# Részecskefizika komplex vizsga témakörök tematikái

# Főtárgyak

## Nuclear physics

1. **Nuclear structure in ground state:** models of nuclei, applicability of independent particle model, neutron skin, quadrupole moments, excited states (rotation, oscillation, density of states). Applications of nuclear phyics. **Exotic nuclei**: structure and reactions.
   Suggested reading:
   - J. Németh, G. Papp, "Magfizika jegyzet" (Hungarian)
   - K.S: Krane, "Introductory Nuclear Physics", John Wiley & Sons, 1988
   - J.-L. Basdevant, J. Rich, M. Spiro, "Fundamentals in Nuclear Physics", Springer, 2005
   - *Physics of Radioactive Beams*, Carlos A. Bertulani, M. S. Hussein, G. Munzenberg. ISBN-13: 978-1590331415, Nova Science Pub Inc (2002)

2. **Nuclear reactions at low energy**: types of interaction, nucleon capture, electron scattering, ablation, resonances, TDHF. Reactions in nuclear astrophysics.
   Suggested reading:
   - H. Stöcker, W. Greiner, Phys. Rep. 137 (1986) 277
   - *Nuclear Physics of Stars*, Christian Iliadis, ISBN: 978-3-527-61876-7, July 2008, John Wiley and Sons Inc.

3. **Nuclear reactions in stars**: fusion, plasma instability, fusion reactor types. Nucleosynthesis (primary and beyond), the source of carbon in the Universe.
   Suggested reading:
   - J. Németh, G. Papp, "Magfizika jegyzet" (Hungarian)
   - J.-L. Basdevant, J. Rich, M. Spiro, "Fundamentals in Nuclear Physics", Springer, 2005

4. **Star evolution**: Neutron stars, TOV equation, supernova explosions.
   Suggested reading:
   - Glendenning, Norman K. Compact Stars Nuclear Physics, Particle Physics, and General Relativity, https://www.springer.com/gp/book/9780387989778

5. **Intermediate energy range reactions and models**: Landau-Vlasov, VUU/BUU, QMD, hydrodynamical models. Resonances, spectral function, its modification in nuclear matter.
   Suggested reading:
   - H. Stöcker, W. Greiner, Phys. Rep. 137 (1986) 277.
   - Gy. Wolf, DSc. Thesis, "Részecskekeltés Nehézion Reakciókban"
   - https://cds.cern.ch/record/732713/files/ext-2004-080.pdf + references to the spectral function
   - J. Aichelin, Phys. Rep. 202 (1991) 233.

6. **High energy reactions**: rQMD, hydro (Landau, Björken, Gubser flow), pQCD. PDF, FF, Glauber- Gribov model, collective phenomena, jets. Hadronization models (coalescence, Lund, etc.).
   Suggested reading:
   - L.P. Csernai, Introduction to Relativistic Heavy Ion Collisions, John Wiley & Sons, 1994, ISBN 0471 93420; http://www.csernai.no/Csernai-textbook.pdf
   - S. S. Gubser, "Symmetry constraints on generalizations of Bjorken flow," Phys. Rev. D82 (2010) 085027, arXiv:1006.0006 [hep-th]; S. S. Gubser and A. Yarom, "Conformal hydrodynamics in Minkowski and de Sitter spacetimes," Nucl. Phys. B846 (2011) 469– 511, arXiv:1012.1314 [hep-th].
   - https://cds.cern.ch/record/302414/files/9605214.pdf
   - https://arxiv.org/pdf/hep-ph/0604108.pdf

7. **Particle creation processes:** implementation in models (BUU, hydro), spectral functions, subthreshold particle creation.
   Suggested reading:
   - https://cds.cern.ch/record/732713/files/ext-2004-0
   - L.P. Csernai, Introduction to Relativistic Heavy Ion Collisions, John Wiley & Sons, 1994, ISBN 0471 93420; http://www.csernai.no/Csernai-textbook.pdf

