# *CP* Violation Studies in ATLAS and CMS

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ABSTRACT

The large number of $b\bar{b}$ events at LHC will offer the possibility to study $CP$ violation in the $B$ system. The two general purpose detectors ATLAS and CMS, primarily designed to study high $p_t$-phenomena, are capable of doing $B$-physics and the possibility of measuring $CP$ has been investigated by both collaborations. We discuss the potential of the two detectors for the measurement the angles alpha and beta of the unitarity triangle during the initial low luminosity phase of the LHC.

## 1 Introduction

The coupling between up- and down-type quarks is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. The precise determination of elements of this matrix is one of the primary goals of heavy-flavour physics. In the Wolfenstein parametrization [2] the matrix is written approximately as

$$V \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{1}$$

Only $V_{ub}$ and $V_{td}$ have a complex phase in this parametrisation and are therefore the relevant terms which could produce $CP$ violation. The unitarity of the CKM matrix implies a relation between the elements

$$V_{ub}^* + V_{td} = \lambda V_{cb} \tag{2}$$

which can be represented as a triangle in the $\rho - \eta$ complex plane, with the three angles $\alpha, \beta, \gamma$, see figure 1. In principle all three angles of this unitarity triangle are accessible to direct experimental measurements. Here we will concentrate on the measurements of the angles $\alpha$ and $\beta$.

There are a variety of ways in which $CP$ can be violated in the $B$ system leading to $\Gamma(B^0 \to f) \neq \Gamma(\bar{B}^0 \to \bar{f})$. The measurable decay rate asymmetry

$$A = \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to \bar{f})}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to \bar{f})} \tag{3}$$

depends on the angle of the unitarity triangle. For example, $A \sim \sin 2\beta$ for $B_d^0 \to J/\psi K_s^0$ and $A \sim \sin 2\alpha$ for $B_d^0 \to \pi^+\pi^-$.

Both time-integrated and time-dependent measurements of this asymmetry can be performed. The time-dependent measurement is done using the position of the reconstructed decay vertex of the $B$ meson.

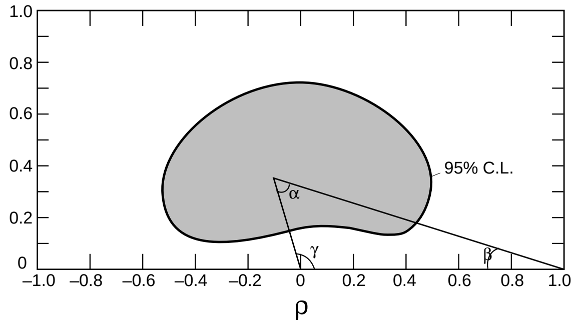

Figure 1: Unitarity triangle of the CKM matrix with current constraint.

## 2 B Physics at the LHC

The initial luminosity of LHC is expected to be $10^{32}$ to $10^{33}$ cm$^{-2}$s$^{-1}$. B-physics studies will be easiest at this initial luminosity, where pile-up effects are small and vertex detectors very close to the beam pipe are expected to survive for several years.

For this study, we assume a center-of-mass energy of $\sqrt{s} = 14$ TeV and an integrated luminosity of $10^4$ pb$^{-1}$, corresponding to $10^7$ seconds at a luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$. In this regime, we expect from 1.5 to 2 underlying events per bunch-crossing.

There is a large uncertainty in the estimation of the production cross-section of $b\bar{b}$ at LHC. For this study we used $\sigma_{b\bar{b}} = 500\ \mu b$. The fraction of $b\bar{b}$ events at the LHC is thus $\sigma_{b\bar{b}}/\sigma_{tot} \approx 0.5\%$. With such a cross-section, we anticipate about $5 \times 10^{12}$ $b\bar{b}$ events/year ($10^7$ s).

The experimental difficulties are the high rates and the large associated multiplicities. What is needed is a powerful trigger system to select the interesting modes, detectors with high granularity, high-resolution vertex detectors, efficient track reconstruction and good momentum resolution.

## 3 Detectors

The two general purpose detectors CMS and ATLAS are extensively described in [3] and [4]. Both detectors are designed to take full benefit of the lower luminosity ($10^{33}$ cm$^{-2}$ s$^{-1}$) to study $B$ physics.

