Kaluza–Klein States of the Standard Model Gauge Bosons: Constraints From High Energy Experiments

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In theories with the standard model gauge bosons propagating in TeV^{-1}-size extra dimensions, their Kaluza-Klein states interact with the rest of the SM particles confined to the 3-brane. We look for possible signals for this interaction in the present high-energy collider data, and estimate the sensitivity offered by the next generation of collider experiments. Based on the present data from the LEP 2, Tevatron, and HERA experiments, we set a lower limit on the extra dimension compactification scale $M_C > 6.8$ TeV at the 95% confidence level (dominated by the LEP 2 results) and quote expected sensitivities in the Tevatron Run 2 and at the LHC.

This contribution is a shortened version of the recent paper [1], with the focus on future high-energy facilities. The detail of the formalism used to obtain the results presented here can be found in [1].

Recently, it has been suggested that the Planck, string, and grand unification scales can all be significantly lower than it was previously thought, perhaps as low as a few TeV [2, 3, 4, 5]. An interesting model was proposed [6, 7, 8, 9], in which matter resides on a p-brane ($p > 3$), with chiral fermions confined to the ordinary three-dimensional world internal to the p-brane and the SM gauge bosons also propagating in the extra $\delta > 0$ dimensions internal to the p-brane. (Gravity in the bulk is not of direct concern in this model.) It was shown [6] that in this scenario it is possible to achieve the gauge coupling unification at a scale much lower than the usual GUT scale, due to a much faster power-law running of the couplings at the scales above the compactification scale of the extra dimensions. The SM gauge bosons that propagate in the extra dimensions compactified on S^1/Z_2, in the four-dimensional point of view, are equivalent to towers of Kaluza-Klein (KK) states with masses $M_n = \sqrt{M_0^2 + n^2/R^2}$ ($n = 1, 2, \ldots$), where $R = M_C^{-1}$ is the size of the compact dimension, M_C is the corresponding compactification scale, and M_0 is the mass of the corresponding SM gauge boson.

There are two important consequences of the existence of the KK states of the gauge bosons in collider phenomenology. (i) Since the entire tower of KK states have the same quantum numbers as their zeroth-state gauge boson, this gives rise to mixings among the zeroth (the SM gauge boson) and the nth-modes ($n = 1, 2, 3, \ldots$) of the W and Z bosons. (The zero mass of the photon is protected by the $\mathrm{U}(1)_{\mathrm{EM}}$ symmetry of the SM.) (ii) In addition to direct production and virtual exchanges of the zeroth-state gauge bosons, both direct production and virtual effects of the KK states of the W, Z, γ, and g bosons would become possible at high energies.

In this proceedings, we study the effects of virtual exchanges of the KK states of the W, Z, γ, and g bosons in high energy collider processes. While the effects on the low-energy precision measurements have been studied in detail [10, 11, 12, 13, 14, 15, 16, 17], their high-energy counterparts have not been systematically studied yet. We attempt to bridge this gap by analyzing all the available high-energy collider data including the dilepton, dijet, and top-pair production at the Tevatron; neutral and charged-current deep-inelastic scattering at HERA; and the precision observables in leptonic and hadronic production at LEP 2.

We fit the observables in the above processes to the sum of the SM prediction and the contribution from the KK states of the SM gauge bosons. In all cases, the data do not require the presence of the KK excitations, which is then translated to the limits on the compactification scale M_C. The fit to the combined data set yields a 95% C.L. lower limit on M_C of 6.8 TeV, which is substan-

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tially higher than that obtained using only electroweak precision measurements. In addition, we also estimate the expected reach on M_C in Run 2 of the Fermilab Tevatron and at the LHC, using dilepton production.

1. Interactions of the Kaluza-Klein States

We use the formalism of Ref. [7, 8, 9], based on an extension of the SM to five dimensions, with the fifth dimension, x^5, compactified on the segment S^1/Z_2 (a circle of radius R with the identification $x^5 \to -x^5$). This segment has the length of πR. Two 3-branes reside at the fixed points $x^5 = 0$ and $x^5 = \pi R$. The SM gauge boson fields propagate in the 5D-bulk, while the SM fermions are confined to the 3-brane located at $x^5 = 0$. The Higgs sector consists of two Higgs doublets, ϕ_1 and ϕ_2 (with the ratio of vacuum expectation values $v_2/v_1 \equiv \tan\beta$), which live in the bulk and on the SM brane, respectively.

