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Search for ADD Extra Dimensional Gravity in Dimuon Channel with the CMS Detector

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Abstract

In this work the possibility to observe TeV-scale gravity signals at the LHC is discussed. The ADD scenario with large extra dimensions contributing to Drell-Yan processes through virtual KK-modes is considered. A detailed simulation and reconstruction analysis was carried out to derive the CMS discovery potential for ADD virtual production by studying muon pairs with large invariant masses.

1 Introduction

Recently several new models of low-scale gravity were proposed based on brane world ideas [1, 2]. In this work we concentrate on the phenomenology of the first of them, the ADD scenario with flat space-time geometry. We derive the LHC discovery potential to observe one of several new phenomena appearing in ADD. Namely, we consider modification of the Standard Model dimuon continuum due to contributions from multiple virtual KK-modes of graviton.

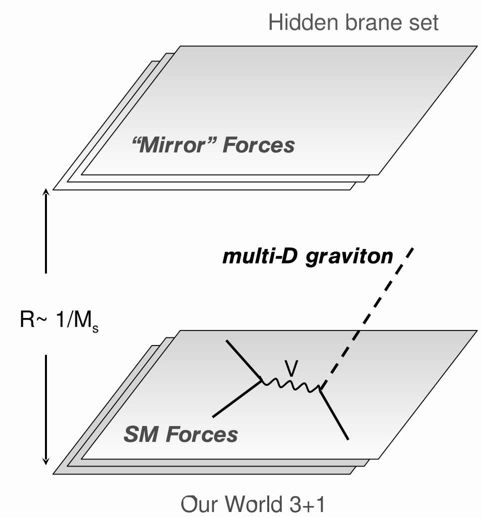

Figure 1: The ADD world with two stacks of branes one of which is hidden.

The ADD model [1] implies that n (n=1–6) extra spatial dimensions can exist in addition to our three ones compactified on a n-sphere with a radius R (the simplest case). Then R is called the compactification radius and it does not have to be the Planckian size, but can be really as large as tenths of millimeter or smaller. Usual consideration is that all of the Standard Model fields are confined on a three-brane embedded in a $(3 + n)$-dimensional space referred to as the bulk (Fig. 1). It is the reason why we do not observe any effects from extra dimensions up to the energy scale $1/R$ when fundamental multidimensional structure can be distinguished. In this model graviton is the only multidimensional field what can travel through the bulk. In the model the Planckian scale M_{Pl} is no longer fundamental but it becomes an effective scale connected with the true fundamental multidimensional scale M_S in the following way:

$$M_{Pl} = M_S^{1+n/2} R^{n/2} \tag{1}$$

So we can observe possible effects from multidimensional gravity at energies above $\approx M_S$, and in order to probe them at the LHC the fundamental mass scale should be of the order of one to a few TeV/c^2.

The characteristic picture of ADD model is the existence of Kaluza-Klein modes of graviton (these modes are massive and the mass value is $m_{KK} = 2\pi k/R$, k is a mode number). These modes must be light: dependent on the number of extra dimensions at the fundamental scale $M_S \approx 1$ TeV/c^2 mass, values for the first graviton excitation start from $\approx 10^{-3}$ eV/c^2 for $n = 2$ up to maximally ≈ 10 MeV/c^2 for $n = 6$. More details about ADD phenomenology can be found, for example in [3, 4].

For setting $M_S \approx 1$ TeV/c^2 one can calculate the extra dimensions radius $R \approx M_S^{-1} \times (M_{Pl}/M_S)^{2/n} \approx 10^{(32/n)} \times 10^{-17}$ cm. The case $n = 1$ gives unacceptably large values of R because the Newton law validity is established down to 0.2 mm [5]. In the case $n = 2$ the radius value is about 1mm, and the fundamental scale value $M_S \approx 1$ TeV/c^2 is most probably excluded by astrophysics and cosmological arguments (see for example [3, 6]). The closest permissible value of M_S for $n = 2$ is about 30 TeV/c^2 that is obviously out of the scope of observations on modern and future accelerators.

From a combined analysis of LEP2 data on Bhabha scattering a limit for four extra dimensions of 1.4 TeV/c^2 for positive and 1.1 TeV/c^2 for negative interference is obtained [7]. The current lower limit on M_S derived at TEVATRON are around 1.1 TeV/c^2 [8, 9]. Thus the most favorable set of parameters appears to be $n = 3$, $M_S \approx 1-$few TeV/c^2 and $R \approx 10^{-4}$ mm.

Above we have pointed out that the characteristic feature of ADD is the existence of light KK-gravitons which could be directly produced at colliders (real graviton production) or observed through contact interactions as virtual KK-graviton exchange. Experimental signals for the ADD scenario might be found in dijet, dilepton, and diphoton mass spectra as well as missing energy distributions. The missing energy phenomenon corresponds to real graviton production, whereas the first three signals account for virtual graviton production. Real gravitons carry away a fraction of the total energy produced in a hard collision, in other words induce energy leakage from the interaction point. Virtual gravitons interfere with the SM diagrams for Drell-Yan processes as well as for gamma pair production, which results in significant modification of these spectra. The amplitude of each separate graviton contribution is suppressed by $\sim 1/M_{Pl}$, however the production cross section counts many contributions (large number of gravitons with the same mass value defined by a mode number k, see above, is taken into account with a state density $N(\mathcal{E})$) and this circumstance induces crucial enhancement of graviton production cross section so effective suppression will be only by $(1/M_S)^2$.

Thus, dimuon production at the LHC is very sensitive to virtual graviton exchange effects, as provided by ADD extra dimensional gravity scenarios.

In this note, an analysis of the CMS discovery potential is given to observe the ADD signal as a deviation of the dimuon spectra from Standard Model predictions for Drell-Yan processes:

$$q\bar{q} \to \gamma/Z^0/G_{KK}^{ADD} \to \mu^+\mu^- \quad (2)$$

The detailed Monte Carlo simulation of the detector response and muon reconstruction with the official CMS simulation package OSCAR version 3_2_4 [10] (based on GEANT4 [11]) and reconstruction package ORCA version 8_13_2 [12] have been used for this study.

