

The search for proton decay

Marco Zito

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Outline

- Motivation
- Theory
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- Ideas

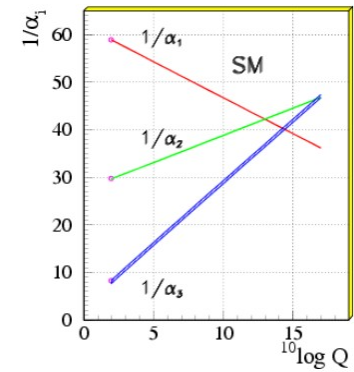
References and Notes

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Motivations

- Proton decay is forbidden within the SM
- Discovering proton decay would be of enormous importance for our understanding of matter and its interactions
- A smoking-gun evidence of new interactions and maybe grand unification

Grand Unification



- Unification of the coupling constants around 10^{14} GeV
- Elegant explanation of the electric charge quantization (why $q_e = -q_p$)
- Prediction of the Weinberg angle
- Quark and leptons sit in the same multiplet

Super-Kamiokande

- $p \rightarrow e^+ \pi^0$ $p \rightarrow K \nu$

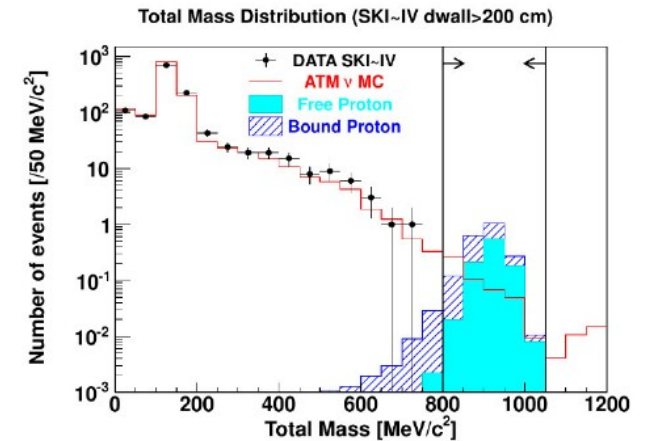


Fig. 14. Reconstructed total mass distributions for the conventional FV [17].

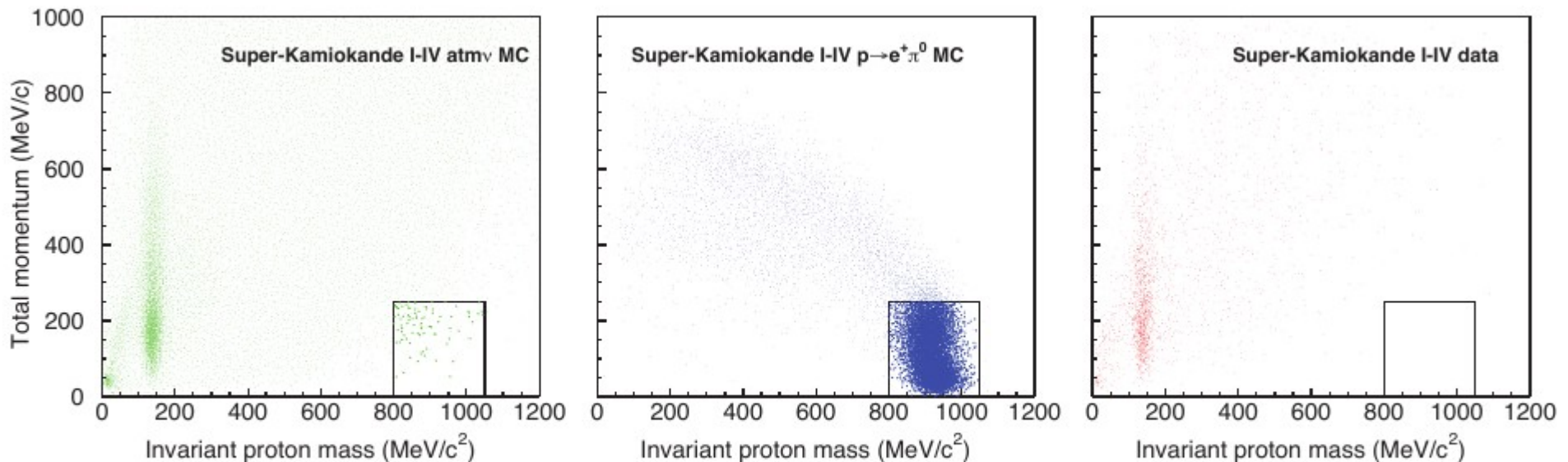


Figure 1-3. The combined SK-I+II+III+IV analysis of $p \rightarrow e^+ \pi^0$.

