Proposed Trigger Scheme for the ICAL Detector Module

(Version 1.1 Dated February 15, 2011)

1. Introduction

Events of interest for the ICAL detector will be of very low rate and the trigger scheme should be designed in order to achieve an optimization between the detection efficiency for desired events and the chance trigger rates. The scheme should also ensure feasibility of hardware implementation considering vast volume (16mx16mx14.5m) of the detector module. Calculation of chance coincidence rates for a variety of combinations of the trigger parameters helps to fix the criteria for an admissible chance trigger rate. Different aspects of a proposed trigger scheme for one module of the ICAL detector have been discussed.

2. Features of Trigger Scheme

i. Each 2mx2m RPC has two planes, each having 64 pick-up strips. The detector is assumed to consist of two independent systems, one comprising of the X-plane strips and the other of the Y-plane strips. Calculations are done for the X-plane and the Y-plane is considered to be a duplicate of the same.

ii. Signal pick-up rate for all strips has been assumed to be identical and uniform.

iii. 64 signals from each RPC plane are reduced to '*L*' level0 trigger (T0) signals where every L^{th} pick-up strips are combined to obtain the signals $T0_1$ to $T0_L$.

iv. '*M-Fold*' coincidence of consecutive T0 signals produces level1 trigger ($T1_M$) signals from each RPC plane.

v. Entire module is logically sub-divided into a no. of segments, each of which is a cuboid consisting of a no. of RPCs in the horizontal plane and a no. of such layers of RPCs in the vertical plane.

vi. No. of RPCs per layer per segment is called '*horizontal spread*' (Hspread) of a segment. Level1 trigger ($T1S_M$) signal of a segment is the combination of $T1_M$ signals from its constituent RPCs in the horizontal plane.

vii. No. of layers per segment is called '*vertical spread*' (Vspread) of a segment. Criterion for Level2 trigger ($T2S_{MxN/P}$) signal of a segment is specified as '*MxN/P*' where N out of any P successive layers of the segment should have M-fold coincidence of consecutive pick-up strips.

viii. Level3 trigger (T3S) signal of a segment is the combination of $T2S_{MxN/P}$ signals of that segment for a no. of trigger criteria with different combinations of M and N.

ix. Global trigger (GT_{Plane}) signal per plane (X/Y) is the combination of T3S signals (belonging to the corresponding plane) from all logical segments that constitute the module.

x. Global trigger (GT) signal per module is the combination of global trigger signals from X-plane and Y-plane, which initiates the recording of strip hit and timing information.

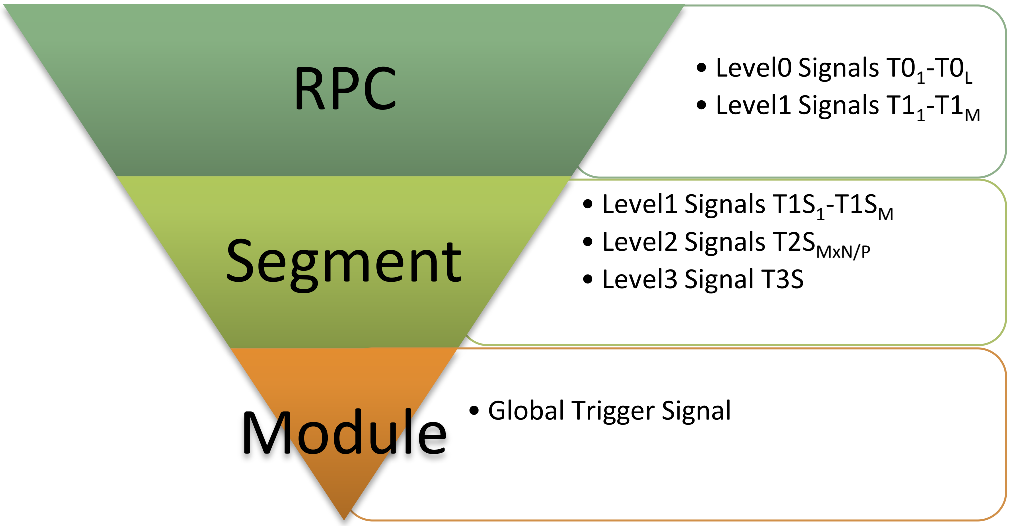
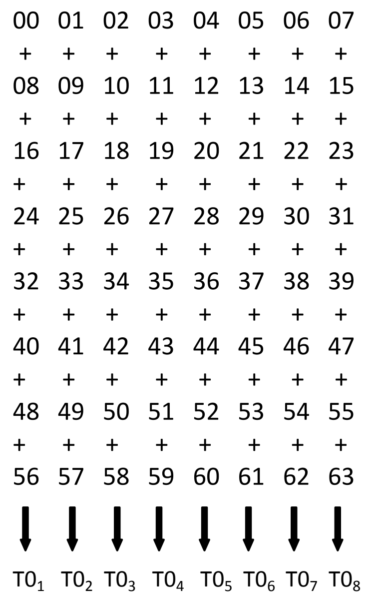


Fig.1. Hierarchy of Trigger Scheme

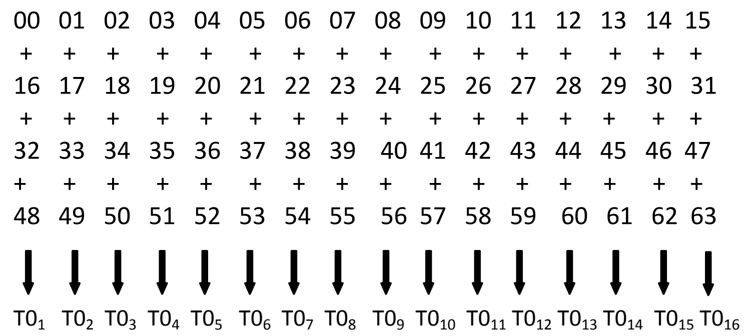
2.1. RPC Level

2.1.1. Level0 Trigger Signal

Signals from every L^{th} pick-up strip out of 64 strips on one plane of 2mx2m RPC are OR-ed to generate L level0 trigger (T0) signals. Combinations for signals $T0_1$ to $T0_L$ are shown below for two different values of L (8, 16). Average noise rate for an RPC strip of dimension 200cmx3cm is taken as 250Hz on earth surface.



Scheme 1. T0 Signals with L=8



Scheme 2. T0 Signals with L=16

L=8 : T0 rate = 8 x 250 = 2KHz

L=16 : T0 rate = 4 x 250 = 1KHz

2.1.2. Level1 Trigger Signal

Level1 trigger ($T1_M$) signals are obtained by demanding M-fold coincidence of consecutive T0 signals from each plane. M-Fold chance rate for a coincidence window of T (seconds) and T0 rate of R (Hz) is given by $\mathbf{MR^{M}T^{M-1}}$ Hz.

Combinations for $T1_M$ signals for M = 1,2,3,4 are shown below.

1-Fold : $T1_1 = T0_1 + T0_2 + \ldots\ldots + T0_{L-1} + T0_L$

2-Fold : $T1_2 = T0_1.T0_2 + T0_2.T0_3 + \ldots\ldots + T0_{L-1}.T0_L + T0_L.T0_1$

3-Fold : $T1_3 = T0_1.T0_2.T0_3 + T0_2.T0_3.T0_4 + \ldots\ldots + T0_{L-1}.T0_L.T0_1 + T0_L.T0_1.T0_2$

4-Fold : $T1_4 = T0_1.T0_2.T0_3.T0_4 + T0_2.T0_3.T0_4.T0_5 + \ldots\ldots + T0_{L-1}.T0_L.T0_1.T0_2 + T0_L.T0_1.T0_2.T0_3$

Assuming a coincidence window of 100 ns, rates of $T1_M$ signals for two different T0 rates (L=8, 16) are given in Table 1.

