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Searches for new resonances from BSM physics at Tevatron and LHC

Fabienne LEDROIT-GUILLON*
On behalf of the ATLAS, CDF, CMS and D0 Collaborations
LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut Polytechnique de Grenoble
E-mail: ledroit@lpsc.in2p3.fr

Several months after the end of the first run of the LHC, the searches for physics beyond the Standard Model (BSM) are now well developed. A powerful tool for such a quest is the search for new resonances. The latest and most interesting results from ATLAS, CDF, CMS and D0 in this field are reviewed, focusing on non supersymmetric resonance searches.

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*Speaker.

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Introduction

The Standard Model has never been better verified than today. The recent discovery of a Higgs boson, however, has hardly changed the list of the numerous questions that the Standard Model leaves unanswered. We still don't know why the Higgs is light, nor what the details of the electroweak symmetry breaking mechanism are; and many other questions, from 'do the couplings of the fundamental interaction unify?' to 'what is dark matter?' remain open. There is thus a continued need to look for beyond the Standard Model (BSM) physics. Several theories have been proposed to guide us in this search, among which supersymmetry is certainly the most popular. Yet, many other well motivated theories are available, such as grand unification, compositeness, technicolor, or theories with extra spatial dimensions. They all predict new particles: new vector bosons, heavy fermions, diquarks, leptoquarks, techni-hadrons, etc, or new states of known particles: excited fermions or bosons, Kaluza-Klein excitations of gauge bosons, black holes, string resonances, etc. All these BSM theories can therefore be revealed by the observation of new resonances!

Theories are not enough, one needs models to derive the phenomenology. We then have several theories, each including several possible models depending on some parameter choice, each in turn predicting many particles with various production and decay modes. The only practical search strategy is therefore to look for signatures, trying to stay as model independent as possible, even if in the end we use benchmark models to interpret and illustrate the search results.

This article presents the latest results from the ATLAS [1], CDF [2], CMS [3] and D0 [4] experiments on searches for non supersymmetric BSM resonances[1], focusing, for what concerns the LHC experiments, on the data collected at 8 TeV These data logically yield more stringent limits on new physics than 7 TeV data in the vast majority of the analyses, thanks to the increased centre of mass energy and integrated luminosity. Following the search strategy, the results are presented here according to the type of final state: one or two leptons, two jets or photons, other signatures. Most of the LHC results were obtained using the 20 fb^{-1}of integrated luminosity of the full 8 TeV data set, but some ATLAS results used only $\sim$ 13 fb^{-1}.

1. Signatures with one or two leptons

The dilepton final state is one of the cleanest signatures, where dilepton means dielectron or dimuon. It has a very low background and therefore the main challenge is the resolution in the transverse momentum of the very energetic leptons. Both ATLAS and CMS have looked for this signature [10, 11], as illustrated in Figure 1. The absence of any bump-shaped distortion in the measured dilepton invariant mass spectra leads to setting limits on various particles expected to decays into two leptons. An upper limit on the production cross section times branching ratio is set first, and then a lower limit on the mass of the particle is derived from the crossing point of the predicted cross section with this limit. In particular, a Sequential Standard Model (SSM) *Z'* is excluded at 95% C.L. with a mass up to 2.86 TeV by ATLAS and 2.96 TeV by CMS, and AT-

[1]The searches for supersymmetry are described in another contribution to this conference [5], as are the searches for pair produced resonances [6] (excited top quarks [7], second generation leptoquarks [8]), top partners with 5/3 electric charge [9],...).

