Precision Measurement of the Radiative Decay Mode of the Free Neutron

Benjamin O'Neill

PhD Defense
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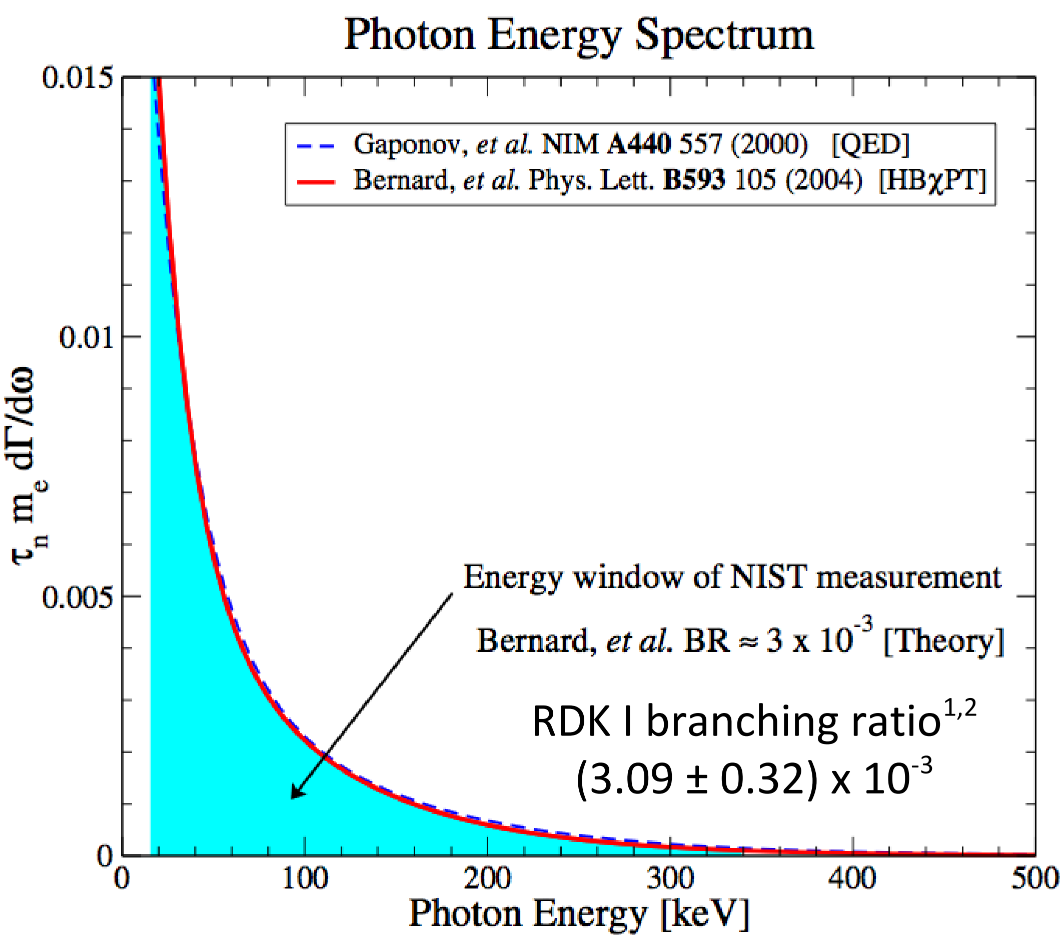
Motivation

- Neutron discovered in 1932 by James Chadwick
- Shortly thereafter discovered to be unstable
  - $n \rightarrow p^{+} + e^{-} + \bar{\nu}_{e}$
- Classical EM and QED predict radiative decay
- Leading order calculations can be done in QED
- Observed in nuclear beta decay as early as 1953
- First observed in free neutrons in 2005

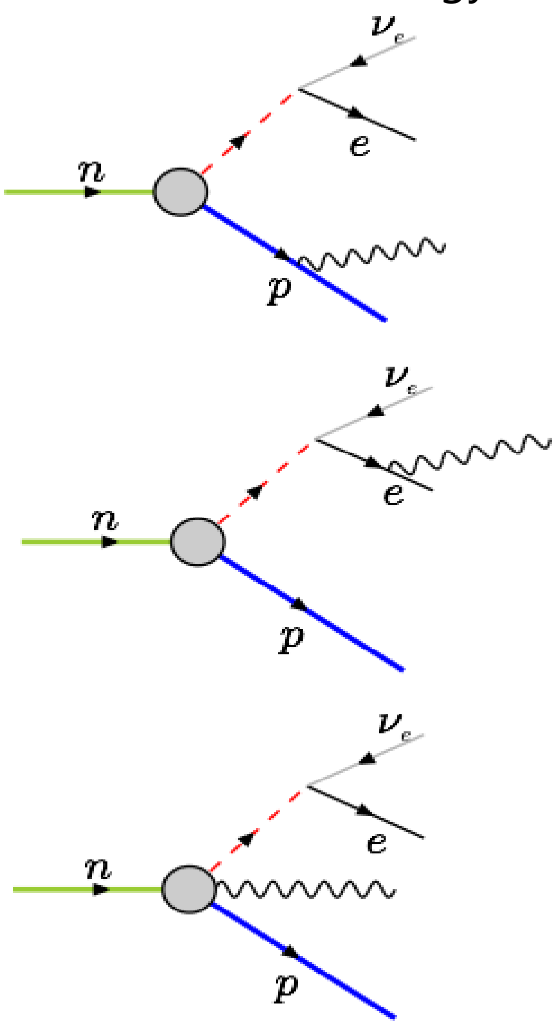
Motivation



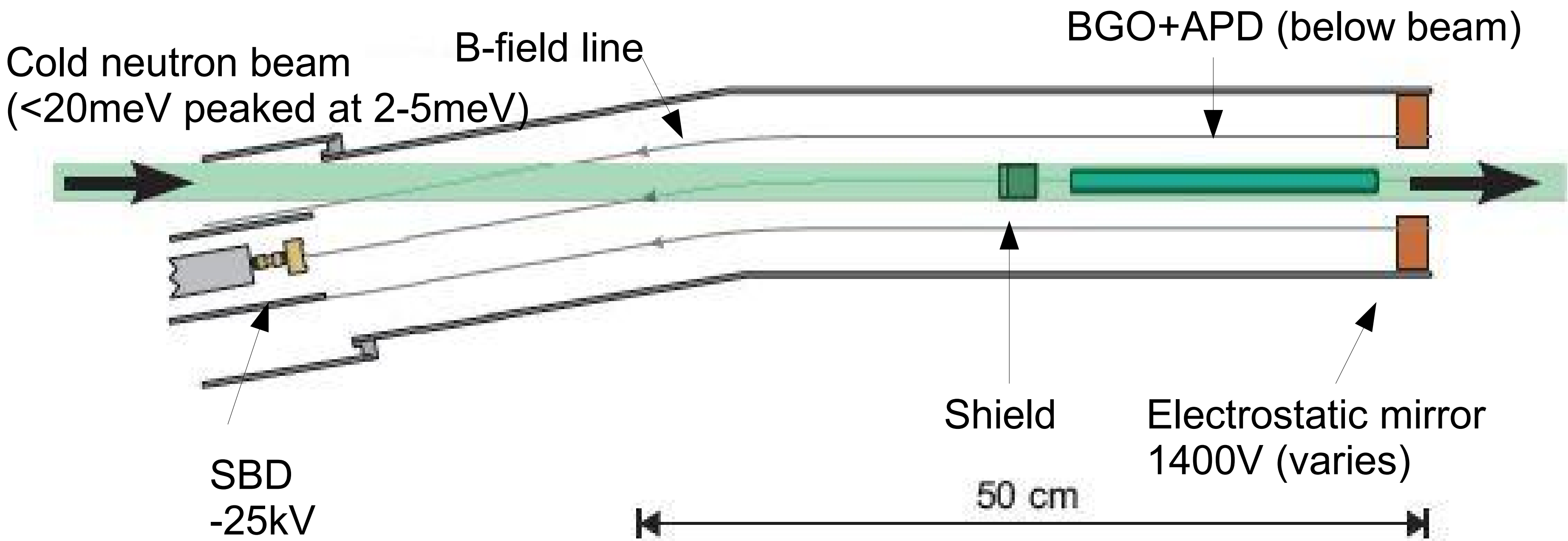
[1]Nico, J. S. *et al. Nature* 444, 1059–1062 (2006)
[2]Cooper, R. L. *et al.* PRC 81, 035503 (2010)

$n \rightarrow p^{+} + e^{-} + \bar{\nu}_e + \gamma$

782 keV free energy

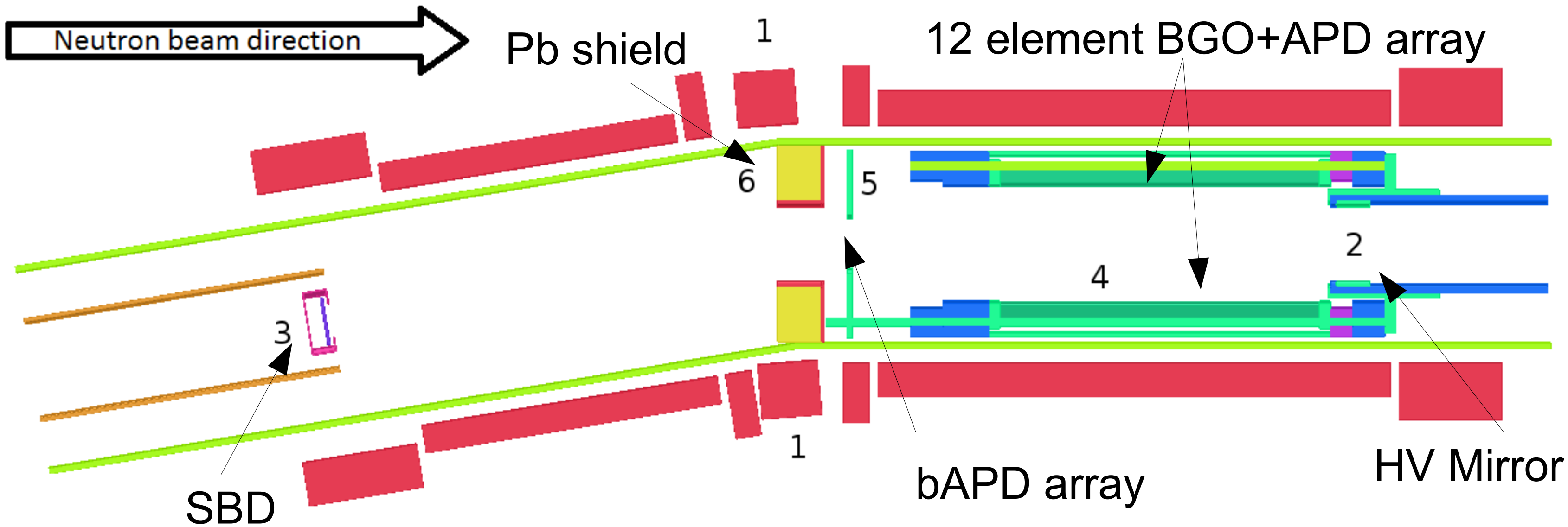


First Observation: RDK I



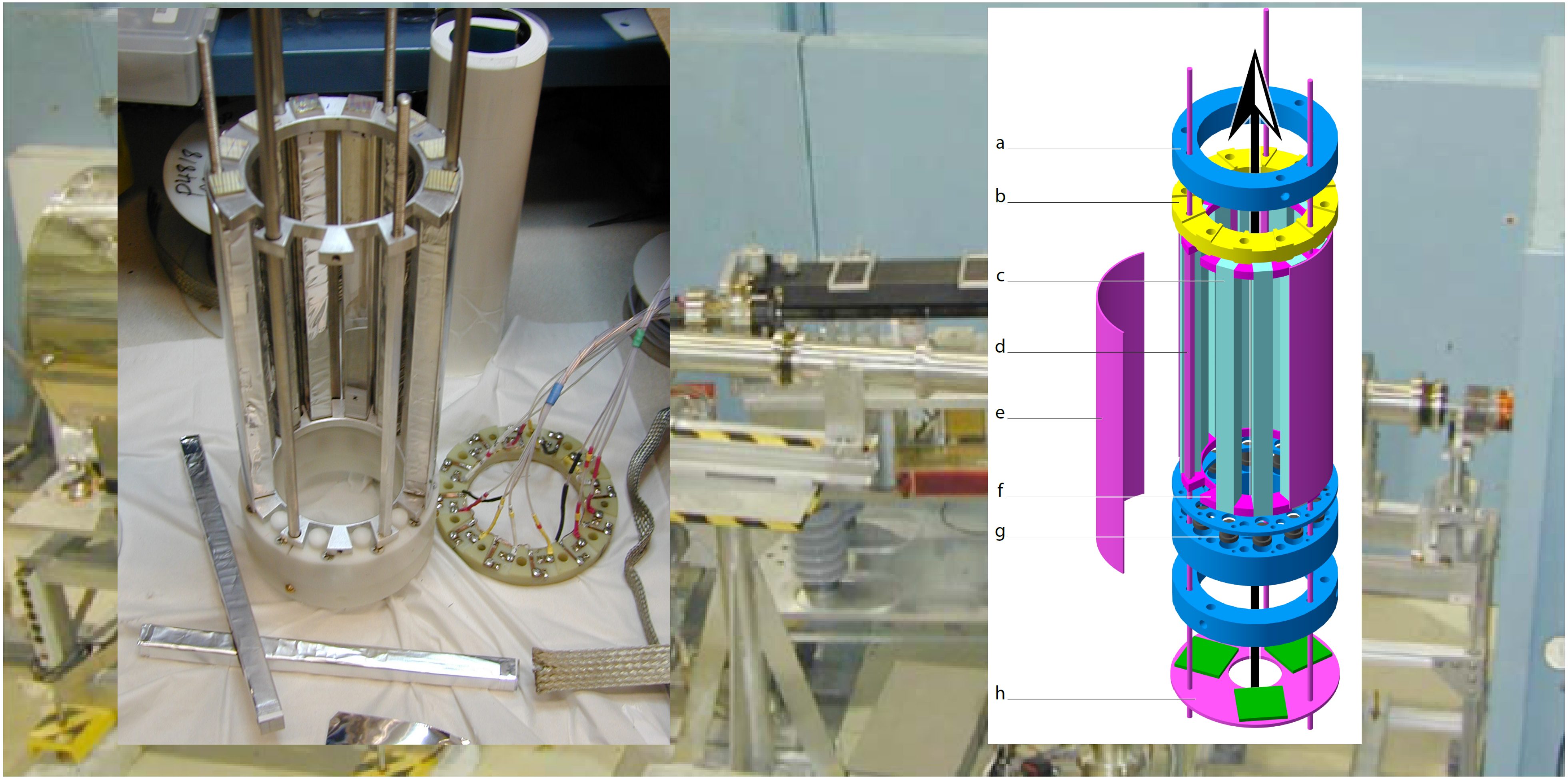
- Nico et al., National Institute of Standards and Technology (NIST) 2005
- Branching ratio for 15-340keV = $(3.09 \pm 0.32) \cdot 10^{-3}$
- 4.6T superconducting magnet
- 9.5^{o} bend

