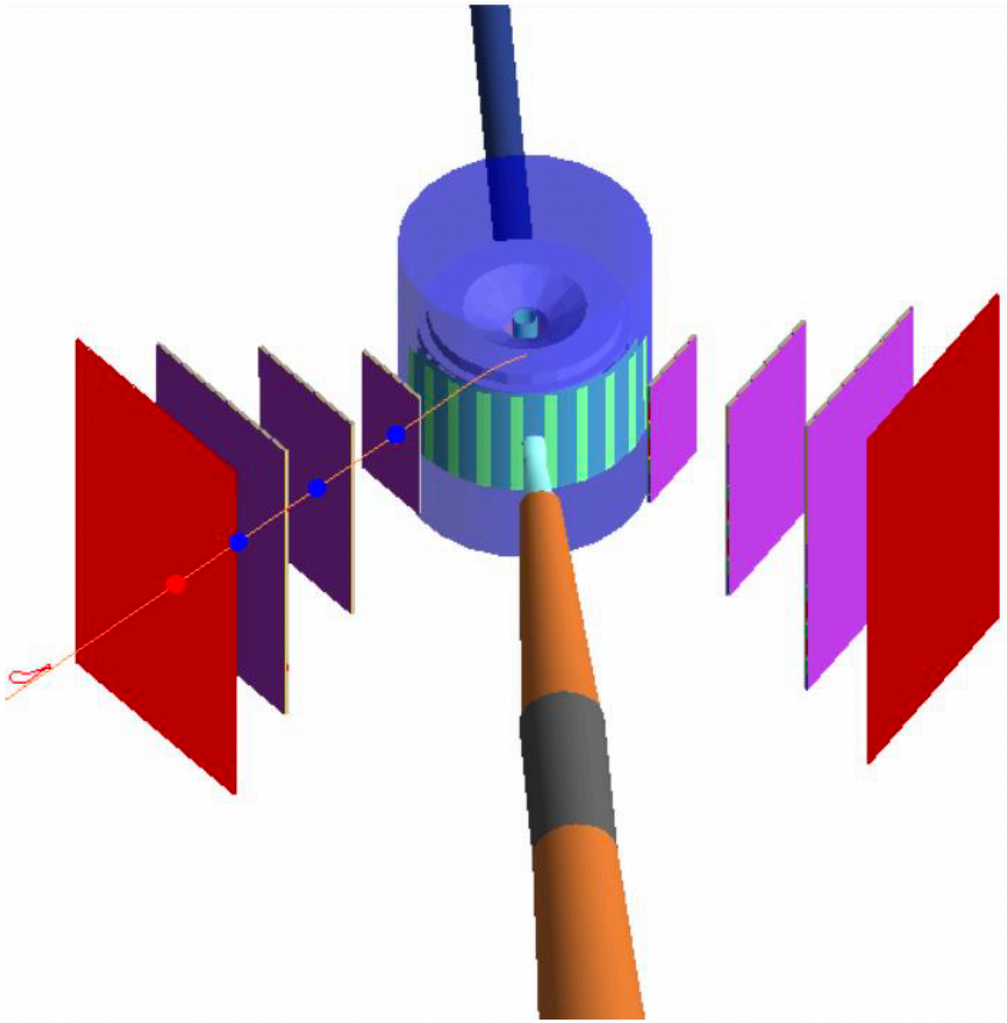
TOF Simulations

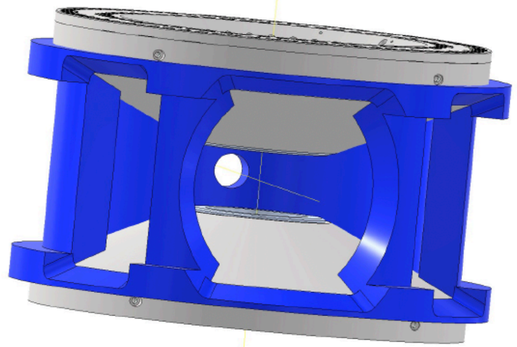


Nilanga Wickramaarachchi

Duke

Recoil detector

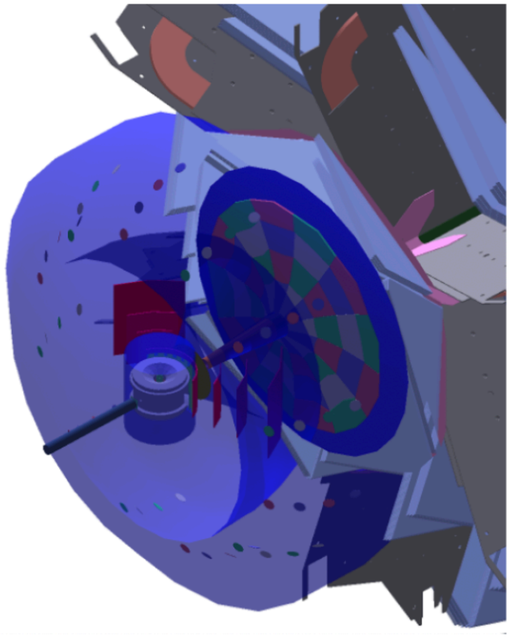
- Protons below 30 degrees will be detected in the CLAS12 forward detector
- Dedicated recoil detector to detect protons at large angles (30-70 degrees)
- Use left and right openings of the magnet structure

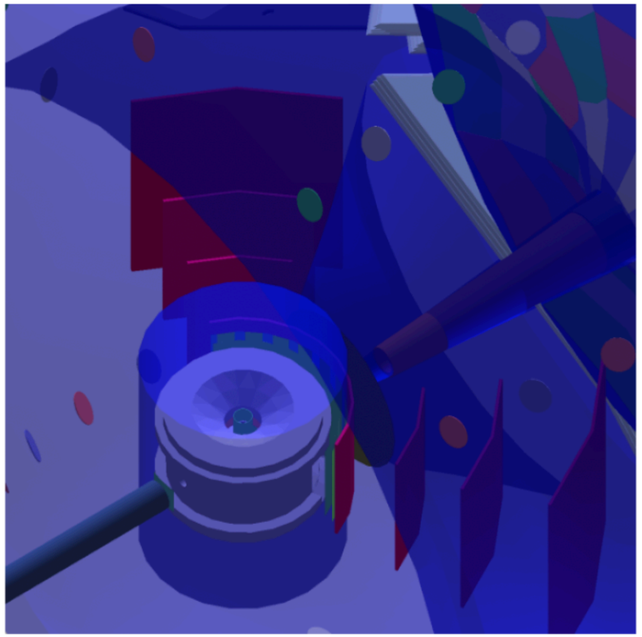


- 2 sectors each having 3 tracking planes (μRwell) and one time-of-flight (TOF)

