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Search for anomalous production of highly boosted Z bosons decaying to $\mu^+\mu^-$ in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

Results are reported from a search for the anomalous production of highly boosted Z bosons with large transverse momentum and decaying to $\mu^+\mu^-$. Such Z bosons may be produced in the decays of new heavy particles. The search uses pp collision data at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1} recorded with the CMS detector. The shape of the observed transverse momentum distribution of Z bosons is consistent with standard model expectations. Constraints are obtained on models predicting the production of excited quarks decaying via electroweak processes. Assuming a compositeness scale that is equal to the excited quark mass as well as transition coupling strengths between Z bosons and excited quarks that are equal to standard model couplings to quarks, masses of excited quarks below 1.94 TeV are excluded at the 95% confidence level. For excited quark production via a novel contact interaction, masses below 2.22 TeV are excluded, even if the excited quarks do not couple to gluons.

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In the standard model (SM) of particle physics, the transverse momentum (p_T) spectrum of Z bosons produced in high energy pp collisions is predicted to be a smoothly falling distribution. A broad range of new physics models such as quark compositeness [1,2], supersymmetry [3], technicolor [4], and extensions of the standard model with new gauge groups [5] predict decays of heavy particles involving Z bosons, which would introduce deviations from a smooth distribution of the Z transverse momentum spectrum. The Z boson transverse momentum distribution was measured by ATLAS [6] and CMS [7] in pp collisions at $\sqrt{s} = 7$ TeV using about 40 pb^{-1} of integrated luminosity, showing good agreement with next-to-next-to-leading order perturbative QCD calculations. This Letter presents a search for new phenomena exploiting the dimuon transverse momentum spectrum, $p_T(\mu\mu)$, of Z boson production in pp collisions. The dimuon spectrum is used to search for a new heavy particle decaying into high momentum Z bosons. Because the search is inclusive, no constraints are imposed on the presence of additional particles in the decay of the hypothetical heavy particle. The final results are interpreted within the framework of specific models of excited quark production, $q^* \to qZ$, $Z \to \mu^+\mu^-$.

Compositeness models explain the observed mass hierarchy of quarks and leptons by introducing quark constituents, predicting a multitude of excited fermion states, including excited quarks [1,2]. In the effective Lagrangian describing the gauge mediated transitions of excited fermions, the couplings to the strong and electroweak sectors are measured in units of the strengths of the SM gauge couplings g_s (strong coupling), $g = e \sin\theta_W$, and $g' = e \cos\theta_W$, where e is the electron charge and θ_W is the weak mixing angle. Thus, the corresponding strengths for the new interactions are parametrized in terms of scale factors f_s, f, and f' with respect to the SM couplings. Moreover, gauge models of excited quarks can be extended with novel four-fermion contact interaction terms arising from new strong dynamics. In hadron collisions, excited quarks are usually sought in the dijet final state. Results from previous studies of dijet mass and angular distributions are consistent with QCD predictions [8–12].

ATLAS recently reported a 95% confidence level (CL) exclusion lower limit on M_{q^*} of 2.83 TeV as well as a 95% CL exclusion of a quark contact interaction with compositeness scale below 7.6 TeV, using 5 fb^{-1} collected at a center of mass energy of 7 TeV [8]. In these previous studies, new couplings are always assumed to be equal to the SM gauge couplings (i.e. $f = f' = f_s = 1$) and the compositeness scale, Λ, is taken to be equal to the excited quark mass, M_{q^*}. Gauge and contact interaction transitions are also typically assumed for excited fermion searches at HERA where a lower limit on M_{q^*} of 252 GeV assuming $f_s = 0$ was set [13]. Finally, production via contact interactions is generally probed in excited lepton searches at hadron colliders [14,15], where excited leptons with masses below 1.9 TeV are excluded for the case where the contact interaction scale equals the excited lepton mass [15].

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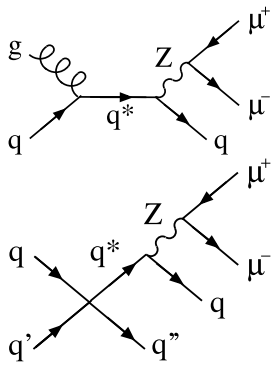

Fig. 1. Feynman diagrams for the production of $q^* \to qZ$, $Z \to \mu^+\mu^-$ via (top) a gauge interaction and (bottom) a contact interaction. Charge conjugation of an initial state quark is implied in both diagrams. Permutation of the quark isospin is implied for the contact interaction diagram.

