

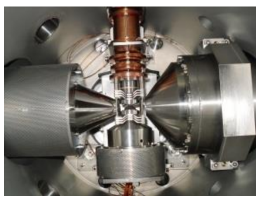
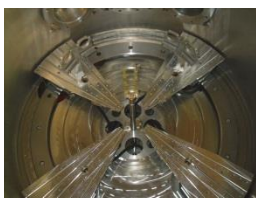
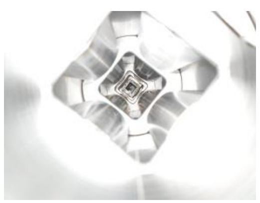

laboratoire de physique corpusculaire

Progress in the measurements of β-ν correlation coefficient in nuclear β decays using LPCTrap

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X. Fléchard, E. Liénard, O. Naviliat-Cuncic,
G. Quéméner, N. Severijns, J-C Thomas

XXIst Colloque GANIL - 09/12/2019

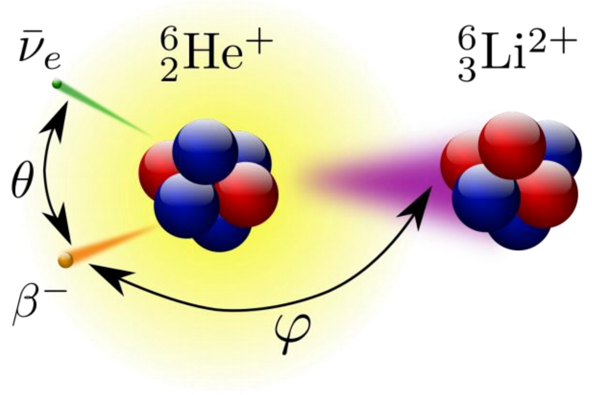
Overview

- Theory
- State of the art
- LPCTrap
- LPCTrap@GANIL
- Simulations
- Latest results

Theory

- Nuclear β-decay:

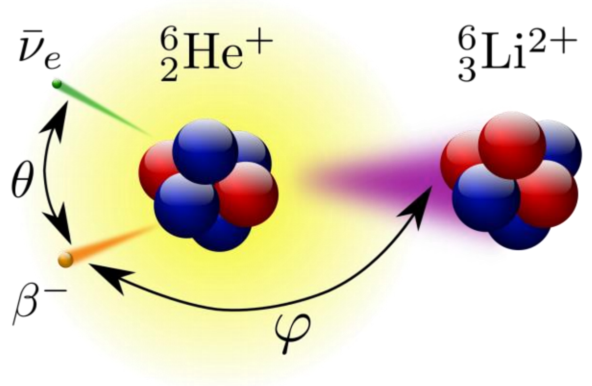
$$w(\vec{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$
$$= \frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$
$$\times \frac{1}{2}\xi\left(1 + \boldsymbol{a}\frac{\overrightarrow{p_e}.\overrightarrow{p_\nu}}{E_e E_\nu} + \boldsymbol{b}\frac{m}{E_e} + \ \ldots\right)$$



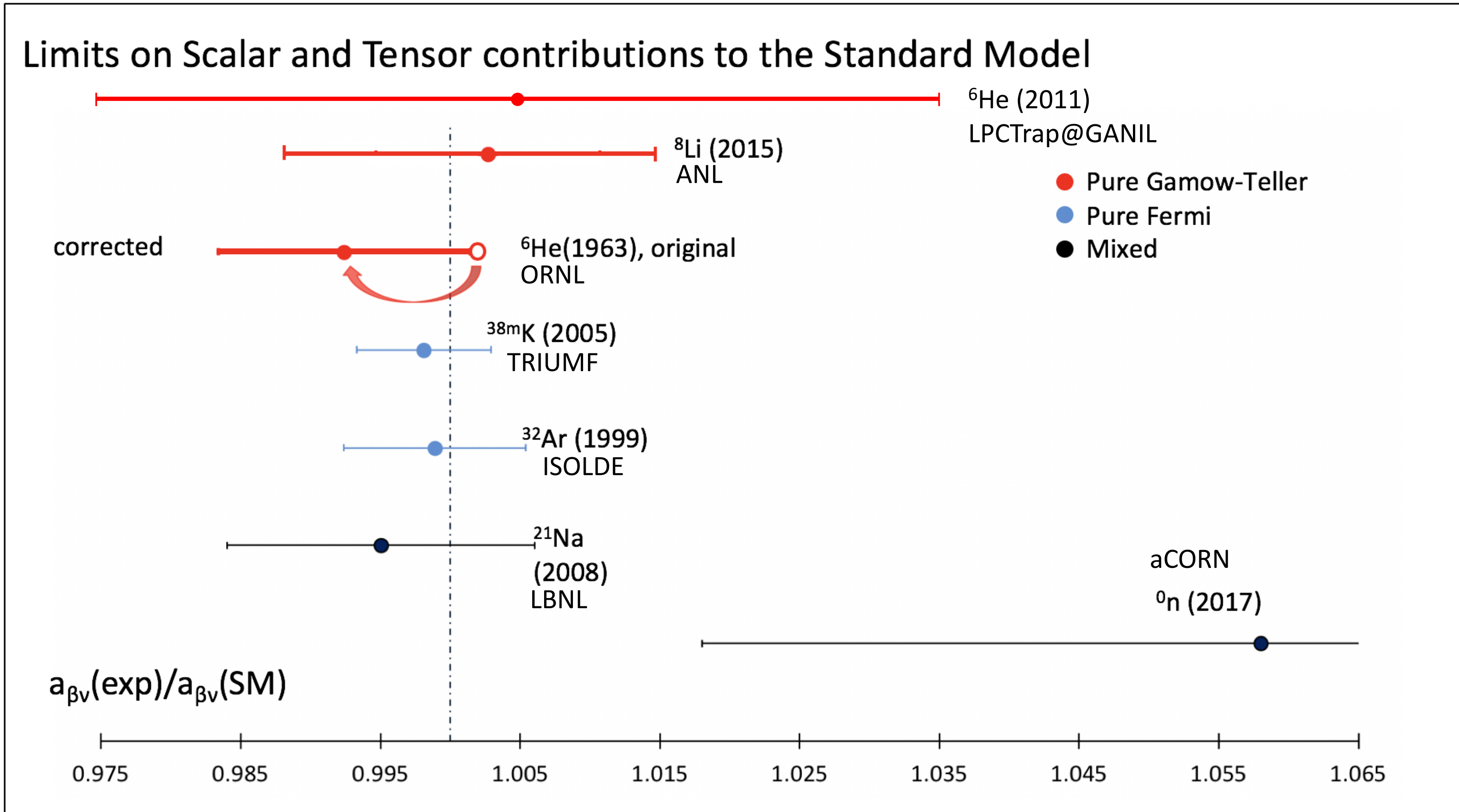
Theory

- Pure Gamov-Teller: $a_{GT} = \frac{|C_V|^2+|C_V'|^2-|C_S|^2-|C_S'|^2}{|C_V|^2+|C_V'|^2+|C_S|^2-|C_S'|^2}$
- Pure Fermi: $a_F = -\frac{1}{3}\frac{|C_A|^2+|C_A'|^2-|C_T|^2-|C_T'|^2}{|C_A|^2+|C_A'|^2+|C_T|^2-|C_T'|^2}$

- Standard Model = Vector-Axial theory:
  - $C_{S,T} = 0\ ,\ \ C_i = C_i'$
  - $a_{GT} = -1/3\ , a_F = \ +1$



