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Novel angular dependence in Drell-Yan lepton production via dimension-8 operators

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ABSTRACT

We study the effects of dimension-8 operators on Drell-Yan production of lepton pairs at the Large Hadron Collider (LHC). We identify a class of operators that leads to novel angular dependence not accounted for in current analyses. The observation of such effects would be a smoking-gun signature of new physics appearing at the dimension-8 level. We propose an extension of the currently used angular basis and show that these effects should be observable in future LHC analyses for realistic values of the associated dimension-8 Wilson coefficients.

1. Introduction

The Standard Model (SM) has so far been remarkably successful in describing all data coming from the Large Hadron Collider (LHC) and elsewhere. Although the search for new particles beyond those predicted in the SM will continue at the high-luminosity LHC, it is becoming increasingly important to search for potentially small and subtle indirect signatures of new physics. A convenient theoretical framework for performing such searches when only the SM particles are known is the SM effective field theory (SMEFT) which contains higher-dimensional operators formed only from SM fields. The SMEFT is an expansion in an energy scale Λ at which the effective theory breaks down and new fields must be added to the Lagrangian. The leading dimension-6 operators characterizing deviations from the SM have been classified [1–3] (there is a dimension-5 operator that violates lepton number [4], which does not play a role in our discussion).

Less is known about terms at dimension-8 and beyond in the SMEFT expansion. The number of operators at each order in the expansion has been determined [5], and initial ideas on how to systematically derive the structure of these operators have appeared [6]. Some phenomenological consequences of dimension-8 operators in the SMEFT have been studied [6–8]. Although their effects are usually suppressed with respect to dimension-6 operators, dimension-8 terms are sometimes the leading contributions to observables due to symmetry considerations or the structure of the corresponding SM amplitudes [9]. In such cases it is important to quantify their effects in order to guide experimental searches.[1]

In this note we point out that a class of dimension-8 operators in the SMEFT generate novel angular dependences in Drell-Yan lepton-pair production not accounted for in current experimental analyses [12–15]. They are not generated at leading-order by dimension-6 operators in the SMEFT, nor by QCD effects in the SM. They are only generated in the SM by higher-order electroweak corrections, which we demonstrate here to be small. This offers the possibility of extending the current experimental studies to search for this potential smoking-gun signature of new physics appearing through dimension-8 effects. We note that such dimension-8 operators could be generated in an ultraviolet completion by vector leptoquarks, which would also induce dimension-6 effects [16]. They could also be generated without dimension-6 contributions by massive spin-two particles [17].

The typical angular analysis of lepton-pair production through either charged or neutral currents proceeds by expanding the differential cross section in terms of spherical harmonics:

$$\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\left\{(1+c_\theta^2)+\frac{A_0}{2}(1-3c_\theta^2)\right.$$

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[1] After the submission of this draft, the complete dimension-8 SMEFT basis was determined [10,11].

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$$+A_1 s_{2\theta} c_\phi + \frac{A_2}{2} s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta + A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta} s_\phi + A_7 s_\theta s_\phi \Big\}. \quad (1)$$

Here, m_{ll} is the invariant mass of the lepton system, y is the rapidity of the W or Z-boson that produces the lepton pair, and Ω_l is the solid angle of a final-state lepton. The lepton angles are typically defined in the Collins-Soper frame [18] and we have used the notation s_α and c_α to represent their sine and cosine, respectively. In the SM, the leptons are produced by an s-channel spin-one current, so in the squared amplitude spherical harmonics up to $l = 2$ are allowed. We show that certain two-derivative dimension-8 operators in the SMEFT populate the $l = 2$ partial wave at the amplitude level, allowing for $l = 3$ spherical harmonics in the angular expansion when interfered with the SM amplitude. Dimension-6 operators cannot generate $l = 2$ partial waves at the amplitude level, making their appearance a hallmark of the dimension-8 SMEFT. Searching for such effects requires extending the usual angular analysis as we demonstrate later in Eq. (18).

Our paper is organized as follows. We first review the operator basis for SMEFT, focusing on operators relevant for lepton pair production at dimension-6 and dimension-8. We consider operators relevant for both leading-order (LO) and next-to-leading-order (NLO) in the QCD coupling constant. We then present formulae for LO production and demonstrate the need to expand the usual spherical harmonic basis. Finally, we present numerical results for neutral-current production at the LHC, where we also show that the predicted SM results for these angular dependences arising from higher-order electroweak corrections are small.

