

Dijet production in generic contact interaction at linear colliders

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We consider dijet production at a e^+e^- collider in a class of effective theories with the relevant operators being four-fermion contact interaction. Despite the nonrenormalizable nature of the interaction, we explicitly demonstrate that calculating QCD corrections is both possible and meaningful. Calculating the corrections for various differential distributions, we show that these can be substantial and significantly different from those within the SM. Furthermore, the corrections have a very distinctive flavor dependence.

I. INTRODUCTION

Measurement of multi-jets rates in electron-positron annihilation provide an excellent test of perturbative quantum chromodynamics (QCD)[1]. In Standard Model (SM), QCD has been tested in the perturbative regime to a high degree of accuracy[2]. Though SM is very successful model in high energy physics, there are theoretical issues that cannot even be addressed within the framework of the SM alone. Examples include the replication of the fermion families, the naturalness problem associated with the Higgs scale, charge quantization, the baryon asymmetry in the universe, the presence of dark matter etc.. Clearly, an answer to such vital questions may be obtained only in a model much more ambitious than the SM. Candidates for the role include, amongst others, supersymmetry [3], grand unification [4, 5] (with or without supersymmetry), family symmetries (gauged or otherwise) and compositeness for quarks and leptons [12]. Therefore the possible existence of new physics beyond SM, involving the four fermion contact interaction would be one of the viable model and may give rise to small effects at present and future linear collider. We illustrate this explicitly in the case of dijet production via electron-positron annihilation process. We limit our calculation for exclusive two-jet cross section in this model.

The replication of fermion families in SM suggests the possibility of quark-lepton composite structure or bound states of more fundamental constituents, called *preons*[6]. 't Hooft has shown that the gauge theory[7] of preon binding naturally reproduce the composite fermions of less massive than the preon binding scale which is called characteristic scale Λ . At this scale Λ , this interaction would become very strong leading to bound states (composites) which are to be identified as quarks and leptons. In most such models[8, 9], quarks and leptons share at least some common constituents. Since the confining force mediates interactions between such constituents. Well below the scale Λ , such interactions would likely be manifested through an effective four fermion contact interaction [10] term that is an invariant under the SM gauge group. A convenient and general parametrization

of such interactions is given by[11, 12]

$$\mathcal{L} = \frac{4\pi}{\Lambda^2} \left[\eta_{ij} (\bar{q} \gamma^\mu P_i q) (\bar{l} \gamma_\mu P_j l) + \xi_{ij} (\bar{q} P_i q) (\bar{l} P_j l) \right], \quad (1)$$

where $i, j = L, R$ and P_i are the chirality projection operators. Note that the Lagrangian of eqn.(1) is by no means a comprehensive one and similar operators involving the quarks alone (or the leptons alone) would also exist. However, for our purpose, it would suffice to consider only eqn.(1). Within this limited sphere of applicability, the strength of the interaction may be entirely absorbed in the scale Λ , and the couplings η_{ij} and ξ_{ij} canonically normalized to ± 1 .

Though the lagrangian presented above eqn.(1) is so-called *4-fermion* contact interaction lagrangian but there are other theories which can give rise to such an effective interaction lagrangian. As is well known, a four-fermion process mediated by a particle with a mass significantly higher than the energy transfer can be well approximated by a contact interaction [10] term with a generic form as in eqn.(1). For examples, theories with extended gauge sectors, leptoquarks [13], sfermion exchange in a supersymmetric theory with broken R -parity [14] etc. are the theories which can give rise to such kind of effective interaction lagrangian by integrating out fields with masses $M_i \gtrsim \Lambda$ [15]. In those eqn.(1) are just the lowest order (in Λ^{-1}) ones among the series of such higher-dimensional terms.

Such operators, in principle, could lead to significant phenomenological consequences in collider experiments, whether e^+e^- [17, 18], eP [16] or hadronic. Given the higher-dimensional nature of \mathcal{L} , the fractional deviation over the SM expectations would be concentrated more at higher invariant masses. Some of the best constraints on compositeness, for example, came from the CDF [19] experiments and more recent measurement of the Drell-Yan cross section[20] at high invariant masses set the most stringent limits [21, 22] on contact interactions of the type given in eqn.(1). For the e^+e^- collider, more recent constraints on compositeness, for example came from the OPAL [18] $\Lambda \gtrsim 1.6-3.4$ TeV within the VA -type interaction scenario.

Recently, we have done the NLO QCD correction [23] in the context of hadron collider by taking into account of this effective lagrangian eqn.(1). In this article, we are going to do similar type of calculation in Linear Collider.

