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New Physics searches in EW physics

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Summary. — In this paper we discuss how LHC measurements of electroweak processes can be very sensitive to new physics. We focus in particular on the high-energy tail of dilepton production and present a general study of the limits in the Standard Model effective field theory which can be obtained from these observables. As an example of the strenght of such limits, we show how they can already put relevant constraints on models addressing the observed deviations from lepton flavour universality in rare B-meson decays.

1. – Introduction

It is well known that precise measurements of Standard Model (SM) processes can test new physics (NP) scales Λ much larger than those directly accessible at experiments. The framework best suited to describe the expected small deviations from the SM is that of effective field theories (EFT). In particular, the SM EFT extends the SM Lagrangian with gauge-invariant operators with dimension bigger than four. The leading deviations, assuming baryon and lepton-number conservation, are described by dimension-six operators,

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots , \tag{1}$$

where Λ represents the NP mass scale and the coefficients c_i depend on the specific ultraviolet (UV) dynamics which generate each operator. In general, these effects can be studied in two broad class of processes:

i) Deviations in on-shell production of SM particles, such as Z couplings measured at LEP or Higgs couplings at LHC. In this case the expected deviations scale as $\delta_{\text{pole}} \sim \mathcal{O}(c_i\, m_{\text{EW}}^2/\Lambda^2)$, where m_{EW} represents a generic electroweak (EW) scale mass. A high precision in the measurement is required to be sensitive to high scales in this case. At the LHC most measurements are instead limited by the experimental systematic and theory uncertainties.

ii) Deviations in the high-energy tails of differential distributions. A typical example is the tail of the p_T or q^2 distribution in $2 \to 2$ scattering processes. The expected deviations from the SM in this case scale as $\delta_{\rm tail} \sim \mathcal{O}(c_i\, E^2/\Lambda^2)$, where E is the typical energy of the process. Since this can be much larger than $m_{\rm EW}$, such measurements have the potential to be sensitive to high scales Λ even if they are not very precise [1].

The high energy of the LHC makes the second class of processes particularly interesting to study. These include, for example, diboson and associated Higgs production, $pp \to VV$ and $pp \to Vh$ (where $V = Z, W$), as well as dilepton and dijet production. The electroweak and Higgs processes have been widely studied in the literature and a characterization of the NP terms growing with the energy and the prospect for their future determination have been studied in ref. [2]. Since these processes involve potentially high energies, one should check that the main hypothesis underlying the EFT expansion, $E \ll \Lambda$, remains valid [2-6]. In the parameter space of Λ *vs.* c_i, this condition selects a region where the EFT exclusion bound, $c_i/\Lambda^2 < \epsilon$, is consistent. This is shown schematically as a green shaded region in fig. 1.

In this paper, based on ref. [7], we concentrate in particular on opposite-sign dilepton production, $p\, p \to \ell^+\ell^-$ ($\ell = e, \mu$), which has been shown to set competitive constraints on new physics when compared to some low-energy measurements [8-10] or electroweak precision tests performed at LEP [1]. In sect. **2** we present limits on the SM EFT operators contributing to these processes and in sect. **3** we apply these bounds to new physics models which address a set of deviations observed in rare B-meson decays. Finally, we conclude in sect. **4**.

2. – New physics in dilepton tails

The operators, in the *Warsaw* basis [11], which can contribute at tree-level to $p\, p \to \ell^+\ell^-$ and which induce an amplitude growing with the energy consist in four-fermion interactions that can be classified in four classes, depending on the chirality: $(\bar{L}L)(\bar{L}L)$,

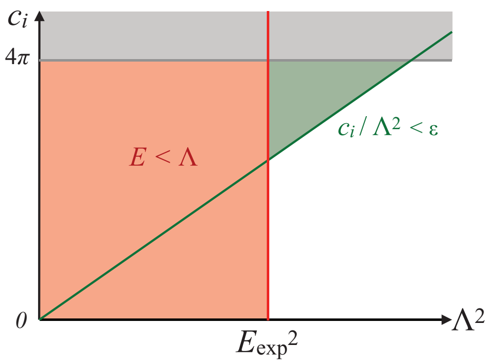

Fig. 1. – Sketch of the region in the parameter space where an EFT exclusion bound is consistent (green region). In the red region the energy of the process is larger than or similar to the cutoff Λ, while in the gray region the theory becomes non-perturbative, $c_i \gtrsim 4\pi$.

