Testing Pauli Exclusion Principle at the LNGS underground laboratories

L. De Paolis

National Laboratory of Frascati (LNF) of INFN

on behalf of the VIP collaboration

Particles and Nuclei International Conference (PANIC 2021) - 22nd edition

5 - 10 September 2021

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

CENTRO FERMI MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

INFN Laboratori Nazionali del Gran Sasso

How it is possible to investigate the PEP with VIP-2

In Quantum Mechanics the Pauli Exclusion Principle (PEP) can be formalized starting from two fundamental principles:

1) All states, including those related to identical particles, are described in terms of wave functions

2) Bosonic and fermionic states have a different behavior in relation to the application of the exchange transformation (permutation) of identical particles: the former are symmetrical and the latter are anti-symmetrical

This superselection rule "does not appear as a necessary feature of the quantum-mechanical description of nature".

Messiah A.M.L. and Greenberg O.W.; *Physics Review* 1964, 136, B248.

States of mixed symmetry could, therefore, in principle, exist

Possible existence of particle states that follow a different statistic than the fermionic or bosonic one.

How it is possible to investigate the PEP with VIP2

The experimental method of VIP2 is based on the introduction of "new" electrons in a copper bar by applying an electric current.

A small violation of PEP can be described in Quantum Mechanics as proposed by Greenberg in

O.W. Greenberg, Nucl. Phys. B (Proc. Suppl.)6, 83–89(1989):

Whenever an electron is captured by an atom, a new state is formed that can have a certain probability of being a mixed symmetry state. This state is highly excited and from its decay one could observe a possible transition prohibited by the PEP.

How it is possible to investigate the PEP with VIP2

Experimental goal: Search for X-rays from PEP violating transitions

Energy transition Kα allowed: 8.05 keV in Cu

PEP forbidden Kα energy transition:

~ 7.74 keV in Cu

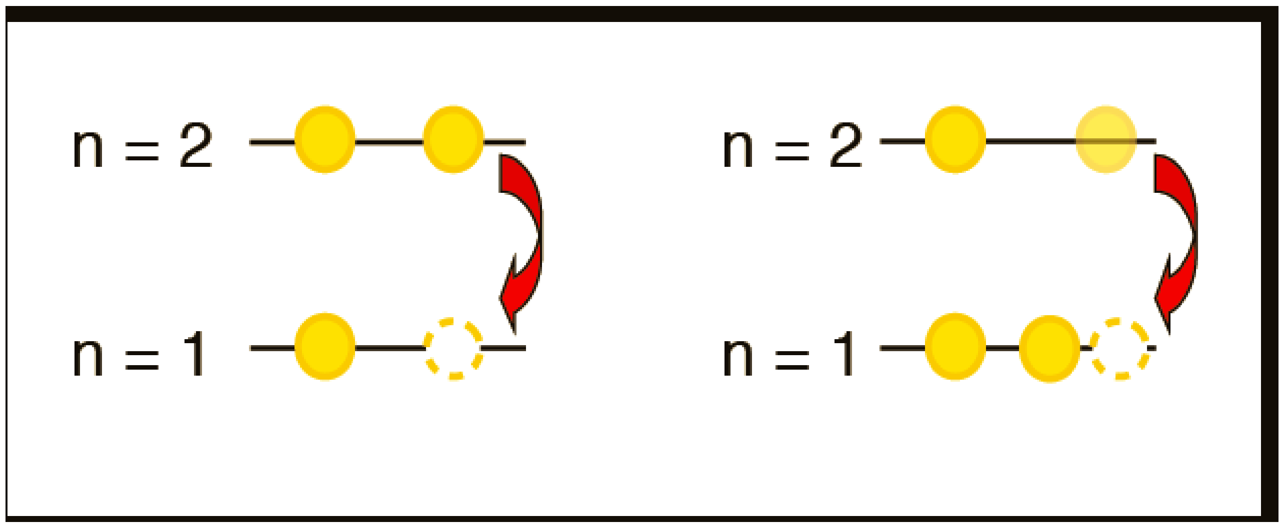
C. Curceanu, L. De Paolis et al., "Evaluation of the X-ray transition energy for the Pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF.

MULTICONFIGURATIONAL DIRAC-FOCK METHOD

Software for muon atoms adapted to non-antisymmetric electrons

Parameter optimization through a self-consistent process

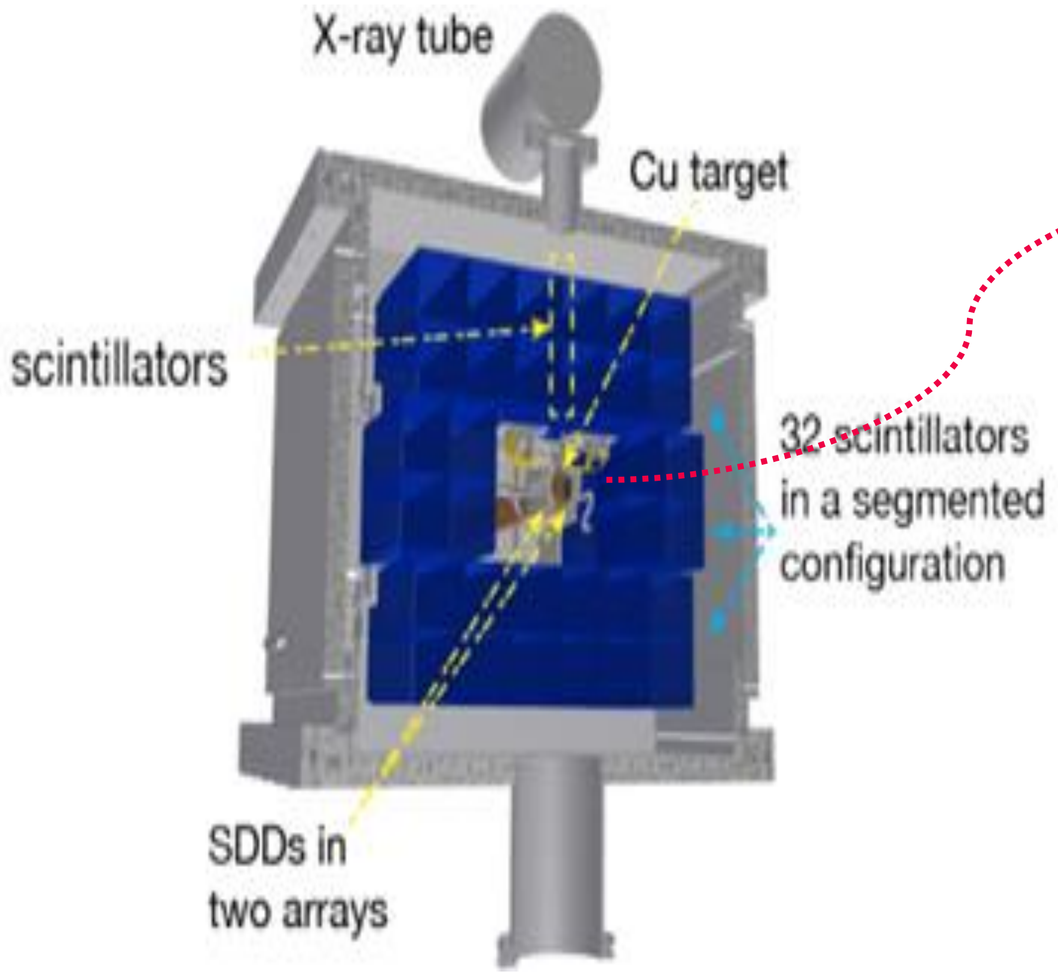
It takes into account: relativistic and radiative corrections, lamb-shift, Breit operator, ...



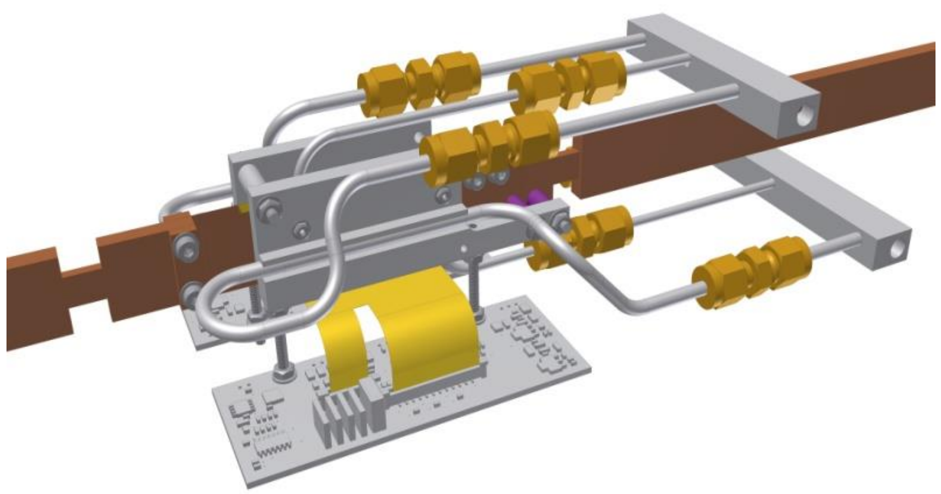
An e- in any level n>2 make a transition to level 2P.
The non-Paulian transition to level 1S produces the emission of a PEP violating X-ray.

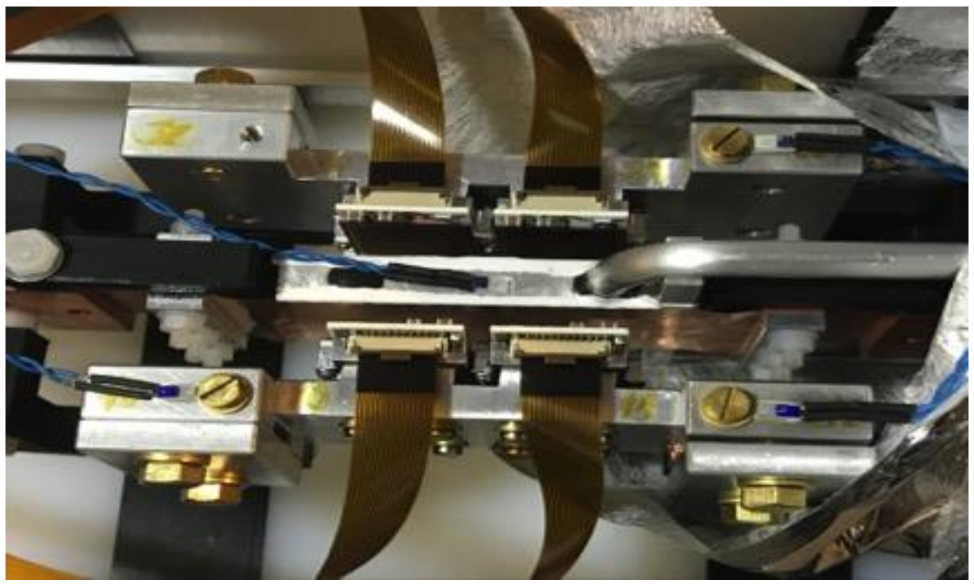
The **VIP2 experiment**: purpose and apparatus.

Schematization of the VIP2 chamber



Target of VIP2

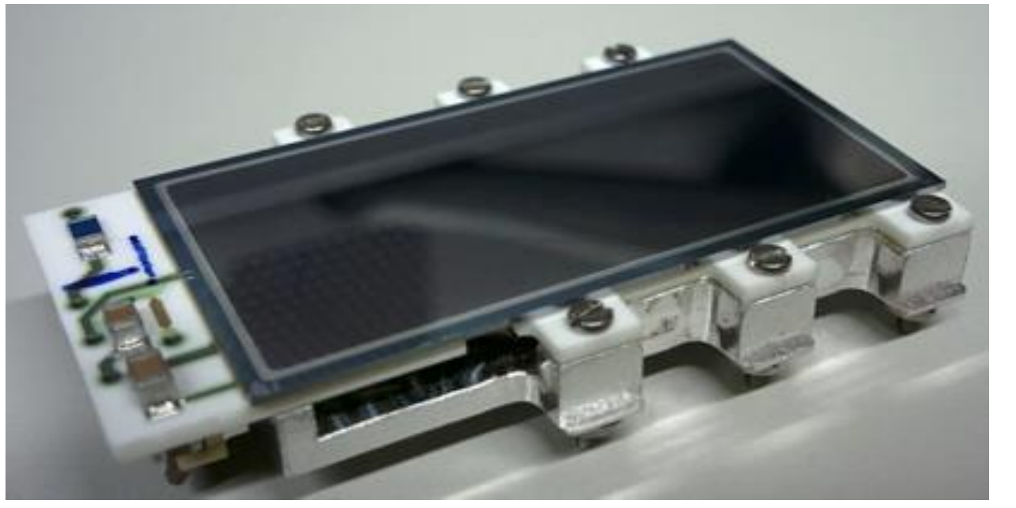




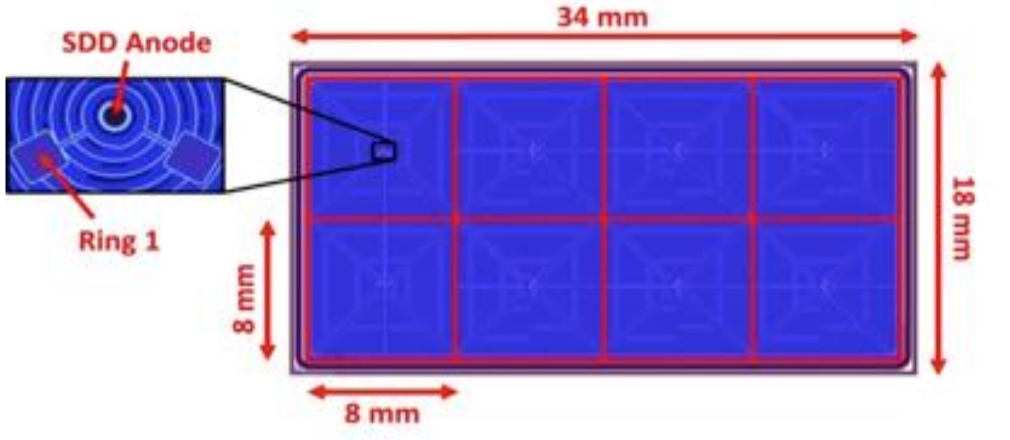
Characteristics of the target: the 2 strips (7 cm x 2 cm x 25 μm) are connected to an external generator by 2 thin copper bars. Due to the Joule effect, the current(100 A) is heating the target to 20 ° C.
A water circuit cools them so that the temperature of the SDDs does not increase by more than 2K.

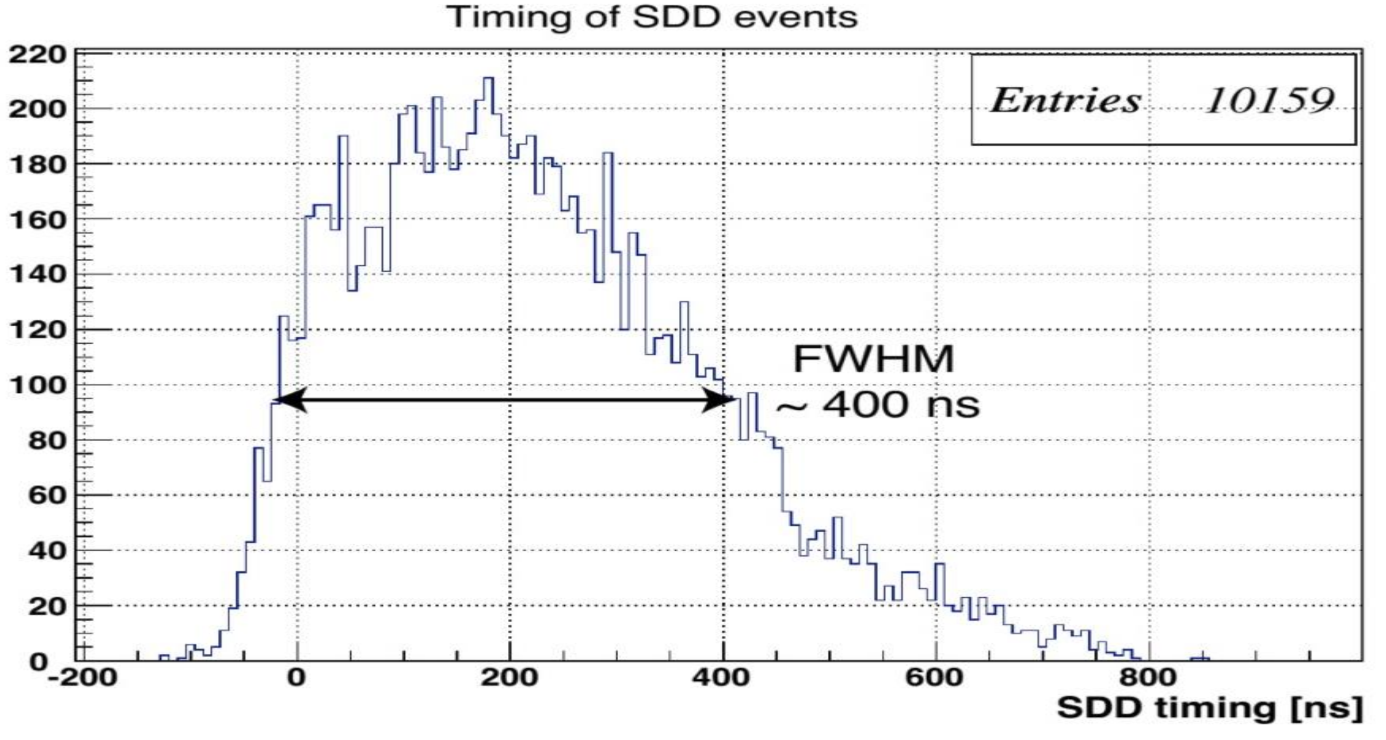
The VIP2 experiment: Silicon Drift Detectors (SDDs)

In the apparatus, detectors are organized in 4 arrays, each consisting of 2 x 4 SDDs, for a total of 32 detector installed in the apparatus. Each SDD cell has an active area of 64 mm^2.



The arrays surround the target to optimize the coverage on a solid angle and are cooled to T≈ 110 K by liquid Argon, thus providing a resolution of **190 eV at 8 KeV**





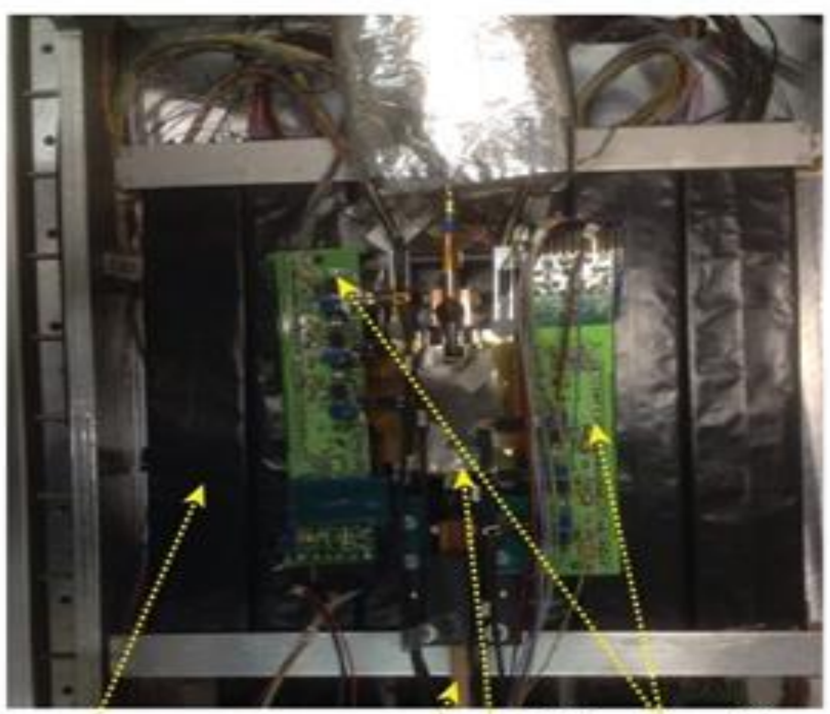
SDDs provide information on radiation energy and timing -> measurement performed with respect to the scintillator trigger: **400 ns (FWHM).**

SUFFICIENT TEMPORAL RESOLUTION TO DISCRIMINATE THE BACKGOUND EVENTS

The VIP2 experiment: the VETO system

Used to select incident events with high energy RC unshielded from rock and environmental background.

