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Luminosity Monitor Topics for RHIC Spin and AA, and pA Interactions

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ABSTRACT

This is a note to define topics to be studied in more depth for the Luminosity monitoring for Spin Asymmetries. My numerical examples here are to stimulate discussion and should be taken with a grain of salt. The RHIC Spin experiments will require a very high degree of coordination between the experiments and the accelerator. For example see AGS/RHIC/SN 035. In this note we list some of the issues to be considered in monitoring the relative luminosity between various beam-beam spin combinations and beam-gas combinations. We give simplified numerical examples of the problems encountered in doing the luminosity monitoring to the 10 ^ -4 level. It is hoped that this will provide a framework for serious study of these problems with simulations and other means. Many of the issues may also be relevant to pA and AA running where there may be sizable beam-gas backgrounds.

INTRODUCTION

In most of this paper we treat the counting aspects of normalizing spin measurements independently of the beam polarization aspects. In the actual analysis of experiments these are generally treated separately as multiplicative factors. Also, our emphasis here is on counting because for example with a raw counting asymmetry of 10^-3 (which may be typical) a systematic error in counting at the 10^-4 level will have as big an effect as a 10% error on polarization.

Monitoring luminosity at an interaction region in a collider is difficult at the 5% level for absolute normalization. For many of the spin physics experiments, the predicted raw asymmetry is on the 10 ^ -3 level, and we need the relative luminosity of the various spin combinations to better than this.

The beam-gas interaction rate near each experiment is of serious concern. The acceptance for Beam-Gas interactions depends on many factors such as forward angle of detectors. The rates could approach KiloHertz for some configurations. While this is lower than the rate from pp collisions, it could be a serious background to both forward physics measurements and to luminosity monitors.

We take it as given that each experiment must monitor the luminosity of it's own interaction point. This is because parameters such as focusing and beam position will be different at each region and may vary with respect to each other over time. Also, the use of more than one monitor is probably necessary to control systematic errors. For example, in STAR one could scale numbers of events with electromagnetic energy above some threshold, and also the number of charged tracks above some multiplicity threshold.

For spin physics, the monitors should ideally use a process that has no spin dependence. Alternately, such effects must average out to high accuracy or else the monitor asymmetry must be measured to high accuracy.

A basic issue that requires study is the question of whether the luminosity monitors must have basically the same acceptance as the experimental events, or whether processes such as forward scattering could be used for the monitor. There are several arguments that the monitors should essentially be a subset of the experiment, but this requires a quantitative study.

For reasons of accumulating sufficient statistics and to avoid overloading the experimental data acquisition system, the luminosity monitors should essentially provide information in the form of scaler data. This will then have the additional advantage that extensive offline processing should not be required.

There are precedents for the required close coordination of beam and experiment. The case most familiar to us is Fermilab E704, where the experimenters designed the beamline and then produced on-line phase-space ellipse plots during the running to monitor its performance.

A typical use of the luminosity information in a spin asymmetry measurement is as follows:

For a parity violation measurement using longitudinally polarized beams, the rate of production of leptons or jets is measured at each lab angle for the various beam spin combinations, and is normalized to the luminosity in those combinations. For example, consider beams A and B respectively in the two rings of RHIC, and helicities + or - of bunches within these beams.

To Extract a single spin asymmetry, A-L, out of these measurements:

A-L = angular factors *

[N(++)/Lum(++) + N(+-)/Lum(+-) - N(-+)/Lum(-+) - N(--)/Lum(--)]

[N(++)/Lum(++) + N(+-)/Lum(+-) + N(-+)/Lum(-+) + N(--)/Lum(--)]

More generally:

With the electromagnetic calorimeter (EMC) in STAR or muon arm(s) in PHENIX, a vertex cut, and some electronics and scalers, we can populate a matrix:

	Bunch A +	Bunch A -	Bunch A Empty
Bunch B +	N + + / Lum + +	N + - / Lum + -	N + empty / Lum + empty
Bunch B -	N - + / Lum - +	N - - / Lum - -	N - empty / Lum - empty
Bunch B Empty	N empty + / Lum Empty +	N empty - / Lum empty -	N empty empty / Lum empty empty

These entries are what is needed to measure an asymmetry such as A-L or A-LL and to measure the backgrounds.

