IL NUOVO CIMENTO Vol. 35 C, N. 3 Maggio-Giugno 2012
DOI 10.1393/ncc/i2012-11242-5

Colloquia: TOP2011

Prospects for $t\bar{t}H$ at the LHC

S. Allwood-Spiers on behalf of the ATLAS and CMS Collaborations

University of Glasgow - Glasgow, G12 8QQ, UK

ricevuto l' 1 Marzo 2012
pubblicato online il 4 Giugno 2012

Summary. — The search for the Higgs boson is a major focus for the ATLAS and CMS experiments at the Large Hadron Collider. If the Higgs boson has a low mass ($m_H < 130\,\text{GeV}$) then its production in association with a top quark pair could be observed. Searching for $t\bar{t}H$ signals is very challenging due to a small signal cross section, large backgrounds, and a high number of jets in the final state. Here we review previous simulation studies of $t\bar{t}H(H \to b\bar{b})$. We show the current status of the major background measurement, $t\bar{t}$+jets. We outline recent improvements in theoretical predictions, Monte Carlo generators and jet reconstruction techniques that will enable us to perform this search in the near future.

PACS 14.65.Ha – Top quarks.
PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

If the Higgs boson exists and has a low mass ($m_H < 130\,\text{GeV}$) then its production in association with a top quark pair, $t\bar{t}H$ production, could be observed. The dominant Higgs decay mode in this region is $H \to b\bar{b}$. The $t\bar{t}H(H \to b\bar{b})$ process is not hopeful as a Higgs discovery channel but would be an important later measurement, to study the Yukawa coupling of the Higgs boson to the top quark and to the b quark. The prospects for a $t\bar{t}H(H \to b\bar{b})$ search are reviewed, concentrating on the channel in which one top quark decays leptonically and the other decays hadronically (the single lepton channel), which has a cross section × branching ratio $\sim 20\,\text{fb}$ for $m_H = 120\,\text{GeV}$ at $\sqrt{s} = 7\,\text{TeV}$.

The signature for $t\bar{t}H$ in the single lepton channel is a high p_T isolated lepton, significant missing transverse energy (E_T^{miss}), and six or more jets, of which four or more are tagged as b-jets. All analyses considered here reconstruct the top quark candidates first and then combine the remaining b-jets to create the Higgs candidate. The major backgrounds are from $t\bar{t}$+light jet events and $t\bar{t}b\bar{b}$ events.

TABLE I. – *Results of a CMS simulation study in the single lepton decay channel of* $t\bar{t}H(H \to b\bar{b})$ *for* $m_H = 120\,\text{GeV}$ *with* $60\,\text{fb}^{-1}$ *of data at* $\sqrt{s} = 14\,\text{TeV}$ [1].

Decay channel	Selection Efficiency	S/B	$S/\sqrt{B}$	$S/\sqrt{B + \delta B^2}$
electron	1.4%	4.4%	1.6	0.17
muon	1.9%	4.8%	1.8	0.15

2. – Simulation studies of $t\bar{t}H(H \to b\bar{b})$ at $\sqrt{s} = 14\,\text{TeV}$

2·1. *CMS study* [1] *(2006).* – The hadronic, dileptonic and single lepton channels for the $t\bar{t}$ decay are considered. In the single lepton channel (the most promising channel in terms of signal significance), preselection cuts are applied to select: an isolated lepton with $p_T > 15\,\text{GeV}$; 6 or 7 jets with $|\eta| < 3.0$ and $p_T > 10\,\text{GeV}$, where jet-finding is performed using a cone algorithm with a radius of $\Delta R = 0.5$; and at least four jets passing a loose b-tagging requirement, defined by a combined secondary vertex tagger. A veto on extra leptons ensures that the single lepton events are orthogonal to those chosen for the dilepton analysis.

To assign the jet combination that gives the best reconstruction of the two top quarks, an event likelihood is defined which uses constraints on the W and top masses, the b-tags and the kinematics. The configuration that gives the maximum event likelihood is chosen. The two remaining b-jets with the most b-like output from the b-tagging discriminator are used to reconstruct the Higgs mass. A second likelihood, using a stronger b-tagging requirement, is employed to improve background rejection. The selection efficiency, signal-to-background ratio, and statistical signficance that would be obtained after all selection are shown in table I.

