IL NUOVO CIMENTO **38 C** (2015) 10
DOI 10.1393/ncc/i2015-15010-9

Colloquia: IFAE 2014

Top quark physics at hadron colliders

F. Margaroli on behalf of the ATLAS, CDF, CMS and D0 Collaborations

Dipartimento di Fisica, Università di Roma Sapienza and
INFN, Sezione di Roma 1 - Roma, Italy

received 7 January 2015

Summary. — The top quark is the heaviest fundamental particle known so far. As such, it is expected to play a crucial role in the study of the electroweak symmetry breaking mechanism and the generation of mass, as well as to serve as an ideal window into new physics. The discovery of a Higgs boson provides us additional experimental opportunities to test our current understanding of top quarks physics. In this contribution I will discuss the status of top quark physics as of 2014, and present a few recent highlights.

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

1. – Introduction

The top quark is the heavies known fundamental particle. In fact, it is so heavy that is the only quark that decays before hadronizing. The top quark thus allows never-attempted-before studies into the details of quantocromodynamics (QCD). Its mass is a fundamental parameter of the model, as are its matrix elements inside the Cabibbo-Kobayashi-Maskawa matrix(1). While the top quark is interesting per se, the discovery of a Higgs boson in 2012 [1] added extra interest to the production of top quarks; in fact, the assumed special relation between the Higgs boson and the top quark can now be explored directly both in the Standard Model (SM) context, and in Beyond Standard Model (BSM) scenario.

The top quark was discovered in 1994 [2] at the first run of the Tevatron proton-antiproton collider, analyzing events where the top quark is produced in pairs; only an handful of recorded events by the CDF and D0 experiments were needed for discovery. With upgraded Tevatron collision energy and an extended Run II, the same experiments

(1) The latter part of the statements holds true only if one relaxes the Standard Model scenario of three simple quark generations.

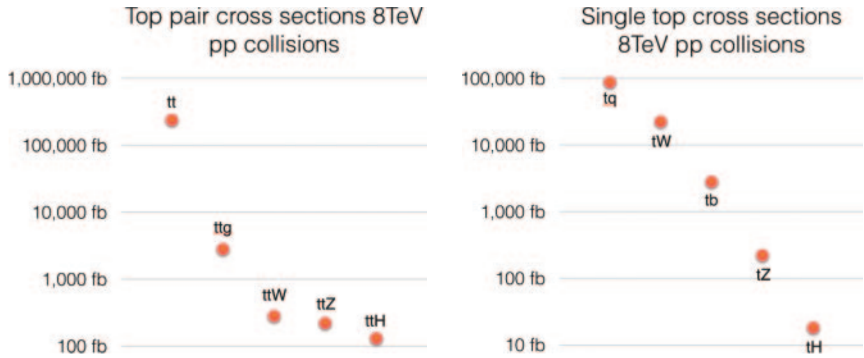

Fig. 1. – The left plot shows the cross sections for the processes giving a pair of top-antitop quarks, plus eventually additional particles, at proton-proton 8 TeV pp collisions. The right plot shows the cross sections for several single top quark production at 8 TeV pp collisions; note the different scale for cross sections. We have observed (5σ) or have evidenced (3σ) of most processes shown in both plots, apart from $t\bar{t}H$, tZ and tH production.

were able to analyze a dataset two orders of magnitude larger, that allowed the first observation of electroweak single top quark production [3], and increased precision on key top quark physics observables. The advent of the LHC era and its proton-proton collisions brought in an addition order of magnitude of top quark events with proton beams colliding at 7 TeV center-of-mass energy, and another order of magnitude with 8 TeV collisions, bringing the grand total to an approximate humber of 20 million top quark events. As the dataset of top quarks has increased in a steadfast manner, the particle physics community is now able to study top quark physics with the ATLAS and CMS detectors using a very large number of top quark production and decay modes. Figure 1 shows the cross section for top quark production in the SM at 8 TeV collisions, split into events with two top quarks and events with a single top quark.

