CNO and pep solar neutrino measurements and perspectives in Borexino

ICPPA

October 6th, 2015

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Gran Sasso Science Institute

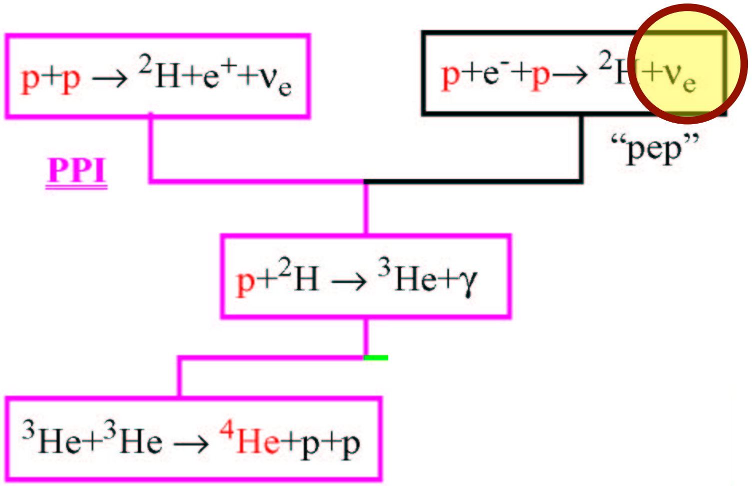
Talk outline

Detection of pep and CNO solar neutrinos in Borexino-I

- **Motivation** of the measurement
- **Cosmogenic** backgrounds rejection
- **Analysis**
- **Results**

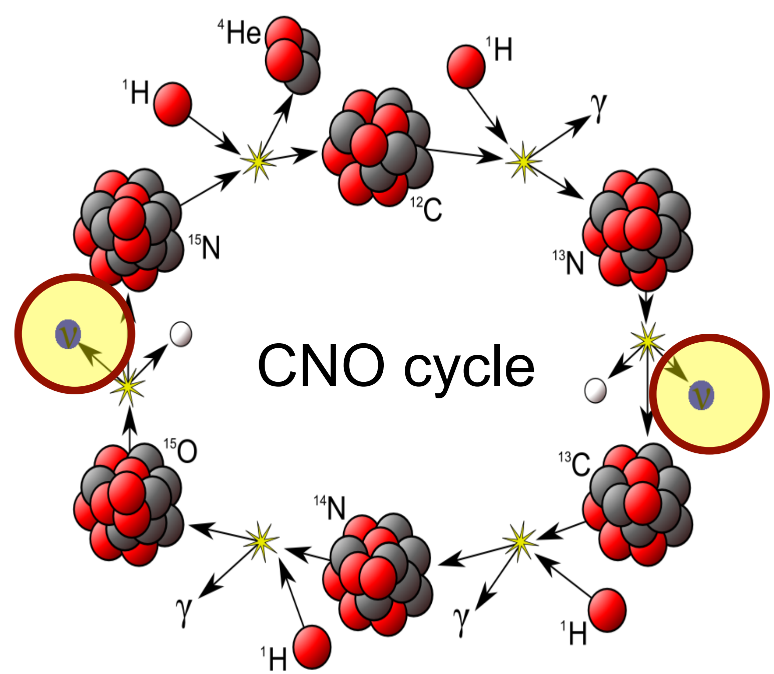
Prospects for Borexino-II

pep and CNO solar neutrinos



p-e-p process, in **proton-proton** chain
Mono-E neutrinos **E=1.44 MeV**
Low flux (1/400 total solar flux)
but predicted with **high accuracy**
Expected rate in BX ~ 3 cpd/100tons

C-N-O cycle
Neutrinos from **^{13}N** and **^{15}O decay**
Continous spectrum Q = 1.74 MeV
Low flux, predicted with low accuracy,
sensibile to Solar **metallicity**
Expected rate in BX ~ 3-5 cpd/100tons

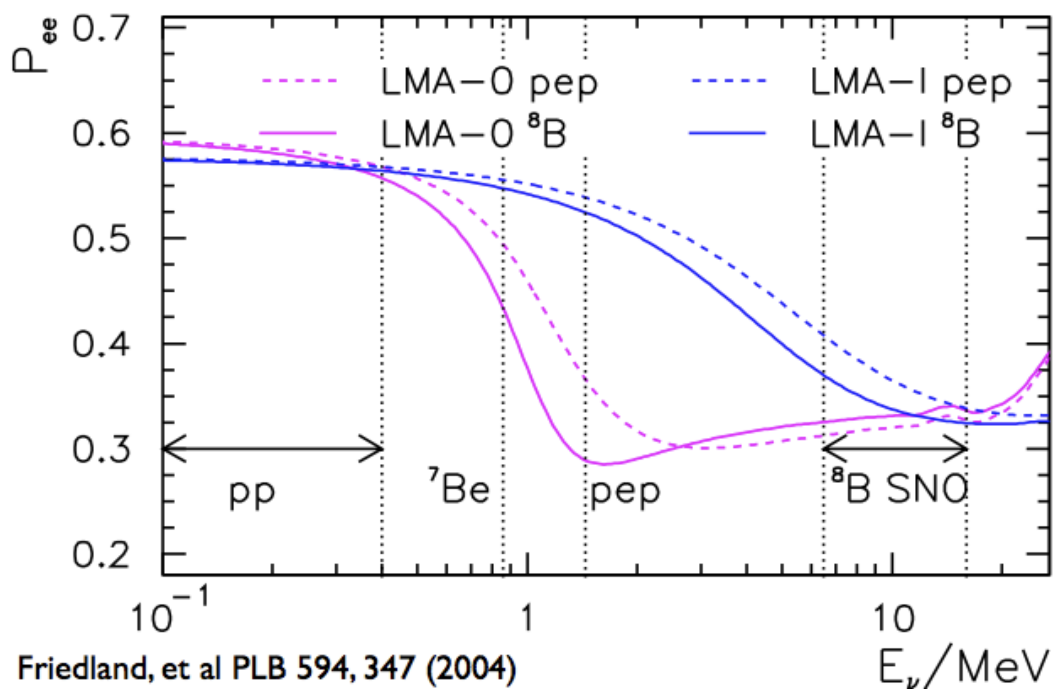


Why measure pep neutrinos?

pep neutrino **flux** predicted by *Standard Solar Model* with **high accuracy** (1.2%)

pep neutrino **energy** (1.44 MeV) in **Pee vacuum-matter transition region**

Precision test of MSW effect and oscillation models



Friedland, et al PLB 594, 347 (2004)

Why measure CNO neutrinos?

Proof that **CNO cycle** happens in **Sun**

Abbundance of heavy elements in Sun have great **impact** on **CNO** neutrino **flux magnitude**

Test of *Solar Models* (**HighZ** vs **LowZ**)

Serenelli, Haxton, Pena-Garay arXiv 1104.1639	**CNO Flux** (10^8 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
$\Delta\ \Phi$	28%

pep and CNO neutrino detection in Borexino-I

Low signal: *few events/day/100tons*

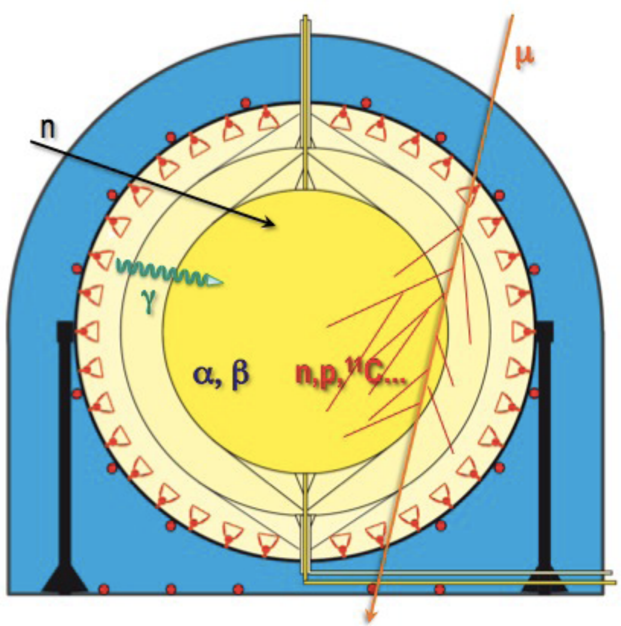
Dominant **background**: cosmogenic **β+** emitter **^{11}C**

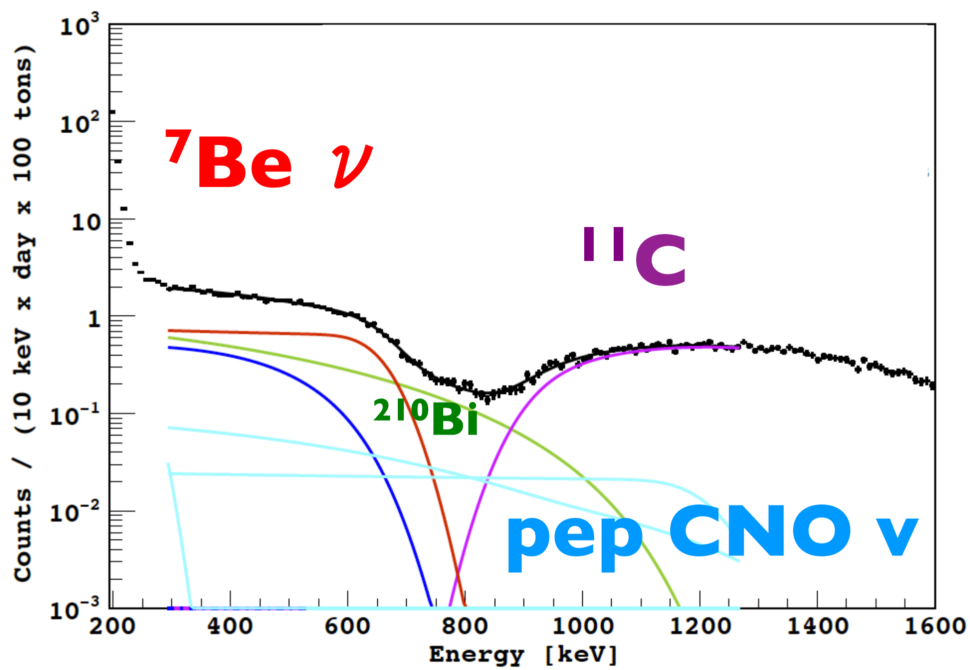
27cpd/100tons → signal/background ~ 0.1

Need **techniques** to suppress **^{11}C background**:

Three **F**old **C**oincidence

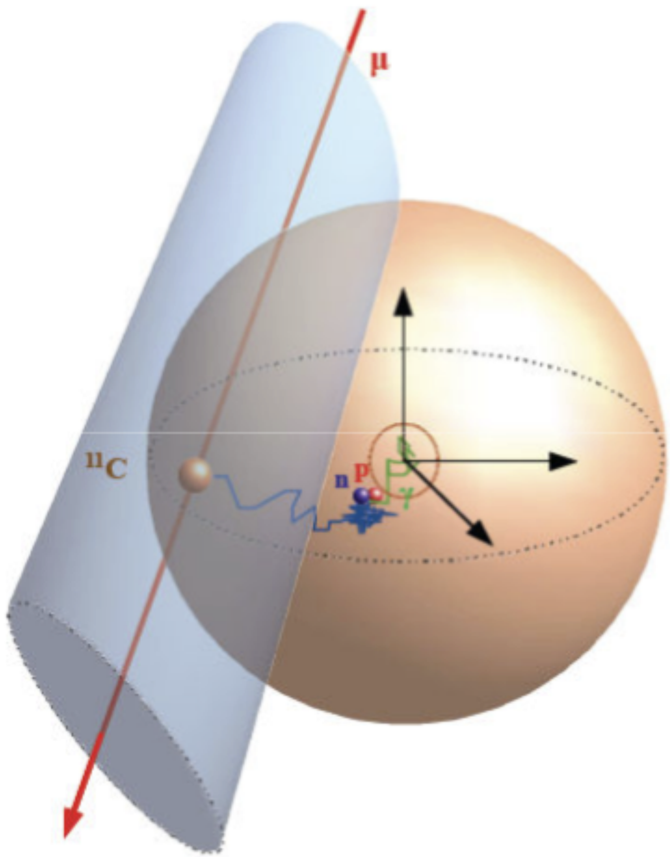
e^{+}/e^{-} pulse **s**hape **d**iscrimination





Suppress ^{11}C - Three Fold Coincidence

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



~**4300** muons/day in Borexino

Spallation neutron in 95% cases
n termalize and captured, mean life **~250 μs**
capture on **H** → **γ** (**2.2 MeV**)

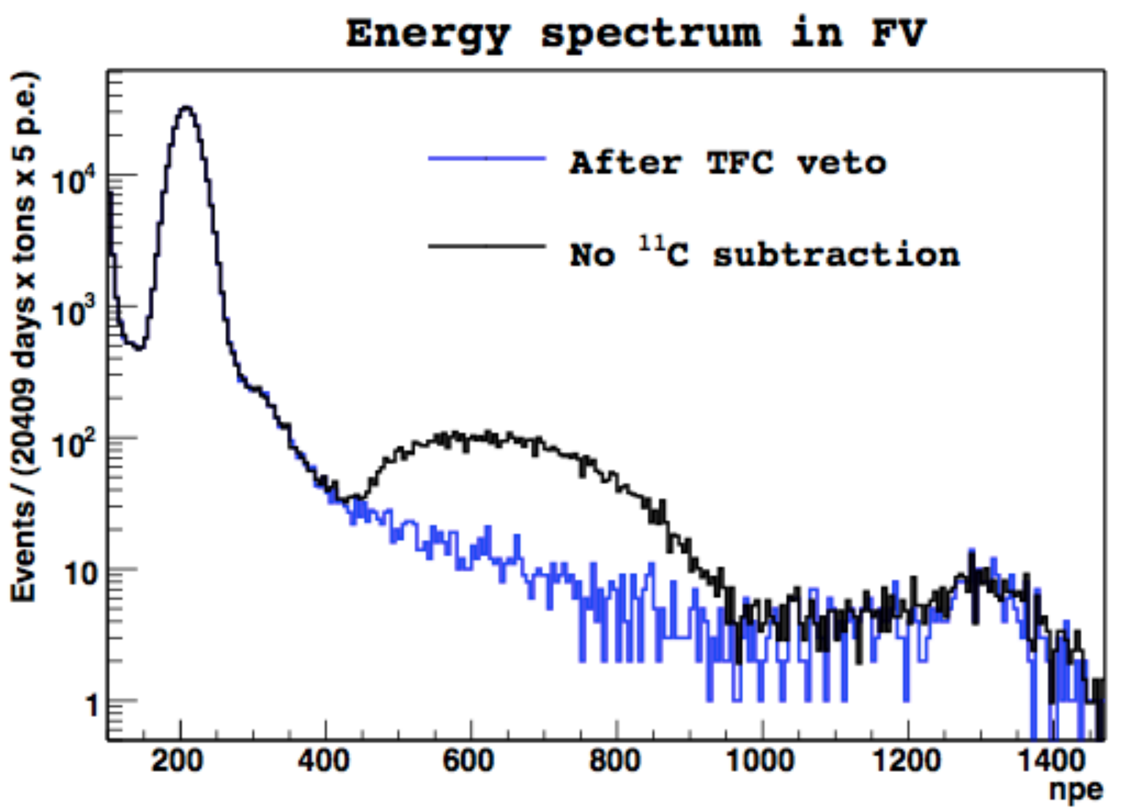
^{11}**C decays β+** mean life **29.4 minutes**
Stays where produced (no convective motions)

Space-time correlation between **muon** track, **neutron** capture, ^{11}**C** decay**:**
Three Fold Coincidence (TFC)

We exclude from analysis space-time regions where we expect ^{11}C decays

Suppress ^{11}C - Three Fold Coincidence

Removed **91%** ^{11}C, keeping **48.5%** scintillation events
^{11}C rate: **27** → **2.5** cpd/100tons



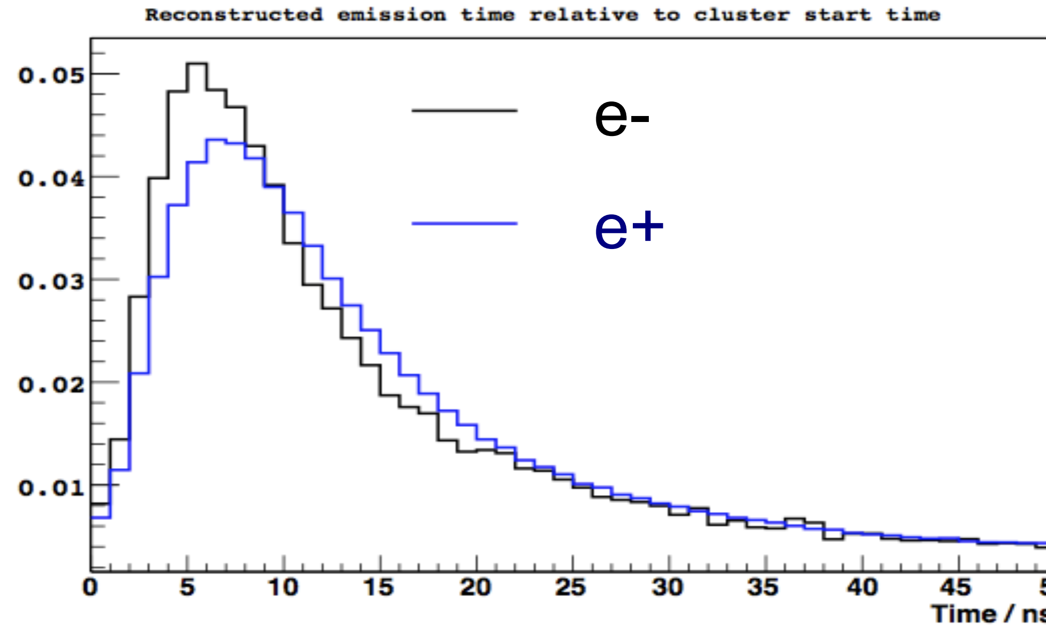
^{11}C events from TFC → pure ^{11}C sample

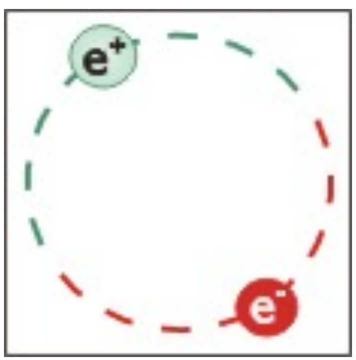
PRL 108 (2012) 051302

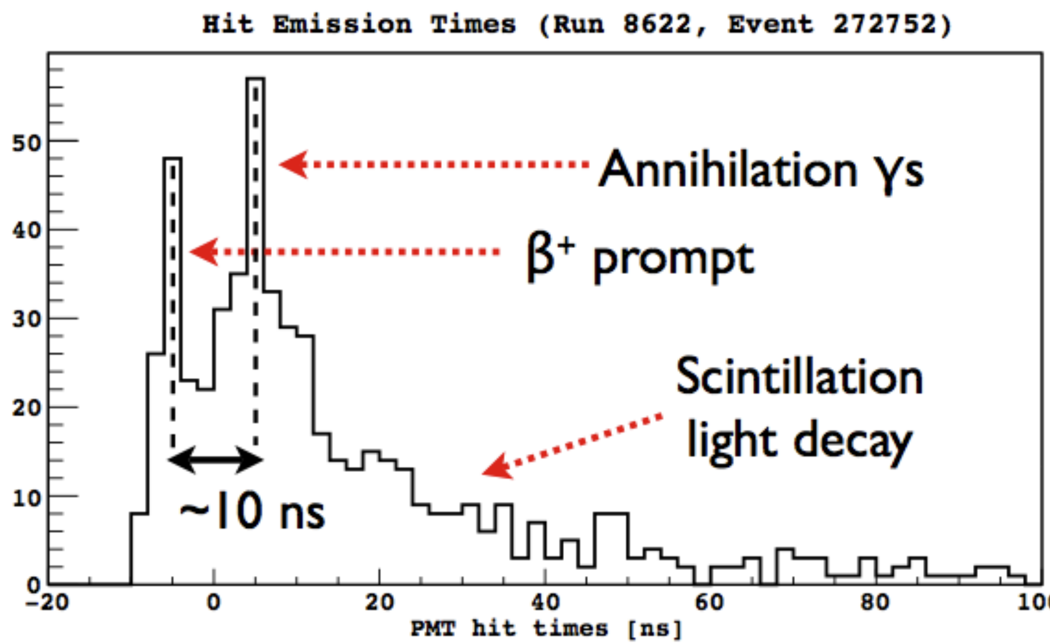
e^+/e^- discrimination

Distribution of scintillation **time signal** for **e+ delayed** with rispect to **e-**
[Phys. Rev. C 83, 0105504]

