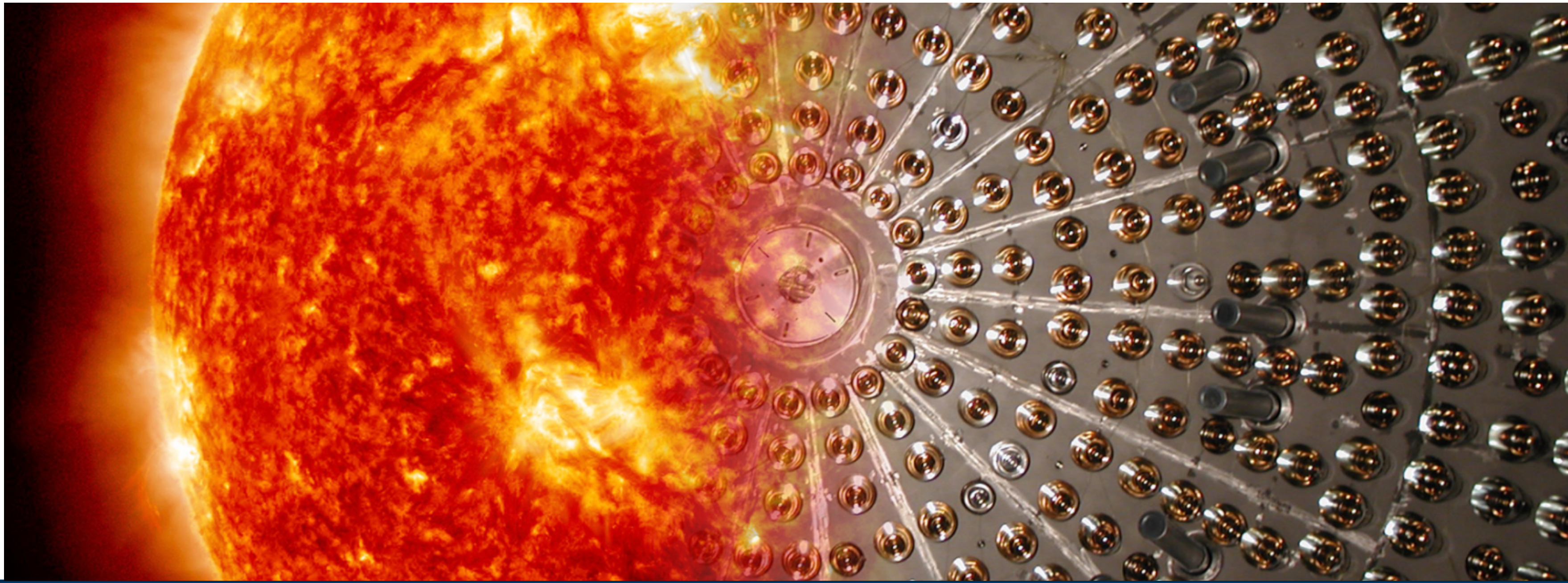


SENSITIVITY TO CNO CYCLE SOLAR NEUTRINOS IN BOREXINO

ÖMER PENEK

On behalf of the Borexino Collaboration

XIX International Workshop on
Neutrino Telescopes
24th February 2021

Mitglied der Helmholtz-Gemeinschaft

JÜLICH
Forschungszentrum

CONTENTS

- Introduction and Motivation
- The Borexino Detector
- Sensitivity to CNO cycle solar neutrinos
- Summary and Conclusions

Introduction and Motivation

SOLAR NEUTRINOS → THE STANDARD SOLAR MODEL

Usage of current physics and input parameters with best fit observations

SSM Inputs:

- Photon luminosity $L_\odot$, the solar mass $M_\odot$, the solar radius $R_\odot$, the oblateness $O_\odot = \frac{R_{equator}}{R_{polar}} - 1$, and the solar age $A_\odot$
- Abundances of Elements (Metallicity, High=HZ or Low=LZ)
  → Solar Surface Metal-to-Hydrogen Ratio $\left(\frac{Z}{X}\right)_\odot$ (Metal = Elements above He)

SSM Outputs:

- Neutrinos Fluxes (HZ-SSM or LZ-SSM)
- Sound speed profiles → Discrepancy in HZ-SSM and LZ-SSM

Helioseismology (Accustic waves, Sun‘s oscillation):

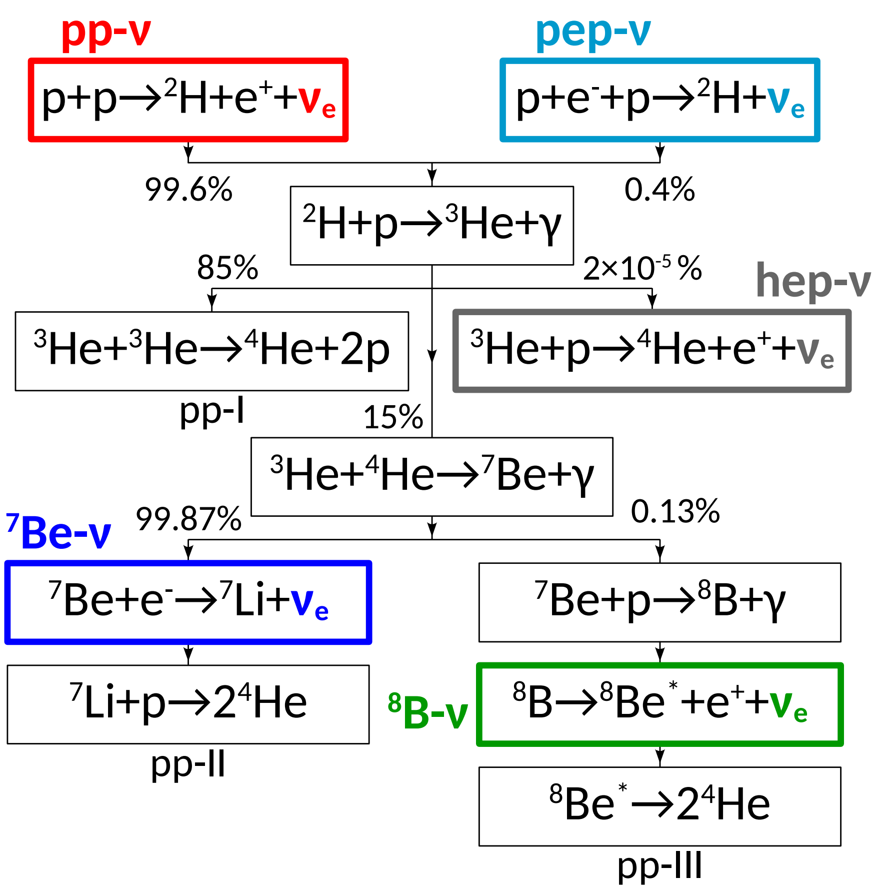
- Excellent Description of Sun‘s interior structure for > 2 decades
- Consistent with older HZ (1D description) but in tension with newer LZ (3D description) → SSM should be consistent with both!!!
- A measurement of CNO can unravel this “solar metallicity problem“

HOW IS THE SUN FUELED? → FUSION → SOLAR NEUTRINOS

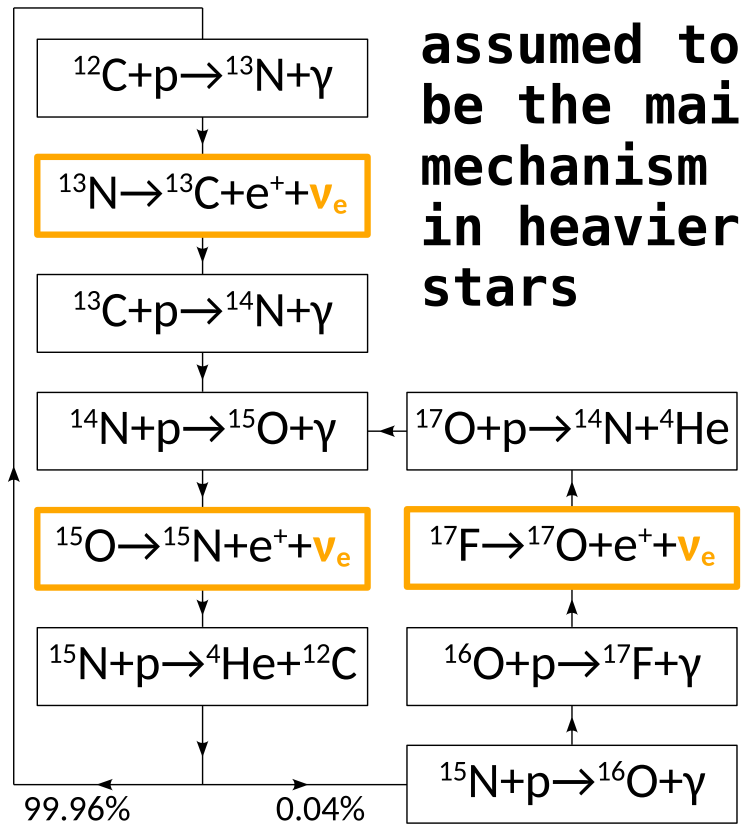
Production in the Core of the Sun → νs on Earth in ~8 minutes

Standard Solar Model (SSM)

