Leptonic top-quark asymmetry predictions at LHCb

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The forward LHCb acceptance offers the possibility of measuring the top-quark pair asymmetry in a kinematic region that does not receive overwhelming dilution from the symmetric gluon-fusion channel. To investigate this possibility, two leptonic final states are identified, and analysis strategies are proposed for each channel with 14 TeV data. Fixed-order predictions, including \( O(\alpha_s^2) \), \( O(\alpha_s^2 \alpha_{e/w}) \), and \( O(\alpha_s^3) \) contributions, are then provided for the relevant leptonic asymmetries in each channel. Statistically, a non-zero asymmetry is estimated to be observable beyond 5\(\sigma\) confidence level with the full LHCb 14 TeV data.

INTRODUCTION

Top-quark production has so far not been observed at very high pseudorapidity. As the LHCb detector is instrumented in this region of phase space, it is important to investigate the feasibility of measuring the properties of top-quark production with the available and expected future LHCb data.

At the LHC, top-quarks are predominantly pair produced via the strong interaction. This production channel is therefore statistically the most promising for performing precision measurements in an extreme kinematic region. Besides the statistical benefits, measurements of forwardly produced top-quark pairs are also well motivated, as they provide sensitivity to partons within the colliding protons with both moderate- and high-\(x\) momentum fractions. Performing cross section measurements of the pair production mechanism within the LHCb acceptance is therefore important for constraining parton distribution functions (PDFs). In particular, as the gluon-fusion (gg) subprocess provides the dominant contribution to the cross section, it will be possible to improve the current constraints on the gluon PDF \[1\].

Another interesting consequence of this kinematic sensitivity is that the relative contribution of quark-initiated subprocesses increases for forwardly produced top-quark pairs — a result of the relative decline of the gluon with respect to the valence quark PDF at high-\(x\). Within the Standard Model (SM), an asymmetry exists in the production of top-quark pairs \[2\ 3\ 4\ 5\] which results in an asymmetric angular distribution of top- and antitop-quarks. This asymmetry arises from quark-initiated processes of the form \( qX \rightarrow tY \), and it has therefore been suggested that asymmetry measurements at LHCb \[6\] may be particularly sensitive.

Measurements of the charge asymmetry in the forward region are also experimentally well motivated, as both the CDF \[7\ 8\] and D0 \[9\ 10\ 11\] experiments at the Tevatron observe asymmetries larger than the corresponding predictions in the SM. Although the overall tension is rather small, there is some indication that this discrepancy increases for very forwardly (backwardly) produced (anti)top-quarks. Measurements at the LHC have already been performed \[12\ 13\ 14\ 15\], but have been so far inconclusive in confirming or refuting the behaviour observed at the Tevatron. Although performed with higher statistics, asymmetry measurements in the central region at the LHC will remain challenging as the observable asymmetric cross section is substantially diluted by the symmetric gg channel.

To investigate the feasibility of asymmetry measurements at LHCb, an analysis strategy is proposed for both single- and di-lepton final states. In each case, a set of analysis cuts are selected after considering background rates, and fixed-order predictions are provided for the asymmetry at the leptonic level.

STRUCTURE OF PREDICTION

Before studying specific leptonic final states, it is important to review the structure of the asymmetry prediction. As demonstrated in \[4\ 5\], the dominant contribution arises from the interference of amplitudes at next-to-leading order (NLO) which are relatively odd under interchange of final state top- and antitop-quarks. The prediction for the asymmetry is therefore cast in terms of a Taylor series expansion in powers of the strong (\(\alpha_s\)) and QED/weak (\(\alpha_{e/w}\)) couplings in the following way

\[
A = \alpha_s^3 \sigma_a^{s(1)} + \alpha_s^2 \alpha_{e/w} \sigma_a^{e/w(1)} + \alpha_s^2 \sigma_a^{e/w(0)} + \cdots,
\]

\[
= \frac{\sigma_a^{s(1)}}{\sigma_s^{(0)}} + \frac{\sigma_a^{e/w(1)}}{\sigma_s^{(0)}} + \frac{\sigma_a^{e/w(0)}}{\sigma_s^{(0)}} + \cdots.
\]

In this notation, \(\sigma_a^{s(1)}\) represents the asymmetric contribution arising from interfering amplitudes at NLO, while \(\sigma_s^{(0)}\) is simply the coupling-stripped, symmetric LO QCD contribution. The additional term \(\sigma_a^{e/w(0)}\) represents the electroweak contribution to the asymmetry arising at LO. In the same fashion as \[16\ 17\ 18\], the expansion in \[4\] is truncated to avoid incomplete terms containing the symmetric NLO QCD contribution to the cross section — \(\sigma_s^{(1)}\). It is important to note that the
leptonic final states which will be considered never involve fully reconstructing a top-quark, and consequently the asymmetry is accessed only indirectly by studying the angular distributions of leptonic top-quark decays. The decay of top-quarks is included at LO by factorising the full amplitude into production and decay amplitudes, under the assumption that the top-quarks are produced on-shell.