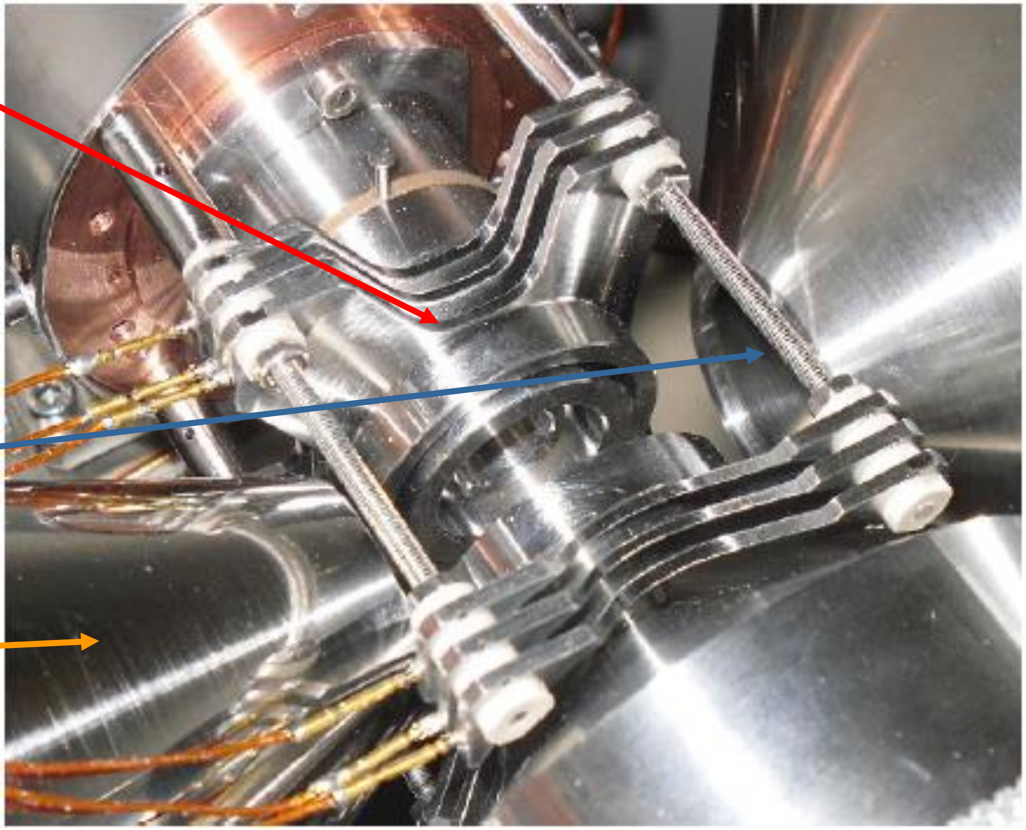
State of the art



Adapted from M. Burkey: *Searching For Tensor Currents In The Weak Interaction Using Lithium-8 Decay,* PhD University of Chicago

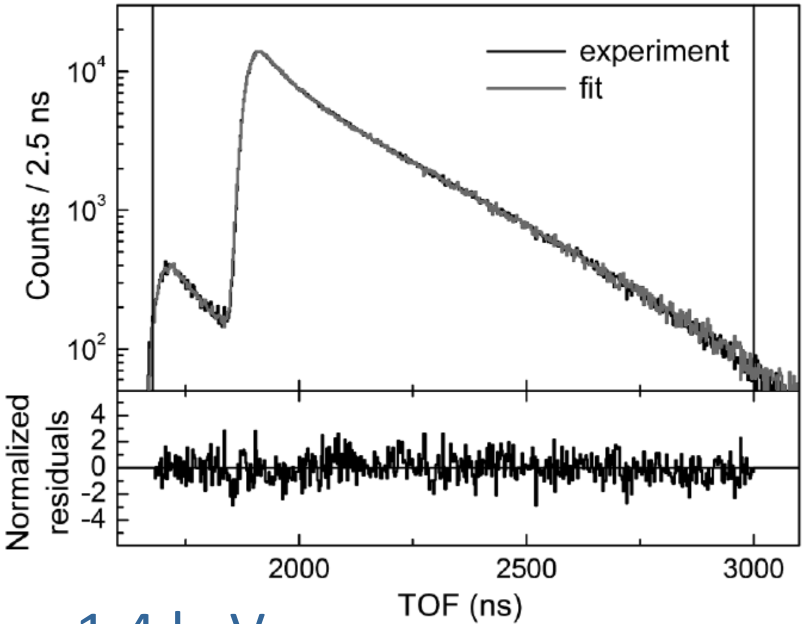
LPCTrap

- Transparent Paul Trap:
  - Three pairs of electrodes:
    - RF electrodes
    - Injection/extraction electrodes
    - Field correction electrodes
- β-Telescope:
  - DSSD + plastic scintillator
- Recoil Ion Detector:
  - -2kV acceleration grid + 250V focusing lens + -4kV polarized MCP



P. Delahaye arXiv:1810.09246

LPCTrap @ GANIL



Three nuclei/ions used:

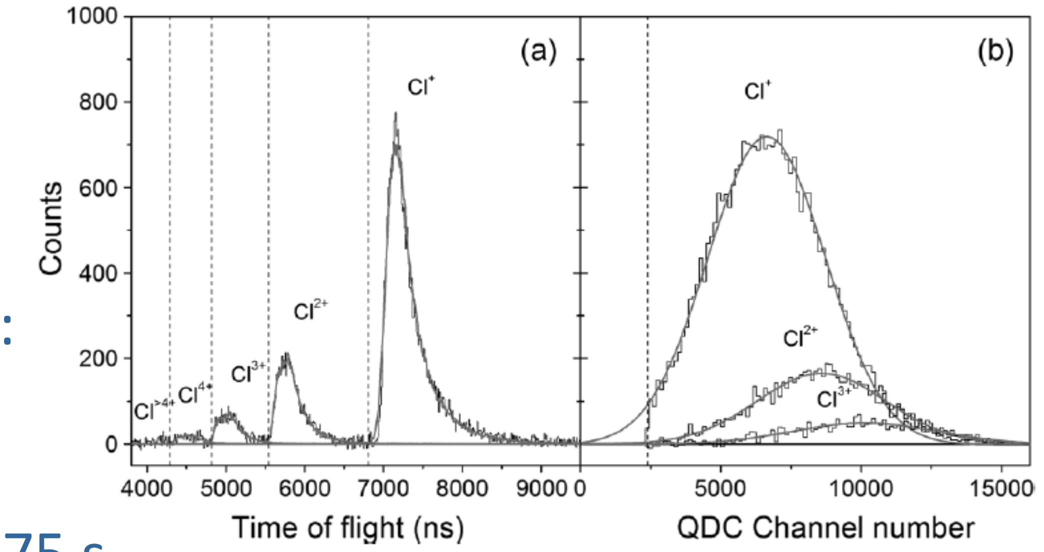
- $^6He^+ \rightarrow {}^6Li^{2+/3+}$ (2005-2010):
    - Pure GT
    - 100% GS→GS
    - Reasonable $T_{1/2}$ = 806.7 ms
    - High Q_β = 3.51 MeV → $T_{RImax} \approx 1.4$ keV
    - High production rate: 2 10^8 ions/s @ SPIRAL

C. Couratin, et al.: Phys. Rev. Lett. 108, 243201 (2012)

LPCTrap @ GANIL

Three nuclei/ions used:

- $^{35}Ar^{+} \rightarrow {}^{35}Cl$ (2011-2012):
  - Mirror transition
  - 98% GS→GS
  - Reasonable $T_{1/2} = 1.775$ s
  - High $Q_\beta = 2.28$ MeV but high daughter mass
    → Low $T_{RImax} = 450$ eV
  - Good production rate : 3.5 10^7 ions/s @ SPIRAL
  - Neutral daughter nucleus + multiple charge states

