Aspirations of the QCD research community

Thomas Gehrmann

Where do we stand?

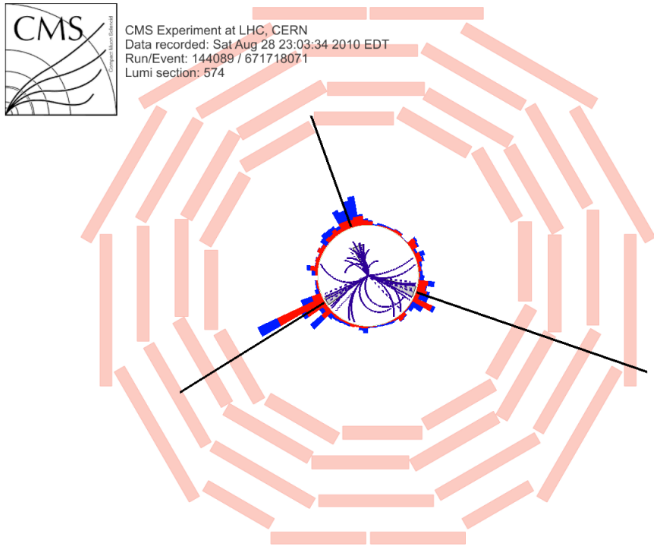
- QCD firmly established as theory of strong interactions
- Remarkably simple Lagrange density

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

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

Where do we stand?

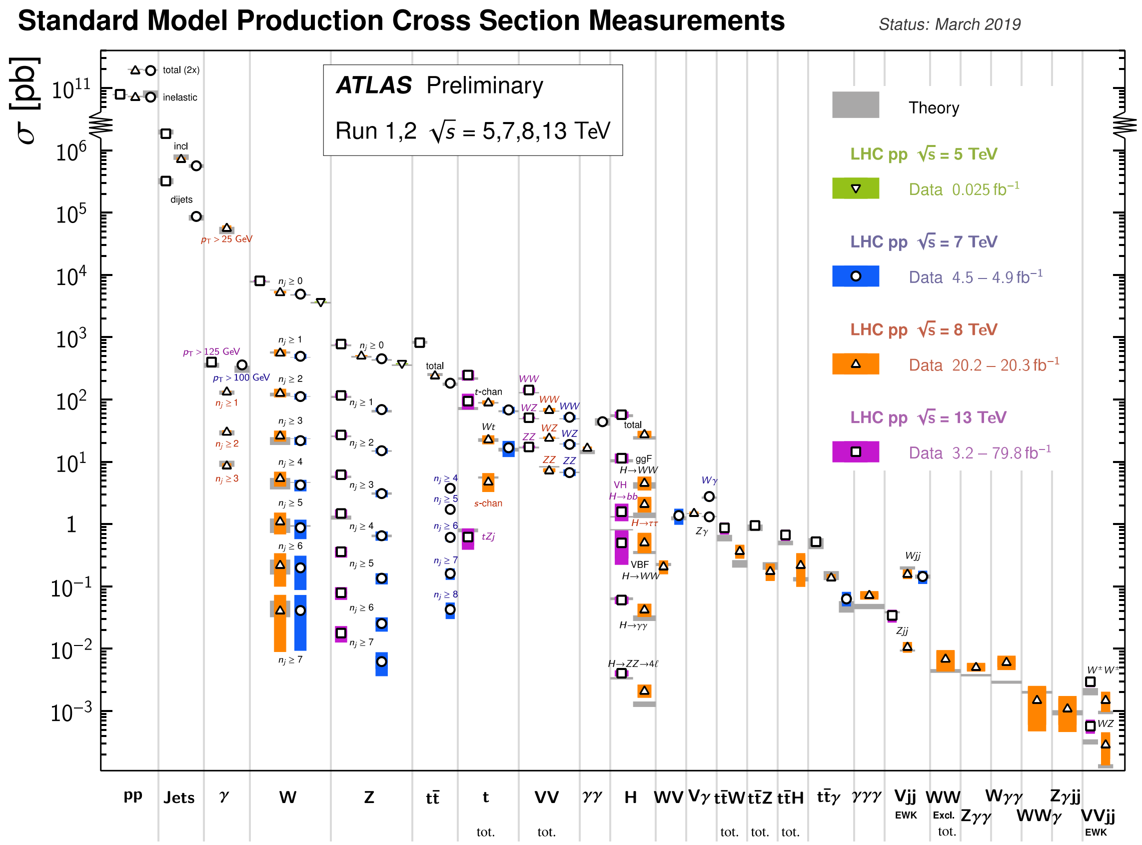
- QCD at high energies: weak coupling and asymptotic freedom
  - Perturbative QCD as quantitative framework
  - Dynamics of quarks and gluons
  - Jet observables were early test of QCD
  - Factorization separates weak from strong coupling effects