To obtain the $\mathcal{O}(\alpha^3_s)$ contribution to the numerator, an adapted version of the publicly available MCFM \[19, 20\] program is used, which separates the individual contributions from the $u\bar{u}$, $d\bar{d}$, $uq$, and $dg$ subprocesses. The $\mathcal{O}(\alpha_s^2\alpha_e/\omega)$ can then be (approximately) obtained from these results by applying a rescaling of couplings and colour factors. The $\mathcal{O}(\alpha_s^2/\omega)$ contribution is also available in MCFM, and has been extended to include hadronic $W$ boson decays, which is necessary for the single-lepton final state. The numerical accuracy of the results is estimated to be $\mathcal{O}(1\%)$, which is found by generating 100 statistically independent samples and calculating the standard deviation. In the $qg$ channels the contribution is slightly poorer, however the contribution of this channel to the total asymmetry is relatively always below 10%.

From diagram inspection, the ratio of the $\mathcal{O}(\alpha_s^2\alpha_e/\omega)$ to the $\mathcal{O}(\alpha_s^3)$ results for $q\bar{q}$- and $gg$-initiated states are

$$R_{q\bar{q}}(\mu) = \frac{36Q_q^X Q_{\bar{q}}^X}{5\alpha_s}, \quad R_{gg}(\mu) = \frac{24Q_q^X Q_{\bar{q}}^X}{5\alpha_s}, \quad (2)$$

where $Q_q^X$ and $Q_{\bar{q}}^X$ are the relevant quark and top-quark charges. The mixed QED-QCD corrections are found by including the electromagnetic charges $Q^e$. The mixed weak-QCD corrections are found with replacement $Q^w = (2\tau^3 - 4 s^w \bar{s}^w)/4s_w c_w$, where $\tau^3$ and $(c)s_w$ are weak isospin and the (co)sine of the weak mixing angle $\theta_w$ respectively — this replacement is valid under the assumption $m_Z^2 / \sqrt{s} \ll 1$ \[15\]. The running of $s^w_\mu(m_Z) = 0.231$, and $\alpha_s(m_Z) = 1/128$ are considered at one-loop.

Finally, the dependence on the choice of PDFs and scales is evaluated in the following way. The numerator of each asymmetry is computed with NNPDF2.3 NLO PDFs with $\alpha_s(m_Z^2) = 0.119$ \[21\]. The denominator is then computed with the LO 0.119, LO 0.130, and NLO 0.119 NNPDF2.3 PDFs. A scale uncertainty is evaluated by simultaneously computing the numerator and denominator of each asymmetry for a specific scale choice $\mu_F = \mu_R = \mu = \{m_t/2, m_t, 2m_t\}$. The central value is then found by averaging these three predictions, and a uncertainty is associated to the total envelope. The top mass is fixed at $m_t = 173.25$ GeV throughout.

**SINGLE-LEPTON ASYMMETRY**

As proposed in \[6\], it is possible to partially reconstruct the full $t\bar{t}$-system within the LHCb acceptance by considering the final state $t\bar{t} \to lbX$, in which a single lepton and $b$-jet are registered by the detector. A differential asymmetry can then be inferred by measuring the rate of $l^+$ to $l^-$ tagged events as

$$\frac{dA}{d\eta} = \left( \frac{d\sigma^{l^+b}/d\eta - d\sigma^{l^-b}/d\eta}{d\sigma^{l^+b}/d\eta + d\sigma^{l^-b}/d\eta} \right)$$

where both the $b$-jet and lepton are required to be within the LHCb kinematic acceptance of $2.0 < \eta < 4.5$. Before studying the properties of this final state, it is necessary to include analysis cuts to manage the various sources of background.

