

This is a part of SFQED-Loops script collection
developed for calculating loop processes in
Strong-Field Quantum Electrodynamics.
The scripts are available on <https://github.com/ArsenyMironov/SFQED-Loops>

If you use this script in your research, please, consider
citing our papers:

- A. A. Mironov, S. Meuren, and A. M. Fedotov, PRD 102, 053005 (2020),
<https://doi.org/10.1103/PhysRevD.102.053005>

If you have any questions, please, don't hesitate to contact me:
mironov.hep@gmail.com

Copyright (C) 2021 Arseny Mironov, <https://scholar.google.ru/citations?user=GQwNEuwAAAAJ>

This program is free software: you can redistribute it and/or modify
it under the terms of the GNU General Public License as published by
the Free Software Foundation, either version 3 of the License, or
(at your option) any later version.

This program is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
GNU General Public License for more details.

You should have received a copy of the GNU General Public License
along with this program. If not, see <https://www.gnu.org/licenses/>.

`NotebookEvaluate[NotebookOpen[NotebookDirectory[] <> "definitions.nb"]]`

FeynCalc 9.2.0. For help, use the documentation center, check out the wiki or write to the mailing list.

See also the supplied examples. If you use FeynCalc in your research, please cite

- V. Shtabovenko, R. Mertig and F. Orellana,
Comput. Phys. Commun., 207C, 432–444, 2016, arXiv:1601.01167
- R. Mertig, M. Böhm, and A. Denner, Comput. Phys. Commun., 64, 345–359, 1991.

Exact photon propagator in momentum representation

$$D_{\mu\nu}^c(l) = D_0(l^2, \chi l) g_{\mu\nu} + D_1(l^2, \chi l) \epsilon_{\mu}^{(1)}(l) \epsilon_{\nu}^{(1)}(l) + D_2(l^2, \chi l) \epsilon_{\mu}^{(2)}(l) \epsilon_{\nu}^{(2)}(l);$$

l^{μ} – the photon propagator 4 – momentum;

$$\begin{aligned}
\chi_l &= \frac{e}{m^3} \sqrt{-(F_{\mu\nu} l^\nu)^2}; \\
\epsilon_\mu^{(1)}(l) &= \frac{e F_{\mu\nu} l^\nu}{m^3 \chi_l}; \\
\epsilon_\mu^{(2)}(l) &= \frac{e F_{\mu\nu}^* l^\nu}{m^3 \chi_l}; \quad F^{*\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\delta\lambda} F_{\delta\lambda}; \\
\left(\epsilon^{(i)}(l)\right)^2 &= -1; \\
D_0(l^2, \chi_l) &= \frac{-i}{l^2 - l^2 \hat{\Pi}}, \quad D_{1,2}(l^2, \chi_l) = \frac{i \Pi_{1,2}}{(l^2 - l^2 \hat{\Pi})(l^2 - l^2 \hat{\Pi} - \Pi_{1,2})}; \\
l^2 \hat{\Pi} &= l^2 \hat{\Pi}(l^2, \chi_l), \\
\Pi_{1,2} &= \Pi_{1,2}(l^2, \chi_l) - \text{polarization operator eigenfunctions};
\end{aligned}$$

Our goal : exact photon propagator in coordinate representation

$$D_{\mu\nu}^c(x) = \frac{\Lambda^{4-D}}{(2\pi)^D} \int d^D l D_{\mu\nu}^c(l) e^{-ilx};$$

Let's define photon momentum and the coordinate variables

NewMomentum["l"]