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In e^+e^- annihilation, the perturbative QCD predicts only parton cross section but experimentally one measured only hadrons though hadronisation process known only phenomenologically. Because of this limited knowledge of hadronisation process one can not directly relate theory and experiment. Since we measured only hadrons in the final state one should include the higher order QCD corrections (which include the more partons in the final state) to the lowest order one to get the better result. In SM, people have done their calculation of next-to-leading order (NLO)[24, 25] and next-to-next-to-leading order (NNLO)[26] QCD corrections for the dijet production in e^+e^- annihilation. However, no calculations exist for the higher order QCD corrections to cross sections mediated by a generic contact interaction. Consequently, all extant collider studies of contact interaction have either been based on just the tree level calculations, or, in some cases, assumed that the higher order corrections are exactly the same as in the SM. Clearly, this is an unsatisfactory state of affairs and, in this paper, we aim to rectify this by calculating the next-to-leading order QCD corrections for both the VA -type and the SP -type contact interactions.

Being nonrenormalisable of such theories, the current-current form of the lagrangian allow us to calculate reliable QCD corrections because of the fact that only one current consists of coloured field. This holds not only for the specific interaction in question, but also for other theories that satisfy the abovementioned criterion [28].

The rest of the article is organised as follows. In Section II, we present our results for the LO and NLO cross section for resolved two parton case only (stated otherwise). The resolved three parton cross section will be divergence free and hence can be evaluated numerically in 4-dimension. Here we also present only the total three parton cross section. In Section III we discuss the numerical results and finally, we summarise in Section IV.

II. NLO CORRECTIONS

Before going to actual calculation of jet cross section, it is necessary to define cross section in perturbation theory. In perturbative QCD, each outgoing hard parton regarded as one jet that means one has to apply a jet resolution criterion to each outgoing partons to define a jet. In other words, a proper definition is to introduce a parton resolution criterion to define when a parton is resolved either as a single parton or as a cluster of partons. Consider the process e^+e^- annihilate to quarks and gluon i.e. $e^+e^- \rightarrow q(p_q) \bar{q}(p_{\bar{q}}) g(p_g)$. This process can be thought of as lowest order three jet production or higher order dijet production depending upon how we define the jet resolution criterion. One possible jet definition is a minimum mass cut so that the invariant mass of pair of jet must be larger than experimentally defined one s_{min} . In the above mentioned process, there are only three invariant mass $s_{ij} = (p_i + p_j)^2, i, j = q, \bar{q}, g$. Therefore the

lowest order three jet cross section is defined by

$$d\sigma(e^+e^- \rightarrow 3 jets) = \Theta d\sigma(e^+e^- \rightarrow q\bar{q}g) \quad (2)$$

and Θ is the jet resolution criterion for the three jet final state defined by

$$\Theta = \theta(s_{min} - s_{q\bar{q}}) \theta(s_{min} - s_{qg}) \theta(s_{min} - s_{\bar{q}g}) \quad (3)$$

where $\theta(x) = 1$ for $x > 0$ and 0 otherwise. For the dijet cross section, it will represent the next-to-leading order (NLO) dijet cross section (where one of the partons (gluon, say) is either soft or collinear to other partons) and the jet resolution criterion for the two-jet final state would be the only one of the invariant masses ($s_{q\bar{q}}$ say) larger than the experimentally defining cut s_{min} i.e.

$$d\sigma(e^+e^- \rightarrow 2 jets) = \Theta d\sigma(e^+e^- \rightarrow q\bar{q}g) \quad (4)$$

where

$$\Theta = \theta(s_{min} - s_{q\bar{q}}). \quad (5)$$

We consider the process e^+e^- annihilation into a quark-antiquark pair i.e. $e^+e^- \rightarrow q\bar{q}$ in the context of generic contact interaction as defined by the lagrangian eqn.(1). In the presence of scalar-pseudoscalar (SP) type contact interaction, the leading order differential cross section for the above process is given by

$$\frac{d\sigma_{SP}^{(0)}}{d\cos\theta} = \frac{3\pi}{2} \sum_{i,j=L,R} |\xi_{ij}|^2 \frac{s}{\Lambda^4} \quad (6)$$

and for the vector-axial-vector (VA) type contact interaction, the leading order differential cross section for that same process (stated above) will be same as the standard model one and is given by (for completeness)

$$\frac{d\sigma_{VA}^{(0)}}{d\cos\theta} = \frac{3\pi\alpha^2}{2s} \left[\left(|f_{LL}|^2 + |f_{RR}|^2 \right) \left(\frac{u}{s} \right)^2 + \left(|f_{LR}|^2 + |f_{RL}|^2 \right) \left(\frac{t}{s} \right)^2 \right] \quad (7)$$

where $t = -\frac{s}{2}(1 - \cos\theta)$, $u = -\frac{s}{2}(1 + \cos\theta)$ and α is the electromagnetic coupling constant. $f_{ij}(i, j = L, R)$ are given by

$$f_{ij} = Q_i Q_j + g_i^q g_j^l \chi(s) + \eta_{ij} \frac{s}{\alpha \Lambda^2}.$$

$$\chi(s) = s/(s - M_Z^2 + iM_Z \Gamma_Z)$$

The left-handed and right handed couplings g_L^f and g_R^f of the fermion to Z -boson are given by,

$$g_L^f = \frac{e}{\sin \theta_W \cos \theta_W} \left(I_3^f - Q_f \sin^2 \theta_W \right),$$

$$g_R^f = \frac{e}{\sin \theta_W \cos \theta_W} \left(-Q_f \sin^2 \theta_W \right) \quad (8)$$

where e is the electron charge, Q_f is the electric charge in units of $|e|$ of the fermion f , I_3^f is the third component of weakisospin and θ_W is the electroweak mixing angle.