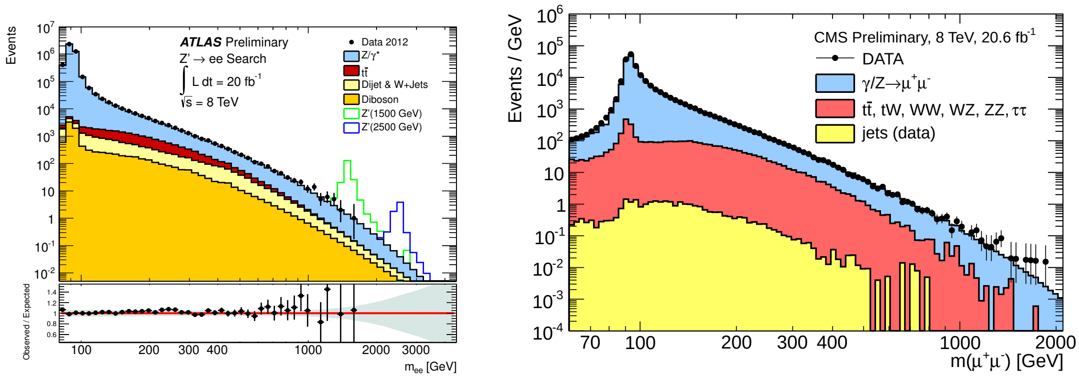

Figure 1: Predicted and observed dilepton invariant mass spectrum. Left: dielectron channel with two example Z' signals (ATLAS) [10]; right: dimuon channel (CMS) [11].

LAS excludes a Randall-Sundrum (RS) graviton with a mass up to 2.47 TeV assuming a coupling $k/\overline{M}_{\rm Pl} = 0.1$.

Since lepton universality is not required in all models, ATLAS has also looked for the ditau signature in the fully hadronic channel [12]. Tau candidates are reconstructed as jets with one or three tracks identified by means of a boosted decision tree. Since there are two missing neutrinos, a transverse mass is reconstructed instead of the invariant mass. The resolution is expectedly worse than for dielectrons or dimuons but a signal would still appear as a wide bump, as can be seen from the example on Figure 2 (left), where it is also obvious that no such deviation was observed. An SSM Z' decaying to a pair of taus is therefore excluded at 95% C.L. with a mass between 500 GeV and 1.9 TeV.

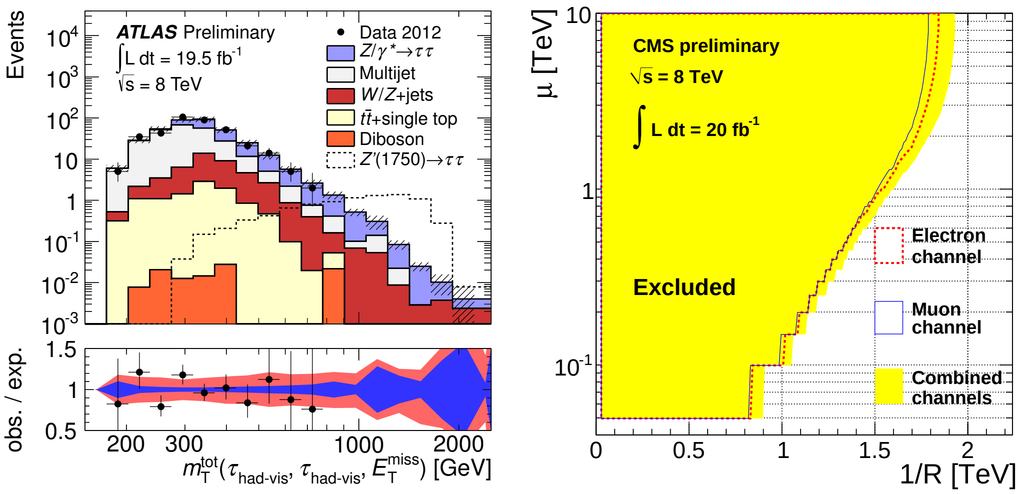

Figure 2: Left: predicted and observed ditau transverse mass spectrum (ATLAS) [12]. Right: region excluded at 95% C.L. by the lepton plus missing transverse energy analysis in the parameter plane of the split-UED model; R is the size of the extra-dimension and μ the mass parameter of the fermions in the bulk (CMS) [13].

