aCORN

A Precision Measurement of the Electron-Antineutrino Correlation "a" in Neutron Beta Decay

F. E. Wietfeldt

Physics Department
Tulane University
New Orleans, LA

aCORN Collaboration

G. Darius, C. DeAngelis, T. Hassan, F. E. Wietfeldt
Tulane University

M. S. Dewey, M. P. Mendenhall, J. S. Nico, H. Park (visitor)
National Institute of Standards and Technology

G. Noid, E. Stephenson
Indiana University

B. Collett, G. L. Jones
Hamilton College

A. Komives
DePauw University

graduate student

Neutron Decay Parameters

Phenomenological (J = 1/2 → J = 1/2) beta decay formula [Jackson, Treiman, Wyld, 1957] :

$$dW \propto \frac{1}{\tau} F(E_e)\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + D\frac{\vec{\sigma}_n \cdot \left(\vec{p}_e \times \vec{p}_\nu\right)}{E_e E_\nu} \right]$$

For allowed beta decay, neglecting recoil order terms, the standard electroweak model (Weinberg, Glashow, Salam, et al.) predicts:

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \qquad b = 0 \qquad A = -2\frac{\lambda^2 + \mathrm{Re}(\lambda)}{1+3\lambda^2} \qquad B = 2\frac{\lambda^2 - \mathrm{Re}(\lambda)}{1+3\lambda^2}$$

$$D = 2\frac{\mathrm{Im}(\lambda)}{1+3\lambda^2} \approx 0 \qquad \tau \propto \frac{1}{g_\nu^2 + 3g_A^2}$$

where $\lambda \equiv \frac{g_A}{g_V}$

Why do we measure neutron decay parameters?

Within Standard Model: Get G_A , G_V

Beyond Standard Model:

Mostovoy Parameters, model-independent consistency test of SM:

predicted	actual	
$F_1 = 1 + A - B - a = 0$	$F_1 = 0.0025 \pm 0.0064$	uncertainties dominated
$F_2 = aB - A - A^2 = 0$	$F_2 = 0.0034 \pm 0.0050$	by "*a*"

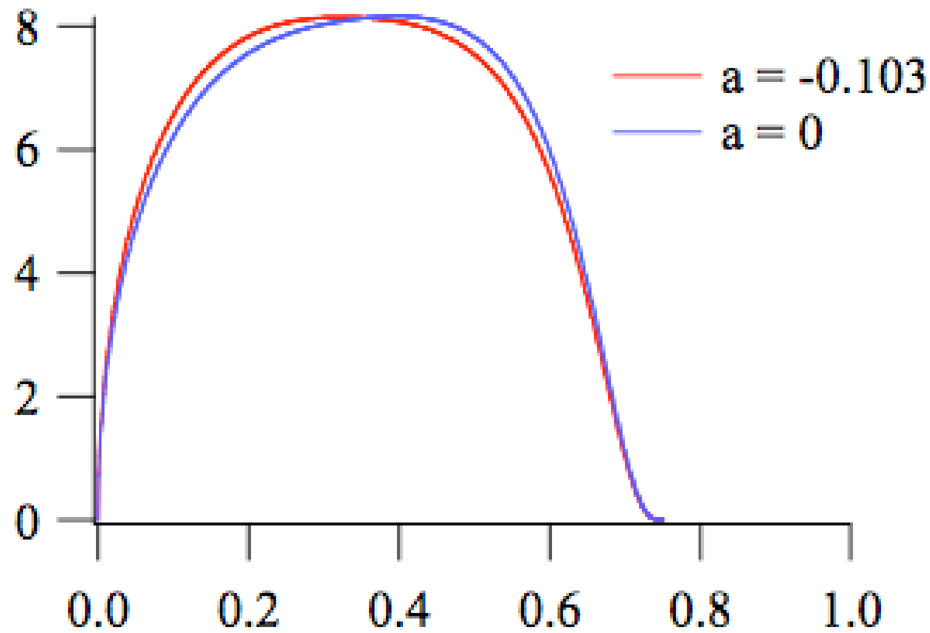
Precise comparisons of a, b, A, B, D are sensitive to:

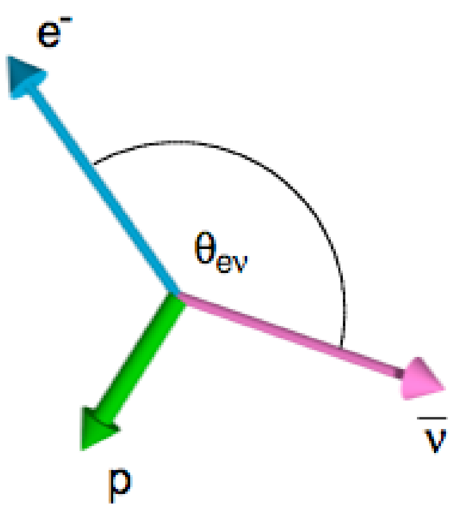
- scalar and tensor weak currents
- right handed weak currents
- new CP violation
- CVC violation and second-class currents (Gardner and Zhang, 2000)
- SUSY (Profumo, Ramsey-Musolf, and Tulin, 2007)

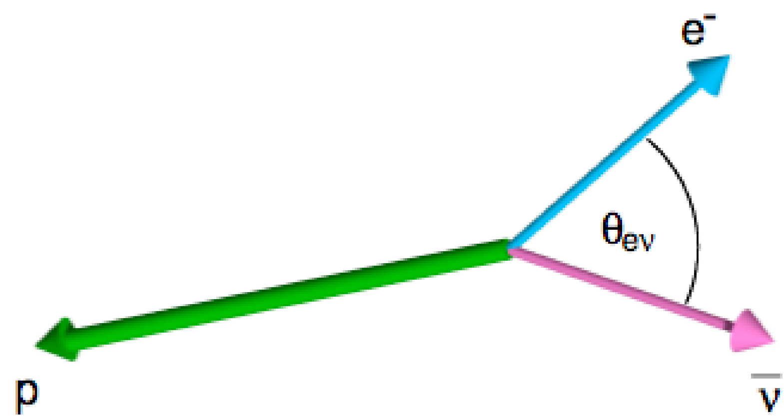
Standard method for measuring the e-ν correlation:

recoil energy spectrum

statistically most advantageous

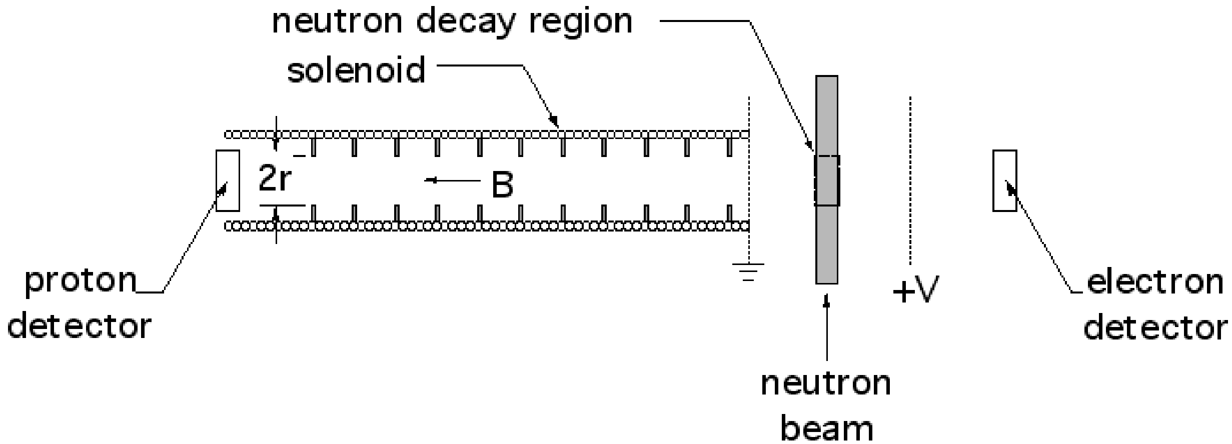


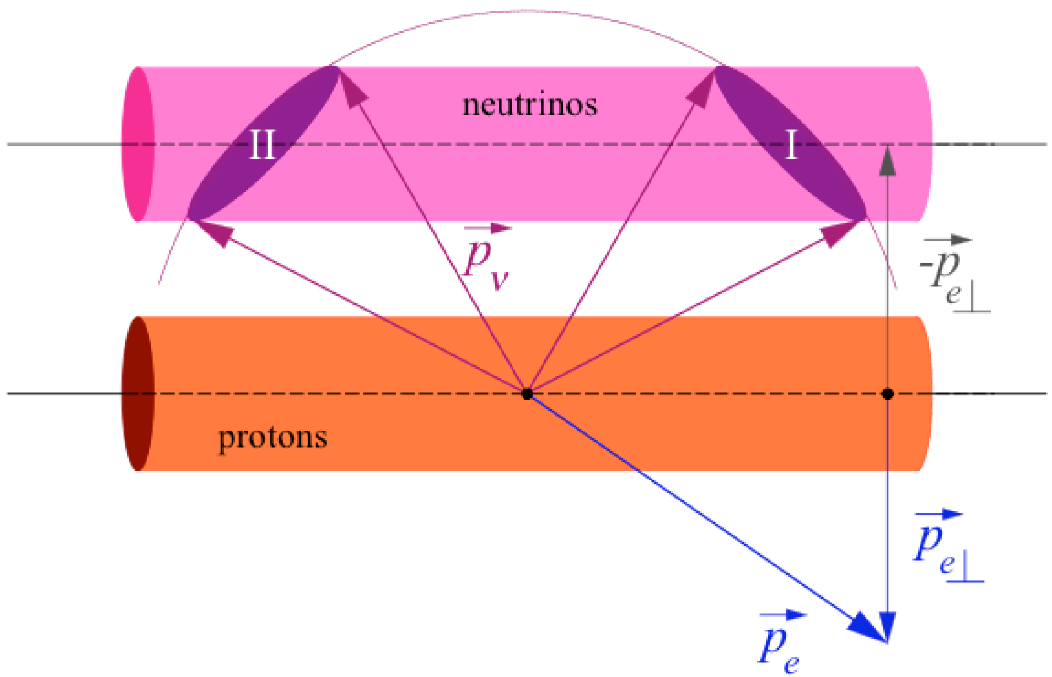




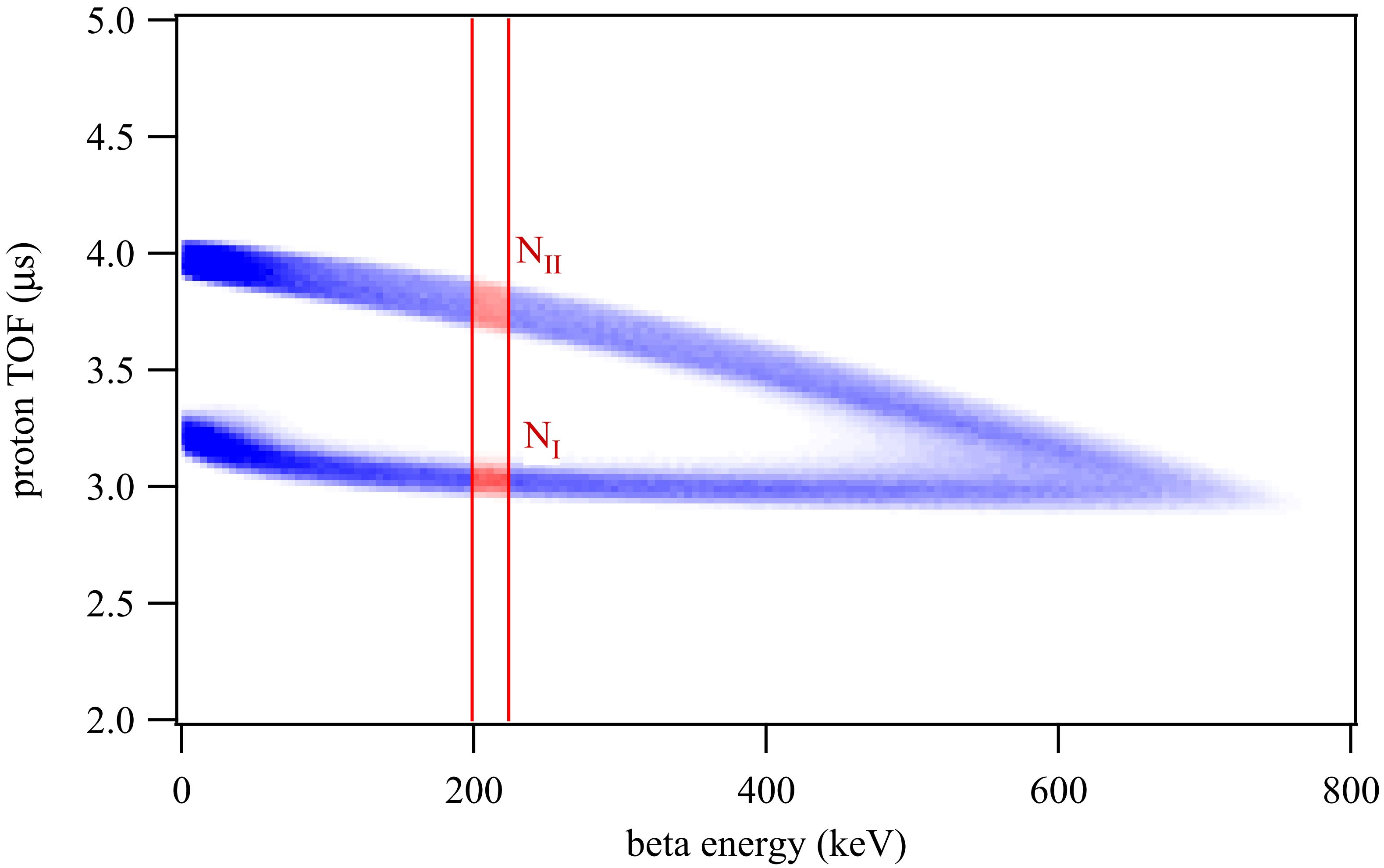
A Novel Method to Measure *a*

(Yerozolimsky and Mostovoy, 1996)





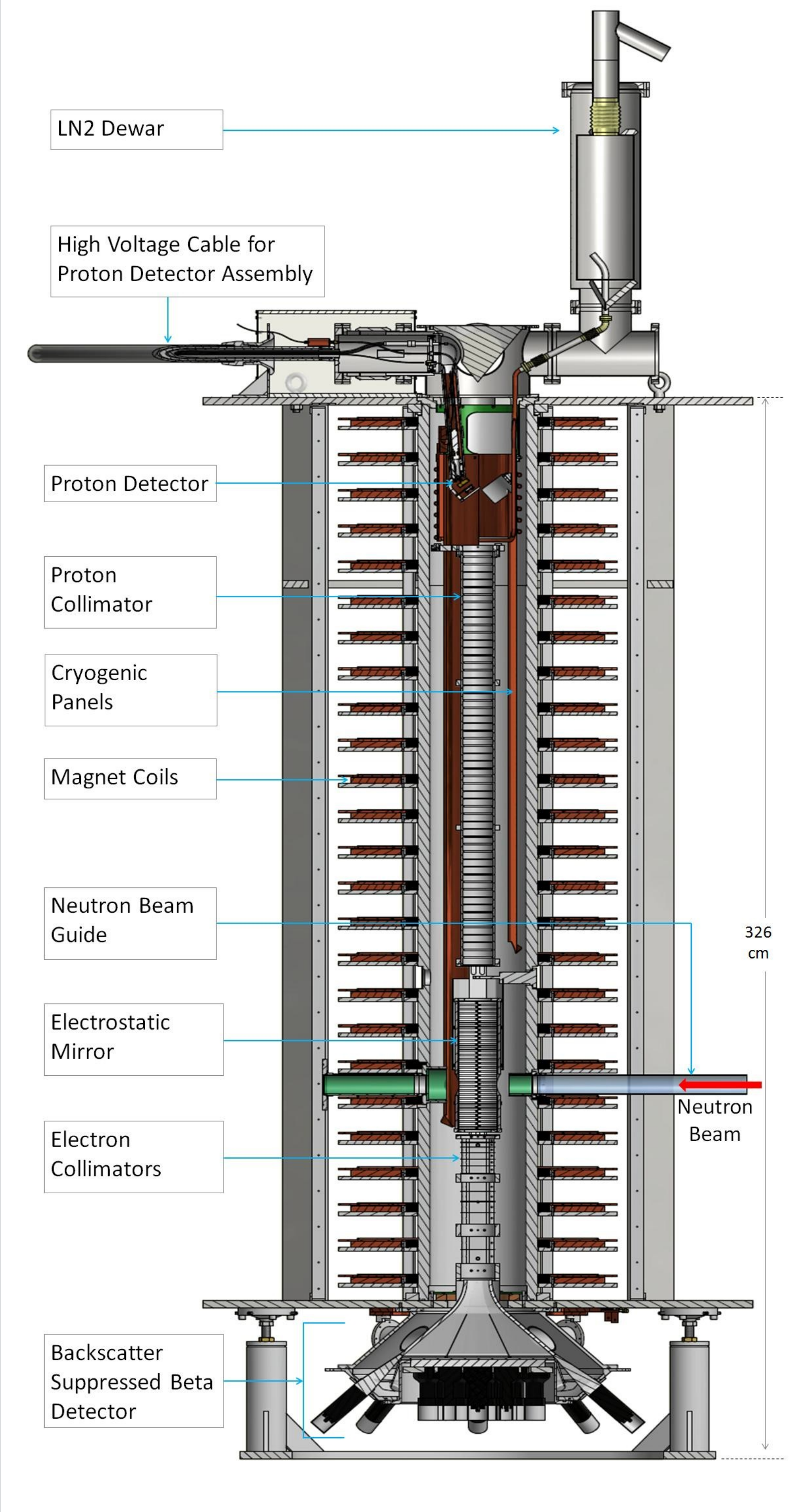
We separate groups I and II by beta energy and proton time-of-flight (TOF)



$$X(E) = \frac{N_I - N_{II}}{N_I - N_{II}} = a\, f_a(E)$$

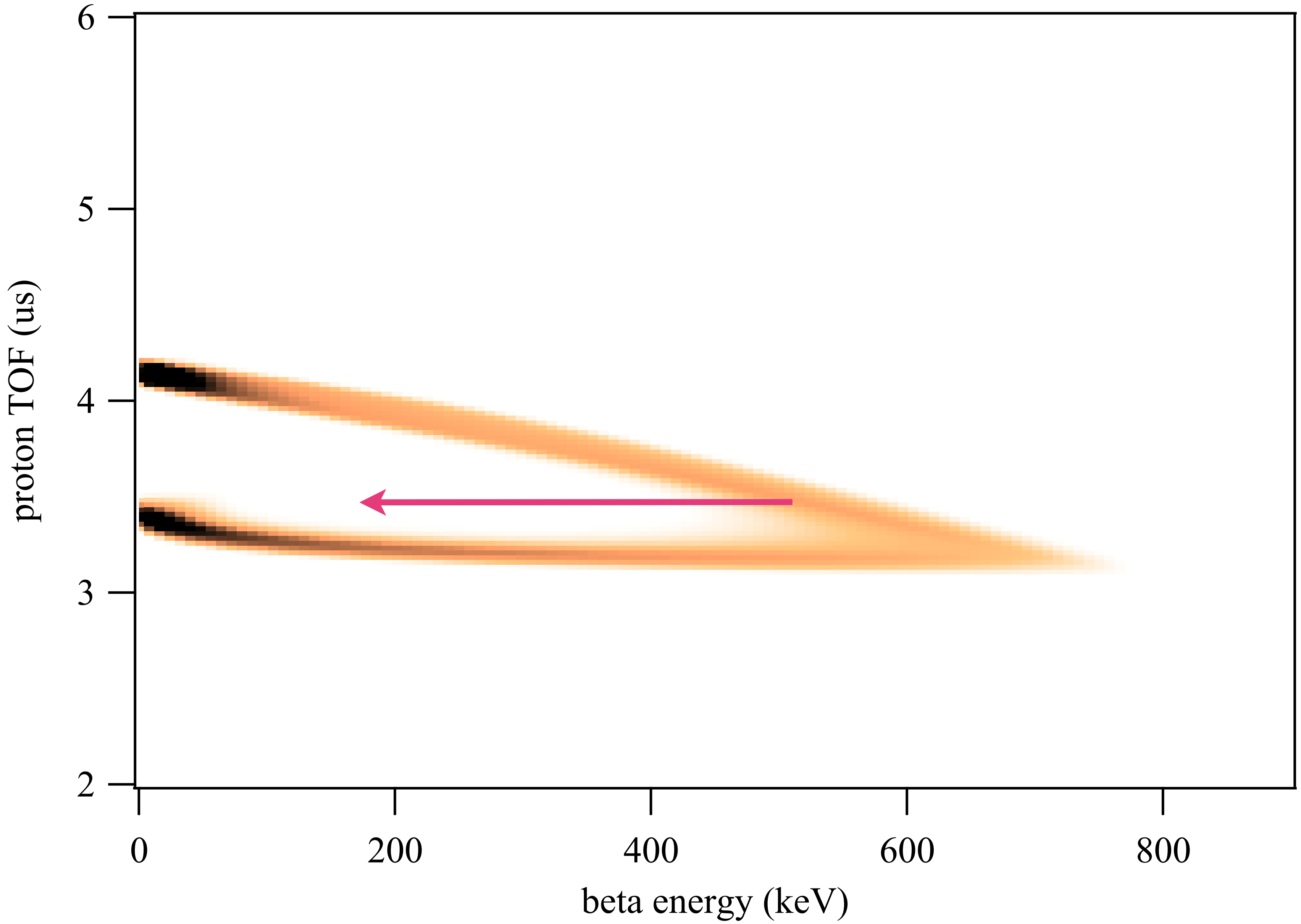
wishbone asymmetry

geometric function


LN2 Dewar
High Voltage Cable for Proton Detector Assembly
Proton Detector
Proton Collimator
Cryogenic Panels
Magnet Coils
Neutron Beam Guide
Electrostatic Mirror
Electron Collimators
Backscatter Suppressed Beta Detector
326 cm
Neutron Beam