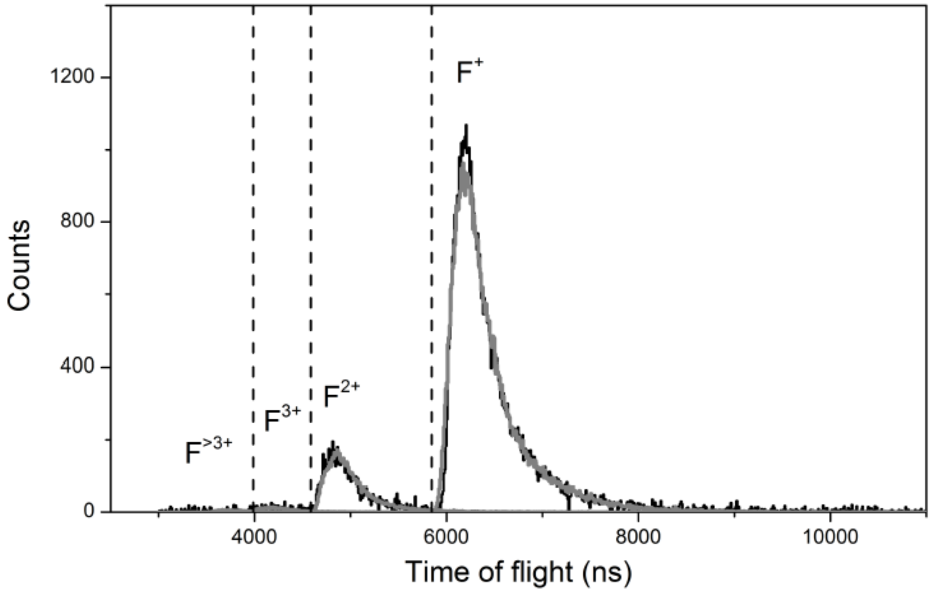


C. Couratin et al., Phys. Rev. A 88, 041403(R) (2013)

LPCTrap @ GANIL

Three nuclei/ions used:

- $^{19}Ne^{+} \rightarrow {}^{19}F$ (2013):
  - Mirror transition
  - 99.988% GS→GS
  - Long $T_{1/2}$ = 17.26 s
  - Low Q_β = 961 keV → Low T_{RImax} = 200 eV
  - High production rate ≈ 3 10^8 ions/s @ SPIRAL
  - Few charge states ($F^{+/2+/3+/4+}$)



X. Fabian *et al*, Phys. Rev. A 97, 023402 (2018)

Simulations

- Previous results dominated by two systematics:
  - Cloud temperature
  - Beta scattering

- New software developed to answer both:
  - Clouda (cloud temperature)
  - Bayeux (β-scattering)
  - + new Data analysis

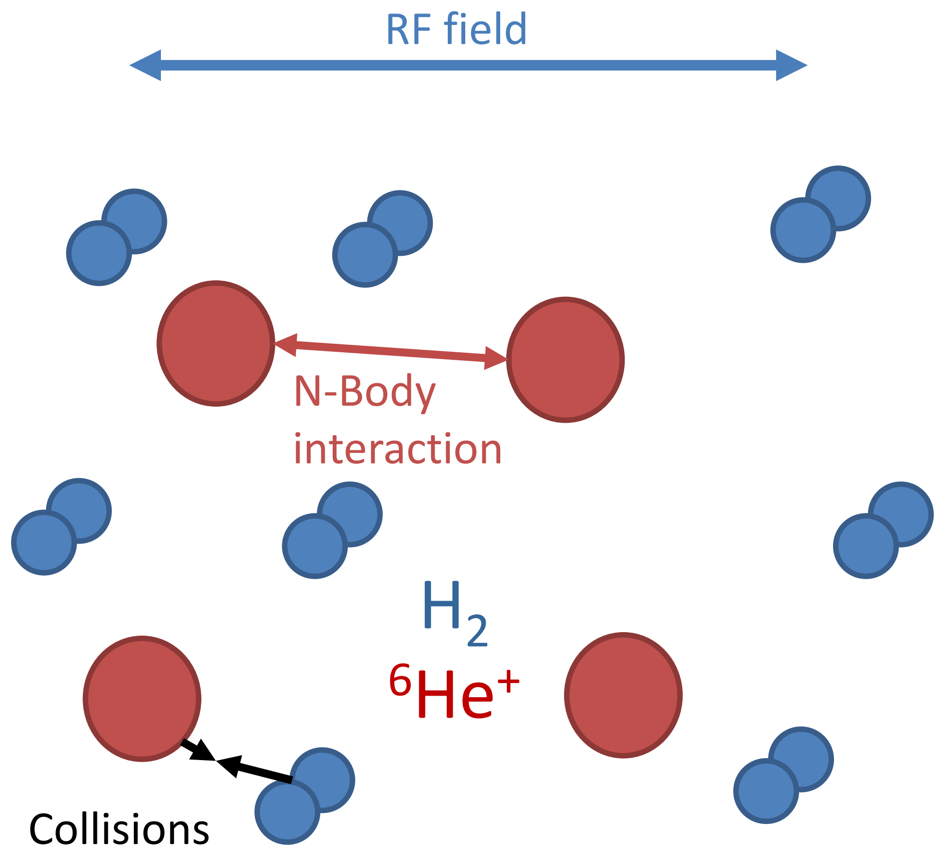
Table 1. Dominant sources of systematic error, systematic uncertainties and impact on the error of $a_{\beta\nu}$. The last column indicates the method used to estimate the parameters.

Source	Uncertainty	$\Delta a_{\beta\nu}$ ($\times 10^{-3}$)	Method
Cloud temperature	6.5%	6.8	Off-line measurement
$\theta x_{\mathrm{MCPPSD}}$	0.003 rad	0.1	Present data
$\theta y_{\mathrm{MCPPSD}}$	0.003 rad	0.1	Present data
MCPPSD offset (x, y)	0.145 mm	0.3	Present data
MCPPSD calibration	0.5%	1.3	Present data
d_{DSSSD}	0.2 mm	0.3	Present data
E_{scint}	see text	0.8	Present data
E_{si}	10%	0.8	GEANT4
'Accidentals' and 'out trap'	See the text	0.9	Present data
β scattering	10%	1.9	GEANT4
Shake-off	0–0.05	0.6	Theoretical calculation
V_{RF}	2.5%	1.7	Off-line measurement
Total		7.5	

X. Fléchard *et al* 2011 *J. Phys. G: Nucl. Part. Phys.* **38** 055101

Ion cloud simulation

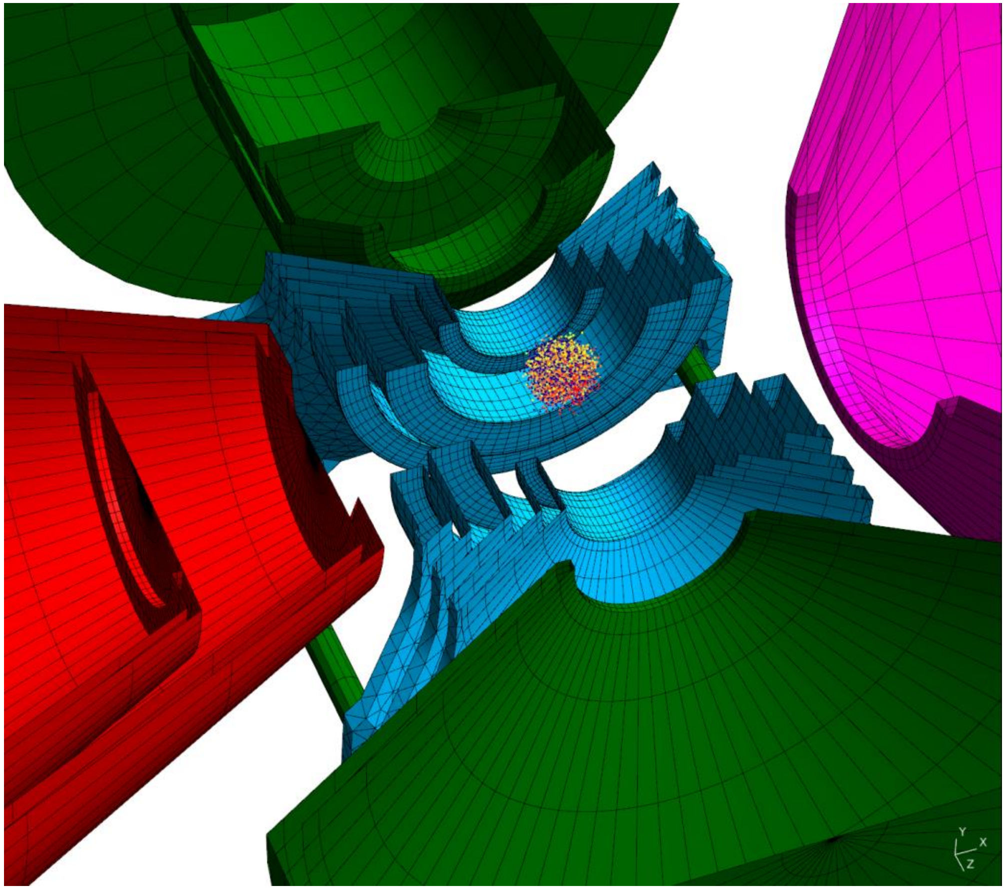
- Clouda software:
  - Simulation of the ion cloud dynamics
  - Massively parallel simulation of individual ions on GPU
  - Trapping field + N-Body space charge considered