2 Signal and background simulations.

The contribution of the KK-modes of ADD gravitons to the Drell-Yan processes is computed using K. Cheung and G. Landsberg's code for the leading-order matrix element [13] which was implemented in the STAGEN generator collection [14] as an external matrix element in the Pythia version 6.227 [15]. Initial and final state radiation was switched on, and the CTEQ6L set [16] from the LHAPDF package [17] of parton distribution functions has been used.

The cross section of the Drell-Yan process with Kaluza-Klein terms can be factorized as:

$$\sigma = \sigma_{SM} + \sigma_4\eta + \sigma_8\eta^2, \quad (3)$$

where the first and the third terms correspond to the SM and Kaluza-Klein contributions respectively, while the second one characterizes an interference between the SM and gravity. Here η is given by

$$\eta = \frac{\mathcal{F}}{M_S^4}, \qquad \mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & for \quad n = 2, \\ \frac{2}{n-2} & for \quad n > 2. \end{cases} \quad (4)$$

where $\hat{s}$ is the center-of-mass energy. Exact expressions for σ_{SM}, $\sigma_4\eta$ and $\sigma_8\eta^2$ can be found at [13].

The characteristic scale value M_S with a number of extra dimensions n pinpoint the region of dilepton invariant masses M_{ll} sensitive to extra dimensions. Figure 2 demonstrates the invariant mass distributions of muon pairs for the pure Standard Model (lower curve) and for scenarios with n = 3, 4, 5, 6 extra dimensions. Cases with four different values of M_S (3, 5, 7, 10 TeV/c^2) were considered. These differential cross sections $d\sigma/dM_{\mu\mu}$ were obtained following [13] taking into account the next-to-leading-order QCD corrections (using the K_{QCD} factor of 1.3 [18]).

Eight samples (10 000 simulated events for each) with $n = 3$ and $n = 6$ for the various fundamental Planck mass values, M_S = 3, 5, 7, 10 TeV/c^2, have been created using the CMS kinematics interface with physics generators CMKIN version 4_1_0 [19]. Also, a sample of Drell-Yan events for the Standard Model has been generated. Only events with at least two muons in the pseudorapidity range $|\eta| \leq 2.5$, transverse momentum $p_T \geq 7$ GeV/c for

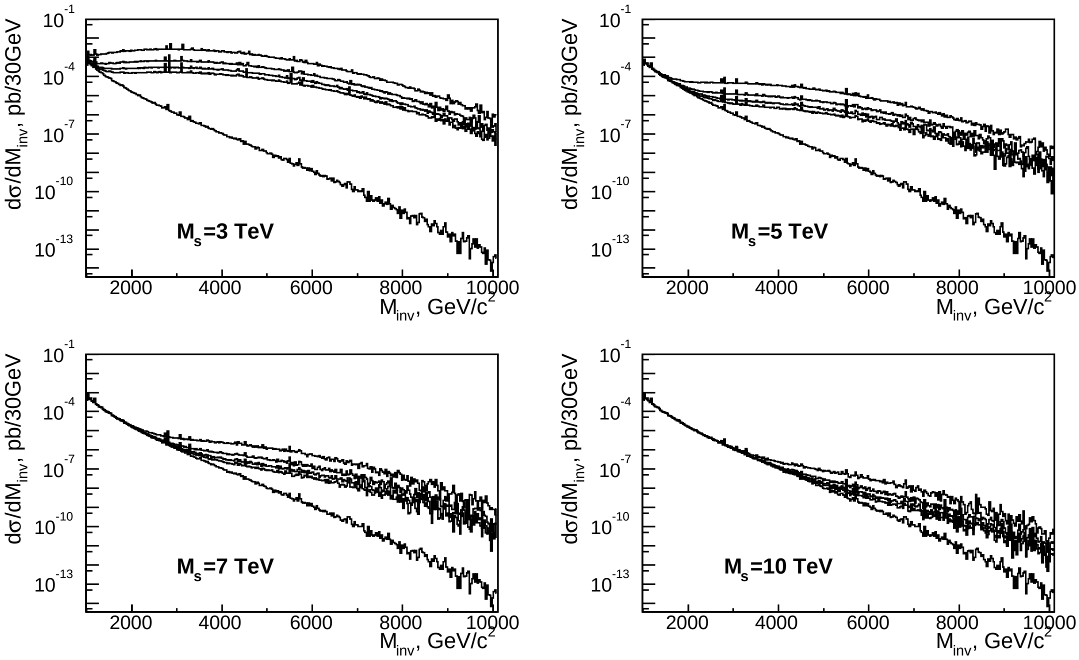

Figure 2: Dimuon invariant mass for different number of extra dimensions n (ADD). From bottom to top: SM, $n = 6$, 5, 4, 3. Four values of the fundamental gravity scale M_S are considered.

each muon and invariant mass greater than 0.8 TeV/c^2 were selected. No cuts on the isolation of muons were made at the preselection stage. The total efficiency of the dimuon preselection, ε, is about 74–96 % depending on the fundamental Planck scale. The preselected cross sections of Drell-Yan production with the ADD scenario are given in Table 1. The preselected Drell-Yan cross section in the Standard Model is 5.77 fb. For this analysis, a K-factor of 1.3 from QCD high-order terms has been used [18].

Table 1: Leading-order cross sections (in fb) of Drell-Yan production for ADD scenario with $n = 3$ and 6 and $M_S = 3$, 4, 5, 7 TeV/c^2.

