Available on CMS information server

CMS CR -2024/316

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

17 November 2024 (v4, 26 November 2024)

Searches for new physics in rare decays of heavy flavors at CMS

Sergey Polikarpov for the CMS Collaboration

Abstract

As direct searches for beyond the Standard model physics at the LHC have not been successful, more and more attention is drawn to the indirect searches. In particular, rare decays of beauty and charm hadrons present a sensitive laboratory for BSM physics and new particles, since they can contribute in loop diagrams, even if their mass is much heavier than that of the final-state particles. In this report, several recent results of the CMS collaboration on rare processes with heavy flavor mesons are discussed. The results are based on pp collision data collected at a centre-of-mass energies of 13 and 13.6 TeV.

Presented at *ICPPA-2024 7th International Conference on Particle Physics and Astrophysics*

SEARCHES FOR NEW PHYSICS IN RARE DECAYS OF HEAVY FLAVORS AT CMS

© 2022 S. M. Polikarpov [1,2*] on behalf of the CMS collaboration

[1] Lebedev Physics Institute of the Russian Academy of Science, Moscow, Russia
[2]Moscow Institute of Physics and Technology (MIPT), Moscow, Russia
* E-mail: spolikar@cern.ch

As direct searches for beyond the Standard model physics at the LHC have not been successful, more and more attention is drawn to the indirect searches. In particular, rare decays of beauty and charm hadrons present a sensitive laboratory for BSM physics and new particles, since they can contribute in loop diagrams, even if their mass is much heavier than that of the final-state particles. In this report, several recent results of the CMS collaboration on rare processes with heavy flavor mesons are discussed. The results are based on pp collision data collected at a centre-of-mass energies of 13 and 13.6 TeV.

1. INTRODUCTION

Rare decays of heavy-flavour hadrons are known to be sensitive to new particles or interactions beyond the Standard model (SM) that can contribute in loop diagrams. In the last 15 years, beauty hadron decays proceeding through b→sll transition have been of particular interest since precision measurements of their differential branching fractions and parameters of angular distributions became possible with the large data samples collected by experiments at the Large Hadron Collider.

A number of deviations between the measurement and the Standard model prediction at the level of 3-4 standard deviations have been observed in b→sll decays, including:

- Differential branching fraction of the $B^+ \to K^+\mu^+\mu^-$ decay in low-q^2 region (here and in the following, q is the dilepton mass) [1],
- Differential branching fraction of the $B^+ \to K^{*+}\mu^+\mu^-$ decay [1],
- Differential branching fraction of the $B^0 \to K^0\mu^+\mu^-$ decay [1],
- Differential branching fraction of the $B^0_s \to \varphi\mu^+\mu^-$ [2] in low q^2 region was found to be 3.6σ below the prediction,
- Parameter of angular distributions P_5' in the $B^0 \to K^{*0}\mu^+\mu^-$ [3] and $B^+ \to K^{*+}\mu^+\mu^-$ [4] decays in low q^2 region.

Moreover, several ratios of branching fractions between decays involving muons and electrons have been measured, and compared to the SM prediction, which is very close to unity, thanks to Lepton Flavor Universality (LFU) of the SM. A few measurements by the LHCb collaboration were showing a consistent deviation from the predictions [5-6]. However, later the LHCb collaboration reported improved analyses of data with the updated results being consistent with the SM expectations [7].

The discussed deviations in rare decays of heavy flavours, together with few other ones, have been collectively called "flavour anomalies" and are a subject of intense discussions over the last years. Therefore, new measurements of decays proceeding through $b \to sll$ and other flavour-changing neutral-current transitions are very important to complement the flavor anomalies picture. The present report discusses several recent results on these topics from the CMS experiment at the LHC [8,9], which is a general-purpose experiment, not initially optimized for flavour physics.

