TOP PHYSICS AT THE LHC

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Top quark physics will be a prominent topic in Standard Model physics at the LHC. The enormous amount of top quarks expected to be produced will allow to perform a wide range of precision measurements. An overview of the planned top physics programme of the ATLAS and CMS experiments at the LHC is given.

1 Introduction

The Large Hadron Collider (LHC) is expected to start operation in 2007. It will accelerate proton beams and bring them to collision at a centre of mass energy of $\sqrt{s}=14$ TeV and at luminosities between $(1-2) \times 10^{33} cm^{-2} s^{-1}$ (initial 'low-luminosity' phase) and $10^{34} cm^{-2} s^{-1}$ ('high-luminosity'). Top quark physics studies will be accomplished by the general purpose experiments ATLAS and CMS.

The reasons to study the physics of top quarks are numerous. The top quark is the heaviest known fundamental particle – its mass being a fundamental parameter of the Standard Model – and the only quark that does not hadronize because of its short lifetime ($\Gamma_t \gg \Lambda_{QCD}$). The top quark mass $m_t$ is of particular interest, because it is related through radiative corrections (the so-called $\Delta r$ parameter) to the mass of the W and Higgs bosons, $m_W$ and $m_H$. Precise measurements of $m_t$ and $m_W$ thus allow to constrain $m_H$. Top quark events will also be a major source of background for many search channels. They can be also very useful to calibrate the detector and reconstruction algorithms, e.g. the jet energy scales and b-tagging performance.

At the LHC, gluon-gluon fusion is the dominant process for $t\bar{t}$ production, contributing about 87% of the production cross section, whereas quark-antiquark annihilation contributes only about 13%. This is contrary to the situation at the TEVATRON. The $t\bar{t}$ production cross-section is about $\sigma_{t\bar{t}} \approx 800pb$. This implies that during the low luminosity phase of the LHC ($10^{33} cm^{-2} s^{-1}$), about one $t\bar{t}$ pair will be produced per second, resulting in about $10^7 t\bar{t}$ pairs per year.

Because of $|V_{tb}| \approx 1$, the top quark decays almost exclusively into a W boson and a b quark, $BR(t \to Wb) \approx 1$. The top quark decay is thus characterised through the decay of the W boson. In $t\bar{t}$ events, about 5% fall into the di-lepton category, $\approx 30\%$ into the semi-leptonic one and $\approx 45\%$ into the fully hadronic one (only electrons and muons are considered as leptons here).

2 Measurements of the top quark mass

The semi-leptonic channel $t\bar{t} \to b\bar{b} l\nu q\bar{q}$ is the most promising for an accurate measurement of the top quark mass. It has a relative large branching ratio and the isolated lepton ($e$ or $\mu$) allows
efficient triggering.

A typical analysis requires an isolated lepton, missing transverse energy, and at least four jets within the tracker acceptance. To suppress backgrounds and to resolve the combinatorics within the event, one or two jets have to be tagged as b-jets. The mass of the hadronically decaying top quark, thus the mass of the $Wb = jjb$ system, is used for the measurement.

Figure 1: Reconstructed top mass in the semi-leptonic channel for ATLAS (left) and CMS (right), for $10 \text{fb}^{-1}$ of integrated luminosity. For CMS, the combinatorial background within the event is included in the signal curve (only non-$t\bar{t}$ events are shown as background), whereas for ATLAS it is shown in the background curve.

Figure 1 shows the reconstructed top masses for ATLAS$^1$ and CMS$^2$. The remaining backgrounds (mainly W and Z boson(s) + jets) are very low. Already after one year of running at low luminosity, the measurement uncertainty is clearly dominated by systematics. Of particular importance is the knowledge of the b-jet energy scale (the sensitivity to the light jet scale is strongly reduced by using the W boson mass as constraint), which has to be determined at the level of a percent to reach the desired accuracy. It seems to be feasible to reach a precision on the top mass of about 2 GeV, maybe an ultimate precision of about 1 GeV could be reached when all effects are well understood.

