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Tables of Divergent Feynman Integrals. II. Light-Cone Gauge with the Mandelstam–Leibbrandt Prescription

M. S. MILGRAM* AND H. C. LEE†

Reactor Physics Branch and Theoretical Physics Branch†, Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0*

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A comprehensive set of two-point integrals for Yang–Mills theories in the light-cone gauge defined in the Mandelstam–Leibbrandt prescription is evaluated and presented in tabulated form. © 1987 Academic Press, Inc

In a previous paper [1] a large set of two-point Feynman integrals encountered in one-loop computations of Yang–Mills theories in the covariant and axial gauges was evaluated using the method of analytic regularization [2] and presented in tabulated form. By two-point integrals we mean integrals with one external momentum that are most naturally associated with the vacuum polarization of two-point functions. Although a general description of the vacuum polarization of an n-point function calls for the evaluation of n-point integrals, it has been shown that, by judicious exploitation of symmetry, a knowledge of the relevant two-point integrals alone is sufficient to determine the one-loop counter Lagrangian which involves two-, three-, and four-point functions [3].

Among the integrals given in Ref. [1] are those appropriate for the light-cone gauge [4] defined by the principal-value (PV) prescription [5]. The light-cone gauge is the special axial gauge [6] defined by a null vector n_+,

$$\mathbf{A}\cdot n_+ \equiv A^+ = 0, \qquad n_+^2 = 0, \tag{1}$$

and the PV prescription in this case defines the inverse of the quantity $p^+ = p\cdot n_+$ as

$$\frac{1}{p^+} = \lim_{\eta\to 0^+} \frac{p^+}{(p^+)^2+\eta}. \tag{2}$$

Recently it has been shown unequivocally that the light-cone gauge prescribed by (2) is nonrenormalizable [7]. On the other hand, it has been demonstrated that the light-cone gauge is one-loop renormalizable [3] if p^+ is defined by the

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Mandelstam–Leibbrandt (ML) prescription [8] ($p^- \equiv p \cdot n_-$, where n_- is the null vector conjugate to n_+)

$$\frac{1}{p^+} = \lim_{\eta \to 0^+} \frac{1}{p^+ + i\eta p^-} \qquad \text{or} \qquad \lim_{\eta \to 0^+} \frac{p^-}{p^+ p^- + i\eta}. \tag{3}$$

In this paper we give the values of a comprehensive set of two-point light-cone gauge integrals based on (3). These integrals have become especially relevant following the recent realization [9] that superstring theories can be easily quantized only in the light-cone gauge.

As in [1], the integrals are evaluated via an analytic representation for the generalized two-point integrals

$$\begin{aligned} M(\omega, \kappa, \mu, \nu, \lambda; p) &\equiv \int d^{2\omega}q[(p-q)^2]^\kappa (q^2)^\mu (q^+)^\nu (q^-)^\lambda \\ &= \frac{i(-\pi)^\omega (p^2)^{\alpha_1 - \nu} (p^+)^\nu (p^-)^\lambda \, \Gamma(\lambda+1)}{\Gamma(-\kappa)\,\Gamma(-\mu)\,\Gamma(-\nu)\,\Gamma(2\omega+\kappa+\mu+\nu+\lambda)} \\ &\quad \times u^{-\nu} G^{2,3}_{3,3}\left(u \,\middle|\, \begin{matrix} 1+\nu, 1-\omega-\mu-\lambda, 1+\alpha_1; \\ 0, \omega+\kappa+\nu; \nu-\lambda \end{matrix}\right). \end{aligned} \tag{4}$$

$$\alpha_1 = \omega + \kappa + \mu + \nu, \qquad u = 2p^- p^- / p^2,$$

where κ, μ, ν, and λ are continuous exponents, 2ω is the continuous dimension of spacetime [10], and G is a Meijer G-function [11]. The derivation of (4) and its various simplifying special cases are given in detail elsewhere [3]. When ν is a non-negative integer and $\lambda = 0$, (4) reduces to a representation identical to that for the PV prescription. When $\nu < 0$ the two prescriptions give different results. In particular, the ML prescription obeys the rule of power counting whereas the PV prescription does not.