At the leading order (LO) dijet calculation is much more simpler (as calculated above eqns.(6,??) than the next-to-leading order. At NLO, it requires careful treatment of cancellation of divergences (soft and collinear divergences against the divergences stemming from virtual corrections). The divergences coming from the fact that at NLO a parton can only be defined through a resolution criterion. There are many form of this resolution criterion. We have used the invariant mass resolution criterion. That is, if the invariant mass of the two parton less than the invariant mass resolution (s_{min}) then these two parton considered as unresolved parton and treated as a one parton (or one jet) by integrating out the unresolved phase space which separates the soft and collinear region of phase space from the resolved bremsstrahlung phase space. After adding this unresolved soft and collinear contribution with virtual corrections, it becomes finite.

For dijet production, the order α_s correction receive two contributions, one is from resolved two parton cross section (which is purely virtual contribution) and other one is the lowest order unresolved three parton cross section (calculated in the soft and collinear limit) where one soft and/or collinear parton clusters with one hard parton to form one jet. These soft and/or collinear divergences can be isolated and it is easy to show that these divergences analytically cancel with soft and collinear singularities coming from virtual correction of resolved two part process upto order s_{min} (or $y_{min} = s_{min}/s_{ij}$) where virtual gluon in the loop becomes soft. The lowest order unresolved three parton cross section will be leading order cross section multiplied by some functions F^{S+C} (a function of all the singularities (soft and collinear), s_{min} (or y_{min}) and the factorisation scale (μ_F)). This F^{S+C} is same for VA -type or SP -type theory and can be found out in the literature (for example see [24]). The lowest order three parton cross section is given by,

$$d\sigma_\eta^{(S+C)} = d\sigma_\eta^{(0)} \times F^{S+C}$$

$$= d\sigma_\eta^{(0)} \times \frac{\alpha_s C_F}{2\pi\Gamma(1-\epsilon)} \left[\frac{2}{\epsilon^2} \left(\frac{4\pi\mu_F^2}{s_{q\bar{q}}} \right)^\epsilon - 2 \ln^2 \left(\frac{s_{q\bar{q}}}{s_{min}} \right) \right.$$

$$\left. + 7 - \frac{2\pi^2}{3} + \frac{3}{\epsilon} \left(\frac{4\pi\mu_F^2}{s_{min}} \right)^\epsilon + \mathcal{O}(s_{min}/s_{q\bar{q}}) \right]$$

$$(\eta = SP, VA) \quad (9)$$

The virtual corrections to the resolved two parton process is also available in the literature (for example they can be read from Refs.[27] for SP -type and Refs.[24, 28] for VA type theory). We follow the dimensional regularisation procedure to regulate all the divergences in $d = 4 - 2\epsilon$ dimensions and we use the \overline{MS} scheme to remove the ultra-violet divergence. For completeness, they are given by

$$d\sigma_\eta^{(0+V)} = d\sigma_\eta^{(0)} \left(1 + \frac{\alpha_s C_F}{4\pi} F_\eta^{(1)} \right) \quad (\eta = SP, VA) \quad (10)$$

where

$$F^{(1)}|_{VA} = \frac{2}{\Gamma(1-\epsilon)} \left(\frac{s_{q\bar{q}}}{4\pi\mu^2} \right)^{-\epsilon} \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \pi^2 \right], \quad (11)$$

$$F^{(1)}|_{SP} = \frac{2}{\Gamma(1-\epsilon)} \left(\frac{s_{q\bar{q}}}{4\pi\mu^2} \right)^{-\epsilon} \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 2 + \pi^2 \right]. \quad (12)$$

From eqns.(II,10), it is clear that the left over soft and/or collinear divergences (from the virtual corrections) cancel against the soft and collinear divergences coming from unresolved three parton process. Therefore next-to-leading order cross section for exclusive dijet production are given by

$$d\sigma_{VA}^{(1)} = d\sigma_{VA}^{(0)} \times \left[1 + \frac{\alpha_s C_F}{2\pi\Gamma(1-\epsilon)} \left(\frac{\pi^2}{3} - 1 - 3 \ln(y_{min}) - 2 \ln^2(y_{min}) \right) + \mathcal{O}(y_{min}) \right] \quad (13)$$

and

$$d\sigma_{SP}^{(1)} = d\sigma_{SP}^{(0)} \times \left[1 + \frac{\alpha_s C_F}{2\pi\Gamma(1-\epsilon)} \left(\frac{\pi^2}{3} + 5 - 3 \ln(y_{min}) - 2 \ln^2(y_{min}) \right) + \mathcal{O}(y_{min}) \right] \quad (14)$$

which are finite as $\epsilon \rightarrow 0$. Here we have considered $\mu = \mu_F$. By integrating over resolved three particle phase space, one can get the $\mathcal{O}(y_{min})$ correction of the above eqns.(II,II). The resolved three parton cross section for the VA -type contact interaction will be same as SM which is available in literature (see for example Ref.[26, 30]) and is given by,