2. ANGULAR ANALYSIS OF THE $B^0 \to K^{*0}\mu^+\mu^-$ DECAY

The CMS experiment has performed an angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay, where $K^{*0} \to K^+\pi^-$, using the data collected in 13 TeV pp collisions between 2016 and 2018. The events are selected using a Boosted Decision Tree (BDT) with 8 input variables describing the reconstructed candidate's kinematics and topology. The BDT was trained to discriminate between signal (from simulations) and background (from data sidebands); dedicated selections using mass vetoes are applied to suppress peaking backgrounds from other B meson decays.

The 8 parameters of interest, defined in Ref. [10], are extracted, in each q^2 bin, using a four-dimensional unbinned maximum-likelihood fit to the distributions of $K^{*0}\mu^+\mu^-$ candidate invariant mass and the three decay angles. The fit setup accounts for the reconstruction efficiency and for the fraction of candidates with kaon and pion swapped by the reconstruction. Projections of this fit for one of the q^2 ranges are shown in Figure 1.

The measured parameters are compared to the theoretical predictions in Figure 2, showing a reasonable agreement in most of the cases, except (most notably) P_5' observable, where the measured values are above the predictions in low-q^2 range. A very similar deviation trend was seen previously by the LHCb experiment [3], and the reported here CMS results are consistent with those by LHCb.

3. LEPTON FLAVOUR UNIVERSALITY IN THE $B^+ \to K^+ l^+ l^-$ DECAYS

In order to record a sample of b hadron decays with no muons in the final state, the CMS experiment has developed in 2018 a special so-called B-parking approach [11], recording about 10^{10} events containing pairs of b hadron decays, one of which ("tag") is semileptonic, and with no requirements on the decay of the second ("probe") b hadron. Due to high luminosity, it is extremely challenging at CMS to trigger on low-momentum hadrons or electrons produced in decays of beauty hadrons. The requirements on the tagging muon were gradually lowered during each LHC fill as the instantaneous luminosity was decreasing, in order to maximally utilize the available bandwidth.

The reconstruction of $B^+ \to K^+ e^+ e^-$ decays is performed using probe-side hadrons, while the $B^+ \to K^+ \mu^+ \mu^-$ decays are reconstructed on the tag side, requiring that one of the muons fired the trigger, to increase the signal yield. A dedicated BDT was developed for low-momentum electrons in order to reconstruct them, correct their energy, and filter out background. Two event categories are used for electron channel, one called PF-PF with two electrons reconstructed by the standard algorithm, and the other one, called "PF-LP", with one of the electrons reconstructed with the new dedicated low-momentum algorithm. The decays with known charmonium resonances J/ψ and $\psi(2S)$ are used as control channels.

The measured invariant mass distributions of the $B^+ \to K^+ e^+ e^-$ candidates are shown in Figure 3 together with the results of an unbinned fit. The extracted number of signal events 17.9±7.2 (PF-PF) and 3.0±5.9 (PF-LP) are much lower than the $B^+ \to K^+ \mu^+ \mu^-$ yield of about 1250 signal [12], which limits the precision of the ratio measurement.

The measured "LFU test" ratio $B(B^+ \to K^+ \mu^+ \mu^-)/B(B^+ \to K^+ e^+ e^-) = 0.78^{+0.47}_{-0.23}$ [12] is consistent with unity and with the previous measurements by LHCb [5, 7], Belle and BaBaR collaborations, as well as with the SM prediction of 1. New triggers have been designed and operated during

Run 3 of the LHC that will allow to significantly improve the precision of this and similar measurements at CMS.

4. SEARCH FOR THE $D^0 \to \mu^+\mu^-$ DECAY

Flavour-changing neutral-current transition $c \to u$ have not yet been thoroughly studied by experiments, unlike the $b \to s$ transitions discussed above. Because loop contributions in charm decays are mediated by lighter quarks, the theoretical predictions for charm decays are less reliable. Nevertheless, it is important to study these transitions, since significant deviations from the SM predictions can still point to contributions from new physics.

