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Top Physics at the LHC

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Abstract

The physics of the top quark has an important role, both in verifying the Standard Model (SM) and in the search for physics beyond the SM. Its mass and Yukawa coupling to the Higgs boson are major parameters in studies of the electroweak symmetry breaking. Also the cross section of top-pair and single-top processes are important measurements to test the consistency of the SM. On the other hand, top quarks are a major source of background for almost all future searches for new physics. Therefore a precise understanding of the top signal is crucial. A review is given of the top physics programme for the CMS and ATLAS detectors at the Large Hadron Collider.

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1 Introduction

The Large Hadron Collider (LHC), currently under construction at CERN, will start its operation in 2007. It will collide protons onto protons at a center of mass energy of 14 TeV and at a luminosity ranging from $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in the initial phase up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at a later stage. Two general purpose detectors are being constructed and installed: A Toroidal LHC Apparatus (ATLAS) [1], and the Compact Muon Solenoid (CMS) [2].

Within the Standard Model physics program at the LHC, top physics plays an important role. The top quark is the least known SM particle. It was discovered in 1995 at the Tevatron, and the latest combined measurement of its mass [3] is $178.0 \pm 4.3 \text{ GeV}/c^2$. It is the most massive elementary particle known to date, and therefore it induces important electroweak corrections to for example the Higgs boson mass. Accurate measurements of the top quark mass and other top related properties allow for further constraining and testing of the Standard Model. At the same time top quarks are a major background for many new physics searches.

The LHC will be a ‘top factory’: $t\bar{t}$ production reaches a cross section at NLO of about 800 pb. At a low luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to $10 \text{ fb}^{-1}/\text{y}$, over 8 million $t\bar{t}$ pairs are expected each year. As a consequence most measurements will be very quickly limited by systematics rather than statistics. The decay of the top quark $t \rightarrow Wb$ has a branching fraction of $\sim 100\%$ in the Standard Model. Due to the very short lifetime ($\sim 10^{-24} \text{ s}$) the decay happens well before hadronization takes place, excluding top hadrons. The signature of a $t\bar{t}$ pair is hence given by the decay topology of the W pair in addition to the two b-quarks in the final state.

2 Top Quark Mass Measurement in $t\bar{t}$ Events

2.1 The golden channel: the semileptonic decay

The decay channel $t\bar{t} \rightarrow b\bar{b}q\bar{q}'\ell\nu$ where one W decays into a muon or electron and the other hadronically, is called the semileptonic channel. It is the golden channel for the measurement of the top mass as the isolated lepton can be used to trigger the events and the top mass can be measured on the hadronic side of the decay. The most important background sources are shown to be combinatorial and originating from $t\bar{t} \rightarrow \tau + X$ and W +jets.

One method to measure the top quark combines the two light quark jets with the W mass constraint and then adds one of the b-tagged jets. In the left plot of Figure 1 the resulting invariant mass distribution [4] is shown for CMS with 10 fb^{-1} .

Another method, exploiting the complete kinematics of the reconstructed event, involves the use of a kinematic fit [5]. In this case a χ^2 function is minimized by variation of the reconstructed particles’ kinematics. In the technique followed by ATLAS, events are classified as a function of the χ^2 value of the kinematic fit. The top mass is estimated in subsamples in each χ^2 slice and the top mass measurement is obtained by extrapolation to $\chi^2 = 0$. The estimated top mass in function of the χ^2 value is shown in the right plot of Figure 1 for 10 fb^{-1} .

Figure 1: Left: reconstructed top mass distribution in the semileptonic channel for 10 fb^{-1} (CMS). Right: estimated top mass in function of the χ^2 value of the kinematic fit (ATLAS).

A detailed estimation of systematic uncertainties has been performed for ATLAS for both methods [5]. For the first method the main contributions come from the b-jet energy scale ($0.7 \text{ GeV}/c^2$) and final state radiation (FSR) ($1.0 \text{ GeV}/c^2$). The second method shows a large improvement on the uncertainty due to FSR ($< 0.5 \text{ GeV}/c^2$). After 10 fb^{-1} a total uncertainty on the top mass measurement of $1.4 \text{ GeV}/c^2$ and $1.0 \text{ GeV}/c^2$ is expected for the first and second method respectively.

2.2 Top mass measurement in other channels

The fully leptonic decay channel $t\bar{t} \rightarrow b\bar{b}\ell_1\nu_1\ell_2\nu_2$ is a cleaner channel, but the kinematics are underconstrained due to the two neutrinos. The top mass can however still be measured indirectly [5]. A first method looks at the number of solutions to the kinematical equations assuming a top mass. With 10 fb^{-1} an accuracy of $1.7 \text{ GeV}/c^2$ is expected. Another proposed method exploits the correlation between the invariant mass of the leptons and the top mass. Here an accuracy of $2 \text{ GeV}/c^2$ is expected after 10 fb^{-1} .

