Latest results on the search for $D^0 \rightarrow \mu \mu$ and $B^0_{s,d} \rightarrow \mu \mu$ decays from CMS

Fabrizio Palla

INFN Sezione di Pisa, Largo Bruno Pontecorvo 3, 56126 Pisa (Italy)
E-mail: Fabrizio.Palla@cern.ch

Abstract.

The rare decays of $D^0 \rightarrow \mu \mu$, $B^0 \rightarrow \mu \mu$ and $B^0_{s,d} \rightarrow \mu \mu$ are sensitive to physics beyond the Standard Model as their branching fraction can be highly enhanced or suppressed in new physics models. The CMS experiment at the LHC has reported the studies of these rare decays in pp collisions at $\sqrt{s} = 7$ TeV using datasets collected in 2010 and 2011. In those searches, the number of observed events is consistent with the expectation from background plus Standard Model signal prediction. Results of the combination of the exclusion limits are presented.

Decays mediated by flavour-changing neutral currents (FCNC) are highly suppressed in the Standard Model (SM), and are sensitive to New Physics (NP) through higher order loop diagrams contributions. Charm and bottom mesons decays into muon pairs are in addition helicity suppressed, and the measurement of their decays are traditionally investigated to search for NP effects, which could enhance the small branching ratios (BR) of these decays.

We will present the status of the searches for the rare decays of $D^0 \rightarrow \mu \mu$, $B^0 \rightarrow \mu \mu$ and $B^0_{s,d} \rightarrow \mu \mu$ in CMS. In Section 1 we review the status of the searches for $D^0$ decays, and in Section 2 the one of the $B^0$ and $B^0_{s,d}$ rare decays.

1. Searches for the rare decays $D^0 \rightarrow \mu \mu$

The rare decay $D^0 \rightarrow \mu^+ \mu^-$ is highly suppressed by the GIM mechanism and by helicity. In the SM it proceeds via a W box diagram, also contributing to the $D^0 - \bar{D}^0$ mixing. Theoretical estimates of this branching ratio are approximately $10^{-18}$ from short range processes, increasing up to $10^{-13}$ when long-distance processes are included [1]. NP can enhance these estimates by several orders of magnitude [2].

CMS has searched for this decay in the data of pp collisions at the LHC, collected in 2011 at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of about 90 pb$^{-1}$[3]. The strategy of the analysis relies upon the determination of the ratio of the BR of the $D^{*+} \rightarrow D^0 (\mu \nu) \pi^+$ over the BR of $D^{*+} \rightarrow D^0 (K^- \mu^+ \nu) \pi^+$ (otherwise explicited, charge conjugation is implied throughout the paper). In this way most of the systematic uncertainties cancel out. CMS has an efficient trigger for dimuon events, while for single-muons the thresholds on the muon transverse momentum ($p_T$) have been steadily increased with the luminosity, to cope with the constraints given by the allowed bandwidth. For this reason, the main challenge of the analysis is the reconstruction of the normalization decay, which has been affordable only

On behalf of the CMS Collaboration
for the 2010 and 2011 data taking period, when the instantaneous luminosity did not exceeded about $4 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$. The trigger selection is the same for both decay modes of the $D^0$. It requires a high quality muon to be reconstructed in the muon chambers at the first level trigger (L1), and confirmed at the High Level Trigger (HLT) where the silicon tracker information is used. As the LHC instantaneous luminosity increased the thresholds increased as well, ranging from $p_T > 3 \text{GeV/c}$ up to $15 \text{GeV/c}$. Seven different taking periods were used: six in 2010 and one in 2011, the latter corresponding to an integrated luminosity of 54 pb$^{-1}$.

The semileptonic and the leptonic decays show the same final topology, with a displaced decay vertex with two charged tracks and a slow pion coming from the $D^0$ decay occurring at the primary vertex. The primary vertex of the event is identified by the one with the largest decay vertex with two charged tracks and a slow pion coming from the $D^0$ decay, and which must be compatible with originating from the primary vertex. Combinations with identical charge.

