Validation of CMS open data in dimuon systems and first results from $D^{*\pm}$ reconstruction

Bridget J. Sheeran[a]

Supervised by: Achim Geiser[b] and Nazar Stefaniuk[b]

[a]University of Manchester, United Kingdom,

[b]Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

September 8, 2015

Abstract

The CMS Open Data project is successfully validated by reconstructing dimuon events produced by quarkonium decays and comparing the outcome to those published by the CMS Collaboration. The merits of the project are also demonstrated in the reconstruction of $D^{*\pm}$ and D^0 mesons, a result that has not previously been published by the CMS Collaboration. The resolution is improved over previous results and may lead to a measurement of the full production cross section.

Contents

1 Introduction

The Compact Muon Solenoid (CMS) Collaboration have released a substantial amount of data to the public as part of the CERN Open Data. This allows members of the public to access, view and analyse the data, with the main goals being research and education. As of writing, the CMS collaboration is the only LHC experiment to release original data sets in this manner.

This project aims to validate the 2010 data release by producing results for comparison with the published works of the CMS collaboration using similar data sets and seeks to explore the applications of CMS Open Data in producing new results.

2 The CMS detector

CMS is one of two general purpose detectors at the Large Hadron Collider (LHC), based at CERN in Geneva, Switzerland. The detector consists of a 6 m diameter superconducting solenoid and produces a 3.8 T magnetic field. Housed within the solenoid are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter and a scintillating brass hadronic calorimeter (Fig 1). The tracker encloses the pseudorapidity range $|\eta| < 2.5$, while the calorimeters extend this range to $|\eta| < 3.0$ [2]. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle measured anti-clockwise from the z axis in the beam direction.

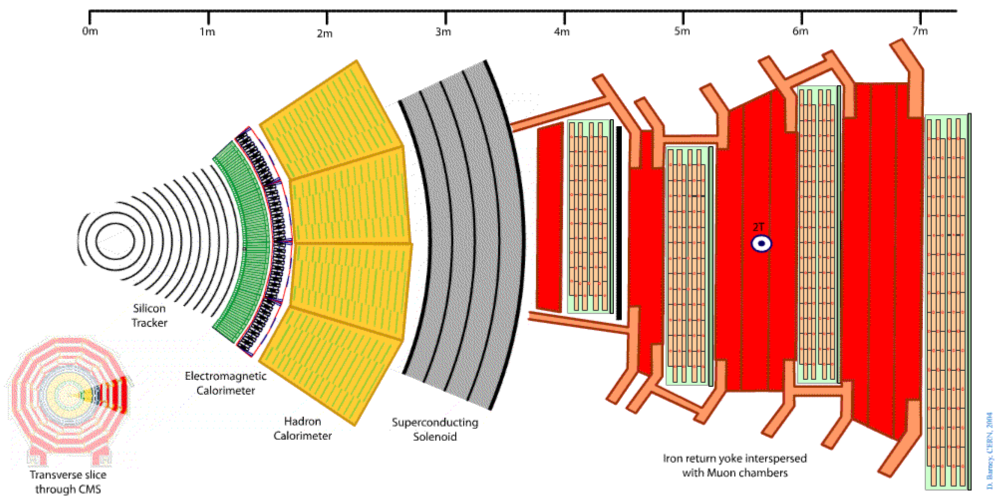

Figure 1: A transverse slice of the CMS detector. Source: CERN

The muon systems account for the remaining volume of the detector and are embedded in a steel return yoke. Three gas-ionisation detectors are present with drift tubes, cathode strip chambers and resistive plate chambers. Theses systems enclose the pseudorapidity region $|\eta| < 2.4$ [2].

2.1 The CMS Open Data release

The 2010 CMS Open Data (CMS-OD) release contains a total of 14 Primary data sets, of which two were used for the majority of these analyses. The first set was the 'MuOnia' data set which was triggered and selected for the presence of two or more muons and required only minimal energy [3]. This data set was used for the reconstruction of the quarkonium states J/ψ and Υ (§ 3) in a continuation of previous work by [4]. A sample of 4.9 million events was used for this analysis or approximately one sixth of the available dataset.

The second data set was the 'Minimum Bias' data set which was triggered and selected for the presence of low energy particles [5]. This was used for the reconstruction of D^* and D^0 mesons (§ 4), which used to demonstrate how new results may be obtained using CMS-OD. A total of 16 million events were used for this analysis or 40 % of the available dataset.

3 Validation using dimuon event reconstruction

J/ψ and Υ mesons were reconstructed via their decays to dimuon final states: J/$\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$ using pairs of oppositely charged muons (Fig. 2). This reconstruction will be used to validate CMS-OD by comparing the results of these reconstructions with those detailed in published works of the CMS collaboration [6] [7].

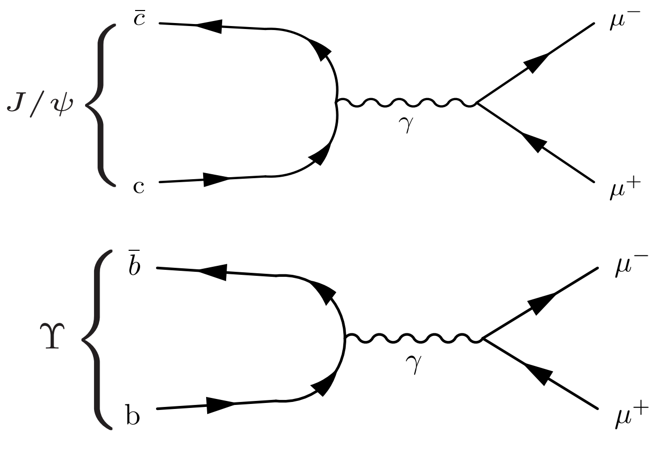

Figure 2: The electromagnetic decays of J/ψ and Υ mesons to $\mu^+\mu^-$ pairs.

