MUSE Test Run Report

The MUon proton Scattering Experiment collaboration (MUSE):

W.J. Briscoe,[1] K. Deiters,[2] E. Downie,[1] R. Gilman,[3] K.E. Myers,[3] E. Piasetzsky,[4] D. Reggiani,[2] P. Reimer,[5] G. Ron,[6] V. Sulkosky,[7] and M. Taragin[8]

[1] *George Washington University, Washington, DC, USA*
[2] *Paul Scherrer Institut, CH-5232 Villigen, Switzerland*
[3] *Rutgers University, New Brunswick, New Jersey, USA*
[4] *Tel Aviv University, Tel Aviv, Israel*
[5] *Argonne National Laboratory, Argonne, IL, USA*
[6] *Hebrew University of Jerusalem, Jerusalem, Israel*
[7] *Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[8] *Weizmann Institute, Rehovot, Israel*

The MUon proton Scattering Experiment (MUSE) collaboration preformed test measurements in the Paul Scherrer Institute (PSI) πM1 beam line during Fall 2012. The measurements were designed to explore the feasibility of measuring simultaneous ep and μp elastic scattering in a beam line developed for π scattering, and thus with significant π backgrounds. Here we report various results of the test measurements.

INTRODUCTION

The Proton Radius Puzzle is the difference between the proton radius of ≈0.84 fm extracted from muonic hydrogen [1] and the radius of ≈0.88 fm extracted from electronic hydrogen [2] and electron-proton scattering measurements [3, 4]. The origin of this discrepancy is not known. Proposed explanations can be categorized as beyond standard model physics, novel hadronic physics, or inaccurate electron data, including underestimated uncertainties. There are several ongoing efforts to provide new data that might give insight into whether there is novel physics or inaccurate data, including additional muonic atom measurements, new electronic hydrogen measurements, lower Q^2 electron scattering measurements, and the MUSE experiment, the subject of this report. MUSE proposes to directly measure muon-proton and electron-proton scattering at the same time, providing new scattering measurements with similar uncertainties to existing ones (≈0.01 fm) and a test of the consistency of muon-proton and electron-proton scattering. Previous such measurements have overall uncertainties ≈10% and are largely not at low Q^2; thus they provide no guidance to the resolution of the proton radius puzzle.

TEST MEASUREMENTS

A major concern of the PSI PAC and the technical review of the MUSE experiment is whether the properties of the πM1 beam are sufficient for the proposed experiment. In particular, the concern is that since the production mechanisms for the different particle types are different, the beam properties might depend on particle type. Charged pions are produced in $C(p, \pi^{\pm})X$ strong reactions, μ's arise from π decays, and $e^{\pm}$ arise largely from $C(p, \pi^0)X$ strong reactions followed by rapid $\pi^0 \rightarrow \gamma\gamma$ decays, with the photons converting in the production target to e^+e^- pairs.

During Fall 2012, nine members of the MUSE collaboration came to PSI for periods ranging from a few days to 3 months to perform test measurements, along with PSI based collaborators. The collaboration assembled a detector system consisting of three planes of scintillating fibers and two high-precision (≈50 ps) scintillators to measure the beam properties. Amplifiers, discriminators, and NIM trigger electronics were PSI equipment previously used in πM1 for the FAST experiment. These were used to generate a trigger that was usually a coincidence of the 4 scintillator phototubes, but was sometimes a "random" pulser trigger. The readout was also recycled from FAST, with VME crates read out into a Linux DAQ computer through a CES PVIC 8025 PCI bridge. VME electronics included a 262 I/O register and CAEN v767 TDC used in FAST, along with CAEN v1190 100-ps TDC, v1290 25-ps TDC, and v792 QDC brought by the collaboration. The DAQ software was a modified version of MIDAS, adjusted for the PVIC bridge, with new v1290 and v767 readout routines. Replay was based on the TRIUMF package ROOTANA.

The measurements tested the fractions of the beam that were π's, μ's, and e's, the spatial distributions of various particle types at the target and at the intermediate focus point (IFP), and the momentum dispersion of particles at the IFP. Measurements were also taken to help validate simulations of energy loss in detectors.

