

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>
- A. A. Mironov, A. M. Fedotov, arXiv:2109.00634 (2021)

If you have any questions, please, don't hesitate to contact:  
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```
Get["FeynCalc`"]
```

```
$PrePrint = TraditionalForm
```

```
FeynCalc is already loaded! To reload it, please restart the kernel.
```

```
$Aborted
```

```
TraditionalForm
```

```

kv[α_] = Pair[LorentzIndex[α, D], Momentum[k, D]];
av[α_] = Pair[LorentzIndex[α, D], Momentum[a, D]];
av2 = Contract[av[α] av[α]];
Ft[α_, β_] =
  TensorFunction[{F, "A"}, LorentzIndex[α, D], LorentzIndex[β, D], Dimension → D];
FFt[α_, β_] = TensorFunction[{FF, "S"}, LorentzIndex[α, D],
  LorentzIndex[β, D], Dimension → D];
FDt[α_, β_] = TensorFunction[{FD, "A"}, LorentzIndex[α, D],
  LorentzIndex[β, D], Dimension → D];
ScalarProduct[k, a] = 0;
ScalarProduct[k, k] = 0;
FieldSubstitutions = {Ft[α_, β_] Ft[β_, γ_] Ft[γ_, δ_] → 0,
  Ft[α_, β_] Ft[β_, ε_] Ft[δ_, ε_] → 0, Ft[α_, β_] Ft[α_, γ_] Ft[γ_, δ_] → 0,
  Ft[α_, β_] Ft[α_, ε_] Ft[δ_, ε_] → 0, Ft[α_, β_] Ft[α_, β_] → 0,
  FDt[α_, β_] FDt[β_, γ_] FDt[γ_, δ_] → 0, FDt[α_, β_] FDt[β_, ε_] FDt[δ_, ε_] → 0,
  FDt[α_, β_] FDt[α_, γ_] FDt[γ_, δ_] → 0,
  FDt[α_, β_] FDt[α_, ε_] FDt[δ_, ε_] → 0, FDt[α_, β_] FDt[α_, β_] → 0,
  FDt[α_, β_] FDt[β_, γ_] → Ft[α, β] Ft[β, γ],
  FDt[α_, β_] FDt[α_, γ_] → Ft[α, β] Ft[α, γ],
  Ft[α_, β_] Ft[β_, γ_] → FFt[α, γ],
  Ft[α_, β_] Ft[α_, γ_] → -FFt[β, γ],
  Ft[α_, γ_] Ft[β_, γ_] → -FFt[α, β],
  Ft[α_, β_] FDt[β_, γ_] → 0,
  Ft[α_, β_] FDt[α_, γ_] → 0,
  FDt[α_, β_] Ft[β_, γ_] → 0,
  FDt[α_, β_] Ft[α_, γ_] → 0,
  Contract[FFt[μ_, ν_] FFt[μ_, ν_] → 0,
  Contract[FFt[α_, ν_] FFt[β_, ν_] → 0,
  Contract[Ft[μ_, ν] kv[ν]] → 0,
  Contract[FDt[μ_, ν] kv[ν]] → 0,
  Contract[FFt[μ_, ν] kv[ν]] → 0,
  Contract[FFt[μ_, ν] av[ν]] → 0,
  Contract[Ft[μ_, ν] av[ν]] → av2 kv[μ],
  Contract[FFt[μ, ν] kv[μ] kv[ν]] → 0};

FTensor[α_, β_] = (kv[α] av[β] - kv[β] av[α])
FDTensor[μ_, ν_] = Contract[1/2 LC[μ, ν, α, β] FTensor[α, β] /. {D → 4}]

$$d^\beta k^\alpha - d^\alpha k^\beta$$


$$-e^{\mu\nu\bar{a}\bar{k}}$$


NewMomentum[p_] := Module[{},
  Print[Map[ToExpression,
    {p <> "v[α_]=Pair[LorentzIndex[α,D],Momentum[" <> p <> ",D]]",
    p <> "v2=Contract[" <> p <> "v[α]" <> p <> "v[α]]",

```

