Kaon mass through kaonic atoms measurements with HPGe detectors at DAΦNE

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C. Curceanu et al. *Laboratori Nazionali di Frascati*
J. Zmeskal et al. *Stefan Meyer Institute, Vienna*
and SIDDHARTA-2

- Motivation and previous measurements of the charged kaon mass
- Preparations for measurements at DAΦNE LNF during SIDDHARTA-2 run: hardware and simulations

Croatian Science Foundation Project 8570

Workshop: Fundamental Physics at the strangeness Frontier at DAFNE, online, 25-26 February 2021

Motivation

- The accuracy of the determination of the charged kaon mass *(m_K=493.677±0.013 MeV, 26 p.p.m.)* is much less than the accuracy of the charged pion mass *(m_π=139. 57061±0.00023 MeV, 1.6 p.p.m.)*, PDG2020.

- Serious disagreement between the two precise measurements

->Large scaling factor: S=2.4 *(m_K=493.677±0.005 MeV)*

- Kaon mass has large influence on the K^-N scattering lengths and through them on the kaon-nucleon sigma terms and eventually degree of chiral symmetry breaking.

Measurements of kaon mass, history

- Q value $K^- \rightarrow \pi^+ + \pi^- + \pi^-$

  W.H. Barkas, Annu. Rev. Nuclear Sci. 15 (1965) 67 m_K=493.75+0.16 MeV

- Range measurements in emulsions

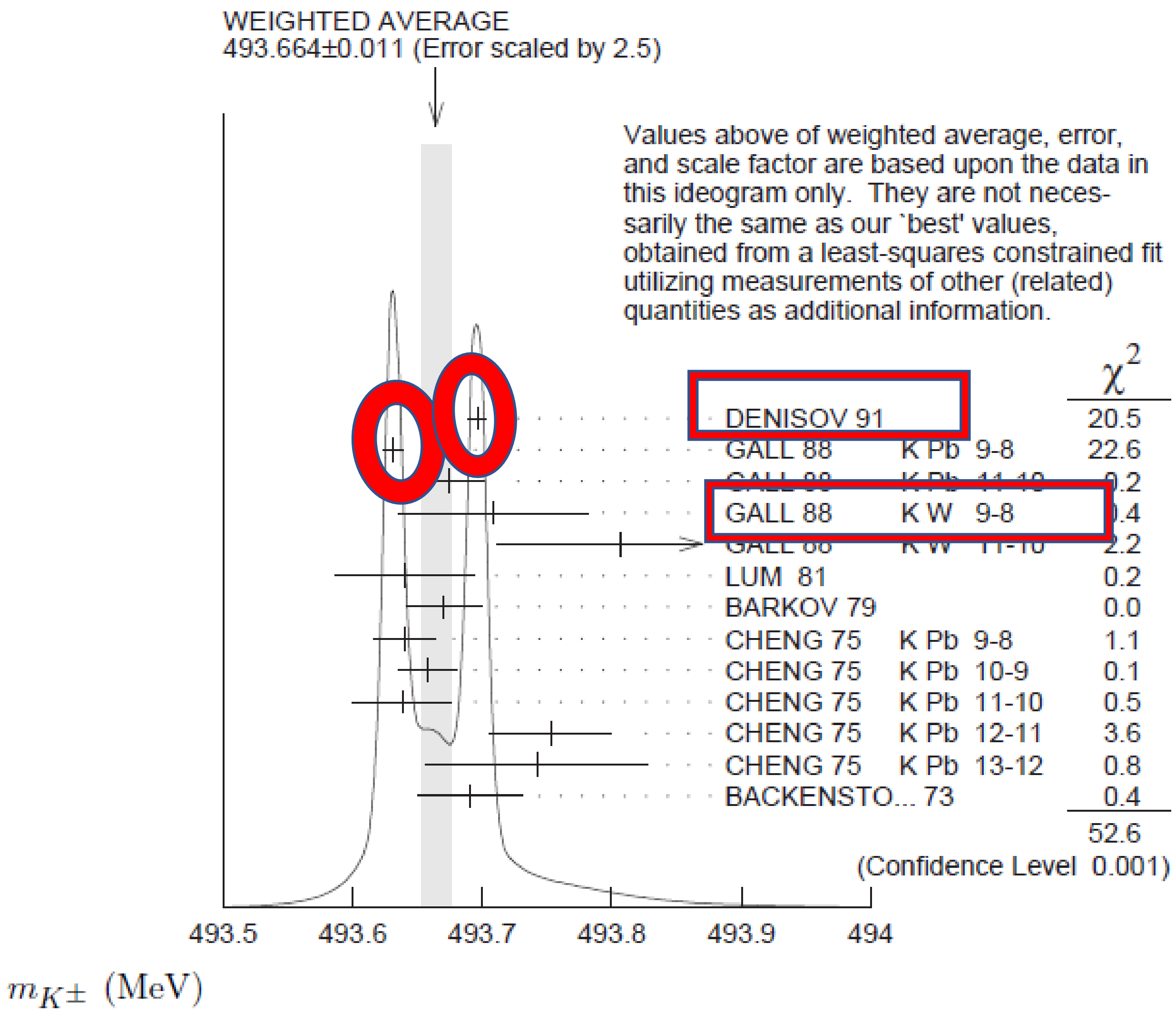
  (A. Barbaro-Galtieri et al., Revs. Mod. Phys. 42 (1970) 87, m_K=493.7+0.3 MeV;

  L.M. Barkov et al. Nucl. Phys. B148 (1979) 53 (ϕ->K+K-) m_K=493.670+0.029 MeV

- **Energies of X-ray transitions in kaonic atoms**, **m_K=493.679 ± 0.013 MeV**

  all with energetic kaons (PDG2020)

PDG 2020:



PDG2020

m_K=493.679 ± 0.013 MeV

The main disagreement is between the two most recent and precise measurements (x-ray energies from kaonic atoms):

m_K=493.696±0.007 MeV

A.S. Denisov et al. JEPT Lett. 54 (1991)558

K^- ^{12}C, crystal diffraction spectrometer

(6.3 eV at 22.1 keV), 4f-3d

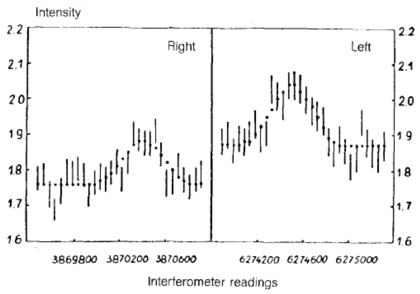


FIG. 1. Right and left reflections of the 4f-3d transition of the K^-–^{12}C atom. The interferometer readings are plotted along the abscissa; the detector count rate per 10^{12} protons is plotted along the ordinate. The vertical lines are the experimental values with the corresponding error; the heavy points are the results of a fit.

m_K=493.636±0.011 MeV

K.P. Gall et al. Phys. Rev. Lett. 60 (1988)186

K^- Pb, K^- W; HPGe detector (1 keV), **K^-Pb (9 -> 8),** K^-Pb (11 -> 10), K^-W (9 -> 8), K^-W (11 -> 10),

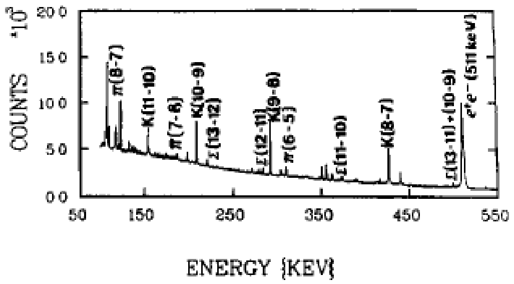
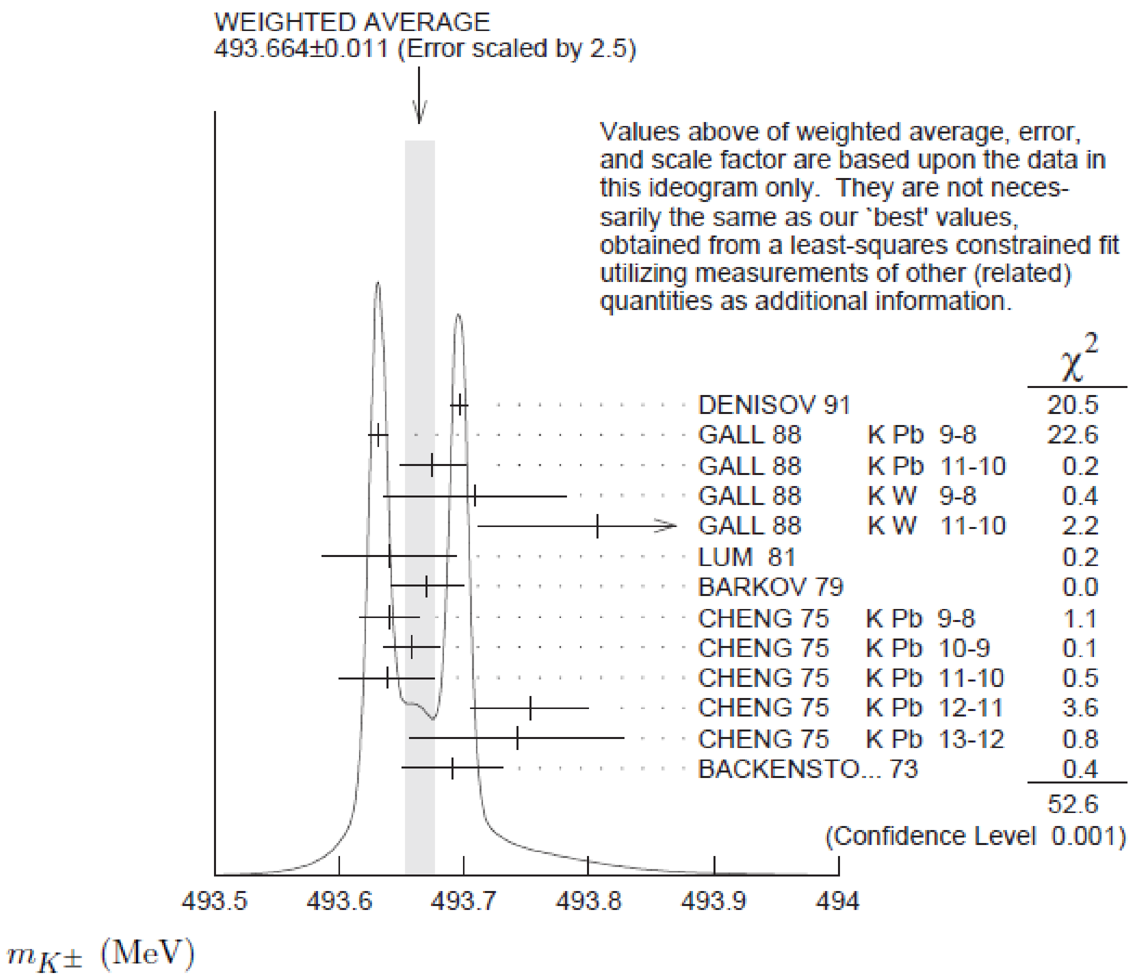


FIG. 1. Untagged Pb x-ray spectrum showing intense kaonic x-ray transitions.

