Extraction of top quark mass using single top and top quark pair production at the LHC

Laia Parets Peris, University of Valencia, Spain

Supervisor: Katerina Lipka

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Abstract

In this project, the xFitter open source QCD analysis framework was interfaced to the calculations of single top quark production at NLO in pole mass and $\overline{MS}$ mass schemes. As an example of possible analysis, the top quark mass is extracted for the first time using the measured cross section of single top production in t-channel at the LHC.

Contents

1 Introduction

The top quark is the heaviest elementary particle in the Standard Model (SM). Since the coupling to the Higgs boson is proportional to the mass of the particle, the top quark has a large coupling to the Higgs boson. This property makes it an ideal candidate to study fermion mass generation mechanism. Furthermore, it decays before hadronisation into a W boson and a b quark. Hence, bare quark properties can be studied by analyzing top quark production.
Top quark mass plays an important role in the consistency tests of the Standard Model. Such, the SM prediction for the stability of the electroweak vacuum, defined by the Higgs self-coupling being positive, depends strongly on the value and precision of the top quark mass. In the QCD Lagrangian, the top quark mass beyond leading order receives self-energy corrections and becomes renormalization scheme dependent.
In my analysis, two representations of the top quark mass are used. The pole mass that corresponds to the on-shell mass for the top quark propagator and the running mass, (Minimal Subtraction renormalization scheme, $\overline{MS}$), which depends on the energy scale.
One way of producing top quarks at the LHC is top quark pair production. Quantum chromodynamics (QCD) predictions for this process are calculated at next-to-next-to-leading order (NNLO). These cross section predictions depend on proton structure (parton distribution function (PDF), in particular the gluon distribution), the strong coupling constant, α_s and the top quark mass. The measurements of top quark production in proton-proton collisions at the LHC can be used to constrain all these parameters.
Another way to produce top quarks is single top quark production. There are three subprocesses at leading order perturbation theory: t-channel, s-channel and Wb-channel. The main channel is the t-channel, happening around seventy per cent of the time. Its Feynman diagram at leading order is shown in Fig. 1.

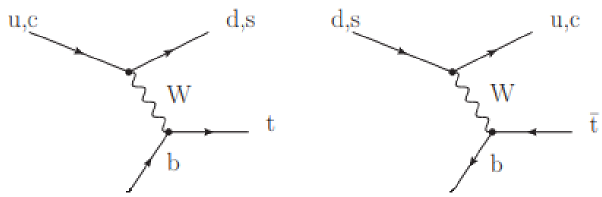

Figure 1: Feynman diagrams at leading order of single top quark and antiquark t-channel production.

The experimental signature of single top quark t-channel production in e.g. the CMS detector is a charged lepton, large transverse missing energy (which gives hint to a neutrino), a jet from a light quark and a b-jet from the top quark decay. QCD predictions are calculated at NLO and approximate NNLO. Measurements of single top quark production can be used for constraining the light quark distributions in the proton and for extration of the top quark mass.

2 Implementation to xFitter

In this project, I have worked with two computer programs: xFitter [1] and HATHOR (Hadronic Top and Heavy quarks crOss section calculatoR) [2]. The former is the only open source fit package that determines PDFs and QCD parameters. The latter calculates the top quark pair production cross section in hadronic collisions to NNLO, in pole mass and running mass schemes (available in xFitter), and single top quark production cross section to NLO in the pole mass scheme.
In the scope of the summer school project, I have provided the interface between xFitter and Hathor calculation for single top quark production in the t channel. In xFitter, a new reaction is introduced in the new theory interface: ReactionHathorSingleTop. It uses similar settings and inputs as the existing interface for top quark pair production, ReactionHathor. ReactionHathorSingleTop is called to calculate the cross section of top quark and top antiquark, while the cross section of $t + \bar{t}$ and the cross section ratio are calculated using the Expression option of xFitter. Furthermore, the $\overline{MS}$ mass scheme for the calculation of the single top quark production cross section is implemented, using the numerical calculation done by Sven Moch. In contrast to top quark pair production, there is no analytical way of re-calculating the top quark mass from pole to the $\overline{MS}$ scheme in the cross section calculation of single top production. Instead, at each order of the cross section calculation, the transformation of the pole mass into $\overline{MS}$ is performed numerically. This is then implemented directly in the ReactionHathorSingeTop of xFitter. The mass scheme is specified in the parameters file (parameters.yaml) via MS MASS variable which switches between pole mass and the $\overline{MS}$ mass schemes, similar to the top quark pair production. Moreover, there is a new variable called `Antitopquark` in the data file that stands for top quark if its value is zero and for top antiquark if its value is one.
To check that the implementations were done correctly, I compared the single top quark and antiquark cross section predictions, their ratio and the inclusive cross section obtained using xFitter with that obtained using Hathor. The comparisons are shown in Table 1 for pole mass and in Table 2 for running mass. These values are obteined setting the center of mass energy to 8 TeV, using ABMP16nnlo as PDF set, with a pole mass m_t = 170.47 GeV and a running mass m_t = 160.86 GeV, and using the calculation at NLO.