~ 99 % **pp chain**



~ 1 % **CNO cycle**



assumed to be the main mechanism in heavier stars

METALLICITY: SOLAR NEUTRINOS FLUXES

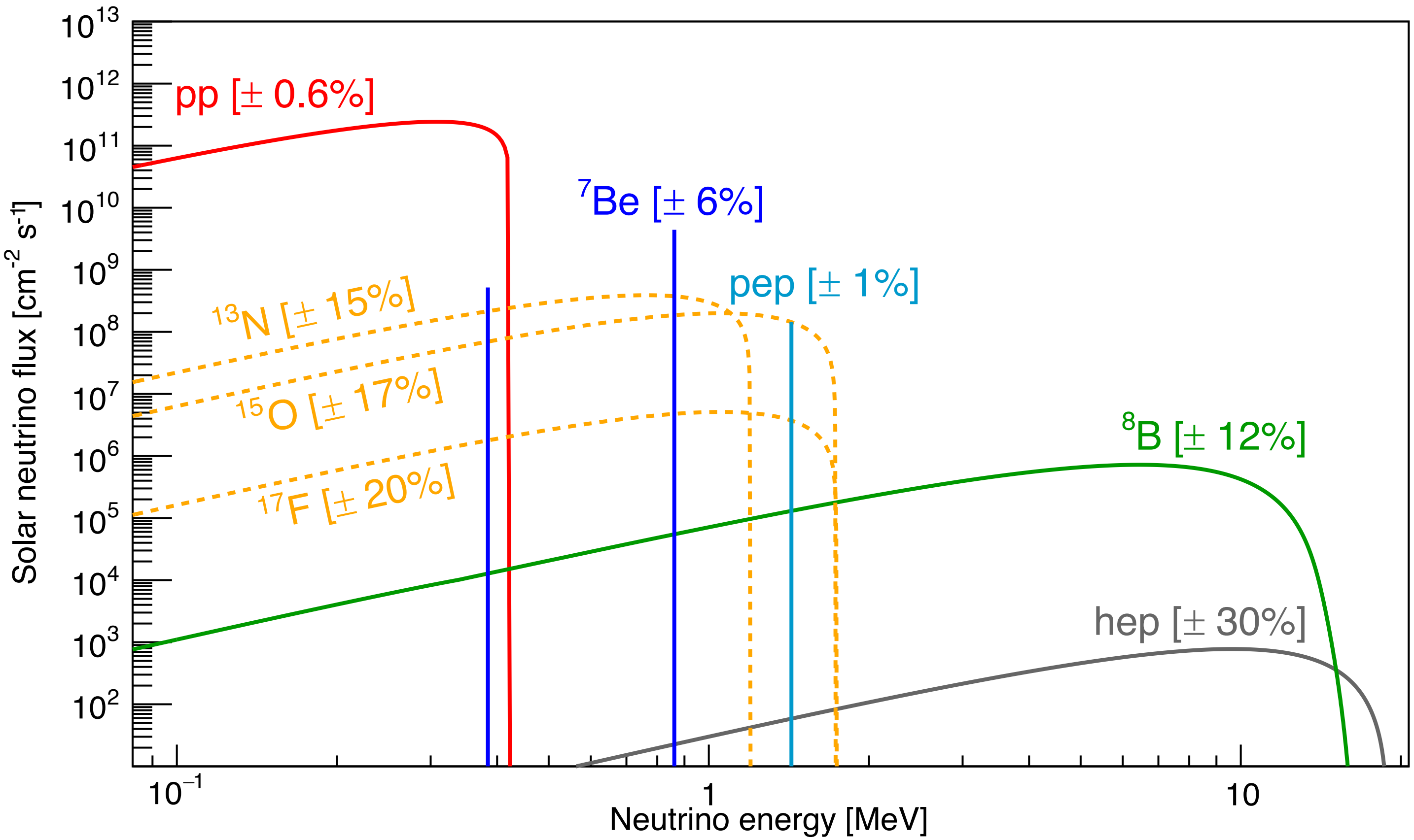
Species	Flux [$cm^{-2}s^{-1}$] GS98 (HZ-SSM)	Flux [$cm^{-2}s^{-1}$] AGSS09met (LZ-SSM)	Difference (HZ-LZ)/HZ %
pp	$5.98(1 \pm 0.006)\times 10^{10}$	$6.03(1 \pm 0.005)\times 10^{10}$	-0.8 %
pep	$1.44(1 \pm 0.01)\times 10^{8}$	$1.46(1 \pm 0.009)\times 10^{8}$	-1.4 %
hep	$7.98(1 \pm 0.30)\times 10^{3}$	$8.25(1 \pm 0.30)\times 10^{3}$	-3.4 %
^{7}Be	$4.93(1 \pm 0.06)\times 10^{9}$	$4.50(1 \pm 0.06)\times 10^{9}$	8.9 %
^{8}B	$5.46(1 \pm 0.12)\times 10^{6}$	$4.50(1 \pm 0.12)\times 10^{6}$	17.6 %
^{13}N	$2.78(1 \pm 0.15)\times 10^{8}$	$2.04(1 \pm 0.14)\times 10^{8}$	26.6 %
^{15}O	$2.05(1 \pm 0.17)\times 10^{8}$	$1.44(1 \pm 0.16)\times 10^{8}$	29.7 %
^{17}F	$5.29(1 \pm 0.20)\times 10^{6}$	$3.26(1 \pm 0.18)\times 10^{6}$	38.3 %

METALLICITY: SOLAR NEUTRINOS FLUXES

Species	Flux [$cm^{-2}s^{-1}$] GS98 (HZ-SSM)	Flux [$cm^{-2}s^{-1}$] AGSS09met (LZ-SSM)	Difference (HZ-LZ)/HZ %
pp	$5.98(1 \pm 0.006)\times10^{10}$	$6.03(1 \pm 0.005)\times10^{10}$	−0.8 %
pep	$1.44(1 \pm 0.01)\times10^{8}$	$1.46(1 \pm 0.009)\times10^{8}$	−1.4 %
hep	$7.98(1 \pm 0.30)\times10^{3}$	$8.25(1 \pm 0.30)\times10^{3}$	−3.4 %
^{7}Be	$4.93(1 \pm 0.06)\times10^{9}$	$4.50(1 \pm 0.06)\times10^{9}$	8.9 %
^{8}B	$5.46(1 \pm 0.12)\times10^{6}$	$4.50(1 \pm 0.12)\times10^{6}$	17.6 %
^{13}N			26.6 %
^{15}O			29.7 %
^{17}F			38.3 %

CNO-ν Flux
→ HZ and LZ separation is high ~30%

EXPECTED SOLAR NEUTRINO SPECTRA



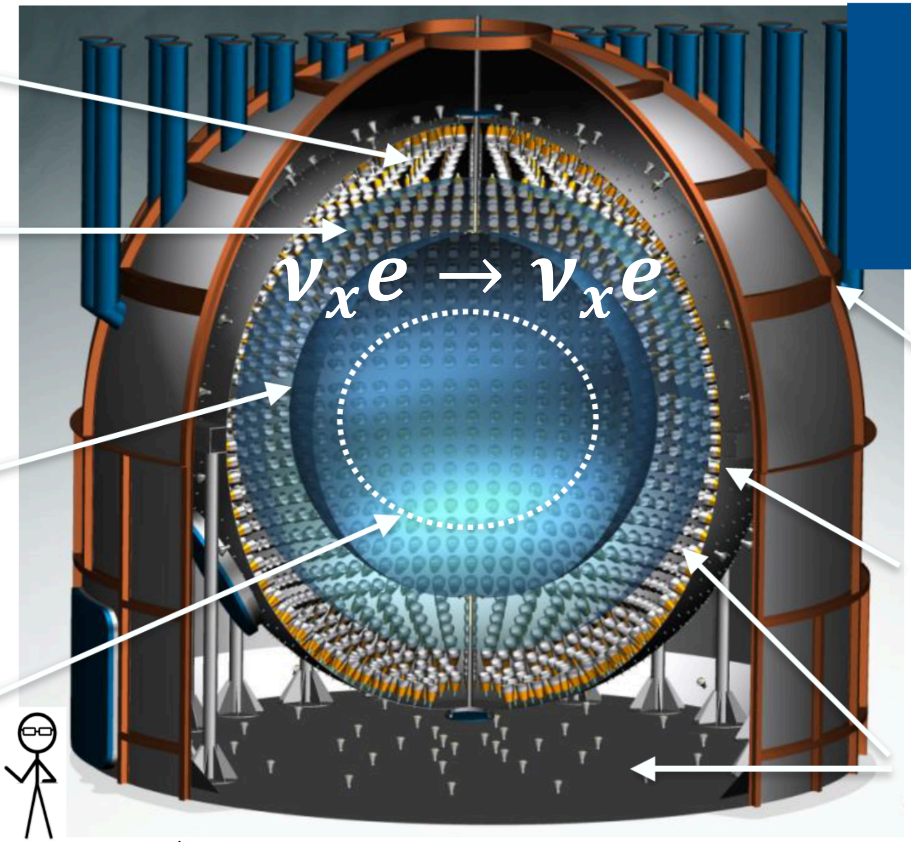
➔ Difference in endpoint energies and shapes gives possibility to distinguish them

The Borexino Detector

JÜLICH
Forschungszentrum

HOW TO "DETECT" THE SUN ?

The Borexino Detector located at LNGS in Italy



2212 inward-facing PMTs

Nylon Outer Vessel

R = 5.5 m

Barrier for Rn from steel, PMTs etc.

Nylon Inner Vessel

R = 4.25 m

~ 300 tons of liquid scintillator: (PC/PPO solution)

Fiducial volume:

~100 tons (software cut)

Detection principle:
elastic scattering on electrons
Technique advantages:
high light-yield
Technique disadvantages:
no directional information

Water tank:

R = 9 m, 2.1 kt of water

- *Shielding*
- *Cherenkov muon veto*

Stainless Steel Sphere:

R = 6.85 m

Scintillator container

PMTs support

208 Outer Detector PMTs

✓ Hardware Threshold ~ 50 keV

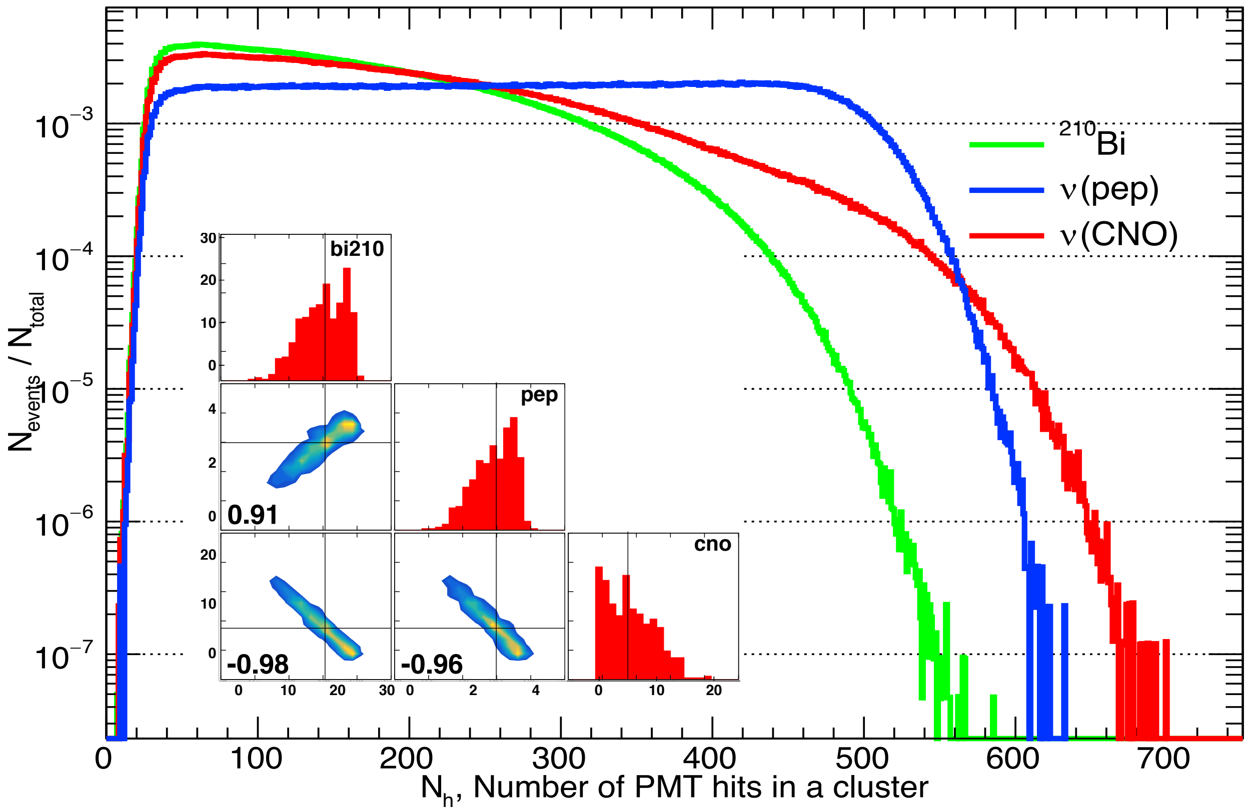
✓ $\frac{\Delta E}{E} \sim \frac{5\ \%}{\sqrt{E[MeV]}}$

