The FMNR⊗PYTHIA interface for Heavy Quark production at HERA

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Abstract.
A method to calculate heavy flavor visible-level cross sections at Next-to-Leading Order (NLO) in Quantum Chromodynamics (QCD), based on an interface of the FMNR program to \textsc{Pythia}, is described. It uses the NLO prediction at quark level provided by FMNR, with a statistical reduction procedure (REDSTAT) that allows a link to \textsc{Pythia} 6.2 to be made, from where the description of the full hadron fragmentation and decay chain is obtained. The method is applied to $e^+p \to b\bar{b}X \to D^*X$ and $\mu^{+}\mu^{-}X$ final states at HERA. Comparisons of the data and NLO cross sections at visible and $b$-quark level were found to be consistent.

1. Introduction
Several heavy flavour production channels have been studied in $e^p$ collisions at HERA by the H1 and ZEUS experiments and compared to NLO QCD predictions based on the FMNR [1] massive fixed order calculations. These calculations are the only ones available at NLO which include a fully differential description of the parton-level final states. For final states with correlated cuts on several final particles, such as in [2, 3], this was not available. One solution is the MC@NLO approach [4] – already implemented for the LHC and Tevatron – which is not yet available for HERA. The alternative discussed here is an interface of the FMNR program to \textsc{Pythia}.

2. The FMNR⊗PYTHIA Interface
The implementation of the interface of the FMNR parton-level predictions to the fragmentation and decay chain from \textsc{Pythia}/JETSET is a two-step process. The first step of this FMNR⊗PYTHIA interface consists in the application of the REDSTAT [5] extension to the FMNR program. REDSTAT is used to transform FMNR into an effective Monte Carlo-like parton-level event generator, through the combination of events with similar kinematics and a sampling approach. The events obtained this way are written to an output file. In the second step, these events are read back into the \textsc{Pythia} 6.2 program through the “Les Houches accord” user interface. At this stage, a “reasonable” (i.e. physically possible) colour flow is assigned to each FMNR parton level process. FMNR does not provide this information, which is needed in the case of string fragmentation. The initial state partons are allowed to have an intrinsic $k_T$ (typically $\sim 300$ MeV) as implemented in \textsc{Pythia}. Parton showering is not allowed in order to avoid double counting of higher order contributions.
For the fragmentation of $b$-quarks the Peterson formula with $\epsilon = 0.0035$ is used for convenience. Three approaches have been considered:

- Independent fragmentation in the PYTHIA model, within FMNR$\otimes$PYTHIA.
  This is used because FMNR does not provide color connections on an event-to-event basis, and color connections are not required in this model.

- Fragmentation in the Lund string model, within FMNR$\otimes$PYTHIA.
  For this, reasonable color connections have to be associated to each FMNR event.

- Independent fragmentation scheme as provided in the context of the original FMNR.
  This implies setting the $B$-hadron momentum equal to the $b$-quark momentum before reducing it according to the Peterson formula. This neglects threshold corrections due to the need of simultaneous conservation of energy and momentum.

In the first two cases, the fragmentation, decay tables and kinematics as implemented in PYTHIA 6.2/JETSET are used to obtain a hadron-level event. Therefore, non-dominant arbitrarily complicated decays are automatically included. The branching ratios were empirically corrected at analysis level to correspond to those obtained from the Particle Data Group [6].

### 3. Applications

#### 3.1. The $ep \rightarrow bbX \rightarrow D^+\mu X'$ channel

The cross section for inclusive beauty production $ep \rightarrow bbX \rightarrow D^+\mu X'$ in the kinematic range $p_T^{D^+} > 1.9$ GeV, $-1.5 < \eta^{D^+} < 1.5$, $p_T^\mu > 1.4$ GeV and $-1.75 < \eta^\mu < 1.3$ was measured to be [2]: $\sigma_{vis} = 160 \pm 37\text{(stat.)}^{+30}_{-57}\text{(syst.)}$ pb. This is larger than, but still compatible with, the corresponding FMNR$\otimes$PYTHIA NLO prediction of $\sigma^{\text{NLO}}_{vis} = 67^{+20}_{-11}(\text{NLO})^{+13}_{-9}(\text{frag.} \oplus \text{br.})$ pb, where the first error refers to the uncertainties of the FMNR parton level calculation, and the second error refers to the uncertainties related to fragmentation and decay.

