Search for the $B^0_S \rightarrow \mu^+\mu^-$ Decay at LHCb

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FPCP 2009, May 27-June 1, Lake Placid, New York

LHCb at LHC

The LHCb experiment at the LHC is dedicated to CP-violation and rare decays studies in the b-hadron realm [1]. The forward peaking fiducial production led to a detector design as a forward spectrometer shown on Figure 1. It is characterized by a high track reconstruction efficiency, good $\pi-K$ separation capability, very good proper-time resolution and high trigger efficiencies, particularly for muons. LHCb is ready to record data as soon as the LHC machine delivers the first collisions expected in Fall 2009.

LHCb Strategy for the $B^0 \rightarrow \mu^+\mu^-$ Decay Search

The LHCb strategy for the $B^0 \rightarrow \mu^+\mu^-$ decay search [2] can be summarized as follows:

- A very efficient selection is applied with the goal to remove obvious background with minimal loss of signal event.
- The analysis relies on three independent classification criteria: the $t$-invariant Mass (M) / Particle Identification (PIDL) of the daughters and a criterion grouping Geometrical informations (GI) from the decay topology. The motivation behind this particular decomposition of the information along three axes is the calibration. Indeed the three axes are uncorrelated and can therefore be calibrated separately. Furthermore, methods have been designed for the calibration to rely solely on data.
- For each event, and for each of the three axes, a likelihood to be signal-like and a likelihood to be background-like are computed. A 3D-space is populated with those values.
- The compatibility of the obtained 3D distribution is tested against the $B^0 \rightarrow \mu^+\mu^-$ branching ratio hypothesis, using the CLs modified frequentist method [3] and the calibrated distributions for signal and background of each axis. The final result is either a measurement or an upper limit of the branching fraction.
- Since the number of $B$ produced is not known, the use of a normalisation channel with a well known branching fraction is required to obtain an absolute measure of the branching fraction.

Normalisation

The branching fraction is expressed as:

$$BR(B^0 \rightarrow \mu^+\mu^-) = \frac{N_{BH}}{2 \left(\sigma_B \times \epsilon_B \times \epsilon_{BH} \right)}$$

where $N_{BH}$ is the measured number of signal events, $\sigma_B$ the proportion of $B$ quark hadronising in a $B^0$ meson, and $\epsilon_B, \epsilon_{BH}$ the efficiency of reconstruction, trigger, and selection. The unknown number of $B$ hadron produced, $2 \sigma_B \epsilon_B \epsilon_{BH}$, is determined using a normalisation channel with a precisely known branching fraction. The $B^0 \rightarrow \mu^+\mu^-$ branching fraction is then:

$$BR(B^0 \rightarrow \mu^+\mu^-) = \frac{BR_{B\to X\mu\nu} \times \epsilon_{B\to X\mu\nu} \times N_{BH}}{\epsilon_B \times \epsilon_{BH}}$$

Possible normalisation channels are $B^0 \rightarrow \mu^+\mu^-K^+$ and $B^0 \rightarrow \mu^+\mu^- \pi^-$. A shared selection is designed for the signal and normalisation channels to cancel out the selection efficiencies. The trigger and reconstruction efficiency ratios are extracted from control channels.

Robust Analysis and LHCb Sensitivity

This analysis has the sensitivity to deliver a competitive result with very early data. In that time frame the detector may not be fully understood yet. Therefore, an alternative robust analysis is designed using variables with a similar physical content to the ones of the standard analysis, but avoiding the use of error estimates. This implies a modified selection and definition of the geometrical likelihood.

Motivation

Theories beyond the Standard Model (SM), gathered under the New Physics (NP) label, are invoked at the TeV scale to solve the hierarchy problem. However, no statistically significant NP signal has been detected yet, despite numerous searches in the electron sector, and in the flavor-changing or CP-violating processes of the $K$ and $B$ sectors.

The measurement of the rare $B^0 \rightarrow \mu^+\mu^-$ decay has the potential to uncover NP effects incompatible with the SM predictions or at least to strongly constrain NP models. Within the SM, this decay occurs through loops diagrams like the one in Figure 2 and its branching ratio is expected to be $BR(B^0 \rightarrow \mu^+\mu^-) = (3.35 \pm 0.82) \times 10^{-8}$ [4].

In minimal supersymmetric extensions of the SM (MSSM), this decay is governed by diagrams of the kind of Figure 3. The branching ratio is then proportional to the square of the ratio of the Higgs vacuum expectation value $\tilde{v} / v$, and can be as large as $10^{-5}$ in particular realizations such as the Non-Universal Higgs Masses model (NUHM) [5].

The Tevatron CDF and D0 experiments have already determined an upper limit of $BR(B^0 \rightarrow \mu^+\mu^-) < 4.7 \times 10^{-8}$ at 90% CL [6].

Invariant Mass Likelihood

The signal likelihood is calculated against the $B^0 \rightarrow K^+K^-$ decay, which is kinematically very close to the signal. A PID cut on the kaons is required, in order to use the mass resolution is extracted from other $B^0 \rightarrow h^+h^-$ control channels and corrected, see Figure 4.

The background likelihood is calculated using $B^0 \rightarrow \mu^+\mu^-K^+$ candidates in the mass-sidebands, outside the $360\,\text{MeV}/\text{c}^2$ region around the nominal $B^0$ mass, as shown in Figure 5.

Particle Identification Likelihood

The identification of the daughter-particles as muons relies mainly on the muon chambers information.

The signal likelihood is calculated using a high-purity muon sample obtained from $B^0 \rightarrow \mu^+\mu^- \pi^0$ decays where one muon is well identified by the muon chambers and the second one is identified independently of the muon system by energy release in the calorimeters.

The background likelihood is obtained from $A \rightarrow p \pi^0$ decays, which is very abundant in LHCb and has a very clean signature given by its good mass resolution and long lifetime.

Figure 6 shows the result of the proposed calibration method.

Geometrical Likelihood

The geometrical likelihood combines a single real number topological information from the following variables:

- the $q^2$ impact parameter,
- the $Q^2$ proper time,
- the lowest impact parameter significance of the two muons,
- the distance of closest approach of the two muons,
- the isolation of each muon track.

This likelihood is defined to take values between 0 and 1. It is trained on MonteCarlo to have a flat distribution for signal events and a distribution peaked at 0 for background events, as shown in Figures 7 and 8.

The signal distribution is obtained from data using $B^0 \rightarrow h^+h^-$ events, which are topologically identical to $B^0 \rightarrow \mu^+\mu^-$ and the background distribution is obtained from events in the $B^0$ mass sidebands.

References

1) The LHCb Collaboration, arXiv:0901.0526
2) Pierre et al., LHCb notes 07/0421
3) Pierre et al., in preparation, LHCb note 2009
5) M. Blanke et al., JHEP 05, 009 (2007)