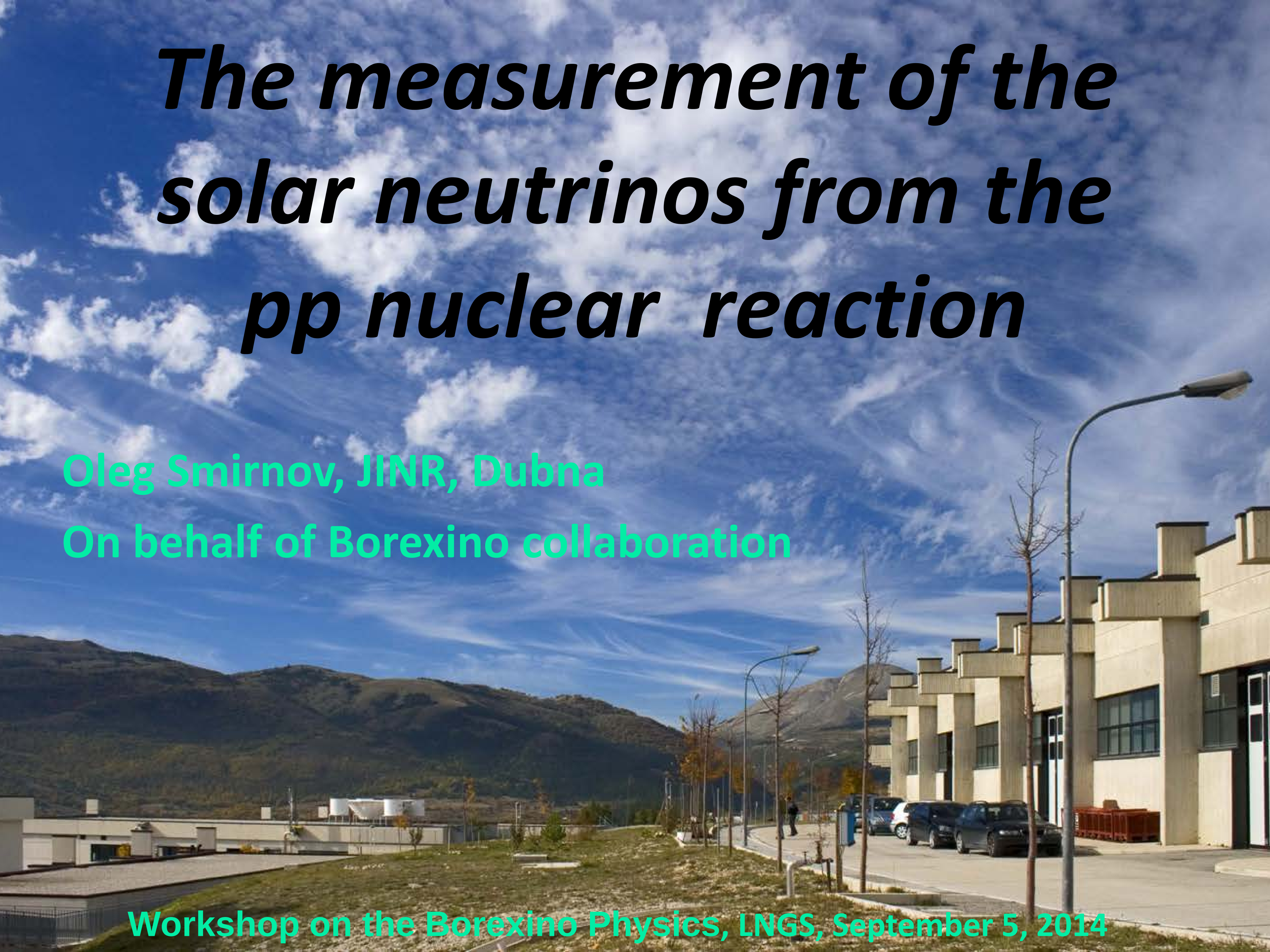


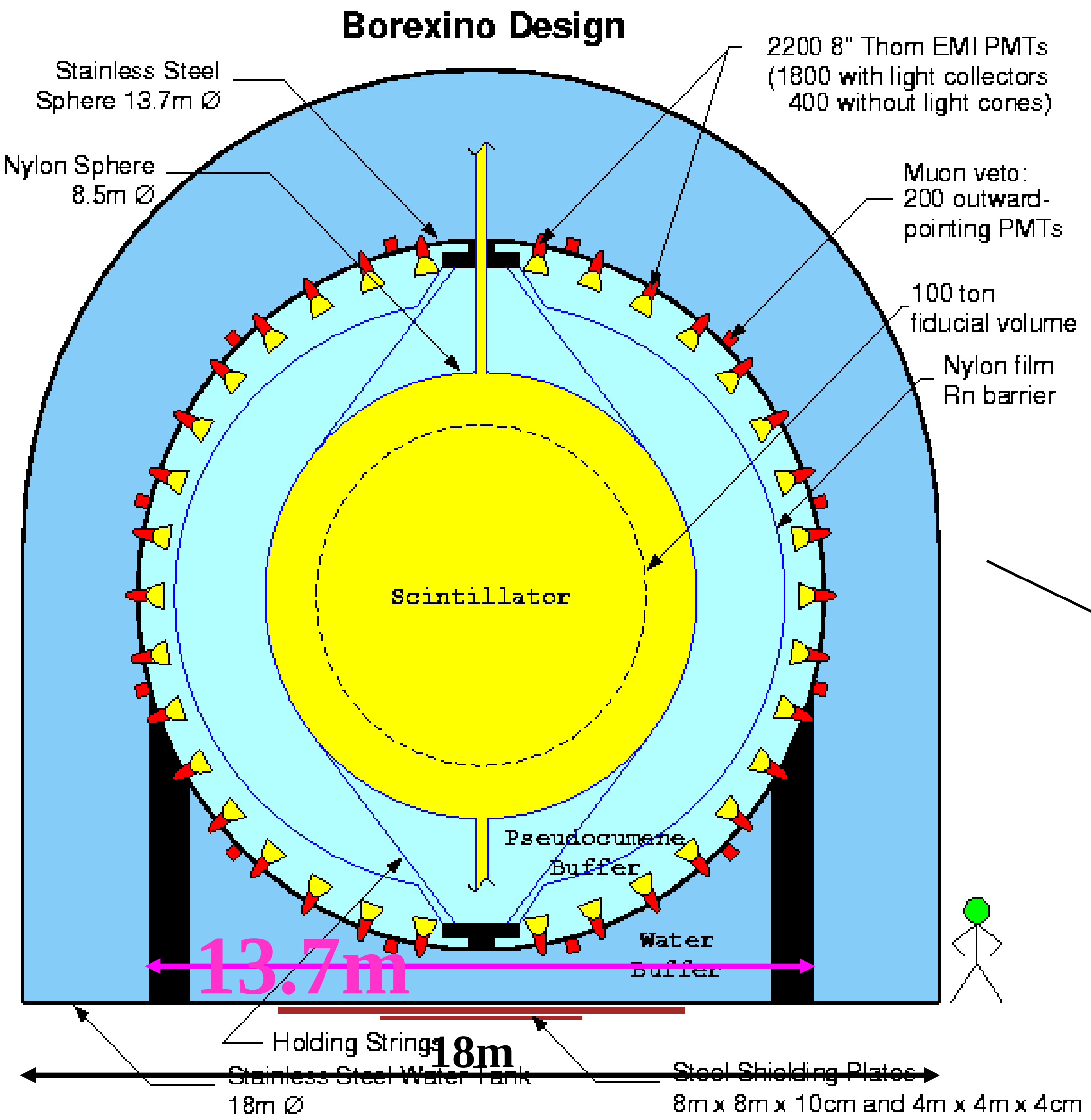
The measurement of the solar neutrinos from the pp nuclear reaction