GENERAL ASSUMPTIONS :

1) 120 bunch positions in each ring with a bunch spacing of 104 ns.

2) Population of the bunch positions so that all 9 possible combinations of spin direction and empty buckets are achieved at each interaction region. The 9 combinations are helicity

++, +-, -+, --, +empty, -empty, empty+, empty-, and emptyempty as in the matrix above. The order matters both for the physics and for the backgrounds. (see Note on Polarized Bunch Arrangement, AGS/RHIC/SN no. 035)

3) The approximate 1/e decay time of the luminosity is 10 hours (20 hours = 1/e decay time for each beam). In reality, the decay is not a single exponential.

4) Adiabatic spin flipping of all the bunches in a beam occurs about once an hour. Flipping of the other beam is out of phase by 1/2 hour. An alternative may be to cog the bunch positions so that different bunches collide to make some kind of average to control systematic errors. This has not been worked out to see if it really works.

5) The distribution of beam in the longitudinal direction in a bunch is unknown. If the bunches in each beam were gaussian with sigma of 21 cm, the overlap over time would have a sigma of 21/root(2)=15 cm. If the bunches had a square distribution, the diamond would have a triangle distribution of FWHM = 1/2 the bunch width. If the bunches were dog-bone shaped, the diamond would have a length of about 0.4 of the bunch length. The distribution is probably not gaussian, and involves synchrotron oscillations in any case.

6) Scalers exist in the experiments for multiple luminosity monitors and multiple physics triggers for each of the 9 beam spin combinations. This is several hundred scalers. See Appendix I on scalers.

7) Luminosity monitoring is done by means of:

A) counting the fraction of crossings with a multiplicity of charged tracks and P_t above some minimum values into some solid angle for each of the 9 spin combinations. Multiple multiplicity thresholds can be done simultaneously.

B) counting the fraction of crossings in which electromagnetic energy is above some threshold for each of the 9 combinations. Multiple energy thresholds can be used simultaneously.

C) the above monitor methods with the addition of vertex cuts. These cuts would be made by means of timing using counters near the beam pipe on either side of an experiment.

D) any better methods that are found.

8) It is possible to measure the spin effects in the luminosity monitor by using the monitor itself along with adiabatic spin flipping in one ring for longitudinal polarization, and by using a detector with symmetric acceptance on both sides of the beam for vertical beam polarization. See Appendix II on Self-Calibrating the Asymmetry in the Monitor..

GENERAL QUESTIONS :

1) What physics processes and what geometrical acceptance are appropriate for the luminosity monitors?

A basic issue that requires study is the question of whether the luminosity monitor must have basically the same acceptance as the experimental events or whether processes such as forward scattering could be used for the monitoring of mid-rapidity events. There are several arguments that the monitor should essentially be a subset of the experiment, but this requires a quantitative study.

Are cuts needed on monitor event positions at the ends of the interaction diamond to match the cuts made on physics acceptance? (This is discussed in detail later.) In both STAR and PHENIX there are questions of how much the physics acceptance changes with position of the interaction in the diamond.

For spin physics, the monitor should ideally use a process that has no spin dependence. Alternately, it must average such effects out to high accuracy or else measure the monitor asymmetry to high accuracy.

For example, pp elastic scattering has about a 1% asymmetry over a broad range in t up to 1/2 GeV ^2 from the coulomb nuclear interference effects. Can we make the left-right acceptance of a forward monitor uniform enough so as to reduce the rate effects from this effect to 10 ^ -4 ? Note, the elastic scattering asymmetry at mid-rapidity (near 90 degrees in CM) is negligible.

In STAR several processes can be used simultaneously as luminosity monitors:

1) Sum of EMC energy. Count events above each Energy Threshold.

2) CTB (charged trigger barrel) multiplicity at level 0 at least 3. Count events above each Multiplicity Threshold.

3) MWC (wires at the ends of the time projection chamber, TPC) multiplicity at least 3. Count events above each Multiplicity Threshold.

4) etc.

Note, each of these quantities are assumed to utilize the same vertex constraint as the data.