✓ Ph. Yield ~ 500 p.e./MeV in 2000 PMTs

✓ Position Reconstruction ~10 cm @1MeV

Sensitivity to CNO *cycle solar neutrinos in* Borexino

CHALLENGES I: CORRELATIONS



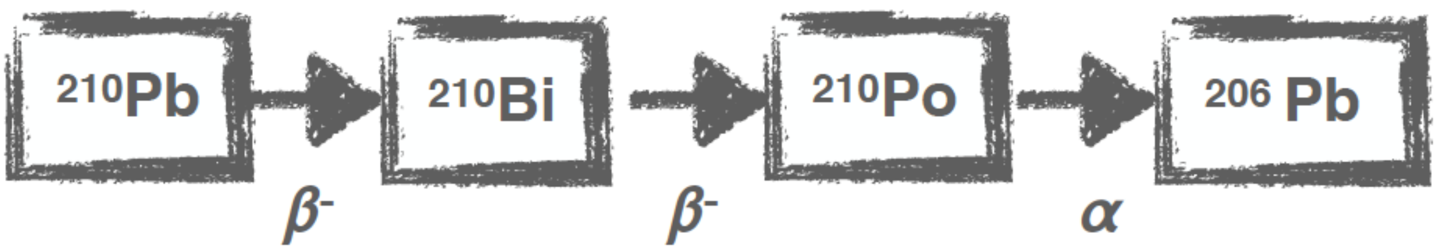
- Shown here: recoiled e^- spectra for CNO-ν, *pep*-ν, and ^{210}Bi β^- decay electrons
- High Spectral Correlation with ^{210}Bi and solar *pep* neutrino signal

CHALLENGES I: SOLUTIONS

pep-ν constraint

- $p + e^- + p \rightarrow d + \nu_e$ and $p + p \rightarrow d + e^+ + \nu_e$ maximal correlated (same matrix element in nuclear physics)
- Φ_{pp}/Φ_{pep} robust prediction without latest data → $\boldsymbol{\sigma(pep) \sim 10\%}$
- Global Analysis on all Solar-ν experiments applying luminosity constraint → $\boldsymbol{\sigma(pep) \sim 1.4\%}$ (Here, 1% CNO contribution negligible)

^{210}Bi constraint



Lifetimes 32 y 7.23 d 199.1 d

Bi-Po-Tagging (Unsupported Po, Migration Po, Supported Po):

In secular equilibrium Rate(210Bi, β^-) = Rate(210Po,α) (Supported Po)

^{210}Po identification:

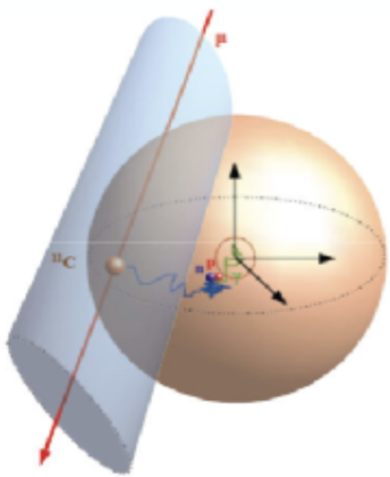
Monoenergetic Decay ("Gaussian") + α-decay in Borexino ⇔ Event-by-Event Pulse Shape Discrimination → Multilayer Perceptron (MLP variable)

CHALLENGES II: ^{11}C

RECIPE→ THREEFOLD COINCIDENCE (TFC)

➔ We have recipe for that

Muon interactions with ^{12}C (~ 4000 muons per day)



1 2 3

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

236 μs: $n + p \rightarrow D + \gamma$ (2.2 MeV)

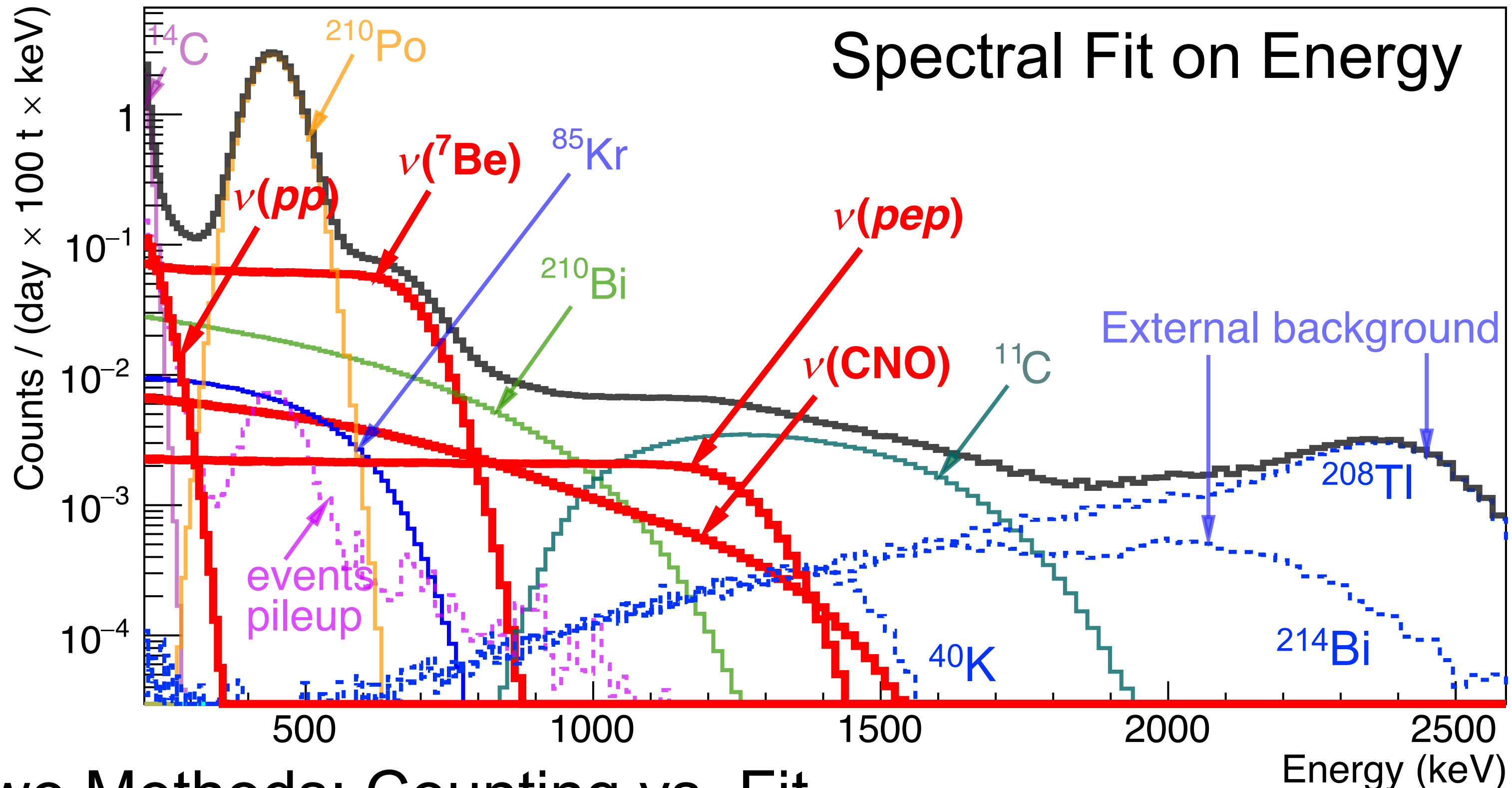
29.4 min: $^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

TFC Algorithm

- Calculate for each event the probability to be ^{11}C (using a Likelihood)
- Divide Total Exposure in **TFC-subtracted** and **TFC-tagged** spectra (also called ^{11}C **depleted** and ^{11}C **enriched** spectra, respectively)

PSEUDO DATASETS

- Fiducial Volume Cut: R < 2.8 m, -1.8 m < z < 2.2 m)
- Exposure: 1000 days × 71.3 tonnes
- **^{11}C depleted spectrum** (TFC)