Searches for q^* production use a range of different strategies. The D0 experiment searched for a mass resonance in the Z plus jet system, with the Z boson detected via its dielectron decay mode [16]. In this Letter we search for signs of boosted Z boson decays in the inclusive $1/p_T(\mu\mu)$ spectrum, without specifying the recoiling system so as to be less model dependent. The choice of $1/p_T(\mu\mu)$ as the variable to use in the search for new physics offers several advantages over $p_T(\mu\mu)$. First, it includes the coverage of the $p_T(\mu\mu)$ spectrum from a cut-off to infinity without missing any events. Second, it allows a more natural binning of the spectrum given the diminishing statistics and worsening resolution with the increasing $p_T(\mu\mu)$. Most importantly, it turns a broad resonance in the $p_T(\mu\mu)$ distribution into a narrow peak on top of a rapidly falling background in $1/p_T(\mu\mu)$, thus allowing usage of the methodologies for searches of new resonances.

The dimuon signature is free of instrumental background, however, it suffers from the low branching fraction (3.36%) of the Z decay to $\mu^+\mu^-$. The high luminosity delivered by the LHC collider makes it possible to present results on this final state for the first time with data recorded at a center of mass energy of 7 TeV. In order to reduce the model dependence of the results, the analysis is not restricted to the common assumptions, $f = f' = f_s = 1$ and $M_{q^*} = \Lambda$, but probes a broader phase space. For instance, searches for new physics in dijet final states do not have sensitivity to models with $f_s = 0$. A reduced parameter space of the excited quark production models is probed assuming $f = f' = 1$ and using three independent parameters: the mass of the excited quark, M_{q^*}, the compositeness scale, Λ, and the strong coupling scale factor, f_s. Only first generation excited quarks, degenerate in mass (u^*, d^*), are considered, as they have the largest production cross sections in proton collisions. The u^* (d^*) branching fraction to Z is 3% (5%) for gauge only couplings with $f_s = 1$, increasing to slightly over 20% (30%) with $f_s = 0$ [1,2]. The production of excited quarks via a gauge transition ($qg \to q^*$) is treated separately from the production via a contact interaction diagram ($qq' \to q''q^*$), though in both cases only the gauge decay to a Z boson ($q^* \to qZ$) is considered. Nevertheless, when production via contact interaction is assumed, the $q^* \to qZ$ decay branching fraction is calculated assuming both gauge and contact interaction mechanisms contribute to the total decay width. The gauge interaction transitions imply that Z bosons are produced in association with a quark (qZ), whereas contact interaction production yields Z bosons accompanied by two quarks (qqZ), as illustrated in Fig. 1.

This study uses proton–proton collisions data at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1} recorded by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Inside the magnet coil are the silicon pixel and strip tracker, the lead tungstate crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are detected in gas ionization detectors embedded in the magnet steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The trigger system, composed of a custom hardware layer feeding into a commercial processor farm (High Level Trigger, HLT), reduces the event rate to approximately 300 Hz for storage and further analysis. A detailed description of the CMS apparatus may be found elsewhere [17].

Anomalous production of Z bosons arising from heavy new particles and decaying into dimuon final states is characterized by a pair of oppositely charged isolated muons with an invariant mass consistent with that of the Z boson and a high dimuon transverse momentum. The dominant irreducible background is due to SM $Z/\gamma^* \to \mu^+\mu^-$ production. The other background sources considered in the analysis are from prompt muon processes. Prompt muons are defined to be muons originating directly at the primary vertex or originating from the decays of short lived particles. The background sources of prompt muons considered are $t\bar{t}$, diboson (WW, WZ, ZZ), and $Z/\gamma^* \to \tau^+\tau^- \to \mu^+\mu^- + X$ production. In addition, jets may be misidentified as muons and contribute to the dimuon transverse momentum spectrum through multijet and W plus jets final states (non-prompt muon backgrounds). The backgrounds were modeled using simulated samples produced with the full GEANT4 [18] based CMS detector simulation, trigger emulation, and event reconstruction chain. Different samples of SM Z boson production were generated with POWHEG v1.1 [19–21] and the MADGRAPH matrix element generator [22], both interfaced to the PYTHIA v6.424 [23] parton shower generator. Diboson and QCD processes with a muon in the final state were modeled using PYTHIA. Events from $t\bar{t}$ and W plus jets were modeled using MADGRAPH interfaced to the PYTHIA parton shower generator. For the excited quark modeling, we relied on simulations assuming separately either gauge or contact interaction production, generated for mass points ranging from $M_{q^*} = 500$ to $M_{q^*} = 2000$ GeV for the gauge interaction and from $M_{q^*} = 500$ to $M_{q^*} = 2300$ GeV for the contact interaction production, both in steps of 100 GeV and using PYTHIA. Gauge decays to a Z boson are assumed for both production choices. Signal samples are based on the leading order (LO) compositeness model described in Refs. [1,2], obtained with the CTEQ6L1 [24] parametrization for the parton distribution functions and the Z2 underlying event tune [25].

