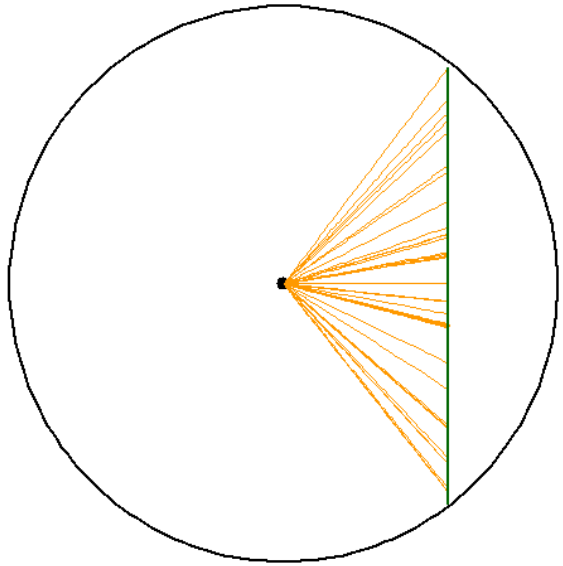
Simulation parameters (SPD setup)

1. Straw diameter: 10 mm
2. Anode diameter: 30 mkm
3. HV: 1750 V
4. Gas mixture: Ar+CO2 / 70:30 [%]
5. Gas mixture temperature: 20 celsius
6. Gas mixture Pressure: 1 atmosphere
7. Ionization particle: muon 1 GeV
8. Track angle α: 90°.
9. Magnetic field: 0 T
10. Gas Gain is fixed $= 4.5 \cdot 10^4$ (Penning coefficient is 0)



A track of 1 GeV muon crossing the straw tube shown together with electron drift lines.

Threshold crossing time

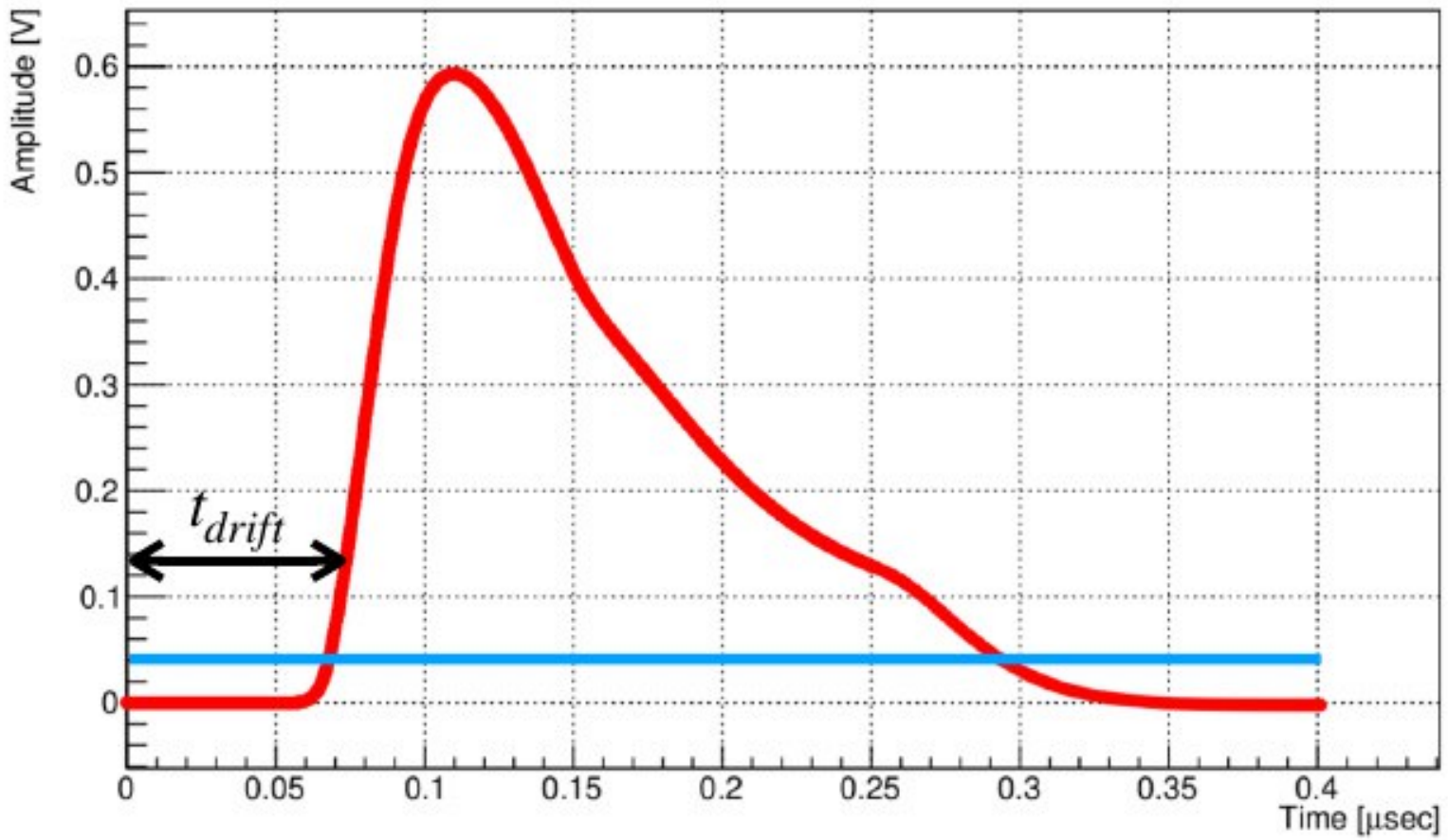


Figure 1: Ordinary Garfield++ and LTSpice signal output (red) with threshold (blue)

Garfield++ vs Geant4

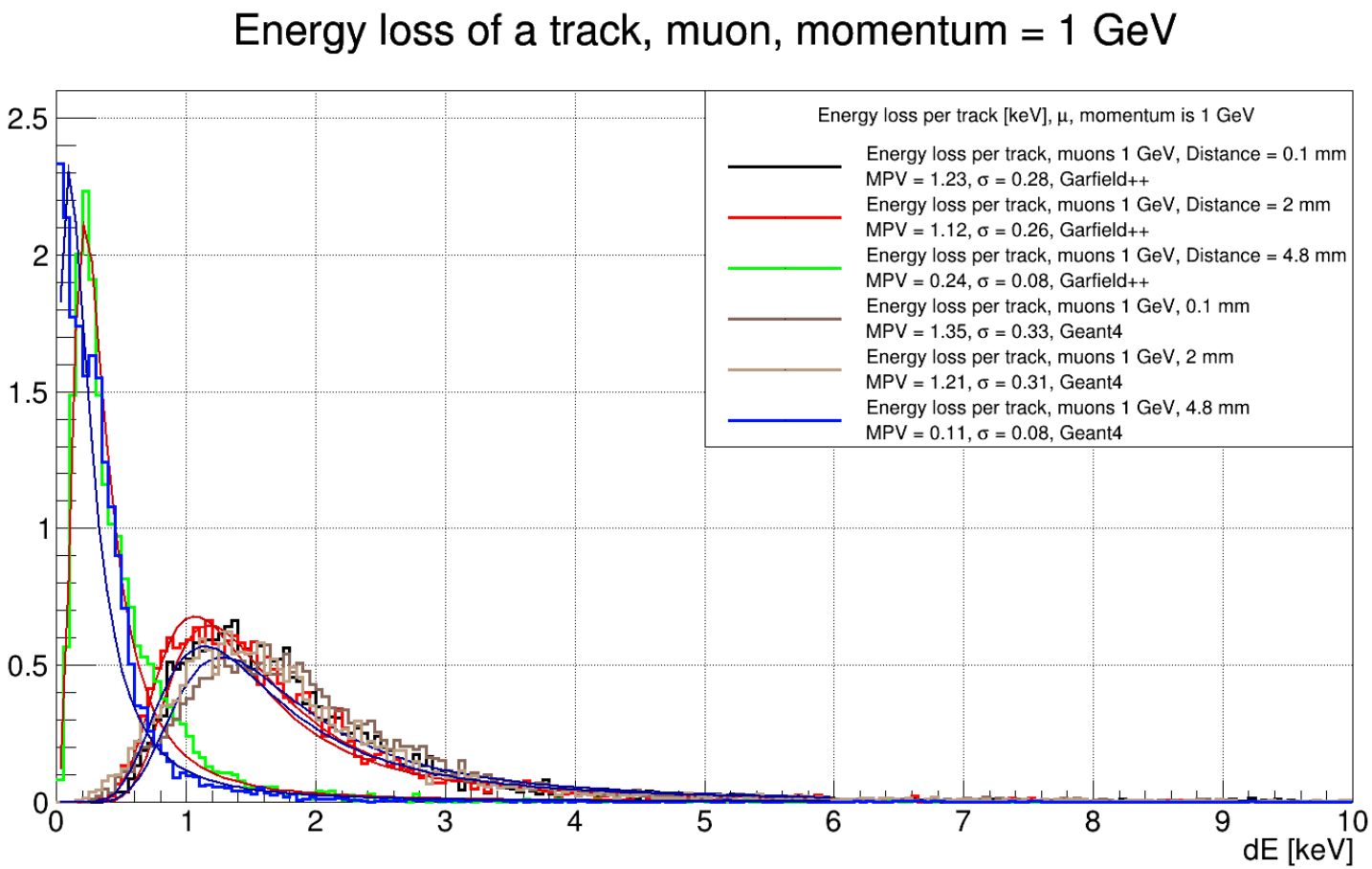
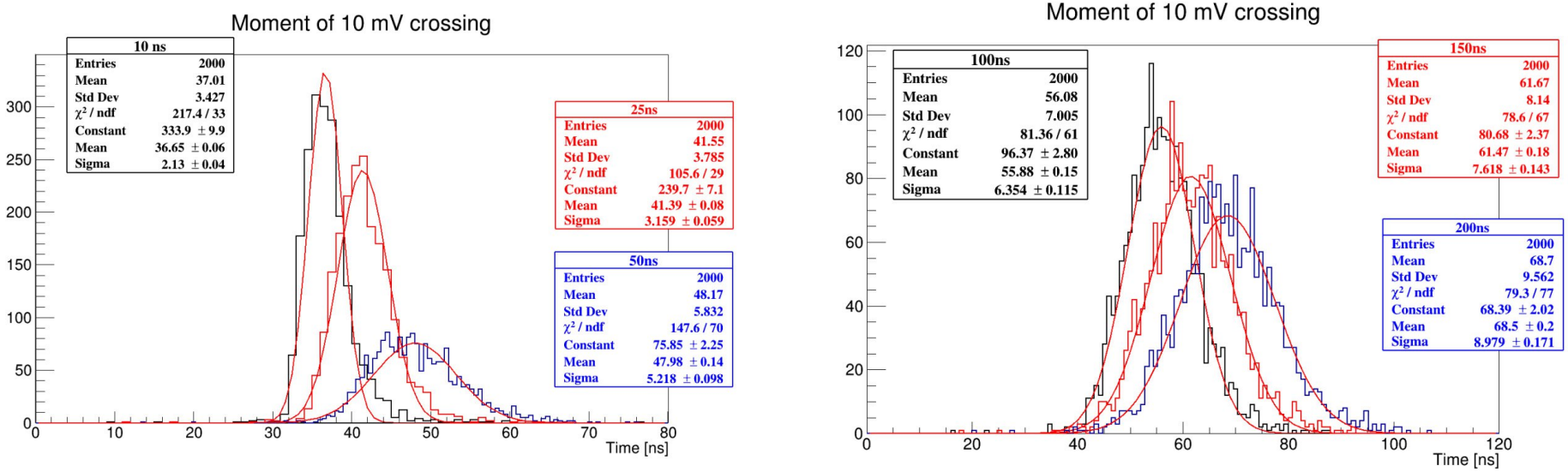


Figure 2: Geant4 vs Garfieldpp. Muon, momentum 1 GeV

Threshold crossing time for 10 mV



a) b)

Figure 3: Threshold crossing time for 2 mm distance. (a) Peaking time 10, 25 and 50 ns (b) Peaking time 100, 150, 200 ns
Electronics parameters: signal amplification 3 mV/fC, noise implemented here is 1500e, threshold 10 mV. VMM-based model

σ due to peaking time

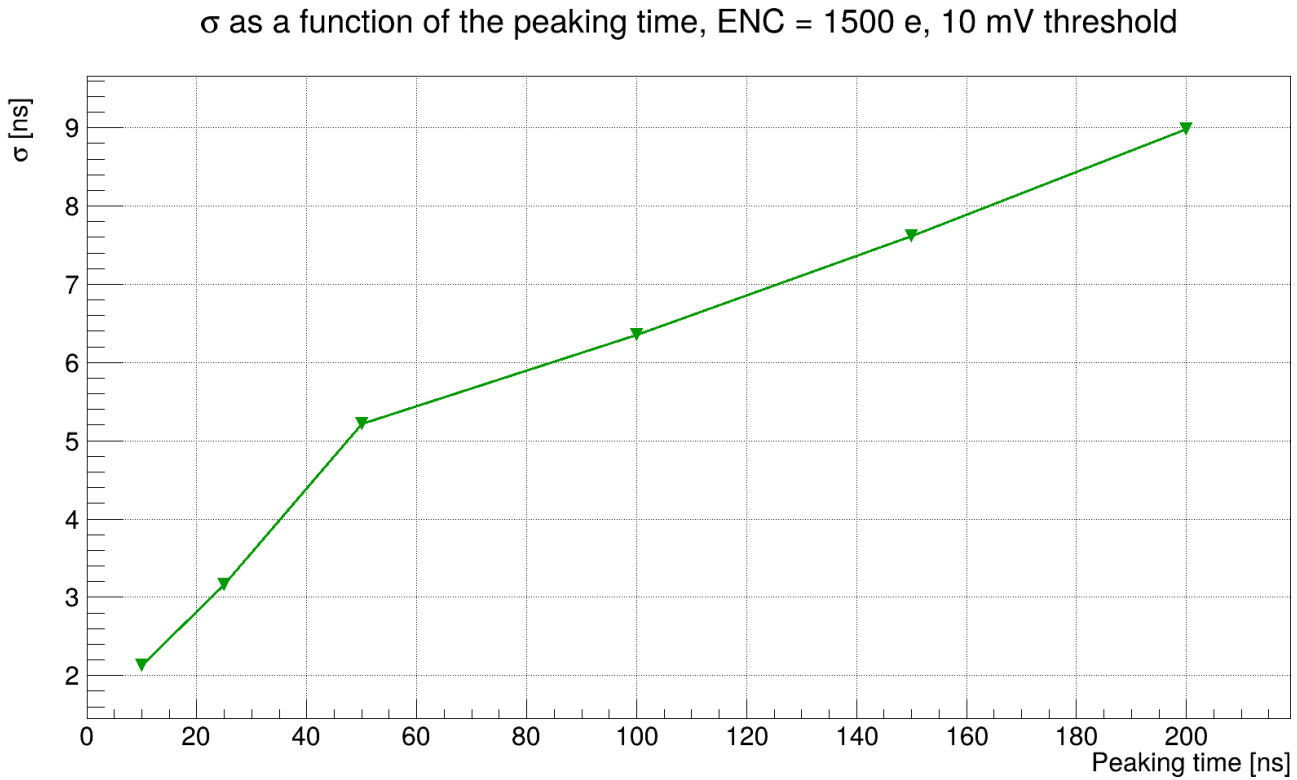
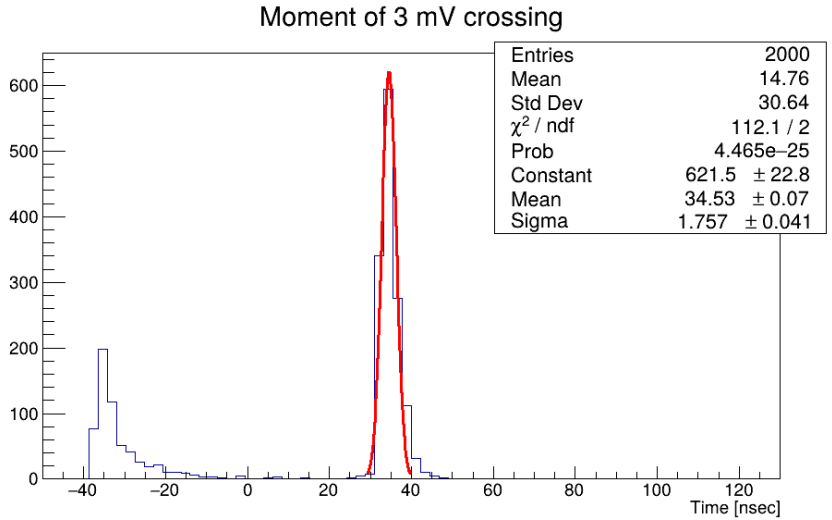
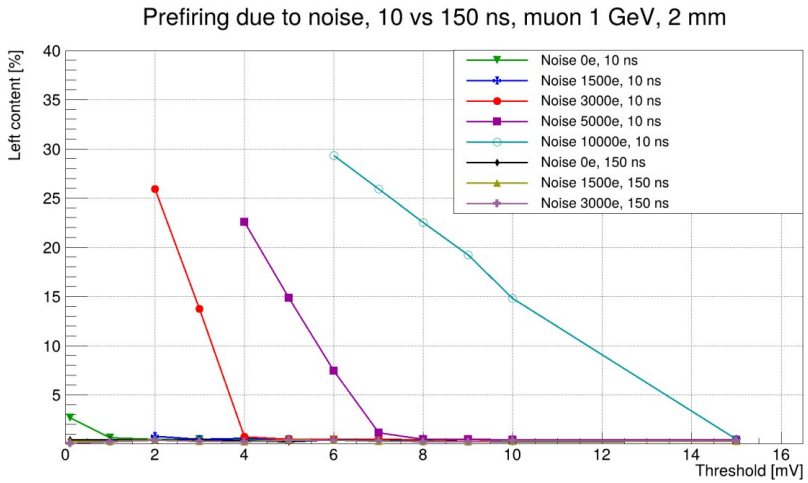


Figure 4: σ as a function of peaking time.

Prefiring due to noise



a)



b)

Figure 5: (a) 3 mV threshold crossing time for 2 mm distance. Peaking time 10 ns, 5000e noise. (b) Prefiling due to noise from 0e to 10000e, Peaking time 10 ns and 150 ns

σ due to threshold crossing time

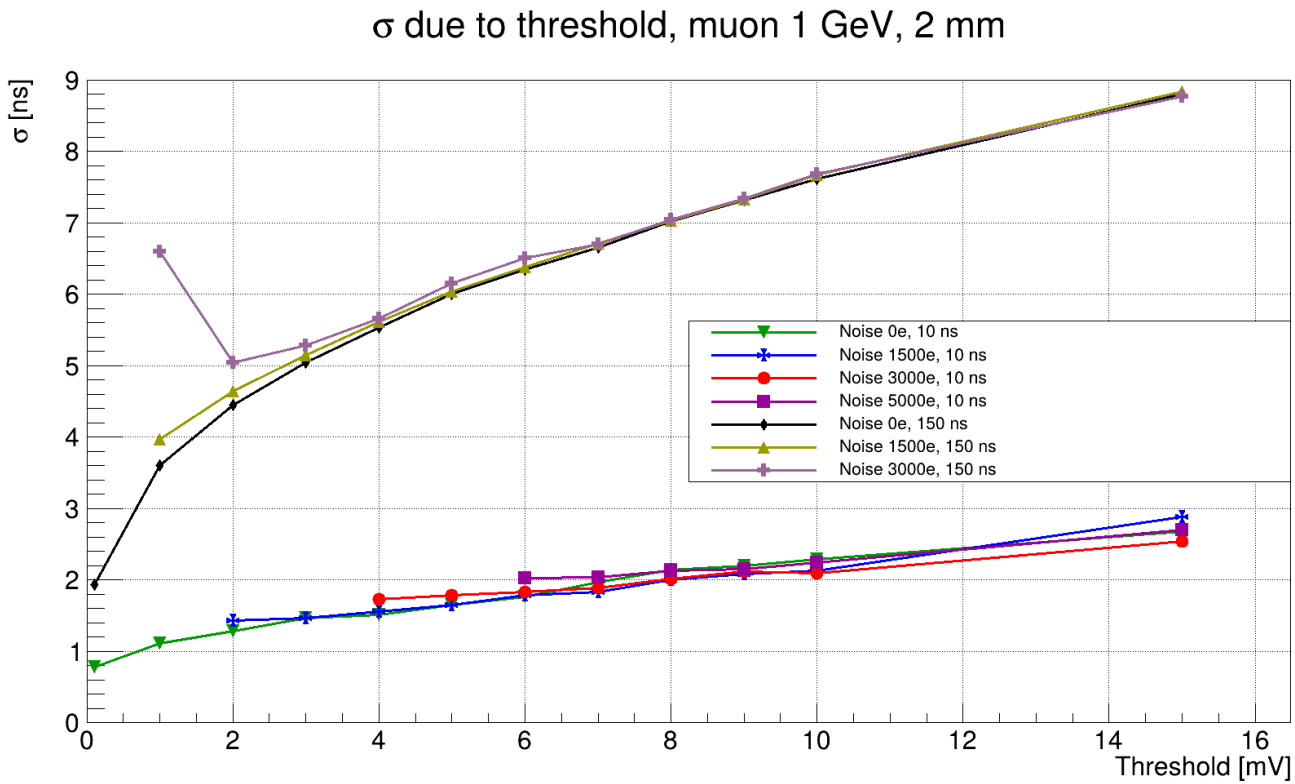


Figure 6: σ of threshold crossing time due to threshold [mV] for 10 ns and 150 ns peaking time. Left content noise percentage greater than 15% is cut off

σ due to threshold crossing time

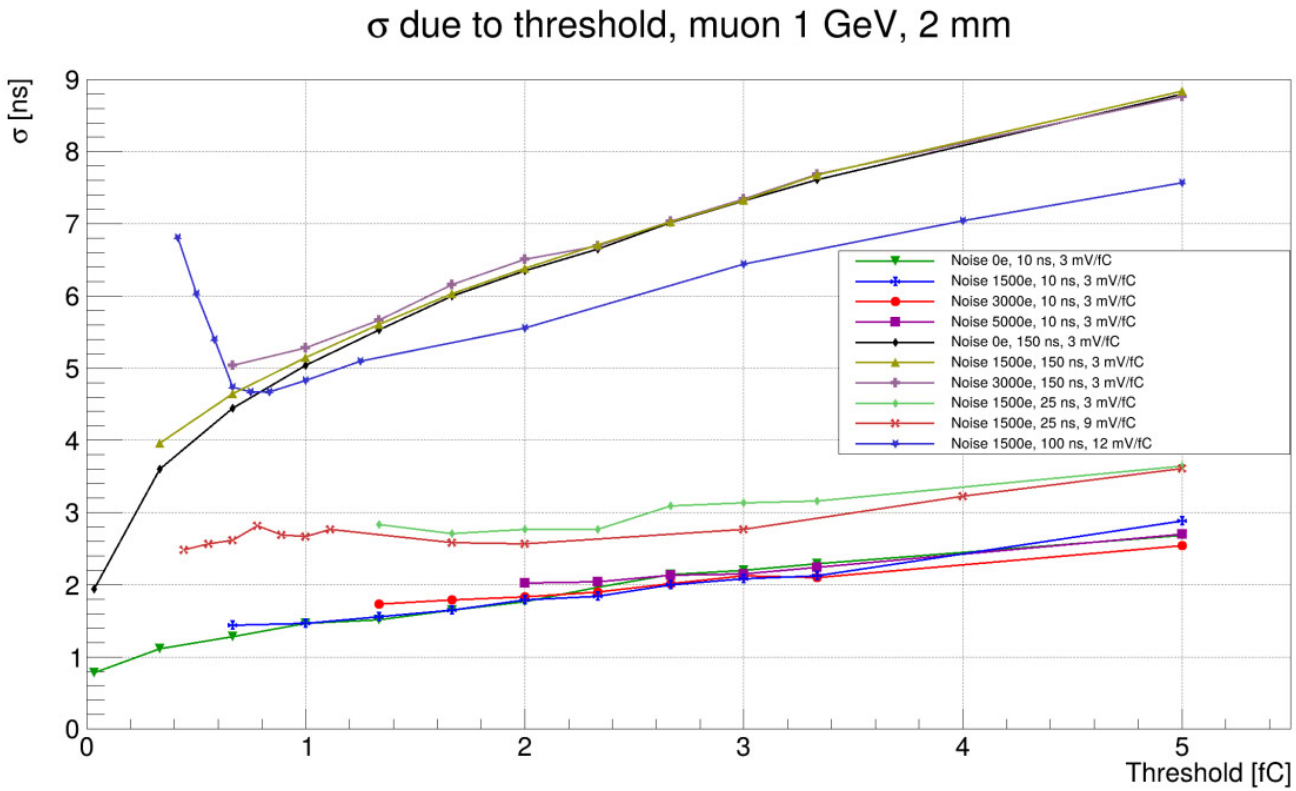


Figure 7: σ of threshold crossing time due to threshold [fC] for 10 ns, 25 ns and 150 ns peaking time. Added 9 mV/fC and 12 mV/fC amplifications

σ due to threshold crossing time

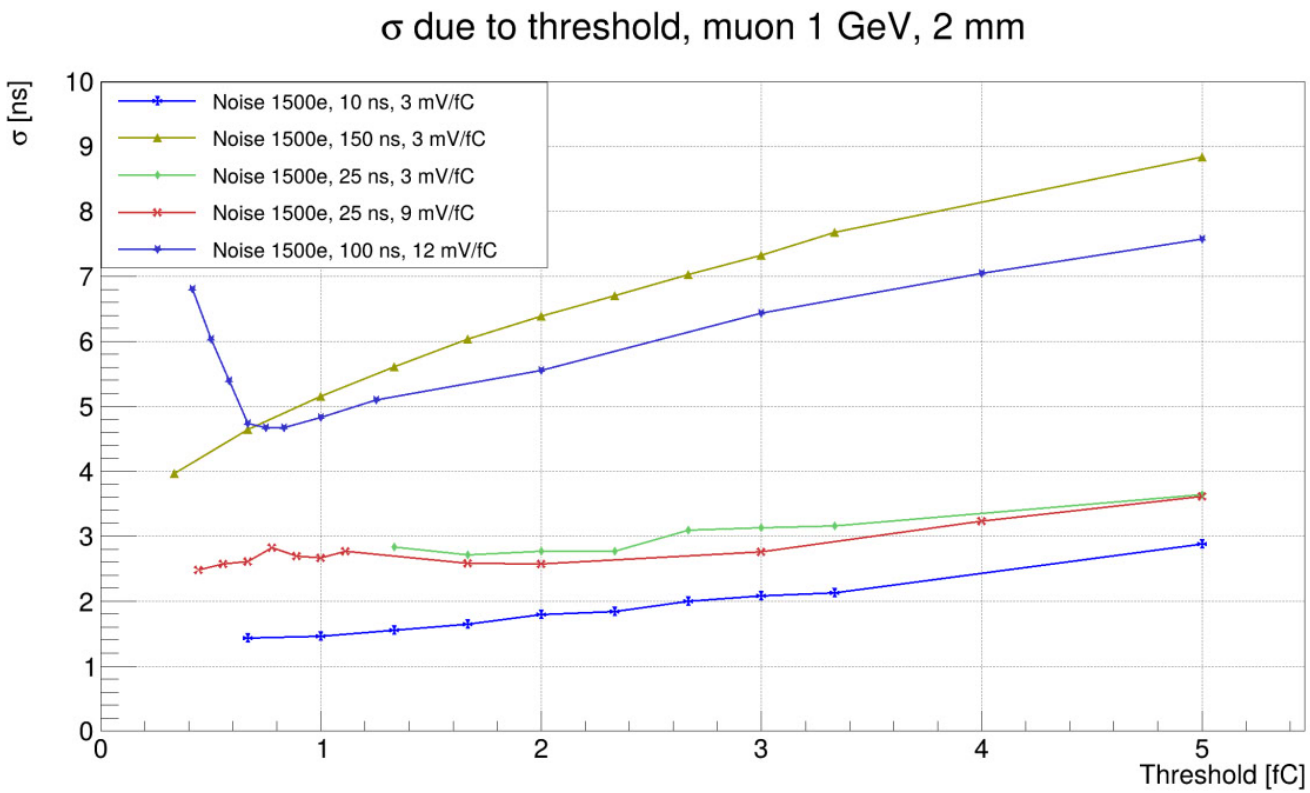
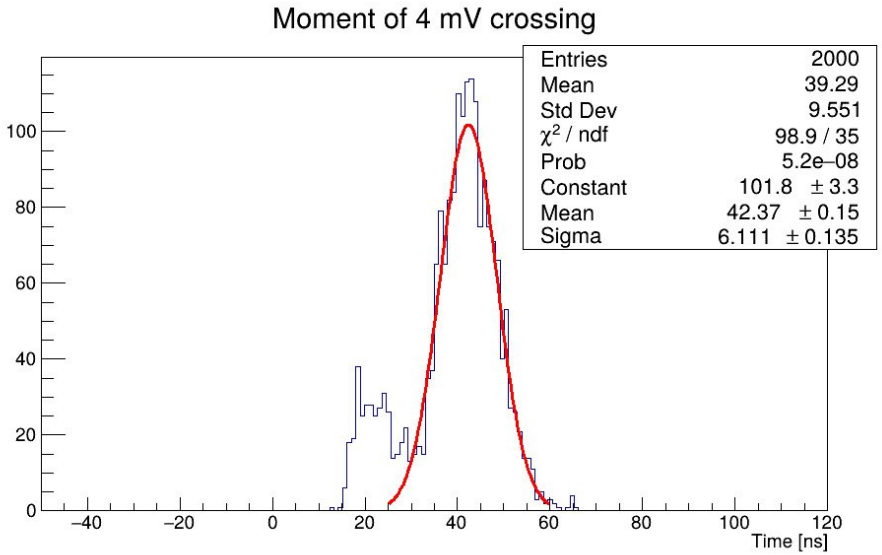
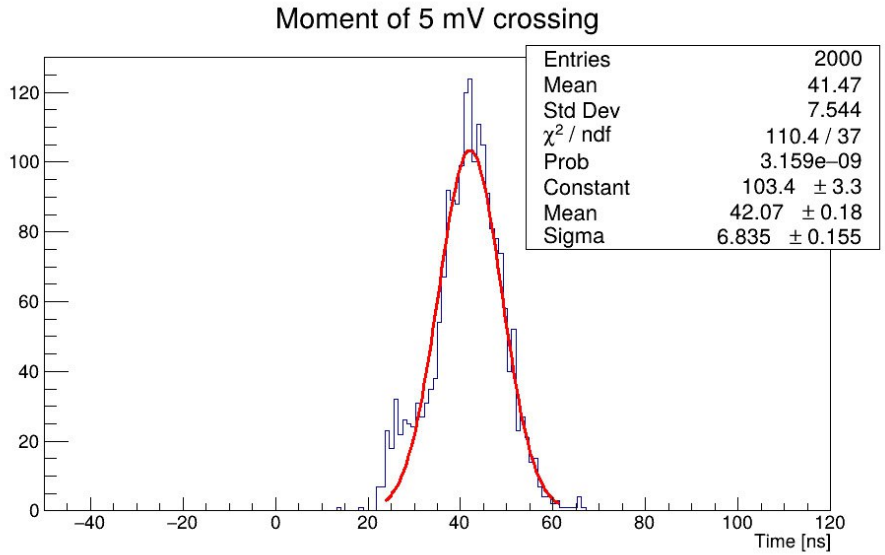