Composed of 32 plastic scintillators measuring $45\,cm \times 3\,cm \times 3\,cm$ and covering a solid angle > 90% compared to the target.



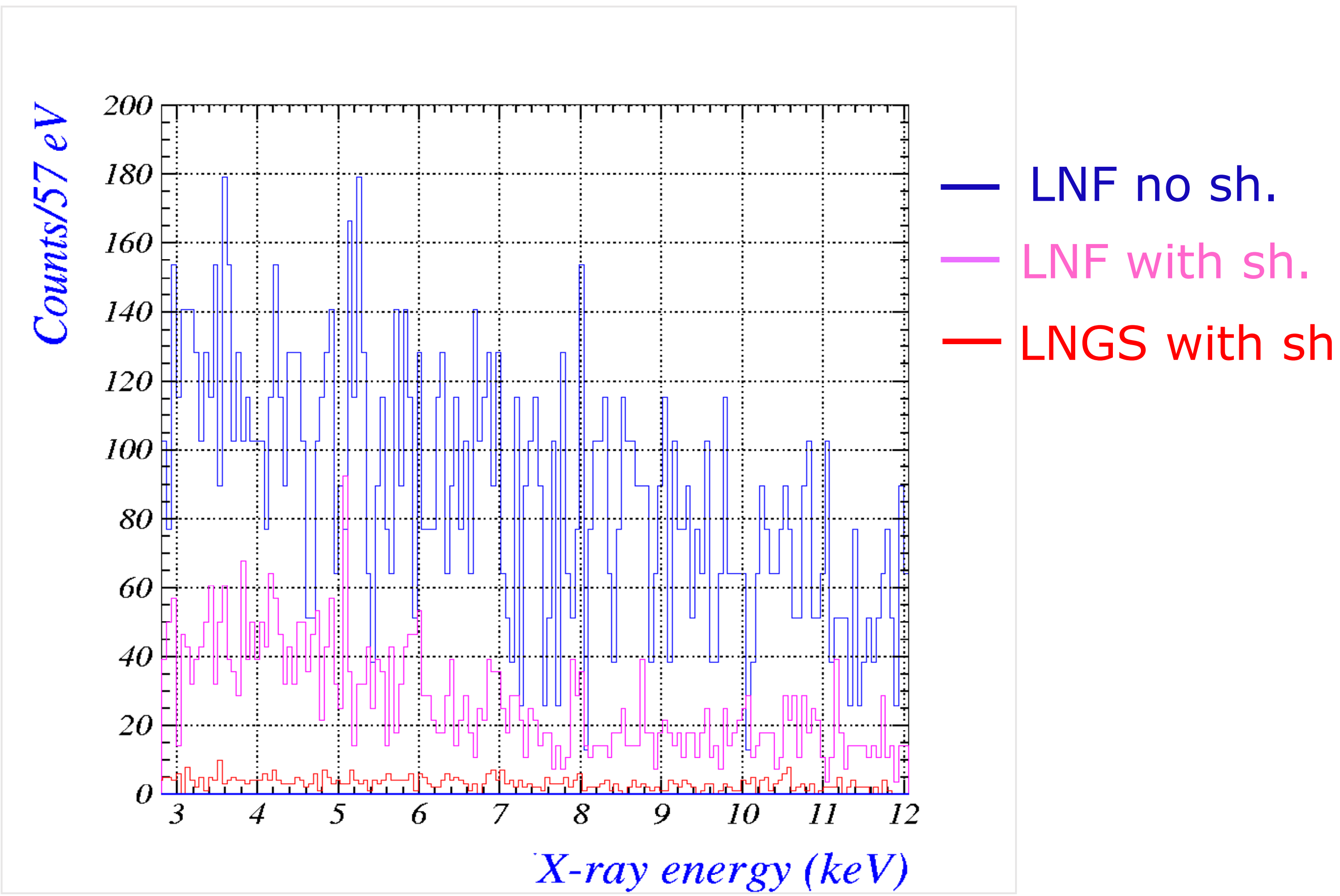
They are read by pairs of SiPM (with $3 \times 3\,cm^2$ of active surface each) located at both ends.

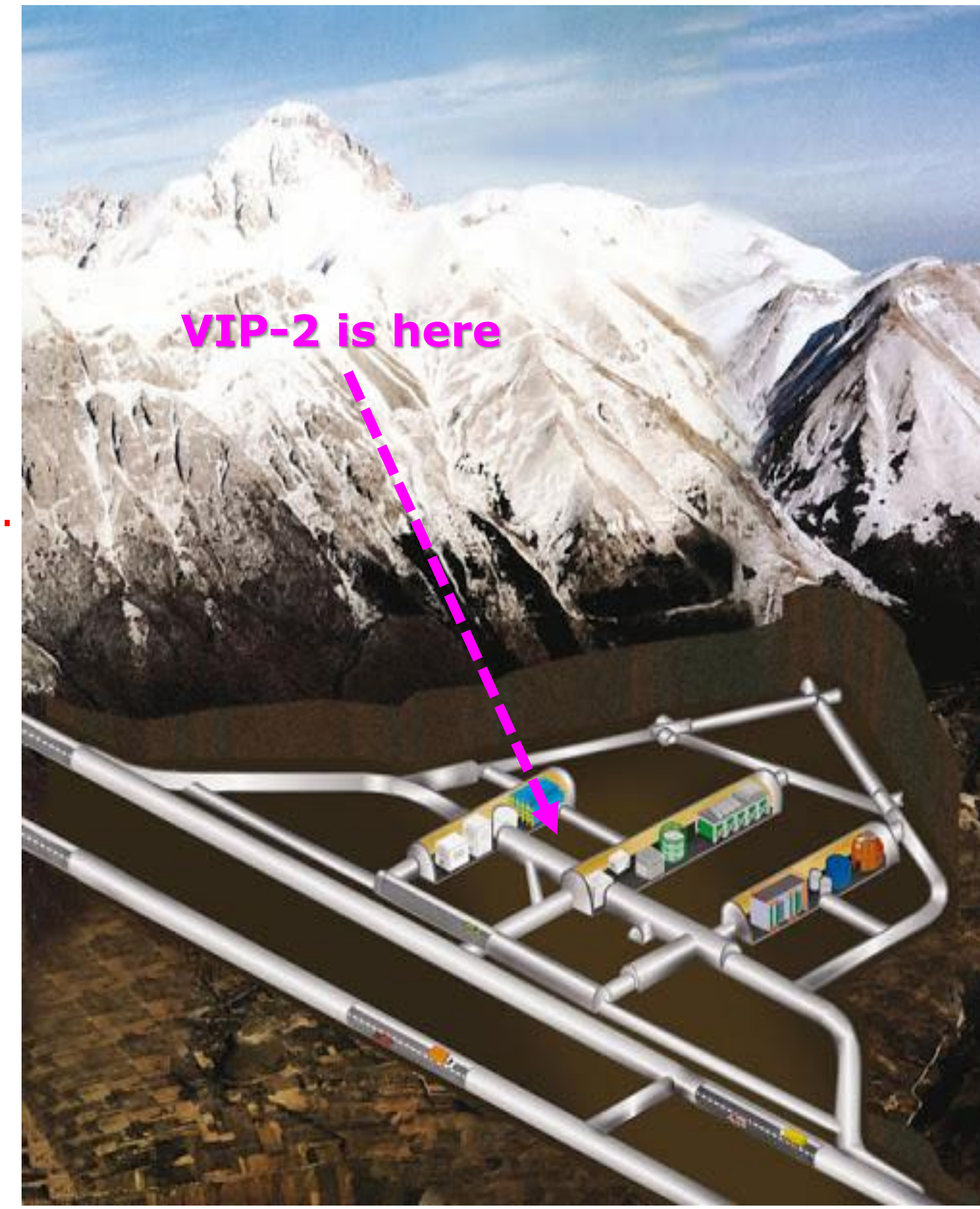
THE ACTIVE SHIELD ALLOWS TO REDUCE THE BACKGROUND IN THE RANGE OF INTEREST FOR A VIOLATION X-RAY OF ABOUT 1 ORDER OF GRANDNESS

The VIP-2 experiment: location.

The experiment is taking place at National Laboratories of Gran Sasso (LNGS), an extremely low background environment inside the Gran Sasso mountain: overburden corresponding to a minimum thickness of 3100 m w.e.

Graphic result of a test done with 2 CCD and normalized distribution





The background is reducted by a factor ≈ 20

The VIP-2 experiment: Improvements and goal

Improvements made compared to VIP:

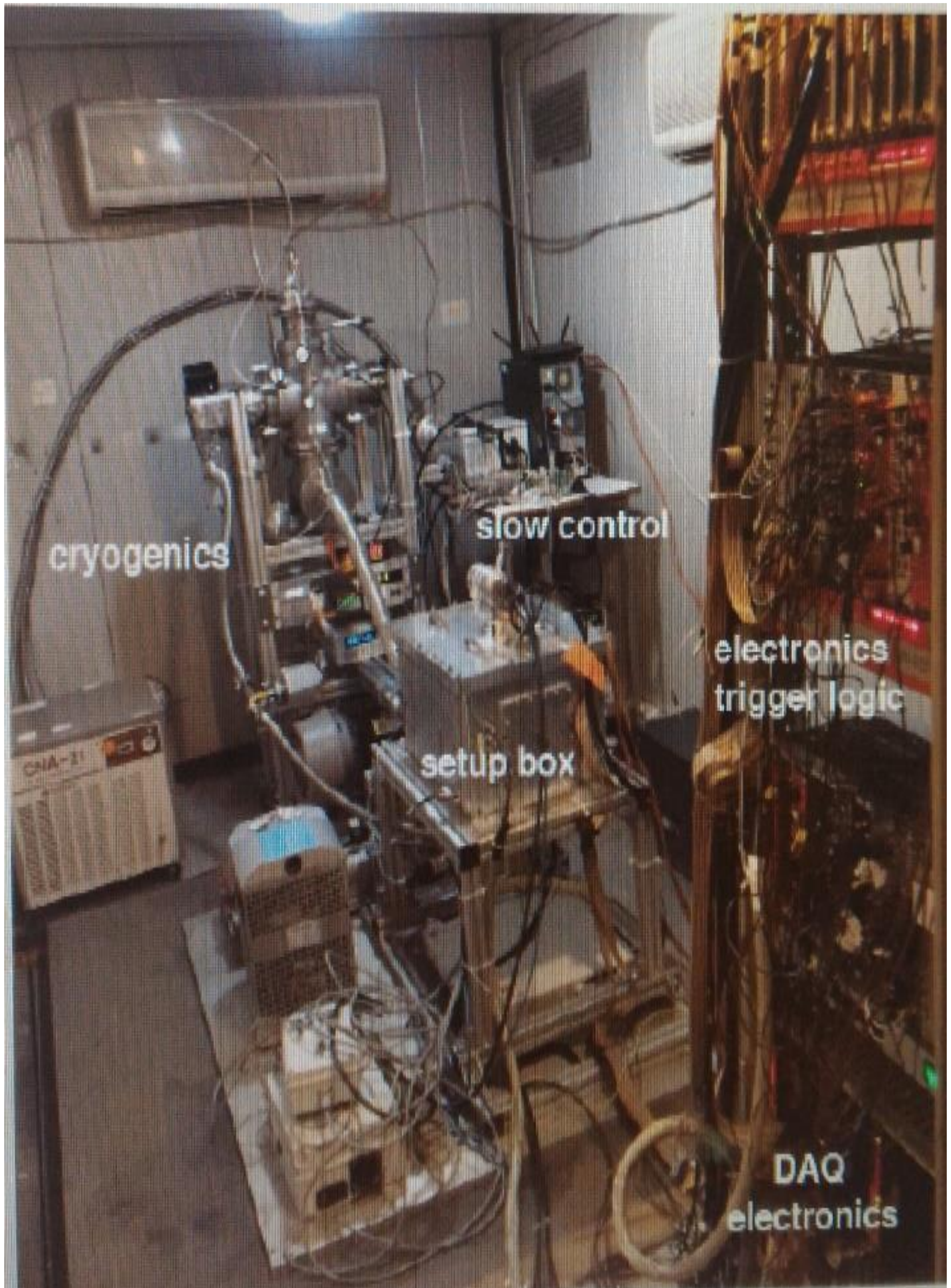
- More compact system → improves acceptance
- New target → 2 strip 7 cm x 2 cm x 25 μm
- Different cooling system for target (water)
- Current flowing into the target > 100 A
- Nitrogen flushing to reduce radon in barrack
- New detectors SDD with better resolution, cooled with liquid Argon (110 K).
- Veto system with plastic scintillators read by SiPM (Silicon Photomultiplier)
- Expected data acquisition 3-4 years.

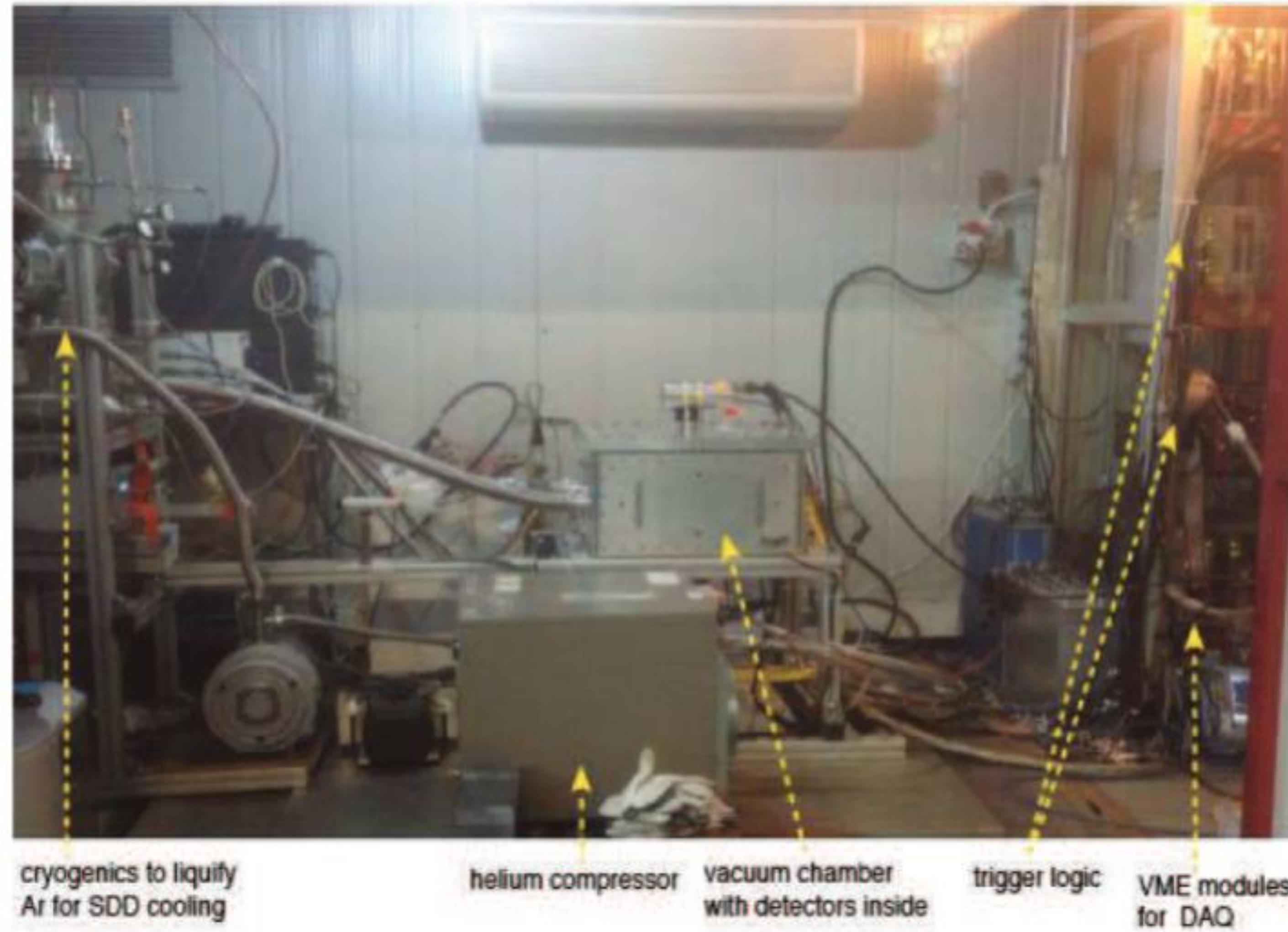
Changes in VIP2	value VIP2 (VIP)	expected gain
acceptance	12 % (~ 1 %)	12
increase current	100 A (40 A)	> 2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV (320 eV) @ 8 keV	4
reduced active area	6 cm ^{2} (114 cm ^{2})	20
better shielding and veto		5-10
higher SDD efficiency		1/2
background reduction		200 - 400
overall improvement		> 120

FUTURE GOAL

$$\boxed{\frac{\beta^2}{2} < 4.7 \times 10^{-29} \rightarrow 10^{-31}}$$

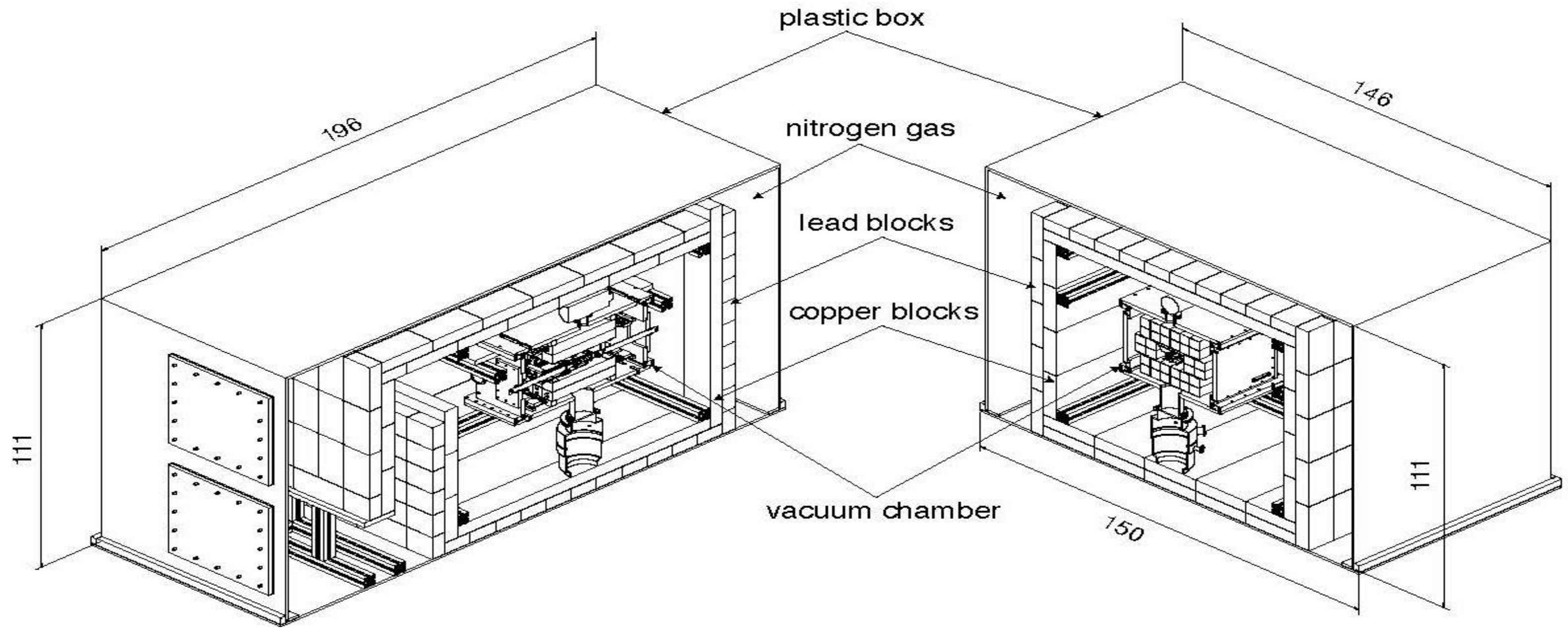
The VIP-2 experiment: photos of the apparatus





Passive shield of VIP-2 apparatus installed in 2018

In November 2018 the final configuration of the VIP-2 experimental apparatus was completed with the passive shielding, made of two layers of lead and copper blocks.



The passive shield will kill most of the background due to environmental gamma radiation.

