Studies of exotic quarkonium states at CMS

Alessandra Fanfani on behalf of CMS Collaboration
Dipartimento di Fisica ed Astronomia, Viale Berti/Pichat 6/2, 40127 Bologna, Italy
E-mail: fanfani@bo.infn.it

Abstract.
Using large data samples of dimuon events in pp collisions at $\sqrt{s} = 7$ TeV, CMS has performed studies in the field of “exotic” quarkonium spectroscopy. The production of the $X(3872)$ is studied measuring the ratio of the $X(3872)$ and $\psi(2S)$ cross sections times their branching fractions into $J/\psi \pi^+\pi^-$ as a function of transverse momentum ($p_T$). In addition, the fraction of $X(3872)$ originating from B decays is determined. From these measurements the prompt $X(3872)$ differential cross section times branching fraction as a function of $p_T$ is extracted. The $\pi^+\pi^-$ mass spectrum of the $J/\psi \pi^+\pi^-$ system in the $X(3872)$ decays is also investigated. Preliminary studies on structures in the $J/\psi \phi$ mass spectrum of the exclusive $B^+ \rightarrow J/\psi \phi K^+$ decay are reported.

1. Introduction
The observation of many new states, with masses above the open-charm threshold, that do not fit into the conventional quark model has renewed the interest in “exotic” quarkonium spectroscopy. There are several interpretations, such as molecular state, tetraquark state and hybrid mesons, however the theoretical picture is not clear and more experimental inputs are needed [1].

Using the pp collision data recorded by the Compact Muon Solenoid (CMS) experiment at the LHC in 2011, at a centre-of-mass energy of 7 TeV, the first targets of the “exotic” spectroscopy program in CMS have been the measurement of the $X(3872)$ production and the search for structures in the $J/\psi \phi$ mass spectrum of the exclusive $B^+ \rightarrow J/\psi \phi K^+$ decay.

The main results from CMS are summarised as follows: after a brief description of the CMS detector in Section 2, measurements of the $X(3872)$ production and its decay properties are presented in Section 3. In Section 4 the preliminary observation of structures in the $J/\psi \phi$ mass spectrum of the exclusive $B^+ \rightarrow J/\psi \phi K^+$ decay, is reported.

2. CMS detector
The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A two-level trigger system selects relevant pp collision events for offline reconstruction. The first level (L1) of the CMS trigger system is composed of custom hardware processors. The L1 trigger conditions are adjusted such as to limit the trigger rate to less than 100 kHz. The high-level trigger (HLT)
runs on a processor farm to further reduce the rate to a few 100 Hz before data storage. A more detailed description can be found in Ref. [2].

3. X(3872) production cross-section measurements
The X(3872) was discovered by the Belle experiment in 2003 [3]. Despite a series of detailed studies at B-factories and Tevatron performed, the nature of the X(3872) still remains unknown. Quantitative predictions have been calculated for the differential production cross section of the X(3872) in pp collisions at the Tevatron and pp collisions at the Large Hadron Collider (LHC) [4]. Measurement of the prompt production rate at the LHC as a function of transverse momentum provides a test of the NRQCD factorization approach to X(3872) production.

In this section the production of the X(3872) is studied in pp collisions at \( \sqrt{s} = 7 \) TeV, using the data recorded by the CMS experiment corresponding to an integrated luminosity of 4.8 fb\(^{-1}\). The event selection is discussed in Section 3.1. The cross section measurement proceeds by determining the ratio of the X(3872) and \( \psi(4.8) \) fb using the data recorded by the CMS experiment corresponding to an integrated luminosity of 4.8 fb\(^{-1}\), as described in Section 3.2. The fraction of nonpromptly produced X(3872) states is also reported in Section 3.3. In Section 3.4 the cross section for prompt X(3872) production is presented. Finally, Section 3.5 gives the measurement of the prompt production rate at the LHC as a function of transverse momentum.

