IL NUOVO CIMENTO Vol. 33 C, N. 4 Luglio-Agosto 2010
DOI 10.1393/ncc/i2010-10681-2

Colloquia: TOP2010

Challenges in New Physics searches in top-like events at the LHC

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(ricevuto il 25 Agosto 2010; approvato il 25 Agosto 2010; pubblicato online il 29 Ottobre 2010)

Summary. — The prospects of exploring physics beyond the standard model involving top quarks and top-like signals at the LHC based on Monte Carlo simulations at $\sqrt{s} = 14$ and 10 TeV are reviewed. A special attention is given to results that can be expected for the early LHC running in 2010-2011. Consequently, the first section deals with the implications of having a center-of-mass energy lower than what was simulated, $\sqrt{s} = 7$ TeV, for the first years of the LHC running. This will be done qualitatively by discussing the impact on the cross section of various production processes. Following this discussion, several searches for physics beyond the standard model that are related to the top quark are described: top-antitop resonances, 4th generation of quarks, top charge, W polarization, anomalous Wtb vertex coupling, top-antitop spin correlation, and flavor changing neutral current. Their order of appearance goes from lower to higher integrated luminosity needed to obtain meaningful results out of each analysis.

PACS `14.65.Ha` – Top quarks.

1. – Rescaling cross sections from $\sqrt{s} = 14$ and 10 TeV

The Large Hadron Collider (LHC) machine has been designed to provide proton-proton collisions with center-of-mass energy ($\sqrt{s}$) of 14 TeV. Initially, it was estimated that for the first year of running, $\sqrt{s} = 10$ TeV would be used, but the LHC is operating with 7 TeV for the 2010-2011 run. At this time, there are very few top-like Monte Carlo (MC) analyses that have been carried out with events simulated at $\sqrt{s} = 7$ TeV. Nevertheless, it is possible to qualitatively predict the feasibility of the $\sqrt{s} = 7$ TeV top-like analyses using the MC analyses that were done assuming $\sqrt{s} = 14$ and 10 TeV. In order to do so, the reduction in the cross section of the involved processes needs to be known. Figure 1 shows the total Standard Model cross section (σ) for top production and some other processes as a function of $\sqrt{s}$ [1], while table I shows the estimated top-antitop cross section for $\sqrt{s} = 7$, 10 and 14 TeV.

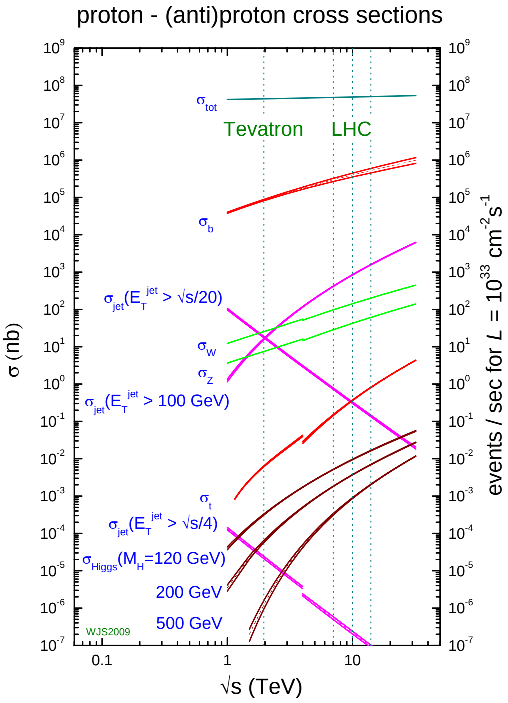


Fig. 1. – The total cross section (σ) for top pair production and several other processes as a function of $\sqrt{s}$ [1].

