In pursuit of QCD instantons: acceptance studies for the ATLAS Roman Pot detector system at the LHC

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Abstract
Instantons are predicted within the standard model as mediators of quantum tunneling process in the Yang-Mills theory. Currently detecting them proves extremely difficult, as they are indistinguishable from other background soft QCD events. This report takes a look at forward detectors, specifically ATLAS Roman Pots, and their potential to alleviate this problem, with an emphasis on using local bumps in the standard accelerator optics to create a sufficient acceptance. Finding that local bumps have the potential to increase the acceptance in ξ for the AFP by about 60 bins. ALFA detector is discussed as the strongest candidate when looking at acceptance. We also briefly touch on the topic of potential future optics at the LHC and how this might affect these forward detectors, while suggesting a solution that could potentially be acceptable for all parties.

1 Motivation and Background

Instantons are classical solution to the Yang-Mills theory. They are predicted in the standard model but have not been observed yet. They thought to lead to the violation of baryon plus lepton number in the electroweak theory and of chirality in QCD [1]. In general, we expect instanton events to posses large sphericity, high multiplicity and flavour democracy, where all kinematically allowed quark flavours are produced. Their observation, however, poses many challenges. For low mass instantons, they are almost indistinguishable from other soft QCD events, meanwhile, for high mass, the cross section is heavily suppressed due to the factor of $e^{-2\pi/\alpha_s}$. To circumvent this problem, we can filter for events with a large rapidity gap. Hence, using forward proton tagging can be the key to identify these events, and therefore to find instantons [2]. In specific, this report looks at ATLAS Roman Pots as potential candidates. Since only a fraction of events are diffractive, the cross sections is further reduced for this case. Meanwhile, double-tagging allows for the reconstruction of the instanton mass, which is well-desired, it proves to be a great challenge.

1.1 Acceptance, ξ and p_{T}

We can characterise protons in the LHC by relative energy loss ξ and transverse momentum p_{T}. For the central diffractive collisions we can write

$$\xi_1\xi_2 = \frac{M_I}{s}, \tag{1}$$

where ξ_1 and ξ_2 are the relative energy losses of the two protons, M_I is the mass of the instanton and s is the total centre of mass energy squared. When constructing the acceptance of a detector we look at the percentage of protons detected for a given ξ and p_{T}. It is therefore a useful tool in visualising the theoretical limits of our detector for tagging protons in a given range.

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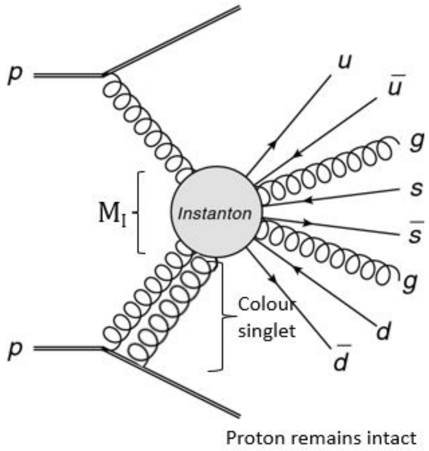

Figure 1: Proton-Pomeron diffractive instanton creation, with M_I being the mass of the instanton. The pomeron exchange is represented by the double gluon. All kinematically allowed quarks are generated in the process, with a specific case shown here. From the incoming interacting protons only the one on the bottom is preserved in this specific case.

1.2 ATLAS Roman Pots

ATLAS Roman Pots (ARPs) are forward proton detectors about 200 metres from the ATLAS interaction point. There are two different ARPs, the AFP (ATLAS Forward Proton) and ALFA (Absolute Luminosity For ATLAS). They are especially useful, as their distance from the beam can be very precisely adjusted. ALFA covers a larger region both above and below the beam, with only a small gap in the vertical for the beam itself, however, as it is not radiation hard, it cannot operate for an extended period of time. The AFP, meanwhile, is radiation hard, but positioned further away from the beam, with a smaller detection area. Furthermore, it is constrained to only one side in the horizontal due to the features of the elements of LHC at its location. This makes the AFP especially sensitive to any changes in the optics.