In order to reject muons produced by the decays of kaons or pions, the muon pairs were required to pass certain quality criteria. For both reconstructions each muon track was required to have at least twelve hits in the silicon tracker, of which at least one must be in the pixel detector. Separate selection criteria were then applied in order to isolate the J/ψ and Υ candidates.

A correction was applied to the transverse momentum in both cases to account for the imperfect measurement of charged track momentum by the CMS detector. The reasons for this are multifold and include subdetector misalignments along with incomplete knowledge of the CMS magnetic field. This is parameterised by $p_T = (1 + a_1 + a_2\eta^2) \cdot p'_T$ where p'_T is the measured transverse momentum, $a_1 = (3.8 \pm 1.9) \cdot 10^{-4}$ and $a_2 = (3.0 \pm 0.7) \cdot 10^{-4}$.

3.1 J/ψ reconstruction and selection

The J/$\psi \to \mu^+\mu^-$ decay channel accounts for (5.96 ± 0.03) % of J/ψ decays [8]. To isolate these candidates the selection criteria obtained from [6] were implemented. Here each muon must have a reduced track $\chi^2 < 4$ and have its reference coordinates fall within a cylinder of diameter 6 cm and length 30 cm centred on the beamspot. Kinematic cuts were applied across three psuedorapidity regions, requiring that the muons satisfy either:

$$\begin{array}{lcccr} p_T^\mu & > & 3.3 \text{ GeV/c} & \text{if} & |\eta^\mu| < 1.3 \\ p^\mu & > & 2.9 \text{ GeV/c} & \text{if} & 1.3 < |\eta^\mu| < 2.2 \\ p_T^\mu & > & 2.4 \text{ GeV/c} & \text{if} & 2.2 < |\eta^\mu| < 2.4\ . \end{array}$$

Following these cuts the J/ψ candidates were produced by calculating the invariant mass of the dimuon system. The candidates were retained if this mass was between 2.6 and 3.5 GeV/c^2. These are shown in rapidity ranges of $|y^{J/\psi}| < 1.2$, $1.2 < |y^{J/\psi}| < 1.6$ and $1.6 < |y^{J/\psi}| < 2.4$ in Figure 3. The rapidity is defined as $y = \frac{1}{2} \ln \frac{E+p_{||}}{E-p_{||}}$ and E is the particle energy and $p_{||}$ the momentum parallel to the beam axis. These are fitted with a Crystal Ball function which is is a Gaussian Signal combined with a power law describing a radiative tail [9]. Figure 4 shows the dimuon invariant mass distribution obtained by the CMS collaboration in [6]. A good resemblance is seen between the two sets, with the standard deviation of the fits in Figure 3 being consistent with those in all but the $|y^{J/\psi}| < 1.2$ range of Figure 4.

In addition to the invariant mass, an additional plot was prepared as an intermediate step towards the investigation of the detector acceptance as a function of p_T and $|y^{J/\psi}|$ (Fig. 5). This shows the number of muon pairs with an invariant mass within ± 100 MeV/c^2 of the Particle Data Group (PDG) world average in bins of p_T and $|y^{J/\psi}|$. The acceptance was evaluated by the CMS Collaboration (Fig. 6) [6], and could not be reevaluated here as a Monte Carlo simulation was not made available as part of the 2010 CMS-OD release.

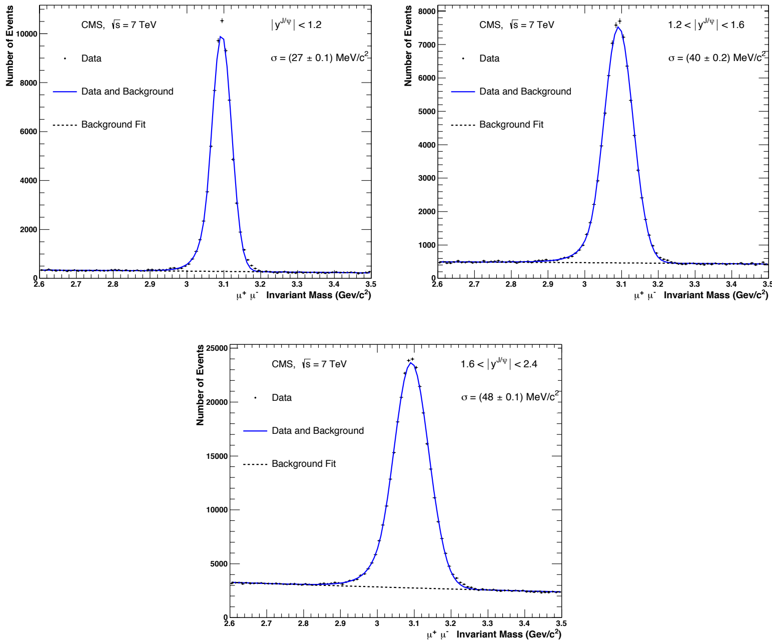

Figure 3: Dimuon invariant mass distributions between 2.6 and 3.5 GeV/c^2 in three rapidity ranges $|y^{J/\psi}| < 1.2$ (top left), $1.2 < |y^{J/\psi}| < 1.6$ (top right) and $1.6 < |y^{J/\psi}| < 2.4$ (bottom). Fitted with Crystal Ball functions and either an exponential ($1.6 < |y^{J/\psi}| < 2.4$) or a polynomial background.