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \rightarrow e^+ \pi^0$	I–IV	450	2.4×10^{34}	[20]	Expanded FV
$p \rightarrow \mu^+ \pi^0$	I–IV	450	1.6×10^{34}	[20]	Expanded FV
$p \rightarrow \nu \pi^+$	I–III	173	3.9×10^{32}	[21]	
$n \rightarrow \nu \pi^0$	I–III	173	1.1×10^{33}	[21]	
$p \rightarrow e^+ \eta$	I–IV	373	1.4×10^{34}	In prep.	
$p \rightarrow \mu^+ \eta$	I–IV	373	7.3×10^{33}	In prep.	
$p \rightarrow e^+ \rho^0$	I–IV	316	7.2×10^{32}	[22]	A part of SK IV data
$p \rightarrow \mu^+ \rho^0$	I–IV	316	5.7×10^{32}	[22]	A part of SK IV data
$p \rightarrow e^+ \omega$	I–IV	316	1.6×10^{33}	[22]	A part of SK IV data
$p \rightarrow \mu^+ \omega$	I–IV	316	2.8×10^{33}	[22]	A part of SK IV data
$n \rightarrow e^+ \pi^-$	I–IV	316	5.3×10^{33}	[22]	A part of SK IV data
$n \rightarrow \mu^+ \pi^-$	I–IV	316	3.5×10^{33}	[22]	A part of SK IV data
$n \rightarrow e^+ \rho^-$	I–IV	316	3.0×10^{31}	[22]	A part of SK IV data
$n \rightarrow \mu^+ \rho^-$	I–IV	316	6.0×10^{31}	[22]	A part of SK IV data

$p \rightarrow e^+ \pi^0 \pi^0$	I–V	401	7.2×10^{33}	In prep.	
$p \rightarrow \mu^+ \pi^0 \pi^0$	I–V	401	4.5×10^{33}	In prep.	
$p \rightarrow e^+ e^+ e^-$	I–IV	373	3.4×10^{34}	[23]	
$p \rightarrow \mu^+ e^+ e^-$	I–IV	373	2.3×10^{34}	[23]	
$p \rightarrow \mu^- e^+ e^+$	I–IV	373	1.9×10^{34}	[23]	
$p \rightarrow e^+ \mu^+ \mu^-$	I–IV	373	9.2×10^{33}	[23]	
$p \rightarrow e^- \mu^+ \mu^+$	I–IV	373	1.1×10^{34}	[23]	
$p \rightarrow \mu^+ \mu^+ \mu^-$	I–IV	373	1.0×10^{34}	[23]	
$p \rightarrow e^+ \nu \nu$	I–IV	273	1.7×10^{32}	[24]	A part of SK IV data
$p \rightarrow \mu^+ \nu \nu$	I–IV	273	2.2×10^{32}	[24]	A part of SK IV data
$p \rightarrow e^+ X$	I–IV	273	7.9×10^{32}	[25]	A part of SK IV data
$p \rightarrow \mu^+ X$	I–IV	273	4.1×10^{32}	[25]	A part of SK IV data
$n \rightarrow \nu \gamma$	I–IV	273	5.5×10^{32}	[25]	A part of SK IV data
$p \rightarrow \nu K^+$	I–IV	365	8.2×10^{33}	[26]	A part of SK IV data
$p \rightarrow \mu^+ K^0$	I–IV	373	3.6×10^{33}	[27]	
$p \rightarrow e^+ K^0$	I	92	1.3×10^{33}	[28]	
$p \rightarrow \mu^+ K^0$	I	92	1.0×10^{33}	[28]	