L-Value	T0 Rate (Hz)	$T1_1$ Rate (Hz)	$T1_2$ Rate (Hz)	$T1_3$ Rate (Hz)	$T1_4$ Rate (Hz)
8	$2x10^3$	$1.6x10^4$	6.4	$1.92x10^{-3}$	$5.12x10^{-7}$
16	$1x10^3$	$1.6x10^4$	3.2	$4.8x10^{-4}$	$6.4x10^{-8}$

Table 1. Level0 and Level1 trigger rates per RPC plane for L=8, 16

It can be seen that T0 and $T1_M$ (except 1-Fold) rates are slightly higher for scheme 1 (L=8) compared to scheme 2 (L=16) but no. of T0 signals in scheme 2 is double that in scheme 1. Adoption of a lower value of L (L=4) would, on the other hand, restrict the hit pattern within 4 consecutive strips only which may not be acceptable in some cases. So, rest of the calculations has been done for scheme 1.

According to the current design of RPC (1.84mx1.95m), there is a gap of 16cm between two RPCs across adjacent roads and 5cm between neighboring RPCs along a road. Thus it is quite unlikely that a particular event will have the hit pattern distributed over adjacent RPCs within a layer. Hence, it is assumed that for any event, the track remains confined within a single RPC along a horizontal layer.

2.2. Segment Level

A distributed architecture is followed for designing the trigger scheme i.e. the module is logically sub-divided into no. of segments, each of which is capable of initiating a global trigger. It is preferable to have the segment cubical in shape in order to make it isotropic for containing an event. Dimension of a segment in the horizontal direction i.e. '*horizontal spread*' (Hspread) is defined in terms of no. of RPCs per layer per segment. Hspread can be further interpreted as the combination of two terms, $Hspread_X$ and $Hspread_Y$, which are the no. of RPCs per layer per segment along X and Y direction respectively (Fig.2). Calculations have been done considering Hspread as 4 (2x2), 9 (3x3) and 16 (4x4). Every two adjacent segments must have overlapping segment in between as depicted in Fig.2.

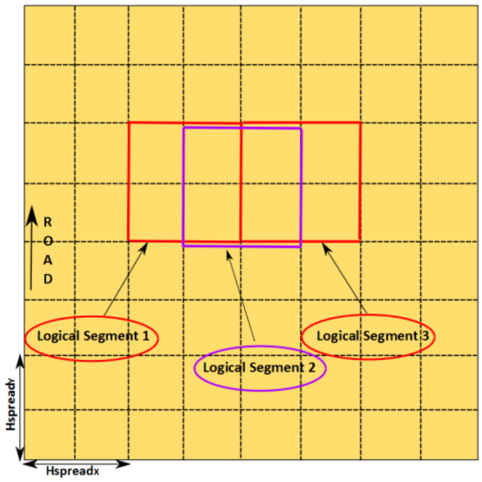


Fig.2. Horizontal Segmentation Pattern for Hspread = 2x2

2.2.1. Level1 Trigger Signal

Level1 Trigger ($T1S_M$) signal for a segment is the OR of $T1_M$ signals of its constituent RPCs in the horizontal plane. $T1S_M$ rates for a segment for different values of Hspread are given in Table 2.

Hspread	$T1S_1$ Rate (Hz)	$T1S_2$ Rate (Hz)	$T1S_3$ Rate (Hz)	$T1S_4$ Rate (Hz)
4 (2x2)	6.4×10^{4}	25.6	7.68×10^{-3}	2.05×10^{-6}
9 (3x3)	1.44×10^{5}	57.6	1.73×10^{-2}	4.61×10^{-6}
16 (4x4)	2.56×10^{5}	102.4	3.07×10^{-2}	8.19×10^{-6}

Table 2. Level1 trigger rates per segment for different sizes of segment

2.2.2. Level2 Trigger Signal

'*Vertical spread*' (Vspread) of a segment is defined in terms of no. of layers per segment. Level2 trigger ($T2S_{MxN/P}$) signal for a segment should suffice '*MxN/P*' criterion where N out of a '*group*' of any P successive layers of the segment must have M-fold coincidence of consecutive pick-up strips. Considering $T1S_M$ rate of R_M (Hz) and coincidence window of T (seconds),

$$MxN/P \text{ chance rate} = C.(NR_M^{\ N}T^{N-1}) \text{ Hz}$$

where C = total no. of combinations

= No. of groups of P consecutive layers in a segment X No. of groups of any N out of P consecutive layers

In order to take care of vertical overlap between successive segments, generation of $T2S_{MxN/P}$ signal for a segment should consider $T1S_M$ signals from P-1 layers of the adjacent vertical segment. Thus, starting from the bottom, each segment, except the topmost ones, will have P-1 additional $T1S_M$ signals from the segment lying immediately above. Total no. of signals for the topmost segments depends on the value of Vspread and may or may not be same as that of other segments. Hence the topmost segments will have partial or no overlap whereas all other segments will have full overlap in the vertical direction. For the sake of convenience, segments with full vertical overlap are named as '*Type A*' while those with partial or no vertical overlap are named as '*Type B*' segments (Fig.3).

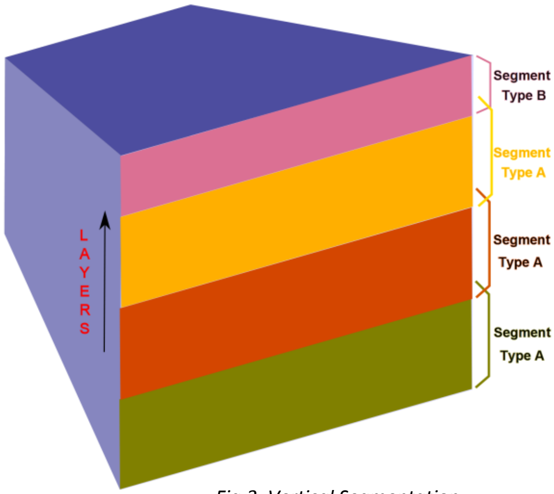


Fig.3. Vertical Segmentation

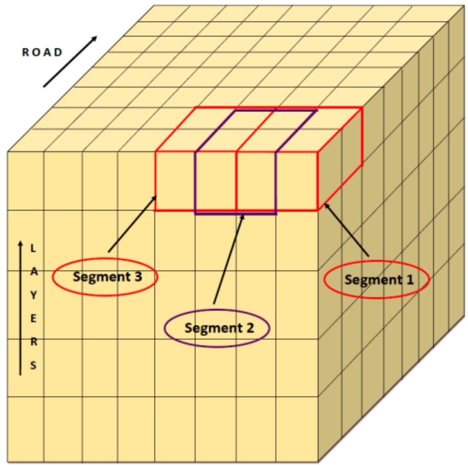


Fig.4. Logical Segmentation of Detector Module

Level3 trigger (T3S) signal for a segment is the OR of $T2S_{MxN/P}$ signals of that segment for a set of trigger criteria involving different combinations of M and N. Over the range of trigger criteria, as the value of M goes higher, that of N goes lower and ideally size of group i.e. value of P should also come down. Since vertical overlap between successive segments depends on the value of P, varying P for different trigger criteria would pose practical problem with regard to routing of signals and hence it is assumed to have the same value of P for all trigger criteria. It can be seen later that this assumption does not affect the chance coincidence rates as the rates corresponding to criteria with M>1 are negligibly small and overall chance trigger rate is dominated by the rate for the criterion with M=1.

