Precision QCD Physics Input to European Strategy Update

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Rudolf Peierls Centre for Theoretical Physics and All Souls College
University of Oxford

Snowmass Energy-Frontier Workshop — Open Questions and New Ideas
21 July 2020, EF01–04 parallel session

* on leave from CERN TH department and from CNRS (LPTHE)
European Particle Physics Strategy Update (EPPSU), 2018 – 2020

➤ http://europeanstrategyupdate.web.cern.ch/welcome

➤ Major preparatory work on approved and proposed future colliders, e.g.
  ➤ Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC
  ➤ FCC physics and design reports

➤ Submitted input: https://indico.cern.ch/event/765096/contributions/ (10pp/doc)

➤ Open Symposium (May 2019), including strong interactions session & summary


➤ January 2020: final closed meeting of European Strategy Group

➤ Final strategy document published June 2020
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Scientific aspirations of the community in strong interactions
Albenz+Machuca Room, Granada Conference Center
09:00 - 09:20

Discussion

Albenz+Machuca Room, Granada Conference Center
09:20 - 09:30

Experimental QCD physics at future pp and e+e- colliders
David d'Enterria
Albenz+Machuca Room, Granada Conference Center
09:30 - 09:50

Discussion

Theoretical path for QCD physics
Gavin Salam
Albenz+Machuca Room, Granada Conference Center
10:00 - 10:20

Discussion

Albenz+Machuca Room, Granada Conference Center
10:20 - 10:35

Reserve

Albenz+Machuca Room, Granada Conference Center
10:35 - 10:50

Coffee break

Albenz+Machuca Room, Granada Conference Center
10:50 - 11:15

Strong Interaction physics with the (HL-)LHC pre-accelerator complex
Gunnar Splitt
Albenz+Machuca Room, Granada Conference Center
11:15 - 11:45

Discussion

Albenz+Machuca Room, Granada Conference Center
11:45 - 12:00

Precision QCD physics at low energies
Klaus Kirch
Albenz+Machuca Room, Granada Conference Center
12:00 - 12:20

Discussion

Albenz+Machuca Room, Granada Conference Center
12:20 - 12:30

Lattice QCD: challenges and opportunities
Herbert Wetzl
Albenz+Machuca Room, Granada Conference Center
12:30 - 12:50

Discussion

Albenz+Machuca Room, Granada Conference Center
12:50 - 13:00

Fixed Target opportunities at the (HL-)LHC
Jean-Philippe Lansberg
Albenz+Machuca Room, Granada Conference Center
13:00 - 13:20

Discussion

Albenz+Machuca Room, Granada Conference Center
13:20 - 13:30

Theory challenges for Heavy Ion physics
Urs Wiedemann
Albenz+Machuca Room, Granada Conference Center
09:00 - 09:20

Discussion

Albenz+Machuca Room, Granada Conference Center
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Heavy Ion collisions at (HL-)LHC
Johanna Sachtje
Albenz+Machuca Room, Granada Conference Center
09:30 - 09:50

Discussion

Albenz+Machuca Room, Granada Conference Center
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Strong interaction physics at future e+e- colliders
Nestor Armesto Perez
Albenz+Machuca Room, Granada Conference Center
10:10 - 10:20

Discussion

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Emerging facilities around the world for strong interaction physics
Tatyana Gadzyuk
Albenz+Machuca Room, Granada Conference Center
11:15 - 11:45

Discussion

Albenz+Machuca Room, Granada Conference Center
11:45 - 12:00

Synergies with astroparticle, nuclear and neutrino physics
Tengy Xing
Albenz+Machuca Room, Granada Conference Center
12:00 - 12:20

Discussion

Albenz+Machuca Room, Granada Conference Center
12:20 - 12:30

Strong interaction physics at future e+e- colliders
Uta Klein
Albenz+Machuca Room, Granada Conference Center
12:30 - 12:50

Discussion

Albenz+Machuca Room, Granada Conference Center
12:50 - 13:00

What strong Interaction physics can one do with the LHC after the HL-LHC?
Daniel Boos
Albenz+Machuca Room, Granada Conference Center
12:50 - 13:15

Open discussion

Albenz+Machuca Room, Granada Conference Center
12:55 - 13:15
two broad roles for QCD

QCD in service of broad particle physics goals (Higgs, EW, DM/BSM, etc.)