The $D^0 \rightarrow \mu^+ \mu^-$ is reconstructed by pairing opposite sign muon candidates, reconstructed in the muon stations and in the silicon tracker, within the pseudorapidity range $|\eta| < 2.1$. One of the two muons is requested to “match” with the one that triggered the event (hence with a minimum $p_T$ which depends on the data taking period), while the $p_T$ of the other muon is required to be larger than 3 GeV/c. The two muon tracks are fit to a common vertex, and the pair retained if the vertex CL is larger than 1% and the primary vertex is recomputed excluding those muon tracks. The angle $\alpha$ between the momentum of the muon pair and the direction joining the primary and secondary vertices should satisfy $\cos \alpha > 0.99$. Finally the $D^0$ candidate is combined with a track (with $p_T > 0.6 \text{GeV/c}$) which is given the pion mass, and which must be compatible with originating from the primary vertex. Combinations with $\Delta M = M(\mu^+ \mu^-) - M(K^+ \pi^-)$ smaller than 180 MeV/c$^2$ are retained as good $D^{*+}$ candidates; if more than one candidate is found, the one with the $\Delta M$ closest to the nominal PDG mass difference is chosen.

The normalization channel, $D^{*+} \rightarrow D^0(K^- \pi^+)\pi^+$, is reconstructed using a technique developed by E691 [4]. In that technique the neutrino momentum is reconstructed by imposing that the $D^0$ momentum is pointing to the primary vertex. The $K^- \mu^+ \nu$ candidate is then combined with a $\pi^+$ to find the $D^{*+}$ as done before. The muon candidate must satisfy the same cuts as the trigger muon of the $D^0 \rightarrow \mu^+ \mu^-$ analysis, and the kaon candidate should have a $p_T > 0.8 \text{GeV/c}$ and $|\eta| < 2.1$. The kaon and the muon are requested to come from the same vertex with a CL> 1% and the neutrino momentum computed using the E691 technique. Finally the $D^{*+}$ candidate is formed in a similar fashion as before. In order to evaluate the level of the background, also wrong sign (WS) combinations between the $K^- \mu^+ \nu$ and the soft pion from the primary vertex (in which a pion with a charge opposite to the muon track) has been chosen, to be distinguished from the Right Sign (RS) combinations where the soft pion and muon tracks have identical charge.

In order to further reduce the backgrounds, both for the signal and normalization modes, the secondary vertex decay length is required to be larger than 3 times its computed uncertainty. The $\Delta M$ distribution of the WS and RS combinations is shown in Fig. 1 (Left). No evidence of peak is found for the WS and the shape of its distribution is taken to model the shape of the combinatorial backgrounds in the RS distribution. The number of $D^0 \rightarrow K^- \mu^+ \nu$ candidates is extracted by a fit to the $\Delta M$ distribution of the RS combinations, in which the signal is described by two Gaussian functions. The fit returns $16458 \pm 204$ $D^0 \rightarrow K^- \mu^+ \nu$ candidates. In order to select the $D^0 \rightarrow \mu^+ \mu^-$ decay mode an additional cut is imposed: $|\Delta M - \Delta M_{PDG}| < 3 \text{MeV/c}^2$, where $\Delta M_{PDG}$ is the nominal $\Delta M$ mass difference between the $D^{*+}$ and the $D^0$. The cut at 3 MeV/c$^2$ corresponds to about 3.6 times the expected Monte Carlo resolution. Figure ??(Right) shows the dimuon invariant mass distribution after all cuts. The events in the signal region (shaded in red) are compatible with the background expectations, as evaluated by interpolating the sidebands (shaded in cyan).
Figure 1. Left: Distribution of $\Delta M = M(K^-\mu^+\nu^+) - M(K^-\mu^-\nu)$ for the 2011 RS sample with the result of the fit superimposed. The points are the data, the blue solid line shows the fit result. The background function modeled from the WS distribution is shown as the dashed red line. Right: The $\mu^+\mu^-$ invariant-mass distribution. The light-red band shows the signal region, while the two cyan bands show the sideband regions.

