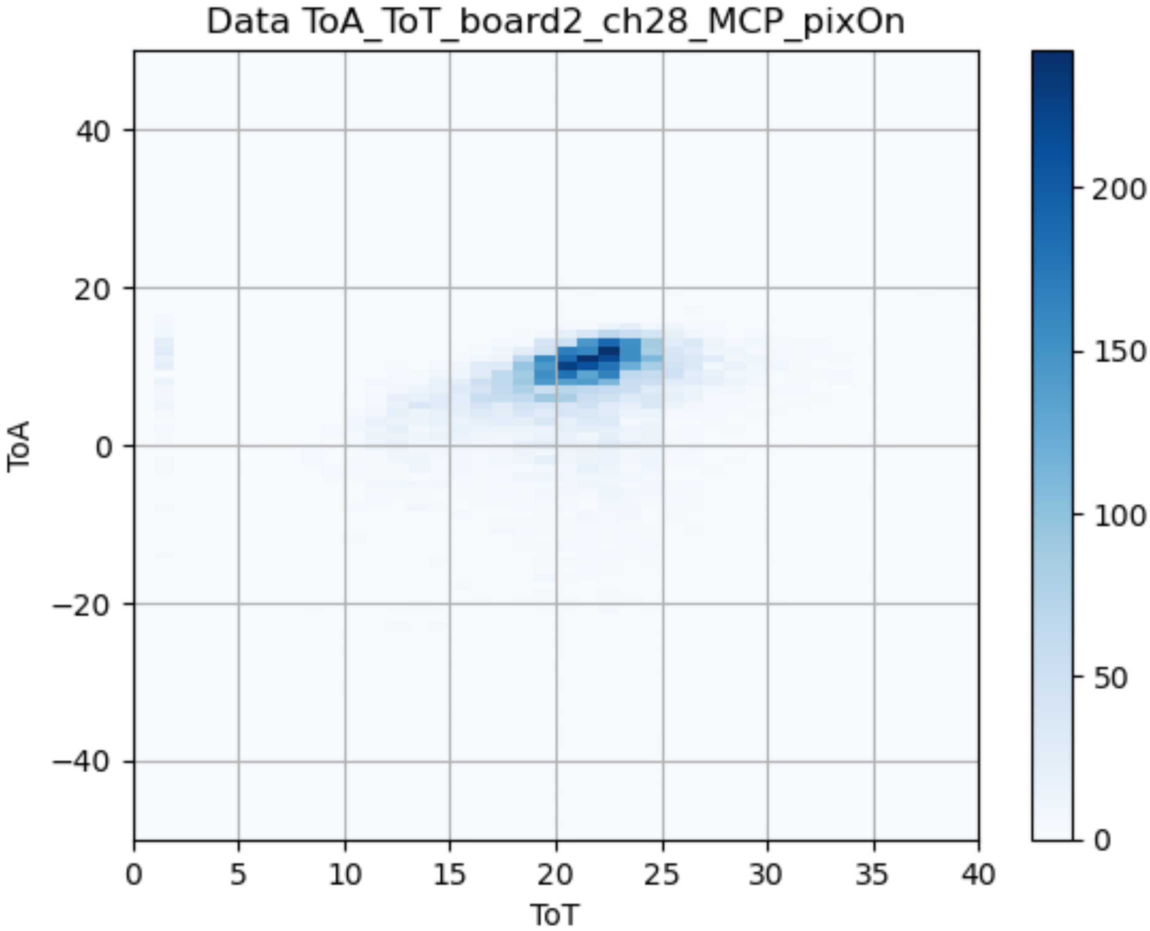
In [1]:
```
import uproot4 as uproot
import matplotlib.pyplot as plt
import numpy as np
import math
import hist
import mplhep

import scipy

from scipy.optimize import curve_fit

root_name = ['RunData-20221017-83800751_PLOTS.root',
             'RunData-20221018-1289979_PLOTS.root',
             'RunData-20221018-4410040_PLOTS.root',
             'RunData-20221018-5262581_PLOTS.root',
             'RunData-20221018-6807935_PLOTS.root']

def tree_names():
    tree_names = [[None]*1]*32
    for i in range (0,32):
        if i <10:
            tree_names[i] = 'ToA_ToT_board2_ch0' + str(i) + '_MCP_pixOn'
        else:
            tree_names[i] = 'ToA_ToT_board2_ch' + str(i) + '_MCP_pixOn'
    return  tree_names
```

In [2]:
```
def import_data(root_name,tree_name):
    '''
    a function which imports data from the CERN ROOT file,
    given the name of the root file & the tree that you
    want to extract data from.
    '''
    root = uproot.open(root_name)
    tree = root[tree_name]

    h = uproot.models.TH.Model_TH2D_v4.to_hist(tree)

    w,x,y = h.to_numpy()
    return w,x,y,h
```

In [3]:
```
#Importing the data from the root file. The index passed into
#tree_names() is the channel number, eg. ch28

name = tree_names()[28]
root = root_name[2]
w,ToT,ToA,h = import_data(root,name)
print('no of photons in this channel = ' + str(w.sum()))
```

```
no of photons in this channel = 11956.0
```

In [4]:
```
#Plotting a 2D histogram of the data before applying any corrections.

plt.pcolormesh(ToT, ToA, w.T,cmap='Blues')
plt.xlabel('ToT')
plt.ylabel('ToA')
plt.ylim([-50,50])
plt.xlim([0,40])
plt.title('Data ' + name)
plt.grid()
plt.colorbar()
plt.savefig('ToAvsToTboard2ch19mcppixon.png')
plt.show()
```

