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Comparison of Instrument Response Functions obtained with D-T neutrons, cosmic-rays, and photons

- University of New Mexico
    - Jed Styron
    - Gary Cooper
    - Jenny Ruth Smith
    - Jeremy Vaughan
- Sandia National Laboratories
    - Carlos Ruiz
    - Kelly Hahn
    - Gordon Chandler
    - Brent Jones
    - Bruce McWatters
    - Jose Torres
    - Perry Alberto

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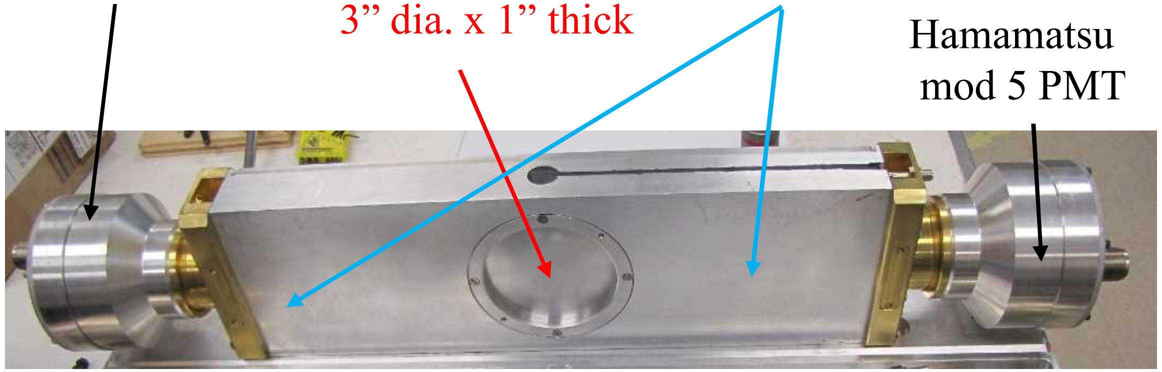
The objective of this work was to quantitatively compare the instrument response function (IRF) for D-T neutrons, cosmic-rays and photons.

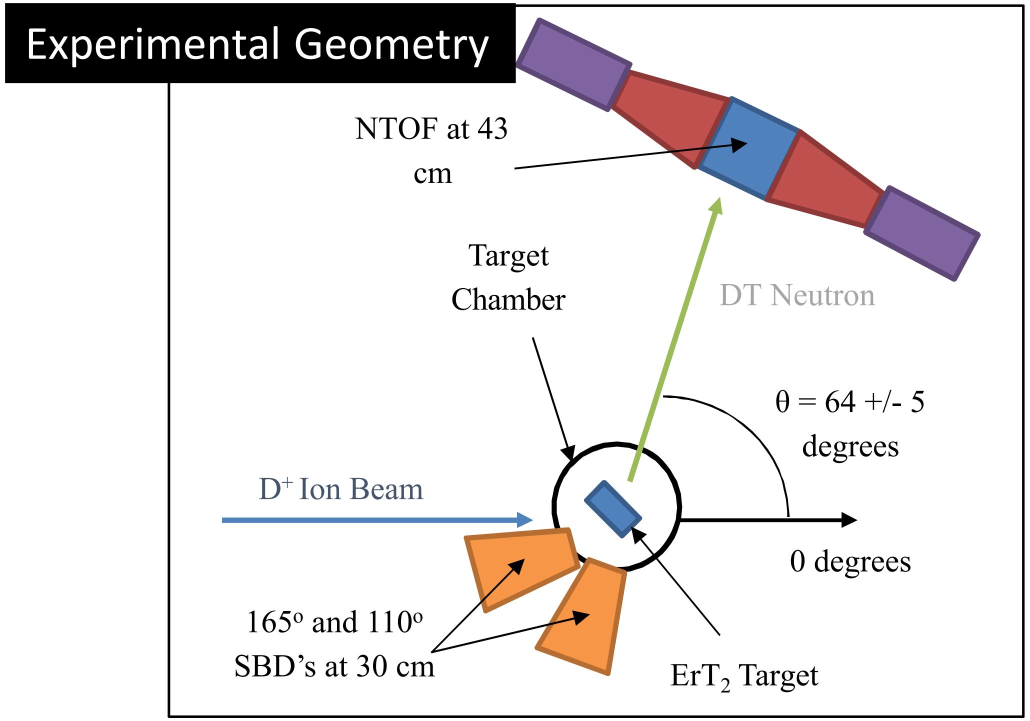
- IRFs were measured using a dual-PMT NTOF design
  - Photek PMT240
  - Hamamatsu mod-5
  - EJ-228 scintillator (BC-418 equivalent)
    - 2.54 cm thick
    - 7.62 cm diameter
- IRF definition
  - Statistical properties
    - Scintillator decay
    - PMT response
  - Excludes
    - Scintillator transit time
    - PMT transit time
    - Cable delays

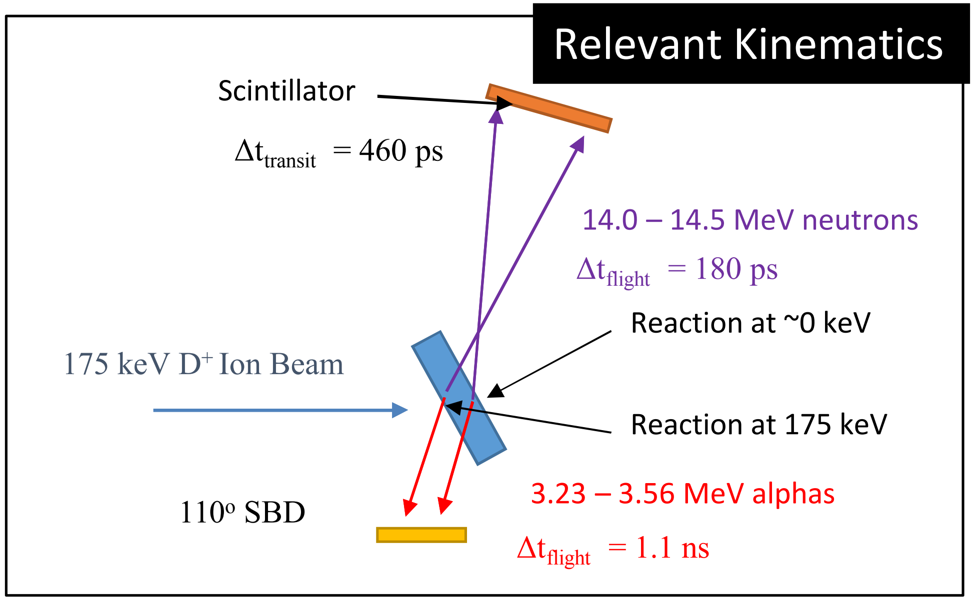
Dual PMT NTOF



A novel IRF measurement utilizing D(t,α)n coincidence at the SNL Ion Beam Laboratory (IBL).

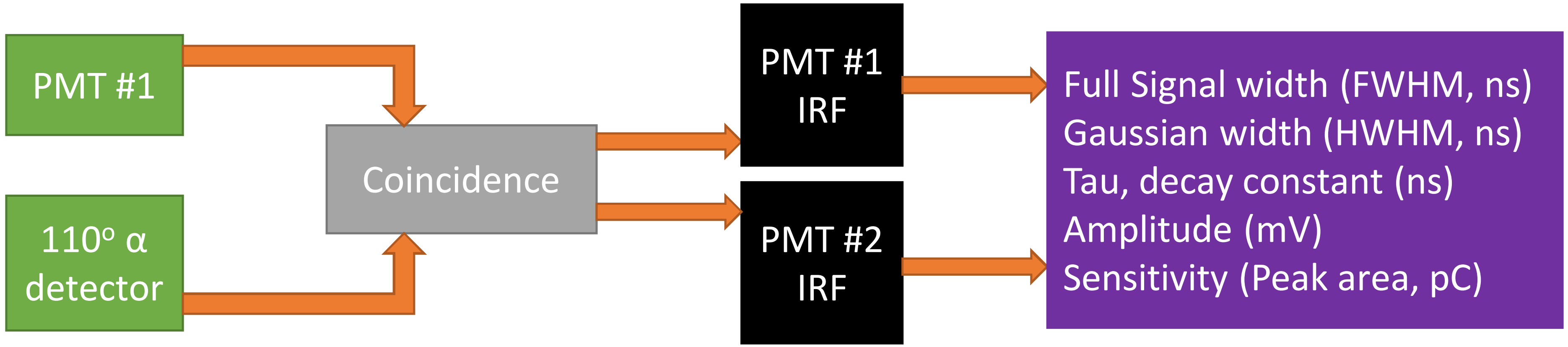
- Experimental set-up
  - 350 keV Cockroft-Walton Accelerator
  - 175 keV D^+ ion energy
  - 3 μm ErT_2 target
  - 2.5 μA beam current
- Coincidence established by kinematic relationships
  - Variability from D^+ ion dE/dx losses in the target
  - Derived from Associated Particle Method (APM)
- Photons measured from D-T activation