2. Review of the SMEFT

We review in this section aspects of the SMEFT relevant for our analysis of the angular dependence of lepton-pair production. The SMEFT is an extension of the SM Lagrangian to include terms suppressed by an energy scale Λ at which the ultraviolet completion becomes important. Truncating the expansion in $1/\Lambda$ at dimension-8, and ignoring operators of odd-dimension which violate lepton number, we have

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_{6,i}\mathcal{O}_{6,i} + \frac{1}{\Lambda^4}\sum_i C_{8,i}\mathcal{O}_{8,i}. \quad (2)$$

Operators of dimension-6 have been extensively studied in the literature [19–25]. The overall electroweak couplings that govern lepton-pair production are shifted in SMEFT. Since these clearly lead to only an overall shift of the couplings and not to any new angular terms we do not explicitly consider them here. In addition, Drell-Yan lepton-pair production receives contributions from several classes of dimension-6 operators that affect angular distributions. Two types of operators have non-vanishing interference with the SM, and lead to genuine dimension-6 effects in the cross sections. In the notation of Ref. [3,26], these belong to the classes

- $\psi^2\varphi^2 D$: these include operators with a single derivative and a fermion bilinear of the form

  $$\mathcal{O}_{6,\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e), \quad (3)$$

  where φ denotes the Higgs doublet, e a right-handed lepton singlet, D_μ a covariant derivative, and $\overleftrightarrow{D}_\mu = \overrightarrow{D}_\mu - \overleftarrow{D}_\mu$. Operators of this form simply shift the SM coupling of the fermions to gauge bosons. In charged-current processes, these interactions involve purely left-handed quarks and leptons and lead to exactly the same angular dependence as in the SM. For neutral currents, operators in this class might shift the relative importance of left- and right-handed couplings with respect to the SM, and could manifest themselves in high-precision measurements of angular coefficients such as A_4.
- ψ^4: four-fermion operators with the same chiral structure as the SM, such as

  $$\mathcal{O}_{6,eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), \quad (4)$$

  where u denotes a right-handed up-quark field. These operators have been extensively studied. It is straightforward to see that these produce the same lepton angular dependences as in the SM, as they can be obtained by integrating out new spin-one W' or Z' gauge bosons.

In addition, the dimension-6 SMEFT Lagrangian contains several more operators that do not interfere with the SM, and thus contribute to the cross section at $\mathcal{O}(v^4/\Lambda^4)$. They belong to the following classes.

- $\psi^2 X\varphi$: these include dipole operators coupled to gauge fields such as

  $$\mathcal{O}_{6,eW} = (\bar{l}\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu}, \quad (5)$$

  where l denotes a left-handed lepton doublet and τ^I an $SU(2)$ Pauli matrix, and similar operators involving quarks and the $U(1)_Y$ gauge boson.
- $\psi^2\varphi^2 D$: in addition to the operators considered before, one can introduce the right-handed charged-current operator

  $$\mathcal{O}_{6,\varphi ud} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}\gamma^\mu d) + \text{h.c.}, \quad (6)$$

  where u and d are right-handed quark fields.
- ψ^4: four-fermion operators with chiral structure different from the SM, such as the scalar operator

  $$\mathcal{O}_{6,ledq} = \bar{l}^i e\, \bar{d} q^i, \quad (7)$$

  where q is a left-handed quark doublet.

As discussed in Ref. [23], these operators can induce dramatic deviations from the SM expectations in the A_i coefficients, especially at large dilepton invariant masses. However, they do not generate any new angular dependence and their effect is fully captured by Eq. (1). This statement remains true upon including QCD corrections, since these diagrammatic contributions feature a gluon connecting the two initial-state quarks and do not affect the spin-one (or spin-zero) current that produces the lepton pair. Only an electroweak correction where a gauge boson connects an initial-state quark to a final-state lepton can populate a $l > 1$ partial wave. We discuss this possibility in the case of the higher-order SM corrections later in this note.

At dimension-8 a larger variety of operator classes can contribute. We use the `HSMethod` code [5] to obtain the correct number of operators with a given field content. We note that many of the operators relevant to our study were previously considered in Ref. [6]. We have confirmed the number and structure of the operators found there.

