



Deutsches Elektronen-Synchrotron DESY

## DESY Summer Student Programme 2021

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Analysis for  $D^0$  and  $D^{*\pm}$  Production in Deep Inelastic  $ep$  Scattering  
at HERA and Comparison with Experimental Measurements

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## Abstract

Charmed mesons  $D^0$  and  $D^{*\pm}$  production in Deep Inelastic electron-proton Scattering (ep-DIS) is studied, analyzed using Rivet analysis, and Rivet-HERAPDF2 analysis depending on events generated on DESY machine, then compared with real experimental data from HERA.

## Acknowledgement

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# 1 Introduction

For particles' constituents and properties studying, the collision of particles at higher energies reaching 14 TeV such as proton-proton collisions at the LHC in CERN, Switzerland is carried out. Also, nucleon-lepton scattering presented some excellent results [1] like electron-proton deep inelastic scattering at HERA. The validation of theoretical models is verified by comparing theoretical expectations with experimental results, hence the analyses are compared to data to confirm the validity of the analyses made to study  $D^0$  and  $D^*$  production.

## 1.1 HERA Collider

Hadron Electron Ring Accelerator (HERA) [1, 2] is a particle collider that collides electron/positrons of energy  $\approx 27.6$  GeV with 920 GeV for protons and with  $\sqrt{s} \approx 320$  GeV. HERA started in 1992 and shutdown in 2007.

HERA collider is composed of four experiments: H1, HERA-B, HERMES, and ZEUS. H1 and ZEUS are parts that involve  $ep$  collision at  $\sqrt{s} = 320$  GeV. In H1 charm quarks production is studied at 27.6 GeV with 820 GeV of electron/positron and proton collision.

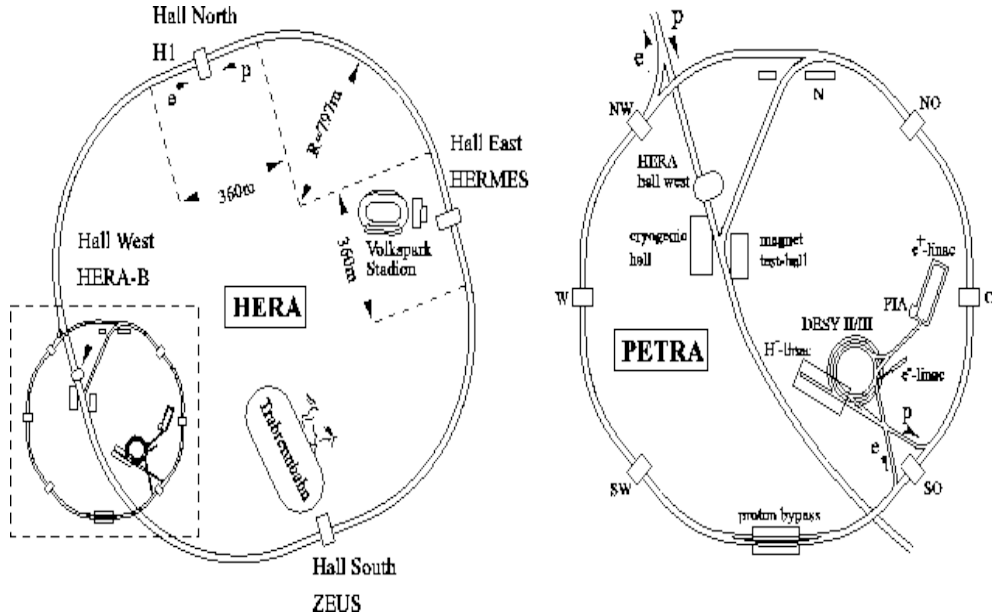


Figure 1: HERA Collider

## 1.2 Electron-Proton Deep Inelastic Scattering

The fusion between the virtual boson (i.e. photon) and the gluon is supposed to be responsible for charm quarks production. As shown in the following Feynman diagram [3], photon ( $\gamma$ ) interacts with gluon ( $g$ ) to produce charm quark and its anti-particle ( $C$ ) and ( $\bar{C}$ ). This process occurs as a result of electron-proton deep inelastic scattering:  $ep \rightarrow eX$ .