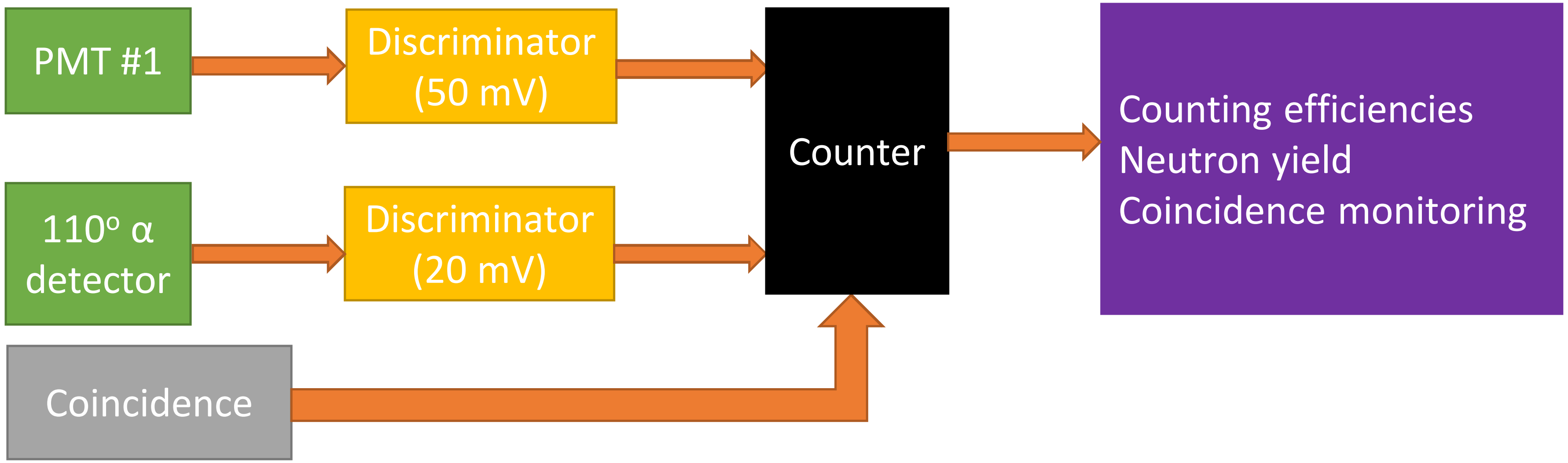




C. L. Ruiz et al., Rev. Sci. Instr.,**83**,(2012)

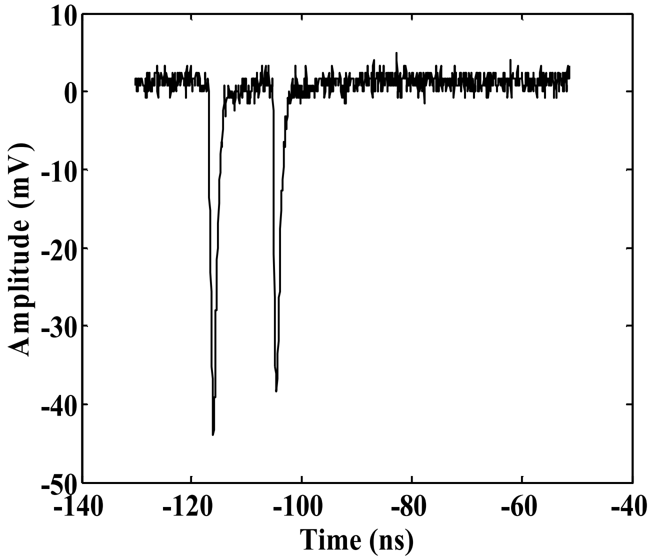
The IRF and the sensitivity (pC/n),can be extracted, individually, from a single experiment.

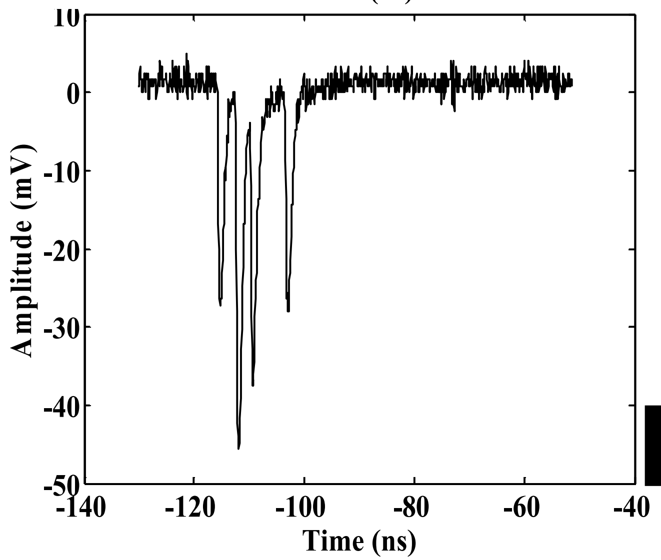


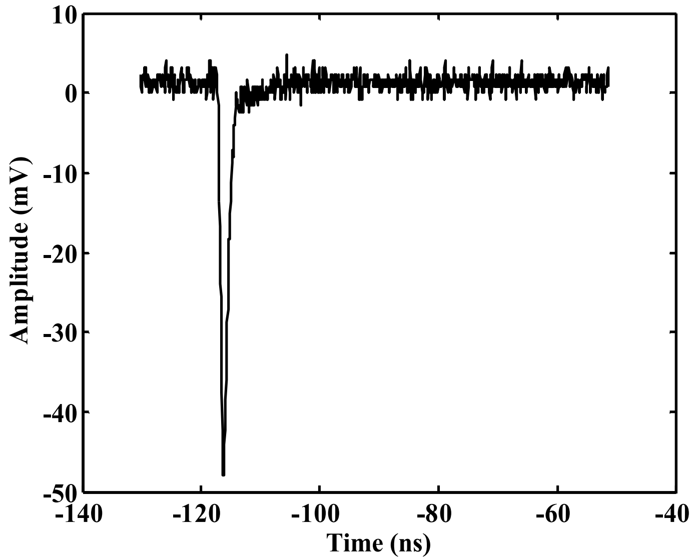


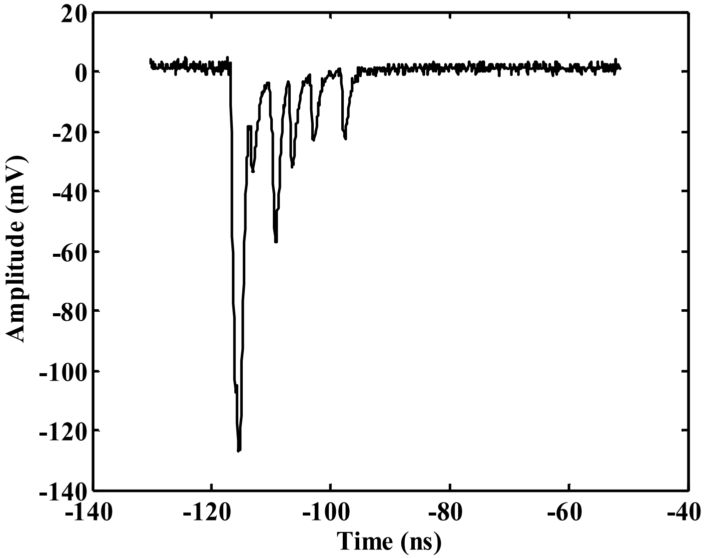
Data acquired from single neutron interactions produce waveforms with varying structure.

- Collected and saved 1000 waveforms
  - Post processed
- Photek PMT240
  - -3.8 to -4.6 kV
- Hamamatsu mod-5
  - -2.0 to 2.5 kV
- 100 ns window w/ 50 ps resolution at 2.5 GHz







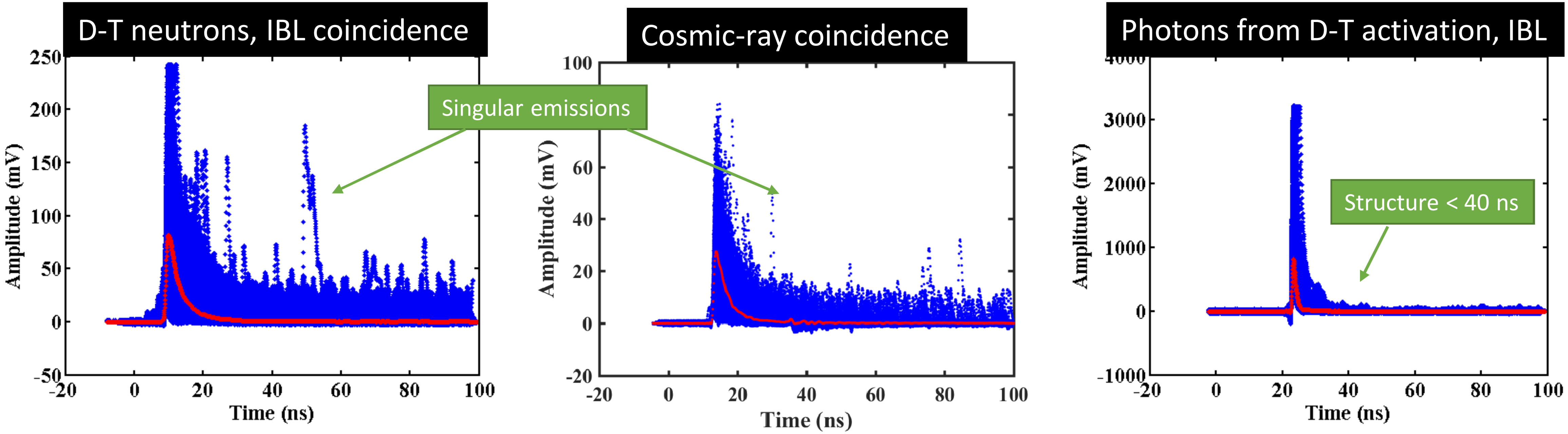


Data shown for the Photek at -4.2 kV

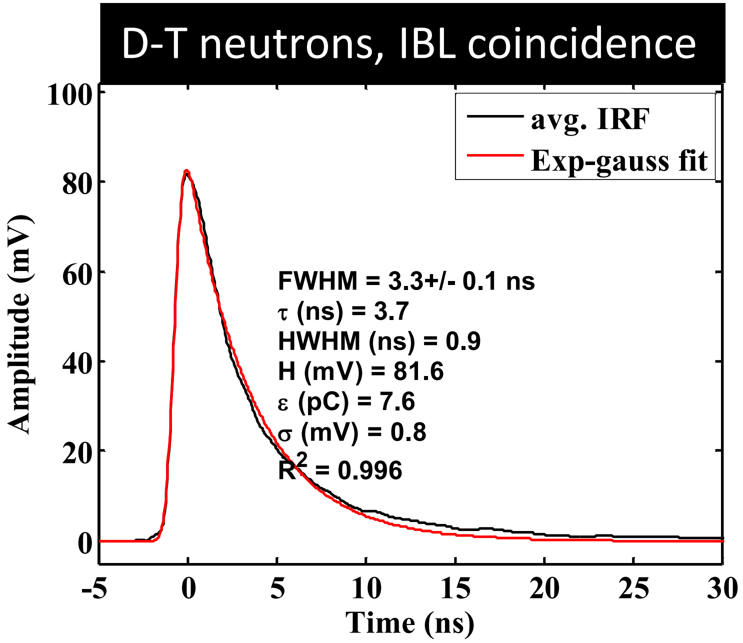
Multiple waveforms were normalized to the leading edge (10% max) and then averaged to extract the IRF.