One of the first analyses with Run-3 data by the CMS experiment is the search for the rare decay $D^0 \to \mu^+\mu^-$, with the SM branching fraction as low as about $3 \cdot 10^{-13}$. In order to increase CMS physics potential, the dimuon triggers in Run-3 were made less restrictive than they were during Run-2 of the LHC, which significantly improved the CMS efficiency to decays like $D^0 \to \mu^+\mu^-$. In order to suppress backgrounds, D^0 candidates are searched for in the products of a well-known $D^{*+} \to D^0\pi^+$ decay, thanks to its near-zero energy release. BDT is used to suppress backgrounds and the $D^0 \to \pi^+\pi^-$ decay is used for the normalization of branching fraction and calibration of the BDT. The signal yields were extracted using a two-dimensional unbinned fits to the distributions of D^0 candidate invariant mass and Δm, the mass difference between D^{*+} and D^0 candidates; projections of this fit in the signal channel are shown in Figure 4 [13]. The fit accounts for various backgrounds from semileptonic and cascade decays of D^0 meson.

No significant signal is observed, and an upper limit of $2.6 \cdot 10^{-9}$ at 90% C.L. is set on the branching fraction of the $D^0 \to \mu^+\mu^-$ decay, which is the strongest limit at the moment of writing.

5. CONCLUSIONS

The CMS experiment at the LHC, not specifically designed for heavy flavour physics, is making a significant contribution to the studies of rare decays of charm and beauty mesons that are sensitive to new physics. The recent CMS results include the angular analysis of the

$B^0 \to K^{*0}\mu^+\mu^-$ decay, with the results confirming a discrepancy in P_5' parameter between the measurements and predictions; the measurement of R_K ratio in $B^+ \to K^+ l^+ l^-$ decays; and world-best upper limit on the branching fraction of the heavily suppressed $D^0 \to \mu^+\mu^-$ decay. The results are obtained using 13 TeV (LHC Run 2) and 13.6 TeV (part of LHC Run 3) pp collision data.

6. ACKNOWLEDGMENTS

The author would like to thank ICPPA 2024 conference organizers for an excellent conference. The author acknowledges the support by the Russian Science Foundation under contract 23-12-00083.

REFERENCES

1. R. Aaij *et al.* [LHCb Collaboration], "Differential branching fractions and isospin asymmetries of $B \to K^{(*)} \mu^+\mu^-$ decays", JHEP **06**, 133 (2014), doi:10.1007/JHEP06(2014)133 [arXiv:1403.8044 [hep-ex]].

2. R. Aaij *et al.* [LHCb Collaboration], "Branching Fraction Measurements of the Rare $B_s^0 \to \varphi\mu^+\mu^-$ and $B_s^0 \to f_2'(1525)\, \mu^+\mu^-$ Decays", Phys. Rev. Lett. **127**, no.15, 151801 (2021), doi:10.1103/PhysRevLett.127.151801 [arXiv:2105.14007 [hep-ex]].

3. R. Aaij *et al.* [LHCb Collaboration], "Measurement of CP-Averaged Observables in the $B^0 \to K^{*0}\mu^+\mu^-$ Decay", Phys. Rev. Lett. **125**, no.1, 011802 (2020), doi:10.1103/PhysRevLett.125.011802 [arXiv:2003.04831 [hep-ex]].

4. R. Aaij *et al.* [LHCb Collaboration], "Angular Analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ Decay", Phys. Rev. Lett. **126**, no.16, 161802 (2021), doi:10.1103/PhysRevLett.126.161802 [arXiv:2012.13241 [hep-ex]]

5. R. Aaij *et al.* [LHCb Collaboration], "Test of lepton universality using $B^+ \to K^+l^+l^-$ decays", Phys. Rev. Lett. **113**, 151601 (2014), doi:10.1103/PhysRevLett.113.151601 [arXiv:1406.6482 [hep-ex]].

