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# CROSSING ANGLE IMPLEMENTATION FOR LUMINOSITY MAXIMIZATION IN A NARROW VERTEX REGION IN RHIC OPERATION

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*Abstract*

The Relativistic Heavy Ion Collider (RHIC) [1] was designed for head-on collisions in the Interaction Regions. However, RHIC operation in recent years necessitated crossing angles to limit collisions to a narrow longitudinal vertex region, which created operating conditions with a large Piwinski angle (LPA). The angles were implemented by adjusting the shunt currents of four dipoles, the D0 and DX magnets, near the IP. The longitudinal bunch profile often deviates from Gaussian due to the utilization of high-order RF cavities, adding complexity to calculating luminosity reduction with crossing angle. This paper introduces a new numerical calculation of luminosity reduction with crossing angle, compares the results with experimental observations, presents two methods for implementing crossing angles, and discusses resultant aperture concerns.

## INTRODUCTION

In recent years, the experimenters requested collisions with crossing angles [2–4] for two purposes: one is to control the collision rate for some of their detectors, and to limit collisions in a narrow longitudinal vertex. The sPHENIX innermost silicon detector (MVTX) spans $\pm 13$ cm along the beam axis. Thus, the "optimal" tracking acceptance for collisions lies within $|z| < 10$ cm. At the same time, lots of collisions with $|z| > 10$ cm create larger distortions in the TPC but are not optimally useful for the sPHENIX physics program [5].

We observed significant discrepancies between measured and predicted luminosity with crossing angle in the 2023 100GeV Au+Au physics program. The discrepancy was believed due to non-Gaussian profile (more specific, profile with multiple satellites in 197 MHz buckets), and long bunches due to Intra-beam scattering. In this paper, we will introduce the calculation of luminosity with crossing angle based on measured longitudinal bunch profiles. The comparison between the new model and the measurements will be presented as well.

Meanwhile, there are two practical concerns regarding the implementation of crossing angles in RHIC: the aperture constraint and the shunt supply current limit. This paper will present the crossing angle tuning range for current and future RHIC operations due to these constraints.

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## LUMINOSITY REDUCTION DUE TO CROSSING ANGLE

In this section, the analytic formula for luminosity with various effects will be introduced, and the comparison of analytic calculation and experimental measurements of luminosity reduction with crossing angle will be shown. Then a new numerical calculation of luminosity with crossing angle based on measured longitudinal profiles will be established, and the agreement of numerical calculation and the measurements will be shown. In the end, the application of the new numerical method in RHIC will be presented.

### *Analytic Model and its Comparison with Measurements*

The luminosity distribution is the convolution of the 3D bunch profiles of the two colliding beams [6]. For head-on collisions with equal but opposite velocity, the luminosity can be expressed as the following:

$$L = 2N_1N_2fN_b \int\int\int\int \rho_1(x,y,s,-s_0) \cdot \rho_2(x,y,s,s_0)\, dx\, dy\, ds\, ds_0 \tag{1}$$

Here $N_1$ is the bunch intensity of beam 1, $N_2$ is the bunch intensity of beam 2, $f$ is the bunch repetition frequency, $N_b$ is the number of bunches, $\rho_1$ and $\rho_2$ are the 3D bunch profile function.

With equal bunch length and 3D Gaussian distribution, this simplifies to be

$$L_0 = \frac{N_1N_2fN_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} \tag{2}$$

Here the $\sigma$'s are the transverse rms beam sizes.

For collision with a full crossing angle of $\phi$, the luminosity becomes

$$L = 2\cos^2\left(\frac{\phi}{2}\right) N_1N_2fN_b \int\int\int\int \rho_1(x,y,s,-s_0) \cdot \rho_2(x,y,s,s_0) dxdydsds_0 \tag{3}$$

If the 3D distribution of the two bunched beams can be represented well by Gaussian distributions, the bunch length is longer than the transverse beam size and the crossing angle is relative small, then the luminosity formula with a horizontal crossing angle can be simplified as follows

$$L = L_0 \cdot \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}\right)^2}} \tag{4}$$

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Here $\sigma_s$ and $\sigma_x$ are the longitudinal and horizontal rms bunch/beam sizes.

For more detailed analysis of the luminosity with crossing angle and/or beam offset, please refer to the reference [6]. For the case that the longitudinal profile is Gaussian, the equation works well for predicting the luminosity reduction factor in RHIC since the bunch length is much longer than the transverse dimension and the crossing angle is relatively small, up to 2 mrad.