Oleg Smirnov, JINR, Dubna

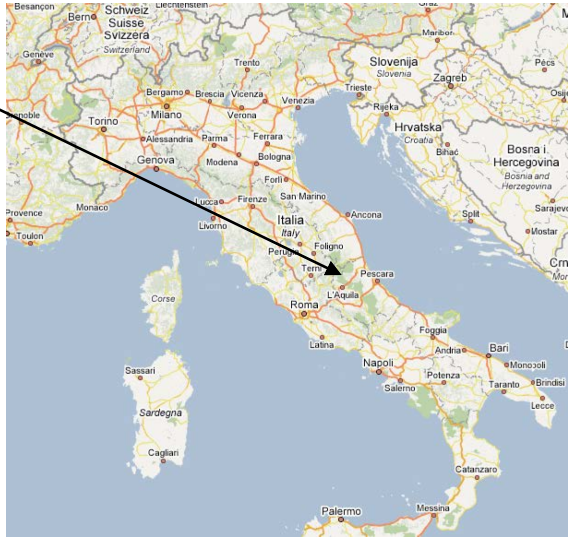
On behalf of Borexino collaboration

Workshop on the Borexino Physics, LNGS, September 5, 2014

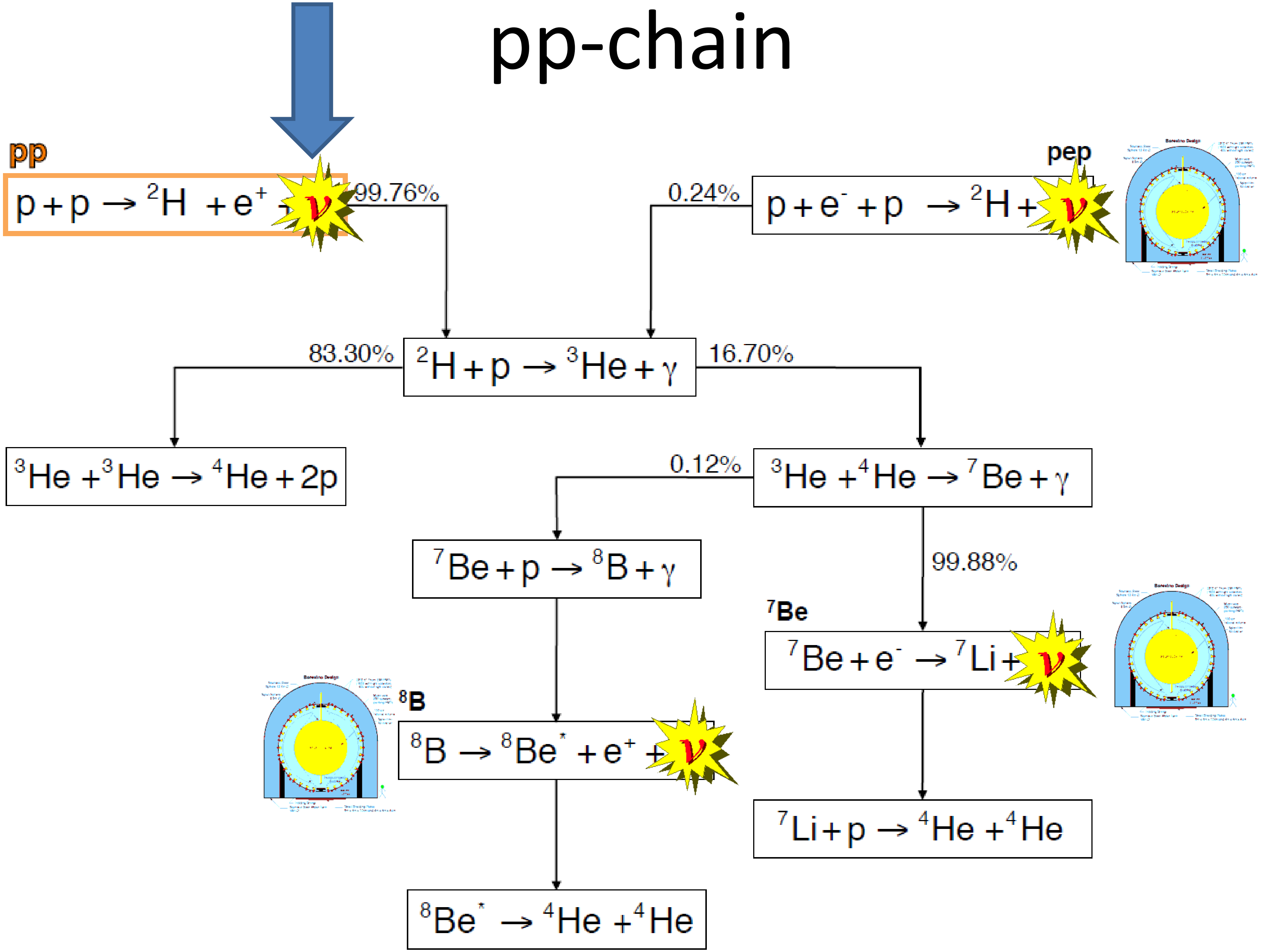
BOREXINO *(in operation from May,2007)*



- •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



pp

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

99.76%

0.24%

pep

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

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

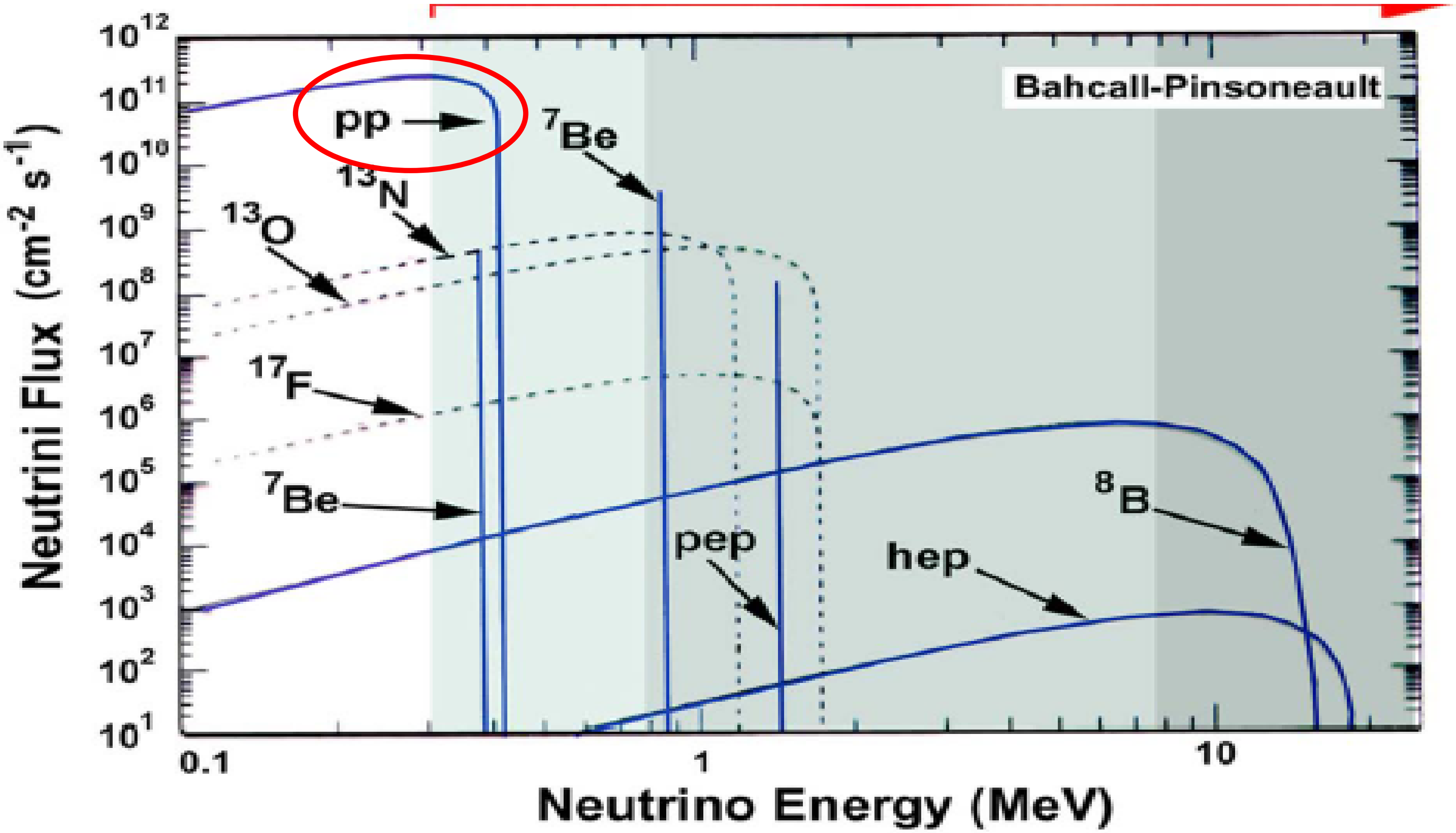
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

^{8}B

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

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

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

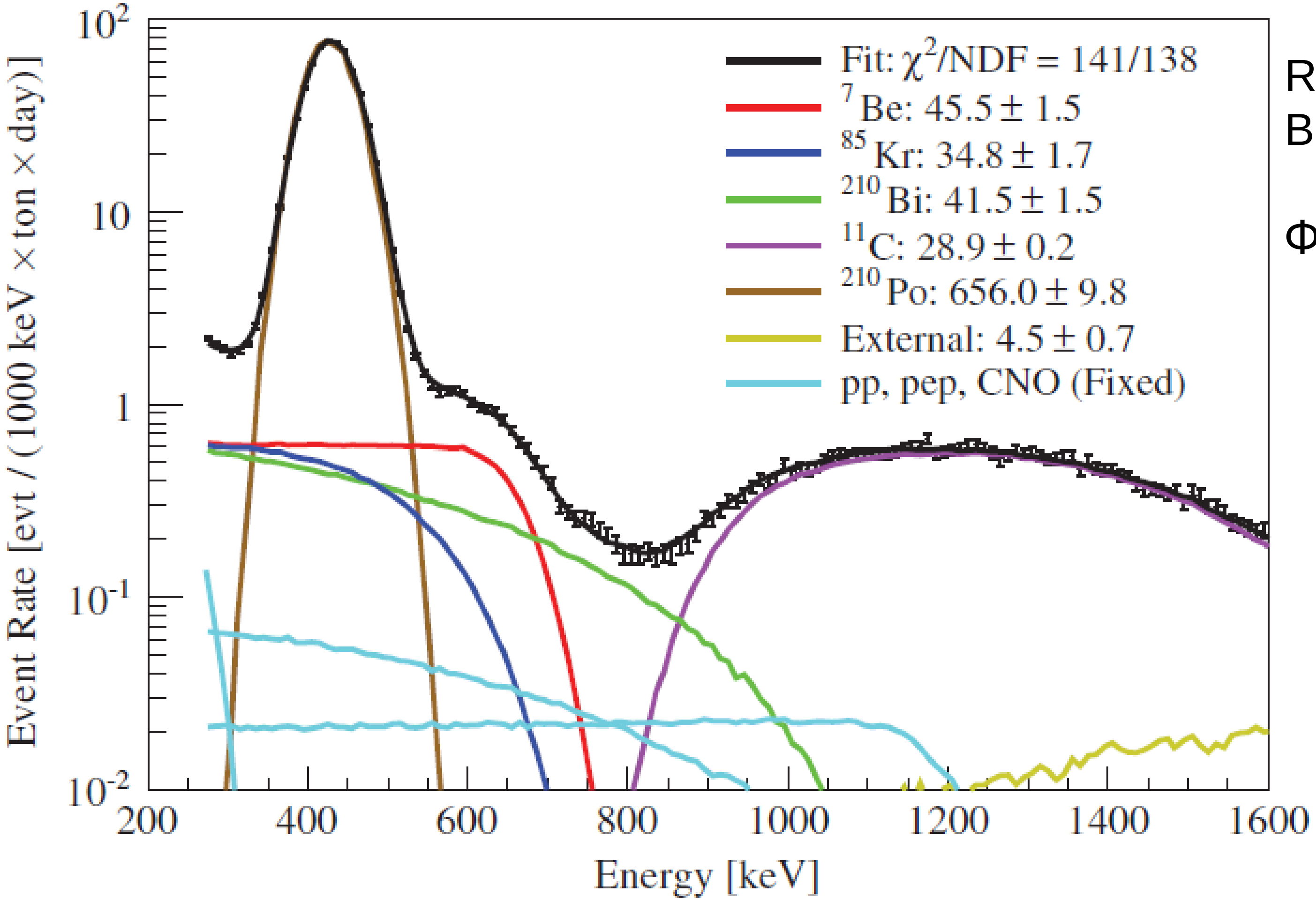


SSM pp neutrino flux ~$6 \cdot 10^{10}$ cm^{-2}s^{-1} (>90% of all solar neutrinos)

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

Other s– much less

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

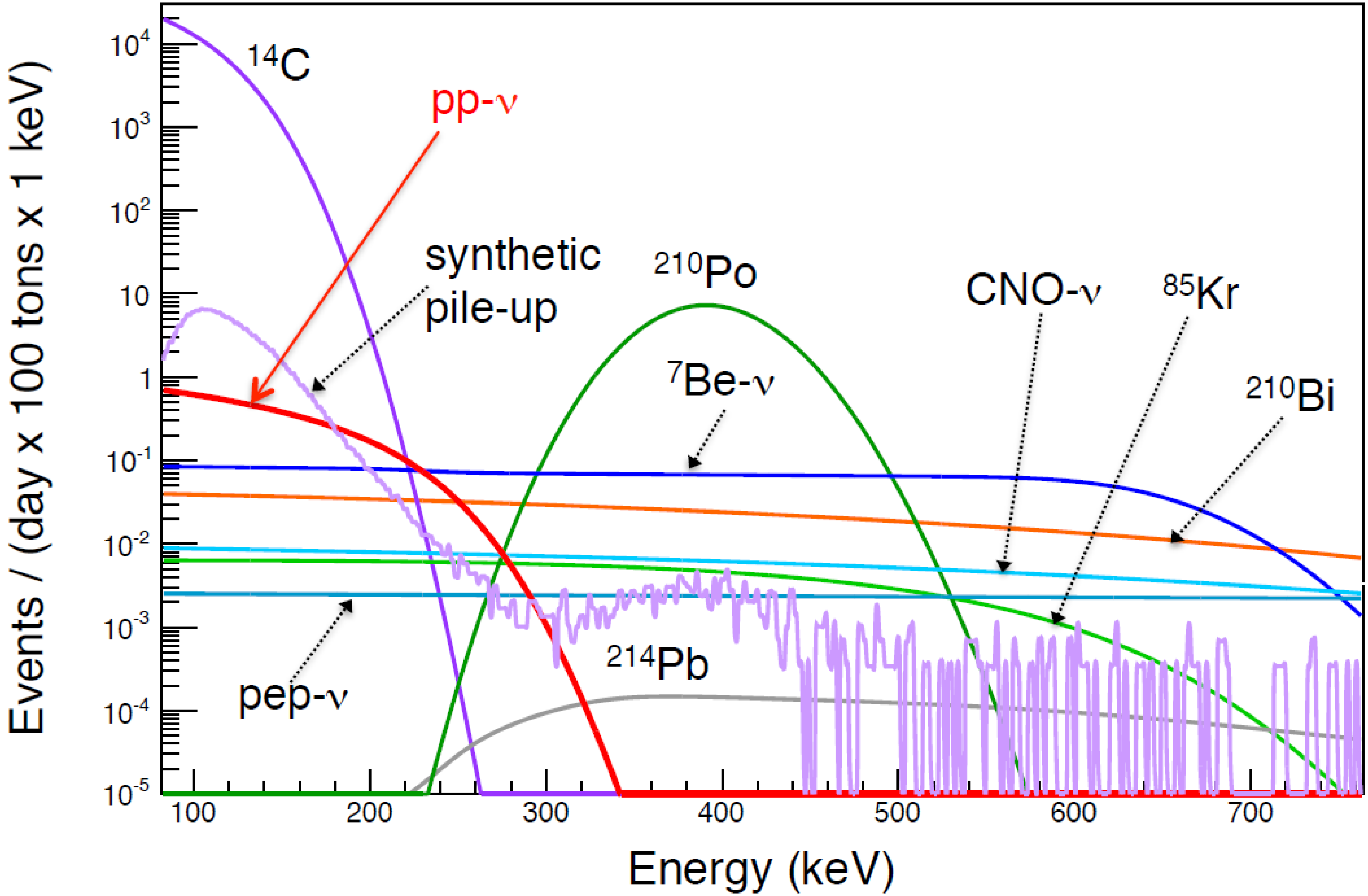


Radiochemical+
Borexino ^{7}Be:

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

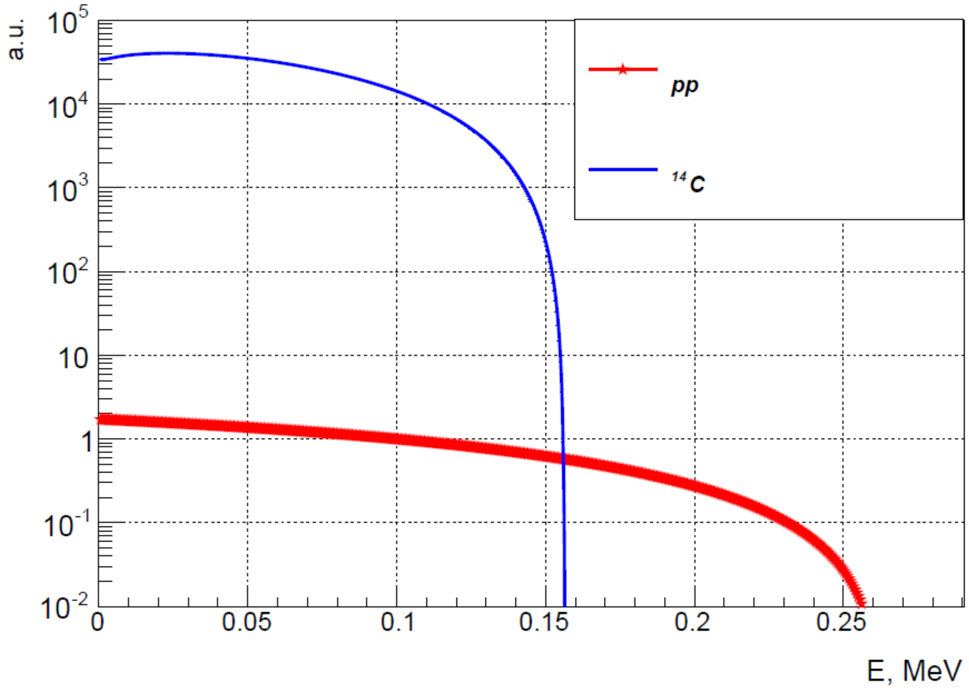
“Precision Measurement of the ^{7}Be Solar Neutrino Interaction Rate in Borexino”
PRL 107, 141302 (2011)

Expected Borexino Spectrum in energy scale



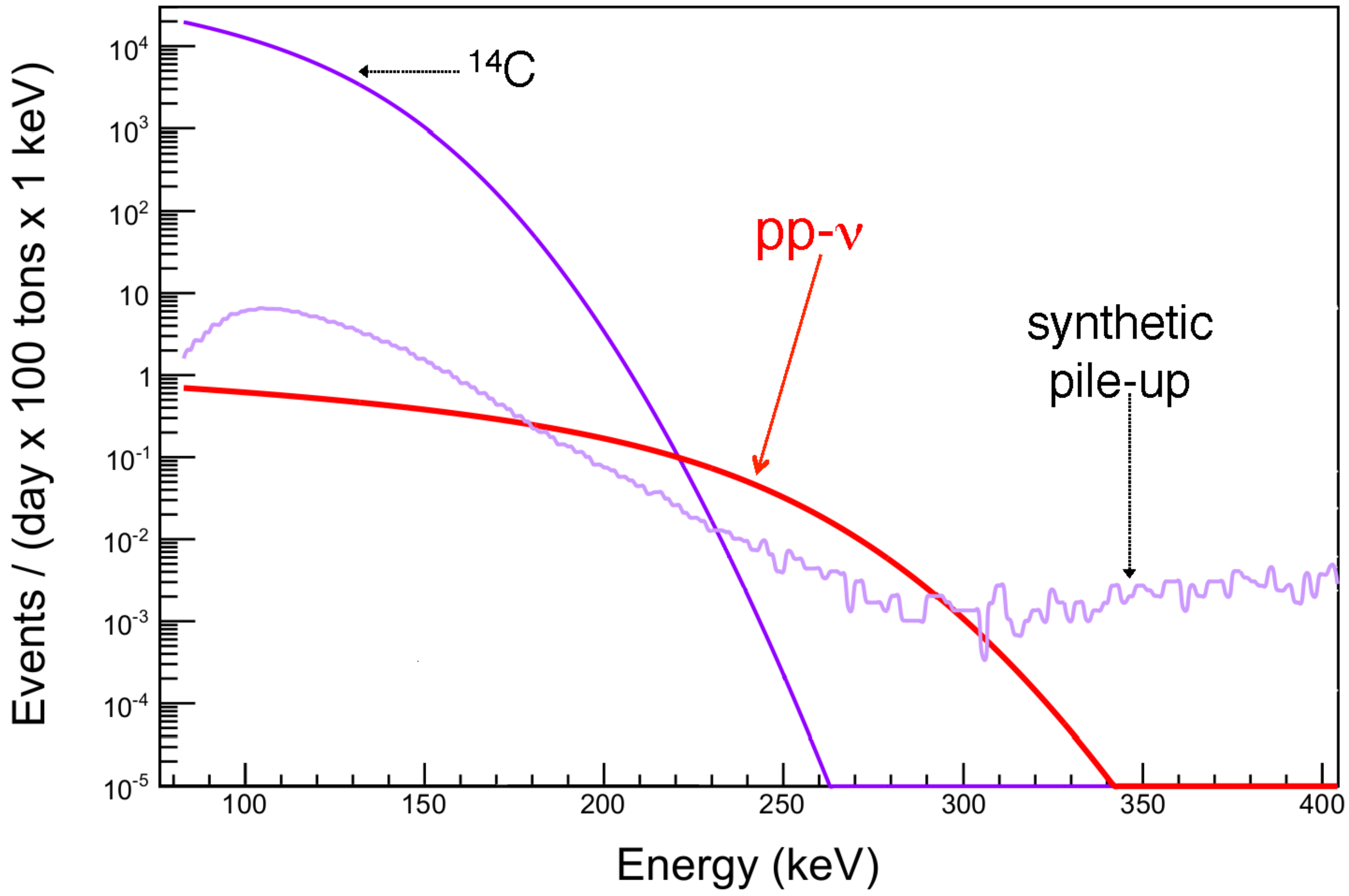
Why spectral measurement of pp-neutrino is possible?

- **Electron recoils spectrum for pp-neutrino has 264 keV end-point**
- **Main background for the measurement in liquid organic scintillator is ^{14}C, 156 keV end-point**
- **Spectra of other identified backgrounds are almost flat in the energy region of interest**

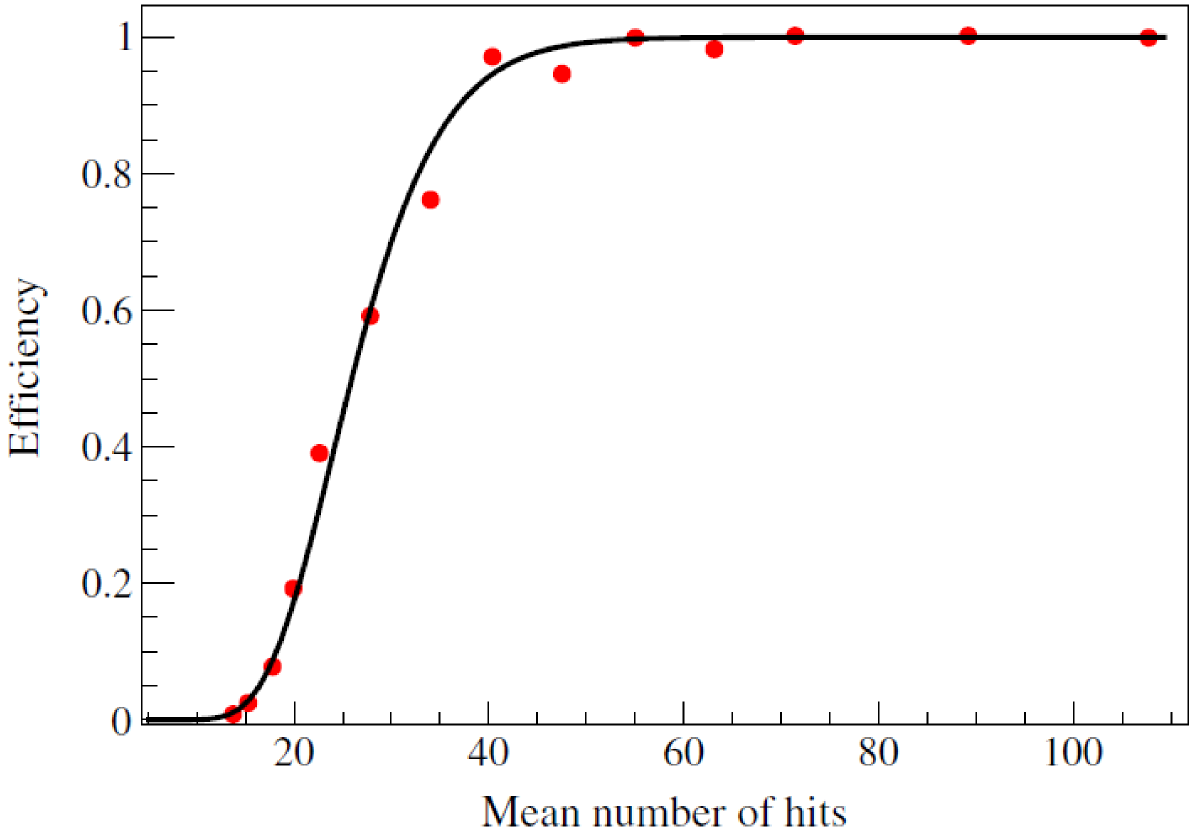


The measurement is feasible with:
1)low energy threshold
2)good energy resolution (~10% at 200 keV)
3)low radioactive backgrounds.
4)low ^{14}C count in view of the tail and pile-up

Effect of energy resolution and pile-up



The threshold on e-recoil



60 hits (of 2000 PMTs) ~120 keV ->

we can go to much lower threshold

Data selection

- The data used for this analysis were acquired from January 2012 to May 2013 (408 days of data; Borexino Phase II).
- Data cuts – the same of ^{7}Be analysis excluding energy-dependent cuts (i.e. soft α/β and some others) to preserve shapes
- no coincidence with muon events : a 300 ms veto is applied following muons crossing the scintillator and buffer volumes, and a 2 ms veto following muons crossing only the water tank
- FV cut – the same of ^{7}Be ($R<3.021$ && $|Z|<1.67$ corresponding to 75.5 tonnes of LS). Independence on energy checked.