For $\sqrt{s}$ going from 14 TeV to 7 TeV and $\sqrt{s}$ going from 10 TeV to 7 TeV, σ_{top} is reduced by a factor of about five and two, respectively. For W production, which is a main background to semi-leptonic top-antitop production, σ_{W} does not scale down as quickly as σ_{top} when $\sqrt{s}$ is reduced, see fig. 1. The $M_{\text{t}\bar{\text{t}}}$ differential cross section ($\text{d}\sigma_{\text{top}}/\text{d}M_{\text{t}\bar{\text{t}}}$) matters in certain analyses. This is the case when searching for top-antitop resonances like Z′. Figure 2 shows how the cross section for producing an invariant mass M_{X} from quark annihilation ($\sum \text{q}\bar{\text{q}}$) and gluon fusion (gg) is affected by $\sqrt{s}$ going from 14 TeV to 7 TeV [1]. Knowing that the dominant top-antitop production mechanism at the LHC is gluon fusion, at $M_{\text{t}\bar{\text{t}}} = 1\,\text{TeV}$, $\text{d}\sigma_{\text{top}}/\text{d}M_{\text{t}\bar{\text{t}}}$ is scaled down by a factor slightly bigger than 10. Comparatively, a Z′ resonance would be produced through quark-antiquark annihilation, meaning that $\sigma_{\text{Z}'}$ for a hypothetical invariant Z′ mass of 1 TeV ($M_{\text{Z}'} = 1\,\text{TeV}$) would be reduced by a factor of roughly 5.

The expected accumulated integrated luminosity by the end of 2010 is between 100 and 200 pb^{-1}, increasing to 1 fb^{-1} by the end of 2011.

Table I. – *Top-antitop total cross section for* $\sqrt{s} = 7$, 10 *and* 14 TeV.

14 TeV	883 ± 45 pb
10 TeV	401 ± 25 pb
7 TeV	170 ± 10 pb

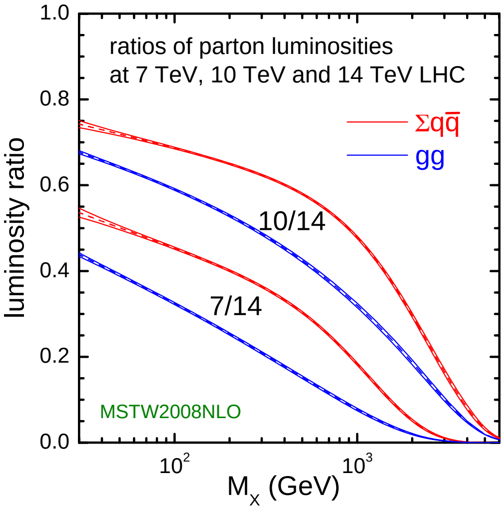


Fig. 2. – Ratios of parton luminosities at 7, 10 and 14 TeV $\sqrt{s}$ as a function of the invariant mass (M_{X}) of quark-antiquark annihilation $\left(\sum \mathrm{q}\bar{\mathrm{q}}\right)$ and gluon fusion (gg) [1].

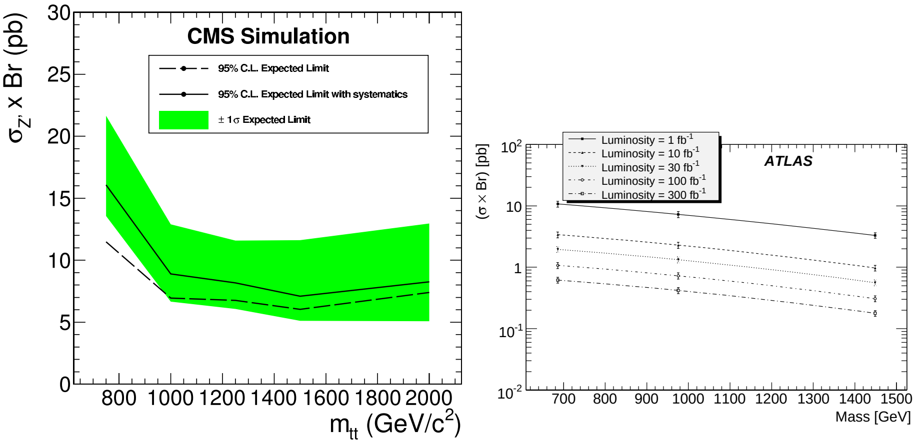
2. – Top-antitop resonances

There are several beyond the standard model (BSM) processes which may produce resonances that decay to top-antitop, *e.g.* Z′, Kaluza-Klein gluon, and graviton resonances. Two studies from CMS [2] and ATLAS that focus on relatively low invariant mass Z′ resonances are reviewed here.

