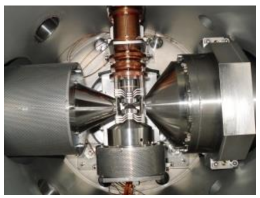
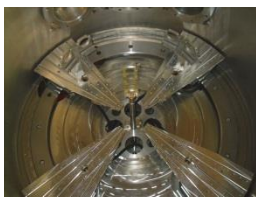
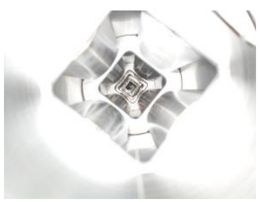



Latest advances in the measurements of β-ν correlation coefficients in nuclear β decays using LPCTrap

Rodolphe Combe

ISOL France – 03/17/2021

Overview

- Motivations
- Theory
- State of the art
- LPCTrap
- LPCTrap @ GANIL
- Data analysis
- Latest results
- Conclusion and prospective

Motivations

- Standard Model of particle physics → huge success!
- Not the end of the story: need Beyond Standard Model physics to explain some measurements (baryogenesis, neutrino masses, etc.)
- Precise measurement of β-decay sensitive to new physics
- Current limits on exotic current existence of the order of 1%
- Complementary to High-Energy physics (looking for the effects vs creating the particle): limits of the order of the ‰
  = limits on the existence of a new boson up to 2.5 TeV

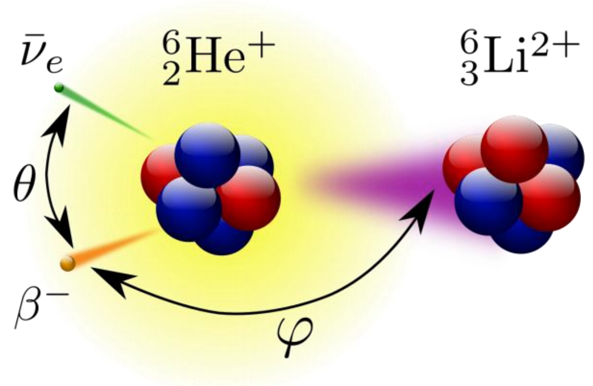
Theory

- Current theory = V-A theory
  - Only Vector and Axial-Vector interactions
  - Neither Scalar nor Tensor interaction
  - Maximum parity violation (no right-handed neutrino)
  - No CP-violation

- To what extend holds the theory?

- At low energy, new physics measurable via correlations

Theory



→ Angular distribution of decay products:

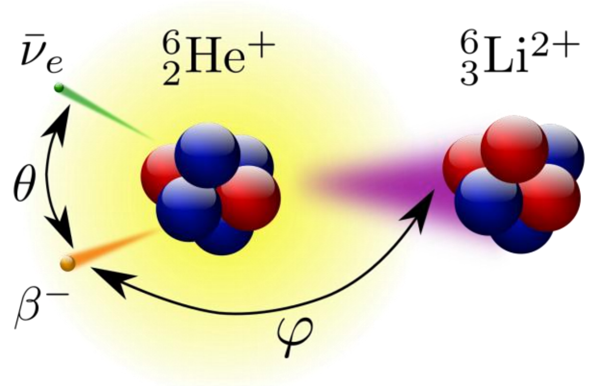
$$w(\vec{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$

$$= \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$

$$\times \frac{1}{2}\xi\left(1 + \boldsymbol{a}\frac{\overrightarrow{p_e}.\overrightarrow{p_\nu}}{E_e E_\nu} + \boldsymbol{b}\frac{m}{E_e} + \boldsymbol{A}\frac{\vec{J}}{J}\frac{\overrightarrow{p_e}}{E_e} + \boldsymbol{D}\frac{\vec{J}(\overrightarrow{p_e}\times\overrightarrow{p_\nu})}{J(E_e E_\nu)} + \cdots\right)$$

- Measurement of *a* = measurement of recoil ions spectrum
  - Give access to $\tilde{a} = \frac{a}{1+b<m_e/E_e>}$

Theory



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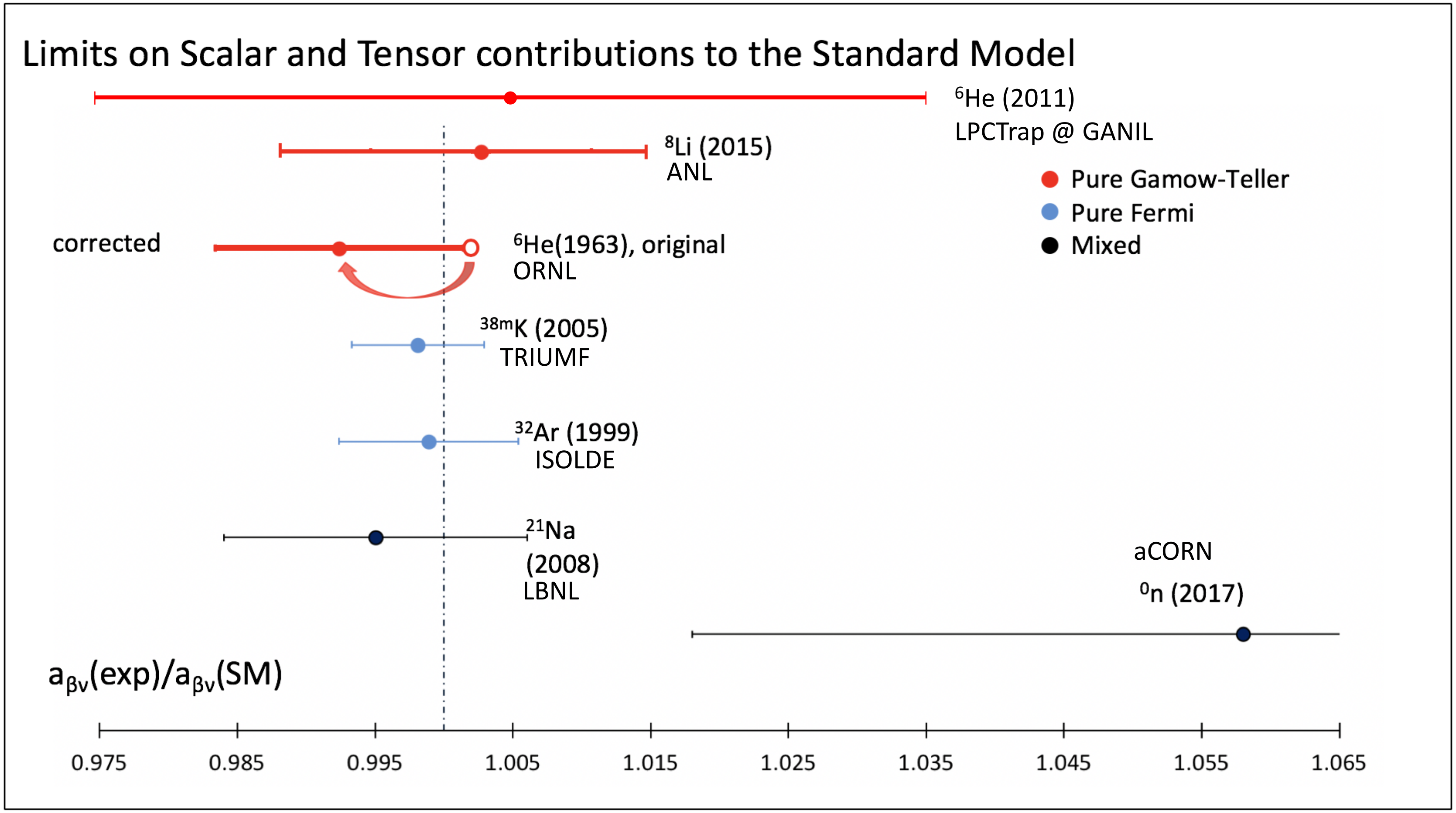
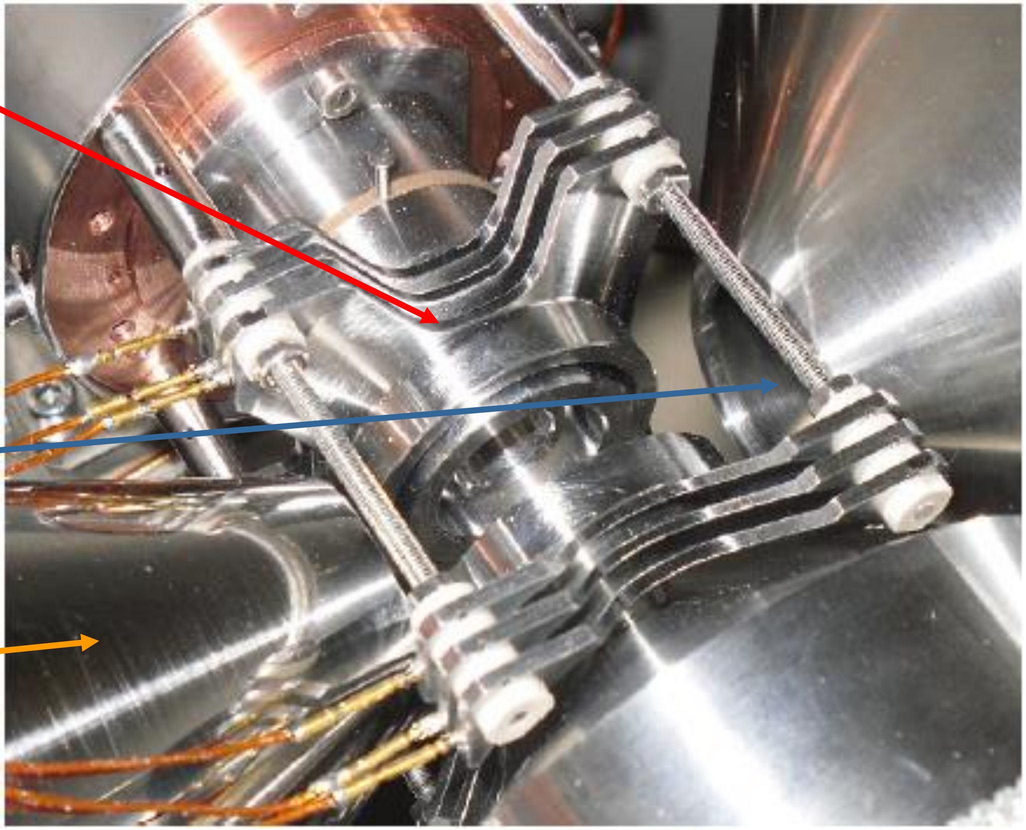
State of the art