8. **Phase transitions in nuclear physics** (liquid – vapor: multifragmentation, chiral, QGP transition, signatures, CGC, various condensates, Hagedorn temperature)
   Suggested reading:
   - B-A. Li, D.H.E. Gross, Nucl. Phys. A554 (1993) 257
   - Y.K Vermani, PhD Thesis, Panjab University, 2010
   - https://arxiv.org/pdf/nucl-th/9612054.pdf
   - https://www.mn.uio.no/fysikk/english/research/doctoral-degree/research-schools/Lectureweek2006/flow_ee.pdf

9. **Detectors**: gas-ionization, semiconductor, scintillator, calorimeter, particle identification (RICH, TOF), summary on recent and planned heavy ion experiments (goal, methods, results).
   Suggested reading:
   - William R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
   - Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

10. **HBT method**: correlation analysis, core-halo model, source functions
    Suggested reading:
    - M.A. Lisa, S. Pratt, R. Soltz, U. Widermann, Femtoscopy in Relativistic Heavy Ion Collisions, https://www.annualreviews.org/doi/abs/10.1146/annurev.nucl.55.090704.151533
    - C.Y. Wong: Introduction to High-energy Heavy-Ion Collisions, World Scientific, 1994
    - U. Heinz, B.V. Jacak, Two-particle Correlations in Relativistic Heavy-Ion Collisions,
    - https://cds.cern.ch/record/378753/files/9902020.pdf

11. **Jet physics**: nuclear effect (RAA, etc.), measurements methods, Glauber(-Gribov) theory, Nbin, Npart, jets original and characterizations, reconstructions algorithms (e.g. anti-kt,), jet suppression, heavy quark physics.
    Suggested reading:
    - R.D .Field, Applications of Perturbative QCD. Font. Phys. 77 (1989) 1-366.
    - Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller, S.I. Troyan: Basics of Perturbative QCD,
    - https://www.lpthe.jussieu.fr/~yuri/BPQCD/BPQCD.pdf
    - Klaus Rabbertz: Jet Physics at the LHC, Springer, 2017
    - C.Y. Wong: Introduction to High-energy Heavy-Ion Collisions, World Scientific, 1994
    - L.P. Csernai, Introduction to Relativistic Heavy Ion Collisions, John Wiley & Sons, 1994, ISBN 0471 93420; http://www.csernai.no/Csernai-textbook.pdf

12. **Heavy ion physics**: kinematics (Lorentz transformation in 3d, center of energy system, Mandelstam variables, rapidity, pseudorapidy, transverse momentum, Lorenz invariance). Anisotropy, flow (longitudinal, transverse, radial, bounce-off, squeeze-out, elliptic flow), change of the sign of bounce-off as a function of energy. Thermal distribution, Jüttner distribution, equation of state at low energies and in the hadron QGP mixed phase.
    Suggested reading:
    - Zabrodin, Collective Flow in Relativistic Heavy-Ion Collisions, https://www.mn.uio.no/fysikk/english/research/doctoral-degree/research-schools/Lectureweek2006/flow_ee.pdf
    - L.P. Csernai, Introduction to Relativistic Heavy Ion Collisions, John Wiley & Sons, 1994, ISBN 0471 93420; http://www.csernai.no/Csernai-textbook.pdf
    - Prog. Theor. Exp. Phys. 2020, 083C01 (2020) p671-674.

