# Glossary of Symbols for

# *Student Friendly Quantum Field Theory*

This glossary has been compiled by Bill Daniel and is posted here for the benefit of other readers.

Thank you, Bill!

# Symbol Glossary

Page numbers (second edition, and in all but a few cases the first edition as well) containing the introduction, definition, or extensive use of a symbol are shown in parentheses. Pages with considerable development of the concept are given in **bold**.

## Non-alphanumeric Symbols

$\partial$slash = $\gamma^\mu \partial_\mu$ = slash notation applied to the partial derivative. (88)

$\partial_\mu \phi = \phi_{,\mu} = \frac{\partial}{\partial x^\mu}$ = alternative notations for the covariant form of the partial derivative. (16)

$\partial^\mu \phi = \phi^{,\mu} = \frac{\partial}{\partial x_\mu}$ = alternative notations for the contravariant form of the partial derivative. (16)

$\partial_\mu \partial^\mu = \partial^\mu \partial_\mu = \square^2$ = alternative notations for the d'Alembertian operator. (42, **49**)

{ , } = Poisson bracket. (3, **24**)

[ , ] = commutator. (4)

$[\ ,\ ]_+$ = anticommutator. (66)

## Roman Alphabet Symbols

### A

**A** = electromagnetic 3-potential. (135)

A = a general operator (as on 325), term (as on 463), or normalization factor (as on 502).

Aslash = $\gamma^\mu A_\mu$ = slash notation applied to vector potential. (195)

$A^\mu(\mathbf{x}, t) = (\Phi, \mathbf{A})$ = electromagnetic 4-potential. (138, 183, 402)

$A^{\mu+}$ = total photon particle lowering operator field. (149)

$A^{\mu-}$ = total photon particle raising operator field. (149)

$A(\Lambda, m) = -\frac{3m}{8\pi^2} \ln\left(\frac{\Lambda}{m}\right)$ = infinite term (as $\Lambda \to \infty$) in $\Sigma(p)$. (323, **324**)

$A'(k, \Lambda) = -2 b_n \ln\left(\frac{k}{\Lambda}\right)$ = infinite term (as $\Lambda \to \infty$) in $\Pi^{\mu\nu}(k)$. (324, 383)

$A^e_\mu(\mathbf{x})$ = the static external electromagnetic potential represented by the photon in the Feynman diagram used in the calculation of the $e^-$ magnetic moment. (415, 431a)

$A^\alpha_e(\mathbf{x})$ or $A^\alpha_e(\mathbf{k})$ = The same as $A^e_\mu(\mathbf{x})$ above. This slightly different (contravariant) notation is used for the static external electromagnetic potential of a "point charge" (such as an atomic nucleus) for Rutherford scattering in position or momentum space. (478)

$A^e_{\mathbf{k}''\mu}(\mathbf{x})$ and $A^{\dagger e}_{\mathbf{k}''\mu}(\mathbf{x})$ = factors in the expansion for $A^e_\mu(\mathbf{x})$. (431a)

$a$ = parameter in a "useful relation" for Feynman parametrization. (378)

$a_n$ = parameter in a "useful relation" for Feynman parametrization ($n$ = 0, 1, ...). (378)

$a(\mathbf{k})$ = scalar particle destruction operator. (50)

$a^\dagger(\mathbf{k})$ = scalar particle creation operator. (50)

$a^\mu(x, z, p, p')$ = shorthand symbol used in the derivation of $\Lambda^\mu(p, p')$. (394)

### B

**B** = magnetic 3-vector field. (135)

B = a general operator (as on 325), or term (as on 463).

