PRAMANA — journal of physics

Vol. 76, No. 3
March 2011
pp. 421–430

Drell–Yan process at Large Hadron Collider

M JINDAL[1], D BOURILKOV[2], K MAZUMDAR[3,*] and J B SINGH[1]
[1]Panjab University, Chandigarh 160 014, India
[2]University of Florida, Gainesville, Florida, USA
[3]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
*Corresponding author. E-mail: mazumdar@tifr.res.in

MS received 2 April 2010; revised 26 July 2010; accepted 5 August 2010

Abstract. Drell–Yan process at LHC, $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$, is one of the benchmarks for confirmation of Standard Model at TeV energy scale. Since the theoretical prediction for the rate is precise and the final state is clean as well as relatively easy to measure, the process can be studied at the LHC even at relatively low luminosity. Importantly, the Drell–Yan process is an irreducible background to several searches of beyond Standard Model physics and hence the rates at LHC energies need to be measured accurately. In the present study, the methods for measurement of the Drell–Yan mass spectrum and the estimation of the cross-section have been developed for LHC operation at the centre-of-mass energy of 10 TeV and an integrated luminosity of 100 pb^{-1} in the context of CMS experiment.

Keywords. Drell–Yan; Linear Hadron Collider; compact moun solenoid.

PACS Nos 12.15.-y; 13.85.Qk

1. Introduction

The production of opposite sign charged lepton pairs in hadron–hadron collision is called the Drell–Yan process [1] first studied with muon final states. In Standard Model (SM) it is described by s-channel exchange of a photon (γ) or a Z-boson: $q\bar{q} \rightarrow Z/\gamma \rightarrow \ell^+\ell^-$. In SM, the invariant mass spectrum of the leptons is a continuously falling spectrum with a resonance peak at Z-mass value. Around the Z peak, the heavy boson exchange process is dominating and the interference term is vanishing. At higher and lower energies, both the photon and Z exchanges contribute resulting in a large amount of forward–backward asymmetry. As the theoretical prediction for the rate is precise and the final state is clean as well as relatively easy to measure, the process can be studied from the start-up phase of the Large Hadron Collider (LHC) with relatively low luminosity. Surely with increasingly accumulated luminosity, the mass reach will be higher and more interesting.

The fermion-pair production above the Z pole is a rich search field for new phenomena at the present and the future high energy colliders (see e.g. [2] and references therein).

Hence the Drell–Yan (DY) process is an irreducible background to several searches beyond SM physics, like, production of additional, heavier, neutral gauge boson Z' whose decay branching to charged lepton pair varies according to the model specifications.

The total cross-section takes into account the s-channel contributions by γ, Z and any other possible New-Physics candidate, like, Z', as mentioned earlier. The angular differential cross-section in the centre-of-mass system has the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2}{4s}[A_0(1+\cos^2\theta) + A_1\cos\theta], \tag{1}$$

where $\sigma = \frac{4\pi\alpha^2}{3s}A_0$ and $A_{\mathrm{FB}} = \frac{3}{8}\frac{A_1}{A_0}$ gives the total cross-section and the forward–backward asymmetry, respectively. The terms A_0 and A_1 are fully determined in SM by the electroweak couplings of the initial- and final-state fermions. Thus the total cross-section and the forward–backward asymmetry as functions of the invariant mass and the rapidity of the final-state lepton pair are good observables to search for New Physics which can be measured well experimentally at the LHC in leptonic final states.

In proton–proton collisions the antiquark in the initial state is from the sea and the quark can have valence or sea origin. At a hadron collider operating at a centre-of-mass energy of $\sqrt{s}$, the momentum fractions carried by the initial-state partons, x_1 and