FIGURE: *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 external air will be circulated inside a plastic box in order to reduce the radon contamination.*

A NEW preliminary upper LIMIT for the PEP violation probability of electrons in copper calculated in the new present configuration of the apparatus

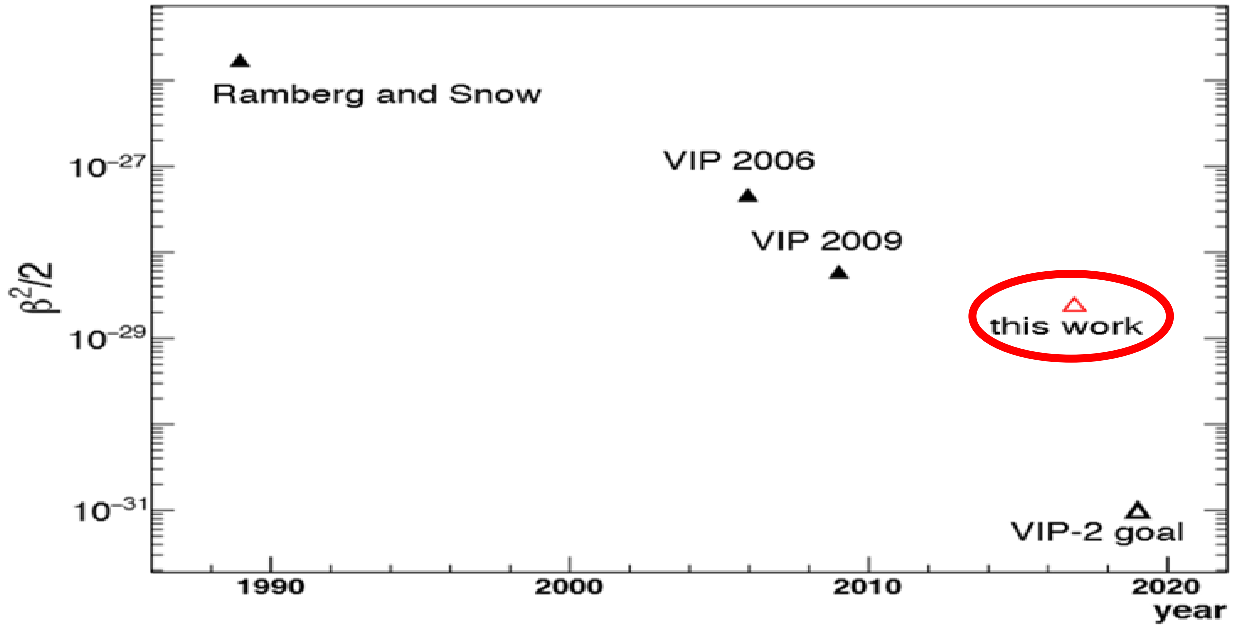
A preliminary result has been calculated using 42 days of data acquired during 2018 in the new present configuration of the apparatus.

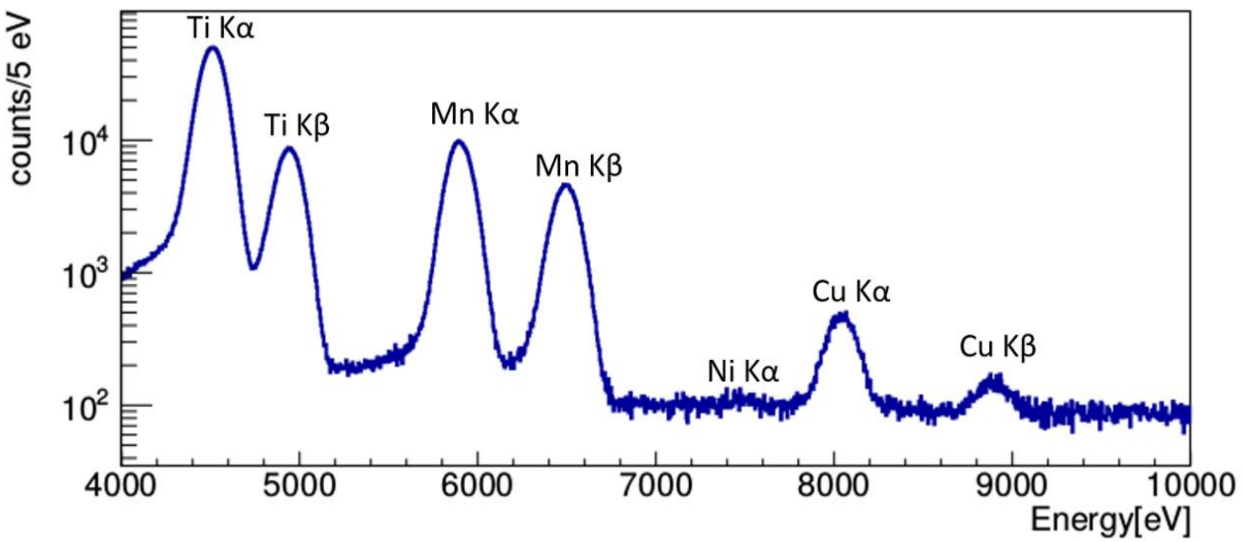
$$\boxed{\Delta N_x = 93 \pm 90}$$

$$\Delta N_x \geq \frac{\beta^2}{2} N_{new} \frac{1}{10} N_{scatt} \times Eff_{riv}$$

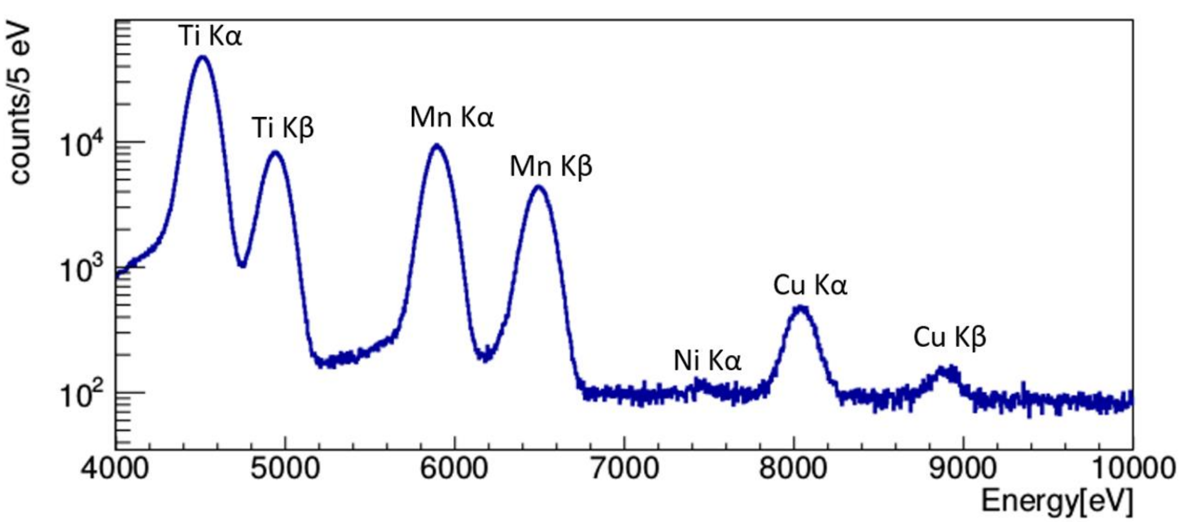
$$\boxed{\frac{\beta^2}{2} \leq 1.6 \times 10^{-29}}$$

Confidence Level: 99.73%





Energy calibrated spectrum with current circulating on target (100 A)



Energy background calibrated spectrum with current off normalized to 42 days

Progress in the VIP-2 experiment

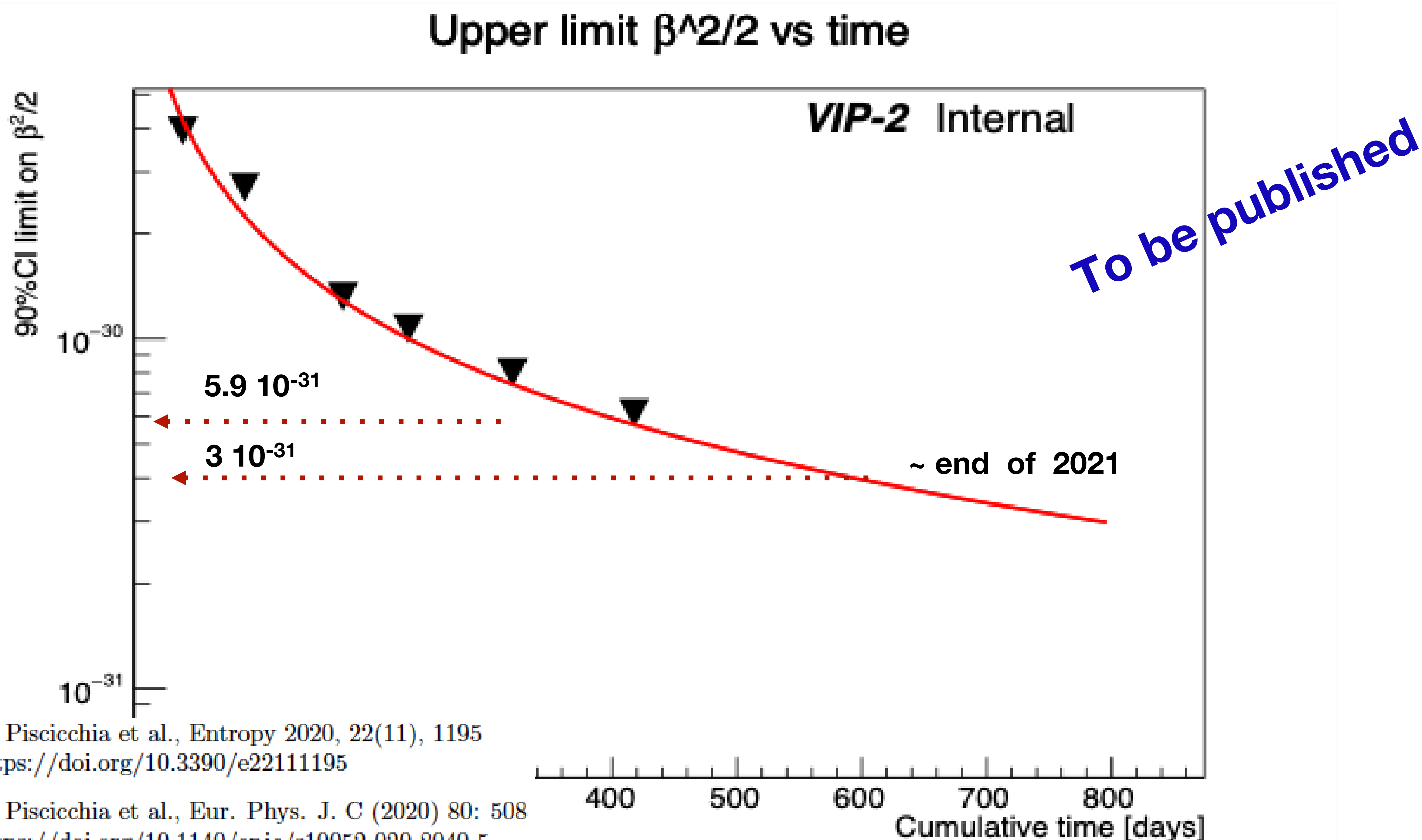
- Regular data taking for the search of signals coming from the violation of the Pauli Exclusion Principle by alternating periods of data taking with current (100 A) and without current (0 A).

- Optimization of the Slow Control system – such as the data taking and all experimental parameters to be controlled from remote

- Continuous energy calibration of the SDD detectors

- New data analyses methods: including new concepts in testing the Pauli exclusion principle in bulk matter and semi-analytical Monte Carlo methods to simulate the signal of the VIP-2 experiment, as well as the development of refined Bayesian analyses methods to extract the limit on the probability for the violation of the Pauli Exclusion Principle for electrons

VIP-2 Sensitivity projection against time



K. Piscicchia et al., Entropy 2020, 22(11), 1195
https://doi.org/10.3390/e22111195

K. Piscicchia et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5

E. Milotti et al., Entropy 2018, 20(7), 515
https://doi.org/10.3390/e20070515

E. Milotti et al., Symmetry 2021, 13(1), 6
https://doi.org/10.3390/sym13010006

How to test Quantum Gravity with the germanium based VIP2 experiment?

The Pauli Exclusion Principle (PEP) is a direct consequence of Spin-Statistics Theorem (SST), which is based on Lorentz Invariance as fundamental assumption.

PEP is a directly related to the fate of space-time symmetry and structure

Lorentz Symmetry may be dynamically broken at a very high energy scale, without this phenomenon accounting for a fundamental breakdown of the symmetry.

In this case, the generation of non-renormalized operators, suppressed as inverse powers of the Lorentz violation scale Λ, is expected.

FROM QUANTUM GRAVITY POINT OF VIEW

There exist approaches to quantum gravity, for which space-time coordinates *do not commute* close to the Planck scale (about $10^{19}\ GeV$), thus deforming Lorentz algebra at a very fundamental level.

The two main classes of non-commutative space-time models embedding deformed Pioncaré symmetries are the one characterized by κ-Poincaré and θ-Poincaré symmetries

How to test Quantum Gravity with the germanium based VIP2 experiment?

For a generic Non Commutative Quantum Gravity (NCQG) inspired model deviations from the PEP in the commutation/anti-commutation relations are parametrized as:

$$a_i a_j^\dagger - q(E) a_j^\dagger a_i = \delta_{ij} \qquad\qquad q(E) = -1 + 2\delta^2(E)$$

where *E* corresponds to the energy level difference, i.e. to the PEP violating X-ray line energy, and *q*(*E*) is related to the PEP violation probability.

For a generic M_k parametrization we have: $M_k : \quad \delta^2(E) = \frac{E^k}{\Lambda^k} + O(E^{k+1})$

- k = 1 corresponds to κ-Poincaré in the Arzano-Marcianò quantization procedure.
- k = 2 corresponds to θ-Poincaré

The transition probability gets a first order correction in Φ_{PEPV} (the PEPV GM energy dependent phase), $\Phi_{PEPV} = \delta^2$ is the quantity under test:

$$W \simeq W_0 \phi_{PEPV} \, ,$$

$$\theta_{0i} = 0 \to \quad \phi_{PEPV} \simeq \frac{1}{2} C \frac{\bar{E}_1}{\Lambda} \frac{\bar{E}_2}{\Lambda}$$

where E_1 and E_2 are the atomic energy levels for the initial and final states

$$\theta_{0i} \neq 0 \to \quad \phi_{PEPV} \simeq \frac{D}{2} \frac{E_N}{\Lambda} \frac{\Delta E}{\Lambda}$$

where ΔE is the transition energy and E_N is the nuclear energy.

The Germanium based VIP-2 experiment: purpose.

Search for the X-rays signature of PEP-violating K_α or K_β transitions in Pb, when the 1s level is already occupied by two electrons.

Transition energies are calculated with an accuracy of few eV, based on a Dirac-Hartree-Slater calculation that includes the Breit interaction and QED corrections (see Ref. *S. R. Elliott, B. H. LaRoque, V. M. Gehman, M. F. Kiddand M. Chen, Found. Phys. 42, 1015-1030 (2012)* for more details and further references concerning the calculation).

The K_α and K_β PEP-violating transitions in Pb are shifted, with respect to the standard lines, as consequence of the shielding effect of the additional electron in the ground state; hence they are distinguishable in precision spectroscopic measurements

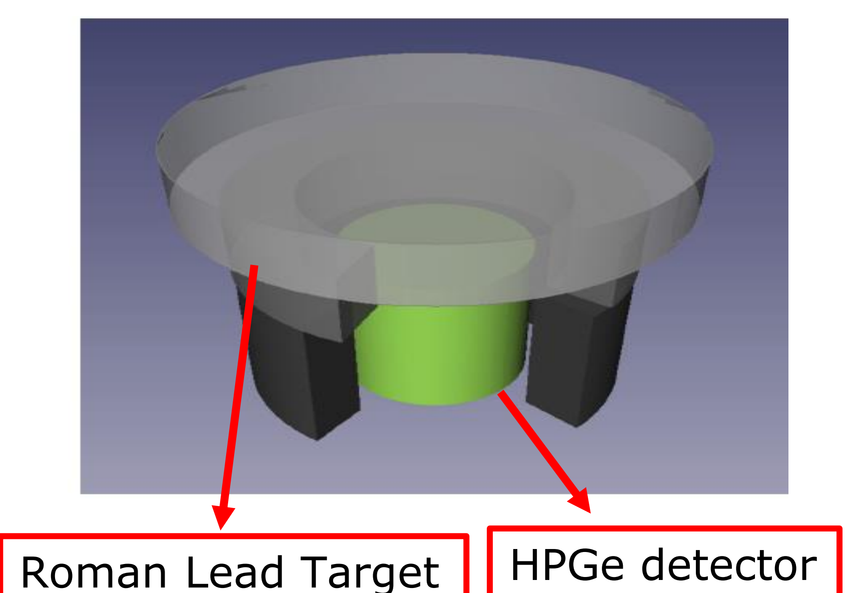
Transitions in Pb	allow.	forb.
1s - $2p_{3/2}$ $K_{\alpha 1}$	74.969	73.713
1s - $2p_{1/2}$ $K_{\alpha 2}$	72.805	71.652
1s - $3p_{3/2}$ $K_{\beta 1}$	84.938	83.856
1s - $4p_{1/2(3/2)}$ $K_{\beta 2}$	87.300	86.418
1s - $3p_{1/2}$ $K_{\beta 3}$	84.450	83.385

Table summarizing the calculated values for the PEP violating K_α and K_β atomic transition energies in Pb (forb.), compared with the allowed ones (allow.).Energies are in keV.

The Germanium based VIP-2 experiment: apparatus.

The VIP-2 germanium based experimental apparatus consist of:

- A high purity co-axial p-type germanium detector (HPGe), with a diameter of 8.0 cm, length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm. The active volume of the detectors is 375 cm^3.
- A target material, composed of three cylindrical sections of radio-pure Roman lead, completely surrounding the detector. The thickness of the target is about 5 cm, for a total volume $V \sim 2.17 \times 10^3 cm^3$
- Passive shielding: inner - electrolytic copper, outer – lead
- 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).



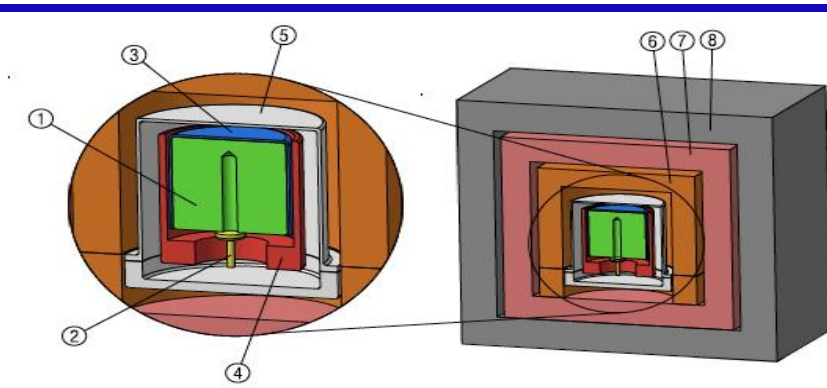
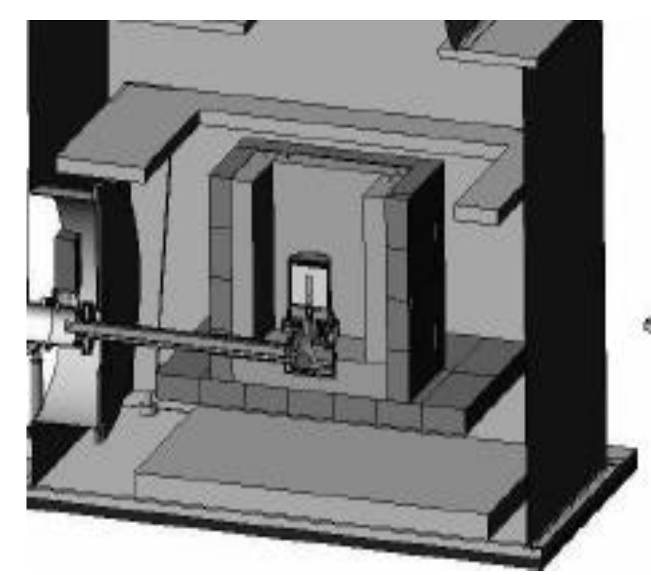


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*



K. P. et al., Eur. Phys. J. C (2020) 80: 508 https://doi.org/10.1140/epjc/s10052-020-8040-5

The Germanium based VIP-2 experiment: measured spectrum and the data analysis

A dedicated Monte Carlo (MC) simulation has been realized, based on the GEANT4 software library and containing all the detailed characteristic of the apparatus, to calculate the efficiency for the detection of photons.