M_S, TeV/c^2	3.0	4.0	5.0	7.0
$n = 3$	1.5×10^3	160	32.1	8.1
$n = 6$	103	11.4	10.1	6.4

The irreducible backgrounds are vector boson pair production, ZZ, WZ, WW, $t\bar{t}$ production etc. In the SM the expected leading-order cross section of ZZ, WZ, WW and $t\bar{t}$ events is negligible in comparison with the Drell-Yan one (for details see [20]). For example, the cross-sections of di-bosons and $t\bar{t}$ production with effective invariant masses greater than 1 TeV/c^2 are equal of 2.59×10^{-4} fb and 2.88×10^{-4} fb respectively.

3 Detector response, triggering and offline reconstruction

To simulate the particle propagation inside the detector, the GEANT4-based OSCAR package version 3_2_4 [10] was used. The digitization was performed with the official CMS reconstruction package ORCA version 8_5_0 [12], without pile-up of minimum-bias collisions.

The trigger simulations are realized on the basis of the ORCA package version 8_13_2 by using the online reconstruction algorithm. We have required that for each event that the "double muon" or "single muon" trigger be satisfied. This means that at least one muon candidate is within pseudorapidity region $|\eta| \leq 2.1$.

The Level-1 trigger performs a first selection over the events. It passes only events containing two muons with a momentum greater than 3 GeV/c or one inclusive muon with a momentum greater 14 GeV/c. The efficiency of the Level-1 trigger for analyzed samples is about 99 %.

All events accepted by Level-1 Trigger go to the High-Level Trigger. The HLT algorithms reconstruct events in two stages. First of all, the Level-2 algorithm using information only from muon chambers is applied to re-evaluate the p_T of muons coming from Level-1. At the next step, Level-3, tracker hits are added to the muon tracks to refine finally the p_T measurements. Additional cuts on tracker isolation of muon track have been applied at the HLT level. The thresholds used at the muon HLT selection are 7 GeV/c for the HLT double muon trigger and 19 GeV/c for the HLT single muon trigger. The total efficiency of triggering including reconstruction and trigger selection efficiency is 98 %. The mass resolution of reconstructed dimuon pairs after HLT is better than 5 %. Note, however, that a significant decrease in the trigger efficiency occurs when calorimeter isolation is applied (down by 15 %). The cause of this drop has to do with electromagnetic radiation and interactions of muons at very high p_T. Tracker isolation, on the other hand, practically does not affect the trigger efficiency. Based on this consideration, calorimeter isolation was not applied in this study.

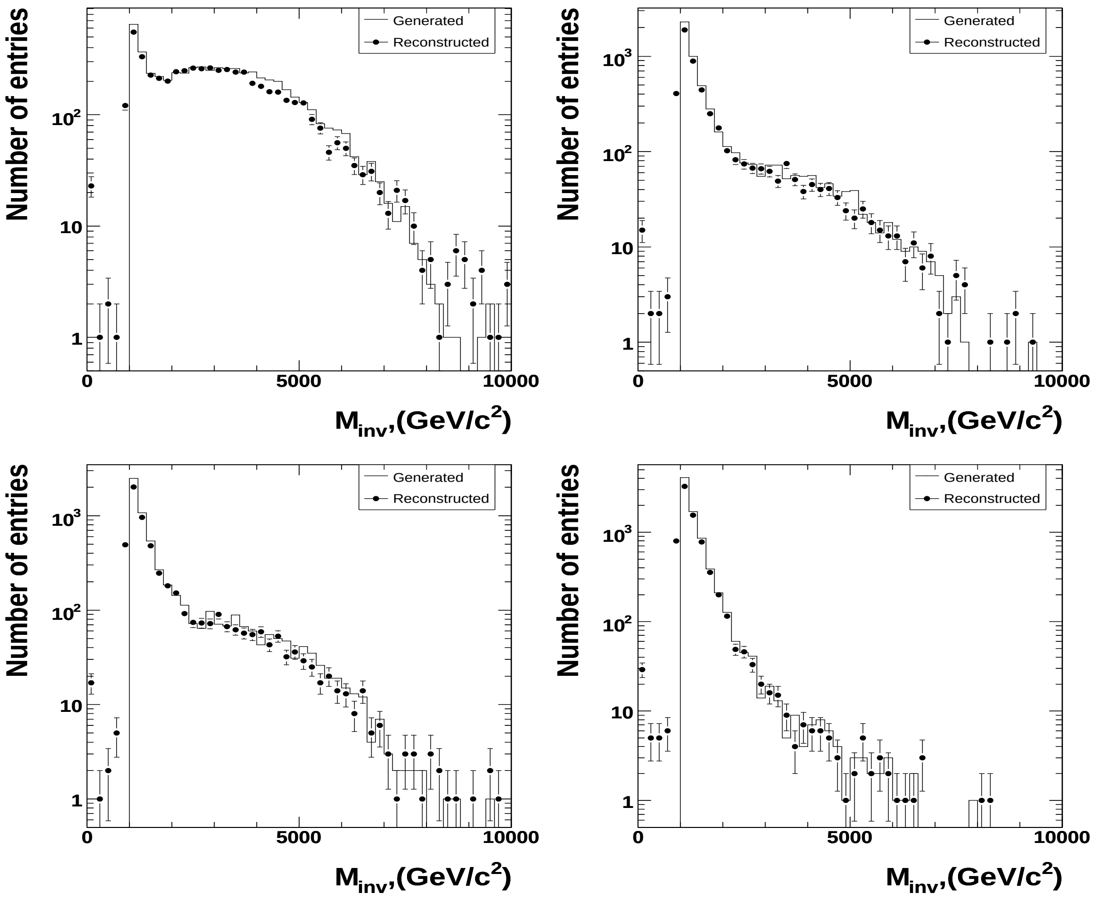

Figure 3: The reconstructed (dots) and generated (histogram) invariant mass spectrum for the ADD events with $M_S = 5.0$ TeV/c^2 and for $M_S = 6.0$ TeV/c^2 for $n = 3$ (left side) and $n = 6$ (right side). The *Long Term* misalignment scenario is considered. A cut-off on the invariant mass of 1 TeV/c^2 is applied.