2) Is there any advantage in attempting to measure luminosity for each of 120 bunch combinations at each experiment, or is it sufficient to accumulate the information for each of the 9 possible spin combinations? The 9 combinations are helicity ++, +-, -+, --,

+empty, -empty, empty+, empty-, and emptyempty, as noted before. The order matters both for the physics and for the backgrounds.

The statistics may be insufficient to do 120 bunch normalizations and there appears to be no good reason to do it.

3) What is the evolution of a bunch during a store? What are the factors that contribute to bunch evolution? What is the maximum shift in the overlap integral of the two beams, and in the diamond shape for this evolution of bunches? How much does the overlap of bunches from the two rings change when the orbit radius changes in one ring? The polarization may be different for the higher emittance part of the beam after passing through the AGS. The polarization is rotated by the low beta quads for particles having large angles at the interaction diamond.

4) We need to consider statistics vs time for both monitor and physics (discussed in detail below).

Accelerator SPECIFIC TOPICS:

1) How do the bunches change during a store? The following effects will need to be considered:

A) Beam-beam ***elastic??*** scattering

B) Beam-gas ***elastic??*** scattering

C) Defocusing by the electromagnetic fields of the bunches in the other beam at the interaction diamond. (This is the same effect that produces the tune shift. It is defocusing for like-charge beams.)

D) Wakefield effects (these may be different adjacent to empty RF buckets than adjacent to filled buckets).

E) Enhancement of the above effects by the higher multipoles in the magnetic fields away from the magnet centers. (effective Aperture)

F) Electrostatic repulsion vs capture by the accelerating RF field.

G) Synchrotron oscillations.

H) Scraping off of particles at large radii either physically or by field imperfections.

2) How does the intersection of the bunches change during a store? Consider:

A) RF phase change of one beam vs the other will move the diamond in the z direction.

B) The orbit radius of one beam can change with respect to the other. How much effect does this have at the low beta focus point?

C) The bunches in one ring may change size and shape independent of the bunches in the other ring due to different gas pressures, different magnet imperfections, etc. This affects the overlap integral of the two beams, and hence the luminosity.

Some Simple Simulations:

I wrote a number of very simple programs to look at the shape of the diamond from colliding bunches of different distributions along the beam direction. For gaussian bunches, the diamond was gaussian, with width of 1/root(2) of the length of a bunch. For bunches with square distribution the diamond is a triangle with FWHM of 1/2 the bunch length. Also, For dogbone shaped bunches, the diamond FWHM is about 0.4 of the bunch length, and somewhat flatter than a gaussian in the middle.

None of this is surprising. The gaussian result is the same result as for combining errors, You can intuitively get the dog bone result from considering a bunch consisting of two delta functions a foot apart. The diamond is then a single delta function in the center.

I did a simulation of the bunches colliding many times and depleting the population in each bunch by the product of the intensities of the bunches at each location, integrated over the region. I tried this for flat bunches and triangle shaped bunches and dog-bone shaped bunches. What I found was no change in shape in the bunches, even after depleting 99% of each bunch. However, many relevant effects were Not Simulated. Synchrotron Oscillations were not included, and bunch collisions were perfectly head on (effectively one-dimensional), and the change in beta (focusing) along the bench length was not included.

3) How is the polarization direction different for different parts of the interaction diamond?

If we assume perfectly aligned polarization over all phase space before the low beta quadrupoles, it can be calculated that the largest angle rays in the diamond can have their polarization vector rotated 20 degrees, but reality will probably be much more complicated.

4) Is the RF frequency a multiple of the approximately 9.6 MHz for 104 ns bunch spacing? If so, particles can leak into what should be empty spaces and complicate both the physics and the monitor events. (This happened in a Los Alamos spin experiment)

TOPICS INVOLVING EXPERIMENT AND ACCELERATOR TOGETHER:

1) The acceptance for products of a beam-gas interaction in either experiment or monitor is a function of the position in the accelerator at which the interaction occurs. The outgoing particles are Lorentz boosted forward, and travel roughly in time with the beam bunch. We must integrate the beam, the gas, the production and the acceptance over some length of the beam on each side of the experiment. Since the secondaries are boosted forward, there will be a *Much Greater Acceptance for beam-gas interactions in a forward luminosity monitor,* compared to either a central monitor or the physics acceptance.

