Aspects of ψ and Υ production at supercollider energies

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We extend previous calculations of large-transverse-momentum ψ and Υ production to Superconducting Super Collider energies. We then consider $\psi\psi$, $\Upsilon\Upsilon$, and $\psi\Upsilon$ production, both from the lowest-order (single-parton-interaction) gluon-fusion diagrams and from multiple-parton interactions. Finally, we discuss combined quarkonium and weak-boson production arising from both single- and multiple-parton interactions. Standard-model $W\psi$ and $W\Upsilon$ production is a potential background to the detection of charged Higgs bosons through their rare decays $H^{\pm}\to W^{\pm}V$.

I. INTRODUCTION

High-precision studies of heavy-quarkonium states[1] (ψ,Υ) in e^+e^- collisions have provided extremely important tests of QCD and the nonrelativistic potential-model description of such bound-state systems. The production mechanism in this case is direct production of the $^3S_1$ states (hereafter V) via $e^+e^-\to\gamma^*\to V$ and subsequent radiative decays. Ever since their initial discovery in p-nucleus collisions, ψ and Υ production has also been an important aspect of hadronic collisions with a much wider variety of differing production mechanisms contributing depending on the energy and other variables.

Exclusive production[2] of charmonium states in $p\bar{p}$ collisions (at $\sqrt{s}=M_\psi^2$), for example, can produce $c\bar{c}$ bound states with virtually any allowed quantum numbers allowing detailed investigations of the $^1P_1$ state and possible discovery of the charmonium D states. The production is mediated in this case by $ggg\to$quarkonium couplings. At higher center-of-mass energies (but still at low p_T), inclusive ψ and Υ production[3] is dominated by $q\bar{q}\to\psi/\Upsilon$ and by $gg\to\chi_{0,2}$ (where $\chi_J\equiv{}^3P_J$ bound states for $J=0,1,2$) followed by radiative decays, $\chi^{c,(b)}\to\psi(\Upsilon)+\gamma$ and fixed-target experiments[4] have measured the relative amounts of ψ and χ^c production.

At higher energies and larger values of p_T (as probed at hadron colliders), there are two sources[5,6] of ψ production, "direct" production (via $gg\to\psi g/\chi g$, etc.) and that from b-quark decays. The two mechanisms can, to a large extent, be studied separately by imposing various isolation cuts on the produced ψ's and have been confronted with UA1 data[7] at CERN energies. On the other hand, single high-p_T Υ production will only arise from direct processes as Υ production from top meson decays will be quite small. While low-p_T Υ production has been observed at CERN energies,[8] detailed studies of large-p_T production including p_T and rapidity distributions would be welcome. Predictions for ψ (Ref. 6) and Υ (Ref. 9) production at both CERN and Fermilab Tevatron energies have appeared in the literature.

The next generation of hadron (super) colliders, the Superconducting Super Collider (SSC) (design energy 40 TeV) and the CERN Large Hadron Collider (LHC) (16 TeV), will open an entirely new regime in which to study physics of the standard model and beyond. The extremely high luminosities and particle multiplicities per event will, however, make the experimental environment at such machines one of the most challenging yet encountered in high-energy physics. Because of this, events containing easily distinguishable features such as jets and weak bosons will be utilized heavily and vector-meson production, with its clean $\mu^+\mu^-$ signal, will likely play an even more important role than at present. While multipole muons have long been touted as a clear indicator of new physics,[10] one extreme suggestion for coping with the large particle fluxes at a high-luminosity LHC machine (namely, surrounding the interaction region with absorber so that only muons are detected in hopes of detecting the Higgs boson via its "gold-plated" signature $H^0\to ZZ\to$muons[11]) would make clean, muon-related events even more important. Even the rather mundane use of ψ and Υ detection as a calibration for mass measurements [as with the present Collider Detector at Fermilab (CDF) experiment[12]] will ensure the continued usefulness of vector mesons in hadronic collisions. Since large-p_T Υ production is completely dominated by gluon-gluon-fusion processes at the parton level, it may also provide a useful calibration of gluon structure functions at supercollider energies.

Several investigations of ψ production as a signal for b-quark production and decays and for use in CP-violation studies in B-meson decays have appeared,[13] and a study of single direct ψ/Υ production at SSC energies would be complementary. Moreover, given the increased energy and rapidly proliferating gluon content of the proton at the SSC, rare processes involving quarkonia which are little or unstudied experimentally at present facilities may well become observable in that environment.

Motivated by these ideas, we begin in Sec. II by extending previous successful calculations of direct ψ/Υ production to SSC energies. In Sec. III we then discuss the prospects for the observation of double V production, namely, $\psi\psi$, $\Upsilon\Upsilon$, and mixed pairs $\psi\Upsilon$. We also examine the possibility that twin quarkonium production at values of $p_T < \sim 20$ GeV could also receive sizable contributions from multiple-parton interactions thereby providing a test of such effects which is complementary to the often discussed use of four-jet events. Finally, in Sec. IV, we calculate the cross sections for quarkonium+electroweak-boson production (Z^0, W^+/W^-, and γ), both from single-parton-induced processes ($gg/q\bar{q}$) and from multiple-parton interactions, and comment on the observability of these reactions.

II. HIGH-p_T SINGLE ψ AND Υ PRODUCTION

Several groups[5,6] have examined high-p_T ψ production at collider energies and have shown that the two sources of such ψ production are so-called direct processes, $gg \to \psi g/\chi g$ and others, and from B-meson decays. Because the ψ's resulting from b-quark decays are accompanied by (strange) hadrons while those from the direct processes have, at most, an accompanying photon (from the radiative χ decay), suitable isolation cuts can be used to separate the two production mechanisms. The UA1 Collaboration[7] has already demonstrated the ability to study the two processes separately and has found reasonable agreement with existing predictions. ψ production from b-quark decays at SSC energies will be an extremely important (indeed even the dominant) source and will provide a clean signature useful in B-meson decay studies helping to make the SSC a B factory of sorts and will also provide tests of QCD and of the recently calculated $O(\alpha_s^3)$ heavy-quark cross sections.[14] In this paper, however, we will concentrate exclusively on "direct" processes, ones not resulting from B-meson decay, assuming that the experimental ability to separate the two production mechanisms for ψ's will continue to be available while for Υ production no such identification problems arise.

