$J/\psi \longrightarrow \Delta^{++}\bar{\Delta}^{--}$
$\psi(2S) \longrightarrow \Delta^{++}\bar{\Delta}^{--}$

$$\Delta^{++} \rightarrow p\pi^{+} \qquad \bar{\Delta}^{--} \rightarrow \bar{p}\pi^{-}$$

TASAWER SHAHZAD AHMAD, HARIS RASHID, TALAB HUSSAIN

Charmonium Group Meeting

Data Samples

- 1310.6 Million and 447 Million data samples were used to study the $J/\psi \longrightarrow \Delta^{++}\bar{\Delta}^{--}$ and $\psi(2S) \longrightarrow \Delta^{++}\bar{\Delta}^{--}$ respectively.
- The sample of 100000 events was generated by using phase space model in case of signal Monte Carlo.
- 1225 Million and 500 Million inclusive MC data samples were used for the background studies of $J/\psi \longrightarrow \Delta^{++}\bar{\Delta}^{--}$ and $\psi(2S) \longrightarrow \Delta^{++}\bar{\Delta}^{--}$ respectively.
- Monte Carlo (MC) samples and real data were reconstructed with the help of BOSS version 664p01

Event Selection

To select 4 good charged tracks the Initial event selection criteria is:

- Range of polar angle in MDC i.e. $|\cos\theta| < 0.93$ with mfit=2.
- The requirements for the vertex is $V_r = \sqrt{V_x^2 + V_y^2} < 10$ cm and $V_z < 15$ cm.
- The threshold value of transverse momentum of each track should be 0.07 GeV i.e.,$Pxy \geq 0.07$ GeV.
- Tracks can be identified by the calculation of energy loss and TOF.
- The energy loss dE/dx in MDC and TOF information were used to identify a particle.

Particle Identification

- Particle identification was performed to get events each having one Proton, one anti-Proton, one $\pi+$ and one $\pi-$, by using the combined information of dE/dx and TOF. For this purpose the following $\chi 2$ values were used.

$$\chi^2_{TOF}(i) = \frac{TOF_{measured}(i) - TOF_{expected}(i)}{\sigma_{TOF}(i)}$$

$$\chi^2_{dE/dx}(i) = \frac{dE/dx_{measured}(i) - dE/dx_{expected}(i)}{\sigma_{dE/dx}(i)}$$

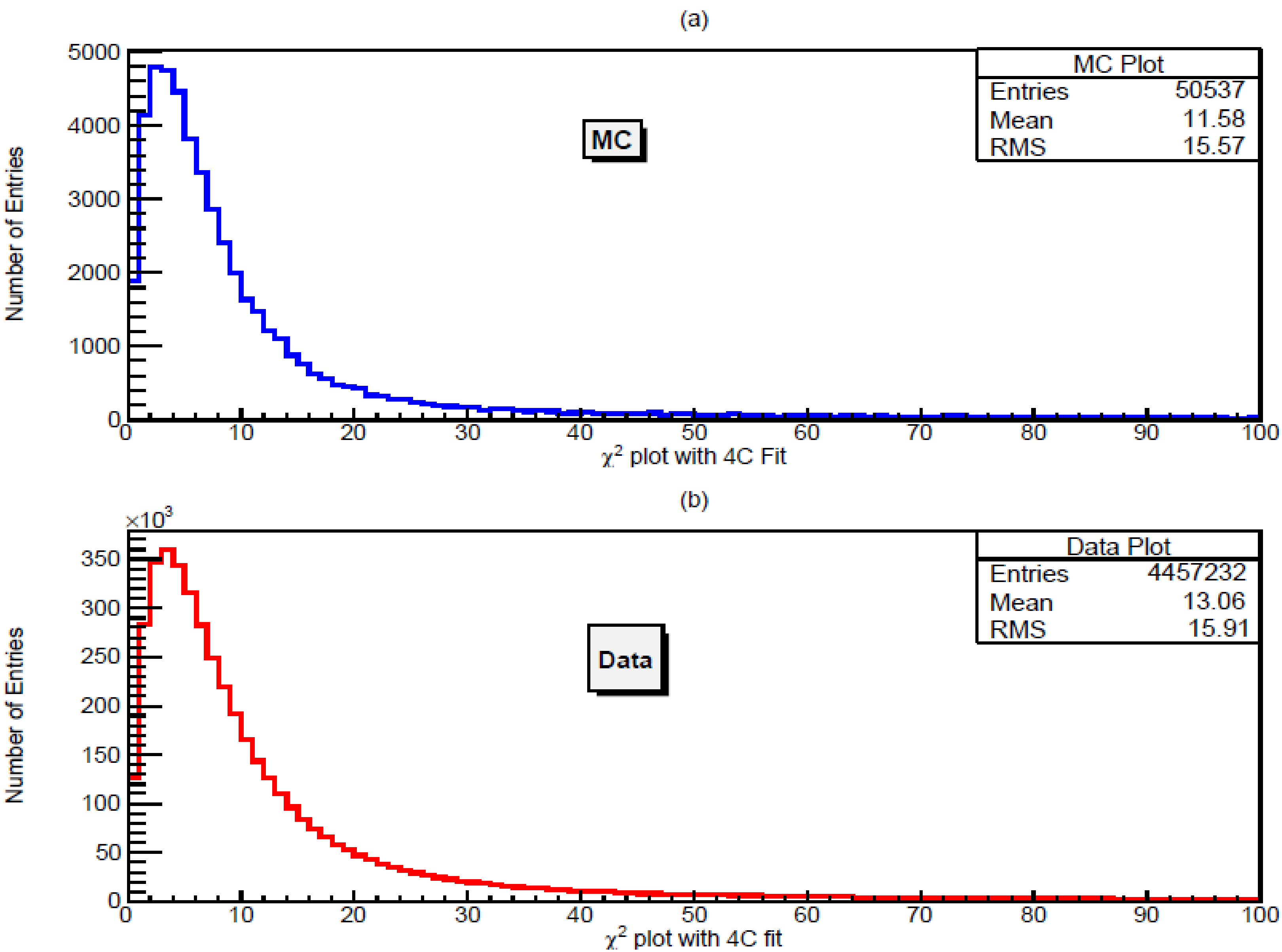
- The $\chi 2$ is assigned to each charged track and is used to decide the type of the particle after applying the following conditions.

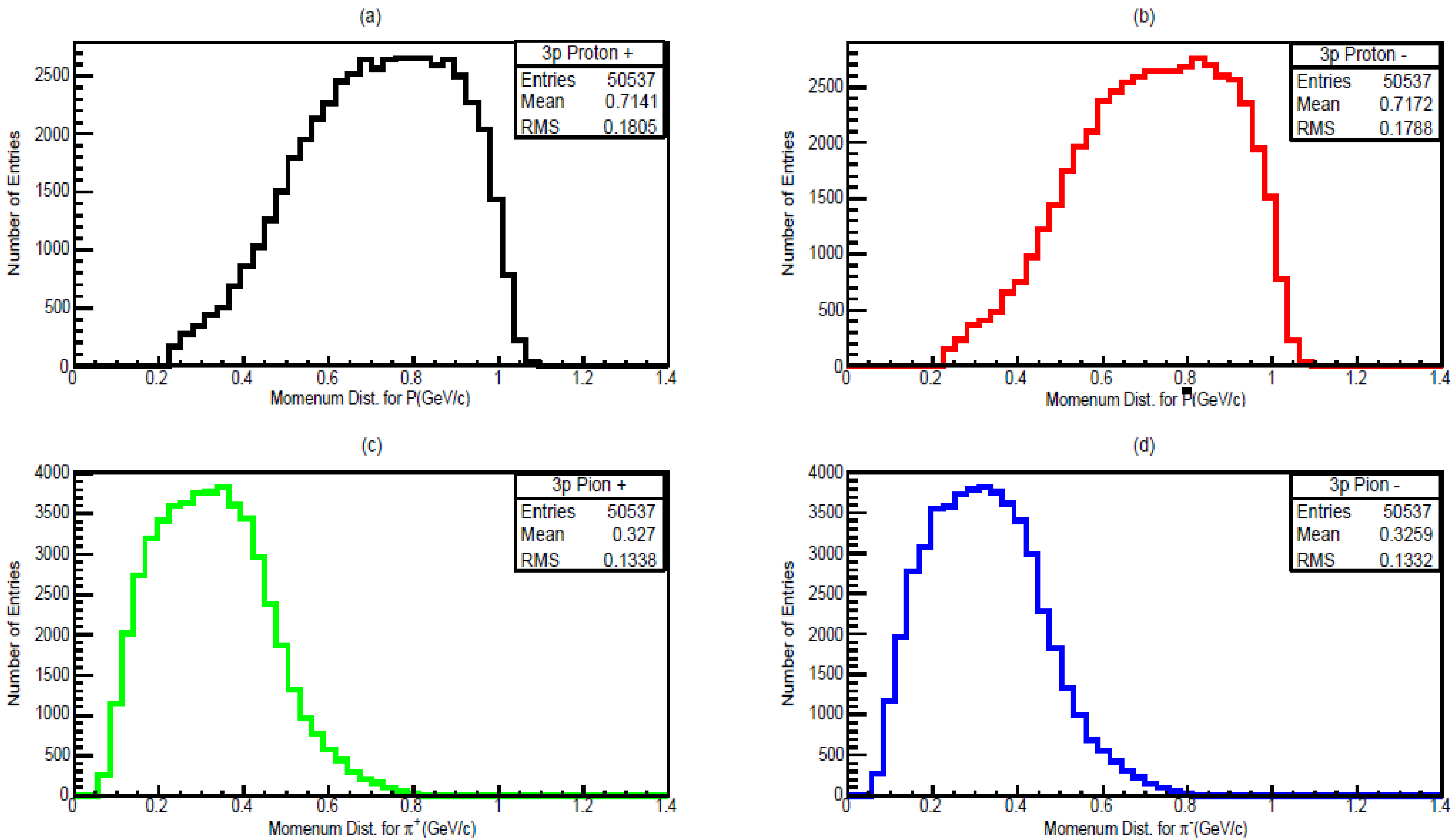
- To identify the positively charged proton, the following inequality relation was required to be satisfied.
- $\chi^2(P) < \chi^2(\pi^+)$ and $\chi^2(P) < \chi^2(K^+)$
- Positively charged pion was identified through the following inequality.
- $\chi^2(\pi^+) < \chi^2(P)$ and $\chi^2(\pi^+) < \chi^2(K^+)$
- Following inequality was used to identify the negatively charged anti-proton.
- $\chi^2(\bar{P}) < \chi^2(\pi^-)$ and $\chi^2(\bar{P}) < \chi^2(K^-)$
- Negatively charged pion was identified with the help of the following inequality.
- $\chi^2(\pi^-) < \chi^2(\bar{P})$ and $\chi^2(\pi^-) < \chi^2(K^-)$

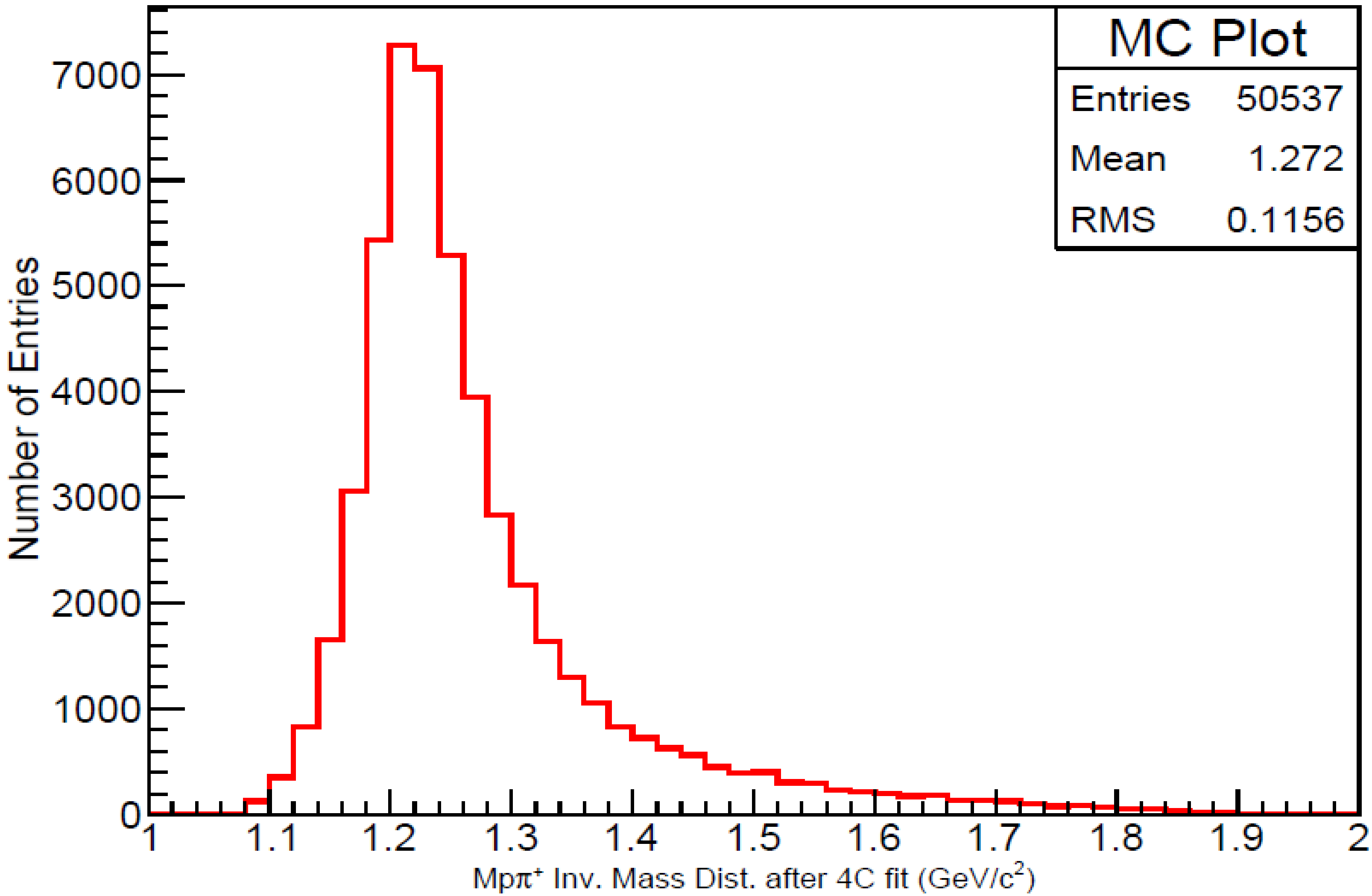
The successful event after particle identification contains one proton, one anti-proton, a positive pion and a negative pion.