In the case of SU(2)$_L\times$ U(1)$_Y$ symmetry, the charged-current (CC) and neutral-current (NC) interactions, after compactifying the fifth dimension, are given by [13]:

$$\begin{aligned}
\mathcal{L}^{\rm CC} &= \frac{g^2 v^2}{8}\left[W_1^2 + \cos^2\beta\sum_{n=1}^{\infty}(W_1^{(n)})^2 + 2\sqrt{2}\sin^2\beta W_1\sum_{n=1}^{\infty}W_1^{(n)} + 2\sin^2\beta\left(\sum_{n=1}^{\infty}W_1^{(n)}\right)^2\right] \\
&+ \frac{1}{2}\sum_{n=1}^{\infty}n^2 M_C^2 (W_1^{(n)})^2 - g(W_1^{\mu} + \sqrt{2}\sum_{n=1}^{\infty}W_1^{(n)\mu})J_\mu^1 + (1\to 2)\,, \qquad (1) \\
\mathcal{L}^{\rm NC} &= \frac{g v^2}{8c_\theta^2}\left[Z^2 + \cos^2\beta\sum_{n=1}^{\infty}(Z^{(n)})^2 + 2\sqrt{2}\sin^2\beta Z\sum_{n=1}^{\infty}Z^{(n)} + 2\sin^2\beta\left(\sum_{n=1}^{\infty}Z^{(n)}\right)^2\right. \\
&+ \frac{1}{2}\sum_{n=1}^{\infty}n^2 M_C^2\left[(Z^{(n)})^2 + (A^{(n)})^2\right] \\
&- \frac{e}{s_\theta c_\theta}\left(Z^{\mu} + \sqrt{2}\sum_{n=1}^{\infty}Z^{(n)\mu}\right)J_\mu^Z - e\left(A^{\mu} + \sqrt{2}\sum_{n=1}^{\infty}A^{(n)\mu}\right)J_\mu^{\rm em}\,, \qquad (2)
\end{aligned}$$

where the fermion currents are:

$$J_\mu^{1,2} = \bar\psi_L\gamma_\mu\left(\frac{\tau_{1,2}}{2}\right)\psi_L\,, \qquad J_\mu^Z = \bar\psi\gamma_\mu(g_v - \gamma^5 g_a)\psi\,, \qquad J_\mu^{\rm em} = \bar\psi\gamma_\mu Q_\psi\psi\,,$$

and $\langle\phi_1\rangle = v\cos\beta, \langle\phi_2\rangle = v\sin\beta$; g and g' are the gauge couplings of the SU(2)$_L$ and U(1)$_Y$, respectively; $g_v = T_{3L}/2 - s_\theta^2 Q$ and $g_a = T_{3L}/2$. Here, we used the following short-hand notations: $s_\theta \equiv \sin\theta_W$ and $c_\theta \equiv \cos\theta_W$, where θ_W is the weak-mixing angle. The tree-level (non-physical) W and Z masses are $M_W = gv/2$ and $M_Z = M_W/c_\theta$. Since the compactification scale M_C is expected to be in the TeV range, we therefore ignore in the above equations the mass of the zeroth-state gauge boson in the expression for the mass of the n-th KK excitation: $M_n = \sqrt{M_0^2 + n^2 M_C^2} \approx nM_C$, $n = 1, 2, \ldots$.

Using the above Lagrangians we can describe the two major effects of the KK states: mixing with the SM gauge bosons and virtual exchanges in high-energy interactions.

1.1. Mixing with the SM Gauge Bosons

The first few terms in the Eqs. (1) and (2) imply the existence of mixings among the SM boson (V) and its KK excitations ($V^{(1)}$, $V^{(2)}$, ...) where $V = W, Z$. There is no mixing for the A^μ fields because of the U(1)$_{\rm EM}$ symmetry. These mixings modify the electroweak observables (similar to the mixing between the Z and Z'). The SM weak eigenstate of the Z-boson, $Z^{(0)}$, mixes with its excited KK states $Z^{(n)}$ ($n = 1, 2, \ldots$) via a series of mixing angles, which depend on the masses of $Z^{(n)}, n = 0, 1, \ldots$ and on the angle β. The Z boson studied at LEP 1 is then the lowest mass eigenstate after mixing. The couplings of the $Z^{(0)}$ to fermions are also modified through the mixing angles. The observables at LEP 1 can place strong constraints on the mixing, and thus on the compactification scale M_C. Similarly, the properties of the W boson are also modified.