Average m_K=493.679 ± 0.006 MeV S=2.4

Previous measurements, motivation

PDG2020:



PDG20 conclusion:

" While we suspect that the GALL 88 K- Pb (9 ->8) measurements could be the problem, we are unable to find clear grounds for rejecting it. Therefore, we retain their measurement in the average and accept the large scale factor until further information can be obtained from new measurements and/or from reanalysis of GALL 88 and CHENG 75 data".

It is sufficient that the new measurement has the same precision (10 keV) as the 2 previously mentioned measurements, which differ by 60 keV (PLB535 (2002)52):
-if the new result agrees with Denisov (and results from Gall are disregarded) the precision would be 5 keV (10 p.p.m)
-it the new results agrees with Gall, the precision would be 7 keV (14 p.p.m.)
-> substantial improvement in the precision

Principles of measurements in kaonic atoms

- Measure X-ray energies in kaonic atoms for transitions not influenced by strong interactions.

- In order to determine the kaon mass, the experimental energies have to be compared with the calculated energies obtained with a certain K-mass value (corrections: vacuum polarization, electron screening, non-circular trasitions)

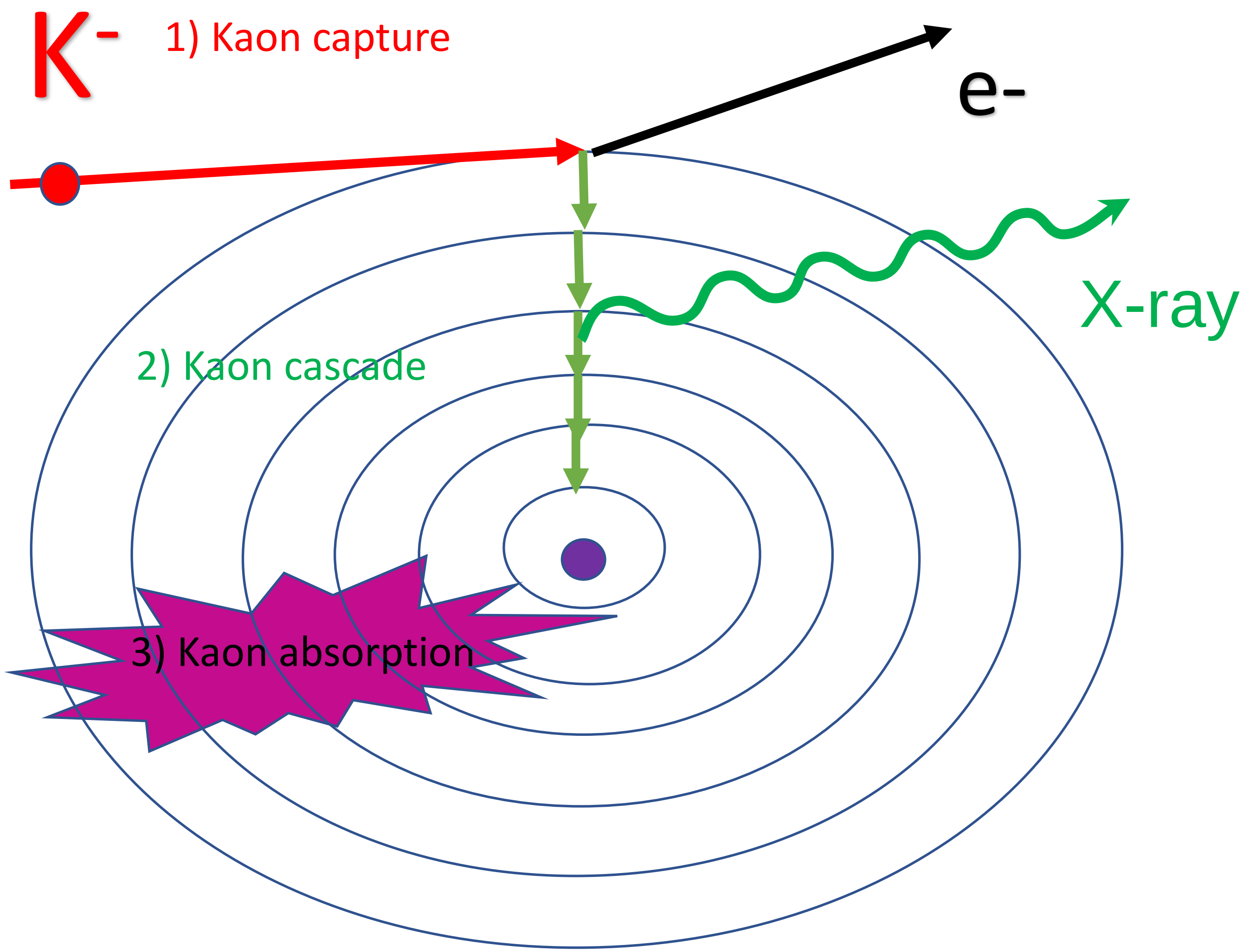
- Measurements with HPGe detectors and with crystal diffraction spectrometer, TES, …

X-ray energies in kaonic atoms

Kaonic atom formation

Kaon cascade -> X-rays

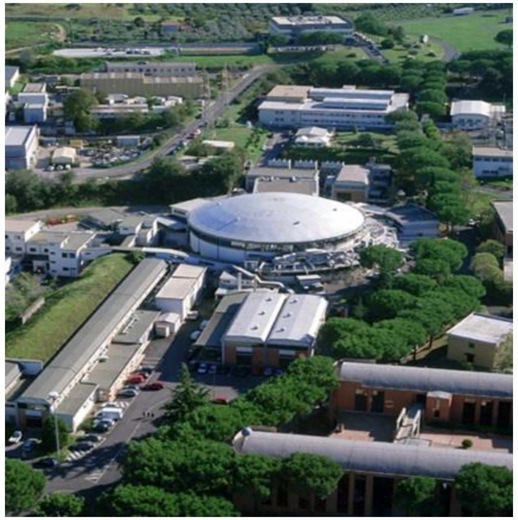
Kaon absorption



Interesting X-rays from the the transitions in the middle of spectrum:

- No influence from strong interaction
- avoid electron screening of nuclei

$e^+e^- \rightarrow \phi \rightarrow K^+K^-$, $E_K \approx 16$ MeV

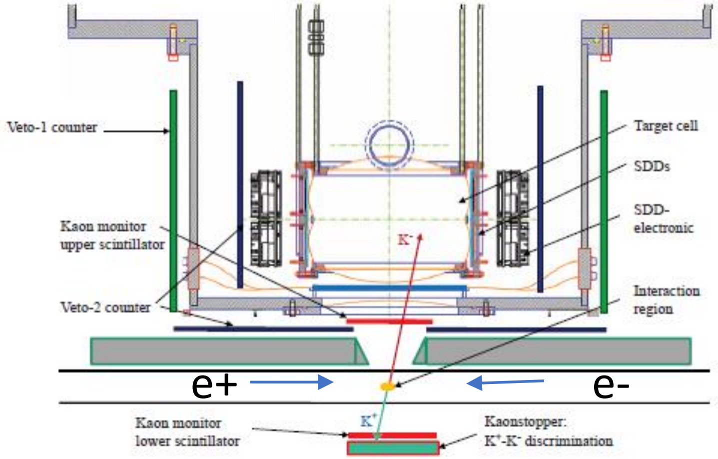


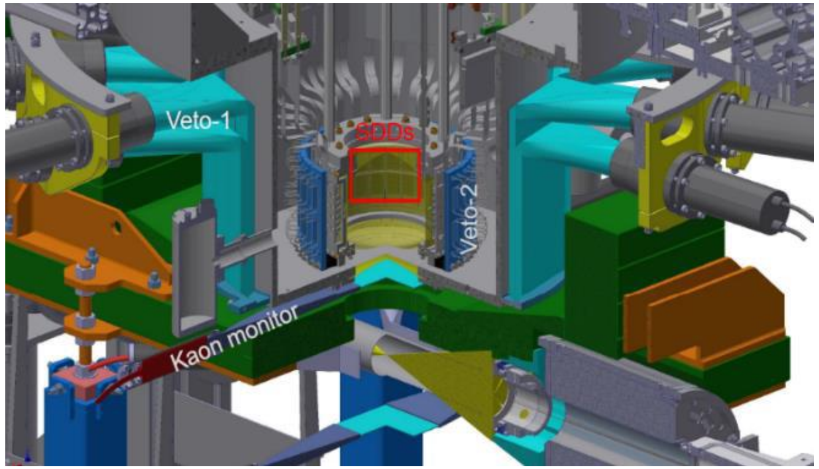
-> Our aim is to do measurements with HPGe detector(s) during SIDDHARTA-2 run at DAϕNE - using the available space at the SIDDHARTA-2 interaction region and with different solid targets.

SIDDHARTA-2 at DAϕNE

Silicon Drift Detector for Hadronic Atom Research by Timing Application

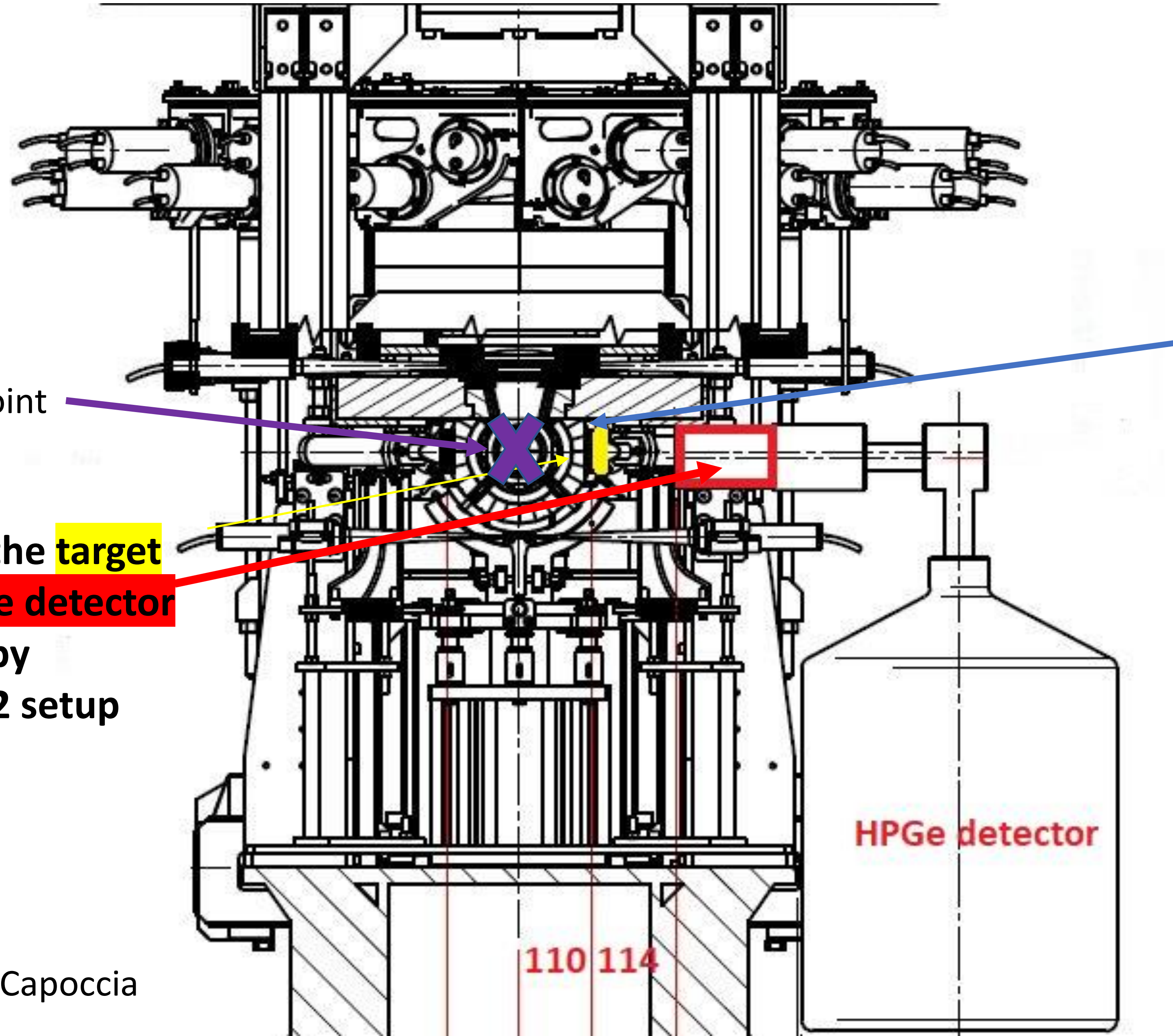
2020/2021 SIDDHARTA-2 run: X-ray transitions in gaseous targets: deuterium, helium, …