RDK II Experimental Setup

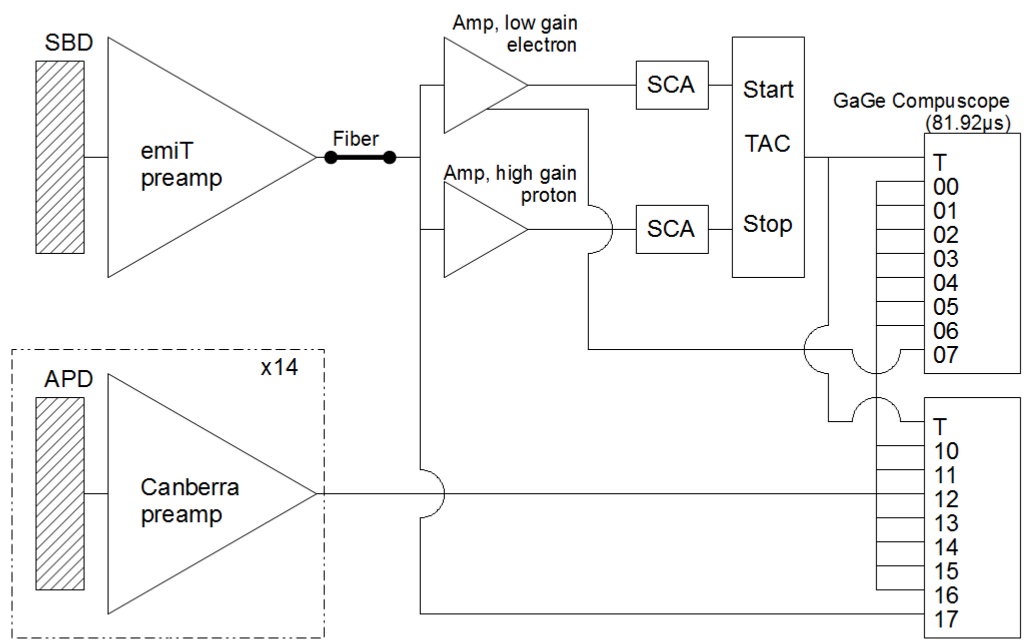


- Improve accuracy to *O*(1%) on BR
- New detectors
  - 12 BGO+APD
  - 3 bAPD (installed later)
- Expanded energy range
  - BGO: <10keV to endpoint
  - bAPD: <1keV to ≈10keV
- Improved statistics: 0.6% for BGO, 2.9% for bAPD

RDK II Experimental Setup

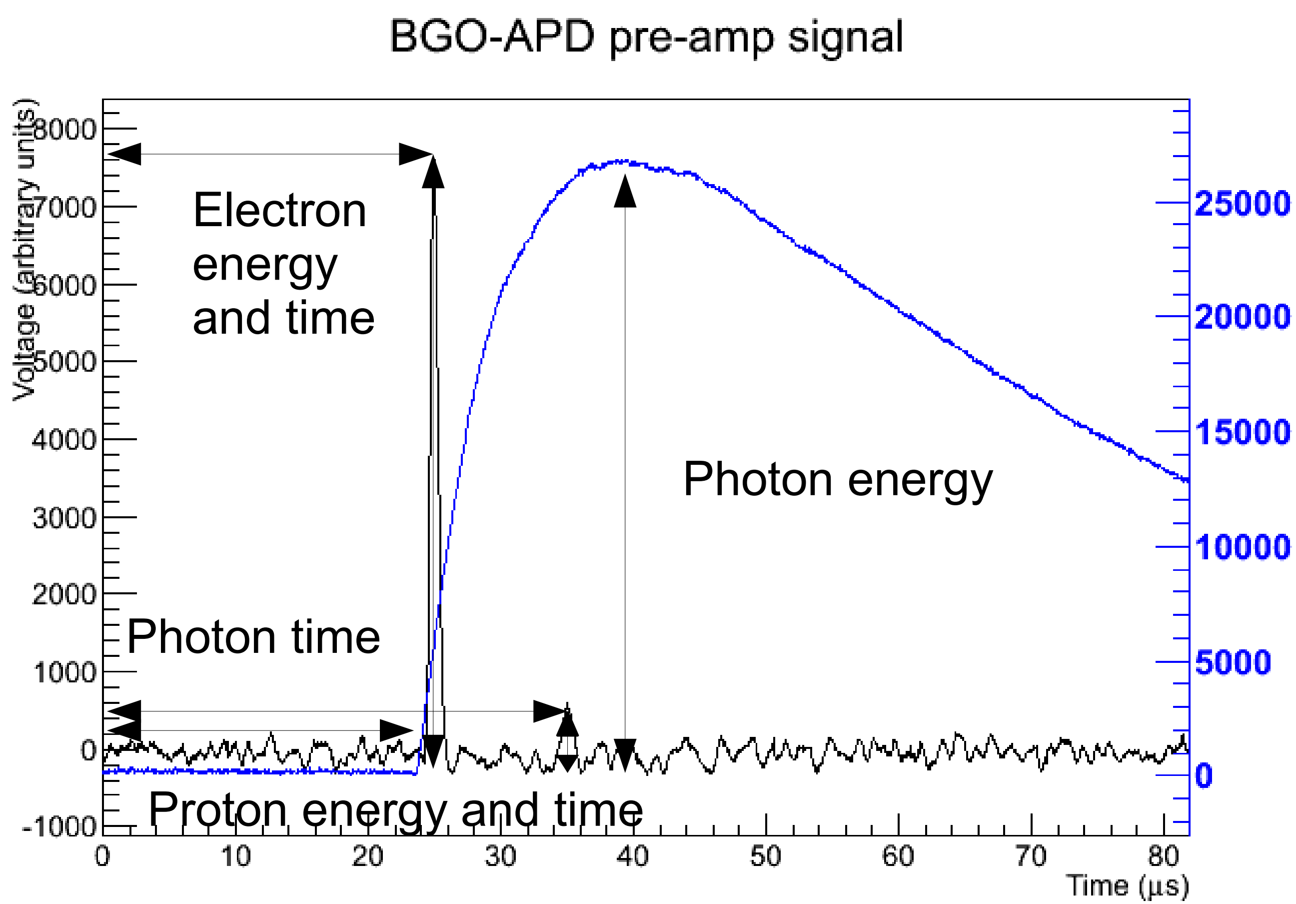


RDK II Data Acquisition



- Electron start, proton stop trigger
- SBD electrically isolated
- Waveforms recorded
  - Less hardware noise
  - Distinguish false triggers
  - Check on hardware

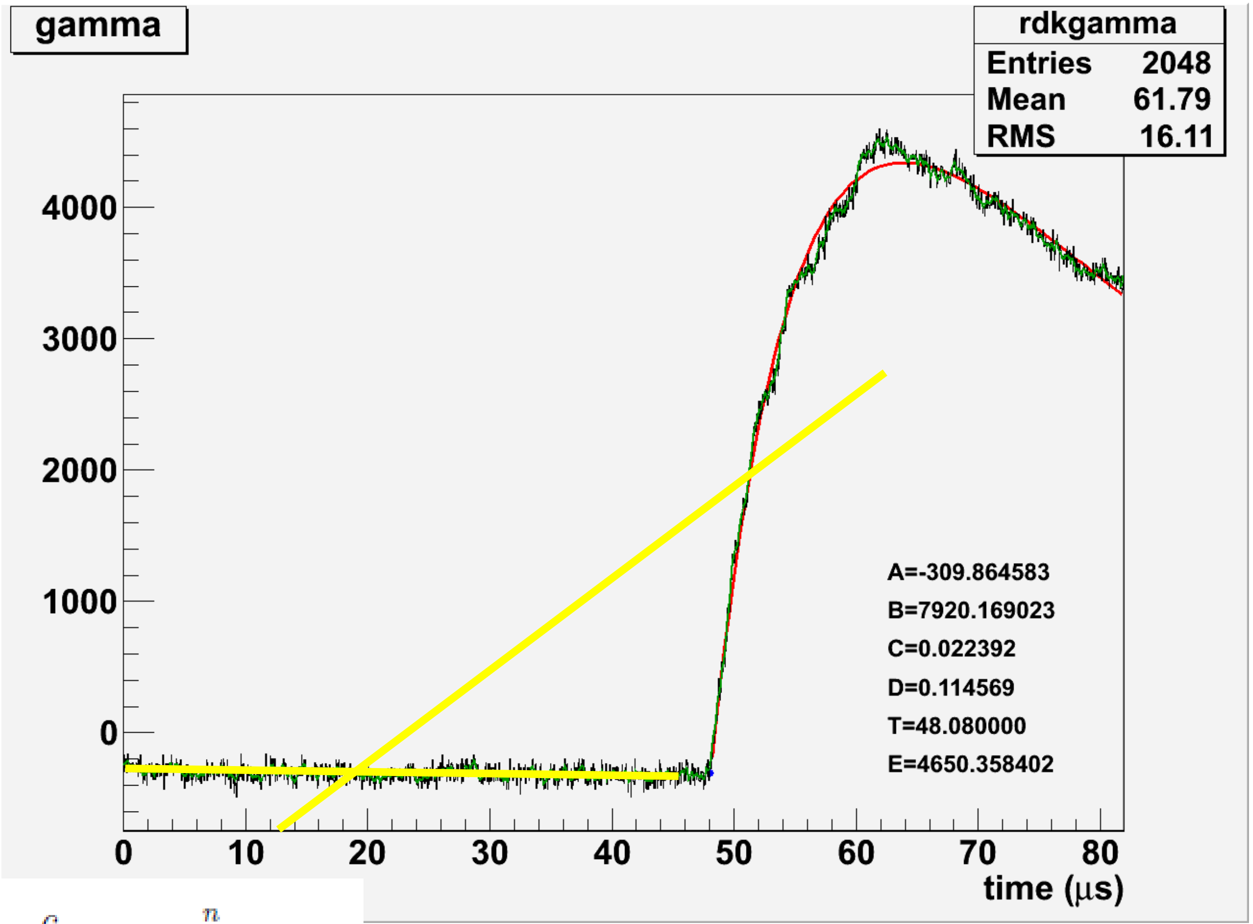
RDK II Signal



RDK II Signal Analysis

- Two independently developed algorithms – Jeff Nico at NIST
- Criteria
  - Peak height at least 300 units above minimum
  - Peak precedes the minimum – no trailing edges
  - Peak not at edges of trace window – full signal trace
  - Peak is below 30000 units – saturation level
  - No spikes – some pathological signals
- Baseline
- Smooth
- Determine energy and time

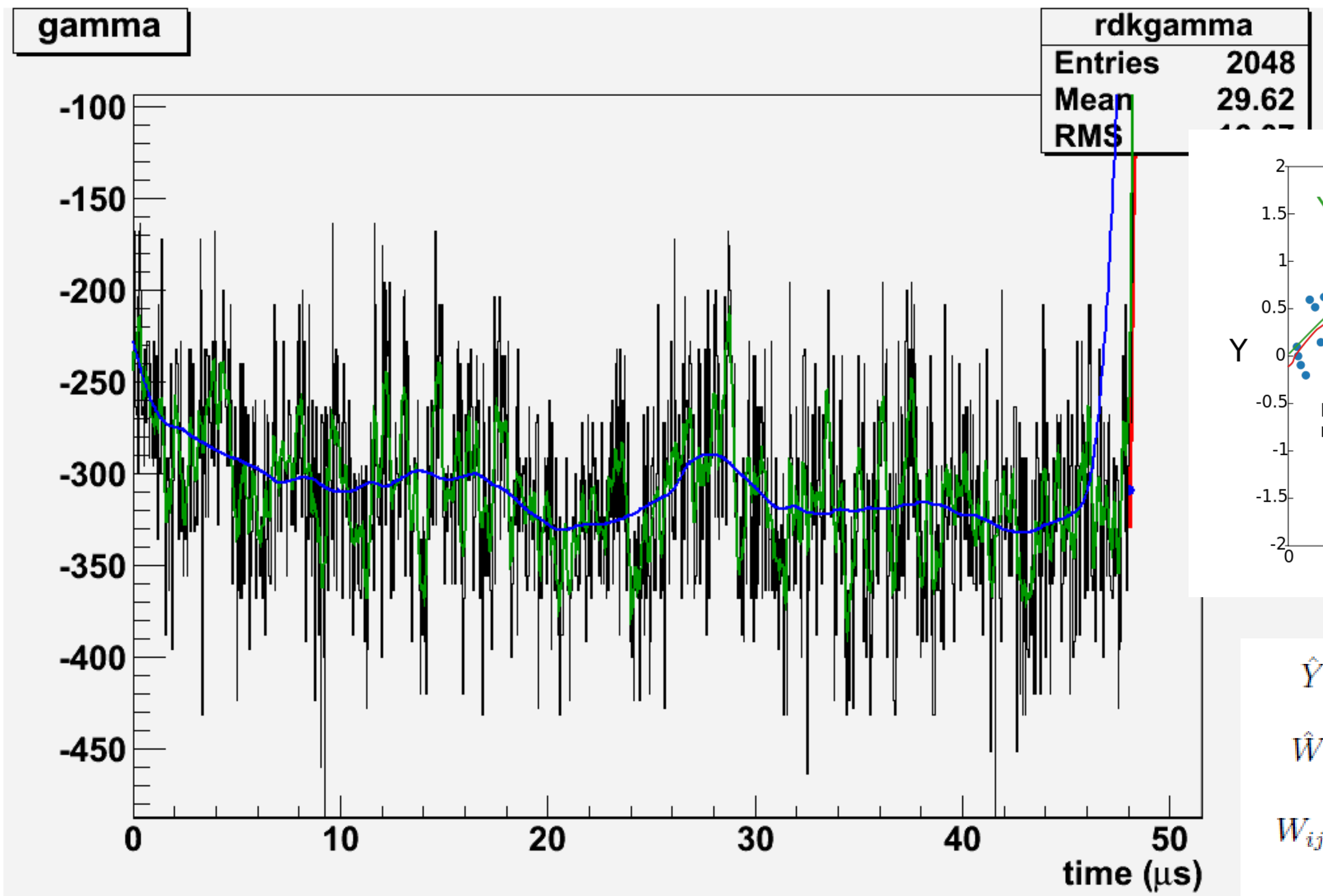
RDK II Signal Analysis

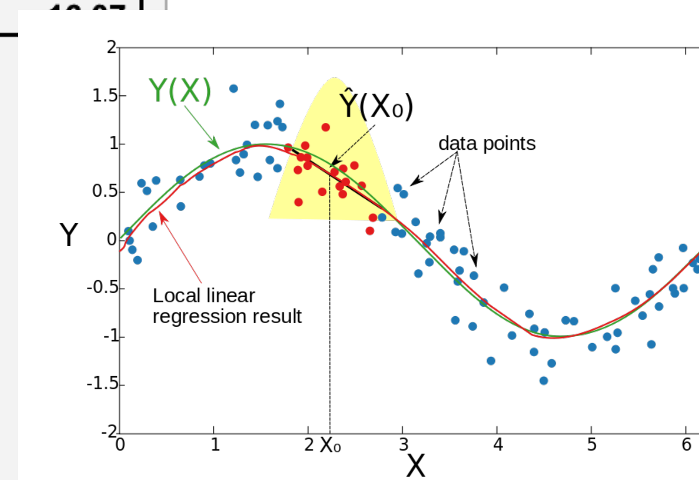


$$\hat{\beta}_0 = \frac{2\left(2n+1\right)}{\left(n+1\right)\left(n+2\right)}\sum_{i=0}^{n} Y_i - \frac{6}{\left(n+1\right)\left(n+2\right)}\sum_{i=0}^{n} iY_i$$

$$\hat{\beta}_1 = \frac{12}{n\left(n+1\right)\left(n+2\right)}\sum_{i=0}^{n} iY_i - \frac{6}{\left(n+1\right)\left(n+2\right)}\sum_{i=0}^{n} Y_i$$

