HEAVY QUARK PRODUCTION AND NON-LINEAR GLUON EVOLUTION AT THE LHC *

KRISZTIAN PETERS
School of Physics & Astronomy, University of Manchester
Manchester, M13 9PL, UK
E-mail: petersk@fnal.gov

We investigate the importance of unitarity corrections to parton evolution in heavy flavor production at the LHC. The gluon distribution is determined with a fit to HERA data applying a unified BFKL-DGLAP approach, in which the non-linear evolution is described by the Balitsky-Kovchegov equation. First we estimate $b\bar{b}$ production at CDF and D0. Then, cross sections for heavy quark production at various LHC experiments are estimated, tracing the impact of the unitarity corrections.

1. Non-linear gluon evolution

HERA measurements found a steep power-like growth of the gluon density with decreasing $x$ which would lead to a violation of unitarity at very small $x$ values. The steep growth has to be tamed by gluon rescattering, corresponding to non-linear effects in the gluon density evolution.

The standard framework to determine parton evolution is the collinear DGLAP formalism. It works rather well for inclusive quantities but, for more exclusive processes, the $k_t$-factorization scheme is more appropriate because both the longitudinal and transverse components of the gluon momenta are considered. In this framework, the process-independent quantity is the unintegrated gluon distribution, connected to the process-dependent hard matrix element via the $k_t$-factorization theorem. Linear evolution of the unintegrated gluon distribution may be described by one of the small $x$ evolution equations using the $k_t$-factorization scheme, the BFKL and CCFM equations. These equations are based on resummation of large logarithmic pQCD corrections, $\alpha_s^n \ln^m(1/x)$, and are equivalent at the leading

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logarithmic level.

The very small $x$ kinematic region is also the regime where the growth of the gluon density must be tamed in order to preserve unitarity. Recently, a successful description of unitarity corrections to DIS was derived within the color dipole formulation of QCD. This is the Balitsky-Kovchegov (BK) equation\textsuperscript{3,4} which describes the BFKL evolution of the gluon in a large target, including a non-linear term corresponding to gluon recombination at high density.

In our analysis, we determine the unintegrated gluon distribution from the BK equation unified with the DGLAP equation following KMS (Kwieciński, Martin and Staśto)\textsuperscript{5,6,7,8}. We use the abbreviation KKMS (Kutak, Kwieciński, Martin and Staśto)\textsuperscript{7,8} for the unified non-linear equation. The linear part of this equation is given by the BFKL kernel with subleading $\ln(1/x)$ corrections, supplemented by the non-singular parts of the DGLAP splitting functions. Thus resummation of both the leading $\ln Q^2$ and $\ln(1/x)$ terms are achieved. The subleading terms in $\ln(1/x)$ are approximated by the so-called consistency constraint and the running coupling constant. The non-linear part is taken directly from the BK equation, ensuring that the unitarity constraints are preserved. One expects that this framework provides a more reliable description of the gluon evolution at extremely small $x$, where $\ln(1/x) \gg 1$ and the unitarity corrections are important, than does DGLAP.

The size of the dense gluon system inside the proton is assumed to be $R = 2.8$ GeV\textsuperscript{−1}, in accord with the diffractive slope, $B_d \simeq 4$ GeV\textsuperscript{−2}, of the elastic $J/\psi$ photoproduction cross section at HERA. In this process, the impact parameter profile of the proton defines the $t$ dependence of the elastic cross section, $B_d \simeq R^2/2$, by Fourier transform.

2. Constraints from HERA and cross checks at the Tevatron

The initial distribution was obtained by fitting the HERA $F_2$ measurements\textsuperscript{9,10} using the Monte Carlo CASCADE\textsuperscript{11,12} for evolution and convolution with the off-shell matrix elements. The fits were repeated both with the standard KMS evolution without the non-linear contribution and with extended KMS evolution including the non-linear part. The predicted $F_2$ is equivalent for both linear and non-linear evolution.

Next, this constrained gluon density was used to calculate the charm structure function $F_2^c$ at HERA and $gg \to b\bar{b}$ production at the Tevatron as
Figure 1. Bottom production, measured by CDF, is compared to predictions using CASCADE with linear and non-linear KKMS evolution. (a) The $p_T$ distribution of $B$ meson decays to $J/\psi$. (b) The azimuthal angle, $\Delta \phi$, distribution of $b\bar{b}$ pair production smeared by the experimental resolution.

A cross-check of the fit and the evolution formalism. We use $m_c = 1.4$ GeV, $m_b = 4.75$ GeV and a renormalization scale in $\alpha_s$ of $Q^2 = 4m^2_q + p_T^2$. Sudakov Form Factor is included in the calculation. The predicted cross section was then compared to both H1 $^{13}$, Zeus $^{14}$ and CDF $^{15,16}$, D0 $^{17}$ measurements respectively. The predictions agree reasonably well with the data.

As an example of these cross-checks, in Fig. 1(a) the cross section for $B$ decays to $J/\psi$ is shown as a function the $J/\psi$ $p_T$ $^{15,16}$. The KKMS gluon density fits the data both in the linear and non-linear scenarios with a comparable accuracy to the NLO collinear approach $^{18}$.