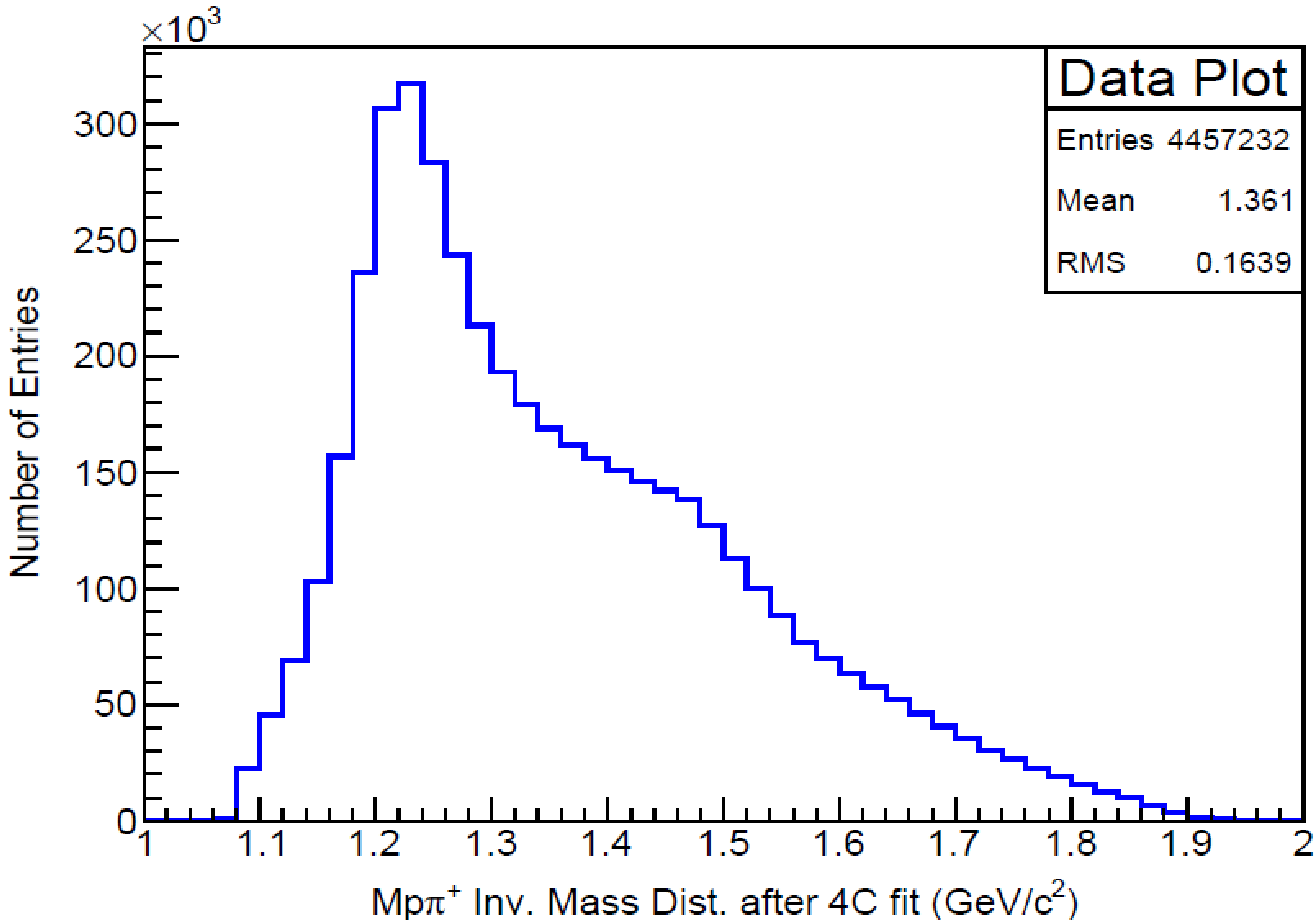
Kinematic Fit

- To conserve total momentum and energy, we applied 4C kinematic fit. Important information related to final state particles and their parent resonant particles such as invariant mass of $P\pi^+$ and $\bar{P}\pi^-$ to reconstruct Δ^{++} and $\bar{\Delta}^{--}$ was saved after 4C fit.
- Such criteria were used on all selected signal MC events, inclusive MC events, exclusive background MC events and real data events to get events.

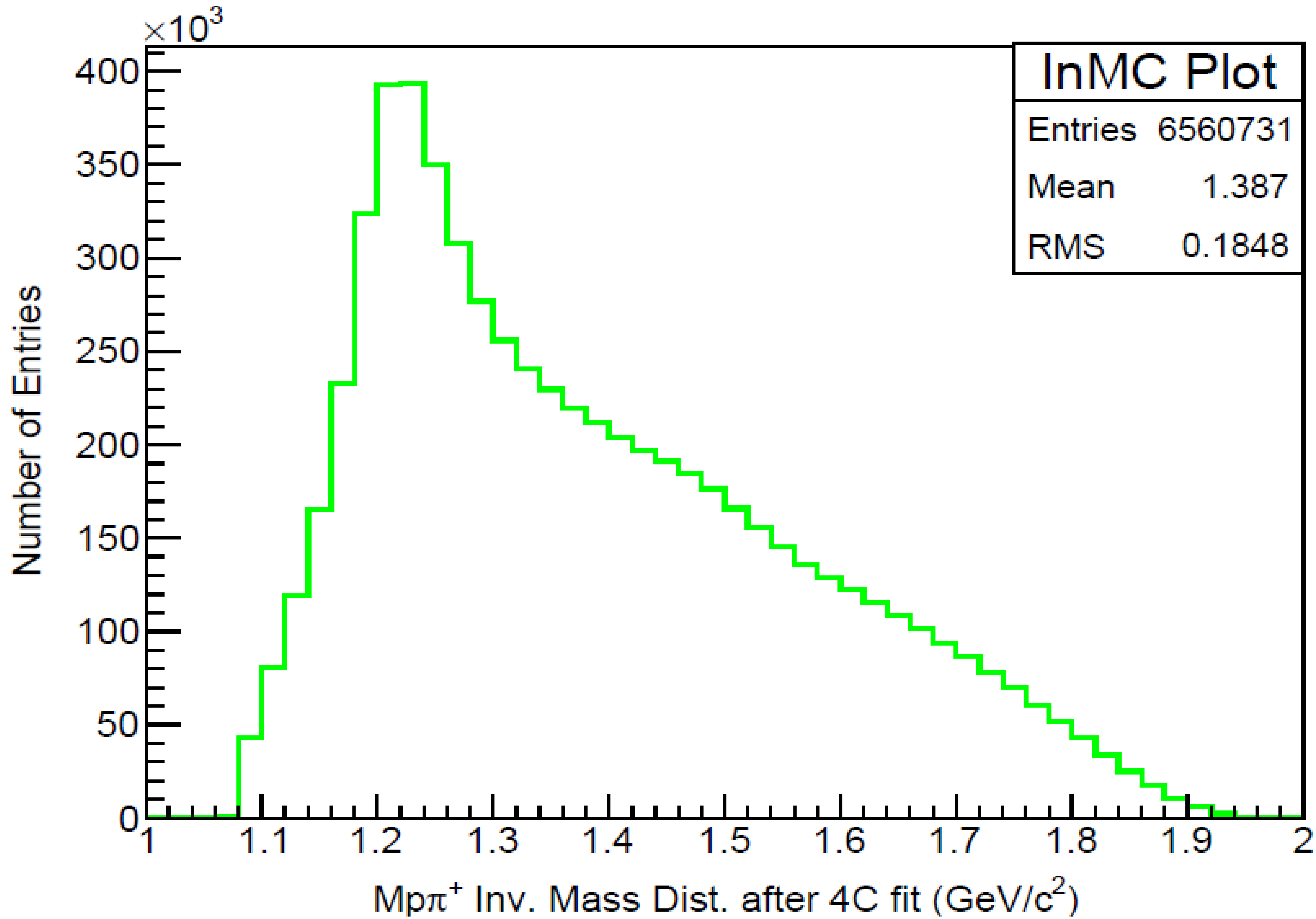

(a)
5000
4000
3000
2000
1000
0
Number of Entries
MC
MC Plot
Entries 50537
Mean 11.58
RMS 15.57
0 10 20 30 40 50 60 70 80 90 100
χ2 plot with 4C Fit
(b)
×10^3
350
300
250
200
150
100
50
0
Number of Entries
Data
Data Plot
Entries 4457232
Mean 13.06
RMS 15.91
0 10 20 30 40 50 60 70 80 90 100
χ2 plot with 4C fit


(a)
3p Proton +
Entries 50537
Mean 0.7141
RMS 0.1805
Number of Entries
Momenum Dist. for P(GeV/c)
(b)
3p Proton -
Entries 50537
Mean 0.7172
RMS 0.1788
Number of Entries
Momenum Dist. for P(GeV/c)
(c)
3p Pion +
Entries 50537
Mean 0.327
RMS 0.1338
Number of Entries
Momenum Dist. for π⁺(GeV/c)
(d)
3p Pion -
Entries 50537
Mean 0.3259
RMS 0.1332
Number of Entries
Momenum Dist. for π⁻(GeV/c)

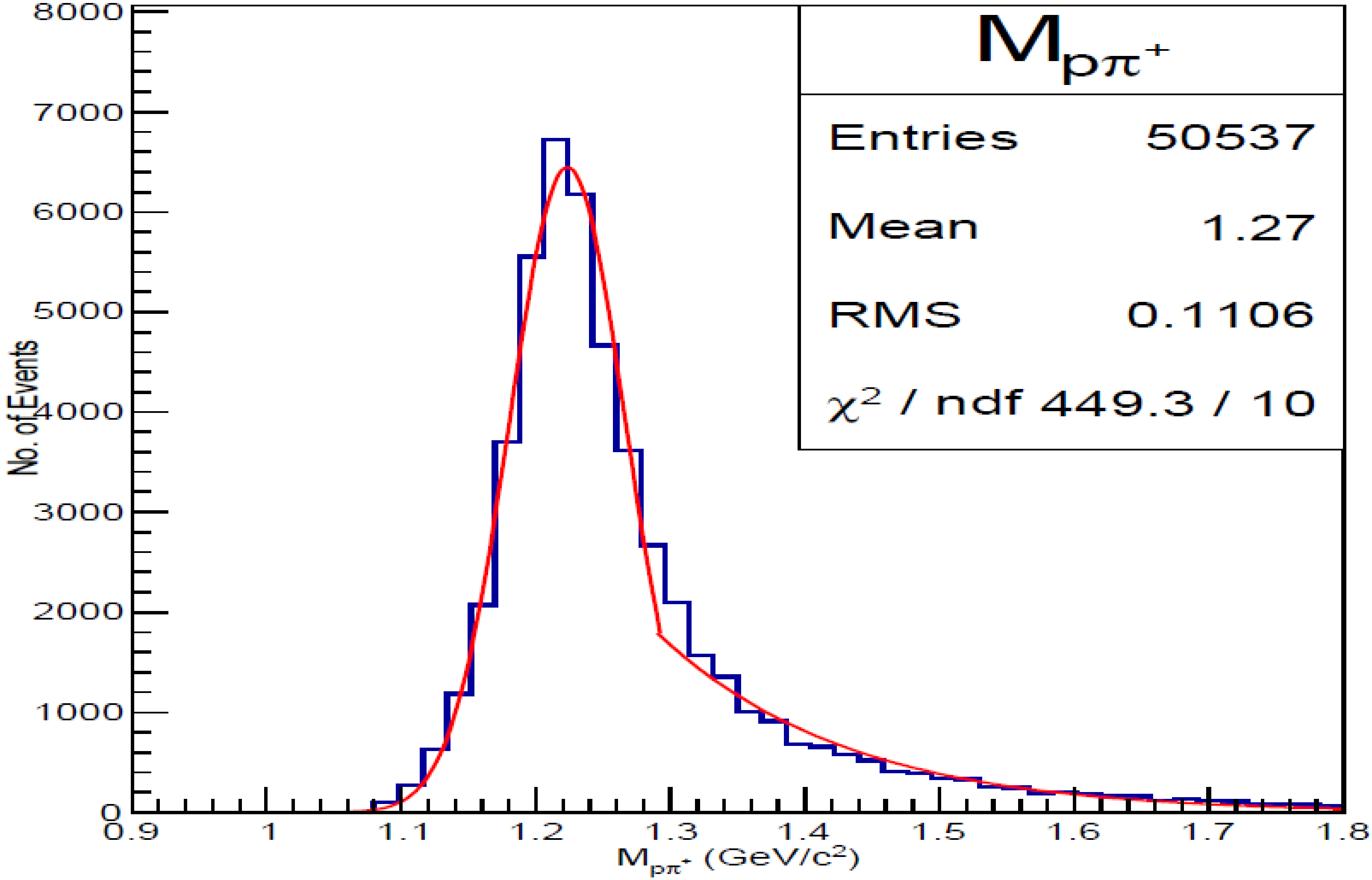

MC Plot
Entries 50537
Mean 1.272
RMS 0.1156
Number of Entries
0
1000
2000
3000
4000
5000
6000
7000
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Mpπ⁺ Inv. Mass Dist. after 4C fit (GeV/c²)



×10^3
Data Plot
Entries 4457232
Mean 1.361
RMS 0.1639
Number of Entries
0
50
100
150
200
250
300
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Mpπ+ Inv. Mass Dist. after 4C fit (GeV/c2)



×10^3
InMC Plot
Entries 6560731
Mean 1.387
RMS 0.1848
Number of Entries
0
50
100
150
200
250
300
350
400
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Mpπ+ Inv. Mass Dist. after 4C fit (GeV/c2)



$M_{p\pi^+}$
Entries 50537
Mean 1.27
RMS 0.1106
χ^2 / ndf 449.3 / 10
No. of Events
0
1000
2000
3000
4000
5000
6000
7000
8000
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
$M_{p\pi^+}$ (GeV/c^2)