RDK II Signal Analysis





$$\hat{Y}(x_0) = \hat{W}(x_0)\, y$$

$$\hat{W}(x_0) = \hat{x}_0 \left(X^T W(x_0) X\right)^{-1} X^T W(x_0)$$

$$W_{ij}(x_0) = \left(1 - \left|\frac{x_i - x_0}{r+1}\right|^p\right) \delta_{ij}$$

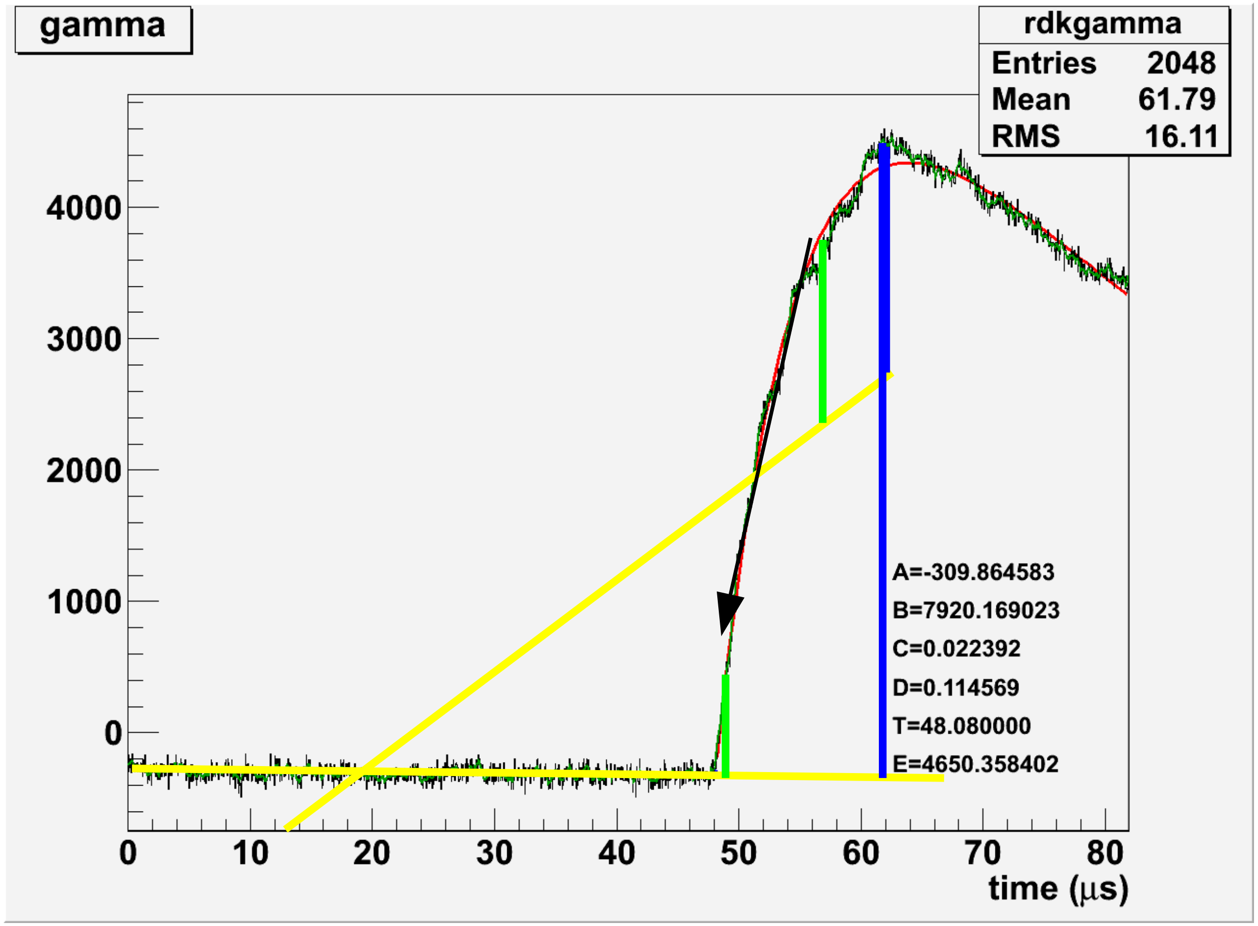
$$y^T = (x_{-r}, x_{-r+1}, \ldots, x_r)$$

$$(\hat{x}_0)_j = x_0^j = \delta_{0j}$$

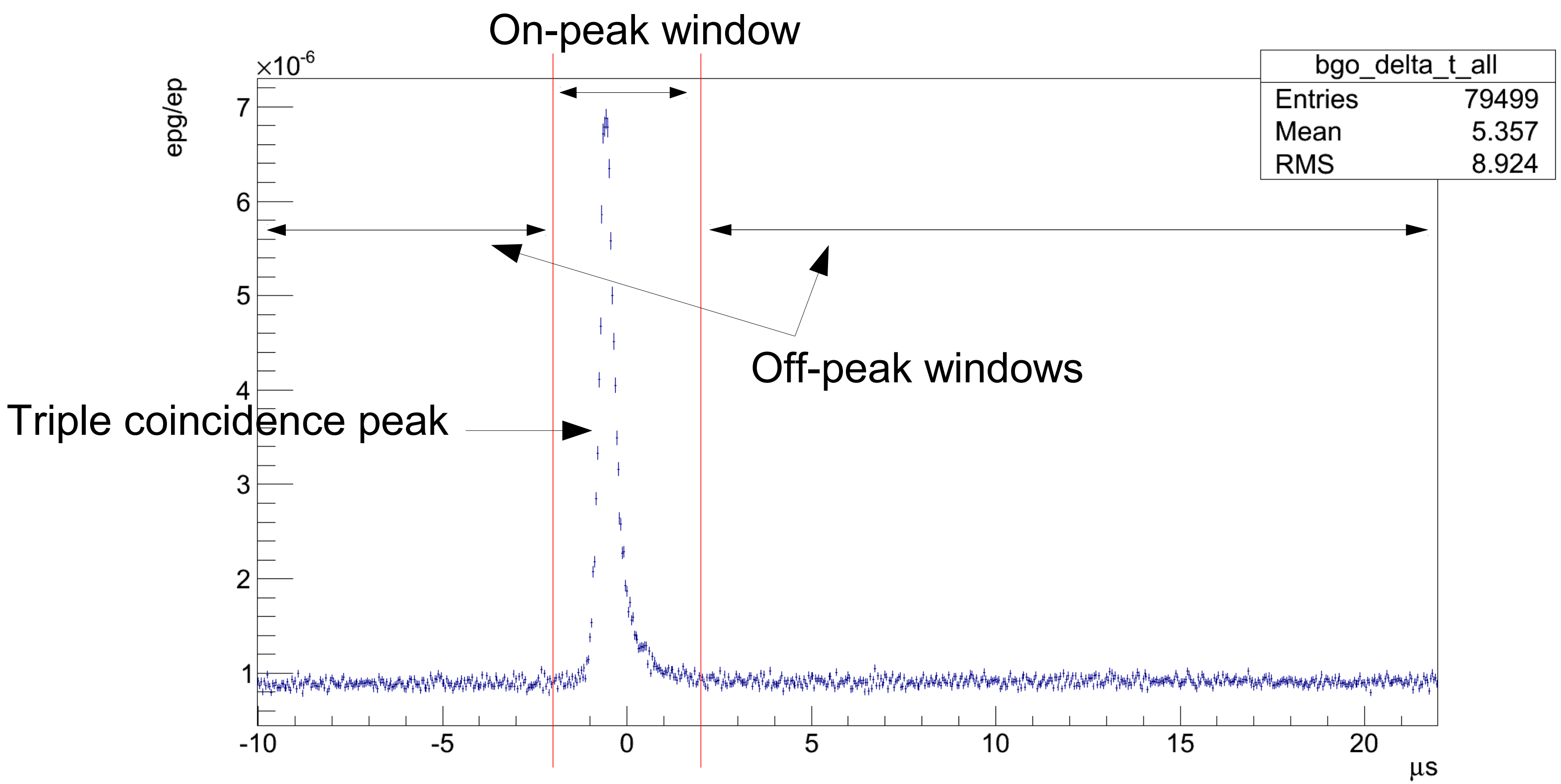
$$X_{ij} = x_i^j = i^j \qquad j \in [0, o]$$

Green – Narrow smoothing (timing)
Blue – Wide smoothing (energy)

