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Lepton Pair Production at the LHC and the Gluon Density in the Proton

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The hadroproduction of lepton pairs with mass Q and finite transverse momentum Q_T is dominated by quark-gluon scattering in the region $Q_T > Q/2$. This feature provides a new independent method for constraining the gluon density with data at hadron collider energies. Predictions are provided at the energy of the LHC.

The production of lepton pairs in hadron collisions $h_1 h_2 \to \gamma^* X; \gamma^* \to l\bar{l}$ proceeds through an intermediate virtual photon via $q\bar{q} \to \gamma^*$, and the subsequent leptonic decay of the virtual photon. Interest in this Drell-Yan process is usually focussed on lepton pairs with large mass Q which justifies the application of perturbative QCD and allows for the extraction of the antiquark density in hadrons [1]. Prompt photon production $h_1 h_2 \to \gamma X$ can be calculated in perturbative QCD if the transverse momentum Q_T of the photon is sufficiently large. Because the quark-gluon Compton subprocess is dominant, $gq \to \gamma X$, this reaction provides essential information on the gluon density in the proton at large x [2]. Alternatively, the gluon density can be constrained from the production of jets with large transverse momentum at hadron colliders [3].

In this report we exploit the fact that, along prompt photon production, lepton pair production is dominated by quark-gluon scattering in the region $Q_T > Q/2$. This realization means that new independent constraints on the gluon density may be derived from Drell-Yan data in kinematical regimes that are accessible at the Large Hadron Collider (LHC) but without the theoretical and experimental uncertainties present in the prompt photon case.

In leading order (LO) QCD, two partonic subprocesses contribute to the production of virtual and real photons with non-zero transverse momentum: $q\bar{q} \to \gamma^{(*)} g$ and $qg \to \gamma^{(*)} q$. The cross section for lepton pair production is related to the cross section for virtual photon production through the leptonic branching ratio of the virtual photon $\alpha/(3\pi Q^2)$. The virtual photon cross section reduces to the real photon cross section in the limit $Q^2 \to 0$.

The next-to-leading order (NLO) QCD corrections arise from virtual one-loop diagrams interfering with the LO diagrams and from real emission diagrams. At this order $2 \to 3$ partonic processes with incident gluon pairs (gg), quark pairs (qq), and non-factorizable quark-antiquark ($q\bar{q}_2$) processes contribute also. An important difference between virtual and real photon production arises when a quark emits a collinear photon. Whereas the collinear emission of a real photon leads to a $1/\epsilon$ singularity that has to be factored into a fragmentation function, the collinear emission of a virtual photon yields a finite logarithmic contribution since it is regulated naturally by the photon virtuality Q. In the limit $Q^2 \to 0$ the NLO virtual photon cross section reduces to the real photon cross section if this logarithm is replaced by a $1/\epsilon$ pole. A more detailed discussion can be found in Ref. [4].

The situation is completely analogous to hard photoproduction where the photon participates in the scattering in the initial state instead of the final state. For real photons, one encounters an initial-state singularity that is factored into a photon structure function. For virtual photons, this singularity is replaced by a logarithmic dependence on the photon virtuality Q [5].

A remark is in order concerning the interval in Q_T in which our analysis is appropriate. In general, in two-scale situations, a series of logarithmic contributions will arise with terms of the type $\alpha_s^n \ln^n(Q/Q_T)$. Thus, if either $Q_T >> Q$ or $Q_T << Q$, resummations of this series must be considered. For practical reasons, such as event rate, we do not venture into the domain $Q_T >> Q$, and our fixed-order calculation should be adequate. On the other hand, the cross section is large in the region $Q_T << Q$. In previous papers [4], we compared our cross sections with available fixed-target and collider data on massive lepton-pair production, and we were able to establish that fixed-order perturbative calculations, without resummation, should be reliable for $Q_T > Q/2$. At smaller values of Q_T, non-perturbative and matching complications in-

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troduce some level of phenomenological ambiguity. For the goal we have in mind, viz., contraints on the gluon density, it would appear best to restrict attention to the region $Q_T \geq Q/2$, but below $Q_T >> Q$.