X. Fabian: *Precision measurement in the weak interaction framework: development of realistic simulations for the LPCTrap device installed at GANIL,* PhD University of Caen

Tracking

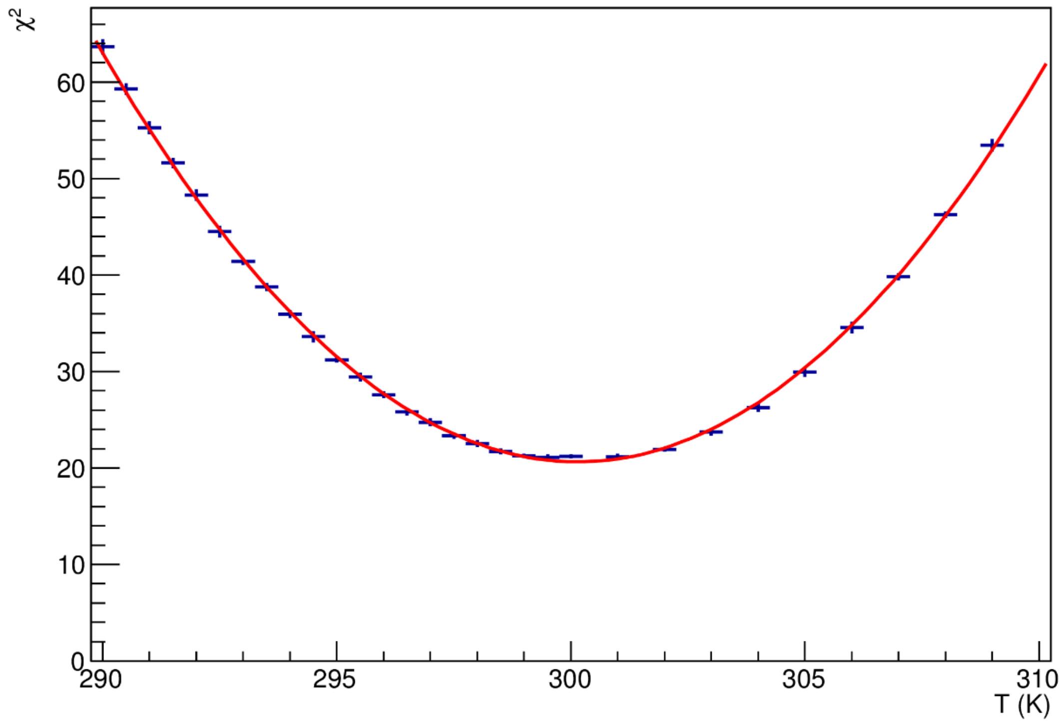
- Bayeux software:
  - Simulation of the ions and electrons propagation in the LPCTrap electric field
  - Built-in β-decay generator with shake-off
  - RF and static electric field



Data analysis

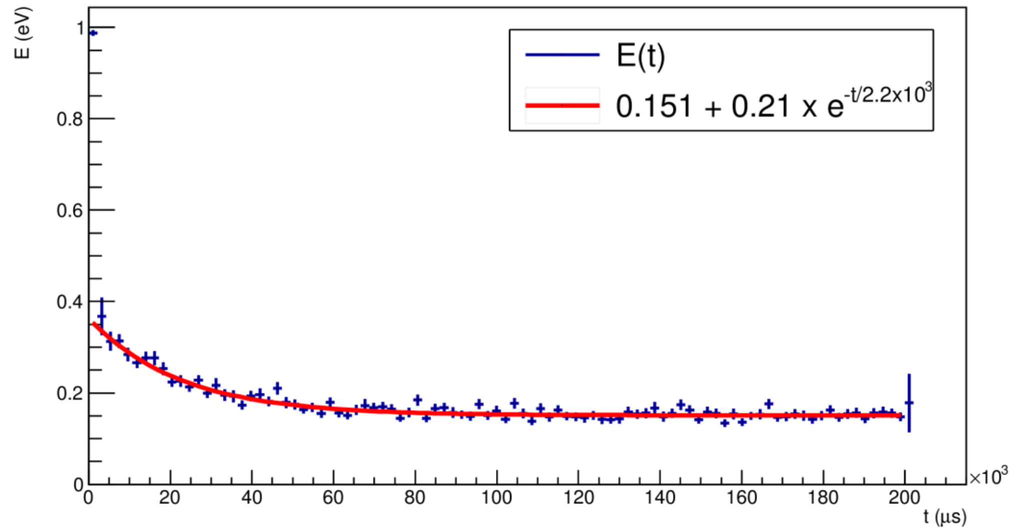
- Two phase analysis:
  - Python script for data reading and calibration
  - ROOT macros for fitting

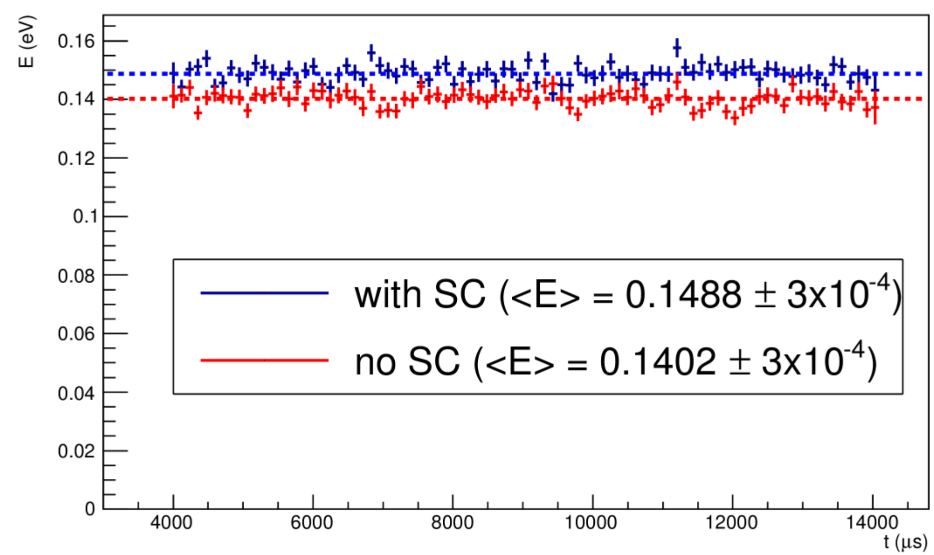
- Systematics analyzed:
  - Buffer gas temperature
  - DSSD and MCP shift
  - Scintillator response function