- ***Ortho-positronium*** formation in **50%** cases, **3 ns** mean life
- different event **topology**



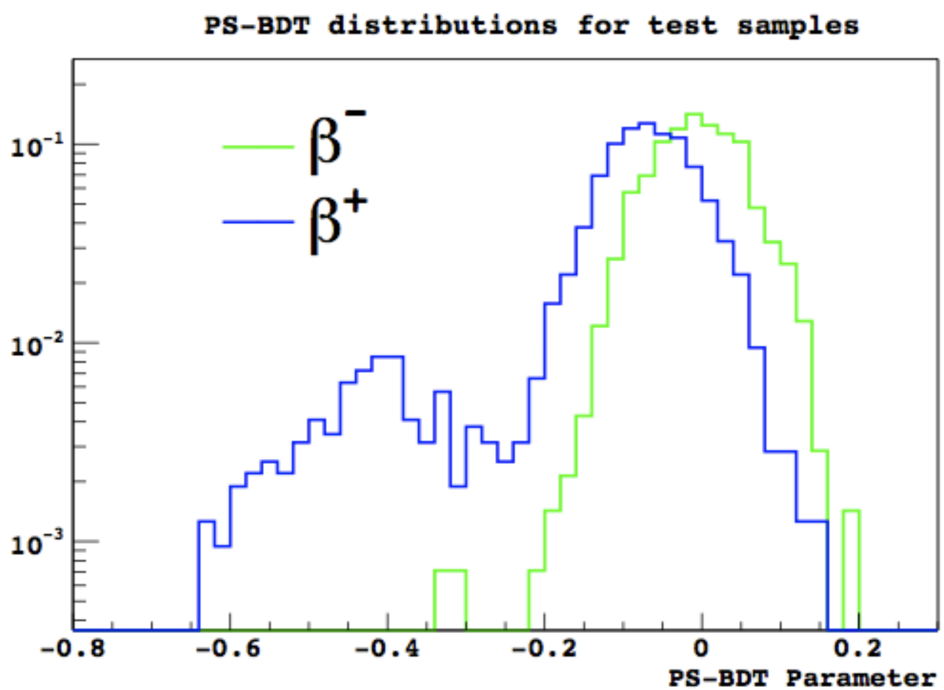




We use such difference to discriminate e+/e- events

e^+/e^- Pulse Shape Discrimination

Development of
Pulse **S**hape **D**iscrimination
variables to discriminate
β- β+ (11C) events



PS parameter
using **B**oosted **D**ecision **T**ree
(using pure ^{11}C sample for training)

pep-CNO neutrino rate measurment: analysis strategy

Multivariate maximum likelihood test to event distribution

Considering:
energy distributions
radial distribution
e+/e- pulse shape (PS-BDT) distribution

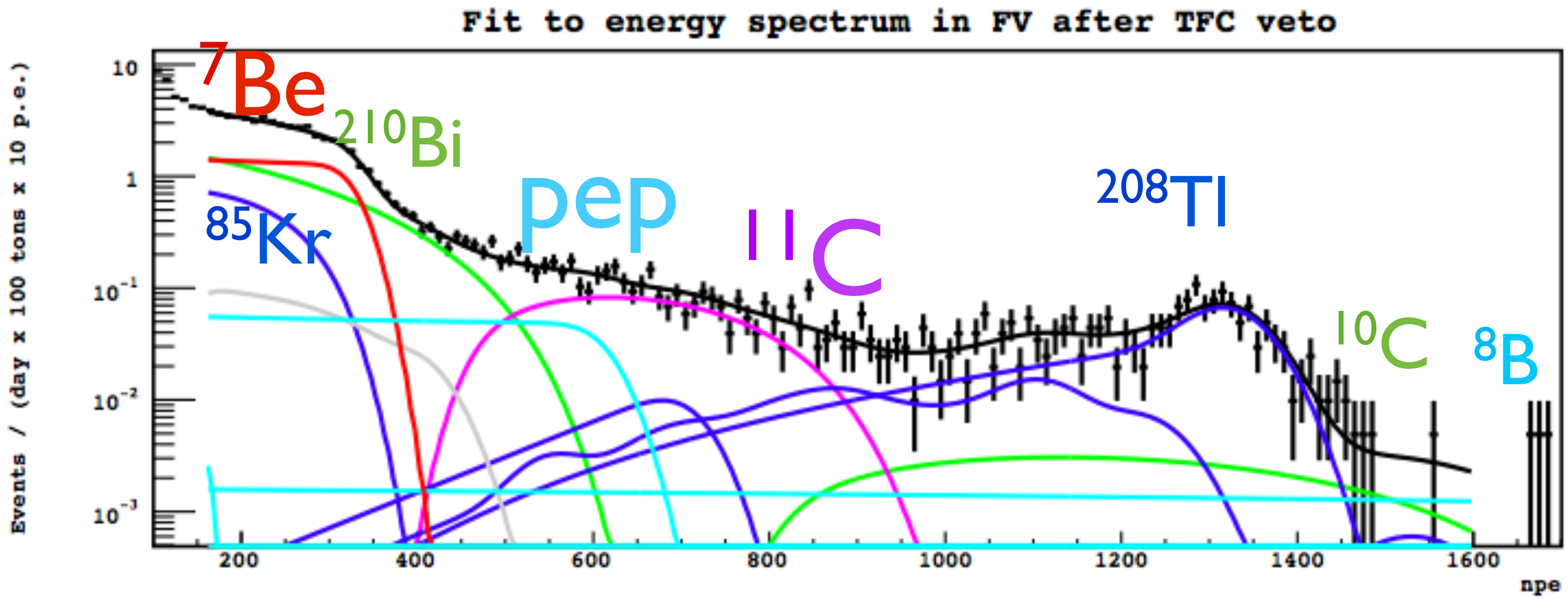
Both ^{11}C**-subtracted** and ^{11}C**-vetoed** energy spectra

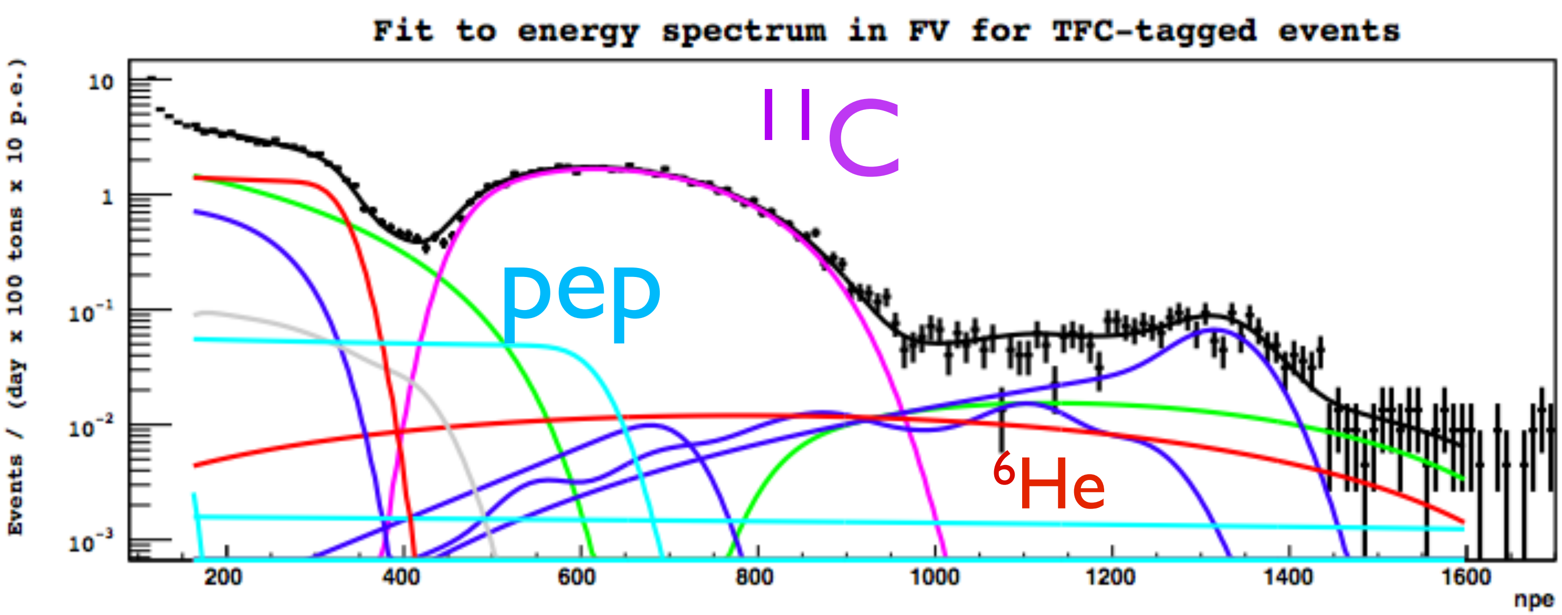
Likelihood maximized at the same time on different variables:

$$L_{TOT} = L_{ENE}\, L_{RAD}\, L_{e+/e-}$$

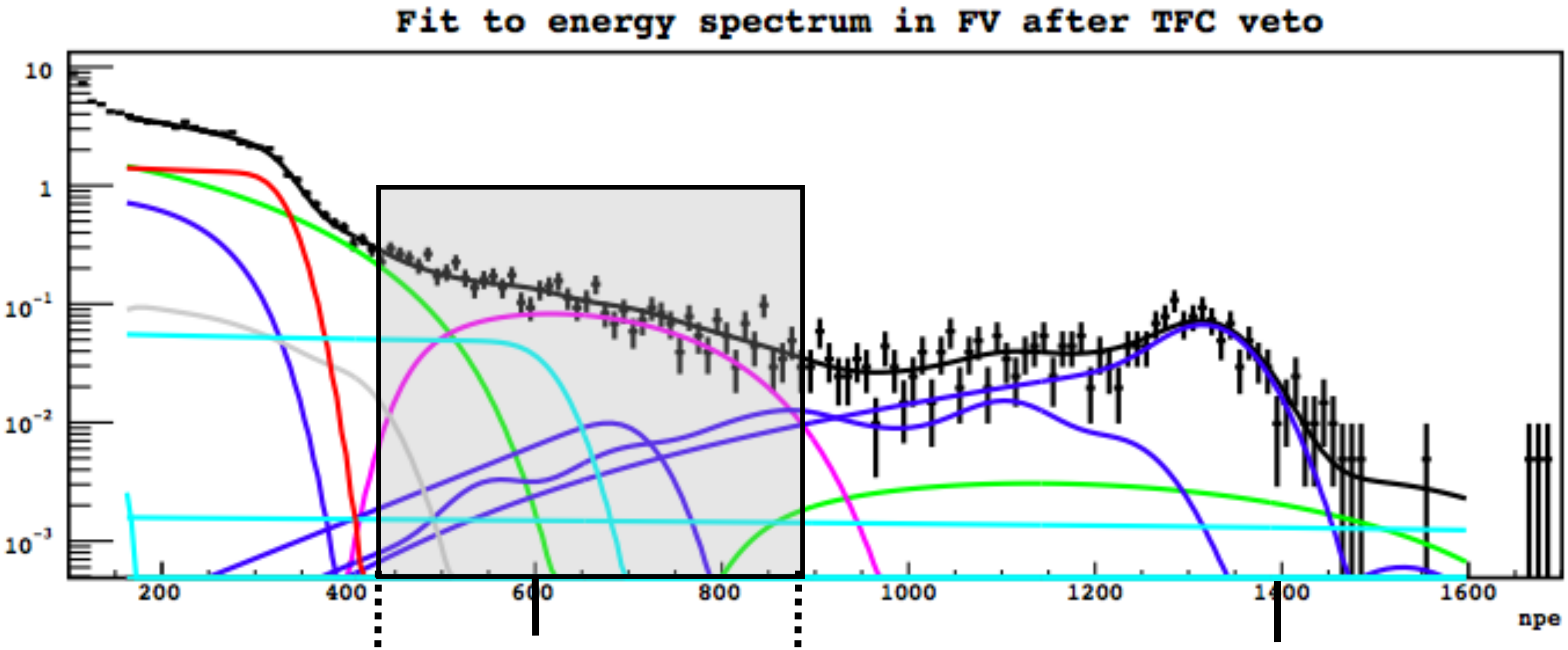
Phys.Rev. D 89 (2014) 112007

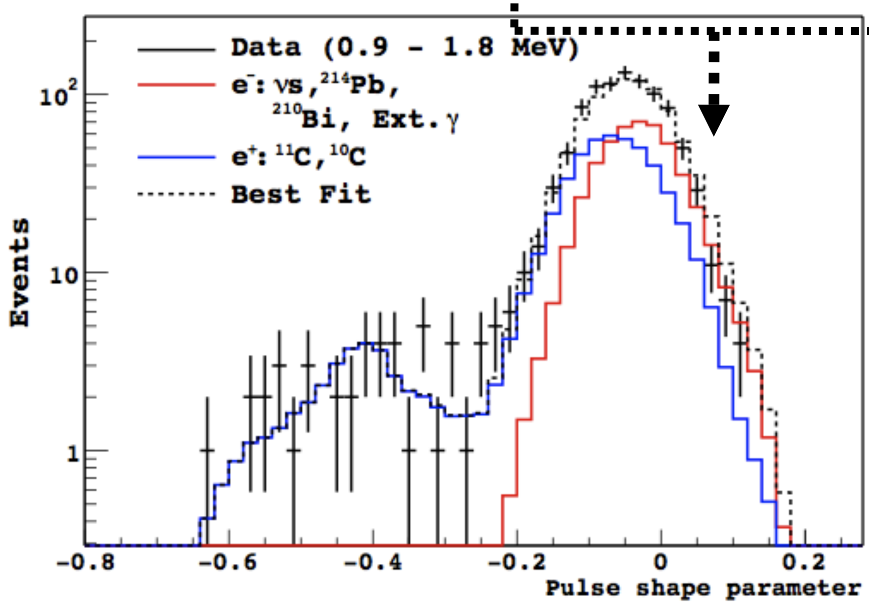
Fit to energy spectrum





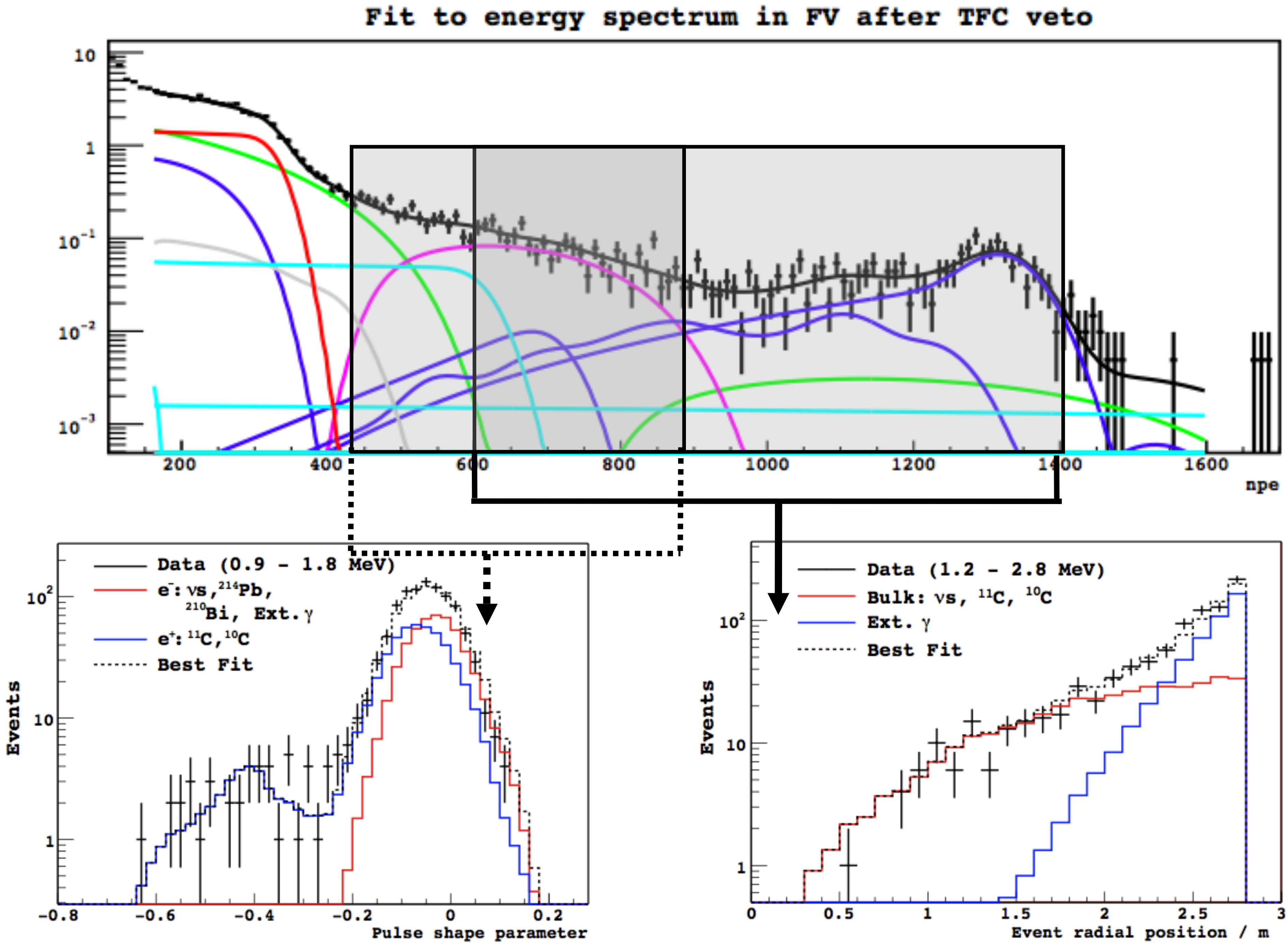
Multivariate Fit



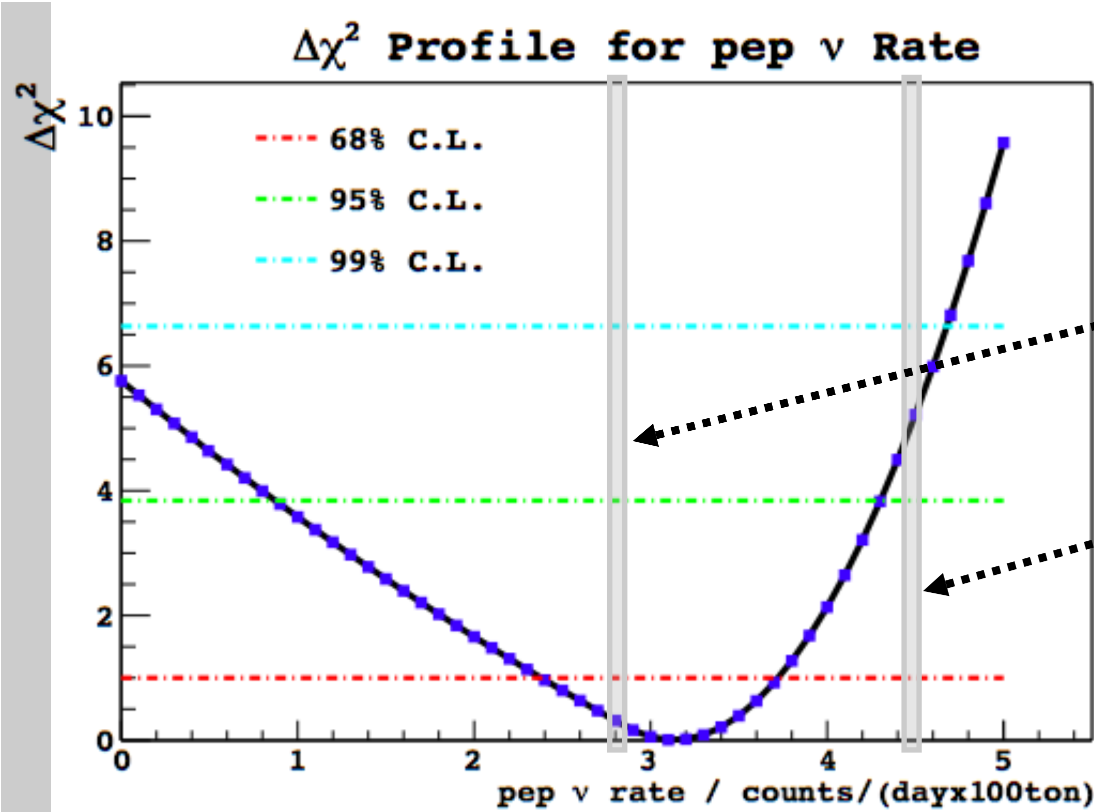


PS distribution of events - Compute **likelihood** for hypotesis:
Electron (neutrino interactions, ^{210}Bi) + **Positron** (^{11}C) rate