$B(\Lambda) = L(\Lambda) = -\frac{1}{8\pi^2}\ln(\Lambda)$ = infinite term (as $\Lambda \to \infty$) in $\Sigma(p)$. (323, **324**)
$b$ = parameter in a “useful relation” for Feynman parametrization. (378)
$b$ = scattering impact parameter (perpendicular distance between the velocity vector of the incoming particle beam and a parallel radius from the potential source). (438)
$b(\mathbf{k})$ = scalar antiparticle destruction operator. (50)
$b^\dagger(\mathbf{k})$ = scalar antiparticle creation operator. (50)
$b_n$ = factor accounting for contributions to *e(p)* from other particle/antiparticle pairs beyond the photon $\left(b_1 = \frac{1}{12\pi^2}\right)$. (313-314)

## C

$c$ = parameter in a “useful relation” for Feynman parametrization. (378)
$c_r(\mathbf{k})$ = spinor particle destruction operator. (103)
$c_r{}^\dagger(\mathbf{k})$ = spinor particle creation operator. (103)

## D

$D$ = number of dimensions of space to be integrated over - not necessarily an integer. (374, **385-391**)
$D_F{}^{\mu\nu}(x-y)$ = photon Feynman 4-position space propagator. (150)
$D_F{}^{\mu\nu}(k)$ = photon Feynman 4-momentum space propagator. (150)
$D^{\text{Mod}}_{F\,\mu\nu\,2\text{nd}}(k) = D_{F\,\mu\nu}(k)\left(1 - e_0{}^2\,\Pi_c\right)$ = convergent (“Mod”) part of tree level $D_{F\,\mu\nu}(k)$ through second order terms in the expansion. (308)
$D^{e_0\,\text{Mod}}_{F\,\mu\nu\,2\text{nd}}(k)$ = convergent part of the photon propagator $D_{F\,\mu\nu}(k)$ using the bare charge (“$e_0$”) through second order terms in the expansion. (347)
$D^{\mu\nu\pm}(x-y)$ = commutator form of vector particle/antiparticle field solution. (160)
$D_\nu = \partial_\nu - i\,e\,A_\nu$ = gauge covariant derivative. (297)
$\mathcal{D}\,x(t)$ = differential element of functional integration. (490)
$d_r(\mathbf{k})$ = spinor antiparticle destruction operator. (103)
$d_r{}^\dagger(\mathbf{k})$ = spinor antiparticle creation operator. (103)

## E

$\mathbf{E}$ = electric field 3-vector. (135)
$E_\mathbf{k} = \omega_\mathbf{k}$ = energy or angular frequency of a wave with wave number $\mathbf{k}$. (43)
$e$ = measured electron charge. Prior to page 307 this symbol is used for the “bare charge,” $e_0$.
$e(p)$ = measured charge on the electron as a function of energy $p$. (311-315)
$e_0$ = bare charge on the electron, i.e., the charge that would result from consideration of only the tree-level diagram. (307)
$e^-{}_{\mathbf{p},r}$ = electron with 3-momentum $\mathbf{p}$ and spin state $r$. (217)

## F

$F^{\mu\nu}$, $F_{\mu\nu}$ = electromagnetic field tensor. (138, 288)
$F_i\left(k_\mu{}^2\right)$ = form factors ($i = 1,\ 2$ or $A,\ B$) in the derivation of the second order (in $e$) magnetic moment of the electron. (421)
$F[x(t)] = F[x]$ = a functional of the function $x$ ($x$ is itself a function of independent variable $t$). In our case, usually $F\left[L\left(x,\ \dot{x},\ t\right)\right] = \int_{t_a}^{t_b} L\,dt = S$, where $L$ is the Lagrangian and $S$ is the action. (489)
$|F\rangle = \sum_f S_{f\,i}\,|f\rangle$ = general final state. (196)
$f(\theta)$ = function whose squared norm is the NRQM scattering differential cross section. (439)
$f_b = n_b\,v_b$ = flux of the incident beam in a scattering experiment. (435)
$f_{\alpha,\beta,\gamma,\ldots\zeta}$ = factors in the nested convolution integral expansion of $U(i,\ f;\ T)$. (503)
$|f\rangle$ = final eigenstate whose probability amplitude is $S_{f\,i}$. (196)

## G

$G_n,\ G_a,\ G_b$ = parts of $\Lambda_c^\mu(p,\ p')$. (424)
$g$ = gyromagnetic ratio or “g-factor”. (412)
$g_{\mu\nu}$ = (In this text) Minkowski metric tensor, covariant metric, or metric. (16, 34)
$g^{\mu\nu}$ = inverse of metric tensor, contravariant metric (in this text $g^{\mu\nu} = g_{\mu\nu}$). (16, 34)