Events are selected offline to have two high p_T ($p_T > 45$ GeV), oppositely charged, isolated muons. Events used in the analysis were collected using a single muon trigger. The algorithm requires a muon candidate to be found in the muon detectors by the first level trigger system. The candidate track is then matched to a silicon tracker track, forming a HLT muon. The HLT muon is required to exceed a p_T threshold of 40 GeV and to be reconstructed in $|\eta| < 2.1$, where the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the direction of the counterclockwise beam. A right-handed coordinate system is used in CMS, with the origin at the nominal collision point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise beam direction. The azimuthal angle ϕ is the angle relative to the positive x axis measured in the x–y plane.

Muon candidates are reconstructed offline with two algorithms whose performance and validations are discussed in Ref. [26]. In the first algorithm, known as "tracker muon", tracks are fit with hits in the silicon tracker, propagated outward, and matched to

hits in the muon system. In the second algorithm, known as "global muon", a global fit is performed to hits both in the silicon tracker and the muon system. At least one muon candidate is required to be successfully reconstructed by both algorithms. Requiring both muons to be reconstructed as global muons would eliminate some background, but would introduce a 35% efficiency loss associated with muon pairs with small opening angles, $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$, which is typical of highly boosted Z candidates ($p_T(\mu\mu) > 600$ GeV). The track associated with each muon candidate is required to have hits in at least 8 layers of the silicon tracker, at least one hit in the pixel detector, and a magnitude of the transverse impact parameter below 0.2 cm to be consistent with a particle emanating from the primary interaction vertex. The candidate reconstructed as a global muon is further required to have hits in at least two different muon detector stations [26]. As the muon passes through the steel of the magnet return yoke, multiple scattering and radiative processes can alter the muon trajectory. To further improve the muon momentum resolution at high p_T, CMS developed a specialized offline reconstruction algorithm to measure the single muon transverse momentum, within the global fit reconstruction algorithm, called "Tune P" [26], which has been employed in this analysis. This algorithm has been shown to give a high efficiency for muons ($\simeq$95%), which is independent of their transverse momentum up to values of a few hundred GeV. The momentum vector of the offline muon candidate reconstructed with the global fit algorithm must be matched in direction to the HLT candidate that triggered the event. If both muons are reconstructed with the global fit algorithm, only one of them is required to match an HLT muon satisfying the trigger requirements. Both muons reconstructed offline must have $p_T > 45$ GeV and $|\eta| < 2.1$. The trigger efficiency for a single muon that passes all offline selection criteria is 92%. Muon candidates from the same vertex are selected by performing a common vertex fit and requiring the vertex χ^2 to be below 10. The muon pair is required to have an invariant mass consistent with the Z boson, 60 GeV $< M_{\mu\mu} <$ 120 GeV.

Finally, events are required to contain at least one reconstructed primary interaction vertex with at least four tracks, located within 2 cm of the center of the detector in the direction transverse to the beam and within 24 cm in the direction along the beam. These requirements help to reject cosmic-rays background. Additional suppression of muons from cosmic rays is obtained by requiring the three-dimensional opening angle between the two muons to be smaller than $\pi - 0.02$ radians. These requirements combined with the offline selection criteria bring down the cosmic-rays background contamination to a negligible level.

For the production processes considered here, simulations show that the muons from Z decay are usually isolated from the hadronic activity in the event. To measure the isolation for each muon candidate, a cone is constructed of radius $R = 0.3$ around the track direction at the primary interaction vertex. We estimate the activity around the lepton by computing the scalar sum of the transverse momenta of charged tracks within this cone, excluding the muon candidate itself. Only tracks with distance of closest approach to the primary vertex less than 0.2 cm along the beam direction are considered. The ratio of this isolation quantity to the p_T of the muon itself is required to be less than 0.1. The efficiency of this requirement for dimuon events in the Z mass window is found to be independent of the number of reconstructed primary vertices, showing that the isolation is insensitive to the effects of multiple pp interactions (pileup), which is on average nine per bunch crossing. The simulated samples are reweighted such that the distributions of the number of reconstructed primary vertices correspond to the measured distributions in data. The isolation efficiency is strongly dependent on the $p_T(\mu\mu)$: for highly boosted Z boson decays, the two muons can approach collinearity, and therefore can affect each other's isolation calculation. We correct the isolation measurement of a muon by excluding the other muon candidate from the isolation sum if the two are closer than $\Delta R = 0.3$ and if the scalar sum of transverse momenta defining the isolation before the correction is applied is greater than 90% of the transverse momentum of the other muon. The correction recovers the inefficiency induced by the isolation algorithm, and a flat isolation efficiency as a function of $p_T(\mu\mu)$ is obtained.