The PEP violation probability is a function of Λ and of the energy

to check the sensitivity of the measured spectrum to the predicted signal, as a function of the energy, a scan is performed searching for deviations from the relevant transitions $(K_{\alpha_1}, K_{\alpha_2})$, $(K_{\beta_1}, K_{\beta_2}, K_{\beta_3})$ and the whole K complex $(K_{\alpha_1}, K_{\alpha_2}, K_{\beta_1}, K_{\beta_2}, K_{\beta_3})$

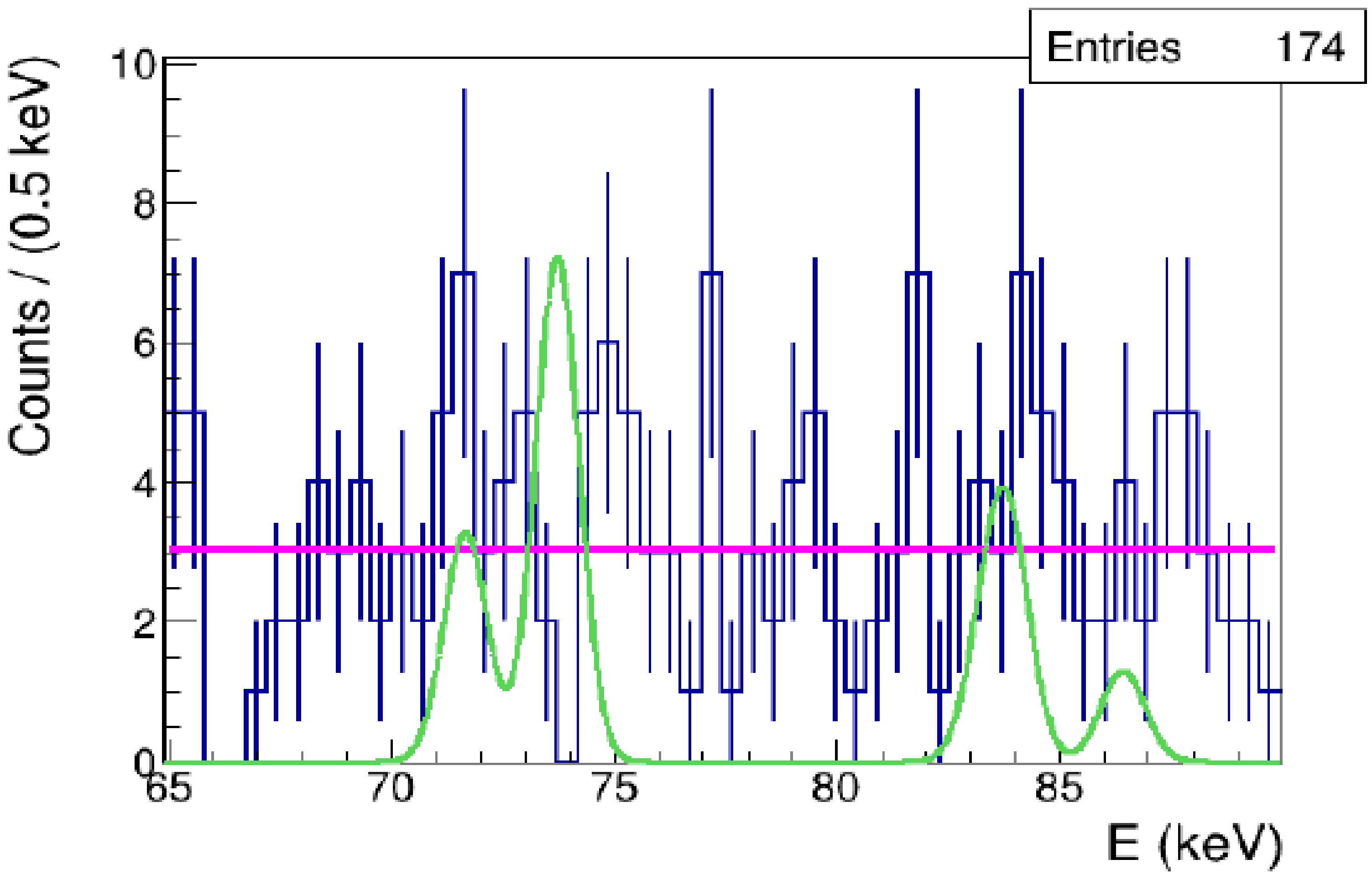
The same procedure has been followed for three independent analyses for each PEP violation parametrization M_k.
The analyses are referred as A_1, A_2, A_3 respectively.

The data analysed in this work correspond to a total acquisition time of:

$\Delta t \approx 70\text{d} \approx 6.1 \cdot 10^6\text{s}$

The **Germanium based VIP-2 experiment**: measured spectrum and the data analysis

The measured x-ray spectrum, in the region of K_α and K_β standard and PEP-violating transitions in Pb, is shown below:



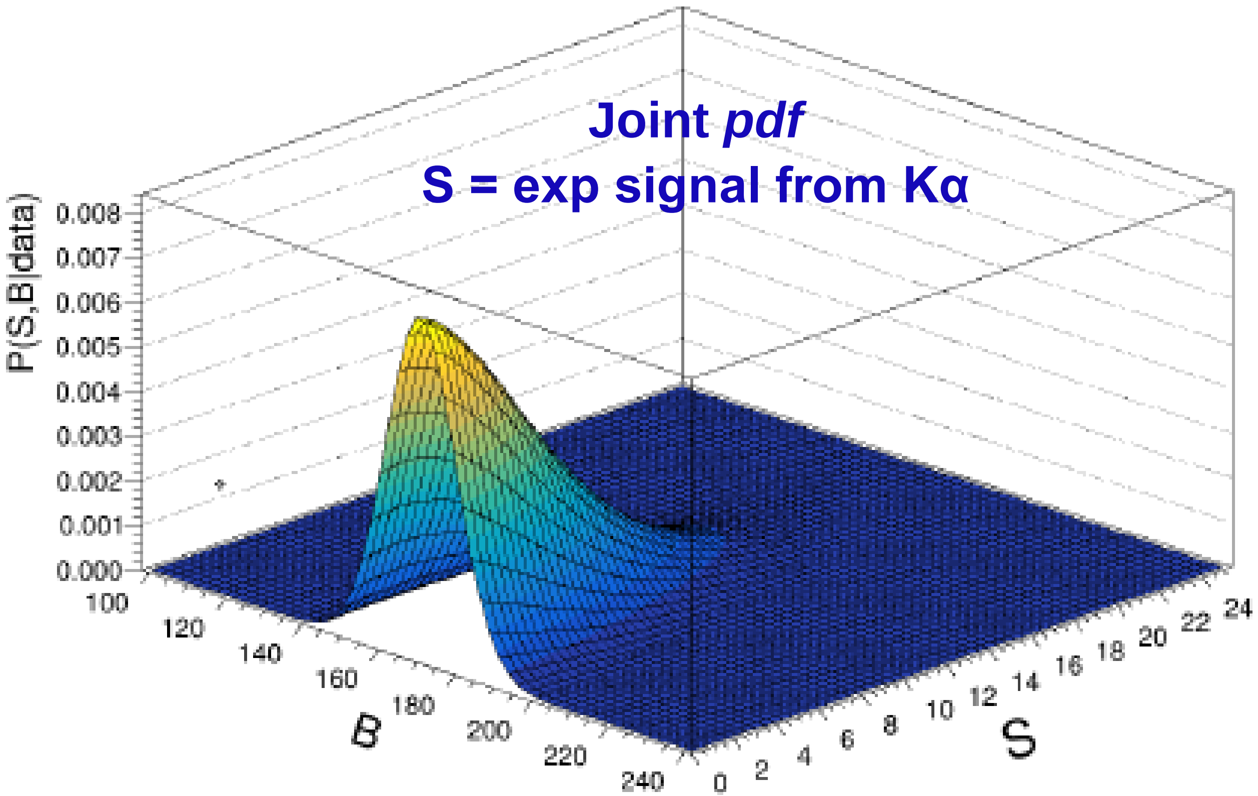
Energy resolution of the detector is: $\boldsymbol{\sigma = 0.5\ keV}$

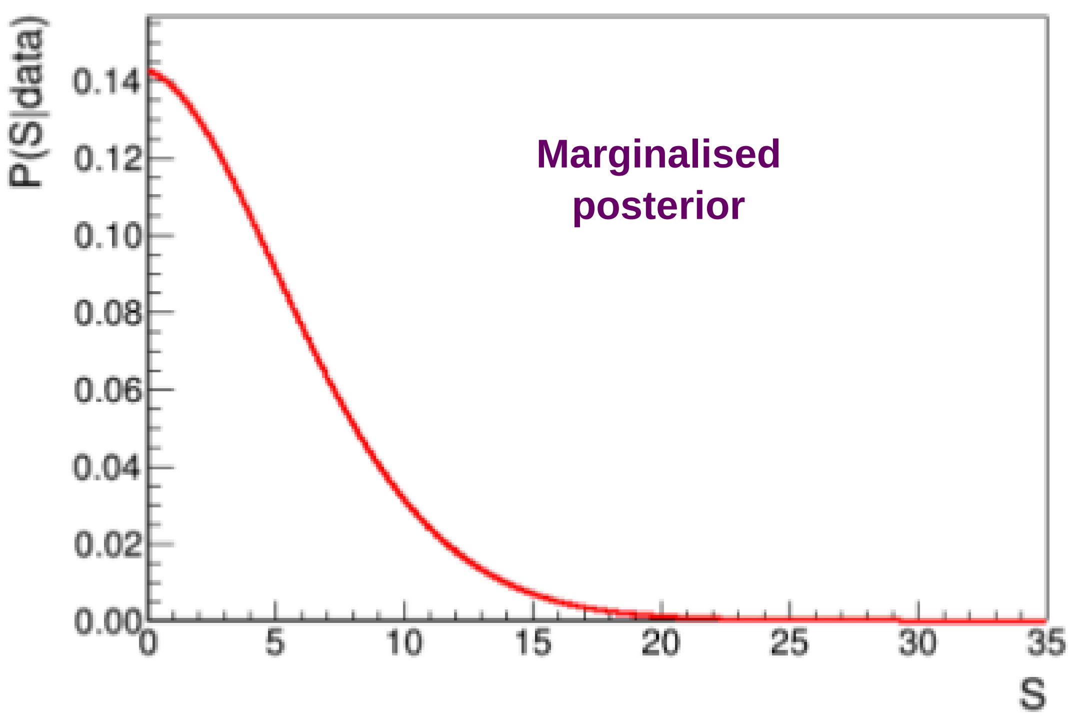
The goal to extract the probability distribution function (*pdf)* of the expected number of photons *S* emitted in $K_{\alpha/\beta}$ violating transitions.

Comparison of $\bar{S}$ with the theoretically expected photons emission, due to PEP violating atomic transitions, provides a limit on the energy scale *Λ* of space-time non-commutativity.

Germanium based VIP-2 data analysis: Upper limit on S

The upper limits on $\bar{S}$ are calculated for each A_i analysis, for each parametrization. As an example the joint posterior *pdf* for A_1 and the parametrization M_1 is:





- The upper limits on $\bar{S}$ are obtained by solving the integral Eq.

$$\tilde{P}(\bar{S}) = \int_0^{\bar{S}} P(S|data)\; dS = \Pi$$

with $\Pi = 0.9$, by means of a dedicated Markov Chain Monte Carlo (MCMC) with relative numerical uncertainty $2 \cdot 10^{-5}$

Germanium based VIP-2 data analysis:
Upper limit on Λ

The comparison of the total expected number of violating transitions predicted by the model and the corresponding upper bound on $\bar{S}$, provides a constraint on the lower limit of the scale, for each A$_i$ and for each parametrization:

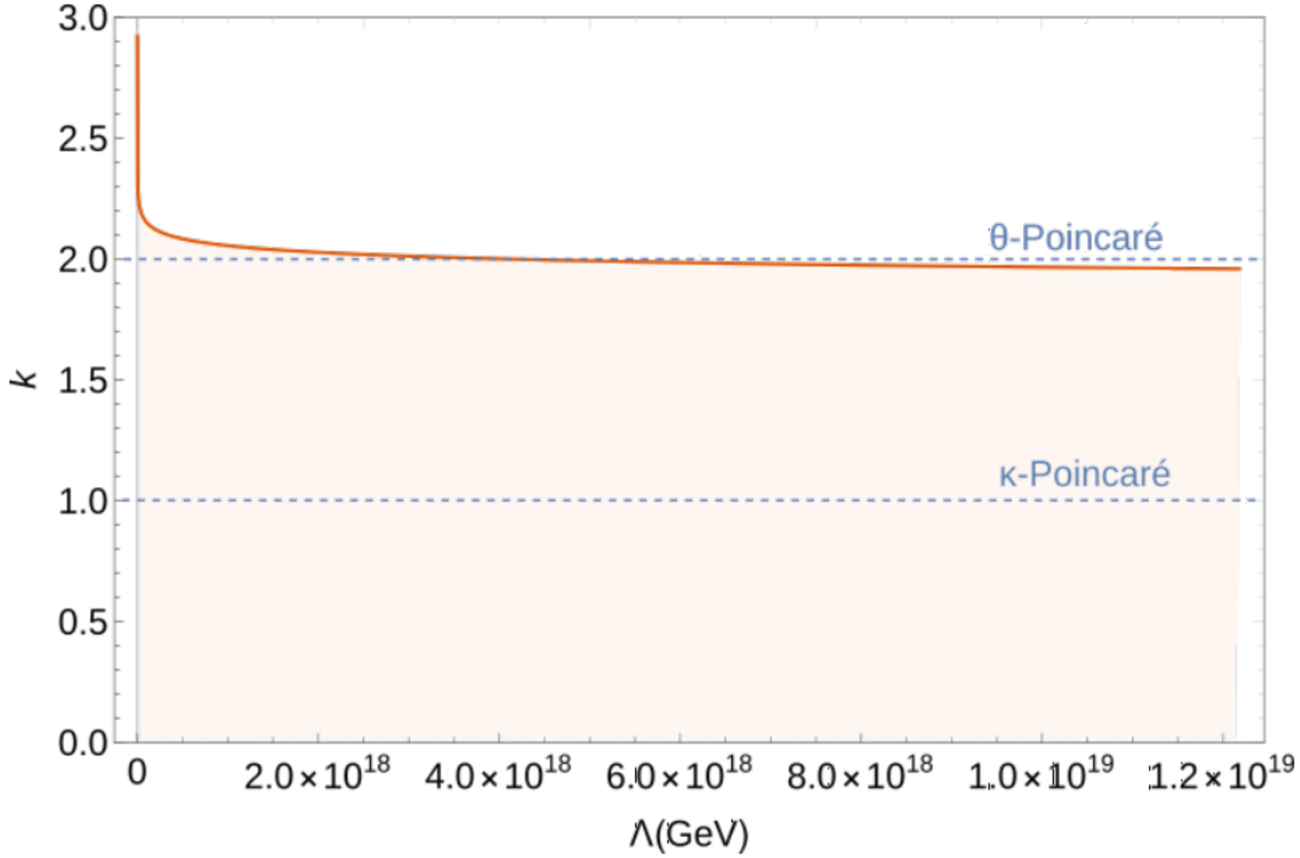
$$\mu = \sum_{K=1}^{N_K} \mu_K = \frac{\aleph}{\Lambda^k} < \bar{S} \Rightarrow \ \Lambda > \left(\frac{\aleph}{\bar{S}}\right)^{1/k}.$$

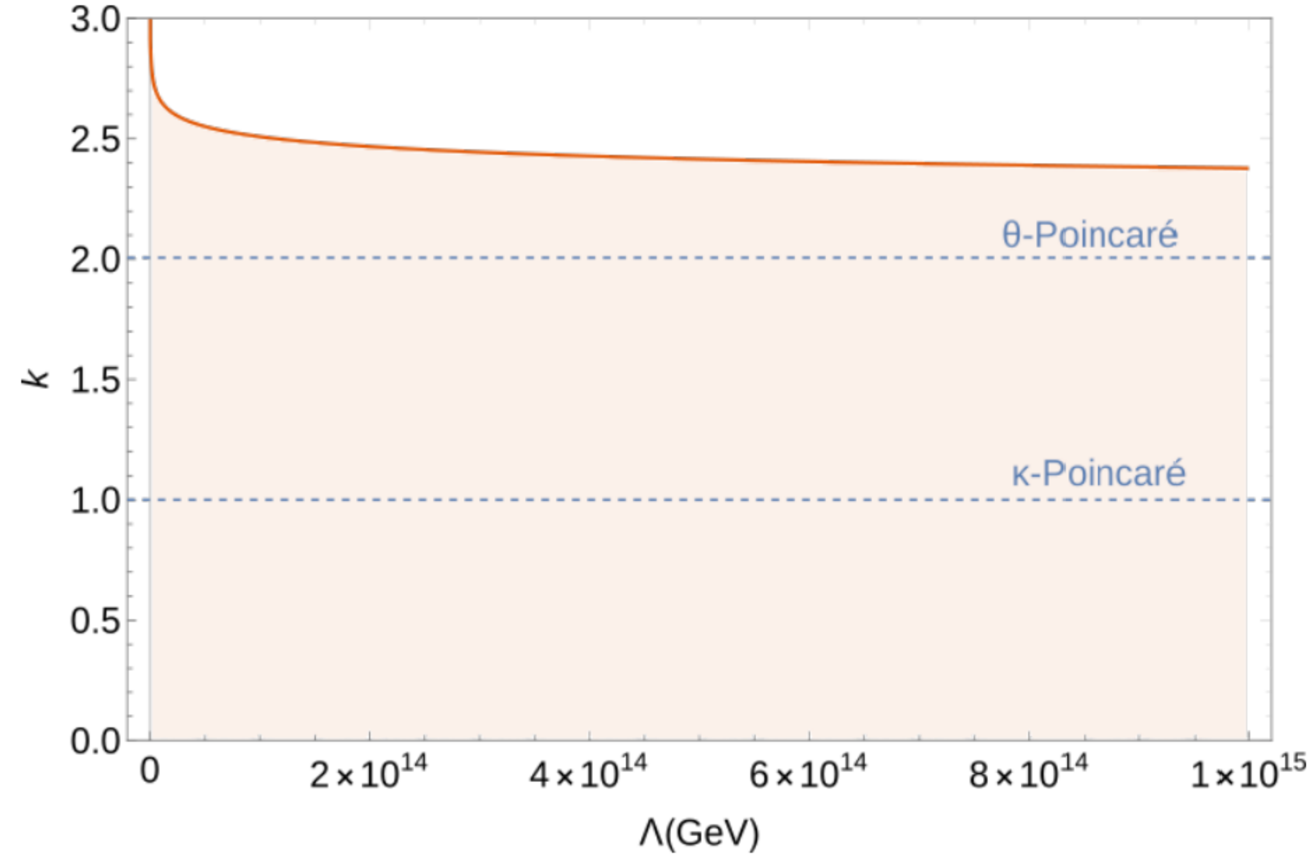
where N_K is the number of PEP violating K transition survived in the analysis A_i.

A_i, M_k	$\bar{S}$	lower limit on Λ in unit of Planck scale
A_1, $k=1$	11.4913	$3.1 \cdot 10^{21}$
A_1, $k=2$	11.3776	$1.4 \cdot 10^{-1}$
A_1, $k=3$	11.2610	$4.9 \cdot 10^{-9}$
A_2, $k=1$	15.1408	$2.8 \cdot 10^{21}$
A_2, $k=2$	15.1640	$1.4 \cdot 10^{-1}$
A_2, $k=3$	15.1859	$5.1 \cdot 10^{-9}$
A_3, $k=1$	18.7270	$4.2 \cdot 10^{21}$
A_3, $k=2$	19.1847	$1.6 \cdot 10^{-1}$
A_3, $k=3$	19.5993	$5.6 \cdot 10^{-9}$

The table summarizes the upper limits $\bar{S}$ on the expected numbers of signal counts, and the corresponding lower bounds on the non-commutativity scale Λ, for each analysis A_i and for the M_k parametrization corresponding to k = 1,2,3.