We have used the Global Muon Reconstructor (GMR) algorithm [21] of ORCA package version 8_13_2 to reconstruct muons and required at least two offline reconstructed muons with opposite charge. The offline reconstruction algorithm was applied only to events which have passed trigger selection. The four examples of the offline reconstructed invariant-mass spectrum for signal plus background (ADD-graviton + Drell-Yan) are given in Fig. 3 for $M_S = 5.0$ TeV/c^2 and $M_S = 7.0$ with $n = 3$ (left side) and $n = 6$ (right side). The generated spectra are also presented for comparison. The cut-off on the invariant mass of 1 TeV/c^2 is used. Note, that detailed comparisons of the mass spectra obtained with OSCAR-ORCA full or FAMOS [22] fast simulation are performed, giving overall good agreement. The residual for invariant mass is given in Figure 4. The offline reconstruction efficiency and dimuon mass resolution for samples with SM Drell-Yan events is about 96 % and 3.7 % respectively. The reconstruction efficiency for ADD events is close to the SM case and depends weakly on the model parameter (drops by 1 % with M_S decreasing) while the mass resolution varies from 4.8 % to 6.8 %. The reason for such behavior of mass resolution is a relative higher rate of high-mass dimuons with decreasing of M_S. Thus, the overall efficiency for the full reconstruction procedure taking into account acceptance, trigger and offline reconstruction inefficiency is 70-90% depending on the model parameters.

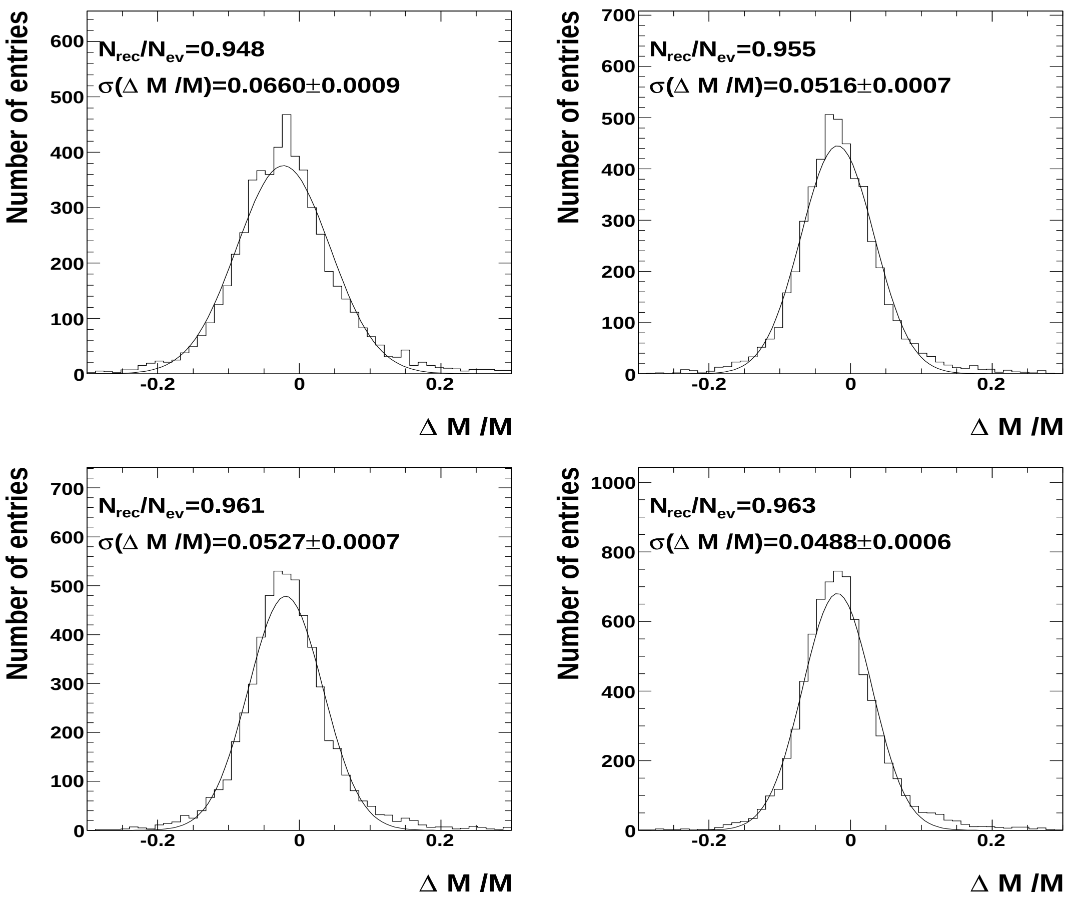

Figure 4: Invariant mass resolution for ADD events with $M_S = 5.0$ TeV/c^2 and $M_S = 7.0$ TeV/c^2 for $n = 3$ (left side) and $n = 6$ (right side). The *Long Term* misalignment scenario is considered. A cut-off on the invariant mass of 1 TeV/c^2 is applied.

Note that in this analysis, the search for final state photons in a small cone around the muon in order to recover any final state radiation or bremsstrahlung is not performed and is expected to have only a negligible effect.

Examples of the main kinematic distributions of muons for ADD events are shown in Figs. 5 and 6. One observes that both the reconstructed pseudorapidity and azimuthal angle are in a good agreement with generated ones. The distribution of reconstructed transverse momentum is somewhat broader than the generated distribution, with some small feed-up of the reconstructed dimuons to the high-mass region due to finite momentum resolution. Note that low M_S values give more events at very high mass, where the momentum resolution is even worse and the smearing effect larger.