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

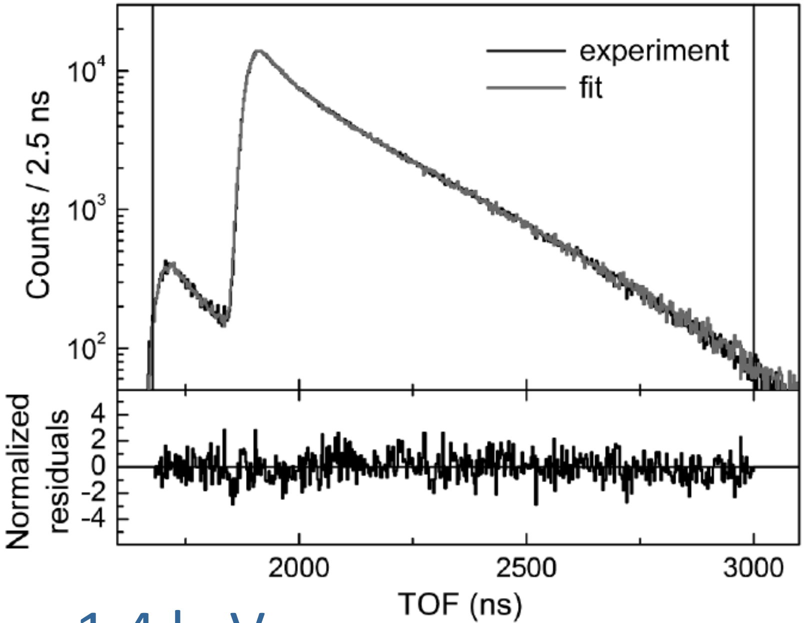
LPCTrap

- Transparent Paul trap:
  - Three pairs of electrodes:
    - RF electrodes
    - Injection/extraction electrodes (200-ms cycles)
    - Field-correction electrodes
- β-telescope:
  - DSSD + plastic scintillator
- Recoil ion detector:
  - 2-kV acceleration grid + -250-V focusing lens + -4-kV polarized MCP



P. Delahaye Eur. Phys. J. A 55 (2019) 101

LPCTrap@GANIL



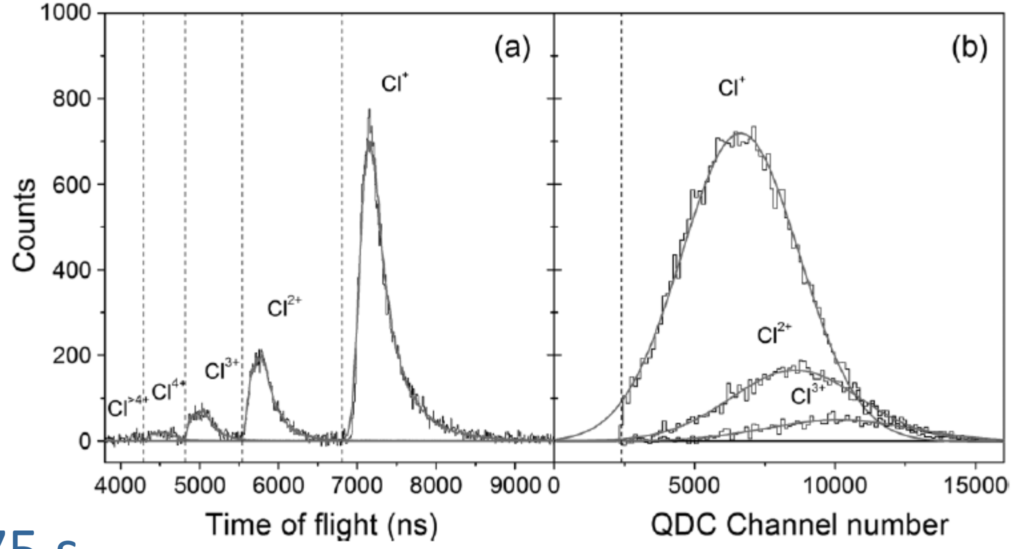
Three ions studied:

- $^6He^+ \rightarrow ^6Li^{2+/3+}$ (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
  - Few nucleons = few radiative corrections

→ C. Couratin, et al.: Phys. Rev. Lett. 108, 243201 (2012) : measurement of the shake-off probability (electron emission during decay) : p = $0.02339(35)_{stat}(07)_{syst}$

LPCTrap @ GANIL

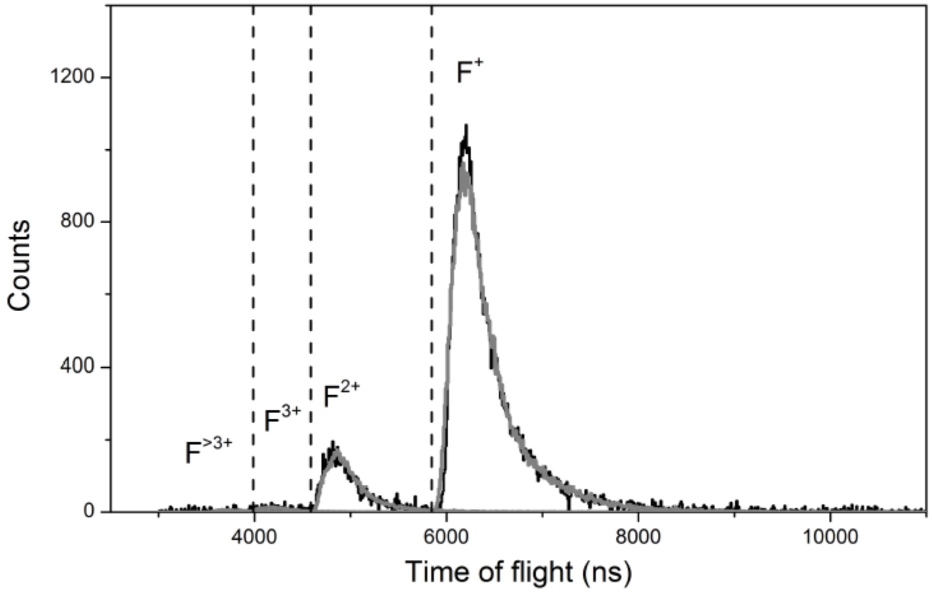
Three ions studied:



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

→ C. Couratin et al., Phys. Rev. A 88, 041403(R) (2013) : good match of shake-off probability with theory

LPCTrap @ GANIL



Three ions studied:

- $^{19}Ne^{+}$ → ^{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
  - Neutral daughter nucleus but only a few charge states ($F^{+/2+/3+/...}$)
  - High production rate ≈ 3 10^{8} ions/s @ SPIRAL

→ X. Fabian et al, Phys. Rev. A 97, 023402 (2018) : shake-off : current theory insufficient

Simulations

- Previous results dominated by two systematics:
  - Cloud temperature
  - β-scattering
- New software developed to improve both:
  - Clouda (cloud temperature)
  - + new data analysis scripts