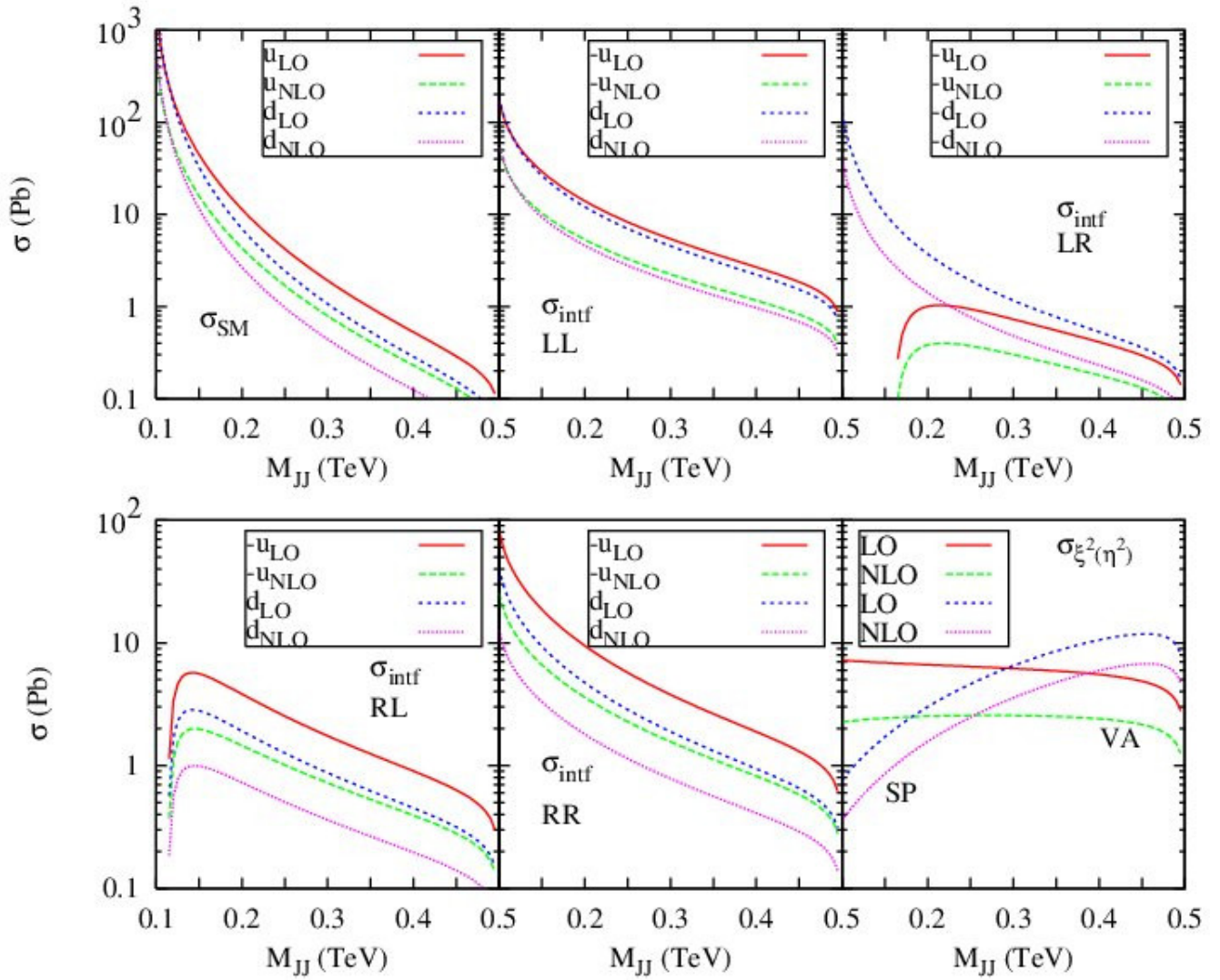


FIG. 1: The dijet production cross section as a function of invariant mass M_{JJ} for $\sqrt{S} = 500$ GeV and $\Lambda = 2$ TeV. The scale is chosen to be $\mu(\mu_F) = M_{JJ}$. The upper set of lines (blue and pink) are for SP-type pure contact interaction (right most, lower panel).

$$\sigma_{3-jet}^{VA} = \sigma_{VA}^{(0)} \frac{\alpha_s C_F}{2\pi\Gamma(1-\epsilon)} \left[-\frac{\pi^2}{3} + \frac{5}{2} + 3 \ln(y_{min}) + 2 \ln^2(y_{min}) + \mathcal{O}(y_{min}) \right]. \quad (15)$$