Table 1: Comparison of single top quark and antiquark production cross section predictions and the inclusive cross section using xFitter with that using Hathor for pole mass.

	σ_t (pb)	$\sigma_{\bar{t}}$ (pb)	$\sigma_{t+\bar{t}}$ (pb)
xFitter	59.7077	30.4972	90.2049
HATHOR	59.7077 $\pm$ 0.0006 (numerical)	30.4972 $\pm$ 0.0003 (numerical)	90.2049

Table 2: Comparison of single top quark and antiquark production cross section predictions and their ratio using xFitter with that using Hathor for running mass.

	σ_t (pb)	$\sigma_{\bar{t}}$ (pb)	$Ratio = \frac{\sigma_t}{\sigma_{\bar{t}}}$
xFitter	59.961	30.648	1.956
HATHOR	59.961	30.650	1.956

3 Analysis

3.1 Cross section and ratio dependency on PDF set

First, the single top quark and antiquark cross section predictions and their ratio for different PDF sets are calculated and fit to the measurements [3, 4]. The results are presented in Tables 3 and 4. In Fig. 2 and 3, the cross section predictions and the ratio of the cross sections are shown using different PDF sets. For all PDF sets, the data are described very well by the theory prediction.

Table 3: Single top quark production cross section predictions for different PDF sets and the χ^2 of the fits to the measurement by ATLAS.

PDF set	σ_t	χ^2
NNPDF3.1nnlo pdfas	42.4 ± 0.3	0.33
CT14nnlo	42.9 ± 0.5	0.33
MMHT2014nnlo68cl	42.5 ± 0.3	0.56
ABMP16nnlo	45.6 ± 0.7	0.030
ATLAS-epWZ16	43.4 ± 0.3	0.37

Table 4: Ratio of single top production cross section predictions for different PDF sets and the χ^2 of the fits to the measurement by CMS.

PDF set	$Ratio = \frac{\sigma_t}{\sigma_{\bar{t}}}$	χ^2
NNPDF3.1nnlo pdfas	1.85 ± 0.03	0.060
CT14nnlo	1.86 ± 0.04	0.060
MMHT2014nnlo68cl	1.80 ± 0.03	0.11
ABMP16nnlo	1.96 ± 0.02	0.010
ATLAS-epWZ16	1.84 ± 0.02	0.070

