Looking at the Sun's core
- CNO and pep
solar neutrino detection
in Borexino

IFAE 2012, Ferrara
April 13th 2012

Stefano Davini
University of Houston
Talk outline

Solar neutrinos
- Introduction to solar neutrino observations
- Motivations of solar neutrino experiments

The Borexino experiment
- Solar neutrino detection in Borexino

Detection of pep and CNO solar neutrinos in Borexino
- Motivation of the measurement
- Cosmogenic backgrounds rejection
- Analysis
- Results
The solar neutrino flux

Provide details on stellar structure and working, directly addresses **Solar Standard Model**

Energetically **broadband**

Free of **flavour background**

Looooong **baseline**

and passes through quantities of **matter** unavailable to terrestrial experiments

Opportunity to study neutrino **oscillations** and **matter** effects (**MSW**)
Solar neutrino experiments - current status and motivations

**MSW-LMA** → current understanding solar neutrino oscillation
Mainly from $^8\text{B} \nu (E>5\text{MeV})$ + radiochemical experiments

No spectroscopy measurement of solar-$\nu$ of $E<1-2 \text{ MeV}$ before Borexino

$^7\text{Be}$, pep $\nu$ → precision test of MSW-LMA $P_{ee}$ in vacuum and transition regions
constrain exotic models of oscillations (NSI, MaVaN...)

Pee measurement before BOREXINO

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**Graphs:**

- **Graph 1:**
  - **MSW-LMA Prediction**
  - **MSW-LMA-NSI Prediction**
  - **MaVaN Prediction**
  - **SNO Data**
  - **Ga/Cd Data Before Borexino**

- **Graph 2:**
  - **Pee Survival Probability vs. $E_{\nu}$ [MeV]**
  - **Pee Measurement**:
    - pp - All solar
    - $^7\text{Be}$ - Borexino
    - pep - Borexino
    - $^8\text{B}$ - SNO LETA + Borexino
    - $^8\text{B}$ - SNO + SK
    - $^8\text{B}$ - SNO LETA + Borexino

**References:****

- PRL 107 (2011) 141302
- PRL 108 (2012) 051302
**Solar neutrino experiments - Motivations**

Measure **solar neutrino flux** $\rightarrow$ **test Solar Standard Model**

Astro-ph probe: neutrinos allow to look at the Sun's core

Solve **solar metallicity problem:**

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

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

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

**pp, pep neutrino flux:** predicted with **SMALL uncertainties**

**CNO neutrino flux:** predicted with **BIG uncertainties**
The Borexino experiment at LNGS

Laboratori Nazionali del Gran Sasso

Under ~1400 meters of rock (3500 m w.e.)

Cosmic-ray shielding
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

Signal ($^7$Be neutrinos) $\rightarrow$ 50 events/day/100tons $\rightarrow$ 6 $\times$ 10$^{-9}$ Bq/kg

Borexino scintillator $\rightarrow$ 9-10 orders of magnitude more radiopure than anything on Earth
Solar neutrino detection in Borexino

Neutrinos detected via elastic scattering on electrons

Recoil electron excites scintillator → emission of light

Scintillation light detected by PMTs

Number of hit PMTs → Energy
Pattern of hit PMTs → position

Energy spectrum simulation

\[^7\text{Be} \, \nu\] and \[\text{pep CNO} \, \nu\] events
Measurement of pep and CNO solar neutrino rates in Borexino
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 $\sim 3$ cpd/100tons

C-N-O cycle
Neutrinos from $^{13}\text{N}$ and $^{15}\text{O}$ decay
Continuous spectrum $Q = 1.74$ MeV
Low flux, predicted with low accuracy,
 sensible to Solar metallicity
Expected rate in BX $\sim 3-5$ 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
Why measure CNO neutrinos?