In these proceedings I will highlight some interesting recent results on top quark physics; as the choice of topics to cover is necessarily limited by paper length and biased by personal taste, the reader is invited to look into the ATLAS, CDF, CMS and D0 experiments webpages to discover more interesting facts about top quarks.

2. – The top quark and the mass generation mechanism

The single most important property of the top quark is its mass; in fact, not only it dictates the phenomenology of top quark production, but more importantly it allows together with the measurement of other SM observables, to predict the Higgs boson mass, and assess the self-consistency of the model itself [4]. More recently, it has been pointed out that the precise knowledge of the top quark and of the Higgs boson allow to predict the stability of the electroweak vacuum, with notable cosmological consequences [5]. Figure 2 shows the current extrapolations using the known top quark and Higgs boson masses.

The motivations above pushed the Tevatron and LHC experiments to spend a great deal of manpower measuring this property with ever increasing precision. A major milestone in that regard is the first combination of direct measurements of the top quark from Tevatron and LHC experiments that provides the value for the top quark mass $m_t = 173.34 \pm 0.76\,\mathrm{GeV/c^2}$ [6]. The measurements entering this combination are shown in fig. 3. It has been also pointed out that being the top quark a colored object, its mass

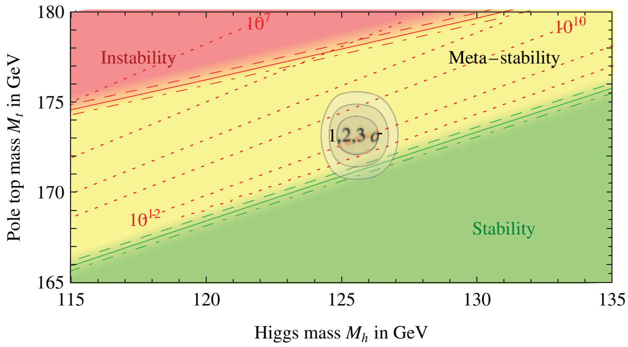

Fig. 2. – The plot shows the current best precision on the Higgs mass (on the x-axis) and on the top quark mass (on the y-axis) and the consequence on the vacuum stability. The current collider data point toward the metastability scenario.

is dependent on the details of the mass scheme used in QCD. A better defined quantity is the dependence of the $t\bar{t}$ cross section from the top quark pole mass. Measurements of the top quark mass extracted from this observable report typically lower values for M_{top}. More work is thus necessary to understand exactly what is being measured and how to use that information in theoretical fits of the model itself. Events where one or more top quark are produced together with a Higgs boson can be used to constrain, respectively, the sign [7] and the magnitude of the Yukawa coupling of the top quark to the Higgs boson. While $t\bar{t}H$ searches are covered in a separate talk, I have shown here the first search for a single top quark with a Higgs boson by CMS [8].

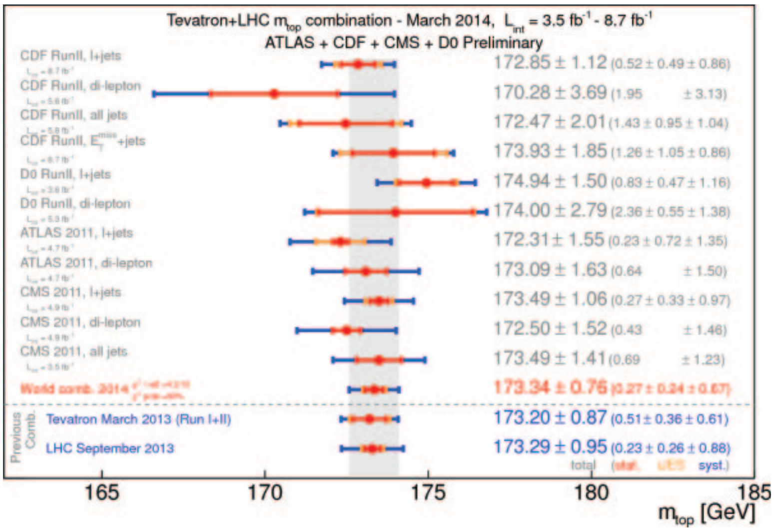

Fig. 3. – Combination of measurements of the top quark mass from the ATLAS, CDF, CMS and D0 experiments [6]. The red number shows the current world combination, while the two blue numbers show the Tevatron and LHC separated results. The firs uncertainty is statistical, the second is the statistical part of the jet energy scale uncertainty (iJES), and the third is the quadrature sum of all remaining systematics.