- 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

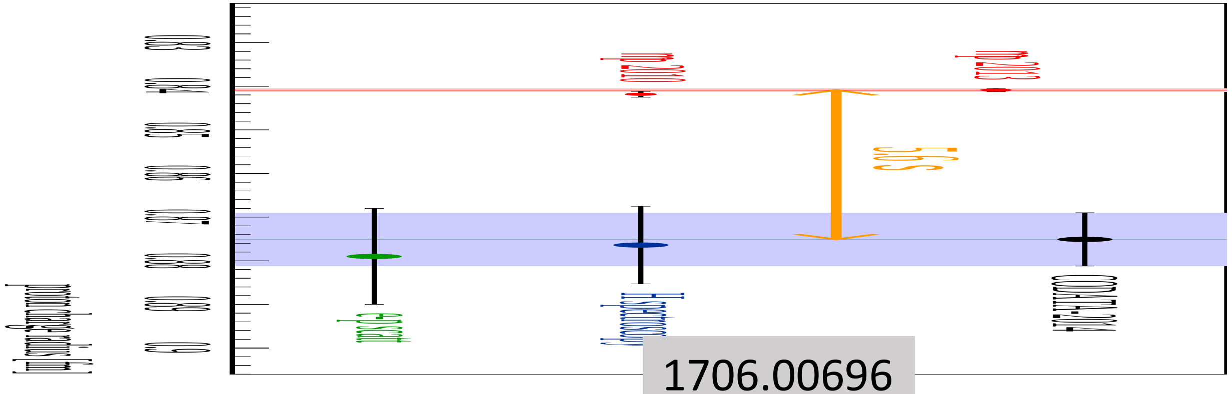
Where do we stand?

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



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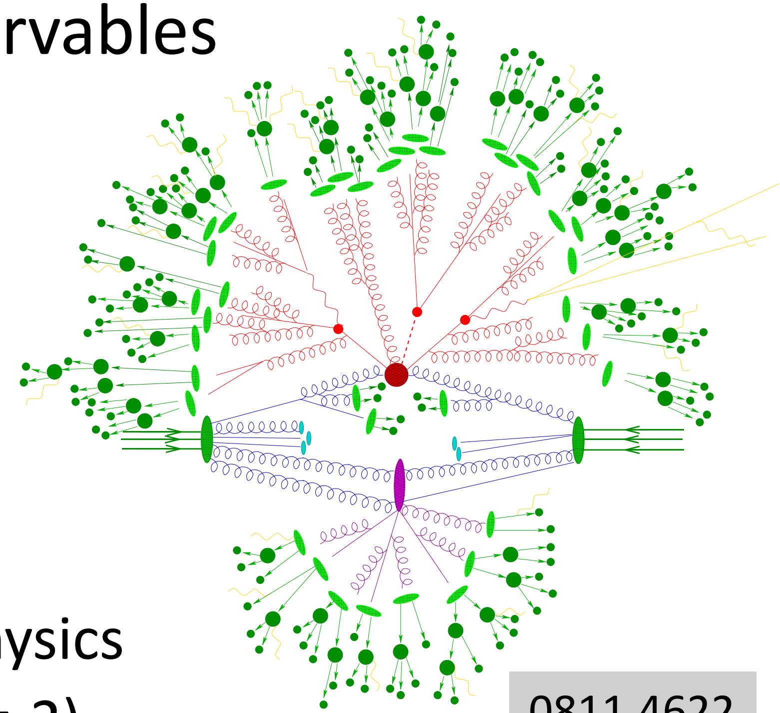
- Demands and drives new quantitative approaches
  - Understanding non-perturbative dynamics of QCD

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



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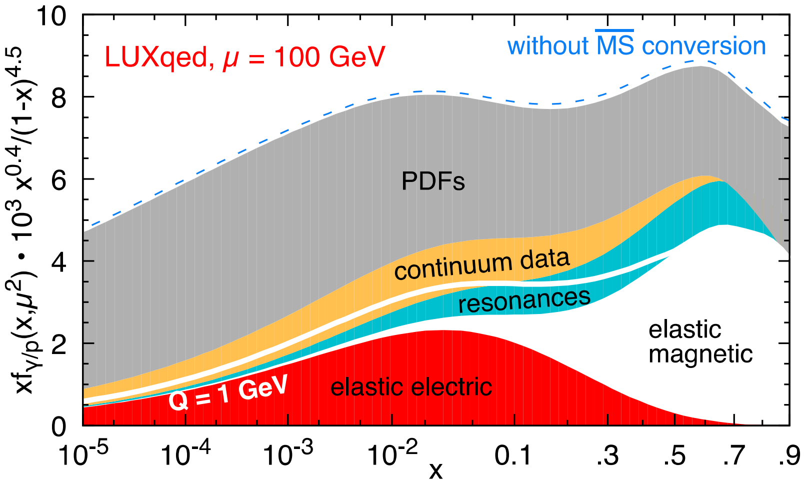
Where do we stand?

