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 CERN LEP 2, Fermilab Tevatron, and DESY 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 CERN LHC.

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I. INTRODUCTION

A possibility that the universe has additional compactified spatial dimensions beyond the familiar four-dimensional space-time has been long discussed [1]. Advances in modern string theory, along with the continuous attempts to solve the hierarchy problem of the standard model (SM), have revived interest in this subject. Recently, it has been suggested that the Planck, string, and grand unification scales can all be significantly lower than was previously thought, perhaps as low as a few TeV [2]. For example, in a viable model suggested by Arkani-Hamed, Dimopoulos, and Dvali [3], the matter is confined to a 3-brane while gravity propagates in extra dimensions of a submillimeter size. In this model, the effective Planck scale is as low as a TeV, thus eliminating the hierarchy problem of the SM. This also yields rich phenomenology within the reach of future collider experiments, including production of monojets (see, e.g., [4–6]), modification of the Drell-Yan spectrum (see, e.g., [4,6,7]), and even creation of mini black holes and string balls [8]. (For a brief summary of current experimental situation, see Ref. [9].)

A more generic picture drawn in string theories is that the SM matter particles reside on a p-brane ($p=\delta+3$; the space-time dimension of the brane is then $p+1$) while gravity propagates in the entire ten-dimensional bulk. The compactification of the δ dimensions occurs *internally* within the brane, while the remaining $(6-\delta)$ dimensions are compactified *transverse* to the brane. Various phenomenology arises, depending on the relative magnitude of the two compactification scales, the string scale, and the Planck scale. The model of Arkani-Hamed, Dimopoulos, and Dvali [3] is a specific example with $\delta=0$.

Another interesting model was also proposed [10,11], 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 [10] that in this scenario it is possible to achieve the gauge coupling unification at a scale much lower than the usual grand unified theory (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 $M_n=\sqrt{M_0^2+n^2/R^2}$ ($n=1,2,\dots$), 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 ($n=1,2,3,\dots$) 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 paper, 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 [12–18] (we shall briefly summarize their findings in a later section), 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,

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dijet, and top-pair production at the Fermilab Tevatron; neutral and charged-current deep-inelastic scattering at the DESY *ep* collider HERA; and the precision observables in leptonic and hadronic production at CERN e^+e^- collider 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 substantially 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 CERN Large Hadron Collider (LHC), using dilepton production.

The organization of this paper is as follows. In the next section, we describe the Lagrangian for the model [11], which has one extra dimension. In Sec. III we briefly summarize the existing constraints from precision measurements. In Sec. IV, we briefly discuss the effects of the KK states of the Z boson on the atomic parity violation (APV) measurements. In Sec. V we describe the high energy data sets that we used in this analysis. In Sec. VI, we present our results on the fits and limits. In Sec. VII, we estimate the sensitivity in Run 2 of the Tevatron and at the LHC. A collection of data sets that we used in our analysis is placed in the Appendix.

II. INTERACTIONS OF THE KALUZA-KLEIN STATES

In what follows, we use the formalism of Ref. [11], 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.

The 5D Lagrangian is given by

$$\mathcal{L}_5=-\frac{1}{4g_5}F_{MN}^2+|D_M\phi_1|^2+(i\bar{\psi}\sigma^\mu D_\mu\psi+|D_\mu\phi_2|^2)\,\delta(x^5),$$

where $D_M=\partial_M+iV_M$, $M=(\mu,5)=(1,\ldots,5)$, and g_5 is the 5D gauge coupling for the gauge boson V. Compactifying the fifth dimension on S^1/Z_2 with the expansion

$$\Phi(x^\mu,x^5)=\sum_{n=0}^{\infty}\cos\left(\frac{nx^5}{R}\right)\Phi^{(n)}(x^\mu),$$

the 4D Lagrangian becomes [11]

$$\begin{aligned}\mathcal{L}_4=\sum_{n=0}^{\infty}\Bigg[&-\frac{1}{4}F_{\mu\nu}^{(n)2}+\frac{1}{2}\left(\frac{n^2}{R}+2g^2|\phi_1|^2\right)V_\mu^{(n)}V^{(n)\mu}\Bigg]\\&+g^2|\phi_2|^2\left(V_\mu^{(0)}+\sqrt{2}\sum_{n=1}^{\infty}V_\mu^{(n)}\right)^2+i\bar{\psi}\sigma^\mu\Bigg[\partial_\mu+igV_\mu^{(0)}\\&+ig\sqrt{2}\sum_{n=1}^{\infty}V_\mu^{(n)}\Bigg]\psi+\cdots,\end{aligned}\qquad(1)$$

where $g=g_5/\sqrt{\pi R}$ is the 4D gauge coupling for the gauge boson V.

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 [14]

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

$$\begin{aligned}\mathcal{L}^{\rm NC}=\frac{gv^2}{8c_\theta^2}\Bigg[&Z^2+\cos^2\beta\sum_{n=1}^{\infty}(Z^{(n)})^2+2\sqrt{2}\sin^2\beta Z\sum_{n=1}^{\infty}Z^{(n)}\\&+2\sin^2\beta\left(\sum_{n=1}^{\infty}Z^{(n)}\right)^2\Bigg]+\frac{1}{2}\sum_{n=1}^{\infty}n^2M_C^2[(Z^{(n)})^2\\&+(A^{(n)})^2]-\frac{e}{s_\theta c_\theta}\left(Z^\mu+\sqrt{2}\sum_{n=1}^{\infty}Z^{(n)\mu}\right)J_\mu^Z\\&-e\left(A^\mu+\sqrt{2}\sum_{n=1}^{\infty}A^{(n)\mu}\right)J_\mu^{\rm em},\end{aligned}\qquad(3)$$

where the fermion currents are

$$J_\mu^{1,2}=\bar{\psi}_L\gamma_\mu\left(\frac{\tau_{1,2}}{2}\right)\psi_L,$$

$$J_\mu^Z=\bar{\psi}\gamma_\mu(g_v-\gamma^5g_a)\psi,$$

$$J_\mu^{\rm em}=\bar{\psi}\gamma_\mu Q_\psi\psi,$$

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; $g_v=T_{3L}/2-s_\theta^2Q$ and $g_a=T_{3L}/2$. Here, we used the following shorthand 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: $M_n=\sqrt{M_0^2+n^2M_C^2}\approx nM_C, n=1,2,\ldots$.

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.

A. Mixing with the SM gauge bosons

The first few terms in Eqs. (2) and (3) imply the existence of mixings among the SM boson (V) and its KK excitations ($V^{(1)}, V^{(2)}, \ldots$) where $V=W,Z$. There is no mixing for the A^μ fields because of the $U(1)_{EM}$ 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. However, so far the mass and couplings of the W are not measured as precisely as the Z observables, so the constraints on M_C coming from the W are weaker than those from the Z.

The effects on electroweak precision measurements have been previously studied [12–18]; we will summarize their results in the next section.

B. 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 [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. (2) and (3) 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.

It has been shown in Ref. [10] that in the presence of the KK states of gauge bosons in the bulk, the renormalization-group evolution of the gauge couplings changes from the normal logarithmic running to a power running for energy scales above M_C. However, the energy scale of the processes that we consider in this paper is well below M_C. Consequently, the running of gauge couplings is the same as the normal logarithmic running in the SM [10].[2] Besides, we are not concerned about the additional real scalars transforming in the adjoint of each gauge group that are required to give masses to the gauge bosons [10]. This is because the scalars usually couple to light fermions via very small Yukawa couplings.

We start with Drell-Yan production of a pair of leptons. The amplitude squared for $q\bar{q}\to l^+l^-$ or $l^+l^-\to q\bar{q}$ (without averaging over the initial spins or colors) is given by

$$\sum |\mathcal{M}|^2=4u^2(|M_{LL}^{lq}(s)|^2+|M_{RR}^{lq}(s)|^2)+4t^2(|M_{LR}^{lq}(s)|^2+|M_{RL}^{lq}(s)|^2),$$

where

$$M_{\alpha\beta}^{lq}(s)=e^2\left\{\frac{Q_lQ_q}{s}+\frac{g_\alpha^l g_\beta^q}{\sin^2\theta_W\cos^2\theta_w}\frac{1}{s-M_Z^2}+2\sum_{n=1}^{\infty}\left[\frac{Q_lQ_q}{s-n^2M_C^2}+\frac{g_\alpha^l g_\beta^q}{\sin^2\theta_W\cos^2\theta_W}\frac{1}{s-n^2M_C^2}\right]\right\}.$$

Here s,t,u are the usual Mandelstam variables, $g_L^f=T_{3f}-Q_f\sin^2\theta_W$, $g_R^f=-Q_f\sin^2\theta_w$, and Q_f is the electric charge of the fermion f in units of proton charge.

If the compactification scale $M_C\gg\sqrt{s},\sqrt{|t|},\sqrt{|u|}$, the above can further be simplified to

$$M_{\alpha\beta}^{lq}(s)=e^2\left\{\frac{Q_lQ_q}{s}+\frac{g_\alpha^l g_\beta^q}{\sin^2\theta_W\cos^2\theta_W}\frac{1}{s-M_Z^2}-\left(Q_lQ_q+\frac{g_\alpha^l g_\beta^q}{\sin^2\theta_W\cos^2\theta_W}\right)\frac{\pi^2}{3M_C^2}\right\}. \quad (4)$$

Based on the above formula the amplitude squared for deep-inelastic scattering at HERA can be obtained by a simple interchange of the Mandelstam variables. In the later section, we will derive the expressions for specific observables used in our analysis.

III. REVIEW OF THE LOW-ENERGY CONSTRAINTS

The effects of KK excitations in the low-energy limit can be included by eliminating their fields using equations of

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

[2] As noted in Ref. [20] the couplings of the higher KK states to the SM fermions may be modified due to the power-law running if the scale for each coupling is chosen at the mass of the corresponding KK state. As shown in Ref. [20], this effect modifies the sum over the KK states by ~10%, which would translate into a ~5% change in sensitivity to the compactification scale M_C. In what follows, we ignore this small effect, but suggest that it may be taken into account on the case-by-case basis in future experimental searches for the TeV-scale extra dimensions.

motion following from the Lagrangians given by Eqs. (2) and (3) [14]:

$$W_{1,2}^{(n)}=-\sqrt{2}\;\frac{\sin^2\beta M_W^2}{n^2M_C^2}W_{1,2}+\sqrt{2}\frac{g}{n^2M_C^2}J^{1,2}+O(1/M_C^4),$$

$$Z^{(n)}=-\sqrt{2}\;\frac{\sin^2\beta M_Z^2}{n^2M_C^2}Z+\sqrt{2}\;\frac{e}{s_\theta c_\theta}\;\frac{1}{n^2M_C^2}J^Z+O(1/M_C^4),$$

$$A^{(n)}=\sqrt{2}\frac{e}{n^2M_C^2}J^{\rm em}+O(1/M_C^4).$$

Substituting back into Eqs. (2) and (3) we obtain the physical W and Z masses and the interaction Lagrangian [14]:

$$M_W^2=M_W^2(1-c_\theta^2\sin_\beta^4X),$$

$$M_Z^2=M_Z^2(1-\sin_\beta^4X),$$

$$\mathcal{L}_{\rm int}^{\rm CC}=-gJ_\mu^1W^{1\mu}(1-\sin^2\beta c_\theta^2X)-\frac{g^2}{2M_Z^2}XJ_\mu^1J^{1\mu}+(1\to2), \tag{5}$$

$$\mathcal{L}_{\rm int}^{\rm NC}=-\frac{e}{s_\theta c_\theta}J_\mu^ZZ^\mu(1-\sin^2\beta X)-\frac{e^2}{2s_\theta^2c_\theta^2M_Z^2}XJ_\mu^ZJ^{Z\mu}$$
$$-eJ_\mu^{\rm em}A^\mu-\frac{e^2}{2M_Z^2}XJ_\mu^{\rm em}J^{{\rm em}\mu}, \tag{6}$$

$$X=\frac{\pi^2M_Z^2}{3M_C^2}.$$

The above low-energy Lagrangian already includes the effects of gauge-boson mixings and of virtual exchange of the KK states and thus can be used to calculate the precision observables. We illustrate this with a few examples. Using Eq. (5) we can calculate G_F in muon decay:

$$G_F=\frac{\sqrt{2}g^2}{8M_W^2}(1+c_\theta^2X)(1-2\sin^2\beta c_\theta^2X).$$

Analogously, the partial width of the Z boson into a pair of fermions can be calculated using Eq. (6):

$$\Gamma(Z\to f\overline{f})=\frac{N_cM_Z}{12\pi}\;\frac{e^2}{s_\theta^2c_\theta^2}(1-2\sin^2\beta X)(g_v^2+g_a^2),$$

where $N_c=1$ (3) for leptons (quarks). Other quantities can be derived similarly.