2·2. *ATLAS study* [2] *(2008).* – This study considers the single lepton channel only. The preselection cuts applied require exactly one isolated lepton, passing a lepton trigger, and at least six jets with $p_T > 20\,\text{GeV}$ and $|\eta| < 2.5$ identified using a cone algorithm with a radius of $\Delta R = 0.4$. At least four jets are required to pass a loose b-tagging requirement, defined by an algorithm whose discriminatory variable is a weight based on track impact parameters and the secondary vertex of the b-hadron.

A constrained mass fit is used, which adjusts the momenta of the reconstructed objects to match the W and top masses. A χ^2 from this fit is then used as input to a likelihood technique to select the best jet combinations, followed by a second likelihood to separate signal and background. The selection efficiency, signal-to-background ratio, and statistical signficance that would be obtained after all selection are shown in table II.

2·3. *Combinatorial background and effect of systematic uncertainties.* – Despite the multivariate techniques employed in both studies to optimise the assignment of jets to the top quarks and the Higgs boson, the two b-jets are correctly assigned to the Higgs boson

TABLE II. – *Results of an ATLAS simulation study in the single lepton channel of* $t\bar{t}H(H \to b\bar{b})$ *for* $m_H = 120\,\text{GeV}$ *with* $30\,\text{fb}^{-1}$ *at* $\sqrt{s} = 14\,\text{TeV}$*, in a mass window of* $90 < m_{bb} < 150\,\text{GeV}$ [2].

Technique	Selection Efficiency	S/B	$S/\sqrt{B}$
Constrained mass fit	2.5%	0.12	2.18

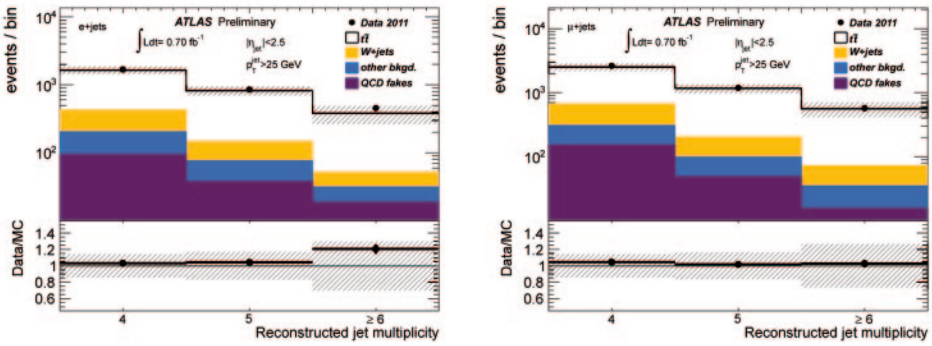

Fig. 1. – The reconstructed-jet multiplicity for final states with one selected electron (left) or muon (right), after $t\bar{t}$ selection cuts [6]. The "other" background includes single top, diboson and Z+jets. The shaded band represents the total uncertainty of the stacked signal and background histograms, constructed from MC simulation and data-driven estimates [6].

candidate in only 30% of events. The systematic uncertainties from the reconstruction for the ATLAS analysis were estimated to be 28%, which reduces the signal significance from $S/\sqrt{B} = 2.2$ to $S/\sqrt{B + \delta B^2} = 0.5$. The largest contributions to this are from the jet energy scale (JES), jet energy resolution (JER), and the b-tagging. The systematic uncertainties in the CMS analysis are also 20–30%.

3. – Current status

The previous studies are outdated, and reconstruction techniques have improved in both ATLAS [3] and CMS [4]. For example, CMS analyses now use a particle flow event reconstruction algorithm which improves identification and reconstruction of all final state objects. Both experiments now use the anti-k_T algorithm for jet reconstruction, improving the jet resolution, efficiency, and linearity.

At $\sqrt{s} = 7\,\text{TeV}$ the next-to-leading order (NLO) cross section for $t\bar{t}H$ production is 100 fb ($m_H = 120\,\text{GeV}$), compared to 685 fb for $\sqrt{s} = 14\,\text{TeV}$ [5]. In reducing the centre-of-mass energy the $t\bar{t} + 2$ jets and $t\bar{t}b\bar{b}$ cross sections are also expected to fall by a similar factor. However, the previous studies used leading order (LO) estimates of $t\bar{t}b\bar{b}$ made at a fixed factorisation and renormalization scale. NLO corrections at an improved scale choice give an increase of 100% for the $t\bar{t}b\bar{b}$ cross section over the previous LO estimate [5].