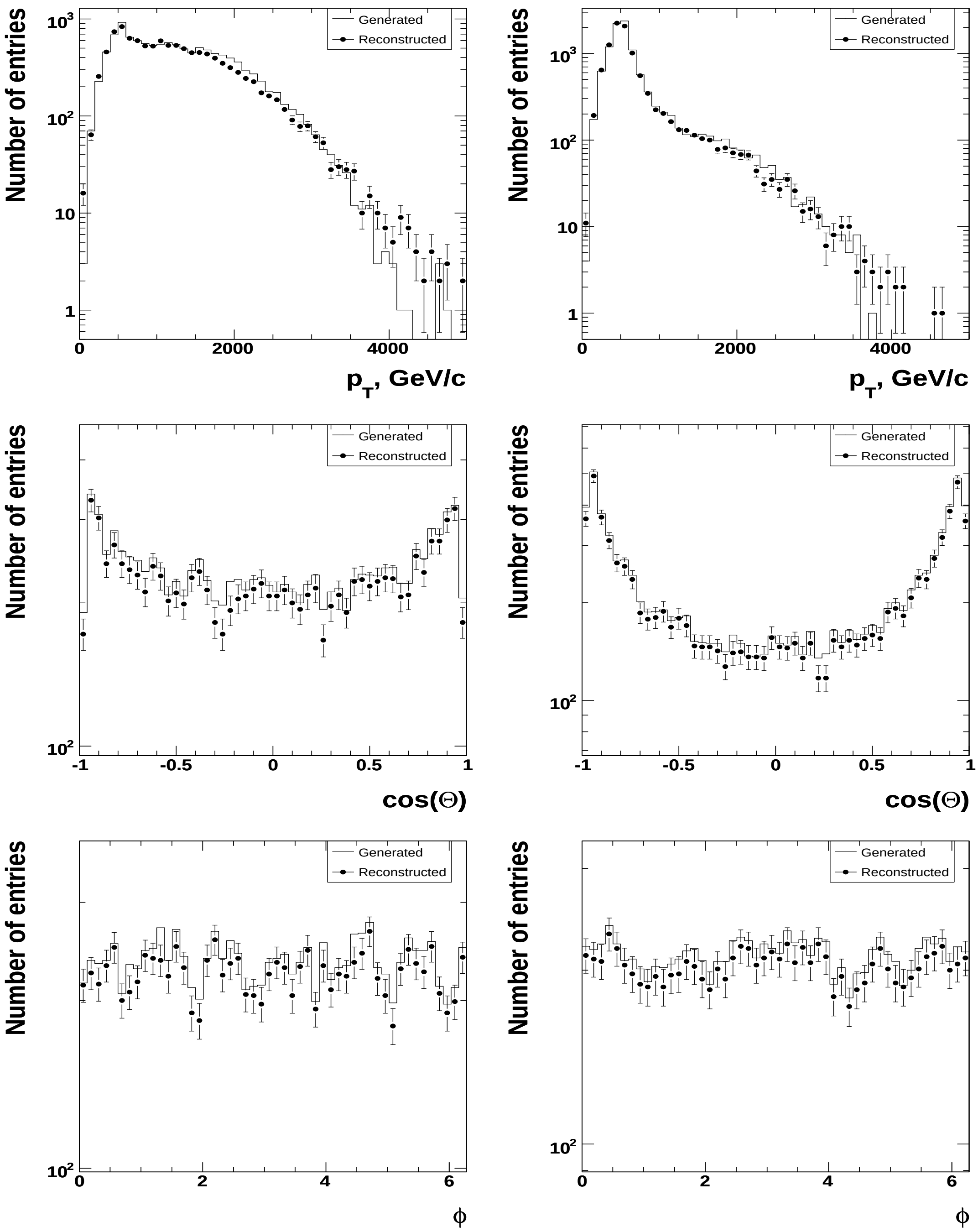

Figure 5: The reconstructed (dots) and generated (histogram) (a) p_T, (b) $\cos\theta$, and (c) ϕ spectra for the ADD events with $M_S = 5.0$ TeV/c^2 for $n = 3$ (left side) and $n = 6$ (right side). The *Long Term* misalignment scenario is considered. The cut-off on the invariant mass of 1 TeV/c^2 is used.

4 CMS discovery potential

For further analysis the offline reconstructed events with at least two muons of opposite charge and invariant masses greater than $M_{\rm cut}$ have been used. To avoid a drop of signal-to-background ratio with increasing M_S, different selection cuts on the invariant mass have been used: $M_{\rm cut}$ = 1 TeV/c^2 for M_S=3 TeV/c^2, $M_{\rm cut}$ = 1.5 TeV/c^2 for M_S=4 and 5 TeV/c^2, $M_{\rm cut}$ = 2.0 TeV/c^2 for M_S=7 and 10 TeV/c^2.

Various significance estimators have been proposed in the literature [23, 24], ranging from the estimators counting the number of the signal and background events in a certain mass range around observed peak to estimators using the ratio of likelihoods for fits with a signal+background hypothesis to that with a pure background hypothesis.

The S_{cP} definition [25] is close to the significance function $S_{cL} = \sqrt{2((N_S + N_B)\ln(1 + N_B/N_B) - N_S)}$