The basis of the CMS detector is a long (13 m) superconducting solenoid with a 6 m bore and a uniform 4 T field, containing the inner tracker and all calorimetry. The most distinguishing feature of the ATLAS detectors is its large air-core toroid muon spectrometer. Inside the air-core muon spectrometer is the calorimeter system. The inner tracking detector is located in 2 T solenoidal magnetic field provided by a superconducting coil that sites in front of the electromagnetic calorimeter. ATLAS and CMS overall lengths are 44 m and 21 m approximately, and their diameters are 22 m and 14 m respectively. Both detectors have very good momentum resolution: $\Delta p_t / p_t$ for tracks with $p_t = 100$ GeV is 2% for ATLAS and 1% for CMS.

The two detectors have foreseen high-resolution vertex detectors for B-physics. The main weakness of the two detectors for $B$ physics compared to dedicated $B$ physics experiments is that they have no hadron identification.

ATLAS and CMS are using the centrally produced $b$'s while LHC-B [5], a dedicated $B$-experiment at the LHC is using forward $b$'s.

## 4 Measuring sin2$\beta$

To determine the angle $\beta$ of the unitarity triangle the most appropriate decay channel is $B_d^0 \to J/\psi K_s^0$ followed by $J/\psi \to \ell^+\ell^-$ ($\ell = \mu, e$) and $K_s^0 \to \pi^+\pi^-$, as it is a $CP$ eigenstate, and has the cleanest signature and the most tractable background. Further advantages are the relatively high branching ratio and the fact that triggering on $J/\psi \to \ell^+\ell^-$ is relatively easy. Recent CDF results are most encouraging in this respect [6].

The experimentally measurable time-integrated asymmetry for this decay channel is related to $\sin 2\beta$:

$$\begin{aligned} A &= \frac{\Gamma(B_d^0 \to J/\psi K_s^0) - \Gamma(\bar{B}_d^0 \to J/\psi K_s^0)}{\Gamma(B_d^0 \to J/\psi K_s^0) + \Gamma(\bar{B}_d^0 \to J/\psi K_s^0)} \\ &= sin2\beta \cdot D \cdot \frac{x_d}{1 + x_d^2} \qquad (4) \end{aligned}$$

where $D$ is the dilution factor and $x_d/(1+x_d^2)$ is a factor due to time-integration ($x_d$ has been measured to be 0.71 [7]). The reconstructed $B_d^0$ meson is tagged as having been produced as a $B_d^0$ or a $\bar{B}_d^0$ using the charge of lepton $(e, \mu)$ from the semileptonic decay of the associated $b$.

### 4.1 Trigger and Event Selection

In principle there are 3 possibilities:

(i) muon-tag with $J/\psi \to \mu^+\mu^-$

(ii) muon-tag with $J/\psi \to e^+e^-$

(iii) electron-tag with $J/\psi \to \mu^+\mu^-$

The ATLAS collaboration has investigated all three possibilities, while in CMS the electron modes are under active study and only the mode $J/\psi \to \mu^+\mu^-$ with $\mu$-tag is included here.

**CMS**:

The trigger is provided by two low-$p_t$ muons with rapidity-dependent trigger thresholds: $p_t^\mu > 4.5$ GeV for $0.0 < |\eta| \leq 1.5$, $p_t^\mu > 3.6$ GeV for $1.5 < |\eta| \leq 2.0$ and $p_t^\mu > 2.6$ GeV for $2.0 < |\eta| \leq 2.5$ The third muon is required to reach at least the first muon station. The following further cuts are applied to all events:

- $\pi$'s from $K_s^0$ within $|\eta^\pi| \leq 2.4$ and $p_t^\pi \geq 0.7$ GeV
- $K_s^0$ decay length in the transverse plane between 2 and 40 cm, to avoid problems due to pattern recognition
- The reconstructed invariant masses of $J/\psi$, $K_s^0$ and $B_d^0$ must lie within $\pm 2\sigma$ of their known masses
- tag muon with $p_t > 4$ GeV

The reconstructed masses have the following resolutions: 16 MeV for $J/\psi$, 8.6 MeV for $K_s^0$ and 12 (22) MeV for $B_d^0$ with (without) mass constraints [8]. To obtain the expected number of events in addition to the trigger efficiency and the geometrical acceptance, a track reconstruction efficiency of 95% for triggered muons and 90% for the third muon is considered. The $K_s^0$ reconstruction efficiency in the case of 2 $\pi$'s from $K_s^0$ with $p_t \geq 0.7$ GeV folded with their momentum distribution is on average 35% [8].