ISSUES

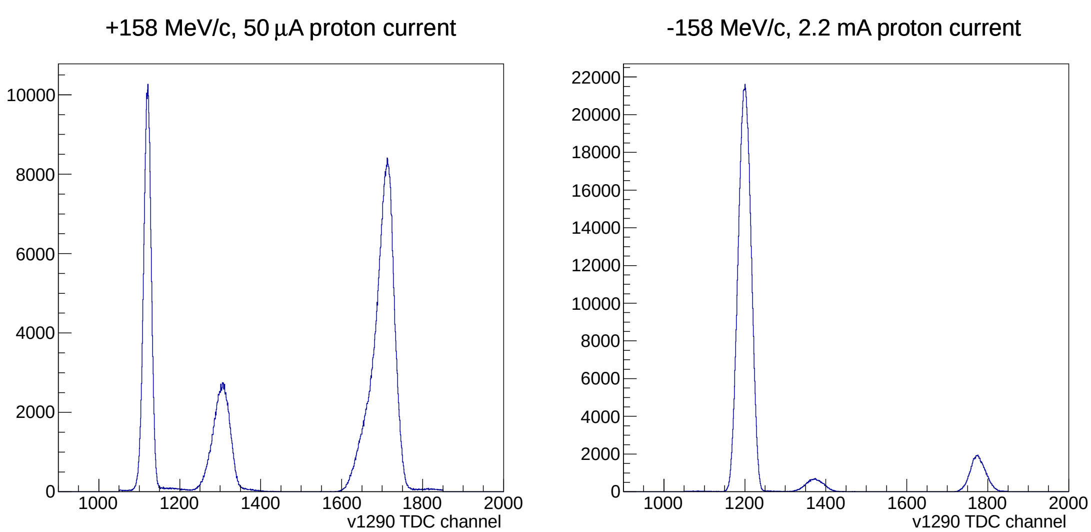
A number of issues were enountered during the test run, typical of any test measurement. Examples include a short in a channel quadrupole and various problems with detectors, electronics modules, cables, trigger, and the data acquisition system. These problems were resolved sufficiently well that they do not affect any of the results presented here.

One problem in particular that we continue to work on is the tuning of the πM1 beam. It has been several years since anyone has requested a small spot from the πM1 channel. For the majority of the results presented here, the data were taken with a spot a few cm wide in the vertical, nondispersive direction, and several cm wide in the horizontal, dispersive direction. It should not be a surprise that the beam tuning of many years ago could not be repoduced in an afternoon. Subsequent beam tuning reduced the spot size to a few cm in each direction. With the smaller spot we reconfirmed that the distributions of the different particle types on target are the same. Old reports on the πM1 beam line indicated that up to $\approx$2% adjustments in quadrupole settings and 50-100% adjustments in dipole trim coils are needed to remove the residual momentum dispersion and fine tune the beam settings. As of this writing, additional beam tuning studies are in progress. We do not view the problem of minimizing the spot width as a fundamental problem, as small spots were routinely obtained 30 years ago, but it will need to be worked on.

RF PEAK WIDTHS

An issue raised by the technical review committee was that the width of the proton beam in time at the M target was about 1 ns – it was not clear if this was σ or FWHM – and this would affect plans to measure beam particle ID through RF time. Subsequently upon investigation, we were told that the rms time width of the proton pulse leaving the cyclotron is about 254 ps.

We further investigated this issue using the measured width of the electron peaks in corrected RF time. An example is shown in Fig. 1. An increase in the time width of particles is expected as higher proton beam currents are achieved in part by having a proton pulse that occupies a larger fraction of the RF phase – that is, the proton pulse is wider in time. No effect is expected from changing the magnetic fields from positive to negative polarity, as the channel set up should be essentially symmetric. The electron peak at 2.2 mA proton beam current has a $\approx$360 ps (σ) width. Pion and muon peaks in these runs are slightly wider, closer to 500 ps. This appears to result in part from variations in β for the π's and μ's due to the momentum acceptance, and partly from the width of the beam in x at the target – our scintillator position – not being entirely corrected out,



(a)Run 180, 158 MeV/c, 50 μA proton beam current. (b)Run 211, -158 MeV/c, 2.2 mA proton beam current.

