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Impact of pixel size and shape on physics analyses

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ABSTRACT

The choice of the pixel shape and size in the $r-\phi$ and z-directions results in different position resolutions, that in turn, influence the impact parameter resolution. A study based on a Monte Carlo simulation is presented to quantify the effect of the impact parameter resolution on the search for new physics using the rare decay $B_s^0 \to \mu^+\mu^-$. The presented study illustrates the performance of this search for different resolution scenarios. For an optimal result, it is found that the transversal and longitudinal impact parameter resolution must be balanced.

1. Introduction

The two general purpose experiments at the LHC [1], ATLAS and CMS, have chosen different pixel geometries for their detectors. CMS has chosen to use a more square pixel, with size of $100 \times 150\ \mu m^2$ [2], while ATLAS has chosen to use a more rectangular pixel with size of $50 \times 400\ \mu m^2$ [3].

Studies of pixel detectors usually report the hit resolution together with the impact parameter resolution. For events with hundreds of tracks, it is crucial to know whether two tracks actually come from the same vertex. This is because the signal for long lived particles is reconstructed by fitting pairs of tracks to a common detached vertex. The more precise the impact parameter, the more combinatorial background can be rejected. On the other hand, physics analyses already start with reconstructed tracks, incorporating the impact parameter and its resolution in a non-transparent way. In general, these analyses do not consider hypothetical detector resolutions and do not estimate what would be gained if the resolution was changed. This leaves a gap as the final goal is not the impact parameter resolution but rather the physics result.

The aim of this study is to investigate the effect of the pixel size and shape on the outcome of a hypothetical search for $B_s^0 \to \mu^+\mu^-$.

2. $B_s^0 \to \mu^+\mu^-$

ATLAS, CMS and LHCb are looking for the rare decay $B_s^0 \to \mu^+\mu^-$ [4–6]. This decay has a clear signal topology, two muons originating from the same vertex displaced from the collision vertex. This channel is sensitive to new physics as it is heavily suppressed in the standard model due to an effective flavor changing neutral current and helicity suppression. The branching fraction can change due to new couplings and new particles entering the loops in the Feynman diagrams [7].

If one assumes a perfect detector resolution of the pixel detector, the signal and the background can be separated completely. Hence, this search provides an excellent candidate for such a study.

3. Tracking

A track can be described by five parameters, a reference point, and the direction of the track. In the special case of a constant magnetic field, these variables can be defined as follows [8]:

- d_0, transversal impact parameter.
- d_z, longitudinal impact parameter.
- ϕ, azimuthal angle of track momentum.
- θ, polar angle of track momentum.
- p_T, magnitude of momentum in plane perpendicular to beam axis describing curvature of helix.

The direction of the track is specified using the variables ϕ, θ, and p_T while the reference point is described by the impact parameters d_0 and d_z. The ability to decide whether two tracks meet in three-dimensional space is given by the resolution of the two impact parameters and these are determined mostly by the pixel detector.

The resolution of the detector itself (σ_{pix}) is given by the size of the pixel cells and the charge sharing between the pixels assuming the charge produced by a ionizing particle can be measured with a sufficient degree of accuracy. To measure the charge and trigger

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the pixel, the size of the readout electronics is limited by the size of the pixel. Therefore smaller pixels suggest a less complex readout for a given technology choice.

The impact parameter resolution can be understood from basically two effects:

(1) Multiple scattering.
(2) Intrinsic detector resolution.

The multiple scattering gives a term which can be described by $\sim A/p_T$. The factor A mainly depends on the amount of material in the first layer and the distance of the first layer to the beam axis. The intrinsic detector resolution, on the other hand, yields a constant term B and is mainly given by the distance of the layers and the pixel resolution.

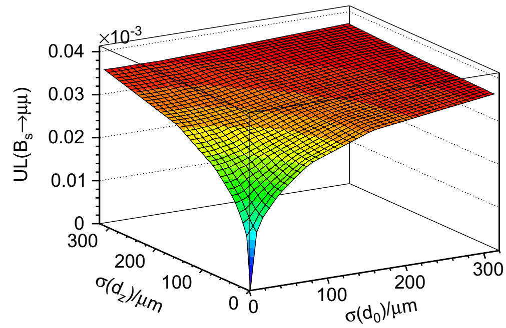

Fig. 1. Upper limit as a function of the impact parameter resolution.