```

"k" <> p <> " =Contract[kv[α]" <> p <> "v[α]]",
"F" <> p <> "v[α_] = Pair[LorentzIndex[α, D], Momentum[F" <> p <> ", D]]",
"FF" <> p <> "v[α_] = Pair[LorentzIndex[α, D], Momentum[FF" <> p <> ", D]]",
"FD" <> p <> "v[α_] = Pair[LorentzIndex[α, D], Momentum[FD" <> p <> ", D]]",
"a" <> p <> " =Contract[av[α]" <> p <> "v[α]]",
"ScalarProduct[k, F" <> p <> "] = 0",
"ScalarProduct[k, FF" <> p <> "] = 0",
"ScalarProduct[a, FF" <> p <> "] = 0",
"ScalarProduct[a, F" <> p <> "] = -av2 Contract[kv[μ] " <> p <> "v[μ]]",
"ScalarProduct[k, FD" <> p <> "] = 0",
"ScalarProduct[a, FD" <> p <> "] = 0",
"ScalarProduct[F" <> p <> ", F" <> p <> "] = -χ" <> p <> "^2*m^6/e^2",
"ScalarProduct[FD" <> p <> ", FD" <> p <> "] = -χ" <> p <> "^2*m^6/e^2",
"ScalarProduct[" <> p <> ", FF" <> p <> "] = χ" <> p <> "^2*m^6/e^2",
"ScalarProduct[" <> p <> ", FD" <> p <> "] = 0",
"ScalarProduct[" <> p <> ", F" <> p <> "] = 0",
"ScalarProduct[F" <> p <> ", FD" <> p <> "] = 0",
"ScalarProduct[FF" <> p <> ", FF" <> p <> "] = 0",
"ScalarProduct[F" <> p <> ", FF" <> p <> "] = 0",
"ScalarProduct[FD" <> p <> ", FF" <> p <> "] = 0"
]]];
FieldSubstitutions = Join[FieldSubstitutions,
Map[ToExpression,
{"Contract[Ft[μ_, v] " <> p <> "v[v]] -> F" <> p <> "v[μ]",
"Contract[FDt[μ_, v] " <> p <> "v[v]] -> FD" <> p <> "v[μ]",
"Contract[FFt[μ_, v] " <> p <> "v[v]] -> FF" <> p <> "v[μ]",
"Contract[Ft[μ_, v] F" <> p <> "v[v]] -> FF" <> p <> "v[μ]",
"Contract[FDt[μ_, v] FD" <> p <> "v[v]] -> FF" <> p <> "v[μ]",
"FF" <> p <> "v[μ_] FF" <> p <> "v[v_] -> χ" <> p <> "^2*m^6/e^2 FFt[μ, v]",
"Contract[FFt[α, β] " <> p <> "v[α] " <> p <> "v[β]] -> χ" <> p <> "^2*m^6/e^2",
"Contract[FFt[μ_, v] FF" <> p <> "v[v]] -> 0",
"Contract[FFt[μ, v] " <> p <> "v[μ] F" <> p <> "v[v]] -> 0",
"Contract[FFt[μ, v] " <> p <> "v[μ] FF" <> p <> "v[v]] -> 0",
"Contract[FDt[μ_, v] F" <> p <> "v[v]] -> 0",
"Contract[FDt[μ_, v] FF" <> p <> "v[v]] -> 0",
"Contract[FFt[μ, v] " <> p <> "v[μ] kv[v]] -> 0",
"Contract[Ft[μ_, v] FD" <> p <> "v[v]] -> 0",
"Contract[FFt[μ_, v] FD" <> p <> "v[v]] -> 0",
"Contract[FDt[μ_, v] F" <> p <> "v[v]] -> 0",
"Contract[FDt[μ_, v] FF" <> p <> "v[v]] -> 0",
"Contract[Ft[μ_, v] FF" <> p <> "v[v]] -> 0"}]
];
]

```