1.3 EasyTracker

EasyTracker is a program that visualises particle trajectories with the specific purpose of aiding understanding. It updates trajectories real time for a change in the magnet settings [5]. EasyTracker has a built-in generator that simply creates protons with equally binned ξ, p_T and ϕ (azimuth angle) values for a given interval.

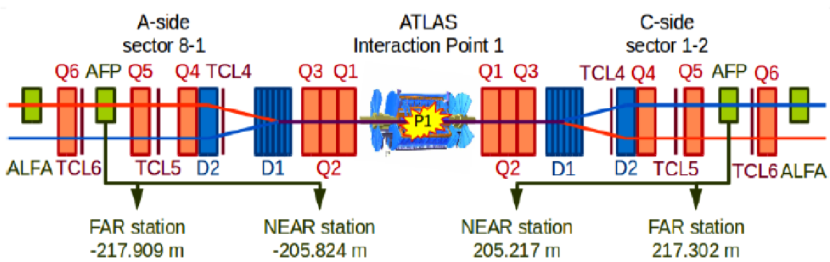

Figure 2: Beamline elements around the ATLAS interaction point. The red lines show the path of outgoing particles, while the incoming are shown in blue. Quadruple magnets are coloured in red, while dipoles in blue. Q1-3 are often referred to as the inner triplet. TLC4 and 5 are collimators.

1.4 Accelerator optics

In the followings, a handful of useful results are presented from accelerator optics. This is with the intent of giving any reader, who is unfamiliar with the topic, an insight to the mathematics behind the discussion. However, in order not to stray too far from the main subject, we are going to refrain from any derivation or longer discussion in this section. We strongly encourage any reader interested in the details, to refer to [6] as the followings are taken from there.

1.4.1 Trajectory equations

Firstly, to make our job easier, instead of using a time parameter t, we use a space parameter $s = vt$, where v is the velocity. To describe the motion of the particles in the electromagnetic field we write

$$\begin{aligned} x'' - (k - \tfrac{1}{\rho^2})x = \tfrac{1}{\rho}\tfrac{\Delta p}{p_0} \\ z'' + kz = 0 \end{aligned} \tag{2}$$

with $\frac{1}{\rho} = \frac{eB_0}{p_0}$ and $k = \frac{eg}{p_0}$ where ρ is the local radius of curvature, g is the local gradient, p_0 is the initial momentum of the particle, Δp is the change in momentum, therefore $\xi := \frac{\Delta p}{p_0}$ is the relative change in momentum, while B_0 is the z component of the magnetic field that we took to be constant. The $\frac{1}{\rho^2}$ term is called the weak focusing. This can be neglected in the case of the LHC, as it is negligible compared to the strong focusing term k. We can rewrite Eq. (2), given that the bending strength $\frac{1}{\rho}$ and focusing strength k are both functions of s. We can introduce a new form as

$$\begin{aligned} x'' + K(s)x = \tfrac{1}{\rho}\tfrac{\Delta p}{p_0} \\ K(s) = -k(s) + \tfrac{1}{\rho^2(s)}. \end{aligned} \tag{3}$$

The general solution of Eq. (3) can be written as

$$x(s) = C(s)x_0 + S(s)x_0' + D(s)\frac{\Delta p}{p_0}, \tag{4}$$

where $D(s) = \frac{x_0}{\Delta p/p_0}$. C(s) and S(s) are two independent solution of the homogeneous equation

$$C'' + K(s)C = 0, \qquad S'' + K(s)S = 0. \tag{5}$$

And so we arrive to

$$\begin{pmatrix} x \\ x' \\ \xi \end{pmatrix} = \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \\ \xi \end{pmatrix} \tag{6}$$

1.4.2 Transformation matrices of the magnets

The transformation matrix in Eq.(6) for specific cases looks as follows:

– **Drift space** has the simplest matrix

$$M_x = M_z = \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

In the drift space there is no magnetic field, and therefore the is no focusing.