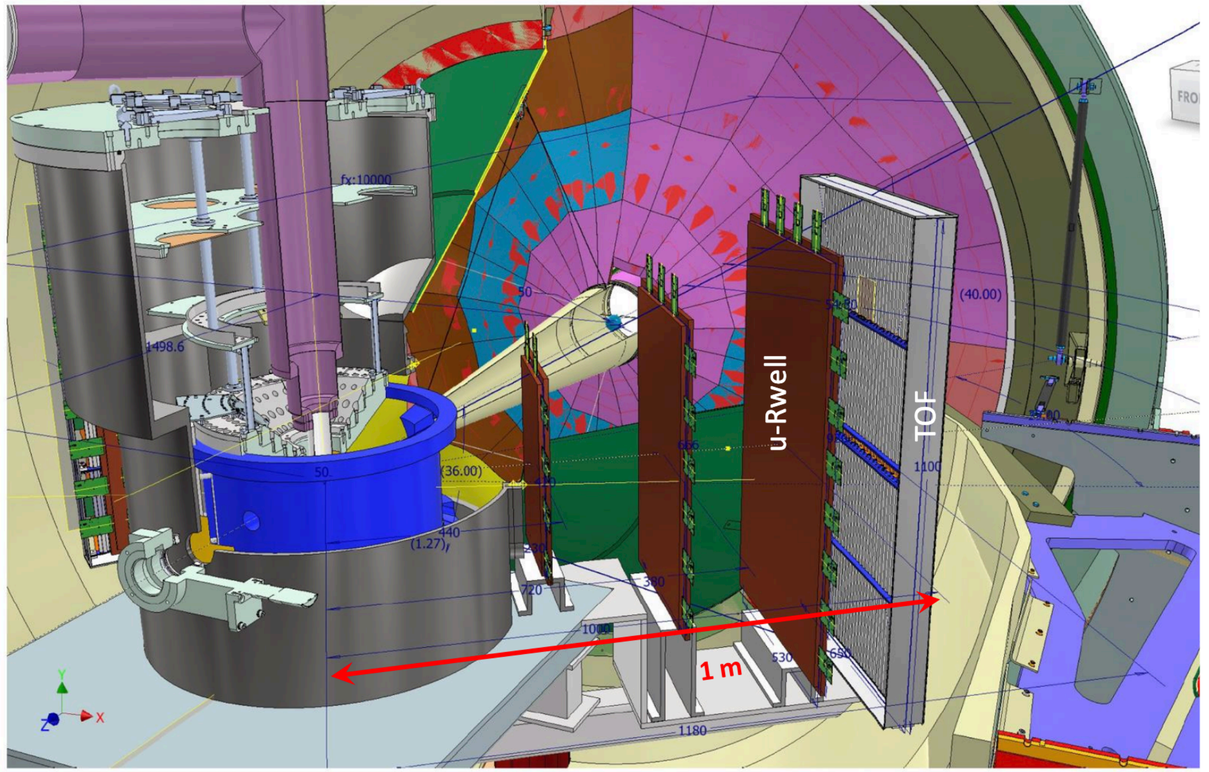
Plane	Name	Distance from IP (mm)	Width (mm)	Height (mm)
1	Tracker Region 1	440	230	420
2	Tracker Region 2	720	380	670
3	Tracker Region 3	1000	530	920
4	Time-of-flight	1180	650	1100

Recoil detector geometry





GEMC Simulation



Recoil TOF

- Plane of scintillating bars readout by SiPM (2 at the front and back ends of the bar)
- Timing resolution better than 100 ps
- Compact detector fitting into HTCC envelope maximizing acceptance

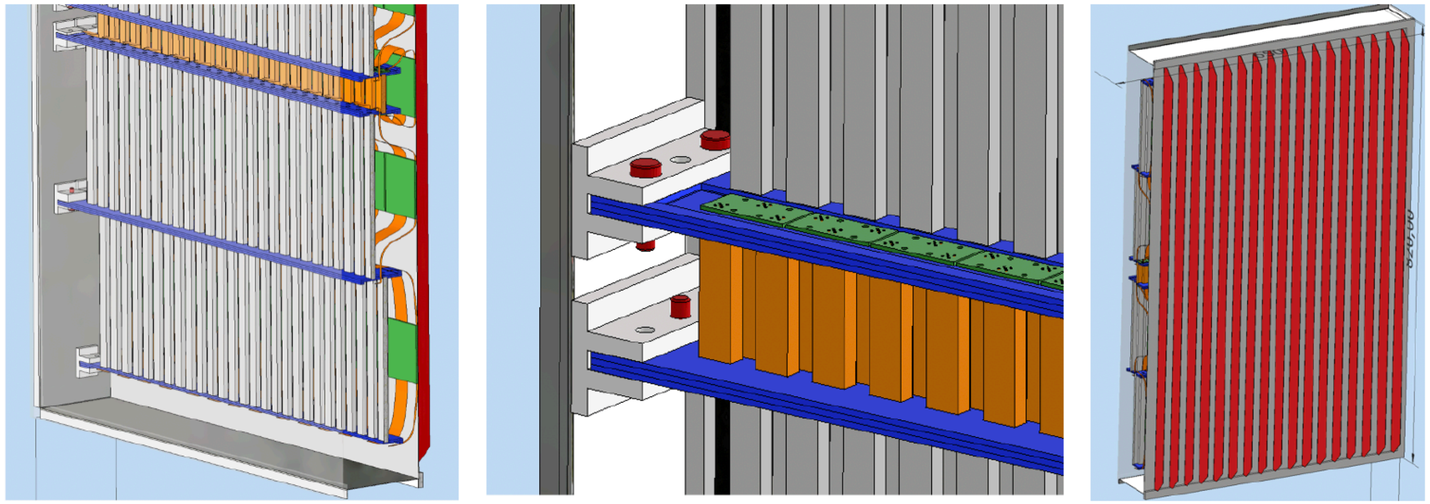


Fig. 37: Concept for the RGH recoil TOF. The timing wall is composed by arrays of vertical scintillating bars readout by SiPMs with the front-end electronics mounted on the downstream support structure (left). Detail of the frame fixing the bars and mounting the sensors (center). The support structure provides cooling and services (right).