FINAL EVENT SELECTION

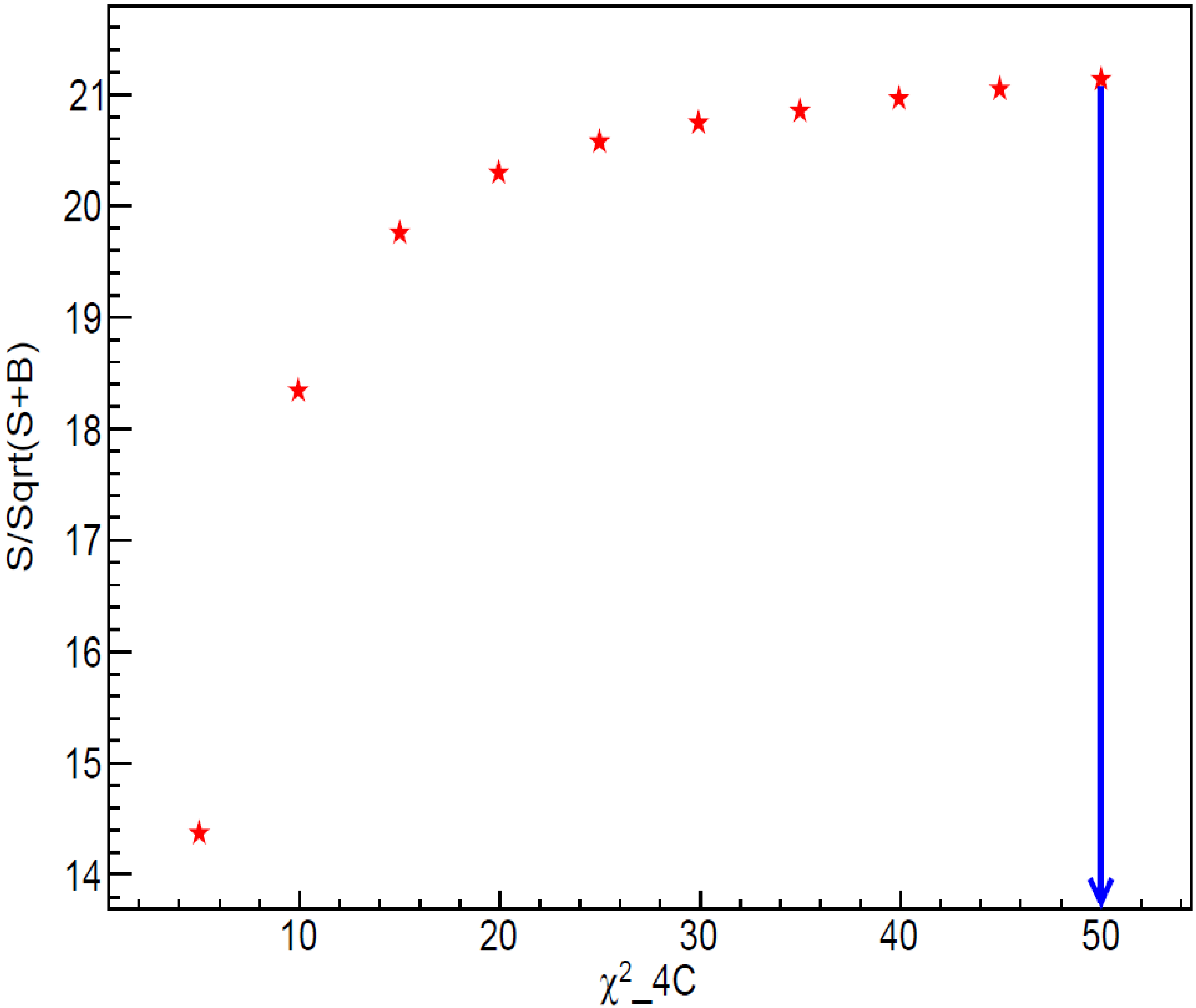
- The following constraints were used
- 3σ mass constraints, decay length ratio cuts for Δ^{++} and $\overline{\Delta}^{--}$ and χ^2_4C cut which was optimized through maximizing the ratio of MC signal and signal plus background from real data.
- To obtain good signals of Δ^{++} and $\overline{\Delta}^{--}$ from real data through invariant mass distributions of $P\pi^{+}$and $\bar{P}\pi^{-}$ in the presence of small background was the main objective of these constraints.

Final Cuts

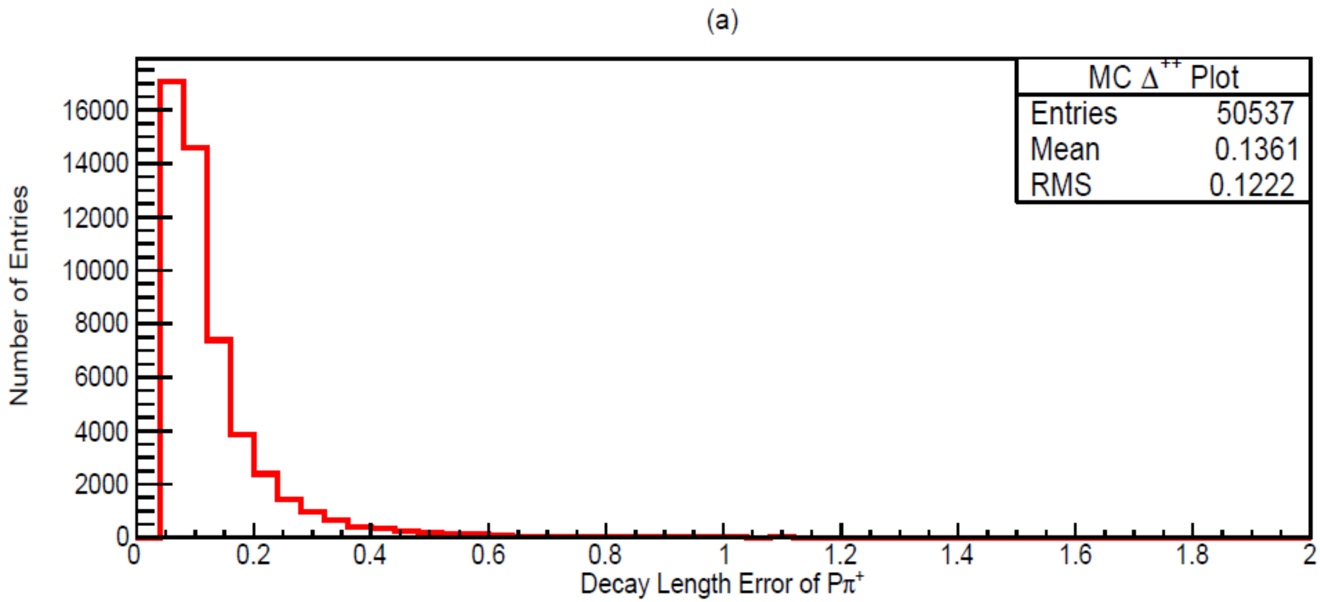
- In addition to $\chi2\_{4C}$ constraint, the following constrains were also applied to obtain final plot of $P\pi^{+}$ invariant mass distribution.
- $\left|M_{\bar{p}\pi^{-}} - M_{\bar{\Delta}^{--}}\right| < 0.2140$
- $\left|M_{p\pi^{-}} - M_{\Lambda}\right| > 0.015$
- $\left|M_{\bar{p}\pi^{+}} - M_{\bar{\Lambda}}\right| > 0.015$
- $\left|M_{p\pi^{-}} - M_{\Delta^{0}}\right| > 0.27$
- $\left|M_{\bar{p}\pi^{+}} - M_{\overline{\Delta^{0}}}\right| > 0.27$
- $|M_{\pi^{+}\pi^{-}} - M_{\omega^{0}}| > 0.031$
- $\left|M_{\pi^{+}\pi^{-}} - M_{\rho^{0}}\right| > 0.03$
- $\left|M_{\pi^{+}\pi^{-}} - M_{f_{2}}\right| > 0.21$
- Decay Length Ratio= $\left|\frac{Decay\ Length\ of\ \Delta^{++}}{Decay\ Length\ Error\ of\ \Delta^{++}}\right| > 3$

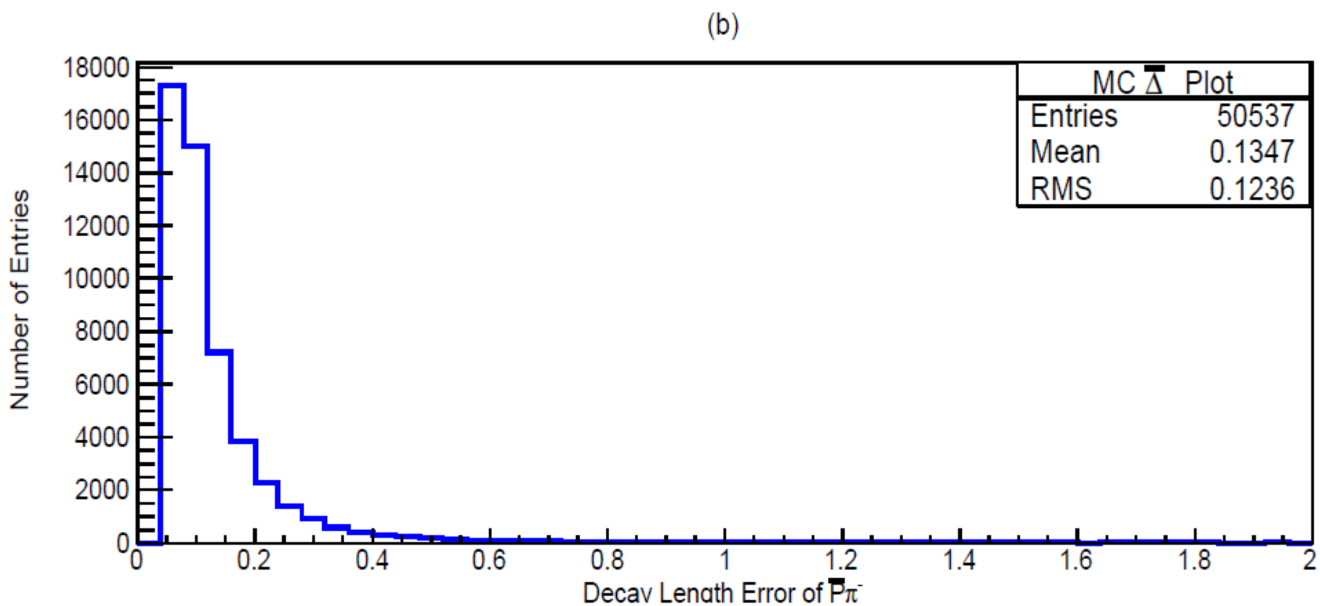
- In addition to $\chi 2\_{4C}$ constraint, the following constrains were applied to obtain final plot of $\bar{P}\pi^-$ invariant mass distribution.
- $\left|M_{p\pi^+} - M_{\Delta^{++}}\right| < 0.2140$
- $\left|M_{p\pi^-} - M_{\Lambda}\right| > 0.015$
- $\left|M_{\bar{p}\pi^+} - M_{\bar{\Lambda}}\right| > 0.015$
- $\left|M_{p\pi^-} - M_{\Delta^0}\right| > 0.27$
- $\left|M_{\bar{p}\pi^+} - M_{\overline{\Delta^0}}\right| > 0.27$
- $|M_{\pi^+\pi^-} - M_{\omega^0}| > 0.031$
- $\left|M_{\pi^+\pi^-} - M_{\rho^0}\right| > 0.03$
- $\left|M_{\pi^+\pi^-} - M_{f_2}\right| > 0.21$
- Decay Length Ratio= $\left|\frac{Decay\ Length\ of\, \bar{\Delta}^{--}}{Decay\ Length\ Error\ of\ \bar{\Delta}^{--}}\right| > 3$