Latest results

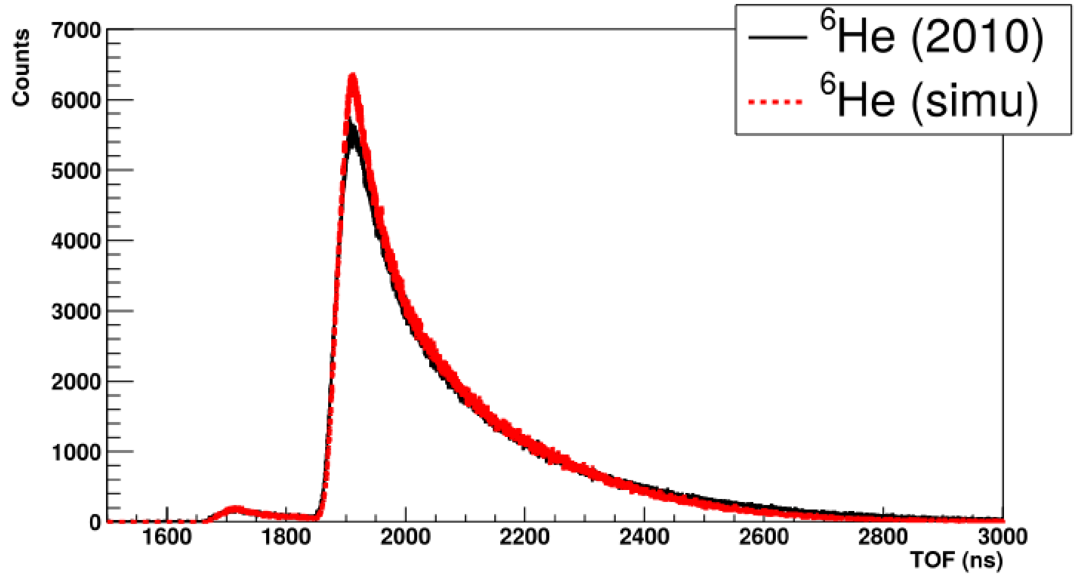
- Clouda software:
  - Good simulation of the dynamics of ions
  - Good reproduction of:
    - cooling time
    - cloud spatial shift
    - space charge effect





Latest results

- Bayeux software:
  - Simulation of TOF measurement
  - Comparison with experimental data
  - Problem: not sensible enough to $a_{\beta\nu}$ because too thin peaks yet
  - $\chi^2_{-1/3}/NDF = 6,65 \pm 0,02$
  - $\chi^2_{-0,3}/NDF = 6,67 \pm 0,01$