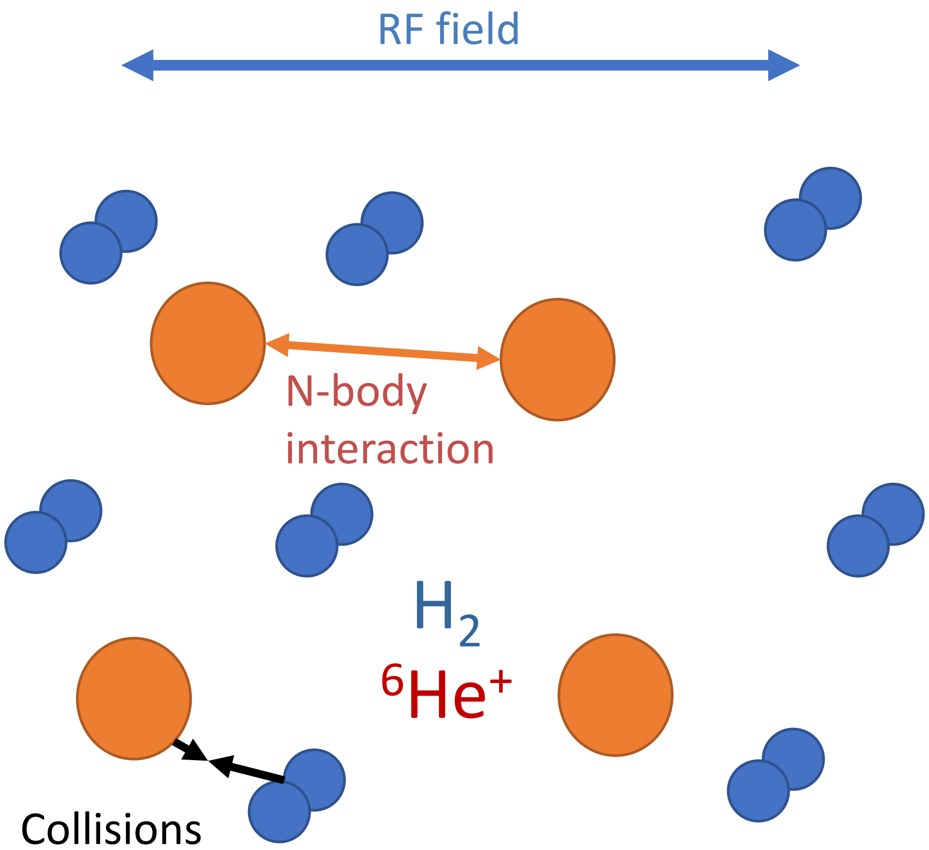
Table 1. Dominant sources of systematic error, systematic uncertainties and impact on the error of $a_{\beta\nu}$. The last column indicates the method used to estimate the parameters.

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

Simulations : Clouda

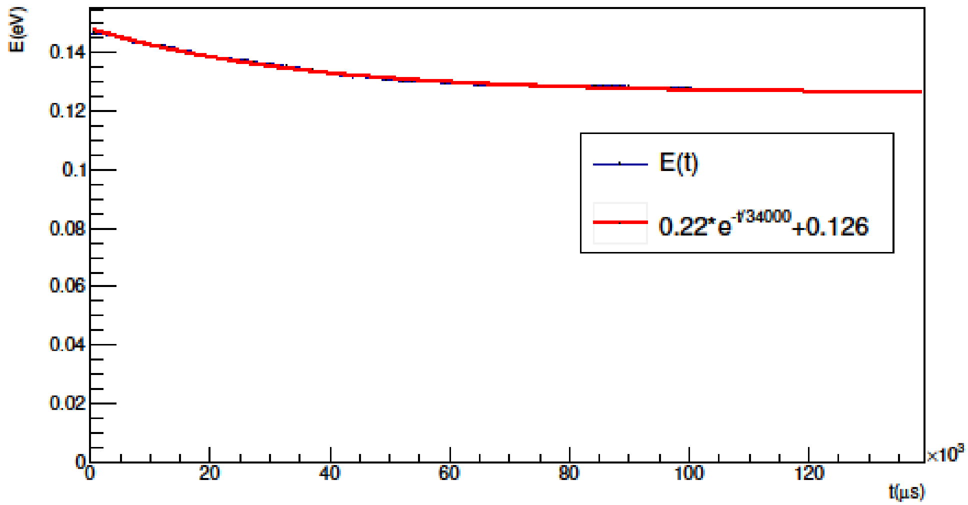
- Clouda software:
  - Simulation of the ion cloud dynamics
  - Massively parallel simulation of individual ions on GPU
  - Trapping field + space charge taken into account



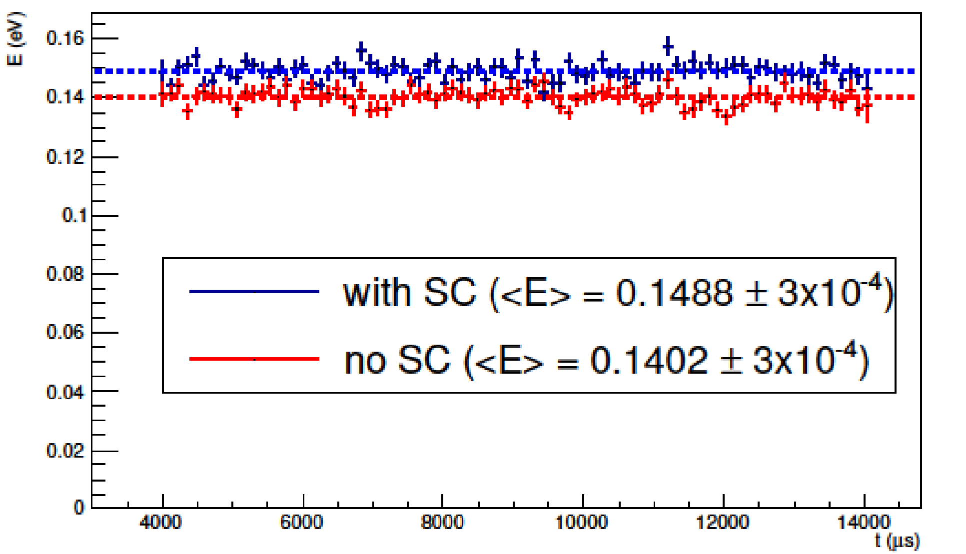
X. Fabian: *Precision measurement in the weak interaction framework: development of realistic simulations for the LPCTrap device installed at GANIL,* PhD University of Caen

Simulations : Clouda

- Good match of cooling time (need to be cross-checked with other simulations)