Background rates

- Shorter bars at the center to mitigate rate of background accidentals
  - < 200 kHz per readout channel

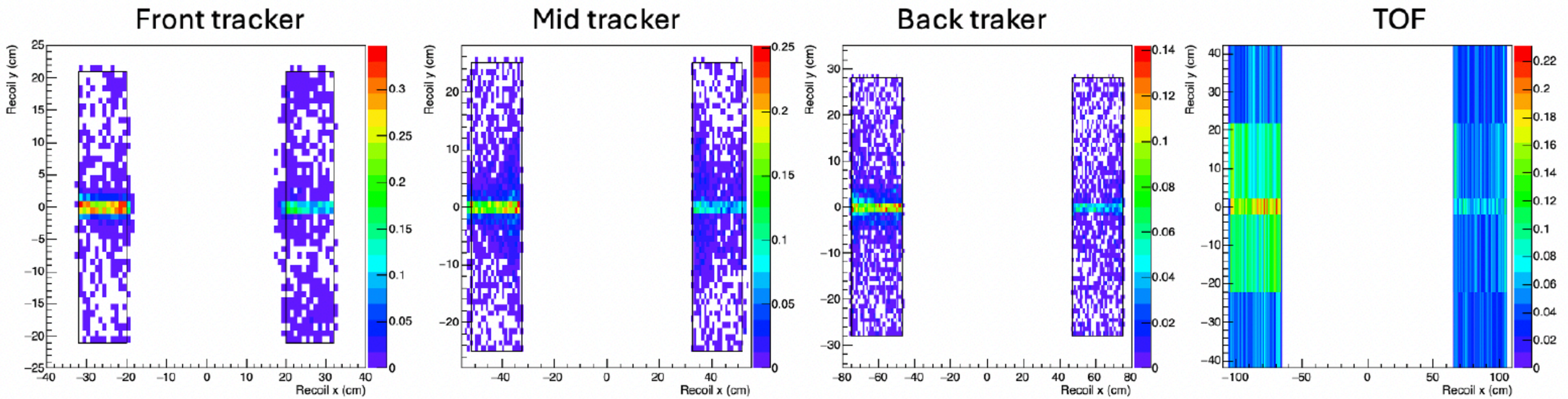
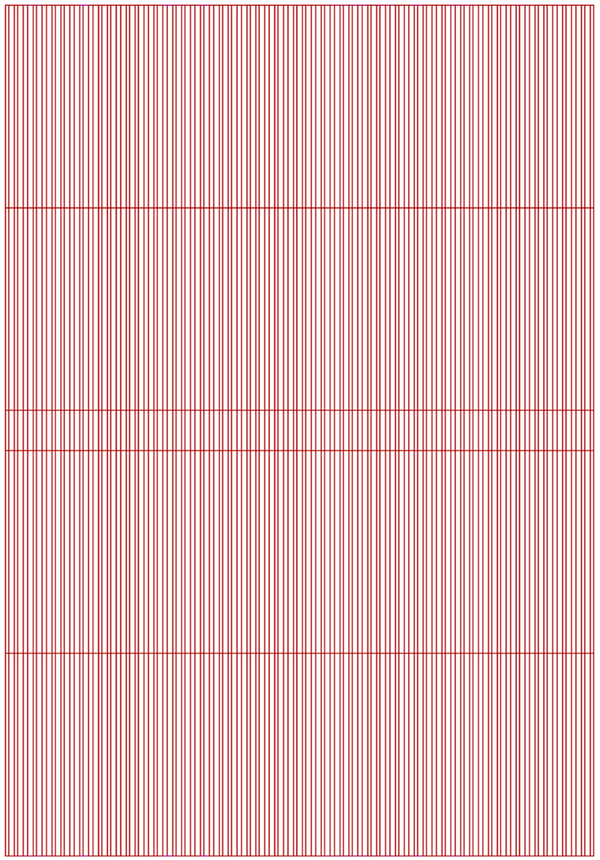


Fig. 36: Expected background rate on the RGH recoil detection planes expressed in MHz/cm^2 for tracking (first three panels) and MHz/ch for TOF (last panel).

GEMC/COATJAVA implementation of Recoil TOF

View in GEMC



1140 x 630 x 5 mm
(L) (W) (T)

Parameters in COATJAVA

```
public class RTOFConstants {

    public final static int NSECTORS    = 2;    //number of sectors
    public final static int NROWS     = 5;    //number of rows of bars in a sector
    public final static int NCOLUMNS   = 63;    //number of columns of bars in a sector

    public final static double LONG_BAR_LENGTH = 27.5; // cm
    public final static double SHORT_BAR_LENGTH = 4; // cm

    public final static double BAR_WIDTH = 1; // cm
    public final static double BAR_THICKNESS = 0.5; // cm

    public final static double HORIZONTAL_STARTING_ANGLE = 40.;
    public final static double HORIZONTAL_OPENING_ANGLE = 29.;
    public final static double RADIUS = 122.; // cm

    public final static double WIDTH = NCOLUMNS * BAR_WIDTH;
    public final static double LENGTH = (NROWS-1) * LONG_BAR_LENGTH + SHORT_BAR_LENGTH;
    public final static double THICKNESS = 0.5; // cm
```

Digitization

- Followed the implementation used for ALERT TOF (ATOF)
  (https://indico.jlab.org/event/928/contributions/16256/attachments/12275/19445/atof_reconstruction_clas_meeting_march_2025.pdf)

  https://github.com/niwgit/clas12Tags/blob/recoil_tof/source/hitprocess/clas12/recoil_tof/recoil_tof_hitprocess.cc

```
double attlength = 1600.0; // Attenuation length in mm (EJ-204: 160 cm; geometry uses mm)
double pmtPEYld  = 10400.0; // Photon yield for EJ-204 scintillator (photons / MeV)
double dEdxMIP   = 1.956;  // Energy loss of a MIP in scintillator (MeV/cm)
```

- Calculate energy deposited on the front and back SiPMs based on the hit position in the bar and attenuation length
- Sum over all Geant4 steps to get total energy deposited
- Calculate mean number of photons and smear the number of photons with a Poisson distribution
- Then calculate energy again to propagate resolution into ADC
- For TDC use energy-weighted time smeared with a Gaussian
  ($\sigma = 100$ ps for long bars and $\sigma = 50$ ps for short bars)

