Calculation of Cross-Sections in STAR

or

How to use the Scaler Board

STAR Note 302

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1.0 Introduction

This document is a first attempt at a description of how to calculate a cross-section in the STAR experiment at RHIC. First I will discuss what the definition of a cross-section is in a collider experiment. Then I will explain where the luminosity information comes from, how it is recorded on the scaler board and finally how these numbers can be used to calculate a cross-section. The final section will be a discussion of exactly what these cross-sections mean.

2.0 Cross-Section Definition

In a collider experiment the cross-section for a process X is defined as:

$$\sigma(X) = \frac{N(X)}{N_1 \times N_2} \times A$$

where:

$\sigma(X)$ = cross-section for the occurrence of process X
N_X = number of times process X occurs in time dt when the experiment is live
N_1 = number of particles in beam 1 in the overlap region when the experiment is live
N_2 = number of particles in beam 2 in the overlap region when the experiment is live
A = area of overlap between beams 1 and 2

The luminosity L is defined as:

$$L = \frac{N_1 \times N_2}{A}$$

so the cross-section can be calculated from:

$$\sigma(X) = \frac{N_X}{L}$$

3.0 Luminosity

In order to calculate a cross-section in STAR we need to know the total luminosity produced by the RHIC accelerator at the STAR intersection point when the experiment is alive. At least one measure of this will be provided by RHIC, in a manner which is the same for all four RHIC intersection points. STAR will also keep track of a number of other quantities that should be proportional to the luminosity.

3.1 RHIC Luminosity Measurement

RHIC management is planning on providing a measure of luminosity at all four intersection points. To do this they will pick a very frequent reaction, R, whose cross-section is known. They will measure N_R for every bunch-crossing. The luminosity in the bunch-crossing can then be defined as:

$$L(bcr) = \frac{N(bcr)_R}{\sigma(R)}$$

The total integrated luminosity in a given time, dt, is then the sum of all the individual bunch-crossing luminosities in that time period:

$$L(dt) = \sum_{bcr(0)}^{bcr(dt)} L(bcr)$$

There are a number of un-answered questions concerning this approach:

- What process can be chosen whose cross-section is known accurately enough and is high enough to allow the luminosity to be calculated for individual bunch-crossings ?
- How do we ensure that the luminosity is actually the luminosity at the STAR intersection point ?
- If process R occurs in the diamond, but outside the small region currently being selected by the VPD should it be included in the luminosity count ?
- How efficiently can the process R be detected ?
- Assuming there is a time-delay between when RHIC measures the luminosity and when they communicate that information to STAR how do we find out what this delay is ?
- If this turns out to be an unreliable/impossible method how else are we going to calculate luminosities ?

3.2 The Scaler Board

Assuming it is possible to calculate the luminosity in this way the STAR trigger system needs to record it. This will be done using the Scaler Board designed by Krista Marks and Vinson Chang.

The Scaler board has one channel for the RHIC luminosity measurement, one channel that counts RHIC strobes, i.e. bunch crossings, and a number of other channels whose use is not yet fully defined.

Each channel works in the same way, as shown schematically in Figure 1. The 6 detector busy bits, the 2 trigger busy bits and the 4 polarization bits are used as the address of a location in the look-up table. The 2 trigger busy bits are the FIFO empty status bits of the two trigger token FIFOs. There are 4096 unique combinations of these 12 bits, so the look-up table has 4096 elements. For every bunch-crossing the twelve bits address one particular element. The luminosity for that crossing is added to the data stored at that address. If the scalers are zeroed at some point, and then read out at time dt later, then the data stored at each address is the total integrated luminosity, seen by the experiment during time dt, for that particular combination of busy and polarization bits.