The integral (4) is ultraviolet (UV) divergent when the UV index α_1 satisfies

$$\alpha_1 = \omega + \kappa + \mu + \nu = \text{integer} \geqslant 0 \tag{5}$$

and is infrared (IR) divergent when either one or both of the conditions

$$\begin{aligned} \omega + \mu + \lambda &= \text{integer} \leqslant 0 \\ \omega + \kappa + \nu &= \text{integer} \leqslant 0 \end{aligned} \tag{6}$$

is or are met. The limiting process

$$\begin{gathered} \nu, \lambda = (N, L) \text{ integers}, \qquad \kappa, \mu = (K, M) \text{ integers} + \sigma, \\ \omega = 2 + \varepsilon, \qquad \sigma \to 0, \qquad \varepsilon \to \text{small} \end{gathered} \tag{7}$$

separates the UV and IR poles in (4) and preserves gauge invariance [12]. In the tabulated results, UV poles are of $O(1/\hat{e}_1)$ and IR poles of $O(1/\hat{e}_0)$, where in the limit (7) $\hat{e}_0$ and $\hat{e}_1$ have identical values, viz.,

$$\frac{1}{\hat{e}_n}=\frac{1}{\varepsilon+2\sigma-n\sigma}+\gamma+lnp^2\to\frac{1}{\varepsilon}+\gamma+lnp^2, \qquad n=0,1 \tag{8}$$

Because in studies of quantum field theories the UV divergent part of vertex functions are usually of particular interest, the integrals to be tabulated will be classified according to the UV index, taking on all values within the range

$$-2\leqslant\alpha_1\leqslant 2. \tag{9}$$

With this classification, integrals have been evaluated for the following ranges of the (integer) exponents.

$$\begin{gathered}-2\leqslant K\leqslant -1\\ -2\leqslant M\leqslant 2\\ -2\leqslant N\leqslant 2\\ 0\leqslant L\leqslant 2.\end{gathered} \tag{10}$$

We remark that in the light-cone gauge integrals with $\lambda<0$ never occur. Note also that integrals with $\lambda=0$ and $\nu>0$ are already given in Ref. [1], but for completeness they will be given again here. So called "tadpole" integrals satisfying either or both of the following conditions

$$\begin{gathered}\kappa\geqslant 0;\\ \mu\geqslant 0 \quad \text{and} \quad \nu\geqslant 0\end{gathered} \tag{11}$$

vanish in the limit (7).

The integrals in Tables I and II for values of α_1 running between -2 and 2, are

TABLE I(A)

$[K, M, N, L]=f\int d^4q((p-q)^2)^K(q^2)^M(q^+)^N(q^-)^L \qquad K=-2,\ \alpha_1=-2$

$[-2, 0, -2, 0]=-1+\log u+1/\hat{e}_0$
$[-2, -1, -1, 0]=\log u+1/\hat{e}_0$
$[-2, -2, 0, 0]=-2+2/\hat{e}_0$
$[-2, 0, -2, 1]=-2+\log u+1/\hat{e}_0$
$[-2, -1, -1, 1]=-1+\log u+1/\hat{e}_0+S_2$
$[-2, -2, 0, 1]=-1+1/\hat{e}_0$
$[-2, 0, -2, 2]=-5/2+\log u+1/\hat{e}_0$
$[-2, -1, -1, 2]=-3/2+\log u+1/\hat{e}_0+2*S_3$
$[-2, -2, 0, 2]=-2+1/\hat{e}_0$

TABLE I(B)

$$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -2,\ \alpha_1 = -1$$

$[-2, 1, -2, 0] = -1 + \log u + u + 1/\hat{e}_0$	$[-2, -1, 0, 1] = -1 + 1/\hat{e}_0$
$[-2, 0, -1, 0] = \log u + 1/\hat{e}_0$	$[-2, -2, 1, 1] = -2 + 1/u + 1/\hat{e}_0$
$[-2, -1, 0, 0] = 1/\hat{e}_0$	$[-2, 1, -2, 2] = -5/2 + \log u + u + 1/\hat{e}_0$
$[-2, -2, 1, 0] = -1 + 1/\hat{e}_0$	$[-2, 0, -1, 2] = -3/2 + \log u + 1/\hat{e}_0$
$[-2, 1, -2, 1] = -2 + \log u + u + 1/\hat{e}_0$	$[-2, -1, 0, 2] = -3/2 + 1/\hat{e}_0$
$[-2, 0, -1, 1] = -1 + \log u + 1/\hat{e}_0$	$[-2, -2, 1, 2] = -5/2 + 1/u + 1/\hat{e}_0$

