Mitglied der Helmholtz-Gemeinschaft

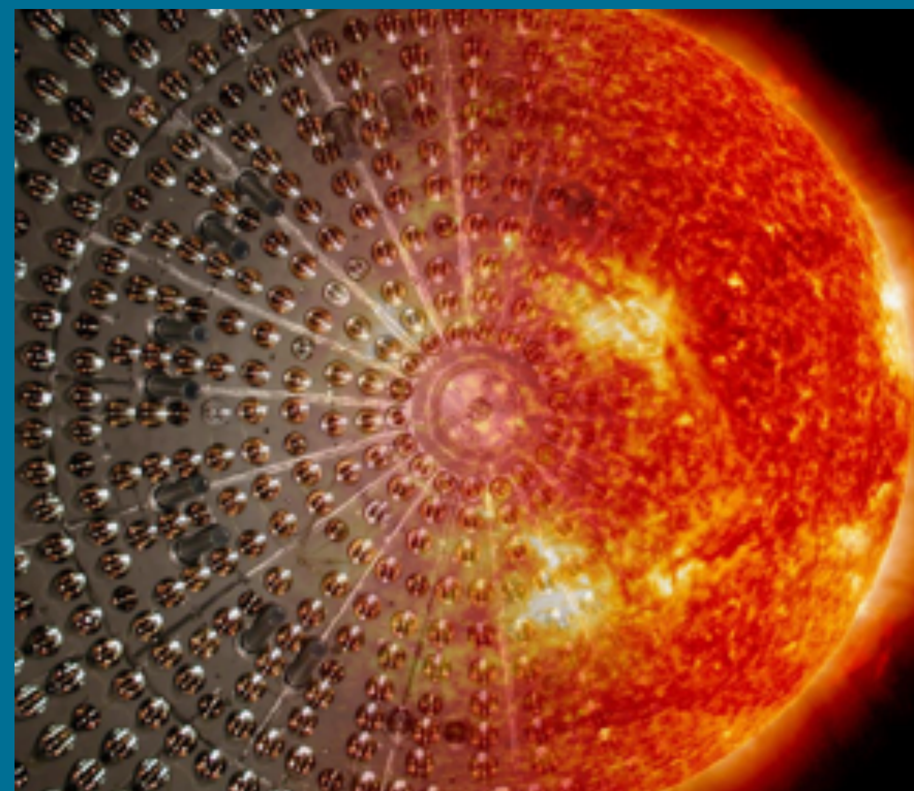
TAUP Topics in Astroparticle and Underground Physics

JÜLICH FORSCHUNGSZENTRUM

Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

Livia Ludhova
on behalf of
the Borexino collaboration

IKP-2 FZ Jülich,
RWTH Aachen,
and JARA Institute, Germany



Outline

1. Borexino and solar neutrinos
2. (Effective) Neutrino Magnetic Moment (NMM)
3. New Borexino analysis and results
4. Comparison to other results on NMM

Borexino collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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University of Massachusetts Amherst 1863

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Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

The University of California UCLA

TECHNISCHE UNIVERSITÄT DRESDEN

APC

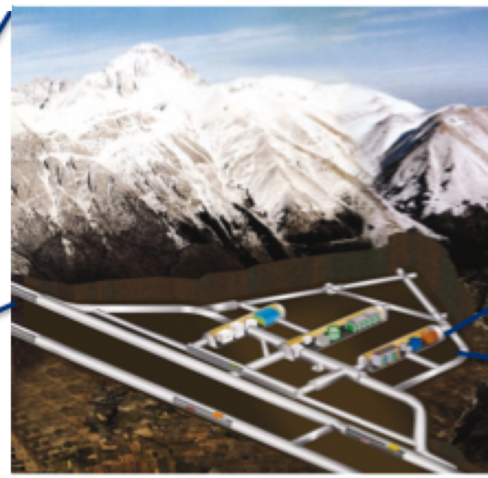
Studium Generale Civitatis Perusii

POLITECNICO MILANO 1863

Borexino at
Laboratori Nazionali del Gran Sasso

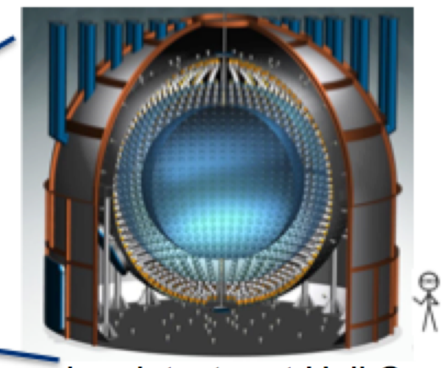
Central Italy
(~170 km from Rome)
Abruzzo

Laboratori Nazionali
del Gran Sasso



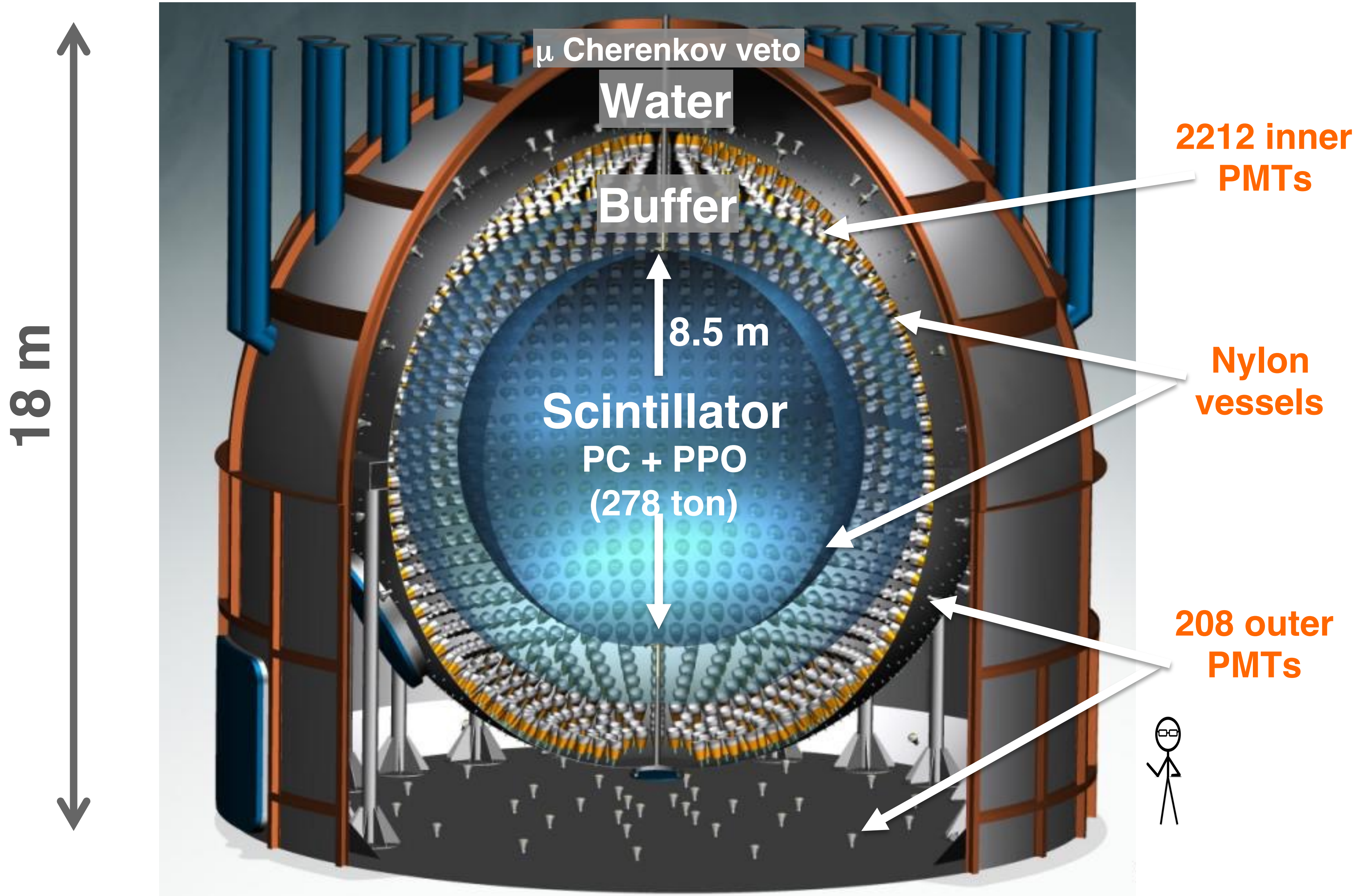
3800 m.w.e shielding against cosmic rays

