A new test for non-universality at proton colliders

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The Standard Model (SM) is characterized by a well-defined pattern of couplings of the gauge bosons to the fermions. Any deviation from this description would correspond to a definitive hint for beyond SM physics. These deviations would manifest in terms of different yields for the final states in a direct search. In this letter we develop a universal framework to extract the extent to which a direct search can probe these differences. Our strategy is effectively demonstrated for a heavy neutral $Z'$ decaying into a pair of electrons and muons with different branching fractions. We note the implications of the drastically different reconstructions (especially in the HL-LHC) on the computation of discovery significance as well as the extraction of non-universality. The potential of the current and future pp colliders, quantifying the extent of the asymmetry (in yields) to which they are sensitive, is explored. While the HL-LHC phase offers an optimistic but a restricted picture, it naturally paves the way for the FCC-hh machine. The latter being sensitive not only to heavier masses but also to minor departures from universality in the couplings for the lighter masses.

INTRODUCTION

The Standard Model (SM) of particle physics has withstood the test of experimental validation to a significant extent. The electroweak sector, in particular, is characterized by a well defined pattern of couplings which manifests in terms of accurate predictions for several processes. Any departure from this paradigm implies the presence of New Physics (NP) effects. One of the most interesting observations in this direction corresponds to the observation of flavour non-universality in terms of the theoretically clean ratios: $R_K$ and $R_{K^*}$. Recent results obtained by the LHCb Collaboration are compatible with the standard model at the level of 2.5 standard deviations \cite{Atre:2020dfv, Khriplovich:2020nzy}. Still leaving room for studies on flavour non-universality. Anyway, independently of these anomalies, it is instructive to investigate the potential of the direct searches in measuring deviations from universality.

In a direct search, non-universality between a set of final states would manifest in the form of correspondingly different yields in the detector. In this paper we present a strategy to evaluate the potential of current and future pp colliders to measure the effects of non-universality. The analysis uses a simple test statistic to estimate the significance of these departures from the universality case.

Since the leptons are very clean objects in a detector, the developed strategy will be used to study flavour non-universality using a simplified model with an additional heavy vector boson ($Z'$) decaying into a pair of leptons. The effective Lagrangian highlighting its coupling to fermions is given as:

$$\mathcal{L} = \frac{Z'\mu}{\cos \theta_w} \left[ g_L \bar{l} \gamma_\mu P_L l + g_q \bar{q} \gamma_\mu P_L q + \ldots \right]$$

where $l$ and $q$ represent leptons and light quarks respectively and $P_{L,R}$ are chirality projection operators. The production mechanism is irrelevant for our analysis, therefore, without loss of generality, we assume the $Z'$ being predominantly produced by light quarks. From a model point of view, the goal of this paper can be restated in terms of extracting the sensitivity of the direct searches to explore the difference $g_e - g_\mu$ and its deviations from 0.

The paper is organized as follows: we begin with the traditional bump hunt searches of a heavy neutral resonance decaying into a di-lepton final state. In this section we point out the role of the different reconstruction resolutions between different flavour leptons in the eventual computation of the discovery significance. This is then followed by the description of the analysis and the estimation of the sensitivity to non-universality of the HL-LHC collider. We note that the study at HL-LHC naturally paves the way for an FCC-hh machine which is characterized by significantly enhanced sensitivities to even smaller deviations from universality. We conclude the paper with the prospects of including tau as a part of future analysis to complete the picture.

BUMP HUNT SEARCHES

The search for a heavy neutral resonance decaying into a di-lepton final state is one of the most prominent
channels being probed at LHC and there exist relatively strong bounds on $\sigma \times B_{ll}$ \cite{3, 4}. A standard search strategy focuses on the possibility for observing an excess of events over the Standard Model (SM) prediction, where the SM background is mainly due to the universal coupling of the $\gamma^* / Z$ to leptons.

In this analysis, we consider the production of a heavy $Z'$ decaying into muons and electrons according to the following matrix element:

$$M(p p \rightarrow Z', Z' \rightarrow l^+ l^-) \text{ where } l = e, \mu.$$  \hspace{1cm} (2)

The signal model is generated using FEYNRULES \cite{5} and the matrix element for the process is produced using MADGRAPH \cite{6} at a centre of mass energy of 14 TeV. Showering and hadronization are described using PYTHIA 8 \cite{7}. CMS cards of DELPHES 3.4 \cite{8} is used for detector simulation at the LHC.