Multivariate Fit



First direct measurement pep ν rate



Standard Solar Model + MSW-LMA oscillation Predicted rate

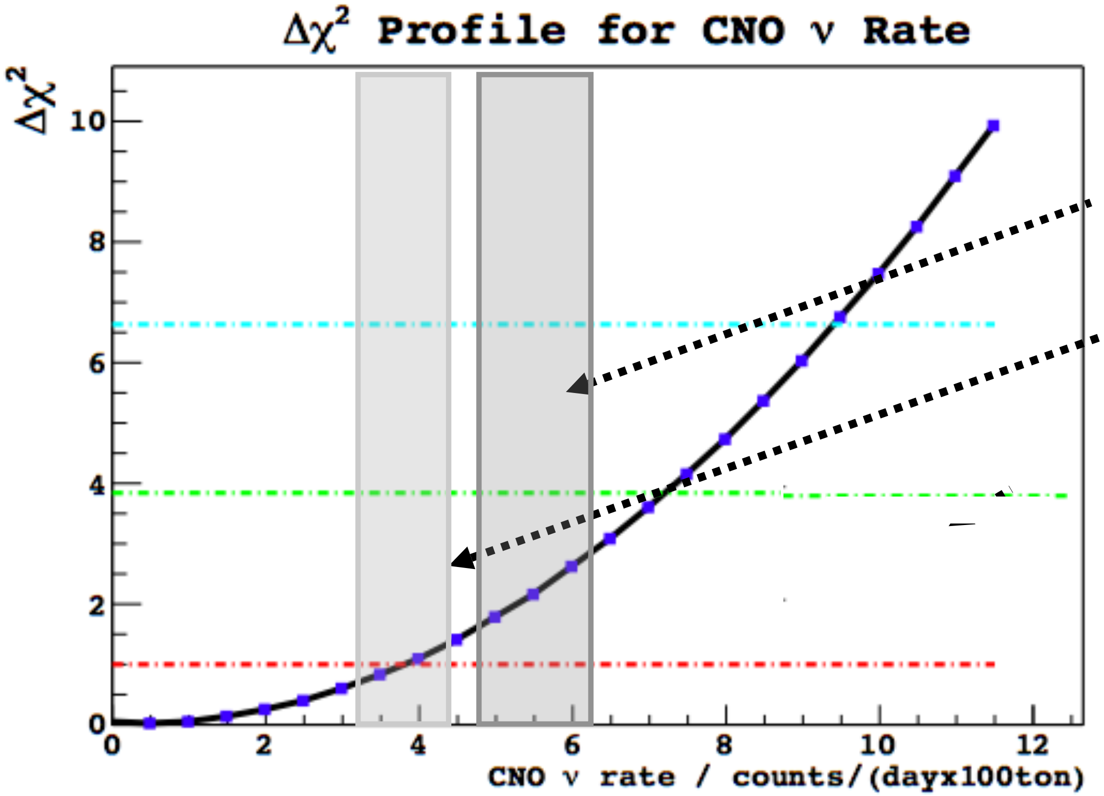
No Oscillations

No oscillation hypotesis disfavoured at 97% CL

$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$ counts/day/100tons

PRL 108 (2012) 051302

Strongest limit on CNO neutrino rate



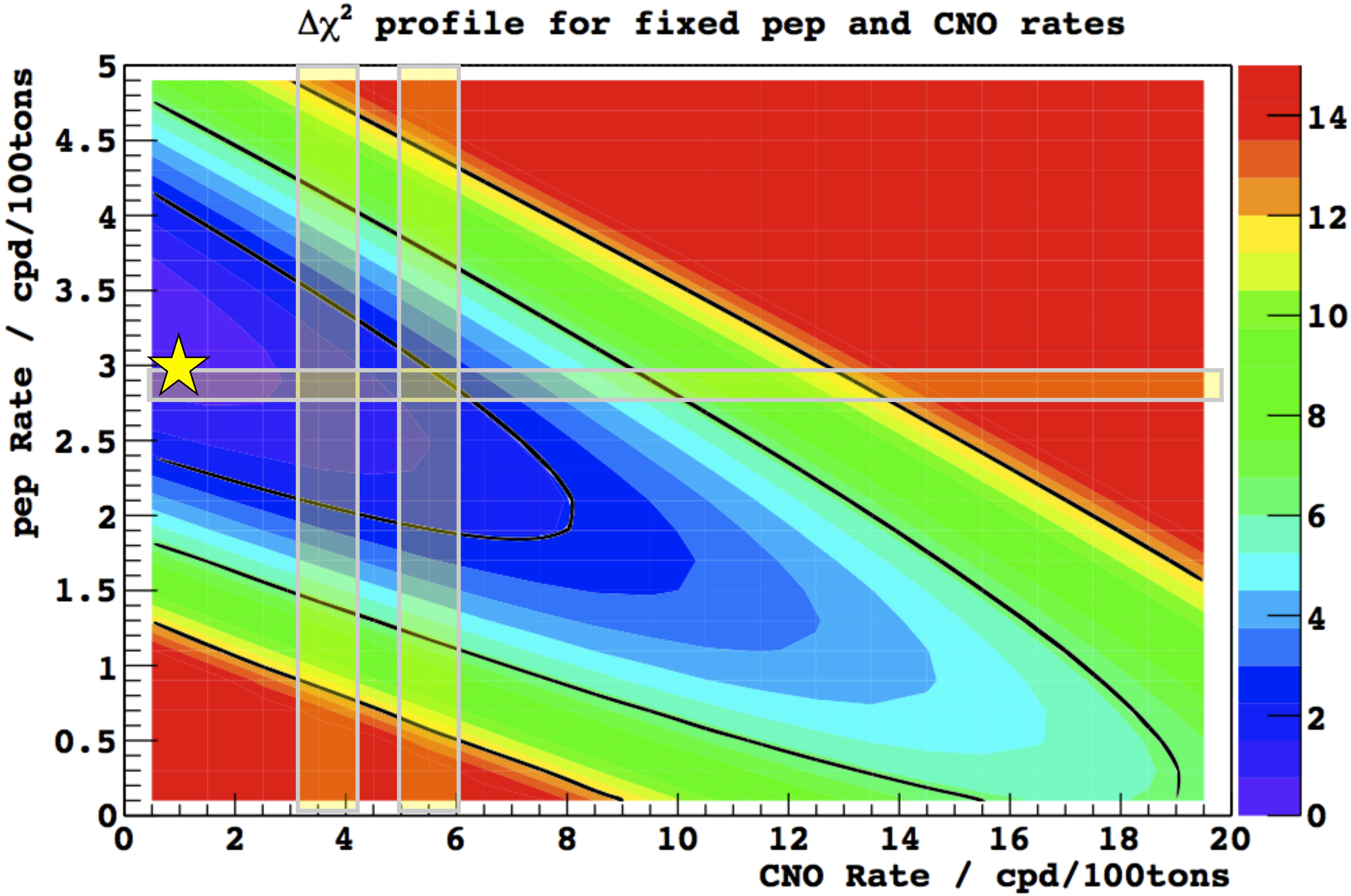
Standard Solar Model
High Z prediction

Low Z prediction

pep interaction fixed to SSM + MSW-LMA prediction:
2.8 cpd/100tons

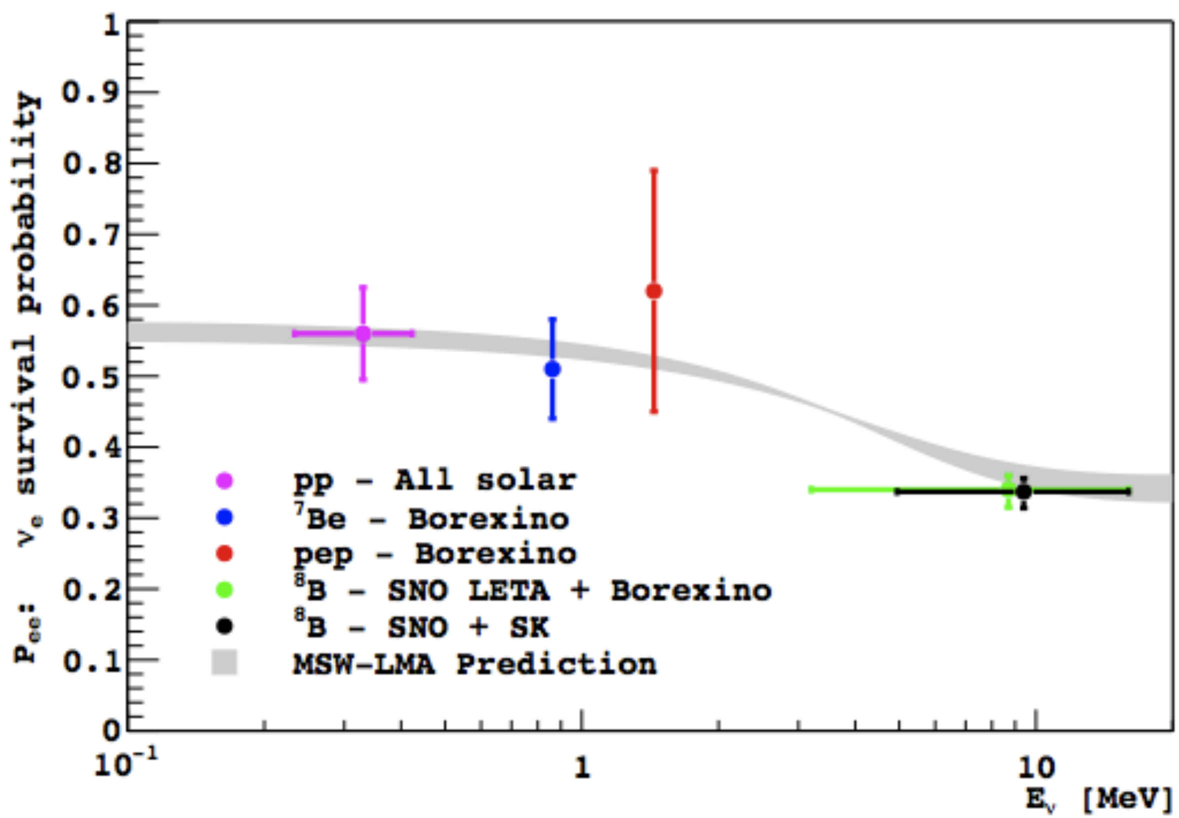
Limit (95% CL) <7.1$_{stat}$ counts/day/100tons

$\Delta\chi^2$ profile pep – CNO rate



pep and CNO solar ν flux

ν	Interaction rate [counts/(day·100 ton)]	Solar-ν flux [$10^8 \mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Data/SSM ratio
pep	$3.1 \pm 0.6_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$	1.6 ± 0.3	1.1 ± 0.2
CNO	$< 7.9\ (< 7.1_{\mathrm{stat\ only}})$	< 7.7	< 1.5



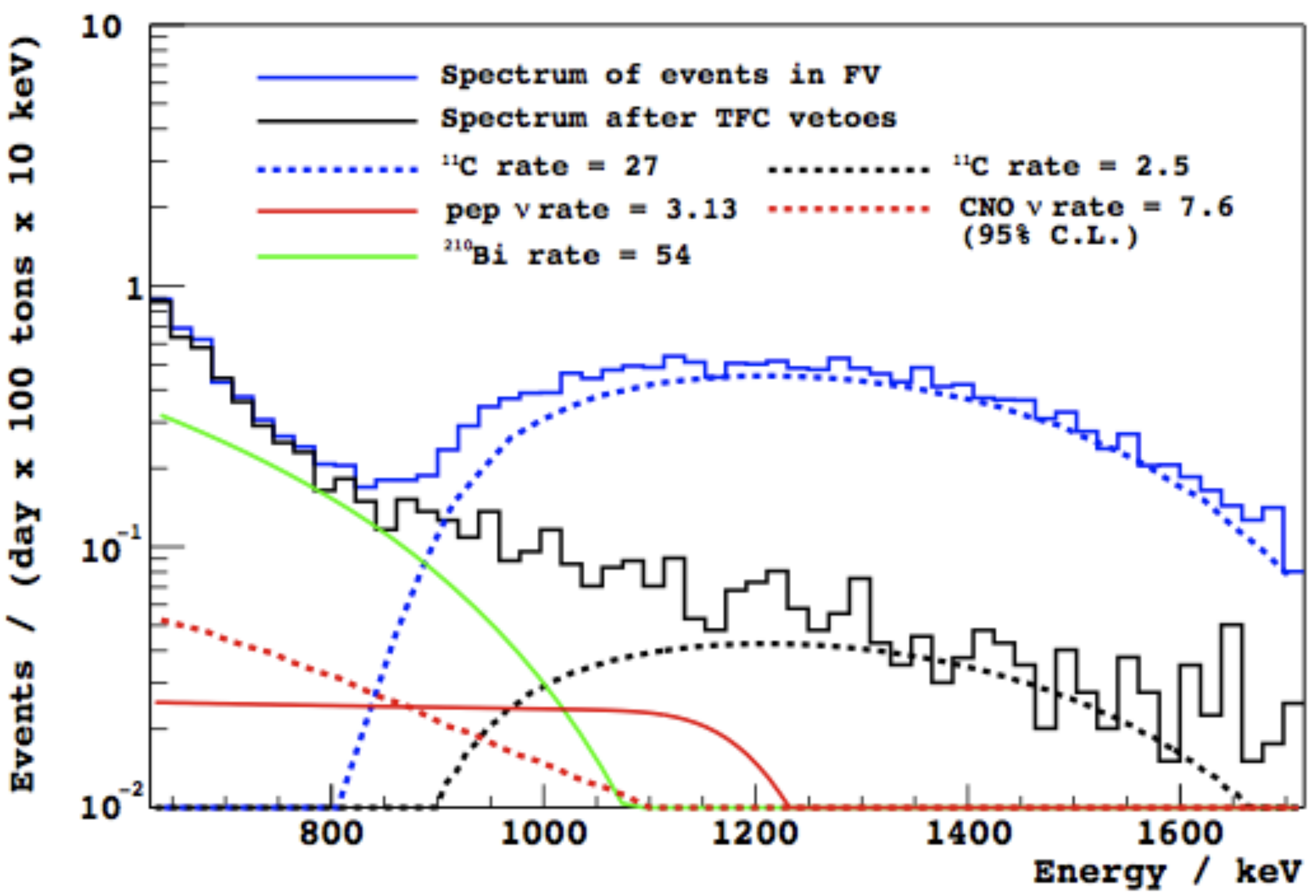
PRL 108 (2012) 051302

Internal ^{210}Bi background

Only **residual** radioactive internal **background** in **pep-CNO** region of interest→ **^{210}Bi decay** (~54 cpd/100ton)

^{210}Bi spectal shape **similar** to e- recoil spectrum from **CNO**

CNO neutrino **spectroscopy** is **tough**



Background levels in Borexino-II

