Single-Arm BigBite Trigger Rates Estimation for the Precision Measurement of the Neutron Magnetic Form Factor - JLab experiment E12-09-019 and GEn-Recoil - JLab experiment E12-17-004

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1. Introduction

In this article, we report the single arm BigBite trigger rates for GMn experiment which have been estimated using the data we have got via simulation. Additionally, we have also estimated HCAL rates for all the Q^2 points to assess the possibility of coincidence trigger between BigBite and HCAL to keep the DAQ rates manageable. In order to make the estimation as realistic as possible, we have tried to imitate the exact experimental setup in the simulation and have also used the original trigger logic for analysis.

2. Procedure

We have used g4sbs to run the simulations. In this experiment the signal process is quasi-elastic electron-nucleon scattering and the dominant background processes contributing to the total single-arm trigger rate in BigBite are inclusive inelastic electron scattering and the inclusive production of single pions. Hence, to get the total trigger rates for each Q^2 point we have added the estimated rates of all the five processes (i.e. elastic, inelastic, π^+, π^0, and π^-) together by investigating them individually.

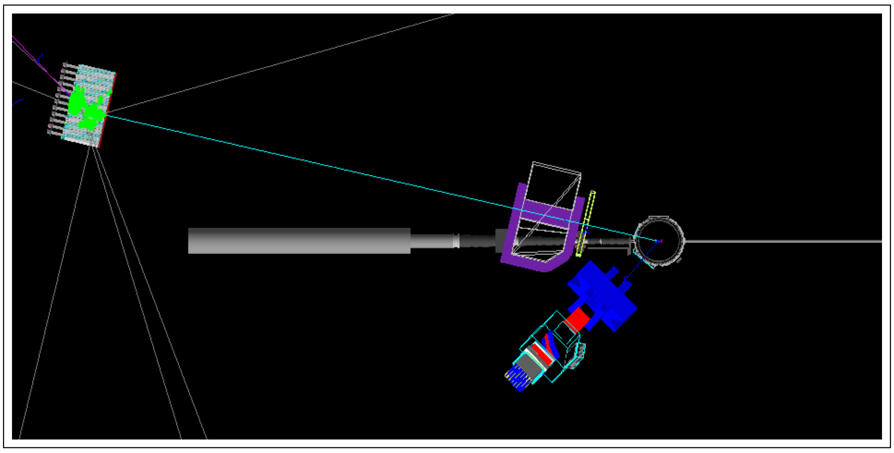

Figure 1: A screenshot of the simulation of GMn experiment for $Q^2 = 12$ GeV^2 setup.

Wiser generators have been used to estimate the BigBite rates for pions but for the HCAL rate estimation we have used "minimum bias" GEANT4 simulations to avoid the fact that Wiser generators overestimate the pion rates significantly in case of forward scattering angles and low energies. A beam current of 30 μA and LD2 target with a length of 15 cm have been assumed for all Q^2 points and all the other parameters have been properly tuned according to the GMn run plan [1].

3. Data Analysis and Results

The data has been collected according to the above described procedure and the analysis have been done in the following two stages.

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3.1. *Threshold Estimation*

We have first estimated the threshold by fitting the rate vs. energy sum plot for elastically scattered electrons using a Gaussian function for each kinematic point. In order to get rid of any unwanted secondary peaks in the rate vs. energy sum plots we have used a few cuts such as selecting only primary particles, selecting the tracks with hits on all five GEMs, the ratio of the track momenta to the initial momenta to be greater than 99% and so on. The trigger rates have been estimated at three threshold values set at 2σ, 2.5σ, and 3σ below the elastic peak for each kinematic point. Fig. 2 shows a few example plots used to estimate the threshold for different Q^2 values.

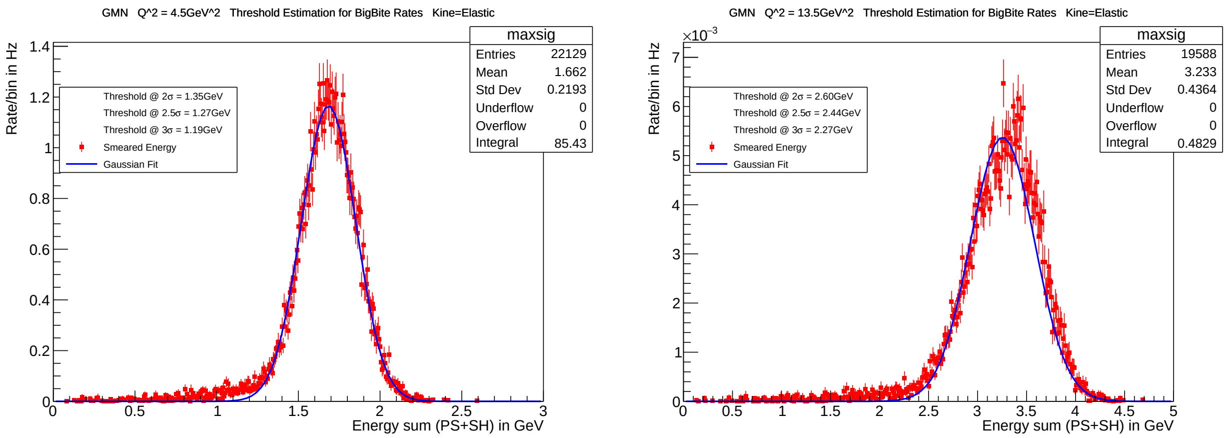

Figure 2: Threshold estimation for $Q^2 = 4.5$ GeV^2 & 13.5 GeV^2 (left to right). Energy sums between Pre-Shower and Shower groups have been calculated using trigger logic described in Sec. 3.2.1 and a few cuts (refer to Sec. 3.1) have been imposed to get rid of any secondary peak. The data have been fitted with Gaussian function (blue line) to find the mean and standard deviation.