The effects of KK excitations in the low-energy limit can be included by eliminating their fields using equations of motion. From the Lagrangians given by Eqs. (1) and (2) the W, Z masses and the low-energy CC and NC interactions are given by [13]:

$$\begin{aligned}
M_W^2 &= M_W^2(1 - c_\theta^2 \sin_\beta^4 X) , \\
M_Z^2 &= M_Z^2(1 - \sin_\beta^4 X) , \\
\mathcal{L}_{\rm int}^{\rm CC} &= -gJ_\mu^1 W^{1\mu}(1 - \sin^2\beta c_\theta^2 X) - \frac{g^2}{2M_Z^2} X J_\mu^1 J^{1\mu} + (1 \to 2) , \\
\mathcal{L}_{\rm int}^{\rm NC} &= -\frac{e}{s_\theta c_\theta} J_\mu^Z Z^\mu (1 - \sin^2\beta X) - \frac{e^2}{2 s_\theta^2 c_\theta^2 M_Z^2} X J_\mu^Z J^{Z\mu} \\
&\quad - e J_\mu^{\rm em} A^\mu - \frac{e^2}{2M_Z^2} X J_\mu^{\rm em} J^{\rm em\mu} , \\
X &= \frac{\pi^2 M_Z^2}{3 M_C^2} .
\end{aligned}$$

In the following, we summarize the results presented in Refs. [11, 12, 13, 14, 15, 16, 17]. Nath and Yamaguchi [11] used data on G_F, M_W, and M_Z and set the lower limit on $M_C \gtrsim 1.6$ TeV. Carone [15] studied a number of precision observables, such as G_F, ρ, Q_W, leptonic and hadronic widths of the Z. The most stringent constraint on M_C comes from the hadronic width of the Z: $M_C > 3.85$ TeV. Strumia [14] obtained a limit $M_C > 3.4 - 4.3$ TeV from a set of electroweak precision observables. Casalbuoni *et al.* [13] used the complete set of precision measurements, as well as Q_W and R_ν's from ν-N scattering experiments, and obtained a limit $M_C > 3.6$ TeV. Rizzo and Wells [12] used the same set of data as the previous authors and obtained a limit $M_C > 3.8$ TeV. Cornet *et al.* [17] used the unitarity of the CKM matrix elements and were able to obtain a limit $M_C > 3.3$ TeV. Delgado *et al.* [16] studied a scenario in which quarks of different families are separated in the extra spatial dimension and set the limit $M_C > 5$ TeV in this scenario.

1.2. Virtual Exchanges

If the available energy is higher than the compactification scale the on-shell production of the Kaluza-Klein excitations of the gauge bosons can be observed [18, 19]. However, for the present collider energies only indirect effects can be seen, as the compactification scale is believed to be at least a few TeV. These indirect effects are due to virtual exchange of the KK-states.

When considering these virtual exchanges, we ignore a slight modification of the coupling constants to fermions due to the mixings among the KK states and so we use Eqs. (1) and (2) without the mixings [1]. This implies that any Feynman diagram which has an exchange of a W, Z, γ, or g will be replicated for every corresponding KK state with the masses nM_C, where $n = 1, 2, \ldots$. Note that the coupling constant of the KK states to fermions is a factor of $\sqrt{2}$ larger than that for the corresponding SM gauge boson, due to the normalization of the KK excitations.

The effects of exchanges of KK states can be easily included by extending reduced amplitudes. In the limit $M_C \gg \sqrt{s}, \sqrt{|t|}, \sqrt{|u|}$, the reduced ampltiudes becomes:

$$M_{\alpha\beta}^{\ell q}(s) = e^2 \left\{ \frac{Q_\ell Q_q}{s} + \frac{g_\alpha^\ell g_\beta^q}{\sin^2\theta_W \cos^2\theta_W} \frac{1}{s - M_Z^2} - \left(Q_\ell Q_q + \frac{g_\alpha^\ell g_\beta^q}{\sin^2\theta_W \cos^2\theta_W} \right) \frac{\pi^2}{3M_C^2} \right\} ,$$

based on which, the high energy processes can be described.

