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First results on precision constraints on $Z-Z'$ mixing with ATLAS and CMS diboson production data at the LHC at 13 TeV and predictions for Run II

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Abstract. The study of electroweak boson pair production provides a powerful tool to search for new phenomena beyond the Standard Model (SM). Extra neutral vector bosons Z' decaying to charged gauge vector boson pairs W^+W^- are predicted in many scenarios of new physics, including models with an extended gauge sector. The diboson production allows to place stringent constraints on the Z-Z' mixing parameter ξ and Z' mass, $M_{Z'}$. We present the Z' exclusion region in the $\xi - M_{Z'}$ plane for the first time by using data comprised of pp collisions at $\sqrt{s}$ = 13 TeV and recorded by the ATLAS and CMS detectors at the CERN LHC, with integrated luminosities of 36.1 and 35.9 fb^{-1}, respectively. The exclusion region has been significantly extended compared to that obtained from the previous analysis performed with Tevatron data, as well as with LHC data collected at 7 and 8 TeV. Also, we found that these constraints on the Z-Z' mixing factor are more severe than those derived from the global analysis of electroweak data. Further improvement on the constraining of this mixing can be achieved from the analysis of data to be collected at higher luminosity expected in Run II.

1 Introduction

Many new physics (NP) scenarios beyond the SM [1], including superstring and left-right-symmetric models, predict the existence of new neutral and charged gauge bosons, which might be light enough to be accessible at current and/or future colliders [2]. The search for these new neutral Z' and charged W' gauge bosons is an important aspect of the experimental physics program of high-energy colliders. In this note we concentrate on the former one.

Present limits from direct production at the LHC and virtual effects at LEP, through interference or mixing with the Z boson, imply that any new Z' boson is rather heavy and mixes very little with the Z boson. Depending on the considered theoretical model, Z' masses of the order of 4.5 TeV [3, 4] and Z-Z' mixing angles at the level of a few per mil are excluded [5] (see also [6, 7]). The mixing angle is strongly constrained by very high-precision experiments at LEP and the SLC [8]. They include measurements from the Z line shape, from the leptonic branching ratios normalized to the total hadronic Z decay width as well as from leptonic

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forward-backward asymmetries. A Z' boson, if lighter than about 5 TeV, could be discovered at the LHC with $\sqrt{s} = 14$ TeV in the Drell-Yan (DY) process $pp \to Z' \to \ell^+\ell^- + X$ with $\ell = e, \mu$.

After the discovery of a Z' boson at the LHC via the DY process, some diagnostics of its couplings and Z-Z' mixing needs to be performed in order to identify the underlying theoretical framework. In this note we investigate the implications of the ATLAS [9] and CMS [10] data in the diboson channel

$$pp \to W^+W^- + X \tag{1}$$

to probe the Z' boson that arises, e.g. in a popular model with extended gauge sector proposed in [11]. The analysis is based on pp collision data at a center-of-mass energy $\sqrt{s} = 13$ TeV, collected by the ATLAS (36.1 fb^{-1}) and CMS (35.9 fb^{-1}) experiments at the LHC. In particular, the data is used to probe the Z-Z' mixing.

The $W^\pm$ boson pair production process (1) is important for studying the gauge coupling strength between the new and the standard-model gauge bosons [12–15]. Furthermore, the coupling strength strongly influences the decay branching ratios and the natural widths of such a new gauge boson. Thus, detailed examination of the process (1) will both test the gauge sector of the SM with high accuracy and shed light on NP that may appear beyond the SM. In this work, we derive bounds on a possible new neutral spin-1 resonance (Z') from the available ATLAS and CMS data on W^+W^- pair production [16].

The paper is organized as follows. In Section II, we give expressions for basic observables (cross sections) of the process under consideration at parton and hadron levels. In Section III, the numerical analysis and constraints on Z-Z' mixing are presented. Section IV presents some concluding remarks.