Energy distribution of elastically scattered nucleons have been used to estimate the thresholds for HCAL rate analysis (Fig. 3). In this case, instead of setting the threshold at multiple standard deviations below the elastic peak we have set it at 90% efficiency for all the Q^2 points. Here efficiency has been defined as the ratio of total rates (for elastically scattered nucleons) above the threshold to the total rates (for elastically scattered nucleons) for the entire energy range.

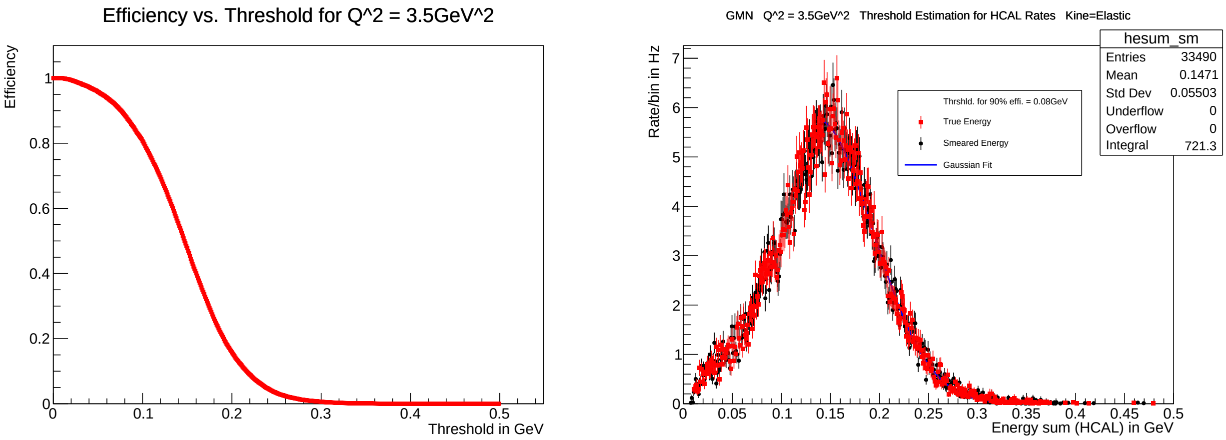

Figure 3: Threshold estimation for HCAL rates analysis: $Q^2 = 3.5$ GeV^2. The left plot is showing efficiency (refer to Sec. 3.1) for definition) as a function of threshold while the right one is showing the rates as a function of energy of the elastically scattered nucleons indicating the threshold at 90% efficiency. In order to get rid of any secondary peak we have required a track in BBGEM for this analysis.

3.2. *Trigger Rate Estimation*

Since there are few differences in the process of estimation let us talk about the BigBite rates and HCAL rates separately.

