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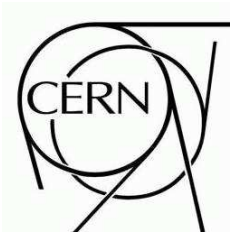

Prospect for Top Mass and properties measurements at the LHC

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Abstract

Top Physics prospects at the LHC are reviewed. A particular emphasis is put on the precision determination of the top mass, the strategies for single-top cross-section measurements and the potential for W boson and top polarizaton property measurements.

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1. Introduction

Since the discovery of the top quark in 1995 at Fermilab's collider by CDF and DØ , many progress have been made in the knowledge of its properties, its mass, spin, charge and couplings to fermions or bosons. However, except for the mass, the precision for most of these measurements is statistically limited and will most presumably still be at the end of the run II.

With more than 8 millions of expected top pairs and more than 2 millions of single top events produced every year during a low luminosity run, the LHC experiments will open a new era of precision measurement in the top quark physics field. Given the nature of their final state and the specificities of their topologies, $t\bar{t}$ events will also constitute one of the main benchmark sample in many fields, from jet energy scale determination to the measurements of the performance for b tagging and lepton identification tools, useful from the very early data taking period.

2. Top quark production at the LHC

At the LHC, top quark production is dominantely produced in pairs, by gluon fusion (90%) or via a quark-antiquark annihilation (10%). The expected top pair cross-section at the Next To Leading Order (NLO) is $\sigma_{t\bar{t}} = 833 \pm 100$ pb [1] for $m_t = 175$ GeV/c^2. This prediction includes (N)NLL soft gluon resummation and is affected by a total uncertainty of 12% coming from both the renormalization scale and PDFs uncertainties.

The Standard Model also allows for the top quark to be produced singly rather than in pairs via the electroweak charged current interaction, a mode typically referred to as single-top quark production. The dominant contribution to the cross-section is the t-channel production, which accounts for about 250 pb at NLO; it is followed by the associated production of a top quark and a W boson, with a cross-section of 62 pb; finally it includes also the s-channel production coming from the exchange of an off-shell W boson, with a cross-section of 10 pb [2] [3] [4]. The uncertainties on those numbers is about 4 to 5% [2] [4].

The main physics background to the top quark production is constituted by the 'W+jets' events. However, the rates of such events relatively to the top production rate is not expected to be as important as it is at the TeVatron collider energies [5], and in most cases top quark events wrongly identified or from other decay channels will constitute the main background to a specific top analyses. Note that in the present studies, no QCD background has been considered.

3. Top quark mass determination at the LHC

Strategies for measuring the top quark mass relies mainly upon the top pair selection, where the level of background contamination and systematic uncertainties are expected to be reasonnably known. We report here on the most promising results, obtained from the 'lepton+jets' and the 'di-lepton' analyses. The use of the 'full hadronic' channel [6] [7], or the use of other methods using the invariant mass of the J/Ψ and the lepton from W [8], decay length reconstruction, or the use of single-top events [9], has been investigated as well and shown to be useful with a higher integrated luminosity.

3.1. top mass in the lepton+jets channel

The golden channel used for the top mass determination is the 'lepton+jets' final state, combining high branching ratio and reasonnably low expected background. The preselection of these events relies on the identification of an isolated high p_T lepton and the reconstruction of at least four high p_T jets in the central pseudo-rapidity region. Events are then classified according to the number of b-taggged jets. The top mass determination is then based on the reconstruction of the three jet invariant mass M_{jjb}.

