PROCEEDINGS OF SCIENCE

WG6 Summary: Higgs, top, and interplay between flavour and high-p_{T} physics

Umberto De Sanctis[a,*] **and Matthias Komm**[b,*]

[a] *University of Rome Tor Vergata and INFN, Rome, Italy*
[b] *Desy, Hamburg, Germany*

E-mail: Umberto.De.Sanctis@cern.ch, Matthias.Komm@cern.ch

In this contribution a summary of the activities of the Working Group 6 (WG6) during the 11th International Workshop on the CKM Unitarity Triangle (CKM2021) is reported. The WG6 is devoted to Higgs and top physics and the interplay between flavour and high-p_{T} physics. The newest results presented and the most interesting topics discussed during WG6 sessions are listed in this document.

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*Speaker

1. Introduction

The WG6 activities during the 11th International Workshop on the CKM Unitarity Triangle (CKM2021) were divided into 4 sessions where both theoretical and experimental results have been shown. The 4 sessions treated the physics related to the Higgs boson, the top quark, the lepton flavour universality and the interpretation of the measurements at low and at high-p_T in the context of the Effective Field Theory (EFT). The main results, together with the arguments of discussion, in each of those topics are reported in this note.

2. Higgs physics

After the discovery of the Higgs boson, dated back to 2012 [1, 2], ATLAS and CMS collaborations [3, 4] collected about 160 fb^{-1} of proton-proton collision data at several centre-of-mass energies (7, 8 and 13 TeV). The latest dataset, collected at $\sqrt{s}$ = 13TeV, corresponding to an integrated luminosity of about 140 fb^{-1} is the ideal place to test the Higgs boson couplings with all particles of the Standard Model (SM). Furthermore, it is also possible to measure with unprecedented accuracy the cross-section and the branching ratios of its decays to both fermions and gauge bosons. The session devoted to the Higgs physics was composed by 4 talks describing each of these aspects in depth, giving a comprehensive state-of-the-art picture of the current experimental situation.

The measurement of the Higgs coupling with fermions has been one of the principal activities for the ATLAS and CMS experiments in the last years. Figure 1 shows the summary of the various measurements made by the two experiments. It is possible to see that all measurements made until now are in agreement with the SM predictions. While the Yukawa coupling with all third generation fermions (i.e. top and bottom quarks and the tau lepton) have been observed, in the last year the first measurements of the Higgs Yukawa couplings with second generation fermions started to appear. In particular, the decays of the Higgs boson into a pair of charm quarks and into a pair of muons have been seen for the first time. An upper limit on the "so-called" signal strength μ (which represents the ratio between the observed and the cross-section predicted by the SM) has been placed at the level of about 26 for the $H \to c\bar{c}$ decay by the ATLAS experiment [5], while a 3σ evidence has been reached for the $H \to \mu\mu$ decay by the CMS experiment when a combination of various channels is performed [6]. The usage of the most advanced statistical techniques, such as multivariate analyses or machine learning approaches, allowed to reach these significant results that were considered almost impossible few years ago due to the very small S/B ratio.

Concerning the coupling of the Higgs boson with gauge bosons, the available statistics allowed both experiments to start concentrating their efforts not only in the extraction of the most precise value of μ (which is now compatible with 1 within a precision of 6-7%[7, 8]), but also in the analysis of the kinematic properties of the Higgs bosons. In fact, a systematic study of μ as a function of the transverse momentum of the Higgs boson within the context of the "so-called" STXS framework [9] has been performed by both ATLAS and CMS, looking for significant deviations from the SM predictions in all the phase-space available for the decay and in the $H \to \gamma\gamma$, $H \to WW$ and ttH channels. Also in this context, no significant deviations form the SM predictions have been found yet.