# Particle physics

1. **Symmetries and conserved quatities**, Noether's theorem. Continuous symmetries and fundamental interactions. Discrete symmetries: CPT-symmetry, parity violation, CP-violation.
2. **Spinors,** Lorentz-transformations, invariant biliniear field operators, Dirac-equation.
3. **Abelian and non-abelian gauge theories**, spontaneous symmetry breaking and Abelian Higgs-mechanism.
4. **Standard model of particle interactions**: lepton and quark families and their quantum numbers, interactions.
5. **Brout-Englert-Higgs mechanism** in the standard model, masses of gauge bosons. Properties of the Higgs particle.
6. **GIM mechanism:** Flavour changing neutral current. Masses of fermions, their mixing, the Cabibbo-Kobayashi-Maskawa matrix.
7. **Neutrinos**: Sources of neutrinos and means of their detection. Masses and mixing of neutrinos and discovery of neutrino oscillations. Neutrinos in the standard model.
8. P**arton model**; quark constituents of hadrons, the quark-quark interaction.
9. **Quantum Chromo-Dynamics**, and its experimental foundations. Asymptotic freedom. Predictions of cross sections and their uncertainties.
10. **Quantization of field theories:** LSZ reduction, Feynman rules.
11. **Decay widths and cross sections:** definitions of their elements and their properties.
12. **UV divergenccwe of loop corrections and regularization:** electron self energy, photon vacuum polarization.
13. **UV renormalization**, Ward identities.
14. **Renormalization group equations,** running coupling and mass, asymptotic freedom.
15. **Anomalous magnetic moment of muon:** experiments, theoretical predictions in QED, SM and beyond SM.
16. **Particle accelerators**: Linear accelerator, cyclotron, synchrocyclotron, synchrotron; Guiding, shaping and cooling of particle beams; storage rings and colliders.
17. **Particle deceleration in matter**: Mechanisms of energy-loss of photons and electrons. Deceleration processes of heavy charged particles. The non-relativistic and relativistic Bethe-Bloch formulae; mean ionazation potential and effective charge.
18. **Particle detection**: Ionization, proportional, streamer, drift and bubble chambers; plastic, cristal, glass, liquid and gas scintillation detectors, scintillation wires; semiconductor and microstrip detectors; particle identification with Cherenkov-detectors; sandwich and shower detectors, hodoscopes, hadron and muon calorimeters.
19. **Data acquisition, storage, analysis:** Event collection, trigger-logic, methods of on-line and off-line analyses. Data bases, event selection, kinematical conditions (discrimination). Monte-Carlo simulations, determination of efficiency and spectrum shape. Curve fitting, $\chi^2$, statistical and systematic errors, covariance and correlation.

20. **Description of a historical particle physics experiment**
(E.g.: CP-violation, discovery of $W^{+-}$, measurement of the decay width of the Z-boson at LEP and its utilization for the determination of number of lepton families.)

Suggested reading:

D. Horváth, Z. Trócsányi: Introduction to Particle Physics, Cambridge Scholars, 2019
F. Halzen, A. D. Martin: Quarks and Leptons, Wiley, New York, 1984.
D. H. Perkins: Introduction to High Energy Physics, Addison-Wesley, Reading, MA, 1982
M.D. Schwartz: Introduction to Quantum Field Theory and the Standard Model, Cambridge University Press, 2014
M.E. Peskin, D.V. Schroeder: An Introduction to Quantum Field Theory, Perseus Books, 1995.
D. Griffiths, Introduction to Elementary Particles, Viley-VCH, 2009.

# Részecskefizika komplex vizsga témakörök tematikái

# Melléktárgyak

## Heavy Ion Physics

1. **Heavy ion colliders and their experiments**: AGS, SPS, RHIC, LHC, their characteristics, discoveries.
2. **Particle detection**: detector structures, trigger, event characterization, tracking, particle identification, calorimetry, data acquisition.
3. **Observable quantities**: particle spectra and their ratios, nuclear modification, fluctuations, cumulants, directed and elliptic flow, higher order anisotropies, femtoscopic correlations, jet correlations, leptons, photons (this topic focuses on how to measure them and what to expect in general; as opposed to topic 7, which focuses rather specifically on QGP signatures in these observables)
4. **Space-time evolution of relativistic heavy ion collisions:** initial state, hard and soft processes, heavy quark processes, thermalization, time evolution, freeze-out processes, hadron gas
5. **Models of relativistic heavy ion collisions:** perturbative QCD, colour glass condensate model, Glauber model, numerical and analytic hydrodynamics, Monte Carlo models, freeze-out models, relativistic QMD.
6. **Properties of quark-gluon plasma (QGP) transport**: Boltzmann equation, speed of sound, shear and bulk viscosity, conductivity, magnetic field.
7. **QGP signatures**: Jets in symmetric and asymmetric systems, angular correlations, second and higher order azimuthal asymmetries in small and large systems, photon distributions, correlations, femtoscopy, heavy quarks.
8. **Studies of the QCD phase diagram**: phase diagram, phase transitions, search for the critical point, signatures in correlations and fluctuations, results.