In ATLAS, the W boson is first reconstructed using the invariant mass formed by all two-jet combinations among non b-tagged jets, keeping the solution with the closest value to the W mass. This approach leads to an overall W purity of 66% (55%) in the '2-btag' ('1-btag') sample for a right combination contained in the $|m_{jj} - m_W| < 20$ GeV/c^2 window, and corresponds to an overall efficiency

of 3.2%. A b-jet must then be associated to the reconstructed W boson to form the top quark. In the '1-btag' sample, the association is performed if the b jet is closer to the W than to the isolated lepton. For '2-btag' events, the b-jet leading to the highest top transverse momentum is chosen. An overall efficiency of 1.2% (2.5%) is achieved for a corresponding purity of 69% (65%) for events such that $|m_{l\nu b} - m_t| < 35$ GeV/c^2. With 10 fb^{-1} the expected yield is 30K events, with a 11 GeV/c^2 resolution and a statistical uncertainty of 0.1 GeV/c^2 [7].

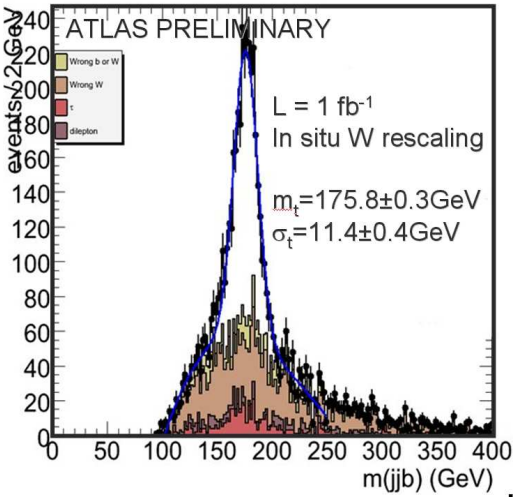

Figure 1. Reconstructed mass in the lepton+jets channel for 1 fb^{-1} in ATLAS

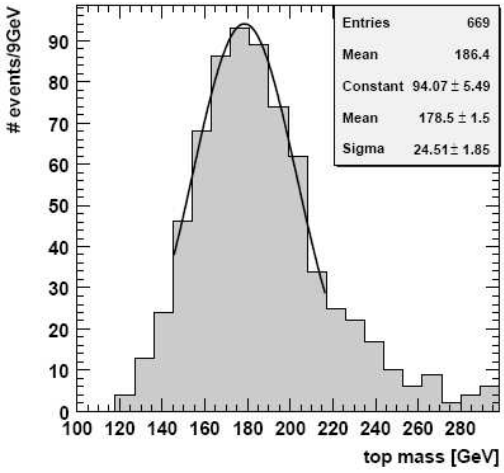

Figure 2. Reconstructed mass in the dilepton channel for 1 fb^{-1} in CMS

In CMS, only the four leading jets are considered to reconstruct the $t\bar{t}$ topology. Two jets must be b-tagged while the two others have to be un-tagged. In a first step, a likelihood ratio method is used to discriminate the 'lepton+jets' channel from the other $t\bar{t}$ decays. In a second step, for each jet combination, a constraint kinematic fit is applied, forcing the hadronic W boson mass to its PDG value. The right combination for the hadronic top quark is then chosen via the use of a likelihood function based on the event kinematics. The combination with the highest value is considered as the best pairing and is converted into a probability for the event to have the correct jet association. By keeping events with a probability above 60% and within a window of ± 25 GeV/c^2 around the generated top mass, the purity reaches 81%. The top mass is then determined by two top quark mass estimators: a simple fit on the reconstructed top mass spectrum, and an event-by-event likelihood methods, convoluting the resolution function of the reconstructed event with the expected theoretical templates [10].

In both experiments, the measurements are dominated by the systematic uncertainties as soon as the few 100 pb^{-1} accumulated data is reached. ATLAS and CMS both claim that an error around 1 GeV/c^2 can be reached with an integrated luminosity of 10 fb^{-1} . The dominant source of uncertainty comes from the knowledge of the jet energy scale. In ATLAS, a 1% mismeasurement in the b-jet energy scale results in a mass shift of 0.7 GeV/c^2 , while it induces a 0.2 GeV/c^2 shift due to light jet miscalibration [7]. Similar results are obtained in CMS [10]. In both experiments, the use of an situ calibration based on the $W \rightarrow jj$ reconstruction will be a determinant factor. Such a procedure not only improves the mass resolution but also reduces the dependence in the JES knowledge of the measured top mass.