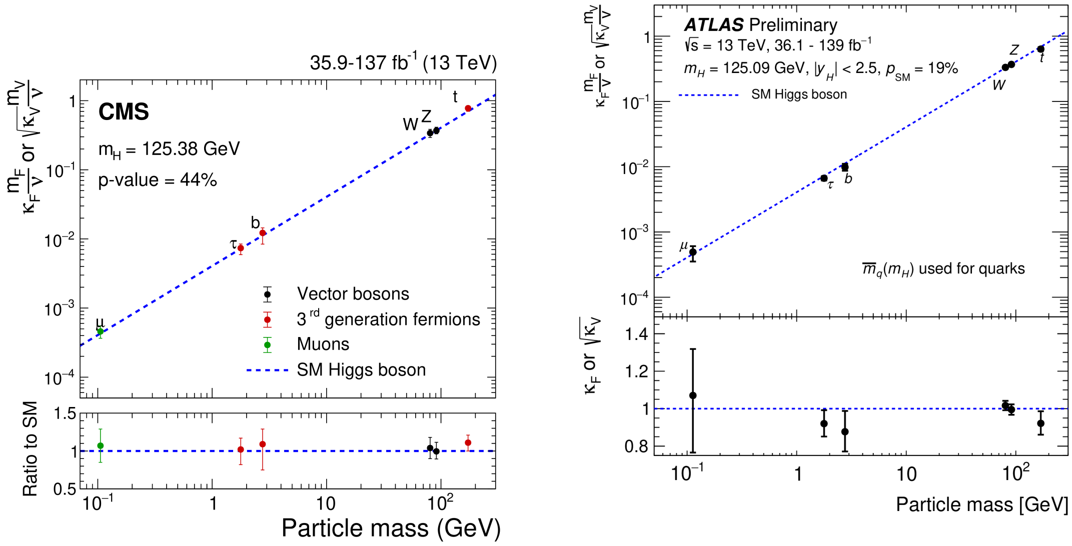

Figure 1: Summary of the Higgs couplings measurements measured by the CMS Collaboration [6] (left) and ATLAS Collaboration [7] (right).

In addition to the Higgs coupling measurements, several efforts has been devoted by the two experiments in the measurements of the CP structure of those couplings and in the search for both FCNC and LFV decays. For the first category, the CP structure of the HVV, Htt, Hgg and $H\tau\tau$ couplings have been investigated by both experiments with the result of confirming the 0^{+} spin-parity SM hypothesis. For the second category, the searches focused on several FCNC channels, such as $t \to Hc$ and $t \to Hu$, as well as on the leptonic decays of the Higgs boson $H \to e\mu$, $H \to e\tau$ and $H \to \mu\tau$. Upper limits at 95% CL have been placed in all channels. In particular, the upper limits are of the order of 4–7 $\times\, 10^{-4}$ for $t \to Hc$ and $t \to Hu$ decays, while Fig. 2 shows the upper limits in the LFV decays $H \to \mu\tau$ and $H \to e\mu$.

In addition to the overview of the current status of the experimental measurements, a theoretical overview of the progresses made in this sector was also given, with particular attention to the implication of the current experimental limits in the definition of potential bounds on New Physics (NP). It is in fact crucial to understand how the precision achieved by the experimental measurements can be translated into limits on the mass (or at least to the energy scale where these particles interact) of potential new particles. To this respect, the biggest room for improvements lie in the measurement of the Higgs couplings with the first and second generation of fermions. The couplings with third generation fermions and gauge bosons are in fact very well measured now and discrepancies with respect to the SM predictions can mainly be searched either in the differential kinematic distributions of the Higgs boson or in its rare decays (such as CP- and flavour violating Higgs decays or $H \to V\gamma$ decays, where V is a low mass vector resonance). To this respect, a first measurement has been made by the ATLAS experiment on a partial dataset in the $H \to \phi\gamma$, $H \to \rho\gamma$ and $H \to J/\psi(nS)\gamma$ channels, setting 95% CL upper limits on the branching ratios at the level of 10^{-3}–10^{-4} [12, 13] (to be compared with SM predictions of about 10^{-6}) In the next decade it will be possible to improve significantly the precision of these measurements and also, for instance, of the Yukawa coupling