Digitization

- RecoilTOF hits are recorded in the RECOILTOF::tdc bank in gemc output hipo file

```
[Choose (n=next,p=previous, q=quit, h=help), Type Bank Name or id : n
*** event *** ::: tag = 0 mask = 00000000000000000000000000000000 size = 390 node count = 0
   0 |                    MC::Particle |       40 |        2 |        1 |       94 |       32
   1 |                        MC::True |       40 |        4 |        2 |      172 |      210
   2 |                     RASTER::adc |    22200 |       11 |        2 |      134 |       30
   3 |                  RECOILTOF::tdc |    22700 |       12 |        2 |       62 |       24
   4 |                     RUN::config |    10000 |       11 |        1 |       16 |       38

[Choose (n=next,p=previous, q=quit, h=help), Type Bank Name or id : RECOILTOF::tdc
 position for [RECOILTOF::tdc ] == 62
* NODE * group =  22700, item =  12, type = 11, size =       24
        sector :          2          2
           row :          4          4
        column :         31         31
         order :          0          1
           TDC :        574        655
           ToT :       3000       2500
```

- order - front / back SiPM
- TDC - time * 1/0.015625 (64 counts per ns)
- ToT - Time over Threshold

Reconstruction

- Combine information from up/downstream (order, TDC, ToT) hits to create a RTOFHit
  - Two hits should be in the same sector, row and column but different order
  - Local Y coordinate calculated using times of up and downstream hits
    - Time = TDC * TDC2Time
    - LocalY = $V_{eff}/2$ * $Time_{up\ hit}$ - $Time_{down\ hit}$

TDC2Time = 0.015625

Veff = 200 mm/ns

  - Local Y coordinate converted to global coordinate system
- RTOFHit time is set as the time of the most energetic hit and corrected for propagation time
- Energy of the up/downstream hits is corrected for attenuation
  - Energy = ToT * ToT2Energy

ToT2Energy = 1.956*0.5/1000 (MeV)

- Energy of the RTOFHit is the sum of the energy of the up/downstream hits

Reconstruction

- Create clusters using the RTOFHit objects
- Hits are compared based on

  Y difference $\rightarrow \Delta Y < 40$ mm

  Time difference $\rightarrow \Delta T < 100$ ns

- Cluster coordinates and time are defined as the coordinates and time of the max energy hit

RTOF::hits

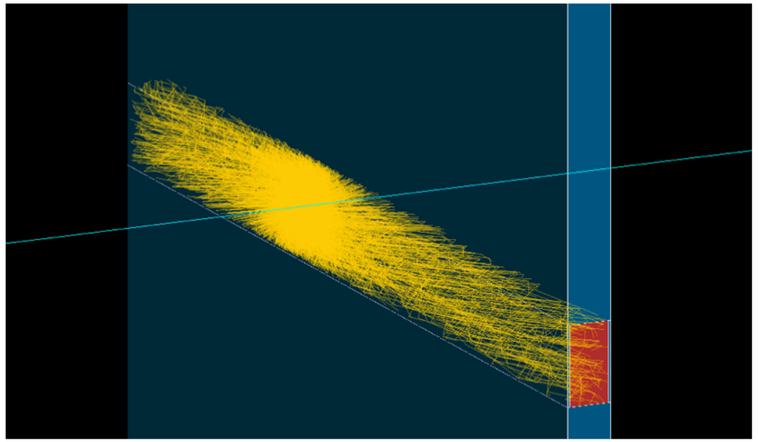
id :	1
sector :	2
row :	4
column :	31
time :	8.9141
x :	987.4139
y :	284.0625
z :	716.5988
energy :	5.8379
clusterid :	1

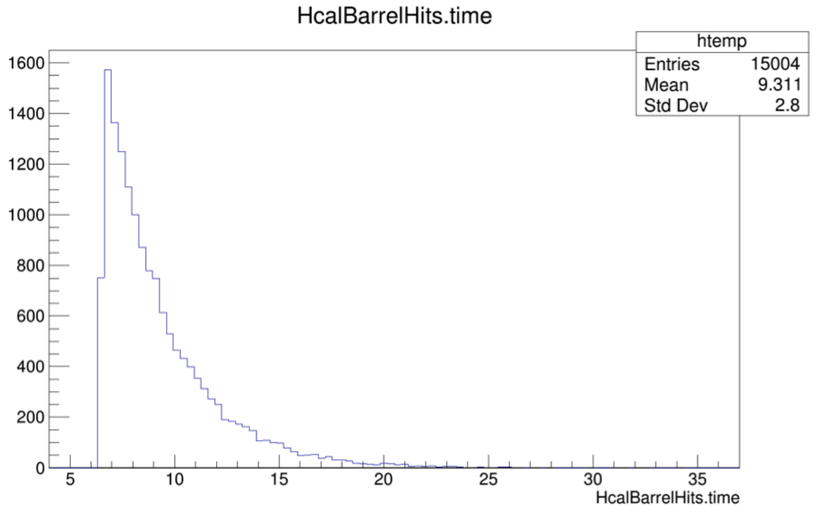
RTOF::clusters

id :	1
N_bar :	1
sector :	2
time :	8.9141
x :	987.4139
y :	284.0625
z :	716.5988
energy :	5.8379

Photon timing from simulation

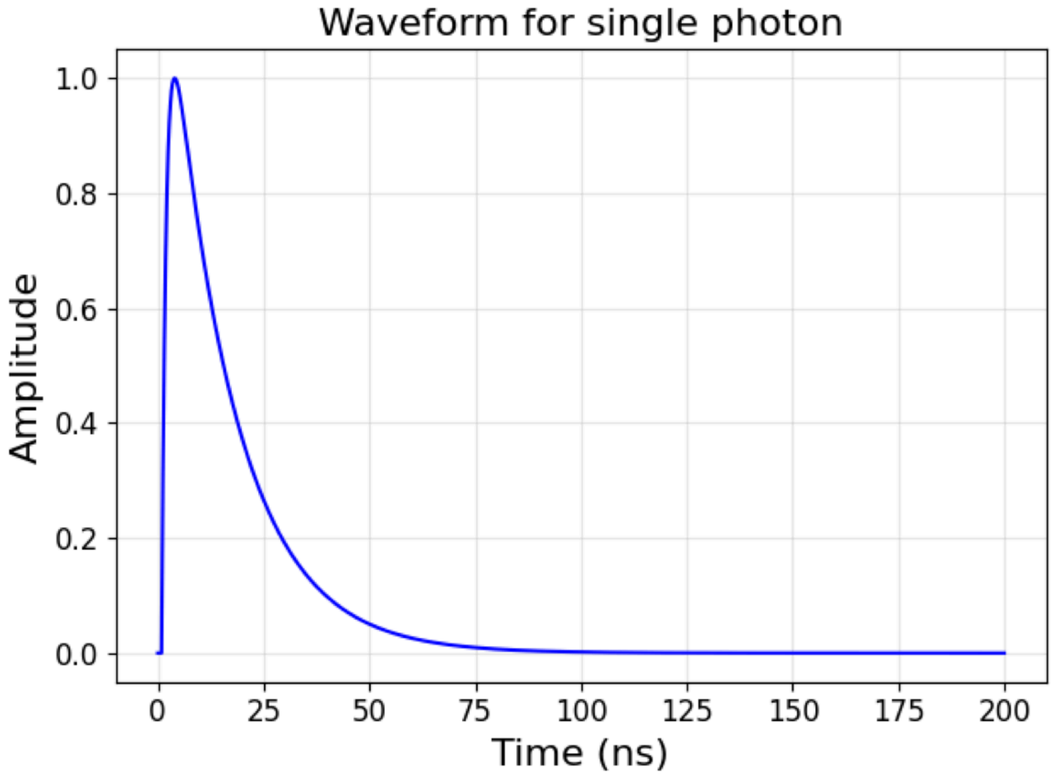
- Scintillator simulated based on EIC KLM geometry in DD4hep
- Just one scintillator bar and a sensor plane at one end of the bar
- 5 GeV/c protons were shot towards scintillator (used Theta = 90 deg)
  - Later changed momentum to 0.5 GeV/c to remove Cherenkov photons
- Photon hit time available in the output
- Subtracted time for track to reach the end of bar from photon hit time
- Look at time of first photon to reach a pixel and at least 10 unique pixels hit was required for each event
- Use a Gaussian to fit first photon arrival time distribution and get timing resolution