The CMS study [3] relies on a complete kinematic reconstruction of the events. The analysis selects semi-muonic $\mathrm{t}\bar{\mathrm{t}}$ by requiring the presence of one highly energetic ($p_{\mathrm{T}} > 35\,\mathrm{GeV}$) isolated muon and the presence of at least 4 jets with $p_{\mathrm{T}} > 35\,\mathrm{GeV}$. To be considered isolated, the muon must be at a distance of $\Delta R = \sqrt{\phi^2 + \eta^2} > 0.4$ from the closest jet *or* have a p_{T} relative to the closest jet axis of more than 35 GeV. The latter part of the *or* conditional significantly increases the number of signal events, without increasing too much the number of background events caused by a muon coming from the semi-leptonic decay of the B-hadron in a b-jet. This cut is important since higher mass resonances lead to tops with higher p_{T}, which then lead to collimated decay products such that the muon and b-jet are close together in ΔR space. The analysis performs well for resonances up to $M_{\mathrm{t}\bar{\mathrm{t}}} = 2\,\mathrm{TeV}$. At higher $M_{\mathrm{t}\bar{\mathrm{t}}}$, different methods need to be used to recover the loss in efficiency from the lack of separation between the final decay products. No b-tagged jets are required.

To reconstruct the full topology of the $\mathrm{t}\bar{\mathrm{t}}$ event, a kinematic fit is used. It helps to improve the resolution ($\Delta M_{\mathrm{t}\bar{\mathrm{t}}}/M_{\mathrm{t}\bar{\mathrm{t}}} \sim 10\%$) and its linearity over $M_{\mathrm{t}\bar{\mathrm{t}}}$. Finally, to extract limits on the production cross section of the narrow Z′, a binned likelihood fit to the $M_{\mathrm{t}\bar{\mathrm{t}}}$ distribution is used. The expected exclusion limits at 95% CL assuming an integrated luminosity of $100\,\mathrm{pb}^{-1}$ at 10 TeV are shown in fig. 3(a).

The Z′ analysis performed by ATLAS [4] assumes more integrated luminosity ($1\,\mathrm{fb}^{-1}$ at 14 TeV) and therefore a better knowledge of the detector. In particular, b-tagging is used: of the required 4 jets with p_{T} greater than 40 GeV, two need to be b-tagged. In addition, the isolated lepton (electron or muon) needs to have $\Delta R > 0.4$ with the closest



(a) (b)

Fig. 3. – Expected limits on $\sigma \times \mathrm{Br}(\mathrm{Z}' \to \mathrm{t\bar{t}})$ (pb) for (a) 95% CL exclusion level from the CMS analysis and (b) 5σ discovery potential for the ATLAS analysis.

jet to be selected and the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) must be larger than 20 GeV. This strict selection removes most of the background, except the irreducible SM $\mathrm{t\bar{t}}$.

The event reconstruction used is a very simple geometric one. The two jets out of the 4 highest p_{T} jets that are not b-tagged are used to form the W boson. They are then paired with the closest (in ΔR space) b-jet to form the hadronic top. The other top is reconstructed using the remaining b-jet, the lepton and by assuming that $E_{\mathrm{T}}^{\mathrm{miss}}$ corresponds to the p_{T} of the undetected neutrino and by constraining the leptonic W mass to obtain the neutrino longitudinal momentum. To reduce the number of misreconstructed $\mathrm{t\bar{t}}$ events, windows cuts around the hadronic W and both top masses are used. The purity (fraction of events for which the $\mathrm{t\bar{t}}$ event is well reconstructed) yields 80–85% for Z′ MC samples.

The 5σ discovery potential for a narrow Z′ resonance is estimated by counting the number of events in a $M_{\mathrm{t\bar{t}}}$ mass window of twice the detector resolution *versus* the expected SM $\mathrm{t\bar{t}}$ events in that window. Results are shown in fig. 3(b) for various integrated luminosities. A narrow $\mathrm{t\bar{t}}$ resonance of 1 TeV with a cross section times branching ratio of at least 7 pb could be discovered with 1 fb^{-1} at 14 TeV.

