

# Index

- Abelian Higgs model, 118  
ADM energy, 241  
AdS space, 395, 427, 428  
AdS–CFT correspondence, 426–428  
Affleck, I., 104, 188  
Affleck–Dine baryogenesis, 273, 277, 284  
 $\alpha'$  expansion, 367, 369, 392, 394, 397, 410  
Altarelli–Parisi equations, 58  
Alvarez-Gaume, L., 291  
anomaly, 76, 77–79  
anomaly, applications, 80  
anomaly, Fujikawa evaluation, 80  
anomaly, two dimensions, 82  
anomaly by point splitting, 80  
anomaly evaluation, Fujikawa, 83  
anomaly matching conditions, 226  
anomaly mediation, 204  
Appelquist, T., 3, 390  
area law, 48  
asymptotic freedom, 6, 10, 35  
Atiyah–Singer index theorem, 95  
ATLAS detector, 29  
auxiliary field, 141  
axion, 102–104  
axion, dark matter, 264  
axion, finite-temperature potential, 266  
axion, qualities, 103  
axion, stars, 266  
axion, string theory, 368
- B* mode polarization, 446  
background field gauge, 41  
background field method, 40  
Bahcall, J. 68  
Banks, T., 222, 262, 426  
Banks–Zaks fixed point, 222  
baryogenesis, 254, 272  
baryogenesis, GUT, 273  
baryogenesis, Sakharov conditions, 272  
baryon asymmetry, 231  
baryon number conservation, 63  
Bekenstein, J., 242  
beta function, 37, 39  
beta function, non-linear sigma model, 357  
beta function, sigma model, 356  
beta function, supersymmetric theories, 312, 467
- Betti number, 374  
Bianchi identity, 121, 237, 373  
Bjorken, J., 4, 57  
black holes, 231, 241  
Boltzmann equation, 268  
bosonic closed string, spectrum, 300  
bosonic open string, spectrum, 299  
bosonic string, 295  
bosonization, 359  
BPS bound, 120  
BPS relations, 214, 216  
Brout, R., 5
- Calabi–Yau spaces, 292, 363, 372, 381  
Calabi–Yau spaces, Standard Model gauge group, 393  
Calabi–Yau manifolds, spectra, 379  
Calabi–Yau manifolds, three-form, 385  
Casimir energy, 349  
central charges, 136  
Chan–Paton factors, 299, 415  
charge quantization, 111  
chargino, 171  
Chern class, 375, 379  
Chern–Simons number, 465  
chiral basis, 451, 452  
chiral superfields, 138  
Christoffel connection, 235  
CKM matrix, 22, 25, 33  
CMS detector, 29  
Coleman, S., 5  
Coleman–Mandula theorem, 135  
collective coordinates, 88, 93, 118, 119, 122  
collective symmetry breaking, 131  
complex structure moduli, 384  
condensate, 89, 127, 279  
conical singularity, 361  
confinement, 16, 44, 45  
conformal field theory, 222, 304, 305  
conformal field theory, commutators, 307  
conformal field theory, stress tensor, 302  
conformal gauge, 295, 301  
continuous symmetries in string theory, 386  
contravariant vector, 233  
cosmic microwave radiation background (CMBR), 252  
cosmological principle, 245

- coupling constant unification, 178  
 covariant derivative, gauge theory, 8  
 covariant vector, 233  
 covariantly constant spinor, 377  
 $CP^N$  model, 84–88  
 critical density, 247, 252  
 curvature tensor, 236  
 custodial symmetry, 127, 436
- Davis, R., 68  
 $D$ -brane, 410, 411  
 $D$ -brane, actions, 413  
 $D$ -brane charges, 326, 412  
 $D$  terms, 148  
 $D$  terms, criteria for vanishing, 185  
 dark energy, 73, 231, 247, 254, 284  
 dark matter, 231, 247, 252, 254  
 de Sitter space, 248  
 decoupling condition, 227  
 decoupling limit, 66  
 Dedekind  $\eta$ -functions, 317  
 deep inelastic scattering, 56  
 determinant, derivative of, 234  