Photon hit time (ns)
120x10x5 mm bar

Including pulse shape

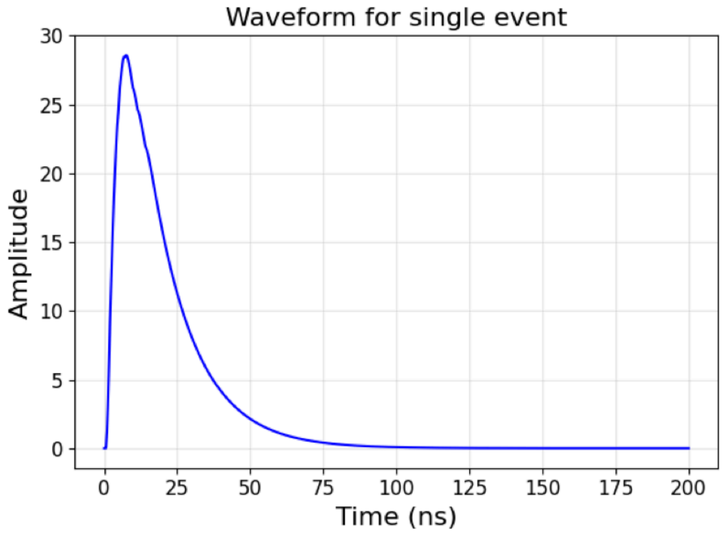


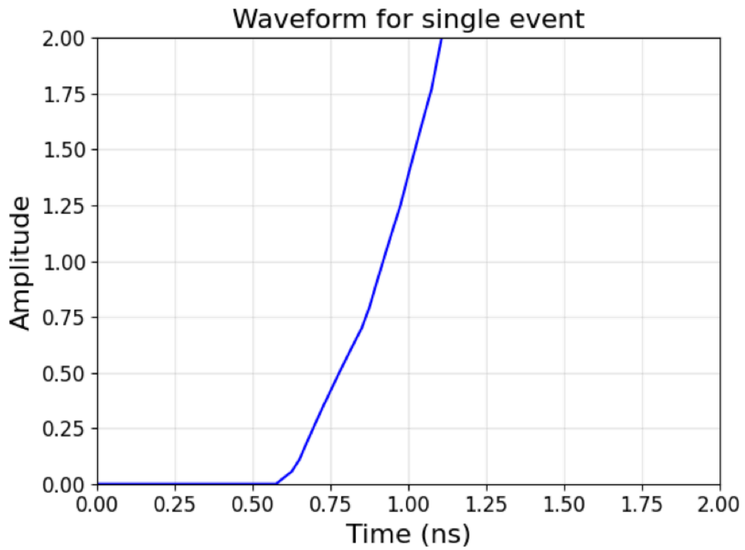
Pulse shape model

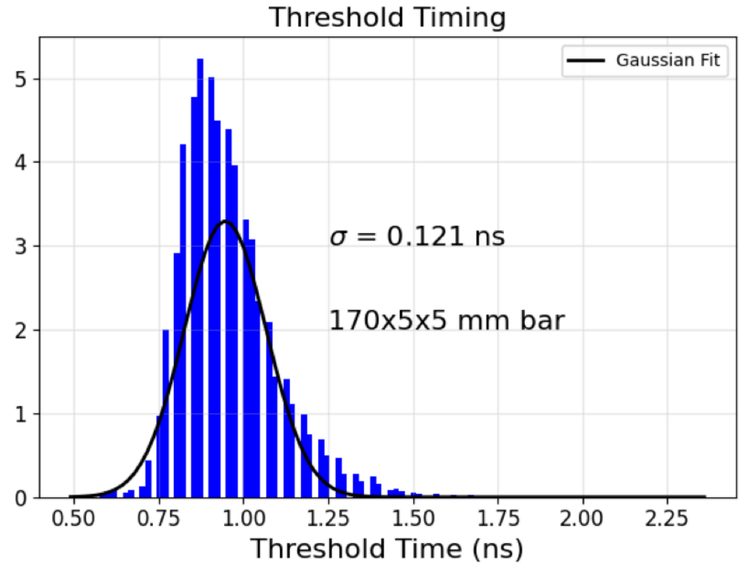
$\exp(-t/\tau_{Fall}) - \exp(-t/\tau_{Rise})$

Rise time = 1.1 ns
Fall time = 15 ns

- For a single photon pulse shape was normalized to have maximum 1
- A pulse was added for each photon arrival time in the event
- The time where the pulse starts is based on photon arrival time