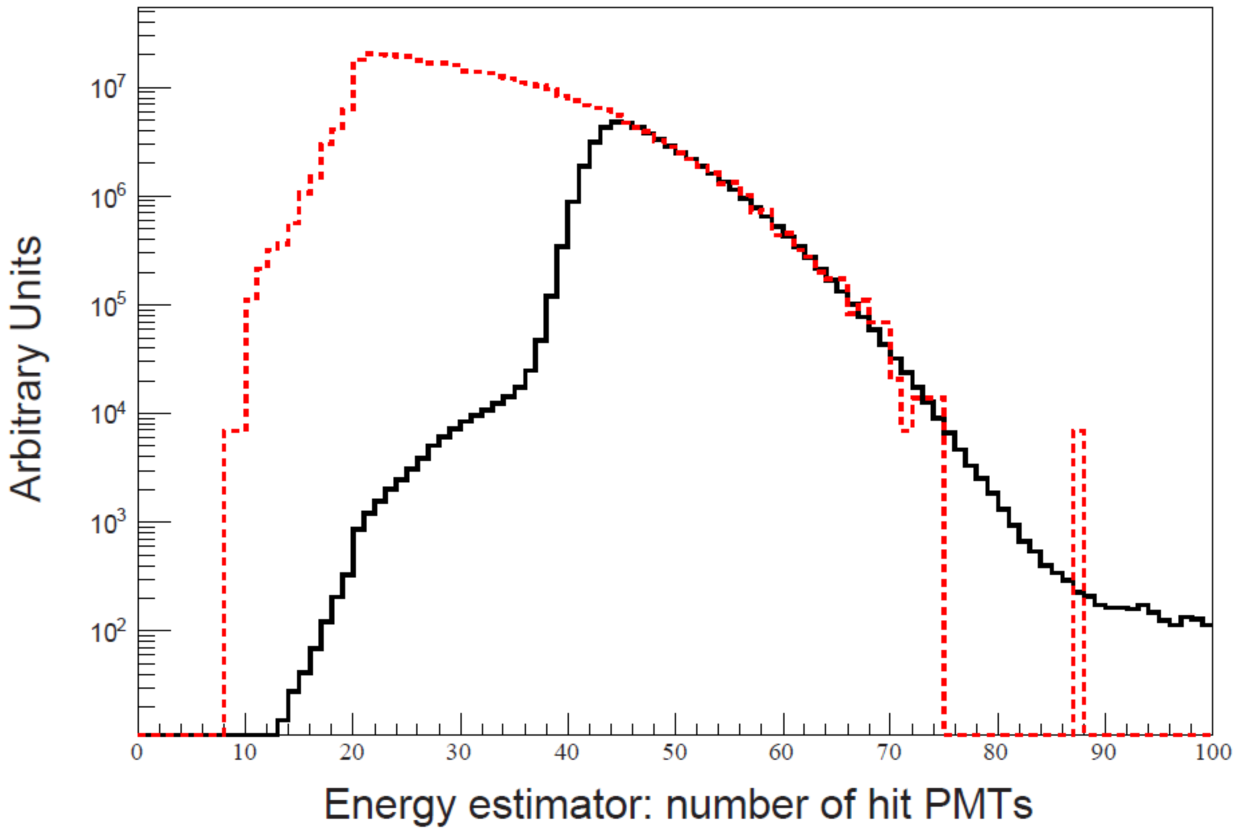
pp-neutrino signal extraction

- **The pp neutrino rate is extracted by fitting experimental spectrum with the expected spectra of signal and backgrounds.**

- **We need to study carefully:**
  - **Spectral shapes involved in the fit**
  - **Rate of 14C and pile-up events**

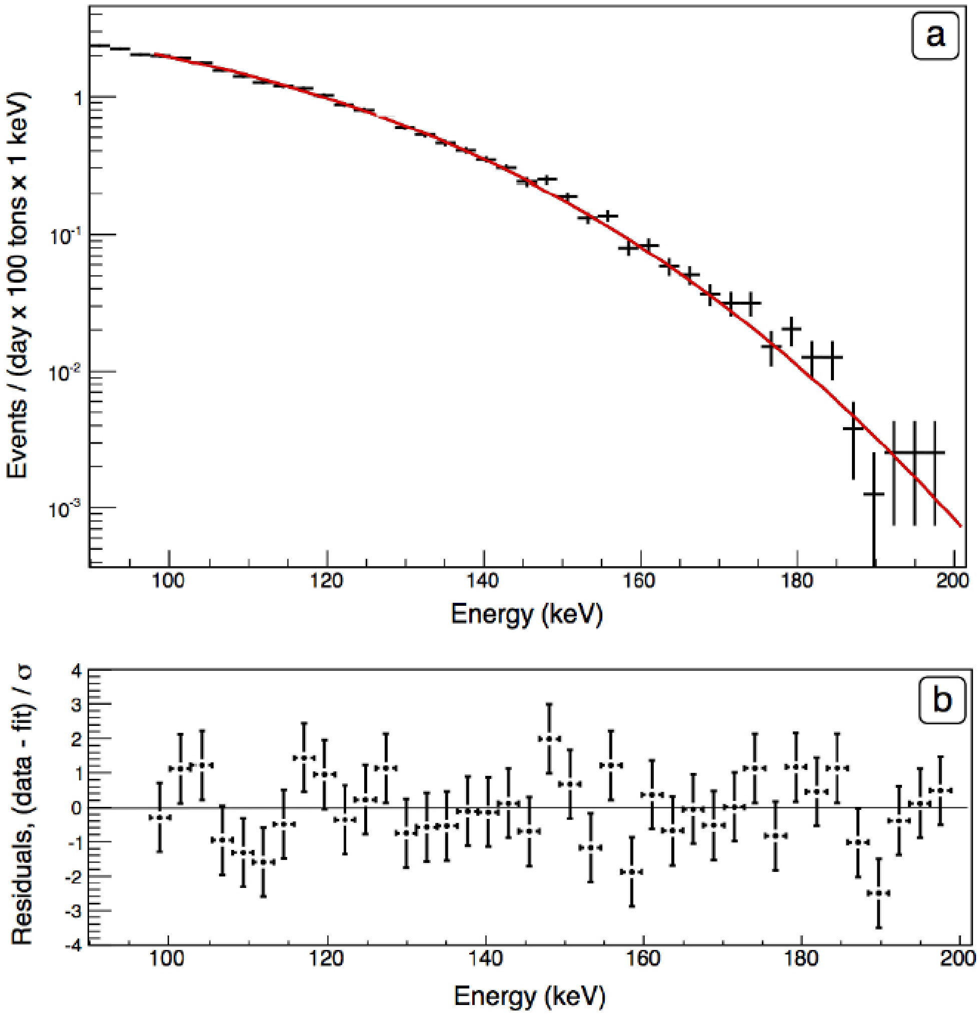
- **Critical issue concerning spectral shape is the analytical description of the energy scale, the analytical description of the energy resolution and the shape of the detector response to the monoenergetic event (the scintillation line shape).**

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 ms. The main events spectrum are shown in the same scale in black.

^{14}C rate estimation using second cluster events



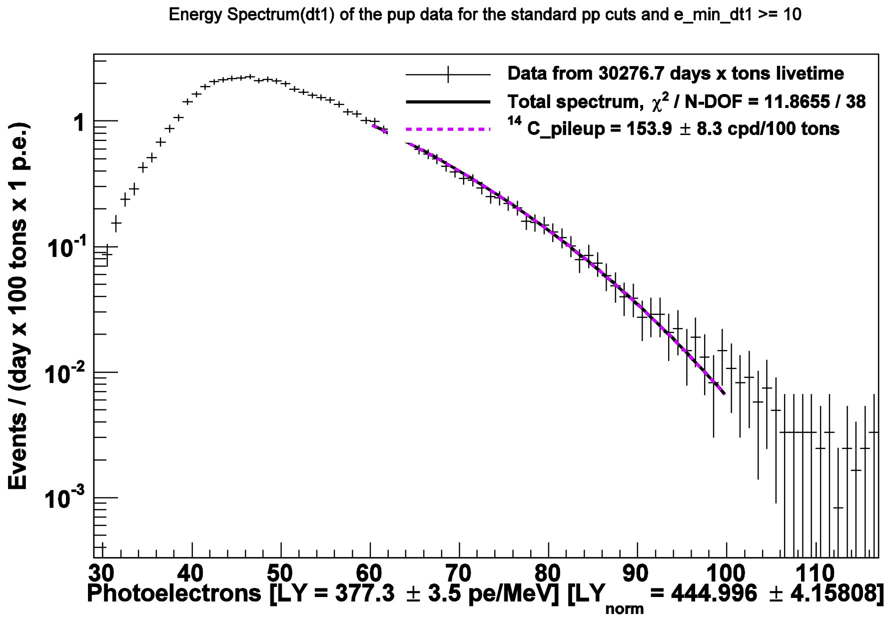
Time acquisition window is 16 ms. Only the data with ΔT>8 ms were used (to exclude PMTs afterpulses) Fitting the data with theoretical β-spectrum shape we obtained:
40±1 Bq/100 t rate.

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



Energy Spectrum(dt1) of the pup data for the standard pp cuts and e_min_dt1 >= 10

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)

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)**

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

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

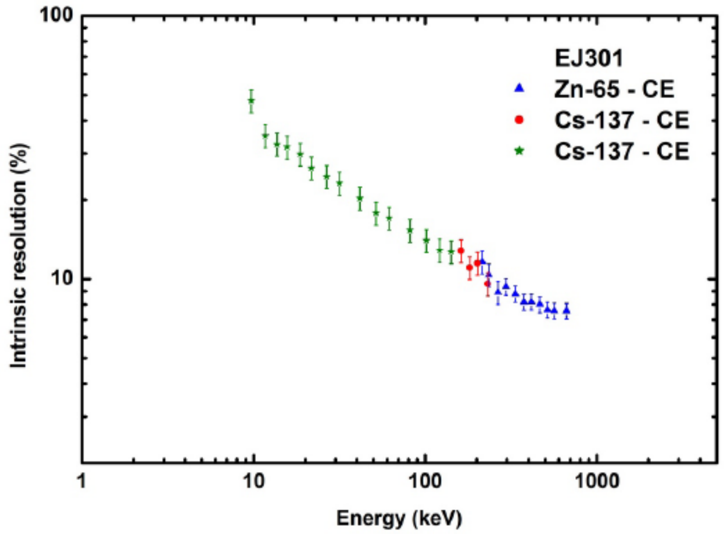
E→Q→Npmts conversion

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 t sqrt($N_{photons}$)) for β-particles (absent or negligible for α).
- v_f - **fixed** at calculated value (variance of the number o live Pmts).
- v_1=0.17 - **fixed** at value found with MC (no sensitivity i 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)

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

The same as in ^{7}Be analysis

+Intrinsic line width

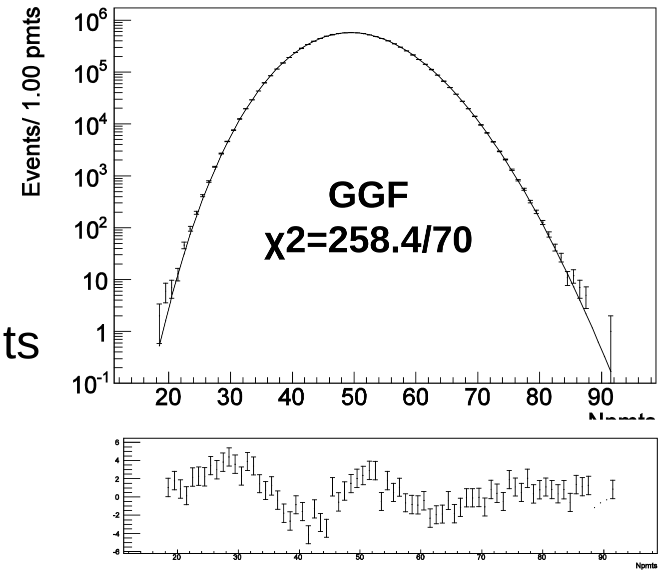
Analytical description of Scintillation Line shape