RDK II Signal Analysis

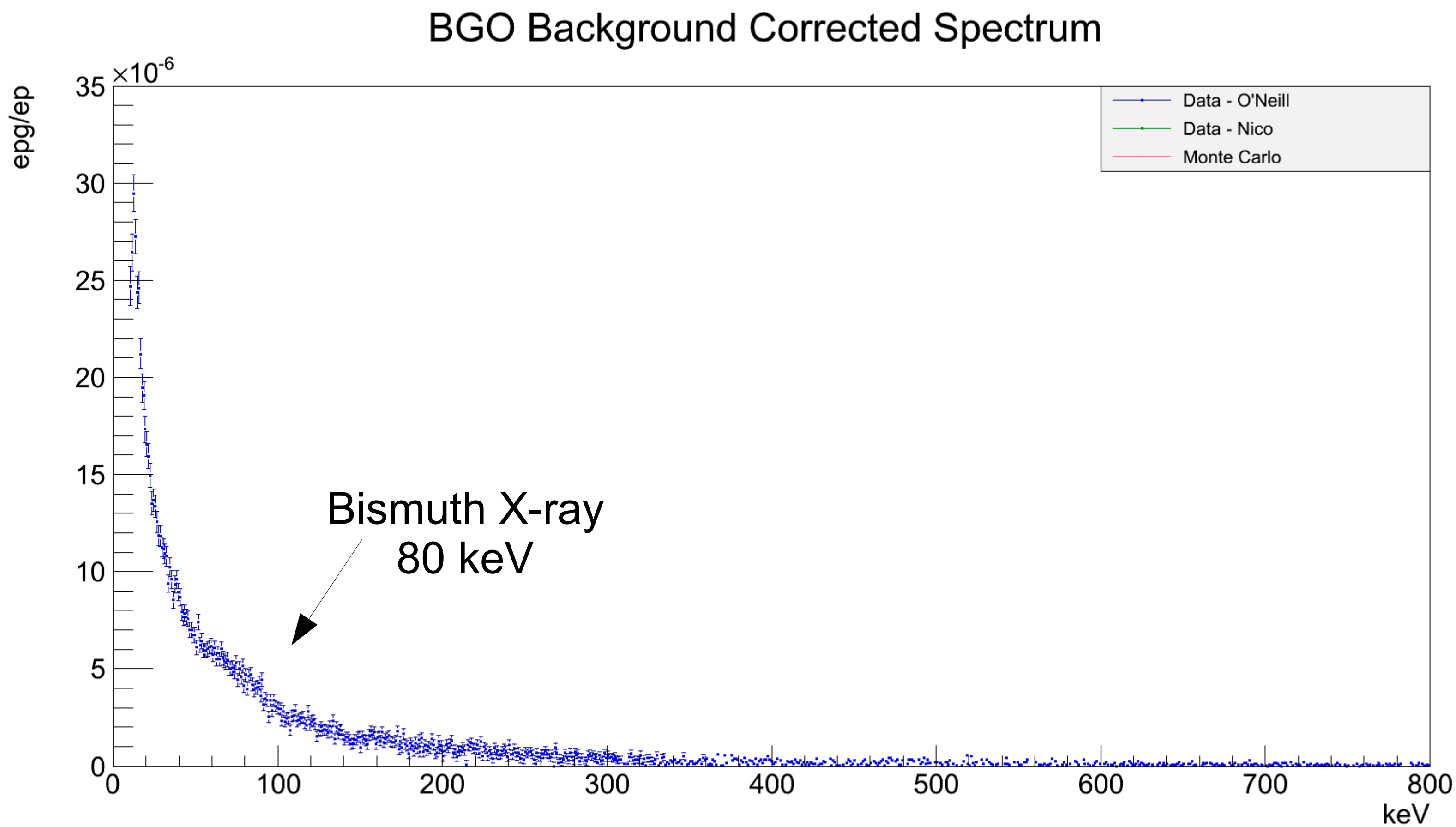


RDK II Current Results



Photon timing relative to electron
BGO

RDK II Current Results

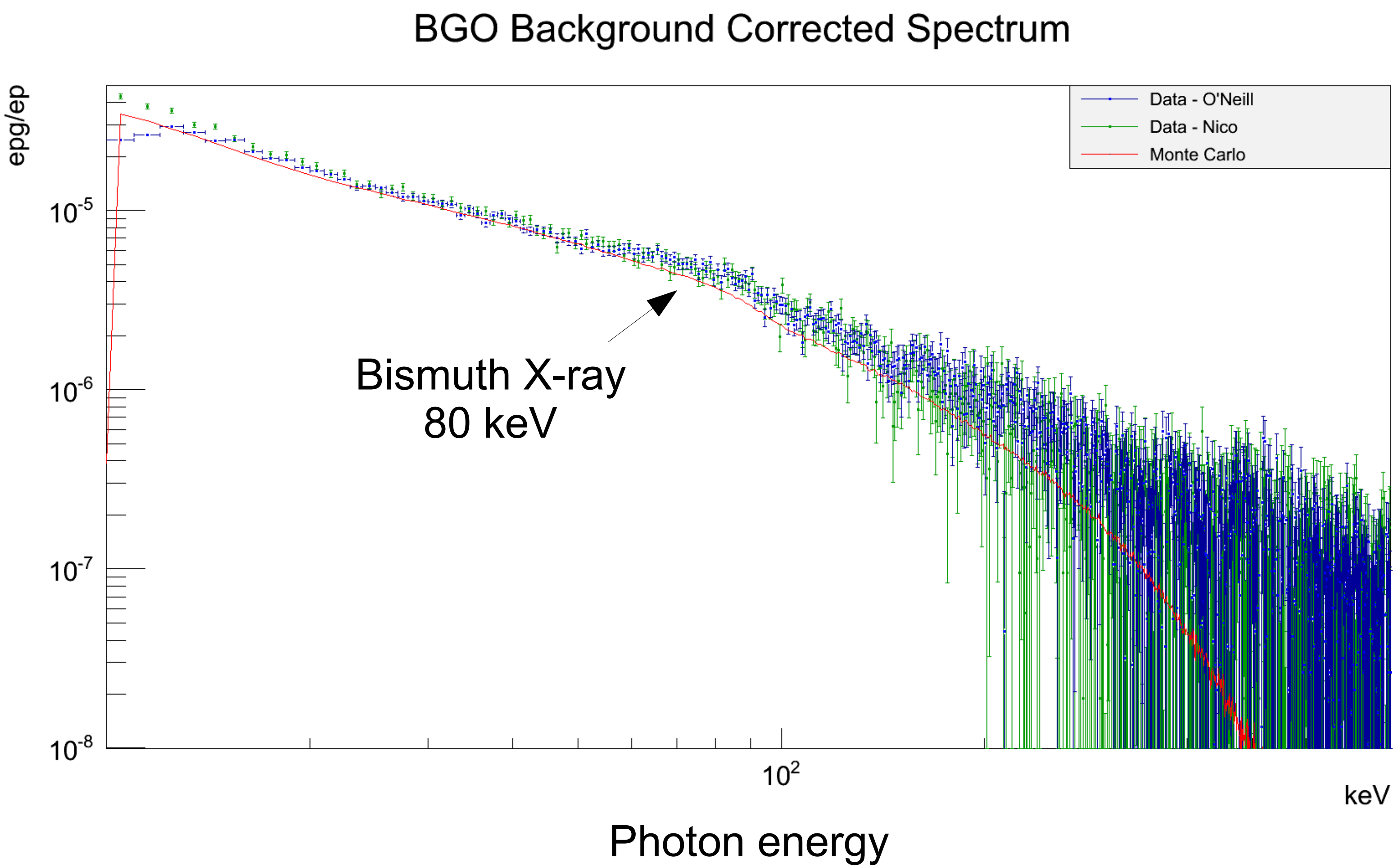


Photon energy

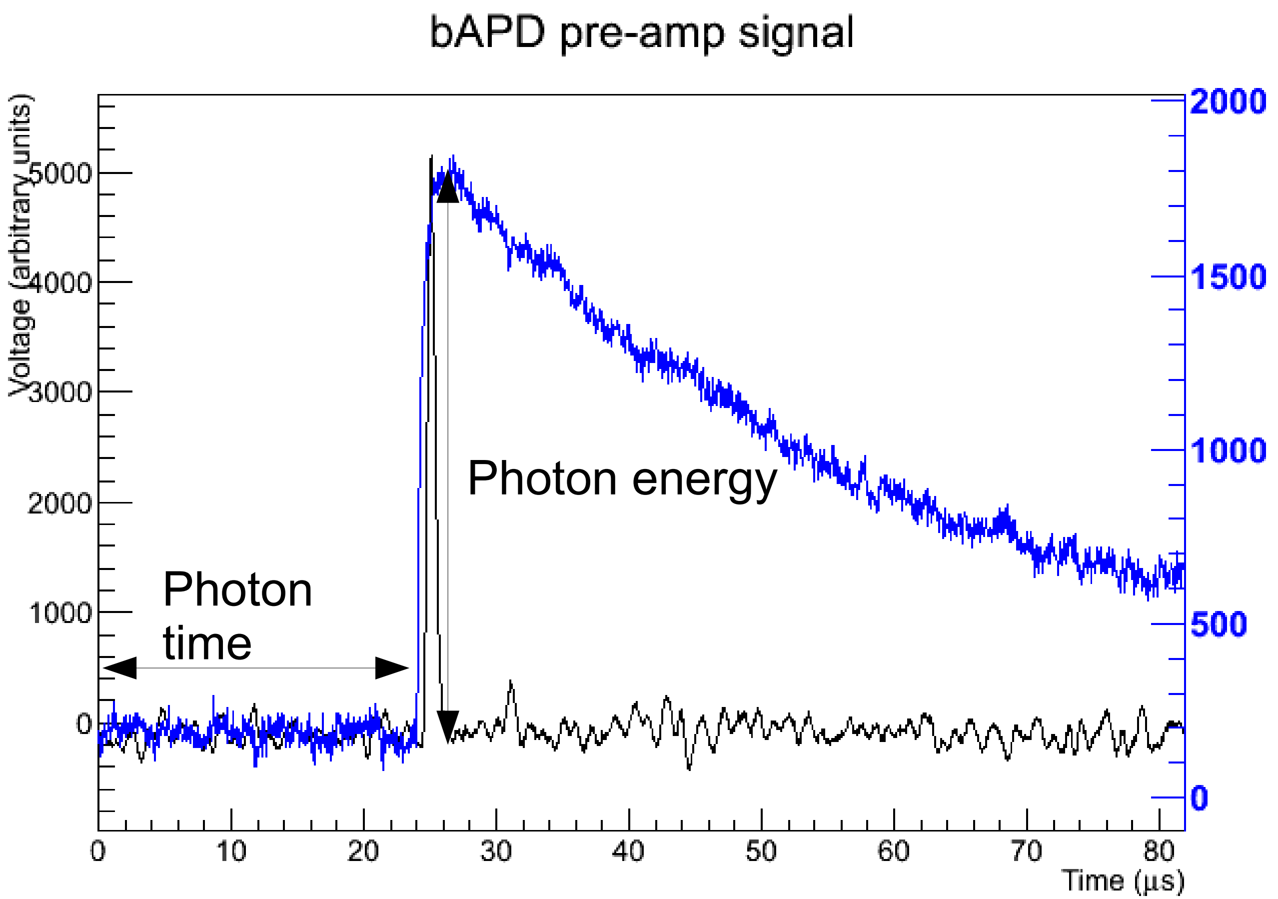
$R_{epg}/R_{ep}=(10.650\pm0.064)\cdot10^{-4}$