Figure 8: σ of threshold crossing time due to threshold [fC] for 10 ns, 25 ns and 150 ns peaking time. Added 9 mV/fC and 12 mV/fC amplifications. Only 1500e noise

Muon signals



a)



b)

Figure 9: Signal of muon, 1 GeV, 2 mm, 100 ns peaking time, 12 mV/fC amplification (a) 4 mV (or 0.33 fC) threshold (b) 5 mV (or 0.42 fC threshold)

Muon signals

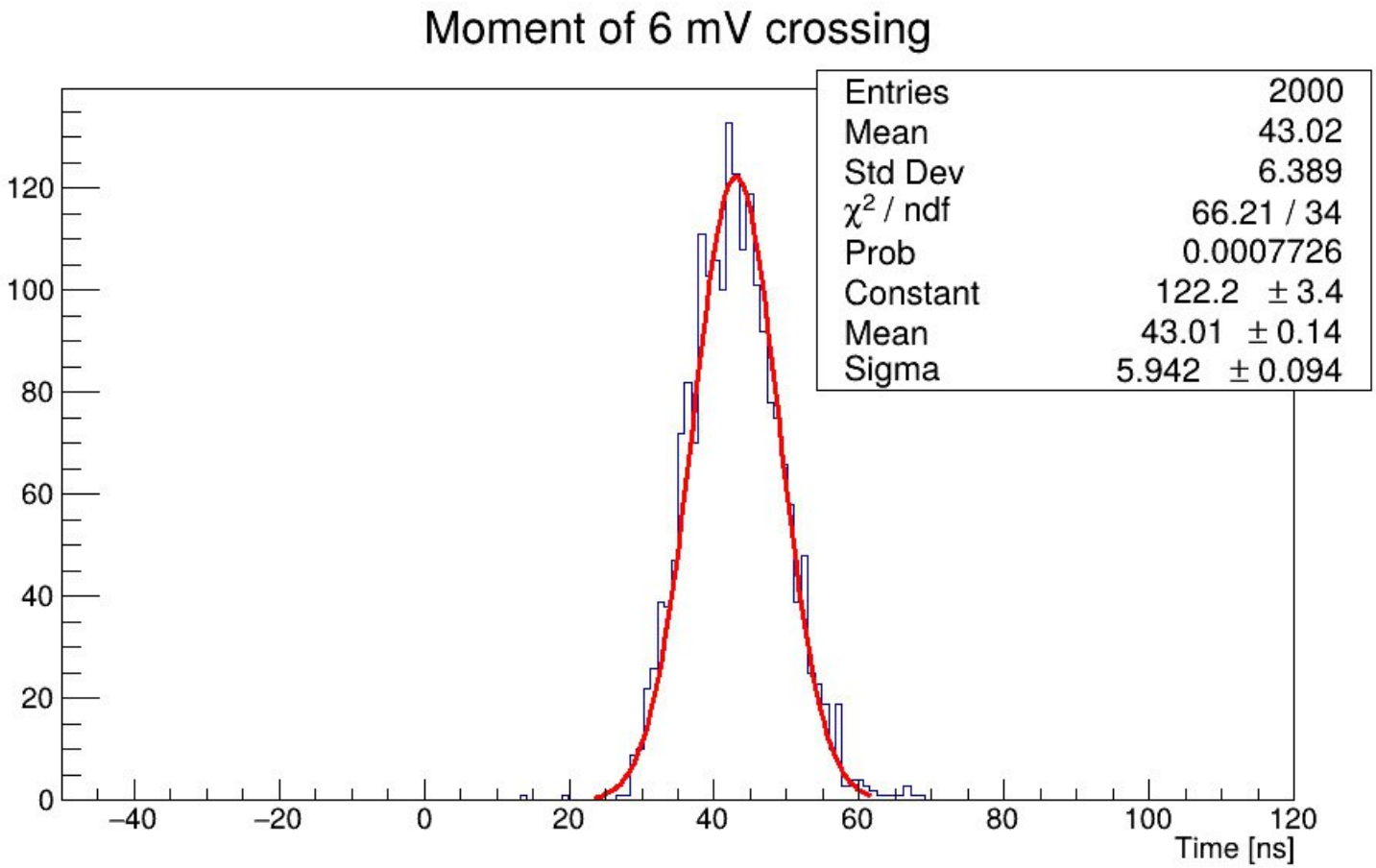


Figure 10: Signal of muon, 1 GeV, 2 mm, 100 ns peaking time, 12 mV/fC amplification, 6 mV (or 0.5 fC threshold)

σ due to threshold crossing time

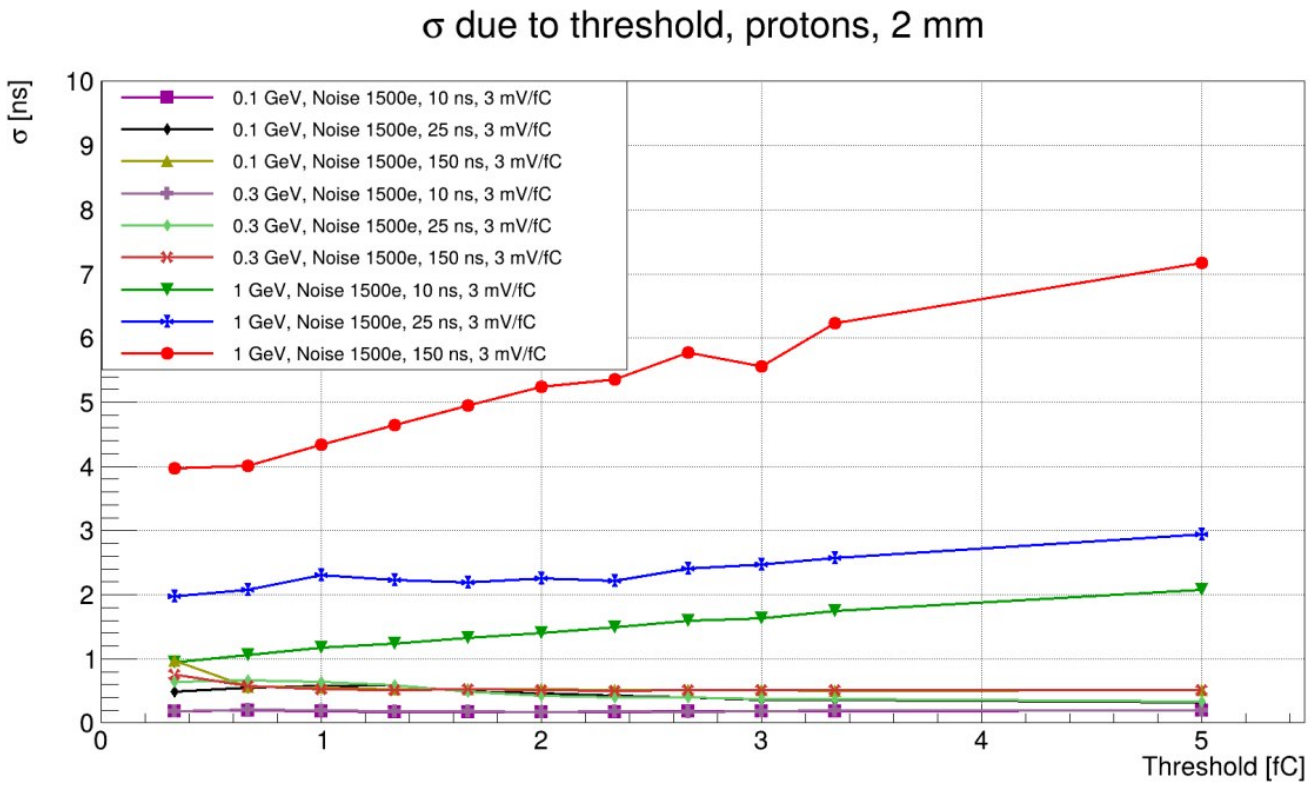
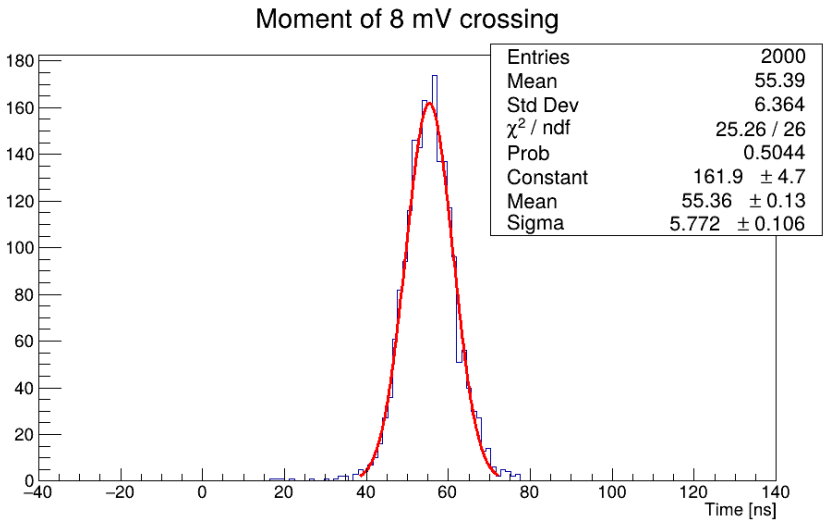
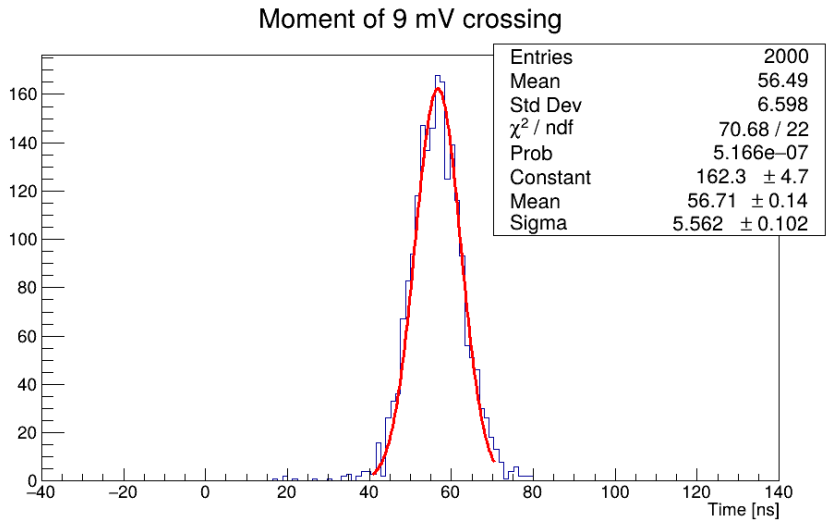


Figure 11: σ of threshold crossing time due to threshold [fC] for 10 ns, 25 ns and 150 ns peaking time. Only protons, 1500e noise

Proton signals



a)



b)

Figure 12: Signal of proton, 1 GeV, 2 mm, 150 ns peaking time, 3 mV/fC amplification (a) 8 mV (or 2.66 fC) threshold (b) 9 mV (or 3 fC threshold)

Proton signals

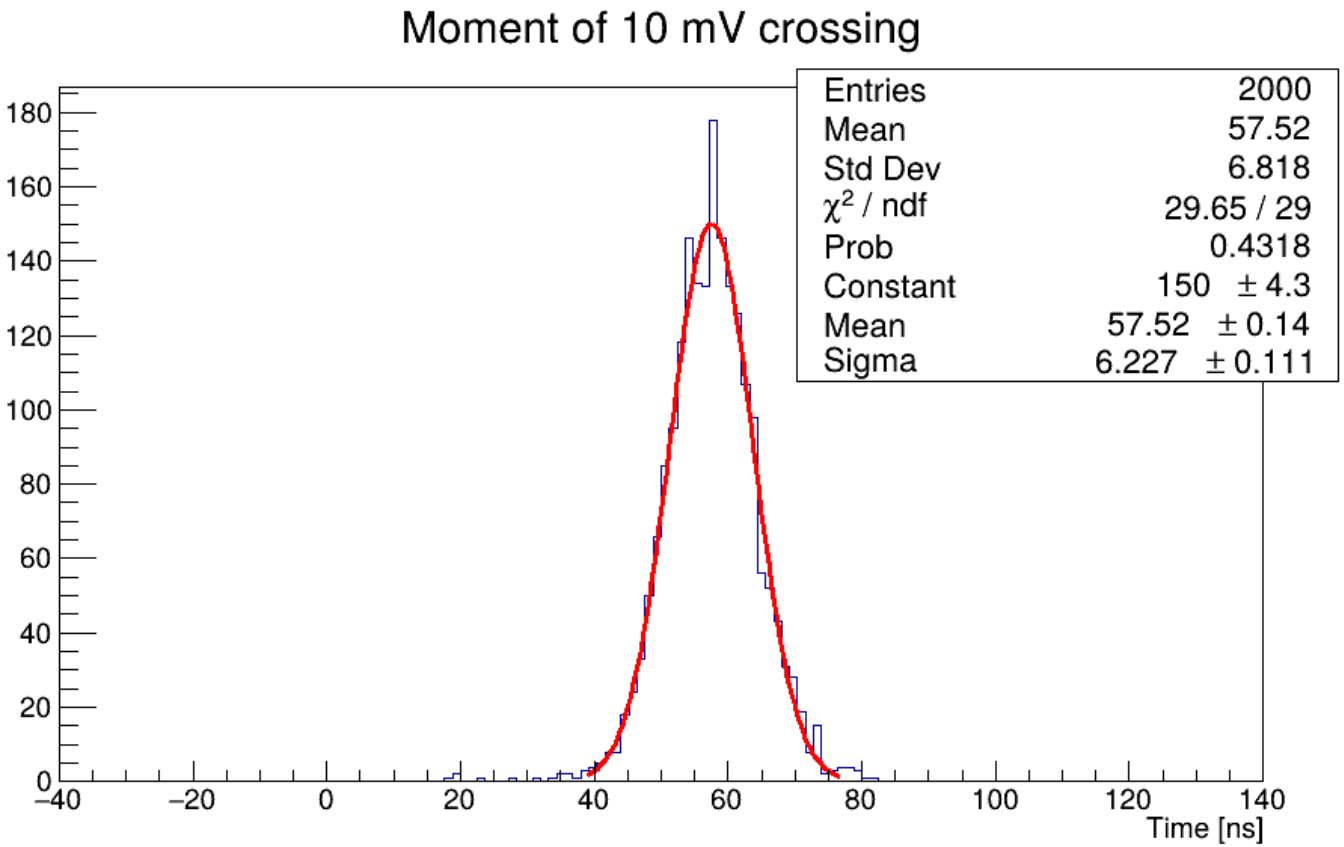
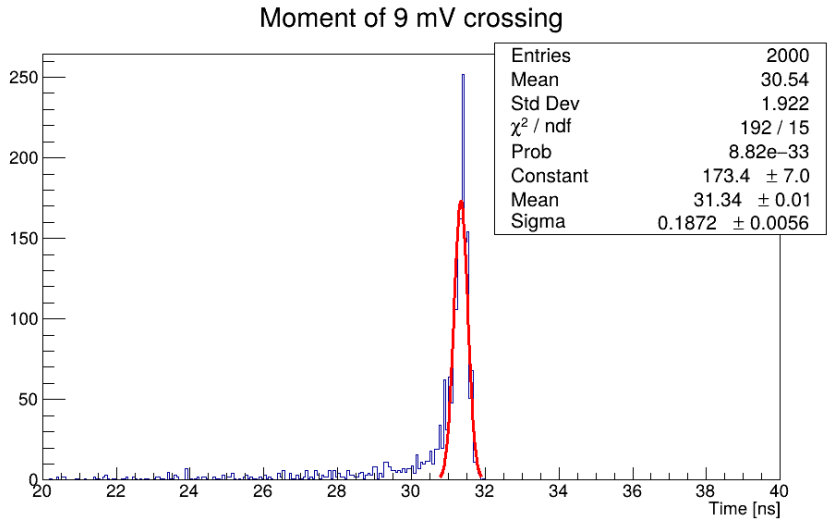
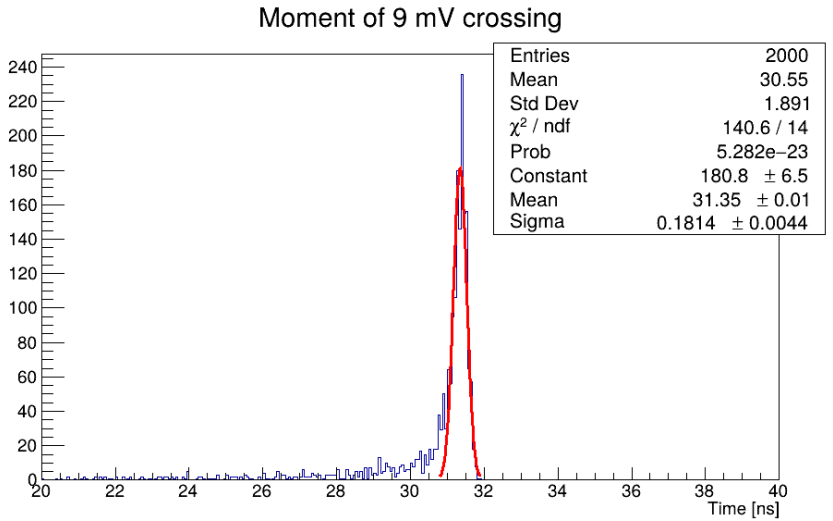


Figure 13: Signal of proton, 1 GeV, 2 mm, 150 ns peaking time, 3 mV/fC amplification, 10 mV (or 3.33 fC threshold)

Proton signals



a)



b)

Figure 14: Signal of proton, 0.1 GeV and 0.3 GeV, 2 mm, 10 ns peaking time, 3 mV/fC amplification (a) 9 mV (or 3 fC) threshold (b) 9 mV (or 3 fC threshold)

σ due to threshold crossing time

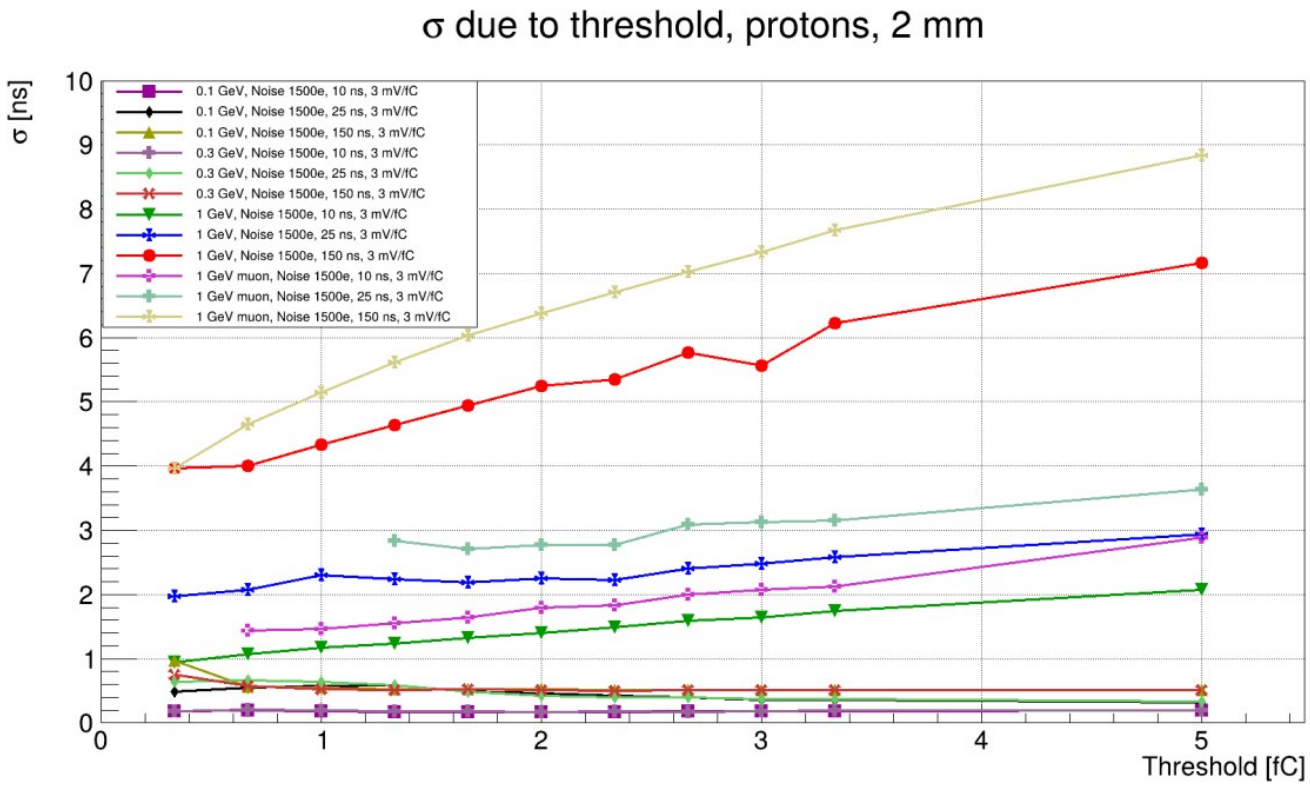


Figure 15: σ of threshold crossing time due to threshold [fC] for 10 ns, 25 ns and 150 ns peaking time. Muon and proton, 1500e noise

σ due to threshold crossing time

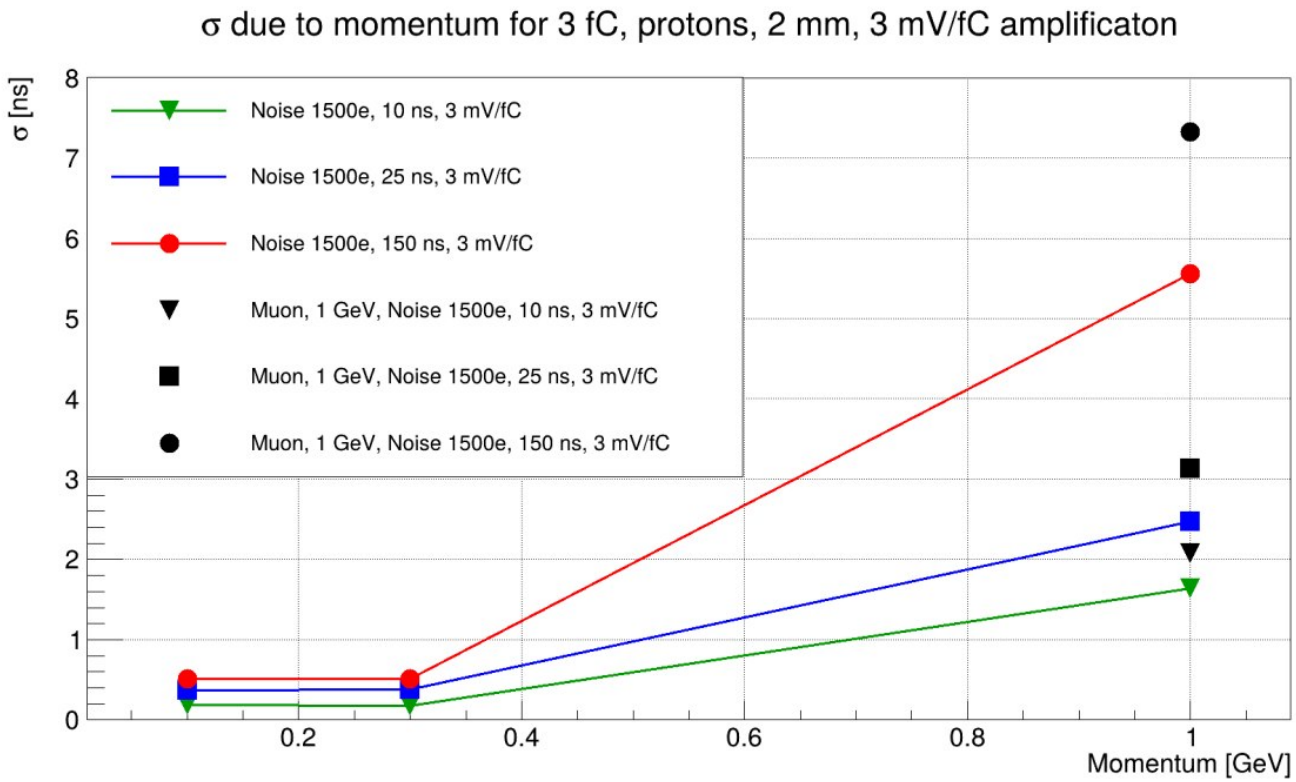


Figure 16: σ of threshold crossing time due to particle momentum [GeV] for 10 ns, 25 ns and 150 ns peaking time. Muon and proton, 1500e noise

MPV due to threshold crossing time

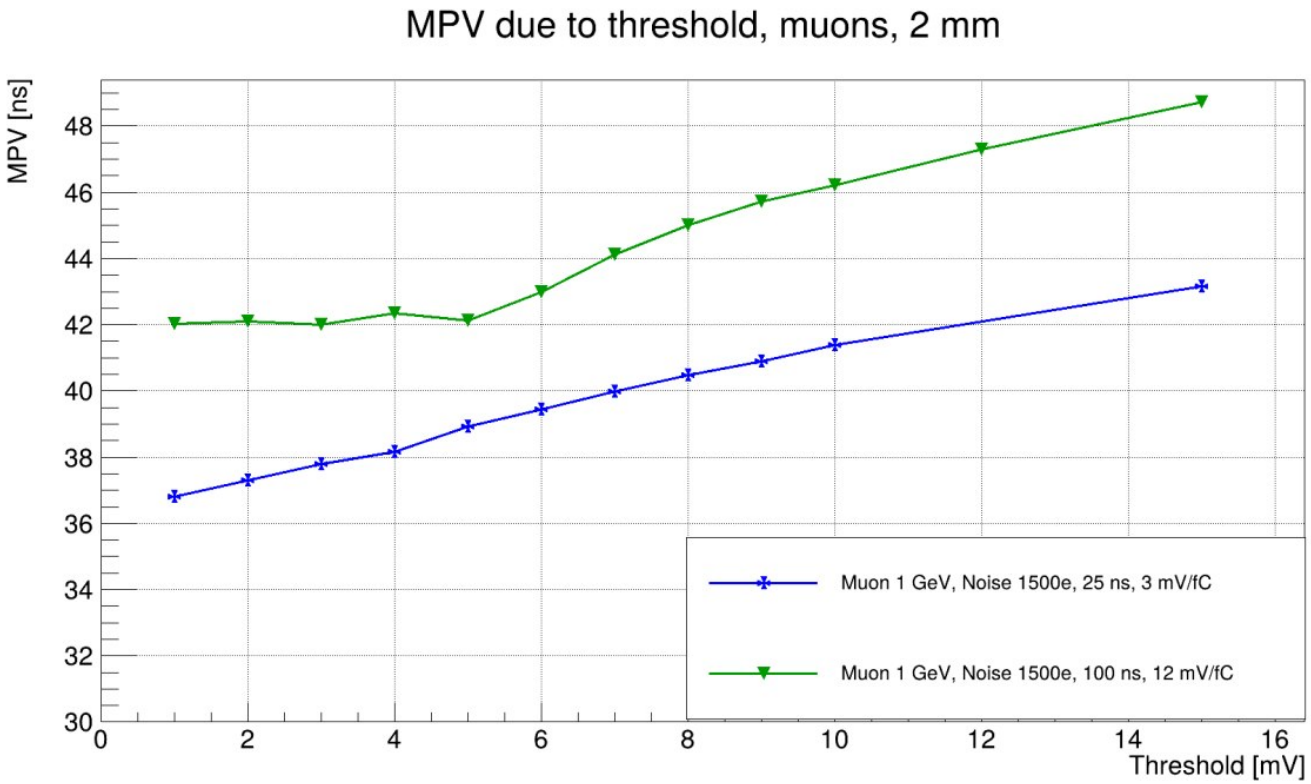


Figure 17: MPV of threshold crossing time due to threshold [mV]. Muon 1 GeV, 2 mm distance, 1500e noise. 25 ns peaking time, 3 mV/fC amplification vs 100 nc peaking time, 12 mV/fC amplification.

Integral under fit function due to threshold crossing time

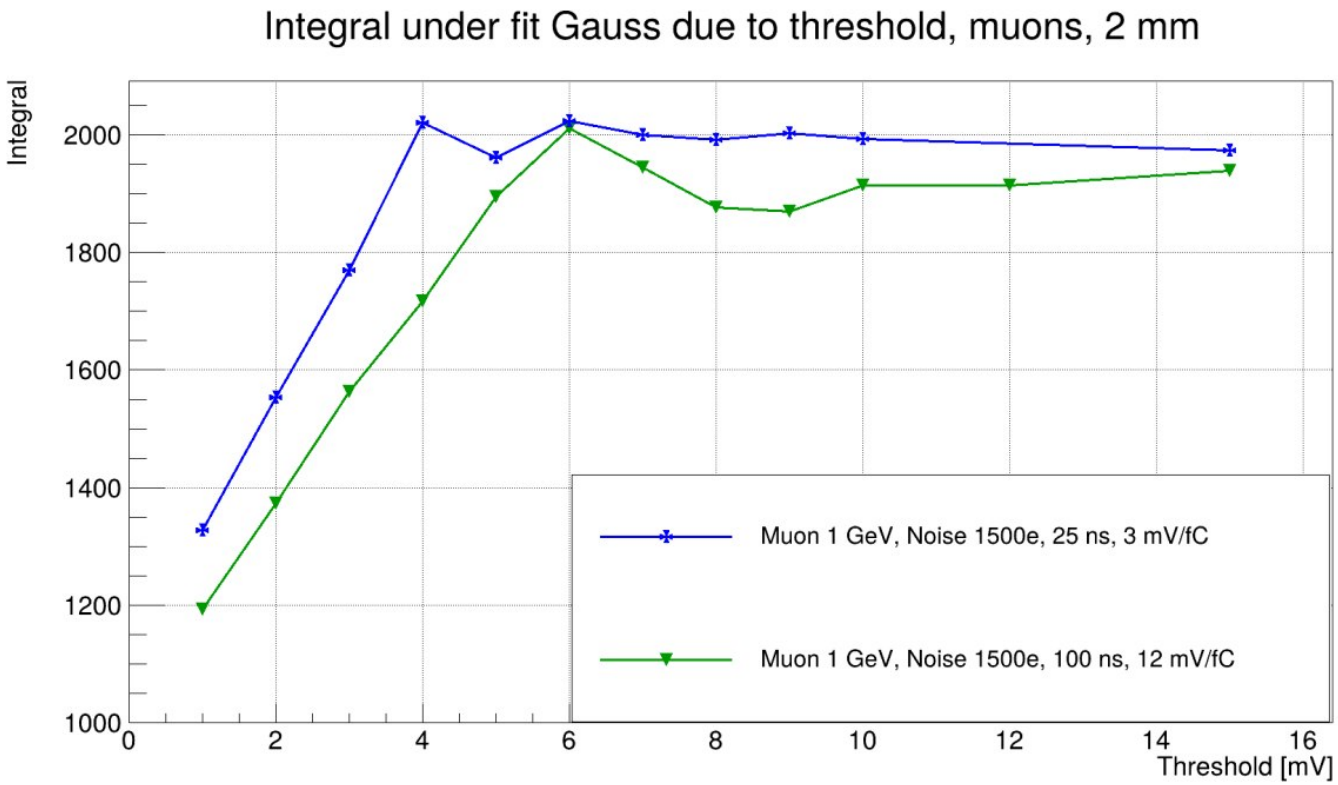
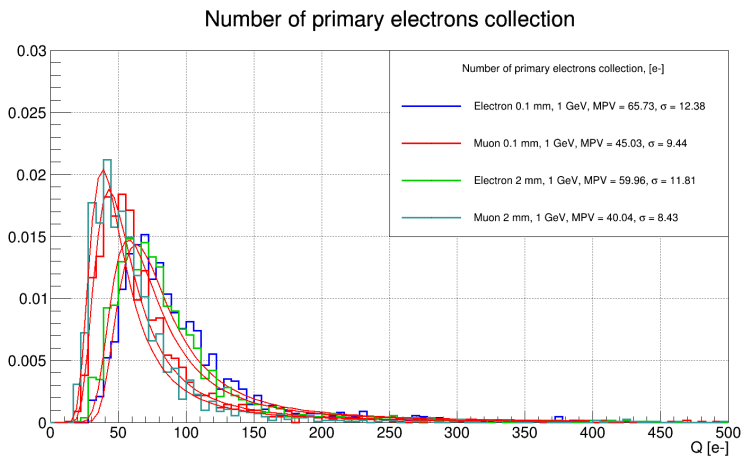
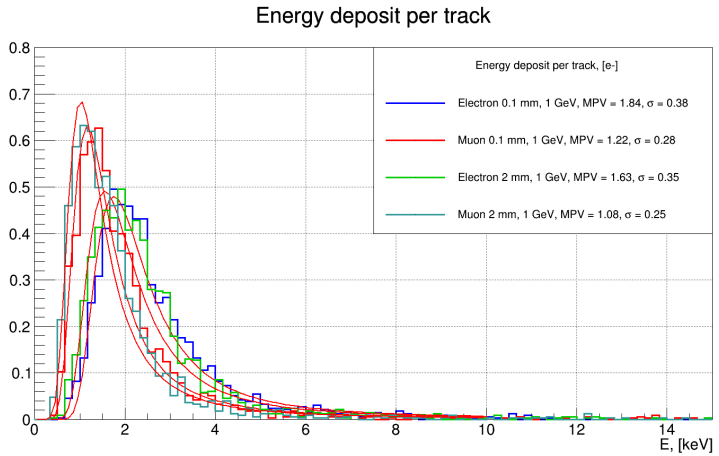


Figure 18: Integral under fit function of threshold crossing time due to threshold for 25 ns and 100 ns peaking time. Muon 1 GeV, 1500e noise

Energy, spent on ion pair creation



a) Charge distribution per track, e-



b) Energy deposit distribution per track, keV

Figure 19: Compare of deposited energy and energy, wasted on ion pair creation. $1840/65.7 = 28$ eV, $1220/45 = 27.$ eV, $1630/59.9 = 27.2$ eV, $1080/40 = 27.0$ eV.