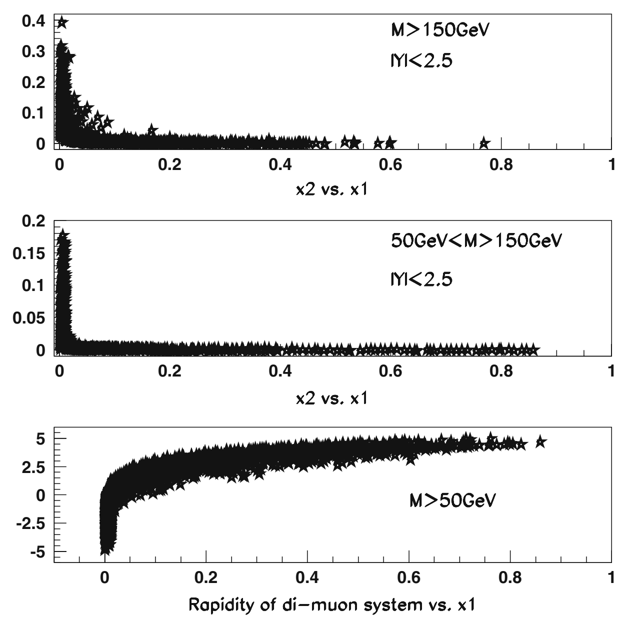

Figure 1. Typical values of the momentum fractions carried by the two incoming partons x_1 and x_2 in Drell–Yan process for different dimuon invariant mass (M) ranges and with absolute rapidity value less than 2.5 at a centre-of-mass energy of 10 TeV. The bottom plot shows the variation of rapidity y of the dimuon system with x_1 for dimuon mass above 50 GeV/c^2.

x_2, are given by $x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y)$ where the mass M is produced at rapidity y. The x-range probed depends on the mass and rapidity of the lepton pair as shown in figure 1 for centre-of-mass energy of $\sqrt{s} = 10\,\text{TeV}$. It is interesting to note that heavier the dilepton invariant mass, the reach in x_2 is higher. At the same time, lower x_1 value corresponds to the mass produced more centrally or with lower rapidity (y). However, in the forward direction, or at higher rapidities the difference between the two structure functions x_1 and x_2 increases. Thus good measurement of DY process upto high mass and higher rapidities will also serve crucially in the global determination of parton density functions of the proton at LHC energies. But, it is to be noted that at the LHC multipurpose experiments, the leptons are measured within limited pseudorapidity range ($|\eta| \leq 2.5$, typically).

Interestingly, the nature of the underlying events (UE) in hadron collisions, consisting of multiparton interaction as well as the beam–beam remnant, can be studied using DY events. Understanding the UE activity, which is a function of the centre-of-mass energy, is crucial for both SM events and discovery analysis at the LHC. The simplistic nature of the DY final state provides a suitable separation of the hard-scattered part with the rest in the proton–proton collision. At LHC the DY events thus form an important component in model-tuning exercise to describe phenomenologically the softer interactions or the so-called minimum bias events. At high instantaneous luminosity, several minimum bias events will get piled up along with the interesting events during the same bunch crossing.

The results based on realistic simulation of DY events are presented here in the context of CMS experiment for a modest amount of integrated luminosity of 100 pb^{-1} at 10 TeV LHC with low luminosity operation without event pile-up. A strategy has been developed, based on detailed Monte-Carlo simulations for controlling the background, as well as extracting the actual cross-section using unfolding method. The mass-dependent experimental numbers will eventually help to fit a theoretical description for the final state.

Higher-order QCD and electro-weak corrections to the value of cross-section are expected to be important for dilepton mass range beyond the Z-resonance (refs [3–5]). However, for low integrated luminosity, the event statistics fall rapidly beyond the Z-region, and hence, only the leading order estimate of the theoretical cross-section is considered for the present study.

2. Compact muon solenoid (CMS) detector

The compact muon solenoid (CMS) is one of the two general purpose detectors at the LHC. The central feature of the CMS apparatus is a superconducting solenoid, of field strength 3.8 T and of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass-scintillator hadronic calorimeter positioned in nested layers around the interaction point. Muons are measured in gas chambers embedded in the outermost part beyond the iron return yoke. Three types of detection systems are used for trigger and sagitta measurements: drift tubes, cathode strip chambers and resistive plate chambers. Besides the barrel and endcap detectors, CMS has extensive forward calorimetry extending to high pseudorapidity ($|\eta|$) values.

The muons are measured in the pseudorapidity fiducial of $|\eta| < 2.4$. Matching the muons to the tracks measured in the innermost subsystem, the silicon tracker, results in a transverse momentum resolution between 1 and 5%, for transverse momentum (p_{T}) values up to 1 TeV/c.

