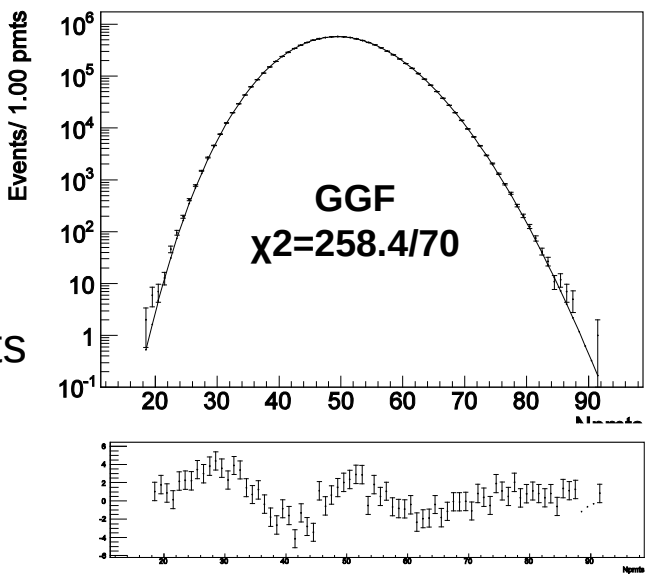
Analytical description of Scintillation Line shape

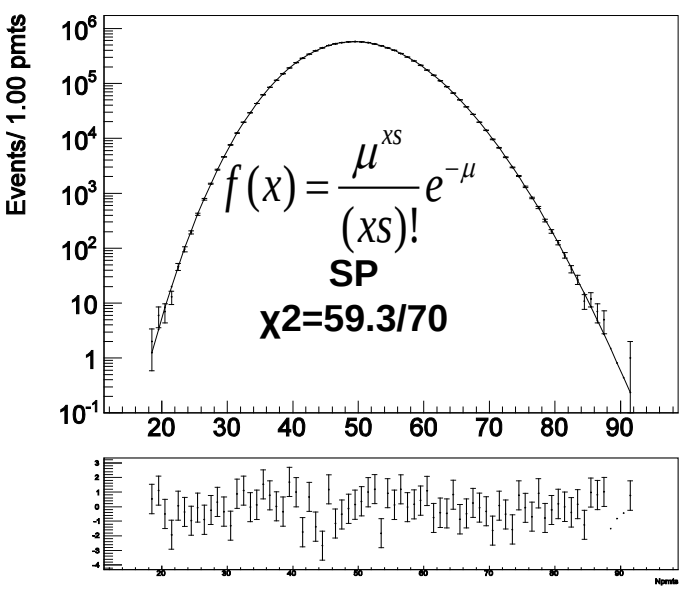
Line shape – the shape of the detector's response for uniformly distributed monoenergetic particle.

Generalized Gamma Function (^{7}Be analysis) substituted with Scaled Poisson

Reason: very high statistics of ^{14}C (compared to ^{210}Po in ^{7}Be analysis)

10^7 MC events in FV
<N>=60





The mean values and variances of both shapes are the same

Scaled Poisson vs GGF

$$f(x) = \frac{\mu^{xs}}{(xs)!} e^{-\mu}$$

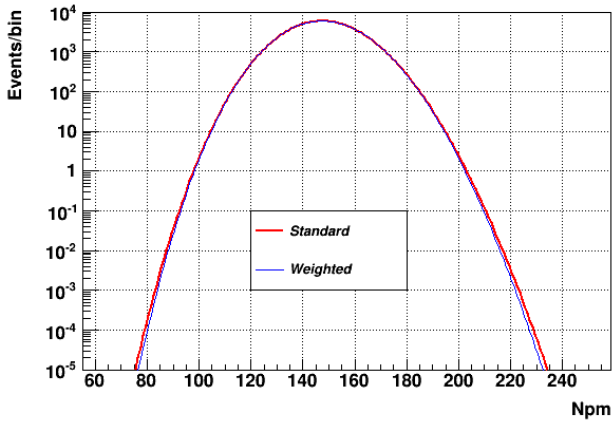
$$f(x) = 2\beta^{\alpha} \frac{x^{2\alpha-1}}{\Gamma(\alpha)} e^{-\beta x^2}$$

