Of Contact Interactions and Colliders

Sacha Davidson†
IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3,
4 rue E. Fermi 69622 Villeurbanne Cedex, France

Sébastien Descotes-Genon‡
Laboratoire de Physique Théorique, CNRS/Univ. Paris-Sud (UMR 8627), 91405 Orsay Cedex, France

Patrice Verdier‡
IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3,
4 rue E. Fermi 69622 Villeurbanne cedex, France

The hierarchy of scales which would allow dimension-six contact interactions to parametrise New Physics may not be verified at colliders. Instead, we explore the feasibility and usefulness of parametrising the high-energy tail of distributions at the LHC using form factors. We focus on the process $pp \to \ell^+\ell^-$ in the presence of $t$ (or $s$)-channel New Physics, guess a form factor from the partonic cross-section, and attempt to use data to constrain its coefficients, and the coefficients to constrain models. We find that our choice of form factor describes $t$-channel exchange better than a contact interaction, and the coefficients in a particular model can be obtained from the partonic cross-section. We estimate bounds on the coefficients by fitting the form factors to available data. For the parametrisation corresponding to the contact interaction approximation, our expected bounds on the scale $\Lambda$ are within $\sim 15\%$ of the latest limits from the LHC experiments.

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I. INTRODUCTION

Suppose that the LHC does not discover new particles in direct production. It can nonetheless be sensitive to new particles just beyond its kinematic reach, from their effects on the high energy tails of distributions. These effects are usually parametrised by contact interactions, which are local, non-renormalisable operators. For instance, the process $pp \to \ell^+\ell^-$ can be sensitive to the four fermion operator

$$
\pm \frac{4\pi}{\Lambda^2} \sum_{q=u,d} (\bar{\ell} \gamma^\alpha P_L q)(\ell \gamma^\alpha P_L \ell)
$$

where $\ell = e, \mu$. With $20$ fb$^{-1}$ of data at $8$ TeV in the centre-of-mass frame, LHC experiments have set bounds on some coefficients $4\pi/\Lambda^2$ of order $\Lambda \gtrsim 10 - 17$ TeV [1-4]. Various recent papers [5] have explored what can be learned from contact interaction studies, if the LHC finds no new particles.

Two difficulties arise in attempting to apply currently available contact interaction (CI) bounds to specific New Physics (NP) Models:

1) Experimental limits exist only for a selection of CIs, among the large collection labelled by the chirality, flavour and gauge charge of participating fermions, as well as the Lorentz structure of the interaction. Since the magnitude and sign of the interference with the Standard Model (SM) depends on these labels, it is improbable that an available limit will be applicable to the interactions induced by a particular model.

2) In the sensitivity range of colliders, it is unlikely that the CI approximation (that $p^2 \ll m^2$ for the heavy mediating particle) is satisfied in any but the most strongly coupled models.

A non-local, or “form factor” parametrisation of the distribution tails might address both points: with a judicious choice of functional form, it may include non-local interactions mediated by propagating particles, and its coefficients may be simply calculated in many models. In this paper, we focus on the process $qq \to \ell^+\ell^-$ at the LHC, and parametrise the $pp \to \ell^+\ell^-$ cross-section as:

$$
\frac{d\sigma}{ds} = \frac{d\sigma_{DY}}{ds} \left(1 + a \frac{\hat{s}}{1 + cs} + b \frac{\hat{s}^2}{(1 + cs)^2}\right),
$$

where $a, b,$ and $c$ are coefficients to be determined, respectively of mass dimension $-2$, $-4$, $-2$, $\sigma_{DY}$ is the Drell-Yann (DY) cross-section for $Z/\gamma$ exchange [17], and $\hat{s}$ is the invariant mass-squared of the final state leptons.

Section II supports the functional form of eq. (2) by studying the partonic cross-section for $t$-channel exchange of a leptoquark with mass just beyond the reach of the LHC. Then section III argues that for a generic model, $a, b$ and $c$ can be estimated from the partonic cross-section with simple approximations to the parton distribution functions (pdfs). Finally, section IV attempts a least-squares fit of eq. (2) to available data.

Constraints on leptoquarks [6-8] and contact interactions involving two quarks and two leptons have been widely studied [9], both from precision and collider data.
It is generically true that colliders have the best sensitivity to flavour-diagonal operators. A parametrisation of contact interactions similar to eq. (2) with \(c \rightarrow 0\), was proposed in [10] to address the first problem above. Our form-factor generalisation is perhaps an old-fashioned version of “simplified models” [11].