6. R. Aaij *et al.* [LHCb Collaboration], "Test of lepton universality with $B^0 \to K^{*0+}l^+l^-$ decays", JHEP **08**, 055 (2017), doi:10.1007/JHEP08(2017)055 [arXiv:1705.05802 [hep-ex]]

7. R. Aaij *et al.* [LHCb Collaboration], "Measurement of lepton universality parameters in $B^+ \to K^+l^+l^-$ and $B^0 \to K^{*0+}l^+l^-$ decays", Phys. Rev. D **108** no.3, 032002 (2023), doi:10.1103/PhysRevD.108.032002 [arXiv:2212.09153 [hep-ex]]

8. CMS Collaboration, "The CMS experiment at the CERN LHC", JINST **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

9. CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", JINST **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064

10. CMS Collaboration, “Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay at $\sqrt{s}$ = 13 TeV”, CMS-PAS-BPH-21-002, https://cds.cern.ch/record/2899589.

11. CMS Collaboration, “Enriching the Physics Program of the CMS Experiment via Data Scouting and Data Parking”, arXiv:2403.16134, CMS-EXO-23-007, *Accepted to Physics Reports*.

12. CMS Collaboration, “Test of lepton flavor universality in $B^\pm \to K^\pm\mu^+\mu^-$ and $B^\pm \to K^\pm e^+e^-$ decays in proton-proton collisions at $\sqrt{s}$ = 13 TeV”, Rept. Prog. Phys. **87**, no.7, 077802 (2024), doi:10.1088/1361-6633/ad4e65 [arXiv:2401.07090 [hep-ex]].

13. CMS Collaboration, “Search for Rare Charm Decays Into Two Muons”, CMS-PAS-BPH-23-008, https://cds.cern.ch/record/2905689.

FIGURE CAPTIONS

Fig. 1. Distributions of the $B^0 \to K^{*0}\mu^+\mu^-$ candidate invariant mass and decay angles with the fit projection overlaid, for q^2 range between 4.3 and 6 GeV [10].

Fig. 2. Measured optimized angular observables P_2, P_3, P'_4, and P'_5 in the $B^0 \to K^{*0}\mu^+\mu^-$ decay compared with the theoretical predictions [10].

Fig. 3. Invariant mass distribution of the selected $B^+ \to K^+e^+e^-$ candidates in the non-resonant channel (top), J/ψ control channel (middle), and ψ(2S) control channel (bottom) [12].

Fig. 4. Invariant mass distribution of the μμ (left) and Δm (right) [13]. The bottom panel shows the data and the fit result after subtraction of the total background component.

Figure 1.