3.1. Event selection
The X(3872) is observed using the decays into \( J/\psi \pi^+ \pi^- \), with the subsequent decay of the \( J/\psi \) into a pair of muons. The data are collected with requirements on the dimuon system imposed at the trigger level (HLT) such as rapidity within 1.25 and transverse momentum threshold initially 6.9 GeV, which was increased to 9.9 GeV near the end of data taking. The \( J/\psi \pi^+ \pi^- \) system is reconstructed by combining the candidate muon tracks from each candidate \( J/\psi \) with pairs of oppositely charged tracks, which are assumed to be pions. Each \( \mu^+ \mu^- \pi^+ \pi^- \) combination is refitted, constraining the four tracks to come from a common vertex and the muon-pair invariant mass to the \( J/\psi \) mass [5]. The event selection is described in detail in Ref. [6]. The analysis is performed in the kinematic range of \( p_T \) of the \( J/\psi \pi^+ \pi^- \) system between 10 and 50 GeV and the rapidity within \( |y| < 1.2 \). Detailed event simulations are used to determine acceptances and efficiencies. Events containing X(3872) or \( \psi(2S) \) states are generated using PYTHIA [7], and decayed using EVTGEN [8], with the signal resonances forced to decay into the \( J/\psi \pi^+ \pi^- \) final state, as described in Ref. [6].

3.2. Measurement of the cross section ratio
The ratio of the cross section times the \( J/\psi \pi^+ \pi^- \) branching fraction is obtained from the measured numbers of signal events for X(3872) and \( \psi(2S) \), \( N_{X(3872)} \) and \( N_{\psi(2S)} \), correcting for the efficiency (\( \epsilon \)) and acceptance (\( A \)) estimated from simulations, according to

\[
R = \frac{\sigma(pp \rightarrow X(3872) + \text{anything}) \cdot B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \cdot B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \epsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \epsilon_{X(3872)}}
\]

The signal yields, \( N_{X(3872)} \) and \( N_{\psi(2S)} \), are determined from unbinned maximum-likelihood fits to the invariant-mass spectra of the \( J/\psi \pi^+ \pi^- \) system, separately for the X(3872) and \( \psi(2S) \), in the mass windows 3.75–4 GeV and 3.6–3.8 GeV, respectively. In the fits, the \( \psi(2S) \) resonance shape is parametrized using two Gaussian functions with a common mean, while a single Gaussian is used for the X(3872) signal. The nonresonant background is fitted with a second-order Chebyshev polynomial. The acceptances and efficiencies of the X(3872) and \( \psi(2S) \) final states are determined from the simulation. Studies are performed to verify the description of the data by the simulations and to determine the systematic uncertainties. A total systematic
uncertainty of 5-13% on $R$ is obtained, as described in Ref. [6]. The main systematic uncertainty is the dependence of the measurement on the $p_T$ spectrum of the X(3872). The rapidly changing acceptance as a function of transverse momentum makes the $R$ measurement very sensitive to the $p_T$ spectrum, in particular for low transverse momentum and for the $p_T$-integrated result. The acceptance determination depends also on X(3872) quantum numbers and polarization. The results are obtained under the assumption that the X(3872) quantum numbers are $J^{PC} = 1^{++}$, as favoured by existing data [1], and that both X(3872) and $\psi(2S)$ states are unpolarized. No systematic uncertainty is assigned to cover other cases.

The cross section ratio is determined in the rapidity region $|y| < 1.2$ as a function of the transverse momentum of the $J/\psi\pi^+\pi^-$ system as shown in Fig. 1(left). The results are also listed in Table 1. No significant dependence on transverse momentum is observed.

3.3. Measurement of the nonprompt fraction

The relative contribution to the total X(3872) yield resulting from decays of B hadrons, often referred to as the nonprompt fraction, is determined from the decay lifetime distribution. The “pseudo-proper” decay length $\ell_{xy}$ is defined in the plane transverse to the beam direction as the distance between the vertex formed by the four tracks of the $J/\psi\pi^+\pi^-$ system and the closest reconstructed primary vertex along the beam direction, corrected by the transverse Lorentz boost of the $J/\psi\pi^+\pi^-$ candidate. An event sample enriched in X(3872) candidates from B decays is selected by requiring that $\ell_{xy}$ be larger than 100 $\mu$m. The nonprompt fraction is then obtained from the ratio between the signal yields in this B-hadron-enriched sample and the signal yields in the inclusive sample, after correction for the efficiencies of the decay-length-selection criteria, as determined from simulations of prompt and nonprompt X(3872) states. The signal yields are extracted from fits to the $J/\psi\pi^+\pi^-$ invariant-mass spectrum, as described in Section 3.2. In the fits to the B-hadron-enriched sample, the fit parameters for the mass and width are fixed to those determined from the full sample.