Suggested reading:

L.P. Csernai, *Introduction to relativistic heavy ion collisions*, Wiley, 1994
R. Stock (ed), *Relativistic Heavy Ion Physics* Springer, 2010
W. Florkowski, *Phenomenology of Ultra-Relativistic Heavy-Ion Collisions*, World Scientific, 2010
R. Vogt, *Ultrarelativistic Heavy-Ion Collisions*, Elsevier, 2007
J. Bartke, *Introduction to relativistic heavy ion physics*, World Scientific, 2008
I. Arsene et al. [BRAHMS Collaboration], *Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment*, Nucl.Phys.A 757 (2005) 1-27
B. B. Back et al. [PHOBOS Collaboration], *The PHOBOS perspective on discoveries at RHIC*, Nucl.Phys.A 757 (2005) 28-101
J. Adams et al. [STAR Collaboration], *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions*, Nucl.Phys.A 757 (2005) 102-183

## Quantum Electrodynamics

1. **Canonical quantization** in field theory, Hilbert space, field operators, dispersion relation, real free scalar field, charged free scalar field
   [Kaku 3, 3.2, 3.3, Lecture notes 4, 4.2.4, Peskin-Schroeder 2]
2. **Symmetries** and their consequences, Noether theorem in quantum field theory, global symmetries, Lorentz and Poincare invariance
   [Kaku 1.8, 1.9, 2]
3. **Free Dirac field**, Dirac Lagrangian, Dirac equation, quantization, particle - anti-particle interpretation, Hilbert space, Hamiltonian, Lorentz invariance, spinor representation
   [Kaku 3.5, 3.6 Lectures notes 5, Peskin-Schroeder 3]
4. **Free electromagnetic field,** gauge invariance, quantization, Gupta-Bleuler method, gauge fixing, Lorentz gauge, Coulomb gauge, physical and unphysical degrees of freedom, polarization
   [Kaku 4, 4.1, 4.2, 4.3, 4.4, Lecture notes 7]
5. **Interacting perturbative quantum field theory**, interaction Lagrangian, interaction picture, Wick theorem and propagators, Feynman graphs, Feynman rules
   [Kaku 3.4, 5.6, 5.7, Lecture notes 6.1, 6.2, 6.3, 6.4, 6.5,
   Peskin-Schroeder 4]
6. **Quantum electrodynamics** scattering processes, Compton scattering, gauge invariance, cross section
   [Kaku 6, 6.1, Peskin-Schroeder 5]

Suggested reading:

Michio Kaku: *Quantum field theory - a modern introduction*, 1993 Oxford University Press
Peskin-Schroeder: *An Introduction to Quantum field theory*, 1995
Lecture notes: http://bodri.elte.hu/~nogradi/rqed/notes_qed.pdf

## Mathematical foundations of relativistic quantum field theory

1. **Structure and representations of the Poincaré group**, Pauli-Lubanski vector, Wigner's classification of relativistic wave equations, higher spins, supersymmetric extensions of the Poincaré algebra.
2. **Functional integrals in quantum field theory**, Grassman-integration, fermion determinants, Fadeev-Popov ghosts.
3. **Axiomatic quantum field theory**, Wightman axioms, Osterwalder-Schrader theorem, cluster decomposition, CPT theorem, spin-statistics theorem.
4. **Superselection sectors and charges**, relation to representations of operator algebras, locality, Doplicher-Roberts-reconstruction.
5. **Geometry of vector bundles,** connections and their curvature, parallel transport and holonomy, characteristic classes.
6. **Conformal invariance** in 2D, Virasoro algebra, Vertex Operator Algebras and Modular Tensor Categories, Verlinde's theorem, modular invariance.

Suggested reading:
Bogolyubov, N.N. (1989): *General Principles of Quantum Field Theory,* Springer Verlag.
Nash, C (1992): *Differential Topology and Quantum Field Theory*, Academic Press.
Di Francesco-Mathieu-Sénéchal (1997): *Conformal Field Theory*, Springer Verlag.