For example, a forward monitor that sees y = 4, P_t ave = 0.3 events from beam-beam collisions will see a broad distribution, centered at ycm = 1 and P_t ave = 0.3, with different y from various places in the straight section of beam pipe, from beam-gas interactions. This is because there is a higher cross section at y = 1 than at y = 4.

2) a) If the experimental acceptance does not include all the interaction diamond because of the length of a vertex detector or some other detector, we must consider fluctuations in the fraction of the diamond outside the acceptance. If the luminosity monitor sees all the diamond, may not be possible to get the ratio of luminosity monitor to physics events correct to within a part in 10 ^ 4.

For example, assume a vertex detector 25 cm long, and a gaussian diamond with typical sigma of 12 cm. Then about 37 % of the diamond is outside the vertex detector. If the center of the diamond is depleted by 10% in 10 hours relative to the ends, the ratio of what is observed by the experiment to what is observed by the monitor changes from 63% to 59%. This does not directly address the issue of the Asymmetry in L.

b) If the experimental acceptance is not symmetric in phi around the beam, there will be changes in acceptance if the diamond position is changed. We would then have to see if there was movement correlated in any way with the polarizations.

c) The diamond can also move along the beam direction, with pats of the diamond moving in and out of the experimental acceptance. Can it be set within 1 cm from run to run? How stable is the RF phase? We will have to know how stable it is during a run and from run to run if we are combining runs, particularly if we do not have vertex cuts on the scaled luminosity monitor events.

3) Since it is possible to measure the spin effects in the luminosity monitor by using the monitor itself, how effectively can we do self-normalization of the physics asymmetries without the monitor? Remember that the monitor self calibration of asymmetry could use extrapolation in P_t or either adiabatic flipping or balanced acceptance on two sides of the

detector and has very high statistics compared to most physics of interest..

EVOLUTION OF MONITOR AND EXPERIMENTAL STATISTICS OVER TIME:

The basic issue here is that the experimental events are acquired over a period of time. If there are changes in running conditions over this time, then for each subset of events with stable conditions it might be desirable to have the monitor error smaller than the final physics statistical error in order to combine the subsets of events, but this appears not to be necessary.

Also, can we see real systematic errors in the data asymmetry by looking at the monitor, or would we be primarily seeing errors in the monitor itself? The luminosity monitor for an experiment also acquires data over time, and at any given time it has a certain statistical error, and systematic shifts due to things such as temperature, drift of HV an phototubes, poor vacuum in the ring, etc.

As a hypothetical example, suppose it is desired to do a determination of the transverse structure function for the proton, h1(x) by measuring 10 ^ 8 jets in 50 days live time with 25 events detected per second. Assume each beam is polarized to 50 %. The statistical error on the raw asymmetry at the end of 50 days is then 1/ (P1 P2 sqrt(N)) = 4 x 10 ^ -4. Assume a parton level asymmetry of 0.10, which is multiplied by h1(x1) times h1(x2), with h1 about 0.25 at moderate x (this is not h1 bar of sea quarks). The raw asymmetry for the good events is then 1.6 x 10 ^ -3. This would be a 4 sigma measurement if we could control the systematic errors with a good luminosity monitor.

We want the statistical error on the luminosity monitor to be smaller than the statistical error on the raw asymmetry. We could assume it to be half as large, and thus require 4 times as many events in the monitor as in the physics events if conditions were stable for the full 50 days. The monitor would then require 4 x 10 ^ 8 events total, or 100 per second.

An extreme point of view would be as follows:
If we think that conditions will change from store to store, we want the monitor statistical error of 2 x 10 ^ -4 for each 8 hour store. This requires 13 k events per second to get 4 x 10 ^ 8 events in 8 hours. This is 10 ^ -3 of the total cross section or 50 micro barns. Clearly, the monitor must have very simple data, perhaps only scalers to be read.

ANOTHER HYPOTHETICAL CALCULATION

NOTE: there are more recent calculations of beam-gas than this !!!!! Many of the numbers in this example are conjectural, but it shows an effect.

Assume that the Luminosity decays exponentially with 1/e in 10 hours. (Each beam has 1/e of 20 hours) (The Luminosity decays 10% in 1 hour.)

Assume that the + bunches have 10% more beam than the - bunches due to the operation of the source.

