Some Improvement of BESII TOF Simulation(Sober)

Peng Haiping
University of Science and Technologe ,China
E-mail: penghp@hpws2.ihep.ac.cn
E-mail: penghp@mail.ustc.edu.cn

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1 Motivation

• The Importance of TOF at BESΠ

The BESΠ is a large general purpose solenoidal detector at BEPC. The wide range of physics that can be studied requires the detector have good momentum resolution and particle identification for charged tracks. Meanwhile it also needs a good simulation including event generator, particle transmission in the detector and its interaction with the detector.

TOF has been upgraded since 1995, and the time resolution is about 180ps for Bhabha events. The separation ability for K/π is greater than 3σ when the momentum is less than 0.8GeV, TOF can be used to do particle ID in a wide momentum range. Therefore a good TOF simulation is urgently required, otherwise it will affect the detected efficiency, increase the difference between M.C. data and real data, and then bring more systematic errors to physics results.

• Time measurment and Time resolution

In order to measure time, we must measure two time points—-T_{start} and T_{end}, then time is $T = T_{end} - T_{start}$. According to the propagation of errors formular, if the two time points are independent, the time resolution is $\sigma = \sqrt{\sigma^2_{start} + \sigma^2_{end}}$, where σ_{start} and σ_{end} are the time resolution of start time point and end time point respectively.

We can not get the resolution of time point directly, but we can get the measured time from TOF information, and we also can get the expected time from the kinematic formula:

$$T_{exp} = \frac{L * \sqrt{P^2 + m_2}}{0.3 * P}$$

Where, L is the length of the path particle flights, P is the momentum of particle, m is the mass of particle, then we can get the difference of the two times $\Delta T = T_{measured} - T_{expected}$ for thousands of particles. According to statistics, ΔT should be a gaussion distribution. Then we can fit ΔT with gaussion function with the σ being the resolution of ΔT.

From the definition of ΔT we can see that if the uncertainties of momenum and passage can be omitted, the resolution of expected time contributed to time resolution equals to 0, the σ should equal to resolution of measured time. However, because of the scattering, the expected time is not the 'real time' of the particle flights in the detector. But when momentum is big, the scattering effect can be omitted, then the σ should be the resolution of measured time, otherwise $\sigma = \sqrt{\sigma^2_{measure} + \sigma^2_{expected}}$

- ## Time correlation and resolutions of T_{start} and T_{end}

After the electron and positron collide, the secondary particles are produced, then each particle flights to TOF along different direction. Since all particles have the same start time point, the flight time of each particle in the same event is correlated.

Now we intruduce how to get the T_{start} and T_{end} resolutions from the measured time resolution σ briefly. We can get the ΔT of each particle in each event, for example we can get the two ΔT of two tracks for Bhabha events, and define $\Delta T' = \Delta T^1 - \Delta T^2$, then we can get:

$$
\begin{aligned}
\Delta T' &= \Delta T^1 - \Delta T^2 \\
&= (T^1_{end} - T_{start} - T^1_{expect}) - (T^2_{end} - T_{start} - T^2_{expect}) \\
&= (T^1_{end} - T^2_{end}) - (T^1_{expect} - T^2_{expect})
\end{aligned}
$$

According to the propagation of errors formular, we can see the resolution of T_{start} does not contribute to the $\Delta T'$ resolution, also if the expected time resolution can be omitted, then we can get the $\sigma = \sqrt{2}\sigma_{end}$. We can get the resolution and $\sigma_{start} = \sqrt{\sigma^2 - \sigma^2_{end}}$

- ## TOF realization

When doing TOF realization, we can get the TOF resolution from bhabha event for each scintillator. For the T_{start} resolution is about 96ps, so we can subtract the T_{start} resolution from time resolution, and get resolution of T_{end} for each scintillator. All the T_{end} resolution will be used when doing simulation.

2 Compare the Real data and M.C. data

From the comparision, we found there are some difference between real data and M.C. data of TOF resolution, we can introduce them one by one.

- **Time Correlation**

  Because all the tracks in the same event have same start time point, so the time is correlative, we can get the $\Delta T'$ and ΔT distribution of real data and M.C. data(Fig.1 & Fig.2). Table 1. shows the values of TOF resolution for real data and M.C. data We can see for the real data the ΔT resolution is about 182.7ps, and $\Delta T'$ resolution is about 218.3ps, so the resolution of T_{end} is about 154.4ps, and T_{start} is about 97.6ps. But for M.C. data , we can see the $\sigma' \approx \sqrt{2}\sigma$, the resolution of T_{start} is about 0. Fig.3 shows the scatter plot distribution of ΔT^1 and ΔT^2, we can see distribution of real data is an oval, which means ΔT^1 and ΔT^2 is correlative. However for the M.C. data, the scatter plot distribution is round. The reason is we do not do the 'time walk' simulation in SOBER so far, and resolution of T_{start} is 0, and the two time is independent.

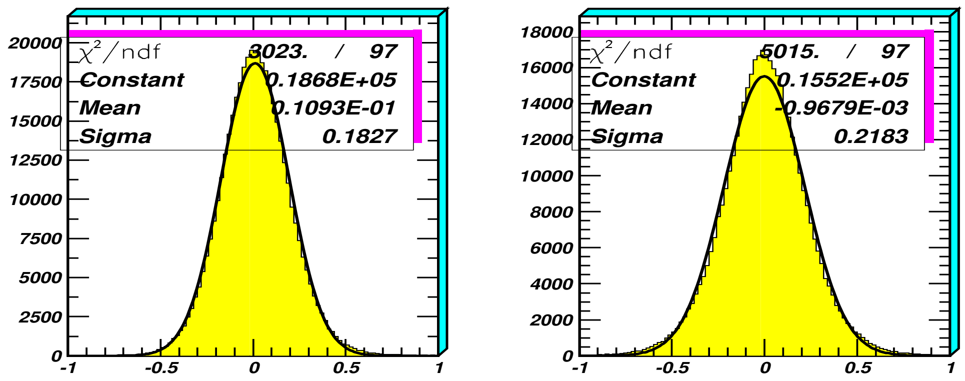


Figure 1: the $\Delta T'$ and ΔT for real data

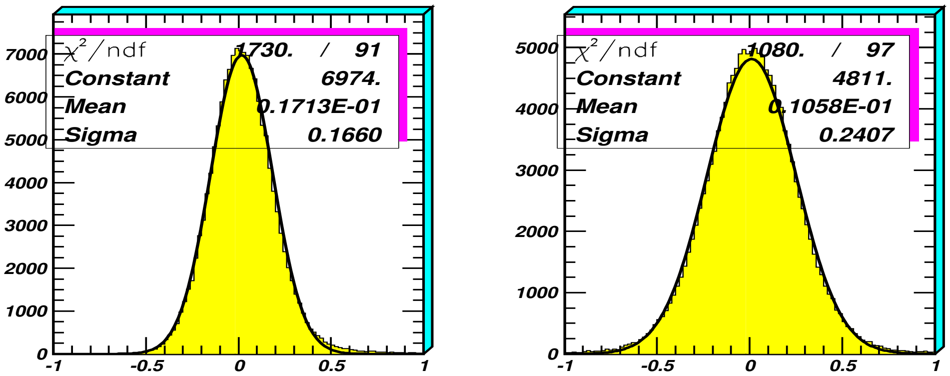


Figure 2: the $\Delta T^{'}$ and ΔT for M.C. data

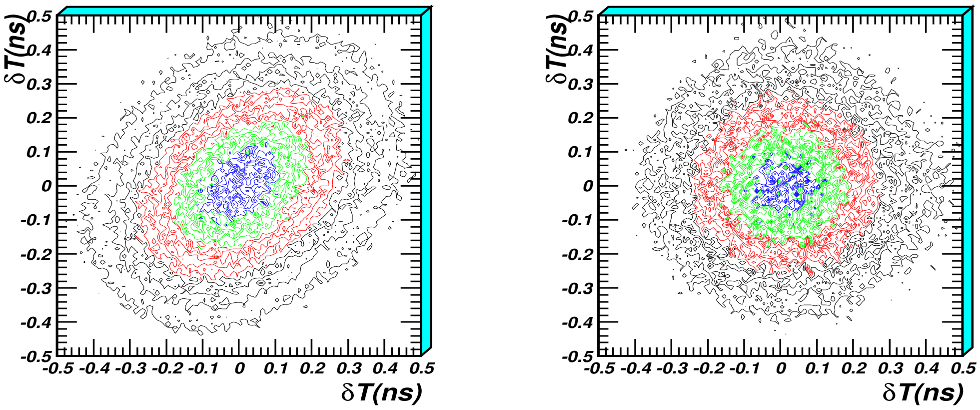


Figure 3: the ΔT^1 and ΔT^2 scatter plot distribution(a. real dat ,b. M.C. data)

• TOF Resolution

From the Fig.1 and Fig.2, we can see the resolution is about 182.7ps for real data, but for the M.C. data , it is about 166.0ps, the resolution of M.C. data is less than real data. Fig.4 shows the resolution varying with counter number for real data and M.C. data. we also can see the resolution of real data is smaller than resolution of M.C. data for each counter number.

We also check the ΔT resolution varying with $cos\theta$. Fig.5 shows the resolution varying with $cos\theta$. There are big difference between real data and

type	σ(ps)	σ_{end}(ps)	$\sigma_{start}(ps)$
Real Data	182.7	154.4	97.7
MC. Data	166.0	168.9	0.0

Table 1: comparision of the resolution between real data and M.C. data

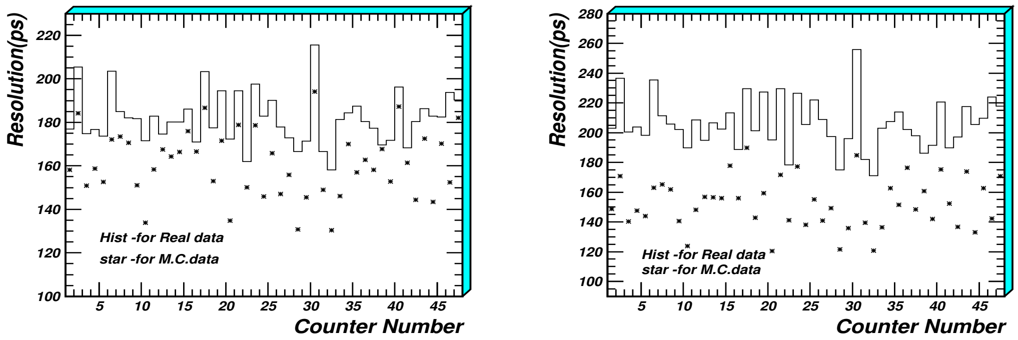


Figure 4: The resolution varying with counter number(a:electron,b:muon)

M.C. data for both electron and muon particles.For hadrons the resolution curve is simalar to that for muon.