$(\bar{R}R)(\bar{R}R)$, $(\bar{R}R)(\bar{L}L)$, and $(\bar{L}L)(\bar{R}R)$. The complete list is

$$\begin{aligned}\mathcal{L}^{\rm SMEFT} \supset\ & \frac{c^{(3)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l) + \frac{c^{(1)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)\\ & + \frac{c_{u_{ij}e_{kl}}}{\Lambda^2}(\bar{u}_i\gamma_\mu u_j)(\bar{e}_k\gamma^\mu e_l) + \frac{c_{d_{ij}L_{kl}}}{\Lambda^2}(\bar{d}_i\gamma_\mu d_j)(\bar{e}_k\gamma^\mu e_l)\\ & + \frac{c_{u_{ij}L_{kl}}}{\Lambda^2}(\bar{u}_i\gamma_\mu u_j)(\bar{L}_k\gamma^\mu L_l) + \frac{c_{d_{ij}L_{kl}}}{\Lambda^2}(\bar{d}_i\gamma_\mu d_j)(\bar{L}_k\gamma^\mu L_l)\\ & + \frac{c_{Q_{ij}e_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{e}_k\gamma^\mu e_l),\end{aligned} \tag{2}$$

where i, j, k, l are flavour indices, $Q_i = (V^*_{ji}u^j_L, d^i_L)^T$ and $L_i = (\nu^i_L, \ell^i_L)^T$ are the SM left-handed quark and lepton weak doublets, while d_i, u_i, e_i are the right-handed singlets. V is the CKM matrix and σ^a are the Pauli matrices acting on $SU(2)_L$ space.

One of the goals of this work is to connect the high-p_T dilepton tails measurements with the recent experimental hints on lepton flavour universality violation in rare semileptonic B meson decays. As discussed in more details in sect. **3**, the pattern of observed deviations can be explained with a new physics contribution to a single four-fermion $b_L s_L \mu_L \mu_L$ contact interaction. For this reason, when discussing the connection to flavour in sect. **3**, we limit our attention to such operators with muons and rearrange the relevant terms as

$$\mathcal{L}^{\rm eff} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar{u}^i_L\gamma_\mu u^j_L)(\bar{\mu}_L\gamma^\mu\mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar{d}^i_L\gamma_\mu d^j_L)(\bar{\mu}_L\gamma^\mu\mu_L), \tag{3}$$

where for convenience we reabsorb the dependence on Λ in the EFT coefficients. The $\mathbf{C}^{U\mu}$ and $\mathbf{C}^{D\mu}$ matrices carry the flavour structure of the operators. Regarding the off-diagonal elements, we keep only the $b - s$ one since it is the one where the flavour anomalies appear, while we set the others to zero for simplicity. In summary:

$$\mathbf{C}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \ \mathbf{C}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}. \tag{4}$$

We derive limits on these semileptonic operators by studying the high-energy tail of the dilepton invariant mass distribution in $p\ p \to \ell^+\ell^-$ at the LHC. We follow closely the recent ATLAS search [12] performed at 13 TeV with 36.1 fb^{-1} of data. At present, theoretical and systematic uncertainties on the expected number of events in the SM are negligible when compared to the statistical one in the high invariant mass region relevant for setting the limits on the contact interactions [1, 12]. While their importance will increase with more luminosity, we still expect statistical uncertainties to be dominant in the highest energy bins, which are the ones most relevant to our limits. The details of the analysis can be found in ref. [7]. The present and projected 2σ limits on the coefficients of all the operators in eq. (2) are also reported in ref. [7] (table I).