Germanium based VIP-2 data analysis:
Results and future perspectives





Exclusion plots represented in the Planck scale window (left) and the GUT scale window (right) of the non-commutativity scale Λ (x-axis). The energy powers k is represented on the y-axis. The excluded region is highlighted in orange, the κ-Poincaré and θ-Poincaré cases are represented by blue dashed lines.

- *For κ-Poincaré in the Arzano-Marcianò quantization procedure, the linear energy dependent PEP phase is already ruled out far above the planck scale.*
- *θ-Poincaré is probed up to 0.3 Planck scales, and already excluded at the Grand Unification scale.*

Germanium based VIP-2 data analysis: Results and future perspectives

Considering the specific calculation of the PEP violating atomic level probabilities for θ-Poincarè, the most sensitive analysis is A_3 with upper limits on S = 19 corresponding respectively to:

$\theta_{0i} = 0 \rightarrow$ **Λ > 6.7 10^{-2}**

$\theta_{0i} \neq 0 \rightarrow$ **Λ > 2.6 10^{2}**

The lower limits (90% Probability) are expressed in units of Planck scale !!!

The feature which sets this measurement apart is high atomic number chosen for the target material which, at the price of a limited efficiency, allows to test the space-time non-commutativity energy scale at an unprecedented high atomic transition energy.

The VIP collaboration is presently working on the realization of an upgraded experimental setup, based on cutting-edge Ge detectors, to get a strong improvement on the δ^2 upper bound, and to improve results obtained probing θ-Poincarè up to the Planck scale.


THANK YOU

How it is possible to investigate the PEP with VIP2

O. Greenberg, one of the pioneers of parastatistic studies, says that a possible violation of the PEP could be due to:

"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….".

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

Ignatiev & Kuzmin Model

I & K built the simplest algebra of creation and destruction operators which incorporates in the parameter β the small violations of the Pauli exclusion principle.

Creation and destruction operators connect 3 states :

- $|0\rangle$ empty
- $|1\rangle$ single occupation state
- $|2\rangle$ no-standard state of double occupation (two fermions in the same state)

These are the operation which connect all the three states:

$$a^+|0\rangle = |1\rangle \qquad a|0\rangle = 0$$
$$a^+|1\rangle = \beta|2\rangle \qquad a|1\rangle = |0\rangle$$
$$a^+|2\rangle = 0 \qquad a|2\rangle = \beta|1\rangle$$

Ignatiev & Kuzmin Model

The parameter β express the violation degree of the transition

$$|1\rangle \rightarrow |2\rangle$$

Two fermions are in the same state

⬇

Forbidden by the Pauli exclusion principle

Note that for $\beta \rightarrow 0$ we find the Fermi-Dirac statistic and the Pauli exclusion principle is absolutely valid.

Ignatiev & Kuzmin Model

(A. Yu. Ignatiev and V. A. Kuzmin, Yad. Fiz. 46 (1987) 786, and ICTP preprint IC/87/13 (1987))

Three basic states: $|0\rangle, |1\rangle, |2\rangle$

The actions of creation and destruction operators:

$$a^+|0\rangle = |1\rangle \qquad a|0\rangle = 0$$
$$a^+|1\rangle = \beta|2\rangle \qquad a|1\rangle = |0\rangle$$
$$a^+|2\rangle = 0 \qquad a|2\rangle = \beta|1\rangle$$

$$a^+ = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \beta & 0 \end{pmatrix} \quad a = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & \beta \\ 0 & 0 & 0 \end{pmatrix} \longrightarrow N = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

With $[N, a^+] = a^+$, $[N, a] = -a$

The following relation is obtained:

$$N = \frac{1}{1 - \beta^2 + \beta^4}\left[\left(2 - \beta^2\right)I + \left(-1 + 2\beta^2\right)a^+ a + \left(-2 + \beta^2\right)aa^+\right]$$

Ignatiev & Kuzmin Model

(A. Yu. Ignatiev and V. A. Kuzmin, Yad. Fiz. 46 (1987) 786, and ICTP preprint IC/87/13 (1987))

By applying the perturbation theory to the Hamiltonian:

$$H = H_0 + H_{\text{int}} = EN + \varepsilon V$$

$$V = a^2 a^+ + a^+ a^2 + a a^+ a + h.c.$$

with $E = \sum_n E_n$ and $V = \sum_{i<j} V_{ij}$

$$\varepsilon = E$$

It's possible to determine the transition probabilities:

$$W_{01} = 2\frac{\varepsilon^2}{E^2}\left(1-\cos Et\right)$$

$$W_{02} = 0$$

$$W_{12} = 2\beta^2\frac{\varepsilon^2}{E^2}\left(1-\cos Et\right)$$

Pauli violating transition rate proportional to β²

Historical quotations

- in the words of W. Pauli

PEP lacks a clear, intuitive explanation

... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.

I HAD ALWAYS THE FEELING AND I STILL HAVE IT TODAY, THAT THIS IS A DEFICIENCY.

... The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.

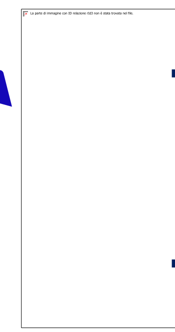
W. Pauli, Nobel lecture 1945

Calculation of limit

$$\Delta N_x \geq \frac{\beta^2}{2} N_{new} \frac{1}{10} N_{scatt} \times Eff_{riv}$$

The factor of detection efficiency has been calculated using a simulation in GEANT4 and it is about 4%

$$\Delta N_x = 93 \pm 90$$



The lenght of the electronic path in copper is ≈7.5 cm

Mean free path

The capture probability of the electron by a copper atom is more than 1/10 respect to the scattering probability.

$$\boxed{\frac{\beta^2}{2} \leq 1.6 \times 10^{-29}}$$

Confidence level (3σ) 99.73%

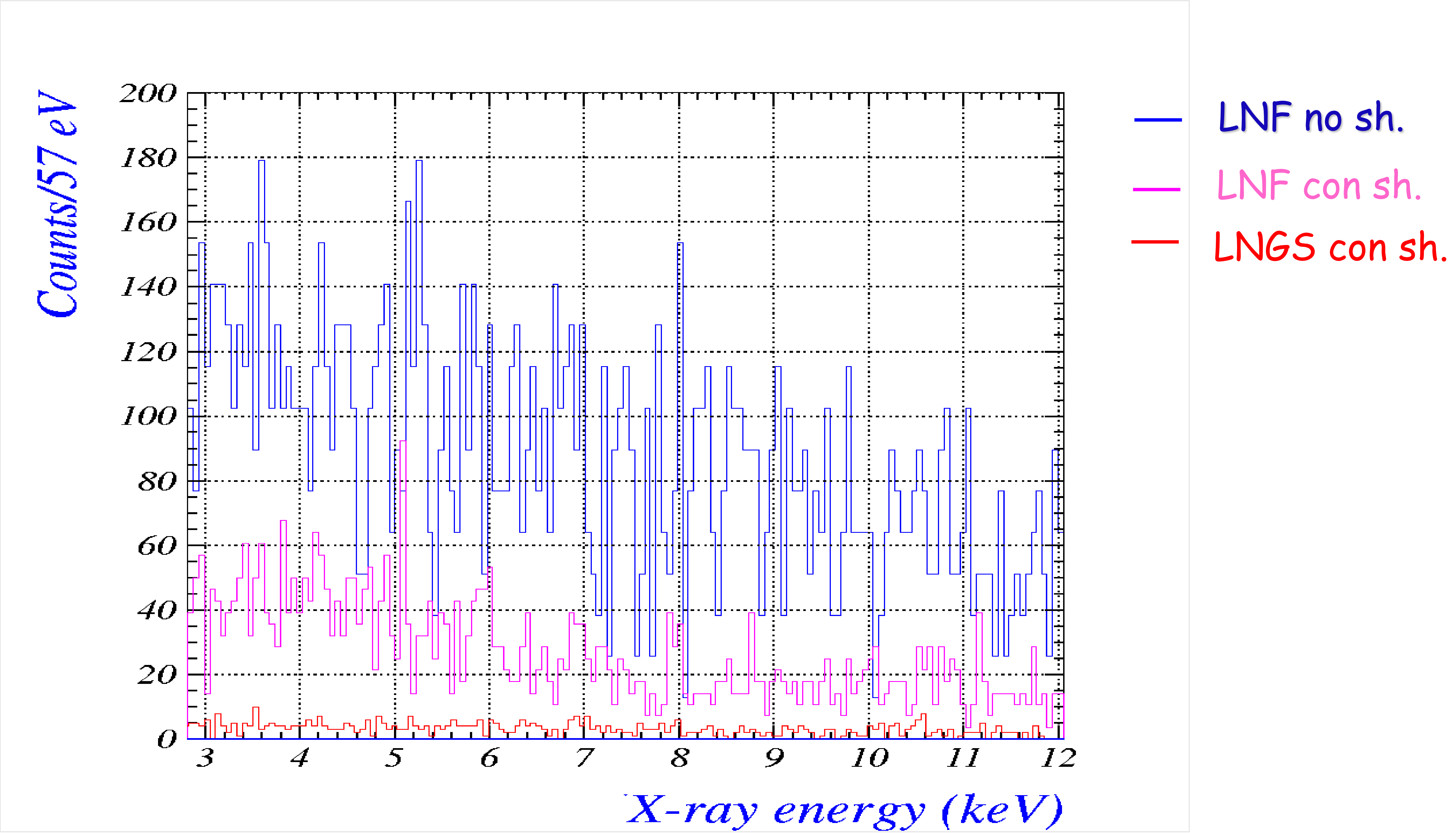
COPPER TRANSITION TABLE

Transition	Pauli Obeyning Transition	Pauli violating transition	Energy Difference
	Standard transition Energy [eV]	Energy [eV]	$E_{standard} - E_{VIP}$ [eV]
$2p_{1/2} \Longrightarrow 1s_{1/2}\ (K_{\alpha 2})$	8,047.78	7,728.92	318,86
$2p_{3/2} \Longrightarrow 1s_{1/2}\ (K_{\alpha 1})$	8,027.83	7,746.73	279.84
$3p_{1/2} \Longrightarrow 1s_{1/2}\ (K_{\beta 2})$	8,905.41	8,529.54	375.87
$3p_{3/2} \Longrightarrow 1s_{1/2}\ (K_{\beta 1})$	8,905.41	8,531.69	373.72
$3d_{3/2} \Longrightarrow 2p_{3/2}\ (L_{\alpha 2})$	929.70	822.84	106.86
$3d_{5/2} \Longrightarrow 2p_{3/2}\ (L_{\alpha 1})$	929.70	822.83	106.87
$3d_{3/2} \Longrightarrow 2p_{1/2}\ (L_{\beta 1})$	949.84	841.91	107.93
$3s_{1/2} \Longrightarrow 2p_{1/2}$	832.10	762.04	70.06
$3s_{1/2} \Longrightarrow 2p_{3/2}$	811.70	742.97	68.73
$3d_{5/2} \Longrightarrow 1s$ Direct Radiative Recombination	8,977.14	8,570.82	406.32

"Evaluation of the anomalous X-ray energy in VIP experiment", 2013, INFN-13-19/LNF
"Evaluation of the anomalous X-ray energy in VIP experiment, some values from Dirac-Fock method", 2013, INFN-13-20/LNF
"Evaluation of the X-ray transition energies for the pauli-principle-violating atomic transitions in several elements by using Dirac-Fock method", 2013, INFN-13-21/LNF

Why at LNGS?

Graphic result of a test done with 2 CCD and normalized distribution



The background is reducted by a factor ≈ 20

Proof of spin-statistics theorem by Lüders and Zumino

Postulates: inhomogeneous Lorentz group, locality – microcausality, vacuum is the state of lowest energy, Hilbert space metric positive definite, vacuum is not identically annihilated by a field $\rightarrow$ (pseudo)scalar fields commute and spinor fields anticommute

Models of PEP violation:

- **Ignatiev & Kuzmin model: Fermi oscillator with a third state**

$$
\begin{aligned}
a^{+}|0\rangle &= |1\rangle & \qquad a|0\rangle &= 0 \\
a^{+}|1\rangle &= \beta\,|2\rangle & \qquad a|1\rangle &= |0\rangle \\
a^{+}|2\rangle &= 0 & \qquad a|2\rangle &= \beta\,|1\rangle
\end{aligned}
$$

- **Greenberg & Mohapatra: Local Quantum Field Theory, q parameter deforms anticommutators, [Phys. Rev. Lett. 1987, 59, 2507]**

$$a_k a_l^{+} - q a_l^{+} a_k = \delta_{k,l}$$

- Rahal & Campa: global w. f. of the electrons not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pairs is small.

EACH MODEL RESPECTS THE M-G SUPER-SELECTION RULE

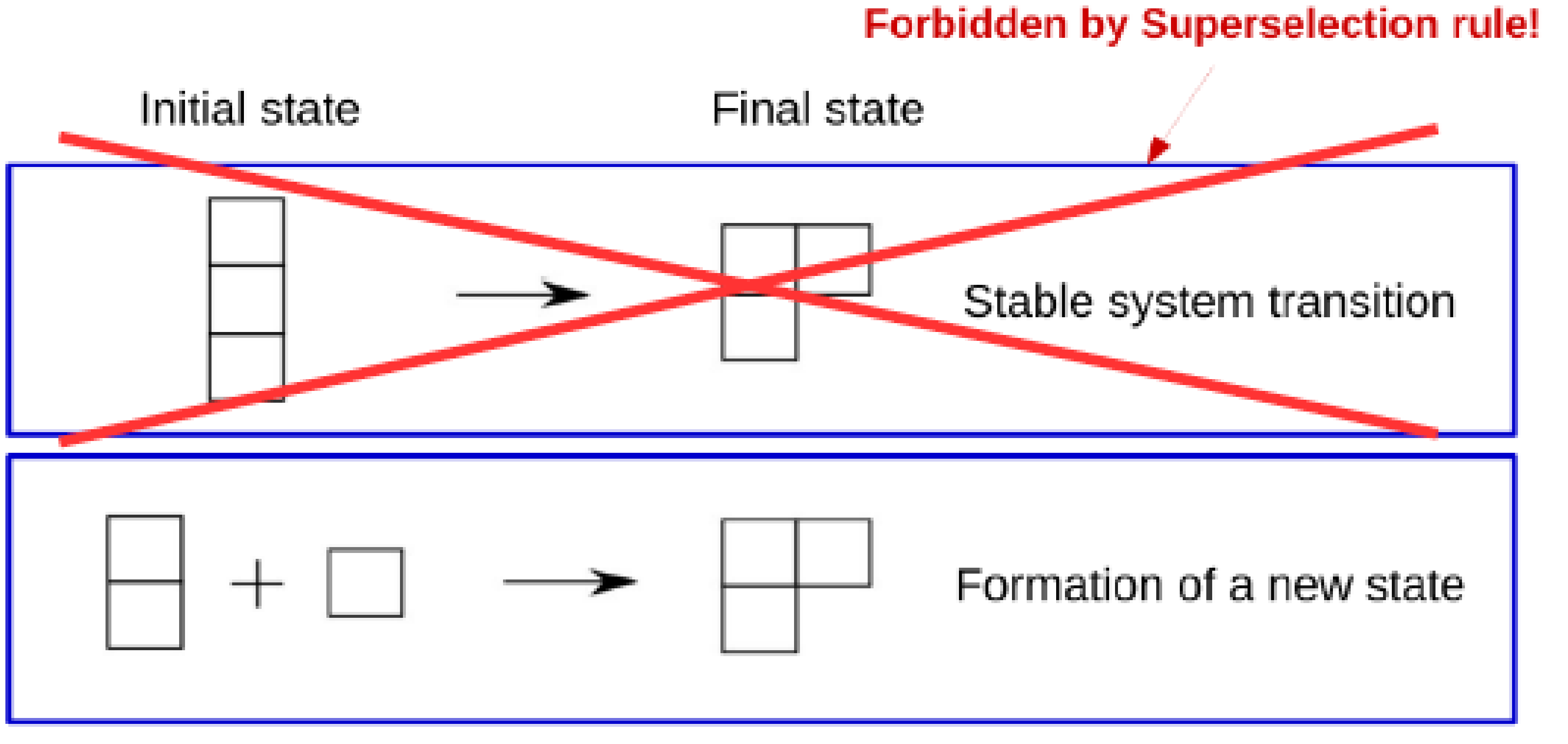
VIP-2 tests the Pauli Exclusion Principle (PEP) (spin-statistics) for electrons in a clean environment (LNGS) using a method which respects the

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

How to test Quantum Gravity with the germanium based VIP2 experiment?

Non-commutativity of space-time is common to several quantum gravity frameworks, to which we refer as Non Commutative Quantum Gravity models (NCQG)

For a generic NCQG inspired model deviations from the PEP in the commutation/anti-commutation relations are parametrized as:

$$a_i a_j^\dagger - q(E) a_j^\dagger a_i = \delta_{ij}$$

where E corresponds to the energy level difference, i.e. to the PEP violating X-ray line energy, and $q(E)$ is related to the PEP violation probability.

$$q(E) = -1 + 2\delta^2(E)$$

For a generic M_k parametrization we have:

$$M_k : \quad \delta^2(E) = \frac{E^k}{\Lambda^k} + O(E^{k+1})$$

- k = 1 corresponds to κ-Poincaré in the Arzano-Marcianò quantization procedure (in the Freidel-Kowalski-Glikman-Nowak quantization the PEP violation is missing), also *G. Amelino-Camelia, M. Arzano, Phys.Rev.D 65 (2002) 084044*.
- k = 2 corresponds to θ-Poincaré

see also A. Addazi, P. Belli, R. Bernabei and A. Marciano, Chin. Phys. C 42 (2018), A. P. Balachandran, G. Mangano, A. Pinzul and S. Vaidya, Int. J. Mod. Phys. A 21 (2006) 3111

How to test Quantum Gravity with the germanium based VIP2 experiment?

Specific calculation of atomic levels PEP violating transitions probabilities for θ-Poincarè have been performed in *A. Addazi, A. Marcianò Int.J.Mod.Phys.A 35 (2020) 32, 2042003*.

The transition probability gets a first order correction in Φ_{PEPV} (the PEPV GM energy dependent phase), $\Phi_{PEPV} = \delta^2$ is the quantity under test:

$$W \simeq W_0 \phi_{PEPV} \,,$$

Depending on the choice:

a) $\theta_{0i} = 0 \rightarrow \quad \phi_{PEPV} \simeq \frac{1}{2} C \frac{\bar{E}_1}{\Lambda} \frac{\bar{E}_2}{\Lambda}$

where E_1 and E_2 are the atomic energy levels for the initial and final states,

b) $\theta_{0i} \neq 0 \rightarrow \quad \phi_{PEPV} \simeq \frac{D}{2} \frac{E_N}{\Lambda} \frac{\Delta E}{\Lambda}$

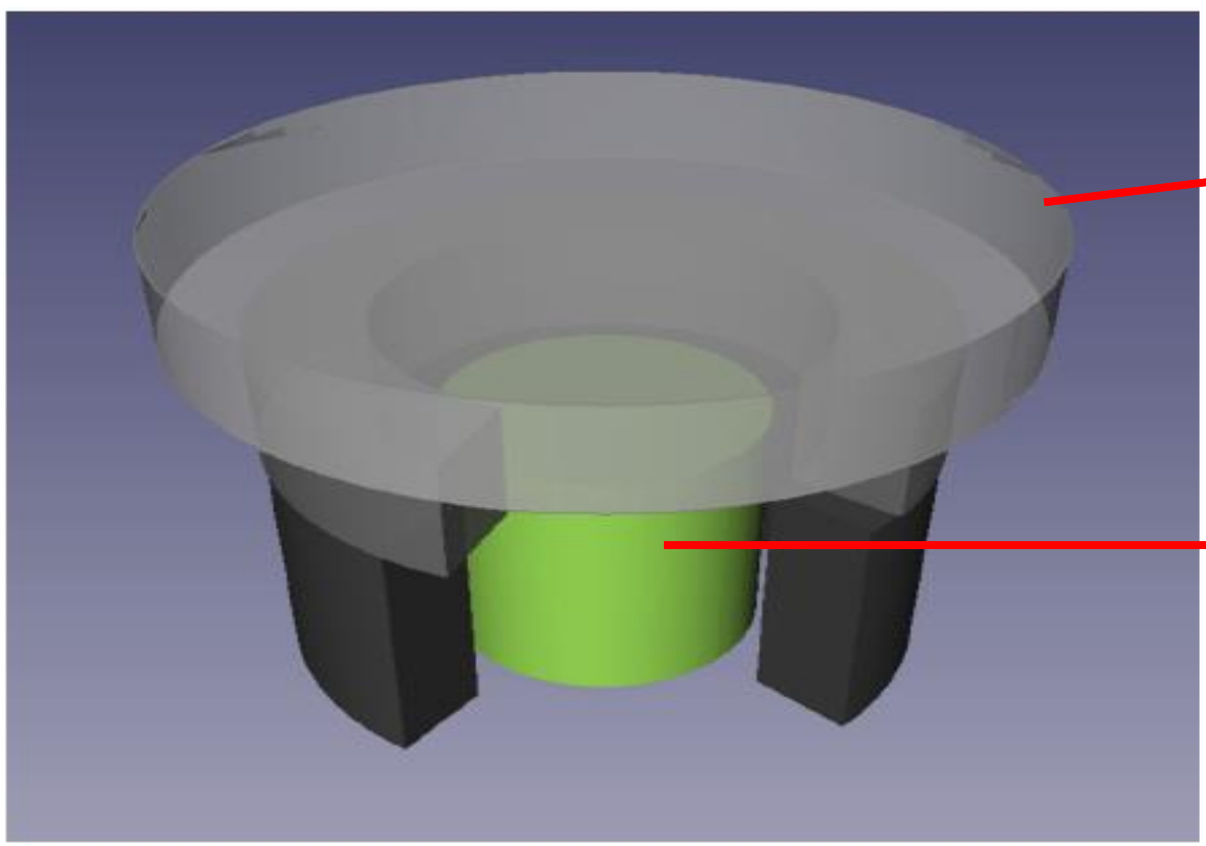
where ΔE is the transition energy and E_N is the nuclear energy.

