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ON $B\overline{B}$ PRODUCTION IN $\gamma\gamma$ COLLISIONS

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Motivated by the excess of the data on the total cross section $\sigma_{tot}(\mathrm{e^+e^-} \to \mathrm{e^+e^-} b\overline{b})$ at LEP2 over theoretical predictions we investigate the dependence of the cross section $\sigma_{tot}(\gamma\gamma \to b\overline{b})$ on the renormalization and factorization scales.

The problem of understanding the $\overline{b}b$ production in $\mathrm{e^+e^-}$ collisions remains a serious challenge for current perturbative QCD. As the reliability of QCD calculations of the corresponding cross section depends crucially on the reliability of the calculations of the cross section $\sigma(\gamma\gamma \to b\overline{b})$ at the $\gamma\gamma$ cms energy W, we investigate in detail one feature of the latter: the stability of the corresponding QCD calculations with respect to the variation of the renormalization and factorizations scales (for details, see [1]).

The standard NLO QCD approximation to $\sigma_{tot}(\gamma\gamma \to Q\overline{Q})$ (like, for instance in [2]) takes into account the first two terms in the perturbation expansions of direct, as well as single and double resolved photon contributions

$$\sigma_{\mathrm{dir}}(M) = \sigma^{(0)}_{\mathrm{dir}} + \sigma^{(1)}_{\mathrm{dir}}\alpha_s(\mu) + \sigma^{(2)}_{\mathrm{dir}}(M,\mu)\alpha_s^2(\mu) + \sigma^{(3)}_{\mathrm{dir}}(M,\mu)\alpha_s^3(\mu) + \cdots, \quad (1)$$

$$\sigma_{\mathrm{sr}}(M) = \sigma^{(1)}_{\mathrm{sr}}(M)\alpha_s(\mu) + \sigma^{(2)}_{\mathrm{sr}}(M,\mu)\alpha_s^2(\mu) + \sigma^{(3)}_{\mathrm{sr}}(M,\mu)\alpha_s^3(\mu) + \cdots, \quad (2)$$

$$\sigma_{\mathrm{dr}}(M) = \sigma^{(2)}_{\mathrm{dr}}(M)\alpha_s^2(\mu) + \sigma^{(3)}_{\mathrm{dr}}(M,\mu)\alpha_s^3(\mu) + \cdots, \quad (3)$$

where PDF of the photon as well as partonic cross sections depend on the factorization scale M whereas the renormalization scale μ appears when the latter are calculated as perturbative expansions in $\alpha_s(\mu)$. As these scales reflect ambiguities in the treatment of different divergences they should better be kept as independent free parameters of any finite order calculation.

At LEP the incoming electrons and positrons acted as sources of transverse quasireal photons described by the flux

$$f_T^\gamma(y,Q^2) = \frac{\alpha}{2\pi}\left(\frac{1+(1-y)^2}{y}\frac{1}{Q^2} - \frac{2m_\mathrm{e}^2 y}{Q^4}\right), \quad (4)$$

where Q^2 stands for photon virtuality. For brevity we shall write instead of $\sigma_{tot}(\mathrm{e^+e^-} \to \mathrm{e^+e^-} b\overline{b})$ simply $\sigma_{tot}(\mathrm{e^+e^-} \to b\overline{b})$.

The pure QED contribution to $\sigma_{tot}(\mathrm{e^+e^-} \to b\overline{b})$ is given as

$$\frac{\mathrm{d}\sigma_{\mathrm{QED}}(\mathrm{e^+e^-} \to b\overline{b})}{\mathrm{d}W} = \frac{6\alpha^4 e_b^4}{\pi S}\frac{A(W)}{W}\left[\left(1+\frac{4m_b^2}{W^2}-\frac{8m_b^4}{W^4}\right)\ln\frac{1+\beta}{1-\beta} - \beta\left(1+\frac{4m_b^2}{W^2}\right)\right] \quad (5)$$

where $A(W)$ results from convolution of photon fluxes (4), integrated over the virtualities up to Q^2_{max}. In Fig. 1 we display by the solid curve the result of

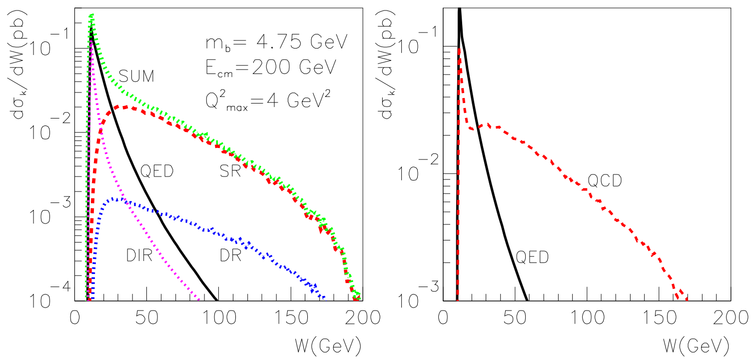

Figure 1. Left: The distributions $\mathrm{d}\sigma_k/\mathrm{d}W$ corresponding to pure QED as well as three lowest order QCD contributions: single resolved (SR), double resolved (DR), and direct (DIR). Right: the comparison of pure QED contribution with the sum of three lowest order QCD ones.