Energy, spent on ion pair creation

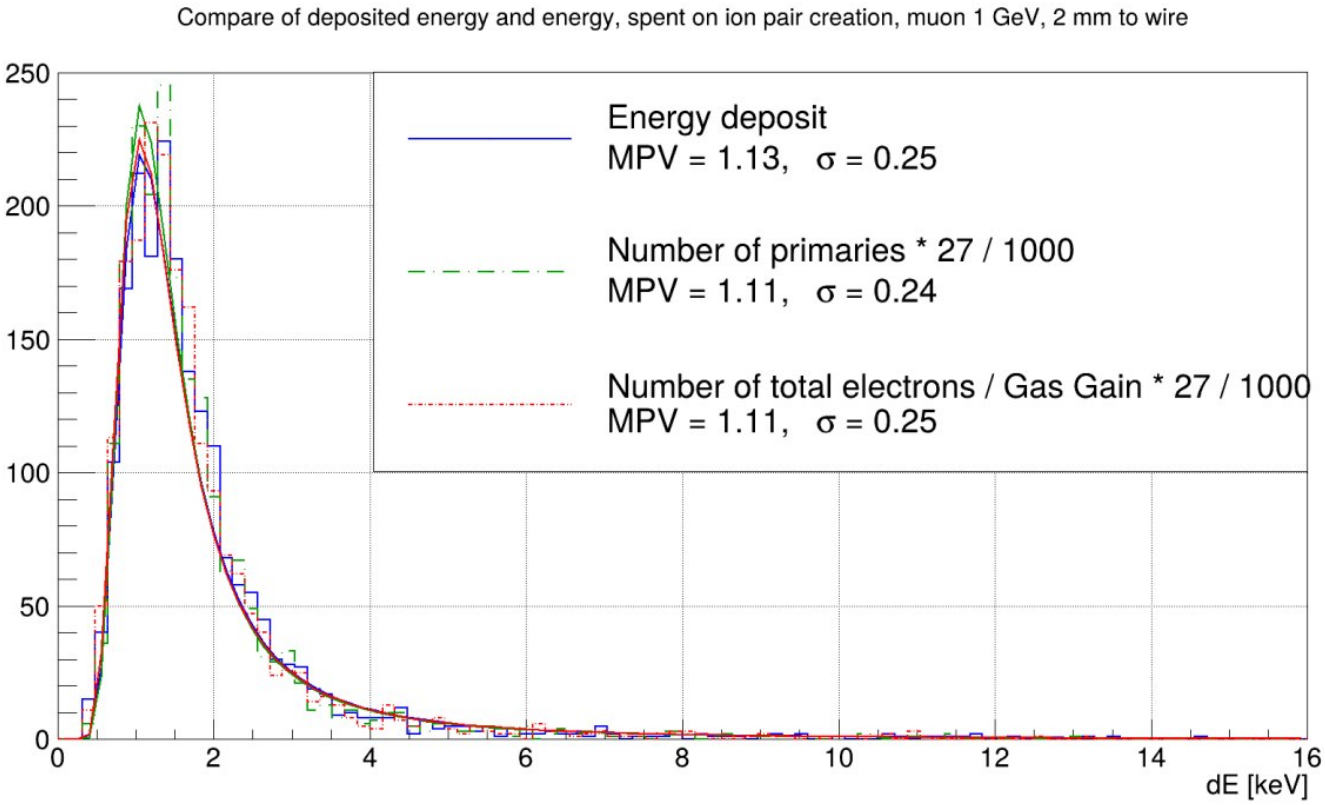
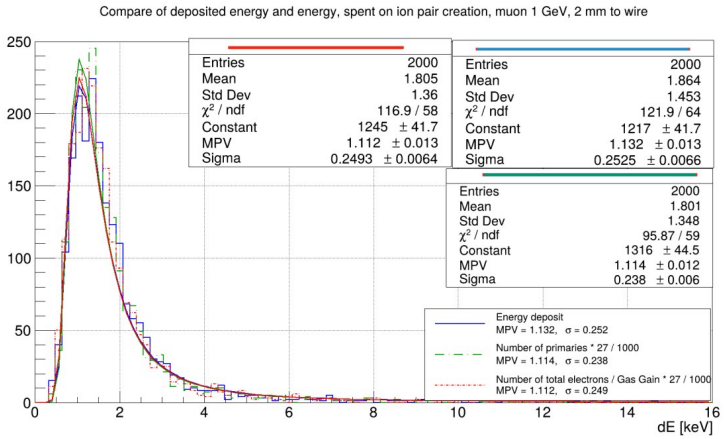
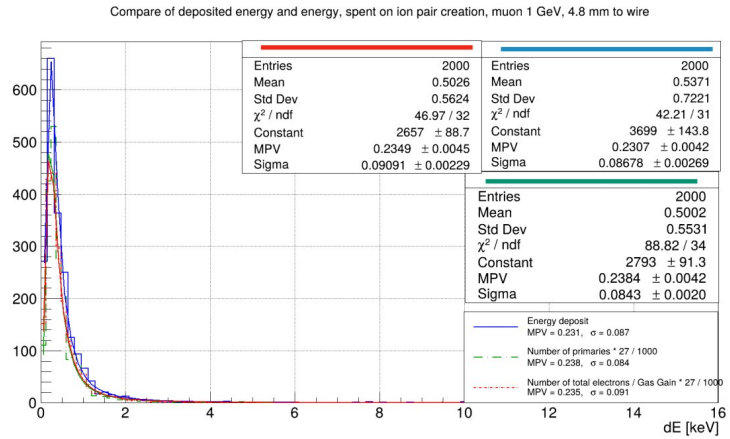


Figure 20: Muon 2 mm 1 GeV. Compare dE (keV) vs total charge divided by gas gain (45000) multiplied by 27 eV vs number of primaries multiplied by 27 eV

Energy spent on ion pair creation



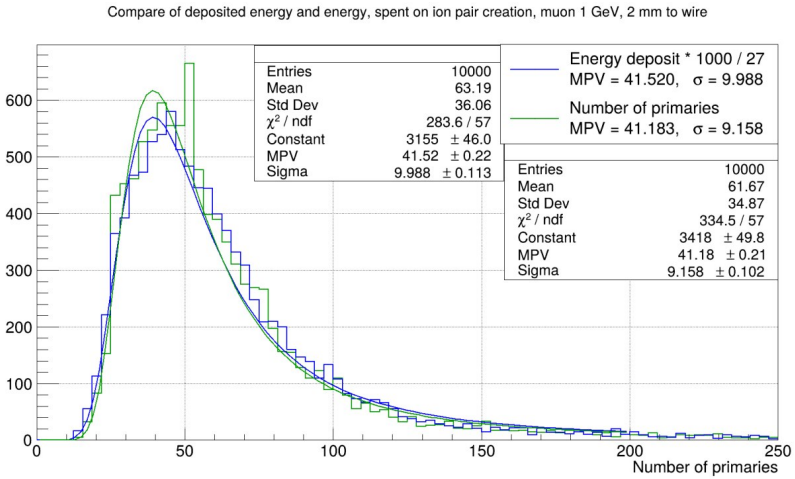
a) 2 mm



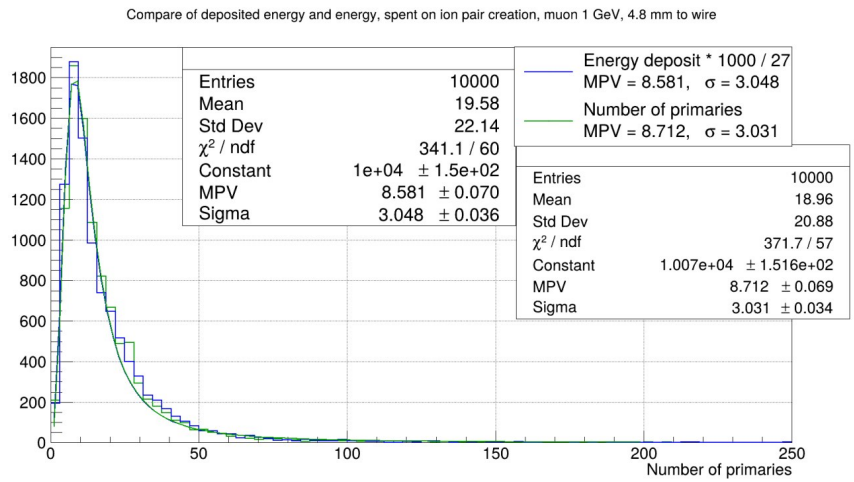
b) 4.8 mm

Figure 21: Compare of deposited energy and energy spent on ion pair creation vs total charge divided by gas gain.

Energy spent on ion pair creation



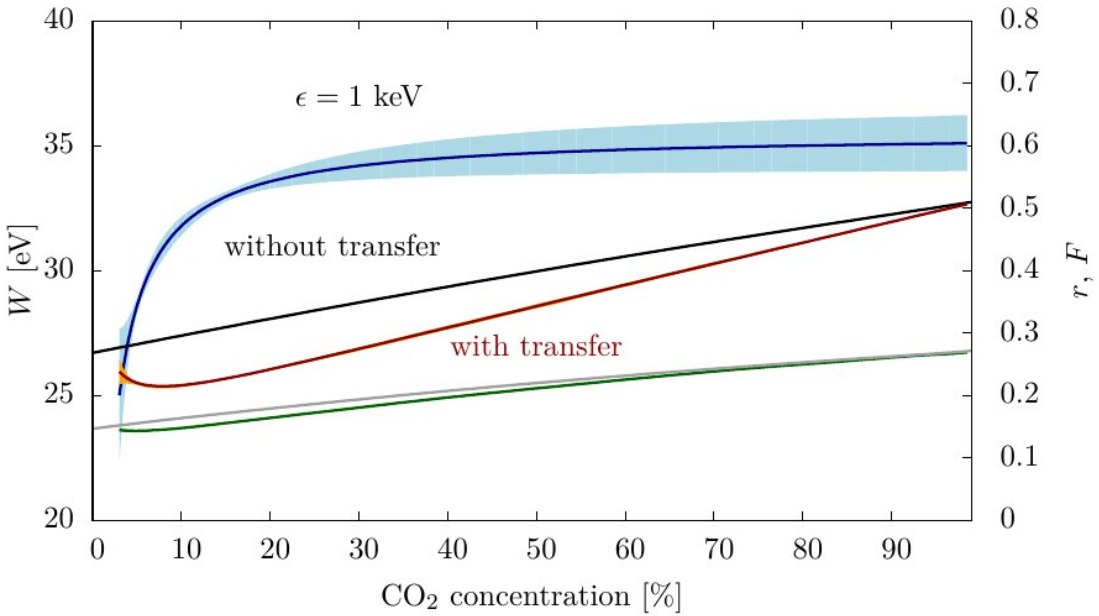
a) 2 mm



b) 4.8 mm

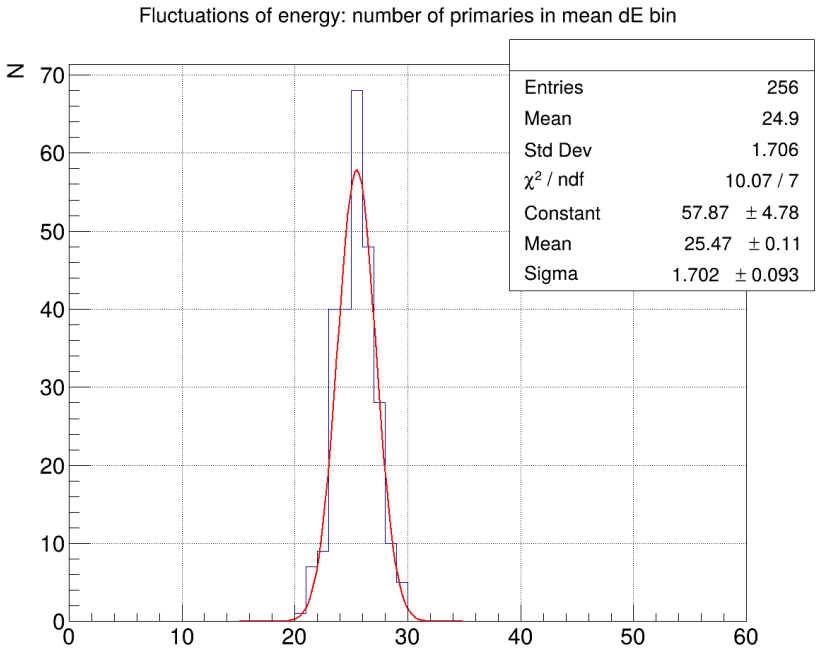
Figure 22: Firstly, turn on all settings default – no penning, default attachment, default gas gain

Energy spent on ion pair creation

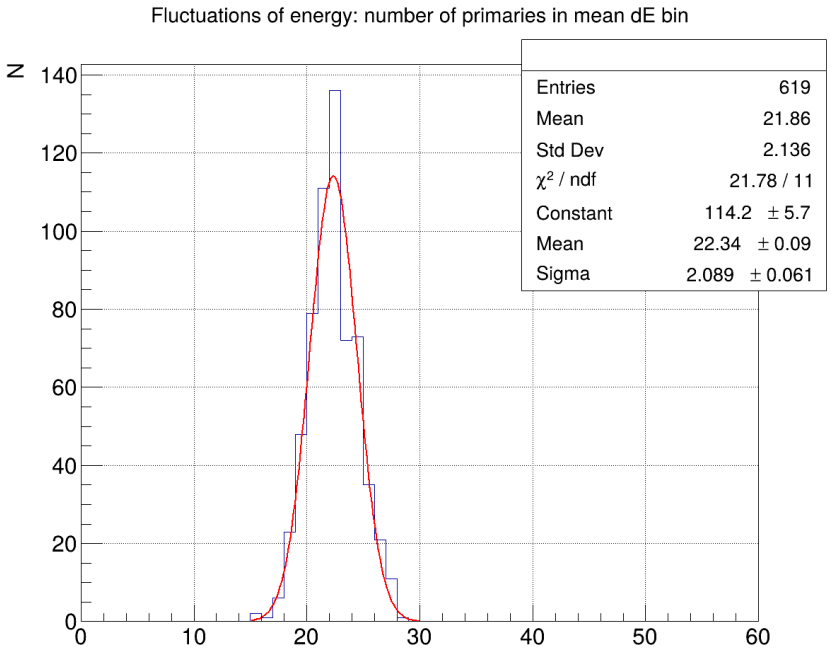


igure 4.4. Calculated W value (left scale) and Fano factor (right scale) in Ar/CO_2 as functions of the CO_2 concentration. Black line: W value without Penning transfer, red line and orange band: W value with Penning transfer, band width indicating the uncertainty due to errors in the transfer efficiency. Grey line: Fano factor without Penning transfer, green line and error band: Fano factor with Penning transfer and its uncertainty due to errors in the transfer efficiency. Blue line and error band: transfer efficiency according to Ref. [50] and associated uncertainty (right-hand scale).

Energy spent on ion pair creation



a) 2 mm



b) 4.8 mm

Figure 23: Secondly, take a small bin from the histogram in Fig. 22(b) - 0.63 ± 0.05 keV dE. For 4.8 mm: Sigma $= \sqrt{Mean \cdot F} = \sqrt{22.34 \cdot 0.2} = 2.11$

Total charge vs voltage amplitude

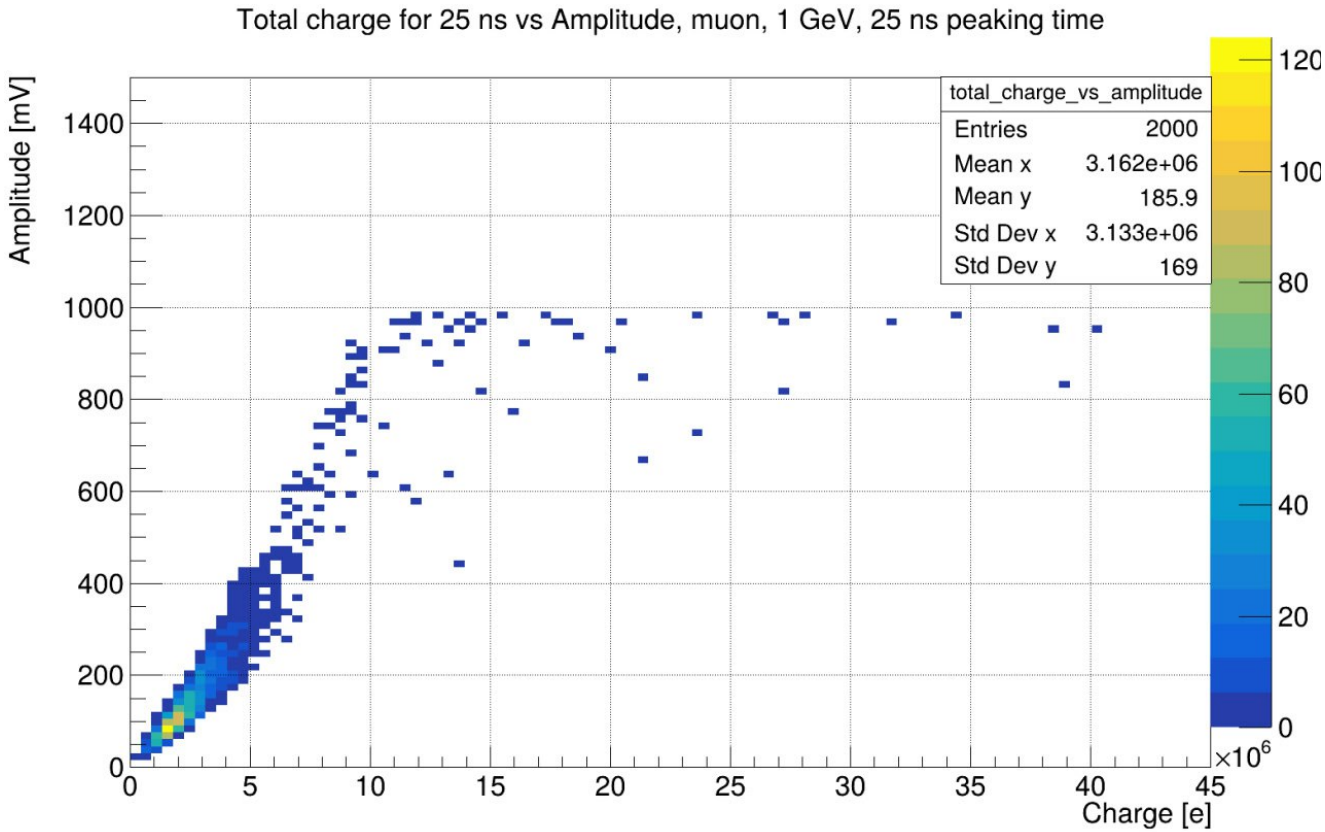


Figure 24: Total charge [e] vs voltage amplitude [mV]. Muon, 1 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

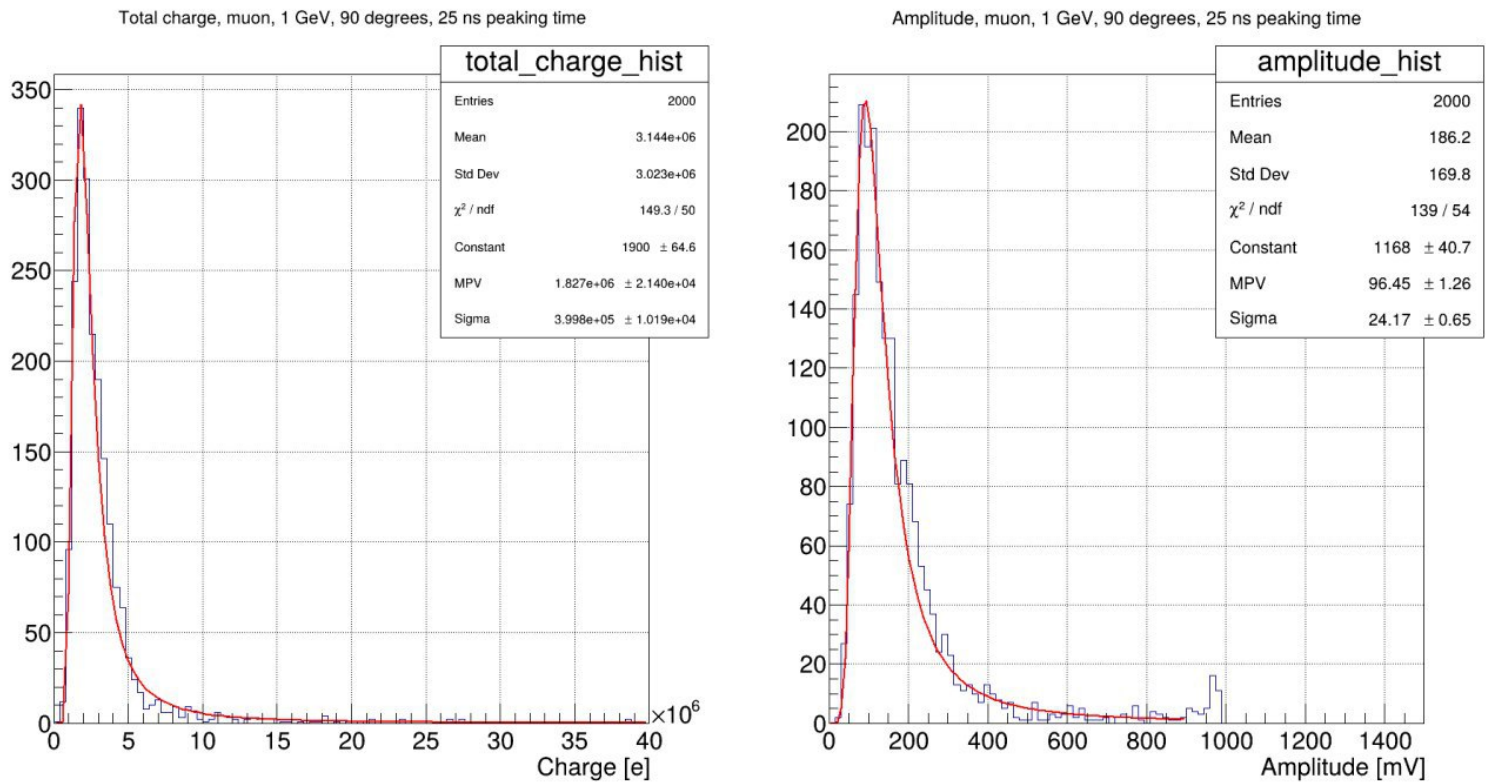


Figure 25: Total charge [e] and voltage amplitude [mV] projections. Muon, 1 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

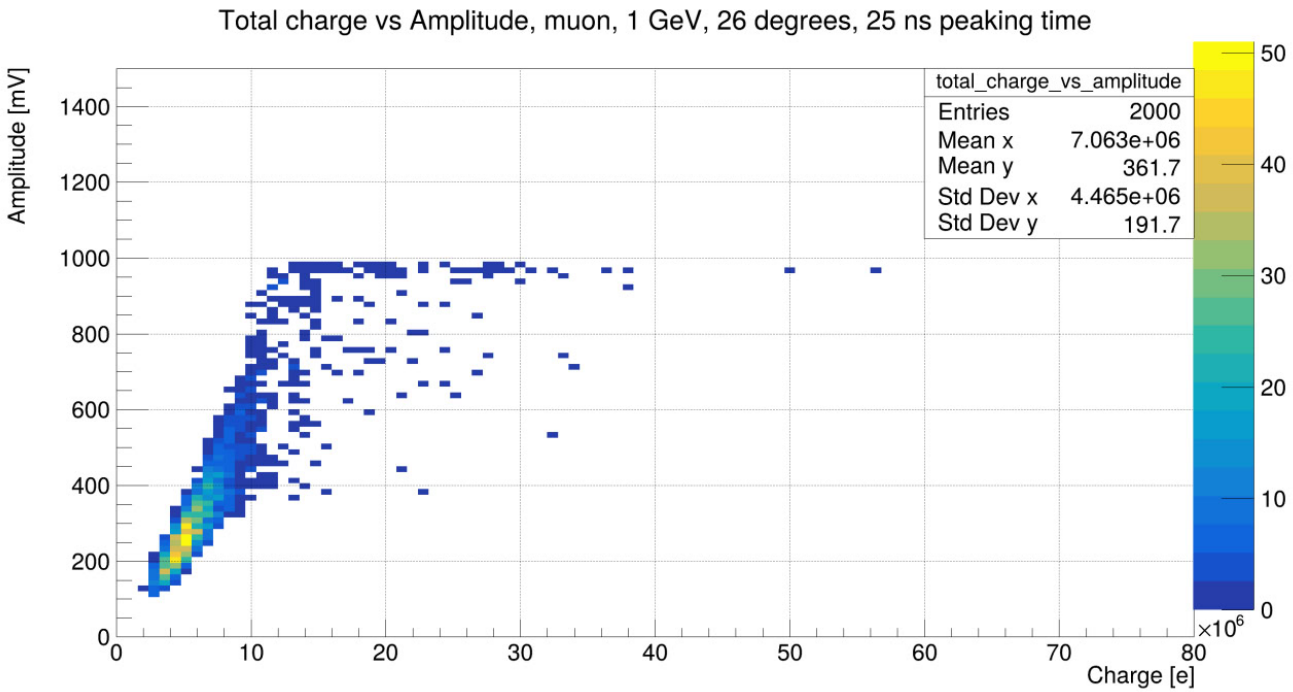


Figure 26: Total charge [e] vs voltage amplitude [mV]. Muon, 1 GeV, 26 degrees, 25 ns peaking time

Total charge vs voltage amplitude

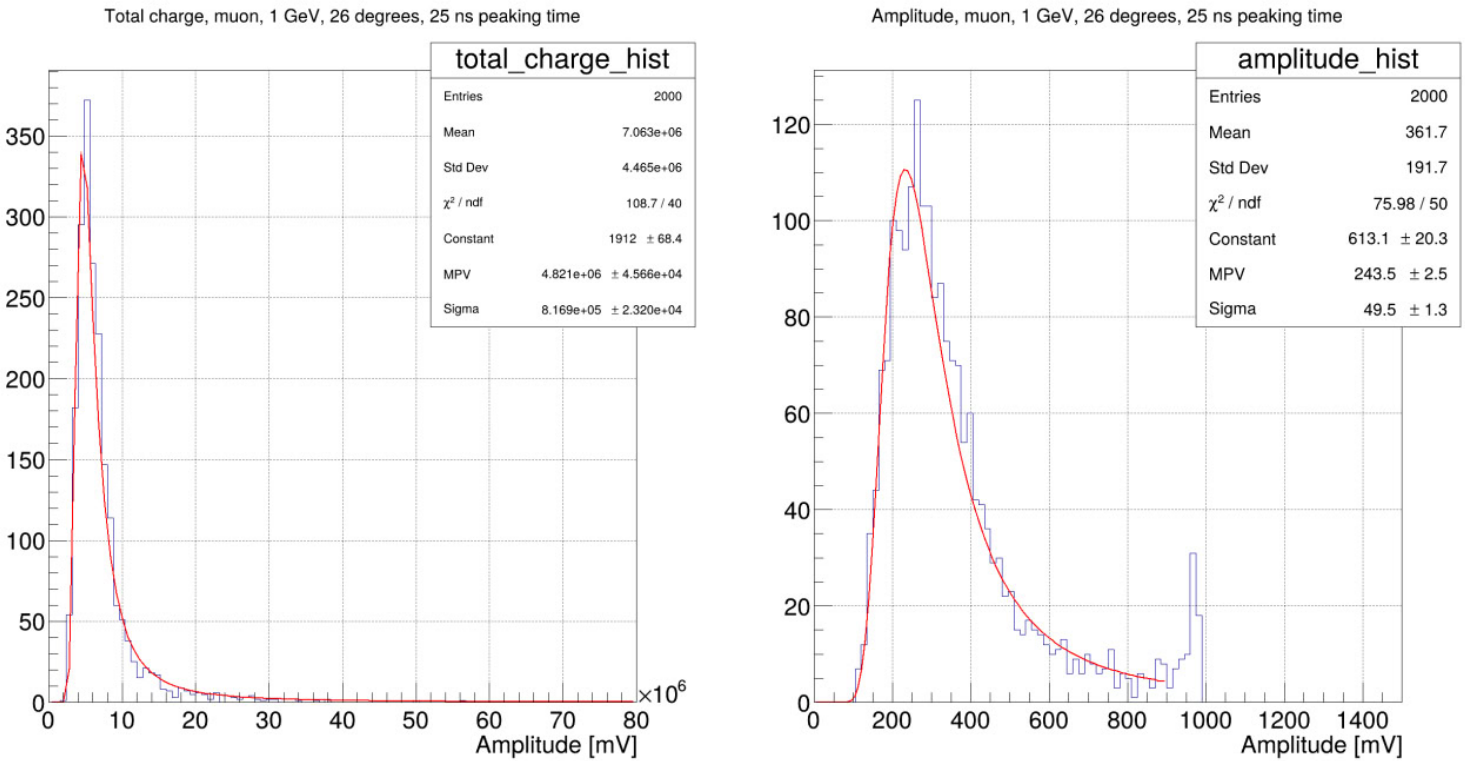


Figure 27: Total charge [e] and voltage amplitude [mV] projections. Muon, 1 GeV, 26 degrees, 25 ns peaking time