An upper limit on the branching ratio $D^0 \rightarrow \mu^+\mu^-$ is determined using the following formula:

$$B(D^0 \rightarrow \mu^+\mu^-) = B(D^0 \rightarrow K^-\mu^+\nu) \times \frac{N_{\mu\mu}}{N_{K\mu\nu}} \times \frac{A_{\mu\mu}}{A_{K\mu\nu}} \times \frac{\epsilon_{\mu\mu}}{\epsilon_{K\mu\nu}}$$  \hspace{1cm} (1)

where $B(D^0 \rightarrow \mu^+\mu^-) = (3.30 \pm 0.13) \times 10^{-2}$ is the normalization branching ratio, taken from the PDG[5], $N_{\mu\mu}$ is the 90% CL upper limit on the $D^0 \rightarrow \mu^+\mu^-$ yield, $N_{K\mu\nu}$ the number of $D^0 \rightarrow K^-\mu^+\nu$ candidates, $A$ and $\epsilon$ the acceptances and the efficiencies of the two decay modes, that are determined from the Monte Carlo simulation. The ratio of the acceptances (defined as the number of events in which both charged tracks are within the angular acceptance $|\eta| < 2.1$, divided by the total number of generated events) is $0.995 \pm 0.006$(stat). The efficiency has two components: the trigger and the selection efficiency. The former is defined as the number of events that pass the trigger requirements divided by the number of events in the acceptance. Given the three body decay of the normalization sample, the ratio of the trigger efficiencies between the signal and the normalization modes decreases with the increase of the $p_T$ threshold of the muon, ranging from $0.149 \pm 0.02$ for the 3 GeV/c threshold down to $0.085 \pm 0.003$ for the 15 GeV/c threshold. The reconstruction efficiency is measured relative to the triggered events, and the ratio of the efficiencies between the signal and normalization channels varies from $2.2 \pm 0.2$ to $0.81 \pm 0.05$ from 3 to 15 GeV/c thresholds.

The systematics uncertainties on the acceptances and efficiencies are of the order of 15-20%, and are dominated by the one on the trigger efficiency, which depends on the correct modeling of the $p_T$ spectrum of the muons from charm decays. This is measured by monitoring the luminosity weighted (and corrected for the efficiency) yield for the triggers in the 7 different periods of data taking.

The 90% CL upper limit is determined in each period of data taking, corresponding to different thresholds of the muon trigger, and then combined, giving

$$B(D^0 \rightarrow \mu^+\mu^-) < 5.4 \times 10^{-7} \text{ at 90 } \% \text{ CL.}$$  \hspace{1cm} (2)
2. Searches for the rare decays $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$

The rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are highly suppressed in the SM due to their FCNC nature. These decays are forbidden at tree level and can proceed only through higher order diagrams, such as electroweak penguin and box diagrams. Furthermore, the decays are helicity suppressed and require an internal quark annihilation within the $B$ meson. The SM predictions for the $B_s^0$ and $B^0$ branching ratios to dimuons are $(3.23 \pm 0.27) \times 10^{-9}$ and $(1.07 \pm 0.10) \times 10^{-10}$, respectively, with the main uncertainty resulting from the value of the $B$ meson decay constant $f_B$ [6]. The comparison with experimental results requires the inclusion of soft-photon radiation and $B_s^0 - B_s^0$ oscillations effects each yielding $O(10\%)$ corrections to the predicted decay rate. Several extensions of the SM, such as supersymmetric models and models with a non-standard Higgs sector, predict enhancements or suppressions to the branching fractions for these rare decays. The rare nature of the processes and the rather precise SM predictions make these decays an excellent probe for physics beyond the SM.

The CMS experiment performed a simultaneous search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ using an integrated luminosity of 5 $\text{fb}^{-1}$ collected at the centre-of-mass energy of $\sqrt{s} = 7$ TeV. An event-counting experiment was performed in dimuon mass regions around the $B_s^0$ and $B^0$ masses and all selection criteria were established before observing the signal region. The analysis has been published in [7].

The main backgrounds are those from semileptonic decays of the B hadrons, in which the two muons are coming from the primary and secondary decays of the $b$ and $c$ hadrons, or those where the reconstructed muons are misidentified hadrons, or rare $B$ decays. In particular, resonant decays of $B$ hadrons in two hadrons where both are misidentified as muons are called "peaking background".