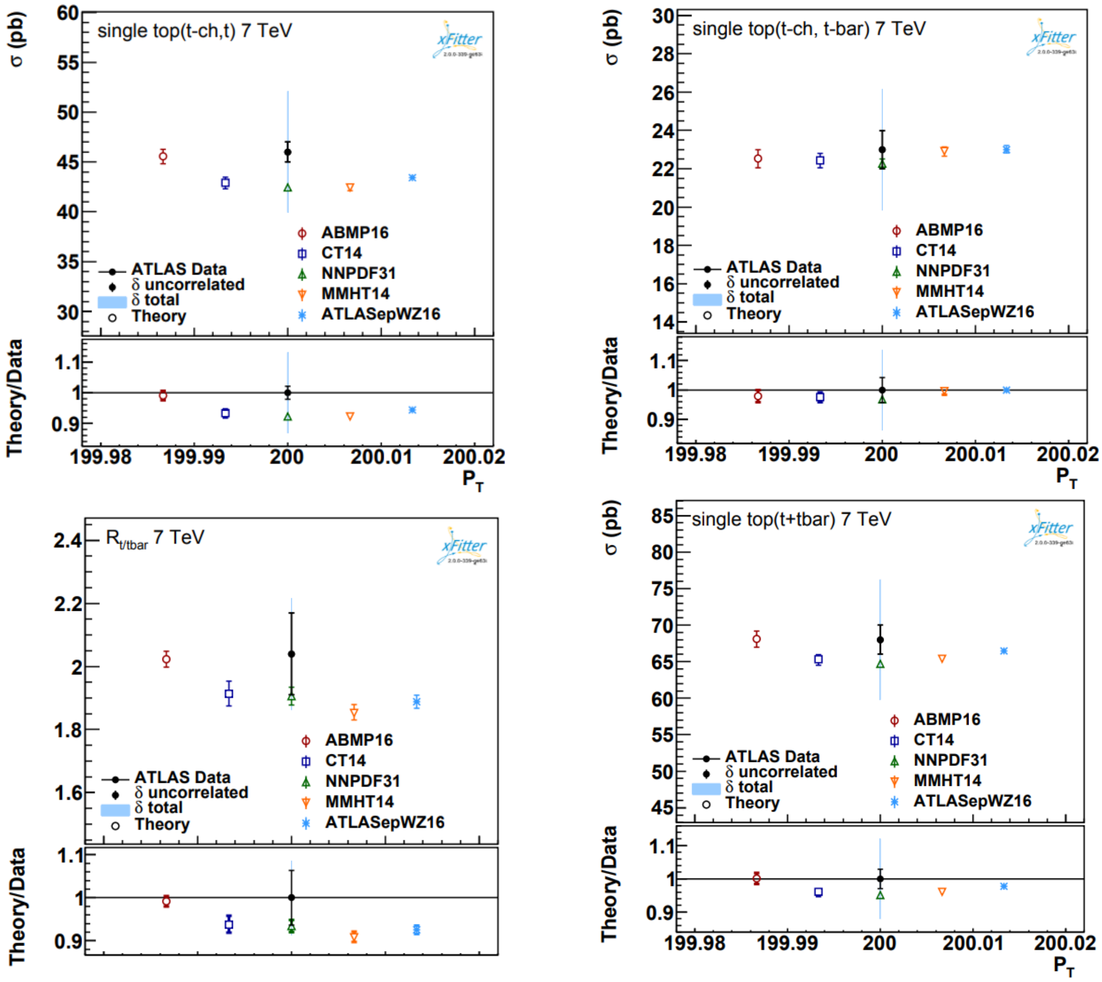

Figure 2: Single top quark and antiquark production cross section predictions, their ratio and the inclusive cross section prediction for different PDF sets (symbols of different style), compared to the ATLAS measurement [3] at $\sqrt{s}$ of 7 TeV (filled circle), shown with its statistical (inner error bar) and total (outer error bar) uncertainties.