The fully hadronic decay channel $t\bar{t} \rightarrow b\bar{b}q_1q'_1q_2q'_2$ suffers from trigger inefficiency and large combinatorial ambiguities. These problems can be tackled [5] by demanding each jet combination forming a top candidate to have a large total transverse momentum (e.g. $p_T > 200 \text{ GeV}/c$). Combinatorics are then reduced due to hemisphere separation between the tops.

A last proposed method [5, 6] uses $J/\Psi \rightarrow \mu^+\mu^-$ decays in $t\bar{t} \rightarrow W(\rightarrow qq')bW(\rightarrow \ell\nu)b(\rightarrow J/\Psi)$. Here the top mass is correlated to the invariant mass of the J/Ψ and the lepton from the corresponding W . Although low in statistics ($\sim 1000 \text{ events/y}$ expected at high luminosity), this channel is free from jet energy scale systematic uncertainties. The expected precision of $1 \text{ GeV}/c^2$ is limited by theoretical uncertainties on b fragmentation.

3 Topics in Top Physics

3.1 Single top production

Single top quarks will be produced at the LHC either in the t channel processes $qb \rightarrow tq'$ and $qg \rightarrow tq'b$ (245 pb) or through the s channel processes $gb \rightarrow Wt$ (60 pb) and $qq' \rightarrow tb$ (10 pb). The largest contribution from the t channel is characterized by an isolated lepton, a b jet and a forward jet.

Single top production is an important test of the SM. Additionally the matrix element V_{tb} can be measured to the percent level and a less accurate but independent top mass measurement can be made [7, 8].

3.2 Top spin correlations

Due to its fast decay, the spin information of the top quark is not diluted by hadron formation. When defining $\mathcal{A}$ as the asymmetry of finding top and anti top in the same or different polarization states, the SM predicts an asymmetry $\mathcal{A} = 0.31$ at the LHC.

In fully leptonic $t\bar{t}$ decays the angles $\theta_{\ell\pm}^*$ between the leptons in the top rest frames and the tops in the $t\bar{t}$ frame can be used to measure $\mathcal{A}$, using

$$\frac{1}{N} \frac{d^2 N}{d \cos \theta_{\ell+}^* d \cos \theta_{\ell-}^*} = \frac{1}{4} (1 - \mathcal{A} \cos \theta_{\ell+}^* \cos \theta_{\ell-}^*).$$

In the left plot of Figure 2 the corresponding distribution is shown. After 30 fb^{-1} a measurement of $\mathcal{A}$ is expected in CMS with a 0.035 statistical and 0.028 systematic uncertainty [9].

3.3 W polarization

Top decays offer the possibility to study W bosons in the longitudinal polarization state, only present for massive bosons. The SM predicts 70% of the W to be in this state, with the rest being left-handed. This prediction can be verified using the angle θ_ℓ^* between the lepton in the W rest frame and the W in the top rest frame.

In the right plot of Figure 2 the distribution of $\cos \theta_\ell^*$ is shown at parton level for left and longitudinal polarization and the SM expectation. With 10 fb^{-1} in the semileptonic decay, the fraction of longitudinally polarized W bosons is expected to be measured with a 0.023 statistical and a 0.022 systematic uncertainty [9].

3.4 Other topics

The $t\bar{t}$ cross section measurement is interesting in itself, but it is additionally sensitive to the top mass as $1/m_t^2$. Also differential cross sections are interesting to study: $d\sigma_{t\bar{t}}/dp_T$ and $d\sigma_{t\bar{t}}/d\eta$ constrain PDFs and $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ can be used to search for resonances, like heavy MSSM Higgs bosons.

Figure 2: Double differential distribution of $\cos \theta_{\ell^\pm}^*$ for 30 fb^{-1} (left) and distribution of $\cos \theta_\ell^*$ at parton level for different W polarization states (right).

Many other measurements are being investigated within the framework of top physics. A non-exhaustive list of undiscussed topics: assignment of the top charge, charged Higgs boson search in $t \rightarrow H^\pm b$, rare top decays and many detector related studies like b-tagging algorithm calibration.

4 Conclusions

Top quarks will be copiously produced at the LHC, allowing for a broad physics program involving top quarks, already at startup of the accelerator. Many precision measurements will considerably increase our SM knowledge, and will be crucial for searches of physics beyond the SM.

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