3˙1. *tt+jets at ATLAS* [6]. – Measurements of $t\bar{t}$ events with additional jets have begun. Figure 1 shows the jet multiplicity for events passing single lepton $t\bar{t}$ selection cuts. The cuts in the electron (muon) channel require a lepton with $p_T > 25\,\text{GeV}$ ($p_T > 20\,\text{GeV}$), $E_T^{miss} > 35\,\text{GeV}$ ($E_T^{miss} > 25\,\text{GeV}$), the transverse mass $m_T(W)$ of the leptonic W candidate $m_T(W) > 25\,\text{GeV}$ ($m_T(W) + E_T^{miss} > 60\,\text{GeV}$), ≥ 4 jets with $p_T > 25\,\text{GeV}$, and ≥ 1 b-tagged jet. With $0.70\,\text{fb}^{-1}$ of data, 457 (574) events with 6 or more jets were observed in the electron (muon) channel. After subtraction of the estimated background the jet multiplicity distribution is in good agreement with Monte Carlo predictions. The systematic uncertainty on the expected number of events in the $\geq$ 6-jet bin is 35% (31%) in the electron (muon) channel, dominated by the JES uncertainty.

The b-tagging applied here is based on a robust secondary vertex finder suitable for early data taking. More advanced combined taggers with better light jet rejection are now available for use. Currently the JES uncertainty is $< \pm 10\%$ per jet for jets with $|\eta| < 2.8$ and $p_T > 20\,\text{GeV}$ and the JER uncertainty is $\sim 10\%$ per jet. These uncertainties are of a similar magnitude to those assumed in the 14 TeV $t\bar{t}H$ simulation studies.

4. – Tools for future studies

There have been many new developments in jet reconstruction algorithms. One area of particular interest is the study of boosted objects, where the decay products of the object are observed as a single jet that can be decomposed to show its substructure. In events containing boosted top quarks, it is possible to observe the decay products of a top quark as a single jet, and this could be exploited in a $t\bar{t}H$ analysis. An approach was developed in a generator-level study [7] to select events with two high-p_T ($p_T > 200\,\text{GeV}$) "fat" jets, reconstructed using the Cambridge-Aachen algorithm [8] with a large radius parameter. One jet contains the decay products from the hadronically decaying top quark, and the other contains the decay products of the Higgs boson. Each jet is decomposed into subjets by undoing the clustering and a "top tagging" algorithm is defined, which searches for two subjets with $m_{jj} \sim m_W$ and three subjets with $m_{jjj} \sim m_t$. A "Higgs tagging" algorithm searches for pairs of b-tagged subjets. Although the high p_T jet cuts sacrifice selection efficiency, the improvement afforded by this approach in terms of signal significance and reduction of combinatorial background is worthwhile investigating.

There are now several event generators that implement the $t\bar{t}H$ signal process at NLO, and $t\bar{t}b\bar{b}$ at LO. Work to implement $t\bar{t}+$ additional jets at NLO is underway ($t\bar{t}+1$ jet is described in the NLO+parton shower approach using POWHEG [9], and $t\bar{t}+2$jets will be implemented in the future).

5. – Summary

The search for $t\bar{t}H$ is challenging. Previous simulation studies of $t\bar{t}H(H \to b\bar{b})$ in the single lepton channel demonstrate the difficulties posed by a 6-jet final state: the large backgrounds from $t\bar{t}+$jets and $t\bar{t}b\bar{b}$, large combinatorial background and large systematics from jet energy scale, jet energy resolution and b-tagging. Measurements of the main background process, $t\bar{t}+$jets, are underway. Improvements in b-tagging algorithms and in JES and JER measurements will help to control the systematic uncertainties. Investigation of new jet reconstruction techniques is vital to reduce backgrounds and control combinatorial problems.

REFERENCES

[1] The CMS Collaboration, *J. Phys. G*, **34** (2007) 995.
[2] The ATLAS Collaboration, CERN-OPEN-2008-020, arXiv:0901.0512v4 [hep-ex] (2009).
[3] The ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[4] The CMS Collaboration, *JINST*, **3** (2008) S08004.
[5] Dittmaier S. *et al.*, CERN-2011-002, arXiv:1101.0593v3 [hep-ph] (2011).
[6] The ATLAS Collaboration, ATLAS-CONF-2011-142 (2011), https://cdsweb.cern.ch/record/1385518.
[7] Plehn T., Salam G. P. and Spannowsky M., *Phys. Rev. Lett.*, **104** (2010) 111801.
[8] Dokshitzer Y. L., Leder G. D., Moretti S. and Webber B. R., *JHEP*, **08** (1997) 001.
[9] Kardos A, Papadopoulos C. and Trocsanyi Z., *Phys. Lett. B*, **705** (2011) 76.