– **Quadrupole magnets** focus in one direction and defocus in the other, which is reflected in the matrix

$$M_x = \begin{pmatrix} \cosh\varphi & \frac{1}{\sqrt{|k|}}\sinh\varphi & 0 \\ \frac{1}{\sqrt{|k|}}\sinh\varphi & \cosh\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad M_z = \begin{pmatrix} \cosh\varphi & \frac{1}{\sqrt{|k|}}\sinh\varphi & 0 \\ -\frac{1}{\sqrt{|k|}}\sinh\varphi & \cosh\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

where $\varphi = s\sqrt{|K|}$. In this case, it is focusing vertically, and defocusing horizontally. Exchanging the matrices will invert the focusing.

– **Dipole sector magnet** are responsible for the overall curving of the the particle trajectory around the accelerator.

$$M_x = \begin{pmatrix} \cos\varphi & \rho\sin\varphi & \rho(1-\cos\varphi) \\ -\frac{1}{\rho}\sin\varphi & \cos\varphi & \sin\varphi \\ 0 & 0 & 1 \end{pmatrix} \qquad M_z = \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{9}$$

– **Rectangular dipole magnet** are rectangular, and mainly used in the beam splitting.

$$M_x = \begin{pmatrix} 1 & \rho\sin\varphi & \rho(1-\cos\varphi) \\ 0 & 1 & 2\tan\rho/2 \\ 0 & 0 & 1 \end{pmatrix} \qquad M_z = \begin{pmatrix} \cos\varphi & \rho\sin\varphi & 0 \\ -\frac{1}{\rho}\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{10}$$

Thin-lens approximation can be a very useful tool. Since the length of the beam line element is significantly smaller than its focal length, we can approximate these elements as having an $l/2$ long drift space in front, a zero length magnet in the middle followed by another $l/2$ long drift space.

1.4.3 Emmitance and the beta function

Emmitance is a conserved quantity, the area of the phase space ellipse. It is sometimes defined with an extra π. Together with the beta function, they are important tools in describing the width of the beam. $\beta*$ is the value of the beta function at the interaction point. The beam envelope can be obtained as $E = \sqrt{\epsilon\beta(s)}$ where ϵ is the emmitance and $\beta(s)$ is the beta function.

2 Current acceptance of ARPs

The acceptance of ARPs for the current collisional optics is shown in Fig. (7). The interesting physics mostly takes place in the small p_{T} region. Hence, having acceptance there is crucial. In this regard both the AFP and ALFA do well. The acceptance of the AFP is near 100% for ξ between 0.03 and 0.8 for p_{T} between 0 and 2.5 GeV. Above $\xi = 0.1$, the collimators clear out the protons. Collimators are beamline elements with the purpose of protecting the magnets from radiation. They have an adjustable rectellipse aperture (the superposition of an ellipse and a rectangle). The zero acceptance for small ξ (< 0.02) comes from the distance of the detector from the beam. Since ALFA is situated closer to the beam, it is not surprisings that it has acceptance in this region as well. However, large p_{T} (> 1 GeV) is far from ideal because of the radiation damage.

3 Improving acceptance through local bump construction

3.1 Crossing angle

At the interaction points the bunches do not necessarily have to collide head on, instead, there can be a crossing angle. This can prevent any unwanted interaction between collision remnants and the incoming bunches. The crossing angle is vertical for the 2023 collisional optics at the ATLAS IP (interaction point).

