Theoretical perspectives on QCD

Thomas Gehrmann

Universität Zürich

European Research Council
Established by the European Commission

Swiss National Science Foundation

Where do we stand?

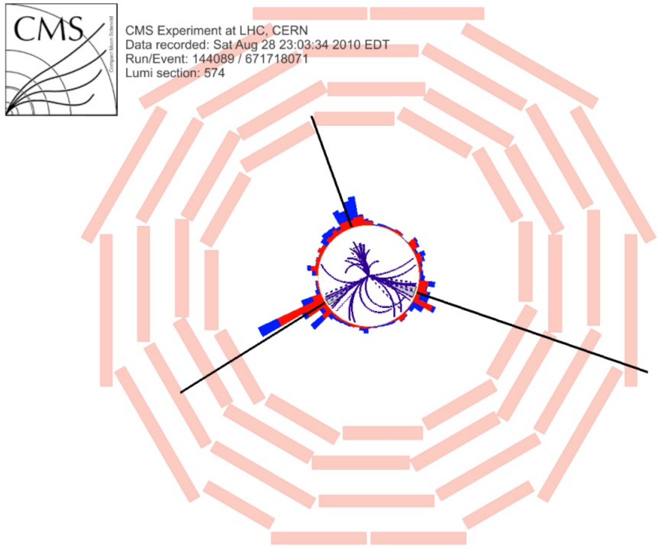
- QCD firmly established as theory of strong interactions
- Remarkably simple Lagrange density

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$$

- Enormously rich phenomenology
- Many successful qualitative explanations and predictions
- Quantitative understanding not always feasible

Where do we stand?

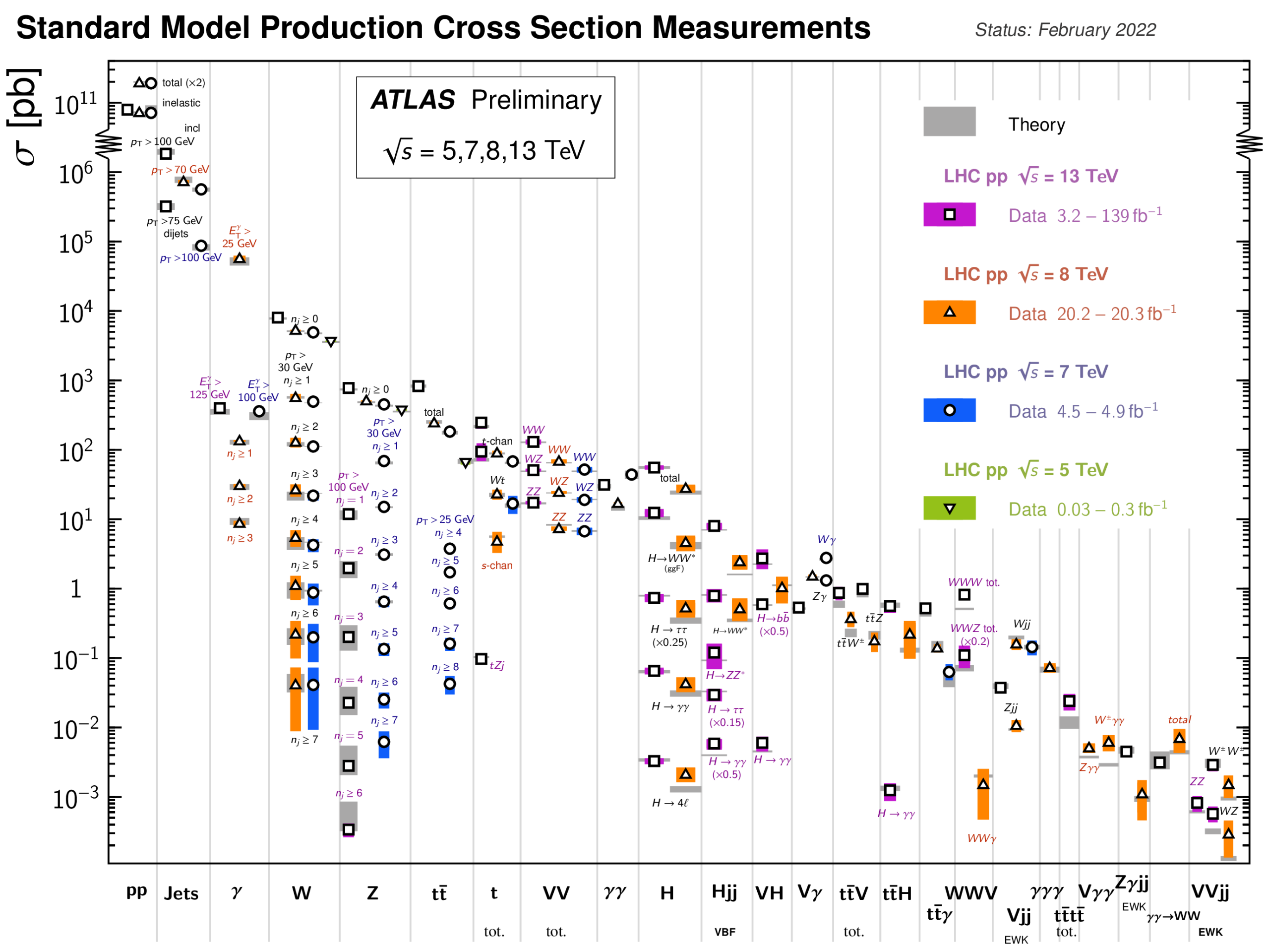
- QCD at high energies: weak coupling and asymptotic freedom
  - Perturbative QCD as quantitative framework
  - Dynamics of quarks and gluons
  - Jet observables were early test of QCD
  - Factorization separates weak from strong coupling effects