**ATLAS**:

ATLAS is triggering at the first-level on a single muon with $|\eta| < 2.2$ and $p_t > 6$ GeV. In addition, the second-level trigger requires at least one of the following: (i) an $e^+e^-$ pair with $p_t^e > 1$ GeV, (ii) an additional muon with $p_t^\mu > 5$ GeV and $|\eta^\mu| < 2.5$ or (iii) an electron with $p_t > 6$ GeV and $|\eta| < 2.5$. The total trigger rate for this three triggers is about 1 kHz. The electrons are identified in the ATLAS TRT. In the case $J/\psi \to \mu^+\mu^-$ both electron tags and muon tags are used. The following cuts are applied to all events at analysis level:

- $\pi$'s from $K_s^0$ within $|\eta^\pi| \leq 2.5$ and $p_t^\pi > 0.5$ GeV
- $K_s^0$ decay length in the transverse plane between 1 and 50 cm

- tag lepton $p_t > 5$ GeV for muons or $p_t > 6$ GeV for electrons
- the $J/\psi K_s^0$ system is required to have a mass within a $\pm 2\sigma$ of the known $B_d^0$ mass and a proper decay time must exceed 0.5 ps

Fig. 2 shows an $B_d^0 \rightarrow J/\psi K_s^0 \rightarrow e^+e^-\pi^+\pi^-$ event with an electron tag reconstructed in the ATLAS Inner detector.

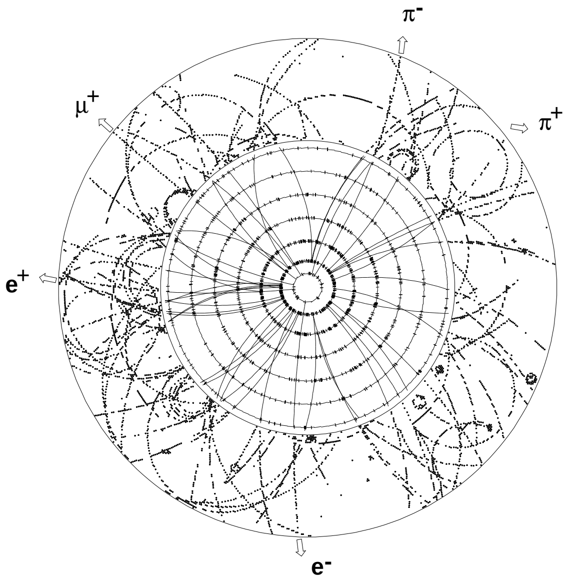

Figure 2: $B_d^0 \rightarrow J/\psi K_s^0 \rightarrow e^+e^-\pi^+\pi^-$ event reconstructed in the ATLAS Inner detector.

For $\mu$-tagged $J/\psi \rightarrow e^+e^-$ decays, a tag muon with $p_t > 6$ GeV and $|\eta| < 2.2$, and two electrons with $p_t > 1$ GeV were required. For $\mu$-tagged $J/\psi \rightarrow \mu^+\mu^-$ decays, a tag muon with $p_t > 5$ GeV, and two other muons with $p_t(\mu^1) > 5$ GeV, $p_t(\mu^2) > 3$ GeV were required; in addition, one of the three muons was required to satisfy the trigger, having $p_t > 6$ GeV, $|\eta| < 2.2$. For electron-tagged $J/\psi \rightarrow \mu^+\mu^-$ events, a tag electron with $p_t > 5$ GeV, and two muons with $p_t(\mu^1) > 6$ GeV, $|\eta(\mu^1)| < 2.2$, and $p_t(\mu^2) > 3$ GeV were required.

The $K_s^0$ mass resolution is in the range of 3-8 MeV for transverse decay lengths of 1-50 cm. The average reconstruction efficiency is 91% and the background under the $K_s^0$ peak is 6% [9]. The reconstructed $J/\psi$ mass has a resolution of 27 MeV and the resolution of the reconstructed $B_d^0$ is 18 (35) MeV with (without) mass constraints [10]. To calculate the expected number of events a reconstruction efficiency of 80% for leptons and 95% for pions is taken into account.