evaluating (5) for $m_b = 4.75$ GeV, $\sqrt{S} = 200$ GeV and $Q^2_{max} = 4$ GeV. The distribution vanishes at the threshold $W = 2m_b$, peaks at about $W = 12$ GeV and then drops rapidly off.

As in the case of pure QED contribution the QCD corrections are given as convolutions of the flux(es) (4) with the appropriate partonic cross sections. In all calculations u, d, s and c quarks were considered as intrinsic and $n_f = 4$ was correspondingly taken in the expression for $\alpha_s(\mu)$. The W dependence of the lowest order QCD correction to the direct photon contribution (1) is given as

$$\frac{\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{dir}}(W)}{\mathrm{d}W} = \frac{6\alpha^4 e_b^4}{\pi S}\frac{A(W)}{W}\alpha_s(\mu)\sigma^{(1)}_{\mathrm{dir}}(W/m_b) \tag{6}$$

The lowest order single and double resolved photon contributions, computed with HERWIG event generator for the LO GRV PDF of the photon, the LO expression for $\alpha_s(\mu)$ with $\Lambda^{(4)} = 0.27$ GeV and $m_b = 4.75$ GeV, are shown in Figs. 1. As expected, the corresponding distributions are much broader than those of pure QED or lowest order QCD direct contributions.

The comparison of the distributions $\mathrm{d}\sigma_k/\mathrm{d}W$ corresponding to four individual contributions reveals large difference in their shapes and magnitude:

- The pure QED as well as the lowest order QCD direct photon contributions peak at very small W and are basically negligible above $W \simeq 50$ GeV.
- The onset of single and double resolved photon contributions are much slower, but these distributions are markedly broader.
- up to about $W \simeq 30$ GeV, $\mathrm{d}\sigma_{tot}/\mathrm{d}W$ is dominated by pure QED contribution, whereas for $W \gtrsim 30$ GeV, QCD contributions take over.
- The double resolved photon contribution is practically negligible everywhere. Only the single resolved photon contribution will therefore be discussed below.

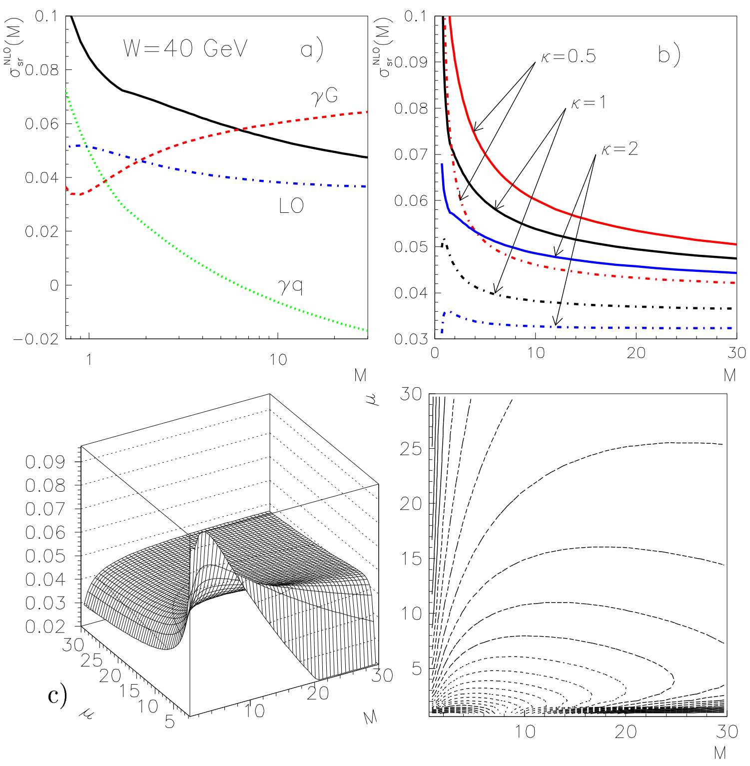

Figure 2. a) The scale dependence of the conventional NLO approximation $\sigma_{\rm sr}^{\rm NLO}(W,M,M)$ for $W=40$ GeV (solid curve) together with the contributions of the γG (dashed) and $\gamma q/\overline{q}$ (dotted) channels. The LO approximation is shown for comparison by the dash-dotted curve. b) $\sigma_{\rm sr}^{\rm NLO}(W,M,\kappa M)$ (solid curve) and $\sigma_{\rm sr}^{\rm LO}(W,M,\kappa M)$ (dash-dotted) for $W=40$ GeV and three values of $\kappa=0.5,1.2$. c) The surface and contour plots of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu)$ for $W=40$ GeV.