**Event selection:** In order to identify the leptons from the $Z'$, the following selection criteria have been applied:

- two isolated leptons (electrons or muons) with a $p_T \geq 50$ GeV;
- no missing energy.

The main source of background is represented by the $pp \rightarrow Z^* \rightarrow ll$ where $l = e, \mu$.

Independently of the relative sizes of the coupling with the vector boson (SM or beyond), the leptons are characterized by different detector acceptances and mass reconstruction resolution. At the LHC, typically the detector acceptance is $\sim 20\%$ higher in di-muon final state, while the mass reconstruction resolution is much narrower for di-electron final state. The mass reconstruction resolution for di-leptons is shown in Fig. 1 for a 5 TeV narrow resonance with a generated mass width $\Gamma$ of 50 GeV. The different mass reconstruction resolution seen can be attributed to the current reconstruction techniques and to the greater momentum smearing of the muons\footnote{Under the assumption of enough statistics (not necessarily equal) for either lepton, the asymmetry in the reconstruction between the electron and muon progressively increases with the resonance mass. Therefore, the smearing increases with the $p_T$ of the di-muons.}.

To calculate the expected significance for $Z' \rightarrow ee$ and $Z' \rightarrow \mu\mu$ at LHC, we use a binned likelihood fit $L(\mu)$. In the case where background is well known we can evaluate the expected significance as the probability of background only hypothesis ($\mu = 0$) using the profiled likelihood ratio test \cite{9}:

$$q_0 = -2 \log \left[ \frac{L(\mu = 0)}{L(\mu = \hat{\mu})} \right].$$ \hspace{1cm} (3)

where $\hat{\mu}$ is the best value of $\mu$ estimated by fitting to the data. The signal discovery significance $Z$ can be evaluated as:

$$Z = \sqrt{q_0}.$$ \hspace{1cm} (4)

and for sufficiently large background we can use the asymptotic formula:

$$Z = \sqrt{q_0^*} = \sqrt{\sum_{i=1}^{N} \left( 2(s_i + b_i) \log \left[ 1 + \frac{s_i}{b_i} \right] - 2s_i \right)}$$ \hspace{1cm} (5)

where the sum runs over the bins, $s_i$ and $b_i$ are the expected numbers for signal and background events in the $i^{th}$ bin. Fig. 2 gives contours in the total di-lepton significance as a function of branching fractions of the $Z'$ decaying into electrons $B_e$ and muons $B_\mu$. We assume $\sigma_{Z'} = 0.35 \text{ fb}$ and at most 20\% total branching fraction.
into leptons. The diagonal dotted line corresponds to
the lepton flavour universality case (\(B_e = B_\mu\)). We perform
a symmetric scan about this diagonal line over the values
of \(B_e\) and \(B_\mu\). The asymmetric behaviour of the contour
plot is due to the different mass resolutions as shown in
Fig.3. Thus a larger coupling to the electrons leads to
a larger evaluated value for the total signal sensitivity.
These considerations lead to the following questions:
1) does the absence of a signal imply no NP or a larger
coupling to the muons?
2) what are the prospects for unearthing non-universality
at the HL-LHC and future colliders?

**NON-UNIVERSALITY TEST**

In real life experiments, the statistic \(q_0\) in Eq.8 is
minimized at the best fit value of \(\sigma B\) for the leptons.
Fig.3 shows the distributions of the test statistic \(q_0\) under
two different assumptions: the left plot corresponds
to the universal coupling case where \((\sigma B)_e = (\sigma B)_\mu\) while
the right plot illustrates \((\sigma B)_e < (\sigma B)_\mu\) and hence non-
universality. The different widths of the parabola reflect
the differences in the mass reconstruction resolutions be-
tween the leptons. The black line represents the 1 \(\sigma\)
measurement uncertainty. The departure from univers-
ality the hypothesis can be quantified by the following
asymmetry variable:

\[
\hat{A} = \frac{(\sigma B)_\mu - (\sigma B)_e}{(\sigma B)_\mu + (\sigma B)_e} \in [-1, 1]. \tag{6}
\]

The two extremities correspond to a very large signal in
the electron channel \((\sigma B)_e \gg (\sigma B)_\mu\) and muon channel
\((\sigma B)_\mu \gg (\sigma B)_e\) respectively. In general, \(\hat{A}\) divides
the phase space into two specific regions: \(\hat{A} > 0\) corresponds
to the case where couplings to muons is larger and is
called the Pro-muon region and \(\hat{A} < 0\) is called the Pro-
electron region. Thus, a measurement corresponding to
\(\hat{A} \neq 0\) could be a hint of non-universality.