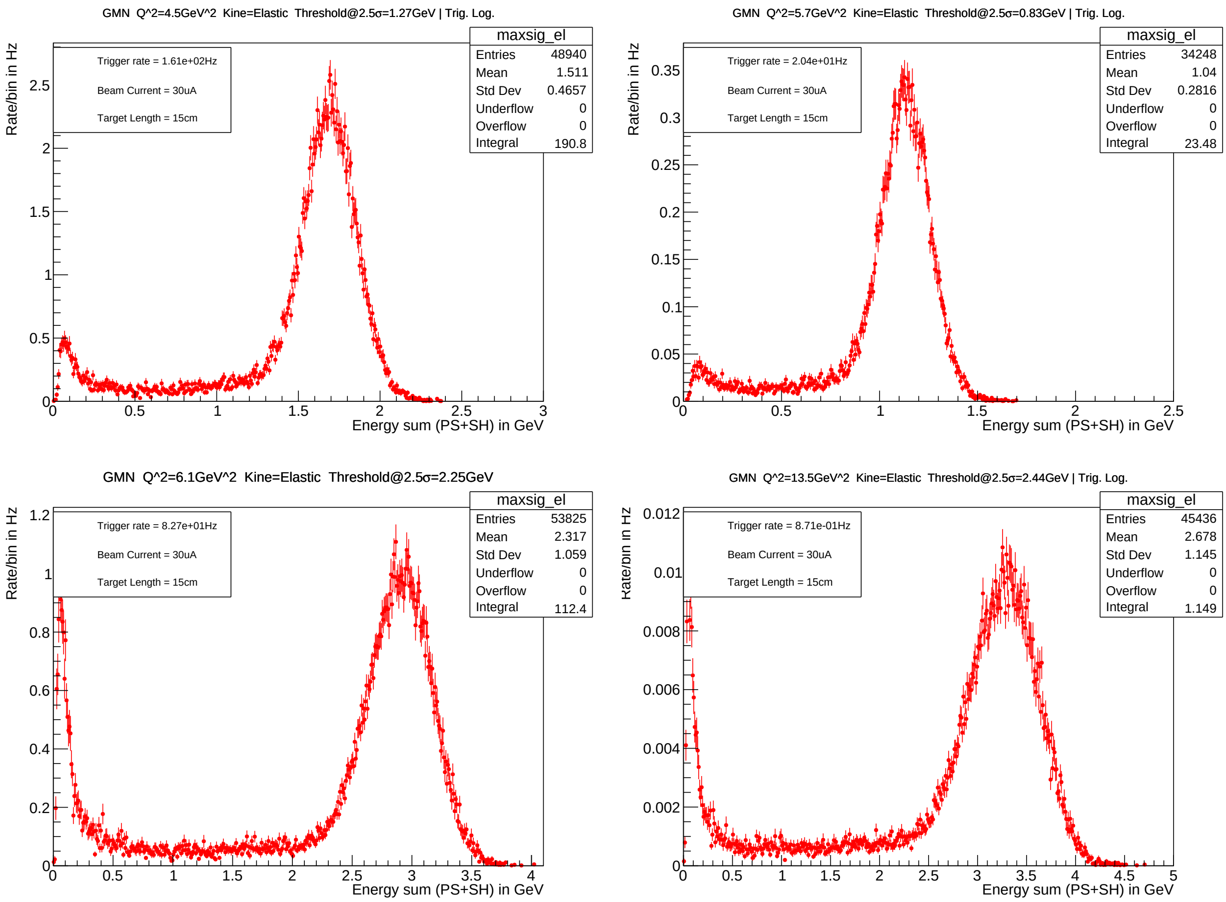

Figure 4: BigBite trigger rate estimation for elastic kinematics for $Q^2 = 4.5$ GeV^2, 5.7 GeV^2, 13.5 GeV^2, & 6.1 GeV^2 at threshold 2.5σ below the elastic peak (clockwise, starting from top left). Energy sums between Pre-Shower and Shower groups have been calculated using trigger logic described in Sec. 3.2.1 and a cut requiring the sum > 0 has been imposed.

3.2.1. BigBite rates

The trigger logic we have used is as follows. First we divide both Pre-Shower (PS) and Shower (SH) into several groups where each group consists of two consecutive rows. This leaves us with 25 groups for PS and 26 groups for SH and we name them in same order (i.e. group 0-25 for PS and group 0-26 for SH, going from bottom of the detector to the top). Now, as can be clearly seen from the geometry that PS rows do not align perfectly with the SH rows, so we needed to find the correlation between them. And as a result we have found that groups $0-8$ of PS have a one-to-one correspondence with the groups $0-8$ of SH and groups $18-25$ of PS have a one-to-one correspondence with the groups $19-26$ of SH but each groups in the range of $9-17$ of PS corresponds to two consecutive groups of SH in the range from 9 to 18. Then we scan through all the hits in a particular event and compute as well as smear the energy depositions at all the PS and SH groups and add the entries of corresponding PS and SH groups together. So for PS groups $9-17$ we need to perform two sums and just one for the others. Then we look for the maxima of all the sums and if the result is greater than the threshold then we count it as trigger. Continuing this procedure for all the events gives us the required trigger rate for a particular setup. Fig. 4 shows a few example of the BigBite trigger rate estimation for elastic kinematics for different Q^2 points whereas Fig. 5, 6, 7, & 8 show the same for dominant background processes.