- $\psi^2\varphi^4 D$: this category has been studied in Ref. [6] and contains operators such as

  $$\mathcal{O}_{8,q1} = i(\bar{q}\gamma^\mu q)(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\varphi^\dagger\varphi). \quad (8)$$

  These clearly lead to shifts in the fermion-gauge boson vertices and no new kinematic effects, as confirmed by explicit calculation in Ref. [6].

- $\psi^2\varphi^2 D^3$: these include operators of the form

$$\mathcal{O}_{8,3q1} = i(\bar{q}\gamma^\mu D^\nu q)(D^2_{(\mu\nu)}\varphi^\dagger\varphi). \tag{9}$$

These only shift the fermion-gauge boson vertices, as confirmed in Ref. [6].

- $\psi^4\varphi^2$: these include four-fermion operators such as

$$\mathcal{O}_{8,eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)(\varphi^\dagger\varphi). \tag{10}$$

These clearly shift the dimension-6 couplings leading to the same angular dependence as before. The remaining operators relevant for lepton-pair production can be obtained by considering both fermion doublets and singlets, and by judicious insertions of the Pauli matrices τ^I.

- $\psi^4 D^2$: we begin by considering operators with left-handed fermion doublets only. There are four such operators, which we write in the following way:

$$\begin{aligned}
\mathcal{O}_{8,lq\partial 1} &= (\bar{l}\gamma_\mu l)\partial^2(\bar{q}\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 2} &= (\bar{l}\tau^I\gamma_\mu l)\partial^2(\bar{q}\tau^I\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 3} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),\\
\mathcal{O}_{8,lq\partial 4} &= (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned} \tag{11}$$

The operators $\mathcal{O}_{8,lq\partial 1}$ and $\mathcal{O}_{8,lq\partial 2}$ lead only to an energy-dependent shift of the dimension-6 four-fermion couplings. This is clear from their form and can also be confirmed by explicit calculation. The remaining two operators are more interesting. Considering the lepton bilinears present in $\mathcal{O}_{8,lq\partial 3}$ and $\mathcal{O}_{8,lq\partial 4}$, we see that they each contain two free Lorentz indices μ and ν. This implies that they can couple to a spin-two current, which can be represented as a two-index polarization tensor $\epsilon_{\mu\nu}$. The amplitude therefore contains a new $l=2$ partial wave not present in previous contributions. We confirm this later by explicit calculation. For charged-current production only $\mathcal{O}_{8,lq\partial 4}$ would contribute.

We now extend our basis of operators to include right-handed fermion fields as well, and focus on operators containing the $\gamma^\nu \overleftrightarrow{D}^\mu$ structure necessary for the angular dependence of interest. We find an additional five operators:

$$\begin{aligned}
\mathcal{O}_{8,ed\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),\\
\mathcal{O}_{8,eu\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),\\
\mathcal{O}_{8,ld\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),\\
\mathcal{O}_{8,lu\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),\\
\mathcal{O}_{8,qe\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned} \tag{12}$$

We arrive at the following seven operators that can contribute to $l=2$ partial waves for the neutral-current amplitude: $\mathcal{O}_{8,lq\partial 3}$, $\mathcal{O}_{8,lq\partial 4}$, $\mathcal{O}_{8,eu\partial 2}$, $\mathcal{O}_{8,ed\partial 2}$, $\mathcal{O}_{8,lu\partial 2}$, $\mathcal{O}_{8,ld\partial 2}$ and $\mathcal{O}_{8,qe\partial 2}$.

We next discuss the dimension-8 operators containing gluons that can contribute to Drell-Yan lepton-pair production at NLO in the QCD coupling constant. As we find that none of these operators contribute to the angular dependence that is the major point of this note, we discuss them briefly for left-handed doublets only.

- $\psi^4 G$: there are four such operators that contribute at dimension-8 for left-handed fermion fields. We list the two distinct operator structures that appear below, the remaining two can be obtained by changing the gluon field-strength tensor to the dual one:

$$\begin{aligned}
\mathcal{O}_{8,lqG1} &= (\bar{l}\gamma^\mu l)(\bar{q}t^A\gamma_\nu q)G^A_{\mu\nu},\\
\mathcal{O}_{8,lqG2} &= (\bar{l}\tau^I\gamma^\mu l)(\bar{q}\tau^I t^A\gamma_\nu q)G^A_{\mu\nu}.
\end{aligned} \tag{13}$$

The lepton bilinears in these operators couple to a spin-one current, indicating that they lead to the usual angular dependence found in the SM. We have confirmed this by explicit calculation.