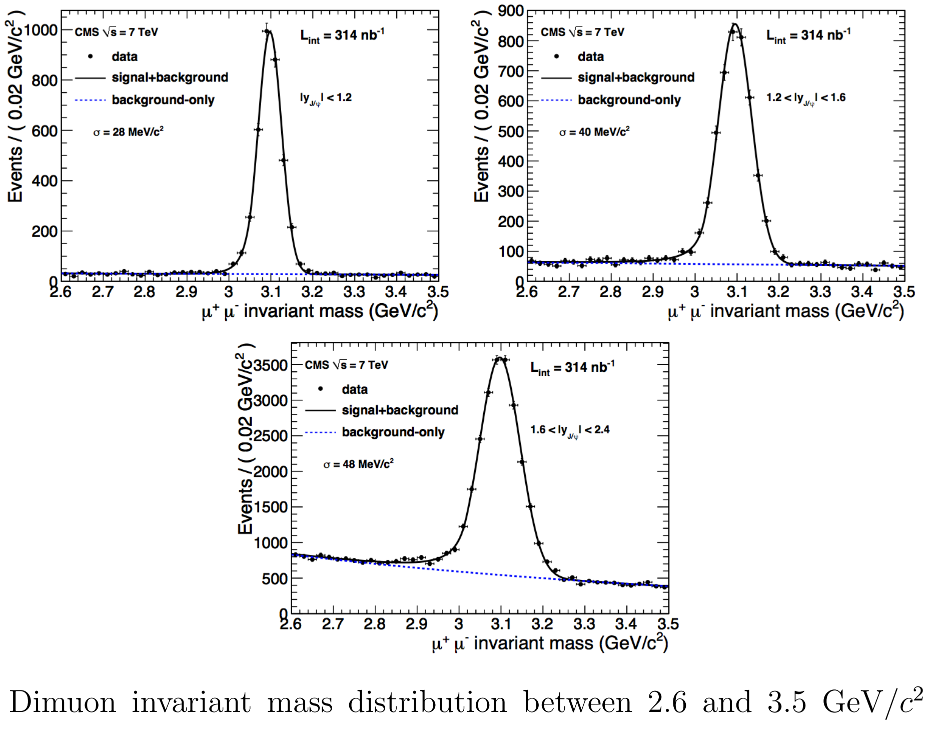

Figure 4: Dimuon invariant mass distribution between 2.6 and 3.5 GeV/c^2 obtained by [6].

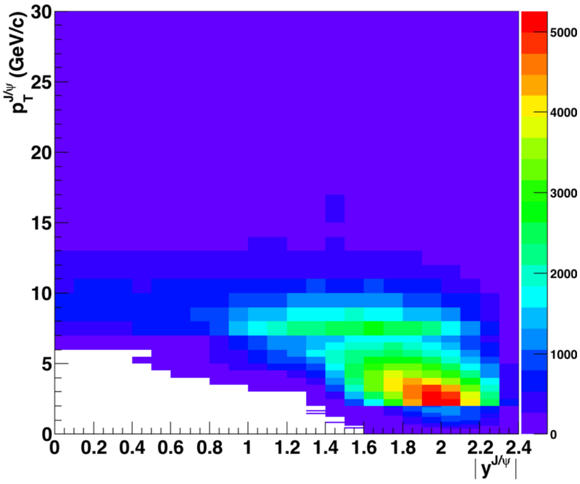

Figure 5: Number of muon pairs within ± 100 MeV/c^2 of the world average J/ψ mass distributed in $p_T^{J/\psi}$ and $|y|$.

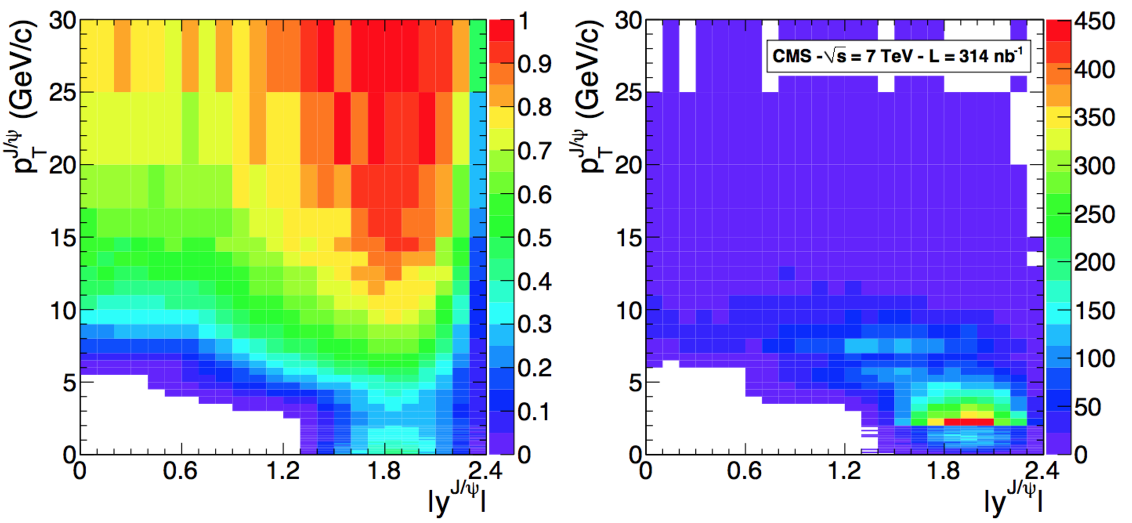

Figure 6: Plots of Detector Acceptance (left) and number of muon pairs (right) within ± 100 MeV/c^2 of the world average J/ψ mass distributed in $p_T^{J/\psi}$ and $|y|$ obtained by [6].