II. FORM FACTORS VS CONTACT INTERACTIONS

The aim of this section is to justify replacing \(4\pi/\Lambda^2\) as the coefficient of a four-fermion operator, by the non-local coefficient \(\sim \lambda^2/(m^2 + \hat{s})\). We focus on a particular model, a scalar leptoquark \(S\) with interaction \(\lambda S \sigma_{\mu\nu} u^\mu e^\nu + \text{h.c.}[3, 8]\), and argue that the partonic cross-section is better approximated by an expansion in \(\hat{s}/(\hat{s} + m^2)\) than in \(\hat{s}/m^2\). We imagine this could be generalised to any particle exchanged in the \(t\)-channel, and will discuss multiple particle exchange in a later publication.

The partonic cross-section for \(u\bar{u} \rightarrow e^+e^-\), mediated by neutral gauge bosons and \(t\)-channel \(S\) exchange, is:

\[
\hat{\sigma}_{\text{LQ}} = \hat{\sigma}_{\text{DY}} + \frac{1}{48\pi \hat{s}} \left[ -\frac{2g^2\lambda^2}{3} \left( \frac{1}{2} - \frac{m^2}{\hat{s}} + \frac{m^4}{\hat{s}^2 \ln(\frac{m^2 + \hat{s}}{m^2})} \right) + \frac{\lambda^4}{4} \left( 1 - \frac{m^2}{\hat{s}} \ln(\frac{m^2 + \hat{s}}{m^2}) + \frac{m^2}{(m^2 + \hat{s})^2} \right) \right]
\]

(3)

where the gauge bosons are taken to be the massless \(W_0, B\) with couplings \(g_2, g'\), because \(\hat{s} \gg M_Z^2\).

The ratio \(\hat{\sigma}_{\text{LQ}}/\hat{\sigma}_{\text{DY}}\) is the solid blue line in figure 1. To obtain the form factor parametrisation, we expand

\[
\ln\left( \frac{m^2 + \hat{s}}{m^2} \right) \approx \frac{\hat{s}}{m^2 + \hat{s}} + \frac{\hat{s}^2}{2(m^2 + \hat{s})^2} + \ldots
\]

(4)

The first terms in expanding \(144\pi \hat{s}(\hat{\sigma}_{\text{LQ}} - \hat{\sigma}_{\text{DY}})\) are:

\[
-\frac{2g^2\lambda^2}{3} \frac{\hat{s}}{m^2 + \hat{s}} + \left( -\frac{g^2\lambda^2}{6} + \frac{\lambda^4}{4} \right) \frac{\hat{s}^2}{(m^2 + \hat{s})^2} + \ldots
\]

(5)

and are plotted in figure 1. Already two terms give a reasonable fit to the exact result, and are only slightly more complicated than a CI, so we opt for the simple form of eq. (2), despite that in principle, form factors can be the most general functions of the available variables, restricted only by symmetries.

Notice that for \(\hat{s} \ll m^2\), we could also expand \(\ln(1 + \hat{s}/m^2) \approx \hat{s}/m^2 - \hat{s}^2/2m^4 + \ldots\), which corresponds to parametrising leptoquark exchange by a tower of local operators, including dimension-eight CIs \(\propto \hat{s}/m^4\). But this expansion is less useful, because it fails in the regime \(\hat{s} \gg m^2\). This is illustrated in figure 1 by the black lines exiting the top and bottom of the plots. The continuous black line is \(\hat{\sigma}_{\text{LQ}}/\hat{\sigma}_{\text{DY}}\) expanded to second order in \(\hat{s}/m^2\) (the CI approximation), and the dashed line includes third order in \(\hat{s}/m^2\). This poor convergence motivates our interest in form factors, as opposed to CIs. So we are abandoning the theoretical attractions of the Operator Product Expansion and local Effective Field Theory [12], because there is insufficient hierarchy between \(\hat{s}\) and \(m^2\) to justify truncating the expansion in local operators at the lowest orders.