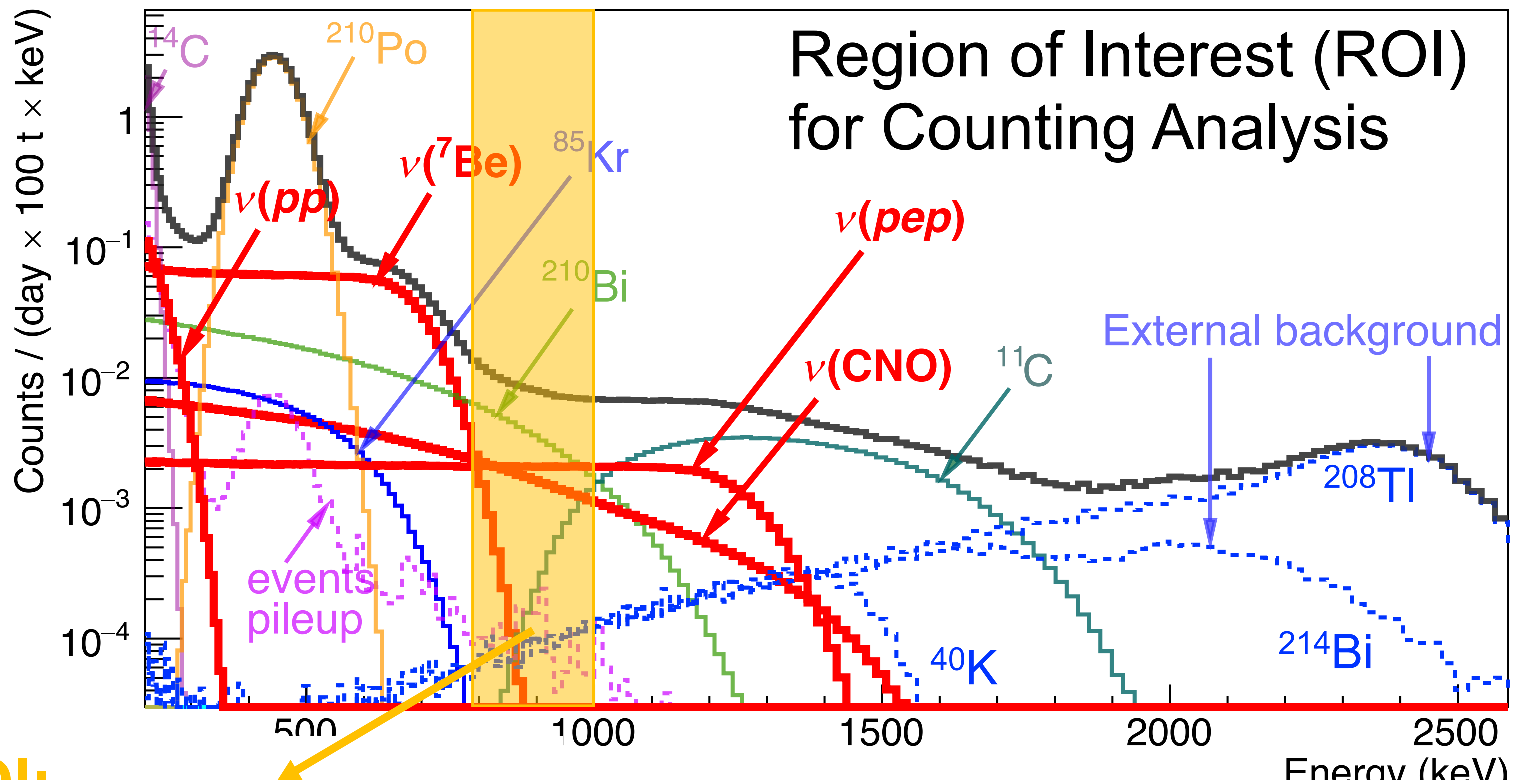


➔ Two Methods: Counting vs. Fit

COUNTING ANALYSIS I

- **Counting Analysis:** Count the number of events in a region of interest (ROI), dominated by ^{210}Bi, CNO, and *pep*

$$N_{total}^{\mathrm{ROI}} = N_{\mathrm{Bi}}^{\mathrm{ROI}} + N_{\mathrm{CNO}}^{\mathrm{ROI}} + N_{pep}^{\mathrm{ROI}} + N_{\mathrm{others}}^{\mathrm{ROI}}$$



ROI:
~0.8 to 1.0 MeV

LICH
Forschungszentrum

COUNTING ANALYSIS II

- Number of events in ROI (~0.8..1.0 MeV) is:

$$N_{model} = \sum_{k=\mathrm{Bi,CNO},pep,others} \varepsilon_k N_k$$

- Here, the efficiency of each species is important:

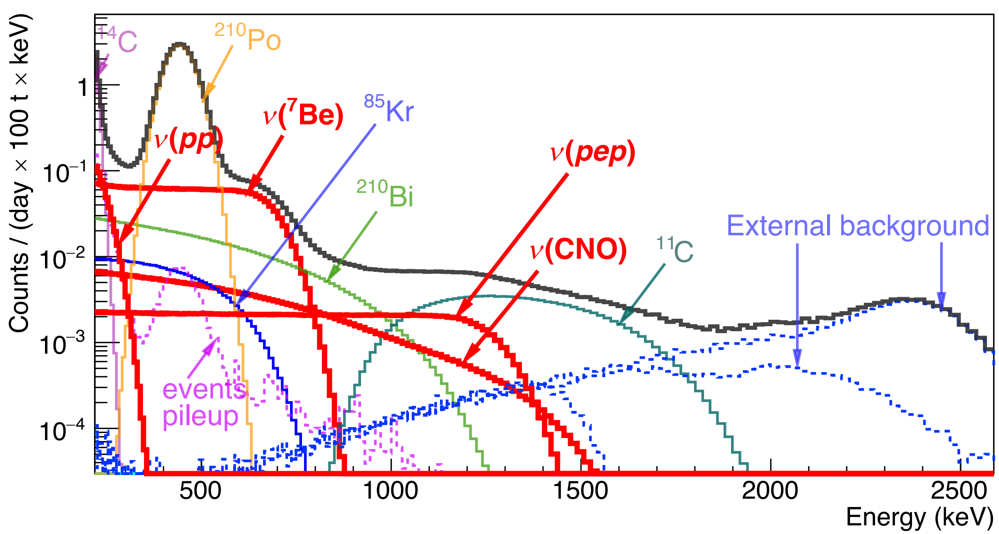
$$\varepsilon_k = \int_{0.8\ \mathrm{MeV}}^{1.0\ \mathrm{MeV}} \mathrm{PDF}_k(E)\, dE$$

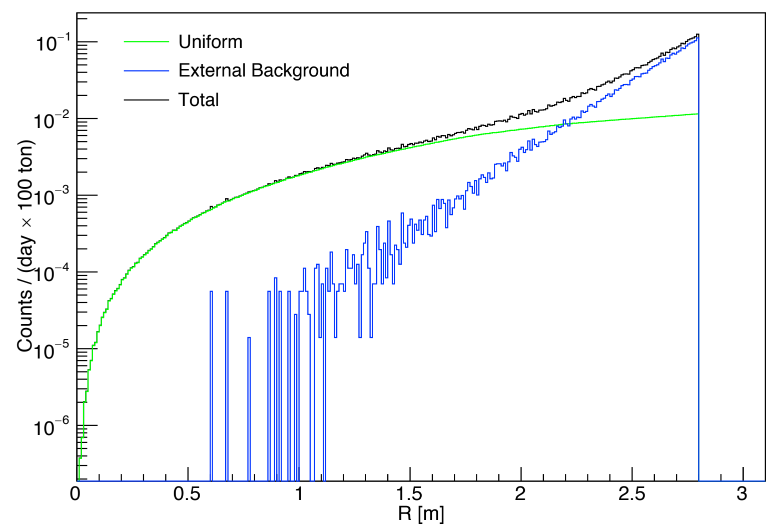
Component	Efficiency in ROI ε_k [%]
CNO-ν	7.37
pep-ν	15.98
^{210}Bi	4.55
^{11}C	4.91

- Other species efficiencies are less than 1.5%
- Robust against systematics

MULTIVARIATE FITTING → ENERGY+RADIAL

- $\rightarrow \mathcal{L}^{2D}_{MV}(\vec{\theta}) = \mathcal{L}^{TFC}_{sub}(\vec{\theta})\, \mathcal{L}^{TFC}_{tag}(\vec{\theta})\mathcal{L}_{radial}(\vec{\theta})$
  (complementary 2D poisson with fit in Energy = TFC subtracted + TFC tagged fit + Radial fit)
- Constraints on *pep* and ^{210}Bi are considered as gaussian or semi-gaussian (=upper limit) pull terms
  → Upper Limit only only applied on ^{210}Bi





Radial Fit:
~1.2 to 2.5 MeV

INJECTED RATES FOR TOY MC STUDY

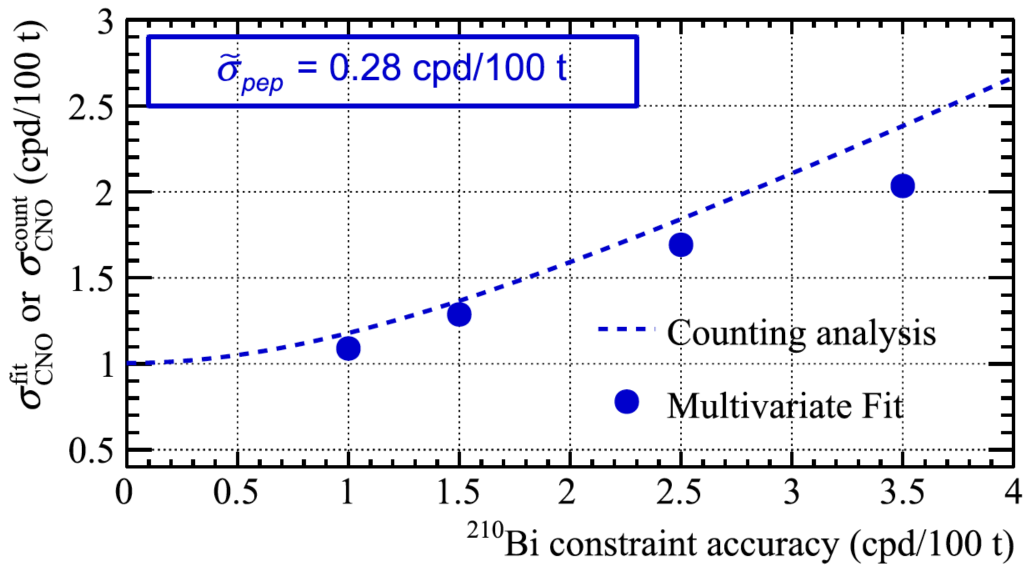
Exposure 1000 days times 71.3 tonnes
Injected Rates for HZ- and LZ-SSM predictions

Component	Injected Rates HZ [cpd/100t]	Injected Rates LZ [cpd/100t]	
CNO-ν	4.92	3.52	
***pep*-ν**	**2.74**	**2.78**	**→ Constrained**
^{7}Be-ν	47.9	43.7	
^{210}Bi	**10**	**10**	**→ Constrained**
^{11}C	28	28	
Ext. ^{40}K	1	1	
Ext. ^{208}Tl	5	5	
Ext. ^{214}Bi	4	4	
^{85}Kr	12	12	
^{210}Po	50	50	

