50 Years of Quantum Chromodynamics + 1

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Strong Interactions

Planetary model of the atom [Rutherford (1911)]

- most of the mass of the atom concentrated in a core – *nucleus*, made of positively charged particles – *protons*, $q_p = +1e$
- negatively charged particles – *electrons*, $q_e = -1e$, orbiting around the nucleus, bound by electromagnetic interactions

Questions:

- how can the proton be bound together in the nucleus despite the strong electromagnetic repulsion?
  $\Rightarrow$ new force – *strong interactions*
- why does the nucleus have often more mass than expected from its charge, $m_{\text{nucleus}}/m_p \geq q_{\text{nucleus}}/q_p$?
  $\Rightarrow$ neutron [Chadwick, 1932]: $m_n \approx m_p$, $q_n = 0$
  $\Rightarrow$ n decays into p via yet another interaction – weak interaction

Yukawa's Meson

Particle interactions = exchange of mediator particles carrying energy, momentum, and other quantum numbers from one particle to another

What are the properties of the mediator of strong interactions?

$$M_{\text{mediator}} \sim \frac{\hbar}{c \cdot \text{range}_{\text{interaction}}}$$

$$\text{range}_{\text{interaction}} \sim \text{size}_{\text{proton}} \sim 1\,\text{fm} \Rightarrow M_{\text{mediator}} \sim 200\,\frac{\text{MeV}}{c^2}$$

Mass intermediate between light electron, $m_e = 0.51\,\frac{\text{MeV}}{c^2}$ – *lepton*, and heavy protons and neutrons, $m_p = 938\,\frac{\text{MeV}}{c^2}$, $m_n = 940\,\frac{\text{MeV}}{c^2}$ – *baryons*

$\Rightarrow$ Yukawa's *meson* [Yukawa (1934)]

Discovered in cosmic rays [Lattes, Occhialini, Muirhead, Powell (1947)]

Three types – *pions* π^+, π^0, π^-, $m_{\pi^0} = 135\,\frac{\text{MeV}}{c^2}$, $m_{\pi^\pm} = 140\,\frac{\text{MeV}}{c^2}$

Strange Particles and the Quark Model

The story so far:
elementary *nucleons* p, n affected by strong interactions $= \pi$ exchange

New meson discovered – *kaon* (K), with strange properties: created quickly via strong interactions, decays slowly via weak interactions
[Rochester, Butler (1947)]

Many more "strange" particles (both baryons and mesons) discovered afterwards – too many to be elementary?

Quark model [Zweig (1964), Gell-Mann (1964)]:
baryons and mesons are bound states of *quarks*

$$\text{baryons} = q_1 q_2 q_3 \qquad\qquad \text{mesons} = q_1 \bar{q}_2$$

Three quark *flavours*: u (*up*), d (*down*), s (*strange*)

+ Model correctly reproduces the observed spectrum of *hadrons*, and predicts new ones – η meson, Ω baryon
− Individual quarks not observed in experiments

Colour

Problem: quarks are spin $\frac{1}{2}$ fermions, Fermi-Dirac statistics requires antisymmetric wave function

$$\psi = \psi_{\text{space}}\psi_{\text{spin}}\psi_{\text{flavour}}$$

For lightest baryons $\Rightarrow \psi_{\text{space}}$ symmetric
$\Omega = sss$, $s_\Omega = \frac{3}{2} \Rightarrow \psi_{\text{flavour}}, \psi_{\text{spin}}$ symmetric $\Rightarrow \psi$ symmetric!

Solution: give quarks another degree of freedom – *colour* [Greenberg (1964)]

- N_c colours $\Rightarrow \mathrm{SU}(N_c)$ unitary symmetry
- no degenerate multiplets of hadrons $\Rightarrow$ physical states must be $\mathrm{SU}(N_c)$ singlets ("colourless")
- associated wave function ψ_{colour} must be antisymmetric for baryons

For $N_c = 3$ suitable ψ_{colour} exists

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Deep Inelastic Scattering

Quark model generally not accepted as describing physical reality

Probe nucleons by deep inelastic scattering with electrons

[Taylor, Friedman, Kendall (1968)]

- inelastic: $e^- N \to e^- X_1 \ldots X_k$
- deep: large transferred momentum $q^2 = (p'_e - p_e)^2$

Results:

- Bjorken scaling of cross section [Bjorken (1968)] $\Rightarrow$ nucleons made of pointlike constituents
- Callan-Gross relation [Callan, Gross (1968)] $\Rightarrow$ constituents have $s = \frac{1}{2}$
- constituents – *partons* behave as almost free at short distances [Feynman (1968)]

What theory can reproduce these properties?