Total charge vs voltage amplitude

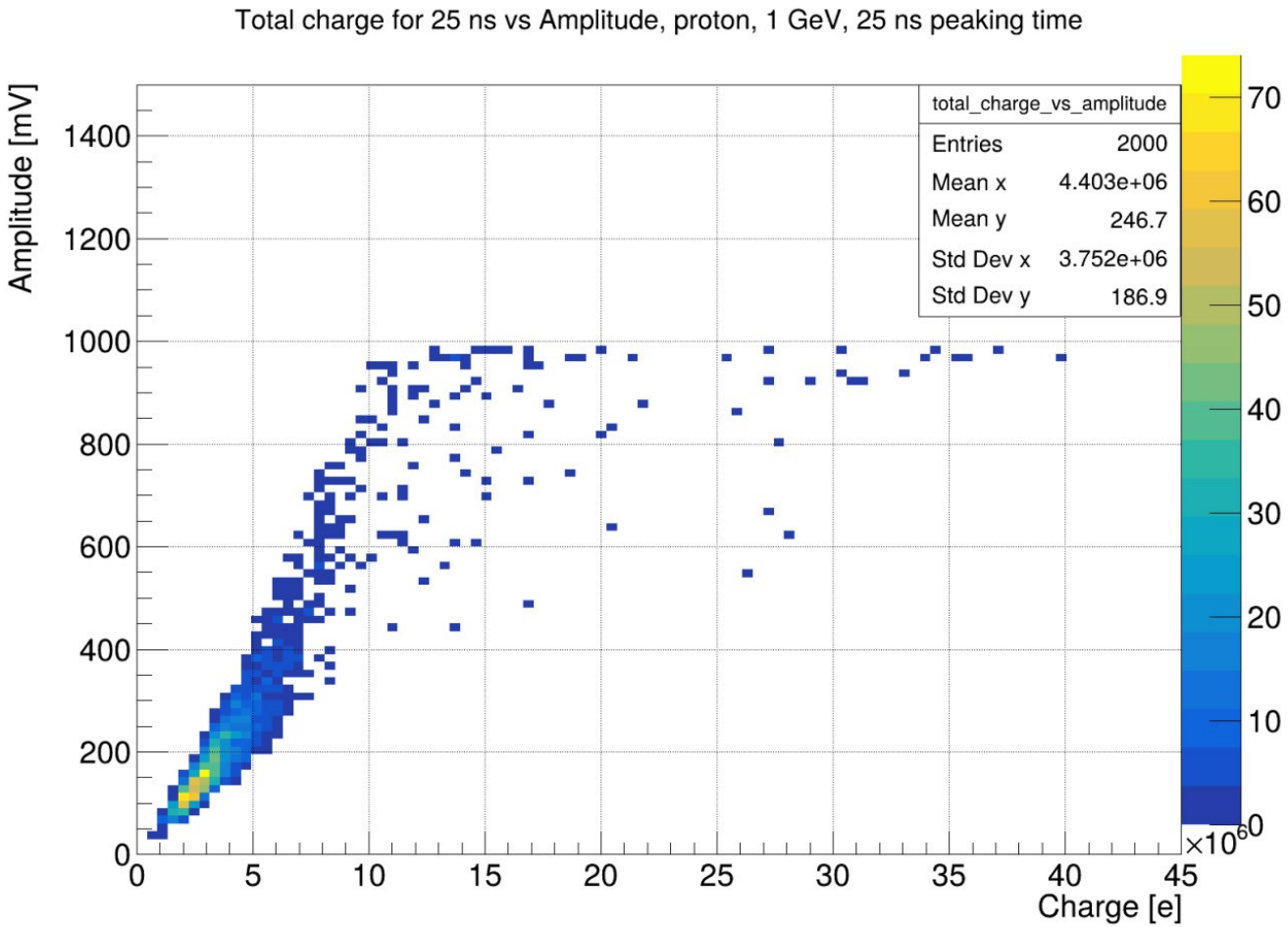


Figure 28: Total charge [e] vs voltage amplitude [mV]. Proton, 1 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

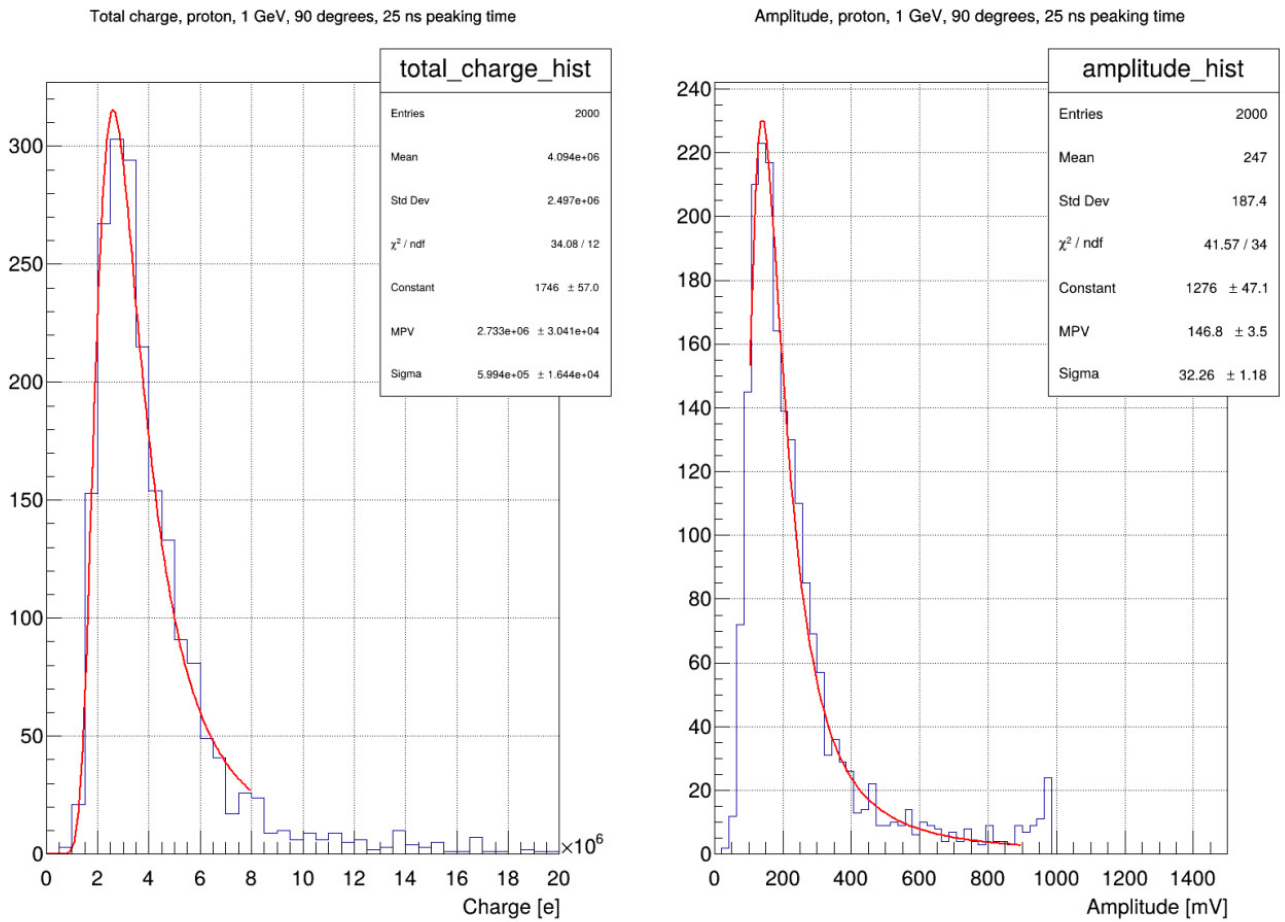


Figure 29: Total charge [e] and voltage amplitude [mV] projections. Proton, 1 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

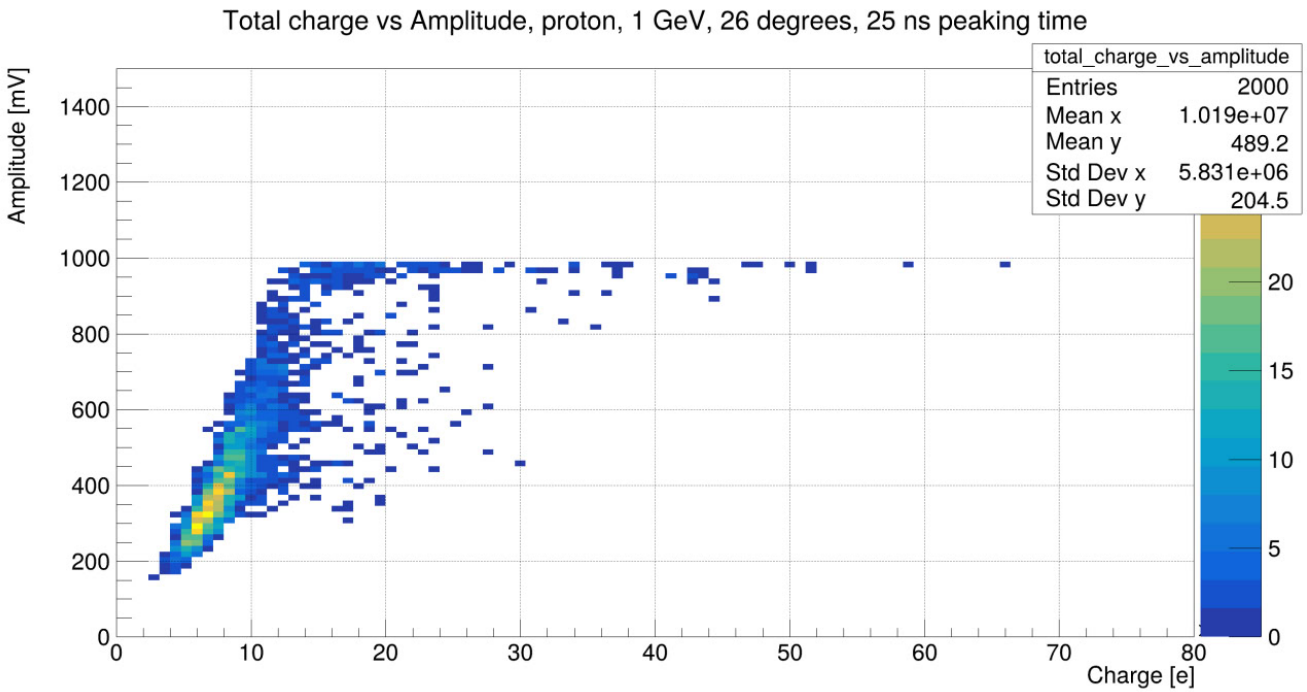


Figure 30: Total charge [e] vs voltage amplitude [mV]. Proton, 1 GeV, 25 ns peaking time, 26 degrees tilt

Total charge vs voltage amplitude

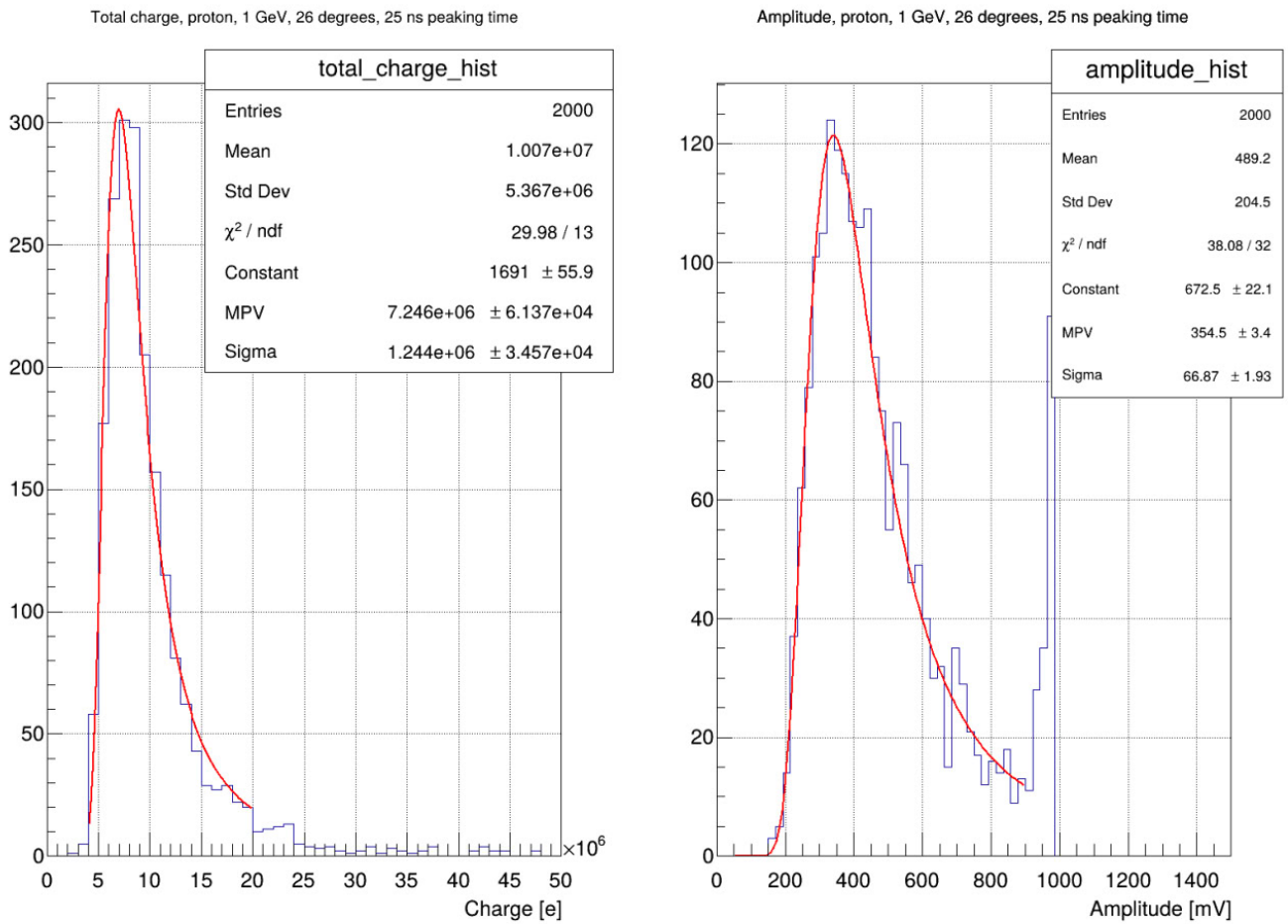


Figure 31: Total charge [e] and voltage amplitude [mV] projections. Proton, 1 GeV, 26 degrees, 25 ns peaking time

Total charge vs voltage amplitude

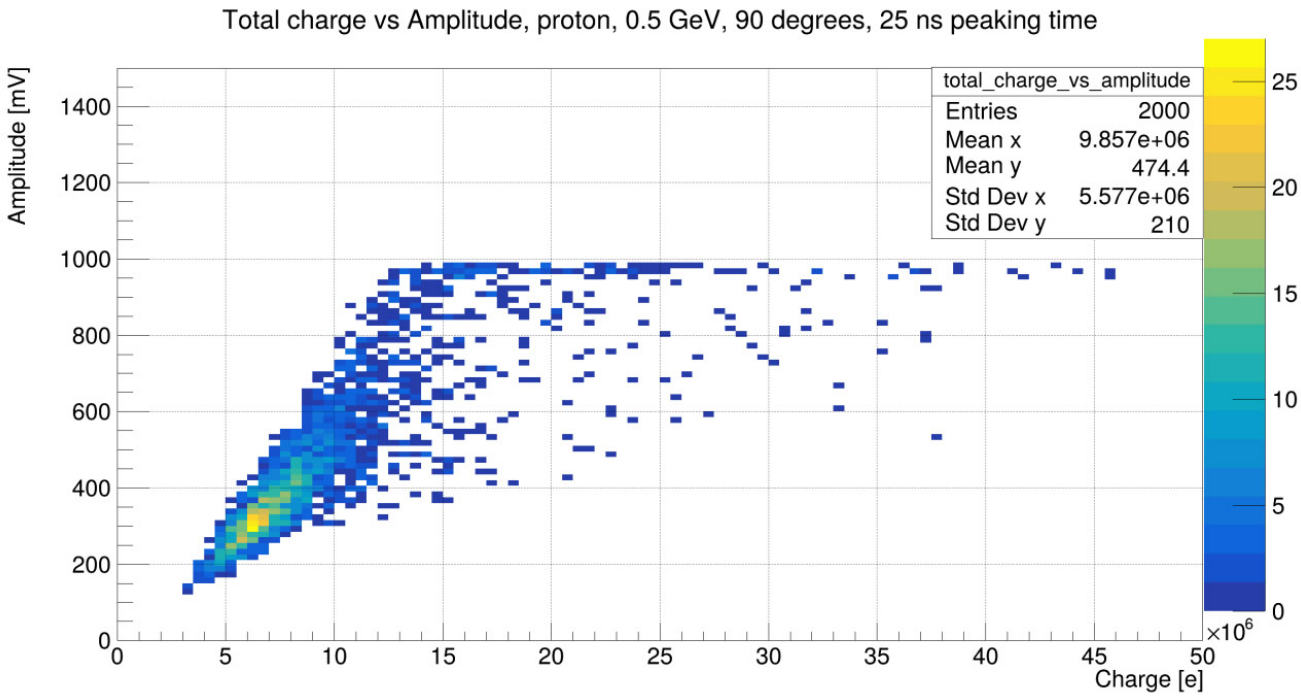


Figure 32: Total charge [e] vs voltage amplitude [mV]. Proton, 0.5 GeV, 25 ns peaking time, 90 degrees.

Total charge vs voltage amplitude

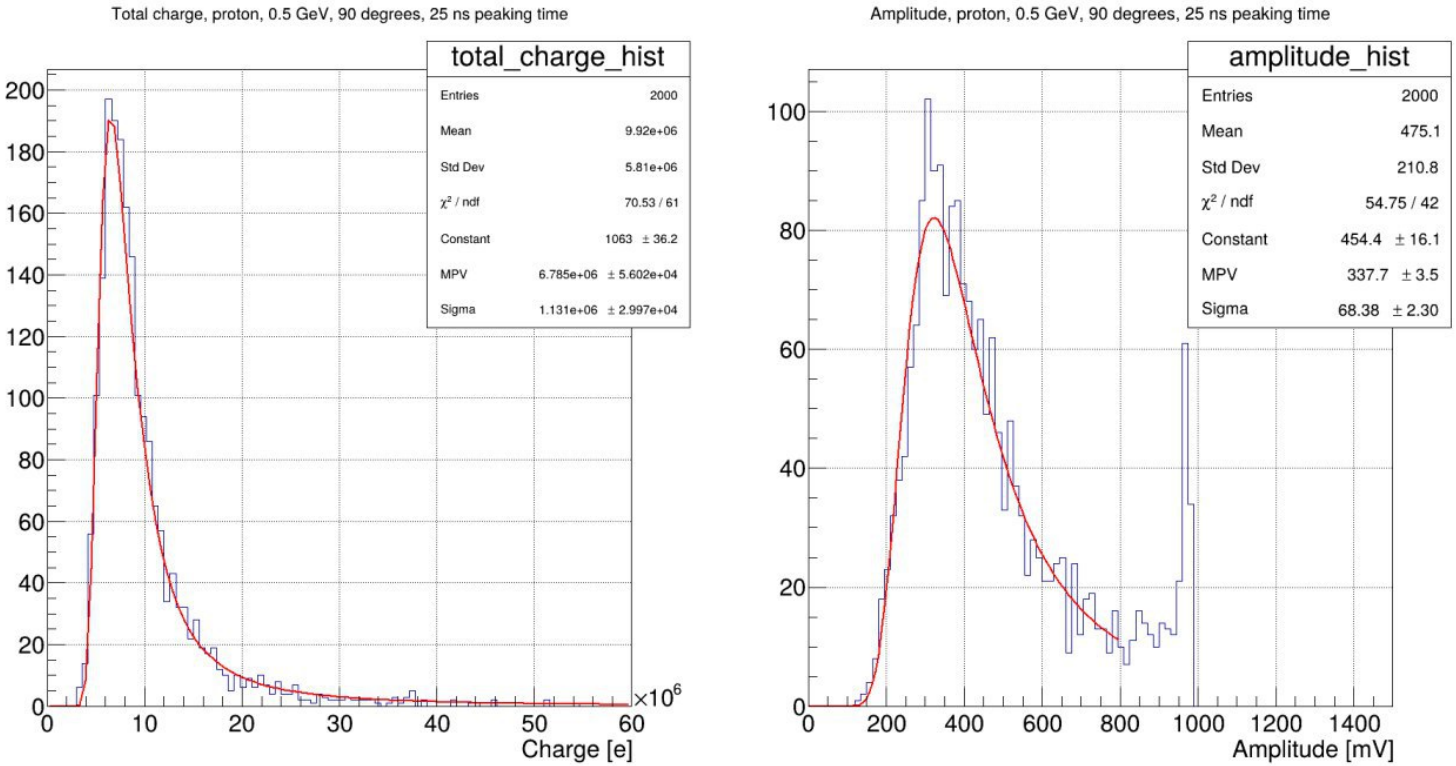


Figure 33: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.5 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

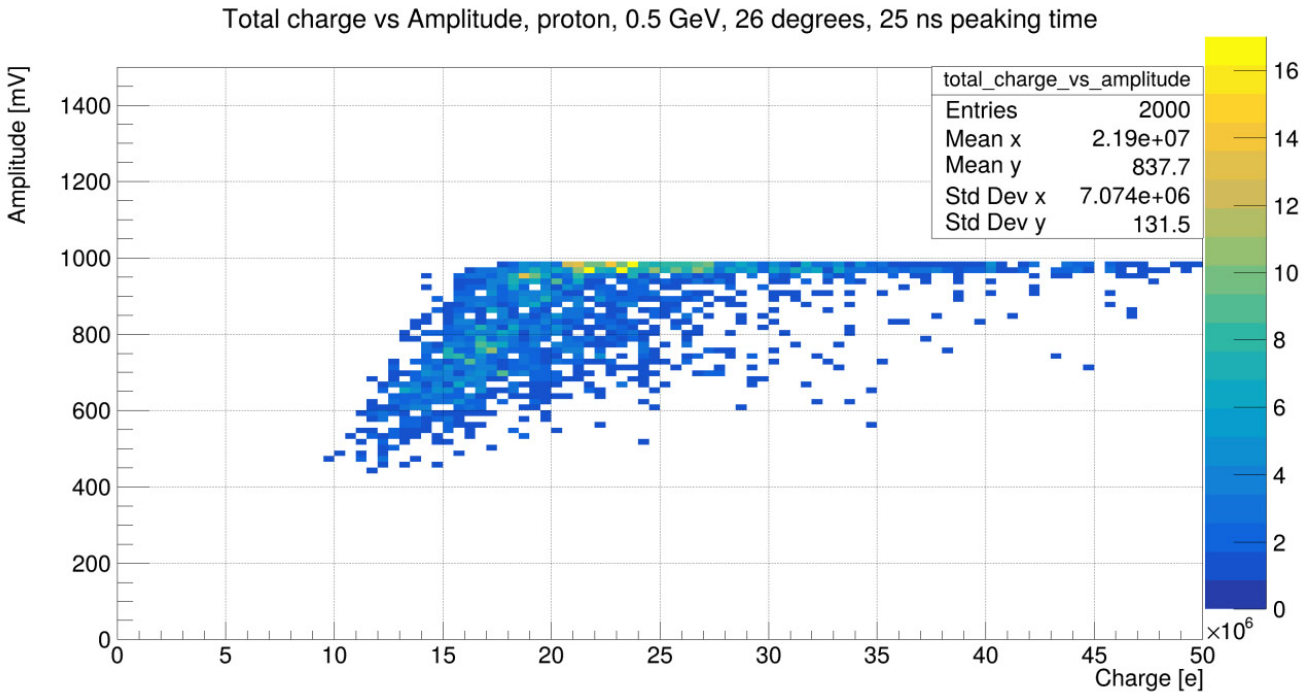


Figure 34: Total charge [e] vs voltage amplitude [mV]. Proton, 0.5 GeV, 25 ns peaking time, 26 degrees tilt

Total charge vs voltage amplitude

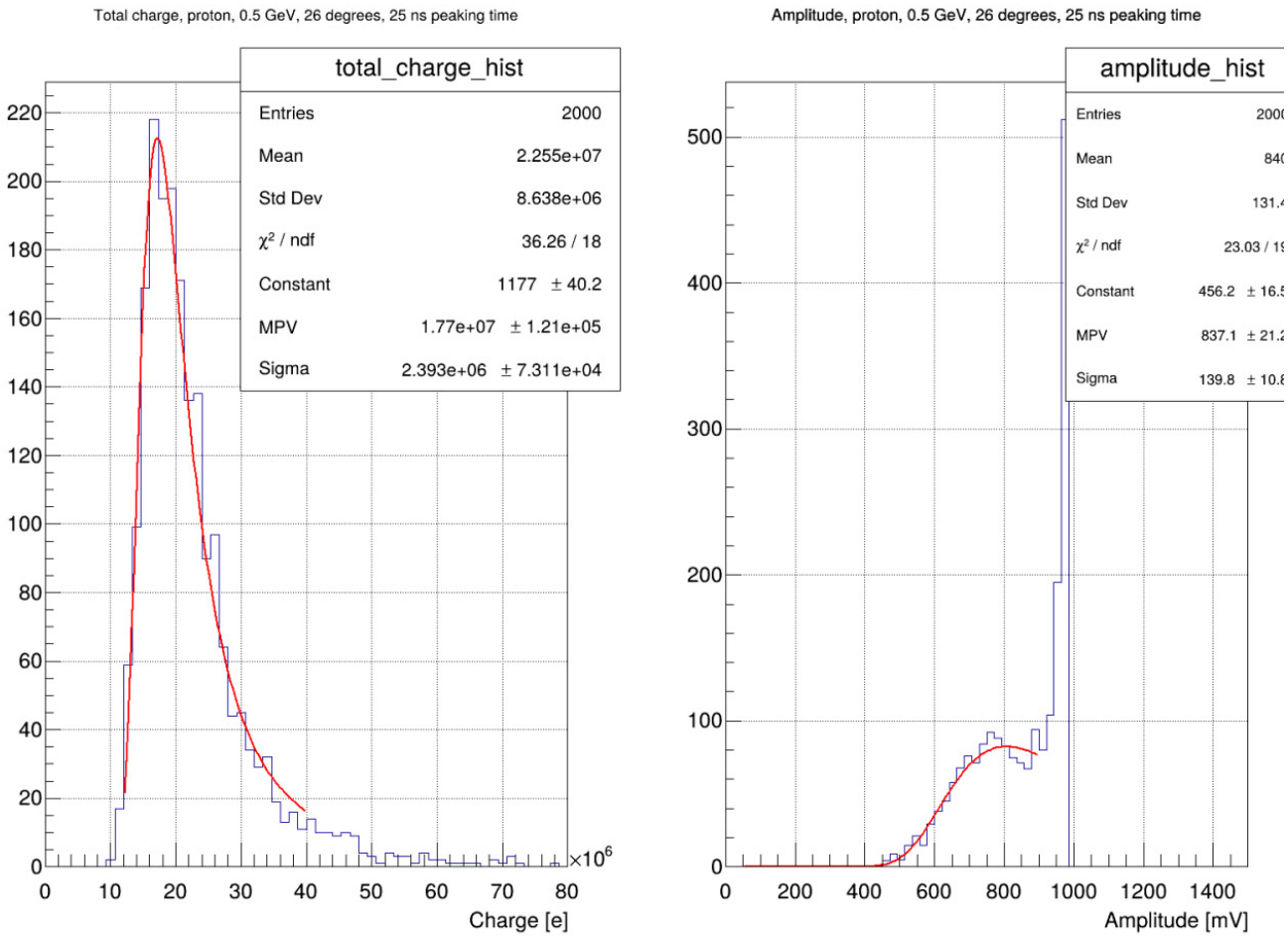


Figure 35: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.5 GeV, 26 degrees, 25 ns peaking time

Total charge vs voltage amplitude

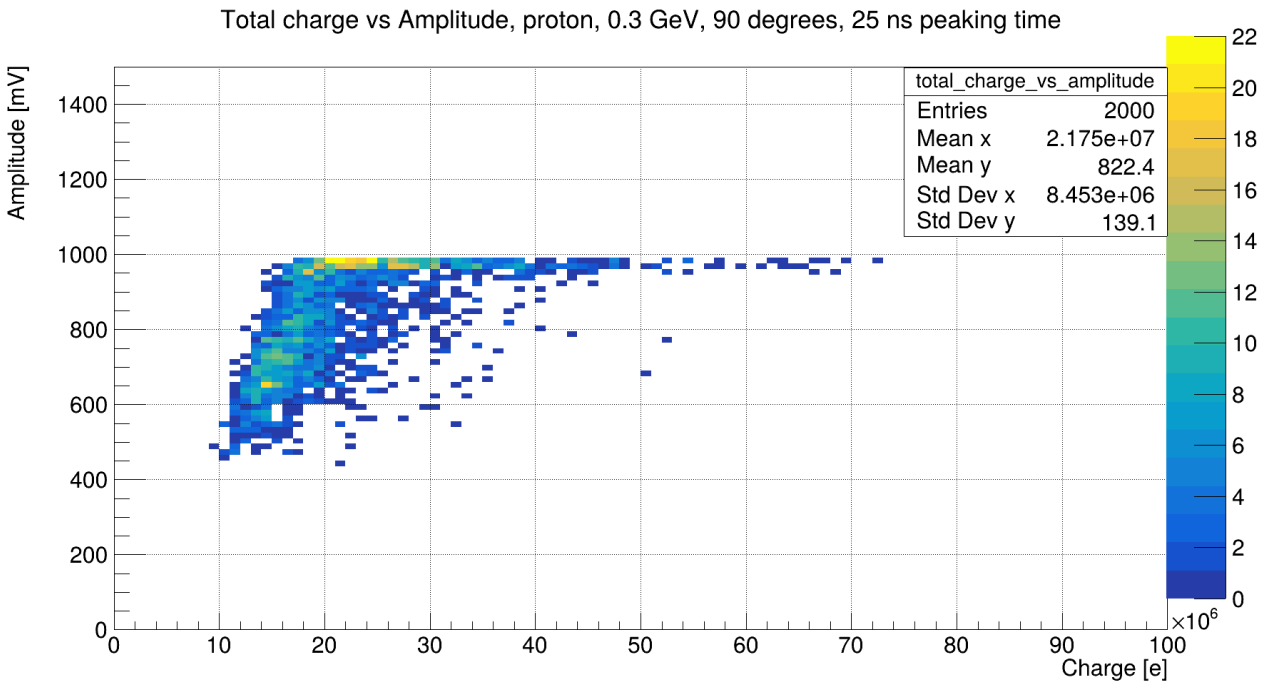


Figure 36: Total charge [e] vs voltage amplitude [mV]. Proton, 0.3 GeV, 25 ns peaking time, 90 degrees