 differential forms, 372, 374  
 dilaton, 344  
 dilaton, as string coupling constant, 344, 419  
 dimension-five operators and proton decay, 179  
 dimension-six operators, 70  
 dimensional regularization, 40  
 dimensional transmutation, 43, 85  
 Dine, M., 188  
 Dirac, P.A.M., 116, 119  
 direct detection of dark matter, 270  
 Dirichlet boundary conditions, 298, 410  
 discrete symmetries, 160, 292  
 discrete symmetries in orbifold models, 365  
 discrete symmetries in string theory, 360, 386, 391  
 Dolbeault operators, 376  
 Douglas, M., 426  
 duality, 290  
 duality, perturbative, 409  
 duality, strong, weak coupling, 409, 417  
 duality, IIA eleven-dimensional supergravity, 418–420  
 dynamical supersymmetry breaking, 182, 198  
 dynamical supersymmetry breaking, (3,2) model, 199  
 dyons, 123  
 Dyson, F., 3
- $e^+e^-$  annihilation, 52, 53  
 effective action, string theory, 314  
 Einstein's equation, 238  
 electric dipole moment, 69, 99  
 electric–magnetic duality, 124, 216  
 electroweak baryogenesis, 445  
 electroweak baryon number violation, 464  
 Englert, F., 5  
 enhanced symmetries, 354
- equilibrium conditions, 251  
 equivalence principle, 232  
 extended technicolor, 129
- Fadeev–Popov ghosts, 5, 18  
 Fayet–Iliopoulos  $D$  term, 152  
 Fermi, E., 3, 63  
 Fermi constant, 27  
 Fermi theory of weak interactions, 63  
 fermion doubling, 50  
 fermions, compactified, 352  
 Feynman, R., 3, 57  
 Feynman rules, Yang–Mills theories, 18  
 fields, hidden-sector, 157  
 fields, visible-sector, 157  
 finite-temperature effective potential, 464  
 finite-temperature field theory, 458, 459, 463  
 fixed points, 361  
 flat directions, 187  
 Friedmann equation, 247  
 FRW metric, 245, 246  
 FRW universe, scalar field equation, 250  
 FRW universe,  $T(t)$ , 251  
 Fujikawa, K., 80, 83  
 fundamental representation, 10, 39
- Gaillard, M., 6  
 gauge-covariant derivative, 139  
 gauge fixing, theories with spontaneous symmetry breaking, 18  
 gauge mediation, 205  
 gaugino condensation, 184  
 gaugino mass, 156, 163  
 Gauss law constraint, 22, 45, 96  
 Gell-Mann, M., 100  
 general coordinate transformations, 233  
 general gauge mediation (GGM), 207  
 geodesic equations, 235  
 Georgi, H., 106, 119  
 ghost fields, 5  
 Glashow, S., 6, 106, 119  
 global symmetries, 160  
 gluino condensation, 196  
 gluon fusion, 30  
 goldstino, 144, 153, 154  
 goldstino decay constant, 154  
 Goldstone's theorem, 454, 455  
 grand unified theories, 106  
 grand unified theories, mass relations, 111  
 grand unified theories, symmetry breaking, 109  
 grand unified theories, Weinberg angle, 108  
 Grassman coordinates, 40, 137  
 gravitational action, 237  
 gravitino, 136, 148  
 gravitino problem, 264  
 graviton, 136, 196, 301  
 Green, M., 291

- Green–Schwarz fermions, 330, 331  
 Green’s function, two-dimensional, 304  
 Greenberg, W., 5  
 Gross, D., 5  
 GSO projection, 325  
 GSO projection, modular invariance, 326  
 Guralnik, G., 5  
 GUT relation, 163  
 Guth, A., 263  
 hadronization, 52  
 Hamiltonian lattice, 49  
 Hawking, black hole puzzle, 242, 290  
 Hawking, S., 242, 290  
 Hawking radiation, 242  
 Hawking temperature, 242  
 heavy quark potential, 39  
 heterotic string, bosonic formulation, 359  
 heterotic string,  $E_8 \times E_8$ , 337  