The relativistic heavy ion collider (RHIC) provides collisions of equal ion species from p-p all the way up to U-U, and operation of unequal species collisions such as protons on gold ions. The transverse density distribution of all species are Gaussian, however, the longitudinal density distribution for different species differ due to different diffusion rate from intra-beam scattering. Various crossing angles were implemented for the O+O physics program for the STAR experiment in 2021 and the Au+Au physics program for the sPHENIX experiment in 2023. We observed significant discrepancy of the predicted and measured luminosity reduction due to crossing angle. In Fig. 1, the calculation was based on Eq. 4 and the following parameters: $\sigma_s = 0.9m$, $\sigma_x = 0.28mm$.

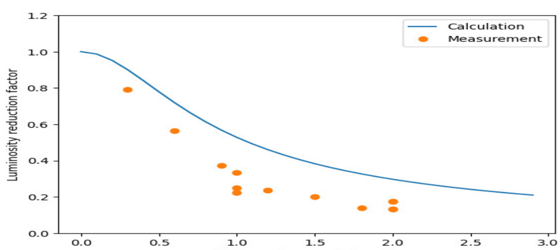


Figure 1: Comparison of the calculated and the measured luminosity reduction factor as a function of the crossing angle. The dots were measurements made during 100GeV O+O physics program in 2021 and Au+Au program in 2023.

## *New Numerical Model and its Comparison with Measurements*

A numerical algorithm for calculating the luminosity is necessary for the case of asymmetric collisions where two beam profiles do not match, especially in the longitudinal direction, and for the case where the longitudinal profile is non-Gaussian. The following will introduce an algorithm for luminosity calculation with crossing angles for these cases.

The bunches of the colliding beams are cut into multiple longitudinal slices. The $i$-th slice and $j$-th slice collide at $(i - j) \cdot ds/2$ away from the IP, where $ds$ is the longitudinal length of the slice. The luminosity of their collision is affected by the hourglass effect and the physical separation due to crossing angle. The luminosity can be expressed as the following,

$$L = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \sum\sum m_i n_j \cdot S_{hg} \cdot S_{angle} \quad (5)$$

Here $m$ and $n$ are the normalized longitudinal intensity profile of the two beams, and $m_i$ and $n_j$ are the $i$-th and the $j$-th slice intensity. The hourglass effect is shown in Eq. 6 and the effect of separation due to crossing angle is shown in Eq. 7.

$$S_{hg} = \frac{\beta^*}{\beta^* + s^2/\beta^*} \quad (6)$$

$$S_{angle} = \left(\frac{s\phi}{2\sigma}\right)^2 \quad (7)$$

The longitudinal intensity samples were based on Wall Current Monitor (WCM) measurements with 0.05 ns time interval between sample points. Integration of all sample points of the WCM profile of one beam and all points of the WCM profile of the opposite beam was calculated with and without hourglass and crossing angle. The reduction factor was calculated as the ratio of luminosity with and without these effects.

The reduction of luminosity due to crossing angle is strongly dependent on the longitudinal profile, therefore it varies from the start to the end of a store as bunch length grows. In Fig. 2, the bunch profile of gold beam at the start of a Au+Au physics store is shown. The corresponding luminosity reduction factor dependency on the crossing angle is shown in Fig. 3. Similarly, the bunch profile of gold beam at the end of a physics store is shown in Fig. 4. The corresponding luminosity reduction factor dependency on the crossing angle is shown in Fig. 5.

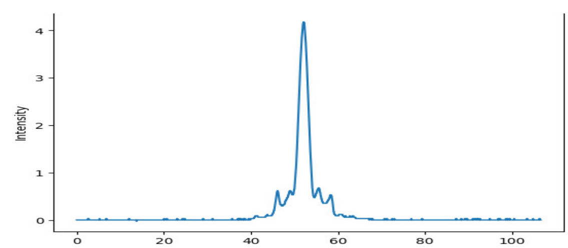


Figure 2: Longitudinal bunch profile measured by WCM at the start of a physics store.

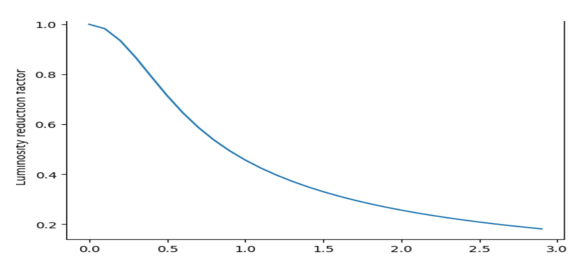


Figure 3: The calculated luminosity reduction factor as a function of the crossing angle at the start of physics store.

Figure 6 consolidated the measured luminosity reduction factors and the calculated using the numerical method introduced above. Please note that the longitudinal profile of both species have multiple peaks due to scattering and

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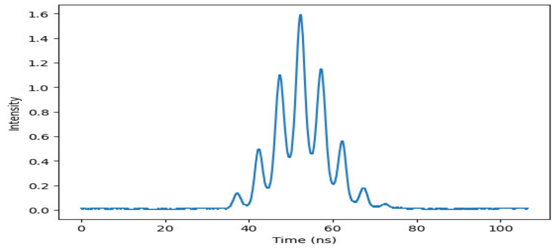


Figure 4: Longitudinal bunch profile measured by WCM at the end of a physics store.