2 Cross section

There are many theoretical models which predict a Z' with mass possibly in the TeV range. We will consider a NP model where Z''s interact with light quarks and charged gauge bosons via their mixing with the SM Z assuming that the Z' couplings exhibit the same Lorentz structure as those of the SM. In particular, in the present analysis we will focus on a gauge boson of the "sequential standard model" (SSM). In the simple reference model described in [11], the couplings of the Z' boson to fermions (quarks, leptons) and W bosons are a direct transcription of the corresponding standard-model couplings. Note that such a Z' boson is not expected in the context of gauge theories unless it has additional couplings to exotic fermions. However, it serves as a useful reference case when comparing constraints from various sources. It could also play the role of an excited state of the ordinary Z in models of compositeness or with extra dimensions at the weak scale.

In many extended gauge models, while the couplings to fermions are not much different from those of the SM, the $Z'WW$ coupling is substantially suppressed with respect to that of the SM. In fact, in an extended gauge model the standard-model trilinear gauge boson coupling strength, g_{WWZ} ($= \cot\theta_W$), is replaced by $g_{WWZ} \to \xi \cdot g_{WWZ}$, where $\xi = C \cdot (M_W/M_{Z'})^2$ is the mixing factor and C the coupling strength scaling factor. We will set cross section limits on such $Z'_{\rm SSM}$ as a function of the mass $M_{Z'}$ and ξ. One should note that most Z' search results report mass limits along the $\xi = (M_W/M_{Z'})^2$ line ($C = 1$ is referred to as "reference model") and we have also done so for comparison.

The differential cross section for Z' production in the process (1) from initial quark-antiquark states can be written as

$$\frac{d\sigma^{Z'}}{dM\,dy\,dz} = K\frac{2M}{s}\sum_q [f_{q|P_1}(\xi_1)f_{\bar{q}|P_2}(\xi_2) + f_{\bar{q}|P_1}(\xi_1)f_{q|P_2}(\xi_2)]\,\frac{d\hat{\sigma}^{Z'}_{q\bar{q}}}{dz}. \tag{2}$$

Here, s denotes the proton-proton center-of-mass energy squared, $z \equiv \cos\theta$, with θ the W^--boson–quark angle in the W^+W^- center-of-mass frame and y is the diboson rapidity. Furthermore, $f_{q|P_1}(\xi_1, M)$ and $f_{\bar{q}|P_2}(\xi_2, M)$ are parton distribution functions for the protons P_1 and P_2, respectively, with $\xi_{1,2} = (M/\sqrt{s})\exp(\pm y)$ the parton fractional momenta. Finally, $d\hat{\sigma}^{Z'}_{q\bar{q}}/dz$ are the partonic differential cross sections. In (2), the K factor accounts for higher-order QCD contributions. For numerical computation, we use CTEQ-6L1 parton distributions. Our estimates will be at the Born level, hence the factorisation scale μ_F enters solely through the parton distribution functions, as the parton-level cross section at this order does not depend on μ_F. As regards the scale dependence of the parton distributions we choose for the factorization scale the W^+W^- invariant mass, $\mu^2_\mathrm{F} = M^2 = \hat{s}$, with $\hat{s} = \xi_1\,\xi_2\,s$ the parton subprocess c.m. energy squared. The obtained constraints presented in the following are not significantly modified when μ_F is varied from $\mu_\mathrm{F}/2$ to $2\mu_\mathrm{F}$.

The cross section for the narrow Z' state production and subsequent decay into a W^+W^- pair needed in order to estimate the expected number of Z' events, $N^{Z'}$, is derived from (2) by integrating the right-hand-side over z, over the rapidity of the $W^\pm$-pair y and invariant mass M around the resonance peak $(M_R - \Delta M/2,\, M_R + \Delta M/2)$:

$$\sigma^{Z'}(pp \to W^+W^- + X) = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} dM \int_{-Y}^{Y} dy \int_{-z_\mathrm{cut}}^{z_\mathrm{cut}} dz \frac{d\sigma^{Z'}}{dM\,dy\,dz}\,, \tag{3}$$

where the phase space can be found, e.g. in [14]. Using Eq. (3), the number of signal events for a narrow Z' resonance state can be written as follows

$$N^{Z'} = \mathcal{L}\cdot\varepsilon\cdot\sigma^{Z'}(pp \to W^+W^- + X) \equiv \mathcal{L}\cdot\varepsilon\cdot A_{WW}\cdot\sigma(pp \to Z')\times \mathrm{Br}(Z' \to W^+W^-). \tag{4}$$

Here, $\mathcal{L}$ denotes the integrated luminosity, and the overall kinematic and geometric acceptance times trigger, reconstruction and selection efficiencies, $A_{WW}\times\varepsilon$, is defined as the number of signal events passing the full event selection divided by the number of generated events. Finally, $\sigma(pp \to Z') \times \mathrm{Br}(Z' \to W^+W^-)$ is the (theoretical) total production cross section times branching ratio extrapolated to the total phase space.