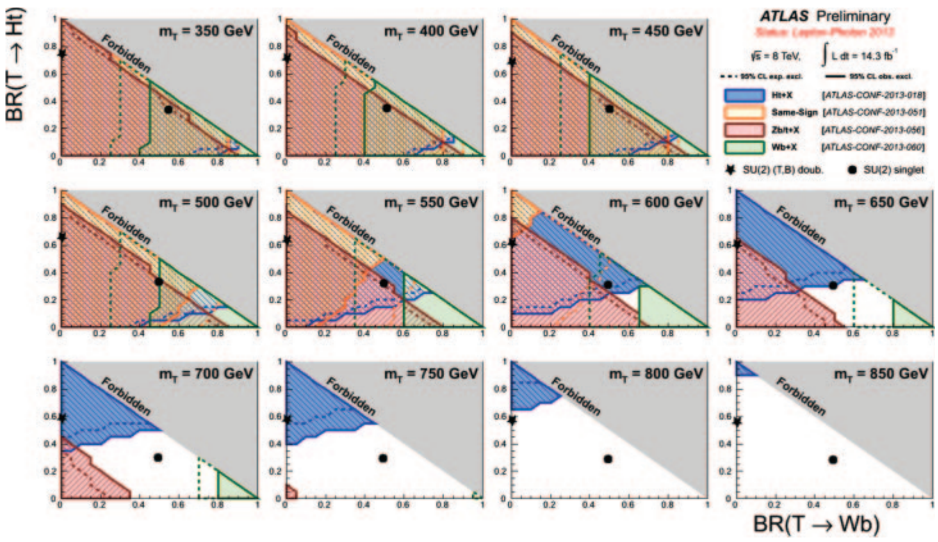

Fig. 4. – Constraints on decay modes for fermionic, vector-like top quark partners. The x-axis shows the decay mode $BR(T \to Wb)$, the y-axis shows the $BR(T \to Ht)$, and the remaining decay mode $BR(T \to Zt)$ can be inferred by requiring that the three branching ratios sum up to unity.

3. – Interesting properties of the top quark

The top quark mass is probably the single observables that has received the largest attention by experimentalists. Other key measurements have been the one of the total and differential cross section for both pair and single top quark production, the measurement of the top quark forward-backward asymmetry, the measurement of the top quark width, and more. In this talk, I chose to cover a brief overview of the measurements of the V_{tb} element of the Cabibbo-Kobayashi-Maskawa matrix, as it is especially important both as a parameter of the Standard Model, as well as a window to new physics. The most precise measurement of this observables comes form the measurement of the total single top quark production cross section, that is proportional to V_{tb}^2. All Tevatron and LHC experiments measure this observable. The most precise such measurement comes from CMS using the t-channel production, and measures $V_{tb} = 1.00 \pm 0.04 \pm 0.02$ consistently with the SM prediction. While a combination of measurements of single top quark production in the t-channel by the ATLAS and CMS collaborations is now available [9], the hope is to have in the near future a combination of all available measurements of V_{tb} from all possible top quark production and decay modes.