Borexino detector
in Hall C

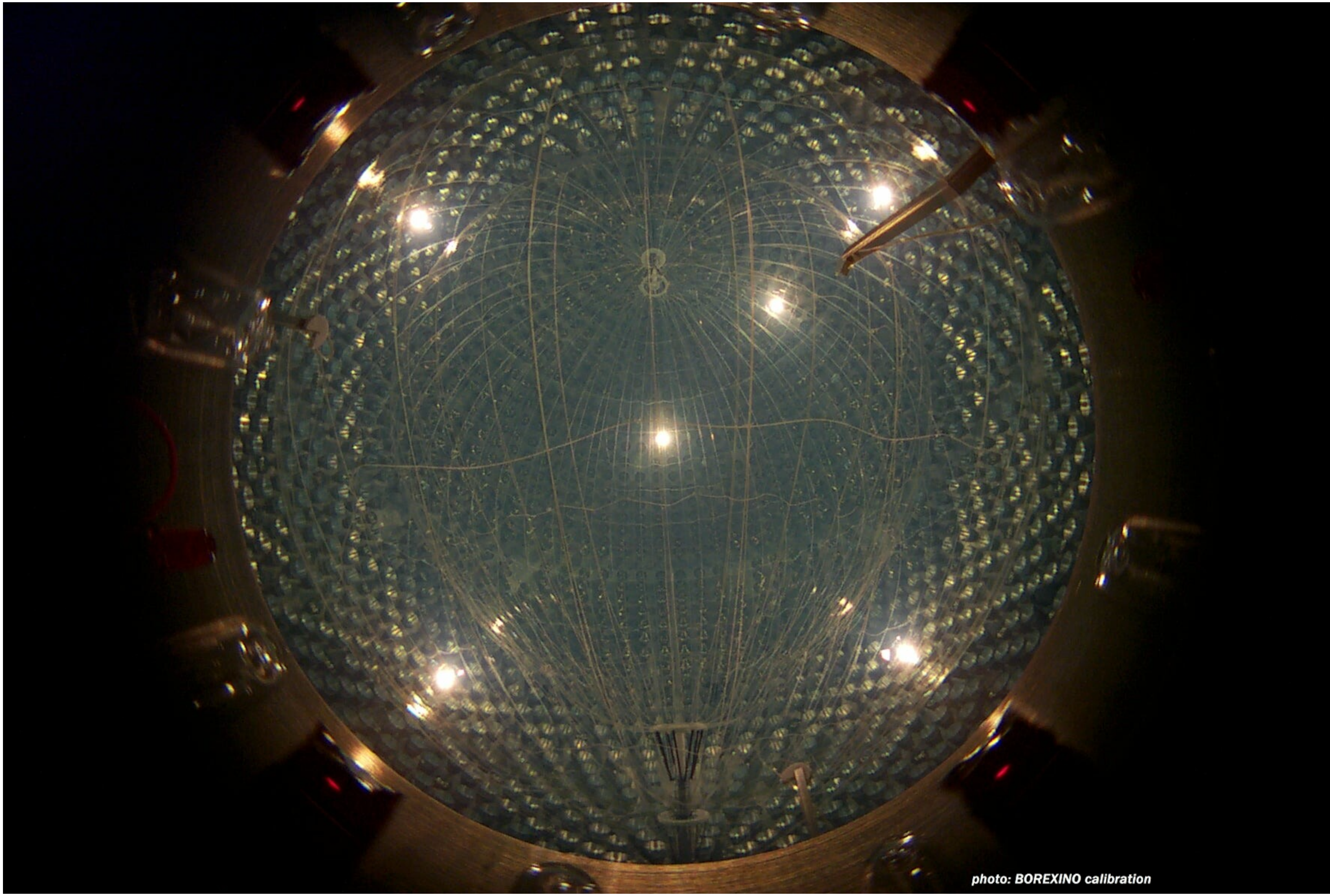


Entrance to underground labs

Borexino detector



Borexino detector



Borexino solar time-line

PHASE I

2007 2010 2012 2017 2018

Solar neutrinos

^{7}Be [1-3]

^{8}B [4]

pep [5]

CNO limit [5]

References:

[1] PRL 101 (2008) 091302.

[2] PLB 658 (2008) 101-108.

[3] PRL 07 (2011) 14130.

[4] PRD 82 (2010) 033006.

[5] PRL 108 (2012) 051302.

Borexino solar time-line

PHASE I	Purification

2007 2010 2012 2017 2018

Solar neutrinos ^{7}Be [1-3] ^{8}B [4] pep [5] CNO limit [5]	**^{85}Kr:** 30 to 6 cpd/100 tons **^{210}Bi**: 41 to 17 cpd/100 tons **^{232}Th/^{238}U** 10^{-19} g/g

References:
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Borexino solar time-line

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[4] PRD 82 (2010) 033006.
[5] PRL 108 (2012) 051302.
[6] **Nature 512 (2014) 383.**

Borexino solar time-line

PHASE I	Purification	PHASE II	SOX
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[6] Nature 512 (2014) 383.

[7] JHEP 1308 (2013) 038.

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NEW

The first spectral fit from (0.186 – 2.97) MeV!

