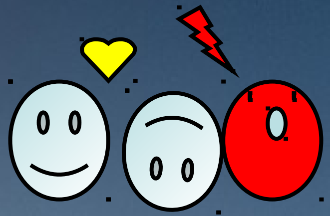
Quantum Mechanics studies in the Cosmic Silence



Kristian Piscicchia

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On behalf of VIP Collaboration

3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

23-28 June 2019, Collegium Maius, Krakow, Poland

<u>Content:</u>

1) The VIP Scientific Case

2) Status of the VIP-2 experiment

3) VIP-2 preliminary results

4) Progress in the theoretical interpretation of the experimental results

5) VIP-lead preliminary limit on Θ - Poincarè

6) test of wave function collapse models


the VIP-2
scientific case
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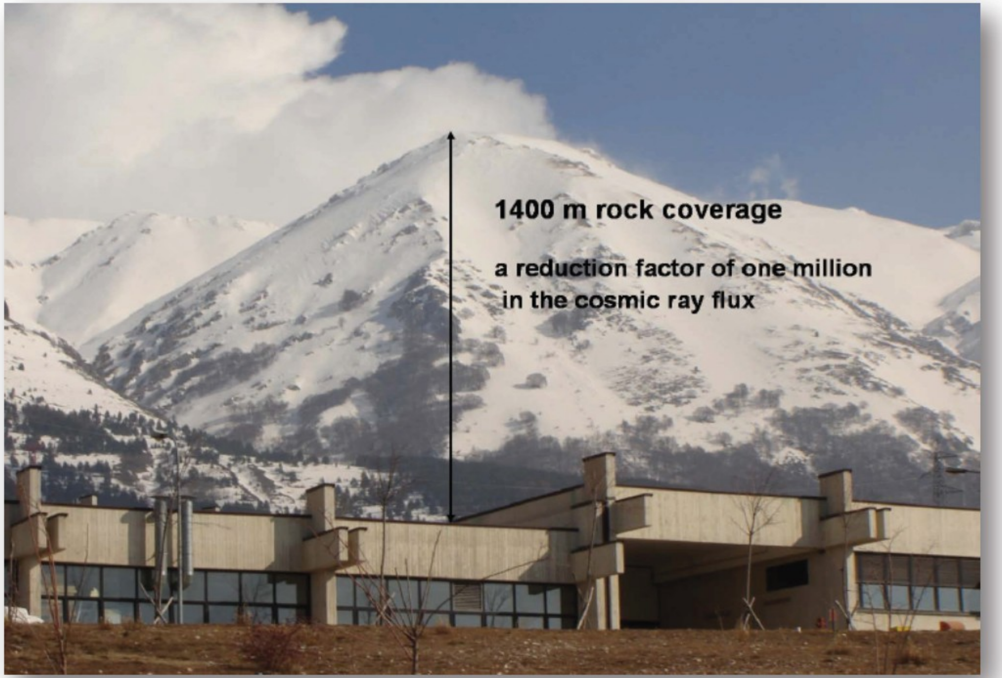
*VIP-2 **tests the Pauli Exclusion Principle** (PEP) (spin-statistics) **for electrons** in a clean environment (LNGS) using a method which respects the Messiah-Greenberg superselection rule.*



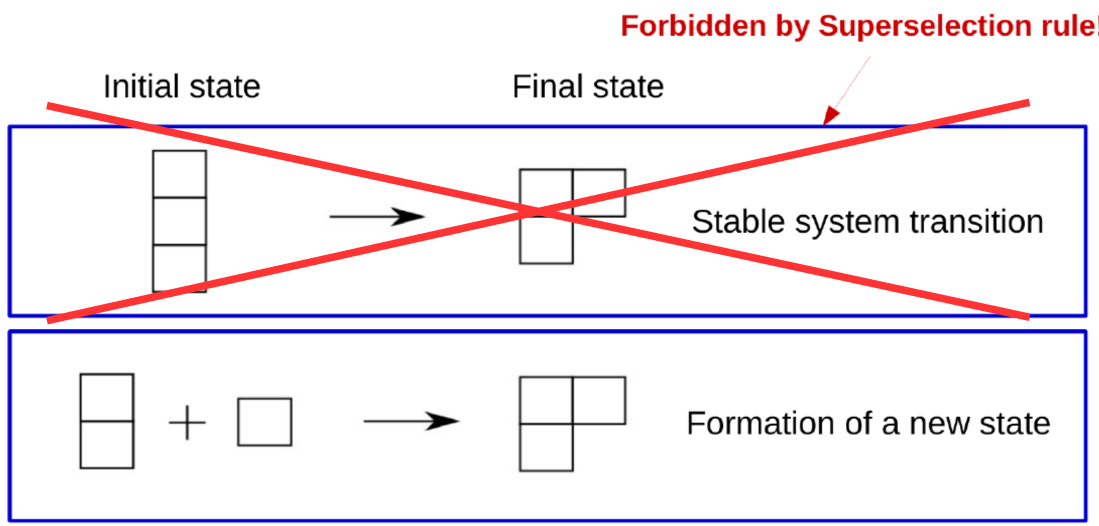
VIP-2 tests the Pauli Exclusion Principle (PEP) (spin-statistics) for electrons in a clean environment (LNGS) using a method which respects the

Messiah-Greenberg superselection rule :

Superpositions of states with different symmetry are not allowed →
transition probability between two symmetry states is ZERO

Closed system →

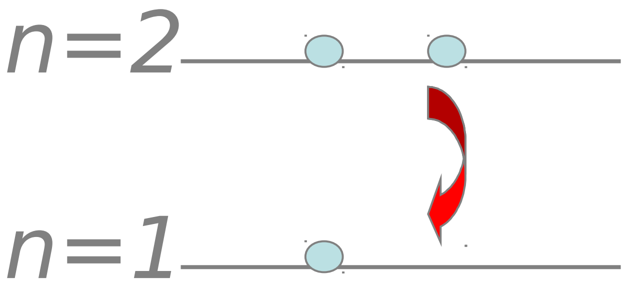
Open system →

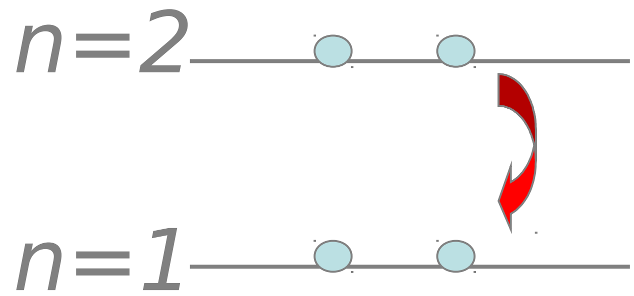


VIP sets the best limit on PEP violation for an elementary particle respecting the M-G superselection rule

Experimental method

Search for anomalous X-ray transitions performed by electrons introduced in a target trough a DC current (open system)





Normal 2p → 1s transition

2p → 1s transition violating Pauli principle

~ 8.05 keV in Cu

~ 7.7 keV in Cu

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

<u>Multiconfiguration Dirac-Fock approach</u>

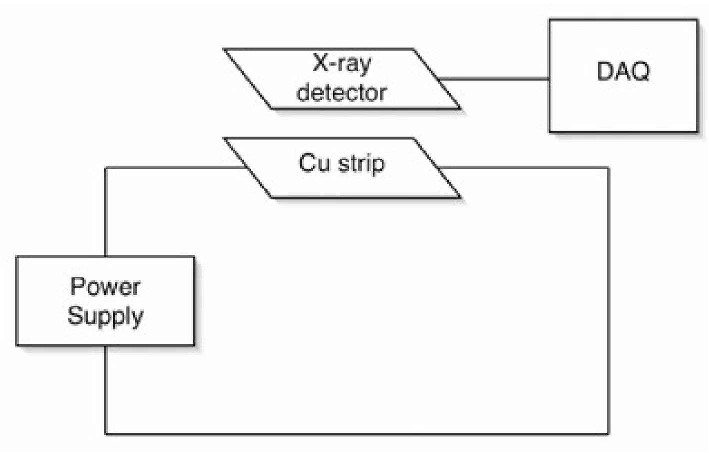
Accounts for the shielding of the two inner electrons

The current-off spectrum provides the estimate of the background.