2. High Energy Processes and Data Sets

Before describing the data sets used in our analysis, let us first specify certain important aspects of the analysis technique. Since the next-to-leading order (NLO) calculations do not exist for

[1]Since $M_C >> M_Z$, the mixings are very small. Furthermore, they completely vanish for $\beta = 0$.

the new interactions yet, we use leading order (LO) calculations for contributions both from the SM and from new interactions, for consistency. However, in many cases, e.g. in the analysis of precision electroweak parameters, it is important to use the best available calculations of their SM values, as in many cases data is sensitive to the next-to-leading and sometimes even to higher-order corrections. Therefore, we normalize our leading order calculations to either the best calculations available, or to the low-Q^2 region of the data set, where the contribution from the KK states is expected to be vanishing. This is equivalent to introducing a Q^2-dependent K-factor and using the same K-factor for both the SM contribution and the effects of the KK resonances, which is well justified by the similarity between these extra resonances and the corresponding ground-state gauge boson. The details of this procedure for each data set are given in the corresponding section. Wherever parton distribution functions (PDFs) are needed, we use the CTEQ5L (leading order fit) set [20].

2.1. HERA Neutral and Charged Current Data

ZEUS [21, 22] and H1 [23, 24] have published results on the neutral-current (NC) and charged-current (CC) deep-inelastic scattering (DIS) in e^+p collisions at $\sqrt{s} \approx 300$ GeV. The data sets collected by H1 and ZEUS correspond to an integrated luminosities of 35.6 and 47.7 pb^{-1}, respectively. H1 [23, 24] has also published NC and CC analysis for the most recent data collected in e^-p collisions at $\sqrt{s} \approx 320$ GeV with an integrated luminosity of 16.4 pb^{-1}. We used single-differential cross sections $d\sigma/dQ^2$ presented by ZEUS [21, 22] and double-differential cross sections $d^2\sigma/dxdQ^2$ published by H1 [23, 24].

We normalize the tree-level SM cross section to that measured in the low-Q^2 data by a scale factor C (C is very close to 1 numerically). The cross section σ used in the fitting procedure is given by

$$\sigma = C\,(\sigma_{\rm SM} + \sigma_{\rm interf} + \sigma_{\rm KK})\ , \quad (3)$$

where $\sigma_{\rm interf}$ is the interference term between the SM and the KK states and $\sigma_{\rm KK}$ is the cross section due to the KK-state interactions only.

2.2. Drell-Yan Production at the Tevatron

Both CDF [25] and DØ [26] measured the differential cross section $d\sigma/dM_{\ell\ell}$ for Drell-Yan production, where $M_{\ell\ell}$ is the invariant mass of the lepton pair. (CDF analyzed data in both the electron and muon channels; DØ analyzed only the electron channel.)

We scale this tree-level SM cross section by normalizing it to the Z-peak cross section measured with the data. The cross section used in the fitting procedure is then obtained similarly to that in Eq. (3).

2.3. LEP 2 Data

We analyze LEP 2 observables sensitive to the effects of the KK states of the photon and Z, including hadronic and leptonic cross sections and forward-backward asymmetries. The LEP Electroweak Working Group combined the $q\bar{q}, \mu^+\mu^-$, and $\tau^+\tau^-$ data from all four LEP collaborations [27] for the machine energies between 130 and 202 GeV. We use the following quantities in our analysis: (i) total hadronic cross sections; (ii) total $\mu^+\mu^-, \tau^+\tau^-$ cross sections; (iii) forward-backward asymmetries in the μ and τ channels; and (iv) ratio of b-quark and c-quark production to the total hadronic cross section, R_b and R_c. We take into account the correlations of the data points in each data set as given by [27].

For other channels we use various data sets from individual experiments. They are [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43]: (i) Bhabha scattering cross section $\sigma(e^+e^- \to e^+e^-)$; (ii) angular distribution or forward-backward asymmetry in hadroproduction $e^+e^- \to q\bar{q}$; (iii) angular distribution or forward-backward asymmetry in the e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ production.