We will follow (and extend) the analysis of Glover, Martin, and Stirling[6] (GMS) who calculate direct ψ production by using existing expressions for the basis partonic cross sections, $gg \to \psi g/\chi g$ (Ref. 15), $qg \to \chi q$, and $q\bar{q} \to \chi g$ (Ref. 16). They fix the overall normalization (K factor) by fitting data from the CERN Intersecting Storage Rings and then show quite reasonable agreement with higher-energy CERN data. Since we wish to extend their method to even higher energies, we make use of parton distributions which are more reliable at supercollider energies, namely, those of Eichten, Hinchliffe, Lane, and Quigg[17] (EHLQ). Repeating their analysis we find we can reproduce their predictions with essentially the same prescriptions but require a slightly smaller K value, $K=1.75$, which is consistent with their claimed 30% QCD/distribution-function uncertainties. Thus, in what follows, we use the same relatively large and constant value of α_s as used in their analysis (and in earlier analyses of ψ electroproduction and photoproduction[18]), namely, $\alpha_s(Q^2=M_\psi^2)$. We also require the values of the various quarkonium wave functions and use values derived from realistic potential models,[19] i.e., $R_S(0)^2=0.70$ GeV^3 and $R_P'(0)^2/M_\chi^2=0.006$ GeV^3. With these values we reproduce the GMS results. For direct Υ production we use the same approach, $K=1.75$, $\alpha_s(Q^2=M_\Upsilon^2)$, and wave functions taken from potential models.[20] Specifically, we use $R_S(0)^2=7.29$, 3.66, 2.87 GeV^3 for $n=1$, 2, 3, and $R_P'(0)^2/M_\chi^2=0.0157$, 0.0160 GeV^3 for $n=1,2$. We consider only contributions from $n=1,2,3$ $^3S_1$ states and $n=1,2$ χ^b radiative decays and do not include $\Upsilon(nS)\to\Upsilon(1S)\pi\pi$ channels as this can give rise to accompanying hadrons as in the b-decay case. Its contribution, in any event, is not very significant. Finally, any

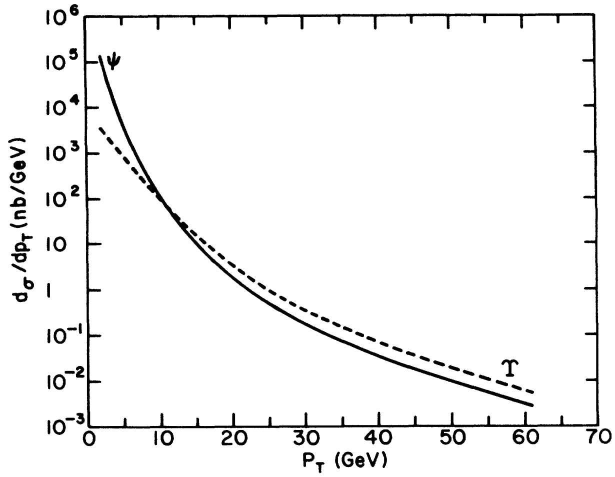

FIG. 1. The differential cross section $d\sigma/dp_T$ vs p_T for inclusive ψ (solid line) and Υ (dashed line) direct production in pp collisions at $\sqrt{s}=40$ TeV. EHLQ 1 distributions are used throughout unless otherwise specified.

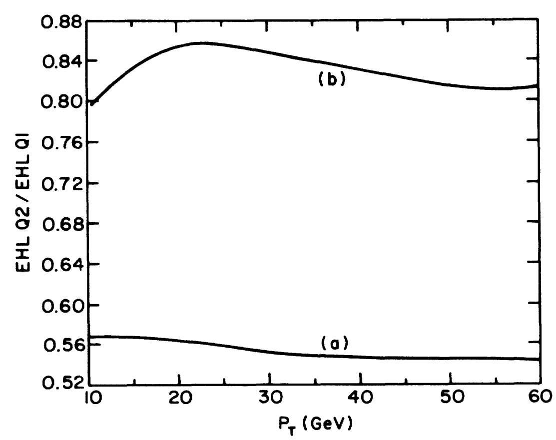

FIG. 2. The ratio of differential cross sections for Υ production vs p_T (GeV) using different parton distributions and Q^2 prescriptions. (a) EHLQ 2 ($Q^2=M^2$)/EHLQ 1 ($Q^2=M^2$); (b) EHLQ 2 ($Q^2=M^2+p_T^2$)/EHLQ 1 ($Q^2=M^2$).

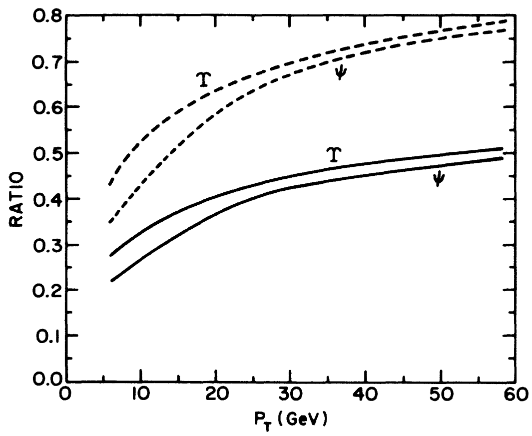

FIG. 3. The ratio of differential cross sections for ψ and Υ production vs p_T (GeV) illustrating the effects of rapidity cuts, $|y| \leq 2.5$ (dashed), $|y| \leq 1.5$ (solid).

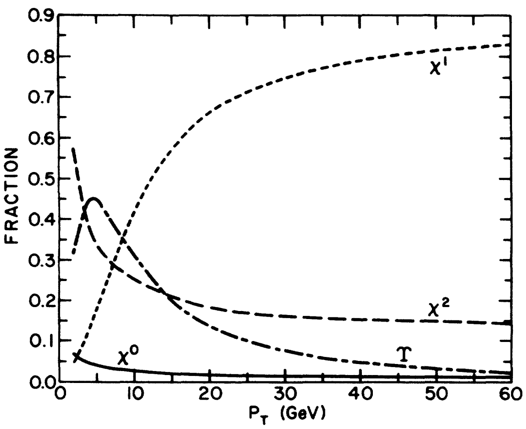

FIG. 5. The same as Fig. 4 except for Υ production.

produced $\Upsilon(2S,3S)$ is counted as a fraction of an $\Upsilon(1S)$, suitably weighted by its $\mu^+\mu^-$ branching ratios. With this prescription we then reasonably reproduce the predictions for high-p_T Υ production of van Eijk and Kinnunen[9] (after taking into account the differences in distributions, wave functions, etc.).

Using these parameters and EHLQ 1 distributions, we can then calculate the differential cross sections ($d\sigma/dp_T$ vs p_T) for ψ and Υ production in pp collisions at SSC energies ($\sqrt{s}=40$ TeV) which appear in Fig. 1. [The corresponding values at LHC energies ($\sqrt{s}=16$ TeV) are 40% smaller over the entire p_T range. In fact, we find quite generally that the cross sections scale nearly linearly with center-of-mass energy.] Figure 2 shows the effects of varying parton distributions by using EHLQ 2 in place of EHLQ 1 and of changing the definition of the momentum transfer used in the evaluation of α_s and in the parton distributions to $Q^2=M^2+p_T^2$, both of which give some measure of the prescription dependence of our results.

