Hadron physics: current state of the art

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Introduction

Basic constituents (quarks, gluons) of QCD have never been observed in isolation. ⟶ color neutral hadrons instead

major challenges:

- hadrons ⟶ why usually mesons or baryons? (X, Y, Z states ⟶ hadronic molecules, four-quark composite particles)
- protons, neutrons ⟶ complex many body systems (sea quarks and gluons) ⟶ contributes to bulk properities of hadrons (mass, spin, magnetic moment)
- matter–antimetter asymmetry ⟶ CP violation? (B-factories: BaBar at SLAC, Belle at KEK)

To understand the physics of hadrons ⟶ large variety of complementary experiments and theoretical tool

Hadron structure

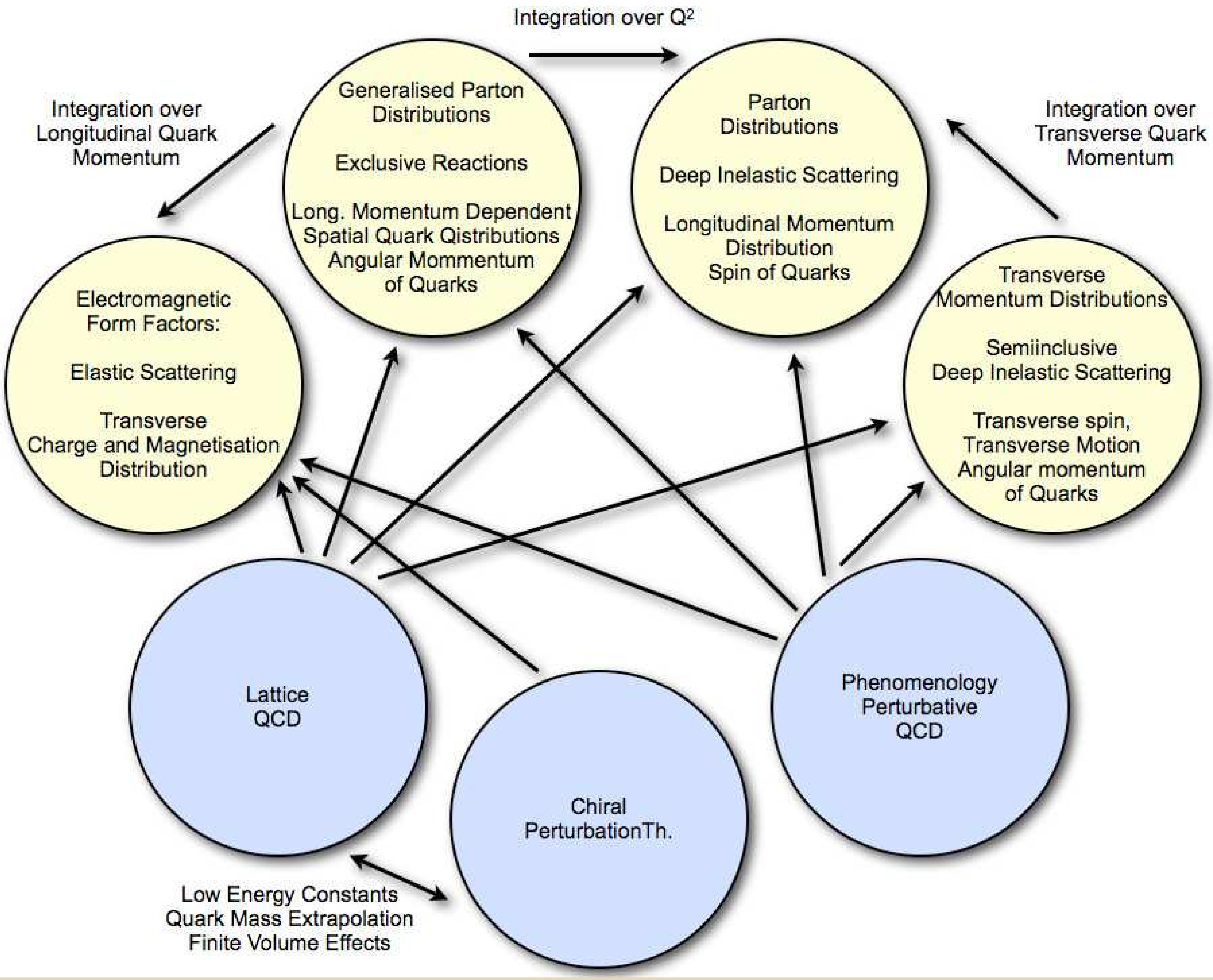
In QCD coupling strength becomes small for particles with high momenta (asymptotic freedom).