3. Signal characteristics and the background processes

For the signal events, effectively there are only two energetic, isolated muons of opposite signs, accompanied occasionally by initial- and final-state gluon and photon radiations. Two large-statistics sets of signal events, based on the value of the dimuon invariant mass, are considered coherently, to cover low-mass region starting from 6 GeV/c^2 and extending upto several hundred GeV/c^2, beyond Z-resonance. We refer to them as DY-low and DY-high respectively, and the invariant mass coverage for the two are respectively, (6–40) GeV/c^2 and 20 GeV/c^2 upwards. DY-low sample is used mainly for studying the event trigger efficiency as a function of muon momentum threshold. For all the off-line selections and subsequent analysis, only the DY-high sample is used. It is anticipated that with the first physics data corresponding to a luminosity of 100 pb^{-1}, one can probe dimuon masses only upto a few hundred GeV/c^2. Hence, though we have studied separate event samples with invariant mass value starting from 100 GeV/c^2 and extending beyond a few hundred GeV/c^2, we do not consider them further in this report.

The event selection is inclusive, simplistic, cut-based and intentionally lenient to have good statistics of signal process. Thus, in addition to the signal process all other physical processes, which may provide two energetic muons in the experimental observation, have been considered and they are:

- QCD hadronic interaction process, which has very high rate at the LHC, contributes maximally in the low-mass region of Drell–Yan invariant mass. The heavy mesons, due to bottom and charm quarks, produced copiously in these events, decay semileptonically into muons with large branching ratios, eventually providing two muons in a large number of events. The muons from the decay of charged pions and kaons in flight are relatively soft and mostly cannot survive the selection thresholds.
- The process $Z \to \tau^+\tau^- \to \mu^+\mu^- + X$ has the potential of mimicking the background, specially when there is no constraint on missing energy during event selection. The branching ratios for Z decays to charged lepton pair is 3.3% and $\tau \to \nu_\tau \mu \nu_\mu$ is about 17%. It must be mentioned here that the mass distribution of the muon pair in this case typically peaks at a value lower than M_Z, as opposed to the direct decay of Z to muons, $Z \to \mu^+\mu^-$.
- $W+$ jets process with W decaying via muon channel (branching ratio of about 11%), can pose as a background, when one of the jets, mostly the leading one, fakes as a muon. Though the corresponding probability is about 10^{-5}, the production rate of $W+$ jets events is large.
- $t\bar{t}$+jets process can be a source of dimuons where the muons are mainly due to leptonic decays of the Ws produced in top and anti-top decays. This process is dominant in the high-mass region of DY mass spectrum as the muons from a top cascade decay is highly boosted.
- Various diboson productions, followed by their leptonic decays, also make a non-negligible contribution as a background.

- $Z+$ jets process has not been considered separately in this analysis. The t-channel process does provide a boost to the boson which is implicitly accounted in the signal channel, which contains two leptons inclusively.

Signal characteristics have been studied using generator level information for the Born process as obtained from the PYTHIA 6.4 Monte Carlo generator package [6]. Since the QCD hadronic events have very large rate, they are generated using PYTHIA, in several contiguous $\hat{p}_{\mathrm{t}}$ interval bins, where $\hat{p}_{\mathrm{t}}$ refers to the minimum transverse momentum of the final-state parton in $2 \to 2$ hard-scatter process. These events are subsequently filtered for muon enrichment by demanding the event to contain at least one muon from a heavy meson decay and the muon transverse momentum is required to be above 5 GeV/c. The $t\bar{t}+$ jets and $W+$ jets events are generated with MadGraph package [7], which have hard jets occasionally in the final state.

Signal as well as all the background events are processed through GEANT4 description of the CMS detector to emulate the response of various detector materials along the passage of the particles. The detector simulation is followed by the reconstruction of the *hits* in the detector units, the measurement of the energy and the momentum of the particles and the subsequent identification of the events through typical signatures. CMS experiment-specific software is used for this purpose.

4. Event selections

Since the signal rate is much lower than all the possible backgrounds, a judicious selection procedure is essential to identify the signal through numerous background events.