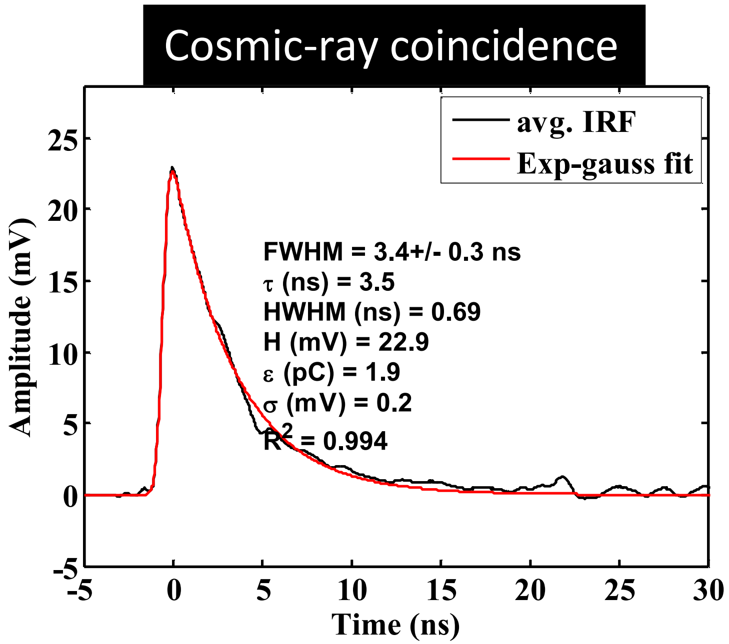
- Average waveform fit with exponentially modified Gaussian

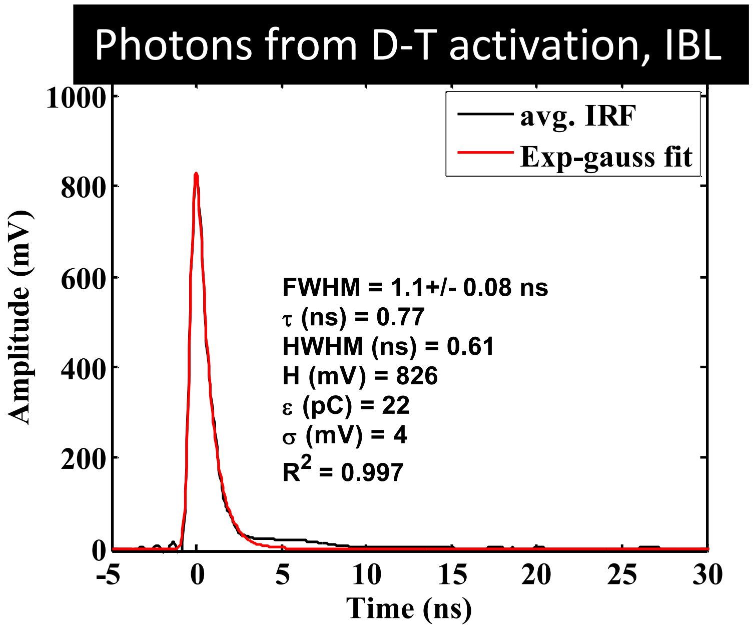
$$IRF(t,\mu,\tau,\sigma,A) = A * \exp\left(-\frac{t-\mu}{\tau}\right) * \exp\left(\frac{\sigma^2}{2\tau^2}\right) * \left(1 + \operatorname{erf}\left(\frac{t-\mu-\frac{\sigma^2}{\tau}}{\sqrt{2\sigma^2}}\right)\right)$$



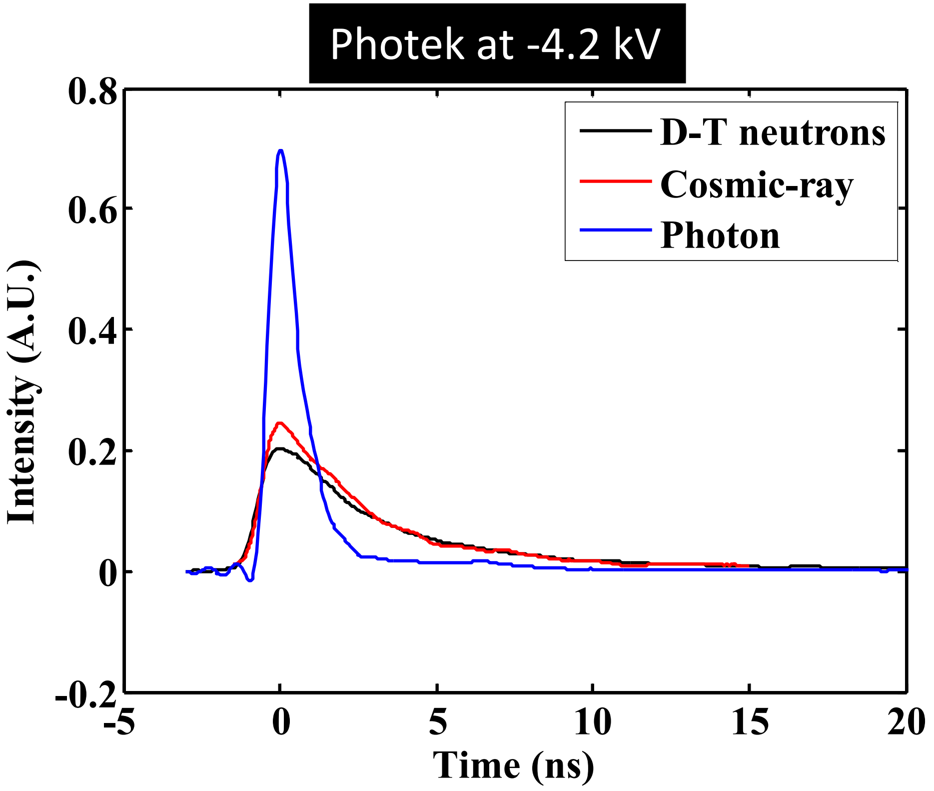
Average IRFs obtained for the Photek PMT240 at -4.2 kV for D-T neutrons, cosmic-rays, and photons.

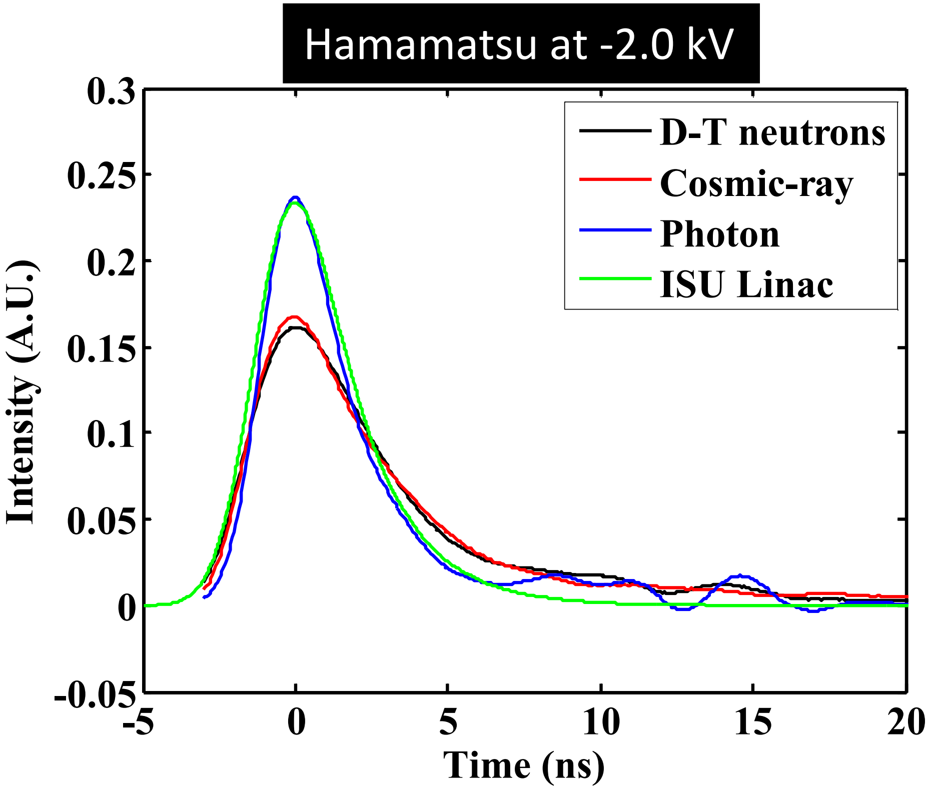






The IRFs generated with D-T neutrons and cosmic-rays show excellent agreement.