## 4.2 Tagging and Dilution

The flavour of the produced $B_d^0$ is tagged by the charge of the lepton produced in the semileptonic decay of the other $b$-quark in the event. However this tagging is not fully efficient and the measured decay asymmetry is affected by dilution effects. The dominant contribution to dilution is from oscillations of $B_d^0$ or $B_s^0$ before decaying to leptons and from cascade decays. The dilution factor due to mixing can be written as:

$$D_{\text{mix}} = \sum_i p_i \frac{1}{1 + x_i^2} \tag{5}$$

where $p_i$ are the production rates for $B^\pm$, $B_d^0$, $B_s^0$ and $\Lambda_b$. With $p^\pm : p_d : p_s : p_\Lambda = 0.38 : 0.38 : 0.14 : 0.1$, $x_d = 0.71$ and $x_s = 10.0$, the dilution factor due to mixing is $D_{\text{mix}} = 0.73$.

The dilution factor $D_{\text{tag}}$ can be defined as: $D_{\text{tag}} = 1 - 2w$, where $w$ is the fraction of wrong tags. Sources of mistags are:

- cascade decays ($b \rightarrow c \rightarrow \ell$)
- muons from additional $b$'s and $c$'s
- hadron decays (K,$\pi$ decays) (for muons)
- punch-through (for muons)
- conversions and Dalitz pairs (for electrons)

Fig. 3 shows the fraction of wrong sign muons plotted as a function of the $p_t^\mu$ cut for various sources of mistags. The major contribution to $w$ is cascade decays. The contribution from punch-through, hadron decays and from conversions is small. The fraction of mistagged

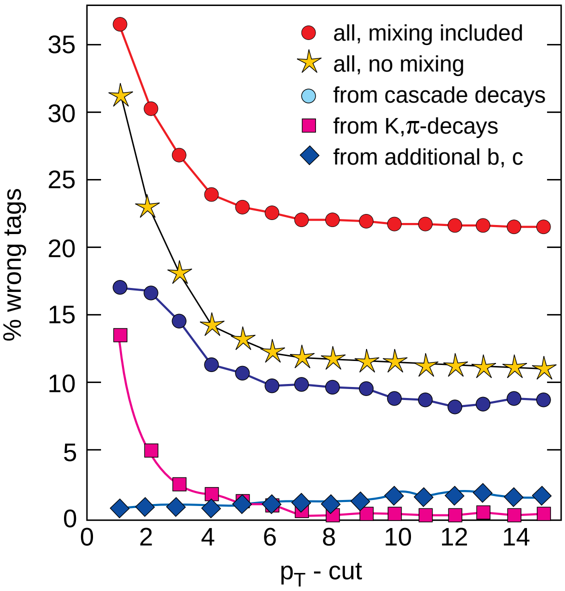

Figure 3: Fraction of wrong tags as a function of the $p_t$-threshold of the tagging muon.

events depends on the requirements placed on the associated lepton, the purity increases with increasing $p_t$.

The presence of background introduces a third dilution factor $D_{\text{background}} = N_{\text{S}}/(N_{\text{S}} + N_{\text{B}})$, where $N_{\text{S}}$ and $N_{\text{B}}$ are the number of signal and background events.

The dilution factor in equation 4 can be written as: $D = D_{\text{mix}} \cdot D_{\text{tag}} \cdot D_{\text{background}}$

### 4.3 Background

The background for this channel is dominated by accidental coincidences between a real $J/\psi$ and a $K_s^0$ from fragmentation. The backgrounds from $B^{\pm} \to J/\psi K^{*\pm}$ and $B^0 \to J/\psi K^{*0}$ peak below the signal mass peak. The signal to background ratio is about 1 : 10. Fig. 4 shows the reconstructed mass distributions (signal and background) for CMS and ATLAS.

