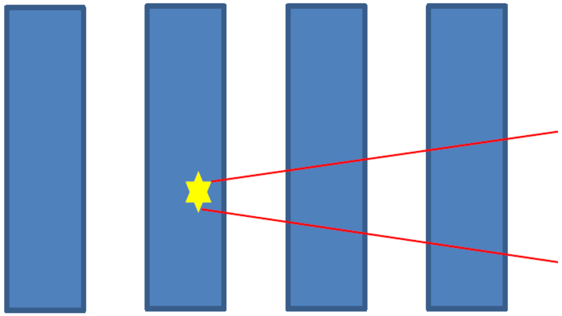
# Neutron Detector Simulation
# 2015 / 04 / 03



Korea University
Nuclear Physics Lab.
BumGon Kim

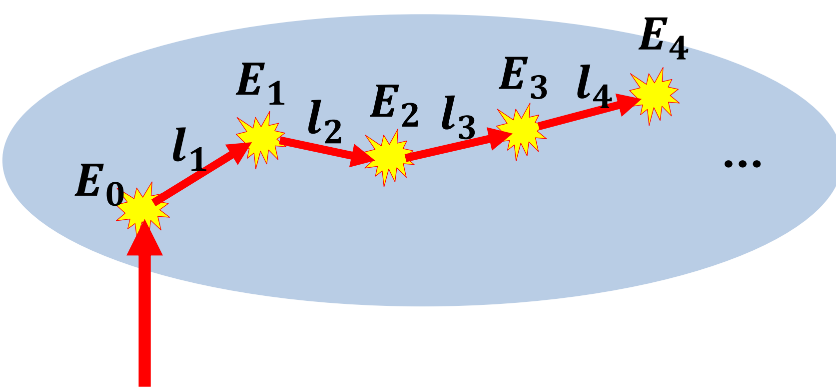
# Birks Formula

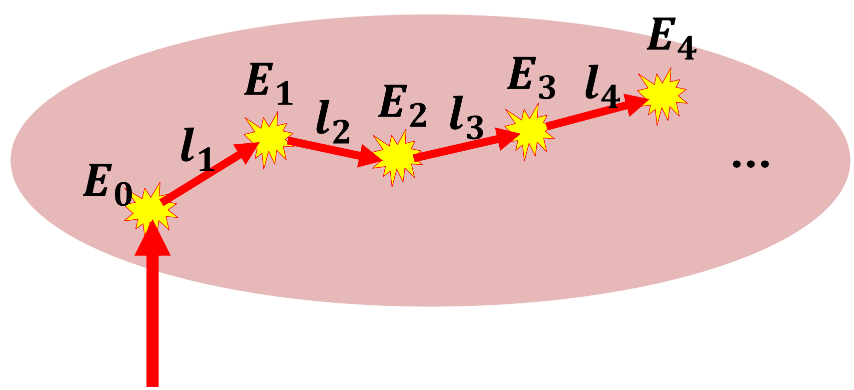
- 각각의 event에서, gate time(= 150 ns) 동안 bar scintillator 에 남겨지는 모든 hit fragment 들을 모은다.

- 실제 실험에서 하나의 bar scintillator 안에 2개 이상의 signal 이 존재할 때,
  - 생성된 위치의 거리가 **18 cm** 이상 떨어져 있거나,
  - 생성 시간이 **30 ns** 이상 차이가 날 때,

  이들을 각각 구분할 수 있다.
  이 결과를 적용하여, hit fragment 들을 각각의 group으로 분류한다.

- 이렇게 구분한 각각의 group 내의 hit fragment 들에 대해서, Birks formula 를 적용한다.



# Birks Formula

- 각각의 group 내의 hit fragment 들을 생성된 시간 순으로 정렬($i = 0, 1, 2, 3, \ldots$)한다.
- 시간 순으로 나열된 인접한 hit fragment 들($(i-1)$-th & $i$-th) 간의 거리 $l_i$ 를 구한다.
- Scintillator 의 밀도 $\rho$ 와 $l_i$ 를 곱하여 path length $dz_i = \rho l_i$ 을 구한다.
- Hit fragment 의 GEANT4 energy deposit($E_i$) value에서 path length 를 나눈 값(energy deposit per path length $p_i = E_i/dz_i$)을 구한다.
  - 단, $E_0$ 의 경우는 $E_1$ 에 더하여 계산한다($p_1 = (E_0 + E_1)/dz_1$)
- Birks formula 를 적용하여 scintillation light energy per path length $p_{corr-i} = E_{corr-i}/dz_i$ 를 구하고, $dz_i$ 를 곱하여 scintillation light energy $E_{corr-i}$ 를 구한다.
- Group 내의 모든 각각의 hit fragment energy deposit value $E_i$ 에 해당하는 scintillation light fragment energy value $E_{corr-i}$ 들을 모두 더하여 scintillation light energy $E_{corr}$ 를 구한다.
- Group 내에서 가장 먼저 만들어진 hit fragment 의 위치를 scintillation light 이 발생한 기준점으로 정하고, 이 위치로부터 scintillator 양 끝을 향해 light이 propagate.

# Birks Formula

- Birks Formula?

$$\frac{dL}{dz} = \frac{SdE/dz}{1 + kBdE/dz + C(dE/dz)^2}$$

  - Empirical formula for the **light yield per path length** as a function of the **energy loss per path length**.
  - $L$ : Scintillation response. In simulation, $L = E_{corr}$
  - $E$ : Specific energy lose at a depth $z$
  - $z$ : Path length
  - $S$ : Electronics response per specific energy loss at the non-quenching limit
    Mostly, $S = 1$
  - $kB$ : 1st order parameter. From experiment, $0.977 \times 10^{-2}\ \mathrm{g\ cm^{-2}\ MeV^{-1}}$
  - $C$ : 2nd order parameter. It is expected strength is about two-order smaller than the one for $kB$.

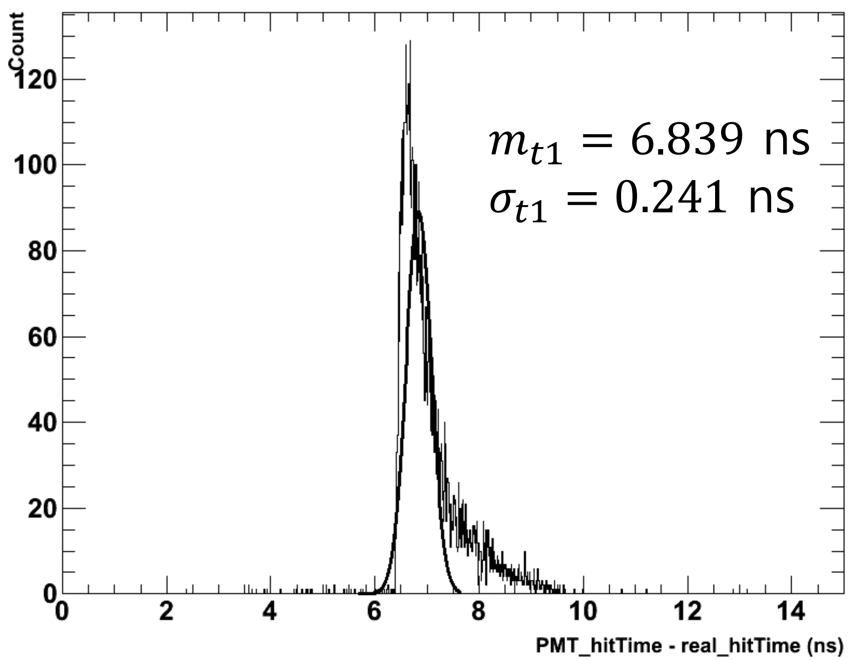
    It becomes significant as the specific energy loss exceeds $50\ \mathrm{MeV\ g^{-1}\ cm^{2}}$.
    Therefore, it does not have to be considered for neutron event.

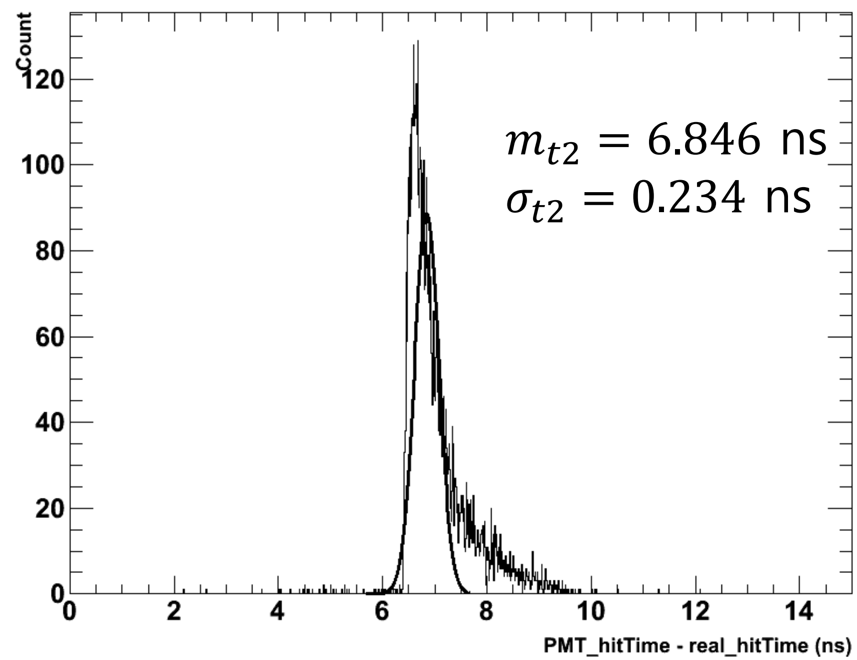
# Result

❖ **300 MeV 중성자의 발사 위치에 따른 PMT signal hitTime 1 & 2 분포 & Position reconstruction**

- Threshold signal integration energy = **20 MeV**
- Light propagation velocity = 160 mm/ns