Isotope	Typical abundance (source)	Borexino goals	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	10^{-12} (cosmogenic)	$\sim 10^{-18}$	$2.7 \cdot 10^{-18}$	$2.7 \cdot 10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	10^{-6}-10^{-5} (dust)	$\sim 10^{-16}$ (1 μБк /т)	$(1.6 \pm 0.1) \cdot 10^{-17}$	$<9.7 \cdot 10^{-19}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	10^{-6}-10^{-5} (dust)	$\sim 10^{-16}$	$(6.8 \pm 1.5) \cdot 10^{-18}$	$<1.2 \cdot 10^{-18}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	100 atoms/cm^3 (air)	10	1	0.1
^{40}K, g[K_{nat}]/g	$2 \cdot 10^{-6}$ (dust)	$\sim 10^{-15}$	$<1.7 \cdot 10^{-15}$ (95%)	---
^{210}Po, ev//d/t	Surface contamination	$\sim 10^{-2}$	80 (initial), $T_{1/2}$=134 days;	2
^{210}Bi, ev/d/100 t	Inequilibrium with ^{222}Rn or ^{210}Pb	Not specified	20-70	~20
^{85}Kr ev/d/100 t	1 Бк/м^3 (technogenic, air)	~1	30.4±5 cpd/100t	< compatble with 0
^{39}Ar ev/d/100 t	17 mБк/м^3 (cosmogenic in air)	~1	<<^{85}Kr	

Conclusions and Outlook - I

Borexino is the first experiment to perform
solar neutrino spectroscopy
at low energy (<2 MeV)

Implication of the measurements important for
Stellar Astropysics (*Solar Standard Model*)
and
Neutrino Physics
(*masses, mixing, oscillation, beyond SM*)

Conclusions and Outlook - II

First direct measurement of
pep solar neutrino **rate**:
direct measurment of **Pee** at *E=1.44 MeV*
probes **MSW-LMA** in **transition** region

Best limits on **CNO** solar neutrino **flux**:
test of Solar **Metallicity**
in agreement with **S**olar **S**tandard **M**odels