Quantum ElectroDynamics - I

QED: quantum relativistic theory of electromagnetic interactions

[Completed by Tomonaga (1946), Schwinger (1948), Feynman (1948, 1949), Dyson (1949)]

A *Quantum Field Theory*: all particles described in terms of *fields* $\phi(x)$, interacting *locally* as $\partial_\mu \phi(x) \partial^\mu \phi(x)$, $\phi(x)^n$, ...

Based on symmetry principle (*gauge principle* [Weyl (1929)]) :

changing the phase of the electron field *locally*
should not affect any physical phenomenon

The phase of the electron wave function is unobservable - but for physics to be truly local it should be arbitrary at every point

Free electrons:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}(x)(i\partial\!\!\!/ - m)\psi(x) \neq \bar{\psi}(x)e^{-i\varphi(x)}(i\partial\!\!\!/ - m)e^{i\varphi(x)}\psi(x)$$

$\partial\!\!\!/ = \partial_\mu \gamma^\mu$

Dirac Lagrangian is not gauge invariant

Quantum ElectroDynamics - II

Add *gauge field* A_μ, use *covariant derivative* D_μ

$$\partial_\mu \to D_\mu = \partial_\mu - ie_0 A_\mu \qquad \mathcal{L}_{\text{Dirac}} \to \bar{\psi}(x)(i\not{D} - m)\psi(x)$$

Invariance under *gauge transformations*

$$\psi(x) \to e^{i\varphi(x)}\psi(x) \qquad A_\mu(x) \to A_\mu(x) - \tfrac{i}{e_0}\partial_\mu\varphi(x)$$

Request of gauge invariance forces the introduction of gauge fields mediating an interaction between electrons

Dynamics for gauge fields must also be (Lorentz- and) gauge-invariant:

$$\mathcal{L}_{\text{QED}} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(x)(i\not{D} - m)\psi(x)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Predictions verified experimentally to 10^{-8} accuracy

Non-Abelian Yang-Mills theories

Gauge transformation in QED:

$$\psi(x) \to U(x)\psi(x) \qquad A_\mu(x) \to U(x)^* A_\mu(x) U(x) - \tfrac{1}{e} U(x)^* \partial_\mu U(x)$$

with $U(x) = e^{i\varphi(x)} \in \mathrm{U}(1)$, Abelian group

Generalise to non-Abelian groups, e.g., special unitary groups $\mathrm{SU}(N_c)$

$$\psi(x) \to U(x)\psi(x) \qquad A_\mu(x) \to U(x)^\dagger A_\mu(x) U(x) + \tfrac{1}{g_0} U(x)^\dagger \partial_\mu U(x)$$

Non-Abelian gauge fields $A_\mu = A_\mu^a t_a$, $U(x) = e^{i\alpha^a t_a} \in \mathrm{SU}(N_c)$

$t_a^\dagger = t_a$, $\mathrm{tr}\, t_a = 0$, $\mathrm{tr}\, t_a t_b = \frac{1}{2}\delta_{ab}$

Invariant Lagrangian [Yang, Mills (1954), Shaw (1956)]:

$$\mathcal{L}_{\mathrm{Yang-Mills}} = -\frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$$
$$D_\mu = \partial_\mu + ig_0 A_\mu \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig_0[A_\mu, A_\nu]$$

Self-interacting field – expect very different behaviour

Consistent QFT ['t Hoof, Veltman (1972)]

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Self-interacting field – expect very different behaviour

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Perturbation Theory

How does a Quantum Field Theory behave at short distances?

Perturbation theory:

- expand physical quantities in powers of a (hopefully) small parameter controlling the strength of the interaction
- in QFT not a single parameter but a function of the energy scale at which you are looking at the theory

$$\sigma(E) = \sum_n a_n(E;\mu)g(\mu)^n = S(E,\mu,g(\mu))$$

For $\mu \approx E$, $a_n(E;\mu) \approx O(1)$, so if $g(E)$ is small one can trust PT, and interactions are weak at that scale

Physics does not depend on $\mu \Rightarrow$ Renormalisation Group equations

$$0 = \mu\frac{d}{d\mu}S(E,\mu,g(\mu)) = \left(\mu\frac{\partial}{\partial\mu} + \mu\frac{dg}{d\mu}\frac{\partial}{\partial g}\right)S(E,\mu,g(\mu))$$