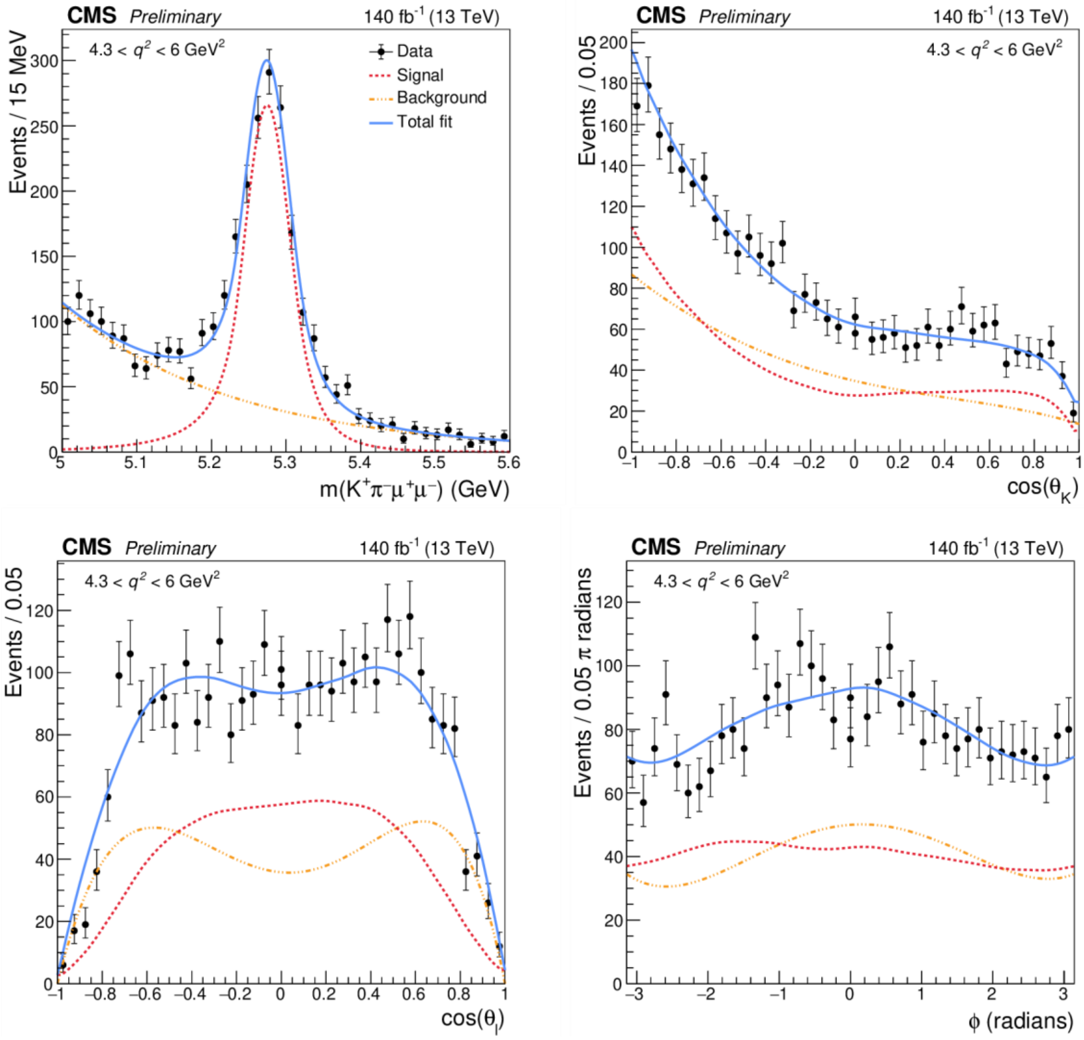

CMS Preliminary
140 fb-1 (13 TeV)
4.3 < q2 < 6 GeV2
Data
Signal
Background
Total fit
Events / 15 MeV
m(K+π−μ+μ−) (GeV)
Events / 0.05
cos(θK)
cos(θl)
Events / 0.05 π radians
ϕ (radians)