A normalization sample of events with $B^+ \to J/\psi K^+$ decays (where the $J/\psi$ decays into a muon pair) was used to remove uncertainties related to the $b$-quark production cross section and the integrated luminosity. Combinatorial backgrounds were evaluated from the data in dimuon invariant mass sidebands while backgrounds from $B$ decays were assessed with Monte Carlo (MC) simulation. The analysis was performed separately in two channels, barrel and endcap, and then combined for the final result. The barrel channel contained the candidates where both muons have $|\eta| < 1.4$ and the endcap channel included those where at least one muon had $|\eta| > 1.4$. $B \to \mu^+\mu^-$ candidates with traverse momentum above 6.5(8.5) GeV/$c$ in the barrel(endcap) were formed by two oppositely-charged muons originating from a common vertex and with an invariant mass in the range 4.9 < $m(\mu\mu)$ < 5.9 GeV/$c^2$. The (sub)leading muon transverse momentum was required to be larger than (4.0) 4.5 GeV/$c$ in the barrel and (4.2) 4.5 GeV/$c$ in the endcap.

The primary vertex (PV) associated to the $B$ candidate is chosen among all the reconstructed PVs in the event as the minimally separated PV from the $B$ candidate along the $z$ axis (where the $z$ coordinate is along the beam direction). The PV is refit removing the tracks that already form the $B$ candidate secondary vertex. Once the PV has been determined, more variables can be constructed, which distinguish the signal from the background:

- the angle between the $B$ meson momentum direction and the one joining the primary and secondary vertex should be smaller than 50 mrad in the barrel and 30 mrad in the endcap.
- the three-dimensional impact parameter of the $B$ meson with respect to the PV ($\delta_{3D}$) and its uncertainty ($\sigma(\delta_{3D})$) are required to satisfy the following criteria: $\delta_{3D} < 80 \mu m$ and $\delta_{3D}/\sigma(\delta_{3D}) < 2$
- the three-dimensional decay length of the $B$ meson should be larger than 13 (15) times its uncertainty in the barrel (endcap).

In order to suppress the abundant semileptonic decays and be insensitive to the simultaneous $pp$ collisions (pileup) (on average 8 events per bunch crossing), a set of isolation
variables have been built:

- an isolation variable $I$

$$I = \frac{p_T(B)}{p_T(B) + \Sigma p_T(i)}$$  (3)

where the sum runs over the track momenta with a minimum $p_T$ of 0.9 GeV/c, for tracks contained in a cone of $\Delta R < 0.7$ with respect to the B momentum. To reduce the sensitivity to the pileup, the sum is performed only on tracks coming either from the same PV or not associated to any PV (but having a distance of closest approach smaller than 0.05 cm). A good isolation is guaranteed by requiring $I > 0.80$.

- less than 2 tracks with $p_T > 0.5$ GeV/c and a distance of closest approach smaller than 0.03 cm with respect to the B candidate decay vertex

- finally, all tracks in the event that are either associated with the same PV as the B candidate or not associated to any other PV should have a distance of closest approach to the B vertex larger than 0.015 cm.

The signal selection has been validated using the normalization $B^+ \to J/\psi K^+$ and control $B^0_s \to J/\psi \phi$ samples. Their reconstruction strategy is very similar to the signal one. The dimuon invariant mass should satisfy $3.0 < m(\mu\mu) < 3.2$ GeV/c$^2$, $p_T(\mu\mu) > 7$ GeV/c, $p_T(K) > 0.5$ GeV/c. For the $B^0_s \to J/\psi \phi$ the $\phi$ selection requires $0.995 < m(KK) < 1.045$ GeV/c$^2$ and $\Delta R(KK) < 0.25$. The number of reconstructed $B^+$ mesons is $(82.7 \pm 4.2) \times 10^3$ in the barrel and $(23.8 \pm 1.2) \times 10^3$ in the endcap. The invariant mass distributions are fit with a double-Gaussian function for the signal and an exponential plus an error function for the background, as shown in Fig. 2.

![Invariant-mass distributions](image_url)

**Figure 2.** $B^+ \to J/\psi K^+$ invariant-mass distributions in the barrel (left) and endcap (right) channels. The solid (dashed) lines show the fits to the data (background).