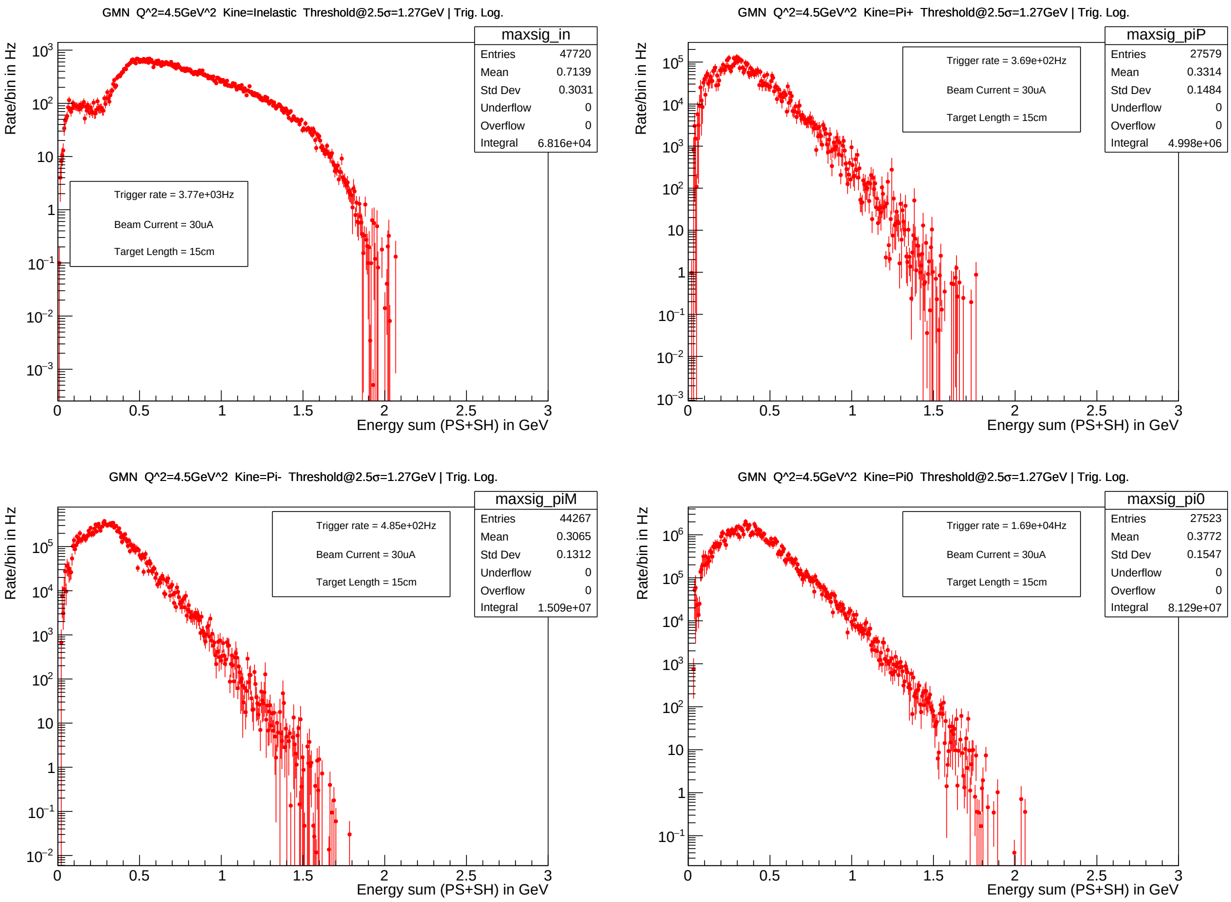

Figure 5: BigBite trigger rate estimation for the dominant background processes (refer to Sec. 2) i.e. inelastic, π^+, π^0, and π^- for $\mathrm{Q}^2 = 4.5$ GeV^2 at threshold 2.5σ below the elastic peak (clockwise, starting from top left). Similar to the elastic kinematics the energy sums between Pre-Shower and Shower groups have been calculated using trigger logic described in Sec. 3.2.1 and a cut requiring the sum > 0 has been imposed.

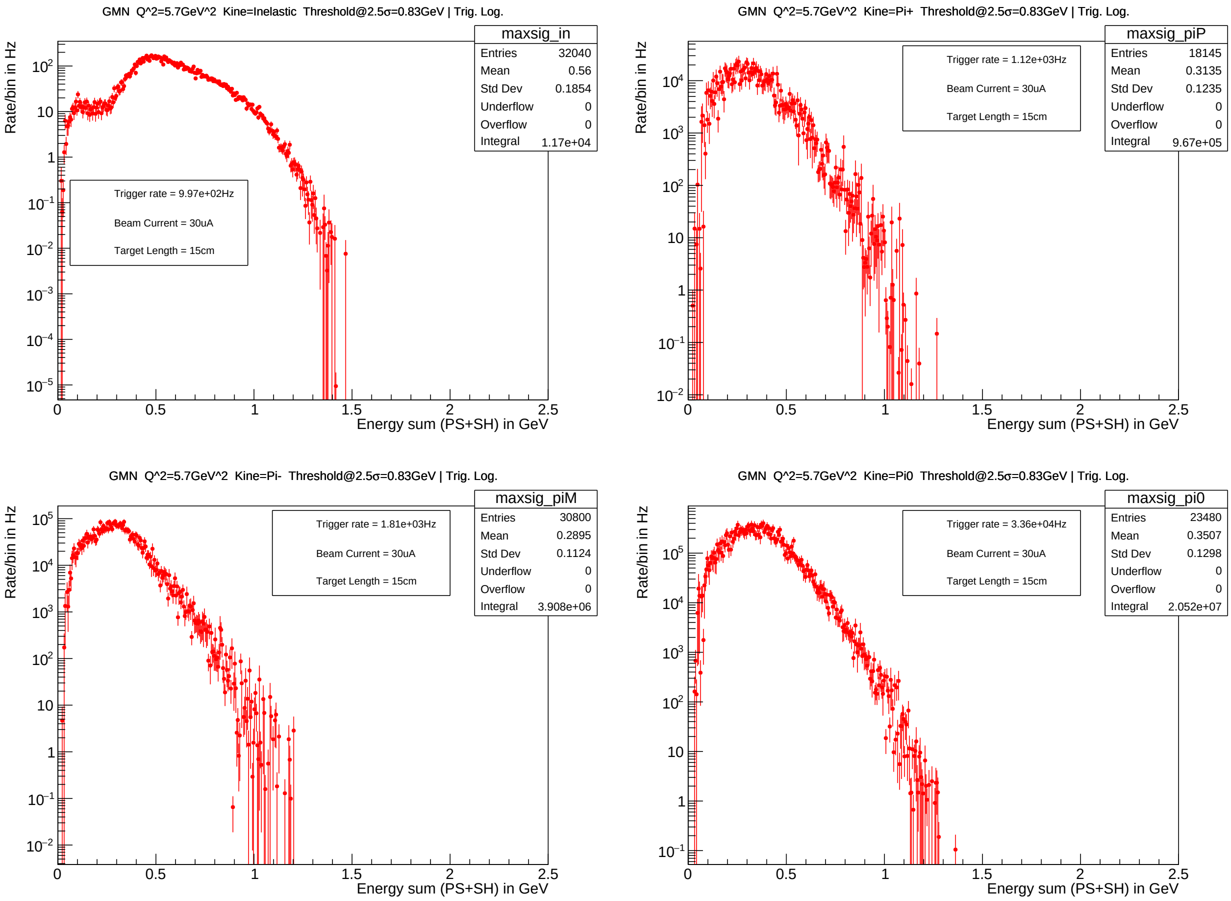

Figure 6: Same as Fig. 5, except for $Q^2 = 5.7$ GeV^2 instead of 4.5 GeV^2.