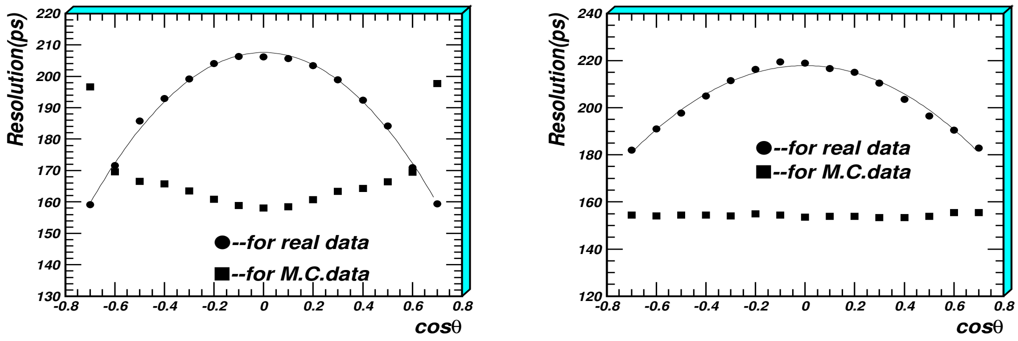


Figure 5: The resolution varying with $cos\theta$ (a:electron,b:muon)

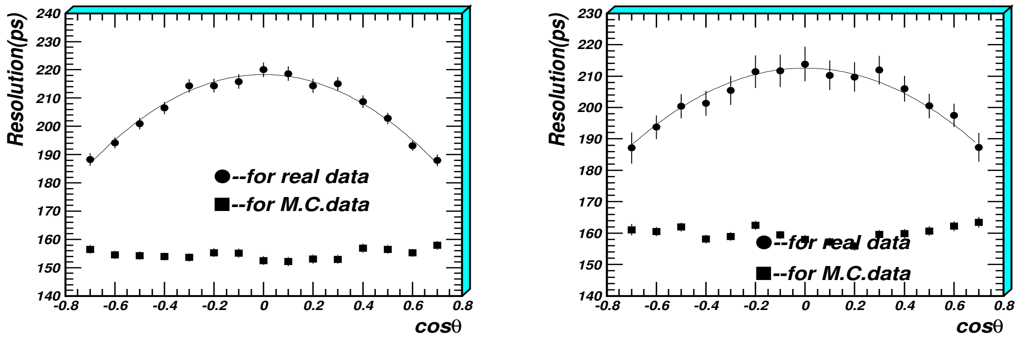


Figure 6: The resolution varying with $cos\theta$ (a:pion,b:kaon)

• Pulse Amplitude

Fig.7 and Fig.8 show the pulse amplitude of real data and M.C. data for the electron and muon. We can see the pulse amplitude is LANDAU distribution for real data, but pulse amplitude simulation is very poor for M.C. data. Also we check the resolution varying with pulse amplitude(Fig.9), for the real data the resolution depends on the Pulse Amplitude, but for M.C. data, it is independent.

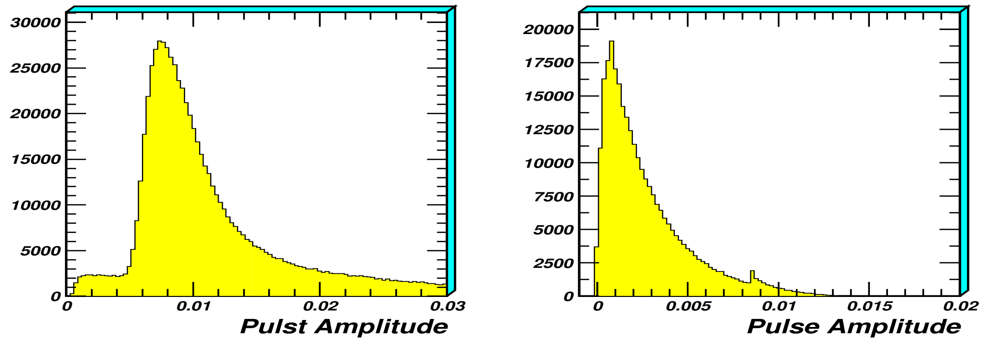


Figure 7: The Pluse Amplitude distribution for electron(a:real data ,b:M.C. data)(electron)

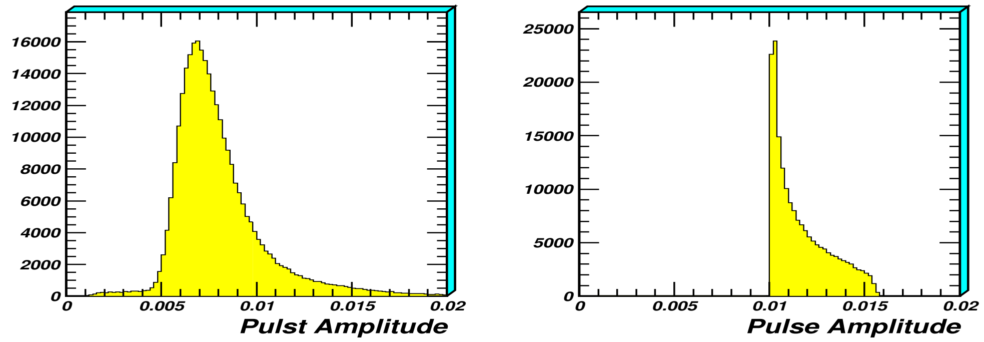


Figure 8: The Pluse Amplitude distribution for muon(a:real data ;b:M.C. data)(muon)

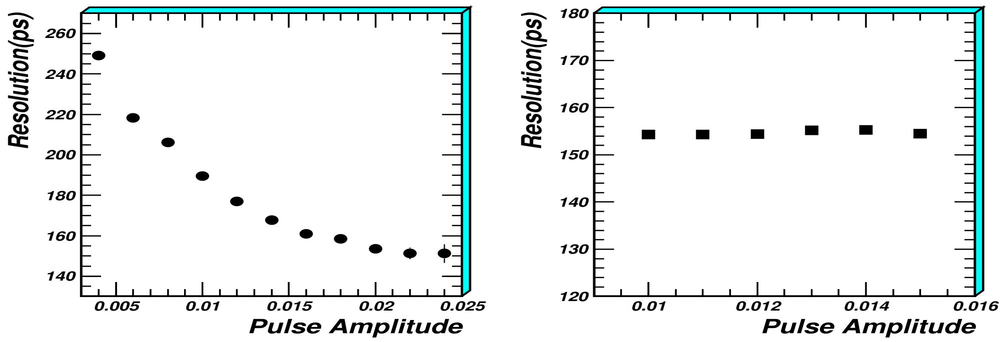


Figure 9: The resolution varying with pulse amplitude (a:real data,b:M.Cdata)(muon)

3 Some results from real data

In order to do simulation well, we must study the behaviours of TOF carefull from real data.

• T_{start} resolution depends on the vertex z position

Now we discuss the T_{start} resolution. Because we can only get the time T_{start} when the two branches overlap completely, while the collision can happen before or after that time, Fig.10 shows the time of the collision happens at the different position. We can see if the collision happen at the position $z = 0$, the time of the branches overlap at z=0 is longest, the collision can happen during the two branchs overlap together, so the T_{start} time walk is longest, if the collision happen at the position z equal to length of branch, then the two branchs overlap together in a twinking, so the collision time exactly equals to 0. So the resolution of T_{start} should depend on the vertex Z position.

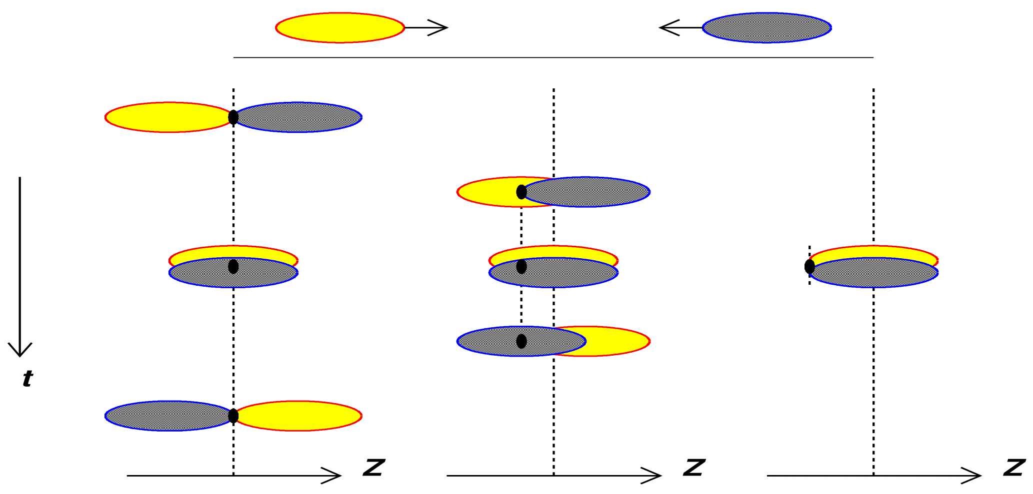


Figure 10: The overlap of the two branchs in different position

• Pulse amplitude

Now we study the pulse amplitude of PMT. Due to the different interaction time and passage in TOF, the pulse amplitude should depend on momentum and cosθ. Fig.11 shows pluse amplitude distribution varying with $cos\theta$ and momentum for proton sample.

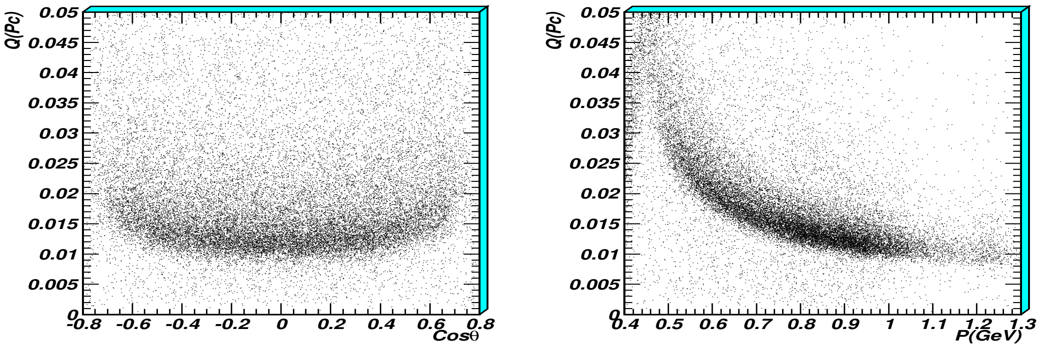


Figure 11: the pluse amplitude vary $cos\theta$ and momentum

The pulse amplitude is a landau distribution, so we can only get the mean and the mean square deviation(RMS) varying with $cos\theta$ and β(Fig.12.& Fig.13), here β is light velocity of particle. we can see the distribution of mean varying with $cos\theta$ can be fit with function $y = a/sin\theta$, the reason is the energy loss is proportion of the passage in TOF, the length which particle passes through TOF is the proportion of $1/cos\theta$. As to the mean varying with β, we can see that when β descreases, the mean increases, so we can fit the distribution with function $y = a + b * exp(-c * x)$. The mean square deviation(RMS) does not depend on the $cos\theta$, but depends on β. We also fit the distribution of RMS with function $y = a + b * exp(-c * x)$.

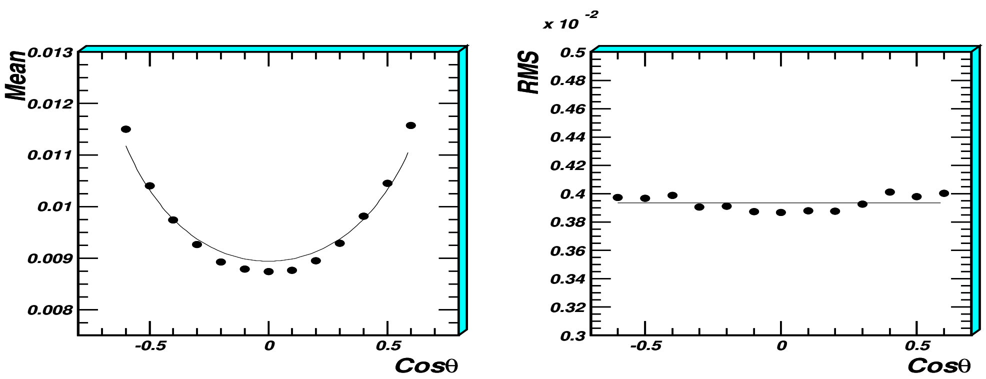


Figure 12: The mean and RMS of pulse amplitude vary with $cos\theta$

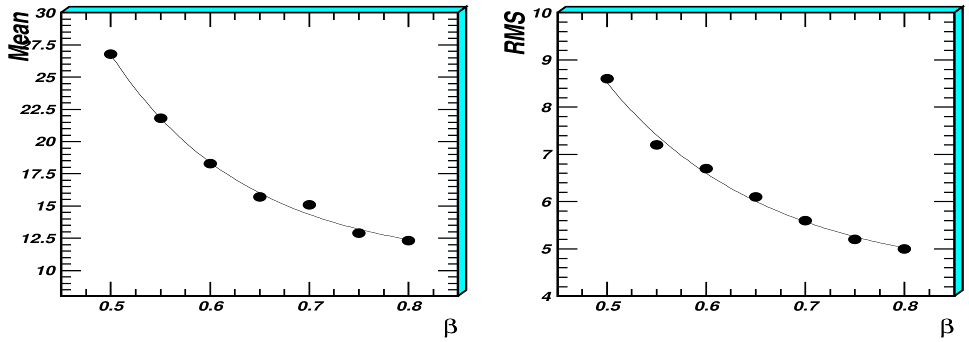


Figure 13: The mean and RMS of pulse amplitude vary with β

So the mean and RMS of pulse amplitude can be given by:

$$Mean = \frac{A}{sin\theta}\frac{B + C * exp(-D * \beta}{B + C * exp(-D * 1)}$$

$$RMS = E * \frac{F + G * exp(-H * \beta)}{F + G * exp(-H * 1)}$$

- **TOF Resolution**

According to what we have discussed above, we can get the resolution of T_{start} and T_{end} from time resolution σ. Also we have known that the measured time resolution depend on $cos\theta$ and T_{start} resolution depends on vertex z position, so we can obtain the resolution of measured time , T_{start}, T_{end} varying with $cos\theta$ and z position.

