QCD CORRECTIONS TO SINGLE TOP QUARK AND W BOSON PRODUCTION AT HERA

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We review theoretical results on QCD corrections to flavour changing neutral current single top as well as single W boson production at HERA. In both cases the inclusion of QCD corrections has a moderate effect on the size of the cross sections but reduces the QCD scale dependence considerably. This writeup summarizes a talk given at the Ringberg Workshop "New Trends in HERA Physics 2003".

1. Introduction

At HERA, 27.5GeV electrons collide with 920GeV protons allowing on the one hand for precise studies of the proton structure and associated non-perturbative aspects of QCD, on the other hand for tests of perturbative QCD and the electroweak (EW) standard model (SM) in general.

We review the production of a single top quark in a FCNC reaction and the production of a single W boson in $e^{\pm}p$ collisions at HERA energies. This work is, thus, concerned with phenomenological aspects of the gauge sector (non-abelian contribution to W boson production) and flavour structure (single top production) of the SM as well as aspects of perturbative QCD. Typical momentum transfers of the reactions we consider define scales at which a perturbative treatment of QCD corrections to the leading-order (LO) EW processes is justified. In fact, the inclusion of such corrections is necessary to obtain theoretical predictions for the relevant observables which are of comparable accuracy as the corresponding experimental measurements at HERA.

In a recent search [1] for events with a high-energy isolated electron or muon and missing transverse momentum the H1 collaboration claimed to find an excess of events with transverse momentum of the hadronic system greater than 25GeV. Within the SM, such events are expected to be mainly

due to W boson production with subsequent leptonic decay. It is, thus, important to control the effects of radiative QCD corrections to the LO EW W boson production mechanism within and beyond the SM. A possible explanation of an excess of W boson production events beyond the SM would be the FCNC production of a short-lived top quark decaying into a bottom quark and a W boson.

In section 2, we review a calculation of QCD corrections to FCNC top quark production at HERA in the eikonal approximation as carried out by Belyaev and Kidonakis in [2].

We proceed in section 3 by describing QCD corrections to the W production cross sections at HERA. Section 3.1 is concerned with corrections to the total cross section. We review the corrections to resolved photoproduction as discussed in [3] by Nason, Rückl and Spira. Section 3.2 is devoted to corrections to the W production cross sections differential in the transverse momentum of the W boson p_T and its rapidity y. We discuss next-to-leading order (NLO) QCD corrections to the direct photoproduction part which is the dominant contribution to these distributions. The results of section 3.2 are quoted from [4].

Section 4 contains a short summary and concluding remarks.

2. Soft Gluon Corrections to FCNC Top Production

In [2], FCNC couplings between a top quark t, an up or charm quark q and a photon ($F^{\mu\nu}$ is the corresponding field strength tensor) are introduced through the effective Lagrangian

$$\Delta\mathcal{L}^{\text{eff}} = \frac{1}{\Lambda}\kappa_{tq\gamma}e\bar{t}\sigma_{\mu\nu}qF^{\mu\nu} + \text{h.c.}, \tag{1}$$

where Λ is a dimensionful scale parameter. Clearly, HERA should be quite sensitive to $\kappa_{tu\gamma}$ through the partonic process $e^{\pm}u \to e^{\pm}t$.

To reduce the theoretical error in the determination of bounds for $\kappa_{tu\gamma}$, the authors of [2] consider gluonic quantum corrections to the LO EW process. They argue, that since the top quark is very heavy top production at HERA occurs — if at all — mostly close to threshold and that in this regime the eikonal approximation suffices to describe first-order QCD effects.