For the SP -type contact interaction we have calculated the resolved three parton cross section as given below

$$\sigma_{3-jet}^{SP} = \sigma_{SP}^{(0)} \frac{\alpha_s C_F}{2\pi\Gamma(1-\epsilon)} \left[-\frac{\pi^2}{3} + \frac{7}{2} + 3 \ln(y_{min}) + 2 \ln^2(y_{min}) + \mathcal{O}(y_{min}) \right]. \quad (16)$$

From eqns.(II,II) (or eqns.(II,16)), it is clear that the theoretical results for resolved two parton and three parton depend strongly on an arbitrary parameter y_{min} . Any physical observable should not depend on this arbitrary parameter. However for physical 2-jet NLO cross section, both two parton and three parton cross section will contribute and hence it is independent of this arbitrariness. This also ensures the KLN (Kinoshita-Lee-Nauenberg) theorem that the fully inclusive e^+e^- cross section is finite as quark mass goes to zero (i.e. free of mass singular).

III. RESULTS AND DISCUSSIONS

In this section, we present numerical result for ILC. We choose the contact interaction scale (Λ) to be 2 TeV

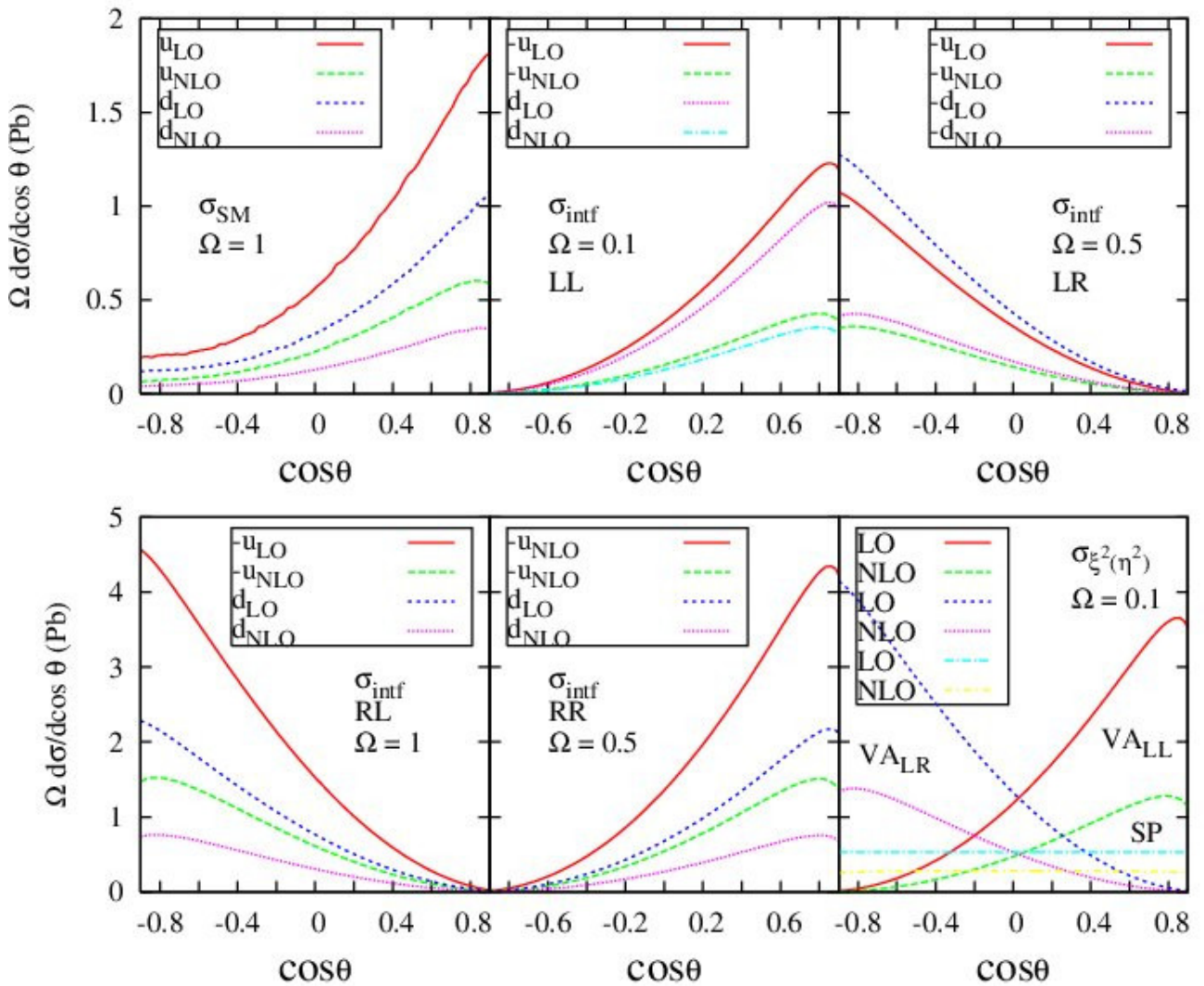


FIG. 2: The angular distribution for dijet production at $\sqrt{s} = 500$ GeV and $\Lambda = 2$ TeV. The scale $\mu(\mu_F) = P_T$. Here Ω is a scale factor.