We also illustrate the effects of imposing various rapidity cuts on ψ and Υ production in Fig. 3. In Fig. 4 (5) we show the relative contribution to ψ (Υ) production from $^3S_1$ and χ^J states and we see that the contributions from χ production (mostly χ^1 and χ^2) completely dominate ψ (Υ) production for $p_T \geq 8$ (15) GeV. Finally, in Fig. 6 we show the integrated cross sections as a function of the minimum p_T (but uncut in rapidity).

This last figure points out that both ψ and Υ production will have large cross sections at SSC energies. Recalling that the integrated SSC design luminosity is expected to correspond to 10^7 events/(nb yr) one finds that there will be 1.5×10^4 (2.2×10^4) $\mu^+\mu^-$ events from direct Υ (ψ) production with $p_T \geq 60$ GeV (only reduced by a factor of ~ 0.8 if the rapidity cut $|y| \leq 2.5$ is imposed). We find as many as $10^3/10^2$ $\mu^+\mu^-$ events arising from Υ production with $p_T \geq 100/150$ GeV (and $|y| \leq 2.5$). Moreover, Υ production is comparable to ψ production for almost all values of p_T so that studies of direct quarkonium production will be possible with Υ's even if ψ direct pro-

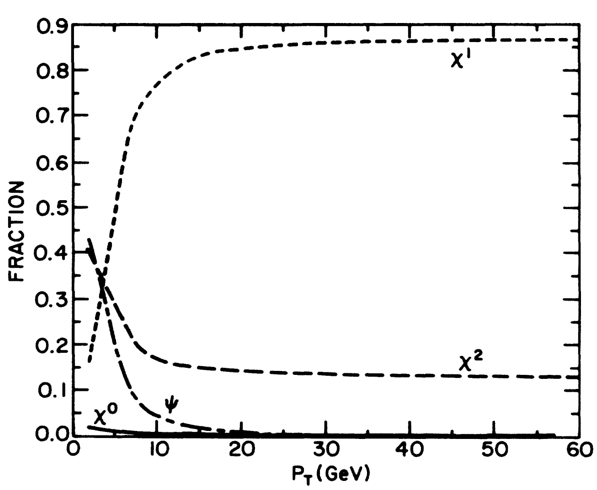

FIG. 4. The relative amounts of ψ production arising from $^3S_1$, χ^1, χ^2, and χ^0 contributions as a function of p_T (GeV) for ψ production.

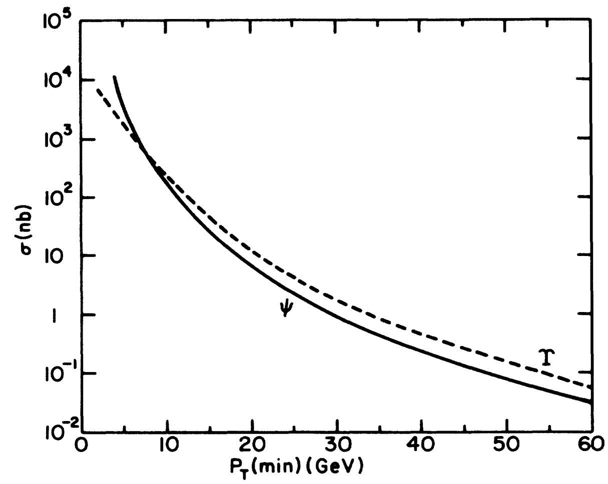

FIG. 6. The integrated (over p_T) cross sections for ψ (solid) and Υ (dotted) production as a function of the minimum value of p_T (GeV) (uncut in rapidity).

duction cannot be successfully disentangled from that from B decays. Given these relatively large rates for single V production, we are naturally led to investigate the prospects for rarer quarkonium production processes and we begin with double V production.

III. $\psi\psi$, $\Upsilon\Upsilon$, AND $\psi\Upsilon$ PRODUCTION

Compared to single ψ or Υ production, double V production is a much rarer process as it is higher order in α_s $[O(\alpha_s^4)]$ and requires the formation of two bound states. Double ψ production has been observed,[21] in only one experiment, in relatively low-energy ($\sqrt{s}=28$ GeV) p-nucleus collisions and has been interpreted[22,23] in terms of the lowest-order $[O(\alpha_s^4)]$ subprocesses $gg/q\bar{q}\to\psi\psi$. (Double ψ production from the decay of a pair of b quarks gives too small a contribution to be relevant at these energies[24] but will, of course, become important at SSC energies. We assume once again that such production mechanisms can be separated as in the single ψ case.) Given the dominant role played by χ states in single ψ production, it is natural to ask whether their effects should be considered in $\psi\psi$ production and VV production provides another laboratory in which to study the relative importance of V and χ production.

In their analysis, Ecclestone and Scott[22] found that the lowest-order QCD calculation had to be normalized by a factor of ~ 4.5 to fit the data and they invoked a factor of $K=2$ (similar to that needed in Drell-Yan processes and single high-p_T ψ production) while they added a factor of $(1.5)^2\approx 2.2$ in an attempt to include the (uncalculated) contributions of χ states (based on an $\sim 50\%$ χ contribution to single, low-p_T ψ production at these energies). If, however, one uses the same values of α_s and $R_S(0)$ as obtained in the fits to *single* ψ production and EHLQ 1 distributions, we find cross sections which are ~ 2.25 larger than those discussed in Ref. 22 (who made use of somewhat older gluon distributions) so that only a $K=2$ factor is needed and the need for any significant contribution from χ states is not clear. A partial calculation of the $gg\to\chi\chi$ cross sections[25] suggests that their contribution is, in fact, quite small and will be neglected in what follows. (This mechanism is, however, the lowest-order contribution to *mixed* quarkonium, i.e., $\psi\Upsilon$, production and will be required below.)

Then, using the $gg/q\bar{q}\to VV$ cross sections derived in Refs. 22 and 23, EHLQ 1 distributions, and the quarkonium wave functions mentioned above, we calculate the differential cross sections for $\psi\psi$ and $\Upsilon\Upsilon$ production (uncut in rapidity) reproduced in Fig. 7, while the total cross sections are given in Fig. 8 (9) for $\psi\psi$ ($\Upsilon\Upsilon$). (The $q\bar{q}$ contributions are never more than a few percent of the total.) Recalling that the muon-pair branching ratios for ψ and Υ are 0.069 and 0.026, respectively, one finds 48 and 6.8 four-muon events/pb yr at SSC luminosities so that there will be only 5–10 events in each channel with $p_T\geq 20$ GeV when rapidity cuts are taken into account; reasonable numbers of events (500–1000 after cuts) are predicted with $p_T\geq 10$ GeV if such low-p_T muons can be triggered upon and detected.