- $\psi^2\varphi^2 DG$: these are corrections to the quark bilinear that also contain a gluon field. Specializing to left-handed quarks we find eight such operators. We list the four distinct operator structures that appear, the remaining four can be obtained by changing the gluon field-strength tensor to the dual one:

$$\begin{aligned}
\mathcal{O}_{8,qG1} &= (\bar{q}t^A\gamma^\nu q)\partial^\mu(\varphi^\dagger\varphi)G^A_{\mu\nu},\\
\mathcal{O}_{8,qG2} &= (\bar{q}t^A\gamma^\nu q)(\varphi^\dagger i\overleftrightarrow{D}^\mu\varphi)G^A_{\mu\nu},\\
\mathcal{O}_{8,qG3} &= (\bar{q}\tau^I t^A\gamma^\nu q)D^\mu(\varphi^\dagger\tau^I\varphi)G^A_{\mu\nu},\\
\mathcal{O}_{8,qG4} &= (\bar{q}\tau^I t^A\gamma^\nu q)(\varphi^\dagger\tau^I i\overleftrightarrow{D}^\mu\varphi)G^A_{\mu\nu}.
\end{aligned} \tag{14}$$

The operator $\mathcal{O}_{8,qG1}$ requires a physical Higgs boson and therefore does not contribute to dilepton production. We have checked by explicit calculation that $\mathcal{O}_{8,qG3}$ contributes in the same way as operators in the $\psi^2\varphi^2 D^3$ category, while $\mathcal{O}_{8,qG2}$ and $\mathcal{O}_{8,qG4}$ give similar contributions as $\mathcal{O}_{8,lqG1}$ and $\mathcal{O}_{8,lqG2}$. None of these operators introduces novel angular dependence.

- $\psi^2 DXG$: these induce local interactions between two quarks, a weak boson and a gluon. We find eight operators with left-handed quarks that contribute to Drell-Yan at NLO. We list the two distinct operator structures that appear, the remaining can be obtained by changing the gluon field-strength tensor to the dual one, and by replacing the $SU(2)_L$ with the $U(1)_Y$ field strength.

$$\begin{aligned}
\mathcal{O}_{8,qWG1} &= \left(\bar{q}t^A\tau^I\gamma^{(\mu} i\overleftrightarrow{D}^{\nu)} q\right) W^I_{\mu\rho}G^{A\,\rho}_{\nu},\\
\mathcal{O}_{8,qWG2} &= \left(\bar{q}t^A\tau^I\gamma^\mu q\right)\left(W^I_{\alpha\beta}\overleftrightarrow{D}_\mu G^{A\alpha\beta}\right).
\end{aligned} \tag{15}$$

Here $\gamma^{(\mu}\overleftrightarrow{D}^{\nu)} = (\gamma^\mu\overleftrightarrow{D}^\nu + \gamma^\nu\overleftrightarrow{D}^\mu)/2$. In this case, the leptons arise from the decay of a spin-one weak boson, and thus the angular distributions are described by Eq. (1). We have verified this by an explicit calculation.

3. Angular dependence with dimension-8 effects

It is straightforward to calculate the matrix elements for the LO partonic process $u(p_1)\bar{u}(p_2) \to l(p_3)\bar{l}(p_4)$ given the operators in the previous section. We focus on $\mathcal{O}_{8,lq\partial 3}$ in Eq. (11) as an example. Keeping only the leading interference of this operator with the SM contribution, we find the following SMEFT-induced correction to the matrix-element squared:

$$\Delta|\mathcal{M}_{u\bar{u}}|^2 = -\frac{C_{8,lq\partial 3}}{\Lambda^4}\,\hat{c}_\theta(1+\hat{c}_\theta)^2\frac{\hat{s}^2}{6}\times \left[e^2 Q_u Q_e + \frac{g^2 g_L^u g_L^e \hat{s}}{c_W^2(\hat{s}-M_Z^2)}\right]. \tag{16}$$