As suggested by Fig. 1, the basic features of the cross section $\sigma_{\rm sr}^{\rm NLO}({\rm e^+e^-}\rightarrow b\bar{b})$ are determined primarily by those of $\sigma_{\rm sr}^{\rm NLO}(\gamma\gamma\rightarrow b\bar{b})$ in the range $30\lesssim W\lesssim 65$ GeV. All the results presented below for the single resolved photon contribution are based on the formulae for the partonic cross sections $\sigma_{ij}^{(k)}$ as given in [6] and were obtained using the GRV HO set of PDF of the photon and setting $\Lambda_{\overline{\rm MS}}^{(4)}=0.27$.

We first follow the conventional procedure and set $M=\mu$. The resulting scale dependence of the sum of first two terms in (2) is shown for $W=40$ GeV in Fig. 2a . Note that the conventional NLO approximation is a monotonously decreasing function of the scale $M=\mu$, falling off even steeper than the LO expression! In other words, in going from the LO to the NLO the sensitivity to the scale variation increases, rather than decreases as one might hope! To check that this feature does not depend on setting exactly $\mu=M$, we plot in Fig. 2b the scale dependence of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu=\kappa M)$ for standard choices of $\kappa=0.5,1,2$. The steep and

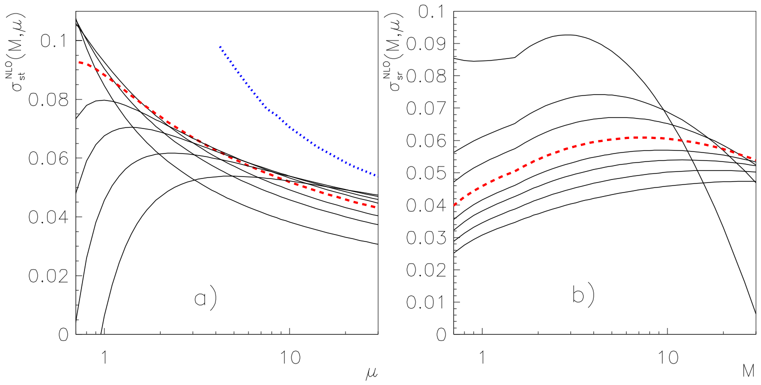

Figure 3. The renormalization scale dependence of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu)$ for fixed values of the factorization scale (a) and vice versa: the factorization scale dependence of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu)$ for the same set of fixed values of the renormalization scale μ (b). All calculations correspond to $W=40$ GeV. In a) the ordering from above of the curves at $\mu=30$ GeV corresponds to $M=30,16,10,7,4.75,3,2,1$ GeV, in b) the curves correspond at $M=0.7$ GeV to the same sequence from below.

monotonous scale dependence of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu=\kappa M)$ is a clear warning that the conventional NLO approximation is unstable.

To see what happens if we relax the usual but arbitrary identification $\mu=\kappa M$ we plot in Fig. 2 the surface and contour plots representing the full M and μ dependence of $\sigma_{\rm sr}^{\rm NLO}(W,M,\mu)$. Contrary to analogous process in $\overline{\rm p}$p collisions [3], it does not exhibit a saddle point, but Fig. 2 seems to indicate some sort of stability region at large scales, say for $M \gtrsim 10$ GeV, $\mu \gtrsim 20$ GeV. This impression is, however, misleading as becomes clear if we plot in Fig. 3 the slices of the surface plot in Fig. 2a along both axis. We see that for $M \lesssim 4.2$ GeV $\sigma_{\rm sr}^{\rm NLO}(M,\mu)$ exhibits no local stability point. For higher M the local maximum in the μ-dependence of $\sigma_{\rm sr}^{\rm NLO}(M,\mu)$ exists at the associated $\mu_{max}(M)$. The M-dependence of $\sigma_{\rm sr}^{\rm NLO}(M,\mu_{max}(M))$, shown in Fig. 3a by the dotted curve, is, however, even steeper that those at fixed M. The above plots and conclusions concerned the results at one typical value of W, but their essence holds for the whole interval relevant for LEP2 data.

In conclusion, we have shown that in the energy range relevant for LEP2 data the renormalization and factorization scale dependence of the conventional NLO calculations of single resolved photon contribution to $\sigma_{tot}(\gamma\gamma \to b\overline{b})$ exhibit no stability region, either as a function of the common scale $\mu=\kappa M$ or as a two dimensional function of μ and M, and are thus inherently unreliable.

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