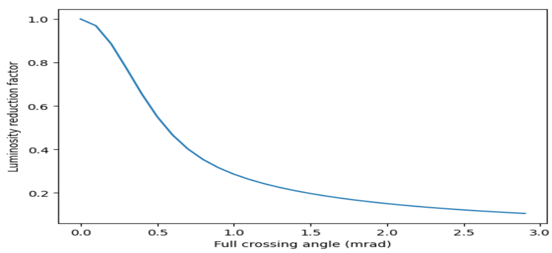


Figure 5: The calculated luminosity reduction factor as a function of the crossing angle at the end of physics store.

higher harmonics cavity, however, the exact shape differs from each other depending on how long the beam has been stored.

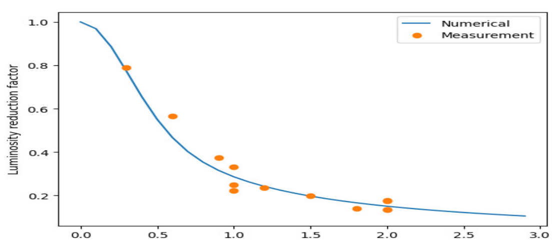


Figure 6: Comparison of the calculated and the measured luminosity reduction factor as a function of the crossing angle. The dots were measurements made during 100GeV O+O physics program in 2021 and Au+Au program in 2023.

### *Application of the Numerical Model in RHIC*

The algorithm for the numerical calculation of luminosity with crossing angle has been implemented in an application called StoreAnalysis. It serves two main purposes: one is to project luminosity with crossing angle for future operation based on past physics operation without crossing angle but otherwise the same operational conditions. It can also calculate the would-be luminosity for physics operations if the crossing angle were not present.

Polarized proton+gold operation were projected for RHIC physics program in 2025. Due to the asymmetric collision and the non-Gaussian longitudinal profile of the gold beam, it is necessary to use the application to make prediction for operation with crossing angle. Figure 7 shows the luminosity delivered in 2015 and the projected luminosity with 2 mrad crossing angle. The upper plot shows the beam intensity of the two beams. In the lower plot: the black curve is the delivered luminosity, the red curve is the reduction factor due to 2 mrad crossing angle and the blue curve is the projected luminosity.

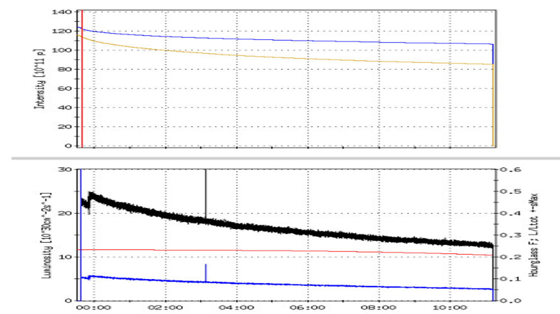

Figure 7: The delivered Luminosity of a p+Au physics store in 2015 and the projected luminosity if a 2 mrad crossing angle is implemented.

At the time of this paper, RHIC was running with polarized proton+proton collisions with 2 mrad crossing angle for sPHENIX physics program. One could use the application to calculate the would-be luminosity without the crossing angle for a comparison with past years. Figure 8 shows the delivered luminosity at sPHENIX with the crossing angle and the luminosity if the angle were taken out.

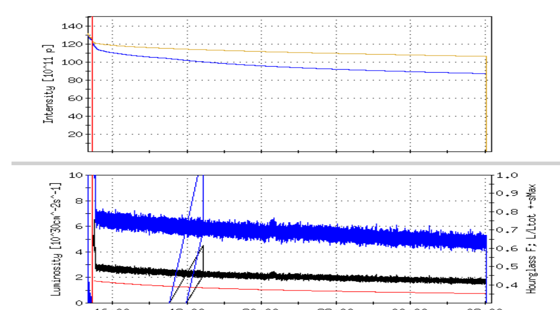

Figure 8: The delivered Luminosity of a p+p physics store in 2024 and the would-be luminosity if the 2 mrad crossing angle were taken out.

## PRACTICAL CONCERNS WHEN IMPLEMENTING CROSSING ANGLE

The aperture limit at the DX magnet (the common dipole magnet for both beams) and shunt supply current limit are the two practical concerns when implementing crossing angles. A crossing angle can be implemented in two ways, a positive angle or a negative angle.

The decision was made to implement −2 mrad crossing angle to provide enough aperture space at the DX magnet for beta squeeze down to 60 cm. As the consequence, one would have to reverse the polarity of the D0 shunt power supply for that.

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