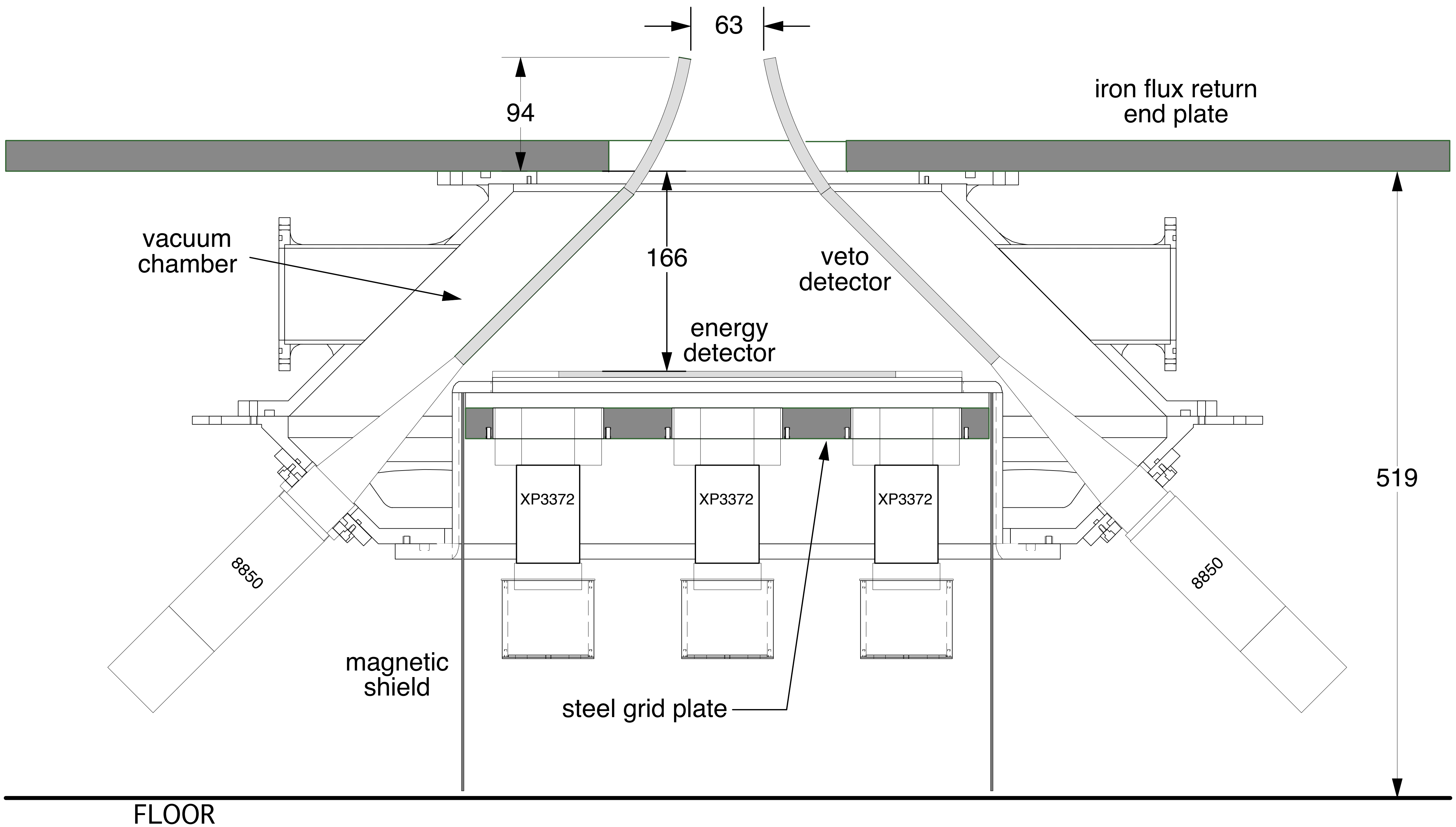
aCORN

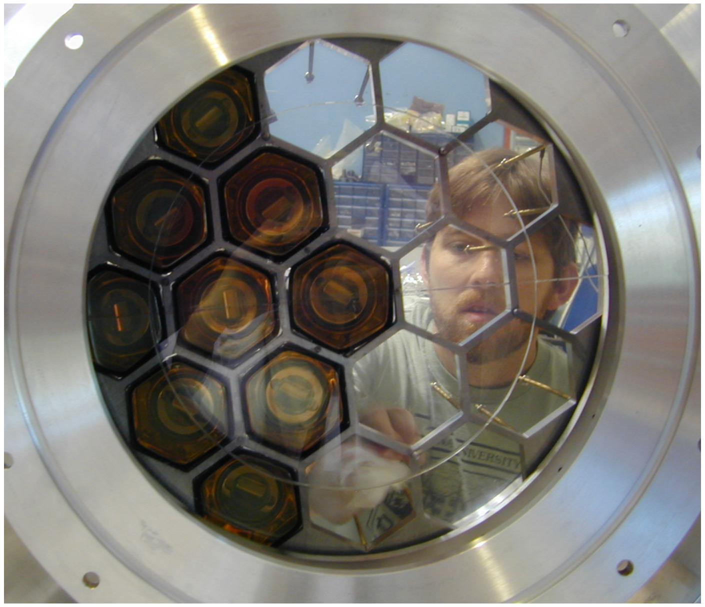
Electron backscatter



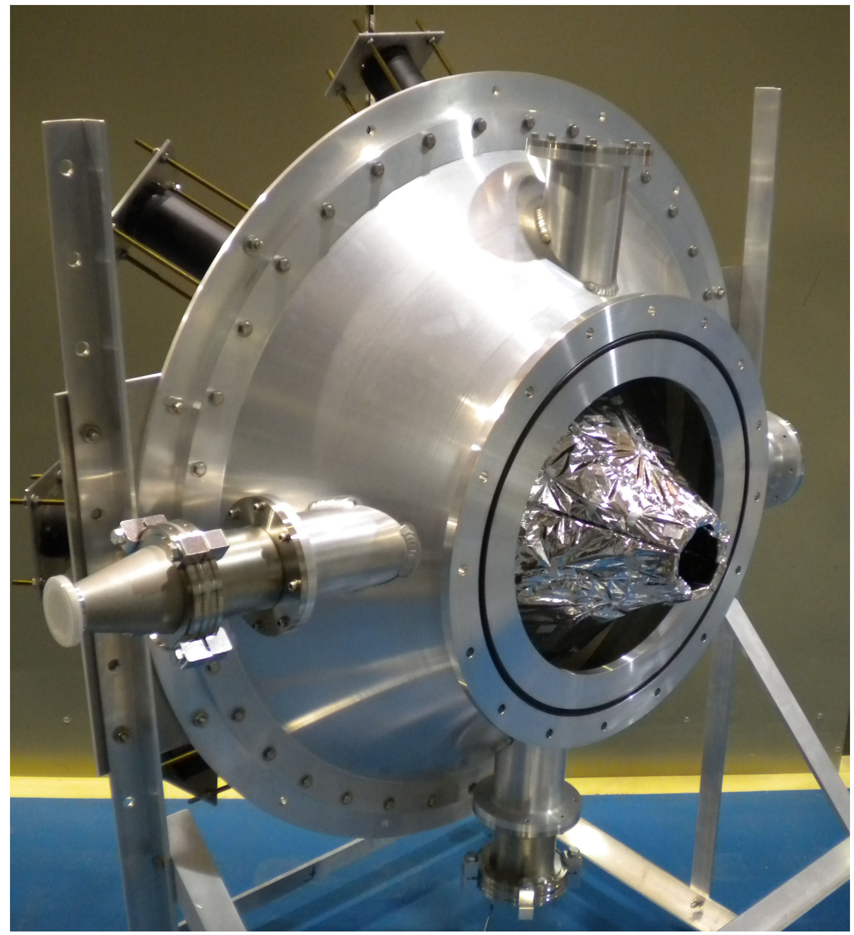
Electron backscatter will cause electrons to appear at a lower, incorrect energy, filling in the gap between the branches.

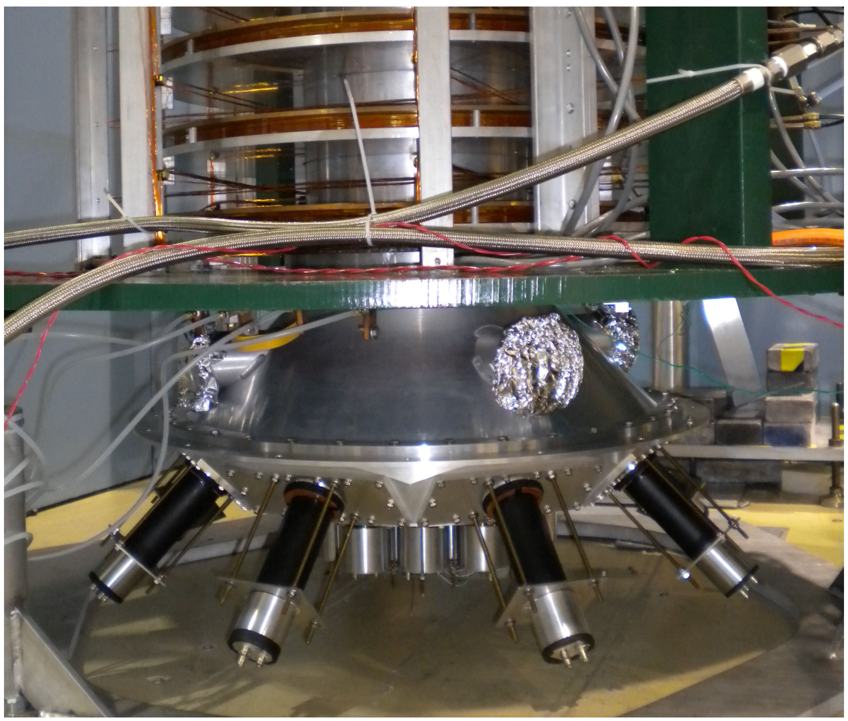
aCORN backscatter suppressed beta spectrometer