The Germanium based VIP-2 experiment: apparatus.

The VIP-2 germanium based experimental apparatus consist of:

- A high purity co-axial p-type germanium detector (HPGe), with a diameter of 8.0 cm, length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm. The active volume of the detectors is 375 cm^3

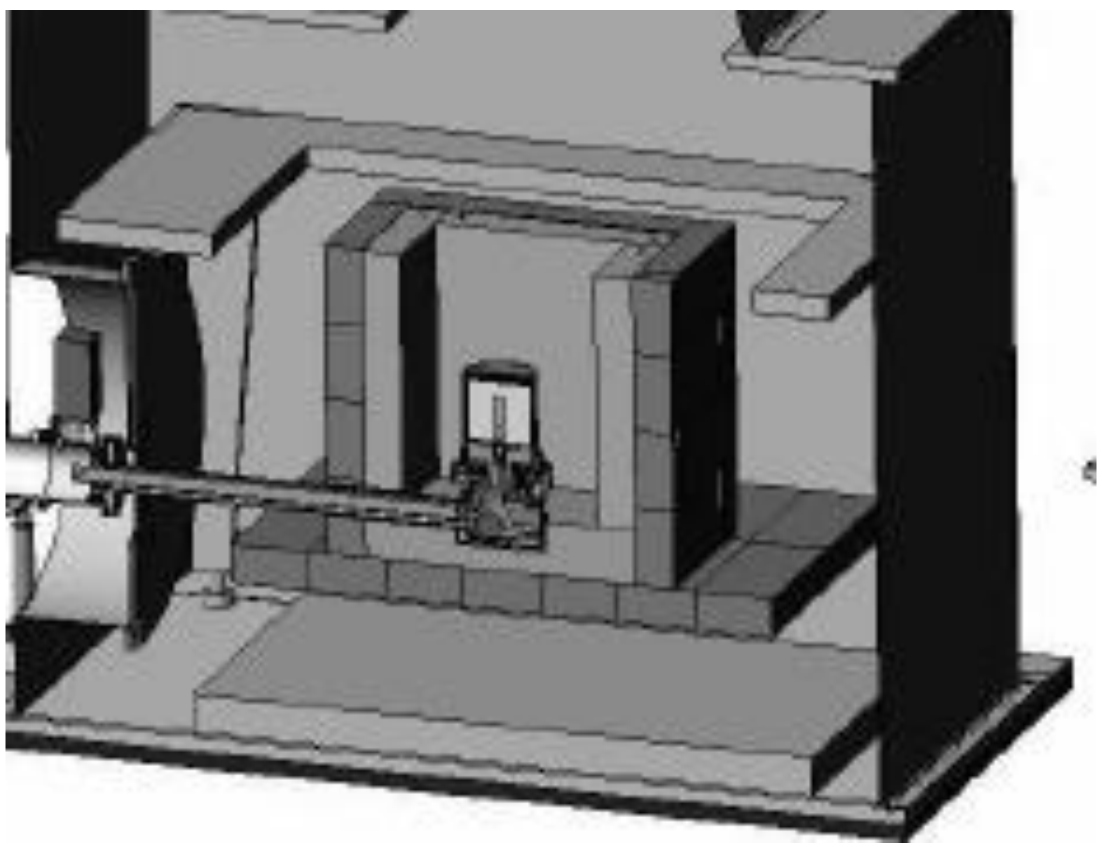
- A target material, composed of three cylindrical sections of radio-pure Roman lead, completely surrounding the detector. The thickness of the target is about 5 cm, for a total volume $V{\sim}2.17 \times 10^3 cm^3$



The **Germanium based VIP-2 experiment**: apparatus.

The VIP-2 germanium based experimental apparatus consist of:

- Passive shielding: inner - electrolytic copper, outer - lead
- 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).



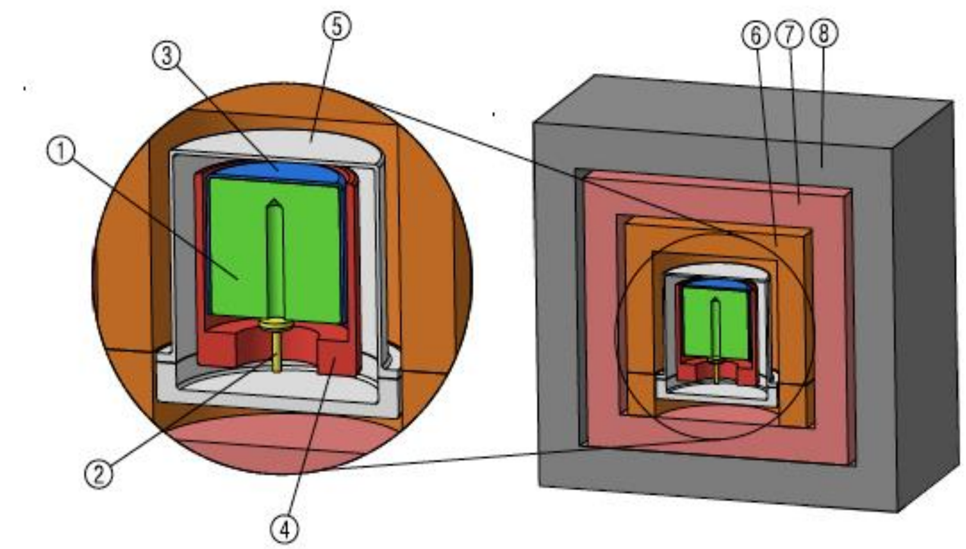


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

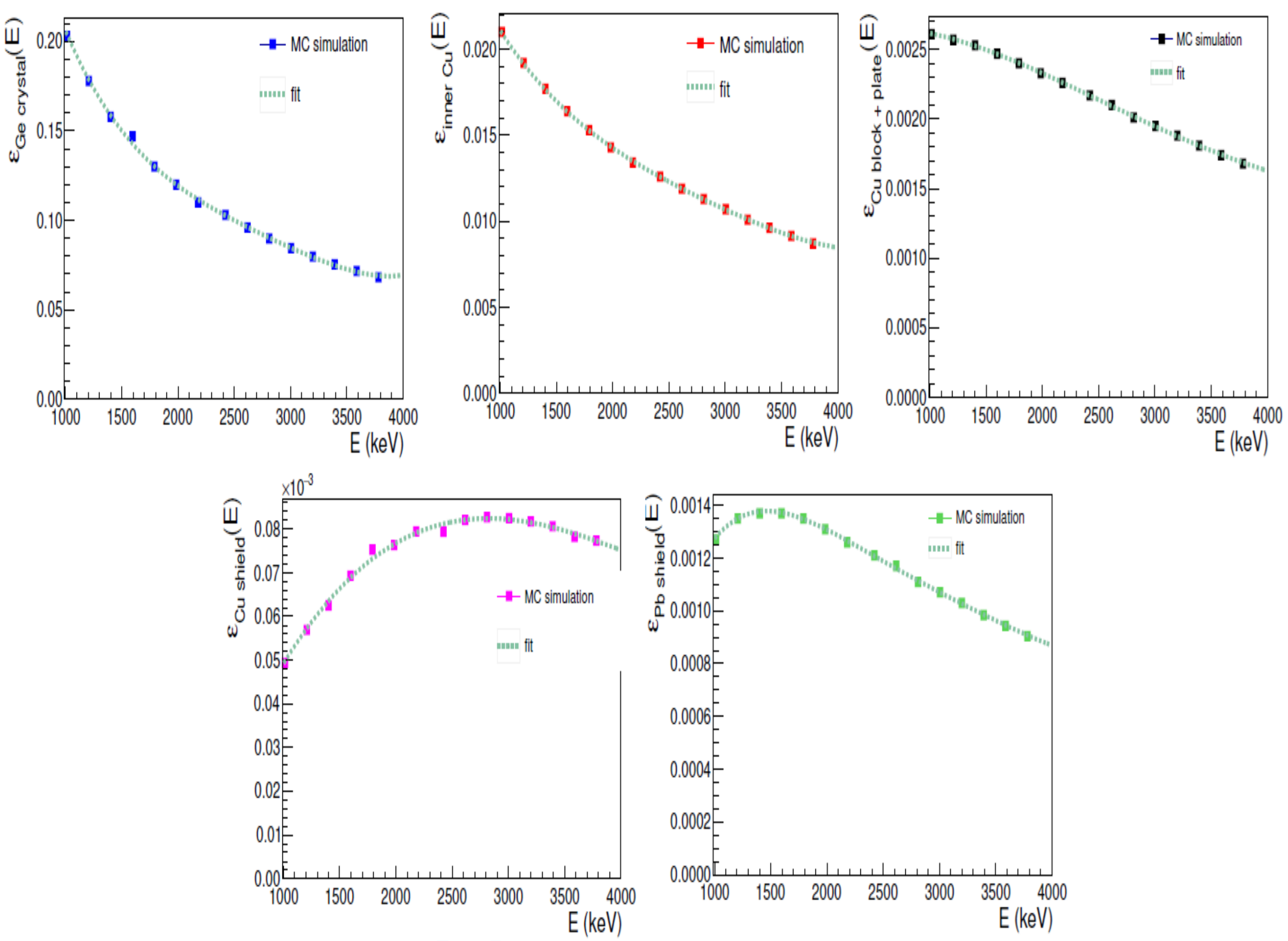
K. P. et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5

The **Germanium based VIP-2 experiment**: Monte carlo simulation and data taking

A dedicated Monte Carlo (MC) simulation has been realized, based on the GEANT4 software library and containing all the detailed characteristic of the apparatus.

The HPGe detector was characterized and all of its components have been put in the MC simulation.

The efficiency for the detection of photons emitted inside the Pb target was determined with MC simulation



Forb. transitions	BR	ϵ
$K_{\alpha 1}$	0.462 ± 0.009	$(5.39 \pm 0.11) \cdot 10^{-5}$
$K_{\alpha 2}$	0.277 ± 0.006	$(4.43^{+0.10}_{-0.09}) \cdot 10^{-5}$
$K_{\beta 1}$	0.1070 ± 0.0022	$(11.89 \pm 0.24) \cdot 10^{-5}$
$K_{\beta 2}$	0.0390 ± 0.0008	$(14.05^{+0.29}_{-0.28}) \cdot 10^{-5}$
$K_{\beta 3}$	0.0559 ± 0.0011	$(11.51^{+0.24}_{-0.23}) \cdot 10^{-5}$

The data analysed in this work correspond to a total acquisition time of:

$\Delta t \approx 70d \approx 6.1 \cdot 10^6 s$

Germanium based VIP-2 data analysis:
The statistical model

The conditional *pdf* of the expected number of total signal couns S, given the measured distribution, is obtained as follows:

$$P(S|data) = \int_0^{\infty} \int_{\mathcal{D}_{\mathbf{p}}} P(S, B|data, \mathbf{p}) \; d^m\mathbf{p} \; dB$$

where the joint posterior distribution of S and the expected number of total background counts B is given by the bayesian theorem

$$P(S, B|data, \mathbf{p}) = \frac{P(data|S, B, \mathbf{p}) \cdot f(\mathbf{p}) \cdot P_0(S) \cdot P_0(B)}{\int P(data|S, B, \mathbf{p}) \cdot f(\mathbf{p}) \cdot P_0(S) \cdot P_0(B) \; d^m\mathbf{p} \; dS \; dB}$$

In order to account for the uncertainties on the experimental parameters *p*, which characterize the measurement and the data analysis, an average likelihood is considered, weighted with the joint *pdf* of *p.*

- Gaussian prior for $B > 0$ $\longrightarrow$ $B_0 = \langle B \rangle_G = \int_{\Delta E} L(E) \; dE$

- Uniform prior for S $\longrightarrow$ $P_0(S) = \begin{cases} \frac{1}{S_{max}} & 0 \leq S \leq S_{max} \\ 0 & \text{otherwise} \end{cases}$

Germanium based VIP-2 data analysis:
The statistical model

The likelihood is parametrized as follows:

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

where n_i are the measured bin contents.

The number of events in the i-th bin fluctuates, according to a Poissonian distribution, around the mean value:

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

where ΔE_i is the energy range corresponding to the i-th bin; $f_B(E,\alpha)$ and $f_S(E,\sigma)$ represent the shapes of the background and the signal distributions normalized to unity over ΔE.

The only uncertainties which significantly affect $\bar{S}$ are those which characterize:

- The shape of background (parametrized with α)
- The resolutions (σ) at the energy of violating transitions

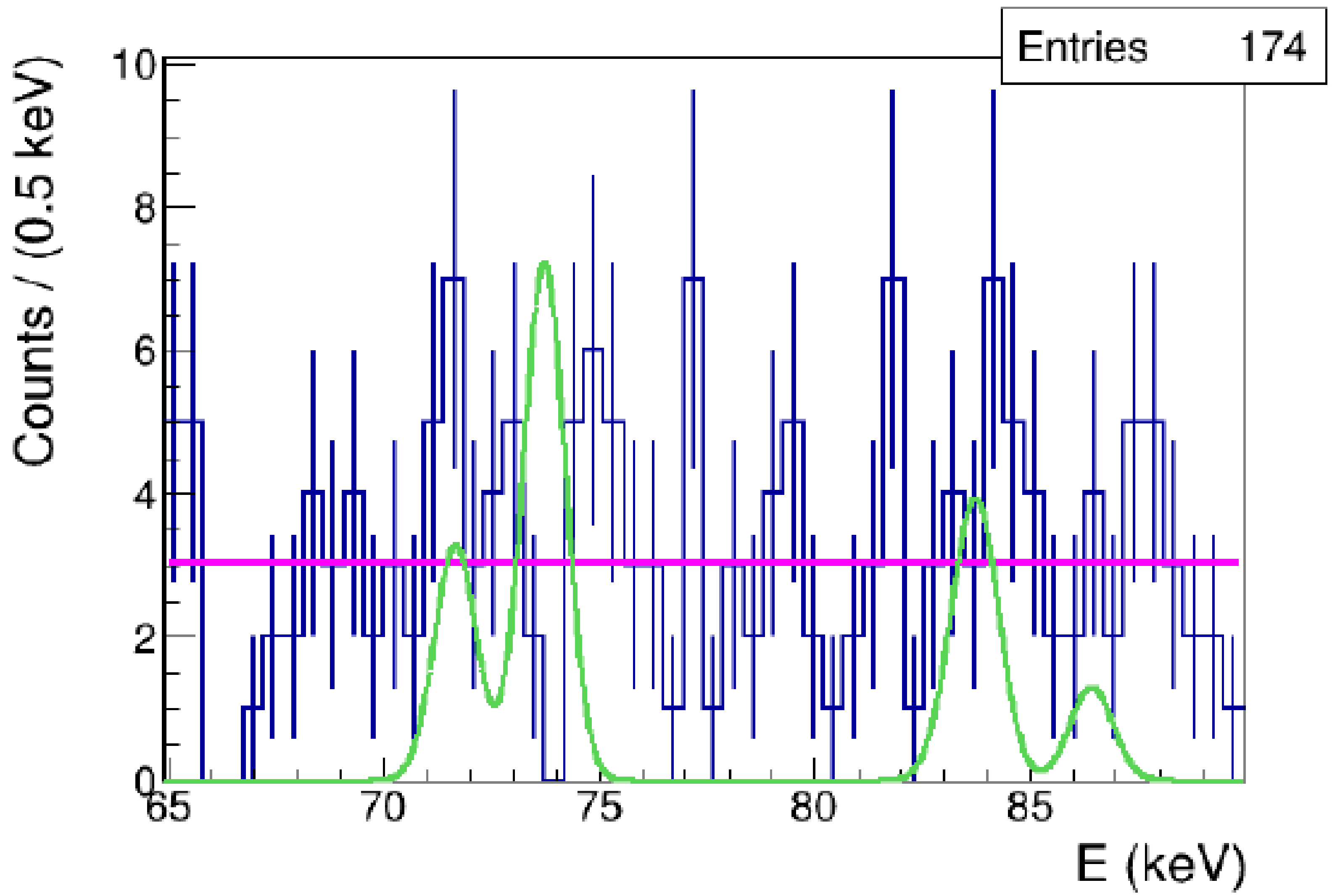
Transitions in Pb	σ	error
$\mathrm{K}_{\alpha 1}$	0.492	0.037
$\mathrm{K}_{\alpha 2}$	0.491	0.037
1s - $3\mathrm{p}_{3/2}$ $\mathrm{K}_{\beta 1}$	0.497	0.036
1s - $4\mathrm{p}_{1/2(3/2)}$ $\mathrm{K}_{\beta 2}$	0.498	0.036
1s - $3\mathrm{p}_{1/2}$ $\mathrm{K}_{\beta 3}$	0.497	0.036

Germanium based VIP-2 data analysis: The statistical model

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

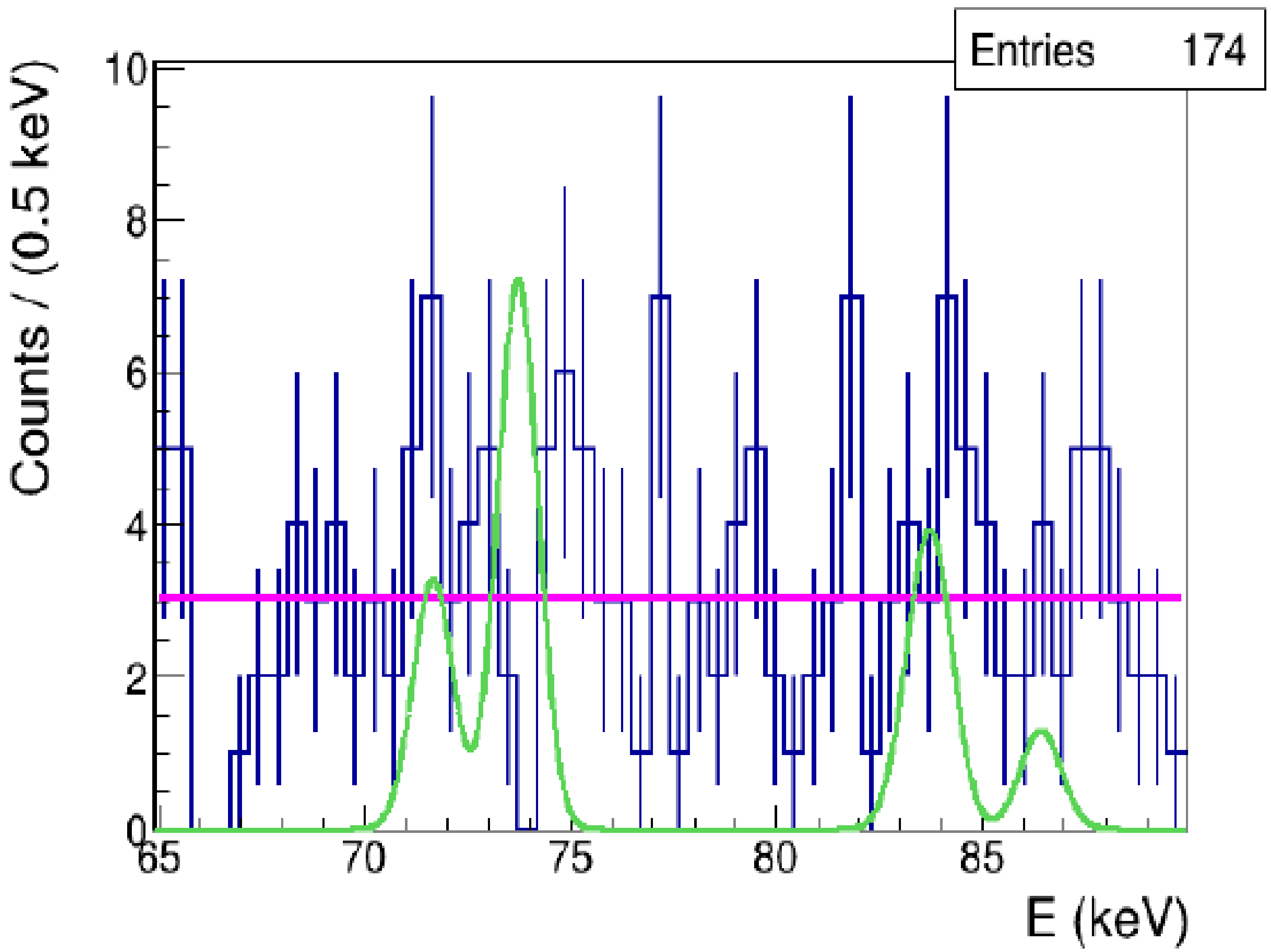
Normalized background shape

Normalised signal shape



Germanium based VIP-2 data analysis:
The normalized background shape

The normalized background shape $f_B(E)$ – common to A_1 ,A_2 *and* A_3 - obtained by best maximum log-likelihood fit excluding $3\sigma_K$ intervals centered on the PEP violating transition energies