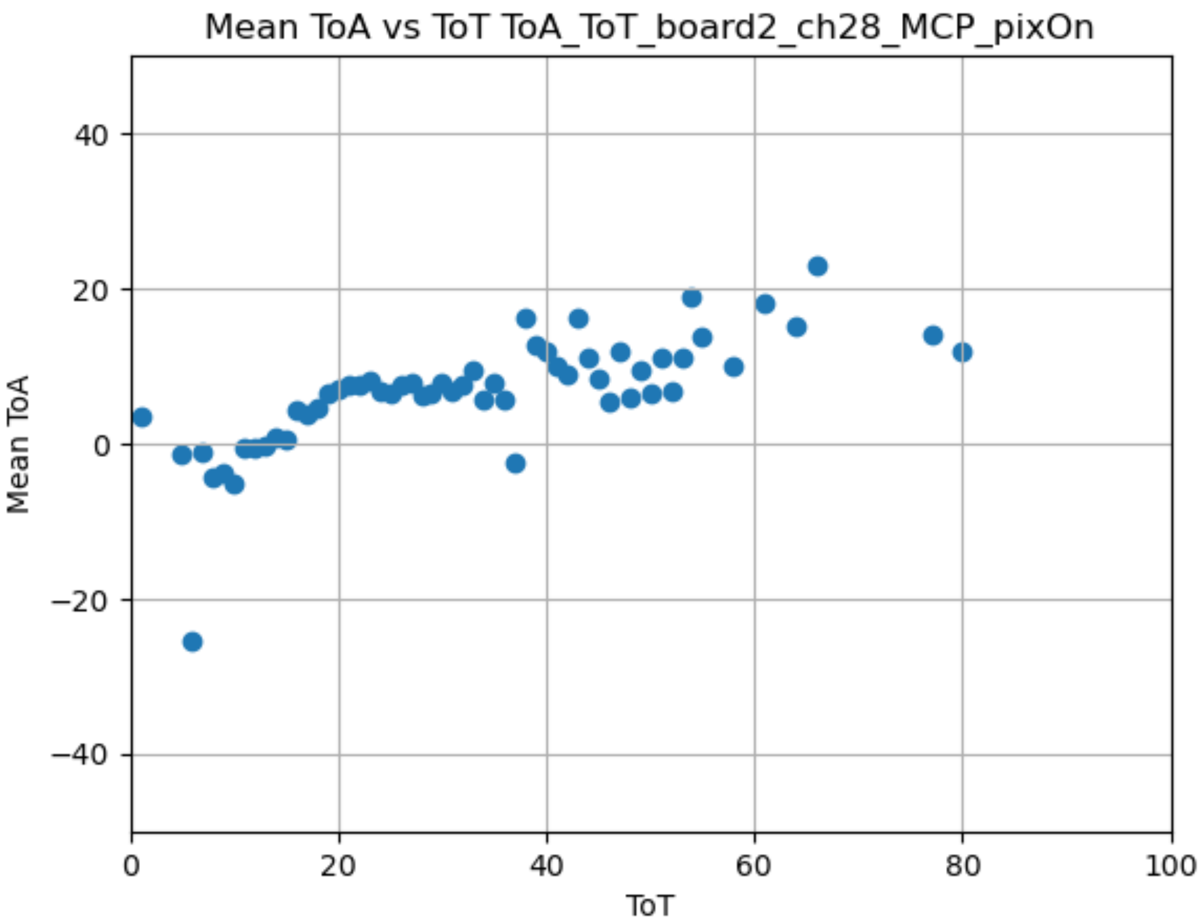


In [5]:
```
#Calculating the mean values of ToA at each ToT slice
mean_ToA = []

for y in w:
    try:
        mean_ToA.append(np.sum(y*np.arange(-224,225,1))/y.sum())
    except:
        mean_ToA.append()
mean_ToA = np.asarray(mean_ToA)
mean_ToA = np.nan_to_num(mean_ToA)
```

```
/var/folders/8k/h3kxl_651x3cg0_0vcmg27wc0000gn/T/ipykernel_37289/13557242
02.py:6: RuntimeWarning: invalid value encountered in double_scalars
  mean_ToA.append(np.sum(y*np.arange(-224,225,1))/y.sum())
```

In [6]:
```
#Removing all the empty columns and rows, where there are 0 events,
#from the data. '_popped' is a reference to list.pop() which removes
#elements from a list

indices =[]
ToA_popped = []
for i in range(0,len(y)-1):
    if w.T[i][:].sum() != 0:
        indices.append(i)
    else:
        pass
for i in indices:
    ToA_popped.append(y[i])

indices =[]
ToT_popped = []
mean_popped = []
for i in range(0,len(ToT)-1):
    if w[i][:].sum() != 0:
        indices.append(i)
    else:
        pass
for i in indices:
    ToT_popped.append(ToT[i])
    mean_popped.append(mean_ToA[i])

ToT_popped = np.array(ToT_popped)
ToA_popped = np.array(ToA_popped)
mean_popped = np.array(mean_popped)


Result = w[:,~np.all(w == 0, axis = 0)]
Result = Result.T[:,~np.all(Result.T == 0, axis = 0)]
w_popped = Result
```