The large number of events available allows to measure the top mass in different sub-samples using different methods showing different sources of systematic errors. ATLAS$^1$ has studied semi-leptonic events, where the top quarks are produced almost back-to-back with large transverse momentum, leading to very collimated top decay products well separated in hemispheres. The top quark mass is computed from the calorimeter towers within a large cone. The dominant systematics using this method is then the contribution from the underlying event and pile-up events.

The top mass can also be measured in the fully leptonic and fully hadronic channels. The Di-Lepton channel ($e, \mu$) is very clean. However, the branching ratio is quite small and because of the presence of two neutrinos in the final state the kinematics is underconstrained. The fully hadronic channel is experimentally very challenging. Efficient triggering is difficult and the QCD background is enormous. However, this channel has the biggest branching ratio ($\approx 45\%$) and the kinematics is fully constrained. Accuracies of about 2-3 GeV seem feasible for these channels$^1$.

ATLAS$^1$ and CMS$^2$ also studied the possibility to measure the top mass in the semi-leptonic channel in final states with an exclusively reconstructed $J/\Psi$ from a b-hadron decay in a b-jet, where the $J/\Psi$ carries a large fraction of the b-hadron momentum because of its large mass. The mass of the $J/\Psi - l$ system is strongly correlated to the top mass. The method is thus rather insensitive to the jet energy scale, the understanding of the b-fragmentation becoming crucial. Because of the tiny branching ratio of this final state, this analysis has to be carried out during the high luminosity phase of the LHC. Even after some $100 \text{fb}^{-1}$, the statistical error is expected to contribute significantly to the total error ($\approx 1$ GeV for a total error of $\approx 1.5$ GeV).
3 $t\bar{t}$ production properties

A measurement of the $t\bar{t}$ production cross section allows to test QCD calculations. Differential cross sections (e.g. $d\sigma_{t\bar{t}}/dt$) give access to parton distribution functions (PDFs). Heavy particles decaying into a $t\bar{t}$ pair could show up as resonances in the $t\bar{t}$ mass spectrum $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ and thus be an indication for new physics. Furthermore, the $t\bar{t}$ production cross section is sensitive to the top quark mass, $\sigma_{t\bar{t}} \propto 1/m_t^2$.

Because of its short lifetime, the top quark does not form bound states and thus there should be no dilution of the spin information in the decay. Top quarks are not expected to be produced polarised but their spins are expected to be correlated. The asymmetry $\mathcal{A} = N(t\bar{t})_L - N(t\bar{t})_R)/N(t\bar{t})_L + N(t\bar{t})_R)$ allows to distinguish between the $g-g$ fusion and $q\bar{q}$ production processes ($\mathcal{A} \approx 0.431$ vs. $\mathcal{A} \approx -0.469$). In fully leptonic events, $\mathcal{A}$ can be extracted from a fit to the double differential distribution of the angles between the leptons in their respective top frame and the top quark in the $t\bar{t}$ rest frame. A CMS study\textsuperscript{11} shows that the following accuracies can be reached after $30 fb^{-1}$ of integrated luminosity: $\sigma(\mathcal{A})_{stat.} \approx 0.035$, $\sigma(\mathcal{A})_{syst.} \approx 0.028$.

4 Top quark properties

The large number of $t\bar{t}$ events will allow precise measurements of top quark properties and tests of the V-A structure of charged current weak interactions.