- 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

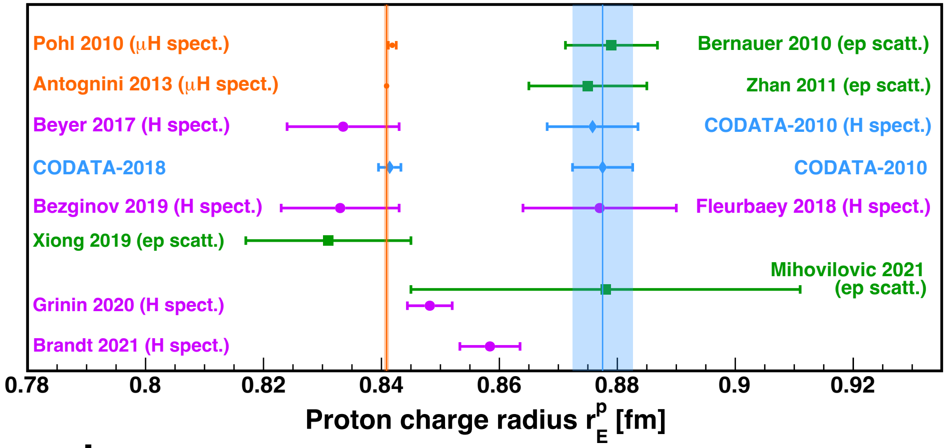
Where do we stand?

- Precision tests of the Standard Model
  - Measurements of masses and couplings
- Interplay of calculations and measurements
  - Accuracy on cross sections ≳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

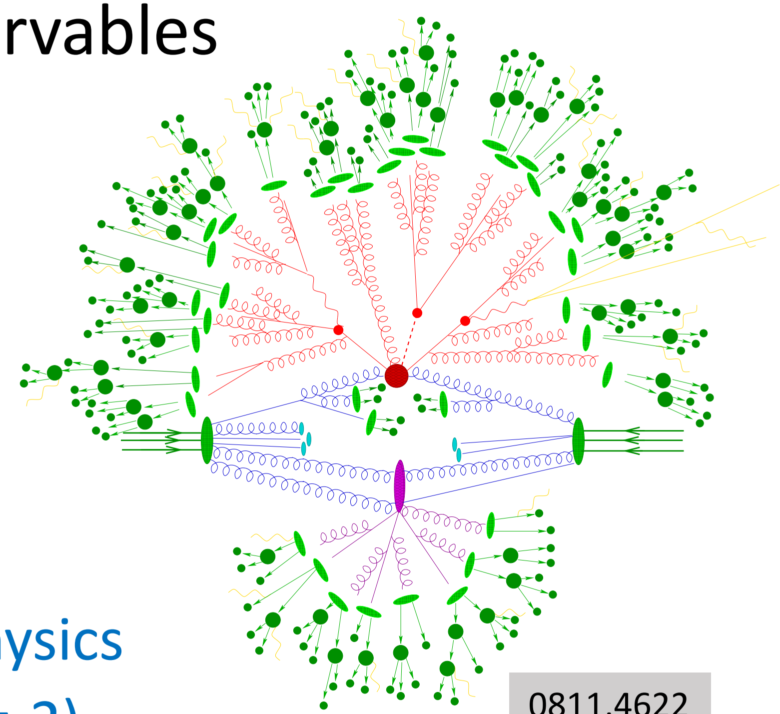


2302.13818

- 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: $\alpha(M_Z)$, $(g-2)_\mu$