3.2 Υ reconstruction and selection.

The $\Upsilon \to \mu^+\mu^-$ decay channel accounts for (2.48 ± 0.05) % of all Υ decays [8]. To isolate these events the selection criteria used by the CMS collaboration in [7] were applied. In order to pass selection each muon must have a reduced track $\chi^2 < 5$ and have its reference coordinates fall within a cylinder of diameter 6 cm and length 30 cm centred on the beamspot. Both muons must have a maximum separation of 2 cm in the direction parallel to the beam axis (z). Kinematic cuts were applied across two psuedorapidity ranges, in which the muons were required to satisfy:

$$p_T^\mu > 3.5 \text{ GeV/c if } |\eta^\mu| < 1.6, \text{ or } p_T^\mu > 2.5 \text{ GeV/c if } 1.6 < |\eta^\mu| < 2.4.$$

Following these cuts, the invariant mass of the dimuon system was calculated to produce Υ candidates. In order for these candidates to be retained, their invariant mass was required to fall between 8 and 14 GeV/c^2 and to have $|y| < 2$. These candidates are shown in for muon psuedorapidity bins of $|\eta^\mu| < 2.4$ and $|\eta^\mu| < 1.0$ in Figure 7, while Figure 8 shows those obtained in [7]. Three Υ(nS) states are seen which are each fitted with a Crystal Ball function along with a polynomial background. The fit to the $|\eta^\mu| < 2.4$ range in yielded a $\Upsilon(1s)$ mass of 9.4572 ± 0.0015 GeV/c^2 which is consistent with the PDG world average value of 9.46030 ± 0.00026 GeV/c^2 [8].

3.3 Validation

One should not expect an identical reproduction between these and the referenced analyses as these were performed on different data subsets and with sample sizes also varying between them. Nevertheless from the consistency of the results obtained here to those published by CMS and the PDG world averages, it is concluded that CMS Open Data project has been successfully validated.

However, it should be noted that the analyses carried out in § 3.1 and § 3.2 required the use of technical cuts. The specifics of these could only be found in the analysis notes corresponding to [6] and [7], and are difficult to discern from the published papers. While access to these notes is not an issue for anyone working within a CMS setting, the enthusiastic amateur would not find this so easy and thus would have difficulty reproducing the analyses of these and other published works by the CMS collaboration.

In addition, due to the lack of a Monte Carlo provision within the 2010 CMS-OD release, the results produced cannot be checked against simulations. Since the comparison with a simulation is often a critical portion of the published analyses, the enthusiastic amateur will again find their attempts to reproduce them hindered. This will also impact on the merit of any independent analysis such an amateur would wish to produce.

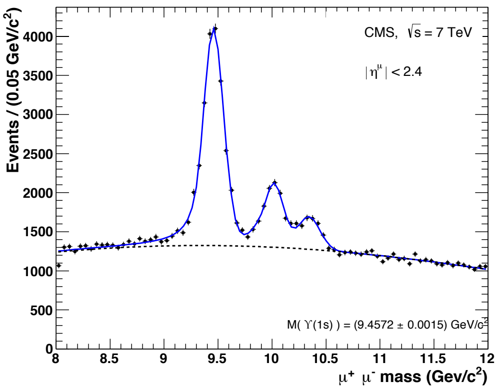

Figure 7: Dimuon invariant mass distributions between 8 and 12 GeV/c^2.

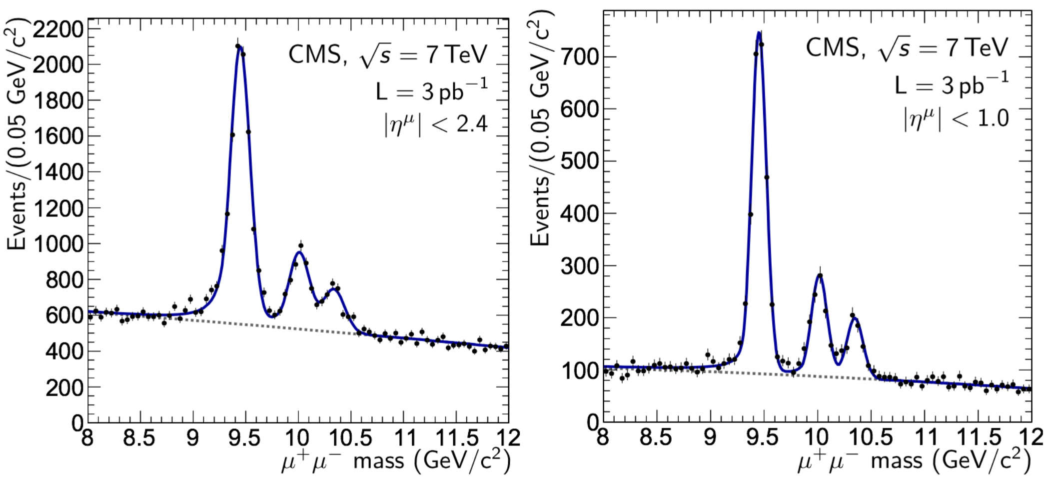

Figure 8: Dimuon invariant mass distribution between 8 and 12 GeV/c^2 from [7].