The differential cross section for the processes $q\bar{q} \to Z'_\mathrm{SSM} \to W^+W^-$, averaged over quark colors, can be written as [14]

$$\frac{d\hat{\sigma}^{Z'}_{q\bar{q}}}{d\cos\theta} = \frac{1}{3}\,\frac{\pi\alpha^2\cot^2\theta_W}{16}\left(v_f^2 + a_f^2\right)\frac{\hat{s}}{\left(\hat{s} - M^2_{Z'}\right)^2 + M^2_{Z'}\Gamma^2_{Z'}}$$
$$\times\,\xi^2\beta_W^3\left(\frac{\hat{s}^2}{M_W^4}\sin^2\theta + 4\frac{\hat{s}}{M_W^2}(4 - \sin^2\theta) + 12\sin^2\theta\right), \tag{5}$$

where $v_f = (T_{3,f} - 2Q_f\,s_W^2)/(2s_Wc_W)$, $a_f = T_{3,f}/(2s_Wc_W)$. Finally, $M_{Z'}$ and $\Gamma_{Z'}$ denote the mass and total width of the Z' boson.

In the calculation of the total width $\Gamma_{Z'}$ we included the following channels: $Z' \to f\bar{f}$, W^+W^-, and ZH, where H is the SM Higgs boson and f are the SM fermions ($f = l, \nu, q$). The total width $\Gamma_{Z'}$ of the Z' boson can be written as follows:

$$\Gamma_{Z'} = \sum_f \Gamma^{ff}_{Z'} + \Gamma^{WW}_{Z'} + \Gamma^{ZH}_{Z'}. \tag{6}$$

The presence of the two last decay channels, which are often neglected, is due to Z-Z' mixing. However for large Z' masses there is an enhancement that cancels the suppression due to tiny $Z-Z'$ mixing parameter ξ. Notice that for all $M_{Z'}$ values of interest for LHC the width of the $Z'_{\rm SSM}$ boson is considerably smaller than the mass resolution ΔM.

The expression for the partial width of $Z' \to W^+W^-$ decay channel can be written as [11]:

$$\Gamma^{WW}_{Z'} = \frac{\alpha}{48}\cot^2\theta_W\, M_{Z'}\left(\frac{M_{Z'}}{M_W}\right)^4\left(1-4\frac{M_W^2}{M_{Z'}^2}\right)^{3/2}\left[1+20\left(\frac{M_W}{M_{Z'}}\right)^2+12\left(\frac{M_W}{M_{Z'}}\right)^4\right]\xi^2. \quad (7)$$

The dominant term in the second line of Eq. (5), for $M^2 \gg M_W^2$, is proportional to $(M/M_W)^4\sin^2\theta$ and corresponds to the production of longitudinally polarized W's, $Z' \to W_L^+W_L^-$. This strong dependence on the invariant mass results in a very steep growth of the cross section with energy and therefore a substantial increase of the cross section sensitivity to Z-Z' mixing at high M. In its turn, for a fixed mixing factor ξ and at large $M_{Z'}$ where $\Gamma^{WW}_{Z'}$ dominates over $\sum_f \Gamma^{ff}_{Z'}$ and $\Gamma^{ZH}_{Z'}$ the total width increases very rapidly with the mass $M_{Z'}$ because of the quintic dependence on the Z' mass of the W^+W^- mode as shown in Eq. (7) [11]. In this case, the W^+W^- mode becomes dominant and Br$(Z' \to W^+W^-) \to 1$, while the fermionic decay channels are increasingly suppressed as demonstrated in figure 1.

