Top Physics Capabilities at the LHC

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The Large Hadron Collider will be considered a top factory, with about 8 million $t\bar{t}$ events produced in the first year of running at low luminosity. This large data set will allow very precise measurements of the properties of the top quark which may also reveal new physics. The mass of the top quark will be measured with a precision of about $1 \text{ GeV}/c^2$. The top quark Yukawa coupling should be determined with a precision of better than 10% for a Higgs mass of about $100 \text{ GeV}/c^2$. $t\bar{t}$ spin correlations will be observed and used to study anomalous couplings or CP violation. Possible heavy resonances decaying to $t\bar{t}$ pairs will be detectable with masses up to $3 \text{ TeV}/c^2$. Rare decays of the top quark with branching ratios as small as 10^{-5} will be seen. Finally, the detailed study of three different mechanisms of electroweak single top production will yield a wealth of information, including precision measurements of V_{tb} , W and top polarizations, and searches for anomalous couplings.

1. Introduction

The Large Hadron Collider (LHC) is currently scheduled to begin operation in April 2007 providing experiments with proton-proton collisions at 14 TeV CM energy. The initial low luminosity is expected to be $\approx 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and will eventually reach the full potential of $\approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The cross section for producing $t\bar{t}$ pairs is $\approx 830 \text{ pb}$ (NLO)[1] which means that there will be over 8×10^6 $t\bar{t}$ events at low luminosity and 10 times that quantity at high luminosity; the LHC will be considered a top factory.

The large data set of top quarks means that precise measurements will be made of its properties. Searches for rare and anomalous decays will also be performed with the possibility of revealing physics beyond the Standard Model.

In the following, the ability of the ATLAS detector to measure some important properties of the top quark will be described. First the measurement of the top mass will be presented. The measurement of the Yukawa coupling to the top is described second. Spin correlations are then discussed. The limits of some FCNC decays will be presented next followed by strategies to measure top quark branching ratios. Resonances that decay to $t\bar{t}$ pairs and physics pertaining to single

top production are discussed last. All results are based on Monte Carlo simulations.

The other general purpose LHC experiment, CMS, will have a similar ability to measure these properties.

2. Top Mass Measurement

A fundamental parameter of the Standard Model is the mass of the top quark, m_t . Also in the SM, the masses of the W and Higgs gauge bosons are related to m_t through radiative corrections. Hence as the top mass is more accurately known, the constraint on the Higgs mass is tightened.

At the LHC, the top mass will best be measured in the lepton plus jets channel of $t\bar{t}$ decay. In this channel, each quark in the top pair decays to a b and a W ; one W decays hadronically, the other decays leptonically:

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bl\nu)(bjj) \quad (l = e \text{ or } \mu). \quad (1)$$

The lepton and the missing energy from the undetected neutrino will be used to tag the event and the invariant mass of the bjj system will be used to make the top mass measurement. The lepton plus jets channel also allows the reconstruction of both the top and anti-top if the W and neutrino masses are assumed to be known and the missing transverse energy is identified as

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Figure 1. Invariant mass of bjj system after 10 fb^{-1} of integrated luminosity. The shaded area is the combinatorial background only.[3]

$p_T(\nu)$.

The following criteria will be typical of the cuts used to select $t\bar{t}$ events for the top mass measurement: a lepton (e or μ) with $p_T > 20 \text{ GeV}/c$, $E_T^{miss} > 20 \text{ GeV}$, and at least 4 jets with $p_T > 40 \text{ GeV}/c$. Two of these jets should be tagged as a b -jet. Candidates for the hadronically decaying W will be found by calculating the invariant mass of non- b -tagged jets, m_{jj} , and comparing it to the known W mass, m_W . The combination of light quark jets that gives the smallest value of $|m_{jj} - m_W|$ will then be combined with the b -jets. The 3-jet combination with the largest transverse momentum will be the resulting top candidate.