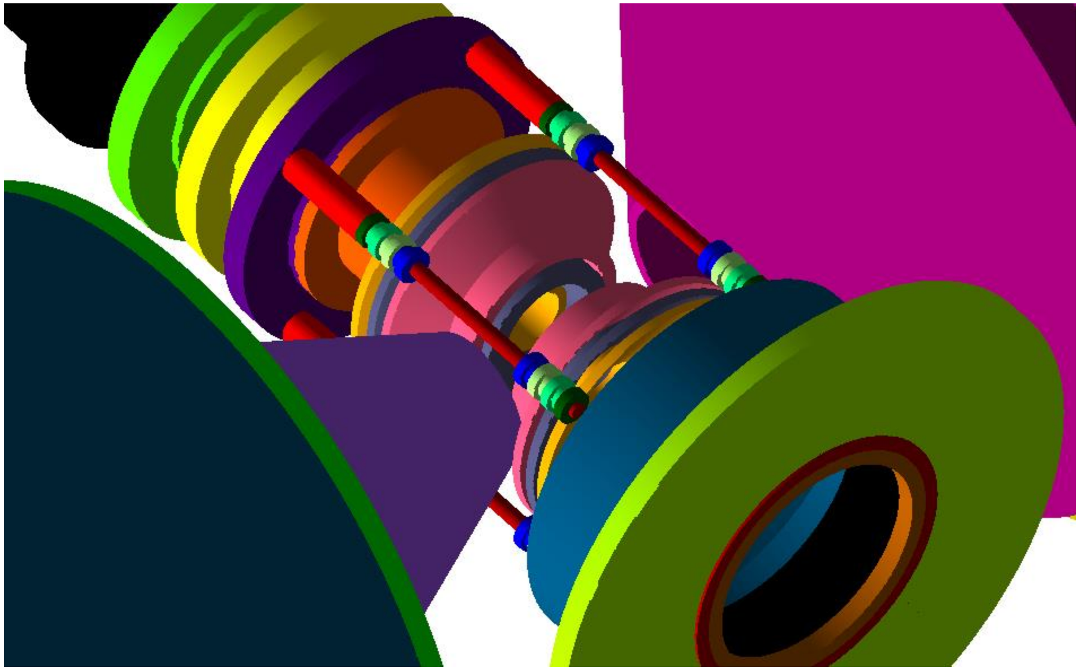


- Good match of the effect of space charge



Simulation : Geant4 + SIMION

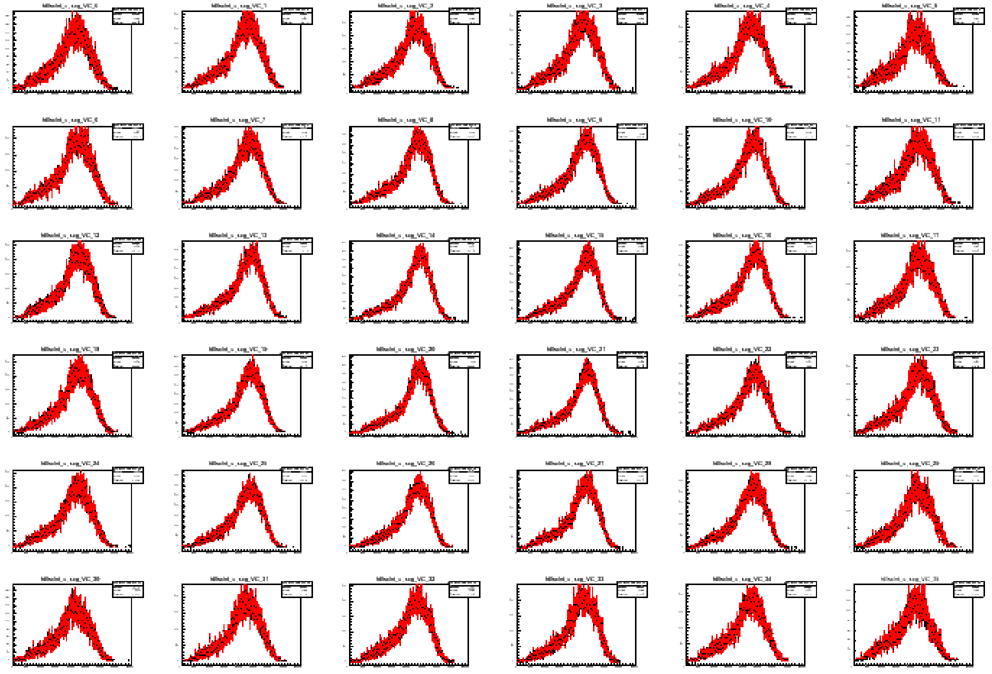
- External β-decay + shake-off generator
- Geant4:
  - Simulation of the electron propagation in LPCTrap
  - No field considered
- SIMION:
  - Simulation of the ion propagation in LPCTrap
  - Axisymmetric field considered



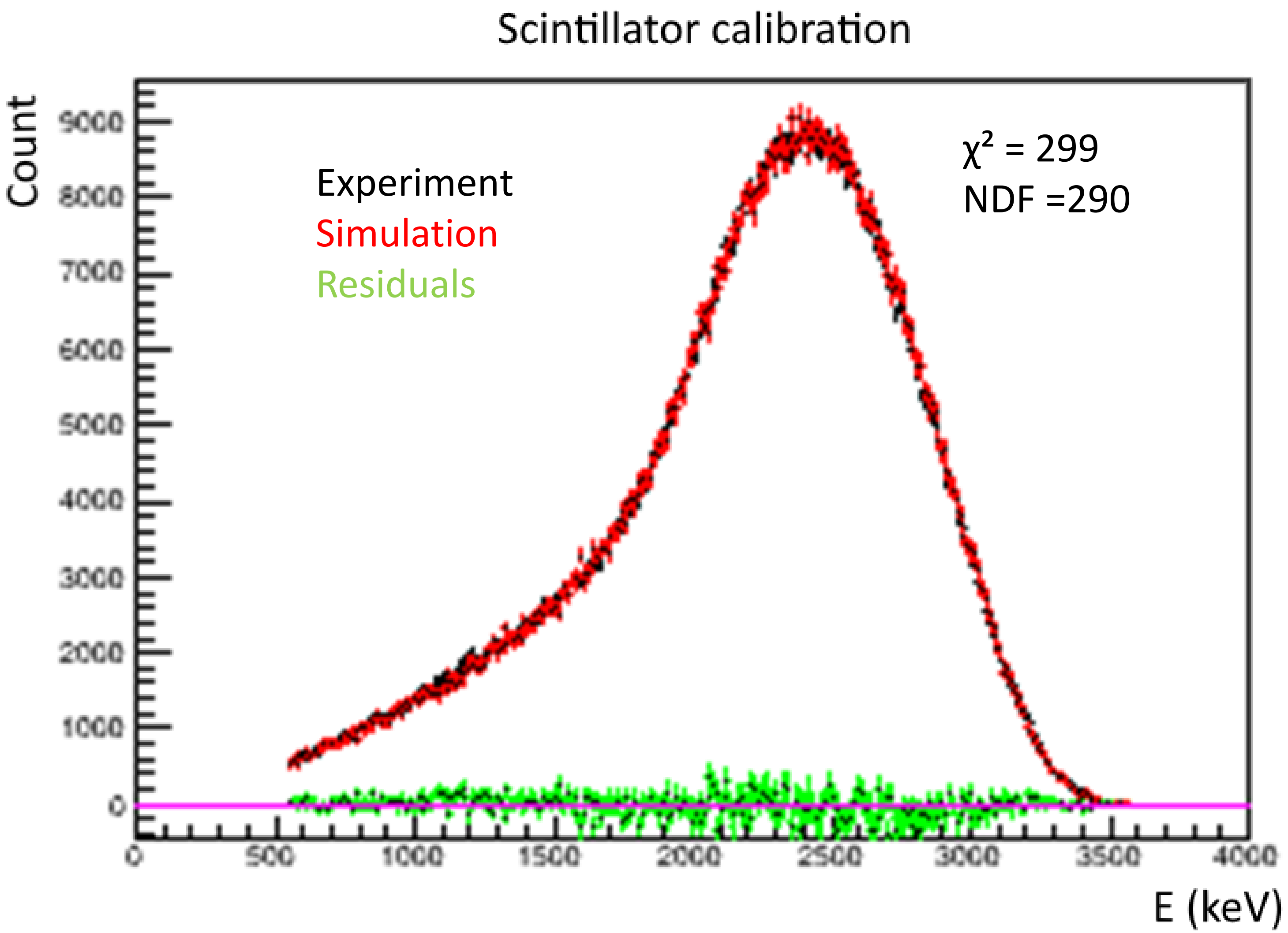
Data analysis

- 2-step analysis:
  - Python script for experimental data reading and calibration
  - ROOT macros for fit

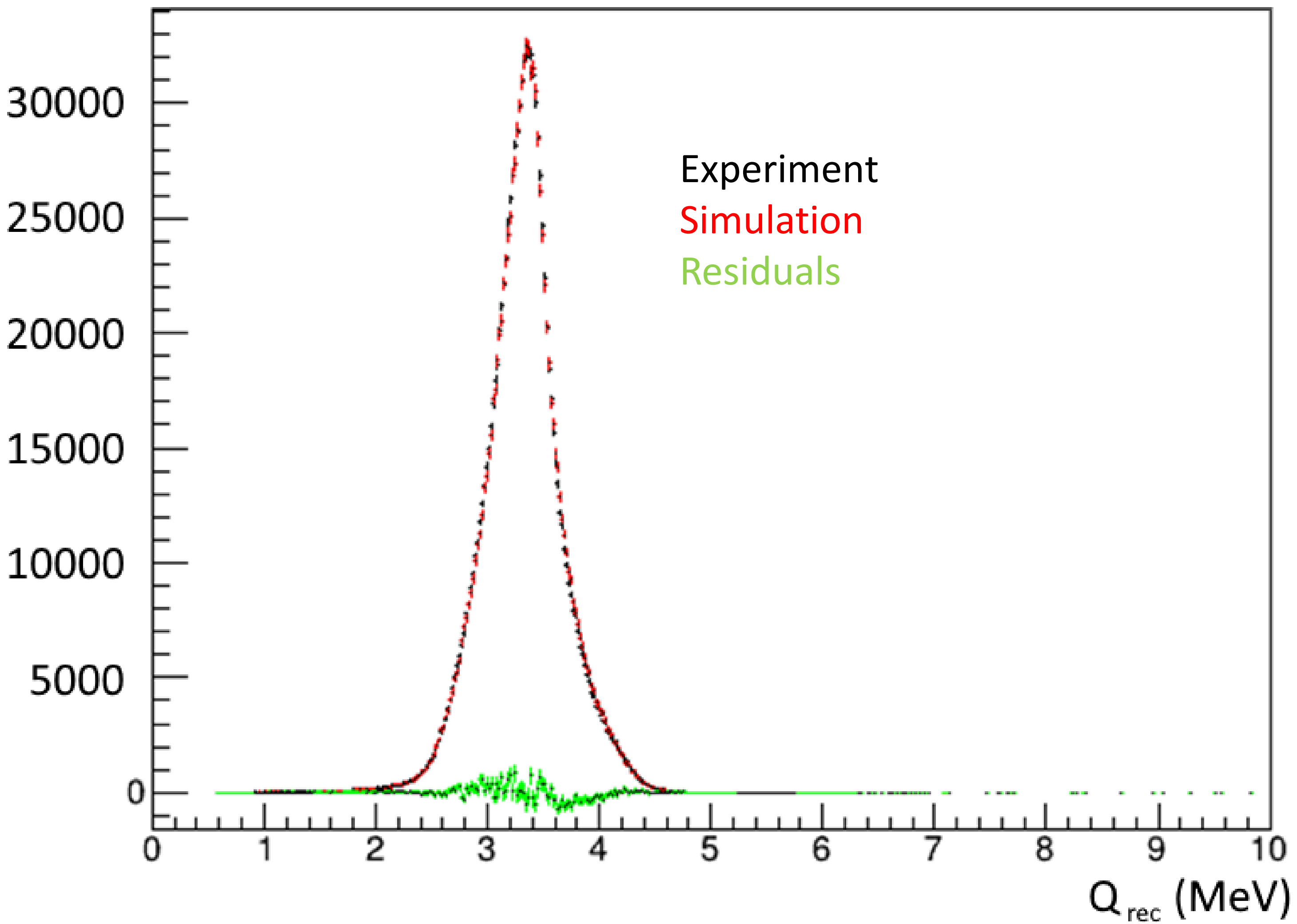
- Analyzed systematics:
  - Buffer gas temperature
  - DSSD, MCP et collimators shifts
  - Scintillator response function (energetic + spatial)
  - Electrode voltage