Online selection of interesting event, or event trigger condition to be applied during actual data collection, which rejects most of the interactions, is achieved via OR condition of two suitable inclusive criteria. The event is required to contain, inclusively, either a muon with p_{T} greater than 9 GeV/c or at least two muons with p_{T} greater than 3 GeV/c. Muons are required to be reconstructed in the muon subsystem of the CMS detector and are within the pseudorapidity range of $|\eta| \leq 2.4$.

For off-line analysis of archived events (after trigger selection), the conditions are strict to achieve a purer collection. At relatively low transverse momentum, the inner tracker subsystem provides the best measurements and the muon subsystem provides the muon identification. A global fit is performed using the tracks reconstructed in the tracker subsystem and the stand-alone muon tracks in the muon subsystem. Eventually, various quality control criteria are applied to this globally reconstructed muon.

The transverse momentum distributions of the leading muon in the event, before any selection, is displayed in figure 2 (left). As the signal is generated with a minimum cut-off for the invariant mass, there is a peak at the lower end. The second peak in the signal distribution at around 45 GeV/c is due to the events when the signal is mediated by on-shell Z. The muon pair naturally experiences substantial boost quite often, as there is no kinematic upper limit for the subprocess energy. From the composition of the distribution it is evident that a muon from a heavy meson decay in QCD hadronic events will be relatively soft. Hence both the muons in the event are required to have p_{T} greater than 10 GeV/c, which is quite effective in reducing the large QCD background.

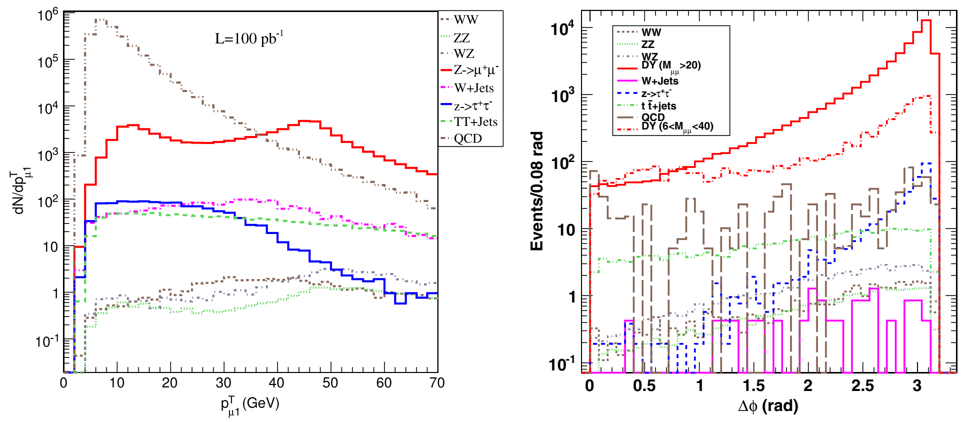

Figure 2. Transverse momentum distribution of the leading muons in signal and various background events (left). Distribution of the acoplanarity angle between two leading isolated muons in signal and background events (right).

To enhance the quality of the muons, and also to reduce the background due to heavy meson decays, each of the fitted track is required to satisfy a set of quality criteria. The minimum number of required hits in the inner subdetector (tracker) is required to be greater than 10 and the maximum allowed value of the normalized chi-square while fitting a track curvature to the hit positions to be less than 11. Additionally, to discard muons coming from the decays of kaons and pions in flight, the absolute value of the sum of the transverse impact parameters of the two leading muons is required to be less than 0.1 mm. It is to be noted that while measurement of single impact parameter requires knowledge of the beam spot, the sum does not. For the start-up phase the measured beam spot position may have large uncertainties. The above condition is quite efficient in reducing a good fraction of the QCD hadronic events where the muons are due to in-flight decays of kaons and pions and hence the corresponding tracks do not share a common vertex or a starting point.