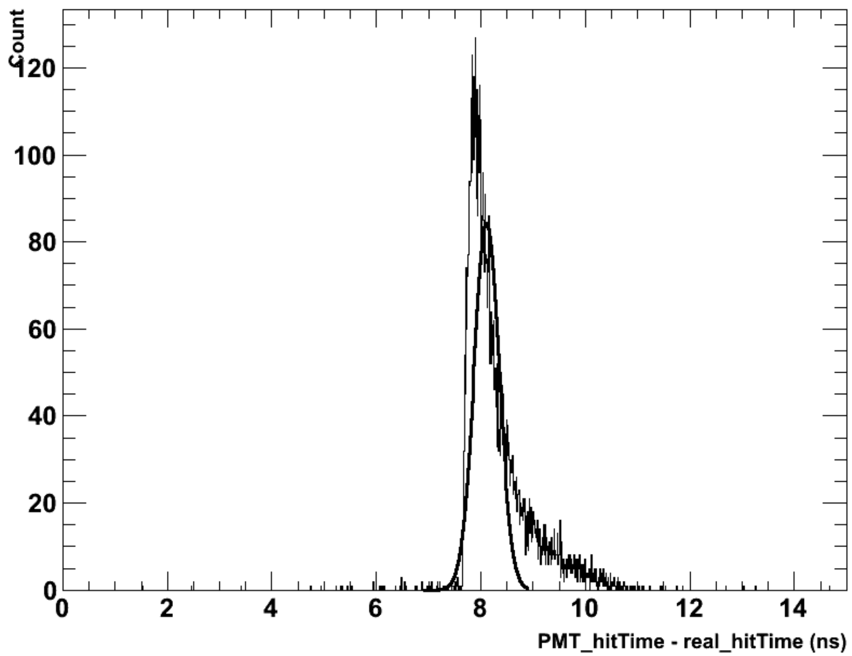
**1. 100 cm – 100 cm (center)**

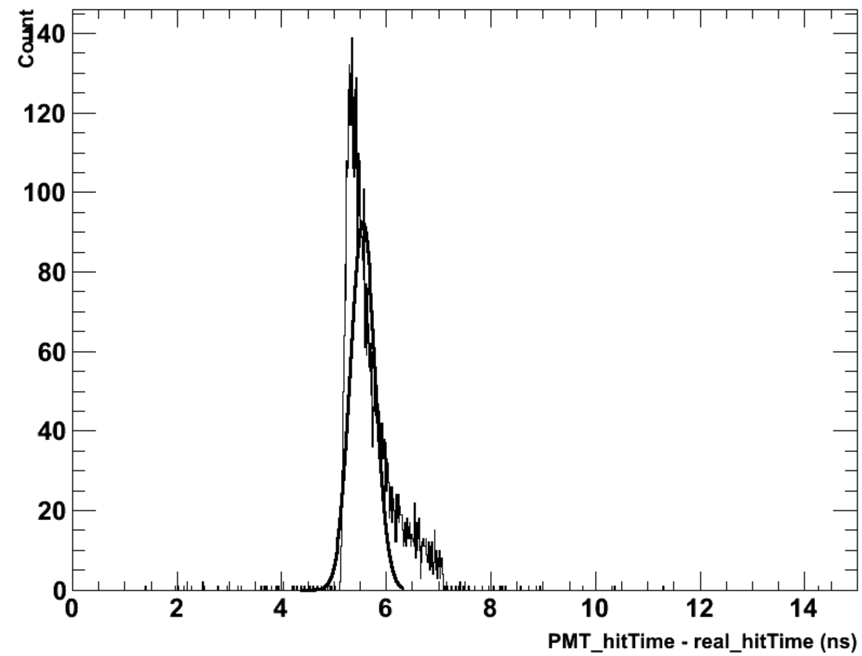


# Result

## 2. 120 cm – 80 cm

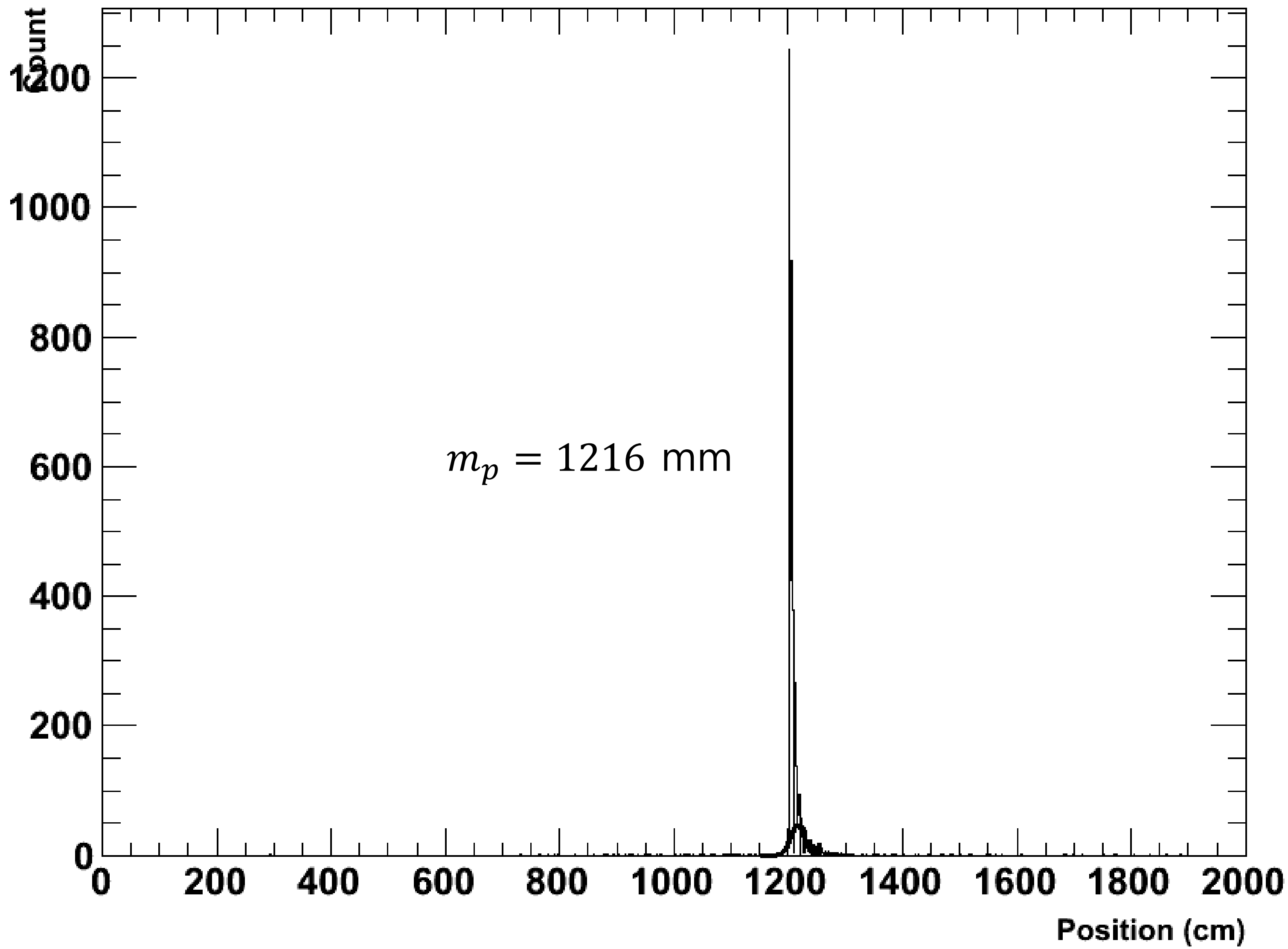



$m_{t1} = 8.111$ ns
$\sigma_{t1} = 0.238$ ns

$m_{t2} = 5.550$ ns
$\sigma_{t2} = 0.235$ ns

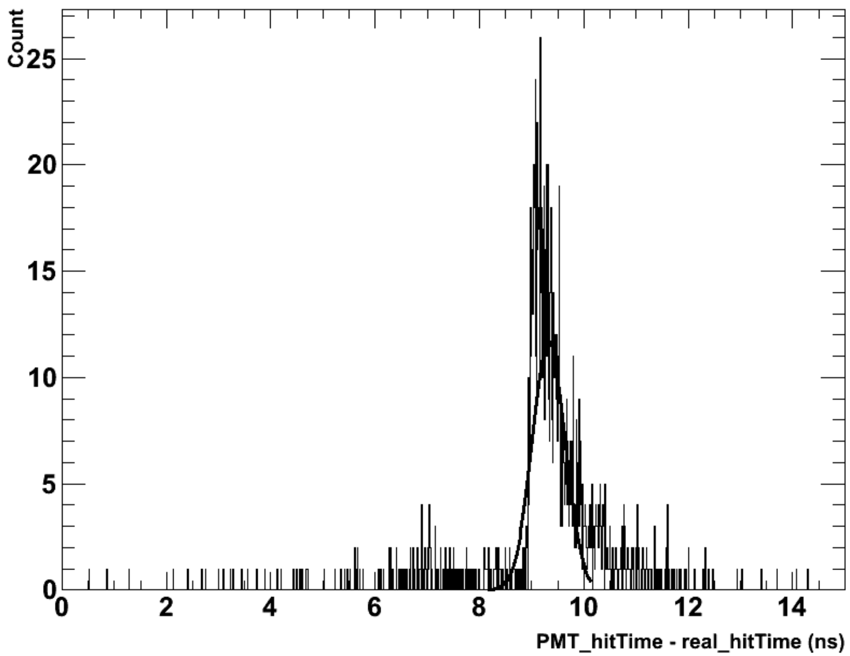
# Result

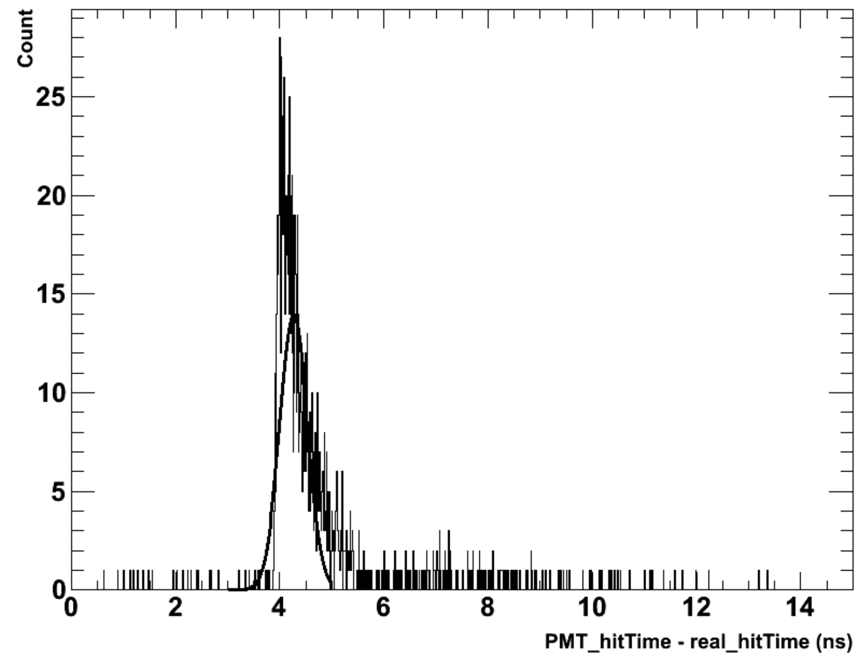


Count
0
200
400
600
800
1000
1200
$m_p = 1216$ mm
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)