The sideband subtracted data in the normalization and control samples have been compared to the MC simulation for the signal, for all the selection variables. The total difference in data and MC has been quantified by summing in quadrature the percentage difference in data and MC in each variable: this leads to 4% uncertainty for the normalization sample and to 3% for the control sample.
Figure 3. Comparison of simulated $B^0_s \rightarrow \mu^+\mu^-$ decays and background (upper row) dimuon distributions as measured in the mass sidebands (upper row) or $B^0 \rightarrow J/\psi \phi$ (lower row), isolation variables: $I$ and number of close tracks. The MC histograms are normalized to the number of events in the data.

The expected number of rare events is evaluated from the MC simulation and normalized to the measured $B^+$ yield, taking into account the muon misidentification probability measured from data in $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ and $\Lambda \rightarrow p\pi^-$ decays.

The branching fraction was estimated by using the following equation:

$$B(B \rightarrow \mu^+\mu^-) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{f_u}{f_s} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \times B(B^+ \rightarrow J/\psi K^+)$$  \hspace{1cm} (4)$$

where $N_{\text{norm}}$ is the number of reconstructed $B^+ \rightarrow J/\psi K^+$ decays, $B(B^+)$ its branching ratio, $\epsilon_{\text{norm}}$ the total efficiency, $N_{\text{sig}}$ is the number of observed candidates (after background subtraction) in the signal mass window, $\epsilon_{\text{sig}}$ the total signal efficiency, and $f_u/f_s = 0.267 \pm 0.021$ the ratio of the $B^+$ and $B^0_s$ production cross sections, is taken from [8] and its uncertainty taken as systematics.
The simulated dimuon mass resolution for signal events depends on the pseudorapidity of the \(B\) candidate and ranges from 37 MeV/c\(^2\) for \(\eta \sim 0\) to 77 MeV/c\(^2\) for \(|\eta| > 1.8\). The dimuon mass scale and resolution in the MC simulation are compared with the measured detector performance by studying \(J/\psi \rightarrow \mu^+\mu^-\) and \(\Upsilon(1S) \rightarrow \mu^+\mu^-\) decays. The residual differences between simulation and data are small and the uncertainty on the efficiency coming from these effects is estimated to be 3%.

Table 1 reports the results of the analysis, whereas Fig. 4 shows the measured dimuon invariant mass distributions after unblinding. In the sidebands the observed number of events is equal to six (seven) for the barrel (endcap) channel. Two (four) events are observed in the signal region in the barrel (endcap) for the \(B_s^0 \rightarrow \mu^+\mu^-\) decay channel, while two (zero) events are observed in the barrel (endcap) channel for the \(B^0 \rightarrow \mu^+\mu^-\).

In addition to the systematics already mentioned, the ones from the trigger and muon identification efficiencies vary between 3% and 8%, depending on the muon kinematics. Different production mechanisms would result in different acceptance, giving an uncertainty between 3.5% and 5%. The mass scale and resolution uncertainties give a 3% systematic uncertainty. Finally the combinatorial and rare decays background uncertainties are evaluated to be 4% and 20%, respectively.

Upper limits on the \(B_s^0 \rightarrow \mu^+\mu^-\) and \(B^0 \rightarrow \mu^+\mu^-\) branching ratios are determined using the CL method [9, 10] by combining the endcap and the barrel channels, and taking into account the statistical and systematic uncertainties. The combined upper limits for the barrel and endcap channels are \(B(B_s^0 \rightarrow \mu^+\mu^-) < 7.7 \times 10^{-9}\) (6.4 \times 10^{-9}) and \(B(B^0 \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-9}\) (1.4 \times 10^{-9}) at 95% (90%) CL. The median expected upper limits at 95% CL are 8.4 \times 10^{-9} (1.6 \times 10^{-9}) for \(B_s^0 \rightarrow \mu^+\mu^-\) (\(B^0 \rightarrow \mu^+\mu^-\)), where the number of expected signal events is based on the SM value. Including cross-feed between the \(B^0\) and \(B_s^0\) decays, the background-only \(p\) value is 0.11 (0.24) for \(B_s^0 \rightarrow \mu^+\mu^-\) (\(B^0 \rightarrow \mu^+\mu^-\)), corresponding to 1.2 (0.7) standard deviations. The \(p\) value for the background plus SM signal hypotheses is 0.71 (0.86) for \(B_s^0 \rightarrow \mu^+\mu^-\) (\(B^0 \rightarrow \mu^+\mu^-\)).