Focusing only on the $(\bar{L}L)(\bar{L}L)$ operators with muons, in the notation of eq. (3), the 2σ limits, both from the present ATLAS search (blue) and projected for 3000 fb^{-1} (red), are shown in fig. 2. The solid lines show the 2σ bounds when operators are taken one at a time, while the dashed ones show the limits when all the others are marginalised. The small difference between the two, especially with present accuracy, is due to the non

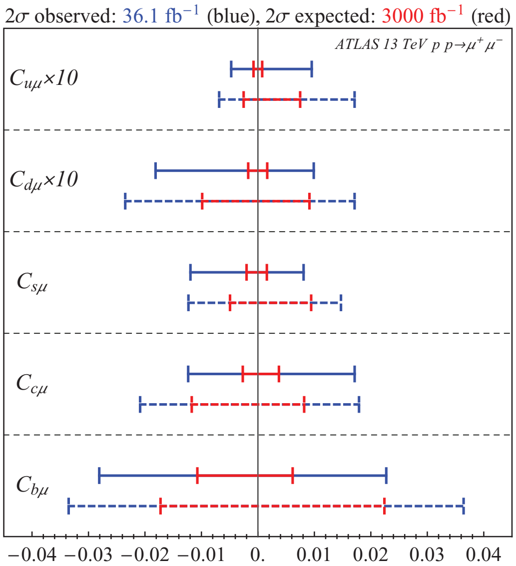

Fig. 2. – In blue (red) we show the present (projected) 2σ limits on $C_{q\mu}$ (flavour conserving $(\bar{L}L)(\bar{L}L)$ operators) where $q = u, d, s, c$ and b, using 13 TeV ATLAS search in $pp \to \mu^+\mu^-$ channel [12]. Dashed lines show the limits when all other coefficients are marginalised, while the solid ones show the results of one-parameter fits.

interference among different operators. Further constraints on the operators with $SU(2)_L$ triplet structure can be derived from the charged-current $pp \to \ell\nu$ processes [1, 8, 9].

3. – Implications for $R(K)$ and $R(K^*)$

Recent measurements in rare semileptonic $b \to s$ transitions provide strong hints for a new physics contribution to the $bs\mu\mu$ local interaction. In particular, a good fit of the anomaly in differential observables and in LFU (Lepton Flavour Universality) violation in R_K and R_{K^*} [13, 14], is obtained by considering a new physics contribution to the $C_{bs\mu}$ coefficient in eqs. (3), (4). In terms of the SMEFT operators at the electroweak scale, this corresponds to a contribution to (at least) one of the two operators in the first row of eq. (2).

Matching at the tree level this operator to the standard effective weak Hamiltonian describing $b \to s$ transitions, one finds

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} = -0.61 \pm 0.12, \tag{5}$$

where α is the electromagnetic fine structure constant, $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$, $|V_{tb}| = 1.009 \pm 0.031$, and we used the 1σ bound from the combined fit of ref. [15].

Using this result one can estimate the mass scale of new physics by defining $C_{bs\mu} = g_*^2 v^2 / \Lambda_{bs\mu}^2$, obtaining $\Lambda_{bs\mu}/g_* \approx 32^{+4}_{-3}$ TeV. Depending on the value of g_*, *i.e.* from the particular UV origin of the operator, the scale of new physics Λ can be within or out of the reach of LHC direct searches. We show that even in the latter case, under some assumptions, it can be possible to observe an effect in the dimuon high energy tail.

We concentrate on UV models in which new particles are above the scale of threshold production at the LHC, such that the EFT approach is applicable in the most energetic dilepton events. We stress however that even for models with light new physics these searches can be relevant.