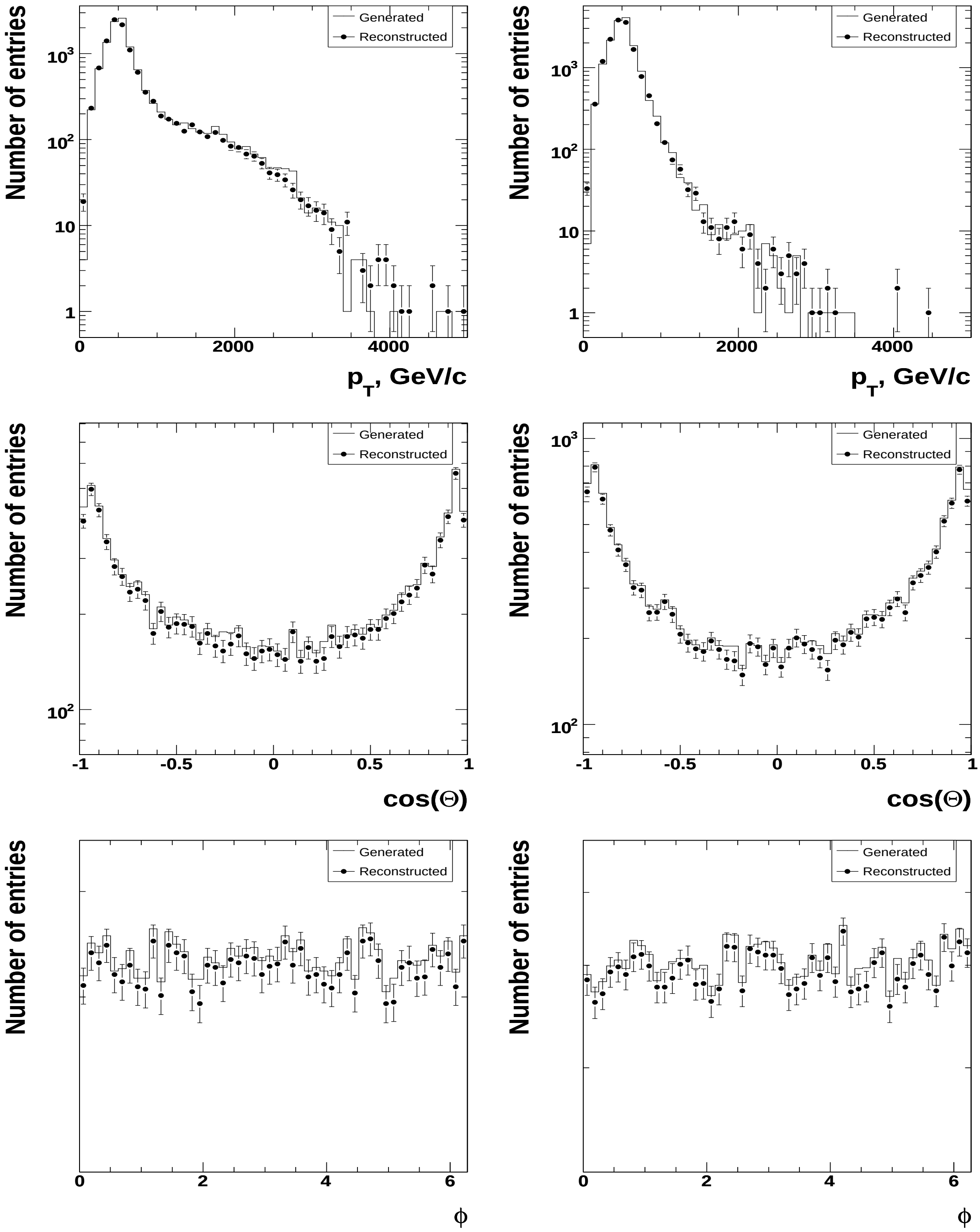

Figure 6: The reconstructed (dots) and generated (histograms) (a) p_T, (b) $\cos\theta$, and (c) ϕ spectra for the ADD events with with $M_S = 7.0$ TeV/c^2 for $n = 3$ (left side) and $n = 6$ (right side). The *Long Term* misalignment scenario is considered. The cut-off on the invariant mass of 1 TeV/c^2 is used.

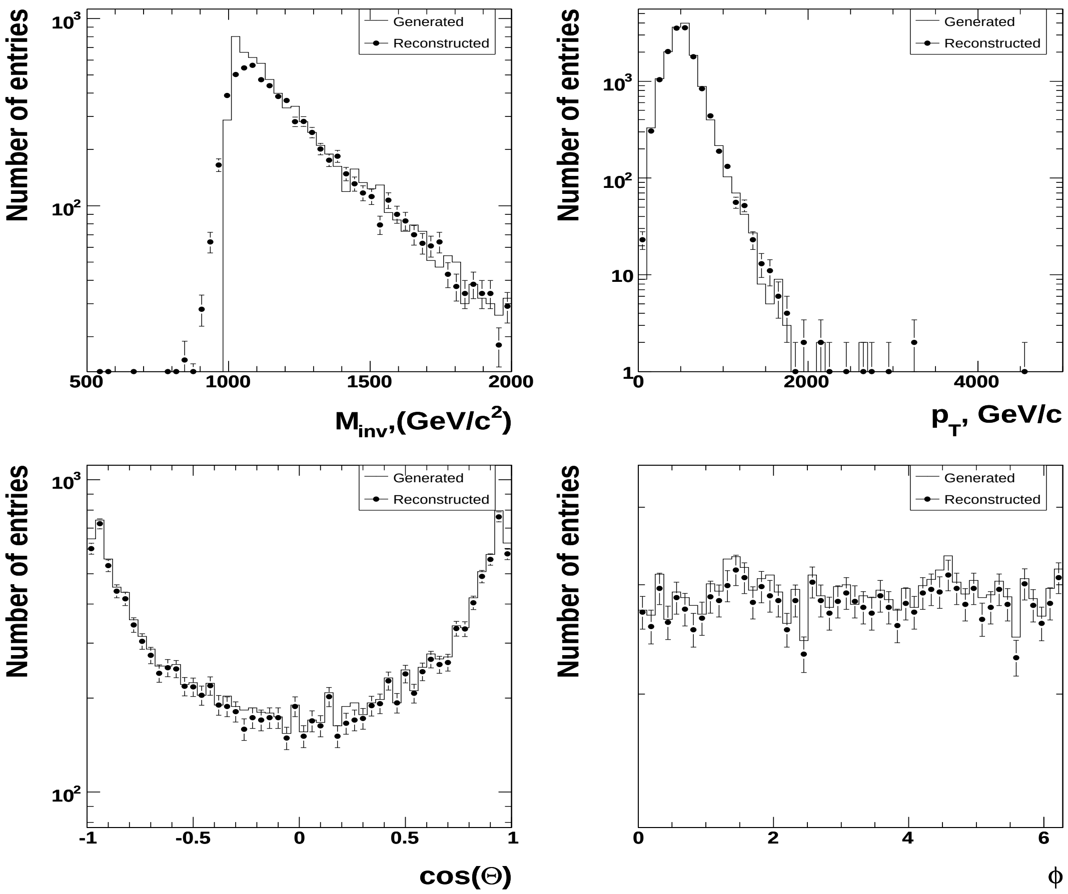

Figure 7: The reconstructed (dots) and generated (histograms) (a) invariant mass, (b) p_T, (c) $\cos\theta$ and (d) ϕ spectra for the DY events. The *Long Term* misalignment scenario is considered. The cut-off on the invariant mass of 1 TeV/c^2 is used.