In conclusion…

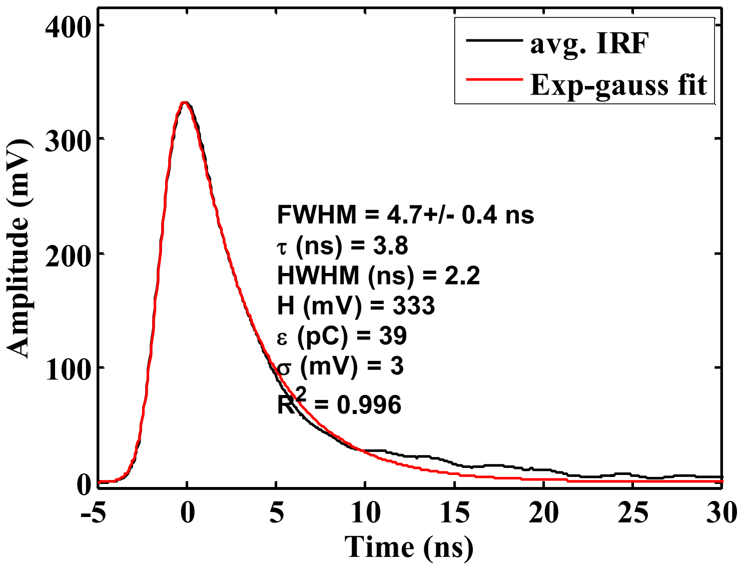
- Almost exact agreement is observed between the neutron and cosmic generated IRFs
  - Implies IRF is independent of secondary particle energy (DT IRF = DD IRF)
    - Ion Beam Laboratory is efficient
    - Cosmic-rays are free
- Excellent agreement observed in the IRFs obtained with photons and the Idaho State University LINAC
  - Suggests averaging is comparable to an intense, multi-photon source
- Photon and neutron induced IRFs are markedly different
  - Need to understand and resolve differences between methods moving forward

Questions?