As mentioned above, "mixed" ($\psi\Upsilon$) quarkonium production, because of charge conjugation and color-conservation arguments, only proceeds to lowest QCD order $[O(\alpha_s^4)]$ via $gg\to\chi^b\chi^c$ and the cross sections for this process have been discussed in Ref. 25. [There are no $O(\alpha_s^4)$ contributions to $q\bar{q}\to\chi^c\chi^b$.] We evaluate the total $\psi+\Upsilon$ production cross sections arising from all nine $(J,J'=1,2,3)$ different $\chi_J^c\chi_{J'}^b$ combinations using essentially the same prescriptions as above, namely, $K=2$, the relevant value of $\alpha_s(Q^2=M^2_{\chi,\Upsilon})$ at each vertex, and EHLQ 1 distribution functions and the resulting differential cross section is included in Fig. 7 while the integrated cross section is plotted in Fig. 10. Note carefully, however, that the $\psi\Upsilon$ curve in Fig. 7 has been multiplied by 10^3. (The relative smallness of this contribution, which arises solely from χ production and radiative decays, is consistent with naive expectations based on the fact that ${}^3S_1$ $[\chi]$ states couple via $R_S(0)$ $[R_P'(0)]$ in am-

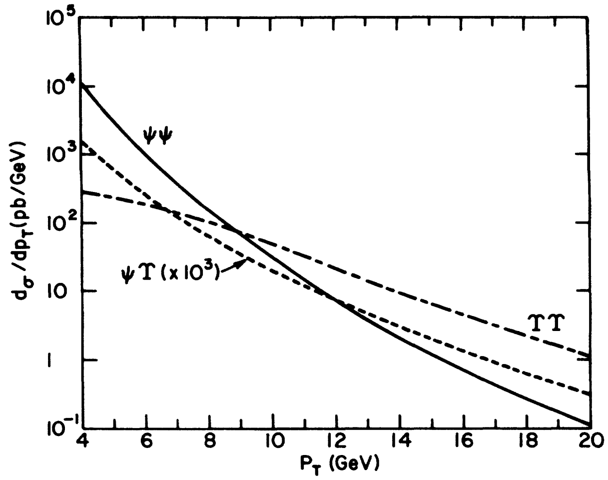

FIG. 7. The differential cross sections, $d\sigma/dp_T$ (pb/GeV) vs p_T (GeV) for $\psi\psi$ (solid), $\Upsilon\Upsilon$ (dot-dash), and $\psi\Upsilon$ (dashed) production. Note: The $\psi\Upsilon$ values have been multiplied by 10^3.

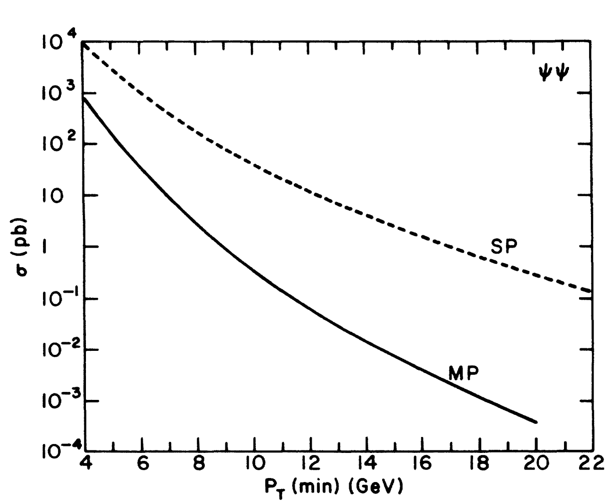

FIG. 8. The integrated (over p_T) cross section (pb) vs minimum p_T (GeV) for $\psi\psi$ production from single-parton interactions (dashed) and multiple-parton interactions (solid).

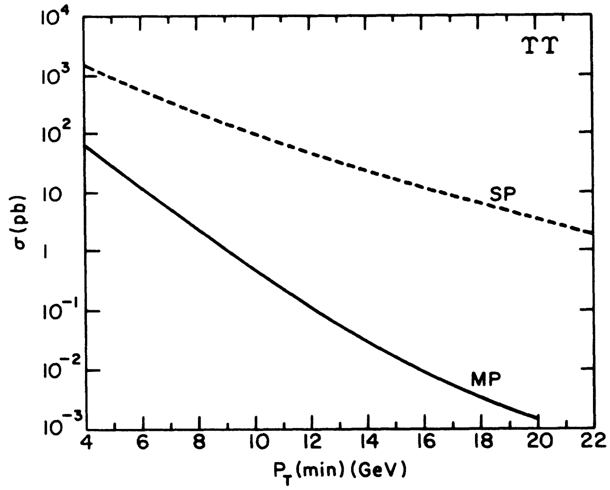

FIG. 9. The same as Fig. 8 except for $\Upsilon\Upsilon$ production.

plitude. This would suggest that single χ production might be suppressed relative to single V production by a factor $R=[R_P'(0)^2/M_\chi^2]/R_S(0)^2\approx 10^{-3}$. The complete domination of single V production by χ states, even considering the enhancements from color factors arising in the $gg\rightarrow\chi g$ diagrams, is still, perhaps, surprising.) Given the smallness of the $\chi^c\chi^b$ contribution, one can well imagine that other processes, while formally of higher order in α_s, might, in fact, dominate $\psi\Upsilon$ production. We have in mind the $O(\alpha_s^5)$ $2\rightarrow 3$ processes $gg\rightarrow\chi^c\Upsilon g$, $\chi^b\psi g$, or even the $O(\alpha_s^6)$ $2\rightarrow 2$ process $gg\rightarrow\psi\Upsilon$. The general conclusion that $\psi+\Upsilon$ is strongly suppressed relative to $\psi\psi$ or $\Upsilon\Upsilon$ production is, however, still unavoidable.