and the center of mass energy to be $\sqrt{s} = 500$ GeV. As is well known, the higher order QCD correction reduces the uncertainties related to scale choice (the renormalisation scale (μ) and the factorisation scale (μ_F)). For the NLO jet calculation, the analytical result does not depend on any of these scale explicitly[29]. The scale dependence comes through the strong coupling constant $\alpha_s(\mu^2)$. We have used the NLO $\alpha_s(\mu^2)$ for the NLO analysis and the scale we choose, both renormalisation and factorisation scale to be $\mu(\mu_F) = P_T$ (otherwise stated). We have also shown that both two-parton and three parton result strongly depends on the cut-off y_{min} . For very small values of y_{min} , two parton cross section become negative and three parton cross section become large positive (because of these terms $\ln(y_{min})$, $\ln^2(y_{min})$). For large enough y_{min} , both the parts produce the meaningful result. Our analytical result is valid for small y_{min} region since we have neglected the term $\mathcal{O}(y_{min})$ in the inte-

gration. Therefore y_{min} should be much less than one ($y_{min} \ll 1$). For this reason, we choose $y_{min} = 0.01$ (detailed discussion can be found in the literature [24, 26]) for all the differential distributions and the total cross section. Furthermore, in presenting our results, we shall consider only one of the couplings η_{AB} and ξ_{AB} to be non-zero and of unit strength.

For the sake of convenience, we parametrize the cross section as

$$\begin{aligned} \sigma &= \sigma_{SM} + \sigma_{intf} + \sigma_{\eta^2} \quad (\text{for the VA case}) \\ \sigma &= \sigma_{SM} + \sigma_{\xi^2} \quad (\text{for the SP case}) \end{aligned} \tag{17}$$

and similarly for the differential cross sections. This has the advantage in that the total cross sections, for an arbitrary value of Λ can be easily reconstructed. We also take care of the so-called *initial state radiation*(ISR) effect[31] through out our numerical analysis otherwise stated.