## Electroweak interaction processes and theory

1. **Muon decay:** Derive the differential decay width for muon decay into electron and electronic antineutrino. Explain the main features of the muon decay width using only the V-A nature of the weak interactions.
   [Okun 3.1, 3.2, 3.4]
2. **Strangeness-conserving semileptonic processes:** Discuss the amplitude for pion decay into muon and antineutrino in lowest order of perturbation theory in the four-fermion theory. Discuss the amplitude for the beta decay of the neutron to lowest order in the four-fermion theory and the role of symmetries and conservation laws in determining the vector form factors.
   [Okun 5.1, 5.3, 5.4 (also 4.2,4.3)]
3. **Neutral kaons:** Discuss neutral kaon decays into pions and CP invariance. Estimate the neutral kaon mass difference in the four-fermion theory and compare it with experiment. Show how the GIM mechanism cures the discrepancy.
   [Okun 10.1, 11.1, 11.2, 12.2
   ]
4. **Heavy leptons and quarks:** Estimate the total decay width of the tau lepton. Discuss the most general parameterization of the unitary CKM matrix for n families in the V-A theory, and show that CP cannot be violated if $n<3$.
   [Okun 13.2, 13.3, 15.1, 15.2]
5. **Basics of the standard model:** Discuss the limitations of the four-fermion theory of weak interaction. Discuss the Goldstone and Higgs mechanisms in scalar theories with global or local U(1) symmetry, respectively.
   [Okun 18.1, 18.2, 20.2, 20.4]

Suggested reading:

L. Okun, *Leptons and quarks*, (North Holland, 1984)
Cheng and Li, *Gauge theory of elementary particle physics*, (Oxford University Press, 1988)
O.Nachtmann, *Elementary particle physics*, (Springer, 1989)

## Quantum Chromodynamics

1. **QCD as a gauge theory**: gauge invariance, Feynman rules, colour algebra.
2. $\sigma_{tot}(e+e- \rightarrow$ hadrons) at LO in perturbation theory.
3. **UV renormalization of QCD**: quark self energy, renormalization of the Lagrangian and of scattering amplitudes.
4. **Renormalization group equation** and its solution using the running coupling, asymptotic freedom. Running masses and the relevance of massless QCD.
5. **NLO correction** to $\sigma_{tot}(e+e- \rightarrow$ hadrons), KLN theorem and IR safe quantities (event shapes, jet algorithms).
6. **Factorization of QCD squared matrix elements** in the soft and collinear limits.
7. **Deeply inelastic scattering**: kinematics, parametrization of the target structure, parton model
8. **Proton structure**: quark and gluon content, improved parton model.
9. **Factorization theorem**: coloured partons in the initial state, factorization of uncancelled infrared divergences, parton distribution functions, DGLAP equations.
10. **Factorization theorem** for and structure of hadron collisions.

Suggested reading:
D. Horváth, Z. Trócsányi: Introduction to Particle Physics, Cambridge Scholars, 2019
G. Sterman et al, *Handbook of perturbative QCD,*
https://www.physics.smu.edu/scalise/cteq/handbook/v1.1/handbook.pdf

## Beyond the Standard Modell

1. **Status of the Standard Model** (SM), experimental hints beyond the SM, the hierarchy problem(HP) and possible solutions.
2. **Precision test of the SM**, S,T,U parameters, constraints on new physics, concept of the SM Effective Field Theory.
3. **Grand Unified Theories**, running couplings, representations, sin 2 θ W , proton-decay, symmetry breaking.
4. **Supersymmetry** as a solution to the hierarchy problem, Coleman Mandula theorem, SUSY algebra (4 dim), consequences of the SUSY algebra.
5. ***N*** **=1 SUSY** invariant action, scalar and vector superields, (F-term, D-term), SUSY-breaking.
6. **Minimal supersymmetric standard model** Lagrangian, soft symmetry breaking terms, matter parity, R-parity, experimental constraints.
7. **Composite Higgs**, QCD analogy.