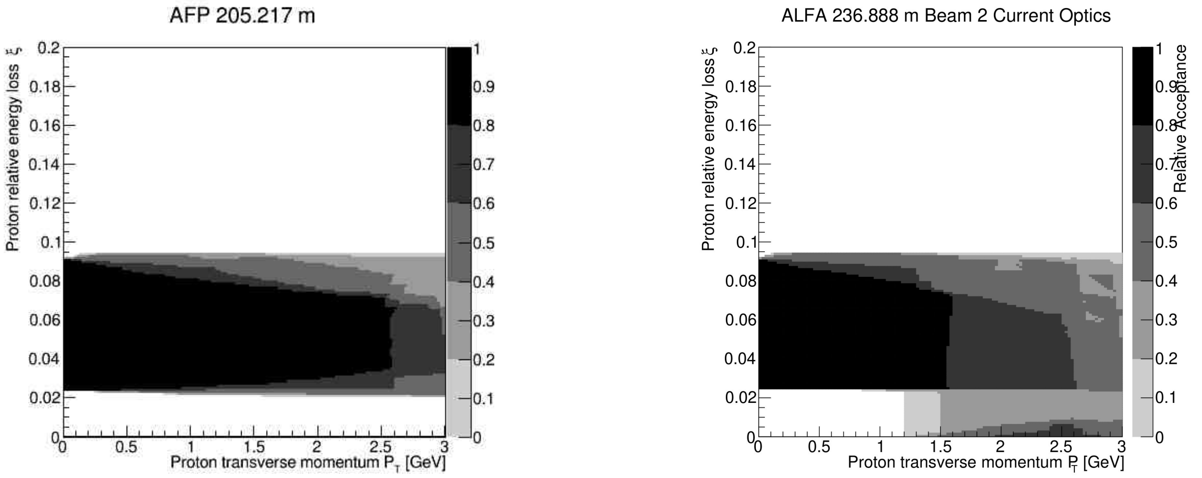

Figure 3: Acceptance of the AFP and ALFA detectors for 2023 collisional optics. Total center of mass energy $\sqrt{s}$ = 13 TeV, $\beta*$ = 0.4 m, and crossing angle θ_c = -185 μrad. TLC4 set at 9.5 mm. Created using EasyTracker, whith particles equally binned in p_{T} = 0-3 GeV, ξ = 0-0.2 and ϕ 0-360°, with the number of bins being $160 \times 160 \times 30$ respectively.

3.2 Orbit correctors

After crossing the beam needs to be readjusted to the centre which is mainly done by so called orbit correctors. Orbit correctors, sometimes also referred to as "kickers", are short dipole magnets that have the ability to deflect the beam by a given angle. The magnitude of the “kick” that can be delivered is subject to many factors, but has a maximal value somewhere around 50 μrad.

3.3 Local Bumps in general

One can not only use these orbit correctors to correct for the crossing angle, but also to create local bumps. A local bump, as the name suggests, is a constructed local deviation of the nominal beam. There are two, three and four point bumps, which differ in the number of kickers used. Since the four point bumps allows for the most freedom, such as deviation and slope adjustment at a given point, they are the most popular. The reason for creating such a local bump can differ, in our case, their property to create dispersion while only affecting the beam locally gives their appeal. The crossing angle is also capable of creating dispersion. However, since it was already near its maximal value, and a larger crossing angle corresponds to a larger dispersion, we did not find it sensible to create models with a different crossing angle. We very briefly discuss the possibility of changing the crossing angle to vertical in Sec. 5. For a more detailed description on local bumps see [7].

3.4 Beamline elements near the interaction point

There are three vertical and three horizontal orbit correctors at the inner triplet. Ideally, these are not used in a local bump construction as their operation greatly complicates the optics, which is best avoided before the splitting of the beam. We also have two vertical correctors and a horizontal at roughly 165 metres from the IP, followed by a horizontal at 193 m and then a vertical at 225 m. This leave us therefore with two degrees of freedom to open the bump. For the first scenario, HK(horizontal kicker) 4 had a value of -40 μrad and HK5 of 30 μrad. In the second case, HK2 and 3 were set at -5 μrad, HK4 at -40 μrad and HK5 at 40 μrad. The position of the detector was adjusted as to keep the same distance from the beam at all times.