The distribution of the inverse of the observed dimuon transverse momentum ($1/p_T(\mu\mu)$) is shown in Fig. 2 for candidates passing all the selection criteria and having $1/p_T(\mu\mu)$ less than 0.008 GeV^{-1} ($p_T(\mu\mu) > 125$ GeV). There are 7044 (29) events observed for $1/p_T(\mu\mu)$ less than 0.008 (0.002) GeV^{-1}. The dimuon candidate with the highest transverse momentum is found to have $p_T(\mu\mu) = 940$ GeV. Simulations predict all background components other than $Z/\gamma^* \to \mu^+\mu^-$ production to contribute from less than 2% for $1/p_T(\mu\mu) < 0.008$ GeV^{-1} up to about 2.5% for $1/p_T(\mu\mu) < 0.002$ GeV^{-1}, resulting in a negligible impact on the overall shape of the $1/p_T(\mu\mu)$ spectrum. The simulation predictions were cross checked by estimating the prompt and non-prompt muon background contributions from the data. The dominant non-Drell–Yan background contributions at high dimuon transverse momentum arise from $Z/\gamma^* \to \tau^+\tau^-$, $t\bar{t}$ and diboson production. All these processes are flavor symmetric and produce twice as many eμ pairs as ee or $\mu\mu$ pairs. The prompt muon non-Drell–Yan background is also estimated by comparing the transverse momentum spectrum of $e^\pm\mu^\mp$ events between data and simulation and correcting for differences in the geometric acceptances and efficiencies. This method predicts 46 ($\ll 1$) isolated $\mu^\pm\mu^\mp$ pairs with $1/p_T(\mu\mu) < 0.008$ (0.002) GeV^{-1}. The estimate of the residual contribution from background events with at least one non-prompt or misidentified muon was made by looking at events selected from the data sample with single muons that pass all selection cuts except the isolation requirement. A probability map is created for a muon to pass the isolation criteria employed in the analysis as a function of p_T and η. This probability map is corrected for the expected contribution from events with single prompt muons from $t\bar{t}$ and W decays and for the observed correlation between the probabilities for two muons in the same event. The probability map is used to predict the number of background events with two isolated muons based on the sample of events that have two non-isolated muons. This procedure, which has been validated using simulated events, predicts a background of less than one event for $1/p_T(\mu\mu) <$ 0.008 GeV^{-1}. More details on similar techniques are described in Ref. [27].

The main background contribution arises from SM processes producing $Z/\gamma^* \to \mu^+\mu^-$, and it is evaluated from a template fit to the distribution observed in data. Both simulations and data driven background estimations showed that all the sources of background other than the $Z/\gamma^* \to \mu^+\mu^-$ have negligible impact on the total background shape template. Therefore, the choice of the analytical template is then driven by studies with $Z/\gamma^* \to \mu^+\mu^-$ simulated events, which were generated with POWHEG and MADGRAPH and hadronized using PYTHIA:

$$y(x) = \mathrm{erf}\big(a \cdot x^b - c\big) - \mathrm{erf}(-c), \tag{1}$$

where erf is the error function and x is $1/p_T(\mu\mu)$. The parameters a, b, and c of the background analytical template are obtained by fitting the region $1/p_T(\mu\mu) \in [0.0028, 0.008]$ GeV^{-1}. This choice avoids potential contamination from a signal with $M_{q^*} \geqslant 1.0$ TeV, which could otherwise bias the fit. This effect has been tested with Monte Carlo pseudo-experiments generated with a sample