## H

$\mathcal{H}$ = Hamiltonian density operator. (18)
$H = \int \mathcal{H}\, d^3 x$ = Hamiltonian operator.
$H^I$ = Hamiltonian in interaction picture. (191)
$H^H$ = Hamiltonian in Heisenberg picture. (28)
$H^S$ = Hamiltonian in Schrödinger picture. (28)
$H_f^s$ = Hamiltonian of field with spin = $s$ and type = $f$, ($f$ = 0 indicates “free”, $f$ = I indicates “interaction”). (49, 190)
$\mathcal{H}_f^s$ = Hamiltonian density of field with spin = $s$ and type = $f$, ($f$ = 0 indicates “free”, $f$ = I indicates “interaction”). (49, 190, **199**)

## I

$I_n^{\mu\nu}$ = subintegrals of $\Pi^{\mu\nu}(k)$; ($n$ = 1, 2 in cutoff regularization; $n$ = 1, 2, 3 in Pauli-Villars regularization). (380)
$|\, i\rangle$ = initial eigenstate in probability amplitude $S_{f\,i}$ calculation. (196)

## J

$J$ = part of $\Lambda_c^\mu(p,\ p')$. (424)
$\mathbf{j}$ = 3-current density. (May be any current.  In QM, often probability current.) (45, 46)
$\mathbf{j}_{\text{charge}}$ = 3-electric current density. (183)
$j^\mu = \begin{pmatrix} \rho \\ \mathbf{j} \end{pmatrix}$ = 4-current density. (45)

## K

$k$ = shorthand for $k^\mu$.   Occasionally and temporarily, for notational convenience, $k = |\mathbf{k}|$. (389)
$k$ = virtual fermion 4-momentum in a Feynman diagram or loop integral; energy level of an interaction. (224)
$\mathbf{k}$ = wave number 3-vector of an incoming fermion. (43)
$\mathbf{k}'$ = wave number 3-vector of an outgoing fermion. (225)
$k_i = \frac{2\pi}{\lambda_i}$ = wave number 3-vector components. (43)
$k_\nu$ = 4-momentum of the external photon in the second order (in $e$) calculation of the magnetic moment of the electron. (420)

## L

$\mathcal{L}$ = Lagrangian density. (31)
$L = L\left(q_i,\ \dot{q}_i,\ t\right) = \int \mathcal{L}\, d^3 x$ = Lagrangian operator. (17)
$\mathcal{L}_f^s$ = Lagrangian density of field with spin = $s$ and type = $f$ ($f$ = 0 indicates “free”, $f$ = I indicates “interaction”). (49, 78)
$L(\Lambda) = B(\Lambda) = -\frac{1}{8\pi^2}\ln(\Lambda)$ = infinite term (as $\Lambda\to\infty$) in $\Lambda^\mu(p,\ p')$. (323, **324**)
$l^\pm$ = lepton or antilepton. (463)

## M

$\mathcal{M} = \sum_{n=1}^{\infty} \mathcal{M}^{(n)}$ = total Feynman amplitude of a specified interaction. (223)
$\mathcal{M}^{(n)}$ = sum of amplitudes from all Feynman diagrams of order $n$ in $e$. (223)
$\mathcal{M}^{(n)\,\mu\,\nu\,\eta\,\cdots}$ = $n^{\text{th}}$ order (in $e$) Feynman amplitude for an interaction involving one or more initial or final photons (the number of

photons being the number of Greek letter superscripts). (323, 461)

$\mathcal{M}_{m\,m}^{(n)}$ = $n^{\text{th}}$ order (in $e$) amplitude associated with the single vertex Feynman diagram used to calculate the magnetic moment of the $e^-$. (416, **421**)

$\mathcal{M}_{T\,i-j}^{(n)}$ = amplitude to $n^{\text{th}}$ order (in $e$) for interaction type, $T$ ($T$ = C for Compton; $T$ = B for Bhabha or Møller); fundamental kind of tree diagram, $i$ ($i$ = 1, 2 for Compton or Bhabha, or $i$ = 3, 4 for Møller); and sub-kind, $j$ ($j$ is not used in the tree level case when $n$ = 2; $j$ = 1, 2, ..., 11, for example, for Bhabha scattering of order $n$ = 4). (259)