SIMULTANEOUS MEASUREMENT OF pp, ^{7}Be, pep neutrinos

References:
[1] PRL 101 (2008) 091302.
[2] PLB 658 (2008) 101-108.
[3] PRL 07 (2011) 14130.
[4] PRD 82 (2010) 033006.
[5] PRL 108 (2012) 051302.
[6] Nature 512 (2014) 383.
[7] JHEP 1308 (2013) 038.

See talk G. Testera on Thursday!

Detecting solar neutrinos

Production

1. Solar neutrinos are produced along nuclear fusion reactions (**dominant pp-cycle**, sub-dominant CNO neutrinos) in the solar core as ***electron*-flavour**
2. Undergoing **MSW-LMA oscillations**, they arrive on Earth as a mixture of all flavours

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JÜLICH FORSCHUNGSZENTRUM

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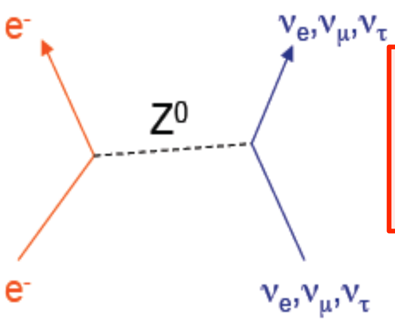
Neutral current



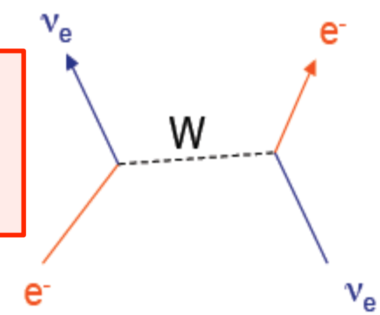
Detection through elastic scattering off electrons

@ 1-2 MeV for electron flavour: $\sigma \sim 10^{-44}$ cm^2

for μ,τ flavours, σ is ~6 x smaller

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

Charged current



Detecting solar neutrinos

JÜLICH FORSCHUNGSZENTRUM

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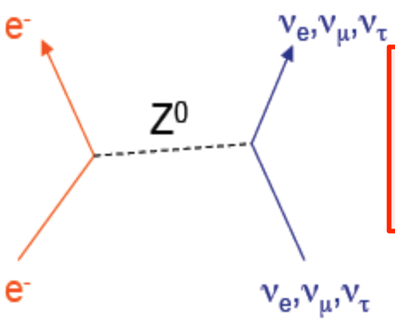

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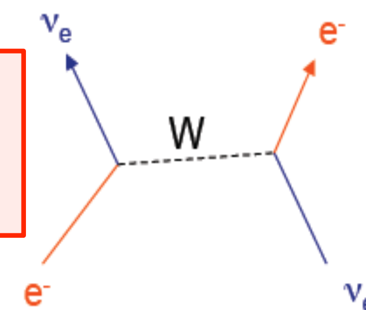


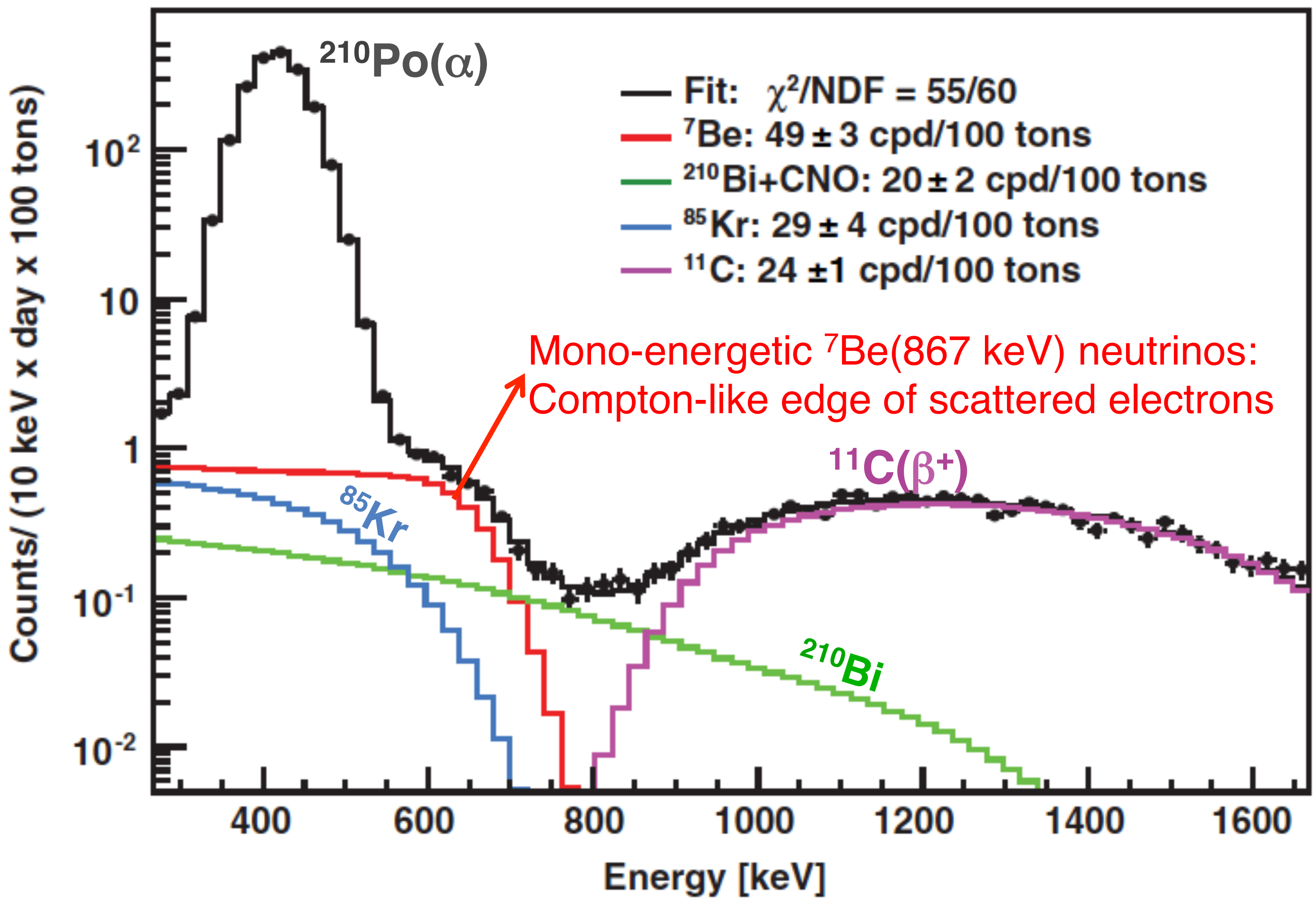
Analysis: measurement of interaction rates

1. Constructing **energy spectra of "good events"** reconstructed in the fiducial volume
2. **Spectral fit** with **signal** (pp, ^{7}Be, pep, CNO solar neutrinos) + **background** (^{14}C + pile up, ^{85}Kr, ^{210}Po, ^{210}Bi, ^{11}C, external bgr.) components