	1σ	2σ	3σ	4σ
Gauss	$1.5 \cdot 10^{-1}$	$2.10 \cdot 10^{-2}$	$1.2 \cdot 10^{-3}$	$2.5 \cdot 10^{-5}$
GGF	$1.5 \cdot 10^{-1}$	$2.45 \cdot 10^{-2}$	$1.9 \cdot 10^{-3}$	$7.8 \cdot 10^{-5}$
SP	$1.5 \cdot 10^{-1}$	$2.45 \cdot 10^{-2}$	$2.0 \cdot 10^{-3}$	$8.4 \cdot 10^{-5}$

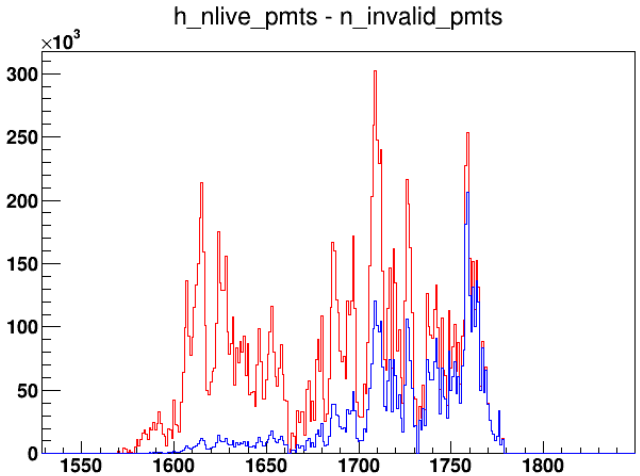
Fraction of events in tail for 3 base functions (<N>=49.9, source at center)

Other factors influencing the scintillation line shape

- **Varying number of live PMTs** : could be taken into account precisely as we know NLivePmt for every event. The response function can be weighted over NLivePmts . The improvement of χ2 is of 2-3 with all the best parameters of the fit unchanged, and with a drawback of heavy calculations.

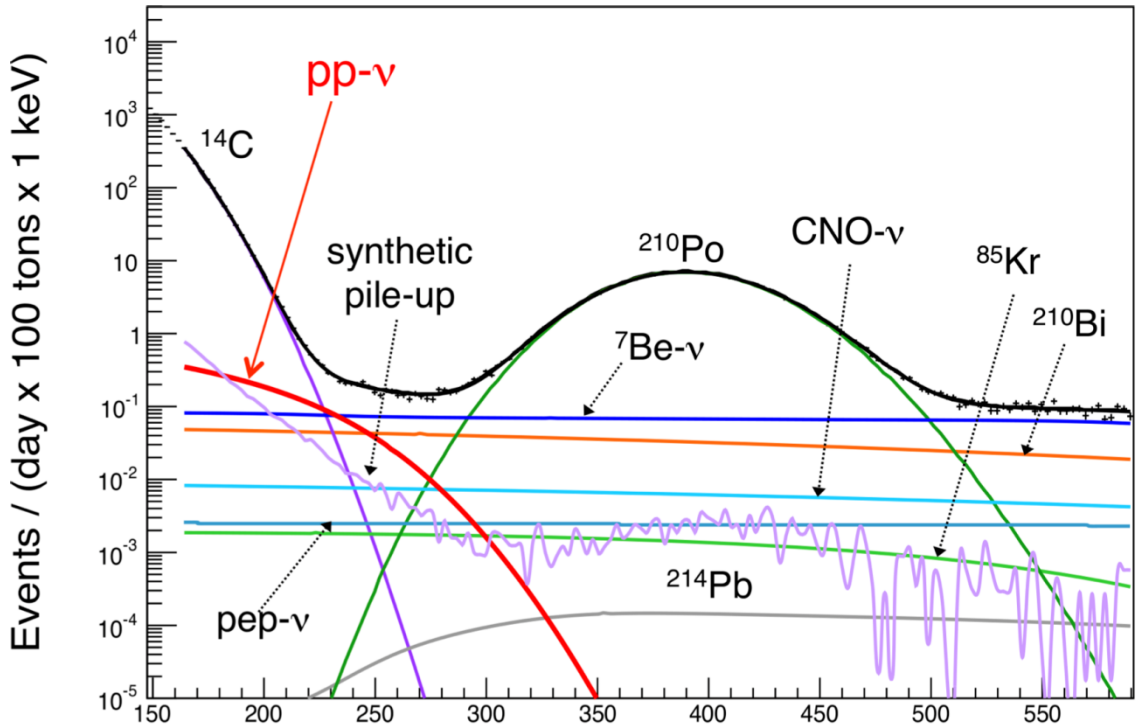


- **Additional spread because of the varying light collection efficiency over the detector : small compared to the "statistical" line width, the "basic" shape remains unchanged**



