BSM Searches from CMS

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Summary. — This proceeding presents an overview of recent experimental searches for physics beyond the Standard Model. These searches are based on data collected by the CMS experiment operating at the Large Hadron Collider at CERN with $\sqrt{s} = 7$ TeV, and most of the presented results use the full dataset collected in 2011 data taking period, corresponding to ~ 5 fb^{-1}. In none of the searches a significant deviation from background prediction is observed, and we set the most stringent limits on new physics phenomena.

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1. – Introduction

While the Standard Model (SM) continues to describe the current collider data well, there is a strong theoretical and astrophysical evidence that the SM is not complete and needs to be extended. The shortcomings of the SM (e.g. the hierarchy problem and origin of dark matter) can be solved at the TeV scale by many proposed theories of beyond SM extensions, and could be accessible at the LHC. A spectrum of new particles is predicted in many theories of beyond SM (BSM) physics, including Grand Unified Theories (GUT), Supersymmetry (SUSY), composite and technicolor models etc. The LHC experiments provide a unique opportunity to shed light on Nature's most fundamental questions.

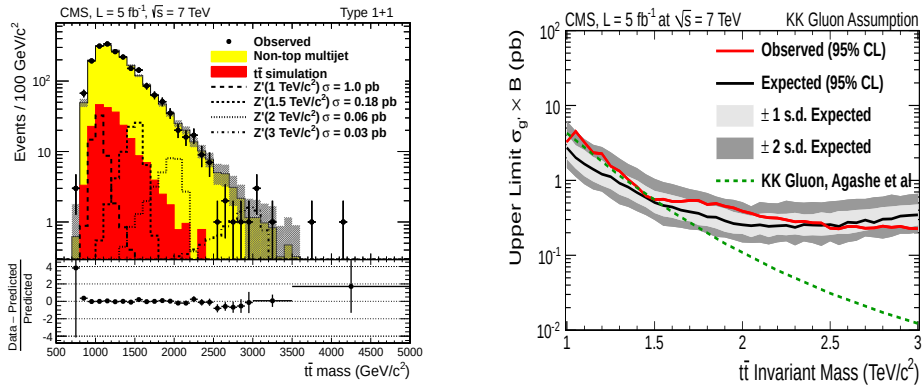
In these conference proceedings we present the results of searches for various new physics phenomena beyond the standard model [1], as they were at the moment of the conference. The analysis use data from proton-proton collisions at $\sqrt{s} = 7$ TeV delivered by the LHC and collected with the Compact Muon Solenoid (CMS) detector in 2011. For the majority of these searches the full dataset has been used, corresponding to an integrated luminosity of almost 5 fb^{-1}.

2. – Heavy Resonsances

2˙1. *Searches with boosted top quarks and vector bosons.* – A number of scenarios for physics beyond the SM (BSM) feature new heavy gauge bosons, generically referred

to as Z'. Models predicting favorable couplings with third-generation quarks result in resonances from $Z' \to t\bar{t}$, such as Kaluza-Klein (KK) gluons. The CMS search focuses on the all-hadronic channel [2], which benefits from the large branching ratio.

Large background from multijet production is reduced exploiting the highly-boosted nature of the top quarks from high-mass resonances. The *top tagging* algorithm (TTA), based on the differences in the jet substructure between top quark jets and QCD jets, is used to identify top jets. The search is performed in two orthogonal samples. The first sample contains dijet events where both jets pass the TTA. The second sample contains events where only one jet passes the TTA, while the other two contain a b-jet and a W-jet candidate, and the combination of the two jets is consistent with a top quark decay. The data is found to be in good agreement with predicted backgrounds (Fig. 1(a)), and the results are interpreted as 95% C.L. upper limits on $\sigma_{Z'} \times \mathrm{Br}(Z' \to t\bar{t})$. Limits in the range of 1 pb on generic Z' and KK gluon are set, as shown in Fig. 1(b).