Strictly speaking, the FMNR predictions are only valid for the photoproduction regime. Here, the Weizsäcker-Williams (WW) approximation with an effective $Q^2_{\max} < 25$ GeV$^2$ cutoff was used to include the $\sim 15\%$ DIS contribution for a combined cross section. This NLO QCD prediction is also listed in Table 1. A cross section for the same kinematic range, but adding

| cross-section | measured | NLO QCD | ratio |
|---------------|----------|---------|-------|
| Visible inclusive | 160 ± 37$^{+30}_{-57}$ pb | 67$^{+24}_{-14}$ pb | 2.4$^{+0.9}_{-0.8}$ |
| $\gamma p$ | 115 ± 29$^{+27}_{-31}$ pb | 54$^{+18}_{-12}$ pb | 2.1$^{+0.9}_{-1.0}$ |
| b level $\gamma p$ | 11.9 ± 2.9$^{+1.8}_{-3.3}$ nb | 5.8$^{+2.1}_{-1.3}$ nb | 2.0$^{+0.8}_{-1.1}$ |

a photoproduction requirement ($Q^2 < 1$ GeV$^2$, $0.05 < y < 0.085$) was also obtained. The result, as well as the corresponding FMNR$\otimes$PYTHIA prediction, are shown in Table 1. As in the inclusive case, the prediction underestimates the measured cross section, but is compatible with the measurement within the large errors.

Finally, these measured visible-level cross sections were extrapolated to $b$-quark level using PYTHIA. The NLO QCD prediction can then be obtained at parton level directly from the original FMNR calculation. From the comparison of the ratios at visible and $b$-quark level in Table 1, one can conclude that the PYTHIA extrapolation was reliable.
Table 2. Comparison of measured and predicted dimuon cross-sections.

| cross-section | measured (prel.) | NLO QCD | ratio |
|---------------|-----------------|---------|-------|
| Visible Total | $63 \pm 7^{+20}_{-18}$ pb | $30^{+9}_{-6}$ pb | $2.1^{+0.8}_{-1.0}$ |

3.2. The $ep \rightarrow b\bar{b}X \rightarrow \mu^+\mu^- X'$ channel

The measured visible cross-section compared to the NLO prediction from FMNR$\otimes$PYTHIA is shown in Table 2. Here, as in the case of the $D^*\mu$ channel, the cross-section comparisons are consistent. The differential cross-sections are shown in Figures 1 and 2.

![Figure 1. Differential cross-section $d\sigma/d\Delta\phi$](image1)

![Figure 2. Differential cross-section $d\sigma/d\eta$](image2)

4. Conclusions

The FMNR$\otimes$PYTHIA interface provides heavy flavour cross-section predictions for channels with complex final states for which NLO QCD predictions are not easily obtained from simple extensions to parton level calculations.

In the $ep \rightarrow b\bar{b}X \rightarrow D^*\mu X'$ and $\mu^+\mu^- X'$ channels, both at visible and quark level, the measured data at ZEUS exceed the FMNR$\otimes$PYTHIA NLO prediction, but are compatible within the errors. The almost constant data to NLO ratio obtained from the cross sections shows that the extrapolation from visible to quark level, or vice versa, is meaningful and reliable.

References

[1] Frixione S, Nason P, and Ridolphi G 1995 *Nucl. Phys.* B **454** 3 (arXiv:hep-ph/9506226).
[2] S. Chekanov *et al.* [ZEUS Collaboration], 2007 *Eur. Phys. J.* C **50** 299 (arXiv:hep-ex/0609050).
[3] Bloch I 2005 *DESY-Thesis-2005-034* 187pp.
[4] Frixione S and Webber B R 2002 *JHEP* 6 29 (hep-ph/0204244).
[5] Geiser A and Nuncio Quiroz A E 2007 *Preprint* arXiv:0707.1632 [hep-ph].
[6] Yao W M *et al.* 2006 *Particle Data Group, J. Phys. G* **33**, 1