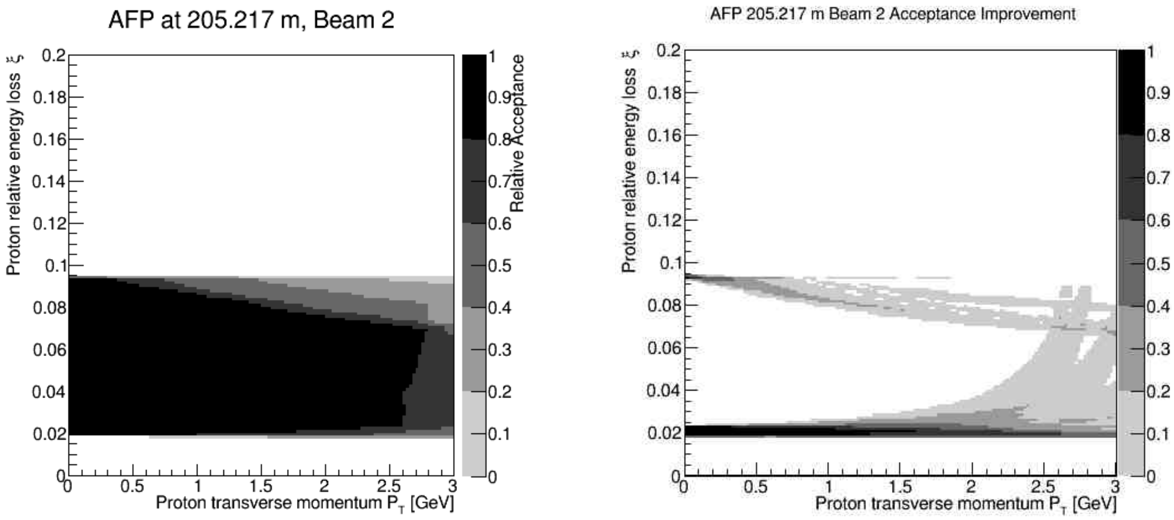

Figure 4: On the left, the acceptance of the AFP detector for the 2023 collisional optics when complemented with a local bump. On the right, the change in acceptance is shown when the bump is implemented compared to the default case shown in Fig. (7), The same generator setup as Fig(7). To achive the bump HK (horizontal kicker) 4 and HK5 were set at -40 μrad and 30 μrad respectively.

4 Results on improved acceptance

The results for two specific bumps are shown in Fig. (4,6). Meanwhile, in the first case, shown in Fig. (4), there is improvement for small ξ, this is only marginal. In the second case, when the kickers in the inner triplet are also used in constructing the bump, the acceptance is further improved. Here, a considerable increase in acceptance can be observed in the low ξ region. It is extended to the ξ = 0.015-0.022 area for the whole p_{T} = 0-3 GeV strip, that has not been covered before. We estimate this to be equal to around 60 bins for the AFP in ξ. However, this scenario comes with its drawbacks, as using the kickers before the rectangular dipoles can cause many complications. Furthermore, the increase we see is almost certainly insufficient for double proton tagging, with single tagging also remains unlikely. This would require an acceptance in the low ξ region (< 0.015), ideally in the small p_{T} region (< 1 GeV). ALFA, on the other hand, already has acceptance in the low ξ region even without a bump. As we have previously mentioned, it is not radiation hard, and going to be dismantled. Another challenge is the eventual change in the collisional optics (discussed in more detail in Sec. 5). Upon investigating the possibility

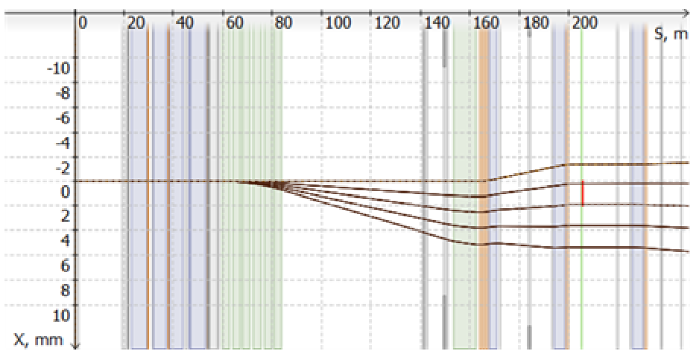

Figure 5: Specific particle trajectories for the bump in Fig. (4). Particles with p_{T} = 0, $\phi = 0$ and equally spaced ξ. Quadruples in blue, dipoles in green, kickers in oragne. The red strip represent the position of the detector, noting that its position in x is incorrectly shifted slightly on this graph, as this feature is not yet fully implemented in EasyTracker.