Total charge vs voltage amplitude

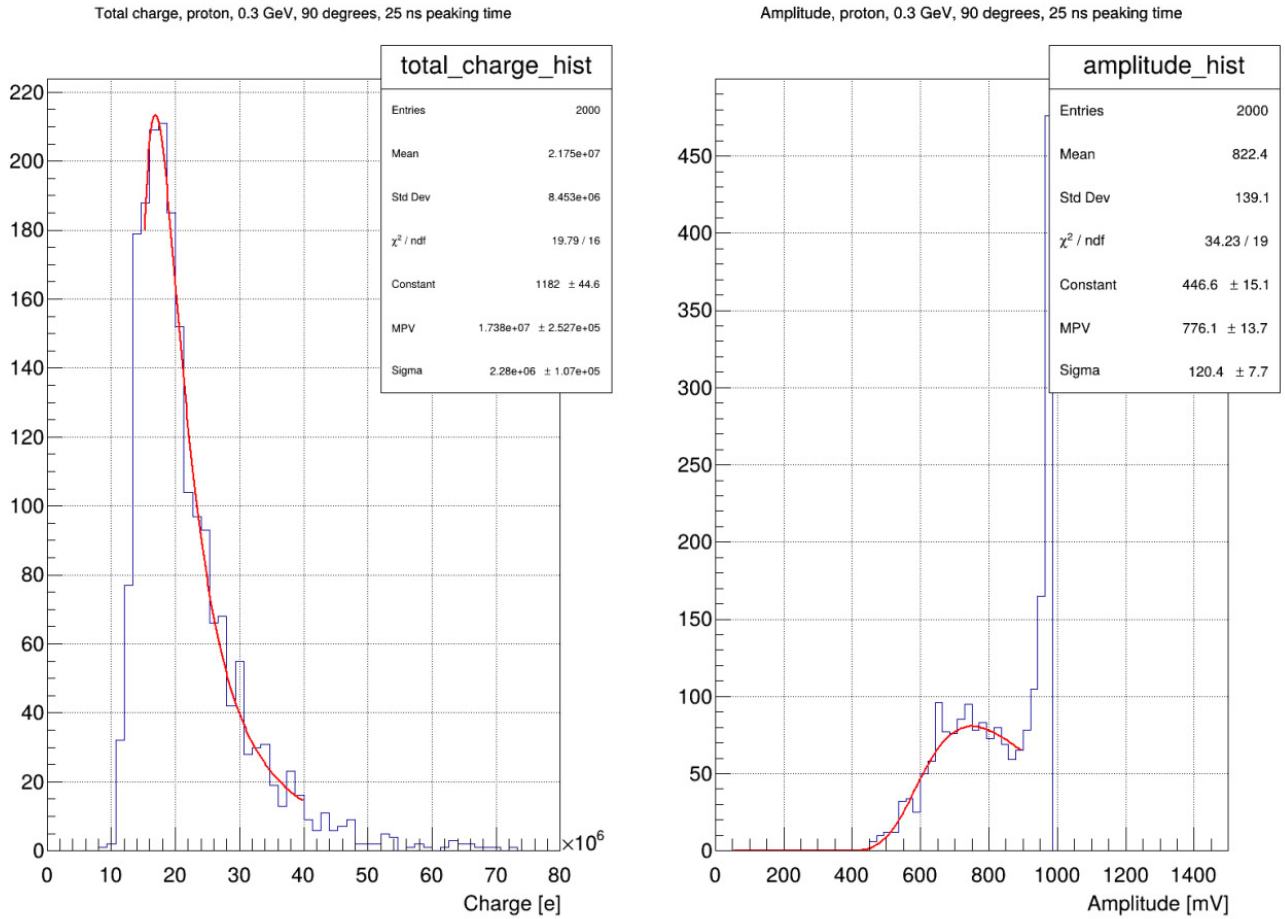


Figure 37: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.3 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

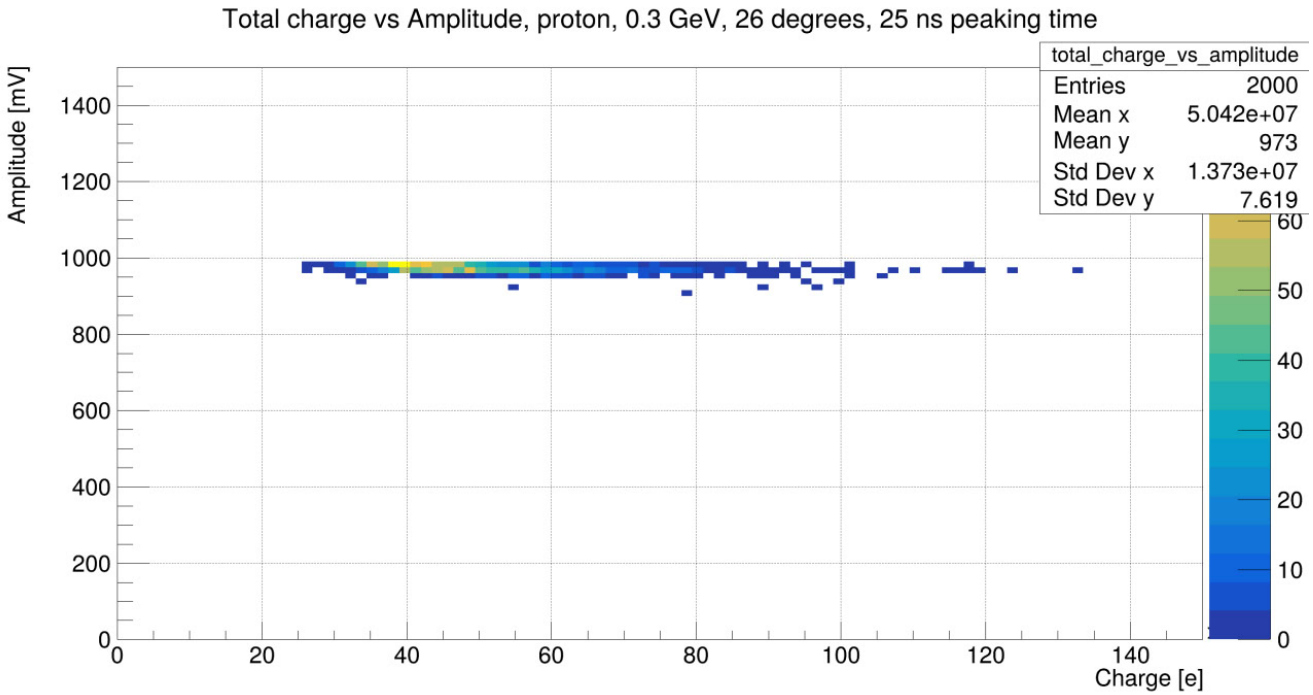


Figure 38: Total charge [e] vs voltage amplitude [mV]. Proton, 0.3 GeV, 25 ns peaking time, 26 degrees

Total charge vs voltage amplitude

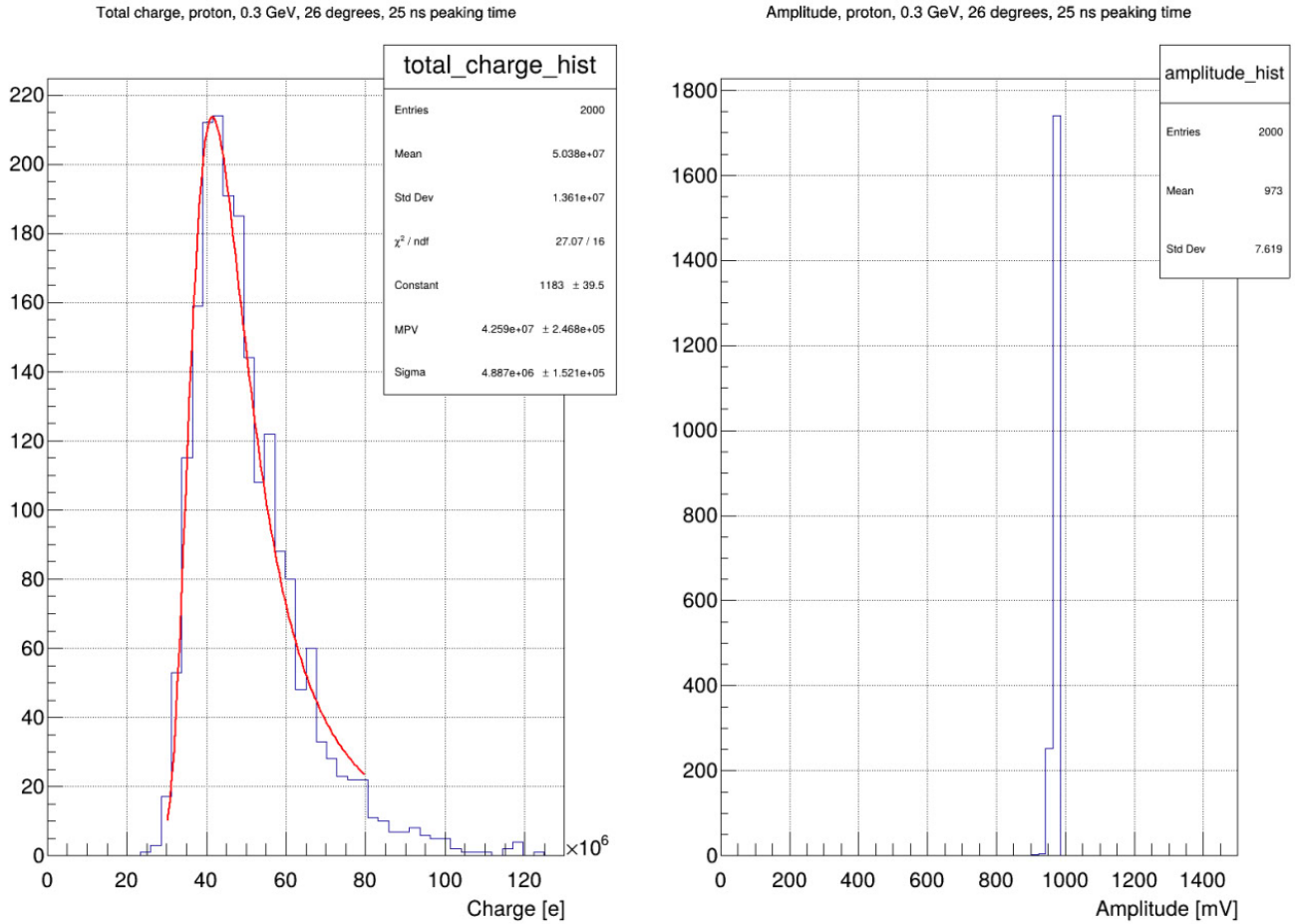


Figure 39: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.3 GeV, 26 degrees, 25 ns peaking time

Total charge vs voltage amplitude

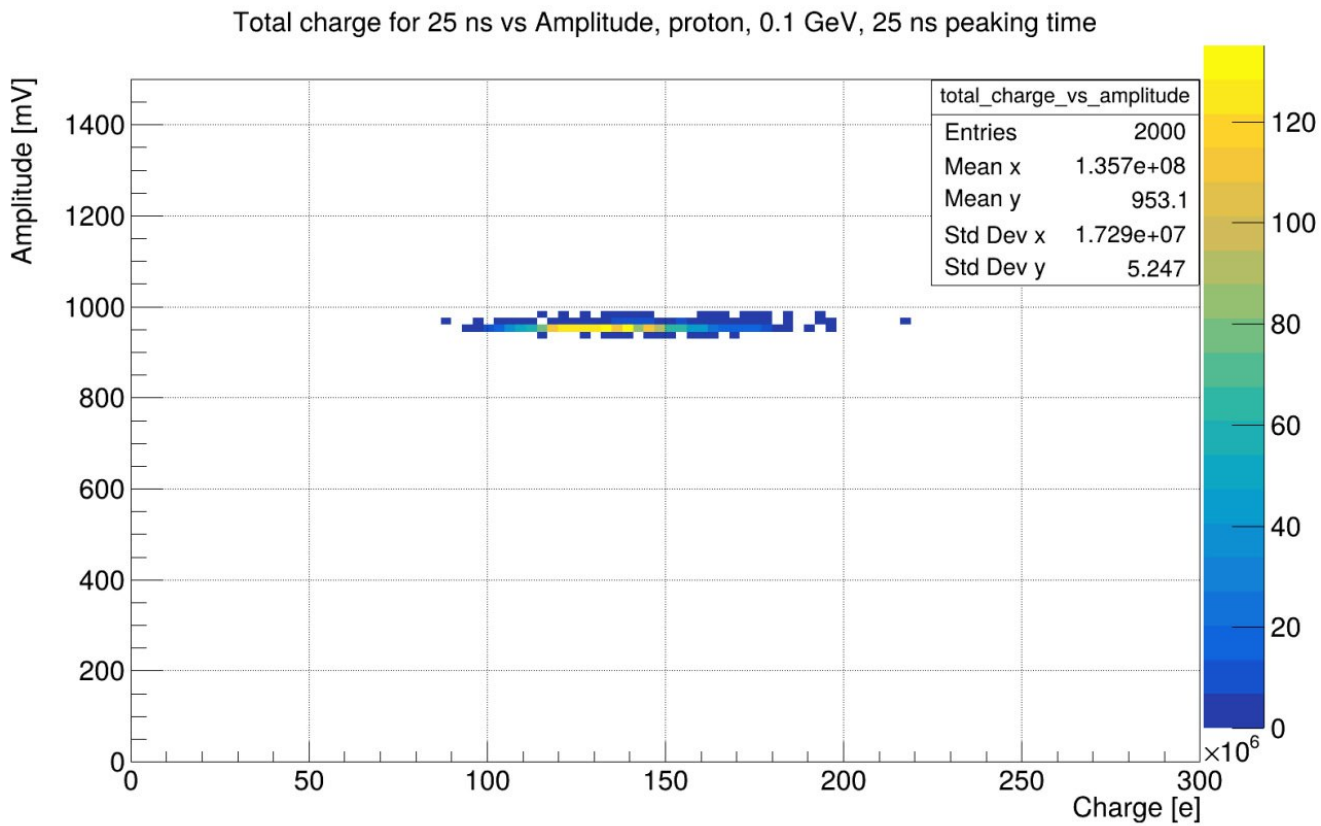


Figure 40: Total charge [e] vs voltage amplitude [mV]. Proton, 0.1 GeV, 25 ns peaking time, 90 degrees

Total charge vs voltage amplitude

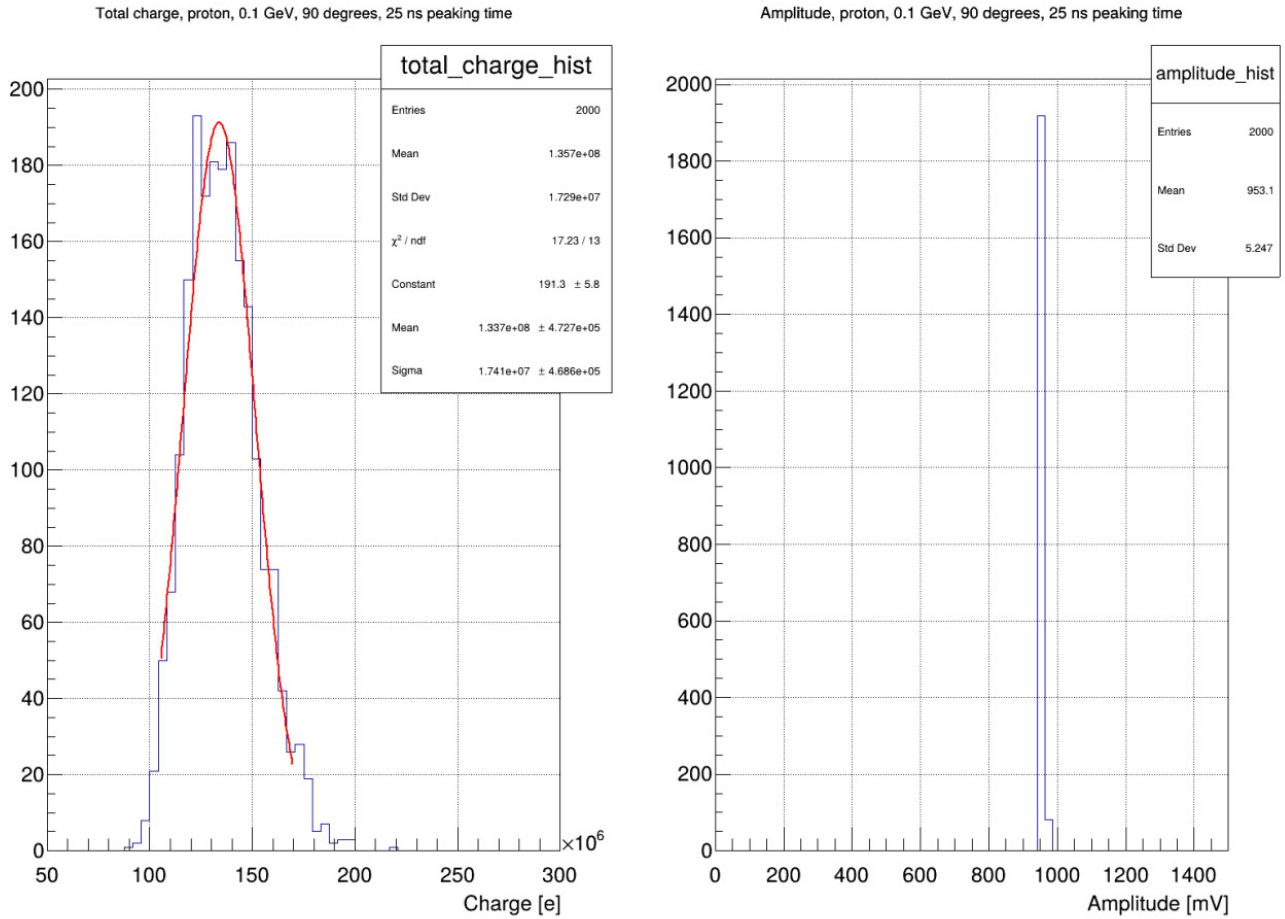


Figure 41: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.1 GeV, 90 degrees, 25 ns peaking time

Total charge vs voltage amplitude

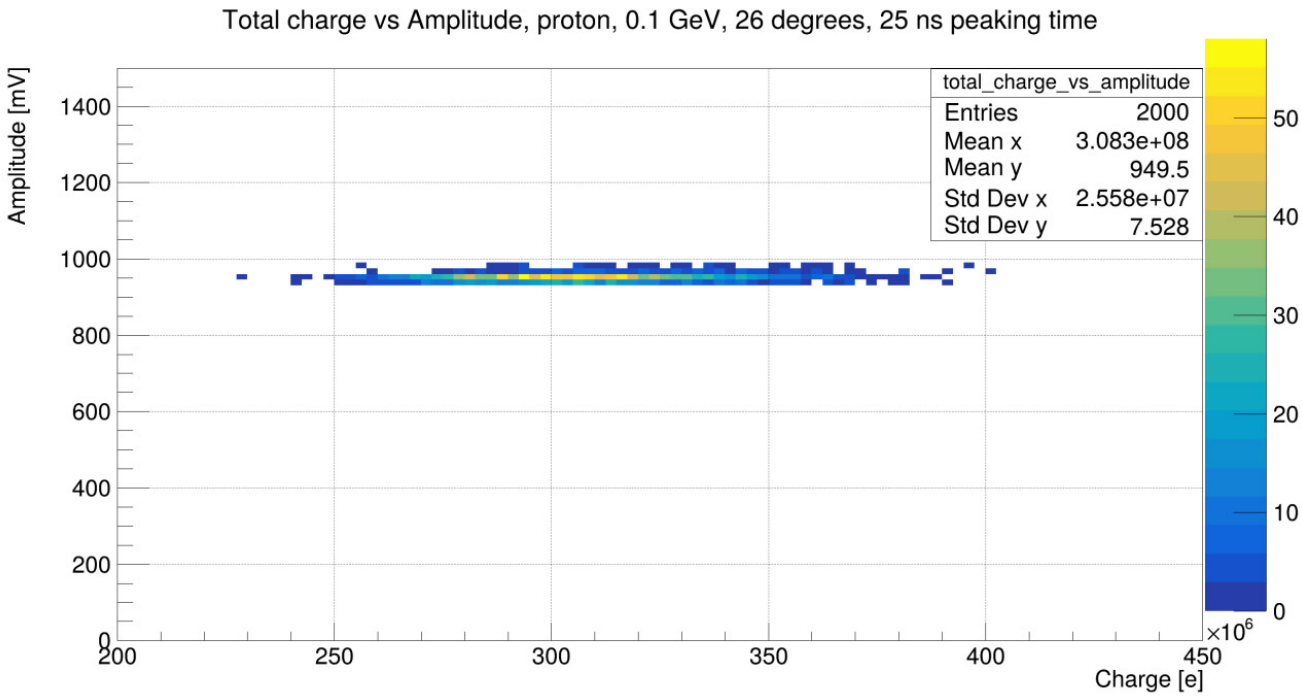


Figure 42: Total charge [e] vs voltage amplitude [mV]. Proton, 0.1 GeV, 25 ns peaking time, 26 degrees

Total charge vs voltage amplitude

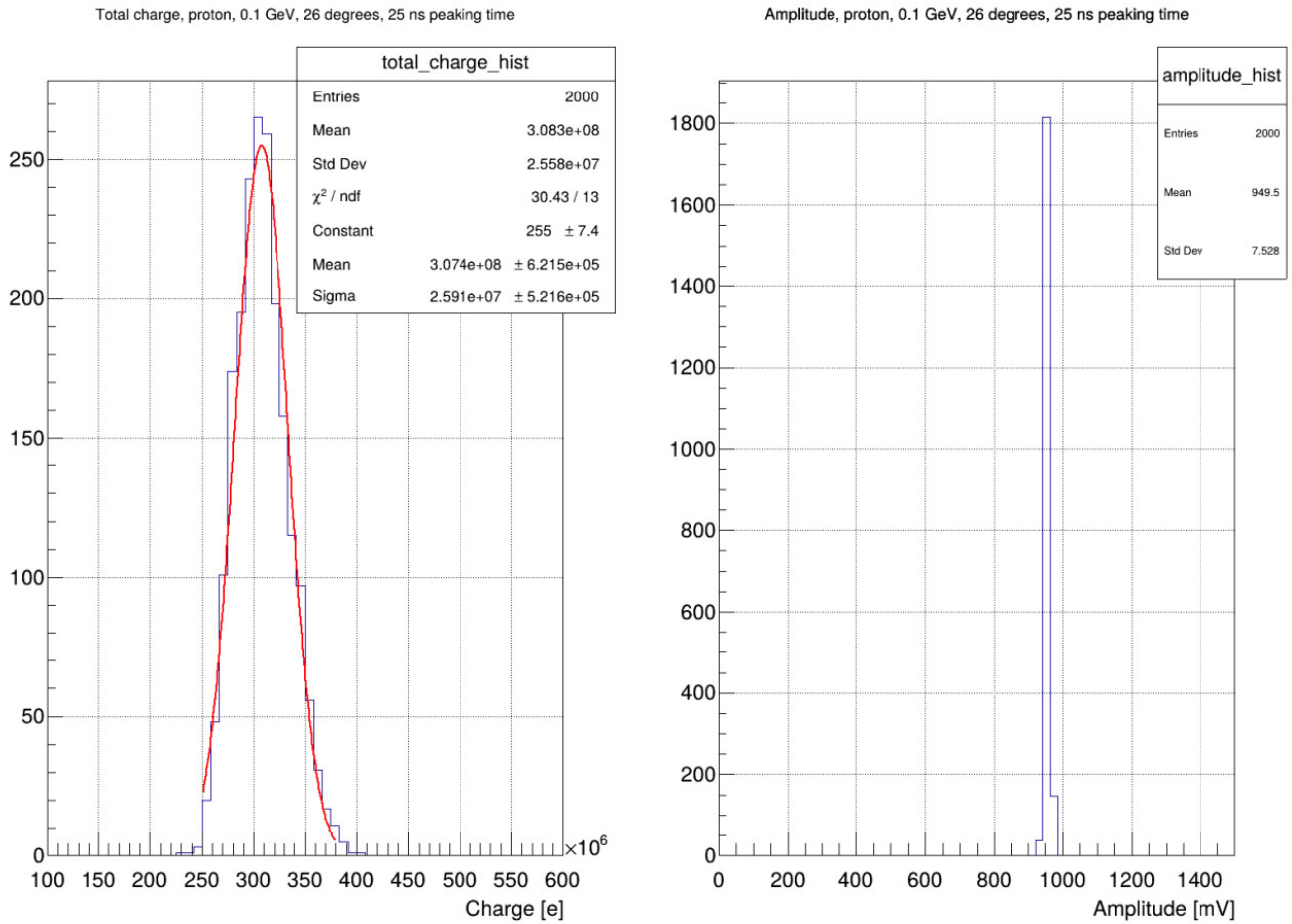


Figure 43: Total charge [e] and voltage amplitude [mV] projections. Proton, 0.1 GeV, 26 degrees, 25 ns peaking time

Overflow (voltage amplitude $>$ 800 mV)