Another interesting signature with leptons is lepton plus missing transverse energy. In this case, only one neutrino is missing, implying again the use of a transverse mass. The resonance has thus to be reconstructed from one single particle, therefore the resolution is not excellent, but sufficient to recognize the Jacobian peak at relatively low masses[2]. CMS has searched for this signature in the 8 TeV data and done several interesting interpretations [13]. The first one concerns a W' in the same SSM model as for the Z', but unlike it, not neglecting the interference effect between the Standard Model W and the W' production. This resulted in three low mass limits of 3.1, 3.35 and 3.6 TeV for the destructive, negligible and constructive interference hypotheses respectively. The other interpretation is on the second KK excitation of the W (W^2_{KK}) in a split Universal Extra Dimensions (UED) model, shown on Figure 2 (right).

2. Signatures with two jets or photons

The simplest resonance signature with jets is a pair of jets. In both LHC experiments, the jets are reconstructed using the anti-k$_T$ algorithm with a radius parameter $R = 0.5$ (CMS) or 0.6 (ATLAS). CMS then adds adjacent jets in a cone of radius $R = 1.1$, obtaining so-called "wide jets". The resolution on the invariant mass of the two leading jets (m_{jj}) is of the order of 5%. After the key selection: $|y(\mathrm{j}_1) - y(\mathrm{j}_2)| < 1.2$ (ATLAS) or equivalently $|\eta(\mathrm{j}_1) - \eta(\mathrm{j}_2)| < 1.3$ (CMS) on the two leading jets in the event j_1 and j_2, the background is still very large but it is smooth. It can be fitted from the data using a functional form that has been shown to fit the data as well as the Quantum Chromo-Dynamic (QCD) predictions:

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}, \tag{2.1}$$

with $x = m_{jj}/\sqrt{s}$ and p_i are free parameters. The fit is performed on the dijet invariant mass distribution above $\sim$ 1 TeV because of trigger constraints at lower masses. Both ATLAS and CMS have designed specific strategies to lower this threshold and gain sensitivity below 1 TeV, which should yield results in a near future. As no deviation from the fit is observed, several limits are derived. CMS sets limits on the production cross section times branching ratio (B) times acceptance (A) of many particles [14] including excited quarks (q^*), SSM Z' and W', RS graviton, string resonance, etc. according to their decay mode, namely gluon-gluon, quark-gluon or quark-quark (see Fig. 3 left). ATLAS also sets limits on q^* production: assuming the compositeness scale $\Lambda = \mathrm{m}(q^*)$ and the coupling factors $f_s = f = f' = 1$, the range [1.5,3.84] TeV is excluded at 95% C.L. with 13 fb^{-1} of data. In addition ATLAS provides a model independent limit on the cross section times acceptance ($\mathscr{A}$) of particles decaying to two jets assuming a Gaussian resonance shape of various widths [15], which are displayed in Figure 3 (right).

One can then replace one of the jets by a photon, which helps a lot the trigger issue, and look for jet plus photon resonances. This probes again the production of excited quarks[3], but also of Quantum Black Holes (QBH). Unlike thermal black holes, their production threshold could be as low as the higher dimensional Planck scale, M$_D$, and they would decay to much lower multiplicities

[2]At high masses, the signal shape is even more distorted by the parton luminosity.

[3]Excited leptons have also been searched for by ATLAS in 13 fb^{-1} of 8 TeV data, where the $\ell\ell\gamma$ invariant mass was used rather than the resonance mass [16].