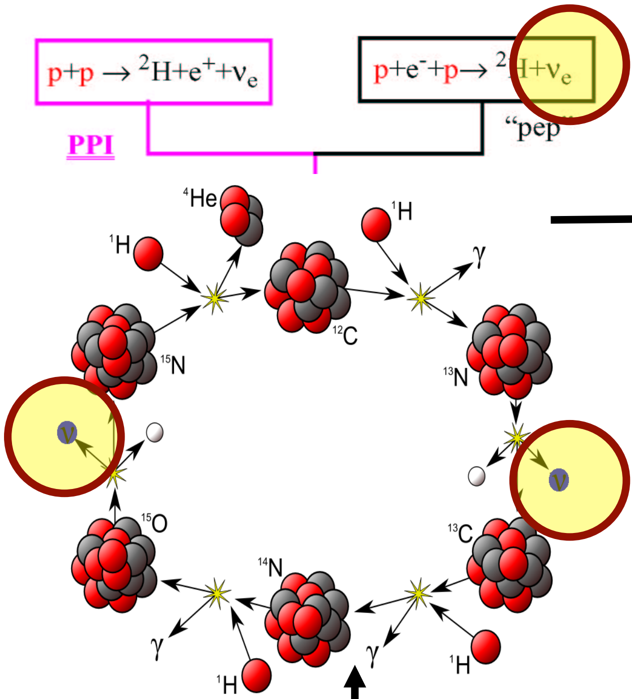
Conclusions and Outlook - III

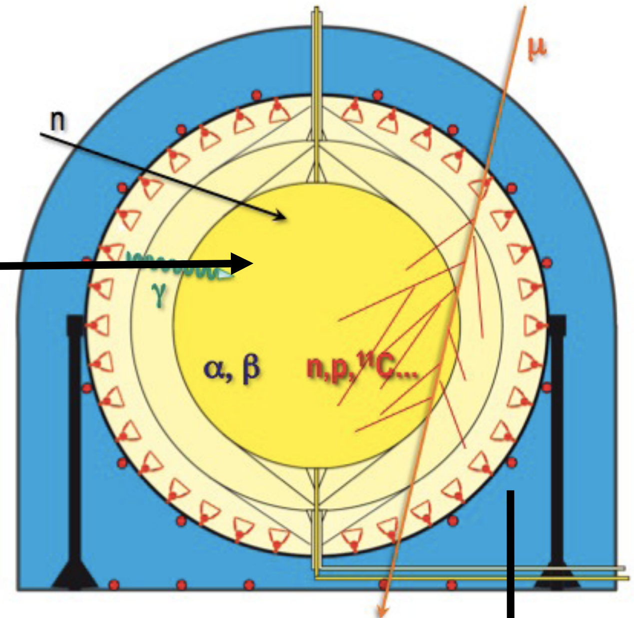
Borexino **Phase-II** (2012-present) **ongoing**

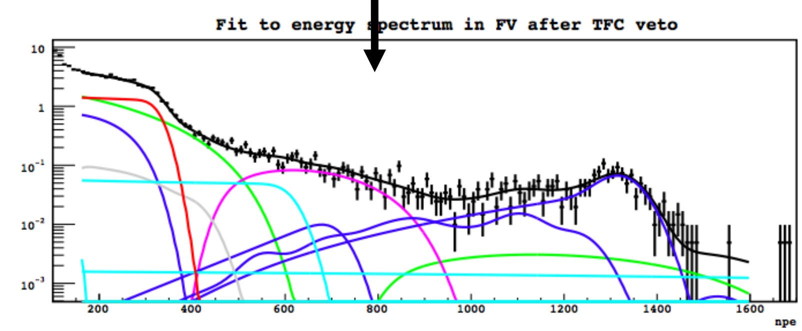
Internal radioactive **backgrounds**
much **lower** than in Phase-I

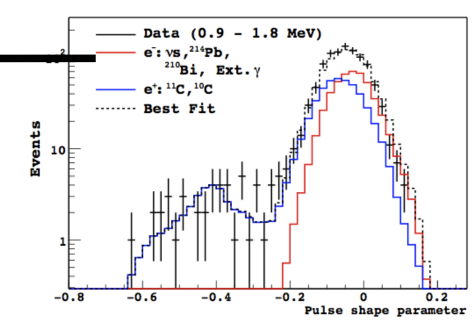
Analysis ongoing,
inproving all aspects of **analysis**

Thanks for your attention!









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CNO	< 7.9 ($< 7.1_{\mathrm{stat\ only}}$)	< 7.7	< 1.5

Backup slides

Short history of solar neutrino experiments

70's-80's: Homestake (R. Davies)

- radiochemical experiment: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ **(E_ν >1.4 MeV)**
- ✓ Deficit observed → new physics or Solar Model unaccurate?
- ✓ Nobel prize 2002

80's-90's: (Super) KamioKande

- ✓ Confirm deficit on ^8B ν **(E> ~5MeV)**
- ✓ Direction of solar neutrinos

90's: Gallex (GNO), Sage

- Radiochemical experiment: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ **(E_ν > 200 keV)**
- ✓ Observed deficit on pp ν **(low energy)**
- ✓ Calibrazion with neutrino souce → real effect

2001: SNO

- ➢ Separate detection of $\boldsymbol{\nu_e}$ and $\boldsymbol{\nu_{\mu,\tau}}$
- ✓ Confirm flavor transition of solar neutrinos
- ✓ Total flux agrees with Standard Solar Model

Why measure solar neutrinos? - II

Measure solar neutrino flux → test Solar Standard Model

- Astro-ph probe: neutrinos allow to look at the Sun's core
- Solve ***solar metallicity problem***

Tension between **High Metalliciy** (**High Z**) and **Low Metallicity** (**Low Z**) Solar Models

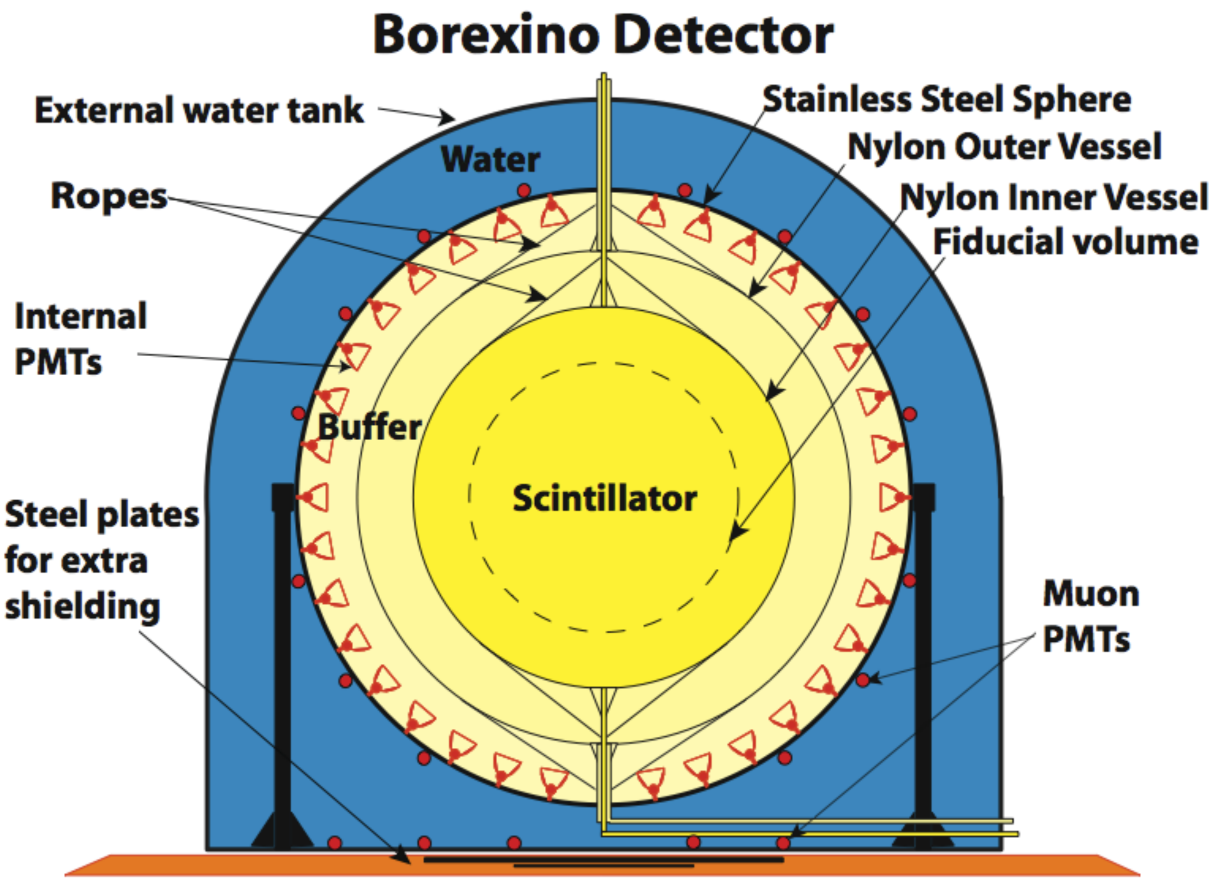
- **High Z (GS)** → older model, higher heavy element abundances, agrees with helioseismology measurments
- **Low Z (AGSS)** → recent model based on new solar atmosphere optical spectroscopy measurments, lower heavy element abundances, in disagreement with helioseismology