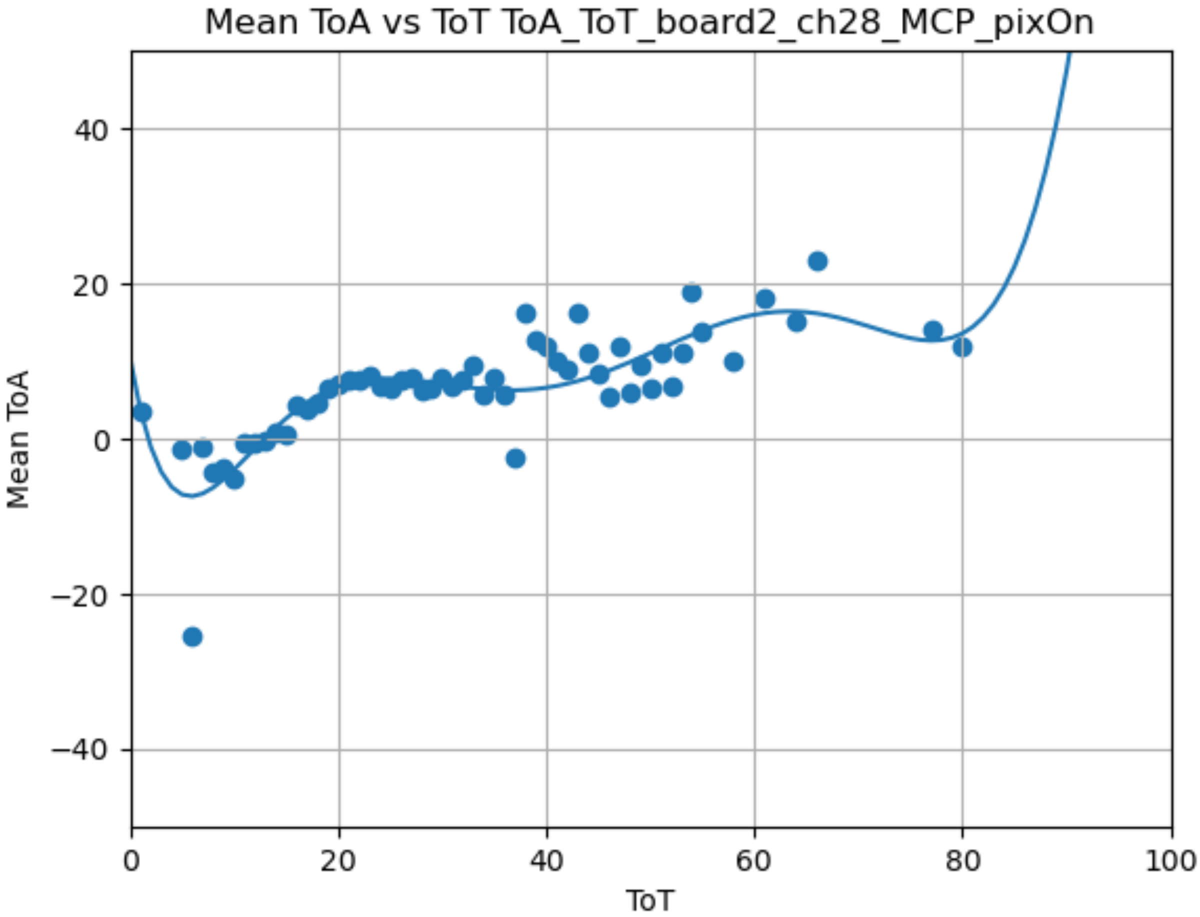
In [7]:
```
#Plotting the Mean ToA against ToT. Without removing the empty values
#from the data, there would be a lot of data points along the
#Mean ToA = 0 axis which would affect the fitting of a function
#to the data.
plt.scatter(ToT_popped,mean_popped)
plt.ylim([-50,50])
plt.xlim([0,100])
plt.xlabel('ToT')
plt.ylabel('Mean ToA')
#plt.xscale('log')
#plt.yscale('log')
plt.title('Mean ToA vs ToT ' + name)

#plt.legend()
plt.grid()
plt.show()
```