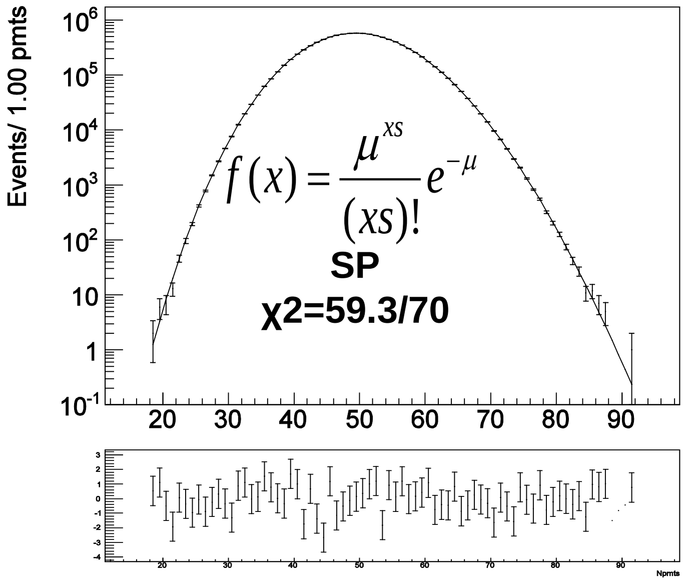
Line shape – the shape of the detector's response for uniformly distributed monoenergetic particle.

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





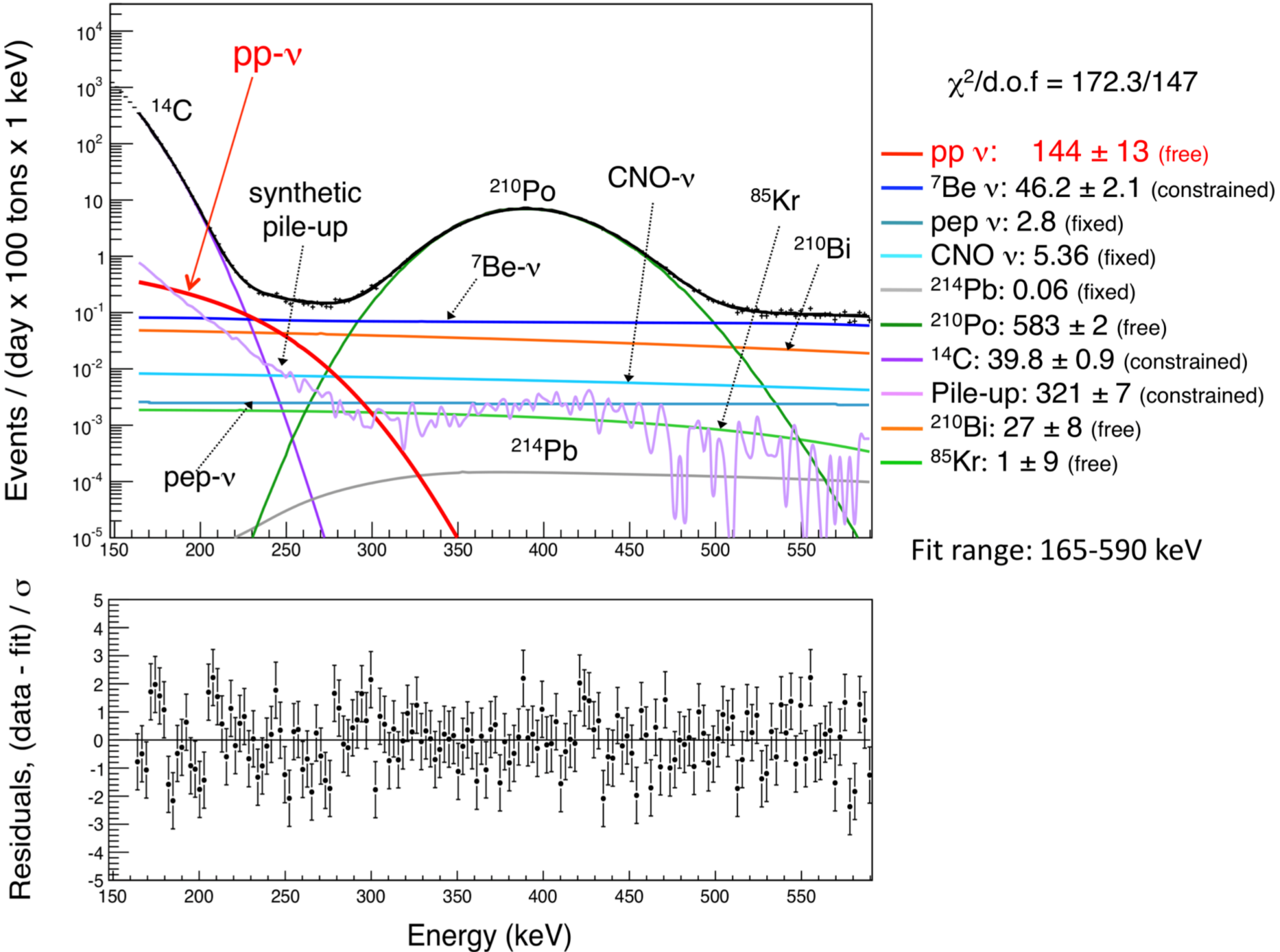
$$f(x) = \frac{\mu^{xs}}{(xs)!} e^{-\mu}$$

The mean values and variances of both shapes are the same

“Standard” fit

- Variable: npmts
- Range: [60-220 Npmts] (corresponds to 165-590 keV)
- Response function shape: Scaled Poisson
- Free spectral components: ^{14}C,^{210}Bi,^{210}Po,pp, ^{85}Kr
- Constrained spectral components: ^{7}Be (paper central value)
- Fixed spectral components: pep+CNO+^{8}B (SSM/LMA(HM))
- Energy scale variables: LY free, k_B fixed, f_{eq} calculated
- Energy resolution vars: σ_{int} and v_T free; v_f calculated
- Synthetic pile-up constrained
- Free: LY+2 resolution vars+Po position+5 spectral components + constrained pup and ^{7}Be
- **9 free parameters and 2 (pileup and ^{7}Be) constrained**

The results of the standard spectral fit



χ^2/d.o.f = 172.3/147

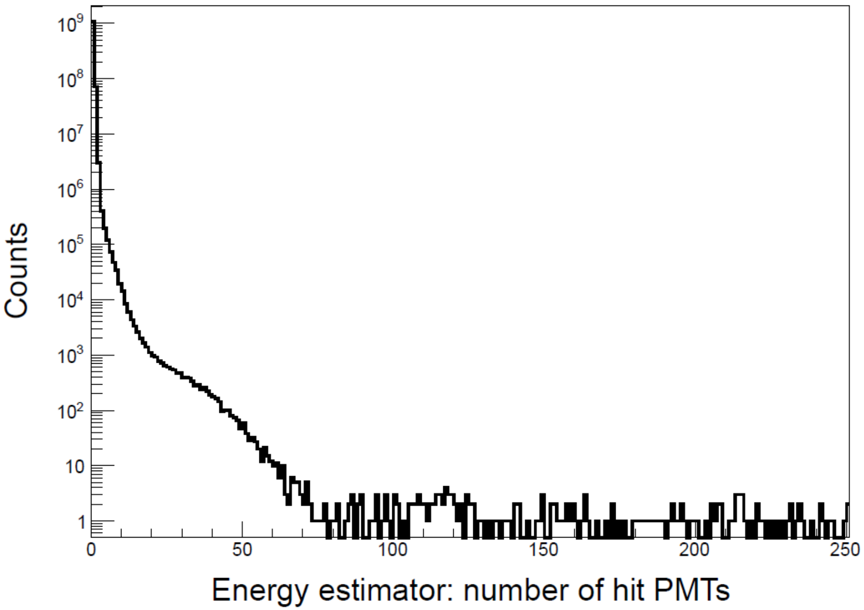
pp ν: 144 ± 13 (free)
^{7}Be ν: 46.2 ± 2.1 (constrained)
pep ν: 2.8 (fixed)
CNO ν: 5.36 (fixed)
^{214}Pb: 0.06 (fixed)
^{210}Po: 583 ± 2 (free)
^{14}C: 39.8 ± 0.9 (constrained)
Pile-up: 321 ± 7 (constrained)
^{210}Bi: 27 ± 8 (free)
^{85}Kr: 1 ± 9 (free)