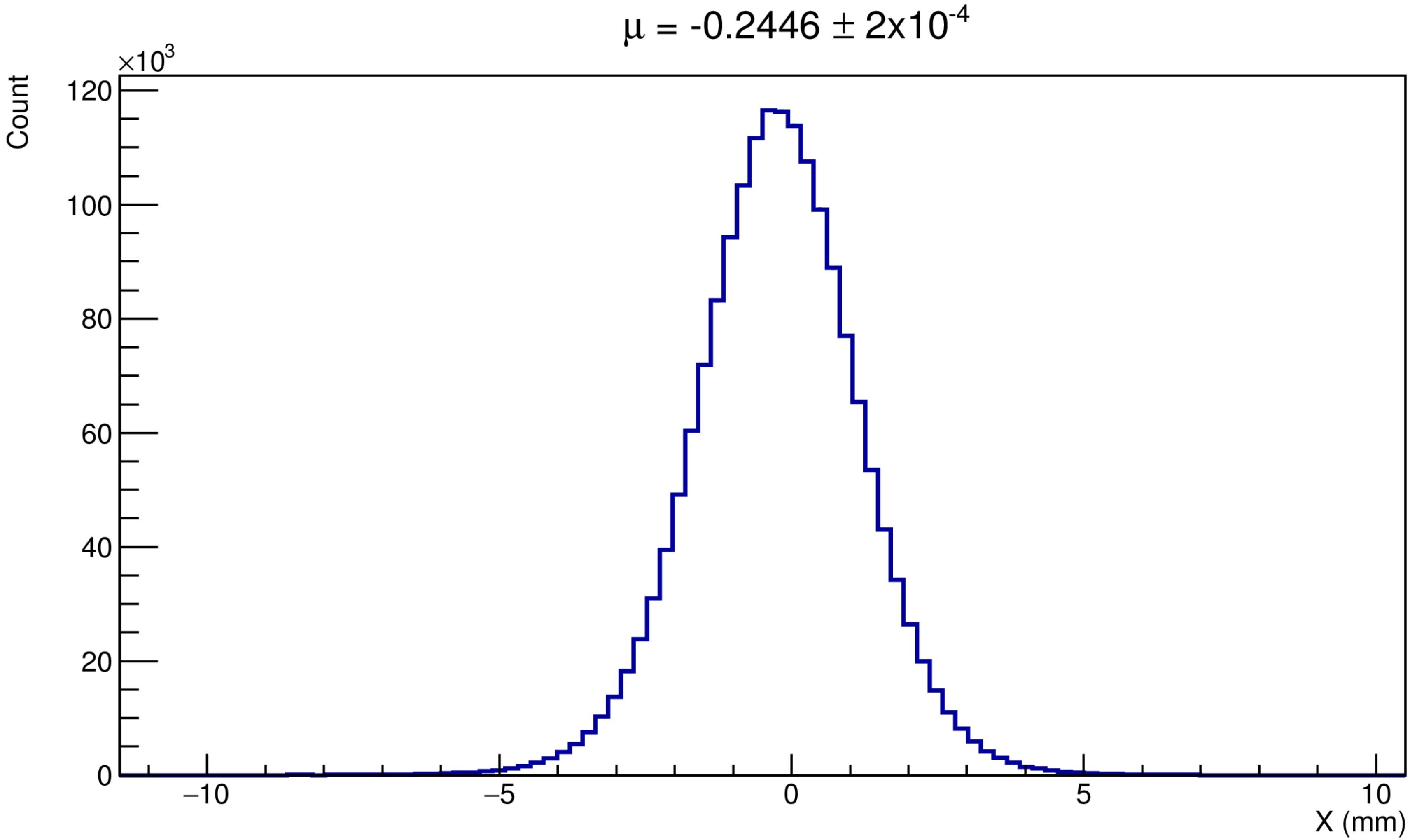


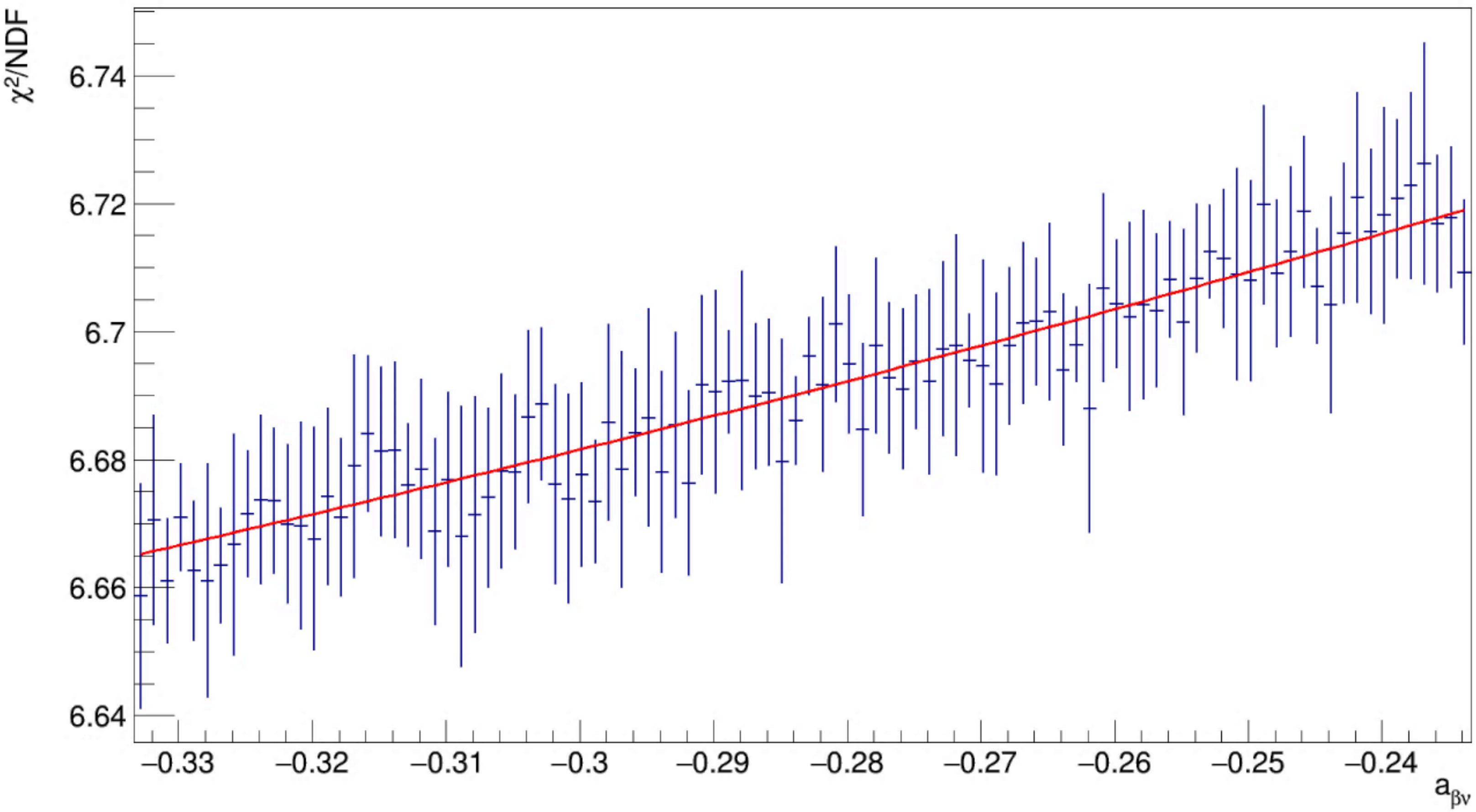
Conclusion and prospective

- Data analysis currently on-going
- ^{6}He data to be analyzed before the end of the year
- ^{35}Ar and ^{19}Ne data to be analyzed before the end of 2020
- Measurement campaign of β-scattering inside LPCTrap to improve the systematics
- Experimental or theorical determination of He+H_2 cross-section
- New beams at SPIRAL: more mirror nuclei: ^{21}Na, ^{23}Mg, ^{33}Cl, ^{37}K