Figure 2

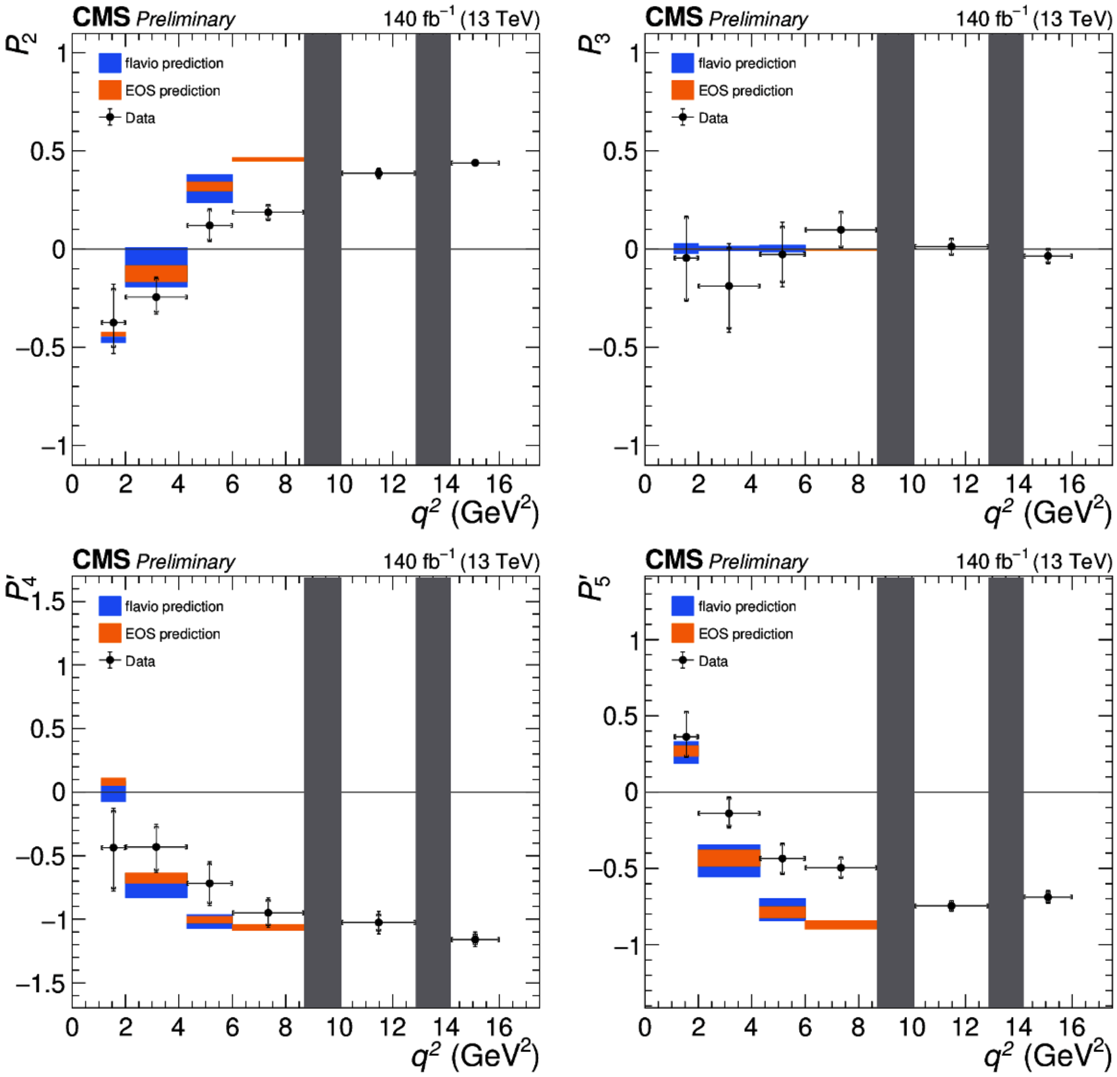

CMS Preliminary
140 fb⁻¹ (13 TeV)
P2
P3
P'4
P'5
flavio prediction
EOS prediction
Data
q² (GeV²)