Other sources enter the top mass uncertainty. The modeling of gluon radiations affects the number of reconstructed jets in the events, and impacts the jet energy reconstruction as well as the selection efficiency. Initial and Final radiations contribute to Δm_{top} to 0.2 to 0.3 GeV/c^2 in CMS (0.5 GeV/c^2 in ATLAS) depending on the jet reconstruction algorithm. Pile-up and underlying event modeling also affect the m_{top} determination, with contributions of 0.2 and 0.3 GeV/c^2 (CMS) to Δm_{top}. The dependence

of the reconstructed b jet to the b quark fragmentation function is shown to contribute to the error by 0.1 GeV/c^2 to 0.3 GeV/c^2 . The uncertainty of b-tagging performance also affects the performance of the jet association procedure and CMS quotes an effect of 0.2 GeV/c^2 . The total uncertainty quoted by both experiments is $\Delta m_{top} = 1.1$ GeV/c^2 for an integrated luminosity of 10 fb^{-1} .

3.2. top mass in the lepton+jets channel

The top quark mass can also be determined in the dilepton channels, relying on a simpler selection but with lower statistics. In both experiments, the event selection rests on the detection of two isolated high p_T leptons of opposite signs, a high transverse missing energy, and at least two high p_T jets, among which one or two at least have to be b-tagged.

A similar procedure is then followed by both ATLAS and CMS experiments: each $t\bar{t}$ event is then fully reconstructed by solving a system of 6 equations and 6 unknowns (3 components of the two neutrino momenta) based upon the conservation of the overall transverse momentum of the $t\bar{t}$ system as well as on mass constraints applied to the W bosons and the two top masses required to be equal. In ATLAS, about 80 K events are expected to be selected in 10 fb^{-1} with a ratio S/B $\approx$ 10 [7]. The reconstruction algorithm is fed with different input top masses and a weight is attributed to each solution by comparing the measured event topology to the expected one. A 'preferred' top mass is thus determined on an event by event basis and the final m_{top} value is obtained by fitting the full event weight distribution. A mass resolution of 13 GeV/c^2 seems achievable with a statistical error below 0.3 GeV/c^2 in ATLAS [7]. Similar results are obtained in CMS [6]. Again, the main systematics comes from the miscalibration effect of b-jets, which accounts for 0.6 GeV/c^2 in the mass, as well as ISR/FSR modelling. Variation of b-quark fragmentation parameters result to an error of 0.6 GeV/c^2 . Another source of uncertainty comes from the high dependence to the MC simulation used to attribute the weight, seen in the PDF contributions to Δm_{top}. An overall systematics of 1.6-2.0 GeV/c^2 seems achievable with 30 fb^{-1} .

4. Single-top cross-section determination at the LHC

Single top events have common features, which allows to define a set of triggers and a pre-selection relevant for all three mechanims. Events are only searched for in the leptonic decays of the W boson originating from the top quark decay, leading to the requirement of an isolated high p_T lepton and a significant missing transverse energy.

Single-top selections are affected by a significant level of background contamination, coming mainly from the $t\bar{t}$ production, leading the analyses to focuse on low multiplicity jet events. This make the analyses very sensitive to the contamination from di-lepton and tau decays of $t\bar{t}$ events. Regarding the W+jets, NLO computations show that the expected ratio of top events production over W+jets is much more favourable at the LHC than at the TeVatron [5]. However a good control of all those backgrounds in shape and normalization (including QCD) appear mandatory to all single-top analyses.

4.1. t-channel

In both collaborations, preslected events are splitted according to the number of jets. CMS uses 2 jet only events, while ATLAS uses both the '1b1j' and '1b2j' final states. Exactly one b jet is required and a jet veto is applied to any extra jet to reduce $t\bar{t}$ events contamination. The other jet(s) present in the event must be un-btagged and one of them is required to point towards the high rapidity region with $|\eta| > 2.5$, as expected from the production mechanism.