QCD as a fascinating subject in its own right
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 \( \gtrsim 5\% \)
  • Limited by PDFs, QCD corrections
• Perturbative QCD as analysis tool
  • Jet substructure techniques
  • Data-driven background predictions

Status: March 2019

ATLAS Preliminary
Run 1,2 \( \sqrt{s} = 5, 7, 8, 13 \) TeV
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
to maximally exploit HL–LHC
QCD theory is workhorse of LHC experiments

Papers commonly cited by ATLAS and CMS (since 2017) as of 2019-02-13, excluding self-citations; all papers > 0.2

(red papers ≡ QCD)
Need for precision @ HL-LHC

- illustrated in the case of Higgs physics
- theory uncertainty (PDF + strong coupling + missing higher orders) dominates in 7/9 channels
- this is **with the assumption of reduction by x2 in today’s theory uncertainties**
- depending on channel, it can be the uncertainties for the signal or the background that dominates.

ATLAS and CMS

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Total</th>
<th>Statistical</th>
<th>Experimental</th>
<th>Theory</th>
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<tr>
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<td>1.7</td>
<td>0.8</td>
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<td>1.8</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
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<td>1.5</td>
<td>0.9</td>
<td>2.5</td>
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<tr>
<td>$\kappa_\mu$</td>
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<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>9.8</td>
<td>1.5</td>
<td>0.8</td>
<td>1.5</td>
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**Figure 1.** Projected uncertainties on $\kappa_i$, combining ATLAS and CMS: total (grey box), statistical (blue), experimental (green) and theory (red). From Ref. [2].
In this section we document cross section predictions for a standard model Higgs boson produced through gluon fusion in 27 TeV $pp$ collisions. To derive predictions we include contributions based on perturbative computations of scattering cross sections as studied in Ref. [47]. We include perturbative QCD corrections through next-to-next-to-next-to-leading order (N$^3$LO), electroweak (EW) and approximated mixed QCD-electroweak corrections as well as effects of finite quark masses. The only modification with respect to YR4 [45] is that we now include the exact N$^3$LO heavy top effective theory cross section of Ref. [48] instead of its previous approximation. The result of this modification is only a small change in the central values and uncertainties. To derive theoretical uncertainties we follow the prescriptions outlined in Ref. [47]. We use the following inputs:

- $E_{CM} = 27$ TeV
- $m_t = (162.7 \pm 0.7)$ GeV
- $m_b = (4.18 \pm 0.18)$ GeV
- $m_c = (3.986 \pm 0.986)$ GeV
- $S(m_Z) = 0.118$

All quark masses are treated in the MS scheme. To derive numerical predictions we use the program iHixs [50].

Sources of uncertainty for the inclusive Higgs boson production cross section have been assessed recently in refs. [47, 51, 52, 45]. Several sources of theoretical uncertainties were identified.

- Missing higher-order effects of QCD corrections beyond N$^3$LO ($\delta$(scale)).
- Missing higher-order effects of electroweak and mixed QCD-electroweak corrections at and beyond $O(\delta(\mathcal{S}))$ ($\delta$(EW)).
- Effects due to finite quark masses neglected in QCD corrections beyond NLO ($\delta(t,b,c)$ and $\frac{1}{m_t}$).

Fig. 1: The figure shows the linear sum of the different sources of relative uncertainties as a function of the collider energy. Each coloured band represents the size of one particular source of uncertainty as described in the text. The component $\delta(PDF + \alpha_S)$ corresponds to the uncertainties due to our imprecise knowledge of the strong coupling constant and of parton distribution functions combined in quadrature.
QCD theory anticipated / needed for full exploitation of HL-LHC

(1) Fixed-order / resummed calculations

- Core processes at high accuracy (2→1 and 2→2): 1%, N3LO
- Splitting functions at N3LO (also needed for potential ep machines)
- Complex processes at few percent accuracy
- Accuracy at high p_T
- Technical requirements for NLO multi-particle precision
- Multi-variate analyses / observables: performance and uncertainties
- Non-perturbative effects
- Resummation (incl. SCET)
- Accurate predictions for BSM effects
QCD theory anticipated / needed for full exploitation of HL-LHC

(2) General purpose Monte Carlo event-generator tools

➤ Perturbative improvements for Matching and Merging (e.g. generalisation of approaches for parton shower + NNLO merging,)