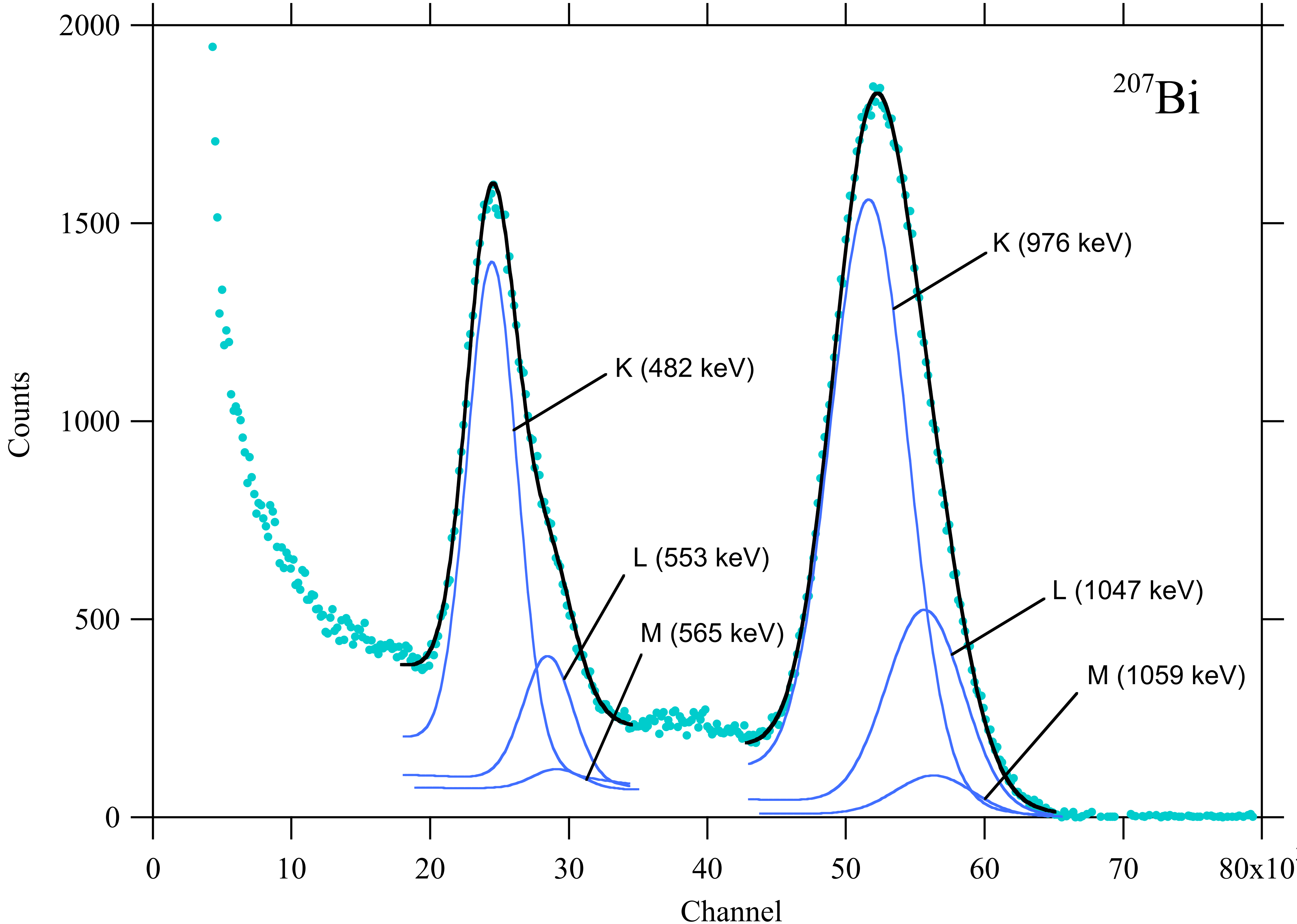




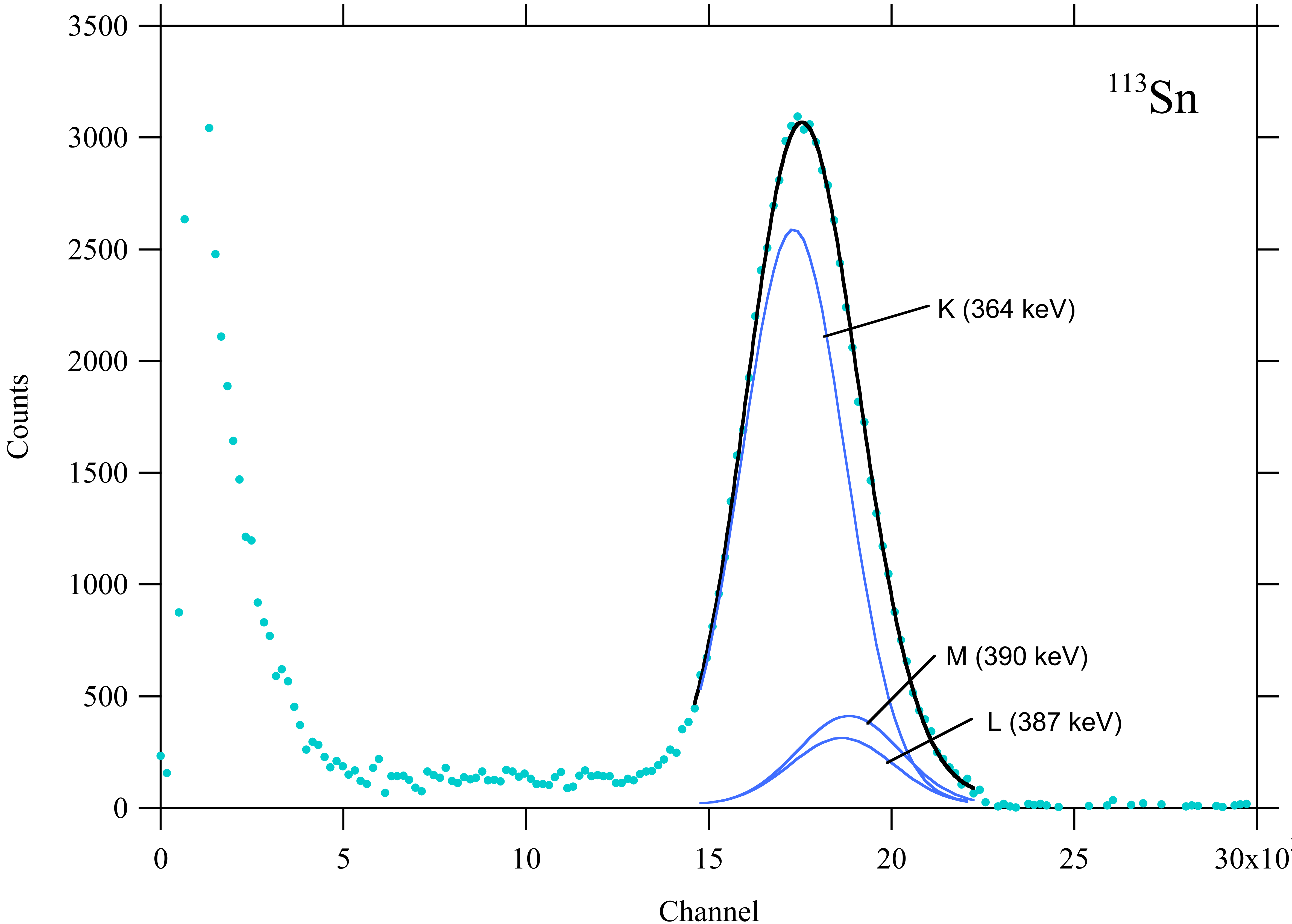
aCORN Beta Spectrometer



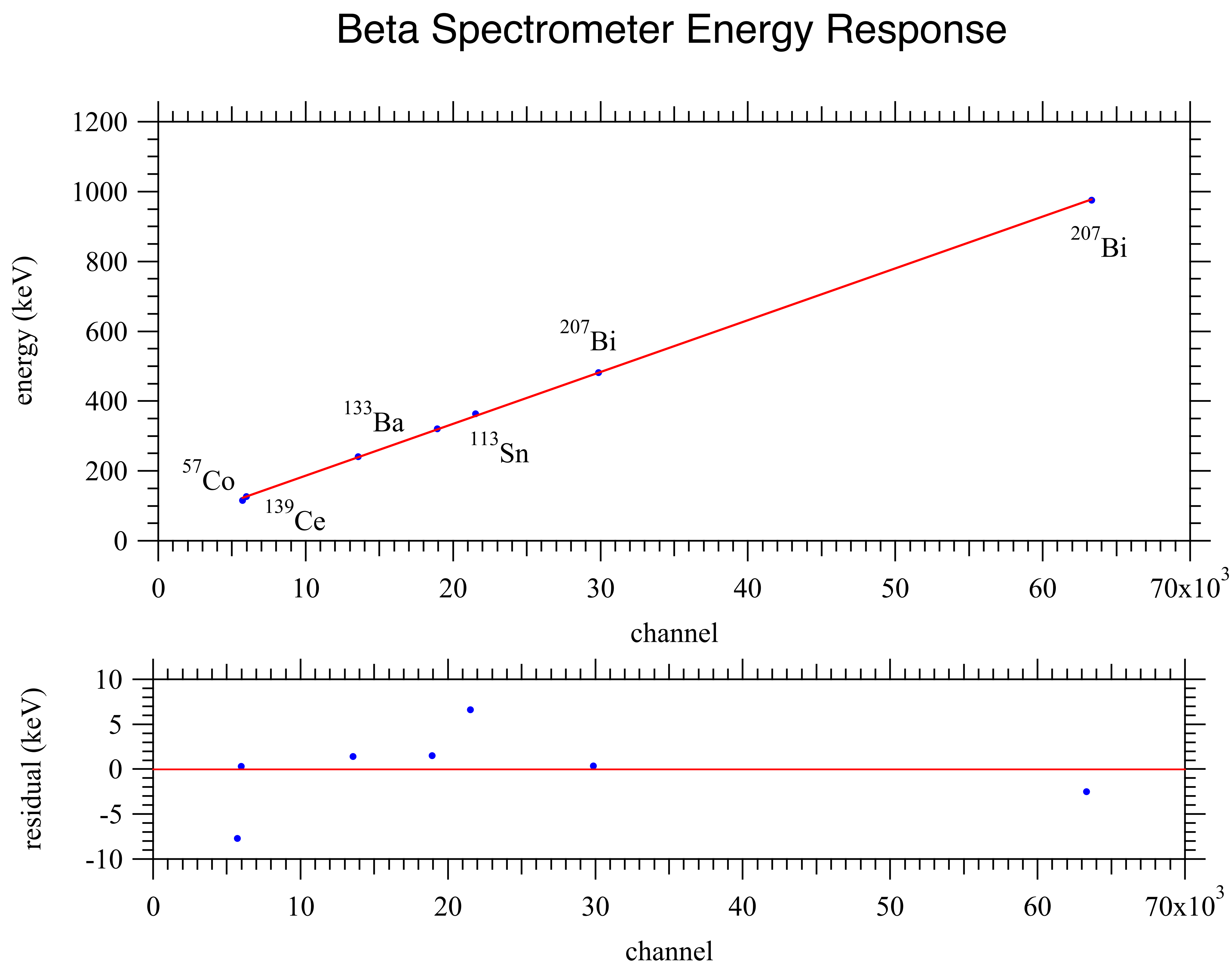




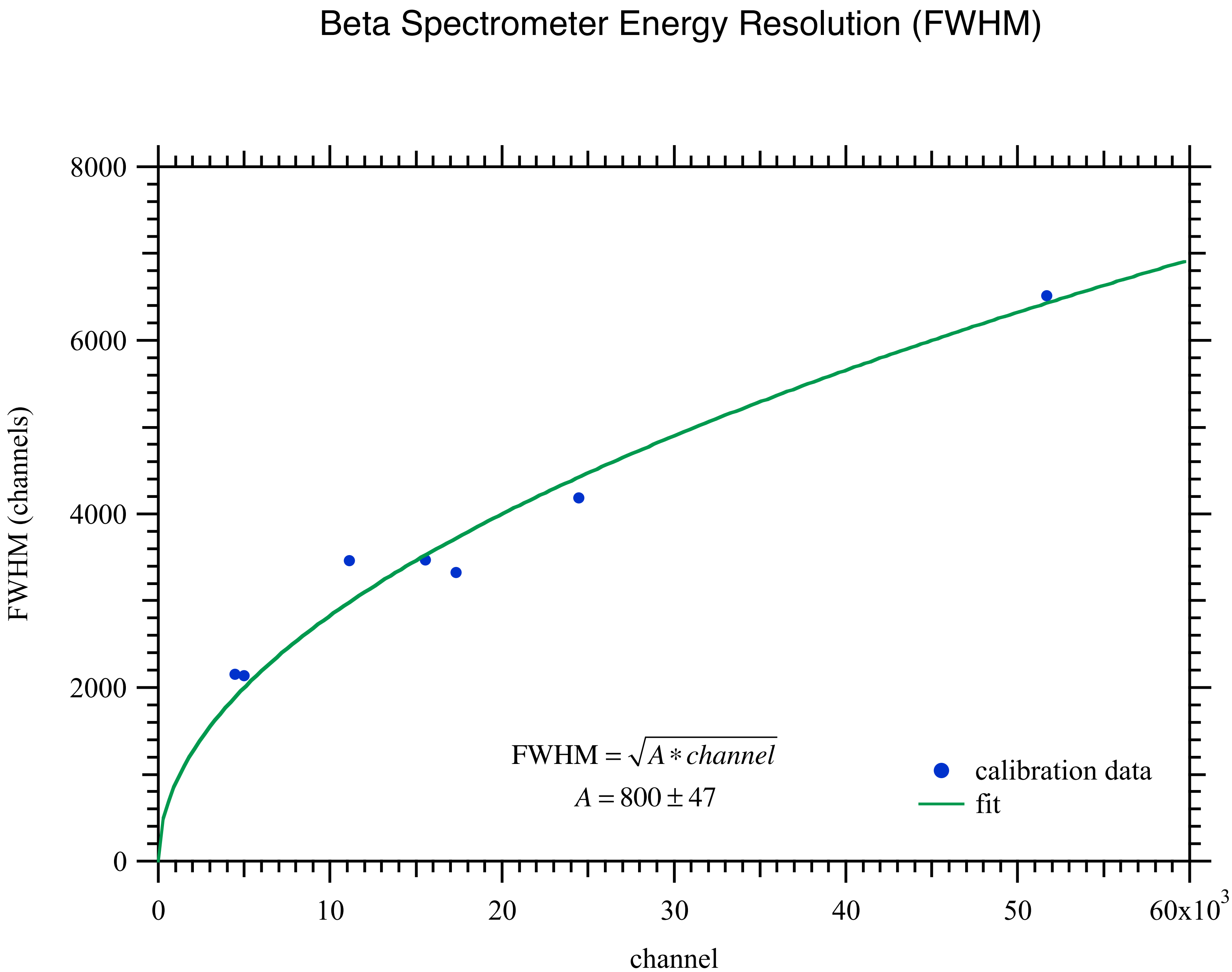
^{207}Bi
K (482 keV)
L (553 keV)
M (565 keV)
K (976 keV)
L (1047 keV)
M (1059 keV)
Counts
Channel
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80x10^3



113Sn
K (364 keV)
M (390 keV)
L (387 keV)
Counts
Channel
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30x10^3

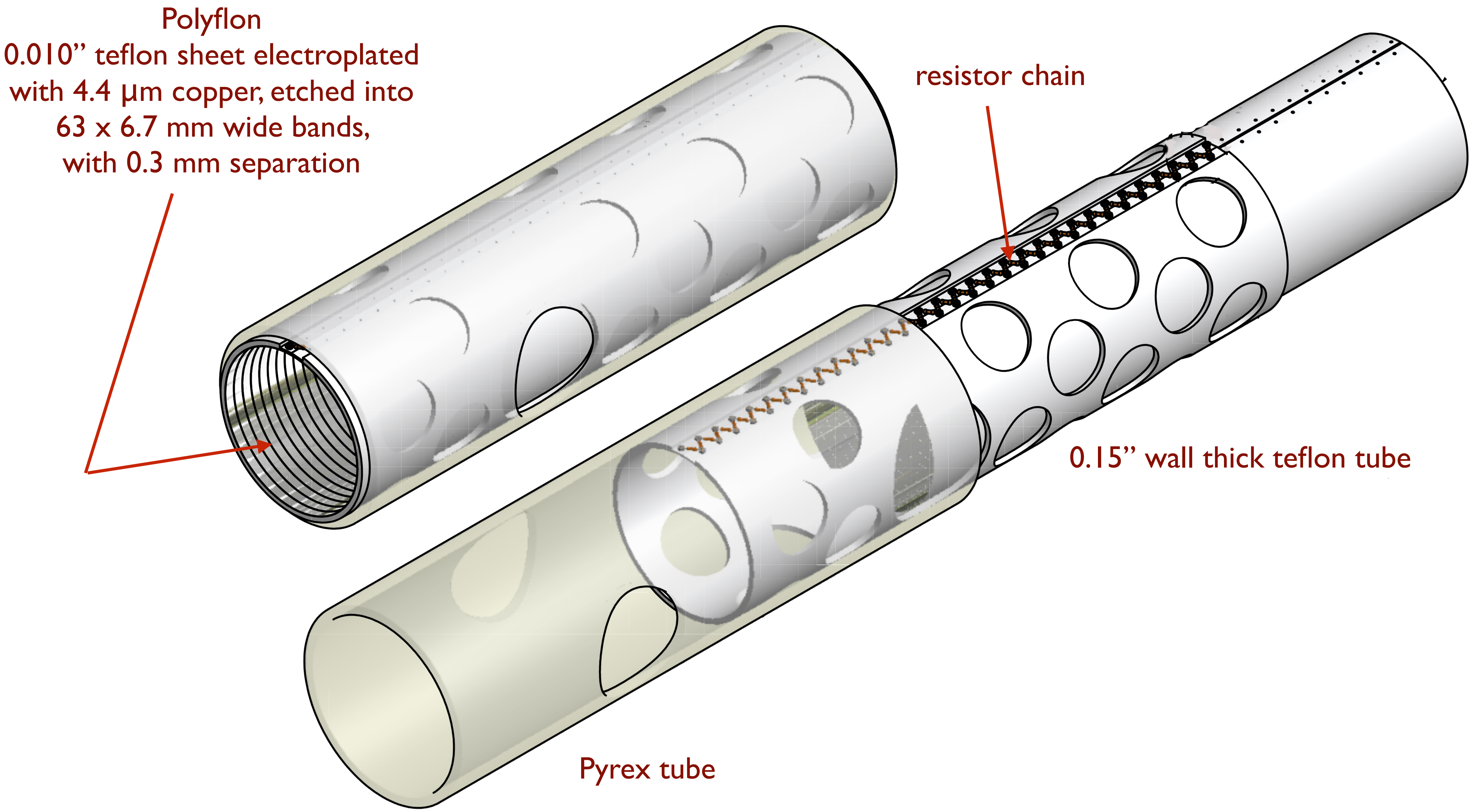


Beta Spectrometer Energy Response
energy (keV)
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70x10^3
channel
57Co
139Ce
133Ba
113Sn
207Bi
207Bi
residual (keV)
10
5
0
-5
-10
0
10
20
30
40
50
60
70x10^3
channel

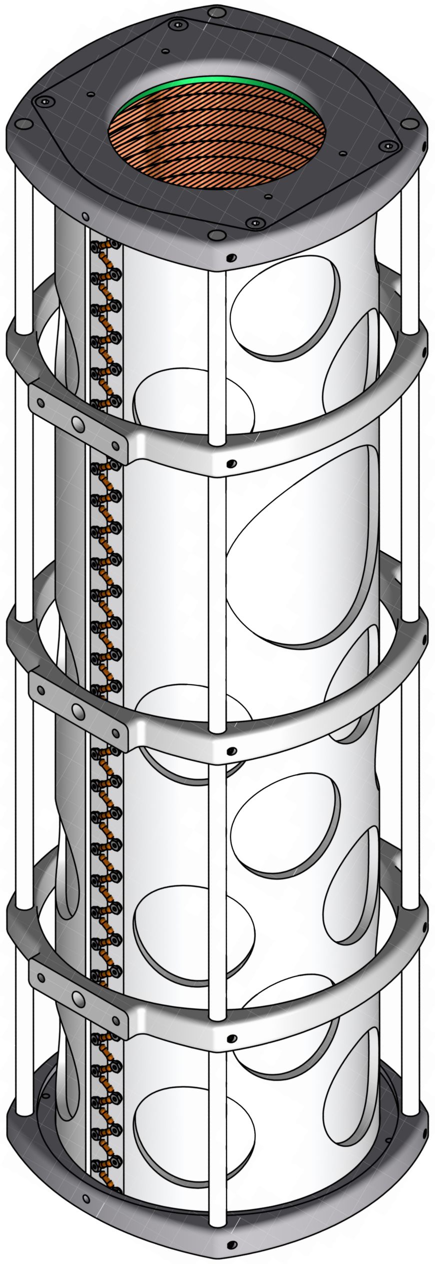


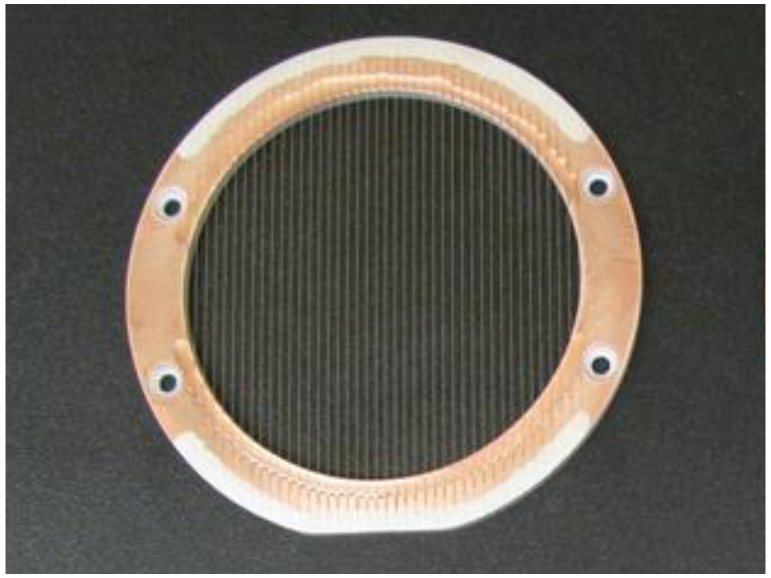
Beta Spectrometer Energy Resolution (FWHM)
8000
6000
4000
2000
0
FWHM (channels)
0
10
20
30
40
50
60x10^3
channel
FWHM = √(A * channel)
A = 800 ± 47
calibration data
fit

Electrostatic mirror



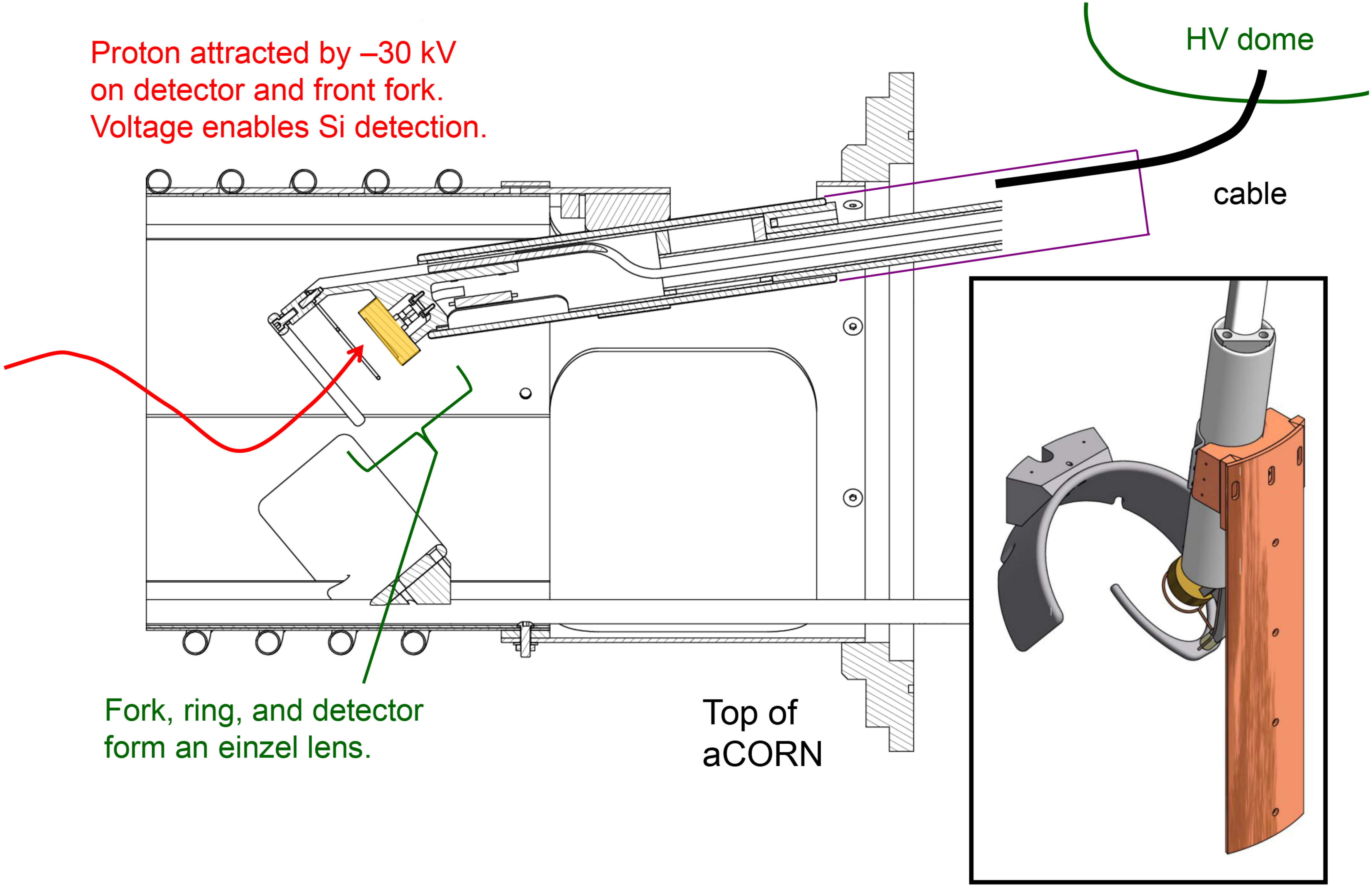
Electrostatic mirror



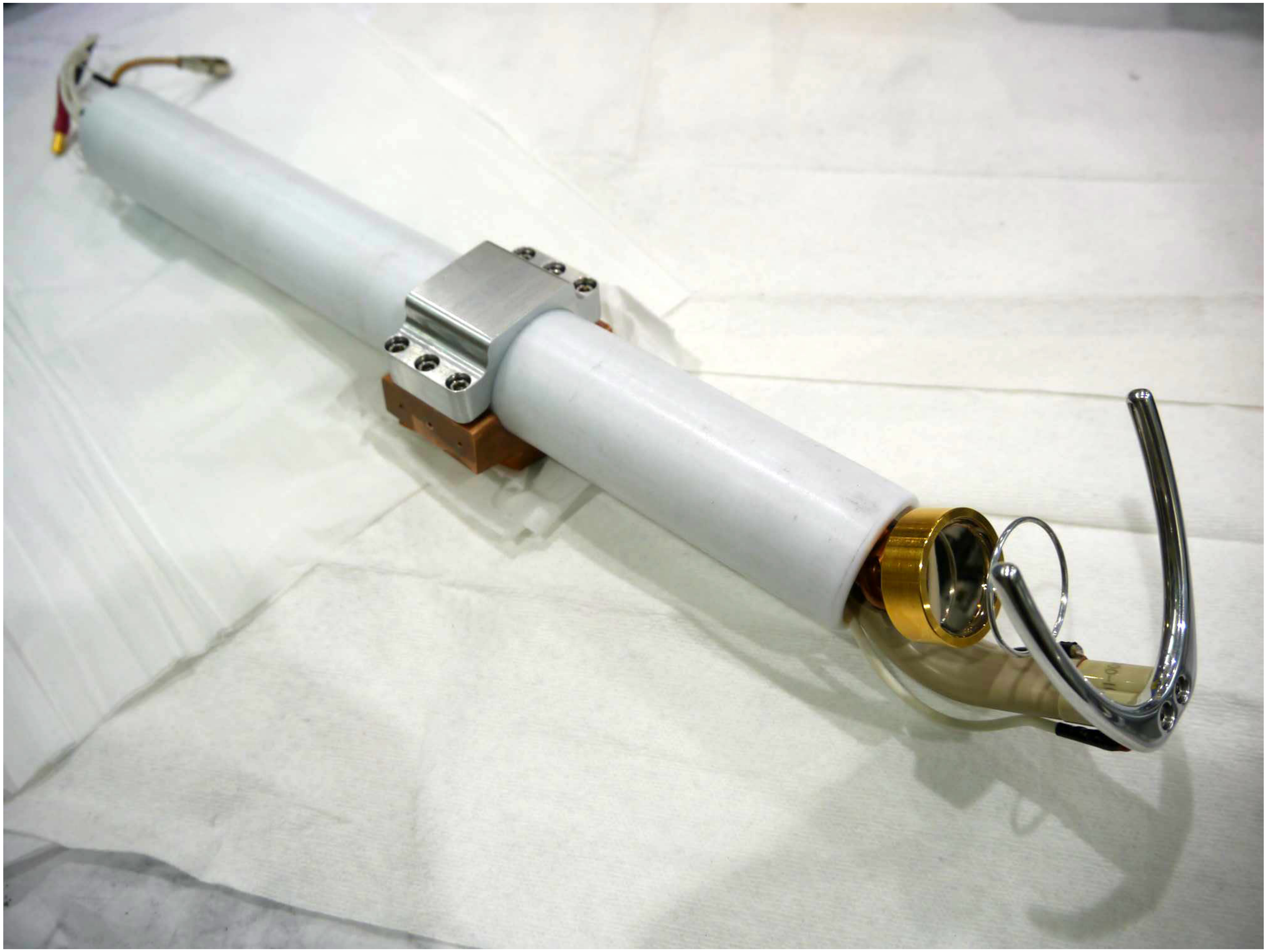


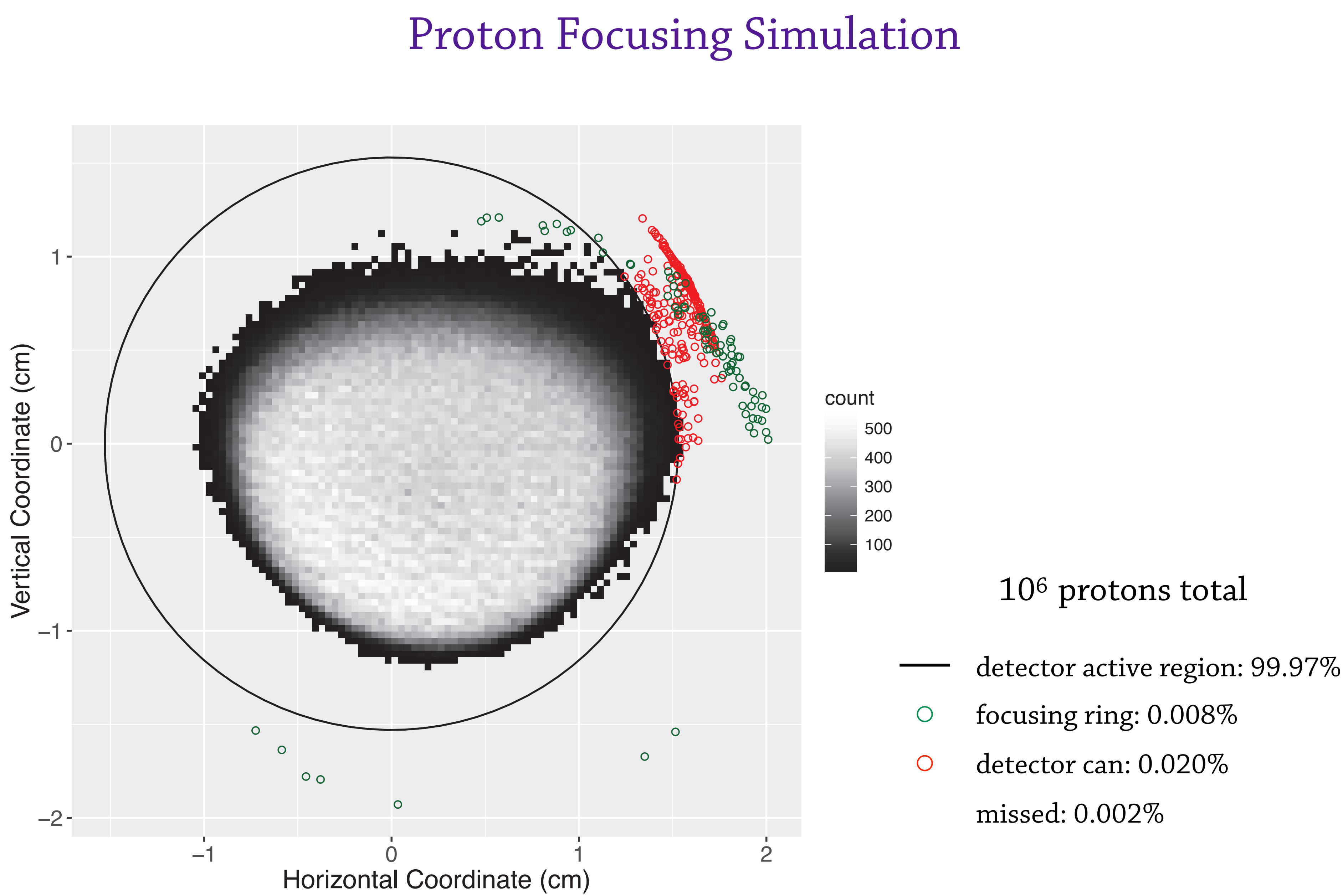
100 μm gold-plated BeCu wire grid,
2-mm spacing