Figure 3

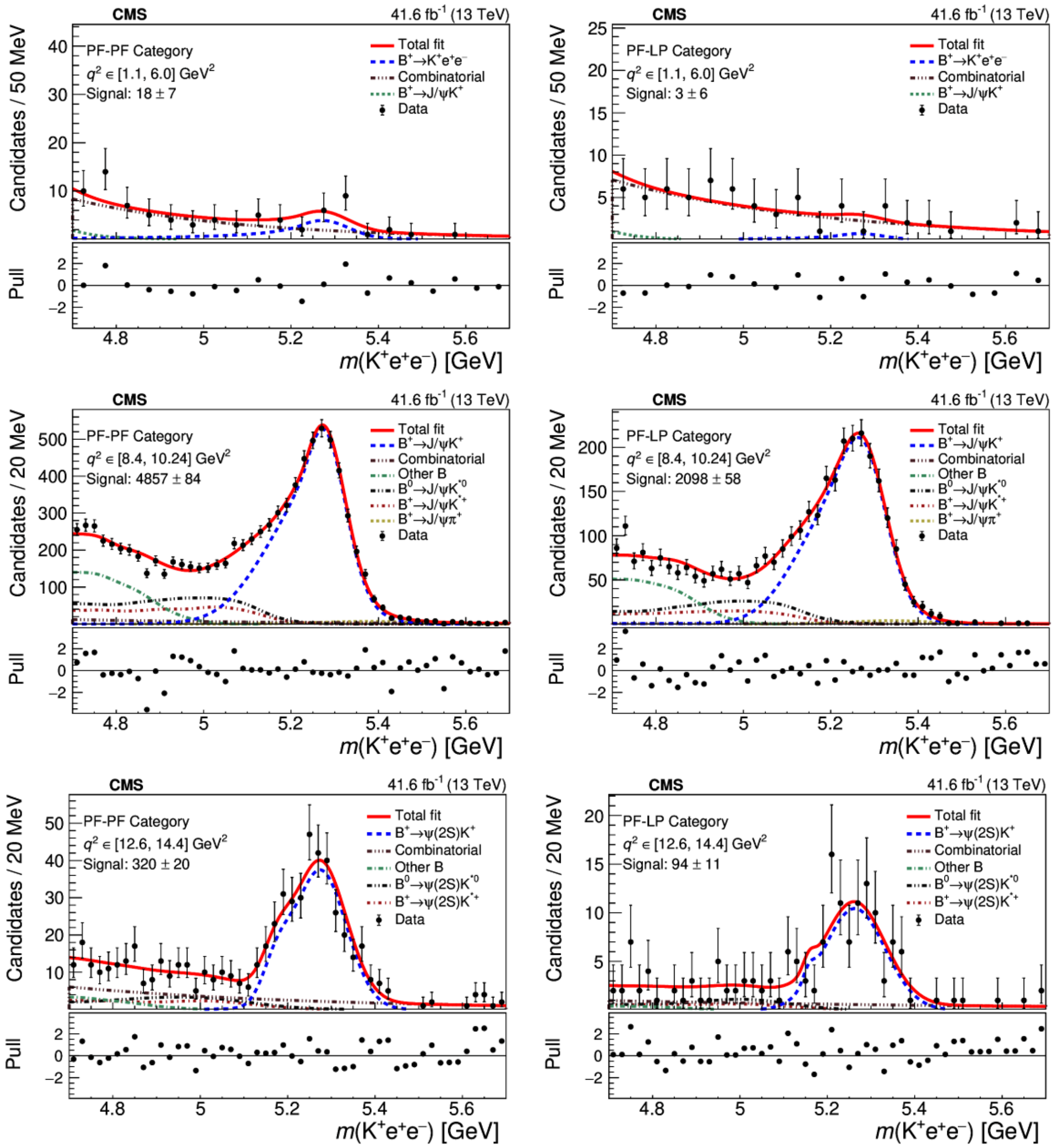
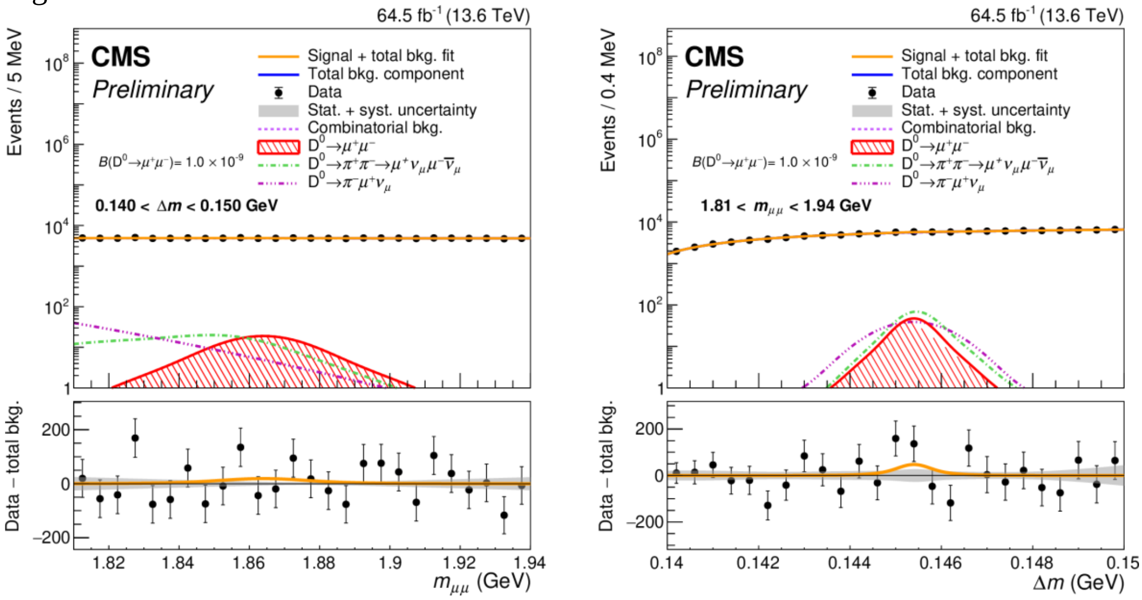