The main backgrounds are identified as single top, $W+(b)\text{jets}$, $Z+(b)\text{jets}$, and QCD. In accordance with LHCb trigger requirements, a minimum $p_T$ of 20 GeV is required for all leptons. It is also necessary to introduce an isolation criterion $\Delta R(l, b, jet) \geq R$, which ensures the QCD contamination is negligible \[6\]. To apply this isolation, jets are clustered with the anti-$k_t$ algorithm \[22\] with the choice $R = 0.5$. Events in which two oppositely charged leptons simultaneously pass these analysis cuts are vetoed, and are considered in the di-lepton analysis. Throughout the single-lepton analysis, a $b$-tagging mis-tag rate of 1.4% is applied to light jets — this is motivated by internal LHCb studies which suggest a mis-tag rate of 1% with an associated efficiency of 70% is achievable \[23\]. A $p_T$ cut of 60 GeV is placed on this $b$-jet.

The contribution from signal and background to the symmetric cross section, including the discussed analysis cuts and efficiencies, is shown in Fig. 1. Note that the contribution from each process has been stacked. The background samples are simulated using POWHEG \[24, 25\] with the central CTE10w PDF set \[28\] and then subsequently matched to Pythia8176 \[29\] — the only exception is $Z+b\text{jets}$ where the matrix element is produced

\[\text{FIG. 1. Stacked contributions from signal and background processes to the symmetric cross section in the single-lepton channel at 14 TeV. Analysis cuts and relevant efficiencies have been applied to all processes. See text for details.}\]
using MadGraph5 [30] with cteq6l1. In the case of single top, only the $t$-channel process is considered, and an uncertainty is associated to the difference between 4- and 5-flavour scheme predictions. The 4-flavour inclusive cross section is also normalised to that of the 5-flavour prediction. For all (N)LO+PS background samples, jet reconstruction is performed with the FastJet software [31], and $b$-jets are found by matching $b$-quarks to jets at the parton level. The shown $t\bar{t}$ sample in Fig. 1 is generated at LO with NLO 0.119 NNPDF2.3 PDFs. In this work, the signal process is studied with NNPDF PDFs as they provide updated sets at (N)LO with varying choices of $\alpha_s(m_Z^2)$. This is important for evaluating the uncertainty of the signal asymmetry prediction, which is considered by computing the denominator with these differing PDFs. The background samples are taken from previous work [1].

The contributions to the inclusive asymmetry, with the discussed analysis cuts applied, from the various $t\bar{t}$ subprocesses are provided. The prediction for the numerator at various scale choices is provided in Table I, while the corresponding denominator and asymmetry predictions are provided in Table II.

The differential leptonic rate asymmetry is presented as function of lepton pseudorapidity in Fig. 2. The dependence on the choice of PDFs used for the computation of the denominator has also been highlighted. Although the symmetric and asymmetric cross section individually exhibit large scale dependence, this approximately cancels in the asymmetry. The dependence on the choice of PDFs is however significant — a consequence of the behaviour of the gluon PDF at large-$x$ which results in an uncertainty of approximately 30%. This uncertainty would be reduced with the inclusion of additional terms in the expansion (1).

The signal contribution to the asymmetry is significant, particularly at large $\eta_l$ where the asymmetry reaches (3-8)%. To experimentally extract this signal, it is however necessary to precisely know the background contribution to the asymmetry. This is demonstrated in Fig. 3, where the contributions from both signal and background processes to the numerator of the asymmetry are shown.

![Figure 2](image2.png)

**FIG. 2.** Differential leptonic rate asymmetry as a function of lepton pseudorapidity at 14 TeV. The choice of analysis cuts, and PDFs used for the computation of the numerator and denominator are highlighted.

![Figure 3](image3.png)

**FIG. 3.** Stacked signal and background contributions to the numerator of the total leptonic rate asymmetry at 14 TeV.
which will ultimately limit the precision of an asymmetry measurement in this channel. In principle, an experimental background fit performed across several different final states — such as $l_j$, $lbj$, $lbb$ — should provide adequate knowledge of the backgrounds for the considered $lb$ final state. Assuming these experimental uncertainties are under control, the statistical feasibility of such a measurement can be estimated by considering the background-subtracted $tt$ sample. This is computed according to $\delta A = \sqrt{(1 - A^2)/N}$, where the number of events $N$ is found by applying a lepton efficiency of 75% (an approximate trigger effect), a $b$-tagging efficiency of 70%, and assuming an integrated luminosity of 50 fb$^{-1}$ — the expected data collected by 2030 [32]. Applying these assumptions to the LO cross section computed with NLO 0.119 PDFs at the scale choice $\mu = m_t$ results in $\approx 1e5$ events. Statistically, when compared to the corresponding asymmetry prediction ($A^t = 1.95\%$), a non-zero asymmetry can be excluded beyond 5$\sigma$.