Advantage: DAϕNE is producing low momenta kaon pairs – no need for degrader. No secondary particles in the beam.
Disadvantage: High electromagnetic background from the beam close to the interaction point (unknown!). Background originating from the kaons absorbed in nuclei.

Measurement at DAϕNE with HPGe during SIDDHARTA-2 run



Interaction point

Positions of the target and the HPGe detector is restricted by SIDDHARTA-2 setup

Figure: Cesidio Capoccia

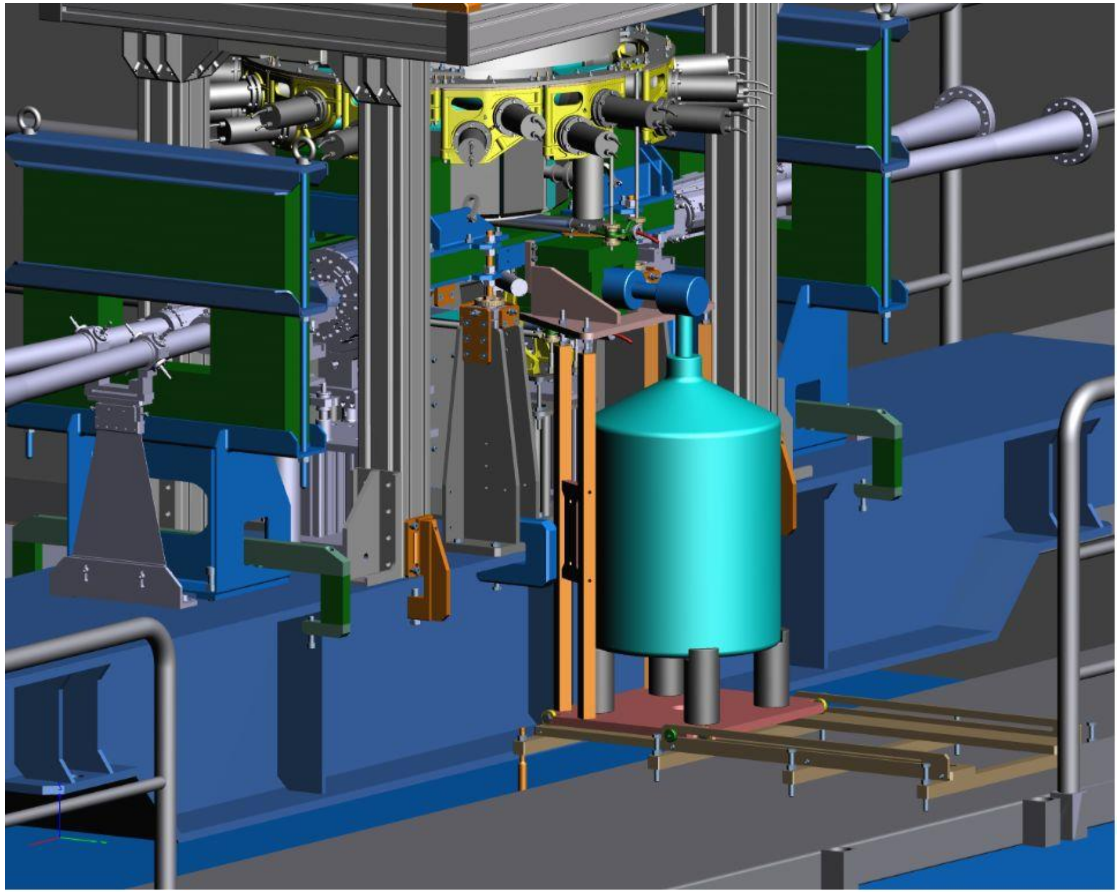
HPGe detector system is independent of SIDDHARTA-2

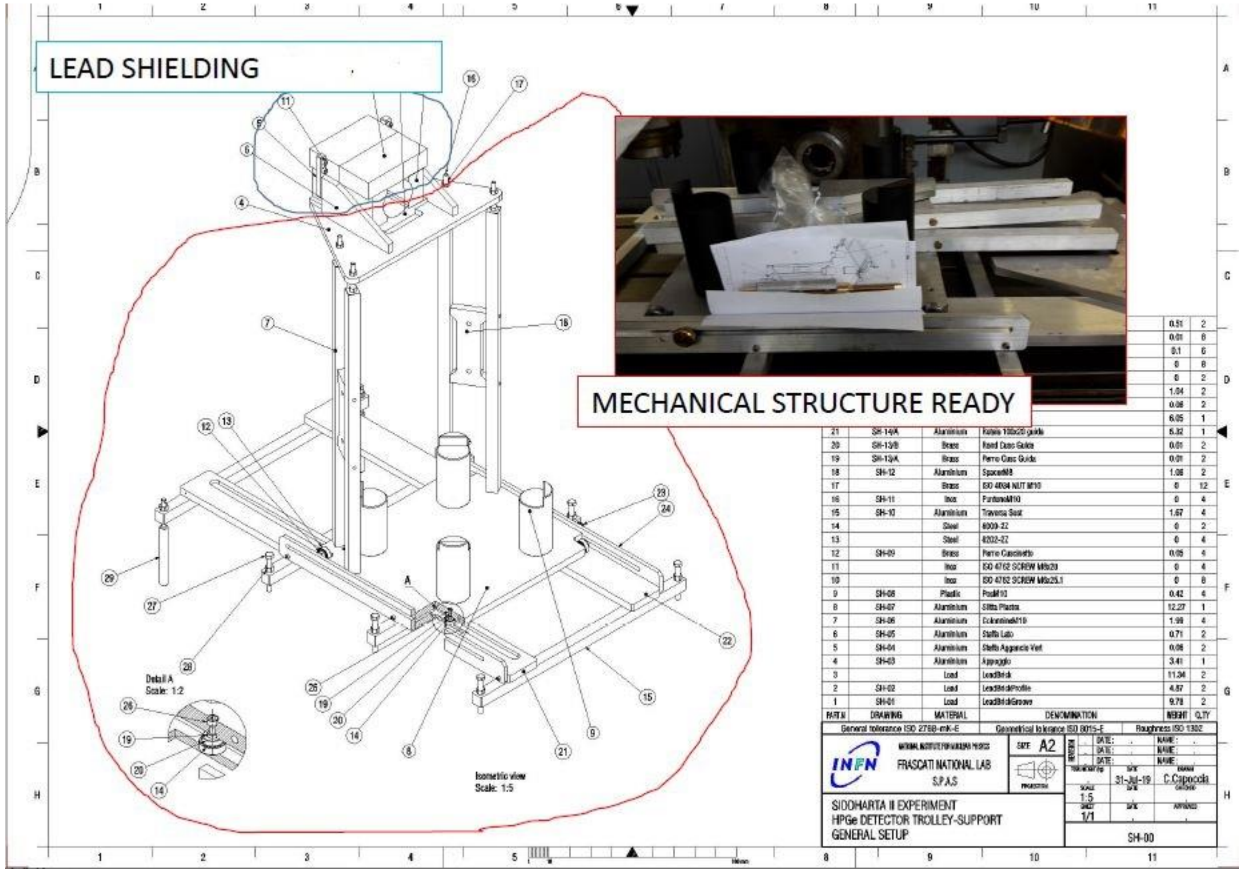
Signal from the luminometer ($80x40x2\ mm^3$) as a trigger for HPGe detector.

-> Hardware preparations

-> Simulations (GEANT4)

Holder and shielding have been prepared at LNF





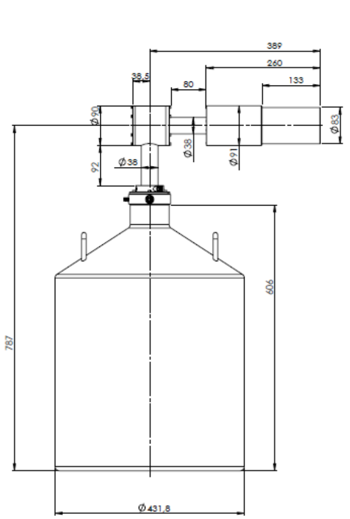
-> Hardware preparations

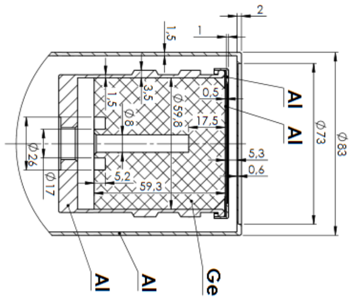
First measurements were foreseen for March/April 2020, unfortunately postponed to 2021

-> Simulations (GEANT4)

Measurement at DAϕNE with HPGe during SIDDHARTA-2

BSI HPGe detector with
transistor reset preamplifier (TRP).





HPGe active detector diameter ~60 mm, height ~60 mm.

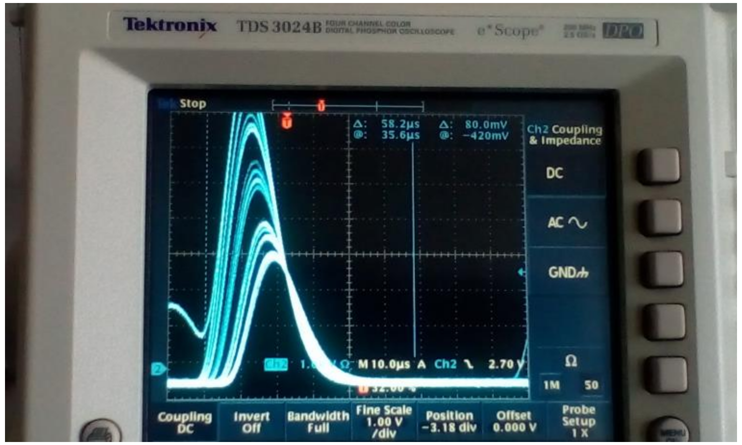
Analog electronics and **fast pulse digitizer**.