In general, for the signal events, the muons are the sole final-state particles produced in the hard scattering and there is less additional activity around the muons except for occasional bremsstrahlung photons. On the contrary, the muons in the background events, in particular those from the heavy meson decays, are produced along with the other particles and hence they are not isolated in the detector. Thus, to select signal-like events, an isolation criterion is required to be satisfied by both the muons in the tracking subdetector. An isolation cone is defined as an annular ring in η–ϕ space of cone size $\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around the muon track with a veto cone of radius 0.01 to allow for brehmsstrahlung. The relative isolation variable is defined as the sum of the momentum of all the additional tracks in the annulus with transverse momentum above 1 GeV/c normalized by the transverse momentum of the candidate muon. This sum is required to be less than 10%, i.e. the fraction $\sum p_{\mathrm{T}}^i(i \neq \mu)/p_{\mathrm{T}}^{\mu}$ should have value less than 0.1, the value being arrived at from optimization of signal-to-background ratio.

Table 1. Cumulative efficiencies of various selection cuts.

Selection	DY-high	DY-low	W+jets	$Z \to \tau^+\tau^-$	$t\bar{t}$ + jets	WW	ZZ	WZ	QCD
Event trigger	0.91	0.47	0.46	0.34	0.54	0.37	0.45	0.39	0.23
Reconstructed muons ≥ 2	0.83	0.41	0.05	0.18	0.32	0.15	0.37	0.25	0.09
Hard muons within fiducial	0.67	0.04	0.004	0.07	0.14	0.09	0.30	0.18	0.004
Muon identification	0.63	0.04	0.002	0.05	0.07	0.07	0.25	0.15	0.0013
Muon isolation	0.57	0.03	7e-5	0.04	0.02	0.06	0.22	0.13	1.5e-0
Opposite charge	0.57	0.03	6e-5	0.04	0.02	0.06	0.21	0.12	1.2e-5
Acoplanarity	0.51	0.02	3e-5	0.04	0.01	0.03	0.12	0.07	5e-6

Subsequently, the two isolated leading muons are required to have opposite electromagnetic charges. This condition helps reducing QCD hadronic, dibosons, as well as $W+$ jets backgrounds.

In the signal process the muons are expected to be mostly back-to-back. At the LHC energy of 10 TeV, a good fraction of the events will also exhibit a significant transverse boost of the dimuon system, i.e. when it is balanced mostly by a jet, or, occasionally by a photon. This jet may not have sufficient transverse energy to be identified in the experiment; and, even if it is identified, no selection is applied on the jet. For an early LHC analysis, applying a jet veto has been intentionally avoided during selection. Thus the event selection being inclusive, such an event will remain in the sample with only the kinematics of the muons being utilized. In such a situation however, the muons are not back-to-back and they are acoplanar. Figure 2 (right) shows the angle between two leading muons in the transverse plane for the signal and the various backgrounds. The acoplanarity angle is required to be greater than 2.25 radians for the event to be selected.

Table 1 shows the sequential cuts and the effects on signal and various background processes.

5. Reconstructed dimuon system

Figure 3 displays the transverse momentum and the absolute value of the rapidity of the reconstructed dimuon system after all the selection cuts for the signal and the background processes. For the transverse momentum beyond 10 GeV/c and almost upto 150 GeV/c, the background is at least one order of magnitude lower compared to the signal. This is also the reachable region with about 100 pb^{-1} data with very good statistical significance. Similarly, for the distribution of the absolute value of the rapidity ($|y|$) of the dimuon system, the signal size is comfortably much higher compared to the total background.

6. Drell–Yan mass spectrum and absolute cross-sections

In figure 4 (left), the invariant mass spectrum of the dimuon system, as anticipated to be measured experimentally with data corresponding to an integrated luminosity of 100 pb^{-1},

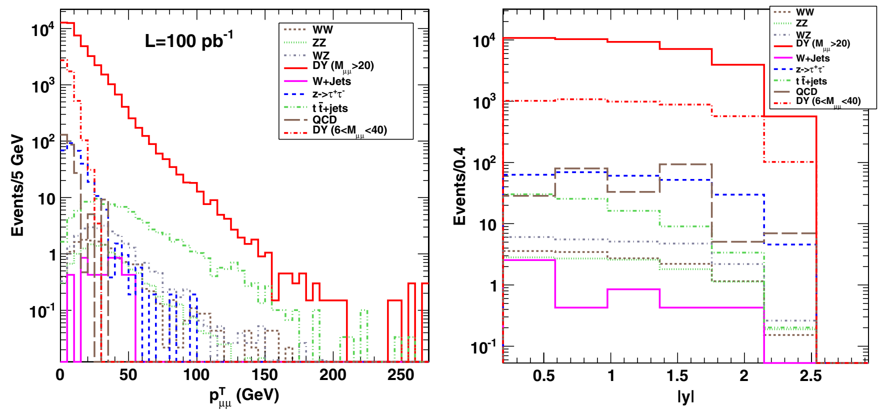

Figure 3. Distributions for the transverse momentum (left) and rapidity of the dimuon system (right) for signal and background events.

