Precise B-Decay Measurements sensitive to Beyond Standard Model Physics at ATLAS

Martin zur Nedden (for the ATLAS Collaboration)
Humboldt-Universität zu Berlin, Institut für Physik, Berlin, Germany
E-mail: nedden@physik.hu-berlin.de

Abstract. The LHC experiments will perform sensitive tests of physics phenomena beyond the Standard Model (BSM). Investigation of decays of beauty hadrons represents an alternative approach in addition to direct BSM searches. The ATLAS efforts concentrate on those B decays that can be selected already at the first and second trigger levels. The most favorable trigger signature will be for B hadrons decaying to \( J/\psi \to \mu \mu \). Using this trigger ATLAS will be able to accommodate unprecedentedly high statistics in so called Golden LHC channel \( B_s \to J/\psi \) allowing a measurement of the CP violation effect, where BSM models predicted values are significantly higher than SM. In the rare decays sector, these are purely di-muon decays, and families of semi-muonic exclusive channels. Already with 1 fb\(^{-1}\) the ATLAS sensitivity in the di-muon channels will be comparable to today world’s statistics. The strategy is to carry on the di-muon channel program up to nominal LHC luminosity. In particular the \( B_s \mu \mu X \) signal with 4.3 \( \sigma \) significance can be measured combining low luminosity samples with those of one year of LHC operation at a luminosity of \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \). This precision allows excluding or confirming the SM unambiguously.

1. ATLAS B-Physics and Trigger Strategy

The expected inclusive production cross section for \( \bar{b}b \) pairs at LHC is estimated to be \( \sigma_{\bar{b}b} \approx 500 \mu \text{b} \), leading to more than \( 10^6 \) produced pairs per second at design luminosity. The experimental precision reached at ATLAS should at least allow the verification of the SM prediction. With an integrated luminosity of 30 fb\(^{-1}\), corresponding to a data taking period of 3 years at the initial luminosity of \( \mathcal{L} \approx 10^{33} \text{ cm}^{-2}\text{s}^{-1} \), this is feasible for most of the B-physics channels in question. In the case of the rare B-decays, clearly more luminosity is needed to achieve sensitive upper limits for the indirect BSM searches. Therefore, the most relevant part of the ATLAS-B-physics program will be taken in the initial phase at lower luminosities with an extension into the high luminosity phase.

1.1. General Strategy for B-Physics

The ATLAS detector is a general-purpose experiment with main emphasis on searches for new phenomena based on high \( p_T \) particles. Since most of the B-physics appears in a lower \( p_T \) range, triggering within the LHC environment on those events is a challenge. Nevertheless, ATLAS has also good capabilities for a rich B-physics program, based on the precise and flexible vertexing and tracking, the good muon identification, the high-resolution calorimetry and on the dedicated and flexible trigger scheme. The B-physics program is well defined for all the stages of the LHC luminosity operation. Huge \( b \)-flavored-hadron production rates allow for precise measurements.
of their properties. Furthermore, theoretical descriptions of heavy flavored hadrons need input from LHC, where precision measurements are already achievable after one year of data taking.

The envisaged measurements in the $B$-physics sector at ATLAS [1] are extending the discovery potential for physics beyond the SM. This is the measurement of $CP$ violation parameters in the $B_s \rightarrow J/\psi\phi(\eta)$ decay, which are predicted to be small in the SM and of rare $B$ decays, as $B_d \rightarrow K^*\mu\mu$, $B_s \rightarrow \phi\mu\mu$, $B_s \rightarrow \gamma\mu\mu$ and $B \rightarrow \mu\mu$. Due to the stiff competitions from $B$-factories, the ATLAS $B$-physics program is focused on topics not accessible to them, as $B_s$ decays and oscillations, $b$-baryons and doubly heavy flavored hadrons as $B_s \rightarrow D_s\pi$, $B_s \rightarrow D_s a_1$, $B_s \rightarrow J/\psi\phi(\eta)$, and $\Lambda_b \rightarrow J/\psi\Lambda^0$, whereas the the $B_s \rightarrow D_s\pi/a_1$ decay will be used for the $\Delta m_s$ measurement (see Chap. 2.2).