Fig. 1 is reproduced from [2] and shows the dependence of the Born, one loop and Born plus one loop cross section on the renormalization and factorization scale $\mu = \mu_R = \mu_F$. The parton densities were implemented in the CTEQ5M [5] parameterization and the numerical input parameters

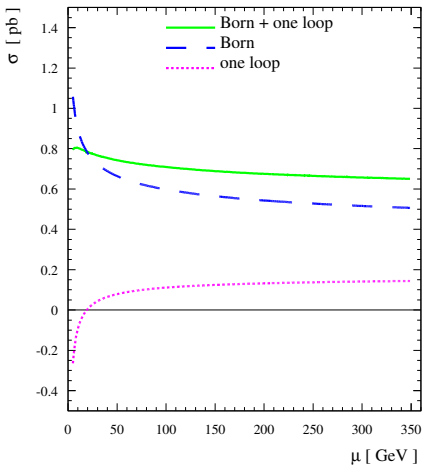

Figure 1. Born, one loop, and Born plus one loop cross section as a function of the QCD scale $\mu = \mu_R = \mu_F$ for FCNC single top quark production at HERA with $m_t = 175\text{GeV}$ and $\kappa_{tu\gamma} = 0.1$ for $\sqrt{S} = 318\text{GeV}$.

were set to

$$\sqrt{S} = 318\text{GeV}, \quad \Lambda = m_t = 175\text{GeV}, \quad \kappa_{tu\gamma} = 0.1.$$

Fig. 1 shows that above $\mu = 10\text{GeV}$ the inclusion of NLO QCD corrections in the eikonal approximation leads to a significant stabilization of the total cross section with respect to simultaneous variation of the renormalization and factorization scale. It can also be inferred that $\mu = m_t = 175\text{GeV}$ as central value for the QCD scale is a sensible choice, unlike $\mu = Q = \sqrt{-(p_e - p_{e'})^2}$, which would lead to significant contributions from very low Q values of the order of m_e where the parton density functions are not well-defined.

In Fig. 2, the Born, one loop and Born plus one loop cross sections are plotted as a function of a) the top mass and b) the centre-of-mass energy. The QCD scale μ is set to its central value m_t and $\kappa_{tu\gamma}$ is chosen as above. A strong dependence of the cross sections on the top mass and CM energy is observed. Indeed, a variation of m_t by $\pm 5\%$ leads to roughly 20% uncertainty in the cross section, a 6% increase in CM energy causes an increase of the cross section by 40%.

Analyses of FCNC single top production from an initial state u quark at HERA have been carried out taking into account the results of [2] discussed

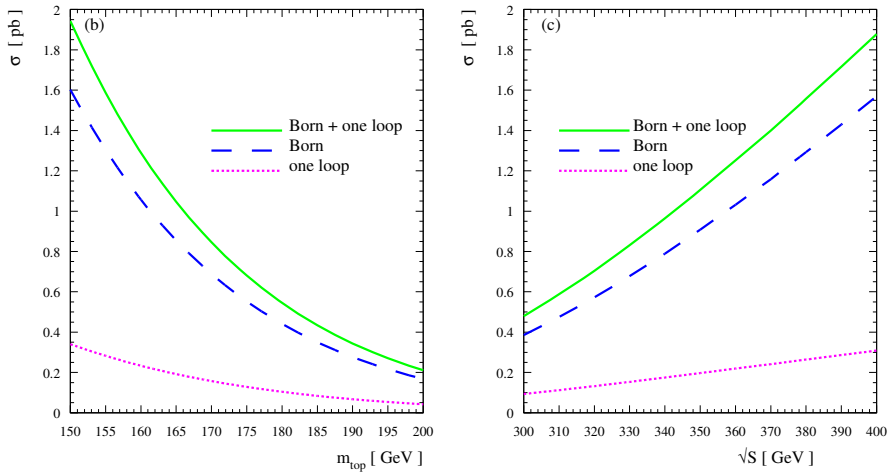

Figure 2. Born, one loop, and Born plus one loop cross section for the FCNC single top quark production at HERA with $\mu = \mu_R = \mu_F = m_t$ and $\kappa_{tu\gamma} = 0.1$ versus (a) the top quark mass with $\sqrt{S} = 318$GeV and (b) the CM energy with $m_t = 175$GeV.

above. The ZEUS collaboration found $\kappa_{tu\gamma} < 0.174$ [6], the H1 collaboration established $\kappa_{tu\gamma} < 0.27$ [7], both at the 95% confidence level.

3. NLO QCD Corrections to W Boson Production

There are three different mechanisms of W boson production in $e^{\pm}p$ collisions:

(1) The deep-inelastic regime defined by the kinematical condition that $Q^2 = -(p_e - p_{e'})^2 > Q^2_{\rm cut}$ and that the hadronic cross section can be written

$$\sigma_{ep} = \hat{\sigma}_{eq} \otimes f_p^q,$$

with the quark density in the proton f_p^q and "$\otimes$" indicating a convolution.