3. – 4th generation of quarks

A fourth generation of quarks, referred to as $(\mathrm{b}', \mathrm{t}')$, coupling dominantly to the third generation of quarks (b, t) would yield an excess of events containing top quarks(^{1}). The CMS Collaboration studied the process $\mathrm{b}'\bar{\mathrm{b}}' \to \bar{\mathrm{t}}\mathrm{W}^+\mathrm{t}\mathrm{W}^- \to \mathrm{W}^-\mathrm{W}^+\mathrm{W}^-\mathrm{W}^+\mathrm{bb}$ [6]. Although the high event multiplicity is a source of challenge in reconstructing this signal, it has the advantage that the final decay products sometimes contain same sign leptons(^{2}) when both W^+ or both W^- decay leptonically. This signature is extremely rare in SM processes. Thus, by requiring two (three) leptons with $p_{\mathrm{T}} > 35$ GeV, two of which have

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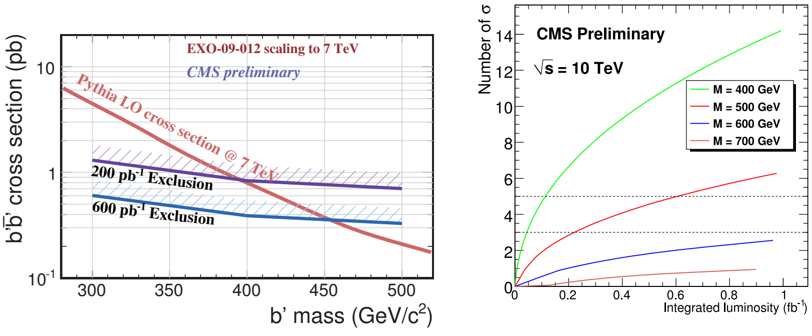
(^{1}) For a study that does not assume that the fourth generation primarily couples with the third, see [5].

(^{2}) Again, only electrons and muons are considered as leptons.



(a) (b)

Fig. 4. – (a) Expected exclusion limits at 95% confidence level on the pp $\rightarrow$ b$'\bar{\text{b}}'$ production cross section for an integrated luminosity of 200 and 60 pb^{-1}. (b) Expected significance for a signal from exotic top partners of mass M as a function of the integrated luminosity.

same sign charge, and four (two) jets with $p_{\mathrm{T}} > 35\,\mathrm{GeV}$, the leading one having $p_{\mathrm{T}} > 85\,\mathrm{GeV}$, the signal events can be selected with negligible SM background. The high object multiplicity and the multiple undetected neutrinos make a parton-level reconstruction of the event impossible. Instead, the scalar sum of the object transverse momenta, known as HT, is used as observable. For a null hypothesis, exclusion limits on the mass of the b$'$ can be extracted using Bayesian statistics, see fig. 4(a). Expectations for the 95% CL lower limits on the b$'$ mass are shown for an integrated luminosity of 60 and 200 pb^{-1}. The analysis was done using MC data with $\sqrt{s} = 10\,\mathrm{TeV}$ and has been rescaled to 7 TeV cross sections [7]. With the data from the 2010 run, the LHC should be able to extend limits on the mass of fourth-generation quarks beyond current limits from the Tevatron.

Another study considered exotic top quark partners, including the $\mathrm{T}_{5/3}$ and B particles, where the 5/3 refers to the charge of the exotic partner [8]. Both are pair-produced and have the same decay products as the fourth-generation analysis, $\bar{\mathrm{t}}\mathrm{W}^+\mathrm{t}\mathrm{W}^-$. In this case, only two same sign leptons and at least five jets are required. In addition, the mass of the $\mathrm{T}_{5/3}$ with a fully hadronic decay signature can be reconstructed from the tW mass peak. Figure 4(b) shows the 5σ (3σ) discovery (evidence) potential at $\sqrt{s} = 10\,\mathrm{TeV}$ as a function of the integrated luminosity for various masses (M) of the exotic top partner. For $M \leq 400\,\mathrm{GeV}$, exotic top partners can probably be discovered before the end of 2011 at the LHC.

4. – Top quark charge

The exotic scenario in which the top quark has a charge of $-4/3$ instead of $+2/3$ has been excluded with 95% and 92% CL at CDF [9] and D0 [10], respectively. Nevertheless, this result will be cross checked at the LHC. Two analyses planned by ATLAS [4] are described below.