FIG. 1. Corrected RF time spectrum measured in the v1290. A 1-cm wide collimator slot limited the channel momentum acceptance to about 0.14%. The three peaks seen in the v1290 spectra are the e peak near channel 1100, the μ peak near channel 1300, and the π peak near channel 1700. (The few ns shift in the peaks between the two runs largely reflect adjustments made to the trigger timing.) At the higher current, the electron rms peak width increases from 9.2 to 14.5 channels, or from 230 to 360 ps.

leading to RF time varying somewhat with position in the scintillator. Comparison of the times in the phototubes on the same sides of the scintillators indicates that our time resolution is at least about 100 ps (rms). We had planned to identify beam particles in hardware with about 1-ns resolution (σ); at this level the few hundred ps width of the particles is not an issue. We conclude from the results here that the rms width of the proton pulse striking the production target is not a significant issue.

We note that the β variation of π's and μ's leads to time variations of several tenths of a ns, much larger than any affect from the intrinsic width of the proton beam. We conclude that there is no indication that the width of the proton beam is a significant issue.

BEAM FRACTIONS

The π, μ, and e fractions of the beam depend on beam polarity and momentum. We separate the different particle types by measuring RF time of the particles arriving at our high-precision scintillators. Our ability to separate the different particle types in RF time depends on the time resolution and position of our detectors. With our detectors positioned at about $z = 23$ m from the M production target, the optimal beam momenta for separating particles in RF time are about 114, 158, and 210 MeV/c. The spectra of Fig. 1 give examples that indicate the peaks are well separated; similar separation was achieved at 114 and 210 MeV/c.

TABLE I. Measured particle fractions in percent. The previously estimated numbers are in parentheses.

Momentum (MeV/c)	114/115	153/158	210
μ^+	8.8 (14.0)	11.8 (15.0)	7.7 (6.2)
e^+	82.3 (84.3)	46.2 (42.0)	10.7 (7.4)
π^+	8.8 (1.7)	42.0 (42.0)	81.5 (86.4)
μ^-	2.7 (3.2)	3.4 (5.1)	15.4 (5.0)
e^-	97.0 (96.4)	85.7 (80.8)	40.0 (35.0)
π^-	0.3 (0.4)	10.9 (14.1)	44.6 (60.0)

DEPENDENCE OF BEAM SIZE AT TARGET ON PARTICLE TYPE

The trigger scintillators at the target, SA and SB, were both $5 \times 5 \times 50$ cm^3. Generally, the runs were performed with scintillator SB immediately behind SA, and the scintillators were positioned so that the center of the beam went approximately through the center of the scintillators. Both scintillators had two phototubes, one at each end, and a trigger usually required signals in all 4 phototubes. Cable lengths were set so that generally the tube SA-right (SAR) determined the timing. For some of the runs there were multiple peaks in the SAR spectrum, indicating that the timing was determined instead by other signals, and in this case software cuts were used to select the SAR self-timing peak. Because the beam is broad in the x direction, this trigger logic leads to the RF time depending on where the particle passes through the scintillator SA. All phototube, coincidence, and RF signals were sent into the v1290 TDC, and as a result the difference in times from SAL and SAR could be used to correct the raw RF time to get a narrower corrected RF time, which was shown previously. The trigger and beam RF time were also included in the v1190 TDC with the target SciFi array. The individual phototube time signals for SAL and SAR were added so that a corrected RF time could be generated, starting with run 215. (However, starting with run 239 the IFP SciFI array was moved into the 1190, along with the trigger, RF, SAL, and SAR times.)

The corrected RF times were used to determine particle types, and then the runs at various beam momenta were analyzed to determine if there were any clear difference between the distributions of the particle types at the target. In the x direction, no clear difference was found; it was found that since RF time varies with position in the scintillators, great care has to be taken in making this comparison. Of course, the distribution is wide in the x direction and we would be insensitive to small differences. In the y direction, no clear difference was found, though there was a hint that the π distribution is marginally wider than the μ or e distributions. A speculation is that, as the π's decay rate is about 10%/m of travel, there is a percent level admixture in our pion distribution of muons from pion decay just before the target, and these μ's have a broader distribution than the π's.

BEAM DISPERSION AT THE IFP

Several measurements were performed using a ≈1 cm slot in a 5-cm thick lead brick wall at the IFP to limit the beam momentum variation. The slot was positioned in three locations: approximately at beam center and at about ±5.5 cm. Our knowledge of the positions is quite approximate. Since the dispersion is 7 cm/%, this implies that we were at the central beam momentum and at about ±0.8% from the central momentum. Some results are shown in Fig 2. The electron RF time was found to be consistent with not moving as a result of shifting the slot.