1.2. Trigger Strategy
Since only a small fraction of the limited bandwidth of the ATLAS trigger system is devoted to the $B$-physics triggers, highly efficient and selective triggers are needed. In addition, $c$- and $b$-events are containing mostly low $p_T$ particles, which is an additional challenge for the trigger. On the other hand, many $b$ decays are containing $J/\psi$ mesons, which are useful for calibration, optimization and understanding of the detector, the trigger system and the topology of $B$-physics events at ATLAS. Most of those triggers are based on single and di-muon events in the final state leading to a clean signature at early trigger levels and giving a flavor tag.

For the run phases at lower luminosities ($\mathcal{L} < 10^{33} \text{ cm}^{-2}\text{s}^{-1}$), the trigger strategy is mainly based on a single muon trigger at the first level, which could be combined with certain calorimeter trigger objects at higher trigger levels to select hadronic final states ($B_s \rightarrow D_s\phi$) or $e/\gamma$ final states ($J/\psi \rightarrow e^+e^-$, $K^{*}\gamma$ or $\phi\gamma$). In order to not exceed the available bandwidth, in the phase of higher luminosities above $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ the main working trigger will be based on di-muons on the first level, enabling a clean measurement of rare $B$-decays ($B \rightarrow \mu\mu$ or $B \rightarrow K^{*0}\mu\mu$), double semi-leptonic decays and the $B \rightarrow J/\psi(\mu\mu)$ decay channel.

2. CP Violation and BSM Sensitivities
2.1. CP Violation in $B_s \rightarrow J/\psi\phi$
The weak phase $\Phi_s$ of the of the decay of the CP eigen state $J/\psi\phi$ of the $B_s$ decay is tiny within the SM ($\Phi_s = -0.036 \pm 0.003$), but the presence of new physics could lead to an enhanced and measurable $CP$ violation within this decay channel. The angular distribution of the decay is described by $7$ parameters: two independent amplitudes ($A_{L,T}(t=0)$) and two phases ($\delta_{1,2}$) as well as three weak decay parameters ($\Delta\Gamma_s, \Gamma_s, \Phi_s$), which are extracted in a maximum likelihood fit. Despite the enormous LHC statistics and the well controlled background several parameters are highly correlated due to experimental resolutions. To avoid unreasonable fit results due to a high correlation of $\Delta m_s$ and $\Phi_s$, the value of $\Delta m_s$ was fixed based on the analysis described in Sec. 2.2. In the future, this should be fitted simultaneously using the results from the $B_s \rightarrow D_s\pi/a_1$ measurements. With an integrated luminosity of $30 \text{ fb}^{-1}$ (Fig. 1) a sensitivity of $\sigma(\Delta\Gamma_s)/\Delta\Gamma_s = 13 \%$ could be achieved, based on about $270,000$ signal events. The main background contamination (ca. $15 \%$) originates from $J/\psi K^{0,*}$ and $B_s \rightarrow J/\psi X$ decays.

2.2. $\Delta m_s$ Measurement
An other sensitive check on BSM is the measurement of $\Delta m_s$ in the $B_s^0/\bar{B}_s^0$ system. Although the precision measurement will be done by LHCb, the aim of the ATLAS measurement of $\Delta m_s$ using the decay channels $B_s \rightarrow D_s\pi$ and $B_s \rightarrow D_s a_1$ will be used to fix or simultaneously fit for the parameters $\Delta m_s$ in the CP-fit for $B_s \rightarrow J/\psi\Phi$. Due to the weak interaction, a mixing in the decay channels $B_s \rightarrow B_s\pi$ and $B_s \rightarrow D_s a_1$ should be measurable. The probability, that an initial pure $B_s^0$ state produced at $t = 0$ is measured after a certain time $t$ as $B_s^0$ is $p_+(t)$ (or as
3. Rare B-Decays