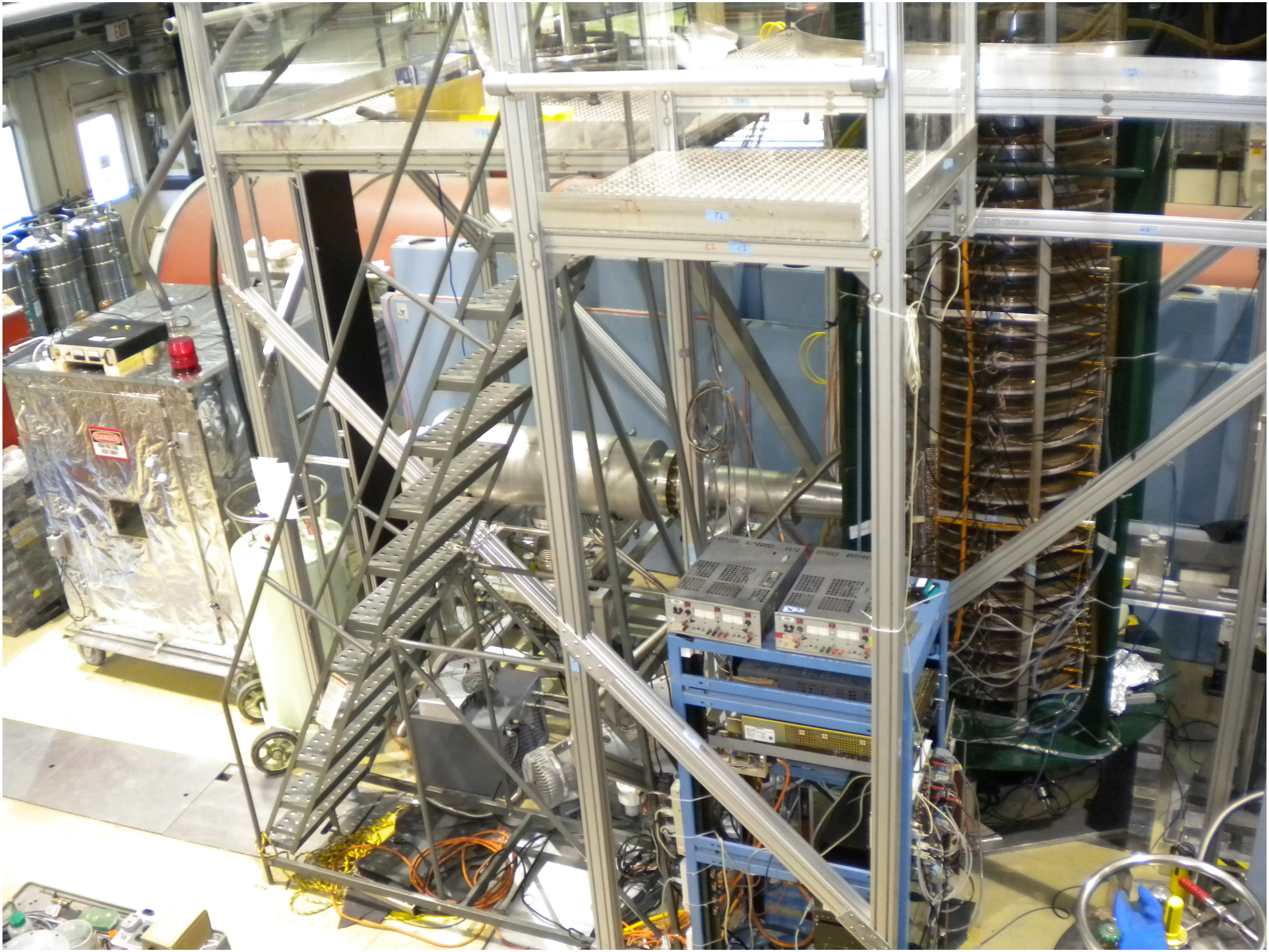
Proton detector



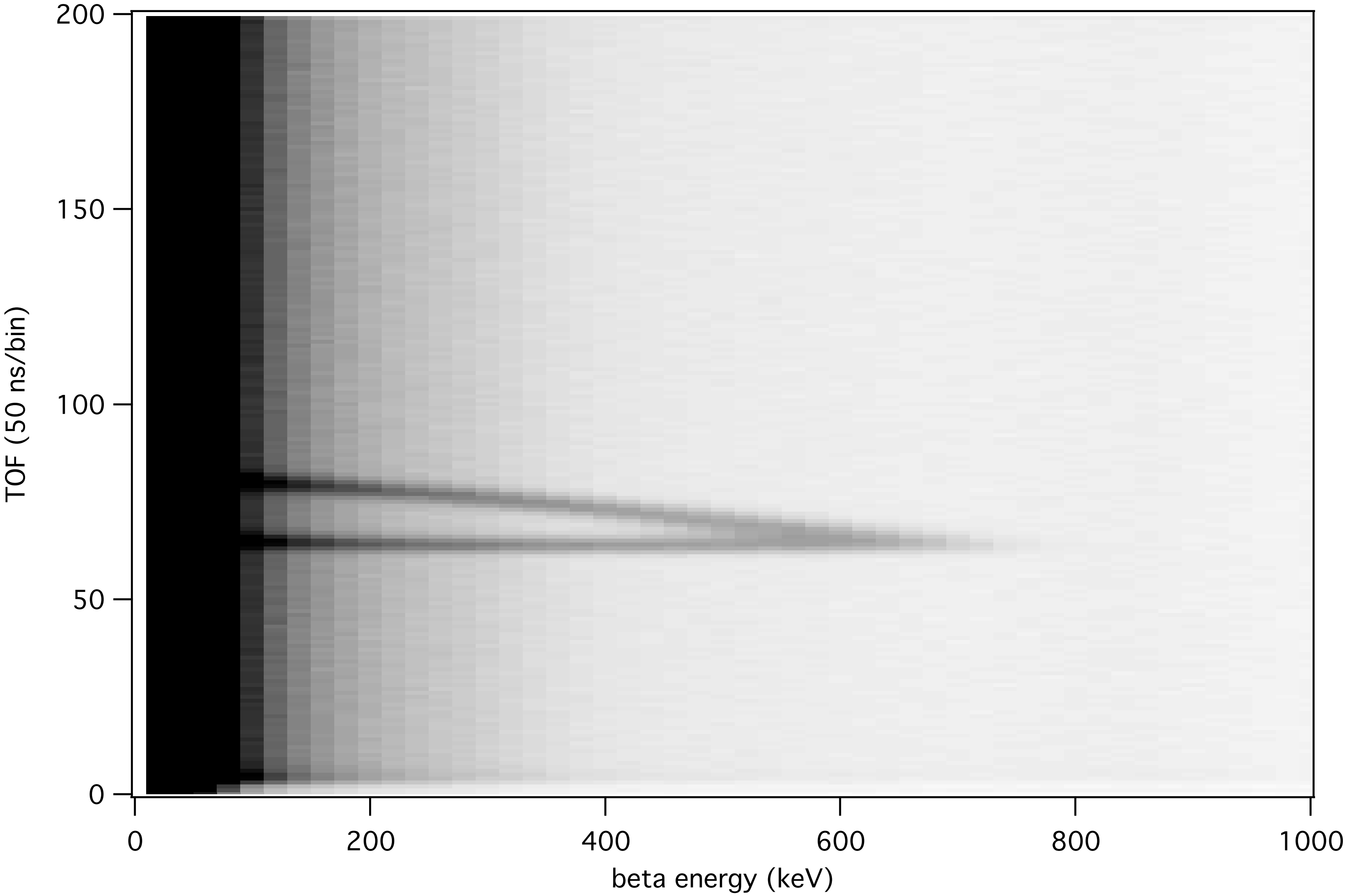
aCORN proton detector



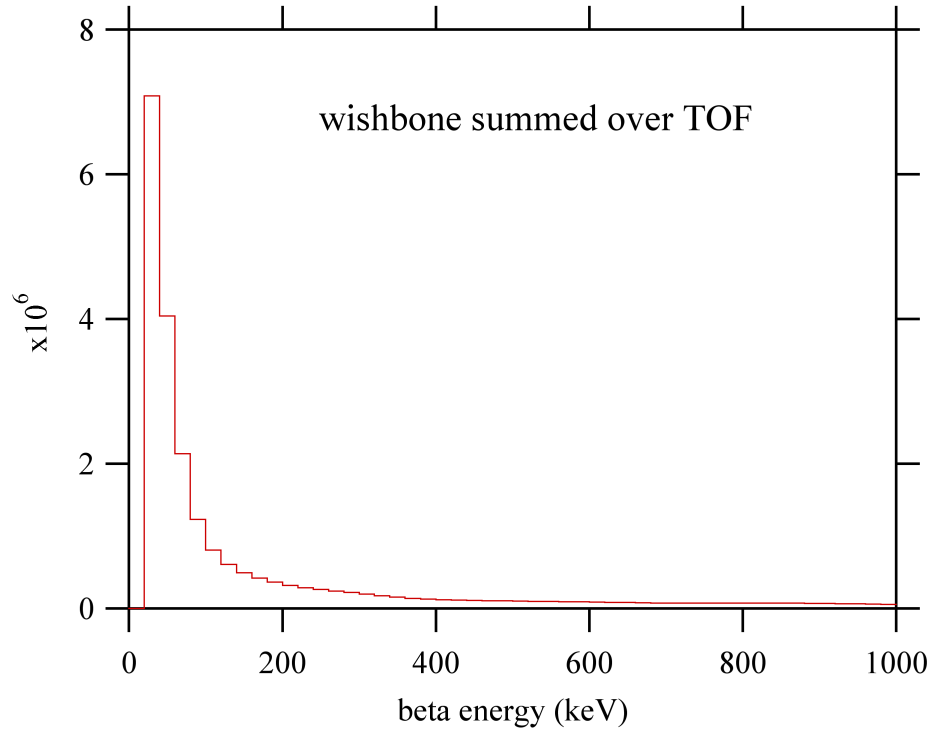

Proton Focusing Simulation
Vertical Coordinate (cm)
Horizontal Coordinate (cm)
count
500
400
300
200
100
1
0
−1
−2
−1
0
1
2
10⁶ protons total
detector active region: 99.97%
focusing ring: 0.008%
detector can: 0.020%
missed: 0.002%

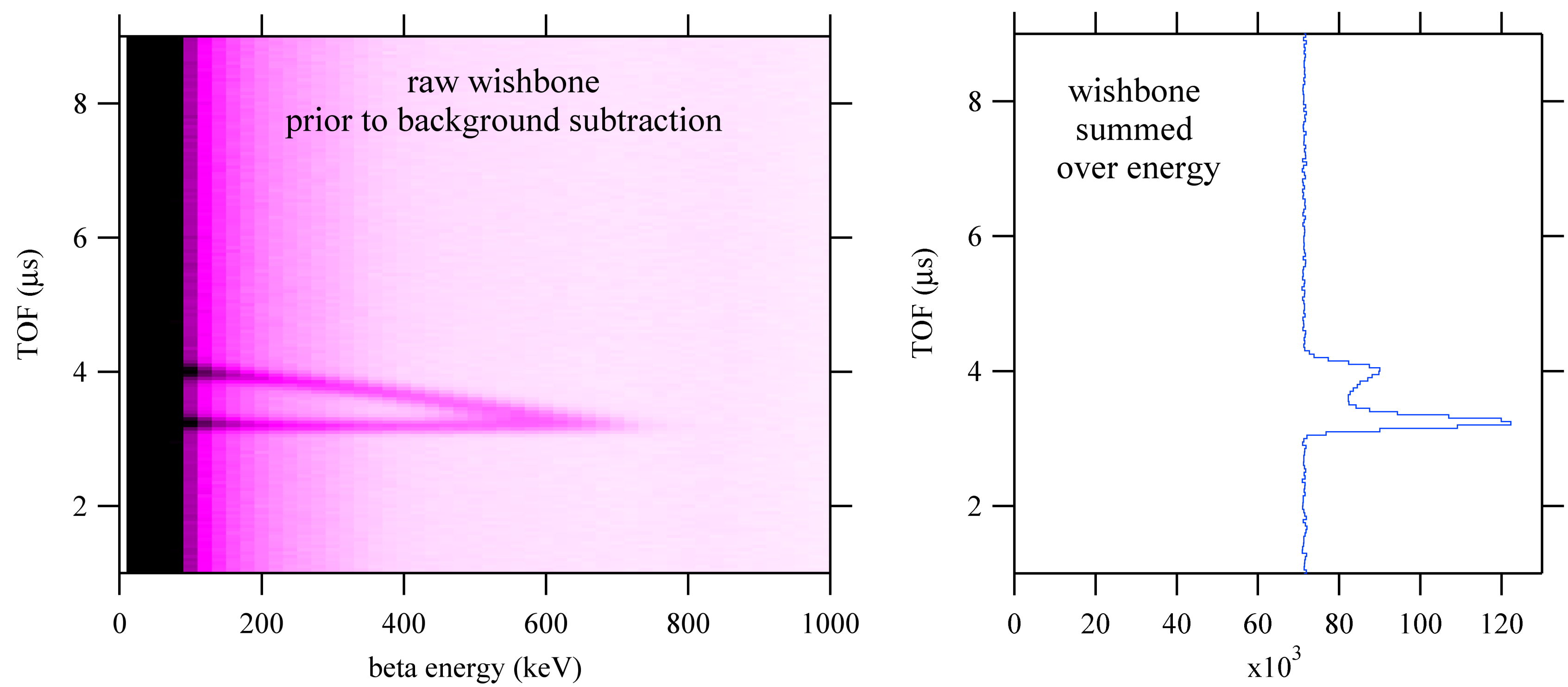


Typical Wishbone

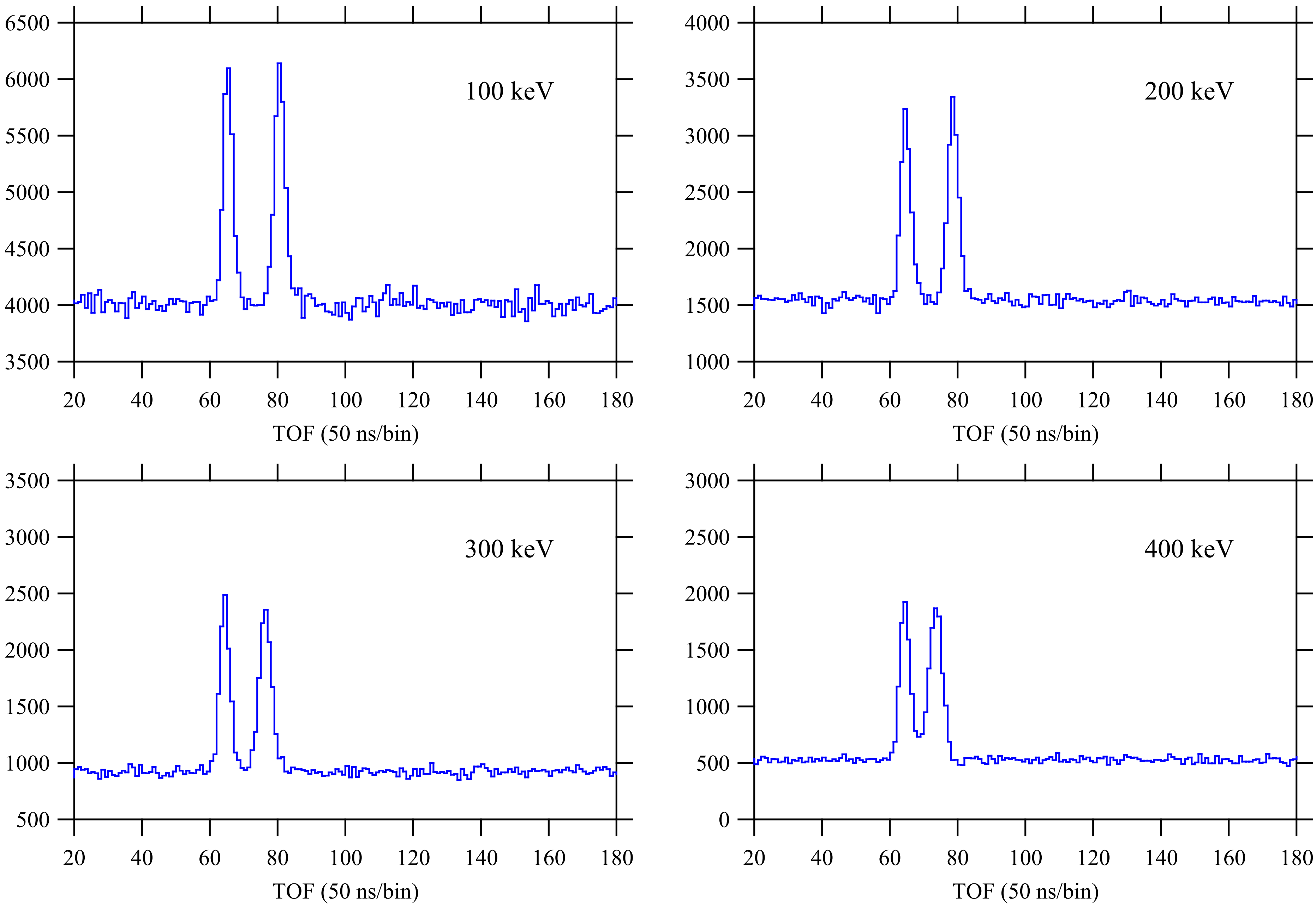


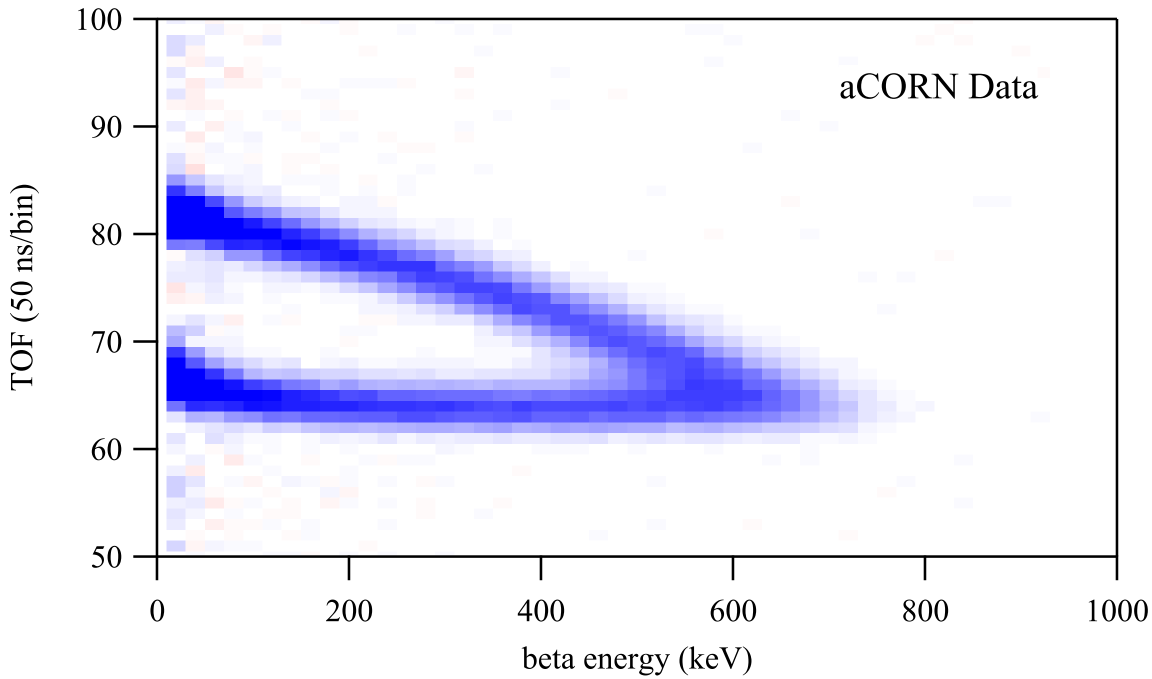
aCORN background (NG-6)