Here, $\hat{s}$ denotes the usual partonic Mandelstam invariant $\hat{s}=(p_1+p_2)^2$, g is the $SU(2)$ coupling constant, c_W is the cosine of the weak mixing angle, e is the $U(1)_{EM}$ coupling constant, Q_i is the charge of fermion i, g_L^i are the left-handed couplings to the Z-boson following the notation of Ref. [27]. $C_{8,lq\partial 3}$ is the Wilson coefficient associated with the operator under consideration, and $\hat{c}_\theta$ is the angle between the beam direction and the outgoing lepton direction. At LO, the cosine of the polar angle c_θ in the Collins-Soper frame used in the LHC analyses of Refs. [14,15] is related to $\hat{c}_\theta$ by $c_\theta = \pm\hat{c}_\theta$, with positive (negative) sign if the longitudinal momentum of the dilepton pair is along (opposite) to the beam direction. We note that the amplitude for $\bar{u}(p_1)u(p_2) \to l(p_3)\bar{l}(p_4)$ can be obtained by taking $\hat{c}_\theta \to -\hat{c}_\theta$. The down-quark channel can be obtained by appropriate changes in the SM couplings.

This contribution to the differential cross section contains a c_θ^3 dependence that cannot be described by Eq. (1). The reason for this was given in the previous section when discussing the operators of Eq. (11): the traditional formulation of the Collins-Soper moments assumes that the lepton pair is produced in the s-channel by a spin-one current, which is not the case for $\mathcal{O}_{8,lq\partial3}$. Only the seven dimension-8 operators in the $\psi^4 D^2$ category identified in the previous section lead to an angular dependence not already described by Eq. (1).

In order to account for this new signature of dimension-8 effects we propose extending the parameterization of Eq. (1) to the following:

$$\begin{aligned}\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\Bigg\{&(1+c_\theta^2) + \frac{A_0}{2}(1-3c_\theta^2)\\ &+A_1 s_{2\theta}c_\phi + \frac{A_2}{2}s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta\\ &+A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta}s_\phi + A_7 s_\theta s_\phi\\ &+B_3^e s_\theta^3 c_\phi + B_3^o s_\theta^3 s_\phi + B_2^e s_\theta^2 c_\theta c_{2\phi}\\ &+B_2^o s_\theta^2 c_\theta s_{2\phi} + \frac{B_1^e}{2}s_\theta(5c_\theta^2-1)c_\phi\\ &+\frac{B_1^o}{2}s_\theta(5c_\theta^2-1)s_\phi + \frac{B_0}{2}(5c_\theta^3-3c_\theta)\Bigg\}.\end{aligned} \tag{17}$$

We have used the combinations of spherical harmonics

$$Y_3^0,\;\; Y_3^1 \pm Y_3^{-1},\;\; Y_3^2 \pm Y_3^{-2},\;\; Y_3^3 \pm Y_3^{-3}, \tag{18}$$

in forming the basis for the new $B_i^{e,o}$ coefficients. The superscripts e, o on the new B_i coefficients refer to either even or odd under T-reversal [28]. The amplitude of Eq. (16) populates the B_0 coefficient. The $B_i^{o,e}$ coefficients with $i > 0$ are first populated at $\mathcal{O}(\alpha_s)$.

4. Numerical results

We present here numerical results for neutral-current lepton-pair production at the LHC to assess the potential observation of these effects. We assume $\sqrt{s} = 14$ TeV collisions. Our hadronic results use the NNPDF 3.1 parton distribution functions extracted to NLO precision [29], and assume an on-shell electroweak scheme with G_μ, M_W, and M_Z taken as input parameters. Since we are interested in higher-dimensional operators that grow with energy we impose the following cut on the invariant mass of the final-state system: $m_{ll} > 100$ GeV. Only B_0 is generated at this leading order in QCD perturbation theory, so we focus on this coefficient here. We set the renormalization and factorization scales to $\mu = m_{ll}$.

As mentioned earlier, while the B_i are not generated in the SM from perturbative QCD corrections, they can be obtained from higher-order electroweak effects. The leading contributions to the B_0 coefficient are the angular-dependent next-to-leading logarithmic (NLL) electroweak Sudakov logarithms (the higher B_i coefficients require a mixed $\mathcal{O}(\alpha\alpha_s)$ perturbative correction which we do not consider). The leading logarithms depend only on the Mandelstam invariant $\hat{s}$, and therefore do not induce any B_i coefficients. We study the leading one-loop NLL electroweak Sudakov logarithms in the SM using the results of Ref. [30].