χ^2 Optimization after 4C Fit



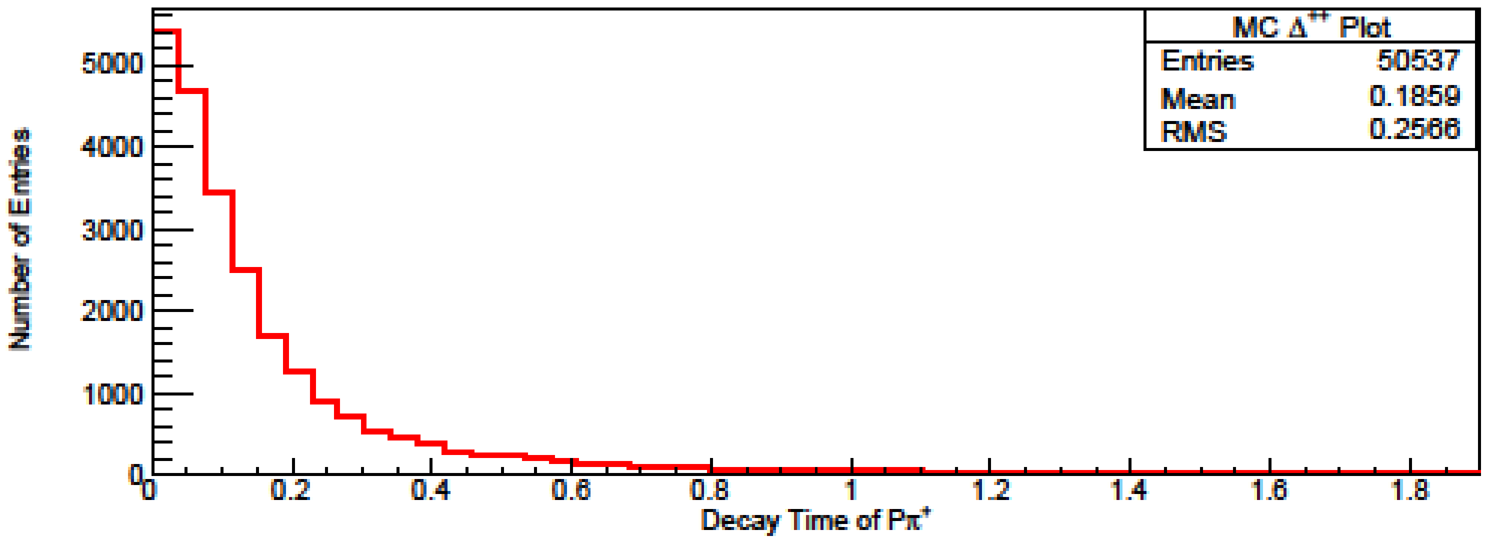
Decay Length Error



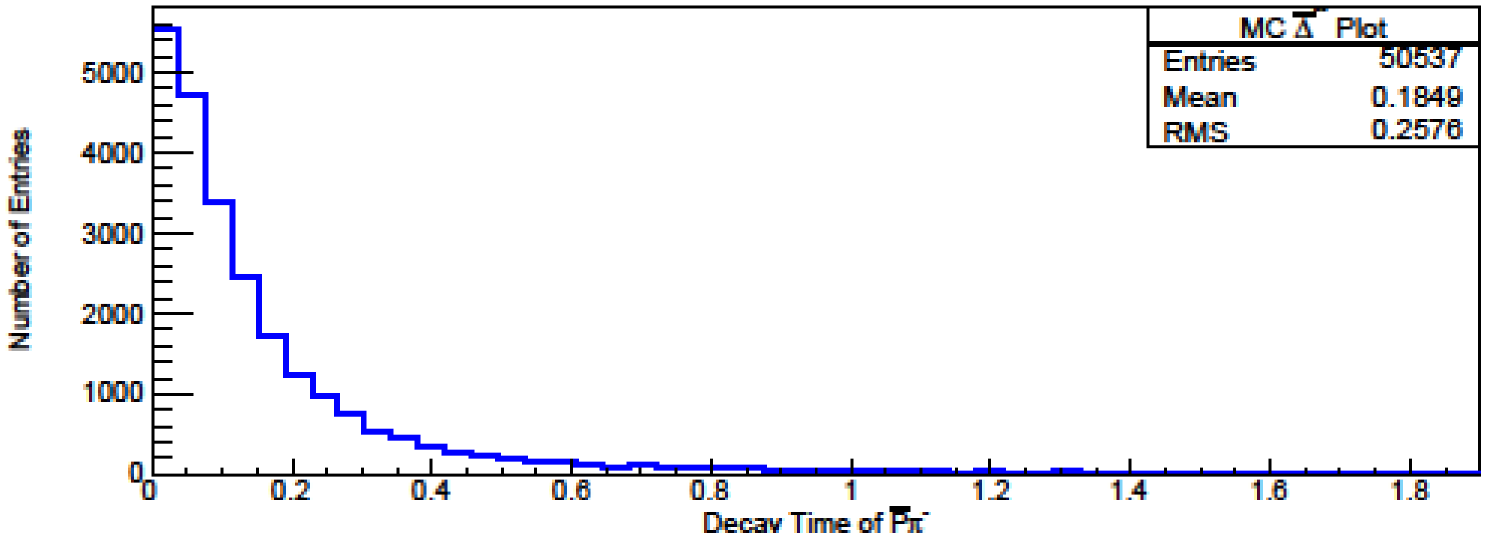


MC Proper Time Distribution

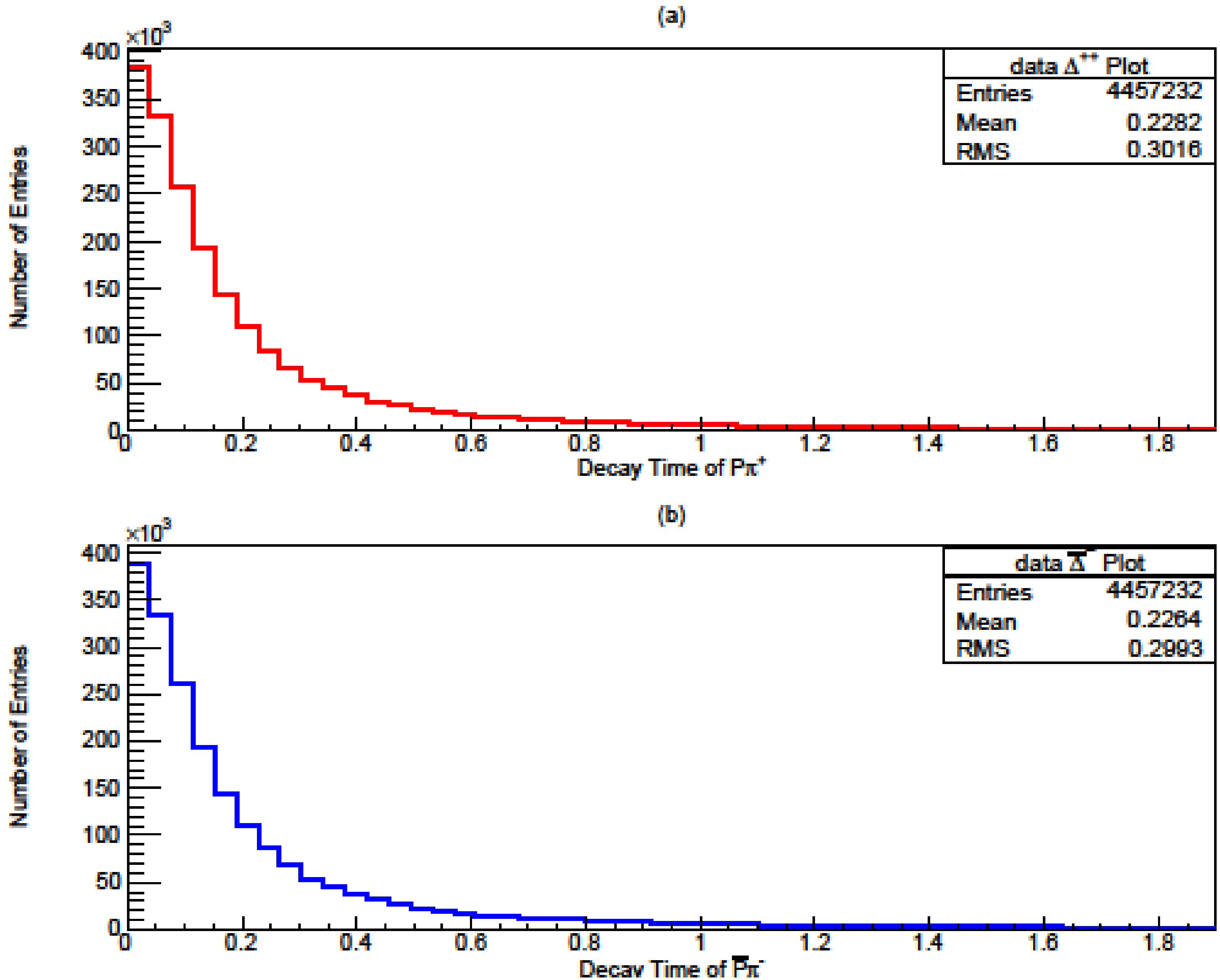
(a)

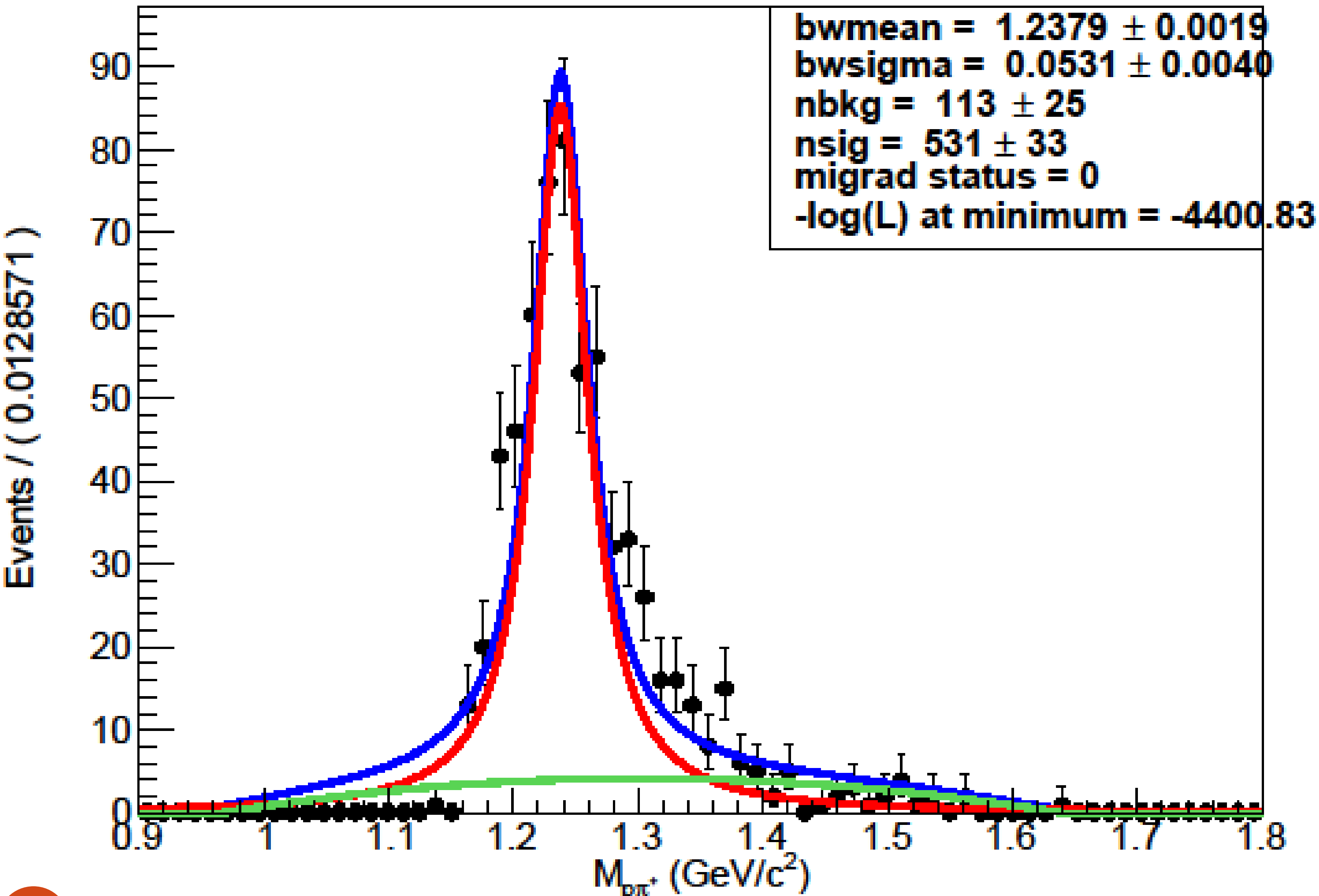


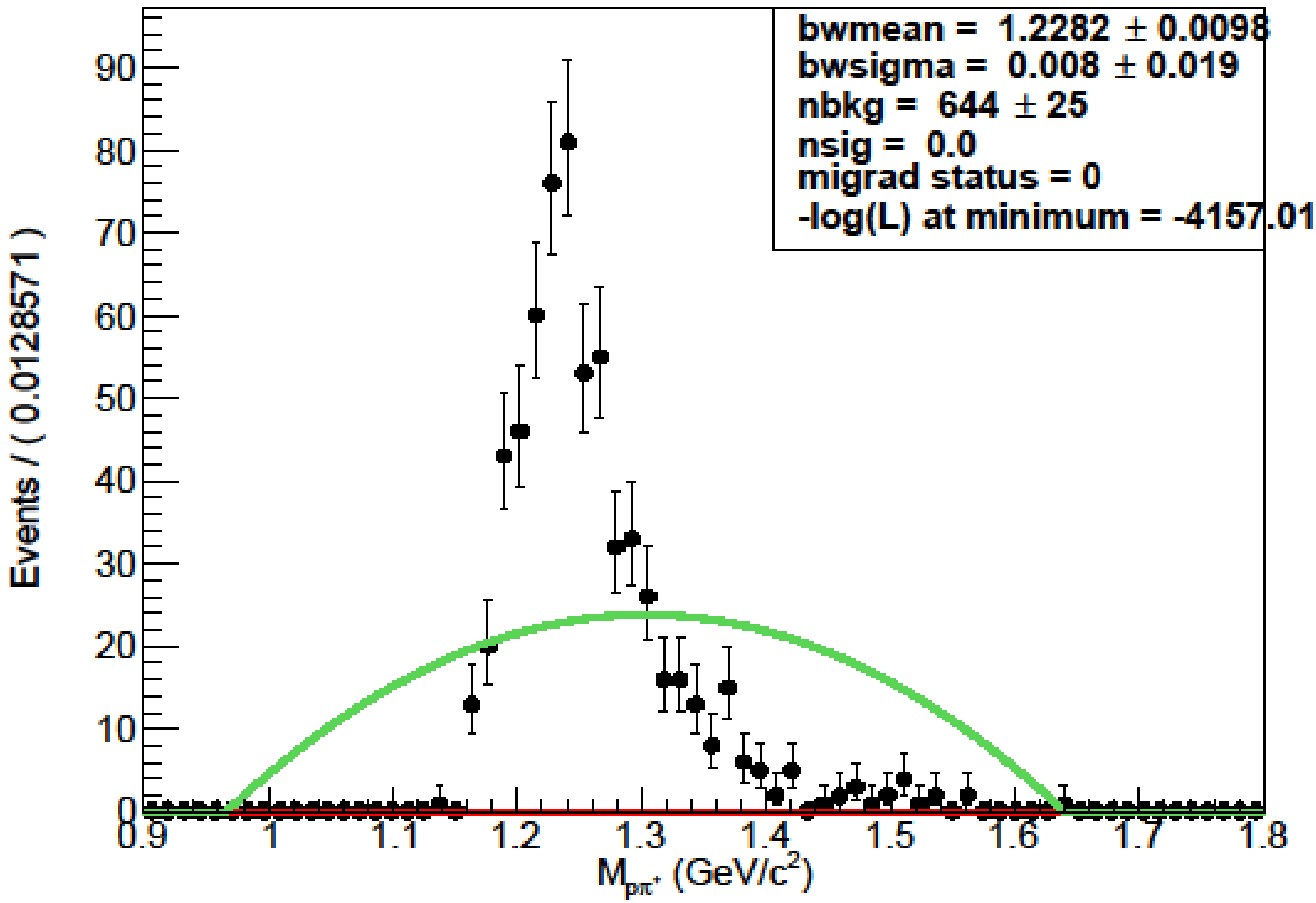
(b)