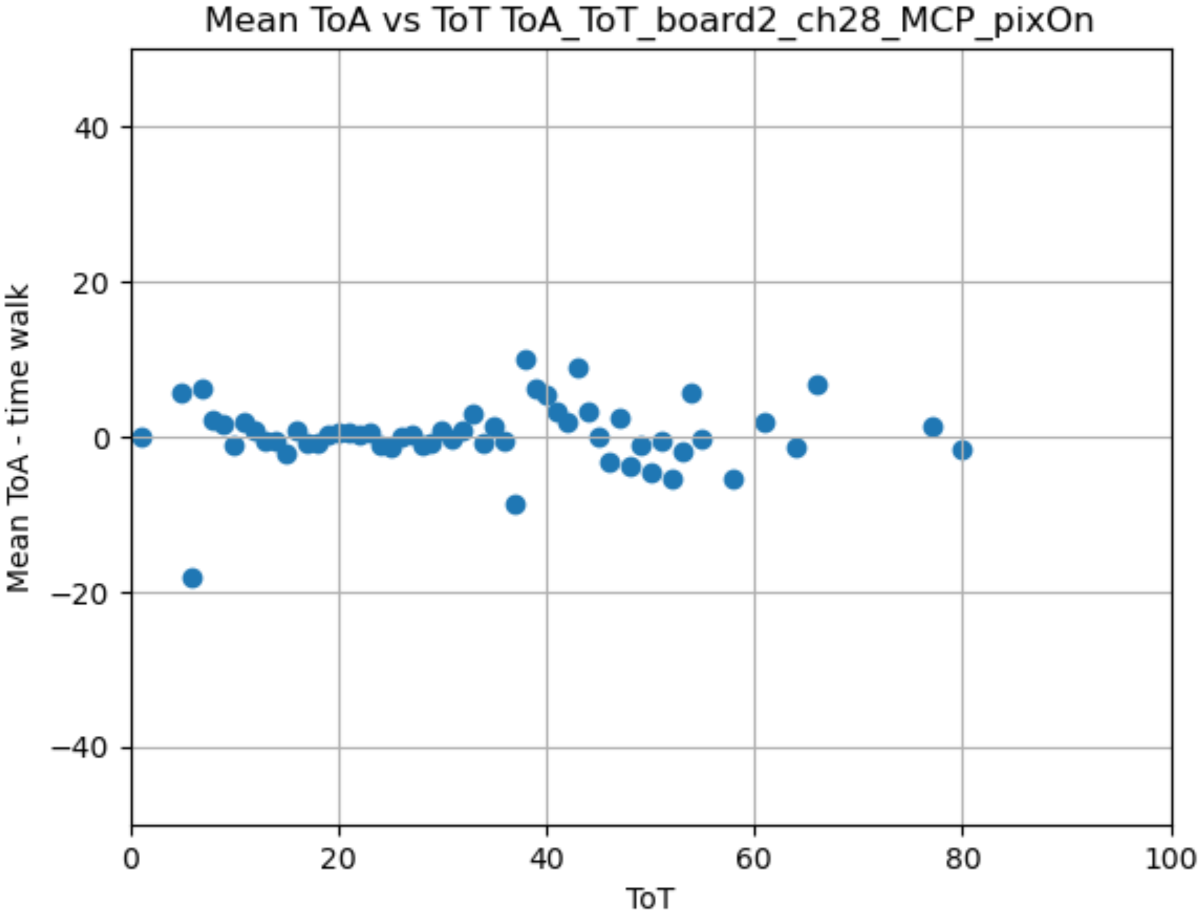


In [8]:
```
#Defining a polynomial function and fitting it to the
#mean ToA vs ToT data for this channel.

def polynomial(x,f,a,b,c,d,e,g,h,j):
    return  a + b * x + c*x**2 + d * x**3  + e *x**4  +  f * np.log(g* x

fit,cov = curve_fit(polynomial,ToT_popped, mean_popped,sigma = np.sqrt((w
```

```
/var/folders/8k/h3kxl_651x3cg0_0vcmg27wc0000gn/T/ipykernel_37289/11762367
06.py:5: RuntimeWarning: invalid value encountered in log
  return  a + b * x + c*x**2 + d * x**3  + e *x**4  +  f * np.log(g* x +
h) + j * x**5
```

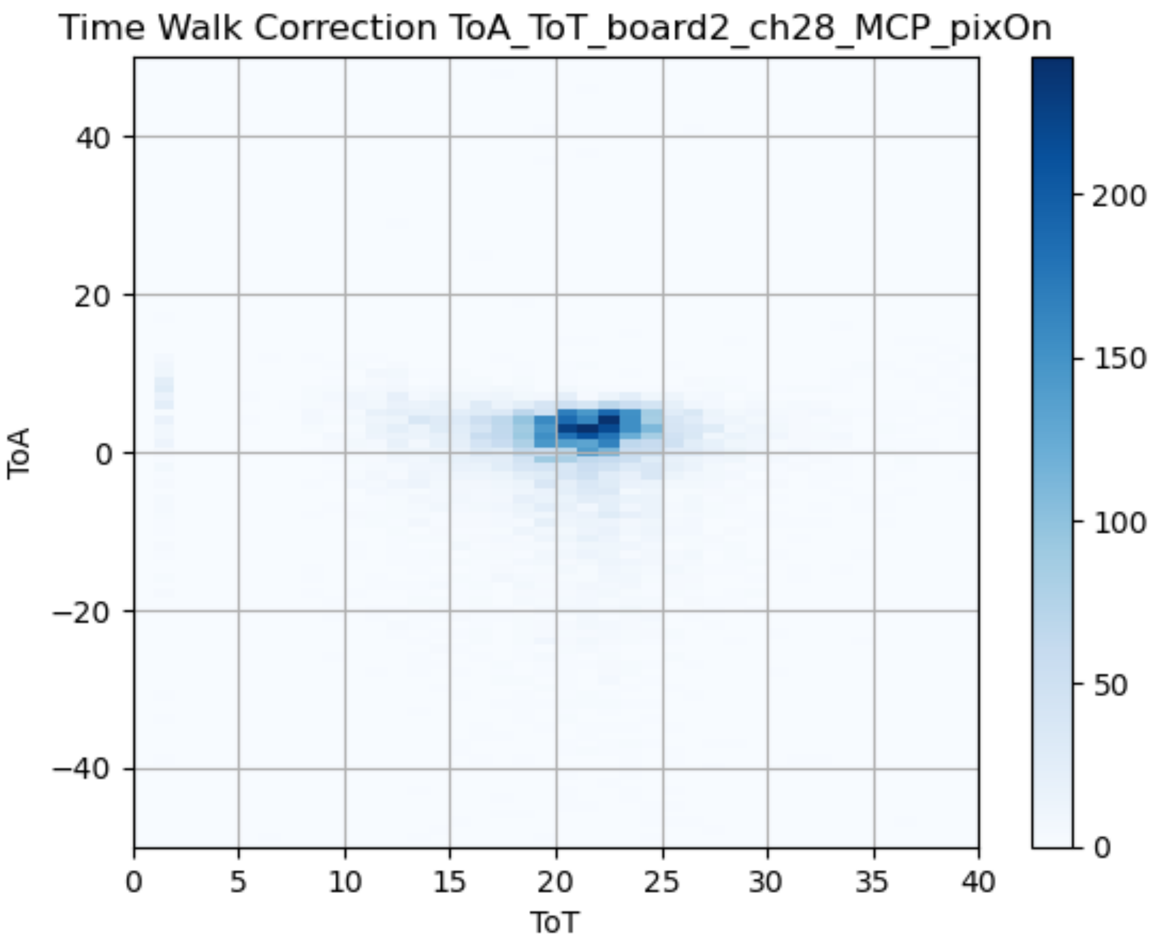
In [9]:
```
#Plotting the data and the fitted curve on the same axes.

plt.plot(ToT,polynomial(ToT,fit[0],fit[1],fit[2],fit[3],fit[4],fit[5],fit
plt.scatter(ToT_popped,mean_popped)
plt.ylim([-50,50])
plt.xlim([0,100])
plt.xlabel('ToT')
plt.ylabel('Mean ToA')
#plt.xscale('log')
#plt.yscale('log')
plt.title('Mean ToA vs ToT ' + name)

#plt.legend()
plt.grid()
plt.savefig('meanToAvsToTwithFitboard2ch19mcppixon.png')
plt.show()

#Subtracting the time walk from the Mean ToA and plotting this against
#the ToT. If the mean ToA is roughly centred on 0 which is encouraging

plt.scatter(ToT_popped,mean_popped - polynomial(ToT_popped,
                                                 fit[0],
                                                 fit[1],
                                                 fit[2],
                                                 fit[3],
                                                fit[4],fit[5],fit[6],fit[7
                                                )

plt.ylim([-50,50])
plt.xlim([0,100])
plt.xlabel('ToT')
plt.ylabel('Mean ToA - time walk')
#plt.xscale('log')
#plt.yscale('log')
plt.title('Mean ToA vs ToT ' + name)

#plt.legend()
plt.grid()
plt.savefig('TWCmeanToAvsToTwithFitboard2ch19mcppixon.png')
plt.show()
```

