Aspirations of the QCD research community

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Where do we stand?

• QCD firmly established as theory of strong interactions
• Remarkably simple Lagrange density

\[ \mathcal{L}_{\text{QCD}} = -\frac{1}{4} F_{\mu \nu}^a F_{\alpha \mu \nu}^a + \bar{\psi}(i \mathcal{D} - m) \psi \]

• Enormously rich phenomenology
• Many successful qualitative explanations and predictions
• Quantitative understanding not always feasible
Where do we stand?

• QCD at high energies: weak coupling and asymptotic freedom
  • Perturbative QCD as quantitative framework
  • Dynamics of quarks and gluons
  • Jet observables were early test of QCD
  • Factorization separates weak from strong coupling effects

• Quantitative predictions
  • Multi-loop calculations for inclusive quantities
  • Higher orders (NLO, NNLO, ...), resummation and parton shower simulation
  • Strong coupling dynamics parametrized in parton distributions, hadronization
Where do we stand?

- Precision tests of the Standard Model
- Measurements of masses and couplings
- Interplay of calculations and measurements
  - Accuracy on most cross sections $\geq 5\%$
  - Limited by PDFs, QCD corrections
- Perturbative QCD as analysis tool
  - Jet substructure techniques
  - Data-driven background predictions
Where do we stand?

• QCD at strong coupling: diverse research program
  • Hadron physics, low-energy dynamics, heavy ions
  • Precision spectroscopy of light hadrons ↔ lattice QCD at high precision
  • Determination of hadron properties
    • Proton radius
    • Form factors
    • Nucleon structure

• Demands and drives new quantitative approaches
  • Understanding non-perturbative dynamics of QCD
Where do we stand?

• Crucial interplay between QCD at strong and at weak coupling

• Non-perturbative effects on precision collider observables
  • Parton distributions
  • Intrinsic transverse momentum
  • Soft underlying event and hadronization

• Hadronic input to SM tests and BSM searches
  • Form factors in flavor physics
  • Hadronic cross sections in neutrino and astroparticle physics
  • Hadronic effects in QED precision observables: $\alpha(M_Z)$, $(g-2)_\mu$
Where do we stand?

• Feed-in and feed-back between strong and weak coupling QCD

• Example: photon content of the proton (photon PDF)
  • Important ingredient to EW corrections of collider processes
  • Required for precision predictions at highest energies
  • Previously ad-hoc models with large uncertainty
  • LUXqed
    • relate to elastic and inelastic form factors
    • Exploit low-energy data
    • Combine with perturbative QCD evolution

• Different motivation to address similar questions
The challenges ahead

- Precision physics at HL-LHC and future high-energy colliders (G. Salam, D.d’Enteria)
- Aiming for ultimate precision in Standard Model tests and searches
  - Direct and indirect probes of physics at much higher energy scales
  - Sub-per-mille level precision on $M_W$, $M_{top}$, $\alpha_s$
  - Requires major leaps in QCD+EW theory and experiment
- QCD theory into novel data analysis techniques

![Graph showing expected relative uncertainty for various processes](image)
The challenges ahead

• Nucleon structure: parton distributions (U.Klein, J.P.Lansberg)
  • Precision on large-\(x\), highest-\(Q^2\), flavor decomposition
  • Reliable quantification of uncertainties (theory and experiment)
  • Ultimate precision on theory framework

• Establish three-dimensional nucleon structure (D. Boer)
  • Spin-dependent parton distributions
  • Transverse-momentum structure
  • Semi-inclusive observables
The challenges ahead

- Understand and predict hadronic cross sections (T. Pierog, D. Boer)
  - Soft production mechanisms in vacuum and QCD medium
  - Interplay with heavy-ion physics (U. Wiedemann, J. Stachel, T. Galatyuk)
  - Quantitative input for high-energy cosmic radiation, neutrino physics

- QCD predictions at strong coupling (H. Wittig)
  - Lattice QCD: improvements and novel applications
  - New methods and approaches
  - Towards first-principles understanding of parton-hadron transition, confinement
The challenges ahead

• Targeted precision studies at low energies (K. Kirch)
  • Searches for new physics: QCD $\theta$-term (strong CP-problem), charge radii
  • Antimatter spectroscopy
  • Exotic bound states: hadronic atoms, multi-quark states
  • QED-QCD interplay: hadronic vacuum polarization, light-by-light scattering

• Better exploit synergies between QCD at weak and strong coupling
QCD at future facilities

- Highest-precision QCD program at FCC-ee (D.d’Enteria)
  - Precision measurements, hadronization, light and heavy flavour spectroscopy

- High-energy frontier: HL-LHC and FCC-hh (G.Salam)
  - Precision QCD predictions crucial to all aspects of physics exploitation
  - Open up new kinematical regimes for QCD studies

- Specific precision experiments (K.Kirch)
  - MuOnE, PSI muon and neutron programs
QCD at future facilities

• Lepton-hadron collisions from low to high energies
  (D. Boer, U.Klein)
  • Elastic, inelastic and deeply inelastic scattering on fixed targets at
    PBC@CERN (COMPASS++/AMBER): nucleon interactions and
    structure
  • Medium energy range US-based EIC project: 3D nucleon structure
  • High-energy frontier LHeC, FCC-eh: ultimate precision on PDF and
    QCD studies

• Fixed-target hadron physics program
  (G.Schnell, J.P.Lansberg)
  • PBC@CERN (DIRAC++, COMPASS++): spectroscopy, hadron structure
  • Fixed target at HL-LHC: benchmark processes
Aspirations of the QCD research community

• Optimal scientific exploitation of present and future measurements
  • QCD effects are ubiquitous in all areas of particle and astroparticle physics
  • Strive for highest accuracy and robustness in description and understanding

• Understanding of the strong interaction
  • Map out nucleon structure
  • Aim for first-principles predictions at strong coupling

• Large scientific diversity as a major strength
  • Fruitful interplay between research at strong and weak coupling