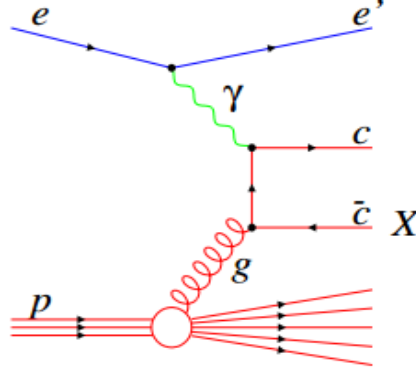


Figure 2:  $ep$  Scattering Feynman Representation and Charm Quarks Production

### 1.2.1 Kinematics of Heavy Quarks Production in DIS

$$Q^2 = 4E_e E'_e \cos^2\left(\frac{\theta_e}{2}\right) \quad (1)$$

$$y = 1 - \frac{E'_e}{E_e} \sin^2\left(\frac{\theta_e}{2}\right) \quad (2)$$

$$x = \frac{Q^2}{ys} \quad (3)$$

$$W^2 = Q^2 \left( \frac{1-x}{x} \right) \quad (4)$$

## 2 Rivet Analysis

Rivet is software that is used for the validation of event generators and analyzing the events produced through C++ programming.

### 2.1 H1\_1996\_I421055.cc File

This File is responsible for the analysis code that will be applied to the events' file of  $ep$  scattering. In my case, the following C++ code was used and build on local and DESY machines to get the four histograms in the results and discussion chapter.

```
#include "Rivet/Analysis.hh"
#include "Rivet/Projections/FinalState.hh"
#include "Rivet/Projections/FastJets.hh"
#include "Rivet/Projections/PromptFinalState.hh"
#include "Rivet/Projections/ChargedFinalState.hh"
#include "Rivet/Projections/DISKinematics.hh"
#include "Rivet/Projections/UnstableParticles.hh"

namespace Rivet {

class H1_1996_I421105 : public Analysis {
public:

RIVET_DEFAULT_ANALYSIS_CTOR(H1_1996_I421105);

void init() {

declare(DISKinematics(), "Kinematics");
declare(UnstableParticles(), "UFS");
// Cuts::abspid == PID::DSTARPLUS

const FinalState fs(Cuts::abseta < 4.9);
declare(fs, "FS");

// Book histograms
book(_Nevt_after_cuts, "TMP/Nevt_after_cuts");
book(_Nevt_after_cuts_D0, "TMP/Nevt_after_cuts_D0");
book(_Nevt_after_cuts_Dstar, "TMP/Nevt_after_cuts_Dstar");

book(_h["p_tD*_norm"], 4, 1, 1);
book(_h["p_tD*"], 4, 1, 2);
book(_h["p_tD0_norm"], 5, 1, 1);
book(_h["p_tD0"], 5, 1, 2);
book(_h["x_D*_norm"], 6, 1, 1);
book(_h["x_D*"], 6, 1, 2);
}
```

```

book(_h["x_D0_norm"], 7, 1, 1);
book(_h["x_D0"], 7, 1, 2);
}

/// Perform the per-event analysis
void analyze(const Event& event) {

    const DISKinematics& dk = applyProjection<DISKinematics>(event, "Kinematics");
    const LorentzTransform hcmboost = dk.boostHCM();

    double y = dk.y();
    double Q2 = dk.Q2()/GeV2;
    double W2 = dk.W2()/GeV2;

    bool cut ;
    cut = Q2 > 10 && Q2 < 100 && y > 0.01 && y < 0.7 ;

    if (! cut ) vetoEvent ;

    _Nevt_after_cuts -> fill();

    for (const Particle& p : apply<UnstableParticles>(event, "UFS").particles()) {
        const FourMomentum hcmMom = hcmboost.transform(p.momentum());
        double p_D = std::sqrt( hcmMom.px()*hcmMom.px() + hcmMom.py()*hcmMom.py()
+ hcmMom.pz()*hcmMom.pz() );
        const double x_D = 2.*p_D/sqrt(W2);

        if (p.abspid() == 421) {
            _h["p_tD0"]->fill(p.momentum().pT()/GeV);
            _h["p_tD0_norm"]->fill(p.momentum().pT()/GeV);
            ///cout << " x_D for D0 " << x_D << endl;
            _h["x_D0"]->fill(x_D);
            _h["x_D0_norm"]->fill(x_D);
            _Nevt_after_cuts_D0 -> fill(); }

        else if (p.abspid() == 413) {
            ///cout << " x_D for D* " << x_D << endl;
            _h["p_tD*"]->fill(p.momentum().pT());
            _h["p_tD*_norm"]->fill(p.momentum().pT());
            _h["x_D*"]->fill(x_D);
            _h["x_D*_norm"]->fill(x_D);
            _Nevt_after_cuts_Dstar -> fill(); }

    }
};

void finalize() {
    scale(_h["p_tD*"], crossSection()/nanobarn/sumW());
}