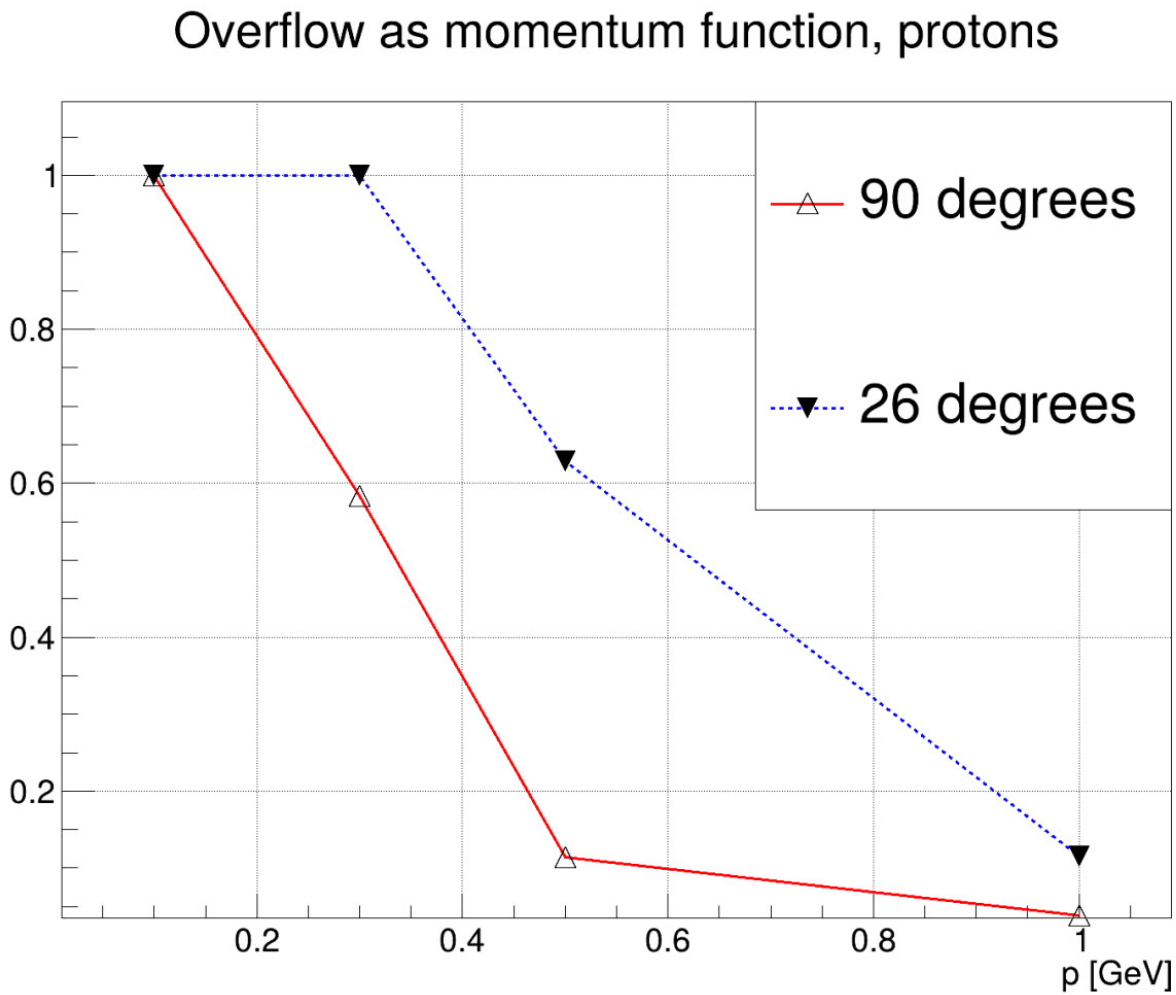


Figure 44: Overflow vs momentum [GeV]. Protons, 25 ns peaking time

Trimmed mean

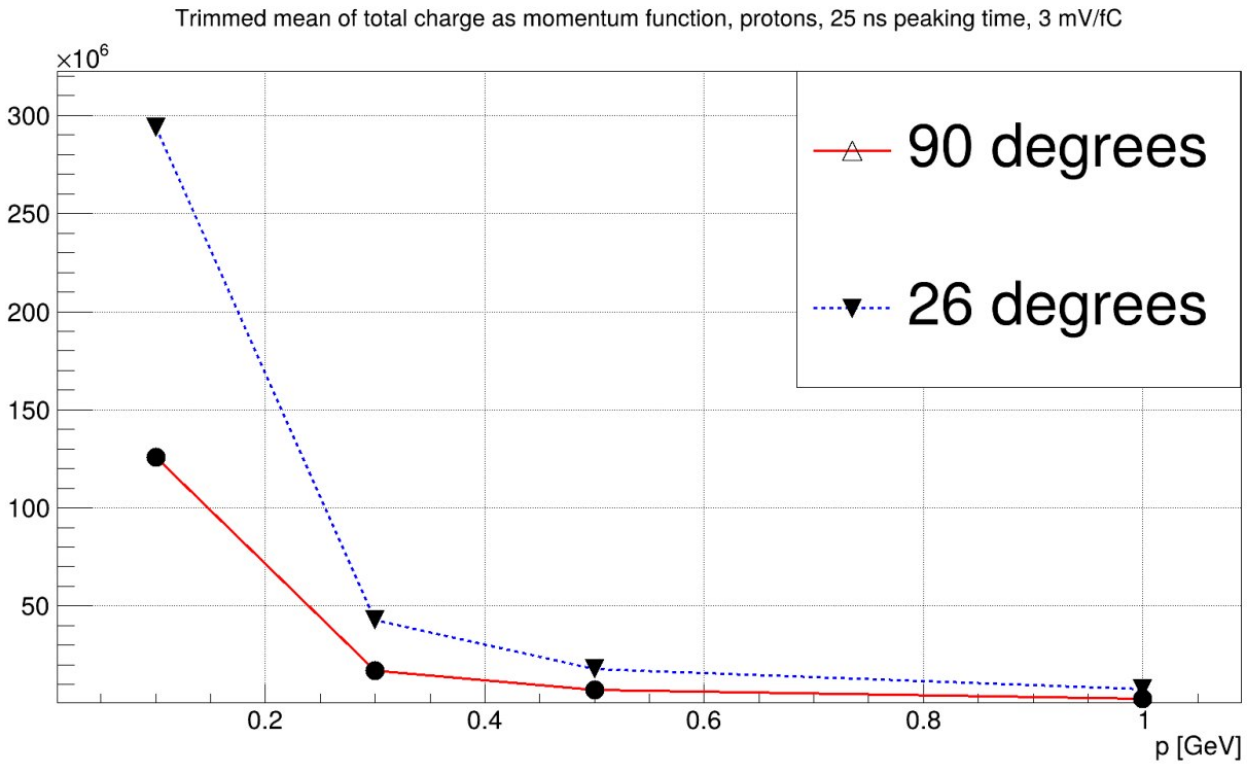


Figure 45: Trimmed mean (30%). Protons, 25 ns peaking time

MPV

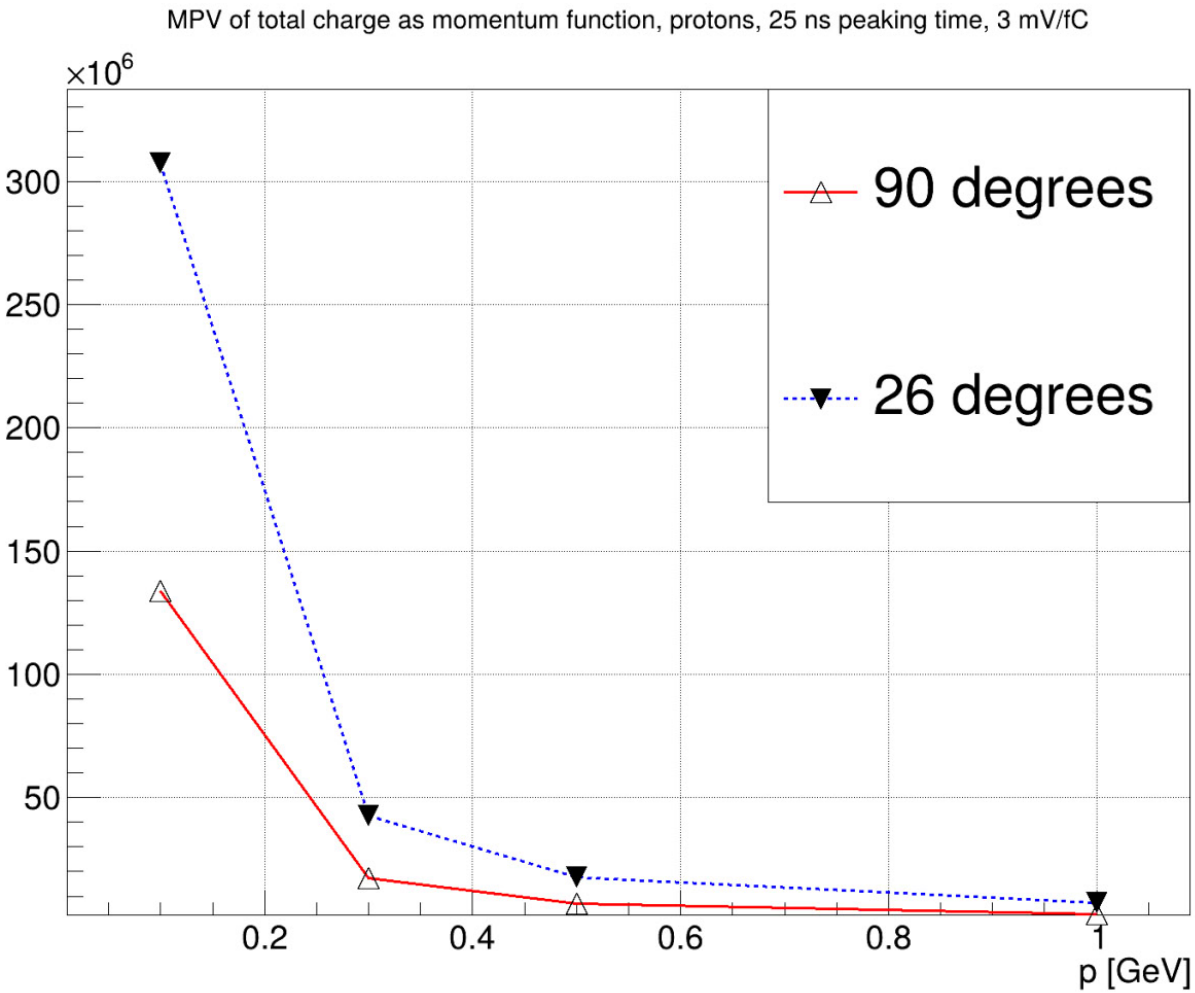


Figure 46: MPV, Protons, 25 ns peaking time

Sigma

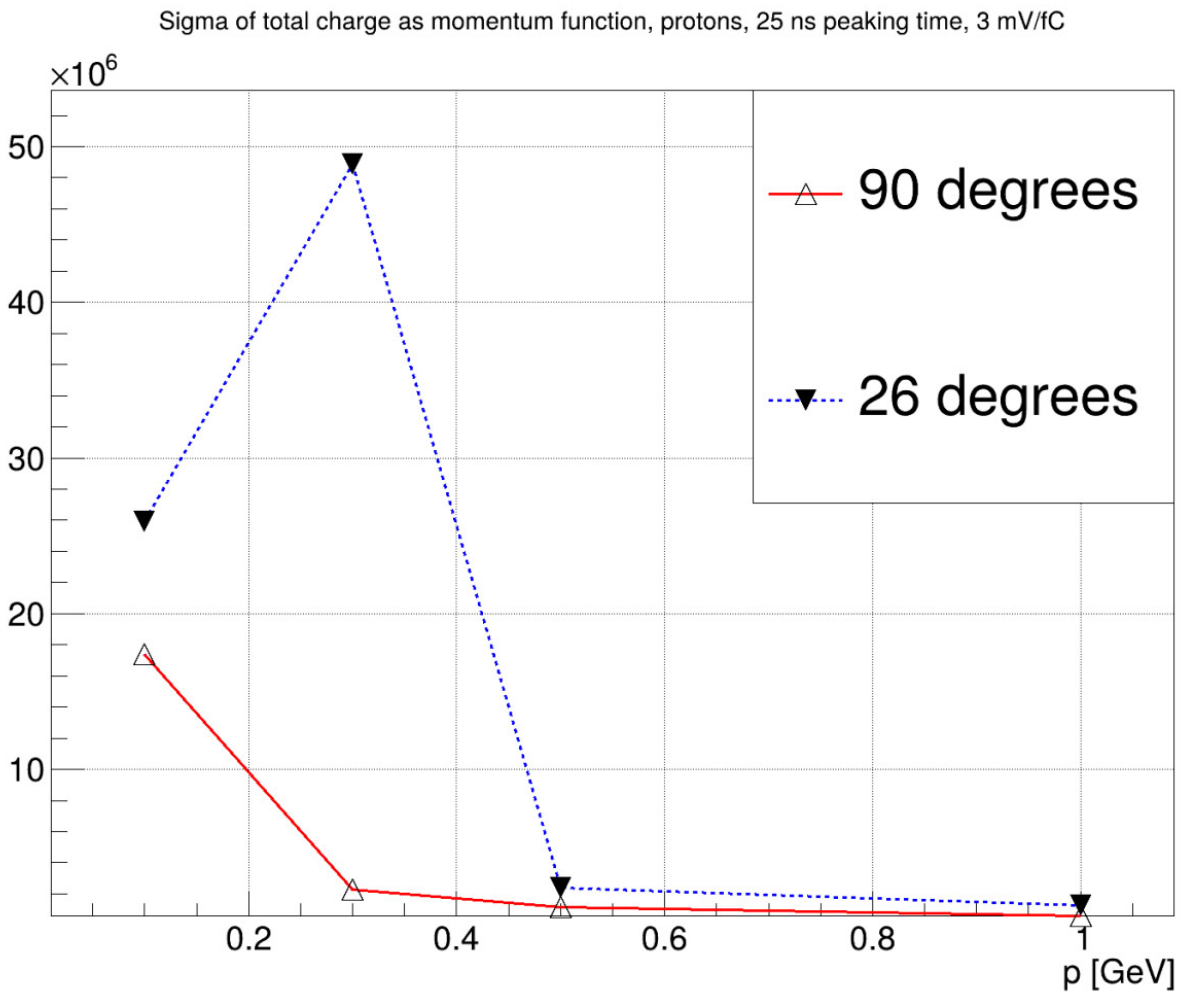


Figure 47: Sigma, Protons, 25 ns peaking time

Sigma divided by MPV

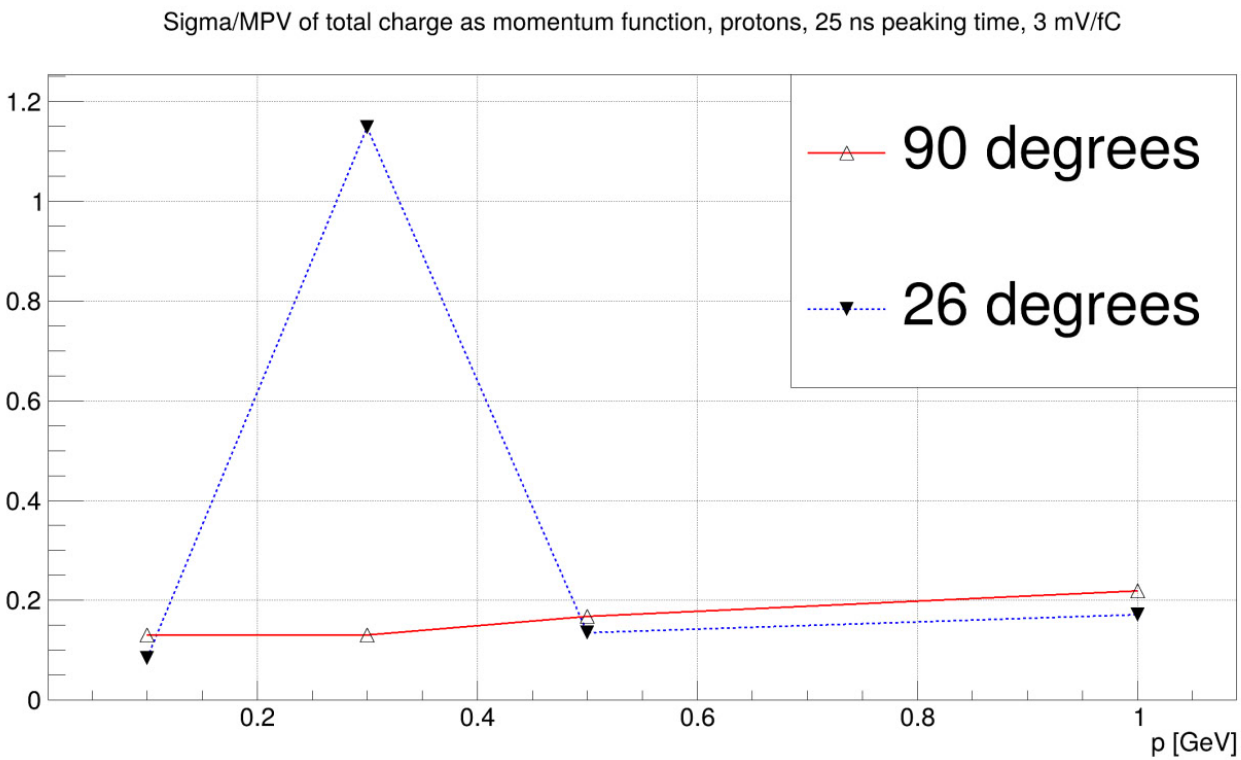


Figure 48: Sigma divided by MPV, Protons, 25 ns peaking time

FWHM

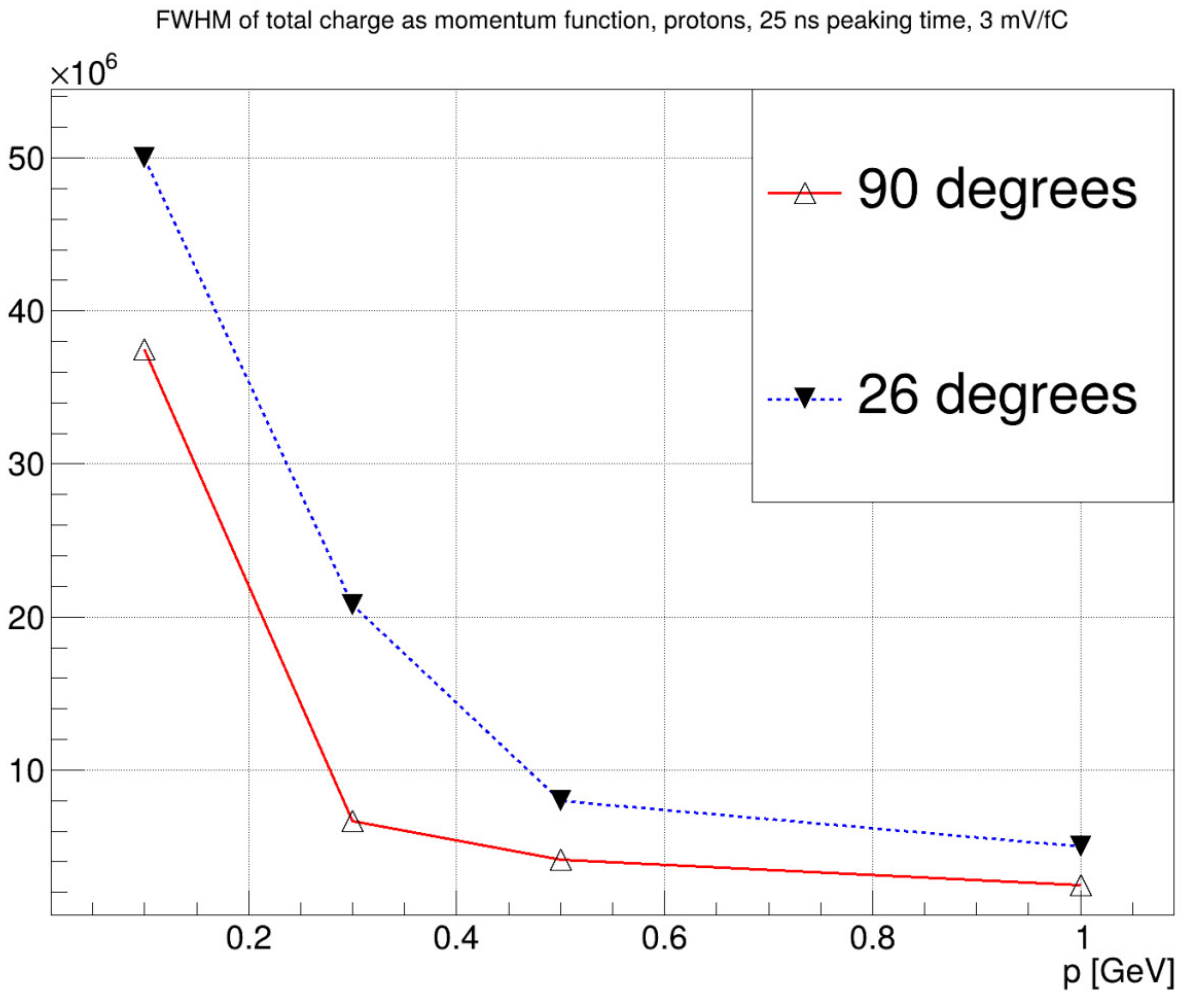


Figure 49: FWHM, Protons, 25 ns peaking time

Trimmed mean

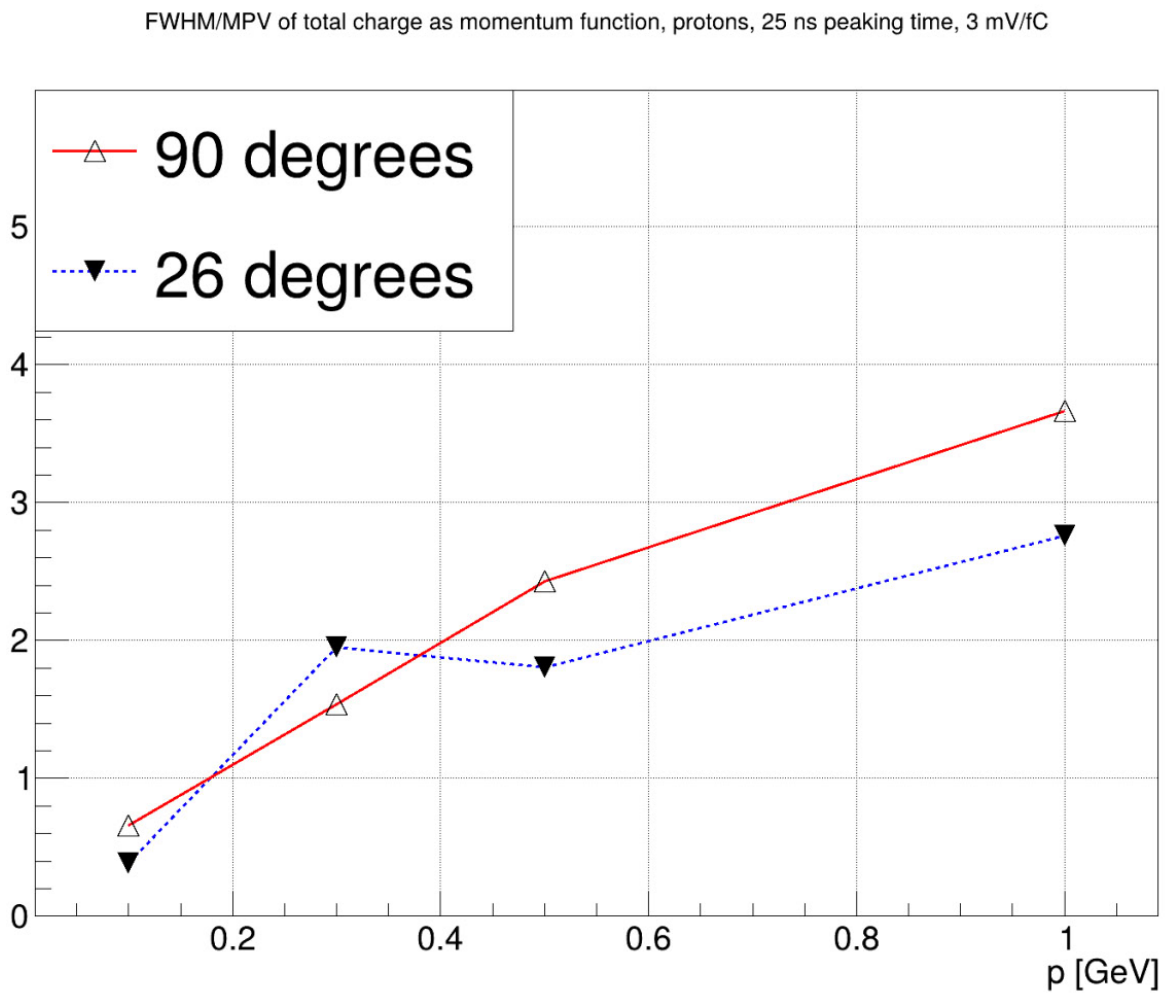


Figure 50: FWHM divided by MPV, Protons, 25 ns peaking time

Energy deposit spectra

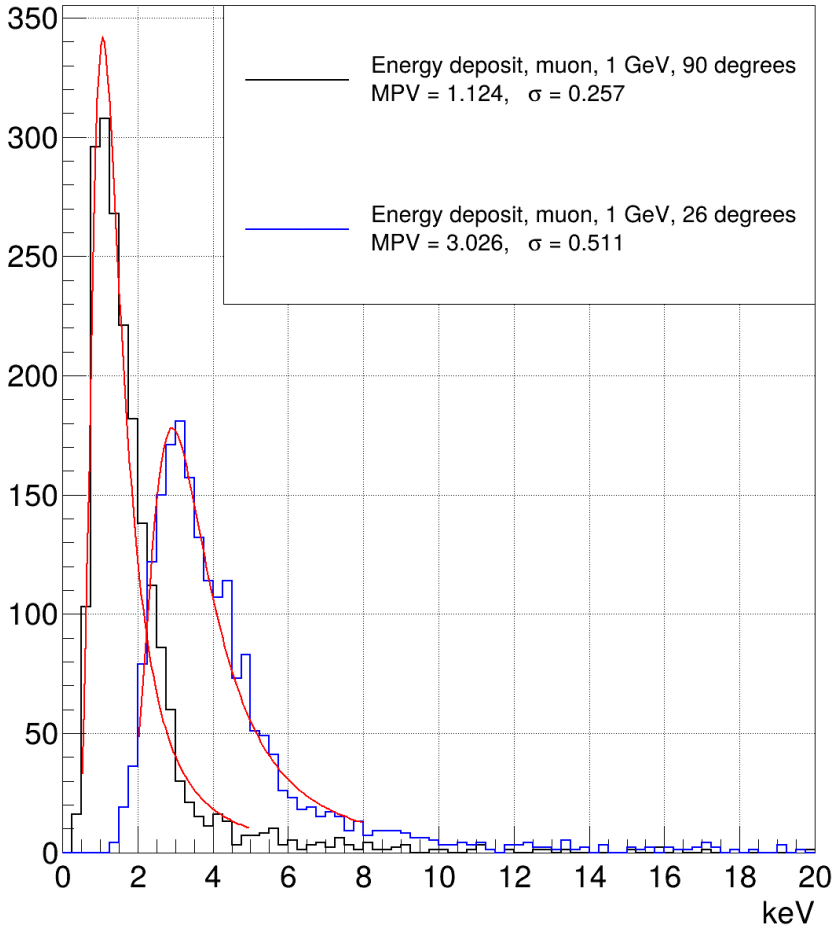


Figure 51: dE, Muons 1 GeV, 25 ns peaking time

Energy deposit spectra

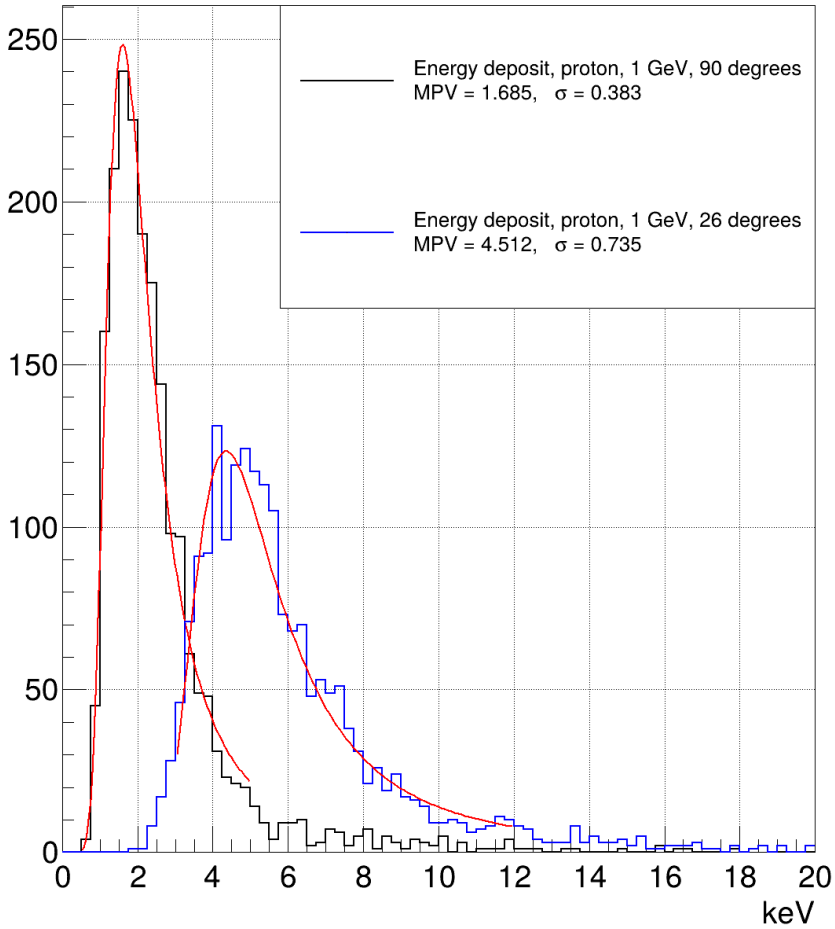


Figure 52: dE, Protons 1 GeV, 25 ns peaking time

Energy deposit spectra

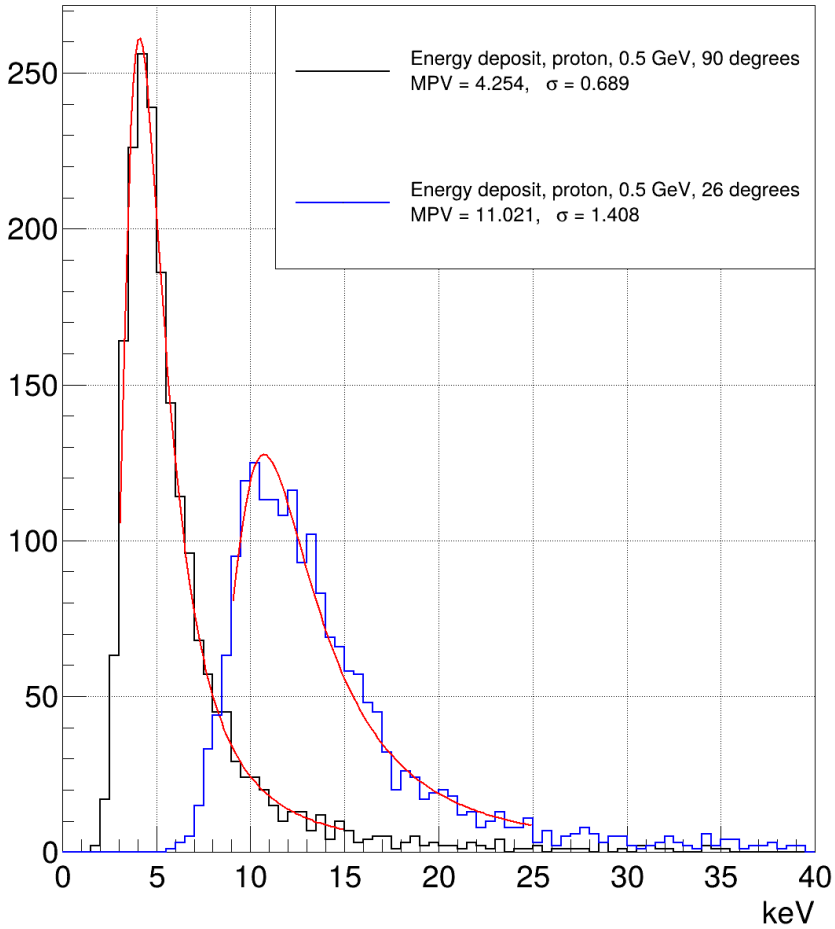


Figure 53: dE, Protons 0.5 GeV, 25 ns peaking time

Energy deposit spectra

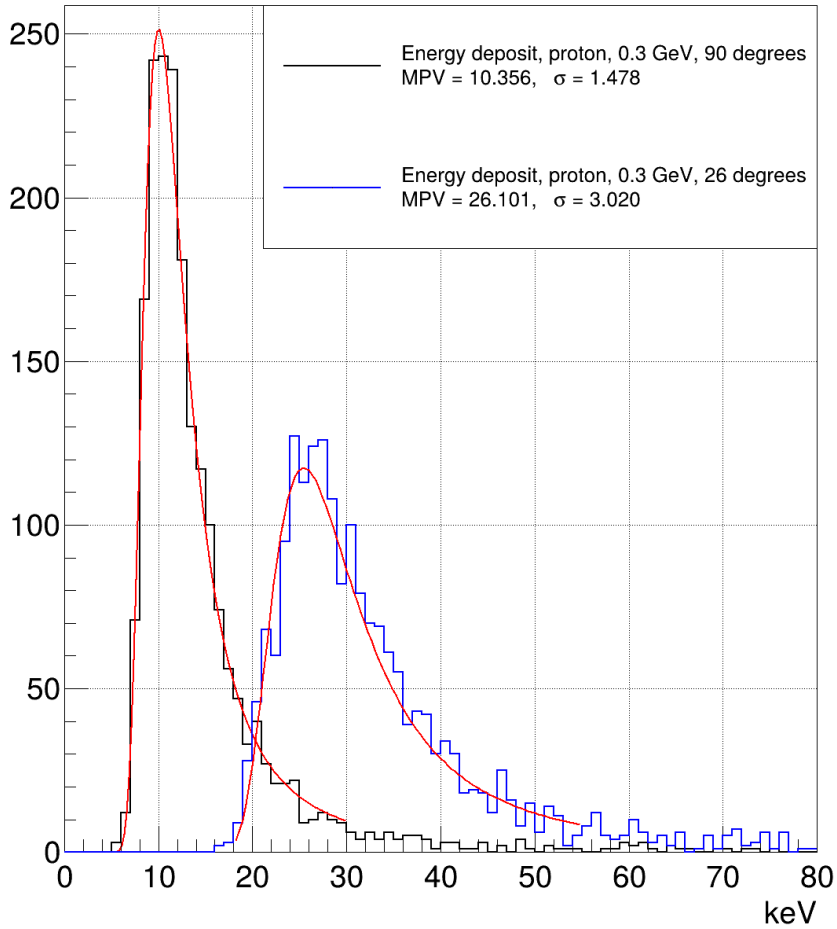


Figure 54: dE, Protons 0.3 GeV, 25 ns peaking time

Energy deposit spectra

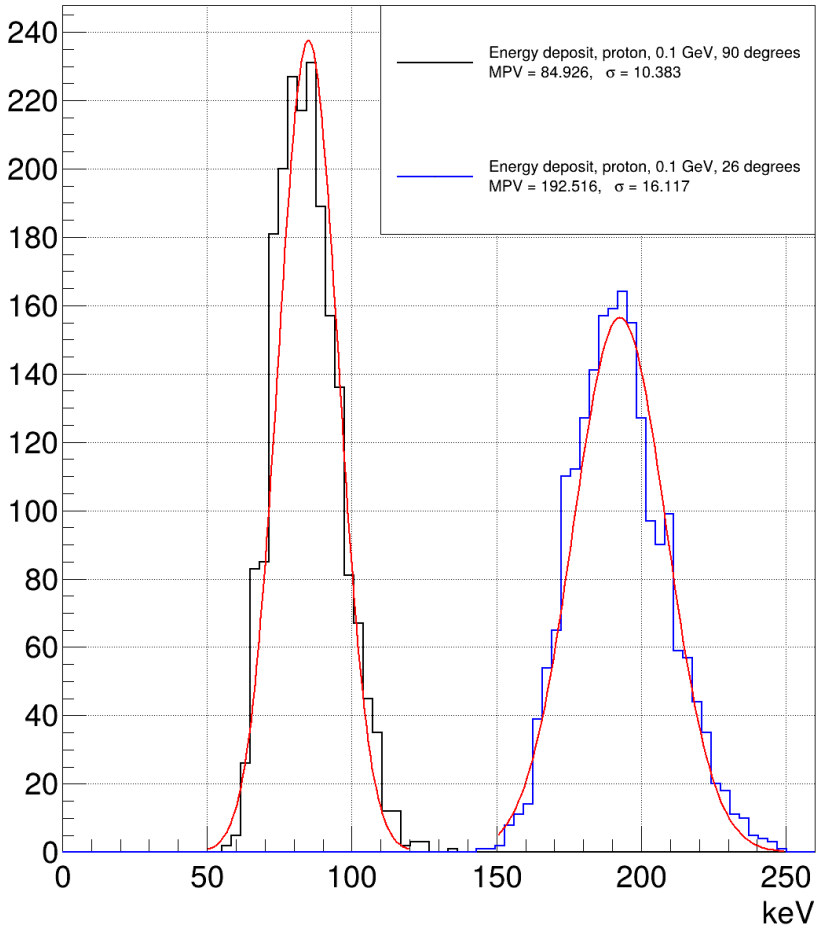


Figure 55: dE, Protons 0.1 GeV, 25 ns peaking time

Sigma/MPV for de

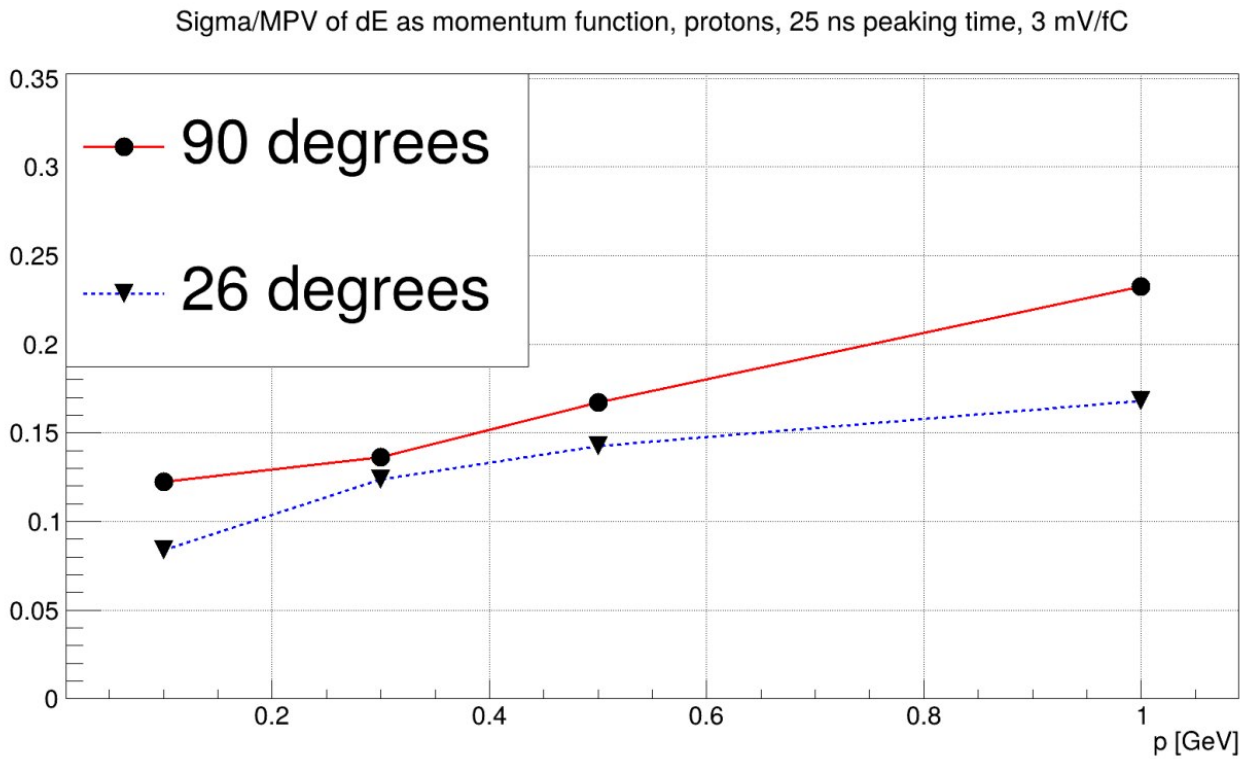


Figure 56: Sigma divided by MPV for de, Protons, 25 ns peaking time

Integrated charge for 250 ns vs voltage amplitude

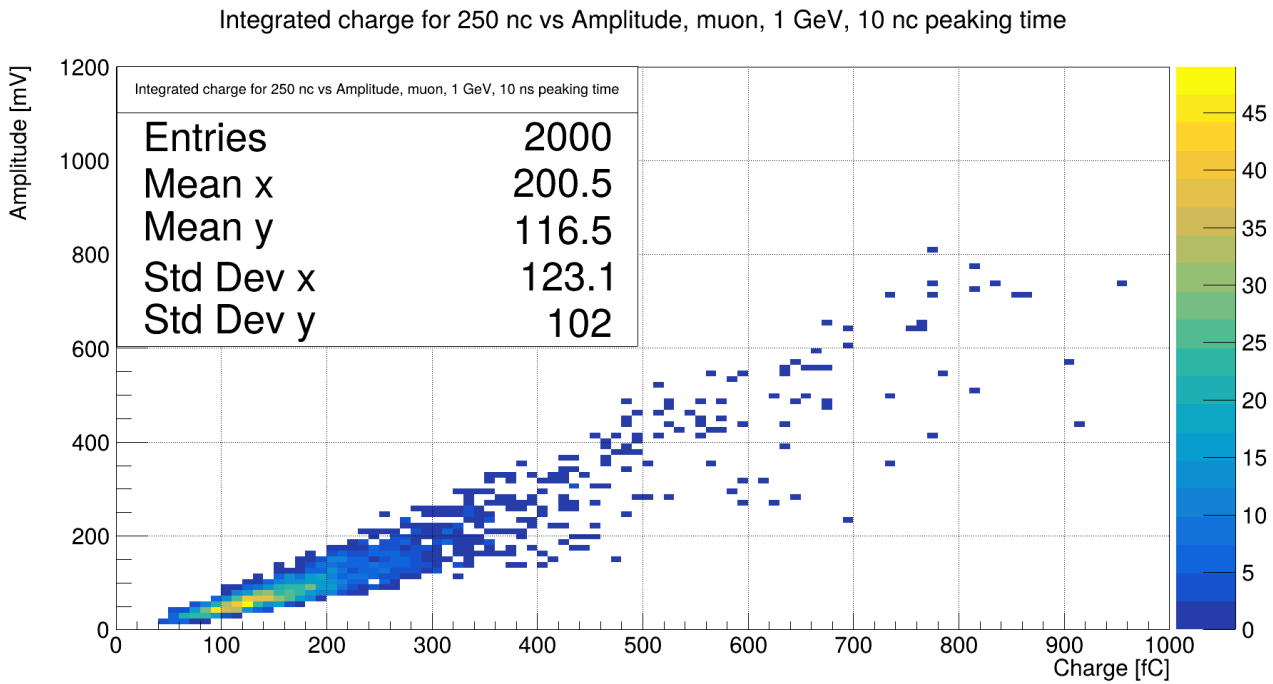
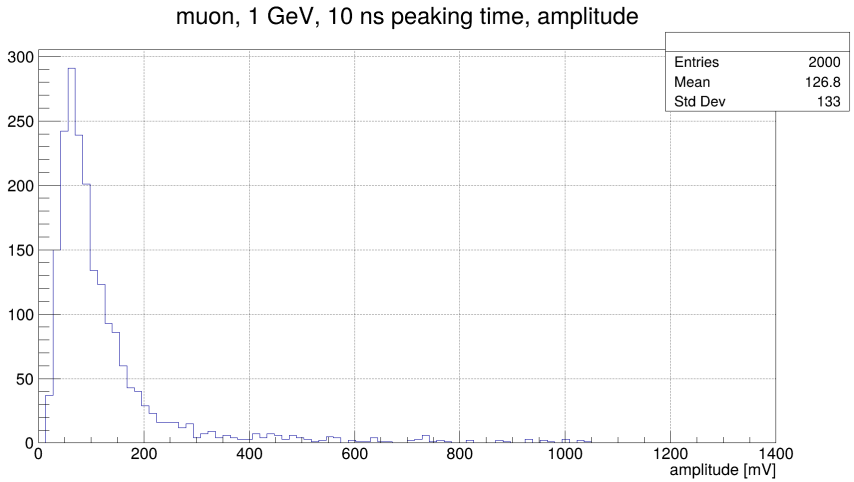