In the semi-leptonic decay channel, the top quark charge is obtained by adding the charge from its associated lepton and b-quark. There are two issues, figuring out which of the two b-jets came from the same top as the lepton and estimating the b-quark charge from the b-jet. The lepton and b-jet pairing is done using the requirement that the invariant mass of the two objects must be less than 155 GeV. In the case that there are two jets that are b-tagged in the event, the invariant mass of the lepton with the other b-jet is required to be greater than 155 GeV. This strict requirement significantly reduces the efficiency of the signal selection (31%), but ensures a high purity (86%).

Two different techniques are used to determine the b-jet charge. The first one is to use a *charge weighting technique* which consists of adding the charges (q_i) of all the tracks (i) weighted by their momenta $\vec{p}_i$ according to

$$Q_{\mathrm{bjet}} = \frac{\sum_i q_i |\vec{j}_i \cdot \vec{p}_i|^{\kappa}}{\sum_i |\vec{j}_i \cdot \vec{p}_i|^{\kappa}}\,, \tag{1}$$

where $\vec{j}_i$ is the b-jet axis and κ, for which an optimal value was found to be 1/2. Notice that the Q_{bjet} is not the actual b-quark charge. It needs to be multiplied by a b-jet charge calibration coefficient found from the MC simulation. The second way to find the b-jet charge is to look for the semi-leptonic decay of the b-quark inside the b-jet: $\mathrm{b} \to \mathrm{c}, \mathrm{u} + l^- + \bar{\nu}$, $\bar{\mathrm{b}} \to \bar{\mathrm{c}}, \bar{\mathrm{u}} + l^+ + \nu$. The charge of the non-isolated lepton inside the b-jet should therefore indicate the charge of the b-quark. Nevertheless, semileptonic decays of D mesons produced in the B decay chain, and $\mathrm{B}^0 - \bar{\mathrm{B}}^0$ mixing can lead to leptons in the b-jet that do not come from the semi-leptonic decay of the b-quark. Moreover, the b-quark does not always decay leptonically inside the b-jet resulting in a reduction of the signal efficiency.

Because of these reasons, it takes less integrated luminosity to determine the top quark charge using the *charge weighting technique* than using the semi-leptonic b-quark decay approach. It was estimated that 5σ significance for top quark charge $-4/3$ *versus* $+2/3$ can be achieved with $100\,\mathrm{pb}^{-1}$ at 14 TeV, so about $500\,\mathrm{pb}^{-1}$ at 7 TeV. It takes $1\,\mathrm{fb}^{-1}$ at 14 TeV to obtain the same results using the semi-leptonic b-quark decay analysis. Therefore, the former analysis will be suitable for the 2010-2011 LHC run, while an independent measurement using the latter will have to wait for subsequent runs.

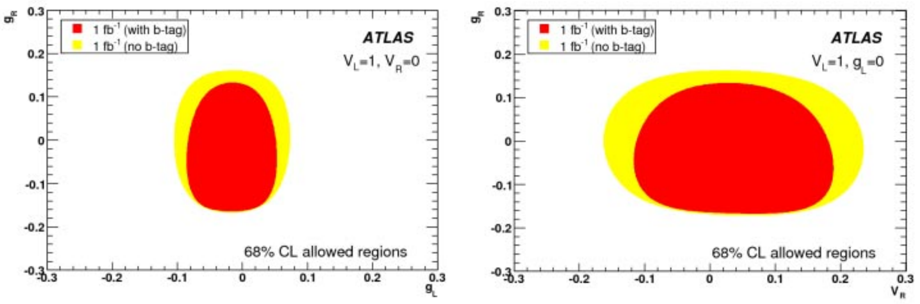
5. – W polarization

The polarization of the W boson from the decay of a top is well predicted in the SM: $F_0 = 0.695$, $F_{\mathrm{L}} = 0.304$ and $F_{\mathrm{R}} = 0.001$, where F_0, F_{L} and F_{R} correspond, respectively, to the fraction of Ws with longitudinal, left- and right-handed polarization. Any measured deviation from these numbers would signal BSM physics.