- The decay of Po and decrease of NLivePmt in time lead to the higher "effective" LY for Po and lower "effective" variance of the Po line : could be calculated analytically following the ^{210}Po decay rate (Fill(1,1)→Fill(1,R(^{210}Po)(T))

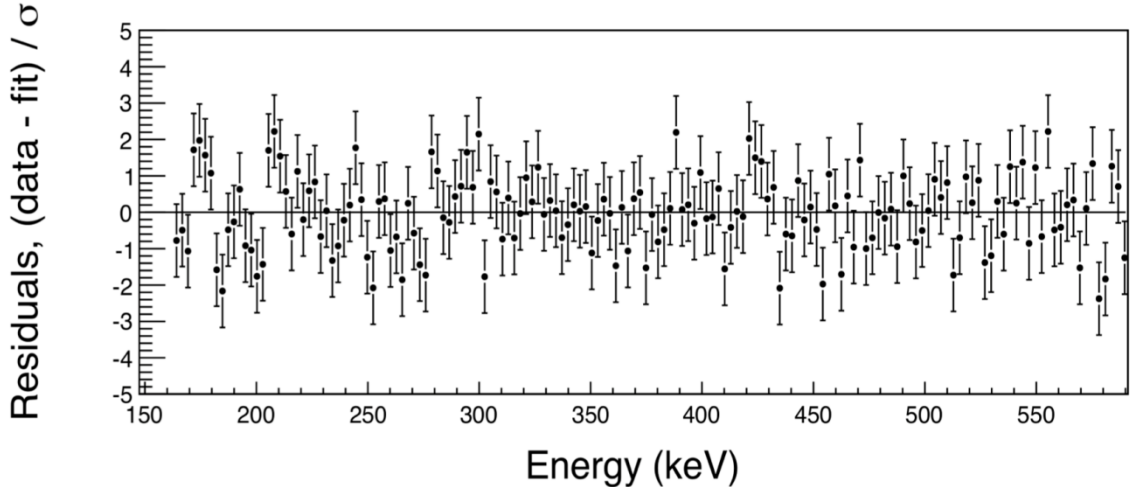
The results of the pp-spectral fit



χ^2/d.o.f = 172.3/147

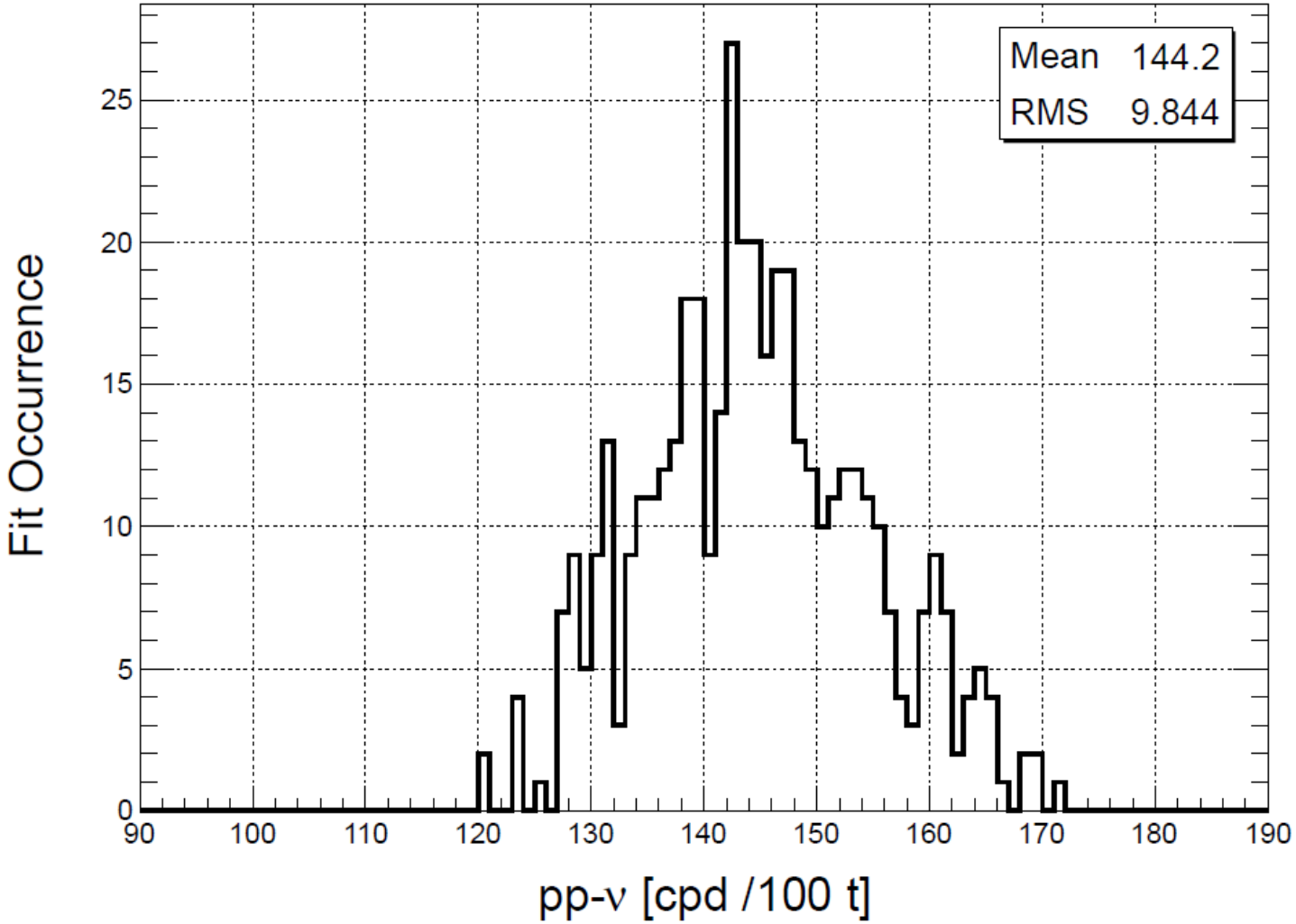
- pp ν: 144 ± 13 (free)
- ^{7}Be ν: 46.2 ± 2.1 (constrained)
- pep ν: 2.8 (fixed)
- CNO ν: 5.36 (fixed)
- ^{214}Pb: 0.06 (fixed)
- ^{210}Po: 583 ± 2 (free)