In the following, we summarize the results presented in Refs. [12–18]. Nath and Yamaguchi [12] used data on G_F, M_W, and M_Z and set the lower limit on $M_C\gtrsim1.6$ TeV. Carone [16] 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 [15] obtained a limit $M_C>3.4$–4.3 TeV from a set of electroweak precision observables. Casalbuoni *et al.* [14] 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 [13] used the same set of data as the previous authors and obtained a limit $M_C>3.8$ TeV. Cornet *et al.* [18] used the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements and were able to obtain a limit $M_C>3.3$ TeV. Delgado *et al.* [17] 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.

IV. ATOMIC PARITY VIOLATION

The 1999 atomic parity violation (APV) measurement on cesium [21] has drawn a great deal of attention because the data showed a 2.3σ deviation from the SM prediction. Several explanations involving physics beyond the SM, such as extra Z bosons [22] and leptoquarks [23], have been suggested. Later, however, the theoretical calculations used in the analysis had been questioned and new calculations appeared since [24]. As a result, data now agree with the SM prediction [25]:

$$\Delta Q_W\equiv Q_W({\rm Cs})-Q_W^{\rm SM}({\rm Cs})=0.44\pm0.44.$$

The KK states of the Z boson act similarly to a large number of extra Z bosons with the same chiral couplings as the SM Z boson. These KK states result in a non-zero ΔQ_W.

The change in Q_W due to the KK states of the Z in terms of chiral couplings is given by [23]

$$\begin{aligned}\Delta Q_W=&(-11.4\;\;{\rm TeV}^2)\left(\frac{-e^2}{\sin^2\theta_W\cos^2\theta_W}\right)\\&\times(-g_L^e+g_R^e)(g_L^u+g_R^u)\,\eta\\&+(-12.8\;\;{\rm TeV}^2)\left(\frac{-e^2}{\sin^2\theta_W\cos^2\theta_W}\right)\\&\times(-g_L^e+g_R^e)(g_L^d+g_R^d)\,\eta\\\approx&(-0.6\;\;{\rm TeV}^2)\,\eta,\end{aligned} \tag{7}$$

where $\eta=\pi^2/(3M_C^2)$, $g_{L,R}^f=T_{3f}-Q_f\sin^2\theta_W$, and θ_W is the weak mixing angle. As seen from Eq. (7), the KK states with the same chiral couplings as the SM Z boson give negative contributions to Q_W's, and therefore are disfavored by the data.

V. 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 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 [26]. The reason to use the LO PDF set is that LO PDFs are extracted using LO cross section calculations, thus making them more consistent with our approach.

A. HERA neutral and charged current data

ZEUS [27] and H1 [28] 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 [28] 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 [27] and double-differential cross sections $d^2\sigma/dxdQ^2$ published by H1 [28]. The double-differential cross section for NC DIS in the e^+p collisions, including the effect of the KK states of the γ and Z, is given by

$$\begin{aligned}\frac{d^2\sigma}{dxdQ^2}(e^+p\to e^+X)&=\frac{1}{16\pi}\Bigg\{\sum_q f_q(x)[(1-y)^2(|M_{LL}^{eq}(t)|^2+|M_{RR}^{eq}(t)|^2)\\&\quad+|M_{LR}^{eq}(t)|^2+|M_{RL}^{eq}(t)|^2]\\&\quad+\sum_{\bar q} f_{\bar q}(x)[|M_{LL}^{eq}(t)|^2+|M_{RR}^{eq}(t)|^2\\&\quad+(1-y)^2(|M_{LR}^{eq}(t)|^2+|M_{RL}^{eq}(t)|^2)]\Bigg\},\end{aligned}\tag{8}$$

where $Q^2=sxy$ is the square of the momentum transfer and $f_{q/\bar q}(x)$ are parton distribution functions. The reduced amplitudes $M_{\alpha\beta}^{eq}$ are given by Eq. (4). The double differential cross section for CC DIS, including the effect of KK states of W, can be written as

$$\begin{aligned}\frac{d^2\sigma}{dxdQ^2}(e^+p\to\bar\nu X)&=\frac{g^4}{64\pi}\left|\frac{1}{-Q^2-M_W^2}-\frac{\pi^2}{3M_C^2}\right|^2\\&\quad\times[(1-y)^2(d(x)+s(x))+\bar u(x)+\bar c(x)],\end{aligned}\tag{9}$$

where $d(x),s(x),\bar u(x),\bar c(x)$ are the parton distribution functions. The single differential cross section $d\sigma/dQ^2$ is obtained from the above equations by integrating over x. The cross section in the e^-p collisions can be obtained by interchanging $(LL\leftrightarrow LR,RR\leftrightarrow RL)$ in Eq. (8) and by interchanging $(q(x)\leftrightarrow\bar q(x))$ in Eq. (9).

We normalize the tree-level SM cross section to that measured in the low-$Q^2(Q^2\lesssim 2000\ \text{GeV}^2)$ 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

$$\sigma=C(\sigma_{\rm SM}+\sigma_{\rm interf}+\sigma_{\rm KK}),\tag{10}$$

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. When normalizing to the low-energy data, we neglect the possible contribution from the KK states, as it is much smaller than the experimental uncertainty on the data that we use.

B. Drell-Yan production at the Tevatron

Both the Collider Detector at Fermilab (CDF) [29] and DØ [30] measured the differential cross section $d\sigma/dM_{ll}$ for Drell-Yan production, where M_{ll} is the invariant mass of the lepton pair. (CDF analyzed data in both the electron and muon channels; DØ analyzed only the electron channel.)

The differential cross section, including the contributions from the KK states of the photon and Z, is given by

$$\begin{aligned}\frac{d^2\sigma}{dM_{ll}dy}&=K\frac{M_{ll}^3}{72\pi s}\sum_q f_q(x_1)f_{\bar q}(x_2)(|M_{LL}^{eq}(\hat s)|^2+|M_{LR}^{eq}(\hat s)|^2\\&\quad+|M_{RL}^{eq}(\hat s)|^2+|M_{RR}^{eq}(\hat s)|^2),\end{aligned}$$

where $M_{\alpha\beta}^{eq}$ is given by Eq. (4), $\hat s=M_{ll}^2$, $\sqrt{s}$ is the center-of-mass energy in the $p\bar p$ collisions, M_{ll} and y are the invariant mass and the rapidity of the lepton pair, respectively, and $x_{1,2}=(M_{ll}/\sqrt{s})e^{\pm y}$. The variable y is integrated numerically to obtain the invariant mass spectrum. The QCD K-factor is given by $K=1+[\alpha_s(\hat s)/2\pi]\frac{4}{3}(1+4\pi^2/3)$. 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. (10).

C. 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 [31] 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 [31].

For other channels we use various data sets from individual experiments. They are [32–35]: (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.

The angular distribution for $e^-e^+\to f\bar{f}$ ($f=q,e,\mu,\tau$) is given by

$$\begin{aligned}\frac{d\sigma}{d\cos\theta}=\frac{N_f s}{128\pi}\{&(1+\cos\theta)^2(|M_{LL}^{ef}(s)|^2+|M_{RR}^{ef}(s)|^2)\\&+(1-\cos\theta)^2(|M_{LR}^{ef}(s)|^2+|M_{RL}^{ef}(s)|^2)\\&+\delta_{ef}[(1+\cos\theta)^2(|M_{LL}^{ef}(s)+M_{LL}^{ef}(t)|^2\\&+|M_{RR}^{ef}(s)+M_{RR}^{ef}(t)|^2-|M_{LL}^{ef}(s)|^2-|M_{RR}^{ef}(s)|^2)\\&+4(|M_{LR}^{ef}(t)|^2+|M_{RL}^{ef}(t)|^2)]\},\end{aligned}$$

where $N_f=1$ (3) for l (q), and $M_{\alpha\beta}^{ef}$ is given by Eq. (4). The additional terms for $f=e$ arise from the t,u-channel exchange diagrams.

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. (10). When fitting angular distribution, we fit to the shape only, and treat the normalization as a free parameter of the fit.

D. 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.) That is why the Lagrangian in Eq. (1) only has the interactions of KK states of the gluon with fermions, but not with gluons. [Furthermore, if we treated the trilinear interaction between the gluons and the KK states of the gluon the same as the SM triple-gluon interaction, the gauge invariance would be violated at the order of $(1/M_C^2)$.]

The formulas for dijet production, including the contributions from KK states of the gluon (summed over the final-state and averaged over the initial-state helicities and colors), are

$$\overline{\sum}|\mathcal{M}(qq'\to qq')|^2=\frac{4}{9}g_s^4(\hat{s}^2+\hat{u}^2)\left(\frac{1}{\hat{t}}-\frac{\pi^2}{3M_C^2}\right)^2,$$

$$\begin{aligned}\overline{\sum}|\mathcal{M}(qq\to qq)|^2=g_s^4\Bigg[&\frac{4}{9}(\hat{s}^2+\hat{u}^2)\left(\frac{1}{\hat{t}}-\frac{\pi^2}{3M_C^2}\right)^2\\&+\frac{4}{9}(\hat{s}^2+\hat{t}^2)\left(\frac{1}{\hat{u}}-\frac{\pi^2}{3M_C^2}\right)^2\\&-\frac{8}{27}\hat{s}^2\left(\frac{1}{t}-\frac{\pi^2}{3M_C^2}\right)\\&\times\left(\frac{1}{\hat{u}}-\frac{\pi^2}{3M_C^2}\right)\Bigg],\end{aligned}$$

$$\overline{\sum}|\mathcal{M}(q\bar{q}\to q'\bar{q}')|^2=\frac{4}{9}g_s^4(\hat{t}^2+\hat{u}^2)\left(\frac{1}{\hat{s}}-\frac{\pi^2}{3M_C^2}\right)^2,$$

$$\begin{aligned}\overline{\sum}|\mathcal{M}(q\bar{q}\to q\bar{q})|^2=g_s^4\Bigg[&\frac{4}{9}(\hat{t}^2+\hat{u}^2)\left(\frac{1}{\hat{s}}-\frac{\pi^2}{3M_C^2}\right)^2\\&+\frac{4}{9}(\hat{s}^2+\hat{u}^2)\left(\frac{1}{\hat{t}}-\frac{\pi^2}{3M_C^2}\right)^2\\&-\frac{8}{27}\hat{u}^2\left(\frac{1}{t}-\frac{\pi^2}{3M_C^2}\right)\\&\times\left(\frac{1}{\hat{s}}-\frac{\pi^2}{3M_C^2}\right)\Bigg],\end{aligned}$$

$$\overline{\sum}|\mathcal{M}(q\bar{q}\to gg)|^2=g_s^4\left\{\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right\},$$

$$\overline{\sum}|\mathcal{M}(gg\to q\bar{q})|^2=g_s^4\left\{\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right\},$$

$$\overline{\sum}|\mathcal{M}(qg\to qg)|^2=g_s^4\left\{\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}\right\},$$

$$\overline{\sum}|\mathcal{M}(gg\to gg)|^2=\frac{9}{4}g_s^4\left\{\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}+3\right\}.$$

In the above, if the final state particles are different, the corresponding equations need to be symmetrized via $u\leftrightarrow t$ substitution. The parton-level differential cross section is given by

$$\frac{d\hat{\sigma}}{d\cos\theta^*}=\frac{1}{32\pi\hat{s}}\overline{\sum}|\mathcal{M}|^2,$$

where the range of cos θ^* is from 0 to 1. This parton-level cross section is then convoluted with the parton distribution functions to give the total cross section. The above equations are reduced to the SM cross sections in the $M_C\to\infty$ limit. The last four equations are the same as the SM cross sections, because of the vanishing trilinear gluon vertex involving two ground-state gluons.

Both CDF [36] and DØ [37] 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. We normalize the tree-level SM dijet cross section to the low dijet invariant mass data, $M_{jj}<400$ GeV.

Collider implications of the KK states of the gluon have also been considered recently in Ref. [38].