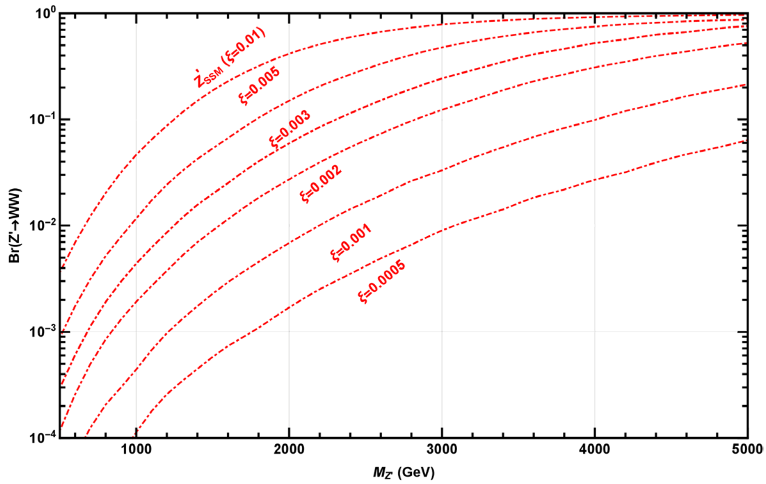

Figure 1. Branching fraction of Br$(Z' \to W^+W^-)$ vs $M_{Z'}$ for SSM model. Labels attached to the curves correspond to an array of values of mixing factor ξ ranging over the set {0.0005, 0.001, 0.002, 0.003, 0.005, 0.01}.

Further contributions of decays involving Higgs and/or gauge bosons and supersymmetric partners (including sfermions), which are not accounted for in (6), could increase $\Gamma_{Z'}$ by a model-dependent amount, as large as 50% [12]. In this case, $\Gamma_{Z'}$ would be larger, with a consequent suppression in the branching ratio to $W^\pm$, and the bounds from LHC (and their ability for observing the $Z-Z'$ mixing effect) would be weaker.

3 Numerical analysis and constraints on Z-Z' mixing

Here, we are making an analysis, employing the most recent measurements of diboson processes provided by the experimental collaborations ATLAS and CMS, which have control on