At this stage, ATLAS uses as extra requirements the reconstruction of a leptonic top mass $M_{l\nu b}$ to reduce the W+jets contamination, and applies a window on $H_T = \Sigma p_T(\text{jet})$. The ratio S/B is found to be about 2.1 where the background source is the $t\bar{t}$ production. In two and three jet events, about 8,500 signal events are expected for an integrated luminosity of 10 fb^{-1} with a S/B of to 1.2 due to the high $t\bar{t}$ contamination [11]. In CMS, only two-jet events have been considered so far, and the event yield is about 2,400 for 10 fb^{-1} with a ratio S/B = 1.3, leading to a significance of $S/\sqrt{S+B} = 37$ [12].

4.2. W+t channel

The selection W+t events is based upon the reconstruction of both hadronic and leptonic decaying W bosons. The event selection is based upon the selection of two or three high p_T jets, among which one must be b-tagged. A second b jet veto, with a looser definition, may be applied. In ATLAS, the reconstructed leptonic top mass, as well as H_T and the total mass of the events are then used to improve the background rejection. For events with more than 3 jets, the reconstructed hadronic W boson mass is used as an additional constraint to further reduce background. Typical efficiencies at the 7% level are found corresponding to about 6,000 events with a ratio $S/B \approx 10\%$, and result in a statistical sensitivity of 2% for 10 fb^{-1} [11].

In CMS, the H_T and top mass window cuts are completed by requirements on the reconstructed p_T of the W boson and the top system. For 10 fb^{-1} , the event yield is about 600 events with a ratio S/B of 37% in the di-lepton channel, and 1,700 events with $S/B \approx 18\%$ in the 'lepton+jets' channel. A ratio method is then used to reduce the systematics related to the dominant $t\bar{t}$ background, using a control region where the kinematics of Wt and to ppair events is similar. This allows to reduce systematics due to the uncertainties in the $t\bar{t}$ cross-section as well as, b-tagging, Jet energy scale and PDF uncertainties [12].

4.3. s-channel

The selection of the s-channel events requires exactly two high p_T b-tagged jets with a veto of any extra jet above 20 GeV/c. In ATLAS, extra requirements are performed on the reconstructed top mass $M(l\nu b)$ and variables as the scalar sum of the event's transverse energy H_T, the invariant mass formed with the lepton, allowing to further purify the selected sample. A total of 220 signal events are expected for 10 fb^{-1} , with a ratio S/B ranging between 10-15%. A statistical sensitivity of 7-8% seems achievable for 30 fb^{-1} [11].

In CMS, the preselection is similar, with an additional constraint to the reconstructed W boson transverse mass. A genetic algorithm analysis is then used to optimize the requirements on the jet momenta and the leptonic top mass and variable as the reconstructed top p_T and H_T. A ratio of $S/B \approx 13\%$ is reached for 10 fb^{-1} for 270 surviving events [12].

4.4. Systematic uncertainties

At the LHC, the single top measurements will be early dominated by a total systematic uncertainties above 10%. Experimental biases affect significantely the selection efficiency. The b tagging efficiency and mistag rates uncertainties affect mostly the s-channel selection (8%), and the W+t analysis and the t-channel (4%). The JES uncertainty affect the analyses where mass reconstruction and total jet energy are used in the selections. A 5% variation of the JES results in a 5% effect on the cross-section in ATLAS and 3% in CMS. Important sources of systematics comes from the gluon radiation modeling, which affects directly the event's jet multiplicity and impacts the performance of the jet veto (7% to 9% quoted). The uncertainty on the expected background is also important (6% in ATLAS, 4% in CMS), and both the normalization and shapes for $t\bar{t}$ and $W+$jets events will require the use of independent measurements to tune MC generators with data and the use of ratio methods as developped in CMS.

5. W boson and top quark polarization

Because of its high mass, the top quark decays before it hadronizes or its spin flips, thus leaving an inprint of its spin on its angular decay distributions [13].