We analyze the invariant cross section $Ed^3\sigma/dp^3$ averaged over the rapidity interval -1.0 $< y <$ 1.0. We integrate the cross section over various intervals of pair-mass Q and plot it as a function of the transverse momentum Q_T. Our predictions are based on a NLO QCD calculation [6] and are evaluated in the $\overline{\rm MS}$ renormalization scheme. The renormalization and factorization scales are set to $\mu = \mu_f = \sqrt{Q^2 + Q_T^2}$. If not stated otherwise, we use the CTEQ4M parton distributions [7] and the corresponding value of Λ in the two-loop expression of α_s with four flavors (five if $\mu > m_b$). The Drell-Yan factor $\alpha/(3\pi Q^2)$ for the decay of the virtual photon into a lepton pair is included in all numerical results.

In Fig. 1 we display the NLO QCD cross section for lepton pair production at the LHC at $\sqrt{S} = 14$ TeV as a function of Q_T for four regions of Q chosen to avoid resonances, *i.e.* from threshold to 2.5 GeV, between the J/ψ and the Υ resonances, above the Υ's, and a high mass region. The cross section falls both with the mass of the lepton pair Q and, more steeply, with its transverse momentum Q_T. The initial LHC luminosity is expected to be 10^{33} cm^{-2} s^{-1}, or 10 fb^{-1}/year, and to reach the design luminosity of 10^{34} cm^{-2} s^{-1} after three or four years. Therefore it should be possible to analyze data for lepton pair production to at least $Q_T \simeq 100$ GeV where one can probe the parton densities in the proton up to $x_T = 2Q_T/\sqrt{S} \simeq 0.014$. The UA1 collaboration measured the transverse momentum distribution of lepton pairs at $\sqrt{S} = 630$ GeV to $x_T = 0.13$ [8], and their data agree well with our expectations [4].

The fractional contributions from the qg and $q\bar{q}$ subprocesses through NLO are shown in Fig. 2. It is evident that the qg subprocess is the most important subprocess as long as $Q_T > Q/2$. The dominance of

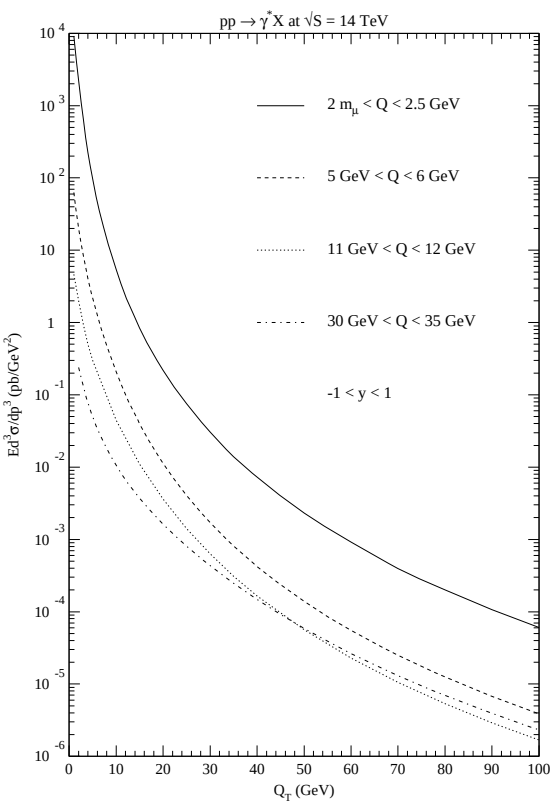

Figure 1. Invariant cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $pp \to \gamma^* X$ at $\sqrt{S} = 14$ TeV.

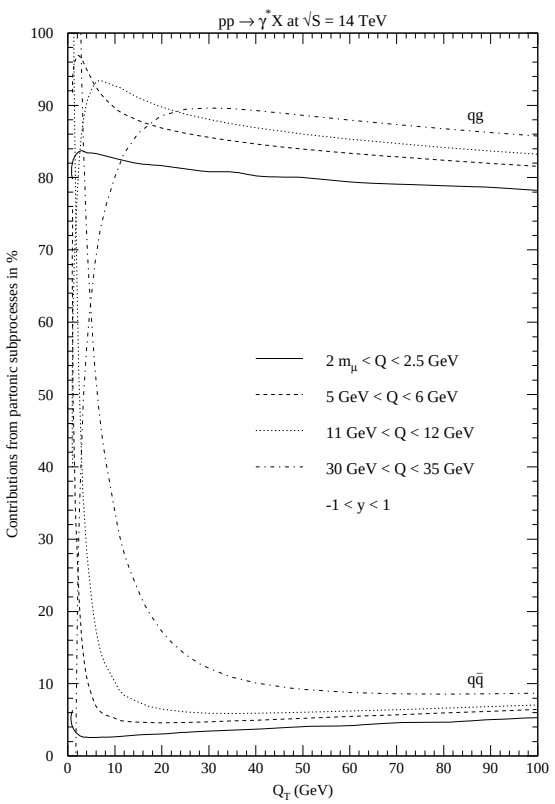

Figure 2. Contributions from the partonic subprocesses qg and $q\bar{q}$ to the invariant cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $pp \to \gamma^* X$ at $\sqrt{S}$ = 14 TeV. The qg channel dominates in the region $Q_T > Q/2$.