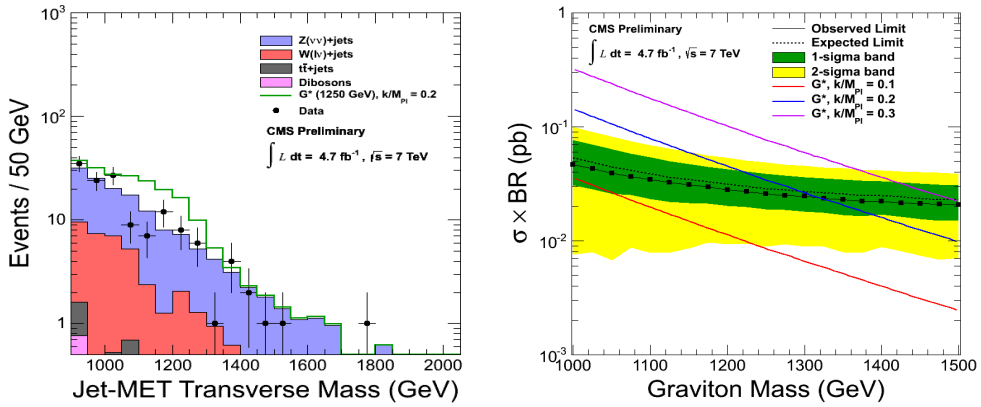
(a) (b)

Fig. 1. – (a) Observed and predicted $t\bar{t}$ invariant mass distribution in the dijet sample, (b) limits on the $\sigma_{Z'} \times \mathrm{Br}(Z' \to t\bar{t})$ of $t\bar{t}$ resonances, using Randall-Sundrum KK gluon samples.

A search for resonance decays into a pair of Z bosons is performed focusing on the reaction $G^* \to ZZ \to q\bar{q}\nu\nu$ [3], which may arise in Randall-Sundrum (RS) model of extra dimensions from decays of a Kaluza-Klein (KK) graviton excitations (G_{KK}). We consider the kinematical configuration where the Z bosons are very boosted, leading to an experimental signature of a single jet plus missing transverse energy ($\not\!\!E_{\mathrm{T}}$). The jet is required to have invariant mass close to the mass of the Z boson.

Candidate events are required to contain at most two jets with $p_T > 30$ GeV, with the leading jet of $p_T > 300$ GeV, no isolated leptons or tracks, and $\not\!\!E_{\mathrm{T}} > 300$ GeV. The signal region is defined as the set of events with the invariant mass of the leading jet $m_j > 70$ GeV and the jet-$\not\!\!E_{\mathrm{T}}$ transverse mass (M_T^G) greater than 900 GeV. Events passing all the requirements but the last two form the sideband region used to derive the data-driven background model. The data in signal region is found to be in good agreement with background model (Fig. 2(a)). We proceed to set 95% C.L. exclusion limits on $\sigma \times Br$ of new resonances in mass range of [1000, 1500] GeV (Fig. 2(b)).

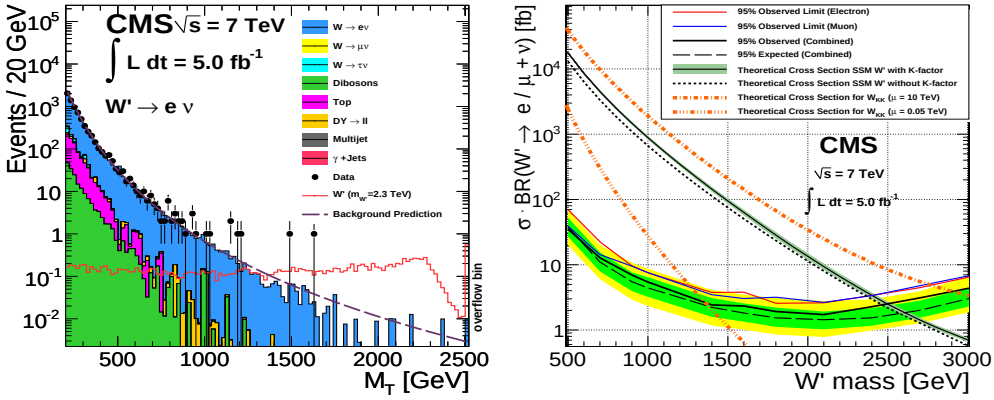
2˙2. *Searches for W'.* – Several models of BSM physics predict the existence of a heavy analogue of the SM W boson, a W' boson. The most sensitive searches for a



(a) (b)

Fig. 2. – (a) Comparison of M_T^G distribution between simulated backgrounds and experimental data, (b) 95% C.L. upper limits on $\sigma \times Br$ for a resonance decaying in $ZZ \rightarrow$massive jet + $\not{E}_{\rm T}$.

production of such a particle are in leptonic final states: $W' \rightarrow e\nu/\mu\nu$. The primary source of background is the high transverse mass tail of the standard model $W \rightarrow \ell\nu$ decays. The shape of the background was determined from simulation by performing a fit by a function optimized to best describe the spectrum in either channel (e or μ) up to very high masses. This function was fitted to simulation and normalized to data in the signal depleted region 200 GeV $< M_T <$ 500 GeV, to estimate the expected number of SM background events for high M_T bins (Fig. 3(a)).