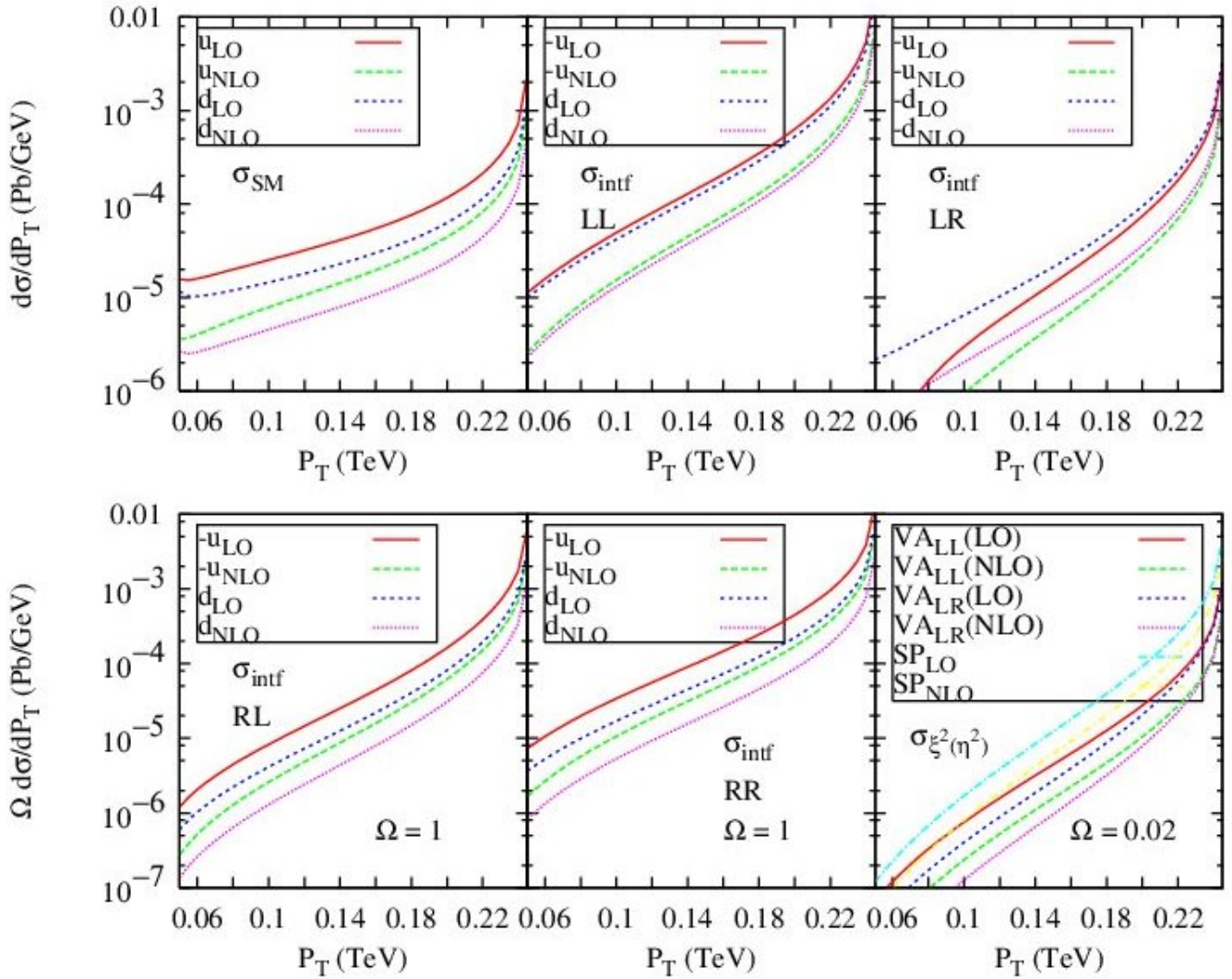


FIG. 3: Single jet P_T differential distribution for $\sqrt{S} = 500$ GeV, $\Lambda = 2$ TeV and $y_{min} = 0.01$. The scale $\mu(\mu_F) = P_T$. Ω is a scale factor.

In figure 1 we have plotted the total cross section as a function of invariant mass of dijet (M_{JJ}). For dijet production, the dijet invariant mass is same as the effective center of mass energy s (due to the *ISR* effect). The rapid fall of σ_{SM} with M_{JJ} is due to s^{-1} where as the interference cross section (σ_{intf}) is independent of s (eqn.??) and hence is almost constant. The slow fall of σ_{intf} reflects the higher dimensional nature of the contact interaction lagrangian. Here we have chosen the scale to be $\mu(\mu_F) = M_{JJ}$. The pure contact interaction cross section $\sigma_{\eta^2(\xi^2)}$ increases with M_{JJ} due to fact that it is proportional to the s (eqns.??,6). The *VA*-type contact interaction cross section increases very slowly with M_{JJ} because of its $V - A$ current structure compare to *SP*-type contact interaction cross section. Consequently larger value of M_{JJ} , contact interaction dominates over the SM one. From figure 1, it is clear that the cross sec-

tion is flavor dependent whereas the purely contact cross section $\sigma_{\eta^2(\xi^2)}$ is flavor independent as we expected. The same argument holds for rest of the analysis.

Figure 2 shows the angular distribution between beam axis and the jet axis. This distribution is almost constant for *SP*-type contact interaction because of the fact that the leading order cross section is independent of θ (which is typical characteristic of scalar vertex) as we see in eqn.(6). This argument holds not only for leading order result but for higher order corrections result as well. The small variation in the NLO result (yellow line) is due to scale variation through the $\alpha_s(\mu^2)$. Whereas this is not so for *VA*-type contact interaction. *VA*-type contact interaction does depend on the θ . These differential distributions for both *VA*-type and *SP*-type contact interaction dominates over the SM piece. For the pure *VA*-type contact interaction, the angular distributions