Example of a spectral fit

PRL **101**, 091302 (2008) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2008

Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data



Neutrino magnetic moment (NMM)

Minimal extension of the Standard Model

1. Discovery of the neutrino oscillations implies **non-zero neutrino mass**
2. **Neutrino magnetic moment μ_ν** is **proportional** to the **neutrinos mass m_ν**

$$\mu_\nu = \frac{3 m_e G_F}{4\pi^2\sqrt{2}} m_\nu \mu_B \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV}\right) \mu_B$$

μ_B = Bohr magneton
G_F = Fermi coupling constant
m_e = electron mass

3. Considering the current limits on m_ν: $\mu_\nu < 10^{-18}\ \mu_B$

$$\mu_B = \frac{eh}{4\pi m_e}$$

That is 7-8 orders of magnitude less than the current experimental limits

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Further extension of the Standard Model && New Physics

1. μ_ν proportional to the mass of charge leptons, not proportional to the mass of neutrino
2. In such extensions:

expectations reach the levels of the current experimental limits

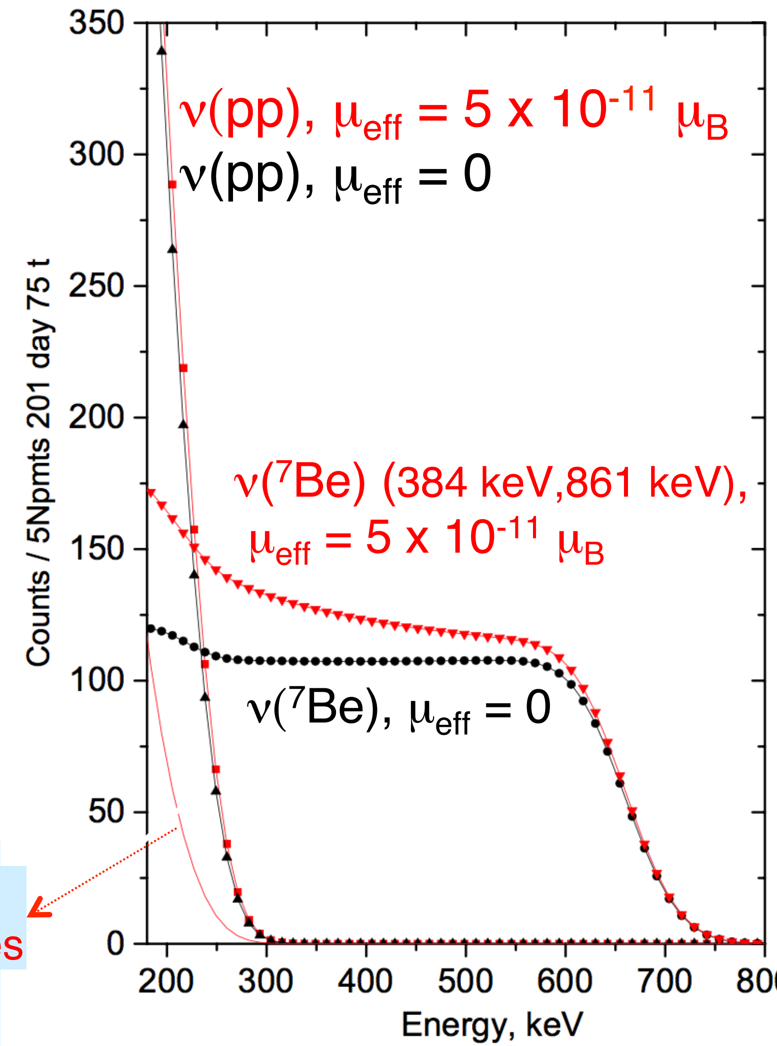
σ(e⁻-ν scattering) with NMM > 0

- In addition to the weak-interaction term σ_{WI}, there appears an **additional electro-magnetic term σ_{EM}, proportional to NMM**:

$$\frac{d\sigma_{EM}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

r_0 = 1.818 x 10^{-13} cm (electron radius)

- μ_{eff}: for a mixture of mass eigenstates
- 1-photon exchange + ν flips helicity (WI and EM terms do not interfere)
- For $T_e << E_\nu$: $\sigma_{TOTAL} \sim 1/T_e$, the spectrum of the scattered electron is influenced mostly at low energies.



^{7}Be-ν: strong change of the shape
MAJOR SENSITIVTY TO NMM

Difference for pp shapes

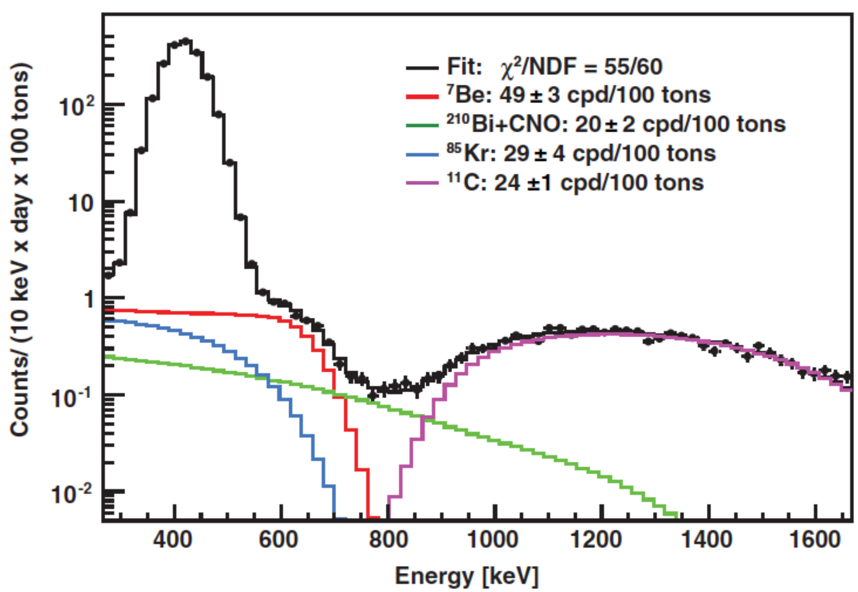
pp-ν: the change of the shape is almost equivalent to the change of only normalization
CONSTRAINING PP FLUX HELPS!