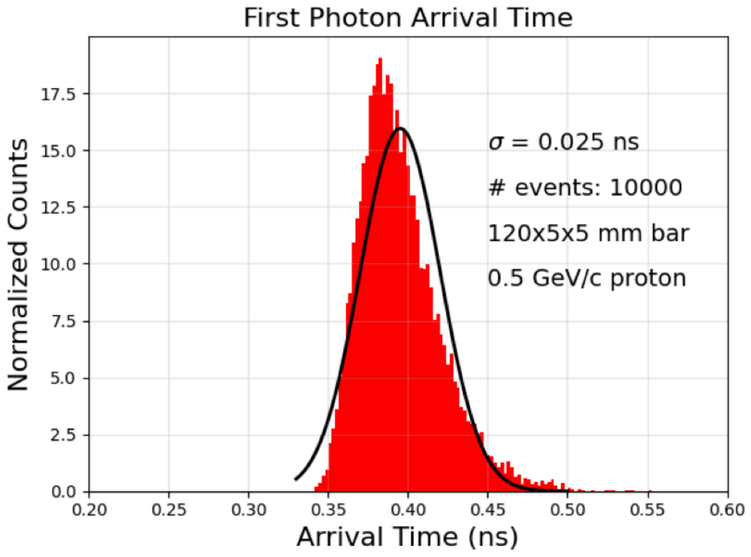


All events

- For each event find the time where the amplitude reaches 1
  - Threshold for 1 photon
- Fit the threshold time distribution with Gaussian and extract timing resolution
- Compare with PANDA measurements
  M. Böhm et al 2016 JINST 11 C05018
- Scale resolution values by ratio of areas of sensors used
  scale factor = sqrt[(3x3)/ cross section of bar]

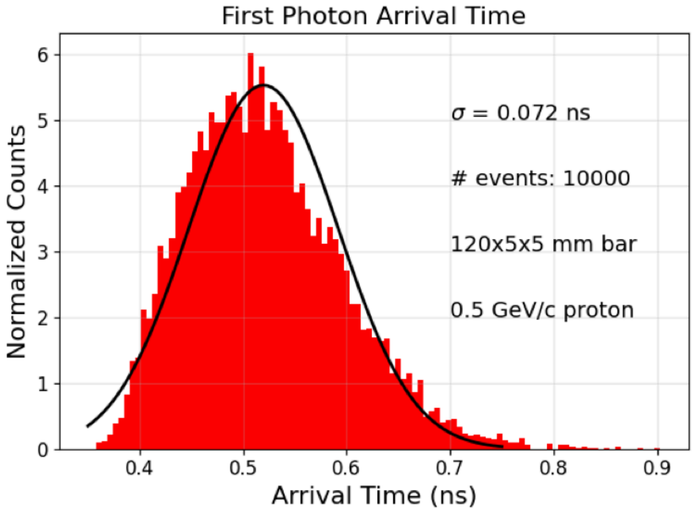
Effect of including rise time of scintillating material

- Including rise time give consistent time resolutions from two methods



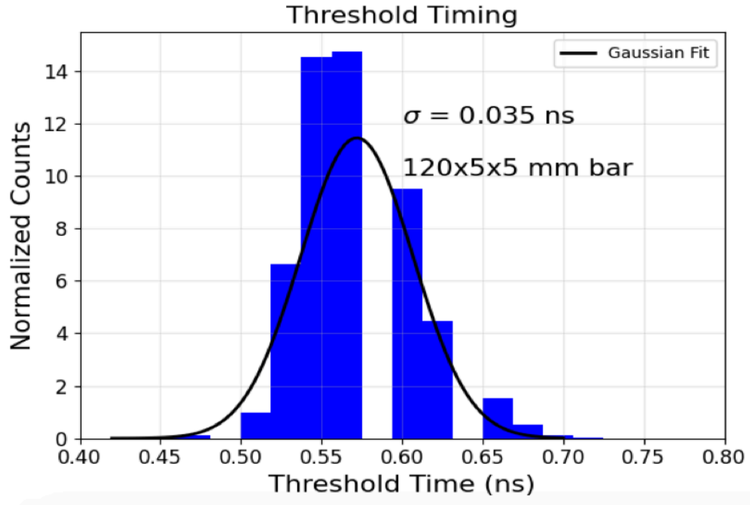
BC408 material

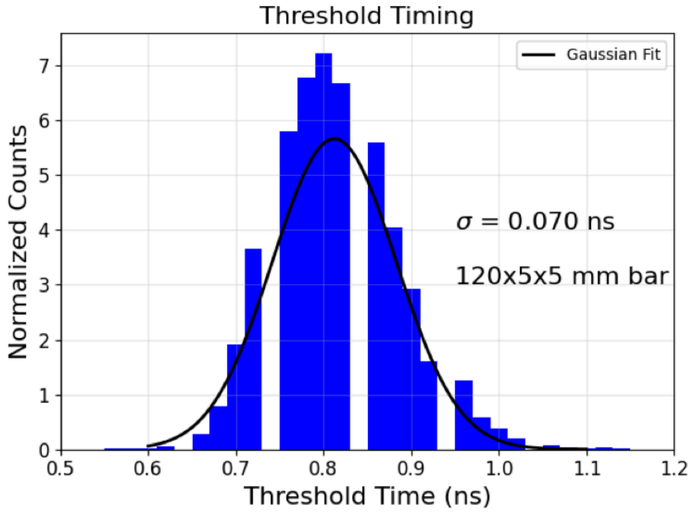
Rise time = 0
Decay time = 2.1 ns



BC408 material

Rise time = 0.9 ns
Decay time = 2.1 ns





Timing resolution results – 0.5 GeV/c

Bar dimensions (mm) L x W x T	Time Resolution (ps) - without electronics	Time Resolution (ps)	Scale factor	New time resolution (ps)	PANDA resolution BC408 (ps)	PANDA resolution BC420 (ps)
170 x 5 x 5	90	87	0.6	145	97 +- 19	
120 x 5 x 5	72	70	0.6	117	81 +- 12	68 +- 10
50 x 5 x 5	43	43	0.6	72	83 +- 6	62 +- 5
120 x 10 x 5	53	49	0.42	117	105 +- 18	93 +- 25
50 x 10 x 5	33	31	0.42	74	109 +- 16	

Conclusions from timing resolution studies

- With rise time included for scintillator material time resolutions are consistent between using first photon arrival time and threshold timing
- Shorter bar gives better timing resolution
- Wider bar gives better timing resolution (more sensor area)
- When scaled to account different sensor areas time resolution does not depend on width of bar
- No clear agreement with PANDA results