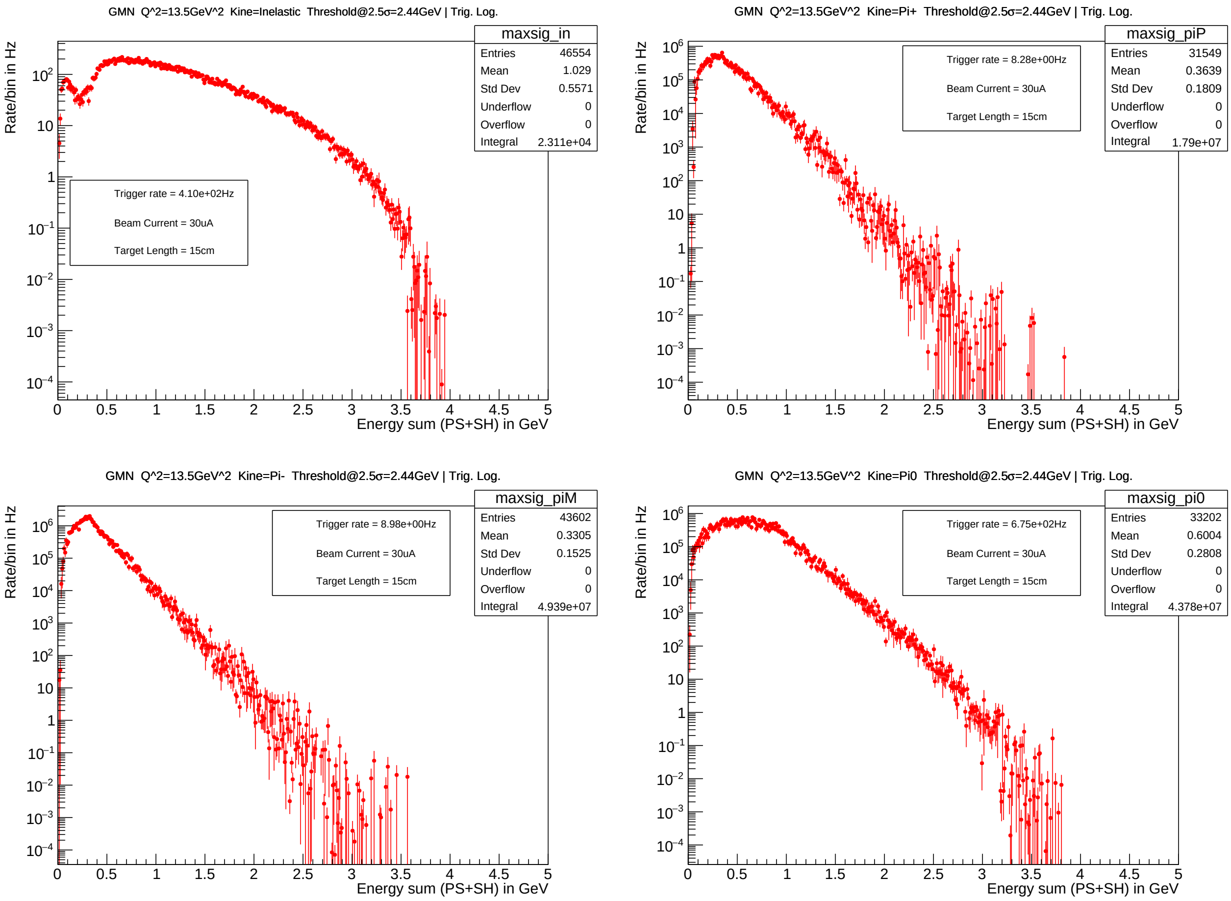

Figure 7: Same as Fig. 5, except for $Q^2 = 13.5$ GeV^2 instead of 4.5 GeV^2.