Fig.14 shows the measured time, T_{start} and T_{end} resolution varying with $cos\theta$ and vertex z position. From the plots we can see the T_{end} resolution depends on the $cos\theta$, while it does not depend on vertex z position, but for the T_{start} resolution, it is contrary. This means the resolutions of T_{start} and T_{end} are independent. With the increasing of vertex z position,the T_{start} resolution become smaller and smaller, it is correspond to what we have discuss above , so we fit the the plot with function $y = a + b * x^2$, and get the T_{start} time resolution as a function of vertex z poisition. Also we check the T_{start} resolution varying with vertex z position for the electron and muon(Fig.15), we can see there is no big difference for the resolution distribution between electron and muon sample, which means the resolution does not depend on the kind of particle.

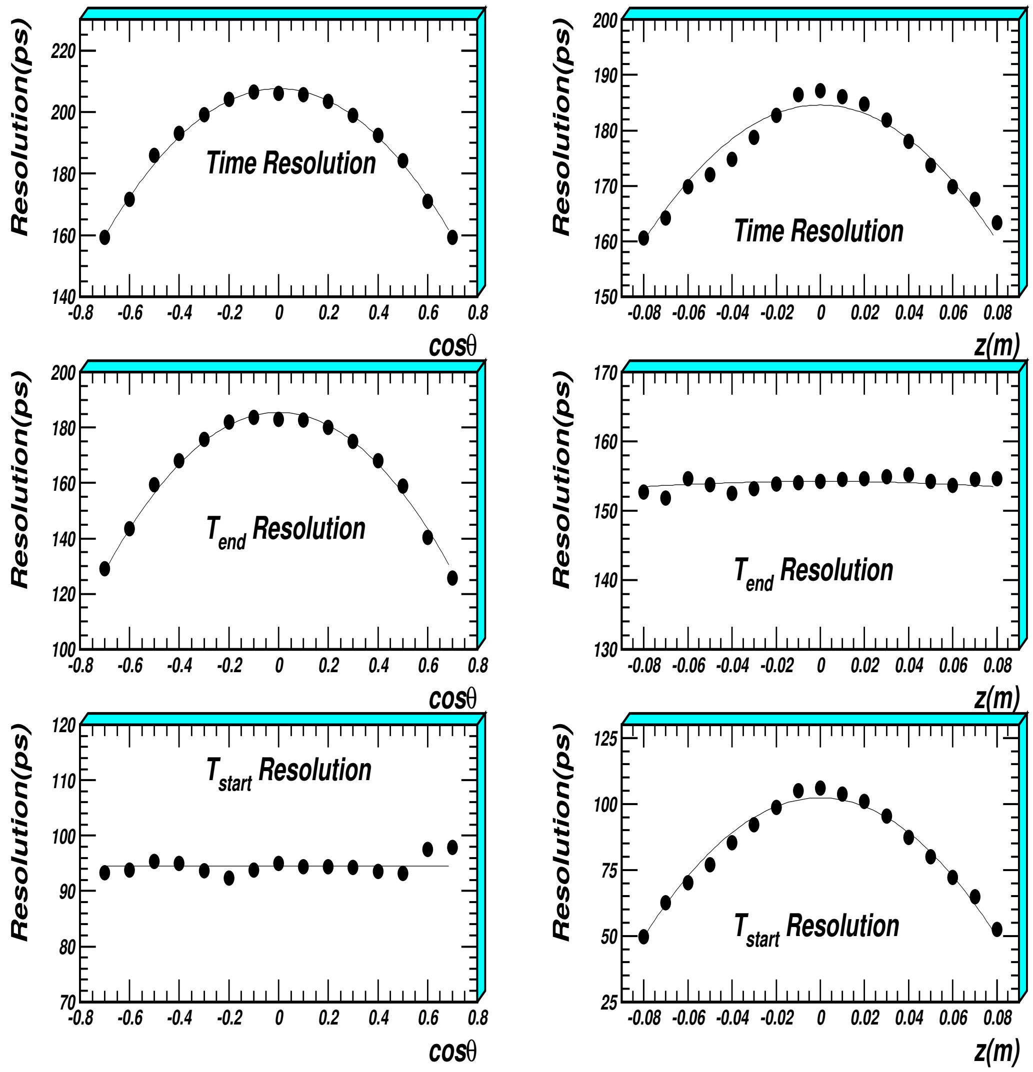


Figure 14: the resolution of measured time, T_{start} and T_{end}

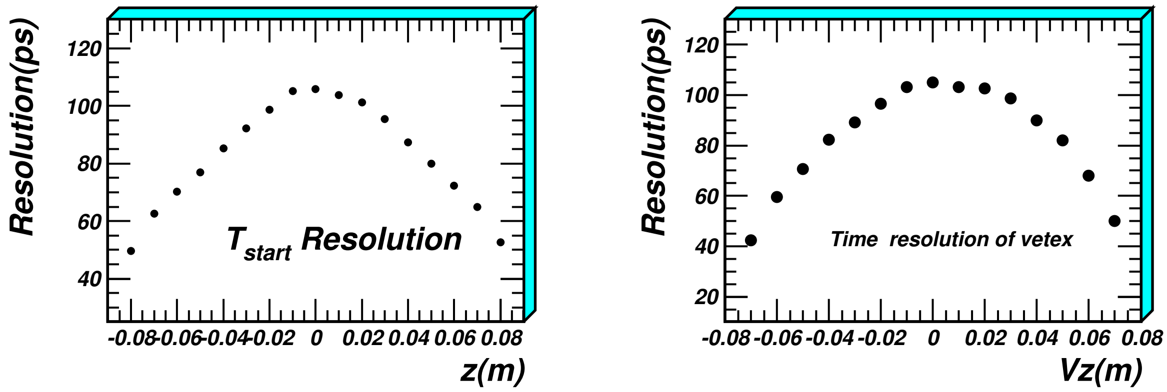


Figure 15: the T_{start} resolution vary with z position(a:electron, b:muon)

Now we check the T_{end} resolution varying with pulse amplitude, Fig.16(a) shows the T_{end} resolution varying with pluse amplitude for electron, we can see with the pulse amplitude increasing, the T_{end} resoltuion becomes smaller and smaller, and when the pulse amplitude is greater than 0.02, the resolution tends to 102ps. So we fit the resolution with function $\sigma = a + b * exp(-c * x)$. and get the resolution as a function of pulse amplitude. Also we can check T_{end} resolution distribution varying pulse amplitude for other kinds of particles. Fig.16(b) show the T_{end} resolution varying with pulse amplitude for muons, kaons and pions, the curved line is the fitting funtion from the electron sample, we can see the muon resolution distribution is very close to electron, for the hadrons when the pulse amplitude is small, it fits the curved line well, but when the pulse amplitude is large, there is difference between the hadrons and leptons, the resolution of hadrons is bigger than that of lepton, this can be explained that when the pulse amplitude is big, the monentum of the hadron is small, and the scatter contribution to time resolution can not be omitted, so the resolution for the hadron is bigger than that of leptons. Therefore the resolution does not depend on the kind of paticles when the momentum is bigger. While we have seen the different resolution for each kinds of particle, which come from the different pulse amplitude for each kinds of particle.

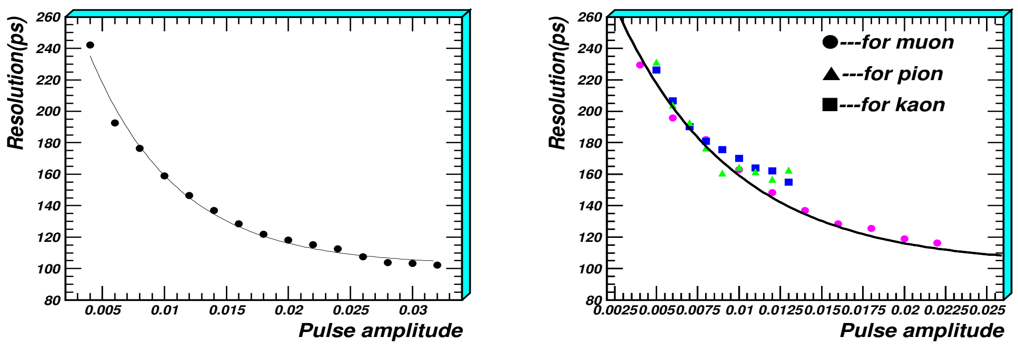


Figure 16: the T_{end} resolution vary with pulse amplitude

We have known the T_{end} resolution depends on the $cos\theta$ and pulse amplitude, and amplitude depends on the $cos\theta$ and the monentum. All these relations are combined together, so we must study the relation carefully.

Firstly we can study the T_{end} resolution varying $cos\theta$ when the pulse amplitude is in the different small range. Fig.17 shows the resolution distribution as a function of $cos\theta$ when the pulse amplitude is in different range for electron. We can see the T_{end} resolution does not depend on the $cos\theta$ too much. The reason of the T_{end} resolution depend on $cos\theta$ when the pulse amplitude in the full range is different pulse amplutide at the different $cos\theta$ position. Fig.18 shows the resolution varying with pulse amplitude when the $cos\theta$ is in different small range, we can see there is no big difference for the resolutions distribution when $cos\theta$ is in small range, which means the resolution difference is dominated by different pulse amplitude.

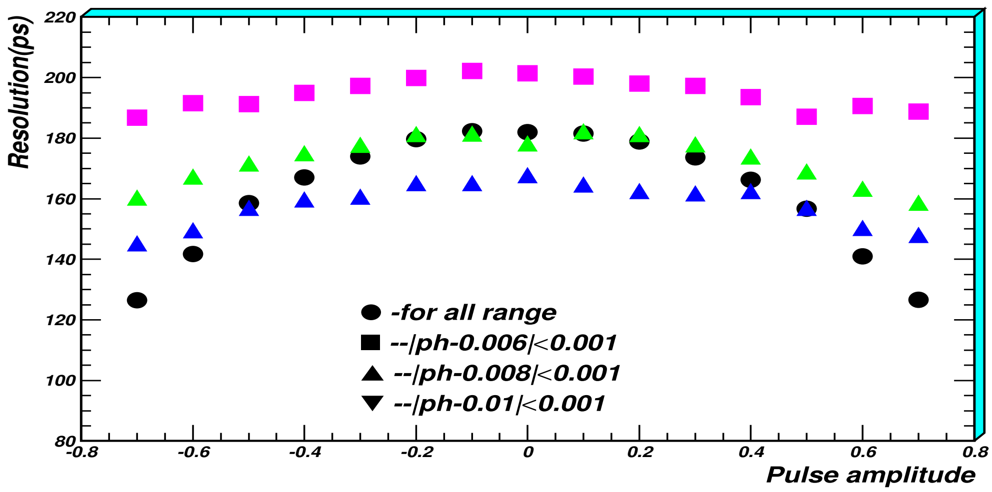


Figure 17: the T_{end} resolution vary with $cos\theta$

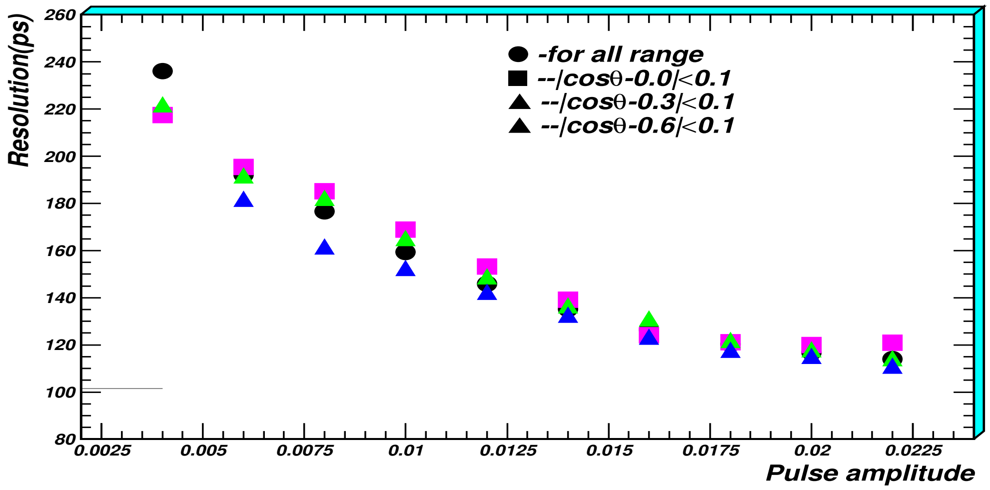


Figure 18: the T_{end} resolution vary with pulse amplitude

About the relation between the resolution and momentum, we assume the resolution does not depend on the momentum. We can compare the resolution varying with momentum after improvement, then we can get the resolution does not depend on momentum too much.