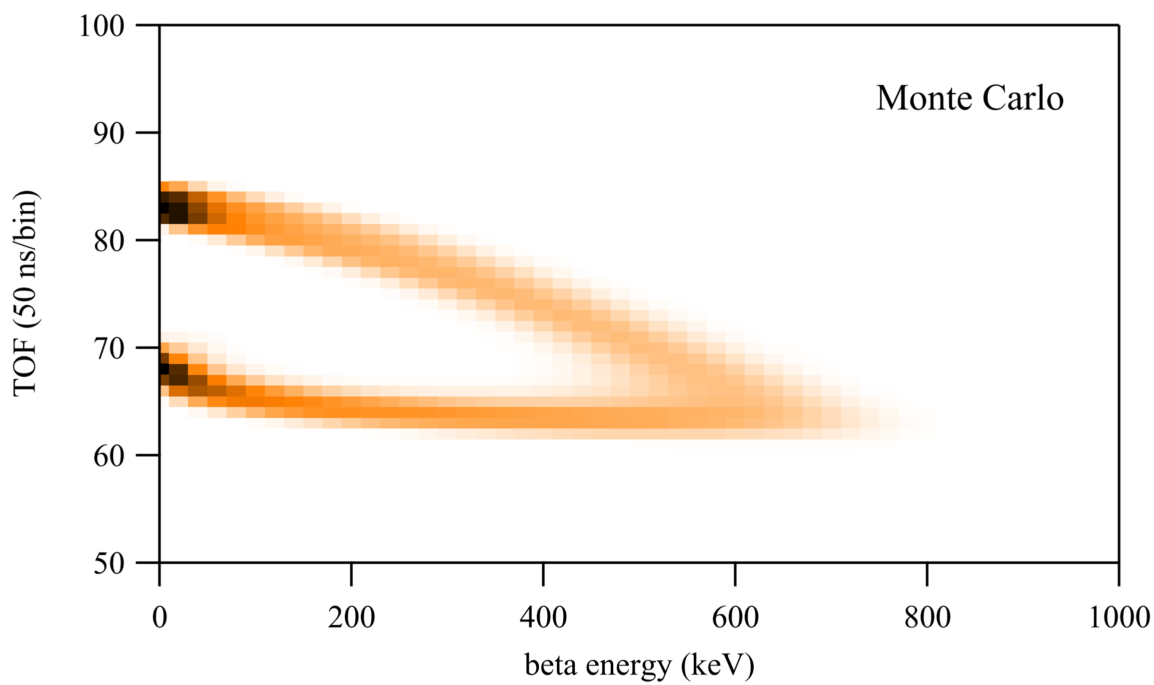


Wishbone Slices

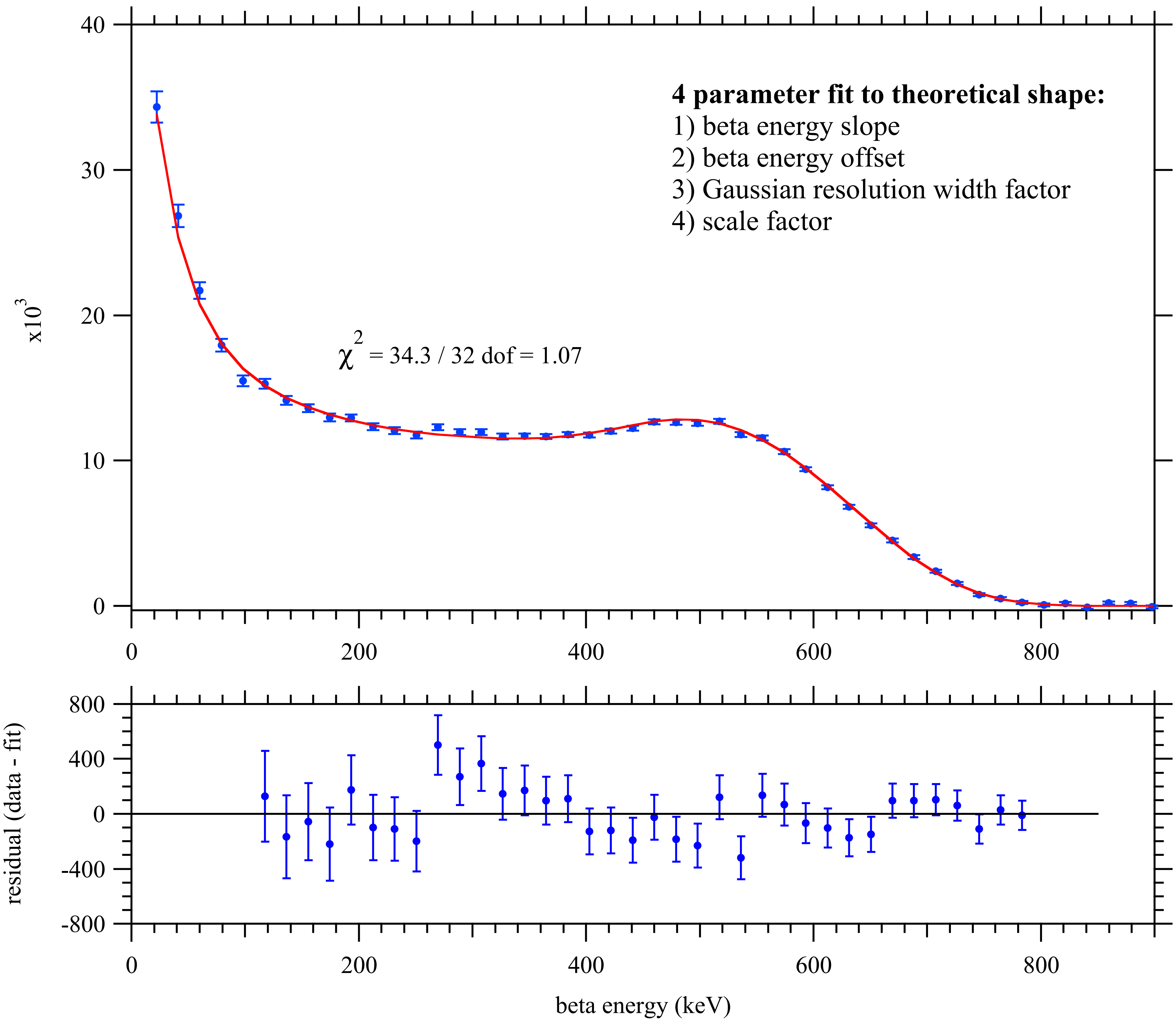




Background Subtracted Wishbone



Energy Calibration Fit



The geometric function $f_a(E)$

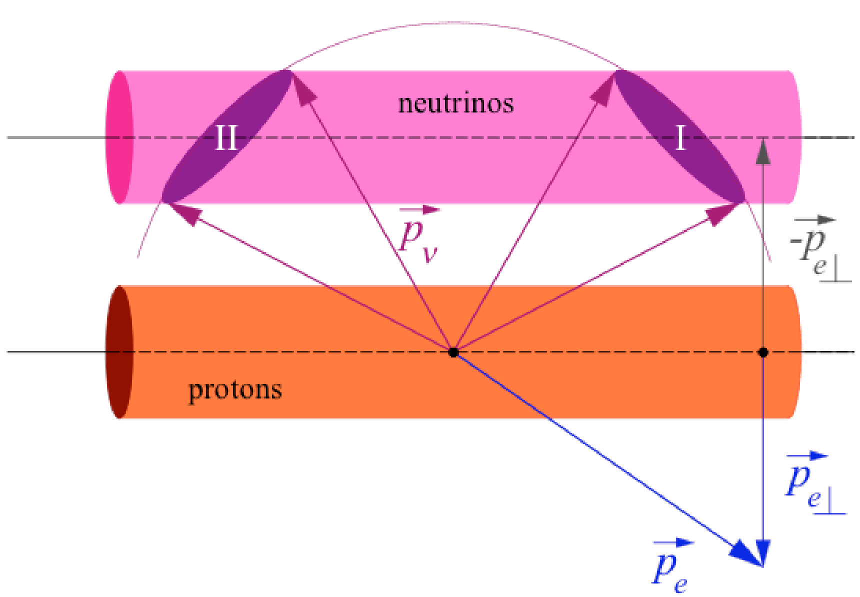
wishbone asymmetry: $X(E) = a\, f_a(E)$

$$f_a(E) = \frac{1}{2} v\left(\phi^I(E) - \phi^{II}(E)\right)$$

$\phi^I(E), \phi^{II}(E)$ are the average angle between electron and antineutrino momentum vectors for all momenta within the aCORN acceptance, independent of the beta decay distributions.

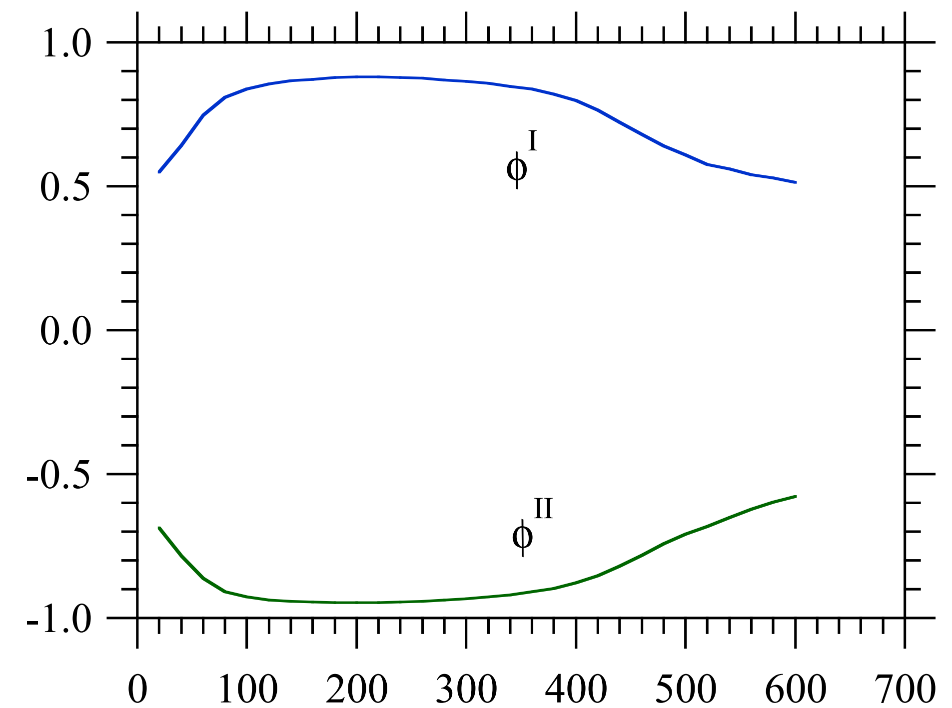
$f_a(E)$ depends ONLY on:

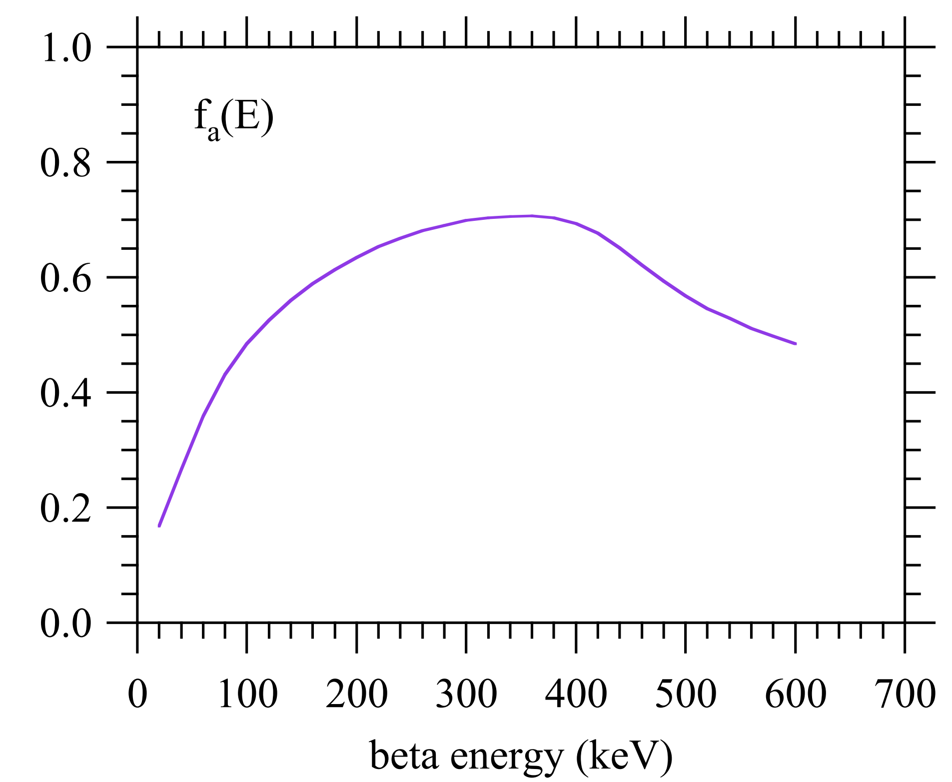
- magnetic field strength
- collimator geometry
- neutron beam density distribution (weakly)



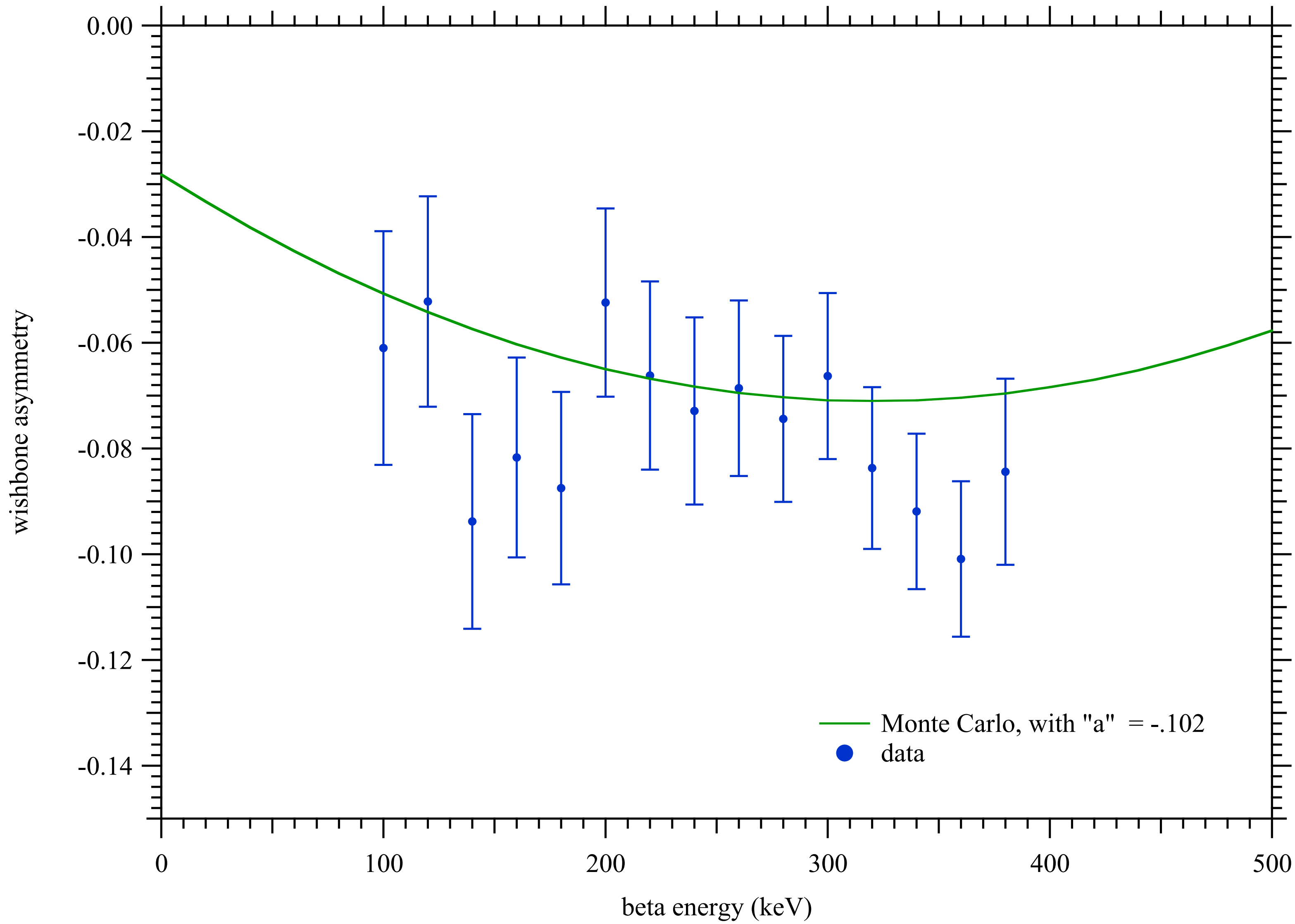
$$\phi^{I}(E) = \frac{\int d\Omega_e \int_I d\Omega_\nu \cos\theta_{e\nu}}{\Omega_e \Omega_\nu^I}$$

$$\phi^{II}(E) = \frac{\int d\Omega_e \int_{II} d\Omega_\nu \cos\theta_{e\nu}}{\Omega_e \Omega_\nu^{II}}$$