Another possible source of double quarkonium production (aside from B-meson decay) is multiple-parton interactions and this possibility has been discussed previously. (See Ref. 26 and extensive references therein.) Evidence for multiple parton interactions (MPI's) leading to double Drell-Yan production at relatively low energies has already been inferred[27] from hadronic production of multiple-muon events. Four-jet production[28] is, however, often discussed as the most likely possible laboratory in which to study such effects. Given the integrated cross sections for single ψ and Υ production in Fig. 6, one can estimate the multiple-parton-interaction contribution to double quarkonium production using $\sigma_{\rm MP}(\psi\psi)\approx\sigma(\psi)^2/2\sigma_{\rm tot}$ (and similarly for $\Upsilon\Upsilon$ states) and $\sigma_{\rm MP}(\psi\Upsilon)\approx\sigma(\psi)\sigma(\Upsilon)/\sigma_{\rm tot}$ where we will use $\sigma_{\rm tot}\approx 60$ mb as an estimate of the effective total cross section.[27] We then add these total cross sections to Figs. 8, 9, and 10. The multiple parton contributions to both $\psi\psi$ and $\Upsilon\Upsilon$ production are small and for the $\psi\psi$ case an observable numbers of events (say 10) would only be possible for $p_T\le 10$ GeV and this is even before realistic rapidity cuts are imposed which would reduce each ψ cross section by a factor of roughly 2 thereby reducing the multiple-parton cross section by a factor of 4. Only in the "mixed" $\psi\Upsilon$ case is the multiple-parton interaction (MPI) the dominant contribution due to the extreme smallness of the single-parton $gg\rightarrow\chi^c\chi^b$ source. Even in this instance, it is necessary to identify vector mesons with $p_T\le\sim 10$ GeV in order to see the signal. If it proves impossible to study $\psi\psi$ production under these circumstances, further tests of this process will only likely be possible in planned B hadroproduction experiments[29] or perhaps in very-high-energy fixed-target experiments at Serpukhov's UNK Collider [where E(beam)=3 TeV corresponds to $\sqrt{s}=77$ GeV].

As with all MPI-induced interactions, suitable kinematic cuts can be used to enhance the MPI contribution relative to that of the single-parton interaction. In this case, the $gg\rightarrow VV$ subprocesses produce V pairs which are back-to-back in transverse momentum (ignoring any small inherent parton p_T) while the MPI-produced V pairs will appear uncorrelated to each other but balanced in p_T by a hard (gluon) jet. In half the cases, the two quarkonia will even appear on the same side of the interaction. For the $\psi\psi$ and $\Upsilon\Upsilon$ cases, this means that the background actually comes from the higher-order single-parton subprocesses $gg\rightarrow VVg$. For the mixed case, the uncalculated $gg\rightarrow\psi\chi^b g$, $\Upsilon\chi^c g$ subprocesses would likely be the chief background.

Finally, MPI-induced processes will generally be more sensitive to the gluon distribution function at low x, depending as they do on $\sigma(\psi)^2$ instead of $\sigma(\psi)$, making their prediction, on the one hand, more uncertain but also providing a separate gauge of the low-x gluon content of the proton.

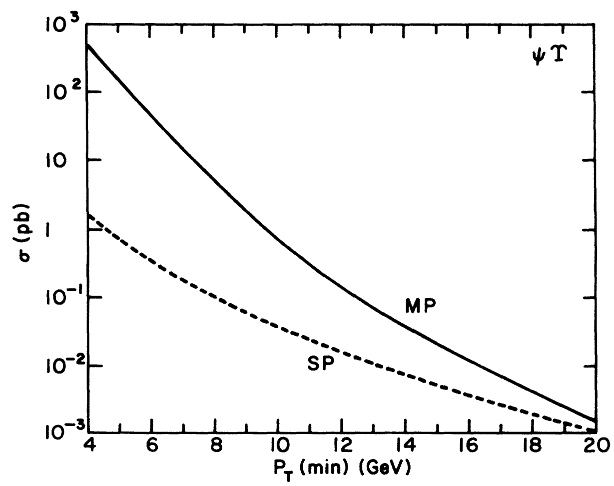

FIG. 10. The same as Fig. 8 except for $\psi\Upsilon$ production.

IV. QUARKONIUM+WEAK-BOSON PRODUCTION

Analyses of high-p_T V production have mainly focused on exclusively strong-interaction processes but events involving weak bosons and quarkonia could be expected to give complementary information to those already discussed. In existing analyses, most attention has been paid to rare Z^0 decays involving quarkonia, namely, $Z\rightarrow V\gamma$, $P\gamma$ (Ref. 30) (with $P\equiv{}^1S_0$ bound state), $Z\rightarrow ggV$ (Ref. 31), $Z\rightarrow Q\bar{Q}V, Q\bar{Q}P$ (Ref. 32), and $Z\rightarrow VV, VP$ (Ref. 33).

At SSC energies, the production of quarkonia in association with weak bosons (Z^0, W^+/W^-, and even γ) becomes, in some cases, large enough to be, in principle, observable. In addition, ZV, ZW, and $Z\gamma$ production all give rise to clean signals which greatly add in their potential observability. In this section we discuss both single-parton-interaction- (gg or $q\bar{q}$) and multiple-parton-interaction-induced production of quarkonia plus weak bosons.

A. $V\gamma$ and VZ production

Both $V\gamma$ and VZ production have been discussed previously[34] and arise primarily from the $gg \to V\gamma, VZ$ subprocesses. The differential cross sections for these processes are shown in Fig. 11. In evaluating these cross sections we have once again used EHLQ 1 distributions, $K=2$, and $\alpha_s(Q^2=M_V^2)$. There are other contributions from $q\bar{q} \to VZ$ which are expected to be smaller as they are $O(\alpha_w^3)$ compared to the $(\alpha_s^2\alpha_w)$ gluon-fusion diagrams. The diagrams contributing to this mechanism are shown in Fig. 12 and we have found that for ψ and Υ quarkonia that only the contributions from Figs. 12(a) and 12(b) where the V couples directly to the γ^* are important, i.e., $q\bar{q} \to Z\gamma^* \to VZ$. We have calculated the partonic cross section for this process (which we discuss in the Appendix) and have evaluated its contribution to both $Z\psi$ and $Z\Upsilon$ and include its effects in Fig. 11. It has at most a 30% effect in the $Z\psi$ channel while its contribution to $Z\Upsilon$ is negligible.