An estimate for the significance in the measurement of
\(\hat{A}\) must also account for the individual uncertainties in
the extraction of \(\sigma B_{e,\mu}\) which correspond to the widths

\[
\sigma \left[ (\sigma B)_e - (\sigma B)_\mu \right] \ll \Delta_{ee} + \Delta_{\mu\mu}.
\tag{7}
\]

where \(\Delta_{e,\mu}\) is the width of the likelihood parabola at 1\(\sigma\)
level.

Typical behaviour of \(\lambda\) as a function of \(\hat{A}\) for a fixed
value of \((\sigma B)_e = 0.027\) is shown in Fig. 4. The
benchmark masses are chosen to be \(M_{Z'} = 3, 5\) TeV and the
integrated luminosity is \(L = 3\) ab\(^{-1}\). By varying \((\sigma B)_\mu\)
about this value of \((\sigma B)_e\), we obtain the solid black curve
as shown. Its intercept with the red (green) line corre-
sponds to the value of \((\sigma B)_\mu\) which is 2(3)\(\sigma\) away from
this benchmark value of \((\sigma B)_e\). The corresponding \(\hat{A}\)
can be trivially extracted from Eq.6. Repeating this exercise
for different values of \((\sigma B)_e\), we obtain the asymmetry-
sensitivity plots shown in the top row of Fig.3 We esti-
mate the value \((\sigma B)_\mu\) (and hence \(\hat{A}\)) which are 3(2) \(\sigma\)
away from each given value of \((\sigma B)_e\), leading to the
red (green) lines as shown. It is expressed as a function
of the signal discovery significance for electrons (\(Z_{ee}\)).
Moving along either curve, from the bottom to the top,
corresponds to increasing values of \((\sigma B)_\mu\) and hence \(Z_{ee}\).

This implies that sensitivity to minor deviations from
non-universality (smaller \(\hat{A}\)) requires a large discovery
sensitivity. As a reference, we also provide the \((\sigma B)_e\) for
a given \(Z_{ee}\) in the bottom rows of Fig.3.

The current non universality tests at LHC, while be-
ing powerful are limited on the following accounts: 1) re-
duced sensitivity to heavier masses 2) Reduced sensitivity
to minor deviations from universality. These considera-
tions naturally lead to evaluate and study the possible
improvements with future colliders as it will be discussed
below.

**FUTURE COLLIDERS**

The advent of the FCC is expected to provide contin-
uity from the tail end of the sensitivity of the HL-LHC.
FIG. 5. Top row: 2 $\sigma$ (Green-dashed lines) and 3 $\sigma$ (Red lines) asymmetry sensitivity plot: expected discovery significance in the electron channel ($Z_{ee}$) with the respect to the asymmetry. Bottom row: cross-section times Branching Fraction for electrons ($\sigma B_e$) as a function of $Z_{ee}$. The plots refers to a $Z'$ with a mass of 3 TeV (left column) and 5 TeV (right column) at a luminosity of 3 ab$^{-1}$.

FIG. 6. Contours of total signal significance as a function of branching fraction into the leptons for 5 TeV (left) and 15 TeV (right) computed at $\mathcal{L} = 10$ ab$^{-1}$ for the FCC. We assume the production cross-section to be $\sigma_{Z'} = 0.1$ fb and at most 20% branching fraction into the leptons which corresponds to the diagonal edge. This is particularly useful for lower masses as compared to the heavier masses and is illustrated Fig. 6 for two masses: 5 TeV (left) and 15 TeV (right). We assume the production cross-section to be $\sigma_{Z'} = 0.1$ fb and at most 20% branching fraction into the leptons which corresponds to the diagonal edge. The behavior of increasing asymmetry between the leptons is similar to that of the LHC albeit at much higher masses: at the LHC one expects a symmetric reconstruction at around the scale of the $Z$ boson mass with the asymmetry increasing progressively.