$\mathcal{M}_{T\,i\;e_0\,\text{Mod},\,2\,\text{nd}}^{(2)}$ = second order (in $e_0$) convergent ("Mod") part of $\mathcal{M}_{T\,i}^{(2)}$ amplitude using the bare charge ("$e_0$"). (346)

$\mathcal{M}_{T\,i\;\text{Mod},\,2\,\text{nd}}^{(2)}$ = second order (in $e$) convergent amplitude above with $e_0$ replaced by $e(k)$. (351)

$m$ = measured (renormalized) mass. Prior to page 307 this symbol is used for the "bare mass," $m_0$. (307, 312)

$m_e$ = measured mass of the electron.

$m_0$ = bare mass, i.e., lepton mass that would result from consideration of only the tree-level diagram. (307)

## N

$N$ = normal ordering operator. (203)

$N(A^\mu)$ = total photon particle number. (149)

$N_a(\mathbf{k})$ = number operator for scalar particles of 3-momentum $\mathbf{k}$. (54, 55)

$N_b(\mathbf{k})$ = number operator for scalar antiparticles of 3-momentum $\mathbf{k}$. (54, 55)

$N_c$ = normal ordering including (anti-)commutation relations operator. (203)

$N_r(\mathbf{p})$ = number operator for spinor particles of 3-momentum $\mathbf{p}$, spin $r$. (108)

$\overline{N}_r(\mathbf{p})$ = number operator for spinor antiparticles of 3-momentum $\mathbf{p}$, spin $r$. (108)

$N_t$ = number of particles in a scattering target. (435)

$N_f$ = number of final states for a scattered particle. (443)

$d\,N_f$ = number of final states of a scattered particle with 3-momentum, $\mathbf{p}$, such that, $\mathbf{p}_f \le \mathbf{p} \le \mathbf{p}_f + d^3\,\mathbf{p}_f$. (443, **455**)

$N^{\mu\nu}(p,\ k)$ = subterms of $\Pi^{\mu\nu}(k)$. (389, 393)

$N_i^{\mu\nu}$ = subterms of $N^{\mu\nu}$ ($i$ = 1, 2, 3). (390)

$n_a(\mathbf{k})$ = eigenvalue of $N_a(\mathbf{k})$ = number of scalar particles of 3-momentum $\mathbf{k}$. (55)

$n_b(\mathbf{k})$ = eigenvalue of $N_b(\mathbf{k})$ = number of scalar antiparticles of 3-momentum $\mathbf{k}$. (55)

$n_r(\mathbf{p})$ = eigenvalue of $N_r(\mathbf{p})$ = number of spinor particles of 3-momentum $\mathbf{p}$, spin $r$. (108)

$\overline{n}_r(\mathbf{p})$ = eigenvalue of $\overline{N}_r(\mathbf{p})$ = number of spinor antiparticles of 3-momentum $\mathbf{p}$, spin $r$. (108)

$n_b$ = beam particle density in a scattering experiment. (435)

$n_t$ = particle density in a scattering target. (434)

## O

$O$ = a general operator. (25)

$O(x)$ = "big $O$" notation indicating higher order terms in $x$.

$\overline{O}$ = expectation value of operator $O$. (25)

$O^H$ = operator $O$ in the Heisenberg picture. (26)

$O^S$ = operator $O$ in the Schrödinger picture. (26)

$O^I$ = operator $O$ in the Interaction picture. (188, 191-193)

## P

$\mathbf{P}$ = 3-momentum operator. (113)

$P^\mu$ = 4-momentum of a system of particles. (16)

$p$ = shorthand for $p^\mu$. (16, 389); energy level of an interaction. (230)

$p$ = parameter in standard integrals useful in regularization. (375)

$\mathbf{p}$ = 3-momentum of an incoming lepton. (43)

$\mathbf{p}'$ = 3-momentum of an outgoing lepton. (225)