# Result

3. **140 cm – 60 cm**

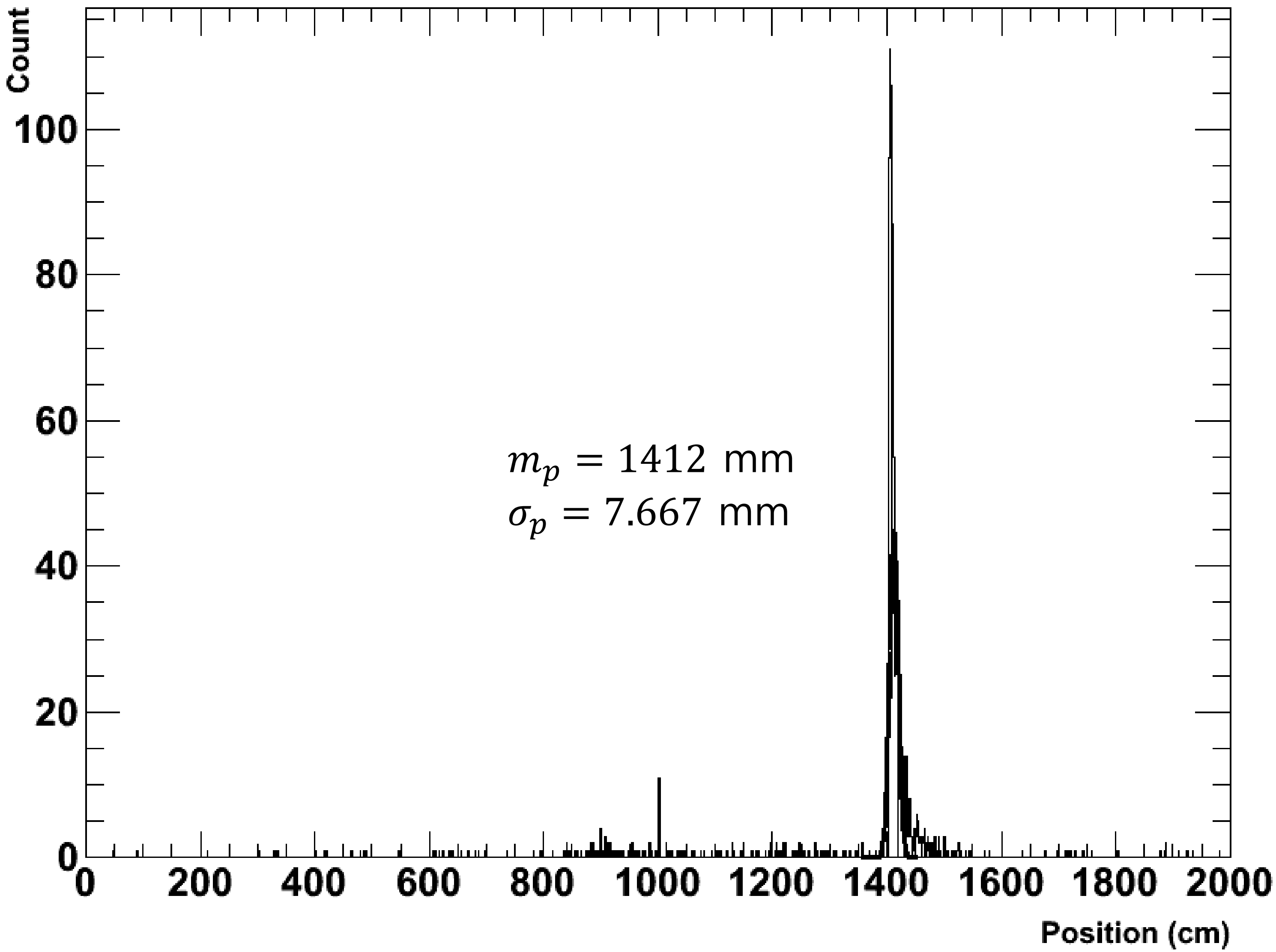



$m_{t1} = 9.327$ ns
$\sigma_{t1} = 0.315$ ns

$m_{t2} = 4.264$ ns
$\sigma_{t2} = 0.265$ ns

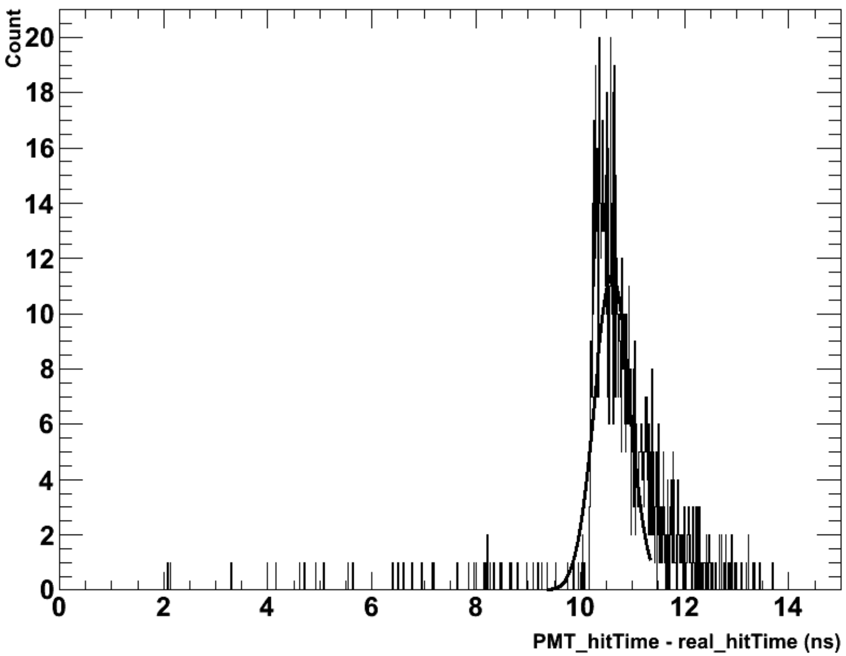
# Result



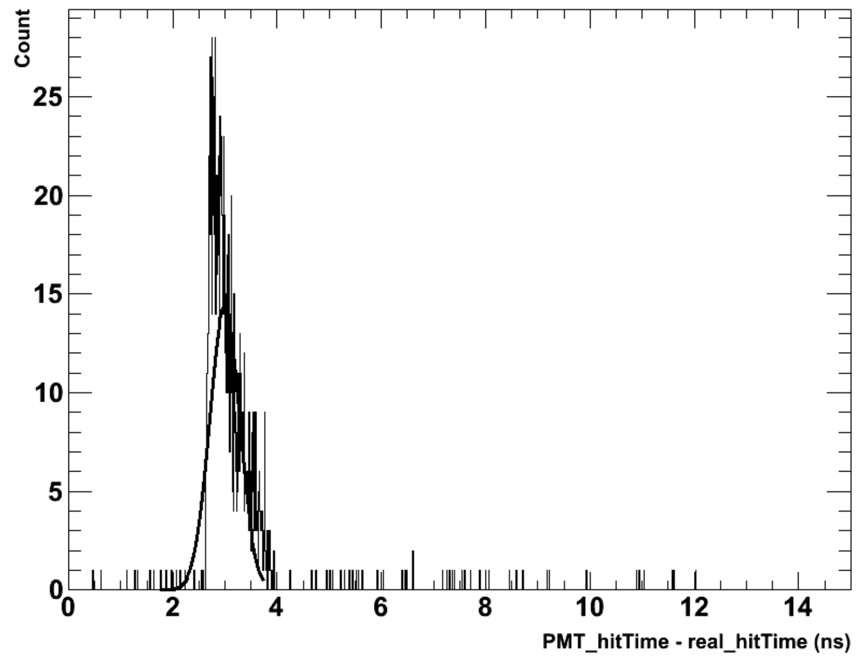
Count
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)
$m_p = 1412$ mm
$\sigma_p = 7.667$ mm