The best linear fit to the flat background is:

$$L(E) = \alpha_1 + \alpha_2 \cdot E$$

where

$$\alpha_1 = (3.05 \pm 0.29)\ counts/bin$$

$$\alpha_2 = (0.000 \pm 0.004)$$

The errors contain both statistical and systematic uncertainties

The normalized background shape is then: $\boxed{f_B(E) = \frac{L(E)}{\int_{\Delta E} L(E)\, dE}}$

Germanium based VIP-2 data analysis:
The normalized signal shape

The normalized signal shape $f_S(E)$ is then given by the sum of Gaussian distributions, whose mean values (E_K) correspond to the energies of the PEP violating transitions in Pb, the widths (σ_K) are given by the experimental resolutions at the energies E_K. The intensities of the violating lines are weighted by the rates Γ_K of the corresponding transitions

$$\boxed{f_S(E,k) = \frac{1}{N} \cdot \sum_{K=1}^{N_K} \Gamma_K \frac{1}{\sqrt{2\pi\sigma_K^2}} \cdot e^{-\frac{(E-E_K)^2}{2\sigma_K^2}}}$$

It is worth to notice that $f_S(E)$ depends on the specific M_k parametrization (through the appropriate energy term appearing in the rate). Each independent analysis A_i is to be accordingly repeated for each M_k, in order to set constrains on the Λ scale of the specific model.

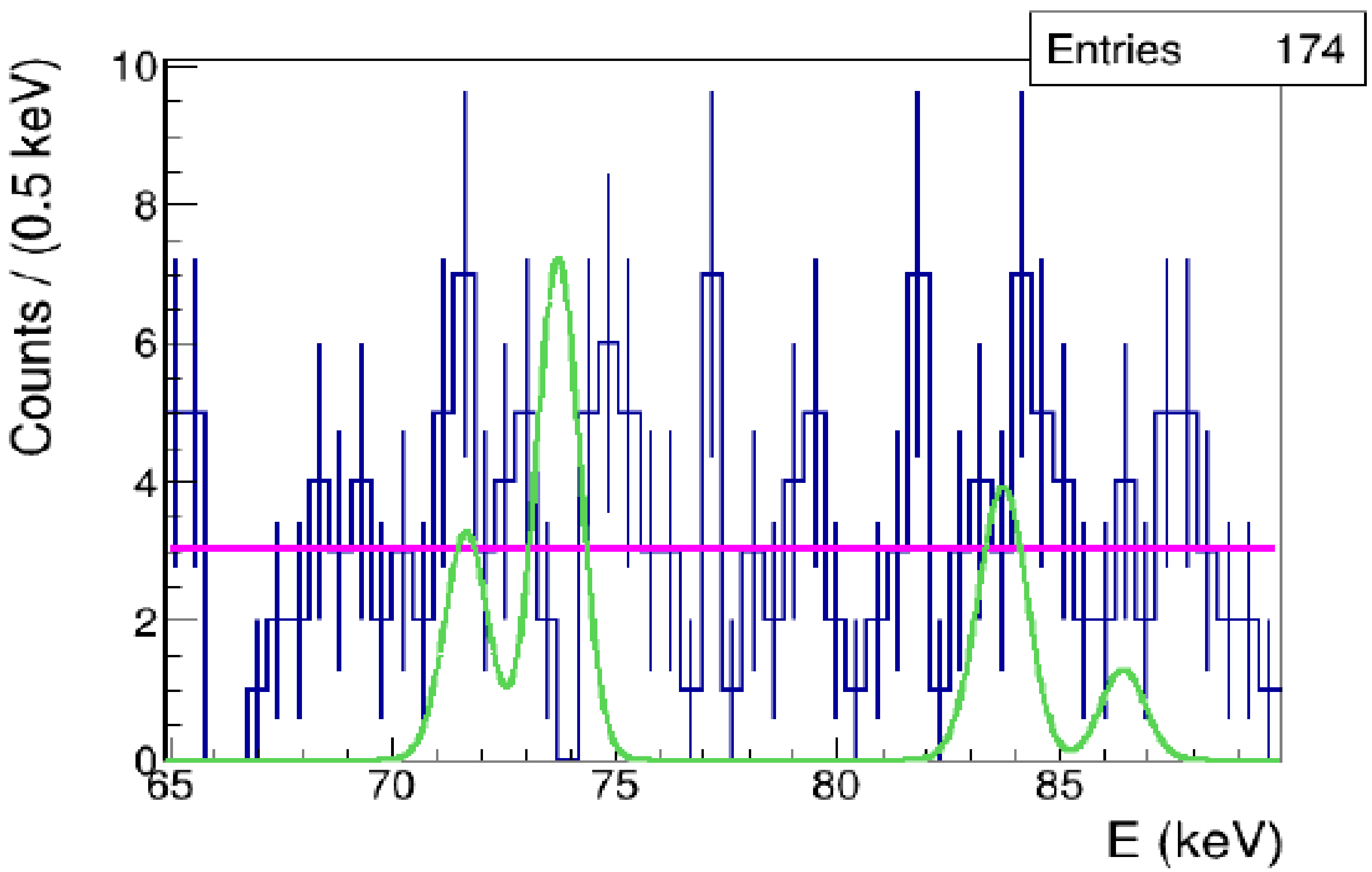
$f_S(E)$ does not instead depend on Λ, since the dependence is re-absorbed by the normalization:

$$\int_{\Delta E} f_S(E) dE = 1 \Rightarrow N = \sum_{K=1}^{N_K} \Gamma_K$$

Germanium based VIP-2 data analysis:
The normalized signal shape

$$f_S(E,k) = \frac{1}{N} \cdot \sum_{K=1}^{N_K} \Gamma_K \frac{1}{\sqrt{2\pi\sigma_K^2}} \cdot e^{-\frac{(E-E_K)^2}{2\sigma_K^2}}$$

As an example the shape of the expected signal distribution (with arbitrary normalization) is shown as a green line in the measured x-ray spectrum, for the A_3 analysis and the M_3 parametrization.



Germanium based VIP-2 data analysis: Prior Distributions

For positive values of B we choose a Gaussian prior distribution, with expected value

$$B_0 = \langle B \rangle_G = \int_{\Delta E} L(E)\, dE$$

And the standard deviation: $\sigma_B = \sqrt{B_0}$

Zero probability is assigned to negative values of B.

As a check a Poissonian prior was tested as well for B. In this case, from the Bayes theorem, the expected value is:

$$\langle B \rangle_P = B_0 + 1 \; and \; \sigma_B = \sqrt{\langle B \rangle_P}$$

The upper limit on $\bar{S}$ is found not to be affected by this choice, within the experimental uncertainty.

Germanium based VIP-2 data analysis:
Prior Distributions

The prior $P_0(S)$, considered the a priori ignorance of the value of S, we opt for a uniform distribution in the range $(0 \div S_{max})$, where S_{max}represents the maximum value of PEP violating X-ray counts in Pb.

S_{max} is obtained from parametric M_k equation, by substituting the number of free electrons in the conduction band of the target, the mean number of interactions and the efficiency with the corresponding parameters which characterize our experimental apparatus.

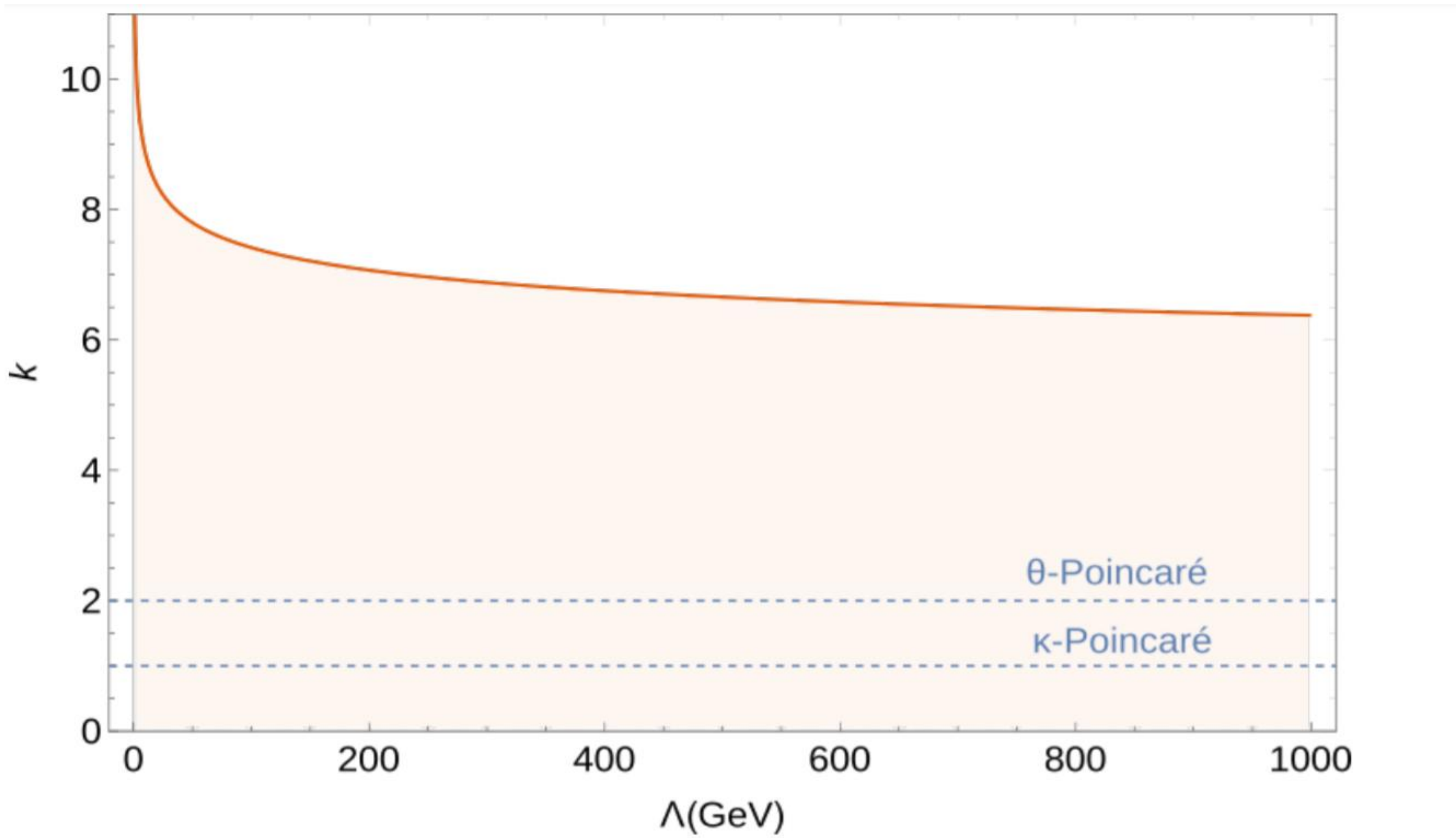
We obtained $S_{max} = 1433$ and S prior :

$$P_0(S) = \begin{cases} \frac{1}{S_{max}} & 0 \leq S \leq S_{max} \\ 0 & \text{otherwise} \end{cases}$$

TABLE V. Values of the parameters which characterise the Roman lead target, from left to right: free electron density, volume, mass and number of free electrons in the conduction band.

$n_e(\mathrm{m}^{-3})$	$V(\mathrm{cm}^3)$	$M(\mathrm{g})$	N_{free}
$1.33 \cdot 10^{29}$	$2.17 \cdot 10^3$	22300	$2.89 \cdot 10^{26}$

Germanium based VIP-2 data analysis:
Results in the electronweak and TeV scale



Exclusion plots in the electroweak and TeV scale window of the non-commutativity scale Λ (x-axis). The energy powers k is represented on the y-axis. The excluded region is highlighted in orange, the κ-Poincaré and θ-Poincaré cases are represented by blue dashed lines.

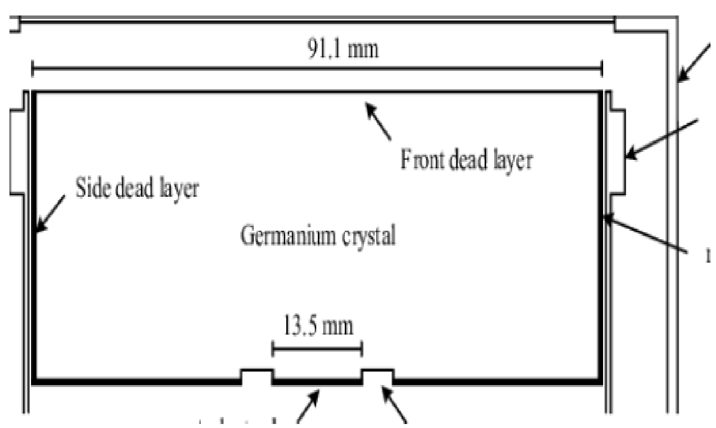
Both κ-Poincaré and θ-Poincaré, as well as large class of NCQG models, are ruled out at the TeV-scale, rendering Large Extra Dimension models, with a non-commutative space-time structure, in strong tension with VIP-2 data.

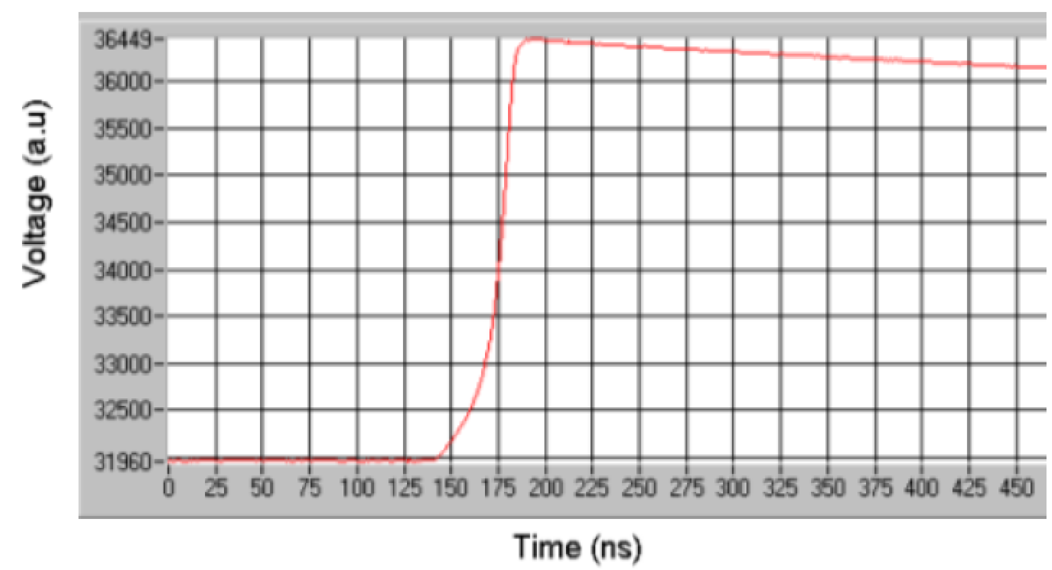
BEGe detector

- In order to improve on this limit → improve on efficiency → use Ge as active material.

- Difficulty: HPGe below 20 keV high background due to electronic noise,

- solution BEGe + Pulse Shape analysis: rejection of electronic noise, disentangle multi vs single hits events (photons from Ge vs photons from outside)



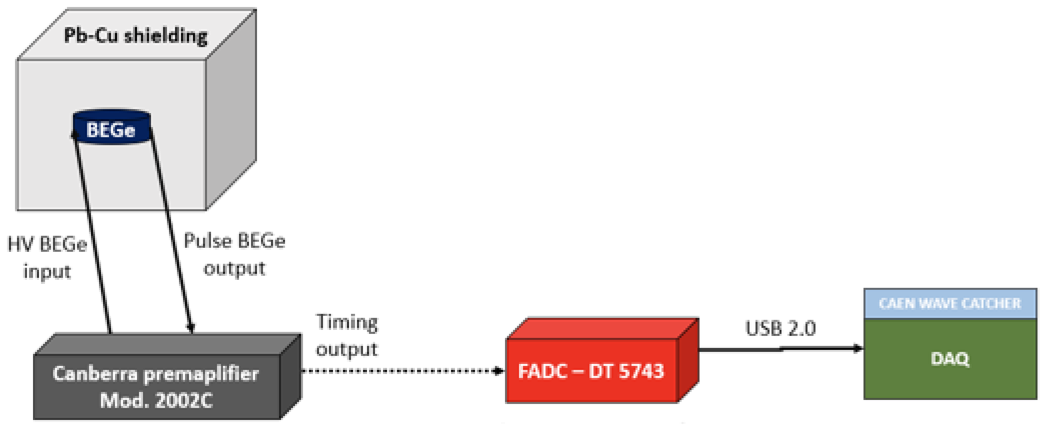


Update on 2020 activity:

1. Front-End - after preliminary configuration at LNF during the COVID-19 restriction phase (CAEN FADC, a PC for data acquisition and elaboration through the CAEN dedicated software “WaveCatcher”) delivered and installed at LNGS.

BEGe detector

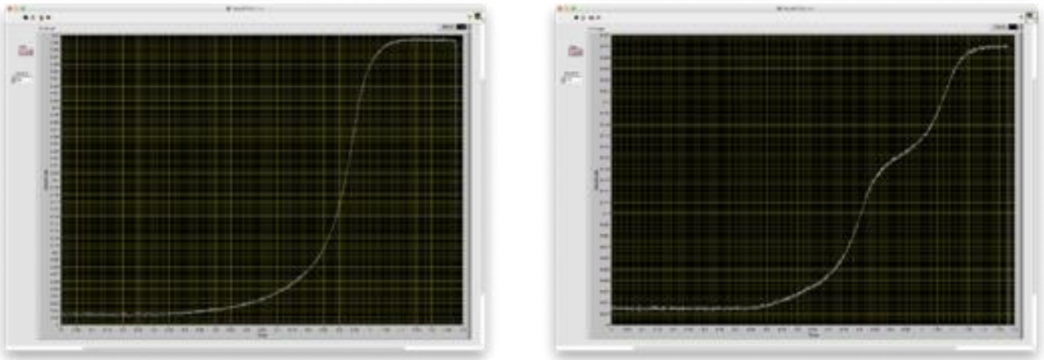
2. signals from preamplifier are directly fed in the 50 ohm impedance input of the CAEN FADC Mod DT5743 to preserve the signal integrity. The 12bit resolution and 3.2Gs/s sampling rate allows to successfully reconstruct the shape of the incoming signals.