Detailed studies are performed to verify the stability of the results and to determine the systematic uncertainties, as described in Ref. [6]. The measurement is dominated by its statistical uncertainty. A total systematic uncertainty of 6-10% is obtained.

The results are listed in Table 1 and shown in Fig. 1(right) as a function of $p_T$. The X(3872) nonprompt fraction reveals no significant dependence on transverse momentum and the integrated value is significantly smaller than that for the $\psi(2S)$ [9]. The results are obtained ignoring effects related to the X(3872) polarization and no systematic uncertainty is assigned for polarization effects.

Table 1. The ratio $R$ between the X(3872) and $\psi(2S)$ cross sections times branching fraction and the X(3872) nonprompt fractions, as a function of $p_T$, for the rapidity range $|y| < 1.2$. The uncertainties shown are statistical and systematic, respectively.

| $p_T$(GeV) | $R$ | X(3872) nonprompt fraction |
|-----------|-----|--------------------------|
| 10–13.5   | 0.0727 ± 0.0079 ± 0.0097 | 0.272 ± 0.057 ± 0.016 |
| 13.5–15   | 0.0671 ± 0.0072 ± 0.0044 | 0.182 ± 0.052 ± 0.013 |
| 15–18     | 0.0687 ± 0.0055 ± 0.0051 | 0.246 ± 0.043 ± 0.015 |
| 18–30     | 0.0601 ± 0.0042 ± 0.0042 | 0.297 ± 0.042 ± 0.021 |
| 30–50     | 0.078 ± 0.013 ± 0.004  | 0.301 ± 0.097 ± 0.030 |
| 10–50     | 0.0656 ± 0.0029 ± 0.0065 | 0.263 ± 0.023 ± 0.016 |
3.4. Determination of the prompt X(3872) production cross section

The cross section times branching fraction for prompt X(3872) production is determined from the measurement of the cross section ratio $R$ and the nonprompt fraction, described above in Section 3.2 and 3.3, respectively, combined with a previous result of the prompt $\psi(2S)$ cross section [9]. The latter measurement was performed using the $\psi(2S) \rightarrow \mu^+\mu^-$ decay mode and provides results as a function of transverse momentum up to 30 GeV and for the rapidity range $|y| < 1.2$. In the calculation, the branching fraction $B(\psi(2S) \rightarrow J/\psi \pi^+\pi^-)$ is taken from Ref. [5], and $B(\psi(2S) \rightarrow \mu^+\mu^-)$ is taken to be equal to the more precisely known $B(\psi(2S) \rightarrow e^+e^-)$ [5]. No cancellation of systematic uncertainties is assumed in the combination. The main sources of systematic uncertainty are related to the measurement of the ratio $R$ and the background lifetime fit in the measurement of the prompt $\psi(2S)$ cross section [9]. The differential cross section for prompt X(3872) production times the branching fraction as a function of $p_T$, in the rapidity region $|y| < 1.2$, is listed in Table 2.

A calculation of the predicted differential cross section for prompt X(3872) production in pp collisions at $\sqrt{s} = 7$ TeV has been made using the NRQCD factorization formalism, assuming the X(3872) is formed from a $c\bar{c}$ pair with negligible relative momentum [4]. This calculation is normalized using Tevatron measurements [10] with the statistical uncertainty obtained from the experimental input data. The predictions from Ref. [4] were modified by the authors to match the phase-space of the measurement presented in this note. Comparisons of this prediction with the data, in Fig. 2, demonstrates that, while the shape is reasonably well described, the predicted cross section is much larger than observed in data.