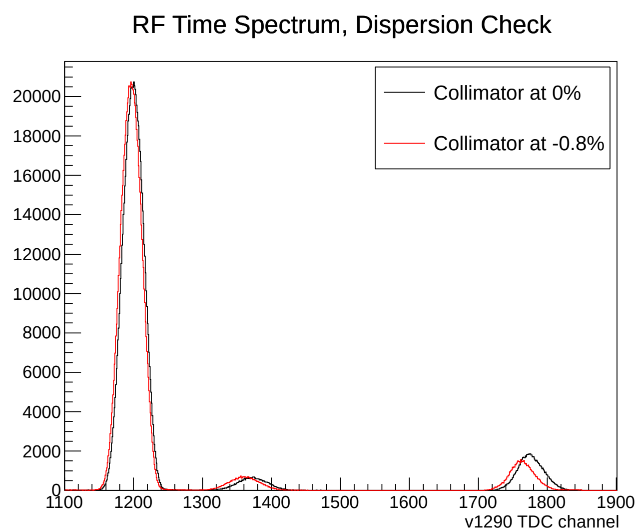


FIG. 2. RF times at the target for some runs checking dispersion with a collimator at ≈0% (black spectrum) and ≈−0.8% (red spectrum). Beam conditions were 2.2 mA of primary protons, with front jaws set to 300. Small shifts in the μ peak at the right near channel 1350 and the π peak near channel 1800 can be seen, while the electron peak position is essentially constant.

The shift in pion and muon times was roughly consistent with expected time shifts; a simple fit to the data implied that the scintillator positions were $z \approx 23$ m, with the shift in the slot being roughly 0.6% in momentum. At this stage of the analysis, the result is preliminary and the uncertainties are not well determined; also it is not clear that the channel dispersion was actually set to 7 cm/%. The important finding is that the shift in π, μ and e peak positions is about what we expect, so that the position at the focal plane can be used to determine particle momentum. A more thorough study of the channel dispersion was not carried out at this time due to the lack of a remotely operated collimator and the radiation levels at the IFP.

BEAM SIZE AND RATES AT THE IFP

The beam size in the IFP region was studied for particles arriving at the target region, and also with a pulser (in effect, a random trigger) to study the full distribution at the IFP and thus backgrounds for a detector setup. The distributions were in all cases determined with a SciFi array consisting of 96 3-mm-wide fibers with active area about 20 cm long. We have not at this time determined the fiber efficiencies adequately, so rates quoted are approximate. The rates were determined by counting the total number of hits from the SciFi array in the ≈270 ns time window of the TDC.

The horizontal distribution was found to be ≈20 cm wide, as expected. We subsequently rotated the SciFi array to determine the vertical distribution. But we first determined the vertical distribution for events reaching the target using a collimator wall. Nominal beam height is 25-30 cm above the IFP "table", and the wall, made of lead bricks oriented to be 5-cm thick should have stopped all articles from reaching the target. In run 221, we had the front jaws set to 75, and a collimator up to 30 cm high above the "table" with a 1-cm gap at $\delta \approx 0\%$ and a 1.2 kHz trigger rate. This implies the full rate without a collimator would be about 20 cm × 1.2 kHz/cm = 24 kHz, assuming the distribution is roughly flat. For run 222, we closed the gap and completely blocked the beam up to 30 cm, leading to a 30 Hz trigger rate. Thus it appears that the fraction of the beam at the IFP that is not in the nominal 5-cm high beam region but that reaches the target anyway is on the order of tenths of a percent.

In runs 269 - 274, the beam momentum was varied in both + and - polarities from 114 to 158 to 210 MeV/c, with a proton beam current of 2.2 mA. A 4 mm plastic shield was placed before the SciFi array to range out any protons. Front jaws were set to 200.[1] Table II shows the resulting rates in the IFP detector. At the time of these measurements the SciFi array was oriented to determine vertical position, and measured particles from about 5 cm below to 25 cm above the central beam height. A "random" pulser trigger determined singles rates in the array, by counting the number of hits per event in the ≈270 ns time window of the v1190 TDC. It should be noted that we have not at this point studied the efficiencies of the fibers carefully, so these numbers should not be taken to be precise.

TABLE II. Rates in IFP SciFi array.