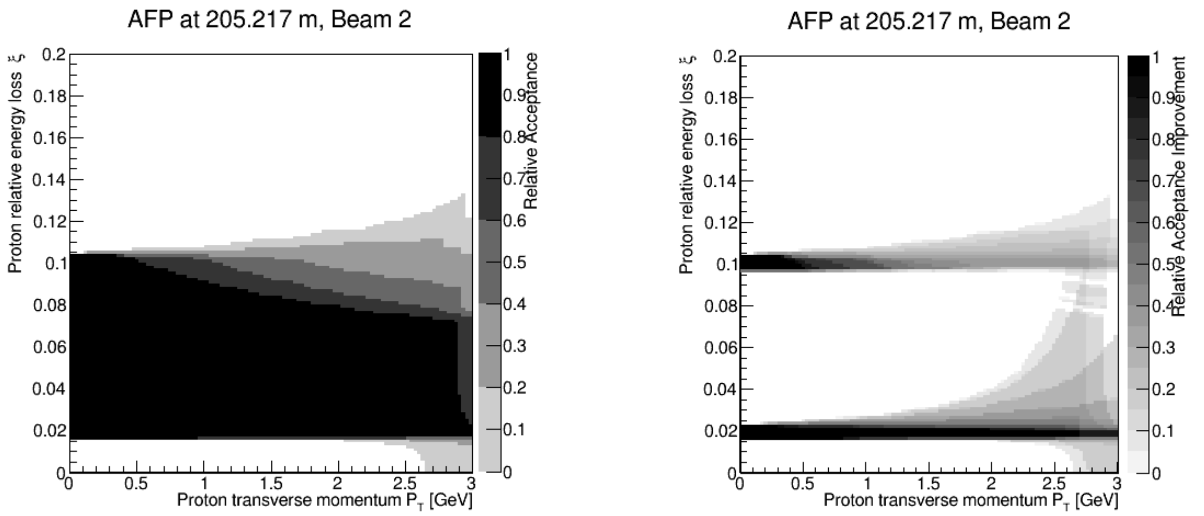

Figure 6: Similarly to Fig. (4), acceptance and its relative change compared to the default case, but this time, the kickers at the triplet are also used for creating the bump. HK2 and 3 at -5μrad HK4 at -40μrad and HK5 at 40μrad.

to use local bumps to correct for the lost acceptance, in this case, can be eliminated, since the effect is near zero. This is due to the focusing quadruple right before the detector that does not allow for any significant divergence. For reference, a similar local orbit bump was constructed for TOTEM in 2016, that increased the divergence by roughly 5-10%.

Finally, despite EasyTracker being excessively useful throughout the project, it still contains some incorrect implementations that need to be addressed. Unfortunately, these were discovered all to late for the results to be mended. However, there is no reason to believe that these have had a significant effect. One such issue is the crossing angle. To simulate the crossing angle, orbit correctors were used. This is incorrect, as orbit correctors create dispersion, which cannot be said about the crossing angle. This is a minor, but noticeable effect. Therefore, the real acceptance is presumably less by a small amount than what was presented.

5 Future optics

Finally, we briefly describe the possible challenges future hold for ARPs and a possible solution. Due to heavy radiation wear accumulated over the years in the magnets, a change for the collisional optics was proposed for 2024, that has been pushed to 2025. This would be, however, bad news for the AFP detector. As it is still an ongoing debate, we will endeavor to briefly summarise the main points of a handful of discussions that have taken place to illustrate the problem and our proposed solution. The followings only represent the understanding of the author, who is evidently biased towards the case of the ARPs. The main concern is the inner quadruple triplet. Replacing these magnets is an extremely costly and time consuming procedure that has to be avoided before the HL-LHC upgrade. To change which area of the magnets are irradiated, the crossing angle can be rotated from vertical to horizontal [11]. This however must be accompanied by the inversion of the inner triplet due to how the beam screen[1] is positioned at ATLAS and CMS. The polarity of the triplet at ATLAS and at CMS must always be the opposite of each other due to restrains in the whole of LHC. If both the crossing angle and the polarity are changed, the acceptances of the ARPs drop significantly (see Fig. (7)), that is to say, conducting science with them would become practically impossible. However, the situation at CMS does not seem

[1]Beam screen is an element with the purpose of protecting the magnets from radiation right after the interaction point. It has a fixed rectellipse aperture. The beam screen at CMS is rotated 90°compared to ATLAS.