To measure these parameters, the angle Ψ between the lepton (in the W rest frame) and the W (in the top rest frame) is evaluated [4]. The distribution over many $\mathrm{t\bar{t}}$ events is then fitted using the following function:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\Psi} = \frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_{\mathrm{L}}\left(\frac{1-\cos\Psi}{2}\right)^2 + F_{\mathrm{R}}\left(\frac{1+\cos\Psi}{2}\right)^2\right], \tag{2}$$

where N is the number of $\mathrm{t\bar{t}}$ events observed. Combining the statistical and systematic errors, the expected precision with the ATLAS detector at 14 TeV and an integrated luminosity of $1\,\mathrm{fb}^{-1}$ is 7% ($6\% \oplus 3\%$), 12% ($7\% \oplus 10\%$) and 0.03 ($0.02 \oplus 0.02$) for F_0, F_{L} and F_{R}, respectively. Here, the relative errors for F_0 and F_{L} are taken with respect to their SM values while the absolute error is used for F_{R}. From these numbers, it can be concluded that for 2010-2011, this analysis will be statistically limited and it is doubtful that the achieved precision will allow to rule out the SM values. However, even though these numbers are expected for the 14 TeV run, they will be a good improvement from the current CDF [11] and D0 [12] values: $F_0 = 0.88 \pm 0.11 \pm 0.06$ (relative error of 18%), $F_{\mathrm{R}} =$



(a) (b)

Fig. 5. – The expected 68% CL allowed regions for (a) g_{R} and g_{L}, and (b) g_{R} and V_{R} with $1\,\mathrm{fb}^{-1}$ of integrated luminosity at 14 TeV. In both cases, V_{L} is set to one and the remaining anomalous coupling is set to zero.

$-0.15 \pm 0.07 \pm 0.06$ (absolute error of 0.09) and $F_0 = 0.49 \pm 0.11 \pm 0.09$ (20%), $F_{\mathrm{R}} = 0.11 \pm 0.06 \pm 0.05$ (0.08). Again, the relative errors are taken with respect to their SM values.

6. – Anomalous Wtb vertex coupling

If the Wtb vertex couplings do not behave as expected ($V_{\mathrm{L}} = 1$, $V_{\mathrm{R}} = 0$, $g_{\mathrm{L}} = 0$ and $g_{\mathrm{R}} = 0$) in the SM [13], the parameters F_0, F_{L} and F_{R} would be affected. However, since high precision on those is hard to achieve, alternative methods were developed to test the Wtb vertex coupling at ATLAS [4]. Using

$$A_t = \frac{N(\cos\Psi > t) - N(\cos\Psi < t)}{N(\cos\Psi > t) + N(\cos\Psi < t)} \tag{3}$$

and taking $t = 0, \pm(2^{2/3} - 1)$, three quantities that depend only on two out of the three polarization parameters (F_0, F_{L} and F_{R}), $A_{\mathrm{FB}}(F_{\mathrm{R}}, F_{\mathrm{L}})$, $A_-(F_0, F_{\mathrm{L}})$ and $A_+(F_0, F_{\mathrm{R}})$ are defined. Feeding in these quantities to TopFit [14], the values for V_{R}, g_{L} and g_{R} can be obtained. The results for $1\,\mathrm{fb}^{-1}$ at 14 TeV are shown in fig. 5. Note that two analyses were performed, one that uses b-tagging and one that does not. The 95% CL limits are $V_{\mathrm{R}} < |0.72|$, $g_{\mathrm{L}} < |0.19|$ and $g_{\mathrm{R}} < |0.20|$ from D0 [15], and $-0.0007 < V_{\mathrm{R}} < 0.0025$, $-0.0015 < g_{\mathrm{L}} < 0.004$ and $-0.15 < g_{\mathrm{R}} < 0.57$ when using the $\mathrm{b} \to \mathrm{s} + \gamma$ process [16].

7. – Top-antitop spin correlations

The correlation between the top and the antitop spins in a $\mathrm{t\bar{t}}$ event is captured through the spin asymmetry parameter:

$$A = \frac{\sigma(\mathrm{t}_\uparrow\bar{\mathrm{t}}_\uparrow) + \sigma(\mathrm{t}_\downarrow\bar{\mathrm{t}}_\downarrow) - \sigma(\mathrm{t}_\uparrow\bar{\mathrm{t}}_\downarrow) - \sigma(\mathrm{t}_\downarrow\bar{\mathrm{t}}_\uparrow)}{\sigma(\mathrm{t}_\uparrow\bar{\mathrm{t}}_\uparrow) + \sigma(\mathrm{t}_\downarrow\bar{\mathrm{t}}_\downarrow) + \sigma(\mathrm{t}_\uparrow\bar{\mathrm{t}}_\downarrow) + \sigma(\mathrm{t}_\downarrow\bar{\mathrm{t}}_\uparrow)}\,, \tag{4}$$

where ↑ and ↓ identify the spin of the top and antitop. By looking at the distribution of the product of the cosines of the angles between the top (anti-top) and the lepton, and the anti-top (top) and the least energetic non-b-jet, A can be obtained. The SM value of $A = 0.422$ can be measured in ATLAS, with $1\,\mathrm{fb}^{-1}$ at 14 TeV, with a precision of 59%