Reaction	Abbr.	Flux ($cm^{-2}\ s^{-1}$)
$pp \to d\, e^+ \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3\mathrm{He}\, p \to {}^4\mathrm{He}\, e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7\mathrm{Be}\, e^- \to {}^7\mathrm{Li}\, \nu + (\gamma)$	$^7\mathrm{Be}$	$5.07(1 \pm 0.06) \times 10^{9}$
$^8\mathrm{B} \to {}^8\mathrm{Be}^*\, e^+ \nu$	$^8\mathrm{B}$	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\, e^+ \nu$	$^{13}\mathrm{N}$	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\, e^+ \nu$	$^{15}\mathrm{O}$	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\, e^+ \nu$	$^{17}\mathrm{F}$	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

pp, pep neutrino flux:
predicted with SMALL uncertainties

CNO neutrino flux:
predicted with BIG uncertainties

The Borexino detector



Ultrapure organic liquid scintillator

~278 tons of **scintillator** (PC)
~75 tons of fiducial mass

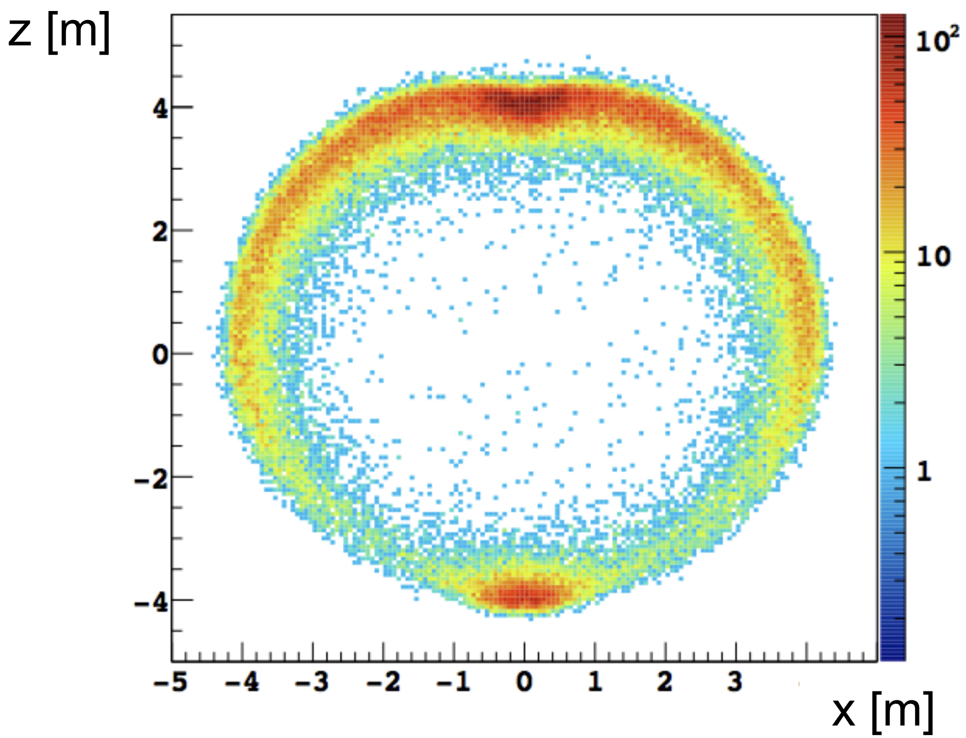
~2200 PMTs on the SSS

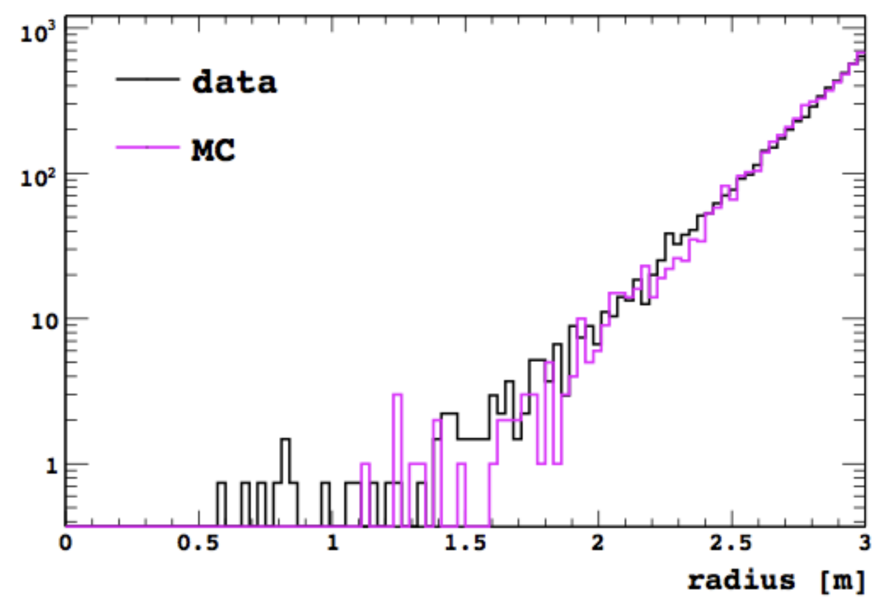
External Water Tank
shielding for n and γ
Cherenkov detector for μ

External Background

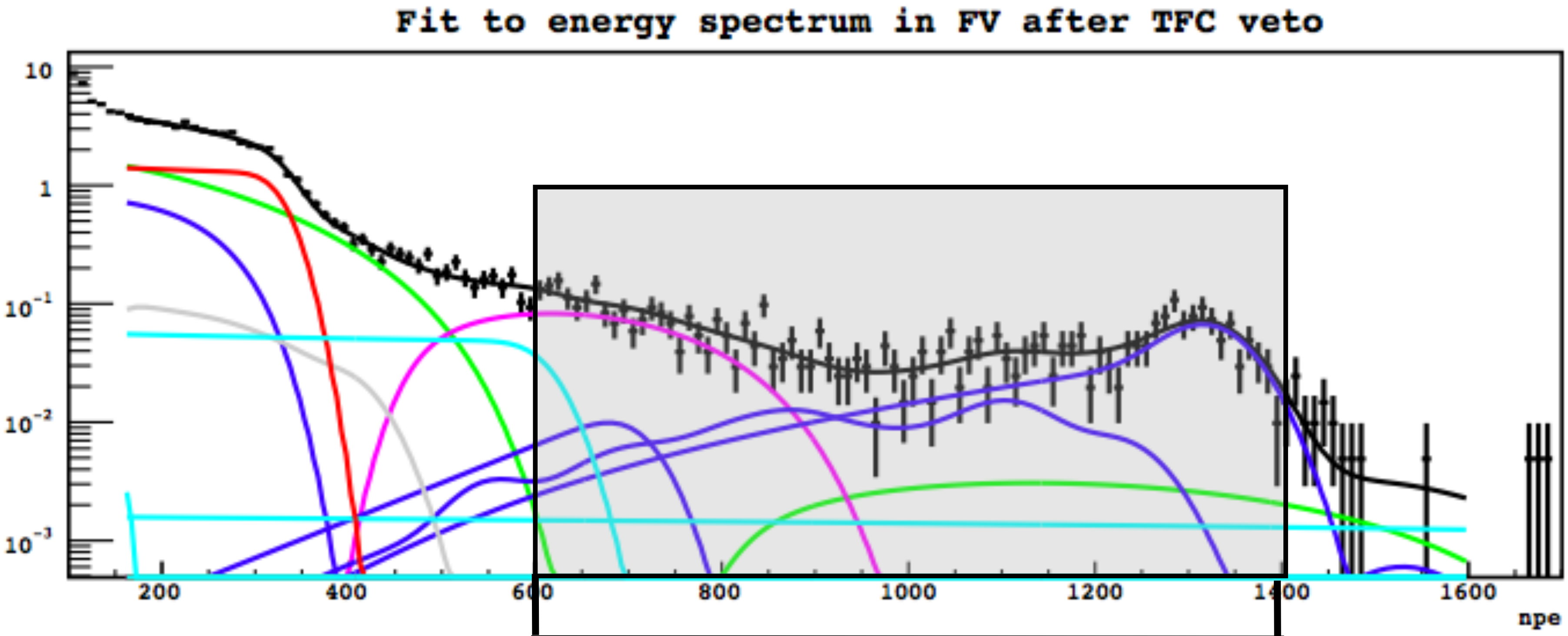
- Radioactive **decays** in **peripheral structure: ^{208}Tl** from PMTs...
- **Fiducial Volume**:
  minimize γ-rays without sacrifice too many events

- Spatial distribution **external bkg** → **NON homogeneus**
- Spatial distribution **internal bkg** and **ν** → **homogeneus**
- **Spatial distribution** from **Monte Carlo** simulation
  and external **calibration** source (^{228}Th)

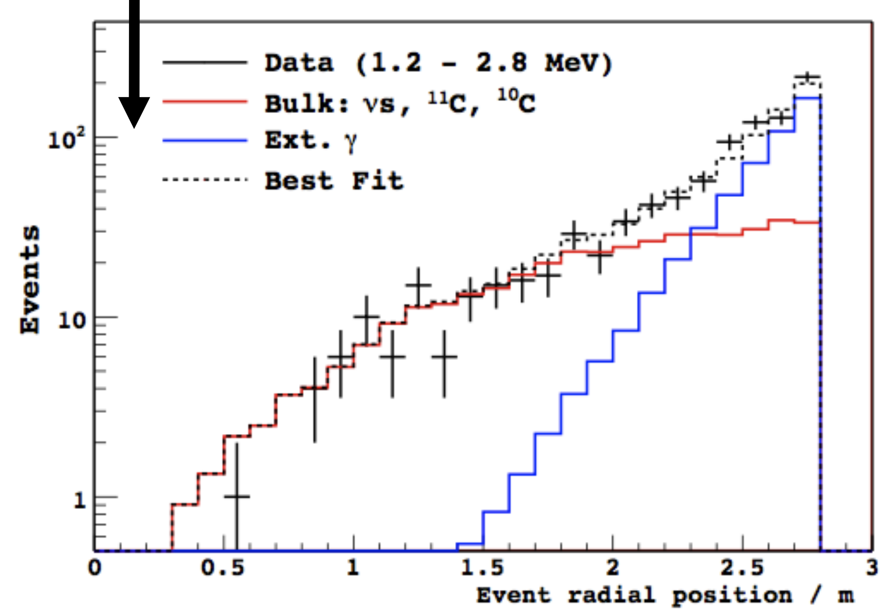




Multivariate Fit – radial distribution



Radial distribution of events - Compute **likelihood** for hypotesis:
homogeneus distribution (neutrino interactions and internal background rates) + **External background** rate



pep systematics

- Float fit **parameters** (binning, range...)
- **Detector** response, energy **scale**
- Uncertainty in ^{210}**Bi** energy **spectrum**
- **γ** in **PS-BDT** distribution
- Low **statistics** for **PS-BDT** **training**
- Fiducial **Volume**, position recostruction
- **Fixed** species in the fit (pp and ^{8}B nu, ^{214}Po)
- Impact of short lived **cosmogenics**

Total systematic uncertainty in pep rate: 10%