- ^{14}C: 39.8 ± 0.9 (constrained)
- Pile-up: 321 ± 7 (constrained)
- ^{210}Bi: 27 ± 8 (free)
- ^{85}Kr: 1 ± 9 (free)

Fit range: 165-590 keV



N.B. fit was performed in the Npmt scale and only then converted to energy. This helps to preserve the energy response shape

Systematics estimation



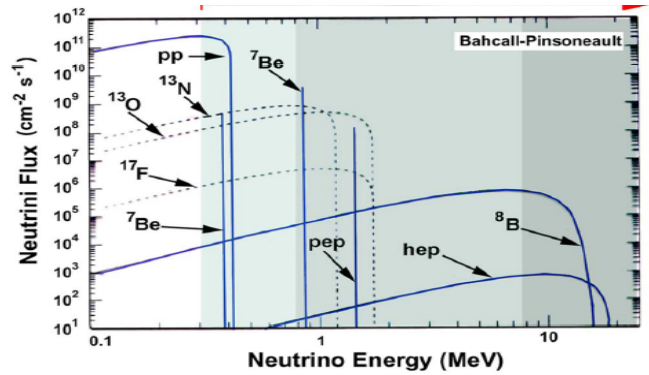
Values are obtained by varying the fit conditions, including the fit energy range, synthetic-versus-analytic pile-up spectral shape, and energy estimator. The distribution shown is peaked around reported value of 144 cpd/ 100 t.