The integrated prompt X(3872) cross section times branching fraction for the kinematic region $10 < p_T < 30$ GeV and $|y| < 1.2$ is also determined to be

$$\sigma_{\text{prompt}}(pp \rightarrow X(3872)+\text{anything}) \cdot B(X(3872) \rightarrow J/\psi \pi^+\pi^-) = 1.06\pm0.11(\text{stat.})\pm0.15(\text{syst.}) \text{ nb}.$$ (2)

This result assumes that the X(3872) and $\psi(2S)$ states are unpolarized. The NRQCD prediction for the prompt X(3872) cross section times branching fraction in the kinematic region of this analysis is $4.01 \pm 0.88 \text{ nb}$ [4], significantly above the measured value.
Figure 2. Measured differential cross section for prompt X(3872) production times branching fraction $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ (B) as a function of $p_T$. The inner error bars indicate the statistical uncertainty and the outer error bars represent the total uncertainty. The data points are placed where the value of the theoretical prediction is equal to its mean value over each bin, according to the prescription in Ref. [11].

Table 2. Prompt X(3872) differential cross section times branching fraction $B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ as a function of $p_T$. The uncertainties shown are statistical and systematic, respectively.

| $p_T$(GeV) | $d\sigma_{X(3872)}^{prompt}/dp_T \cdot B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)$ (nb/GeV) |
|------------|------------------------------------------------------------------------------------------------------------------|
| 10–13.5    | 0.211 ± 0.034 ± 0.035                                                                                          |
| 13.5–15    | 0.081 ± 0.013 ± 0.010                                                                                          |
| 15–18      | 0.0390 ± 0.0054 ± 0.0042                                                                                        |
| 18–30      | 0.0068 ± 0.0009 ± 0.0009                                                                                        |

3.5. Measurement of the $\pi^+ \pi^-$ invariant-mass distribution

The decay properties of the X(3872) are further investigated with a measurement of the $\pi^+ \pi^-$ invariant-mass distribution from X(3872) decays to $J/\psi \pi^+ \pi^-$, within the kinematic range $10 < p_T < 50$ GeV and $|y| < 1.25$. To extract the dipion invariant-mass spectrum from X(3872) decays, the event sample is divided into twelve intervals of dipion invariant mass in the range $0.5 < m(\pi^+ \pi^-) < 0.78$ GeV. In each interval, a maximum-likelihood fit to the $J/\psi \pi^+ \pi^-$ invariant-mass distribution is performed, where the signal is modelled with a single Gaussian. The position and width of the X(3872) signal are fixed to the values obtained in the fit to the full sample, except for the last interval, 0.765–0.78 GeV, where the mean and width of the Gaussian are left free to accommodate possible distortions of the signal shape near the upper kinematic limit. The X(3872) dipion invariant-mass distribution is extracted from the signal yields obtained from the fits to the data in each interval, after correction for detector acceptance and efficiencies, as estimated from the simulation. The systematic uncertainties on the signal extraction and on correction due to acceptance and efficiency are estimated, yielding to variations of 10-20% and 4-6%, respectively.

The resulting dipion invariant-mass spectrum, normalized to the total cross section in the interval $0.5 < m(\pi^+ \pi^-) < 0.78$ GeV, is presented in Fig. 3. The data are compared to X(3872) signal simulations with and without an intermediate $\rho^0$ in the $J/\psi \pi^+ \pi^-$ decay. The assumption of an intermediate $\rho^0$ decay gives better agreement with the data, confirming previous measurements [12, 13].
4. Structures in the $J/\psi\phi$ mass spectrum of the exclusive $B^+ \rightarrow J/\psi\phi K^+$ decay

The CDF collaboration has reported an evidence for a narrow structure, called $Y(4140)$, near the $J/\psi\phi$ threshold in the exclusive $B^+ \rightarrow J/\psi\phi K^+$ decay [14]. Recently, the LHCb collaboration reported a result in conflict with that of CDF using the same exclusive $B^+ \rightarrow J/\psi\phi K^+$ decays [15].