suitable for small event samples [23] which has been shown to give practically the same numerical values as the S_{cP} estimator, where N_S is the number of signal events passed through all kinematics cuts and N_B is the number of background events.

The computed significance values S_{cL} for the ideal detector as a function of a fundamental theory scale, M_S, are presented in Fig. 8 for integrated luminosities of 0.1, 1.0, 10, 100, 300, 1000 fb^{-1}. The main observations are:

- $\int \mathcal{L}dt = 1$ fb^{-1}, even a low luminosity regime allows one to measure the effect from the virtual contributions of ADD gravitons to the Drell-Yan process for the effective fundamental Planck scale of 4.0 TeV/c^2 for the most unfavorable case with $n = 6$. For more the promising scenario where the number of extra dimensions is minimal ($n = 3$) the reach limit is extended up to 5.8 TeV/c^2.
- $\int \mathcal{L}dt = 10$ fb^{-1}, M_S values of 4.8 and 7.2 TeV/c^2 can be reached for $n = 3$ and $n = 6$ respectively.
- $\int \mathcal{L}dt = 100$ fb^{-1}, one year of LHC operation in the high luminosity regime provides observation of the ADD signal at 5.8–8.7 TeV/c^2 on the model scale depending on the number of extra dimensions.
- $\int \mathcal{L}dt = 300$ fb^{-1}, in asymptotic regime the CMS sensitivity to fundamental Planck scale is increased up to values of 6.5–9.3 TeV/c^2.

Another common method used in experimental physics to estimate the significance is the estimator S_{c12} proposed by S. Bityukov and N. Krasnikov [26]. S_{c12} is closest to the likelihood estimator $S_{\mathcal{L}}$ that is the most optimal for the small-statistics background as was discussed in [24]. The values of the significance computed by other methods, $S_{c12} = 2(\sqrt{N_S + N_B} - \sqrt{N_B})$, are given in the Appendix (Table 2). The ambiguity due to the usage of different estimators (2–40 %) leads to uncertainties in the M_S reach up to 8.6 % depending on the signal-to-background ratio.

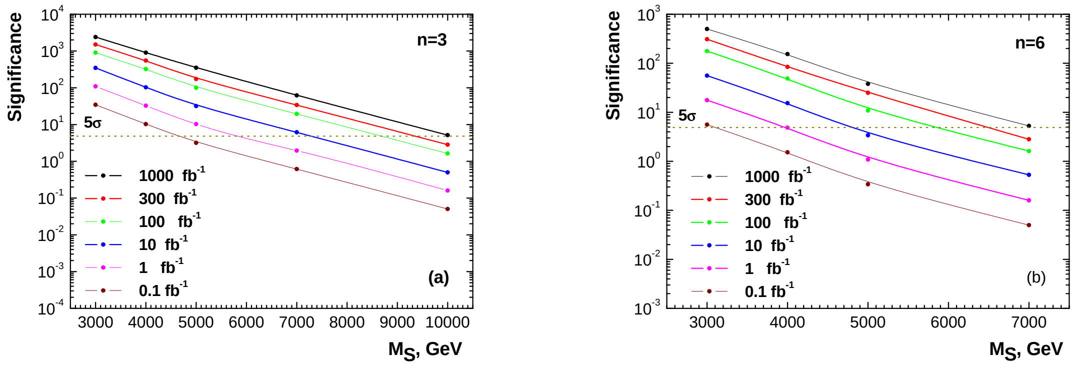

Figure 8: Significance as a function of M_S for (a) $n = 3$ and (b) $n = 6$.

Note that these estimates are reasonably close to earlier results [13] which were obtained having used the maximum likelihood method and a Bayesian approach but without a detailed simulation of the detector response. They conclude that using a combination of both the electron and the muon channels, the sensitivity to M_S for 100 fb^{-1} is about 6.9 to 10.2 TeV/c^2 for $n = 6$–2.

The earlier analysis does not include the possible impact of systematic effects on the obtained results. To extract correctly the signal events from the background we should understand the reliability of calculations of the dilepton spectrum within the Standard Model to keep under control all possible sources of errors and systematic uncertainties. These systematics include the accuracy of theoretical calculations, the accuracy of the phenomenological determination of PDFs, and imperfections of experimental data – detector resolution, misalignment, goodness of fits, etc.

Unfortunately, the S_{cL} method does not take into account systematics uncertainties. To estimate the ADD discovery limit accounting for both statistical and systematic uncertainties of the background one can use the significance estimator S_{cP} defined as the probability from a Poisson distribution with mean N_B to observe greater or equal than $(N_S + N_B)$ events, converted to the equivalent number of sigmas of a Gaussian distribution [25].

The experimental uncertainties: In this analysis we assume that the CMS Muon System and Tracker will suffer from different effects significantly distorting both their ideal geometry and reconstruction efficiency.

To take into account the misalignment effect, two misalignment scenarios were considered during the reconstruction procedure: the *First Data* scenario [27] for 0.1 and 1.0 fb^{-1} and the *Long Term* scenario [27] for 10, 100, 300, and 1000 fb^{-1}.