E. Kaluza-Klein states of the gluon in the $t\bar{t}$ production at the Tevatron

In Ref. [39], 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 ~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 subprocess cross sections are given by

$$\frac{d\hat{\sigma}}{d\cos\theta^*}(q\bar{q}\to t\bar{t})=\frac{g_s^4\beta}{72\pi\hat{s}}\left(\frac{1}{\hat{s}}-\frac{\pi^2}{3M_C^2}\right)^2\times[(m_t^2-\hat{t})^2+(m_t^2-\hat{u})^2+2\hat{s}m_t^2],$$

$$\frac{d\hat{\sigma}}{d\cos\theta^*}(gg\to t\bar{t})=\frac{g_s^4\beta}{768\pi\hat{s}}\Bigg\{\frac{4}{(\hat{t}-m_t^2)^2}(-m_t^4-3m_t^2\hat{t}-m_t^2\hat{u}+\hat{u}\hat{t})+\frac{4}{(\hat{u}-m_t^2)^2}\times(-m_t^4-3m_t^2\hat{u}-m_t^2\hat{t}+\hat{u}\hat{t})+\frac{m_t^2}{(\hat{u}-m_t^2)(\hat{t}-m_t^2)}(2m_t^2+\hat{t}+\hat{u})+18\frac{1}{\hat{s}^2}(m_t^4-m_t^2(\hat{t}+\hat{u})+\hat{t}\hat{u})+\frac{9}{\hat{t}-m_t^2}\frac{1}{\hat{s}}(m_t^4-2m_t^2\hat{t}+\hat{u}\hat{t})+\frac{9}{\hat{u}-m_t^2}\frac{1}{\hat{s}}(m_t^4-2m_t^2\hat{u}+\hat{u}\hat{t})\Bigg\},$$

where $\beta=\sqrt{1-4m_t^2/\hat{s}}$ and $\hat{s},\hat{t},\hat{u}$ are Mandelstam variables. The above cross section is reduced to the SM top quark pair production cross section in the $M_C\to\infty$ limit.

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 [40]. The present data on the $t\bar{t}$ cross sections are [41]

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

$$\sigma_{t\bar{t}}(\text{D}\emptyset)=5.9\pm1.7\ \text{pb},$$

and the top-quark mass measurements are

$$m_t(\text{CDF})=176.1\pm6.6\ \text{GeV},$$

$$m_t(\text{D}\emptyset)=172.1\pm7.1\ \text{GeV}.$$

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. (10)].

The effects of KK states of the W boson on single top quark production were recently considered in Ref. [42].

VI. CONSTRAINTS FROM HIGH ENERGY EXPERIMENTS

In the previous section, we have described the data sets from various high energy experiments used in our analysis. 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. As seen from Eq. (4), the effects of the KK states always enter the equations in the form $\pi^2/(3M_C^2)$. Therefore, we parametrize these effects with a single fit parameter η:

$$\eta=\frac{\pi^2}{3M_C^2}.$$

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

$$0.95=\frac{\int_0^{\eta_{95}}d\eta P(\eta)}{\int_0^{\infty}d\eta P(\eta)}, \tag{11}$$

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 and ang. dist.	$0.09^{+0.18}_{-0.18}$	0.42	2.8
ee cross section and 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 quark 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

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

VII. 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. Since the typical $\sqrt{\hat s}$ in Run 2 is well below the limit obtained in the previous section, the approximation $M_C^2 \gg \hat s, |\hat t|, |\hat u|$ is still valid. Therefore, we can use the reduced amplitudes of Eq. (4). This approximation also holds well for the LHC, which was tested by a direct comparison of the approximate cross section given by Eq. (4) and exact sum over the KK resonances, for values of $M_C \sim 10$ TeV.

In Ref. [43], we showed that using the double differential distribution $d^2\sigma/M_{ll}d\cos\theta$ 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. The double differential cross section for Drell-Yan production, including the interactions of the KK states of the γ and Z, is given by

$$\frac{d^3\sigma}{dM_{ll}dy\,d\cos\theta^*} = K\sum_q \frac{M_{ll}^3}{192\pi s} f_q(x_1) f_{\bar q}(x_2) \times[(1+\cos\theta^*)^2(|M_{LL}^{eq}(\hat s)|^2+|M_{RR}^{eq}(\hat s)|^2) + (1-\cos\theta^*)^2(|M_{LR}^{eq}(\hat s)|^2+|M_{RL}^{eq}(\hat s)|^2)],$$

where $M_{\alpha\beta}^{eq}$'s are given by Eq. (4), θ^* is the scattering angle in the rest frame of the initial partons, $\hat s = M_{ll}^2$, $dx_1dx_2=(2M_{ll}/s)dM_{ll}dy$, and $x_{1,2}=M_{ll}e^{\pm y}/\sqrt{s}$.

We follow the prescription of Ref. [43] and use the Bayesian approach, which correctly takes into account both the statistical and systematic uncertainties, in the estimation of the sensitivity to $\eta \equiv \pi^2/(3M_C^2)$.[3] Because of 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 [44] 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.[4]

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.

[3] Note that the maximum likelihood method, as given by Eq. (11), 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 $\eta<0$.

[4] The electroweak radiative corrections have recently been computed in Ref. [45].

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 ($120\mathrm{pb}^{-1}$)		
Dilepton	1.62	1.4
Run 2a (2 fb^{-1})		
Dilepton	0.40	2.9
Run 2b (15 fb^{-1})		
Dilepton	0.19	4.2
LHC (14 TeV,100 fb^{-1}, 3% systematics)		
Dilepton	1.81×10^{-2}	13.5
LHC (14 TeV,100 fb^{-1}, 1% systematics)		
Dilepton	1.37×10^{-2}	15.5

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.

When this work is completed, we learned of a preliminary study on a similar topic for the LHC [46], which yielded a somewhat lower sensitivity. Very recently, a complementary paper [47] on the effects of KK excitations of gauge bosons at high-energy e^+e^- colliders has appeared in LANL archives.

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APPENDIX

Tables III–XXII are the data sets that we used in our analysis.

TABLE III. ZEUS: differential cross section $d\sigma/dQ^2$ of the $e^+p\to e^+X$ production. The following quantities are given for each bin: the Q^2 range, the measured Born-level cross section, and the SM prediction for the Born-level cross section.

Q^2 range (GeV^2)	$d\sigma/dQ^2$ ($\mathrm{pb/GeV}^2$) Measured	SM
400.0–475.7	$2.753\pm0.035^{+0.066}_{-0.051}$	2.673
475.7–565.7	$1.753\pm0.024^{+0.047}_{-0.039}$	1.775
565.7–672.7	$1.187\pm0.018^{+0.022}_{-0.023}$	1.149
672.7–800.0	$(7.71\pm0.13^{+0.14}_{-0.36})\times10^{-1}$	7.65×10^{-1}
800.0–951.4	$(4.79\pm0.09^{+0.10}_{-0.21})\times10^{-1}$	4.93×10^{-1}
951.4–1131.4	$(3.21\pm0.07^{+0.06}_{-0.06})\times10^{-1}$	3.13×10^{-1}
1131.4–1345.4	$(2.01\pm0.05^{+0.04}_{-0.03})\times10^{-1}$	2.04×10^{-1}
1345.4–1600.0	$(1.27\pm0.03^{+0.03}_{-0.02})\times10^{-1}$	1.28×10^{-1}
1600.0–1902.7	$(8.49\pm0.26^{+0.17}_{-0.30})\times10^{-2}$	8.26×10^{-2}
1902.7–2262.8	$(4.97\pm0.18^{+0.11}_{-0.16})\times10^{-2}$	5.01×10^{-2}
2262.8–2690.9	$(3.05\pm0.13^{+0.06}_{-0.14})\times10^{-2}$	3.13×10^{-2}
2690.9–3200.0	$(1.99\pm0.10^{+0.07}_{-0.09})\times10^{-2}$	2.09×10^{-2}
3200.0–4525.5	$(9.00\pm0.39^{+0.20}_{-0.24})\times10^{-3}$	9.77×10^{-3}
4525.5–6400.0	$(3.30\pm0.19^{+0.17}_{-0.10})\times10^{-3}$	3.49×10^{-3}
6400.0–9050.0	$(1.32\pm0.10^{+0.02}_{-0.07})\times10^{-3}$	1.20×10^{-3}
9050.0–12800.0	$(3.69^{+0.53}_{-0.47}{}^{+0.08}_{-0.11})\times10^{-4}$	3.64×10^{-4}
12800.0–18102.0	$(8.9^{+2.5}_{-2.0}{}^{+0.7}_{-0.6})\times10^{-5}$	10.0×10^{-5}
18102.0–25600.0	$(2.4^{+1.2}_{-0.8}{}^{+0.4}_{-0.1})\times10^{-5}$	2.2×10^{-5}
25600.0–36203.0	$<6.0\times10^{-6}$	3.7×10^{-6}
36203.0–51200.0	$(2.6^{+3.5}_{-1.7}{}^{+0.7}_{-0.2})\times10^{-6}$	0.4×10^{-6}

TABLE IV. ZEUS: differential cross section $d\sigma/dQ^2$ of the $e^+p\to\overline{\nu}_eX$ production. The following quantities are given for each bin: the Q^2 range; the measured Born-level cross section $d\sigma/dQ^2$, and the SM prediction for the Born-level cross section.

Q^2 range (GeV^2)	$d\sigma/dQ^2$($\mathrm{pb/GeV}^2$) Measured	SM
200–400	$(2.94\pm0.28^{+0.35}_{-0.34})\times10^{-2}$	2.80×10^{-2}
400–711	$(1.82\pm0.14\pm0.08)\times10^{-2}$	1.87×10^{-2}
711–1265	$(1.29\pm0.08\pm0.03)\times10^{-2}$	1.15×10^{-2}
1265–2249	$(5.62\pm0.40\pm0.08)\times10^{-3}$	6.07×10^{-3}
2249–4000	$(2.62\pm0.20^{+0.04}_{-0.09})\times10^{-3}$	2.61×10^{-3}
4000–7113	$(7.91^{+0.93}_{-0.83}{}^{+0.38}_{-0.31})\times10^{-4}$	8.29×10^{-4}
7113–12649	$(2.00^{+0.35}_{-0.30}\pm0.17)\times10^{-4}$	1.65×10^{-4}
12649–22494	$(2.61^{+0.95}_{-0.72}{}^{+0.45}_{-0.38})\times10^{-5}$	1.71×10^{-5}
22494–60000	$(5.9^{+14.}_{-4.9}{}^{+1.8}_{-1.5})\times10^{-7}$	6.24×10^{-7}

TABLE V. H1: reduced NC cross section $\tilde{\sigma}_{NC}(x,Q^2)$ in the e^+p collisions obtained by dividing $d^2\sigma_{NC}/dxdQ^2$ by the kinematic factor $xQ^4/(Y_+2\pi\alpha^2)$, with its statistical (δ_{stat}), systematic (δ_{sys}), and combined (δ_{tot}) uncertainties. The additional normalization uncertainty, not included in the systematic error, is 1.5%.