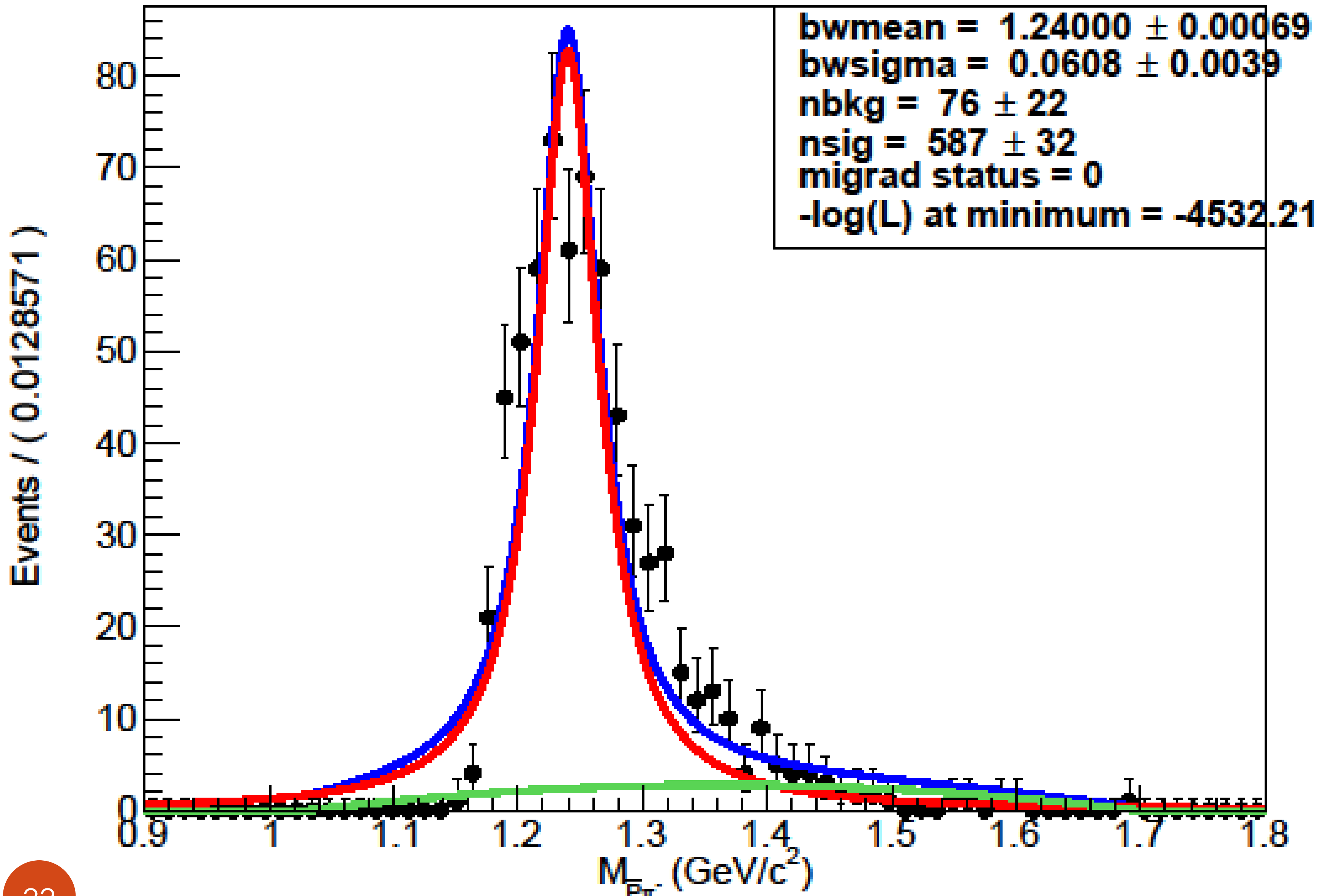


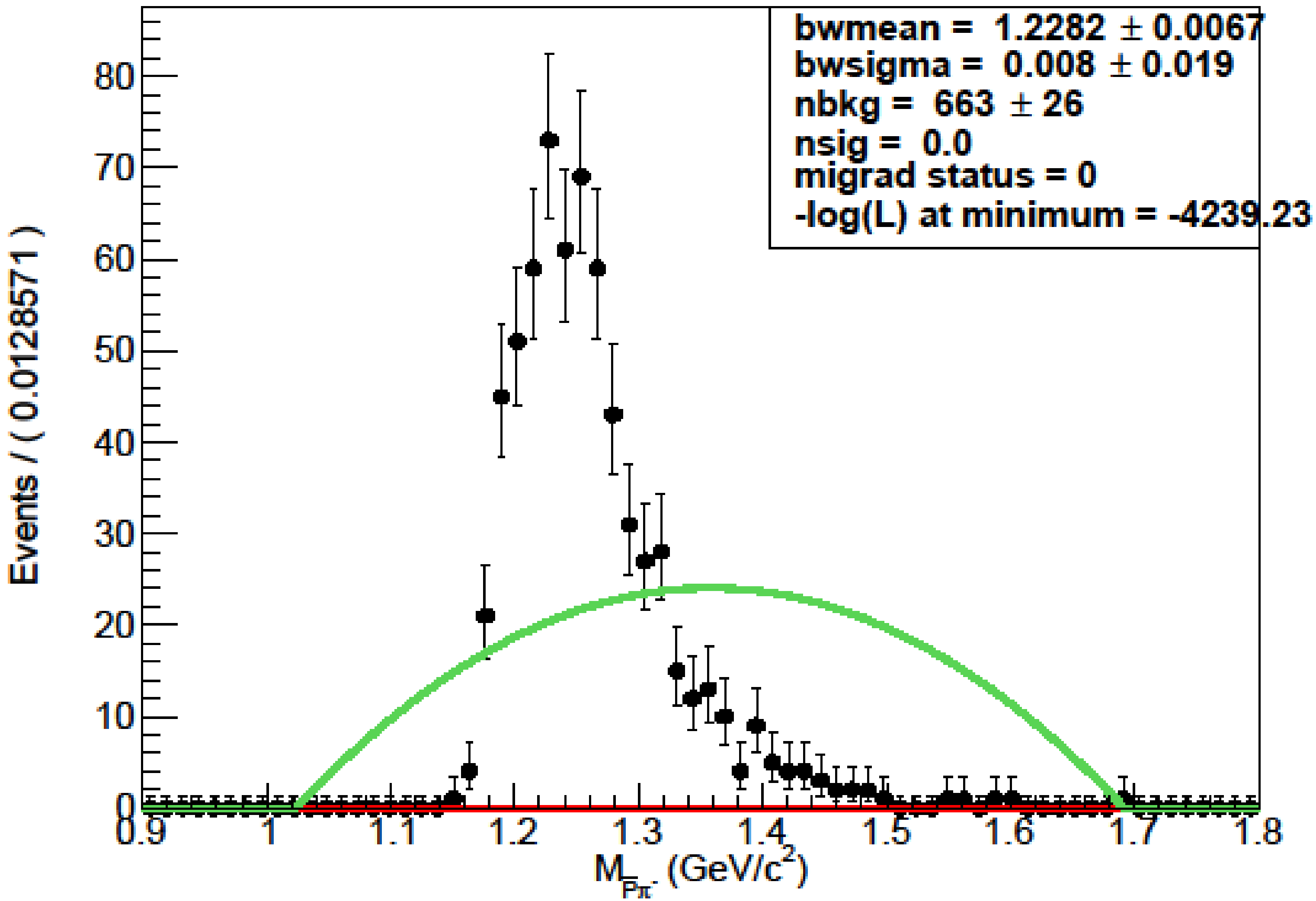
Data Proper Time Distribution




bwmean = 1.2379 ± 0.0019
bwsigma = 0.0531 ± 0.0040
nbkg = 113 ± 25
nsig = 531 ± 33
migrad status = 0
-log(L) at minimum = -4400.83
Events / (0.0128571)
0
10
20
30
40
50
60
70
80
90
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Mpπ+ (GeV/c2)


bwmean = 1.2282 ± 0.0098
bwsigma = 0.008 ± 0.019
nbkg = 644 ± 25
nsig = 0.0
migrad status = 0
-log(L) at minimum = -4157.01
Events / (0.0128571)
90
80
70
60
50
40
30
20
10
0
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
M$_{p\pi^+}$ (GeV/c^2)


bwmean = 1.24000 ± 0.00069
bwsigma = 0.0608 ± 0.0039
nbkg = 76 ± 22
nsig = 587 ± 32
migrad status = 0
-log(L) at minimum = -4532.21
Events / (0.0128571)
$M_{P\pi^-}$ (GeV/c^2)



bwmean = 1.2282 ± 0.0067
bwsigma = 0.008 ± 0.019
nbkg = 663 ± 26
nsig = 0.0
migrad status = 0
-log(L) at minimum = -4239.23
Events / (0.0128571)
M_{Pπ^-} (GeV/c^2)

Statistical Significance

- To measure statistical significance, we made two maximum likelihood fits to each of the Δ^{++} and $\bar{\Delta}^{--}$invariant mass distributions.
- First fit was made by using respective fixed Monte Carlo histogram as signal and the second fit was made by setting signal to zero (mean no signal function)
- In order to obtain the significance level, the values of log likelihood, obtained from the two fits were used in the following formula

$$S = \sqrt{|2lnL_{max}(s + b) - 2lnL_{max}(b)|}$$

- where 2lnLmax(s+b) represents the value of log likelihood obtained from first fit and 2lnLmax(b) represents the log likelihood value from second fit. The statistical significance of Δ^{++} and $\bar{\Delta}^{--}$ signals was determined to be 15.5σ and 17σ respectively.

Systematic Error Analysis

Sources of Uncertainty	Uncertainty(%)
MDC Tracking	8
Particle Identification	6
Hadron Interaction Models	1.27
4C Kinematic Fit	0
Intermediate Resonances	0
MC Statistics	0.18
Total Number of J/ψ Events	0.8
4C Vertex Fit	0
Total Uncertainty	10

Summary of the Systematic Error Analysis

Branching Fraction

- The Branching Fraction of $J/\psi \rightarrow \Delta^{++}\bar{\Delta}^{--}$ can be determined by using the following relation

$$B(J/\psi \to \Delta^{++}\overline{\Delta}^{--}) = \frac{N_{Observed}}{\varepsilon N_{J/\psi} B(\Delta^{++} \to P\pi^{+}) B(\overline{\Delta}^{--} \to \bar{P}\pi^{-})}$$

- Where detection efficiency ε = 50%. *NObserved* is the average of total number of observed signals equal to 559. Total number of J/ψ events NJ/ψ = 1310.6 Million. The Branching fractions of B(Δ++ →*P*π+) and B(Δ−− →*P*π−) are equal to 0.994.
- B($J/\psi \rightarrow \Delta^{++}\bar{\Delta}^{--}$)=(0.86±0.08)× 10^{-6}

Background Analysis for $J/\psi \to \Delta^{++}\overline{\Delta}^{--}$

Background Channels	$N_{\text{generated}}$	Branching Fraction (10^{-3})	N_{observed}
$J/\psi \to \Lambda\overline{\Lambda}$	1×10^5	1.61 ± 0.15	0
$J/\psi \to \Delta^{++}\overline{P}\pi^-$	1×10^5	1.6 ± 0.5	0
$J/\psi \to \overline{\Delta}^{--}P\pi^+$	1×10^5	–	0
$J/\psi \to \Delta^0\overline{\Delta^0}$	1×10^5	–	0
$J/\psi \to \Delta^0\overline{P}\pi^+$	1×10^5	–	1
$J/\psi \to \overline{\Delta^0}P\pi^-$	1×10^5	–	1
$J/\psi \to P\overline{P}\pi^+\pi^-$	1×10^5	6.0 ± 0.5	0
$J/\psi \to P\overline{P}\omega$	1×10^5	0.98 ± 0.1	0
$J/\psi \to P\overline{P}\rho$	1×10^5	–	1
$J/\psi \to P\overline{P}f_2$	1×10^5	–	2

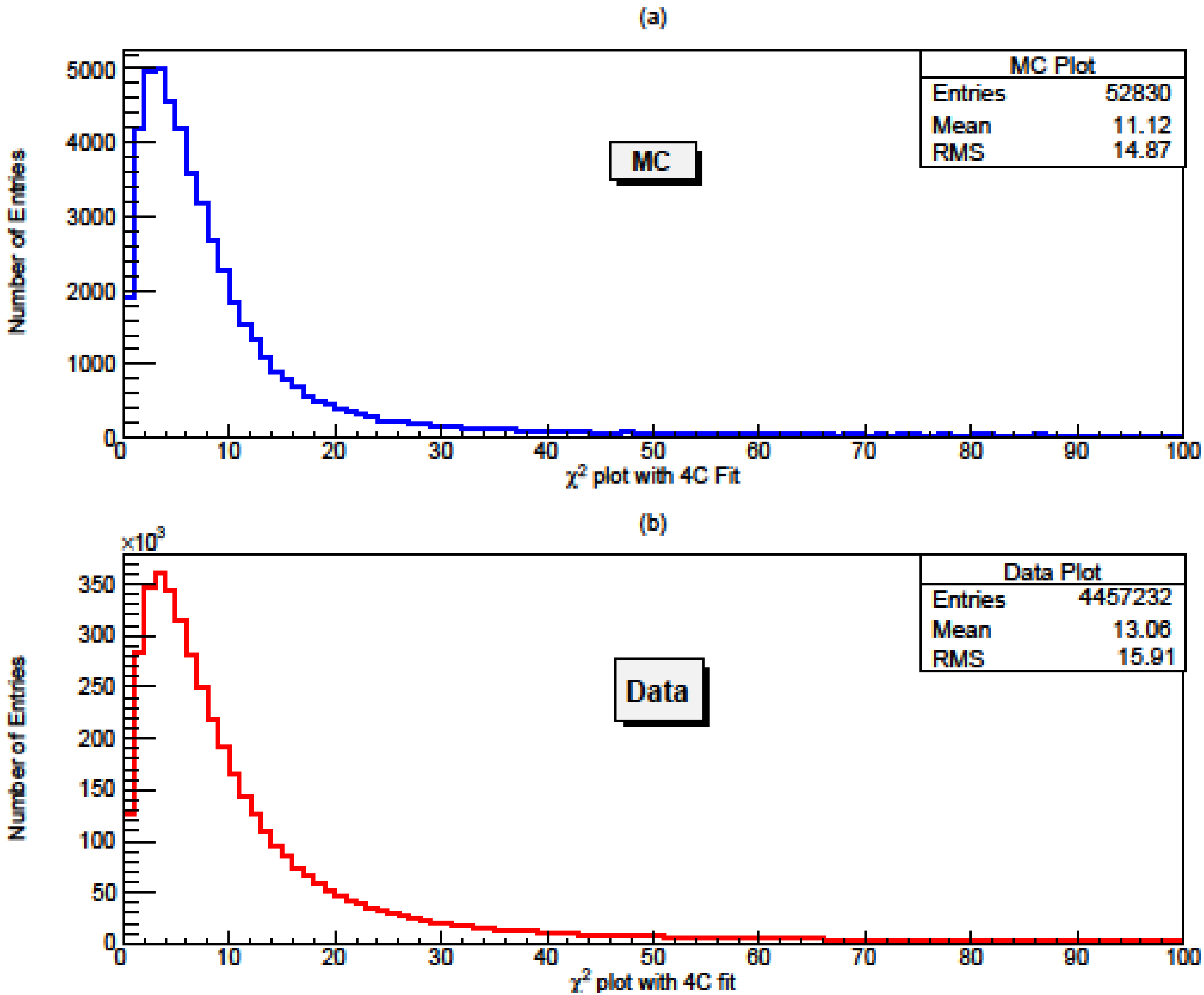
Table 5.1 The Exclusive Backgrounds Obtained for $J/\psi \to \Delta^{++}\overline{\Delta}^{--}$ Channel with $\Delta^{++} \to P\pi^+$ and $\overline{\Delta}^{--} \to \overline{P}\pi^-$.