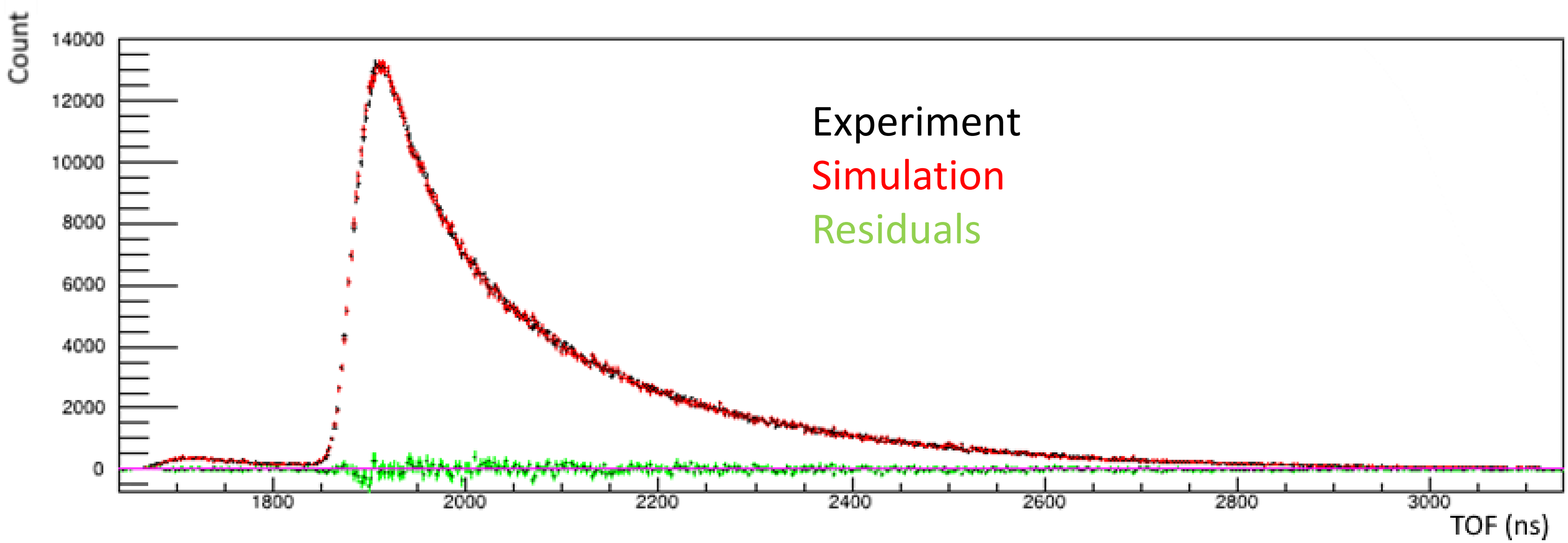
Latest results



Latest results



Latest results



- More simulation running to improve statistics
- Precise fit of *a* coming soon
- Expected uncertainty : 0.4% stat. + 1% syst.

Conclusion and prospective

- Data analysis in progress
  - Needs more ions simulated
  - Priority given to ^{6}He data
  - ^{35}Ar and ^{19}Ne should be analyzed before the end of the year
  - New simulation software being developed : Ouroboros-BEM

- $He+H_2$ differential cross-section measurement around 1 eV would be useful

- New beams @ SPIRAL: new mirror nuclei: ^{21}Na, ^{23}Mg, ^{33}Cl, ^{37}K

Thank you for your attention

Theory

Allowed transitions: $\Delta L = 0$	**$\Delta\pi = 1$**
Pure Fermi (F) transitions: $\Delta S = 0$	$\Delta J = 0$
Pure Gamow-Teller (GT) transitions: $\Delta S = 1$	$\Delta J = 0, \pm 1$
Forbidden transitions: $\Delta L \neq 0$	**$\Delta\pi = (-1)^L$**

Mixed transition: transition possible via F or GT

- Example: ^{21}Na ($3/2^+$) → ^{21}Ne ($3/2^+$)

Theory

- Pure Fermi: $a_F = -\frac{1}{3}\frac{|C_A|^2+|C'_A|^2-|C_T|^2-|C'_T|^2}{|C_A|^2+|C'_A|^2+|C_T|^2+|C'_T|^2}$
- Pure Gamow-Teller: $a_{GT} = \frac{|C_V|^2+|C'_V|^2-|C_S|^2-|C'_S|^2}{|C_V|^2+|C'_V|^2+|C_S|^2+|C'_S|^2}$
- Mirror transition (mixed) : $a_m = \frac{(1-\rho^2/3)}{(1+\rho^2)}$ with ρ the mixing coefficient GT/F → determination of V_{ud} (alternative to $0^+ \rightarrow 0^+$)

- Standard model = V-A theory :
  - $C_{S,T} = 0$, $C_i = C'_i$ real

  → $a_{GT} = -1/3$, $a_F = +1$

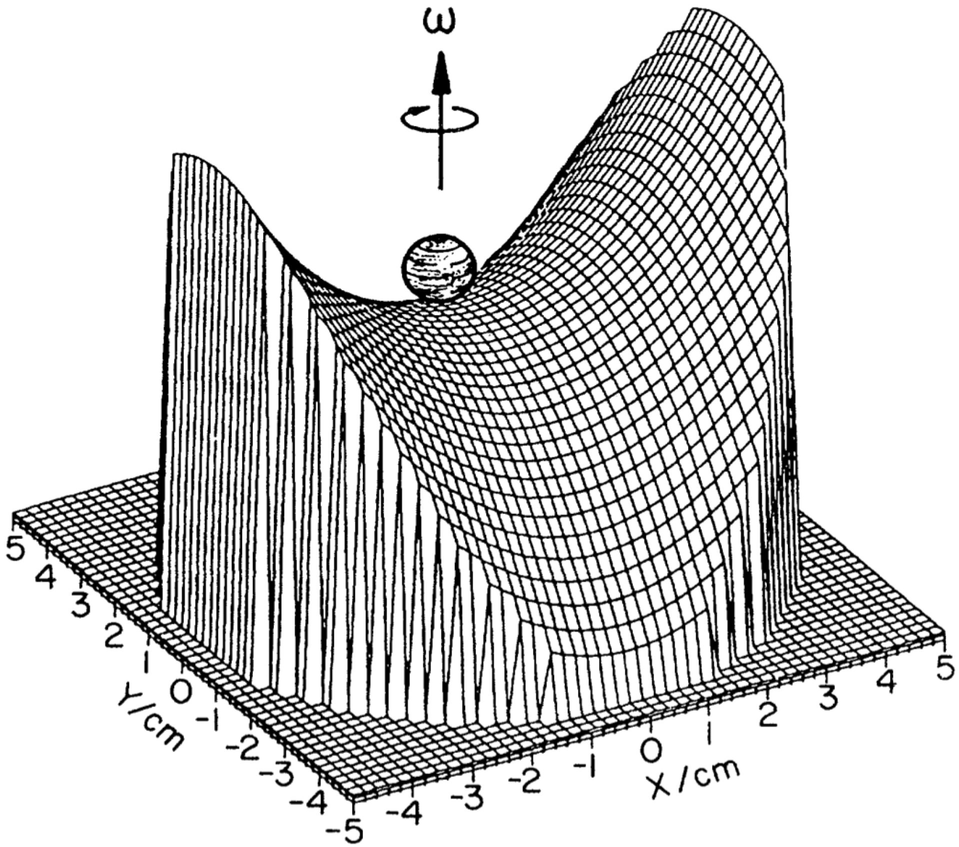
State of the art: V_{ud}

Transition	$\lvert V_{ud} \rvert$
Super-allowed pure Fermi	$0.97420(10)_{exp}(18)_{RC}$
Neutron	$0.9763(5)_{\tau_n}(15)_{g_A}(2)_{RC}$
Pion	0.9749(26)
Super-allowed mirror	0.9719(17)

PDG 2018 et Naviliat *et al* PR102 (2009)

LPCTrap : Paul trap

- Static 3D potential well = impossible
  → Quadripolar potential whose trapping and escape directions switch with time = Paul trap
- RF frequency depends on mass
  - LPCTrap :
    $0.48 < f_{RF} < 1.15$ MHz
- Geometrical efficiency: 33% of 4π
- Capacity ≈ 10^5 ions