Our procedure to evaluate the signal discovery significance for FCC will be exactly similar to the one shown for HL-LHC. For the purpose of continuity we begin with $M_{Z'} = 5$ TeV and compare the results with that at HL-LHC and is shown in Fig. 7. The results are compared at the end of the expected run of the corresponding machines: 3 ab$^{-1}$ for HL-LHC and 30 ab$^{-1}$ for FCC. All the lines represent 3 $\sigma$ sensitivity to non-universality. The FCC curve is characterized by two distinct features: A) more symmetric sensitivity on either side of $\hat{A}$ owing to symmetric reconstruction for 5 TeV $Z'$ mass and B) higher sensitivity to minor deviations from non-universality corresponding to the regions around $\hat{A} = 0$. FCC results for a $Z'$ mass of 5 and 10 TeV are shown in Fig. 8.

As noted before, the strength of the FCC at 30 ab$^{-1}$ is demonstrated by its ability to probe regions very close to $\hat{A}$. Table I summarizes the $\hat{A}$ bounds for a $Z'$ of 5 TeV at 10 $\sigma$ level for HL-LHC and FCC. The 10 $\sigma$ number for FCC corresponds to $\sigma B = 0.0051$. We first begin with the discovery prospect of such states at the FCC. For the purpose of FCC studies, we use the FCC-hh card reported in this reference [8]. One major difference between the HL phase is that the electron and muon reconstruction is expected to be fairly democratic. This is particularly true for lower masses as compared to the heavier masses and is illustrated Fig. 9 for two masses: 5 TeV (left) and 15 TeV (right). We assume the production cross-section to be $\sigma_{Z'} = 0.1$ fb and at most 20% branching fraction into the leptons which corresponds to the diagonal edge. The behavior of increasing asymmetry between the leptons is similar to that of the LHC albeit at much higher masses: at the LHC one expects a symmetric reconstruction at around the scale of the $Z$ boson mass with the asymmetry increasing progressively.

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FIG. 8. 3 σ (red shadowed region) and 2 σ (green-dashed lines) asymmetry sensitivity plot for the FCC with the respect to expected discovery significance in the electron channel for a $Z'$ mass of 5 and 10 TeV with a luminosity of 30 ab$^{-1}$. The red shadowed region illustrates regions of non-universality that can be excluded at 3σ at this luminosity.

| $Z'$ | $Z_{ee}$ | HL-LHC | FCC |
|------|---------|--------|-----|
| 5 TeV | 10 | (-0.76, 0.52) | (-0.35, 0.21) |
|      | 15 | (-0.62, 0.39) | (-0.22, 0.17) |
| 10 TeV | 10 | -        | (-0.41, 0.27) |
|      | 15 | -        | (-0.29, 0.22) |

TABLE I. 3σ $\tilde{A}$ bounds for a 5 and 10 TeV $Z'$ at $Z_{ee} = 10.15$ level for HL-LHC and FCC. We do not quote the sensitivity for 10 TeV at HL-LHC as it is out of reach for practical values of $\sigma B$.

CONCLUSIONS

Universality in the neutral current sector is one of the defining features of the SM. Observation of any hints deviating from this prescription points towards a definitive hint for NP. In this work, using a simple test statistic, we present a strategy to estimate the extent of non-universality from proton colliders. We find that the performance of the HL-LHC phase of the LHC is limited owing to asymmetric reconstruction resolution between the leptons. This motivates a detailed analysis in the future FCC-hh machines where the differences between the electron and the muon are ironed out for relatively lighter masses. Furthermore, this machine is sensitive to minor deviations from non-universality. This work also offers a nice complementarity between the observations in flavour factories and direct searches. This strategy can also be extended to tau final states which are mainly identified by their hadronic decays. Using the techniques introduced in this paper and adapting improved identification criteria for the tau, will enable us to get a complete picture of (non-)universality in the neutral current sector and constitutes work in progress.

ACKNOWLEDGEMENTS

We are grateful to M. Mangano for his continuous suggestions throughout the course of the project. G.D and A.I. wish to thank useful discussions with Alberto Orso Maria Iorio. AI wishes to thank Michael Winn for useful observations during the GdR-InF 2019 meeting. We wish to thank Sabyasachi Chakraborty, Seema Sharma and Tuvin Roy for a careful reading of the manuscript and several useful comments. A.I would like to thank CEFIPRA Indo-French research network. G.D. was supported in part by MIUR under Project No. 2015P5SBHT and by the INFN research initiative ENP. G.D. thanks “Satish Dhawan Visiting Chair Professorship” at the Indian Institute of Science.

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