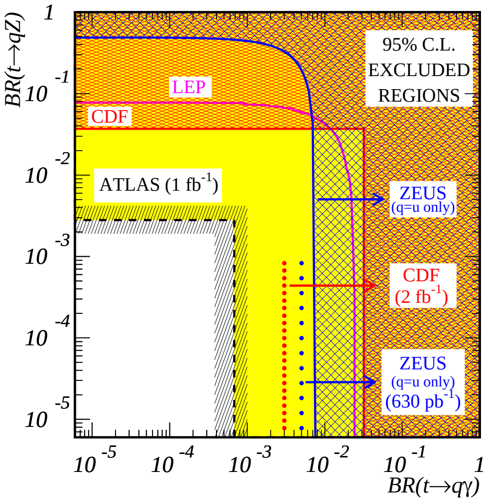


Fig. 6. – The present 95% CL observed limits on the BR(top → qγ) *versus* BR(top → qZ) plane are shown as full lines for the LEP, ZEUS and CDF Collaborations. The expected sensitivity at ZEUS, CDF and ATLAS (together with the statistic-plus-systematic 1σ band) is also represented by the dotted and dashed lines.

[83%] (40% ⊕ 43% ⊕ [60%]), where the square brackets reflect the uncertainty from using fast simulation [4]. For an integrated luminosity of 10 fb^{-1} at 14 TeV, CMS estimates a total relative uncertainty of 17% for the same angle combination, and of 27% when exchanging the least energetic non-b-jet with the b-jet [17].

8. – Flavor Changing Neutral Currents

Flavor Changing Neutral Current (FCNC) processes like top → qγ, top → qZ and top → qg are highly suppressed in the SM. Figure 6 shows the expected 95% CL exclusion limits on the branching ratio (BR) of the first two processes for ATLAS with 1 fb^{-1} at 14 TeV [4] and for other experiments. The expected upper limits for the BR(top → qγ), BR(top → qZ) and BR(top → qg) at 95% CL are 6.8×10^{-4}, 2.8×10^{-3} and 1.2×10^{-2}, respectively. For 10 fb^{-1} at 14 TeV, CMS estimates the smallest branching ratios detectable with a significance of 5 sigma to be BR(top → qZ) $= 14.9 \times 10^{-4}$ and BR(top → qγ) $= 8.4 \times 10^{-4}$ [17].

9. – Conclusion

The revised 7 TeV center-of-mass energy for 2010-2011 LHC running allows for discovery of new physics involving top quarks. This is especially true for analyses that depend primarily on a higher $\sqrt{s}$, like $\mathrm{t\bar{t}}$ resonances and a fourth generation of quarks, instead of a large amount of statistics, which is the case for most of the top properties analyses. The former analyses are where the LHC will be competitive the quickest with previous and current experiments.

No matter whether the 2010-2011 LHC run yields exciting evidence of new physics or not, it will be a wonderful opportunity to refine these analyses using information extracted from data. That should speed up our searches when the 14 TeV operations will start at the LHC.

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First, we would like to thank the organizers of the 3rd International Workshop on Top Quark Physics 2010. It was a very gratifying learning experience. We would like also to thank our respective collaborations, ATLAS and CMS, for allowing us to present their analyses. In particular, we would like to acknowledge all our colleagues who helped reviewing the presentation, with a special thank to R. Hawkings and A. Onofre who helped significantly refining the talk through their pertinent comments, as well as, M. Lefebvre for a thorough review of the talk and proceedings. We are very grateful for financial support of the Ministerium für Innovation, Wissenschaft, Forschung und Technologie des Landes Nordrhein-Westfalen, the Bundesministerium für Bildung und Forschung (BMBF), and the Deutsche Forschungsgemeinschaft (DFG).

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