Uncorrected wishbone asymmetry



Energy-dependent corrections

Energy-dependent corrections

Electrostatic mirror

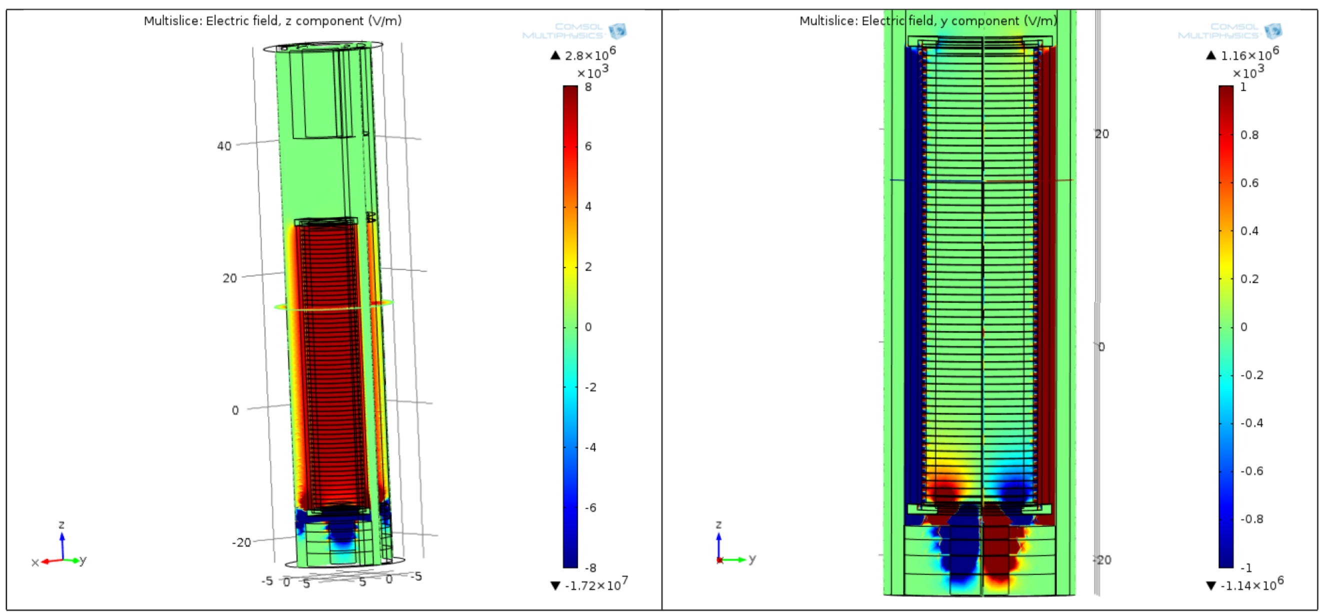
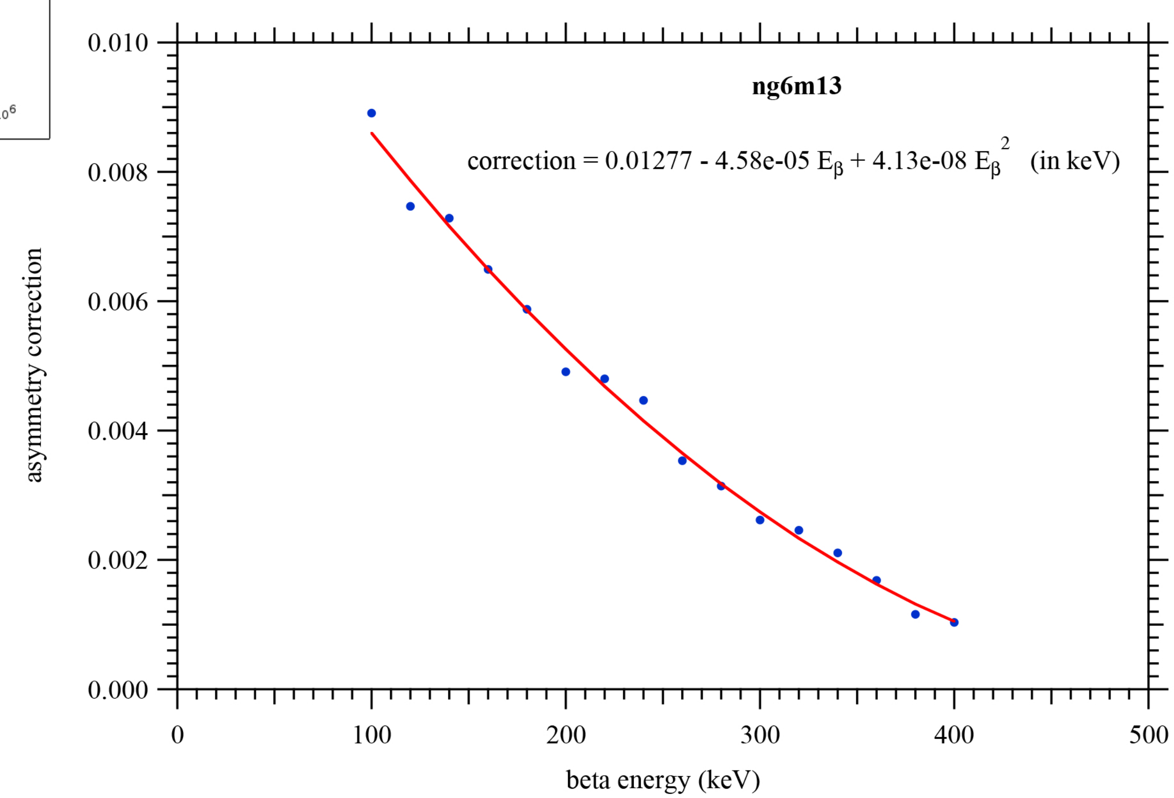


Figure 2: Axial (l) and Transverse (r) Electric fields in NG6Mirror13

fully realistic 3D COMSOL model

4th order RK proton transport simulation



Energy-dependent corrections

Electrostatic mirror

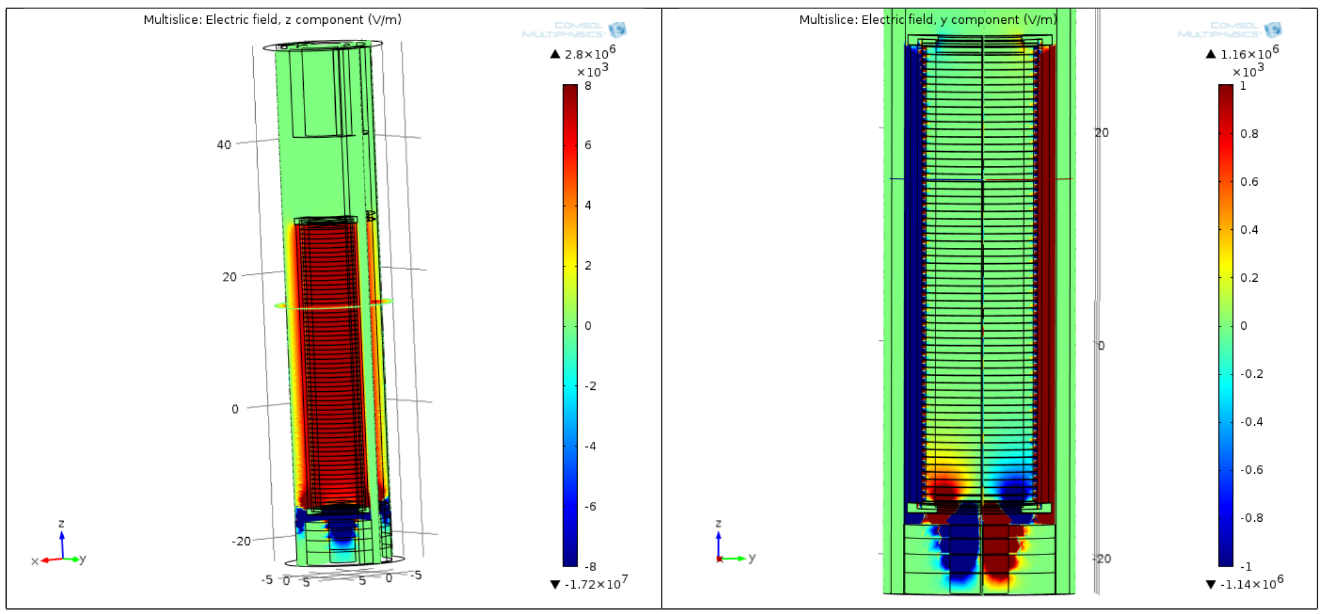
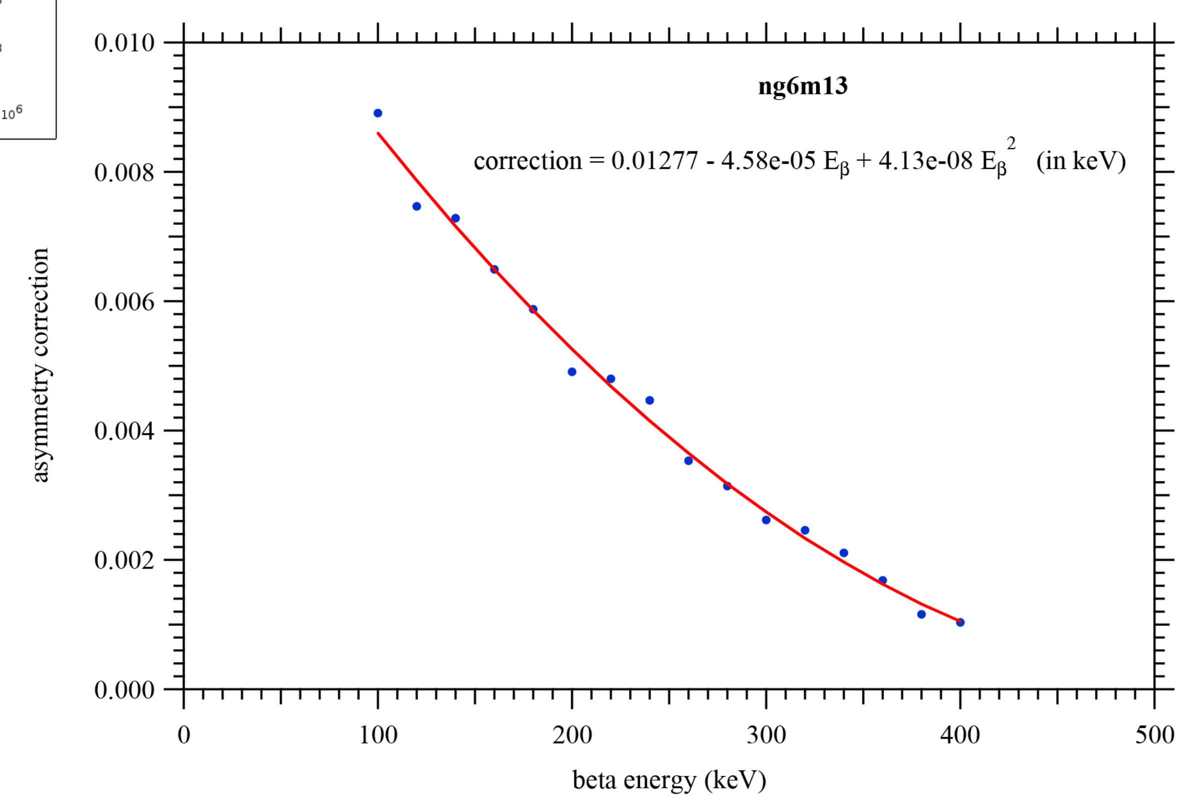


Figure 2: Axial (l) and Transverse (r) Electric fields in NG6Mirror13

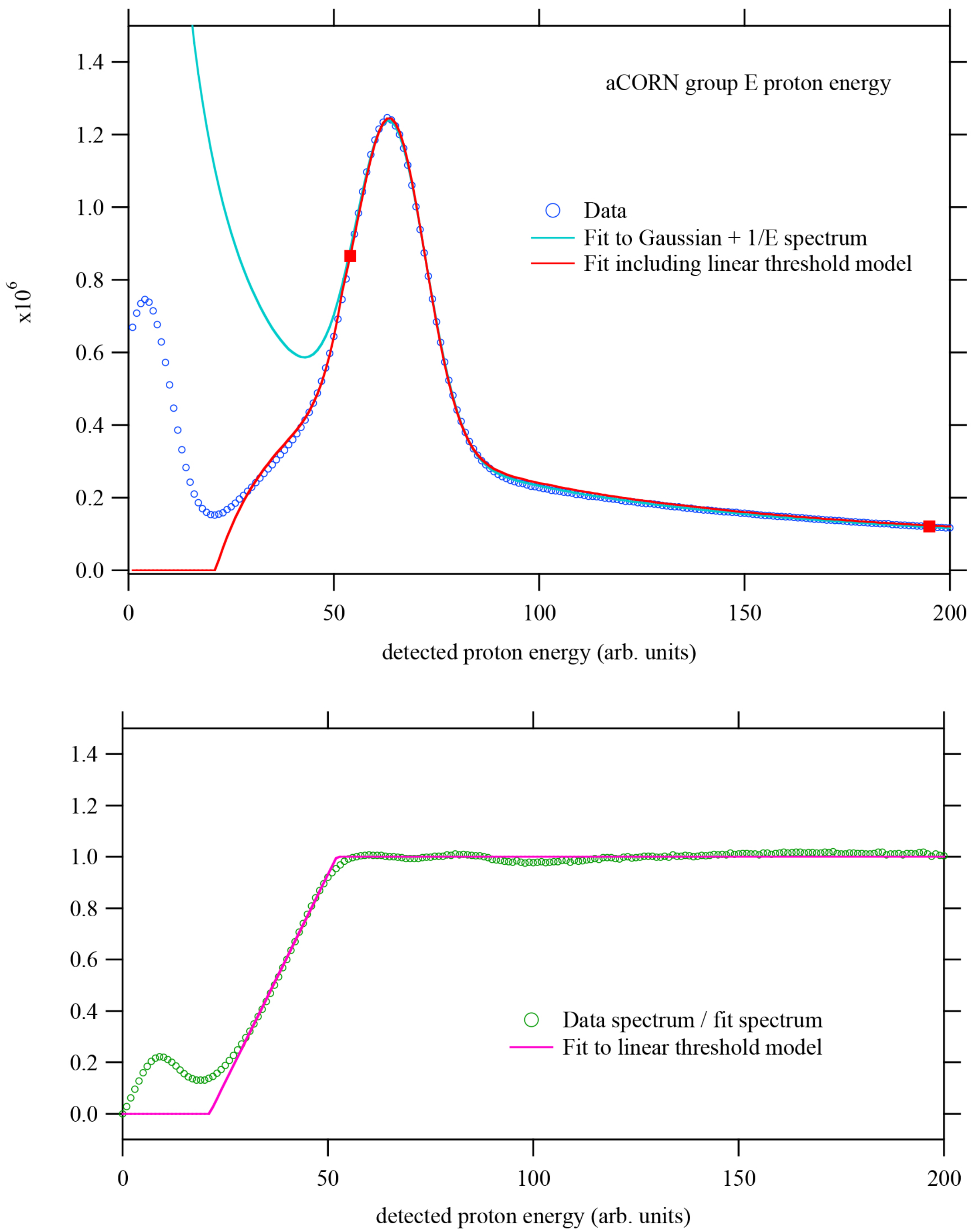
fully realistic 3D COMSOL model

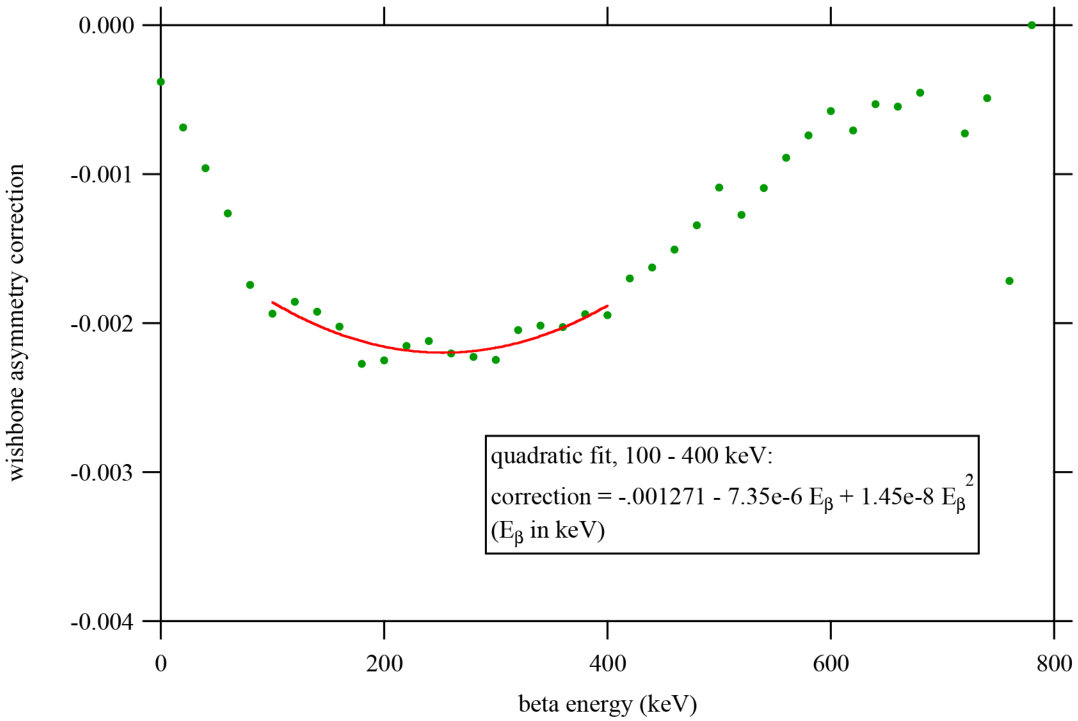


4th order RK proton transport simulation

a +5.5% net correction to "a"