# Result

4. **160 cm – 40 cm**

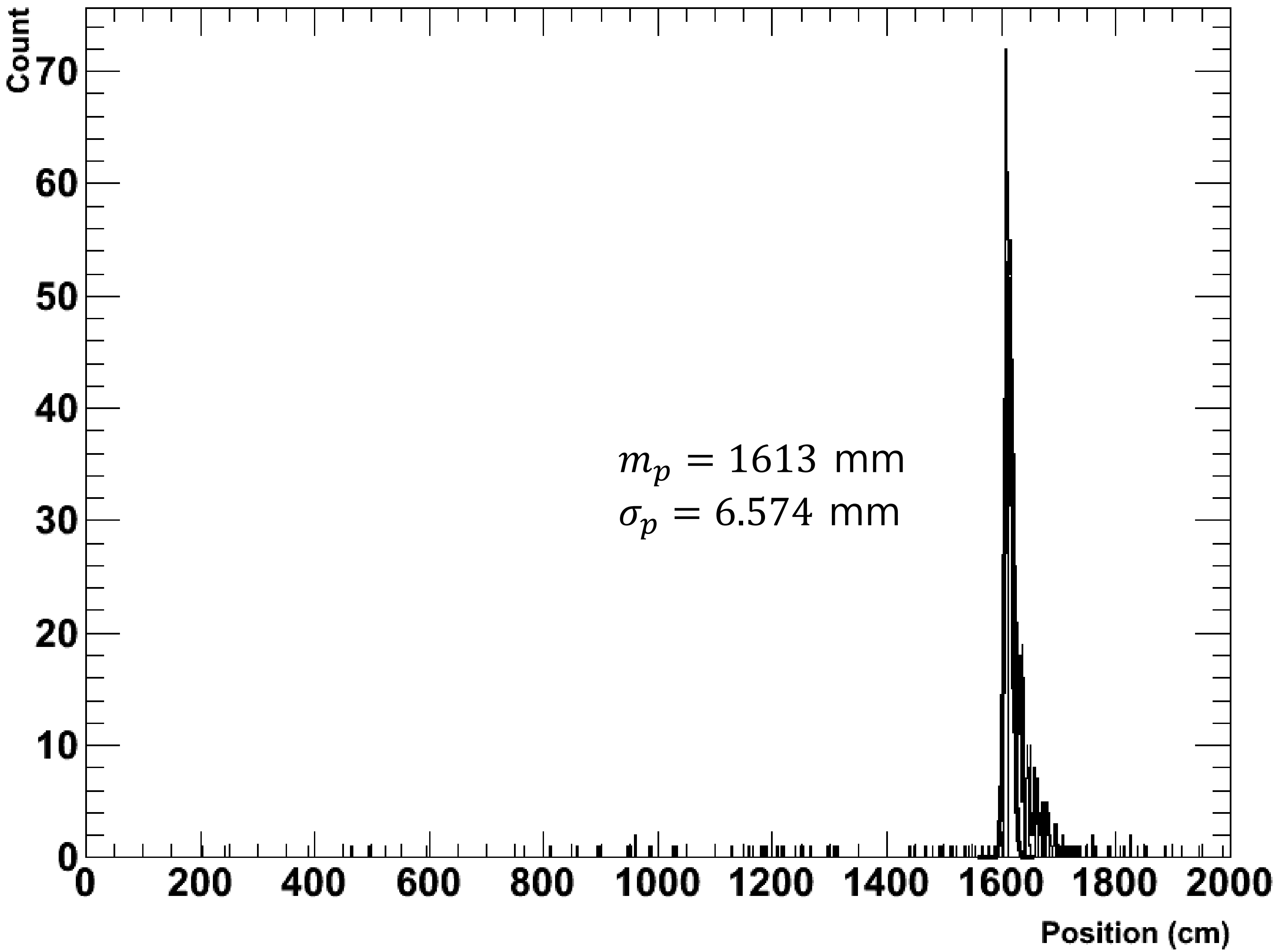



$m_{t1} = 10.61$ ns
$\sigma_{t1} = 0.338$ ns




$m_{t2} = 2.992$ ns
$\sigma_{t2} = 0.287$ ns

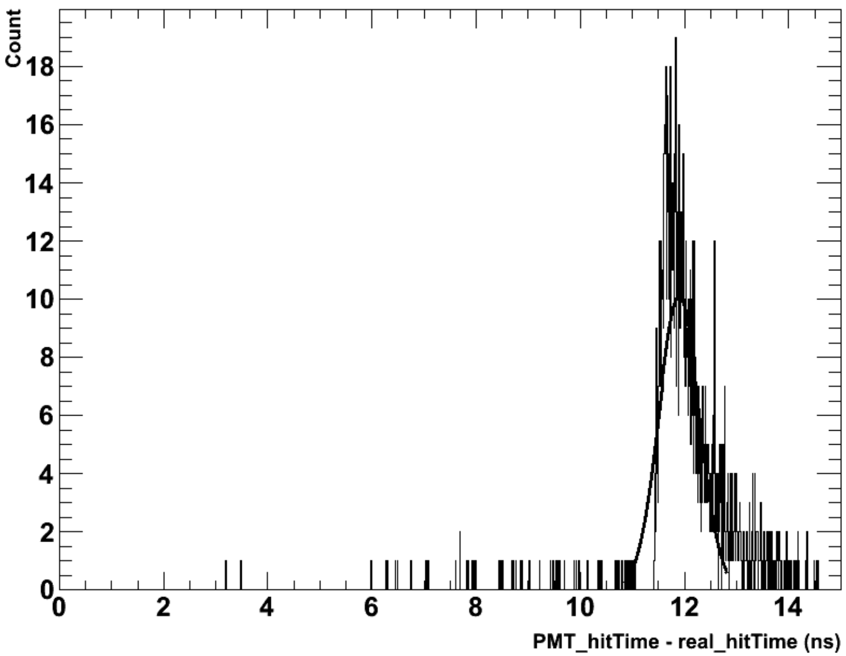
# Result

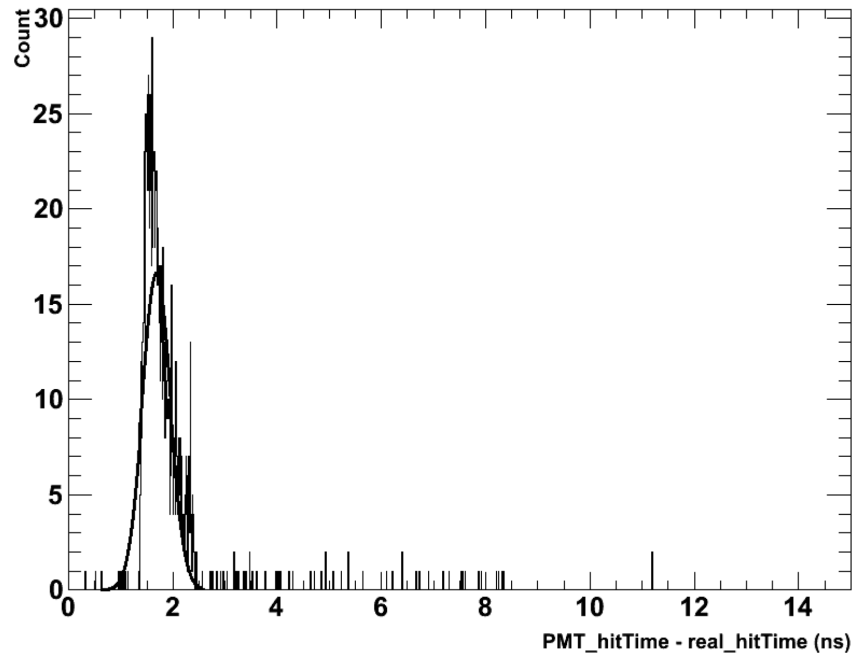



$m_p = 1613$ mm
$\sigma_p = 6.574$ mm

# Result

## 5. 180 cm – 20 cm

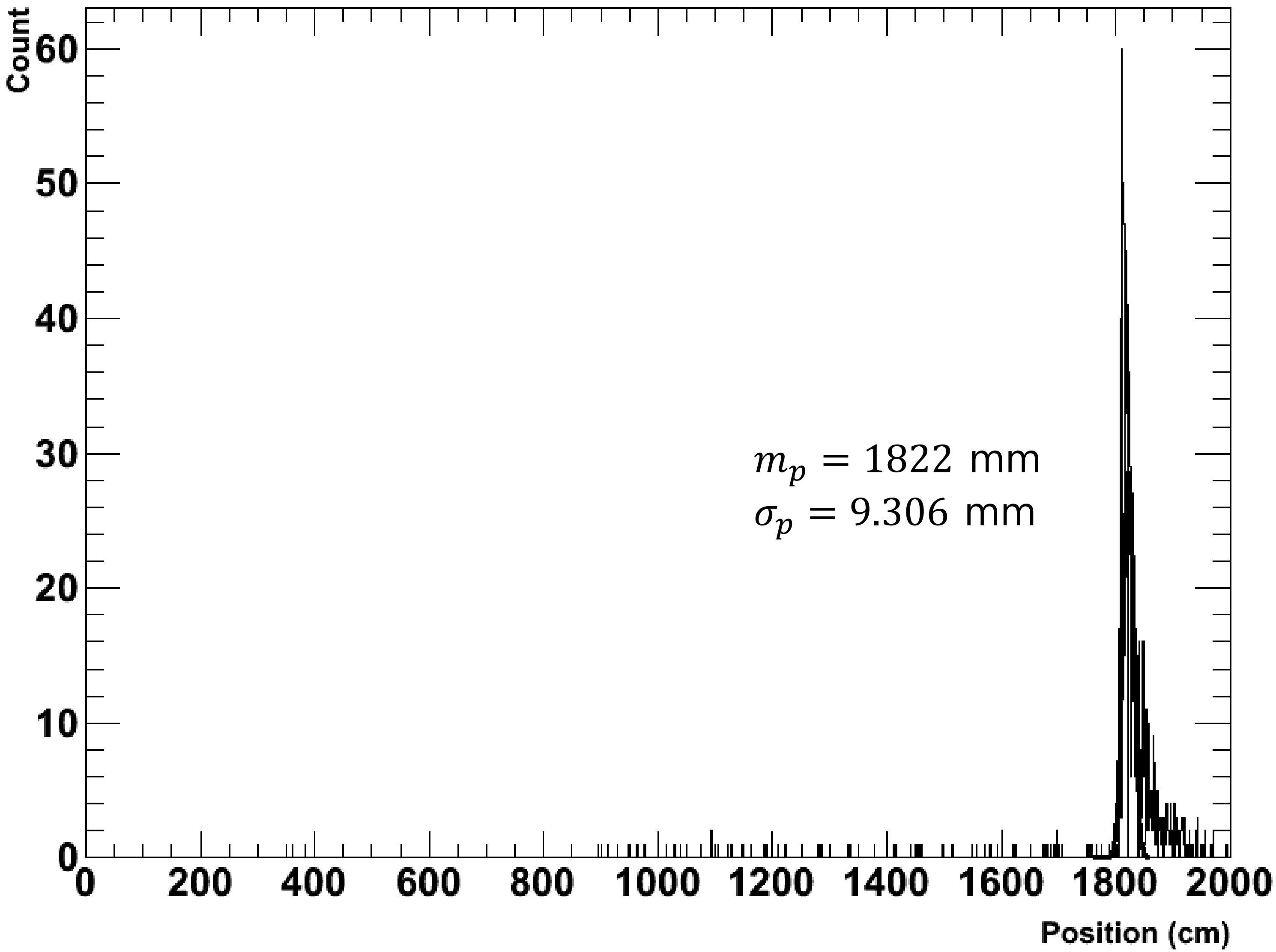



$m_{t1} = 11.90$ ns
$\sigma_{t1} = 0.386$ ns

$m_{t2} = 1.684$ ns
$\sigma_{t2} = 0.265$ ns

# Result

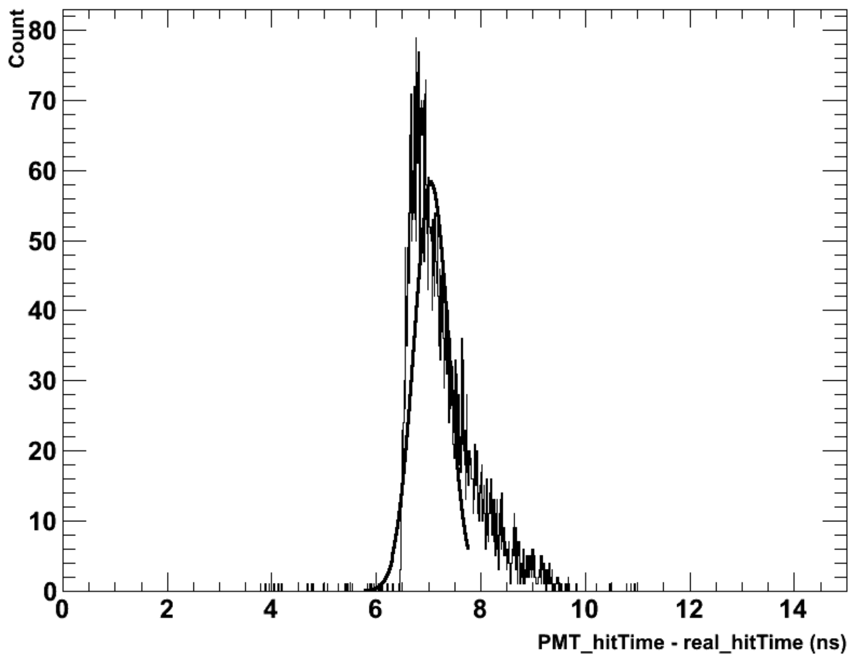


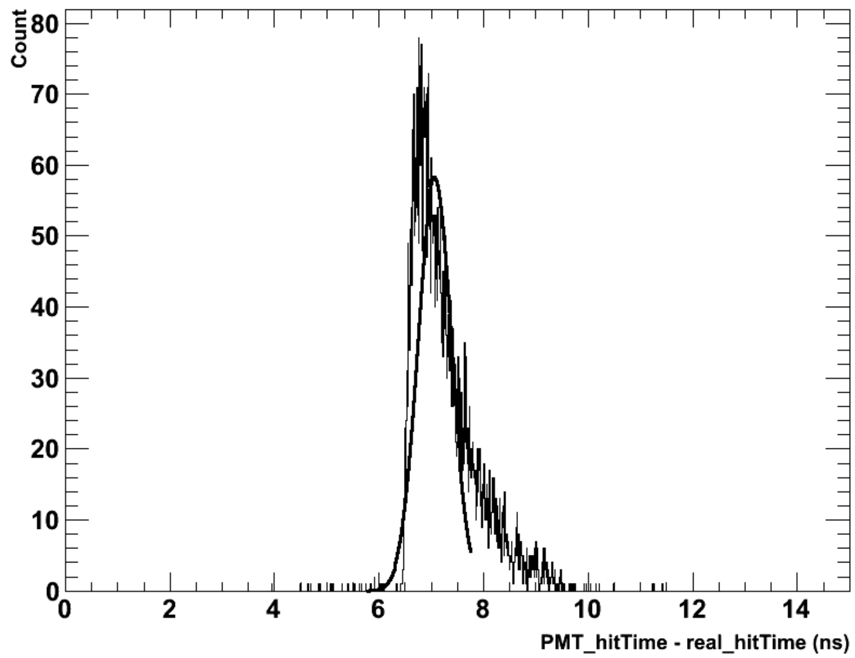
Count
0
10
20
30
40
50
60
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)
$m_p = 1822$ mm
$\sigma_p = 9.306$ mm

# Result

- Threshold signal integration energy = **30 MeV**

**1. 100 cm – 100 cm (center)**



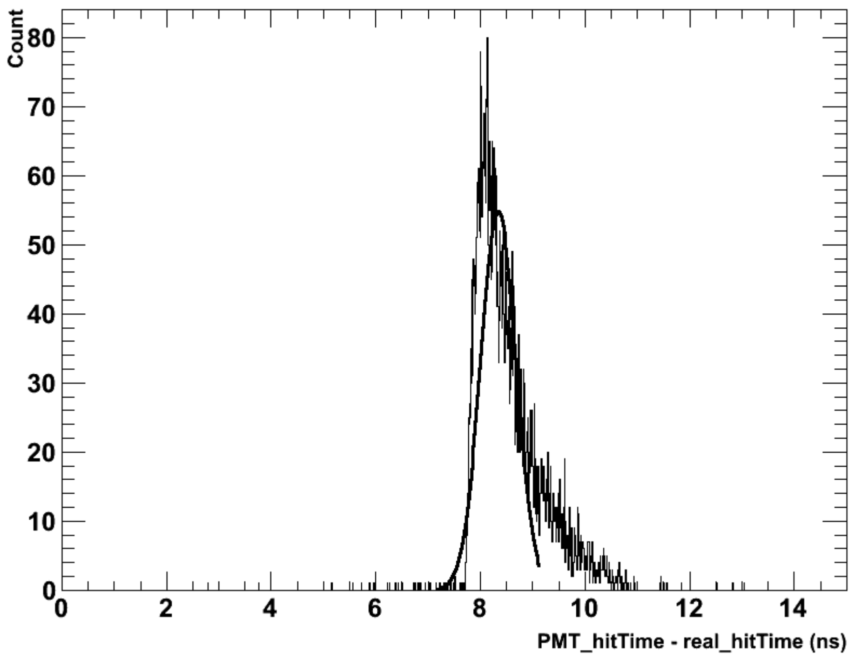




$m_{t1} = 7.049$ ns
$\sigma_{t1} = 0.332$ ns

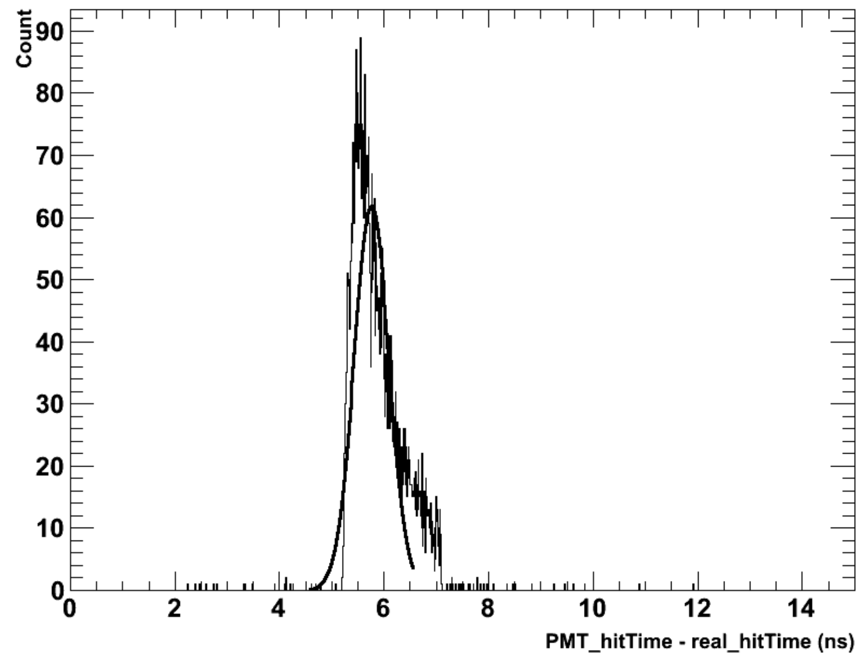
$m_{t2} = 7.064$ ns
$\sigma_{t2} = 0.318$ ns