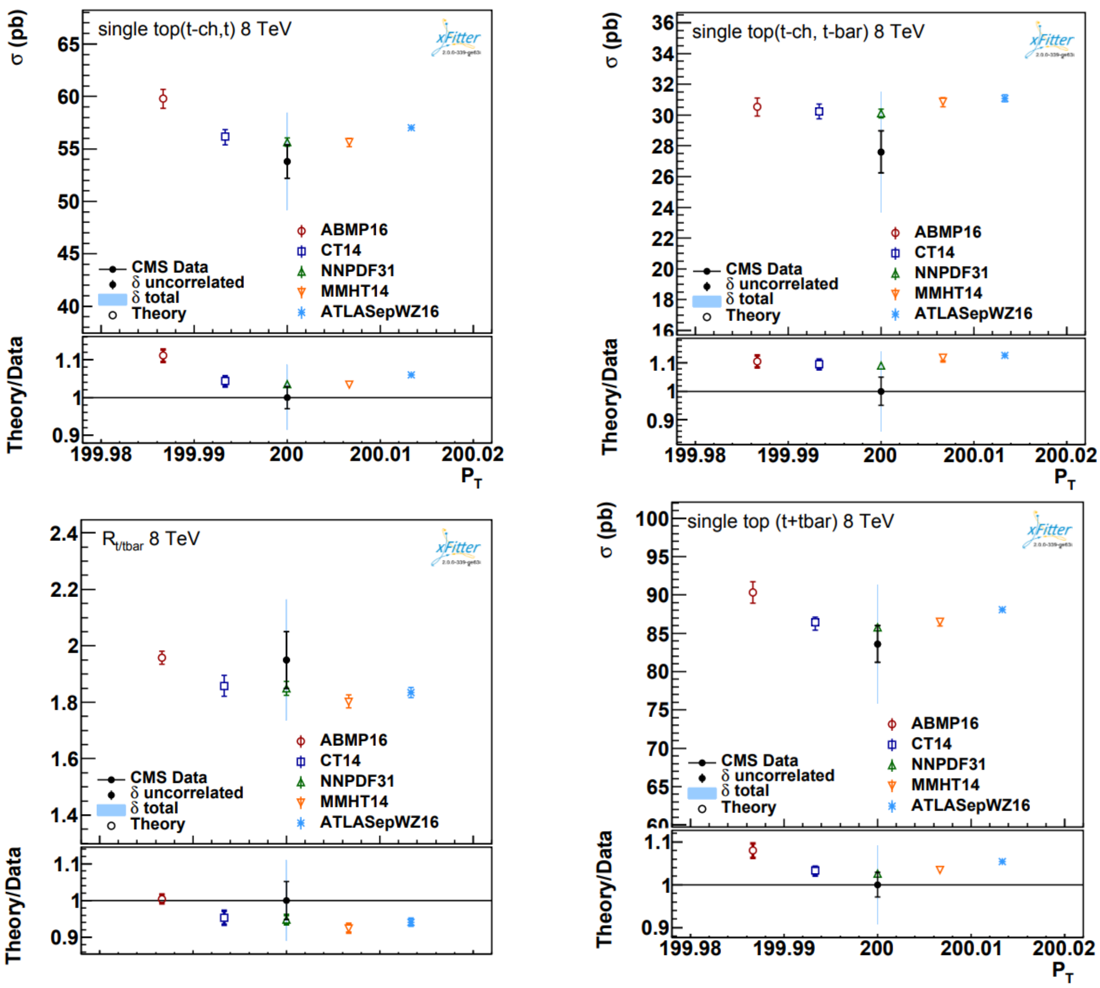

Figure 3: Single top quark and antiquark production cross section predictions, their ratio and the inclusive cross section prediction for different PDF sets (symbols of different style), compared to the CMS measured value [4] at $\sqrt{s}$ of 8 TeV (filled circle), shown with its statistical (inner error bar) and total (outer error bar) uncertainties.

3.2 Fit for top quark mass

The top quark mass can be extracted from the inclusive cross section of top quark pair production. For this purpose, the prediction for the cross section of top quark pair production is obtained for different values of top quark mass in either pole mass or $\overline{MS}$ scheme and fit to the corresponding measured value. The resulting χ^2 distribution is fitted by $\chi^2 = \chi^2_{min} + (\frac{(m_t - m_t^{min})}{\delta m})^2$. The value of the top quark mass corresponding to the minimum value of the χ^2 is the one taken as the top quark mass (m_t^{min}) and δm is its uncertainty which accounts for PDF uncertainties and that of the experimental measurement. The resulting parabolas are presented in Figure 4. The values obtained for the top quark mass with their uncertainties are shown in Table 5.

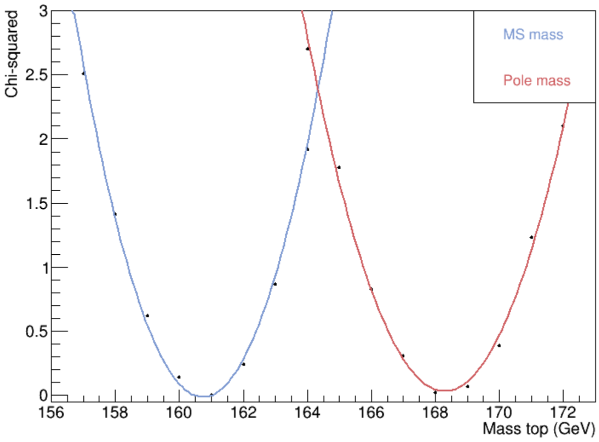

Figure 4: Fits for top quark mass from $t\bar{t}$ production for pole (red line) and running mass (blue line) using cross section measurement from [6].

Table 5: Top quark masses obtained from fits shown in Fig. 4.

	m_t (GeV)
Running mass	161 ± 2 (PDF+fit)
Pole mass	168 ± 3 (PDF+fit)

The same procedure is used to extract the top quark mass from the single top production. The top quark masses obtained from these fits are shown in Table 6, where cross sections measurements from [3], [4] and [5] have been used respectevily. The top quark mass obtained using ATLAS 7 TeV and CMS 8 TeV data differs systematically. The one obtained using ATLAS 7 TeV single top production data and CMS 13 TeV top quark pair production data are in agreement. The one obtained using CMS 8 TeV and 13 TeV data is the same, although the uncertainty for 13 TeV data is bigger. The fits corresponding to these comparisons are shown in Fig. 5, 6 and 7 respectively. For all these figures and for Fig. 4, the ABMP16nnlo PDF is used with its native $\alpha_s(m_z) = 0.115$.