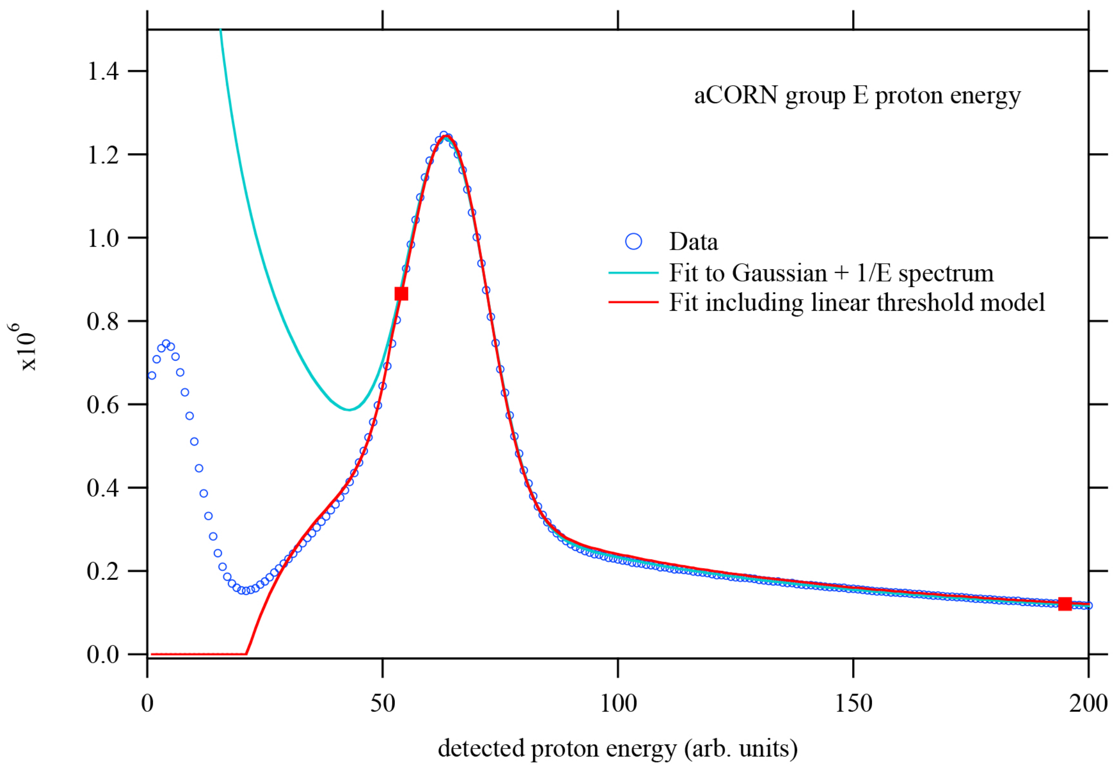
Soft proton threshold

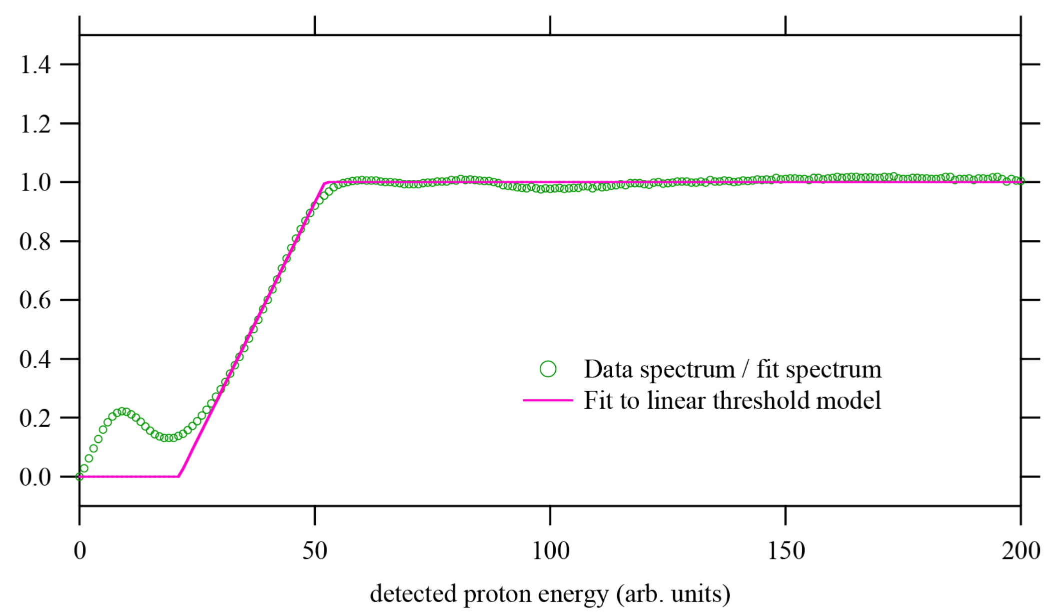


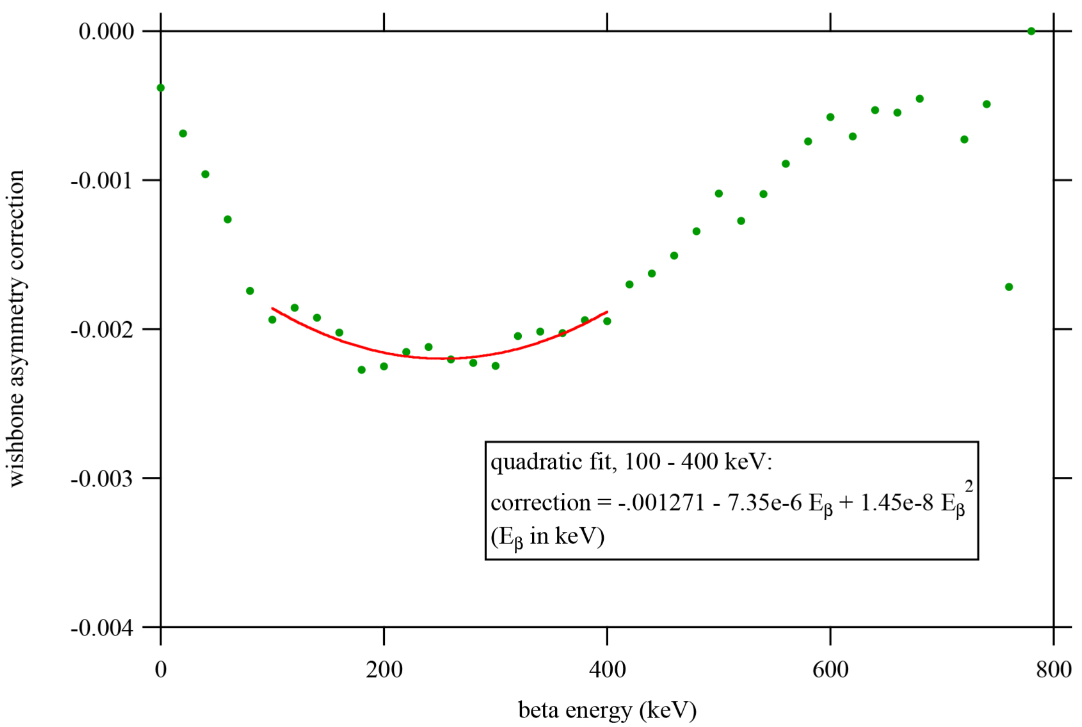


aCORN Monte Carlo calculation of the proton threshold effect

Soft proton threshold







aCORN Monte Carlo calculation of the proton threshold effect

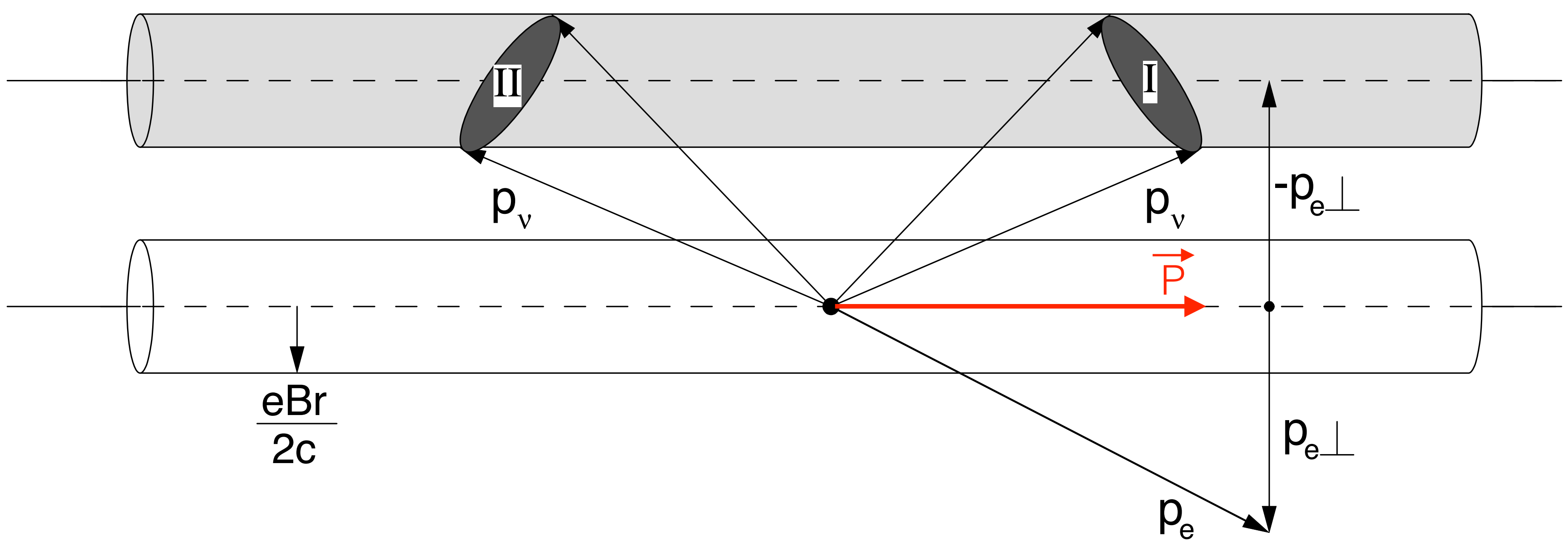
a -3.0% net correction to "a"

Beam Polarization

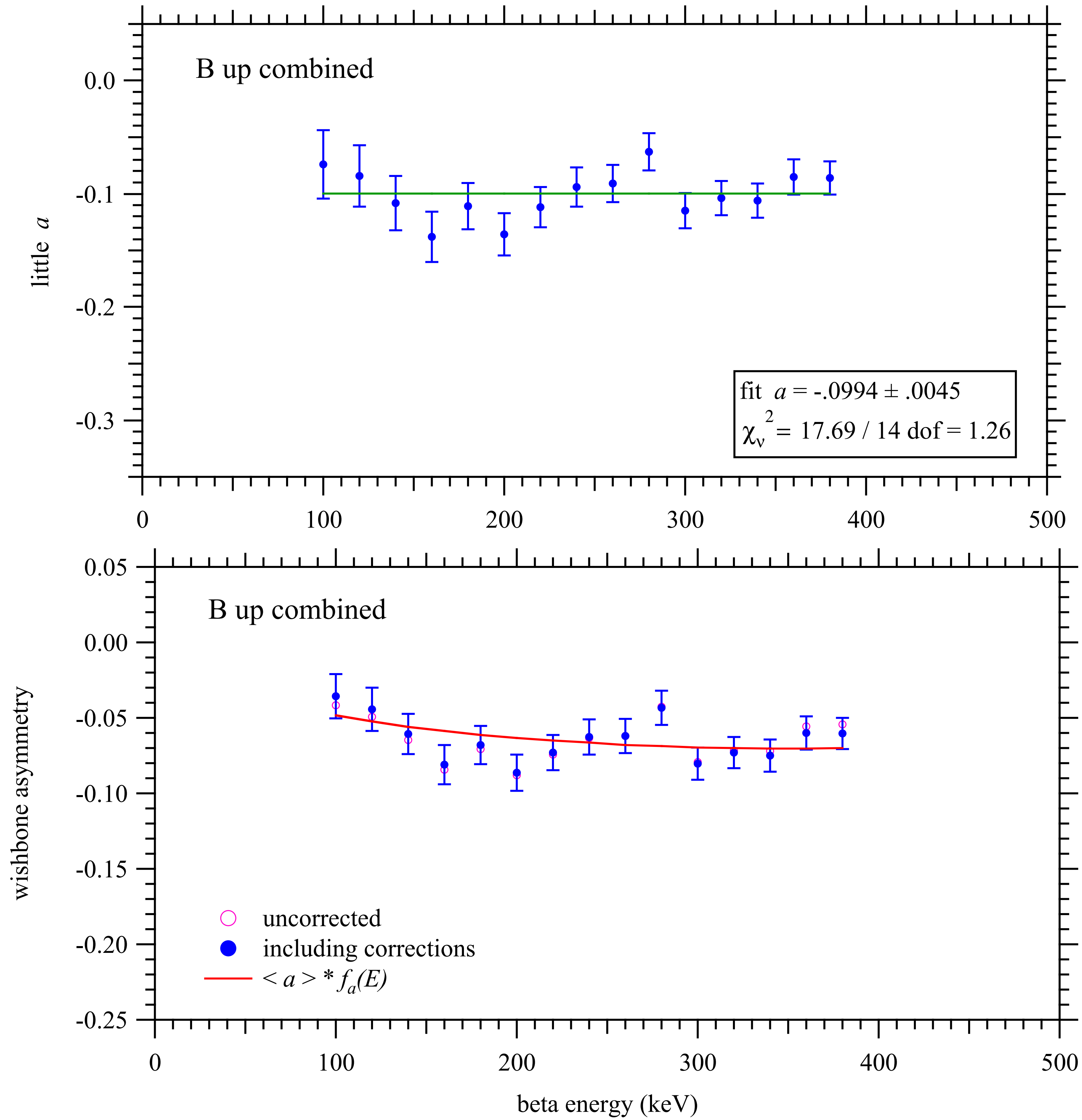
With a polarized neutron beam:

$$\text{wishbone asymmetry } A_{wb} = af_a(E_\beta) + PBf_B(E_\beta)$$

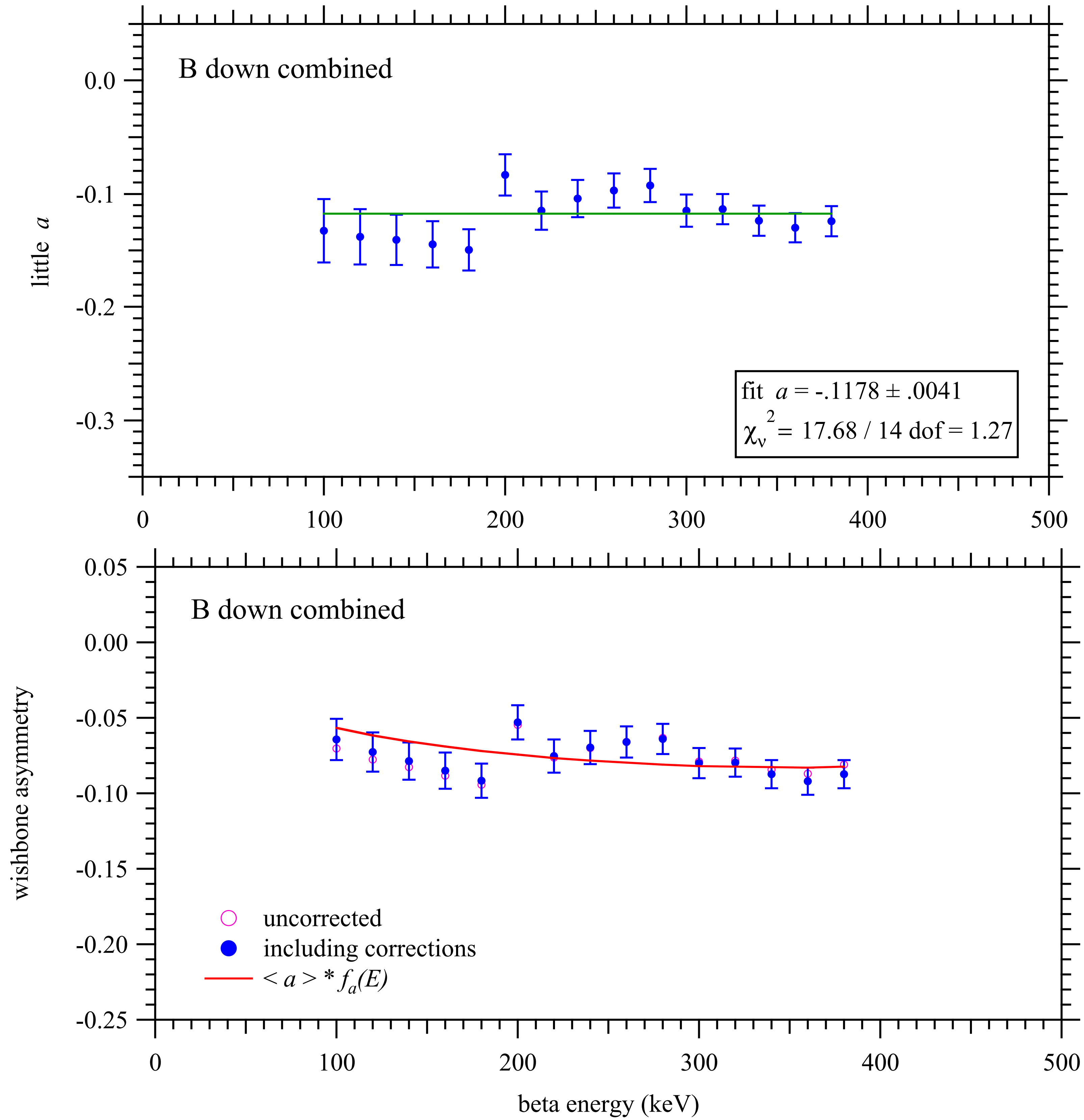
$$\frac{Bf_B(E_\beta)}{af_a(E_\beta)} \approx 14$$

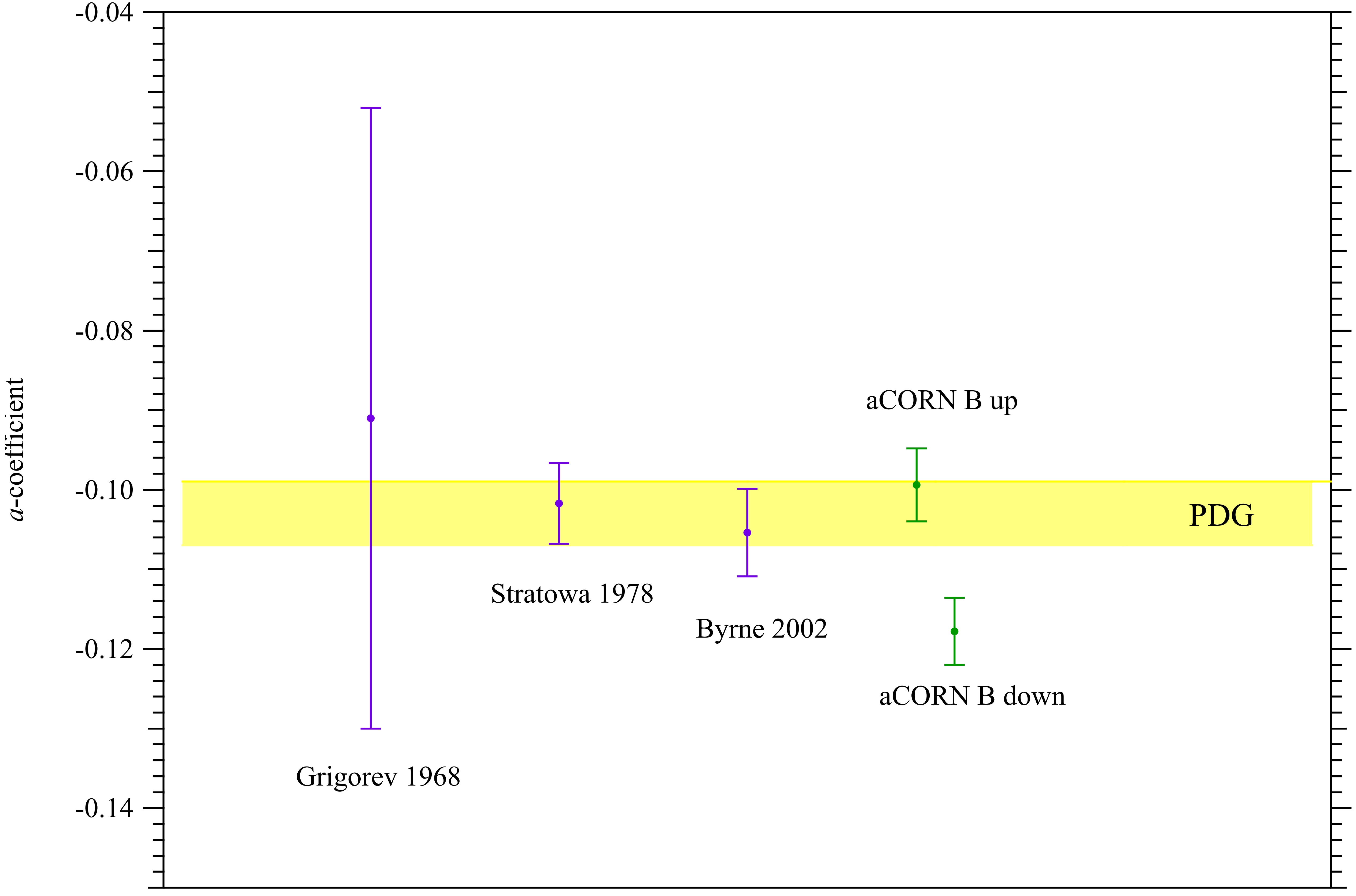


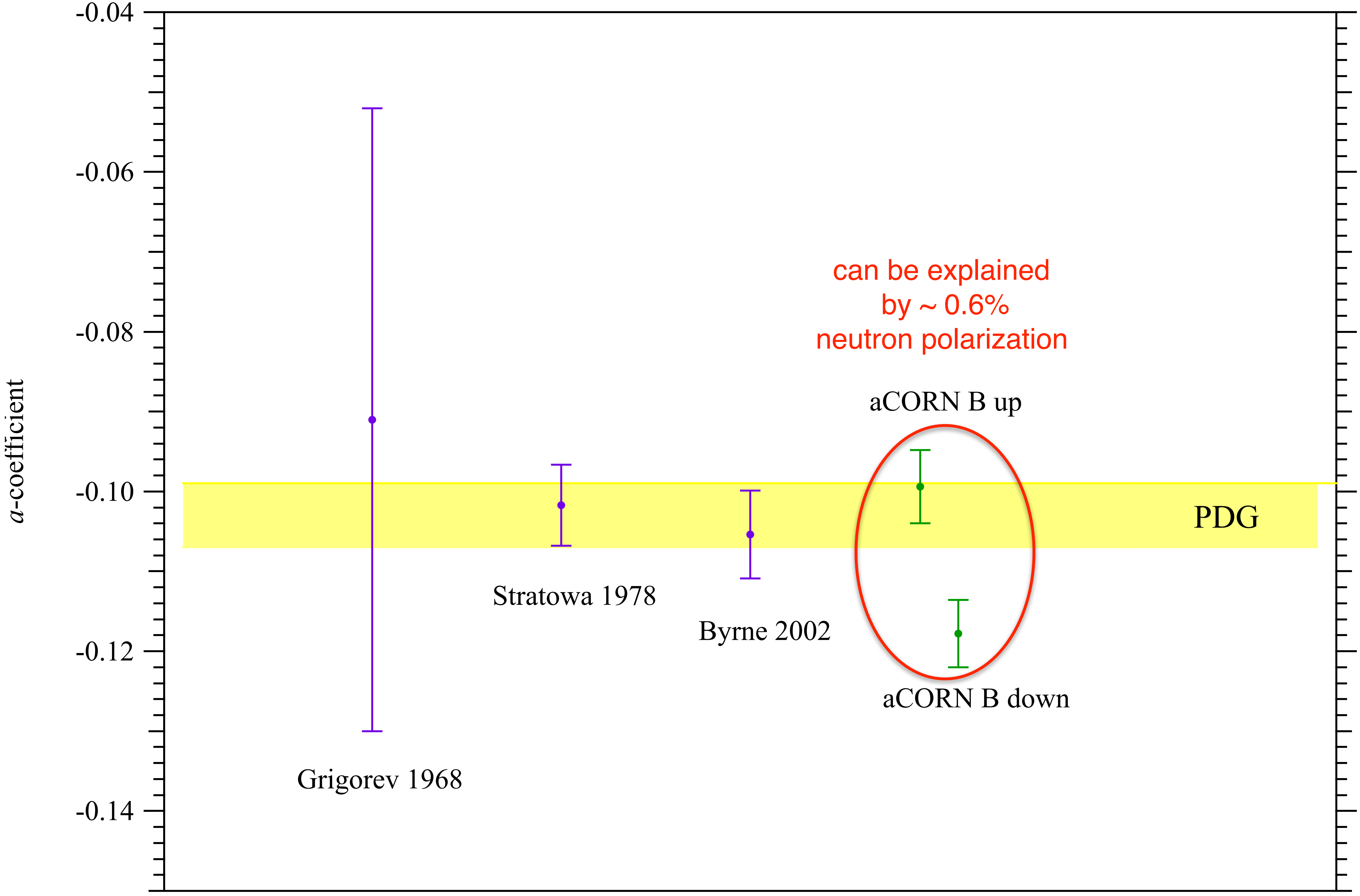
Ratio of X(E) / f_a(E)