Borexino Phase-1 and effective NMM

Since i) solar neutrinos arriving at Earth are an incoherent admixture of mass eigenstates and ii) NMM is intrinsic to mass eigenstates, the **NMM limits obtained on solar neutrinos represent an effective value typical for a certain flavour composition μ_{eff}**

PRL **101**, 091302 (2008) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2008

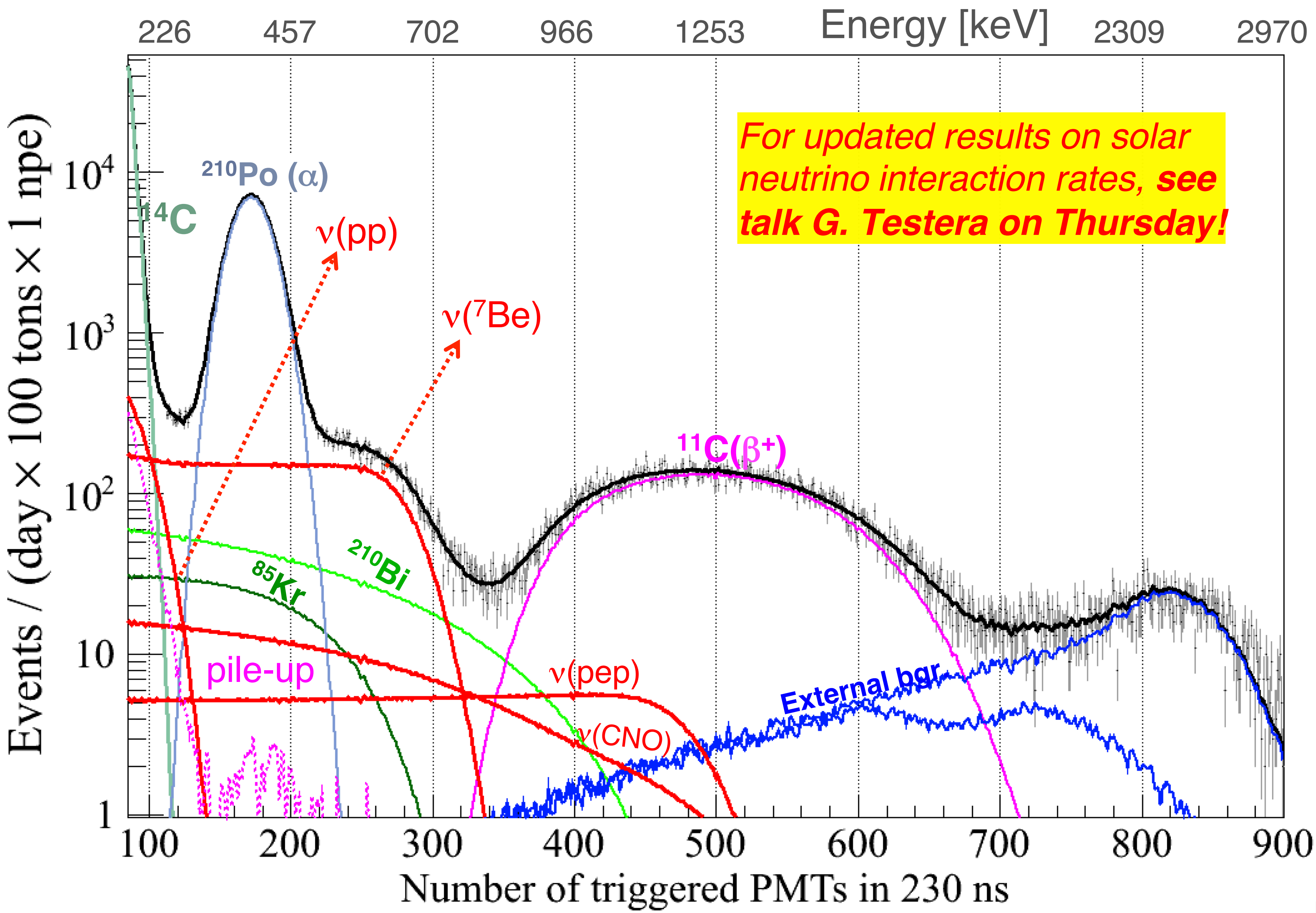
Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data



Phase I data (2007-2008)
192 days only
^{7}Be spectrum

$\mu_{eff} < \mathbf{5.4\ x10^{-11}}\mu_B$ **(90% C.L>)**

Example of a Phase 2 fit



Phase-2 improvements towards a new NMM limit

Data

1. Background reduction: ^{210}Bi: factor ~2 and ^{86}Kr: factor ~5
correlation with these backgrounds are critical for the sensitivity to μ_ν
2. Increased statistics: 192 days -> 1291 days

Analysis

3. Extended energy range of the fit covering pp-ν & ^{7}Be-ν & pep-ν (from 260-1670 keV to 186 - 2970 keV)
4. Improved data selection algorithm ***see poster S. Caprioli!***
5. Better understanding of the detector response function both in the low- and in the high-energy region: specific resolution parameters, Cherenkov light contribution... ***see poster Z. Bagdasarian!***
6. Treatment of the pile-up (mostly ^{14}C-^{14}C) in the fit of the low energy part of the spectrum (synthetic pile-up, convolution with random-data spectrum, energy estimators in a constant time)
7. Improved Geant-4 based Monte Carlo simulation
arxiv:1704.02291 and see talk S. Marcocci on Wednesday!

Constraints from radiochemical experiments

SAGE + Gallex/GNO combined data , Phys. Rev. C 80 (2009) 1

CC-interaction: ν_e + ^{71}Ga → ^{71}Ge + e^- (E_{th} > 233 keV includes pp-ν, only e-flavour)

CONSTRAIN ON INTEGRAL ν-RATE R, NOT SENSITIVE TO NMM

$$R = \sum_i R_i^{Ga} = \sum_i \Phi_i \int_{E_{th}}^{\infty} s_i^{\odot}(E) P_{ee}(E) \sigma(E) dE = \sum_i \Phi_i < \sigma_i^{\odot} >= 66.1 \pm 3.1\,\text{SNU}$$

SNU = solar neutrino unit = 10^{-36} captures/ atom/second

E.... neutrino energy

i...runs through the species of solar neutrinos (pp, ^{7}Be, pep, CNO, ^{8}B)

Φ_i.... Standard Solar Model (SSM) predictions for neutrino fluxes

$s_i(E)$....solar neutrino spectral shape

$P_{ee}(E)$...solar electron-neutrino survival probability

$\sigma(E)$...^{71} Ga-reaction cross section

Radiochemical constraint applied to Borexino takes the form:

$$\sum_i \frac{R_i^{Brx}}{R_i^{SSM}} R_i^{Ga} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

δ_R ~4% … mostly due to Ga-$\sigma(E)$

δ_{FV} ~2% …Borexino FV selection

R_i^{Ga}...Gallium experiments expected rates, re-estimated using updated oscillation parameters [Esteban et al. 2017]

R_i^{Brx}/R_i^{SSM}... ratio of corresponding rates measured in Borexino and predicted in the SSM (using the same SSM as for R_i^{Ga})