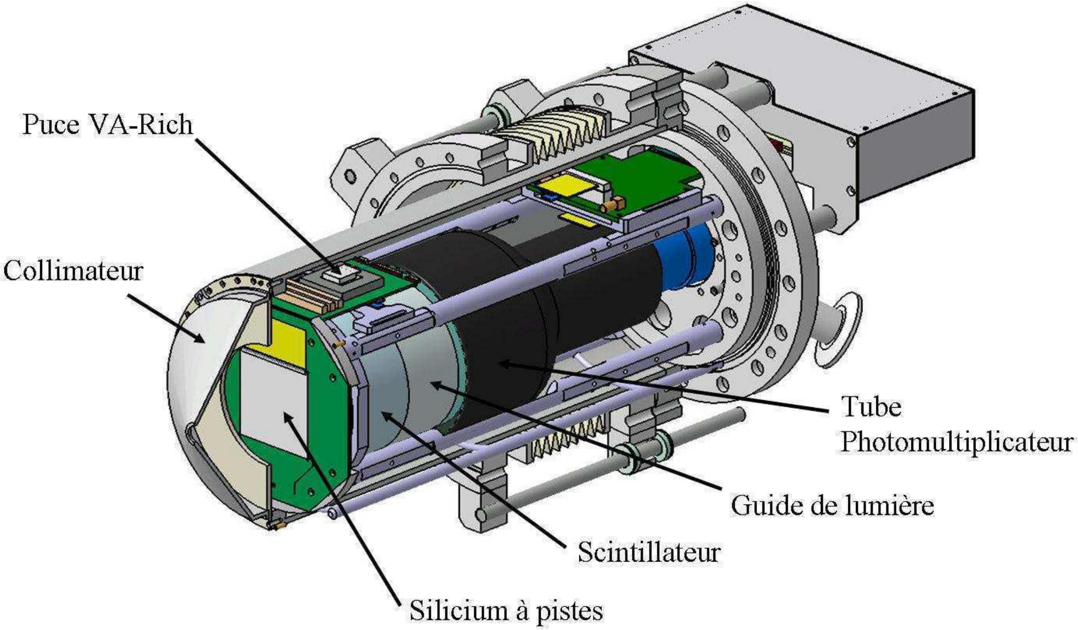


LPCTrap : β-telescope

- Detection in coincidence :
  - Electron position = DSSSD
  - Electron energy = plastic scintillator

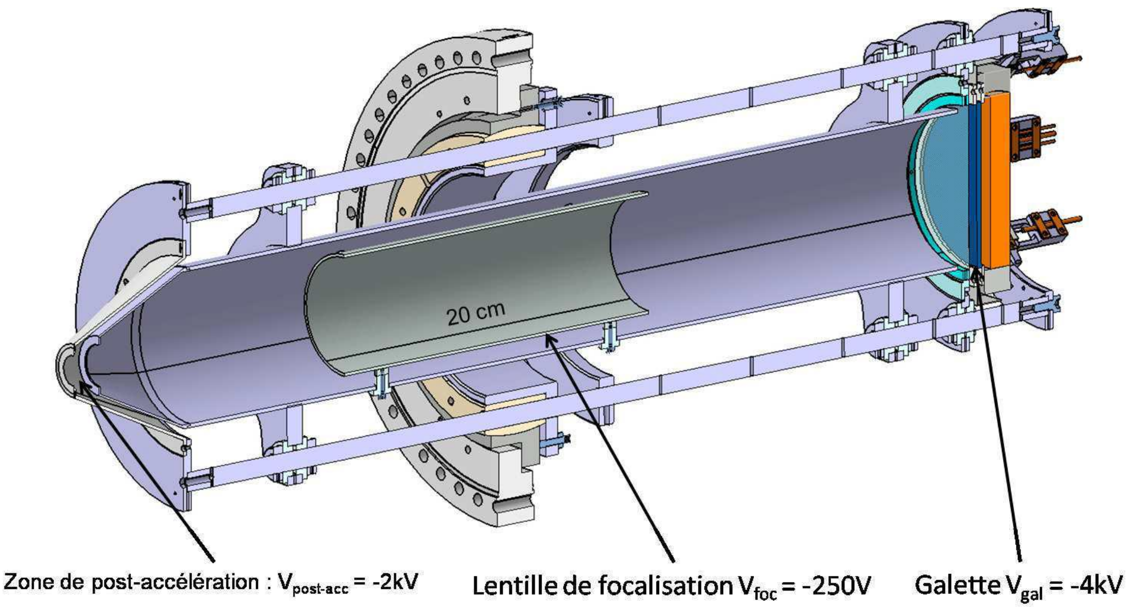
- DSSSD :
  - 2 x 60 1-mm strips (horizontal + vertical)
  - 300-µm thickness
  - Dead time ≈ 240 µs

- BC400 plastic scintillator
  - Time resolution: 200 ps
  - Energy resolution: $\approx 0.08/\sqrt{E}$
  - Threshold after cuts: 400 keV



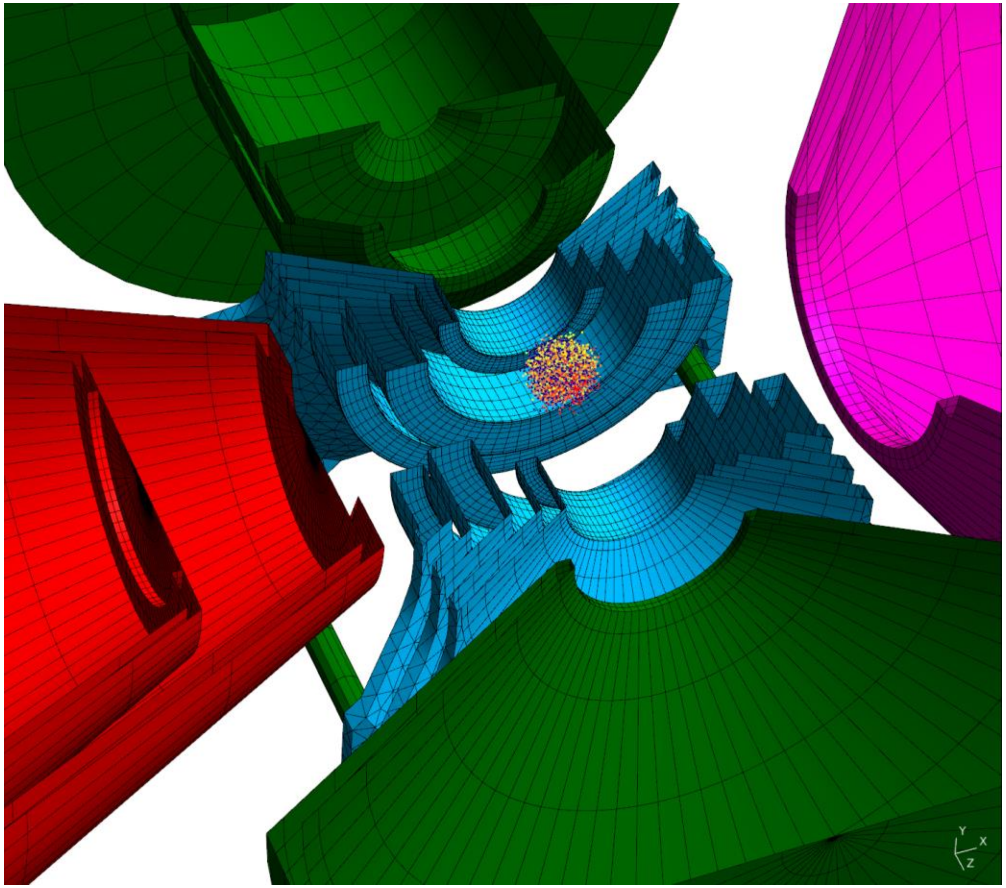
LPCTrap : recoil ions spectrometer

- Ion acceleration with a -2-kV potential
  → charge separation
- Time of flight ↔ initial ion energy + initial ion position
- Sensor = MCP plate (STOP signal) + delay line (ion position)
  - Time resolution <200 ps
  - Spatial resolution ≈ 110 µm