In contrast to large-p_T $V+$gluon production, the contribution coming from decays of the χ states is quite small in these processes. This was conjectured in Ref. 34 and we have verified it by explicitly performing the calculation of $gg \to Z + \chi_0$. The differential cross section is too complicated to be displayed here; for χ^c we typically find

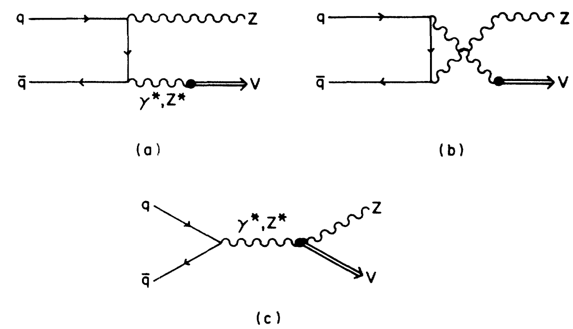

FIG. 12. Diagrams leading to $q\bar{q} \to VZ$.

it to be a factor of 100 smaller than the direct $gg \to \psi Z$ production even before branching ratios are included. This is consistent with simple estimates based on the appropriate wave function couplings and with previous calculations of the contributions of χ states to quarkonium$+Z^0$ processes.[30]

The integrated (over p_T) cross sections are then plotted in Figs. 13 and 14 and assuming that the Z^0 is only detected in its $\mu^+\mu^-$ mode one finds that there will be 23 (8.5) 4μ events/pb yr arising from $Z\psi$ ($Z\Upsilon$) production so that there could be of order 10–20 4μ events per year with $p_T(V) \geq 10$ GeV in the $Z\Upsilon$ mode (depending on rapidity cuts). In this case, only the Υ itself is required to be at sufficiently large p_T as the muons from the Z^0 decay can have p_T values up to $M_Z/2$. If electron pairs from the Z^0 decay are also counted, the number of observable events would be doubled.

Another possibility for VZ production arises from multiple-parton interactions via the zero-p_T production of a Z^0 (via $q\bar{q} \to Z^0$) accompanied by the single-parton-interaction production of a vector meson. The cross section for this is then estimated to be $\sigma_{MP}(VZ) \approx \sigma(Z)\sigma(V)/\sigma_{tot}$ and making use of the integrated ψ and Υ cross sections in Fig. 5 we show the multiple-parton contributions to the VZ total cross sections in Figs. 13

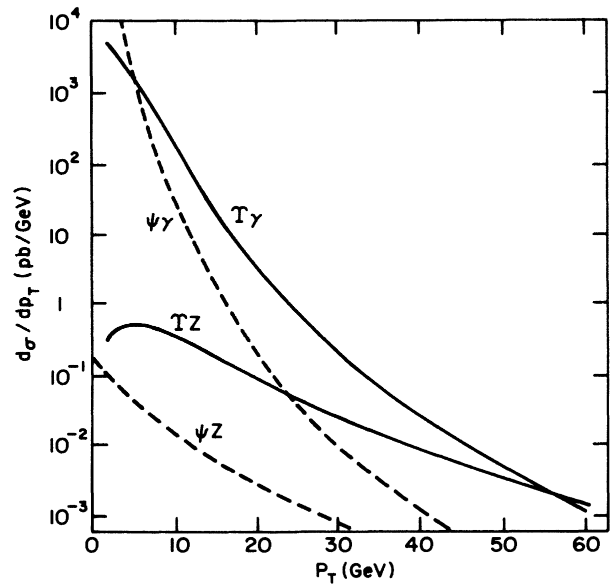

FIG. 11. Differential cross sections, $d\sigma/dp_T$ (pb/GeV) vs p_T (GeV) for $\psi\gamma$, $\Upsilon\gamma$, ψZ^0, and ΥZ^0 production.

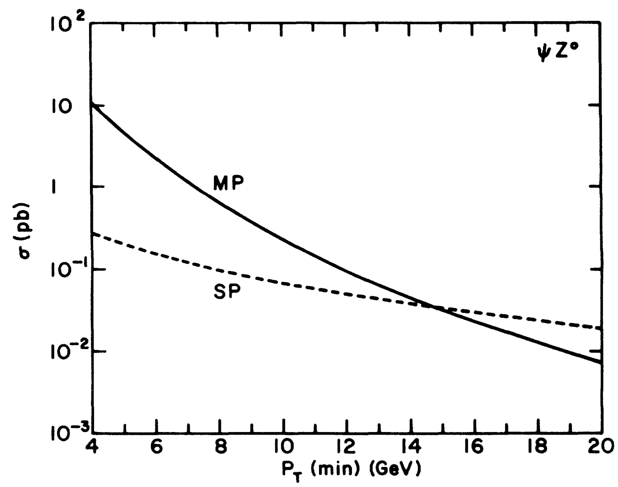

FIG. 13. Integrated (over p_T) cross section (pb) vs minimum p_T (GeV) for single-parton-interaction (SP) and multiple-parton (MP) induced ψZ^0 production.

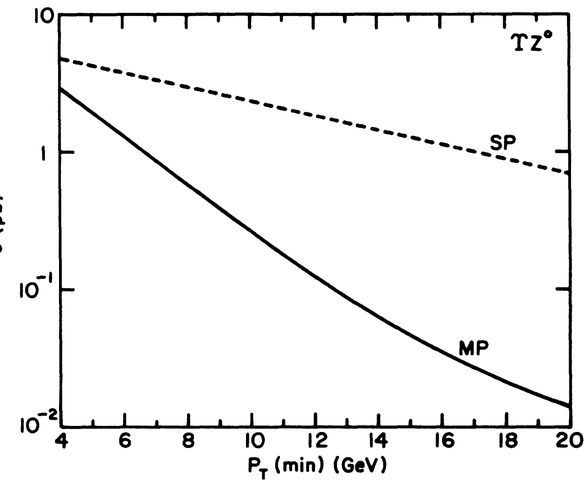

FIG. 14. Integrated (over p_T) cross section (pb) vs minimum p_T (GeV) for ΥZ^0 production.

and 14. We use the value $\sigma(Z)=65$ nb taken from Ref. 17 (with no rapidity cuts applied).

It is obvious from the figures that the "direct" $V\gamma$ and VZ production through gluon fusion drops very rapidly at large p_T. This can be directly traced to the form of the contributing Feynman diagrams. By inspection, one sees that for large-p_T production a large momentum has to flow in two quark propagators, which gives a big suppression at large momentum transfers. This is in contrast to the "mixing" process $q\bar{q}\to Z$, $\gamma+\gamma^*\to Z$, $\gamma+V$, where only one quark propagator (from the initial state) is off mass shell. At very large p_T (above 60 GeV in the $\psi\gamma$ case) the latter type of process will dominate. However, there the cross sections are already quite small anyway. We also note that the γ^*-V mixing diagrams are always much less important for the Υ case. This is because the γ^*-V mixing factor $12\alpha e_Q^2|R(0)|^2/m_V^3$ is around a factor of 10 smaller for Υ than for ψ. In fact, at SSC energies a good approximation to the contribution from the mixing diagrams can be obtained by just multiplying the cross sections for real γ production by this factor.

B. *WV* production

In contrast with VZ production, there are no $O(\alpha_s^2\alpha_w)$ gluon fusion contributions to WV production so that its standard model value is expected to be quite small. A realistic evaluation of WV production is important as it is an important background to the rare decay mode $H^\pm\to W^\pm V$ which has been discussed[35] as a potentially very clean signal for the production of charged Higgs bosons. Moreover, a small single-parton-induced contribution could make any possible multiple-parton-interaction contribution more observable.

