Topical Group EF05: Precision QCD

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https://snowmass21.org/energy/qcd

Quantum Chromo Dynamics

- Firmly established as theory of strong interactions
- Remarkably simple Lagrangian

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

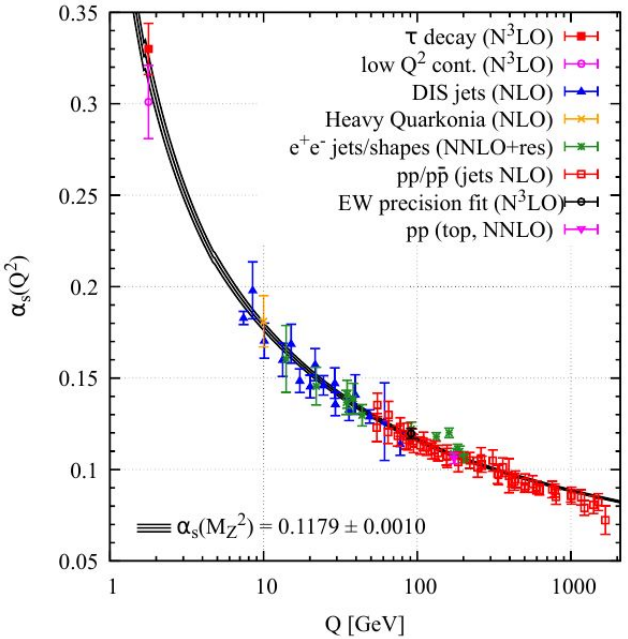
$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu$$

- Rich phenomenology
- Many successful predictions
- Quantitative understanding often challenging

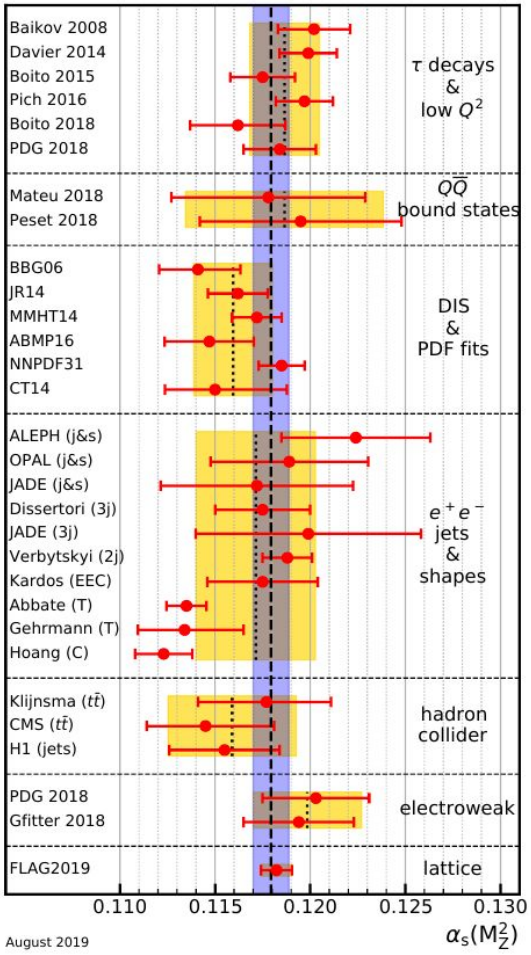
QCD is not the driving force for many future experiments,
but it is crucial for understanding them!

Strong Coupling

- Least well known coupling in SM
- What precision can be attained in next 10 years?