# Result

## 2. 120 cm – 80 cm

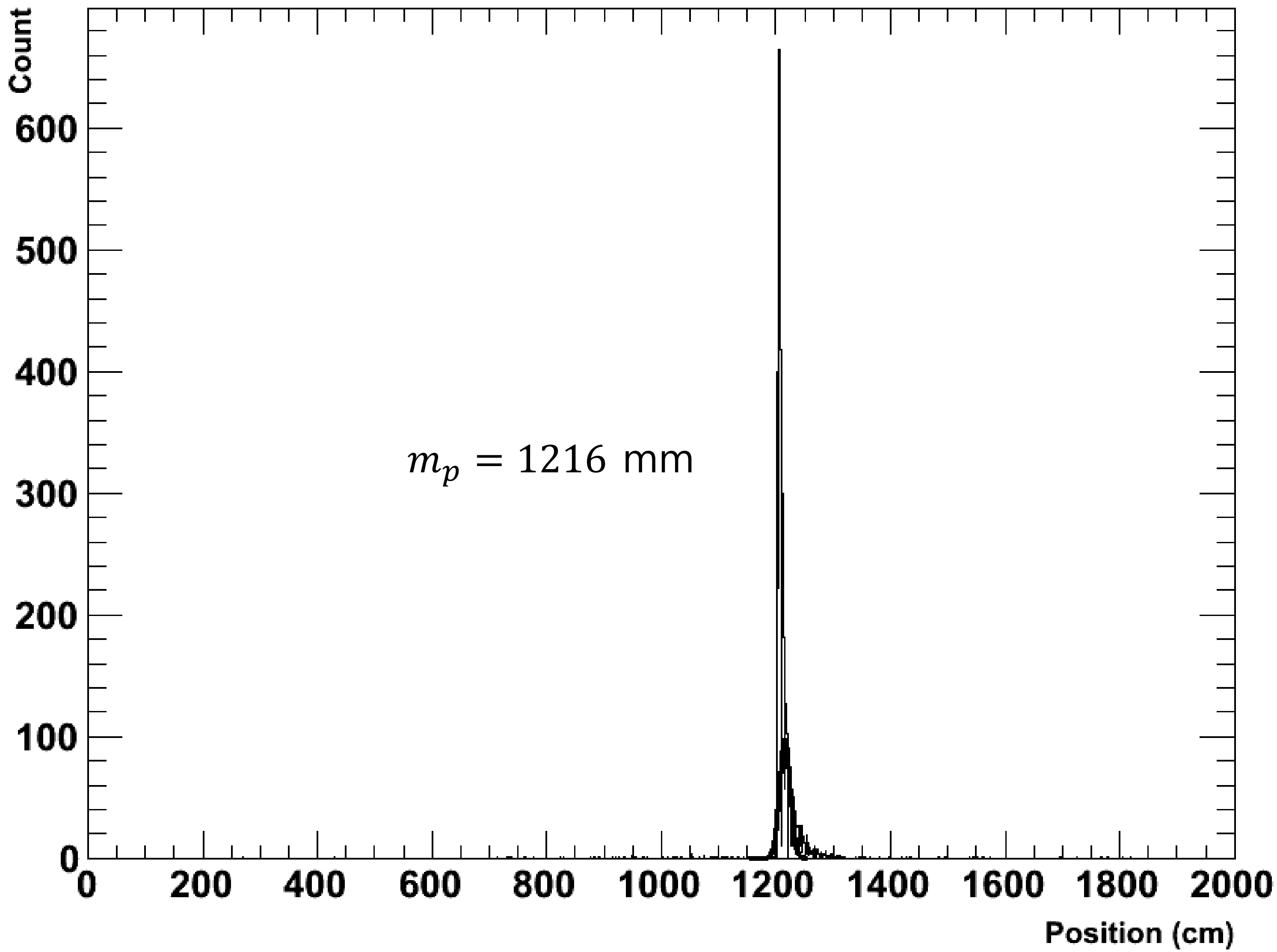



$m_{t1} = 8.342$ ns
$\sigma_{t1} = 0.335$ ns




$m_{t2} = 5.759$ ns
$\sigma_{t2} = 0.330$ ns

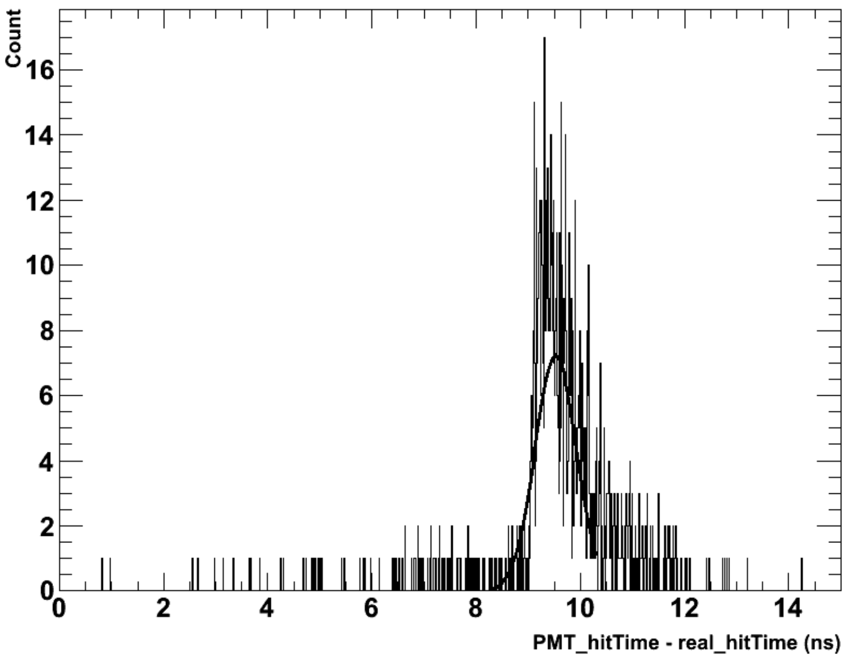
# Result

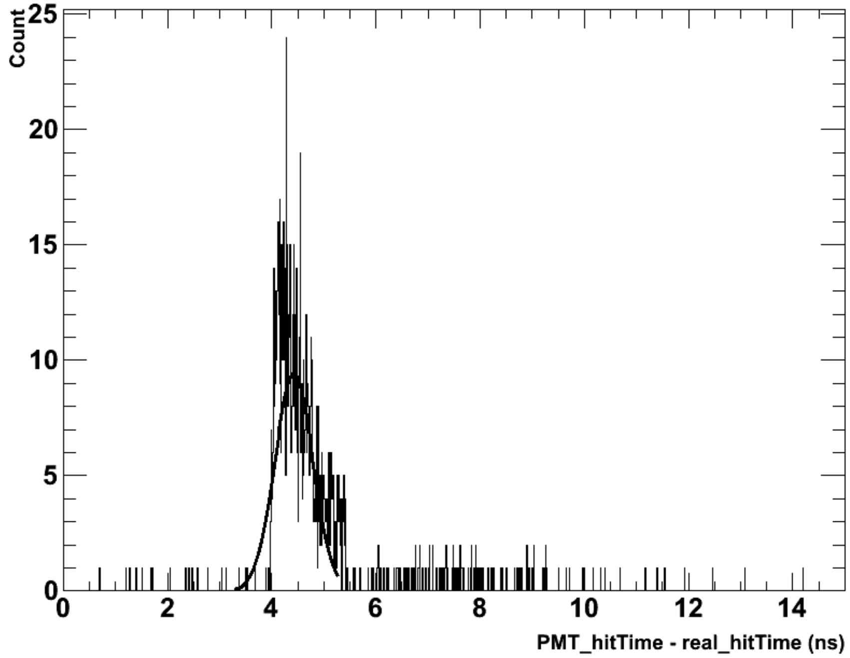


Count
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)
$m_p = 1216$ mm

# Result

3. **140 cm – 60 cm**

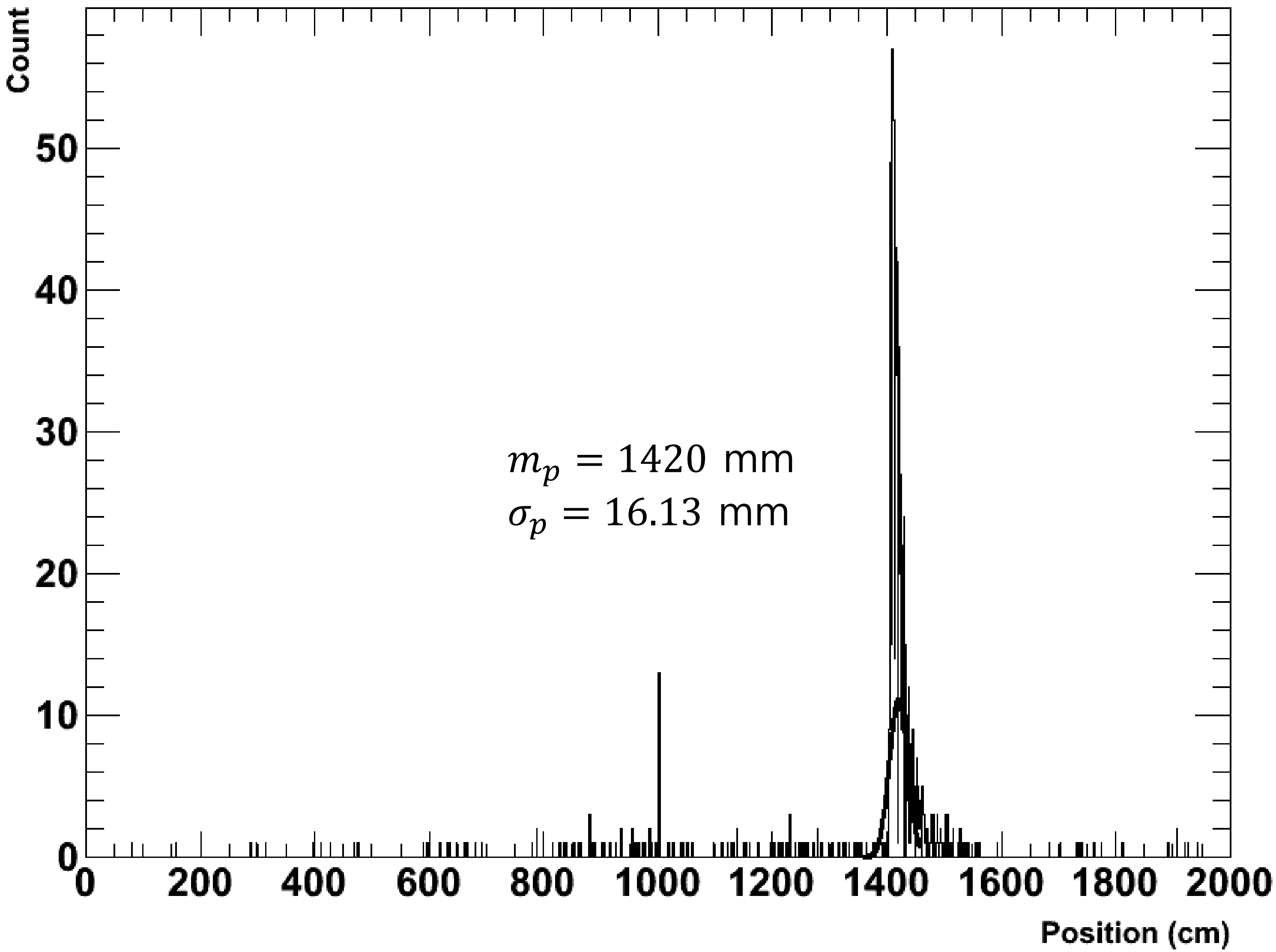



$m_{t1} = 9.528$ ns
$\sigma_{t1} = 0.397$ ns

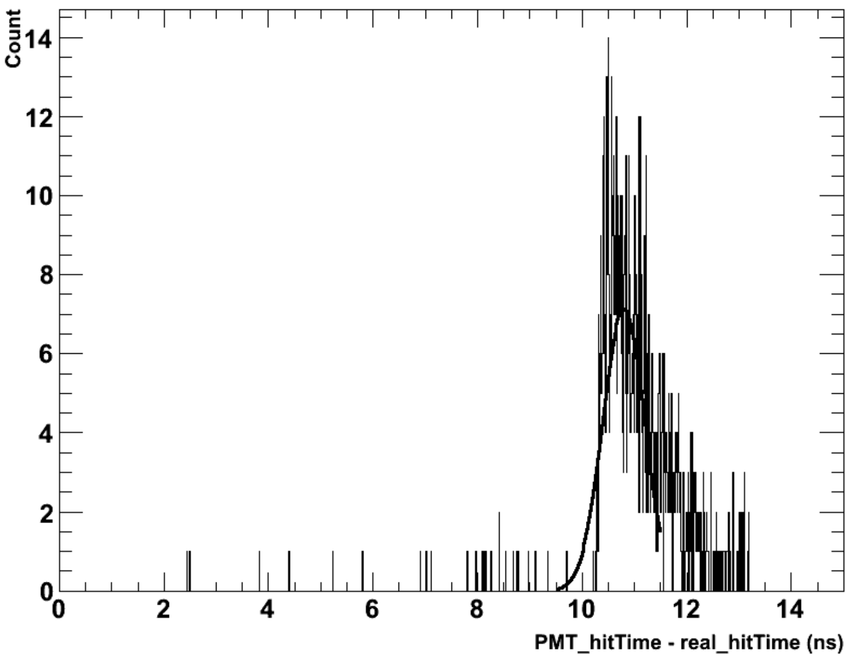
$m_{t2} = 4.424$ ns
$\sigma_{t2} = 0.362$ ns