4. Setup

Two Monte Carlo simulations have been produced at a center of mass energy $\sqrt{s}=8$ TeV:

- Signal simulation, each containing one $B_s^0 \to \mu^+\mu^-$.
- Background simulation, minimum bias events containing b quarks and two muons with $p_T > 2.5$ GeV.

In both simulations, candidates are created as follows:

- Combine two muons to form a candidate.
- Apply a loose preselection given in Table 1 where $d_{3,\mathrm{truth}}$ means the Monte Carlo three-dimensional flight length for signal simulation. For background simulation it is the distance from the primary vertex to the point of closest approach of the two muons.
- Randomize kinematic variables of the candidate according to an assumed resolution scenario.

Only one variable was used to discriminate the signal from background due to the low statistics of the background Monte Carlo simulation. The distance of closest approach (doca) of the two muons was used as the selection criteria and it was chosen in such a way that the signal efficiency is $\varepsilon_{\mathrm{sig}}=0.9$. In a perfect detector, this variable is enough to completely differentiate the signal from the background candidates. The performance of a given resolution scenario was evaluated computing the expected upper limit (UL) on the branching fraction.

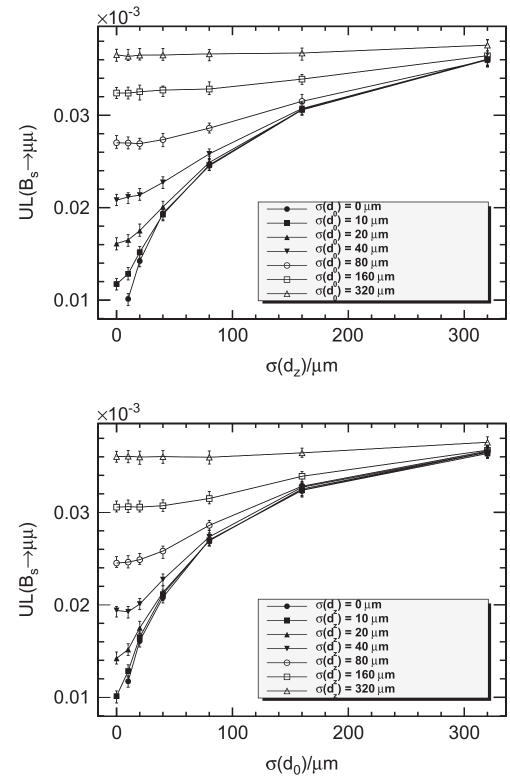

Fig. 2. One-dimensional curves along constant resolutions.

5. Results

5.1. Intrinsic detector resolution

To understand qualitatively the effect of the asymptotic term, the multiple scattering term has been set to zero. An overview can be seen in Figs. 1 and 2.

For perfect resolution $\sigma(d_0)=\sigma(d_z)=0$ μm, one can clearly see the drop in the expected upper limit. Also, the contour lines of constant upper limit tend to have an elliptic shape around the perfect detector. For a fixed z impact parameter resolution, there is a corresponding transverse impact parameter resolution where improvement in the transverse plane does not further improve the UL. The same is true if one fixes the transverse impact parameter resolution.

The upper limit sensitivity dependence on the pseudo rapidity (η) of the tracks was also studied. Analogously to Fig. 1 plots showing η dependence are shown in Fig. 3. It can be seen that for high η−region, improvement of $\sigma(d_0)$ is much more effective in improving the UL, while for the low η−region, the improvement of $\sigma(d_z)$ is more effective. The physical result should depend on the error ellipse around the track. For high η−tracks, the z-resolution is measured almost parallel to the track direction, thus the semi-axis of the error ellipse actually is given by $\sin\theta \cdot \sigma(d_z)$. Hence, for the high η−region, the measurement of this error ellipse is dominated by the uncertainty in the xy-plane. For the low η−region one can consider the extreme case $\eta=0$. For $\eta=0$ tracks, the only important quantity for two tracks to meet is the z coordinate of the tracks.

Table 1
Preselection cuts.

p_T (GeV)	> 2.5
$\lvert\eta(\mu)\rvert$	< 2.5
$d_{3,\mathrm{truth}}$ (μm)	> 25