$\mathbf{p}'$ = 3-momentum in a primed coordinate system. (126)
$\not{p}^i$ = components of physical 3-momentum density. (23)
$p_i = -p^i = \int \not{p}_i \, d^3 x$ = covariant components of 3-momentum of a single lepton. (17, **23**)
$p_\mu = \begin{pmatrix} E \\ -\mathbf{p} \end{pmatrix}$ = covariant 4-momentum of single lepton (16, 43)
$p^\mu = \begin{pmatrix} E \\ \mathbf{p} \end{pmatrix}$ = contravariant 4-momentum of single lepton. (16, 43)
$p^0$ = used post page 445 for $E$. For elastic collisions, $p^0 = E = K\,E$, i.e., all energy is kinetic. (445)
$p_E = +\sqrt{E^2 + \mathbf{p}^2}$ = Wick rotated 4-momentum. (376)

## Q

$Q = \int s^0 \, d^3 x$ = charge operator. (64, 111, 175)
$Q_a$ = charge of a particle pair in units of $e_0$ used in the calculation of $b_n$. (314)
$q$ = parameter in standard integrals useful in regularization. (386)
$q = p - k\,z$ = variable used in derivation of $\Pi^{\mu\nu}(k)$ in dimensional regularization. (389)

## R

$r(x, z, p, p')$ = shorthand symbol used in the derivation of $\Lambda^\mu(p, p')$. (394)
$r$ (as a subscript) = spin state for spinors. (89); = polarization state for photons. (146) ($r$ =1, 2)

## S

$\mathbf{S}$ = spin 3-vector. (99)
$S = \int L \, dt$ = action. (18)
$S$ = time ordered infinite spacetime $S_{\text{oper}}$. (201)
$S_F(x - y)$ = Feynman position space spinor propagator. (118-**121**)
$S_F(p)$ = Feynman 4-momentum space spinor propagator. (121, 312)
$S_F^{2\text{nd}}(p)$ = approximation to $S_F(p)$ through second order (in $\alpha$) terms in the expansion (14-4). (343)
$\overset{e_0\,\text{Mod}}{S_F^{2\text{nd}}}(p + k) = S_F(p + k)\left(1 - e_0{}^2\,\Sigma_c\right)$ = convergent part of $S^{2\text{nd}}_F(p + k)$. (346)
$S_{f\,i}$ = transition amplitude for transition from initial eigenstate $|i\rangle$ to final eigenstate $|f\rangle$; element of the S-matrix. (195)
$S_{F\,i}$ = transition amplitude for all final scattered states $|f\rangle$ with the same initial state $|i\rangle$. (443)
$d\,S_{F\,i}$ = differential $S_{F\,i}$ within a solid angle $d\Omega$ (at polar angle $\theta$, for $0 \le \phi \le 2\pi$). (443)
$S_i$ = NRQM spin operator. (94)
$S^{(n)}$ = the $n^{\text{th}}$ term of the Dyson expansion of the $S$ operator. (216)
$S^{(n)}{}_m$ = the $m^{\text{th}}$ sub-term of the $n^{\text{th}}$ term of the Dyson expansion of the $S$ operator. (217)
$S_{\text{mm}}^{(n)}$ = $n^{\text{th}}$ order (in $\alpha$) $S$ operator associated with the single vertex Feynman diagram used to calculate the magnetic moment of the $e^-$. (415)
$S_{\text{oper}}$ = an operator whose expectation value for transition from initial eigenstate $|i\rangle$ to final eigenstate $|f\rangle$ is $S_{f\,i}$; $S_{f\,i} = \langle f \,|\, S_{\text{oper}} \,|\, i \rangle$. (196-197)
$S^\pm$ = anti-commutator form of spinor particle/antiparticle field solution. (119-120)
$s$ = parameter in standard integrals useful in regularization. (375)
$s^\mu = q\,j^\mu$ = charge density operator. (63)

## T

$T$ = time ordering operator. (72)
$T_c$ = time ordering including (anti-)commutation relations operator. (205)
$t^\mu(x, z, p, p')$ = shorthand symbol used in the derivation of $\Lambda^\mu(p, p')$. (394)