Table 6: Top quark mases obtained from fits shown in Fig. 5 and 7.

	pole mass (GeV)	running mass (GeV)
ATLAS 7 TeV	171 $\pm$ 11 (PDF+fit)	162 $\pm$ 11(PDF+fit)
CMS 8 TeV	179 $\pm$ 10 (PDF+fit)	169 $\pm$ 9 (PDF+fit)
CMS 13 TeV	179 $\pm$ 18 (PDF+fit)	169 $\pm$ 17 (PDF+fit)

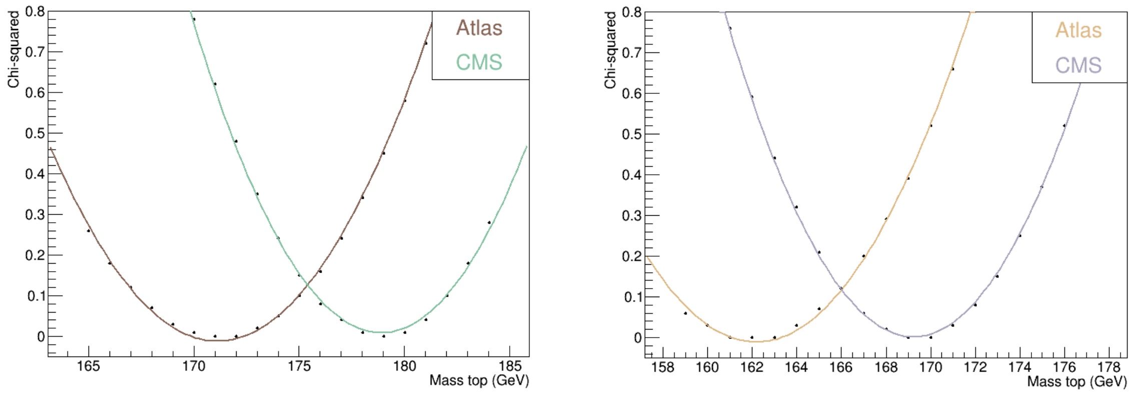

Figure 5: Comparison of fits for top quark mass from single top production, for pole mass (left figure) and running mass (right figure), between ATLAS 7 TeV [3] and CMS 8 TeV [4].

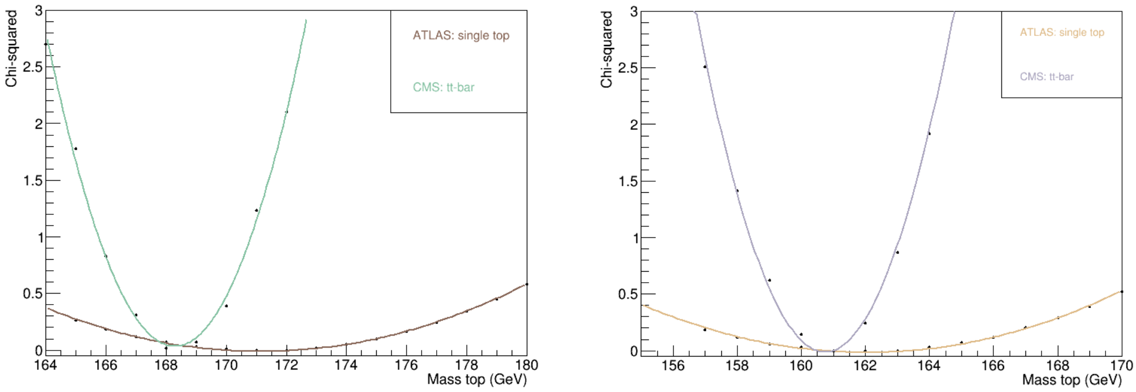

Figure 6: Comparison of fits for top quark mass, for pole mass (left figure) and running mass (right figure), between ATLAS 7 TeV single top production [3] and CMS 13 TeV top quark pair production [6].