In CMS the study of the $J/\psi\phi$ mass spectrum from the $B^\pm \rightarrow J/\psi\phi K^\pm$ decays (when a decay mode is referenced, its charge conjugate is implied) is performed using an integrated luminosity of 5.2 fb$^{-1}$. The $\mu^+\mu^-$ channel is used to reconstruct $J/\psi$ candidates that are selected by the HLT dimuon trigger. $B^\pm \rightarrow J/\psi\phi K^\pm$ candidates are reconstructed by combining three additional charged tracks pointing to the displaced $J/\psi$ vertex with a total charge of $\pm1$ and with kaon mass assigned (kaon track). The $p_T$ of the kaon tracks is required to be greater than 1 GeV. The five tracks, with $\mu^+\mu^-$ mass constrained to the $J/\psi$ nominal value, are required to form a good 3D vertex with $\chi^2$ probability greater than 1%. The reconstructed mass of the $K^+K^-$ pair with the lower mass must satisfy $1.008 < m(K^+K^-) < 1.035$ GeV to be considered as a $\phi$ candidate. These selection requirements, which were designed to maximize the signal yield, were determined before the $J/\psi\phi$ mass spectrum was examined.

In order to search for possible structures in the $J/\psi\phi$ mass spectrum, the $J/\psi\phi K^+$ candidates are divided into bins of the mass difference, $\Delta M \equiv m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$, and the $J/\psi\phi K^+$ mass distributions are fit to extract the B signal yield for each $\Delta M$ bin. A polynomial function is used for the combinatorial background and a double Gaussian for the B signal. The mean values of the two Gaussians are fixed to the nominal B mass, and the width values of the Gaussians, as well as their relative ratio are fixed to the values obtained from simulation.

The $\Delta M$ distribution is corrected for relative efficiency, estimated from simulation. The relative-efficiency-corrected $\Delta M$ distribution from the exclusive $B^+ \rightarrow J/\psi\phi K^+$ signal is shown in Fig. 4. The nonresonant decay of a real or quasi-particle state into three objects ($B^+ \rightarrow J/\psi\phi K^+$) can be described by a three-body phase space model. The $\Delta M$ continuum shape is also investigated with an event-mixing technique by applying the same kinematic constraint to $J/\psi$, $\phi$, and $K^+$ each chosen from a different event. The three-body phase space background lies above the event-mixed background in all $\Delta M$ bins in the range of interest, as shown in Fig. 4(left). There are enhancements, relative to the phase-space continuum, at the $J/\psi\phi$ mass threshold and around $\Delta M = 1.2$ GeV. The observed structures, as shown in Fig. 4 (right), are modelled with S-wave relativistic Breit-Wigner functions convoluted with a Gaussian resolution function whose width is fixed to values obtained from simulation.

Various checks have been done to validate the robustness of the two structures. Each selection valid.
requirement has been varied. The analysis was repeated with tighter selection criteria that lowered the combinatorial background level by a factor of ten and retained 40% of the B signal events. The relative efficiencies for the first five bins are varied to confirm the robustness of the significance of the first structure. The sPlot formalism [16] projected to the ΔM distribution from the fit to the \( J/\psi \phi K^+ \) mass distribution is used to compare to the ΔM distribution obtained from previous fits to each ΔM bin. This is a background-subtraction technique by weighting each event based on the observed signal to background ratio. From these checks no indication of a possible bias is found.

Interpreting the two structures as \( J/\psi \phi \) resonances with S-wave relativistic Breit-Wigner line shapes over a three-body phase-space nonresonant component, a significance exceeding 5-sigma for the first structure is obtained. The fitted mass of the first structure is \( m = 4148.2 \pm 2.0(\text{stat.}) \pm 4.6(\text{sys.}) \) MeV. This observation is consistent with a previous evidence for a narrow structure near \( J/\psi \phi \) threshold by the CDF Collaboration [14]. There is evidence for a second structure with fitted mass \( m = 4316.7 \pm 3.0(\text{stat.}) \pm 7.3(\text{sys.}) \) MeV.

5. Summary
The studies in the “exotic” quarkonium sector performed using large data samples of dimuon events in pp collisions at \( \sqrt{s} = 7\text{TeV} \) by the CMS experiment are summarised in this note.