Q^2 (GeV^2)	x	y	$\tilde{\sigma}_{NC}$	δ_{stat} (%)	δ_{sys} (%)	δ_{tot} (%)
150	0.003	0.518	1.240	1.8	5.2	5.5
150	0.005	0.331	1.100	1.8	3.3	3.8
150	0.008	0.207	0.920	2.9	8.9	9.3
200	0.005	0.442	1.102	1.8	5.0	5.3
200	0.008	0.276	0.915	1.9	3.5	4.0
200	0.013	0.170	0.765	2.2	3.7	4.3
200	0.020	0.110	0.696	2.6	4.9	5.5
200	0.032	0.069	0.601	3.2	7.5	8.1
200	0.050	0.044	0.516	3.7	8.2	9.0
200	0.080	0.028	0.439	4.2	9.0	9.9
250	0.005	0.552	1.113	2.3	5.1	5.6
250	0.008	0.345	1.018	2.0	3.7	4.2
250	0.013	0.212	0.807	2.1	3.9	4.4
250	0.020	0.138	0.721	2.1	3.6	4.1
250	0.032	0.086	0.606	2.2	3.6	4.3
250	0.050	0.055	0.529	2.4	3.4	4.2
250	0.080	0.035	0.430	2.7	3.6	4.5
250	0.130	0.021	0.334	3.4	4.3	5.5
250	0.250	0.011	0.240	3.3	7.4	8.1
250	0.400	0.007	0.122	5.9	12.1	13.4
300	0.005	0.663	1.139	3.4	5.6	6.5
300	0.008	0.414	0.989	2.4	5.1	5.7
300	0.013	0.255	0.846	2.4	3.8	4.5
300	0.020	0.166	0.740	2.4	3.9	4.6
300	0.032	0.104	0.629	2.4	3.7	4.4
300	0.050	0.066	0.499	2.6	3.6	4.5
300	0.080	0.041	0.456	2.7	3.9	4.8
300	0.130	0.025	0.346	3.4	5.8	6.8
300	0.250	0.013	0.250	3.1	8.1	8.7
300	0.400	0.008	0.140	5.7	14.5	15.6
400	0.008	0.552	0.976	3.1	5.1	6.0
400	0.013	0.340	0.841	2.8	3.9	4.8
400	0.020	0.221	0.739	2.8	3.7	4.7
400	0.032	0.138	0.619	2.8	3.6	4.6
400	0.050	0.088	0.513	3.0	3.8	4.8
400	0.080	0.055	0.455	3.1	4.0	5.1
400	0.130	0.034	0.373	3.8	4.5	5.9
400	0.250	0.018	0.241	3.5	6.5	7.4
400	0.400	0.011	0.155	6.2	11.6	13.2
500	0.008	0.690	1.026	4.2	5.1	6.6
500	0.013	0.425	0.906	3.3	5.2	6.2
500	0.020	0.276	0.792	3.3	3.9	5.2
500	0.032	0.173	0.654	3.3	4.0	5.2
500	0.050	0.110	0.508	3.5	4.1	5.4
500	0.080	0.069	0.445	3.6	3.7	5.2
500	0.130	0.042	0.368	4.3	4.3	6.1
500	0.180	0.031	0.287	4.9	5.4	7.3
500	0.250	0.022	0.220	5.9	8.5	10.4
500	0.400	0.014	0.143	8.6	15.3	17.5
650	0.013	0.552	0.903	4.0	4.3	5.9
650	0.020	0.359	0.718	4.1	3.9	5.7
650	0.032	0.224	0.633	4.0	4.0	5.7
650	0.050	0.144	0.521	4.1	3.9	5.7
650	0.080	0.090	0.436	4.0	4.0	5.7
650	0.130	0.055	0.413	4.6	4.7	6.6
650	0.180	0.040	0.309	5.3	5.8	7.9
650	0.250	0.029	0.246	6.2	8.7	10.6
650	0.400	0.018	0.125	9.9	11.5	15.2
650	0.650	0.011	0.021	14.3	15.7	21.3
800	0.013	0.680	1.000	5.0	4.7	6.8
800	0.020	0.442	0.796	4.6	4.3	6.3
800	0.032	0.276	0.709	4.5	4.0	6.0
800	0.050	0.177	0.540	4.6	3.9	6.0
800	0.080	0.110	0.474	4.6	4.2	6.2
800	0.130	0.068	0.370	5.4	4.8	7.2
800	0.180	0.049	0.333	6.0	4.9	7.8
800	0.250	0.035	0.208	7.5	5.8	9.4
800	0.400	0.022	0.150	9.6	10.5	14.2
800	0.650	0.014	0.018	19.6	18.4	26.9
1000	0.020	0.552	0.754	5.4	3.8	6.6
1000	0.032	0.345	0.639	5.6	4.1	6.9
1000	0.050	0.221	0.566	5.1	3.8	6.4
1000	0.080	0.138	0.431	5.3	3.7	6.5
1000	0.130	0.085	0.385	6.1	4.8	7.7
1000	0.180	0.061	0.341	6.7	4.3	7.9
1000	0.250	0.044	0.244	7.8	5.4	9.5
1000	0.400	0.028	0.111	12.1	13.4	18.1
1000	0.650	0.017	0.013	25.0	15.1	29.2
1200	0.020	0.663	0.737	7.2	3.7	8.1
1200	0.032	0.414	0.645	6.4	3.8	7.4
1200	0.050	0.265	0.531	6.0	3.5	6.9
1200	0.080	0.166	0.448	5.9	3.6	6.9
1200	0.130	0.102	0.391	6.8	3.7	7.8
1200	0.180	0.074	0.338	7.5	4.7	8.9
1200	0.250	0.053	0.250	8.7	6.7	10.9
1200	0.400	0.033	0.129	12.1	8.5	14.8
1200	0.650	0.020	0.017	24.2	17.5	29.9
1500	0.020	0.828	0.789	9.2	5.0	10.5
1500	0.032	0.518	0.581	8.1	4.3	9.2
1500	0.050	0.331	0.486	7.2	3.8	8.1
1500	0.080	0.207	0.457	6.8	3.7	7.8
1500	0.130	0.127	0.376	8.0	3.9	8.9
1500	0.180	0.092	0.345	8.6	4.2	9.6
1500	0.250	0.066	0.268	9.4	5.8	11.0
1500	0.400	0.041	0.110	14.6	7.8	16.6
1500	0.650	0.025	0.009	37.8	19.6	42.6
2000	0.032	0.690	0.614	9.0	4.1	9.9
2000	0.050	0.442	0.541	8.7	4.3	9.7
2000	0.080	0.276	0.428	8.3	3.9	9.1
2000	0.130	0.170	0.340	9.6	4.3	10.6

TABLE V. (*Continued*).

Q^2 (GeV^2)	x	y	$\tilde{\sigma}_{NC}$	δ_{stat} (%)	δ_{sys} (%)	δ_{tot} (%)
2000	0.180	0.123	0.331	10.1	4.8	11.1
2000	0.250	0.088	0.249	10.7	5.9	12.2
2000	0.400	0.055	0.114	15.1	8.2	17.2
2000	0.650	0.034	0.011	37.8	18.7	42.2
3000	0.050	0.663	0.513	7.3	4.1	8.4
3000	0.080	0.414	0.458	7.7	4.2	8.7
3000	0.130	0.255	0.347	9.1	4.8	10.2
3000	0.180	0.184	0.324	9.2	4.1	10.0
3000	0.250	0.133	0.242	9.9	4.9	11.1
3000	0.400	0.083	0.127	12.5	9.0	15.4
3000	0.650	0.051	0.012	30.1	14.9	33.6
5000	0.080	0.690	0.353	10.4	4.7	11.4
5000	0.130	0.425	0.392	10.4	5.0	11.6
5000	0.180	0.307	0.223	13.4	4.5	14.1
5000	0.250	0.221	0.217	13.9	6.6	15.4
5000	0.400	0.138	0.127	17.1	8.8	19.3
5000	0.650	0.085	0.012	37.8	14.9	40.6
8000	0.130	0.680	0.283	16.5	4.9	17.2
8000	0.180	0.491	0.284	15.5	6.4	16.7
8000	0.250	0.353	0.273	15.1	7.0	16.6
8000	0.400	0.221	0.093	24.2	9.9	26.2
8000	0.650	0.136	0.013	44.7	19.8	48.9
12000	0.180	0.736	0.153	34.4	4.3	34.6
12000	0.250	0.530	0.127	32.1	6.2	32.7
12000	0.400	0.331	0.085	33.3	11.4	35.2
12000	0.650	0.204	0.015	57.7	24.2	62.6
20000	0.250	0.884	0.090	61.9	5.5	62.2
20000	0.400	0.552	0.142	35.7	9.9	37.0
20000	0.650	0.340	0.021	70.7	41.6	82.0
30000	0.400	0.828	0.182	71.9	9.6	72.6

TABLE VI. H1: double differential CC cross section $d^2\sigma_{CC}/dxdQ^2$ with its statistical (δ_{stat}), systematic (δ_{sys}), and combined (δ_{tot}) uncertainties in the e^+p collisions. The additional normalization uncertainty, not included in the systematic error, is 1.5%.

Q^2 (GeV^2)	x	y	$d^2\sigma_{CC}/dxdQ^2$ (pb/GeV^2)	δ_{stat} (%)	δ_{sys} (%)	δ_{tot} (%)
300	0.013	0.255	0.637×10^{0}	27.4	16.0	31.8
300	0.032	0.104	0.124×10^{0}	28.1	10.3	30.0
300	0.080	0.041	0.532×10^{-1}	23.8	7.5	25.5
500	0.013	0.425	0.468×10^{0}	25.1	15.7	29.7
500	0.032	0.173	0.177×10^{0}	17.0	8.7	19.2
500	0.080	0.069	0.546×10^{-1}	17.0	6.5	18.9
500	0.130	0.043	0.289×10^{-1}	27.8	8.0	29.4
1000	0.032	0.345	0.124×10^{0}	15.0	8.0	17.1
1000	0.080	0.138	0.487×10^{-1}	13.3	6.1	14.8
1000	0.130	0.085	0.199×10^{-1}	20.9	6.5	22.5
1000	0.250	0.044	0.105×10^{-1}	31.7	11.7	34.1

TABLE VI. (*Continued*).

Q^2 (GeV^2)	x	y	$d^2\sigma_{CC}/dxdQ^2$ (pb/GeV^2)	δ_{stat} (%)	δ_{sys} (%)	δ_{tot} (%)
2000	0.032	0.690	0.716×10^{-1}	15.7	8.8	18.1
2000	0.080	0.276	0.264×10^{-1}	13.5	5.8	14.8
2000	0.130	0.170	0.949×10^{-2}	20.6	5.7	21.4
2000	0.250	0.088	0.566×10^{-2}	23.0	7.3	24.6
3000	0.080	0.414	0.156×10^{-1}	15.2	6.7	16.8
3000	0.130	0.255	0.872×10^{-2}	17.0	5.9	18.1
3000	0.250	0.133	0.283×10^{-2}	23.6	8.2	25.1
5000	0.130	0.425	0.402×10^{-2}	21.0	7.4	22.3
5000	0.250	0.221	0.111×10^{-2}	26.8	6.5	27.6
8000	0.130	0.680	0.125×10^{-2}	35.7	14.3	38.5
8000	0.250	0.354	0.530×10^{-3}	33.5	11.2	35.4
8000	0.400	0.221	0.235×10^{-3}	50.0	15.6	52.4
15000	0.250	0.663	0.774×10^{-4}	71.2	18.1	73.5
15000	0.400	0.414	0.114×10^{-3}	40.9	17.4	44.5

TABLE VII. H1: reduced NC cross section $\tilde{\sigma}_{NC}(x,Q^2)$ with its combined (δ_{tot}), statistical (δ_{stat}), and systematic (δ_{sys}) uncertainties in the e^-p collisions. The additional normalization uncertainty of 1.8% is not included in the errors.

Q^2 (GeV^2)	x	$\tilde{\sigma}_{NC}$	δ_{tot} (%)	δ_{stat} (%)	δ_{sys} (%)
150	0.0032	1.218	4.7	2.7	3.8
150	0.0050	1.154	4.4	2.8	3.4
150	0.0080	0.968	9.1	4.1	8.2
200	0.0032	1.271	6.1	4.1	4.5
200	0.0050	1.107	4.6	2.8	3.6
200	0.0080	0.915	4.5	3.0	3.3
200	0.0130	0.860	4.7	3.2	3.5
200	0.0200	0.677	6.5	3.8	5.3
200	0.0320	0.558	8.6	4.5	7.4
200	0.0500	0.506	9.9	5.2	8.4
200	0.0800	0.407	12.4	5.9	10.9
250	0.0050	1.123	5.3	3.5	4.0
250	0.0080	1.021	5.3	3.2	4.2
250	0.0130	0.825	5.7	3.4	4.5
250	0.0200	0.691	5.4	3.5	4.0
250	0.0320	0.569	6.1	3.8	4.7
250	0.0500	0.493	5.7	4.3	3.7
250	0.0800	0.407	6.1	4.7	3.9
250	0.1300	0.311	7.8	5.3	5.8
250	0.2500	0.225	12.1	7.5	9.5
250	0.4000	0.138	11.8	9.3	7.2
300	0.0050	1.152	7.2	5.6	4.6
300	0.0080	1.026	5.1	3.6	3.6

TABLE VII. (*Continued*).