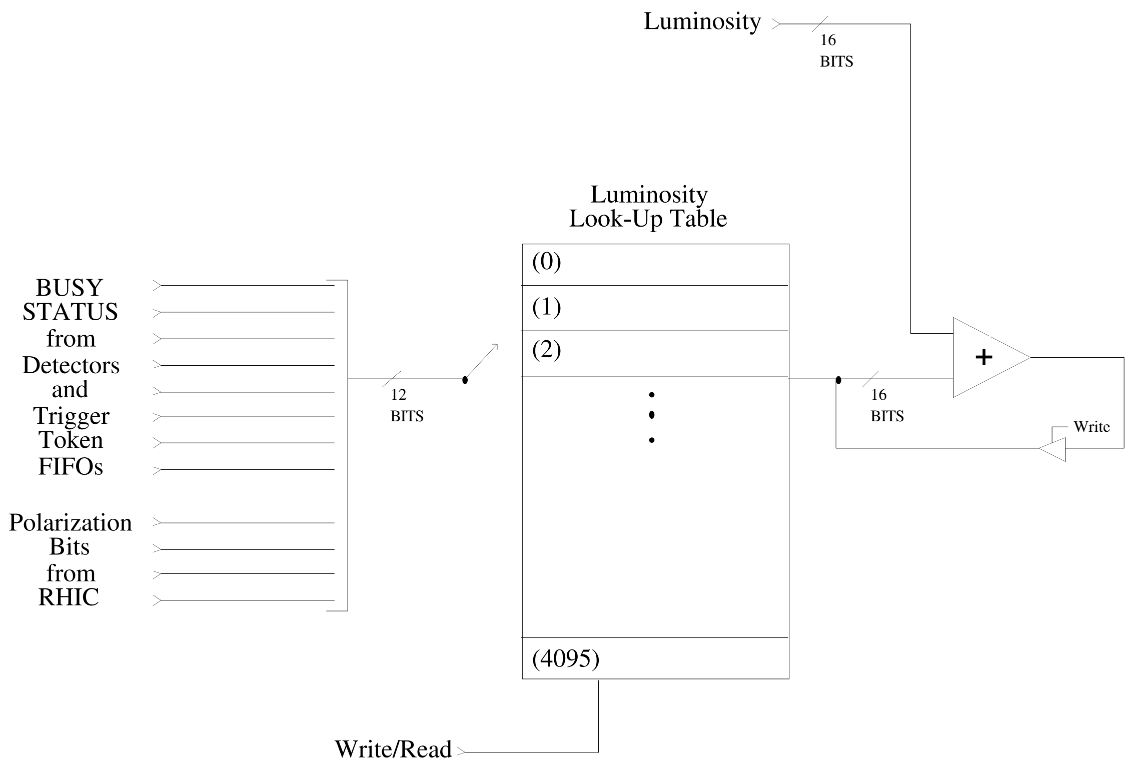

Figure 1: Schematic Diagram of One Scaler Board Channel

4.0 Cross-Section Calculation

4.1 Sample Trigger Configuration

Let us assume we want to calculate the cross-section for the production of a particle X in very high multiplicity events, and in all events with greater than 100 produced particles. X is a very rare particle that is detected by reconstructing its decay products in the full STAR detector set - TPC, SVT, EMC and TOF. One way of configuring the trigger system (i.e. the TCU board) to do this is shown in Table 1.

Data will be taken with all 3 event classes simultaneously, each event class with its own pre-scale factor.

TCU Input	Event Class	Pre-Scale Value
Any set of busy bits Any set of physics bits from the DSM bit Minimum bias bit is set	Minimum Bias (MB)	PSF_{MB}
All detectors NOT busy Interaction was in the diamond 2000 < CTB+MWC multiplicity 1 EMC high tower Minimum bias bit is NOT set	A	PSF_A
All detectors NOT busy Interaction was in the diamond 100 < CTB+MWC multiplicity < 2000 1 EMC high tower Minimum bias bit is NOT set	B	PSF_B

Table 1: Sample Trigger Configuration

The minimum bias trigger basically just triggers on whatever happens in the next bunch-crossing. It should provide a completely unbiased, if small, set of data.

4.2 Calculation of Cross-Section for X at High Multiplicity

The high multiplicity events are those in event class A. If we took just minimum bias data then we would eventually detect the production of X in a high multiplicity event. However, since X is rare, high multiplicity events are rare and the system is mostly dead in this mode of running, this would take a very long time. Instead we pre-scale minimum bias events by a large factor. The experiment is then more likely to be alive whenever an event of type A occurs so they can be taken with a much smaller pre-scale factor.

Here I will describe two methods of calculating the cross-section for production of X in event class A, one using the minimum bias data the other using the pre-scale values.

4.2.1 Method 1 - Using the Minimum Bias Dataset

Probability of finding X in event type A is:

$$P(X)_A = \frac{N(X)_A}{N_A}$$

where:

$N(X)_A$ = number of times X was produced in dataset A

N_A = number of events in dataset A

Probability of producing an event of type A per bunch-crossing is the probability of producing event type A in a minimum bias event:

$$P(A)_{MB} = \frac{N(A)_{MB}}{N_{MB}}$$

where:

$N(A)_{MB}$ = number of times events of type A are produced in the minimum bias dataset

N_{MB} = number of events in the minimum bias dataset when all detectors are NOT busy

Cross-section for producing X in event type A is:

$$\boxed{\sigma(X)_A = P(X)_A \times P(A)_{MB} \times \frac{N_{bcr}}{L}}$$

where:

N_{bcr} = number of bunch-crossings in data-taking time when all detectors are NOT busy

L = integrated luminosity over all bunch crossings when all detectors are NOT busy

N_{bcr} is the final value read from the channel on the scaler board that just counts bunch-crossings. L is the value read from the channel on the scaler board that monitors luminosity.