4. – The top quark as a window to new physics

One of the most striking consequences of the top quark very large mass, is its induced corrections to the Higgs mass through radiative loops. The very large fine tuning necessary to bring the Higgs mass to the observed value mandates for an explanation. These loops would automatically cancel out in presence of fermionic or bosonic top quark partners, as predicted by the Composite Higgs scenario, or Supersymmetry (SUSY); the exact mechanism for such cancellations is different in the two models. The SUSY scenario

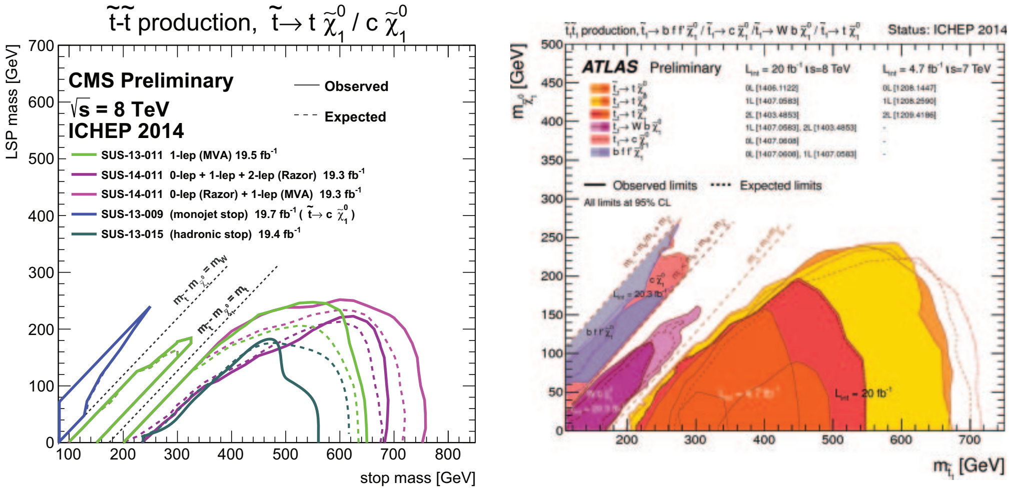

Fig. 5. – Plots showing the excluded region for the supersymmetric top partner mass and the lightest supersymmetric particle (LSP) masses. Both CMS (on the left) and ATLAS (on the right) investigate several decay chains of the stop pair. The plot includes results shown after this conference.

is especially appealing as SUSY would solve not only the hierarchy problem but also the dark matter puzzle. The ATLAS and CMS experiments are especially well suited for these searches, and study a large number of top partners decay modes.

In the Composite Higgs scenario, there would exist new fermions T that would undergo decays such as $T \to tH, tZ, bW$ with varying branching ratios depending on the specific model. Figure 4 shows the excluded T masses for all possible decay mode assumptions for the ATLAS analyses [10]. Fermionic top quark partners masses are allowed up to a few TeV, so these searches will receive special attention at the new LHC run.

In SUSY, the bosonic top partner (stop) would decay mainly to a top quark and a neutralino $\to t\chi_1^0$, to a bottom and a chargino $\to \chi^{\pm}b$, or to a charm and a neutralino $\to c\chi_1^0$. Again, ATLAS and CMS search for stop quark pair production in all of the above decay modes using several experimental signatures, finding none [11]. Figure 5 shows a visual summary of the existing searches by ATLAS and CMS experiments. The existing constraints require already some level of fine-tuning even in the presence of new physics. Experimentalists are now turning their attention to stop quark decay chains including neutral bosons such as a Z or a H.

Just as in the flavor physics paradigm, new physics could manifest itself at mass scales not accessible at the current or future run of the LHC, but still be observable through the enhancement of the rates of otherwise very rare SM processes. Of particular interests are the flavor-changing neutral-current (FCNC) decays of top quarks as they proceed through penguin diagrams and are thus very heavily suppressed $O(10^{-12}$–$10^{-15})$ in the SM. New physics could push these values as high as to the 10^{-4} level. The CMS and ATLAS collaborations look for $t \to Zq/Hq/\gamma q$ and gq decay modes, where $q = u/c$. The constraints on the branching ratio to such rare decays ranges from 10^{-3} to 10^{-5} depending on the boson involved; given the large number of results, the reader is invited to look for the corresponding papers in the CMS and ATLAS webpages [12]. The new run will allow us to enter in the region where we would be sensitive to several new physics model.