- 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



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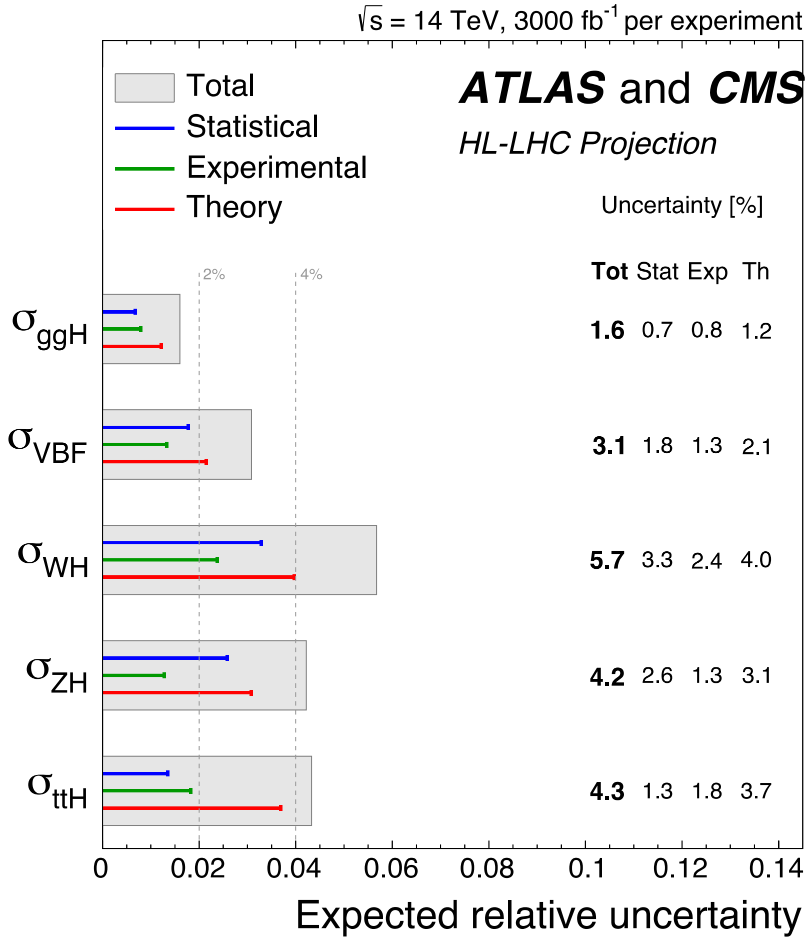
The challenges ahead

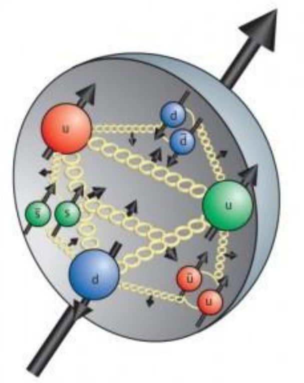
- Precision physics at HL-LHC and future high-energy colliders (G. Salam, D.d'Enteria)
- Aiming for ultimate precision in Standard Model tests and searches
  - Direct and indirect probes of physics at much higher energy scales
  - Per-mille level precision on M_W, M_{top}, α_s
  - Requires major leaps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



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

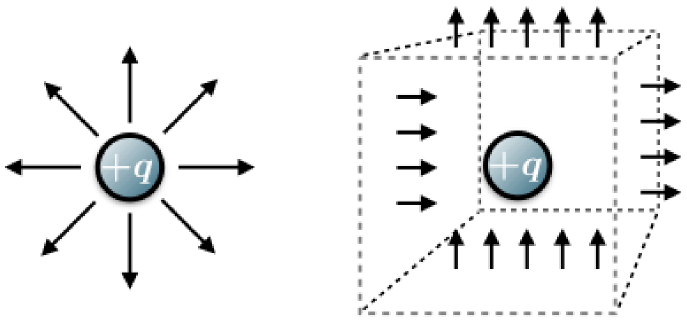
- Establish three-dimensional nucleon structure (D. Boer)
  - Spin-dependent parton distributions
  - Transverse-momentum structure
  - Semi-inclusive observables