➤ Understanding & exploiting relation between parton-shower algorithms and resummation

➤ Phenomenological Models (hadronisation, underlying event, also connects with HI physics, neutrino programmes, low energy QCD, various “beyond colliders” experiments, cosmic-ray physics)
Projected improvements in PDFs & strong coupling

- Plot illustrates use of pseudodata with HL-LHC stats to obtain estimates of expected PDF uncertainties at HL-LHC
- PDF extractions will need to move to N3LO once available
- Strong coupling remains contentious
  - Tensions between different groups' extractions (PDFs, event shapes, and to a lesser extent lattice QCD)
- What ultimate accuracy on 10-15 year timescale?
to maximally exploit proposed future colliders (ee, eh, hh)
future e+e− colliders

- 3-loop and partial 4-loop calculations of Zff vertex for Tera-Z for EW pseudo-observables
- precision for decays, e.g. in Higgs physics and top-quark physics
- new generations of MC programs for QED and EW effects, understanding two-photon physics

<table>
<thead>
<tr>
<th></th>
<th>δΓ_Z [MeV]</th>
<th>δR_l [10^{-4}]</th>
<th>δR_b [10^{-5}]</th>
<th>δ sin^{2/4}_eff θ [10^{-6}]</th>
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<tbody>
<tr>
<td>Present EWPO theoretical uncertainties</td>
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<tr>
<td>EXP-2018</td>
<td>2.3</td>
<td>250</td>
<td>66</td>
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<td>TH-2018</td>
<td>0.4</td>
<td>60</td>
<td>10</td>
<td>45</td>
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<td>EWPO theoretical uncertainties when FCC-ee will start</td>
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<tr>
<td>EXP-FCC-ee</td>
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<tr>
<td>TH-FCC-ee</td>
<td>0.07</td>
<td>7</td>
<td>3</td>
<td>7</td>
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</tbody>
</table>

Table 1: Comparison for selected precision observables of present experimental measurements (EXP-2018), current theory errors (TH-2018), FCC-ee precision goals at the end of the Tera-Z run (EXP-FCC-ee) and rough estimates of the theory errors assuming that electroweak 3-loop corrections and the dominant 4-loop EW-QCD corrections are available at the start of FCC-ee (TH-FCC-ee). Based on discussion in [2].
future pp colliders

- combination of higher energies and luminosities will continue to push potential for precision

- need for precision will extend to high transverse momenta → requires improved treatment of EW corrections, including mixed QCD-EW effects

- very high-multiplicity final states, possibly involving multiple scales → needs understanding of regions of validity of perturbation theory, interplay with parton showers, etc., including for EW objects
PDFs: Still work to do for FCC...

- Still large PDF uncertainties in pp at 100 Teraelectronvolts in key (x,Q^2) regions:

- FCC-ep required to reach O(1%) uncertainty for σ(W,Z,H) at FCC-pp

from David d’Enterria’s EPPSU talk
The ep Physics at the Energy Frontier
and unfold hadron sub-structure for LHC and FCC-hh unambiguously

from Uta Klein’s EPPSU talk

New ep colliders beyond HERA c.m.s.

Extensions of both x and Q^2 ranges are crucial for pp experiments and HEP theory developments;

HERA established the validity of pQCD down to x > 10^{-4} (DGLAP) due to a very high lever arm in Q^2:

→ high luminosity colliders with high c.m.s. energy of 1.3 – 3.5 TeV
High-precision gluon & quark jet studies (FCC-ee)

- Exploit FCC-ee $H(gg)$ as a "pure gluon" factory:
  $H \rightarrow gg$ (BR~8% accurately known) provides $O(100,000)$ extra-clean digluon events.

- Multiple handles to study gluon radiation & $g$-jet properties:
  - Gluon vs. quark via $H \rightarrow gg$ vs. $Z \rightarrow qq$
    (Profit from excellent $g,b$ separation)
  - Gluon vs. quark via $Z \rightarrow bbg$ vs. $Z \rightarrow qq(g)$
    ($g$ in one hemisphere recoiling against 2-$b$-jets in the other).
  - Vary $E_{\text{jet}}$ range via ISR: $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow jj(\gamma)$
  - Vary jet radius: small-$R$ down to calo resolution

- Multiple high-precision analyses at hand:
  - BSM: Improve $q/g/Q$ discrimination tools
  - pQCD: Check $N^n$LO antenna functions. High-precision QCD coupling.
  - non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs? Leading $\eta$'s, baryons?

from David d’Enterria’s EPPSU talk

LH angularities

$H \rightarrow gg$
Proton-proton collisions at 100 TeV provide unique conditions to produce & study highly-boosted objects: top, W, Z, H, $R_{BSM}(jj)$,... Resolving small angular dijet sep. $\Delta R \approx 2M(jj)/p_T(j)$.