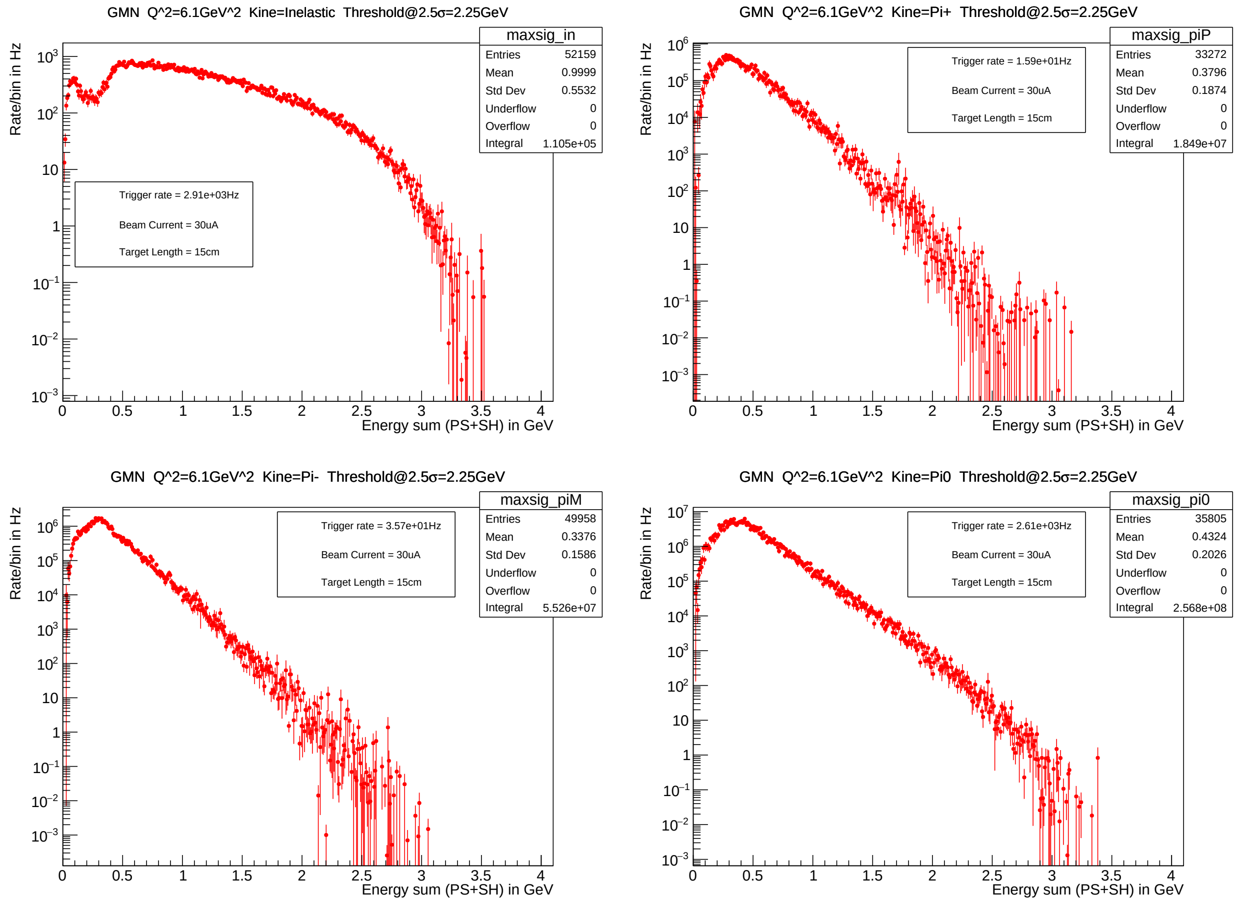

Figure 8: Same as Fig. 5, except for $Q^2 = 6.1$ GeV^2 instead of 4.5 GeV^2.

As can be seen from Fig. 6 that for 5.7GeV^2 the π^0 rate is significantly high which can prove to be challenging for the DAQ to handle. In order to address this problem the collaboration has proposed to replace 5.7GeV^2 with 6.1GeV^2, which requires a higher beam energy and lower BigBite angle. As expected, this change lowers the pion rates significantly which can be seen in Fig. 8.

3.2.2. HCAL rates

Significantly high pion rates and at the same time very low elastic rate have indicated the importance of coincidence trigger between BigBite and HCAL for $Q^2 = 4.5$ GeV^2 and 5.7 GeV^2. For the pion rate estimation in HCAL we have used "minimum bias" GEANT4 simulations instead of Wiser generators to avoid the fact that the later process significantly overestimates the pion rates for lower energies and/or forward scattering angles. We also have used the MC truth information regarding total detector sum per event instead of implementing the full trigger logic in order to get the rate vs. energy sum plots for the estimation of HCAL rates. This is because the energy resolution of HCAL is dominated by the sampling fraction and fluctuations of the energy deposition in the active material of HCAL. Fig. 9 shows the rate vs. energy sum plots we have used to estimate the HCAL trigger rates for $Q^2 = 4.5$ GeV^2 and 5.7 GeV^2. The results confirm the fact that for 4.5 GeV^2 in particular, we will need a coincidence trigger between BigBite and HCAL to keep the DAQ rates manageable.