### 4.4 Expected Sensitivity

The statistical error on $\sin 2\beta$ for the time-integrated analysis is calculated as:

$$\delta(\sin 2\beta) \approx \frac{1}{D \cdot x_d/(1+x_d^2) \cdot \sqrt{N_{\text{tot}}}} \qquad (6)$$

The results of the time-dependent and time-integrated $J/\psi K_s^0$ analyses are summarized in Table 1. It has to be stressed out that the electron tag in CMS is under investigation and is not included yet. The theoretical and systematical error is of the order of 1%.

| Parameter | CMS | ATLAS |
|---|---|---|
| $\text{BR}[B_d^0 \to J/\psi K_s^0]$ | $3.3 \times 10^{-4}$ | $3.75 \times 10^{-4}$ |
| $N[\mu\text{-tag}, J/\psi \to e^+e^-]$ | – | 10120 |
| $N[\mu\text{-tag}, J/\psi \to \mu^+\mu^-]$ | 8000 | 6590 |
| $N[e\text{-tag}, J/\psi \to \mu^+\mu^-]$ | – | 5680 |
| $N(\text{signal})$ | 8000 | 22390 |
| $N(\text{background})$ | 800 | 2590 |
| $N(\text{total})$ | 8800 | 24980 |
| $D_{\text{background}}$ | 0.91 | 0.90 |
| $D_{\text{tag}} \cdot D_{\text{mix}}$ | 0.53 | 0.56 |
| $\delta(\sin 2\beta)$ time-dep. | 0.045 | 0.018 |
| $\delta(\sin 2\beta)$ time-int. | 0.048 | 0.020 |

Table 1: Sensitivity to $\sin 2\beta$ for $10^4$ pb$^{-1}$.

## 5 Measuring sin2$\alpha$

The most promising channel for the measurement of the angle $\alpha$ of the unitarity triangle is $B_d^0 \to \pi^+\pi^-$. The trigger of such events is provided by the semileptonic decay of the associated $b$-hadron in the event which is used to tag the flavour of the produced $B_d^0$. The time-integrated asymmetry $A$ for this decay channel is:

$$A = \frac{N^+ - N^-}{N^+ + N^-} = D \cdot \frac{x_d}{1+x_d^2} \cdot \sin 2\alpha \qquad (7)$$

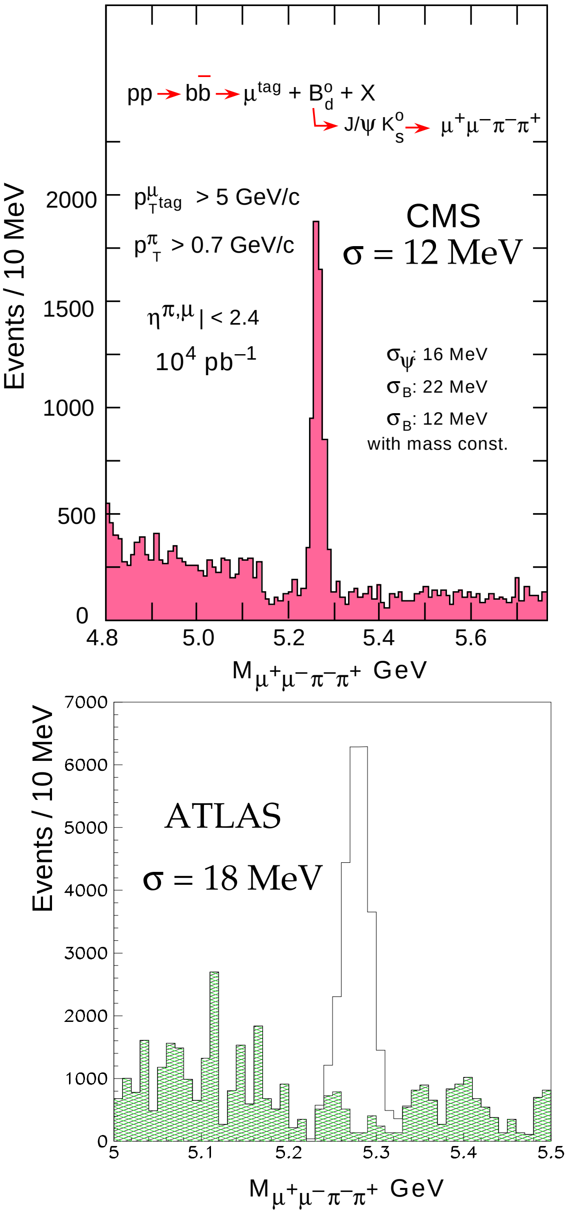

Figure 4: $B_d^0 \to J/\psi K_s^0$ in CMS and ATLAS.

where $N^+$ and $N^-$ are the number of reconstructed events with positively and negatively charged tagging muons and $D$ is the dilution factor discussed in section 4.2.

The study of this decay channel is experimentally more difficult than for $B_d^0 \to J/\psi K_s^0$ because one lacks the clean signature of the leptonic $J/\psi$ decay.