NewCoordinate["x"]

$$\begin{aligned}
&\left\{ l^\alpha, l^2, k \cdot l, F l^\alpha, F F l^\alpha, F D l^\alpha, a \cdot l, 0, 0, 0, -a^2 (k \cdot l), 0, 0, -\frac{m^6 \chi l^2}{e^2}, -\frac{m^6 \chi l^2}{e^2}, \frac{m^6 \chi l^2}{e^2}, 0, 0, 0, 0, 0, 0 \right\} \\
&\left\{ x^\alpha, x^2, k \cdot x, a \cdot x, F x^\alpha, F F x^\alpha, F D x^\alpha, k \cdot x, 0, 0, 0, -a^2 (k \cdot x), \right. \\
&\quad \left. 0, 0, -\frac{m^2 \xi^2 (k \cdot x)^2}{e^2}, -\frac{m^2 \xi^2 (k \cdot x)^2}{e^2}, \frac{m^2 \xi^2 (k \cdot x)^2}{e^2}, 0, 0, 0, 0, 0, 0 \right\}
\end{aligned}$$

Eigenvectors and tensor structures

We intentionally leave tensors and vectors uncontracted

```

e1[μ_, ν_] = e Ft[μ, ν] lν[ν] / m^3 / χl
e2[μ_, ν_] = e FDt[μ, ν] lν[ν] / m^3 / χl
T0[μ_, ν_] = MTD[μ, ν]
T1[μ_, ν_] = e1[μ, α] e1[ν, β]
T2[μ_, ν_] = e2[μ, α] e2[ν, β]
Contract[Contract[T1[μ, μ]] /. FieldSubstitutions]
Contract[Contract[T2[μ, μ]] /. FieldSubstitutions]

$$\frac{e l^\nu F(\mu, \nu)}{m^3 \chi l}$$


$$\frac{e l^\nu FD(\mu, \nu)}{m^3 \chi l}$$


$$g^{\mu \nu}$$


$$\frac{e^2 l^\alpha l^\beta F(\alpha, \mu) F(\beta, \nu)}{m^6 \chi l^2}$$


$$\frac{e^2 l^\alpha l^\beta FD(\alpha, \mu) FD(\beta, \nu)}{m^6 \chi l^2}$$

-1
-1

```

We write $D^c_{\mu\nu}$ in the following form

$$\int d^D l \left[\text{Coeff} * \text{Matrix} * \text{Exp} (i \text{ Phase}) \right],$$

where

Coeff – is a general multiplier for all terms,

Matrix – tensor part,

Phase – total phase of the expression,

We assume

$$Dk = Dk (l^2, \chi l)$$

$$\text{Coeff} = \Lambda^4 (4 - D) / (2 \pi)^D$$

$$\text{Matrix} = D0 * T0[\mu, \nu] + D1 * T1[\mu, \nu] + D2 * T2[\mu, \nu]$$

$$\text{Phase} = -\text{Contract}[xv[\alpha] \, lv[\alpha]]$$

$$(2 \pi)^{-D} \Lambda^{4-D}$$

$$\frac{D1 \, e^2 \, l^\alpha \, l^\beta \, F(\alpha, \mu) \, F(\beta, \nu)}{m^6 \, \chi l^2} + \frac{D2 \, e^2 \, l^\alpha \, l^\beta \, FD(\alpha, \mu) \, FD(\beta, \nu)}{m^6 \, \chi l^2} + D0 \, g^{\mu \nu}$$

$$-(l \cdot x)$$

We need to calculate the integrals of two types

$$\int d^D l \, D_0(l^2, \chi l) \, e^{-i l x};$$

and

$$\int d^D l \, l_\alpha \, l_\beta \, D_{1,2}(l^2, \chi l) \, e^{-i l x} = i \frac{\partial}{\partial x^\alpha} i \frac{\partial}{\partial x^\beta} \int d^D l \, D_{1,2}(l^2, \chi l) \, e^{-i l x};$$

Symbol $d_{\alpha,\beta}$ means that we need to differentiate the expression later

Let us now change the variables

$$l_m = l_- = l_0 - l_3;$$

$$l_p = l_+ = \frac{l_0 + l_3}{2};$$

$$l_t = l_{\perp} \text{ -- transverse components of } l \text{ (in } D=4 \text{ } l_{\perp} = (l_1, l_2));$$

$$l_2 = l^2$$

$$l^2 = 2 l_- l_+ - l_{\perp}^2;$$

Proper time

$$s = x_- / 2 l_- = kx / 2 kl;$$

$$l_- = x_- / 2 s;$$

$$l_+ = (l^2 + l_{\perp}^2) / 2 l_- = s (l^2 + l_{\perp}^2) / x_- \text{ -- expressed via } l^2;$$