[Stückelberg, Petermann (1953), Gell-Mann, Low (1954)]

Asymptotic Freedom

β-function of YM theory with $N_{f,s}$ fundamental fermions and scalars:

$$\mu \frac{d}{d\mu} g(\mu) = \beta(g(\mu)) = \beta_0 \frac{g(\mu)^3}{(4\pi)^2} + \ldots$$

$$\beta_0 = -\frac{11}{3} N_c + \frac{2}{3} N_f + \frac{1}{6} N_s = -b_0$$

For $N_c = 0$, $b_0^{\text{QED}} < 0$

For $N_c \neq 0$, $b_0^{\text{QCD}} > 0$ if $N_{f,s}$ small

$N_c = 3$, $N_f = 6$, $N_s = 0$ in the real world

$$\alpha_{\text{QED}} = \frac{e^2}{4\pi} = \frac{1}{\frac{1}{\alpha_0^{\text{QED}}} - \frac{b_0^{\text{QED}}}{2\pi} \ln \frac{\mu_0}{\mu}} = \frac{1}{-\frac{b_0^{\text{QED}}}{2\pi} \ln \frac{\Lambda^{\text{QED}}}{\mu}} \underset{\mu \to 0}{\to} 0$$

$\Rightarrow e(\mu)$ small at low energy/large distance

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For $N_c \neq 0$, $b_0^{\mathrm{QCD}} > 0$ if $N_{f,s}$ small — $N_c = 3$, $N_f = 6$, $N_s = 0$ in the real world

$$\alpha_{\mathrm{QCD}} = \frac{g^2}{4\pi} = \frac{1}{\frac{1}{\alpha_0^{\mathrm{QCD}}} + \frac{b_0^{\mathrm{QCD}}}{2\pi} \ln \frac{\mu}{\mu_0}} = \frac{1}{\frac{b_0^{\mathrm{QCD}}}{2\pi} \ln \frac{\mu}{\Lambda^{\mathrm{QCD}}}} \underset{\mu \to \infty}{\longrightarrow} 0$$

$\Rightarrow g(\mu)$ small at high energy/short distance – *asymptotic freedom*

[Gross, Wilczek (1973), Politzer (1973)]

Asymptotic Freedom

β-function of YM theory with $N_{f,s}$ fundamental fermions and scalars:

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$\Rightarrow g(\mu)$ small at high energy/short distance – *asymptotic freedom*

[Gross, Wilczek (1973), Politzer (1973)]

. . . but *infrared slavery* – $g(\mu)$ large at large distances, PT not working

Quantum ChromoDynamics

Non-Abelian gauge theories can describe interactions getting weak at short distance - which one do we choose?

- Use quarks ($s = \frac{1}{2}$ partons)
- Make colour dynamical, allowing it to be exchanged between quarks $\Rightarrow \mathrm{SU}(N_c)$ gauge theory with non-Abelian *gluon* fields
- $N_c = 3$ colours $\Rightarrow N_c^2 - 1 = 8$ gluon fields

$\Rightarrow$ **Quantum ChromoDynamics** (QCD)

[Fritzsch, Gell-Mann, Leutwyler (1973)]

Is it the right theory?

- Incorporates quark model
- Explains DIS
- Through PT, successful description of high-E, high-q processes

Nonperturbative QCD

If QCD is the right theory for strong interactions, it must be rich in nonperturbative phenomena in order to explain

- hadron spectrum
- matrix elements governing weak hadronic decays ($n \to pe^- \bar{\nu}_e$, $\pi^+ \to \mu^+ \nu_\mu$, $K^0 \to 2\pi, 3\pi, \ldots$)
- confinement of quarks and gluons

Main approaches:

- symmetries (+ effective theories)
- lattice QCD

Isospin and Chiral Symmetry

Isospin symmetry: $m_p \simeq m_n \Rightarrow$ two states of the same particle (*nucleon*)

[Heisenberg (1932)]

$\mathrm{SU}(2)_V$ isospin symmetry: can "rotate" protons into neutrons

Phenomenological consequences:

- hadron multiplets (nucleons, pions, kaons, ...)
- relations between matrix elements, scattering amplitudes

Origin of symmetry: $m_u \simeq m_d$, two states of the same *light quark* particle