0.1% agreement between independent analyses

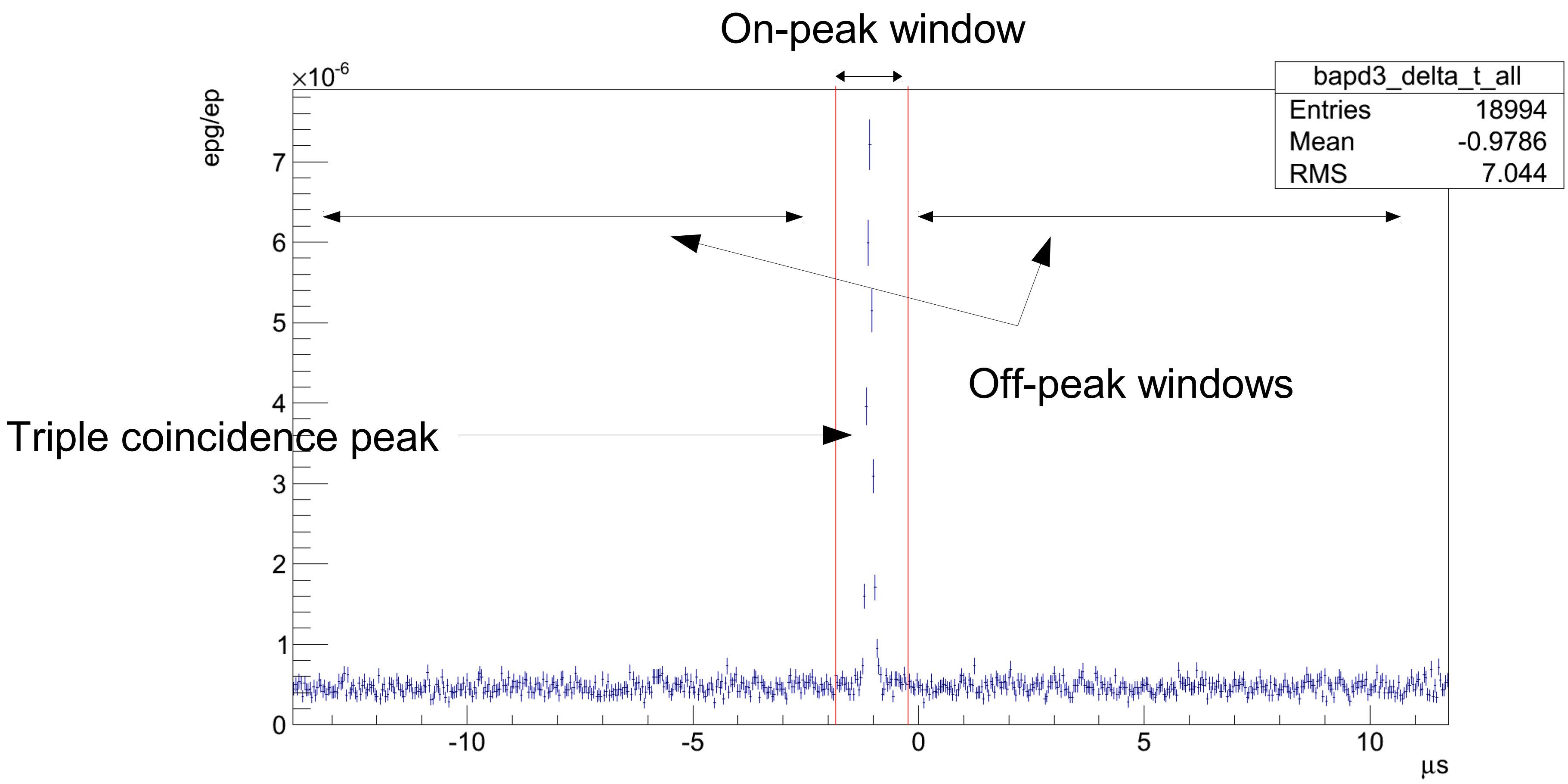
RDK II Current Results



RDK II Signal

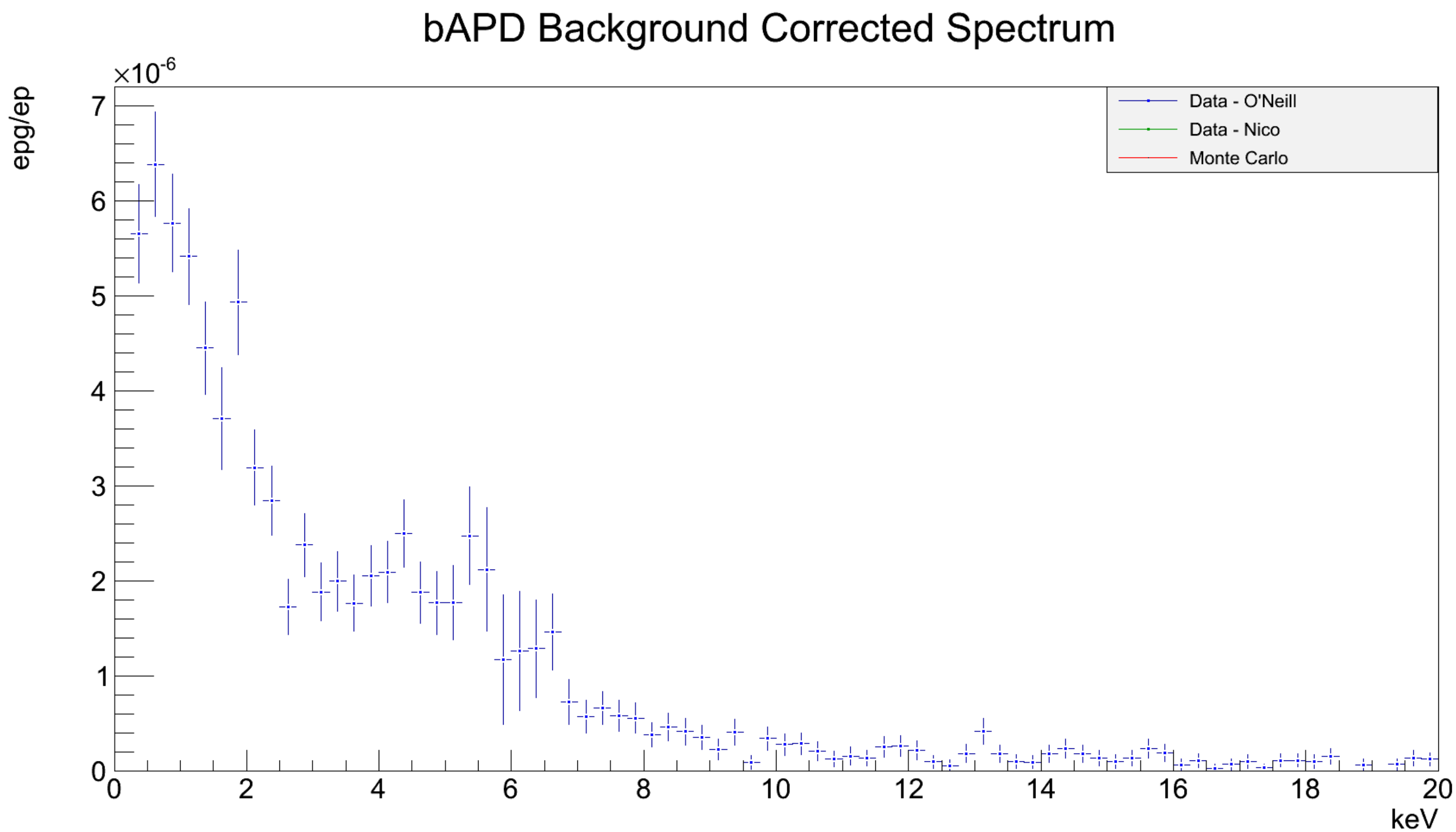


RDK II Current Results



Photon timing relative to electron
bAPD

RDK II Current Results



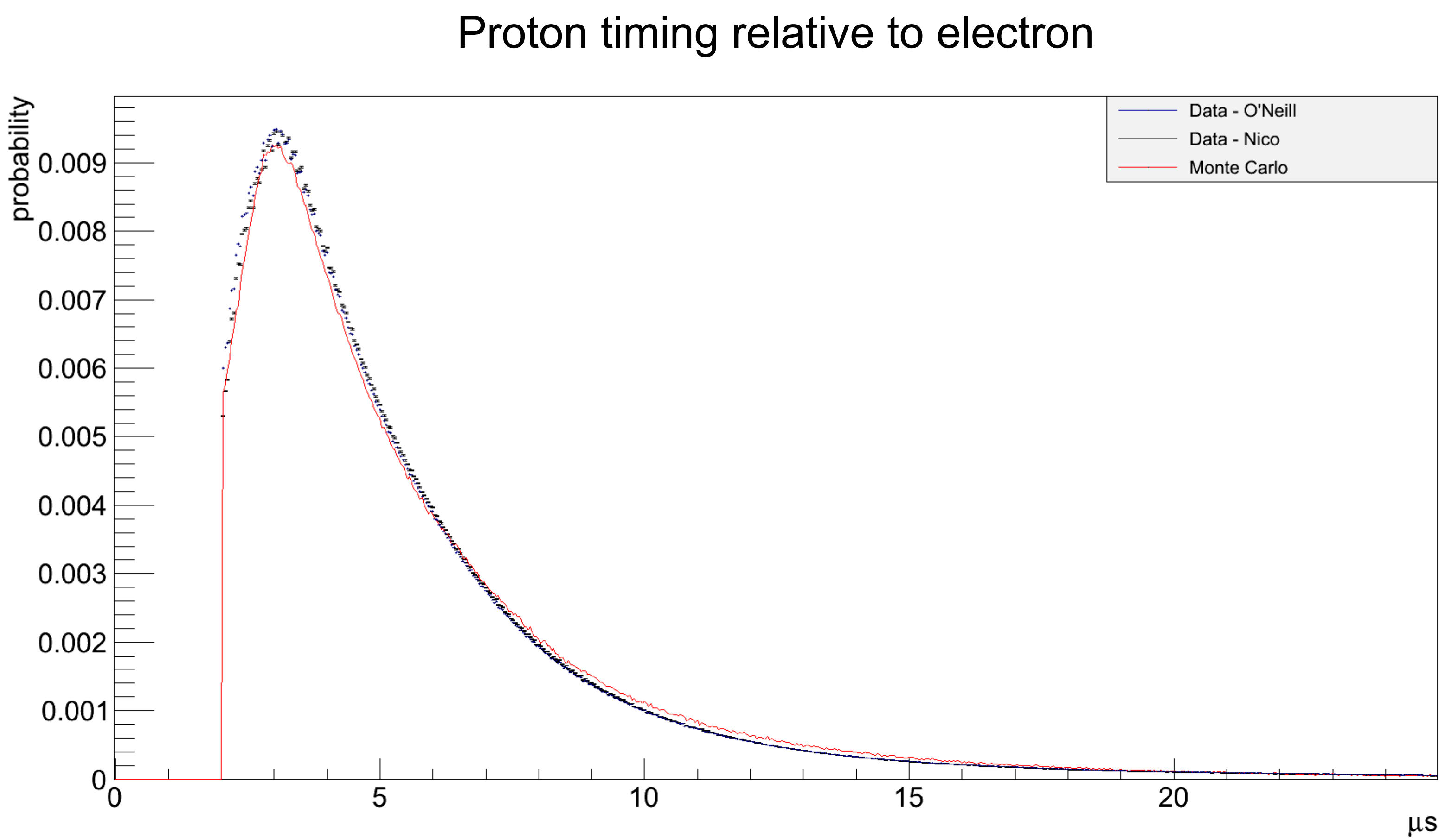
Photon energy

$R_{epg}/R_{ep}=(8.512\pm0.243)\cdot10^{-5}$

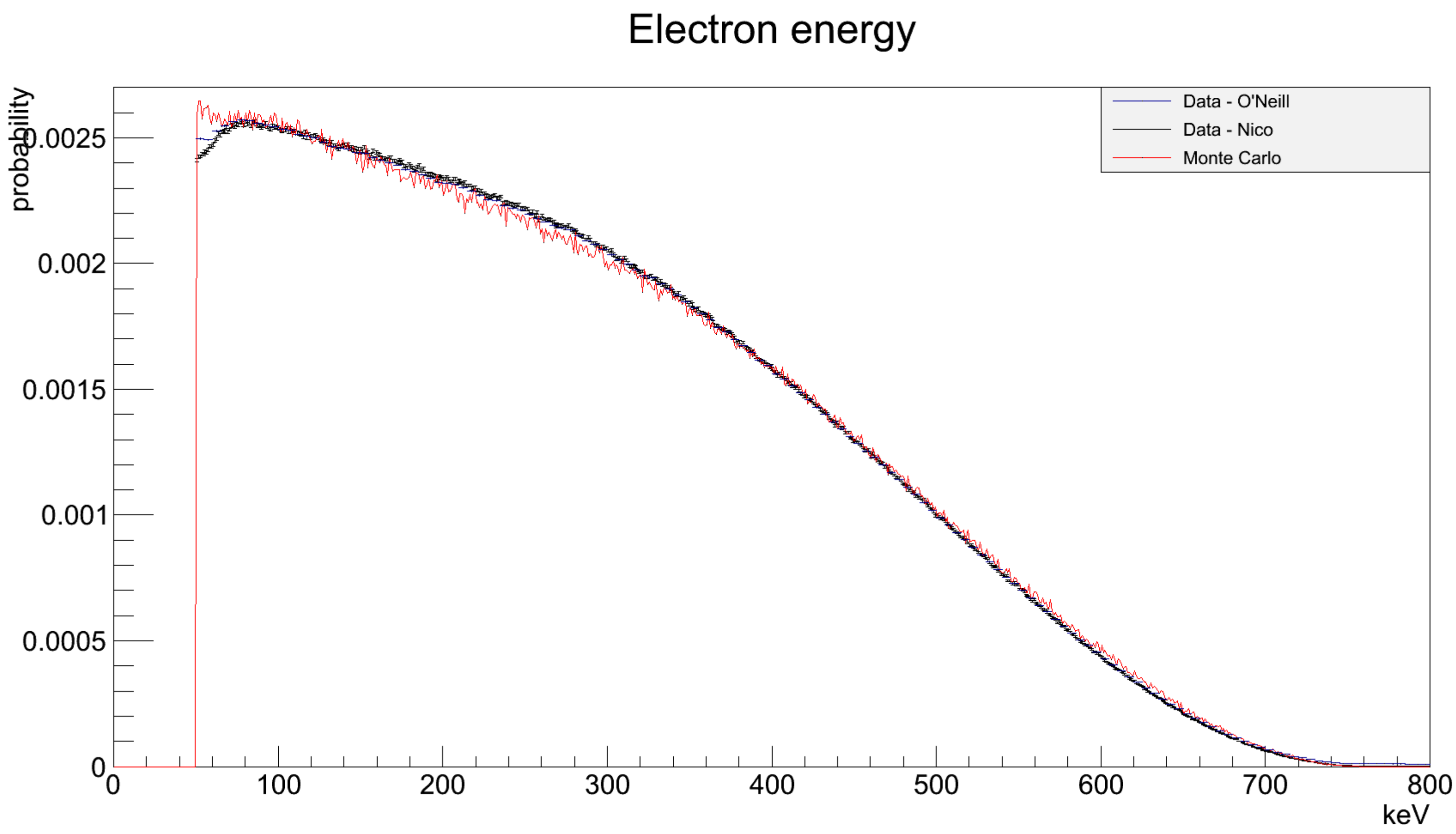
RDK II Monte Carlo

- R_{epg}/R_{ep} proportional to the branching ratio
- Complex detector
  - Effective solid angle of the SBD
  - Detector response
  - Secondary reactions
- Geant4 – Matthew Bales at Univ. of Michigan
- Chi-squared fit to determine branching ratio

