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B_s^0 oscillation measurement with the CMS detector

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Abstract

We discuss here the performances for oscillation measurement expected at the Large Hadron Collider (LHC) with the Compact Muon Solenoid (CMS) experiment. The CMS tracker performances are described with emphasis on the secondary vertex measurement. Two independent methods for the oscillation measurement are then investigated. The first one ("direct") is tagging the charge of the b quark at the production and at the decay in the channel $B_s^0 \rightarrow D_s \pi$, while the second one ("indirect") is making use of the lifetime measurement of the B_s^0 and of the CP states separation in the channel $B_s^0 \rightarrow J/\psi \phi$.

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Figure 1: The Compact Muon Solenoid Detector

I will concentrate my description on the tracking devices which have been used for this study. The calorimeter description and performances can be found in [3]. The vertex detector of the inner tracker (figure 2) of CMS is constituted of silicon pixels. In the barrel region, 2 layers located at radii of 7.5 cm and 11.5 cm are made of pixels of $125\text{ by }125\text{ }\mu\text{m}^2$, and provide a space point resolution of $15\text{ }\mu\text{m}$, while the forward region is equipped with 3 layers. The layers can be placed closer to the beam pipe ($r = 5\text{ cm}$) in the early phase of LHC at low luminosity. The silicon strips (3 layers) that surrounds the vertex detector will provide a high spatial and time resolution. The outer tracking layers employ MicroStrip Gas Chamber (7 layers) with a (r,ϕ) resolution of $40\text{ }\mu\text{m}$ and extend up to a radius of 1.3 m . The rapidity coverage extends up to 2.4. The tracking devices will provide on average 12 hits per high p_T track, while the reconstruction efficiency for an isolated track is expected to be about 98%.

Figure 2: CMS Inner tracker

2.2 Tracking performances

Figure 3 shows the impact parameter resolution in the central and forward regions for 3 different positions of the first layer. At high p_T a resolution of $20 \mu m$ can be achieved everywhere with the present design and could reach

Figure 3: Impact parameter resolution

$10 \mu m$ with a first layer at $r = 3 cm$. The expected momentum resolution $\frac{\Delta p}{p}$ (see figure 4) without vertex point, in the central region and for low p_T tracks ($p_T < 15 GeV/c$) is about 0.5% and degrades to 1% at $\eta = 2.25$.

3 MIXING IN $B_s^0/\bar{B}_s^0$ SYSTEM

B_s^0 mixing is estimated through the measurement of $x_s = \frac{\Delta m_s}{\Gamma}$ (where Δm_s is the mass difference of the eigenstates and Γ the B_s^0 width). The mixing parameter x_s is proportional to the oscillation frequency of the $B_s^0/\bar{B}_s^0$

Figure 4: Momentum resolution

3.1 Direct Method

The direct measurement is performed in the channel: $\mu^{tag} \leftarrow b\bar{b} \rightarrow B_s^0 \rightarrow D_s^\mp \pi_1^\pm \rightarrow \phi \pi_2^\mp \pi_1^\pm$ where the charge of the π_1 is tagging the charge of the b quark at the decay while the muon is tagging at the production, see reference [4] for details. We then can measure the asymmetry:

$$A(t) = \frac{dn_{++}}{dt} - \frac{dn_{+-}}{dt} \propto D \cos(x_s \frac{t}{\tau}) e^{-\Gamma t}$$

Figure 5: Direct measurement of x_s

where D is the overall dilution factor:

$$D = D_{tag} * D_{res} * D_{mix} \sim 0.3$$

including respectively the uncertainty coming from the tagging efficiency (cascade decay $b \rightarrow c \rightarrow \mu$, wrong B-hadron determination), the mixing (we assume $x_d = 0.73$), the remaining background and the measurement of the decay time. From $A(t)$ we derive x_s by applying a Fourier transform. The following selection is used for the $B_s^0 \rightarrow D_s^\mp \pi^\pm$ decay: we require 3 charged particles with $p_t^{had.} > 1.5 \text{ GeV}/c$, 1 charged particle with $p_t^{had.} > 3 \text{ GeV}/c$, all in the range $|\eta| < 2.4$. The invariant mass of two particles (respectively 3 and 4) should be reconstructed in the window $\Delta m < \pm 2\sigma_m$ of the ϕ (respectively D_s and B_s^0). We impose a vertex pointing cut, $\Delta\alpha < 0.1 \text{ rad}$ where $\Delta\alpha$ is the angle difference between the B_s^0 direction reconstructed from the 4 particle momenta and the one reconstructed from the secondary vertex determination. The B_s^0 decay distance d is required to exceed $300 \mu\text{m}$. For the tagging side we impose $p_T(\mu^{tag}) > 10 \text{ GeV}/c$. For an integrated luminosity of 10^4 pb^{-1} we obtain 2400 signal events (we assume $B(B_s^0 \rightarrow D_s \pi) = 3.5 \times 10^{-3}$) and a background of about 800 events. Figure 5 shows the result of a simulation with $x_s = 30$ and a secondary vertex resolution of $150 \mu\text{m}$. The range of measurable x_s value depends on several factors, e.g. the secondary vertex resolution achievable in CMS. In figure 6 we see on the left side the expected resolution as function of the first pixel layer radius for different space point resolutions of the silicon pixels. The resulting x_s sensitivity is shown on the right side. We find that a value of 50 can be reached with a first layer at 5 cm.

