Top physics prospects at LHC

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On behalf of ATLAS and CMS

Abstract

With a high instantaneous luminosity and the large top quark pair production cross section, the Large Hadron Collider (LHC) will be a “top factory” allowing the analysis of millions of top events. After a short description of the top quark pair production mechanism and the cross section measurement, the accuracy of the top mass measurement needed for a sound consistency check of the Standard Model is briefly discussed. Different top mass measurement methods are presented. The observability of the single top quark production is described. Finally the observation of the Higgs boson produced in association with a top quark pair is discussed.

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Top physics prospects at LHC

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With a high instantaneous luminosity and the large top quark pair production cross section, the Large Hadron Collider (LHC) will be a “top factory” allowing the analysis of millions of top events. After a short description of the top quark pair production mechanism and the cross section measurement, the accuracy of the top mass measurement needed for a sound consistency check of the Standard Model is briefly discussed. Different top mass measurement methods are presented. The observability of the single top quark production is described. Finally the observation of the Higgs boson produced in association with a top quark pair is discussed.

1 Top quark pair production

1.1 A top factory

Whereas the centre-of-mass energy of the collisions at the LHC is seven times higher than at the TeVatron, the production cross section of top quark pairs is about hundred times larger. It reaches \[ \sigma_{\text{t\bar{t}}} \approx 840 \text{pb} (1 \pm 5\%_{\text{scale}} \pm 3\%_{\text{PDF}}) \] where the error terms represent the systematic uncertainties related to the choice of the renormalization and factorization scales and to the proton function structures respectively. At \( \sqrt{s} = 14 \text{TeV} \), the top quarks are mostly produced by gluon fusion (90%). The quark annihilation, dominant at the TeVatron, amounts to only 10% of the top quark pair production.

In the Standard Model (SM), the top quark always decays into a W and a b quark. As a result, the topology of the final state is mostly driven by the decay channels of the W’s. The events where one of the W’s decays into a lepton \(^{a}\) have a clear signature: one isolated lepton, missing transverse energy from the undetected neutrino and at least four jets of which two b jets. At “low” luminosity, \( L = 10^{33} \text{cm}^{-2}\text{s}^{-1} \), there will be such so-called “lepton+jet” event every 4 s while one top quark pair will be produced every second. The LHC will thus be a “top factory”.

1.2 Top observation and cross section measurement

The production cross section is so large that the top signal will be visible after the equivalent of one week of data taking at low luminosity \(^{2}\) in the lepton+jet channel. By requiring one isolated lepton with a transverse momentum \( p_T > 20 \text{GeV}/c \), and exactly four jets with high transverse energy \( (E_T > 40 \text{GeV}) \), the top signal is clearly visible above the \( W+4 \text{ jets} \) background in the invariant mass distribution of the most energetic three jets (Fig. 1).

\(^{a}\)Hereafter, “lepton” means electron or muon
The cross section can thus be measured. With the large number of events collected, the statistical error will soon be negligible. After “one month” at low luminosity, it will be at the level of 0.4%. The overall error will be dominated by the systematic uncertainty related to the luminosity measurement. A 5% uncertainty is achievable. Because of its strong dependence on the top mass, a measurement of the production cross section together with a precise measurement of the top mass will provide a test of QCD. Alternatively, within the SM, the cross section measurement provides a mass estimate, with a potential accuracy of 3 GeV/c² precision can be reached. A direct measurement can, however, be done with a better precision.

2 The top mass measurement

2.1 Why measuring (precisely) the top mass?

Because of its mass, the top plays a particular rôle in the electroweak sector. In the SM, the W and Z boson masses are connected through the relation the Fermi constant and ∆r contains the one-loop corrections. The top mass arises in ∆r via the loops in the W and Z boson propagators and gives rise to terms proportional to $m_t^2/m_Z^2$. Similarly, the Higgs boson loops give terms proportional to $\log m_H/m_Z$. The relationship thus obtained between the Higgs boson and top quark masses is currently used as an indirect prediction of the Higgs boson mass: $m_H = 126^{+12}_{-13}$ GeV/c² for $m_t = 178 \pm 4$ GeV/c². The allowed region in the $(m_W,m_t)$ plane for different Higgs boson masses is displayed in Fig. 2 as well as the direct and direct measurements of $m_W$ and $m_t$.

At LHC, a direct measurement of the Higgs boson mass will be carried out towards a consistency test of the SM by checking the relation between $m_t$, $m_W$ and $m_H$. To ensure a similar accuracy in the combination, the precision on $m_t$ and $m_W$ must fulfil $\Delta m_t \approx 0.7 \times 10^{-2} \Delta m_W$ corresponding to the slope of the constant Higgs boson mass lines in Fig. 2. As can be seen in Table 1, a 2 GeV/c² precision on $m_t$ will allow a consistency check of the SM with similar relevance as a 15 MeV/c² accuracy on $m_W$, reachable at LHC. The LHC, however, can even do better and achieve a 1 GeV/c² on $m_t$ as described in the following. A higher precision might be needed in case of new physics discovery. Such an accuracy would be obtained with an $e^+e^-$ linear collider.
Figure 2: Direct and indirect measurements of the W boson and top quark masses with lines of constant Higgs boson masses in the Standard Model.