In Fig. 1(b), the azimuthal angle distribution between the $b$ and $\bar{b}$ quarks, $\Delta \phi$, is given. The $\Delta \phi$ and $b\bar{b}$ $p_T$ distributions are correlated since $\Delta \phi < 180^\circ$ corresponds to higher pair $p_T$. Since the $k_T$-factorization formula allows the incoming gluons to have sizable transverse momenta, the calculated $\Delta \phi$ distribution agrees very well with the data for $\Delta \phi > 60^\circ$ with only smearing due to the experimental resolution. It is interesting to note that the inclusion of the Sudakov From Factor improves the description significantly. For a comparison, we also plotted the result as obtained without the Sudakov Form Factor (dotted line). The enhancement of the data relative to the calculations at low $\Delta \phi$ requires further study.
3. Heavy quark production at the LHC

Since the Tevatron measurements are well described using the unintegrated parton densities constrained by HERA and convoluted with the off-shell matrix elements, the same approach may be used for heavy quark production at the LHC at e.g. \( \sqrt{s} = 14 \text{ TeV} \). As discussed previously, heavy quark production at this energy is already in the region where saturation effects may be relevant.

We computed heavy quark cross sections for various kinematical regions of the LHC. In Fig. 2(a), the \( b\bar{b} \) production cross section is computed within the ATLAS and CMS acceptance (\( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.5 \) for both the \( b \) and \( \bar{b} \) quarks). In Fig. 2(b), the same cross section is computed within the LHCb acceptance where the \( b \) quark \( p_T \) can be measured to 2 GeV for \( 1.9 < \eta < 4.9 \). Similarly, we investigated \( c\bar{c} \) production at ALICE, Fig. 2(c). In ALICE, it will be possible to measure the \( D^0 \) down to \( p_T \sim 0.5 \text{ GeV} \) in \( |\eta| < 0.9 \). In the computations the same quark masses and scale was used as described in the previous section.

In all three cases the results of the linear evolution (solid line) and the results of the non-linear evolution (dashed line) are very similar. There is no significant effect observable for non-linear evolution due to gluon saturation. For \( c\bar{c} \) production at ALICE saturation effects have been predicted \(^{20}\) within the GLR approach \(^{19}\) in the collinear limit (even with a larger saturation radius). This result \(^{20}\) could not be confirmed with our calculations.

Figure 2. (a) and (b) show \( b\bar{b} \) production as a function of pair \( p_T \) in the ATLAS/CMS (a) and the LHCb acceptance (b). The \( D^0 \) meson \( p_T \) distribution in the ALICE acceptance is shown in (c).
The presented results, Fig. 2, suggests that linear gluon evolution and \( k_T \)-factorization can safely be applied in the discussed kinematical regions of the LHC.

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References

1. L. N. Lipatov, *Sov. J. Nucl. Phys.* 23 (1976) 338;
   E. A. Kuraev, L. N. Lipatov and V. S. Fadin, *Sov. Phys. JETP* 45 (1977) 199;
   I. I. Balitsky and L. N. Lipatov, *Sov. J. Nucl. Phys.* 28 (1978) 338
2. M. Ciafaloni, *Nucl. Phys.* B 296 (1988) 49; S. Catani, F. Fiorani and G. Marchesini, *Phys. Lett.* B 234 (1990) 339; S. Catani, F. Fiorani and G. Marchesini, *Nucl. Phys.* B 336 (1990) 18; G. Marchesini, *Nucl. Phys.* B 445 (1995) 49
3. I. I. Balitsky, *Nucl. Phys.* B463 (1996) 99; *Phys. Rev. Lett.* 81 (1998) 2024;
   *Phys. Rev. D* 60 (1999) 014020; *Phys. Lett.* B518 (2001) 235
4. Yu. V. Kovchegov, *Phys. Rev.* D60 (1999) 034008
5. J. Kwiecinski, A. D. Martin and A. M. Stasto, *Phys. Rev.* D 56, (1997) 3991
6. M. A. Kimber, J. Kwiecinski and A. D. Martin, *Phys. Lett.* B 508 (2001) 58
7. K. Kutak and J. Kwiecinski, *Eur. Phys. J.* C 29 (2003) 521
8. K. Kutak and A. M. Stasto, *Eur. Phys. J.* C 41 (2005) 343
9. S. Aid et al. [H1 Collaboration], *Nucl. Phys.* B 470 (1996) 3
10. M. Derrick et al. [ZEUS Collaboration], *Z. Phys.* C 69 (1996) 607
11. H. Jung, *Comput. Phys. Commun.* 143 (2002) 100
12. H. Jung and G. P. Salam, *Eur. Phys. J.* C 19 (2001) 351
13. C. Adloff et al. [H1 Collaboration], *Phys. Lett.* B 528 (2002) 199
14. J. Breitweg et al. [ZEUS Collaboration], *Eur. Phys. J.* C 12 (2000) 35
15. D. Acosta et al. [CDF Collaboration], *Phys. Rev.* D 71 (2005) 032001
16. D. Acosta et al. [CDF Collaboration], *Phys. Rev.* D 71 (2005) 092001
17. B. Abbott et al. [D0 Collaboration], *Phys. Lett.* B 487 (2000) 264
18. M. Cacciari, S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, *JHEP* 07 (2004) 033
19. L. V. Gribov, E. M. Levin and M. G. Ryskin, *Phys. Rept.* 100 (1983) 1
20. A. Dainese, R. Vogt, M. Bondila, K. J. Eskola and V. J. Kolhinen, *J. Phys.* G 30 (2004) 1787