```

NewCoordinate[x_] := Module[{},
  Print[Map[ToExpression,
    {x <> "v[" <math>\alpha</math> "]" = Pair[LorentzIndex["<math>\alpha</math>"], Momentum["<math>x</math>"], D]]",
    x <> "v2 = Contract["<math>x</math> "v["<math>\alpha</math>"] "v["<math>\alpha</math>"]",
    "k" <> x <> " = Contract[kv["<math>\alpha</math>"] "v["<math>\alpha</math>"]",
    "a" <> x <> " = Contract[av["<math>\alpha</math>"] "v["<math>\alpha</math>"]",
    "F" <> x <> "v[" <math>\alpha</math> "] = Pair[LorentzIndex["<math>\alpha</math>"], Momentum["F" <math>x</math>"], D]]",
    "FF" <> x <> "v[" <math>\alpha</math> "] = Pair[LorentzIndex["<math>\alpha</math>"], Momentum["FF" <math>x</math>"], D]]",
    "FD" <> x <> "v[" <math>\alpha</math> "] = Pair[LorentzIndex["<math>\alpha</math>"], Momentum["FD" <math>x</math>"], D]]",
    "ScalarProduct[k, " <math>x</math> "] = k" <math>x</math> ",
    "ScalarProduct[k, F" <math>x</math> "] = 0",
    "ScalarProduct[k, FF" <math>x</math> "] = 0",
    "ScalarProduct[a, FF" <math>x</math> "] = 0",
    "ScalarProduct[a, F" <math>x</math> "
    x <> "] = -av2 Contract[kv["<math>\mu</math>"] "v["<math>\mu</math>"]",
    "ScalarProduct[k, FD" <math>x</math> "] = 0",
    "ScalarProduct[a, FD" <math>x</math> "] = 0",
    "ScalarProduct[F" <math>x</math> "
    x <> ", F" <math>x</math> "] = - $\xi^2$  k" <math>x</math> " $\wedge^2 m^2 / e^2$ ",
    "ScalarProduct[FD" <math>x</math> ", FD" <math>x</math> "] = - $\xi^2$  k" <math>x</math> " $\wedge^2 m^2 / e^2$ ",
    "ScalarProduct[" <math>x</math> ", FF" <math>x</math> "] =  $\xi^2$  k" <math>x</math> " $\wedge^2 m^2 / e^2$ ",
    "ScalarProduct[" <math>x</math> ", FD" <math>x</math> "] = 0",
    "ScalarProduct[" <math>x</math> ", F" <math>x</math> "] = 0",
    "ScalarProduct[F" <math>x</math> ", FD" <math>x</math> "] = 0",
    "ScalarProduct[FF" <math>x</math> ", FF" <math>x</math> "] = 0",
    "ScalarProduct[F" <math>x</math> ", FF" <math>x</math> "] = 0",
    "ScalarProduct[FD" <math>x</math> ", FF" <math>x</math> "] = 0"
  ]];
FieldSubstitutions = Join[FieldSubstitutions,
  Map[ToExpression,
    {"Contract[Ft["<math>\mu</math>"], v] " <math>x</math> "v[v]]→F" <math>x</math> "v["<math>\mu</math>"]",
    "Contract[FDt["<math>\mu</math>"], v] " <math>x</math> "v[v]]→FD" <math>x</math> "v["<math>\mu</math>"]",
    "Contract[FFt["<math>\mu</math>"], v] " <math>x</math> "v[v]]→FF" <math>x</math> "v["<math>\mu</math>"]",
    "Contract[Ft["<math>\mu</math>"], v] F" <math>x</math> "v[v]]→FF" <math>x</math> "v["<math>\mu</math>"]",
    "Contract[FDt["<math>\mu</math>"], v] FD" <math>x</math> "v[v]]→FF" <math>x</math> "v["<math>\mu</math>"]",
    "FF" <math>x</math> "v["<math>\mu</math>"] FF" <math>x</math> "v[v]→ $\xi^2$  k" <math>x</math> " $\wedge^2 m^2 / e^2$  FFt["<math>\mu</math>"], v]",
    "Contract[FFt["<math>\alpha</math>"], <math>\beta</math>"] " <math>x</math> "v["<math>\alpha</math>"] " <math>x</math> "v["<math>\beta</math>"]→ $\xi^2$  k" <math>x</math> " $\wedge^2 m^2 / e^2$ ",
    "Contract[FFt["<math>\mu</math>"], v] F" <math>x</math> "v[v]]→0",
    "Contract[FFt["<math>\mu</math>"], v] FF" <math>x</math> "v[v]]→0",
    "Contract[FFt["<math>\mu</math>"], v] " <math>x</math> "v["<math>\mu</math>"] F" <math>x</math> "v[v]]→0",
    "Contract[FFt["<math>\mu</math>"], v] " <math>x</math> "v["<math>\mu</math>"] FF" <math>x</math> "v[v]]→0",
    "Contract[FDt["<math>\mu</math>"], v] F" <math>x</math> "v[v]]→0",
    "Contract[FDt["<math>\mu</math>"], v] FF" <math>x</math> "v[v]]→0",
  ]
];

```