Proof that CNO cycle happens in Sun

Abundance 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

<table>
<thead>
<tr>
<th></th>
<th>CNO Flux ($10^8$ cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH Z</strong> SSM</td>
<td>5.24 ± 0.84</td>
</tr>
<tr>
<td><strong>LOW Z</strong> SSM</td>
<td>3.76 ± 0.60</td>
</tr>
<tr>
<td>ΔΦ</td>
<td>28%</td>
</tr>
</tbody>
</table>
pep and CNO neutrino detection in Borexino

Low signal: few events/day/100tons
Dominant background: cosmogenic $\beta^+$ emitter $^{11}\text{C}$
$27\text{cpd/100tons} \rightarrow \text{signal/background} \sim 0.1$

Need novel techniques to suppress $^{11}\text{C}$ background:
Three Fold Coincidence
$e^+/e^-$ pulse shape discrimination
Suppress $^{11}\text{C}$ - Three Fold Coincidence

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

$\sim 4300$ muons/day in Borexino

**Spallation neutron** in 95% cases

$n$ thermalize and captured, mean life $\sim 250 \mu s$

capture on $H \rightarrow \gamma \ (2.2 \text{ MeV})$

$^{11}\text{C}$ decays $\beta^+$ mean life 29.4 minutes

Stays where produced (no convective motions)

Space-time correlation between muon track, neutron capture, $^{11}\text{C}$ decay:

Three Fold Coincidence (TFC)

We exclude from analysis space-time regions where we expect $^{11}\text{C}$ decays
Suppress $^{11}\text{C}$ - Three Fold Coincidence

Removed **91%** $^{11}\text{C}$, keeping **48.5%** scintillation events

$^{11}\text{C}$ rate: **27 → 2.5** cpd/100tons

*Energy spectrum in FV*

![Energy spectrum graph](image_url)
e⁺/e⁻ Pulse Shape Discrimination

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

Ortho-positronium formation in 50% cases, 3 ns mean life

We use such difference to discriminate e⁺/e⁻ events: Pulse Shape Discrimination
pep-CNO neutrino rate measurement: analysis strategy

Multivariate maximum likelihood test to event distribution

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

Likelihood maximized at the same time on different variables:

\[ L_{TOT} = L_{ENE} L_{RAD} L_{e+/e-} \]
Multivariate Fit

Fit to energy spectrum in FV after TFC veto

Data (0.9 - 1.8 MeV)
- e\textsc{vs,213Pb,}
- e\textsc{vs,210Bi, Ext. γ}
- e\textsc{vs,11C,10C}

Best Fit

Data (1.2 - 2.8 MeV)
- Bulk: vs, 11C, 10C
- Ext. γ

Best Fit
Results
First direct measurement \( \text{pep} \nu \text{ rate} \)

\[ \Delta \chi^2 \text{ Profile for pep \( \nu \) Rate} \]

- Standard Solar Model + MSW-LMA oscillation
- Predicted rate
- No Oscillations
- No oscillation hypothesis disfavoured at 97% CL

\[ 3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} \text{ counts/day/100tons} \]
Strongest limit on CNO neutrino rate

Limit (95% CL) <7.1\text{stat counts/day/100tons}
pep and CNO solar $\nu$ flux

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>Interaction rate [counts/(day·100 ton)]</th>
<th>Solar-$\nu$ flux [$10^8$ cm$^{-2}$ s$^{-1}$]</th>
<th>Data/SSM ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>pep</td>
<td>$3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}$</td>
<td>$1.6 \pm 0.3$</td>
<td>$1.1 \pm 0.2$</td>
</tr>
<tr>
<td>CNO</td>
<td>$&lt; 7.9$ ($&lt; 7.1_{\text{stat only}}$)</td>
<td>$&lt; 7.7$</td>
<td>$&lt; 1.5$</td>
</tr>
</tbody>
</table>

PRL 108 (2012) 051302
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 \textit{pep} solar neutrino rate:
direct measurement of \textit{Pe}e at $E=1.44$ MeV
probes MSW-LMA in transition region

Best limits on \textit{CNO} solar neutrino flux:
test of Solar Metallicity
in agreement with Solar Standard Models
Thanks for your attention!

\[
p+p \rightarrow ^2H+e^++\nu_e \quad p+e^-+p \rightarrow ^2H+\nu_e
\]

**PPI**

**“pep”**

\[
\text{Fit to energy spectrum in FV after TPC veto}
\]