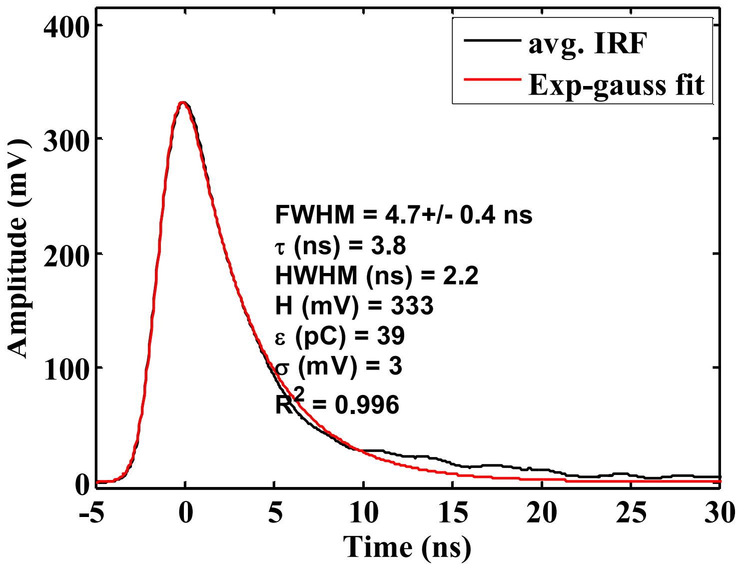
Back-up

Hamamatsu IRF

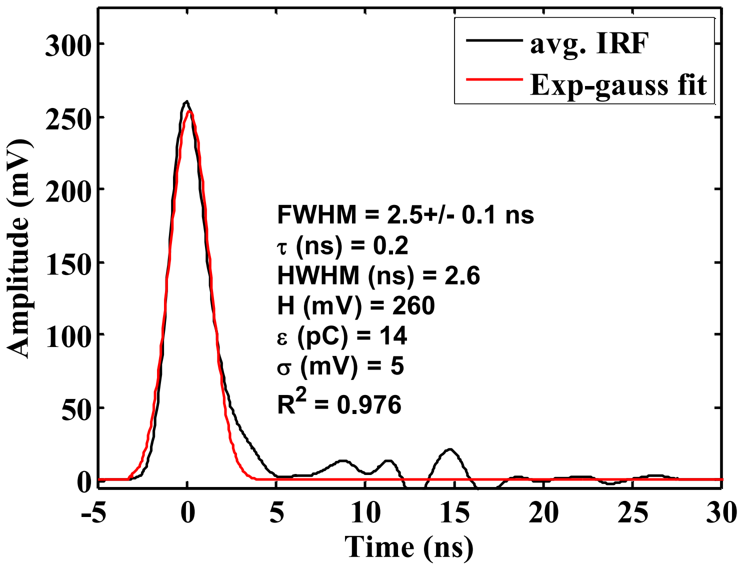
D-T neutrons, IBL coincidence



Cosmic-ray coincidence

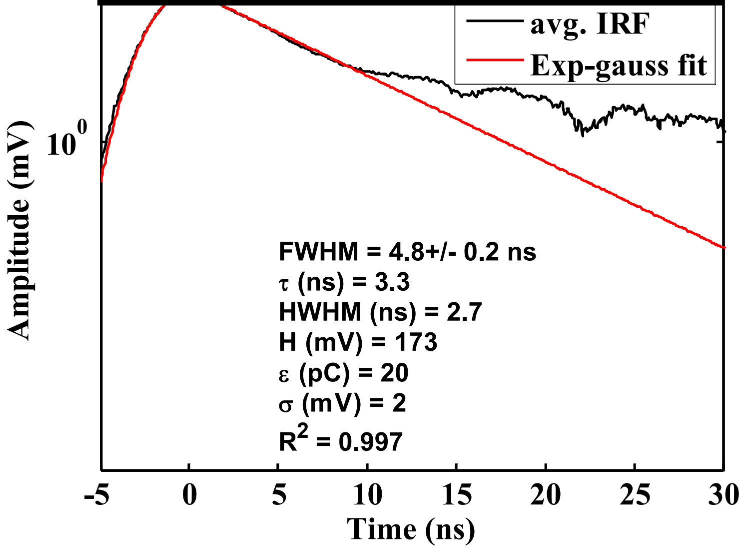


Photons from D-T activation, IBL

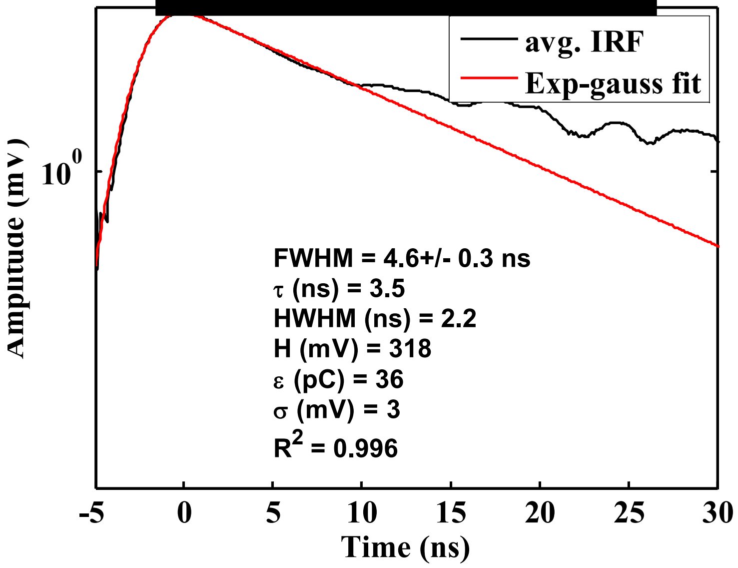


Hamamatsu IRF

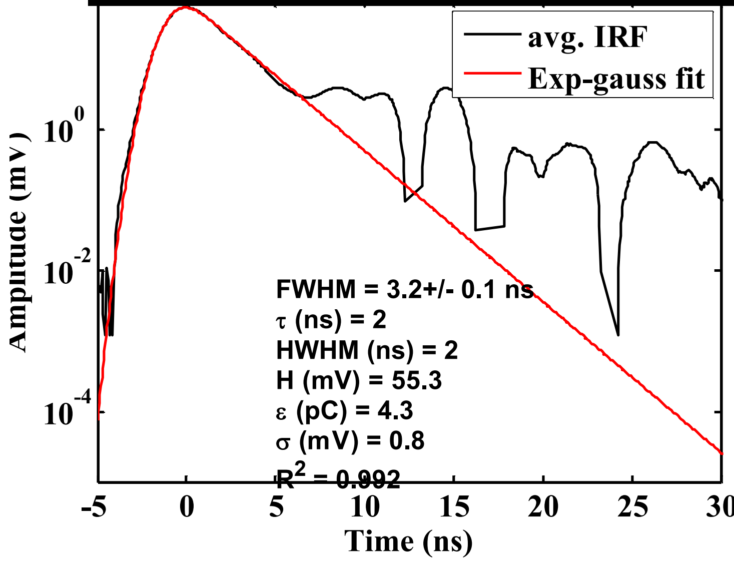
D-T neutrons, IBL coincidence



Cosmic-ray coincidence

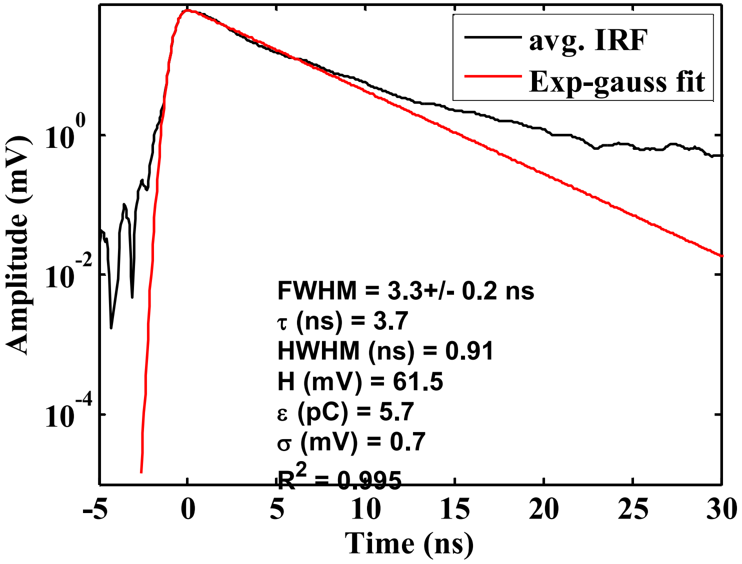


Photons from D-T activation, IBL

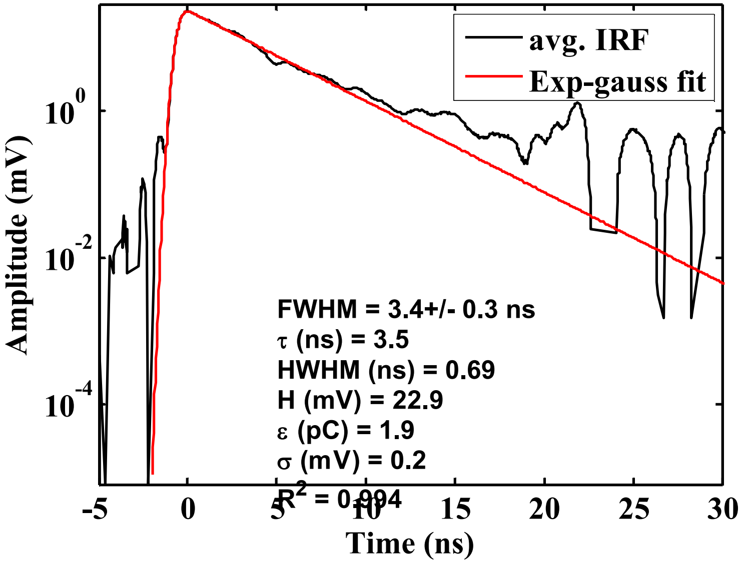


Photek IRF

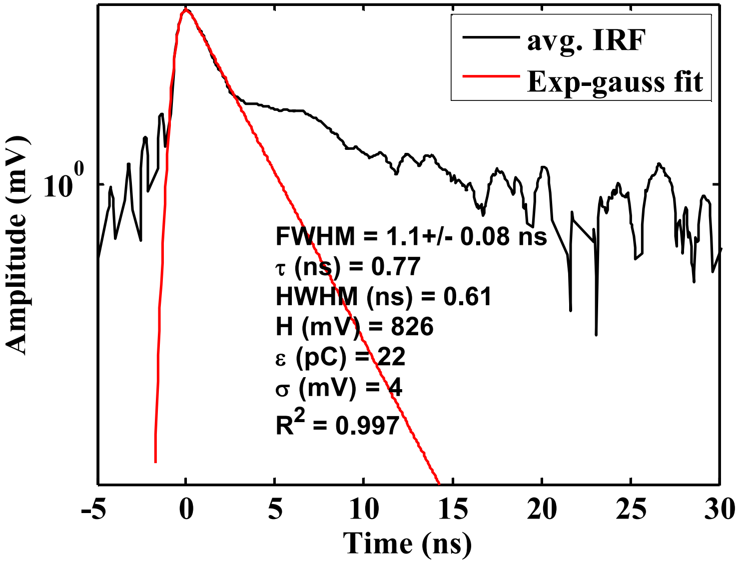
D-T neutrons, IBL coincidence



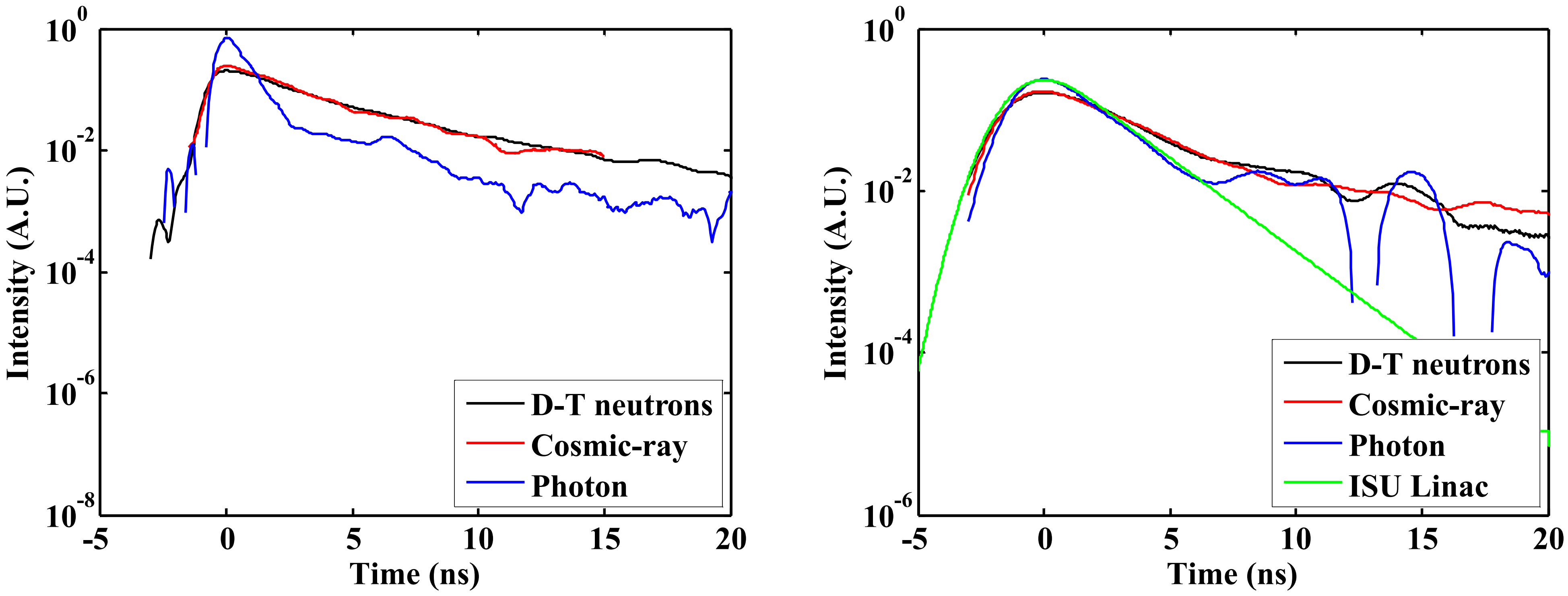
Cosmic-ray coincidence



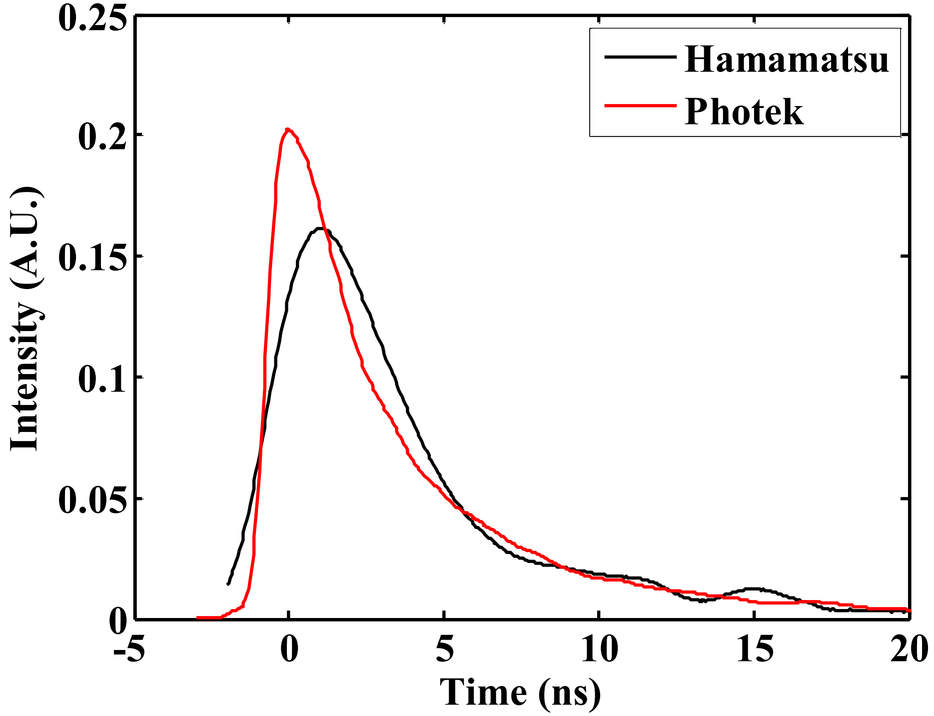
Photons from D-T activation, IBL



Comparison of IRF methods



Hamamatsu vs. Photek

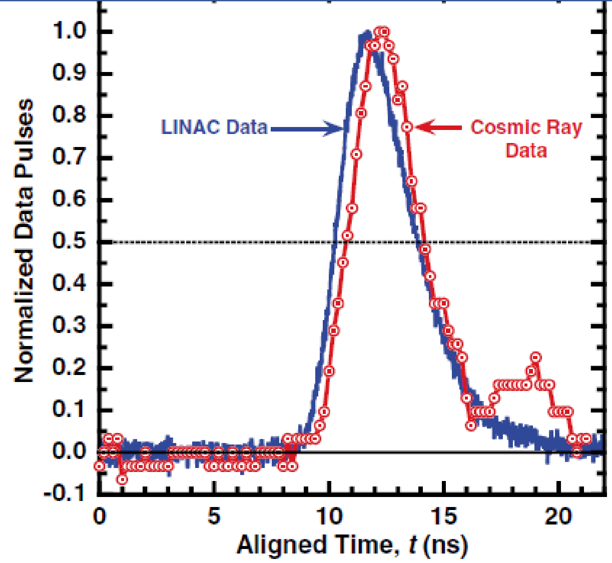


Experimental methods for extracting the instrument response function.