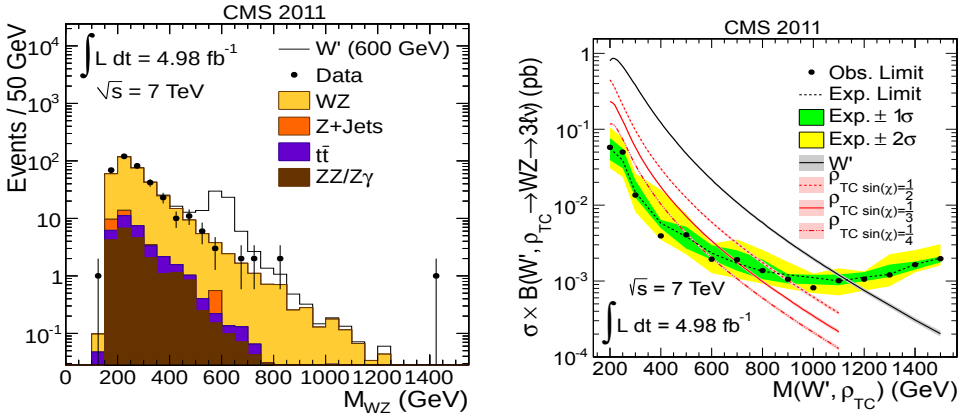


(a) (b)

Fig. 3. – (a) Comparison of M_T distribution between simulated backgrounds and experimental data in the electron channel, (b) 95% C.L. observed limits for the electron (red line) and the muon channels (blue line) and their combination (black).

No significant excess over predicted backgrounds was observed in the 2011 dataset. We set upper limits on $\sigma_{W'_R} \times Br(W'_R \rightarrow \ell\nu)$ (Fig. 3(b)). Interpreting the results in

the Sequential Standard Model (SSM) framework we exclude W'_R of a mass less than 2.5 TeV at 95%CL. For the first time in such a study, $W - W'$ interference effects have been taken into account, and we exclude W'_L with a mass below 2.63 TeV and 2.43 TeV for constructive and destructive interference respectively.



(a) (b)

Fig. 4. – (a) WZ invariant mass for the full mass range, (b) expected and observed upper limit on $\sigma \times Br(W'/\rho_{TC} \to 3\ell\nu)$ as a function of the WZ mass for W' and ρ_{TC}.

In many W' models coupling to the leptons is suppressed, resulting in an enhancement of the triple gauge couplings that could lead to a WZ final state. In technicolor models the lightest ρ_{TC} and ω_{TC} are expected to have masses below ≈ 700 GeV, with distinctive decay signatures (e.g. $\rho_{TC} \to WZ$). Therefore, searches for $W' \to WZ$ can be considered as complementary to the searches in the leptonic channels.

We focus on the search in $W' \to WZ \to 3\ell\nu$ [5], with $\ell = e, \mu$, where one of the lepton pairs is required to be consistent with originating from a Z boson, and the event has a significant amount of $\not{E}_{\rm T}$. The backgrounds are estimated using PYTHIA program, and the cross-sections are corrected for higher order effects using MCFM. The background estimation technique is cross-checked using an alternative, data-driven method which is found to be in a good agreement with simulation. Several search regions in bins of H_T are defined to optimize the sensitivity of the search, and good agreement with data is observed (Fig. 4(a)). Therefore, we proceed to set the 95%C.L. upper limits, excluding W' bosons with masses below 784 GeV and ρ_{TC}s with masses below 382 GeV.

3. – Fourth generation fermions

The possible existence of a fourth generation of fermions remains an important subject for experimental searches. The additional fourth generation of quarks could introduce a source of large CP violation, thus generating the baryon asymmetry of the universe.