- On distance scales smaller than 0.1 Fermi ⟶ perturbative QCD (point-like quarks and gluons)

- On distance scales of the order of 1 Fermi (the size of a nucleon)
  ⟶ the running coupling becomes large ⟶ non-perturbative regime
  (corresponds to the energies and momenta relevant to most of nuclear physics)
  ⟶ observed particles are not quarks and gluons but colourless baryons and mesons

How does the internal structure of baryons and mesons emerge from the dynamics of quarks and gluons?

Investigating by response to probes (virtual or real photons)



Integration over Q^2

Integration over Longitudinal Quark Momentum

Integration over Transverse Quark Momentum

Generalised Parton Distributions

Exclusive Reactions

Long. Momentum Dependent Spatial Quark Qistributions Angular Mommentum of Quarks

Parton Distributions

Deep Inelastic Scattering

Longitudinal Momentum Distribution
Spin of Quarks

Electromagnetic Form Factors:

Elastic Scattering

Transverse Charge and Magnetisation Distribution

Transverse Momentum Distributions

Semiinclusive Deep Inelastic Scattering

Transverse spin, Transverse Motion Angular momentum of Quarks

Lattice QCD

Chiral PerturbationTh.

Phenomenology Perturbative QCD

Low Energy Constants
Quark Mass Extrapolation
Finite Volume Effects

Electromagnetic form factors

FFs of baryons ⟶ fundamental observables in hadron physics

⟶ Directly related to the distribution of charge and magnetization of the baryon

Explored in elastic lepton scattering ⟶ negative (space-like) momentum transfer ⟶ spatial charge and magnetization distribution

Annihilation processes ⟶ positive (time-like) momentum transfer ⟶ coupling of photon to hadron trough vector mesons

EFT models (constituent quark model, bag model) and ChPT and LQCD ⟶ estimate form factors

Other fields:

- hydrogen hyperfine splitting (measured to 13 digits, to similar accuracy calculated in QED)
- experiments on parity violating electron scattering ⟶ extraction of strange form factors

experimental programs $\longrightarrow$ JLAB (high momentum transfer), MAMI (low momentum transfer)

Interesting result: $\lim_{q^2 \to 8} G_E = 0$, while G_M follows a dipole form

For time-like form factors $\longrightarrow$ precise experimental data from the B-factory e^+e^- colliders and from antiproton-annihilation experiments at LEAR

Parton distributions

The internal quark-gluon structure encoded in correlation functions $\longrightarrow$ the simplest ones the unpolarised and polarised parton distribution functions (PDFs)

$\longrightarrow$ accessed in DIS (number density of partons of type q inside a proton, carrying a momentum fraction x and seen at a distance 1/Q)

Successful prediction of the scale (Q^2) dependence of the PDFs

Still unsolved puzzle: spin of the proton is carried only to about one third by the quark spins $\longrightarrow$ polarised strange quark sea, gluon helicity distribution (COMPASS, HERMES)

Transverse momentum dependent parton distributions

Information on the intrinsic motion of quarks and gluons inside a fast moving nucleon

Semi inclusive deep inelastic scattering (SIDIS) $\longrightarrow$ The hadron, which results from the fragmentation of a scattered quark, “remembers” the original transverse motion of the quark

TMD experiments $\longrightarrow$ HERMES at DESY, COMPASS at CERN

Open issues:

- Q^2 evolution of transversity must be tested (double transverse spin asymmetry)
- Sivers effect (relating intrinsic motion of unpolarized partons to parent nucleon spin) must be confirmed
- Collins effect (relating transverse spin of a fragmenting quark to transverse motion of the resulting hadron) $\longrightarrow$ Q^2 evolution

Generalised parton distributions

Establish a connection between fundamental QCD, phenomenology and experimental observables.

Accessed in hard exclusive leptoproduction of a photon or a meson, where the virtual photon four-momentum transfer provides the hard scale

GPDs provide a way to access the contribution of the orbital angular momentum of the quarks to the nucleon's spin $\longrightarrow$ largely unknown

GPDs are Fourier transforms of matrix elements in QCD for lightcone bilocal operators between nucleon states of different momenta

Current/finished experiments: JLAB, HERMES, ZEUS

Future experiments: COMPASS, upgraded JLAB

Hadron spectroscopy

Relevant degrees of freedom of the QCD Lagrangian are not the relevant ones for hadrons