NEW

NMM results from Phase 2

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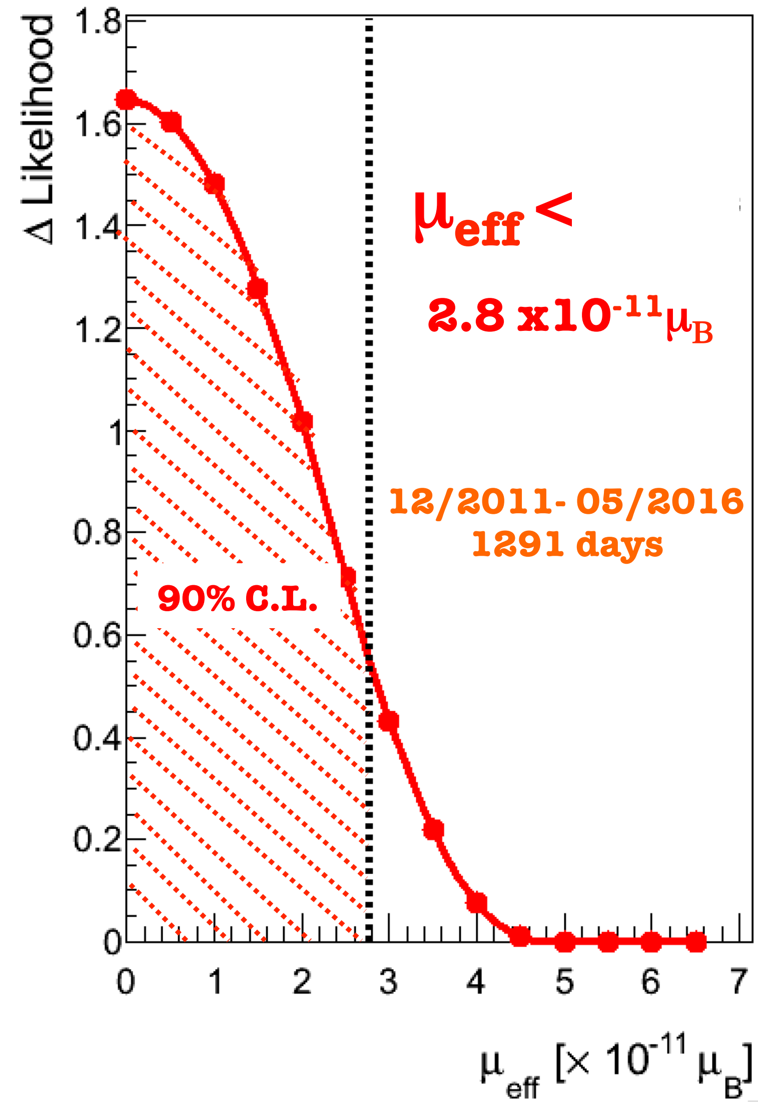
Data selection:
Fiducial volume: R < 3.021 m, |z| < 1.67 m
Muon, ^{214}Bi-^{214}Po, and noise suppression
Free fit parameters: solar-ν (pp, ^{7}Be) and **backgrounds** (^{85}Kr, ^{210}Po, ^{210}Bi, ^{11}C, external bgr.), **response parameters** (light yield, ^{210}Po position and width, ^{11}C edge (2 x 511 keV), 2 energy resolution parameters)
Constrained parameters: ^{14}C, pile up
Fixed parameters: pep-, CNO-, ^{8}B-ν rates
Systematics: treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

Without radiochemical constraint
$\mu_{eff} < 4.0 \times 10^{-11} \mu_B$ (90% C.L.)

With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ **(90% C.L.)**

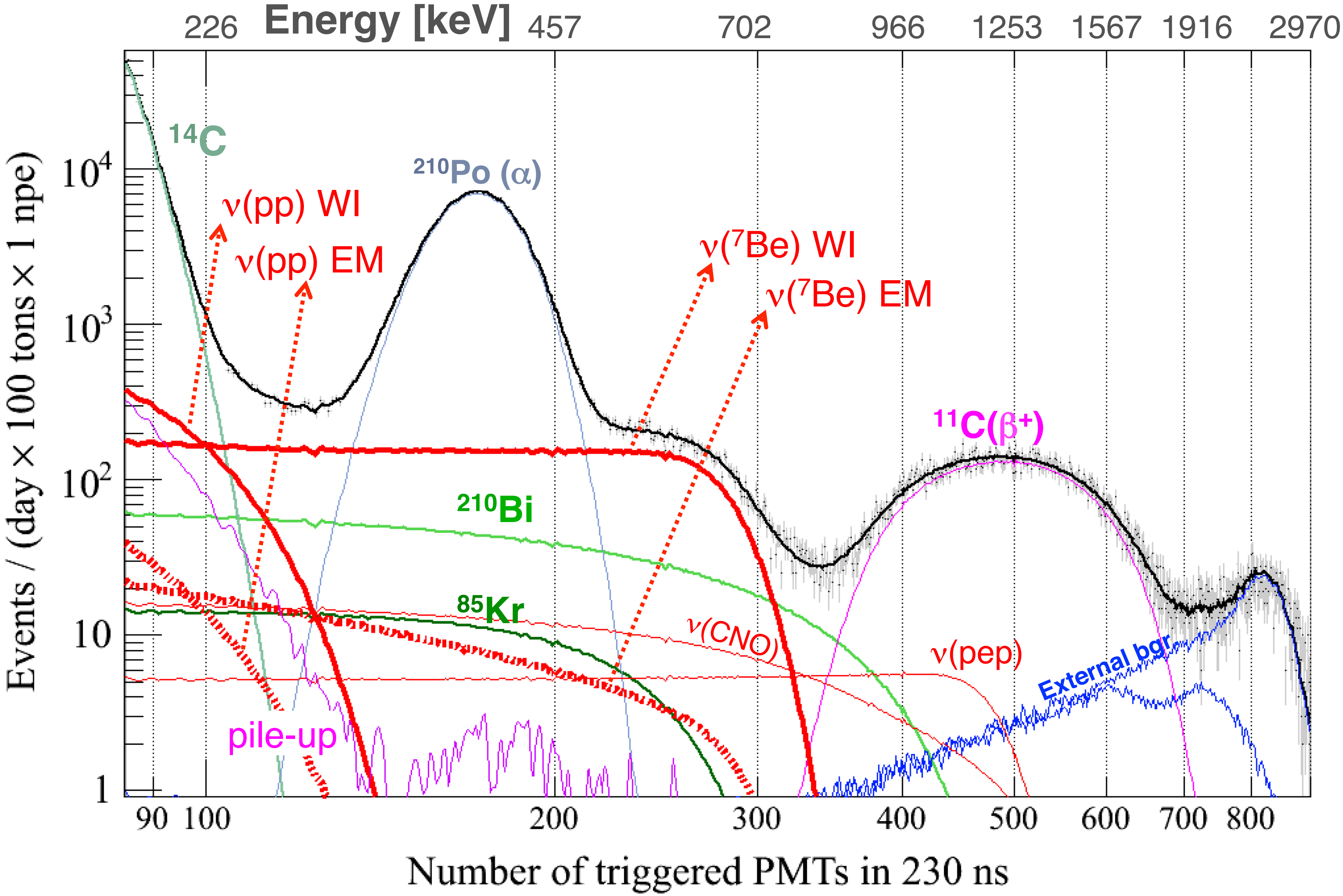
Profiling μ_{eff} with σ_{EM} for pp & ^{7}Be