We search for the production of a b' quark assuming the decay chain $b' \to tW \to bW^+W^-$ dominates [6]. Striking signatures of b' production are expected, with two isolated leptons of the same charge, or three isolated leptons. These two signatures may be present in 7.3% of $b'\bar{b}'$ events, while the SM background is very rare, mostly from $t\bar{t}$ events. The observed event yields are consistent with the estimated background. We

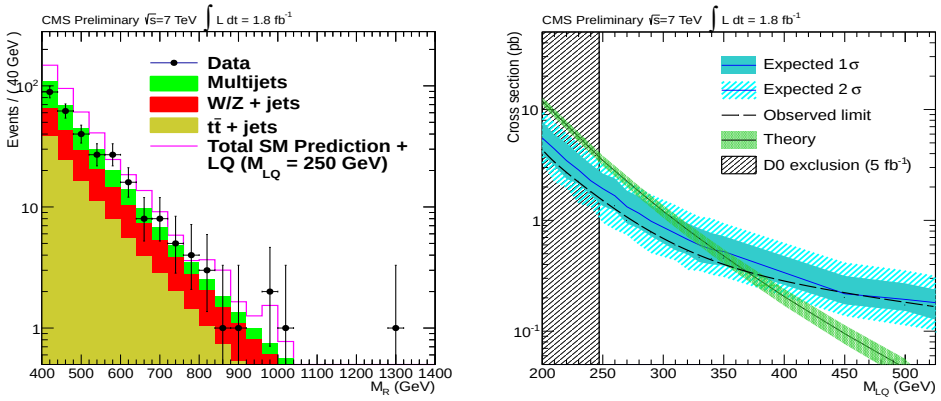
proceed to set upper limits on the b' masses, excluding those below 611 GeV at 95% C.L.

Similarly, we perform a search for the fourth generation top quarks in the $t' \to bW \to b\ell\nu$ final state [7]. We use data collected with a set of double-lepton triggers: ee, $e\mu$ or $\mu\mu$. The dominant backgrounds from misidentification of b jets and leptons are modeled using data in an orthogonal sample. The number of expected events from background processes is 1.8 ± 1.1, and one event is observed in the $e\mu$ channel. Assuming a branching fraction of 100% for $t' \to bW$, we set 95% C.L. lower bounds on the t' mass at 557 GeV.

4. – Leptoquarks

Many BSM models predict existence of leptoquarks (LQ): color-triplet bosons with fractional electric charge, and both lepton and baryon quantum numbers. Usually it is assumed that LQs couple to only one generation to avoid constraints on flavor-changing neutral currents, thus classifying LQs as first-, second-, or third-generation.

A CMS search for third-generation leptoquarks in $LQ3 \to b\nu_\tau$ is performed in events with two high p_T b-jets and $\not\!\!E_{\rm T}$ [8]. The search is performed using razor variables R and M_R. The razor R is sensitive to the ratio of missing and visible momentum in the event, while M_R peaks at the characteristic scale of the physics process. Distributions of SM backgrounds have an exponential dependence on razor variables R and M_R, allowing one to extract their shapes directly from data. The kinematic distributions and number of observed events in the signal sample are found to be in good agreement with the background description (Fig. 5(a)). We set an upper limit on the LQ pair production cross section (Fig. 5(b)), excluding scalar $LQ3$ with masses below 350 GeV.



(a) (b)

Fig. 5. – (a) Comparison of M_R distribution between background model and observed data, (b) the 95% C.L. upper limits as a function of LQ3 mass, assuming 100% branching ratio to $b\nu_\tau$.

5. – Dark Matter and Extra Dimensions

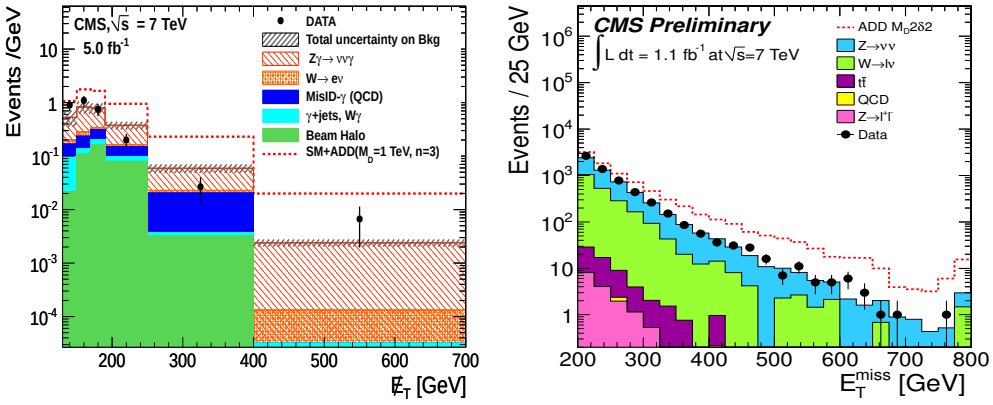
Final states that contain a single high p_T photon (or jet) and $\not\!\!E_{\rm T}$ provide a unique opportunity to investigate new scenarios of BSM physics [9, 10]. This type of signature can be produced from direct production of dark matter particles (χ) in the reaction