Two different sets of trigger criteria have been considered (Fig.5), with the size of group as 8. Calculation of $T2S_{MxN/P}$ and T3S rates has been done for both types of segments for different values of Hspread and Vspread as given in Table 3 and 4.

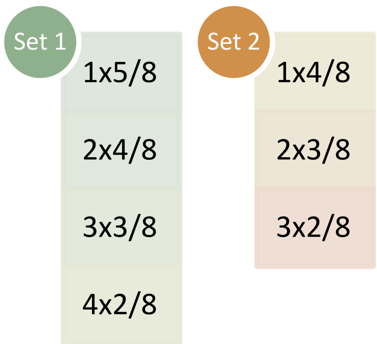


Fig.5. Two Different Sets of Trigger Criteria

Hspread	Vspread	Segment Size	Segment Type	$T2S_{1x5/8}$ Rate (Hz)	$T2S_{2x4/8}$ Rate (Hz)	$T2S_{3x3/8}$ Rate (Hz)	$T2S_{4x2/8}$ Rate (Hz)	T3S Rate (Hz)
4 (2x2)	10	4mx4mx1m	A	0.30	1.20×10^{-12}	7.61×10^{-18}	2.35×10^{-16}	0.30
			B	0.09	3.61×10^{-13}	2.28×10^{-18}	7.05×10^{-17}	0.09
	20	4mx4mx2m	A	0.60	2.41×10^{-12}	1.52×10^{-17}	4.70×10^{-16}	0.60
			B	0.09	3.61×10^{-13}	2.28×10^{-18}	7.05×10^{-17}	0.09
	40	4mx4mx4m	A	1.20	4.81×10^{-12}	3.04×10^{-17}	9.40×10^{-16}	1.20
			B	0.69	2.77×10^{-12}	1.75×10^{-17}	5.40×10^{-16}	0.69
9 (3x3)	30	6mx6mx3m	A	52.01	9.25×10^{-11}	2.60×10^{-16}	3.57×10^{-15}	52.01
			B	39.88	7.09×10^{-11}	1.99×10^{-16}	2.73×10^{-15}	39.88
	40	6mx6mx4m	A	69.35	1.23×10^{-10}	3.47×10^{-16}	4.76×10^{-15}	69.35
			B	39.88	7.09×10^{-11}	1.99×10^{-16}	2.73×10^{-15}	39.88
	60	6mx6mx6m	A	104.02	1.85×10^{-10}	5.20×10^{-16}	7.13×10^{-15}	104.02
			B	39.88	7.09×10^{-11}	1.99×10^{-16}	2.73×10^{-15}	39.88
16 (4x4)	40	8mx8mx4m	A	1.23×10^{3}	1.23×10^{-9}	1.95×10^{-15}	1.50×10^{-14}	1.23×10^{3}
			B	708.09	7.08×10^{-10}	1.12×10^{-15}	8.64×10^{-15}	708.09
	60	8mx8mx6m	A	1.85×10^{3}	1.85×10^{-9}	2.92×10^{-15}	2.25×10^{-14}	1.85×10^{3}
			B	708.09	7.08×10^{-10}	1.12×10^{-15}	8.64×10^{-15}	708.09
	80	8mx8mx8m	A	2.46×10^{3}	2.46×10^{-9}	3.90×10^{-15}	3.01×10^{-14}	2.46×10^{3}
			B	1.94×10^{3}	1.94×10^{-9}	3.07×10^{-15}	2.37×10^{-14}	1.94×10^{3}

Table 3. Level2 and Level3 trigger rates for different types of segments for trigger criteria of Set 1

Hspread	Vspread	Segment Size	Segment Type	$T2S_{1x4/8}$ Rate (Hz)	$T2S_{2x3/8}$ Rate (Hz)	$T2S_{3x2/8}$ Rate (Hz)	T3S Rate (Hz)
4 (2x2)	10	4mx4mx1m	A	46.98	$2.82x10^{-7}$	$3.3x10^{-9}$	46.98
			B	14.09	$8.46x10^{-8}$	$9.91x10^{-10}$	14.09
	20	4mx4mx2m	A	93.95	$5.64x10^{-7}$	$6.61x10^{-9}$	93.95
			B	14.09	$8.46x10^{-8}$	$9.91x10^{-10}$	14.09
	40	4mx4mx4m	A	187.91	$1.13x10^{-6}$	$1.32x10^{-8}$	187.91
			B	108.05	$6.48x10^{-7}$	$7.6x10^{-9}$	108.05
9 (3x3)	30	6mx6mx3m	A	$3.61x10^{3}$	$9.63x10^{-6}$	$5.02x10^{-8}$	$3.61x10^{3}$
			B	$2.77x10^{3}$	$7.38x10^{-6}$	$3.85x10^{-8}$	$2.77x10^{3}$
	40	6mx6mx4m	A	$4.82x10^{3}$	$1.28x10^{-5}$	$6.69x10^{-8}$	$4.82x10^{3}$
			B	$2.77x10^{3}$	$7.38x10^{-6}$	$3.85x10^{-8}$	$2.77x10^{3}$
	60	6mx6mx6m	A	$7.22x10^{3}$	$1.93x10^{-5}$	$1x10^{-7}$	$7.22x10^{3}$
			B	$2.77x10^{3}$	$7.38x10^{-6}$	$3.85x10^{-8}$	$2.77x10^{3}$
16 (4x4)	40	8mx8mx4m	A	$4.81x10^{4}$	$7.22x10^{-5}$	$2.11x10^{-7}$	$4.81x10^{4}$
			B	$2.77x10^{4}$	$4.15x10^{-5}$	$1.22x10^{-7}$	$2.77x10^{4}$
	60	8mx8mx6m	A	$7.22x10^{4}$	$1.08x10^{-4}$	$3.17x10^{-7}$	$7.22x10^{4}$
			B	$2.77x10^{4}$	$4.15x10^{-5}$	$1.22x10^{-7}$	$2.77x10^{4}$
	80	8mx8mx8m	A	$9.62x10^{4}$	$1.44x10^{-4}$	$4.23x10^{-7}$	$9.62x10^{4}$
			B	$7.58x10^{4}$	$1.1x10^{-4}$	$3.33x10^{-7}$	$7.58x10^{4}$

Table 4. Level2 and Level3 trigger rates for different types of segments for trigger criteria of Set 2

Calculation of $T2S_{MxN/P}$ rates needs to determine the no. of layers per segment. Different cases may arise according to the relationship between Vspread and total no. of layers (150) and are listed below.

i. Vspread is a factor of total no. of layers. Each segment (both type A and B) has no. of layers equal to Vspread.
ii. Vspread is not a factor of total no. of layers. No. of layers for each segment of type A is equal to Vspread but that for type B is different and depends on the remainder of total no. of layers divided by Vspread. There can be two cases,
    a. The remainder is greater than the size of group.
    b. The remainder is less than the size of group.

All the three cases have been taken into consideration while calculating the Level2 trigger rates.
Choice of logical segments in this manner takes into account the case of diagonal tracks too as $T1S_M$ signal for a particular layer of a segment is the OR of $T1_M$ signals from all the constituent RPCs of that layer. Fig.6 shows a segment consisting of four RPCs, where RPCs A and B form one layer and C and D constitute another layer. The track goes diagonally through the segment with the hit pattern involving RPC B in the top layer and RPC C in the bottom layer.