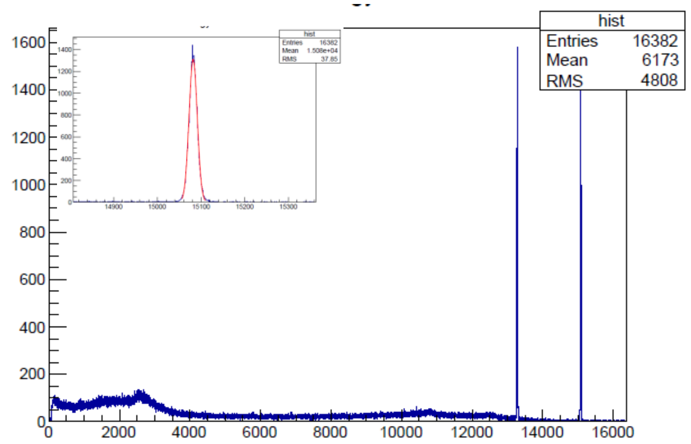
3.1. Detection unit GCD-30185 characteristics

#	Parameter	Value
1.	Relative efficiency (with respect to 3'' x 3'' NaI detector and Co-60 source mounted 25 cm above the detector) at 1.33 MeV γ-photon	> 30 %
2.	Energy resolution* at • 122 keV • 477.6 keV • 1.33 MeV **Measured with spectrometric device MS Hybrid at input count rate 1000 pulses/sec, shaping time constant = 6 μsec*	875 eV 1400 eV 1850 ± 30 eV
3.	Peak shape: • FWTM/FWHM • FW.02M/FWHM	< 1.9 < 2.65
4.	Spectral Broadening of FWHM up to 100,000 counts/sec for 1.33 Mev	< 8 %
5.	Peak position shift	< +/- 0.018 %
6.	Peak to Compton ratio, not worse	58 : 1
7.	Energy range of detector operation	40 keV – 3 MeV
8.	Material of input window	Al
9.	Cooling time	< 8 hours
10.	Liquid nitrogen holding time in Dewar vessel	> 15 days
11.	Dewar volume	30 l
12.	Preamplifier (built – in detector capsule) with cooled FET and transistor reset preamplifier (TRP) • Preamplifier power supply is ±12 V with 9 pin connector compatible with NIM standards • TTL signal to shut down the HV: - detector warm -0V; - detector cold: +5V • HV INHIBIT – BNC	

Laboratory tests of HPGe (BSI - TRP preamp) & analog electronics

Signal from spectroscopy amplifier

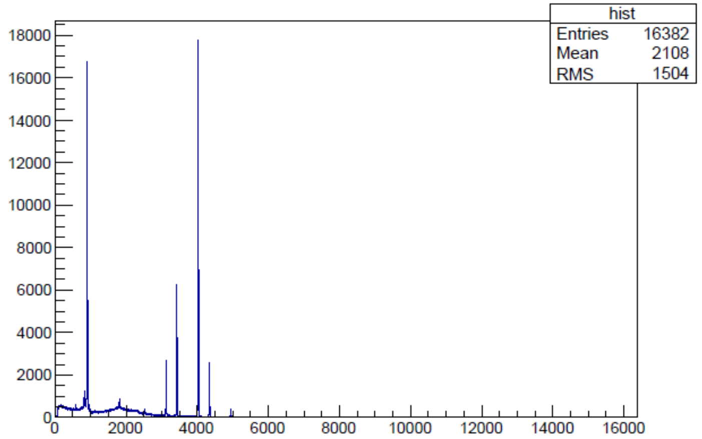




Signal from preamp of HPGe with TRP

Pb lines

Stability tests



^{60}Co, ^{133}Ba spectra,

resolutions: 0.870 keV at 81 keV
1.06 keV at 302.9 keV
1.11 keV at 356 keV
1.67 keV at 1330 keV

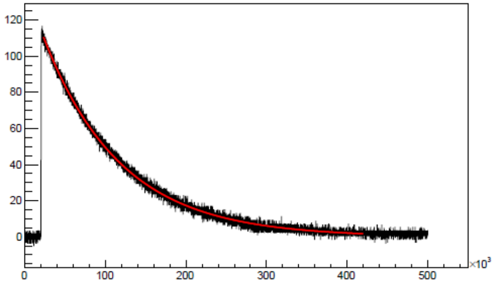
CAEN spectroscopy amplifier N968, Canberra Multiport II, Canberra Genius DAQ + analysis

Laboratory tests of HPGe (BSI - TRP preamp) & fast pulse digitizer, CAEN DT5781 4 ch, 14 bit,

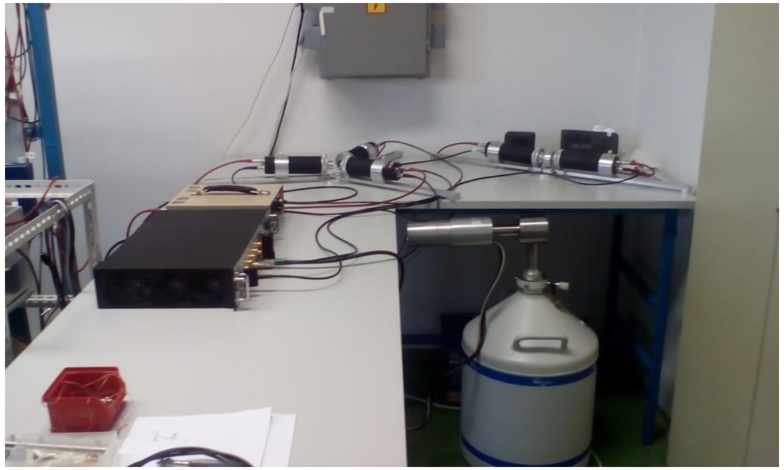
CAEN DT5781 4 ch, 14 bit, 10ns sampling time

Signal from spectroscopy amplifier ~20 μs (shaping time 6 μs), restriction on the rate.

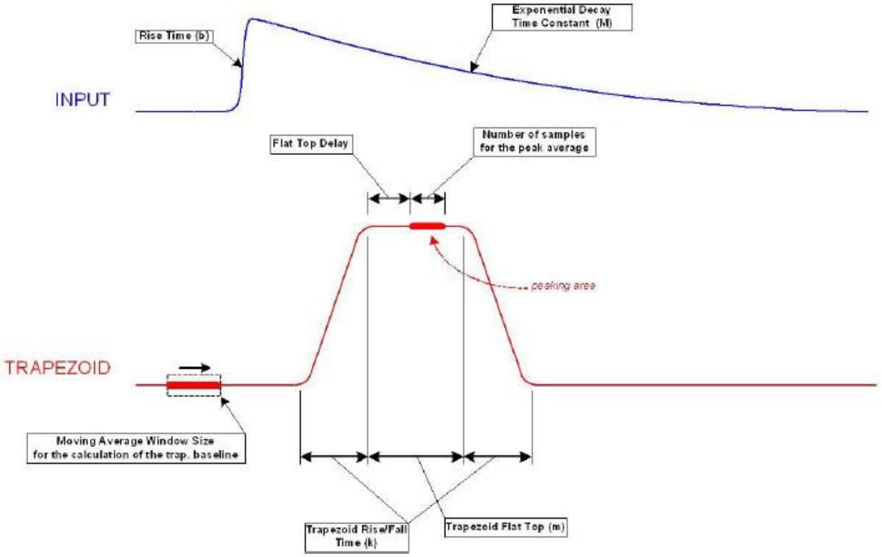
Signal from HPGe with RC preamp



Signal from preamp of HPGe with TRP



- **Digital Pulse Processing** for Pulse Height Analysis firmware , based on V.T. Jordanov et al. Nucl. Instr. Meth. A 353 (1994) 337

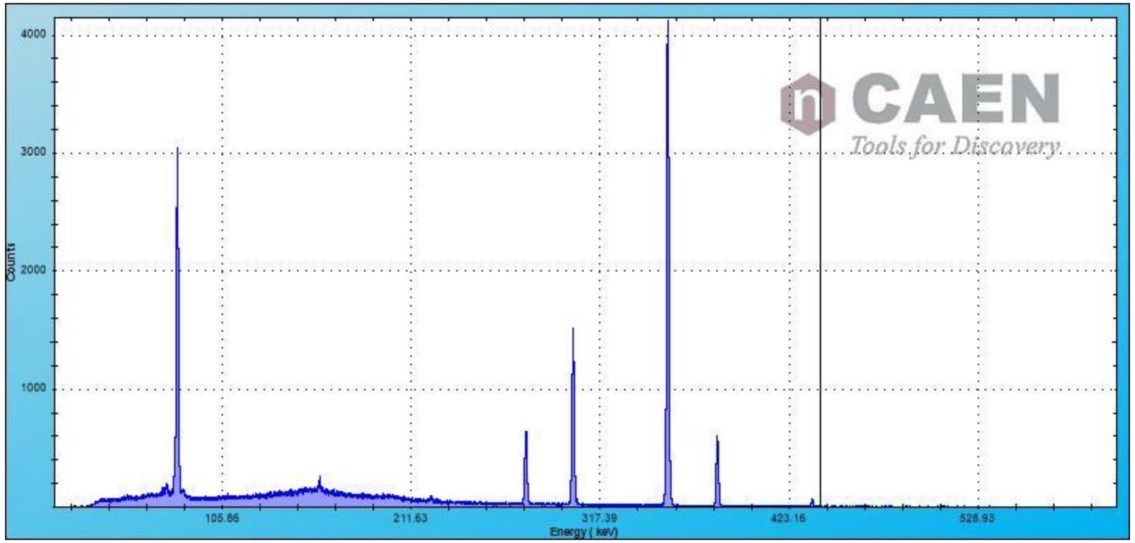


Possible rates up to 150 kHz, slightly worse resolution

Laboratory tests of HPGe (BSI - TRP preamp) & fast pulse digitizer, CAEN DT5781 4 ch, 14 bit,

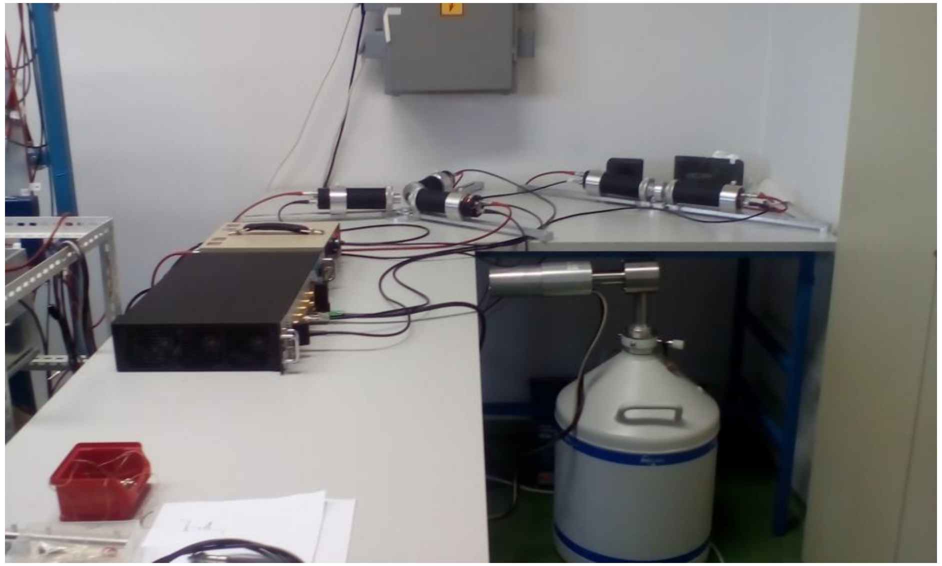
CAEN DT5781 4 ch, 14 bit, 10ns sampling time

Tests: ^{133}Ba



Low rates – same resolution as with conventional electronics
High rates – 10-20% worse resolution

- **Digital Pulse Processing** for Pulse Height Analysis firmware , based on V.T. Jordanov et al. Nucl. Instr. Meth. A 353 (1994) 337



- **Coincidences** – HPGe + luminometer

Setup ready for measurements!