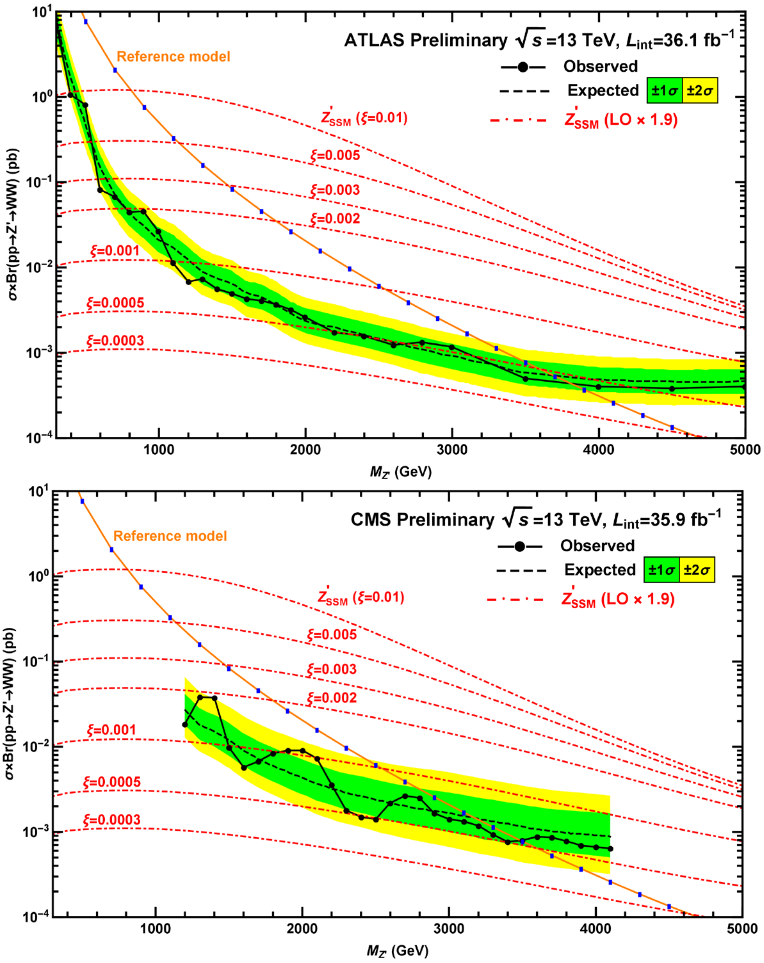

Figure 2. Observed and expected 95% C.L. upper limits on the production cross section times the branching fraction for $Z' \to W^+W^-$ as a function of Z' mass, $M_{Z'}$. Theoretical production cross sections $\sigma \times Br(Z' \to W^+W^-)$ for $Z'_{\rm SSM}$ and reference model are calculated from PYHTHIA 6.409 with a K-factor of 1.9, and given by dash-dotted curves. Labels attached to the curves for the $Z'_{\rm SSM}$ cross section correspond to the considered mixing factor ξ. Upper panel: ATLAS data for 36.1 fb^{-1}, lower panel: CMS data for 35.9 fb^{-1}.

all the information needed to perform it in a more accurate way. In particular, for $Z'_{\rm SSM}$ we compute the LHC Z' production cross-section multiplied by the branching ratio into two W bosons, $\sigma(pp \to Z') \times {\rm Br}(Z' \to W^+W^-)$, as a function of two parameters $(M_{Z'}, \xi)$, and compare it with the limits established by the ATLAS and CMS experiments. ATLAS [9] and CMS [10] analyzed the W^+W^- production in process (1) through the semileptonic and hadronic final states, respectively. Our strategy in the present analysis is to use the SM backgrounds that have been carefully evaluated by the experimental collaborations and we simulate only the Z' signal. Figure 2 shows the observed and expected 95% C.L. upper limits on the production cross section times the branching fraction for $Z' \to W^+W^-$ as a function of Z' mass, $M_{Z'}$. The data analyzed comprises pp collisions at $\sqrt{s} = 13$ TeV, recorded by the ATLAS (36.1 fb^{-1}) and CMS (35.9 fb^{-1}) detectors at the LHC. The inner (green) and outer (yellow) bands