Table 1: Expected precisions on the W boson and top quark masses at present and future colliders.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m_W$ (MeV/$c^2$)</th>
<th>$\Delta m_W/0.7 \times 10^{-2}$ (GeV/$c^2$)</th>
<th>$\Delta m_t$ (GeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeVatron</td>
<td>25</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>LHC</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
<td>LC</td>
<td>6</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

2.2 Measurement in the lepton+jet channel

The lepton+jet channel is the golden channel for the top mass measurement. Indeed, the leptonic-decaying W boson allows the top events to be efficiently triggered and selected. After the selection of the events with an energetic isolated lepton ($p_T > 20$ GeV/$c$) and a missing transverse energy in excess of 20 GeV, the characteristics of the $t\bar{t}$ events are then used to improve the purity of the sample. The events must contain at least four energetic jets ($E_T > 20$ GeV) of which two identified b jets. The b$\bar{b}$+jets, W+jets and Z+jets backgrounds are highly suppressed by this event selection.\(^8\)

The top mass is reconstructed from the two light jets from the W decay and the b jet from the top decay. As a result, the jet energy scale and angular resolutions are crucial. The non b-jet pair minimizing the $(M_{jj} - m_W)^2$ difference, where $M_{jj}$ is the invariant mass of the two jets, is assumed to originate from the hadronically decaying W. A difference smaller than 20 GeV/$c^2$ is required. It is finally combined with the b jet giving the highest reconstructed top transverse momentum.

The cone algorithm used to reconstruct the jets tends to underestimate the opening angle between the two jets from the W.\(^9\) An in-situ calibration can however be applied to correct the jet energies and directions.

The distribution of the three-jet invariant mass is displayed in Fig. 3. The reconstructed top quark mass is deduced from the fit value of the peak. The combinatorial background is dominant. With an integrated luminosity of 10 fb$^{-1}$, the statistical uncertainty on the top mass is at the level of 100 MeV/$c^2$. The systematic uncertainties are summarized in Ref.\(^8\). The main two sources of systematic uncertainty are the final state radiation (FSR) and the b-jet energy...
scale. The FSR systematic error is conservatively evaluated as 20% of the shift in the fit top mass when disabling the FSR and amounts to 1 GeV/$c^2$. At LHC, the light and b-jet energy scales are expected to be determined with a 1% precision. In this analysis, the b-jet energy scale systematic uncertainty is 0.7 GeV/$c^2$ whereas the light-jet energy scale uncertainty is mostly canceled by the in-situ calibration and amounts to 0.2 GeV/$c^2$. Altogether a 1.3 GeV/$c^2$ error on the top mass is achievable. The effect of the FSR can be lowered down to 0.5 GeV/$c^2$ if a kinematic fit is implemented. Indeed, the events with large FSR tend to have a high $\chi^2$ and can be removed from the analysis. The systematic uncertainty thus becomes 0.9 GeV/$c^2$, dominated by the b-jet energy scale determination. As explained in the next section, it is possible to get rid of the heavy-flavour-jet-energy-scale related uncertainty.

2.3 Measurement in leptonic final state with $J/\psi$

A determination of the top mass quark mass can be carried out in the lepton+jet events where a $J/\psi$ arises from the b quark associated to the leptonic decaying W (Fig. 4). The top quark is partially reconstructed from the isolated lepton coming from the W and corresponding b quark.

Figure 3: Distribution of the jjb invariant mass of the selected events as obtained from a fast simulation of the ATLAS detector for a 5 fb$^{-1}$ integrated luminosity. The shaded area represents the combinatorial background.

Figure 4: Diagram of the top decay to leptonic final state with $J/\psi$(left). Example of lepton-$J/\psi$ invariant mass in the four-lepton final state as obtained from a fast simulation of the CMS detector after four years at high LHC luminosity (right).
To solve the twofold ambiguities on the b quark origin, a flavour identification, requiring a muon of the same electric charge as the isolated lepton, is applied. The J/ψ can be precisely identified and reconstructed when it decays into a muon pair. As a result, one isolated lepton and three non isolated muons are required, two of them being consistent with the J/ψ. This configuration is very seldom: one thousand events per year will be collected at high luminosity ($L = 10^{34}$ cm$^{-2}$s$^{-1}$). The isolated lepton-J/ψ invariant mass is determined (Fig. 4) and the fit value of the peak turns out to depend linearly on the generated top mass$^{11}$ (Fig. 5).

The background is essentially combinatorial, and its shape can be extracted from the data. The main systematic uncertainty comes from the b-quark fragmentation and is the combination of the uncertainty on the b hadron spectrum in top decays and that of the J/ψ spectrum in b hadron decays. The B factories can help in the determination of the latter. An overall error on the top mass of the order of 1 GeV/$c^2$ can be achieved.