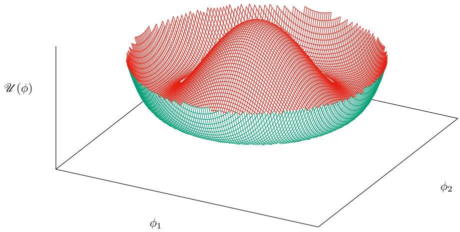
Since $m_{u,d} \ll \Lambda_{\mathrm{QCD}} \approx$ massless particles $\Rightarrow$ extended, chiral symmetry

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \sim \mathrm{SU}(2)_V \times \mathrm{SU}(2)_A$$

Can rotate "left-handed" and "right-handed" components of $\psi = \psi_L + \psi_R$ independently

Spontaneous Breaking of Chiral Symmetry

$\mathrm{SU}(2)_A$ is *spontaneously broken*: vacuum state <u>not</u> $\mathrm{SU}(2)_A$-symmetric



Goldstone theorem: SSB of a continuous symmetry $\Rightarrow$ massless spinless excitations (*Goldstone bosons*), one per broken symmetry generator

[Goldstone (1961), Goldstone, Salam, Weinberg (1962)]

Three $\mathrm{SU}(2)_A$ broken generators $\Rightarrow$ three massless pseudoscalars – pions!

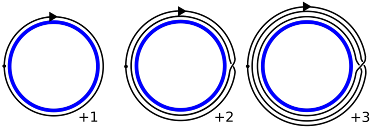
[Nambu, Jona-Lasinio (1961)]

SχSB explains lightness of pions, $m_\pi \ll m_p$

Effective theory + $m_{u,d} \neq 0$ corrections $\Rightarrow$ correct low-energy physics

Gauge Field Topology

Gauge field configurations can be classified in disjoint topological sectors



Cannot continuously deform configurations
from different sectors into one another

Topological charge Q, topological charge density q

$$Q = \int d^4x\, q(x) \qquad\qquad q(x) \propto \epsilon_{\mu\nu\rho\sigma} \mathrm{tr}\, F_{\mu\nu}(x) F_{\rho\sigma}(x)$$

Nontrivial topology depends on spacetime dimension d and gauge group G, e.g., $d = 2,\ G = \mathrm{U}(1)$; $d = 4,\ G = \mathrm{SU}(N_c)$

Anomalous $\mathrm{U}(1)_A$ Symmetry

Full symmetry group for $m_{u,d} = 0$

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_L \times \mathrm{U}(1)_R \sim \mathrm{SU}(2)_V \times \mathrm{SU}(2)_A \times \mathrm{U}(1)_V \times \mathrm{U}(1)_A$$

Continuous global symmetry $\Rightarrow$ conserved current, $\partial_\mu j^\mu = 0$ [Noether (1918)]

Ex.: $\mathrm{U}(1)$ in QED $\Rightarrow$ conserved electric current

$\mathrm{U}(1)_V \Rightarrow$ baryon number conservation
$\mathrm{U}(1)_A \Rightarrow$ *anomalous* symmetry [Adler (1969); Bell, Jackiw (1969)]

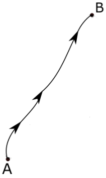
Classical symmetry that does not survive quantisation

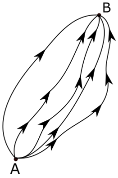
$$\partial_\mu j^\mu_{\mathrm{U}(1)_A} \propto q$$

Explains heavy η' meson, $m_{\eta'} \gg m_\pi$ [Witten (1979), Veneziano (1979)]
Topology crucial for anomaly (also important role in explaining SχSB)

Path Integral

DOF of QCD are quarks and gluons, but the spectrum consist of hadrons
Cannot get it from perturbation theory, need nonperturbative approach
Path integral quantisation [Feynman (1948)]:





classical description:
definite path
Γ_0

quantum description:
weighted sum over paths
$\sum_\Gamma e^{iS(\Gamma)}$

Can do the same for configurations of QCD fields

$$Z = \int DA \int D\psi \int D\bar{\psi}\, e^{iS_{\mathrm{QCD}}[A,\psi,\bar{\psi}]}$$

. . . but mathematically ill-defined quantity

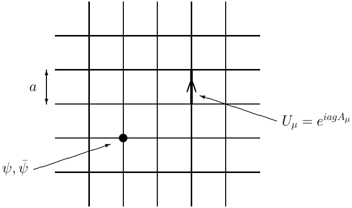
Lattice QCD

Replace continuum with a discrete, finite Euclidean lattice

$$Z_{\mathrm{lat}} = \int DU \int D\psi \int D\bar{\psi} e^{-S_{\mathrm{lat}}[U,\psi,\bar{\psi}]}$$

[Wilson, 1974]

- Fields associated with lattice elements: fermions → sites, gauge fields → edges
- Just a high-dimensional integral, can put on a computer
- Eventually thermodynamic ($V \to \infty$) and continuum ($a \to 0$) limits
- Continuum limit (likely) exists, thanks to asymptotic freedom
- "Rotate" back to Minkowski spacetime (very tricky, often not needed)



NP Physics on the Lattice - I

What physics can we study?