A curious feature of eq. (5) is the \(O(g^2\lambda^2)\) contribution to the \(O(\hat{s}^2)\) term, which is usually absent in the CI approximation. This neglect is justified, because the CI limit is \(m^2 \gg \hat{s}\), and colliders are sensitive to CI with \(\lambda^2/2m^2 \gtrsim g^2/\hat{s}\), which implies \(g^2 \ll \lambda^2\). In the case of form factors, it is convenient to neglect this contribution in our preliminary analytic estimates eqns (10) - (12), but we will see that it should be included.

We now briefly comment on the \(s\)-channel exchange of a new particle (or resonance) of mass \(M\), which generates a peak in the partonic cross-section at \(\hat{s} = M^2\). The rise towards this peak, for \(\hat{s} \ll M^2\) can be parametrised as a contact interaction (eq. (2) with \(c \rightarrow 0\)). However, the expansion in \(\hat{s}/(\hat{s} + M^2)\), which was useful for \(t\)-channel exchange, has no advantages in this case. For \(M^2 < \hat{s}\), it is possible that an \(s\)-channel resonance could contribute a shoulder (like \(t\)-channel exchange) in the binned \(pp \rightarrow \ell^+\ell^-\) data. However, this depends on pdfs, binning and the particle’s properties, so we will discuss in

FIG. 1: Thick blue is the partonic cross-section for \(u\bar{u} \rightarrow e^+e^-\), mediated by \(Z, \gamma\) and a leptoquark \(S_0\) of mass 2 TeV and \(\lambda^2 = 1\) in the \(t\)-channel, and normalised to \(\hat{\sigma}\) for \(Z, \gamma\) exchange. The dotted (dot-dashed) blue are the \(O(\hat{s}^2), O(\hat{s}^3)\) terms of a “form factor” approximation to leptoquark exchange (see eq. (4)). Black solid (exits the upper plot border) is the dimension-six CI approximation, and black dashed (exits lower border) includes the first correction in \(\hat{s}/m^2\) to the CI approximation. The leptoquark has destructive interference (first plot), for illustration, we also plot the same model but with constructive interference.
III. FROM PARTONS TO FORM FACTORS

This section aims to relate the partonic cross-section \( \sigma(\bar{q}q \to \ell^+\ell^-) \), mediated by arbitrary New Physics, to the differential cross-section for pp \( \to \ell^+\ell^- \):

\[
\frac{d\sigma}{d\hat{s}} = \frac{2}{s} \sum_{q=u,d} \int d\eta_+ d\eta_- f_q(x_1) f_{\bar{q}}(x_2) \frac{d\hat{\sigma}}{d\hat{s}}(\bar{q}q \to \ell^+\ell^-) \quad (6)
\]

where \( f_q \) is the pdf of the quark \( q \), and \( x_1 = \frac{M_+}{\sqrt{s}} e^{u_+}, x_2 = \frac{M_-}{\sqrt{s}} e^{-\eta_+} \) are the fractions of the proton's momentum carried by the colliding partons.

Our first approximation is to suppose a single density for sea quarks, and that there are twice as many valence up as ds. Concretely, we take:

\[
\int d\eta_+ f_u(x_1) f_d(x_2) = \frac{2}{3} \sum_{q=u,d} \int d\eta_+ f_q(x_1) f_{\bar{q}}(x_2) = \frac{2}{3} F(\hat{s}) \\
\int d\eta_+ f_d(x_1) f_d(x_2) = \frac{1}{3} \sum_{q=u,d} \int d\eta_+ f_q(x_1) f_{\bar{q}}(x_2). \quad (7)
\]

The second approximation is to take simple integration limits [0, \( \hat{s} \)] for \(-\hat{\ell} \), despite that experiments restrict the angular distribution to be away from the beam-pipe. This should be acceptable if the NP and SM events have the same angular distribution, as is the case for the V+A four-fermion interactions [18].

These approximations allow to factorise the pp \( \to \ell^+\ell^- \) cross-section as a pdf integral multiplying an “averaged” partonic cross-section \( \bar{\sigma} = \frac{1}{2}\sigma(uu \to \ell^+\ell^-) + \frac{1}{2}\sigma(\bar{d}\bar{d} \to \ell^+\ell^-) \):

\[
\frac{d\sigma}{d\hat{s}} \simeq \frac{2F(\hat{s})}{s} \bar{\sigma} \quad (8)
\]

where, for Drell-Yann, with \( \sin^2 \theta_W = 1/4 / 1280\pi^2 s \),

\[
\bar{\sigma}_{DY} \simeq \frac{g_4^2}{1280\pi s}. \quad (9)
\]