## U

$U$ = general unitary operator. (26, **27**)
$U(n)$ = unitary group of dimension $n$. (296)
$U\left(\psi_i,\ \psi_f;\ T\right)$ = the amplitude in the path integral formulation for a transition from state $\psi_i$ to $\psi_f$ after a finite time $T$. Note that as $T \to \infty$, $U \to S_{f\,i}$, the transition amplitude between the same two states in the canonical quantization formulation of QFT. (491)
$u_r(\mathbf{p})$ = spinors ($r$ = 1, 2). (89)
$\overline{u}_r(\mathbf{p})$ = adjoint spinors ($r$ = 1, 2). (91)

## V

$V$ = volume. (45)
$V_t$ = volume of the scattering target. (434)
$V(\mathbf{x})$ = electromagnetic potential field. (406)
$\tilde{V}(\mathbf{k})$ = Fourier transform of $V(\mathbf{x})$. (406)
$V(r)$ = radial (Coulomb) potential. (408)
$v_b$ = scattering beam velocity (target stationary). (435)
$v_{\text{rel}} = v_1 - v_2$ = relative co-linear velocity between two particle beams. (453)
$v_r(\mathbf{p})$ = antispinors ($r$ = 1, 2). (89)
$\overline{v}_r(\mathbf{p})$ = adjoint antispinors ($r$ = 1, 2). (91)

## X

$X^{\eta\rho}(k,\ \Lambda)$ = a portion of the expression for Feynman amplitude with integration limits of $\pm\Lambda$. (308)
$x_\mu = \begin{pmatrix} t \\ -X_i \end{pmatrix}$ = covariant components of 4D position in Minkowski coordinate space. (15)
$x^\mu = \begin{pmatrix} t \\ X_i \end{pmatrix}$ = contravariant components of 4D position in Minkowski coordinate space. (15)
$x$ = shorthand for $x^\mu$. (16)
$x_i$ and $x_f$ = initial and final 1-dimensional positions of a particle in the path integral development. Note that $x_i$ is also denoted $x_0$ and $x_f$ is denoted $x_n$, where $n$ is the number of spatial slices. (502)

## Z

$Z_\gamma^{2\,nd} = 1 - {e_0}^2\,A'$ = shorthand symbol associated with the photon in Feynman amplitude expression through second order (in $\alpha$) terms in the expansion. (344)
$Z_f^{2\,nd} = \frac{1}{1+{e_0}^2\,B} \approx 1 - {e_0}^2\,B$ = shorthand symbol associated with a fermion in Feynman amplitude expression through second order (in $\alpha$) terms in the expansion. (344)
$Z_V^{2\,nd} = 1 + {e_0}^2\,L$ = shorthand symbol associated with a vertex in Feynman amplitude expression through second order (in $\alpha$) terms in the expansion. Because $B = L$, $Z_V^{2\,nd} = \frac{1}{Z_f^{2\,nd}}$. (344)
$Z_\gamma^{nth} = \frac{1}{1+{e_0}^2\,A'_{nth}}$ = shorthand symbol associated with the photon in Feynman amplitude expression through $n^{\text{th}}$ order (in $\alpha$) terms in the expansion. (360)
$Z_f^{nth} = \frac{1}{1+{e_0}^2\,B_{nth}}$ = shorthand symbol associated with a fermion in Feynman amplitude expression through $n^{\text{th}}$ order (in $\alpha$) terms in the expansion. (360)
$Z_V^{nth} = 1 + {e_0}^2\,L_{nth}$ = shorthand symbol associated with a vertex in Feynman amplitude expression through $n^{\text{th}}$ order (in $\alpha$) terms in the expansion. Because $B_{nth} = L_{nth}$, $Z_V^{nth} = \frac{1}{Z_f^{nth}}$. (360)
$z,\ z_n$ = dummy integration variables in Feynman parametrization. (378)