```

"Contract[FFt[μ,ν] " <> x <> "v[μ] kv[ν]]→0",
"Contract[Ft[μ_,ν] FD" <> x <> "v[ν]]→0",
"Contract[FFt[μ_,ν] FD" <> x <> "v[ν]]→0",
"Contract[FDt[μ_,ν] F" <> x <> "v[ν]]→0",
"Contract[FDt[μ_,ν] FF" <> x <> "v[ν]]→0",
"Contract[Ft[μ_,ν] FF" <> x <> "v[ν]]→0"]];
]

(*Preparing symbolic substitutions for thriple γ-
matrix combinations and recollecting F-tensors from vectors a[μ] and k[μ]*)
TripleGamma = {DiracGamma[Momentum[a_, D], D], D} →
DiracGamma[Momentum[b_, D], D].DiracGamma[Momentum[c_, D], D] →
Contract[Pair[LorentzIndex[α1, D], Momentum[a, D]] Pair[LorentzIndex[α2, D],
Momentum[b, D]] Pair[LorentzIndex[α3, D], Momentum[c, D]] (MTD[α1, α2] GAD[α3] +
MTD[α2, α3] GAD[α1] - MTD[α1, α3] GAD[α2] -  $\frac{i}{2}$  LCD[β, α1, α2, α3] GAD[β].GA[5])] }
EpsToF = {Eps[LorentzIndex[α_, D], Momentum[a, D], Momentum[k, D], Momentum[V_, D],
Dimension → D] → -Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]],
Eps[LorentzIndex[α_, D], Momentum[k, D], Momentum[a, D], Momentum[V_, D],
Dimension → D] → Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]],
Eps[LorentzIndex[α_, D], Momentum[V_, D], Momentum[a, D], Momentum[k, D],
Dimension → D] → -Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]],
Eps[LorentzIndex[α_, D], Momentum[V_, D], Momentum[k, D], Momentum[a, D],
Dimension → D] → Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]],
Eps[LorentzIndex[α_, D], Momentum[a, D], Momentum[V_, D], Momentum[k, D],
Dimension → D] → Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]],
Eps[LorentzIndex[α_, D], Momentum[k, D], Momentum[V_, D], Momentum[a, D],
Dimension → D] → -Contract[FDt[α, β] Pair[LorentzIndex[β, D], Momentum[V, D]]]}
akToF = {DiracGamma[Momentum[k, D], D] Pair[Momentum[a, D], Momentum[x, D]] -
DiracGamma[Momentum[a, D], D] Pair[Momentum[k, D], Momentum[x, D]] →
DiracGamma[Momentum[Fx, D], D],
-DiracGamma[Momentum[k, D], D] Pair[Momentum[a, D], Momentum[x, D]] +
DiracGamma[Momentum[a, D], D] Pair[Momentum[k, D], Momentum[x, D]] →
-DiracGamma[Momentum[Fx, D], D],
DiracGamma[Momentum[a, D], D].DiracGamma[Momentum[k, D], D] →  $\frac{i}{2}$  σF,
DiracGamma[Momentum[k, D], D].DiracGamma[Momentum[a, D], D] → - $\frac{i}{2}$  σF}
{(γ.a). (γ.b). (γ.c) → -i γβ.γ5 εβabc + (a.b) γ.c - (a.c) γ.b + γ.a (b.c)}
{εα-akV- → -FD(α, V), εα-kaV- → FD(α, V), εα-V-ak → -FD(α, V),
εα-V-ka → FD(α, V), εα-av-k → FD(α, V), εα-kV-a → -FD(α, V)}
{(a.x) γ.k - γ.a (k.x) → γ.Fx, γ.a (k.x) - (a.x) γ.k → -(γ.Fx), (γ.a).(γ.k) →  $\frac{i}{2}$  σF, (γ.k).(γ.a) → - $\frac{i}{2}$  σF}

```