(2) The photoproduction region with $Q^2 = -(p_e - p_{e'})^2 < Q^2_{\rm cut}$ where a further distinction is made between

(a) direct photoproduction with an initial state photon instead of the electron in the partonic subprocess, i.e.,

$$\sigma_{ep} = \hat{\sigma}_{\gamma q} \otimes f_p^q \otimes f_e^{\gamma},$$

where f_e^γ is given by the Weizsäcker–Williams spectrum and

(b) resolved photoproduction where the initial state photon is split into a $q, \bar{q}$ pair and the photon in the initial state of the partonic subprocess is thus replaced by a (anti) quark:

$$\sigma_{ep} = \hat{\sigma}_{\bar{q}q} \otimes f_p^q \otimes f_e^\gamma \otimes f_\gamma^{\bar{q}}.$$

Which of the production mechanisms is dominant depends to a large extent on whether we consider total or differential cross sections. At lowest order there is no contribution from resolved photoproduction to the p_T distribution of the W as the partonic process in this case is $2 \to 1$ with vanishing p_T in the final state. The resolved contributions to the total cross section are, however, quite significant and we shall thus proceed by reviewing the total and differential W boson production cross sections separately.

3.1. *Corrections to the Total Cross Section*

In [3], Nason, Rückl and Spira showed that resolved photoproduction is the dominant contribution to the LO total W boson production cross section in $e^\pm p$ collisions. It contributes about 60%, while direct photoproduction and deep-inelastic scattering account for roughly 15% and 25%, respectively. Their analysis of QCD quantum corrections was, thus, confined to the resolved part.

Fig. 3 shows the dependence of the total cross section for $W^\pm$ production with subsequent muonic decay on the QCD renormalization and factorization scale $\mu = \mu_R = \mu_F$. The plots are reproduced from [3] with CTEQ4M [8] and ACFGP [9] parton densities for the proton and the photon, respectively. The calculation was carried out in the $\overline{\text{MS}}$ scheme using an NLO strong coupling constant with $\Lambda_5 = 202$MeV and an angular cut of 5° (instead of a fixed Q^2_{cut}) to separate photoproduction from deep inelastic scattering (DIS). At $\mu = M_W$, the QCD corrections enhance the resolved contribution by about 40%. It can be observed that the scale dependence in the sum of direct and resolved contributions is significantly reduced, once the NLO corrections to the resolved part are included. The full curves show the total sum of NLO resolved, LO direct and LO DIS contribution, which is the prediction of [3] for the total $W^\pm$ production cross sections. The residual scale dependence is about 5%. Since the remaining dependence on Q^2_{cut} is of similar size, Nason, Rückl and Spira estimate the total theoretical uncertainty to be less than about 10%.

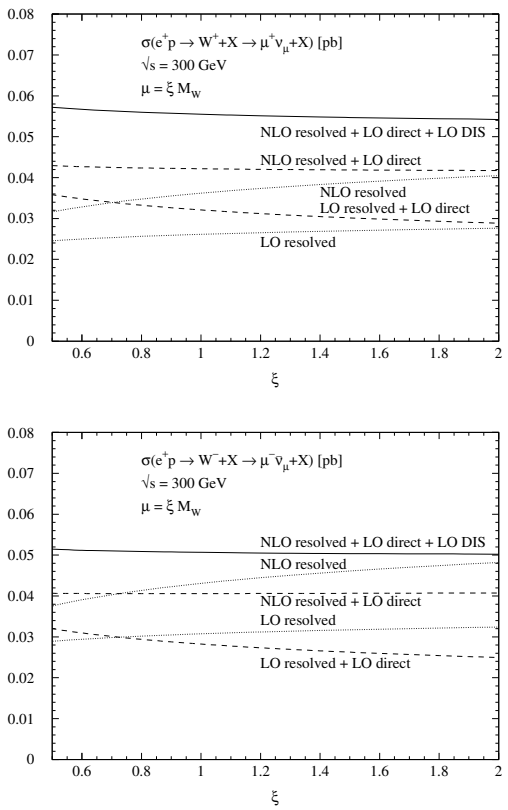

Figure 3. Dependence of the individual contributions to W^+ (up) and W^- (down) production with subsequent muonic decay on the renormalization and factorization scale $\mu = \mu_R = \mu_F = \xi M_W$. The full curves represent the final predictions for the total cross section of $W^\pm$ production in e^+p collisions.