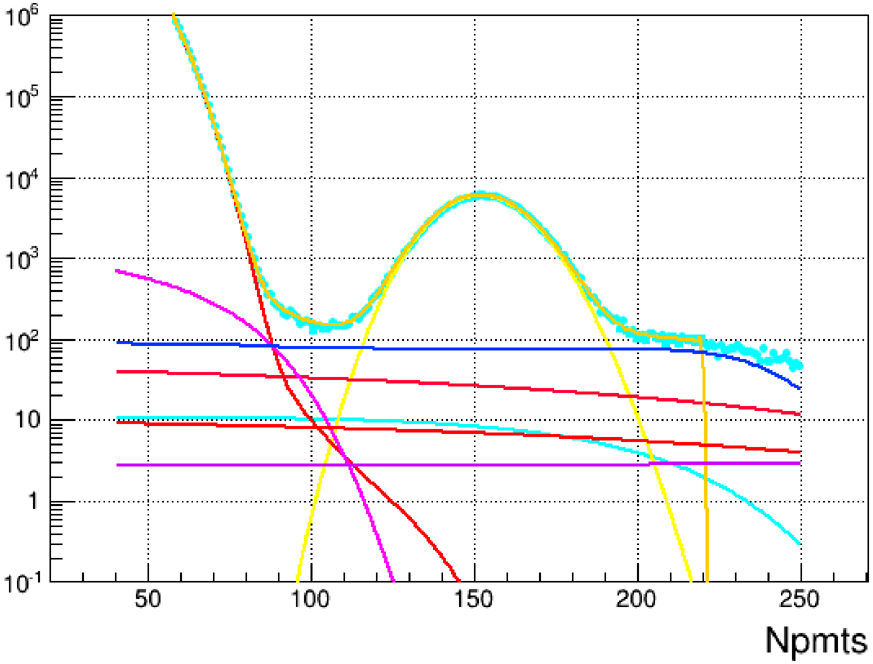
Fit range: 165-590 keV

Cross-check of pile-up

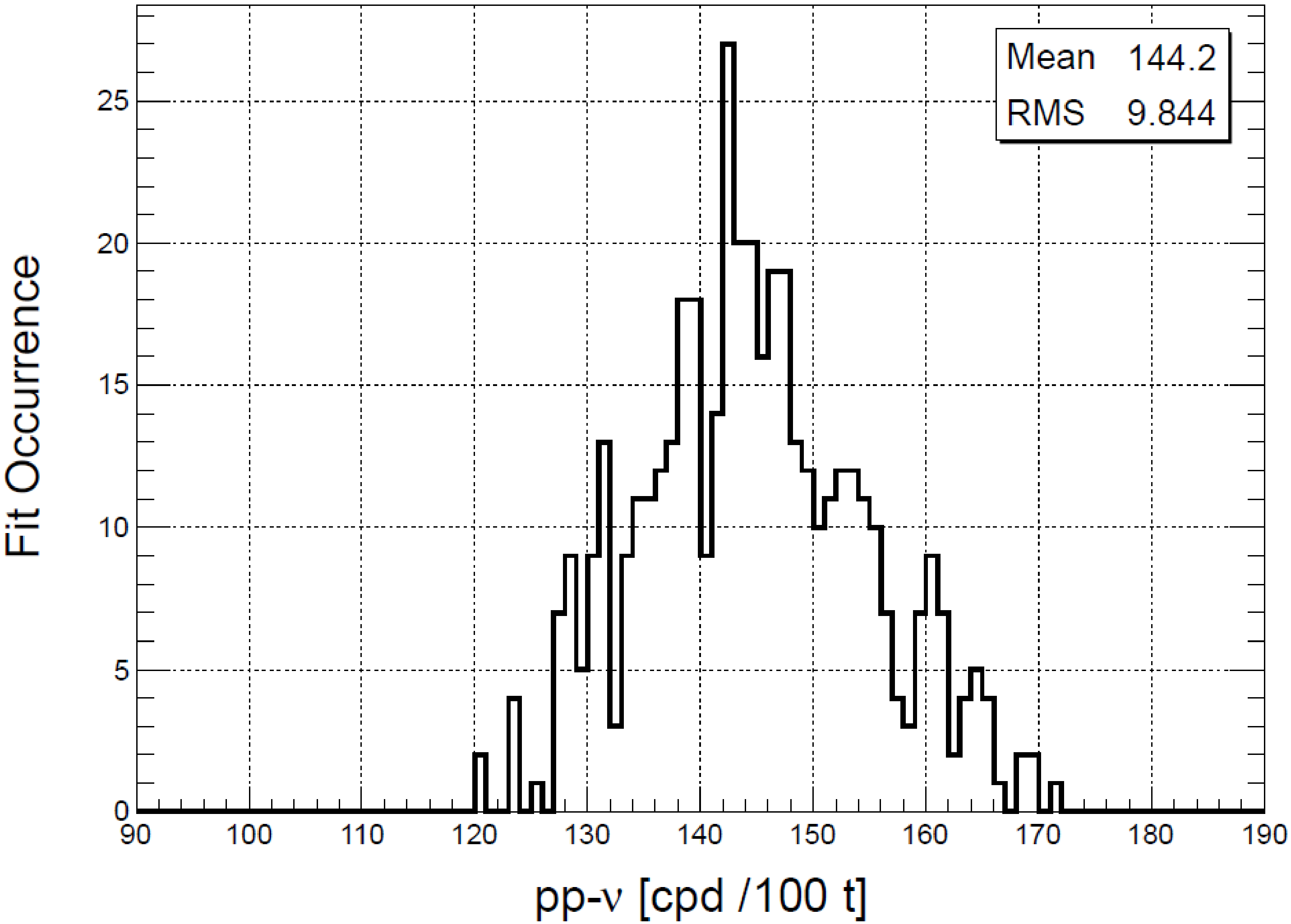
Convolution with randomly sampled data (trivial once randomly sampled data are provided)

Used for cross checks ("convolution" method), the effect can be seen in the tail of ^{14}C in the plot.





Systematics estimation

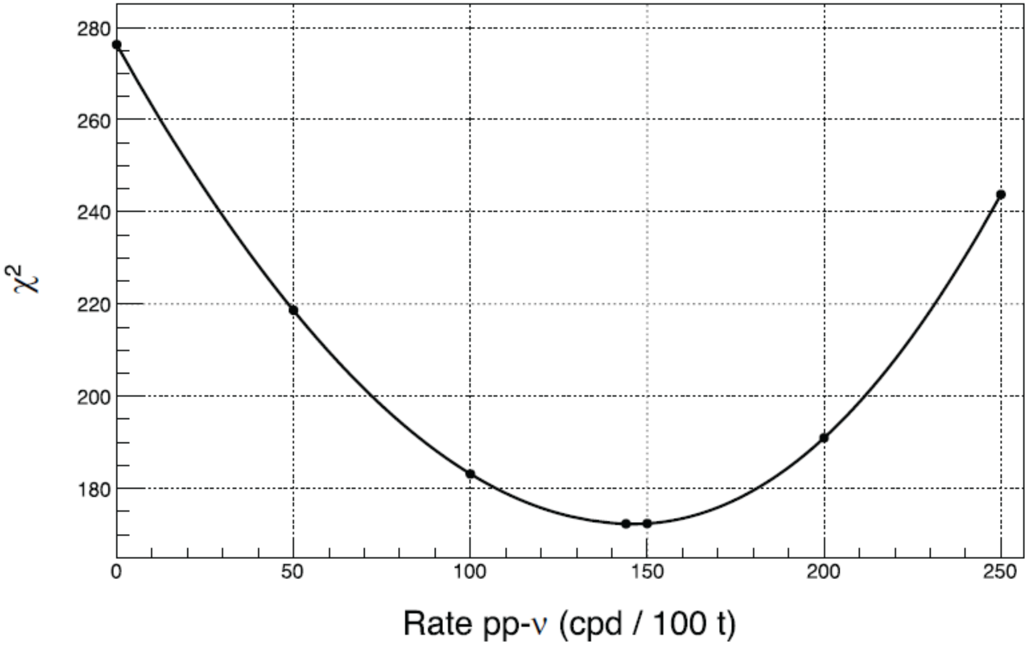


Values are obtained by varying the fit conditions, including the fit energy range, synthetic-versus-analytic pile-up spectral shape, and energy estimator. The distribution shown is peaked around reported value of 144 cpd/100 t.

First real-time measurement of pp-neutrino flux (~11% precision)

pp = 144 ± 13 (stat) ± 10 (syst) cpd/100 t

compared to expected (MSW/LMA,HM)
131±2 cpd/100 t



pp neutrino flux:

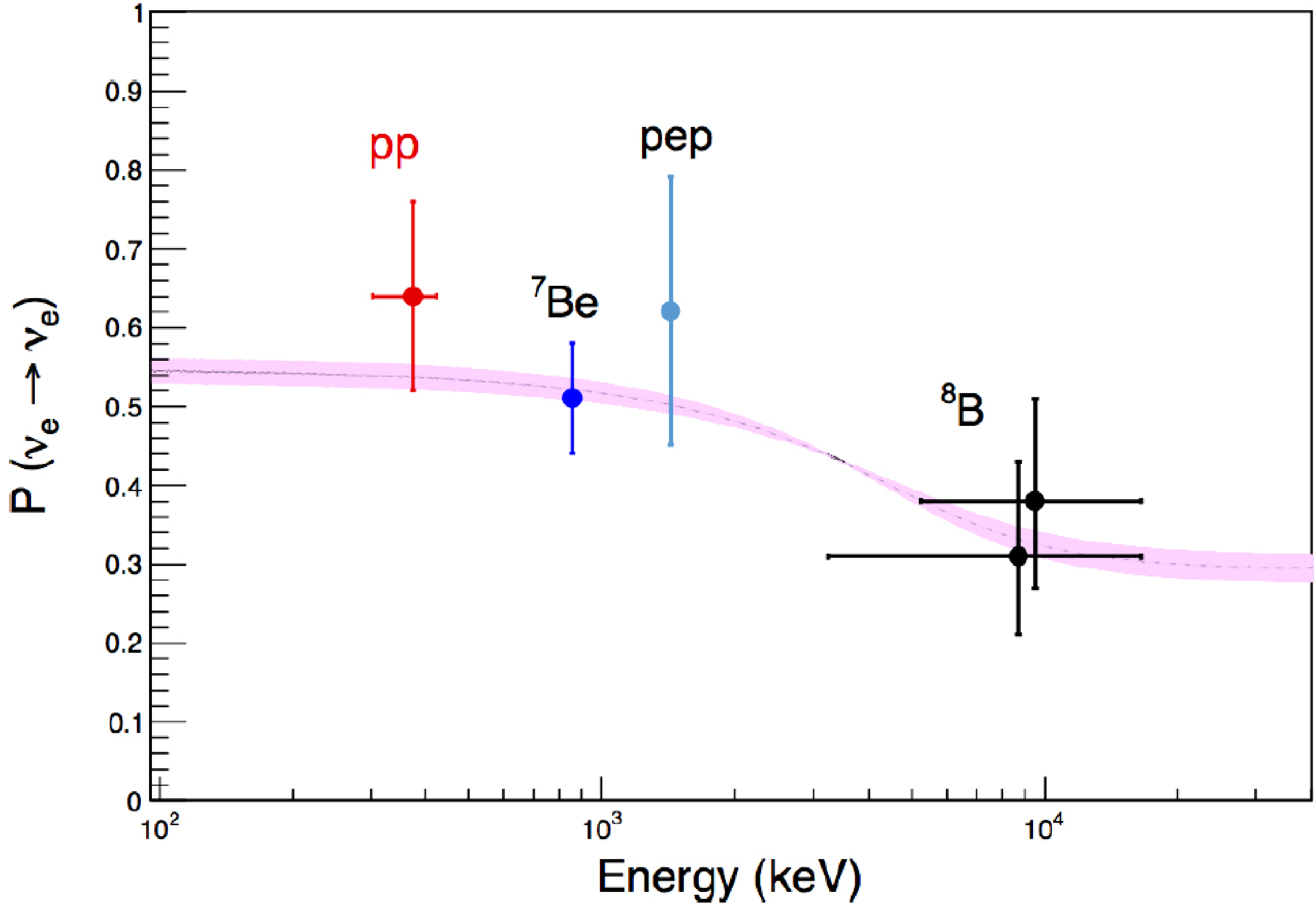
$(6.6\pm0.7)\cdot10^{10}$ cm^{-2}s^{-1}

vs

$(5.98\pm0.04)\cdot10^{10}$ cm^{-2}s^{-1}

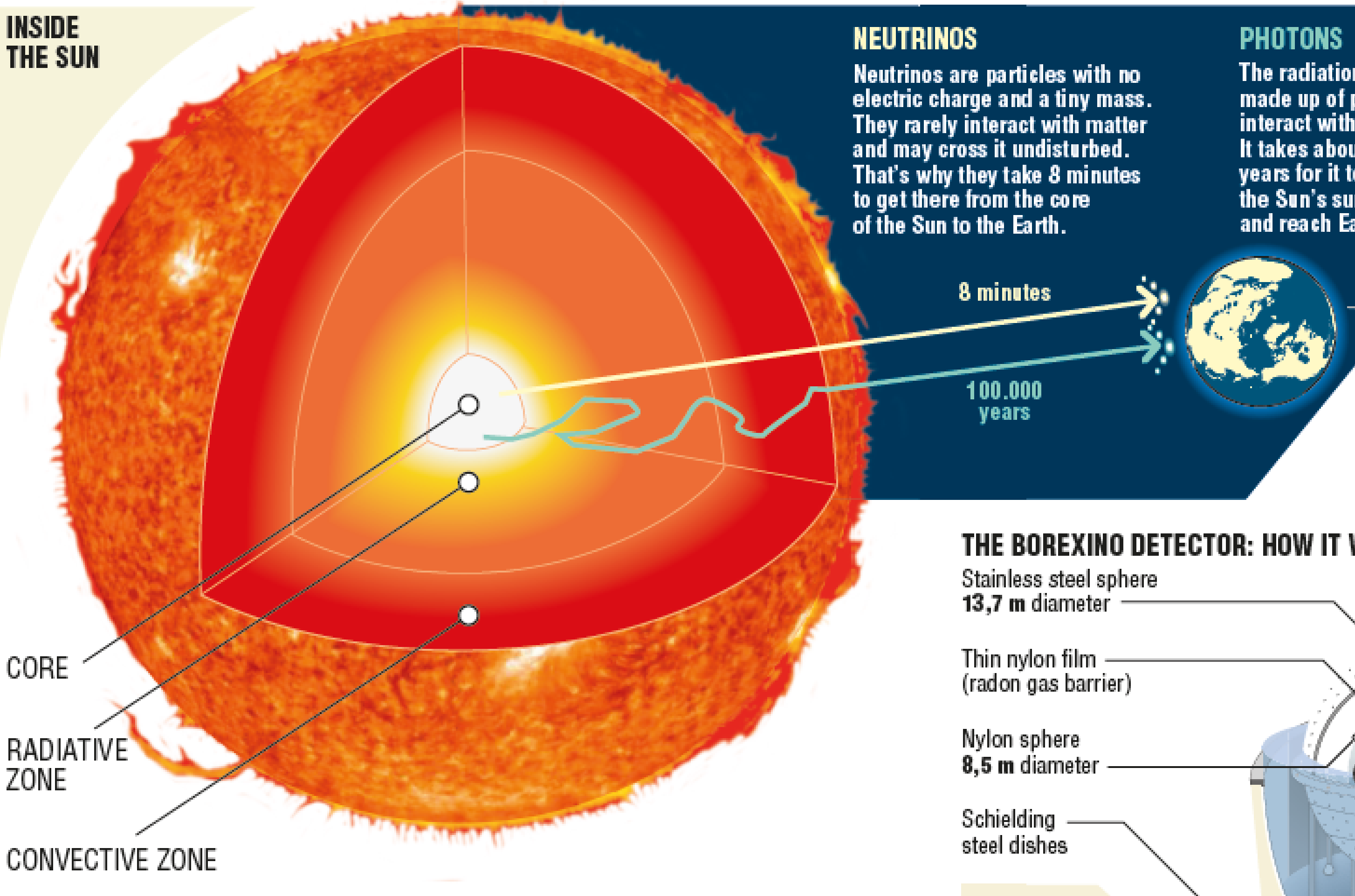
Zero pp count is excluded at 10σ level

Borexino measured electron neutrino survival probability for 4 different nuclear reactions



THE SUN AS BOREXINO SEES IT IN REAL TIM

INSIDE THE SUN

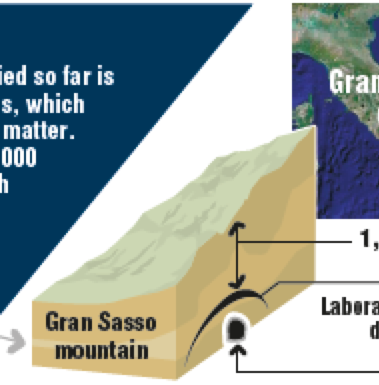


NEUTRINOS

Neutrinos are particles with no electric charge and a tiny mass. They rarely interact with matter and may cross it undisturbed. That's why they take 8 minutes to get there from the core of the Sun to the Earth.

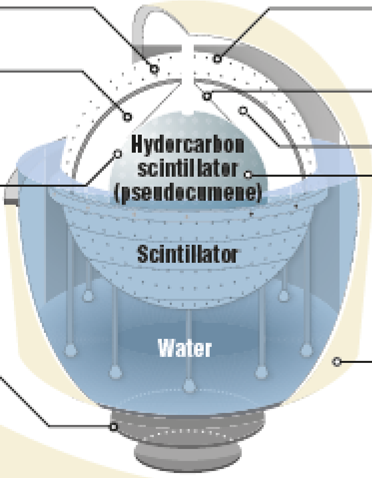
PHOTONS

The radiation studied so far is made up of photons, which interact with solar matter. It takes about 100.000 years for it to reach the Sun's surface and reach Earth.



By analyzing P-P neutrino emissi Borexino has shown that the ene produced today in the Sun's core to that produced 100.000 years

THE BOREXINO DETECTOR: HOW IT WORKS



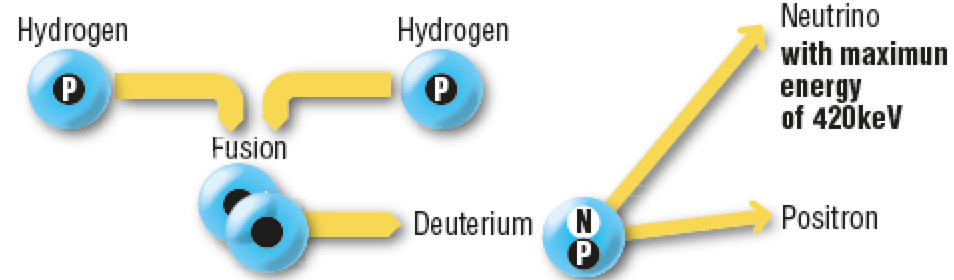
Borexino displays a russian doll structure. Surrounded by 2.400 tons of highly purified water, a stainless steel sphere contains 1.000 tons of a liquid hydrocarbon (pseudocumene). At its center, within a smaller nylon sphere, are 300 tons of scintillating liquid.

Within this innermost sphere neutrinos interact with the liquid scintillator producing small flashes of light.

The photomultiplier tubes, acting as ultra-sensitive artificial eyes, detect and record the light flashes produced by the neutrinos.

Borexino observes dozens of these signals every day.

THE THERMONUCLEAR FUSION REACTION THAT PRODUCES THE P-P NEUTRINOS RECENTLY STUDIED BY BOREXINO



the Borexino Collaboration

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Virginia Tech

Houston

Paris

Moscow

JINR Dubna

Los Angeles

Princeton

UMass Amherst

St. Petersburg

Kurchatov Moscow


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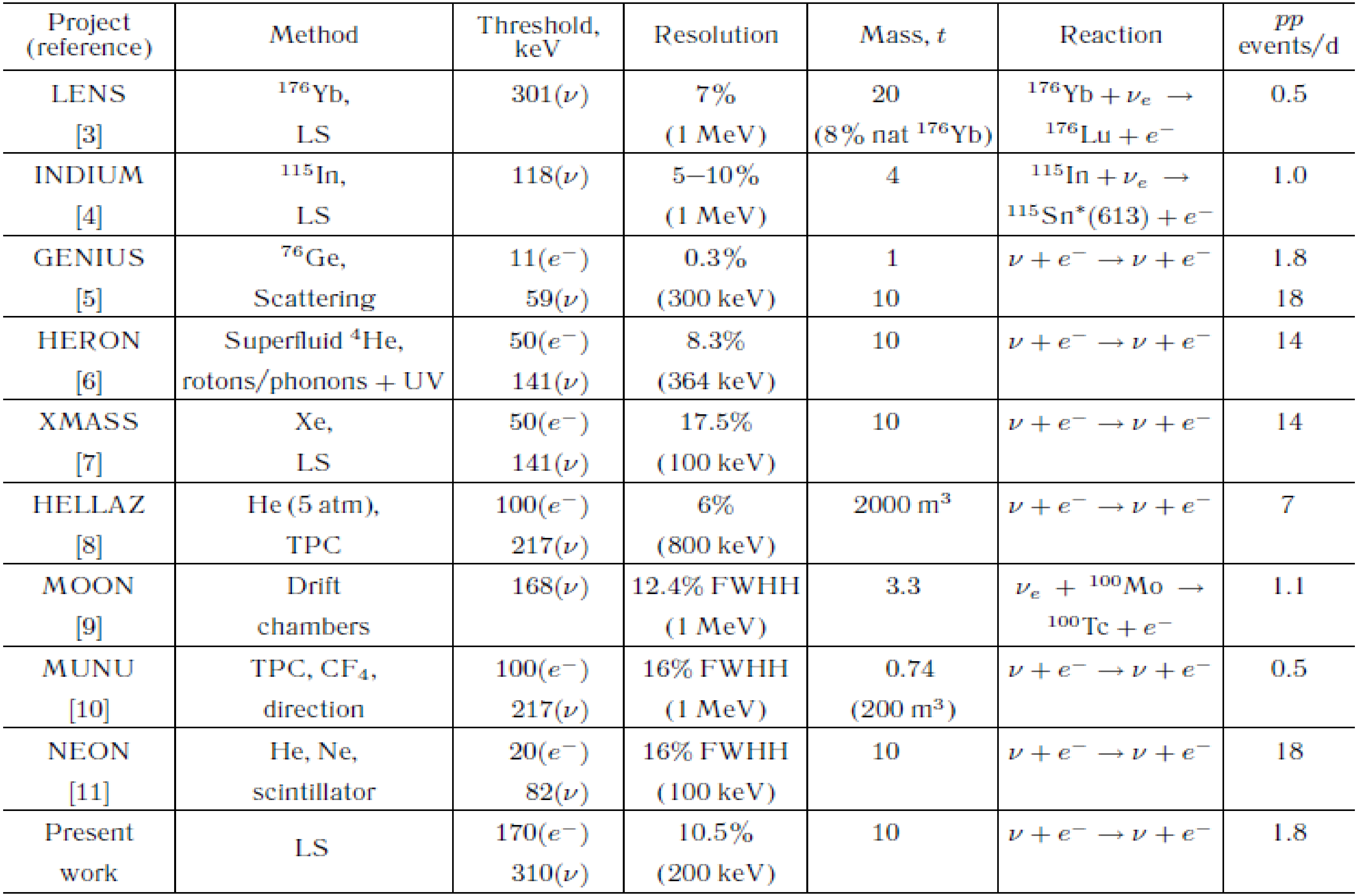
ν
The three musketeers
and
the four Mi...ladies
Nature