5.1. W boson polarization

W bosons decay of top quarks are produced with a longitudinal, left-handed or a right-handed polarization. In SM $t\bar{t}$ events, W bosons are mainly produced longitudinally with the corresponding probabilities $F_0 = 0.695$, $F_L = 0.304$ and $F_R = 0.001$ for a W^+ [16]. Any deviation of F_0 from the SM value would pintpoint an inconsistency in the Higgs mechanism, responsible for the longitudinal degree

of freedom of the massive bosons, while deviations in F_L or F_R would be a sign of additional (V+A) admixture as predicted in the $SU(2)_L \times SU(2)_R \times U(1)$ extensions of the SM [17].

Both 'di-leptonic' and 'lepton+jets' samples have been used. The polarization is assessed via the measurement of Ψ defined as the angle between the lepton direction in the W rest frame and the W direction in the top quark rest frame:

$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\Psi}{2}\right)^2 + F_R\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

As both rest frames are used in the analysis, the event topology has to be fully reconstructed, which makes the 'lepton+jets' sample the best choice for such analysis. In the 'di-lepton' sample, because of the presence of two neutrinos, the Ψ angle is reconstructed using the following relation [18]: $\cos\Psi \approx 2M_{lb}^2/m_t^2 - m_W^2 - 1$, where m_t and m_W are set to 175 GeV/c^2 and 80.41 GeV/c^2 . Table 1 reports the performance expected in the SM framework for an integrated luminosity of 10 fb^{-1} in ATLAS. Combining 'lepton+jets'and 'di-lepton' analyses, F_L and F_R are determined at a few percent precision level. Similar results are found in CMS.

Measurements are largely dominated by the systematic uncertainties. At the generation level, the main systematics originate from the scale used for the parton generation, the uncertainty in the generated top mass and the choice of the pdf's. Biases due to the event simulation and reconstruction come from the effects of ISR/FSR on the angles and energy reconstruction, the uncertainty on the top mass knowledge as well as the b-jet energy scale that directly affects the determination of $\cos\Psi$. Uncertainty in the determination of the background and pile-up effects have also been taken into account.

F_L	$0.303 \pm 0.003_{stat} \pm 0.024_{syst}$
F_0	$0.697 \pm 0.004_{stat} \pm 0.015_{syst}$
F_R	$0.000 \pm 0.003_{stat} \pm 0.012_{syst}$

Table 1. *Sensitivity to the measurements of the W boson polarization parameters with an integrated luminosity of 10* fb^{-1}

5.2. top quark polarization measurement

In the top pair production, top quarks are not polarized. However, the top and anti-top spins are correlated due to their production mechanism: the $q\bar{q}$ anihilation generates a $^3S_1$ state resulting in aligned top and anti-top spins directions, while the gluon fusion produces a $^1S_0$ final state leading to opposite direction spins. In the helicity basis, the following observable is used :

$$\mathscr{A} = \frac{\sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_R) - \sigma(t_L\bar{t}_R) - \sigma(t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_R) + \sigma(t_R\bar{t}_L)}$$

$\mathscr{A}$ can be written as function of the measured angular distributions of θ_1 and θ_2, where θ_1 (θ_2) of the $t(\bar{t})$ spin analyzer in the $t(\bar{t})$ rest frame and the $t(\bar{t})$ direction in the $t\bar{t}$ center of mass of the system, are used to estimate the $t\bar{t}$ correlation.

A precision of 6.5% in $\mathscr{A}$ and below 5% in $\mathscr{A}_{\mathscr{D}}$ can be achieved in the SM framework. These results can be compared with the TeVatron 40% precision (stat.) expected with a luminosity of 2 fb^{-1}. Any deviation from the SM predictions can sign the presence of new heavy resonances in the $t\bar{t}$ production of spin-0 particule ($H \to t\bar{t}$) or spin-2 particule (Kaluza-Klein gravitons). It can also probe presence of technicolor or topcolor theories.

6. Acknowledgments

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