```



```

scale(_h["p_tD0"], crossSection()/nanobarn/sumW());
cout << "_Nevt_Dstar" << dbl(*_Nevt_after_cuts_Dstar) << endl;
scale(_h["p_tD*_norm"], 1.0/ *_Nevt_after_cuts_Dstar);
scale(_h["p_tD0_norm"], 1.0/ *_Nevt_after_cuts_D0);

scale(_h["x_D*"], crossSection()/nanobarn/sumW());
scale(_h["x_D0"], crossSection()/nanobarn/sumW());
cout << "_Nevt_Dstar" << dbl(*_Nevt_after_cuts_Dstar) << endl;
scale(_h["x_D*_norm"], 1.0/ *_Nevt_after_cuts_Dstar);
scale(_h["x_D0_norm"], 1.0/ *_Nevt_after_cuts_D0);  }

map<string, Hist1DPtr> _h;
map<string, Profile1DPtr> _p;
map<string, CounterPtr> _c;
CounterPtr _Nevt_after_cuts;
CounterPtr _Nevt_after_cuts_D0;
CounterPtr _Nevt_after_cuts_Dstar;  };

RIVET_DECLARE_PLUGIN(H1_1996_I421105);

}

```

## 2.2 Histogramming

After applying this code to the events' file, we will have a generated RivetAnalysis.yoda file which is essentially responsible for plotting the histograms. Depending on the generated .yoda file and after running "rivet-mkhtml RivetAnalysis.yoda", histograms will be obtained. The ".plot" file contains all of booked and non-booked histograms; the histogram title, x, and y labels can be edited.

### 3 Results and Discussion

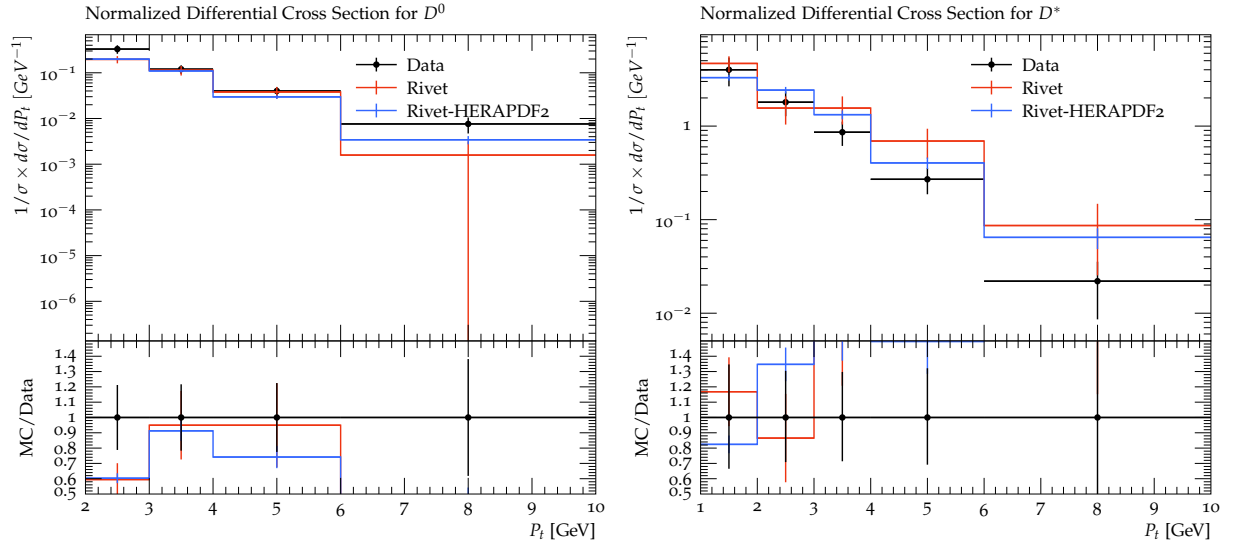
Depending on Rivet and Rivet-HERAPDF2 analyses the production of  $D^0$  and  $D^*$  in DIS is compared with the experimental data from HERA paper [3]. In RIVET analysis tool using 1000 events generated, working on local machine and analysis tool by using 100,000 events generated on DESY machine. The analyses were found to be similar to the data from the paper as shown in Figures 3a, 3b, 4a and 4b.