The challenges ahead

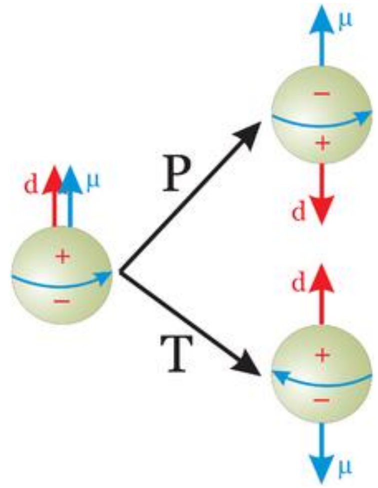
- Understand and predict hadronic cross sections (T. Pierog, D.Boer)
  - Soft production mechanisms in vacuum and QCD medium
  - Interplay with heavy-ion physics (U.Wiedemann, J.Stachel, T.Galatyuk)
  - Quantitative input for high-energy cosmic radiation, neutrino physics

- 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

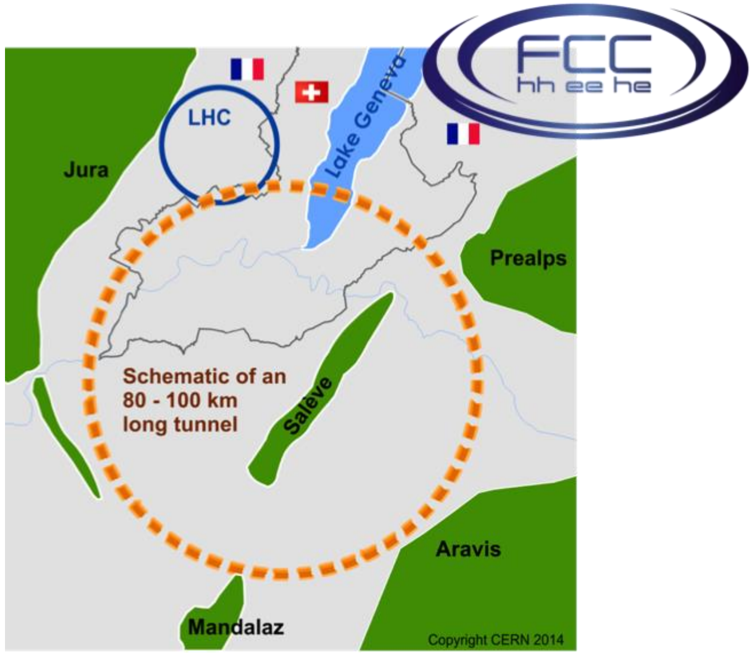
- Targeted precision studies at low energies (K.Kirch)
  - Searches for new physics:
    QCD θ-term (strong CP-problem), charge radii
  - Antimatter spectroscopy
  - Exotic bound states: hadronic atoms, multi-quark states
  - QED-QCD interplay: hadronic vacuum polarization,
    light-by-light scattering



- Better exploit synergies between QCD at weak and strong coupling

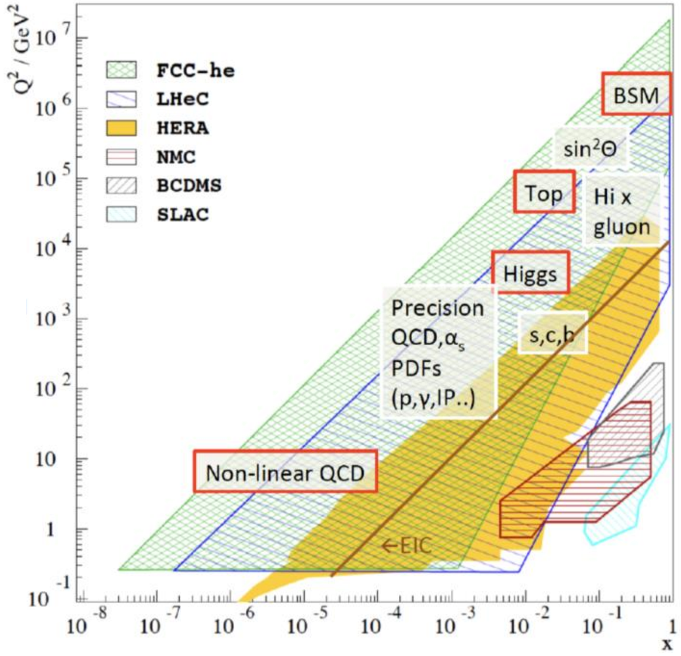
QCD at future facilities

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