Q^2 (GeV^2)	x	$\tilde{\sigma}_{NC}$	δ_{tot} (%)	δ_{stat} (%)	δ_{sys} (%)
300	0.0130	0.878	5.3	3.8	3.7
300	0.0200	0.735	5.9	4.0	4.3
300	0.0320	0.605	5.8	4.2	4.1
300	0.0500	0.509	6.8	4.5	5.1
300	0.0800	0.390	6.9	5.2	4.6
300	0.1300	0.332	8.8	5.4	7.0
300	0.2500	0.277	12.8	6.9	10.8
300	0.4000	0.143	14.2	10.3	9.8
400	0.0080	1.088	6.1	4.5	4.1
400	0.0130	0.897	5.6	4.3	3.6
400	0.0200	0.732	5.8	4.5	3.6
400	0.0320	0.560	6.1	4.8	3.8
400	0.0500	0.514	6.3	5.0	3.7
400	0.0800	0.429	7.0	5.5	4.3
400	0.1300	0.352	7.5	5.6	5.0
400	0.2500	0.240	10.6	7.6	7.4
400	0.4000	0.143	13.7	10.8	8.4
500	0.0080	1.044	9.3	7.8	5.1
500	0.0130	1.003	6.8	5.1	4.5
500	0.0200	0.765	7.0	5.1	4.8
500	0.0320	0.604	7.0	5.3	4.5
500	0.0500	0.517	6.9	5.6	4.0
500	0.0800	0.392	9.2	6.4	6.5
500	0.1300	0.363	8.7	7.2	4.9
500	0.1800	0.283	11.5	8.2	8.1
500	0.2500	0.254	14.2	10.5	9.5
500	0.4000	0.139	21.6	15.4	15.1
500	0.6500	0.026	22.4	19.6	10.9
650	0.0130	0.988	7.3	6.0	4.1
650	0.0200	0.791	7.7	6.3	4.4
650	0.0320	0.684	7.4	6.1	4.3
650	0.0500	0.538	8.3	6.5	5.2
650	0.0800	0.436	9.2	7.1	5.8
650	0.1300	0.343	10.5	8.8	5.8
650	0.1800	0.330	11.8	9.1	7.5
650	0.2500	0.251	15.9	11.9	10.6
650	0.4000	0.090	24.9	22.9	9.6
800	0.0130	0.842	11.7	10.2	5.8
800	0.0200	0.806	8.8	7.2	4.9
800	0.0320	0.721	8.7	7.1	5.0
800	0.0500	0.587	8.6	7.4	4.4
800	0.0800	0.518	9.4	7.8	5.2
800	0.1300	0.411	11.8	10.0	6.2
800	0.1800	0.302	13.4	11.6	6.7
800	0.2500	0.212	16.4	14.1	8.2
800	0.4000	0.117	24.4	20.9	12.9
800	0.6500	0.015	26.5	21.8	14.9
1000	0.0130	0.773	13.5	11.5	6.9
1000	0.0200	0.787	9.2	7.9	4.7
1000	0.0320	0.572	10.0	9.0	4.4
1000	0.0500	0.577	9.5	8.4	4.5
1000	0.0800	0.450	10.8	9.3	5.6

TABLE VII. (*Continued*).

Q^2 (GeV^2)	x	$\tilde{\sigma}_{NC}$	δ_{tot} (%)	δ_{stat} (%)	δ_{sys} (%)
1000	0.1300	0.491	11.6	10.3	5.3
1000	0.1800	0.249	14.6	13.5	5.7
1000	0.2500	0.311	15.9	13.0	9.2
1000	0.4000	0.122	26.9	22.9	14.0
1200	0.0200	0.839	10.0	9.1	4.0
1200	0.0320	0.719	9.9	9.2	3.7
1200	0.0500	0.645	9.9	9.3	3.6
1200	0.0800	0.415	11.2	10.7	3.4
1200	0.1300	0.384	13.4	12.6	4.5
1200	0.1800	0.341	14.6	13.6	5.3
1200	0.2500	0.251	17.3	15.8	7.0
1200	0.4000	0.110	27.7	25.0	12.0
1500	0.0200	0.860	13.5	12.4	5.5
1500	0.0320	0.704	11.4	10.4	4.7
1500	0.0500	0.515	12.2	11.7	3.6
1500	0.0800	0.512	11.7	11.0	4.0
1500	0.1300	0.390	14.8	13.9	5.0
1500	0.1800	0.260	19.1	18.6	4.3
1500	0.2500	0.197	21.1	19.6	7.7
1500	0.4000	0.145	27.4	24.3	12.8
1500	0.6500	0.014	38.9	35.4	16.1
2000	0.0320	0.796	11.9	11.1	4.4
2000	0.0500	0.599	13.9	13.0	5.0
2000	0.0800	0.582	13.0	12.3	4.3
2000	0.1300	0.224	20.6	20.0	4.6
2000	0.1800	0.249	22.7	21.9	6.3
2000	0.2500	0.197	23.4	22.4	6.8
2000	0.4000	0.108	29.5	27.7	10.1
3000	0.0500	0.606	12.4	10.6	6.4
3000	0.0800	0.556	11.8	10.9	4.5
3000	0.1300	0.464	13.0	12.4	4.0
3000	0.1800	0.347	16.1	15.3	5.1
3000	0.2500	0.255	19.1	17.8	7.0
3000	0.4000	0.128	25.5	23.0	10.9
5000	0.0800	0.707	11.7	10.6	4.8
5000	0.1300	0.536	14.2	13.1	5.3
5000	0.1800	0.442	14.9	14.0	5.2
5000	0.2500	0.361	20.3	17.4	10.5
5000	0.4000	0.091	33.5	31.6	11.1
5000	0.6500	0.010	45.1	41.0	18.8
8000	0.1300	0.722	17.2	16.0	6.5
8000	0.1800	0.386	21.2	20.4	5.8
8000	0.2500	0.295	23.3	21.8	8.2
8000	0.4000	0.197	32.4	27.7	16.8
12000	0.1800	0.471	28.8	27.8	7.6
12000	0.2500	0.298	30.2	28.9	8.6
12000	0.4000	0.083	53.7	50.0	19.6
20000	0.2500	0.349	52.2	51.1	10.8
20000	0.4000	0.182	46.7	44.7	13.3
20000	0.6500	0.014	79.8	70.7	36.9
30000	0.4000	0.268	72.9	70.7	17.5

TABLE VIII. H1: double differential CC cross section $d^2\sigma_{CC}/dxdQ^2$ with its overall (δ_{tot}), statistical (δ_{stat}), and systematic uncertainties (δ_{sys}) in the e^-p collisions. The additional normalization uncertainty of 1.8% is not included in the errors.

Q^2 (GeV^2)	x	$d^2\sigma_{CC}/dxdQ^2$ (pb/GeV^2)	δ_{tot} (%)	δ_{stat} (%)	δ_{sys} (%)
300	0.013	0.458×10^{0}	57.6	55.4	15.7
300	0.032	0.399×10^{0}	27.3	24.5	12.0
300	0.080	0.690×10^{-1}	42.3	40.7	11.6
500	0.013	0.433×10^{0}	39.9	37.6	13.3
500	0.032	0.285×10^{0}	21.0	19.6	7.8
500	0.080	0.790×10^{-1}	22.4	21.8	5.1
500	0.130	0.551×10^{-1}	29.9	29.0	7.0
1000	0.032	0.186×10^{0}	18.2	17.5	4.9
1000	0.080	0.556×10^{-1}	18.4	17.9	4.3
1000	0.130	0.310×10^{-1}	24.5	24.0	4.6
1000	0.250	0.139×10^{-1}	39.1	37.6	10.6
2000	0.032	0.132×10^{0}	16.2	15.5	4.9
2000	0.080	0.571×10^{-1}	13.6	13.0	3.9
2000	0.130	0.197×10^{-1}	21.7	21.2	4.5
2000	0.250	0.855×10^{-2}	26.4	25.6	6.5
3000	0.080	0.324×10^{-1}	14.8	14.0	4.8
3000	0.130	0.250×10^{-1}	15.2	14.0	6.1
3000	0.250	0.749×10^{-2}	20.1	18.9	7.0
3000	0.400	0.251×10^{-2}	40.3	35.2	19.6
5000	0.080	0.213×10^{-1}	19.2	17.9	6.7
5000	0.130	0.108×10^{-1}	18.2	16.8	7.0
5000	0.250	0.550×10^{-2}	16.9	16.3	4.4
5000	0.400	0.123×10^{-2}	35.6	33.1	13.1
8000	0.130	0.722×10^{-2}	21.1	18.9	9.3
8000	0.250	0.342×10^{-2}	17.4	16.3	6.2
8000	0.400	0.946×10^{-3}	30.4	28.6	10.3
15000	0.250	0.139×10^{-2}	27.3	22.1	16.0
15000	0.400	0.419×10^{-3}	29.5	27.5	10.7

TABLE IX. CDF: Drell-Yan data in the muon and electron channels.

Muon channel	
Mass bin	$d^2\sigma/dMdy\|_{\|y\|<1}$ (pb/GeV)
40–50	0.367 ± 0.057
50–60	0.129 ± 0.030
60–70	0.107 ± 0.019
70–78	0.124 ± 0.019
78–86	0.360 ± 0.037
86–90	2.36 ± 0.21
90–94	12.38 ± 1.08
94–102	0.550 ± 0.052
102–110	0.161 ± 0.025
110–120	0.069 ± 0.016
120–150	0.024 ± 0.005
150–200	0.0047 ± 0.0016
200–250	0.0021 ± 0.0011
250–300	0.00107 ± 0.00076
300–400	0.00024 ± 0.00024
400–500	0.0 ± 0.00019

TABLE IX. (*Continued*).

Electron channel		
Mass bin	M_{mean}(GeV)	$d\sigma/dM$(pb/GeV)
40–50	44.5	$(2.300\pm0.448\pm0.126)\times10^{0}$
50–60	54.6	$(8.038\pm0.978\pm0.478)\times10^{-1}$
60–70	63.8	$(6.005\pm0.547\pm0.293)\times10^{-1}$
70–78	74.7	$(5.829\pm0.439\pm0.148)\times10^{-1}$
78–86	82.9	$(1.638\pm0.061\pm0.011)\times10^{0}$
86–88	87.1	$(5.895\pm0.222\pm0.027)\times10^{0}$
88–90	89.2	$(1.828\pm0.051\pm0.009)\times10^{1}$
90–92	90.6	$(5.485\pm0.135\pm0.033)\times10^{1}$
92–94	92.8	$(2.275\pm0.065\pm0.015)\times10^{1}$
94–100	96.2	$(3.796\pm0.117\pm0.019)\times10^{0}$
100–105	102.2	$(9.120\pm0.733\pm0.126)\times10^{-1}$
105–120	111.2	$(2.631\pm0.237\pm0.044)\times10^{-1}$
120–140	128.8	$(6.554\pm1.017\pm0.191)\times10^{-2}$
140–200	164.2	$(2.083\pm0.320\pm0.051)\times10^{-2}$
200–300	240.6	$(2.599\pm0.847\pm0.039)\times10^{-3}$
300–400	342.2	$(8.080\pm4.677\pm0.127)\times10^{-4}$
400–600	478.8	$(1.433\pm1.433\pm0.037)\times10^{-4}$
>600	725.6	$(0.000\pm0.964\pm0.000)\times10^{-4}$

TABLE X. DØ: Drell-Yan data in the electron channel.

Electron channel	
M_{ll} range (GeV)	σ (pb)
120–160	$1.93\ ^{+0.43}_{-0.44}$
160–200	$0.49\ ^{+0.16}_{-0.18}$
200–240	$0.28\ ^{+0.09}_{-0.10}$
240–290	$0.066\ ^{+0.052}_{-0.058}$
290–340	$0.033\ ^{+0.032}_{-0.030}$
340–400	$0.057\ ^{+0.042}_{-0.047}$
400–500	$<0.063(0.039)$
500–600	$<0.060(0.037)$
600–1000	$<0.058(0.035)$

TABLE XI. Preliminary combined LEP results on the $e^-e^+ \to f\bar{f}$ production at $\sqrt{s}=130$–202 GeV. The standard model predictions are from ZFITTER [48] v6.10.