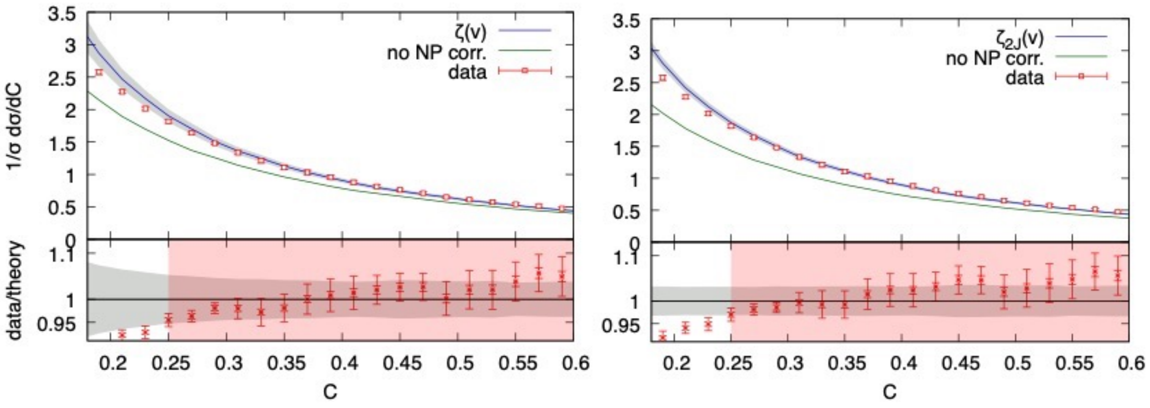


0811.4622

Where do we stand?

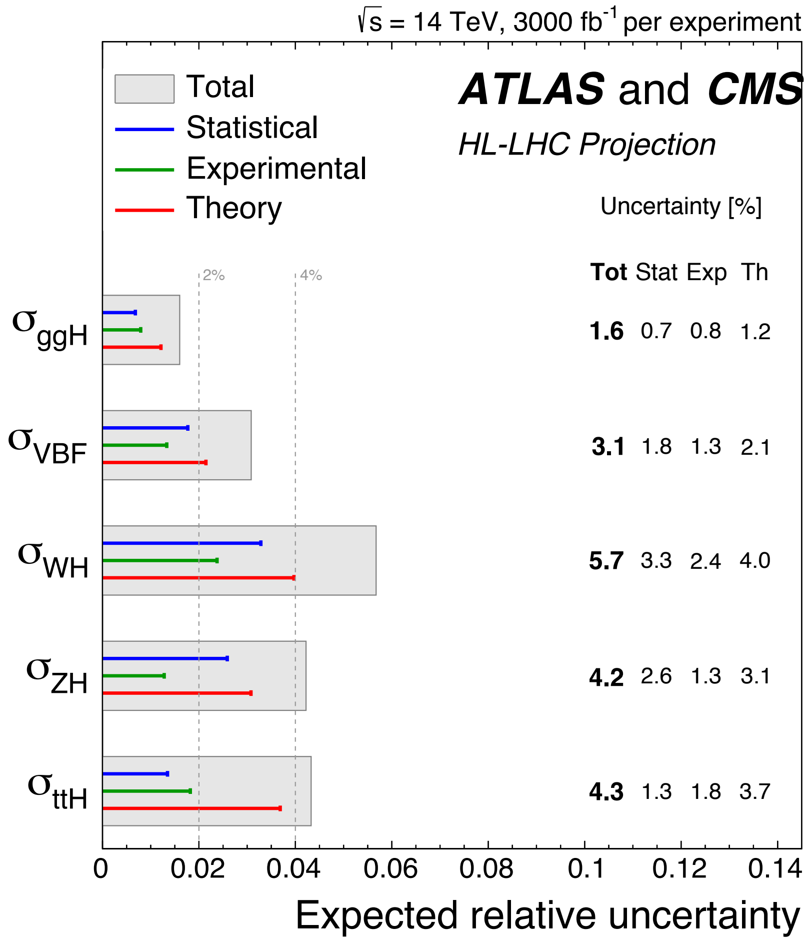
- Feed-in and feed-back between strong and weak coupling QCD
- Example: hadronization effects and power corrections
  - QCD at colliders predicts partons, experiments observe hadrons
  - hadronization effects typically power-suppressed
  - quantitative description required for precision physics
  - re-assessment of power corrections to event shapes in e^+e^-
    - dispersive model for full kinematics
    - major effect on interpretation of LEP data: $\alpha_s(M_Z)$: 0.1128(11) $\rightarrow$ 0.1174(12)
- Precision versus accuracy !