### Table 1

| Variable | Barrel | Endcap |
|----------|--------|--------|
| \(\varepsilon_{\text{tot}}(\%)\) | 0.29 ± 0.02 | 0.29 ± 0.02 | 0.16 ± 0.02 | 0.16 ± 0.02 |
| \(N_{\text{signal}}^{\exp}\) | 0.24 ± 0.02 | 2.70 ± 0.41 | 0.10 ± 0.01 | 1.23 ± 0.18 |
| \(N_{\text{peak}}^{\exp}\) | 0.33 ± 0.07 | 0.18 ± 0.06 | 0.15 ± 0.03 | 0.08 ± 0.02 |
| \(N_{\text{comb}}^{\exp}\) | 0.40 ± 0.34 | 0.59 ± 0.50 | 0.76 ± 0.35 | 1.14 ± 0.53 |
| \(N_{\text{total}}\) | 0.97 ± 0.35 | 3.47 ± 0.65 | 1.01 ± 0.35 | 2.45 ± 0.56 |
| \(N_{\text{obs}}\) | 2 | 2 | 0 | 4 |

### 3. Conclusions

The CMS collaboration has looked for rare decays of \(B_{s,d}^0\) and \(B^0\) mesons decaying into \(\mu^+\mu^-\) in pp collisions at \(\sqrt{s} = 7\) TeV. The data sample corresponds to an integrated luminosity of 5 fb\(^{-1}\) in 2011 for beauty mesons, and to 90 pb\(^{-1}\) for charm. The \(B_{s,d}^0 \rightarrow \mu^+\mu^-\) result supersedes our
Figure 4. Dimuon invariant mass distributions in the barrel (left) and endcap (right) channels. The signal windows for $B_s^0$ and $B^0$ are indicated by horizontal lines.

previous measurements and gives a 95% CL upper limit on the branching fraction of $7.7 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-9}$.

The $D^0 \to \mu^+\mu^-$ is normalized to $D^0 \to K^-\mu^+\nu_{\mu}$ decay mode, giving $5.4 \times 10^{-7}$ upper limit at 90% CL. The main limitation in the analysis relies on the efficiency of the normalization sample.

With the luminosity to be collected by the end of the 2012 LHC run (a factor 4 larger than the one used here), we will be having good chances to reach the $B_{s,d}^0$ standard model predicted BR.

References
[1] G. Burdnam et al., Phys. Rev. D 66, 014009 (2002).
[2] E. Golowich et al., Phys. Rev. D 79, 114030 (2009).
[3] CMS Collaboration, "Search for the Flavour-Changing Neutral Current decay $D^0 \to \mu^+\mu^-$ with the experiment CMS at $\sqrt{s} = 7$ TeV", CMS-PAS-BPH-11-017 (2011).
[4] J. Anjos et al., "A Study of the Semileptonic Decay Mode $D^0 \to K^-e^+\nu_{e}$", Phys. Rev. Lett. 62 (1989) 1587.
[5] K. Nakamura et al., Review of Particle Physics, J. Phys. G 37 (2010) 075021.
[6] A.J.Buras, J.Girrbach, D.Guadagnoli and G.Isidori, Eur. Phys. J. C 72 (2012) 2172.
[7] S. Chatrchyan et al., "Search for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays", JHEP 1204 (2012) 033.
[8] R. Aaij, et al., "Measurement of b hadron production fractions in 7 TeV pp collisions", Phys.Rev. D85 (2012) 032008.
[9] A. L. Read, J. Phys. 28 (2002) 2693.
[10] T. Junk, Nucl. Instrum. Meth. A 434 (1999) 435.
[11] S.Chatrchyan et al. [CMS Collaboration], JHEP1204, (2012) 033.