Measurement at DAϕNE with HPGe during SIDDHARTA-2 run

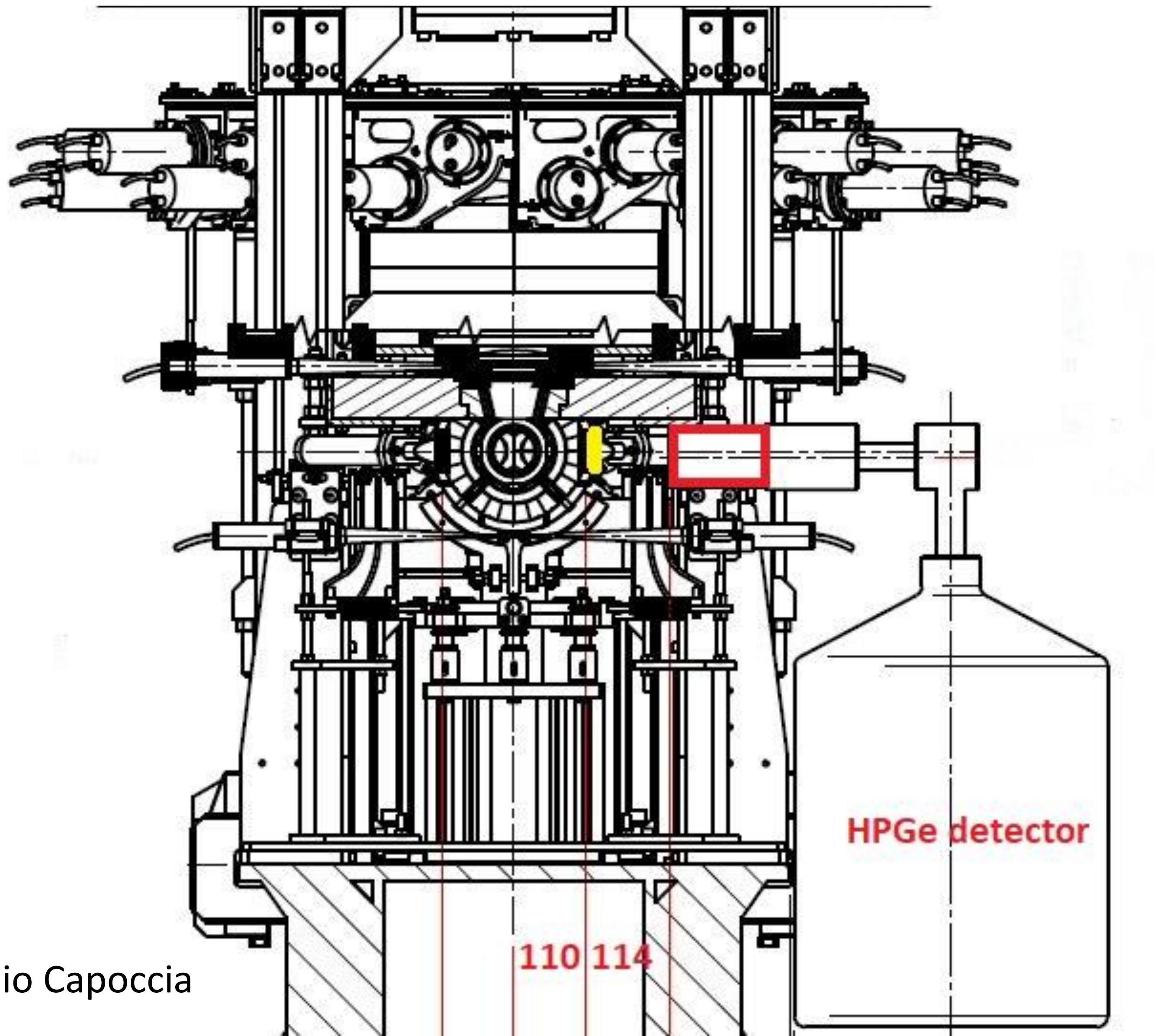


Figure: Cesidio Capoccia

Signal from the luminometer ($80x40x2\ mm^3$) as a trigger for HPGe detector.

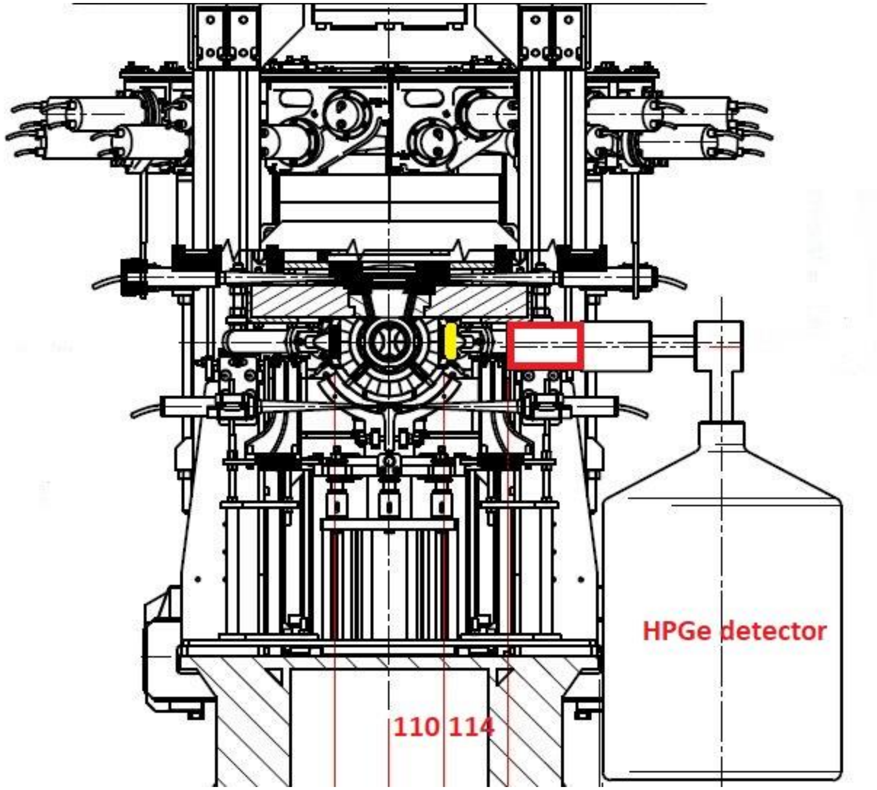
The position of luminometer 110 mm from the interaction point (+30 mm) .

Targets (Pb, W) just behind the luminometer,
80mm x 40mm x 0.6mm
no degrader
min. 100 mm from the HPGe

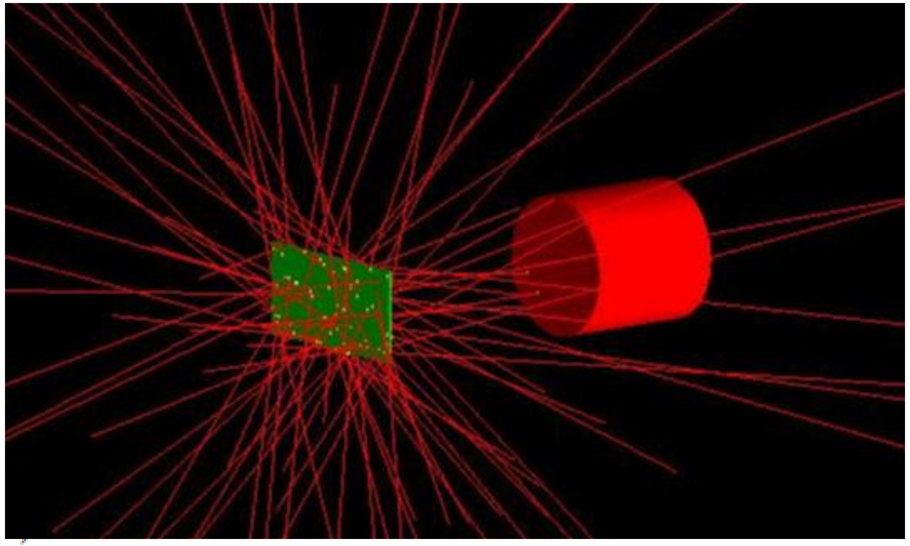
Positions of the detector and the target (size) are being determined by GEANT4 simulations.

- **Efficinency**
- **Background (kaon absorption)**

Simple GEANT4 Simulations – HPGe efficiency



X-rays are generated in the lead plate



E(keV) (trans.)	Eff. (%) (0.3 mm)	Eff. (%) (1.1 mm)
90.9 (13 → 12)	0.36	0.11
116.9 (12 → 11)	0.50	0.19
153.9 (11 → 10)	0.64	0.34
208.2 (10 → 9)	0.72	0.51
291.6 (9 → 8)	0.76	0.65
426.2 (8 → 7)	0.76	0.71

d (mm)	Eff. (%) (0.3 mm)	Eff. (%) (1.1 mm)
110	1.28	1.09
150	0.76	0.65
200	0.45	0.38
300	0.21	0.18
400	0.12	0.11
500	0.07	0.06

Table 1. Efficiencies of the HPGe detector for the X-rays from transitions in kaonic lead for two thicknesses of the target, left. Efficiencies of the HPGe detector for different distances of the HPGe detector from the target, for the X-rays of 291.6 keV and two thicknesses of the target (0.3 mm and 1.1 mm).