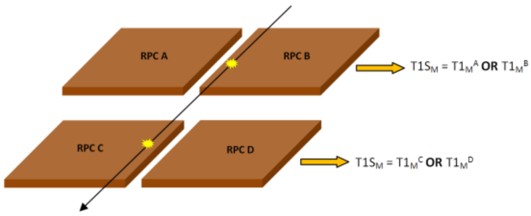


Fig.6. Diagonal track through a segment

2.3. Module Level

2.3.1. Global Trigger Signal

Global trigger (GT_{Plane}) signal per plane (X/Y) is the OR of T3S signals (belonging to the corresponding plane) from all the constituent segments of the module. Thus total no. of each type of segment in a module has to be determined. No. of segments of each type have been calculated taking into account all the three cases mentioned earlier. Global trigger (GT) signal for the detector module is obtained as the OR of global trigger signals from X and Y plane (Fig.7). A GT signal to the data acquisition system invokes registering of strip hit pattern and timing information.

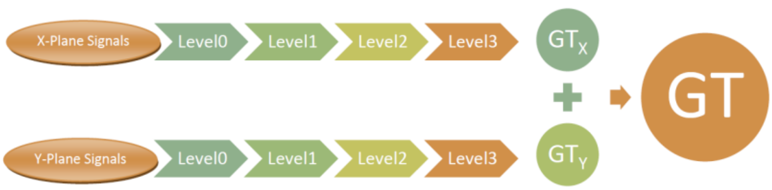


Fig.7. Complete Flow of Generation of Global Trigger Signal

GT rates and total no. of segments for all combinations of Hspread and Vspread and for the two sets of trigger criteria as shown in Table 3 and 4 are shown in Table 5. GT rates have been found to be the same for segments with different values of Vspread but having a fixed value of Hspread, as is evident from the figures in Table 5.

Hspread	Vspread	Segment Size	Total Segments	Trigger Criteria (Set 1)		Trigger Criteria (Set 2)	
				GT_{Plane} Rate (Hz)	GT Rate (Hz)	GT_{Plane} Rate (Hz)	GT Rate (Hz)
4 (2x2)	10	4mx4mx1m	735	210.66	421.33	3.29×10^4	6.58×10^4
	20	4mx4mx2m	392	210.66	421.33	3.29×10^4	6.58×10^4
	40	4mx4mx4m	196	210.66	421.33	3.29×10^4	6.58×10^4
9 (3x3)	30	6mx6mx3m	180	8.9×10^3	1.78×10^4	6.2×10^5	1.24×10^6
	40	6mx6mx4m	144	8.9×10^3	1.78×10^4	6.2×10^5	1.24×10^6
	60	6mx6mx6m	108	8.9×10^3	1.78×10^4	6.2×10^5	1.24×10^6
16 (4x4)	40	8mx8mx4m	100	1.1×10^5	2.2×10^5	4.3×10^6	8.6×10^6
	60	8mx8mx6m	75	1.1×10^5	2.2×10^5	4.3×10^6	8.6×10^6
	80	8mx8mx8m	50	1.1×10^5	2.2×10^5	4.3×10^6	8.6×10^6

Table 5. Global trigger rate and total no. of segments per module for different segment dimensions and trigger criteria

2.3.2. Underground Trigger Rates

Two cases have been considered in calculating underground trigger rates, in which average noise rate per RPC strip (200cmx3cm) in the underground is assumed to be $1/5^{th}$ and $1/10^{th}$ of that on the surface (250Hz), i.e. 50Hz and 25Hz respectively. Corresponding figures are given in Table 6 and 7.

Hspread	Vspread	Segment Size	Total Segments	Trigger Criteria (Set 1)		Trigger Criteria (Set 2)	
				GT_{Plane} Rate (Hz)	GT Rate (Hz)	GT_{Plane} Rate (Hz)	GT Rate (Hz)
4 (2x2)	10	4mx4mx1m	735	6.75×10^{-2}	0.135	52.67	105.33
	20	4mx4mx2m	392	6.75×10^{-2}	0.135	52.67	105.33
	40	4mx4mx4m	196	6.75×10^{-2}	0.135	52.67	105.33
9 (3x3)	30	6mx6mx3m	180	2.856	5.712	9.9×10^2	1.98×10^3
	40	6mx6mx4m	144	2.856	5.712	9.9×10^2	1.98×10^3
	60	6mx6mx6m	108	2.856	5.712	9.9×10^2	1.98×10^3
16 (4x4)	40	8mx8mx4m	100	35.22	70.44	6.9×10^3	1.38×10^4
	60	8mx8mx6m	75	35.22	70.44	6.9×10^3	1.38×10^4
	80	8mx8mx8m	50	35.22	70.44	6.9×10^3	1.38×10^4

Table 6. Underground trigger rates for different segment dimensions and trigger criteria for average noise rate per strip = 50Hz

Hspread	Vspread	Segment Size	Total Segments	Trigger Criteria (Set 1)		Trigger Criteria (Set 2)	
				GT_{Plane} Rate (Hz)	GT Rate (Hz)	GT_{Plane} Rate (Hz)	GT Rate (Hz)
4 (2x2)	10	4mx4mx1m	735	2.1×10^{-3}	4.2×10^{-3}	3.29	6.58
	20	4mx4mx2m	392	2.1×10^{-3}	4.2×10^{-3}	3.29	6.58
	40	4mx4mx4m	196	2.1×10^{-3}	4.2×10^{-3}	3.29	6.58
9 (3x3)	30	6mx6mx3m	180	8.93×10^{-2}	0.1785	62	1.24×10^2
	40	6mx6mx4m	144	8.93×10^{-2}	0.1785	62	1.24×10^2
	60	6mx6mx6m	108	8.93×10^{-2}	0.1785	62	1.24×10^2
16 (4x4)	40	8mx8mx4m	100	1.1	2.2	4.3×10^2	8.6×10^2
	60	8mx8mx6m	75	1.1	2.2	4.3×10^2	8.6×10^2
	80	8mx8mx8m	50	1.1	2.2	4.3×10^2	8.6×10^2

Table 7. Underground trigger rates for different segment dimensions and trigger criteria for average noise rate per strip = 25Hz

As evident from the figures in Table 5,6 and 7, loosening the trigger criteria by 1 layer leads to a substantial increase in chance trigger rates. Chance coincidence rates for trigger criteria of set 1 seem to be quite acceptable but those for trigger criteria of set 2 are much higher than the tolerable limit.

3. Further Issues

i. The proposed trigger scheme must be feasible from the perspective of physical routing of signals distributed over a wide volume of 16mx16mx14.5m and appropriate delay compensation has to be provided so as to ensure availability of all coincidence signals within a specific time-window.
ii. The user must be able to vary a no. of parameters online, for deciding the trigger logic according to physics requirement, without going for any hardware reconfiguration. No. and types of parameters to be made programmable depends on the feasibility of hardware implementation.

iii. An optimization between size and no. of segments has to be achieved considering chance trigger rates as well as routing problems.
iv. Signal transmission scheme for pre-trigger and final trigger signals has to be chosen properly so as to minimize trigger latency and hence reduce dead time.
v. Results from physics simulation will help to fix the trigger criteria for different kind of physics events as well as to determine trigger efficiency of the proposed scheme.

4. Trigger Simulation Framework

The design of the proposed trigger scheme has to be substantiated by trigger efficiency of the scheme for different events of interest for the ICAL detector. This necessitates development of a simulation framework which is capable of evaluating performance of the trigger scheme as a function of different trigger parameters and over the range of all desired events.