The first level trigger for this analysis is an inclusive muon trigger with $p_t > 9$ GeV and $|\eta| < 2.4$ in the case of CMS and $p_t > 6$ GeV and $|\eta| < 1.6$ in the case of ATLAS. In addition the ATLAS second level trigger requires an unlike-charge pair of particles with $p_t > 6$ GeV and with the sum $p_t$ of the two particles larger than 15 GeV.

The branching ratio for the decay $B_d^0 \to \pi^+\pi^-$ was assumed to be $2 \times 10^{-5}$.

## 5.1 Background and Event Selection

Without particle identification the largest background is from two-body B-meson decays when the charged hadrons are assigned pion mass. One has to rely on mass resolution to suppress this background. In particular, the decay $B_d^0 \to K\pi$ peaks just below the $B_d^0$ mass, while the decay $B_s^0 \to K\pi$ is just above. The decay $B_s^0 \to KK$ is peaked on top of the signal; however, the smaller $B_s^0$ production probability suppresses this background. An asymmetric contribution comes from the decay $\Lambda_b \to p\pi$. Other quasi-two body decays like $B_d^0 \to \rho\pi$, $B_s^0 \to K^*\pi$, $B_s^0 \to K\rho$ and $\Lambda_b \to K\rho$ contribute less than 1%. Fig. 5 shows the contribution from the two-body decay backgrounds. In CMS the reconstructed mass has a resolution $\sigma_B = 25$ MeV and in total the two body decays contribute to a background to signal ratio, $B/(S+B)$, of $\approx 45\%$ in a mass window of $\pm 1\sigma$. In ATLAS the $\pi^+\pi^-$ mass resolution is 50 MeV.

The combinatorial background adds an almost flat background contribution, which is around 10% of the total.

All other sources of background are highly suppressed using the following selection criteria: [8, 9]

**CMS**:

- two opposite-sign hadrons with $p_t^h > 5$ GeV within $|\eta| < 2$
- distance between the two pions $\Delta R < 1$
- isolation $I < 0.1$, where $I$ is defined as the $\sum p_t$ of the hadrons within a cone $\Delta R < 1$ around the $B_d^0$ direction, normalized to the $p_t$ of the $B$ candidate (only charged tracks with $p_t > 2$ GeV are considered and the two pions are not included in the sum)
- impact parameter significance $d/\sigma_d > 2$ for each pion, where $\sigma_b$ is the impact parameter resolution
- $\alpha < 100$ mrad where $\alpha$ is the angle in the transverse plane between the direction defined by the primary and decay vertex and the reconstructed $\pi\pi$ sum-momentum

**ATLAS**:

- two hadrons with $p_t > 6$ GeV and sum $p_t$ larger than 15 GeV
- scaled impact parameters of the two pions $d/\sigma_d > 3$
- angle between the reconstructed B-meson and the line joining the primary and secondary vertices in the transverse plane $< 6°$
- transverse decay length $> 300\ \mu$m
- distance of closest approach of the two particles $< 55\ \mu$m

Fig. 6 shows the invariant mass distributions for the signal and background after all cuts for CMS and ATLAS.

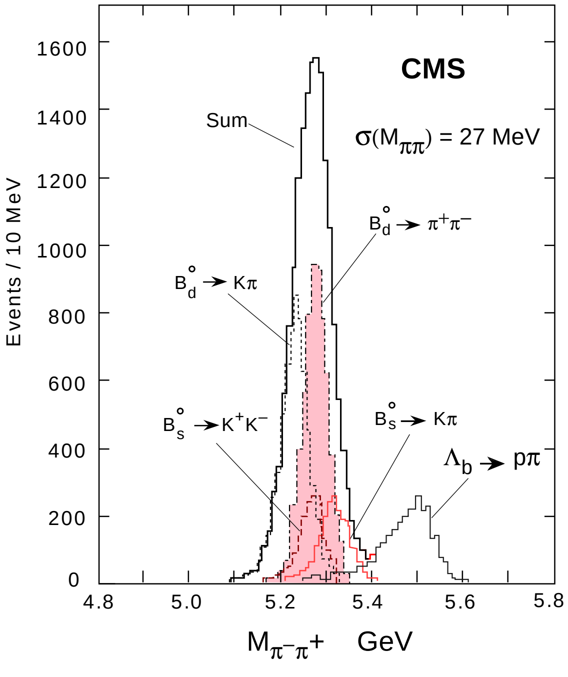

Figure 5: $B \to \pi^+\pi^-$ mass resolution and 2-body decay backgrounds.