CMS
41.6 fb^{-1} (13 TeV)
PF-PF Category
$q^2 \in$ [1.1, 6.0] GeV^2
Signal: 18 ± 7
Total fit
$B^+ \to K^+e^+e^-$
Combinatorial
$B^+ \to J/\psi K^+$
Data
Candidates / 50 MeV
Pull
$m(K^+e^+e^-)$ [GeV]
CMS
41.6 fb^{-1} (13 TeV)
PF-LP Category
$q^2 \in$ [1.1, 6.0] GeV^2
Signal: 3 ± 6
Total fit
$B^+ \to K^+e^+e^-$
Combinatorial
$B^+ \to J/\psi K^+$
Data
Candidates / 50 MeV
Pull
$m(K^+e^+e^-)$ [GeV]
CMS
41.6 fb^{-1} (13 TeV)
PF-PF Category
$q^2 \in$ [8.4, 10.24] GeV^2
Signal: 4857 ± 84
Total fit
$B^+ \to J/\psi K^+$
Combinatorial
Other B
$B^0 \to J/\psi K^{*0}$
$B^+ \to J/\psi K^{*+}$
$B^+ \to J/\psi \pi^+$
Data
Candidates / 20 MeV
Pull
$m(K^+e^+e^-)$ [GeV]
CMS
41.6 fb^{-1} (13 TeV)
PF-LP Category
$q^2 \in$ [8.4, 10.24] GeV^2
Signal: 2098 ± 58
Total fit
$B^+ \to J/\psi K^+$
Combinatorial
Other B
$B^0 \to J/\psi K^{*0}$
$B^+ \to J/\psi K^{*+}$
$B^+ \to J/\psi \pi^+$
Data
Candidates / 20 MeV
Pull
$m(K^+e^+e^-)$ [GeV]
CMS
41.6 fb^{-1} (13 TeV)
PF-PF Category
$q^2 \in$ [12.6, 14.4] GeV^2
Signal: 320 ± 20
Total fit
$B^+ \to \psi(2S)K^+$
Combinatorial
Other B
$B^0 \to \psi(2S)K^{*0}$
$B^+ \to \psi(2S)K^{*+}$
Data
Candidates / 20 MeV
Pull
$m(K^+e^+e^-)$ [GeV]
CMS
41.6 fb^{-1} (13 TeV)
PF-LP Category
$q^2 \in$ [12.6, 14.4] GeV^2
Signal: 94 ± 11
Total fit
$B^+ \to \psi(2S)K^+$
Combinatorial
Other B
$B^0 \to \psi(2S)K^{*0}$
$B^+ \to \psi(2S)K^{*+}$
Data
Candidates / 20 MeV
Pull
$m(K^+e^+e^-)$ [GeV]

Figure 4



64.5 fb^{-1} (13.6 TeV)
CMS
Preliminary
Signal + total bkg. fit
Total bkg. component
Data
Stat. + syst. uncertainty
Combinatorial bkg.
$D^0 \to \mu^+\mu^-$
$D^0 \to \pi^+\pi^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$
$D^0 \to \pi^-\mu^+\nu_\mu$
$B(D^0 \to \mu^+\mu^-) = 1.0 \times 10^{-9}$
$0.140 < \Delta m < 0.150$ GeV
Events / 5 MeV
Data − total bkg.
$m_{\mu\mu}$ (GeV)
64.5 fb^{-1} (13.6 TeV)
CMS
Preliminary
$1.81 < m_{\mu\mu} < 1.94$ GeV
Events / 0.4 MeV
Data − total bkg.
Δm (GeV)