The background channels were observed after the topological background study

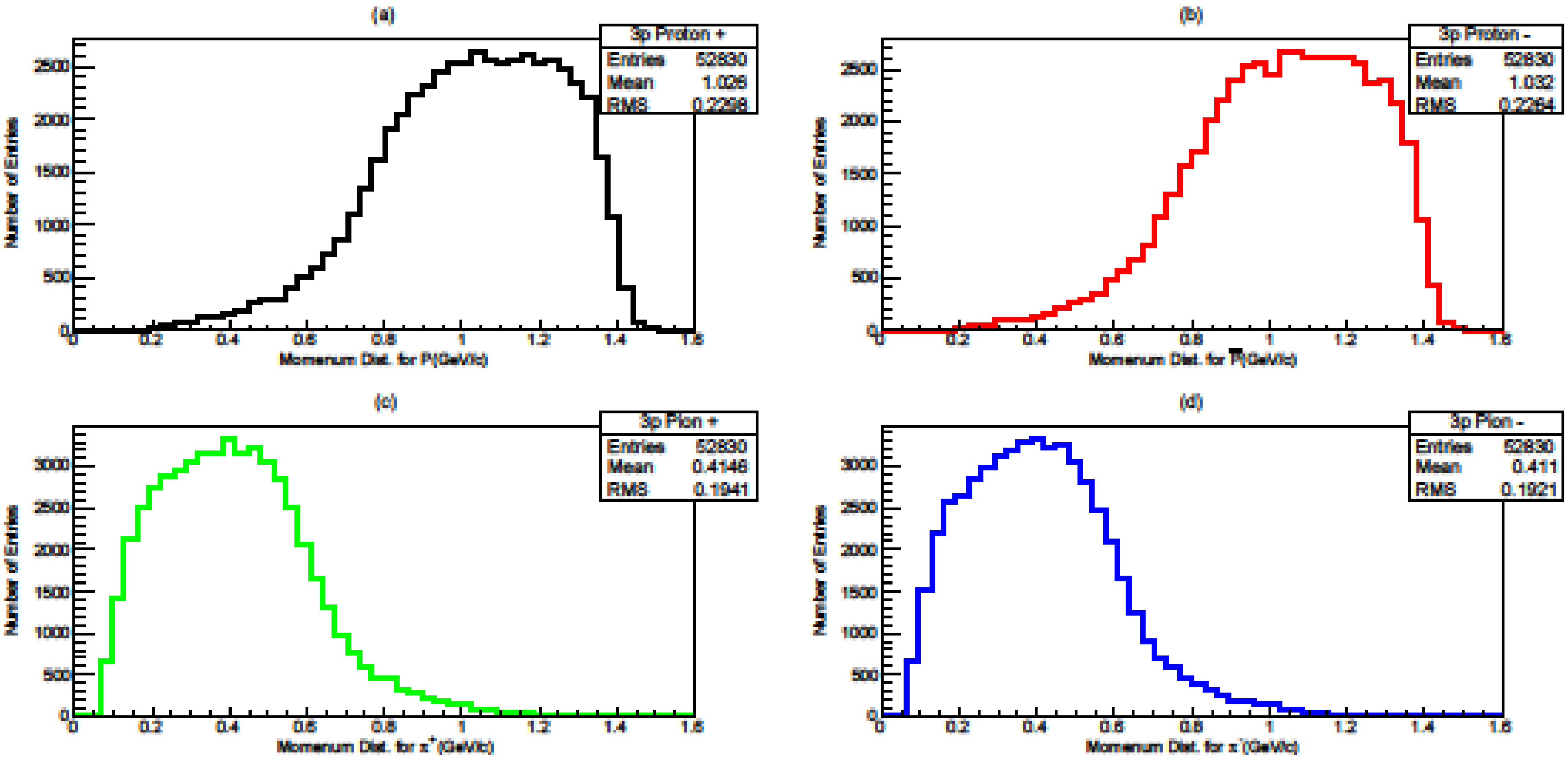
Analysis of $\psi(2S) \to \Delta^{++}\overline{\Delta}^{--}$

- In addition to $\chi2\_4C$ constraint, the following constrains were applied to obtain final plot of $P\pi^+$ invariant mass distribution.
- $|M_{\bar{p}\pi^-} - M_{\bar{\Delta}^{--}}| < 0.2140$
- $|M_{p\pi^-} - M_{\Lambda}| > 0.015$
- $|M_{\bar{p}\pi^+} - M_{\bar{\Lambda}}| > 0.015$
- $|M_{p\pi^-} - M_{\Delta^0}| > 0.27$
- $|M_{\bar{p}\pi^+} - M_{\overline{\Delta^0}}| > 0.27$
- $|M_{\pi^+\pi^-} - M_{\omega^0}| > 0.031$
- $|M_{\pi^+\pi^-} - M_{\rho^0}| > 0.03$
- $|M_{\pi^+\pi^-} - M_{f_2}| > 0.21$
- Decay Length Ratio= $\left|\frac{Decay\ Length\ of\ \Delta^{++}}{Decay\ Length\ Error\ of\ \Delta^{++}}\right| > 3$

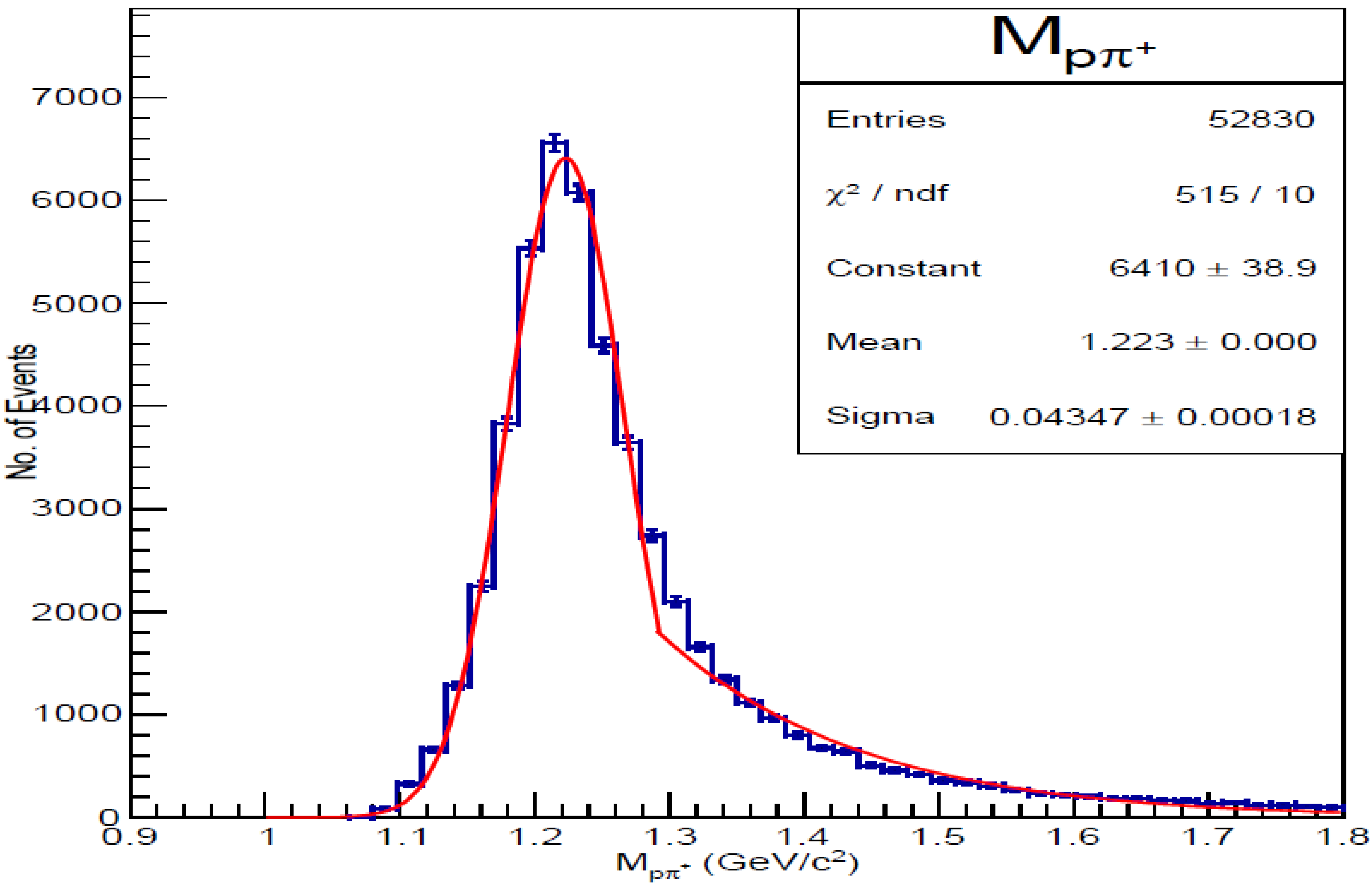
- In addition to $\chi 2\_{4C}$ constraint, the following constrains were applied to obtain final plot of $\bar{P}\pi^-$ invariant mass distribution.
- $\left|M_{p\pi^+} - M_{\Delta^{++}}\right| < 0.2140$
- $\left|M_{p\pi^-} - M_{\Lambda}\right| > 0.015$
- $\left|M_{\bar{p}\pi^+} - M_{\bar{\Lambda}}\right| > 0.015$
- $\left|M_{p\pi^-} - M_{\Delta^0}\right| > 0.27$
- $\left|M_{\bar{p}\pi^+} - M_{\overline{\bar{\Delta}^0}}\right| > 0.27$
- $|M_{\pi^+\pi^-} - M_{\omega^0}| > 0.031$
- $\left|M_{\pi^+\pi^-} - M_{\rho^0}\right| > 0.03$
- $\left|M_{\pi^+\pi^-} - M_{f_2}\right| > 0.21$
- Decay Length Ratio= $\left|\frac{Decay\ Length\ of\,\bar{\Delta}^{--}}{Decay\ Length\ Error\ of\ \bar{\Delta}^{--}}\right| > 3$



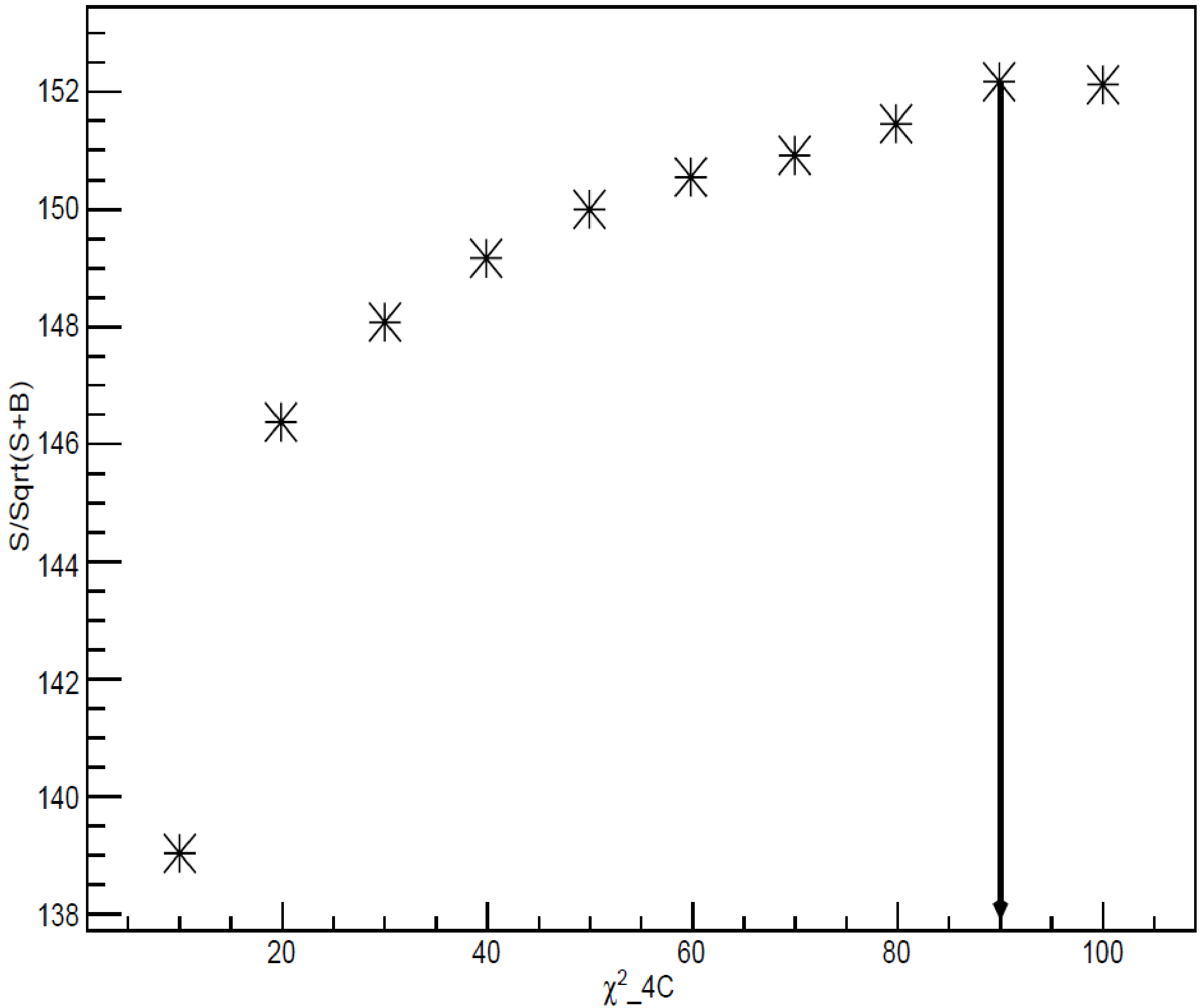
(a)
MC Plot
Entries 52830
Mean 11.12
RMS 14.87
MC
Number of Entries
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
100
χ^2 plot with 4C Fit
(b)
$\times10^3$
Data Plot
Entries 4457232
Mean 13.06
RMS 15.91
Data
Number of Entries
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
χ^2 plot with 4C fit


(a)
3p Proton +
Entries 52830
Mean 1.026
RMS 0.2298
Number of Entries
Momenum Dist. for P(GeV/c)
(b)
3p Proton -
Entries 52830
Mean 1.032
RMS 0.2284
Number of Entries
Momenum Dist. for P̄(GeV/c)
(c)
3p Pion +
Entries 52830
Mean 0.4146
RMS 0.1941
Number of Entries
Momenum Dist. for π+(GeV/c)
(d)
3p Pion -
Entries 52830
Mean 0.411
RMS 0.1921
Number of Entries
Momenum Dist. for π-(GeV/c)