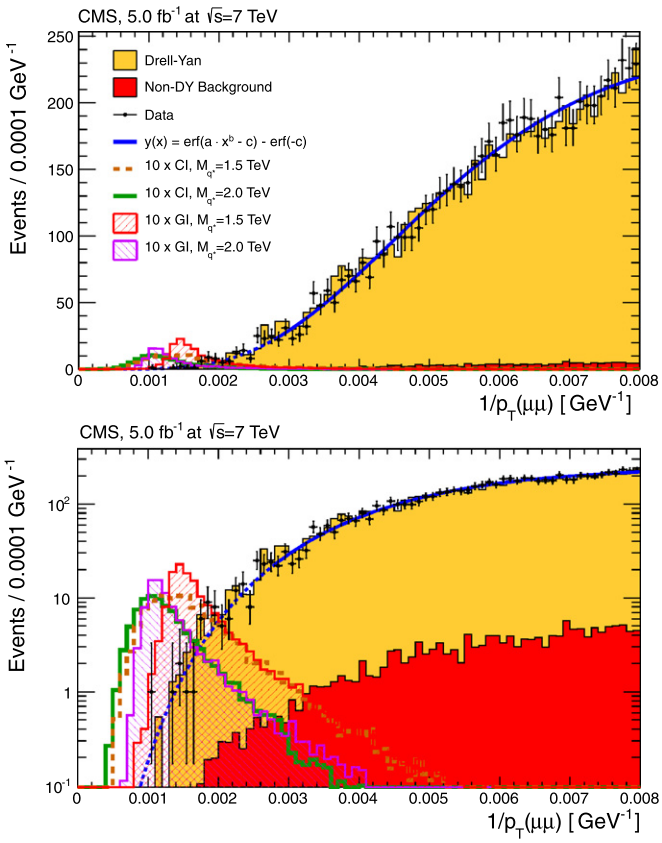

Fig. 2. Distributions of $1/p_T(\mu\mu)$ for data (points with error bars), simulated SM backgrounds (stacked histograms), and simulated signal models (overlaid histograms). Top: linear scale. Bottom: logarithmic scale. The signal models use either gauge interaction (GI) or contact interaction (CI) simulated with the assumptions of $f = f' = f_s = 1$ and $M_{q^*} = \Lambda$. The blue solid line corresponds to the analytical template fit in the region defined as $1/p_T(\mu\mu) \in [0.0028, 0.008]$ GeV^{-1}. The contribution labeled "Non-DY Background" represents the sum over all the other sources of prompt backgrounds, $t\bar{t}$, $Z \to \tau^+\tau^-$, diboson, and non-prompt backgrounds, jets misidentified as muons through multijet and W plus jets final states. The total number of SM background events is rescaled to the number of events observed in data, using the relative background contributions as obtained from simulation. The normalization of the signal distributions is increased by a factor ten. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this or Letter.)

statistically equivalent to 5.0 fb^{-1} and based on analytical forms of the $1/p_T(\mu\mu)$ spectrum to describe both the background and the signal shapes. Conversely, the larger number of events in the higher $1/p_T(\mu\mu)$ region provides a robust estimation of the background, hence potential contamination due to q* signals with $M_{q^*} < 1.0$ TeV negligibly biases the fit. Simulated Drell–Yan events were used to demonstrate that the number of events predicted by the fit to the $1/p_T(\mu\mu)$ distribution is not sensitive to the choice of the $1/p_T(\mu\mu)$ fitting region. The resulting fit to the data is shown in Fig. 2. The fit predicts 7021 ± 110 (19.6 ± 0.3) events for $1/p_T(\mu\mu)$ less than 0.008 (0.002) GeV^{-1}. The uncertainty on the estimated number of events includes the uncertainties associated with the shape predictions as well as the uncertainty on the total event yield from the fitting procedure.

The observed $1/p_T(\mu\mu)$ spectrum shape agrees with expectations based on SM processes. With no evidence for new physics, we proceed to set 95% CL upper limits on the cross section (σ) for an excited quark production and decay process $q^* \to qZ$. For the calculation of the limits, we adopt the frequentist construction CL_s [28,29]. We use an extended likelihood [30], built from characteristic signal and background probability density function templates. In all cases, we use the `RooStats` implementation of the algorithm [31]. In order to parametrize the underlying shape from the excited quark decay model, we rely on simulations of models assuming only gauge interaction production and models assuming only contact interaction production. The upper limit on the cross section for a model of interest is obtained from the upper limit on the number of signal events divided by the integrated luminosity, $\int \mathcal{L}\,dt$, and the detector acceptance times the efficiency, $\mathcal{A} \times \epsilon$. The acceptance, $\mathcal{A}$, is defined as the fraction of generated dimuon candidates that have invariant mass 60 GeV $< M_{\mu\mu} <$ 120 GeV and both muons with $|\eta| < 2.1$ and $p_T > 45$ GeV. For the excited quark model produced with gauge interaction, the signal acceptance times efficiency after the complete selection criteria for dimuon $1/p_T(\mu\mu) < 0.008$ GeV^{-1} is between 42% ($M_{q^*} = 0.5$ TeV) and 73% ($M_{q^*} = 2.0$ TeV). For the contact interaction production scenario, the acceptance times efficiency is between 51% ($M_{q^*} = 0.5$ TeV) and 73% ($M_{q^*} = 2.3$ TeV).