Jet substructure: key to separate dijets from QCD & (un)coloured resonance decays, e.g. $R_{10-TeV} \rightarrow tt, qq, gg, WW$.

Diffs. in MC generators for quark vs. gluon jets (& jet radius).

Also unique multijet ($N>>>10$) BSM, QCD studies.

From David d’Enterria’s EPPSU talk.
resources & the next generation
incoming / early-stage researchers and subsequent career development

➤ early-stage researchers need recognition for a variety of types of contribution (e.g. including the technical work that simply “makes things work” but that comes neither with glory nor even necessarily papers)

➤ how do we ensure recognition for early-stage researchers working within the medium-sized teams \((O(10))\) researchers) that are increasingly common?

➤ specialisation v. broad training

➤ successful projects need skills that span interface with maths (incl. computer algebra), interface with computing, machine-learning, and a range of physics/pheno applications → **individuals specialise**

➤ at same time we need to ensure future generation can combine specific expertise with broad physics ability within the field
issues of long-term support

➤ funding for projects that last longer than typical funding cycles

➤ support for codes:
  ➤ state-of-the-art physics codes often developed in small groups, but subsequent long-term maintenance & user-support of successful codes often requires substantial dedicated expert time, which can be a substantial burden
  ➤ the “glue” codes (e.g. LHAPDF, HepMC): may not be seen as physics by funding agencies, but support (people/resources) & evolution essential for long-term smooth operation of the field
  ➤ “mechanisms need to be developed to share the effort between event generator projects and their user communities” [Id114] (& we need to ensure that conditions are attractive for those who do this well, e.g. in terms of career recognition)

➤ computing aspects
  ➤ adapting codes to new architectures
  ➤ availability of state-of-the-art hardware (e.g. hundreds of GPUs, very high-memory machines)
  ➤ many university groups can’t afford to keep up with disparate landscape of hardware. How best to share nationally and internationally?
Summary
Advances in QCD theory are essential to exploit HL-LHC and future colliders (and already built into some projections!)

They will involve a wide range of topics, spanning calculations of amplitudes to Monte Carlo event generations, including phenomenological work to connect with data

Theory advances can bring light also on many topics of intrinsic interest in QCD, including proton structure, exotic hadrons, connections with “theorists’s theories” like N=4 SUSY

Continued support of QCD theory is essential for success of European collider programme, and community needs to keep in mind

- recognition of contributions of early-stage researchers as teams grow larger
- funding structure for increasingly long-term theory projects
- positions and career development for individuals who provide essential “support” roles (maintenance of widely used tools, interfacing with & support for users, …)
- computing (access to hardware and expertise)
backup
In this section we document cross section predictions for a standard model Higgs boson produced through gluon fusion in 27 TeV $pp$ collisions. To derive predictions we include contributions based on perturbative computations of scattering cross sections as studied in Ref. [47]. We include perturbative QCD corrections through next-to-next-to-next-to-leading order (N$^3$LO), electroweak (EW) and approximated mixed QCD-electroweak corrections as well as effects of finite quark masses. The only modification with respect to YR4 [45] is that we now include the exact N$^3$LO heavy top effective theory cross section of Ref. [48] instead of its previous approximation. The result of this modification is only a small change in the central values and uncertainties. To derive theoretical uncertainties we follow the prescriptions outlined in Ref. [47].

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PDF PDF4LHC15_nnlo_100 [49]

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Theoretical path for QCD physics: main inputs

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<thead>
<tr>
<th>ID</th>
<th>Description</th>
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<tr>
<td>Id100</td>
<td>Precision calculations for high-energy collider processes</td>
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<td>Id101</td>
<td>Theory Requirements and Possibilities for [ee colliders]</td>
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<td>Id114</td>
<td>MC event generators for HEP physics event simulation</td>
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<td>Id163</td>
<td>Quantum Chromodynamics: Theory</td>
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