Once again, there are several diagrams contributing to $q\bar{q}\to WV$ and these are illustrated in Fig. 15. We have found for light quarkonia (ψ/Υ as opposed to toponium) that only the contributions from (a), (b), and (c) where the V couples directly to the γ^* give important contributions and we present the partonic cross section for

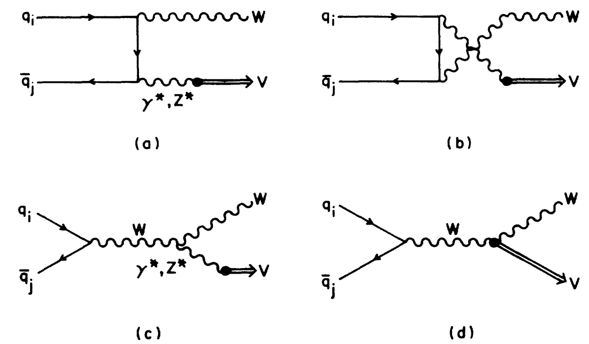

FIG. 15. Diagrams leading to $q\bar{q}\to WV$.

$q\bar{q}\to W\gamma^*\to WV$ in the Appendix and calculate the differential cross sections for WV production shown in Fig. 16. Both W^+ and W^- contributions are included and we use $K=2$ and EHLQ 1 distributions as always. The integrated cross sections are then displayed in Fig. 17.

Because the single-parton contributions to WV production are so much smaller than in the VZ case, the multiple-parton contribution will be expected to play a larger role than before. Moreover, the larger production cross section for W versus Z^0 production, the ability to use both W^+ and W^-, and the relatively large branching ratio into observable states ($W\to e\nu_e,\mu\nu_\mu$) enhance this channel over the VZ MPI case. We then estimate the MPI-induced contribution to WV production as $\sigma_{\rm MP}\approx\sigma(W^\pm)\sigma(V)/\sigma_{\rm tot}$ where we include W's of both signs and use the value $\sigma(W^\pm)\approx 200$ nb (from Ref. 17). We then include these cross sections in Fig. 17 and we see that the MPI-induced contributions dominate for both $W\psi$ and $W\Upsilon$ production out to $p_T\approx 20$ GeV. Since the W's will likely be observable in both their $\mu\nu_\mu$ and $e\nu_e$

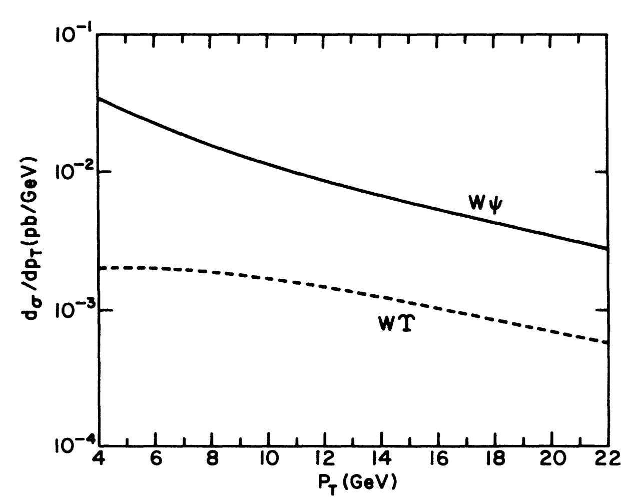

FIG. 16. Differential cross sections, $d\sigma/dp_T$ (pb/GeV) vs p_T (GeV) for $W\psi$ (solid) and $W\Upsilon$ (dashed) production via $q\bar{q}\to WV$.

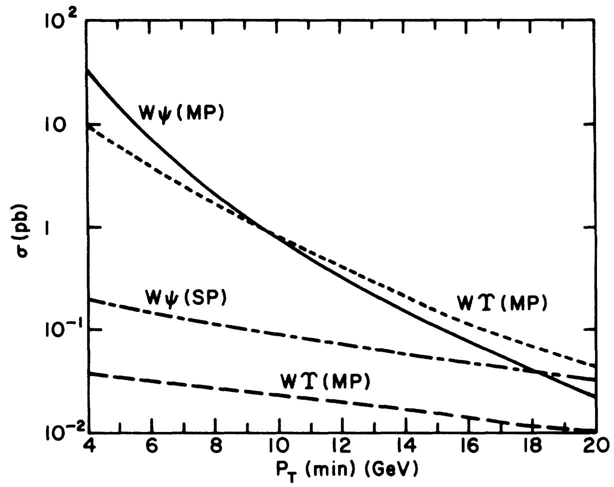

FIG. 17. Integrated cross sections (pb) vs minimum p_T (GeV) for single-parton (SP) and multiple-parton (MP) induced WV production.

modes one would have 150/56 [$\mu^+\mu^-$ (charged lepton+missing p_T)] events/pb yr for these $W\psi/(W\Upsilon)$ processes and several events of this type might be observed in both channels.

The background problems for the kind of processes studied here remain to be investigated in greater detail. One type of background is, however, easy to estimate. For processes such as $q\bar{q}\to WV$, which are dominated by γ^*-V mixing, there is for a given invariant-mass resolution (for the lepton pair used to detect the V meson) an irreducible background coming from the direct conversion of the γ^* to a lepton pair. For an invariant-mass resolution Δ (assumed $\ll m_V$) the conversion probability to a lepton pair with invariant mass within a range Δ of m_V is (see Ref. 34) $2\alpha/(3\pi)(\Delta/m_V)$. Comparing this with the conversion probability to a V meson $12\alpha e_Q^2|R(0)|^2/m_V^3$ and demanding that the signal be greater than background one finds the requirement on the detector resolution:

$$\frac{\Delta}{m_V}<\frac{18\pi e_Q^2|R(0)|^2\Gamma(V\to l^+l^-)}{m_V^3\Gamma(V\to\text{all})},$$

which means $\Delta/m_\psi<4.1\%$ and $\Delta/m_\Upsilon<0.13\%$. The value for ψ is reasonable for a realistic detector, whereas the Υ case could be more problematic.

V. CONCLUSIONS

We have seen that high-p_T ψ and Υ production will have large cross sections out to p_T values of over 100 GeV. Single ψ and Υ production give almost identical numbers of $\mu^+\mu^-$ events for $p_T\geq 20$ GeV. The large numbers of Υ's mean that detailed studies of direct quarkonium production will be possible even if the various ψ production mechanisms cannot be separated. Twin quarkonium production will only be observable if vector mesons with $p_T\leq 20$ GeV are detectable. In that case, $\psi\Upsilon$ production receives a large contribution from multiple-parton-interaction-induced events although certain, perhaps important, higher-order subprocesses have yet to be calculated. Finally, WV production also receives important MPI-induced contributions which should clearly stand out against the small standard-model single-parton events. As this channel is also one in which important new physics (rare decays of charged Higgs bosons, for example) may appear, we urge its further study.