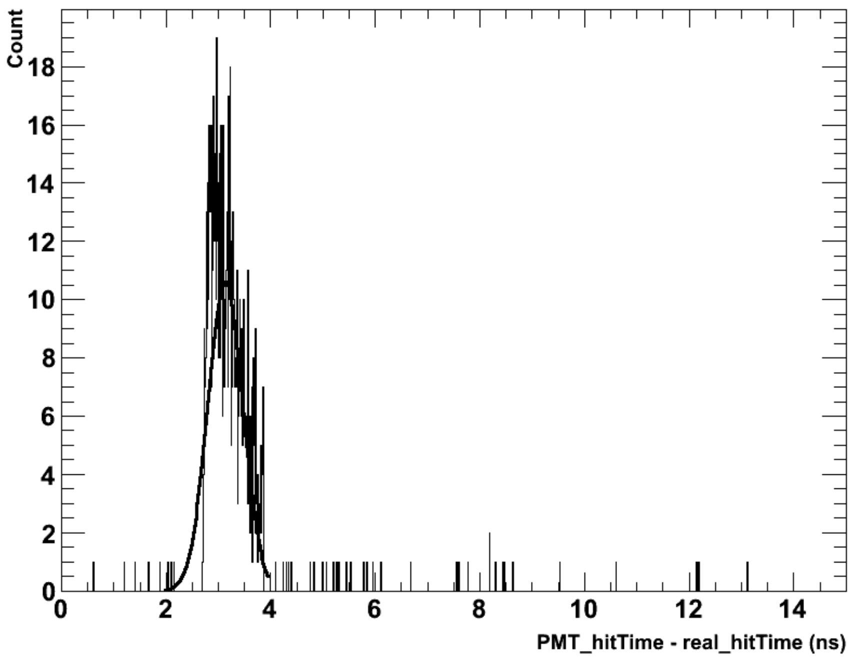
# Result


Count
0
10
20
30
40
50
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Position (cm)
$m_p = 1420$ mm
$\sigma_p = 16.13$ mm

# Result

## 4. 160 cm – 40 cm

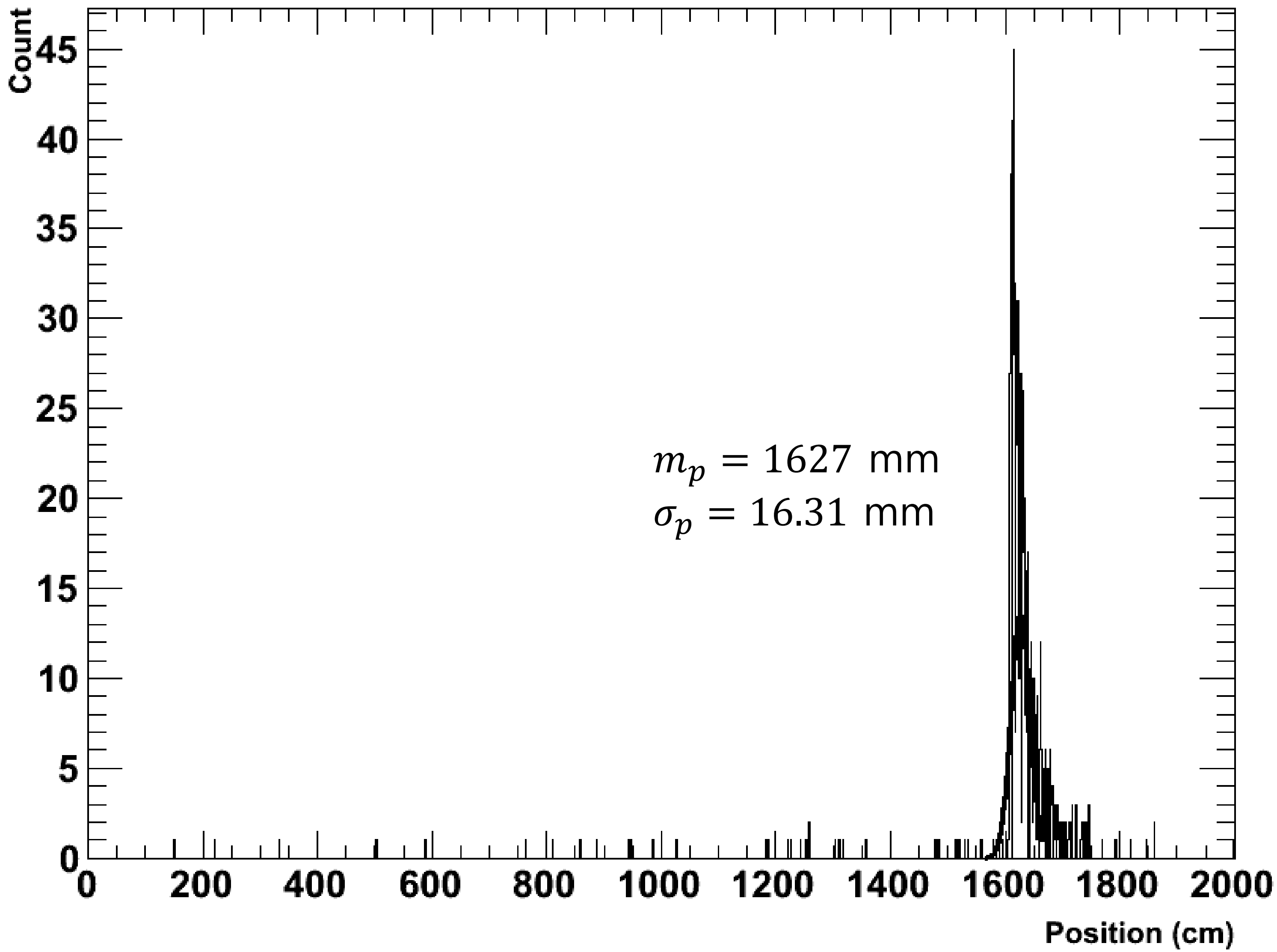



$m_{t1} = 10.80$ ns
$\sigma_{t1} = 0.398$ ns

$m_{t2} = 3.135$ ns
$\sigma_{t2} = 0.333$ ns

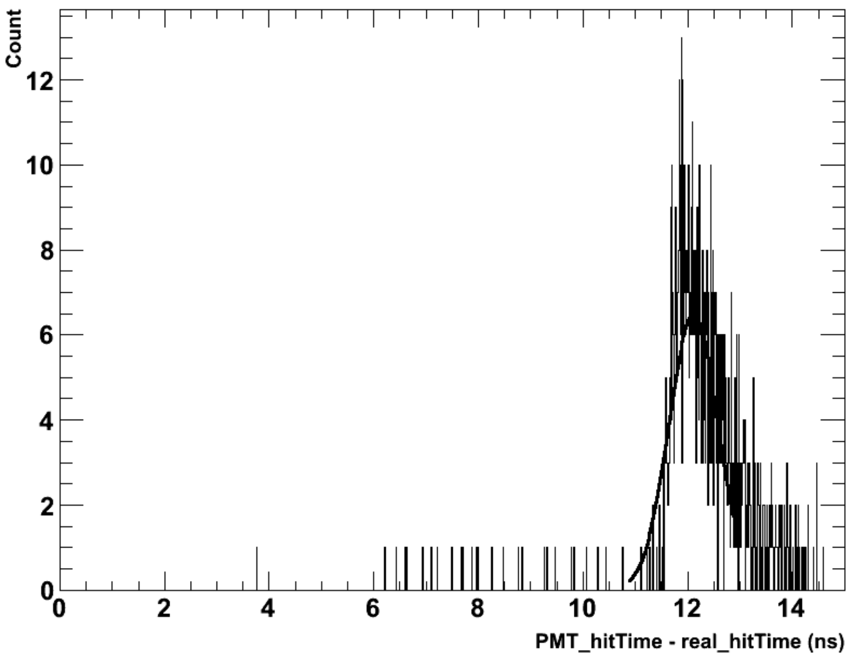
# Result

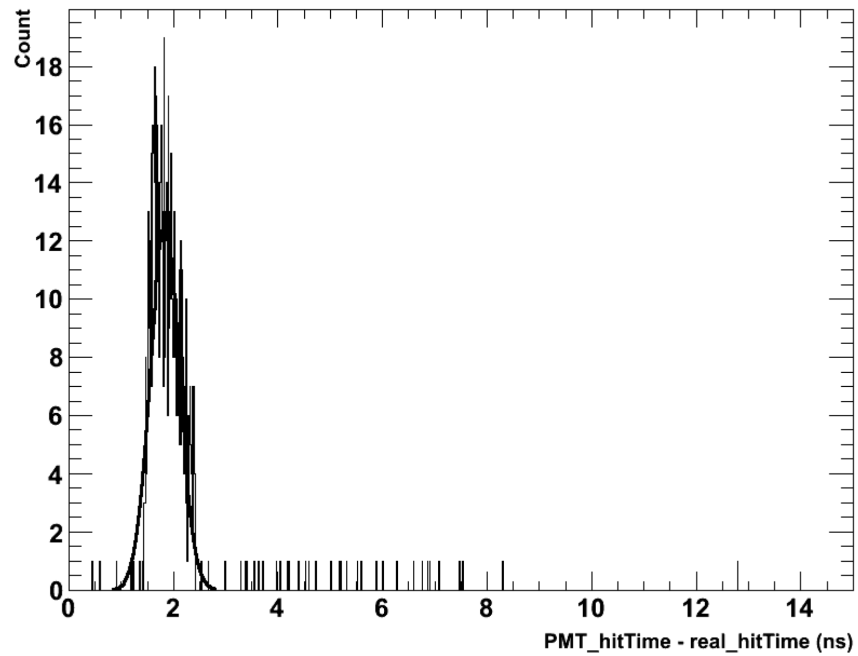


Count
45
40
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)
$m_p = 1627$ mm
$\sigma_p = 16.31$ mm