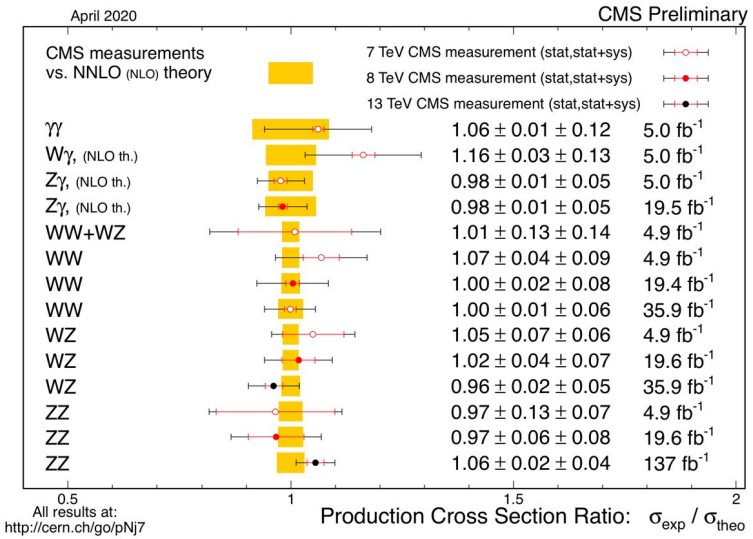


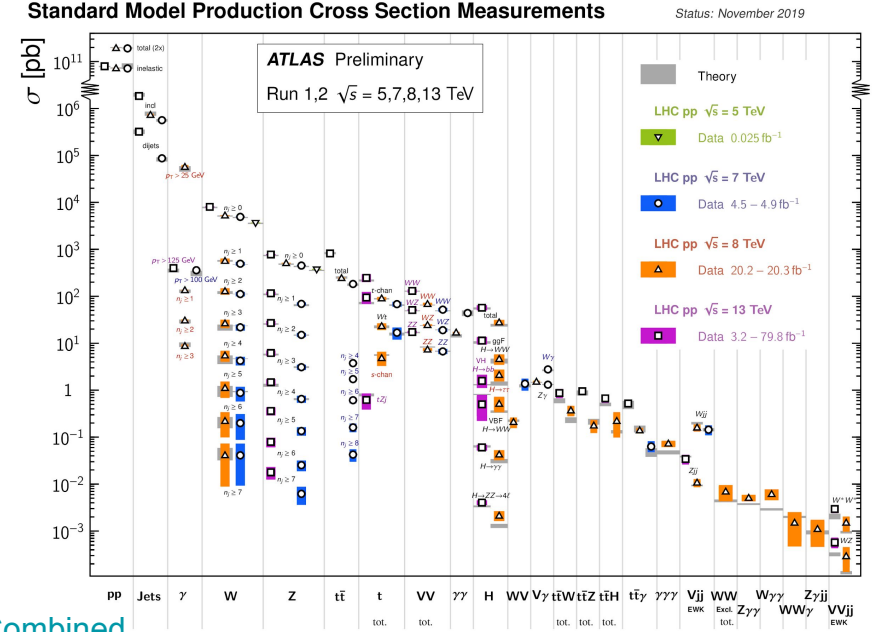
http://pdg.lbl.gov/



Precision tests of the Standard Model

- Precision QCD as an analysis tool (e.g. studies of Higgs & top quarks)
- Accuracy limited by both PDFs and perturbative expansion

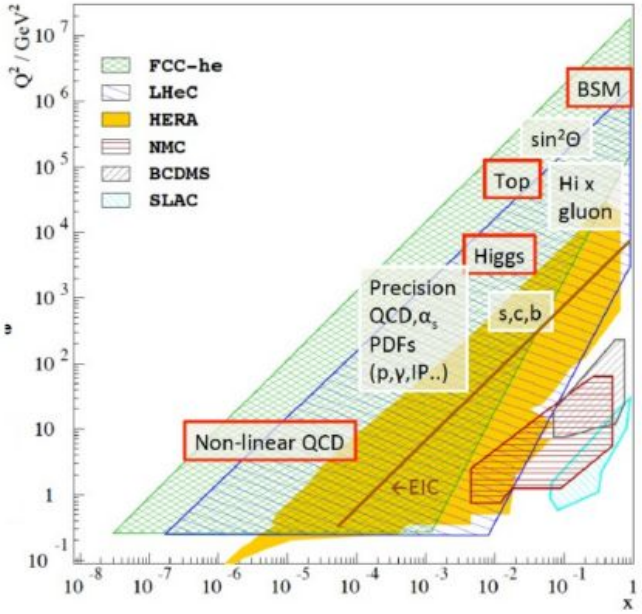


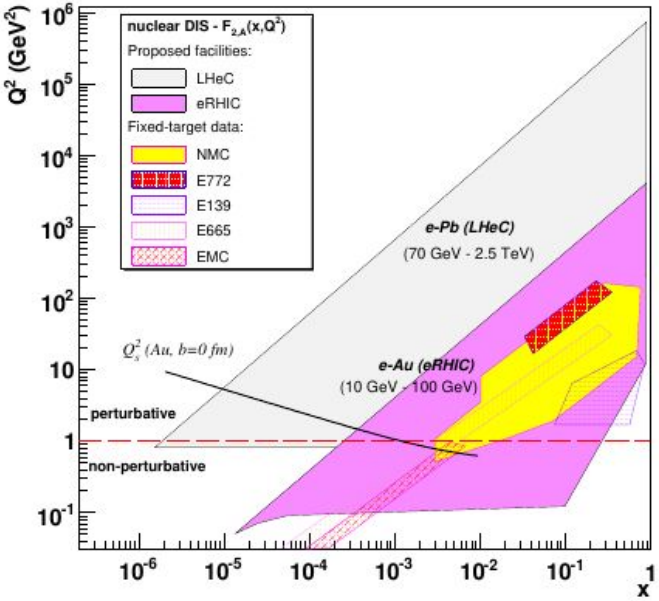


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Parton Distributions

- Probed in a wide range by collider analyses
- Which calculations & measurements are needed to improve fits?
- EIC is a new frontier and an exciting development