Fit with $\mu_{eff} = 2.8 \times 10^{-11} \mu_B$

NEW

JÜLICH FORSCHUNGSZENTRUM



Limits on NMM of flavour states

NEW

$$\mu^2_{eff} = P^{3\nu}\,\mu^2_e + (1 - P^{3\nu})\,(\cos^2\theta_{23}\,\mu^2_\mu + \sin^2\theta_{23}\,\mu^2_\tau)$$

$$P_{ee} = P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}$$
$$P^{2\nu} = \sin^2\theta_{12}\,\sin^2(\Delta m^2_{12}\,L/4E)$$

Assuming
LMA-MSW
$P^{2\nu}$ for pp- and ^{7}Be-ν is the same

- **Individual contribution of each flavour state is positive,** so the limit on each contribution can be obtained by setting other two contributions to zero
- since **$\sin^2\theta_{23}$ depends on the MH**, we quote for the NMM limts the most **conservative case**

(Dec 2011- May 2016)
1291 days
90% C.L.
from $\mu_{eff} < 2.8 \times 10^{-11} \mu_B$:
$\mu_e < 4.8 \times 10^{-11} \mu_B$
$\mu_\mu < 6.4 \times 10^{-11} \mu_B$
$\mu_\tau < 6.8 \times 10^{-11} \mu_B$

Conclusions and comparison to other results

Borexio has set a new upper limit on the effective NMM

$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.),

using constraints on the sum of the solar neutrino fluxes implied by the radiochemical gallium experiments.

Experiment/authors	Source of neutrinos	$\times 10^{-11}$ μ_B 90% C.L.
GEMMA [Phys. Part. Nucl. Lett. 10 (2013) 139]	reactor anti-ν_e	$\mu_{\nu e} < 2.9$
TEXONO [PRD. 75 (2007) 012001]	reactor anti-ν_e	$\mu_{\nu e} < 7.4$
Raffelt & Dearborn [PRD 37 (1988) 2] **Arcea-Díaz et al**. [Astrop. Ph. 2015 1]	astrophysical sources (red giants cooling)	~0.1
SuperK: [PRL 93 (2004) 021802]	solar ^{8}B-ν above 5 MeV + combined other solar + KamLAND	$\mu_{eff} < 36$ $\mu_{eff} < 11$
Borexino: [PRL 101 (2008) 091302]	solar ^{7}Be-ν	$\mu_{eff} < 5.4$
Borexino will be on arXive on Wednesday	**solar pp- and ^{7}Be-ν**	**$\mu_{eff} < 2.8$**


Thank you!

Back-up slides

Cañas et al.
[PLB 753 (2016) 191 + Add. in B755 (2016) 568]

based on Borexino data

$\mu_{eff} < 5.4$

Physics Letters B 757 (2016) 568

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Addendum

Addendum to "Updating neutrino magnetic moment constraints" [Phys. Lett. B 753 (2016) 191–198]

B.C. Cañas [a], O.G. Miranda [a,*], A. Parada [b], M. Tórtola [c], J.W.F. Valle [c]

[a] Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 Mexico, DF, Mexico
[b] Universidad Santiago de Cali, Campus Pampalinda, Calle 5 No. 6200, 760001, Santiago de Cali, Colombia
[c] AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València, Parc Científic de Paterna, C/Catedratico José Beltrán, 2, E-46980 Paterna (València), Spain

ARTICLE INFO

Article history:
Available online 4 April 2016

After the publication of this work we noticed that the uncertainties in the considered backgrounds in Borexino may affect our reported limit on the neutrino magnetic moment from Borexino data. Indeed, we have found that a more precise treatment of the uncertainties in the total normalization of these backgrounds results in a weaker sensitivity on the neutrino magnetic moment. This point will be hopefully improved in the near future thanks to the purification processes carried out in the second phase of the Borexino experiment. Meanwhile, however, we think it would be more reliable to adopt the bound on the neutrino magnetic moment reported by Borexino: $\mu_\nu < 5.4 \times 10^{-11} \mu_B$ [1]. In this case, our Fig. (3) should be replaced by the new version shown below (see Fig. 1). There, we have added a new region obtained by allowing the free normalization of backgrounds in Borexino. The grey region, in contrast, has been obtained for fixed normalization of the backgrounds in Borexino. We thank Gianpaolo Bellini from the Borexino Collaboration for pointing out this issue.

Limits on NMM of mass eigen-states

NEW

$$\mu^2_{eff} = \sum_j |\sum_k \mu_{kj} A_k(E_\nu, L)|^2,$$

A_k = probability amplitude of the k-mass state at the scattering point

Generally, complicated interference terms in mass-eigenstates basis.

For the case of solar neutrinos, incoherent mixture of solar neutrinos

Dirac case:

$$\mu^2_{eff} = P^{3\nu}_{e1}\mu^2_{11} + P^{3\nu}_{e2}\mu^2_{22} + P^{3\nu}_{e3}\mu^2_{33}$$

$$P^{3\nu}_{ei} = |A_i(E,L)|^2$$

Majorana case:

$$\mu^2_{eff} = P^{3\nu}_{e1}(\mu^2_{12} + \mu^2_{13}) + P^{3\nu}_{e2}(\mu^2_{21} + \mu^2_{23}) + P^{3\nu}_{e3}(\mu^2_{31} + \mu^2_{32})$$

NMM is a 3x3 matrix $\mu_{k=ij}$

Dirac case:

only diagonal elements μ_{ii}

Majorana case:

CPT: diagonal elements = 0

$\mu_{ij} = \mu_{ji}$

(Dec 2011- May 2016)

1291 days

$\times 10^{-11}\mu_B$ [90% C.L.]