Backgrounds include the production of Z +jets, W +jets, pairs of massive gauge bosons. The resulting signal-to-background ratio will be ~ 65 . [3]

The m_{bjj} distribution is shown in Figure 1. The statistical uncertainty in m_t after 10 fb^{-1} of integrated luminosity will be $0.070 \text{ GeV}/c^2$.

The largest systematic uncertainty in m_t will arise from the jet energy scale and final state radiation. If the jet energy scale is known to 1%, then the systematic uncertainty in m_t will be below $2 \text{ GeV}/c^2$. Many strategies can be used to improve on this value. For example, larger cones that define jets will reduce the sensitivity to FSR. As well, light jets can be calibrated on an event-by-event basis by assuming the W mass. As a

result, the systematic uncertainty in m_t at the LHC will be $1 \text{ GeV}/c^2$. [2,4]

3. Yukawa Coupling

In the SM, the Yukawa coupling to the top quark, y_t , is very close to unity for $m_t \sim 175 \text{ GeV}/c^2$. To measure this quantity, events with $pp \rightarrow t\bar{t}HX$ with $H \rightarrow b\bar{b}$ will be searched for using similar criteria to measure the top mass in the lepton plus jets channel (Section 2) except at least 4 b -jets will be required. Once the b -jets associated with the top pair decay have been identified, pairs of the remaining b -jets can be taken to look for a Higgs mass signal. The relative statistical uncertainty of measuring y_t after 30 fb^{-1} integrated luminosity is 11.9% and 16.2% for m_H values of $100 \text{ GeV}/c^2$ and $120 \text{ GeV}/c^2$, respectively. [3]

4. Spin Correlations

Top quark pairs produced at the LHC will have correlated spins most of the time. [5] Specifically, the top and anti-top will both have right-handed helicity, $t_R\bar{t}_R$, or both have left-handed helicity, $t_L\bar{t}_L$ at the 65% level. The large mass of top quarks means that they decay ($\tau \sim 10^{-24} \text{ s}$) on a time scale much faster than the time hadronisation can take place. Therefore, the angular distributions of the top decay products can be used to analyse the spin of top quarks, measure the degree of spin correlation, and look for possible anomalous couplings and CP violation.

Many methods exist for investigating the spin correlations. [6] One method would be to look at the opening angle between the two oppositely charged leptons, $\cos\theta_{ll}$, in the dilepton channel ($t\bar{t} \rightarrow (b\nu)(b\nu)$) which is sensitive to the amount of spin correlation. Other methods include looking at the lepton plus jets channel, reconstructing the $t\bar{t}$ system, and measuring the angular distributions of the decay products directly.

5. FCNC decays

Flavour changing neutral current (FCNC) decays will be investigated. [6] In each case, the limits predicted by the SM and MSSM are too

small to be measured, but an opportunity for new physics to be revealed is provided. All limits in this section correspond to 100 fb^{-1} integrated luminosity. Also, events thought to be likely contributors to the background have been considered.[3]

5.1. $t \rightarrow qZ$

The SM and MSSM predicts $\text{BR}(t \rightarrow qZ)$ to be on the order of 10^{-12} and 10^{-8} , respectively. The optimal way to measure this branching ratio is to look at top pair events where one top decays as usual to a b -quark and a W boson, and the other top decays to qZ with $Z \rightarrow ll$ (ie. $t\bar{t} \rightarrow (bW)(qZ)$). When the W decays leptonically a clean signal can be obtained with the resulting 3-lepton tag and a branching ratio as small as 1.1×10^{-4} can be measured.

5.2. $t \rightarrow q\gamma$

The SM and MSSM predicts $\text{BR}(t \rightarrow q\gamma)$ to be on the order of 10^{-12} and 10^{-8} , respectively. Top pair events are again used with the W decaying leptonically, $t\bar{t} \rightarrow (b\nu)(q\gamma)$ gives a lepton and hard gamma from which these events can be selected. A branching ratio as small as 1.0×10^{-4} can be measured.

5.3. $t \rightarrow qg$

This decay is difficult to see because it is dominated by QCD backgrounds. However, same sign top production ($qq \rightarrow t\bar{t}$) with a t -channel gluon has two tgq couplings at tree level and it will be relatively easy to detect these events. In this case, a branching ratio as small as 7.4×10^{-3} can be measured.