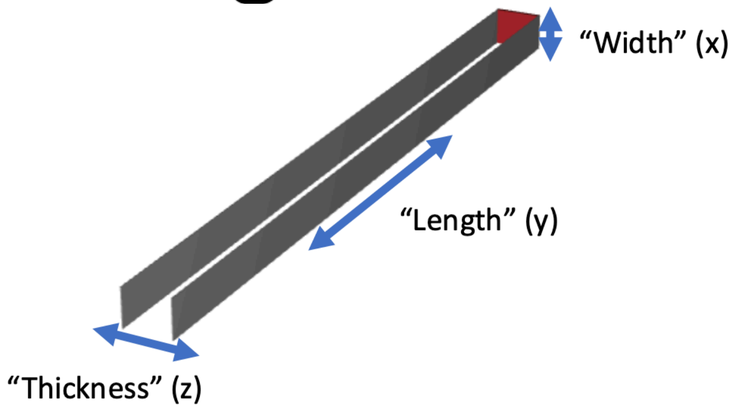
From Tyler Hellstern (Duke)

Generating a Lookup Table for $\sigma(L, W, T)$

- Based on this single bar simulation, I can calculate the timing resolution for different combinations of bar dimensions and plug this into the gemc simulation
- I generated a Look Up Table of sigma values for different (L,W,T) coordinates. I use linear interpolation to create an approximate function for sigma to be used in the existing gemc simulation.
- Here is where I correct for SiPM size by scaling by a factor related to the cross sectional area: $\left(\frac{A_{SiPM}}{A_{bar}}\right)^{-\frac{1}{2}}$
  - Assuming a 6x6 mm SiPM coverage
- Chosen range of values in the table:

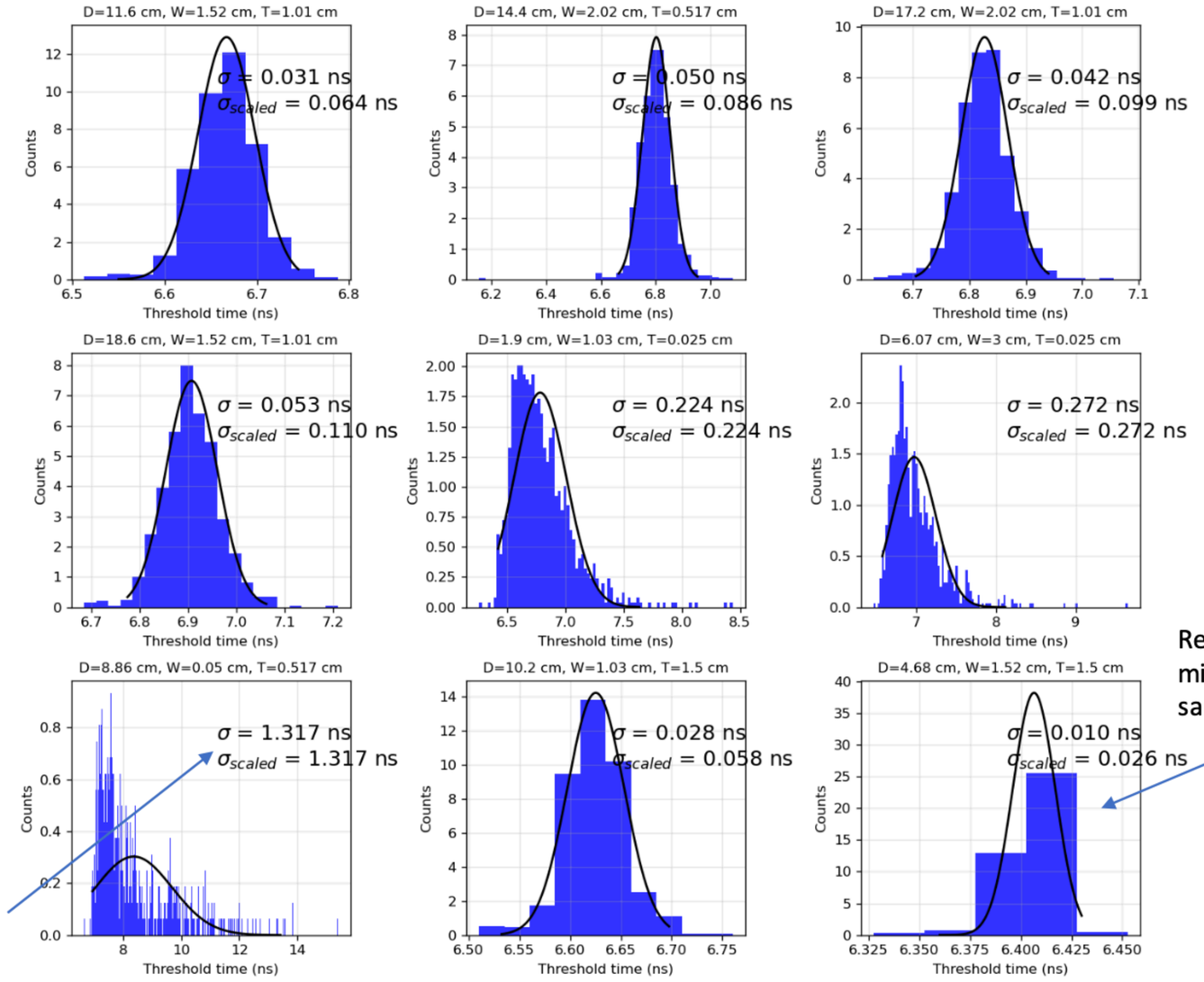
```
number of simulations to run: 420
L values: [1.0, 3.79, 6.57, 9.36, 12.14, 14.93, 17.71, 20.5, 23.29, 26.07, 28.86, 31.64, 34.43, 37.21, 40.0] cm
W values: [0.5, 5.42, 10.33, 15.25, 20.17, 25.08, 30.0] mm
T values: [0.25, 5.17, 10.08, 15.0] mm
L step: 2.79 cm, W step: 4.92 mm, T step: 4.92 mm
```

Visualizing the Lookup Table



- Bin width set by sampling rate (0.025ns)
- Scaled value is the corrected time resolution assuming a 6x6 mm SiPM