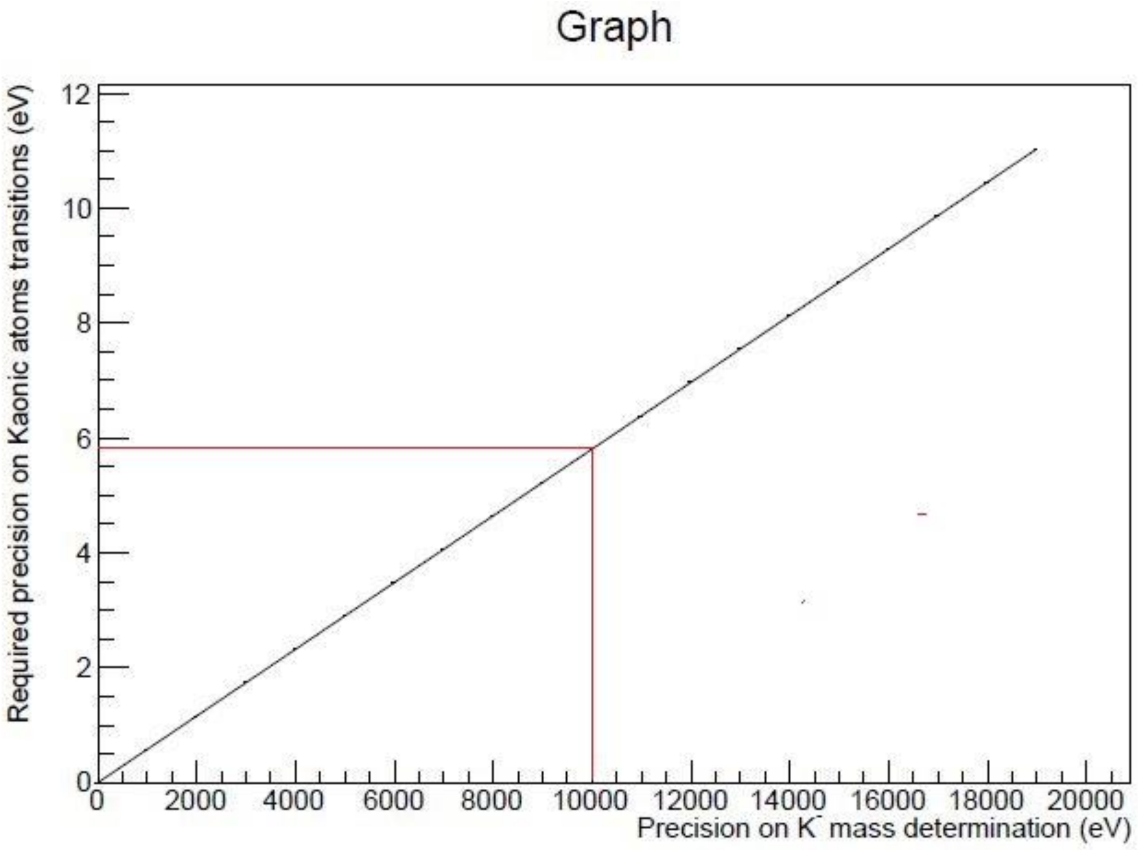
D. Bosnar et al. Acta Phys. Pol.B51 (2020) 115

Estimation of the requested number of X-rays in the peak (Pb, 9->8 transition,291 keV)

$$\text{precision(trans.)} = \frac{\sigma}{\sqrt{N}}$$

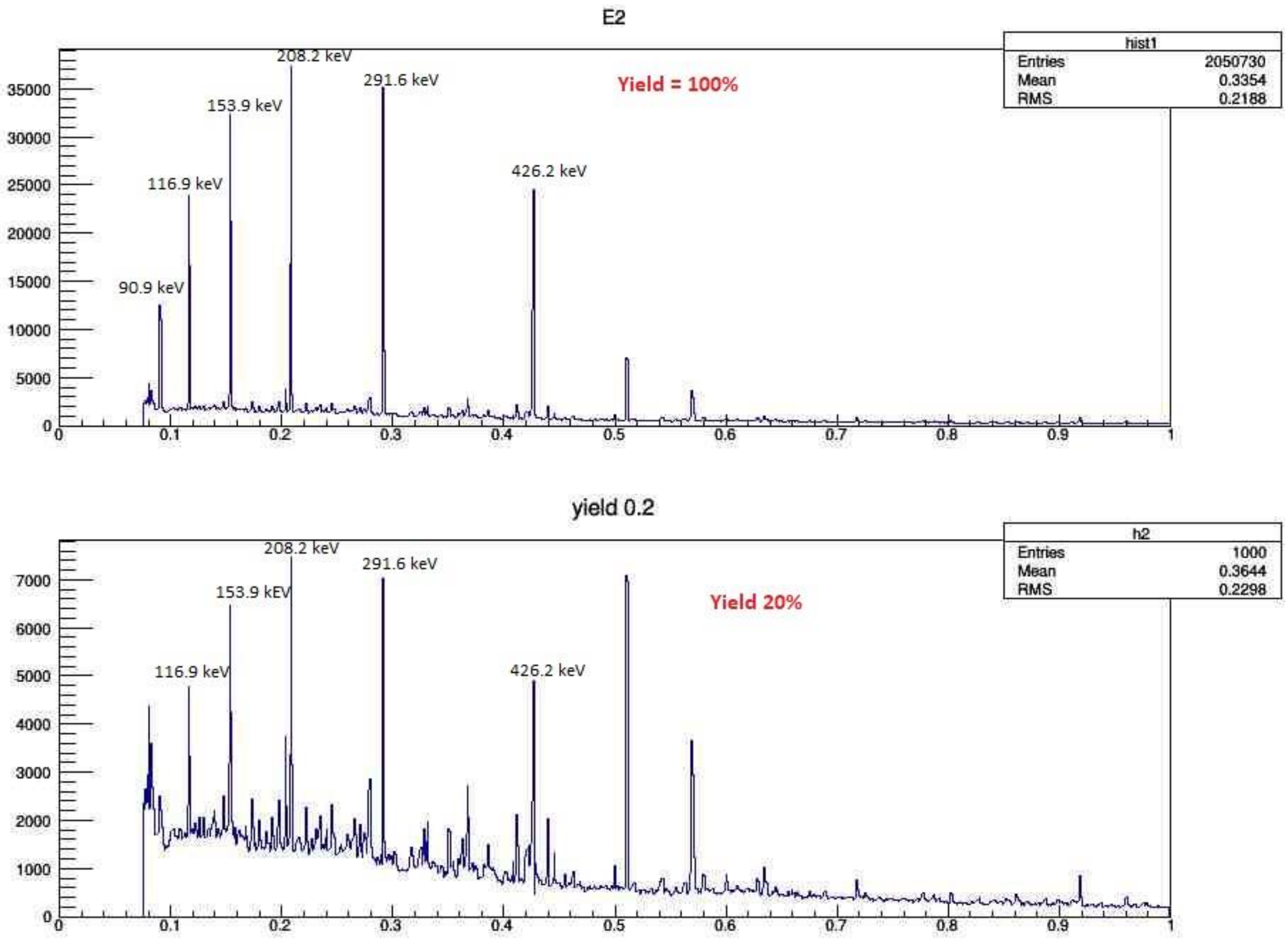
FWHM(302.9 keV)=1.1 keV -1.3 keV (depending on the rate)

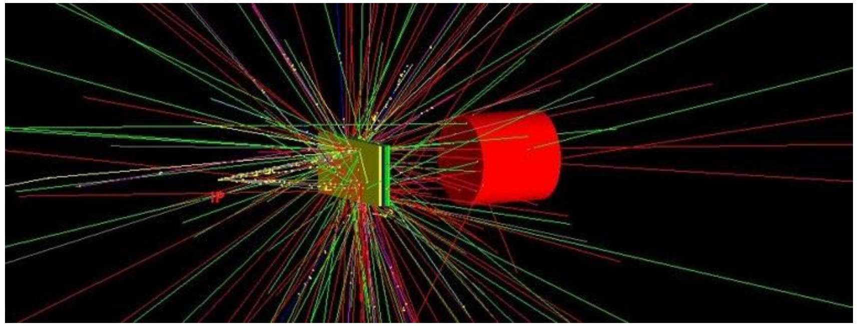
N≈6.000-9.000 X-rays in the peak (291.6 kEV) to reach the precision of previous measurements (10 keV).