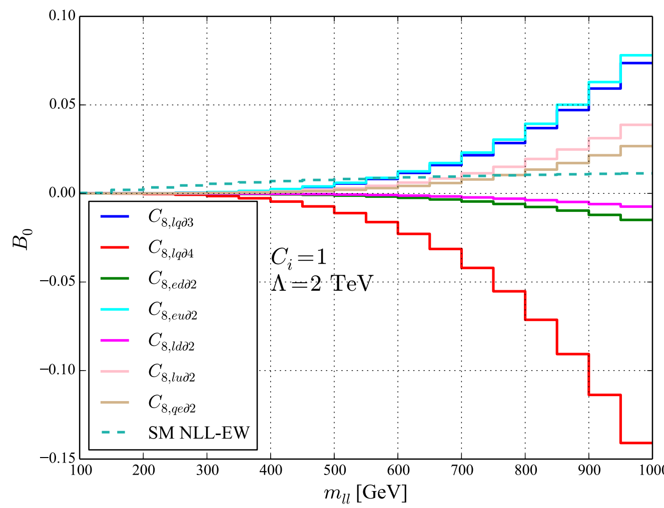

Fig. 1. B_0 coefficient as a function of the dilepton invariant mass.

We show in Figs. 1 numerical results for B_0 as a function of the invariant mass m_{ll} for the seven contributing operators. We set $\Lambda = 2$ TeV and each Wilson coefficient separately to $C_i = 1$ while setting the others to zero to obtain these seven curves. Although the allowed values of these coefficients have not been determined, the value of the energy scale $\Lambda = 2$ TeV suggested by this choice is consistent with values allowed for dimension-6 four-fermion operators found in global fits [31]. We stop our plots at $m_{ll} = 1$ TeV to have a convergent EFT expansion. The SM contribution is small since it grows only logarithmically with invariant mass as $\log(m_{ll}/M_Z)$. This can be seen explicitly using the analytic expressions in Ref. [30]. The dimension-8 contributions grow polynomially as m_{ll}^4, as can be seen from the example matrix element in Eq. (16) upon setting $\hat{s} = m_{ll}^2$. We have verified that the operator $\mathcal{O}_{8,lq\partial4}$ induces similarly large effects in charged-current Drell-Yan.

To ensure we are working in the regime of validity of the EFT, we have calculated the corrections quadratic in the dimension-8 coefficients. For the operators with the largest interference with the SM, $C_{8,lq\partial3}$, $C_{8,lq\partial4}$ and $C_{8,eu\partial2}$, the correction to the cross section due to the quadratic terms is 30%-50% of the linear dimension-8 terms in the highest invariant mass bins. The total correction from dimension-8 operators is at most 30% of the SM. B_0 receives corrections of similar size. We therefore conclude that the linear dimension-8 terms contribute the dominant correction to both the cross section and the B_0 angular coefficient in the invariant mass region considered, and that the truncation of the EFT expansion to the linear dimension-8 level is justified in our study.

In order to estimate the sensitivity of the LHC to this effect we follow the method of Ref. [32] to form an optimal observable sensitive to the B_0 coefficient. This technique associates with each event a weight designed to maximize the sensitivity to this angular effect. The statistical significance is then given as

$$\mathrm{Sig} = |B_0|\sqrt{N}\sqrt{\frac{\left[\int d\phi_i f(\phi_i)\frac{d\sigma}{dm_{ll}^2 dy}\frac{1}{2}(5c_\theta^3-3c_\theta)\right]^2}{\sigma_{tot}\int d\phi_i f^2(\phi_i)\frac{d\sigma}{dm_{ll}^2 dy}(1+c_\theta^2+A_4^{SM}c_\theta)}}. \tag{19}$$

Here, N denotes the number of events in a given experimental bin, ϕ_i denotes the relevant phase space variables (in our case m_{ll}^2, y and c_θ), and σ_{tot} is the total cross section in the experimental bin. For our choice of coefficients, the dimension-8 operators give at most a 30% correction to the SM cross section, corresponding to a number of events in the highest invariant mass bin that varies