4 Some Improvement

After study the TOF behavior carefully, We can do some inprovement at TOF simulation in SOBER.

- ## To reduce the difference of resolution between electron and muon for M.C data

We have seen that the tendency of the resolution varying with $cos\theta$ is different between electron and muon for M.C. data(see Fig.5). At first, we think maybe the scattering of electron in MDC is more obvious than that of muon, but we checked the time resolution before the particle reachs the outwall, we find no big difference between the electron and muon, so our first hypothesis is ruled out. Later we found the problems is that we simulate electron with EGS after the electron reach the out wall of MDC. Because of the cluster, some secondary particles are produced, then the TOF time should be determinated by the average time of all particle reaching TOF, but so far the TOF time is determinated by the last pursuited particle. We have done some modification in tof.f file, and simply assume the TOF time is determined by the mother particle. Fig.19 shows the TOF resolution varying with $cos\theta$ after modification, we can see the tendency of electron is very close to that of muon.

- ## Time Correlation

We know we does not do the time walk simulation at the vertex, so we add the simulation. We use a gaussion sample to simulate time walk, the resolution is a function of vertex z position:

$$\sigma_{start} = A + B * z^2$$

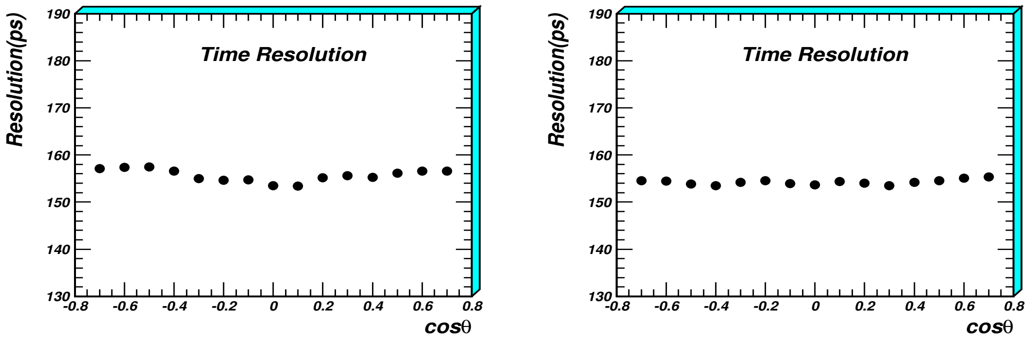


Figure 19: the TOF resolution vary with $cos\theta$(a:electron; b:muon)

the parameters can be given by the fit of the electron sample of real data.

• Pulse amplitude

We know the pulse amplitude simulation is very poor in SOBER, From the study we can see that pulse amplitude depends on $cos\theta$,β and the kind of particle. And pulse amplitude is a landau distribution. So we can get the mean and RMS of pluse amplitude as a function of $cos\theta$ and β for electron, The mean and RMS as:

$$mean = \frac{A}{sin\theta} * \frac{B + C * exp(-D * \beta)}{B + C * exp(-D * 1)}$$

$$RMS = E * \frac{F + G * exp(-H * \beta)}{F + G * exp(-H * 1)}$$

here A is a factor reflects the mean varying with $cos\theta$, and $B+C*exp(-D*\beta)$ is the mean as a function of β, and $B + C * exp(-D * 1)$ is the mean when $\beta = 1$, $F + G * exp(-H * \beta)$ reflects the RMS varying with β, $F + G * exp(-H * 1)$ is the RMS when β is 1, and E is the factor of the RMS varying with $cos\theta$. For other kinds of particles, we multiple a factor which is the ratio between the other partilces and electrons to the Mean and RMS respectly. All the parameters can be gotten from the real data. Now we instroduce the pluse amplitude simulation briefly. We first get a landau distribution sample, the do linear shift, which makes the mean of landau distribution equal to 0, and RMS equal to 1, then do and another linear shift, which makes the mean and RMS correspond to the function which we have given.

- **TOF resolution**

We know the T_{end} resolution is a function of pulse amplitude and $cos\theta$, and it is also dominated by pulse amplitude. So we add the TOF resolution correction simulation in SOBER, the resolution is a function of pulse amplitude and $cos\theta$:

$$\sigma = \sigma_i * \frac{A + B * exp(-C * PH)}{\sigma_{ave1}} * \frac{D + E * cos^2\theta}{\sigma_{ave2}}$$

Where, PH is the pulse amplitude and $A + B * EXP(-C * PH)$ reflects the resolution varying with pulse amplitude, and $D + E * cos^2\theta$ reflects the dependence between resolution and $cos\theta$ when the pulse amplitude is in a small range. σ_i is the resolution of the ith block scintillator which can be obtained from the realiztion, σ_{ave1} is the average resolution of electron sample, and σ_{ave2} is the average resolution when the pluse amsplitude is in a small range.

5 Compare the resolution between real data and M.C data after improvement

Now we can compare the resolution distribution between the real data and M.C data after improvement. We compare the result for each kinds of particles.

1. Electron sample

- **Pulse amplitude**

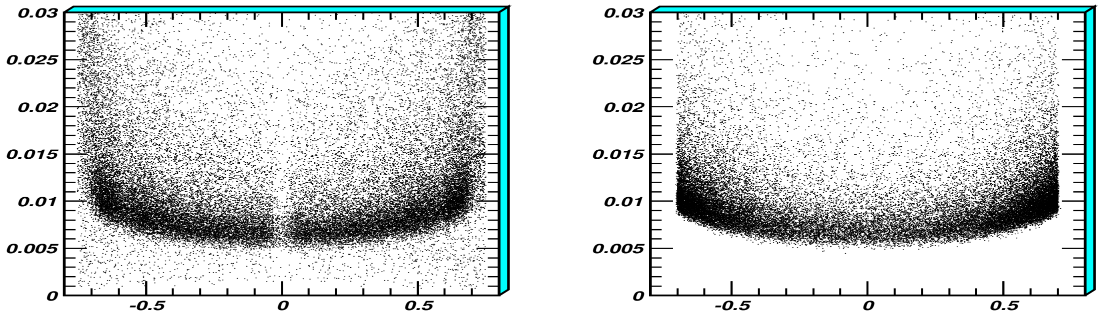


Figure 20: The scatter plot of pulse amplitude distribution (a:real data,b:MC. data)

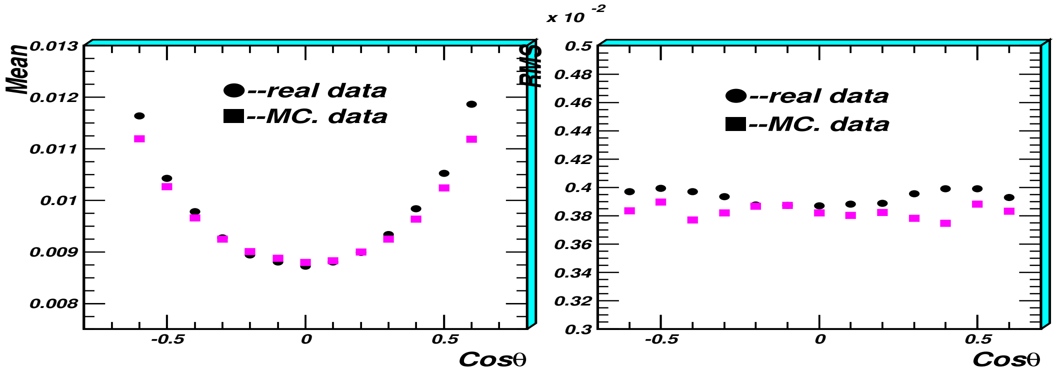


Figure 21: The mean and Rms distribution for real data and MC. data

- **TOF resolution**

Comparing the pulse amplitude varying with $cos\theta$, we can see the MC. data is simillar to the real data, We also can see the time of MC data is correlative now, and the T_{start} is about 97ps, which is very close to the real data. About the resolution varying with $cos\theta$, we can see σ_{end} of MC data is a little greater than that the real data when $cos\theta = 0.7$, also

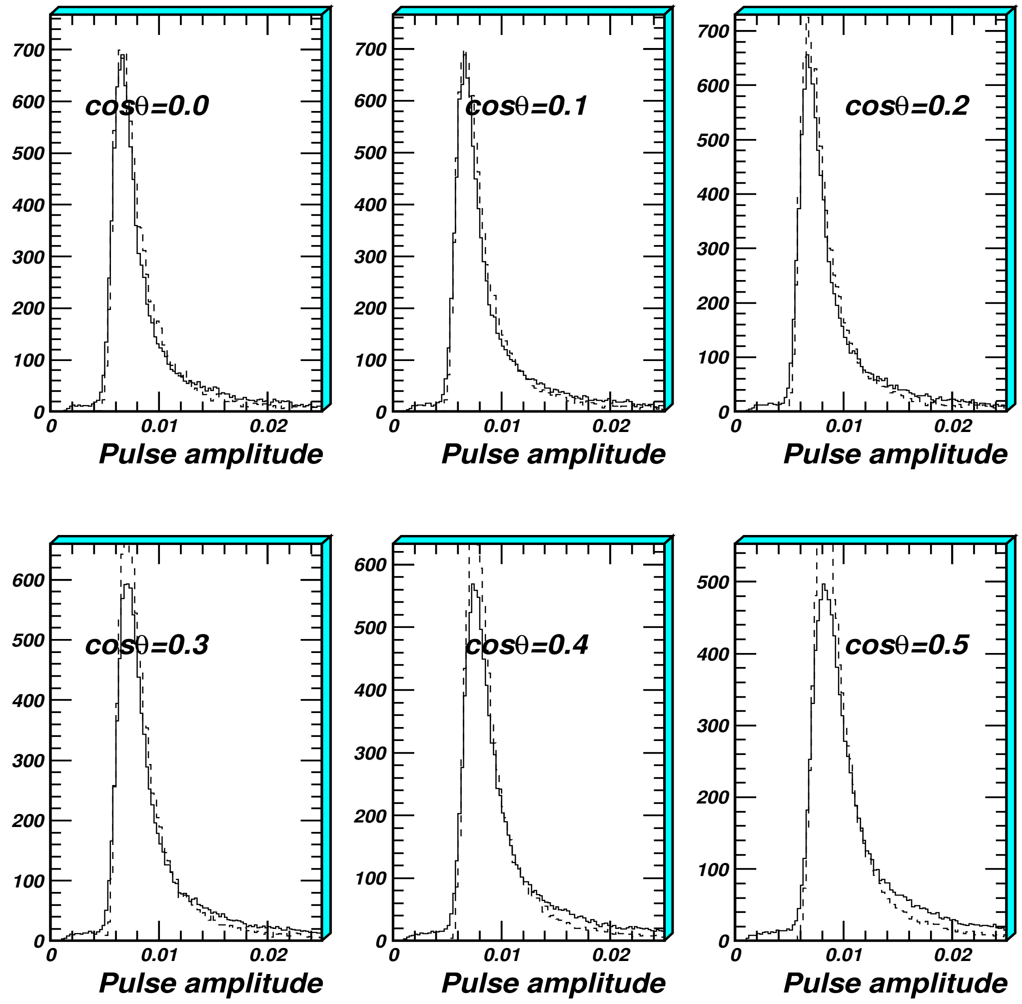


Figure 22: The pulse amplitude distribution(solid:real data;dash: MC. data)