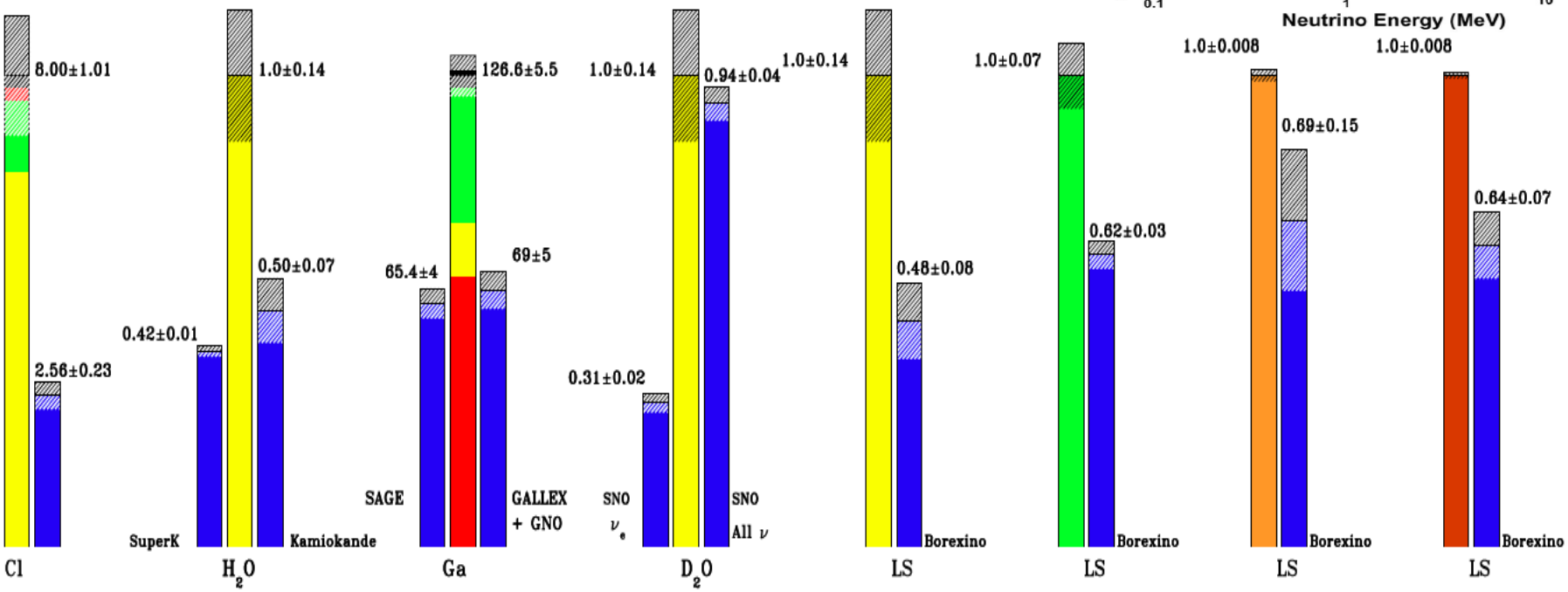
+2% on the FV

Solar neutrino fluxes: theory vs experiment

Reaction	GS98	AGS09	$cm^{-2}s^{-1}$	Measurement	Experiment
pp	5.98±0.04	6.03±0.04	$x10^{10}$	6.14±0.61 6.6±0.7	all Solar BX
pep	1.44±0.012	1.47±0.012	$x10^{8}$	1.6±0.3	BX
^{7}Be	5.0±0.07	4.56±0.07	$x10^{9}$	4.87±0.24	BX
^{8}B	5.58±0.14	4.59±0.14	$x10^{6}$	5.2±0.3 $5.25\pm0.16^{+0.011}_{-0.013}$	SNO+SK+BX+KL SNO LETA
hep	8.0±2.4	8.3±2.5	$x10^{3}$	$<2.3x10^{4}$ 90% C.L.	SNO
^{13}N	2.96±0.14	2.17±0.14	$x10^{8}$	Integral CNO flux $<7.4x10^{8}$ 90% C.L.	BX
^{15}O	2.23±0.15	1.56±0.15	$X10^{8}$		
^{17}F	5.52±0.17	3.40±0.16	$x10^{6}$		

