1 Term Project: (Due in class Monday March 31, 2025)

The term project part of the course asks you to choose one of the following list of classic subatomic papers and explain in your own words why it was important and what it was trying to convey. (These may or may not be the same thing.) Provide a concise assessment of the paper, such as you might read in *The Economist*. The goal is digested and well-argued information rather than a general fact-dump on the subject.

You should check through and choose which paper you will study by **Thursday February 13, 2025**. On (or before) that day you should officially submit your choice to the class TA. You may also suggest another paper you would like to do that is not on the attached list, but if so pass it by me for approval first. What I am looking for is papers that are on the foundations of quantum field theory as applied in any area of science (or, if more speculative, were influential in the way the field developed).

You may work in groups if you wish, but if so when specifying which paper you must specify who else is in your group. Groups of more than one person will be expected to have commensurately more information in their report. Every member of the group should write and submit their own report.

When tracking down papers, particularly in particle physics, two useful sites are InSPIRE: (https://inspirehep.net/?ln=en) and the arXiv: (https://arxiv.org/), both of which often point to downloadable version of the papers.

When preparing this essay you are allowed to consult internet sources for conceptual and historical information, provided that you cite this properly in the essay. You are never permitted to plagiarize material from the internet when preparing any marked work, including essays. You may (but need not) provide *in addition to your own composition* an AI generated text if you like, but you should also write your own thoughts and clearly mark which is which. (The main benefit to you comes from the writing of the essay, not from reading what AI thinks is important.) I will ask about your essay in the final exam, which will have an oral component.

Inevitably people ask how long the report should be. The answer is that it is not being marked by the pound so should not be too long. A scientific essay like this should start with a statement of the point; perhaps something like: *In this essay it is argued that X is true and this is important because of Y*. Then the rest of the essay is devoted to explaining these points and so should be just long enough to clearly and concisely make the points you wish to make and no more. (If you absolutely must have a number you might aim for around 5-10 pages of text, not including possible figures and references.)

List of possible papers

1. Noether, E. 1918. "Invariante Variationsprobleme." *Nachrichten von der Gesellschaft der Wissenschaften, Gottingen*, Mathematisch-Physikalische Klasse **2** (1918) 98.[English translation: in *Transport Theory and Statistical Physics* **1** 186. This is available online at [arXiv:physics/0503066].]

2. "Zum Unitätsproblem in der Physik," Theodor Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin. (Math. Phys.) (1921) 966 and "Quantentheorie und fünfdimensionale Relativitätstheorie", Oskar Klein, Zeitschrift für Physik A 37, (1926) 895.

3. Dirac, P.A.M. 1927. "The Quantum Theory of the Emission and Absorption of Radiation." *Proceedings of the Royal Society of London* **A 114** 243.

4. Dirac, P. A. M. 1928. "The Quantum Theory of the Electron." *Proceedings of the Royal Society A*: **117** 610.

5. "Gehorchen die Stickstoffkerne der Boseschen Statistik?" ("Does the Nitrogen nucleus obey Bose statistics?") W. Heitler, G. Herzberg, Naturwiss. 17, 673 (1929).

6. Fermi, E. 1932. "Quantum Theory of Radiation." *Reviews of Modern Physics* **4** 87.

7. "Über den Bau der Atomkerne" ("On the structure of atomic nuclei"), W. Heisenberg, Z. Phys. **77** (1932) 1.

8. "An attempt of a theory of beta radiation. 1.," E. Fermi, Z. Phys. **88** (1934) 161.

9. "On the Interaction of Elementary Particles I," H. Yukawa, Proc. Phys. Math. Soc. Jap. **17** (1935) 48 [Prog. Theor. Phys. Suppl. **1** 1].

10. Bloch, F. and Nordsieck, A. 1937. "Note on the Radiation Field of the Electron." *Physical Review* **52** (1937) 54.

11. "Space-time approach to nonrelativistic quantum mechanics," R. P. Feynman, Rev. Mod. Phys. **20** (1948) 367.

12. Casimir, H.B.G. 1948. "On the Attraction between Two Perfectly Conducting Plates." *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen* **51** 793.

13. "The Theory of positrons," R. P. Feynman, Phys. Rev. **76** (1949) 749.