![Figure 5: Correlation between the fit value of the peak of the lepton-J/ψ invariant mass distribution ($M_{\text{inv}}$) and the generated top mass as obtained from a fast simulation of the CMS detector.](image)

### 3 Search for single top

The top quark can also be produced by electroweak interaction. In this case, one single top is produced at a time. The total production cross section reaches is 310 pb. The production diagrams at tree level are displayed in Fig. 6. The dominant process is the W-gluon fusion ($t$ channel) with a cross section of about 250 pb. In the $t$ and $s$ channels, the production rate of top quarks is about 50% higher than anti-tops$^{12}$, while at the TeVatron, they are identical. The associate production cross section is about 50 pb and is one of the dominant backgrounds to the search for the Higgs boson in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel$^{10}$.

![Figure 6: Electroweak top production diagrams in the $t$ and $s$ channels (left) and associate production (right).](image)

The event preselection, as in the lepton-jet channels, requires a leptonically decaying W. The different event topologies need dedicated final selections. The $t$ channel is taken here as an example. The full analysis is described in Ref$^{13}$. The b jet from the initial gluon splitting is lost in the beam pipe. The events with one forward non b-tagged jet and one central b-tagged jet (coming from the top) are selected. The Wb invariant mass is then computed, the twofold ambiguity on the neutrino longitudinal momentum is solved by choosing the smallest one. This is true in only 55% of the cases. The result is shown in Fig. 7. The overall efficiency (including the W to lepton branching ratio) is 0.3%. More than 6000 events are expected in 10 fb$^{-1}$ of
integrated luminosity. The main backgrounds are $t\bar{t}$ and $W+\geq 2$ jets. A signal-to-background ratio of 3.5 is obtained.

The single top production cross section can be measured with a 10% precision, which is equivalent to a 5% precision on the measurement of the $V_{tb} (=1)$ element of the CKM matrix. The single-top polarization can also be measured in this channel with a 1.6% statistical precision\(^3\) with 10 fb\(^{-1}\).

4 Associate Higgs boson production

For small Higgs boson masses ($\lesssim 130\text{ GeV/c}^2$), the $H \to b\bar{b}$ decay channel is dominant. Unfortunately, it is impossible to efficiently trigger the acquisition of these events due to the huge di-jet $b\bar{b}$ background present at LHC. To observe the $b\bar{b}$ decay of the Higgs boson, an associate production mode (with $W$, $Z$ bosons or with a $t\bar{t}$ pair) has to be considered. The $t\bar{h}$ production diagrams are presented in Fig. 8. These channels allow the top Yukawa coupling to be measured. The cross section is small: $\sigma(m_H = 120\text{ GeV/c}^2) = 0.8$ pb, while the $t\bar{t}b\bar{b}$ background has a 3 pb cross section.

![Associate t\bar{h} production diagrams](image)

The lepton+jet events are first selected. The final state is intricate, since in addition of the “usual” lepton+jet event, two additional $b$ jets from the Higgs boson are present. As a result, the event selection requires at least six jets in the final state of which exactly four $b$ jets.

Both $W$’s are fully reconstructed. The two $b$’s from the top decays have to be identified and the pair giving the “best” reconstructed top quarks pair is chosen. The remaining two $b$’s are combined to reconstruct the Higgs boson. The resulting invariant mass distribution is shown in Fig. 9, showing a nice agreement between the ATLAS and CMS analyses and a peak due to the presence of the Higgs boson.
Figure 9: Signal plus background expectation for the Higgs boson reconstructed mass in the t\bar{t}H channel with H \rightarrow b\bar{b} in the CMS and ATLAS detectors for m_H = 115 GeV/c^2 and m_H = 120 GeV/c^2 with 30 fb^{-1} and 100 fb^{-1} respectively. In both cases, fast simulations of the detectors have been used.

The shape of the background can be extracted from t\bar{t}j data. With 30 fb^{-1}, 40 signal events are expected\(^3\), with a significance of 3.6 \sigma. A 16\% precision on the Yukawa coupling should be reached. The combination of the low and high luminosity runs giving a integrated luminosity of 100 fb^{-1} will allow a 4.8 \sigma significance and a 12\% precision on the Yukawa coupling to be reached. All these numbers are relative to a Higgs boson mass of 120 GeV/c^2.

Conclusion

The physics of the top quark will be one of the LHC main topics. Many exciting analyses will be carried out. Only a few of them have been summarized in this paper. Most of the analyses can be done with the the first 10 fb^{-1}. Due to the large production cross section, the statistical uncertainty will be, in most of the cases, quickly negligible.

The top mass measurement will be a key issue. A 1 GeV/c^2 precision can be reached provided that an excellent understanding of the detectors to control the systematic uncertainties. The study of the top quark sector highlights several theoretical challenges like the high order QCD calculations and the b fragmentation. Finally, most of the analyses presented in this report make use of fast simulation of the ATLAS and CMS detectors. As a result, the systematic studies are ahead of us.

Acknowledgments

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