3.2. *Corrections to the Differential Cross Section*

We proceed with the discussion of QCD quantum corrections to the doubly and singly differential W boson production cross sections $\mathrm{d}^2\sigma/\mathrm{d}y\mathrm{d}p_T$ and $\mathrm{d}\sigma/\mathrm{d}p_T$ as discussed in [4]. As pointed out there, the resolved contribution to the p_T distribution is negligible for $p_T > 15\mathrm{GeV}$. Instead, direct photoproduction is the dominant mechanism whereas deep-inelastic scattering is smaller but comparable. Thus, the authors of [4] confined the discussion of QCD corrected differential cross section distributions to the case of direct photoproduction. Events with one jet in the final state in

addition to the W boson are distinguished from events with two final state jets by requiring that their cones of size $R = 1$ defined by an inclusive k_T algorithm do not overlap and that both partons have a transverse energy of more than 5GeV. All other configurations (especially with LO kinematics) define one-jet events.

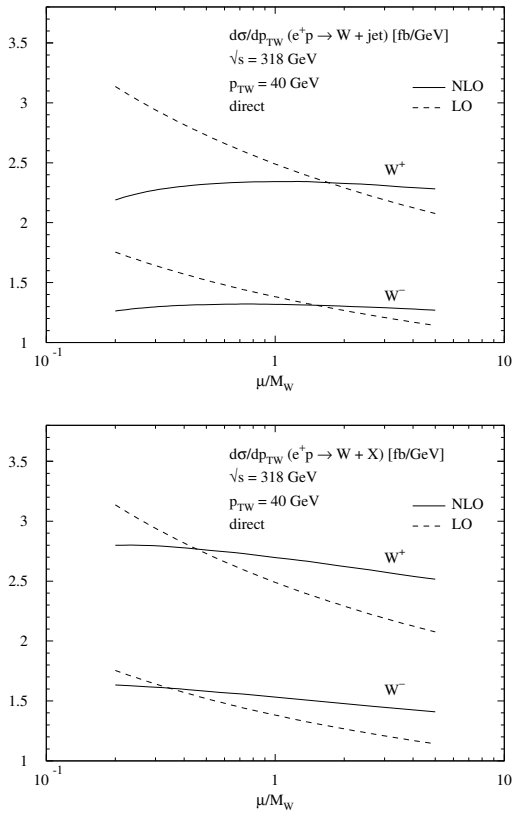

Figure 4. Dependence of the direct contribution to the W production cross section on the renormalization and factorization scale $\mu = \mu_R = \mu_F = \xi M_W$ for $p_T = 40$GeV. The full curves represent the NLO predictions and the broken curves the LO scale dependences. The upper plot presents $W + 1$jet production, the lower one presents the sum of $W + 1$jet plus $W + 2$jets.

To estimate the theoretical uncertainties, the QCD scale dependence of the direct contributions to the processes $e^+p \to W^\pm + X$ is presented in Fig. 4. The scale dependence is significantly smaller, once the NLO

corrections are included. The residual scale dependence is reduced from about 20% down to around 5%. The plots of Fig. 4 clearly indicate that the NLO QCD corrections are small at the central value of the QCD scale m_W. Since the uncertainties of the parton densities are of similar size, the total theoretical uncertainty can be estimated to be less than about 10%.