4.1. Analysis Input

Muon events as well as different kinds of neutrino events have been studied. The INO-ICAL simulation code has its own Monte-Carlo event generator using which muon events have been generated while NUANCE has been used for generating neutrino events, over a wide energy range and different incident directions. These events have been simulated using the INO-ICAL simulation code and the output of '*Digitization*' stage, which provides hit position information in the detector in the format as will be available from the real detector data acquisition system, has been used as input for the current analysis. The hit information content is shown in Fig.8, which provides the actual geographical position of particle hit in the detector.

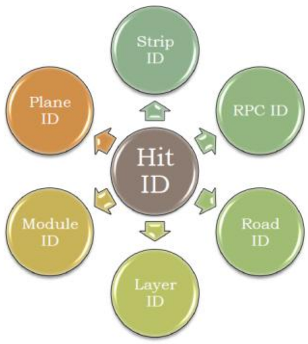


Fig.8. Hit Position Information from Digitization Output

4.2. Algorithm

The algorithm for determining trigger efficiency has been developed in accordance with the hierarchy of the proposed trigger scheme and is illustrated in Fig.9. Trigger efficiency is defined as,

$$Trigger\ Efficiency = \frac{No. of\ events\ satisfying\ the\ trigger\ criteria}{Total\ no. of\ events}$$

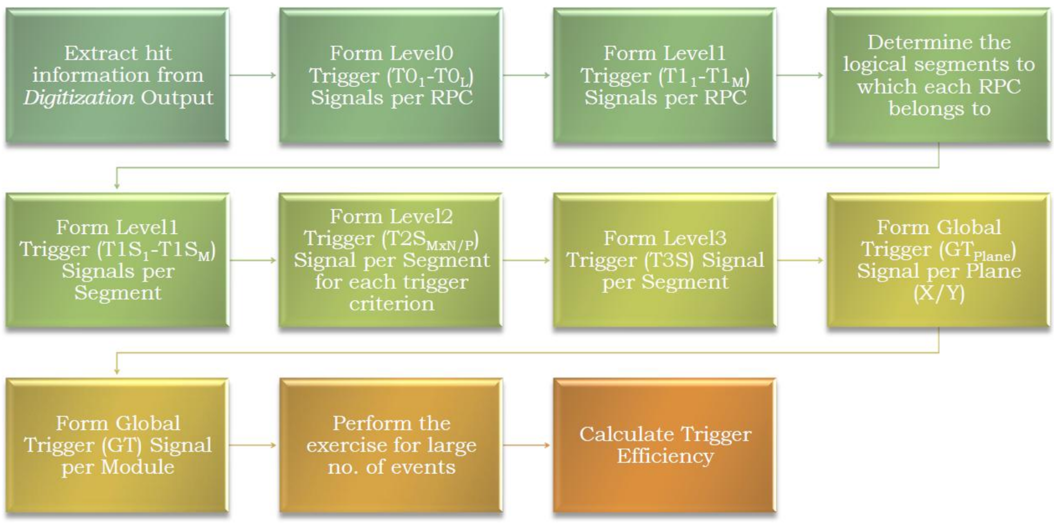


Fig.9. Analysis Algorithm

4.3. Features

The analysis framework has been developed using software tools like Qt, ROOT and QtRoot and is equipped with an intuitive GUI, which contains all the necessary functions and user-entry fields that can be customized by the user and is thus helpful in troubleshooting and debugging various issues. Different features offered by the trigger simulation framework are listed below.

i. All trigger parameters are user programmable.
ii. Graphical display of the event (Fig.10).
iii. Plot of trigger efficiency vs particle energy and incident direction.
iv. Plot of trigger efficiency vs trigger parameters.

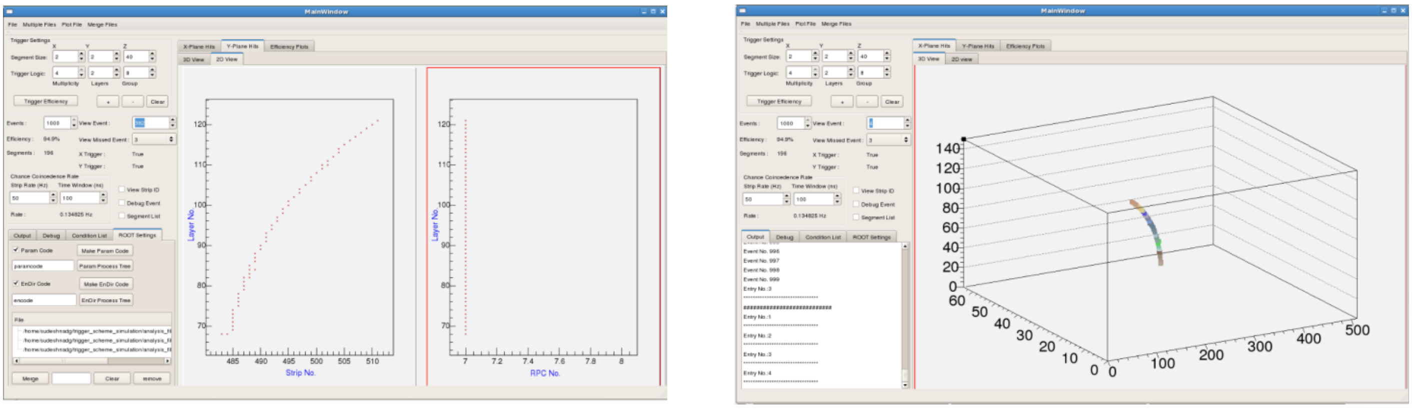


Fig.10. Screenshot of the GUI Showing 2D and 3D Event Display

4.4. Results

Trigger efficiency has been determined corresponding to the trigger criteria of Set 1 (Fig.5) and segment size of 4mx4mx4m, for muon events as well as different types of neutrino events, as a function of energy and direction of the incident particle. Variation of trigger efficiency as a function of the following trigger parameters has also been obtained.

i. Multiplicity (M)
ii. No. of layers (N)
iii. Size of group (P)
iv. Segment dimensions ($Hspread_X$, $Hspread_Y$, Vspread)

4.4.1. Muon Events

Muon events in the energy range of 0.5 to 5GeV with the incident direction varying from 0˚ to 90˚ have been analyzed. Fig.11 shows the variation of trigger efficiency with muon energy for different incident directions. The efficiency is less for lower energies (up to 1GeV) but goes up with energy and reaches 100% at higher energies (beyond 2GeV). This is because with the increase in energy, the particle traverses a longer path through the detector and the probability of it satisfying the trigger criteria becomes higher. However, for large incident angles, efficiency is lower even at higher energy.

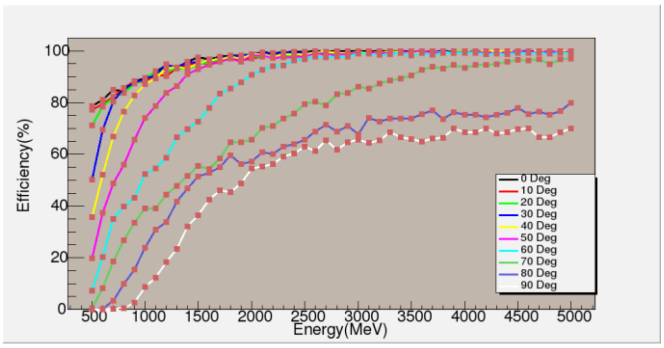


Fig.11. Trigger Efficiency vs Energy for Different Incident Directions

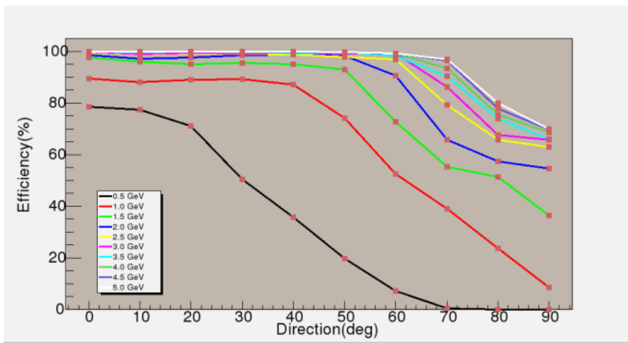


Fig.12. Trigger Efficiency vs Incident Direction for Energy 0.5-5GeV

Fig.12 shows the variation of trigger efficiency with the incident direction of muon over different energies. Since the particles incident at a large angle traverse lesser no. of layers, their chance of satisfying the trigger criteria is lower and hence at a particular energy, the efficiency is quite high for lower angles but becomes lesser for higher angles.