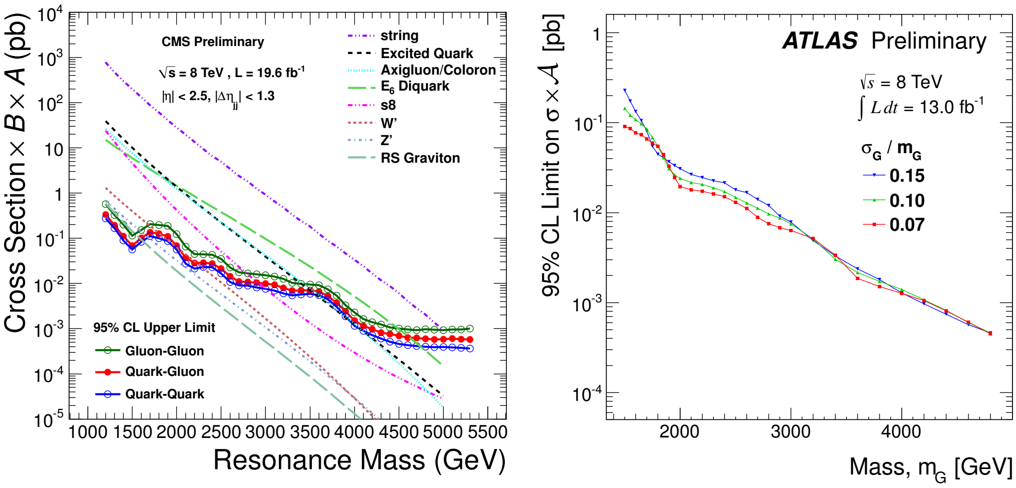

Figure 3: Observed 95% C.L. upper limits on the production cross section times acceptance of resonances decaying to a pair of jets. Left: limits on narrow resonances of type gluon-gluon, quark-gluon and quark-quark, compared to various theoretical predictions (CMS) [14]; right: model independent limits assuming a Gaussian-shaped reconstructed resonance (G) with various widths (ATLAS, 13 fb^{-1}) [15].

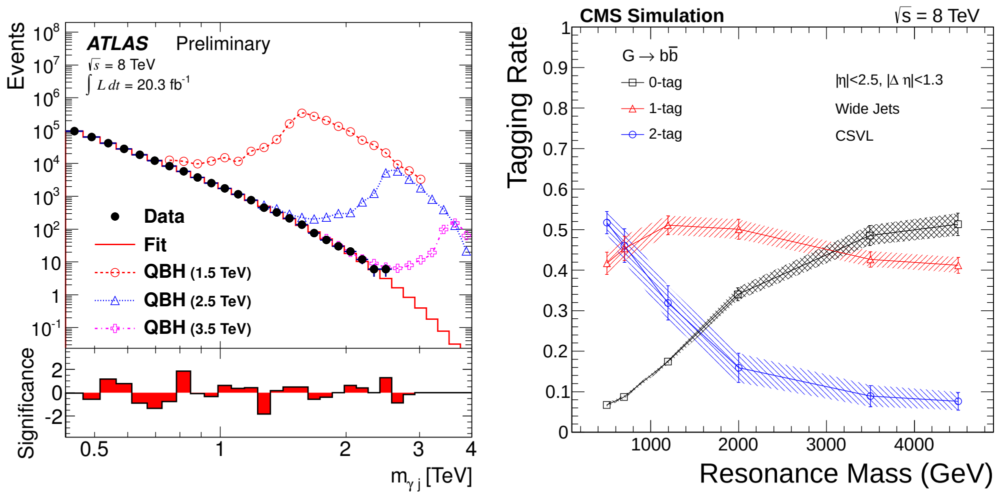

Figure 4: Left: observed jet plus photon invariant mass spectrum, together with the shape prediction of some Quantum Black Hole signals (ATLAS) [17]. Right: tagging rates for 0, 1, and 2 b-tags as a function of the RS graviton mass for the $G^* \to b\bar{b}$ decay mode (CMS) [18].

of particles. The jet-photon invariant mass measured by ATLAS [17] is shown in Figure 4, together with examples of signals (notice the particular shape of these signals, stemming from their insensitivity to parton luminosity). The smooth distribution is fitted with the same function as before (Eq. 2.1). Since no deviation is seen, limits are set both on q^*, that are competitive with the ones obtained in the dijet analysis, and on QBH where, assuming six extra dimensions and a threshold mass equals to M_D, the range [1.0,4.65] TeV is excluded at 95% C.L.