6. Top Quark Branching Ratios

6.1. $\text{BR}(t \rightarrow Wb)$

To measure $\text{BR}(t \rightarrow Wb)$, the ratio of $t\bar{t}$ events in the lepton plus jets channel with two b -tagged jets to single b -tagged jets will be determined. The first b -jet is used to identify the event as $t\bar{t}$ and the second b -jet is used to determine the fraction of top quarks decaying to bW (SM predicts 99.9%). The statistical uncertainty, $\delta R_{2b/1b}/R_{2b/1b}$ in the ratio after 10 fb^{-1} of integrated luminosity will be $\sim 0.2\%$. [3]

Figure 2. Invariant mass of the $t\bar{t}$ system for a narrow resonance of mass 1600 GeV.[3]

6.2. $\text{BR}(t \rightarrow WX)$

The SM predicts $\text{BR}(t \rightarrow WX) = 100\%$ and can be tested at the LHC. In a similar way to the $\text{BR}(t \rightarrow Wb)$ measurement, the ratio of $t\bar{t}$ events with two leptons to single leptons will be determined. The SM predicts $R_{2l/1l} \approx 2/9$. The statistical uncertainty, $\delta R_{2l/1l}/R_{2l/1l}$ in the ratio after 10 fb^{-1} of integrated luminosity will be $\sim 0.5\%$. [3]

7. Resonances

The invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$, may reveal s -channel resonances in $gg, q\bar{q} \rightarrow t\bar{t}$. [6] For example, the MSSM predicts $\text{BR}(H, A \rightarrow t\bar{t}) \approx 100\%$ for $m_{H/A} > 2m_t$ and $\tan \beta \approx 1$. Figure 2 shows how a possible resonance at 1600 GeV may appear.

8. Single Top Production

Certain measurements of top quark properties can be made with single top quarks. [6] The tree level processes by which single tops will be produced at the LHC are shown in Figure 3. In order to select single tops, events with a high p_T lepton ($p_T > 20 \text{ GeV}/c$) from $t \rightarrow Wb \rightarrow l\nu b$ will be identified. The other selection criteria will be optimised depending on which process is of interest. Backgrounds to single top production include Wjj , $Wb\bar{b}$, and $t\bar{t}$ events.

Figure 3. Tree level diagrams for single top production processes at the LHC. The first two diagrams represent W -gluon fusion (250 pb) followed by Wt production (60-110 pb) and s -channel W^* process (10 pb).[3]

8.1. V_{tb}

The CKM matrix element V_{tb} is well determined if unitarity is assumed as it is in the SM. At the LHC, there will be the opportunity to measure V_{tb} directly.

A determination of V_{tb} depends on the cross section measurements of the single top production processes. For example, an expected statistical uncertainty of 0.71% (30 fb^{-1}) in the cross section of the W -gluon process implies an uncertainty of 0.36% in the V_{tb} measurement. However, in this case, the errors are dominated by uncertainties in the parton distribution functions of the proton and cross sections of background processes, and the uncertainty in m_t . The relative uncertainty in the cross section from these sources is 11% for the W -gluon process.

8.2. Top and W polarisation

The SM predicts single top quarks produced in the s -channel W -gluon process are 100% polarised at leading order. The angular distributions of the top quark decay products will retain the information about the polarisation. An obvious choice to study would be angular distributions of leptons in the top rest frame which go as $(1 \pm \cos \theta_l)/2$ for right- (+) and left-handed (-) top quarks.

The SM predicts that W bosons from top decay are longitudinally polarised at the 70% level with the remaining 30% having left-handed helicity. Angular distributions can again be used to

determine the left, right and longitudinal components of the W polarisation and whether or not the SM prediction holds.

9. Conclusion

The LHC will provide a large data sample of top quarks from which precision measurements of the top quarks can be made. Measurements that will be made include the mass, couplings, and polarisations of the top quark. Predictions of the SM will be tested and new physics may be revealed.

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