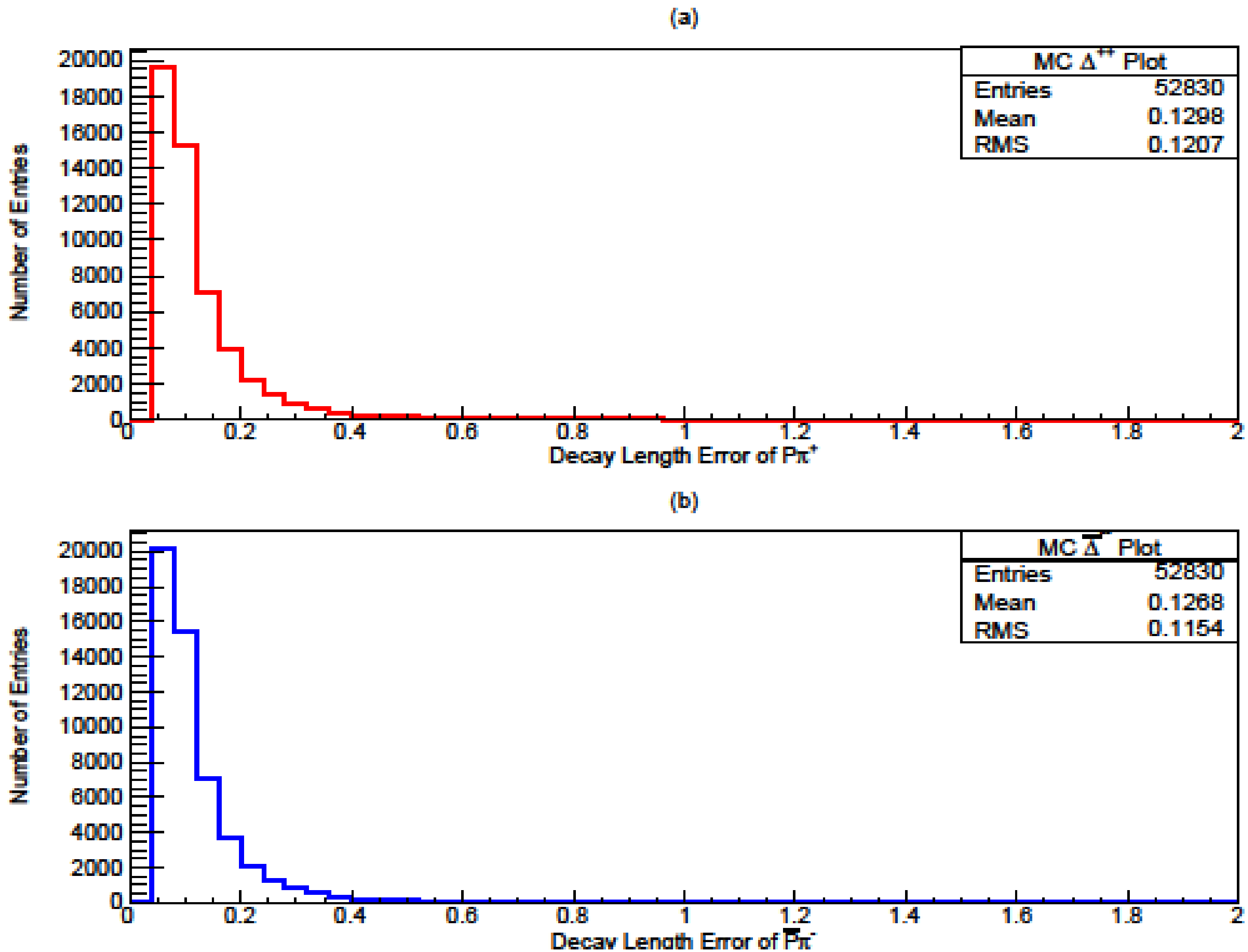
MC Mass Distribution of $P\pi^+$



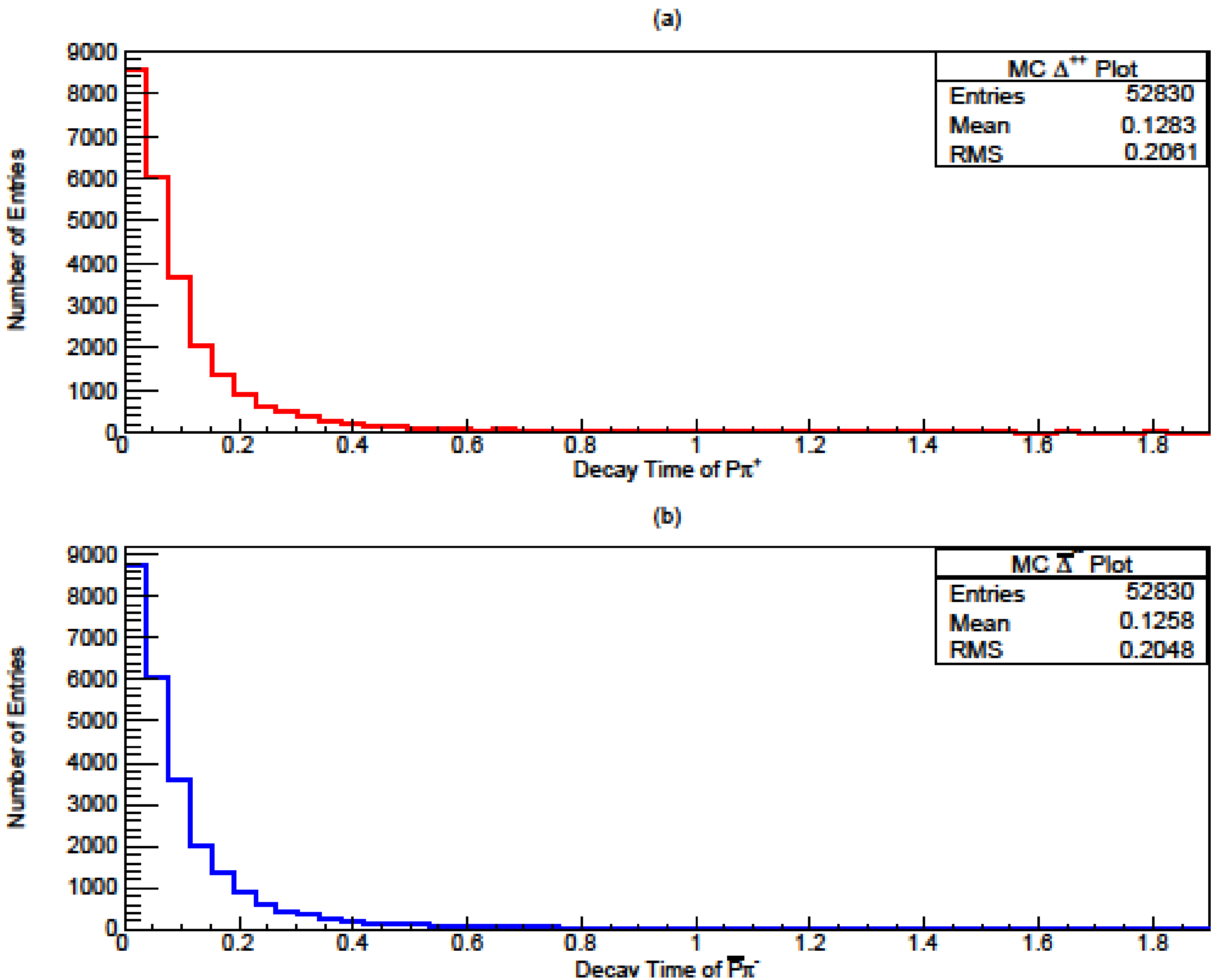
χ^2 Optimization after 4C Fit



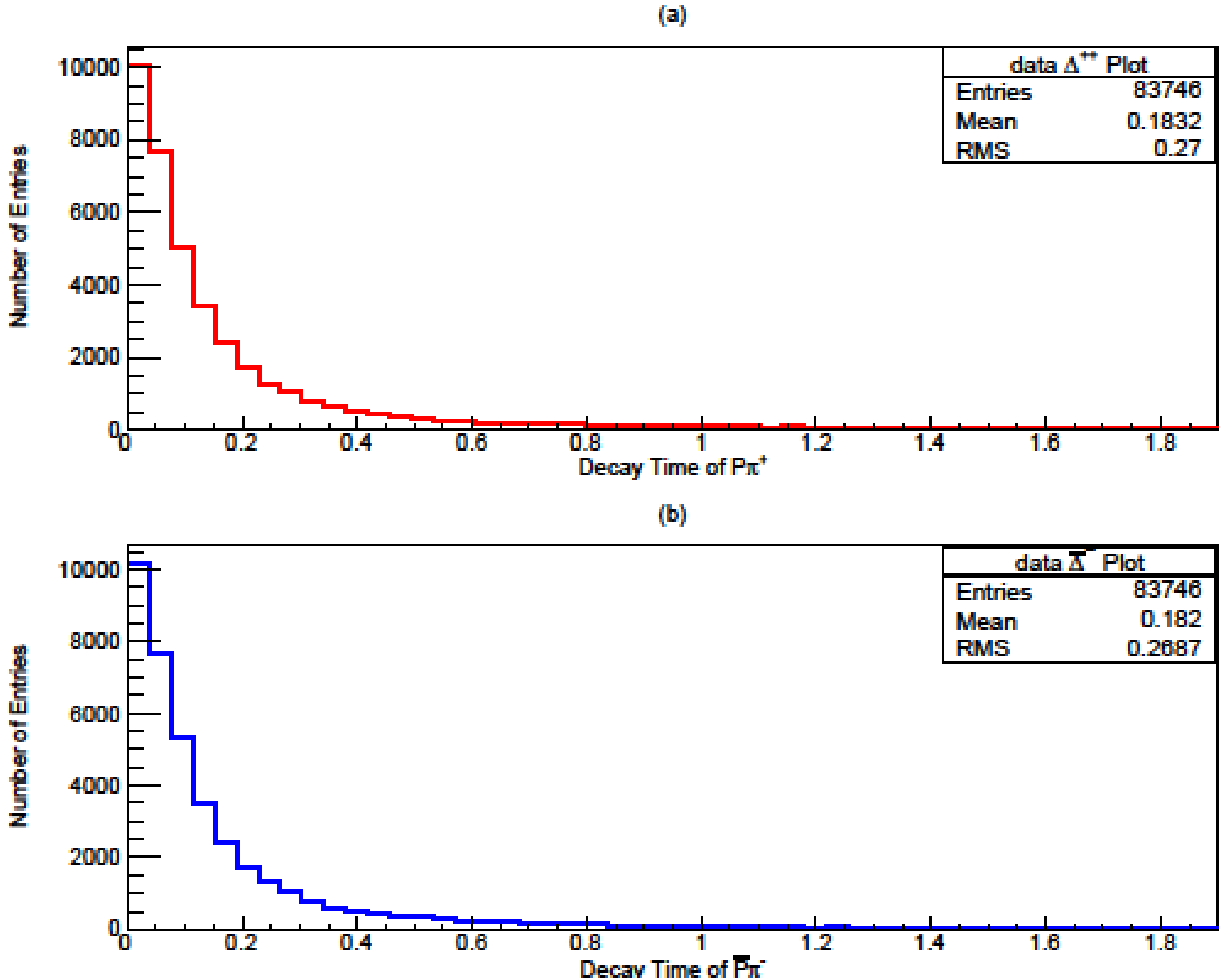
Decay Length Error

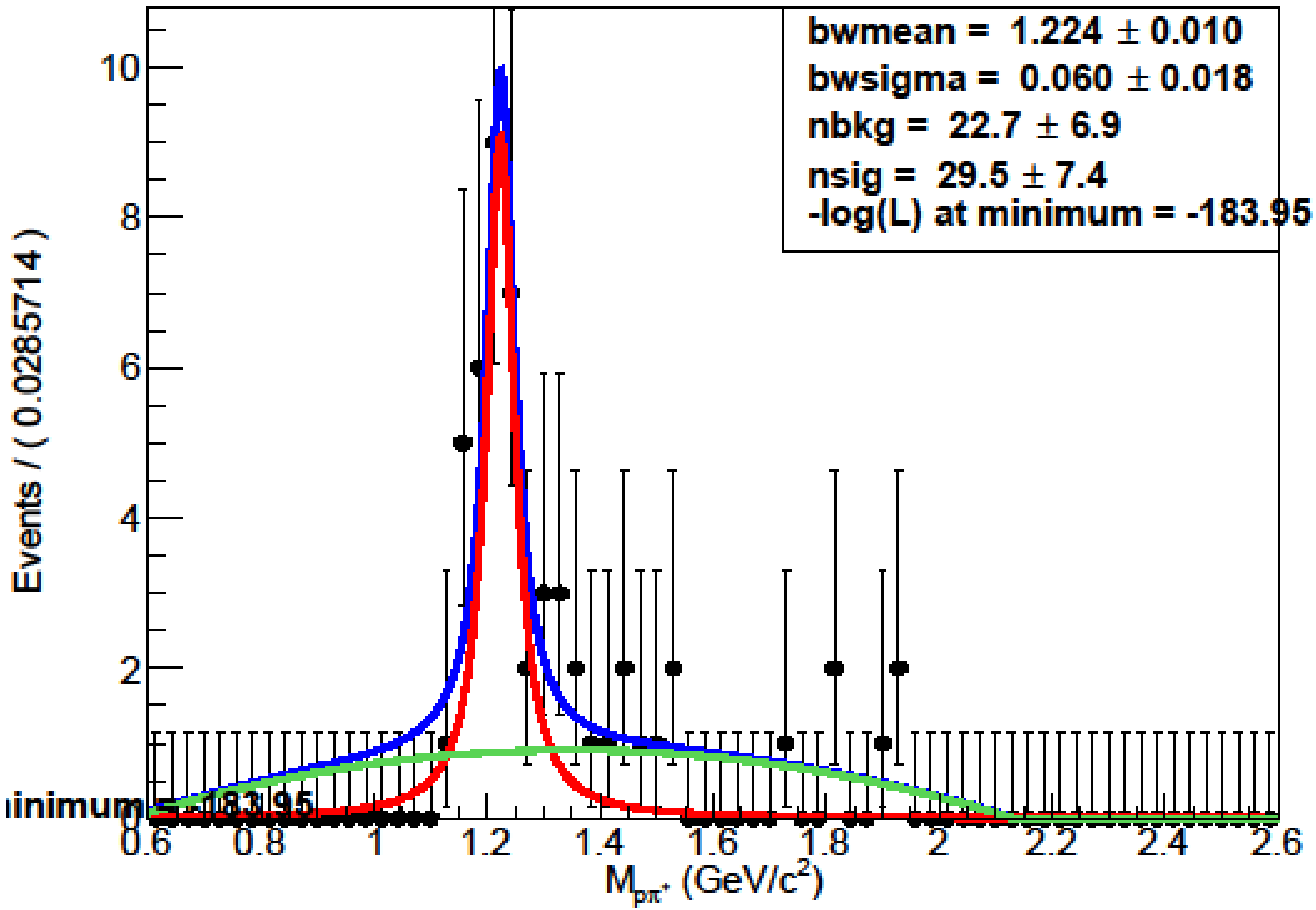


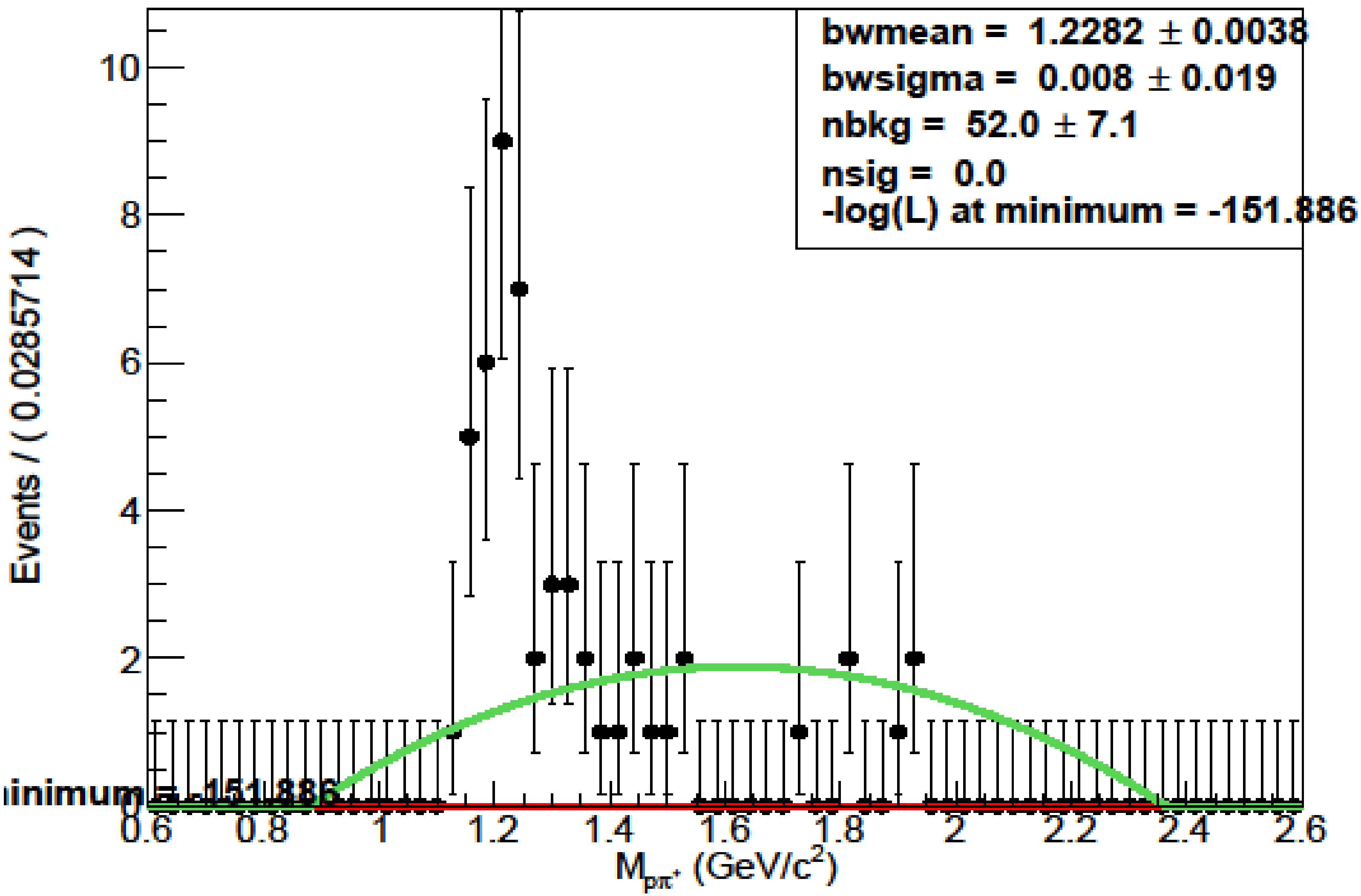
MC Proper Time Distribution

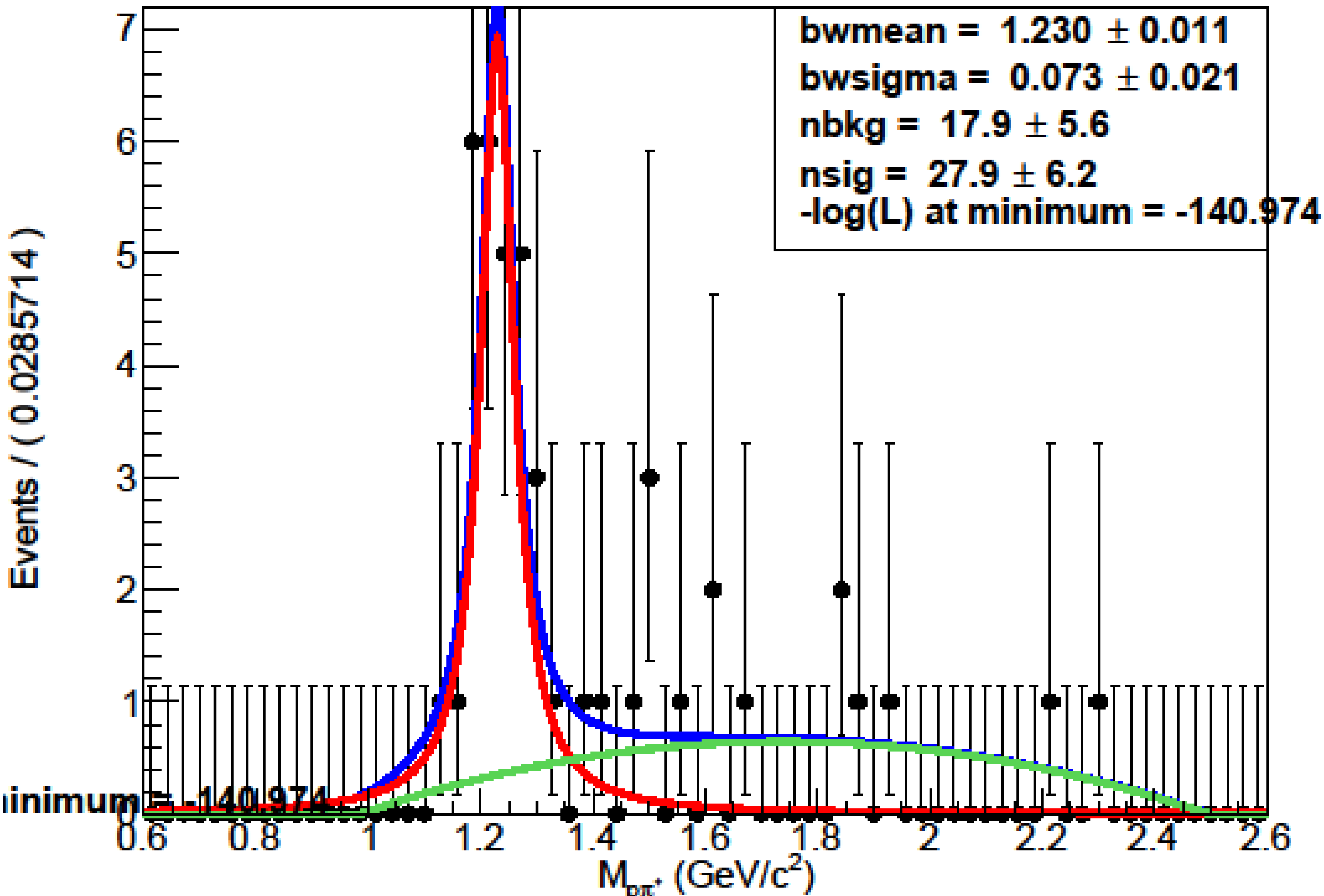


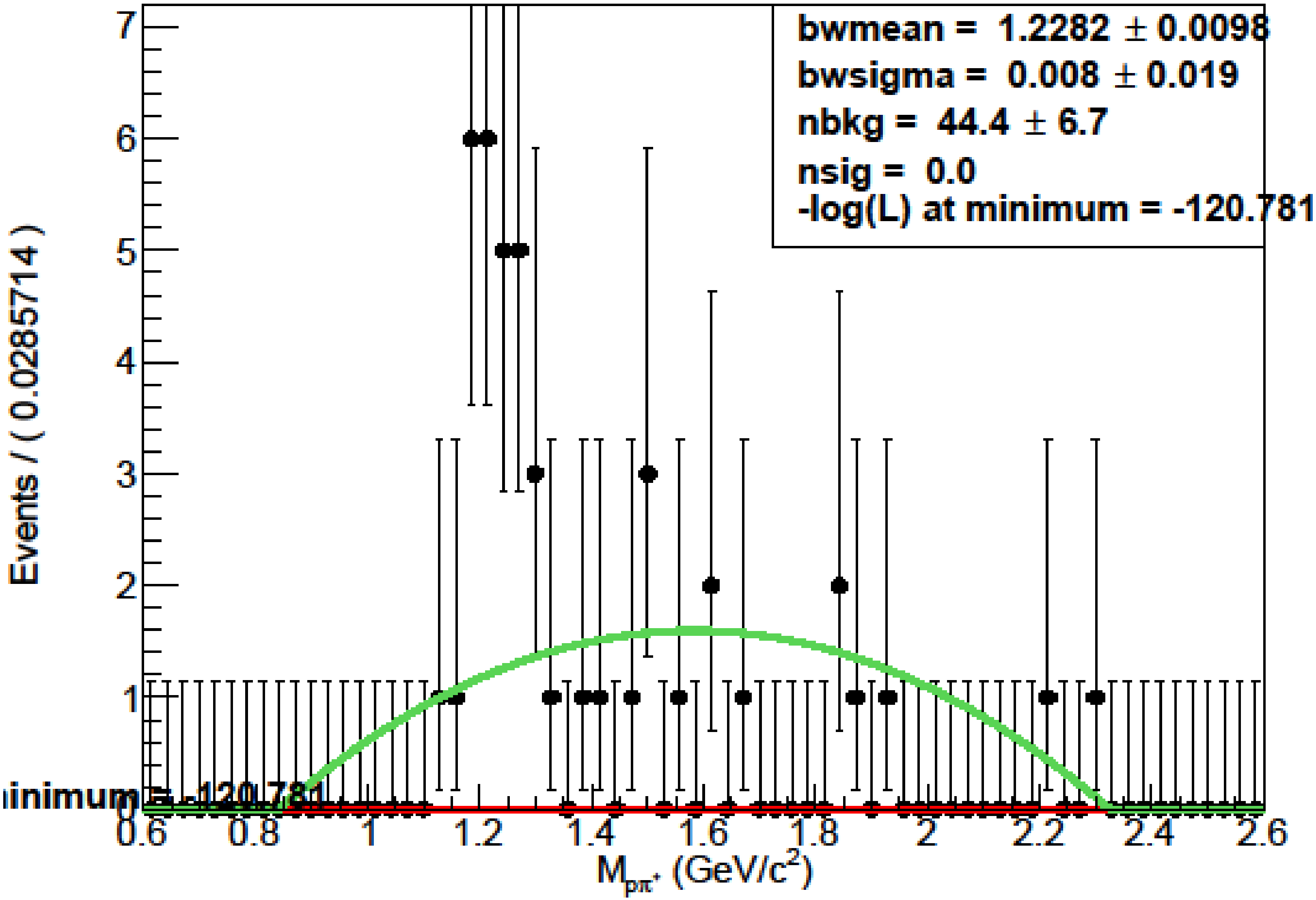
Data Proper Time Distribution




bwmean = 1.224 ± 0.010
bwsigma = 0.060 ± 0.018
nbkg = 22.7 ± 6.9
nsig = 29.5 ± 7.4
-log(L) at minimum = -183.95
Events / (0.0285714)
$M_{p\pi^+}$ (GeV/c^2)


bwmean = 1.2282 ± 0.0038
bwsigma = 0.008 ± 0.019
nbkg = 52.0 ± 7.1
nsig = 0.0
-log(L) at minimum = -151.886
Events / (0.0285714)
10
8
6
4
2
0
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
$M_{p\pi^+}$ (GeV/c^2)


bwmean = 1.230 ± 0.011
bwsigma = 0.073 ± 0.021
nbkg = 17.9 ± 5.6
nsig = 27.9 ± 6.2
-log(L) at minimum = -140.974
Events / (0.0285714)
$M_{p\pi^+}$ (GeV/c^2)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
1
2
3
4
5
6
7
inimum = -140.974


bwmean = 1.2282 ± 0.0098
bwsigma = 0.008 ± 0.019
nbkg = 44.4 ± 6.7
nsig = 0.0
-log(L) at minimum = -120.781
Events / (0.0285714)
$M_{p\pi^+}$ (GeV/c^2)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
1
2
3
4
5
6
7

Statistical Significance

- To measure statistical significance, we made two maximum likelihood fits to each of the Δ^{++} and $\bar{\Delta}^{--}$invariant mass distributions.
- First fit was made by using respective fixed Monte Carlo histogram as signal and the second fit was made by setting signal to zero (mean no signal function)
- In order to obtain the significance level, the values of log likelihood, obtained from the two fits were used in the following formula

$$S = \sqrt{|2lnL_{max}(s+b) - 2lnL_{max}(b)|}$$

- where 2lnLmax(s+b) represents the value of log likelihood obtained from first fit and 2lnLmax(b) represents the log likelihood value from second fit. The statistical significance of Δ^{++} and $\bar{\Delta}^{--}$ signals was determined to be 5.6σ and 4.49σ respectively.

Systematic Errors

Sources of Uncertainty	Uncertainty(%)
MDC Tracking	8
Particle Identification	6
Hadron Interaction Models	11
4C Kinematic Fit	0
Intermediate Resonances 0	