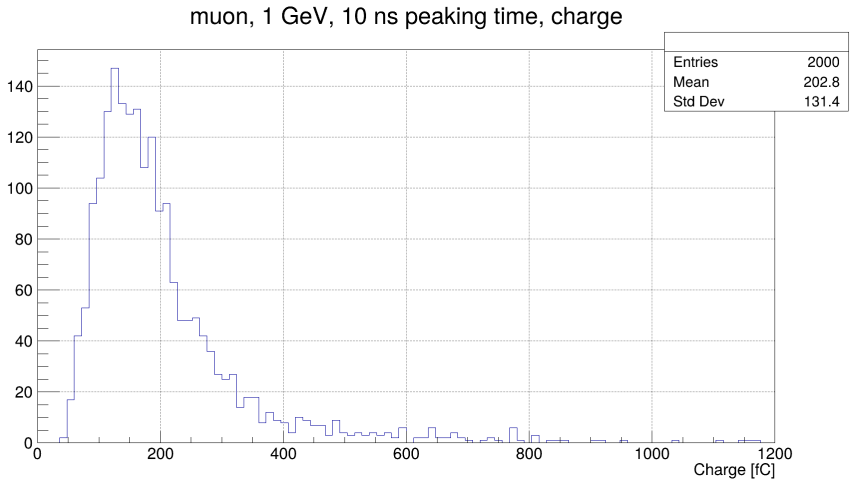


Figure 57: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 10 ns peaking time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 58: Muon, 1 GeV, 2 mm. Peak time 10 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge for 250 ns vs voltage amplitude

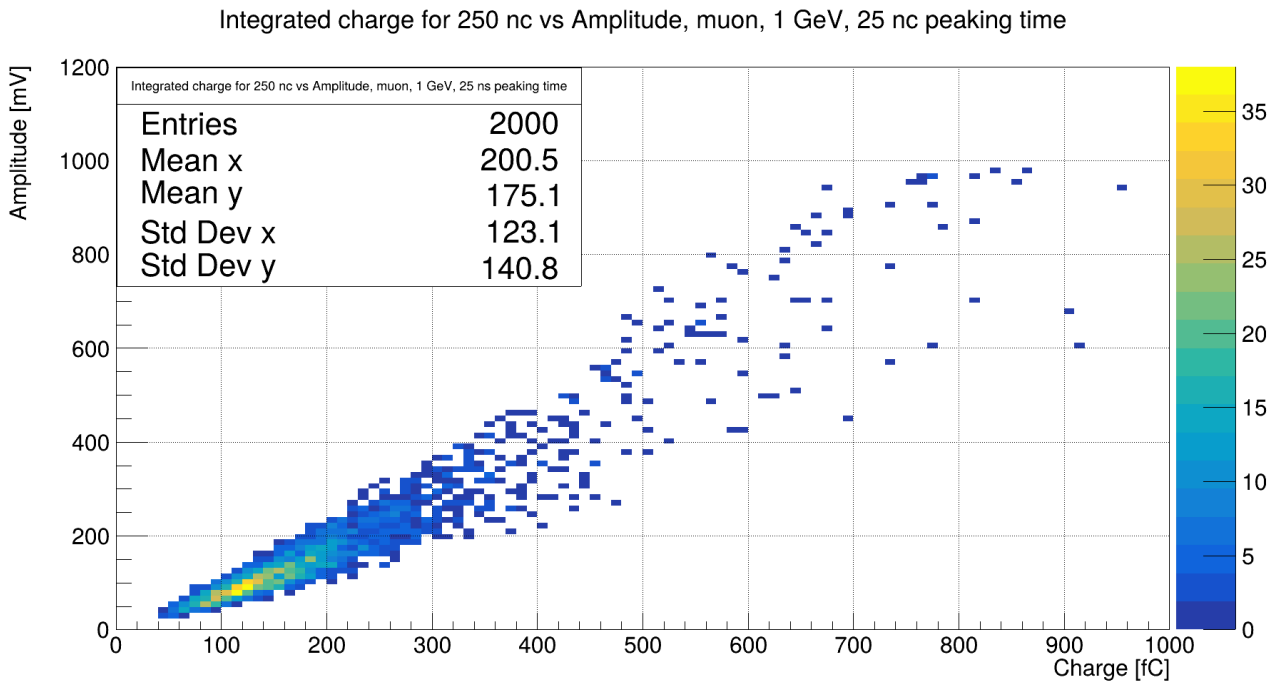
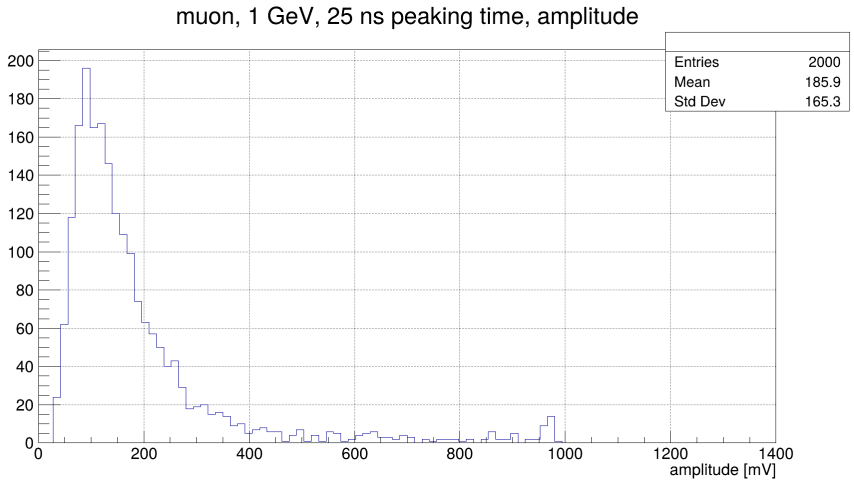
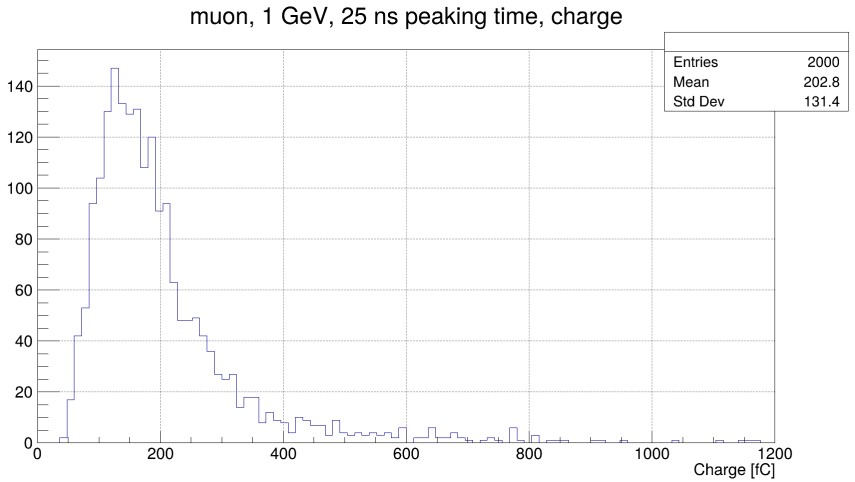


Figure 59: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 25 ns peaking time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 60: Muon, 1 GeV, 2 mm. Peaking time 10 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge for 250 ns vs voltage amplitude

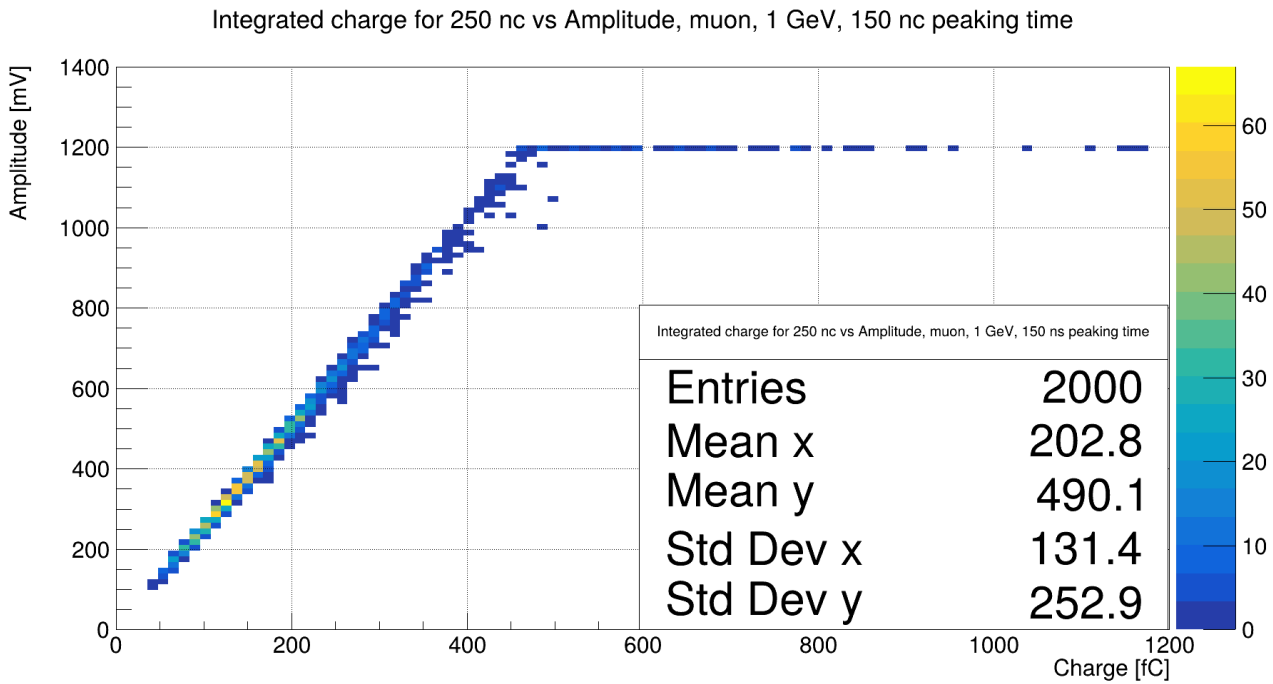
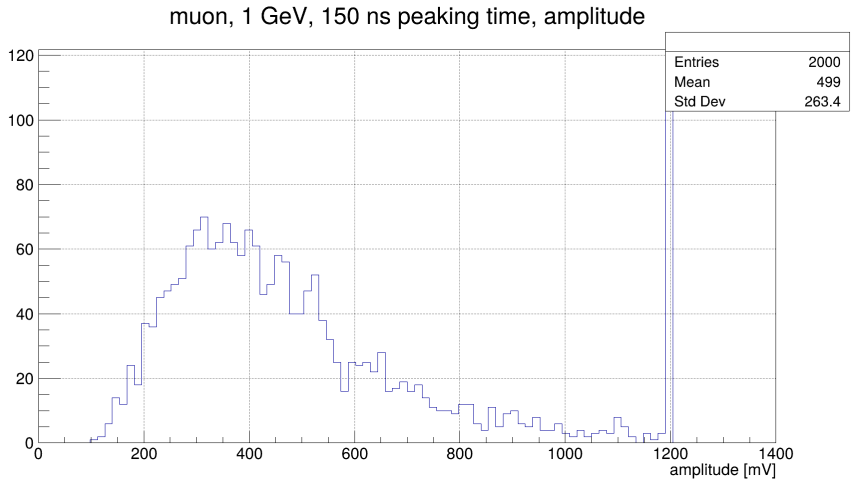
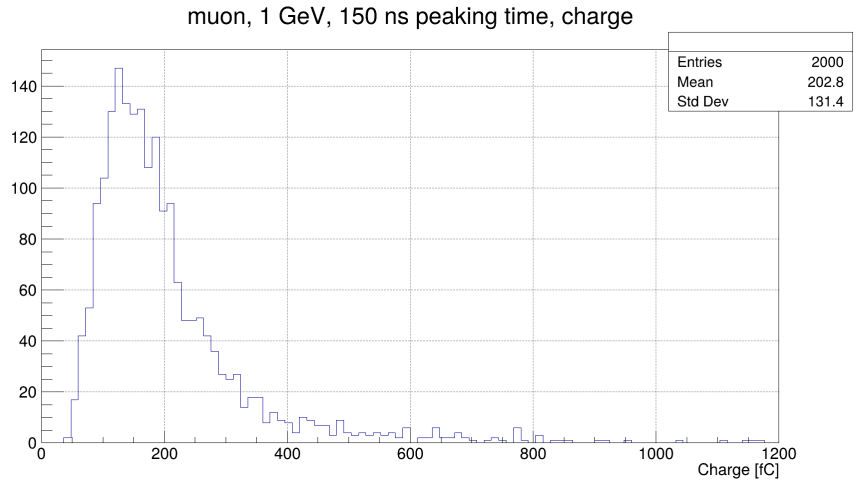


Figure 61: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 150 ns peaking time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 62: Muon, 1 GeV, 2 mm. Peaking time 150 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge for 250 ns vs voltage amplitude

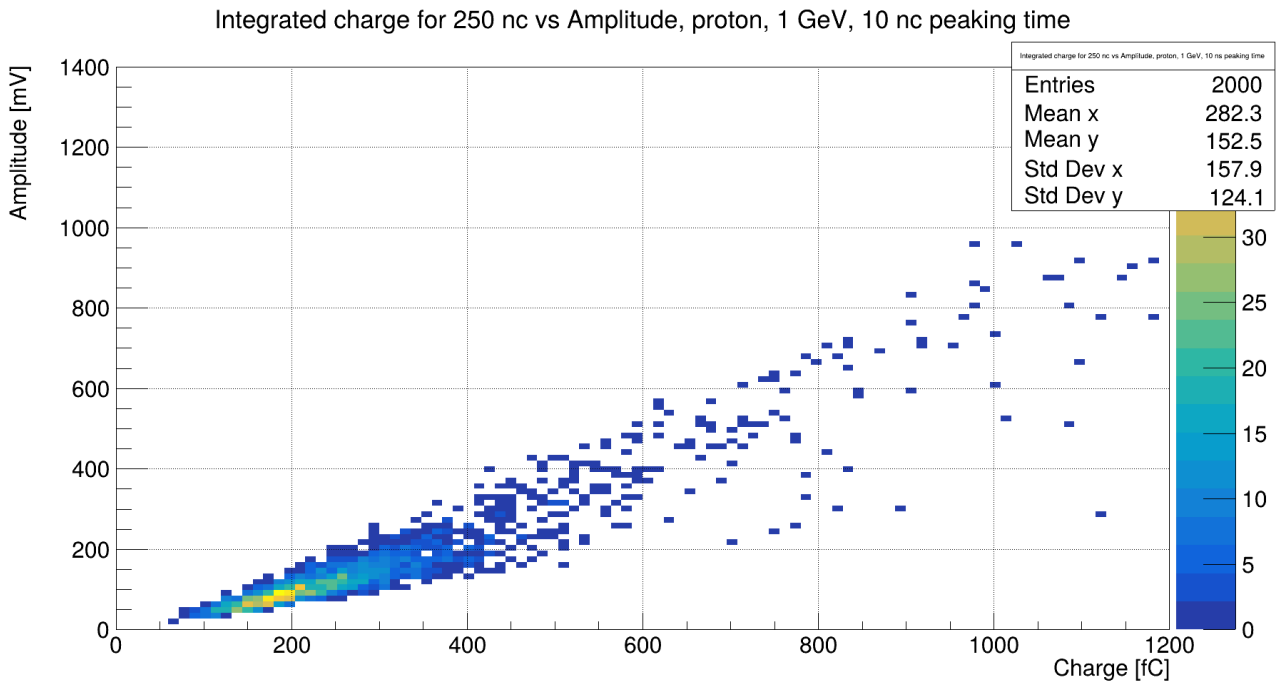
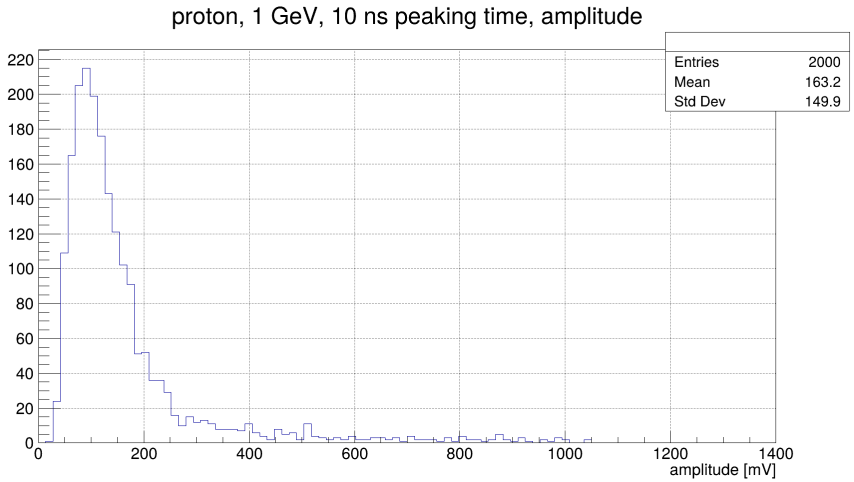
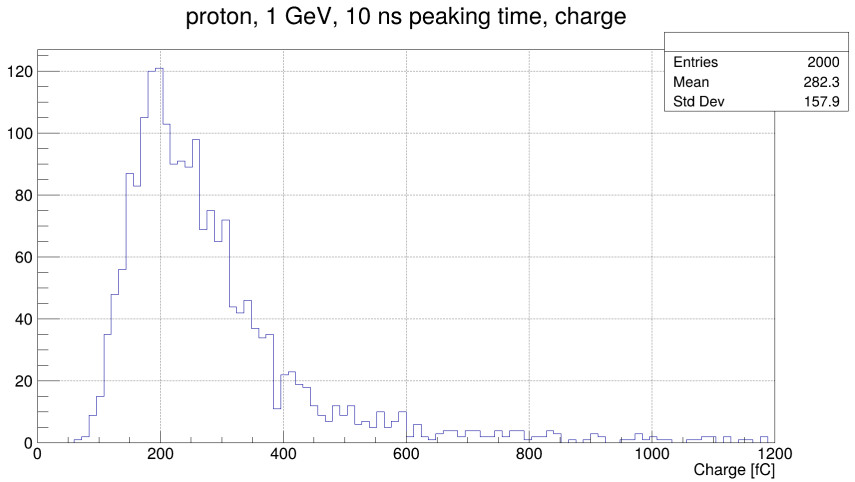


Figure 63: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Proton, 1 GeV, 10 ns peak time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 64: Proton, 1 GeV, 2 mm. Peaking time 10 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge for 250 ns vs voltage amplitude

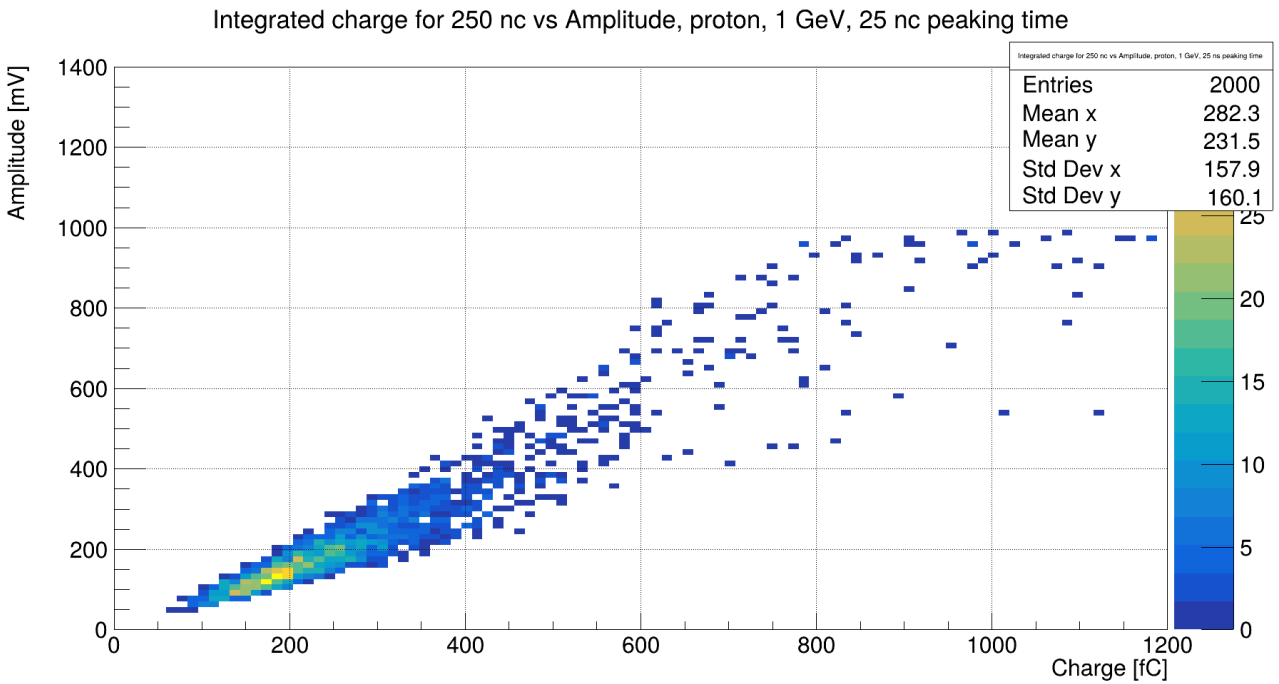
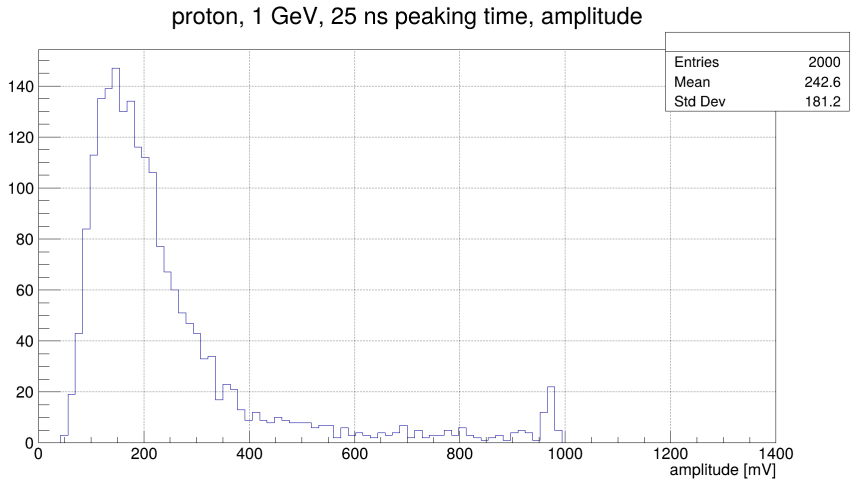
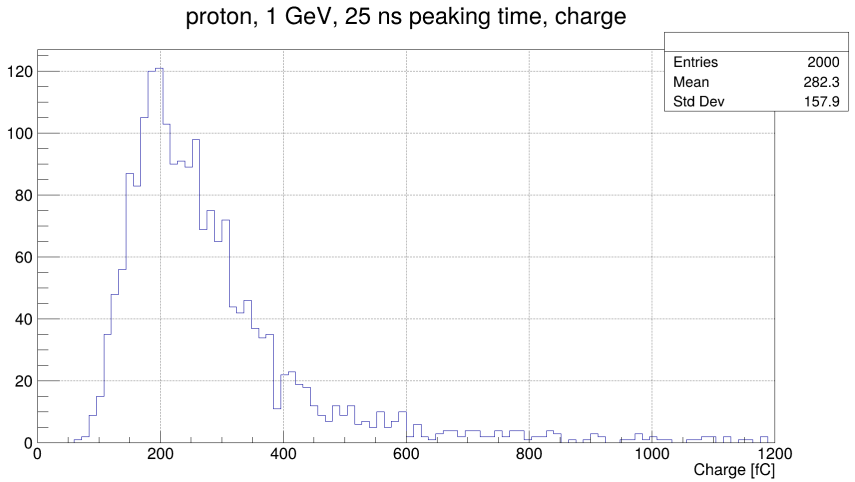