TABLE I(C)

$$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -2,\ \alpha_1 = 0$$

$$[-2, 2, -2, 0] = -1 + \log u - 3u^2 * \log u + 4u - 7u^2/2 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-3u^2)$$
$$[-2, 1, -1, 0] = \log u - 2u * \log u + 1/\hat{e}_0 + 1/e_1^*(-2u)$$
$$[-2, 0, 0, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 1, 0] = -1 + 1/\hat{e}_0$$
$$[-2, -2, 2, 0] = -2 + 1/\hat{e}_0$$
$$[-2, 2, -2, 1] = -2 + \log u - 2u^2 * \log u + 3u - 2u^2/3 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-2u^2)$$
$$[-2, 1, -1, 1] = -1 + \log u - 3u/2 * \log u + 5u/4 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-3u/2)$$
$$[-2, 0, 0, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 1, 1] = -3/2 + 1/u + 1/\hat{e}_0 + 1/\hat{e}_1^*(-1/(2u))$$
$$[-2, -2, 2, 1] = -5/2 + 1/u + 1/\hat{e}_0$$
$$[-2, 2, -2, 2] = -5/2 + \log u - 5u^2/3 * \log u + 8u/3 + 11u^2/36 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-5u^2/3)$$
$$[-2, 1, -1, 2] = -3/2 + \log u - 4u/3 * \log u + 16u/9 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-4u/3)$$
$$[-2, 0, 0, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 1, 2] = -11/6 + 13/(9u) + 1/\hat{e}_0 + 1/\hat{e}_1^*(-2/(3u))$$
$$[-2, -2, 2, 2] = -17/6 + 5/(9u^2) + 4/(3u) + 1/\hat{e}_0 + 1/\hat{e}_1^*(-1/(3u^2))$$

TABLE I(D)

$$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -2,\ \alpha_1 = 1$$

$$[-2, 2, -1, 0] = \log u - 6u * \log u + 6u^2 * \log u + 2u - 2u^2 + 1/\hat{e}_0 + 1/e_1^*(-6u + 6u^2)$$
$$[-2, 1, 0, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, 0, 1, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 2, 0] = -3/2 + 1/\hat{e}_0$$
$$[-2, 2, -1, 1] = -1 + \log u - 4u * \log u + 10u^2/3 * \log u + 4u - 28u^2/9 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-4u + 10u^2/3)$$
$$[-2, 1, 0, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, 0, 1, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 2, 1] = -11/6 + 13/(9u) + 1/\hat{e}_0 + 1/\hat{e}_1^*(-2/(3u))$$
$$[-2, 2, -1, 2] = -3/2 + \log u - 10u/3 * \log u + 5u^2/2 * \log u + 43u/9 - 27u^2/8 + 1/\hat{e}_0 + 1/\hat{e}_1^*(-10u/3 + 5u^2/2)$$
$$[-2, 1, 0, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, 0, 1, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$$
$$[-2, -1, 2, 2] = -25/12 - 4/(9u^2) + 7/(3u) + 1/\hat{e}_0 + 1/\hat{e}_1^*(1/(6u^2) - 1/u)$$

TABLE I(E)

$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -2,\ \alpha_1 = 2$

$[-2, 2, 0, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 2, 0, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 2, 0, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$
$[-2, 1, 1, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 1, 1, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 1, 1, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$
$[-2, 0, 2, 0] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 0, 2, 1] = 1/\hat{e}_0 - 1/\hat{e}_1$	$[-2, 0, 2, 2] = 1/\hat{e}_0 - 1/\hat{e}_1$

TABLE II(A)

$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -1,\ \alpha_1 = -2$

$[-1, -1, -2, 0] = u$
$[-1, -2, -1, 0] = -u^* \log u - u + u/\hat{e}_0$
$[-1, -1, -2, 1] = u/2 - u^*(S_2 - 2^*S_3)$
$[-1, -2, -1, 1] = -S_2$
$[-1, -1, -2, 2] = u/3 - u^*(4^*S_3 - 6^*S_4)$
$[-1, -2, -1, 2] = 2^*S_2 - 4^*S_3$

TABLE II(B)

$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -1,\ \alpha_1 = -1$

$[-1, 0, -2, 0] = u$	$[-1, -2, 0, 1] = 1$
$[-1, -1, -1, 0] = -S_1$	$[-1, 0, -2, 2] = u/3$
$[-1, -2, 0, 0] = 1/\hat{e}_0$	$[-1, -1, -1, 2] = -S_3$
$[-1, 0, -2, 1] = u/2$	$[-1, -2, 0, 2] = 1/2$
$[-1, -1, -1, 1] = -S_2$	