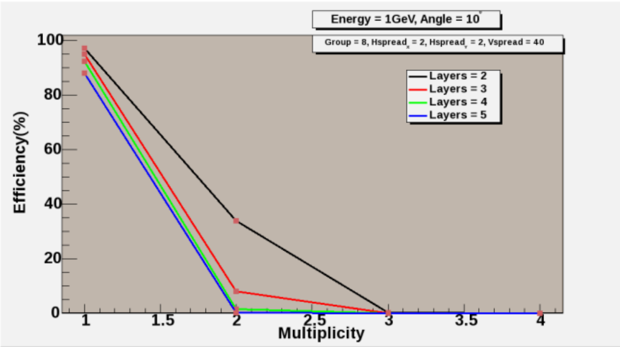


Fig.13. Trigger Efficiency vs Parameters (M,N)

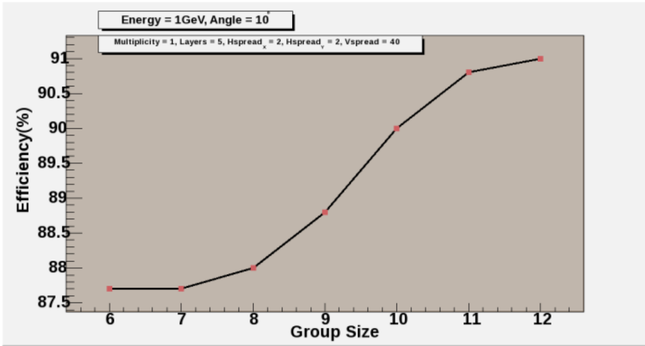


Fig.14. Trigger Efficiency vs Size of Group (P)

Fig.13 shows the trigger efficiency for different combinations of the trigger parameters M and N. The plot illustrates the individual contribution of each trigger criterion in generating a trigger and it is evident that in case of muon events, the efficiency is mainly dominated by the 1-Fold criterion. Variation of trigger efficiency as a function of the parameter P is shown in Fig.14. Efficiency goes up with higher value of P as chance of meeting the trigger criteria increases with increase in the size of group. Efficiency remains the same or changes slightly with the variation in segment size, as shown in Fig.15.

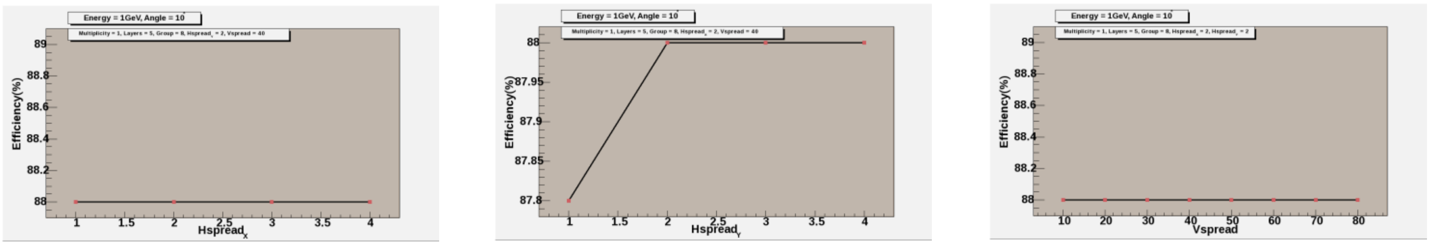


Fig.15. Trigger Efficiency vs Segment Dimensions

Subsequent sections deal with the estimation of trigger efficiency for different kinds of neutrino events. Nature of variation of trigger efficiency as a function of trigger parameters like group size and segment dimensions for neutrino events are found to be similar to that observed in case of muon events and hence those plots have not been included in the discussion that follows.

4.4.2. Neutrino Events (Charged Current)

Charged current neutrino events in the energy range of 1 to 10 GeV with the incident direction varying from 0˚ to 90˚ have been studied. Fig.16 shows trigger efficiency varying as a function of neutrino energy for different incident directions. The efficiency clearly goes up with the increase in energy. Fig.17 shows the variation of trigger efficiency with the incident direction of neutrino for different energies. The efficiency gradually becomes lesser for larger incident angles.

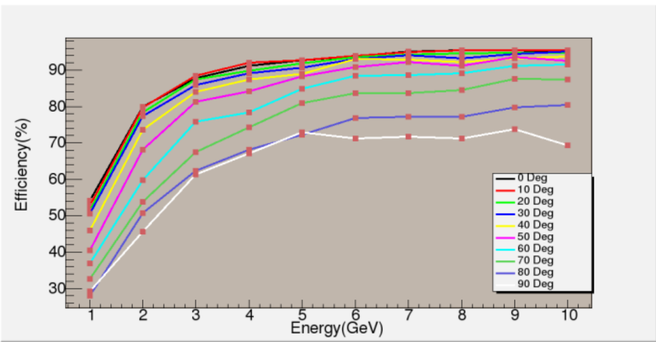


Fig.16. Trigger Efficiency vs Energy for Different Incident Directions

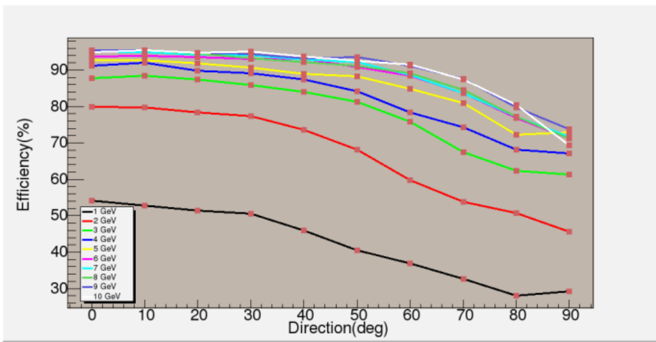


Fig.17. Trigger Efficiency vs Incident Direction for Energy 1-10GeV

Variation of trigger efficiency for different combinations of the trigger parameters M and N is shown in Fig.18 and the contribution of trigger criteria with M>1 seems to be quite significant for charged current neutrino events in comparison with muon events (Fig.13). This is due to the pions produced as a result of the interaction which mainly satisfy the 3-Fold and 4-Fold trigger criteria.