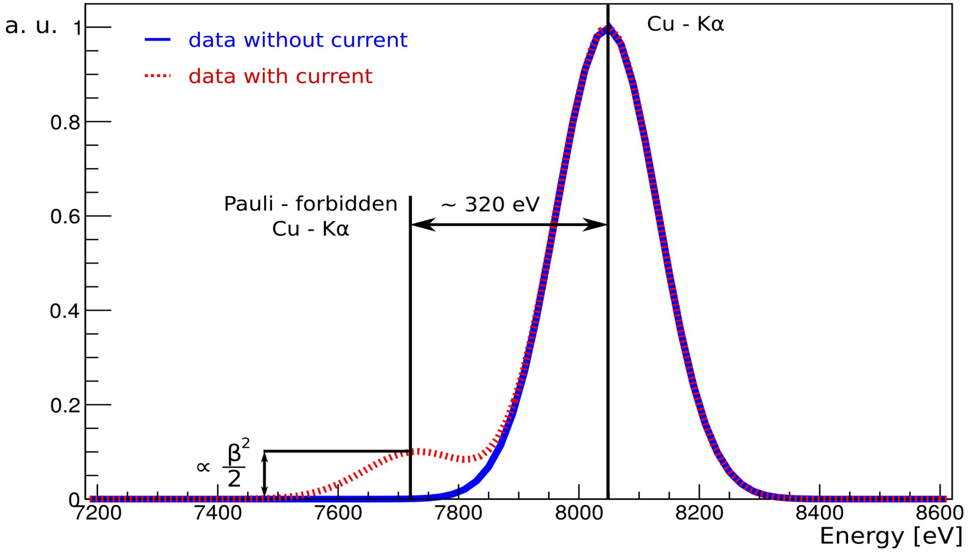
Experimental method

Phys. Lett. ***B238*** *(1990) 438*

Search for anomalous electronic transitions in Cu induced by a circulating current ("new" external electrons, which interact with the valence electrons), namely transition from 2p to 1s already filled by 2 electrons, alternated to X-ray background measurements without current

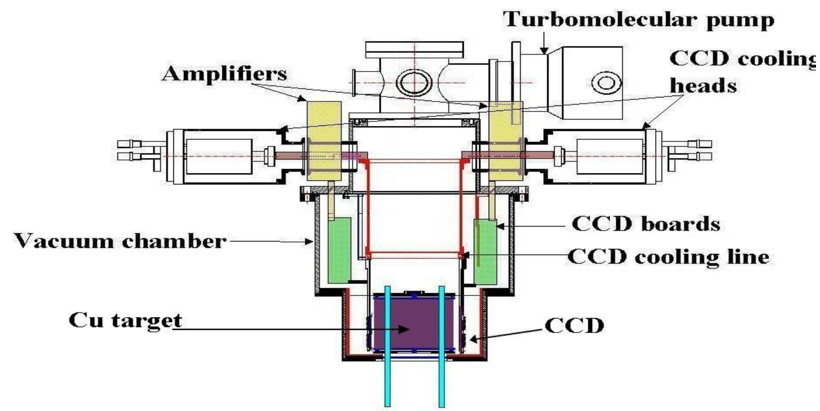


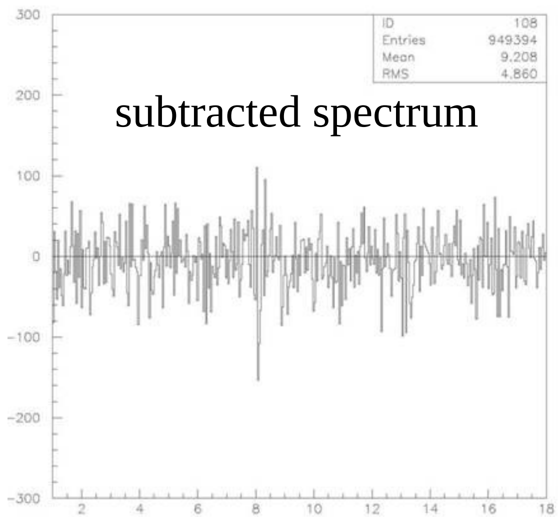
Undesired result :



From VIP to VIP-2, the goal

a) copper ultrapure cylindrical foil
b) surrounded by 16 Charge Coupled Devices (CCD) res. at 8 keV 320 eV (FWHM)
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system
d) amplifiers + read out ADC boards.





$$\beta^2/2 \leq 4.7 \times 10^{-29}$$

improved the limit obtained by Ramberg & Snow by a factor ~ 400

(Foundation of Physics 41 (2011) 282+ other papers)

GOAL OF VIP-2 : improve the VIP result of 2 orders of magnitude

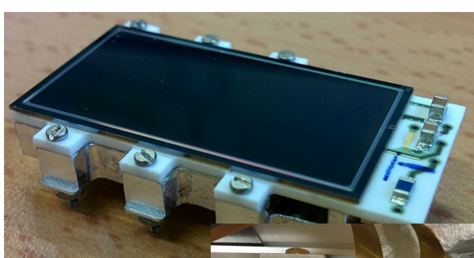
VIP-2 major upgrade

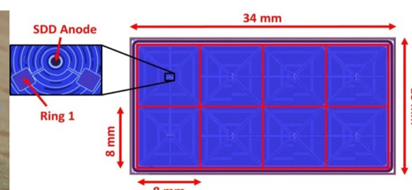
a) Silicon Drift Detectors (SDDs) → higher resolution (190 eV FWHM at 8.0 keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling - 170 °C

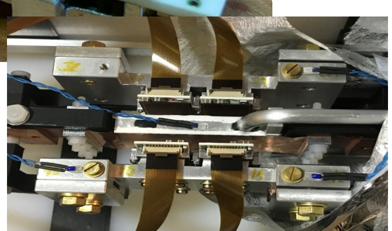
b) 2 strip shaped Cu targets (25 µm x 7 cm x 2 cm) more compact target → higher acceptance, thinner → higher efficiency

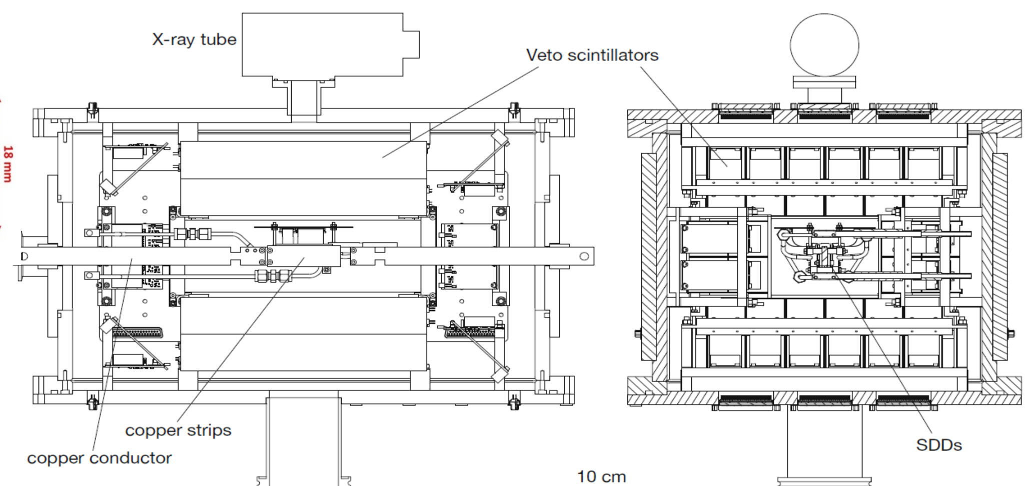
DC current supply to Cu bars

c) VETO system (32 plastic scintillators + SiPMs read out) → rejection of background (high energy charged particles) from outside the detector