Hereinafter

$$x_m = x_- = x_0 - x_3;$$

$$x_p = x_+ = \frac{x_0 + x_3}{2};$$

$$x_t = x_{\perp}$$

Change of variables

$$l^{\mu} \rightarrow \{l_-, l_+, l_{\perp}\} = \left\{ \frac{x_-}{2s}, \frac{s}{x_-} (l^2 + l_{\perp}^2), l_{\perp} \right\} \rightarrow \{s, l^2, l_{\perp}\}$$

New integration measure

$$d^D l \dots = \frac{ds}{2|s|} dl^2 d^{D-2} l_{\perp}$$

(*Checking Jacobian*)

$$D[\{x_m/2/s, s(l^2 + l_{\perp}^2)/x_m\}, \{\{s, l^2\}\}]$$

$$\text{Jac} = \text{Abs}[\text{Det}[\%]]$$

$$\begin{pmatrix} -\frac{x_m}{2s^2} & 0 \\ \frac{l^2 + l_{\perp}^2}{x_m} & \frac{s}{x_m} \end{pmatrix}$$

$$\frac{1}{2|s|}$$

Coeff1 = Coeff * Jac

Matrix1 = Matrix /. {lv[α_] → d_α}

Phase1 = Phase;

$$\frac{2^{-D-1} \pi^{-D} \Lambda^{4-D}}{|s|}$$

$$\frac{D1 \, e^2 \, d_\alpha \, d_\beta \, F(\alpha, \mu) \, F(\beta, \nu)}{m^6 \, \chi l^2} + \frac{D2 \, e^2 \, d_\alpha \, d_\beta \, FD(\alpha, \mu) \, FD(\beta, \nu)}{m^6 \, \chi l^2} + D0 \, g^{\mu \nu}$$

Integration over

$$\int d^{D-2} l_\perp \dots$$

$$\begin{aligned} I_\emptyset &= \int d^{D-2} l_\perp \text{Exp} \left[-I \, A \, l_\perp^2 + I \, (\mathbf{J} \cdot \mathbf{l}_\perp) \right] = \\ &= \text{Exp} \left[-I \, \frac{\pi}{2} \, \frac{D-2}{2} \right] \pi^{\frac{D-2}{2}} (\det A)^{-\frac{1}{2}} \text{Exp} \left[I \, \frac{1}{4} \, \mathbf{J} \cdot \mathbf{A}^{-1} \cdot \mathbf{J} \right] \end{aligned}$$

where

$$A = s,$$

$$\mathbf{J} = \mathbf{x}_\perp,$$

$$\det A = s^{D-2},$$

$$A^{-1} = 1 / s$$

In effect,

integration results into multiplication of Coeff by I_\emptyset and changing Phase

Coeff2 = Coeff1;

Matrix2 = Matrix1;

Phase2 =

$$\text{Expand} \left[\text{Phase1} /. \{ \text{Pair}[\text{Momentum}[\mathbf{x}, D], \text{Momentum}[\mathbf{l}, D]] \rightarrow \mathbf{x}_m \mathbf{l}_p + \mathbf{x}_p \mathbf{l}_m - \mathbf{x}_t \mathbf{l}_t \} /. \right. \\ \left. \{ \mathbf{l}_m \rightarrow \mathbf{x}_m / 2 / s, \mathbf{l}_p \rightarrow s (\mathbf{l}_v 2 + \mathbf{l}_t^2 2) / \mathbf{x}_m \} /. \{ \mathbf{x}_p \rightarrow (\mathbf{x}_v 2 + \mathbf{x}_t^2 2) / 2 / \mathbf{x}_m \} \right]$$

$$-l^2 s + l t^2 (-s) + l t x t - \frac{x^2}{4 s} - \frac{x t^2}{4 s}$$

Amatr = -Coefficient[Phase2, lt^2]