The values for the $\mathcal{A} \times \epsilon$ are obtained from simulation, but the efficiency of passing the offline selection criteria, ϵ, is corrected by a factor S_ϵ, which accounts for data simulation discrepancies. The single muon triggering and particle identification efficiencies are measured in a sample of inclusive $Z/\gamma^* \to \mu^+\mu^-$ events in data and MC simulation separately using a tag and probe technique [26,32]. The difference between the efficiency measured in data and simulation is found to be flat as a function of $p_T(\mu\mu)$ and a single scale factor is used to correct the dimuon selection efficiency, ϵ. The final value of S_ϵ used in the analysis is 0.98 ± 0.03. Most of the systematic uncertainty in the scale factor arises from the low statistics region where ΔR between the muons is < 0.3. We assign a systematic uncertainty of 2% for the detector acceptance, evaluated by varying the final and initial state radiation, as well as parton distribution functions (PDF) sets in the simulation of the signal models. The leading order prediction for the signal cross section is assumed to have no uncertainty. The PDF uncertainties on the final selection signal acceptance have been calculated using the PDF4LHC [33] prescription, using the PDF sets CT [24], MSTW [34] and NNPDF [35]. The PDF uncertainties are found to be well below 1% for the q* model considered. The systematic uncertainty in the integrated luminosity is estimated to be 2.2% [36]. The background yield is treated as a nuisance parameter in the limit setting procedure, and its estimated value is compatible with the previous fit estimation of the background normalization. Its systematic uncertainty comes directly from the fit to the data and is estimated to be 2%. The uncertainties derived on the shape parameters of the template fit do not affect the final results. Other fit templates were tried, but gave fits that tended to over estimate the background yield, resulting in more stringent exclusion limits. For each systematic uncertainty, we use a log normal distribution for the nuisance parameters in the likelihood construction.

The 95% CL upper limits on cross section for both gauge interaction and contact interaction are shown in Fig. 3. The expected limits and the one and two standard deviation bands are overlaid on top of the observed limit. Generally, the limits are within the two standard deviation bands. A small excess in the number of observed events in data over the fit predictions, at the level of two standard deviations, is found in the region $1/p_T(\mu\mu) <$ 0.002 GeV^{-1}, resulting in limits that are less stringent than expected for the gauge interaction models with $1.0 < M_{q^*} < 1.4$ TeV. Since the gauge interaction yields a two body final state while the contact interaction production yields a three body final state, the gauge interaction signal distributions are generally narrower than the contact interaction distributions. Owing to this and the sharp left edge of the gauge interaction distributions (Fig. 2), a small excess in this region is sufficient for favoring the signal hypothesis.

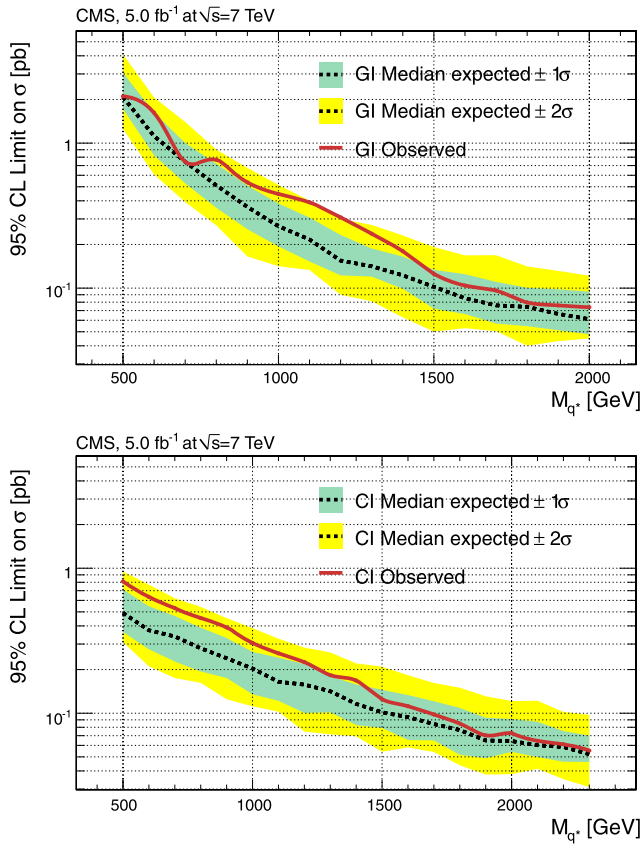

Fig. 3. Observed and expected 95% CL upper limits on the cross section of $q^* \to qZ$ for the benchmark models derived with the CL_s limit setting criterion: (top) gauge interaction production, (bottom) contact interaction production. The results shown are obtained assuming all new couplings equal to the SM couplings between ordinary fermions ($f = f' = f_s = 1$) and $\Lambda = M_{q^*}$.