$q\bar{q} \to \gamma(g)\chi\bar{\chi}$, where the photon ($\gamma$) or gluon ($g$) is radiated by one of the incoming quarks. Additionally, these final states have good sensitivity to models of Extra Dimensions (ED), such as ADD, by probing direct production of graviton (G) in reaction $qq \to \gamma(g)G$.

5˙1. *Mono-photon and mono-jet final states.* – The primary background for the mono-photon search is the irreducible background from $Z\gamma \to \nu\nu\gamma$. Backgrounds that are out of time with collisions (mostly from beam halo muons) are estimated from data, using a template fit of the p_T and time-of-arrival information of the most energetic crystal. Backgrounds from processes where an electron or a jet fake a photon are estimated from data. The remaining backgrounds are estimated using MC simulation.

The main backgrounds in the mono-jet analysis arise from Z+jets where $Z \to \nu\nu$ and W+jets where the lepton is missed. The model of the $Z \to \nu\nu$ background is constructed using $Z \to \mu\mu$ events. These are expected to have the same topology as the $Z \to \nu\nu$ events, with the difference that $\not\!\!E_{\rm T}$ is replaced by the momentum of the Z boson. The background from W+jets is obtained from the single-muon sample, where a clean sample of W events is obtained by requiring $50 < M_T < 100$ GeV.

The observed number of events and kinematic distributions agree with the expected background in both searches (Fig. 6). The mono-photon search is interpreted by setting 90% C.L. upper limits on χ production at 13.6-15.4 fb, and most stringent limits on spin-dependent χ-nucleon scattering for $1 < M_\chi < 100$ GeV. The mono-jet search is interpreted in the ADD model, and for the ED parameter $\delta = 2$ we exclude production of extra dimensions with $M_D < 3.7$ TeV at 95% C.L.



(a) (b)

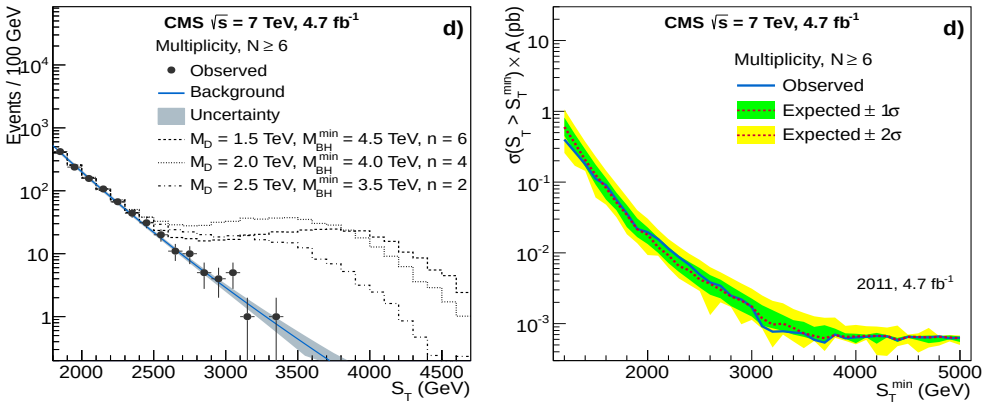
Fig. 6. – (a) Comparison of $\not\!\!E_{\rm T}$ distribution between estimated backgrounds and experimental data, (b) the 90% C.L. upper limits on the χ-nucleon cross section as a function of M_χ for spin-dependent scattering.

5˙2. *Microscopic black holes.* – Many theoretical models with extra dimensions and low-scale quantum gravity predict the possibility of production of black holes in LHC. Due to a democratic decay via Hawking radiation, black holes would manifest appear as events with large total energy with multiple high-energy jets, leptons, and photons.