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>Interaction rate</th>
<th>Solar-( \nu ) flux</th>
<th>Data/SSM ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{pep} )</td>
<td>( 3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} )</td>
<td>( 1.6 \pm 0.3 )</td>
<td>( 1.1 \pm 0.2 )</td>
</tr>
<tr>
<td>( \text{CNO} )</td>
<td>&lt; 7.9 (&lt; 7.1_{\text{stat}} only)</td>
<td>&lt; 7.7</td>
<td>&lt; 1.5</td>
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</table>
Backup slides
Nuclear reactions in the Sun

Energy production in the Sun:
- **pp chain** → 99% of energy in Sun
- **CNO cycle** → minor contribution (<1%)

**pp chain**
- $p + p \rightarrow ^2H + e^+ + \nu_e$
- $p + e^- + p \rightarrow ^2H + \nu_e$

**CNO cycle**
- $p + ^2H \rightarrow ^3He + \gamma$
- $^3He + ^3He \rightarrow ^4He + p + p$
- $^3He + ^4He \rightarrow ^7Be + \gamma$
- $^7Be + e^- \rightarrow ^7Li + \nu_e$
- $^7Li + p \rightarrow ^4He + ^4He$
- $^8B \rightarrow ^8Be + e^+ + \nu_e$
- $^8Be \rightarrow ^4He + ^4He$
Nuclear reactions in the Sun

Solar-ν flux and spectrum computed by Standard Solar Model

- \( pp \pm 1\% \)
- \( 7\text{Be} \pm 7\% \)
- \( \text{Borexino} \rightarrow 5\% \)
- \( \text{pep} \pm 1.2\% \)
- \( \text{Borexino} \rightarrow 20\% \)
- \( 8\text{B} \pm 11\% \)
- \( \text{SNO, SuperK, Bx} \)
Detection of solar neutrinos

The sun produces $\nu_e$

**Detection** possible via 3 **fundamental processes**

**Inverse $\beta$ decay** on proton or nucleus
- **Charged Current (CC) interaction**
  - $E\sim$MeV $\rightarrow \nu_e$ only

**Elastic scattering on nucleus**
- **Neutral Current (NC) interaction**
  - neutrino not absorbed
  - **same** cross section for $\nu_e$, $\nu_{\mu,\tau}$

**Elastic scattering on electron**
- **Charged Current + Neutral Current**
  - **different** cross section for $\nu_e$, $\nu_{\mu,\tau}$

$\sigma \sim 10^{-44}\text{ cm}^2$
Short history of solar neutrino experiments

70's–80's: Homestake (R. Davies)
- radiochemical experiment: $\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- (E > 1.4 \text{ MeV})$
- Deficit observed → new physics or Solar Model unaccurate?
- Nobel prize 2002

80's–90's: (Super) KamioKande
- Confirm deficit on $^8\text{B}\nu$ (E> ~5MeV)
- Direction of solar neutrinos

90's: Gallex (GNO), Sage
- Radiochemical experiment: $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- (E > 200 \text{ keV})$
- Observed deficit on pp $\nu$ (low energy)
- Calibration with neutrino source → real effect

2001: SNO
- Separate detection of $\nu_e$ and $\nu_{\mu,\tau}$
- Confirm flavor transition of solar neutrinos
- Total flux agrees with Standard Solar Model
Short history of solar neutrino experiments - I

70's–80's: Homestake (R. Davies)
- radiochemical experiment: $\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- (E > 1.4 \text{ MeV})$

✔ Deficit observed → new physics or Solar Model inaccurate?
✔ Nobel prize 2002
Short history of solar neutrino experiments - II

80's–90's: (Super) KamioKande
✓ Confirm deficit on $^8$B ν (E $> \sim$5MeV)
✓ Direction of solar neutrinos

A beautiful image of the Sun in neutrinos
90's: **Gallex (GNO), Sage**
- Radiochemical experiment: $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- (E > 200 \text{ keV})$
- Observed deficit on pp $\nu$ (low energy)
- Calibration with neutrino source $\rightarrow$ real effect
Solar neutrino oscillations