The trigger, reconstruction and selection systematics can be estimated in the following way. The overall efficiency for the full reconstruction procedure, taking into account the L1+HLT trigger and offline reconstruction inefficiency, changes from 97% to 93 %. So very conservatively we may assign half of this change with mass, i.e. 2 % [20], as the systematic uncertainty.

Other possible uncertainties come from luminosity and magnetic field uncertainties. These sources of systematic effects will need to be taken into account in future studies.

The theoretical uncertainties: A K-factor of $K = 1.30 \pm 0.05$ is used both for the ADD signal and Drell-Yan background. The size of additional electroweak corrections varies from 9.5 to 13.5 % for the invariant mass range of M_{inv} = 1–2 TeV/c^2 [28] (for details see [20]). We have normalized the dimuon spectra to this scale to take into account the EW high-order terms.

As the systematic variations of the cross section for background we take uncertainties from the hard process scale, PDFs and QCD-corrections for Drell-Yan processes.

The dependence of the cross section for the background on the definition of the hard process scale (Q^2) varies within a few percent, 4.8–7.7%, for the CTEQ6 PDF set [16]. This value was calculated by the way described in [29].

The PDF uncertainties come from the accuracy of the global analysis of experimental data and from experimental measurement errors. A recently developed PDF building technique goes beyond the ”standard” paradigm of extracting only one "best fit". The latest versions of PDF sets contain various alternative fits obtained by subjective tuning of specific degrees of freedom for this PDF [17]. We have calculated the PDF uncertainty using the CTEQ6 set by two master equations [29]:

$$\Delta X = \frac{1}{2}\sqrt{\sum_{k-1}^{d} D_k^2} \quad (a) \quad \text{and} \quad \Delta X_C = \frac{1}{2}\sqrt{\sum_{k=1}^{2d} R_k^2} \quad (b), \tag{5}$$

here $D_k = X_{2k} - X_{2k-1}$ (k = 1–d) and $R_k = X_k - X_0$ (k = 1–2d), where X_0 is the cross section evaluated with the "best-fit" PDF (CTEQ6m) and $X_k^{\pm}$ is the cross section evaluated with the k-th PDF subset. The obtained value for the uncertainty so obtained is equal to 5.6–6.8 % and 4.8–5.8 % for formulas 5(a) and 5(b) respectively in depending on the Drell-Yan invariant mass range (for details see [20]).

Generally, both types of uncertainties decrease the significance by 2–30 % depending on the signal-to-background ratio, and, as a consequence worsen the discovery limit by 100–500 GeV/c^2.

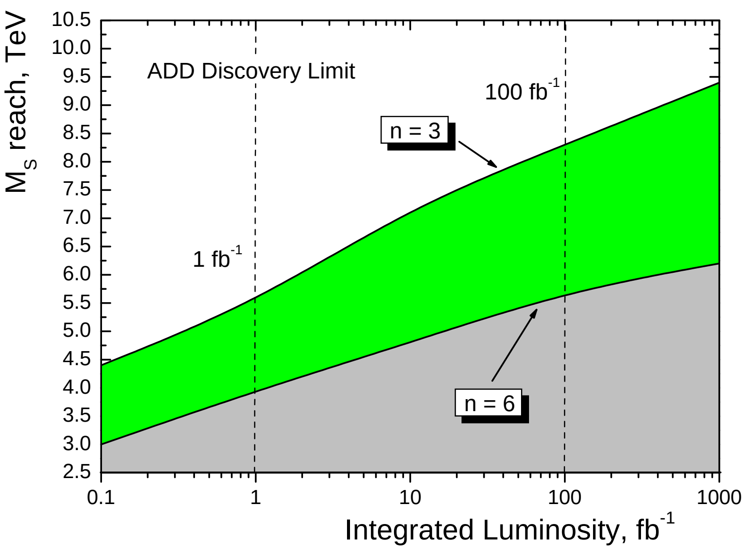

Figure 9: 5σ limit on M_S for the number of extra dimensions n = 3, 4, 5, 6.

5 Conclusions

In this work the analysis of the CMS discovery potential to observe the signal from virtual ADD gravitons in the dimuon channel has been carried out. The fundamental Planck scale reachable with the CMS detector has been computed for various values of integrated luminosity. The uncertainties related to misalignment and trigger systematic effects, PDFs, QCD-scale errors, EW and QCD corrections were taken into account. These results are summarized in Figure 9 where the reachable values of the fundamental Planck mass, M_S, with 5σ significance for various number of extra dimensions, n, are shown as a function of an integrated luminosity. The filled area between two curves (n = 3 and n = 6) shows the discovery limit on M_S for different possible numbers of extra dimensions: n = 3, 4, 5, 6. It shows that even the first LHC run with an integrated luminosity of 1 fb^{-1} allows exploration of the new ADD model scale region between 3.9 and 5.5 TeV/c^2 uncovered so far by other colliders (LEP and TEVATRON). An increase of the collected luminosity up to 100 fb^{-1} makes it possible to probe low-scale gravity with the fundamental Planck scale of 5.7–8.3 TeV/c^2. In the LHC asymptotic regime the CMS sensitivity to the fundamental Planck scale is increased up to values of 5.9–8.8 TeV/c^2.

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Appendix

Table 2: The significance values S_{cL}

M_S, GeV	3000	4000	5000	7000	10000
$n=3$					
1 fb^{-1}	69	22	7.7	1.7	-
10 fb^{-1}	219	68	24	5.2	0.5
100 fb^{-1}	694	215	78	16.6	1.6
300 fb^{-1}	1201	373	133	29	2.8
1000 fb^{-1}	2193	680	243	52	5.0
$n=6$					
1 fb^{-1}	14	4.1	1.0	0.16	-
10 fb^{-1}	44	13	3.2	0.51	-
100 fb^{-1}	141	41	10	1.6	-
300 fb^{-1}	243	70	18	2.82	-
1000 fb^{-1}	445	129	32	5.1	3.4