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APPENDIX

In this appendix we present the differential cross sections, $d\sigma/d\hat{t}$ for the processes $q\bar{q}\to Z\gamma^*\to VZ$ and $q\bar{q}\to W\gamma^*\to WV$ discussed in the text.

For the $q\bar{q}\to VZ$ process, the diagrams of Fig. 12 all contribute but we have checked that only those in (a) and (b) where the V couples directly to the γ^* are important for light quarkonia, here meaning ψ and Υ as opposed to toponium. We have, for example, calculated the subset of diagrams in Fig. 12(c) (after first checking that we reproduce known expressions[36] for $V\to ZZ,Z\gamma$ using our methods) and found them to have a negligible contribution in our case. (They are, however, important in the production or decays of a superheavy quarkonium.) To project into the quarkonium bound state we use the formalism of Kuhn, Kaplan, and Safiani[37] and we find the resulting differential cross sections of interest in our case. For the process $q(k_1)+\bar{q}(k_2)\to Z(p_1)+V(p_2)$ we find, with $\hat{s}=(k_1+k_2)^2$, $\hat{t}=(k_1-p_1)^2$, $\hat{u}=(k_1-p_2)^2$, and including an average over color

$$\frac{d\sigma}{d\hat{t}}(q\bar{q}\to Z\gamma^*\to VZ)=\frac{2(g_a^2+g_v^2)\alpha^2e_q^2e_Q^2|R(0)|^2}{m_V^3\hat{s}^2\hat{t}^2\hat{u}^2}[m_V^4(\hat{t}^2+\hat{u}^2)-m_V^2(\hat{s}\hat{t}^2+\hat{s}\hat{u}^2+\hat{t}^3+\hat{t}^2\hat{u}+\hat{t}\hat{u}^2+\hat{u}^3)$$
$$-2\hat{s}^2\hat{t}\hat{u}+2\hat{s}\hat{t}^2\hat{u}+2\hat{s}\hat{t}\hat{u}^2+\hat{t}^3\hat{u}+\hat{t}\hat{u}^3]\,. \quad (\text{A1})$$

Here g_a and g_v are the axial-vector and vector $Zq\bar{q}$ couplings [$g_a=g/(4\sin\theta_W\cos\theta_W)$, etc.], e_q is the electromagnetic charge of the incident quark, e_Q that of the quark forming the V meson. We note that in the limit $m_V\to 0$, the kinematic part of Eq. (A1) reduces to known expressions for $f\bar{f}\to Z\gamma$ (Ref. 38).

For the case of $q\bar{q}\to WV$, we find that only the diagrams of Figs. 15(a)–15(c) where the V couples directly to the virtual photon are important. We have also considered the complete subset of diagrams in Figs. 15(c) and 15(d) and found them to be negligible for light-quarkonium production. (We do, in the process, reproduce existing results[36] for $V\to W^+W^-$.) We then find the differential cross section

$$
\begin{aligned}
\frac{d\sigma}{d\hat{t}}&(q\bar{q}\to W\gamma^*\to WV)\\
&=\frac{\alpha^2 e_Q^2\alpha_w\pi|V_{ab}|^2|R(0)|^2}{2m_V^3(m_W^2-\hat{s})^2 m_W^2\hat{s}^2\hat{t}^2\hat{u}^2}\\
&\quad\times\{[2(8\hat{t}^2+5\hat{t}\hat{u}+\hat{u}^2)m_W^2\hat{u}+2(2\hat{t}^2-12\hat{t}\hat{u}-3\hat{u}^2)m_W^4\\
&\qquad+8m_W^6\hat{u}-\hat{t}\hat{u}^3]m_V^2\hat{t}^2+[(20\hat{t}+11\hat{u})m_W^2\hat{u}+8(\hat{t}-2\hat{u})m_W^4-2\hat{t}\hat{u}^2-2\hat{u}^3]m_V^4\hat{t}^2\\
&\qquad+8(m_W^6\hat{t}-2m_W^4\hat{s}\hat{t}-m_W^4\hat{t}^2-2m_W^4\hat{t}\hat{u}+m_W^4\hat{u}^2+m_W^2\hat{s}^2\hat{t}+m_W^2\hat{s}^2\hat{u}+m_W^2\hat{s}\hat{t}^2\\
&\qquad\quad+3m_W^2\hat{s}\hat{t}\hat{u}+2m_W^2\hat{t}^2\hat{u}-m_W^2\hat{u}^3-\hat{s}^3\hat{u}-2\hat{s}^2\hat{u}^2-\hat{s}\hat{u}^3-\hat{t}^2\hat{u}^2+\hat{t}\hat{u}^3)(m_W^2-\hat{s})e_i m_W^2\hat{t}\\
&\qquad+4(m_W^4\hat{t}^2+m_W^4\hat{u}^2-m_W^2\hat{s}\hat{t}^2-m_W^2\hat{s}\hat{u}^2-m_W^2\hat{t}^3-m_W^2\hat{t}^2\hat{u}-m_W^2\hat{t}\hat{u}^2-m_W^2\hat{u}^3\\
&\qquad\quad+2\hat{s}^2\hat{t}\hat{u}+2\hat{s}\hat{t}^2\hat{u}+2\hat{s}\hat{t}\hat{u}^2+\hat{t}^3\hat{u}+\hat{t}\hat{u}^3)(m_W^2-\hat{s})^2 e_i^2 m_W^2+2(2m_W^4+4m_W^2\hat{u}-\hat{u}^2)m_V^6\hat{t}^2\\
&\qquad+4(\hat{t}^2+\hat{u}^2)m_W^2\hat{t}^3\hat{u}-8(\hat{t}+\hat{u})m_W^4\hat{t}^3\hat{u}+8m_W^6\hat{t}^3\hat{u}\}\;,
\end{aligned}
\tag{A2}
$$

with $\alpha_w=\alpha/\sin^2\theta_W$ and with V_{ab} being the Kobayashi-Maskawa matrix element for the coupling of the W to the initial quarks. The formula given is for W^+ production, and here $e_i=e_u=+\frac{2}{3}$; for W^- production, let $\hat{t}\leftrightarrow\hat{u}$ and put $e_i=e_d=-\frac{1}{3}$. In this case, when $m_V\to 0$, we find that we reproduce the very simple kinematics (and remarkable factorization property) of the $q\bar{q}\to W\gamma$ cross sections first found in Ref. 39.

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