MC Statistics	0.23
Total Number of $\psi(2S)$ Events	0.6
4C Vertex Fit	0
Total Uncertainty	14.8

Summary of the Systematic Error Analysis

Branching Fraction

The Branching Fraction of $\psi(2S) \rightarrow \Delta^{++}\bar{\Delta}^{--}$ can be determined by using the following relation

$$B(\psi(2S) \rightarrow \Delta^{++}\overline{\Delta}^{--}) = \frac{N_{Observed}}{\varepsilon N_{\psi(2S)} B(\Delta^{++} \rightarrow P\pi^{+}) B(\overline{\Delta}^{--} \rightarrow \overline{P}\pi^{-})}$$

Where Detection efficiency $\varepsilon = 52.8\%$. *NObserved* is total number of observed signals equal to 28. Total number of ψ events $N\psi = 448$ Million. The Branching fractions of $B(\Delta^{++} \rightarrow P\pi^{+})$ and $B(\Delta^{--} \rightarrow P\pi^{-})$ are equal to 0.994.

$$B(\psi(2S) \rightarrow \Delta^{++}\bar{\Delta}^{--}) = (1.07 \pm 0.16) \times 10^{-7}$$

Background Estimation

Background Channels	$N_{generated}$	Branching Fraction (10^{-3})	$N_{observed}$
$\psi(2S) \to J/\psi\pi^+\pi^-$	1×10^5	1.61 ± 0.15	18
$\psi(2S) \to \Lambda\overline{\Lambda}$	1×10^5	1.61 ± 0.15	0
$\psi(2S) \to \Delta^{++}\overline{P}\pi^-$	1×10^5	1.6 ± 0.5	12
$\psi(2S) \to \overline{\Delta}^{--}P\pi^+$	1×10^5	–	21
$\psi(2S) \to \Delta^0\overline{\Delta}^0$	1×10^5	–	0
$\psi(2S) \to \Delta^0\overline{P}\pi^+$	1×10^5	–	4
$\psi(2S) \to \overline{\Delta}^0P\pi^-$	1×10^5	–	4
$\psi(2S) \to P\overline{P}\pi^+\pi^-$	1×10^5	6.0 ± 0.5	14
$\psi(2S) \to P\overline{P}\omega$	1×10^5	0.98 ± 0.1	0
$\psi(2S) \to P\overline{P}\rho$	1×10^5	–	4
$\psi(2S) \to P\overline{P}f_2$	1×10^5	–	9

The background channels were observed after the topological background study

Conclusion

- Through these analyses, it is found that the 12% rule is nearly obeyed by these channels i.e. The ratio of $\psi(2S) \to \Delta^{++} \overline{\Delta}^{--}$ and that of $J/\psi \to \Delta^{++} \overline{\Delta}^{--}$ is about 12%

$$Q_h = \frac{1.07 \pm 0.16 \times 10^{-7}}{0.86 \pm 0.08 \times 10^{-6}} = 12.4\%$$

- It is also found that our measured branching fractions are better than the PDG values of branching fractions of these decay channels by about of order three.
- With increased statistics of data at BESIII, these measurements can be further improved through their precision and accuracy.