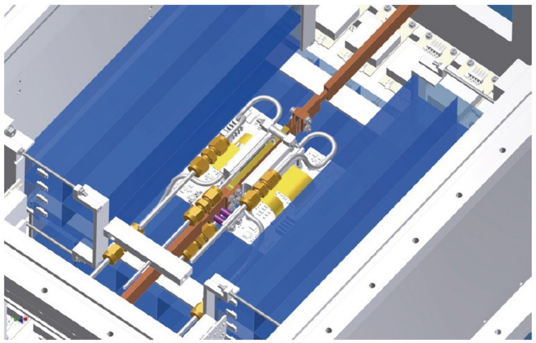


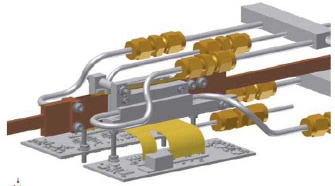


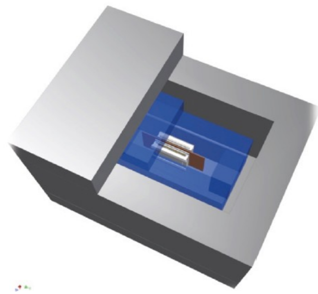


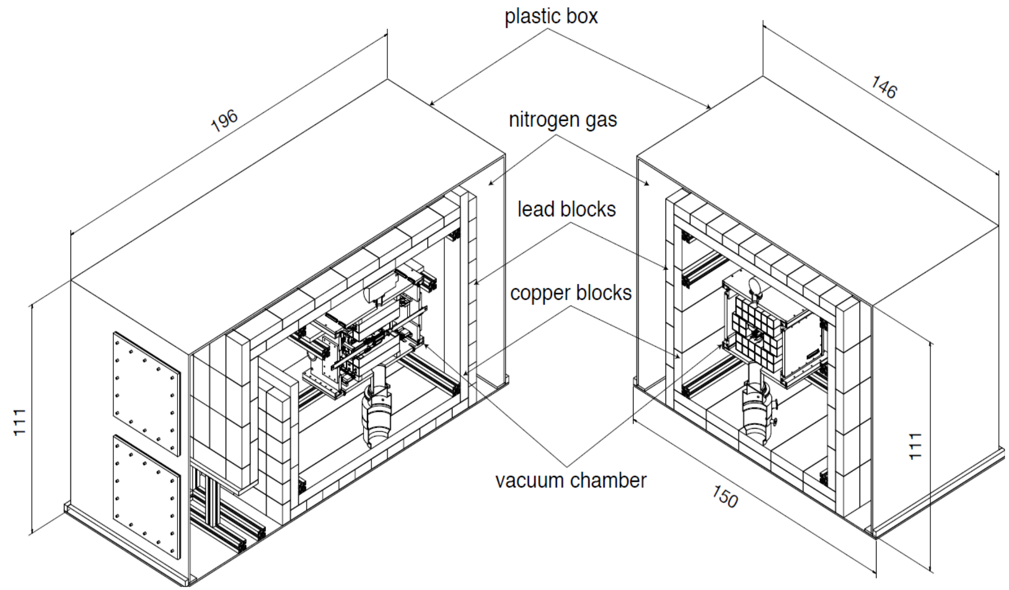


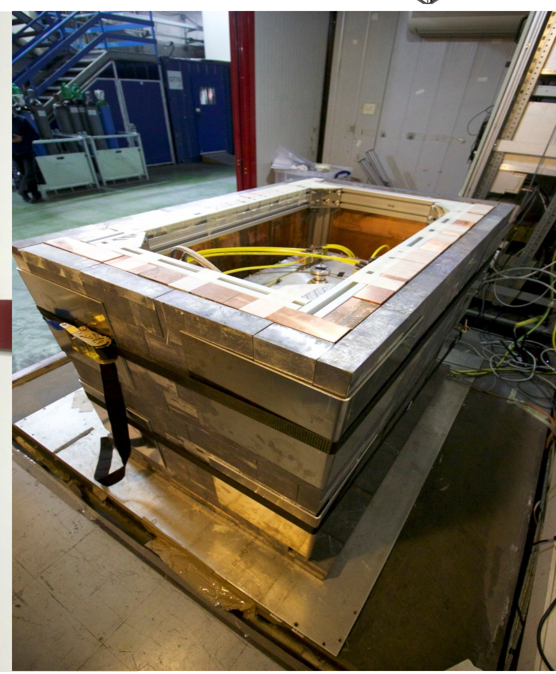
VIP-2 setup April 2019











VIP-2 preliminary results

May – June 2019

May – June … preliminary results

Bayesian data analysis procedure was implemented (inspired to A. Caldwell, K. Kröninger, Phys. Rev. D 74, 092003 (2006))

$$p(S, B|\text{data}) = \frac{p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B)}{\int p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B) dS dB}.$$

Joint *p.d.f.* from the Bayes theorem. Number of events in each bin fluctuate around the mean according to a Pois. Dist.

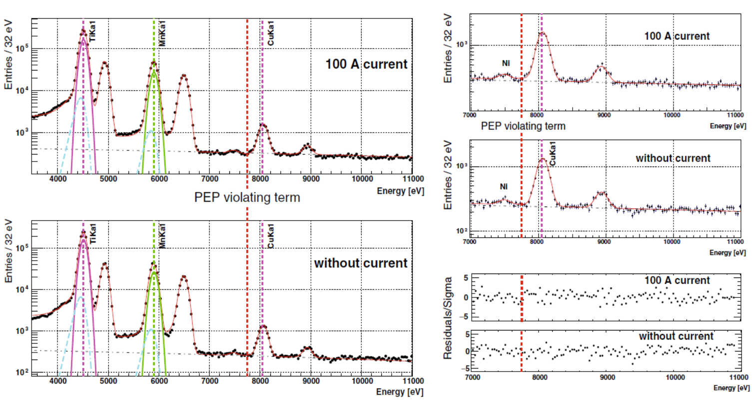
Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):

$$P(S|data) = \int P(S, B|data)\; dB$$

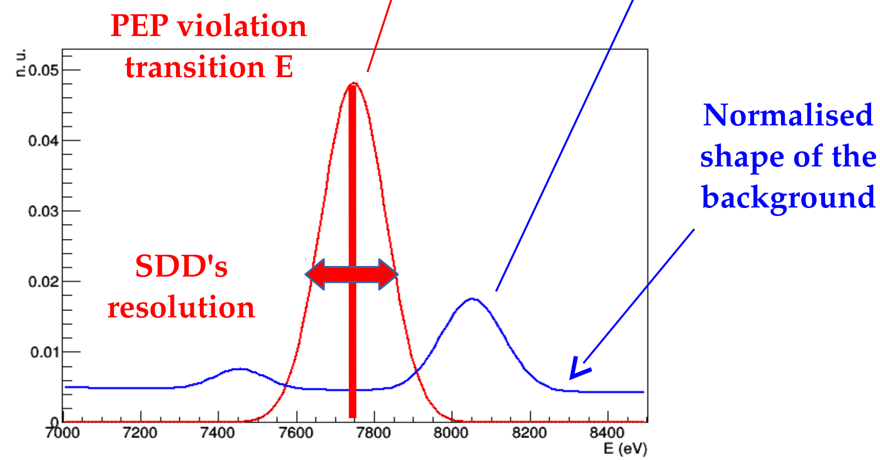
Likelihood $\rightarrow$ $$P(data|S, B) = \prod_{i=1}^{N} \frac{\lambda_i(S, B)^{n_i} \cdot e^{-\lambda_i(S,B)}}{n_i!}$$

$$\lambda_i = \lambda_i(S, B) = S \cdot \int_{\Delta E_i} f_S(E) dE + B \cdot \int_{\Delta E_i} f_B(E) dE,$$

Taking advantage of our last analysis the input normalised shape of the bkg spectrum is obtained from a symultaneous fit:



Eur. Phys. J. C (2018) 78:319



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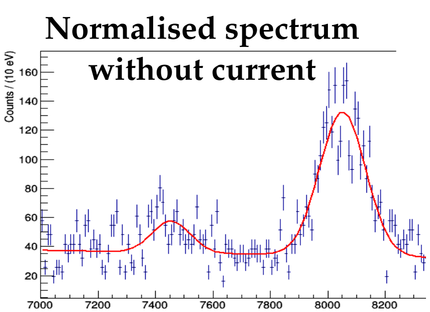
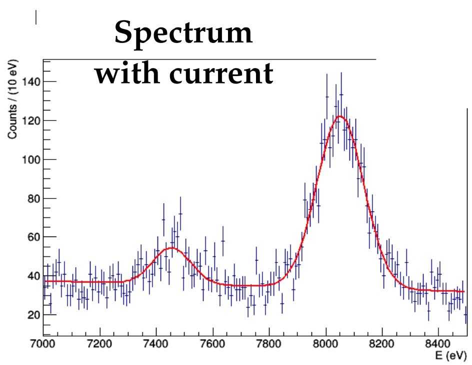
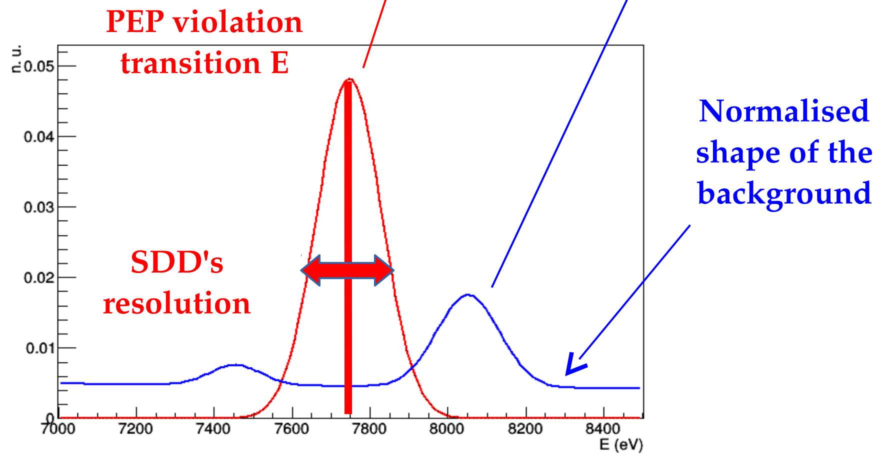






May – June … preliminary results

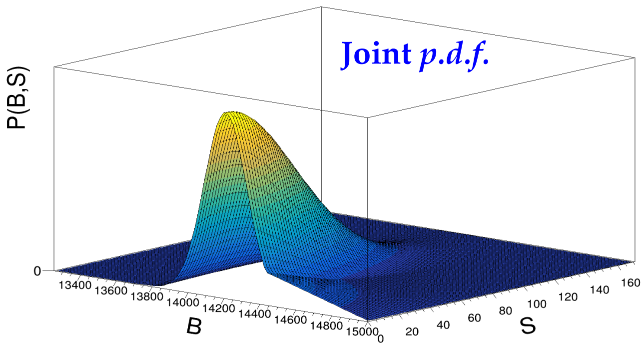
The prior probability for the number of expected signal events is assumed flat up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319].

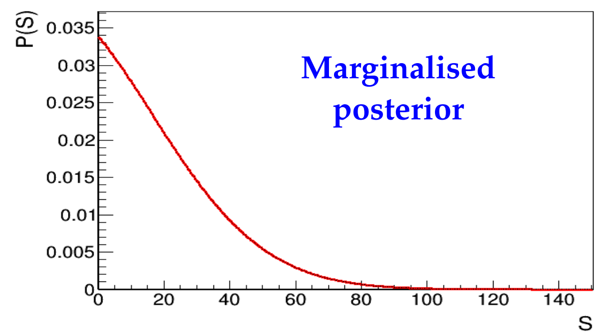
$$p_0(S) = \begin{cases} \frac{1}{S_{max}} & 0 \leq S \leq S_{max} \\ 0 & \text{otherwise} \end{cases}$$

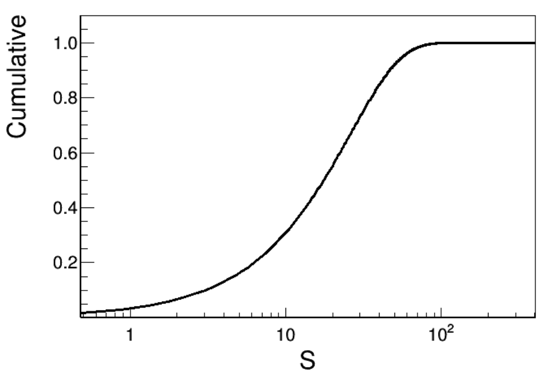
The mean value for the expected number of bkg. Events μ_b mediated from the measured bkg. Spectrum. Prior is assumed Gaussian with a width $\sigma_b = \mu_b/2$.

$$p_0(B) = \begin{cases} \frac{e^{-((B-\mu_B)^2/2\sigma_B^2)}}{\int_0^\infty e^{-((B-\mu_B)^2/2\sigma_B^2)} dB} & B \geq 0 \\ 0 & B < 0 \end{cases}$$

The posterior is calculated by means of Markow chain Monte Carlo techniques





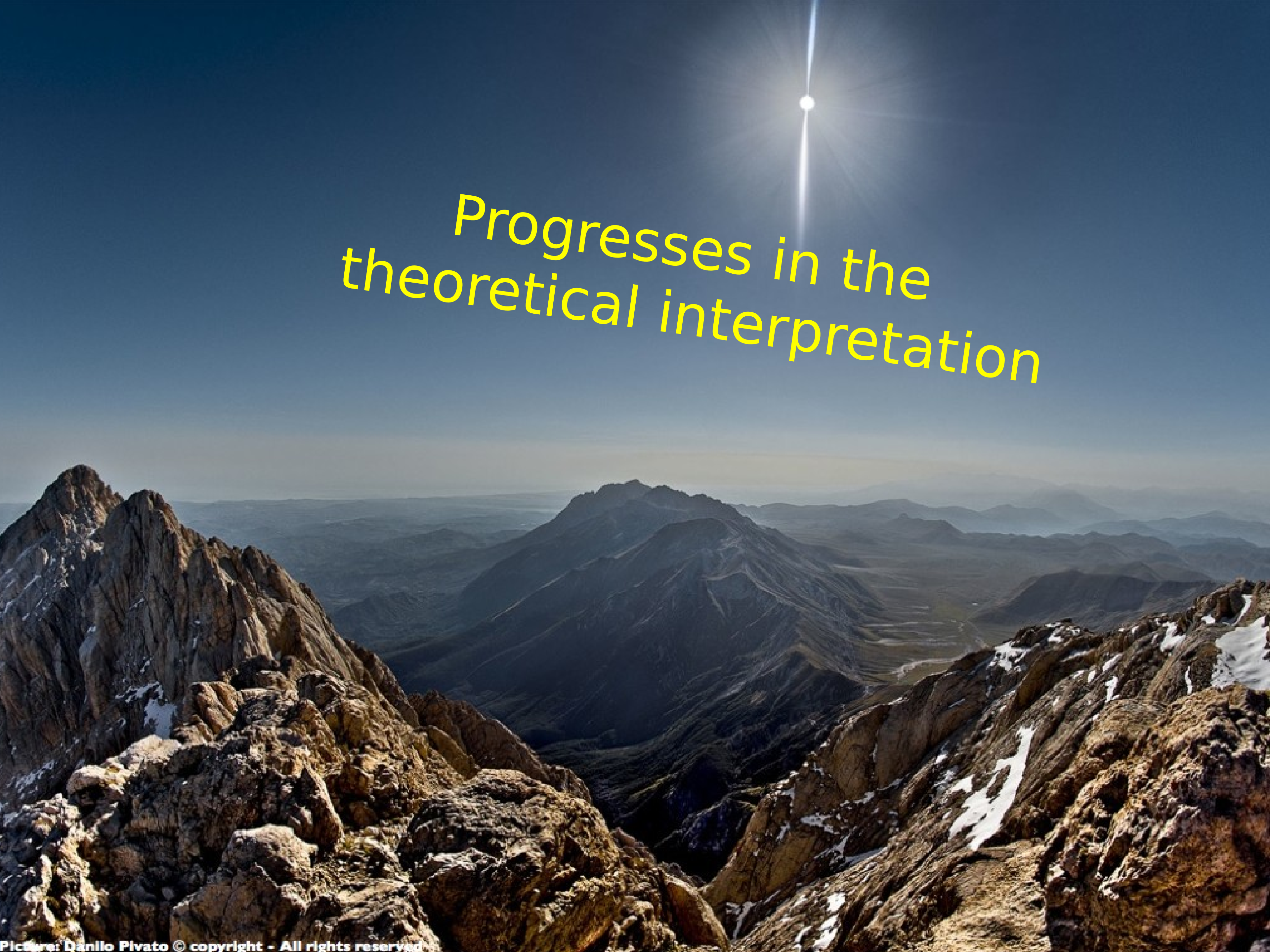


From which an upper limit on the PEP violation probability is obtained (90% Probability):

$$\beta^2/2 < 2.6 \cdot 10^{-30}$$ scattering

$$\beta^2/2 < 1.6 \cdot 10^{-41}$$ close encounters

Progresses in the theoretical interpretation



Theories of Violation of Statistics

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) ***extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime****. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible…………..*

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only bose and fermi statistics occur in Nature."