To minimize the uncertainties from higher-order corrections, we normalize the tree-level SM calculations to the NLO cross section, quoted in the corresponding experimental papers. We then scale our tree-level results, including contributions from the KK states of the Z and γ, with this normalization factor, similar to Eq. (3). When fitting angular distribution, we fit to the shape only, and treat the normalization as a free parameter.

2.4. Kaluza-Klein states of the Gluon in the Dijet Production at the Tevatron

Since the gauge bosons propagate in extra dimensions, the Kaluza-Klein momentum conservation applies at their self-coupling vertices. Because of this conservation, the triple interaction vertex with two gluons on the SM 3-brane and one KK state of the gluon in the bulk vanishes. (However, the quartic vertex with two gluons on the SM 3-brane and two gluon KK states in the bulk does exist.) Cross section of the dijet production, including the contributions from KK states of the gluon, are given in Ref. [1].

Both CDF [44, 45] and DØ [46, 47] published data on dijet production, including invariant mass M_{jj} and angular distributions. In the fit, we take into account the full correlation of data points in the data sets, as given by each experiment.

2.5. Kaluza-Klein States of the Gluon in the $t\bar{t}$ Production at the Tevatron

In Ref. [48], it was shown that the $t\bar{t}$ production in Run 2 of the Tevatron can be used to probe the compactification scales up to $\sim$ 3 TeV. In this paper, we consider the sensitivity from the existing Run 1 data by using the tree-level $t\bar{t}$ production cross section, including the contribution of the KK states of the gluon in the $q\bar{q} \to t\bar{t}$ channel. (The $gg \to t\bar{t}$ channel does not have the triple vertex interaction with two gluons from the SM 3-brane and one KK state of the gluon in the bulk, as explained in the previous subsection.)

The latest theoretical calculations of the $t\bar{t}$ cross section, including higher-order contributions, at $\sqrt{s} = 1.8$ TeV correspond to 4.7 – 5.5 pb [49, 50]. The present data on the $t\bar{t}$ cross sections are [51, 52]

$$\sigma_{t\bar{t}}\ (\text{CDF}) = 6.5\ ^{+1.7}_{-1.4}\ \text{pb}; \quad \sigma_{t\bar{t}}\ (\text{DØ}) = 5.9 \pm 1.7\ \text{pb},$$

and the top-quark mass measurements are

$$m_t\ (\text{CDF}) = 176.1 \pm 6.6\ \text{GeV}; \quad m_t\ (\text{DØ}) = 172.1 \pm 7.1\ \text{GeV}.$$

In our analysis, we normalize the tree-level SM cross section to the mean of the latest theoretical predictions (5.1 pb), and use this normalization coefficient to predict the cross section in presence of the KK states of the gluon (similar to Eq. (3)).

3. Constraints from High Energy Experiments

Based on the above individual and combined data sets, we perform a fit to the sum of the SM prediction and the contribution of the KK states of gauge bosons, normalizing our tree-level cross section to the best available higher-order calculations, as explained above. The effects of the KK states always enter the equations in the form $\eta = \pi^2/(3M_C^2)$ [1]. Therefore, we parameterize these effects with a single fit parameter η. In most cases, the differential cross sections in presence of the KK states of gauge bosons are bilinear in η.

The best-fit values of η for each individual data set and their combinations are shown in Table I. In all cases, the preferred values from the fit are consistent with zero, and therefore we proceed with setting limits on η. The one-sided 95% C.L. upper limit on η is defined as:

$$0.95 = \frac{\int_0^{\eta_{95}} d\eta\, P(\eta)}{\int_0^{\infty} d\eta\, P(\eta)}\ , \tag{4}$$

where $P(\eta)$ is the fit likelihood function given by $P(\eta) = \exp(-(\chi^2(\eta) - \chi^2_{\text{min}})/2)$. The corresponding upper 95% C.L. limits on η and lower 95% C.L. limits on M_C are also shown in Table I.

Table I Best-fit values of $\eta = \pi^2/(3M_C^2)$ and the 95% C.L. upper limits on η for individual data set and combinations. Corresponding 95% C.L. lower limits on M_C are also shown.