Solar experiments vs models





Theory

^{7}Be

^{8}B

pp+pep

CNO

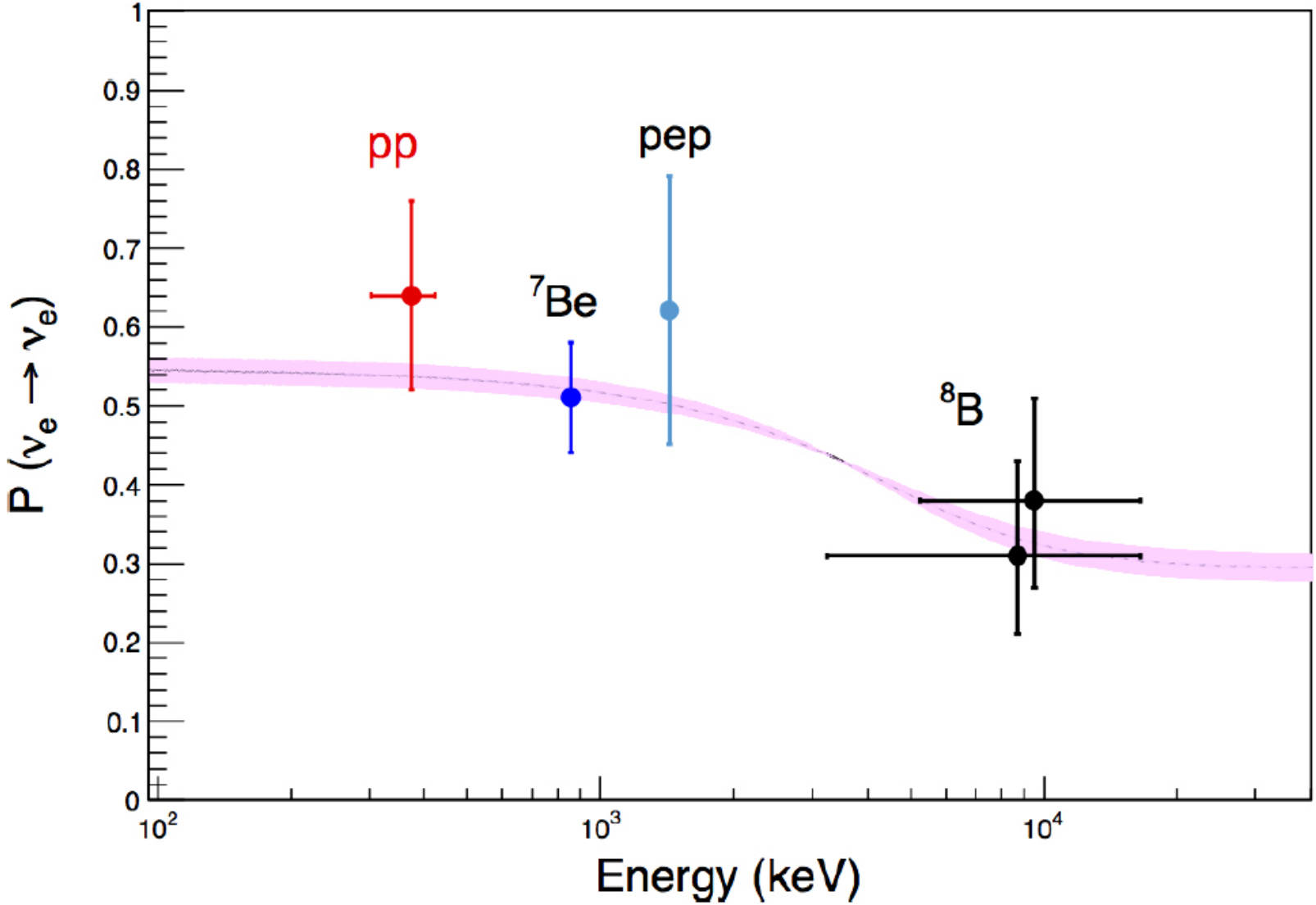
pep

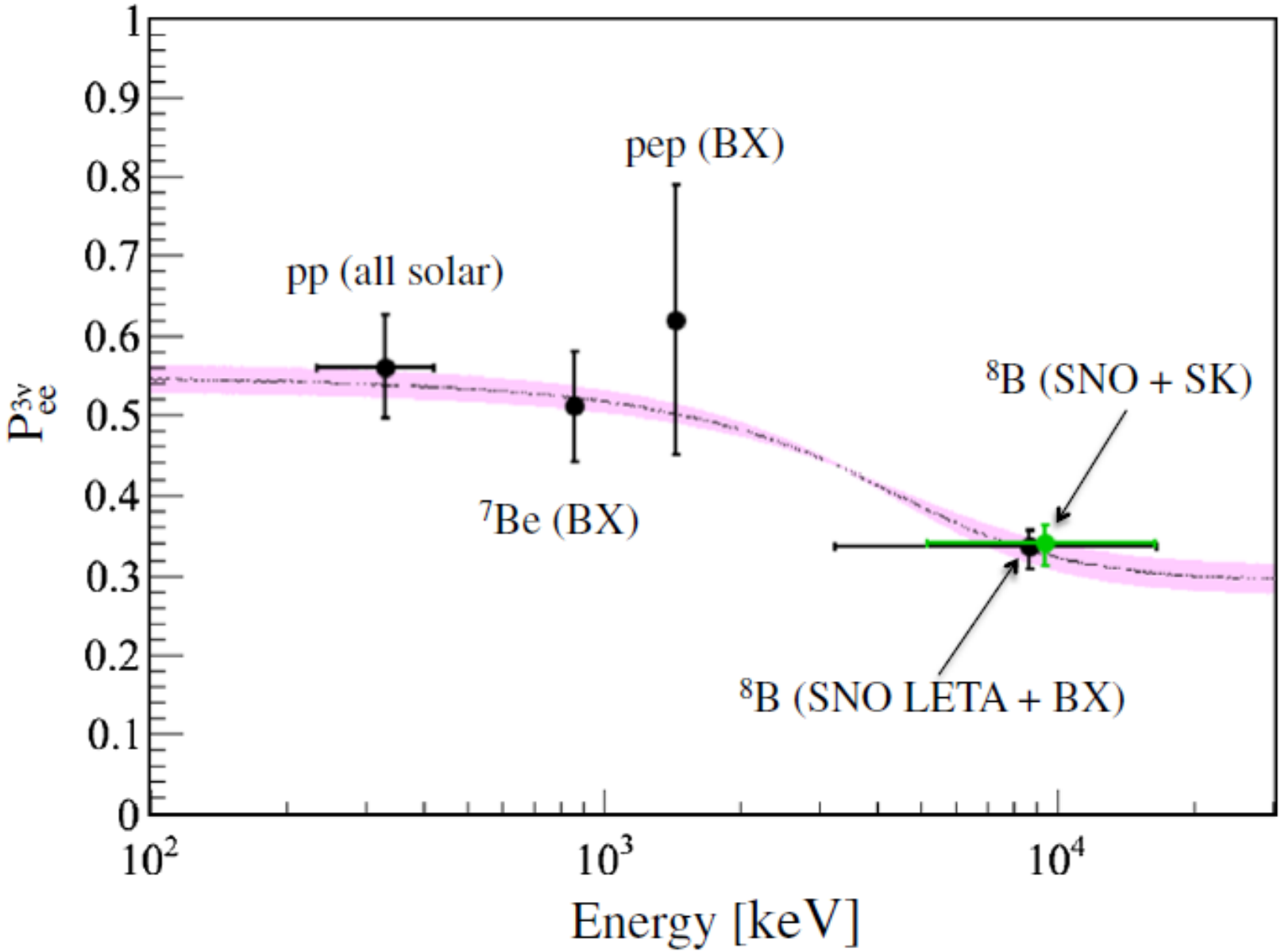
pp

Exper.