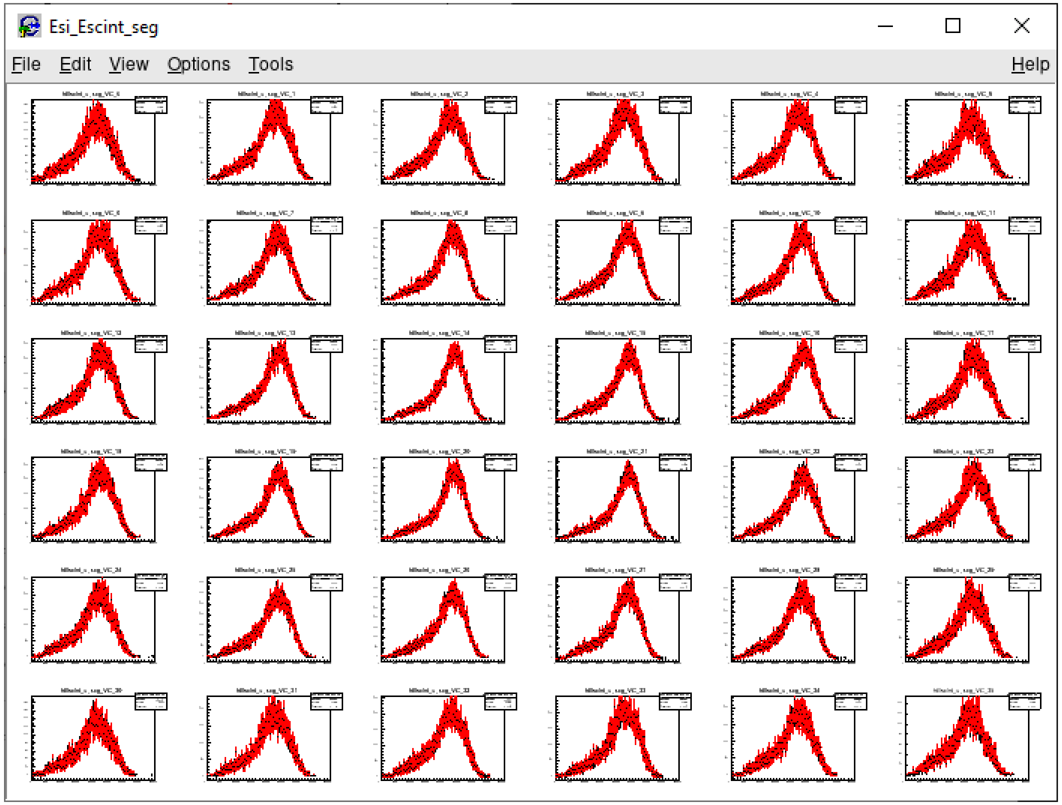
Simulation : Ouroboros-BEM

- Ouroboros-BEM:
  - Simulation of the ion propagation in the LPCTrap electric field on GPU
  - External β-decay + shake-off generator
  - RF and static electric field considered
  - Still under development



Quick study of scintillator response function

Work with 500K low stat (best match for temperature)



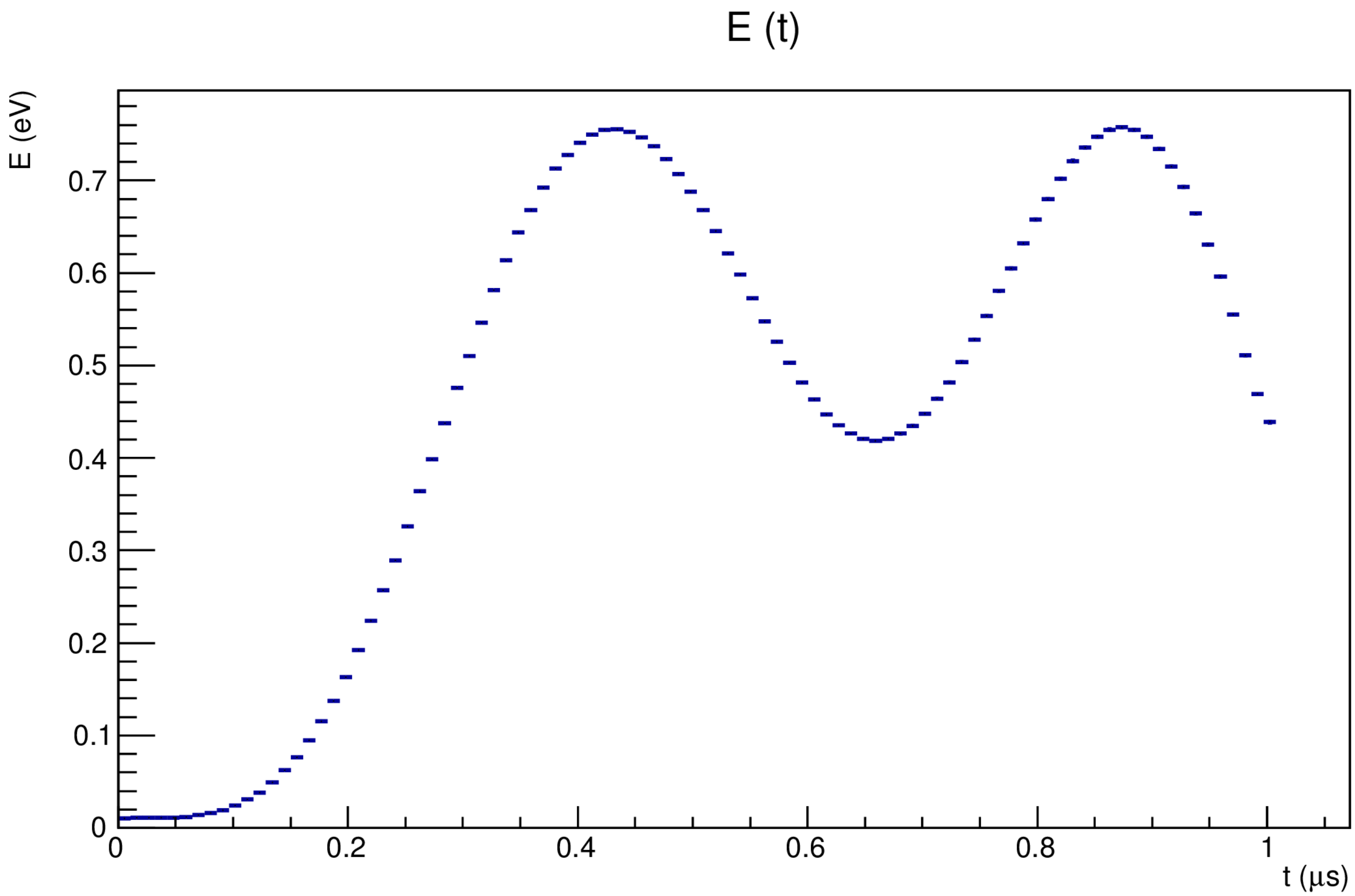
-Correction of light yield vs position (up to 10% difference)

- Adjustment on Etot to account for differences in Esi

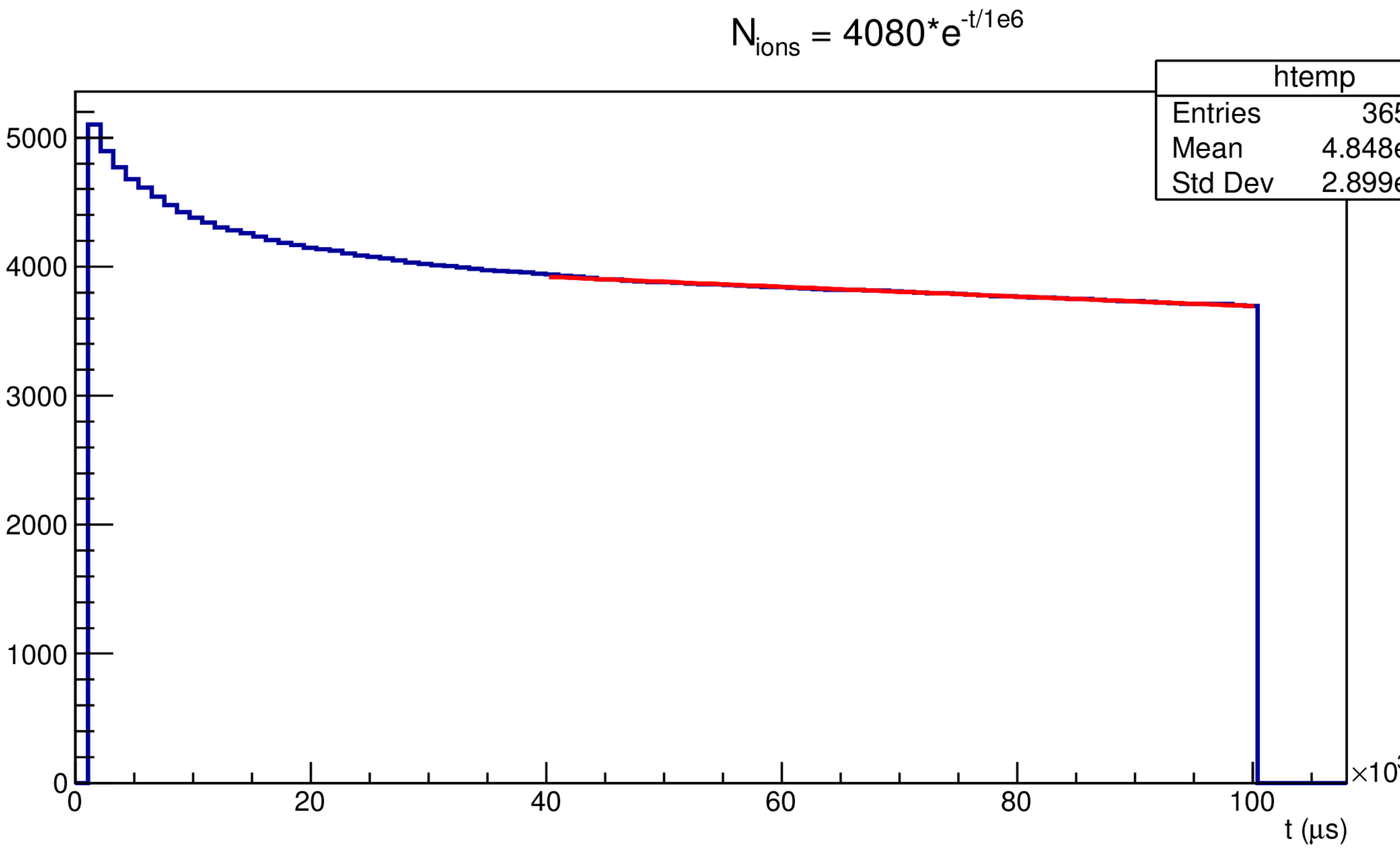
-Use of free birks parameter instead of offset