Block diagram of BEGe experimental apparatus

Connection of the Front-End electronic to the BEGe's Canberra preamplifier (Mod. 2002C), behind the liquid N2 dewar

3. First data taking phase aimed to test the stability of the system and the background conditions. Development of the LabvieW software and the preliminary data analysis ongoing.



Single site event (left) and multiple site evens (right)

BEGe detector

Germanium based VIP-2 data analysis: The normalized signal shape

Probability that one electron belonging to the 2p shell undergoes the searched violating Kα1 transition, conditioned to the fact that no other electron performs a transition to the 1s:

$$\delta^2(E_{K_{\alpha 1}}) \cdot \Big[1 - 5 \cdot \delta^2(E_{K_{\alpha 1}}) \frac{BR_{K_{\alpha 1}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} +$$

$$- 5 \cdot \delta^2(E_{K_{\alpha 2}}) \frac{BR_{K_{\alpha 2}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} +$$

$$- 6 \cdot \delta^2(E_{K_{\beta 1}}) \frac{BR_{K_{\beta 1}}}{BR_{K_{\beta 1}} + BR_{K_{\beta 3}}} +$$

$$-6 \cdot \delta^2(E_{K_{\beta 3}}) \frac{BR_{K_{\beta 3}}}{BR_{K_{\beta 1}} + BR_{K_{\beta 3}}} - 6 \cdot \delta^2(E_{K_{\beta 2}}) . \Big] =$$

$$= \delta^2(E_{K_{\alpha 1}}) \cdot [1 + C_{K_{\alpha 1}}] \, .$$

The ratios among branching fractions are needed to weight over the relative intensities of transitions which occur from levels with the same (*n*,*l*) quantum numbers, but different j *(e.g. the* $2p_{1/2}$ *and the* $2p_{3/2}$*).*

$C_{K\alpha 1}$ introduces a second order correction in the PEP violation probability

Germanium based VIP-2 data analysis:
The normalized signal shape

The rate of violating K_{α_1} transitions, predicted by the model, for the whole sample of Pb atoms in the target, which would be measured by the detector, is then given by:

$$\Gamma_{K_{\alpha 1}} = \frac{\delta^2(E_{K_{\alpha 1}})}{\tau_{K_{\alpha 1}}} \cdot \frac{BR_{K_{\alpha 1}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} \cdot 6 \cdot N_{atom} \cdot \epsilon(E_{K_{\alpha 1}})$$

where $\tau_{K_{\alpha 1}}$ is the lifetime of the PEP-allowed $2p_{3/2} \rightarrow 1s$ transition, and $\epsilon(E_k)$ factors represent the detection efficiencies for photons emitted inside the Pb target, at the corresponding violating transition energies E_k.

$\tau_{K_{\alpha 1}}$	$1.64 \cdot 10^{-17}$ s
$\tau_{K_{\alpha 2}}$	$3.6 \cdot 10^{-17}$ s
$\tau_{K_{\beta 1}}$	$5.85 \cdot 10^{-17}$ s
$\tau_{K_{\beta 2}}$	$1.42 \cdot 10^{-16}$ s
$\tau_{K_{\beta 3}}$	$1.62 \cdot 10^{-16}$ s

Forb. transitions	BR	ϵ
$K_{\alpha 1}$	0.462 ± 0.009	$(5.39 \pm 0.11) \cdot 10^{-5}$
$K_{\alpha 2}$	0.277 ± 0.006	$(4.43^{+0.10}_{-0.09}) \cdot 10^{-5}$
$K_{\beta 1}$	0.1070 ± 0.0022	$(11.89 \pm 0.24) \cdot 10^{-5}$
$K_{\beta 2}$	0.0390 ± 0.0008	$(14.05^{+0.29}_{-0.28}) \cdot 10^{-5}$
$K_{\beta 3}$	0.0559 ± 0.0011	$(11.51^{+0.24}_{-0.23}) \cdot 10^{-5}$

Germanium based VIP-2 data analysis:
The normalized signal shape

The probability to observe *n* violating Kα1 transitions in the time *t* is:

$$P(n;t) = \frac{(\Gamma_{K_{\alpha 1}}\, t)^n e^{-\Gamma_{K_{\alpha 1}}\, t}}{n!},$$

The expected number of Kα1 events, predicted by the model, which would be detected in the acquisition time *Δt* is:

$$\mu_{K_{\alpha 1}} = \Gamma_{K_{\alpha 1}} \cdot \Delta t \qquad \mu = \sum_{K=1}^{N_K} \mu_K$$

Besides the *one step* processes, two (or more) step violating transitions populating the same lines can occur, e.g. an electron from an atomic shell *i* undergoes a PEP violating transition to the *np* level (*n* = 2; 3; 4), followed by the violating K transition. The two step process probability scales as:

$$\delta^2(E_{i \to np}) \cdot \delta^2(E_{np \to 1s})$$

thus introducing a second order correction to *μ*.

The contribution of two (or more) step violating transitions is neglected.

Germanium based VIP-2 data analysis: The normalized signal shape

Another set of processes to be accounted for consists in subsequent violating transitions from the same atomic shell *np* (*n* = 2; 3; 4) to 1*s*.

Subsequent violating transitions would populate violating K lines which are shifted in energy with respect to the transitions listed in Table.

Transitions in Pb	allow.	forb.
1s - $2p_{3/2}$ $K_{\alpha 1}$	74.969	73.713
1s - $2p_{1/2}$ $K_{\alpha 2}$	72.805	71.652
1s - $3p_{3/2}$ $K_{\beta 1}$	84.938	83.856
1s - $4p_{1/2(3/2)}$ $K_{\beta 2}$	87.300	86.418
1s - $3p_{1/2}$ $K_{\beta 3}$	84.450	83.385

The subsequent violating transition probability scales with the products of the δ^2, calculated at the energies of the two transitions, the corresponding correction to μ is then of the second order.

Subsequent violating transition processes are neglected in this analysis.

The «Ramberg & Snow» model

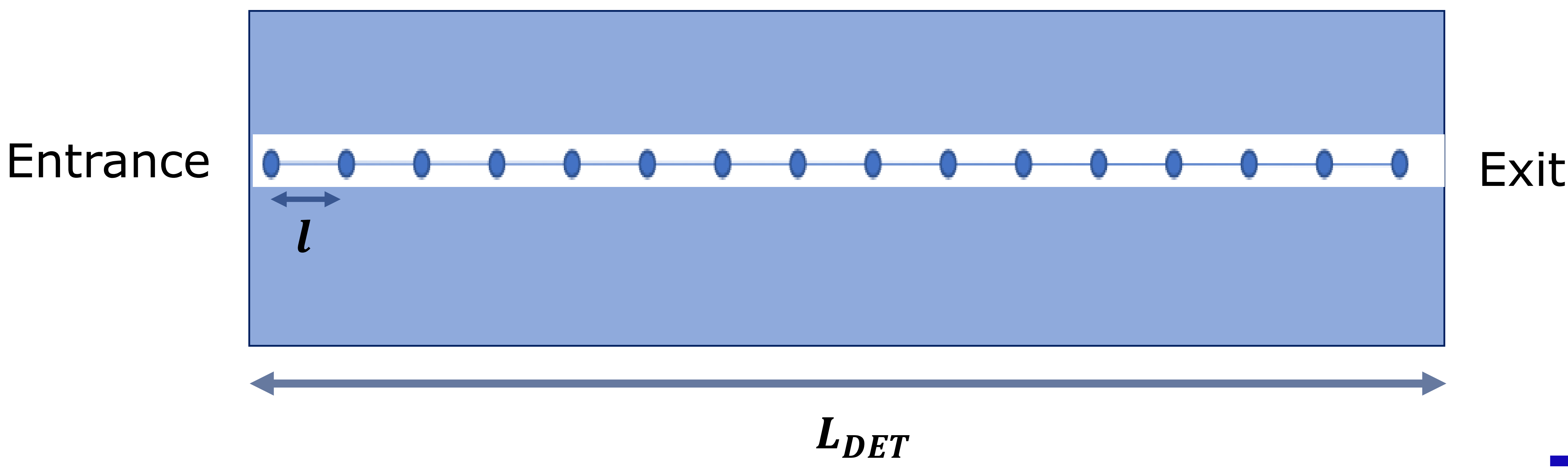
In the experiment VIP the number of scatterings for the single electron was calculated as:

$$\frac{L_{DET}}{l}$$

L_{DET} → Linear length of the target

l → Average free electron path

In VIP2 the target length is 10 cm (≈7.5 cm actually crossed by current) and the free electron average path in copper is 40 nm. The number of scatterings of the single electron for RS is $\sim\mathbf{2\times10^{6}}$



The «Random Walk» model

The drift velocity of the electron in the copper is:

$$v_d = \frac{I}{newz} \sim 5\ mm/s$$

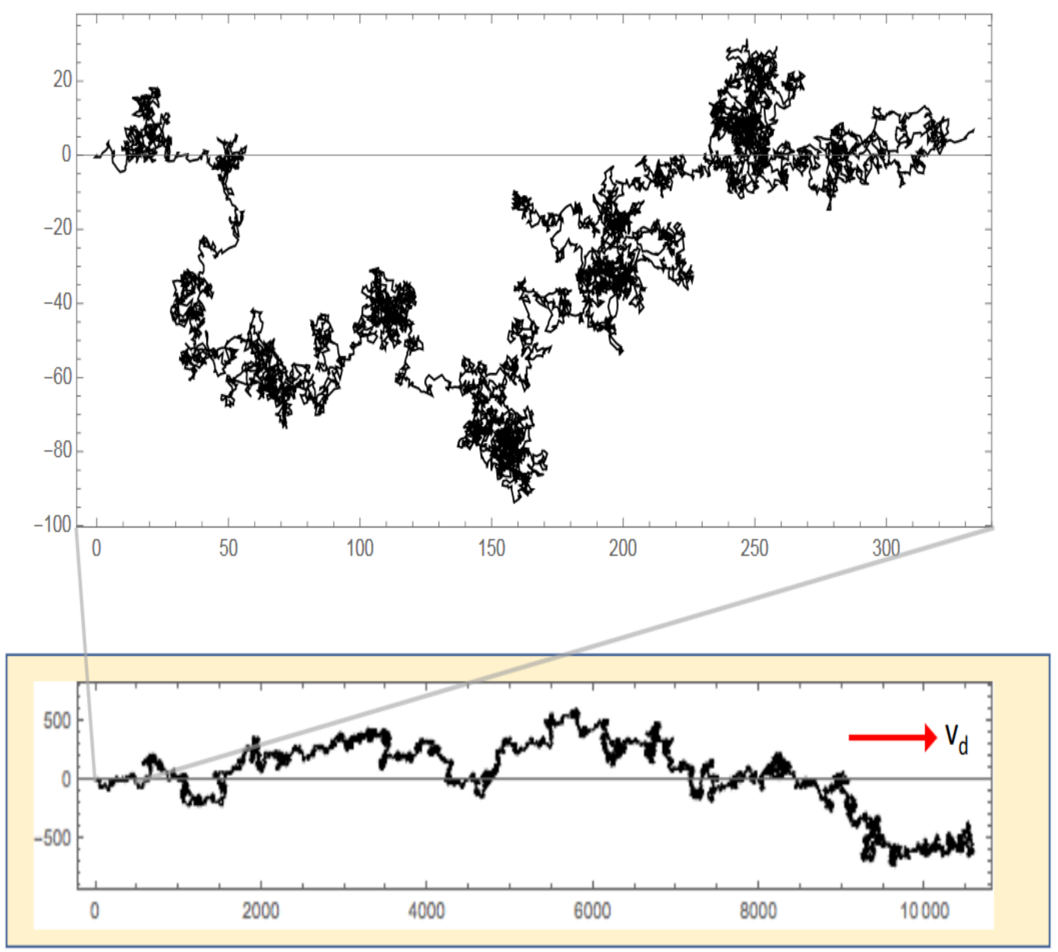
n is the density of electrons at m ^ 3, and is the elementary charge, w and z are the width and thickness of the target

The mean time of crossing the target for the single electron is **Δt=<u>16 seconds</u>**.

Average time between two collisions is: $\tau = 2,5 \times 10^{-14} s$

The number of scatterings of the single electron can be calculated as:

$$\frac{\Delta t}{\tau} = 6,4 \times 10^{14}\ scatterings \gg 2 \times 10^{6}$$



The limit of the recalculated acquisition is:

$$\boxed{\frac{\beta^2}{2} \leq 2,6 \times 10^{-40}}$$

E.Milotti et al., «On the importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle», Entropy, 2018.

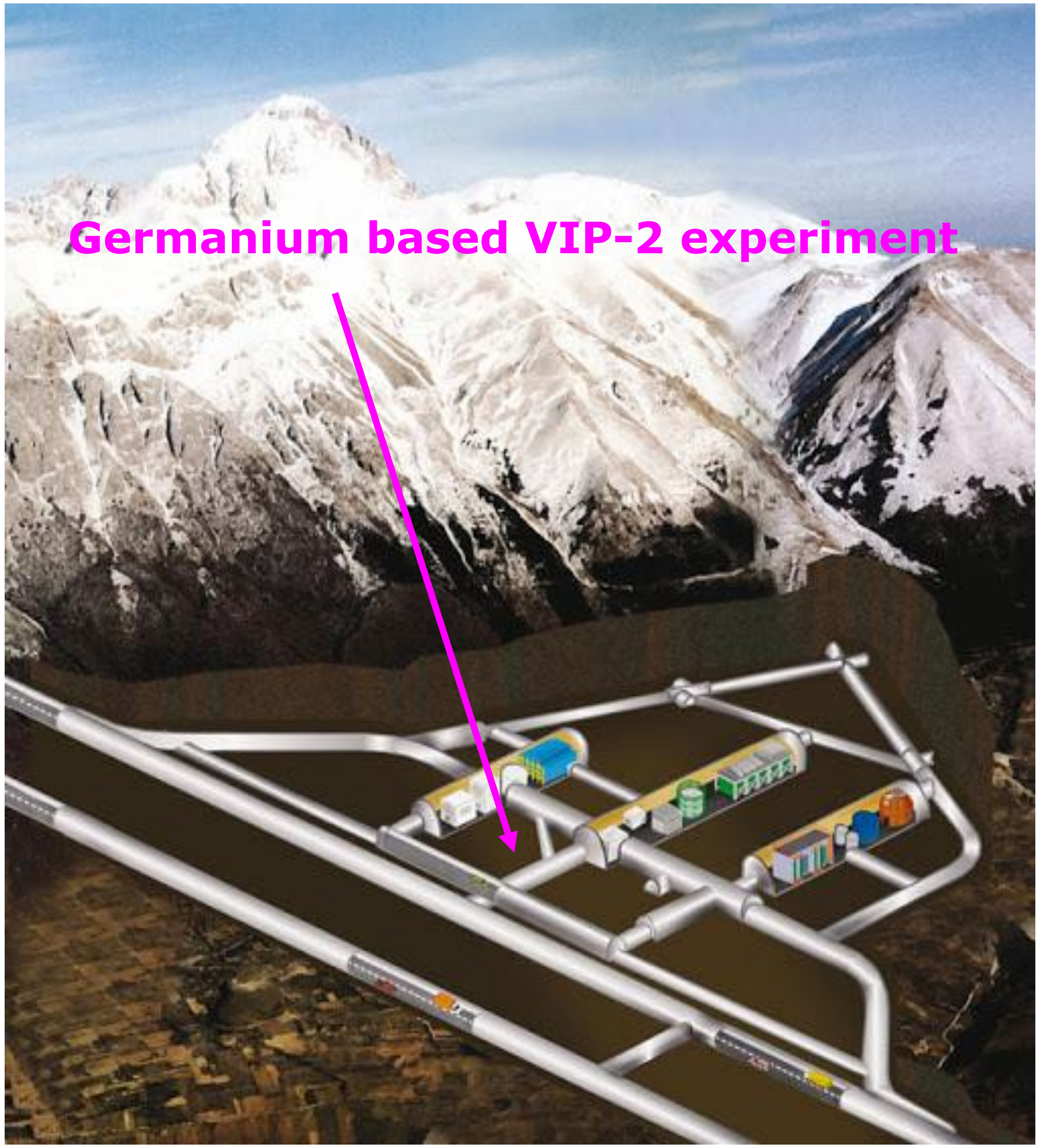
The Germanium based VIP-2 experiment: location.

The experiment is taking place at National Laboratories of Gran Sasso (LNGS), an extremely low background environment inside the Gran Sasso mountain: overburden corresponding to a minimum thickness of 3100 m w.e.

The muon flux is reduced by almost six orders of magnitude.

The neutron flux is reduced by almost three orders of magnitude.

The main background source consists of γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.



A particular recognition goes to ....

The support from the Foundational Question Institute (FQXi) in the framework of the project:
"Events' as we see them: experimental test of the collapse models as a solution of the measurement-problem." (FQXi Grant number: FQXi-RFP-1505)

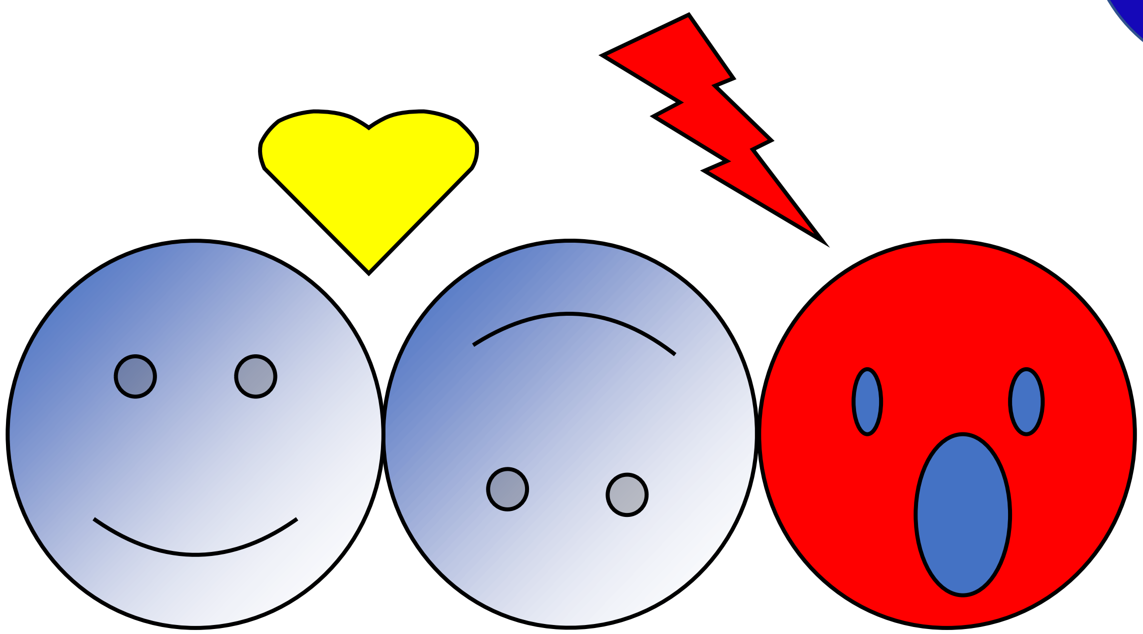
The support from the John Templeton Foundation in the framework of the project:
58158: Hunt for the "impossible atoms": the quest for a tiny violation of the Pauli Exclusion Principle, Implications for physics, cosmology and philosophy.

The Germanium based VIP-2 experiment: measured spectrum and the data analysis

The PEP violation probability is a function of Λ and of the energy

to check the sensitivity of the measured spectrum to the predicted signal, as a function of the energy, a scan is performed searching for deviations from the relevant transitions $(K_{\alpha_1}, K_{\alpha_2})$, $(K_{\beta_1}, K_{\beta_2}, K_{\beta_3})$ and the whole K complex $(K_{\alpha_1}, K_{\alpha_2}, K_{\beta_1}, K_{\beta_2}, K_{\beta_3})$

The same procedure has been followed for three independent analyses for each PEP violation parametrization M_k.
The analyses are referred as A_1, A_2, A_3 respectively.



THANK YOU ALL FOR YOUR ATTENTION !!!

CONTENTS

- How it is possible to investigate the Pauli exclusion principle (PEP) with VIP2
- The VIP2 experiment: purpose and apparatus
- The VIP2 experiment: results and future perspectives
- The Germanium based VIP2 experiment: testing Quantum Gravity models
- The Germanium based VIP2 experiment: purpose and apparatus
- The Germanium based VIP2 experiment: results and future perspectives