**DI-LEPTON ASYMMETRY**

With the large data expected by 2030, measurements in the di-lepton channel at LHCb also become feasible. In this case, the full $tt$-system can be partially reconstructed by considering the final state $tt \rightarrow \mu ebX$, which opens the possibility of measuring the rapidity difference of reconstructed leptons on an event-by-event basis. A differential asymmetry can then be inferred by measuring a forward-backward asymmetry as

$$\frac{dA_{fb}^{ll}}{d\Delta y} = \frac{(d\sigma^{\mu eb}(\Delta y > 0) - d\sigma^{\mu eb}(\Delta y < 0)) / d\Delta y}{d\sigma^{\mu eb} / d\Delta y}, \quad (4)$$

where $\Delta y = y_+ - y_-$, and both leptons and the $b$-jet are within the acceptance $2.0 < \eta < 4.5$. The choice of opposite flavour leptons is required to remove, the otherwise overwhelming, $Z$ background processes. With this requirement in place, the main backgrounds are identified as $Z \rightarrow \tau\tau$, $WW$, $WZ$, $tW$, and QCD. In a similar fashion to the single-lepton analysis, leptons are required to be isolated, and to have a minimum $p_T$ of 20 GeV. In this analysis, a $p_T$ cut of 20 GeV is also placed on the $b$-jet, and a looser $b$-tagging mis-tag rate of 5% is assumed in favour of efficiency.

The contribution from signal and background to the symmetric cross section is shown in Fig. 3. The background samples are simulated using POWHEG [33, 34] with the central CT10w PDF set, and then subsequently matched to Pythia8176. The QCD background, which is expected to arise from multi-jet production, is not considered in this study. It is possible to account for this background experimentally by measuring the event rate and kinematic distributions of same-sign $\mu$ and $e$ leptons. Internal studies with the 8 TeV data at LHCb indicate that, after isolation and impact parameter cuts, the QCD contribution is expected to be below 10% of the $tt$ signal [35].

Following the procedure in the single-lepton channel, the prediction for the numerator at various scale choices is provided in Table III while the corresponding denominator and asymmetry predictions are provided in Table IV

$$\begin{pmatrix}
\hline
N_{fb}^{ll} (fb) & \mu = m_t/2 & \mu = m_t & \mu = 2m_t \\
\hline
u\bar{u} & 0.977 & 0.799 & 0.536 \\
\bar{d}d & 0.344 & 0.239 & 0.181 \\
u\bar{g} & 0.095 & 0.070 & 0.045 \\
\bar{d}g & 0.031 & 0.021 & 0.013 \\
\hline
O(\alpha_s^3) & 0.179 & 0.146 & 0.120 \\
\approx O(\alpha_s^3) & 0.009 & 0.007 & 0.006 \\
O(\alpha_s^2) & 0.006 & 0.005 & 0.005 \\
\hline
\text{Total} & 1.642 & 1.198 & 0.907 \\
\hline
\end{pmatrix}$$

**TABLE III.** Signal contribution to the numerator of the inclusive leptonic forward-backward asymmetry at 14 TeV. The analysis cuts discussed in the text have been applied.

$$\begin{pmatrix}
\hline
PDF & \mu = m_t/2 & \mu = m_t & \mu = 2m_t & A_{fb}^{ll} (%) \\
\hline
NLO 119 & 110.4 & 85.0 & 67.4 & 1.41 (8) \\
LO 119 & 160.7 & 120.7 & 93.3 & 0.99 (3) \\
LO 130 & 176.6 & 130.0 & 98.8 & 0.92 (1) \\
\hline
\end{pmatrix}$$

**TABLE IV.** Signal contribution to the denominator and leptonic forward-backward asymmetry at 14 TeV. The analysis cuts and efficiencies discussed in the text have been applied.

Finally, the differential leptonic forward-backward
asymmetry is presented as function of lepton pseudorapidity difference in Fig. [5]. The dependence of the resultant asymmetry on the choice of PDFs used for the computation of the denominator has also been highlighted. The statistical significance of a measurement in this channel is also estimated applying the procedure adopted in the single-lepton analysis. Under the same assumptions, except a slightly looser $b$-tagging efficiency of 90%, leads to $\delta A_{\text{stat}} \approx 1.9\%$, which slightly exceeds the corresponding prediction of $A_{FB} = 1.41\%$.

CONCLUSIONS

Leptonic top quark asymmetry measurements at LHCb with the full data at 14 TeV are statistically feasible. A Measurement in the single-lepton channel is particularly promising, but will require careful experimental consideration of backgrounds. In the di-lepton channel, background rates are extremely low which allows for clean differential cross section measurements to be performed. Although statistically limited, asymmetry measurements in this channel should also be pursued.

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