4 D^* and D^0 reconstruction

Following the validation of CMS-OD, the project scope shifted towards the production of new results using the environment. For this the reconstruction of D^* and D^0 mesons was selected. The reconstruction of these mesons has been used for calibration purposes by the CMS Collaboration without any publications produced to date [10] and thus is of interest for CMS-OD analysis.

D^* and D^0 mesons were reconstructed using the hadronic decay channel $D^{*\pm} \to D^0\pi_s^\pm \to K^\mp\pi^\pm\pi_s^\pm$ (Fig. 9). The pion produced in the $D^{*\pm}$ decay was customarily given the assignment of 'soft' or 'slow' (π_s) as the small mass difference between D^* and D^0 limits its momentum due to the lack of phase space for the decay.

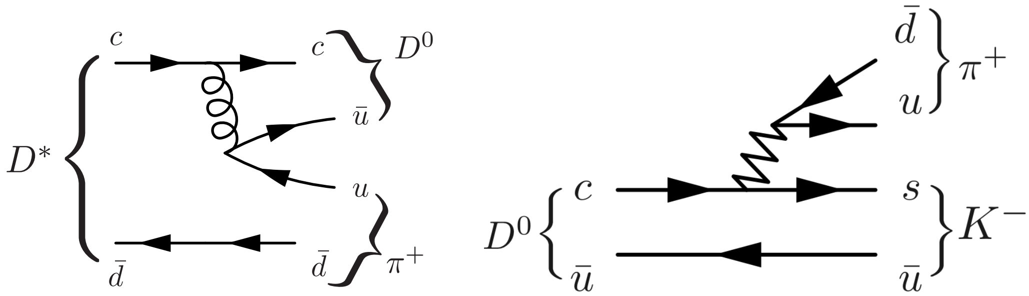

Figure 9: Feynman diagrams showing the decay channel $D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$.

Following the example of a successful reconstruction of D^* and D^0 by the ATLAS Collaboration in [11], pairs of oppositely charged tracks were alternatively designated as 'pions' or 'kaons' and assigned the corresponding masses. D^0 candidates were then reconstructed from these tracks provided that both tracks had $p_T > 1$ GeV/c and originated from within a cylinder of 1 mm radius and length of 1 mm with respect to the other track. If the tracks were of the same charge then the D^0 candidate was retained, but was flagged as 'wrong charge' in order to later produce a pure background distribution, pairs of oppositely charged tracks were likewise flagged as 'right charge'. An η selection was not applied, such that the full scope of the tracker is included in this analysis.

Prior to the inclusion of the slow pion, credible D^0 candidates were selected using a loose window of 600 MeV centred on the PDG world average of 1864.8 MeVc^2 [8]. The slow pion was then added using a third track of opposite charge to the 'kaon' track. This track was required to have $p_T > 0.25$ GeV/c and originate from the same cylinder as used for the D^0 candidates, and be of opposite charge to the Kaon track.

Following these cuts, D^* candidates were reconstructed and used to calculate the mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$. To reduce the impact of the background D^* candidates were required to have $z > 0.05$, where z is defined as $\frac{p_T(D^*)}{\sum p_T(\text{All Tracks})}$ and

$\sum p_T(All\ Tracks)$ is the total scalar transverse momentum of all tracks originating within the same cylinder as the 'kaon' and 'pion' tracks. To reduce overflow any candidates with $\Delta M > 0.17$ MeV/c^2 were rejected. Despite the cuts made here, a large background is expected due to the lack of particle identification within the CMS detector, thus the sample size was increased considerably compared to that used in § 3.

The ΔM distribution for D^0 candidates within 25 MeV of the PDG world average is shown in Figure 10 for both right (black) and wrong charge (blue) combinations. The distribution was fitted with a combination of a Gaussian Signal for and a Granet function to describe the background. The background function was of the form $A \cdot x^B \cdot e^{C \cdot x}$, where $x = |\Delta M - m_\pi|$ and A, B and C are the free fit parameters [12]. This returned a central value of 145.43 ± 0.04 MeV with a yield of 1077 ± 118 D^* mesons. Figure 11 shows the invariant mass of the D^0 candidates with corresponding mass difference ΔM within 1 MeV of the world average central value of 145.4 MeV [8]. The D^0 mass distribution was fitted with a Gaussian Signal and a second order polynomial background. This produced a central value of 1862.7 ± 1.0 MeV/c^2 with a yield of 1045 ± 105 D^0 mesons. Both central values of the fits are consistent with those given in [8].

Figures 12 and 13 show the ΔM and D^0 mass distributions obtained by the ATLAS Collaboration in [11]. A much improved resolution is obtained in this analysis, which enhances the prospects for future analyses in which the cross section of D^* and D^0 production may be measured. As of writing, this cross section has not been measured at $\sqrt{s} = 7$ TeV by the CMS collaboration.

In anticipation of such analyses, the previous kinematic cuts were relaxed to only require 'pion' and 'kaon' track transverse momenta of > 0.5 GeV/c without any implicit cuts on $p_T(D^*)$ or $p_T(\pi_s)$, the latter being determined by the acceptance of the detector. The D^0 mass cut for the ΔM distribution was also relaxed to a 60 MeV range to account for a wider peak. Figures 14 and 15 show the ΔM and D^0 mass distributions produced from these relaxed cuts. These have central values which remain consistent with the world averages and the improved resolution over those produced by the ATLAS collaboration is retained

5 Conclusion

The CMS 2010 Open Data release has been successfully validated via the reconstruction of quarkonium states using dimuon events. Results obtained from the Open Data are consistent with the world averages and those produced by the CMS collaboration.