$\sqrt{s}$ (GeV)	Quantity	Value	SM
130	$\sigma(q\bar{q})$ [pb]	81.938 ± 2.220	82.803
	$\sigma(\mu^+\mu^-)$ [pb]	8.592 ± 0.682	8.439
	$\sigma(\tau^+\tau^-)$ [pb]	9.082 ± 0.931	8.435
	$A_{fb}(\mu^+\mu^-)$	0.692 ± 0.060	0.705
	$A_{fb}(\tau^+\tau^-)$	0.663 ± 0.076	0.704
136	$\sigma(q\bar{q})$ [pb]	66.570 ± 1.967	66.596
	$\sigma(\mu^+\mu^-)$ [pb]	8.231 ± 0.678	7.281
	$\sigma(\tau^+\tau^-)$ [pb]	7.123 ± 0.821	7.279
	$A_{fb}(\mu^+\mu^-)$	0.704 ± 0.060	0.684
	$A_{fb}(\tau^+\tau^-)$	0.752 ± 0.088	0.683
161	$\sigma(q\bar{q})$ [pb]	36.909 ± 1.071	35.247
	$\sigma(\mu^+\mu^-)$ [pb]	4.586 ± 0.364	4.613
	$\sigma(\tau^+\tau^-)$ [pb]	5.692 ± 0.545	4.613
	$A_{fb}(\mu^+\mu^-)$	0.535 ± 0.067	0.609
	$A_{fb}(\tau^+\tau^-)$	0.646 ± 0.077	0.609

TABLE XI. (*Continued*).

$\sqrt{s}$ (GeV)	Quantity	Value	SM
172	$\sigma(q\bar{q})$ [pb]	29.172 ± 0.987	28.738
	$\sigma(\mu^+\mu^-)$ [pb]	3.556 ± 0.317	3.952
	$\sigma(\tau^+\tau^-)$ [pb]	4.026 ± 0.450	3.951
	$A_{fb}(\mu^+\mu^-)$	0.672 ± 0.077	0.591
	$A_{fb}(\tau^+\tau^-)$	0.342 ± 0.094	0.591
183	$\sigma(q\bar{q})$ [pb]	24.567 ± 0.421	24.200
	$\sigma(\mu^+\mu^-)$ [pb]	3.484 ± 0.147	3.446
	$\sigma(\tau^+\tau^-)$ [pb]	3.398 ± 0.174	3.446
	$A_{fb}(\mu^+\mu^-)$	0.558 ± 0.035	0.576
	$A_{fb}(\tau^+\tau^-)$	0.608 ± 0.045	0.576
189	$\sigma(q\bar{q})$ [pb]	22.420 ± 0.248	22.156
	$\sigma(\mu^+\mu^-)$ [pb]	3.109 ± 0.077	3.207
	$\sigma(\tau^+\tau^-)$ [pb]	3.140 ± 0.100	3.207
	$A_{fb}(\mu^+\mu^-)$	0.565 ± 0.021	0.569
	$A_{fb}(\tau^+\tau^-)$	0.584 ± 0.028	0.569
192	$\sigma(q\bar{q})$ [pb]	22.292 ± 0.514	21.237
	$\sigma(\mu^+\mu^-)$ [pb]	2.941 ± 0.175	3.097
	$\sigma(\tau^+\tau^-)$ [pb]	2.863 ± 0.216	3.097
	$A_{fb}(\mu^+\mu^-)$	0.540 ± 0.052	0.566
	$A_{fb}(\tau^+\tau^-)$	0.610 ± 0.071	0.566
196	$\sigma(q\bar{q})$ [pb]	20.730 ± 0.330	20.127
	$\sigma(\mu^+\mu^-)$ [pb]	2.965 ± 0.106	2.962
	$\sigma(\tau^+\tau^-)$ [pb]	3.015 ± 0.139	2.962
	$A_{fb}(\mu^+\mu^-)$	0.579 ± 0.031	0.562
	$A_{fb}(\tau^+\tau^-)$	0.489 ± 0.045	0.562
200	$\sigma(q\bar{q})$ [pb]	19.376 ± 0.306	19.085
	$\sigma(\mu^+\mu^-)$ [pb]	3.038 ± 0.104	2.834
	$\sigma(\tau^+\tau^-)$ [pb]	2.995 ± 0.135	2.833
	$A_{fb}(\mu^+\mu^-)$	0.518 ± 0.031	0.558
	$A_{fb}(\tau^+\tau^-)$	0.546 ± 0.043	0.558
202	$\sigma(q\bar{q})$ [pb]	19.291 ± 0.425	18.572
	$\sigma(\mu^+\mu^-)$ [pb]	2.621 ± 0.139	2.770
	$\sigma(\tau^+\tau^-)$ [pb]	2.806 ± 0.183	2.769
	$A_{fb}(\mu^+\mu^-)$	0.543 ± 0.048	0.556
	$A_{fb}(\tau^+\tau^-)$	0.580 ± 0.060	0.556

TABLE XII. Combined LEP 2 data on the R_b and R_c along with the standard model predictions.

$\sqrt{s}$ (GeV)	R_b	R_c
133	0.1809 ± 0.0133	–
	(0.1853)	–
167	0.1479 ± 0.0127	–
	(0.1708)	–
183	0.1616 ± 0.0101	0.270 ± 0.043
	(0.1671)	(0.250)
189	0.1559 ± 0.0066	0.241 ± 0.024
	(0.1660)	(0.252)
192	0.1688 ± 0.0187	–
	(0.1655)	–
196	0.1577 ± 0.0109	–
	(0.1648)	–
200	0.1621 ± 0.0111	–
	(0.1642)	–
202	0.1873 ± 0.0177	–
	(0.1638)	–
206	0.1696 ± 0.0182	–
	(0.1633)	–

TABLE XIII. The LEP 2 $e^+e^-\to e^+e^-$ production cross sections.

$\sqrt{s}$ (GeV)	σ_{ee} (pb)	$\sigma_{ee}^{\rm SM}$ (pb)
	ALEPH	
130	$191.3\pm6.2\pm3.5$	186.7
136	$162.2\pm5.6\pm3.5$	167.3
161	$119.7\pm3.7\pm2.3$	119.0
172	$107.8\pm3.5\pm2.1$	102.5
183	$90.9\pm1.4\pm1.7$	90.9
189	$84\pm0.72\pm0.71$	87.25
192	$80.00\pm1.90\pm0.87$	81.9
196	$78.74\pm1.10\pm0.76$	79.2
200	$73.95\pm1.02\pm0.70$	76.3
202	$75.42\pm1.50\pm0.80$	74.6
204.9	$75.33\pm1.20\pm0.90$	74.36
206.7	$73.40\pm0.91\pm0.70$	74.50
	DELPHI	
130.2	$42.0\pm4.0\pm0.80$	48.7
136.2	$47.1\pm4.2\pm0.71$	44.6
161.3	$27.1\pm1.8\pm0.41$	31.9
172.1	$30.3\pm1.9\pm0.36$	28.0
183	25.6 ± 0.8	24.7
189	22.6 ± 0.4	23.1
192	24.03 ± 1.03	22.29
196	22.43 ± 0.56	21.36
200	20.56 ± 0.51	20.52
202	21.30 ± 0.75	20.08
	L3	
130.1	$45.0\pm2.7\pm0.2$	49.7
136.1	$43.6\pm2.8\pm0.2$	45.4
161.3	$31.1\pm1.8\pm0.9$	32.4
172.3	$26.7\pm1.8\pm0.8$	28.3
182.7	$25.6\pm0.7\pm0.1$	25.0
188.7	$23.5\pm0.4\pm0.1$	23.4
	OPAL	
130.25	$615\pm16\pm8$	645
136.22	$580\pm15\pm8$	592
161.34	$434\pm7\pm5$	425
172.12	$365\pm6\pm5$	375
183	$333\pm3\pm4$	333
189	$304.6\pm1.3\pm1.4$	311.6
192	$301.4\pm3.3\pm1.5$	299.4
196	$285.8\pm2.0\pm1.5$	287.7
200	$273.0\pm1.9\pm1.4$	276.3
202	$272.0\pm2.8\pm1.4$	270.6

TABLE XIV. The $e^+e^-\to e^+e^-$ differential cross section $d\sigma/d\cos\theta^*$ measured by ALEPH.

$\cos\theta^*$ range	130 GeV		136 GeV		161 GeV	
	σ (pb)	σ_{SM} (pb)	σ (pb)	σ_{SM} (pb)	σ (pb)	σ_{SM} (pb)
$-0.9--0.7$	0.19 ± 0.34	0.37	0.73 ± 0.20	0.22	0.46 ± 0.21	0.37
$-0.7--0.5$	1.41 ± 0.35	0.55	1.16 ± 0.36	0.62	0.88 ± 0.21	0.44
$-0.5--0.3$	1.36 ± 0.45	1.09	0.54 ± 0.35	0.49	0.55 ± 0.28	0.79
$-0.3--0.1$	1.23 ± 0.48	1.19	0.52 ± 0.41	0.89	0.39 ± 0.26	0.62
-0.1–0.1	2.60 ± 0.69	2.45	1.46 ± 0.62	2.09	1.24 ± 0.40	1.43
0.1–0.3	3.78 ± 0.83	3.82	2.09 ± 0.74	2.96	2.37 ± 0.47	2.07
0.3–0.5	8.88 ± 1.18	7.36	6.68 ± 1.08	6.13	5.35 ± 0.73	4.95
0.5–0.7	21.63 ± 2.12	22.20	16.58 ± 1.97	20.50	14.38 ± 1.27	14.10
0.7–0.9	149.61 ± 6.22	148.0	132.55 ± 5.85	133.0	93.76 ± 3.76	94.20
	172 GeV		183 GeV			
$-0.9--0.7$	0.32 ± 0.19	0.28	0.24 ± 0.07	0.21		
$-0.7--0.5$	0.88 ± 0.19	0.34	0.29 ± 0.07	0.25		
$-0.5--0.3$	0.66 ± 0.24	0.58	0.46 ± 0.10	0.51		
$-0.3--0.1$	0.61 ± 0.23	0.44	0.71 ± 0.12	0.64		
-0.1–0.1	0.95 ± 0.36	1.23	0.83 ± 0.14	0.90		
$0.1-0.3$	1.80 ± 0.47	1.93	1.42 ± 0.20	1.83		
0.3–0.5	4.92 ± 0.71	4.24	3.90 ± 0.29	3.66		
0.5–0.7	13.07 ± 1.20	12.40	12.47 ± 0.56	11.10		
0.7–0.9	84.61 ± 3.51	81.10	71.90 ± 1.86	71.80		

TABLE XV. The $e^+e^-\to\mu^+\mu^-$ and $e^+e^-\to\tau^+\tau^-$ differential cross sections $d\sigma/d\cos\theta^*$ measured by ALEPH.