Figure 65: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Proton, 1 GeV, 25 ns peak time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 66: Proton, 1 GeV, 2 mm. Peaking time 25 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge for 250 ns vs voltage amplitude

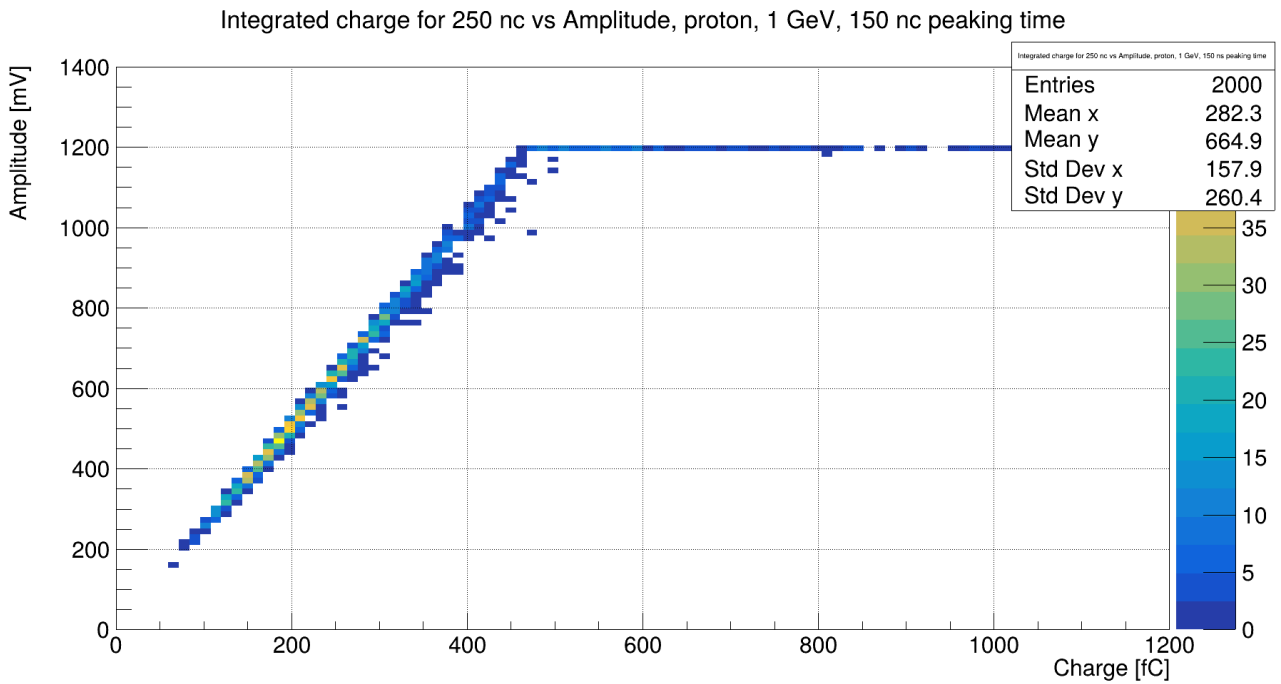
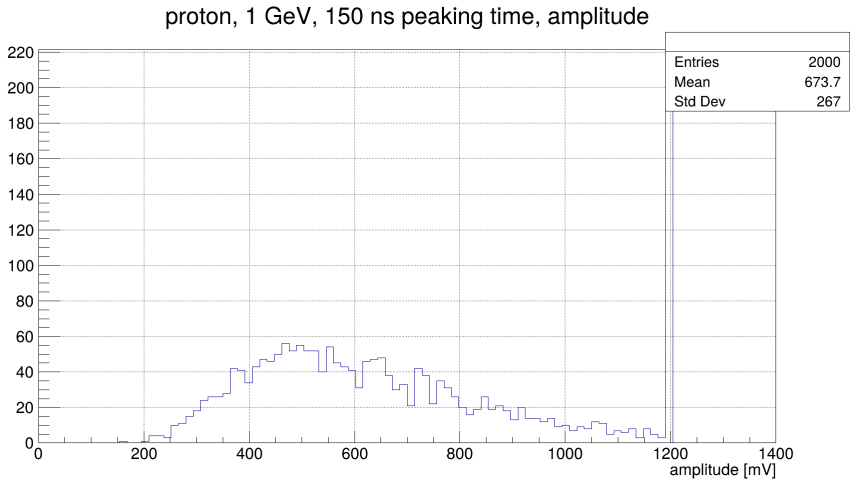
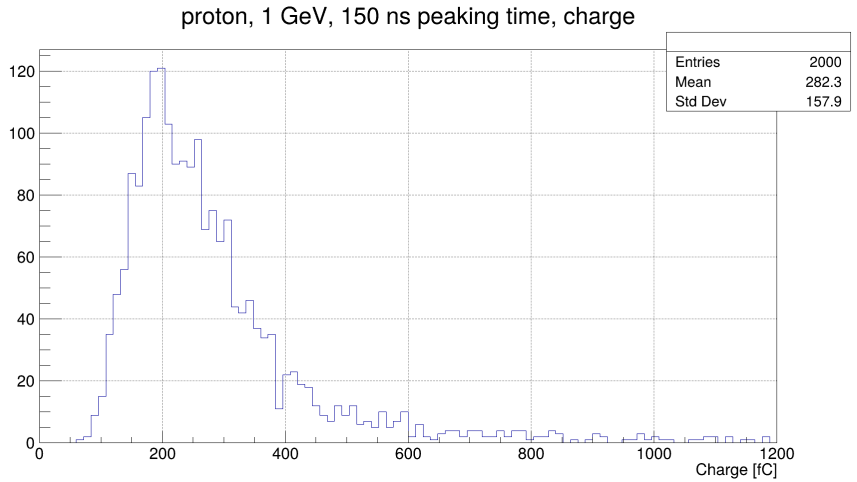


Figure 67: Integrated charge for 250 ns [fC] vs voltage amplitude [mV]. Proton, 1 GeV, 150 ns peak time

Integrated charge for 250 ns vs voltage amplitude



a)



b)

Figure 68: Proton, 1 GeV, 2 mm. Peaking time 150 ns (a) Maximum voltage, 250 nc (b) integrated charge for 250 nc

Integrated charge vs voltage amplitude

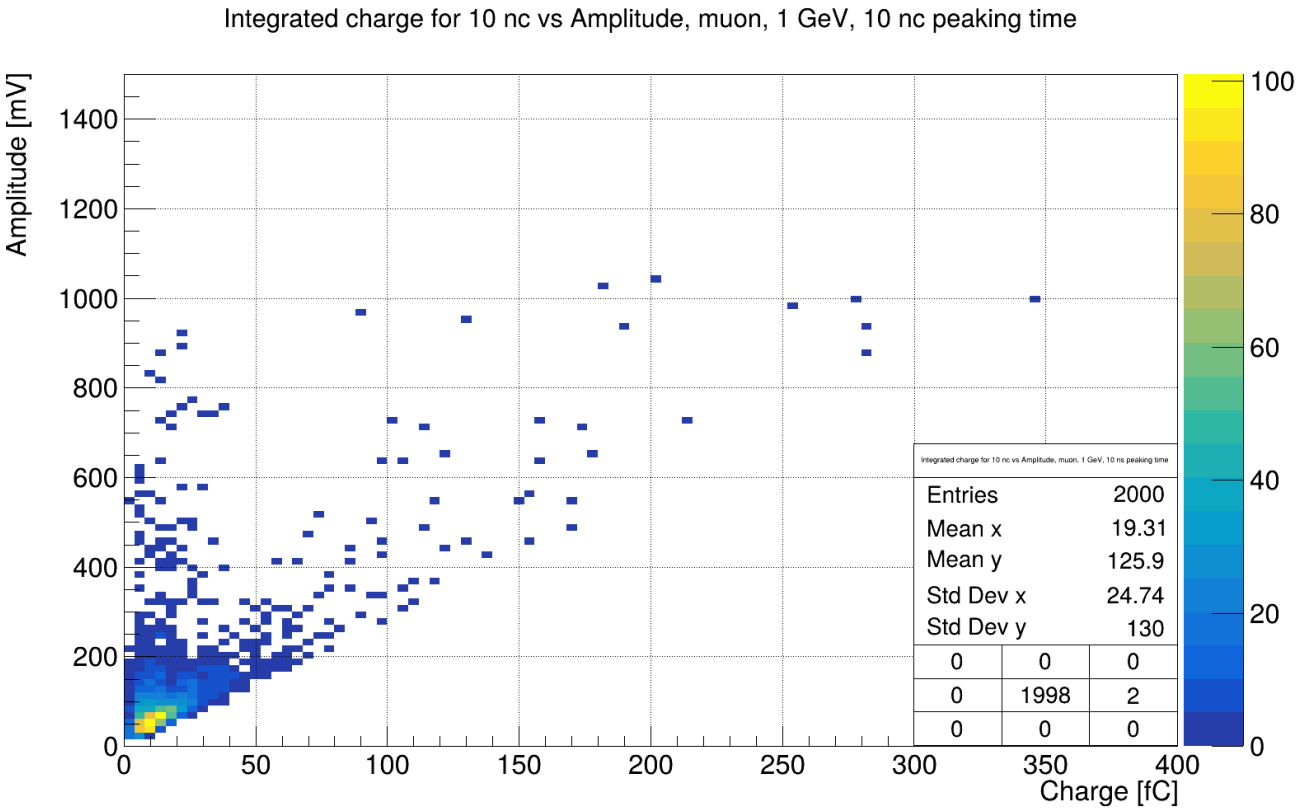
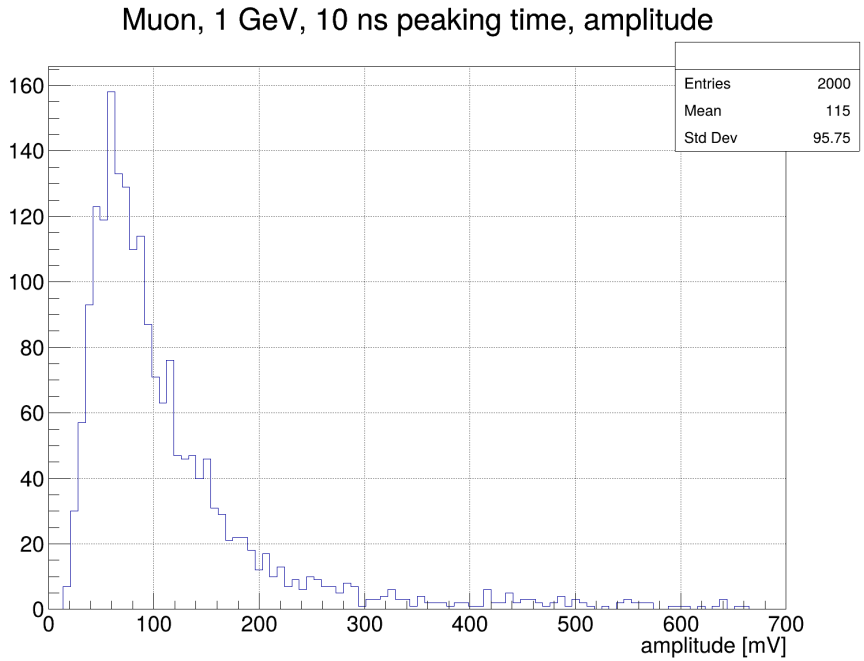
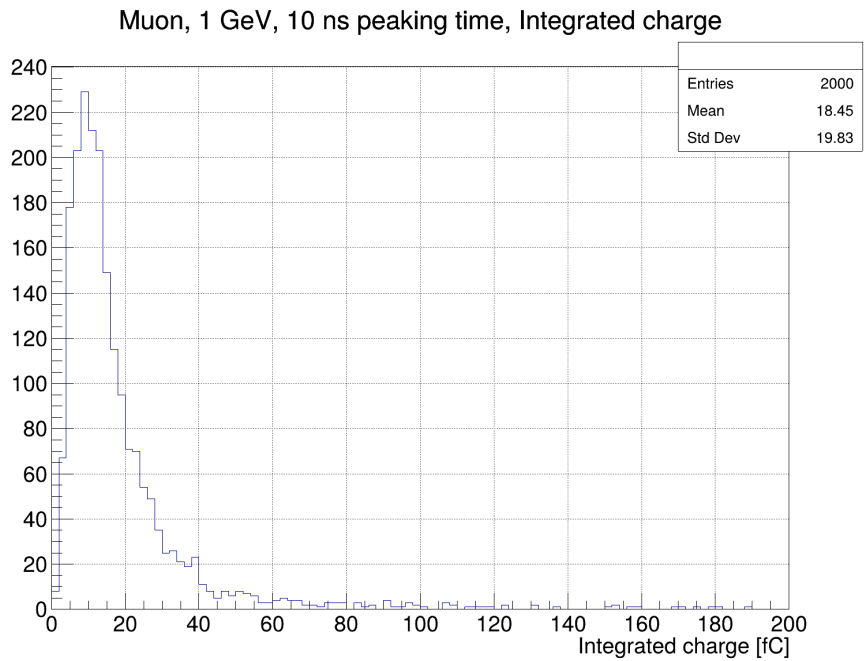


Figure 69: Integrated charge for 10 nc [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 10 ns peak time

Integrated charge vs voltage amplitude



a)



b)

Figure 70: Muon, 1 GeV, 2 mm (a) Maximum voltage, 10 nc (b) Integrated charge for 10 nc

Integrated charge vs voltage amplitude

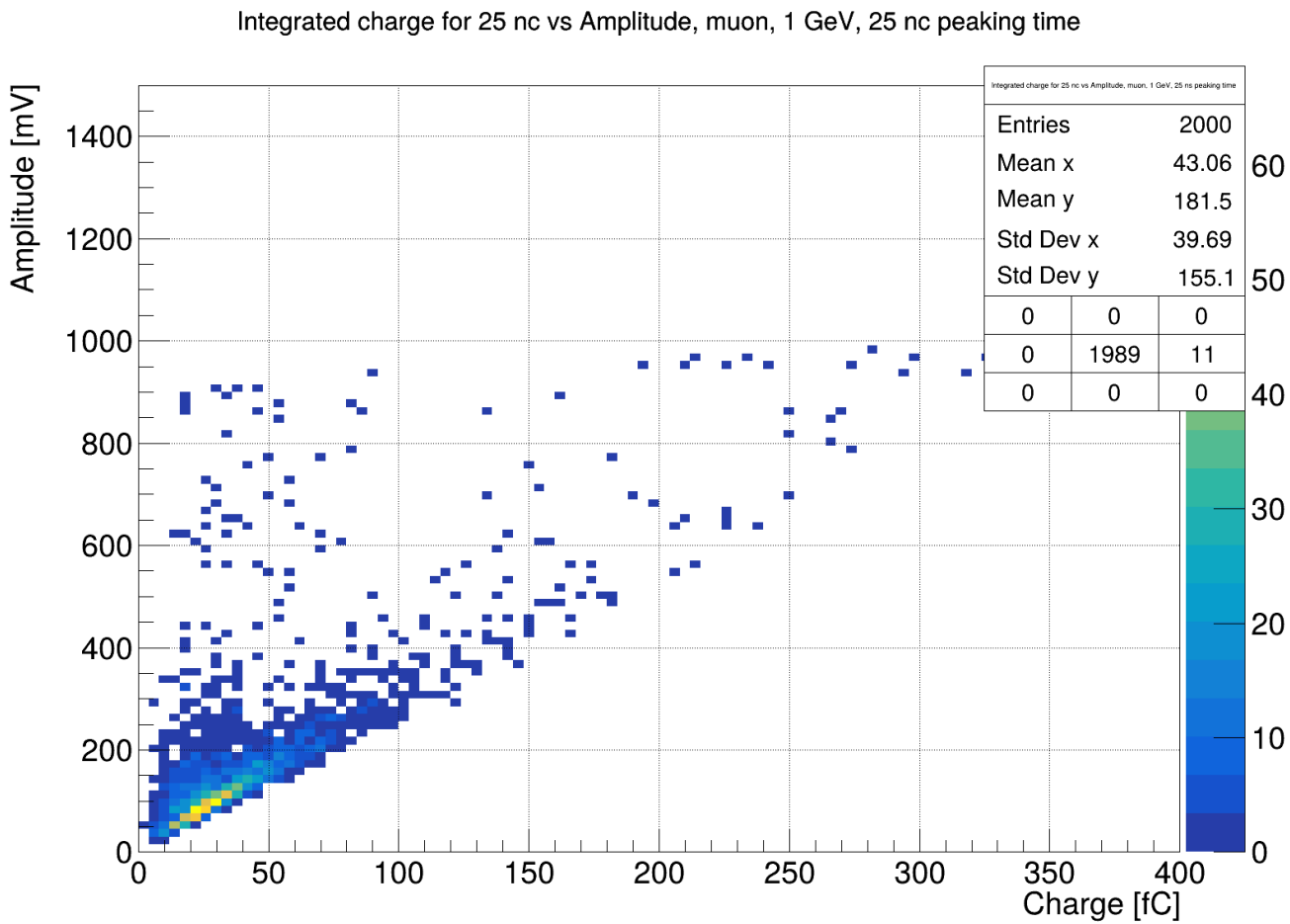
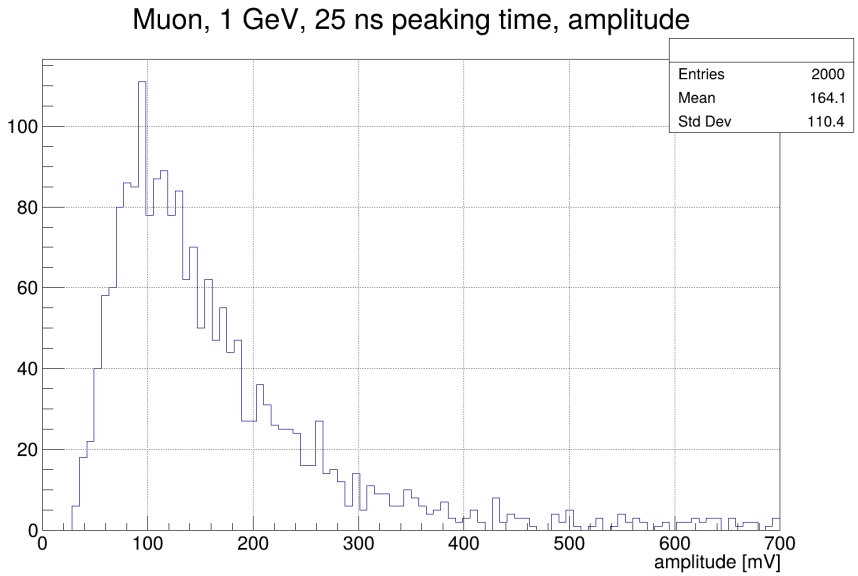
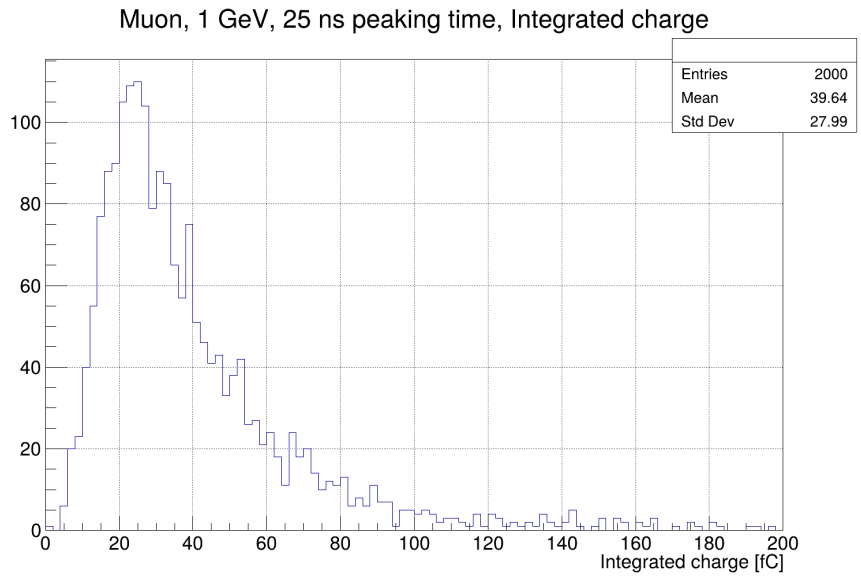


Figure 71: Integrated charge for 25 nc [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 25 ns peak time

Integrated charge vs voltage amplitude



a)



b)

Figure 72: Muon, 1 GeV, 2 mm (a) Maximum voltage, 25 nc (b) Integrated charge for 25 nc

Integrated charge vs voltage amplitude

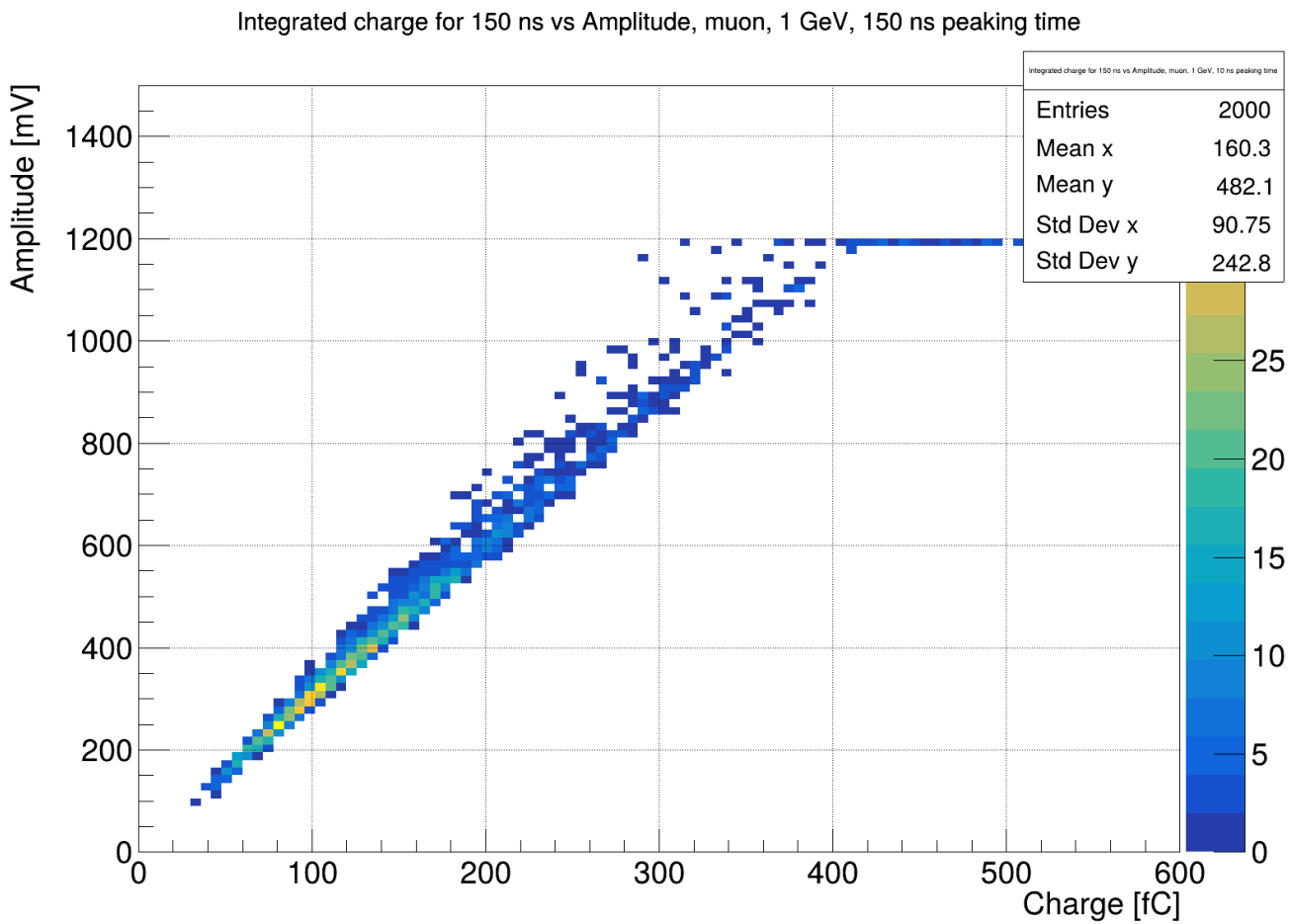
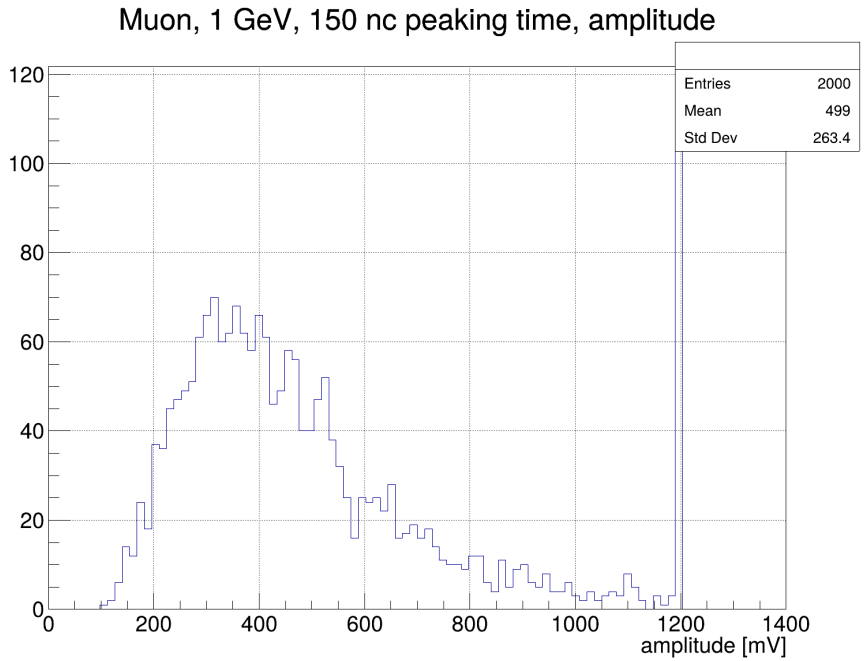
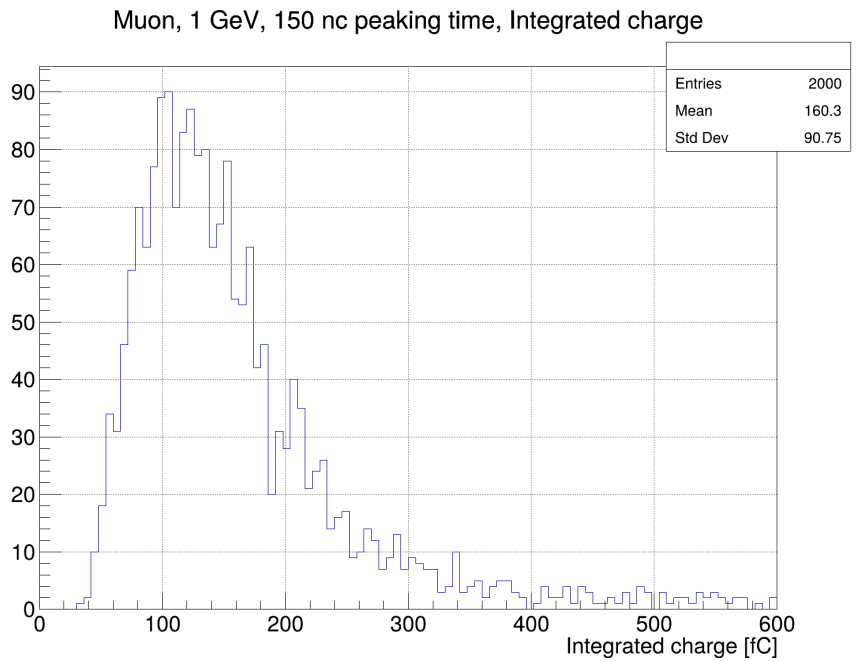


Figure 73: Integrated charge for 150 nc [fC] vs voltage amplitude [mV]. Muon, 1 GeV, 150 ns peak time

Integrated charge vs voltage amplitude



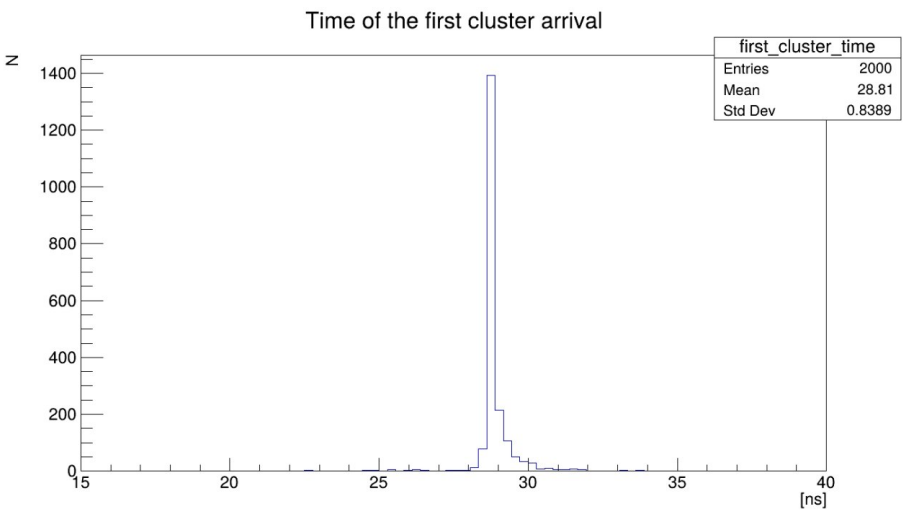
a)



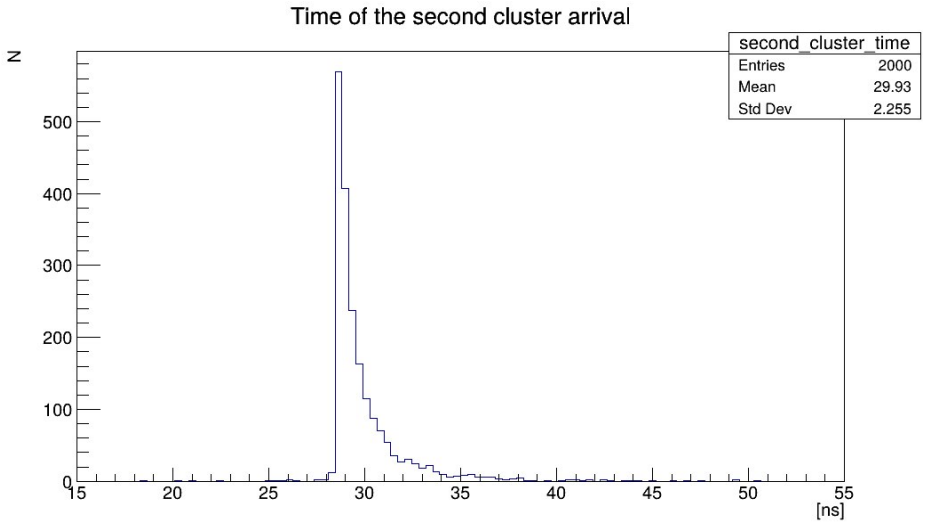
b)

Figure 74: Muon, 1 GeV, 2 mm (a) Maximum voltage, 150 nc (b) Integrated charge for 150 nc

First and second cluster time arrival



a)



b)

Figure 75: Muon, 1 GeV, 2 mm, 1 atm pressure (a) First cluster time arrival (b) Second cluster time arrival