$D^{*\pm}$ and D^0 mesons were successfully reconstructed finding central values of distributions that are consistent with world averages and results previously published by other collaborations. This demonstrates the merits of CMS Open Data for producing new results and may lead to a future measurement of the $D^{*\pm}$ meson production by the CMS Collaboration.

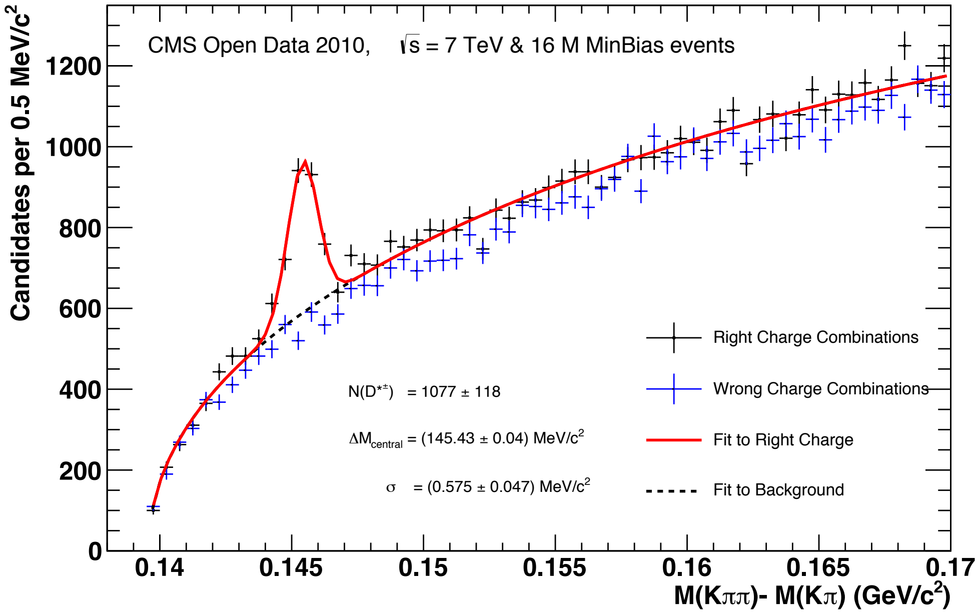

Figure 10: ΔM distribution for $D^{*\pm}$ and D^0 candidates, corresponding to a 50 MeV range centred on the world average D^0 mass.

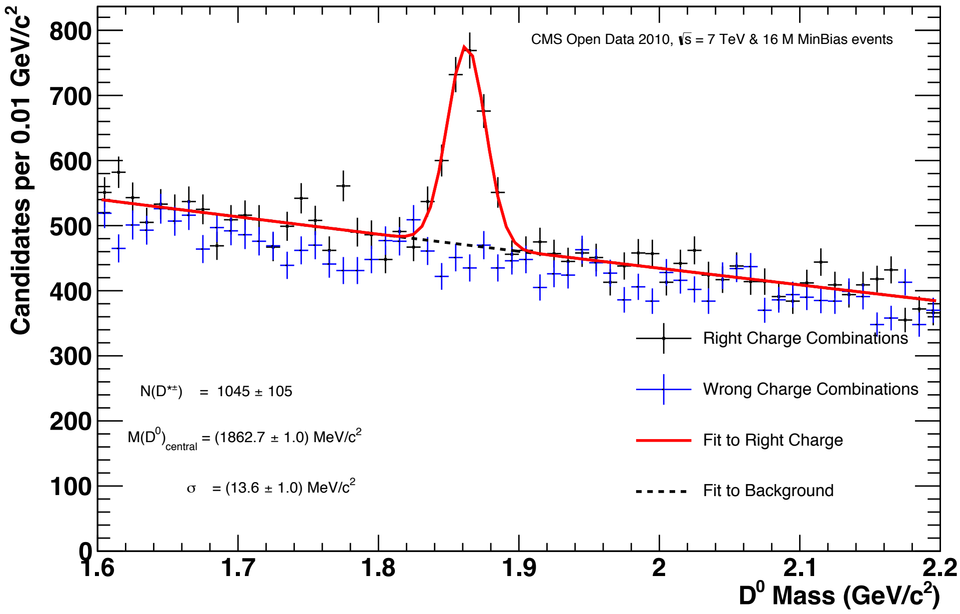

Figure 11: D^0 mass distribution for $D^{*\pm}$ and D^0, which correspond to a 2 MeV range centred on the world average central value of ΔM.