 heterotic string, interactions, 337  
 heterotic string, modular invariance, 338  
 heterotic string,  $O(16) \times O(16)$ , 338  
 heterotic string,  $O(32)$ , 336  
 heterotic theory, 335  
 heterotic theory on Calabi–Yau manifolds, 387  
 hidden sector, 157  
 hierarchy on naturalness problem, 72, 126  
 Higgs, P., 5  
 Higgs decays, 30  
 Higgs field, 22  
 Higgs mass, fine tuning, 170  
 Higgs mechanism, 14  
 Higgs particle, 5, 29  
 Hodge numbers, 376, 380  
 holomorphy, 147, 196, 426, 467  
 holonomy,  $SU(3)$ , 377, 378  
 Horava, P., 423  
 Horava–Witten theory, 423  
 hybrid inflation, 263  
 hypermultiplet, 212  
 Iliopoulos, J., 6  
 indirect detection of dark matter, 270  
 inflation, 256, 257  
 inflation, chaotic, 262  
 inflation, flatness puzzle, 255  
 inflation, fluctuations, 259, 261  
 inflation, homogeneity puzzle, 255  
 inflation, reheating, 259  
 inflaton, 259, 263  
 instantons, 76, 81, 86–88, 191  
 instantons, fermion zero modes, 93  
 instantons, QCD, 86  
 instantons, scale size integral, 94  
 instantons, singular gauge, 192  
 instantons, spontaneously broken gauge theories, 96  
 instantons, symmetry violation, 95  
 Intriligator–Thomas models, 225  
 ISS model, 201  
 jets, 53  
 Kac–Moody algebra, 338  
 Kahler derivative, 157  
 Kahler metric, 381  
 Kahler manifolds, 378  
 Kaluza, F., 347, 348  
 Kaluza–Klein theory, 347  
 Kibble, T.W.B., 5  
 kink, 117  
 $K\bar{K}$  mixing, 174  
 Klein, O., 347, 348  
 landscape, 7, 74, 285, 293, 437, 439  
 Large Hadron Collider, 29  
 large- $N$  expansion, QCD, 98  
 large- $N$  limit, 85  
 lattice, 34  
 lattice gauge theory, 44, 45  
 Lee, B., 6  
 leptogenesis, 275–277  
 lepton masses, 32  
 lepton number conservation, 63  
 light cone gauge, 295, 297–299  
 light element abundances, 251  
 lightest supersymmetric particle (LSP), 161  
 lightest supersymmetric particle, dark matter, 268  
 magnetic dipole moment, 69  
 magnetic monopole, 111, 116  
 Maiani, L., 6  
 Majorana mass, 67  
 Maldacena, J., 427  
 mass basis, 25  
 mass singularities, 56  
 matrix model, 426  
 matter-dominated era, 248  
 metastable supersymmetry breaking, 198, 200  
 metaverse, *see* landscape  
 metric tensor, 232  
 Mills, R., 4  
 missing energy, 172  
 Möbius group, 312  
 modding out, 366  
 model-independent axion, 368  
 modular invariance, one-loop amplitudes, 316, 317  
 modular transformations, 315  
 moduli, 146, 185, 189, 349  
 moduli, and inflation, 262  
 moduli, in string theory, 347  
 moduli, lifetime, 271  
 moduli, stabilization in string theory, 405  
 moduli problem, 270

- moduli space, 146, 189  
 moduli space, approximate, 198  
 moduli space, quantum, 225  
 monopole problem, 255, 256  
 MSSM, 135, 160, 162  
 MSSM, breaking of  $SU(2) \times U(1)$ , 166  
 MSSM, Higgs mass limits, 168  
 MSSM, parameters, 163  
 mu term, 160, 162, 164, 207  
 multiverse, 7
- $N = 2$  theories, 211  
 $N = 2$  vector multiplet, 212  
 $N = 4$  Yang–Mills as a regulator for  $N = 1$  theories, 467  
 $N = 4$  Yang–Mills theory, 213  
 Nambu, Y., 290  
 Nambu–Goldstone bosons, 12  
 naturalness, 72, 74, 437  
 Ne’eman, Y., 100  
 Neuman boundary conditions, 297, 410  
 neutralino, 171, 208  
 neutrino mass, 67  
 neutrino oscillations, 67  
 neutron electric dipole moment, 70, 99  