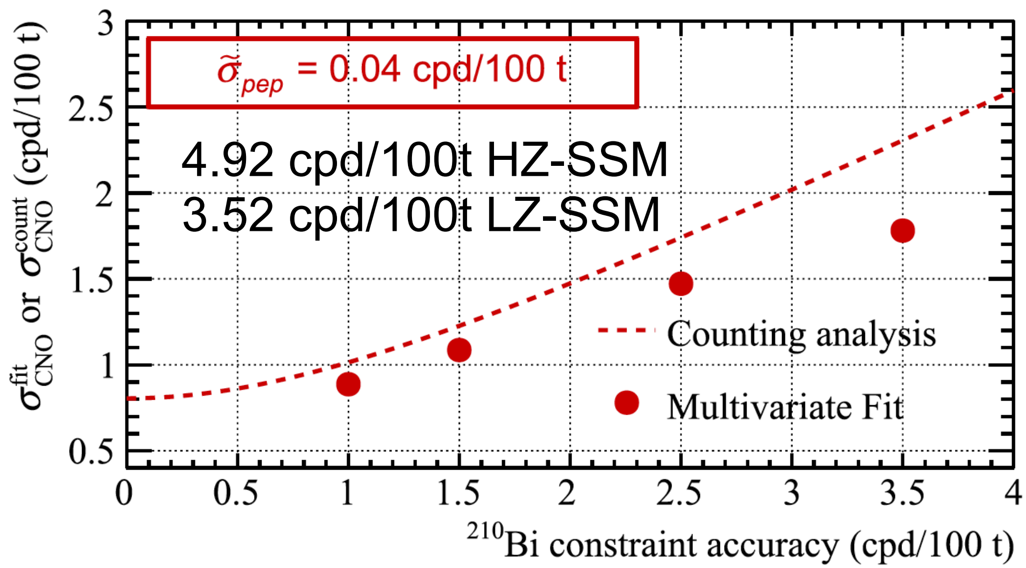
JÜLICH
Forschungszentrum

CNO PRECISION: COUNTING VS. FIT

- **^{210}Bi and *pep* rates → symmetric gaussian pull term**



- *pep* @ ~10% precision



- *pep* @ ~1.4% precision

Multivariate Fit has overall better performance if ^{210}Bi precision is getting weaker

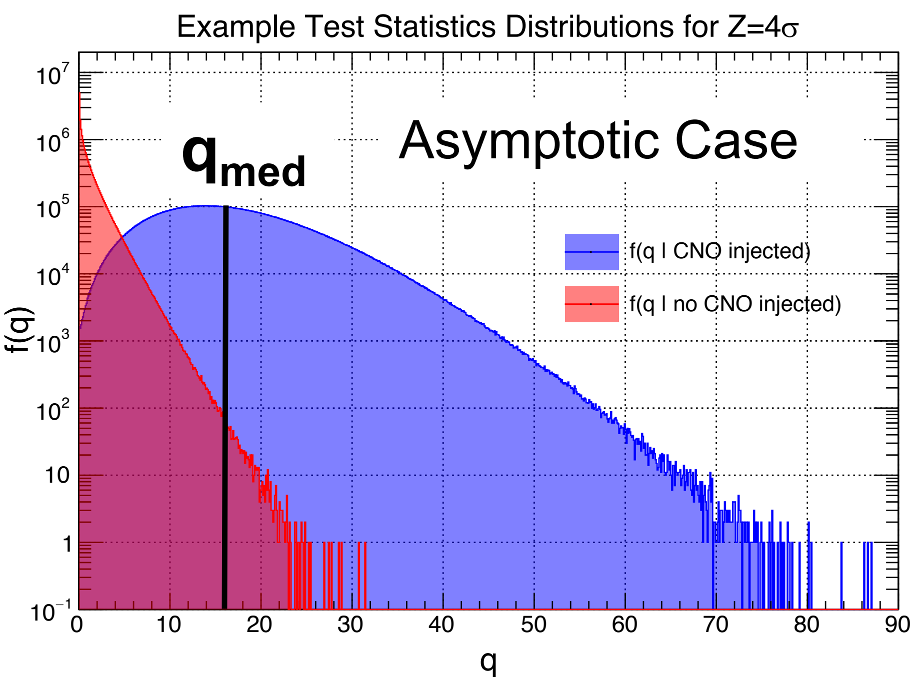
SENSITIVITY STUDIES I: DISCOVERY POTENTIAL

I. **Fit Pseudo Datasets w/ CNO injected and w/o CNO injected twice: 1. CNO leaving free and 2. CNO fixed to 0**

II. **Define test statistics** $q(\theta) = -2\times\log\frac{L(\theta=CNO=free)}{L(CNO=0)}$ **(log-likelihood-ratio on each dataset)**

III. **Evaluate** p**-value:** $p = \int_{q_{med}}^{\infty} f(q|\text{no CNO injected})\,dq$ **(**q_{med}**: Median of** q**)**

Asymptotic Limit Case: $f(q|\mu) = \left(1-\Phi\left(\frac{\mu}{\sigma}\right)\right)\delta(q) + \frac{1}{2}\frac{1}{\sqrt{2\pi q}}\mathrm{Exp}\left(-\frac{1}{2}\left(\sqrt{q}-\frac{\mu}{\sigma}\right)^2\right)$

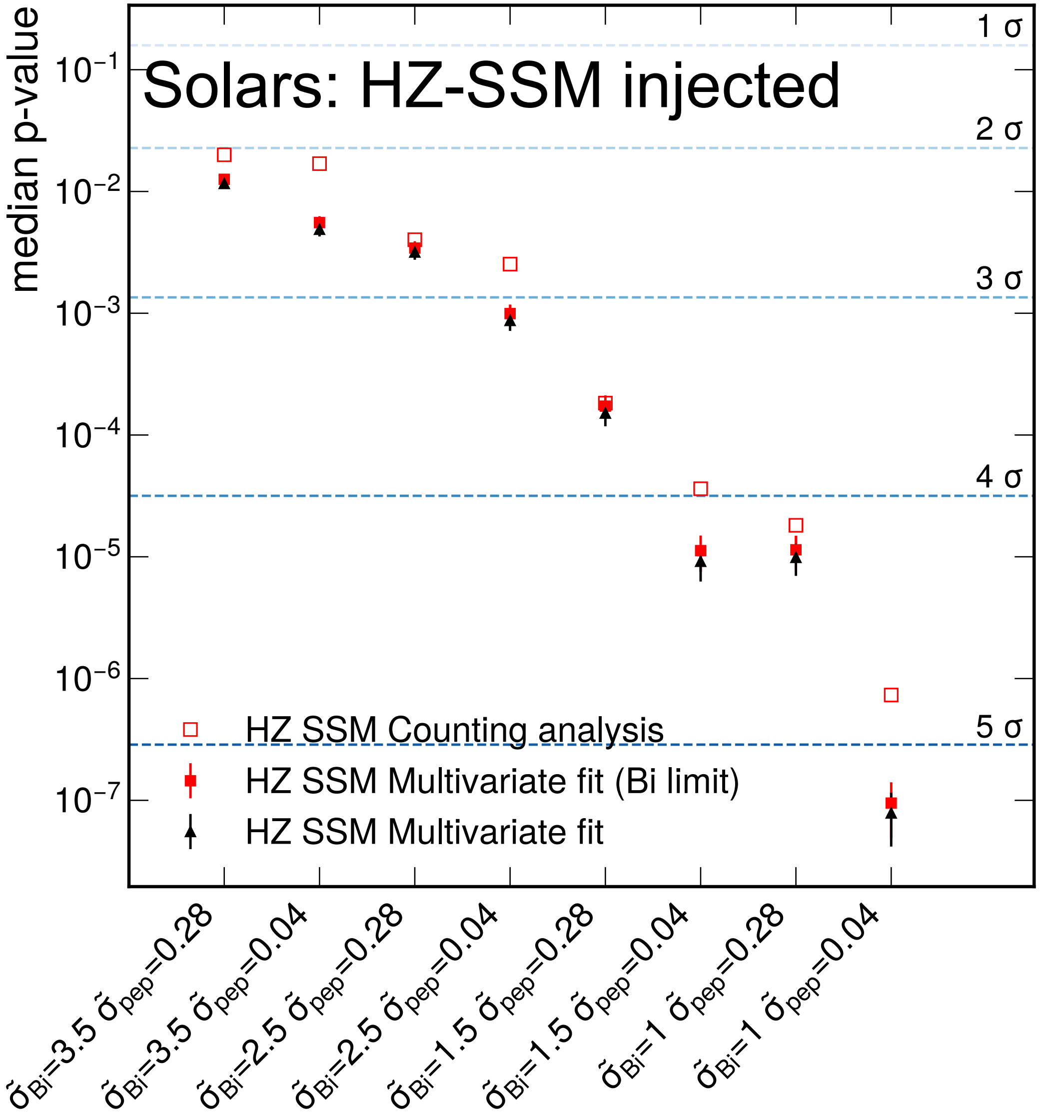


- Blue Distribution: $f(q|\mu)$ ⇔ CNO injected
- Red Distribution: $f(q|0)$ ⇔ No CNO injected

JÜLICH Forschungszentrum

SENSITIVITY STUDIES II: DISCOVERY POTENTIAL

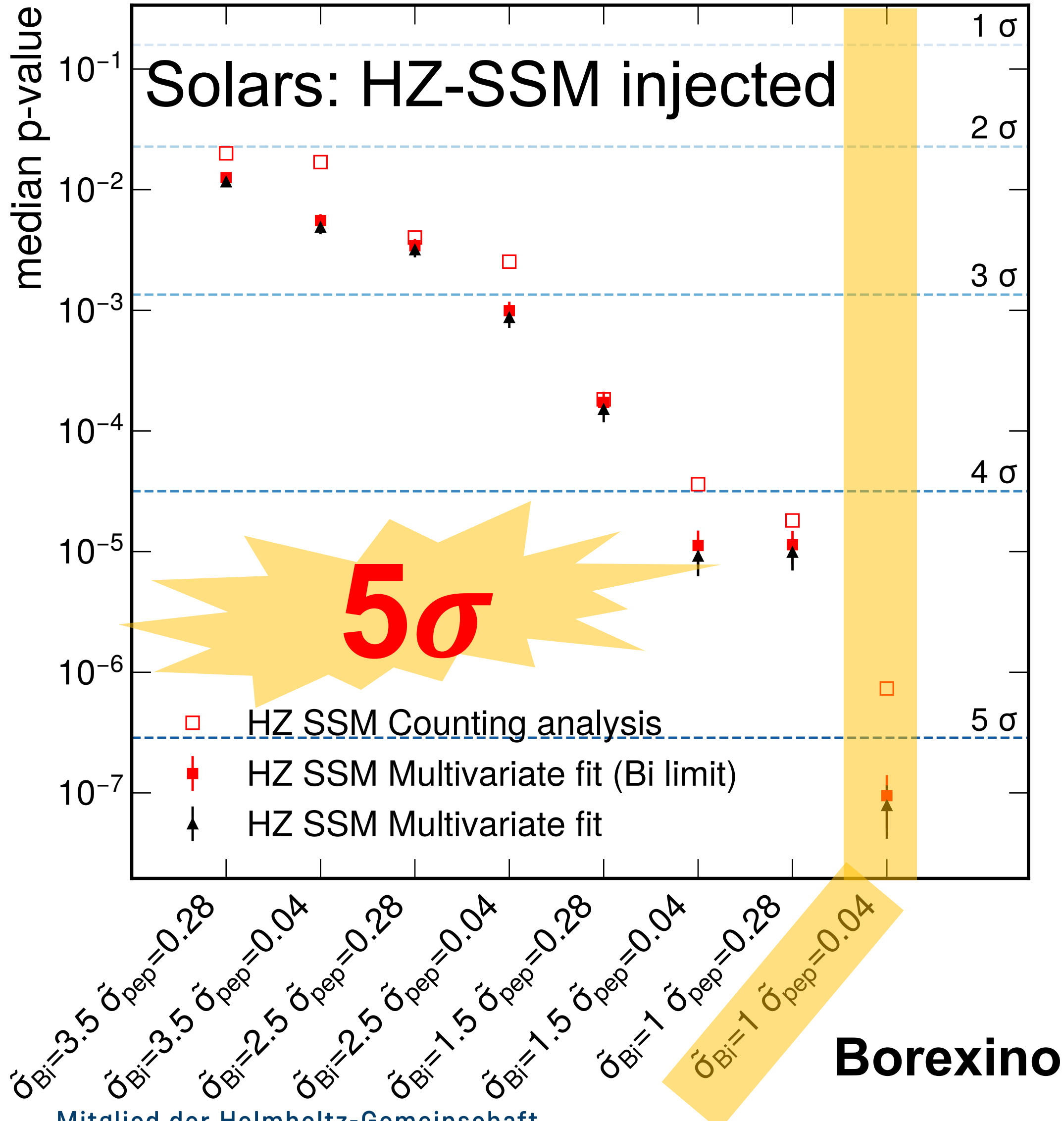
Using an exposure of 1000 days times 71.3 tonnes