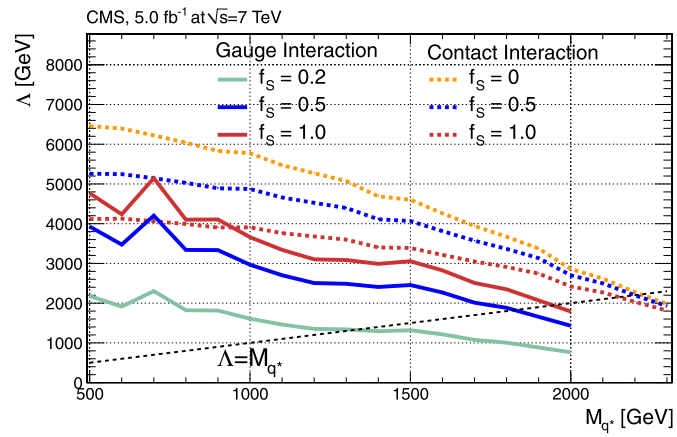

Fig. 4. Contours of excluded parameters for the gauge and contact interaction q^* production mechanisms. For a given f_s assumption, each (M_{q^*}, Λ) below the limit curve is excluded. The bump in the Λ contour at $M_{q^*} = 700$ GeV for the gauge interaction production models is a direct consequence of the downward fluctuation on the upper limit on the cross section observed at $M_{q^*} = 700$ GeV (Fig. 3).

The limits at the q^* mass value probed are correlated as a result of the large width of the signal shapes present in the $1/p_T(\mu\mu)$ spectrum.

The limits on cross section are then translated into contours in the parameter space of the gauge interaction and contact interaction models. For a given pair of values of f_s and M_{q^*}, we probe different values of the compositeness scale Λ in steps of 100 GeV and select the value of Λ producing the closest cross section to the observed limit. We use PYTHIA to compute the u^* and d^* cross section values at leading order. The excited quark branching fractions are computed according to the equations reported in Ref. [1]. In Fig. 4 we report the final limit contours in the M_{q^*} and Λ plane for different assumptions of the strong coupling, f_s, separately in gauge interaction and contact interaction production. The limit contours directly translate the results obtained on the cross section: a lower value for the upper limit on the cross section corresponds to a higher value for the lower limit on Λ; e.g., the downward statistical fluctuation at $M_{q^*} = 700$ GeV in the gauge interaction production model translates into a bump in the corresponding Λ contour.

In summary, a search for anomalous production of highly boosted Z bosons in the dimuon decay channel has been performed using proton–proton collision data with an integrated luminosity of 5.0 fb^{-1} collected at $\sqrt{s} = 7$ TeV by the CMS experiment. The Z transverse momentum distribution observed is consistent with SM expectations. Limits are derived on the specific model of excited quark production and decay in $q^* \to qZ$. We report 95% exclusion contours in the compositeness scale versus excited quark mass plane for two production scenarios and for several choices of the relative coupling to gluons. Under the assumptions for the parameters $M_{q^*} = \Lambda$ and $f = f' = f_s = 1$, our limits exclude excited quarks at 95% CL with $M_{q^*} < 1.94$ TeV for gauge production and $M_{q^*} < 2.15$ TeV for the contact interaction respectively. In comparison, the corresponding best exclusion limits for the gauge production of q^* from a search in the dijet final state is $M_{q^*} < 2.83$ TeV [8]. Nevertheless, the results from this analysis probe a complementary q^* electroweak decay and extend the limits to regions where the default assumptions on $M_{q^*} = \Lambda$ and $f_s = 1$ have been relaxed. For q^* created through the contact interaction scenario, we exclude a large section of the strong coupling phase space, including $f_s = 0$ with a mass up to 2.22 TeV, much higher than the $f_s = 0$ limit of 252 GeV set by H1 [13] in ep collisions.