2204.02247
2301.03607



The challenges ahead

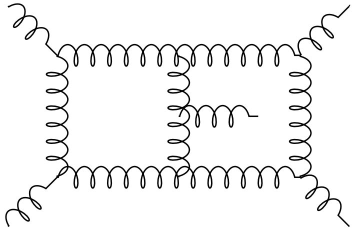
- Precision physics at HL-LHC and future high-energy colliders
- Aiming for ultimate precision in Standard Model tests and searches
  - Direct and indirect probes of physics at much higher energy scales
  - Sub-per-mille level precision on M_W, M_{top}, α_s
  - Requires major leaps in QCD+EW theory and experiment
- QCD theory into novel data analysis techniques



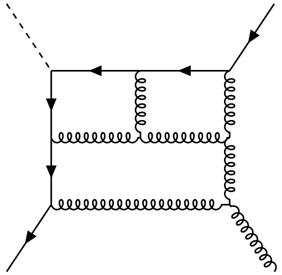
1902.00134

The challenges ahead

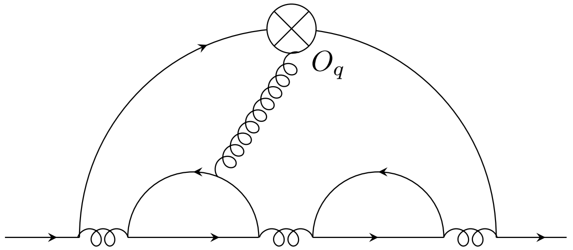
- Precision calculations in perturbative QCD
  - major technical challenges in computation of loop amplitudes
  - analytical versus numerical approaches
  - often triggering developments in mathematics and computer algebra
- Application in precision phenomenology
  - theory prediction closely mimics experimental analysis
  - require fast and reliable numerical implementations



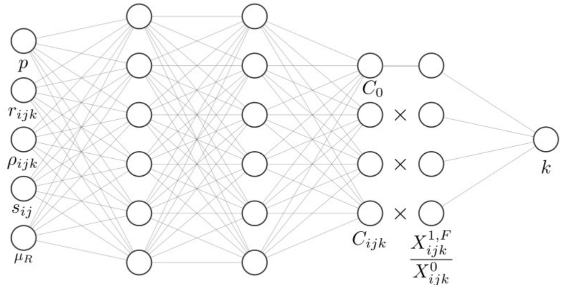
2311.10086



2307.15405



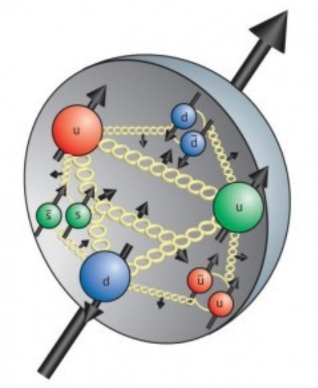
2308.07958



2302.04005

The challenges ahead

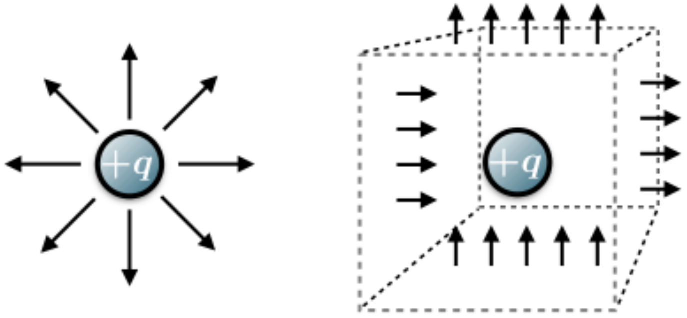
- Nucleon structure: parton distributions
  - Precision on large-x, highest-Q^2, flavour decomposition
  - Reliable quantification of uncertainties (theory and experiment)
  - Ultimate precision on theory framework
- Establish three-dimensional nucleon structure
  - Spin-dependent parton distributions
  - Transverse-momentum structure
  - Semi-inclusive observables