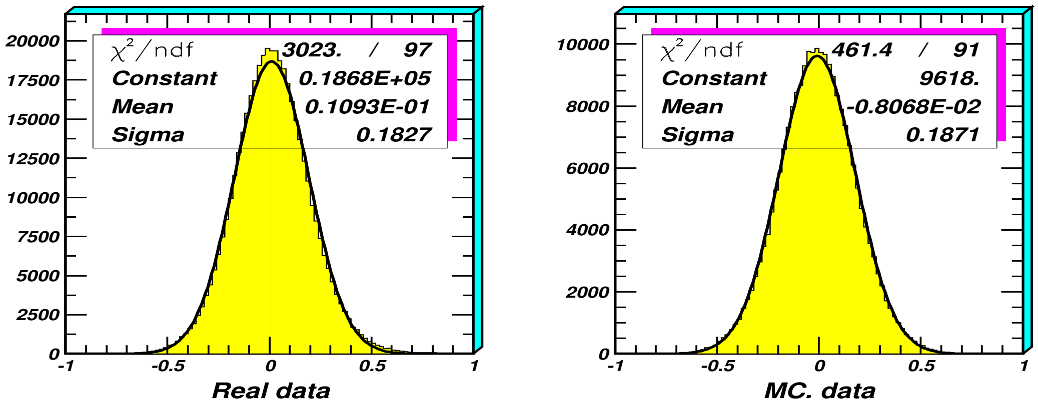


Figure 23: The ΔT distribution

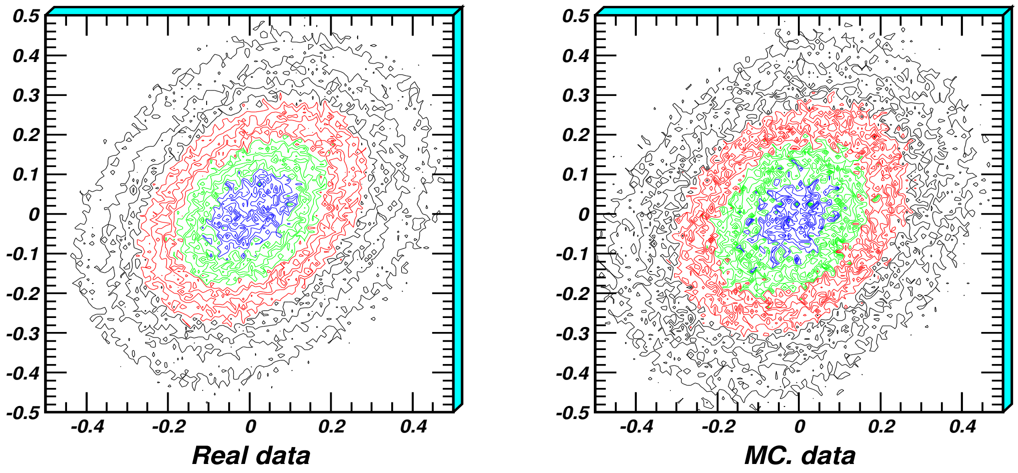


Figure 24: The scatter plot of ΔT distribution

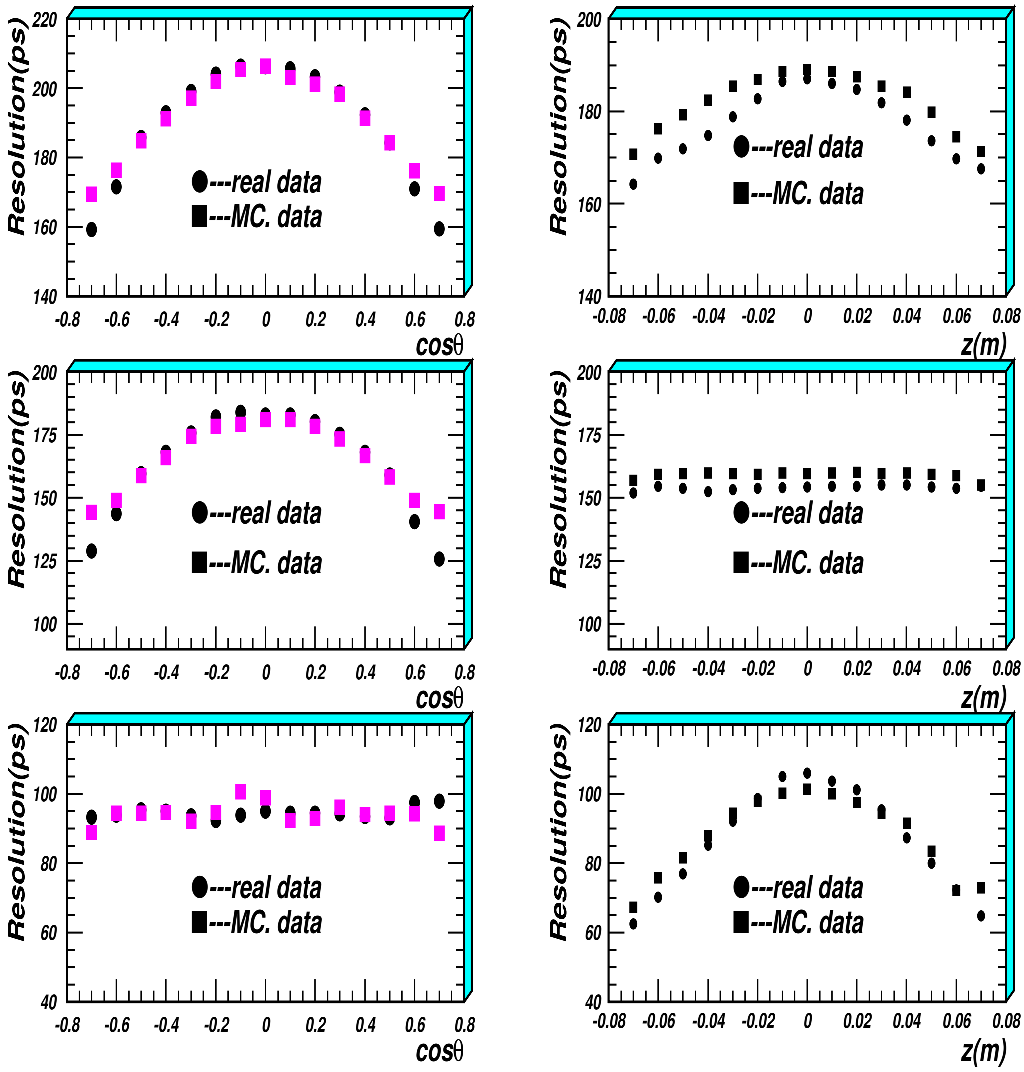


Figure 25: TOF resolution vary with $cos\theta$ and Z

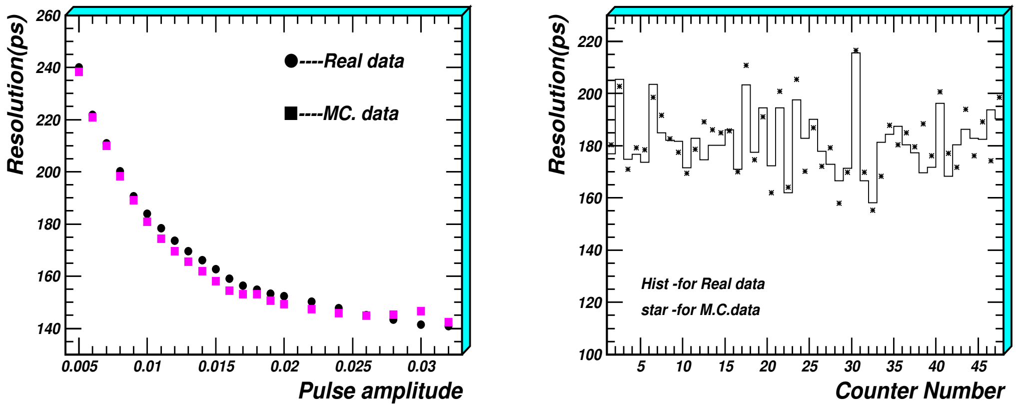


Figure 26: TOF resolution vary with Ph and C.N.

we can see the T_{end} resolution of MC data is larger than that of the real data when it varying with z position. The reason is we are unble to not simulate the pulse amplide at the end of the TOF scintillation well, so the pulse amplitude of real data is greater than that for MC data at the edge of TOF. We also compare the resolution varying with cosθ and counter number respectively, and find there are not too many difference between real data and M.C. data.

2. Muon sample

- **Pulse amplitude**

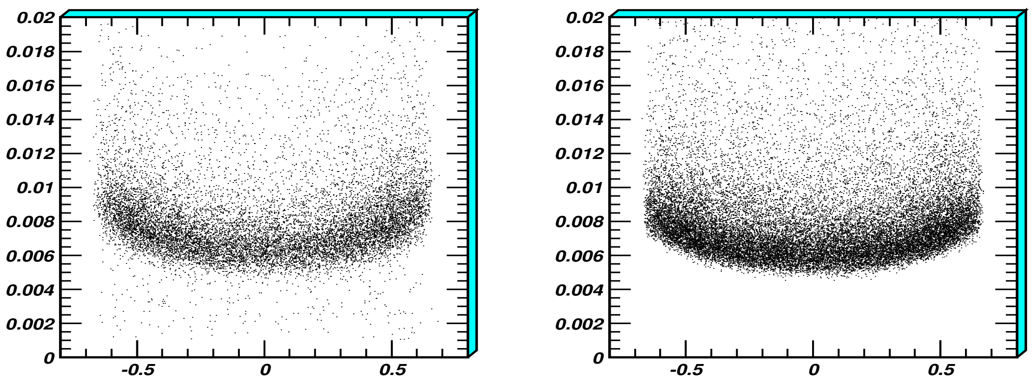


Figure 27: The scatter plot of pulse amplitude distribution (a:real data,b:MC. data)

- **TOF resolution**

From the comparision, we can see the pulse amplitude and resolution distribution of M.C. data are very close to these of real data.