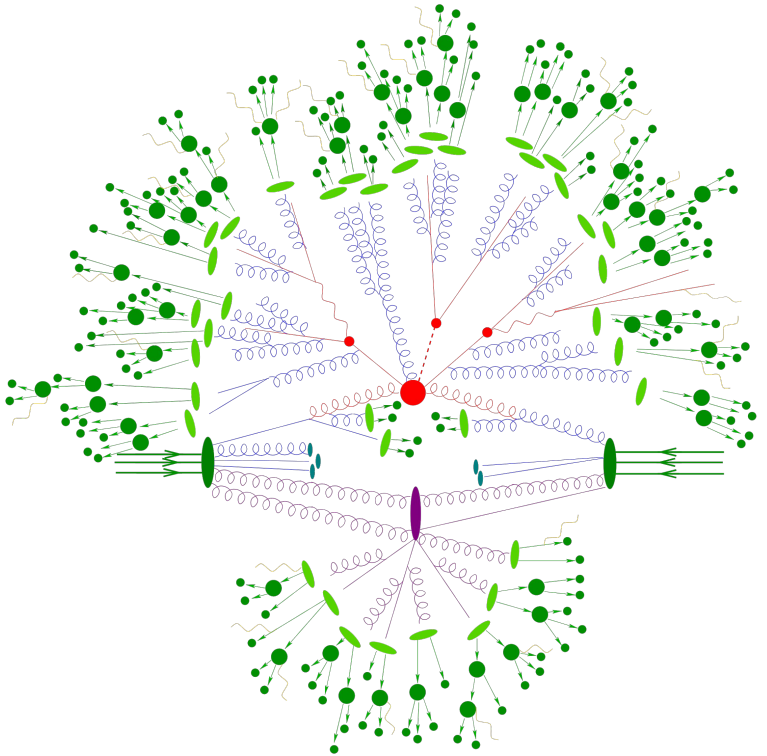




https://arxiv.org/abs/1910.11775

Interplay between strong and weak coupling

- Impact of non-perturbative effects on precision collider observables and modeling by MC simulations
  - Intrinsic transverse momentum
  - Hadronization & color reconnection
  - Underlying event and beam remnants
- Hadronic input to SM tests and BSM searches
  - Form factors in flavor physics
  - Hadronic cross sections in neutrino / astrophysics
  - Hadronic effects in QED observables



https://arxiv.org/abs/1101.2599

EF05 proposed study topics

- Strong coupling
  - Measurements and Lattice QCD calculations
  - Level of precision and test of running
- Parton Distributions [with EF06]
  - Measurements needed to improve PDF fits
  - PDF fits needed for higher-order calculations
- Overlap between hadronic physics programs at HL-LHC and EIC
  - Precision calculations for polarized scattering
  - MC simulation for EIC and knowledge transfer from/to LHC [with EF07]
  - Polarized PDFs [with EF06]
- Jet substructure
  - Theoretical calculations and MC modeling
  - Experimental techniques
  - W/Z/H/top tagging

EF05 proposed study topics

- Theoretical calculations - Fixed order pQCD
  - NLO & NNLO calculations → TF04 & TF06 topical groups
    - Survey of results needed for precision physics (NNLO wishlist)
    - Automation of NNLO calculations & embedding in experiments?
  - More advanced calculations needed to reduce theoretical uncertainties
  - Interplay of QCD and EW corrections
- Theoretical calculations - Resummation
  - Event shape variables in e+e-
  - Hadronic event shapes
  - Non-global logarithms (VBF etc.)
  - Usage of Effective Field Theories → TF02 topical group
- Non-perturbative aspects
  - Connections between central and forward QCD [with EF06]
  - Non-perturbative corrections to experimental observables
  - Connections to QIS