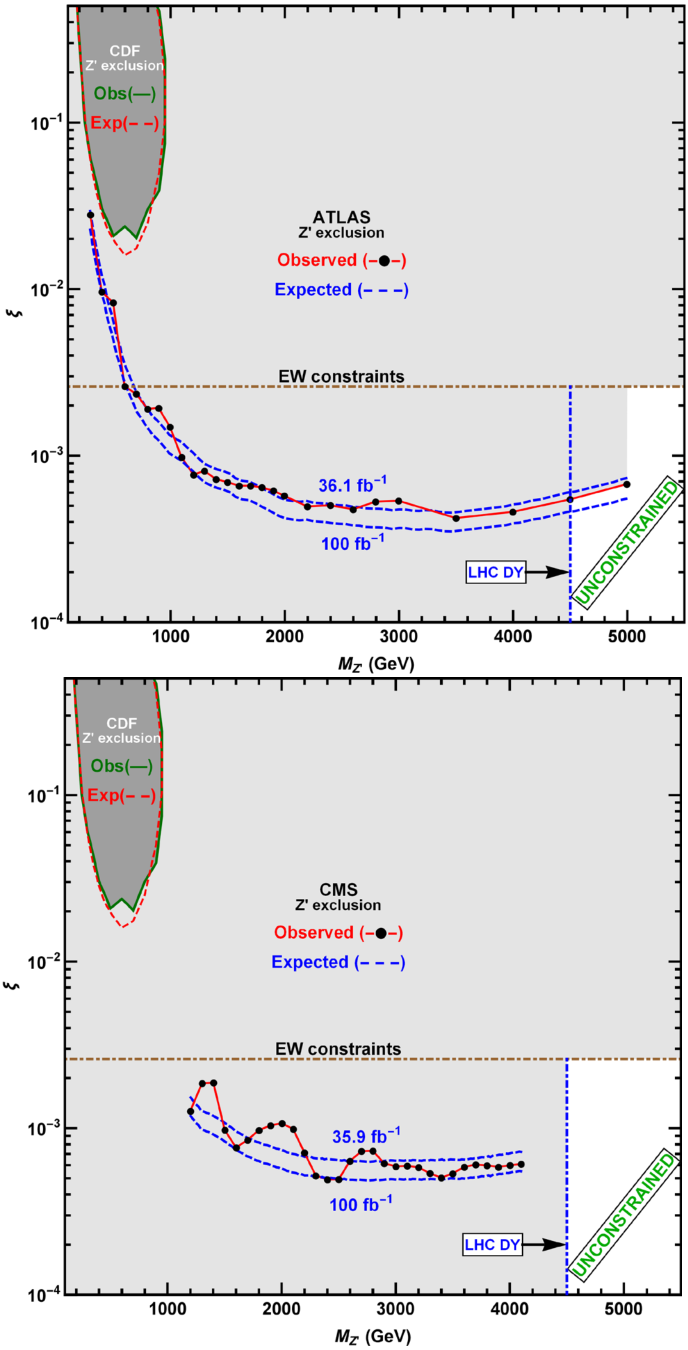

Figure 3. Z' exclusion regions in the two-dimensional plane of $(M_{Z'}, \xi)$ obtained from CDF (Tevatron), precision electroweak (EW) data and LHC data as analyzed here. The vertical dot-dashed line corresponds to the $Z'_{\rm SSM}$ mass constraints obtained from the DY process at the LHC. Left panel: ATLAS data for 36.1 fb^{-1}, right panel: CMS data for 35.9 fb^{-1}. Exclusion plots with 100 fb^{-1} of data correspond to an extrapolation of the expected sensitivity.

around the expected limits represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively. Also shown are theoretical production cross sections $\sigma \times \mathrm{Br}(Z' \to W^+W^-)$ for Z'_{SSM}, calculated from PYTHIA 6.409 adapted for such kind of analysis. Higher-order QCD corrections for the SM and Z' boson cases were estimated using a K-factor, for which we adopt a mass-independent value of 1.9. These theoretical curves for the cross sections, in descending order, correspond to values of the Z-Z' mixing factor ξ from 0.01 to 0.0005. The intersection points of the expected (and observed) upper limits on the production cross section with these theoretical cross sections for various ξ give the corresponding lower bounds on $(M_{Z'}, \xi)$ displayed in figure 3. The line with the attached label "Reference model" indicates PYTHIA defaults (except for the above-mentioned K-factor) which is commonly used for mass exclusion regions. We found that the expected (observed) exclusion limits are $M_{Z'} < 3.7$ (3.8) TeV (ATLAS) and $M_{Z'} < 3.2$ (3.5) TeV (CMS).

In figure 3, we collect limits on the Z' parameters, starting with the Tevatron studies of diboson W^+W^- pair production [6]. The limits on ξ and $M_{Z'}$ at the Tevatron assume that no decay channels into exotic fermions or superpartners are open to the Z'. Otherwise, the limits would be moderately weaker. Interestingly, figure 2 shows that at heavy Z' masses, the limits on ξ obtained from the ATLAS and CMS diboson resonance production data at the LHC at 13 TeV are stronger than those derived from the global analysis of the precision electroweak data [5].

Also, here we have extrapolated the experimental sensitivity curves for higher expected luminosity downwards by a factor of $1/\sqrt{D}$ where D is the ratio of the expected integrated luminosity of 100 fb^{-1} that will be collected at Run II by 2018 to the current integrated luminosities of 36.1 fb^{-1} and 35.9 fb^{-1}. It is clear that further improvement on the constraining of this mixing can be achieved from the analysis of such data.

4 Concluding remarks

This paper presents an analysis of Z-Z' mixing in the process of W pair production. The analysis is based on preliminary pp collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV, collected by the ATLAS and CMS experiments at the LHC. We analyze the popular Z'_{SSM} model and determine limits on its mass, $M_{Z'}$, as well as on the Z-Z' mixing (angle) factor, ξ. We present the Z' exclusion region in the $\xi - M_{Z'}$ plane for the first time by using these data. The exclusion limits represent a large improvement over previously published results obtained at the Tevatron, and also over precision electroweak data and results obtained from proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV. These are the most stringent exclusion limits to date on the $\xi - M_{Z'}$ plane. Further improvement on the constraining of this mixing can be achieved from the analysis of data which will be collected at higher luminosity in the near future at Run II of the LHC.

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