The CMS collaboration has also specifically looked for b-tagged dijets [18]. Using the same wide jets and the same $\Delta\eta$ selection to reduce QCD multijet background as before, the tagging rates for 0, 1 and 2 b-tags are computed from Monte Carlo simulations on signals with 0, 1 and 2 b jets. Figure 4 (right) shows for example the tagging rates for a RS graviton decaying to $b\bar{b}$. Using this information, a simultaneous fit is performed on the measured spectra with 0, 1 and 2 b-tagged leading jets, using again the function of Eq. 2.1. As no deviation is observed, the following mass ranges are excluded at 95% C.L. [1.20,1.68] TeV, [1.42,1.57] TeV and [1.34,1.54] TeV for an SSM Z' (assuming a branching fraction to $b\bar{b}$ $f_{b\bar{b}}$ of 20 %), an RS graviton (assuming $f_{b\bar{b}} = 0.2$ and $k/\overline{M}_{\rm Pl} = 0.1$) and an excited b quark (b^*) respectively[4].

CMS has performed a dijet analysis with gauge boson (W or Z) tagging [20]. If a heavy resonance decays to one or two gauge bosons, and the gauge bosons in turn decay into two jets, they are sufficiently boosted such that the jets merge and form a single big jet (not to be confused with the wide jets mentioned previously). These big jets are reconstructed with the Cambridge-Aachen algorithm using a distance parameter $R = 0.8$ and W/Z are tagged with an algorithm based on jet substructure observables, initially designed for boosted top-jet tagging. Applying again the same $\Delta\eta$ selection between the two leading jets, both the 1 and 2 W/Z-tagged spectra are fitted with the usual function, and the non deviating results are used to derive exclusions on mass ranges: the 1 tagged sample allows the exclusion of a $q^* \to qW$ or qZ in [1.0,3.23] TeV or [1.0,3.00] TeV respectively; the 2 tagged sample allows the exclusion of an SSM $W' \to WZ$ in [1.0,1.73] TeV, and an RS $G^* \to WW$ or ZZ in [1.0,1.59] TeV or [1.0,1.17] TeV respectively[5].

Finally, it is possible to search for $t\bar{t}$ resonances in the fully hadronic channel using similar techniques. The CMS collaboration has done so, using the same jet algorithm as for W/Z tagging and exploiting both jet substructure and mass observables to "top-tag" the two leading jets [22]. The resulting resolution is very good, of the order of a few percent. Here only the multijet background is derived from data, the Standard Model $t\bar{t}$ production is taken from Monte Carlo, both with a $|\Delta y| <$

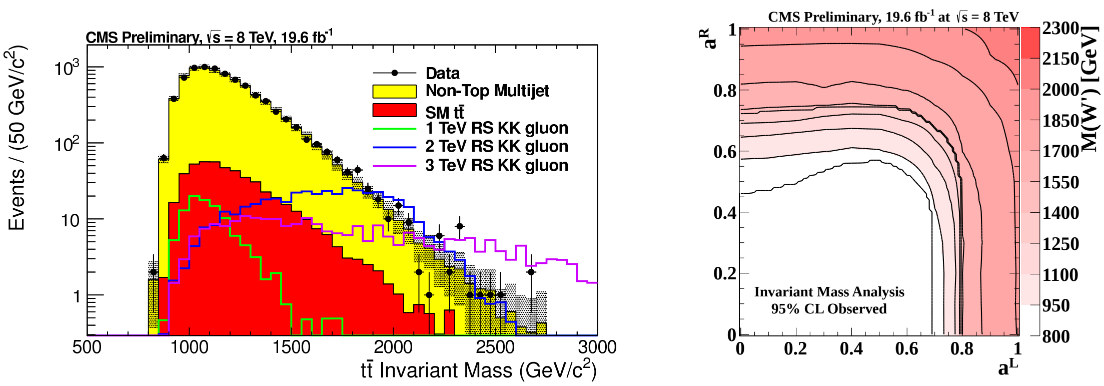

Figure 5: Left: predicted and observed top quark pair invariant mass distributions with, as example, g_{KK} signals [22]. Right: contours of m(W') in the plane of the normalized left-handed and right-handed couplings (a_L,a_R) at which the 95% C.L. observed cross section limit equals the predicted cross section in the semileptonic $t\bar{b}$ analysis [23].

[4] See also ATLAS limits on $b^* \to Wt$ from 7 TeV data analysis [19].