Spares

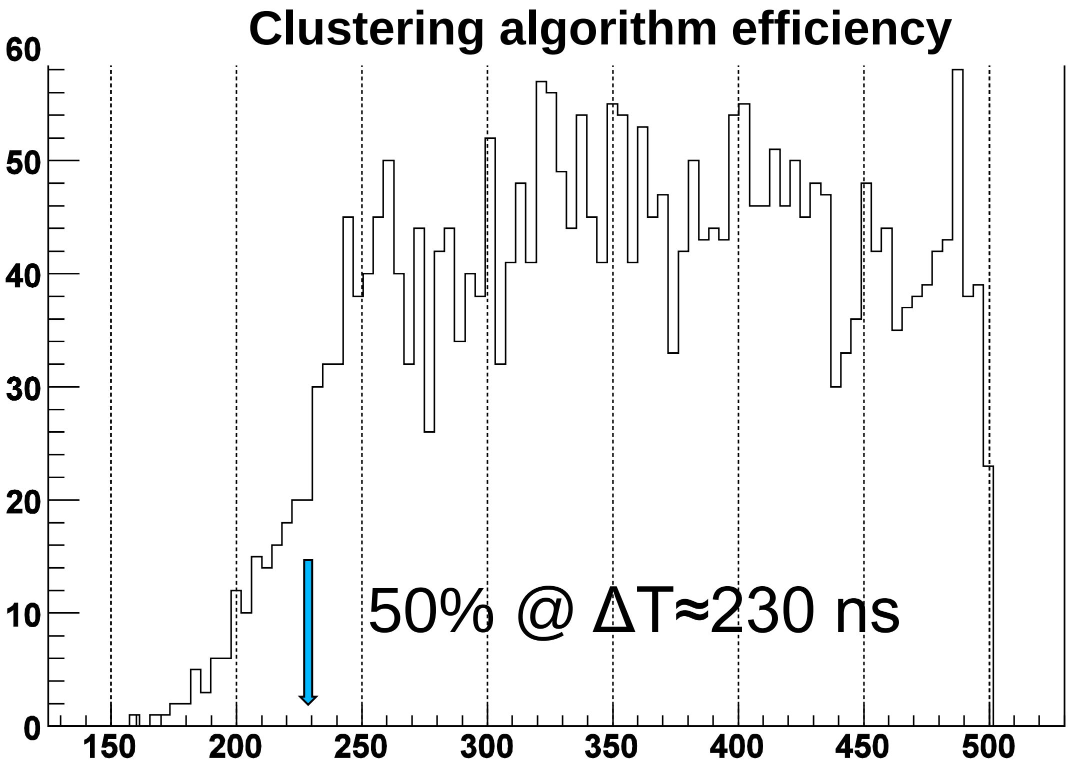
List of proposals on pp-neutrino search



Project (reference)	Method	Threshold, keV	Resolution	Mass, t	Reaction	pp events/d
LENS [3]	^{176}Yb, LS	$301(\nu)$	7% (1 MeV)	20 (8% nat ^{176}Yb)	$^{176}\mathrm{Yb} + \nu_e \rightarrow$ $^{176}\mathrm{Lu} + e^-$	0.5
INDIUM [4]	^{115}In, LS	$118(\nu)$	5–10% (1 MeV)	4	$^{115}\mathrm{In} + \nu_e \rightarrow$ $^{115}\mathrm{Sn}^*(613) + e^-$	1.0
GENIUS [5]	^{76}Ge, Scattering	$11(e^-)$ $59(\nu)$	0.3% (300 keV)	1 10	$\nu + e^- \rightarrow \nu + e^-$	1.8 18
HERON [6]	Superfluid ^{4}He, rotons/phonons + UV	$50(e^-)$ $141(\nu)$	8.3% (364 keV)	10	$\nu + e^- \rightarrow \nu + e^-$	14
XMASS [7]	Xe, LS	$50(e^-)$ $141(\nu)$	17.5% (100 keV)	10	$\nu + e^- \rightarrow \nu + e^-$	14
HELLAZ [8]	He (5 atm), TPC	$100(e^-)$ $217(\nu)$	6% (800 keV)	2000 m^3	$\nu + e^- \rightarrow \nu + e^-$	7
MOON [9]	Drift chambers	$168(\nu)$	12.4% FWHH (1 MeV)	3.3	$\nu_e + {}^{100}\mathrm{Mo} \rightarrow$ $^{100}\mathrm{Tc} + e^-$	1.1
MUNU [10]	TPC, CF$_4$, direction	$100(e^-)$ $217(\nu)$	16% FWHH (1 MeV)	0.74 (200 m^3)	$\nu + e^- \rightarrow \nu + e^-$	0.5
NEON [11]	He, Ne, scintillator	$20(e^-)$ $82(\nu)$	16% FWHH (100 keV)	10	$\nu + e^- \rightarrow \nu + e^-$	18
Present work	LS	$170(e^-)$ $310(\nu)$	10.5% (200 keV)	10	$\nu + e^- \rightarrow \nu + e^-$	1.8

Energy variables

Two of them: **npmts_dt1** and **npmts_d2** (non-normalized to 2000 PMTs in contrast to what have been done in ^{7}Be analysis)
Both are based on the number of triggered PMTs in the fixed-length energy window (230 ns for dt1 and 400 ns for dt2), easier to model the pile-up. Pile-up is scaled as dT while other components remains unchanged - possibility for pile-up cross-checks.

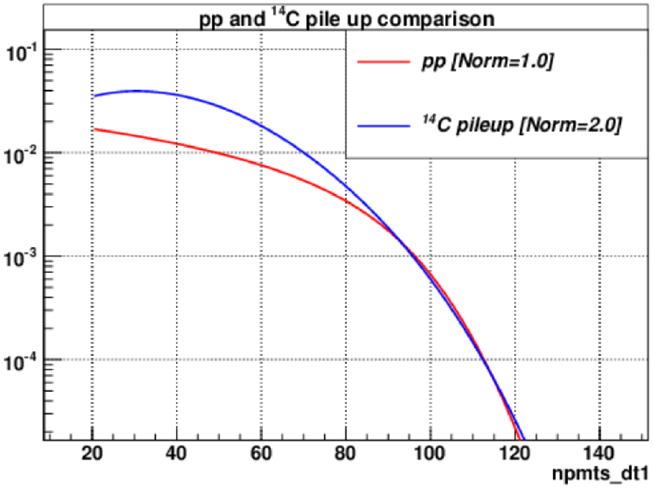


Naïve ^{14}C pile-up rate estimation

- Estimated count rate of ^{14}C in IV is

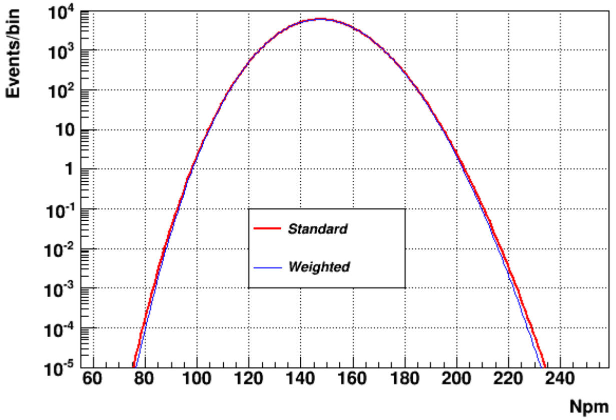
  108 Bq for 270 t
- In one day we got $(108)^2 \cdot 8.64 \cdot 10^4 \cdot 4 \cdot 10^{-7} = 403$ cpd of ^{14}C pile-up in ΔT=400 ns gates in IV or 150 cpd in 100 tones;
- For ΔT=230 ns the pile-up rate reduces to 232±12 cpd in IV or:

  86±5 cpd/100 tones
- We need the shape and the counting rate/both the shape and the counting rate could be influenced by the reconstruction alrorithm

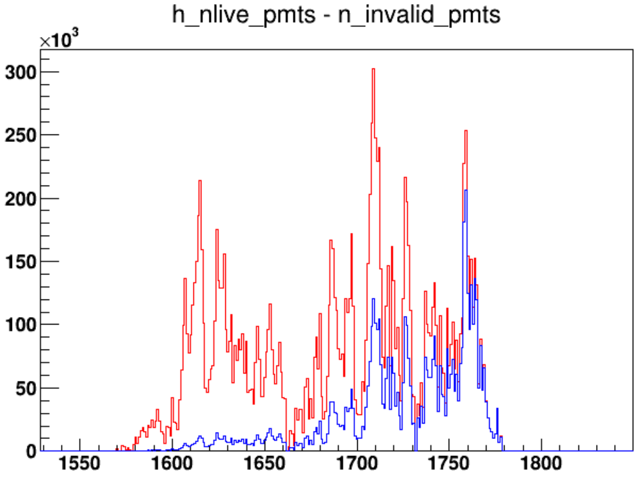


Comparison of pp and analytical pileup shape

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 (Fill(1,1)→Fill(1,$e^{-(t-t_0)/T}$))

Scaled Poisson vs GGF

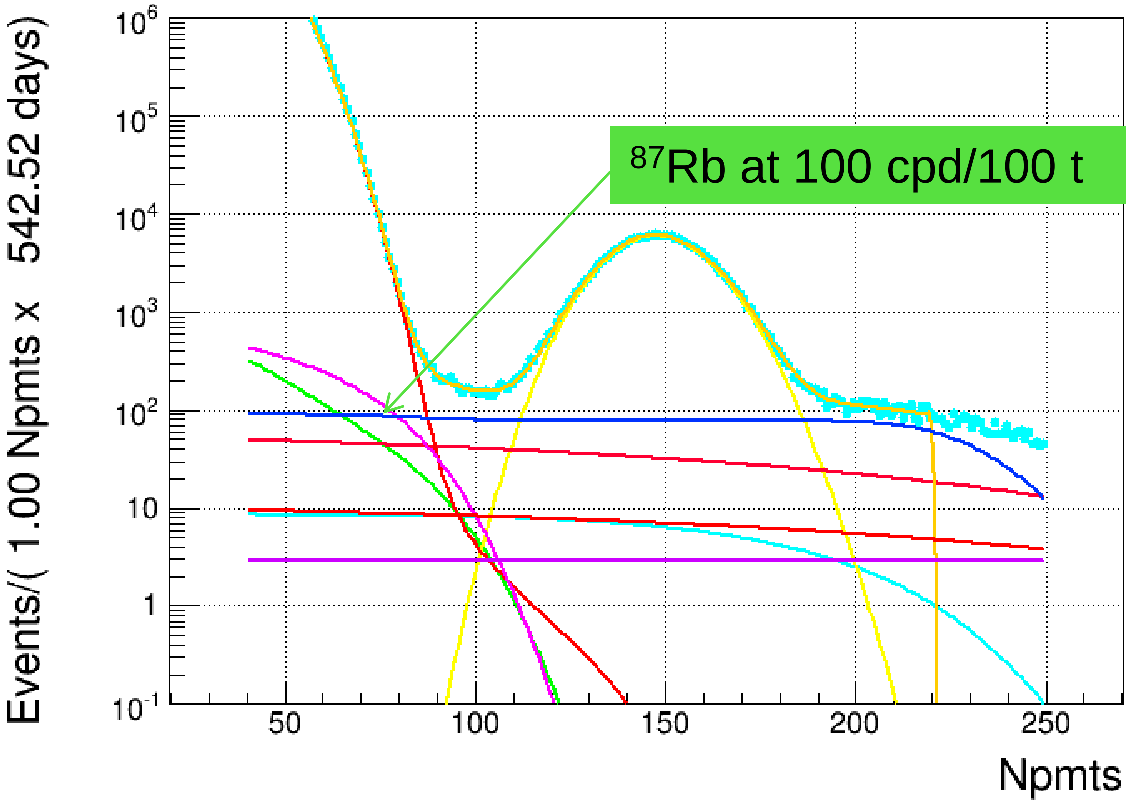
$$f(x) = \frac{\mu^{xs}}{(xs)!} e^{-\mu}$$

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

	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)

^{87}Rb – could it change the result?



^{87}Rb at 100 cpd/100 t

Second forbidden β-decay with E_0=283.3 keV end-point

Δχ2=+1
@
100 cpd of ^{87}Rb/100t

with corresponding pp count decrease of 40 cpd/100 t

Correlation: 1 cpd/100t of ^{87}Rb simulates 0.4 cpd/100t of pp

^{87}Rb vs ^{40}K

- **though the Rb is quite abundant in nature (the twenty-third most abundant element in the Earth's crust) the typical abundance of Rb is factor (2-4)·10^3 lower than that of K (which is one of most abundant and contributes 1.5% of the crust weight).**
- **Taking into account the abundance of radioactive isotopes: 0.278 of ^{87}Rb against 1.17·10^{-4} of ^{40}K, and the ratio of live-times 47.2 vs 1.28 billions yr, we get the ratio for the typical activity of ^{87}Rb:**

$$\frac{Activity(Rb)}{Activity(K)} = \frac{abund(^{87}Rb)}{abund(^{40}K)} \cdot \frac{T_{1/2}^{^{40}K}}{T_{1/2}^{^{87}Rb}} \cdot \frac{At(Rb)}{At(K)} = 64.5 \cdot \frac{At(Rb)}{At(K)}$$

Location	K (ppb by Atoms)	Rb (ppb by Atoms)	R(Rb/K)	Activity ratio
Universe	100	0.1	10-3	0.065
Sun	100	0.4	4·10-3	0.26
Meteorite (carbonaceous)	370000	770	2.1·10-3	0.14
Crustal rocks	7800000	14000	1.8·10-3	0.12
Sea water	65800	8.7	1.3·10-4	0.08
Human	32000	340	1.1·10-2	0.7

- **The chemistry of the elements is the same, Rb substitutes K, so we can expect the same purification factor if started from the natural ratio of Rb/K.**
- **^{40}K limit from the pep-analysis is <0.11 cpd/100 t (68% C.L.)*** **<4.6·10^{-16} Knat [g/g Sc]**

*published value is <0.4 cpd/100 t corresponding to 95% C.L. (<1.7·10^{-15} Knat [g/g Sc])