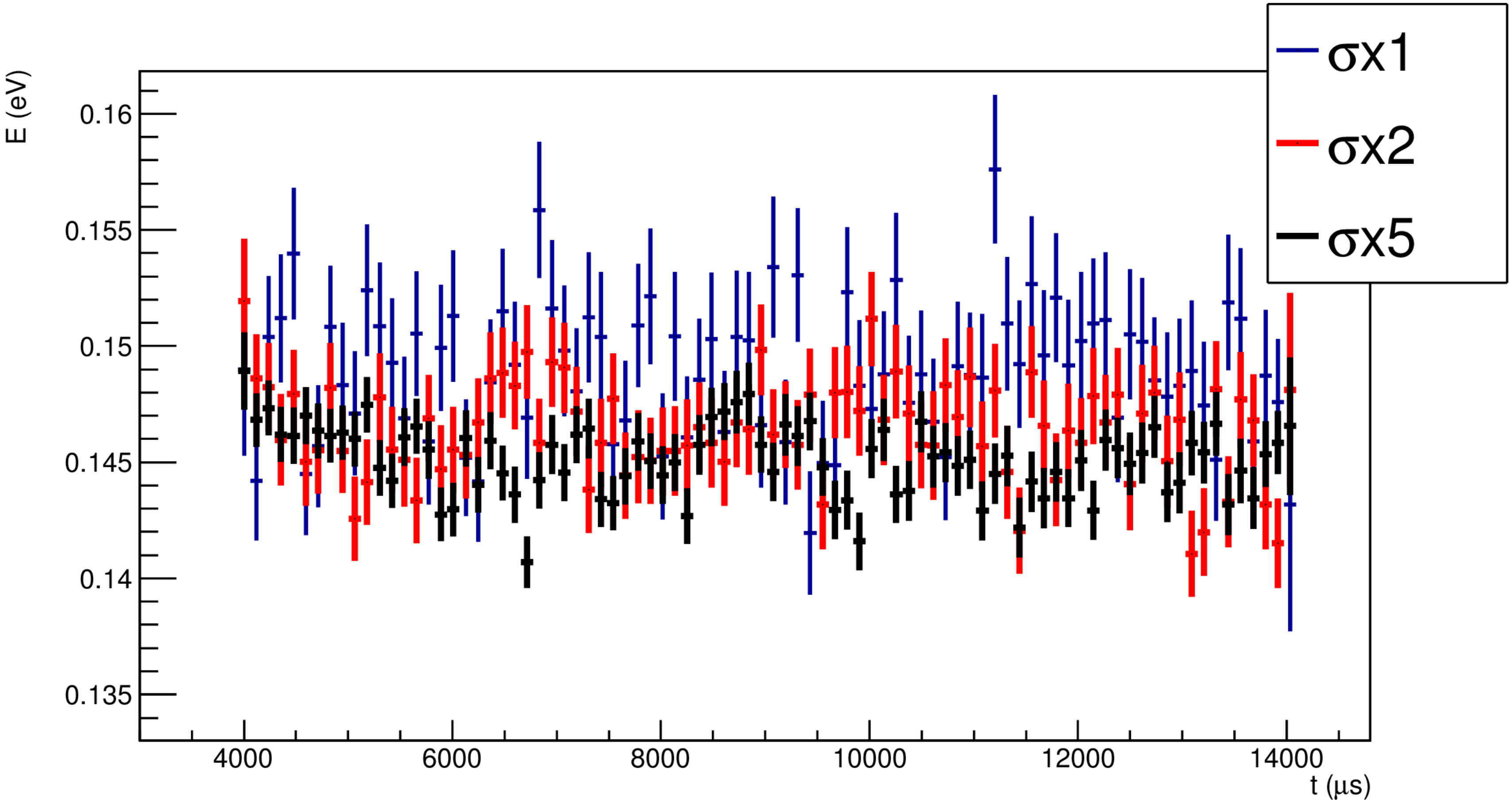
Thank you for your attention

This work is funded by Région Normandie

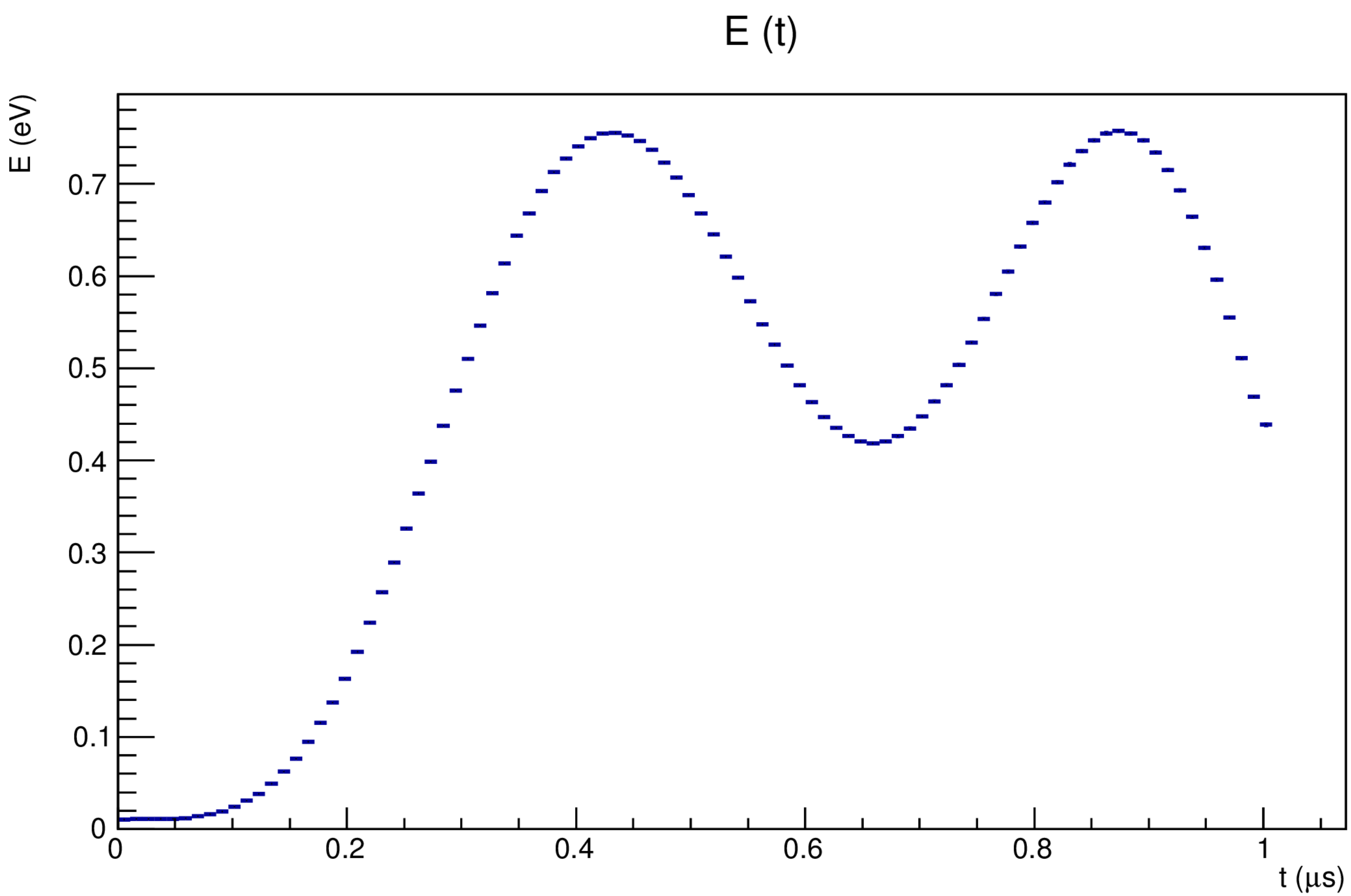

μ = -0.2446 ± 2x10-4
×10³
Count
120
100
80
60
40
20
0
−10
−5
0
5
10
X (mm)