Flavor changing neutral currents, a direct transition from $b \to d, s$, are forbidden at the tree level in the SM and occur at the lowest order through one loop diagrams. Since they are a sensitive test of the SM and its possible extension, delivers information on the long distance QCD effects and enable a determination of the CKM matrix elements $|V_{td}|$ and $|V_{ts}|$ they are taken into the $B$-physics program of ATLAS. Furthermore, some of the rare decay channels contribute to the background for others channels, which are very sensitive to BSM effects. Generally, precision measurements of rare $B$-decays are sensitive tools for searches for new physics at LHC.

3.1. Search for $B_s \to \mu^+\mu^-$

The upper limit to the branching ratio $BR(D^0_s \to \mu^+\mu^-)$ can be extracted from the data with expected $n_{\text{signal}} = 7$ signal- and $n_{\text{bg}} = (20\pm12)$ background-events corresponding to a luminosity of 30 fb$^{-1}$:

$$BR(B^0_s \to \mu^+\mu^-) \leq \frac{N(n_{\text{signal}}, n_{\text{bg}})}{2\sigma_{B_s} \times \alpha \times \epsilon_{\text{total}}}$$  \hspace{1cm} (3)

After four years of data taking, the sensitivity of the the SM predictions could be reached (Fig. 2). The continuation of this measurement at nominal LHC luminosities has been proven leading to a clear statement with a 5 $\sigma$ sensitivity after on more additional year of data taking at design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. The selection for this events is based on cuts on $p_T$, the invariant mass $M_{\mu\mu}$ and the transverse decay length $L_{xy}$ of the di-muon system.

3.2. Semi-muonic Exclusive Searches

A study has been performed on the feasibility of measuring the production polarization of beauty hadrons by analyzing of the angular distributions of secondary particles in the decay $\Lambda^0_b \to \Lambda^0 J/\psi(\mu^+\mu^-)$. The shape of the asymmetry $A_{FB}$ provides a strong indirect test for BSM physics. The shape of the distribution is sensitive to trigger and off-line selection cuts especially in the low $q^2$ region, since the detector acceptance and muon trigger prefer higher $p_T$ due to the $p_T$-cut causing an $A_{FB}$ reduction by a factor of 0.6 at $q^2/M_{\Lambda_b^0}^2 < 0.1$. Furthermore, the small $\mu^+\mu^-$-opening angle constitutes a challenge to the trigger. With 30 fb$^{-1}$ an amount of 800 events could be expected for the $\Lambda^0_b \to \Lambda^0 \mu^+\mu^-$

4. Conclusion

The ATLAS experiment has a well defined $B$-physics program based on clearly defined trigger strategies for all luminosity phases of the LHC. These measurements will contribute to $CP$ violation studies with $B_c$-mesons and its sensitivity to BSM as well in studies of rare $B$ decays. The precision measurement of $B$-physics processes are an alternative method to explore the presence of new physics at LHC in addition to the direct SUSY searches.
**Figure 1.** Correlation of the weak phase $\Phi_s$ and $\Delta m_s$ in $CP$ violation in the decay $D_s \rightarrow J/\psi\phi$ and the achievable sensitivity with an integrated luminosity of 30 fb$^{-1}$.

**Figure 2.** Sensitivity of ATLAS for the upper limit for the rare decay $B_s \rightarrow \mu^+\mu^-$ as a function of the integrated LHC luminosity. After 4 years of data taking, the sensitivity of the SM prediction could be reached.

**References**

[1] Atlas Detector and Physics Performance, ATLAS TDR 15, CERN/LHCC 99-15

[2] B. Epp et al., Atlas Physics Note, ATL-PHYS-PUB-2006-020