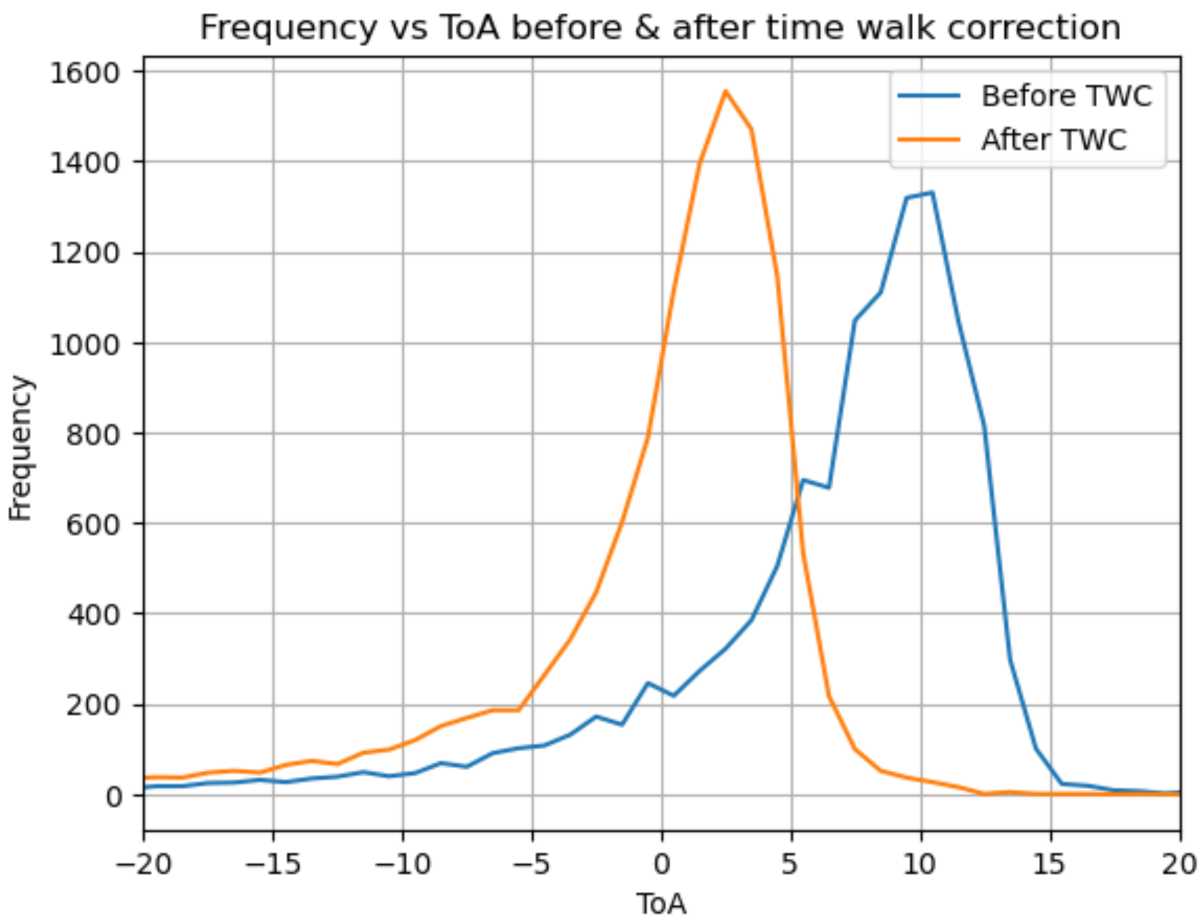

Mean ToA vs ToT ToA_ToT_board2_ch28_MCP_pixOn
Mean ToA
ToT
40
20
0
−20
−40
0
20
40
60
80
100


Mean ToA vs ToT ToA_ToT_board2_ch28_MCP_pixOn
Mean ToA - time walk
ToT
40
20
0
−20
−40
0
20
40
60
80
100

In [10]:

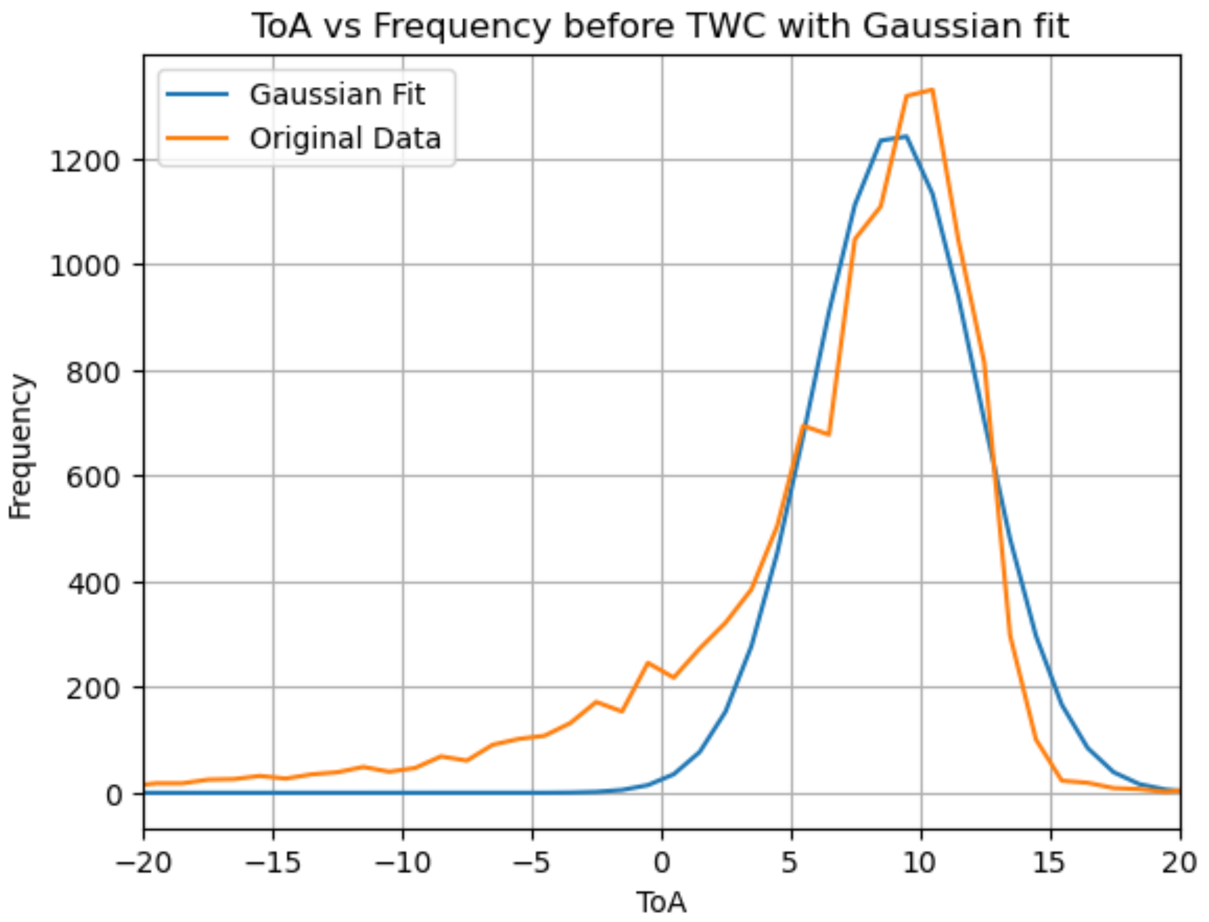
```
#Taking a vertical slice of the data & subtracting the time walk,
#then repeating for each vertical slice and plotting plt.pcolormesh
#really didn't want to cooperate and so it took way longer than it
#should have to get this to work. Finally, I'm also plotting ToA vs
#Frequency before and after the time walk is subtracted. Each slice
#is plotted individually. It is clear to see that the means is
#shifted closer to zero, but it appears that a tail still remains.

time_walks = []
for i in range (0,w.shape[0]):
    time_walk = polynomial(ToT[i],fit[0],fit[1],fit[2],fit[3],fit[4],fit[
    time_walks.append(time_walk)

twc = np.empty([w.shape[0],w.shape[1]])
for i in range(0,w.shape[0]):
    indx = np.digitize(ToA + time_walks[i],ToA)
    for j in range(0,len(indx)):
        if indx[j]>448:
            indx[j] = 448
    indx = indx[0:-1]
    twc[i] = w[i][indx]

plt.pcolormesh(ToT, ToA, twc.T,cmap='Blues')
plt.xlabel('ToT')
plt.ylabel('ToA')
plt.ylim([-50,50])
plt.xlim([0,40])
plt.title('Time Walk Correction ' + name)
plt.grid()
plt.colorbar()
plt.show()


plt.plot(ToA[0:-1],w.sum(axis=0),label='Before TWC')
plt.xlim([-20,20])
plt.title('Frequency vs ToA before & after time walk correction')
plt.xlabel('ToA')
plt.ylabel('Frequency')

plt.plot(ToA[0:-1],twc.sum(axis=0),label='After TWC')
plt.xlim([-20,20])
plt.xlabel('ToA')
plt.ylabel('Frequency')
plt.legend()
plt.grid()
plt.show()
```


Time Walk Correction ToA_ToT_board2_ch28_MCP_pixOn
ToA
ToT
40
20
0
−20
−40
0
5
10
15
20
25
30
35
40
200
150
100
50
0