Let us discuss the flavour structure of the $\mathbf{C}_{ij}^{D(U)\mu}$ matrices in eqs. (3), (4). New physics aligned only to the strange-bottom coupling $C_{bs\mu}$ will not be probed at the LHC, in fact we obtain that the present (projected) 95% CL limits from the 13 TeV ATLAS $pp \to \mu^+\mu^-$ analysis with 36 fb^{-1} (3000 fb^{-1}) of luminosity correspond to

$$|\Lambda_{bs\mu}/g*| > 2.5\ (4.1)\ \text{TeV}, \tag{6}$$

which should be compared with the ~ 32 TeV value required to fit the anomalies, eq. (5). However, while such a peculiar flavour structure is possible, it is not very motivated from the model building point of view. One would instead expect that this off-diagonal term is accompanied by, and suppressed with respect to, some other flavour-diagonal coupling $C_{q\mu}$.

In this case, since $C_{bs\mu}$ is fixed by eq. (5), we can use the LHC upper limit on $|C_{q\mu}|$ from the dimuon high-p_T tail in order to set a lower bound on $|\lambda^q_{bs}|$, defined as the ratio

$$\lambda^q_{bs} \equiv C_{bs\mu}/C_{q\mu}. \tag{7}$$

In the following we study such limits for two particularly interesting scenarios.

3·1. *Minimal flavour violation (MFV).* – Under this assumption [16] the only source of flavour violation are the SM Yukawa matrices $Y_u \equiv V^\dagger \text{diag}(y_u, y_c, y_t)$ and $Y_d \equiv \text{diag}(y_d, y_s, y_b)$. Using a spurion analysis one can estimate

$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(\mathbf{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}, \tag{8}$$

where $\alpha, \beta \sim \mathcal{O}(1)$, which implies the following structure:

$$\begin{aligned} C_{u\mu} \approx C_{c\mu} \approx C_{t\mu} \equiv C_{U\mu}, \\ C_{d\mu} \approx C_{s\mu} \approx C_{b\mu} \equiv C_{D\mu}, \end{aligned} \tag{9}$$

while flavour-violating terms are expected to be CKM suppressed, for example $|C_{bs\mu}| \sim |V_{tb}V^*_{ts}y_t^2 C_{D\mu}|$. In this case the contribution to rare B meson decays has a $\lambda^D_{bs} \sim V_{ts}$ suppression, while the dilepton signal at high-p_T receives a universal contribution dominated by the valence quarks in the proton. The flavour fit in eq. (5) combined with this flavour structure would imply a value of $|C_{D\mu}| \sim 1.4 \times 10^{-3}$ which, as can be seen from the limits in fig. 2, is already probed by the ATLAS dimuon search [12] and will definitely be investigated at high luminosity([1]). Allowing for more freedom and setting $C_{bs\mu} \equiv \lambda_{bs} C_{D\mu}$, we show in the left panel of fig. 3 the 95% CL limit in the $C_{D\mu}$-$|\lambda_{bs}|$

([1]) It should also be noted that the triplet combination is bounded from the semileptonic hadron decays (CKM unitarity test) $C_{U\mu} - C_{D\mu} = (0.46 \pm 0.52) \times 10^{-3}$ [9], in the absence of other competing contributions.