Assume that the beam-gas rate into the luminosity monitor is about 20% of the rate from real beam-beam luminosity. (Roughly 10% from each beam) (This is a Gross Overestimate)

Then the Luminosity measured for ++ is 1.1A * 1.1B + 1.1A*0.1 + 1.1B * 0.1 = 1.43 while the true luminosity is 1.21.

The luminosity measured for -- is 1.0A * 1.0B + 1.0A * 0.1 + 1.0B * 0.1 = 1.20 while the real luminosity is 1.0.

The relative errors on ++ and -- are 1.181818 vs 1.20000 or about 2 % which is much bigger than the 10^-4 desired.

If we take data for 2 hours and flip the spins in both beams after 1 hour, then the relative error is 0.2 % or 2* 10^-3.

The real problem in this particular example is that the vacuum could change over a 3 month run so that the scale factors could have major changes.

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Appendix I on Scalers in Experiments

What I came up with for the scalers for spin physics after presentations to RHIC Spin group over a couple of years was as follows:

There are 9 Bunch combinations at an interaction region in the machine, so any quantity we want scaled has to be scaled 9 times to keep track of it all. The combinations are ++, --, +-, -+, +empty, -empty, empty+, empty- emptyempty. (STAR is asymmetric with only one end cap and furthermore we need all the ordered linear combinations of these for things like the parity conserving and parity violating parts of the Z0 coupling)

For the Luminosity monitoring we have for example three types of monitors each scaled with and without the VTB vertex cut, and with two thresholds since we don't yet know all the physics at this energy.

For example,
EMC global energy, 2 thresholds (lower than physics, say 400 MeV and around 1 GeV, with and without vtx cut

CTB global multiplicity ....2 thresholds, etc

MWC or else something that we find experimentally to work better. This gives 108 scalers just for the Luminosity monitor, without any physics to tie it on to.

For the Physics, We want to normalize the final results to the number of level 0 triggers, and the number of level 0 triggers to the luminosity.

We could scale the following for level 0 normalization:

EMC global energy, 2 thresholds, maybe 5 GeV and 15 GeV ? with and without Vtx cuts

EMC supertower energy 2 thresh, etc

EMC single tower, 2 thresholds, etc

This gives 108 scalers for the physics quantities for normalization.

So this is 216 scalers already. I think there will be many more scalers to keep track of things like multiple dead times and to look for systematic correlations, etc.

Appendix II on Self-Calibrating the Asymmetry in the Monitor..

A) i) For the 2 spin case with spin directions either longitudinal or vertical, and adiabatic spin flipping in one ring assumed to be done every hour or so (a time short compared to a store time), define:

L(++) is the luminosity monitor counts for a +helicity bunch on a +helicity bunch for a certain number of + + crossings.

L(++)bef uses bunches a and b before b is flipped (a and b in different rings)

L(+-)bef uses bunches e and f before f is flipped

L(+-)aft uses bunches a and b after b is flipped

L(++)aft uses bunches e and f after f is flipped

Then the spin asymmetry in the monitor itself is:

A_ll = [(L(++)bef + L(++)aft) - (L(+-)bef + L(+-)aft)] / [(L(++)bef + L(++)aft) + (L(+-)bef + L(+-)aft)] or equivalently,

A_ll = [(L(ab)bef + L(ef)aft) - (L(ef)bef + L(ab)aft)] / [( ) + ( )]

Note that we have to keep a count of how many ab and ef crossings were used as a way of doing the normalization.

ii) Another method is to use multiple luminosity monitors at central rapidity with several different P_t thresholds. The asymmetry in one can be found using another as the luminosity monitor. With at least 3 of these, it may be possible to find the asymmetry as one extrapolates to P_t = 0.

B) For the single spin transverse case, we use the usual method with two arms: An = [sqrt({left+} * {right-}) - sqrt({left-} * {right+})] /
[sqrt( ) + sqrt( )]

This is the way the AGS polarimeter is used without a monitor.

C) For the 1 spin longitudinal case, this is basically the 2 spin longitudinal asymmetry with an average over one beam to get 0 polarization. It is done in the same way as for the single spin parity violating measurement described before.