TABLE II(C)

$[K, M, N, L] = f\int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -1,\ \alpha_1 = 0$

$[-1, 1, -2, 0] = -u^{2*} \log u + u - u^2/2 + 1/\hat{e}_1^*(-u^2)$
$[-1, 0, -1, 0] = -u^* \log u + u + 1/\hat{e}_1^*(-u)$
$[-1, -1, 0, 0] = 2 - 1/\hat{e}_1$
$[-1, -2, 1, 0] = 1$
$[-1, 1, -2, 1] = -u^2/2^* \log u + u/2 + u^2/12 + 1/\hat{e}_1^*(-u^2/2)$
$[-1, 0, -1, 1] = -u/2^* \log u + 3u/4 + 1/\hat{e}_1^*(-u/2)$
$[-1, -1, 0, 1] = 1 - 1/2/\hat{e}_1$
$[-1, -2, 1, 1] = 1/2 + 1/u + 1/\hat{e}_1^*(-1/(2u))$
$[-1, 1, -2, 2] = -u^2/3^* \log u + u/3 + 7u^2/36 + 1/\hat{e}_1^*(-u^2/3)$
$[-1, 0, -1, 2] = -u/3^* \log u + 11u/18 + 1/\hat{e}_1^*(-u/3)$
$[-1, -1, 0, 2] = 13/18 - 1/3/\hat{e}_1$
$[-1, -2, 1, 2] = 1/3 + 5/(9u) + 1/\hat{e}_1^*(-1/(3u))$

TABLE II(D)

$[K, M, N, L] = f \int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -1, \alpha_1 = 1$

$$[-1, 2, -2, 0] = -3u^2 * \log u + 4u^3 * \log u + u - u^2/2 - 2u^3/3 + 1/\hat{e}_1^*(-3u^2 + 4u^3)$$
$$[-1, 1, -1, 0] = -u * \log u + 3u^2/2 * \log u + u - 5u^2/4 + 1/\hat{e}_1^*(-u + 3u^2/2)$$
$$[-1, 0, 0, 0] = 0$$
$$[-1, -1, 1, 0] = 1 - 1/2/\hat{e}_1$$
$$[-1, -2, 2, 0] = 1/2$$
$$[-1, 2, -2, 1] = -4u^2/3 * \log u + 5u^3/3 * \log u + u/2 + 4u^2/9 - 41u^3/36 + 1/\hat{e}_1^*(-4u^2/3 + 5u^3/3)$$
$$[-1, 1, -1, 1] = -u/2 * \log u + 2u^2/3 * \log u + 3u/4 - 8u^2/9 + 1/\hat{e}_1^*(-u/2 + 2u^2/3)$$
$$[-1, 0, 0, 1] = 0$$
$$[-1, -1, 1, 1] = 13/18 - 4/(9u) + 1/\hat{e}_1^*(-1/3 + 1/(6u))$$
$$[-1, -2, 2, 1] = 1/3 + 5/(9u) + 1/\hat{e}_1^*(-1/(3u))$$
$$[-1, 2, -2, 2] = -5u^2/6 * \log u + u^3 * \log u + u/3 + 41u^2/72 - 21u^3/20 + 1/\hat{e}_1^*(-5u^2/6 + u^3)$$
$$[-1, 1, -1, 2] = -u/3 * \log u + 5u^2/12 * \log u + 11u/18 - 101u^2/144 + 1/\hat{e}_1^*(-u/3 + 5u^2/12)$$
$$[-1, 0, 0, 2] = 0$$
$$[-1, -1, 1, 2] = 7/12 - 4/(9u) + 1/\hat{e}_1^*(-1/4 + 1/(6u))$$
$$[-1, -2, 2, 2] = 1/4 - 4/(9u^2) + 5/(9u) + 1/\hat{e}_1^*(1/(6u^2) - 1/(3u))$$

TABLE II(E)