is shown. It is evident from the figures that the selection cuts have been very effective in reducing various background processes and enhancing the signal-to-background ratio. The QCD hadronic events contribute mainly in the low mass region while $t\bar{t}$ + jets process contribute in the higher mass region.

In table 2 we present, as a function of dilepton mass bin, the number of total events (signal + background) and only signal events (after background subtraction) expected in CMS experiment for 100 pb^{-1} at 10 TeV LHC. The 4th column presents the uncorrected, experimentally measured, cross-section (in pb) while the 5th column provides the derived value of the actual cross-section after taking into account the selection efficiency and the acceptance cuts in the detector. This unfolded value of the cross-section matches very

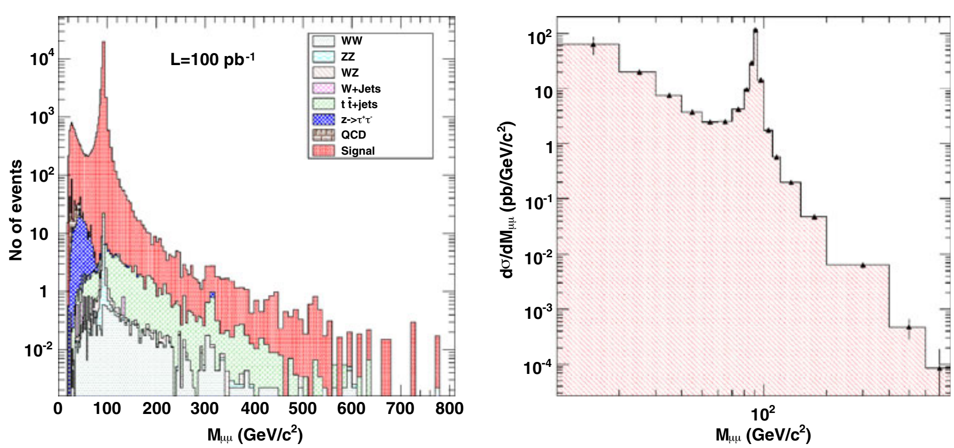

Figure 4. Invariant mass distribution of the two muons passing all the selection cuts on linear scale (left) and the distribution for the corrected dimuon invariant mass on logarithmic scale (right).

Table 2. The number of total signal + background events expected to be observed in a real experiment and the estimated number of background subtracted signal-only events in various mass windows for an integrated luminosity of 100 pb^{-1} at 10 TeV LHC. The measured and derived cross-sections are provided as a function of dilepton invariant mass.

Mass bin (GeV/c^2)	Signal + background events	Signal events	Uncorrected cross-section (pb)	Corrected cross-section (pb)
10–20	15.56 ± 3.94	15.56 ± 3.94	0.16	638.87 ± 229.03
20–30	3044.48 ± 55.18	2875.31 ± 73.43	28.75	201.84 ± 5.13
30–40	2685.33 ± 51.82	2547.68 ± 57.50	25.48	75.28 ± 1.92
40–50	1578.75 ± 39.73	1435.31 ± 45.38	14.35	37.22 ± 1.25
50–60	1127.17 ± 34.04	1044.97 ± 34.61	10.45	24.88 ± 0.97
60–70	1167.8 ± 33.57	1119.23 ± 35.18	11.19	25.27 ± 0.94
70–80	1949.46 ± 44.15	1929.09 ± 44.94	19.29	42.12 ± 1.19
80–85	2422.97 ± 49.22	2414.6 ± 49.74	24.15	48.38 ± 1.21
85–89	6600.36 ± 81.24	6589.81 ± 82.04	65.90	116.57 ± 1.72
89–93	20170.0 ± 142.02	20147.3 ± 143.4	201.47	472.33 ± 4.17
93–100	5793.75 ± 76.12	5781.98 ± 76.93	57.82	100.29 ± 1.57
100–110	891.53 ± 29.86	881.626 ± 30.49	8.82	17.55 ± 0.72
110–120	288.69 ± 17.00	280.042 ± 17.70	2.80	5.68 ± 0.42
120–150	316.14 ± 17.78	296.892 ± 19.04	2.97	5.96 ± 0.42
150–200	138.29 ± 11.76	119.662 ± 13.68	1.20	2.42 ± 0.27
200–400	87.57 ± 9.36	71.766 ± 11.84	0.72	1.29 ± 0.18
400–600	8.78 ± 2.96	7.645 ± 3.84	0.08	0.1 ± 0.04
600–800	1.24 ± 1.11	1.09 ± 1.50	0.01	0.02 ± 0.02