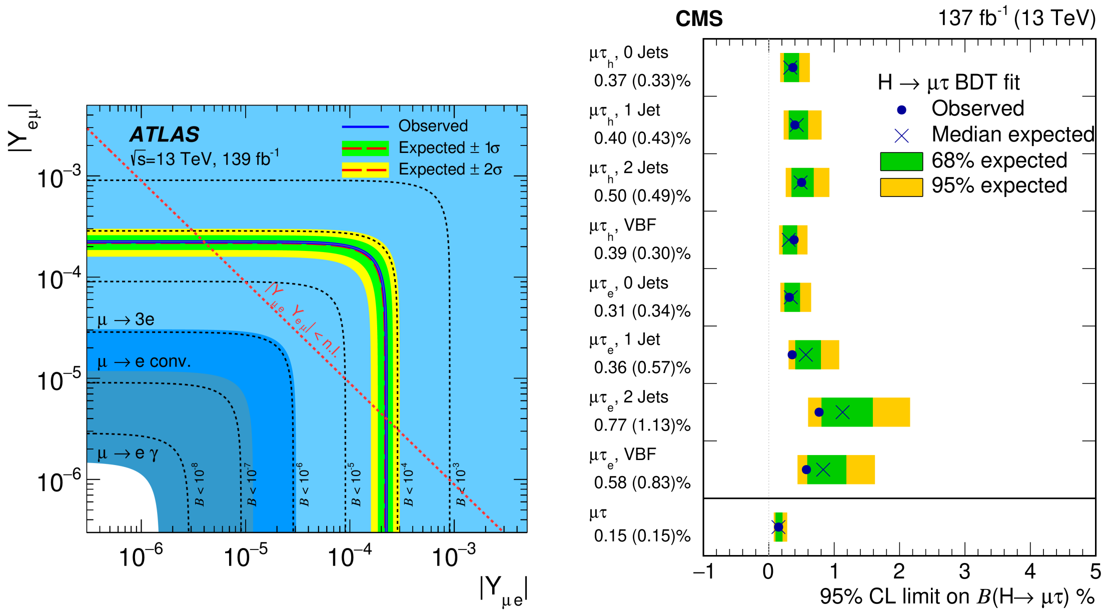

Figure 2: Upper limits on the $H \to e\mu$ decay measured by the ATLAS Collaboration [10] (left) and on the $H \to \mu\tau$ decay measured by the CMS Collaboration [11] (right).

of the Higgs boson with muons and charm quarks. This increased precision will be crucial to thoroughly test the SM, to give eventual hints on the scale of NP and also to make more stringent bounds on the NP theoretical models that have been proposed in the last years.

3. Lepton Flavour Universality

The second session of the WG6 program has been devoted to Lepton Flavour Universality (LFU) measurements and their implications in terms of New Physics. Four talks have been given covering both the theoretical and the experimental progresses on this topic. In order to be coherent with the mandate of the WG, the focus of the talks was on the implications at high-p_T of the "so-called" anomalies seen at low-p_T rather than on the description of the measurements of those anomalies, that is covered in other Working Groups.
The first talk was related to the possible interpretations, in terms of New Physics, of the set of measurements constituting the "low-p_T anomalies problem". In summary, few measurements concerning the semi-leptonic decay of B-mesons (such as $B \to D\tau\nu$ and $B \to \mu\nu$) or the $b \to sll$ transitions, where $l = e, \mu$) seem to point out that the Lepton Flavour Universality (LFU) is not conserved. In fact, the ratios $R_D = \frac{BR(B\to D\tau\nu)}{BR(B\to D\mu\nu)}$ and $R_{K^{(*)}} = \frac{BR(B\to K^{(*)}\mu\mu)}{BR(B\to K^{(*)}ee)}$ have been measured by the LHCb experiment and both results singularly showed a discrepancy of about 2.5–3σ with respect to the predictions of the SM. Furthermore, the angular analysis of several decays related to $b \to s\mu\mu$ transitions showed, in some corner of the phase-space, some tension with the SM predictions, more or less at the same level as R_D and $R_{K(*)}$ one. Finally, if one includes in the discussion also other measurements related to the $b \to s\mu\mu$ transitions (such as the BR($B_s \to \mu\mu$)) and combines all of them in a unique fit to test the LFU at low-p_T in the SM, a global tension of