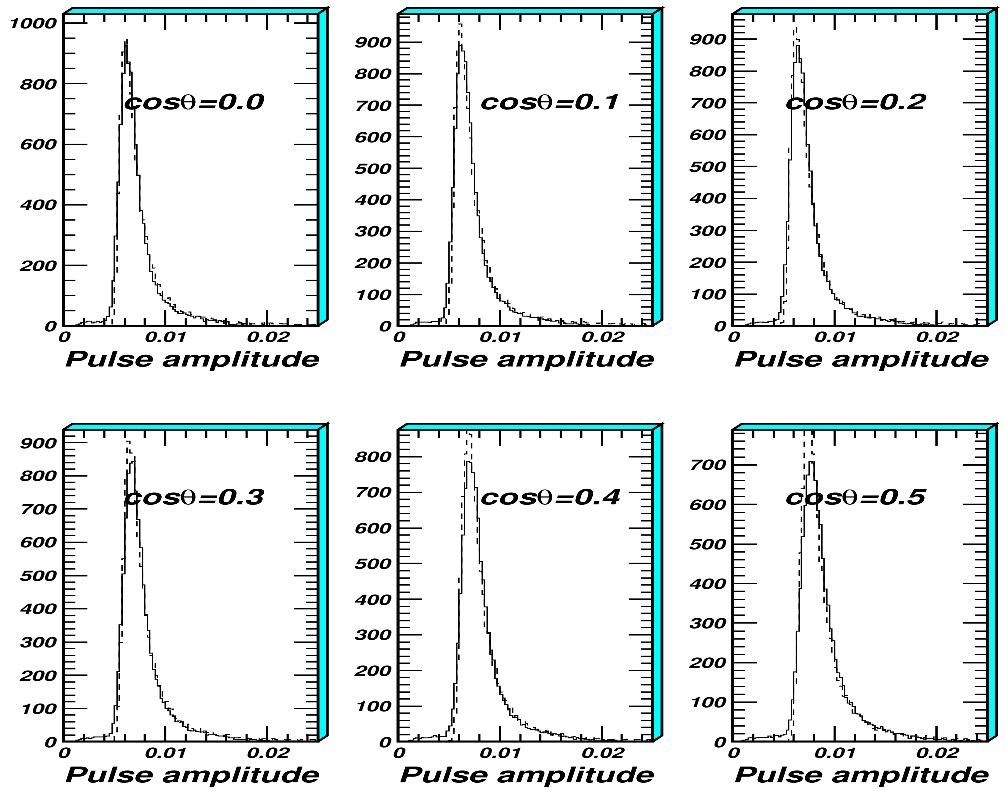


Figure 28: The pulse amplitude distribution(solid:real data;dash: MC. data)

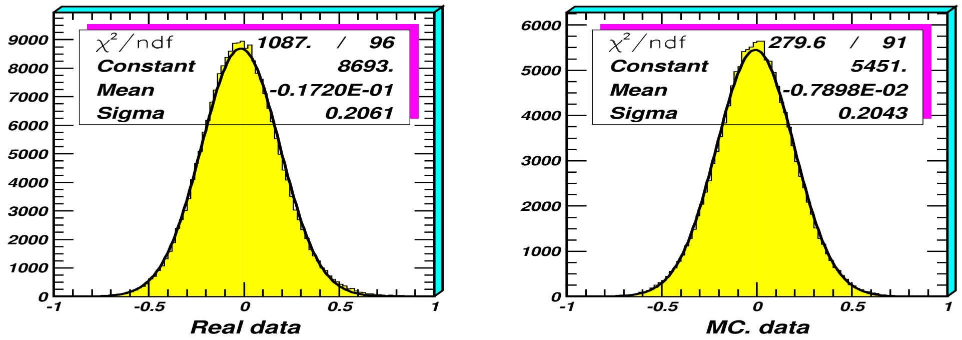


Figure 29: The ΔT distribution

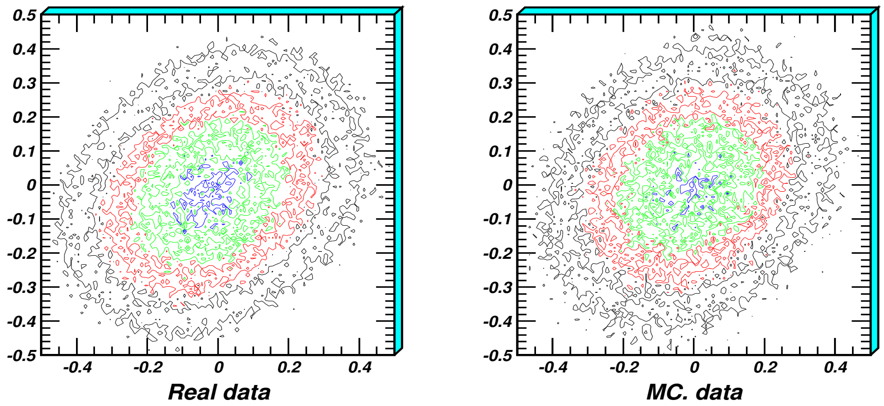


Figure 30: The scatter plot of ΔT distribution

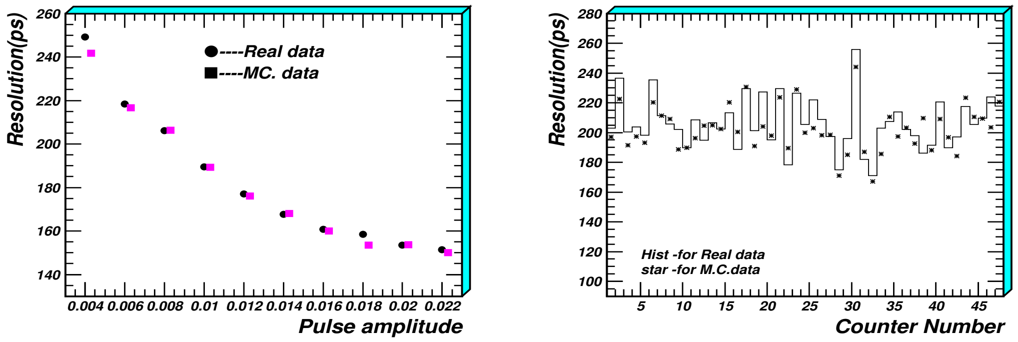


Figure 31: TOF resolution vary with Ph and C.N.