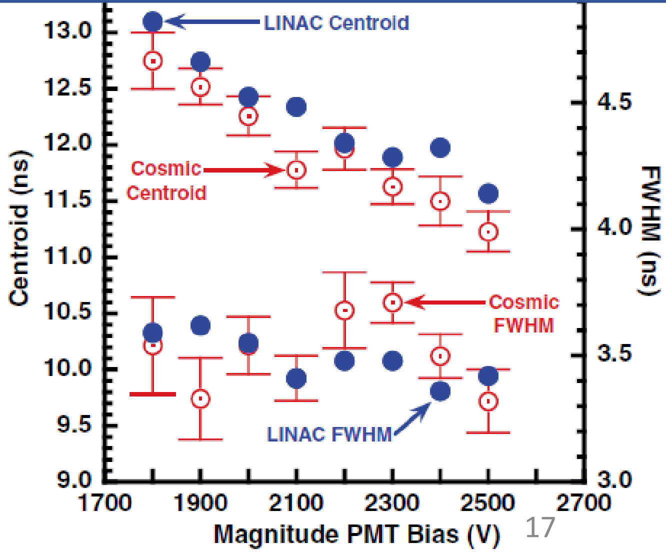
- Traditional characterization methods
  - High Fluence Cs-137 or Co-60 sources
  - Cosmic Rays
  - Bremsstrahlung
  - Laser Illumination
  - Cross-calibration with CVD diamond
- Neutron Characterization
  - Mono-energetic, single event sources are generally unavailable
    - Approximated by increasing source to detector distance
  - Spectral sources
    - AmBe or PuBe
    - Ion induced break-up (Accelerator)

M.A. Bonura et al., Rev. Sci. Instr.,**85**,(2014)
D. Klir et al., Rev. Sci. Instr., **82**, (2011)
J. A. Brown et al., Jour. App. Phys, **115,** (2015)
R. Hatarik et al., Rev. Sci. Instr., **83**, (2012)

Typical IRF Waveforms
(Linac and Cosmic-ray data shown)

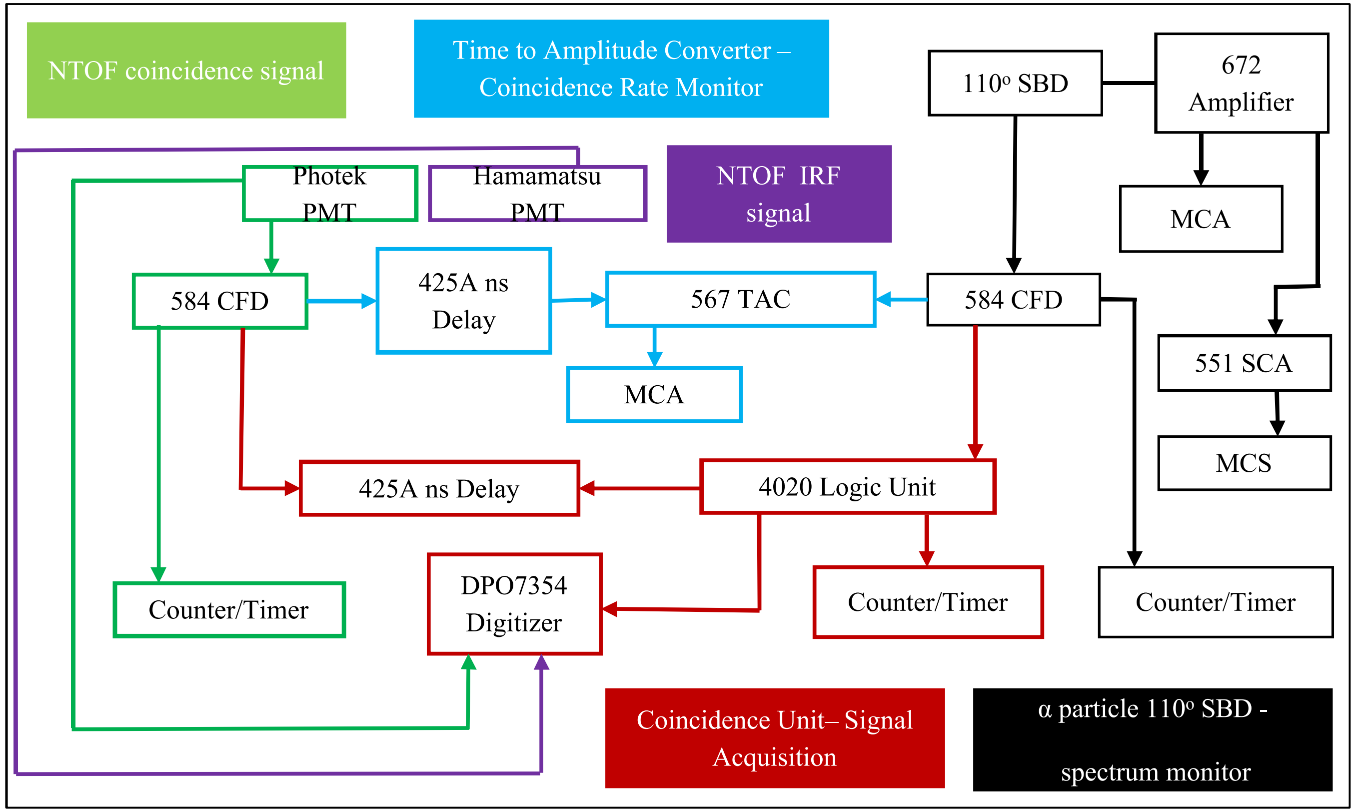


Centroid and FWHM comparison



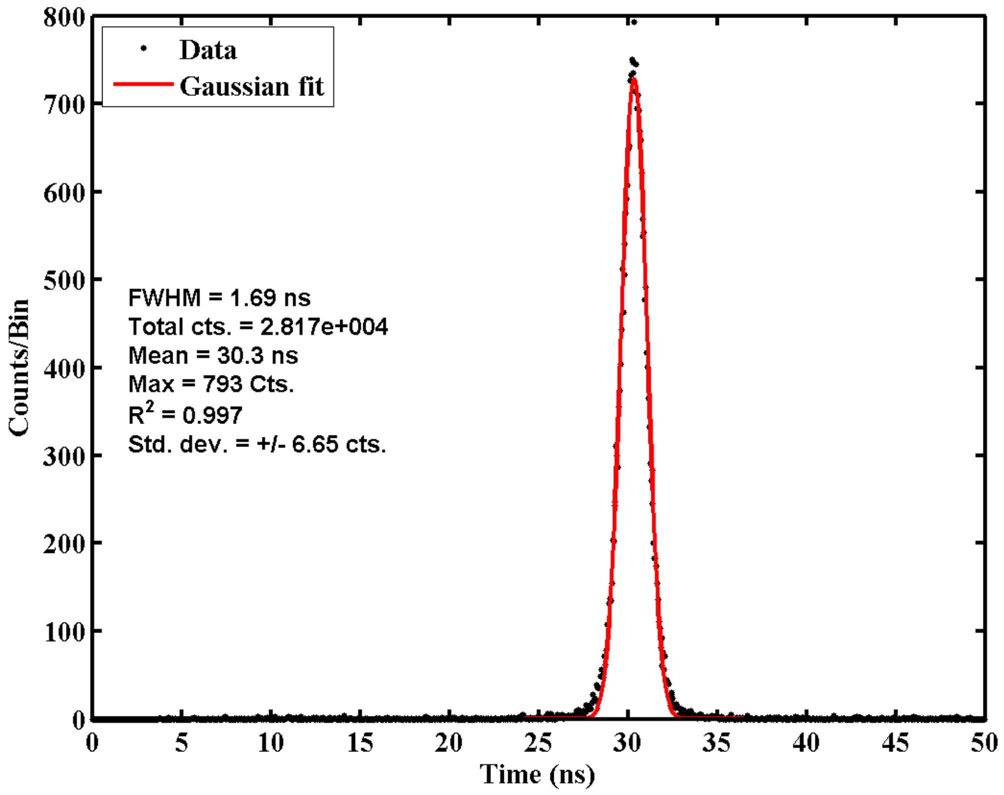
Data acquisition system for measuring IRF waveforms.

- Variability
  - Hamamatsu-mod 5, 1.6 to 2.4 kV
  - Photek-PMT240, 3.8-4.6 kV
  - NTOF discriminator, 8 – 50 mV (bias dependent)
  - SBD discriminator, 15 mV
  - Ion Potential, 50 keV and 175 keV
- IRF measurement
  - Viewed each PMT in primary and secondary coincidence modes
  - Collected and saved ~ 1000 waveforms per PMT per bias setting on the digitizer
  - Post processed data
- Coincident measurement
  - Established w/ 584 constant fraction and cable delay
  - Logic unit – start data acquisition
  - TAC – visual verification of coincidence curve and count rate monitor
- Individual rates
  - 110° α detector – infer incident neutron rate
  - Coincident PMT – infer tube counting efficiency
  - Logic unit – quality monitor of coincidence events
  - Current Integrator – monitor beam and target condition

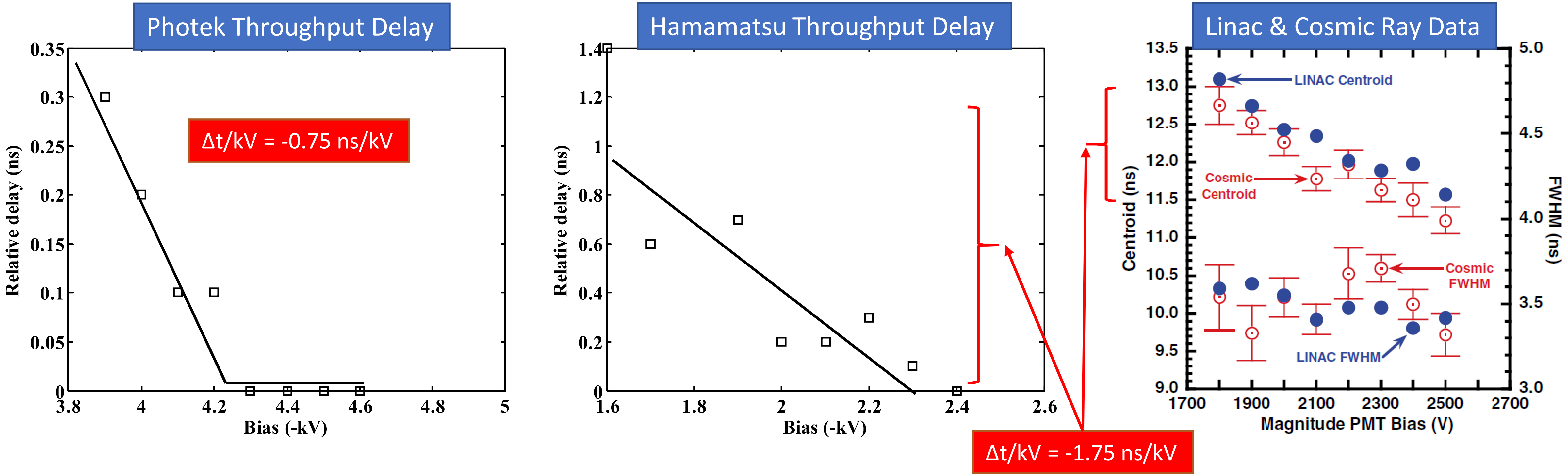


Observed coincidence curve is consistent with the timing determined from the kinematics.