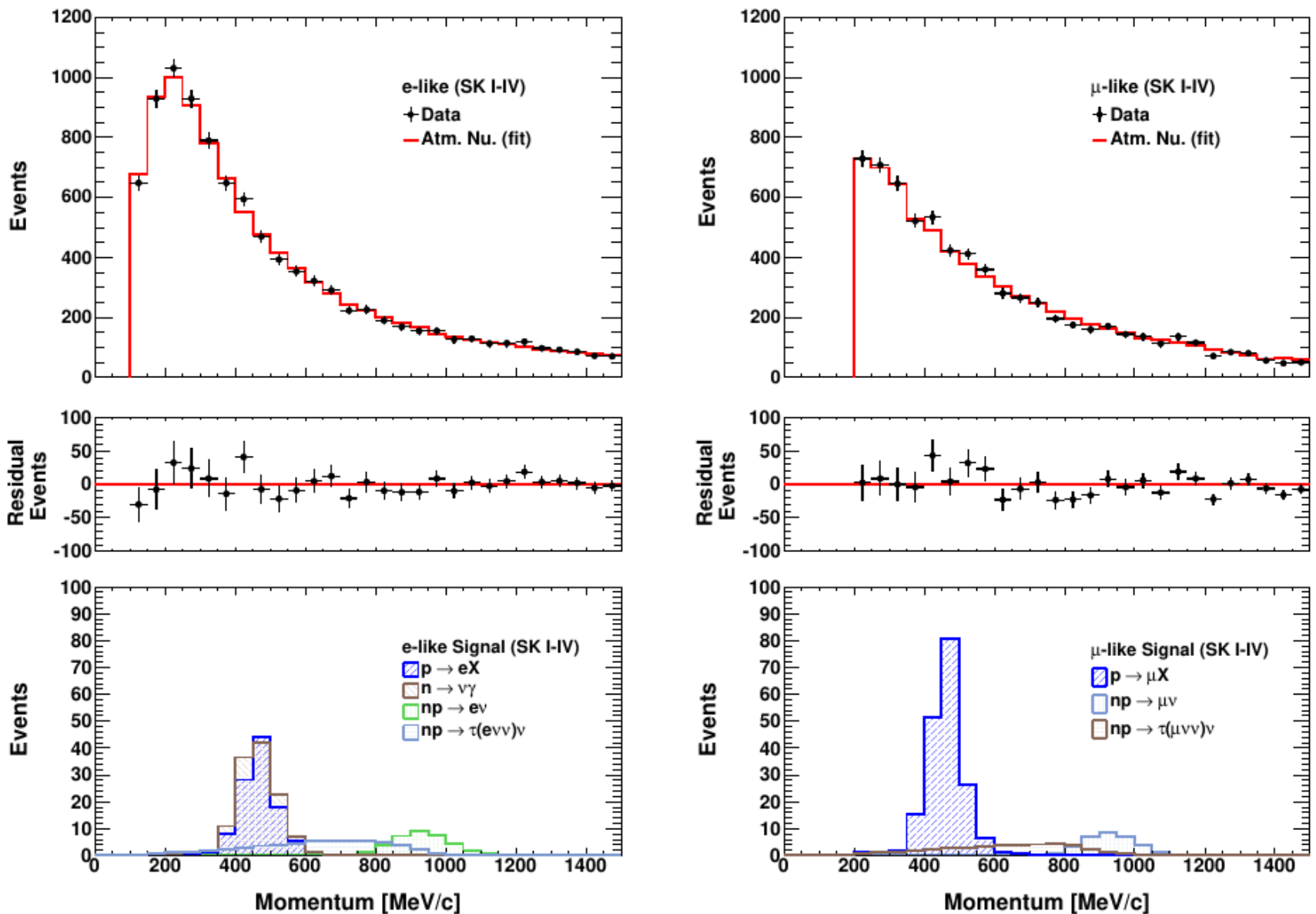


FIG. 1: [Top] Reconstructed momentum distribution for 273.4 kton · years of combined SK data (black dots) and the best-fit result for the atmospheric neutrino background Monte Carlo (solid line). The corresponding residuals are shown below, after fitted background subtraction from data. [Bottom] The 90% confidence level allowed nucleon decay signal (hatched histograms), from the signal and background MC fit to data. All modes are shown (overlaid), with e -like channels on the left and μ -like channels on the right.