Explanation of solar neutrino deficit:
if neutrino has mass + flavor defined state is not mass eigenstate → flavor oscillation during propagation
(analogy in quark sector: CKM-mixing → neutral K oscillations...)

if only $\nu_e$ detected → deficit

With just 2 flavors and perfect coherence

$$P_{e\rightarrow \mu} = \sin^2(2\theta) \sin^2 \left[ \frac{1.27 \Delta m^2 L}{E_\nu} \right]$$

$\Delta m$ in eV
$L$ in m
$E_\nu$ in MeV

Solar neutrinos: production region $>>$ oscillation length
→ oscillation term averaged out

Solar neutrino oscillation in vacuum

But
propagation
NOT in vacuum:
Sun matter
Neutrino oscillations in matter

**Matter** made of e\(^-\) (no \(\mu, \tau\))
- coherent \(\nu-e^-\) scattering affects oscillations (Wolfenstein, '78)
- \(\nu_e\) interactions different from \(\nu_{\mu,\tau}\)
- "Refraction index" for \(\nu_e\) different from \(\nu_{\mu,\tau}\)

**Resonant effect** (Mikheyev & Smirnov, 1985)
- **Survival probability** (Pee)
  becomes energy dependent

**MSW Effect in the Sun**
- Low energy neutrinos (pp \(\nu\)) \(\rightarrow\) oscillations as in **vacuum**
- High energy neutrinos (\(^8\)B \(\nu\)) \(\rightarrow\) **Matter enhanced** oscillations
- **Transition region** between 1-3 MeV
Discovery of solar neutrino oscillations

**SNO, 2001:**
- Detects $\nu_e$ and $\nu_{\mu,\tau}^{8B}$
- **CC and NC interactions on d**
- **ES interactions on e^-**
- Total $\nu_e + \nu_{\mu,\tau}$ flux is **SSM predicted flux**
- **Disappearance of $\nu_e$**
- **Appearence of $\nu_{\mu,\tau}$**

**KamLAND, 2002:**
- Observation of reactor anti $\nu_e$ oscillations
- **Precise $\Delta m^2$ measurement**
**MSW-LMA scenario**

**SNO** and **KamLAND** measurements evidence

\[ \nu_e \text{ oscillation into } \nu_{\mu,\tau} \text{ in trip from Sun's core to Earth} \]

**Total flux** \((\nu_e + \nu_{\mu,\tau})\) agrees with **Standard Solar Model**

**MSW effect** → **Energy dependent** \(P_{ee}\)

Global Fit

**Solar exp + KamLAND evidence:**

- **Large Mixing Angle**

**Solar neutrino oscillations** described by

**MSW-LMA scenario**
Borexino detector - Backgrounds

Radioactive backgrounds
radioactive traces in scintillator
radioactivity from PMTs, ...

Neutrino interaction
NOT distinguishable from $\beta/\gamma$
radioactive decays in scintillator

Strict radiopurity requirements
on materials
graded shielding:
closer to FV → more pure

Signal ($^7$Be neutrinos) → 50 events/day/100tons → $6 \times 10^{-9}$ Bq/kg

Typical radioactive concentration (air, water): $\sim$10 Bq/kg

Solar neutrino spectroscopy with scintillator → detector 9-10 orders of magnitude more radiopure than anything on Earth
# Borexino detector – Internal Backgrounds

<table>
<thead>
<tr>
<th>Radio-Isotope</th>
<th>Concentration</th>
<th>Reduction Strategy</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Source</strong></td>
<td><strong>Typical</strong></td>
<td><strong>Required</strong></td>
</tr>
<tr>
<td>14C</td>
<td>intrinsic organic scint.</td>
<td>$\sim 10^{-12}$ g/g</td>
<td>$\sim 10^{-18}$ g/g</td>
</tr>
<tr>
<td>238U 232Th</td>
<td>dust, metallic</td>
<td>$10^{-5}$-$10^{-6}$ g/g</td>
<td>$&lt; 10^{-16}$ g/g</td>
</tr>
<tr>
<td>40K</td>
<td>dust</td>
<td>$\sim2 \times 10^{-6}$ g/g (dust)</td>
<td>$&lt; 10^{-18}$ g/g</td>
</tr>
<tr>
<td>210Po</td>
<td>Surface cont. from 222Rn</td>
<td></td>
<td>$&lt; 1$ c/d/t</td>
</tr>
<tr>
<td>222Rn</td>
<td>Emanation from materials, rock</td>
<td>10 Bq/l air, water 100-1000 Bq rock</td>
<td>$&lt; 10$ cpd 100 t</td>
</tr>
<tr>
<td>85Kr</td>
<td>air, nuclear weapons</td>
<td>$\sim 1$ Bq/m$^3$ (air)</td>
<td>$&lt; 1$ cpd 100 t</td>
</tr>
</tbody>
</table>
Borexino Detector Calibration