Run #	Momentum (MeV/c)	Rate (MHz)
272	+114	120
273	+158	190
274	+210	180
271	-114	55
270	-158	100
269	-210	10

The rates in Table II are about an order of magnitude greater than the rates at the target, for several reasons. First, a good fraction of the particles, particularly at higher momenta, are π's, and the π survival fraction from the IFP to the target is about 21%, 31%, and 43% at 114, 158, and 210 MeV/c, respectively. Second, as can be seen from Fig. 3 and the discussion above, about half of the rate is particles outside the envelope of the beam that will reach the target – and which our detector in the experiment should not measure. Third, there is the background of apparent neutrons at the IFP that does not reach the target; this background is spread out in RF time. A measurement with the πM1 channel magnets off and the beam plug closed yieleded a 6 MHz rate

[1] Note that rates at the IFP with jaw settings of 200 cannot be easily compared with rates at the target with jaw settings of 75 discussed earlier. The jaws are apparently fully closed when set to ≈50, so if the distribution were flat, which we do not expect, increasing all jaw settings to 200 increases the beam flux by a factor of about $6^4 \approx$ 1300.

in the IFP SciFi; with the beam plug open the rate was 30 MHz. We expect all of these events are neutrons. The IFP used in the test measurment was at least a factor of 6 larger than needed for the beam envelope, so the rate during the actual experiment will be significantly less than the numbers in Table II.

Thus there are a number of particles that might contribute to detector rates without being able to reach the target. It is clear that rates at the IFP need to be kept at no more than 10s of MHz, so that there are not too many accidental coincidences with real triggering particles that would impair triggering efficiency and data analysis. The observed rates appear to require that we implement a collimator in the IFP region so that background and singles rates can be limited; the distribution shown in Fig. 3 indicates that about half of the rate at the IFP is unwanted backgrounds that will not reach the target. Also, it is clear the IFP detector has to be carefully designed so that it is only sensitive to the region from which particles can reach the target.

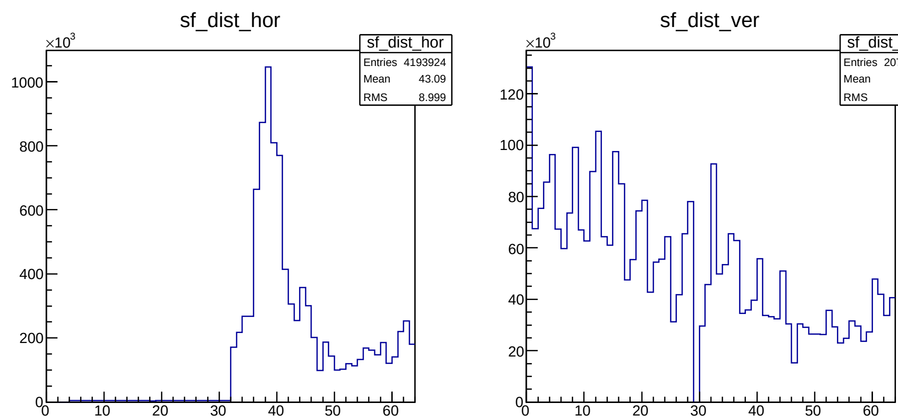


FIG. 3. Hits as a function of fiber number for the SciFi array at the IFP. *Here the 96 fibers are put into the final 32 channels of the horizontal histogram and the 64 channels of the vertical histogram.* Data were taken with positive beam polarity at 158 MeV/c, using a random pulser trigger. Due to the construction of the array and the configuration at the IFP, the array was offset vertically so that the beam went through the array close to one end.

For runs 285-287, the vertical distribution at the IFP was measured with the SciFi array turned sideways. The vertical distribution of hits at the IFP region is shown in Fig. 3. It was observed that while the distribution is 10s of cm's broad, it basically consists of a narrow peak about 3 cm FWHM and 5 cm at the base above a broad background. We believe these observations are consistent with our description to the technical review committee. The pions form a well-defined beam at the intermediate focus. Muons at the intermediate focus have a much broader distribution than the pions, because of pion decays near the IFP. But muons that reach the target occupy the same phase space as the pions that reach the target.

Finally, in run 288, we ran with a random trigger, channel magnets off, and the KSD11 plug in. The total rate in the SciFi array was about 6 MHz with 2.2 mA proton beam current. The distribution of events was broad. The conditions suggest that the events arise from low-energy neutrons that bounce up the πM1 channel. Note that the active area of the array was about 20 cm $\times$ 29 cm. In the experiment, this will be reduced at least by using a detector with an active area about 5$\times$ smaller, and perhaps that is insensitive to neutrons.