PEP violation in quantum gravity

Quantum gravity models can embed PEP violation transitions!

Prototipe example is θ-Poincarè non-commutative space-time.

θ-Poincarè is explicitely unitary at tree level but S-matrix does not commute with CPT.

Moreover non-commutative space time implies non-locality and a-causality at the microscopic non-commutativity scale.

The spin statistics theorem was conceived assuming:

causality, locality, Lorentz invariance ..

↓

θ-Poincarè can elude the Pauli theorem

PEP violation in quantum gravity

Differences of θ-Poincarè w. r. to effective models:

- does not respect the M-G superselection rule (transition amplitude from a state of two different fermions to a state of two identical fermions is not zero) →

can be tested with closed systems (ex. using Fermi see electrons in the conductor as test electrons, no current);

- the violation probability depends on the PEP violating process transition energy (suppressed with the non-commutativity energy scale) →

it is important to test different atomic species → different Z → different ΔE for the measured transition;

Preliminary test was already performed for $_{82}$Pb, we plan to repeat with other elements ($_{73}$Ta, $_{23}$V ...)

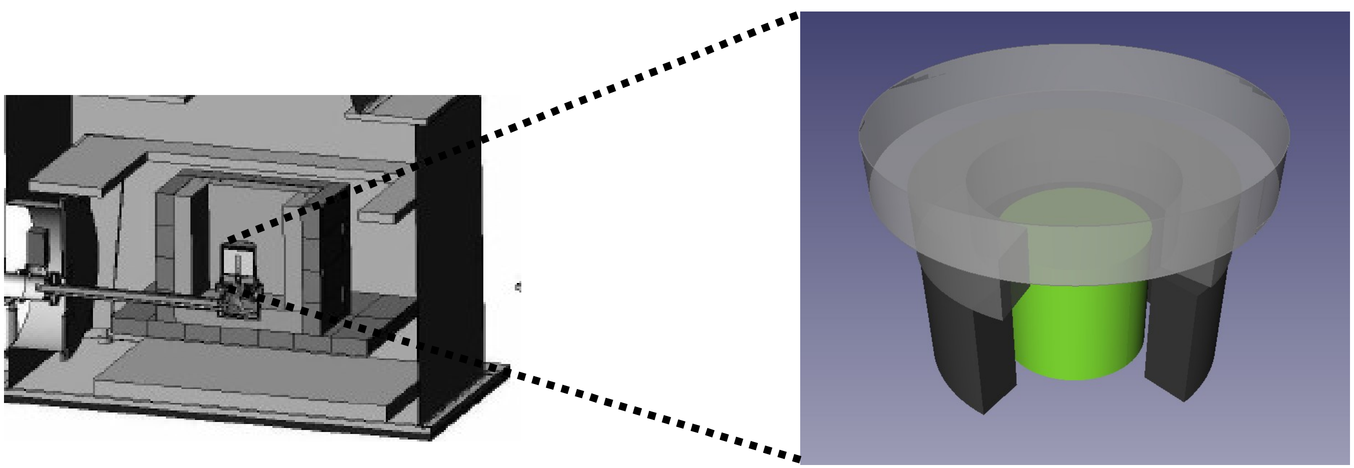
Pb target HPGe detectord

High purity Ge detector measurement (Matthias Laubenstein):

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

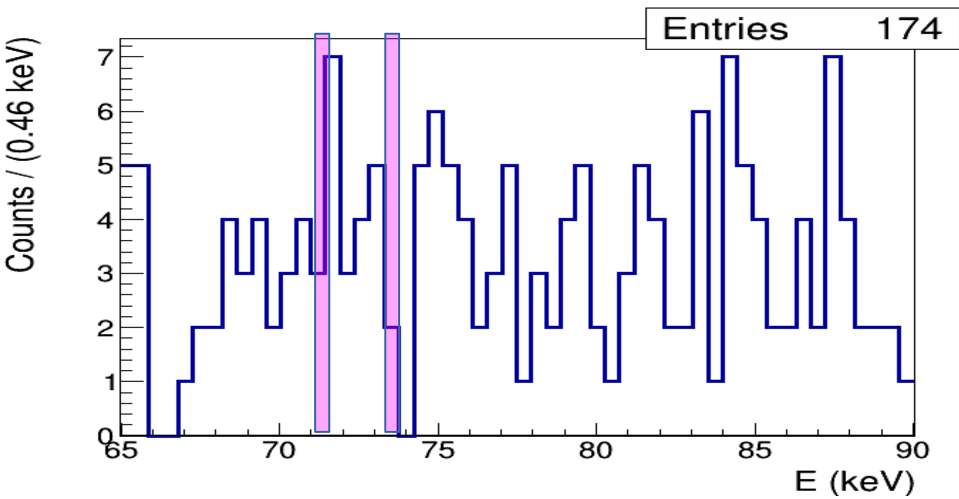
- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).



Data analysis – normalised sig and bkg shapes

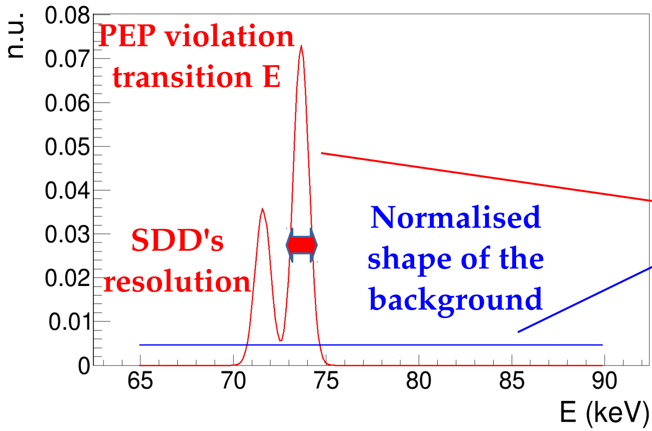
- **Two data sets (total 71 days) August 2016-August 2017**
- **$f_B(E)$ flat in the range ΔE = (65 - 90)keV (standard transition lines do not emerge over flat bkg) mean bkg per bin : b ~ 7 counts/keV**



Transitions in Pb	forb.	allow.
1s - $2p_{3/2}$ $K_{\alpha 1}$	73713	74961
1s - $2p_{1/2}$ $K_{\alpha 2}$	71652	72798

$$\lambda_i(S,B) = B \cdot \int_{\Delta E_i} f_B(E)\, dE + S \cdot \int_{\Delta E_i} f_S(E)\, dE$$

$$f_B(B) = \frac{1}{\Delta E}$$



$$f_S(E) = \frac{1}{\sqrt{2\pi\sigma^2}} \cdot \left[p_1 \cdot e^{-\frac{(E-E_1)^2}{2\sigma^2}} + p_2 \cdot e^{-\frac{(E-E_2)^2}{2\sigma^2}} \right]$$

$$p_1 = \frac{BR_{K_{\alpha_1}}}{BR_T}, \qquad p_2 = \frac{BR_{K_{\alpha_2}}}{BR_T},$$

Data analysis – priors

- **PRIOR ON B - a Poissonian distribution is assumed with expected value :** $$B_0 = b \cdot \Delta E$$