Suggested reading:
Cheng-Li: Gauge Theory of Elementary Particle Physics, Oxford University Press,
C. Csáki, P. Tanedo arXiv: 1602.04228
G.G. Ross: Grand Unified Theories, 1985 (Frontiers in Physics)
PDG (particle data group) Chapter 10.
Peskin, Schroder: An Introduction to QFT, 21.3, James Wells, ArXiv:0512342
I. Brivio, M. Trott: The SM as an Effective Field Theory, 1706.08945,
S. Dawson: TASI 2016, EWSB and EFT (shorter), arXiv:1712.07232 (Gradzkowski et al. 1084884)
J. Wess and J. Bagger: Supersymmetry and supergravity, ISBN: 9780691025308
J. Lykken: Introduction to supersymmetry hep-th/961214
John Terning: Modern Supersymmetry Dynamics and Duality, Oxford Science Publications, 2006, th/0201253
S.P. Martin: Supersymmetry primer, arXiv:hep-ph/9709356, v7 2016

## Low energy hadron physics and non-perturbative quantum chromodynamics

1. **Chiral symmetry QCD** Lagrangian and its explicit breaking, the divergence of the singlet and octet currents. Charge algebra and current algebra. The U(1)A anomaly and the $\pi^0 \to \gamma\gamma$ decay. [SS: 1.3, 1.4.3; S: from Ch. 30; WS: 4.5 and 7.1]
2. **Spontaneous symmetry breaking (SSB) in QCD**: absence of parity partners, the scalar singlet quark condensate, Goldstone theorem and the necessary and sufficient condition for SSB; PCAC and the Goldberger–Treiman relation. [SS: Ch. 2, 3.2; CL: from Ch 5.]
3. **Chiral symmetry breaking effects**: the sigma-commutator and the sigma term; the Gell-Mann– Oakes–Renner (GMOR) relation, the ratio of current quark masses; the pion-nucleon sigma term and the strangeness content in the nucleon. [CL: from Ch 5.]
4. **Unitarity, optical theorem**; the role of crossing symmetry and analyticity in the determination of the singularities of the scattering amplitude in the complex s plane. [S: Ch.24 (pp. 452-456); D: 1.1-1.7]
5. **SU(3) symmetry and the quark model**. Nonrelativistic potential model: spin-spin interaction and the hadron masses in the quark model. [BJ: 10.1-10.6; LS: 3.1]
6. **Effective models of QCD**: The concept of effective field theory; SSB in the linear sigma model. Basics of the Chiral Perturbation Theory. [W; SS: 3.1; CL: part of 5.3; SS: 3.1, 3.4]
7. **Lattice QCD**: gauge fields and fermions on the lattice; Polyakov loop; Wilson loop and quark confinement (static quark-antiquark potential and area law); hadron spectrum (determination of hadron masses) [MM: 3.1-3.2, 4.1-4.3, 5.1; R: Ch.7, 20.2]
8. **The phase diagram of dense QCD**: Methods and results, Columbia mass plot, conjectured phase diagram in the baryochemical potential – temperature plane, the critical end point (CEP) [FH: Sec. 1-5]

Suggested reading:

SS: S. Scherer and M. R. Schindler, *A Primer for Chiral Perturbation theory* (Lecture Notes in Physics 830, Springer, 2012)

S: M. D. Schwartz, *Quantum Field Theory and the Standard Model* (Cambridge Univ. Press, 2014)

WS: B. de Wit and J. Smith, *Field theory in particle physics* (North-Holland Physics Publishing, 1986)

W: S. Weinberg, *Particle Physics, From Rutherford to the LHC*, in M. Henley and S. D. Ellis, Eds., 1*00 Years of Subatomic Physics* (World Scientific, 2013)

CL: T.-P. Cheng, L.-F. Li, *Gauge theory of elementary particle physics* (Clarendon Press, Oxford, 1992)

D: S. Donnachie et al., *Pomeron Physics and QCD* (Cambridge Univ. Press, 2002) BJ: W. E. Burcham and M. Jobes, *Nuclear and Particle Physics* (Longman Group Limited, 1995) LS: W. Lucha and F. F. Schoberl, *Phenomenological aspects of nonrelativistic potential models* https://inspirehep.net/literature/286021

MM: I. Montvay and G. Münster, *Quantum fields on a lattice* (Cambridge Univ. Press, 1994)

R: H. J. Rothe, *Lattice Gauge Theories – An Introduction* (World Scientific, 2005, 3rd ed.)