$\cos\theta^*$ range	$d\sigma/d\cos\theta^*$(pb)						
	189 GeV	192 GeV	196 GeV	200 GeV	202 GeV	204.9 GeV	206.7 GeV
			$\mu^+\mu^-$				
$-0.95--0.8$	0.69 ± 0.17	0.23 ± 0.25	0.61 ± 0.24	0.64 ± 0.23	0.83 ± 0.38	0.42 ± 0.20	0.51 ± 0.18
$-0.8--0.6$	0.31 ± 0.10	0.17 ± 0.18	0.56 ± 0.20	0.58 ± 0.19	0.10 ± 0.13	0.29 ± 0.15	0.43 ± 0.14
$-0.6--0.4$	0.38 ± 0.11	1.07 ± 0.45	0.51 ± 0.19	0.90 ± 0.24	0.86 ± 0.33	0.17 ± 0.13	0.25 ± 0.11
$-0.4--0.2$	0.75 ± 0.16	0.72 ± 0.37	0.58 ± 0.20	1.02 ± 0.26	0.48 ± 0.26	0.56 ± 0.31	1.00 ± 0.21
-0.2–0.0	1.11 ± 0.19	0.89 ± 0.42	0.88 ± 0.25	1.20 ± 0.28	0.73 ± 0.32	0.94 ± 0.25	0.60 ± 0.16
0.0–0.2	1.07 ± 0.19	1.80 ± 0.59	1.09 ± 0.28	1.59 ± 0.32	1.22 ± 0.41	1.00 ± 0.27	1.06 ± 0.21
0.2–0.4	2.09 ± 0.26	0.88 ± 0.42	1.89 ± 0.37	1.97 ± 0.36	1.70 ± 0.48	1.17 ± 0.29	1.61 ± 0.26
0.4–0.6	1.93 ± 0.25	2.28 ± 0.66	2.38 ± 0.40	1.78 ± 0.34	2.42 ± 0.56	1.64 ± 0.34	1.94 ± 0.28
0.6–0.8	3.24 ± 0.32	3.96 ± 0.85	2.84 ± 0.44	3.03 ± 0.43	2.22 ± 0.54	1.65 ± 0.35	2.84 ± 0.35
0.8–0.95	3.80 ± 0.40	3.83 ± 0.99	3.12 ± 0.54	3.35 ± 0.54	3.81 ± 0.82	2.33 ± 0.48	2.95 ± 0.42
			$\tau^+\tau^-$				
$-0.95--0.8$	0.43 ± 0.33	-0.35 ± 0.42	0.80 ± 0.49	0.76 ± 0.47	0.94 ± 0.77	0.65 ± 0.46	0.35 ± 0.27
$-0.8--0.6$	0.49 ± 0.18	0.36 ± 0.47	1.02 ± 0.39	0.93 ± 0.35	0.09 ± 0.28	0.50 ± 0.28	0.38 ± 0.21
$-0.6--0.4$	0.17 ± 0.13	0.18 ± 0.33	-0.03 ± 0.17	0.70 ± 0.32	0.36 ± 0.34	0.39 ± 0.27	0.38 ± 0.21
$-0.4--0.2$	0.99 ± 0.24	1.64 ± 0.75	0.58 ± 0.29	0.68 ± 0.31	0.43 ± 0.44	0.21 ± 0.23	0.60 ± 0.25
-0.2–0.0	0.82 ± 0.24	0.76 ± 0.58	0.82 ± 0.36	1.27 ± 0.42	0.45 ± 0.42	0.20 ± 0.25	0.37 ± 0.20
0.0–0.2	0.70 ± 0.24	1.98 ± 0.83	0.72 ± 0.34	1.44 ± 0.43	1.20 ± 0.59	1.14 ± 0.41	1.37 ± 0.34
0.2–0.4	1.98 ± 0.34	1.90 ± 0.85	2.50 ± 0.58	1.71 ± 0.48	2.01 ± 0.72	1.73 ± 0.50	1.27 ± 0.34
0.4–0.6	2.16 ± 0.37	2.65 ± 0.98	1.68 ± 0.48	1.84 ± 0.49	0.94 ± 0.58	1.43 ± 0.48	1.35 ± 0.35
0.6–0.8	2.40 ± 0.39	2.55 ± 0.99	2.65 ± 0.65	2.86 ± 0.63	4.71 ± 1.13	1.60 ± 0.52	1.85 ± 0.41
0.8–0.95	7.09 ± 1.22	3.74 ± 1.89	6.24 ± 1.24	2.65 ± 1.36	3.33 ± 2.09	3.09 ± 1.08	2.67 ± 0.72

TABLE XVI. Differential cross section $d\sigma/d\cos\theta^*$ for the $e^+e^-\rightarrow e^+e^-,\mu^+\mu^-,\tau^+\tau^-$, $q\overline{q}$ production measured by OPAL.

$\cos\theta^*$ range	$d\sigma/d\cos\theta^*$ (pb)							
	130.12 GeV	136.08 GeV	182.69 GeV	189 GeV	192 GeV	196 GeV	200 GeV	202 GeV
				e^+e^-				
$-0.9--0.7$	4^{+3}_{-2}	5^{+3}_{-2}	$1.2^{+0.4}_{-0.3}$	1.4 ± 0.2	$1.7^{+0.7}_{-0.5}$	1.4 ± 0.3	1.6 ± 0.3	$2.3^{+0.7}_{-0.6}$
$-0.7--0.5$	4^{+3}_{-2}	4^{+3}_{-2}	2.1 ± 0.4	2.0 ± 0.2	$1.9^{+0.8}_{-0.6}$	1.6 ± 0.3	1.9 ± 0.3	$1.6^{+0.6}_{-0.5}$
$-0.5--0.3$	6^{+3}_{-2}	8^{+4}_{-3}	2.3 ± 0.5	2.4 ± 0.3	$1.9^{+0.8}_{-0.6}$	2.6 ± 0.4	2.3 ± 0.4	3.2 ± 0.7
$-0.3--0.1$	6^{+4}_{-2}	9^{+4}_{-3}	4.8 ± 0.7	3.0 ± 0.3	$1.5^{+0.7}_{-0.5}$	2.7 ± 0.4	2.4 ± 0.4	$2.5^{+0.7}_{-0.6}$
-0.1–0.1	13^{+5}_{-4}	8^{+4}_{-3}	6.1 ± 0.7	4.3 ± 0.3	5.4 ± 1.0	3.7 ± 0.5	5.2 ± 0.6	4.4 ± 0.8
0.1–0.3	23 ± 5	18 ± 4	9.5 ± 0.9	8.3 ± 0.5	9.6 ± 1.3	8.3 ± 0.7	7.4 ± 0.7	8.5 ± 1.1
0.3–0.5	45 ± 7	35 ± 6	21.1 ± 1.4	19.3 ± 0.7	19.3 ± 1.8	17.0 ± 1.1	17.0 ± 1.1	14.5 ± 1.4
0.5–0.7	113 ± 11	122 ± 10	62 ± 2	61.4 ± 1.4	59.0 ± 3.2	56.7 ± 2.0	55.6 ± 2.0	54.6 ± 2.8
0.7–0.9	839 ± 30	725 ± 27	458 ± 8	415 ± 5	396 ± 9	388 ± 6	369 ± 6	361 ± 8
				$\mu^+\mu^-$				
$-1.0--0.8$	0^{+3}_{-1}	-1^{+1}_{-0}	$0.4^{+0.4}_{-0.2}$	$0.67^{+0.21}_{-0.17}$	$1.2^{+0.8}_{-0.5}$	$0.19^{+0.24}_{-0.12}$	$0.52^{+0.33}_{-0.22}$	$1.1^{+0.7}_{-0.5}$
$-0.8--0.6$	3^{+3}_{-2}	2^{+3}_{-2}	$0.7^{+0.4}_{-0.3}$	$0.36^{+0.14}_{-0.11}$	$0.7^{+0.6}_{-0.4}$	$0.35^{+0.26}_{-0.17}$	$0.20^{+0.22}_{-0.13}$	$0.2^{+0.4}_{-0.1}$
$-0.6--0.4$	0^{+2}_{-1}	0^{+2}_{-1}	$0.5^{+0.4}_{-0.2}$	$0.50^{+0.16}_{-0.13}$	$0.3^{+0.5}_{-0.3}$	$0.84^{+0.34}_{-0.25}$	$0.49^{+0.29}_{-0.20}$	$0.2^{+0.4}_{-0.2}$
$-0.4--0.2$	6^{+4}_{-3}	5^{+3}_{-2}	$0.9^{+0.4}_{-0.3}$	0.66 ± 0.14	$0.8^{+0.6}_{-0.4}$	$0.60^{+0.28}_{-0.20}$	$0.56^{+0.28}_{-0.20}$	$0.3^{+0.4}_{-0.2}$
-0.2–0.0	3^{+3}_{-2}	1^{+2}_{-1}	$1.2^{+0.5}_{-0.3}$	1.33 ± 0.20	$2.0^{+0.8}_{-0.6}$	$0.55^{+0.28}_{-0.20}$	$0.83^{+0.32}_{-0.24}$	$1.2^{+0.6}_{-0.4}$
0.0–0.2	2^{+3}_{-2}	3^{+3}_{-2}	1.8 ± 0.4	1.20 ± 0.19	$1.0^{+0.6}_{-0.4}$	1.5 ± 0.3	$1.2^{+0.4}_{-0.3}$	$1.0^{+0.6}_{-0.4}$
0.2–0.4	6^{+4}_{-3}	6^{+3}_{-2}	2.4 ± 0.5	1.85 ± 0.24	$2.1^{+0.8}_{-0.6}$	1.6 ± 0.3	2.0 ± 0.4	$1.0^{+0.6}_{-0.4}$
0.4–0.6	5^{+4}_{-2}	10^{+4}_{-3}	1.9 ± 0.5	2.04 ± 0.27	$1.5^{+0.8}_{-0.6}$	2.0 ± 0.4	1.4 ± 0.3	$1.2^{+0.6}_{-0.5}$
0.6–0.8	5^{+4}_{-3}	9^{+4}_{-3}	2.5 ± 0.5	2.64 ± 0.30	$2.5^{+1.0}_{-0.8}$	3.0 ± 0.5	2.8 ± 0.5	$2.5^{+0.8}_{-0.7}$
0.8–1.0	9^{+5}_{-4}	18^{+7}_{-5}	4.7 ± 0.9	3.96 ± 0.43	$1.9^{+1.1}_{-0.8}$	3.9 ± 0.6	3.7 ± 0.6	$2.8^{+1.0}_{-0.8}$
				$\tau^+\tau^-$				
$-1.0--0.8$	-1^{+10}_{-0}	-1^{+9}_{-0}	$0.7^{+0.9}_{-0.5}$	$0.99^{+0.44}_{-0.33}$	$0.9^{+1.7}_{-0.9}$	$1.2^{+0.8}_{-0.5}$	$0.6^{+0.7}_{-0.4}$	$2.4^{+1.7}_{-1.1}$
$-0.8--0.6$	0^{+1}_{-0}	0^{+1}_{-0}	$0.0^{+0.3}_{-0.1}$	$0.39^{+0.19}_{-0.15}$	$0.1^{+0.6}_{-0.2}$	$1.3^{+0.5}_{-0.4}$	$0.2^{+0.3}_{-0.2}$	$0.4^{+0.6}_{-0.3}$
$-0.6--0.4$	-1^{+2}_{-0}	2^{+3}_{-2}	$0.0^{+0.3}_{-0.1}$	0.75 ± 0.18	$0.7^{+0.7}_{-0.4}$	$0.6^{+0.4}_{-0.2}$	$0.5^{+0.3}_{-0.2}$	$0.7^{+0.7}_{-0.4}$
$-0.4--0.2$	2^{+4}_{-2}	0^{+1}_{-0}	$0.7^{+0.5}_{-0.3}$	0.76 ± 0.18	$0.3^{+0.7}_{-0.3}$	$0.7^{+0.4}_{-0.3}$	$1.0^{+0.4}_{-0.3}$	$0.9^{+0.7}_{-0.4}$
-0.2–0.0	3^{+4}_{-2}	1^{+3}_{-1}	$1.5^{+0.6}_{-0.5}$	0.84 ± 0.19	$0.4^{+0.6}_{-0.3}$	$0.8^{+0.4}_{-0.3}$	$1.0^{+0.4}_{-0.3}$	$0.5^{+0.6}_{-0.3}$
0.0–0.2	2^{+4}_{-2}	4^{+3}_{-2}	$1.6^{+0.6}_{-0.5}$	1.68 ± 0.27	$2.0^{+1.0}_{-0.7}$	$1.1^{+0.4}_{-0.3}$	$1.4^{+0.4}_{-0.3}$	$0.9^{+0.7}_{-0.4}$
0.2–0.4	1^{+4}_{-2}	4^{+4}_{-2}	$1.5^{+0.6}_{-0.5}$	2.00 ± 0.30	$2.0^{+1.0}_{-0.7}$	$1.3^{+0.5}_{-0.4}$	2.0 ± 0.5	$1.5^{+0.8}_{-0.6}$
0.4–0.6	7^{+5}_{-3}	7^{+4}_{-3}	2.5 ± 0.6	2.52 ± 0.33	$1.9^{+1.0}_{-0.7}$	2.2 ± 0.5	2.4 ± 0.5	$3.7^{+1.1}_{-0.9}$
0.6–0.8	7^{+5}_{-3}	8^{+5}_{-3}	4.3 ± 0.8	3.29 ± 0.40	$3.9^{+1.3}_{-1.0}$	2.4 ± 0.5	3.7 ± 0.6	$3.4^{+1.1}_{-0.9}$
0.8–1.0	14^{+19}_{-11}	7^{+15}_{-7}	$3.9^{+1.6}_{-1.3}$	5.1 ± 0.8	$6.3^{+2.7}_{-2.0}$	4.8 ± 1.1	5.5 ± 1.2	$3.2^{+1.9}_{-1.3}$
				$q\overline{q}$				
$0.0-0.1$	70 ± 12	48 ± 9	17.0 ± 1.8	17.5 ± 1.0				
$0.1-0.2$	52 ± 9	64 ± 10	17.6 ± 1.8	17.7 ± 1.1				
$0.2-0.3$	70 ± 11	56 ± 10	17.7 ± 1.9	16.8 ± 1.0				
$0.3-0.4$	70 ± 11	63 ± 10	19.9 ± 2.0	18.2 ± 1.1				
$0.4-0.5$	64 ± 10	44 ± 9	23.1 ± 2.1	18.8 ± 1.1				
$0.5-0.6$	79 ± 12	39 ± 8	24.6 ± 2.2	21.6 ± 1.2				
$0.6-0.7$	81 ± 12	78 ± 11	27.2 ± 2.3	24.2 ± 1.2y				
$0.7-0.8$	94 ± 13	81 ± 11	26.1 ± 2.2	26.0 ± 1.3				
$0.8-0.9$	85 ± 12	82 ± 11	31.2 ± 2.4	27.7 ± 1.3				
$0.9-1.0$	160 ± 23	123 ± 19	32.0 ± 3.2	31.4 ± 1.7				

TABLE XVII. Differential cross section $d\sigma/d\cos\theta^*$ for the $e^+e^-\rightarrow\mu^+\mu^-,\tau^+\tau^-$ production measured by DELPHI. For $\sqrt{s}=183$ GeV the $\cos\theta^*$ range for $\mu^+\mu^-$ channel is from -0.94 to 0.94.