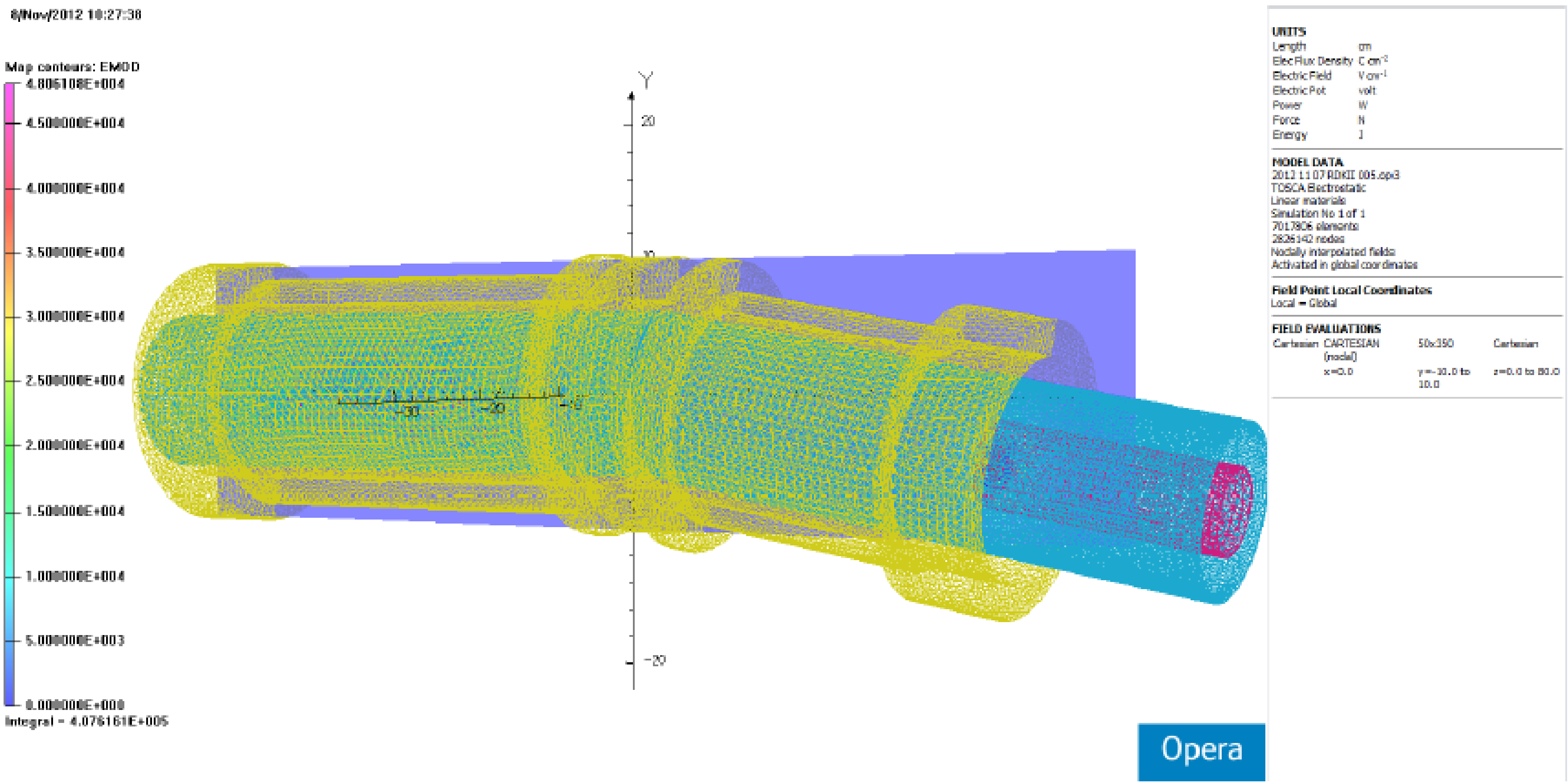
RDK II MC Benchmark



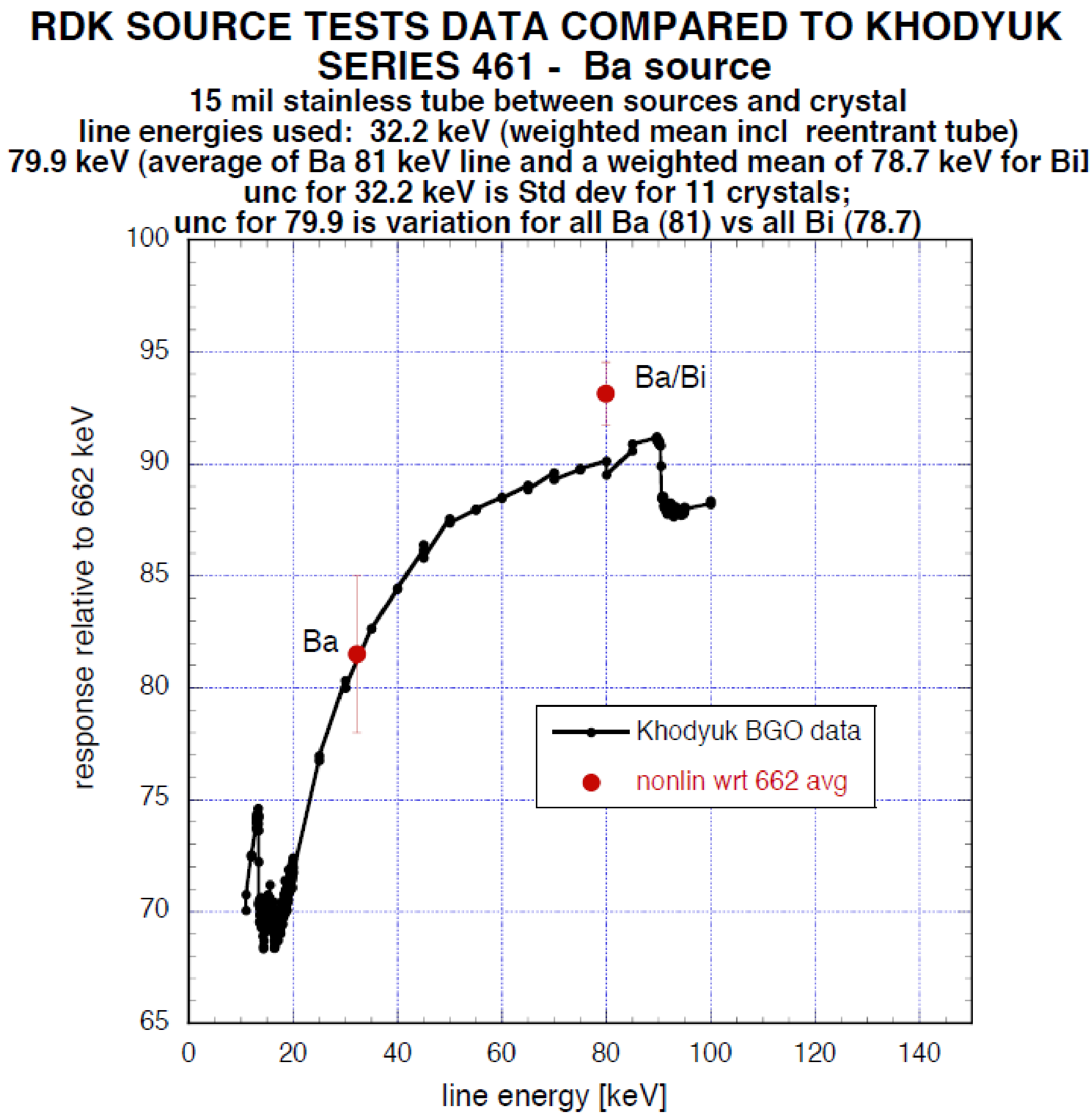
RDK II MC Benchmark



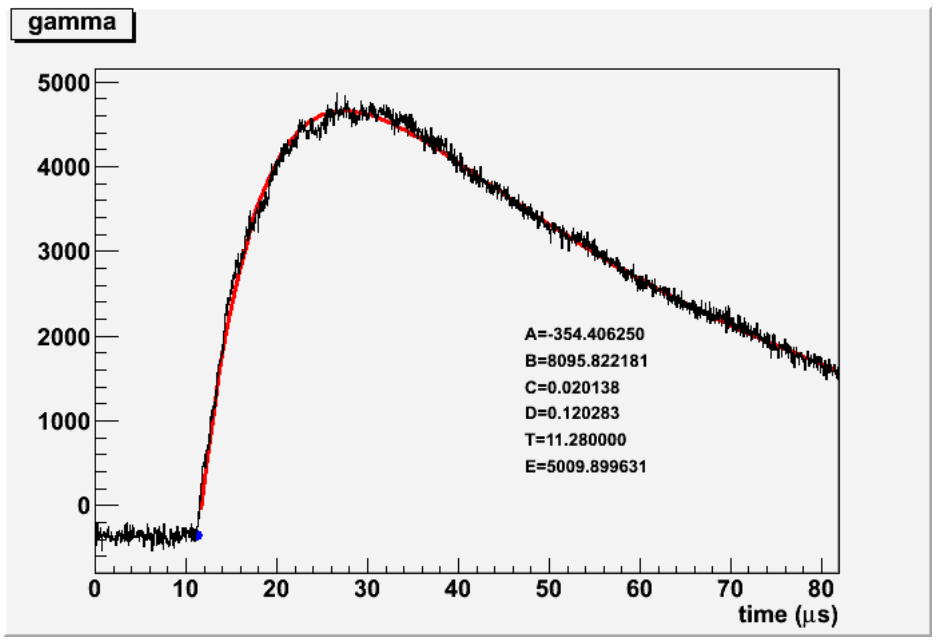
Ongoing Work



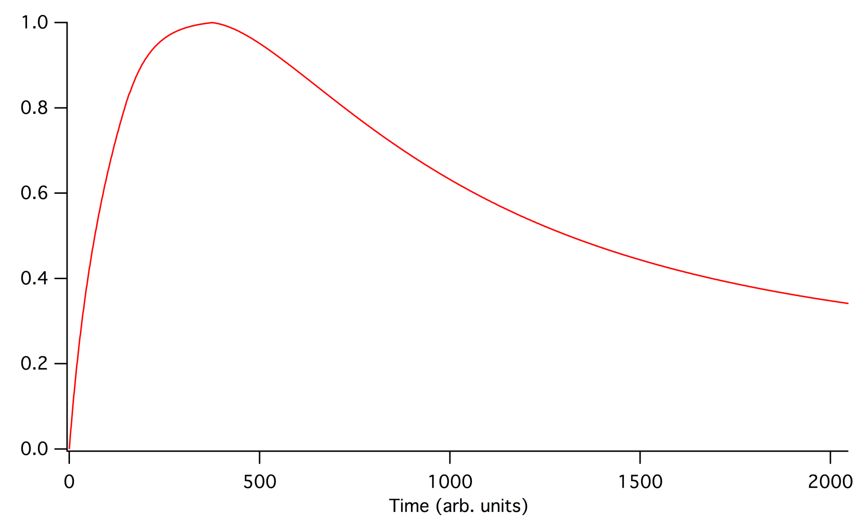
Ongoing Work



Ongoing Work



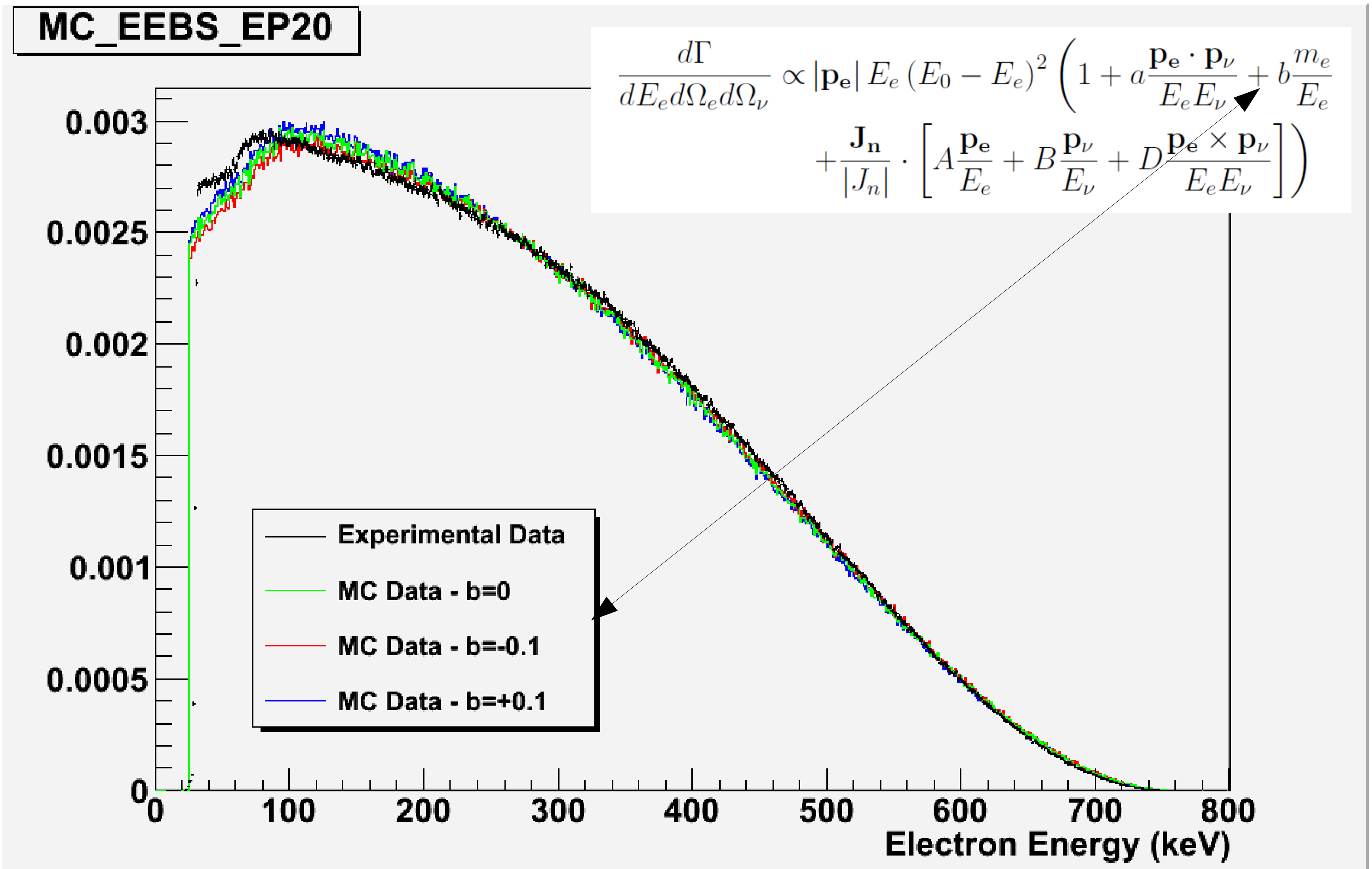
$$y = A + Be^{-C(x-t)}(1 - e^{-D(x-t)})$$
while $x > t$



Template used in RDK I

- CPU limited
- 2-3 keV shift in energy

Ongoing Work



Status

- Achieved 0.6% statistics on BR
- Expanded energy range down to 250 eV and up to the endpoint (approx 780 keV)
- Work continues on systematic errors
  - Analysis and calibrations
    - BGO non-linearity
    - Photon signal fit
  - Monte Carlo
    - New field calculations
  - Goal of *O*(1%) systematic error on BR

RKD II Collaboration

- Arizona State University
  - R. Alarcon, B. O'Neill
- National Institute of Standards and Technology (NIST)
  - C. Bass, K. Coakley, S. Dewey, C. Fu, T. Gentile, P. Mumm, J. Nico, A. Thompson
- Tulane University
  - K. Pulliam, F. Wietfeld
- University of Maryland
  - E. Beise, H. Breuer
- University of Michigan
  - M. Bales, T. Chupp, R. Cooper
- University of Sussex
  - J. Byrne

Runtime Metrics

- On beam from July 2008 to November 2009
- Off beam calibrations from January 2010 to July 2010

	All voltages	Full mirror
Run time	164.4d	97.8d
Live time	147.1d	87.5d
Total triggers	$9.7 \cdot 10^7$	$6.8 \cdot 10^7$
Run data	6.4TB	4.4TB
Total data	25TB	

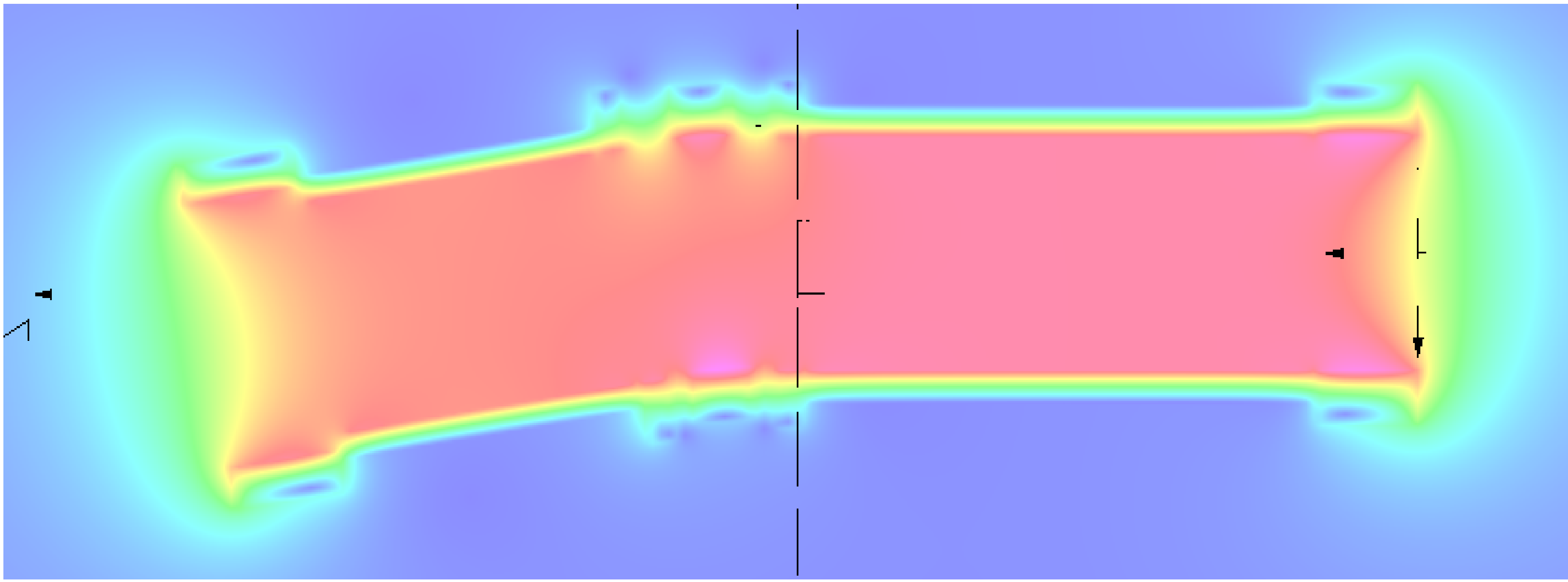
Previous Measurements: ILL

- Beck et al., Institut Laue-Langevin (ILL) 2002
- Electron-delayed proton-photon triple coincidence measurement
- Electron detector: plastic scintillator
- Proton detector: microchannel plate (MCP)
- Photon detector: Six CsI(T1) scintillators
- Result: BR for 35-100keV less than $6.9 \cdot 10^{-3}$
- Predicted: $1.1 \cdot 10^{-3}$

Previous Measurements: RDK I

- Nico et al., National Institute of Standards and Technology (NIST) 2005
- Triple coincidence measurement
- Electron-proton detector: surface barrier detector (SBD)
- Photon detector: bismuth germanate (BGO) scintillator + avalanche photo-diode (APD)
- Result: BR for 15-340keV = $3.09 \pm 0.32 \cdot 10^{-3}$
- Predicted: $2.85 \cdot 10^{-3}$