FH: K. Fukushima and T. Hatsuda, *The phase diagram of dense QCD*,
Rep. Prog. Phys. 74, 014001 (2011)

## Renormalization and renormalization group

1. **Perturbative renormalization**: computation of Feynman graphs. Ultraviolet divergences and their regularization methods (cu-off, dimensional, lattice). Power counting. Counterterm formalism, multiplicative renormalization. Renormalization of composite operators.
2. **Renormalization at any order in PT**: BPHZ renormalization, definition of renormalized graph. R and T operations, Zimmermann's forest formula. Generation of renormalized graphs from the Lagrangian. Weinberg's theorem.
3. **Renormalization group in field theory**: Renormalization conditions, choice of renormalization scheme. Tuning the renormalization scale: renormalization group, β-function, anomalous dimension. Running coupling, resummation of leading logarithms. Landau pole, triviality.
4. **Renormalization group in statistical physics**: Second order phase transitions, Landau theory, critical exponents, universality, scaling laws. Infrared divergences, Wilson's renormalization group, fixed points. Relevant, irrelevant and marginal terms. ε-expansion.
5. **Renormalization and scaling invariance**. Ward identities. Dilatations. Scaling violations, dimensional transmutation. Ward identity of the anomalous scale invariance: Callan-Symanzik equation. Relation to the renormalization group equation.

Suggested reading:

M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*, Westview Press, 1995.

J. Collins, *Renormalization*, Cambridge University Press, 1984.

D. J. Amit and V. Martin-Mayor, *Field Theory, the Renormalization Group, and Critical Phenomena*, World Scientific, 2005.

J. Zinn-Justin, *Quantum Field Theory and Critical Phenomena*, Oxford University Press, 1989.

## Experimental and data analysis methods of particle physics

1. **Radiation in matter**: Interactions of particles and radiation with matter, and their applications for particle detection. Ionization and specific energy loss of heavy charged particles in matter. Interactions of photons in matter. Cherenkov and transition radiation. Multiple scattering. Neutron detection. Basic concepts of radiation protection, dose definitions, ALARA, radiation dose limits. Deterministic and stochastic biological effects of ionizing radiation.
2. **Accelerators**: Natural sources (radioactivity, cosmic rays). Laboratory particle sources. Penning trap and ion source. Duoplasmatron. Electron cyclotron resonance ion source. Electron, proton, pion, muon, neutrino beams. Electrostatic accelerators. Van de Graaff and cascade accelerators. Linear accelerators. Pulsed drift tube, Wideroe, Alvarez linac. Radiofrequency quadrupole. Cyclotron, weak focusing, betatron, synchrotron and synchrotron radiation, strong focusing. Beam dump, beam extraction, kicker magnets, dipole and quadrupole magnets, beam optics. Stochastic cooling. Electron cooling. Damping rings in linear accelerators. Decelerators for antimatter research.
3. **Tracking**: Charged particle tracking. Momentum measurement and resolution. Vertex detectors, impact parameter and its resolution. Pattern recognition, Hough-transform. Tracking detectors and their design considerations. Visual tracking detectors. Tracking detectors with electronic read-out. Gaseous detectors, MWPC, TPC. Transition radiation. Microstructure detectors. Semiconductor detectors. Material budget and its determination. Examples of important discoveries using tracking detectors.
4. **Calorimeters:** Photon detection at high energy and electromagnetic calorimeters. Brehmsstrahlung, critical energy, mean free path, interactions of photons with matter. Scintillators and low-energy photon detection. Organic and inorganic, small-Z and high-Z scintillator materials (plastic, NaI, BGO, PbWO). Light guides. Photodiodes. Electromagnetic showers and calorimeters. Hadron calorimeters. Hadron showers. Sampling and omogeneous structures. Compensated calorimeter. Particle Flow. Energy resoluion. Photon conversion in tracker detectors. Calibration of calorimeters.
5. **Particle identification:** Time-of-flight. Specific energy loss. Cherenkov detectors. Transition radiation detectors. Discrimination based on shower shape. Photon and electron reconstruction. Identification by kinks and decay topology: charged and neutral kaons, lambdas, photons.
6. **Jets**: Jet reconstruction, energy scale and resolution. Discoveries involving jets. Iterative cone, Cambridge-Aachen and anti-kT algorithms. Jet tagging, heavy flavour jets. Quark and gluon jets. Event pileup. Jet grooming. Jet mass. Jet substructure. N-subjetiness. Mass drop, trimming, pruning. Jet energy corrections. Missing transverse energy.
7. **Muons, b-jets and taus**: Muon, b-jet and tau reconstruction. Global muons, tracker muons, muon detectors. Calorimeter muons. Impact parameter and secondary vertices. b-jet efficiency and misidentification. Tau decay modes. Hadronic tau decays and their identification. Isolation in muon and tau reconstruction. Multivariate analysis concept. Tag-and-probe method.
8. **Read-out and trigger**: Detector read-out and trigger systems. Electronics used in particle detectors. Pulse shaping, digitalization. Read-out in LHC experiments. Purpose of trigger systems. Trigger objects, concept, levels and architecture of the trigger systems in LHC experiments. Dead time, efficiency and purity.