[5] See also ATLAS $G^* \to ZZ \to llqq$ analysis in the 2 lepton plus 2 jet and the 2 lepton plus 1 big jet topologies [21].

1.0 requirement; the resulting top pair invariant mass distributions are shown in Figure 5 (left). No signal being observed in the data, limits are derived on the production of two particles, a narrow (or wide) topcolor Z' is excluded between 1.0 and 1.7 TeV (or 1.0 and 2.35 TeV respectively), and a bulk RS excitation of the gluon (g_{KK}) between 1.0 and 1.8 TeV.

3. Other signatures

So far we have shown limits on the W' production in the leptonic ($e\nu$, $\mu\nu$), dijet and diboson (boosted WZ decaying hadronically) channels. The $W' \to t\bar{b}$ decay should also be searched for specifically. The $W' \to q\bar{q}'$ channel is important in leptophobic models (and the diboson one in the case where new physics couples preferentially to bosons). In addition, for a right handed W', the leptonic decay is suppressed if the right handed neutrino is too heavy. The CMS collaboration has performed a search for $W' \to t\bar{b}$ in the leptonic channel [23]. The final state is an isolated lepton, two b jets and missing transverse energy. The invariant mass is reconstructed by constraining the ($l^{\pm}$,E_T^{miss}) invariant mass to the W mass and keeping the W-jet pair with mass closest to the top mass. At least one jet must be identified as a b jet. No signal has been observed and therefore limits have been derived on the production of a purely right handed W' (W'_R) which is excluded up to 2.03 TeV. These limits are then generalized to arbitrary combinations of the normalized right-handed and left-handed couplings, a_R and a_L, shown on Figure 5 (right)[6], assuming the right handed neutrino to be lighter than the W' (which is conservative).

A complementary analysis to the fully hadronic $t\bar{t}$ search described earlier is the semileptonic channel search. Although more complex, it has a better signal to background ratio (and a better branching ratio than the fully leptonic channel). The final state consists of one isolated lepton, four jets including two b jets and missing transverse energy. Both ATLAS and CMS have performed such an analysis [25, 26]. They have designed two analysis each in order to maximize the coverage of the resonance mass: a "resolved" (or "threshold") analysis optimized for low masses and a "boosted" one optimized for high masses, the transition occurring around m($t\bar{t}$) = 1 TeV. The resolved/threshold analyses are close to the standard $t\bar{t}$ analyses (meant for cross section measurements for instance), whereas the boosted ones are optimized, as their name says, for boosted top decays. Therefore they have less stringent isolation requirements, use lower jet multiplicities, wider jets and exploit jet substructure observables. In the resolved/threshold case, the constraints in the W and top masses are used in the the reconstruction of the $t\bar{t}$ invariant mass, based on a stan-

Particle/model	ATLAS (14 fb^{-1})	CMS (20 fb^{-1})
Narrow topcolor Z'	[0.5,1.8] TeV	[0.5,2.10] TeV
Wide topcolor Z'		[0.5,2.68] TeV
Bulk RS g_{KK}	[0.5,2.0] TeV	[0.5,2.54] TeV

Table 1: Observed 95% C.L. mass exclusions in the semileptonic $t\bar{t}$ analysis performed by ATLAS (14 fb^{-1}) [25] and CMS [26].

[6]See also ATLAS analysis with 13 fb^{-1} in which the output of a boosted decision tree is fitted instead of the invariant mass [24].