The potential $\longrightarrow$ Coulomb like part and a confining part

Not sufficient to bind the quark and the antiquark by the exchange of a single gluon $\longrightarrow$ a flux of multiple gluons confined to a tube (due to the gluon self-interaction)

Interaction between gauge bosons $\longrightarrow$ prediction of bound states containing solely gluons (glueballs) or states where gluonic excitations of the flux tube contribute to the overall features of a bound quark-antiquark pair (hybrids)

Glueball candidate: $f_0(1500)$ $\longrightarrow$ not unanimously accepted

Hybrid searches: $\pi_1(1400), \pi_1(1600)$ $\longrightarrow$ not confirmed

Investigation of baryon resonances $\longrightarrow$ final states include $\eta N, \omega N, \pi\pi N, \pi\eta N, K\Lambda, K\Sigma$

Important role of EFTs and LQCD

Meson spectroscopy

Direct charmonium formation in e^+e^- annihilations $\longrightarrow$ states with quantum numbers of the photon: $J/\psi, \psi', \psi(3770)$ resonances

Charmonium states with different quantum numbers $\longrightarrow$ decay of these resonances (BESIII experiment)

At higher energies $\longrightarrow$ photon-photon fusion, initial state radiation and B-meson decay

Radiative decays of charmonia are considered to be glueball rich

All charmonium states can be directly formed in antiproton-proton annihilations

At the B-factories discovered several states not fitting into the pattern $\longrightarrow$ X, Y, Z states (e.g. Z^+ particles must be a multiquark state containing two lighter quarks together with the charm-anticharm quarks) $\longrightarrow$ can be investigated in the future by PANDA at FAIR

Lowest-mass charmonium hybrids are predicted to have exotic quantum numbers $\longrightarrow$ identification is possible

Baryon spectroscopy

The very nature of the degrees of freedom building up baryons (and mesons) still an open problem

The constituent quark model predicts far more states than actually observed for masses larger than ≈ 1.9 GeV $\longrightarrow$ Not observed, because they couple primarily to channels (e.g. twomeson-or vector-meson-production) which have not been well-studied experimentally in contrast to the πN channel, or the dynamical assumption that all possible combinations of three quark states compatible with the colour symmetry exist as physical states is not correct $\longrightarrow$ LQCD calculations

Multi-meson final states provide important information to study the decay dynamics of highly excited baryon resonances $\longrightarrow$ ELSA, JLAB, MAMI

PANDA experiment $\longrightarrow$ charmed baryon production from antiproton-proton collisions $\longrightarrow$ no production of extra kaons or D mesons is required to conserve strangeness or charm $\longrightarrow$ reduced energy threshold as e.g. compared to pp collisions

Theory: study of excited states on the lattice combined with EFT

Hadronic interactions

A good description of the N-N interaction ⟶ understanding of the nuclear world

The theoretical work at low energies ⟶ either purely phenomenological interaction potentials or potentials based on the meson-exchange picture (Yukawa)

Recent theoretical progress to derive the nuclear force potential with LQCD ⟶ long-range attraction and short-range repulsion at the same time

EFTs: used to relate experimental observables to quantities that can be calculated with LQCD

Progress in the derivation of nuclear forces from chiral EFT

Techniques are now being extended to Hyperon-Nucleon and Hyperon-Hyperon forces

More experimental data on the $Y-N$ and $Y-Y$ interactions is needed

Hyperons ⟶ short life ⟶ Hypernuclei instead

$Y - N$ interaction by the non-mesonic decays

Λ is embedded in a nucleus ⟶ new non-mesonic weak decay modes (NMWD), $\Lambda + n \rightarrow n + n, \Lambda + p \rightarrow n + p$

The study of the NMWD is of fundamental importance ⟶ it provides primary means of exploring the four baryons, strangeness changing, weak interaction $\Lambda + N \rightarrow N + N$

Searching for $\Lambda\Lambda-$Hypernuclei ⟶ 5 event up to now ⟶ importance: production of $H-$particle (dihyperon predicted by Jaffe) ⟶ PANDA at FAIR

In medium effects ⟶ Theory predicts strong modifications of the kaon and anti-kaon properties in a dense hadronic environment (mass and with change)

Recently indication for the so-called Anti-Kaon Nuclear Clusters (AKNC) was found ⟶ states in which a $K(K^-)$ is strongly bound to some nucleons ⟶ confirmation required

Conclusion

- Hadron physics is at the interface of elementary particle physics that deals with pointlike particles in the high-energy limit and our existing world of complex, structured objects that are an ensemble of these fundamental particles

- The complexity of understanding hadrons and ultimately nuclei requires a coordinated research effort