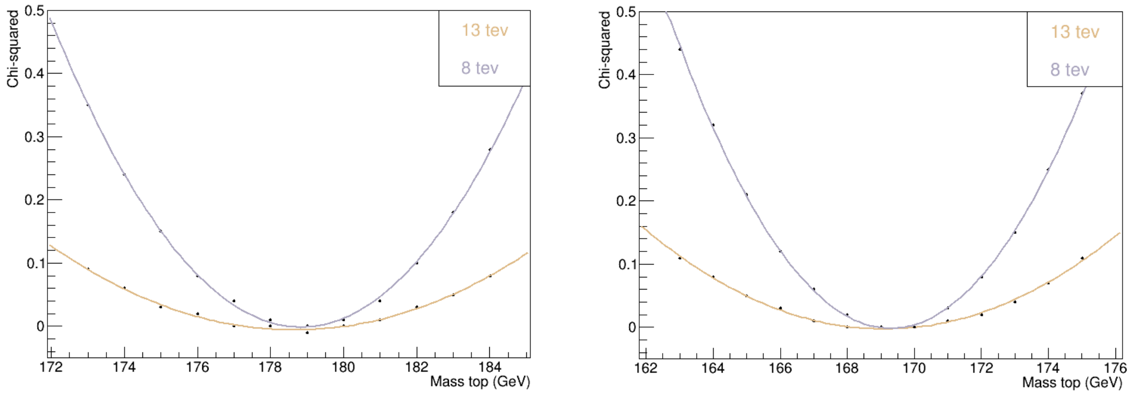

Figure 7: Comparison of fits for top quark mass from single top production, for pole mass (left figure) and running mass (right figure), between CMS 13 TeV [5] and CMS 8 TeV [4].

Finally, I fit for top quark mass from single top production for different PDF sets using cross section measurement from [4]. In Table 7, the obtained values for the top quark mass are shown and Fig. 8 shows the fits.

Table 7: Top quark mases obtained from fits shown in Fig. 8.

PDF set	pole mass (GeV)	running mass (GeV)
NNPDF3.1nnlo pdfas	176 ± 10 (PDF+fit)	166 ± 9 (PDF+fit)
CT14nnlo	177 ± 10 (PDF+fit)	167 ± 9 (PDF+fit)
MMHT2014nnlo68cl	178 ± 10 (PDF+fit)	168 ± 10 (PDF+fit)
ABMP16nnlo	179 ± 10 (PDF+fit)	169 ± 9 (PDF+fit)

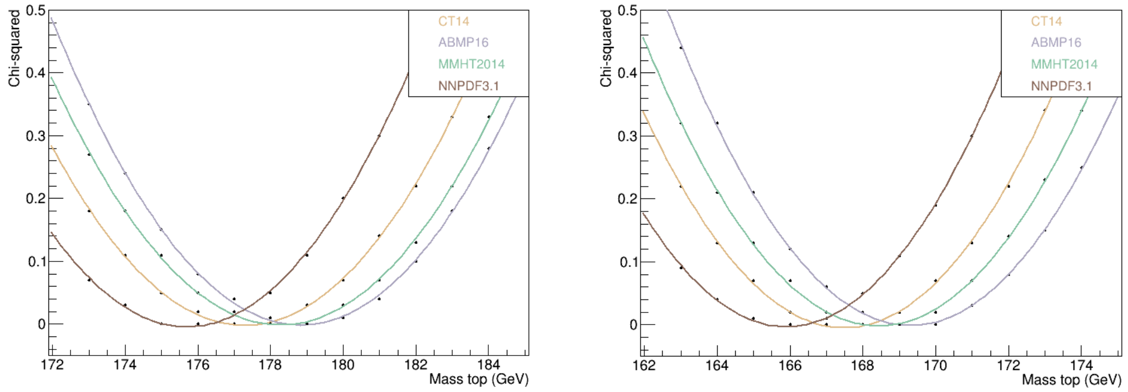

Figure 8: Fits for top quark mass from single top production for different PDF sets, for pole mass (left figure) and running mass (right figure), using cross section measurement by the CMS experiment [4].

4 Conclusions

The implementation of single top t-channel in xFitter provides a fast way to perform phenomenological analysis (PDF comparison, χ^2 of cross sections or of ratio) of single top quark/antiquark production.
The top quark mass was extracted using top quark pair production and the single top quark production at the LHC. The results obtained by using ATLAS measurements from single top quark production is similar to the ones obtained from top quark pair production. However, the ones obtained by using CMS measurements from single top production differs systematically from that of top quark pair production. This might be a hint to a difference in the dependences of the top cross section measurements on the assumed value of the top quark mass in ATLAS and CMS simulation and should be investigated in the future. As a future improvement in the analysis, scale variation uncertainties could be estimated and the electroweak corrections to the single top quark production cross sections could be applied.

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