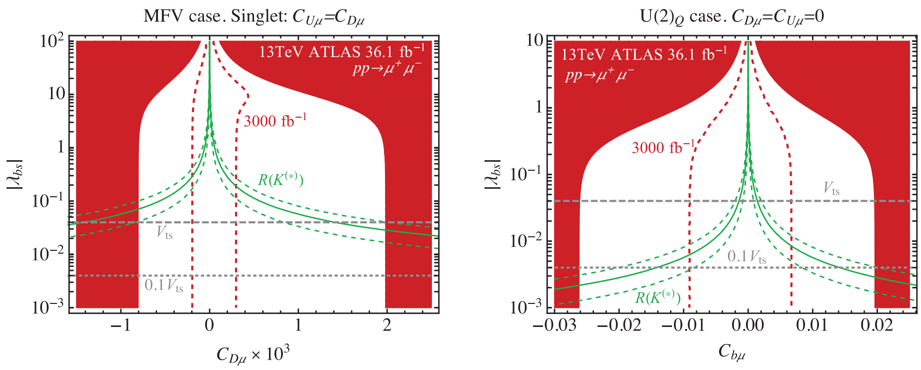

Fig. 3. – We show the present (solid red) and projected (dashed red) 95% CL limit from $pp \to \mu^+\mu^-$ in the $C_{q\mu}$-$|\lambda_{bs}|$ plane. The solid (dashed) green line corresponds to the best fit (2σ interval) from the fit of the flavour anomalies in eq. (5).

plane, where $C_{U\mu}$ is related to $C_{D\mu}$ by assuming the singlet structure. The intersection of the green region (fitting $R(K^{(*)})$ and the red excluded region is for values of $\lambda_{bs} \sim V_{ts}$, meaning that the LHC is already starting to probe the MFV structure putting relevant lower bounds on λ_{bs}.

3˙2. *$U(2)_Q$ flavour symmetry.* – This symmetry distinguishes light two generations of fermions from the third ones. The leading symmetry-breaking spurion is a doublet, whose flavour structure is unambiguously related to the CKM matrix [17]. In this case, in general the leading terms would involve the third generation quarks, as well as diagonal couplings in the first two generations. The relevant parameters for the dimuon production would then be

$$\begin{aligned} C_{u\mu} = C_{c\mu} \equiv C_{U\mu}, &\qquad C_{d\mu} = C_{s\mu} \equiv C_{D\mu}, \\ C_{b\mu}, &\qquad C_{bs\mu} \equiv \lambda_{bs} C_{b\mu}, \end{aligned} \tag{10}$$

where the flavour violating coupling is expected to be $|\lambda_{bs}| \sim |V_{ts}|$, as in MFV. As already done in the MFV case, in the following we leave λ_{bs} free to vary and perform a four-parameter fit to the dimuon spectrum. The resulting limits on $C_{U\mu}$ and $C_{D\mu}$ are very similar to those obtained in the MFV scenario, the limit on $C_{b\mu}$ is instead weaker since the bottom content in the proton is smaller.

In the right panel of fig. 3 we show the present and projected limits in the $C_{b\mu}$-λ_{bs} plane (we set $C_{D\mu} = C_{U\mu} = 0$, after checking that no large correlation with them is present). As for the MFV case, the fit of the flavour anomalies in eq. (5), combined with the upper limit on $|C_{b\mu}|$, provides a lower bound on $|\lambda_{bs}|$. In this case, while at present this limit is much lower than the natural value predicted from $U(2)$ symmetry, $\lambda_{bs} \sim V_{ts}$, with high luminosity an interesting region will be probed.

3˙3. *Z' model.* – As a simple scenario with a mediator capable of generating the required operator to fit the neutral-current B anomalies, let us consider a vector singlet $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$, with a MFV structure of the couplings. This gives rise to an s-channel resonant contribution to the dilepton invariant mass distributions if $M_{Z'}$ is kinematically accessible. Otherwise, the deviation in the tails is described well by the dimension-six

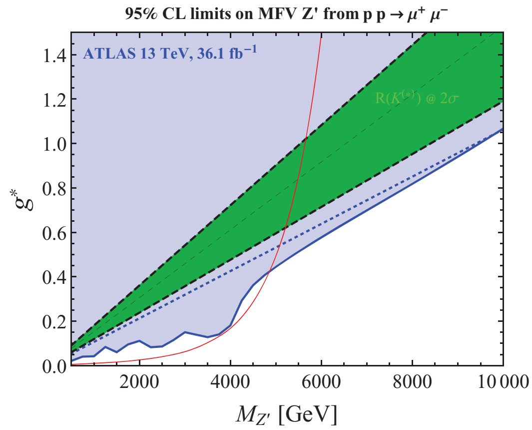

Fig. 4. – Limits on the Z' MFV model from $pp \to \mu^+\mu^-$. See text for details.