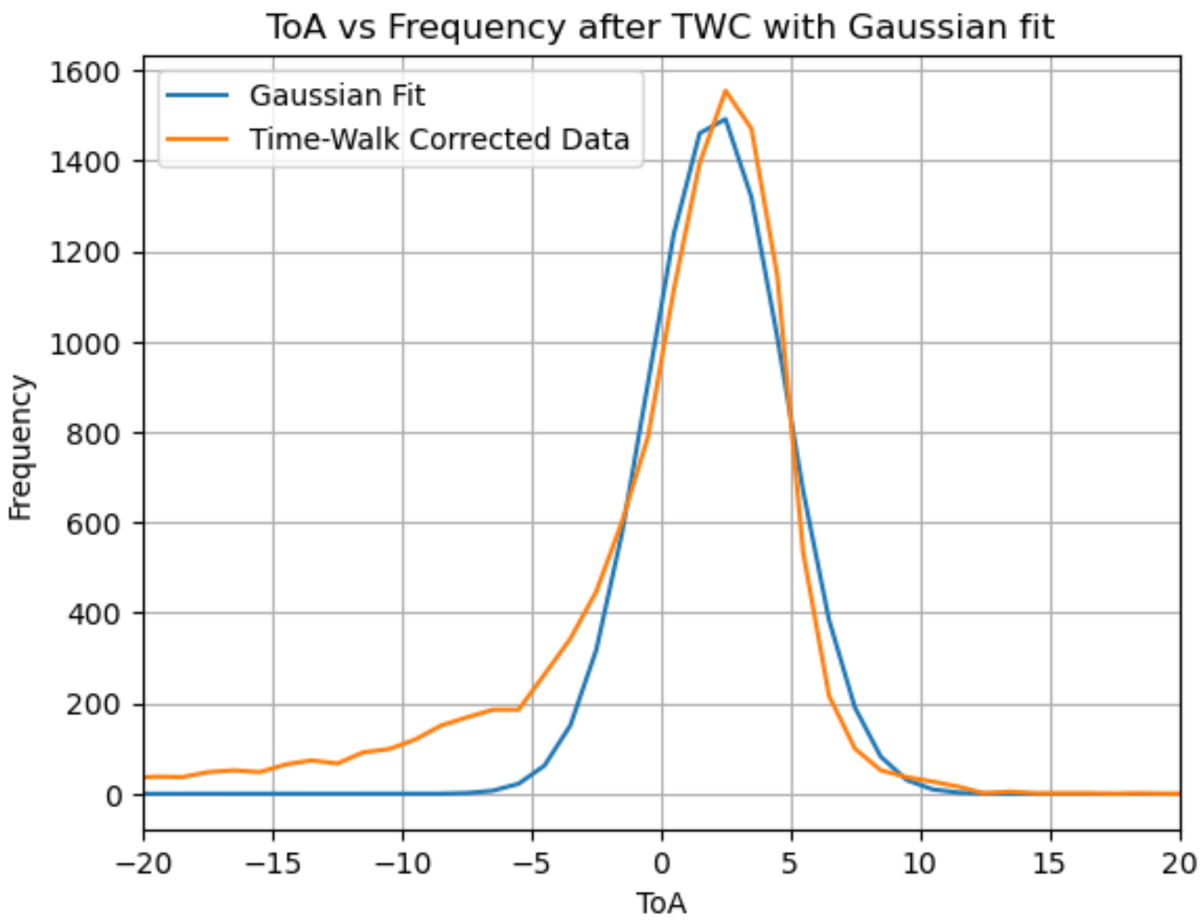

Frequency vs ToA before & after time walk correction
Before TWC
After TWC
Frequency
ToA
1600
1400
1200
1000
800
600
400
200
0
−20
−15
−10
−5
0
5
10
15
20

In [11]:
```
def gaussian(x,r,sigma,N):
    return np.array(scipy.stats.norm.pdf(x,r,sigma)) * N
```

In [12]:
```
fit2,cov2 = curve_fit(gaussian,ToA[0:-1],w.sum(axis=0))
plt.plot(ToA[0:-1],gaussian(ToA[0:-1],fit2[0],fit2[1],fit2[2]),label='Gau
plt.plot(ToA[0:-1],w.sum(axis=0),label='Original Data')
plt.xlim([-20,20])
plt.legend()
plt.title('ToA vs Frequency before TWC with Gaussian fit')
plt.xlabel('ToA')
plt.ylabel('Frequency')
plt.grid()
plt.show()
```



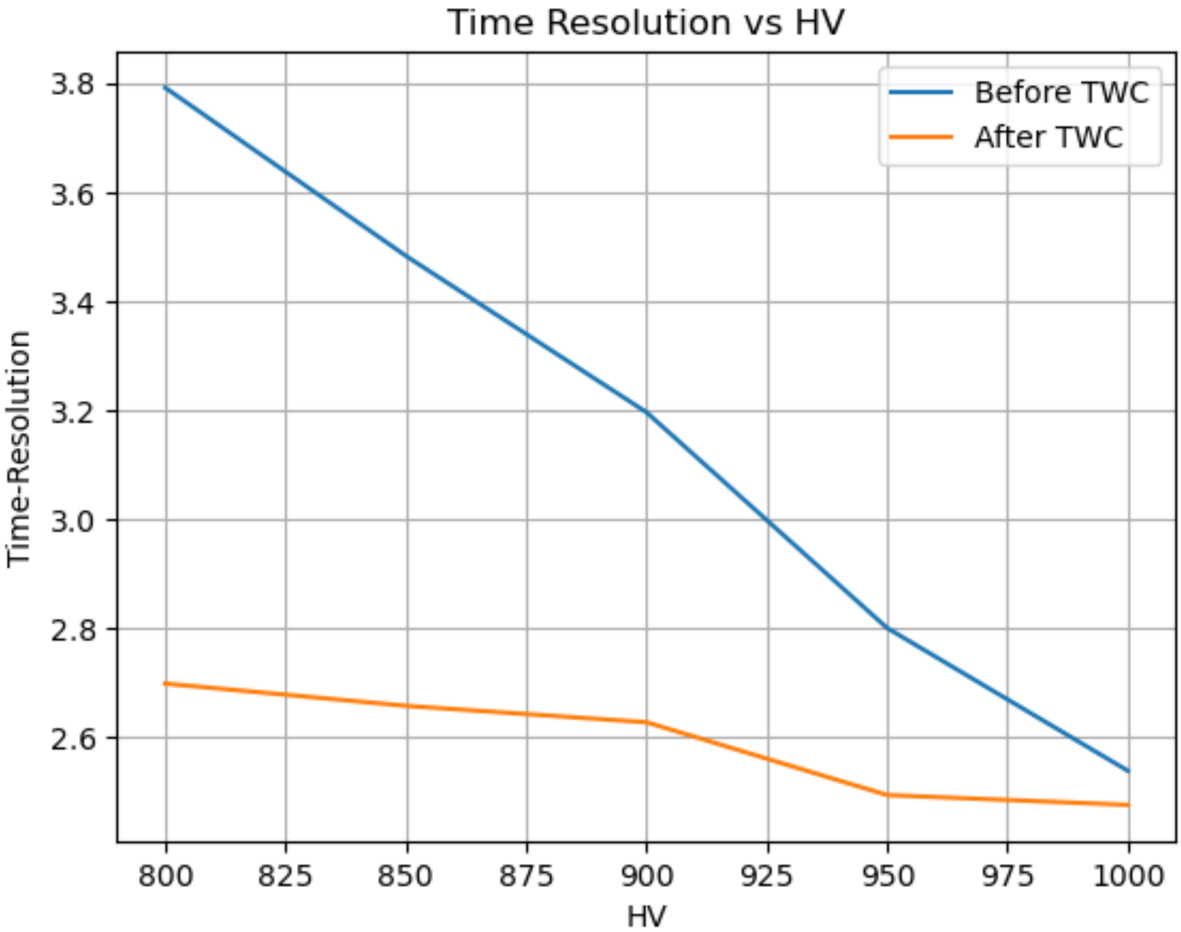
In [13]:
```
fit3,cov3 = curve_fit(gaussian,ToA[0:-1],twc.sum(axis=0),p0=(0,5,1000))
plt.plot(ToA[0:-1],gaussian(ToA[0:-1],fit3[0],fit3[1],fit3[2]),label='Gau
plt.plot(ToA[0:-1],twc.sum(axis=0),label='Time-Walk Corrected Data')
plt.xlim([-20,20])
plt.legend()
plt.title('ToA vs Frequency after TWC with Gaussian fit')
plt.xlabel('ToA')
plt.ylabel('Frequency')
plt.grid()
plt.show()
```