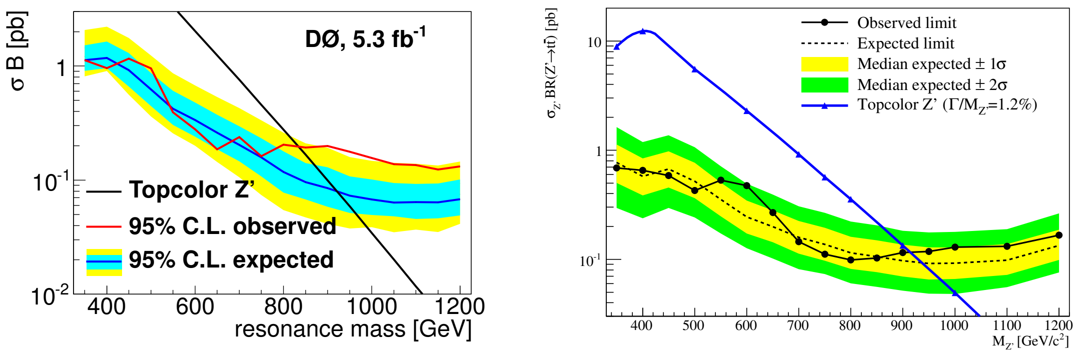

Figure 6: Expected and observed 95% C.L. upper limits on the production cross section times branching ratio of a narrow Z' resonance decaying to a pair of top quarks in the semileptonic channel, together with the theoretical prediction. Left: DO (5.3 fb^{-1}) [28], right: CDF (9.45 fb^{-1}) [27].

dard χ^2 procedure. Unfortunately no signal has been seen and both experiments set limits on the same particles as before in the fully hadronic analysis, as shown in Table 1. As can be seen from this table, the LHC experiments do not exclude any $t\bar{t}$ resonance with mass below 500 GeV, and the other two decay channels (the fully leptonic and fully hadronic ones) do not go lower either. Therefore the results obtained by the Tevatron experiments [27, 28], CDF and D0, are still the best in this region, since they have set limits from around the $t\bar{t}$ production threshold ($\sim$ 350 GeV), as can be seen in Figure 6.

Moving back to diboson resonances, a search for WZ resonances has been performed by ATLAS and CMS, in the fully leptonic channel [29, 30]. Regarding the W' interpretation, the WZ channel is complementary (that was already true in the dijet analysis) to the lepton plus missing transverse energy and the $t\bar{b}$ analyses, which assumed a branching ratio to diboson $BR(W' \to WZ) = 0$. It also has a lower threshold than the W/Z-tagged dijet analysis, thanks to the lepton trigger. The invariant mass spectrum measured by CMS is shown in Figure 7 (left) and the limits on the W' production cross section times branching ratio obtained by ATLAS are displayed in Figure 7 (right). The lower mass limits are 1.18 TeV (ATLAS, 13 fb^{-1}) and 1.45 TeV (CMS). A second interpretation of this analysis was performed by both experiments in the Low Scale Technicolor (LSTC) model, triggered by the LSTC interpretation of the CDF anomaly, observed in dijet production associated with a W, which could imply the existence of a techni-pion of mass m($\pi_{\rm T}$) $\sim$ 160 GeV and a techni-rho of mass m($\rho_{\rm T}$) $\sim$ 280 GeV. The exclusion region in the (m($\rho_{\rm T}$),m($\pi_{\rm T}$)) derived by CMS is shown in Figure 8 (left); the ATLAS exclusion is similar; both exclude the CDF point, while in the meantime, the CDF anomaly disappeared after the collaboration analyzed its full data set [31].

ATLAS also performed a dedicated search with the same motivation in the exact same channel as CDF, looking for a low mass dijet resonance associated with a W or a Z [32]. No signal was found and limits where derived assuming m($\rho_{\rm T}$) $= 3/2$m($\pi_{\rm T}$) $+ 55$ GeV on the production cross section times branching ratio (shown on Fig. 8, right) leading to a limit of m($\pi_{\rm T}$) $>$ 180 GeV at 95% C.L. on the mass of the techni-pion.

Finally, there are more resonance searches performed by the CDF Collaboration, which could