Previous Measurements: RDK I

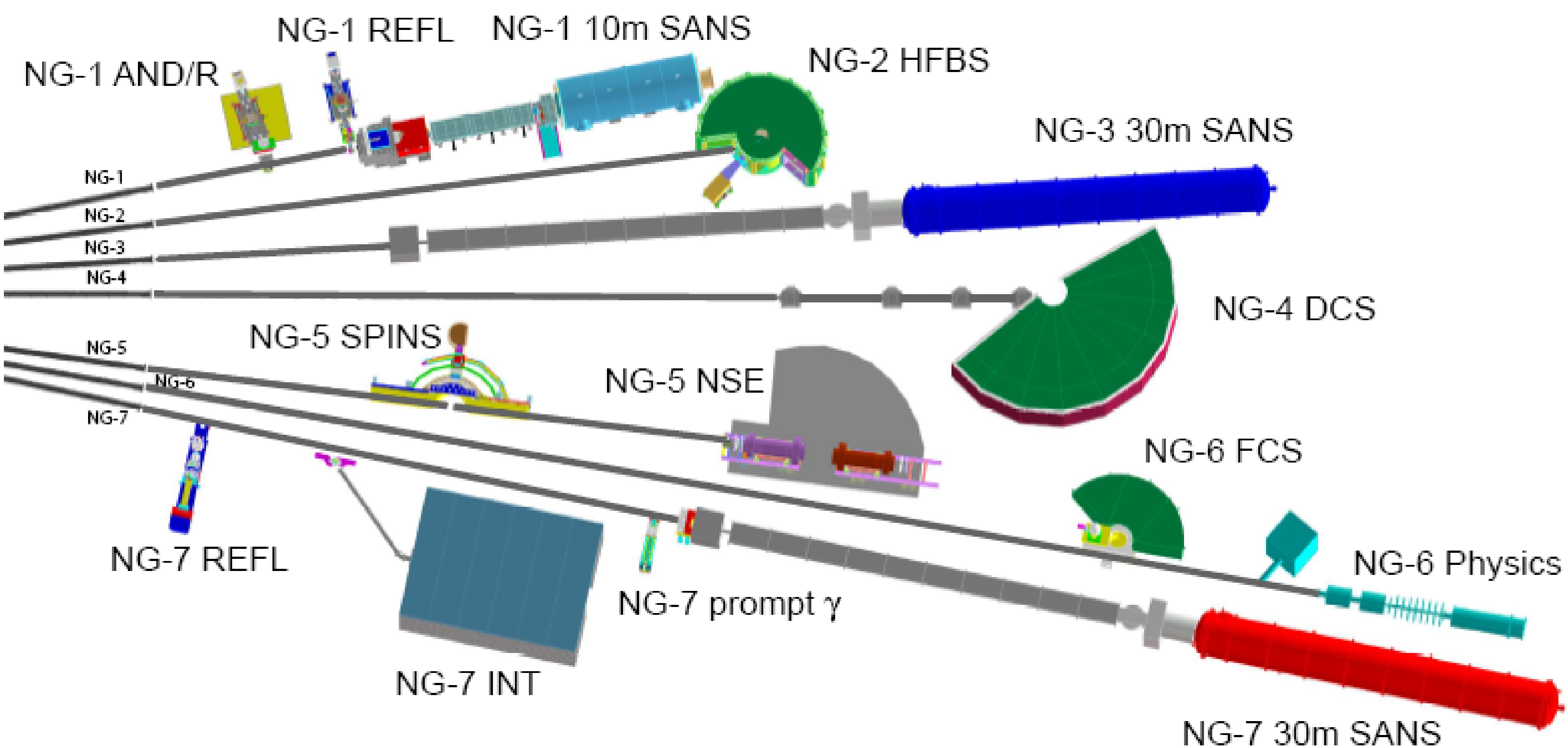


- 4.6T superconducting magnet
- 9.5^o bend

Improvements in RDK II

- Twelve BGO+APD detectors
- Three bare APD (bAPD) detectors
- Neutron counter
- In situ calibration runs
- Improved statistics: O(0.1%) for BGOs
- Greater energy range
  - <10keV to the endpoint on BGO
  - <1keV to ≈10keV for bAPD

NIST Beam Line



NIST Beam Line

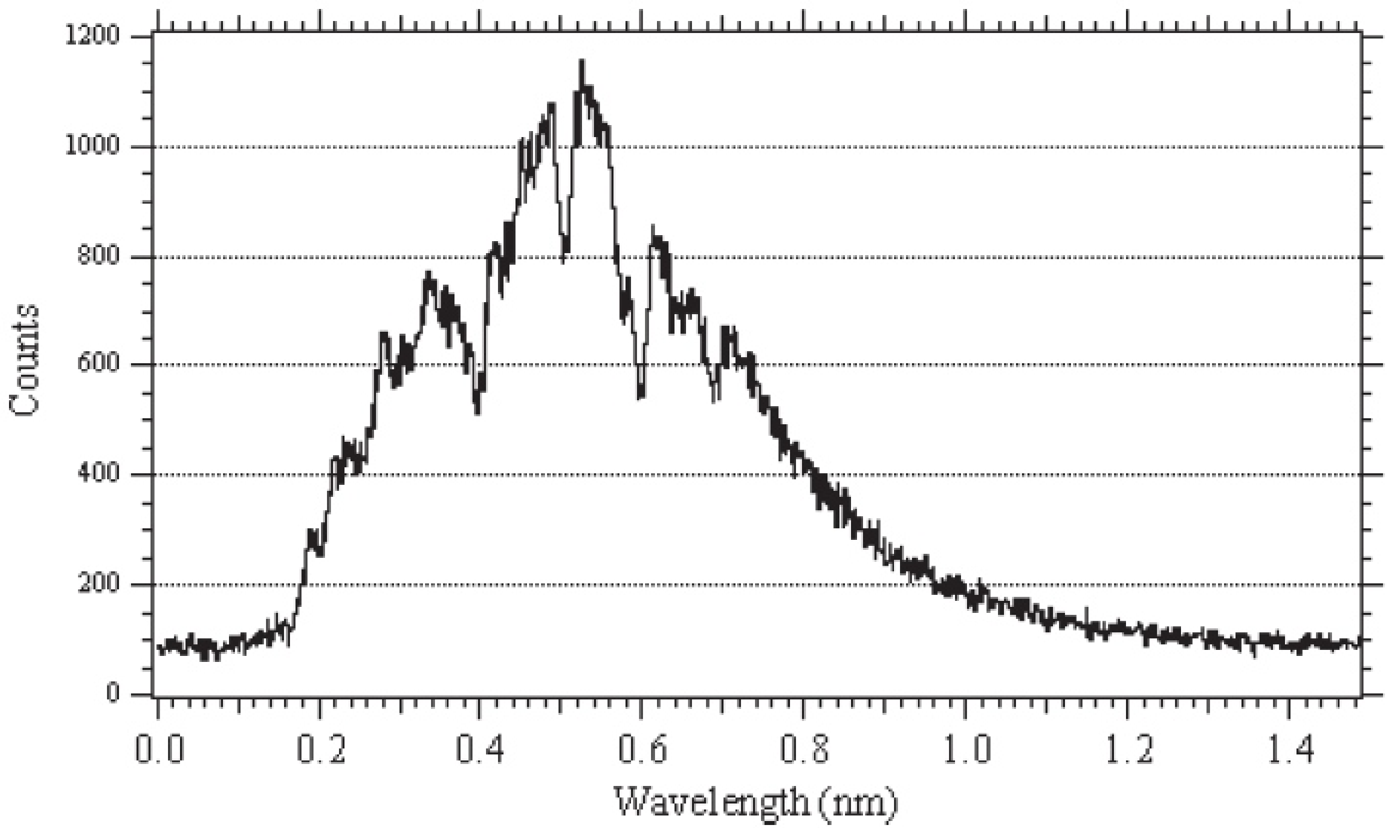
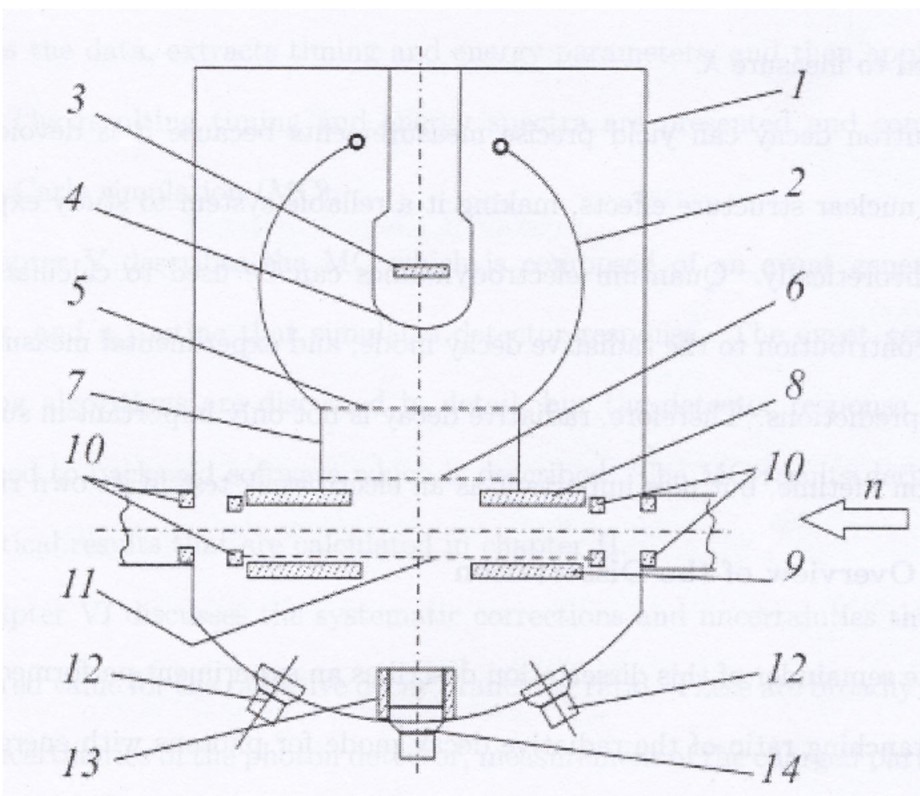
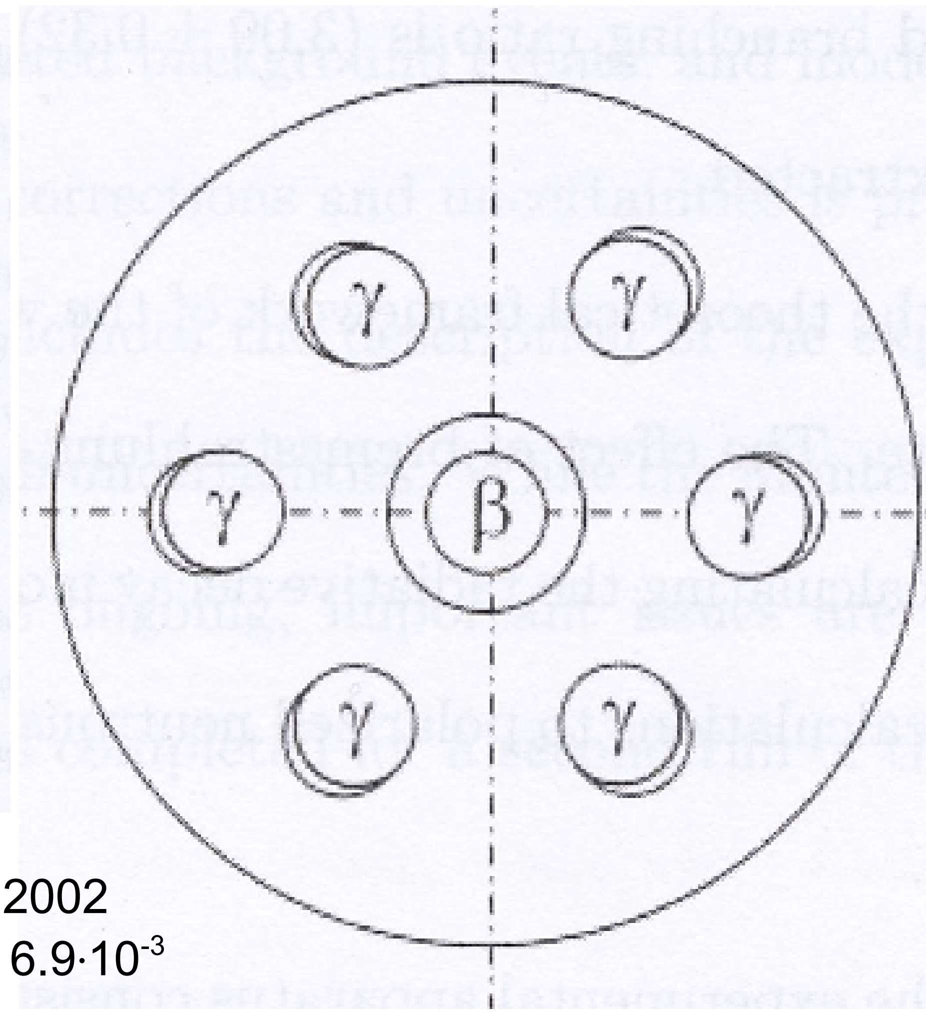


Fig. 2. Wavelength spectrum of the NG-6 polychromatic beam. The dips in the spectrum correspond to Bragg-edges from materials upstream, typically aluminum and bismuth. The dip at 0.6 nm appears due to an upstream monochromator. The data were obtained with a 15 cm bismuth filter, polarizing supermirror, and neutron collimation in the beam.