EF05 proposed study topics

- Physics Observables
  - Higgs production (including non-SM Higgs)
  - Top-quark production and threshold corrections
  - Drell-Yan, for the extraction of sin2thetaW
  - Di-boson and tri-boson production
  - V+jets, top+jets, Higgs+jets
  - The “ridge” [with EF07]
- MC Event Generators
  - Precision simulation of resolved processes (photons, heavy flavor, ...)
  - Double-parton scattering / multiple parton interactions [with EF06]
  - Hadronization / formation of jets
  - Color reconnection (important at e+e-)
  - Parton showers and connection to resummation
  - Monte Carlo tuning

Please add topics of interest to this list and/or volunteer for a study

Connection to other Frontiers and Topical Groups

EF05 overlaps with many other topical groups

- EF01: EW Physics: Higgs Boson properties and couplings
- EF03: EW Physics: Heavy flavor and top quark physics
- EF04: EW Precision Physics and constraining new physics
- EF06: QCD and strong interactions: Hadronic structure and forward QCD
- EF07: QCD and strong interactions: Heavy Ions
- EF10: BSM: Dark Matter at colliders

- TF02: Effective field theory techniques
- TF04: Scattering amplitudes
- TF05: Lattice gauge theory
- TF06: Theory techniques for precision physics
- TF07: Collider phenomenology

Connection to other Frontiers and Topical Groups

EF05 overlaps with many other topical groups

- CompF1: Experimental Algorithm Parallelization
- CompF2: Theoretical Calculations and Simulation
- CompF3: Machine Learning

- AF3: Accelerators for EW/Higgs
- AF4: Multi-TeV Coliders

- IF3: Solid State Detectors and Tracking
- IF4: Trigger and DAQ
- IF6: Calorimetry
- IF7: Electronics/ASICs
- IF8: Noble Elements
- IF9: Cross Cutting and Systems Integration

Survey of interests

- Conducted a survey among the participants of EF05
- Received 160 replies
- Distribution of interests
  - Physics Observables (Higgs, heavy quarks, Drell-Yan, multi-boson, jets, ...) 56%
  - Perturbative calculations for total and differential cross sections 49.3%
  - Measurements and calculations needed to improve PDF fits 49.3%
  - Jet substructure (Theory & MC modeling, Experimental techniques, Tagging) 48%
  - Monte Carlo event generators (incl. tuning) 46.7%
  - Connections between central and forward QCD 44.7%
  - Interplay of QCD and EW effects 42%
  - Strong coupling determination 42%
  - Simulations for EIC and knowledge transfer from/to LHC 40%
  - Precision resummation 33.3%
  - Non-factorizable corrections, double-parton scattering, color reconnections 30%
  - Non-perturbative QCD & connections to QIS 30%
  - Strong coupling and PDFs from Lattice 18%

Survey of interests

Additional suggestions

- **Connections to AI / Machine Learning**
- Jets at the EIC (including nuclear modification effects in eA collisions)
- Hadron structure from lattice QCD
- Precision small-x calculations, interplay between central & forward
- Applicability region of Regge asymptotics

Community kick-off meeting

Kick-off meeting was held on May 18 https://indico.fnal.gov/event/43273/
Organizational introduction (30min) and discussion (30min)

Comments and suggestions from the discussion:

- There will be a large overlap with the theory frontier
  - Theory groups are also very broad, for example EFTs goes well beyond SCET, Lattice goes well beyond QCD, etc. This might help define boundaries between TF & EF
  - Energy frontier subgroups should focus on applications of theory techniques
- Snowmass is a far reaching study, it should explore new ideas
  - Attack any interesting topics, go beyond just varying collider scenarios
- Synergy with Les Houches workshop should be exploited
- Need mechanism to include existing / ongoing studies as contributed papers, possibly by creating short summary
- Spin physics is a topic to be added [joint with EF06]

Upcoming EF05 topical group meetings

Joint meeting with EF06 & EF07, June 1 https://indico.fnal.gov/event/43488/

- Lessons from Snowmass 2013 - John Campbell & Joey Huston
- Physics Input to European Strategy Update - Gavin Salam
- Accelerator Developments - Dmitri Denisov
- Updates from EIC community - Abhay Deshpande

Following up on this, June 15 https://indico.fnal.gov/event/43490/

- Identification of major topics for the study
- Discussion of technical details (e.g. MC production)
- Exploration of connections to other topical groups

Conclusion

Thank you for joining the Snowmass 2021 effort. This is an exciting time in HEP!

We look forward to your ideas and contributions. We are especially glad to work with such a vibrant and enthusiastic group.

Please join with us at our bi-weekly meetings (Mondays @ 10 AM EDT), on our mailing list (SNOWMASS-EF-05-PRECISION_QCD@FNAL.GOV) and our SLACK channel (ef05-precision_qcd).

We hope to see you at our next meeting on June 1st