9. **Data analysis**: Data processing and analysis. Online and offline analysis. Data reduction. Data storage. Simulation and its role. Objects and their reconstruction. Analysis workflow. Cross section measurement. Steps of data analysis. Energy cluster reconstruction in calorimeters. Statistical uncertainties. Systematic uncertainties and their estimation. Blind analysis. Background estimation. ABCD method. Closure tests.
10. **Statistical methods**: Random variables and probability distributions, Poissonian, Binomial, Gaussian. Central limit theorem. Statistical uncertainties. Multidimensional random variables, conditioning and marginalization. Covariance and correlation. SQRT decorrelation. Error propagation. Frequentist and Bayesian statistics. Hypothesis testing. Significance and p-value. Parameter estimation. Maximum likelihood. Goodness of fit. Classical confidence level. Monte Carlo techniques. Numerical integration. Metropolis and Gibbs sampling algorithm. Unfolding and regularisation.
11. **Luminosity**: Luminosity measurement. Luminosity of bunched beams. Beam-beam effects. Luminosity calibration. Absolute luminosity. Van der Meer method and visible cross section. Zero counting method. Length scale calibration. Instrumentation for luminosity measurements.
12. **Complex detector systems:** Architecture and design considerations of complex detector systems. Fix target and collider experiments. Trigger concepts and trigger systems. Magnet configurations and role of the magnetic field. Examples of complex detectors: ALICE, ATLAS, CMS, LHCb, PHENIX, STAR, AMS.
13. **Neutrinos:** Neutrino detection techniques. Counting, ring imaging, tracking detectors used in neutrino physics. The Reines-Cowan and Raymond Davis experiments. Super-Kamiokande experiment. Majorana and Dirac neutrinos. Neutrino mass measurements. Detecting neutrinos of different flavors. The atmospheric neutrino and solar neutrino puzzle. Neutrino oscillation experiments. Neutrinoless double-beta decay experiments. The SNO (Sudbury) detector. KATRIN, Ice Cube, Antares experiments.
14. **Discoveries**: Discoveries of the positron, muon, tau, neutrinos, charged and neutral pion, Omega baryon, antiproton, J/Ψ, gluon, top quark, Z, W and Higgs bozonok, P and CP violation, verification of CPT symmetry, number of light neutrino families, proton decay, quark-gluon plasma.

Suggested reading:
http://cms.elte.hu/Teaching/detrendsz2020.html
https://sites.google.com/site/nagyenergiasfizika/tematika-2019
http://cms.elte.hu/Teaching/ExpMeth_phD2019.html
William R. Leo: Techniques for Nuclear and Particle Physics Experiments
CERN Summer Student Lectures
CERN Schools of High-Energy Physics
Particle Data Group: review of particle physics – Particle detectors for accelerators