Calculation: A. Scordo

HPGe detector on d=110mm from the Pb target (closest position), 400 pb^-1

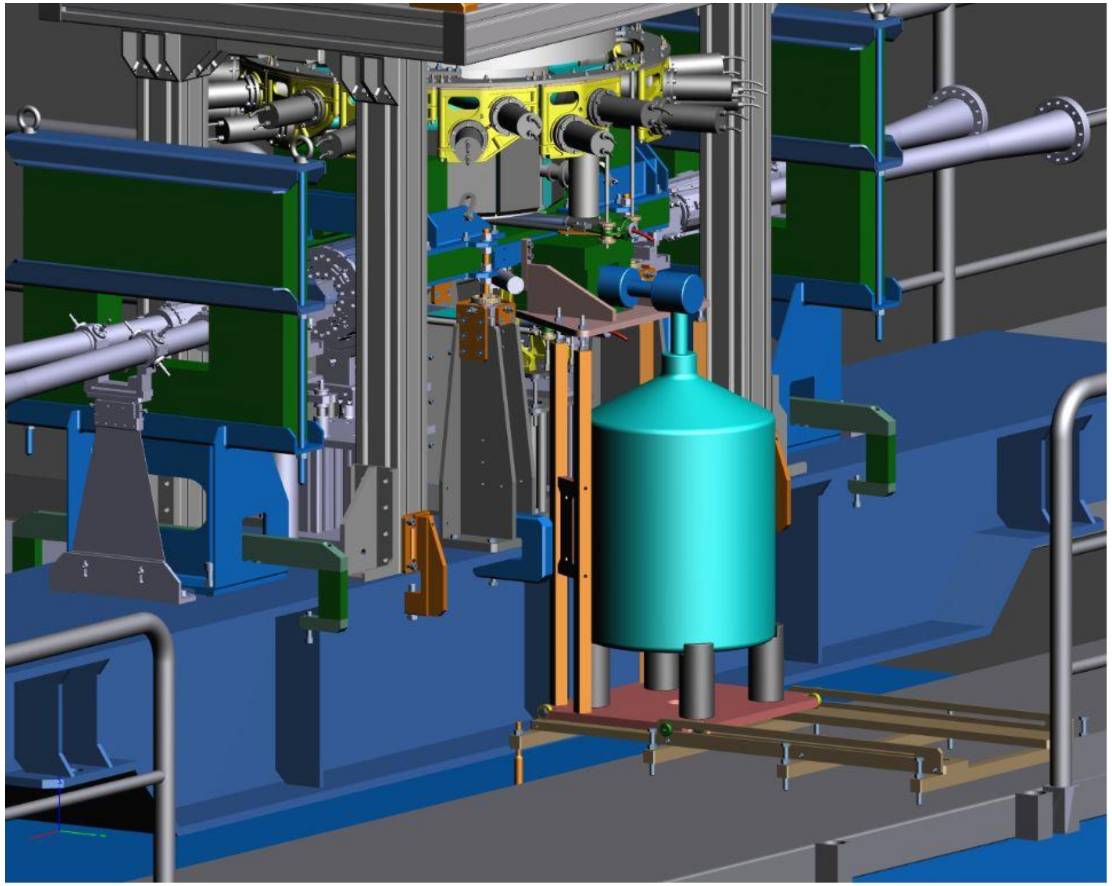




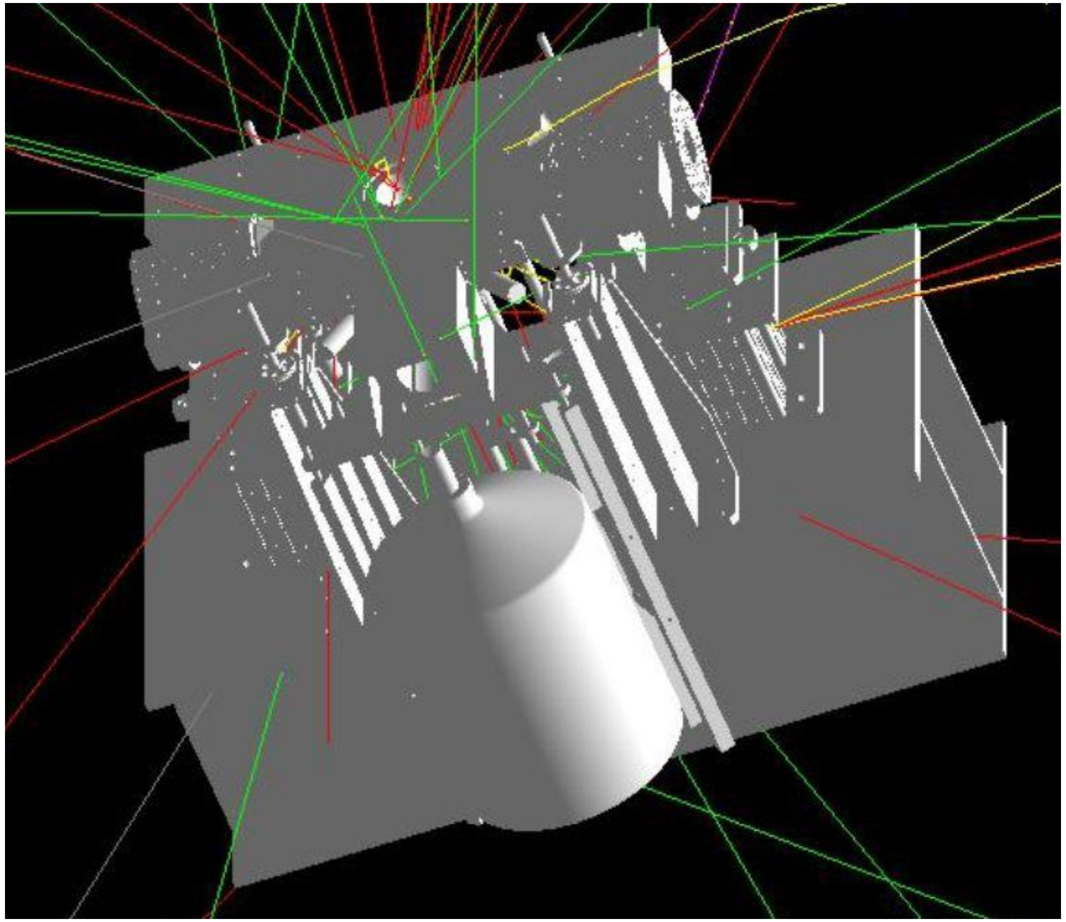
X-rays from Pb, in the peak at 291.6 keV there are approx 9.144 X-rays (yield 20%).
Approx. 9.000 X-rays in the 291.6 keV are needed for the required precisison
Only hadronic background, peaks are smeared with the detector resolution.

GEANT4 full simulation – work in progress

CAD drawing

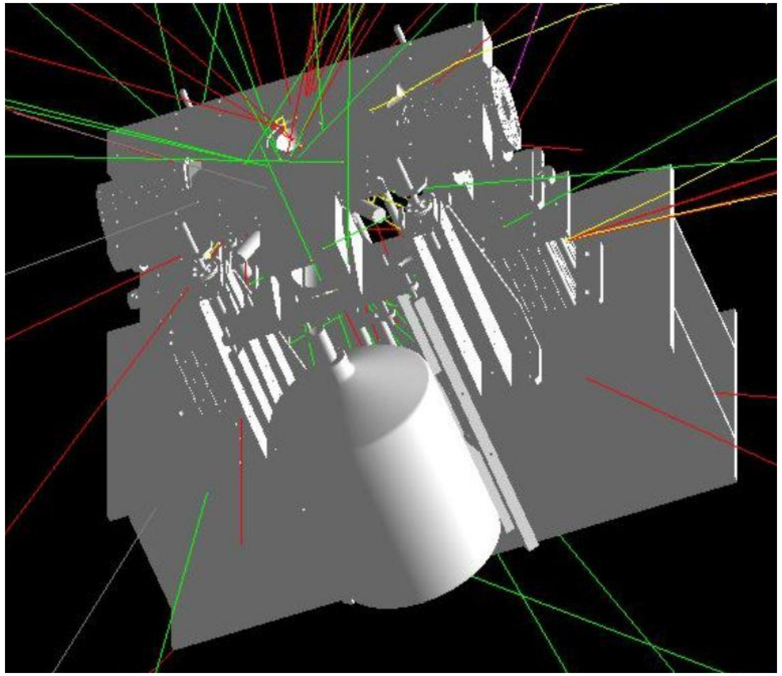


GEANT4 simulation

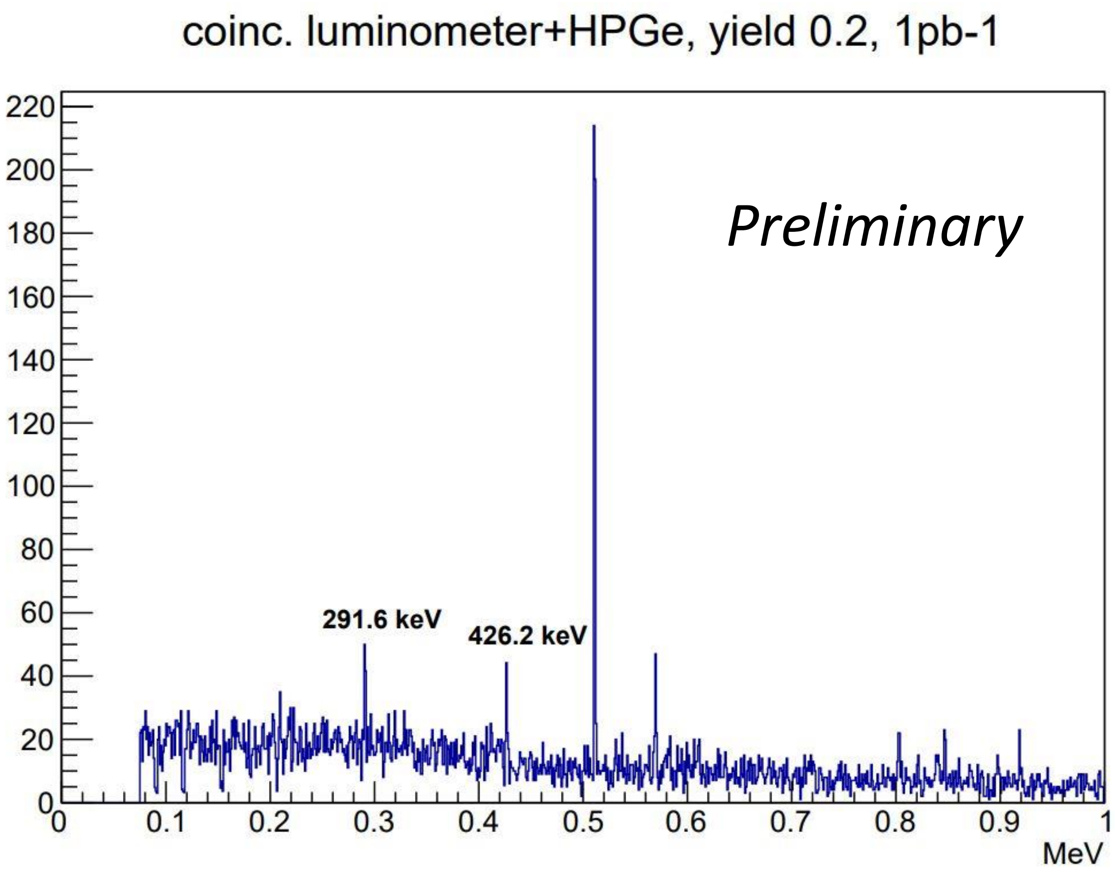


CAD files for selected objects are converted in GEANT4 gdml files for geometry description, different materials are taken into account

GEANT4 full simulation – work in progress



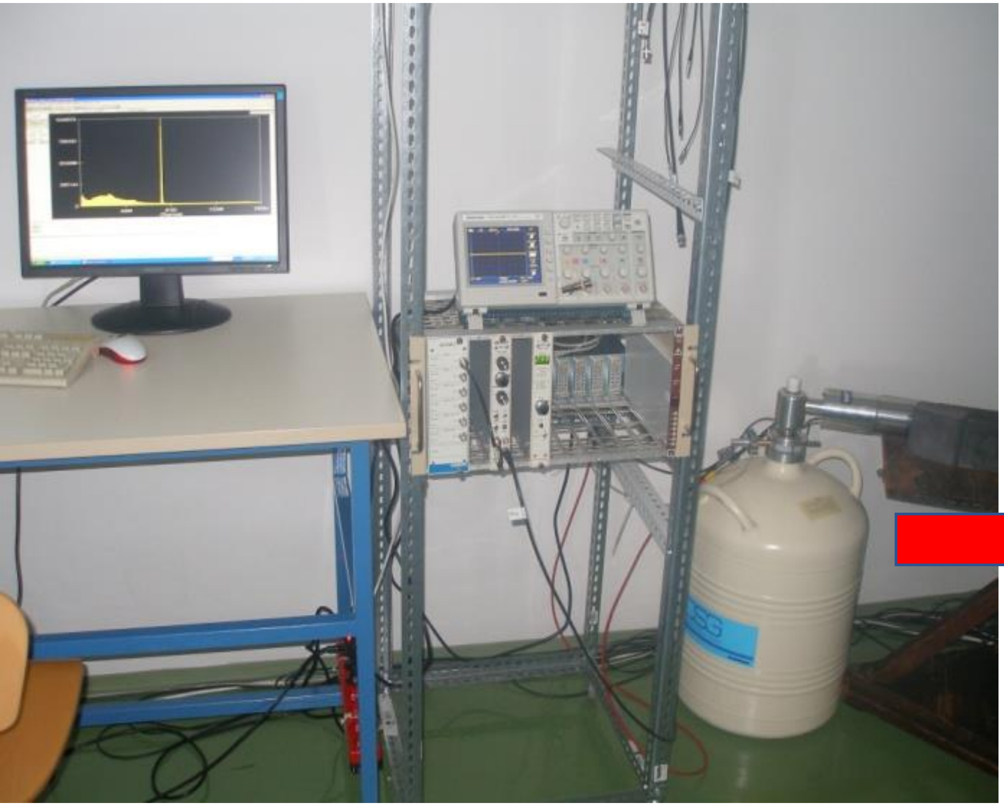
Kaons are generated uniformly in 4π
Only hadronic background., no background from e+e- beams
Front shielding of HPGe detector should be optimized