-use of a quadratic term

RF warm-up

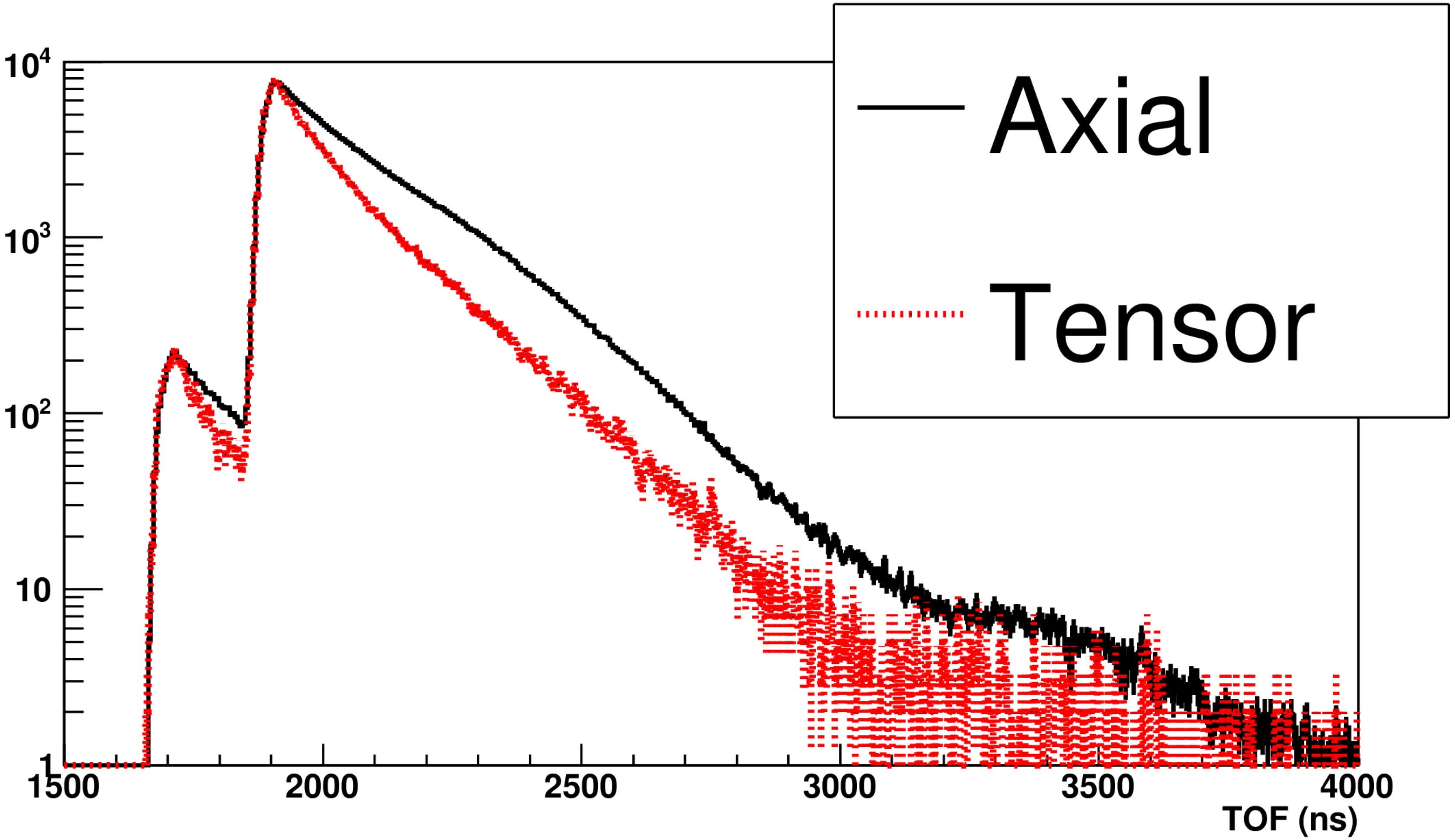


Ion loss

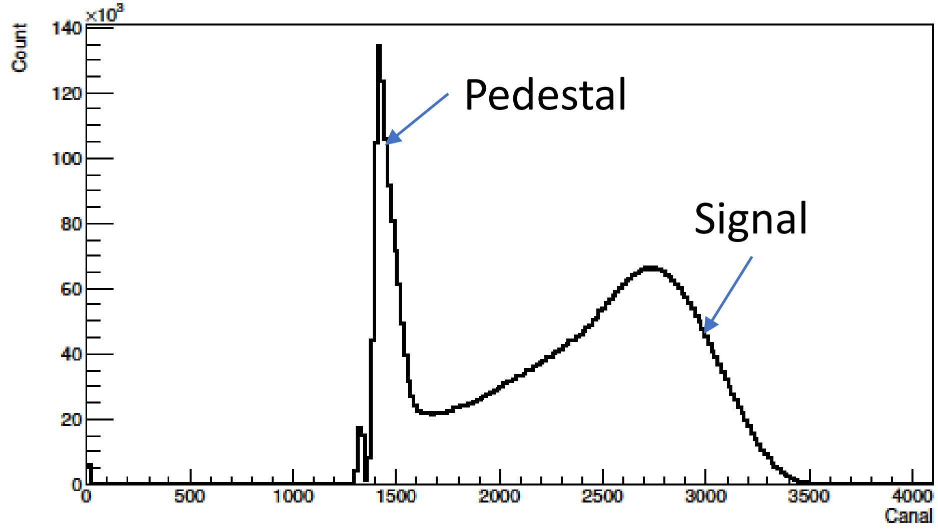


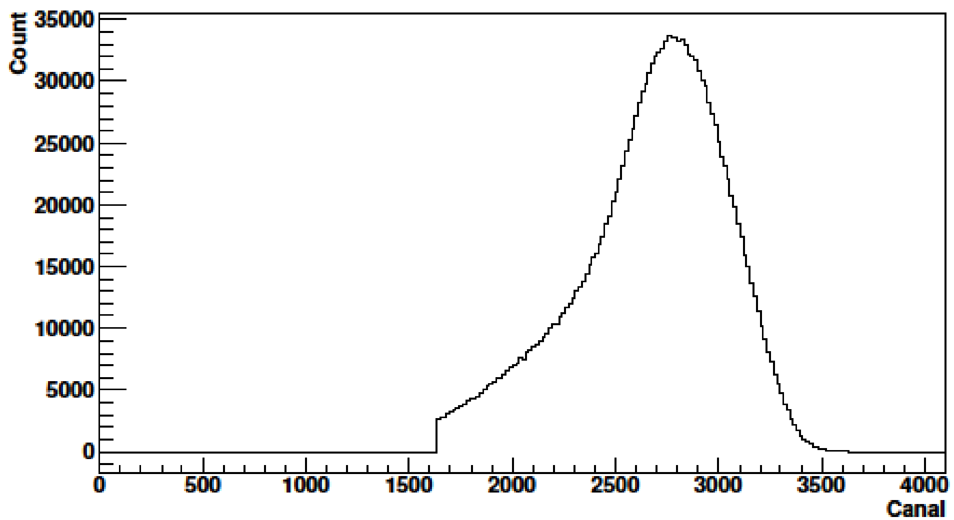
N_{ions} = 4080*e$^{-t/1e6}$
htemp
Entries 365636
Mean 4.848e+04
Std Dev 2.899e+04
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
×10^3
t (μs)

Axial vs Tensor



QDC cut


×10³
Count
Pedestal
Signal
0
20
40
60
80
100
120
140
0
500
1000
1500
2000
2500
3000
3500
4000
Canal


Count
0
5000
10000
15000
20000
25000
30000
35000
0
500
1000
1500
2000
2500
3000
3500
4000
Canal

Formulas

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

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:

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

Formulas

Hamiltonian of β-decay:

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

Mirror transition:

$$Ft = f_V t_{1/2}(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{2K}{V_{ud}^2(1+\Delta_R)\left(1+\frac{f_A}{f_V}\rho^2\right)}$$