well with the value expected from SM as in the simulation study, non-SM processes were not considered. The errors for total number of events are only statistical in nature. For the derived number of signal events, however, the statistical uncertainty in the background subtraction is also taken into account.

Figure 4 (right) shows the Drell–Yan differential cross-section as a function of dilepton invariant mass. The points with error bars represent the cross-section values expected for an integrated luminosity of 100 pb^{-1}. It has been calculated using the formula:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M}\right)_i = \frac{N_i^{\mathrm{obs}} - N_i^{\mathrm{bkd}}}{\beta \mathcal{L} \varepsilon_i \Delta M_i},$$

where for an integrated luminosity $\mathcal{L}$ and for the ith mass bin of width ΔM_i, the total number of observed events is N_i^{obs} and the estimated number of background events is N_i^{bkd}. The cross-section has been corrected for the selection efficiency in the ith bin, ε_i, and for detector acceptance β. Whereas the selection efficiency is dependent on the invariant mass, the value of the acceptance is constant. It has been determined by taking the ratio of the reconstructed invariant mass of the dimuon system before and after the detector acceptance cuts, i.e., muon tranverse momentum greater than 10 GeV/c and absolute pseudorapidty less than 2.4.

From the analysis reported here, our main conclusion is that the Drell–Yan mass spectrum upto about 40 GeV/c^2 can be easily compared with Standard Model prediction with very good statistical accuracy using data collected in CMS experiment with a luminosity of 100 pb^{-1}. With more accumulated data, the statistical error will reduce and hence the systematic uncertainties have to be taken into account. Some of the major sources of systematics are the uncertainties in the measurement of luminosity and the parton-density functions [8–10]. This analysis can be extended for higher mass when more data are available. Surely with different LHC operational scenario (energy, instantaneous luminosity) the selection strategy has to be tuned since the event kinematics as well as production rates of some of the background processes will change considerably. The experimental definition of isolated lepton also has to be revisited. Most importantly, the analysis method outlined above for lower mass region will enable establishing the Standard Model shortly after the start-up and auger the search strategy of a high mass resonance decaying into muon pairs.

References

[1] S D Drell and T M Yan, *Phys. Rev. Lett.* **25**, 316 (1970); Erratum, *ibid.* **25**, 902 (1970)
[2] S Haywood *et al*, arXiv:hep-ph/0003275
[3] U Baur and D Wackeroth, *Nucl. Phys. Proc. Suppl.* **116**, 159 (2003), arXiv:hep-ph/0211089
[4] C M C Calame *et al*, *J. High Energy Phys.* **0505**, 019 (2005)
C M C Calame *et al*, arXiv:0710.1722v1 [hep-ph]
[5] K Melnikov and F Petriello, *Phys. Rev.* **D74**, 114017 (2006), arXiv:hep-ph/0609070
[6] T Sjostrand, S Mrenna and P Skand, *J. High Energy Phys.* **05**, 026 (2006)
[7] J Alhwal *et al*, MadGraph/MadEvent v4: The New Web Generation, *J. High Energy Phys.* **0709**, 028 (2007)
[8] D Bourilkov, arXiv:hep-ph/0305126
[9] M R Whalley, D Bourilkov and R C Group, arXiv:hep-ph/0508110
[10] D Bourilkov, R C Group and M R Whalley, arXiv:hep-ph/0605240