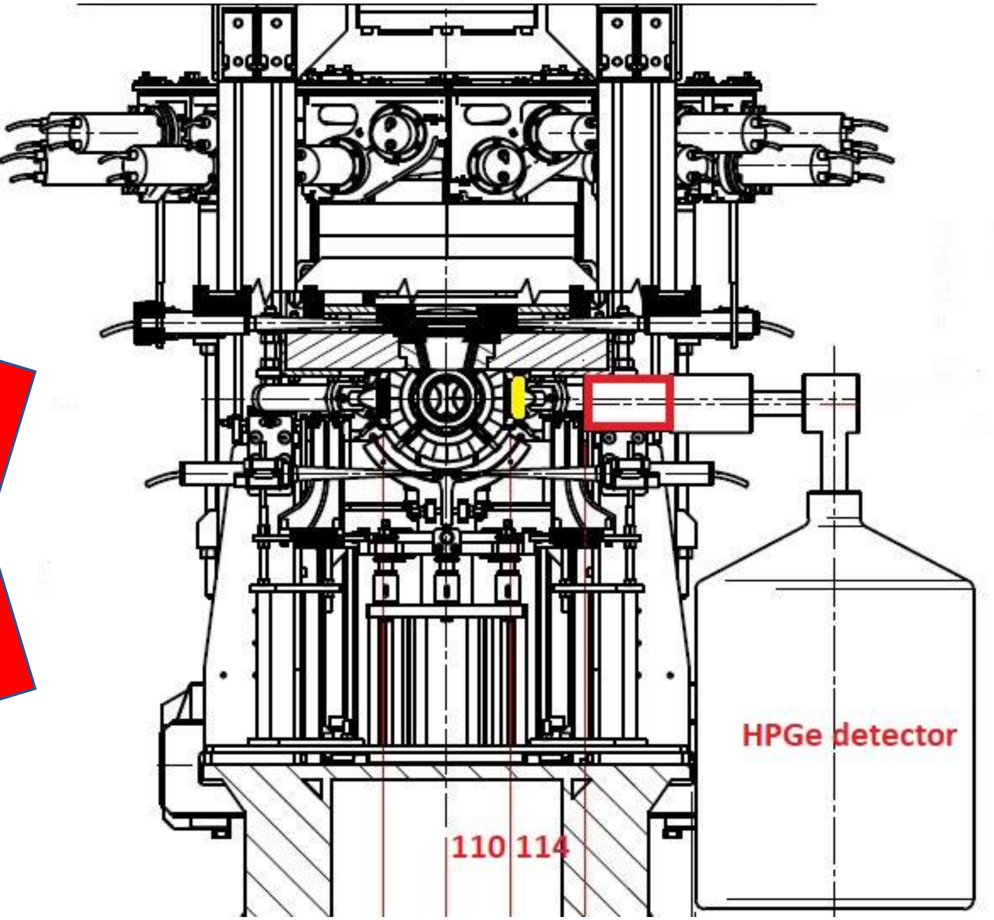


Approx. 50 events (291.6 keV) / pb^{-1},
12 pb^{-1} /day -> approx. 600 events/day.

~9.000 events -> 10 keV precision (15 days)
~25.000 events-> 5 keV precision (40 days)

Second HPGe detector





Additional HPGe detector
with RC preamplifier (DSG)

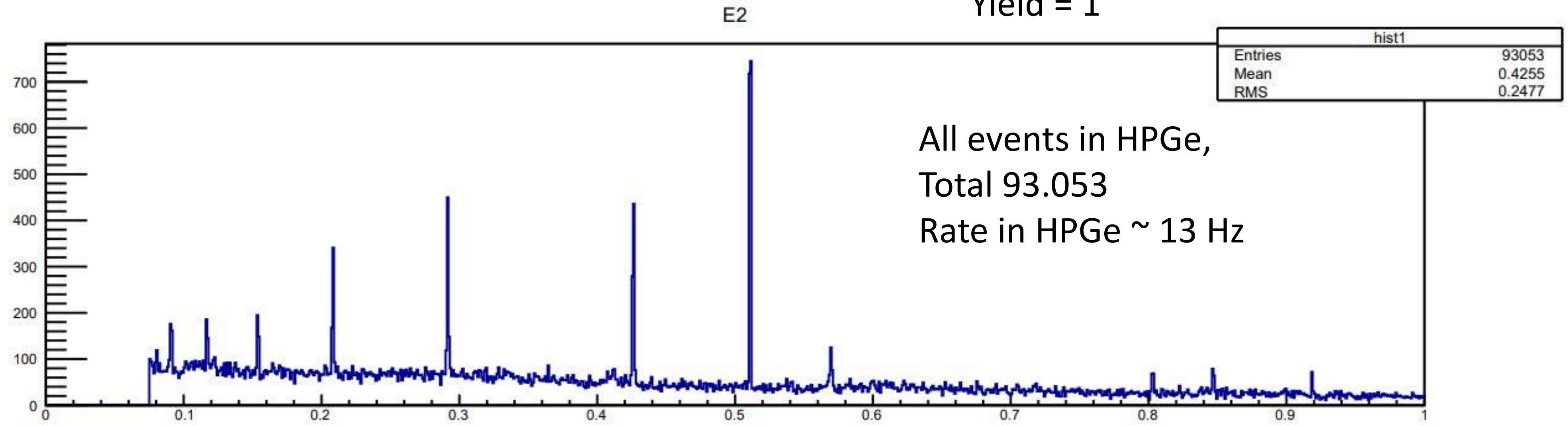
Hopefully, we will start the measurement soon (after Easter?) ☺

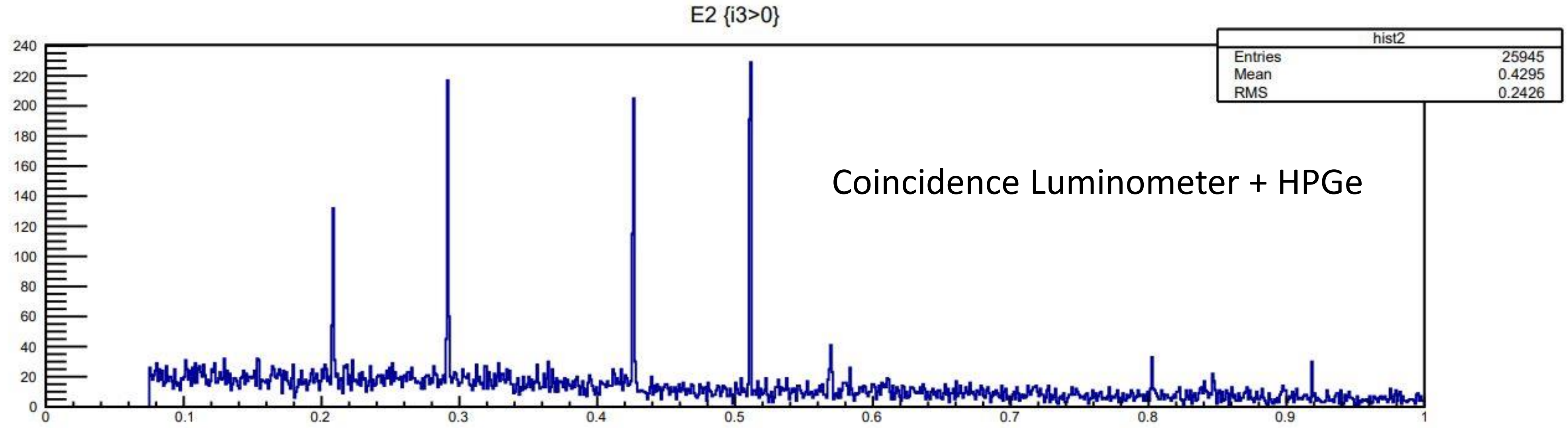
Thank you for your attention !

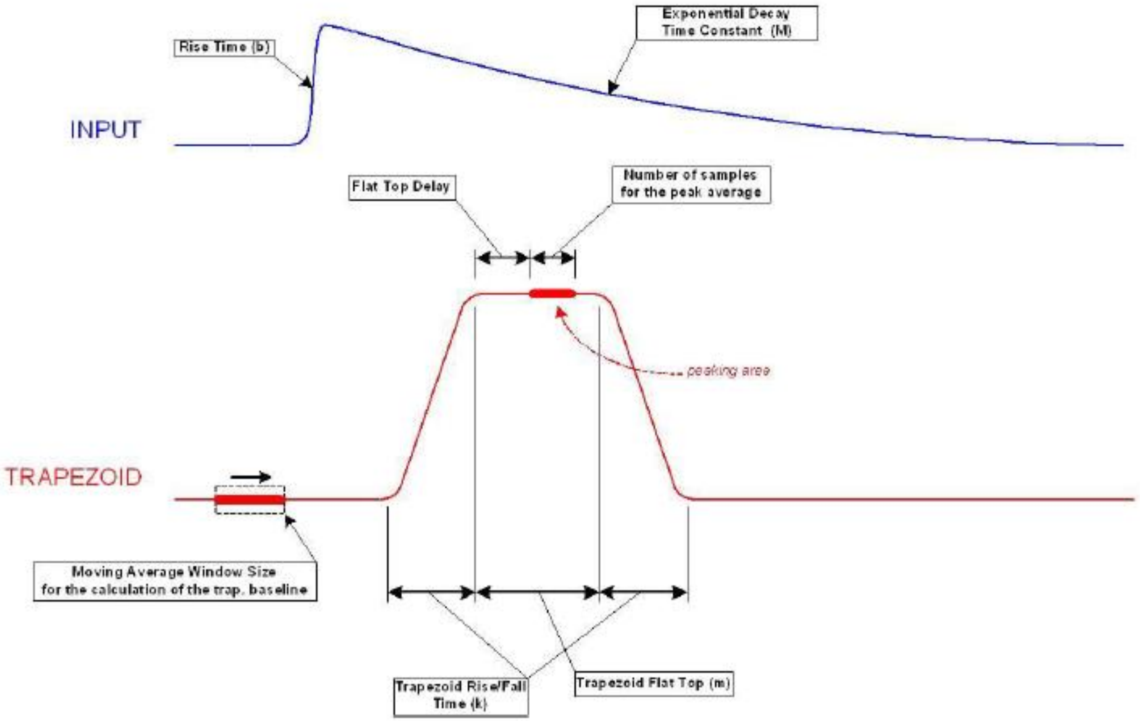
Backup slides

1pb-1 (~2h)

Yield = 1






Rise Time (b)
Exponential Decay
Time Constant (M)
INPUT
Flat Top Delay
Number of samples
for the peak average
peaking area
TRAPEZOID
Moving Average Window Size
for the calculation of the trap. baseline
Trapezoid Rise/Fall
Time (k)
Trapezoid Flat Top (m)