about 4.3σ is found [14]. The natural question arising in this situation is whether this coherent set of measurement might be the hint of new physics beyond the SM. Clearly, this would only be an indirect evidence of some new dynamics, but still something of definite interest for the whole community. Therefore, the theoretical community became immediately very active by proposing several models that could explain these anomalies. In absence of experimental evidence of new particles, the first question concerns the energy scale where the New Physics potentially responsible of these effects. By combining all measurements and using the Effective Field Theory (EFT) approach, it is possible to estimate the scale of new physics to be around 40 TeV, a value that is outside of the LHC reach. But this value should be considered as an upper limit for new physics, since the strength of the coupling of this eventual new particle with the SM matter is basically unknown. Therefore the searches must continue at the LHC exploiting the full integrated luminosity expected before the end of the physics program (i.e. about 3000 fb^{-1}). Among the plethora of models proposed to describe these anomalies, two of them were presented: a massive Z' and the leptoquarks (both scalar and vector). In both cases, two scenarios were considered in terms of couplings with the second and the third generation of leptons: a democratic scenario where the couplings g_μ and g_τ, with muons and taus respectively, were of the same magnitude, and a hierarchical scenario where $g_\tau \gg g_\mu$. By exploiting the direct searches at LHC and the indirect constraints coming for instance from $\Delta F = 2$ transitions, it is possible to define an interval of validity of these models in terms of the mass of the new particles involved. Depending on the coupling scenario considered, the interval can go: from few TeV to 20–40 TeV for the democratic scenario and from 2 to 5 TeV for the hierarchical one. Especially this last scenario is therefore very interesting because it would imply a new particle within the reach of the LHC.

Another model that has been brought to the attention is the one foreseeing a specific spin-1 leptoquark in the $SU(2)_L$ singlet or triplet configuration [15]. While sizeable couplings of the leptoquark with electrons cannot be excluded, the peculiarity of the model lies in the fact that it assumes a sizeable coupling to muons, which would lead to a cleaner experimental signature. The energy scale where the leptoquarks might live is function of the leptoquark coupling with muons and can go from 40 TeV (in the case of unitary coupling) to few TeV (in case of couplings of the order of 10^{-2}–10^{-3}). Also in this model, few coupling scenarios were considered (democratic, hierarchical or flipped). Two main leptoquark production processes are involved: the pair-production (dominant at low leptoquark mass) and the single leptoquark production (dominant at high-mass). For each of these processes, respectively, the main experimental signature consists in a pair of muons and a pair of b-quarks or in a single muon and a pair of $b-$quarks. Among the various possibilities, the hierarchical scenario looks very favourable for a direct discovery at the LHC in the high-luminosity phase, with a sensitivity in terms of production cross-section for the leptoquarks of about 0.1 fb for a leptoquark mass between 3 and 5 TeV.

Leptoquarks were also the main character of the third talk of the session. An overview of the most recent direct leptoquarks searches made by the ATLAS and the CMS experiments was given. The main production process at LHC is the leptoquark pair-production, but also the single production can contribute in setting limits on the leptoquark mass/production cross-section. Experimental searches are mainly focused on the decay of leptoquarks into the third generation of quarks and leptons, namely top and bottom quarks and the tau lepton (with its neutrino). Hence, in the last years, both experiments focused on the improvement of the reconstruction techniques

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	LQ_S (TeV)		LQ_V $k = 0$ (TeV)		LQ_V $k = 1$ (TeV)	
Pair	0.95 (1.03)		1.29 (1.39)		1.65 (1.77)	
	$\lambda = 1.5$	2.5	1.5	2.5	1.5	2.5
Single	0.55 (0.56)	0.75 (0.81)	1.03 (1.12)	1.25 (1.35)	1.20 (1.29)	1.41 (1.53)
Pair+Single	0.98 (1.06)	1.02 (1.10)	1.34 (1.46)	1.41 (1.54)	1.69 (1.81)	1.73 (1.87)

Figure 3: Summary of the lower limits on the scalar and vector leptoquarks masses, based on the pair- and single-production mechanisms taken either separately or together, as measured by the CMS Collaboration [16].