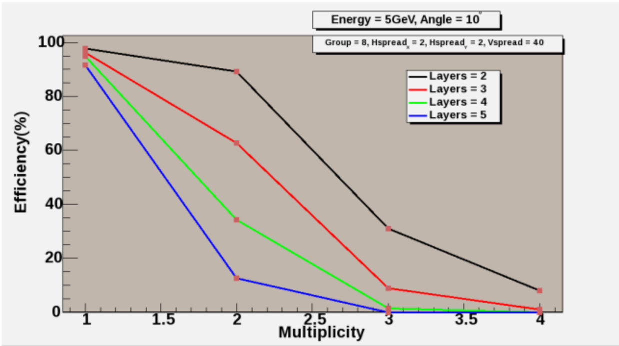


Fig.18. Trigger Efficiency vs Parameters (M,N)

A comparison of trigger efficiency for different sets of trigger criteria (Fig.19) is shown in Fig.20. Efficiency corresponding to set2 is slightly higher than that for set1 and both have identical chance coincidence rates. Set3 has about 15% higher efficiency in comparison with set1 and set2 but as discussed earlier, the chance trigger rates are also substantially higher.

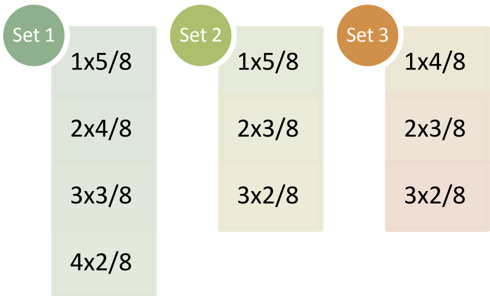


Fig.19. Three Different Sets of Trigger Criteria

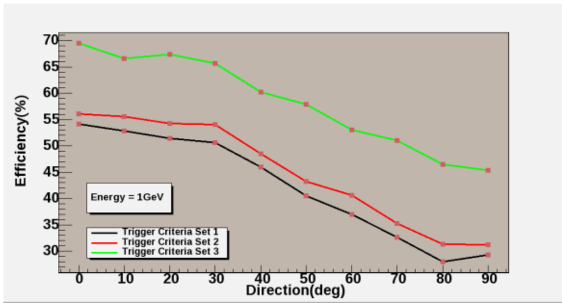


Fig.20. Comparison of Trigger Efficiency for Three Sets of Trigger Criteria

Charged current neutrino events can be sub-divided into different categories like quasi-elastic, resonant and deep-inelastic events and determination of trigger efficiency has been done for each set of event.

4.4.3. Neutrino Events (Quasi-elastic)

Quasi-elastic neutrino events in the energy range of 1 to 10 GeV with the incident direction varying from 0˚ to 90˚ have been studied. Fig.21 shows trigger efficiency varying as a function of neutrino energy for different incident directions where the efficiency clearly goes up with the increase in energy. Fig.22 shows the variation of trigger efficiency with the incident direction of neutrino for different energies with the efficiency gradually becoming lesser for larger incident angles.

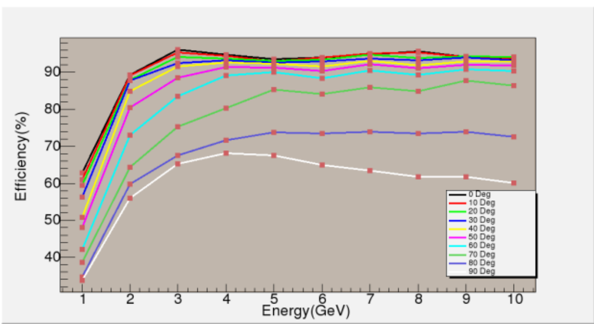


Fig.21. Trigger Efficiency vs Energy for Different Incident Directions

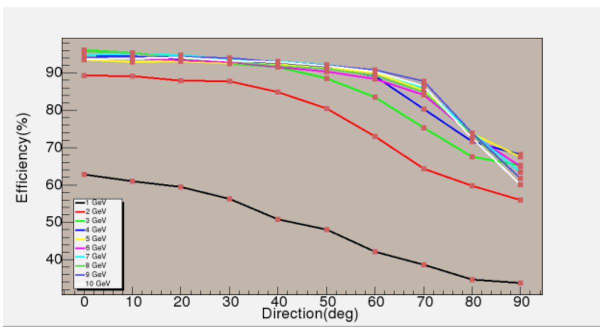


Fig.22. Trigger Efficiency vs Incident Direction for Energy 1-10GeV

Variation of trigger efficiency for different combinations of the trigger parameters M and N is shown in Fig.23. In case of quasi-elastic neutrino events, most of the neutrino energy is carried away by the muon and hence the trigger efficiency is dominated by the 1-Fold trigger criterion and contribution of criteria with M>1 is quite insignificant.

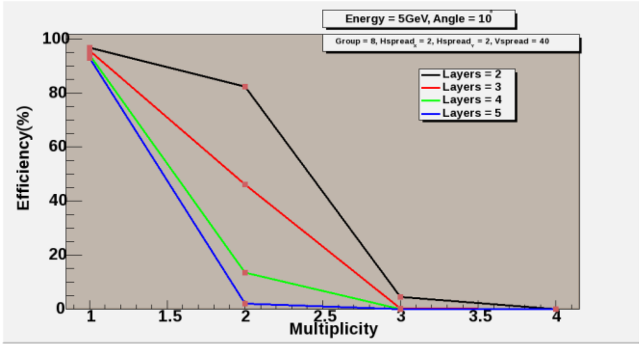


Fig.23. Trigger Efficiency vs Parameters (M,N)

4.4.4. Neutrino Events (Resonant)

Resonant neutrino events in the energy range of 1 to 10 GeV with the incident direction varying from 0˚ to 90˚ have been analyzed. Fig.24 shows the variation of trigger efficiency with neutrino energy for different incident directions where the efficiency increases with the increase in energy. Variation of trigger efficiency as a function of incident direction of neutrino for different energies is shown in Fig.25. The efficiency is evidently lower for higher incident angles.

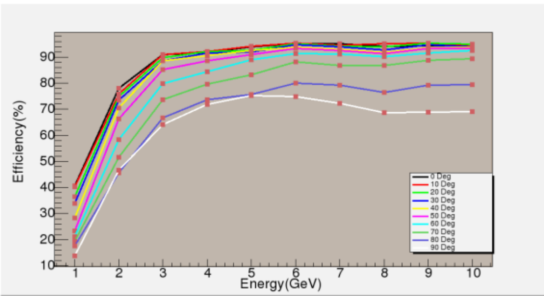


Fig.24. Trigger Efficiency vs Energy for Different Incident Directions

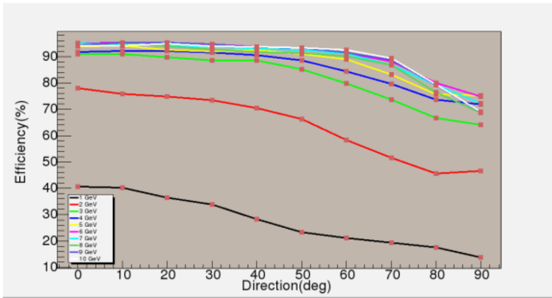


Fig.25. Trigger Efficiency vs Incident Direction for Energy 1-10 GeV

Fig.26 shows the variation of trigger efficiency for different combinations of the trigger parameters M and N. Contribution of trigger criteria with M>1 appears to be slightly higher for resonant events than that for quasi-elastic events (Fig.23). This is because of the single pion produced in the resonant interaction which sometimes satisfies the 3-Fold and 4-Fold criteria.