L(+0)bef uses bunch a and c in one beam and bunch b and d in the other beam. The a and c bunches are + helicity, while b is + helicity and d is -.

A_l = [(L(+0)bef + L(+0)aft) - (L(-0) bef + L(-0)aft)] / [( ) + ( )]

Someone should do the algebra to see if there is something like the square-root formula for A_n for this case, but using "before" and "after" instead of "left" and "right".

Appendix III MORE ON BEAM-GAS INTERACTIONS FOR RHIC SPIN

We estimate the beam-gas interaction rates for colliding beam regions such as those for STAR and PHENIX as well as for PP2PP elastic and the fixed target pion polarimeters. The backgrounds due to the interactions at colliding beam experiments are difficult to estimate. They depend on the angular distribution of secondaries, which is very forward for beam-gas interactions. They also depend as well on the location of the beam-gas event.

We refer to a similar note for backgrounds in heavy ion running by W. B. Christie.

Gas as a target:

We need to know the pressure of the gas, the temperature, and the molecular composition, to find the density of nucleons. We will also need to know the length of beam pipe in which the gas is an effective target, but this depends on the distribution of secondaries and sweeping by dipoles and quadrupoles in the beamline.

The gas may be a mixture of H2, CO and H2O, but we assume H2 for simplicity. The temperature in both the crossing regions and the polarimeter regions may be near room temperature. A temperature of eg. 2.7 K would make the gas density 100 times higher at a given pressure.

We assume the pressure is 10^-9 torr. It is unknown if pp running at 10 times the nominal luminosity (120 bunches vs 60, 2x10^11 per bunch vs 10^11, and lower beta at the intersections) will cause heating and more gas emitted from beam pipe walls. Note, one atmosphere is 760 torr. With a density of .09 x 10^-3 gm/cm3 at atmospheric pressure, we then get a density of 1.2 x 10^-16 gm/cm3 in the pipe. Using Avogadro's number, there are 7 x 10^6 hydrogen atoms per cm3.

For the colliding beam regions, the length of pipe from a DX magnet to the intersection was considered a potential gas target. The DX magnets should sweep away most secondaries from upstream. Interactions downstream of the crossing before the other DX magnet will have only low energy backward secondaries. This length is about 9 meters.

Thus for the crossing regions, there is a gas target of 6 x 10^9 protons/cm2. This exists on one side for one beam and on the other side for the other beam.

The Beam Flux:

We can assume nominal luminosity with roughly 60 bunches and 10^11 per bunch, or upgraded with roughly 120 bunches and 2 x 10^11 / bunch. The size of the beam (low beta focusing, etc.) does not affect the number of beam-gas interactions. It does affect the ratio of good beam-beam interactions to beam-gas interactions. The beam flux is 77266/second * 120 bunches x 2*10^11 = 1.8 x 10^18 per second.

Distribution of beam-gas products:

We can make a crude estimate of the possible secondaries from beam-gas interactions. We must assume a both a simple rapidity distribution, d-n/d-eta and a P_t distribution.

A typical pion from beam-gas interactions has a laboratory rapidity of 2 to 4 and a P_t of

0.3 GeV/c. The rapidity in the c.m. frame is boosted by about 3 units to the laboratory.

Some aspects of the distribution are mean P_t = 0.3 GeV/c, P_t distribution about exp(-6*P_t) out to about 1 or 2 GeV/c, and a slower fall off crudely like P_t^-5 out further. The kinematic limit for 200 GeV fixed target is about P_t= 9 GeV/c.

Note that in the case of the fixed target pion polarimeters, the secondaries are exactly the same as in the desired events except for source location.

In the spin physics program, most of the particles of interest have relatively high P_t, except some pions from jet fragmentation. Particles from beam-gas interactions at large angles in the laboratory with respect to the beam have low limits on possible transverse momentum from kinematic constraints.

BACKGROUND INTERACTION RATES FOR POLARIMETERS:

If we assume the polarimeters are sensitive to beam-gas interactions from about +/- 2 meters from the target, we can calculate a background rate. The gas has 7 x 10^6 /cm3 * 400 cm = 3 x 10^9 protons/cm2. The beam flux is 1.8x10^18/sec, and the cross section is about 40x 10^-27 cm2. The rate of beam-gas interactions is then about 200 per sec.