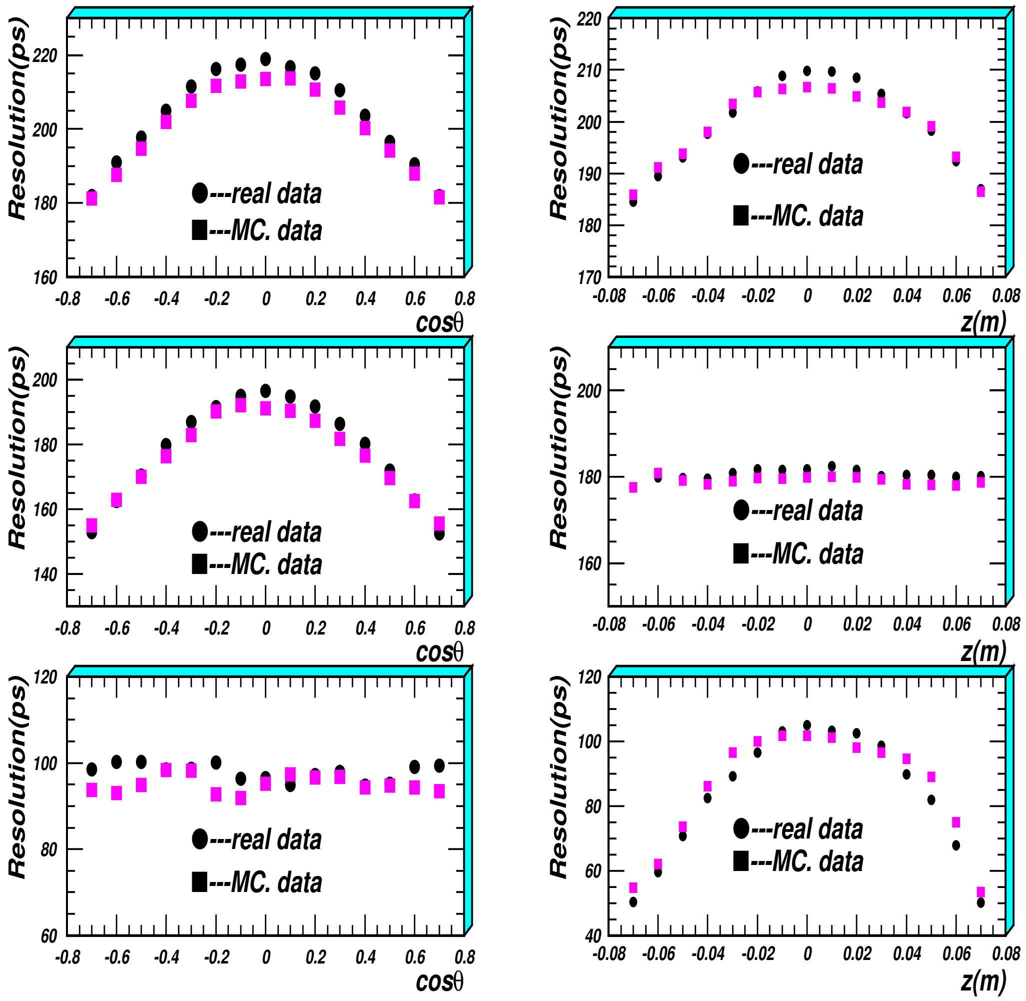


Figure 32: TOF resolution vary with $cos\theta$ and Z

3. pion sample

- **Pulse Ampltude**

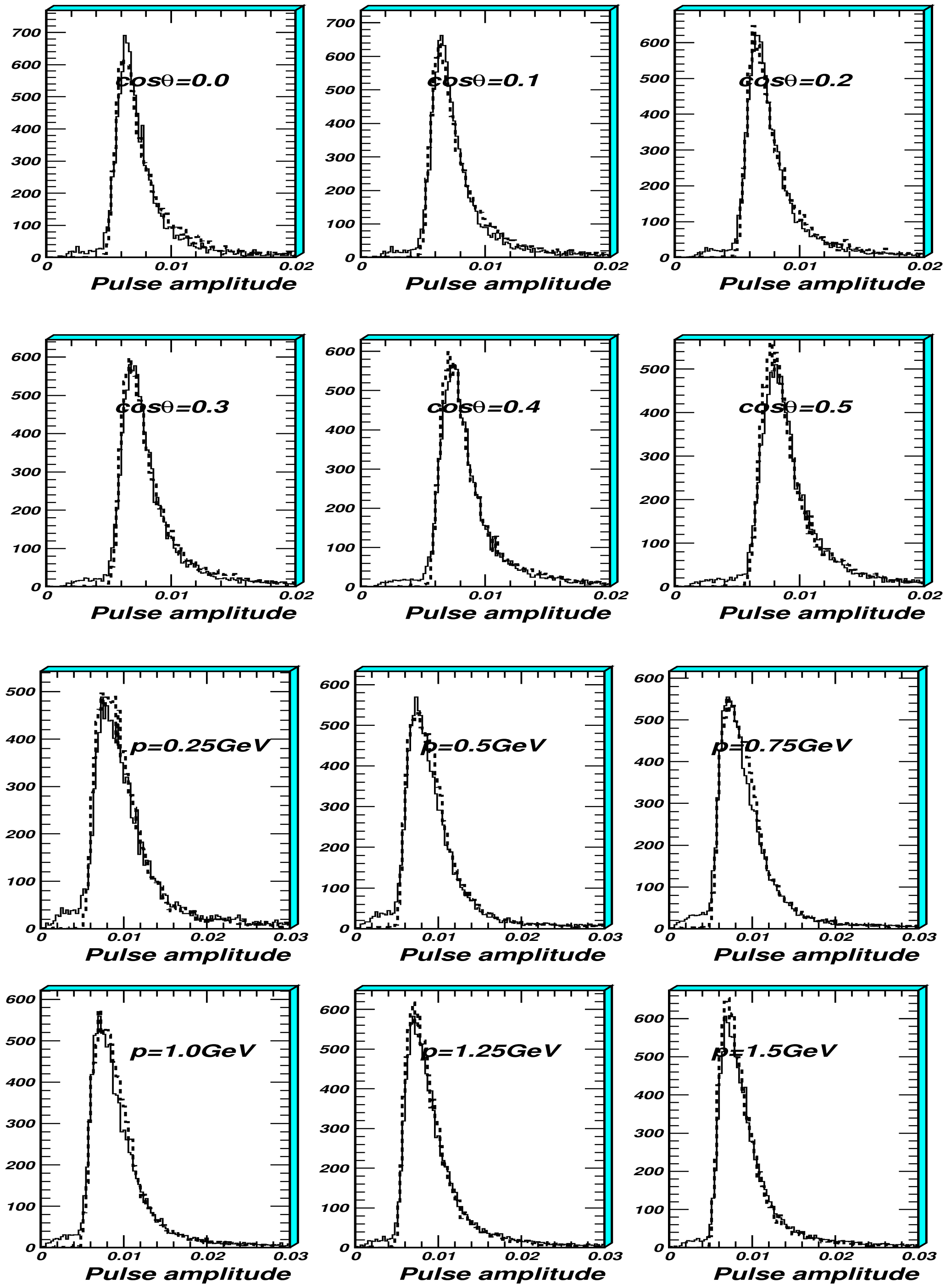


Figure 33: Pulse amplitude vary with $cos\theta$ and momentum

- **TOF resolution**

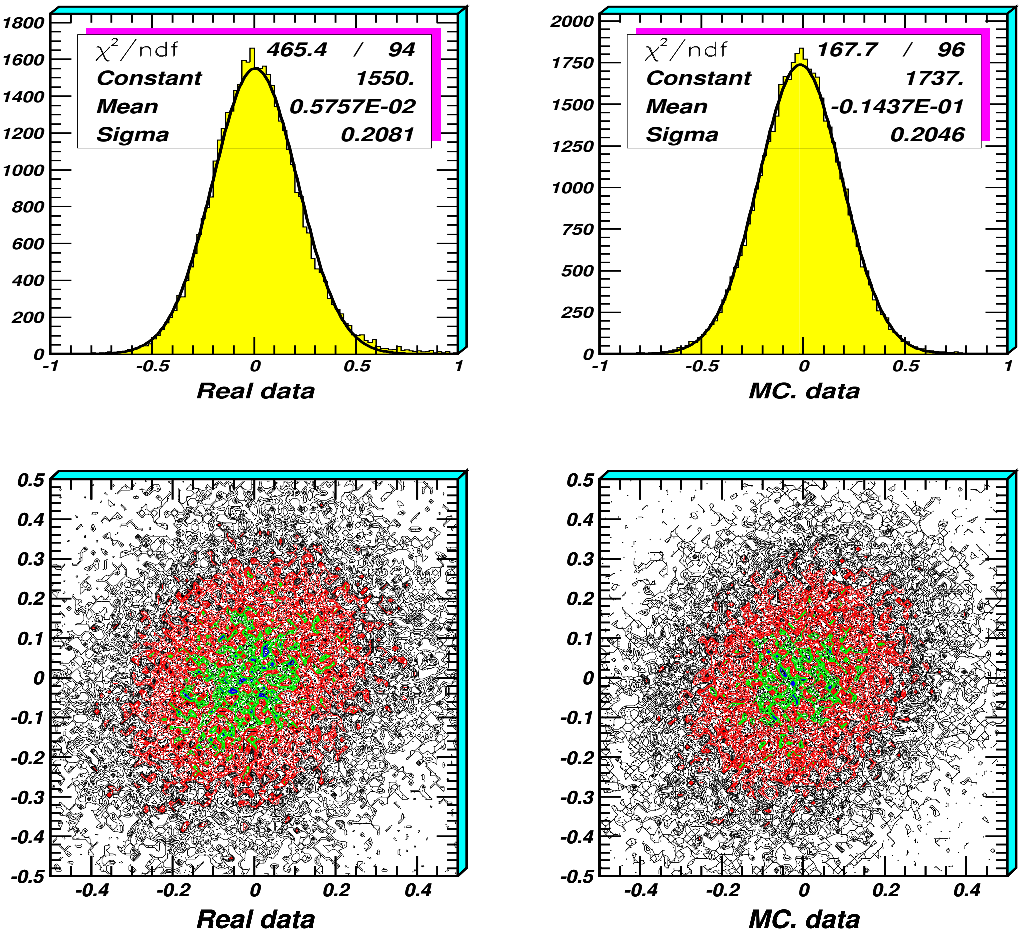


Figure 34: ΔT distribution

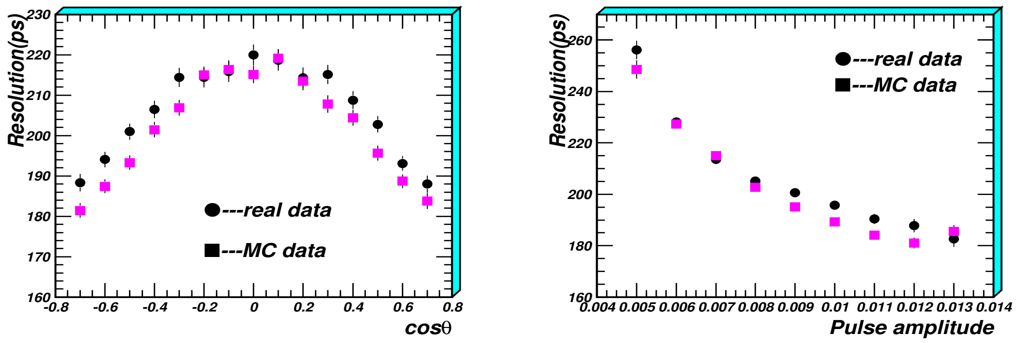


Figure 35: Resolution varying with cosθ and pulse amplitude

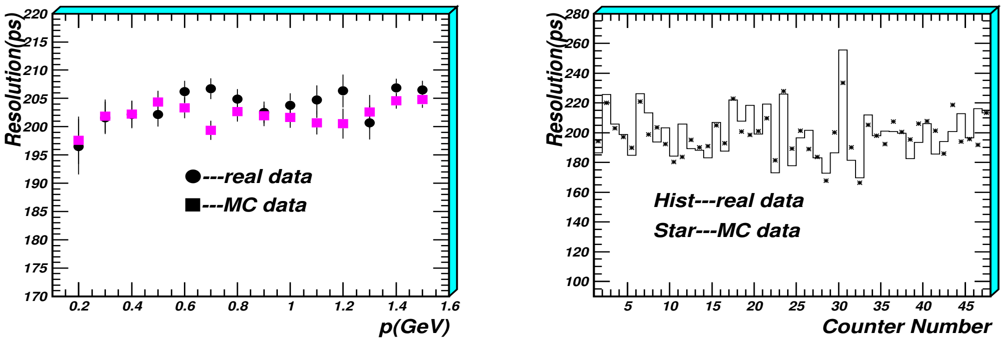
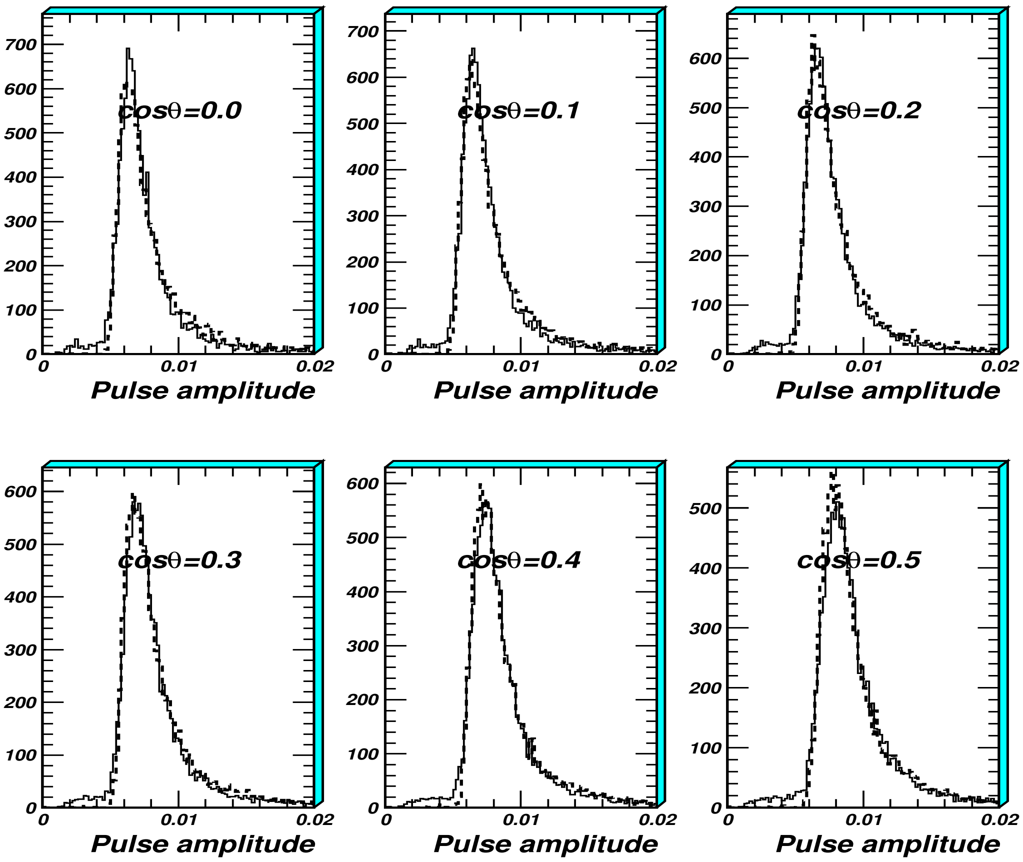


Figure 36: Resolution varying with momentum and counter number

From the comparision, we can see the pulse amplitude and resolution distribution are very similar between real data and M.C. data for pion sample.

4. kaon sample

- **Pluse Amplitude**



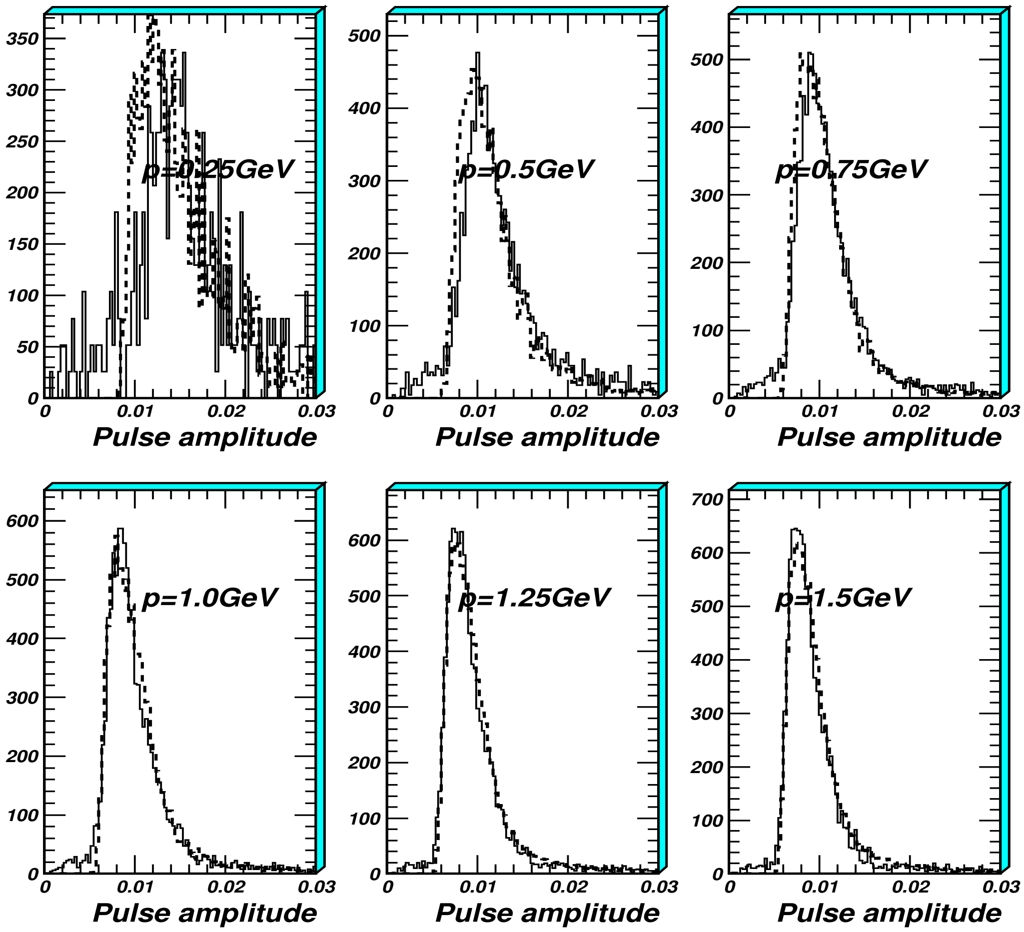
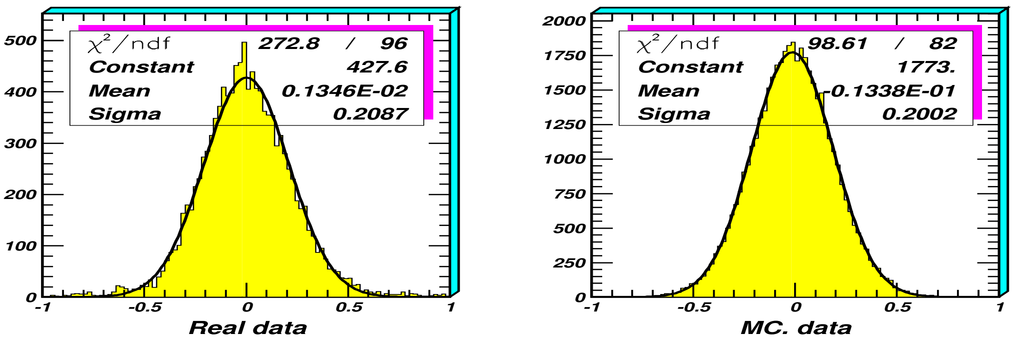