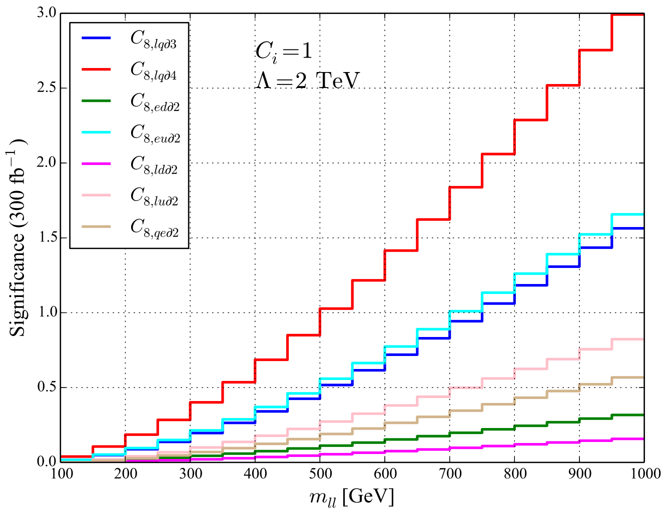

Fig. 2. Statistical significance of the B_0 angular dependence as a function of the dilepton invariant mass.

between about 340 in the case of $C_{8,lq\partial 4}$ to 510 in the case of $C_{8,ld\partial 2}$. $f(\phi)$ denotes the weight assigned to each measured event. The optimal choice that maximizes the significance to B_0 can be found to be [32]

$$f(\phi_i) = \frac{5c_\theta^3 - 3c_\theta}{1 + c_\theta^2 + A_4^{SM} c_\theta} \tag{20}$$

where the numerator is the angular dependence of the B_0 coefficient while the denominator is the SM angular dependence at leading order. We show in Fig. 2 the statistical significance of Eq. (19) as a function of dilepton invariant mass for each of the dimension-8 coefficients assuming 300 fb^{-1} of integrated luminosity. The statistical significance for 3000 fb^{-1}, the target of the High Luminosity LHC (HL-LHC), is obtained by rescaling Fig. 2 by $\sqrt{10}$. We see that the statistical significance per bin reaches 3 for the $C_{8,lq\partial 4}$ coefficient at high invariant mass, while for $C_{8,lq\partial 3}$ and $C_{8,eu\partial 2}$ it reaches 1.5. This indicates that the effects of $C_{8,lq\partial 4}$ should be significantly larger than statistical fluctuations in the data at the LHC Run 3. For $\Lambda = 2$ TeV, all three coefficients should be visible at the HL-LHC. The statistical significance is further increased by considering correlations between different invariant mass bins. Considering all bins between 650 and 1000 GeV, the significance with 300 fb^{-1} of integrated luminosity reaches more than 6 for $C_{8,lq\partial 4}$, more than 3.5 for $C_{8,lq\partial 3}$ and $C_{8,eu\partial 2}$, and more than 1.5 for $C_{8,lu\partial 2}$. Searches for the B_0 coefficient at the future LHC are therefore promising.

The results presented here have been obtained without applying selection cuts on the final-state leptons. Cuts on the individual lepton transverse momenta and rapidities distort the shapes of the θ and ϕ distributions, so that they cannot be described in terms of Eqs. (1) or (18). In standard analyses of the A_i coefficients, the issue is addressed by generating templates for the polynomials in c_θ, s_θ, c_ϕ, s_ϕ appearing in Eq. (1) [14,15]. A similar strategy generalized to include the third-order polynomials in Eq. (18) must be pursued to obtain the B_i in the presence of lepton cuts.

5. Conclusions

In this note we have studied the effects of dimension-8 operators in the SMEFT on Drell-Yan lepton-pair production at the LHC. We have tabulated all operators that can contribute to this process at both LO and NLO in the QCD coupling constant. A new angular dependence appears associated with a class of two-derivative dimension-8 operators that is not accounted for in current studies. Due to its angular-momentum structure it does not appear in the SM nor in the dimension-6 truncation of the SMEFT to any order in the QCD perturbative expansion. It can only be generated at higher orders by diagrammatic contributions that connect the initial-state partons with the final-state leptons, such as electroweak corrections. We have shown here that these effects are small in the SM. To capture these new dimension-8 SMEFT effects we have proposed an extension of the usual angular basis used when analyzing lepton pair production. We have demonstrated that for allowed values of the dimension-8 Wilson coefficients that these effects would be visible at the LHC over statistical errors. We urge the experimental collaborations to revisit this analysis in order to search for this clean and new signature of dimension-8 new physics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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