The error on this cross-section, $\Delta\sigma(X)_A$ can be calculated assuming $\Delta N_A = \sqrt{N_A}$ etc.. In this case:

$$\Delta\sigma(X)_A = \sigma(X)_A \times \sqrt{\frac{1}{N(X)_A} + \frac{1}{N_A} + \frac{1}{N(A)_{MB}} + \frac{1}{N_{MB}} + \frac{1}{N_{bcr}} + \frac{1}{L}}$$

4.2.2 Method 2 - Using the Pre-scale Factors

Probability of finding X in event type A is:

$$P(X)_A = \frac{N(X)_A}{N_A}$$

where:

$N(X)_A$ = number of times X was produced in dataset A

N_A = number of events in dataset A

Number of events of type A that are produced during the data-taking time are:

$$N(A)_{tot} = N_A \times PSF_A$$

where:

PSF$_A$ = Pre-scale factor for events of type A at Level 0

Total number of X that were produced in event type A during the data-taking period is:

$$N(X)_{Atot} = P(X)_A \times N(A)_{tot} = N(X)_A \times PSF_A$$

Therefore the cross-section for producing X in event type A is:

$$\boxed{\sigma(X)_A = \frac{N(X)_A \times PSF_A}{L}}$$

where:

L = integrated luminosity over all bunch crossings when all detectors are NOT busy

Again, the error on this cross-section can be calculated assuming $\Delta L = \sqrt{L}$ etc... In this case:

$$\Delta\sigma(X)_A = \sigma(X)_A \times \sqrt{\frac{1}{N(X)_A} + \frac{1}{L}}$$

4.2.3 Comparison between Methods 1 and 2

Assuming that the conditions stay the same during a run then these two methods should give the same answer. This implies:

$$PSF_A = \frac{P(A)_{MB} \times N_{bcr}}{N_A}$$

If any small subset of the run is taken, and the quantity on the right hand side of this equation is calculated from the data, then the answer should be the same as the pre-scale value downloaded into the trigger at the start of the run. If these two are not equal, then the probability of producing an event of type A per bunch crossing has changed. This could be due to a change in the detector system, e.g. an EMC tower becoming noisy so that it is always high. In this case Method 1, using the minimum bias data set, would have to be used in the cross-section calculation.

A side effect of this is that the error on the cross-section would then become correspondingly larger. The error on any cross-section calculated using method 1 will always be large than that calculated using method 2. Using method 1 involves using two datasets (minimum bias and A) and so the sizes of both datasets are involved. If only a small minimum bias dataset was taken, then $N(A)_{MB}$ could become the dominant factor in the error calculation.

4.3 Calculation of Cross-Section for X at Any Multiplicity

In order to calculate the cross-section for the production of X averaged over all multiplicities we need to combine event classes A and B. Since A and B are mutually exclusive the cross-section for producing X in event type A or B is:

$$\boxed{\sigma(X)_{A+B} = \sigma(X)_A + \sigma(X)_B}$$

in which case the error on this cross-section can be calculated using:

$$\Delta\sigma(X)_{A+B} = \sqrt{(\Delta\sigma(X)_A)^2 + (\Delta\sigma(X)_B)^2}$$

5.0 Discussion and Conclusions

So far in this paper we have discussed two methods of calculating a cross-sections in STAR. Both methods have their advantages and drawbacks. If we use the minimum bias sample to normalize the data then we don't depend on the experimental conditions staying constant through-out the run. Any effects due to suddenly noisy detectors, drifting ADC calibrations etc... can be seen in the minimum bias data and corrected for. However, the error on any cross-section calculated this way can be dominated by the size of the minimum bias data set, rather than number of interesting events. This is a bad feature. On the other hand, if we use the pre-scale values to correct the number of events taken, then the error depends only on the number of interesting events and the luminosity. Unfortunately, to use this method we have to rely much more the experimental conditions (which determine what the pre-scale actually means) staying constant.

Whichever method we use the result will be a cross-section for the occurrence of a process in a particular event type or types. This is not necessarily an absolute cross-section. In our example we specified that there was to be only one EMC high tower. In reality there would be events with background processes that could hide the high tower, or produce more then one high tower. In order to calculate an absolute cross-section it would be necessary to do some analysis of all the events that occurred with the same set of busy bits as event types A and B (i.e. all detectors NOT busy).

Finally, all the calculation so far have used $N(X)_Y$ to mean the number of times a process X occurs in dataset Y. In reality X will not be detected every time, there will be some acceptance and efficiency corrections to be made. So;

$$N(X)_Y = \frac{N(X)_{Ydet}}{eff(X)_Y \times acc(X)_Y}$$

where:

$N(X)_{Ydet}$ = number of time X is actually detected in dataset Y
$acc(X)_Y$ = acceptance for X in this particular experimental setup
$eff(X)_Y$ = efficiency for detecting X given that it was accepted

Both the acceptance and efficiency will have to be determined using a simulation of the experiment. These calculations will introduce their own errors which will have to be included in the error on the final cross-section.