# Result

**5. 180 cm – 20 cm**

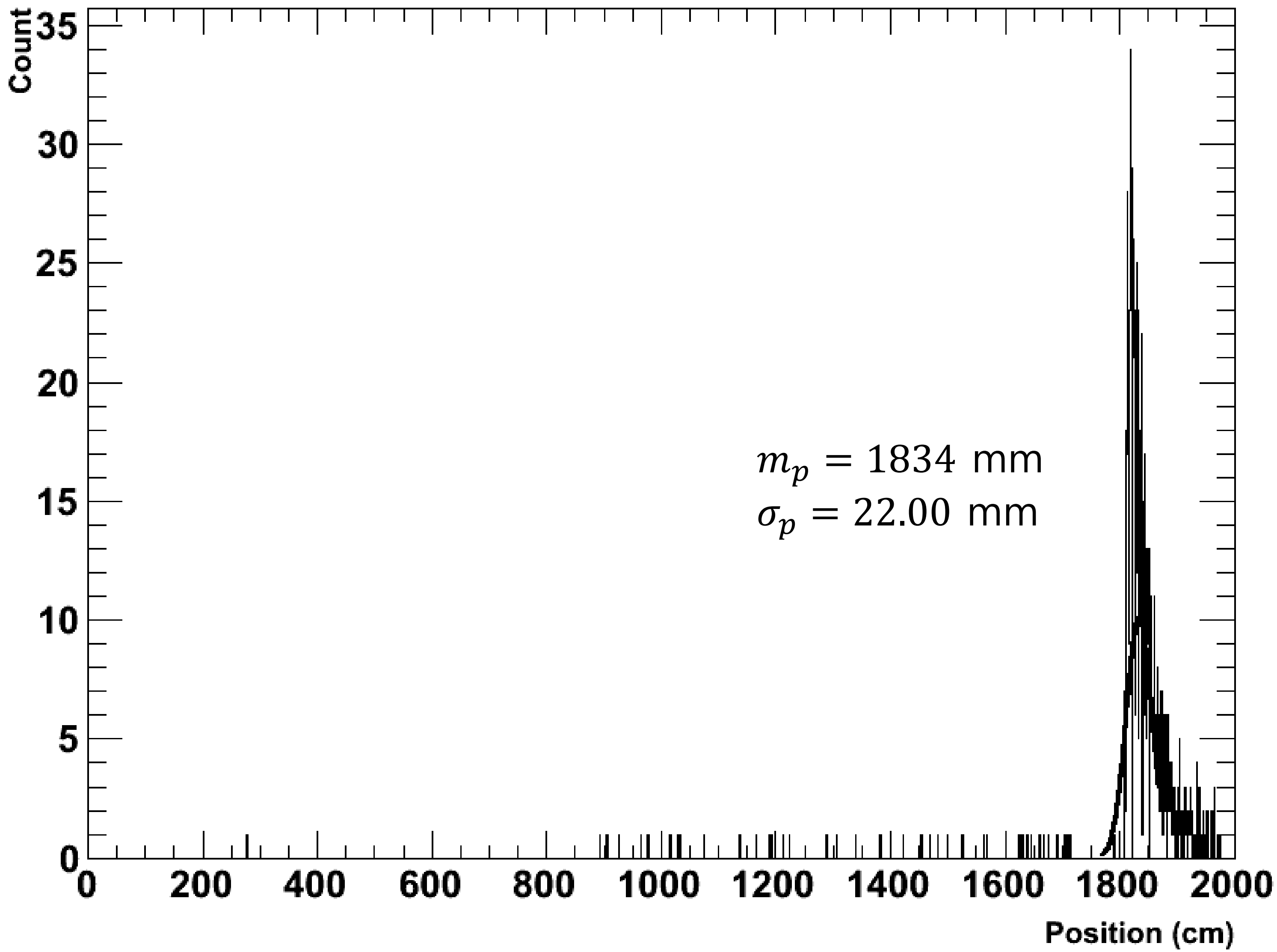


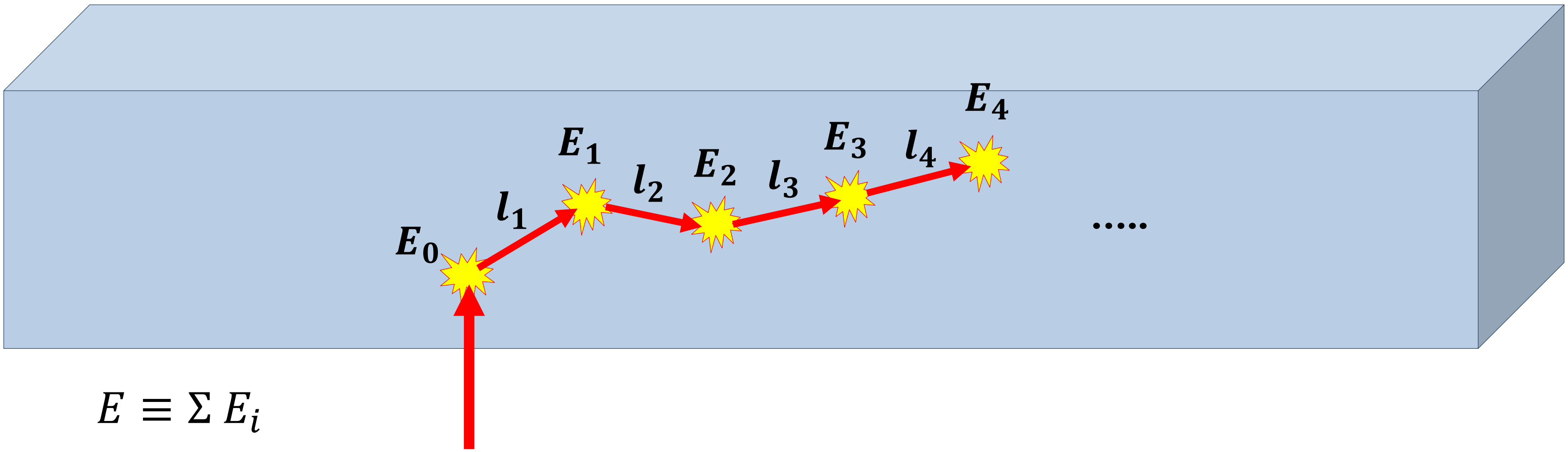

$m_{t1} = 12.11$ ns
$\sigma_{t1} = 0.469$ ns

$m_{t2} = 1.836$ ns
$\sigma_{t2} = 0.280$ ns

# Result


Count
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Position (cm)
$m_p$ = 1834 mm
$\sigma_p$ = 22.00 mm

# Birks Formula




$E \equiv \Sigma E_i$

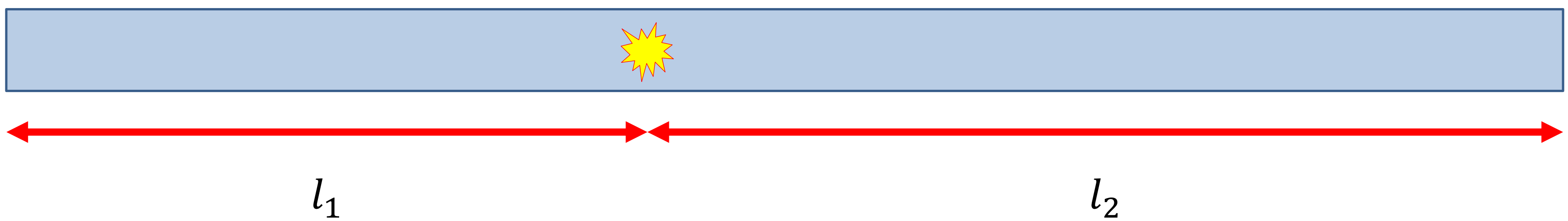
- $E_{corr-i}$ : Scintillation-response-correction of deposited energy $E_i$
- $\rho$ = (scintillator(BC-408) density) = 1.032 $\mathrm{g\,cm^{-3}}$
- $dz_i$ = (density)*(distance between (i – 1)-th & i-th hit) = $\rho l_i$ $(\mathrm{g\,cm^{-2}})$
- $E_i/dz_i$ = (i-th GEANT4 deposited energy)/$dz_i$ = $E_i/\rho l_i$ $(\mathrm{MeV\,g^{-1}\,cm^{2}})$
- ((i-th corrected deposited energy) / $dz_i$) / ((i-th GEANT4 deposited energy) / $dz_i$)

$$= \frac{E_{corr-i}/dz_i}{E_i/dz_i} = \frac{1}{1 + kB(E_i/dz_i)}$$

- $E_{corr} \equiv \Sigma E_{corr-i}$ : Scintillation-response-corrected total deposited energy

# Light Attenuation

- As the light moves through scintillator, it loses its energy.




$$E_{PMT1} = E_{corr}\exp[-\frac{l_1}{3800}]$$

$$E_{PMT2} = E_{corr}\exp[-\frac{l_2}{3800}]$$

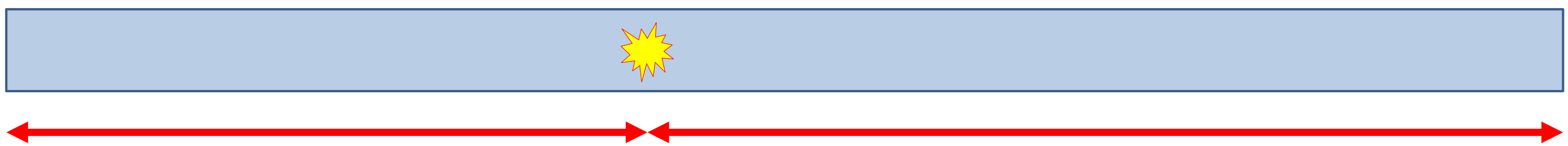
- BC-408 bulk attenuation length : 380 cm = 3800 mm

# Signal generation

$$t_{start1} = t_0 + t_{p1} = t_0 + \frac{l_1}{v}$$

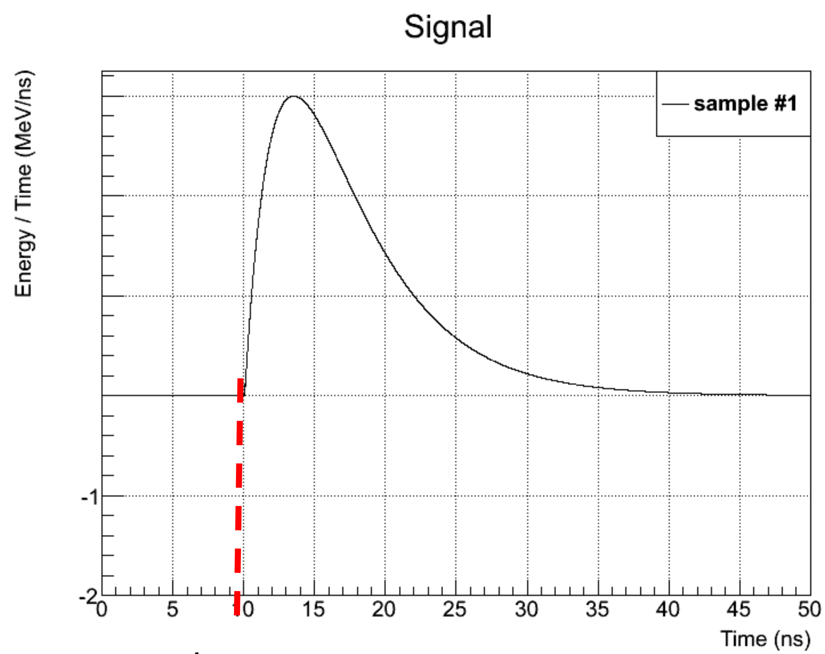
$t_0$

$$t_{start2} = t_0 + t_{p2} = t_0 + \frac{l_2}{v}$$



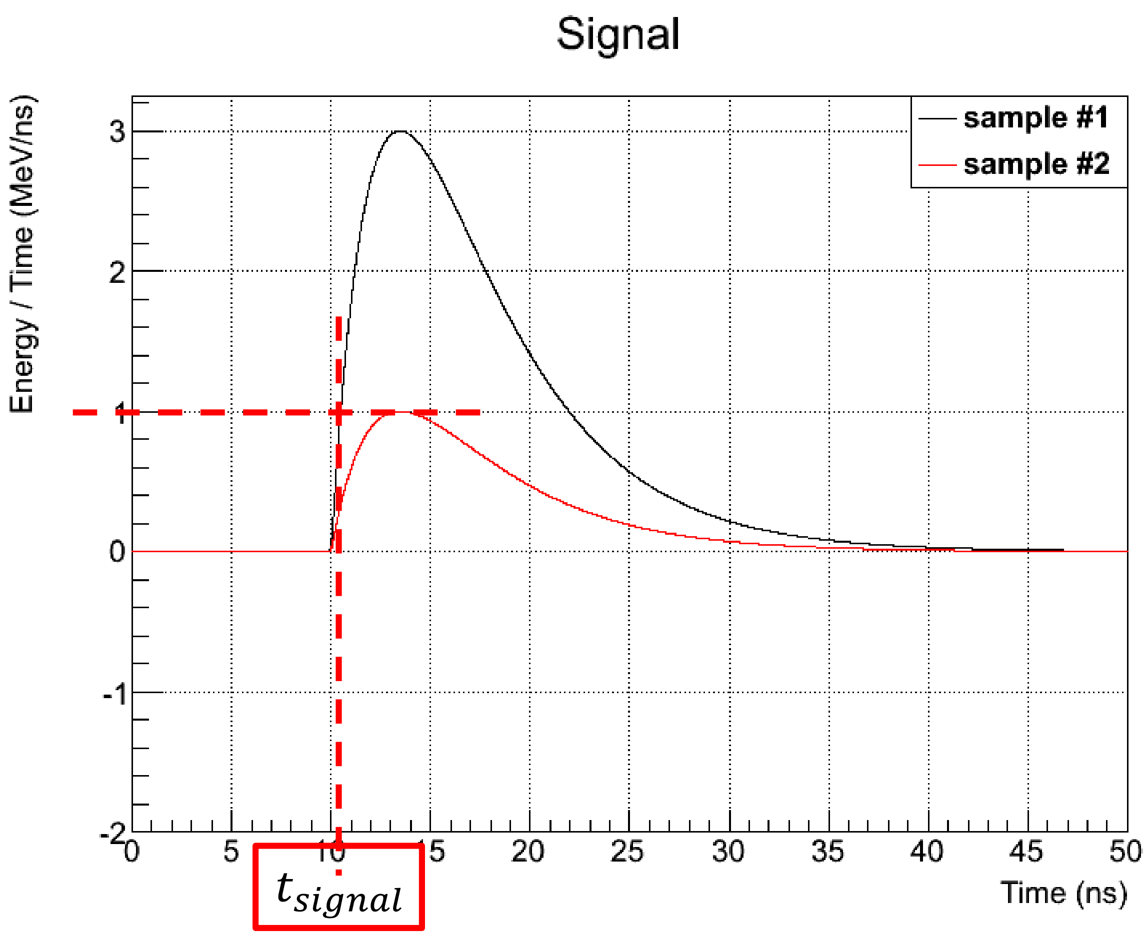
$l_1$ $l_2$

- Light arrival time at the end of the scintillator = signal start time($t_{start1}, t_{start2}$)