```

antiTripleGamma =
{DiracGamma[LorentzIndex[β_, D], D].DiracGamma[5] Eps[LorentzIndex[β_, D],
  Momentum[a_, D], Momentum[b_, D], Momentum[c_, D], Dimension → D] →
-i Contract[Pair[LorentzIndex[α1, D], Momentum[a, D]]
  Pair[LorentzIndex[α2, D], Momentum[b, D]]
  Pair[LorentzIndex[α3, D], Momentum[c, D]] (MTD[α1, α2] GAD[α3] +
  MTD[α2, α3] GAD[α1] - MTD[α1, α3] GAD[α2] - DiracGamma[LorentzIndex[α1, D], D] .
  DiracGamma[LorentzIndex[α2, D], D].DiracGamma[LorentzIndex[α3, D], D])}]
{γβ-.γ5 eβ- a- b- c- → -i ((a · b) γ · c - (a · c) γ · b + γ · a (b · c) - (γ · a).(γ · b).(γ · c))}

Ep[z_, p_] := {
  1 - e/2/Pair[Momentum[k, D], Momentum[p, D]]
  Pair[Momentum[k, D], Momentum[z, D]] DiracSlash[k, a, Dimension → D],
  - Pair[Momentum[z, D], Momentum[p, D]] + e Pair[Momentum[a, D], Momentum[p, D]]/2/
  Pair[Momentum[k, D], Momentum[p, D]] (Pair[Momentum[k, D], Momentum[z, D]])^2 +
  e^2 av2/6/Pair[Momentum[k, D], Momentum[p, D]]
  (Pair[Momentum[k, D], Momentum[z, D]])^3
}
EpC[z_, p_] := {
  1 - e/2/Pair[Momentum[k, D], Momentum[p, D]]
  Pair[Momentum[k, D], Momentum[z, D]] DiracSlash[a, k, Dimension → D],
  - (- Pair[Momentum[z, D], Momentum[p, D]] +
  e Pair[Momentum[a, D], Momentum[p, D]]/2/Pair[Momentum[k, D], Momentum[p, D]]
  (Pair[Momentum[k, D], Momentum[z, D]])^2 +
  e^2 av2/6/Pair[Momentum[k, D], Momentum[p, D]]
  (Pair[Momentum[k, D], Momentum[z, D]])^3)
}
DiracElectronPropagatorXRepr[x_, X_, s_] := Module[{s1},
  {DiracSimplify[
    Contract[DotSimplify[(1/2/m/s1 GAD[α] (Pair[Momentum[x, D], LorentzIndex[
      α, D]] - s1 e (kv[α] Pair[Momentum[a, D], Momentum[x, D]] -
      av[α] Pair[Momentum[k, D], Momentum[x, D]] ) +
      s1^2/3 e^2 (-av2 Pair[Momentum[k, D], Momentum[x, D]] kv[α])) + 1) .
      (1 + e s1 DiracSlash[a, k, Dimension → D]) /. {s1 → s/m^2}]]],
    Exp[-I Pi/2 (D/2 - 1)] Δ^((4 - D)/2) Δ^D/Pi^((D/2) * m^((D - 1)/s^((D/2)),
    - s - m^2 Pair[Momentum[x, D], Momentum[x, D]] /4/s -
    s/12 e^2/m^2 Contract[Pair[Momentum[x, D], LorentzIndex[α, D]]
      FTensor[α, β] FTensor[β, γ] Pair[Momentum[x, D], LorentzIndex[γ, D]]] +
    e Pair[Momentum[a, D], Momentum[x, D]] Pair[Momentum[k, D], Momentum[X, D]]
    ] /. {av2 → -m^2 ξ^2/e^2}
  ]
}

```