- Counting Analysis in ROI
- **HZ-SSM Multivariate fit** ➔ done with ^{210}Bi symmetric Gaussian constraint
- HZ-SSM Multivariate fit **(Bi limit)** ➔ ^{210}Bi Semi-Gaussian constraint
- ^{210}Bi constraint: for sensitivity precision is important rather than central value

SENSITIVITY STUDIES II: DISCOVERY POTENTIAL

Using an exposure of 1000 days times 71.3 tonnes



- Counting Analysis in ROI
- **HZ-SSM Multivariate fit**
  ➔ done with ^{210}Bi symmetric Gaussian constraint
- HZ-SSM Multivariate fit **(Bi limit)**
  ➔ ^{210}Bi Semi-Gaussian constraint
- ^{210}Bi constraint: for sensitivity precision is important rather than central value

CNO CYCLE 80-90 YEARS AFTER BETHE AND WEIZSÄCKER

nature | View all

Explore our content ⌄ | Journal information ⌄ | Subscribe

nature › articles › article

Article | Published: 25 November 2020

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The Borexino Collaboration

Nature **587**, 577–582(2020) | Cite this article

191 Altmetric | Metrics

Abstract

For most of their existence, stars are fuelled by the fusion of hydrogen into helium. Fusion proceeds via two processes that are well understood theoretically: the proton–proton (*pp*) chain and the carbon–nitrogen–oxygen (CNO) cycle[1,2]. Neutrinos that are emitted along such fusion processes in the solar core are the only direct probe of the deep interior of the Sun. A complete spectroscopic study of neutrinos from the *pp* chain, which produces about 99 per cent of the solar energy, has been performed previously[3]; however, there has been no reported experimental evidence of the CNO cycle. Here we report the direct observation, with a high statistical significance, of neutrinos produced in the CNO cycle in the Sun. This experimental evidence was obtained using the highly radiopure, large-volume, liquid-scintillator detector of Borexino, an experiment located at the underground Laboratori Nazionali del Gran Sasso in Italy. The main experimental challenge was to identify the excess signal—only a few counts per day above the background per 100 tonnes of target—that is attributed to interactions of the CNO neutrinos. Advances in the thermal stabilization of the detector over the last five years enabled us to develop a method to constrain the rate of bismuth-210 contaminating the scintillator. In the CNO cycle, the fusion of hydrogen is
catalysed by carbon, nitrogen and oxygen, and so its rate … emitted CNO
neutrinos—depends directly on the abundance of t… his
result therefore paves the way towards a direct … g
CNO neutrinos. Our findings quantify the re…
be of the order of 1 per cent; however, in m…
energy production. This work provides e…
for the stellar conversion of hydrogen in…

physicsworld TOP 10 BREAKTHROUGH 2020

Alessandra Re's talk –A successful strategy for the CNO measurement

Alex Goettel's talk – Data analysis of a low-Po field for the CNO discovery

Davide Basilico's talk – How the CNO neutrinos detection can unravel the solar metallicity problem

(All 3 talks, Friday 19/02/2021)

Gianpaolo Bellini's Plenary Talk – Neutrino, Solar, and Star Physics with Borexino (Tuesday 23/02/2021, 2pm)

SUMMARY – CONCLUSIONS – OUTLOOK

✓It has been proven through the sensitivity studies that Borexino has sensitivity to CNO cycle solar neutrinos

✓5σ are clearly reached when constraining the pep-ν rate to 0.04 cpd/100t precision and ^{210}Bi to 1 cpd/100t precision
→ This case is comparable to the observation on data

✓There is 3σ sensitivity to CNO without ^{210}Bi constraint when doubling the statistics (while keeping the *pep* constraint)

The European Physical Journal volume 80 · number 11 · november · 2020

EPJ C

Recognized by European Physical Society

Particles and Fields

Internal view of the Borexino liquid scintillator containment liquid scintillator vessel. From the photo several parts of the detector are visible: the photomultipliers (silver-like color) the mu-metal shielding (brass-like color) the bottom of the outer nylon vessel (upper part of the photo).

From the Borexino collaboration on: Sensitivity to neutrinos from the solar CNO cycle in Borexino

Società Italiana di Fisica

Springer

Grazie Infinite

Thanks a lot

Questions?

Discussion

Backup

BOREXINO RESULTS OVERVIEW

2007 | **^{7}Be, *pep*, ^{8}B** | **Geo-Nu** | **Calibrations** | **2010** | **2012**

pp
Improved Measurement of I
***pep* Discovery (5σ)**
^{7}Be seasonal modulation

2016 | **2020+**

Bx Phase I | Bx Phase II | Bx Phase III

Scintillator Purification

Improved Thermal stability
CNO analysis

Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy (Phys. Rev. D 89, 112007 (2014))

Measuremnt of the solar ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector (Phys. Rev. D 82, 033006 (2010))

Improved Radiopurity:
^{85}Kr ~ 4.6
^{210}Bi ~ 2.3

Measurement of geo-neutrinos from 1353 days of Borexino (Phys. Let. B 722 295-300 (2013))

Neutrinos from the primary proton-proton fusion process in the Sun (Nature 512, 383-386 (2014))

Spectroscopy of geoneutrinos from 2056 days of Borexino Data (Phys. Rev. D 92, 031101® (2015))

Seasonal modulation of the ^{7}Be solar neutrino rate in Borexino (Astroparticle Phys. Vol. 92, 21-29 (2017))

Simultaneous Precision Spectroscopy of *pp*, ^{7}Be, and *pep* Solar Neutrinos with Borexino Phase-II (arXiv:1707.09279v2 (2017)) → Phys. Rev. D **100**, 082004 (2019)

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure (arXiv:1709.00756v1 (2017)) → Phys. Rev. D **101**, 062001 (2020)

Comprehensive measurement of *pp*-chain solar neutrinos (Nature 562, 505–510 (2018))

Comprehensive geoneutrino analysis with Borexino (Phys. Rev. D **101**, 012009 (2020))

Search for low-energy neutrinos from astrophysical sources with Borexino (Astropart. Phys. Vol. 125, Feb. 2021, 102509)

Constraints on flavor-diagonal non-standard neutrino Interactions from Borexino Phase-II (JHEP 2020, 38 (2020))

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun (Nature 587, 577-582 (2020))

Sensitivity to neutrinos from the solar CNO cycle in Borexino (*Eur. Phys. J. C* **80,** 1091 (2020))

BISMUTH-210 FROM POLONIUM-210

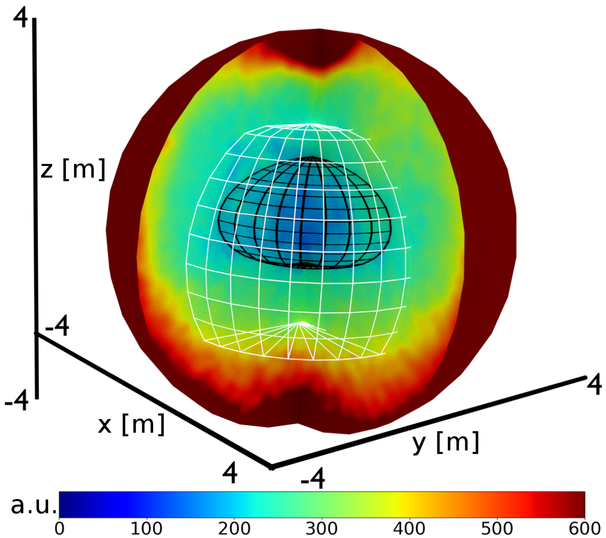
- Two components: ^{210}Po in sec. Equilibrium with ^{210}Bi in the FV (supported Po) and ^{210}Po from the ^{210}Pb in inner vessel leaking inside the active liquid (via diffusion or convection) (unsupported Po)

Minimum ^{210}Po Rate ⇔ Upper Limit of ^{210}Bi Rate :

$$R(\mathrm{Po}_{min}) = R(\mathrm{Bi}) + R(\mathrm{Po}^U) \geq R(\mathrm{Bi})$$

- Identification of the low polonium field (LPoF)

20 tonnes



$\varepsilon_{\mathrm{Ene}}, \varepsilon_{\mathrm{MLP}}$ efficiency Energy and MLP (αs)