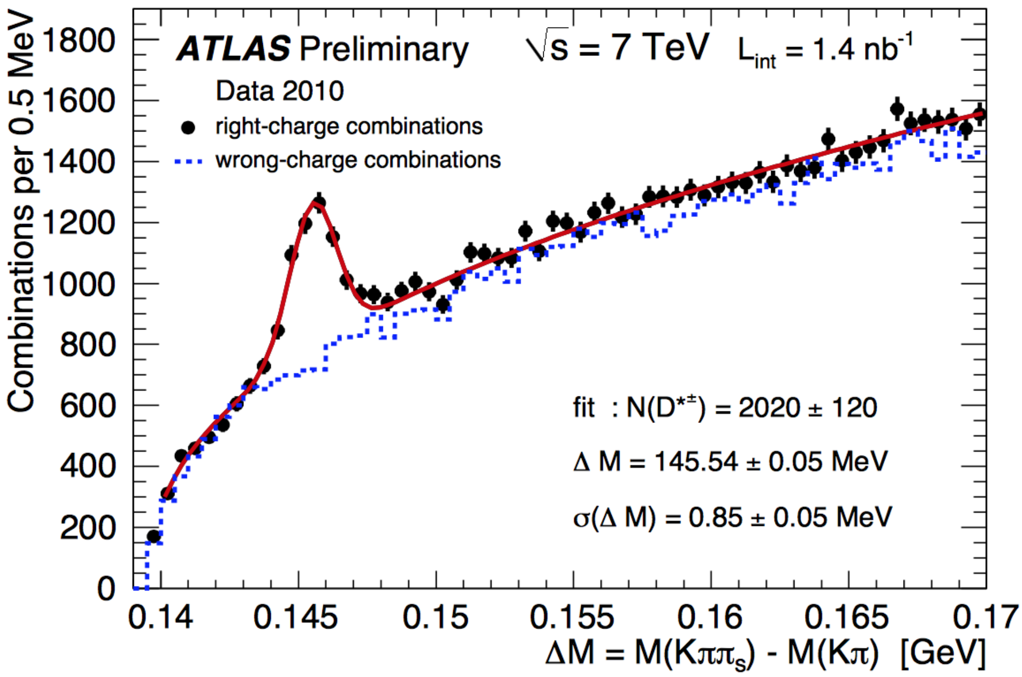

Figure 12: D^0 mass distribution for $D^{*\pm}$ and D^0 obtained by [11].

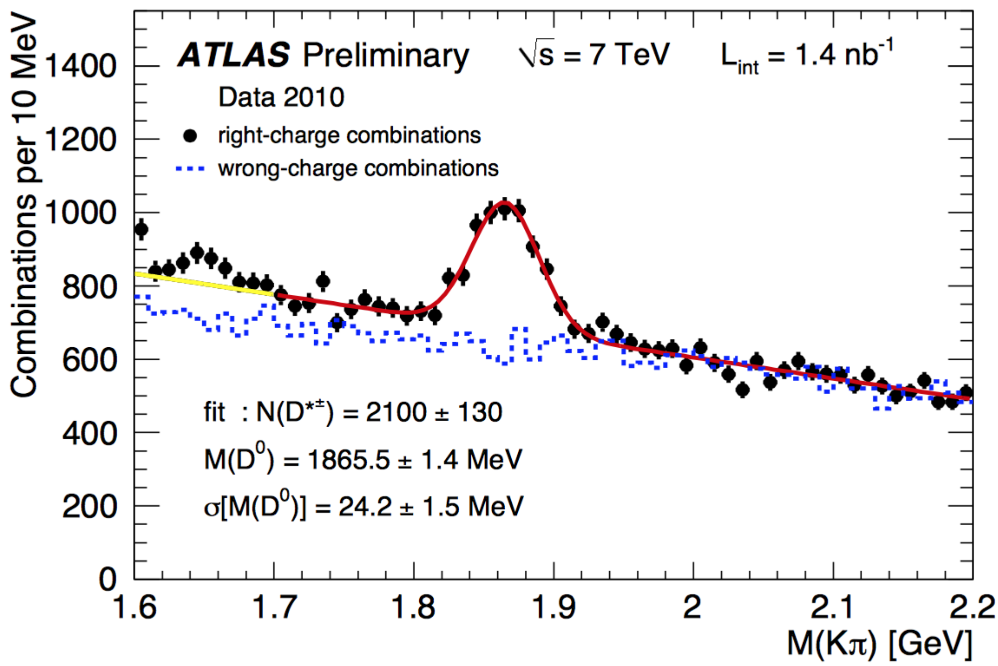

Figure 13: D^0 mass distribution for $D^{*\pm}$ and D^0 obtained by [11].

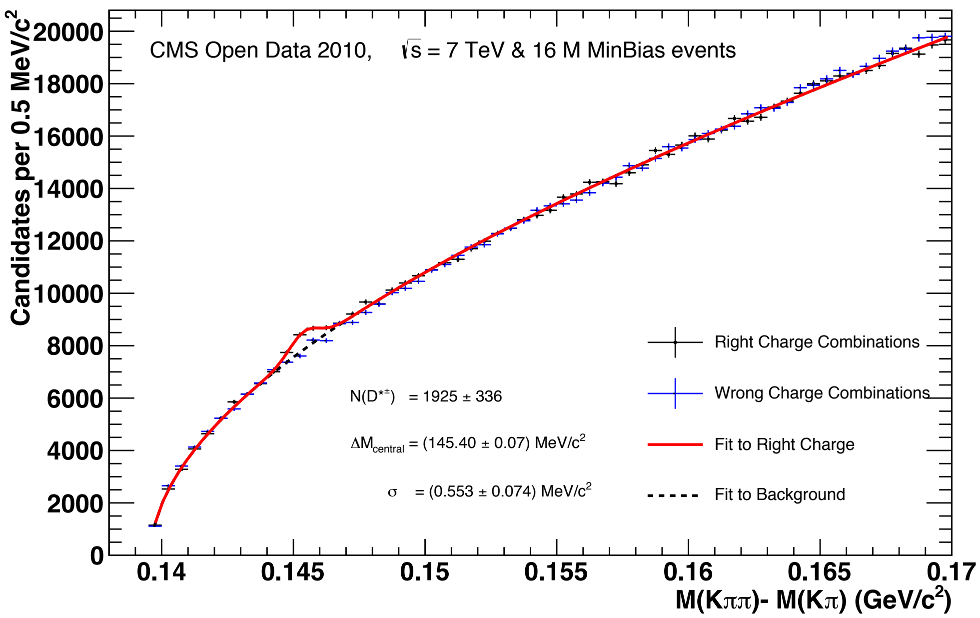

Figure 14: ΔM distribution for $D^{*\pm}$ and D^0 candidates. Produced using a 30 MeV cut around the world average D^0 mass and a kinematic cut of $p_T(\pi\&K) > 0.5$ GeV/c.