The expected SM rate includes non-DY processes (dibosons, etc) which amount to 10-20% of the rate in the data to which we will compare [2]. We augment \( \sigma_{DY} \) by \( \sim 10\% \) to account for this, which allows to write \( \frac{d\sigma}{d\hat{s}} \) in the presence of NP as

\[
F(\hat{s}) \left( \frac{g_4^2}{8\pi s} + \epsilon_{int} g_2^2 \frac{4\pi/\Lambda^2}{1 + \hat{s}/m^2} + \epsilon_{NP} \frac{16\pi^2/\Lambda^4}{1 + \hat{s}/m^2} \right) \quad (10)
\]

where \( 4\pi/\Lambda^2 \) is the coefficient of the CI induced by the NP, and \( \epsilon_{int} \) and \( \epsilon_{NP} \) are constants, predicted by the model and obtainable from the partonic cross-section, which respectively parameterise the SM-NP interference, and account for the partons involved in the NP interactions. The \( \epsilon_{int} \) and \( \epsilon_{NP} \) for leptoquarks are tabulated in [8]; the leptoquark considered here (see eq. [5]) has:

\[
\epsilon_{NP} = \frac{2s}{3}, \quad \epsilon_{int} = -\frac{8}{27}, \quad \frac{4\pi}{\Lambda^2} = \frac{\lambda^2}{2m^2_{LQ}}, \quad (11)
\]

and the interaction [11] has \( \epsilon_{NP} = 1, \epsilon_{int} = \mp 1/6 \). These parameters can be translated to the \( a, b, c \) which are more convenient for fitting:

\[
a = \frac{72\pi}{\Lambda^2} \epsilon_{int}, \quad b \simeq \frac{\epsilon_{NP}}{8\epsilon_{int}} a^2 \quad (12)
\]

and the bound on \( \lambda \) (or \( \lambda^2/2m^2 \)) will arise at the point where this parabola leaves the allowed ellipse.

IV. ESTIMATED BOUNDS FROM DATA?

The usual way to set bounds on a model, is to fix the parameters to representative values, simulate the expected signal, and compare it to data. Our a, b, c parameters could be constrained in this way, following the recipe given in [10]. Here, we explore instead, naively to fit the difference between data and SM expectation to a function, and constrain that function.

CMS compared 20 fb\(^{-1}\) of pp \( \to \ell^+\ell^- \) data to the NNLO SM predictions [14], and in a separate publication [2], obtained bounds on the CI of eq. (11). We use the CI analysis, and start with the \( \mu^+\mu^- \) data because it shows a slight preference for NP with destructive interference [19]. The data is binned, which poses a problem in comparing to eq. (12), because the pdfs only cancel in the ratio at the same value of \( \hat{s} \). We will quantify the resulting uncertainty in a later publication; here we take the uncertainty in \( \hat{s} \) to be the bin-width.

From the CMS plots, we read the ratio of data to SM expectation with statistical and systematic uncertainties, for \( \sqrt{s} > 300 \) GeV. We perform a least-squares fit (minuit\([15]\)) of a and b to these points for four fixed values of \( c = 1/m^2 \) corresponding to \( m = 1, 2, 3 \) TeV and \( m \to \infty \). The resulting \( 2\sigma \) ellipses are plotted in figure [2]. They lean left because the destructive interference...
of a negative $a$-term partially cancels the excess events generated by a positive $b$-term.

To extract bounds on a particular model from this plot, recall that the form factor parametrisation allows to constrain both the coupling and mass of an exchanged particle, rather than the CI combination $\sim \lambda^2/m^2$. However, in the interests of performing a linear fit, we fixed the value of the mass and fit to $a$ and $b$. The recipe to extract a bound is therefore to choose an ellipse labelled by a mass, then identify the parabola which represents the model. The value of $b$ where the parabola leaves the ellipse can be combined with eq. (12) to constrain the CI induced in the model, which for finite $m$, gives a bound on $\lambda$.