Super-Kamiokande

TABLE I: Best fit parameter values, signal detection efficiency for each SK running period, 90% C.L. value of β parameter, allowed number of nucleon decay events in the full 273.4 kiloton $\cdot$ year exposure (SK-I: 91.7, SK-II: 49.2, SK-III: 31.9, SK-IV: 100.5) and a partial lifetime limit for each decay mode at 90% C.L.

Decay mode	Best fit values (α, β)	Signal efficiency for SK-I, -II, -III, -IV (%) (efficiency uncertainty)	$\beta_{90\text{CL}}$	Signal events at 90% C.L. ($N_{90\text{CL}}$)	$\tau/\mathcal{B}$ ($\times 10^{32}$ yrs)
$p \rightarrow e^+ \nu \nu$	(1.05, 0.03)	88.8, 88.0, 89.2, 87.8 ($\pm 0.5, \pm 0.5, \pm 0.5, \pm 0.5$)	0.06	459	1.7
$p \rightarrow \mu^+ \nu \nu$	(0.99, 0.02)	64.4, 65.0, 67.0, 78.4 ($\pm 0.7, \pm 0.7, \pm 0.7, \pm 0.6$)	0.05	286	2.2

The selection requires electron energy > 100 MeV

Low-Q decays

- What if the proton decays into heavy invisible particle(s) $p \rightarrow e + X$ with low Q ($m_X \sim m_p$) ?