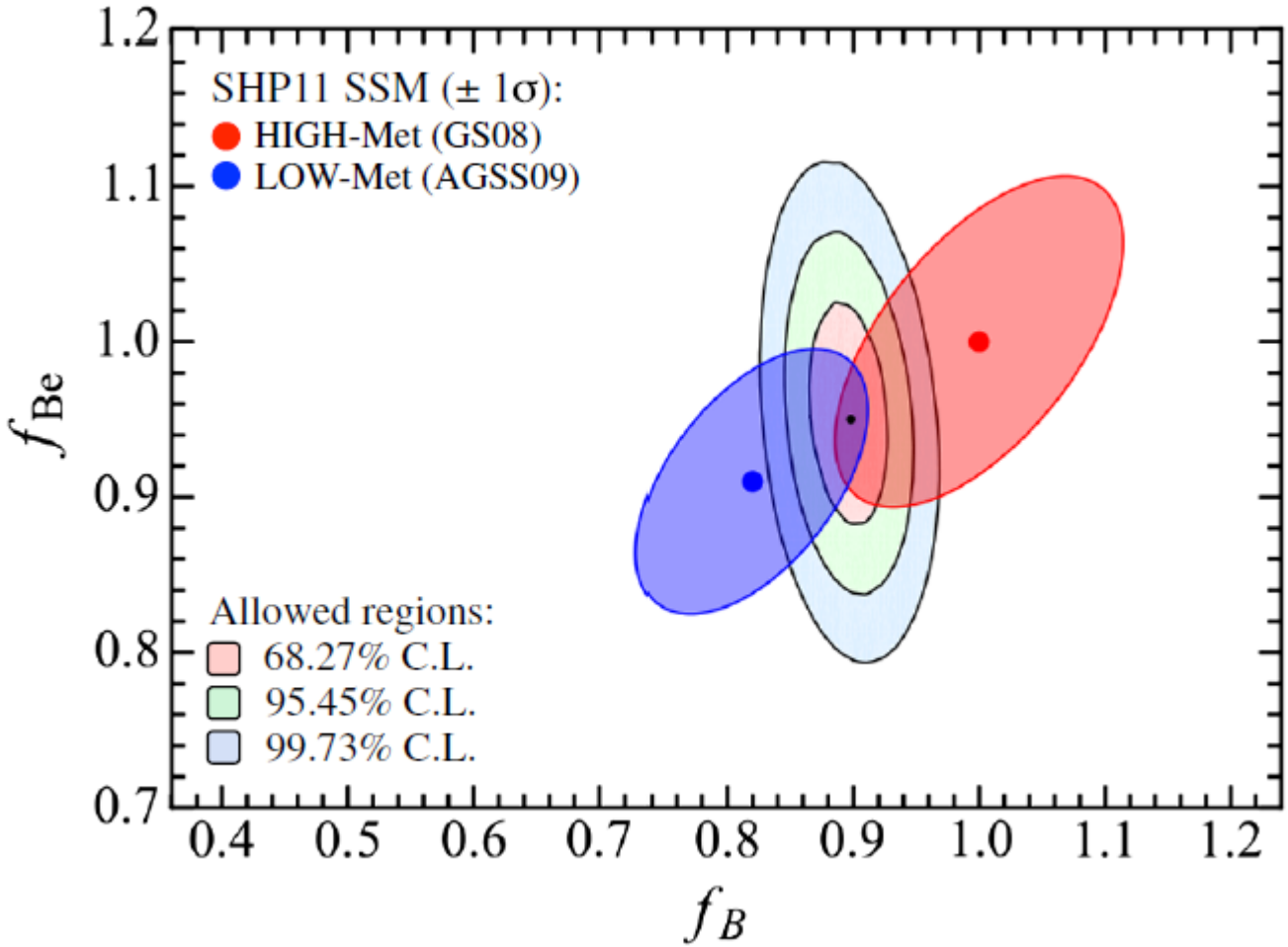
Borexino

Borexino measured electron neutrino survival probability for 4 different nuclear reactions




pp (all solar)
pep (BX)
^{7}Be (BX)
^{8}B (SNO + SK)
^{8}B (SNO LETA + BX)
$P^{3\nu}_{ee}$
Energy [keV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^2
10^3
10^4

^{7}Be & ^{8}B fluxes



SHP11:
A.M. Serenelli, W. C.Haxton and C. Pena-Garay, arXiv:1104.xxxx [astro-ph]

GS98:
N. Grevesse and A. J. Sauval, Space Sciences Reviews 85, 161 (1998)

AGSS09:
Aldo M. Serenelli *et al 2009 ApJ* ***705 L123***

Combining results on pp-neutrino

- All Solar + ^{7}Be Borexino:

$$\Phi(pp) = (6.14 \pm 0.61)10^{10} \quad cm^{-2}s^{-1}$$

- Borexino only:

$$\Phi(pp) = (6.6 \pm 0.7)10^{10} \quad cm^{-2}s^{-1}$$

- Combined

$$\Phi(pp) = (6.37 \pm 0.46)10^{10} \quad cm^{-2}s^{-1} \ (7\%)$$

Solar neutrino fluxes and Solar luminosity

Reaction	Measurement	$cm^{-2}s^{-1}$	MeV/1ν	L $x10^{26}$ W/s
pp	6.37±0.46	$x10^{10}$	13.10	3.76±0.28
pep	1.6±0.3	$x10^{8}$	11.92	0.009±0.002
^{7}Be	4.87±0.24	$x10^{9}$	12.60	0.276±0.014
^{8}B	5.25±0.16	$x10^{6}$	6.63	$(1.57\pm0.05)10^{-4}$

Measured (0.4%) $L_{\odot} = 3.846 \cdot 10^{26}$ W/s

$$\sum L = (4.04 \pm 0.28) \cdot 10^{26} \text{ W/s}$$

90% C.L. lower limit for energy production is $3.68 \cdot 10^{26}$ W/s, i.e. we can guarantee at 90% C.L. that no more than $0.15 \cdot 10^{26}$ W/s (i.e. <4% of the total energy) is produced in reactions not cited in the table