operators in eq. (2) with $\Lambda = M_V$ and

$$c^{(1)}_{Q_{ij}L_{kl}} = -g_Q^{(1),ij} g_L^{(1),kl}, \tag{11}$$

obtained after integrating out the heavy vector with interactions

$$\mathcal{L} \supset Z'_\mu (g_Q^{(1),ij} (\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl} (\bar{L}_k \gamma^\mu L_l). \tag{12}$$

A quark flavour-violating $g_Q^{(x),23}$ coupling and $g_L^{(x),22}$ are required to explain the flavour anomalies, while the limits from $pp \to \mu^+\mu^-$ reported in fig. 2, can easily be translated to the flavour-diagonal couplings and mass combinations.

For example, assuming a Z' with $g_Q^{(1),ii} = g_L^{(1),ii} = g^*$ and MFV structure $g_Q^{(1),23} = V_{ts} g^*$, we derive limits on g^* as a function of the mass $M_{Z'}$, both fitting the data directly in the full model and in the EFT approach. The results are shown in fig. 4. The limits in the full model are shown with solid blue while those in the EFT are shown with dashed blue. We see that for a mass $M_{Z'} \gtrsim$ 4–5 TeV the limits in the two approaches agree well, while for lower masses the EFT still provides conservative bounds([2]). On top of this, we show with green lines the best fit and 2σ interval which reproduce the $b \to s\mu\mu$ flavour anomalies, showing how LHC dimuon searches already exclude such a scenario independently of the Z' mass. This can be avoided by relaxing the strict relation between the bs coupling and the flavour-diagonal ones. The red solid line indicates the naive bound obtained when interpreting the limits on the narrow-width resonance production $\sigma(pp \to Z') \times \mathcal{B}(Z' \to \mu^+\mu^-)$ from ref. [12].

([2]) See ref. [1] for a more detailed discussion on the EFT validity in high-p_T dilepton tails.

4. – Conclusions

In this proceedings we discussed the contribution from flavour non-universal new physics to the high-p_T dilepton tails in $pp \to \ell^+\ell^-$, where $\ell = e, \mu$. In particular, we set the best up-to-date limits on all 36 chirality-conserving four-fermion operators in the SMEFT which contribute to these processes by recasting ATLAS analysis at 13 TeV with 36.1 fb^{-1} of data, as well as estimate the final sensitivity for the high-luminosity phase at the LHC.

Recent results in rare semileptonic B meson decays show some intriguing hints for possible violation of lepton-flavour universality beyond the SM. It is particularly interesting to notice that several anomalies coherently point toward a new physics contribution in the left-handed $b_L \to s_L \mu_L^+ \mu_L^-$ contact interaction. In most flavour models, the flavour-changing interactions are related (and usually suppressed with respect) to the flavour diagonal ones. These, in turn, are probed via the high-p_T dimuon tail, allowing us to already set relevant limits on the parameter space of some models.

In particular, our limits exclude or put in strong tension scenarios which aim to describe the flavour anomalies using MFV structure that directly relates the $bs\mu\mu$ contact interaction to the ones involving first generation quarks, tightly constrained from $pp \to \mu^+\mu^-$. On the other hand, scenarios with $U(2)_Q$ flavour symmetry predominantly coupled to the third generation quarks lead to milder constraints. To illustrate our point further, we discuss a few explicit examples with heavy mediator states (colourless vectors and leptoquarks) and show a comparison of the limits obtained in the EFT with those obtained directly in the model.

If the flavour anomalies get confirmed with more data, correlated signals in high-p_T processes at the LHC will be crucial in order to decipher the responsible dynamics. We show how high-energy dilepton tails provide very valuable information in this direction.

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