14. Dyson, F. 1949. "The Radiation Theories of Tomonaga, Schwinger, and Feynman." *Physical Review* **75** 486.

15. "On the Equivalence of Invariance under Time Reversal and under Particle-Antiparticle Conjugation for Relativistic Field Theories", G. Lüders, Kongelige Danske Videnskabernes Selskab, Matematisk-Fysiske Meddelelser 28 (1954) 1

16. 'Relativistic Field Theories of Elementary Particles," W. Pauli, Rev. Mod. Phys. **13** (1941) 203.

17. Yennie, D.R., Frautschi, S.C. and Suura, H. 1955. "The infrared divergence phenomena and high-energy processes." *Annals of Physics (NY)* **13** (1955) 379.

18. "Question of Parity Conservation in Weak Interactions," T. D. Lee and C. N. Yang, Phys. Rev. **104** (1956) 254.

19. "Conservation of Isotopic Spin and Isotopic Gauge Invariance," C. N. Yang and R. L. Mills, Phys. Rev. **96** (1954) 191.

20. "Theory of Fermi interaction," R. P. Feynman and M. Gell-Mann, Phys. Rev. **109** (1958) 193,

21. "Chirality invariance and the universal Fermi interaction," E. C. G. Sudarshan and R. e. Marshak, Phys. Rev. **109** (1958) 1860.

22. "Electron and Muon Neutrinos," B. Pontecorvo, Sov. Phys. JETP **10** (1960) 1236 [Zh. Eksp. Teor. Fiz. **37** (1959) 1751].

23. "The Eightfold Way: A Theory of strong interaction symmetry," M. Gell-Mann, California Institute for Technology Synchrotron Laboratory Report CTSL-20 (1961)

24. "Derivation of Strong Interactions from a Gauge Invariance," Y. Ne'eman, Nuclear Physics 26 (1961) 222.

25. Nambu, Y. 1960. "Quasiparticles and Gauge Invariance in the Theory of Superconductivity." *Physical Review* **117** (1960) 648.

26. Borchers, H. 1960. "Über die mannigfaltigkeit der interpolierenden felder zu einer kausalen S-matrix." *Nuovo Cimento* **15** (1960) 784.

27. Goldstone, J. 1961. "Field Theories with Superconductor Solutions." *Nuovo Cimento* **19** (1961) 154.

28. Froissart, M. 1961. "Asymptotic Behavior and Subtractions in the Mandelstam Representation." *Physical Review* **123** 1053.

29. Goldstone, J., Salam, Abdus and Weinberg, S. 1962. "Broken Symmetries." *Physical Review* **127** (1962) 965.

30. Kinoshita, T. 1962. "Mass Singularities of Feynman Amplitudes." *Journal of Mathematical Physics* **3** (1962) 650.

31. "Broken Symmetries and the Masses of Gauge Bosons," P. W. Higgs, Phys. Rev. Lett. **13** (1964) 508.

32. Weinberg, S. 1964. "Feynman Rules for Any Spin." *Physical Review* **133** (1964) B1318.

33. Weinberg, S. 1964. "Feynman Rules for Any Spin 2: Massless Particles." *Physical Review* **134** (1964) B882.

34. Weinberg, S. 1964. "Photons and Gravitons in S Matrix Theory: Derivation of Charge Conservation and Equality of Gravitational and Inertial Mass." *Physical Review* **135** (1964) B1049.

35. Weinberg, S. 1965. "Infrared photons and gravitons." *Physical Review* **140** (1965) B516.

36. "Photons and gravitons in perturbation theory: Derivation of Maxwell's and Einstein's equations," S. Weinberg, Phys. Rev. **138** (1965) B988.

37. "A Model of Leptons," S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264.

38. "Neutrino Experiments and the Problem of Conservation of Leptonic Charge," B. Pontecorvo, Sov. Phys. JETP **26** (1968) 984 [Zh. Eksp. Teor. Fiz. **53** (1967) 1717].

39. "All Possible Symmetries of the S Matrix," S. R. Coleman and J. Mandula, Phys. Rev. **159** (1967) 1251.

40. Weinberg, S. 1968. "Nonlinear realizations of chiral symmetry." *Physical Review* **166** (1968) 1568.

41. Coleman, S. R., Wess J., and Zumino, B. 1969. "Structure of phenomenological Lagrangians, 1." *Physical Review* **177** (1969) 2239.

42. Callan, C. G., Coleman, S. R., Wess J., and Zumino, B. 1969. "Structure of phenomenological Lagrangians, 2." *Physical Review* **177** (1969) 2247.