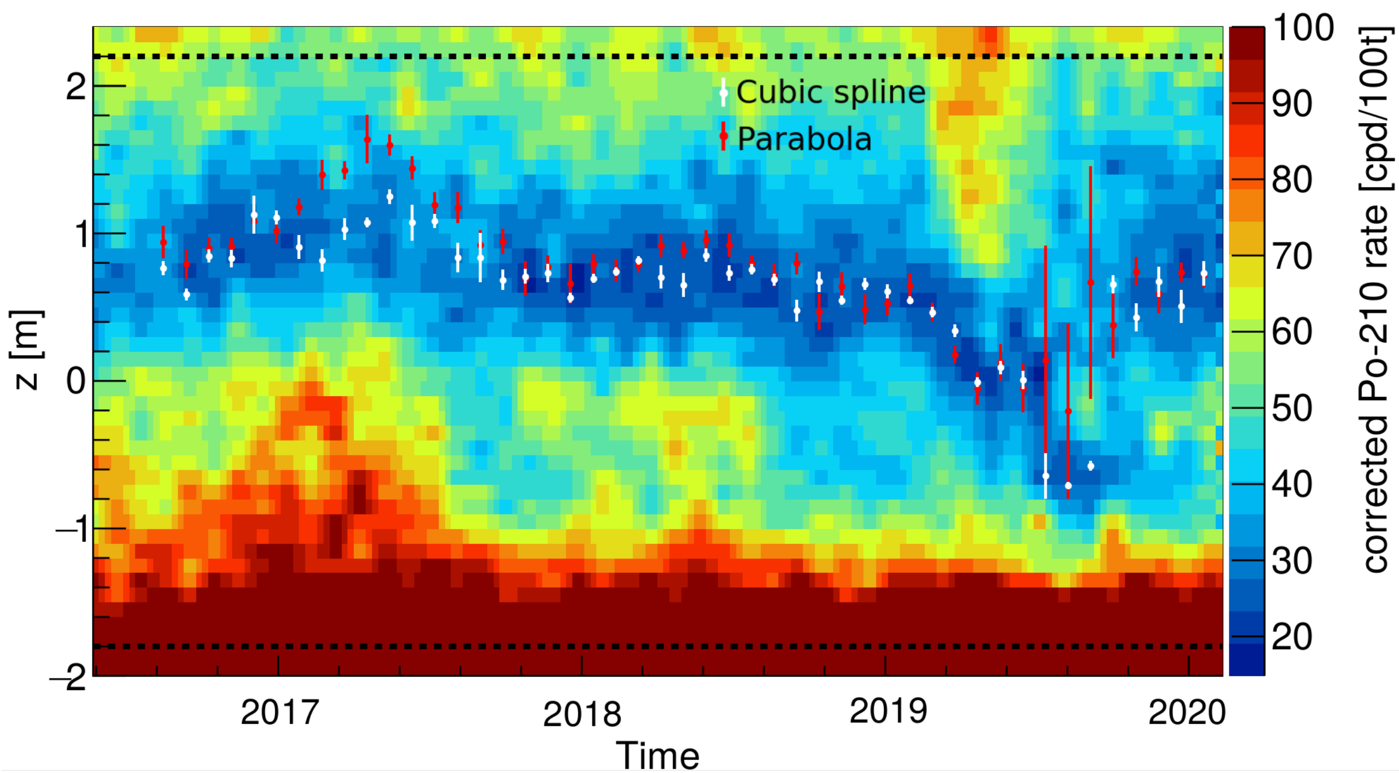
R_β beta rate after α selection

$$\frac{d^2 R\left(\mathrm{Po_{min}}\right)}{d\left(\rho^2\right) dz} = \left[R\left(\mathrm{Po_{min}}\right)\varepsilon_{\mathrm{Ene}}\varepsilon_{\mathrm{MLP}} + R_\beta\right] \times \left(1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right).$$

BISMUTH-210 FROM POLONIUM-210

Minimum ^{210}Po Rate ⇔ Upper Limit of ^{210}Bi Rate :

$$R(\mathrm{Po}_{min}) = R(\mathrm{Bi}) + R(\mathrm{Po}^U) \geq R(\mathrm{Bi})$$



Binning 1 or 2 months

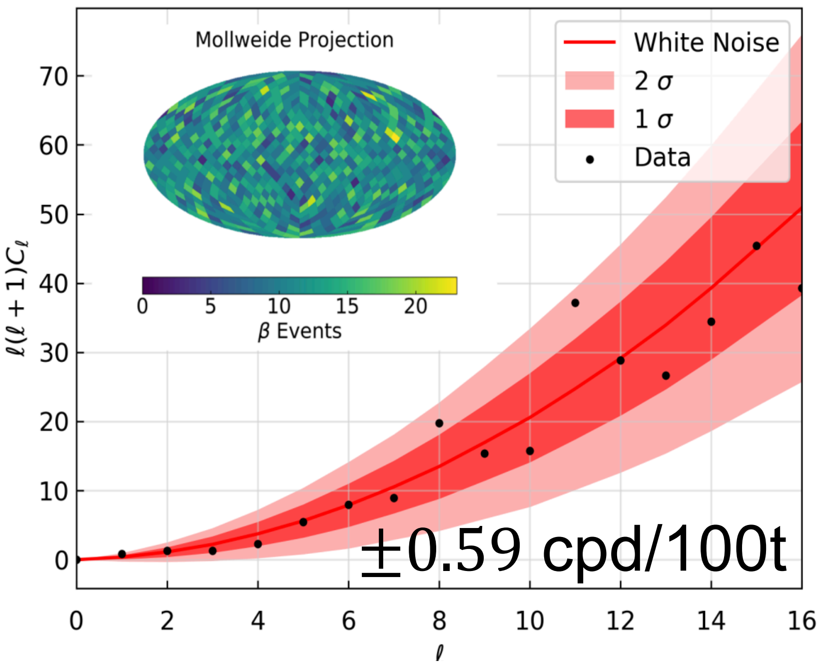
Two methods:

1) Cubic Spline Fit 2) Paraboloidal Fit

BISMUTH-210 HOMOGENEITY

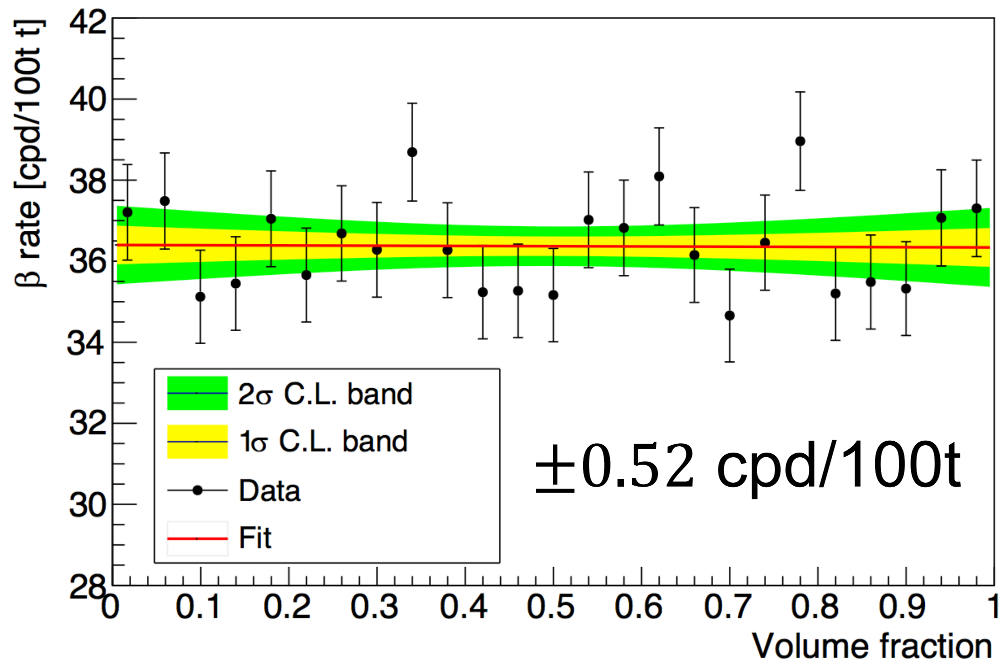
Question: ^{210}Bi in 20 tonnes. But FV is 71.3 tonnes. So, is the ^{210}Bi rate homogenous? ➔ Compare the angular and radial distribution of events with homogeneous distribution

Angular



(QM) $\hat{L}^2 C_l$ vs. l

Radial



Radial fraction r/2.5m

Answer: YES!

JÜLICH Forschungszentrum

BISMUTH-210 UPPER LIMIT + SYSTEMATICS

What do we get?

$R\,(\mathrm{Po_{min}})$	σ_{fit}	σ_{mass}	σ_{bin}	$\sigma_{angular}^{hom.}$	$\sigma_{radial}^{hom.}$	σ_{β}^{leak}	σ_{tot}
11.5	0.88	0.36	0.31	0.59	0.52	0.30	1.30

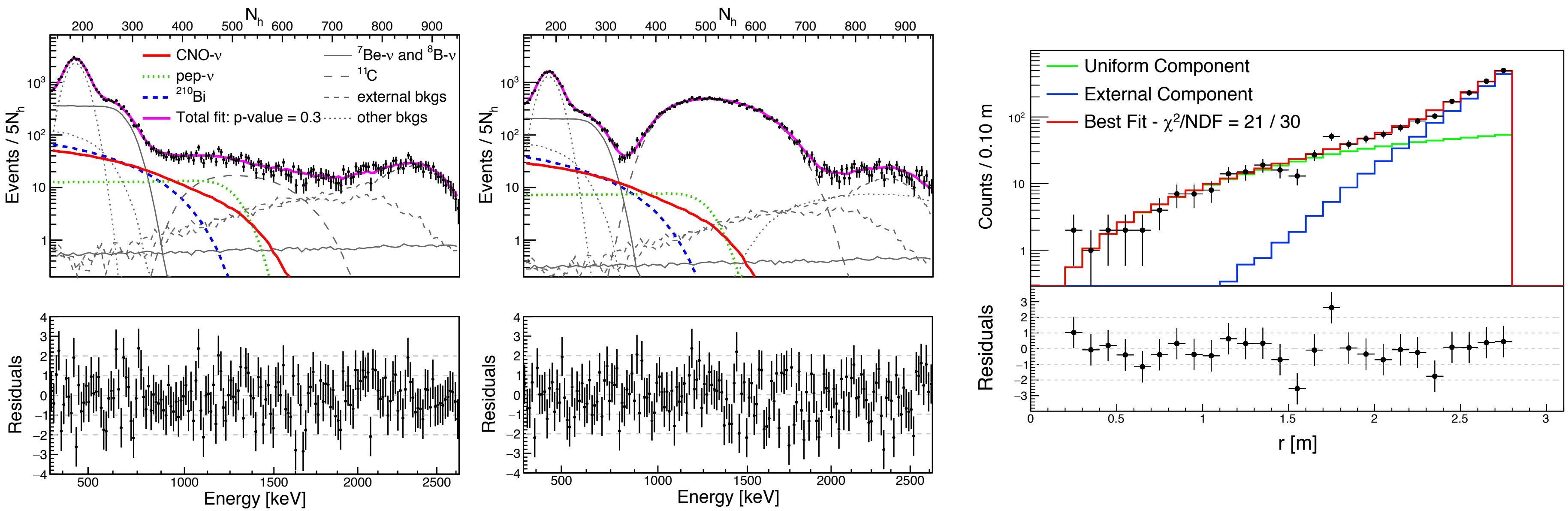
- σ_{fit}: paraboloidal/spline fit uncertainty
- σ_{mass}: LPoF mass uncertainty
- σ_{bin}: Uncertainty due to data binning (10 – 30 cm)
- $\sigma_{angular}^{hom.}$ and $\sigma_{radial}^{hom.}$: see previous slide
- $\sigma_{\beta}^{leak.}$: R_β uncertainty (β leakage)