 next-to-lightest supersymmetric particle (NLSP), 208  
 NMSSM, 170  
 non-Abelian gauge theories, 4  
 non-linear sigma model, 105, 128  
 non-linear sigma model, world sheet, 344, 355  
 non-perturbative superpotential, 188  
 non-renormalization theorems, 146, 147  
 non-renormalization theorems, string theory, 398–400  
 normal ordering, 324  
 NS five-brane, 421  
 NS sector, 320  
 nucleosynthesis, 251
- $O(10)$ , 112  
 one-loop potential, 155  
 open strings, 297  
 open superstrings, 319  
 operator product expansion, 305  
 O’Raifeartaigh models, 151  
 orbifolds, 360–363  
 orbifolds, discrete symmetries, 365  
 orbifolds, discrete symmetries and flat directions, 365  
 orbifolds, effective actions, 367  
 orbifolds, modular invariance, 366  
 orbifolds,  $N = 1$  supersymmetry, 363  
 orientifolds, 413
- parity, 21  
 partons, 4, 57  
 Pauli–Villars regulator, 78  
 Peccei, R., 102  
 Peccei–Quinn symmetry, 102
- Penzias, A., 252  
 perimeter law, 48  
 pion masses, 456  
 pions as Goldstone bosons, 90  
 Planck experiment, 261, 283  
 Planck mass, 432  
 Planck satellite, 248, 264, 285  
 PMNS matrix, 68  
 PMSSM, 173  
 point splitting, 8  
 Politzer, D., 5, 6  
 Polonyi model, 158  
 Prasad, M. K., 120  
 Prasad–Sommerfield monopole, 120  
 prepotential, 218  
 proton decay, 71, 112  
 proton decay, supersymmetric GUTs, 179  
 pseudo-Goldstone bosons, 13, 130
- QCD at high temperature, infrared divergences, 463  
 QCD instantons, 91  
 QCD theta, 99  
 QCD theta and spontaneous CP violation, 101  
 QCD theta parameter, 71, 81, 89, 91  
 quadratic divergences, cancelations in supersymmetry, 164  
 quantum moduli space, 200, 225  
 quark, 4  
 quark condensate, 89, 127  
 quark distribution functions, 58  
 quark mass matrix, 25  
 quark masses, 34  
 Quinn, H., 102
- $R$ -parity, 161, 180  
 $R$  symmetry, 144, 161, 163, 185  
 radiation-dominated era, 248, 249  
 Ramond sector, 320, 321  
 Randall, L., 263  
 Randall–Sundrum models, 434  
 red giants, 103  
 reduced Planck mass, 149  
 Regge slope, 297  
 Regge trajectories, 310  
 retrofitting, 202  
 Ricci scalar, 237  
 Ricci tensor, 237  
 Riemann tensor, 236  
 right-handed neutrino, 114
- $S$ -matrix, factorization, 313  
 $S$ -matrix, string theory, 311  
 Sakharov, A., 272  
 Salaam, A., 5  
 Scherk, J., 291  
 Schwarz, J., 291  
 Schwarzschild metric, 239, 240, 241

- Schwarzschild radius, 241  
 Schwinger, J., 3  
 seesaw mechanism, 69, 112  
 Seiberg, N., 147, 188, 196, 218, 221, 226, 228  
 Seiberg duality, 228  
 Seiberg–Witten theory, 216–221  
 Shenker, S., 426  
 Shifman, M., 467  
 sigma model, 84, 105  
 SLAC, 4  
 slow-roll approximation, 257  
 small gauge transformations, 97, 122  
 soliton, 117  
 Sommerfield, C., 120  
 spectral index, 261  
 sphaleron, 274, 464, 465  
 spin connection, 243  
 spinor, general relativity, 243  
 spinor representations of orthogonal groups, 113  
 split supersymmetry, 205, 442  
 spontaneous CP violation as a solution of the strong CP problem, 101  
 spontaneous supersymmetry breaking, 151  
 spurion, 206  
 squark, 161  
 Standard Model, 5, 6  
 stop, particle, 168  
 stress tensor, 237  
 stress tensor, perfect fluid form, 246  
 string coupling, 343  
 string theory, Fayet–Iliopoulos terms, 401–404  
 string theory, finiteness, 290  