The main background in this search [11] arises from multijet and direct photon production, which dominates the event rates at large S_T. W/Z+jets and $t\bar{t}$ production

contribute less than 1% to the total background at large values of ST, and are estimated from MC simulation. The dominant background is estimated from data using the S_T multiplicity invariance technique. This technique allows one to predict the shape of the S_T spectrum for any number of objects using the dijet data, which is depleted in signal.

The search is performed in events with high multiplicity using the background shape from low multiplicity events, as shown in Fig. 7(a). The data agree well with the background shapes, and the results are interpreted as limits on cross section times acceptance for new physics production (Fig. 7(b)). We also set limits on the minimum black hole and string balls mass in the 4-5 TeV range for a large variety of model parameters.



(a) (b)

Fig. 7. – (a) Total transverse energy S_T, for events with the multiplicity of $N \geq 6$, (b) the 95% C.L. upper limits on a signal cross section × acceptance for $N \geq 6$.

6. – Heavy stable charged particles (HSCP)

Various BSM theories allow for the possibility that new massive elementary particles could be long-lived with life-time greater than $\sim$ 1 ns. Because of their high mass, a significant fraction of the HSCPs could be detectable as high momentum tracks with large rate of energy loss through ionization (dE/dx) and long time-of-flight (TOF).

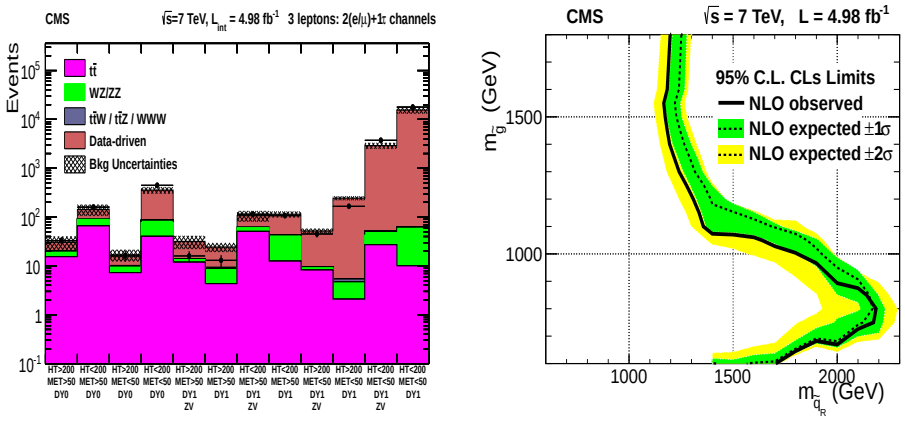
The CMS search [12] is performed based on the distinctive signature of HSCPs, using two separate data-samples: one that uses highly ionizing tracks reconstructed in the inner tracker, and a second requiring that these tracks also be identified in the CMS muon system and have long time-of-flight. The former is model-independent in that it is insensitive to the details of R-hadron nuclear interactions. In both analysis, the observed number of events is consistent with the expected background. Limits on production cross section and masses of stable, weakly- and strongly-interacting particles have been established, ranging from 223 GeV for scalar tau, to 1098 GeV for a gluino.

7. – Multileptons

Events with three or more prompt leptons are rarely produced by SM processes, and therefore serve as highly sensitive probe of BSM physics. Many scenarios of new physics

predict enhancement in multilepton production, such as SUSY. In R-parity conserving models, the stable, weakly-interacting LSPs produce $\not\!\!E_{\rm T}$ signatures, while the lack of a stable LSP in R-parity violating (RPV) models $\not\!\!E_{\rm T}$ is a poor signal discriminator.

In order to increase sensitivity to a wide range of new physics, the CMS search [13] is performed in exclusive bins of lepton multiplicity (e, μ or τ), comparing small versus large S_T and $\not\!\!E_{\rm T}$, the presence of an opposite-sign same-flavor lepton pair or not, and whether such pair falls in our out of a invariant mass window around the Z-boson mass. Over all search bins the data is in fair agreement with the SM expectation (an example is shown in Fig. 8(a)). Fig. 8(b) shows the 95% C.L. exclusion limit contours for an interpretation in RPV models.



(a) (b)

Fig. 8. – (a) Background breakdown in events with one τ, (b) exclusion plot for hadronic RPV.

8. – Conclusions

I would like to thank the organizers of the "Rencontres de Physique de la Vallee d'Aoste" for the rich physics program, and the beautiful location of the conference.

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