	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33\,^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09\,^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62\,^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28\,^{+0.092}_{-0.092}$	0.076	6.6
HERA:			
NC	$-2.74\,^{+1.49}_{-1.51}$	1.59	1.4
CC	$-0.057\,^{+1.28}_{-1.31}$	2.45	1.2
HERA combined	$-1.23\,^{+0.98}_{-0.99}$	1.25	1.6
TEVATRON:			
Drell-yan	$-0.87\,^{+1.12}_{-1.03}$	1.96	1.3
Tevatron dijet	$0.46\,^{+0.37}_{-0.58}$	1.0	1.8
Tevatron top production	$-0.53\,^{+0.51}_{-0.49}$	9.2	0.60
Tevatron combined	$-0.38\,^{+0.52}_{-0.48}$	0.65	2.3
All combined	$-0.29\,^{+0.090}_{-0.090}$	0.071	6.8

4. Sensitivity in Run 2 of the Tevatron and at the LHC

At the Tevatron, the best channel to probe the KK states of photon or Z boson is Drell-Yan production. In Ref. [53], we showed that using the double differential distribution $d^2\sigma/M_{\ell\ell}d\cos\theta$ can increase the sensitivity to the KK states of the graviton compared to the use of single-differential distributions. Similarly, we expect this to be the case for the KK states of the photon and the Z boson.

We follow the prescription of Ref. [53] and use the Bayesian approach, which correctly takes into account both the statistical and systematic uncertainties, in the estimation of the sensitivity to $\eta \equiv \pi^2/(3M_C^2)$ [2]. Due to the high statistics in Run 2 and particularly at the LHC, the overall systematics becomes dominated by the systematics on the $\hat{s}$-dependence of the K-factor from the NLO corrections. (Systematic uncertainties on the integrated luminosity and efficiencies are not as important as before, because they get canceled out when normalizing the tree level SM cross section to the Z-peak region in the data.) The uncertainty on the K-factor from the NLO calculations for Drell-Yan production [54] is currently known to a 3% level, so we use this as the correlated systematics in our calculations on M_C. For the LHC we quote the limits for the same nominal 3% uncertainty and also show how the sensitivity improves if the uncertainty on the K-factor shape is reduced to a 1% level. It shows the importance of higher-order calculations of the Drell-Yan cross section, which we hope will become available by the time the LHC turns on.

In the simulation, we use a dilepton efficiency of 90%, a rapidity coverage of $|\eta| < 2.0$, and typical energy resolutions of the Tevatron or LHC experiments. The simulation is done for a single collider experiment in the combination of the dielectron and dimuon channels.

As expected, the fit to double-differential cross sections yields a $\sim 10\%$ better sensitivity to M_C than just using one-dimensional differential cross sections. We illustrate this by calculating the sensitivity to M_C in Run 1, which is slightly higher than the result obtained from the fit to the invariant mass spectrum from CDF and DØ. The sensitivity, at the 95% C.L., to M_C in Run 1 (120 pb^{-1}), Run 2a (2 fb^{-1}), Run 2b (15 fb^{-1}), and at the LHC (100 fb^{-1}) is given in Table II. While the Run 2 sensitivity is somewhat inferior to the current indirect limits from precision electroweak data, LHC would offer a significantly higher sensitivity to M_C, well above 10 TeV.

[2] Note that the maximum likelihood method, as given by Eq. (4), artificially yields 10% higher sensitivity to M_C, as it does not properly treat the cases when the likelihood maximum is found in the unphysical region $\eta < 0$.

Table II Sensitivity to the parameter $\eta = \pi^2/3M_C^2$ in Run 1, Run 2 of the Tevatron and at the LHC, using the dilepton channel. The corresponding 95% C.L. lower limits on M_C are also shown.

	η_{95} (TeV^{-2})	95% C.L. lower limit on M_C (TeV)
Run 1 (120 pb^{-1})	1.62	1.4
Run 2a (2 fb^{-1})	0.40	2.9
Run 2b (15 fb^{-1})	0.19	4.2
LHC (14 TeV, 100 fb^{-1}, 3% systematics)	1.81×10^{-2}	13.5
LHC (14 TeV, 100 fb^{-1}, 1% systematics)	1.37×10^{-2}	15.5

When this work is completed, we learned of a preliminary study on a similar topic for the LHC [55], which yielded a somewhat lower sensitivity.

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