The CI of eq. (11) corresponds to the dash-dotted parabola, and the inner ellipse, so the above recipe, applied to the $\mu^+\mu^-$ plot, gives $\Lambda_{\text{des}} \gtrsim 10.3$ TeV and $\Lambda_{\text{cons}} \gtrsim 20.7$ TeV, to be compared with the CMS 95\% C.L. exclusions: $\Lambda_{\text{des}} \gtrsim 12.2$ TeV, $\Lambda_{\text{cons}} \gtrsim 15.0$ TeV. The difference is partially due to the data's slight deviation from the SM: the dotted parabola of eq. (1) passes close to the central value of the CI fit, which translates to $\Lambda_{\text{des}} = 13.7$ TeV. If instead we estimate an expected limit (by centering the ellipses on the origin), we obtain $\Lambda_{\text{des}} \gtrsim 12.6$ TeV, $\Lambda_{\text{cons}} \gtrsim 18.1$ TeV, to be compared to CMS’s expected limits of 13 and 17 TeV. In the case of the $e^+e^-$ data, our estimates give $\Lambda_{\text{des}} \gtrsim 16.3$ TeV, $\Lambda_{\text{cons}} \gtrsim 19.0$ TeV, to be compared to CMS’s bounds of 13.5 and 18.3 TeV.

Finally, we can estimate bounds on the first generation leptoquark $S_0$, interacting with $W^\pm e^-$. This model corresponds roughly to the dashed parabola, and bounds can be obtained from ellipses corresponding to the $e^+e^-$ data (see figure 2). The current LHC direct production bound on the mass of leptoquarks decaying to electrons is 830 GeV [16], so it is interesting to study the couplings of leptoquarks with masses of 1, 2 and 3 TeV. We obtain $\Lambda_{\text{des}} \gtrsim 21.0$ TeV, $\Lambda_{\text{cons}} \gtrsim 20.3$ TeV in the contact interaction limit, and $|\lambda_R| \lesssim 0.3, 0.5$ and 0.75 for $m = 1, 2, 3$ TeV. Retaining the $O(g^2\lambda^2s^2)$ term of eq. (13) gives $\lambda_R \lesssim 0.4$ at $m = 1$ TeV. These bounds are stronger, by factors of few, than those obtained in [7] by simulating leptoquark exchange in MadGraph, and excluding parameters that generate excess events. We imagine that our more restrictive bound could arise from requiring that the leptoquark’s destructive interference not reduce the event rate at $\sqrt{s} \lesssim$ TeV.

V. SUMMARY

The differential cross-section $d\sigma/d\hat{s}(pp \rightarrow \ell^+\ell^-)$ can almost be written as a partonic cross-section multiplied by an integral over parton distribution functions (see section III). When the partonic cross-section includes the exchange of a heavy new particle in the $t$-channel, such as a leptoquark, then, as shown in section III it is better approximated by the “form factor” expansion in $\hat{s}/(\hat{s}+m^2)$, than by the usual local expansion in $\hat{s}/m^2$, which gives contact interactions. If experimental limits were set on the coefficients of the form factor parametrisation given in eq. (2), these could be translated to any combination of contact interactions, or the exchange of an arbitrary leptoquark, by a simple analytic calculation.

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FIG. 2: $2\sigma$-allowed ellipses for the $a, b$ parameters of eq. (2), with fixed values of $c = 1/m^2$, obtained from $e^+e^-$ (upper) and $\mu^+\mu^-$ (lower) data [2]. Decreasing ellipse size corresponds to $m = 1, 2, 3, \infty$ TeV. The dotted 1 TeV $\mu^+\mu^-$ ellipse (lower plot), extends to $b \simeq 3.5$. The inner green ellipse (lower plot) is the 1$\sigma$-allowed contour for the contact interaction. The parabola, in decreasing width, represent models described by $b = 1/4a^2, a^2, 4a^2, 10a^2$. 
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[19] The Drell-Yann cross-section depends on parton distribution functions (pdfs), so bounds on NP extracted this way suppose that the pdfs are reliably obtained in some other process. From a theoretical perspective, the pdf dependence could be avoided by studying $d\sigma(\to e^+e^-)/d\sigma(\to \mu^+\mu^-)$ which would be sensitive to New Physics which coupled differently to $e$ and $\mu$.

[20] Non-$V$ operators will be discussed in a subsequent publication. Their cross-section may have a different angular distribution, which for instance could affect event migration among bins. However, since the difference is only in the numerator (upstairs), it should not induce dangerous effects like a divergence along the beampipe.

[21] The CMS study[2] does not appear to allow the CI to reduce the number of events with respect to the SM expectation, so is perhaps less sensitive to this solution than our simplistic fit.