J = Coefficient[Phase2, lt]

CI0 = Exp[-I Pi / 2 (D / 2 - 1)] Pi ^ (D / 2 - 1) / Amatr ^ (D / 2 - 1)

s

xt

$$e^{-\frac{1}{2} i \pi \left(\frac{D-1}{2} \right)} \pi^{\frac{D-1}{2}} s^{1-\frac{D}{2}}$$

Coeff3 = Coeff2 * CI0

Matrix3 = Matrix2;

Phase3 = Expand[((Phase2 /. {lt -> 0}) + 1 / 4 J^2 / Amatr)]

$$\frac{2^{-D-1} e^{-\frac{1}{2} i \pi \left(\frac{D}{2}-1\right)} \pi^{-\frac{D}{2}-1} \Lambda^{4-D} s^{1-\frac{D}{2}}}{|s|}$$

$$\ell^2(-s) - \frac{x^2}{4s}$$

The integrals

$$\int_{-\infty}^{\infty} \frac{ds}{2|s|} e^{-i \frac{x^2}{4s}} \int_{-\infty}^{\infty} dl^2 D_k(l^2, \chi_l) e^{-i l^2 s}$$

will remain

Let us introduce

$$J_k = J_k(s) =$$

$$-i \int_{-\infty}^{\infty} dl^2 D_k(l^2, \chi_l) e^{-i l^2 s} \text{ - note that this integral is dimensionless}$$

It can be shown that $J_k(s \leq 0) = 0$

Coeff4 = Simplify[Coeff3 * I, Assumptions -> {s > 0}]

Matrix4 = Matrix3 /. {D0 -> J0, D1 -> J1, D2 -> J2}

Phase4 = Phase3 /. {lv2 -> 0}

$$-2^{-D-1} e^{-\frac{1}{4} i \pi D} \pi^{-\frac{D}{2}-1} \Lambda^{4-D} s^{-D/2}$$

$$\frac{e^2 J_1 d_\alpha d_\beta F(\alpha, \mu) F(\beta, \nu)}{m^6 \chi l^2} + \frac{e^2 J_2 d_\alpha d_\beta FD(\alpha, \mu) FD(\beta, \nu)}{m^6 \chi l^2} + J_0 g^{\mu \nu}$$

$$-\frac{x^2}{4s}$$

Calculation of the tensor structure

Let us perform the remaining differentiation

and contract the resulting vectors and tensors

```

Expand[Simplify[
  I FourDivergence[I FourDivergence[Exp[I Phase4], xv[α]], xv[β]] Exp[-I Phase4]]]
Matrix4 /. {dα dβ → %}
Matrix5 = Collect[
  Contract[Contract[%] /. FieldSubstitutions /. FieldSubstitutions], {J0, J1, J2}]
Coeff5 = Coeff4
Phase5 = Phase4

$$\frac{x^\alpha x^\beta}{4 s^2} + \frac{i g^{\alpha\beta}}{2 s}$$


$$\frac{e^2 J1 F(\alpha, \mu) F(\beta, \nu) \left( \frac{x^\alpha x^\beta}{4 s^2} + \frac{i g^{\alpha\beta}}{2 s} \right)}{m^6 \chi l^2} + \frac{e^2 J2 FD(\alpha, \mu) FD(\beta, \nu) \left( \frac{x^\alpha x^\beta}{4 s^2} + \frac{i g^{\alpha\beta}}{2 s} \right)}{m^6 \chi l^2} + J0 g^{\mu\nu}$$


$$J2 \left( \frac{e^2 FDx^\mu FDx^\nu}{4 m^6 s^2 \chi l^2} - \frac{i e^2 FF(\mu, \nu)}{2 m^6 s \chi l^2} \right) + J1 \left( \frac{e^2 Fx^\mu Fx^\nu}{4 m^6 s^2 \chi l^2} - \frac{i e^2 FF(\mu, \nu)}{2 m^6 s \chi l^2} \right) + J0 g^{\mu\nu}$$


$$-2^{-D-1} e^{-\frac{1}{4} i \pi D} \pi^{-\frac{D}{2}-1} \Lambda^{4-D} s^{-D/2}$$


$$-\frac{x^2}{4 s}$$