The top quark charge has not yet been experimentally confirmed to be $2/3$. Two approaches have been studied by ATLAS\textsuperscript{12} to distinguish between $t(Q = 2/3) \rightarrow W^+b$ and $t(Q = -4/3) \rightarrow W^-b$. The first approach investigates $t\bar{t}\gamma$ events. Since the radiation of photons in these events is roughly proportional to $Q_t^2$ for the production process (radiation can also occur in the decay), the $p_T$ spectrum of the photons in $t\bar{t}\gamma$ allows to distinguish the two top quark charge values. The second approach measures the charges of all top quark decay products. Whereas for the leptonic W boson decay the charge is given by the charge of the lepton ($e$ or $\mu$), a jet-by-jet estimation of the b-quark charge is not possible. However, quantities correlated to the charge of the b-quark allow to distinguish between the cases on a statistical basis. As an example, the jet charge $Q_{jet} = \sum_i q_i |\vec{p}_Ti| / \sum_i |\vec{p}_Ti|$ has been studied. Both methods should allow an unambiguous measurement of the top quark charge after one year of data taking at low luminosity ($10 fb^{-1}$).

Because of the V-A structure of weak charged current interactions, the W bosons in top quark decays are expected to be polarised. The predicted population of the helicity states of the W boson are: $h_W(-1) \approx 0.3$, $h_W(0) \approx 0.7$, $h_W(+1) \approx 0$. In semi-leptonic events, the angle between the lepton in the W boson rest frame and the W boson in the top quark frame, $\Theta_l^*$, can be analysed. A CMS study\textsuperscript{13} gives the following accuracies for the longitudinal helicity state after an integrated luminosity of $10 fb^{-1}$: $\sigma(h_W = 0)_{stat.} \approx 0.023$, $\sigma(h_W = 0)_{syst.} \approx 0.022$.

5 Single top production

Single top quark events can be created via electro-weak processes. The contributing diagrams together with their expected cross-sections are shown in Figure 2. Single top events give direct access to the absolute value of the CKM matrix element $V_{tb}$. Backgrounds ($t\bar{t}$, $Wj\bar{j}$, $Wbb$) are more severe than for $t\bar{t}$ events and the ability to extract clear signals depends more critically on the detector performance. The different production processes show different final states and are thus typically studied separately. To reject the enormous QCD background, the leptonic decay channel $t \rightarrow b\ell\nu$ ($\ell = e, \mu$) is studied. An ATLAS study\textsuperscript{14} gives the following statistical experimental errors on $|V_{tb}|$ after $30 fb^{-1}$: $\sigma(|V_{tb}|)_{(W-g)} \approx 0.4\%$, $\sigma(|V_{tb}|)_{(W-t)} \approx 1.4\%$.\textsuperscript{15}
\[\sigma(|V_{tb}|) \approx 2.7\%.\] The dominating systematic uncertainties are expected to come from theoretical uncertainties of the cross section calculations and the luminosity measurement.

6 Calibration with $t\bar{t}$ events

The possibility to isolate clean samples of $t\bar{t}$ events allows the calibration of reconstruction algorithms. Using the W boson mass as a constraint allows to calibrate the jet energy scale of light quark jets. Jet samples enriched in b-quark jets (from the top quark decay) and light quark jets can be isolated and used to determine the b-tagging efficiencies on the data themselves.

7 $t\bar{t}$ in associated Higgs production

For low Higgs masses ($m_H \lesssim 135$ GeV), the dominant decay mode of the Higgs boson is $H \rightarrow b\bar{b}$. However, this decay mode can only be exploited in channels of associated Higgs production, $t\bar{t}H$ being the most promising one. From the experimental point of view, this channel is complementary to the channel $H \rightarrow \gamma\gamma$. Furthermore, this channel would allow a measurement of the top-Higgs Yukawa coupling. In order to find the b quark jets from the Higgs boson decay, the $t\bar{t}$ system can be fully reconstructed. ATLAS\(^7\) and CMS\(^8\) studies indicate that this channel might support a discovery of a light Higgs boson.

8 Conclusions

At the LHC, top quarks will be produced abundantly. The goal for the top mass measurement is to reach an accuracy of approximately 1 GeV. The large available statistics will also allow to determine many top quark properties both in production and decay. Single top production will make a precise determination of $|V_{tb}|$ possible.

References

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