Combined, these observations support our argument at the technical review that the IFP distribution of particles that make it to the target is narrow, consistent with the π distribution. While the distributions of μ's at the IFP is broader, the broader component of the μ beam does not reach the target.

PROTONS

In principle there is an enormous rate of protons that can pass through the channel when it is set to positive polarity. Since the channel in the proposed experiment is set to low momenta, 115 - 210 MeV/c, the protons have small β's that vary by large fractions across the acceptance, leading to broad peaks in RF time. The protons, being low in energy, can be ranged out before the detectors by using plastic absorbers ranging in thickness from sub mm up to several mm. In the test measurements, with a range of momenta up to +225 MeV/c, there was no clear indication of protons in our data. Protons appear to be more of an issue at higher momenta. Many of our measurements used a 4 mm plastic shield in the IFP region, and this might have been sufficient along with other material in the beam line to range out any protons – but we would expect about 6-7 mm of plastic is needed. The similarity in rates at the IFP between +158 and +210 MeV/c indicates that protons are not a problem for our selected momentum range.

SIMULATIONS

Several runs were taken in various configurations to provide data that would help validate the simulations. Here we show two examples.

Figure 4 shows how the RF time spectrum at the target changes when an additional 2 cm of plastic is added at the IFP region, leading to multiple scattering and energy loss for beam particles. These runs were at -150 MeV/c. The three peaks are (from left) the π's, e's, and μ's. Note that for the π and μ peaks the higher β particles tend to be on the right side of the peak, while the smaller β particles tend to be on the left side of the peak. The basic effect of adding in the additional plastic is to broaden the π and μ peaks about 15%, creating more tail on the left, slower side of the peaks.

Figure 5 shows QDC spectra for the South Carolina trigger scintillators for two runs. In both cases we see more indication of peaks corresponding to different particle types for the rear (SB) scintillator than for the front, due to the lower energy and greater dE/dx separation. In run 223, the trigger was a 4/4 coincidence, plus a small number of pulser triggers leading to the small

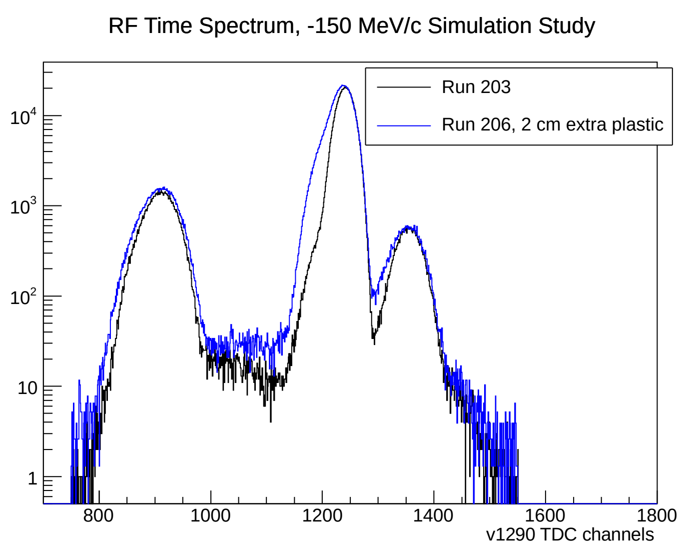


FIG. 4. RF time spectra for run 203 (black) and run 206 (blue). Conditions were the same, except for an extra 2 cm of plastic added into the IFP region for run 206.

pedestal peaks. The small low signal bump is more prominent for the rear scintillator; it was expected from simulations, and it results from particles passing through a corner of the scintillator leading to reduced energy deposition. Due to the coincidence, this is suppressed for the front scintillators, but can occur for rays still coming to a focus. For run 232 scintillator SB was moved 2 cm back from SA and was taken out of the trigger. Now the low signal bump appears more prominently in SA, since incoming beam particles that scatter out of SA can still lead to a trigger, and there are more pedestals and low dE/dx events in SB as it is no longer in the trigger.