```

PhotonPropagator0[z_, t_, μ_, ν_] :=
{MTD[μ, ν],
 - Exp[-I Pi/2 (D/2 - 1)] Λ^ (4 - D) / 2^D / Pi^ (D/2) * m^ (D - 2) / t^ (D/2),
 - m^2 Pair[Momentum[z, D], Momentum[z, D]] / 4 / t}

PhotonPropagatorExactXRepr[z_, t_, μ_, ν_] := Module[{TFzFzμν, TFDzFDzμν},
  TFzFzμν = Expand[Contract[
    Ft[μ, α] Pair[Momentum[z, D], LorentzIndex[α, D]] Ft[ν, β] Pair[Momentum[z, D],
      LorentzIndex[β, D]] /. {Ft[α_, β_] → kv[α] av[β] - kv[β] av[α]}
  ]];
  TFDzFDzμν = Expand[Contract[
    - Pair[Momentum[z, D], Momentum[z, D]] FFt[μ, ν] + FFt[μ, α] Pair[Momentum[z, D],
      LorentzIndex[α, D]] Pair[Momentum[z, D], LorentzIndex[ν, D]] +
    FFt[ν, α] Pair[Momentum[z, D], LorentzIndex[α, D]] Pair[Momentum[z, D],
      LorentzIndex[μ, D]] - TFzFzμν - Pair[Momentum[z, D], LorentzIndex[α, D]]
      Pair[Momentum[z, D], LorentzIndex[β, D]] FFt[α, β] MTD[μ, ν] /.
    {Ft[α_, β_] → kv[α] av[β] - kv[β] av[α], FFt[α_, β_] → -av2 kv[α] kv[β]}
    (* /. {av2 → -m^2 ξ^2 / e^2} *)
  ]];
  {MTD[μ, ν] * J0[m^ (-2) t, ξ Pair[Momentum[k, D], Momentum[z, D]] / 2 / t] +
    (- 2 i t kv[μ] kv[ν] / m^2 / Pair[Momentum[z, D], Momentum[k, D]]^2 +
      e^2 TFzFzμν / m^2 / ξ^2 / Pair[Momentum[z, D], Momentum[k, D]]^2)
    J1[m^ (-2) t, ξ Pair[Momentum[k, D], Momentum[z, D]] / 2 / t] +
    (- 2 i t kv[μ] kv[ν] / m^2 / Pair[Momentum[z, D], Momentum[k, D]]^2 +
      e^2 TFDzFDzμν / m^2 / ξ^2 / Pair[Momentum[z, D], Momentum[k, D]]^2)
    J2[m^ (-2) t, ξ Pair[Momentum[k, D], Momentum[z, D]] / 2 / t],
    Exp[-I Pi/2 (D/2 - 2)] Λ^ (4 - D) / 2^D / Pi^ (D/2) * m^ (D - 2) / t^ (D/2) / (2 Pi),
    - m^2 Pair[Momentum[z, D], Momentum[z, D]] / 4 / t}]

```

Uncomment to see examples

```

(*uncomment to see example*)
(*Contract[DiracGamma[LorentzIndex[μ,D],D].GA[5]FDxv[μ] /.
  {FDxv[μ_]→LCD[μ,α1,α2,α3]xv[α1]kv[α2]av[α3]}}
  %/.antiTripleGamma
  %/.TripleGamma*)

(*NewMomentum["p"]
NewCoordinate["x"]
FieldSubstitutions
Expand[Contract[Ft[μ,α]xv[α]Ft[ν,β]xv[β]]/.FieldSubstitutions/.
  {Fxv[α_]→kv[α] ax-av[α] kx}*)

```

```

(*uncomment to see examples*)
(*NewCoordinate["o"]
  NewCoordinate["0"]*)
(*Ep[x,p]
  EpC[y,q]*)
(*DiracElectronPropagatorXRepr[ov,0v,s]
  DiracElectronPropagatorXRepr1[o,0,s]*)
(*PhotonPropagator0[x,t, $\lambda$ , $\delta$ ]*)

(*NewCoordinate["z"]
  PhotonPropagatorExact[z,t, $\mu$ , $\nu$ ]*)

```