The search for dark matter has recently intensified in the high energy physics community; particle colliders proved to be excellent instruments to search for weakly interactive massive particle (WIMP) as dark matter candidates in all the 1 GeV–1 TeV mass spectrum. In particular, dark matter could be produced in association with one or more top quarks in a number of scenarios beyond the already mentioned SUSY. The production of single top quark in association with dark matter is investigated by CDF [13] and recently by CMS [14]. In the scenario of Yukawa-like Lagrangian, dark matter would couple preferentially to the most massive particles. The possible existence of dark matter produced together with a pair of top quark events has also been recently investigated in this hypothesis at CMS [15]. The model presented here is kinematically different from the stop pair decaying to top quarks and neutralinos; thus the latter limits do not apply here. The searches mentioned in this paragraph proved to more sensitive than the generic dark matter searches in mono-jet events in specific dark matter scenarios.

5. – Conclusions

The top quark physics programme is central in the current and future high energy physics program. The end of the Tevatron era lead us to the the first run of LHC data at 7 TeV and 8 TeV collisions, which in turn gave us a two-order-of-magnitude larger dataset to investigate top quark physics. Very rare SM processes are already under study by the CMS and ATLAS collaborations, and the new LHC run will allow even deeper investigations of the Standard Model. The possible role the top quark could play in BSM is now under heavy scrutiny by the experimental and theoretical community. Still, new ideas are being developed and tested against collider data. The new LHC run will bring exceptional insight into the nature of the heaviest elementary known particle, its relation to the newly discovered boson, and the existence of new physics at higher mass scale.

* * *

The author wishes the thank the conference organizers for the excellent organization, and the organizers and attendees for the lively discussions and interest in the topics discussed here.

REFERENCES

[1] Aad G. *et al.* (ATLAS Collaboration), *Phys. Lett. B*, **716** (2012) 1, arXiv:1207.7214; Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **716** (2012) 30, arXiv:1207.7235.

[2] Abe F. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2626; Abachi S. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2632.

[3] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **103** (2009) 092002, arXiv:0903.0885; Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **103** (2009) 092001, arXiv:0903.0850.

[4] Baak M., Goebel M., Haller J., Hoecker A., Kennedy D., Kogler R., Moenig K., Schott M. *et al.*, *Eur. Phys. J. C*, **72** (2012) 2205, arXiv:1209.2716.

[5] Degrassi G., Di Vita S., Elias-Miro J., Espinosa J. R., Giudice G. F., Isidori G. and Strumia A., *JHEP*, **08** (2012) 098, arXiv:1205.6497.

[6] ATLAS and CDF and CMS and D0 Collaborations, arXiv:1403.4427 [hep-ex].

[7] Biswas S., Gabrielli E. and Mele B., *JHEP*, **01** (2013) 088, arXiv:1211.0499; Farina M., Grojean C., Maltoni F., Salvioni E. and Thamm A., *JHEP*, **05** (2013) 022, arXiv:1211.3736; Biswas S., Gabrielli E., Margaroli F. and Mele B., *JHEP*, **07** (2013) 073, arXiv:1304.1822.
[8] Chatrchyan S. *et al.* (CMS Collaboration), CMS-HIG-14-001.
[9] CMS-PAS-TOP-12-002; ATLAS-CONF-2013-098.
[10] ATLAS webpage for top quark partner searches:
`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`;
CMS webpage for top quark partner searches:
`https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G`.
[11] ATLAS webpage for SUSY searches:
`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults`;
CMS webpage for SUSY searches:
`https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS`.
[12] ATLAS webpage for top quark physics:
`https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults`;
CMS webpage for top quark physics:
`https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP`.
[13] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **108** (2012) 201802, arXiv:1202.5653.
[14] Khachatryan V. *et al.* (CMS Collaboration), arXiv:1410.1149.
[15] Khachatryan V. *et al.* (CMS Collaboration), CMS-B2G-14-004.