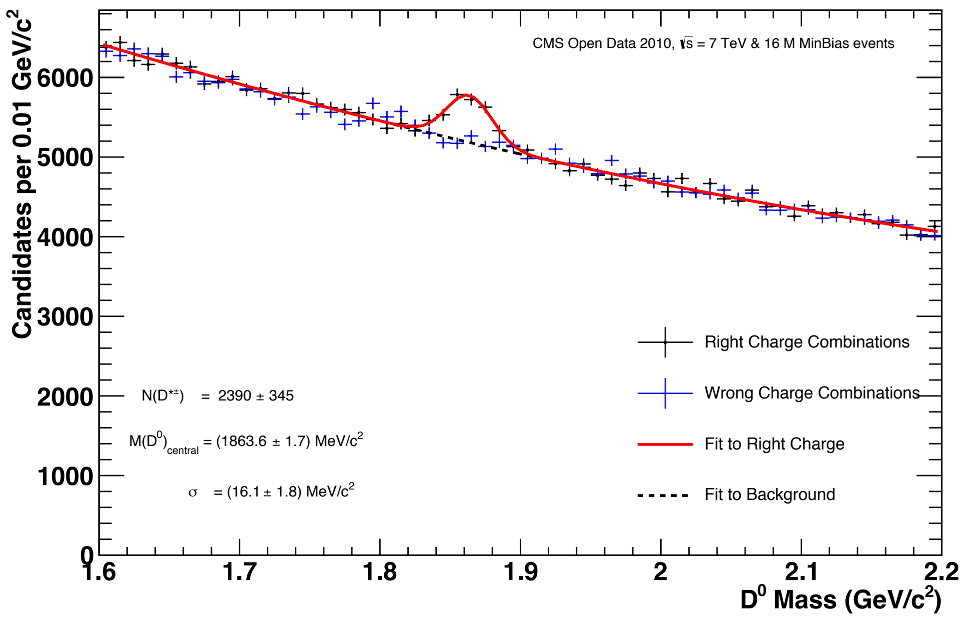

Figure 15: D^0 mass distribution for $D^{*\pm}$ and D^0. Produced using a cut of 1 MeV on the value of ΔM around world average central value and a kinematic cut of $p_T(\pi\&K) > 0.5$ GeV/c.

Acknowledgements

I have highly enjoyed my time working here at DESY and wish to thank: The summer student organisers, who made this opportunity possible, my supervisors: Achim Geiser and Nazar Stefaniuk for their patience, understanding and encouragement throughout the project. Irene Dutta who began this project and was extremely helpful when it came to my takeover. Olaf Beneke for all the interesting discussions and also the shortbread! Finally I express my gratitude to everyone working on the DESY Hamburg Campus, who never ceased in their helpfulness and friendliness.

References

[1] CERN. *CMS Open Data* Cited: September 2015. Available from:http://opendata.cern.ch/research/CMS.

[2] CMS Collaboration.*The CMS experiment at the CERN LHC*. doi:10.1088/1748-0221/3/08/S08004.

[3] CMS collaboration (2014). *MuOnia primary dataset in AOD format from RunB of 2010 (/MuOnia/Run2010B-Apr21ReReco-v1/AOD)*. CERN Open Data Portal. DOI: 10.7483/OPENDATA.CMS.TME9.7FP2

[4] I. Dutta. *Validation of CMS 2010 Open Data*. Summer Report. DESY, Hamburg July 2015.

[5] CMS collaboration (2014). *MinimumBias primary dataset in AOD format from RunB of 2010 (/MinimumBias/Run2010B-Apr21ReReco-v1/AOD)*. CERN Open Data Portal. DOI: 10.7483/OPENDATA.CMS.6BPY.XFRQ

[6] CMS Collaboration. *Prompt and non-prompt J/ψ production in pp collisions at $\sqrt{s}$ = 7 TeV*. arXiv:1011.4193.

[7] CMS Collaboration. *Upsilon production cross section in pp collisions at $\sqrt{s}$ = 7 TeV*. arXiv:1012.5545.

[8] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).

[9] M. J. Oreglia, *A Study of the Reactions psi prime → gamma gamma psi*, Ph.D. Thesis SLAC-R-236 (1980) Appendix D.

[10] CMS Collaboration. *Measurement of Tracking Efficiency*. CMS Physics Analysis Summary. CMS PAS TRK-10-002. July 2010.

[11] ATLAS Collaboration. *$D^{(*)}$ mesons reconstruction in pp collisions at $\sqrt{s}$ = 7 TeV*. ATLAS Note. ATLAS-CONF-2010-034. June 2010.

[12] O. Bachynska. *Measurement of the $D^{*\pm}$ Meson Production in Deep-Inelastic Scattering at HERA*. PhD Thesis. Deutsches Elektron-Synchrotron, Hamburg Germany; 2012