#### 3.1 Event Selection

The electron beam energy is 27.6 GeV and for proton 820 GeV. For the squared momentum the range was  $10 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$  and with inelasticity of  $0.01 < y < 0.7$ .

#### 3.2 Normalized Differential Cross Section

Figures 3a and 3b represent the normalized differential cross-section distribution  $\frac{1}{\sigma} \times \frac{d\sigma}{dP_t}$  variation with transverse momentum  $P_t$  for  $D^0$  and  $D^*$  production in  $ep$  DIS scattering at HERA.

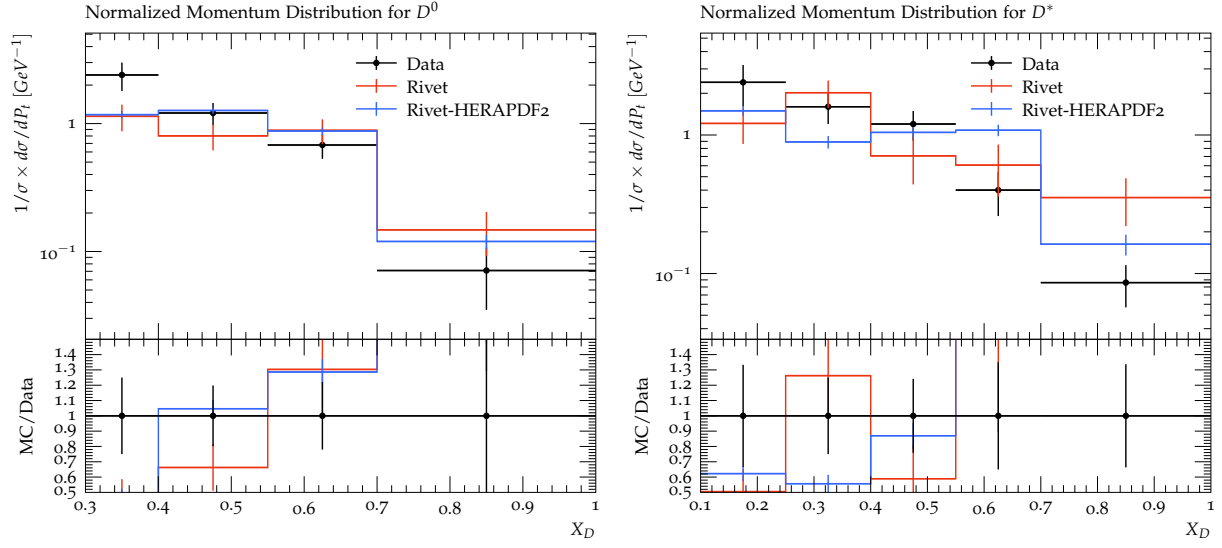


(a) Normalized Differential Cross-Section Distribution for  $D^0$  (b) Normalized Differential Cross-Section Distribution for  $D^*$

Figure 3: A comparison between the Normalized Differential Cross-Section Distribution for  $D^0$  and  $D^*$

### 3.3 Normalized $X_D$ Distribution in DIS

Figures 4a and 4b represent the normalized differential cross-section distribution  $\frac{1}{\sigma} \times \frac{d\sigma}{dP_t}$  variation with the longitudinal momentum  $X_D$  for  $D^0$  and  $D^*$  production in  $ep$  DIS scattering at HERA.



(a) Normalized Momentum Distribution for  $D^0$  (b) Normalized Momentum Distribution for  $D^*$

Figure 4: A comparison between the Normalized Momentum Distribution for  $D^0$  and  $D^*$

## 4 Conclusion

In conclusion, some analyses are performed using Rivet and Rivet-HERAPDF2 with experimental data from the original paper discussing the  $D^0$  and  $D^*$  in deep inelastic scattering at HERA. The analyses were consistent with the real experimental data.

## References

- [1] Halina Abramowicz and Allen C Caldwell. Hera collider physics. *Reviews of Modern Physics*, 71(5):1275, 1999.
- [2] B. Foster. Deep inelastic scattering at hera. *International Journal of Modern Physics A*, 1997.
- [3] Catherine Adloff, S Aid, M Anderson, V Andreev, B Andrieu, R-D Appuhn, C Arndt, A Babaev, J Bähr, J Ban, et al. Inclusive  $d^0$  and  $d^{*\pm}$  production in neutral current deep inelastic ep scattering at hera. *Zeitschrift für Physik C: Particles and Fields*, 72(4):593–605, 1996.