$[K, M, N, L] = f \int d^4q((p-q)^2)^K (q^2)^M (q^+)^N (q^-)^L \qquad K = -1, \alpha_1 = 2$

$$[-1, 2, -1, 0] = -u * \log u + 4u^2 * \log u - 10u^3/3 * \log u + u - 4u^2 + 28u^3/9 - 1/\hat{e}_1^*(u - 4u^2 + 10u^3/3)$$
$$[-1, 1, 0, 0] = 0$$
$$[-1, 0, 1, 0] = 0$$
$$[-1, -1, 2, 0] = 13/18 - 1/3/\hat{e}_1$$
$$[-1, 2, -1, 1] = -u/2 * \log u + 5u^2/3 * \log u - 5u^3/4 * \log u + 3u/4 - 43u^2/18 + 27u^3/16 + 1/\hat{e}_1^*(-u/2 + 5u^2/3 - 5u^3/4)$$
$$[-1, 1, 0, 1] = 0$$
$$[-1, 0, 1, 1] = 0$$
$$[-1, -1, 2, 1] = 7/12 - 4/(9u) + 1/\hat{e}_1^*(-1/4 + 1/(6u))$$
$$[-1, 2, -1, 2] = -u/3 * \log u + u^2 * \log u - 7u^3/10 * \log u + 11u/18 - 7u^2/4 + 233u^3/200 + 1/\hat{e}_1^*(-u/3 + u^2 - 7u^3/10)$$
$$[-1, 1, 0, 2] = 0$$
$$[-1, 0, 1, 2] = 0$$
$$[-1, -1, 2, 2] = 149/300 + 23/(225u^2) - 41/(75u) + 1/\hat{e}_1^*(-1/5 - 1/(30u^2) + 1/(5u))$$

labelled by their individual exponents. The integrals are normalized by the omission of a factor

$$f = i(-\pi)^{\omega} (p^2)^{\alpha_1 - N} (p^+)^N (p^-)^L \tag{12}$$

so that with the exception of the two quantities $1/\hat{e}_0$ and $1/\hat{e}_1$, they are functions of the single variable $u = 2p^+p^-/p^2$. The finite parts sometimes contain an infinite sum defined by

$$S_n = \sum_{l=0}^{\infty} \frac{u^{l+1}}{l+n}\left(\log u - \frac{1}{l+n}\right). \tag{13}$$

The generation of the tables from representation (4) was carried out on CDC computers using the algebraic programming code SCHOONSCHIP [13], and on-line editors.

Finally, we remark that although (4) only applies to integrals with integrands not containing uncontracted Lorentz indices, any integral with indices can be straightforwardly reduced [3] to a linear combination of those without indices. It was shown in [3] that, for tensors of up to rank 4, the reduction is achieved by replacing tensor integrands as follows:

$$\begin{aligned} q_i q_j q_k q_l \rightarrow & \tfrac{1}{3}(x-y^2)\, \hat{p}^4(\delta_{ij}\,\delta_{kl} + 2 \text{ symmetric terms}) \\ & - \tfrac{1}{3}(x-y^2)(x-4y^2)\, \hat{p}^2(p_i p_j\, \delta_{kl} + 5 \text{ terms}) \\ & + (x^2 - 8xy^2 + 8y^4)\, p_i p_j p_k p_l \end{aligned} \tag{14a}$$

$$q_i q_j q_k \rightarrow y(x-y^2)\, \hat{p}^2(\delta_{ij} p_k + 2 \text{ terms}) + y(-3x+4y^2)\, p_i p_j p_k \tag{14b}$$

$$q_i q_j \rightarrow (x-y^2)\, \hat{p}^2\, \delta_{ij} + (-x+2y^2)\, p_i p_j \tag{14c}$$

$$q_i \rightarrow y p_i, \tag{14d}$$

where

$$\hat{p}^2 \equiv (1-u)\, p^2 \tag{15a}$$

$$\hat{p}^2 x \equiv \hat{q}^2 = 2q^+ q^- - q^2 \tag{15b}$$

$$\hat{p}^2 y \equiv \hat{p} \cdot \hat{q} = p^+ q^- + p^- q^+ - \tfrac{1}{2}[p^2 + q^2 - (p-q)^2]. \tag{15c}$$

In conjunction with these relations, the expression (4) actually covers all two-point integrals (up to rank 4) that will ever need to be evaluated in the light-cone gauge. Integrals with integrands containing one-, two-, and three-component tensors have also been computed using (14) and tabulated for the same range of variables cited in (9) and (10). Because of space limitations they are not reproduced here, but are available elsewhere [14]. The computer code used to evaluate the integrals is completely general for any value of the indices κ, μ, ν, $\lambda \geqslant 0$ (and ω if need be), and tensor integrands with up to 4 uncontracted Lorentz indices.

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