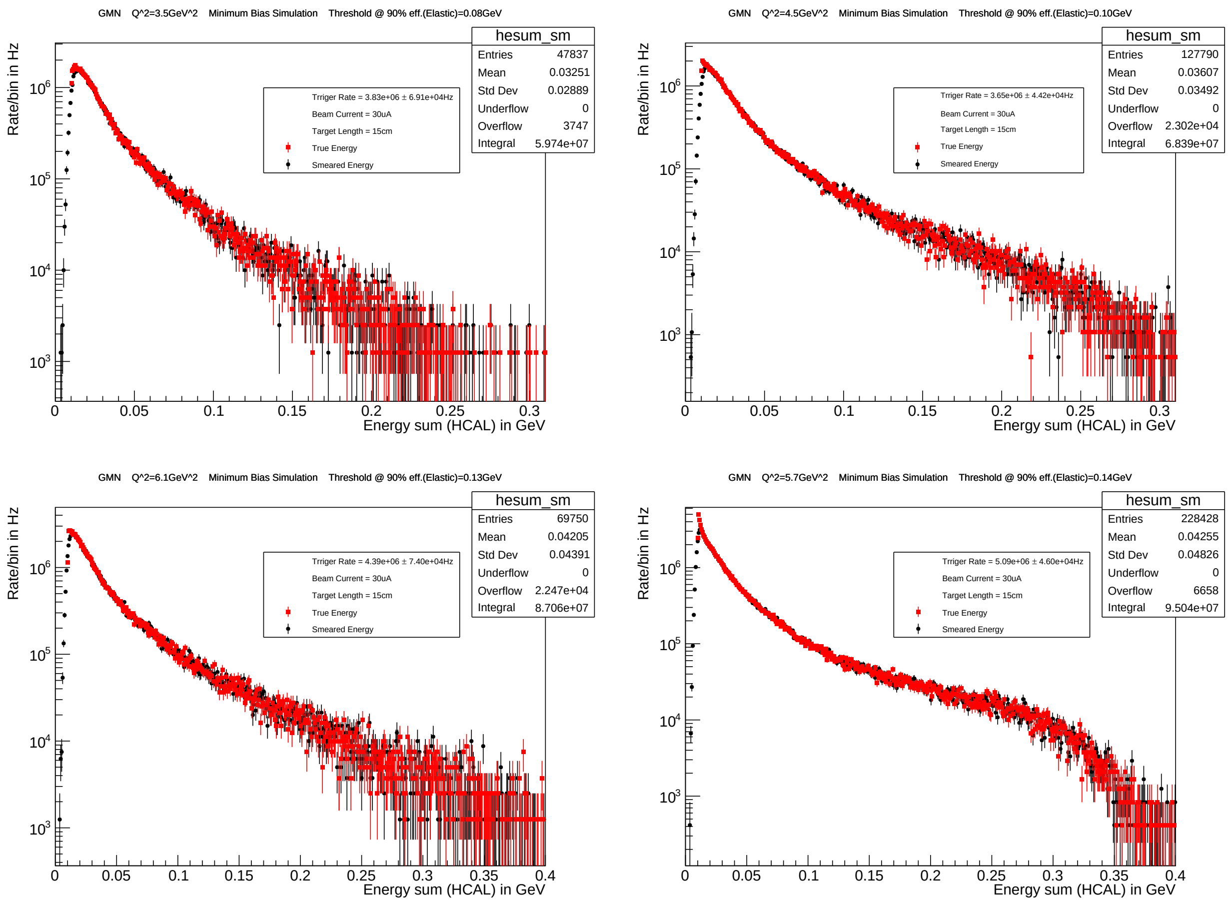

Figure 9: HCAL trigger rates estimation for $Q^2 = 3.5$ GeV^2, 4.5 GeV^2, 5.7 GeV^2, & 6.1 GeV^2 with threshold set at 90% efficiency (clockwise, starting from top left). "Minimum bias" GEANT4 simulations with $\sim$ 150 billion events for each Q^2 points have been performed to get the statistics with reasonable precision. The rates have been summarized in Table 4.

4. Summary

Let us now summarize the trigger rates (both BigBite and HCAL) for all Q^2 points in tabular form.

4.1. BigBite trigger rates

Table 1: Summary of estimated single-arm BigBite trigger rates for elastic kinematics as well as for all the dominant background processes in GMn experiment for all the proposed Q^2 points with the threshold set at 2σ below the elastic peak. Q^2 is the central Q^2, E_e is the beam energy, θ_{BB} (d_{BB}) is the BigBite central angle (target-magnet distance), E'_e is the average scattered electron energy, "Thrsh." is the BigBite trigger threshold, and "Eff." is the trigger efficiency for quasi-elastic events. "El." is the quasi-elastic rate (the "signal" process). "Inel." is the rate due to inclusive inelastic electron scattering, and $\pi^{+/-/0}$ are the rates due to inclusive single pion production.

Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Trig. Rate. (kHz)					Total (kHz)
						El.	Inel.	π^+	π^0	π^-	
3.5	4.4	32.5/1.80	2.18	1.81	96.9	0.8	5.3	0.04	3.5	0.1	9.7
4.5	4.4	41.9/1.55	1.70	1.35	94.0	0.2	2.3	0.2	7.3	0.2	10.2
5.7	4.4	58.4/1.55	1.14	0.89	94.8	0.02	0.6	0.4	12.9	0.6	14.5
6.1	6.6	30.3/1.55	2.90	2.38	95.9	0.08	1.7	0.006	1.0	0.02	2.8
8.1	6.6	43.0/1.55	1.94	1.56	95.5	0.007	0.4	0.06	1.6	0.03	2.1
10.2	8.8	34.0/1.75	2.92	2.37	96.8	0.003	0.3	0.003	0.3	0.002	0.6
12	8.8	44.2/1.55	2.05	1.62	95.4	0.0008	0.1	0.005	1.2	0.02	1.3
13.5	11	33.0/1.55	3.30	2.60	94.0	0.0008	0.2	0.003	0.2	0.002	0.4

Tables 1, 2, and 3 show the estimated single-arm BigBite trigger rates for the assumption of setting the threshold at 2σ, 2.5σ, and 3σ below the elastic peak, respectively. By the time of the GMN/GEN-RP run, it is expected that the Hall A DAQ system will be capable of handling up to 5 kHz event rate to disk with

Table 2: Same as Table 1, except for threshold has been set at 2.5σ instead of 2σ below the elastic peak.

Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Trig. Rate. (kHz) El.	Inel.	π^+	π^0	π^-	Total (kHz)
3.5	4.4	32.5/1.80	2.18	1.72	98.7	0.8	8.4	0.1	7.8	0.2	17.3
4.5	4.4	41.9/1.55	1.70	1.27	95.8	0.2	3.8	0.4	16.9	0.5	21.8
5.7	4.4	58.4/1.55	1.14	0.83	96.6	0.02	1.0	1.1	33.6	1.8	37.5
6.1	6.6	30.3/1.55	2.90	2.25	97.6	0.08	2.9	0.02	2.5	0.03	5.5
8.1	6.6	43.0/1.55	1.94	1.47	97.0	0.007	0.6	0.04	4.5	0.07	5.2
10.2	8.8	34.0/1.75	2.92	2.23	98.5	0.003	0.5	0.008	1.1	0.02	1.6
12	8.8	44.2/1.55	2.05	1.52	97.1	0.0008	0.2	0.06	2.9	0.04	3.2
13.5	11	33.0/1.55	3.30	2.44	96.2	0.0009	0.4	0.008	0.7	0.009	1.1

Table 3: Same as Table 1, except for threshold has been set at 3σ instead of 2σ below the elastic peak.

Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Trig. Rate. (kHz) El.	Inel.	π^+	π^0	π^-	Total (kHz)
3.5	4.4	32.5/1.80	2.18	1.63	99.4	0.8	12.3	0.1	16.0	0.3	29.5
4.5	4.4	41.9/1.55	1.70	1.19	97.0	0.2	5.6	0.9	33.6	0.9	41.2
5.7	4.4	58.4/1.55	1.14	0.77	97.7	0.02	1.6	2.0	87.4	4.1	95.1
6.1	6.6	30.3/1.55	2.90	2.12	98.3	0.08	4.5	0.04	6.4	0.07	11.1
8.1	6.6	43.0/1.55	1.94	1.37	97.7	0.007	1.0	0.1	11.1	0.3	12.5
10.2	8.8	34.0/1.75	2.92	2.10	99.3	0.004	0.8	0.02	2.2	0.04	3.1
12	8.8	44.2/1.55	2.05	1.41	97.9	0.0008	0.4	0.1	9.1	0.2	9.8
13.5	11	33.0/1.55	3.30	2.27	97.1	0.0009	0.7	0.02	1.9	0.02	2.6

acceptably low dead-time. As such, all the kinematics for $Q^2 \geq 6$ GeV^2 should be able to use a single-arm BigBite trigger, as the rates (at least for a threshold 2σ below the elastic peak) are all well below 5 kHz. For the three highest Q^2 points, the threshold could be set at 2.5σ below the peak to increase the efficiency for the very low rate elastic events, while still staying comfortably below 5 kHz. This assumes that the 5.7 GeV^2 setting is replaced with the 6.1 GeV^2 setting.

At the lowest $Q^2 = 3.5$ GeV^2, the single-arm BigBite trigger rate is relatively high at about 10 kHz, but the elastic rate is also quite high at about 800 Hz. Since the accuracy of this measurement will be systematics-limited and not statistically limited, the luminosity can be lowered to stay within the limits of the DAQ. This is arguably also true of the GMN measurement at 4.5 GeV^2, for which the elastic rate is about 200 Hz and the BigBite single-arm trigger rate is about 10 kHz. As such, assuming replacement of the 5.7 GeV^2 point with the 6.1 GeV^2 point with more favorable signal/background ratio, only the GEN-RP measurement will require the implementation of a coincidence with HCAL.

4.2. HCAL trigger rates

Table 4: Summary of estimated HCAL trigger rates using "minimum bias" simulation for all the proposed Q^2 points for GMn and GEn-RP experiments with the threshold set at 90% efficiency (refer to Sec. 3.1 for definition).

Expt.	Q^2 (GeV^2)	BeamE (GeV)	SBS ang./dst. (deg)/(m)	SBS Bdl	HCAL dst. (m)	Thrsh. (GeV)	HCAL Trigger Rates (MHz)
GMn	3.5	4.4	31.1/2.00	1.71	7.2	0.08	3.83 ± 0.07
GMn	4.5	4.4	24.7/2.25	1.71	8.5	0.10	3.65 ± 0.04
GEn-RP	4.5	4.4	24.7/2.25	1.71	8.5	0.08	1.25 ± 0.04
GMn	5.7	4.4	17.5/2.25	1.71	11.0	0.14	5.09 ± 0.05
GMn	**6.1**	6.6	24.7/2.25	1.71	8.5	0.13	4.39 ± 0.07
GMn	8.1	6.6	17.5/2.25	1.65	11.0	0.20	5.31 ± 0.08
GMn	10.2	8.8	17.5/2.25	1.60	11.0	0.23	5.91 ± 0.08
GMn	12	8.8	13.3/2.25	1.50	14.0	0.28	8.08 ± 0.10
GMn	13.5	11	14.8/3.10	0.97	17.0	0.26	4.46 ± 0.01

Table 4 shows the estimated single-arm trigger rates in HCAL, using GEANT4 minimum-bias simulations of the relevant configurations and the simplifying assumption that the "trigger" would be based on the sum of all signals across the entire calorimeter. In reality, it will be based on overlapping sums of 8×8 modules. In general, the estimated HCAL singles rates are quite high, ranging between 1-10 MHz, which is arguably too high for use in triggering. For the GEn-RP measurement, the combination of the steel analyzer of the charge-exchange polarimeter and the extra shielding of the downstream beamline and the "beamline notch" in the SBS dipole reduces the HCAL rate substantially compared to the GMN situation for the same kinematics, from which these extra materials are absent. The estimated HCAL singles rate for GEn-RP is 1.25 MHz, which is acceptable for use in a coincidence trigger. Assuming a 30-ns window for the coincidence between BigBite and HCAL, the estimated accidental coincidence rate between BigBite and HCAL is about 380 Hz, which is well within the capabilities of the DAQ system to handle, even with all the extra GEM channels associated with the GEn-RP detectors. An estimate of the real coincidence rate for this Q^2 due to inelastic background processes is forthcoming, but is expected to be of the same order of magnitude as the accidental rate. As such, the simple BigBite-HCAL coincidence trigger will be sufficient for the DAQ requirements of GEn-RP.

References

[1] B. W. B. Quinn, B. Sawatsky, JLab experiment E12-09-019Precision Measurement of the Neutron Magnetic Form Factorand JLab experiment E12-17-004 GEn-RecoilPreparation and GMn Run Plan (September 10, 2019).
URL `https://hallaweb.jlab.org/12GeV/SuperBigBite/Experiments/GMn_GEn-RP/Webpage_Files/GMN_plan_6Sep.pdf`