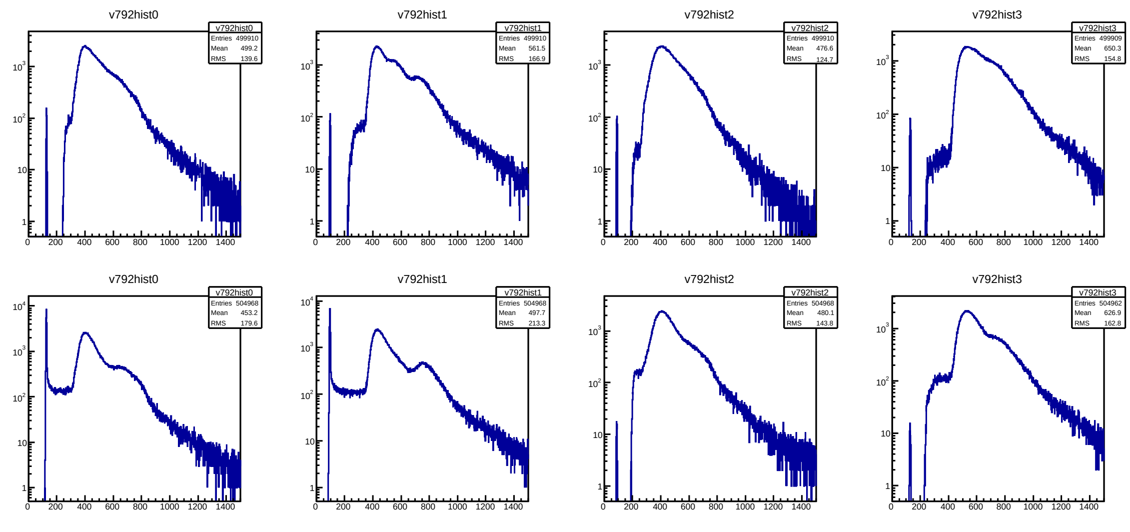


FIG. 5. QDC spectrum for trigger scintillator phototubes from runs 223 (top) and 232 (bottom) at -158 MeV/c. The spectra are for (from left) SBL, SBR, SAL, and SAR. See text for details.

SUMMARY

During Fall 2012, the MUSE collaboration undertook a series of beam studies in the PSI πM1 channel to check whether the channel is suitable for measuring precise μp and ep elastic scattering cross sections. Many of the potential issues suggested to us turn out to not be issues, but several difficulties have arisen that we do not believe are issues in principle. The positive results reported here include the following:

- *One concern expressed was that the time-width of the proton beam is about 1 ns, which would prevent our identifying particle types in hardware.* We find that the time-width is 250 - 500 ps (σ), and is not an issue, given the ≈1.25 ns binning planned for hardware particle identification.

- *One concern was that the sizes of the π, μ, and e beams at the target are different.* We found no significant difference between the π, μ, and e distributions in our SciFi array at the target position. There is a small indication that the π beam is slightly wider, perhaps due to μ's from π's near the target being identified as π's. This finding needs further study once the beam tune is further developed.

- *One concern was that the momentum dispersion of π's, μ's and e's would be different at the intermediate focal point.* We studied the time variation of π, μ, and e RF time peaks as a narrow collimator about 0.14% wide in momentum was moved between nominal positions of -0.8%, 0%, and 0.8% in δ. The shift in the peaks was consistent with a 0.6% shift, basically consistent with the expected dispersion given the uncertainties in the beam tune and measurements. This finding needs further study once the beam tune is further developed.

- *One concern was that the distribution of different particle types is different at the IFP.* We find that essentially all particles that reach the target are within the envelope calculated for pions with TURTLE, a region at the IFP that is about 5 cm high by 20 cm wide.
- *One concern was with high proton rates in positive polarity.* We find no significant proton rate for the momenta of this experiment.

On the other hand, there are several issues needing work, some of which will require additional test time. There include the following:

- The beam tune needs to be re-established.
- Backgrounds from the channel need to be better studied. We believe it is a better technique to reduce beam flux by using a collimator at the IFP region rather than the front jaws; it appears that the front jaws should simply be left opened.
- Our SciFi detector design for the IFP needs to be reworked, to have improved time resolution and decreased sensitivity to backgrounds.
- While the electronics for the measurement will be different from the test run, we need to understand better the signal being uncorrelated when read out in two different modules.

We do not believe that any of the difficulties represents fundamental problems for the experiment. They merely make it clear that we need to thoroughly study our equipment and electronics to validate that the experiment works in practice.

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