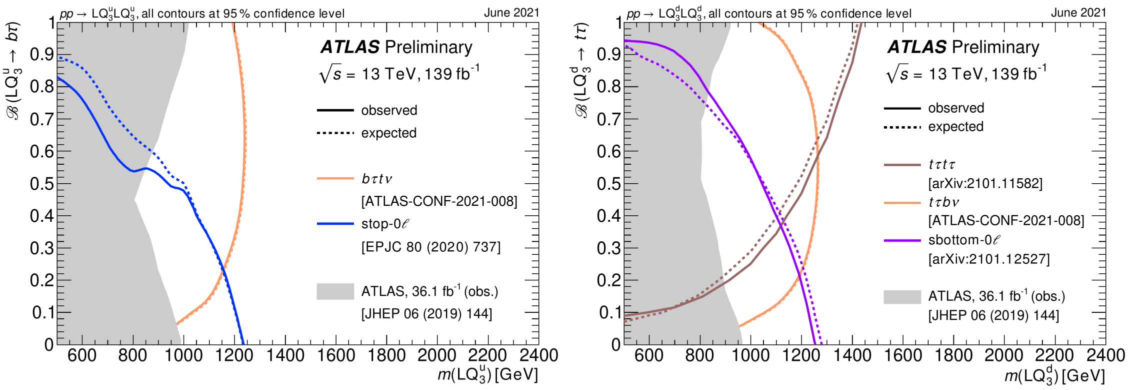

Figure 4: Expected and observed exclusion contours at the 95% confidence level for pair-produced scalar third-generation up-type leptoquarks with decays in $t\nu$ / $b\tau$ (left) and down-type leptoquarks with decays in $b\nu$ / $t\tau$ (right) as a function of the leptoquark mass and the branching fraction into a charged lepton and a quark as measured by the ATLAS experiment [17].

mainly for tau leptons and top quarks (both in the resolved and in the boosted regime). Using the full Run2 dataset, the CMS Collaboration performed leptoquark searches (both scalar and vector) in the final states characterised by the presence of a top quark, a tau lepton and its neutrino (leptoquark pair-production) or a top and a bottom quark, a tau lepton and its neutrino (leptoquark single production). Limits on the leptoquark mass have been set for scalar and vector leptoquarks and for different couplings of the leptoquark with SM quarks and leptons. Figure 3 summarises the results of these searches.

Similarly, the ATLAS Collaboration performed several searches depending on the final state. Depending on the decay topology, the final state can be characterised by the presence of a top quark, a tau lepton, one or more b- or c-jets, electrons, muons and missing transverse energy due to the presence of the tau neutrino. Figure 4 shows the summary plots of the limits on the masses of up-type and down-type leptoquarks, as a function of their branching ratios into third generation leptons and quarks. Furthermore, the ATLAS Collaboration set up limits on the leptoquarks mass in the scenario where they couple to mixed generation fermions (e.g. $bb\mu\mu$, te or $t\mu$). The mass limits range from 1.2 to 1.8 TeV depending on the channel and the leptoquark type.

Finally, the last talk was dedicated to the interpretation of the measurements related to the anomalies via the Contact Interaction (CI) formalism, which is base on the more general EFT approach. In this context, it is possible to set limits on the energy scale of potential new particles and on their type of interference with the SM. Two main channels have been considered: the $q\bar{q}l^+l^-$

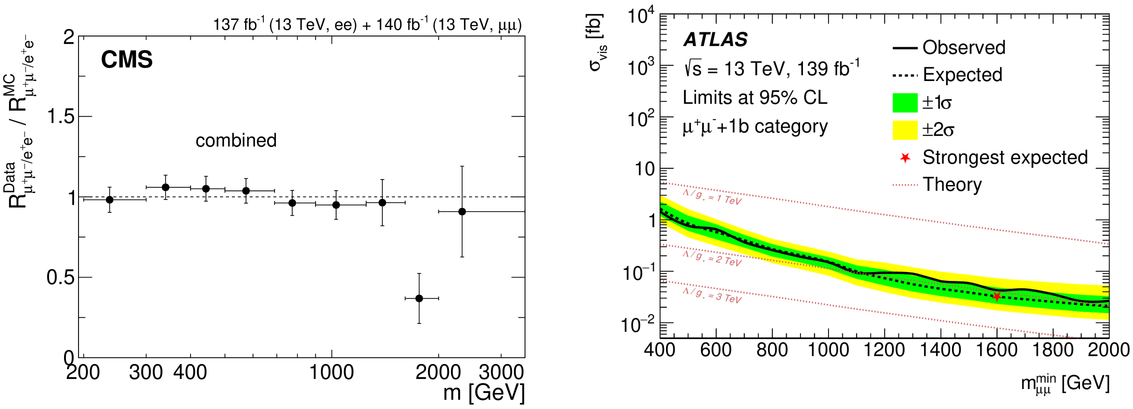

Figure 5: Ratio of the differential dilepton production cross section in the di-muon and di-electron channels $R_{\mu^+\mu^-/e^+e^-}$, as a function of the dilepton mass as measured by the CMS Collaboration (left). Model-independent observed (solid line) and expected (dashed line) upper limit on the visible cross section for the final state with two muons and a b-jet as a funciton of the di-muon invariant mass as measured by the ATLAS experiment. The theory lines (dotted lines) correspond to particular $\Lambda/g*$ values of the signal model, and the red marker presents the strongest expected lower limit on $\Lambda/g*$.