Previous Measurements: ILL





- Beck et al., Institut Laue-Langevin (ILL) 2002
- Branching ratio for 35-100keV less than $6.9 \cdot 10^{-3}$

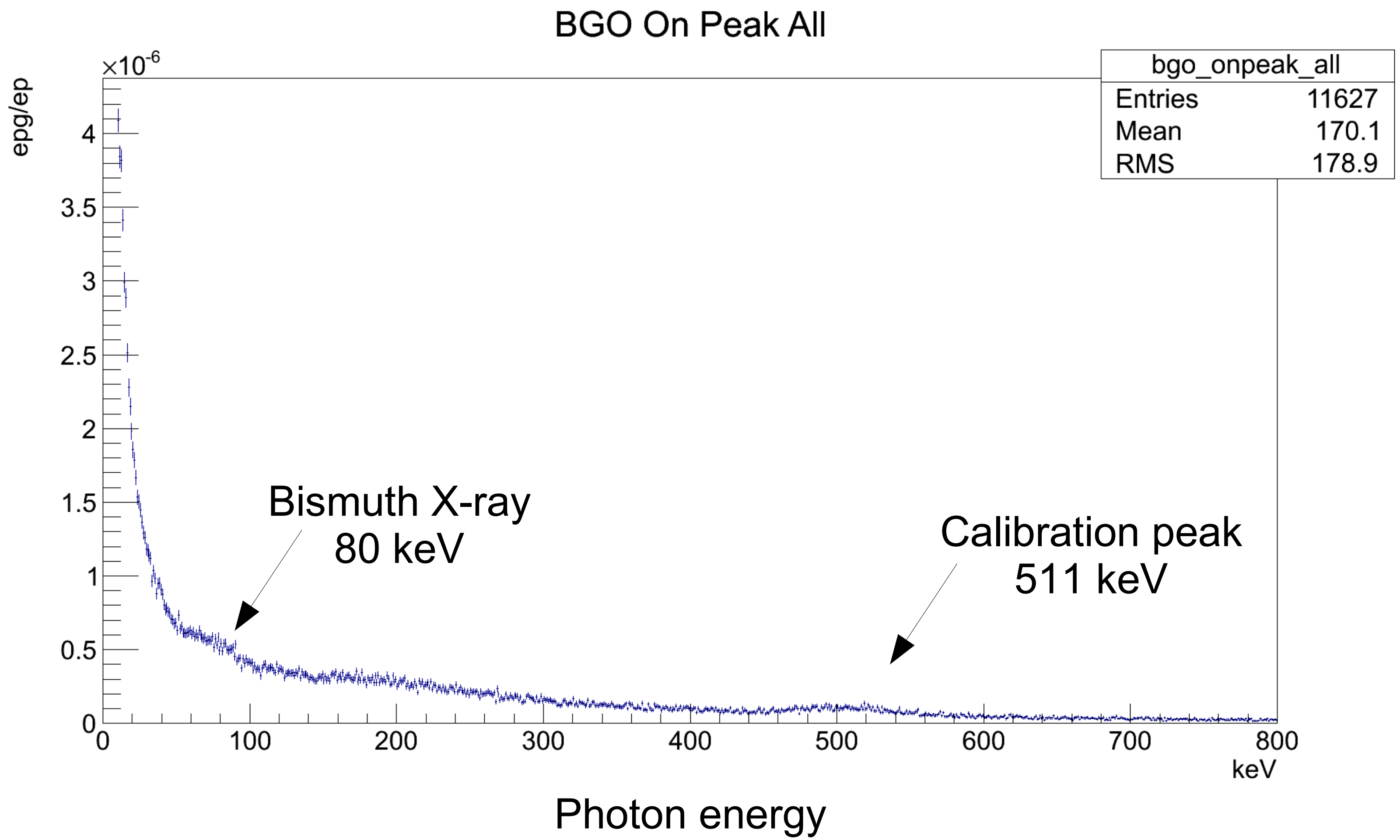
Motivation

Measurement and year	Neutron lifetime (s)	Measurement type
Byrne 1996	889.2±3.0[syst.]±3.8[stat.]	Beam, Penning trap
Arzumanov 2000	885.4±0.9[syst.]±0.4[stat.]	Bottle, UCN gravitational trap
Nico 2005	886.3±1.2[syst.]±3.2[stat.]	Beam, Penning trap
PDG World Average	885.7±0.8	
Seberov 2005	878.5±0.7[syst.]±0.3[stat.]	Bottle, UCN gravitational trap

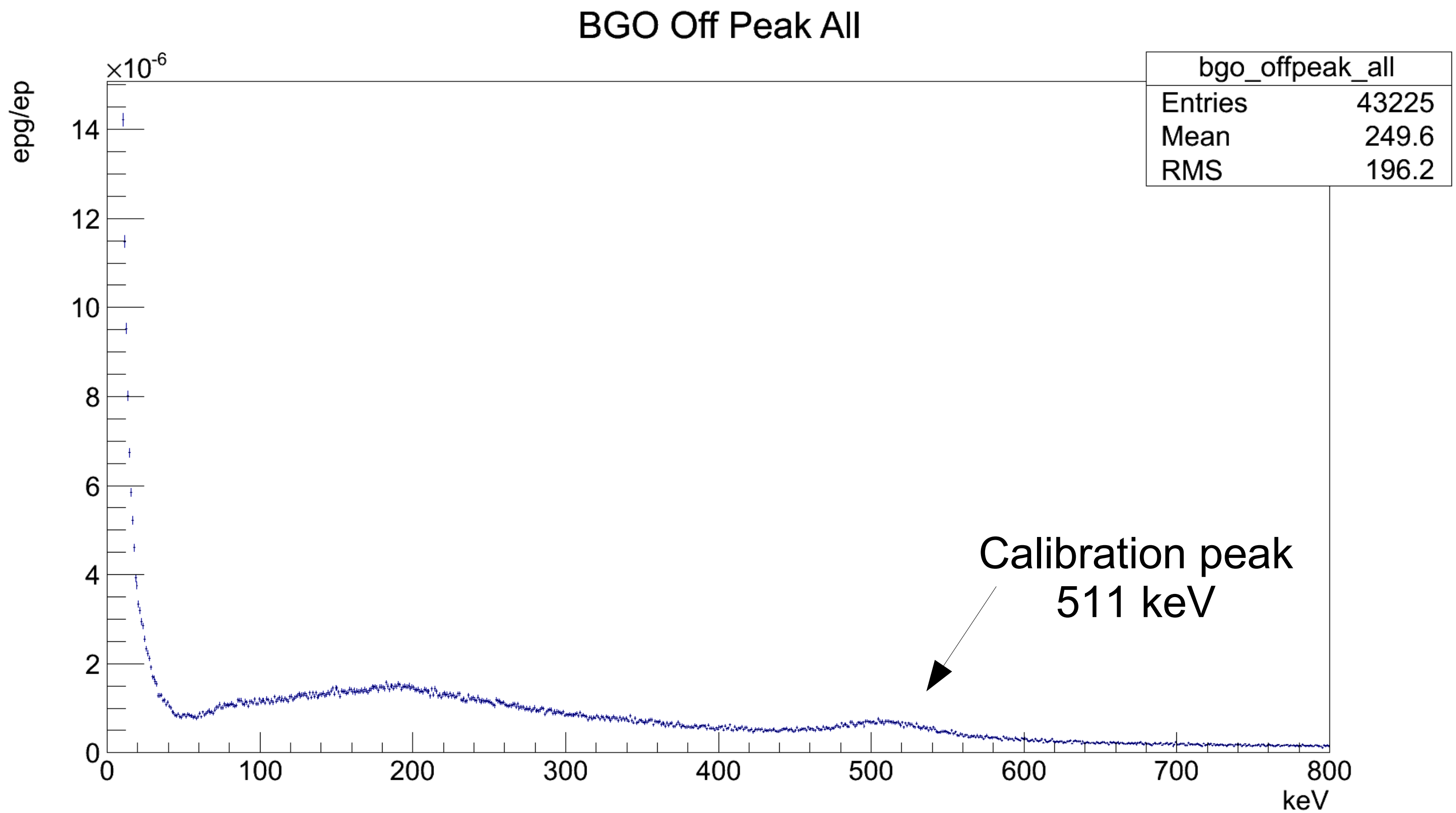
Radiative corrections

- Electron energy spectrum
- Angular correlation
- Correlated background

RDK II Current Results

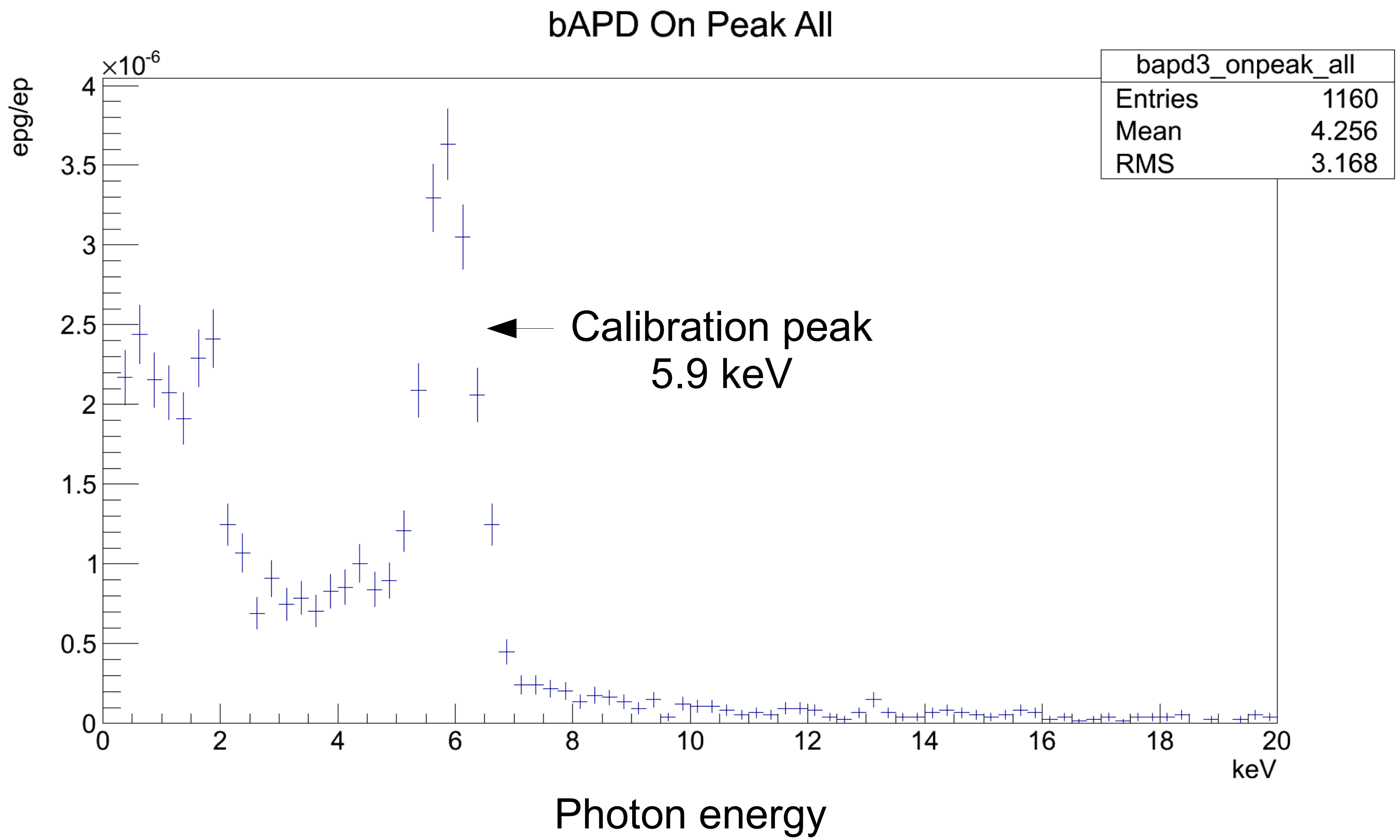


RDK II Current Results



Photon energy

RDK II Current Results



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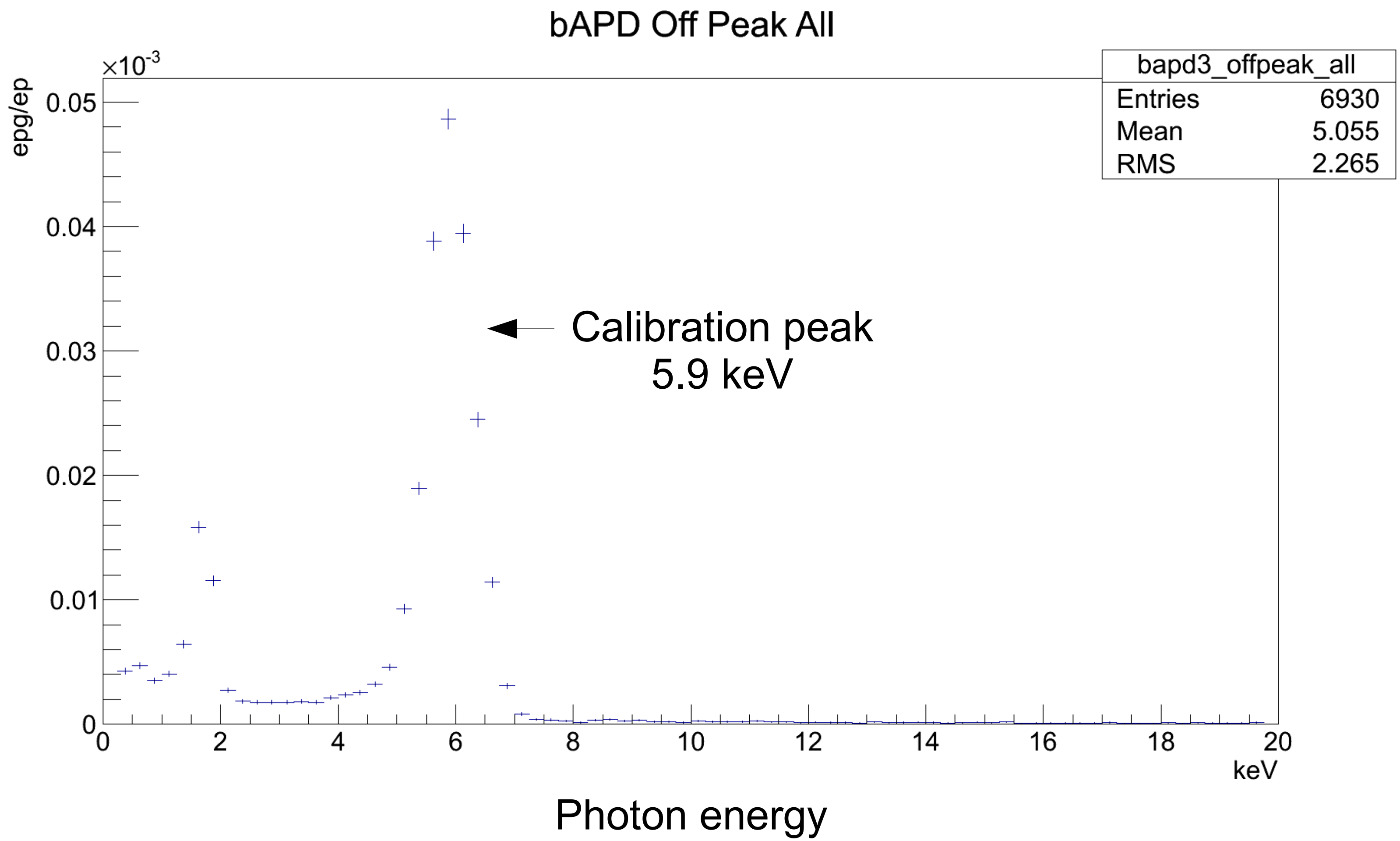

Ongoing Work