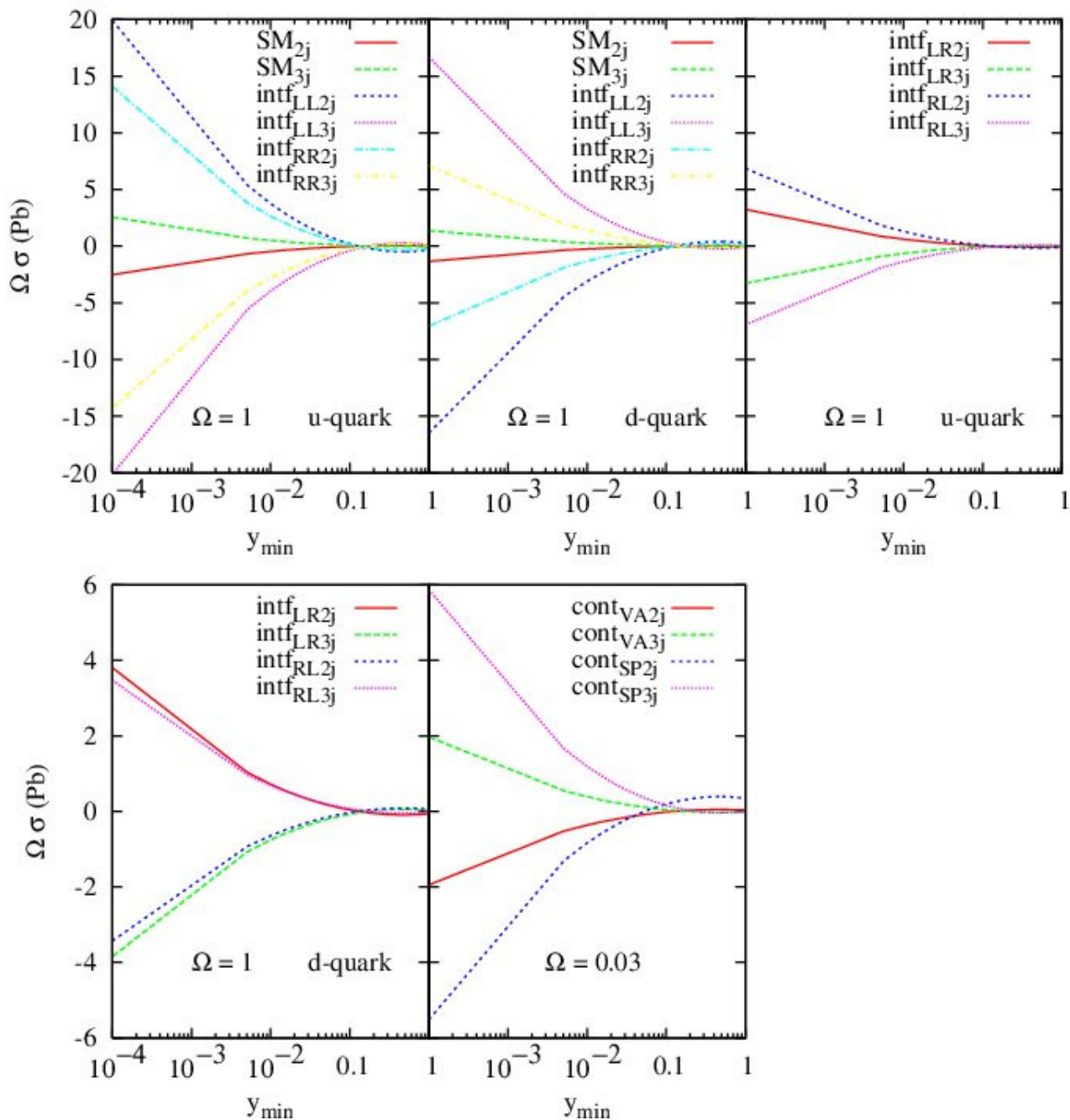


FIG. 4: Dijet and 3-jet cross section as a function of y_{min} for $\sqrt{s} = 500$ GeV, $\Lambda = 2$ TeV. The scale $\mu(\mu_F) = P_T$. Ω is a scale factor. Here “intf” signifies the interference cross section and “cont” signifies the pure contact interaction cross section.

are different for $LL(RR)$ and $LR(RL)$ sector. This is because of the sign of $\cos \theta$ are different (eqn.(??)). In other words, their chirality structures are quite different. This is also true for P_T -distributions (see figure 3).

In figure 3 we have shown the transverse momentum (P_T)-distribution of a single jet. Since at the leading order, the transverse momentum of the two jets balanced each other ($P_{T1} = P_{T2} = P_T$). For the NLO, the unobserved third parton can be taken infinitely soft for IR safety which is the artifact of fixed order perturbation

theory. Therefore this momentum relation still holds even at NLO. From the figure it is clear that as P_T approaches towards $\sqrt{S}/2$ the differential cross section approaches infinity as we expected. Though the interference P_T differential distribution of RL and LR are of the same order or less but LL and RR distributions are of the order one more than the SM whereas for pure contact interaction it is $\sim 10^2$ over the SM for both the cases (SP as well as VA).

In figure 4 , we have plotted dijet cross section (only

$\mathcal{O}(\alpha_s)$) and resolved 3-jet cross section as function of y_{min} (without *ISR* effect). From the figure, one can easily see that large values of y_{min} , both two-parton and three parton cross section produce the meaningful result compared to very small valued y_{min} . We have also checked numerically that the sum of these dijet and resolved three jet cross section is independent of y_{min} (as it is cleared from the analytic structure in Section II) which essentially reproduce the inclusive results for e^+e^- annihilation to quark-antiquark pair upto $\mathcal{O}(\alpha_s)$.

IV. CONCLUSION

To summarise, we have performed a systematic calculation of the next-to-leading order QCD corrections for the dijet production via e^+e^- annihilation in theories with contact interactions. Contrary to naive expectations, we demonstrate explicitly that the QCD correc-

tions are meaningful and reliable in the sense that no undetermined parameters need be introduced.

For the *VA*-type interactions, the analytical structure of the corrections are similar to those for the SM. However, a significant dependence on the flavor structure is found and needs to be carefully accounted for in obtaining any experimental bounds. For the *SP*-type interaction, not only are the analytical results quite different, but the results are typically larger than those within the SM. Finally, we have investigated the sensitivity of our results to y_{min} (or s_{min} the invariant mass cut).

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