- Cable delays with respect to SBD detector to establish coincidence
  - Hamamatsu – 54 ns delay
  - Photek – 63 ns delay
- Coincidence acquisition
  - 50 ns data acquisition window
  - ~ 50 ps resolution
- Observed quantities
  - 99.2% of counts are coincidence events
  - 0.8% of observed counts are random or incidental events
- Variable kinematics
  - Coincidence FWHM = 1.7 ns =
  - 1.1 ns (α) + .480 ns (scintillator) + .18 (n)



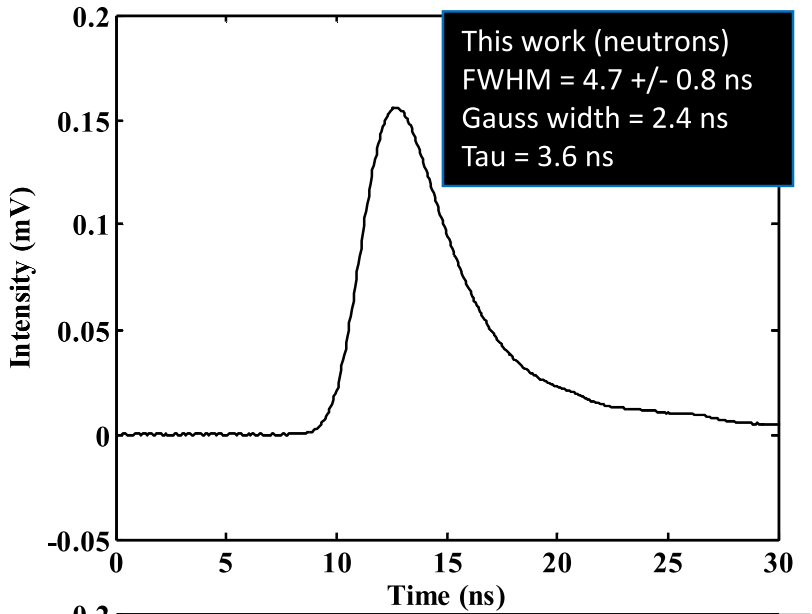
Relative throughput delay determined from the centroid shift in the coincidence curve as a function of applied voltage.

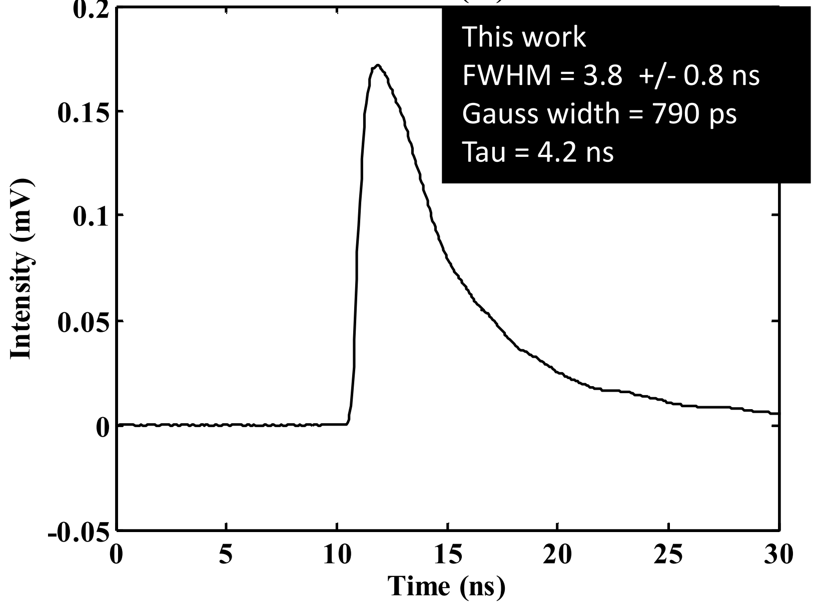


- Measured throughput delay for the Hamamatsu mod 5 is consistent with the measured value for the Hamamatsu mod 4 PMT
- Throughput delay observed for the Photek PMT240 is negligible. This is consistent with the dynode structure of the PMT.

Representative average IRF functions for both the Hamamatsu and Photek PMTs'.

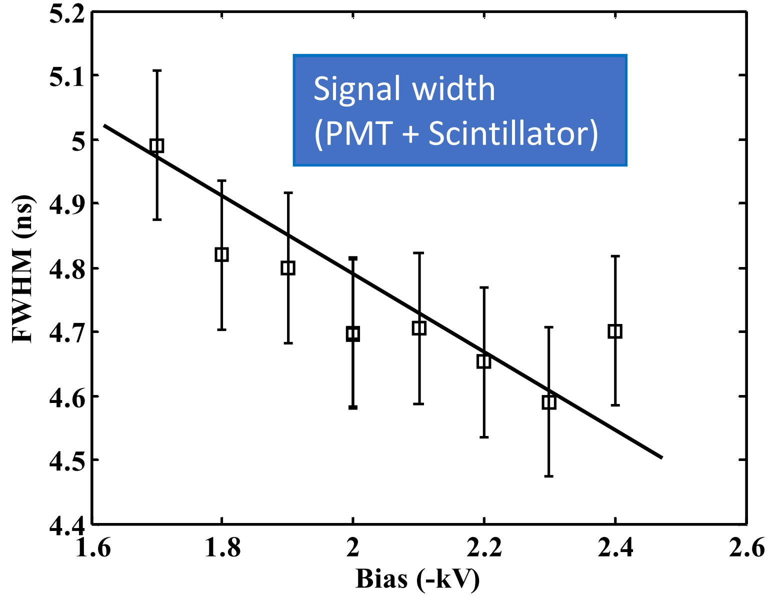
- Fit average waveform with exponentially modified Gaussian and extracted the following parameters:
  - FWHM (total width)
  - HWHM (Gaussian portion of the fit)
  - Tau (decay parameter)
- Uncertainty in width parameter determined from the distribution of the time stamp of leading edge
  - Uncertainty consistent with width of coincident measurement, FWHM ~ 1.7 ns or σ = 750 ps
- Comparison
  - Measured IRF is consistently 1.2 ns wider than the cosmic ray or LINAC data
  - Scintillator decay is larger than specified by the manufacturer (1.4 ns)
  - However, manufacturer only provides prompt decay information

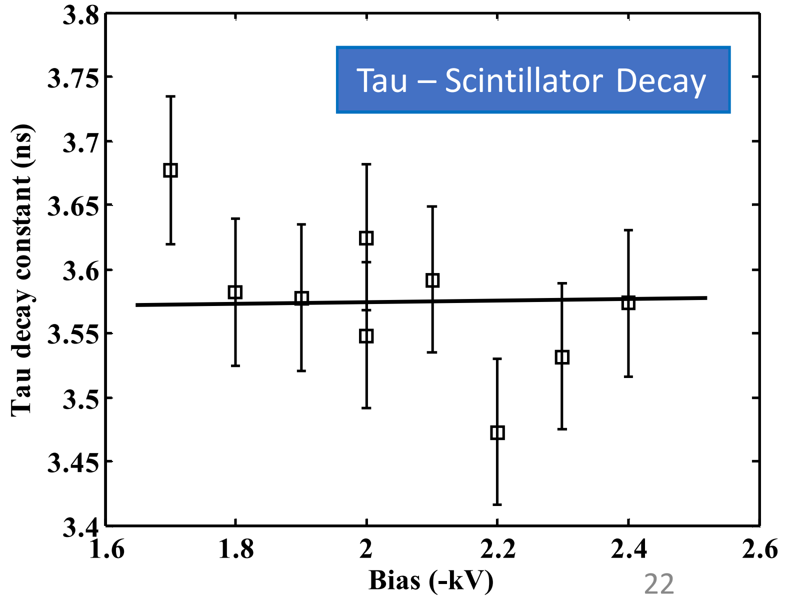




IRF Results as a function of bias for the Hamamatsu tube exhibit expected behavior.