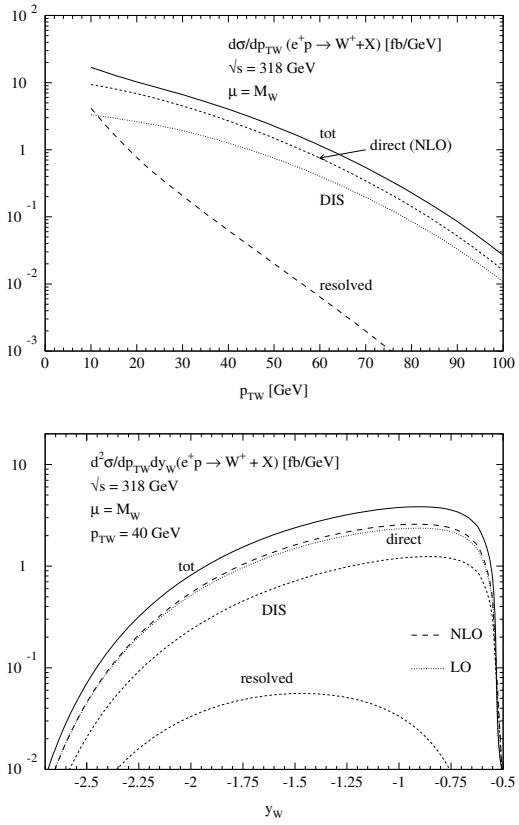

Figure 5. Shown are the transverse momentum distributions (up), and rapidity distribution (down) at $p_T = 40$GeV of W^+ bosons at HERA. The full curves show the total distributions including the NLO corrections to the direct contribution, while the broken lines exhibit the individual parts at LO and the direct part at NLO.

Fig. 5 depicts the transverse momentum (up) as well as rapidity (down) distribution of W^+ bosons produced at HERA with $\sqrt{S} = 318$GeV.

The upper plot clearly demonstrates the dominance of the direct photoproduction part, while the DIS part is smaller but still relevant. The

resolved photoproduction part can safely be neglected for p_T values larger than about 10–15GeV. The rising total sum at p_T values below about 15GeV signals the breakdown of the purely perturbative results and underlines the necessity of a soft gluon resummation to describe W boson production for smaller transverse momenta which, however, is beyond the scope of [4].

The rapidity distribution of W^+ boson production at HERA for $p_T = 40$GeV is presented in the lower plot of Fig. 5 for the individual production mechanisms. The direct photoproduction part is shown at LO and NLO. As in the case of the transverse momentum distribution, the QCD corrections to the direct contribution amount to less than about 10–15% and are, thus, of moderate size. The figure shows that W bosons are preferably produced at larger rapidity values.

4. Conclusions

We have reviewed FCNC single top quark as well as single W boson production at HERA.

As the authors of [2] could show, the inclusion of lowest-order QCD quantum effect in the eikonal approximation leads to a stabilization of the FCNC single top production cross section with respect to variation of the renormalization and factorization scales. The stabilization is most pronounced for $10\text{GeV} < \mu_R = \mu_F < 75\text{GeV}$. For $\mu_R = \mu_F = m_t$ QCD quantum effects lead to a 25% increase in cross section, rendering reliable control of the radiative corrections an indispensable prerequisite for a precise determination of FCNC couplings.

There are several competing mechanisms to produce W bosons at HERA. The most important contributions to the total cross section stem from resolved photons, whereas the transverse momentum and rapidity distributions (for finite p_T) are dominated by direct photoproduction.

In their analysis of the dominant resolved part the authors of [3] found that QCD corrections enhance the total W production cross section by about 40% while reducing the dependence on the renormalization and factorization scale to 5%. The total remaining theoretical uncertainty is estimated to be smaller than 10%.

Direct photoproduction is the dominant contribution to distributions of the W production cross section in (W) transverse momentum and rapidity. The lowest-order QCD radiative corrections constitute a $\pm$10–15% effect and reduce the renormalization and factorization scale dependence to about

5%. The total theoretical uncertainty is estimated to be roughly 10%.

We remark that neither anomalous top quark production (with subsequent decay into a W boson and a b quark) nor higher-order QCD corrections to W boson production within the SM can explain the lepton flavour asymmetry in the excess of isolated single lepton events as observed in [1].

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Note Added in Proof

Meanwhile, the soft-gluonic corrections to FCNC single top production at HERA (and the Tevatron) have been evaluated up to next-to-next-to-leading order level [10]. The authors observe a further stabilization of the cross section with respect to variations of the QCD scale in comparison to the NLO order soft gluon-corrected result.

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