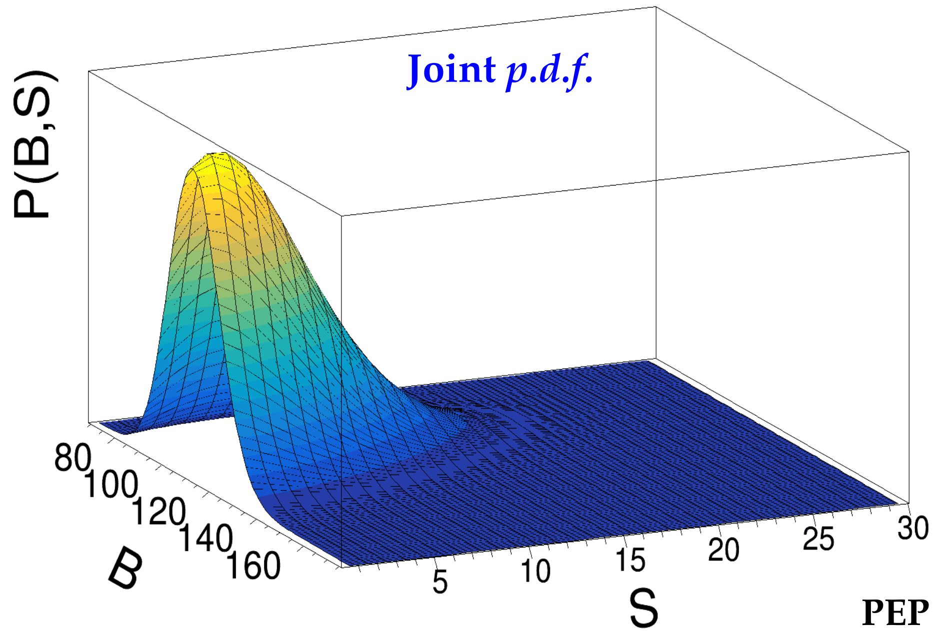
(as a systematic effect a Gaussian prior was tried with no appreciable difference on the result)

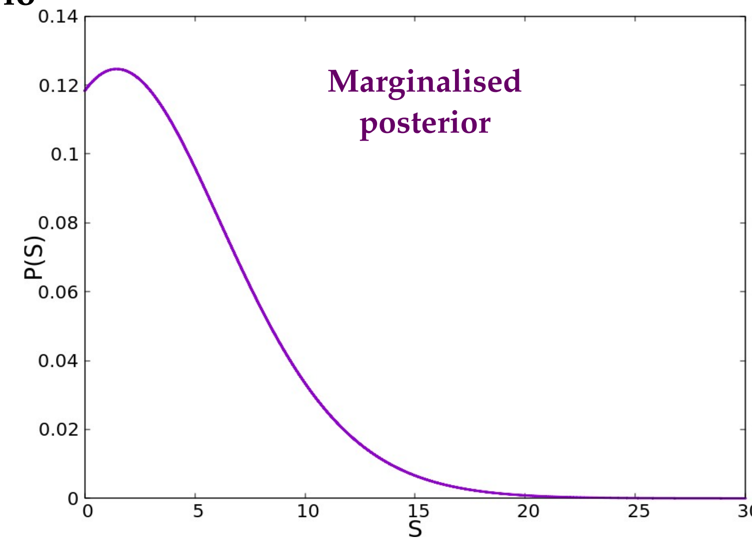
- **PRIOR ON S - given the maximum expected number of signal events S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319] we checked :**
  - **uniform prior** → $$p_0(S) = \begin{cases} \frac{1}{S_{\max}} & 0 \le S \le S_{\max} \\ 0 & \text{otherwise} \end{cases}$$
  - **exponential prior** → $p_0(S) = 1/S_{max} \exp(-S/S_{max})$

(no appreciable systematic effect from the prior choice on the result)

Data analysis – *preliminary results*

posterior is calculated by means of Markow chain Monte Carlo

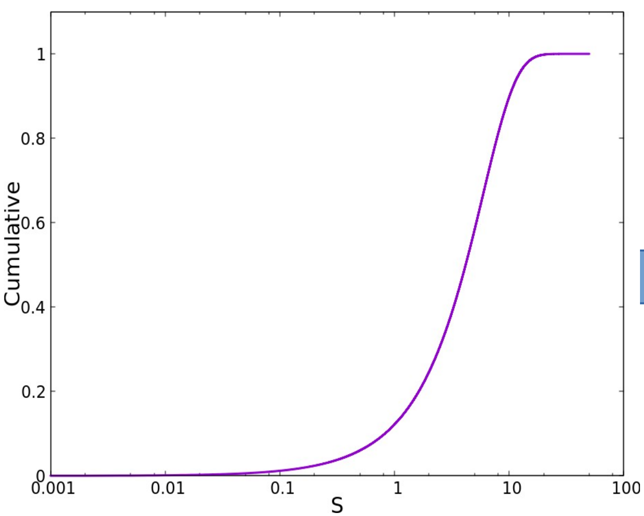




From which an upper limit on the PEP violation probability is obtained (90% Probability):

$$\frac{\beta^2}{2} = \frac{\bar{S}}{\epsilon_{tot} \cdot N_{Pb} \cdot \frac{\Delta t}{\tau_0}}$$

$$\beta^2/2 < 4.7 \cdot 10^{-46}$$

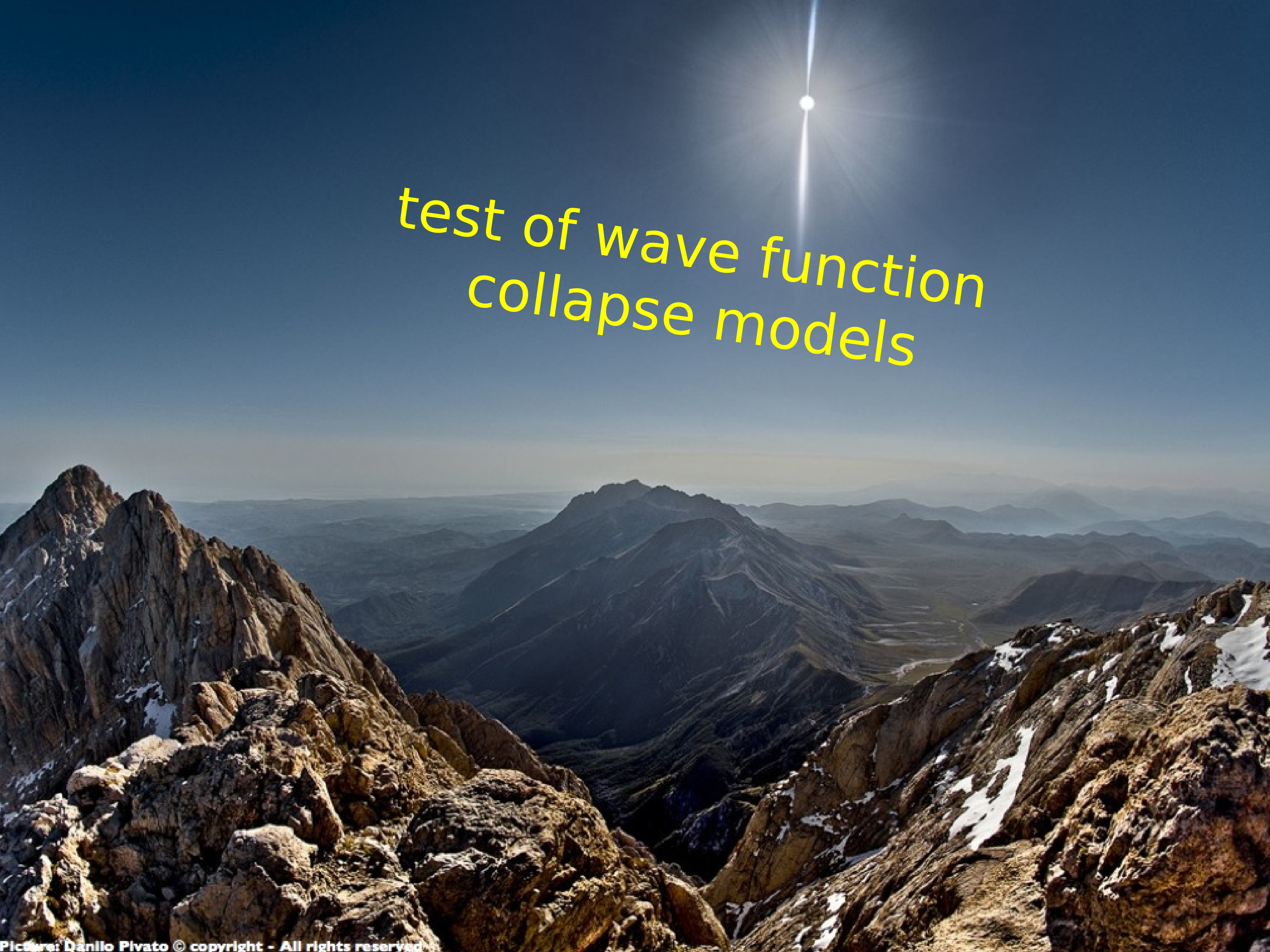


See also:

Bernabei, R., Belli, P., Cappella, F. et al. Eur. Phys. J. C (2009) 62: 327

F. Reines and H. W. Sobel, Phys. Rev. Lett. 32 (17), 1974

A. Addazi et al., Chinese Physics C 42(9), 2017


test of wave function
collapse models
Picture: Danilo Pivato © copyright - All rights reserved

Measurement problem

The linear nature of QM allows superposition of macro-object states → *Von Neumann measurement scheme* (A. Bassi, G. C. Ghirardi Phys. Rep 379 257 (2003))

↓

If we assume the theory is complete .. two possible ways out

- **Two dynamical principles: a) evolution governed by Schrödinger equation (unitary, linear) b) measurement process governed by WPR (stochastic, nonlinear). But .. where does quantum and classical behaviours split?**

- **Dynamical Reduction Models: non linear *and* stochastic modification of the Hamiltonian dynamics:**

(Ghirardi, Rimini, and Weber, Phys. Rev. D 34, 470 (1986); ibid. 36, 3287 (1987); Found. Phys. 18, 1 (1988))

CSL - stochastic and nonlinear terms in the Schrödinger equation induce diffusion process for the state vector → reduction.

DIOSI – PENROSE - selfgravitating energy of the superposition gives the mean-life of the superposition - **superposition of two space-times is suppressed proportionally to the mass**

characteristic parameter R_0 prediction ~ 1 fm

Test of the CSL and gravity-related collapse models

HPGe & LNGS 2014/2015 data campaigns
In coll. With A. Bassi & S. Donadi

According to collapse models a collapsing *white noise* field induces *spontaneous radiation* emission

↓

the pdf of the models parameters is obtained within a Bayesian model:

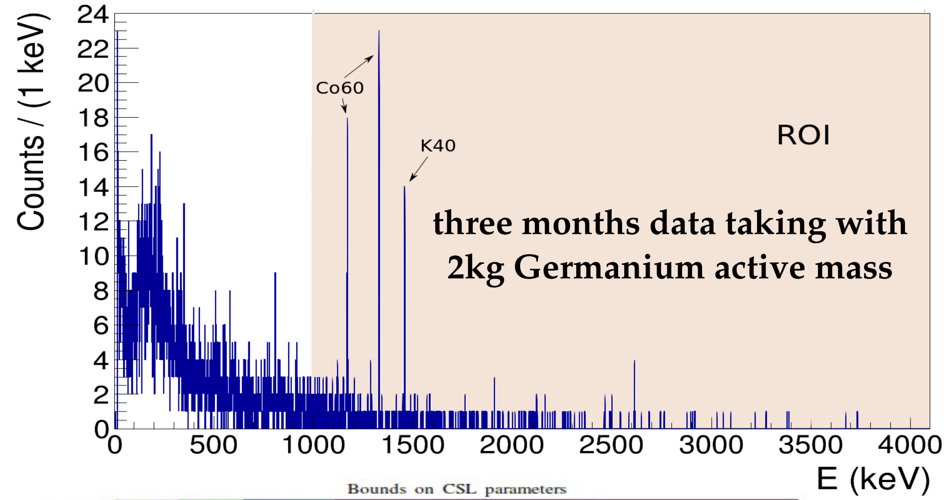
$$\tilde{p}\left(\Lambda_c|p(z_c|\Lambda_c)\right) = \frac{\Lambda_c^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c}$$

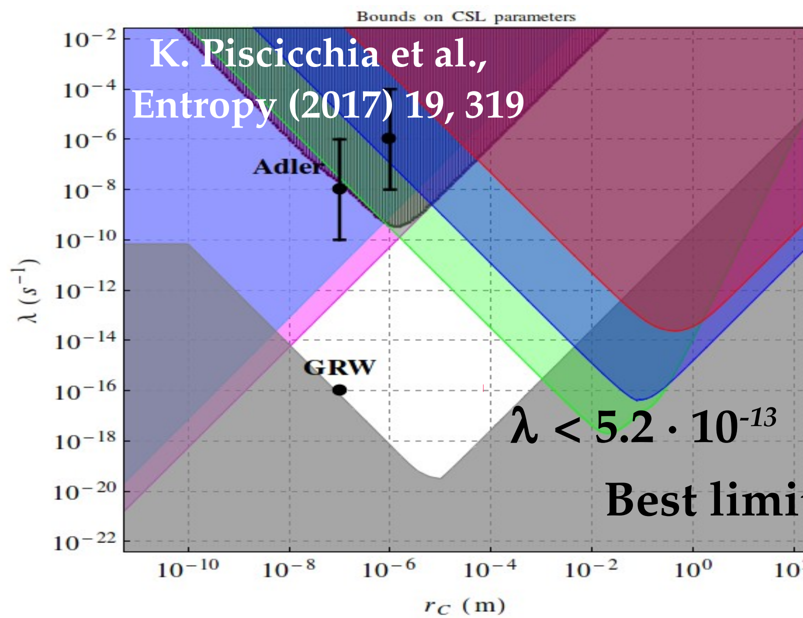
$R_0 > 0.54 \times 10^{-10}$ m **95% C. L.**

Diosi – Penrose ruled out in standard interpretation
Paper submitted to Science

Region Of Interest ΔE=(1000 – 3800)keV compatible with theoretical constrains

cosmic rays, bremsstrahlung from ^{210}Pb & daughters





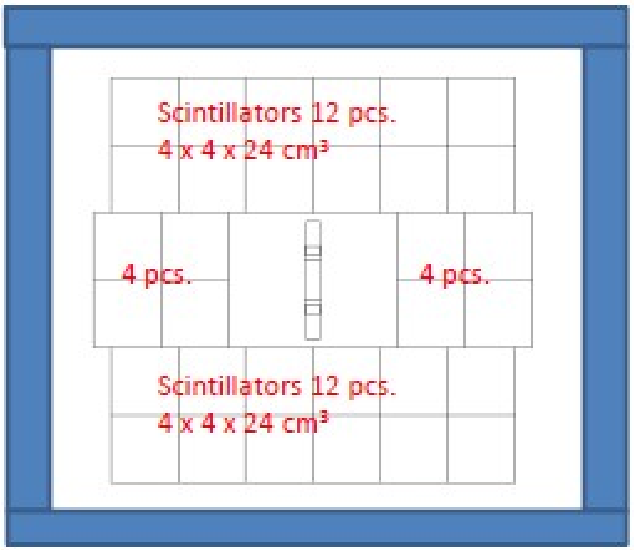
$\lambda < 5.2 \cdot 10^{-13}$ 95% C. L.