## 5.2 Expected Sensitivity

The results of the time-dependent and time-integrated $B_d^0 \to \pi^+\pi^-$ analyses are summarized in Table 2. It can be seen, that performing a time-dependent measurement will improve the sensitivity. Theoretical uncertainties in this measurement are larger than in the case of $\sin 2\beta$ because of contributions from possible penguin diagram decays.

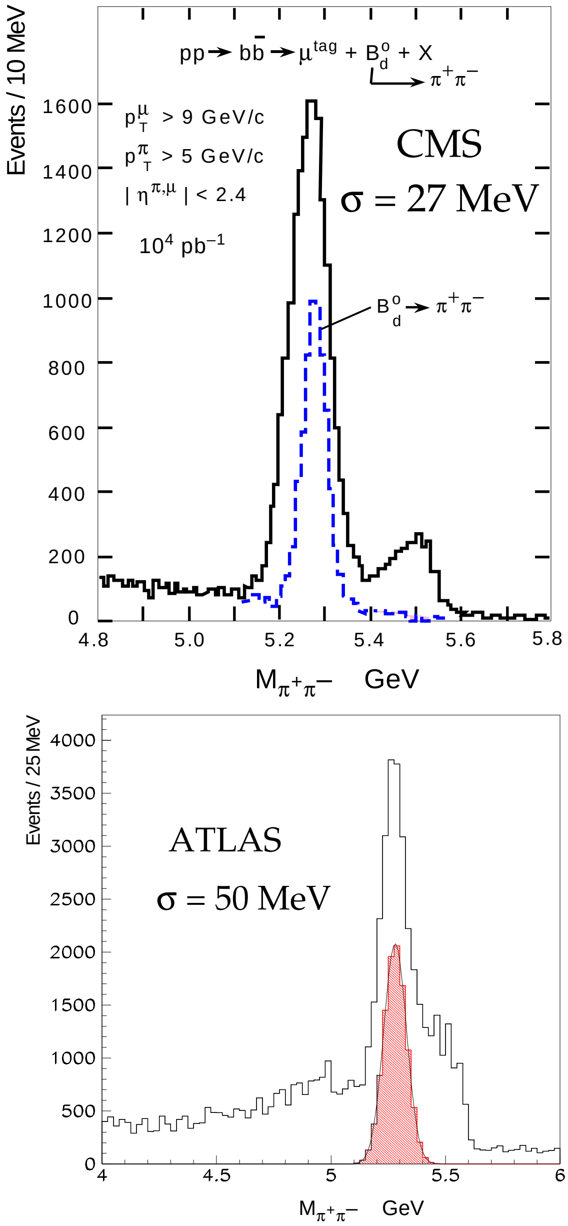

Figure 6: $B_d^0 \to \pi^+\pi^-$ in CMS and ATLAS.

| Parameter | CMS | ATLAS |
|---|---|---|
| $N[B_d \to \pi\pi]$ | 4300 | 7120 |
| $N[B_d \to K\pi]$ | 1525 | 2890 |
| $N[B_s \to KK]$ | 1250 | 1070 |
| $N[B_s \to K\pi]$ | 510 | 1495 |
| other backgrounds | 515 | 1585 |
| $N$(background) | 3800 | 7040 |
| $N$(total) | 8100 | 14160 |
| $D_{\text{background}}$ | 0.47 | 0.50 |
| $D_{\text{tag}} \cdot D_{\text{mix}}$ | 0.57 | 0.56 |
| $\delta(\sin 2\alpha)$ time-dep. | 0.070 | 0.043 |
| $\delta(\sin 2\alpha)$ time-int. | 0.050 | 0.047 |

Table 2: Sensitivity to $\sin 2\alpha$ for $10^4$ pb$^{-1}$.

## 6 Summary

Both collaborations, ATLAS and CMS, studied the possibility of measuring $CP$ violation. Even without particle identification they perform well for $B_d^0 \to \pi^+\pi^-$ thanks to their good mass resolution and are are able to compete with dedicated B physics experiments in the channel $B_d^0 \to J/\psi K_s^0$.

## Acknowledgements

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