```

Change to dimensionless proper time

```

Coeff6 = Simplify[Coeff5 / m^2 /. {s → t / m^2}, Assumptions → {m > 0}]
Matrix6 = Matrix5 /. {χ l → ξ k l / m^2} /. {k l → k x / 2 / s} /. {k x → φ} /.
  {FFt[μ, ν] → -av2 kv[μ] kv[ν]} /. {av2 → -m^2 ξ^2 / e^2} /. {s → t / m^2}
Phase6 = Phase5 /. {s → t / m^2}

$$-2^{-D-1} e^{-\frac{1}{4} i \pi D} \pi^{-\frac{D}{2}-1} \Lambda^{4-D} m^{D-2} t^{-D/2}$$


$$J2 \left( \frac{e^2 FDx^\mu FDx^\nu}{m^2 \xi^2 \phi^2} - \frac{2 i t k^\mu k^\nu}{m^2 \phi^2} \right) + J1 \left( \frac{e^2 Fx^\mu Fx^\nu}{m^2 \xi^2 \phi^2} - \frac{2 i t k^\mu k^\nu}{m^2 \phi^2} \right) + J0 g^{\mu\nu}$$


$$-\frac{m^2 x^2}{4 t}$$


```

Final result

$$\begin{aligned}
D^c_{\mu\nu}(x) &= \frac{\Lambda^{4-D}}{(2\pi)^D} \int d^D l D^c_{\mu\nu}(l) e^{-ilx} = \\
&= \text{Exp} \left[-i \frac{\pi}{2} \left(\frac{D}{2} - 2 \right) \right] \frac{\Lambda^{4-D}}{2^{D+1} \pi^{D/2+1}} \\
&\quad \int_0^\infty \frac{ds}{s^{D/2}} e^{-i \frac{x^2}{4s}} \left\{ g_{\mu\nu} J_0(s) - i \frac{1}{2s m^6 \chi_1^2} \left(e^2 (F^2)_{\mu\nu} + i \frac{1}{2s} e^2 Fx_\mu Fx_\nu \right) J_1(s) \right. \\
&\quad \left. - i \frac{1}{2s m^6 \chi_1^2} \left(e^2 (F^2)_{\mu\nu} + i \frac{1}{2s} e^2 FDx_\mu FDx_\nu \right) J_2(s) \right\} = \\
&= \text{Exp} \left[-i \frac{\pi}{2} \left(\frac{D}{2} - 2 \right) \right] \frac{1}{2^{D+1} \pi^{D/2+1}} \frac{\Lambda^{4-D}}{m^{2-D}} \\
&\quad \int_0^\infty \frac{dt}{t^{D/2}} e^{-i \frac{m^2 x^2}{4t}} \left\{ g_{\mu\nu} J_0(m^{-2}t) + \left(-2i t \frac{k_\mu k_\nu}{m^2 \phi^2} + \frac{e^2 Fx_\mu Fx_\nu}{m^2 \xi^2 \phi^2} \right) J_1(m^{-2}t) \right. \\
&\quad \left. + \left(-2i t \frac{k_\mu k_\nu}{m^2 \phi^2} + \frac{e^2 FDx_\mu FDx_\nu}{m^2 \xi^2 \phi^2} \right) J_2(m^{-2}t) \right\}; \\
J_k(s, \chi_1) &= -i \int_{-\infty}^\infty dl^2 D_k(l^2, \chi_1) e^{-il^2 s}; \\
\phi &= kx; \\
\chi_1 &= \xi k l / m^2 = \xi \phi / 2 m^2 s = \xi \phi / 2 t; \\
\xi^2 &= -e^2 a^2 / m^2; \\
Fx_\mu &= F_{\mu\nu} x^\nu; \\
FDx_\mu &= F^*_{\mu\nu} x^\nu;
\end{aligned}$$