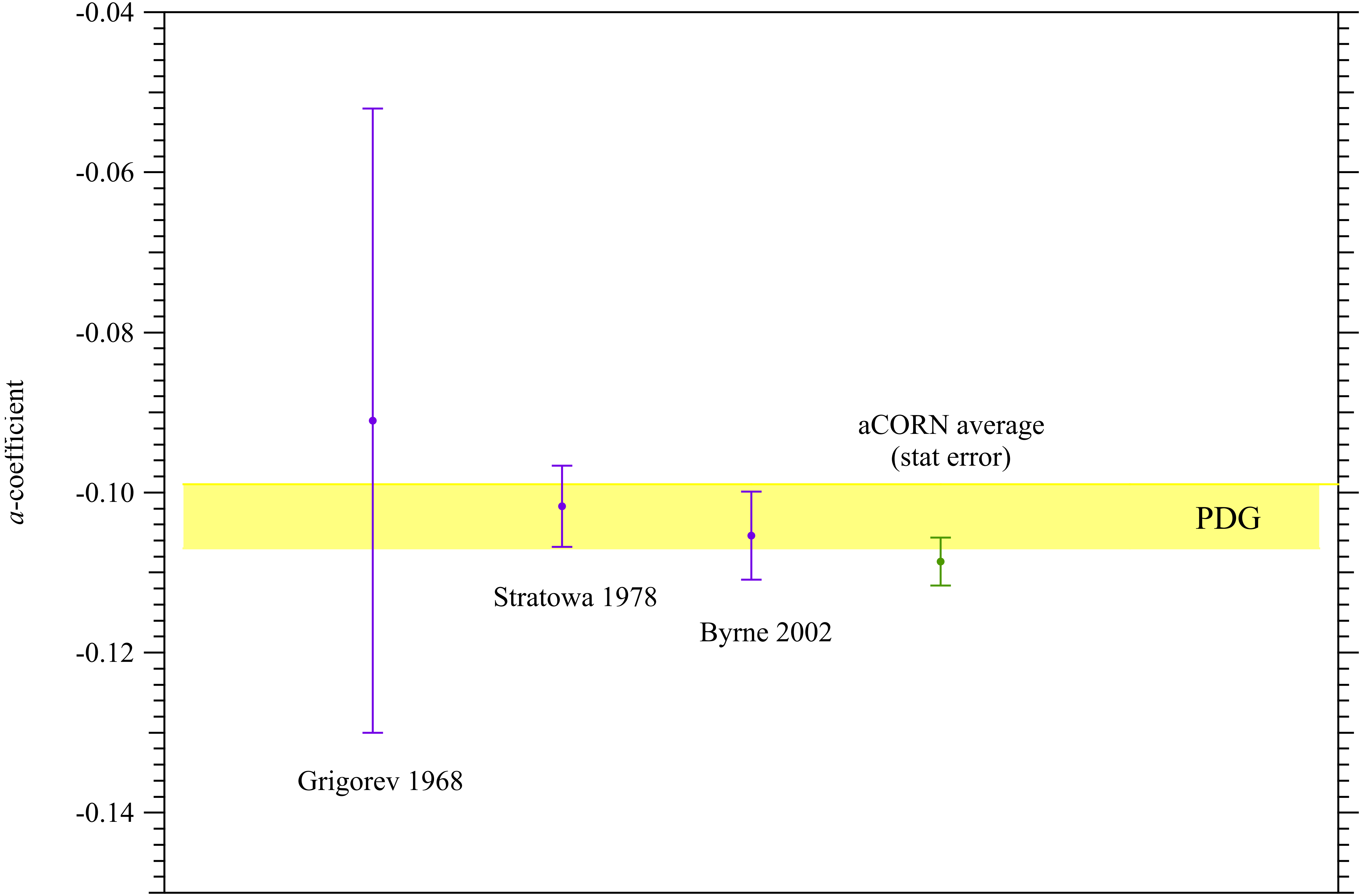
Ratio of X(E) / f_a(E)

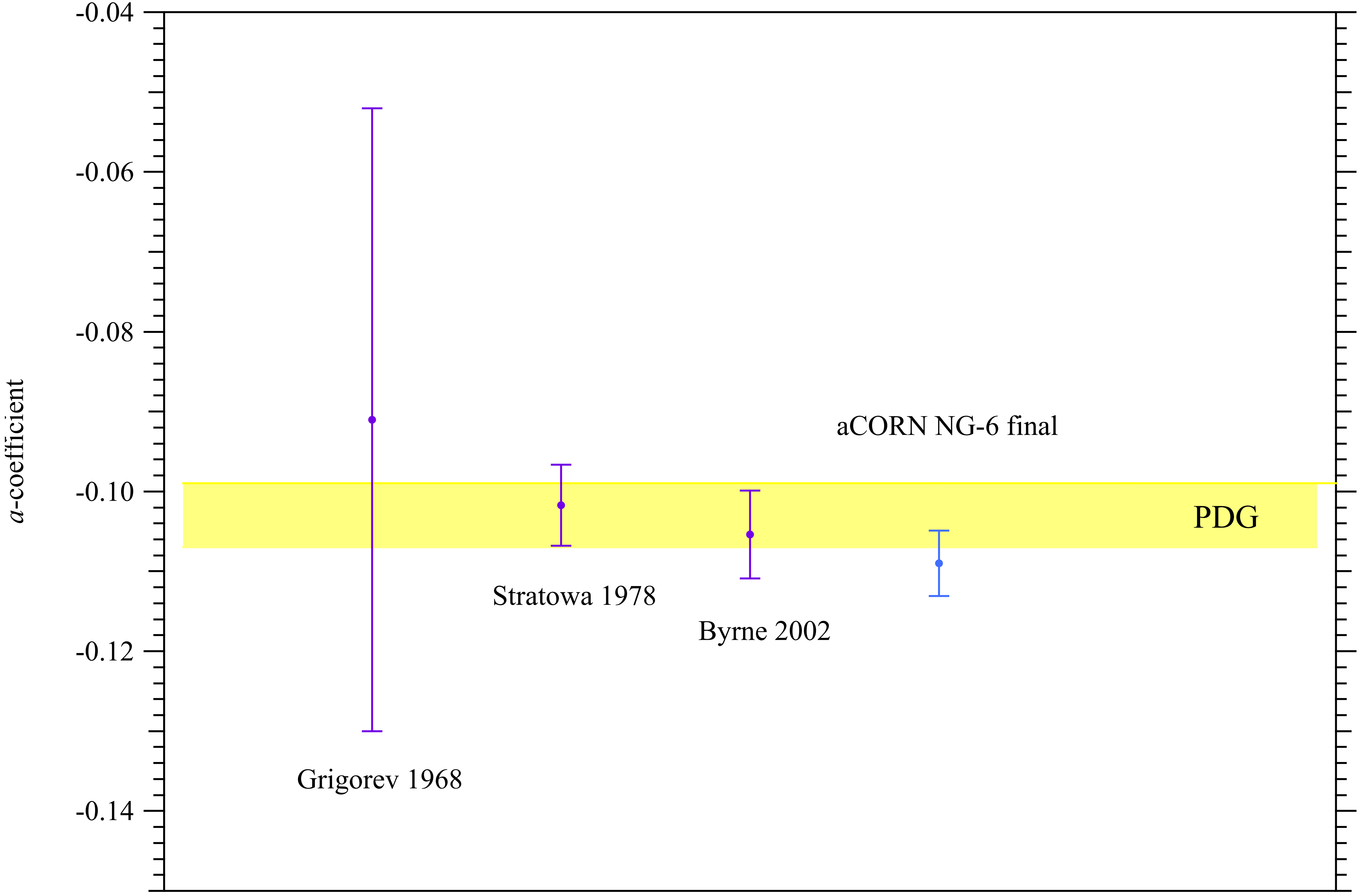



-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
a-coefficient
aCORN B up
PDG
Stratowa 1978
Byrne 2002
aCORN B down
Grigorev 1968



-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
a-coefficient
can be explained
by ~ 0.6%
neutron polarization
aCORN B up
PDG
Stratowa 1978
Byrne 2002
aCORN B down
Grigorev 1968


-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
a-coefficient
aCORN average
(stat error)
PDG
Stratowa 1978
Byrne 2002
Grigorev 1968


-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
a-coefficient
aCORN NG-6 final
PDG
Stratowa 1978
Byrne 2002
Grigorev 1968

aCORN NG-6 Result

	correction	$1\ \sigma$ uncert.	relative
electrostatic mirror	0.00571	0.00114	0.0105
proton threshold	-0.00318	0.00076	0.0070
energy loss in grid	-0.00111	0.00022	0.0020
absolute B field	-0.00010	0.00050	0.0046
B field shape	0.00031	0.00082	0.0075
residual gas	0.00046	0.00046	0.0042
e scattering	-0.00153	0.00153	0.0140
beta energy calibration		0.00031	0.0028
proton collimator align.		0.00050	0.0046
p scattering	0.00041	0.00050	0.0046
p focusing	0.00010	0.00010	0.0009
wishbone asymmetry		0.00100	0.0091
beam polarization		0.00102	0.0094
total systematic	0.00107	0.00283	0.0260
statistical		0.00302	0.0277
total uncertainty		0.00414	0.0380

aCORN NG-6 Result

	correction	1 σ uncert.	relative
electrostatic mirror	0.00571	0.00114	0.0105
proton threshold	-0.00318	0.00076	0.0070
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absolute B field	-0.00010	0.00050	0.0046
B field shape	0.00031	0.00082	0.0075
residual gas	0.00046	0.00046	0.0042
e scattering	-0.00153	0.00153	0.0140
beta energy calibration		0.00031	0.0028
proton collimator align.		0.00050	0.0046
p scattering	0.00041	0.00050	0.0046
p focusing	0.00010	0.00010	0.0009
wishbone asymmetry		0.00100	0.0091
beam polarization		0.00102	0.0094
total systematic	0.00107	0.00283	0.0260
statistical		0.00302	0.0277
total uncertainty		0.00414	0.0380

$$a = -0.1090 \pm 0.0030\ (\text{stat}) \pm 0.0028\ (\text{sys})$$

G. Darius, *et al.* Phys. Rev. Lett. **119**, 042502 (2017)

aCORN on new NG-C beamline

- aCORN moved to new NG-C end position at NIST in 2015
- Ran on NG-C from July 2015 - September 2016
- ~ 5x wishbone event rate, signal/bkgd similar to NG-6
- Collected a good data set ~10 times NG-6
- Improved systematics
- Analysis in progress
- We expect a new result with relative uncertainty < 2%

aCORN B

Neutron Decay Parameters

Phenomenological (J = 1/2 → J = 1/2) beta decay formula [Jackson, Treiman, Wyld, 1957] :

$$dW \propto \frac{1}{\tau} F(E_e)\left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + D\frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)}{E_e E_\nu} \right]$$

For allowed beta decay, neglecting recoil order terms, the standard electroweak model (Weinberg, Glashow, Salam, et al.) predicts:

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \qquad b = 0 \qquad A = -2\frac{\lambda^2 + \mathrm{Re}(\lambda)}{1+3\lambda^2} \qquad B = 2\frac{\lambda^2 - \mathrm{Re}(\lambda)}{1+3\lambda^2}$$

$$D = 2\frac{\mathrm{Im}(\lambda)}{1+3\lambda^2} \approx 0 \qquad \tau \propto \frac{1}{g_v^2 + 3g_A^2}$$

where $\lambda \equiv \frac{g_A}{g_V}$

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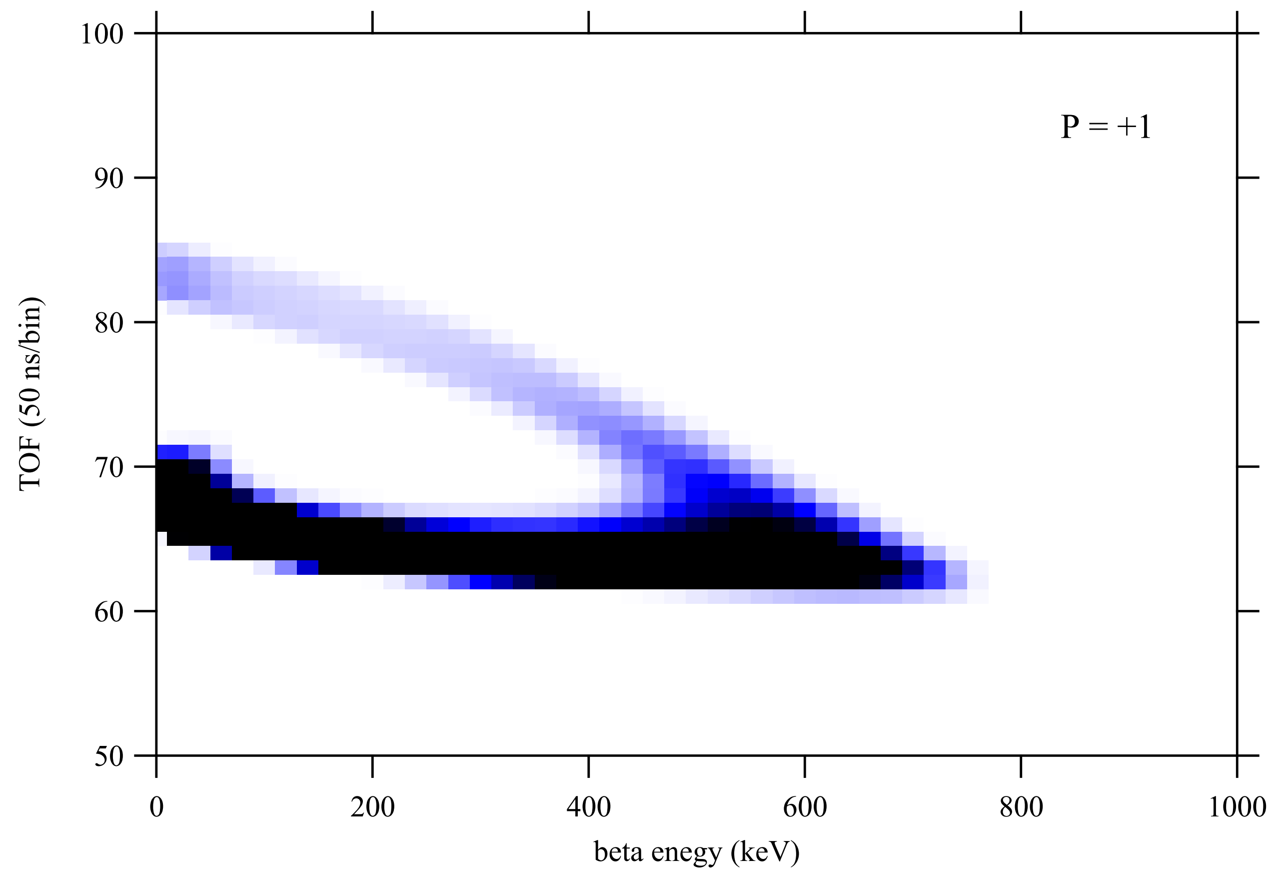
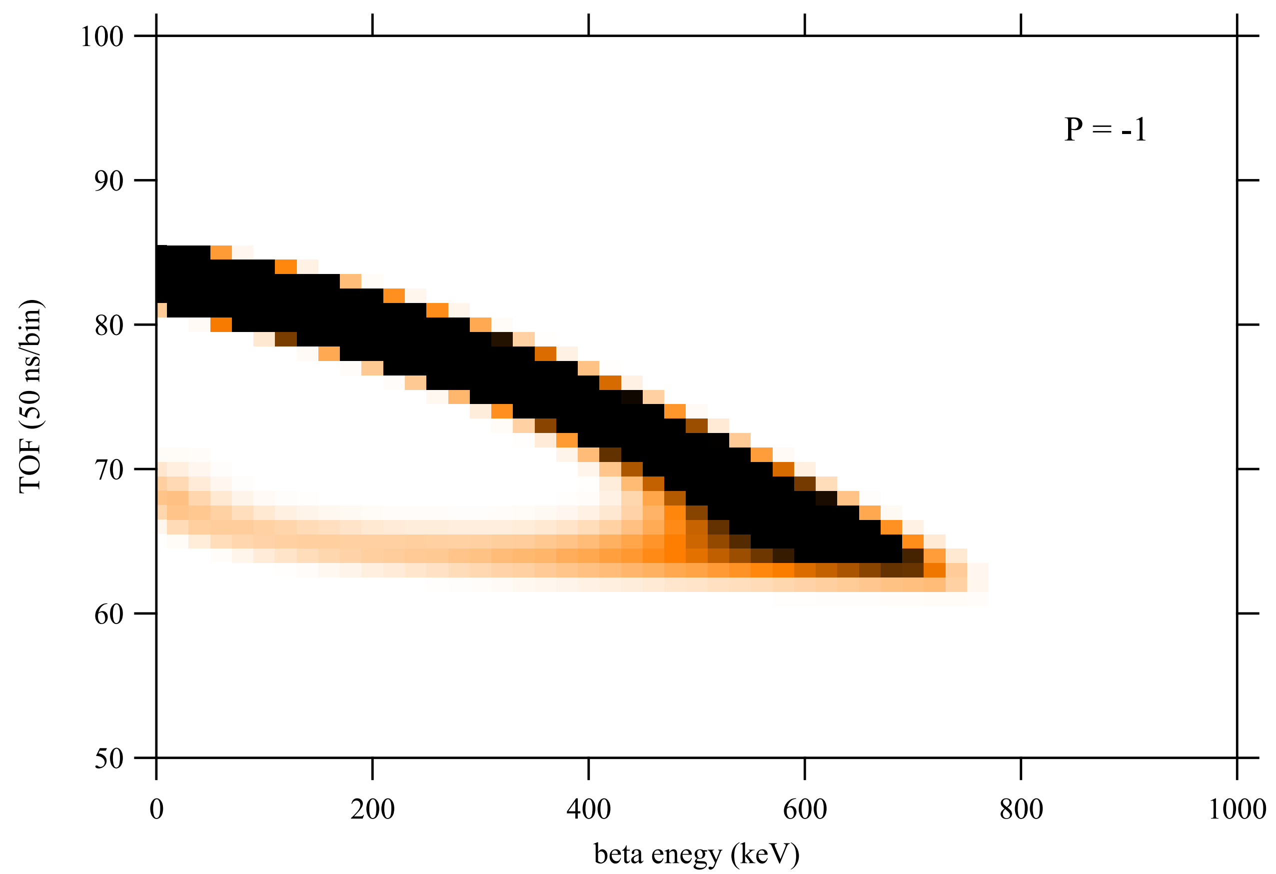
of these correlation coefficients, B has the least sensitivity to λ but the most sensitivity to possible right-handed currents

Monte Carlo:



measure both flip states:

$$\frac{A_{wb}^{+} - A_{wb}^{-}}{2} = PBf_B(E_\beta)$$



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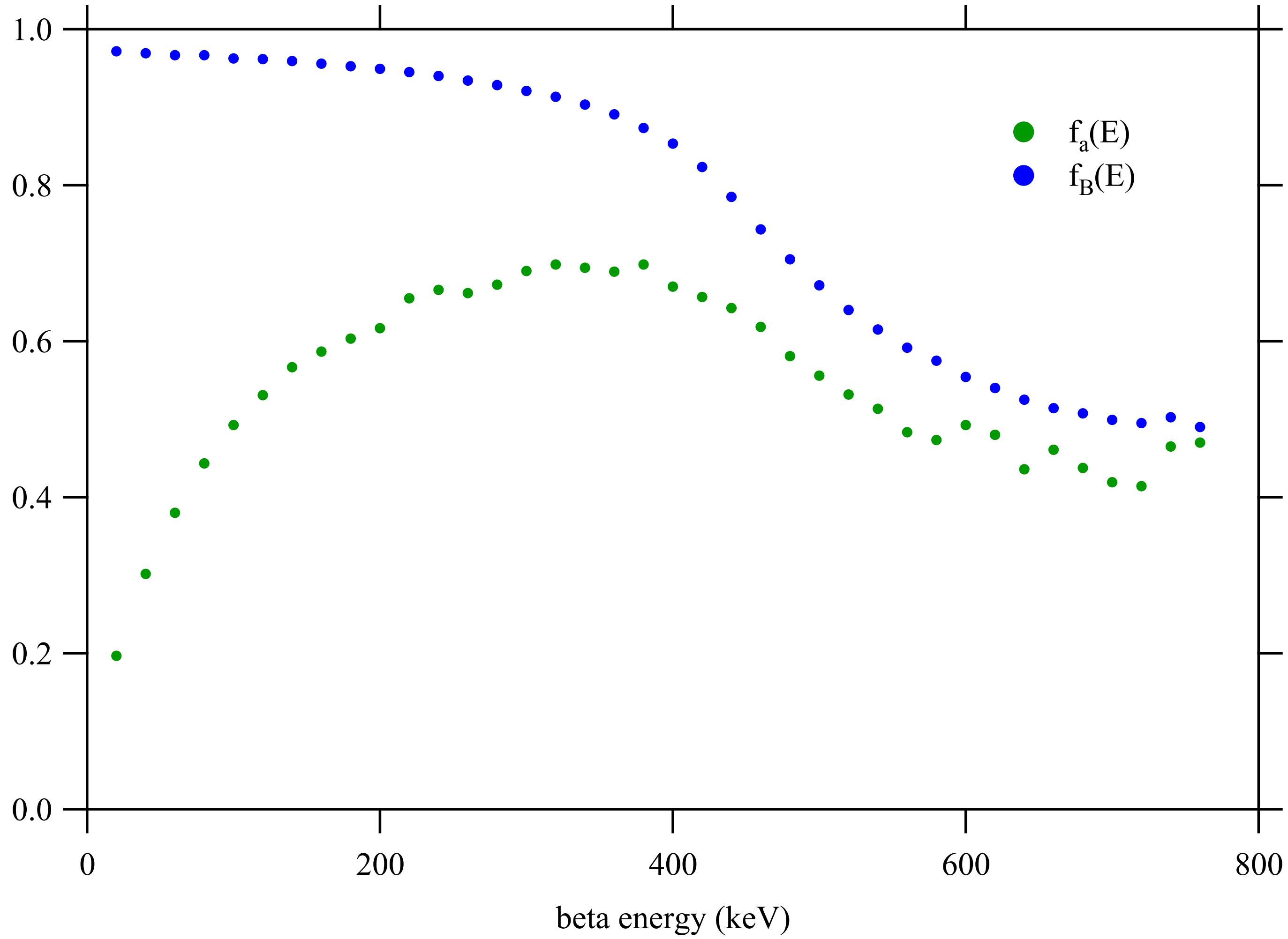

Statistics estimate:

- assume factor 10 lower neutron flux (XSM polarizer, collimation)
- 150 beam days (~1 year) → 1% little "a"
- 14x larger asymmetry signal
- assume S/B same as aCORN

$$\frac{\sigma_B}{B} \approx \frac{\sqrt{10}}{14}(1\%) = 0.0023 \text{ (stat)}$$

aCORN

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