Best limit ever


Thank you
:)
Picture: Danilo Pivato © copyright - All rights reserved

New veto system

Experimental setup and Monte Carlo model



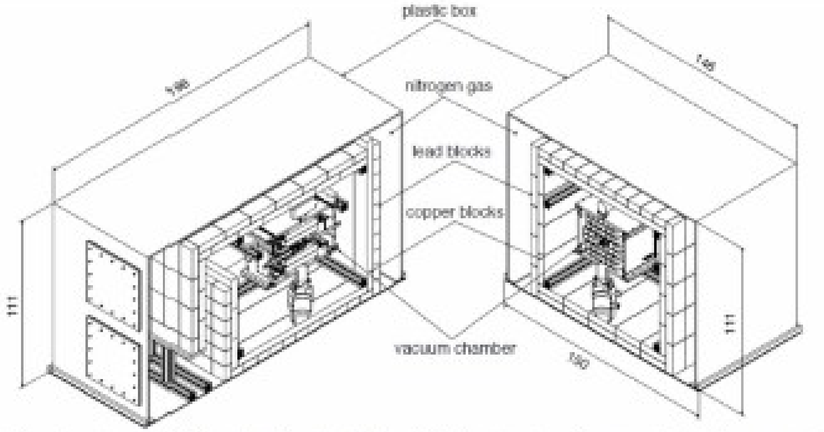
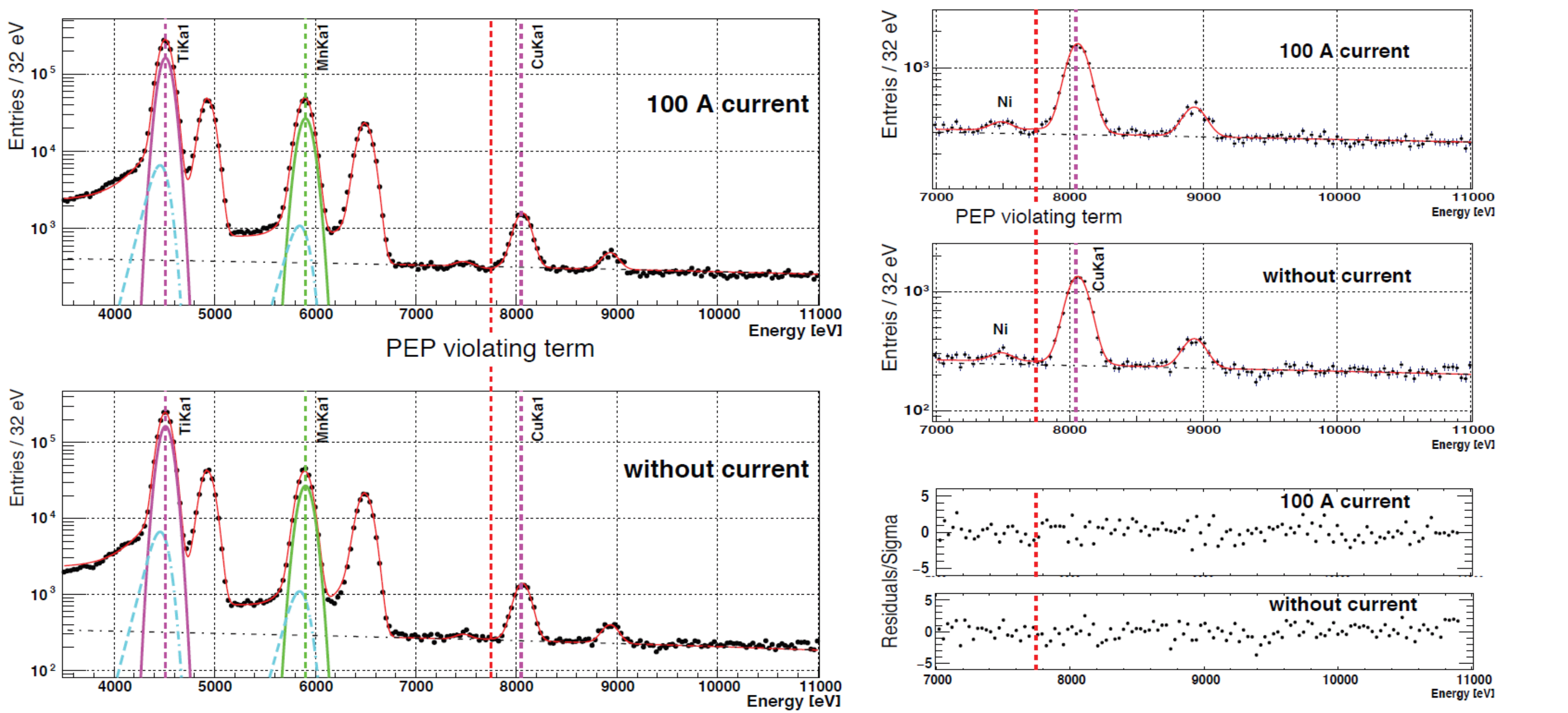


Fig. 3 Perspective views of the VIP-2 apparatus with passive shielding, with the dimensions in cm. Nitrogen gas with a slight over pressure with respect to the outside air will be circulated inside the plastic shielding.

scheme of the setup with plastic scintillators as active shielding

new setup 2018
2 modules of 3.2 x 1.6 cm^2 (4x2 cells) SDDs on each side, each 500 μm thick
Cu: 2.0 x 9.0 cm^2 25 μm thick

New refined data anlysis (same data set) - simultaneous fit of the "sig + bkg" and bkg spectra, in order to use all the information available for the background shape from the data. The obtained fits:



(a) (b)

Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. (a) : the fit to the wide energy range from 3.5 keV to 11 keV; (b) : the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source.

Improved limit on PEP violation probability:

$$\frac{\beta^2}{2} \leq \frac{3 \times 67}{6.0 \times 10^{30}} = 3.4 \times 10^{-29}$$

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Regular Article - Experimental Physics

Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

VIP-2 final setup gain factors

	VIP	VIP2	Gain
acceptance	1 %	7.7 %	~8
current	40 A	100 A	~2
X ray detection efficiency	0.4	0.99	~Sqrt(2)
Energy resolution @ 8 keV	~350 eV	~190 eV	~Sqrt(4)
Reduced active area	114 cm^2	20 cm^2	~Sqrt(6)
Passive Shielding	Yes	No (Yet)	~Sqrt(0.1)

+ ***MC simulations (preliminary) passive shielding contribution to the background reduction ~ sqrt(10)***

Transition energies of the anomalous X-rays in Copper

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

core: (1s)2(2s)2(3s)2(2p*)2(3p*)2(2p)4(3p)4(3d*)4(3d)

Transition	Initial en.	Final en.	Transition energy	Radiative transition rate (s-1)	Multipole order	
$2p_{1/2}$ - $1s_{1/2}$	-45799	-53528	7729	2.63E+14	E1	K_α
$2p_{3/2}$ - $1s_{1/2}$	-45780	-53528	7748	2.56E+14	E1+M2	K_β
$3p_{1/2}$ - $1s_{1/2}$	-44998	-53528	8530	2.78E+13	E1	
$3p_{3/2}$ - $1s_{1/2}$	-44996	-53528	8532	2.68E+13	E1+M2	

Normal copper: ~ 8050 eV (2p → 1s)

Note: similar value obtained by S. Di Matteo e L. Sperandio in the “sudden approximation” – preprint LNF this β can be simply related to the q parameter of the quon theory of Greenberg and Mohapatra

$$\frac{1}{2}\beta^2 = \frac{1+q}{2}$$

quon algebra is a sort of weighted average between fermion and boson algebra:

$$\frac{1+q}{2}\left[a_k, a_l^+\right]_- + \frac{1-q}{2}\left[a_k, a_l^+\right]_+ = \delta_{kl}$$

or also

$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$

Pauli Exclusion Principle (PEP)

Several proofs exist in QFT which differ in clarity and quality of physical insight.

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

1 - The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)

2 - Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)

3 - The vacuum is the state of lowest energy

4 - The metric of the Hilbert space is positive definite

5 - The vacuum is not identically annihilated by a field

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. 110 (1958) 1450)

Effective field theories of PEP violation

Ignatiev & Kuzmin model: Fermi oscillator with a third state

$a^{+}\|0\|1$	$a\|0\ 0$
	$a\|1$
$a^{+}\|1=\beta\ \|2\ a^{+}\|2=0$	$\|0\ a\|2=\beta\ \|1$

β quantifies the degree of violation in the transition $|1\rangle \rightarrow |2\rangle$

Greenberg, O.W.; Mohapatra, R.N. $a_k a_l^{+} - q a_l^{+} a_k = \delta_{k,l}$

Local Quantum Field Theory, *q* parameter deforms anticommutators, quon theory

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Measurement problem

The linear nature of QM allows superposition of macro-object states → *Von Neumann measurement scheme* (A. Bassi, G. C. Ghirardi Phys. Rep 379 257 (2003))

↓

If we assume the theory is complete .. two possible ways out

- Two dynamical principles: a) evolution governed by Schrödinger equation (unitary, linear) b) measurement process governed by WPR (stochastic, nonlinear). But .. where does quantum and classical behaviours split?

- Dynamical Reduction Models: non linear *and* stochastic modification of the Hamiltonian dynamics:

QMSL - particles experience spontaneous localizations around appropriate positions, at random times according to a Poisson distribution with $\lambda = 10^{-16}$ s^{-1}.

(Ghirardi, Rimini, and Weber, Phys. Rev. D 34, 470 (1986); ibid. 36, 3287 (1987); Found. Phys. 18, 1 (1988))

CSL - stochastic and nonlinear terms in the Schrödinger equation induce diffusion process for the state vector → reduction.