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References

[1] U. Baur, I. Hinchliffe, D. Zeppenfeld, Int. J. Mod. Phys. A 02 (1987) 1285, http://dx.doi.org/10.1142/S0217751X87000661.
[2] U. Baur, M. Spira, P.M. Zerwas, Phys. Rev. D 42 (1990) 815, http://dx.doi.org/10.1103/PhysRevD.42.815.
[3] K.T. Matchev, S.D. Thomas, Phys. Rev. D 62 (2000) 077702, http://dx.doi.org/10.1103/PhysRevD.62.077702, arXiv:hep-ph/9908482.
[4] R. Foadi, M.T. Frandsen, T.A. Ryttov, F. Sannino, Phys. Rev. D 76 (2007) 055005, http://dx.doi.org/10.1103/PhysRevD.76.055005, arXiv:0706.1696.
[5] E. Eichten, I. Hinchliffe, K. Lane, C. Quigg, Rev. Mod. Phys. 56 (1984) 579, http://dx.doi.org/10.1103/RevModPhys.56.579.
[6] ATLAS Collaboration, Phys. Lett. B 705 (2011) 415, http://dx.doi.org/10.1016/j.physletb.2011.10.018, arXiv:1107.2381.
[7] CMS Collaboration, Phys. Rev. D 85 (2012) 032002, http://dx.doi.org/10.1103/PhysRevD.85.032002, arXiv:1110.4973.
[8] ATLAS Collaboration, JHEP 1301 (2013) 029, http://dx.doi.org/10.1007/JHEP01(2013)029, arXiv:1210.1718.
[9] CMS Collaboration, Phys. Lett. B 704 (2011) 123, http://dx.doi.org/10.1016/j.physletb.2011.09.015, arXiv:1107.4771.
[10] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. D 79 (2009) 112002, http://dx.doi.org/10.1103/PhysRevD.79.112002, arXiv:0812.4036.
[11] V.M. Abazov, et al., D0 Collaboration, Phys. Rev. Lett. 103 (2009) 191803, http://dx.doi.org/10.1103/PhysRevLett.103.191803, arXiv:0906.4819.
[12] CMS Collaboration, JHEP 1205 (2012) 055, http://dx.doi.org/10.1007/JHEP05(2012)055, arXiv:1202.5535.
[13] F.D. Aaron, et al., H1 Collaboration, Phys. Lett. B 678 (2009) 335, http://dx.doi.org/10.1016/j.physletb.2009.06.044, arXiv:0904.3392.
[14] ATLAS Collaboration, Phys. Rev. D 85 (2012) 072003, http://dx.doi.org/10.1103/PhysRevD.85.072003, arXiv:1201.3293.
[15] CMS Collaboration, Search for excited leptons in pp collisions at $\sqrt{s} = 7$ TeV, arXiv:1210.2422, 2012.
[16] V.M. Abazov, et al., D0 Collaboration, Phys. Rev. D 74 (2006) 011104, http://dx.doi.org/10.1103/PhysRevD.74.011104, arXiv:hep-ex/0606018.
[17] CMS Collaboration, JINST 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[18] S. Agostinelli, et al., GEANT4 Collaboration, Nucl. Instrum. Meth. A 506 (2003) 250, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.
[19] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 0807 (2008) 060, http://dx.doi.org/10.1088/1126-6708/2008/07/060, arXiv:0805.4802.
[20] P. Nason, JHEP 0411 (2004) 040, http://dx.doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
[21] S. Frixione, P. Nason, C. Oleari, JHEP 0711 (2007) 070, http://dx.doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
[22] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, JHEP 1106 (2011) 128, http://dx.doi.org/10.1007/JHEP06(2011)128, arXiv:1106.0522.
[23] T. Sjostrand, S. Mrenna, P.Z. Skands, JHEP 0605 (2006) 026, http://dx.doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
[24] P.M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, C.-P. Yuan, Phys. Rev. D 78 (2008) 013004, http://dx.doi.org/10.1103/PhysRevD.78.013004, arXiv:0802.0007.
[25] R. Field, Early LHC underlying event data – findings and surprises, arXiv:1010.3558, 2010.
[26] CMS Collaboration, J. Instrum. 7 (2012) P10002, http://dx.doi.org/10.1088/1748-0221/7/10/P10002.
[27] CMS Collaboration, Phys. Lett. B 714 (2012) 158, http://dx.doi.org/10.1016/j.physletb.2012.06.051, arXiv:1206.1849.
[28] T. Junk, Nucl. Instrum. Meth. A 434 (1999) 435, http://dx.doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[29] A.L. Read, J. Phys. G 28 (2002) 2693, http://dx.doi.org/10.1088/0954-3899/28/10/313.
[30] Particle Data Group, J. Beringer, et al., Phys. Rev. D 86 (2012) 010001, http://dx.doi.org/10.1103/PhysRevD.86.010001.
[31] L. Moneta, K. Belasco, K.S. Cranmer, A. Lazzaro, D. Piparo, G. Schott, W. Verkerke, M. Wolf, The RooStats Project, in: 13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT2010), SISSA, http://pos.sissa.it/archive/conferences/093/057/ACAT2010_057.pdf, arXiv:1009.1003, 2010, PoS(ACAT2010)057.
[32] CMS Collaboration, JHEP 1101 (2011) 080, http://dx.doi.org/10.1007/JHEP01(2011)080, arXiv:1012.2466.
[33] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNulty, T. Sjöstrand, R.S. Thorne, The PDF4LHC Working Group Interim Recommendations, arXiv:1101.0538, 2011.
[34] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur. Phys. J. C 63 (2009) 189, http://dx.doi.org/10.1140/epjc/s10052-009-1072-5, arXiv:0901.0002.
[35] R.D. Ball, L. Del Debbio, S. Forte, A. Guffanti, J.I. Latorré, J. Rojo, M. Ubiali, Nucl. Phys. B 838 (2010) 136, http://dx.doi.org/10.1016/j.nuclphysb.2010.05.008, arXiv:1002.4407.
[36] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-SMP-12–008 (2012), http://cdsweb.cern.ch/record/1434360.

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