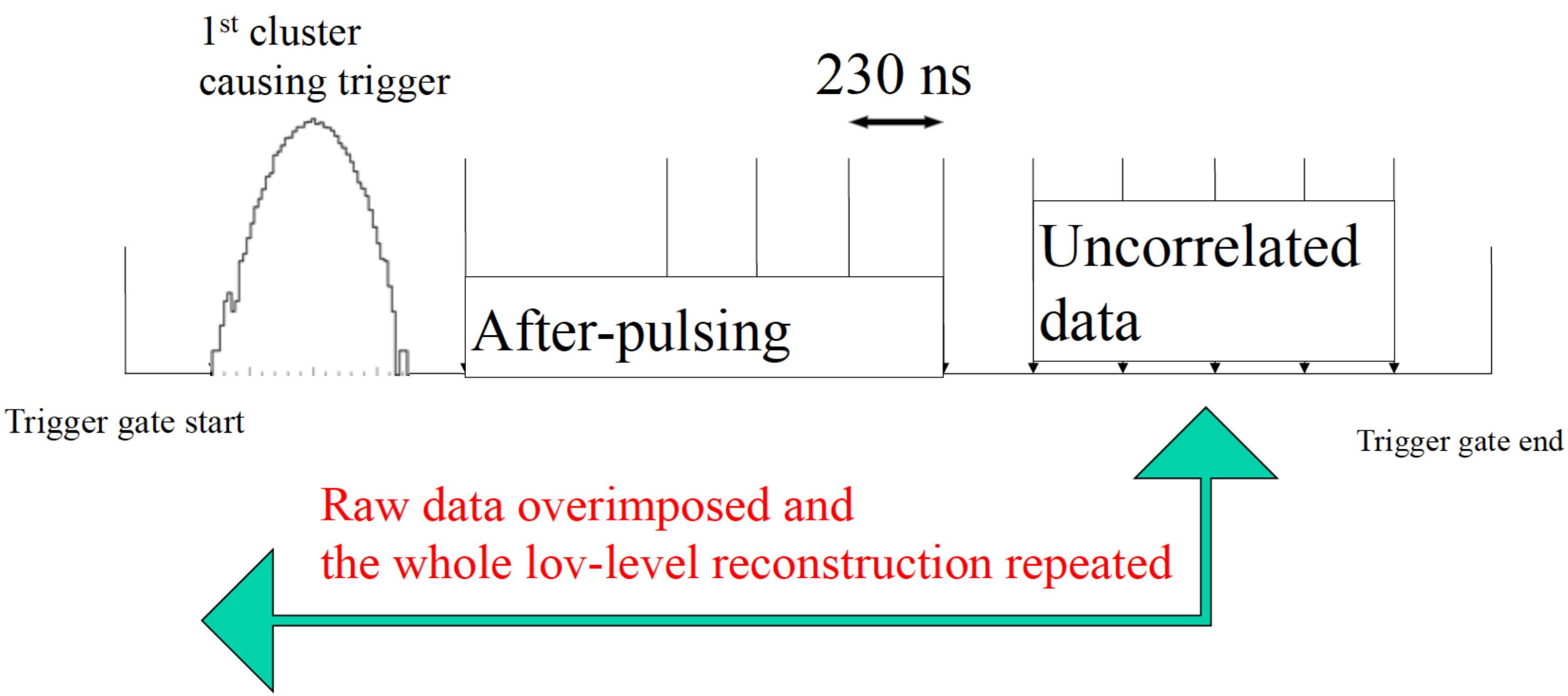
from $\mu_{eff} < 2.8$

$\mu_{11} < 3.4$; $\mu_{22} < 5.1$; $\mu_{33} < 18.7$

$\mu_{12} < 2.8$; $\mu_{13} < 3.4$; $\mu_{23} < 5.0$

pp-ν analysis: constraining ^{14}C-pilep

Synthetic pile-up: overlap uncorrelated data with regular events



Result (spectral shape + rate) used to constrain pile-up in the final fit

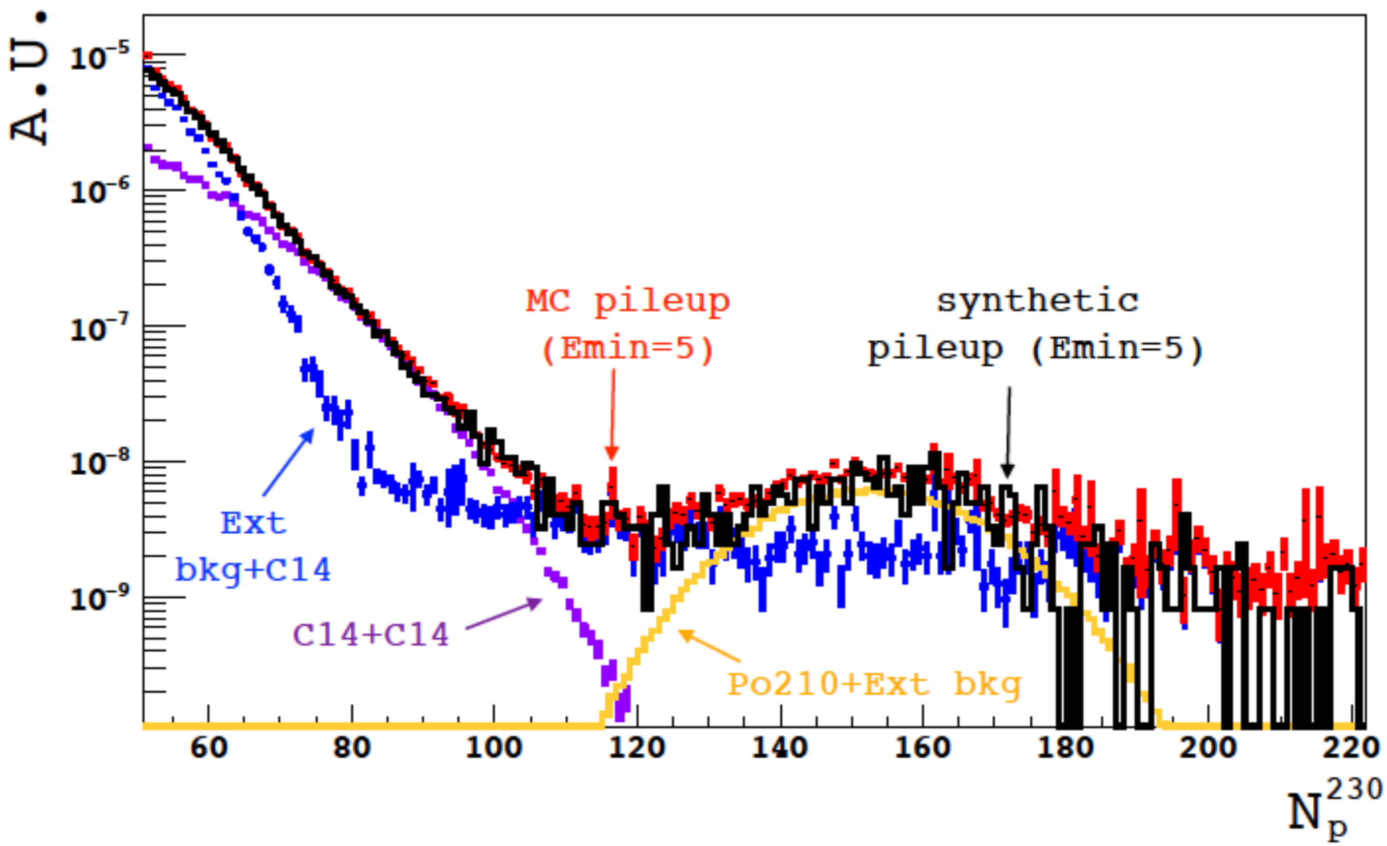


FIG. 30. Synthetic and MC pileup for $E_{min} = 5\, N_p^{230}$. The different components are shown in various colors.