## Greek Alphabet Symbols

### A

$\alpha = \frac{e^2}{4\pi}$ = fine structure "constant"; electromagnetic coupling "constant." Prior to page 307 this symbol is used for the "bare coupling constant," $\alpha_0$. (215, 307, 311); at large distances (low energies) $\alpha \approx \frac{1}{137}$. (317)
$\alpha(p) = \alpha(\mu)$ = running QED coupling "constant" at energy $p$ or $\mu$. (316)
$\alpha(x^\mu)$ = gauge that preserves local invariance of $\mathcal{L}$. (326, 178, 294)
$\alpha_0$ = bare coupling constant; i.e., the coupling constant that would result from consideration of only tree-level diagrams. (307)

### B

$\beta(p,\ b_n)$ = beta function that specifies the energy scale dependence of $\alpha$ and $e$. (317)

### Γ

$\Gamma(n)$ = gamma function ($n$ need not be an integer). Note: $\Gamma(n) = (n-1)!$ if $n$ is an integer. (375)
$\Gamma_s$ = all of the Feynman amplitude $\mathcal{M}$ except for the external fermions - used in spin sum calculations ($s$ = 1, 2 for spin states, or no subscript for their sum). (459)
$\tilde{\Gamma} = \gamma^0\,\Gamma^+\,\gamma^0$ = shorthand symbol used in spin sum calculations. (459)
$\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ = Lorentz factor. (33)
$\gamma\ (\approx 0.5772)$ = Euler-Mascheroni constant. (387)
$\gamma_{\mathbf{k},s}$ = photon with wave vector **k** and spin state $s$. (217)
$\gamma^\mu$ = Dirac matrices. (87)
$\gamma^\mu_{\alpha\beta} = \gamma^\mu$ with spinor indices specified. (223)
$\gamma^\mu_{2\,\mathrm{nd}}$ = vertex modification through second order (in $\alpha$) terms in the expansion (13-13). (344)
$\gamma^\mu_{\substack{e_0\,\mathrm{Mod} \\ 2\,\mathrm{nd}}} = \gamma^\mu + {e_0}^2\,\Lambda^\mu_c$ = convergent part of tree level $\gamma^\mu$ through second order (in $\alpha$) terms in the expansion. (346)

### Δ

$\Delta_F\,(x-y)$ = scalar Feynman 4-position space propagator. (70-**77**)
$\Delta_F\,(k)$ = scalar Feynman 4-momentum space propagator. (78)
$\Delta^\pm$ = commutator form of scalar particle/antiparticle field solution. (74)
$\delta^{(4)}$ = 4D delta function. (218, 239)
$\delta\,m$ = change in mass from bare mass to give measured mass. (312)

### E

$\epsilon$ = variable in "leading log" approximation: $f(\epsilon) = \ln(\Lambda' + \epsilon) \approx \ln(\Lambda')$ for $\epsilon \ll \Lambda'$ (378)
${\epsilon_r}^\mu$ = photon 4-polarization vector. (141)
$\epsilon^\mu_s\,(\propto r\,A^\mu)$ = solution to the charge-free Coulomb field equation. (403)
$\epsilon^{2\,\mathrm{nd}}_\mu$ = photon external line through second order (in $\alpha$) terms in the expansion (13-13). (344)

### Z

$\zeta_\mu$: defined as $\zeta_0 = -1$; $\zeta_{1,2,3} = 1$. (142)

### H

$\eta$ = dimension adjustment parameter in dimensional regularization. (374, **385**)

## Θ

$\theta$ = polar scattering angle. (436)

## Λ

$\Lambda$ = parameter that is taken to be finite in the regularization process and later allowed $\rightarrow\infty$. (306, 319, 323)
$\Lambda$ = parameter in standard integrals useful in regularization. (375)
$\Lambda^{\mu}(p,\ p')$ = vertex loop correction integral. (323, **397**)
$\Lambda_c^{\mu}(p,\ p')$ = convergent part of vertex loop correction integral. (323, **396**)
$\Lambda_i^{\mu}(p,\ p')$ = subterm in the derivation of $\Lambda^{\mu}(p,\ p')$, ($i = 0, 1, 2$). (395)
$\Lambda_{\nu}^{\mu}$ = Lorentz transformation. (168)
$\lambda$ = fictitious virtual photon mass used to avoid infrared divergences. (393)
$\lambda_a$ = number of particle/antiparticle pair types in the calculation of $b_n$. (314)