511 KeV from our Galaxy

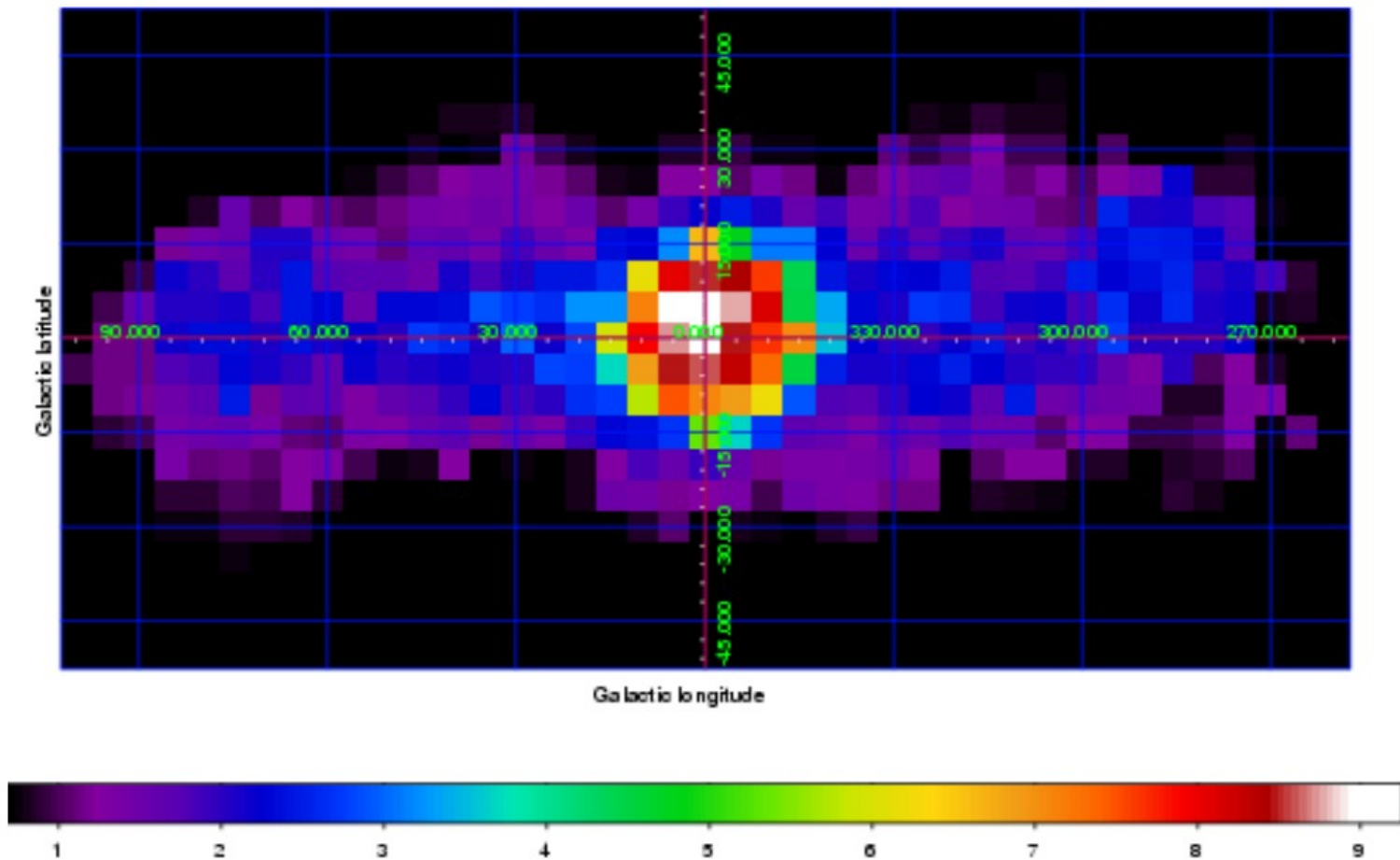


Fig. 6.— 508.25-513.75 keV *INTEGRAL* SPI smoothed (top hat of 2 pixels) significance map. Pixel size is $5^\circ \times 5^\circ$.

The detection of the 511 keV positron annihilation line emission from the central region of our Galaxy was one of the early and important successes of gamma-ray astronomy (Leventhal et al., 1978). Although positron annihilation gives rise to the strongest γ -ray line signal from our Galaxy, three decades of dedicated observational and theoretical efforts failed to unveil the origin of the Galactic positrons.

As illustrated in Fig. 4 the Bulge component is best fitted by a quasi mono-energetic injection of positrons with kinetic energies of ~ 2 MeV into the ISM. This excludes radioactive β^+ decays as noticeable contributors to the Bulge component, since their positron spectra are limited to sub-MeV energies, producing γ -ray spectra that cut off below ~ 1 MeV. Some reacceler-

explain the extended morphology of the emission. Thus, the precise origin of positrons in the Galactic bulge remains unknown, but our observations exclude many sources previously proposed (Prantzos et al. 2011). In particular, β^+ decays from radioactive isotopes and sources producing highly relativistic positrons, such as cosmic-ray secondaries produced from π^+ decays, normal pulsars, millisecond pulsars, and magnetars, can be clearly discarded as primary source of Galactic bulge positrons.