- σ_{tot}: add all these uncertainties in quadrature ➔ total

$$R_{\mathrm{Bi}} \leq (11.5 \pm 1.3)\ \text{cpd/100t}$$

SPECTRAL FIT

Multivariate Fit: $\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}_{sub}^{TFC}(\vec{\theta})\,\mathcal{L}_{Tag}^{TFC}(\vec{\theta})\,\mathcal{L}_{Radial}(\vec{\theta})$



Fit Conditions:

Monte Carlo Fit

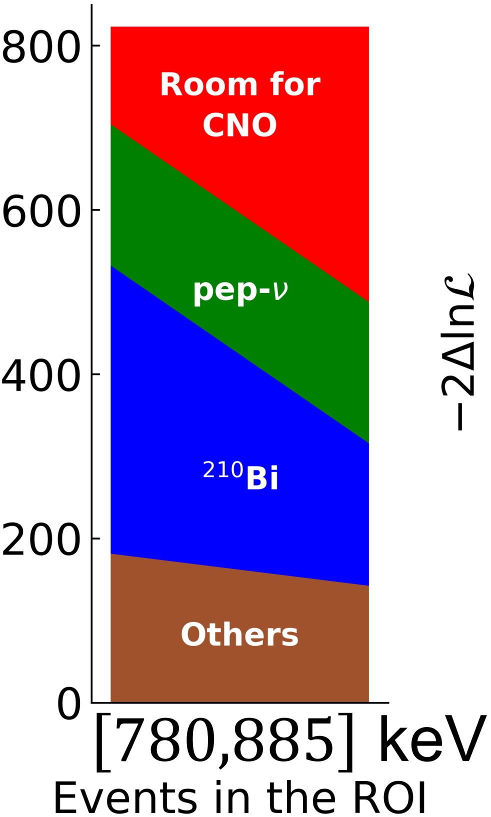
Fit Range: 320 to 2640 keV

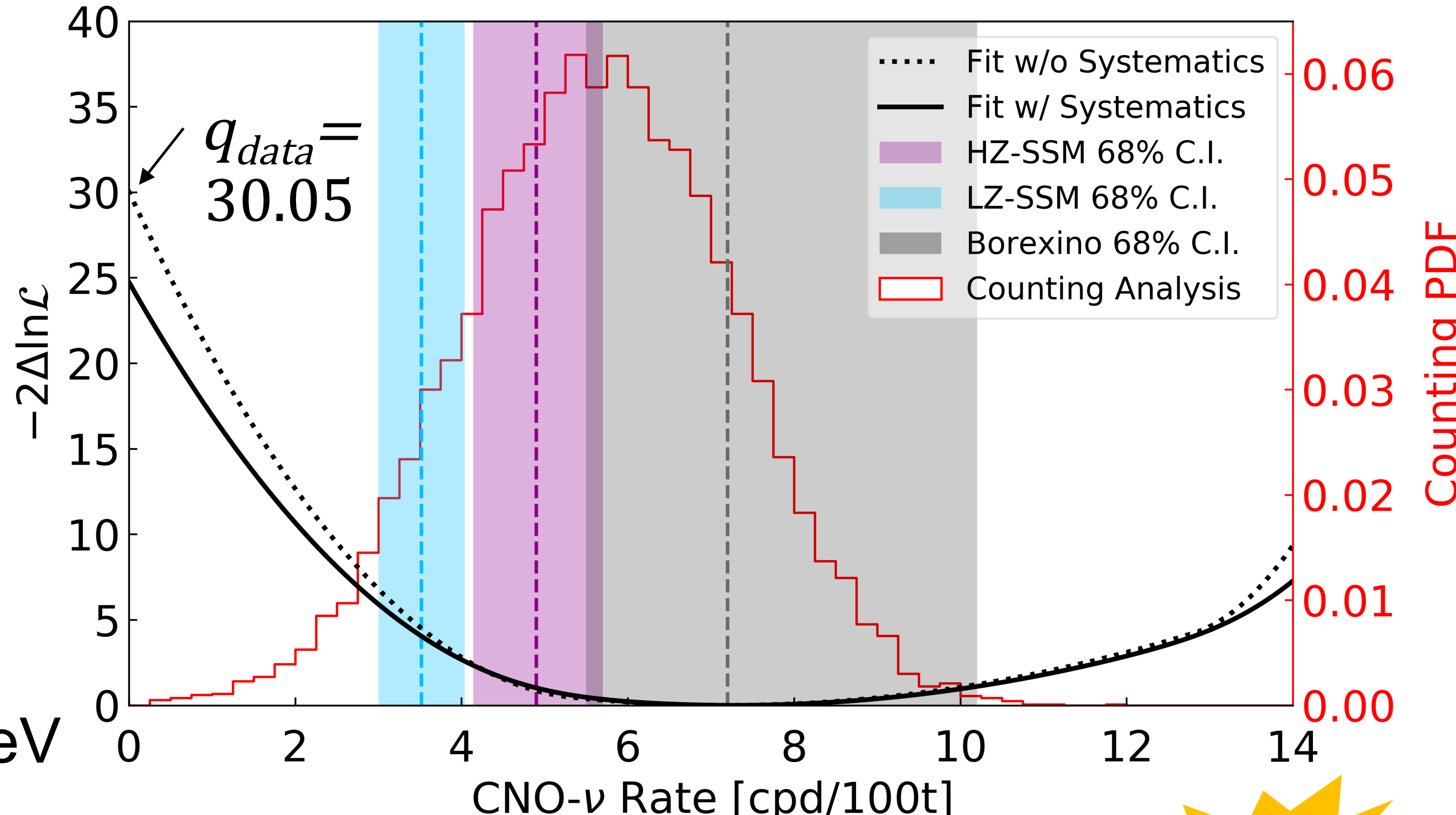
$R_{pep} = (2.74 \pm 0.04)$ cpd/100t → symmetric gaussian penalty

$R_{\mathrm{Bi}} \leq (11.5 \pm 1.3)$ cpd/100t upper limit !

CNO MEASUREMENT → FIT

Counting Analysis → Pick Ene. window where FOM is maximal





CNO Discovery

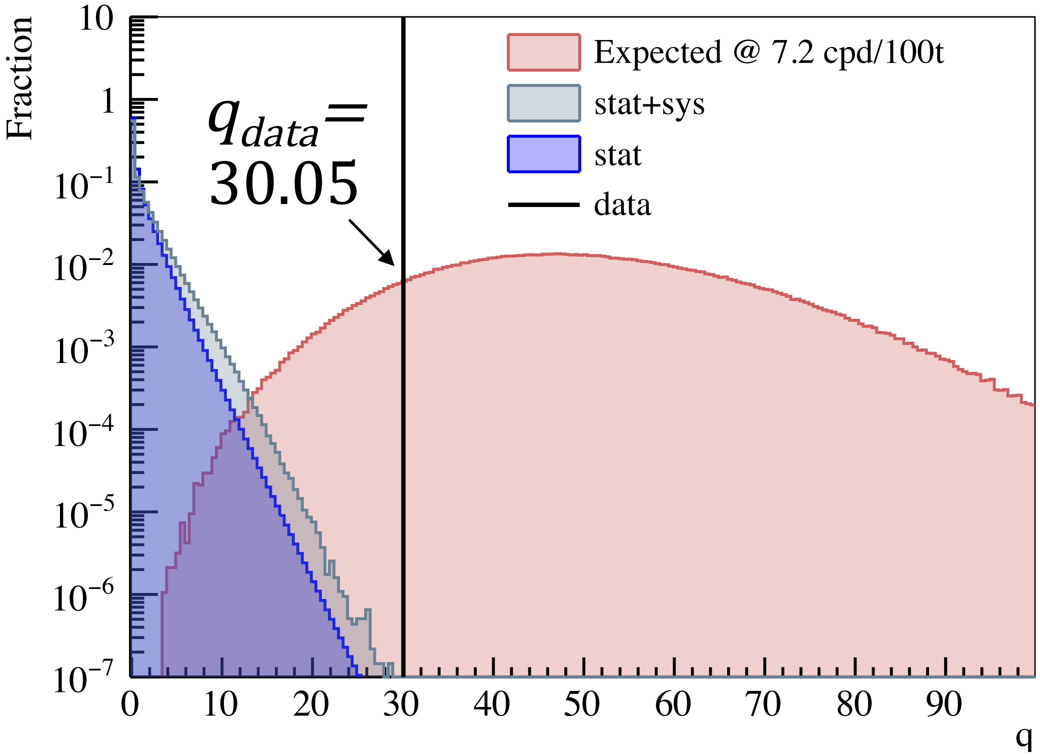
$$R_{\text{CNO}} = (7.2^{+3.0}_{-1.7})\ \text{cpd/100t}$$

$$\Phi_{\text{CNO}} = (7.0^{+3.0}_{-2.0})\times 10^{8}\ \text{cm}^{-2}\text{s}^{-1}$$

⇔ 5.1σ from profiling w/ systematics

DISCOVERY POTENTIAL → TOY MC APPROACH

Inject all systematics in a toy study based on non-linearity of the energy scale (0.4%), spatial non-uniformity z-axis (0.28%), light yield (0.32%), ^{11}C peak position, other ^{210}Bi spectral shapes (18%) (area of ^{210}Bi is constrained by the upper limit)



- Create pseudo datasets w/ CNO (H_1) injected and w/o CNO injected (H_0)
- Fit both datasets leaving CNO free $\ln_{0,1} \text{CNO}_{=free}$ and CNO fixed to zero $\ln_{0,1} \text{CNO}_{=0}$
- Evaluate Test Statistics:

$$q = -2 \ln \frac{\ln_{0,1} \text{CNO}_{=free}}{\ln_{0,1} \text{CNO}_{=0}}$$

- ➢ Gray function 13.8 million simulations
- ➢ Integral of gray from 30.05 to infinity gives the p-value: **5σ at 99% C.L.**

JÜLICH Forschungszentrum

SENSITIVITY HZ-SSM VS. LZ-SSM

Using an exposure of 1000 days times 71.3 tonnes