Study detector response as function of position and energy using $\alpha$, $\beta$, $\gamma$, $n$ sources

Improved energy response understanding and modeling
Improved position reconstruction algorithm

Calibration $\gamma$ sources: Data VS MC

57Co 139Ce 203Hg 85Sr 54Mn 65Zn 40K 60Co
$^7$Be analysis: Data Selection

- All data after cuts (i) - (iii)
- After cuts (iv) - (v)
- After statistical subtraction of α's
Few residual radioactive backgrounds: $^{210}$Po, $^{85}$Kr, $^{210}$Bi

Fit to energy spectrum to separate signal/backgrounds contributions

Two independent methods to generate energy spectra pdfs:
MC and analytical
Precision measurement of the $^7$Be solar $\nu$ interaction rate

$46.0 \pm 1.5_{\text{stat}}^{+1.6}_{-1.5_{\text{syst}}} \text{ counts/day/100tons}$

No oscillations hypothesis rejected at $4.8 \sigma$ [74$\pm$5 cpd / 100 t]
Day-night asymmetry

As neutrinos pass through the earth (at night), matter effect can cause regeneration: \( \nu_\mu \) can be converted back to \( \nu_e \) if \( \Delta m^2_{21} \) in a certain range.

\[
A_{dn} = 2 \frac{R_N - R_D}{R_N + R_D} = 0.001 \pm 0.012 \pm 0.007
\]
Absence of day-night asymmetry

Rules out the low $\Delta m^2$ parameter space at more than 8$\sigma$

Confirms MSW-LMA oscillations without using KamLand anti $\nu_e$ data

i.e. without assuming CPT invariance in neutrino sector

PLB 707 (2012) 22-26
Implication of the absence of $^7$Be rate day-night asymmetry: $\Delta m^2_{21}$ profile

LOW $\Delta m^2_{21}$ parameter space

LMA parameters
Development of Pulse Shape Discrimination variables to discriminate $\beta^-/\nu$ interactions from $\beta^+ (^{11}\text{C})$

- Optimized PS parameter using Boosted Decision Tree (TFC pure $^{11}\text{C}$ sample for training)
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** homogenenous
- Spatial distribution **internal bkg** and $\nu$ → **homogeneus**
- Spatial distribution from **Monte Carlo** simulation
  and external **calibration** source ($^{228}$Th)
Internal $^{210}\text{Bi}$ background

Only residual radioactive internal background in pep-CNO region of interest $\rightarrow$ $^{210}\text{Bi}$ decay ($\sim 54$ cpd/100ton)

$^{210}\text{Bi}$ spectral shape similar to e- recoil spectrum from CNO

CNO neutrino spectroscopy is tough
Fit to energy spectrum

- $^7\text{Be}$
- $^{210}\text{Bi}$
- $^{85}\text{Kr}$
- pep
- $^{11}\text{C}$
- $^{208}\text{Ti}$
- $^{10}\text{C}$
- $^8\text{B}$
- $^{6}\text{He}$

Fit to energy spectrum in FV after TFC veto

Fit to energy spectrum in FV for TFC-tagged events
Radial distribution of events - Compute likelihood for hypothesis: 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 reconstruction
- Fixed species in the fit (pp and $^8$B nu, $^{214}$Po)
- Impact of short lived **cosmogenics**

**Total systematic uncertainty in pep rate: 10%**
$\Delta\chi^2$ profile pep – CNO rate

$\Delta\chi^2$ profile for fixed pep and CNO rates