Figure 6: Extension of the direct measurement

3.2 Indirect Method

We have here investigated an x_s measurement in the decay $B_s^0 \rightarrow J/\psi \phi$ by a transversity analysis (reference [7]). It has been shown that x_s is related to the lifetime difference of the Heavy (H) and Light (L) CP eigenstates of B_s^0 . Theoretical calculations give in first order :

$$\Delta m \sim 200(\Gamma_L - \Gamma_H) \Rightarrow x_s \sim 200 \frac{\Delta \Gamma}{\Gamma}$$

We thus can access x_s by separating the CP eigenstates and measuring their lifetime. For this we use a frame to define a transverse variable. In the J/ψ restframe we define: $\vec{i}$ as the ϕ direction, $\vec{j}$ as orthogonal to $\vec{i}$ in the (K^+, K^-) plane with $p_y(K^+) > 0$, $\vec{k} = \vec{i} \wedge \vec{j}$, θ as the angle between $\vec{k}$ and $\vec{p}(\mu^+)$. In this frame we obtain the following relation:

$$\frac{d^2 \Gamma}{d \cos \theta dt} = \frac{3}{8} p(t) * (1 + \cos^2 \theta) + \frac{3}{4} m(t) * (1 - \cos^2 \theta)$$

where $p(t) = p(0)e^{-\Gamma_L t}$ is CP even and $m(t) = m(0)e^{-\Gamma_H t}$ is CP odd

Different $\cos \theta$ distributions for Heavy and Light mass states enable us to separate Γ_H and Γ_L statistically. This is done in the following way:

$$E = \int_{-0.5}^{0.5} \frac{d^2 \Gamma}{d \cos \theta dt} d \cos \theta = \frac{13}{32} p(t) + \frac{11}{16} m(t) \text{ and } P = \left(\int_{-1}^{-0.5} + \int_{0.5}^1 \right) \frac{d^2 \Gamma}{d \cos \theta dt} d \cos \theta = \frac{19}{32} p(t) + \frac{5}{16} m(t)$$

So we finally extract :

$$p(t) \propto \frac{d\Gamma}{dt} + \frac{8}{3}(P - E) \text{ and } m(t) \propto \frac{d\Gamma}{dt} - \frac{16}{3}(P - E)$$

For this study Pythia 5.7 has been used for the generation with CTEQ2L structure function while the tracking simulation was based on a parametrisation of the momentum resolution and on a Geant [8] description of the secondary vertex resolution. To obtain the signal events $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+$, we impose the following selection: we require the hadrons to be in the range $|\eta| < 2.4$ with $p_t^{had.} > 2 \text{ GeV}/c$. The muons are expected to fulfill the two low p_t muon trigger criteria:

$$\begin{array}{ll} p_t > 4.5 \text{ GeV}/c & 0.0 < |\eta| < 1.5 \\ p_t > 3.6 \text{ GeV}/c & 1.5 < |\eta| < 2.0 \\ p_t > 2.6 \text{ GeV}/c & 2.0 < |\eta| < 2.4 \end{array}$$

The invariant mass of the μ pair (respectively K pair and all four particles) should be reconstructed in the window $\Delta m < \pm 2\sigma_m$ of the J/ψ (respectively ϕ and B_s^0). The decay time should be $t_{B_s^0} > 0.2 \text{ ps}$. A good vertex is required: $\chi^2_{\mu^+ \mu^- K^+ K^-} < 5$. We impose also a vertex pointing cut: $\Delta\alpha < 0.1 \text{ rad}$. For an integrated luminosity of 10^4 pb^{-1} we retain 150000 signal events (we assume $B(B_s^0 \rightarrow J/\psi \phi) = 10^{-3}$ [9]) while the background is kept at about 1%. Figure 7 shows the time resolution for the B_s^0 decay achieved for a four tracks vertex with $p_t^{had.} > 2 \text{ GeV}/c$ and the muons passing the trigger requirement. We see in figure 8 the mass resolution for J/ψ , ϕ and B_s^0

Figure 7: Time resolution for a four tracks secondary vertex reconstruction

(the last one with background included), showing very good precision. Figure 9 illustrates the x_s measurement in the range 10 to 50. It shows a good agreement between the generated and the reconstructed value and doesn't degrade at high x_s , thus allowing a complete coverage of the range allowed by Standard Model and even beyond.

4 CONCLUSIONS

Due to a large $b\bar{b}$ cross section and a very good secondary vertex and momentum measurement, the CMS experiment is well prepared to investigate various aspect of B-physics. For the first time a new method to extract x_s has been used showing a good capability to determine B_s^0 oscillation over the complete range allowed by the standard model as well as beyond. Together with the classical ("direct") method it should as the data will be ready, provide a new measurement in the unitarity triangle and hence a test of the standard model.

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Figure 8: Mass resolutions for $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$

Figure 9: Indirect measurement of x_s