The production of the \( X(3872) \) is studied measuring the ratio of the \( X(3872) \) and \( \psi(2S) \) cross sections times their branching fractions into \( J/\psi \pi^+ \pi^- \) as a function of transverse momentum \( (p_T) \). The fraction of \( X(3872) \) originating from B-hadron decays is \( 0.263 \pm 0.023(\text{stat.}) \pm 0.016(\text{sys.}) \). No significant dependence on \( p_T \) is found. From these measurements, the cross section for prompt \( X(3872) \) production times branching fraction into \( J/\psi \pi^+ \pi^- \) has been extracted for the first time as a function of \( p_T \). A value of \( \sigma^{\text{prompt}}(pp \rightarrow X(3872) + \text{anything}) \cdot B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = 1.06 \pm 0.11(\text{stat.}) \pm 0.15(\text{sys.}) \) nb is found for the kinematic range \( 10 < p_T < 30 \text{ GeV} \) and \( |y| < 1.2 \). This result is made under the assumption that the \( X(3872) \) and \( \psi(2S) \) states are unpolarized. The NRQCD predictions for prompt \( X(3872) \) production at the LHC significantly exceed the measured value, while the \( p_T \) dependence is reasonably well described. The measured dipion mass spectrum for \( X(3872) \rightarrow J/\psi \pi^+ \pi^- \) clearly favours the presence of an intermediate \( \rho^0 \) state.

Using the large \( B^+ \rightarrow J/\psi \phi K^+ \) sample collected by CMS preliminary results on observation of structures in the \( J/\psi \) mass spectrum are reported. A structure near \( J/\psi \phi \) threshold is observed,
consistent with a previous evidence by the CDF Collaboration, and there is evidence for a second structure around 4317 MeV.

Acknowledgments
We would like to thank Pierre Artoisenet and Eric Braaten for modifying their theoretical predictions [4] to match the phase-space of our measurement.

References
[1] Brambilla N et al 2011 Heavy quarkonium: progress, puzzles, and opportunities Eur. Phys. J. C 71 1534
[2] CMS Collaboration 2008 The CMS experiment at the CERN LHC JINST 3 S08004
[3] Belle Collaboration 2003 Observation of a new narrow charmonium state in exclusive $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}\psi$ decays Phys. Rev. Lett. 91 262001
[4] Artoisenet P and Braaten E 2010 Production of the X(3872) at the Tevatron and the LHC Phys. Rev. D 81 114018
[5] Particle Data Group 2012 Review of Particle Physics Phys. Rev. B 86 010001
[6] CMS Collaboration 2013 Measurement of the X(3872) production cross section via decays to $J/\psi\pi^{+}\pi^{-}$ in pp collisions at $\sqrt{s} = 7$ TeV Preprint arXiv:1302.3968
[7] Sjöstrand T, Mrenna S and Skands P Z 2006 PYTHIA 6.4 physics and manual JHEP 05 026
[8] Lange D J 2001 The EvtGen particle decay simulation package Nucl. Instrum. Meth. A 462 152
[9] CMS Collaboration 2012 $J/\psi$ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV JHEP 02 011
[10] CDF Collaboration 2005 The X(3872) at CDF II Int. J. Mod. Phys. A 20 3765
[11] Lafferty G D and Wyatt T R 1995 Nucl. Instrum. Meth. A 355 541
[12] CDF Collaboration 2006 measurement of the dipion mass spectrum in X(3872) → $J/\psi\pi^{+}\pi^{-}$ decays Phys. Rev. Lett. 96102002
[13] Belle Collaboration 2011 Bounds on the width, mass difference and other properties of X(3872) decays Phys. Rev. D 84 052004
[14] CDF Collaboration 2009 Evidence for a narrow near-threshold structure in the $J/\psi\phi$ mass spectrum in $B^{+} \rightarrow J/\psi\phi K^{+}$ decays Phys. Rev. Lett. 102 242002
[15] LHCb Collaboration 2012 Search for the X(4140) state in $B^{+} \rightarrow J/\psi\phi K^{+}$ decays Phys. Rev. D 85 091103
[16] Pivk M and LeDiberder F R 2005 SPlot: A statistical tool to unfold data distributions Nucl. Instrum. Meth. A 555 356