$t_{start}$

# Threshold & Signal hitTime




- Signal 과 시작점이 같고, 파형이 같은 threshold signal 을 만든다.
- Signal 의 높이가 threshold signal 의 최대값과 같아지는 지점의 시간
  = simulation 에서 사용하는 signal hitTime
  ≈ 실제 실험에서 얻어지는 signal hitTime

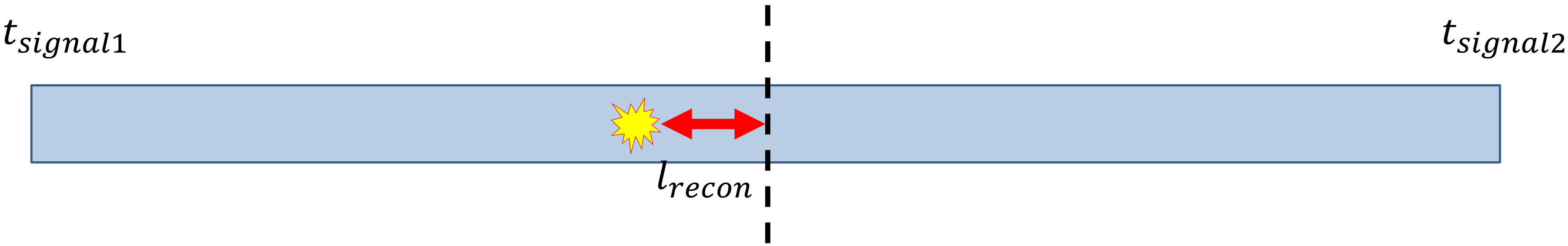
# Time Resolution

- Signal hitTime $t_{signal}$
  = (중성자에 의해 scintillator 에 light 이 발생하는 시간 $t_0$)
  + (light propagation time $t_p = \frac{l}{v}$)
  + (PMT 에서 발생한 signal 의 높이가 threshold signal 의 최대값과 같아질 때까지 걸리는 시간)

- Deposited energy 값에 따라, 중성자가 같은 위치를 지나가는 경우만을 비교하더라도 signal hitTime 이 달라질 수 있다.
  - Time resolution

- 양 쪽 PMT 에서 만들어지는 두 signal 모두 threshold height 를 넘길 때에만 true 로 간주하고, true signal hitTime 을 계산하여 저장한다.
  - True signal hitTime = 0.5*($t_{signal1} + t_{signal2}$)

# Position Reconstruction

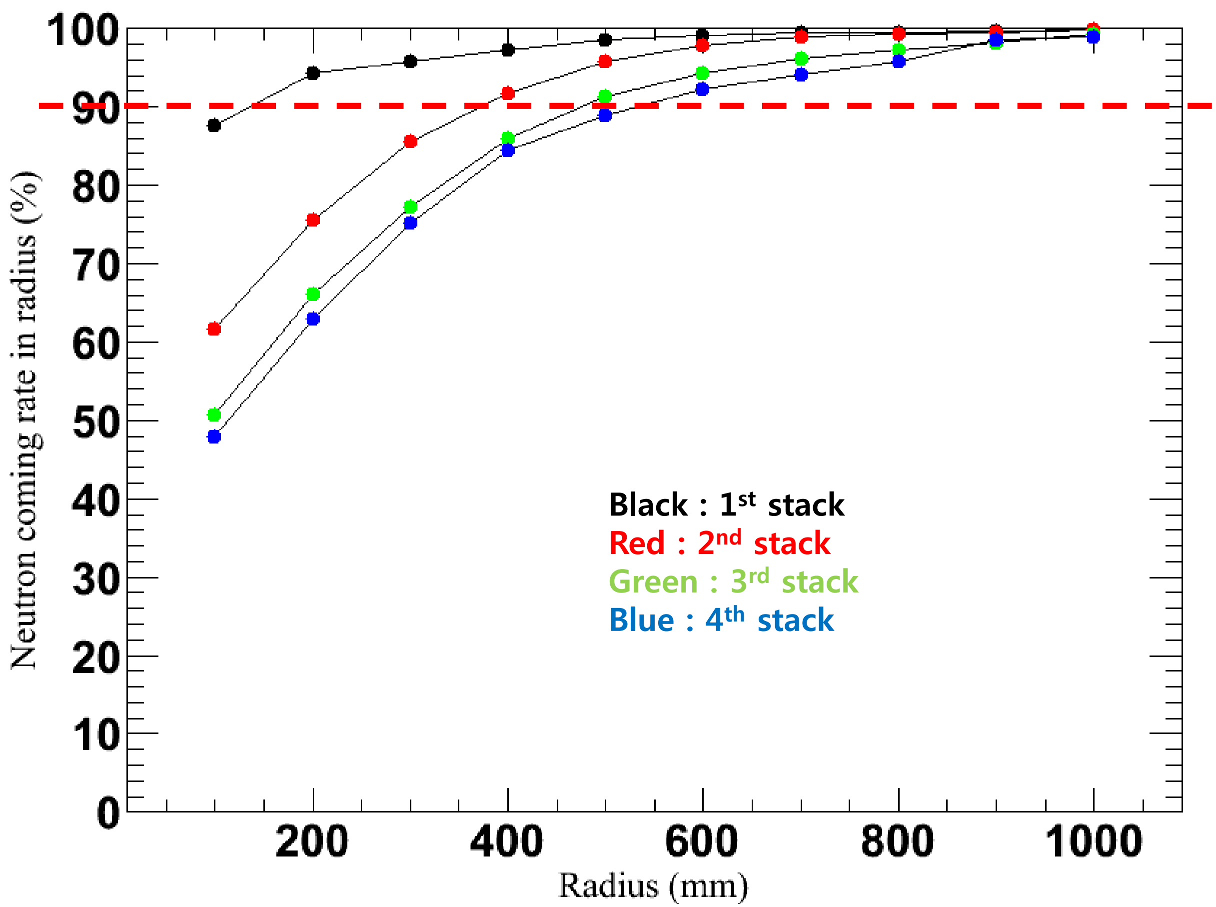



- 양쪽 PMT 의 signal hitTime 의 차이를 이용하여, light 이 발생한 위치(≈ 중성자가 지나간 위치)를 reconstruct.

- Reconstructed position = $0.5(t_{signal1} - t_{signal2})v$

# Neutron coming rate in radius (gap = 40 cm)

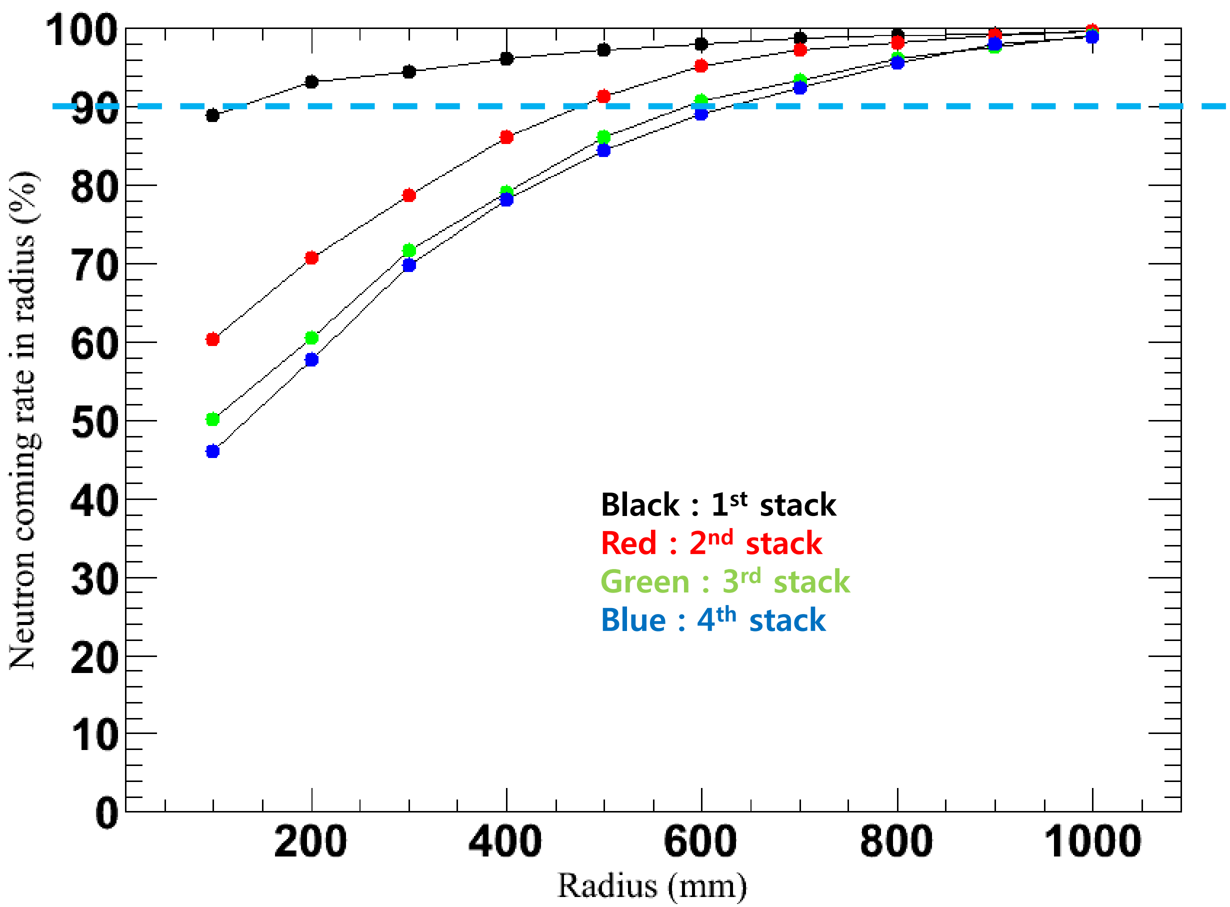
- Threshold : **30 MeV**
- $x$ **axis** : 중성자 발사위치를 기준으로, 검출기에 신호를 남기는 지점의
  x-y 평면상에서의 거리
- $y$ **axis** : 각각의 stack 에 남겨지는 신호들 중 반경 내(< $x$)에 들어오는 신호의 비율
  - **$y$ = (반경 내(< $x$)에 들어오는 신호의 개수) / (Stack 에 남겨지는 총 신호의 개수)**




각 stack에 남겨지는 hit들의 90 % 가 들어오는 반경
1st stack : 10 cm
2nd stack : 40 cm
3rd stack : 50 cm
4th stack : 50 cm

# Neutron coming rate in radius (gap = 60 cm)

- Threshold : **30 MeV**
- $x$ **axis** : 중성자 발사위치를 기준으로, 검출기에 신호를 남기는 지점의
  x-y 평면상에서의 거리
- $y$ **axis** : 각각의 stack 에 남겨지는 신호들 중 반경 내($< x$)에 들어오는 신호의 비율
  - ➢ **$y$ = (반경 내($< x$)에 들어오는 신호의 개수) / (Stack 에 남겨지는 총 신호의 개수)**




각 stack에 남겨지는 hit들의
89 % 가 들어오는 반경
1st stack : 10 cm
2nd stack : 50 cm
3rd stack : 60 cm
4th stack : 60 cm