and the bsl^+l^- final states. For the first channel, both ATLAS and CMS experiments focused on the final states with a pair of electrons or muons setting up limits on the New Physics scale between 20 and 30 TeV depending on the type of interference (constructive or destructive) with the SM. In addition, CMS experiment measured the ratio of the differential cross-sections between electrons and muons as a function of the invariant mass of the electron/muon pair, to test the LFU in this specific context. The results, visible in Figure 5 (left), seem to suggest in general a marginal compatibility with the SM predictions [18]. More data during Run 3 LHC campaign will be needed to confirm the result. For the second channel, the ATLAS experiment performed a specific search targeting the bsl^+l^- EFT operator. The final state was characterised by the presence of one jet, one b-jet and a pair of electrons or muons. By measuring the visible cross-section as a function of the invariant mass of the lepton pair, it is possible to set limits on the $\Lambda/g*$ parameter (where Λ and g^* represent the energy scale and the coupling constant of the CI vertex respectively). Figure 5 (left) shows the result for the muon channel where the lower limit is set to 2.4 TeV [19].

4. Top quark

Another session of the WG6 program was dedicated to theoretical and experimental progress in top quark research. The top quark occupies a special place in the SM since it is the heaviest SM particle and its mass is in the vicinity of the Higgs vacuum expectation value resulting in a Yukawa coupling close to unity. Measurements in the top quark sector allow to probe the underlying theory at high scales for which precise theoretical predictions are required.

The session was kicked off with an overview of theoretical progress concerning the calculation of (differential) top quark cross sections at higher orders in α_S and α_{EW}. Nowadays, the precision of experimental results are found to be on par with theoretical predictions and thus being sensitive even to missing terms beyond NLO. For example, the $t\bar{t}W$ production process is important for validating

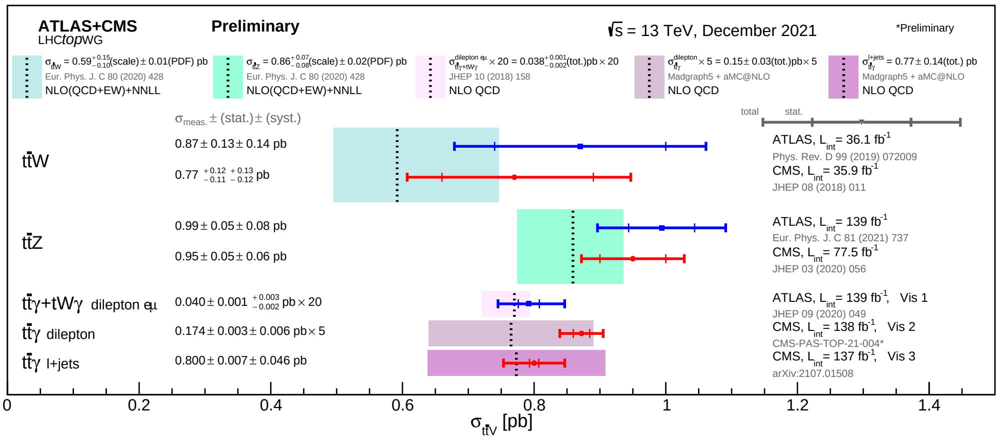

Figure 6: Summary of ATLAS and CMS measurements of $t\bar{t}X$ (X = W, Z or γ) cross sections at 13 TeV. The $t\bar{t}$W and $t\bar{t}$Z cross section measurements are compared to the NLO QCD and EW theoretical calculation complemented with NNLL resummation, while the $t\bar{t}\gamma$ cross section measurement is compared to the NLO QCD theoretical calculation.

electroweak interactions while also being a dominant background in $t\bar{t}$H and $tt\bar{t}\bar{t}$ measurements. Since its discovery at the LHC small tensions have been found between theoretical calculations and experimental results, which can be attributed to off-shell corrections that were missing in previous calculations, performed in narrow width approximation, among others [20].

The experimental status of top quark production in association with vector bosons was reviewed as well. In particular, several new results on inclusive and differential tZq, $t\bar{t}$Z, and $t\bar{t}\gamma$ cross section measurements by the ATLAS and CMS Collaborations have been discussed. A comparison of the measured inclusive cross sections with predictions from theory is given in Fig. 6. The results are found to be compatible across experiments and with the predictions within uncertainties.