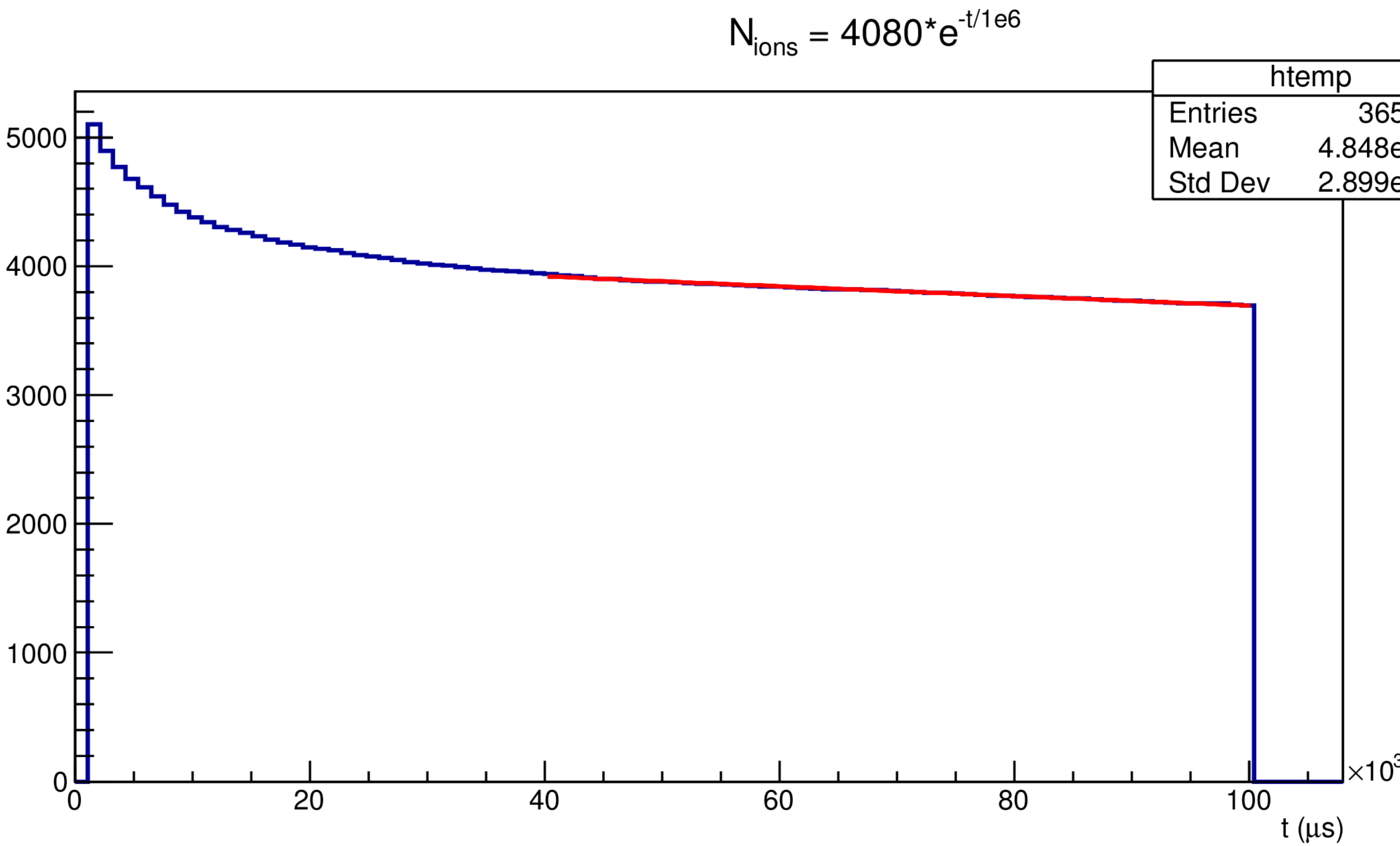


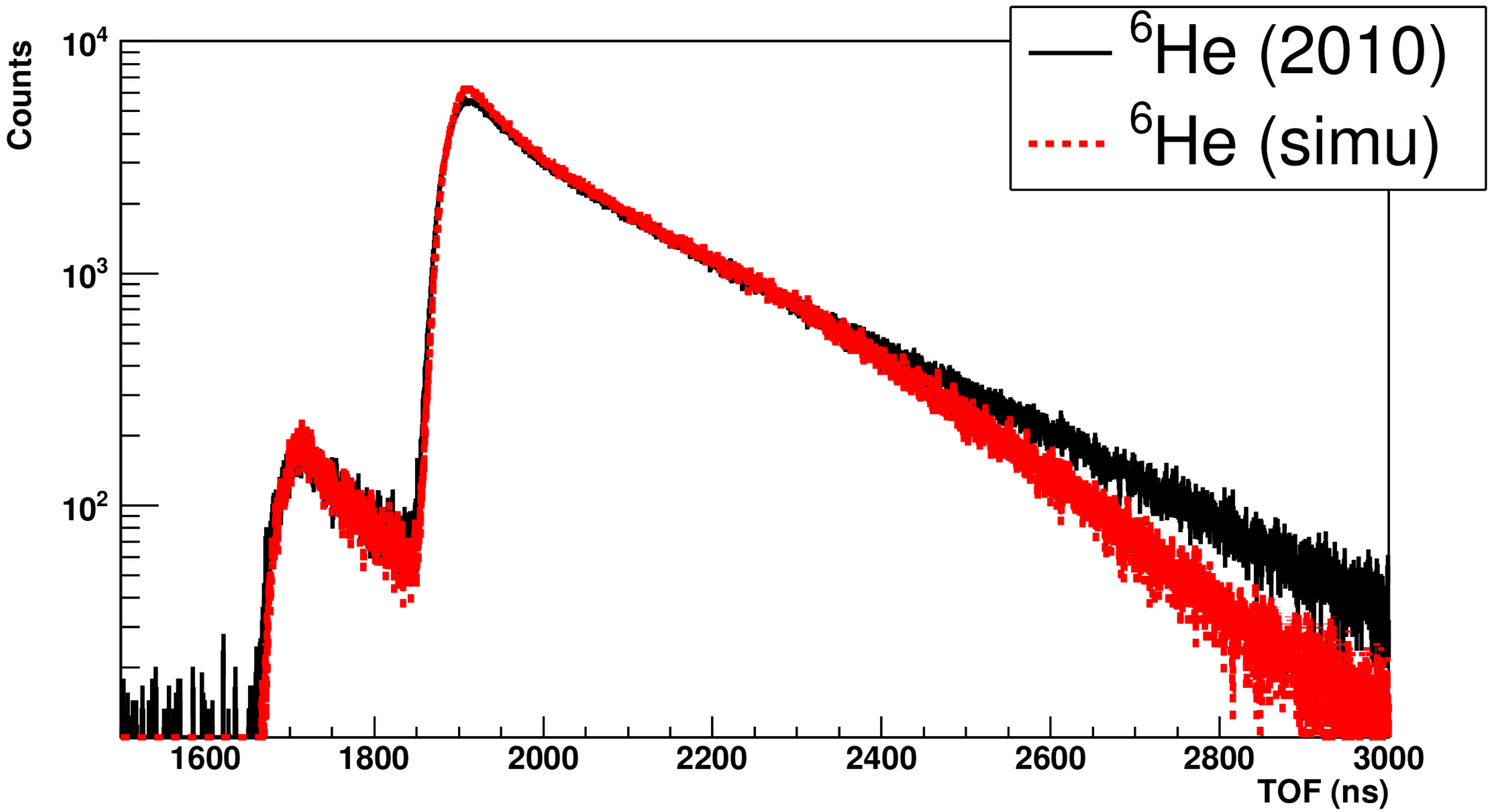
χ²/NDF
6.74
6.72
6.7
6.68
6.66
6.64
−0.33
−0.32
−0.31
−0.3
−0.29
−0.28
−0.27
−0.26
−0.25
−0.24
$a_{\beta\nu}$

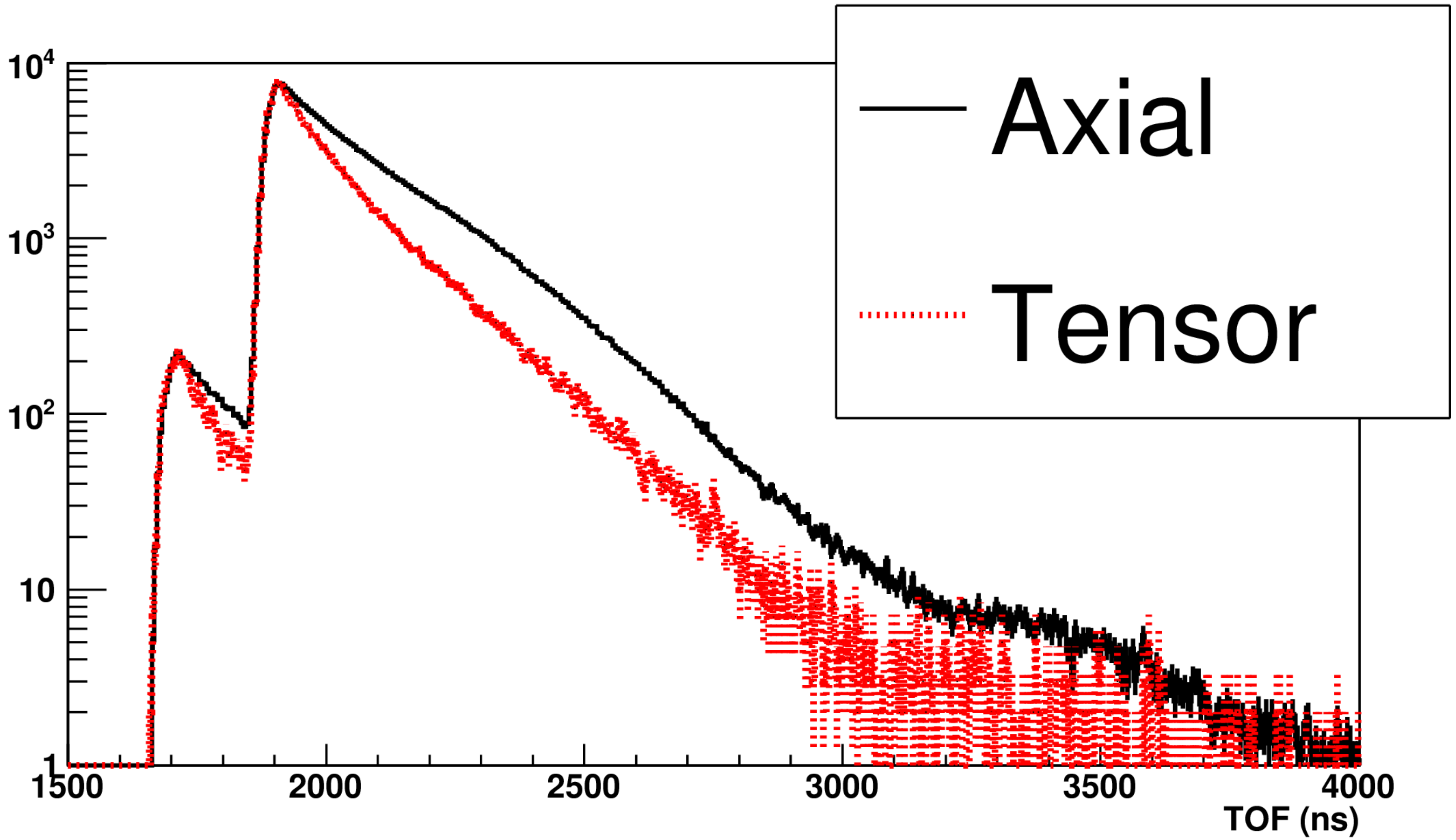


σx1
σx2
σx5
E (eV)
0.16
0.155
0.15
0.145
0.14
0.135
4000
6000
8000
10000
12000
14000
t (µs)


E (t)
E (eV)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
t (μs)


N_{ions} = 4080*e$^{-t/1e6}$
htemp
Entries 365636
Mean 4.848e+04
Std Dev 2.899e+04
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
×10^3
t (µs)


Counts
10^4
10^3
10^2
1600
1800
2000
2200
2400
2600
2800
3000
TOF (ns)
^{6}He (2010)
^{6}He (simu)



10^4
10^3
10^2
10
1
1500
2000
2500
3000
3500
4000
TOF (ns)
Axial
Tensor

$$\epsilon a_{\beta\nu} = |M_F|^2 \left(|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2\right)$$
$$-\frac{1}{3}|M_{GT}|^2\left(|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2\right)$$

with $\epsilon = |M_F|^2 \left(|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2\right)$

$$-\frac{1}{3}|M_{GT}|^2\left(|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2\right)$$

For b close to 0, the effectively measured parameter is

$\tilde{a} = \frac{a}{1+\langle b' \rangle}$ with $b' = \frac{m_e}{E_e}\, b$

Hamiltonian of β decay:

$$\hat{\mathrm{H}} = \frac{G_F}{\sqrt{2}} \sum_{i=V,A,S,T,P} \left(\overline{\psi_p} O_i \psi_n\right)\left(\overline{\psi_e} O^i (C_i + C_i' \gamma^5) \psi_\nu\right) + h.c.$$