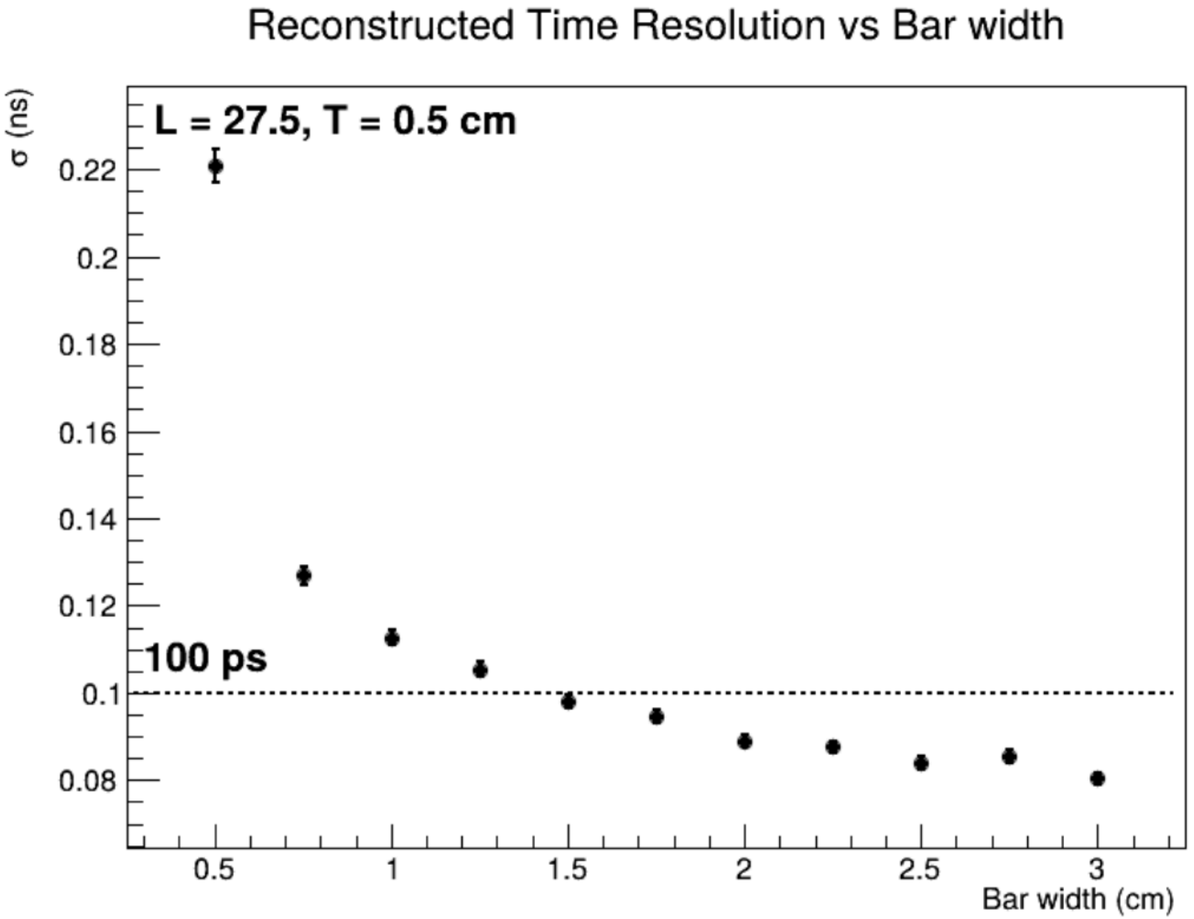
Random Sample of 9 Simulations in the Table:

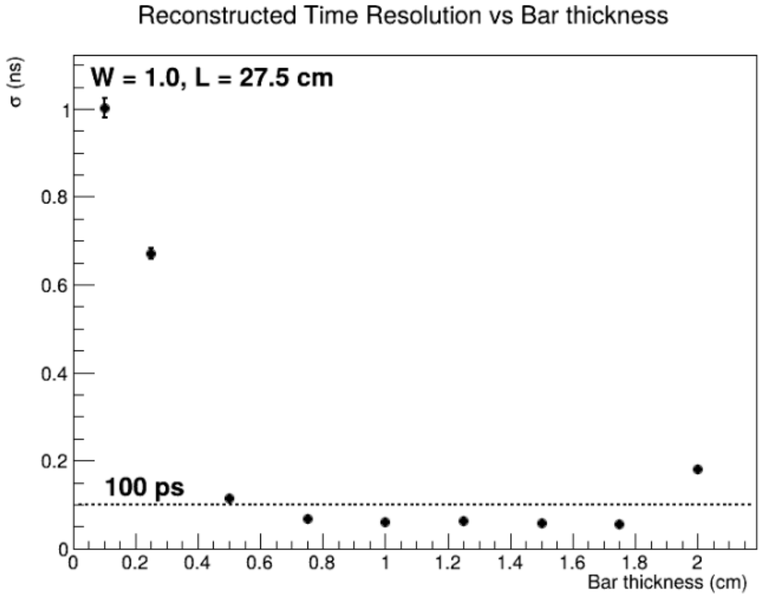


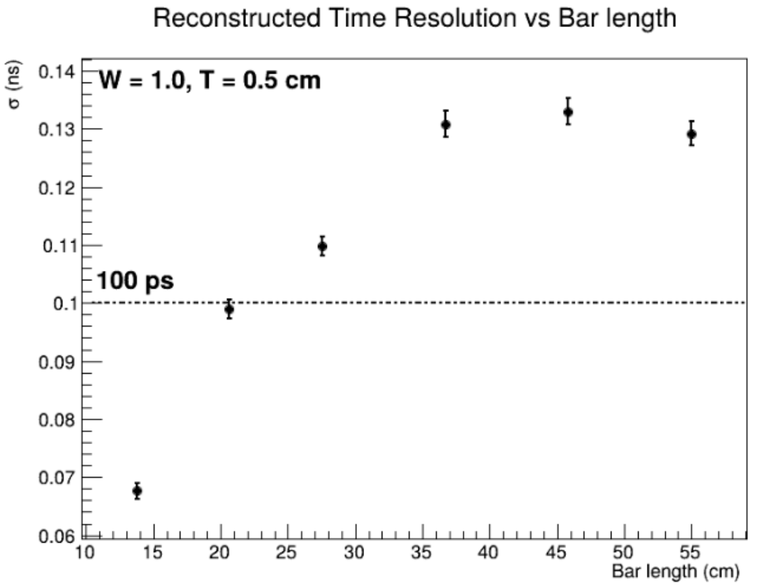
Resolution minimum due to sampling rate

Scale factor of 1 when the cross section of the bar is smaller than the SiPM

Plugging Lookup Table into full ToF gemc sim:







Current dimension values used in GEMC
(27.5, 1, 0.5) gives ~100 ps timing resolution!

Summary and outlook

- Recoil TOF detector simulation and reconstruction has been successfully implemented with GEMC and COATJAVA
  - COATJAVA part of code has been merged to the development branch (PR #1312)
  - GEMC part of code hasn't been merged yet (need minor modifications)
- Studies using scintillation photon simulations show 100 ps timing resolution is achievable
  - Tools are available to optimize time resolution with respect to bar dimensions