Searches for rare decays of the top quark were investigated, which can point to physics beyond the SM. This includes searches for flavour-changing neutral currents (FCNC) that are heavily suppressed in the SM through the GIM mechanism, which is a consequence of the unitarity of the CKM matrix. However, various new theories beyond the SM (BSM) predict an enhancement of such interactions that can result in decays of the top quark to a light quark and a neutral boson (Higgs, Z, photon, or gluon). A rich search program for FCNC decays of the top quark is being conducted by the ATLAS and CMS Collaborations. An overview of the latest results is given in Fig. 7, where the observed limits on the FCNC branching ratios at the 95% confidence level are compared to the expectations from the SM and possible BSM models.

Besides FCNC interactions, various new models predict also decays of the top quark through charged lepton flavour violations (CLFV), which are forbidden in the SM but can be described in an EFT approach. Searches for $t \to q\ell\ell'$ decays, where the leptons, ℓ, are not of the same flavour, have been performed by the ATLAS and CMS Collaborations [21, 22] using LHC Run 2 data. No evidence was found and upper limits on the branch ratios have been determined.

Since the top quark decays before hadronisation its spin stays coherent and can be inferred from the decay products. This enables studies of the polarisation and spin correlations of top quarks in production and decay processes, that are ultimate tests of the underlying coupling structure.

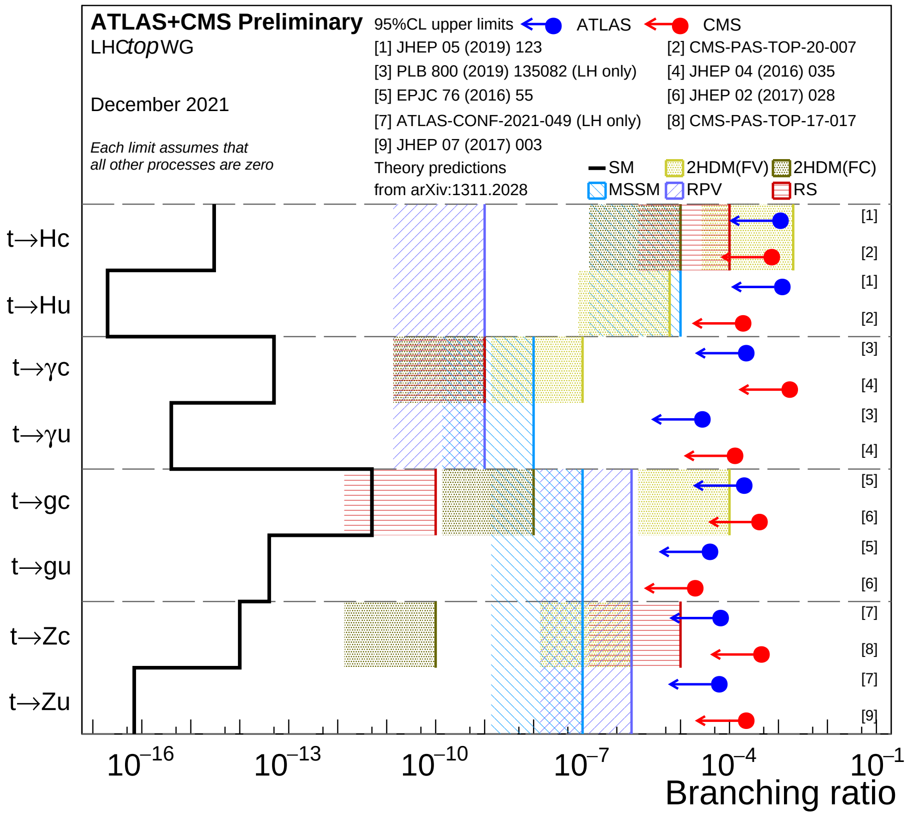

Figure 7: Summary of the current 95% confidence level observed limits on the branching ratios of the top quark decays via flavour changing neutral currents to a quark and a neutral boson $t \to Xq$ (X = g,Z, γ or H; q = u or c) by the ATLAS and CMS Collaborations compared to several new physics models.