Borexino

Fit result for the electron decay rate = 1.23 cpd/100 tons

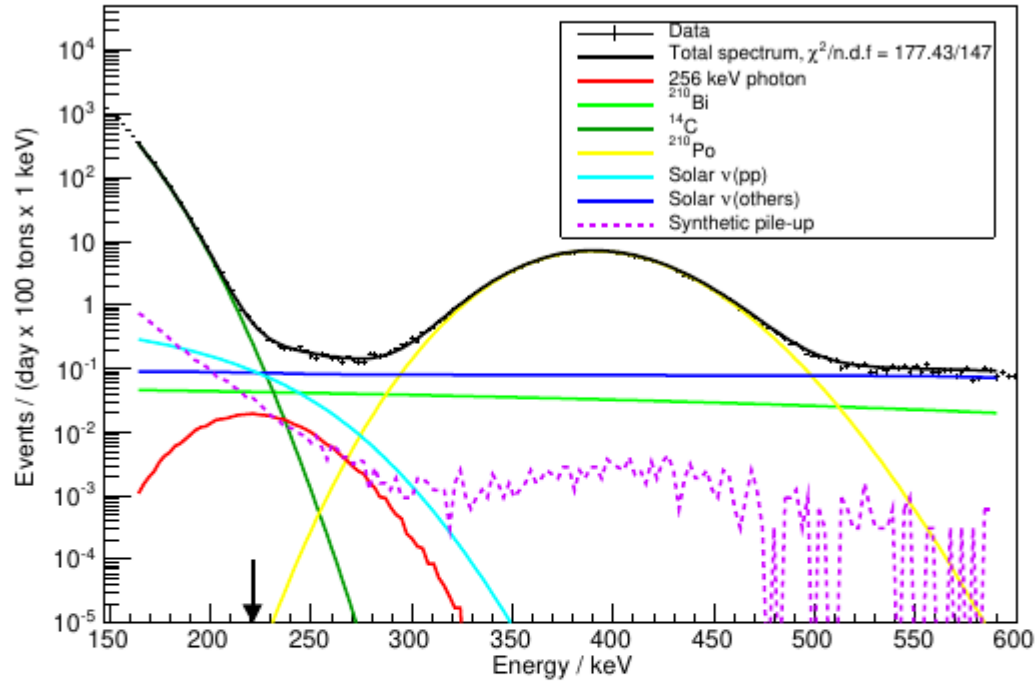


FIG. 1. Energy spectrum between 150 and 600 keV. The most prominent features are the ^{14}C β -spectrum (green), the peak at about 400 keV from ^{210}Po α -decays, and the solar neutrinos, grouped in the blue curve except the crucial pp neutrinos, which are shown in cyan. The effect of event pile-up, mostly overlapping ^{14}C events, is shown in dashed-pink. The hypothetical mono-energetic 256 keV γ line is shown in red at its 90% exclusion C.L. with an arrow indicating the mean value of the detected energy, which is lower than 256 keV because of quenching. The fit is done in the range 164-590 keV.

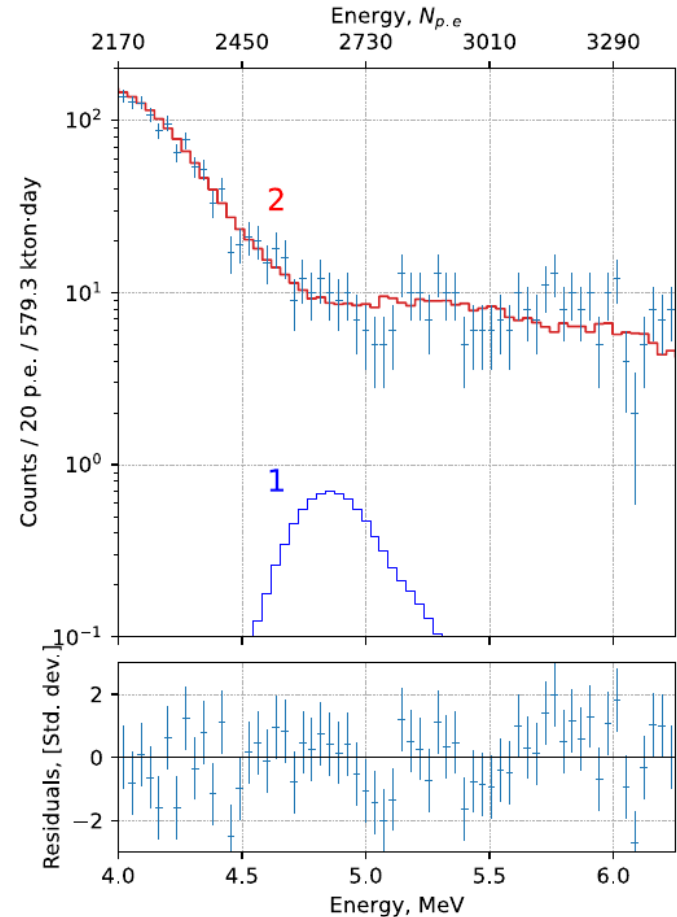


Fig. 5 Fit of the Borexino energy spectrum in the (4.4 – 6.8) MeV range. Curve 1 is the detector response function for axio-electric effect on carbon atoms and corresponds to 90% c.l. upper limit ($S = 5.6$ events). The fit (curve 2) is complementary to the radial fit on Fig. 6

Thoughts

- Can we close the loophole between a few MeV and 100 MeV of electron momentum ?
- What about three body decays ?
- Total em energy or rate of positron production ?