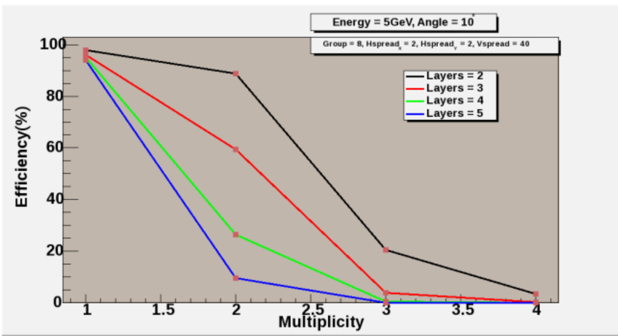


Fig.26. Trigger Efficiency vs Parameters (M,N)

4.4.5. Neutrino Events (Deep-Inelastic)

Deep-inelastic neutrino events in the energy range of 2 to 10 GeV with the incident direction varying from 0˚ to 90˚ have been studied. Fig.27 shows trigger efficiency varying as a function of neutrino energy for different incident directions where the efficiency clearly goes up with the increase in energy. Fig.28 shows the variation of trigger efficiency with the incident direction of neutrino for different energies with the efficiency gradually becoming lesser for larger incident angles.

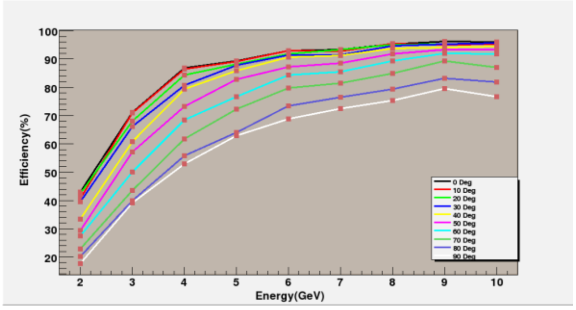


Fig.27. Trigger Efficiency vs Energy for Different Incident Directions

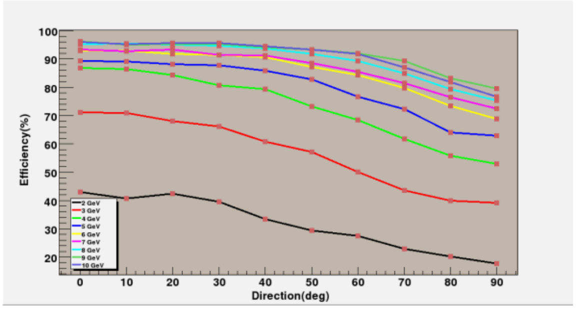


Fig.28. Trigger Efficiency vs Incident Direction for Energy 2-10 GeV

Variation of trigger efficiency for different combinations of the trigger parameters M and N is shown in Fig.29. Due to the production of multiple pions in case of deep-inelastic events, contribution of trigger criteria with M>1 appears to be much higher in comparison with that for quasi-elastic (Fig.23) and resonant (Fig.26) events.

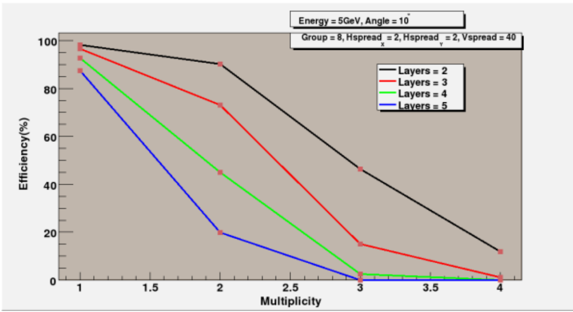


Fig.29. Trigger Efficiency vs Parameters (M,N)

4.4.6. Trigger Efficiency w.r.t. Reconstructed Events

Deterioration of trigger efficiency, as observed in the preceding sections, is mostly attributed to two types of events, the events incident at large angles which do not traverse requisite no. of layers and the events generated in the gap region which produce less no. of hits not sufficient enough to meet the trigger criteria. However, such events with very few hits are of less interest to us as they cannot be reconstructed eventually even if they satisfy the trigger criteria. Thus, the trigger efficiency is expected to improve significantly if efficiency is calculated w.r.t. the reconstructed events only instead of the whole set of events.

Reconstruction information for all events in the '*Digitization*' output can be obtained from the corresponding '*Reconstruction*' output of the INO-ICAL simulation code. Trigger efficiency w.r.t. reconstructed events is defined as,

$$Trigger\ Efficiency = \frac{No. of\ reconstructed\ events\ satisfying\ the\ trigger\ criteria}{Total\ no. of\ reconstructed\ events}$$

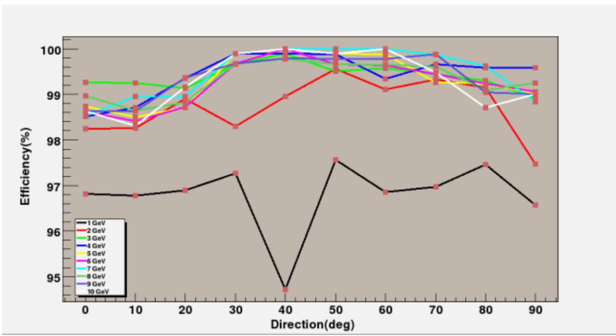


Fig.30. Trigger Efficiency w.r.t. reconstructed events for quasi-elastic neutrino events

Fig.30 illustrates the trigger efficiency w.r.t. reconstructed events for quasi-elastic neutrino events over the energy range of 1 to 10 GeV and incident direction varying from 0˚ to 90˚. The trigger efficiency is found to be greater than 97% for almost all events which ensures that substantially high trigger efficiency can be achieved for the events of interest under the proposed trigger scheme.

Hence, the simulation results provide us with a good assessment of the efficiency of the proposed trigger scheme for different events of interest over a wide range of energy and incident direction. The nature of variation of trigger efficiency as a function of different trigger parameters are also understood which would be eventually helpful in fixing those parameters in order to attain an intended efficiency.

5. Data Rate Estimation

An estimate of the data rate that would need to be handled under the proposed trigger scheme helps to fix the requirements for the data acquisition system and computing resources. The data acquisition system would deal with two types of data, *'event data'*, which would be recorded on a global trigger and *'monitor data'*, which would be recorded periodically at a rate pre-determined by the user. Assuming average strip noise rate to be 50Hz in the underground, global trigger rate per module is taken as 0.1Hz (Table 6) and monitoring period, which would be user programmable, is considered as 10 seconds. Each pick-up strip and RPC is assumed to be 100% efficient in order to arrive at the maximal data rate. The data rate is decided by a no. of parameters that are listed in Table 8.

No. of RPCs per module	64x150 = 9600
Hit data per RPC (X-plane and Y-plane)	64 + 64 = 128 bits
TDC data (16 bit per T0 Signal) per RPC	(8+8)x16 = 256 bits
RPC data packet ID	16 bits
Monitor data per pick-up strip	56 bits (Channel identity = 8 bits, RPC identity = 16 bits, Rate data = 24 bits, Other information = 8 bits)

Table 8. Parameters affecting the data rate

5.1. Event Data

Event data per RPC = EDR = Hit data + TDC data + RPC data packet ID

Event data per module = EDM = EDR x Total no. of RPCs per module

= (Hit data + TDC data + RPC data packet ID) x Total no. of RPCs per module

= (128+256+16) x 9600

= 4 Mbits.

Considering global trigger rate of 0.1Hz, event data rate per module = 0.4 Mbps.

5.2. Monitor Data

It is assumed that one pick-up strip per plane of an RPC will be monitored at a time over a period of 10 seconds.

Monitor data per strip per RPC per plane = MDR = 56 bits.

Monitor data per module per 10 seconds = MDM = MDR x No. of planes per RPC x No. of RPCs per module

= 56 x 2 x 9600

= 1.08 Mbits.

Monitor data rate per module = 0.1 Mbps.

Hence, net data rate per module = Event data rate + Monitor data rate = 0.5 Mbps.