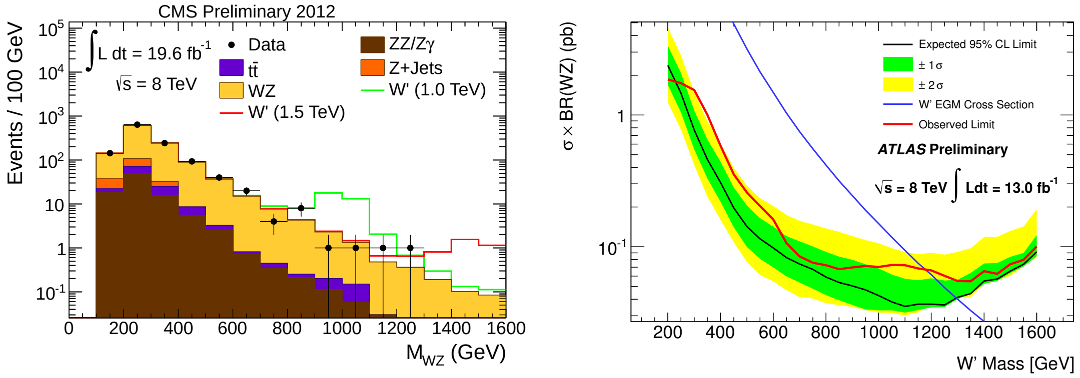

Figure 7: Left: predicted and observed WZ invariant mass distribution in the all leptonic channel (CMS) [30]. Right: expected and observed 95% C.L. upper limits on the production cross section times branching ratio of a W' resonance decaying to WZ, together with the theoretical prediction (ATLAS, 13 fb^{-1})[29]; the Extended Gauge Model (EGM) is another name for the SSM in the WZ decay case.

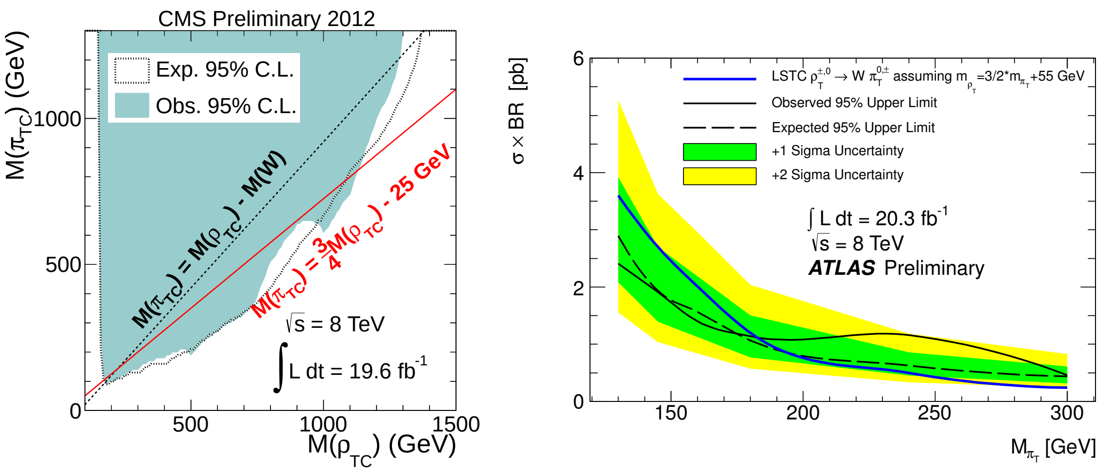

Figure 8: Low Scale Technicolor interpretations: expected and observed regions excluded at 95% C.L. by the all leptonic WZ analysis in the parameter plane (m(ρ_T),m(π_T)) [30] (left); expected and observed 95% C.L. upper limits on the production cross section times branching ratio of $\rho_T^{\pm,0} \rightarrow W\pi_T^{0,\pm}$ in the dijet associated with W/Z analysis [32] (right).

not be shown for lack of time: a chromophilic Z' search [33], a top plus jet resonance search in $t\bar{t}$ plus jets events with a Z' interpretation [34] and a four jet resonance search with an axigluon interpretation [35].

Conclusion and outlook

The LHC has provided a wealth of data that the ATLAS and CMS collaborations are exploiting to set more and more stringent direct limits on new resonances, since no such resonances have been observed so far. Higher and higher masses are probed, keeping in mind that low mass searches must be continued in order to detect weakly coupled new physics. Advanced techniques are developed to identify the boosted decay products of very massive resonances; these techniques will become

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even more important with the coming increase of centre of mass energy. With 13 or 14 TeV centre of mass energy data, the reach for new resonances will obviously be considerably extended, so the results presented here are clearly not the end of the story!

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