Figure 37: Pulse amplitude vary with $cos\theta$ and momentum

- **Resolution**



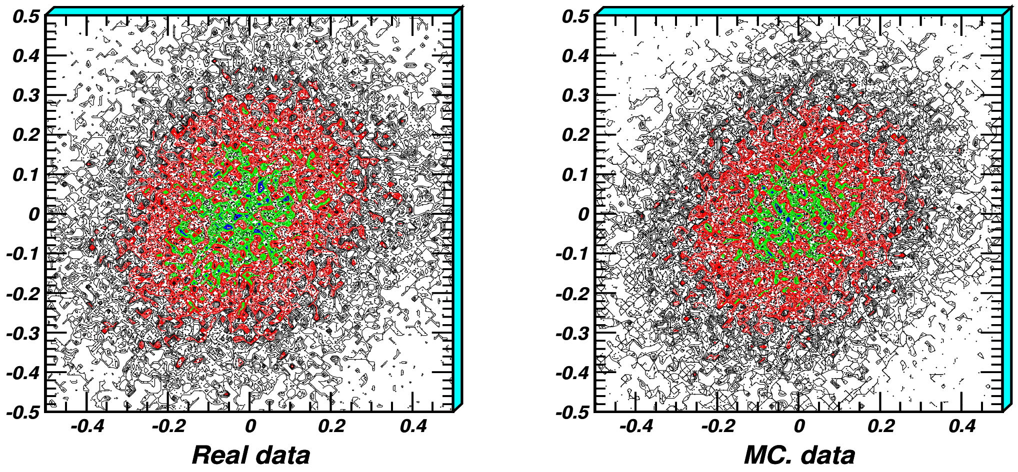


Figure 38: ΔT distribution

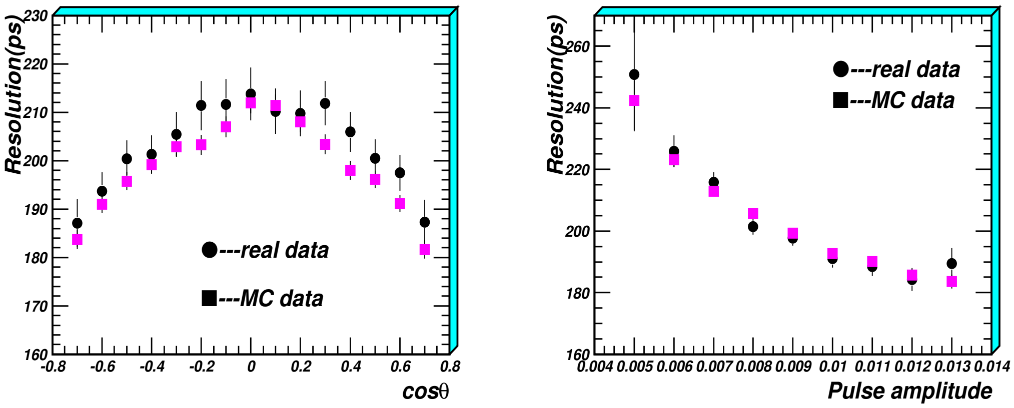


Figure 39: Resolution varying with $\cos\theta$ and pulse amplitude

From the comparision, we can see the pulse amplitude and resolution distribution are very similar between real data and M.C. data for Kaon sample.

5. Proton sample

- **Pluse Amplitude**

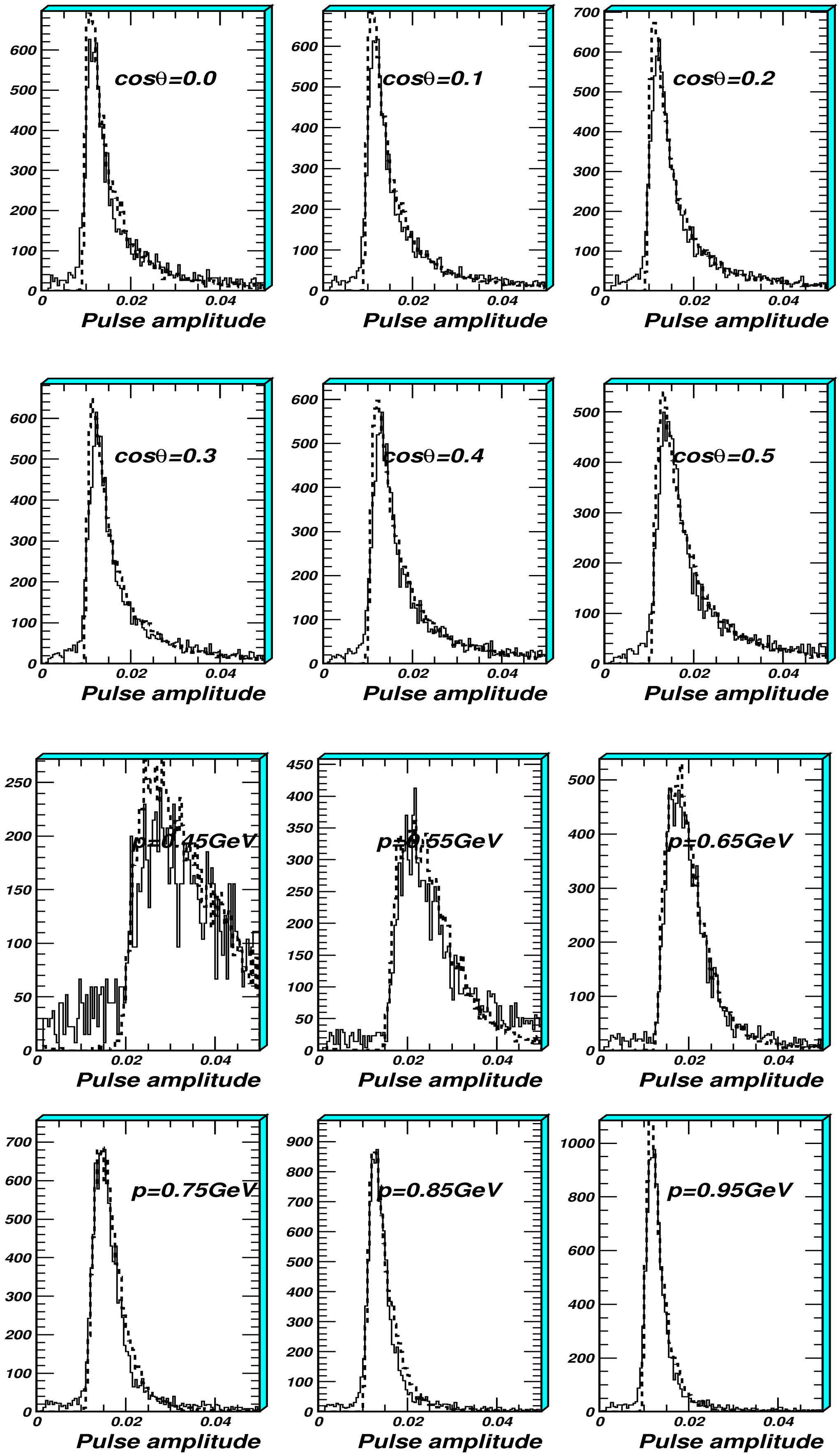


Figure 40: Pulse amplitude vary with $cos\theta$ and momentum

- **Resolution**

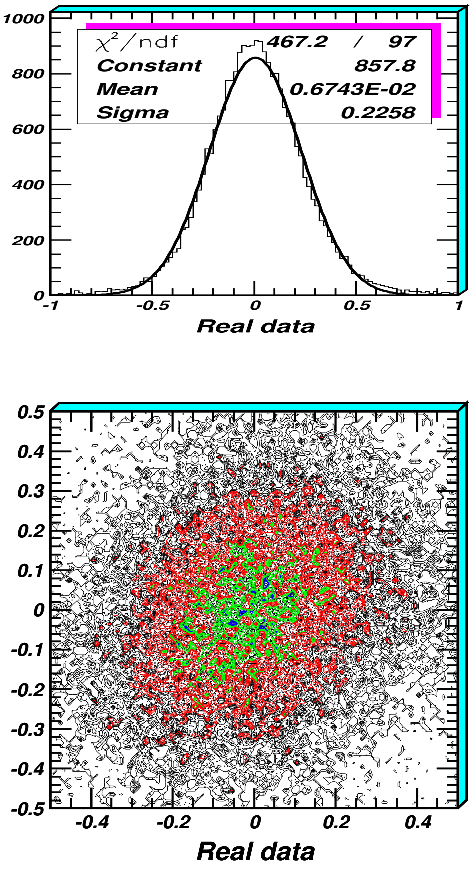


Figure 41: ΔT distribution

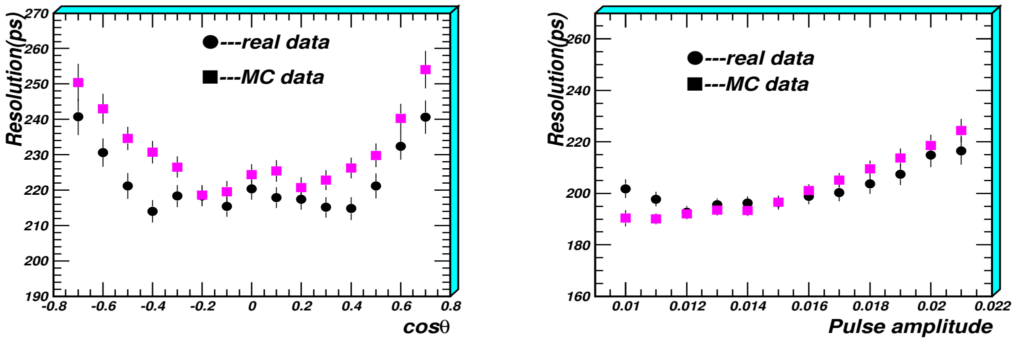


Figure 42: Resolution varying with cosθ and pulse amplitude

From the comparision, we can see the pulse amplitude and resolution distribution are very similar between real data and M.C. data for Proton sample.

6 Conclusion

- TOF has been upgraded since 1995, TOF resolution is about 180ps for Bhabha events, it is used to do PID widely. In order to decrease the difference between real data and M.C. data, good TOF simulation is urgently required at BESΠ.

- From the comparision between the real data and M.C. data, we find that the 'time walk' at vertex has not been simulated in SOBER so far, and TOF resolution and pulse amplitude have some differences between real data and MC. data.

- From the stud of the real data carefully, we know that time is correlated, and time walk resolution depends on vetex z position. T_{end} resolution is dominated by pulse amplitude and $cos\theta$, and pulse amplitude depends on $cos\theta$ and β.

- We add the time walk simulation, TOF resolution dependence simulation and pulse amsplitude simulation in SOBER.

- After improvement, we check the time resolution varying with $cos\theta$, pulse amsplitude, momentum and counter number respectively, and get the resolution difference between real data and MC. data is less than:

type	electron	muon	pion	kaon	proton
difference(ps)	5.0	5.0	10.0	10.0	15.0

Table 2: The difference of resolution between real data and M.C. data after correction