$\cos\theta^*$ range	$d\sigma/d\cos\theta^*$ (pb) 183 GeV	189 GeV	192 GeV	196 GeV	200 GeV	202 GeV
			$\mu^+\mu^-$			
−0.97–−0.8	.000±.178±.013	.495±.143±.008	.000±.331±.005	.716±.253±.018	.560±.211±.016	1.077±.407±.029
−0.8–−0.6	.514±.230±.013	.478±.128±.008	.202±.202±.005	.520±.196±.013	.266±.133±.007	.585±.292±.017
−0.6–−0.4	.989±.313±.024	.448±.120±.007	.814±.407±.020	.614±.205±.015	.885±.236±.023	.259±.183±.007
−0.4–−0.2	.972±.307±.023	.391±.113±.006	.385±.272±.009	.208±.120±.005	.699±.211±.018	.249±.176±.007
−0.2–0.0	1.298±.360±.032	1.287±.212±.021	1.068±.477±.027	.875±.253±.022	1.053±.263±.029	.392±.226±.011
0.0–0.2	1.591±.398±.039	1.129±.197±.018	.619±.357±.016	1.459±.318±.035	1.301±.291±.035	.515±.257±.014
0.2–0.4	1.605±.401±.039	1.908±.248±.029	2.595±.720±.063	1.279±.301±.031	1.694±.326±.044	2.385±.562±.065
0.4–0.6	3.377±.579±.081	2.445±.290±.039	1.859±.620±.046	2.171±.396±.054	2.957±.436±.079	1.325±.419±.036
0.6–0.8	2.466±.503±.061	2.927±.325±.048	2.592±.748±.067	3.337±.503±.085	2.877±.439±.079	2.051±.530±.057
0.8–0.97	4.978±.841±.119	3.986±.413±.065	3.191±.885±.080	2.791±.493±.070	3.656±.533±.099	3.125±.717±.088
			$\tau^+\tau^-$			
−0.96–−0.8	−0.13±0.24±0.04	0.58±0.34±0.05	0.70±0.77±0.06	0.70±0.44±0.06	0.10±0.42±0.06	−0.15±0.60±0.06
−0.8–−0.6	0.48±0.31±0.04	0.12±0.13±0.03	0.31±0.48±0.05	0.18±0.27±0.05	1.01±0.26±0.05	0.89±0.38±0.05
−0.6–−0.4	0.52±0.28±0.04	0.48±0.16±0.04	0.49±0.43±0.06	0.97±0.25±0.06	0.53±0.24±0.06	0.45±0.34±0.06
−0.4–−0.2	0.56±0.30±0.04	0.67±0.19±0.05	0.50±0.50±0.07	0.69±0.29±0.07	0.53±0.27±0.07	0.45±0.39±0.07
−0.2–0.0	1.62±0.54±0.12	0.75±0.22±0.06	0.94±0.60±0.09	1.28±0.34±0.09	1.06±0.33±0.09	1.40±0.48±0.09
0.0–0.2	1.56±0.51±0.12	1.57±0.31±0.13	1.22±0.68±0.12	0.98±0.39±0.12	1.20±0.38±0.12	0.89±0.54±0.12
0.2–0.4	1.65±0.51±0.12	2.05±0.32±0.16	1.60±0.73±0.16	1.58±0.42±0.16	1.98±0.40±0.16	2.55±0.58±0.17
0.4–0.6	2.49±0.61±0.19	2.96±0.39±0.23	1.51±0.84±0.21	2.19±0.48±0.21	1.81±0.46±0.21	2.10±0.67±0.22
0.6–0.8	3.91±1.00±0.29	3.26±0.51±0.26	3.45±1.17±0.28	3.28±0.67±0.28	2.05±0.65±0.28	1.38±0.93±0.29
0.8–0.96	6.77±1.80±0.50	2.87±0.71±0.24	−0.23±1.63±0.31	3.34±0.94±0.31	3.76±0.90±0.31	2.63±1.29±0.31

TABLE XVIII. Differential cross section $d\sigma/d\cos\theta^*$ for the $e^+e^-\to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ production measured by L3.

$\cos\theta^*$ range	$d\sigma/d\cos\theta^*$ (pb) 182.7 GeV	188.7 GeV
	e^+e^-	
−0.719– −0.575	0.404±0.157	0.167±0.075
−0.575– −0.432	0.306±0.115±0.013	0.300±0.065
−0.432– −0.288	0.532±0.127	0.526±0.070
−0.288– −0.144	0.539±0.122	0.524±0.067
−0.144–0.0	0.930±0.153	0.708±0.075
0.0–0.144	0.930±0.153	0.973±0.087
0.144–0.288	1.638±0.199	1.405±0.103
0.288–0.432	2.779±0.259	2.561±0.139
0.432–0.575	5.025±0.347	5.054±0.194
0.575–0.719	12.39±0.54	11.23±0.29
	$\mu^+\mu^-$	
−0.9– −0.7	0.115±0.101	0.008±0.037
−0.7– −0.5	0.057±0.044	0.160±0.036
−0.5– −0.3	0.139±0.066	0.138±0.034
−0.3– −0.1	0.080±0.049	0.111±0.032
−0.1–0.1	0.396±0.127	0.193±0.050
0.1–0.3	0.190±0.078	0.393±0.056
0.3–0.5	0.703±0.139	0.383±0.056
0.5–0.7	0.427±0.111	0.521±0.066
0.7–0.9	0.415±0.164	0.569±0.079
	$\tau^+\tau^-$	
−0.9– −0.7	0.103±0.098	0.121±0.055
−0.7– −0.5	0.092±0.065	0.161±0.043
−0.5– −0.3	0.209±0.087	0.177±0.045
−0.3– −0.1	0.328±0.108	0.145±0.042
−0.1–0.1	0.272±0.101	0.228±0.055
0.1–0.3	0.255±0.099	0.328±0.061
0.3–0.5	0.375±0.119	0.382±0.067
0.5–0.7	0.529±0.143	0.460±0.075
0.7–0.9	1.079±0.299	0.450±0.113

TABLE XIX. The e^+e^- and hadronic forward-backward asymmetry, as measured at LEP 2.

$\sqrt{s}$ (GeV)	A_{FB} e^+e^-	$q\bar{q}$
	ALEPH	
183	–	0.33±0.19($b\bar{b}$)
		$0.95\pm0.27^{+0.11}_{-0.09}$($c\bar{c}$)
189	–	0.34±0.19±0.02($b\bar{b}$)
	DELPHI	
130.2	0.81±0.06±0.015	–
136.2	0.89±0.04±0.013	–
161.3	0.82±0.04±0.012	–
172.1	0.81±0.04±0.01	–
183	0.814±0.017	–
189	0.810±0.010	–
192	0.831±0.024	–
196	0.818±0.015	–
200	0.789±0.016	–
202	0.829±0.020	–
	L3	
130	0.806±0.043±0.006	–
136.1	0.879±0.039±0.006	–
161.3	0.818±0.046±0.012	–
172.1	0.795±0.056±0.012	–
182.7	0.778±0.021±0.004	–
188.7	0.819±0.012±0.003	–
	OPAL	
189	–	0.43±0.15±0.08 ($b\bar{b}$)
		0.57±0.18±0.09 ($c\bar{c}$)

TABLE XX. Dijet differential cross section $d\sigma/dM$ measured by CDF.

Bin edge (GeV)	Average M (GeV)	$d\sigma/dM$ (pb/GeV)	Statistical uncertainty	Systematic uncertainty
180	188	6.07×10^{2}	3.2%	$^{+20}_{-17}$%
198	207	3.42×10^{2}	4.1%	$^{+19}_{-17}$%
217	228	1.81×10^{2}	1.0%	$^{+19}_{-16}$%
241	252	9.81×10^{1}	1.4%	$^{+19}_{-16}$%
265	277	4.98×10^{1}	1.8%	$^{+19}_{-17}$%
292	305	2.78×10^{1}	1.1%	$^{+19}_{-17}$%
321	335	1.43×10^{1}	1.4%	$^{+20}_{-17}$%
353	368	7.41×10^{0}	1.9%	$^{+20}_{-18}$%
388	405	3.83×10^{0}	0.9%	$^{+21}_{-18}$%
427	446	1.89×10^{0}	1.2%	$^{+21}_{-19}$%
470	491	9.07×10^{-1}	1.7%	$^{+22}_{-19}$%
517	539	4.50×10^{-1}	2.3%	$^{+23}_{-20}$%
568	592	1.90×10^{-1}	3.3%	$^{+25}_{-21}$%
625	652	7.42×10^{-2}	5.1%	$^{+26}_{-22}$%
688	716	2.92×10^{-2}	7.7%	$^{+28}_{-23}$%
756	784	1.18×10^{-2}	11%	$^{+30}_{-25}$%
832	865	3.57×10^{-3}	20%	$^{+32}_{-26}$%
915	968	9.03×10^{-4}	33%	$^{+34}_{-28}$%

TABLE XXI. Dijet invariant mass distribution measured by DØ for $|\eta_{\rm jet}|<1$.

M_{jj} mass bin (GeV)	$d^3/dM_{jj}d\eta_1 d\eta_2$ (nb/GeV) ± stat. error	syst. low (%)	syst. high (%)
200–220	$(3.78\pm0.12)\times10^{-2}$	−11.4	+11.8
220–240	$(2.10\pm0.09)\times10^{-2}$	−11.3	+11.6
240–270	$(1.16\pm0.06)\times10^{-2}$	−11.5	+11.7
270–300	$(6.18\pm0.11)\times10^{-3}$	−11.5	+12.0
300–320	$(3.55\pm0.11)\times10^{-3}$	−11.5	+12.1
320–350	$(2.12\pm0.07)\times10^{-3}$	−11.9	+12.3
350–390	$(1.18\pm0.01)\times10^{-3}$	−11.1	+11.6
390–430	$(5.84\pm0.09)\times10^{-4}$	−11.5	+12.2
430–470	$(2.89\pm0.06)\times10^{-4}$	−11.9	+12.9
470–510	$(1.64\pm0.05)\times10^{-4}$	−12.4	+13.5
510–550	$(8.74\pm0.34)\times10^{-5}$	−12.8	+14.3
550–600	$(4.49\pm0.17)\times10^{-5}$	−13.5	+15.3
600–700	$(1.73\pm0.07)\times10^{-5}$	−14.9	+17.2
700–800	$(4.58\pm0.38)\times10^{-6}$	−17.6	+20.8
800–1400	$(2.39\pm0.35)\times10^{-7}$	−23.2	+28.9

TABLE XXII. Dijet angular distribution in various dijet invariant mass bins measured by (a) DØ and (b) CDF. DØ defines $R_\chi \equiv N(\chi<4)/N(4<\chi<\chi_{\rm max})$ while CDF defines $R_\chi \equiv N(\chi<2.5)/N(2.5<\chi<5)$. The covariance matrix is given by $V_{ii}=\sigma_i^2(\text{stat})+\sigma_i^2(\text{syst})$ and $V_{ij}=\sigma_i(\text{syst})\sigma_j(\text{syst})$.

M_{jj} range (GeV)	R_χ	Stat. error	Syst. error
(a) DØ			
260–425	0.191	0.0077	0.015
425–475	0.202	0.0136	0.010
475–635	0.342	0.0085	0.018
>635	0.506	0.0324	0.028
(b) CDF			
241–300	0.678	0.012	0.018
300–400	0.695	0.010	0.025
400–517	0.703	0.009	0.033
517–625	0.738	0.023	0.054
>625	0.732	0.046	0.103

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