The challenges ahead

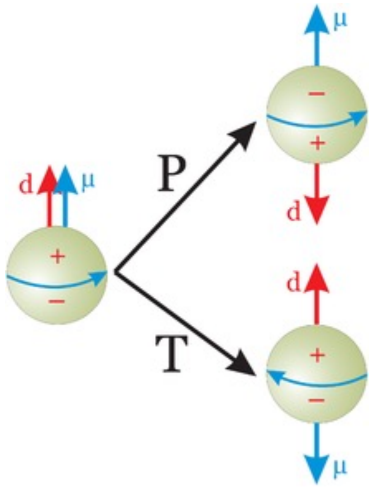
- Understand and predict hadronic cross sections
  - Soft production mechanisms in vacuum and QCD medium
  - Interplay with heavy-ion physics
  - Quantitative input for high-energy cosmic radiation, neutrino physics

- QCD predictions at strong coupling
  - 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
  - Searches for new physics:
    QCD θ-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

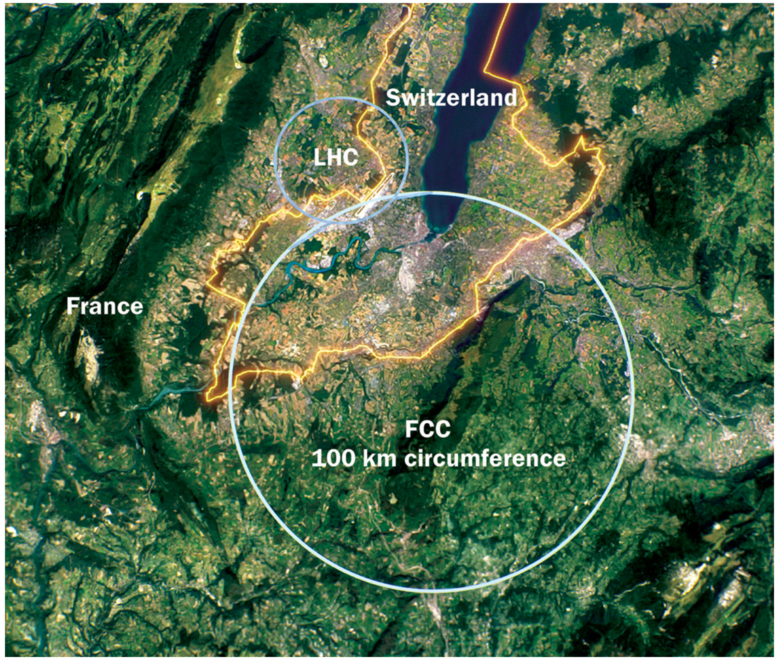


- Better exploit synergies between QCD at weak and strong coupling

QCD at future facilities

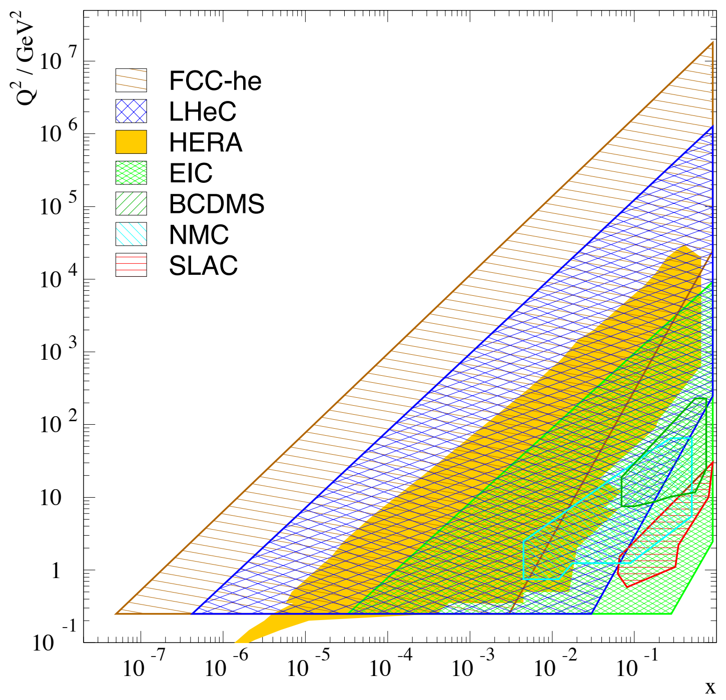
- Highest-precision QCD program at FCC-ee/CEPC
  - Precision measurements, hadronization, light and heavy flavour spectroscopy

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



QCD at future facilities

- Lepton-hadron collisions from low to high energies
  - Elastic, inelastic and deeply inelastic scattering on fixed targets at CERN (AMBER): nucleon interactions and structure
  - EIC project at BNL: 3D nucleon structure
  - High-energy frontier proposals LHeC, FCC-eh: ultimate precision on PDF and QCD studies
- Specific precision experiments
  - MuOnE, PSI muon and neutron programs



2007.14491

Perspectives for QCD research

- 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