Examples include the W boson helicity fractions, which can be measured in top quark pair and single top production. A combination by the ATLAS and CMS Collaborations determined the longitudinal and left helicity fractions to be 0.693 ± 0.014 and 0.315 ± 0.011, respectively [23], which are found well in agreement with theoretical predictions. In single top quark production, the top quark (antiquark) spin is often (anti)aligned with the spectator quark that recoils against the W boson through the V-A coupling at the Wtb vertex, resulting in a high degree of polarisation. Various measurements of the polarisation angle have been performed at 8 and 13 TeV. A recent measurement by the CMS Collaboration determined the polarisation in t-channel single top quark events produced in association with a Z boson [24].

Single top quark production can be used to probe directly the CKM matrix elements without making assumptions about the number of quark generations or requiring unitarity of the CKM matrix. By, approximating $|V_{td}|$, $|V_{ts}| \ll |V_{tb}|$ one finds that single top quark cross sections are directly proportional to $|V_{tb}|^2$. A combination of such measurements by the ATLAS and CMS Collaborations can be sought in Ref. [25]. A novel measurement using t-channel single top quark events has also been conducted without neglecting $|V_{td}|$ and $|V_{ts}|$ contributions [26]. Various scenarios are probed including a SM case that assumes unitarity of the CKM matrix and two BSM scenarios, where the top quark width is either fixed to the SM or can also account for hidden top

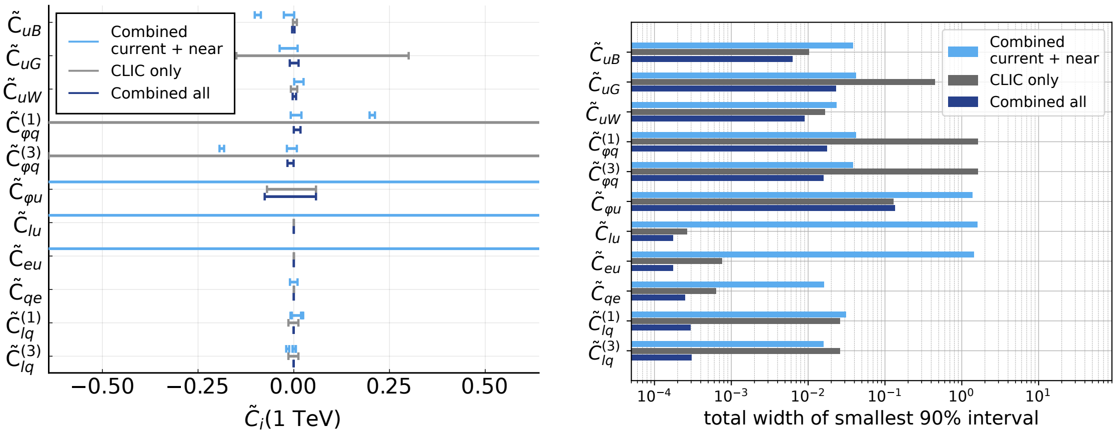

Figure 8: Constraints on SMEFT Wilson coefficients, C_i, obtained by fitting simultaneously to top quark and b-physics results and near-future projections at HL-LHC and Belle II: (left) 90% CL posterior intervals; (right) interval widths. Projections for CLIC are also given. Figure is taken from Ref. [27].

quark decays. In the latter case that has the least assumptions, one finds $|V_{\mathrm{tb}}| = 0.988 \pm 0.024$, and $|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 = 0.06 \pm 0.06$.

5. Top and beauty synergies

The last session was dedicated to effective interactions in the top quark and b-physics sectors and their interconnection in the light of lepton flavour violations. This is motivated by recent anomalies seen in lepton flavour universality tests involving $\mathrm{b} \to \mathrm{s}$ transitions, which suggest a corresponding counterpart in the top quark sector following an EFT approach. A combination of results from the top quark and b-physics sectors has recently been performed within the SMEFT framework including projections from HL-LHC, Belle II and CLIC [27]. The obtained 90% CL intervals on the relevant dimension-six Wilson coefficients are presented in Fig. 8, revealing synergies between the different sectors and colliders.

6. Summary

A summary of the WG6 activities during the CKM2021 workshop are given in this note. The sessions were focused on high-p_{T} physics, which includes measurements and theoretical progress in the Higgs boson and top quark sectors, their connection with low-p_{T} physics, and interpretations in effective field theories.

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