the qg subprocess increases somewhat with Q, rising from over 80 % for the lowest values of Q to about 90 % at its maximum for $Q \simeq 30$ GeV. Subprocesses other than those initiated by the $q\bar{q}$ and qg initial channels are of negligible import.

The full uncertainty in the gluon density is not known. We estimate the sensitivity of LHC experiments to the gluon density in the proton from the variation of different recent parametrizations. We choose the latest global fit by the CTEQ collaboration (5M) as our point of reference [3] and compare results to those based on their preceding analysis (4M[7]) and on a fit with a higher gluon density (5HJ) intended to describe the CDF and D0 jet data at large transverse momentum. We also compare to results based on global fits by MRST [2], who provide three different sets with a central, higher, and lower gluon density, and to GRV98 [9][1].

In Fig. 3 we plot the cross section for lepton pairs with mass between the between $Q_T = 50$ and 100 GeV ($x_T = 0.007 \ldots 0.014$). For the CTEQ parametrizations we find that the cross section increases from 4M to 5M by 5 % and does not change from 5M to 5HJ in the whole Q_T-range. The largest differences from CTEQ5M are obtained with GRV98 (minus 18 %).

The theoretical uncertainty in the cross section can be estimated by varying the renormalization and factorization scale $\mu = \mu_f$ about the central value $\sqrt{Q^2 + Q_T^2}$. In the region between the J/ψ and Υ resonances, the cross section drops from $\pm 39\%$ (LO) to $\pm 16\%$ (NLO) when μ is varied over the interval interval $0.5 < \mu/\sqrt{Q^2 + Q_T^2} < 2$. The K-factor ratio (NLO/LO) is approximately 1.3 at $\mu/\sqrt{Q^2 + Q_T^2} = 1$.

We conclude that the hadroproduction of low mass lepton pairs is an advantageous source of information on the parametrization and size of the gluon density. With the design luminosity of the LHC, regions of $x_T \simeq 0.014$ should be accessible. The theoretical uncertainty has been estimated from the scale dependence of the cross sections and found to be small at NLO QCD.

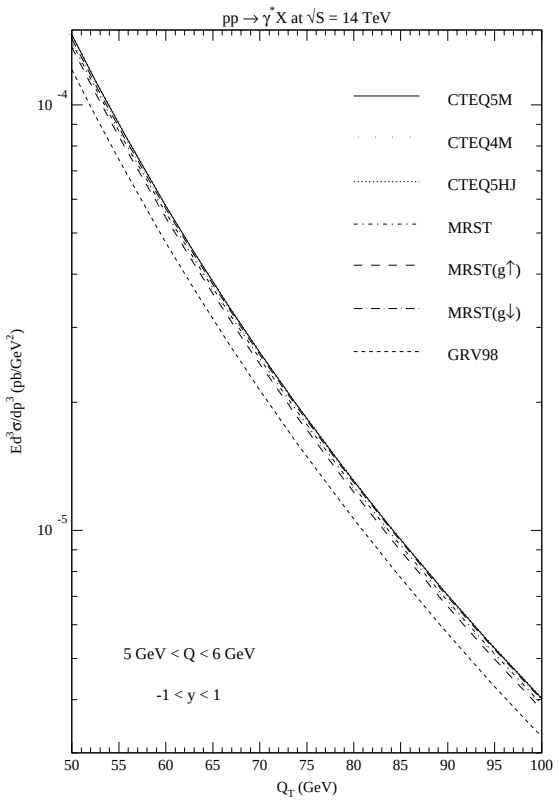

Figure 3. Invariant cross section $Ed^3\sigma/dp^3$ as a function of Q_T for $pp \to \gamma^* X$ at $\sqrt{S} = 14$ TeV in the region between the J/ψ and Υ resonances. The largest differences from CTEQ5M are obtained with GRV98 (minus 18 %).

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[1] In this set a purely perturbative generation of heavy flavors (charm and bottom) is assumed. Since we are working in a massless approach, we resort to the GRV92 parametrization for the charm contribution [10] and assume the bottom contribution to be negligible.