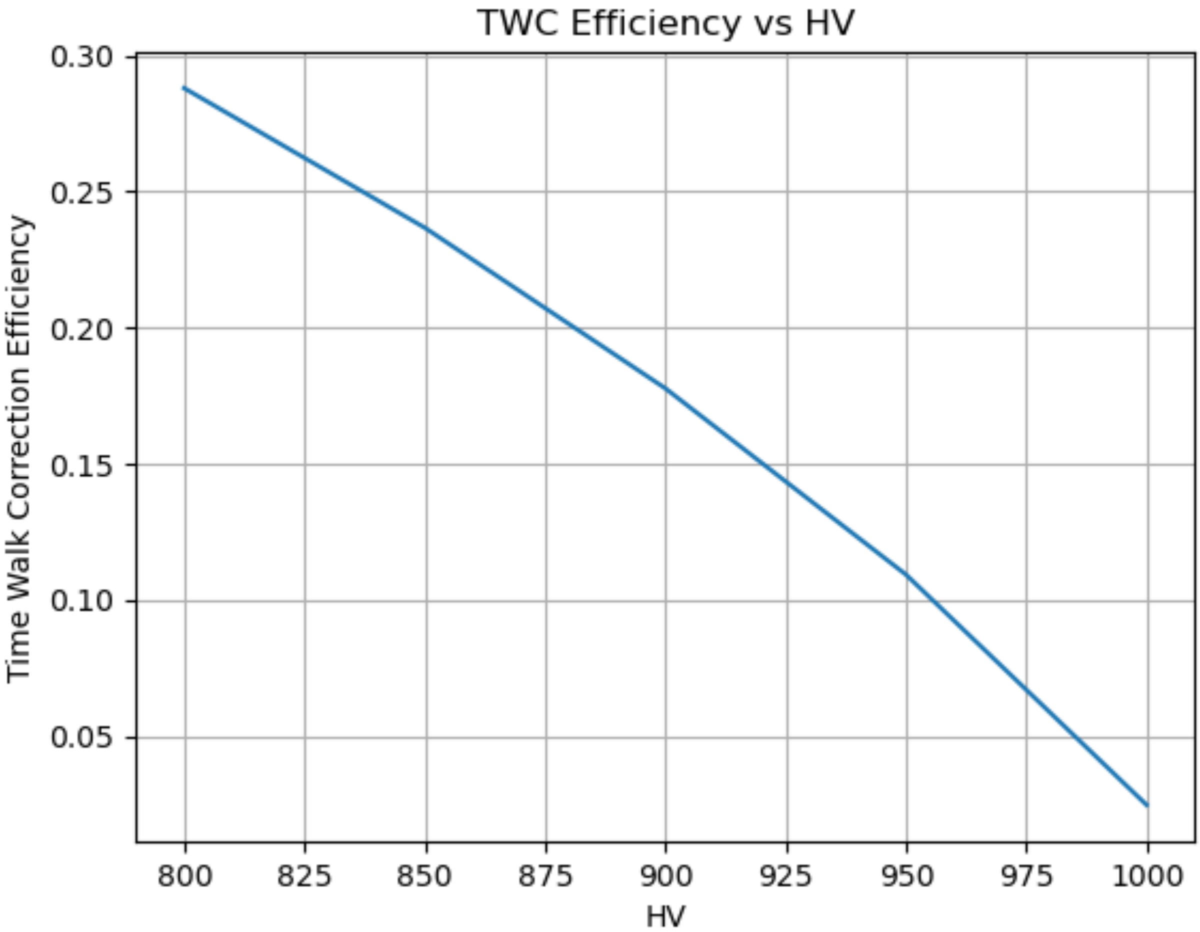


In [14]:
```
print('time resolution without the time walk correction is ' + str(fit2[1
print('time resolution with the time walk correction is ' + str(fit3[1]))
```

```
time resolution without the time walk correction is 3.196553384748066
time resolution with the time walk correction is 2.628456756607356
```

In [15]:
```
HV = [1000,950,900,850,800]

sigma_before = [2.539485194902906,2.8010578972580045,3.196553384748066,3.

sigma_after = [2.47697425768142,2.4949759751327467,2.628456756607356,2.65

plt.plot(HV,sigma_before,label='Before TWC')
plt.plot(HV,sigma_after,label='After TWC')
plt.legend()
plt.grid()
plt.title('Time Resolution vs HV')
plt.xlabel('HV')
plt.ylabel('Time-Resolution')
plt.show()

plt.plot(HV,1-np.array(sigma_after)/np.array(sigma_before))
plt.grid()
plt.title('TWC Efficiency vs HV')
plt.xlabel('HV')
plt.ylabel('Time Walk Correction Efficiency')
plt.show()
```


Time Resolution vs HV
Before TWC
After TWC
Time-Resolution
HV
3.8
3.6
3.4
3.2
3.0
2.8
2.6
800
825
850
875
900
925
950
975
1000


TWC Efficiency vs HV
Time Walk Correction Efficiency
HV
0.30
0.25
0.20
0.15
0.10
0.05
800
825
850
875
900
925
950
975
1000