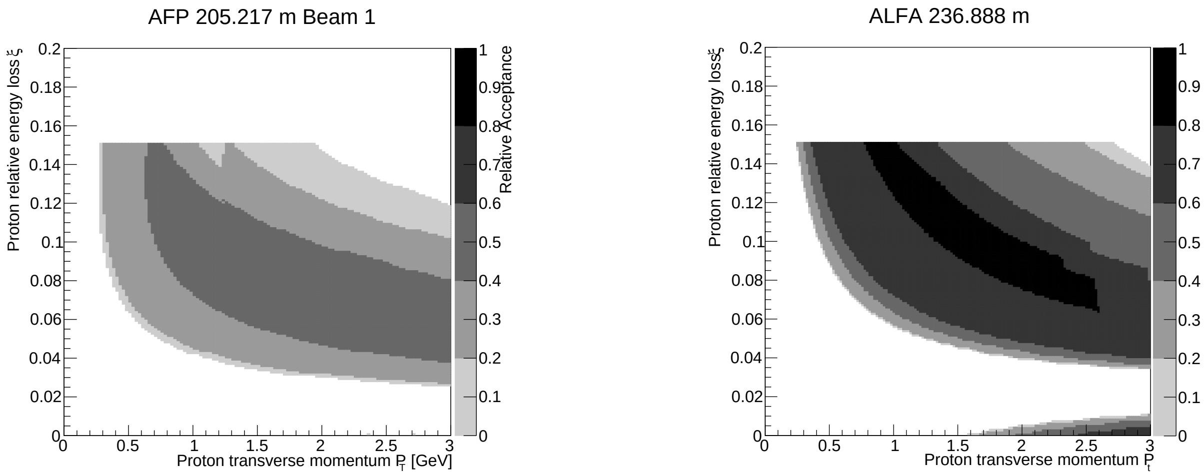

Figure 7: Acceptance estimate of the AFP and ALFA detectors for the proposed 2025 collisional optics. $\sqrt{s}$ = 13.6 TeV, $\beta*$ = 0.3 m, θ_c = 160 μrad. Created using EasyTracker, whith particles equally binned in p_{T} = 0-3 GeV, ξ = 0-0.15 and ϕ = 0-360°, with the number of bins being $160 \times 160 \times 30$ respectively.

so bleak, as they would have the optics that is currently at ATLAS. The question naturally arose from our side: why ATLAS would not simply have the current optics from CMS? After a discussion with Riccardo de Maria and Jorg Wenninger, we asked Francesco Cerutti about radiation damage, where we discovered that switching the optics might be possible, but the beam screens have to be rotated. Stephane Fartoukh's input from the angle of the optics only reinforced us in our beliefs. However, rotating the beam screens is obviously a costly and time consuming procedure. Until Bernard Holzer pointed out to us that, arguably, a procedure like this would be on an equivalent time scale as changing the polarity of all quadruple magnets in the LHC, which requires an intensive and long testing, and calibrating period. This has to be done in a slow manner to avoid any quenching of the magnets. Therefore, we are confident that rotating the beam screens is a sensible option, that deserves further consideration.

6 Conclusion

We discussed how forward physics might be the key in discovering instantons. This still has to wait however, as the AFP, the ideal forward detector candidate at ATLAS, does not posses the required acceptance. The scenarios investigated in this report have the possibility to improve this situation. Meanwhile, double tagging would still remain unlikely, there may be a significant improvement for the AFP when a local orbit bump is implemented, that we estimate around 60 bins in ξ. ALFA detector, despite being vulnerable to radiation, might prove to be a better choice to detect instantons than the AFP detector, however, it is going to be dismantled. Another difficulty is an eventual change in optics. This seems inevitable due to the accumulated radiation dose in the magnets. With the intent of presenting a new direction in this discussion, we cited a possible, hypothetical solution, that would satisfy both the LHC and the ARPs. This mainly consists of the rotation of the beam screen. It is also expected that the AFP in this case would have a better acceptance for instantons.

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