 string theory, gaugino condensation, 404, 405  
 string theory, unification of couplings, 385, 393  
 strings, background fields, 355, 356  
 strong CP problem, 77, 98  
 strongly coupled heterotic string theory, 423, 424  
 $SU(5)$ , 106  
 superconformal zero modes, 193  
 superfields, 138  
 supergravity, eleven dimensions, 340, 341  
 superpotential, 141  
 superspace, 136  
 superspace covariant derivatives, 138  
 superstring action, 319  
 superstring mode expansion, 320  
 superstrings, space–time fermions, 321  
 superstrings, vertex operators, 332  
 supersymmetric GUTs, 177  
 supersymmetric QCD, 185  
 supersymmetric QCD,  $N_f = N - 1$ , 191  
 supersymmetric QCD,  $N_f < N - 1$ , 190  
 supersymmetry, 135  
 supersymmetry, component Lagrangian, 141  
 supersymmetry, world-sheet, 323  
 supersymmetry algebra, 136  
 supersymmetry breaking, early universe, 281  
 supersymmetry breaking, gauge mediated, 205  
 supersymmetry breaking, soft, 155, 156, 162  
 supersymmetry breaking, soft, constraints, 174  
 supersymmetry breaking, soft, experimental constraints, 171, 173  
 supersymmetry breaking, supergravity, 157  
 supersymmetry breaking, vanishing of the ground state energy, 143  
 supersymmetry currents, 142  
 supersymmetry generators, 138  
 supersymmetry representations, 136  
 supersymmetry zero modes, 193  
 Susskind, L., 290, 426  
*T*-duality, 354  
*T*-duality, open strings and *D*-branes, 415  
 tachyon, 291, 310  
 target space, 355  
 technicolor, 126  
 tension, 410, 412, 413  
 theta parameter, 89  
 theta term, 123  
 theta functions, 327  
 't Hooft, G., 5, 40, 93, 95, 191, 226  
 't Hooft  $\eta$  symbol, 92  
 't Hooft–Polyakov monopole, 120  
 Tomanaga, S., 3  
 top quark, 40  
 top quark, symmetry breaking in MSSM, 170  
 topological charge, 86  
 toroidal compactification, 358  
 toroidal compactification, momentum lattice, 353  
 toroidal compactification, non-supersymmetric, 369  
 Type I– $O(32)$  duality, 422  
 Type II strings, spectra, 325  
 Type IIA supergravity, 341  
 Type IIB self duality, 421  
 Type IIB supergravity, 341  
 $u$  quark mass, 101  
 $U(1)$  problem, 98  
 unification of couplings, 109  
 unitarity triangle, 34  
 Vainshtein, A., 467  
 vector superfields, 139  
 Veltman, M., 5, 40  
 Veneziano, G., 290  
 Veneziano amplitude, 313  
 vertex operators, 309, 310,  
 vielbein, 243, 341  
 Virasoro algebra, 307  
 Virasoro–Shapiro amplitude, 313  
 visible sector, 157  
 vortices, 118

- W* boson, 24, 27, 128, 130  
weak anthropic argument, 285  
Weinberg, S., 5, 102  
Wess–Zumino model, 144  
Weyl basis, 451, 452  
Weyl rescaling, 349  
Wilczek, W., 5  
Wilson, K., 36, 45, 47, 72  
Wilson line, 45, 47  
Wilson line, compactified, 352  
Wilson line, link variables, 47  
Wilson line, plaquette, 47  
Wilson lines on Calabi–Yau manifolds, 389  
Wilson loop, 47  
Wilson, R., 252  
wimp, 270, 272  
wimp miracle, 270, 445  
winding modes, 351  
wino, 205, 442  
Witten, E., 123, 182, 218, 221, 291, 423  
Witten effect, 123  
Witten index, 182, 198  
WMAP experiment, 261  
Wolfenstein parameterization, 33  
world line, 295  
world sheet, 295  
Yang, C. N., 4  
Yang–Mills action, 9  
Yang–Mills theory, 8  
Yoneya, T., 291  
Yukawa, H., 3  
*Z* boson, 24, 27, 128, 130  
Zaks, A., 222  
zeta function, 324, 350