- extract hadron masses and hadronic matrix elements

$$\langle O(t)O(0)\rangle \underset{t>0}{=} \langle 0|\hat{O}(t)\hat{O}(0)|0\rangle = \sum_n e^{-E_n t}|\langle n|\hat{O}(0)|0\rangle|^2$$

$$\underset{t\to\infty}{\to} e^{-E_{n_0} t}|\langle n_0|\hat{O}(0)|0\rangle|^2$$

n_0: lightest state with $\hat{O}(0)$ quantum numbers

- confinement

$$e^{-TV_{q\bar{q}}(R)} = \langle \mathcal{W}(T,R)\rangle \to \begin{cases} e^{-\kappa P} & \text{perimeter law} \to \text{no confinement} \\ e^{-\sigma A} & \text{area law} \to \text{confinement} \end{cases}$$

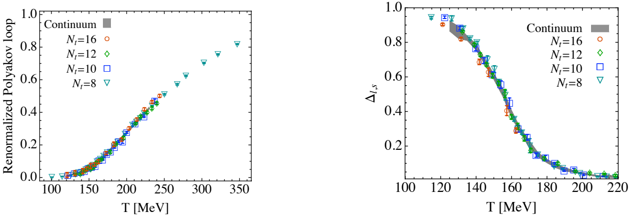
$\mathcal{W}(T,R)$: Wilson loop – product of links around $T \times R$ rectangular path

Area law $\Rightarrow$ linearly rising potential $V_{q\bar{q}}(R) = \sigma R$

Effective string description (not fully understood)

NP Physics on the Lattice - II

- topology:
  - measure topological susceptibility $\langle Q^2 \rangle / V$ (important for axion cosmology)
  - properties of instantons and other topologically nontrivial configurations (monopoles, fractional instantons,. . .)
- thermodynamics:
  - finite-temperature transition to quark-gluon plasma (QGP)
  - properties of the QGP, equation of state of hadronic matter



[Budapest-Wuppertal collaboration (2010)]

- low-energy scattering phase shifts
- . . . a lot, but not everything

Open problems - I

Lattice not always the best choice (but often the only first-principles one)

1. Sometimes lattice approach can be used, but is inefficient:
   - QCD at finite baryon density
     - relevant to QGP, early universe, neutron stars
     - lattice integration measure not positive-definite, cannot use standard numerical methods (**sign problem**)
   - QCD with a topological term $S \to S - i\theta Q$
     - allowed by gauge symmetry, but experimental bounds on $\theta < 10^{-10}$ – why? (**strong** CP **problem**)
     - complex action, sign problem again

2. Sometimes lattice approach has serious theoretical uncertainties:
   - reconstruction of spectral functions and transport coefficients of QGP
   - reconstruction of real-time (Minkowski) dynamics

Open problems - II

3. Lattice good for long-distance physics, PT for short-distance physics, but mixed settings are hard to deal with – e.g., high-E, low-q scattering (**rising total cross sections**, Pomeron and Odderon physics)

4. Lattice mostly numerical, analytic understanding of NP physics needed (e.g., confinement, hadronisation, . . .)

Other NP (analytic) tools:

- Dyson-Schwinger equations
- Functional Renormalisation Group
- Effective Lagrangians

Summary and Outlook

- QCD successfully describes strong-interaction phenomena
- Very rich theory, but hard to study
- Important problems still open after 50+1 years

Open issues studied in our group (Katz, Kovács, Nógrádi, Pásztor, MG):

- Finite-temperature properties of QCD
- QCD transition and quark localisation
- Topology, chiral symmetry restoration, and deconfinement
- Finite-density QCD and the sign problem
- QCD in a magnetic field
- QCD in the chiral limit

References I

- Exhaustive list of references in F. Gross, E. Klempt, *et al.*, "50 Years of Quantum Chromodynamics," Eur. Phys. J. C **83** (2023), 1125 [arXiv:2212.11107 [hep-ph]]
- Figure on slide 16: adapted from
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References II

- Recent papers from our group

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