43. Weinberg, S. 1969. "Feynman Rules for Any Spin III." *Physical Review* **181** (1969) 1893.

44. "Very high-energy collisions of hadrons," . P. Feynman, Phys. Rev. Lett. **23** (1969) 1415

45. "Inelastic Electron Proton and gamma Proton Scattering, and the Structure of the Nucleon," J. D. Bjorken and E. A. Paschos, Phys. Rev. **185** (1969) 1975.

46. "Axial vector vertex in spinor electrodynamics," S. L. Adler, Phys. Rev. **177** (1969) 2426.

47. "Weak Interactions with Lepton-Hadron Symmetry," S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D **2** (1970) 1285.

48. Taylor, J.C. 1971. "Ward Identities and Charge Renormalization of the Yang-Mills Field." *Nuclear Physics* **B33** (1971) 436.

49. Wess, J. and Zumino, B. 1971. "Consequences of anomalous ward identities." *Physics Letters* **B37** (1971) 95.

50. Slavnov, A.A. 1972. "Ward Identities in Gauge Theories." *Theoretical and Mathematical Physics* **10** (1972) 99 [*Teoreticheskaya i Matematischeskaya Fizika* **10** (1972) 153].

51. Weinberg, S. 1972. "Approximate symmetries and pseudoGoldstone bosons," *Physical Review Letters* **29** (1972)1698.

52. "Regularization and Renormalization of Gauge Fields," G. 't Hooft and M. J. G. Veltman, Nucl. Phys. B **44** (1972) 189.

53. "Critical exponents in 3.99 dimensions," K. G. Wilson and M. E. Fisher, Phys. Rev. Lett. **28** (1972) 240.

54. "Ultraviolet Behavior of Nonabelian Gauge Theories," D. J. Gross and F. Wilczek, Phys. Rev. Lett. **30** (1973) 1343,

55. "Reliable Perturbative Results for Strong Interactions?," H. D. Politzer, Phys. Rev. Lett. **30** (1973) 1346.

56. Appelquist, T. and Carazzone, J. 1974. "Infrared Singularities and Massive Fields." *Physical Review* **D11** (1974) 2856.

57. "Confinement of Quarks," K. G. Wilson, Phys. Rev. D **10** (1974) 2445.

58. "Unity of All Elementary Particle Forces," H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32** (1974) 438.

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61. "Magnetic Monopoles in Unified Gauge Theories," G. 't Hooft, Nucl. Phys. B **79** (1974) 276

62. "Pseudoparticle Solutions of the Yang-Mills Equations, "A. A. Belavin, A. M. Polyakov, A. S. Schwartz and Y. S. Tyupkin, Phys. Lett. B **59** (1975) 85.

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65. S. W. Hawking, "Particle Creation by Black Holes," Commun. Math. Phys. **43** (1975) 199 Erratum: [Commun. Math. Phys. **46** (1976) 206].

66. S. W. Hawking, "Zeta Function Regularization of Path Integrals in Curved Space-Time," Commun. Math. Phys. **55** (1977) 133.

67. "Jets from Quantum Chromodynamics," G. F. Sterman and S. Weinberg, Phys. Rev. Lett. **39** (1977) 1436.

68. "Spontaneously Broken Supersymmetric Theories of Weak, Electromagnetic and Strong Interactions," P. Fayet, Phys. Lett. B **69** (1977) 489.

69. "CP Conservation in the Presence of Instantons," R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38** (1977) 1440.

70. "A New Light Boson?," S. Weinberg, Phys. Rev. Lett. **40** (1978) 223,

71. "Problem of Strong P and T Invariance in the Presence of Instantons," F. Wilczek, Phys. Rev. Lett. **40** (1978) 279.

72. "Phenomenological Lagrangians," S. Weinberg, Physica A **96** (1979) 327.

73. "Mass Without Scalars," S. Dimopoulos and L. Susskind, Nucl. Phys. B **155** (1979) 237.

74. "Baryon and Lepton Nonconserving Processes," S. Weinberg, Phys. Rev. Lett. **43** (1979) 1566.

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76. Weinberg, S. and Witten, E. 1980. "Limits on Massless Particles." *Physics Letters* **96B** (1980) 59.

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78. "Why The Renormalization Group Is A Good Thing," S. Weinberg, In *Cambridge 1981, Proceedings, Asymptotic Realms Of Physics*, 1-19.

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