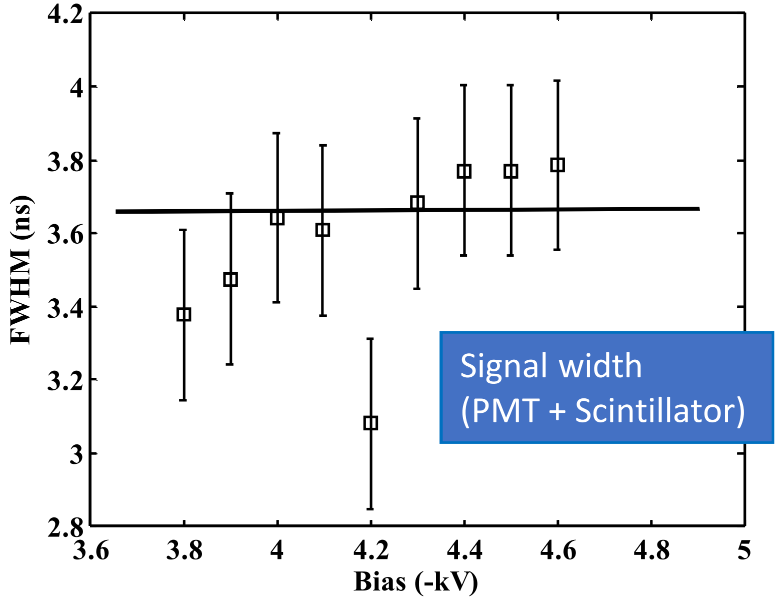
- Fit average waveform with exponentially modified Gaussian and extracted the following parameters:
  - FWHM (total width)
  - HWHM (Gaussian portion of the fit)
  - Tau (decay parameter)
- Comparison
  - Measured IRF is consistently 1.2 ns wider than the cosmic ray or LINAC data
  - Trend in FWHM is consistent with LINAC data
  - Gaussian width is consistent with expected values for Hamamatsu PMT
  - Scintillator decay is constant and is 2 ns larger than prompt decay specified by the manufacturer

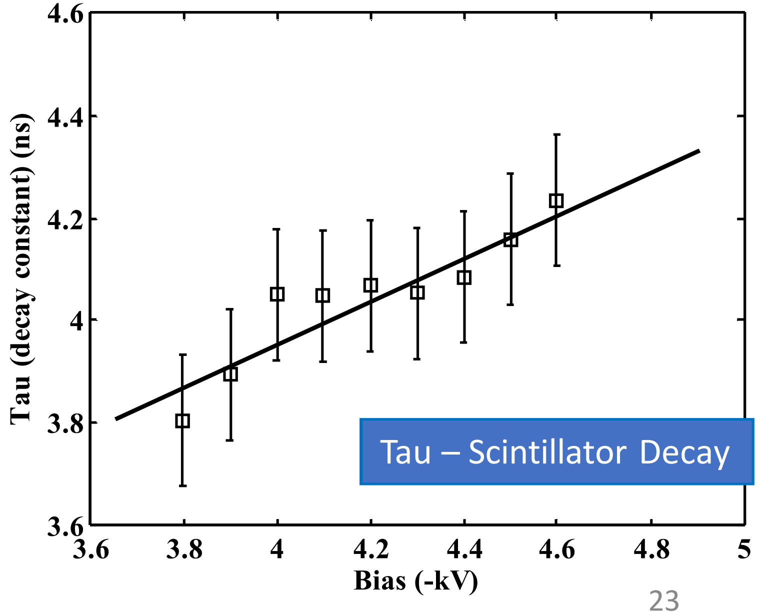




IRF Results as a function of bias for the Photek tube are consistent with expected values.

- Fit average waveform with exponentially modified Gaussian and extracted the following parameters:
    - FWHM (total width)
    - HWHM (Gaussian portion of the fit)
    - Tau (decay parameter)
- Comparison
    - Gaussian portion is consistent with 850 ps width specified by the manufacturer
    - Tau tends to increase as a function of bias, but still consistent with the value observed with the Hamamatsu
    - Similar width and structure obtained by LLNL time-correlated single photon counting technique (unpublished)



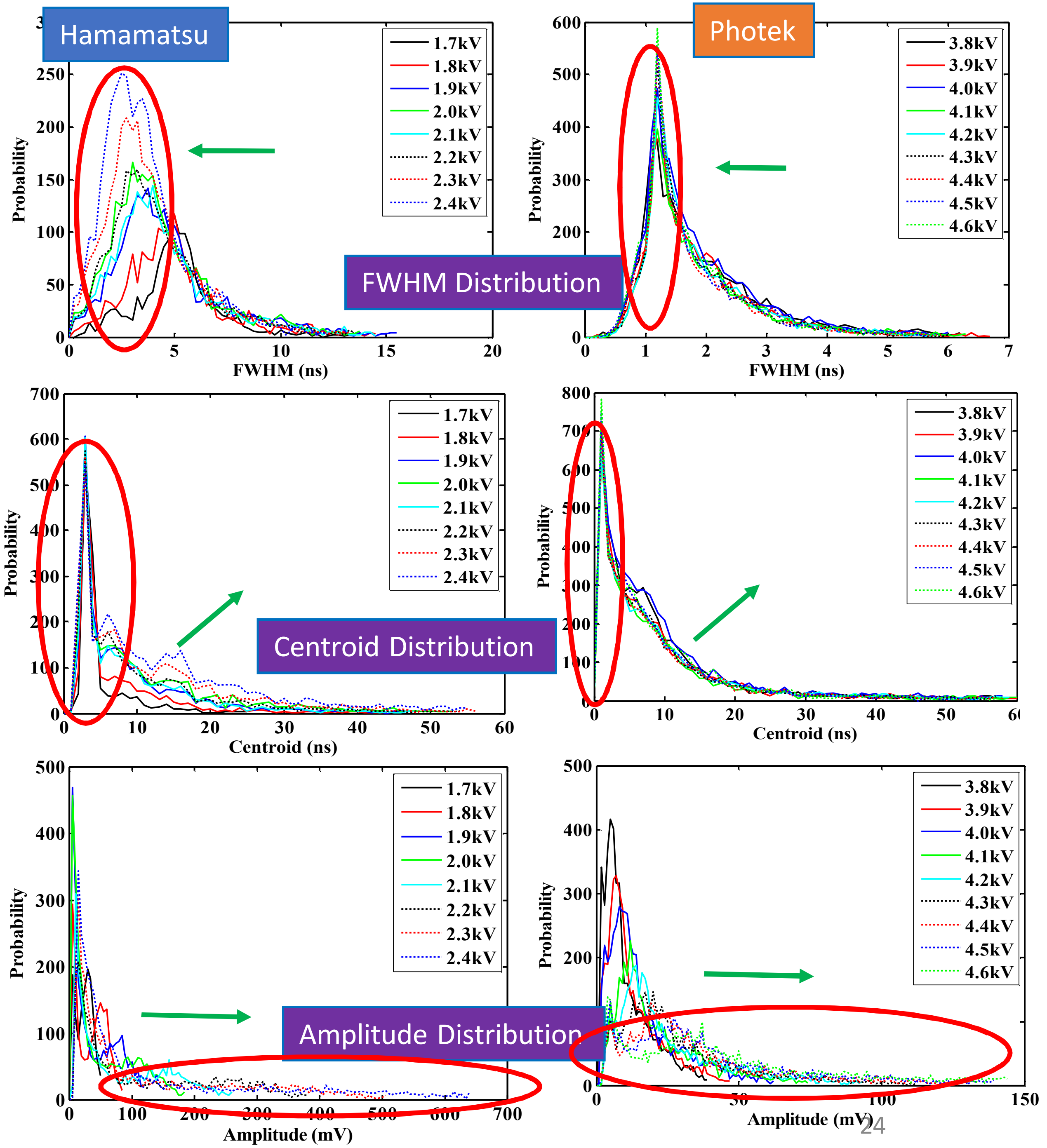


Results – IRF Individual peak analysis

- Fit individual peaks using a sum of Gaussians
- Generated probability distributions of the following parameters:
  - FWHM (total width)
  - Centroid location
  - Amplitude and Sensitivity (Area under each peak)
- Data is qualitative due to poor statistics in signal quality
  - 50 ps resolution in acquired data
  - Analysis required smoothing data to 500 ps for the Photek and 0.8 to 1.8 ns for the Hamamatsu
- Parameters are heavily correlated
  - Large fraction of peaks later in time have very small amplitudes
  - Peaks later in time have wider widths
- Comparison
  - FWHM values are comparable to avg. values
  - Centroid distribution has ~ 5 ns decay, comparable to 3.6 ns avg. decay if resolution is considered
  - Continuum in amplitude distributi

Note: Bias Increasing

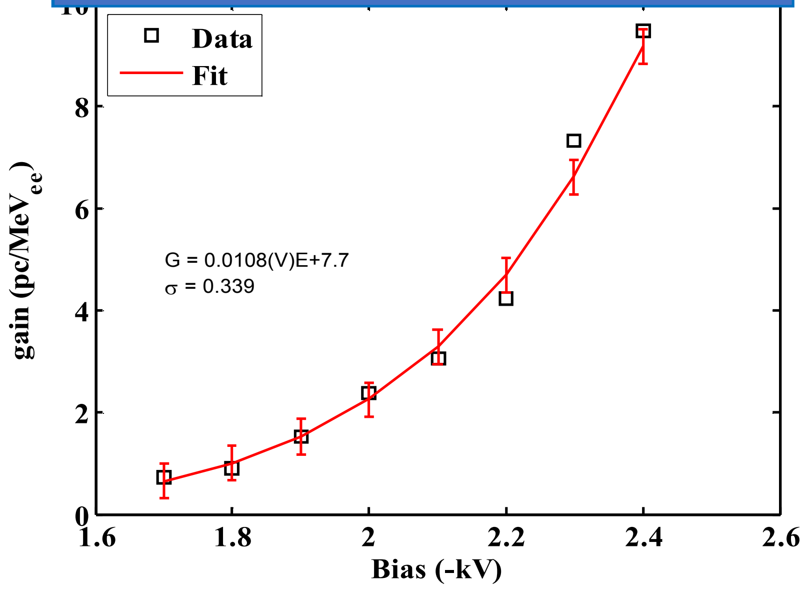
Note: Correlated data



The detector gain can be expressed as the MeVee constant as a function of bias and the avg. sensitivity is the product of the gain and the average light output value.

- Gain and sensitivity determined for both the Hamamatsu and the Photek
  - Gain is MeVee constant as a function of detector bias
  - Sensitivity proportional to gain and defined here as pC/interacting neutron
    - This definition of sensitivity is more useful for implementing into MCNP
- Sensitivity can be derived from this work in terms of pC/incident neutron
  - Requires knowing count rate and discriminator/energy equivalence
  - Values obtained here, with this correction, agree with previous experimental work at the Primary Standards Lab

Type equation here.Extracted gain curve for the Hamamatsu as a function of bias



Light output correlation used in Stanton code

$$Ly(MeVee) = -10.68(1 - \exp(-.007E^{0.89}) + .929E$$

Inferring average detector sensitivity

$$\bar{\epsilon}\left(\frac{pC}{interacting\ neutron}\right) = Gain * Ly(\bar{E})$$