## M

$\mu^2 = \frac{m^2 c^4}{\hbar^2}$ $\left(= m^2\right.$ in natural units). (42)
$\boldsymbol{\mu} = I\,\boldsymbol{A}$ = magnetic moment due to a current ($I$) loop enclosing and area ($A$). (411)
$\mu_B$ = Bohr magneton. (411)

## Π

$\Pi^{\mu\nu}(k)$ = photon self-energy integral. (323, 379-383, 389-393)
$\Pi_c\left(k^2\right)$ = convergent part of photon self-energy integral. (323, 383)
$\pi_s$ = conjugate momentum density of field $\phi_s$. (4)

## P

$\rho$ = density (may be any density.  In QM, often probability density). (45, 46)
$\rho_{\text{charge}}$ = charge density. (**183**, 422)
$\overline{\rho}_{\nu}$ = vacuum energy density of the zero point energy. (279)

## Σ

$\Sigma(p)$ = fermion self-energy integral. (323)
$\Sigma_c(\text{pslash} - m)$ = convergent part of fermion self-energy integral. (323)
$\boldsymbol{\Sigma}$ = RQM spin operator. (93)
${}_{\text{QFT}}\Sigma_i$ = QFT Dirac spin operator. (114)
$\Sigma_{\mathbf{p}}$ = RQM helicity operator. (100)
$\Sigma_{\text{eig}}^{i}$ = eigenvalue of the $\Sigma_i$ spin operator. (417)
$\sigma$ = scattering cross section; "effective" cross section. (432)
$d\sigma$ = cross section for $dN_f$ states. (444)
$\sigma_i$ = Pauli matrices. (94)
$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^{\mu},\ \gamma^{\nu}]$ = function of the commutator of the $\gamma$ matrices. (414)
$\frac{d\sigma}{d\Omega}(\theta)$ = differential scattering cross section. (436)

## T

$\tau$ = proper time. (32)

## Φ

$\Phi$ = scalar potential. (135)
$\phi(x)$ = plane wave eigensolutions of the Klein-Gordon equation for a scalar particle. (43, **50**)

$\phi_{\mathbf{k}}$ = eigensolution of the Klein-Gordon equation for wave number vector **k**. (44)
$\phi$ = total scalar particle lowering operator field. (**50**, 60)
$\phi^{+}$ = scalar particle destruction operator field. (**50**, 60)
$\phi^{-}$ = scalar antiparticle creation operator field. (**50**, 60)
$\phi^{\dagger}$ = total scalar particle raising operator field. (**50**, 60)
$\phi^{\dagger+}$ = scalar antiparticle destruction operator field. (**50**, 60)
$\phi^{\dagger-}$ = scalar particle creation operator field. (**50**, 60)

## Ψ

$\Psi$ = general wave function; solution of the time dependent Schrödinger equation. (45)
$\psi$ = general state solution to Dirac equation; total spinor particle lowering operator field. (103, **111**)
$\psi^{+}$ = spinor particle destruction operator field. (103, **111**)
$\psi^{-}$ = spinor antiparticle creation operator field. (103, **111**)
$\overline{\psi}$ = general state solution to adjoint Dirac equation; total spinor particle raising operator field. (103, **111**)
$\overline{\psi}^{+}$ = spinor antiparticle destruction operator field. (103, **111**)
$\overline{\psi}^{-}$ = spinor particle creation operator field. (103, **111**)
$|\psi^{(n)}\rangle$ = eigensolutions to the Dirac equation ($n$ = 1, 2, 3, 4). (89)
$\psi_{\text{state}}$ = discrete plane wave general state solution to the Dirac equation. (91)
$\overline{\psi}_{\text{state}}$ = discrete plane wave general state solution to the adjoint Dirac equation. (91)

## Ω

$\omega_{\mathbf{k}}$ ( $= E_k$ in natural units) = angular frequency (or energy in natural units) of a wave with wave number vector **k**. (43)
$d\,\Omega = \sin\theta\ d\,\phi\ d\,\theta$ = solid angle subtended by the detector in a scattering experiment. (436)